Physics Motivation for a Muon Collider!

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Various versions of a physics case...

The case so simple even a 2 year old gets it

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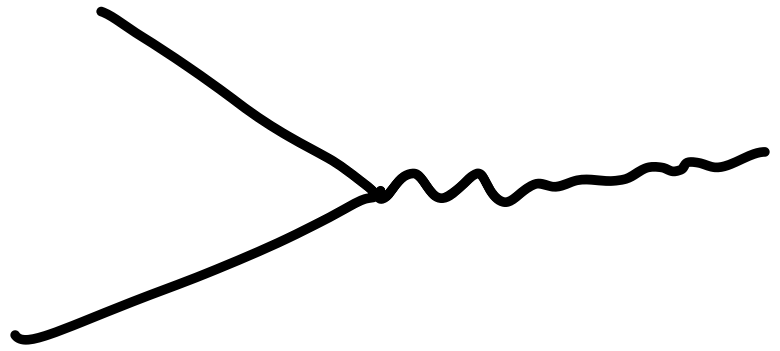
Add in QM + Relativity

The outcome of which is QFT (slightly beyond a 2 year old)

 New physics!!

$$N_{events} = \sigma \cdot L$$

$$\sigma \sim \frac{1}{E^2}$$

And we reach the inevitable ask for the AF...

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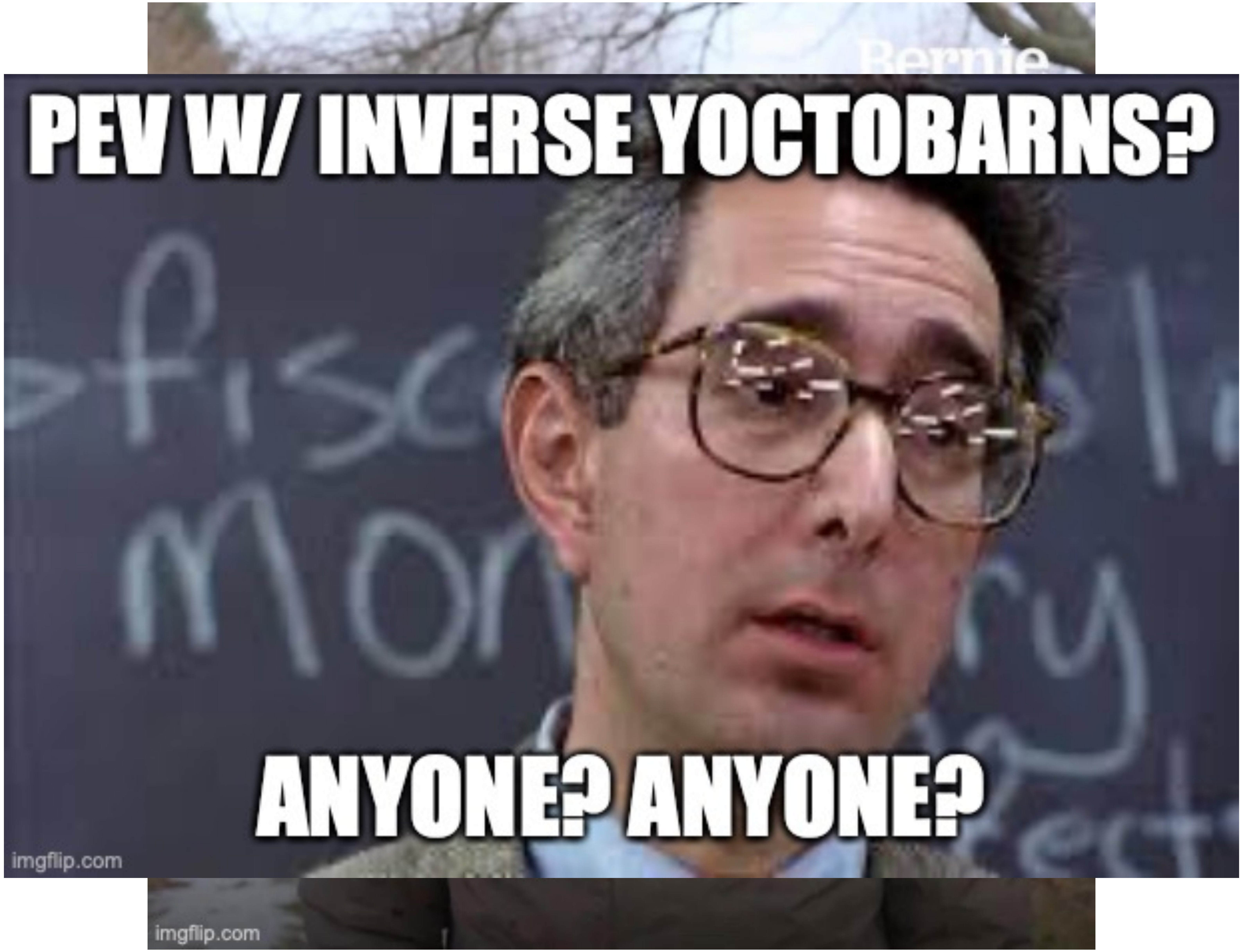


All jokes aside, the AF is very pragmatic!

- *F1* "Technology Readiness" :

Green	- TDR
Yellow	- CDR
Red	- R&D

- *F2* "Energy Efficiency"

Green	: 100-200 MW
Yellow	: 200-400 MW
Red	: > 400 MW

- *F3* "Cost" :

Green	: < LHC
Yellow	: 1-2 x LHC
Red	: > 2x LHC

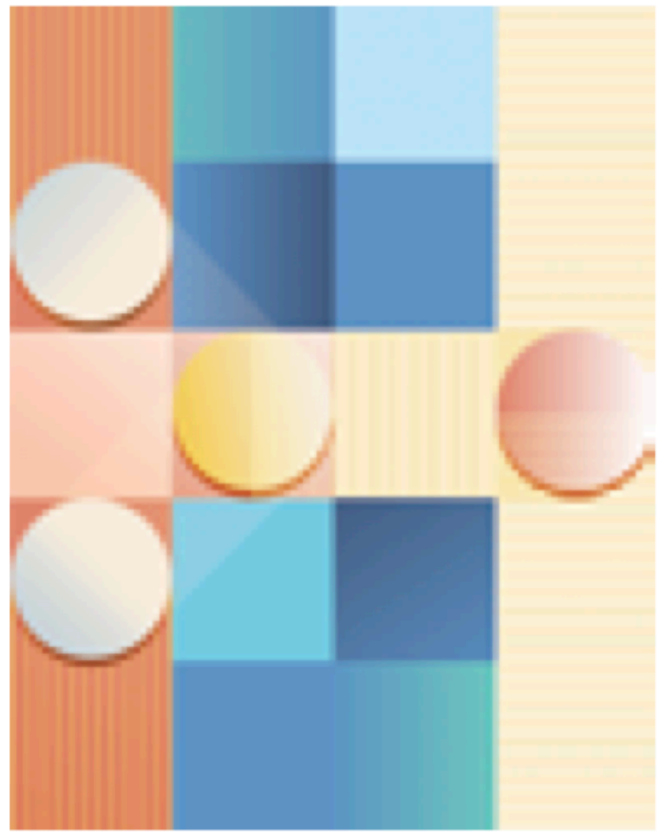
Nevertheless *any* new project will take a significant investment, so are there interesting targets/motivations along the way other than exploring the unknown?

We do more handwringing than other parts of our field because our costs are larger…

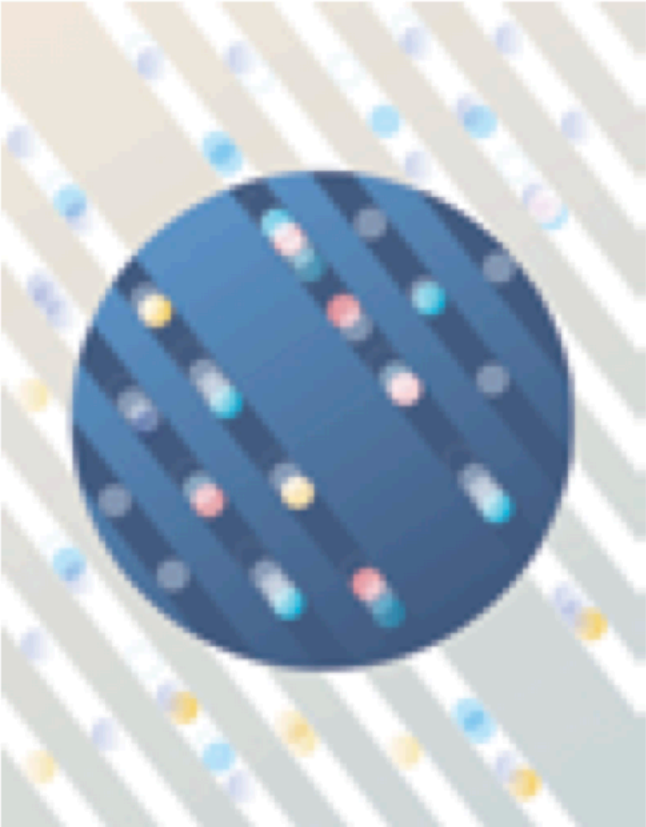
Last P5 - Motivations are *still* there

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

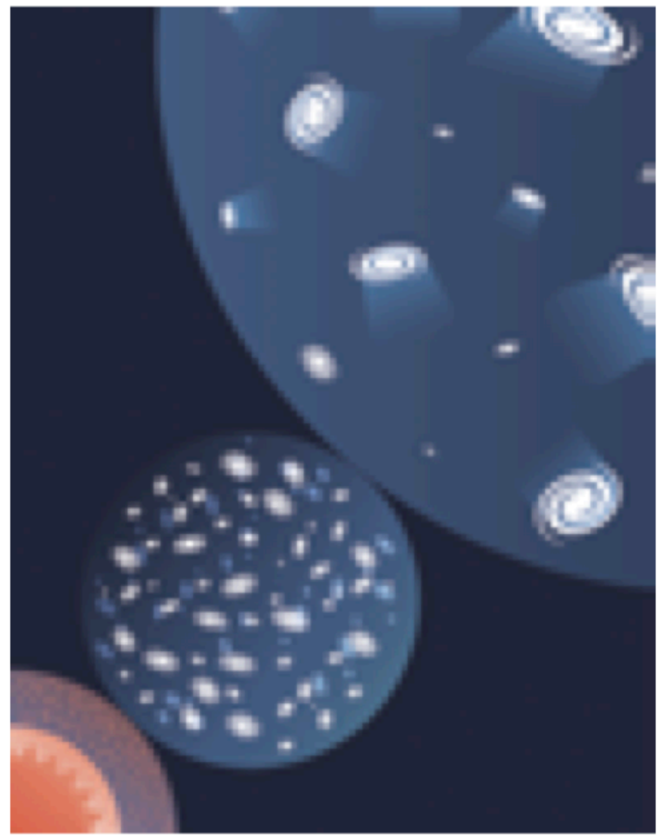


Higgs boson



Neutrino mass

Dark matter



Cosmic acceleration

Explore the unknown

We often silo ourselves off without thinking about the big picture

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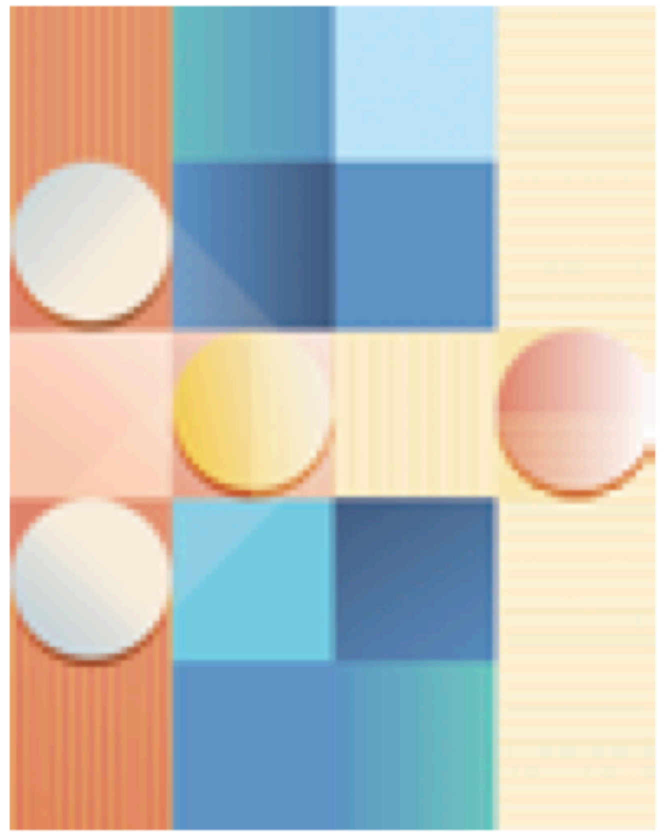

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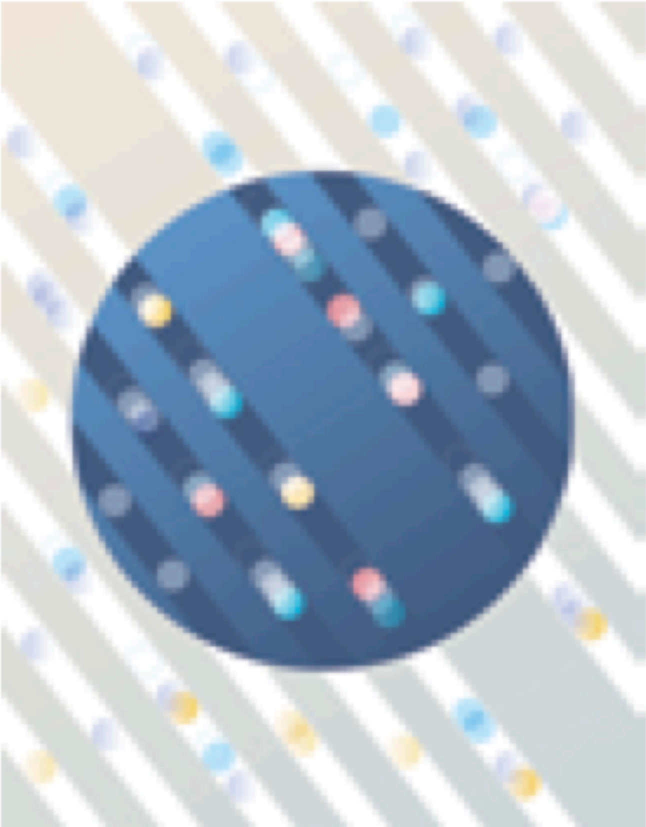
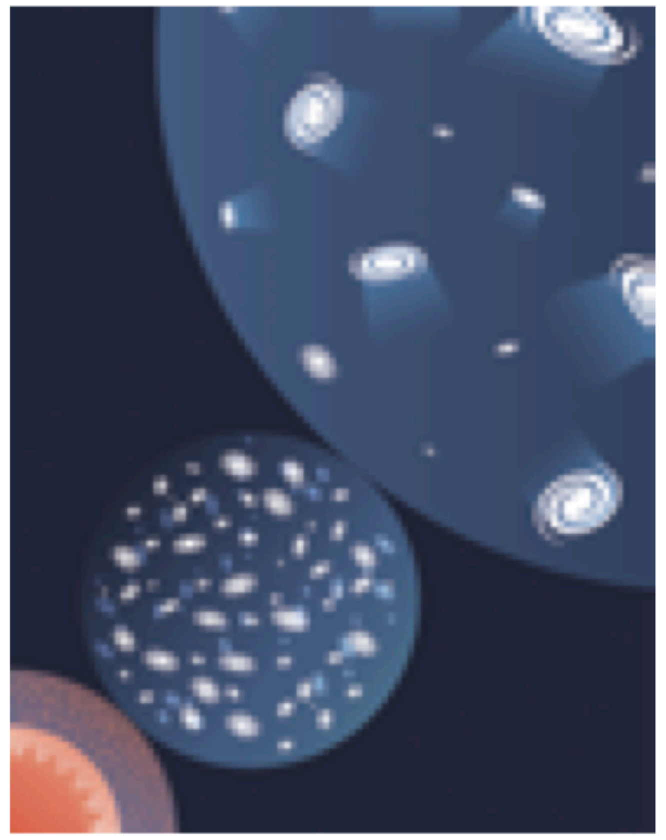


Neutrino mass

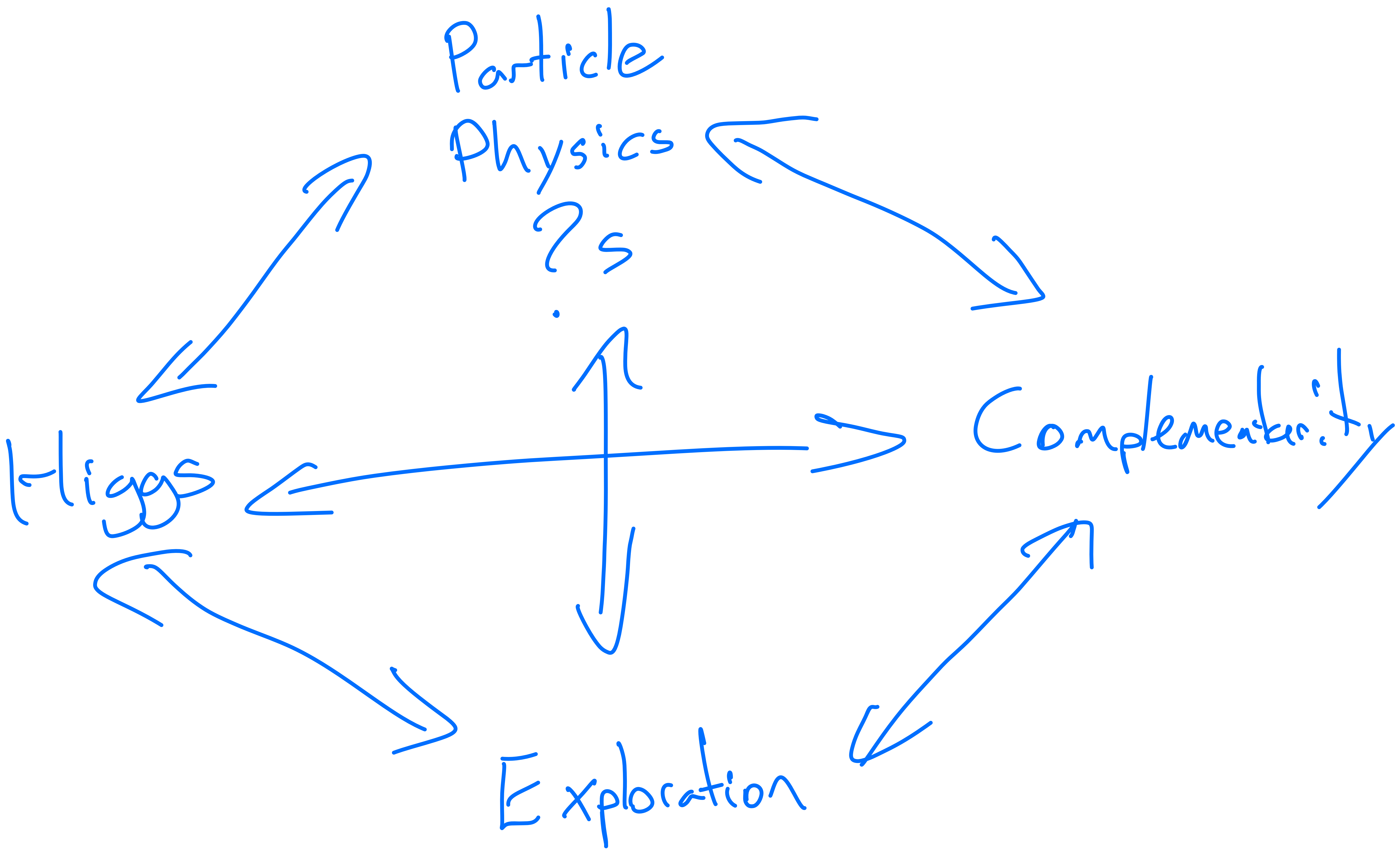
Dark matter



Cosmic acceleration

Explore the unknown

In reality it is a much more intertwined picture



That a high energy muon collider can shed light on many questions *simultaneously!*

Standard Particle Physics Questions

- Why is there more matter than antimatter?
- What is dark matter? Dark energy?
- Why do atoms exist? (How does the electron get its mass?)
- What is flavor? Why 3 generations and mixing?
- Origin of neutrino mass and mixings?
- Cosmic history before Big Bang Nucleosynthesis?
- Origin of Electroweak Symmetry Breaking/Higgs potential?
- (Meta)Stability of our Universe?
- Strong CP problem solution?
- Naturalness of Quantum Field Theory (most successful theory ever)?
- …

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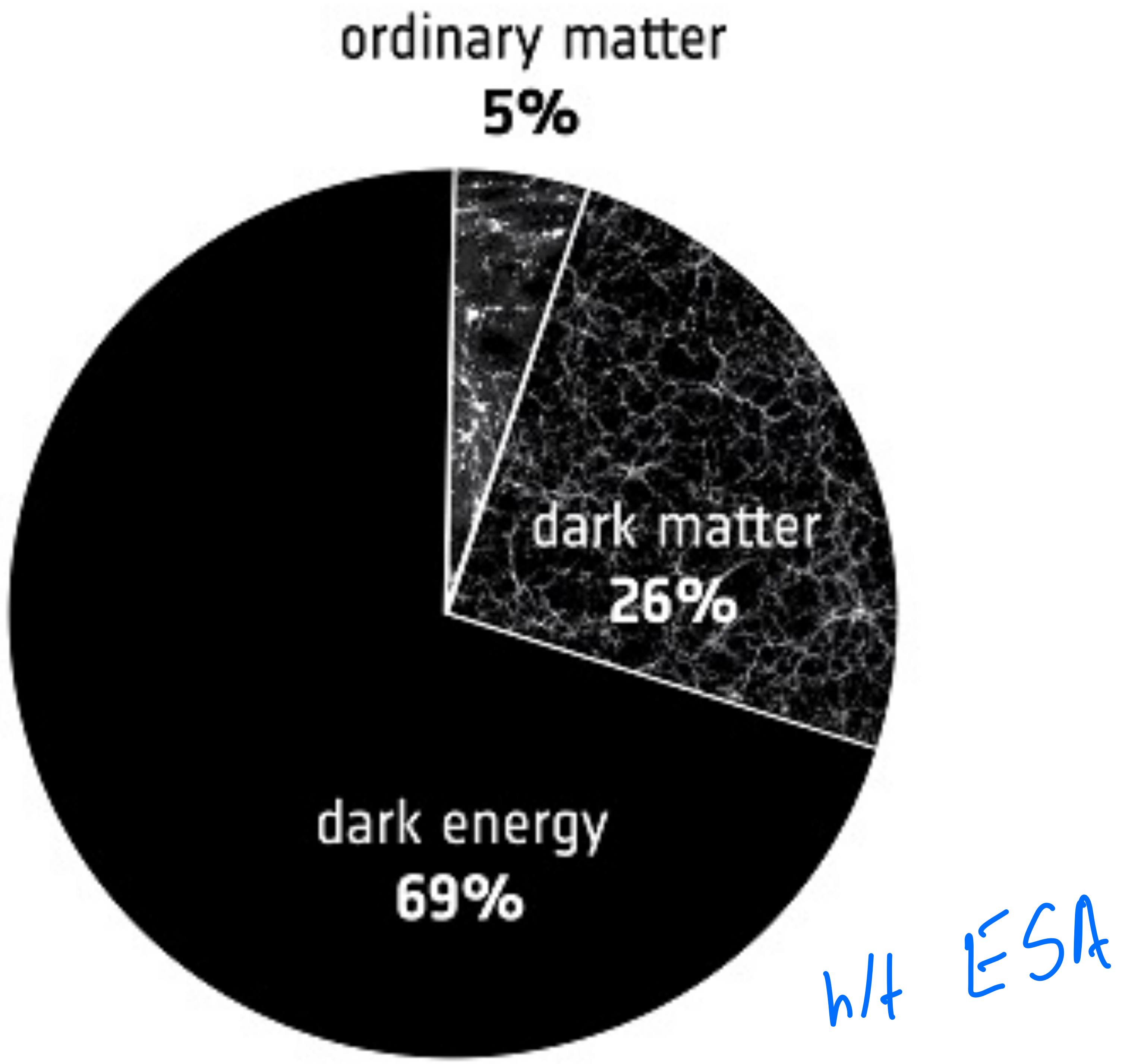
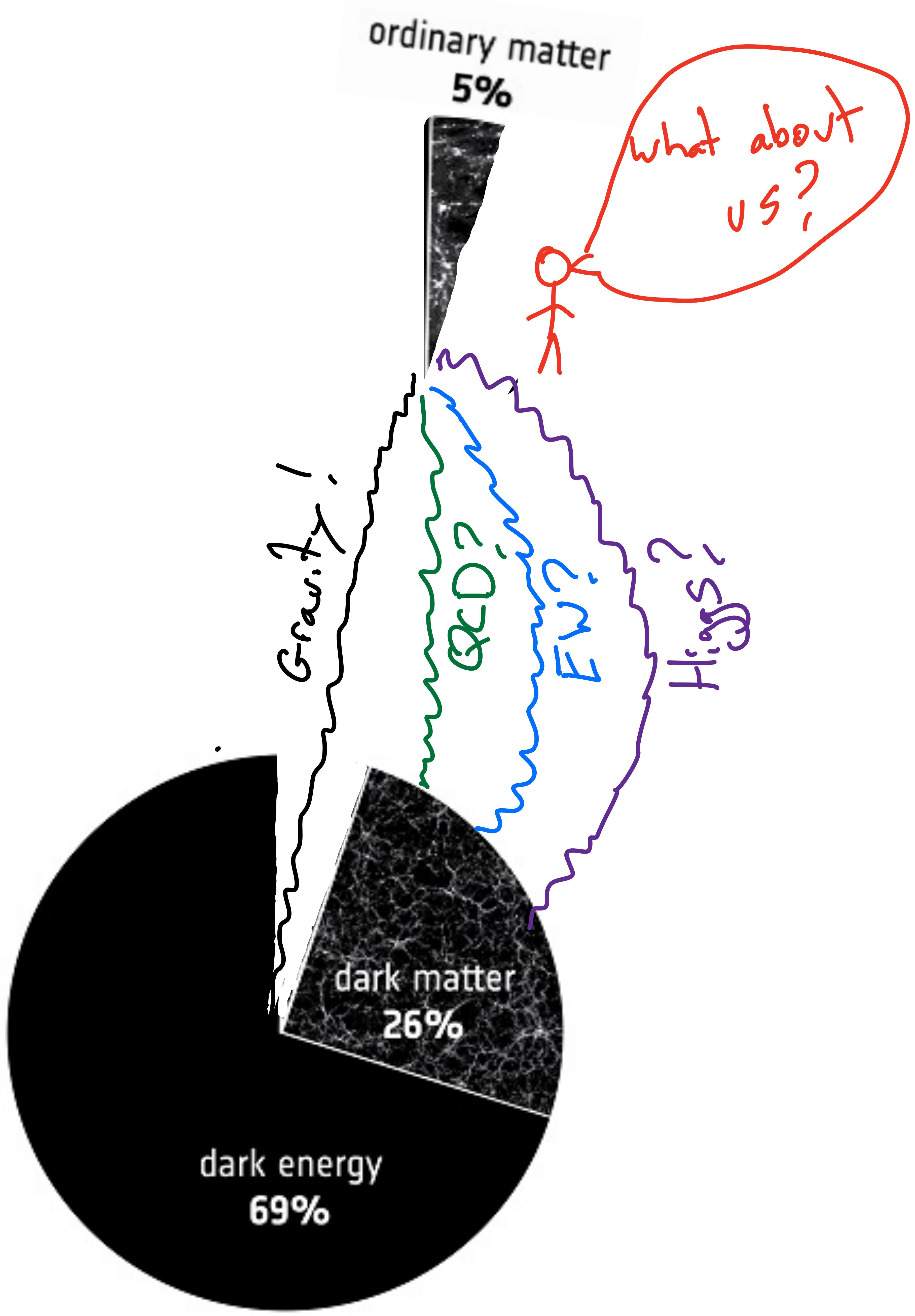
While lots of experiments can attack these separately,
a high energy muon collider can shed light across many questions

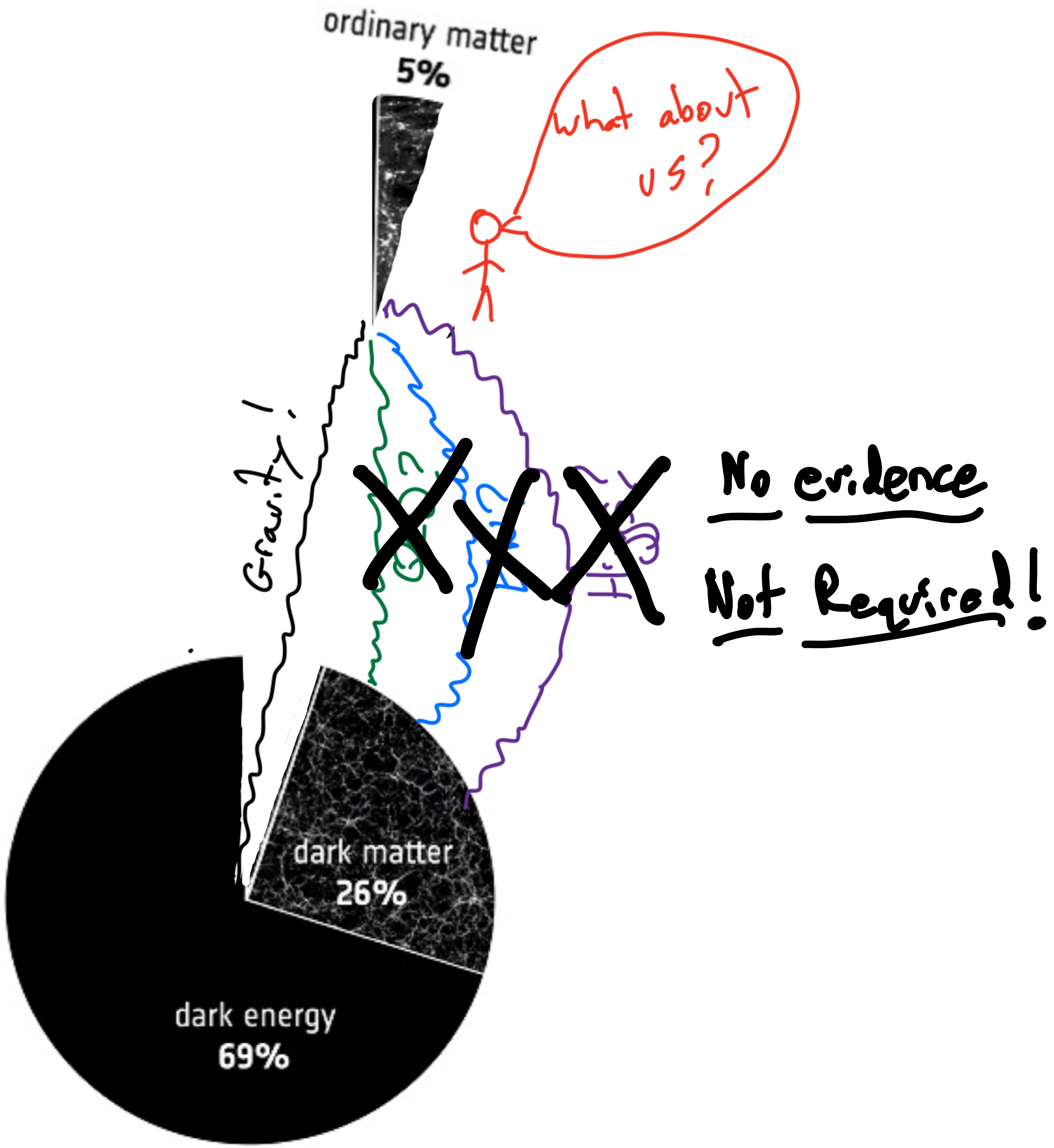
No guaranteed answers *other* than measurements



But *every* experiment has this issue

Let's take an example that everyone loves Dark Matter!

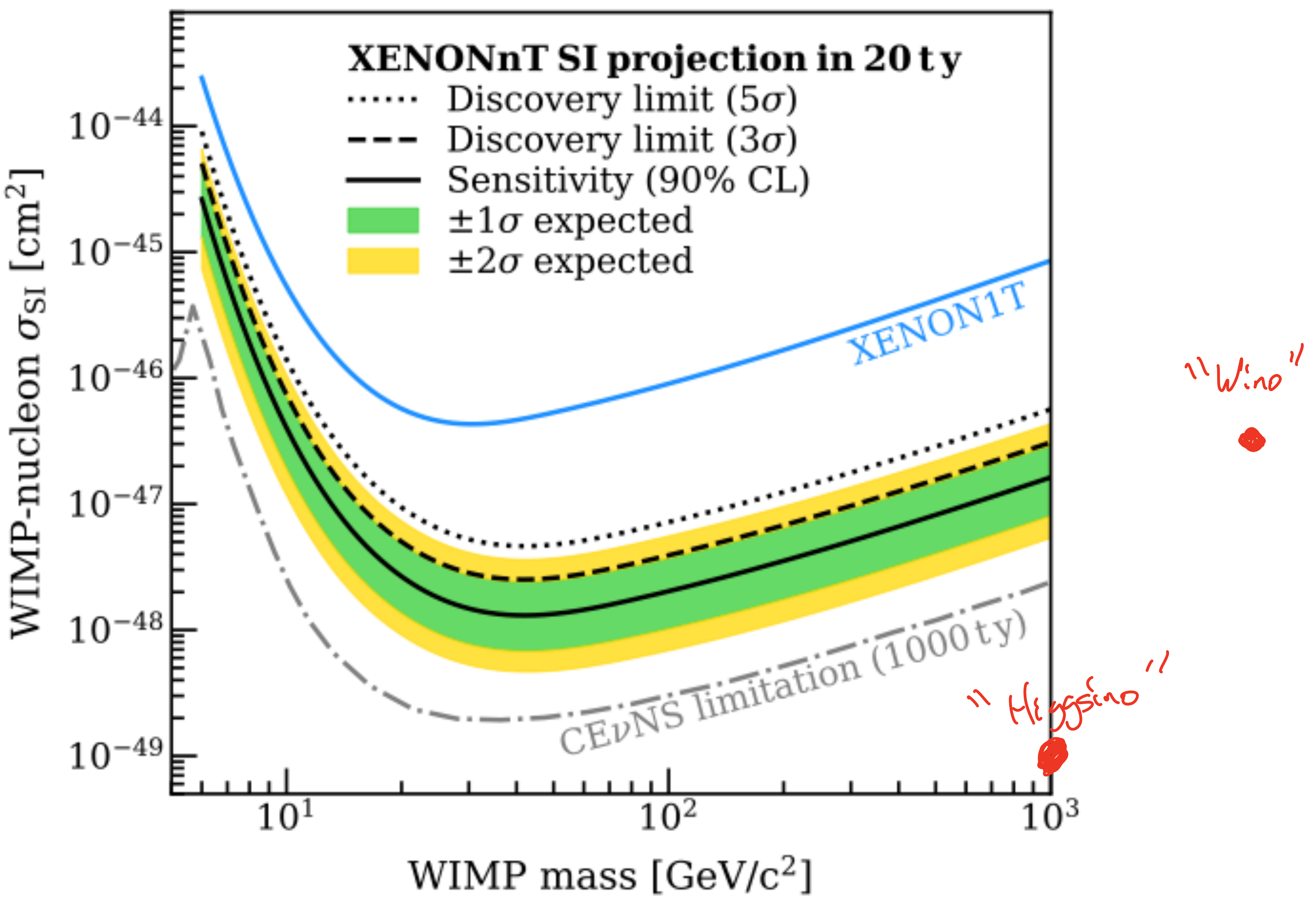

ordinary matter
5%
what about us?
Gravity!
QCD?
EW?
Higgs?
dark matter
26%
dark energy
69%



What we test through indirect/ direct detection is the same as what we do for particle physics

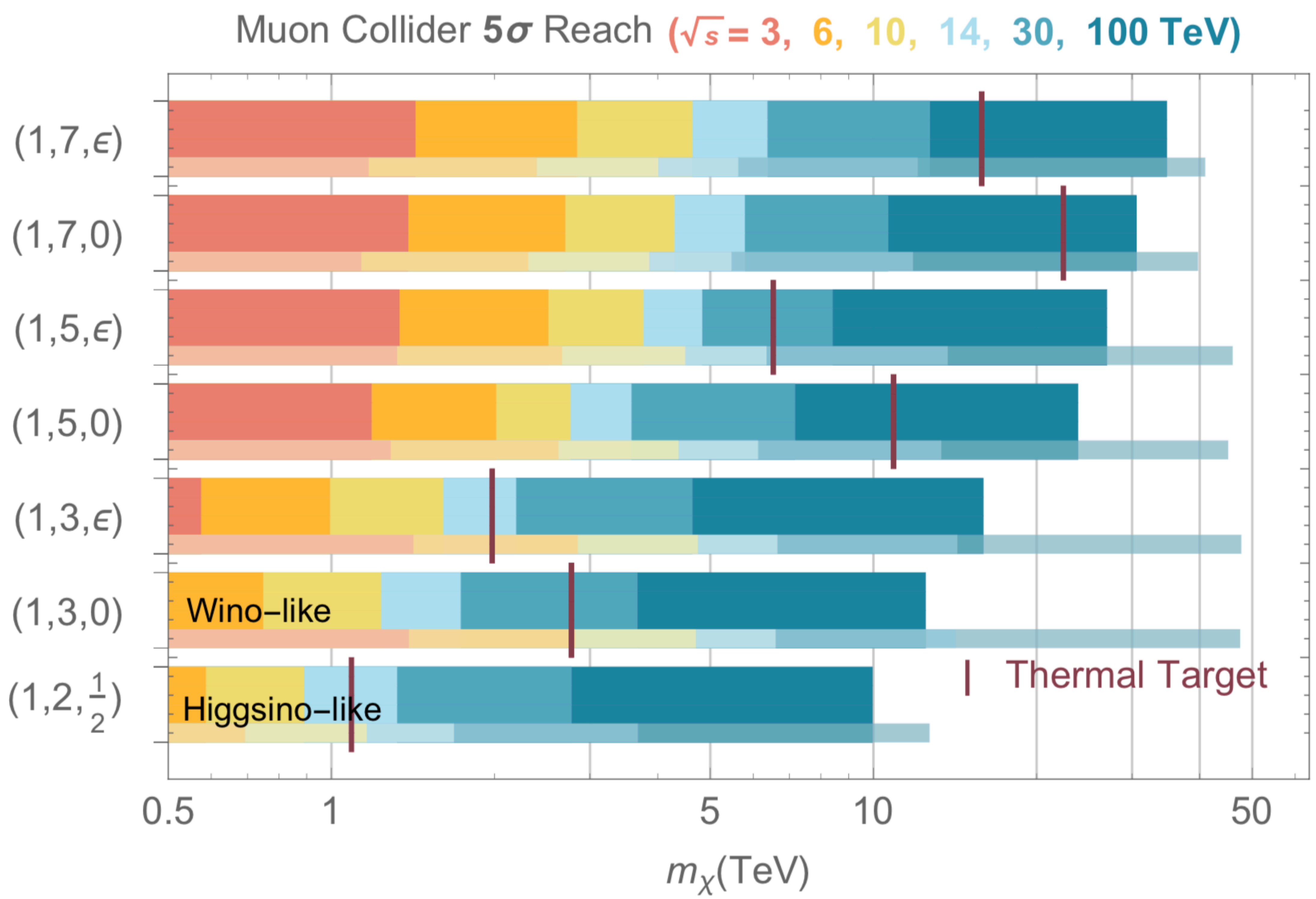
Motivate with interesting possibilities that attempt to *explain* properties and are *consistent* experimentally and theoretically!

WIMP "miracle"



Still exists in its fundamental form

A high energy muon collider can test this possibility!



2009.11287 T. Han, Z. Liu, L. Wang, X. Wang

Figure 10: Summary of the discovery reaches of various muon collider running scenarios. The thicker bars represent the combined reach from missing mass searches through mono-photon, mono-muon, and VBF di-muon channels. The thinner and faint bars are our estimates of the mono-photon plus one disappearing track search. The burgundy vertical bars represent the thermal target for a given EW-multiplet model. More details, including the detailed reaches for each channels and different muon collider energies, can be found in Ref. [32].

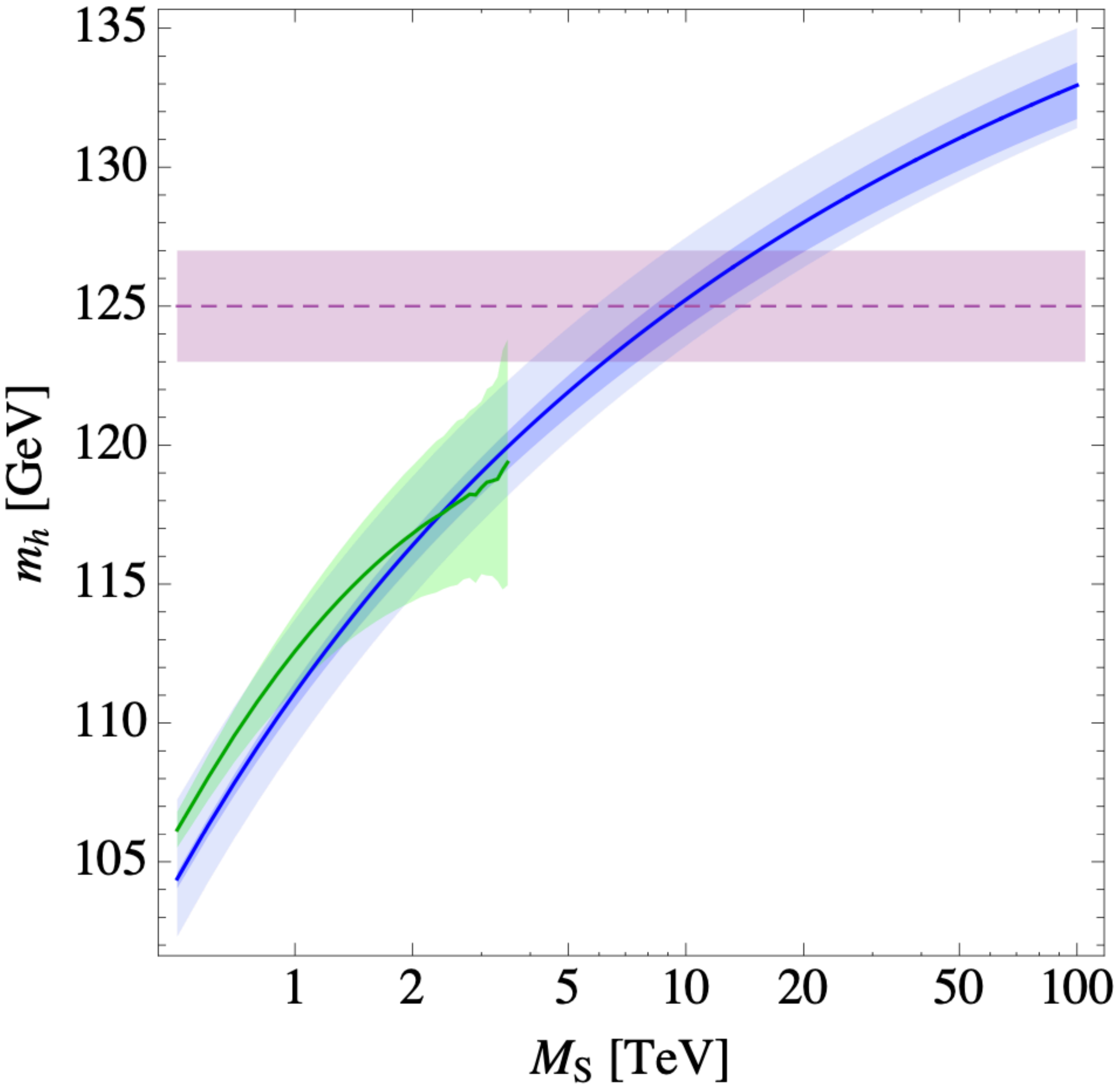
Testing QFT and Naturalness

There is no reason the Higgs mass should be what it is

It should be quadratically sensitive to the scale of new physics!

Obviously we'd like to test this to the highest scales possible, there could be entirely new paradigms at work, "Copernican Revolution" as someone bolder might say

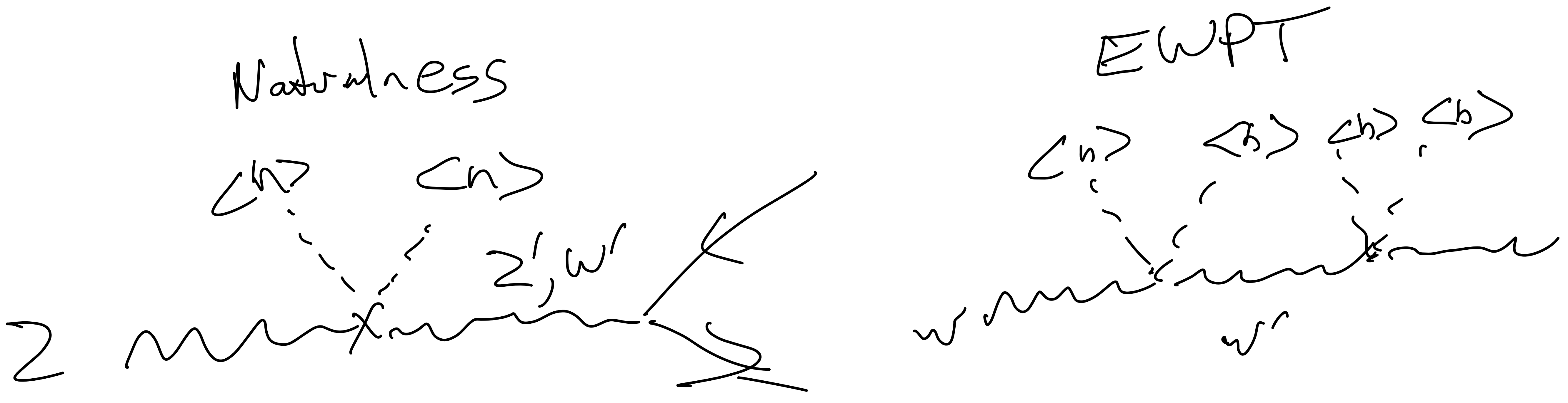
However, in theories that can explain the Higgs Mass, the scale could be much higher and we've known a long time!



December 2011

This concept has existed even before the Higgs- Electroweak Precision!

1 TeV ⟺ 10 TeV scale



$$\frac{\delta\Gamma_Z}{\Gamma_Z} \sim 1 + c\,\frac{v^2}{f^2}$$

$$\frac{\delta m_W^2}{m_W^2} \sim 1 + c'\,\frac{v^8}{f^2}$$

w/ c's $\mathcal{O}(1)$

f > 5.5 TeV 95% CL

20 years ago!!

We need a technology that can get us to higher energies - Muon Colliders!

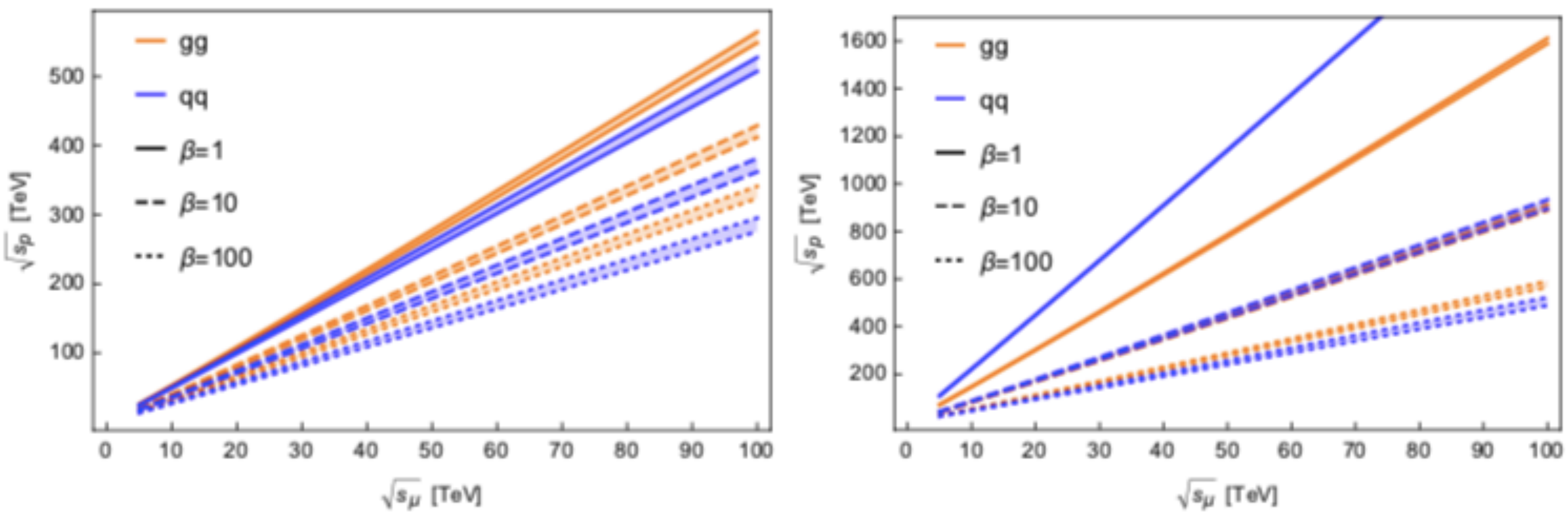


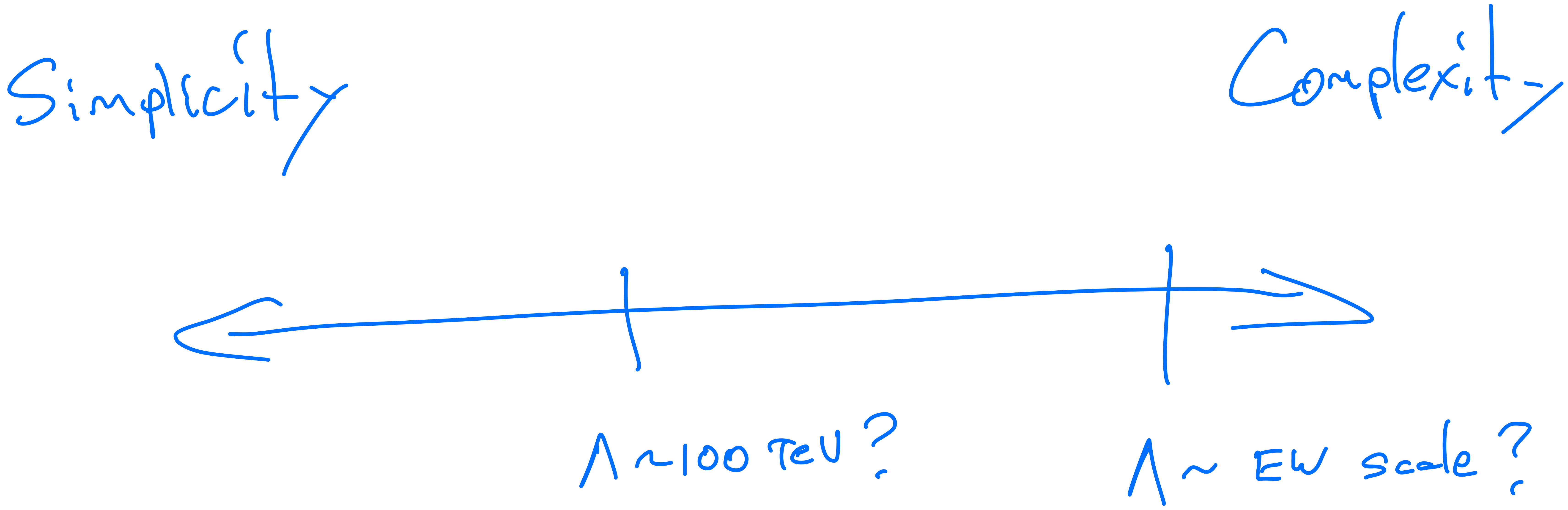
Figure 1: The c.m. energy $\sqrt{s_p}$ in TeV at a proton-proton collider versus $\sqrt{s_\mu}$ in TeV at a muon collider, which yield equivalent cross sections. Curves correspond to production via a gg (orange) or $q\bar{q}$ (blue) initial state at the proton-proton collider, while production at the muon collider is determined by $\mu^+\mu^-$. The partonic cross sections are related by $\beta \equiv [\hat{\sigma}]_p/[\hat{\sigma}]_\mu$. The bands correspond to two different choices of proton PDF sets, `NNPDF3.0 LO` (as in [1]) and `CT18NNLO`. Left: $2 \to 1$ scattering. Right: $2 \to 2$ scattering.

Roughly there is equivalence to a 100 TeV pp collider for

$2 \to 1$	$2 \to 2$
$\sqrt{s_\mu} \sim 20\,\text{TeV}$	$\sqrt{s_\mu} \sim 5-7\,\text{TeV}$

The devil is in the details always… but O(10) TeV is also interesting from Higgs

With any of these of course nothing is a guarantee!

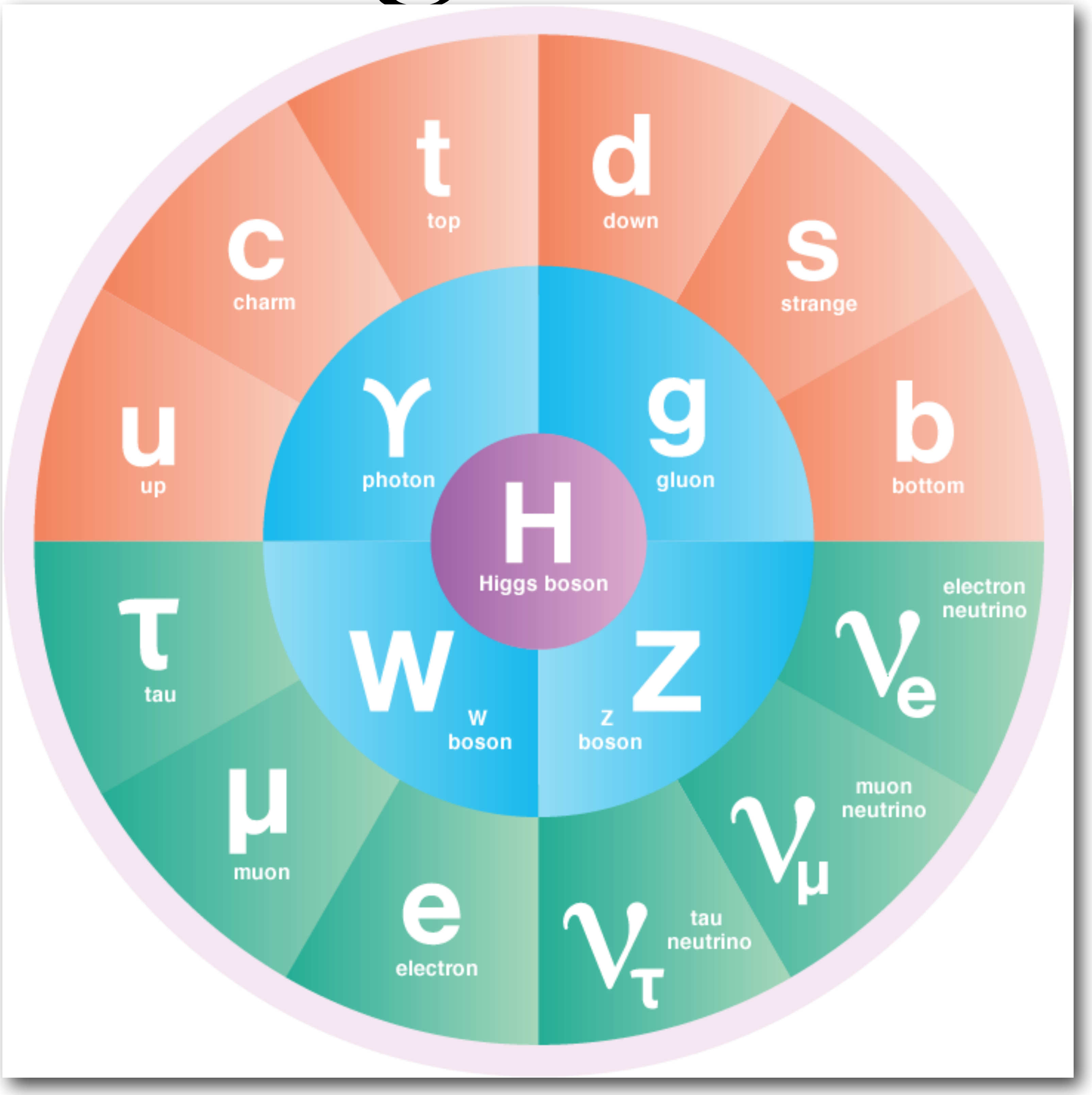


However we do have this basic understanding of what *could* be there

Foundational Physics Potential Cases

If you want a ***guaranteed*** return it's a lot harder

We are just scratching the surface of the Higgs!



The Higgs is the *most* unique particle in the SM

We must measure *all* its couplings to complete SM

22/26 parameters in SM governed by Higgs!

COMPLETE THE SM!

Higgs

BSM

Biggest open areas post HL-LHC

Self couplings!

Light Flavor!

Needs Energy

Needs Precision

Both need a lot of Higgs!

How Many Higgs??

Take this with many grains of salt…

ESG run plans 1905.03764

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{inst}$ $[10^{34}]$ $cm^{-2}s^{-1}$	$\mathscr{L}$ $[ab^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[13]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[13]	HE-LHC
FCC-hh(*)	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		$FCC\text{-}ee_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		$FCC\text{-}ee_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 14]	ILC_{250}
		350 GeV	±80/±30	1	1.6	0.2	1		ILC_{350}
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC_{500}
							(+1)		(1y SD after 250 GeV run)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5	[4]	ILC_{1000}
							(+1-2)		(1-2y SD after 500 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[15]	$CLIC_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		$CLIC_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		$CLIC_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[12]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

HL-LHC $\sim .35 \times 10^9$ — End of LHC ~ O(100) million Higgses!

ILC250/350 $\sim .6 \times 10^6$
FCC-ee 240/365 $\sim 1.2 \times 10^6$
CEPC 240 $\sim 1.1 \times 10^6$
CLIC-380 $\sim .2 \times 10^6$

} Low energy e+e- Higgs factories
~ 1 million Higgs

ILC500/1000 $\sim 4.5 \times 10^6$
CLIC 1500/3000 $\sim 3.4 \times 10^6$

} Moderate energy e+e- Higgs factories
~ few million Higgs

FCC-hh $\sim 27 \times 10^9$ — 27 billion Higgses

Speculative high energy options (run plans specified here)

Muon (or electron colliders)

6 TeV 4/ab $\sim 3.2 \times 10^6$
10 TeV 10/ab $\sim 9.5 \times 10^6$
14 TeV 20/ab $\sim 22 \times 10^6$
30 TeV 90/ab $\sim .12 \times 10^9$
100 TeV 100/ab $\sim .18 \times 10^9$

Millions to 100s of millions

Collider in the sea

500 TeV 50/ab $\sim 400 \times 10^9$ — Can approach a trillion Higgs

Different energies access different dominant processes (different physics you can access), have different experimental challenges

This is to understand orders of magnitude and what you *could* do *if* you could exploit them all!

Figure of merit LEP had 17 Million Zs

How Many Higgs??

Take this with many grains of salt...

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Remember though the Higgs is highly non-egalitarian!

LEP 17 M Z's

"Major" BFs $\mathcal{O}(\%)$

Higgs Factory $\mathcal{O}(1)$ M H's

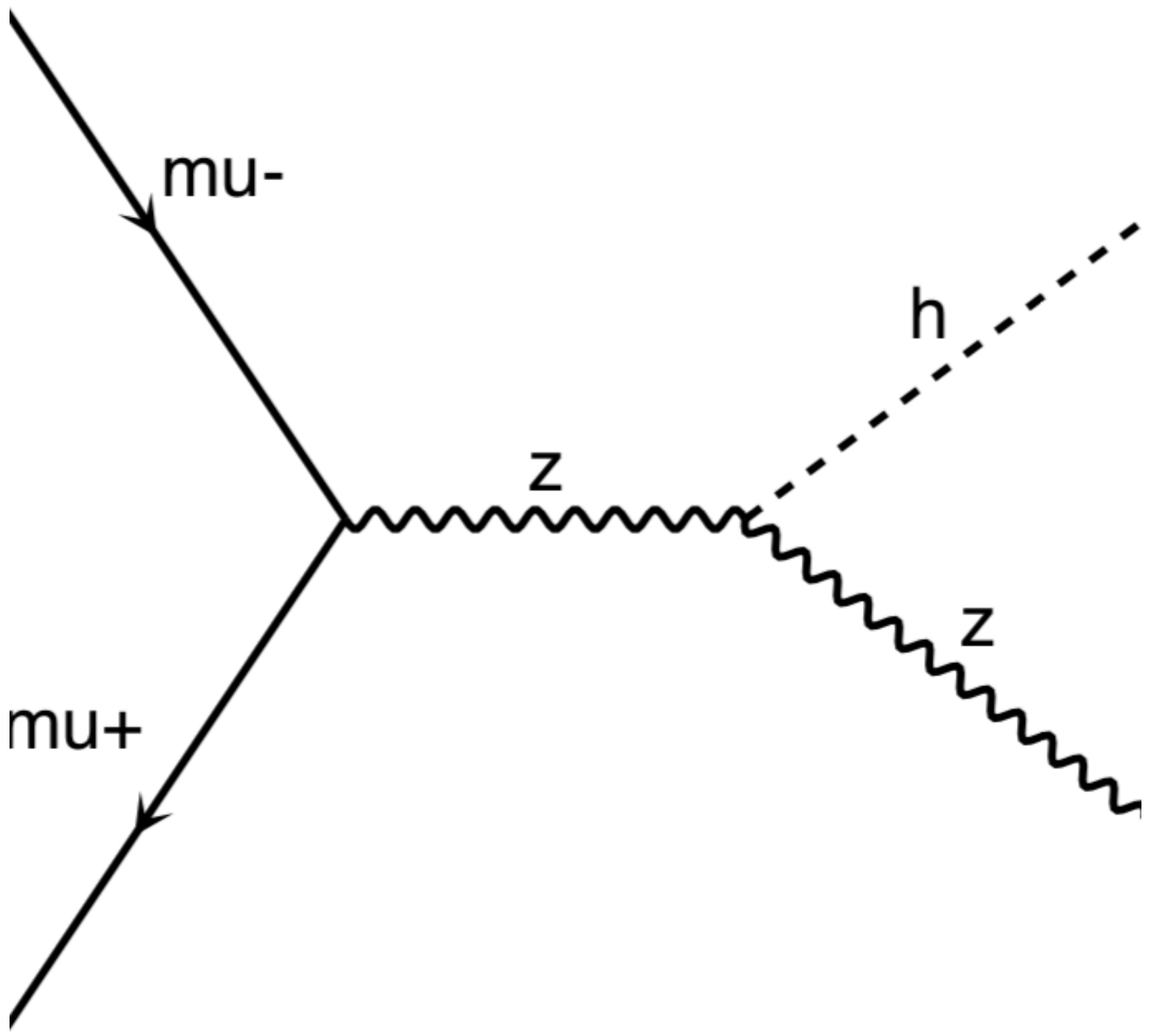
"Major" $\gamma\gamma \sim 10^{-3}$ $\sim 10^{3}$ events

$\mu\mu \sim 10^{-4}$ $\sim 10^{2}$ events

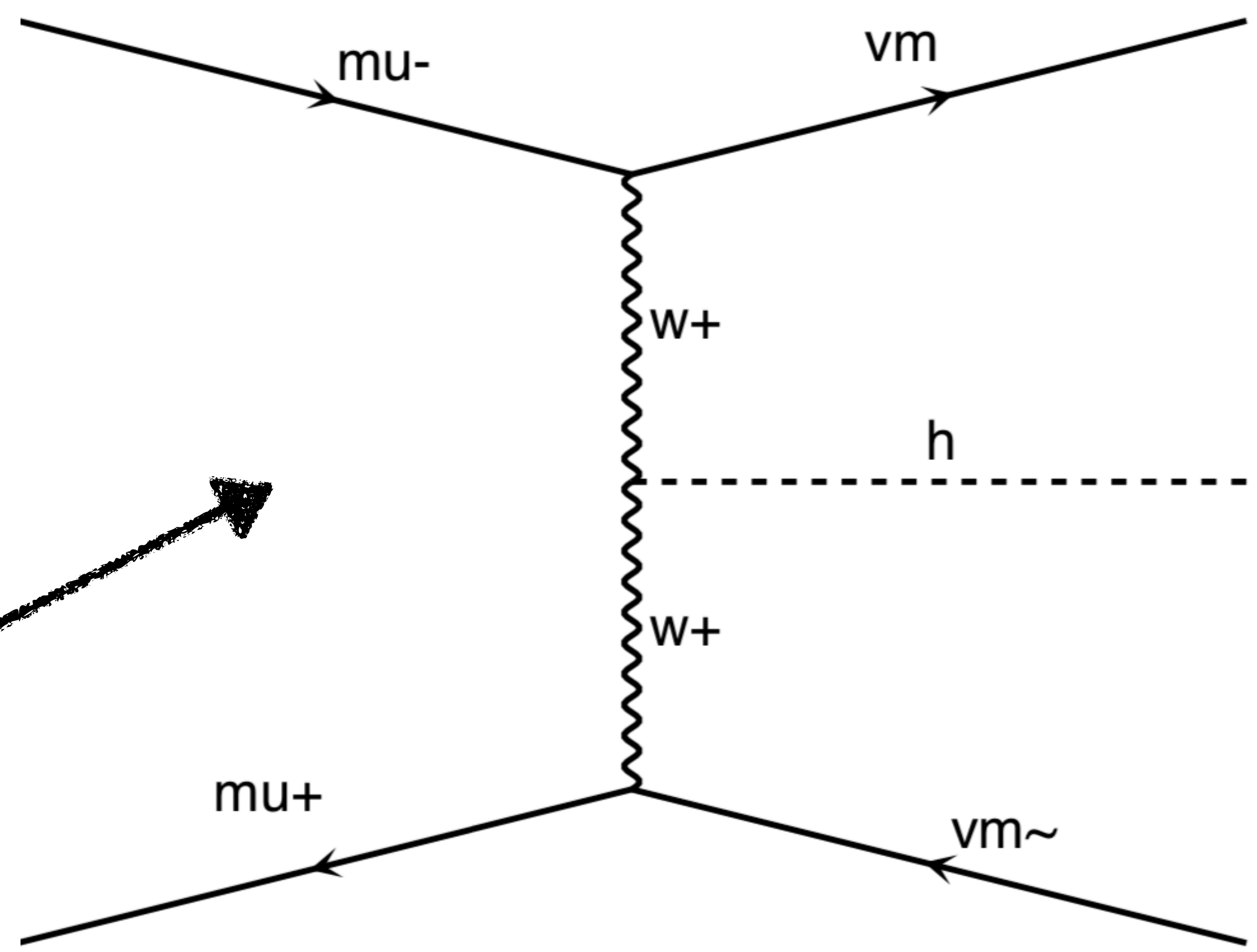
$ss \sim 10^{-4}$

$u/d/e \sim 10^{-8}$ CRAP!!

To complete the SM we need more luminosity *or* more energy



$$\sim \frac{1}{E^2}$$

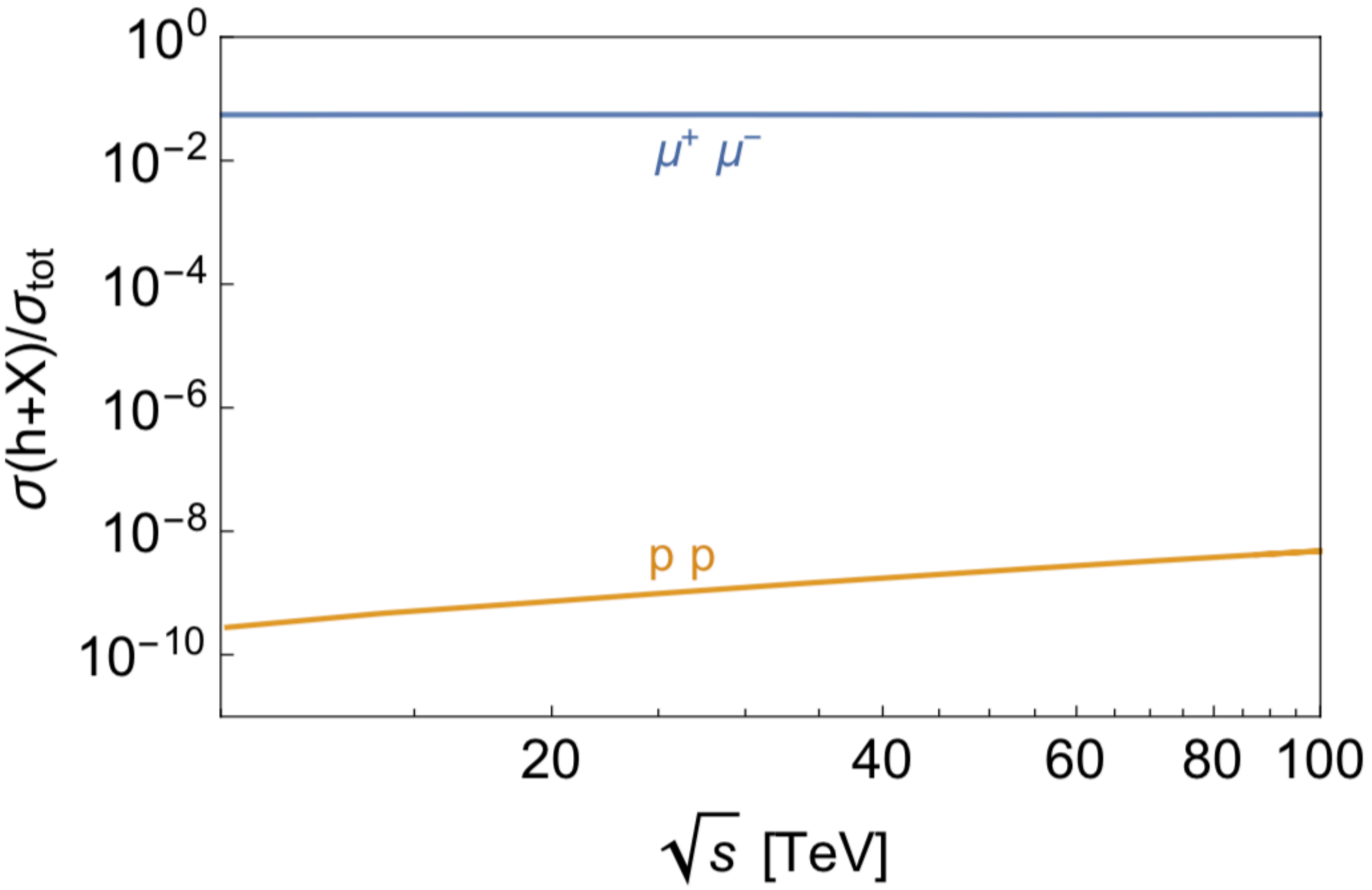


$$\sim \log E^2$$

Winner at moderate energies!

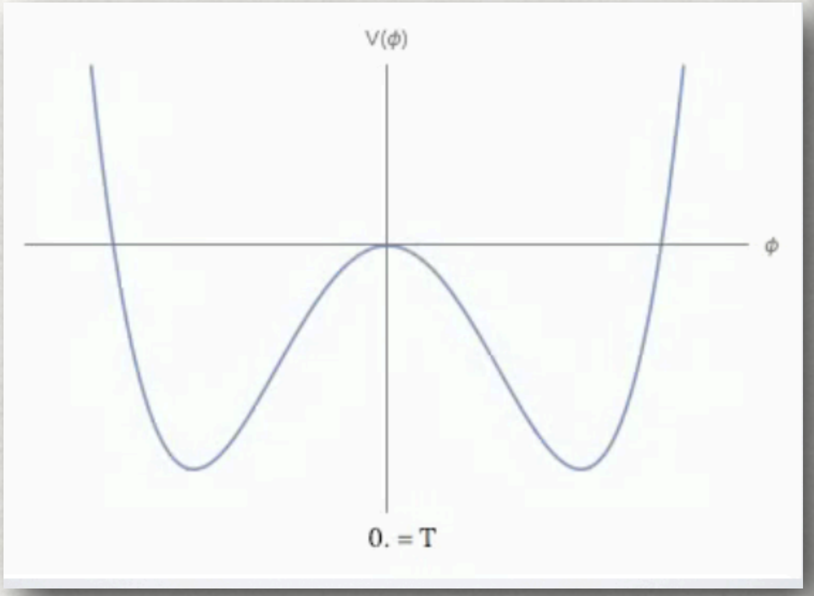
Can think of this as VV to H fusion, with VV initial states (PDF like for hadron colliders)

We also need a clean environment!



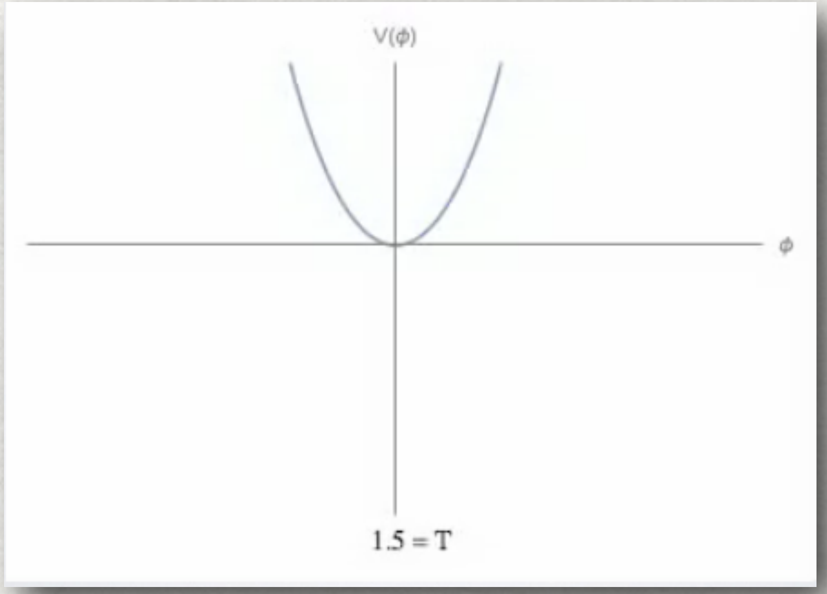
FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION

Imperfect analogy:



Universe now

Early universe was hotter!



Early Universe

FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION

Imperfect analogy:

Universe now

Early universe
was hotter!

Early Universe????????????

PM, H. Ramani
1807.07578

Unrestored Electroweak Symmetry

Multi-Higgs results

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Table 7: Summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

2008.12204 T. Han, D. Liu, I. Low, X. Wang

What's our cosmological History?
What's the Higgs potential?
What's our Cosmological Future?

$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only, acceptance cuts		
		1 σ	2 σ	3 σ
6	12	$[-0.50, 0.70]$	$[-0.74, 0.95]$	$[-0.93, 1.15]$
10	20	$[-0.37, 0.54]$	$[-0.55, 0.72]$	$[-0.69, 0.85]$
14	33	$[-0.28, 0.43]$	$[-0.42, 0.58]$	$[-0.52, 0.68]$
30	100	$[-0.15, 0.30]$	$[-0.24, 0.38]$	$[-0.30, 0.45]$
3	100	$[-0.34, 0.64]$	$[-0.53, 0.82]$	$[-0.67, 0.97]$

Table 6: Constraints on δ_4 ($\delta_3 = 0$) for the c.m. energies and the instantaneous luminosities in table 1 once the geometric acceptance cuts $p_T > 20$ GeV and $|\eta| < 3$ are applied to the Higgs decay products. The bounds are obtained from the total expected cross sections for the process $\mu^+\mu^- \to HHH\nu\bar{\nu}$. The Higgs bosons are produced on-shell and decayed to $b\bar{b}$ pairs but no branching ratio is applied.

Triple Higgs bounds!!!

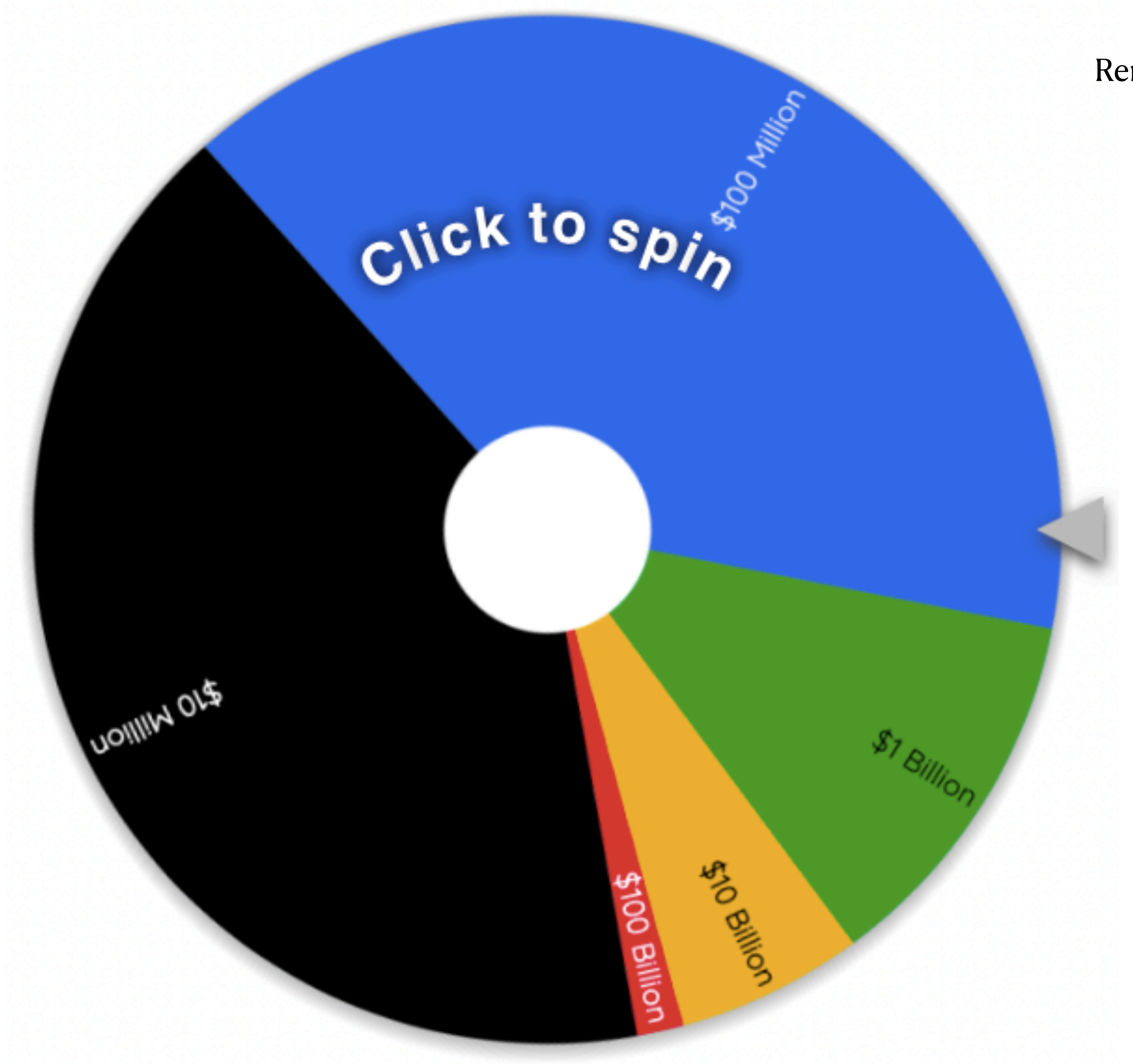
2003.13628 M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini, X. Zhao

We NEED energy to answer these questions

What's the takeaway from this for the Higgs? That *potentially* there is...

What’s realistic?

DOE new funding for new HEP projects?



Remember **our field** has more remembered trauma than our Government!

Members of Congress that were there in 1993
SSC
7/100 Senators
26/435 House Members

Conclusions

- There are numerous questions that a muon collider can go after, and many in particle physics that *need* energy
    - A Higgs factory isn't *just* a low energy thing!
- There are many things pointing to the 10 TeV energy scale as interesting
- I just chose a few but I'm happy to answer questions!
    - Synergy with muon anomalies?
- The multipurpose nature of the project justifies the cost AND creates incredible synergy in our field (not just technologically like neutrinos), it's not a one off!
- R&D is a must if we want to go forwards!