Electric Dipole moments (EDM)   and also some Magnetic Dipole Moments (MDM).

I am not an AI. “Beepboop”   But….
On the topic of particle physics theory.
I am sort of a small language model.
Beware!

Surprise, young graduate student!!!!

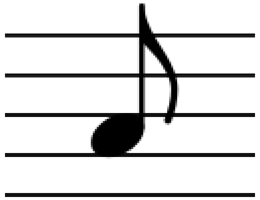
You have just stepped out of a time machine, and you are six years older, and you are now in charge!

What are you going to do?

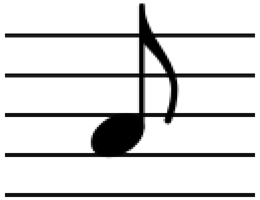
How to think about setting up an impactful, successful dipole moment experimemt. (more generally, a successful precision measurement experiment in service of finding new physics.)

Unfortunately my advice will be six years out of date when you emerge from the machine, but hopefully there will be things you can keep.

“When you kiss me, kiss me like you mean it”



~~“When you kiss me, kiss me like you mean it”~~



Turns out here is not a song with exactly these lyrics, but several kind of like it.

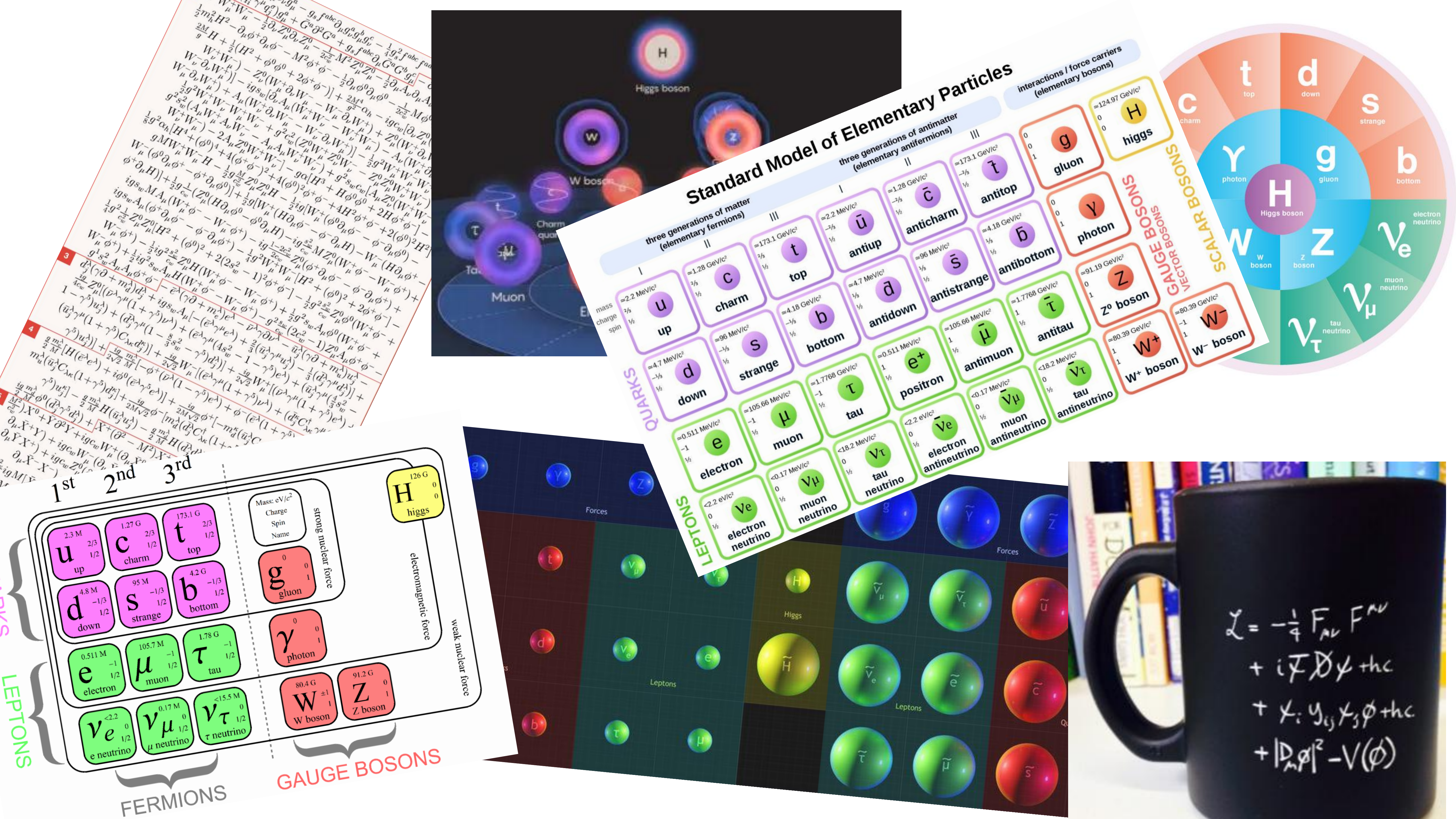
In any case, today’s sermon is, instead:

When you measure it, measure it like you mean it

(that is, not as a routine polite thing to do but instead
with ***intention***,
with ***passion***, and with
the hope that it means something*)*

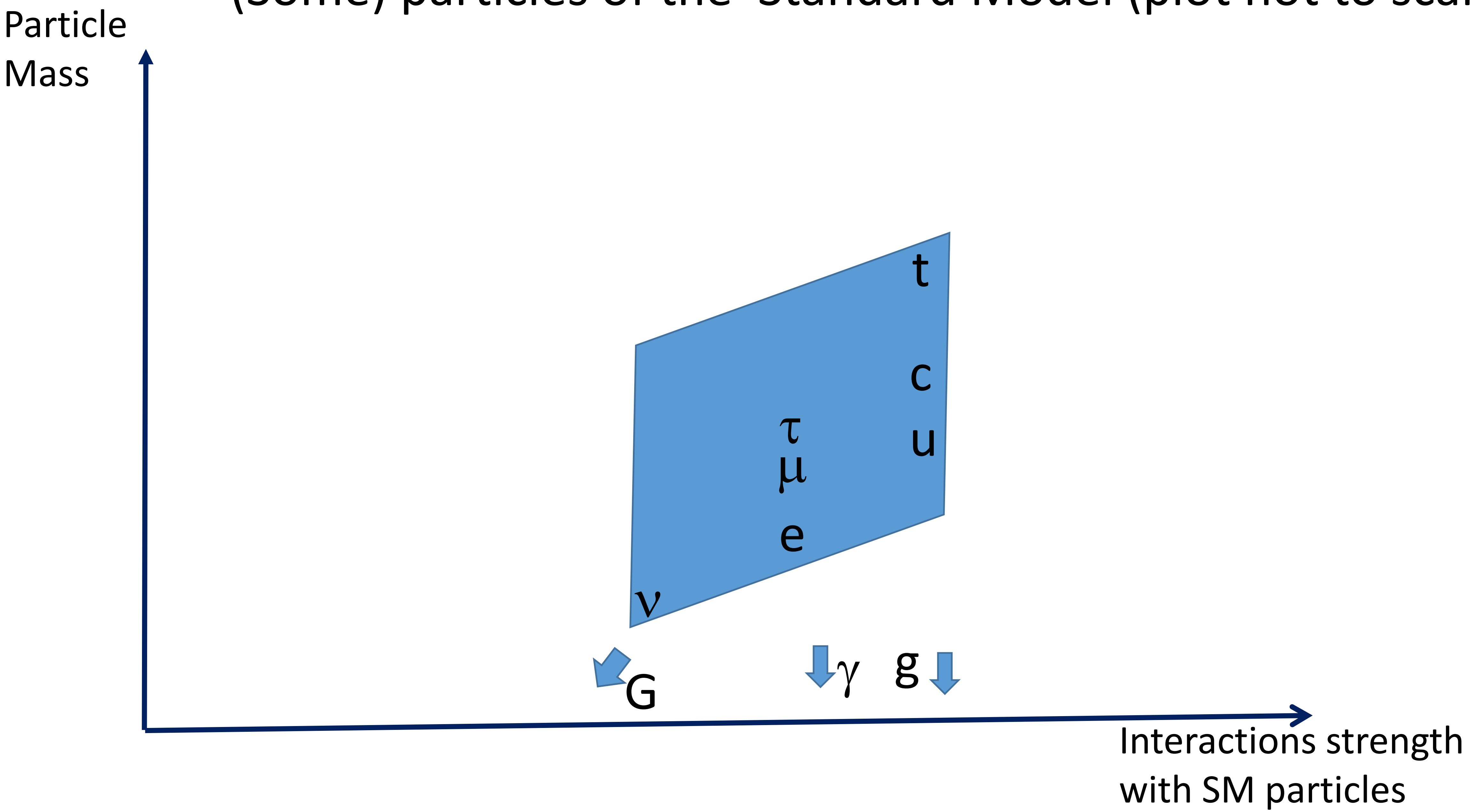
When you measure it, measure it like you mean it

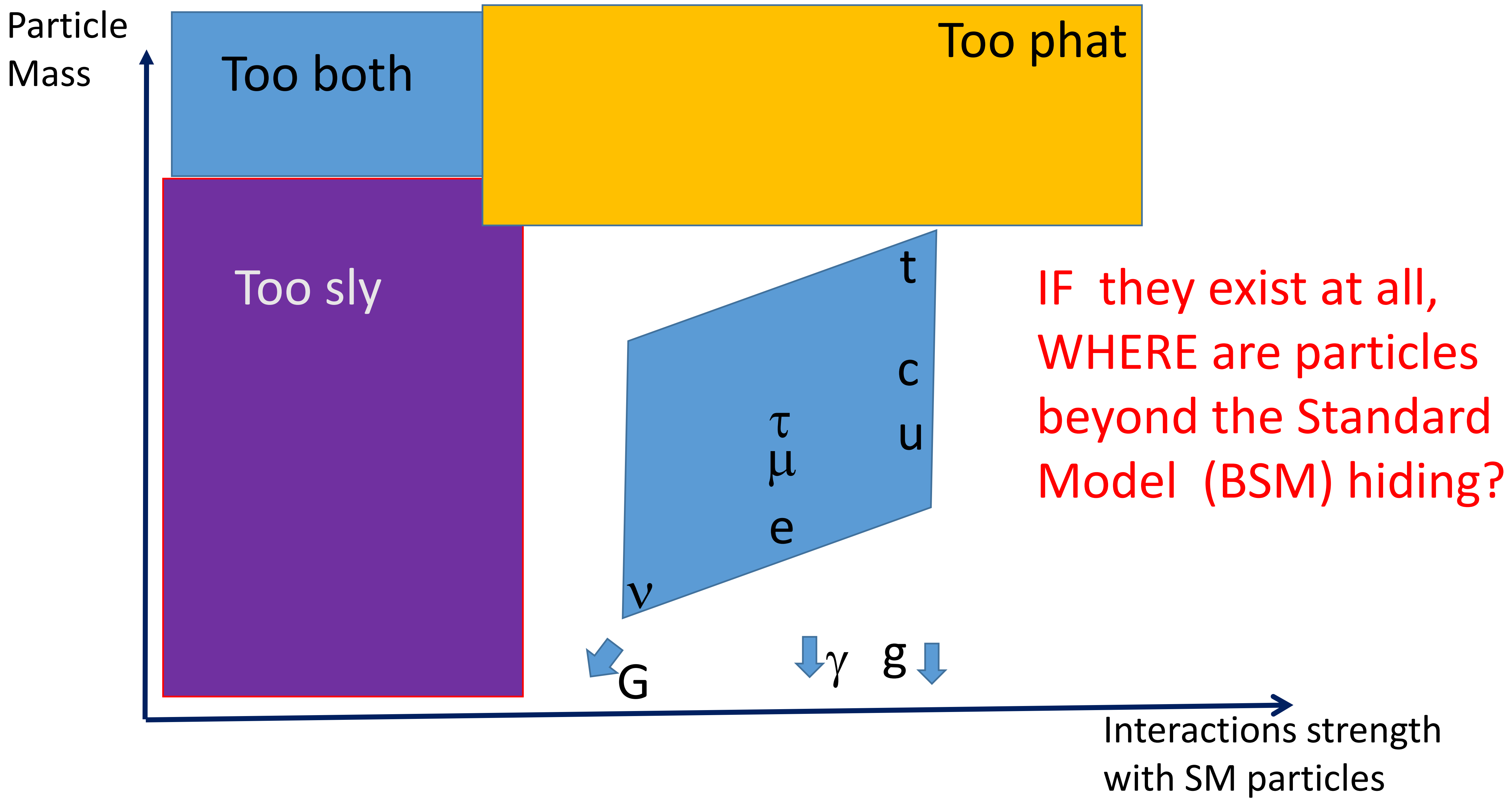
Where are you looking?

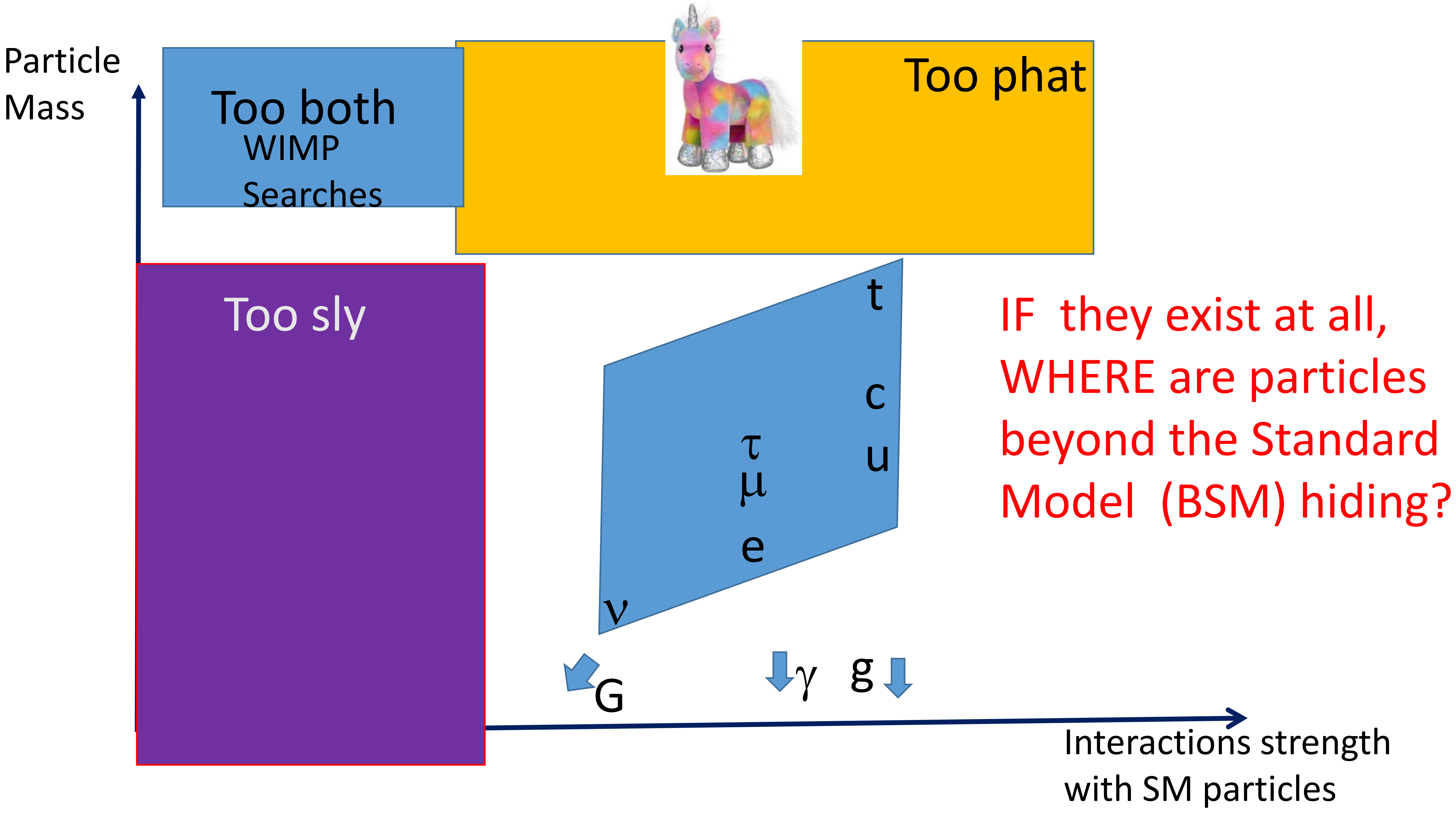


Higgs boson
W
W boson
Charm quark
Tau
Muon
Standard Model of Elementary Particles
three generations of matter (elementary fermions)
three generations of antimatter (elementary antifermions)
interactions / force carriers (elementary bosons)
I
II
III
mass
charge
spin
≈2.2 MeV/c² 2/3 1/2 u up
≈1.28 GeV/c² 2/3 1/2 c charm
≈173.1 GeV/c² 2/3 1/2 t top
≈4.7 MeV/c² −1/3 1/2 d down
≈96 MeV/c² −1/3 1/2 s strange
≈4.18 GeV/c² −1/3 1/2 b bottom
≈0.511 MeV/c² −1 1/2 e electron
≈105.66 MeV/c² −1 1/2 μ muon
≈1.7768 GeV/c² −1 1/2 τ tau
<2.2 eV/c² 0 1/2 νe electron neutrino
<0.17 MeV/c² 0 1/2 νμ muon neutrino
<18.2 MeV/c² 0 1/2 ντ tau neutrino
antiup
anticharm
antitop
antidown
antistrange
antibottom
positron
antimuon
antitau
electron antineutrino
muon antineutrino
tau antineutrino
0 0 1 g gluon
0 0 1 γ photon
≈91.19 GeV/c² 0 1 Z Z⁰ boson
≈80.39 GeV/c² 1 1 W⁺ W⁺ boson
≈80.39 GeV/c² −1 1 W⁻ W⁻ boson
≈124.97 GeV/c² 0 0 H higgs
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS
c charm
t top
d down
s strange
b bottom
γ photon
g gluon
H Higgs boson
W w boson
Z z boson
νe electron neutrino
νμ muon neutrino
ντ tau neutrino
1st
2nd
3rd
2.3 M 2/3 1/2 u up
1.27 G 2/3 1/2 c charm
173.1 G 2/3 1/2 t top
4.8 M −1/3 1/2 d down
95 M −1/3 1/2 s strange
4.2 G −1/3 1/2 b bottom
0.511 M −1 1/2 e electron
105.7 M −1 1/2 μ muon
1.78 G −1 1/2 τ tau
<2.2 0 1/2 νe e neutrino
0.17 M 0 1/2 νμ μ neutrino
<15.5 M 0 1/2 ντ τ neutrino
Mass: eV/c²
Charge
Spin
Name
0 0 1 g gluon
0 0 1 γ photon
80.4 G ±1 1 W W boson
91.2 G 0 1 Z Z boson
126 G 0 0 H higgs
strong nuclear force
electromagnetic force
weak nuclear force
LEPTONS
FERMIONS
GAUGE BOSONS
Forces
Leptons
Higgs
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \chi_i y_{ij} \chi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

(Some) particles of the Standard Model (plot not to scale)




Particle
Mass
Too both
Too phat
Too sly
t
c
u
τ
μ
e
ν
G
γ
g
IF they exist at all,
WHERE are particles
beyond the Standard
Model (BSM) hiding?
Interactions strength
with SM particles


Particle
Mass
Too both
WIMP
Searches
Too phat
Too sly
t
c
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g
IF they exist at all,
WHERE are particles
beyond the Standard
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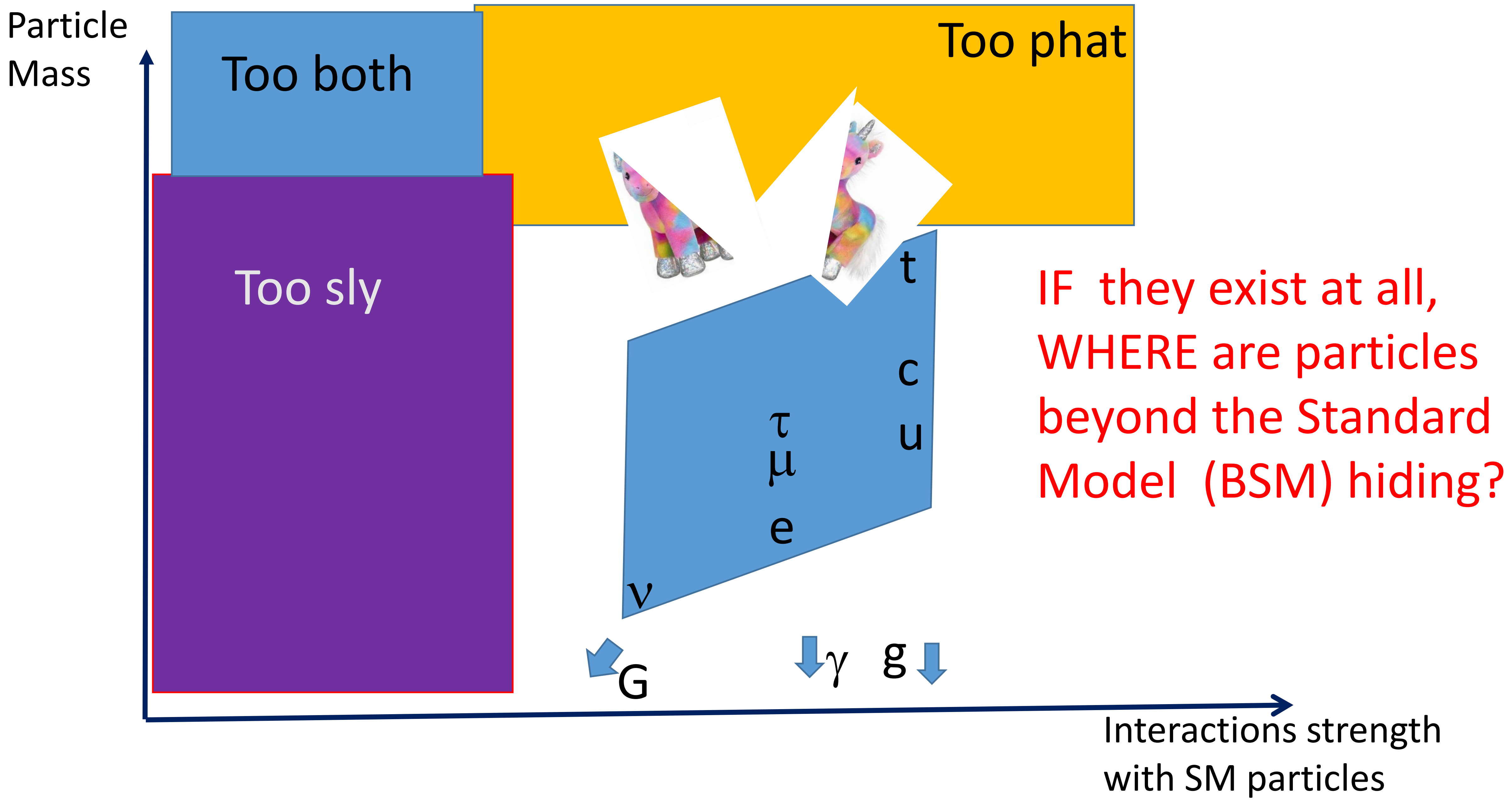
Particle Mass
Too both
Too phat
Too sly
t
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g
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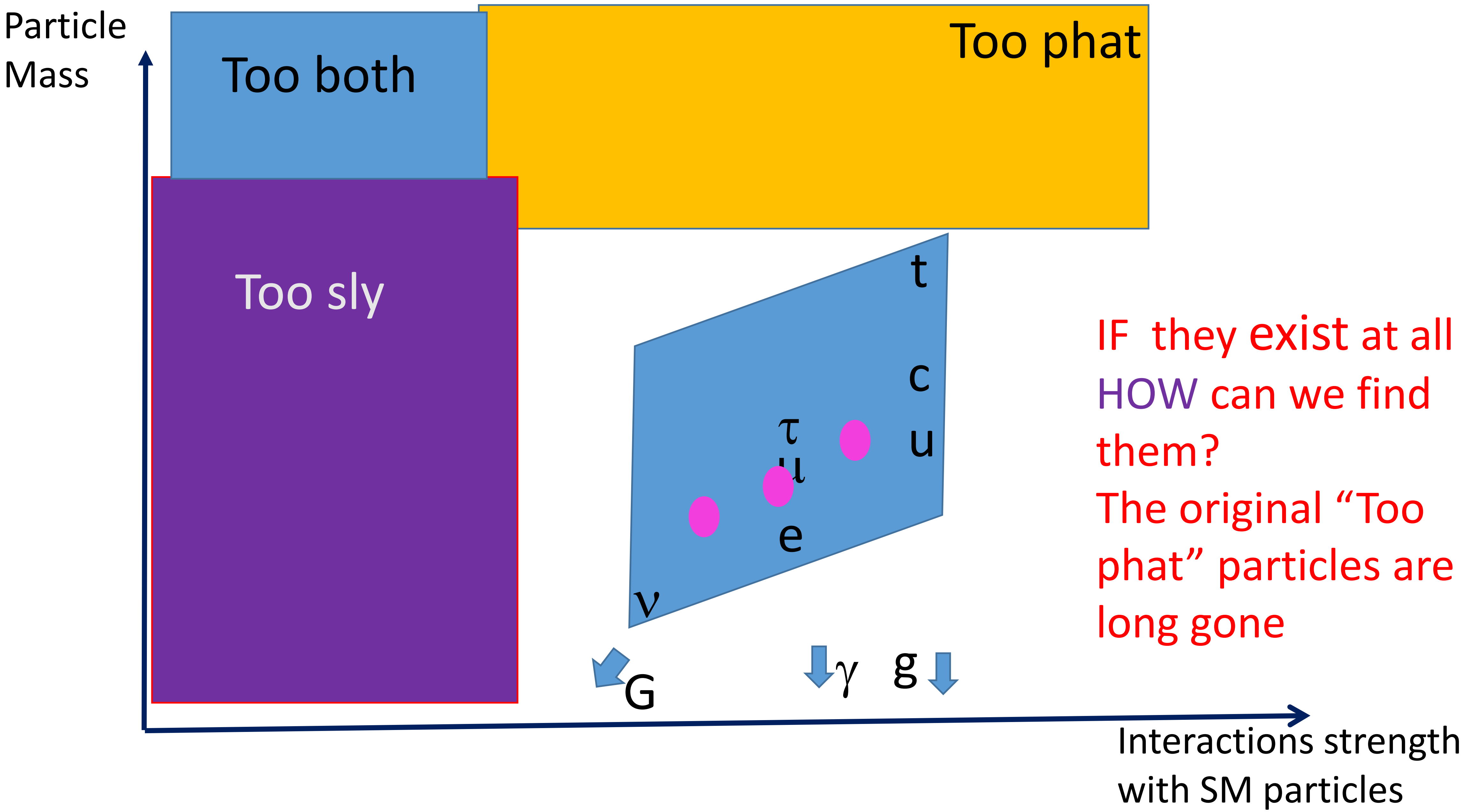
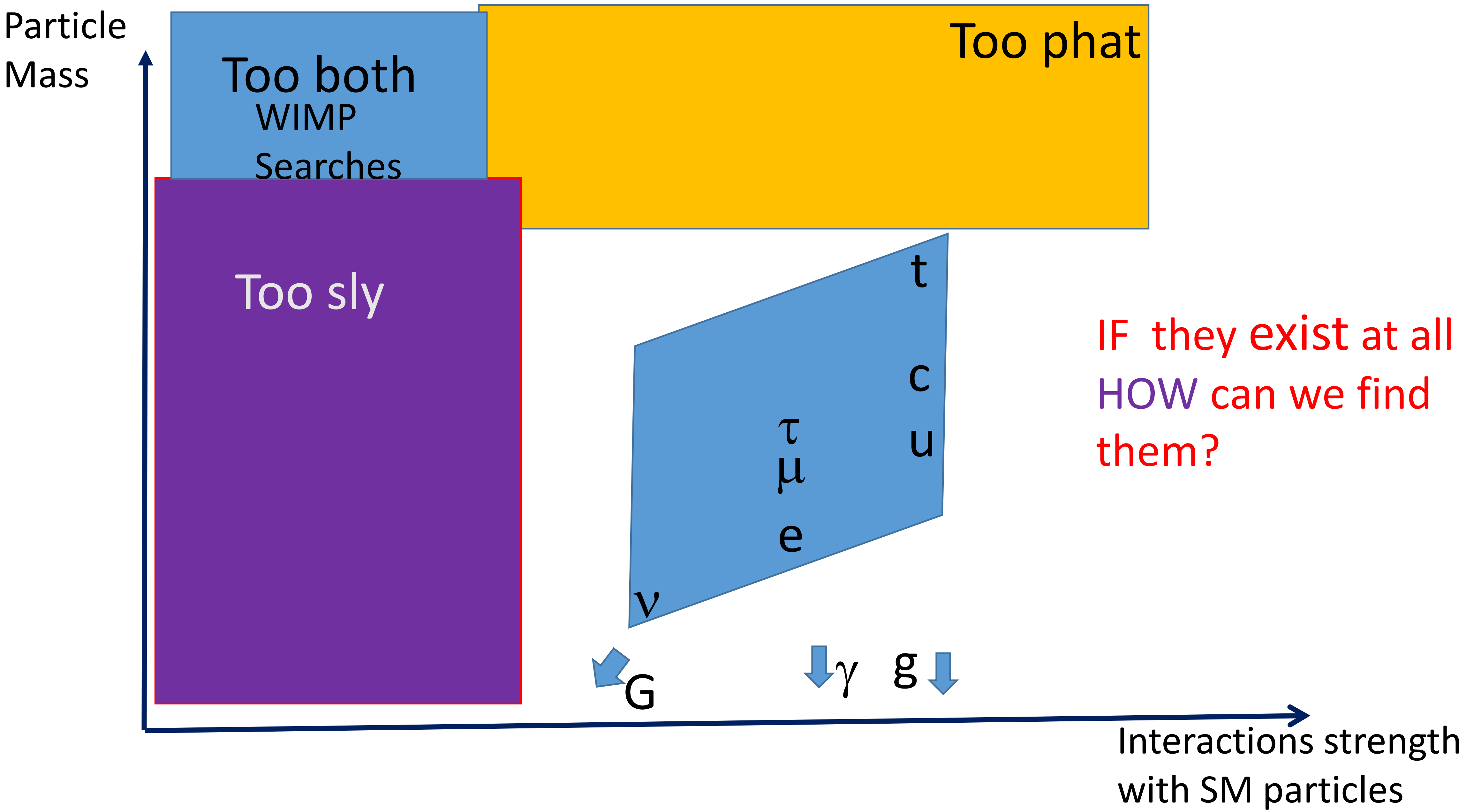
Interactions strength with SM particles


Particle
Mass
Too both
Too phat
Too sly
t
c
u
τ
e
ν
G
γ
g
IF they exist at all
HOW can we find
them?
The original “Too
phat” particles are
long gone
Interactions strength
with SM particles



Particle Mass
Too both
WIMP
Searches
Too phat
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g
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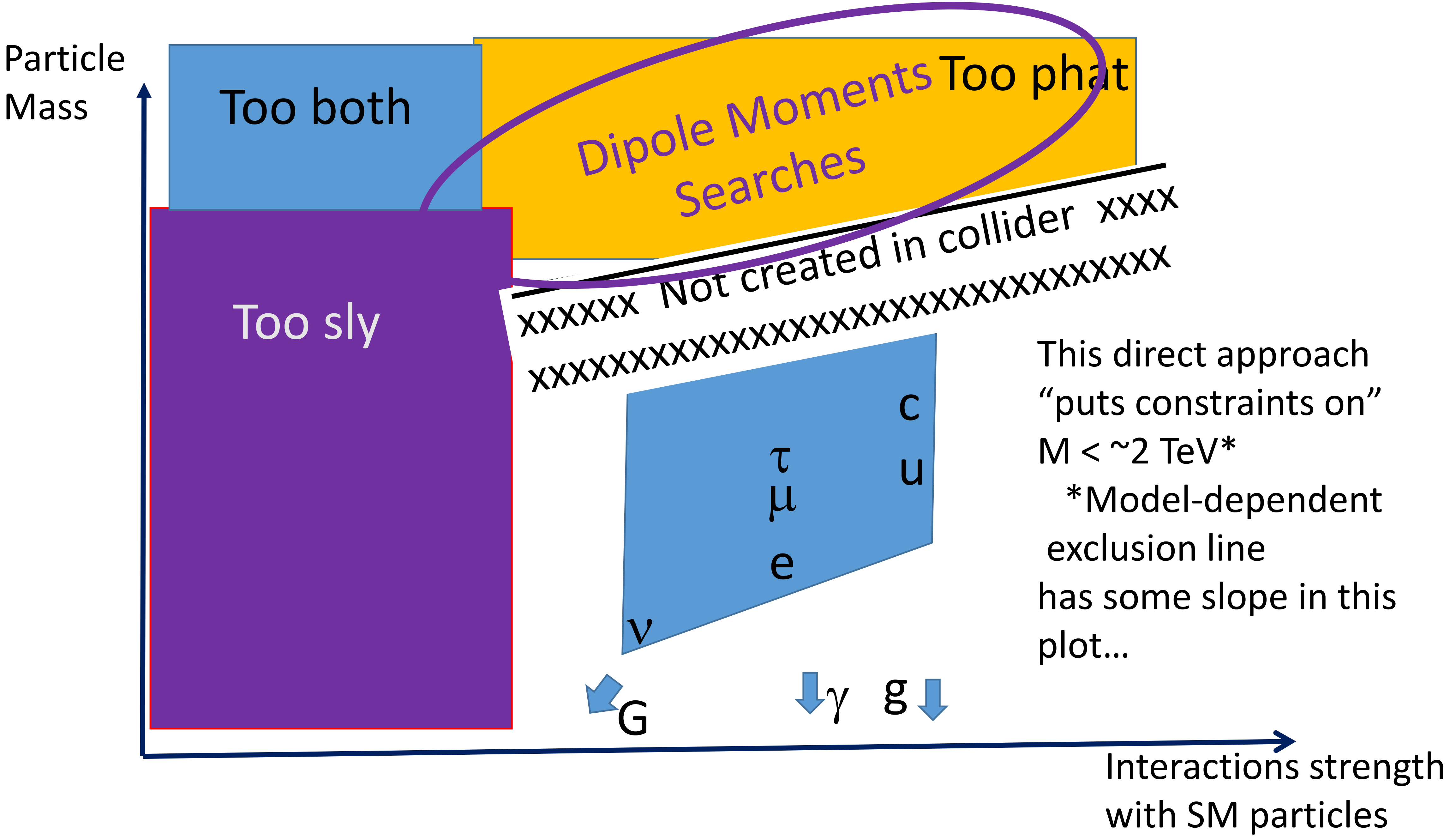
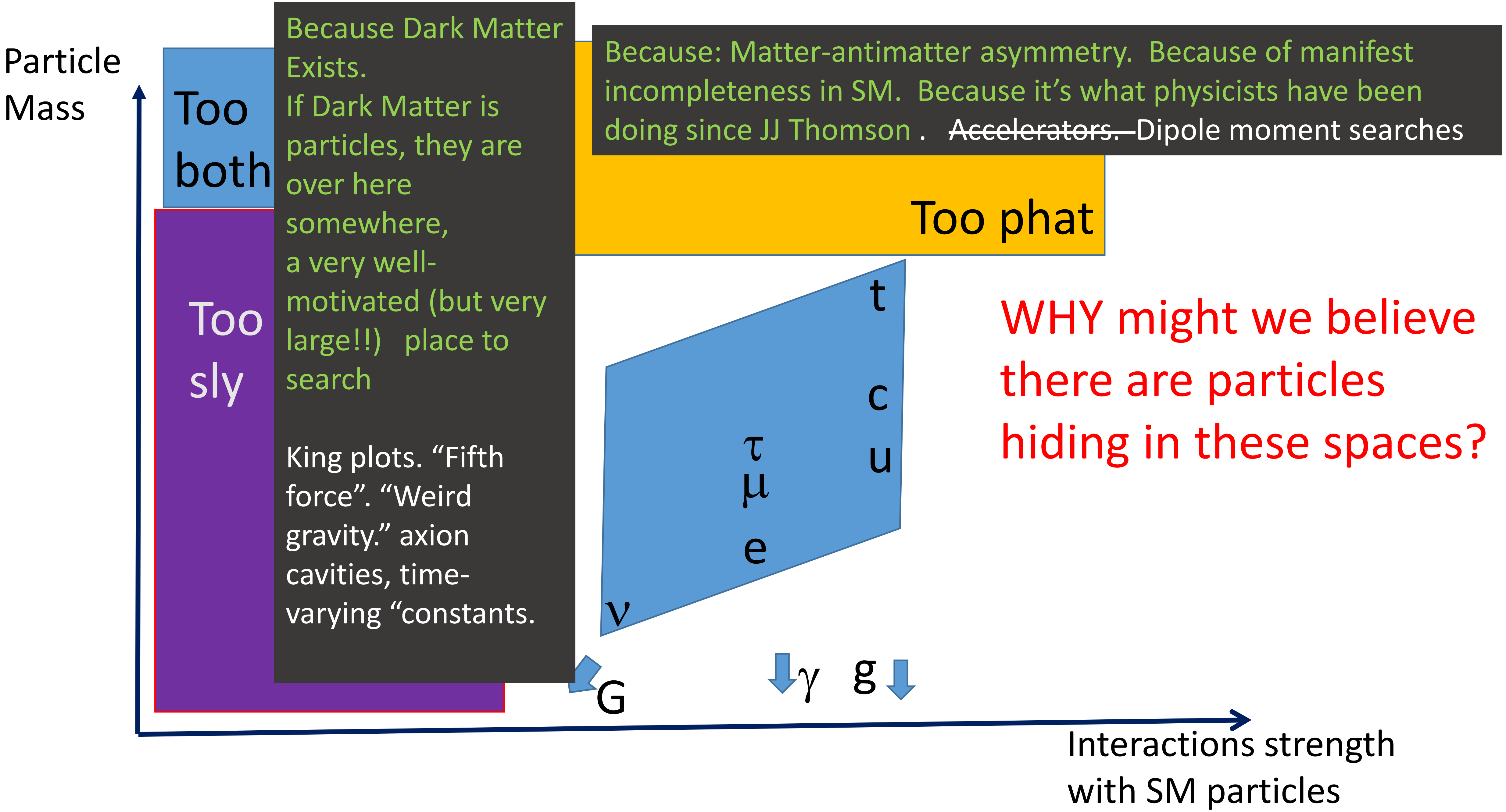
Interactions strength with SM particles


Particle Mass
Too both
Dipole Moments Searches
Too phat
Too sly
xxxxxx Not created in collider xxxx
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
c
u
τ
μ
e
ν
G
γ
g
This direct approach "puts constraints on" M < ~2 TeV*
*Model-dependent exclusion line has some slope in this plot…
Interactions strength with SM particles



Particle Mass
Too both
Too sly
Because Dark Matter Exists.
If Dark Matter is particles, they are over here somewhere, a very well-motivated (but very large!!) place to search
King plots. “Fifth force”. “Weird gravity.” axion cavities, time-varying “constants.
Because: Matter-antimatter asymmetry. Because of manifest incompleteness in SM. Because it’s what physicists have been doing since JJ Thomson . ~~Accelerators.~~ Dipole moment searches
Too phat
t
c
u
τ
μ
e
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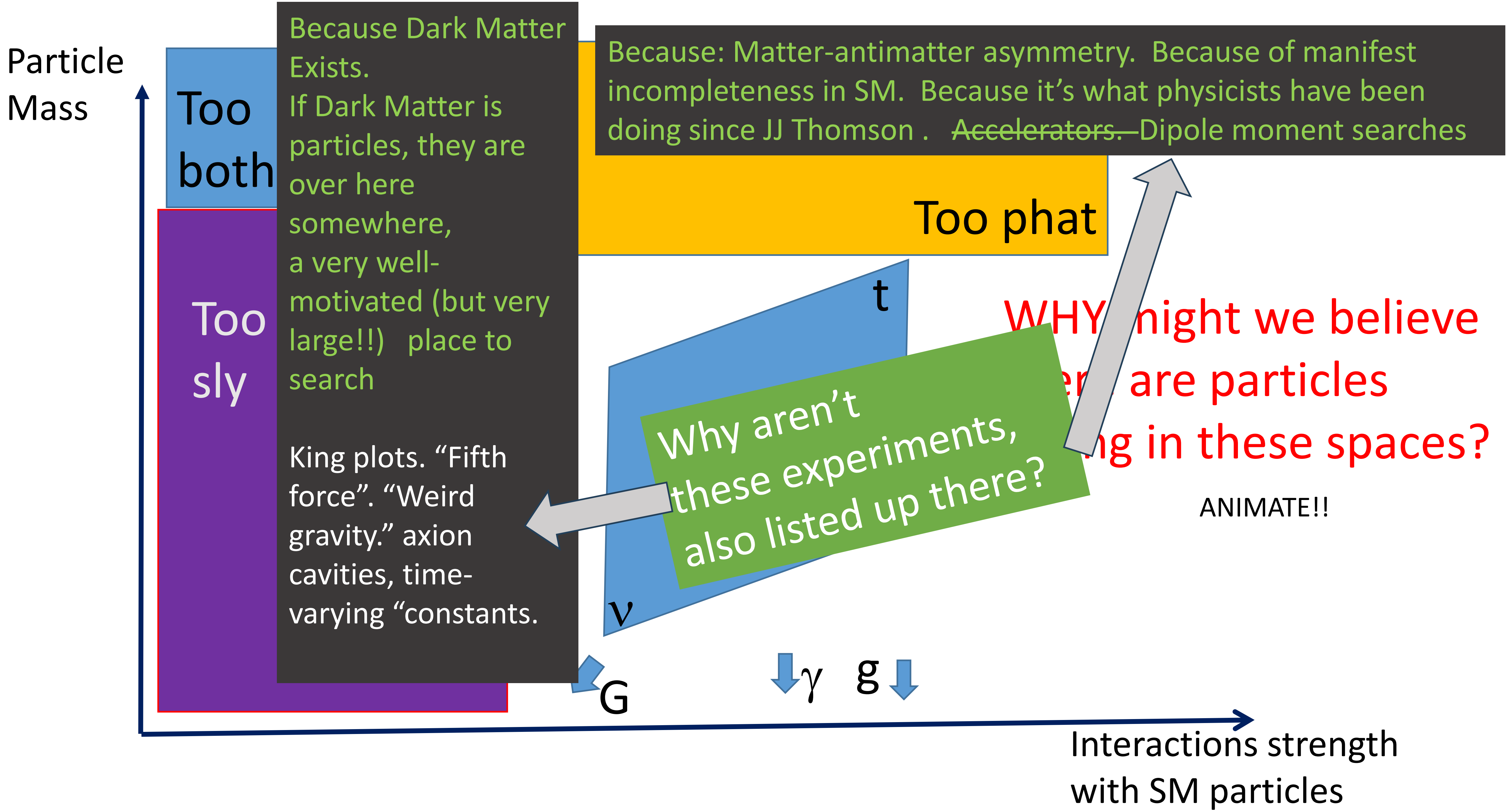
G
γ
g
WHY might we believe there are particles hiding in these spaces?
Interactions strength with SM particles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Too sly
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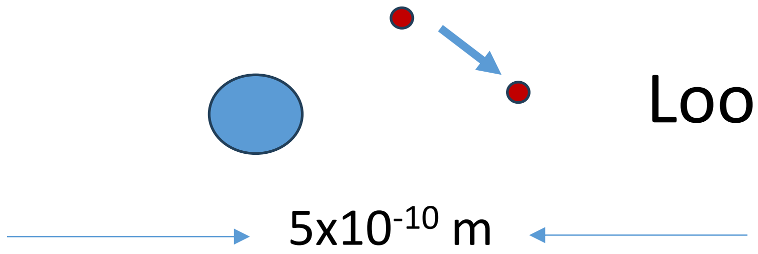
Too phat
t
WHY
might we believe
are particles
ng in these spaces?
Why aren’t these experiments, also listed up there?
ANIMATE!!
ν
G
γ
g
Interactions strength with SM particles

Compton wavelength

Unstable particles can have effects out to reduced Compton wavelength,   hbar/mc

For hypothetical 500 TeV particle, range is 5×10^{-22} m



Looking at anomalies in atomic spectra…

Dipole moment corrections instead arise from shorter-range physics

When you measure it, measure it like you mean it

How will you know if it’s “new?”

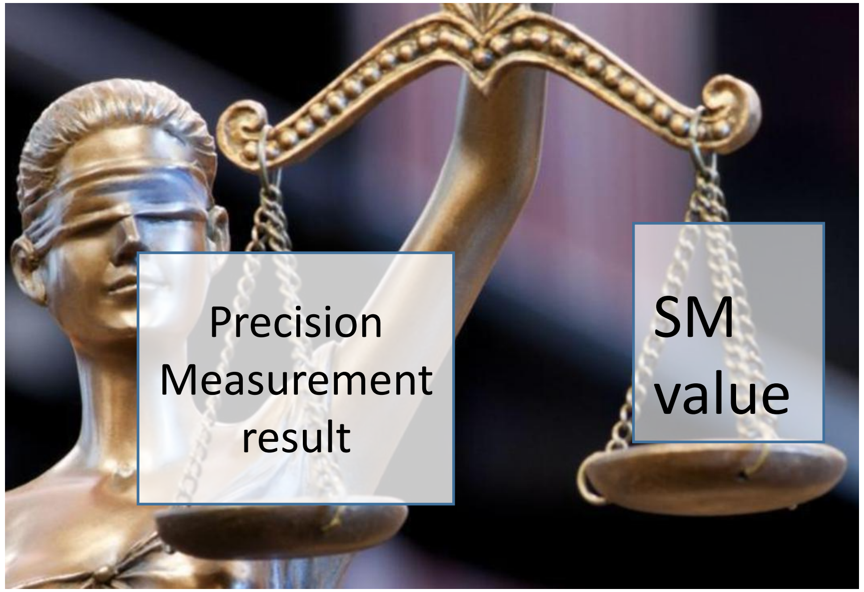
Statue on the Gerechtigkeitsbrunnen,
in Bern Old City, dating to ~1550

Said to be the oldest known artistic representation of metaphorical “blind justice” .

Note:

(i) a metrological apparatus (!) and
(ii) a blindfold – thus unbiased by the social status (or lack of it) of the people appearing before her court.

Aside:
To this day, many precision metrologists follow her example, and collect data “blind”, to avoid being unduly influenced by our own biases towards what makes data more appealing



Precision measurement searches for new physics.
What goes in the right-hand scale pan?

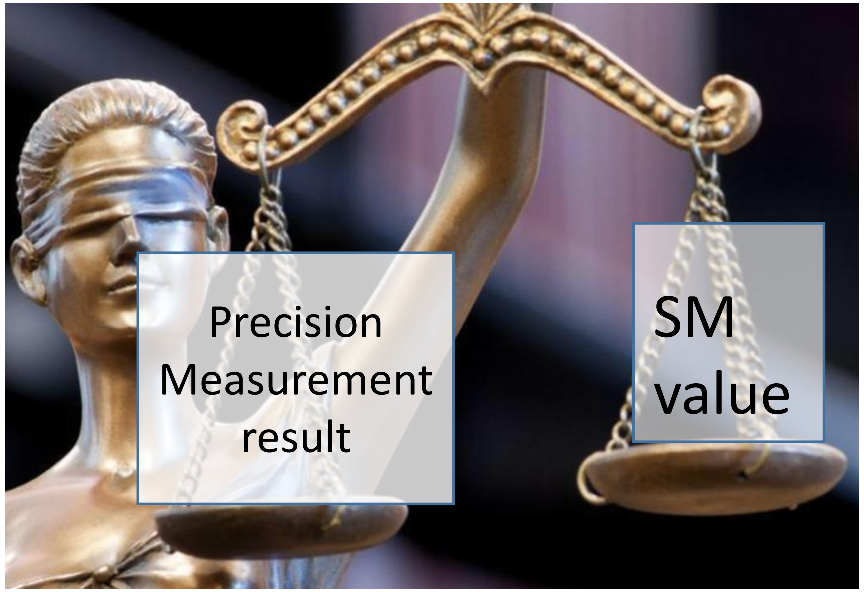
A: Differential measurements. (think "King Plots".)

B: Time-varying measurements. (maybe a subset of differential measurements)

C: Weird force range (gravity, E&M: $\lambda \rightarrow$ inf. Strong, weak forces: $\lambda \rightarrow$ 1 fm. Else: BSM)

D: "Easy" to calculate SM values (only leptons and photons. think "g-2")

E. "Forbidden" effects (Effects that are zero or near-zero in Standard Model)
1. Fractional charge. 2. Spin statistics violation 3. Poltergeist powers 4. Violations of P, T, CPT, CP



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Precision measurement searches for new physics
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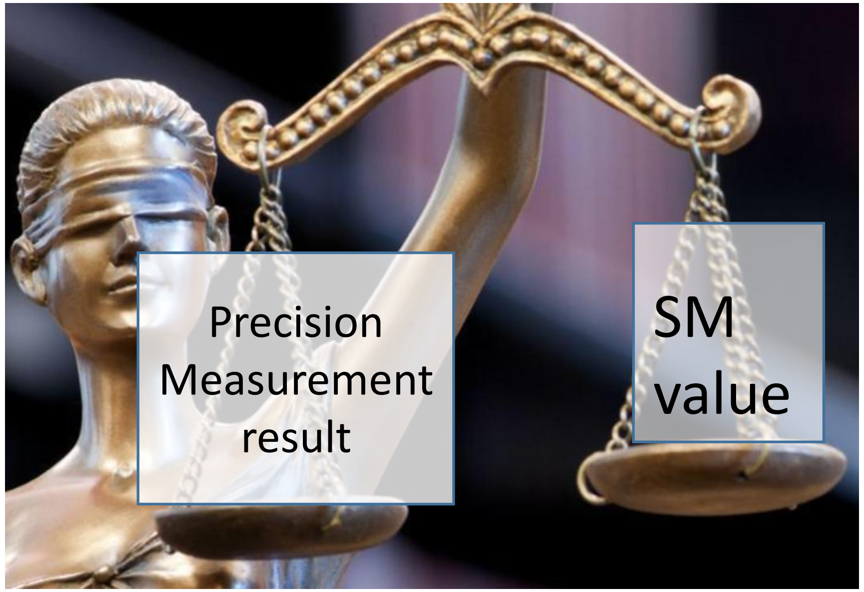

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(only leptons and photons. think “g-2”)

E. “Forbidden” effects 1. Fractional charge. 2. Spin statistics violation 3. Poltergeist powers 4. Violations of P, T, CPT, CP

Magnetic dipole moments “MDM” or “g-2” for fundamental leptons* are calculable to ~part-per-trillion accuracy.
We know what value to put in the right-hand pan!

The standard model predictions for electric dipole moments EDMs, are vey small – they violate CP.
If we measure a nonzero EDM on the left, we can compare it with “0” on the right.

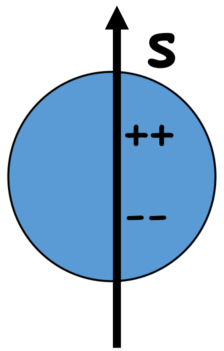
→ We can take good advantage of precision measurements of EDMs and MDMs

*the MDM of composite particles like protons, neutrons, are NOT amenable to precision calculation; less useful for new physics searches

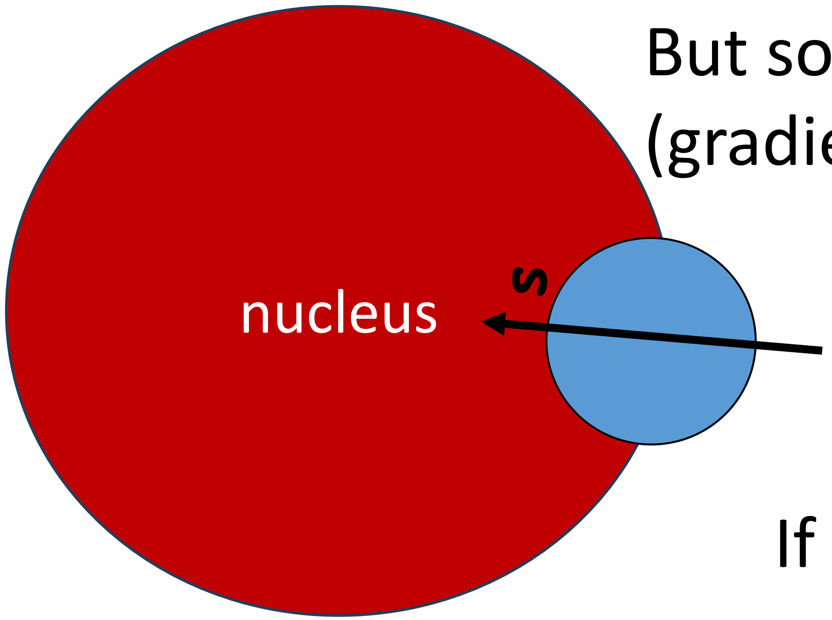
When you measure it, measure it like you mean it

It’s worth spending some time thinking about what you expect.

How to measure MDM, or EDM?



An electric dipole moment of an electron violates T-reversal



But so does a contribution to energy that goes like (gradient of nuclear density) dot (electron spin)

If we see a T-violating effect in our spectroscopy, can we tell which is the underlying mechanism?

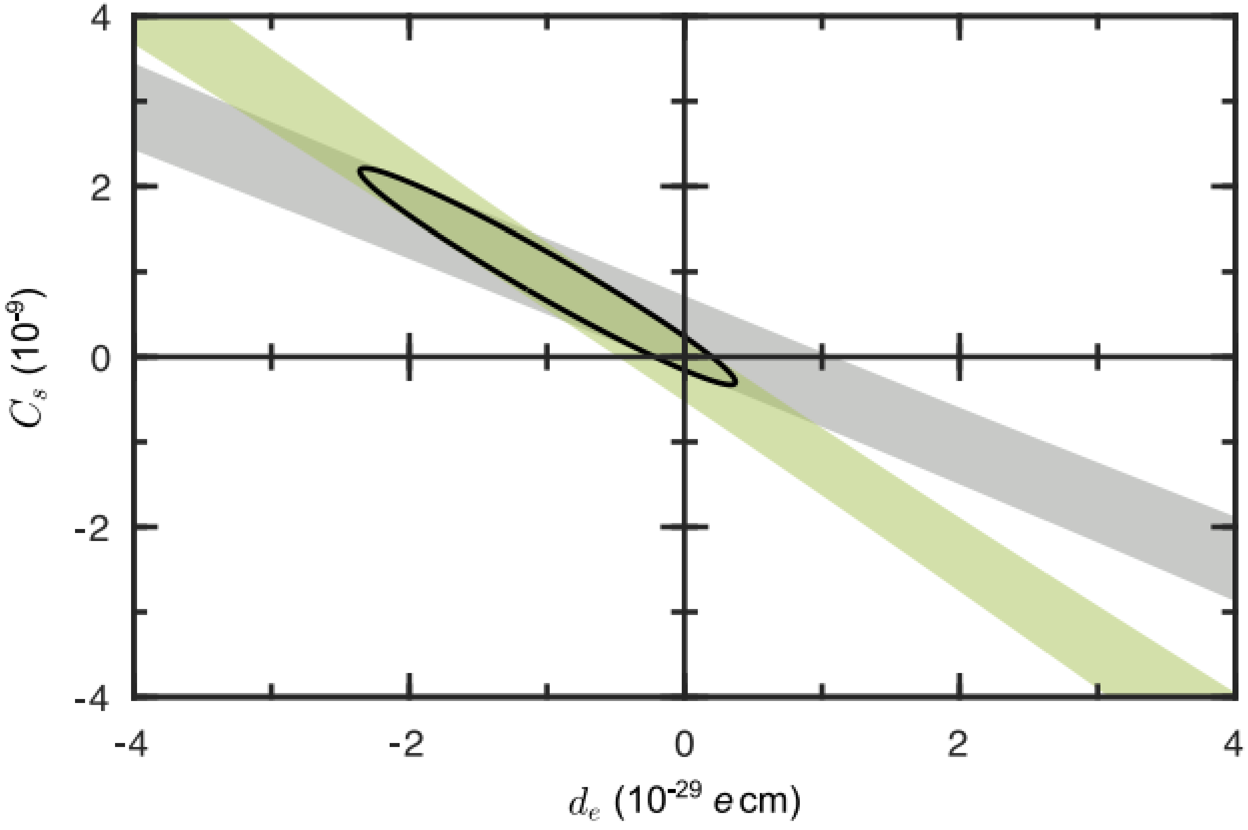


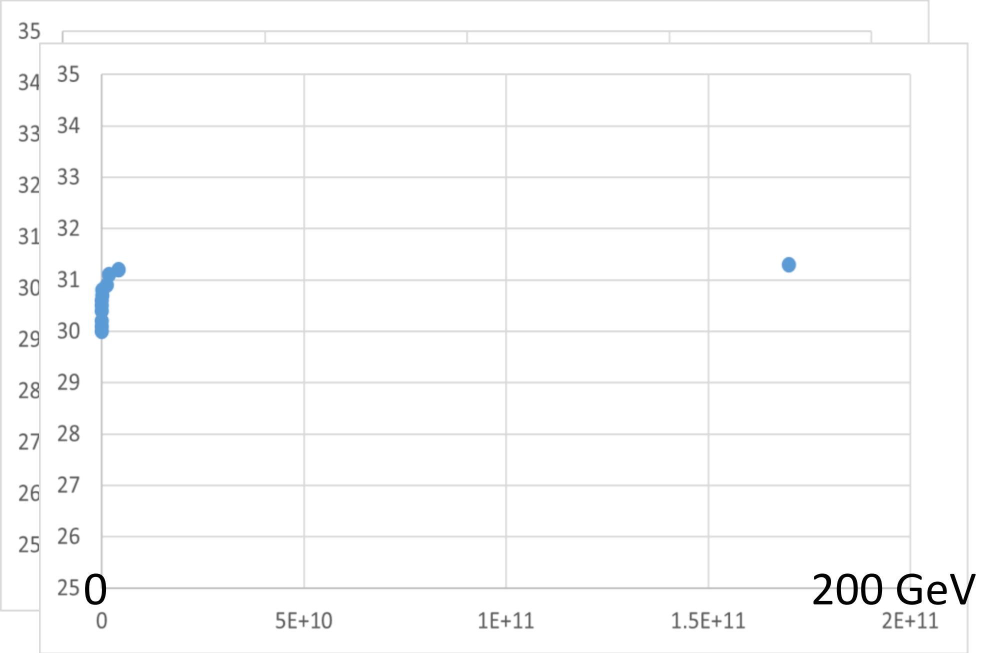
FIG. 5. Fit to results of this work and Ref. [5]. Green and grey shaded regions show 90% confidence bands for HfF^+ and ThO respectively. Ellipse shows 90% confidence limit for global fit. Parameters used in fits are from Ref. [29].

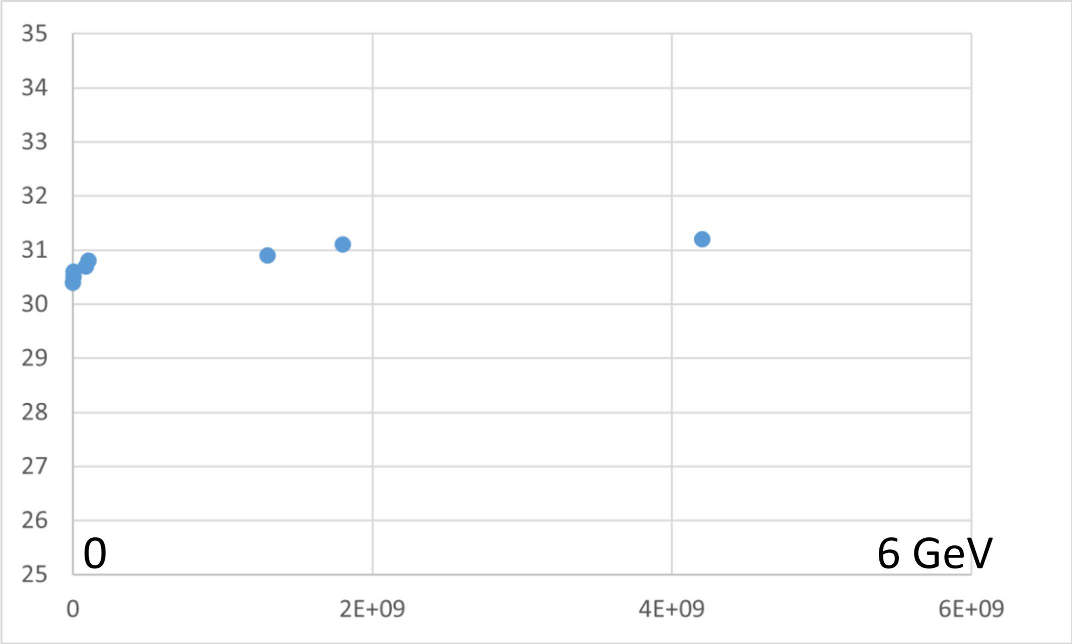
This plot appeared in a paper
I co-authored.
Do I agree with the interpretation?

Yes and no.

“Interpretation” often depends on prior expectations.

For an example, let’s think about fermion masses.


35
34
33
32
31
30
29
28
27
26
25
0
200 GeV
0
5E+10
1E+11
1.5E+11
2E+11


35
34
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31
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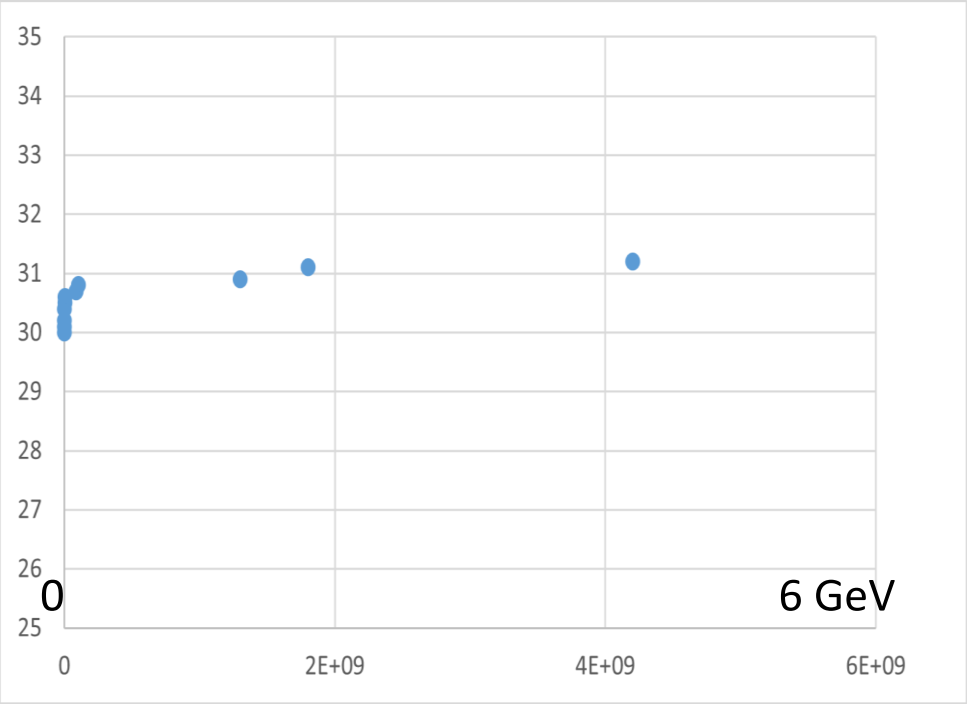
28
27
26
25
0
6 GeV
0
2E+09
4E+09
6E+09


35
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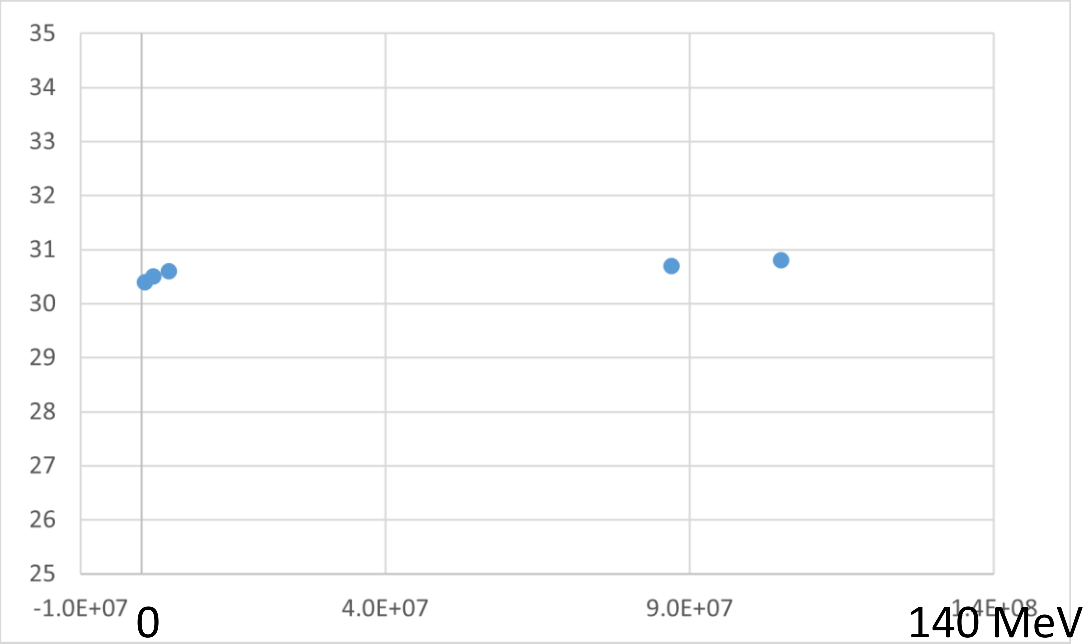
27
26
25
0
6 GeV
0
2E+09
4E+09
6E+09


35
34
33
32
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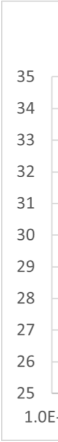
26
25
-1.0E+07
0
4.0E+07
9.0E+07
140 MeV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31
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28
27
26
25


35
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32
31
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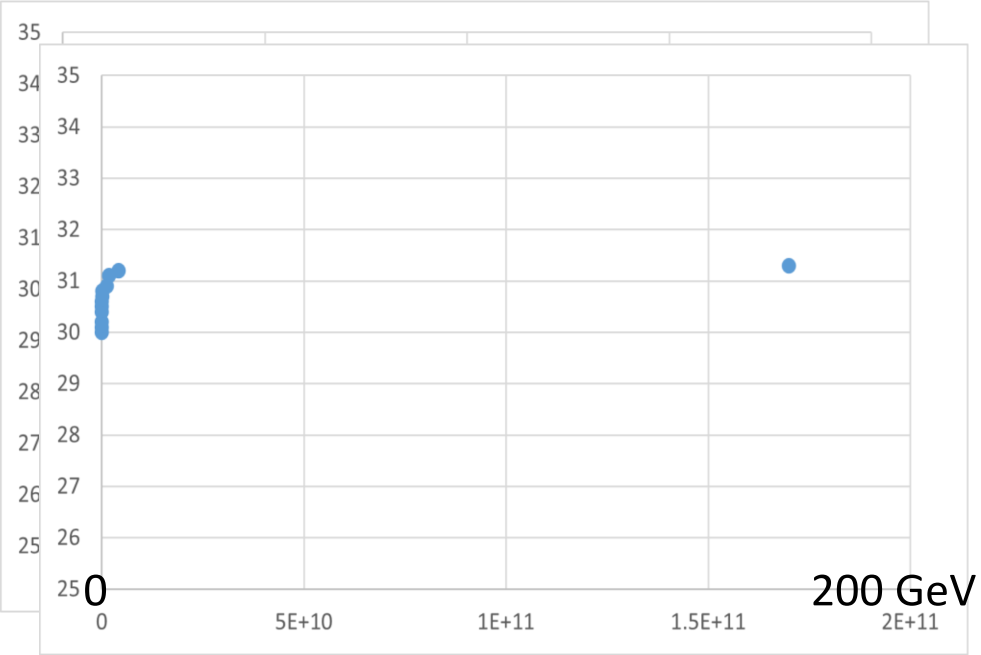
27
26
25
1.0E+04


35
34
33
32
31
30
29
28
27
26
25
0
5E+10
1E+11
1.5E+11
2E+11
0
200 GeV

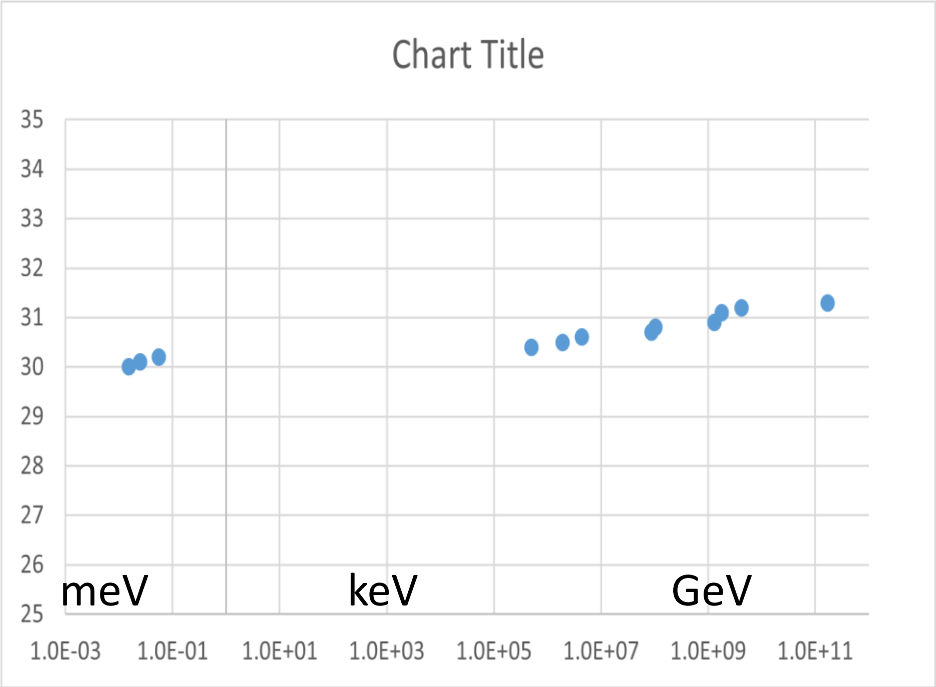
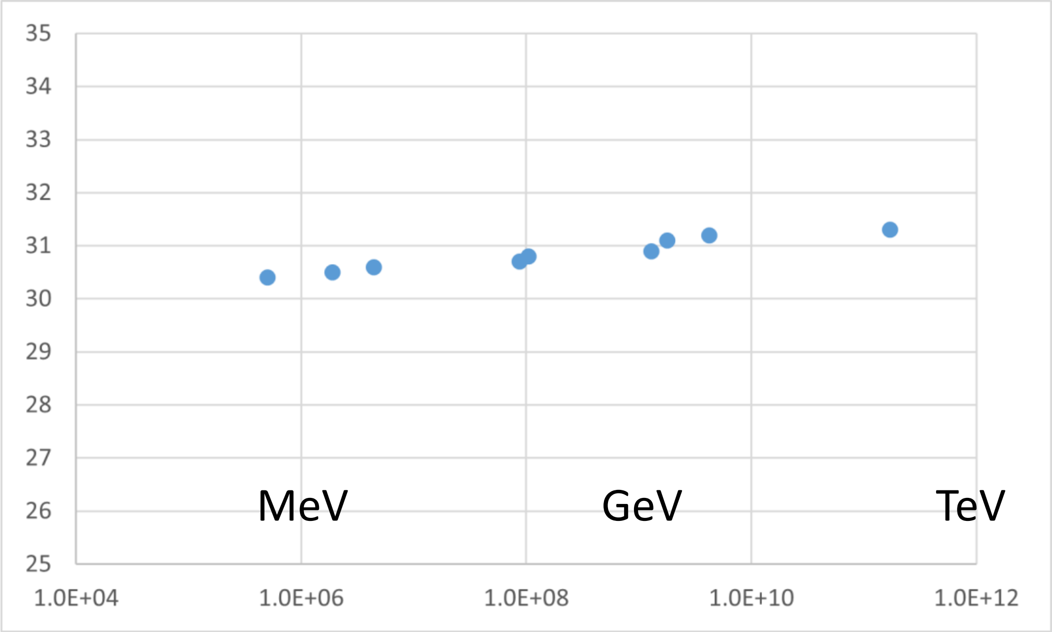


Chart Title
35
34
33
32
31
30
29
28
27
26
25
1.0E-03
1.0E-01
1.0E+01
1.0E+03
1.0E+05
1.0E+07
1.0E+09
1.0E+11
meV
keV
GeV


35
34
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26
25
1.0E+04
1.0E+06
1.0E+08
1.0E+10
1.0E+12
MeV
GeV
TeV

CODATA RECOMMENDED VALUES OF THE FUNDAMENTAL PHYSICAL CONSTANTS: 2014

NIST SP 961 (Sept/2015) Values from: P. J. Mohr, D. B. Newell, and B. N. Taylor, arXiv:1507.07956

A more extensive listing of constants is available in the above reference and on the NIST Physics Laboratory Web site physics.nist.gov/constants.

The number in parentheses is the one-standard-deviation uncertainty in the last two digits of the given value.

Quantity	Symbol	Numerical value	Unit
speed of light in vacuum	c, c_0	299 792 458 (exact)	m s^{-1}
magnetic constant	μ_0	$4\pi \times 10^{-7}$ (exact)	N A^{-2}
		$= 12.566\,370\,614... \times 10^{-7}$	N A^{-2}
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	F m^{-1}
Newtonia			
Planck co			
in			
$h/2\pi$			
in			
elementar			
magnetic			
Josephsor			
von Klitzi			
Bohr mag			
in eV			
nuclear m			
in eV			
fine-struc			
invers			
Rydberg			
energy			
Bohr radi			
Hartree e			
in eV			
electron n			
in			
energy			
electron-n			
electron-p			
electron c			
Compton			
$\lambda_C/2\pi$			
classical e			
Thomson			
electron n			
to Bol			
to nuc			
electron n			
electron g-factor $-2(1+a_e)$	g_e	−2.002 319 304 361 82(52)	
electron-proton magnetic moment ratio	μ_e/μ_p	−658.210 6866(20)	
muon mass in u	m_μ	0.113 428 9257(25)	u
energy equivalent in MeV	$m_\mu c^2$	105.658 3745(24)	MeV
muon-electron mass ratio	m_μ/m_e	206.768 2826(46)	
muon magnetic moment	μ_μ	$-4.490\,448\,26(10) \times 10^{-26}$	J T^{-1}
to Bohr magneton ratio	μ_μ/μ_B	$-4.841\,970\,48(11) \times 10^{-3}$	

Quantity	Symbol	Numerical value	Unit
muon g-factor $-2(1+a_\mu)$	g_μ	−2.002 331 8418(13)	
muon-proton magnetic moment ratio	μ_μ/μ_p	−3.183 345 142(71)	
proton mass	m_p	$1.672\,621\,898(21) \times 10^{-27}$	kg
in u		1.007 276 466 879(91)	u
in eV K^{-1}		$8.617\,3303(50) \times 10^{-5}$	eV K^{-1}
molar volume of ideal gas RT/p ($T = 273.15$ K, $p = 101.325$ kPa)	V_m	$22.413\,962(13) \times 10^{-3}$	m^3 mol^{-1}
Stefan-Boltzmann constant $\pi^2 k^4/60\hbar^3 c^2$	σ	$5.670\,367(13) \times 10^{-8}$	W m^{-2} K^{-4}
first radiation constant $2\pi hc^2$	c_1	$3.741\,771\,790(46) \times 10^{-16}$	W m^2
second radiation constant hc/k	c_2	$1.438\,777\,36(83) \times 10^{-2}$	m K
Wien displacement law constant			

In NIST's codata tables of physical constants, 100 numerical values range from 10^{-34} to 10^{23}

If they were uniformly distributed, 90 of them would be between 6×10^{22} and 6×10^{23}.

Instead, we look at the first digit of the numerical values (ignoring units, and base 10)

27 numbers start with the digit "1"

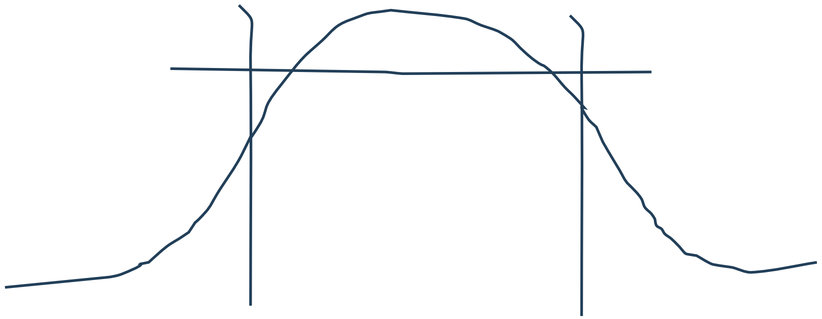
4 numbers start with the digit "8"

ratio is 27/4 = 6.7.

Compare with ln (2/1) / ln (9/8) = 5.9. Just about right.

Why should physical values be distributed roughly uniformly in log space?

If I SUM a large number of random numbers,
the total is normally distributed.



A "normal distribution" is actually very much a "uniform" distribution.

If you know you are looking at a number generated this way, your priors might be "linear uniform".

ie Probability $x_1 < x < x_2 \sim x_2 - x_1$

BUT.
If I take the PRODUCT of a large number of random numbers:

Product= A*B*C*D….*W*X*Y*Z,
then
log product = log A + log B + log C…. + log Z
The log of the product will be a normal distribution,
ie. the product itself is fairly uniformly distributed across a log plot

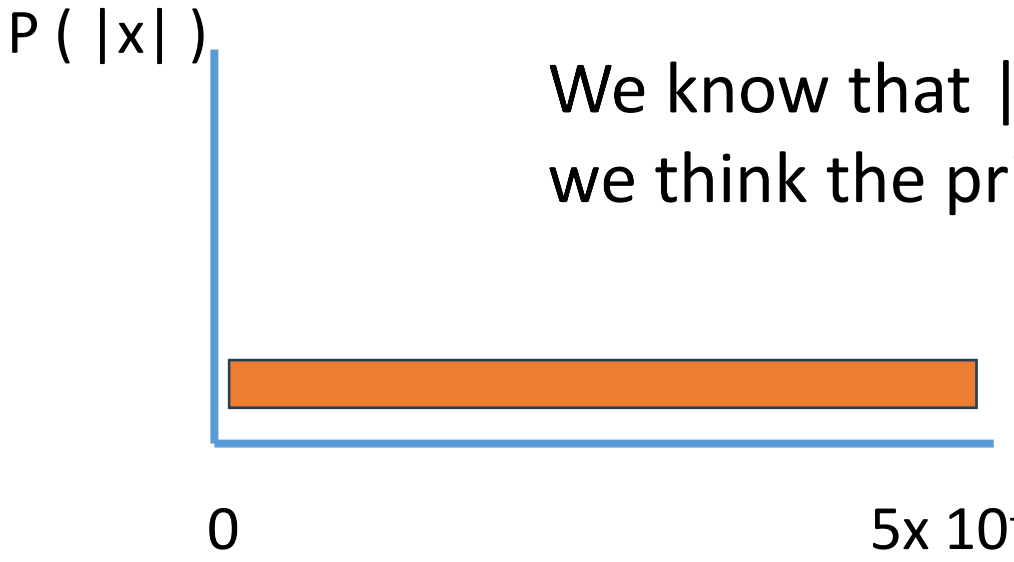
ie Probability $x_1 < x < x_2 \sim \log(x_2 / x_1)$

Benford's Law (in e.g. accounting)

example:
profit of a corporation per year
profit per item* #items sold/store * number of stores city * number cities in a country
Answer varies by may orders of magnitude but the
distribute of first digit follows Benford's Law.

How many "random facts" go into determining the mass or interaction strength of an as yet unobserved particle?

We know that $|d_e| < 5 \times 10^{-30}$ Do we think the priors are uniform on a linear plot?



No one thinks this.

Should we make assumptions about what is true before we measure?

“Should”?

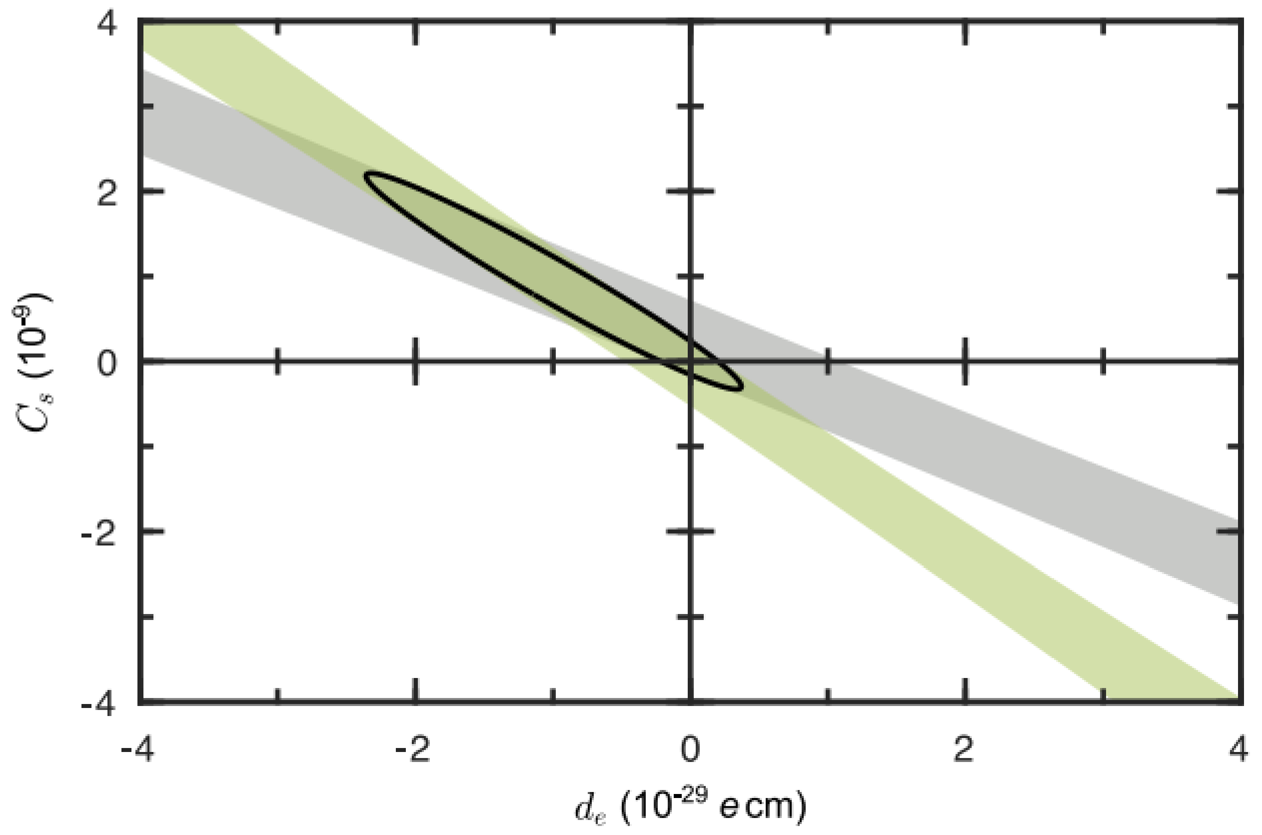
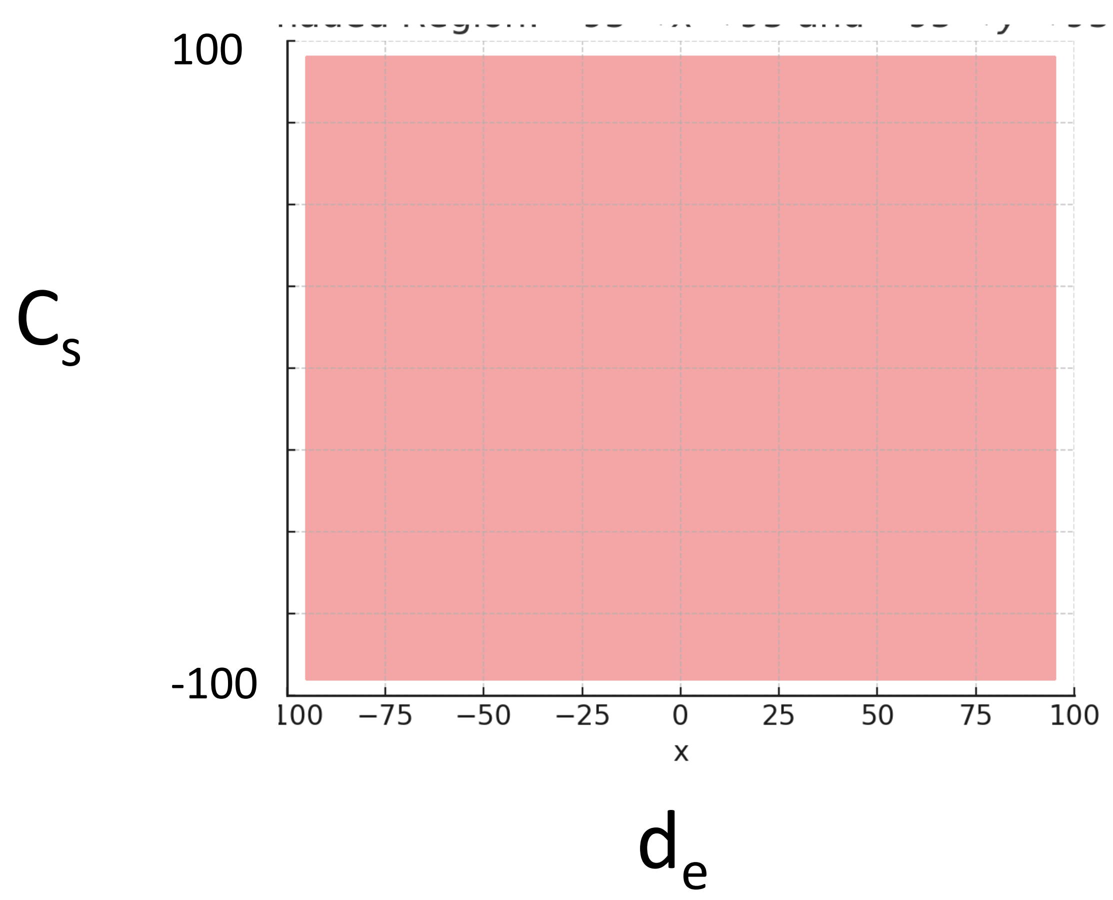
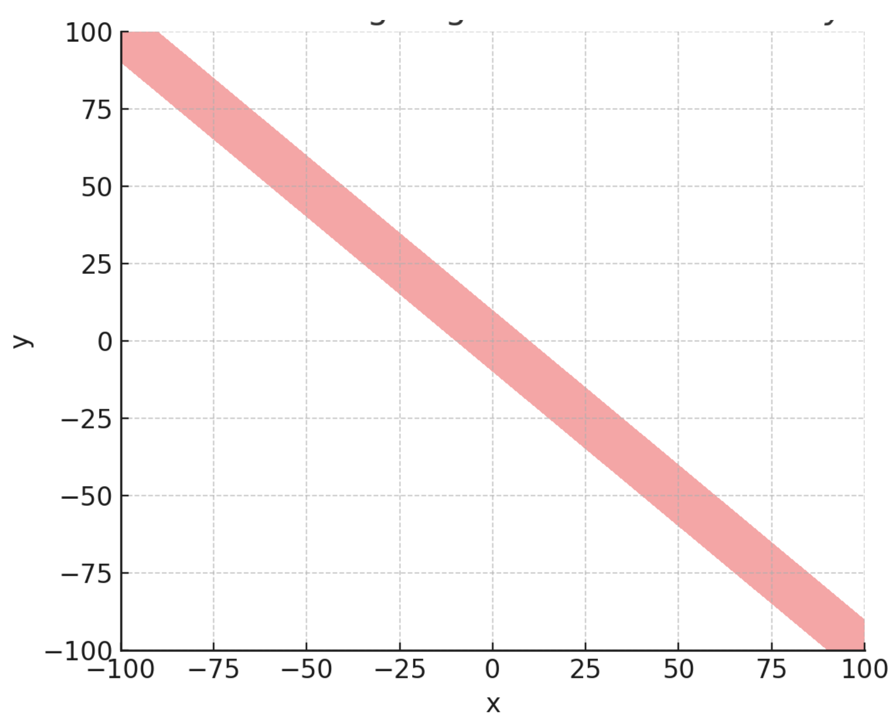
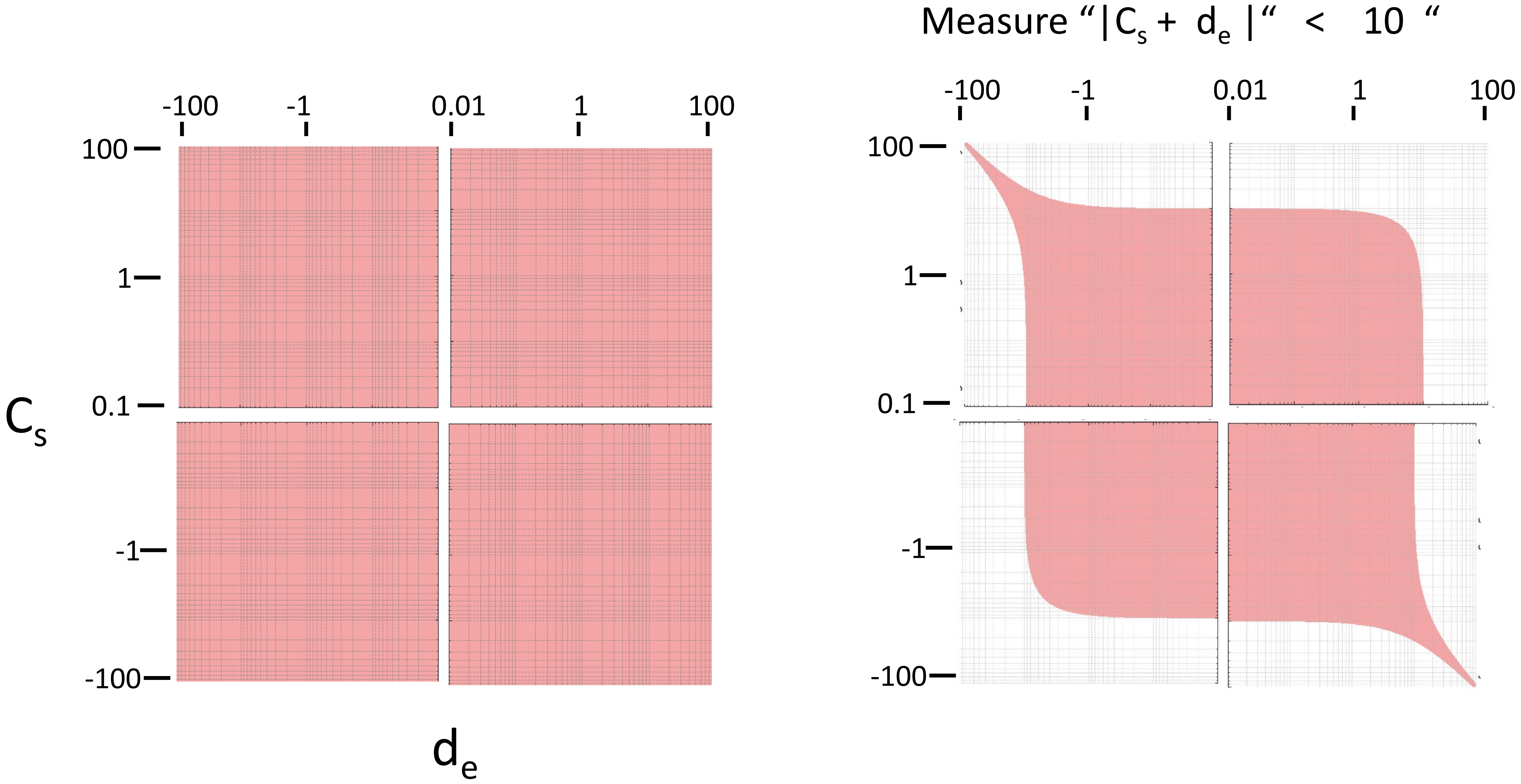


FIG. 5. Fit to results of this work and Ref. [5]. Green and grey shaded regions show 90% confidence bands for HfF^+ and ThO respectively. Ellipse shows 90% confidence limit for global fit. Parameters used in fits are from Ref. [29].

Measure "$|C_s + d_e|$" < 10 "

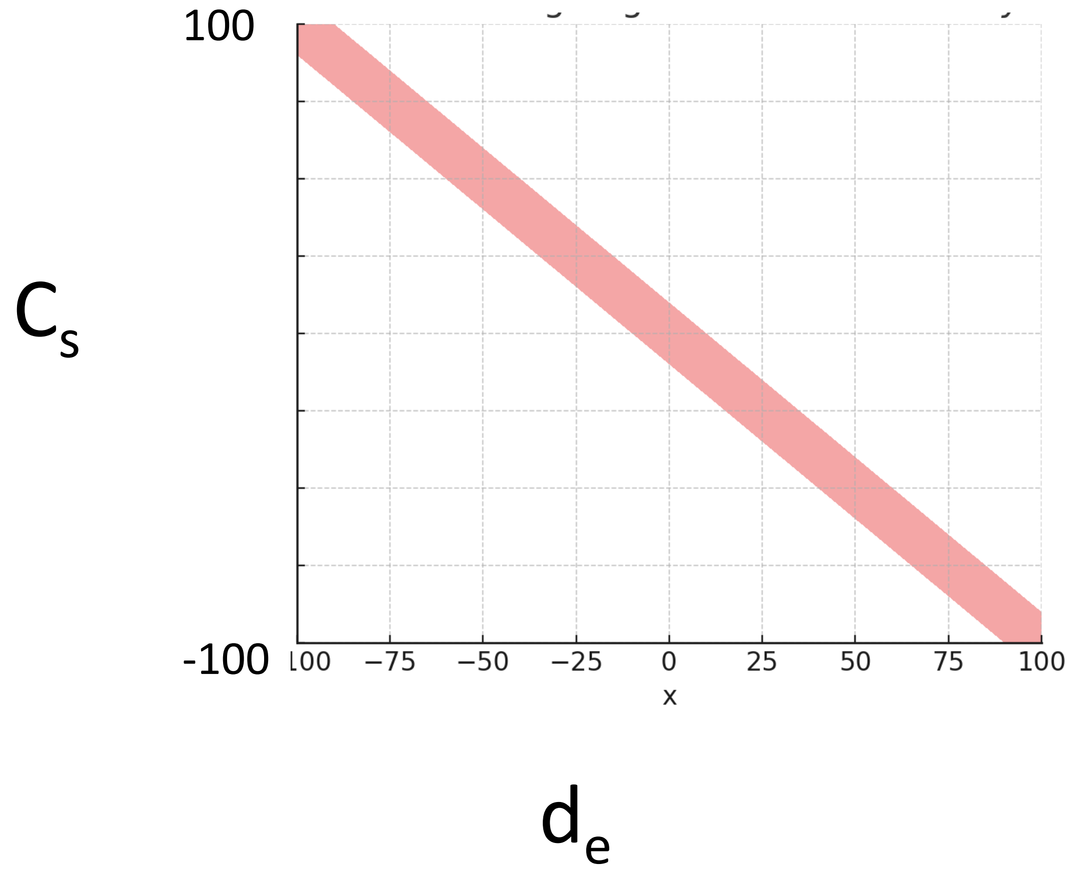






Measure "|C_s + d_e|" < 10 "
-100
-1
0.01
1
100
100
1
0.1
-1
-100
C_s
d_e

Measure "$|C_s + d_e|$" < 10 "



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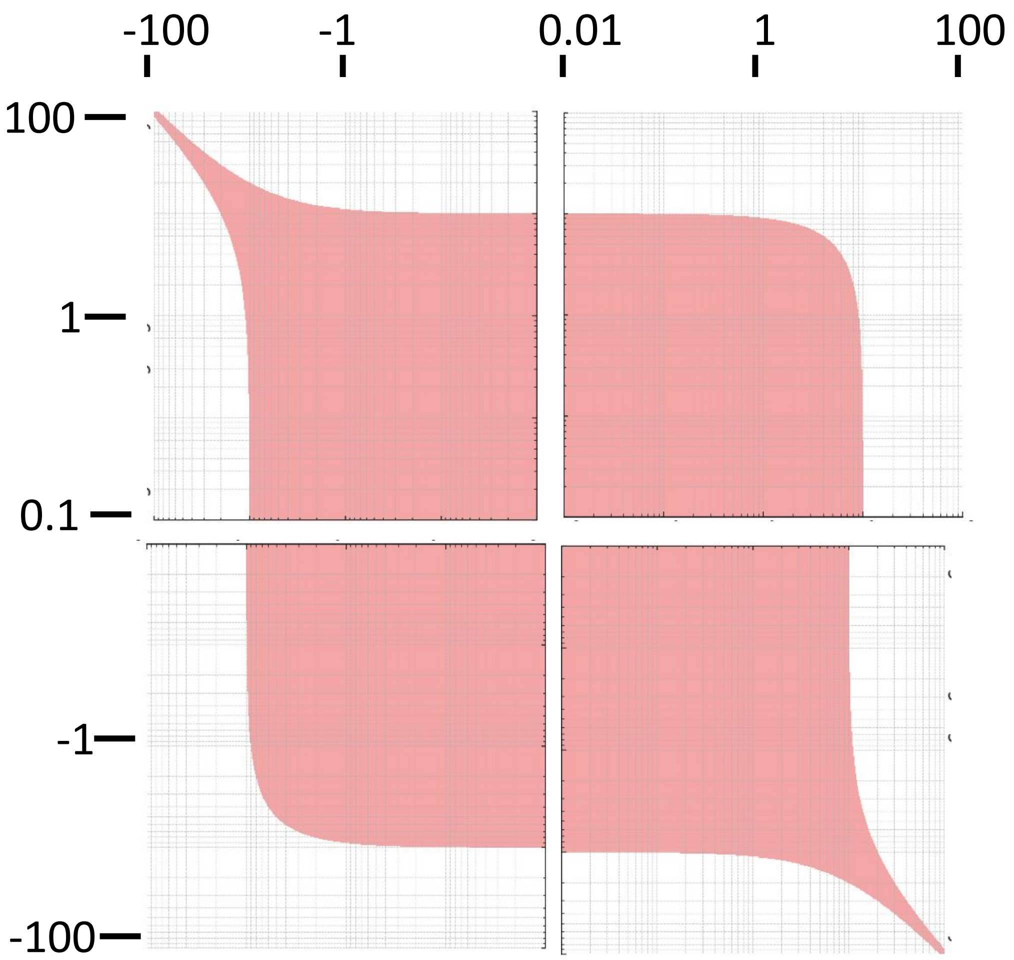
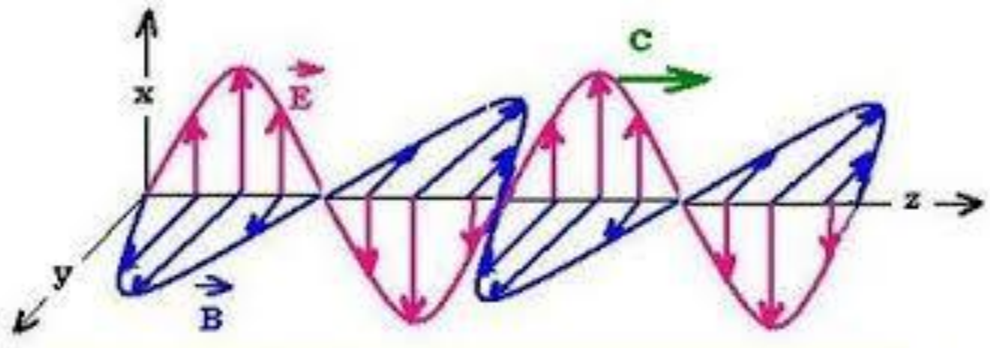


If you believe in your log-uniform priors, you now think

$|C_s| < \sim 10$ AND $|d_e| < 10$

Quick digression on dipole-moment units



Linearly polarized plane electromagnetic wave

The hidden shame of Système International.

E&M wave in a vacuum: |E|=|B|

Dimensions [E] = [B] = [force/charge]

= [(energy/charge)/distance]   e.g., volts/cm

Dimensions [E . d] = [B . μ] = [energy] or [frequency]

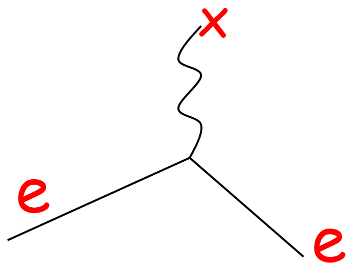
Dimensions of [d] = [μ] = [charge * distance]   e.g. e-cm

So, for instance, 1 μ_B = 1.9 x 10^{-11} e-cm

and 1 Tesla = 3 x 10^6 V-cm

Electric and magnetic dipoles of electron in standard model

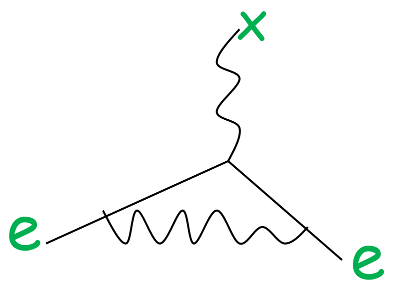
"Tree level"



$\mu = g \; \mu_B \; \mathbf{s}$

$\mathbf{d} = 0$

"One loop "



this diagram adds

$\delta\mu_e = \alpha/\mathrm{pi}$

$\delta d_e = 0$

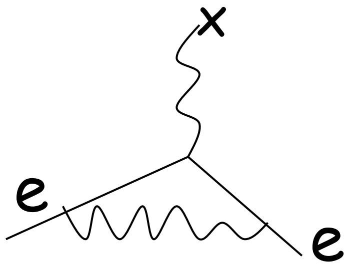
"Many loops"

[Up to five loops, ~10,000 distinct diagrams up to order α^5 in MDM, ppt accuracy!]

μ = [ppt accuracy in calculation and experiment]

$d_e \sim 10^{-35}$ e-cm (first nonvanishing term is 4-loop!)

$\mu_e = 2 + \text{alpha/pi}$



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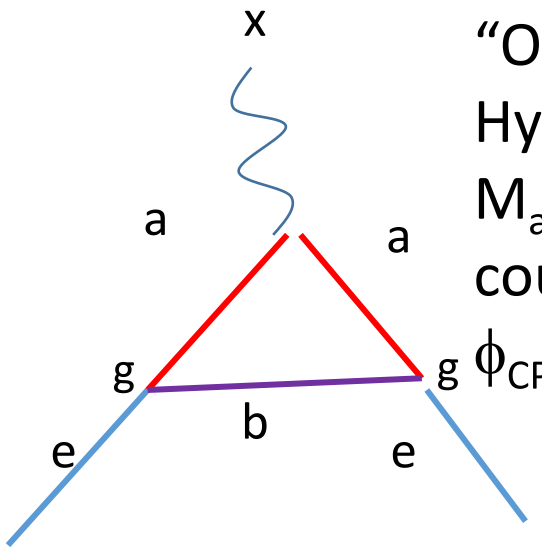


"One-loop" model for discovery.
Hypothetical undiscovered new particles
$M_a \sim M_b \sim M$ [Ramsey-Musolf; Reece]
coupling strength g at the e-a-b vertex
ϕ_{CP} is CP-violating angle
ADDS:

$$\delta(d_e/e) \sim (a_0 \alpha g^2)/(4\pi) \sin\phi_{CP} (m^2/M^2)$$

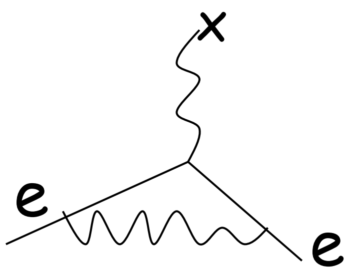
$$\delta(\mu_e/e) \sim (a_0 \alpha g^2)/(4\pi) \cos\phi_{CP} (m^2/M^2)$$

So, make a good measurement of μ_e or d_e and have sensitivity to possible new particles with mass up to M:

$$M \sim \text{(various constants)} * [(m/\delta d_e) g^2 \sin\phi_{CP}]^{1/2}$$

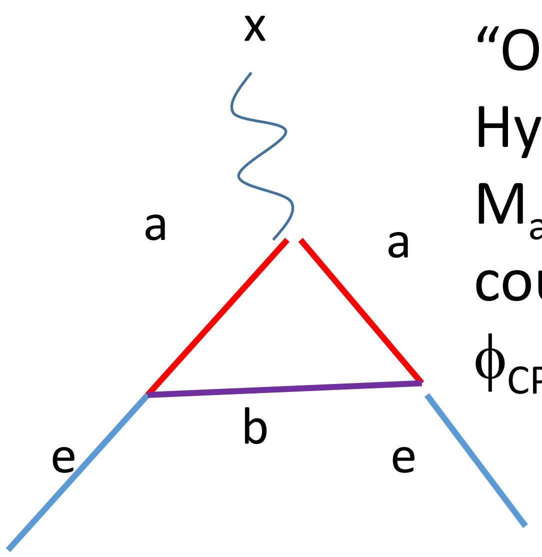
$$M \sim \text{(various constants)} * [(m/\delta\mu_e) g^2 \cos\phi_{CP}]^{1/2}$$

$g_e = 2$ + alpha/pi



this diagram adds

$\delta\mu_e = \mu_B \, \alpha/\pi$



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Question: Exotic supersymmetric result? No!

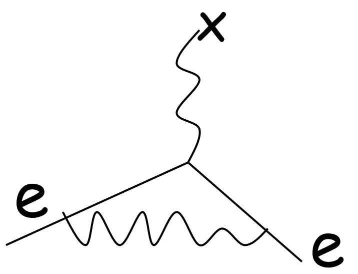
For "a" and "b", plug in "electron" and "photon". M_a n.e. M_b but take $M = (M_a + M_b)/2 = m_e/2$

The g = $\alpha^{1/2}$ and this is maximally CP preserving so $\cos\phi_{CP} = 1$

We get $\delta(\mu_e/e) \sim (a_0 \, \alpha \; \alpha)/\pi$

But recall $\mu_B/e = \alpha \; a_0 \; /2$ So $\delta(\mu_e) \sim 2\,\mu_B \, \alpha/\pi$

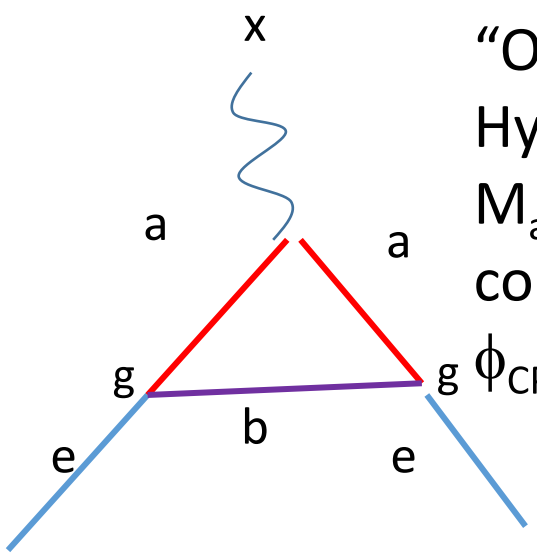
μ_e= 2 + alpha/pi



this diagram adds

$\delta\mu_e$= alpha/pi

δd_e = 0



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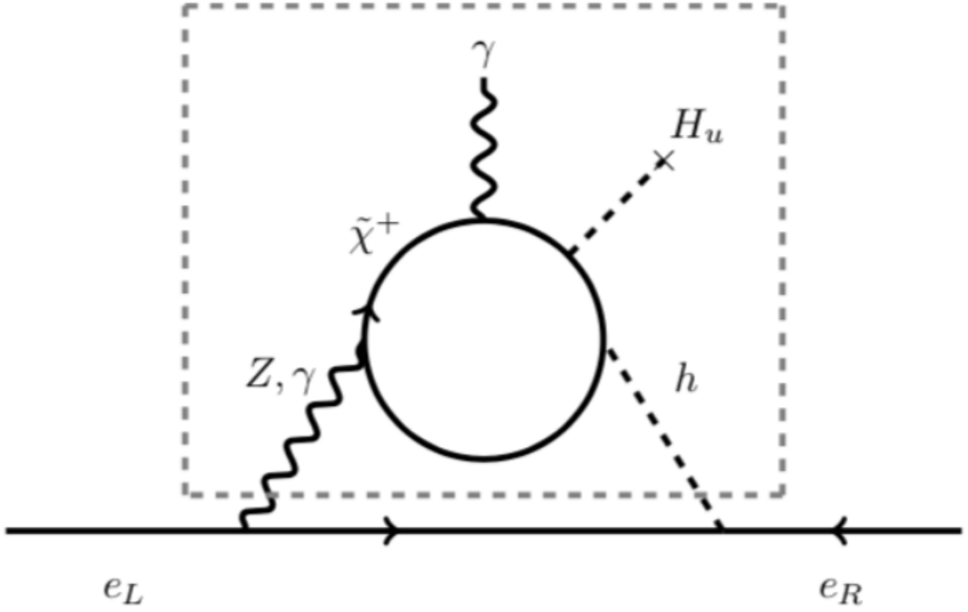
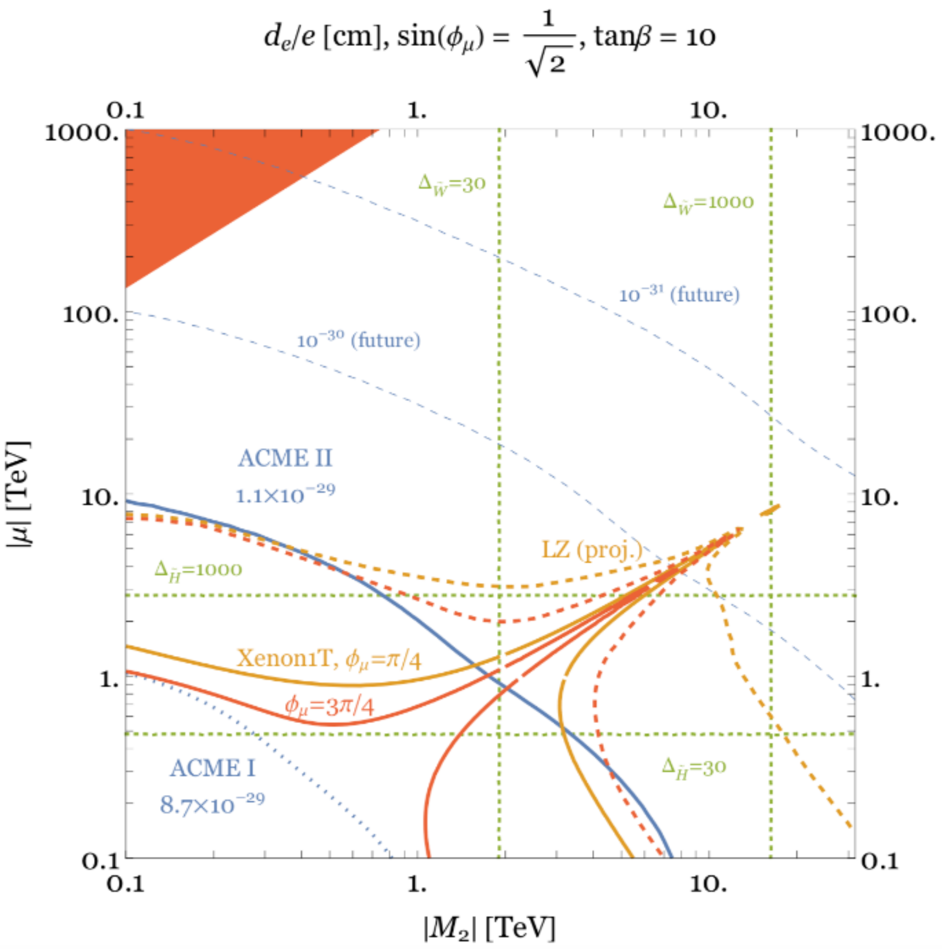
Slide borrowed from Matt Reece

Quite generally, electroweak new physics coupling to the Higgs boson gives rise to an electron EDM (Barr-Zee).



[Cesarotti, Lu, Nakai, Parikh, MR, '18]

Powerful split SUSY electroweakino constraints from ACME 2!



The one-loop pictures are a very specific model. Within these models, EDM limits
can set constrains for masses out to ~40 TeV.

Multi-loop models look at a much wider, general range of new physics,
but with corresponding less mass reach, very roughly, out to 5 TeV (= a little bigger than LHC)

Multi-loop   "new physics" are too complicated for me to understand. BUT
it is clear that, complicated model or simple model,
whatever the current limits on new-particle masses, those limits will
go up as   the square root of improvements on accuracy in d_e

When you measure it, measure it like you mean it

Will your measurement have ground-breaking precision?

How to measure MDM, or EDM?

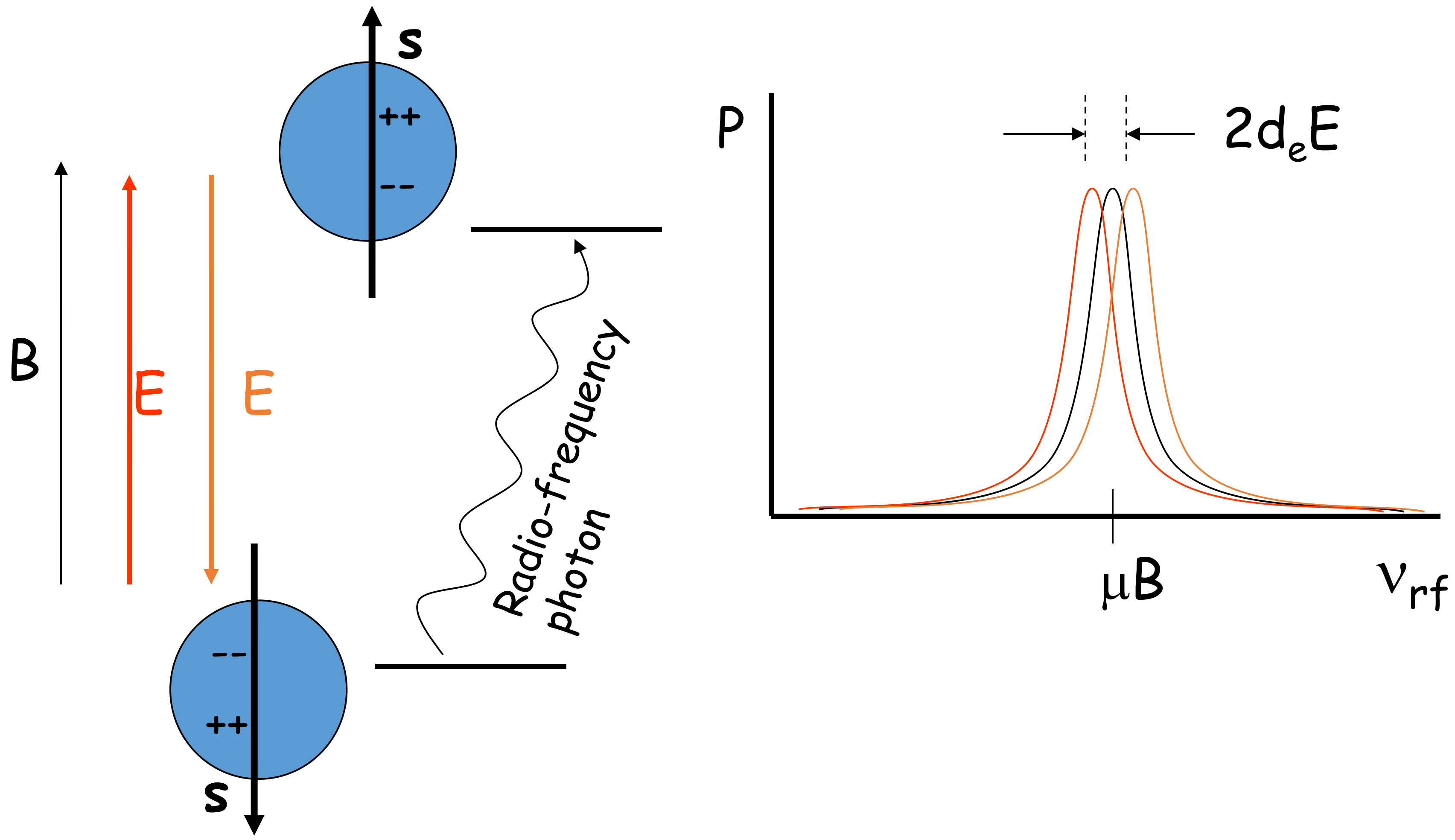
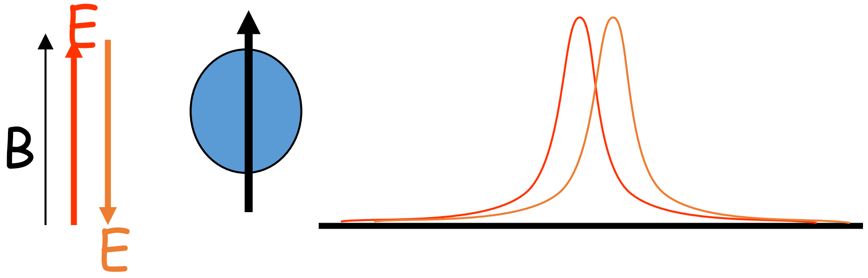
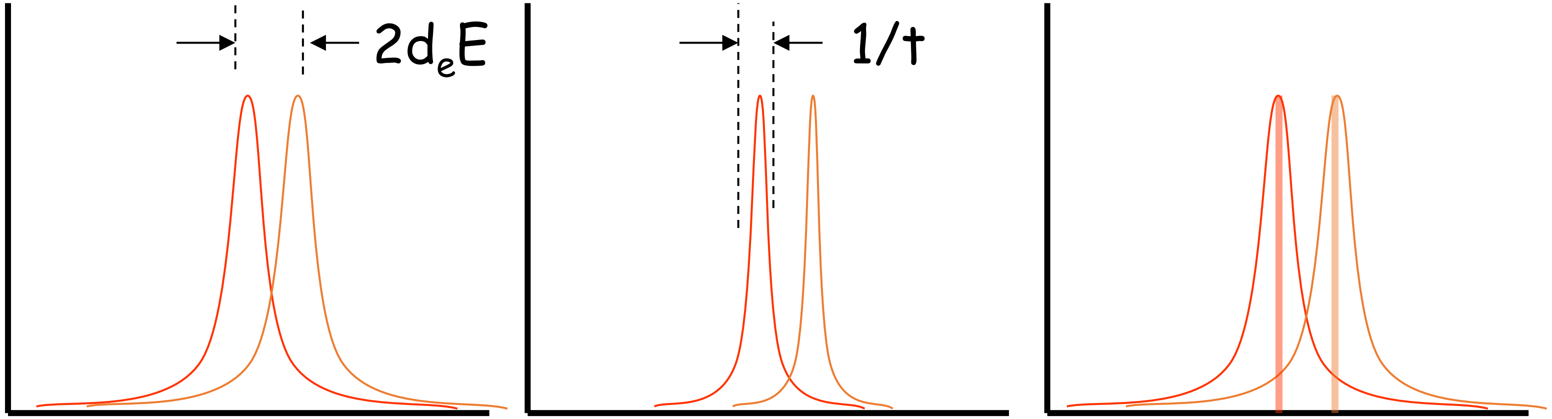


Figure-of-merit: What makes a good EDM experiment?

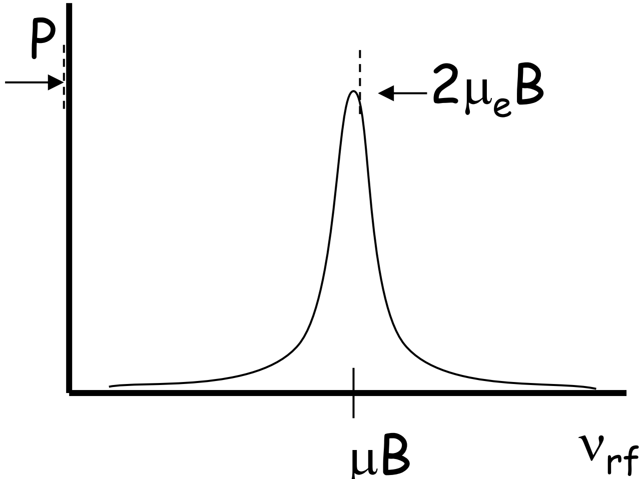




Big Electric or Magnetic Field!

Long Coherence Time (narrow resonances)!

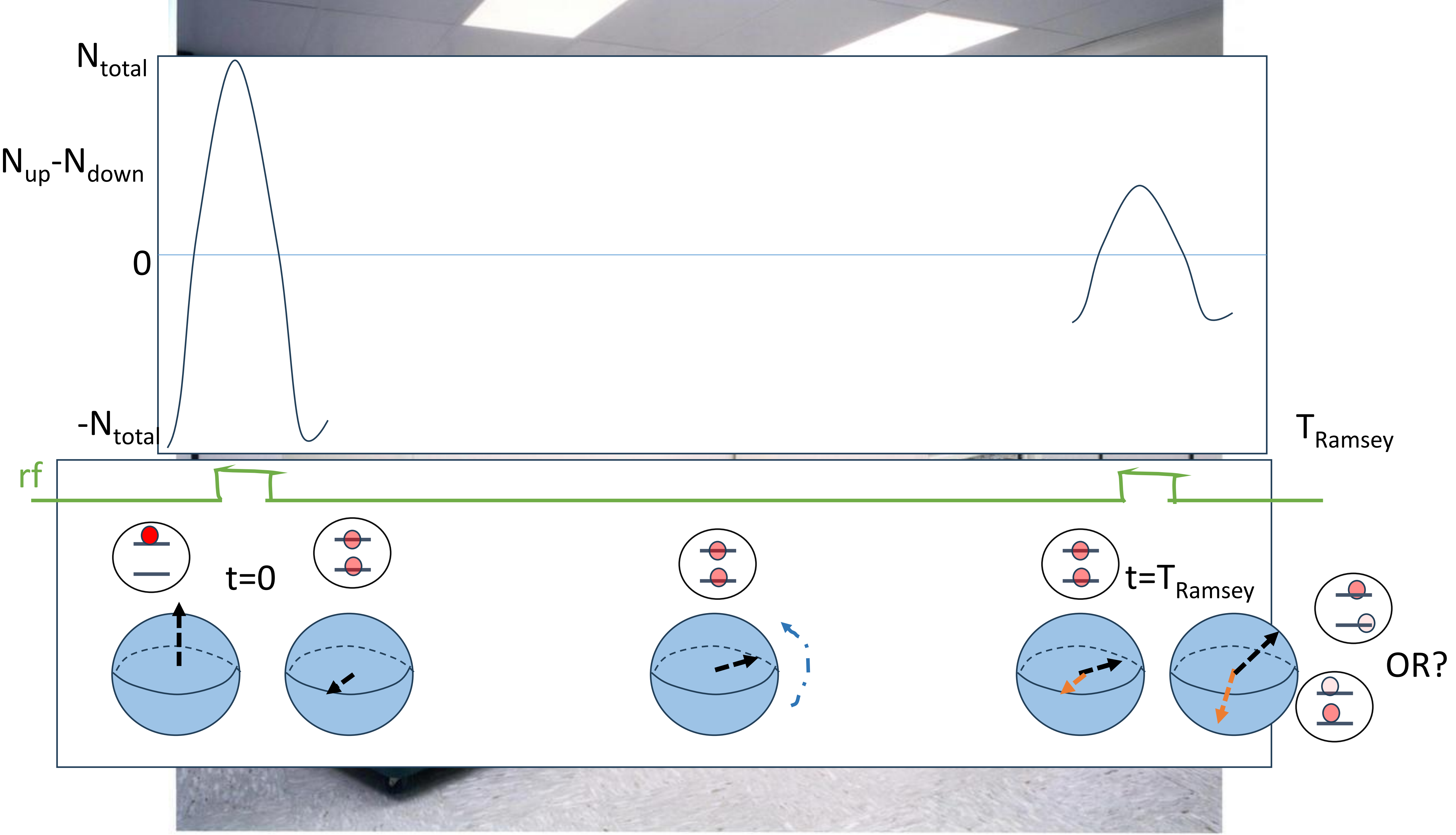
Large count rate (split resonance by $\sqrt{N_{eff}}$)



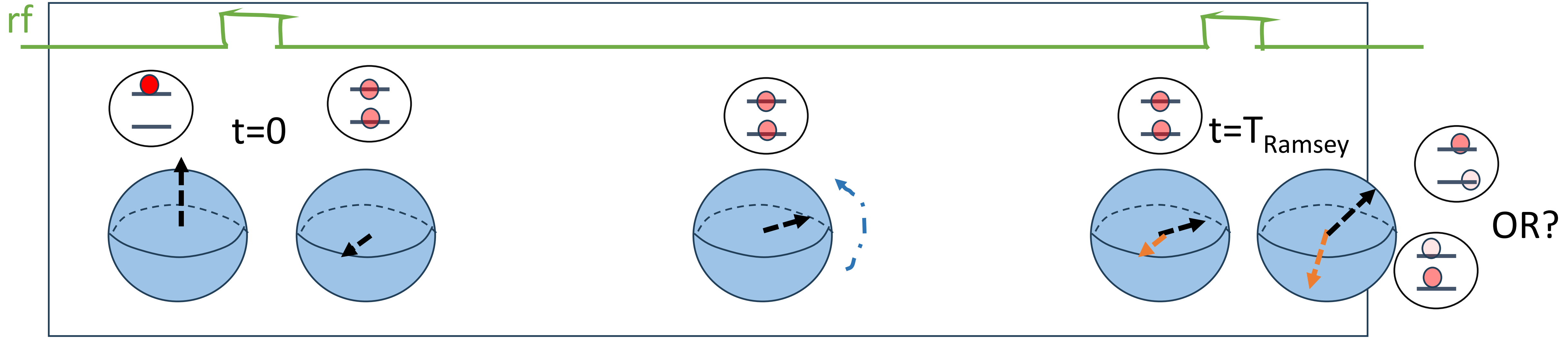
Combined Figure-of-merit:

$$(\text{Field})\ \tau\ \sqrt{N_{eff}}$$

An EDM experiment is just a clock with an electric field applied



N_{total}
N_{up}-N_{down}
0
-N_{total}
T_{Ramsey}
rf
t=0
t=T_{Ramsey}
OR?



Why “two pulses”? Why not just leave the rf on weakly the whole time?

i) two-pulses: modestly narrower lines.

ii) along a several meter beam, hard otkeep sample uniform;y illuminated by rf, microwave, or optical beam

iii) Differential measurement removes uncharacterized shifts from “rf”.

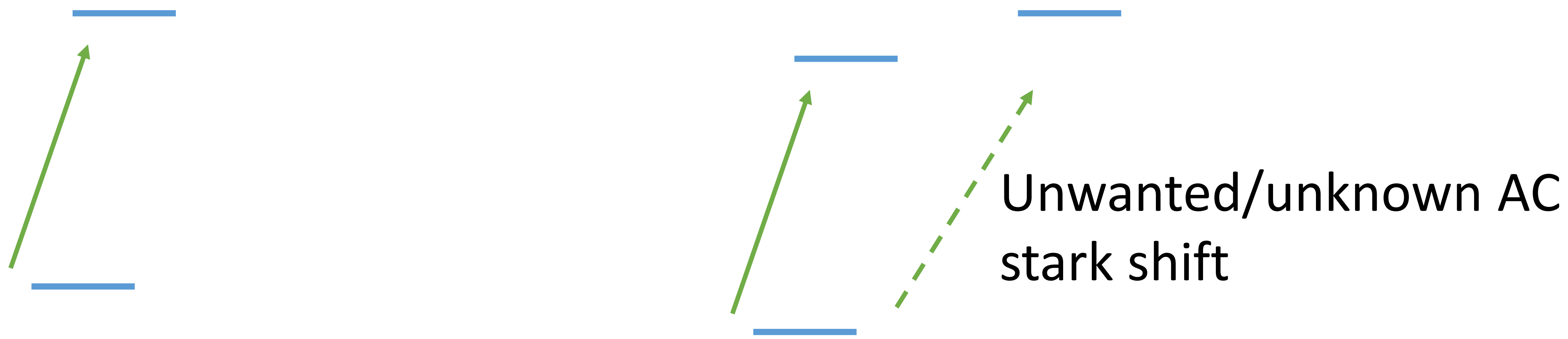
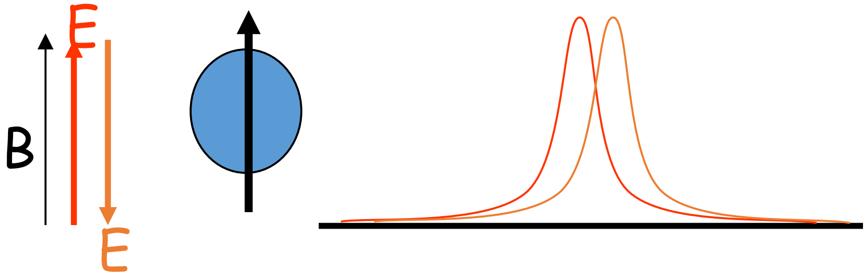
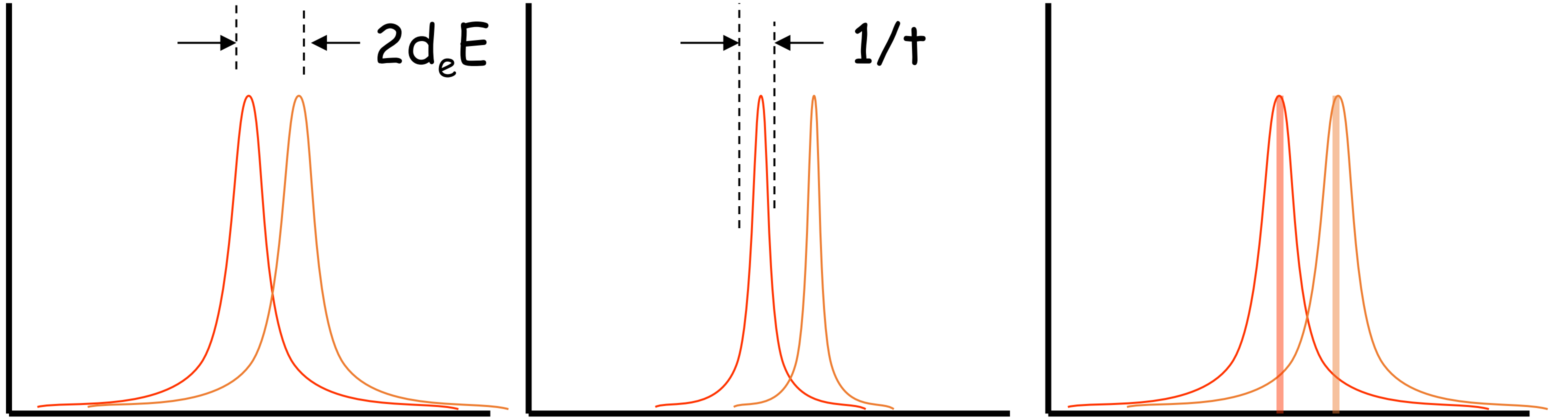

Unwanted/unknown AC
stark shift

Figure-of-merit:
What makes a good EDM experiment?





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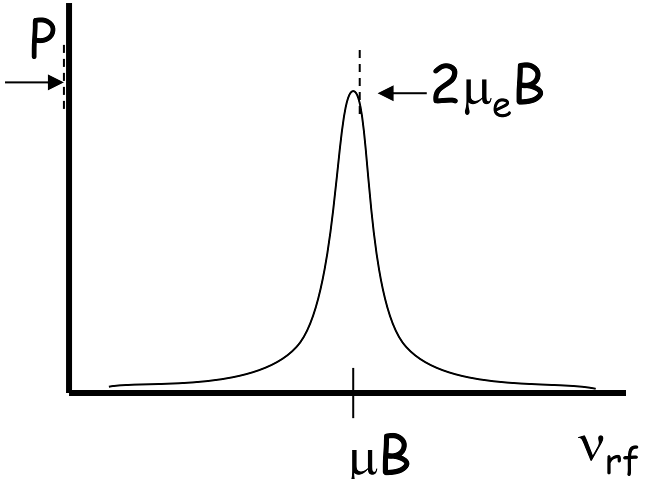


Combined Figure-of-merit:

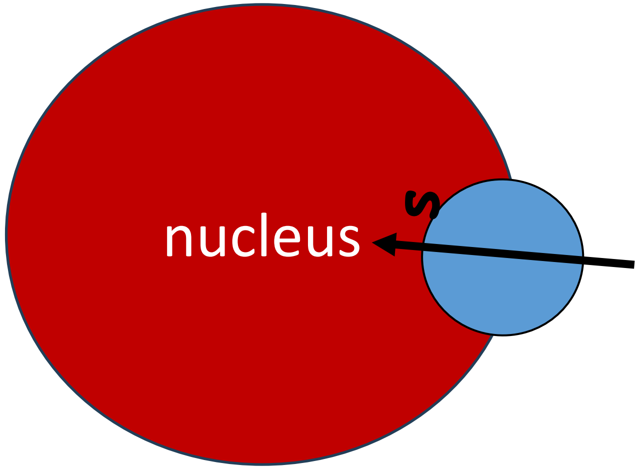
$$(\text{Field})\,\tau\sqrt{N_{eff}}$$

A. E-field.

(More generically, in precision measurement, "Electric field" is a stand-in for the constant of proportionality that takes "size of exotic physics quantity" and maps it into "frequency".

So, yes,

$$f = E_{eff} * d_e + W * C_s$$



There is a contribution to energy that goes like

C_s (gradient of nuclear density) dot (electron spin)

A given atomic or molecular experiment is characterized by an E_{eff}, and a W

A. E-field.

#start with neutron. simple enough. max appliable fields are ~ 10^5 v/cm (but maybe $5x10^5$ V/cm?

#for MDM, max appliable fields are about 10 T (about 10^5 G, about $3x10^7$ V/cm.

"appliable field" is not so obvious for electron

More on E-fields tomorrow.