Physics Case for the 10 TeV Scale: Muon Collider and FCC-hh

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*And don't forget about WFA e^+e^-

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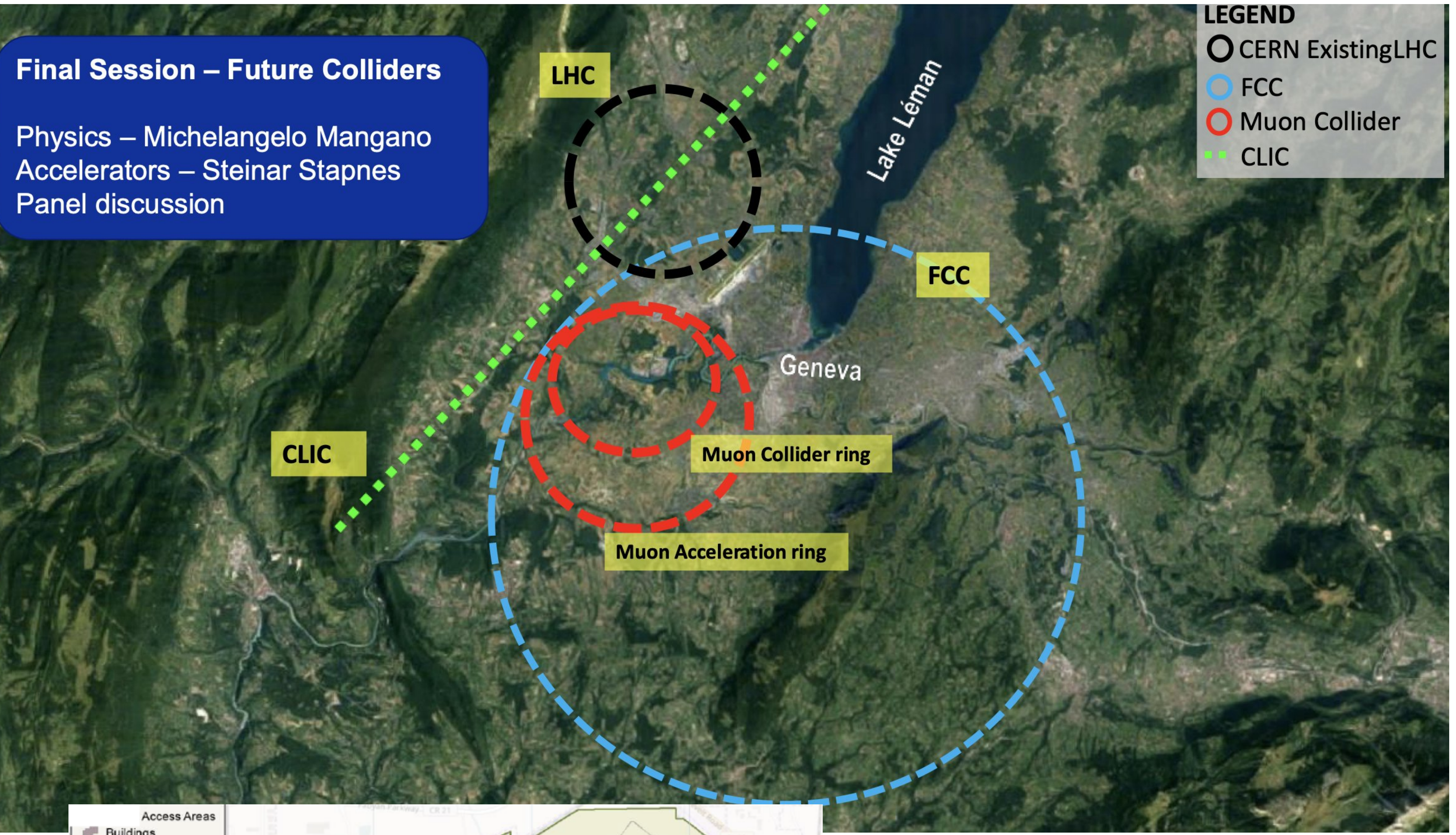
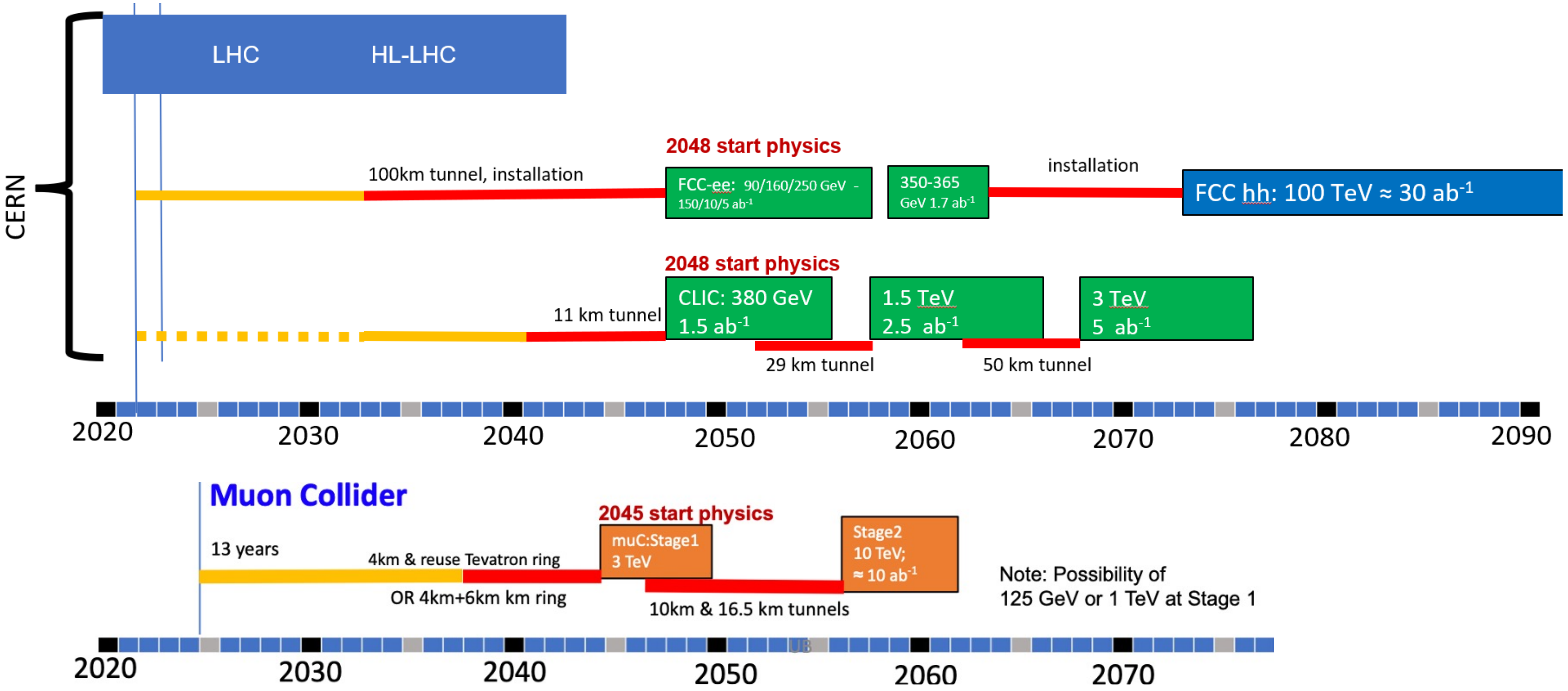
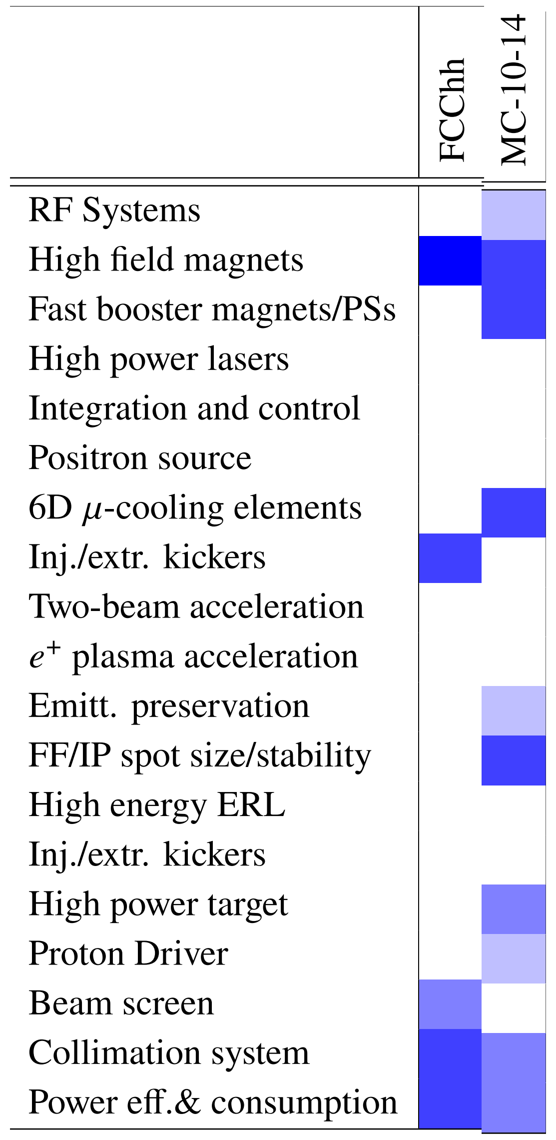
A single talk on μCol and FCC?





Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
MC (14 TeV)	~300	27 km	III	III
FCC-hh (100 TeV)	~560	91 km	II	III



A single talk on μCol and FCC?

Naively as projects they don’t have a lot in common

Different particles, size, locations, staging, power, carbon footprint, cost, component readiness, timelines, staging, etc.
(most of this is for the SLAC town hall)

So what’s the unifying theme that also makes it easy to put them in one talk?

FCC-hh (100 TeV)	~560	91 km	II	III

Proton Driver		
Beam screen		
Collimation system		
Power eff.& consumption		

Energy!

These were the two options investigated in the most detail during Snowmass for the "Energy Frontier" of the… Energy Frontier

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If you have an e^+e^- with identical beam properties to a μCol the physics reach will be similar (although there are subtle differences you can ask me about)

So, as a theorist…

However, what I hope to convince you is there is both an *urgency* <u>and</u> *a physics case* for 10 TeV already!

This is why the EF report emphasized work in *parallel* on Higgs Factories and Multi-TeV machines not sequentially!

The Energy Frontier Report

2021 US Community Study on the Future of Particle Physics

organized by the APS Division of Particles and Fields

The US EF community has also expressed renewed interest and ambition to bring back energy-frontier collider physics to the US soil while maintaining its international collaborative partnerships and obligations.

For the five year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs factory detector R&D program,
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US,
4. Support critical detector R&D towards EF multi-TeV colliders.

For the five year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support construction of an e^+e^- Higgs factory,
3. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders.

Any inferred sequencing of HF and multi-TeV stems from the fact that unfortunately we're not ready to build a 10 TeV scale machine *yet*

HF represent a good opportunity now, *not* a fundamental ordering

So what does the 10 TeV scale case rest on?

New
experimental
data

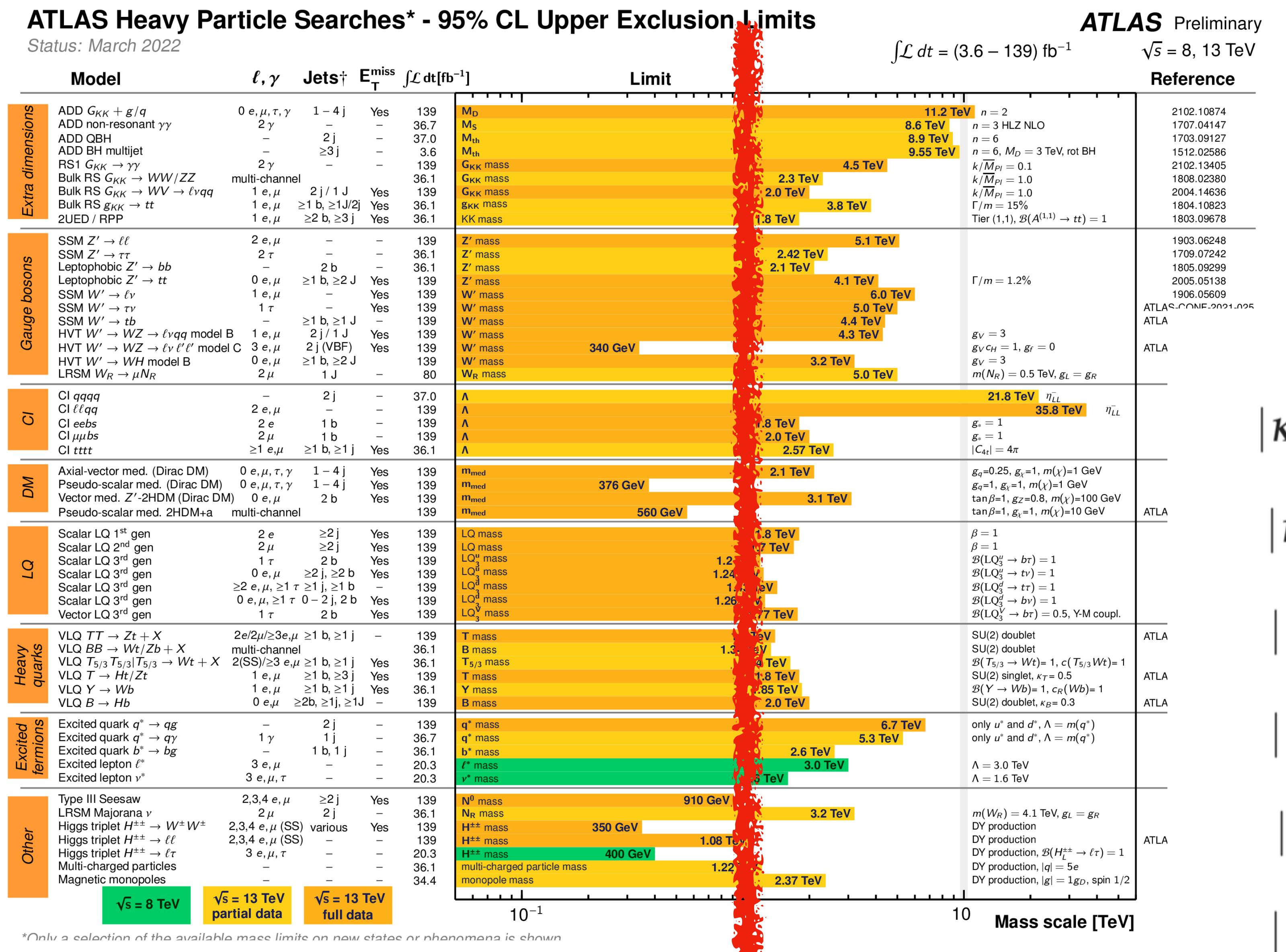
Theoretical
understanding
of data

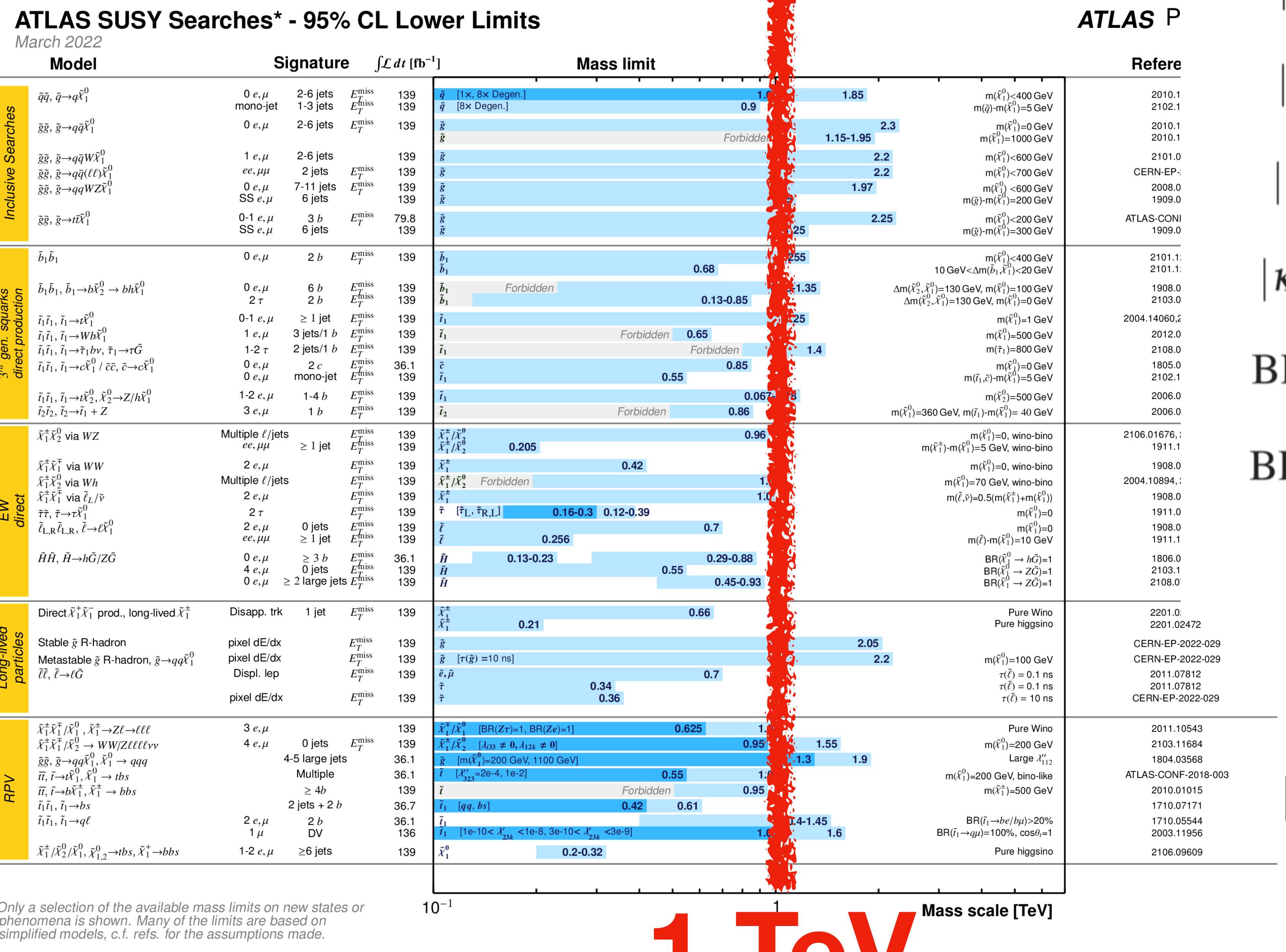
Theoretical
advances

The physics landscape evolves!

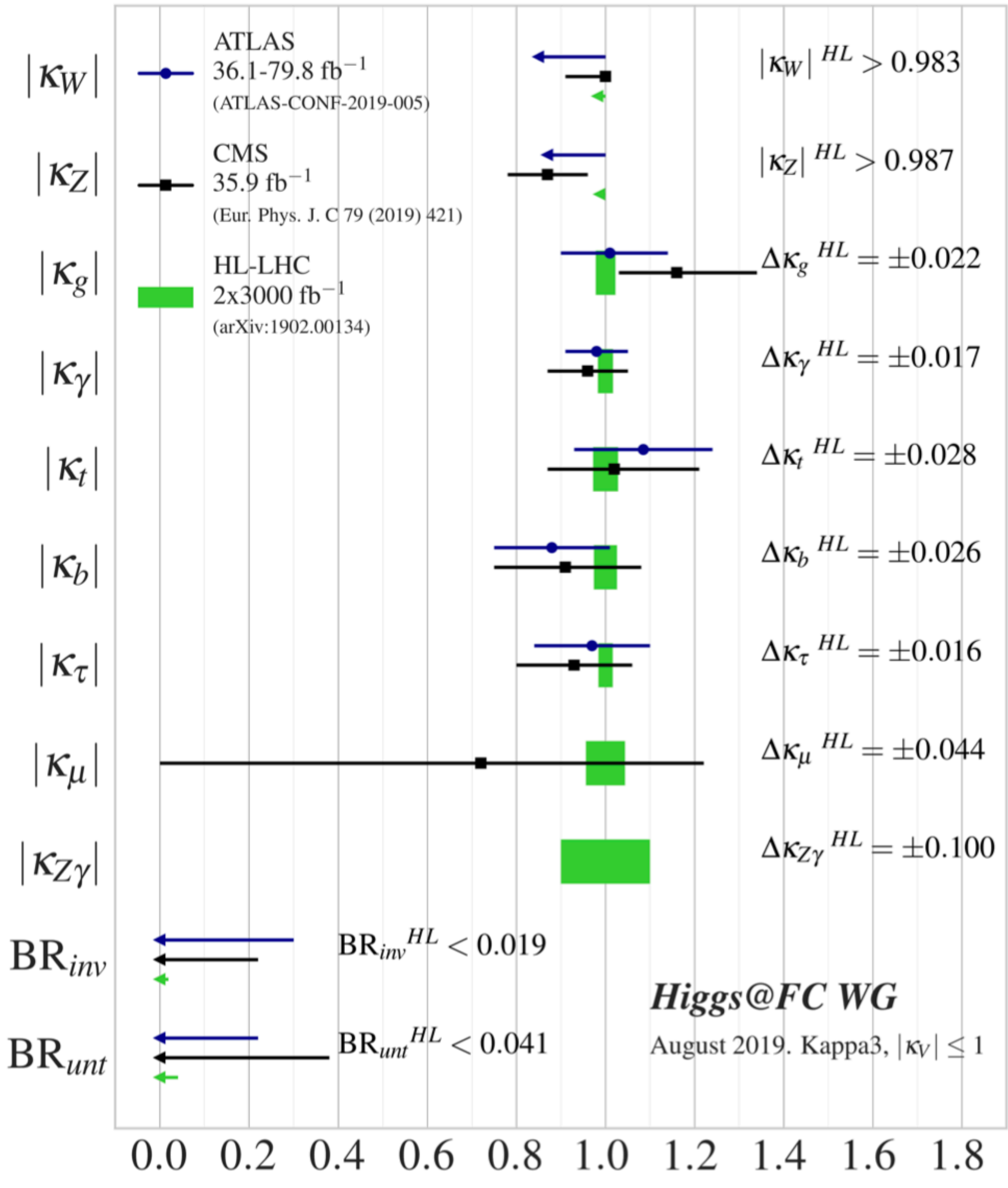
Generic Lessons from LHC?

The physics landscape has significantly changed since 2013 P5 -
13 TeV LHC hadn't even started!





1 TeV



~1% tests on Higgs
Implies roughly the ~ TeV scale for NP which could cause such a deviation

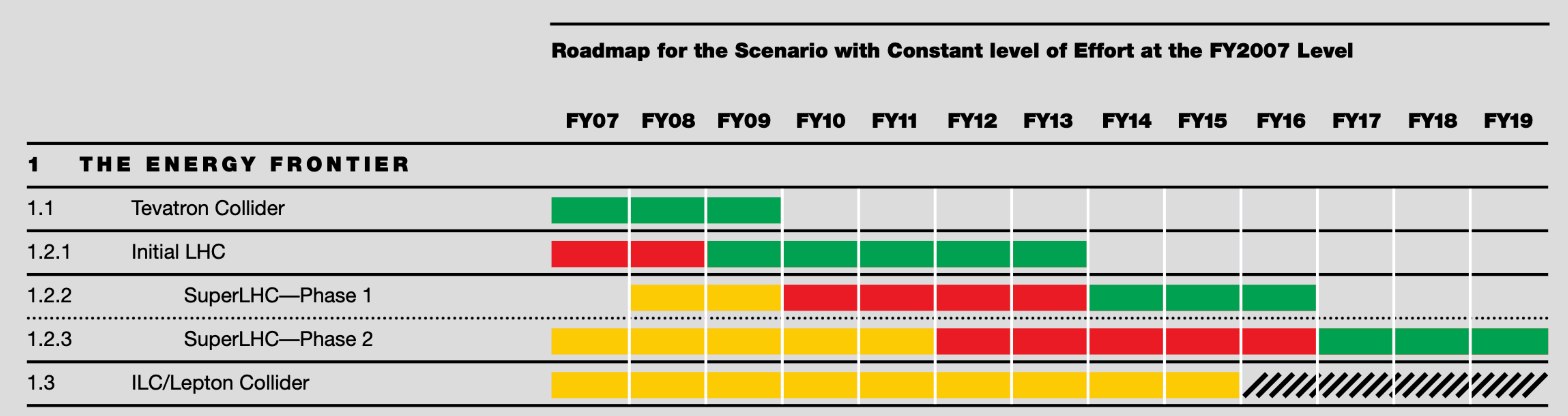
There *could* still be new physics at LHC/HL-LHC… but we need to invest *NOW in R&D*

<u>Data</u> suggests generically there is a *gap* from EW scale to scale of New Physics

We need to be able to probe ≫1 TeV

10 TeV is interesting as a step into unknown but <u>*also*</u> for *physics targets*

Just to assuage any HL-LHC fears



KEY
R&D
Contruction
Operation

The approximate timescales for R&D (yellow), construction (red) and operation (green) are indicated. Line 1.3 reflects the uncertain timescale of a lepton collider. If LHC results point to a 500 GeV collider, the international community could select the ILC and decide on a construction start at that time. In this roadmap we indicate a possible construction start for an international project late in the next decade with black shading. If LHC results indicate that a higher-energy lepton collider is required, R&D after 2012 or so will shift to the new technology required for such a collider. On line 3.6, High Energy Particles from Space, the program beyond 2012 will be addressed by the proposed HEPAP subpanel on particle astrophysics; this is indicated by black shading past 2013 on the roadmap.

Preparing for the future *isn't* crazy just look 2 P5's ago

If the lesson of the LHC is Higgs + nothing...

Isn't a Higgs factory sufficient?

Since then (1990s), the paths of different colliders have diverged: **hadron colliders continued the quest for record high energies** in particle reactions and the LHC was built at CERN, while in parallel highly productive **e^+e^- colliders called particle factories focused on precise exploration of rare phenomena at *much lower energies***.

(V. Shiltsev, F. Zimmermann 2021 Reviews of Modern Physics)

Are record energies a luxury for after a deviation?

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Are record energies a luxury for after a deviation? NO

Why aren't Higgs Factories enough* just for the SM Higgs?

(* don't misinterpret, Higgs factories are great they just don't do everything for SM Higgs and they are long overdue)

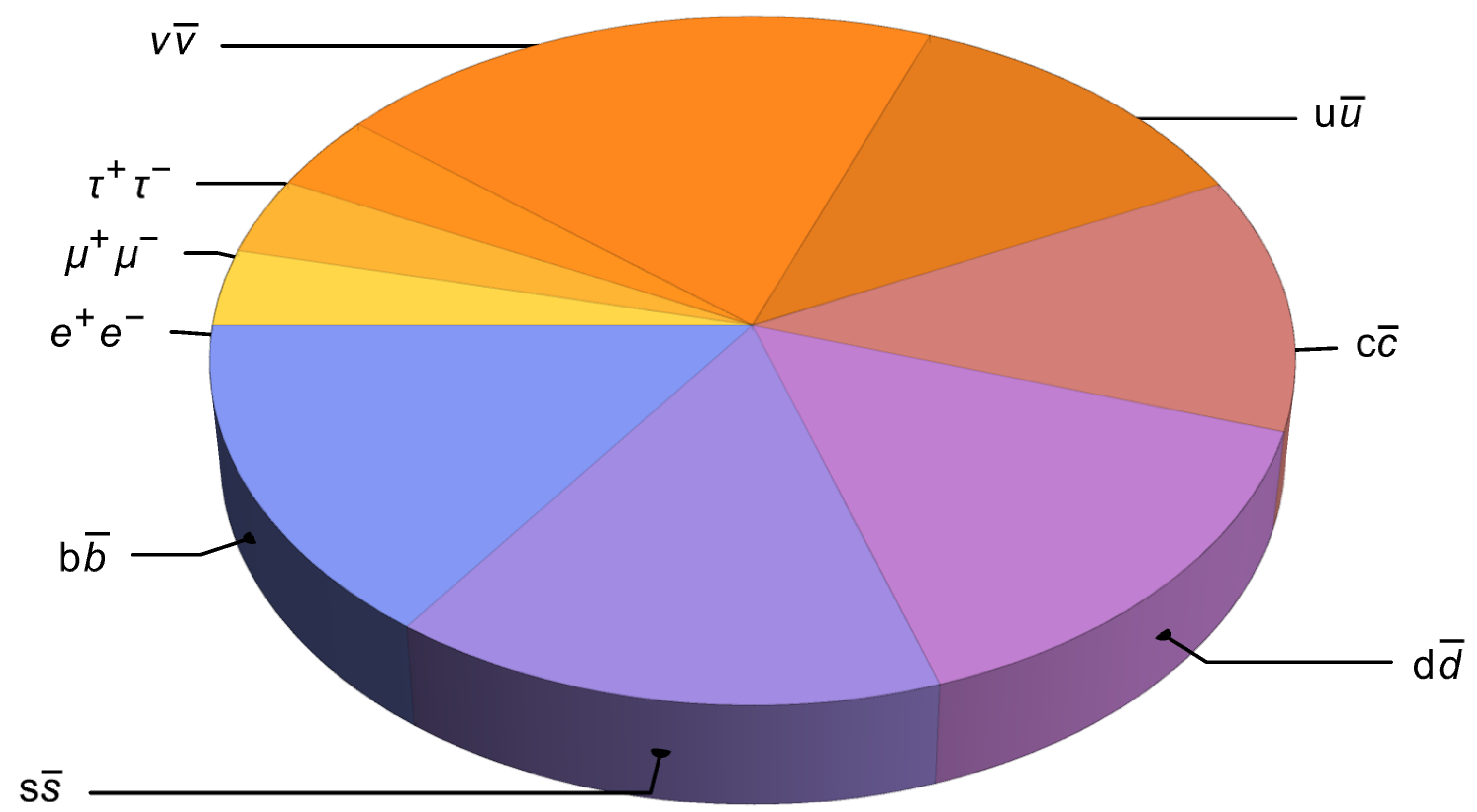
Number of Higgs and Number of *Multiple* Higgs produced at things currently called a Higgs Factory

The SM Higgs is an unprecedented particle.

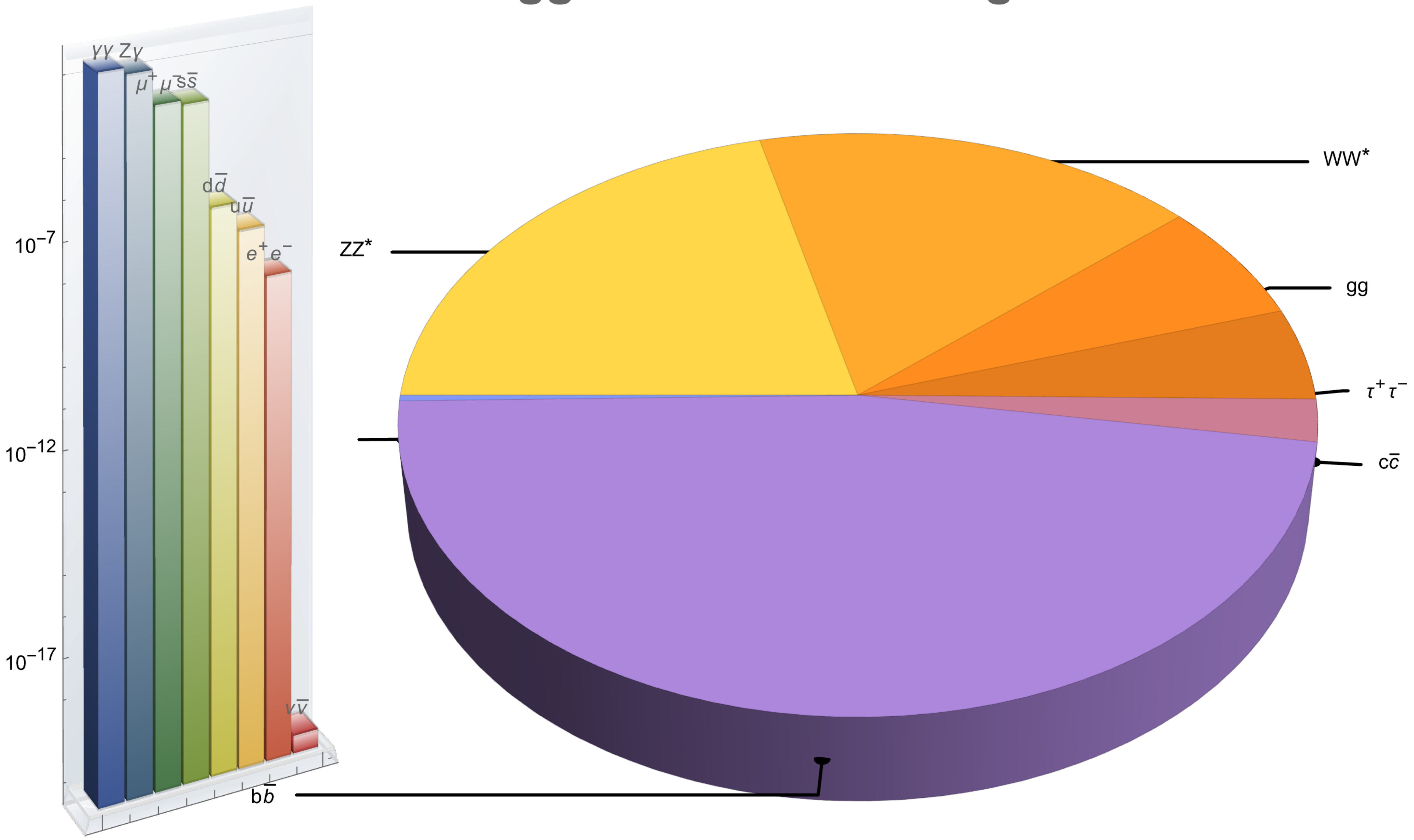
LEP was a Z boson factory and produced ~ 17 Million Z bosons

Higgs Factories produce ~ 1 Million Higgs bosons

Z boson Branching Fractions



Higgs boson Branching Fractions



All major Branching Fractions are $\gtrsim \mathcal{O}(1\%)$

The *same* Higgs Branching Fractions span 8 to 20 ORDERS OF MAGNITUDE or more!

A Higgs factory is a great <u>start</u> but without the ability to increase luminosity by orders of magnitude we *need* more Energy

For a first stage LC or *any* circular Higgs Factory there are effectively *no* Di-Higgs events produced!

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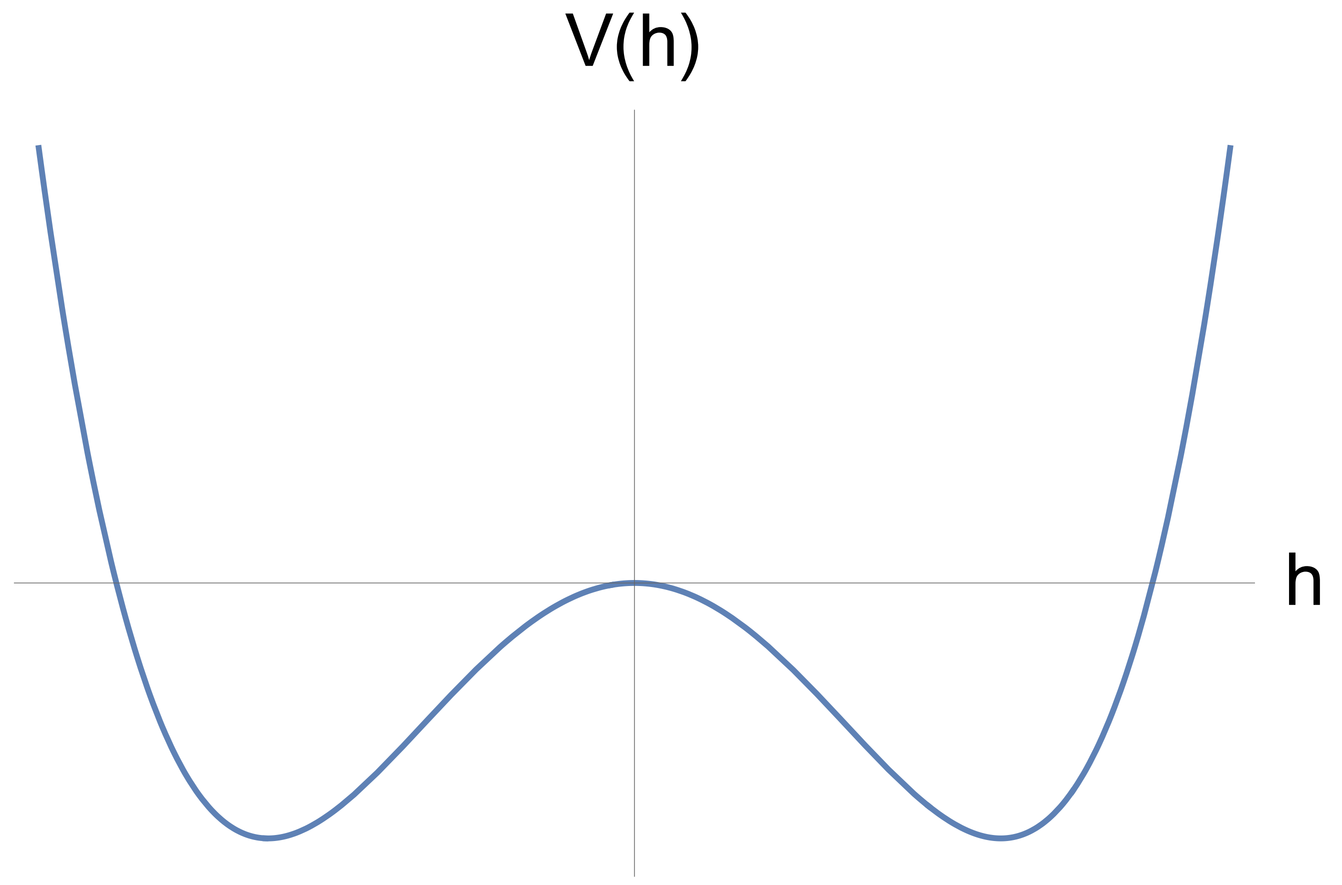
Why does this matter?

Testing the Higgs potential experimentally



$$\left.\frac{\partial V(h)}{\partial h}\right|_{h=v} = 0$$

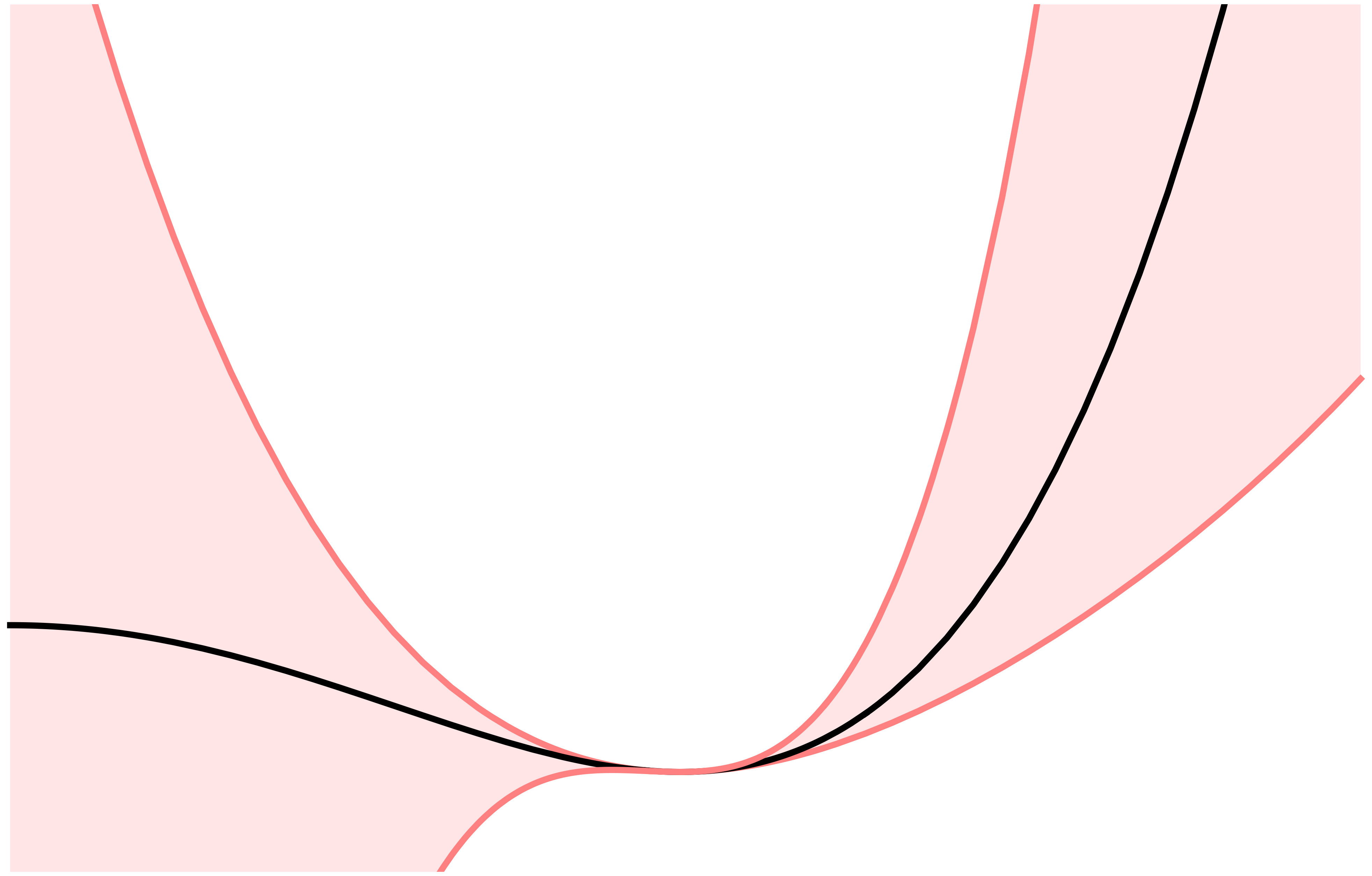
$$\left.\frac{\partial^2 V(h)}{\partial h^2}\right|_{h=v} = m_h^2$$

+ more derivatives = self-interactions

Experimentally we look for multi-Higgs production

Can we demonstrate the *qualitatively* new self coupling and test the validity of SM? (BSM later)

Current status of LHC Higgs Potential Measurements?



H/T N.Craig, R. Petrossian-Byrne

Final state	Collaboration	allowed κ_λ interval at 95% CL observed	expected
$b\bar{b}b\bar{b}$	ATLAS	-3.5 – 11.3	-5.4 – 11.4
	CMS	-2.3 – 9.4	-5.0 – 12.0
$b\bar{b}\tau^+\tau^-$	ATLAS	-2.4 – 9.2	-2.0 – 9.0
	CMS	-1.7 – 8.7	-2.9 – 9.8
$b\bar{b}\gamma\gamma$	ATLAS	-1.6 – 6.7	-2.4 – 7.7
	CMS	-3.3 – 8.5	-2.5 – 8.2
comb	ATLAS	-0.6 – 6.6	-1.0 – 7.1
	CMS	-1.2 – 6.8	-0.9 – 7.1

Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510

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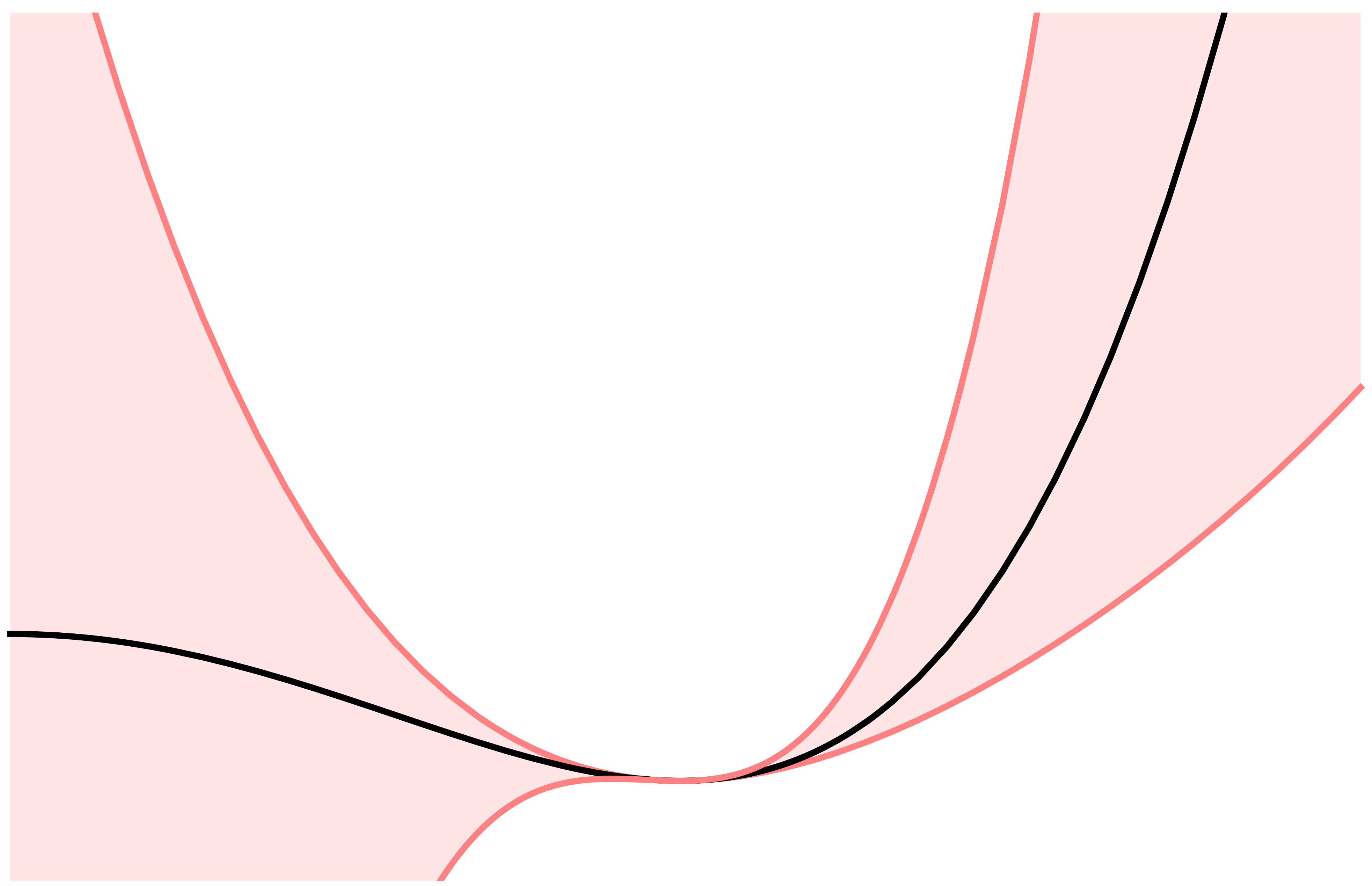
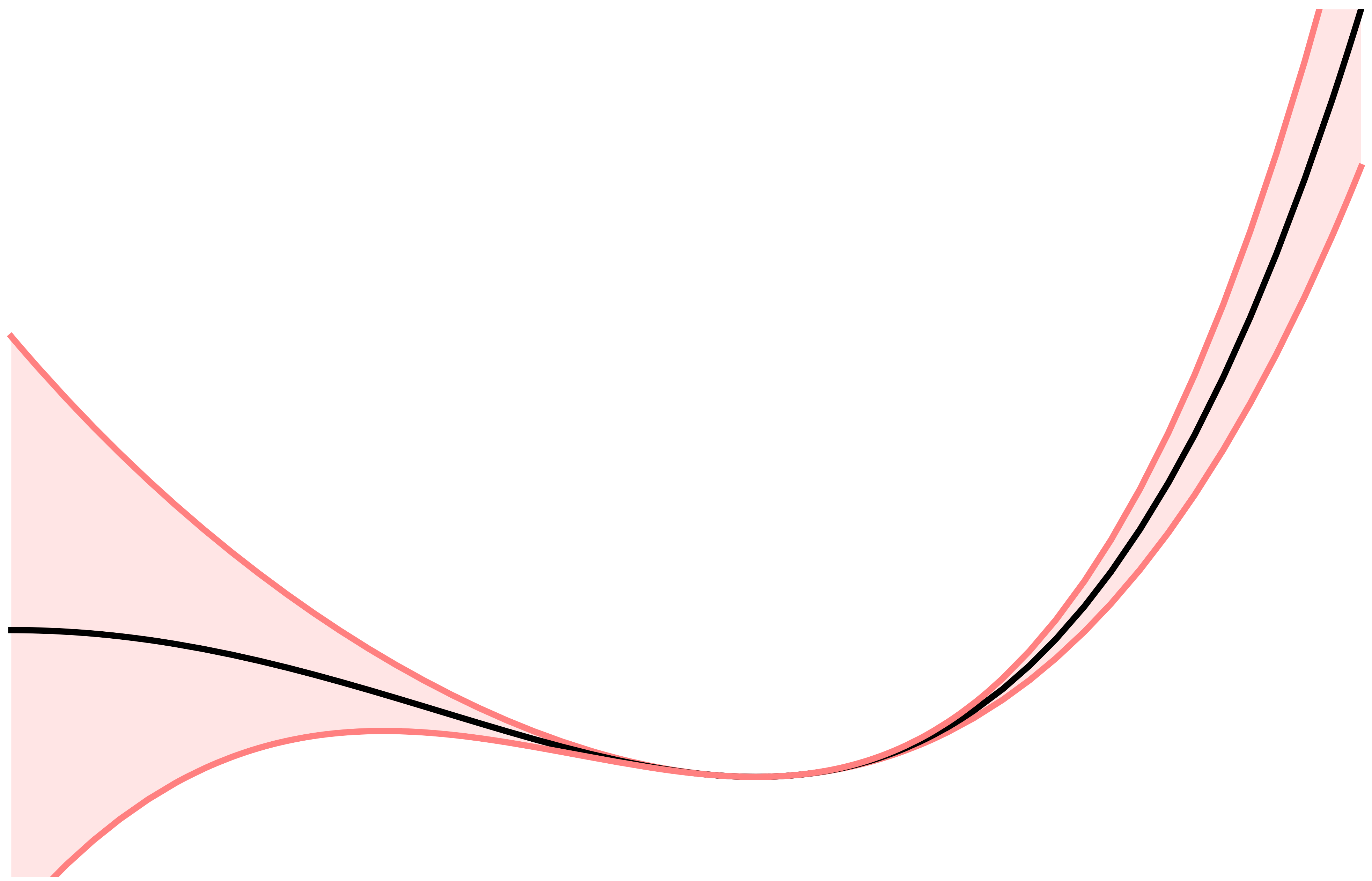
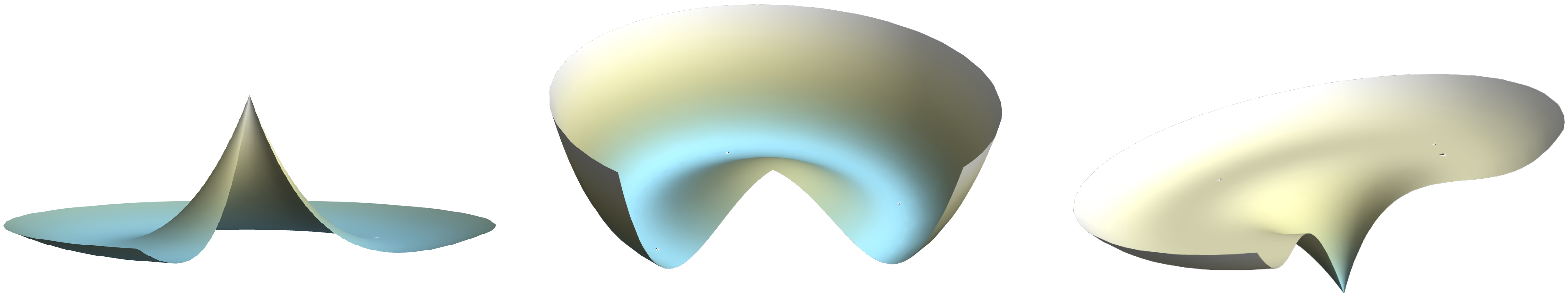




H/T N.Craig, R. Petrossian-Byrne

Current LHC → **HL-LHC**

Current status of LHC Higgs Potential Measurements?



We clearly need to do better and we *must* have <u>higher energies</u> *beyond the LHC* to do so!

Even if we *only* care about the SM Higgs we'd actively need to pursue R&D for higher Energy to have any hope of "completing" the SM

Energy → Precision

How much Precision/Energy is needed?
Are there other arguments for a *scale* other than going beyond LHC/HF? →

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Energy $\longrightarrow$ **Precision**

How much Precision/Energy is needed?
Are there other arguments for a *scale* other than going beyond LHC/HF?

$\longrightarrow$ Must ask sharper questions about physics (BSM)

Potential Foundational Physics Cases for High Energy Colliders

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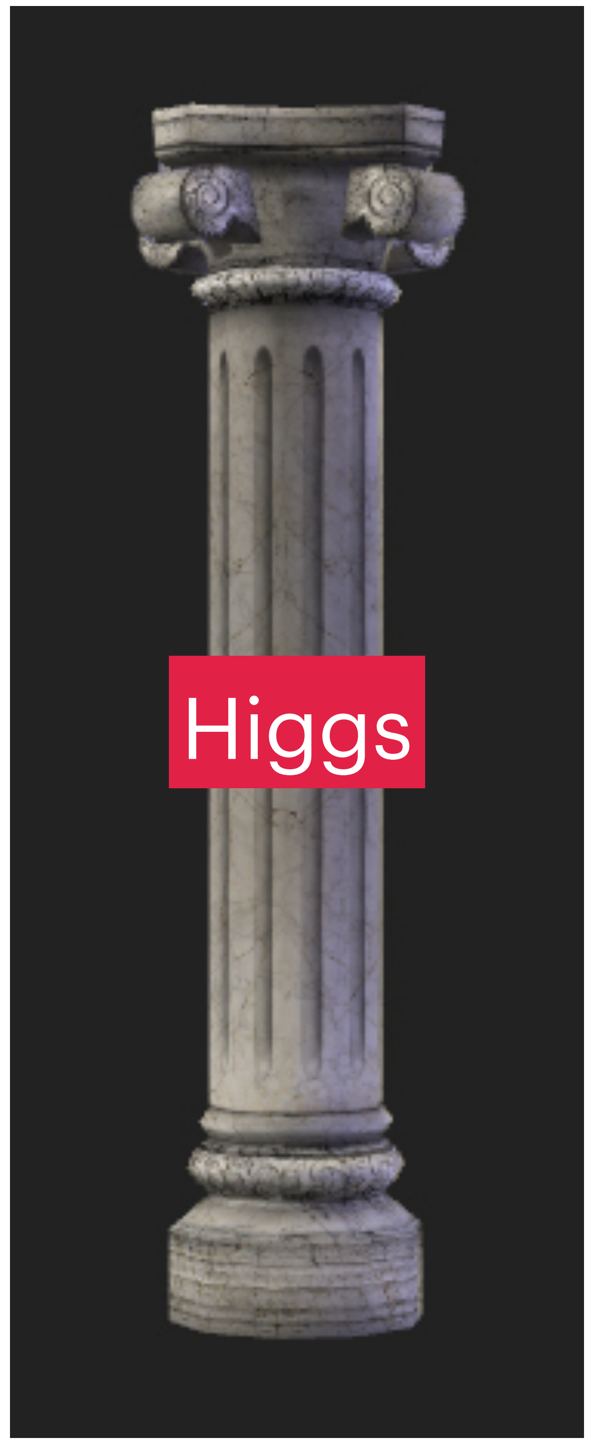
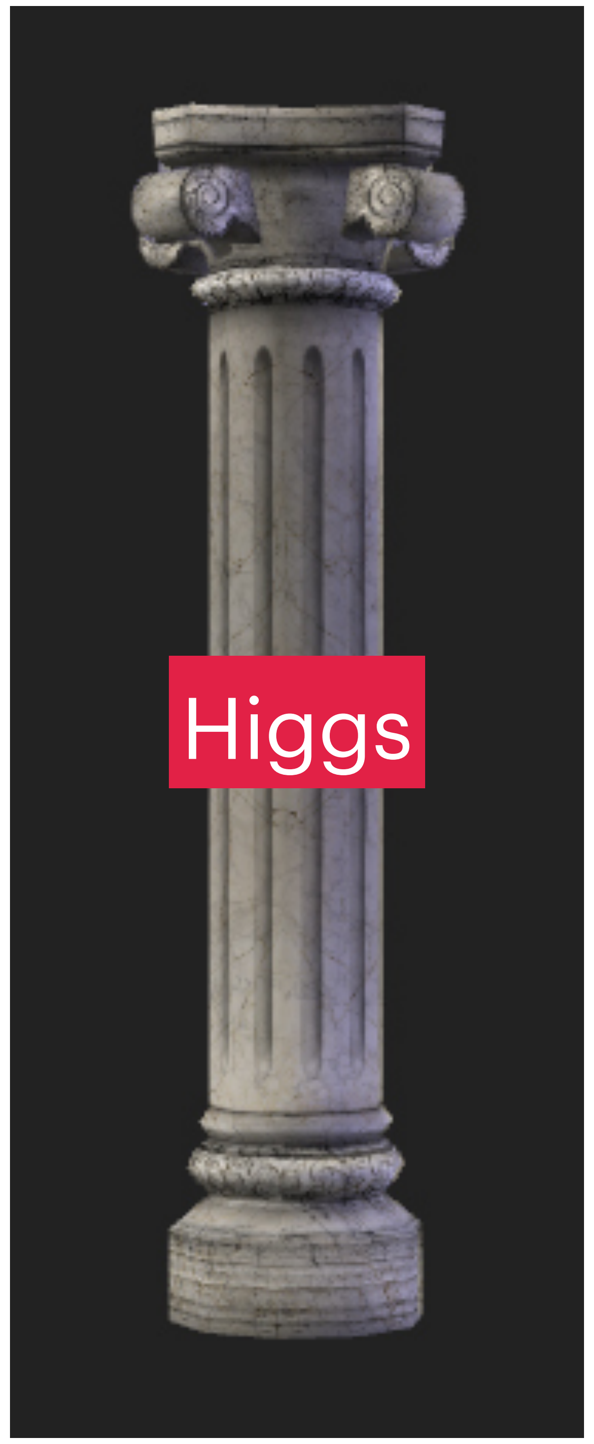


+...

The unknown doesn't set a scale...

Potential Foundational Physics Cases for High Energy Colliders

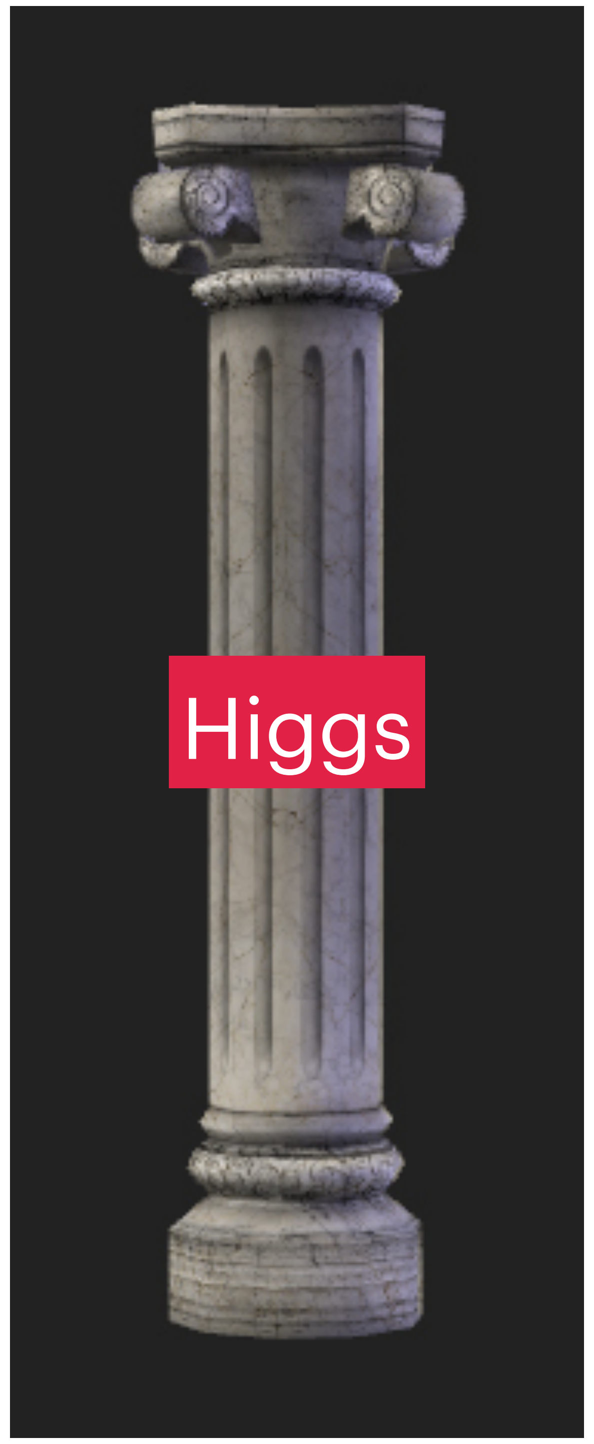


UNKNOWN

+...

and it's harder to get a guaranteed return on the unknown!

Potential Foundational Physics Cases for High Energy Colliders



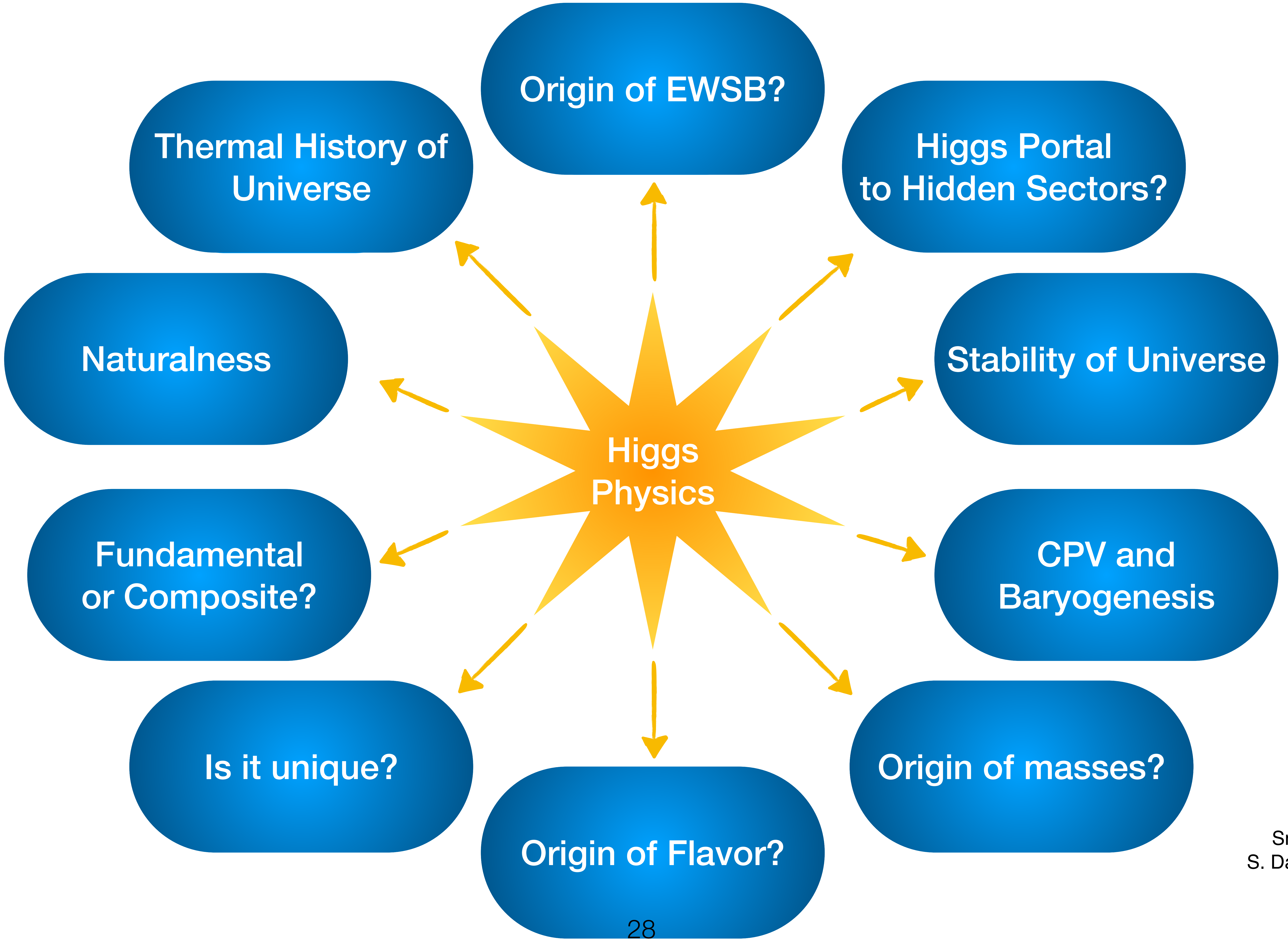
UNKNOWN

Dark Matter

+...

Testing WIMP DM is a pillar but whether it exists is far less certain so let's start with the Higgs

The centrality of the Higgs is **underrated**, not commonly understood, and not appreciated how weird the Higgs actually is!



Snowmass EF Higgs Topical Report
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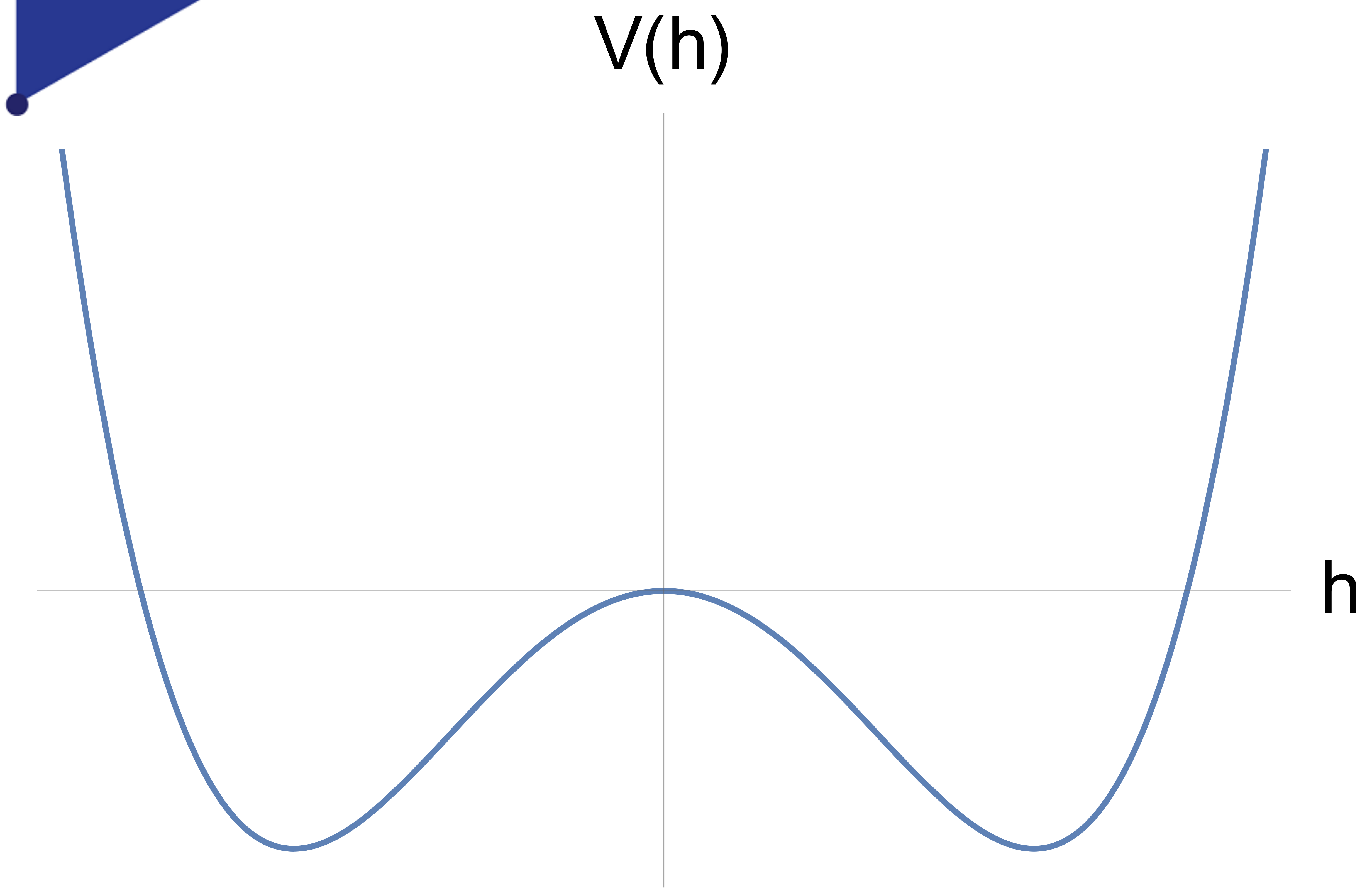
2209.07510

We want to *understand* the origin of EWSB (AKA everything around us)

We want to *understand* the origin of EWSB

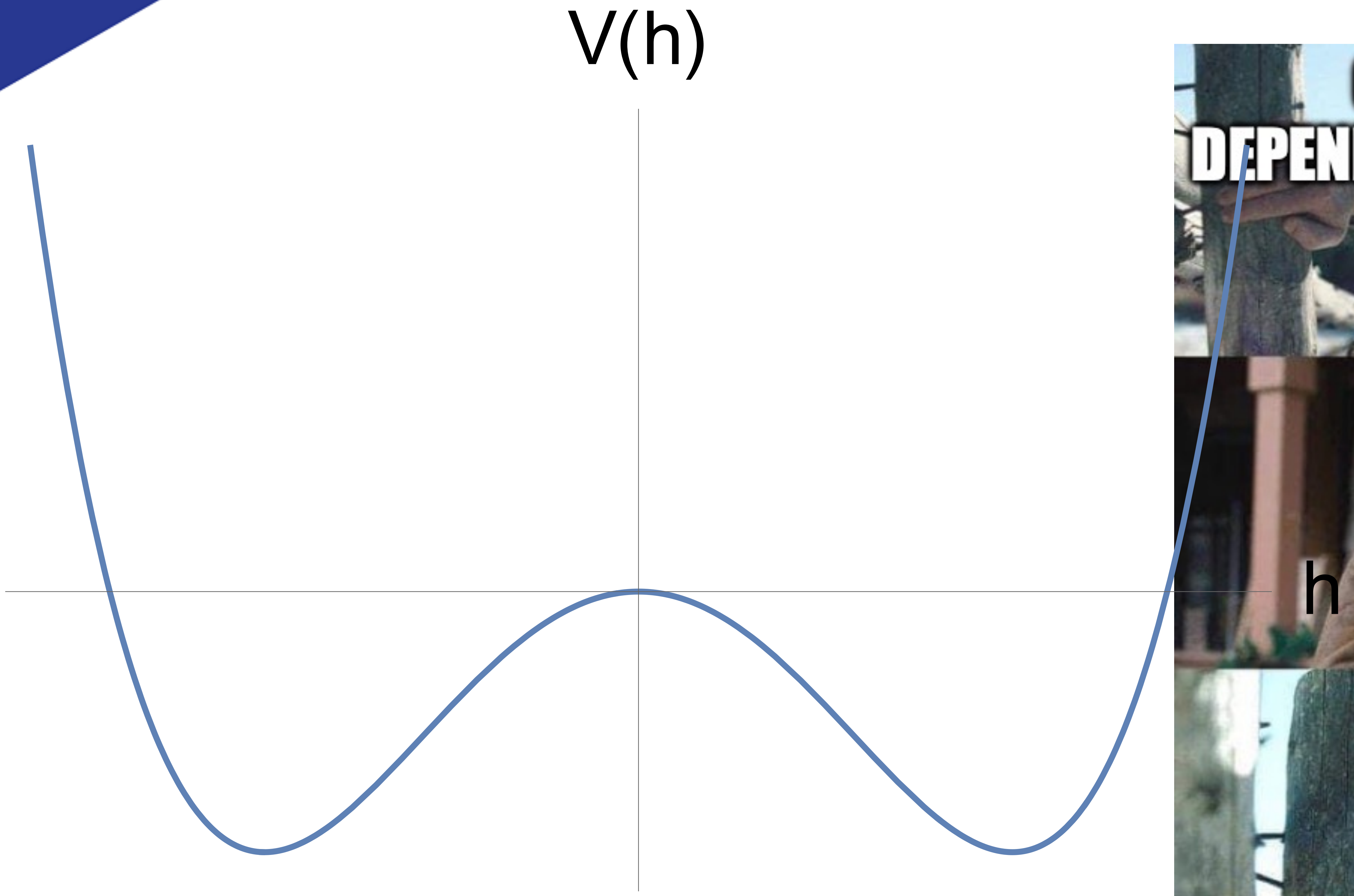
years
HIGGS boson
discovery

Wait what?

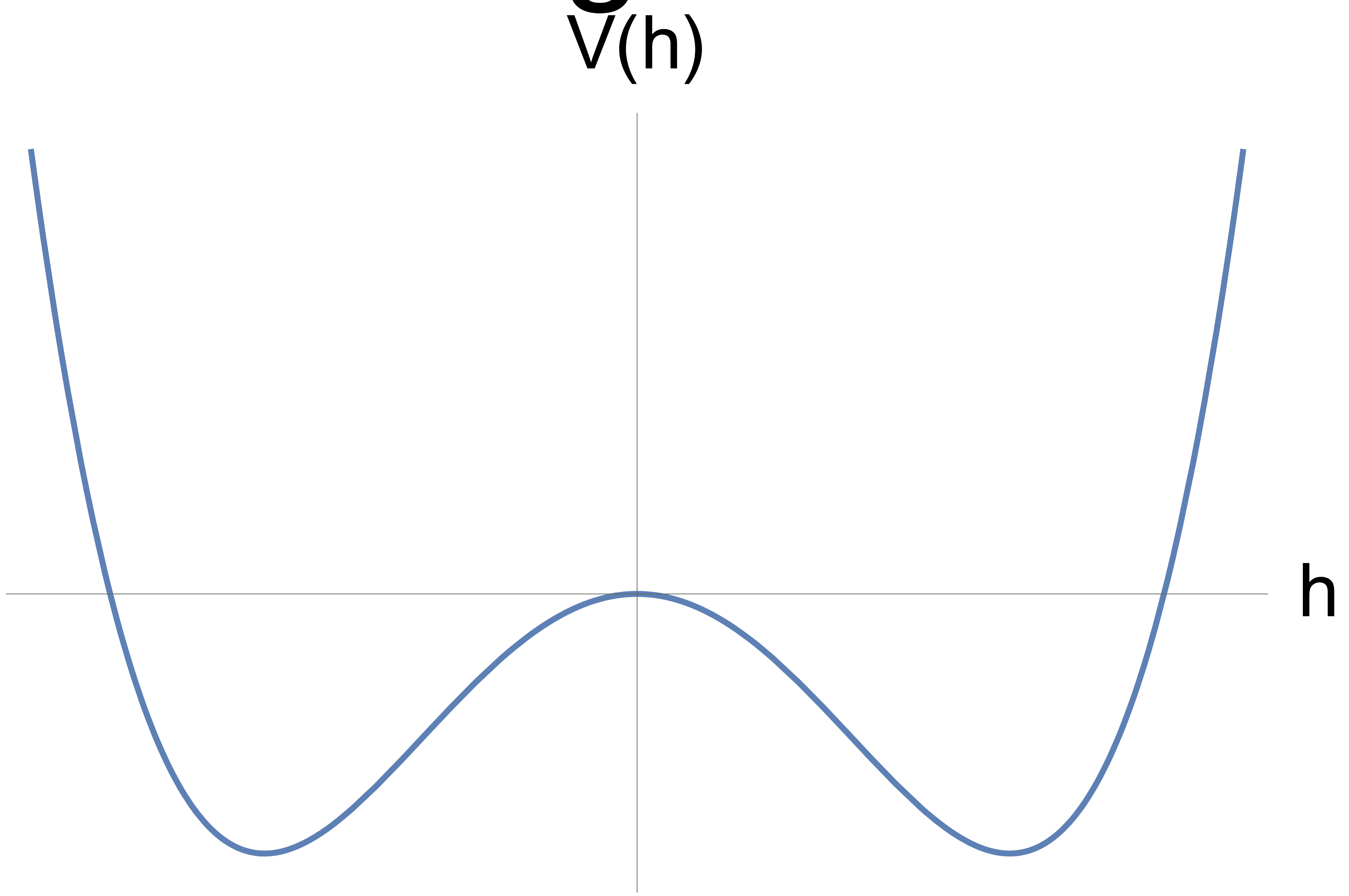


We want to *understand* the origin of EWSB

Wait what?



We want to *understand* the origin of EWSB



A more elegant way pointed out to me by N. Craig is a quote from Frank Close -

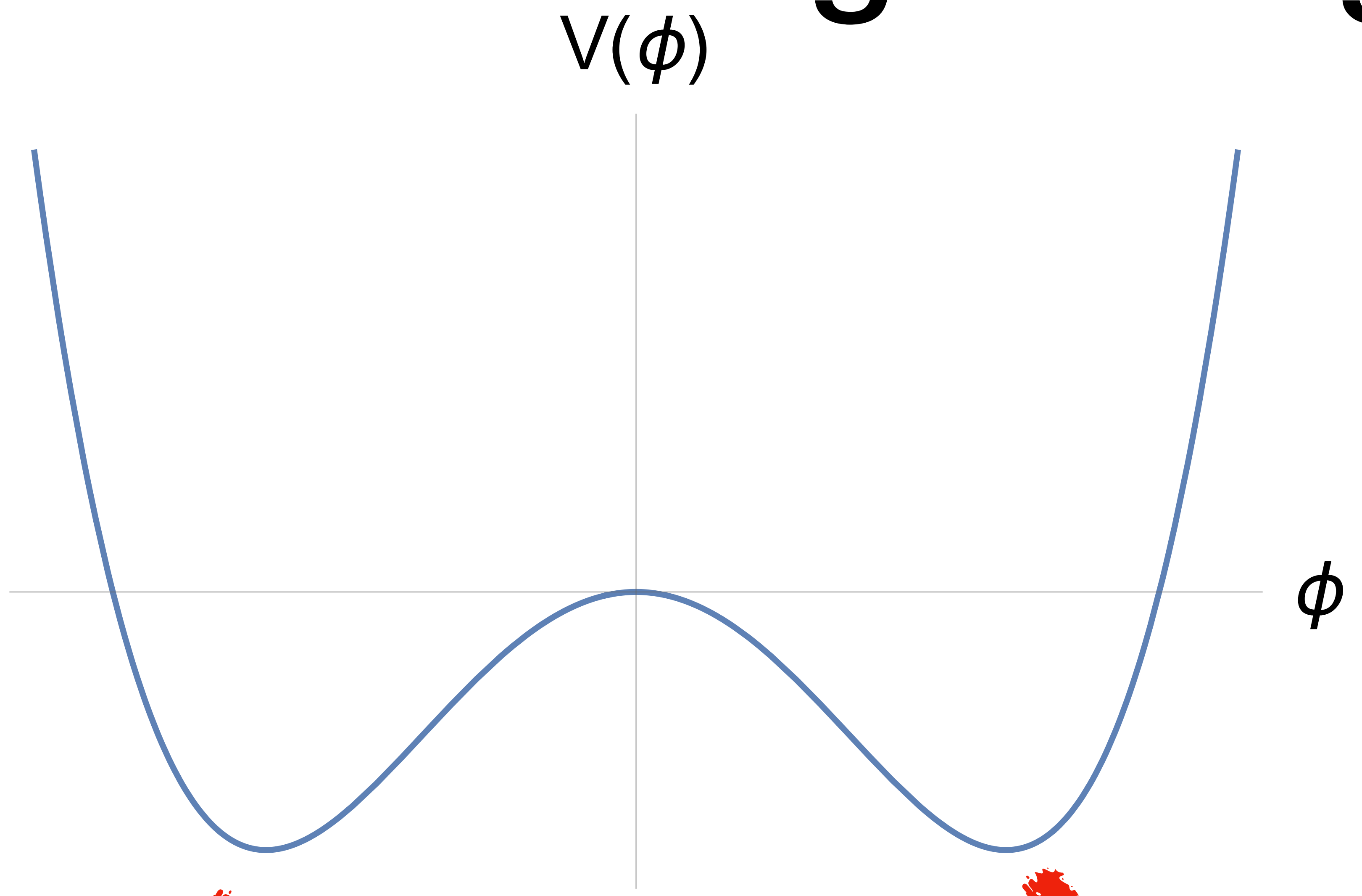
"The more ambitious goal…is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald. "

We want to *understand* the origin of EWSB

Superconducting Analogy

Powerful
phenomenological model

Its effectiveness belies a deeper origin of underlying symmetry breaking



Landau-Ginzburg
Model
1950

Type I superconductor

Type II superconductor

The why? BCS theory (1957)

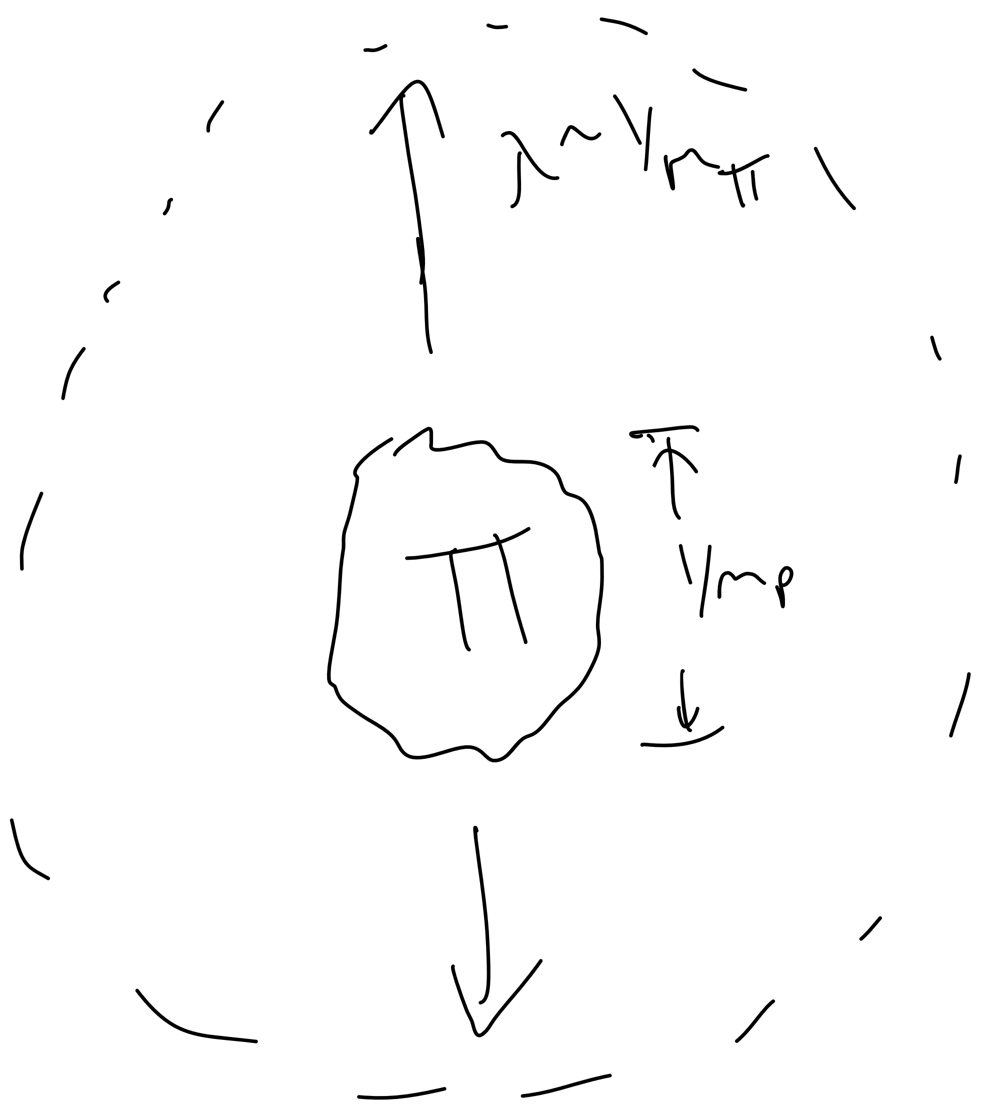
Superexchange?

We want to *understand* the origin of EWSB

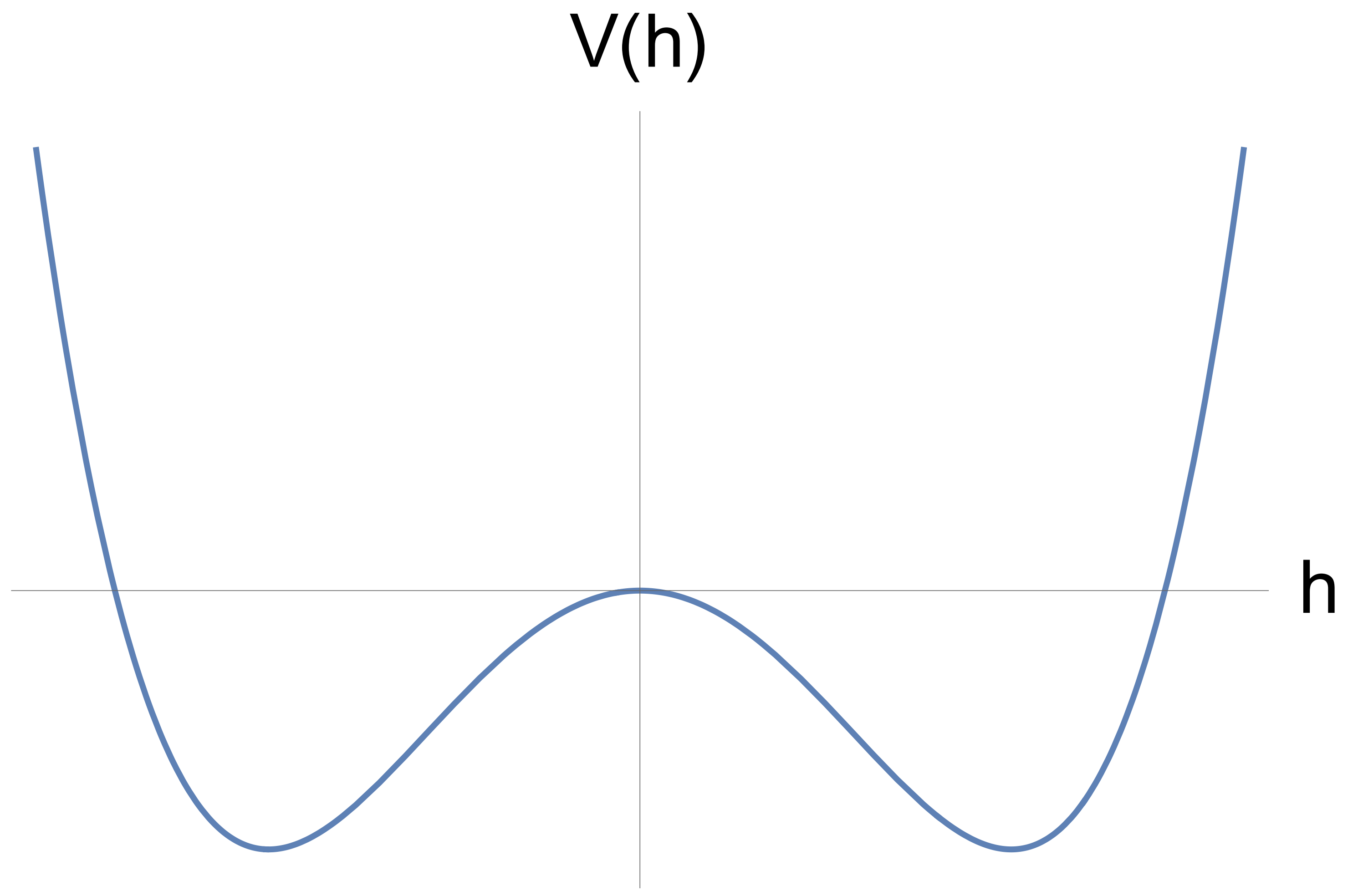
Fundamental or Composite?

Origin of EWSB?

Naturalness



These questions are tightly intertwined



Is the Higgs "pion like"?

Dynamical explanation for EWSB

Search for resonances, constituents at high energy

It is *not* QCD like so effective operators are powerful

If the Higgs is fundamental there still could be a *deeper* origin

SUSY Radiative EWSB

Higgs mass correlation

Corresponding direct searches

Neutral Naturalness

Higgs portal effects

Cosmic Selection

+...

Naturalness/Radiative EWSB

One under appreciated consequence of a *robust* solution of this problem is that it should also "predict" the Higgs mass

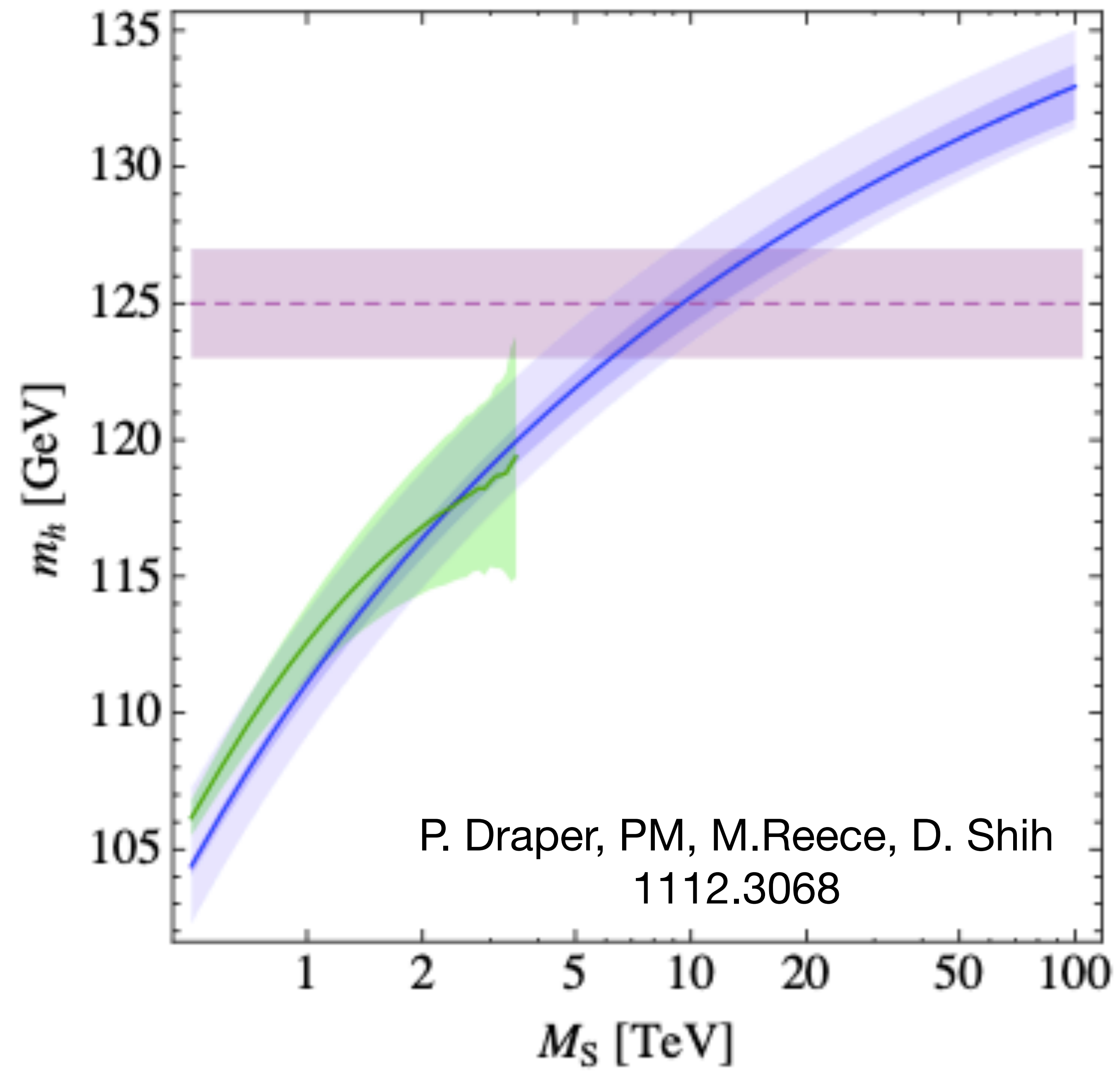


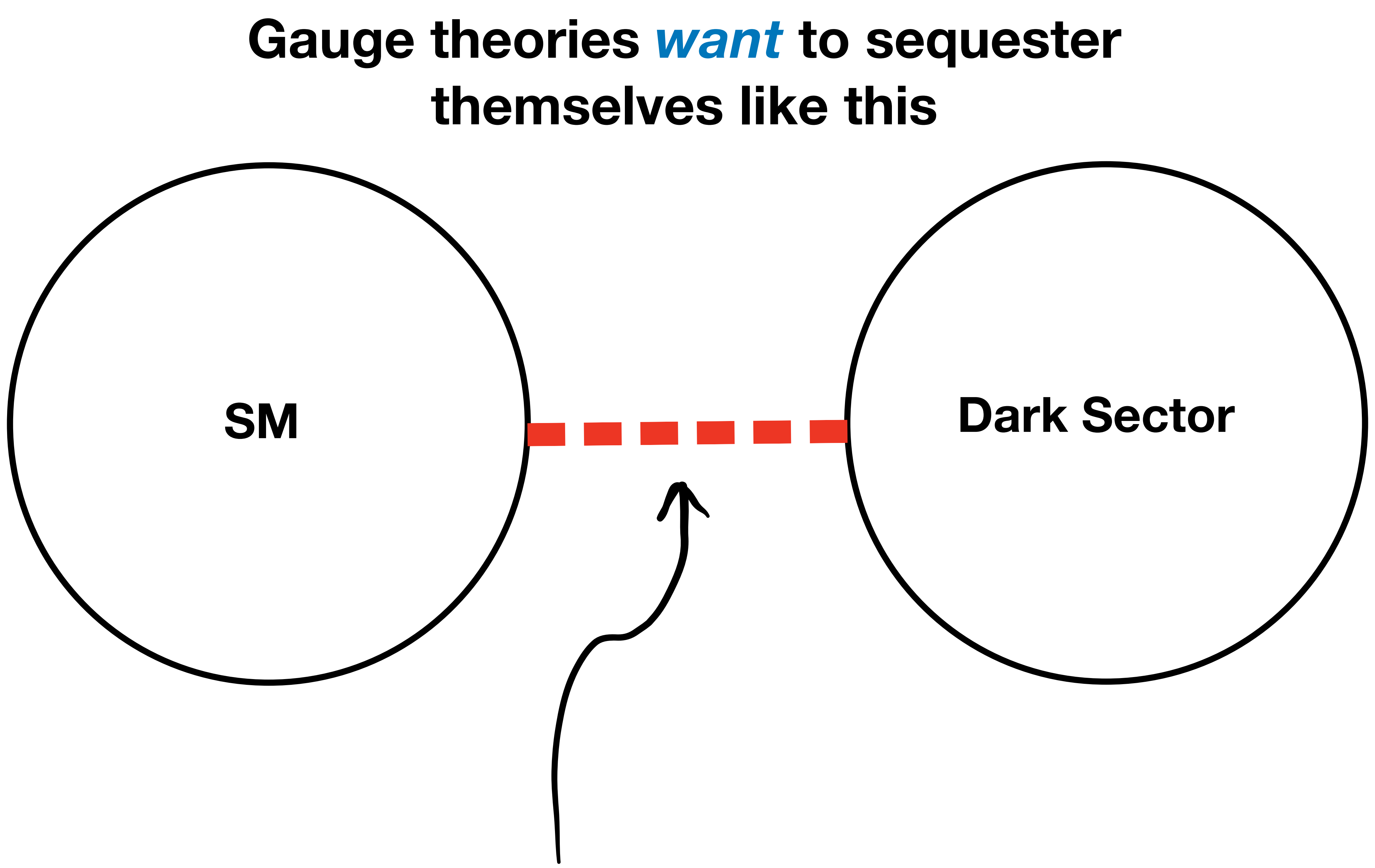
FIG. 6. Higgs mass as a function of M_S, with $X_t = 0$. The green band is the output of FeynHiggs together with its associated uncertainty. The blue line represents 1-loop renormalization group evolution in the Standard Model matched to the MSSM at M_S. The blue bands give estimates of errors from varying the top mass between 172 and 174 GeV (darker band) and the renormalization scale between $m_t/2$ and $2m_t$ (lighter band).

Supersymmetry isn't dead, the Higgs told us the LHC would have a hard time immediately!

The 10 TeV scale is particularly interesting for SUSY and I don't scoff at consistent extensions of spacetime symmetry

Higgs Portal

If the Higgs is a fundamental scalar particle…



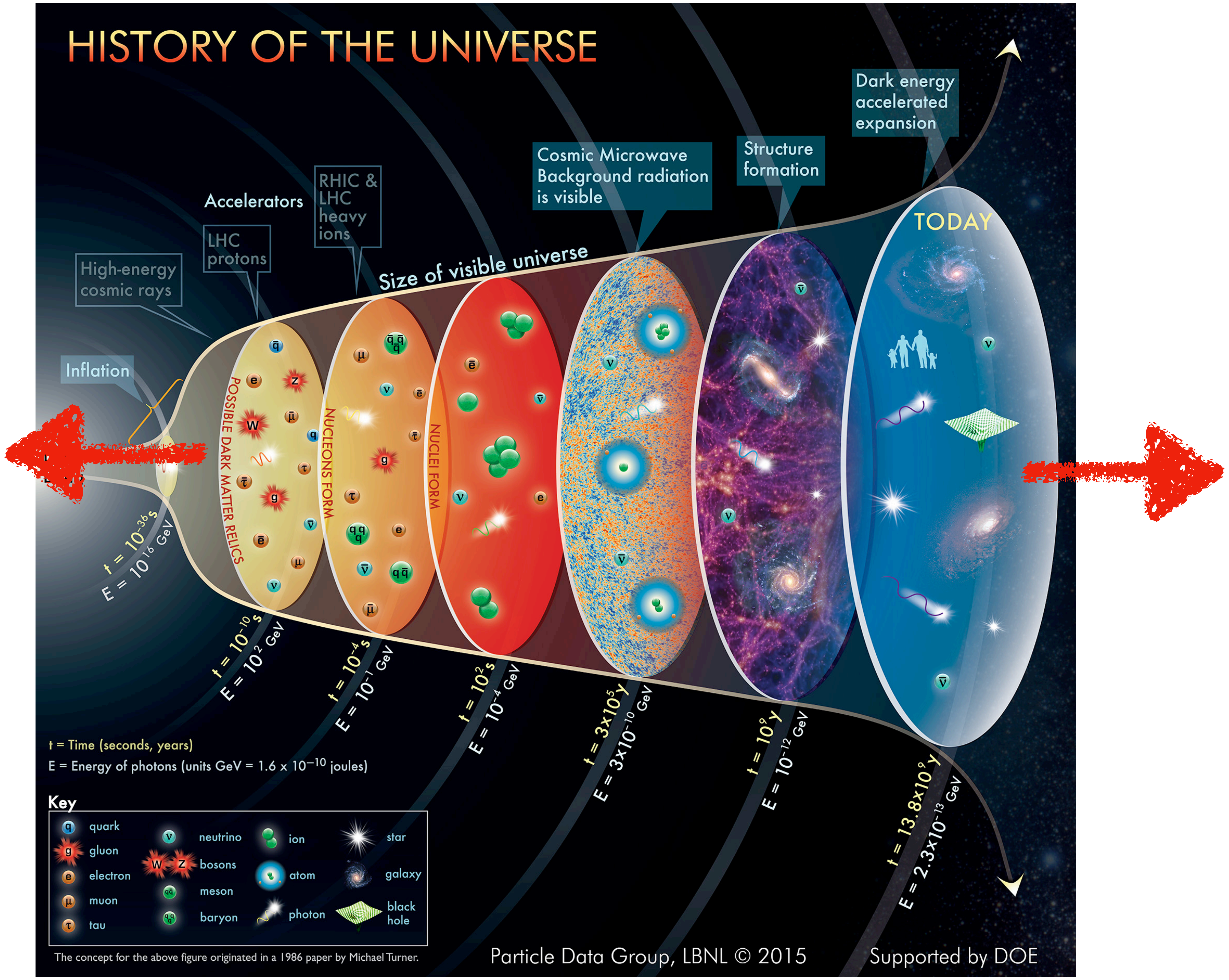
$$\mathscr{L} \supset H^\dagger H \mathcal{O}_{DS}$$

The Higgs provides the lowest dimension Lorentz and Gauge Invariant Operator… *It should be a leading contribution*

Needs: Probe the Higgs couplings, new states coupled to Higgs

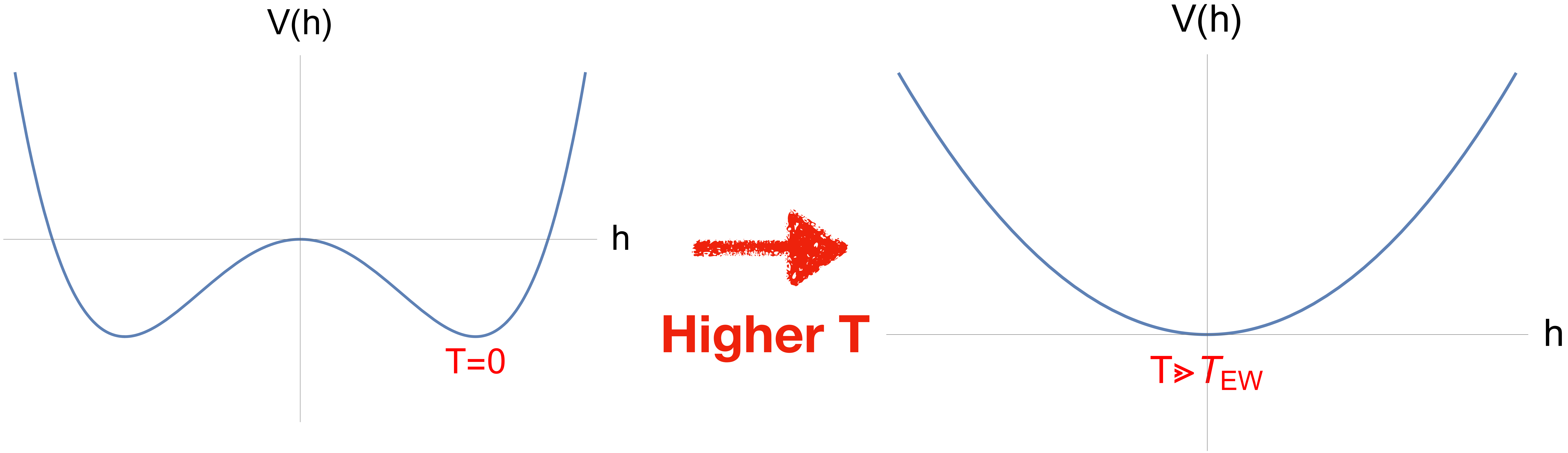
Origin and Fate of the Universe?

Higher T



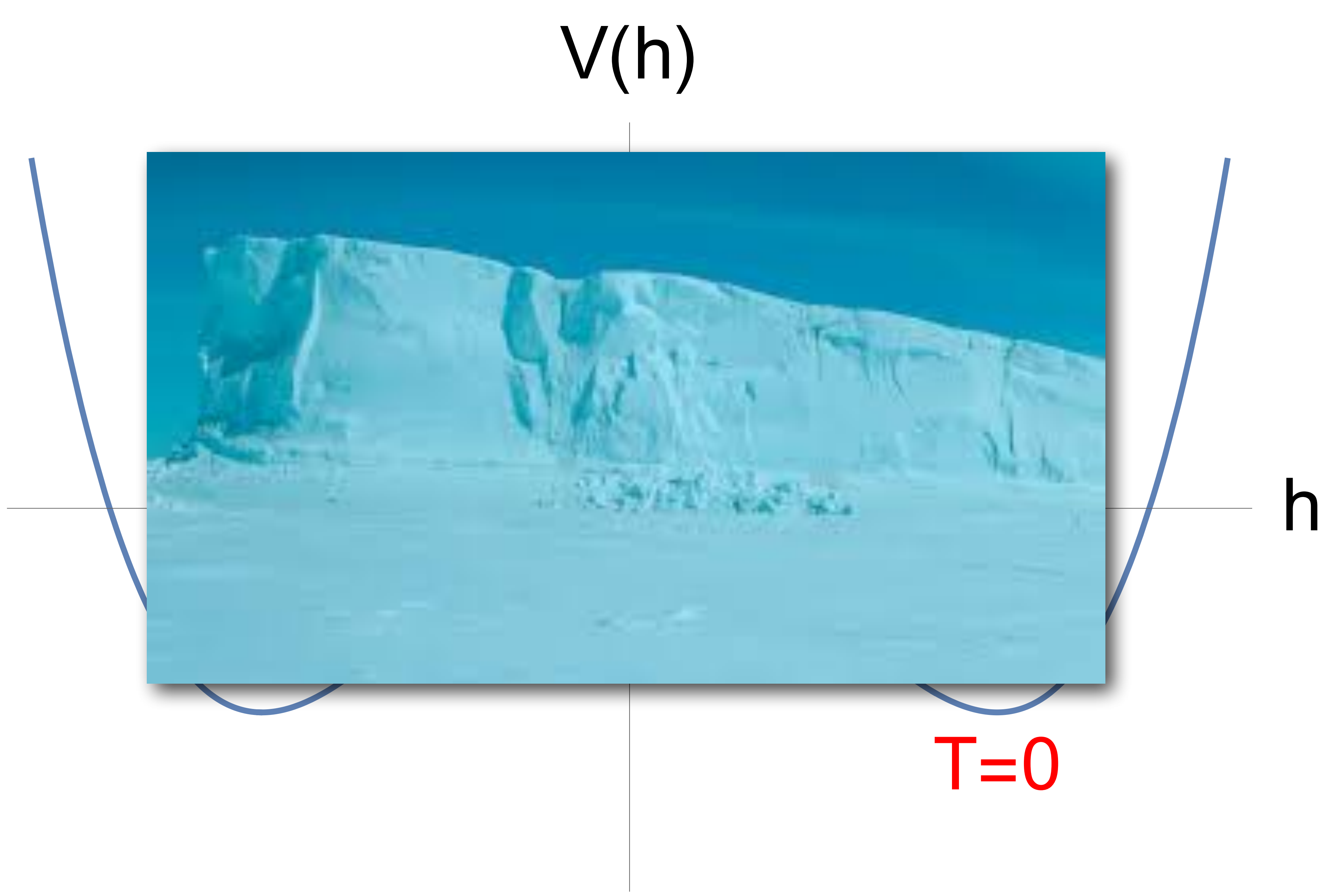
Stability of Vacuum?

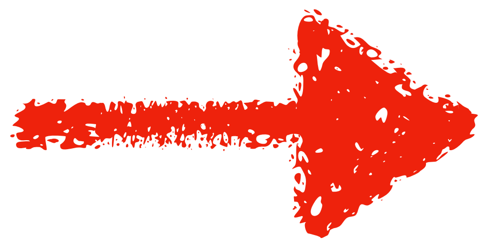
Next era in SM history is the "Electroweak Phase Transition"

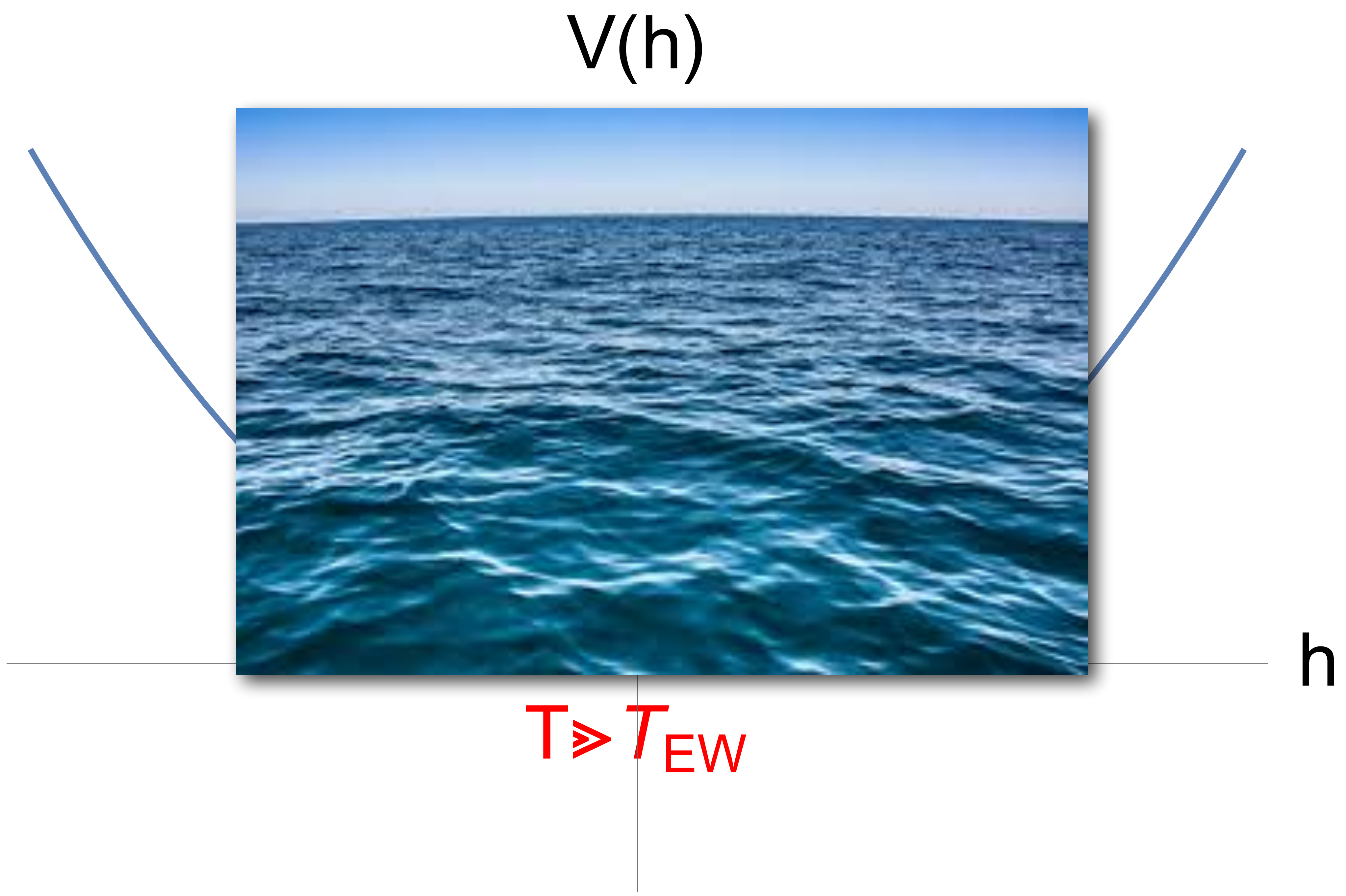


What is the phase diagram of the Electroweak Symmetry?

Next era in SM history is the "Electroweak Phase Transition"

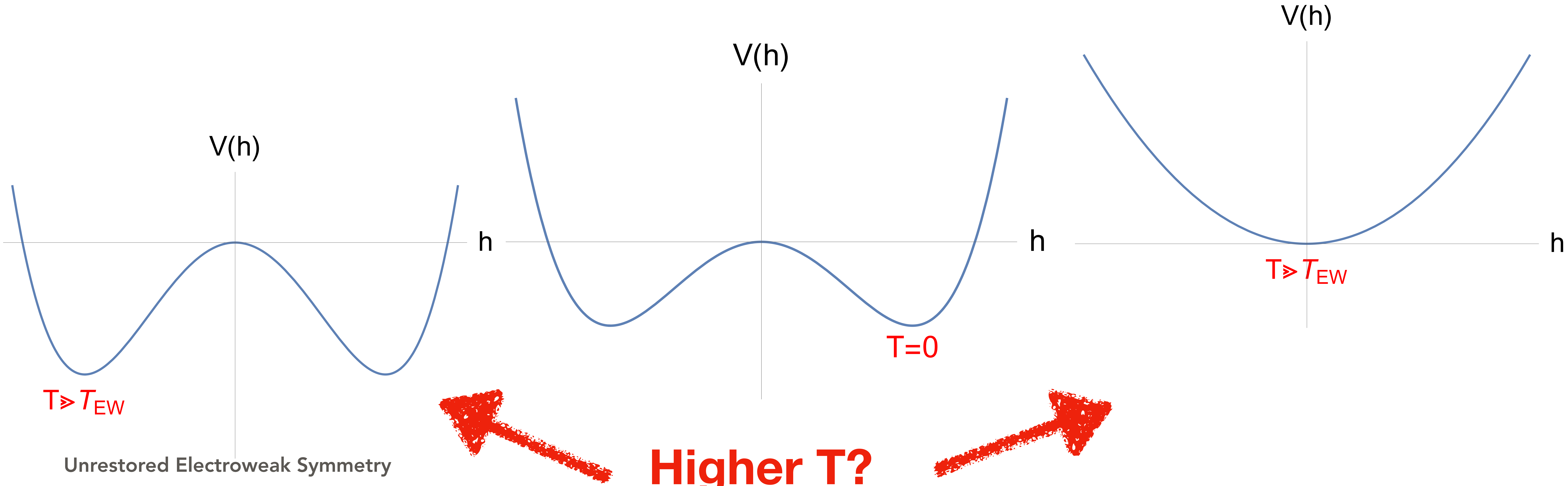






What is the phase diagram of the Electroweak Symmetry?

However, we don't know that there *was* symmetry restoration at temperatures $\gg$ EW scale!



PM, H. Ramani
1807.07578

Even if it is restored we don't know the order of the phase transition *experimentally*

Proxy for understanding the early Universe are Higgs self interactions:

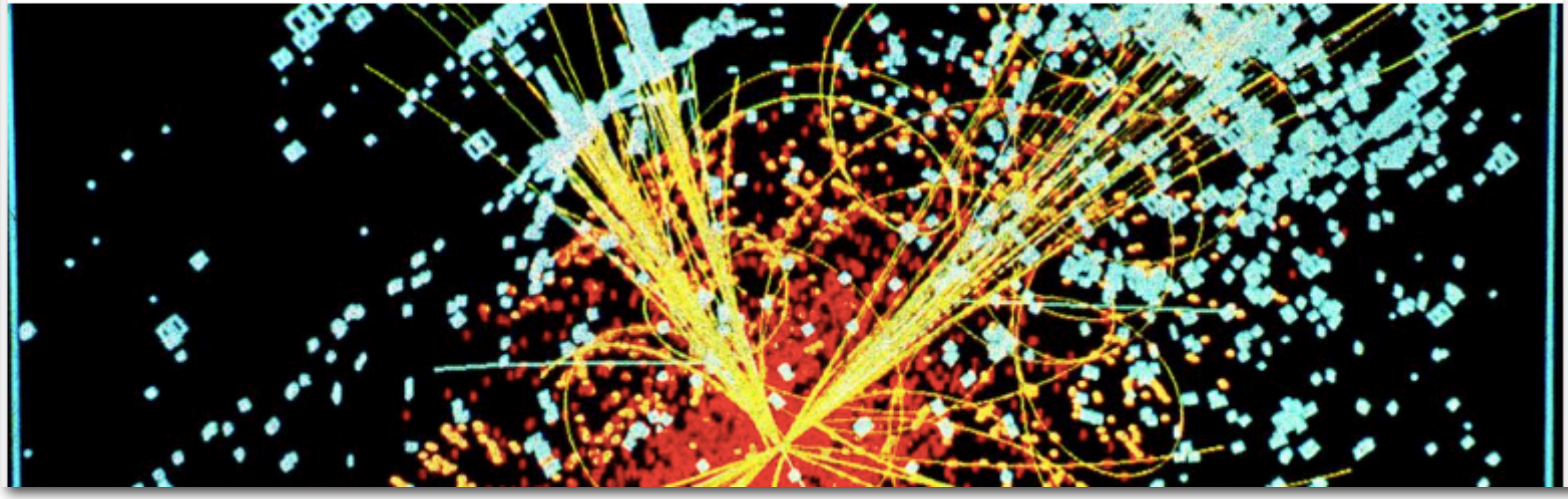
Probe the Higgs self interactions to *at least* $\lambda_3 \sim \mathcal{O}(1)\,\%$

What is the fate of the Universe?

Physicists Accidentally Discover a Self-Destruct Button for the Entire Universe

Unfortunately, humanity will never see it coming.

PHILIP PERRY 01 November, 2016

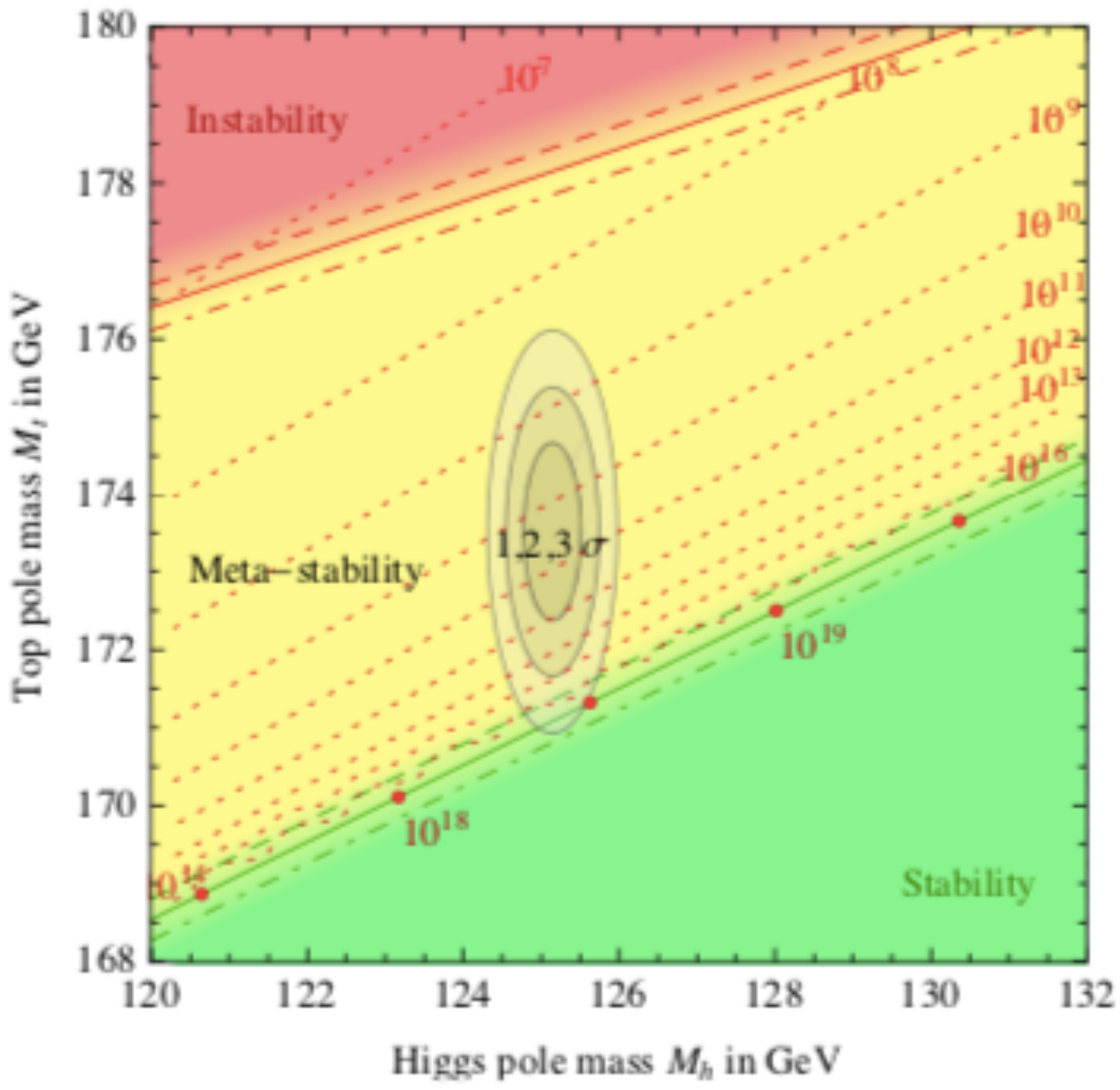


The fate of the Universe?

$$V(h) \sim -h^2 + \lambda h^4$$

Quantum Corrections to the Higgs

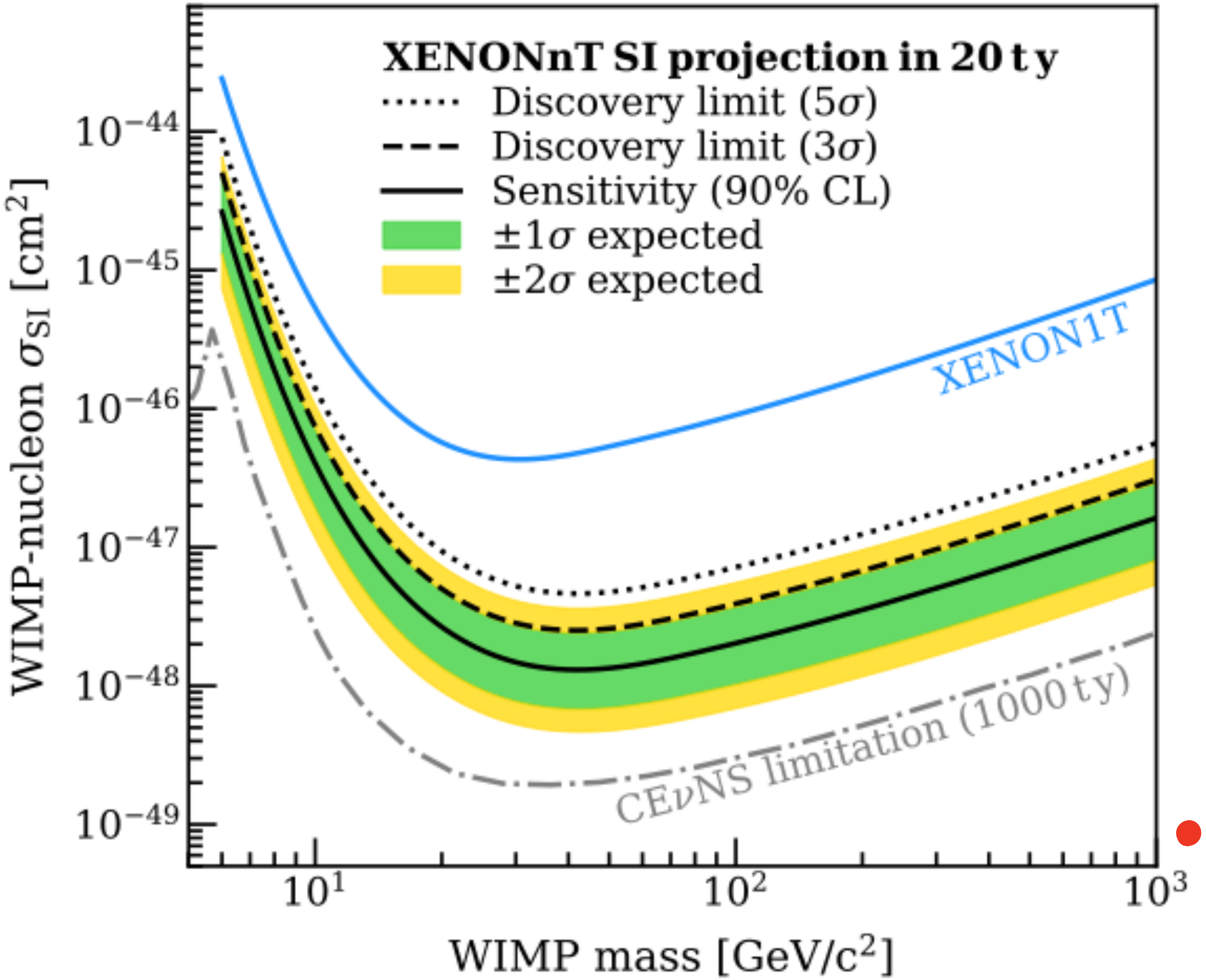
$$\mu \frac{d\lambda}{d\mu} \propto \lambda^4 - y_t^4$$



e.g. J. Elias-Miro et al. 1112.3022

Needs: Probe the Higgs self interactions, measure top quark properties better

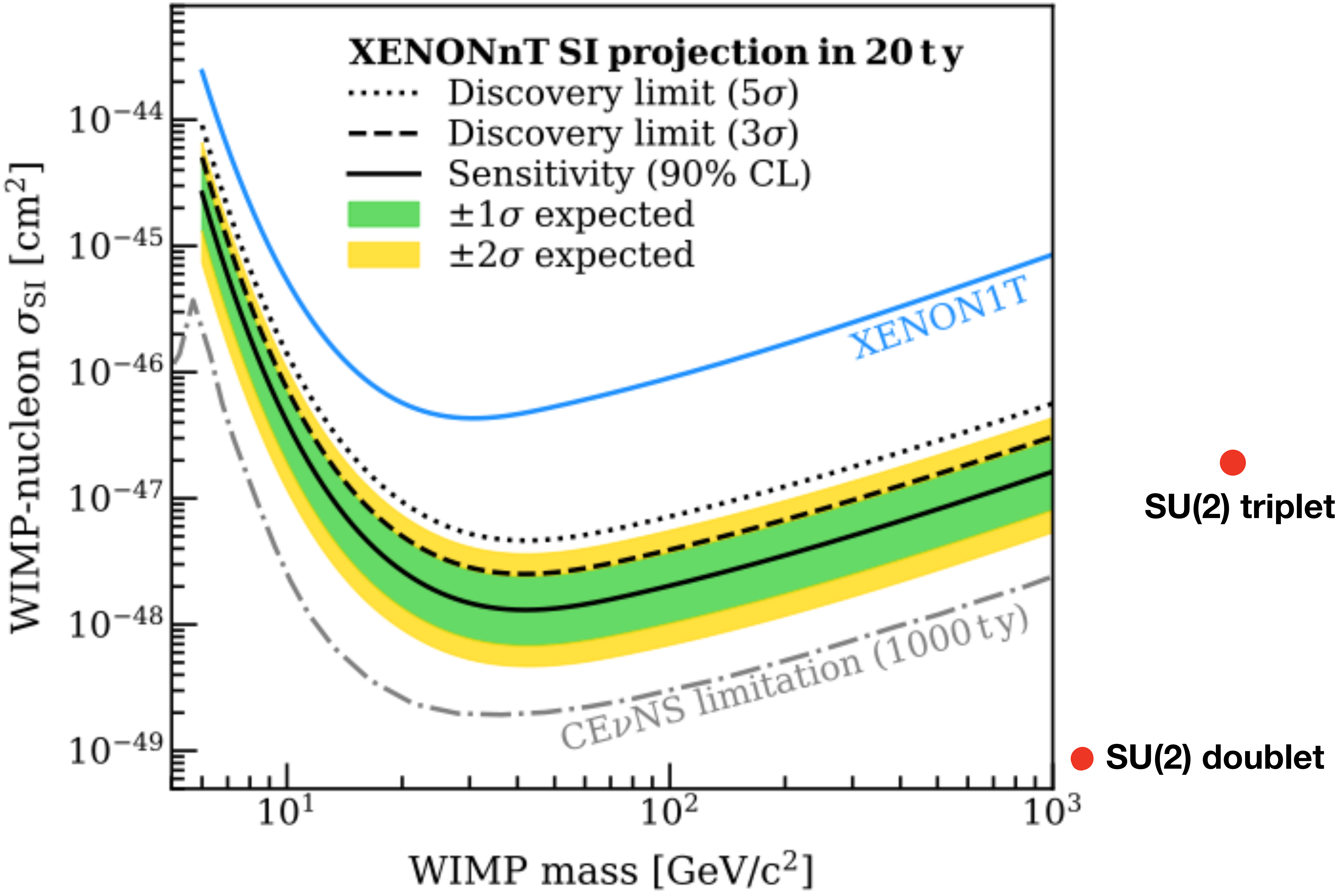
WIMP where W is *our* weak interactions!



- SU(2) triplet- “Wino”
- SU(2) doublet- “Higgsino”

The simplest WIMP possibilities remain *and* colliders are the most robust way to test

The WIMP is dead, long live the WIMP



A collider that can pair produce EW states with mass of ~ 3 TeV is needed

Unfortunately the LHC won't come close to testing this

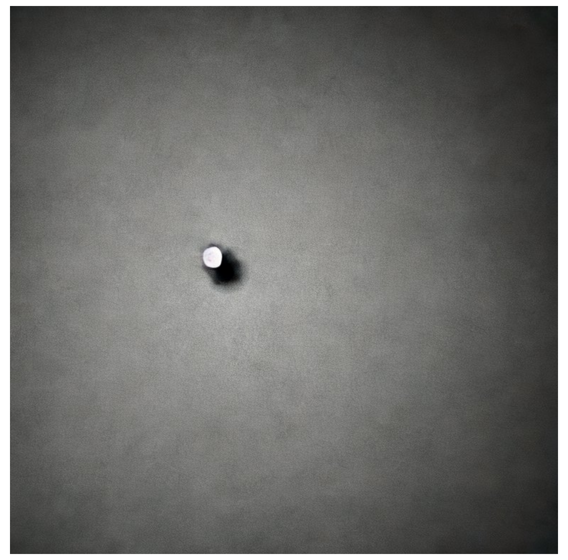
For simplest WIMP DM we need a more collider with more energy

Generic case for multi-TeV colliders at the 10+ TeV scale is clear

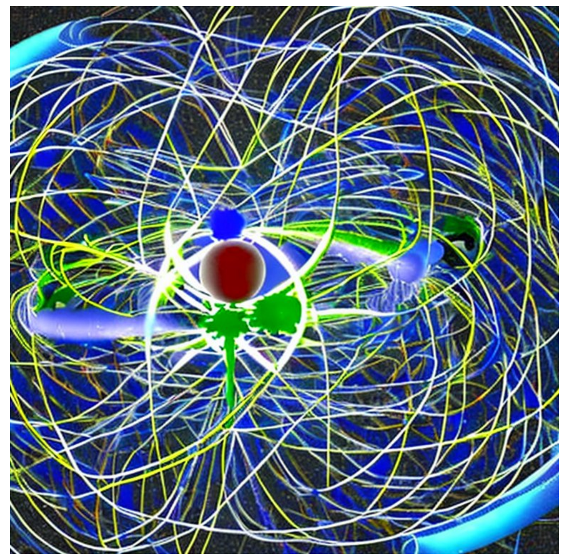
To quantify further we need to look at specific collider options and how they differ

(and many aren't as familiar with a μCol)

What's the most basic difference between μCol and FCC-hh?



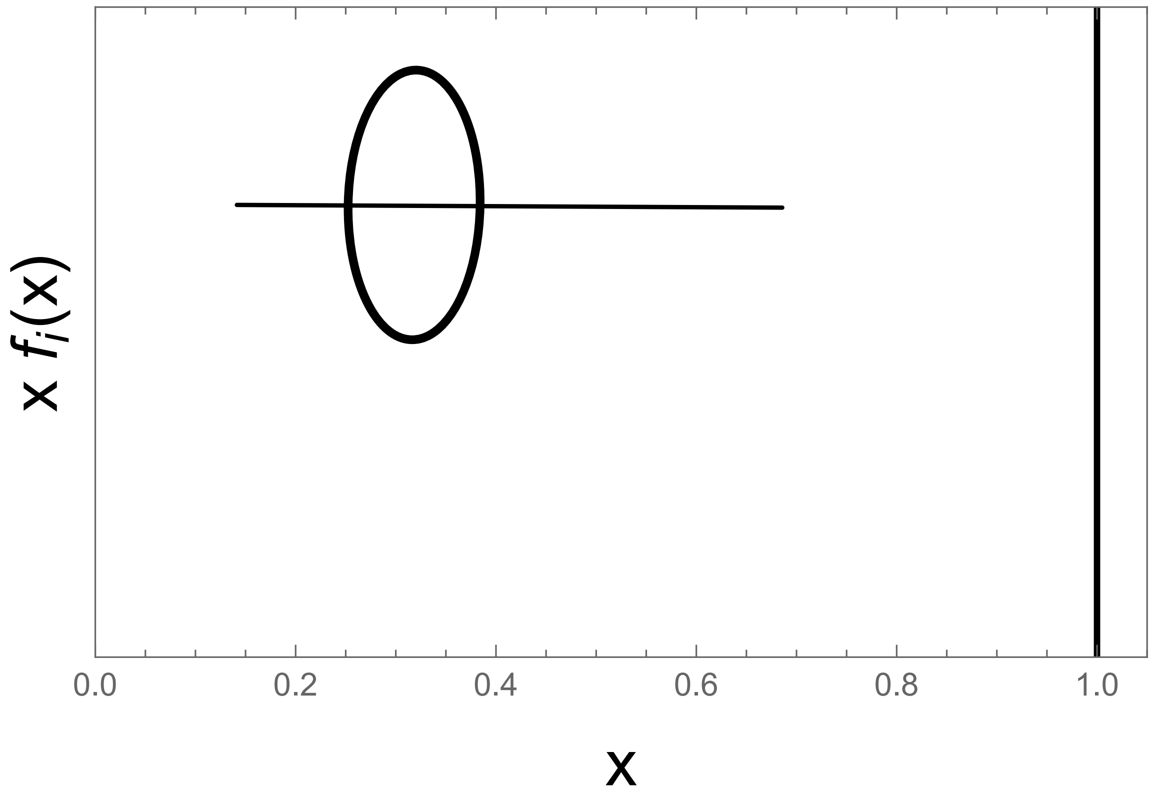
The μ is fundamental



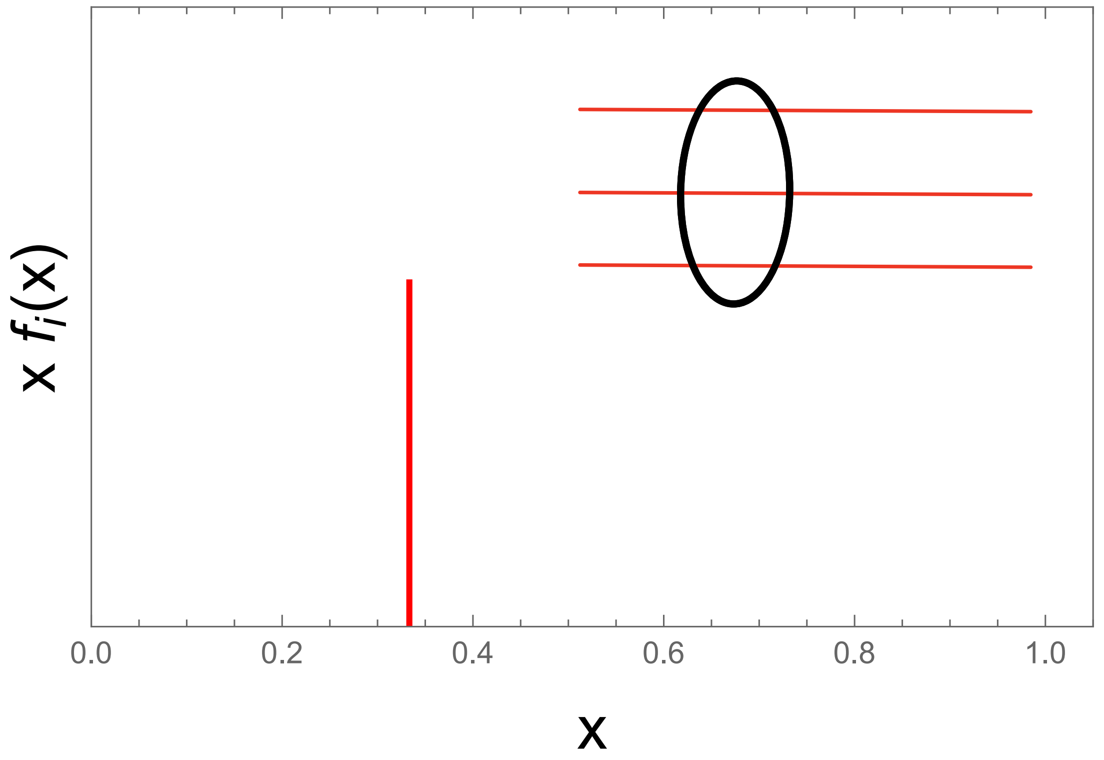
The proton is composite

$$\hat{p} = xp, \quad 0 \le x \le 1 \implies \hat{s} = x_1 x_2 s$$

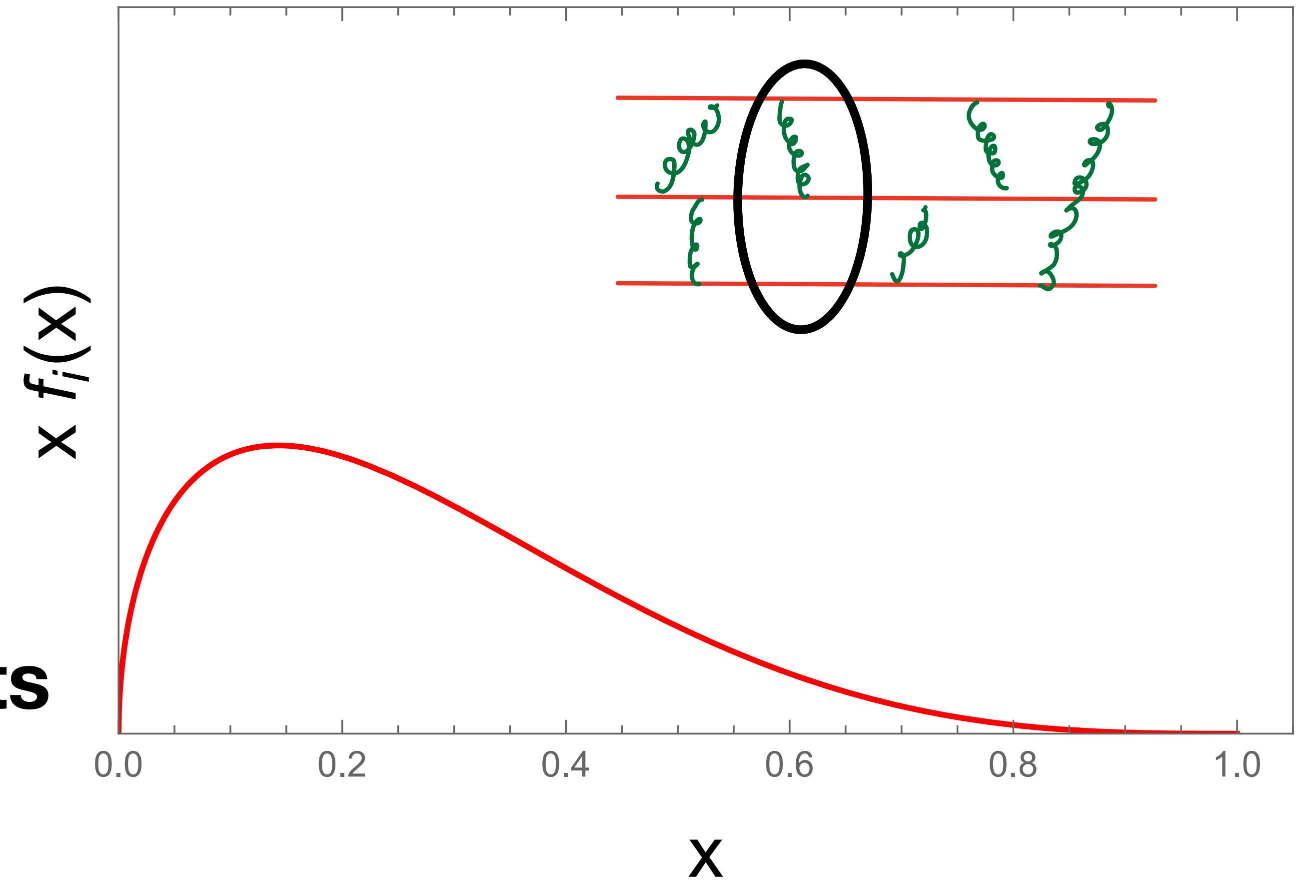
Full COM energy not available - Described by Parton Distribution Functions



Fundamental particle

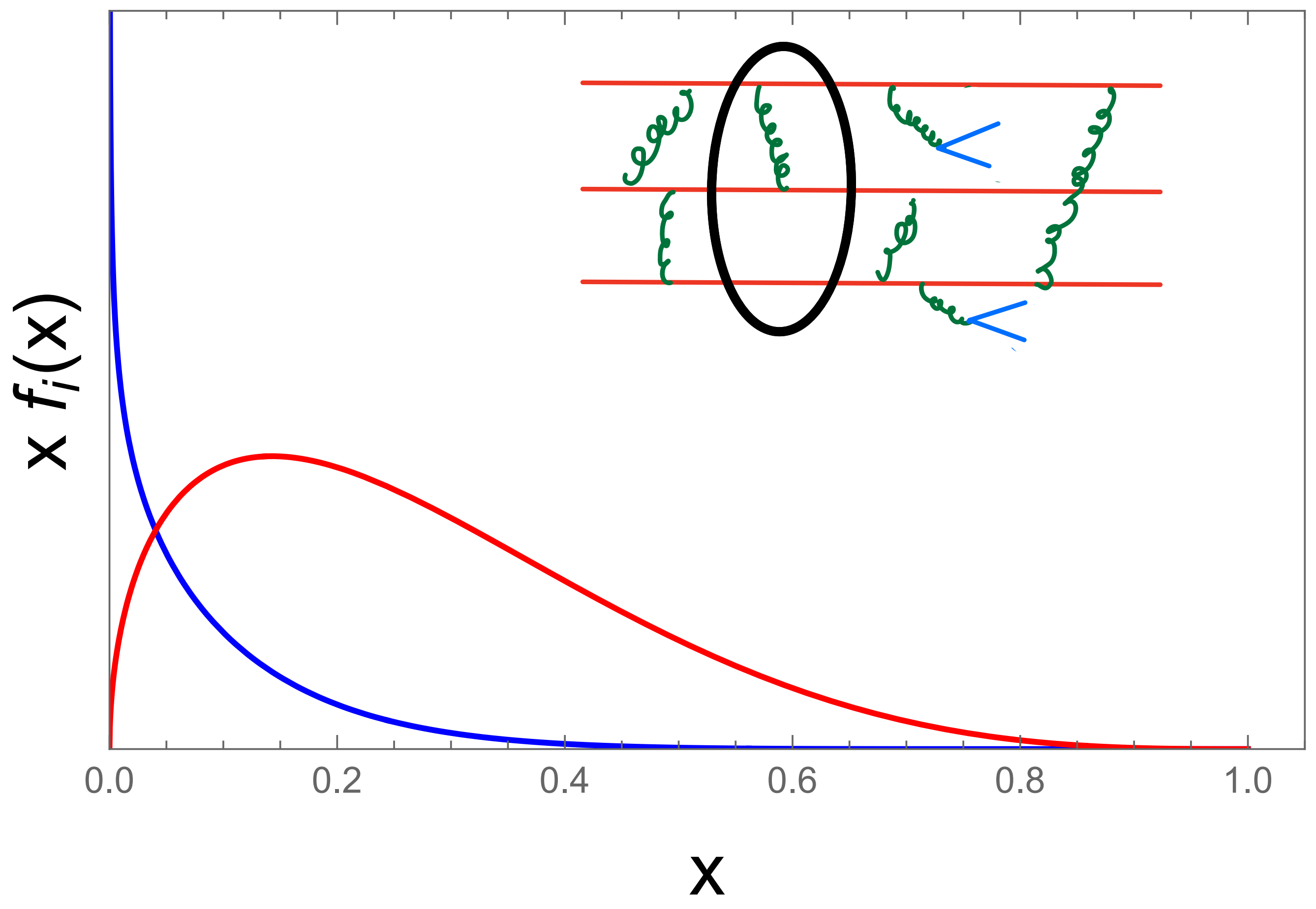


Non-dynamical constituents



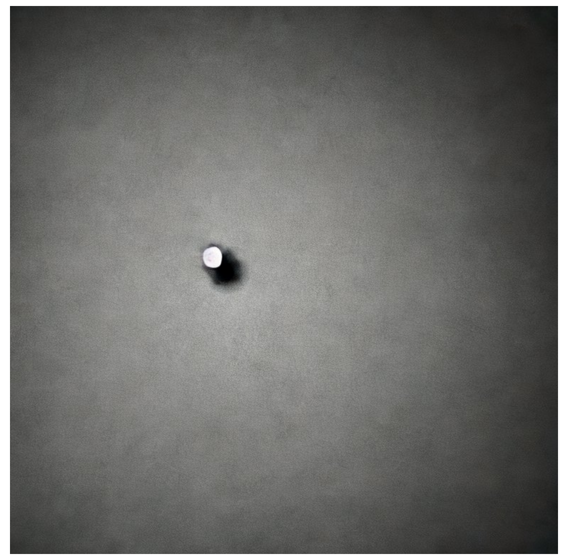
Dynamical valence quarks

H/T Halzen & Martin

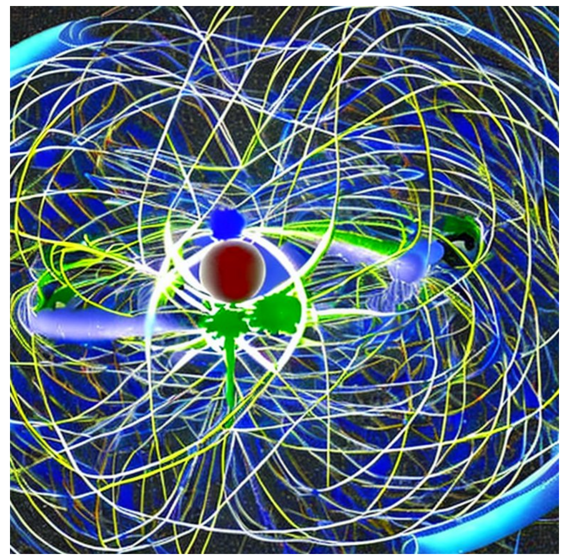


Valence + "Sea"

What's the most basic difference between μCol and FCC-hh?

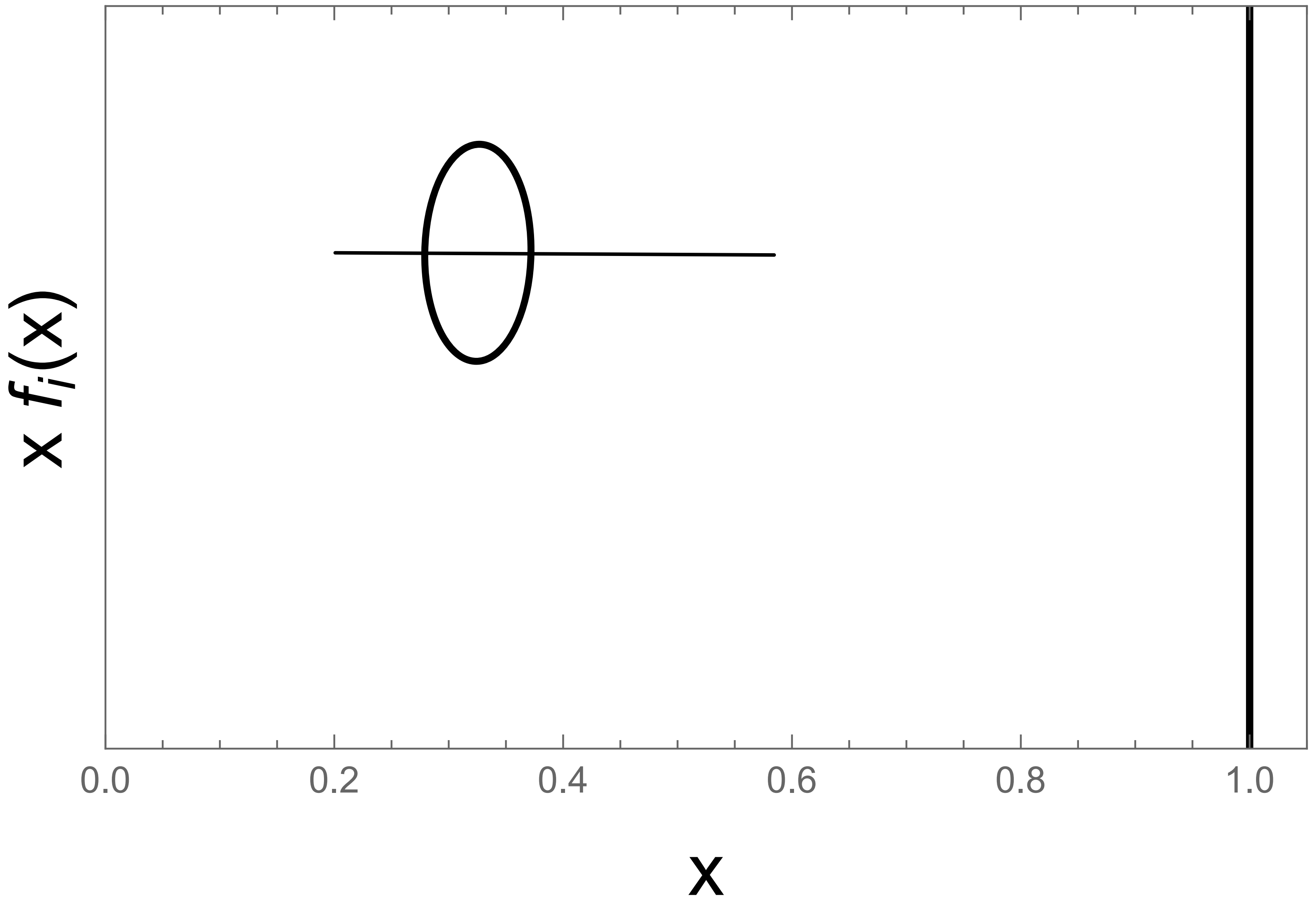


The μ is fundamental

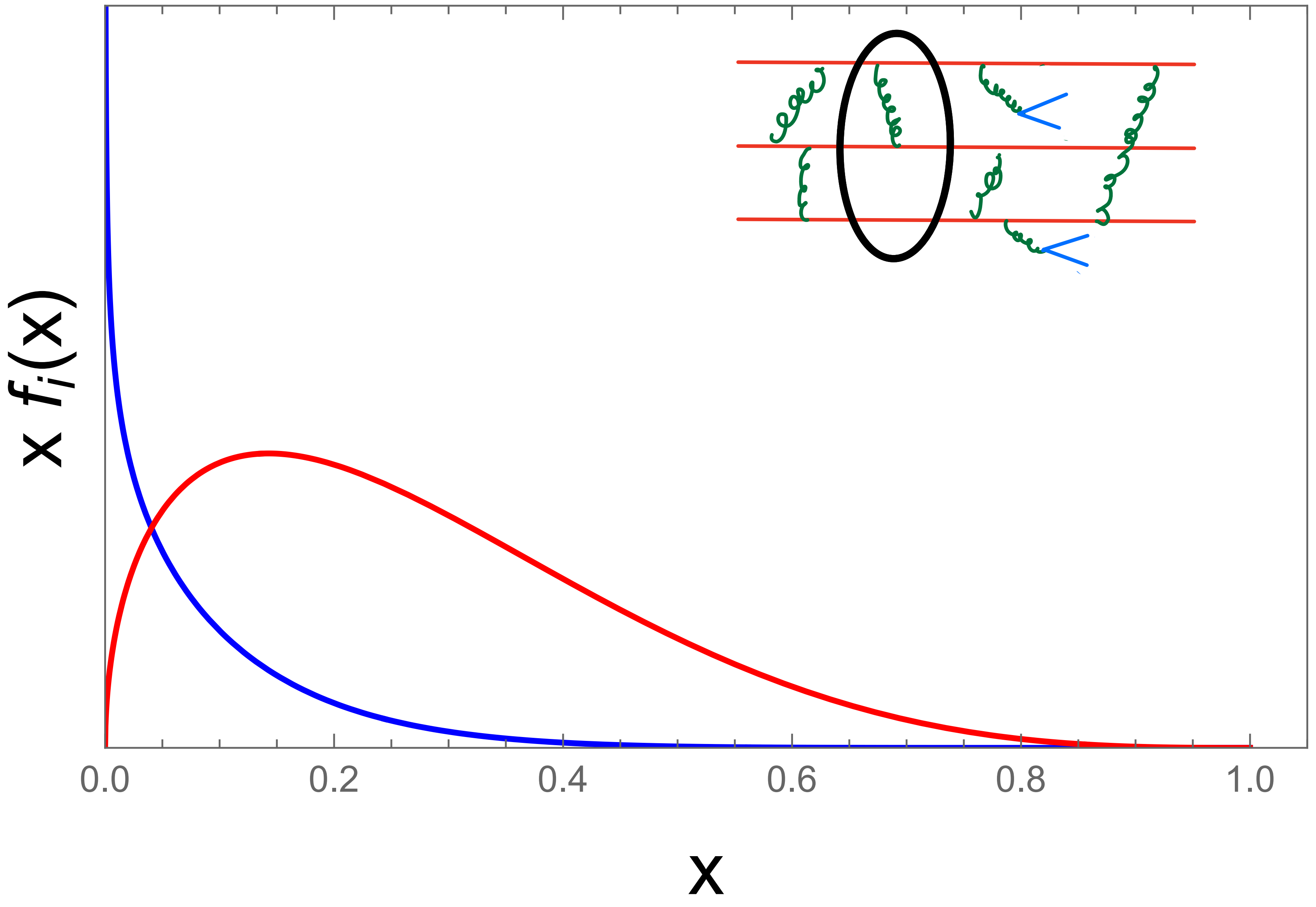


The proton is composite

$$\hat{p} = xp, \quad 0 \leq \mathrm{x} \leq 1 \implies \hat{s} = x_1 x_2 s$$



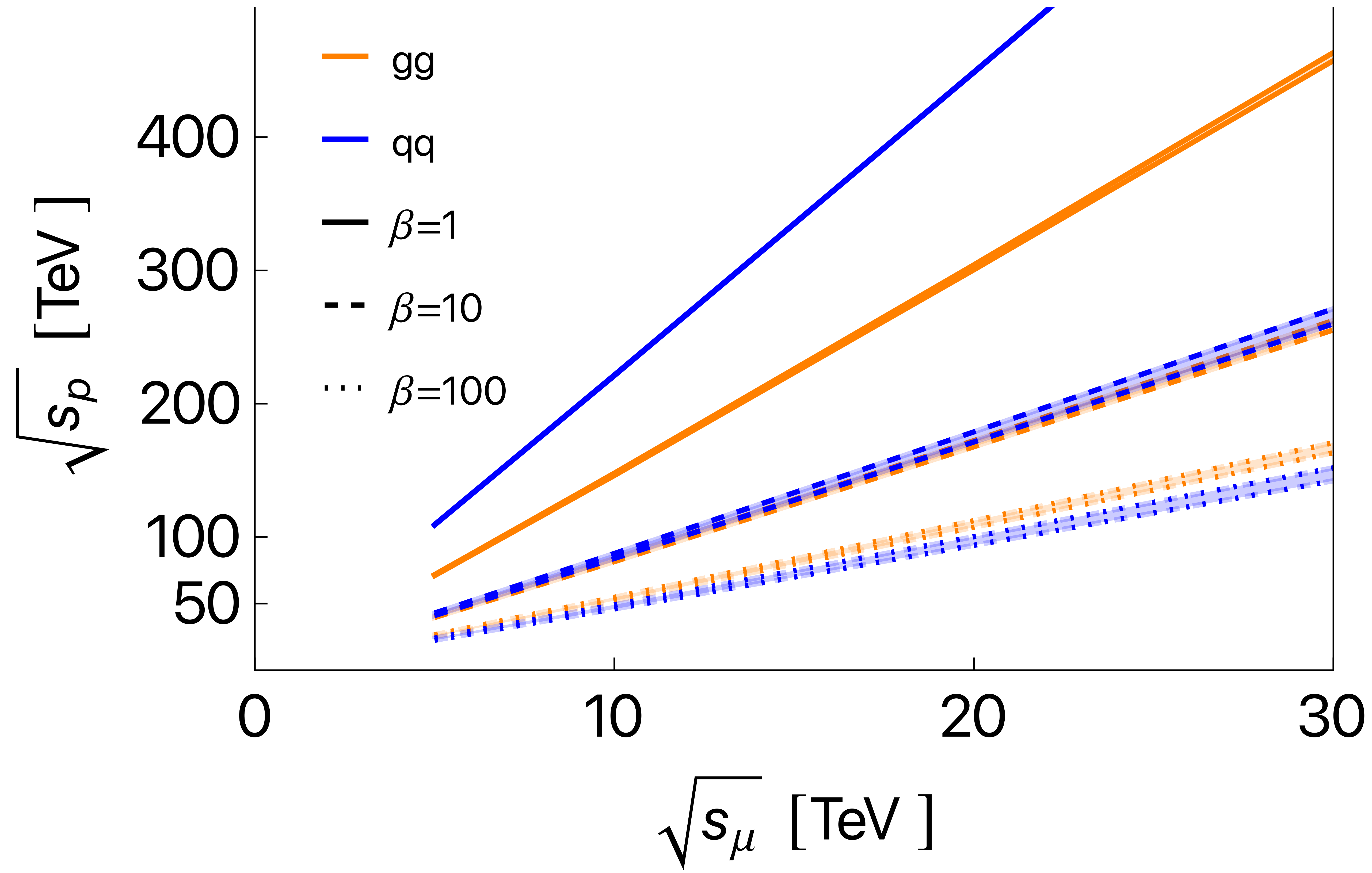
Muon



Proton

This isn't the full story but to *first* approximation fundamental vs composite explains a good amount

What's the most basic difference between μCol and FCC-hh?



Can ask what collider energy yield same total σ when using "Parton Luminosity"

e.g. this case $2 \to 2$ process w/ $\beta \equiv \hat{\sigma}_p / \hat{\sigma}_\mu$

This doesn't mean:

$\sqrt{s_\mu}$ **TeV μCol** $=$ $\sqrt{s_p}$ **pp collider**

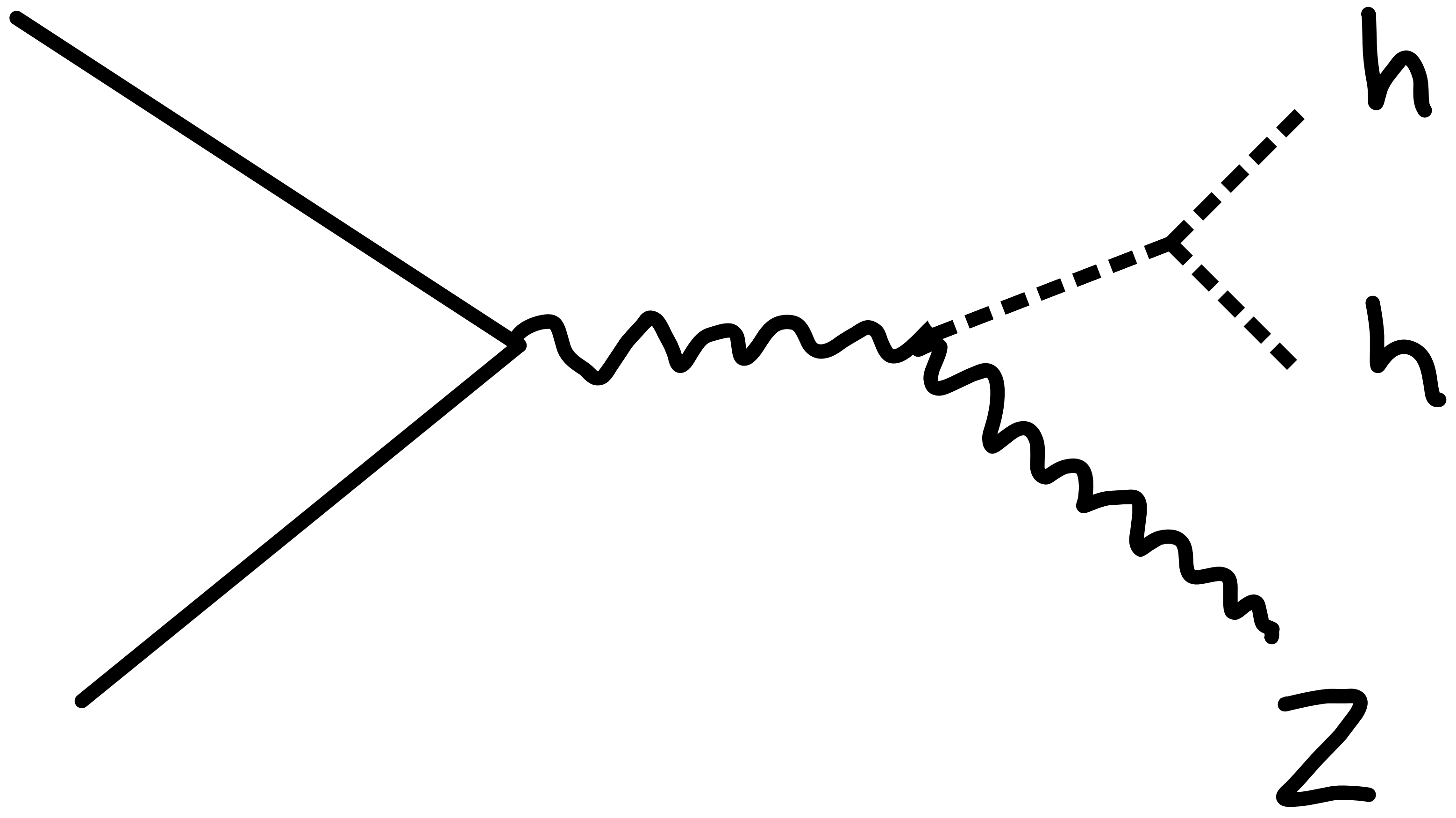
Corollary:

10 TeV μCol $\neq$ FCC-hh

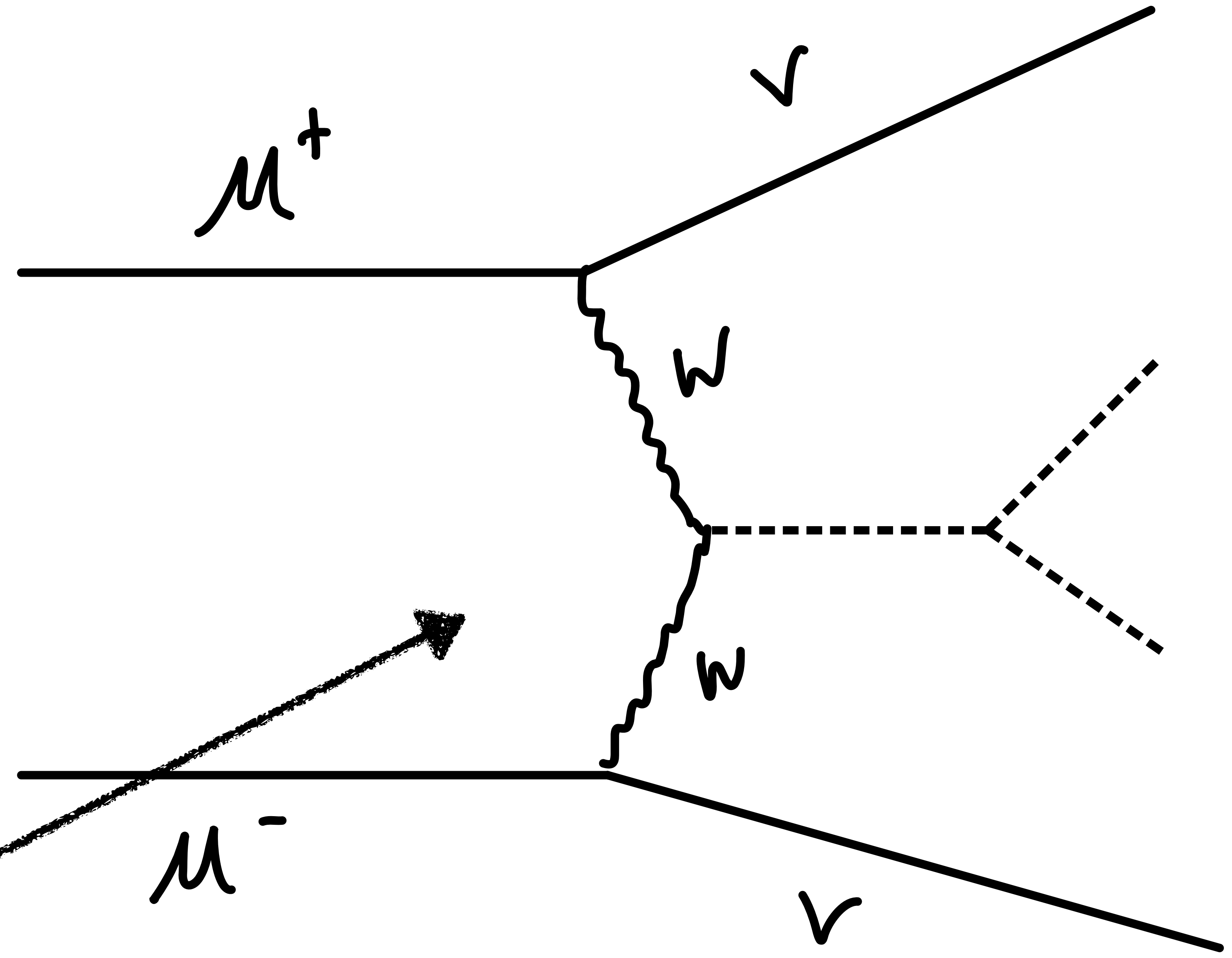
This argument is *not* saying that the physics is equivalent!

It does give a sense for why the energies of the colliders can be so different while going after similar physics

Muon colliders are *also* gauge boson colliders!



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



$\sim \log^2 E^2$

Winner at moderate energies!

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

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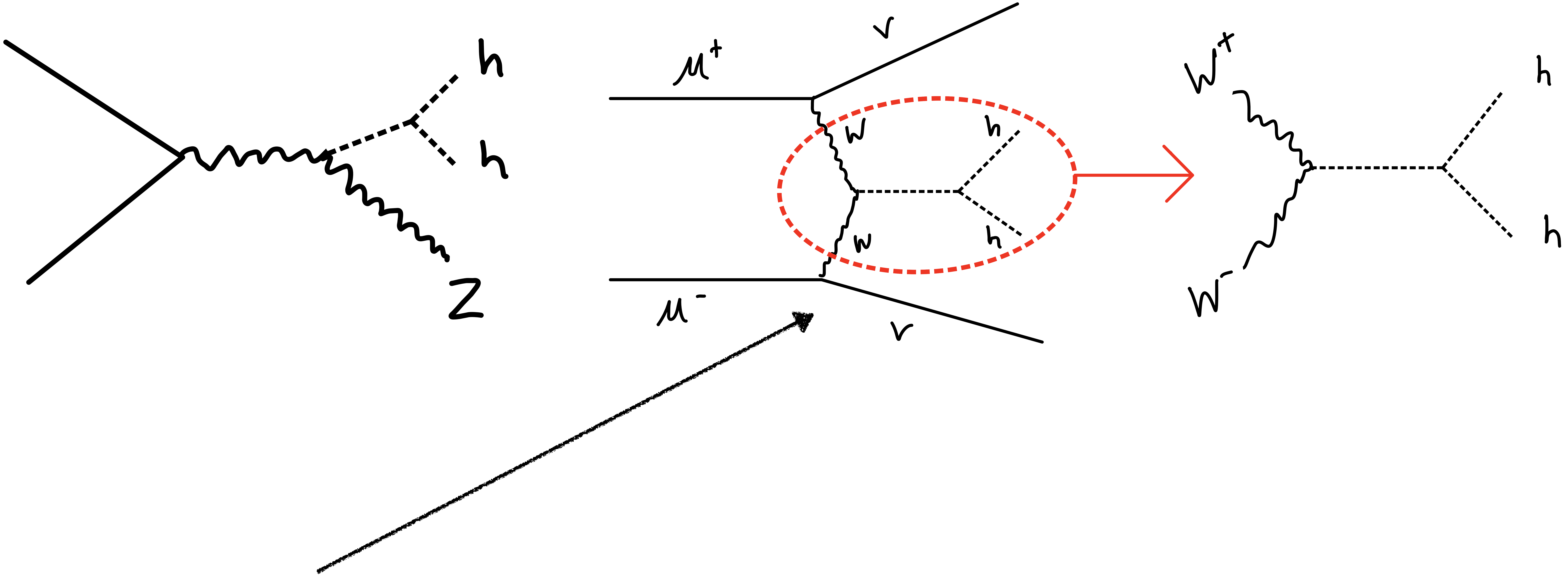

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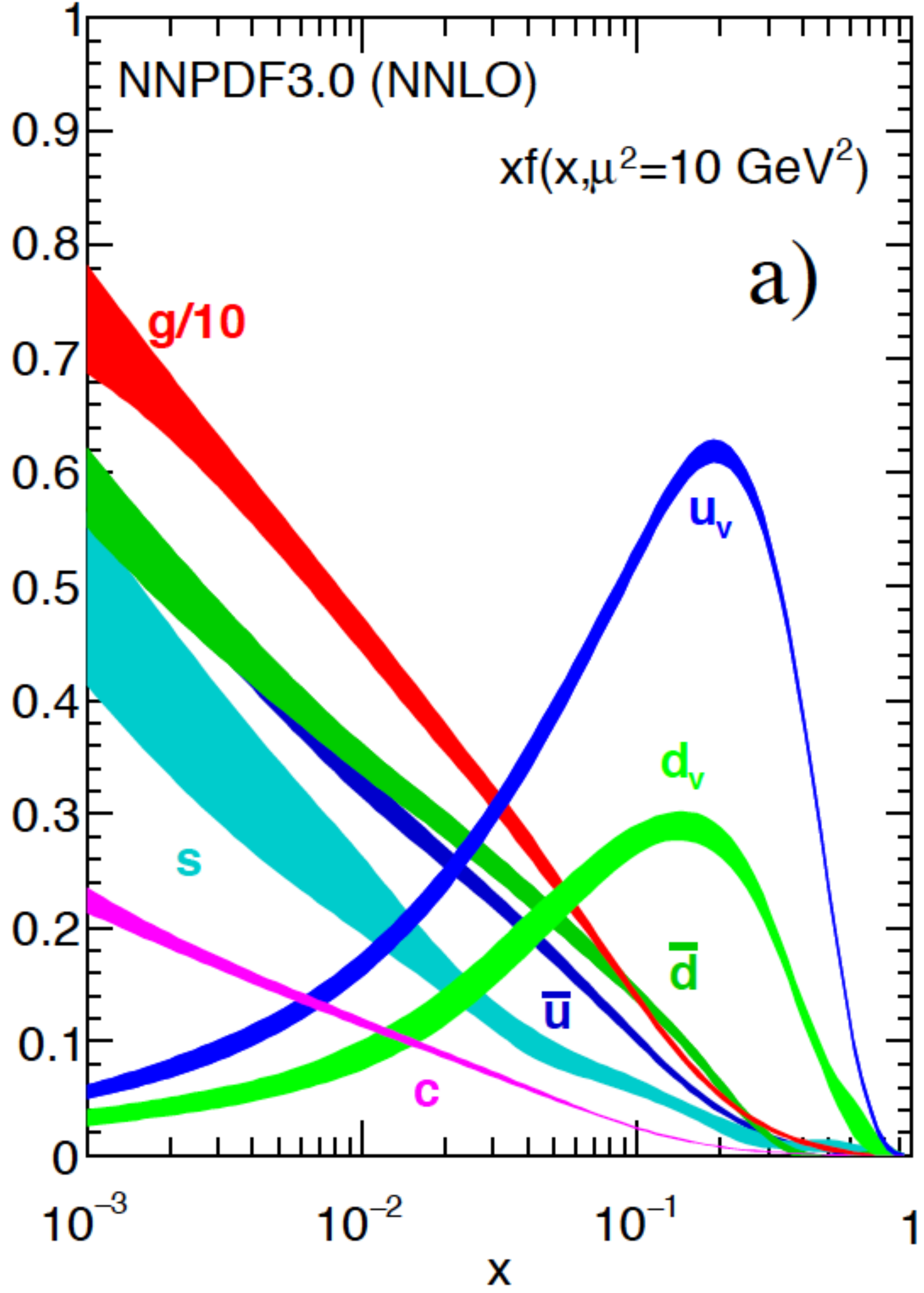
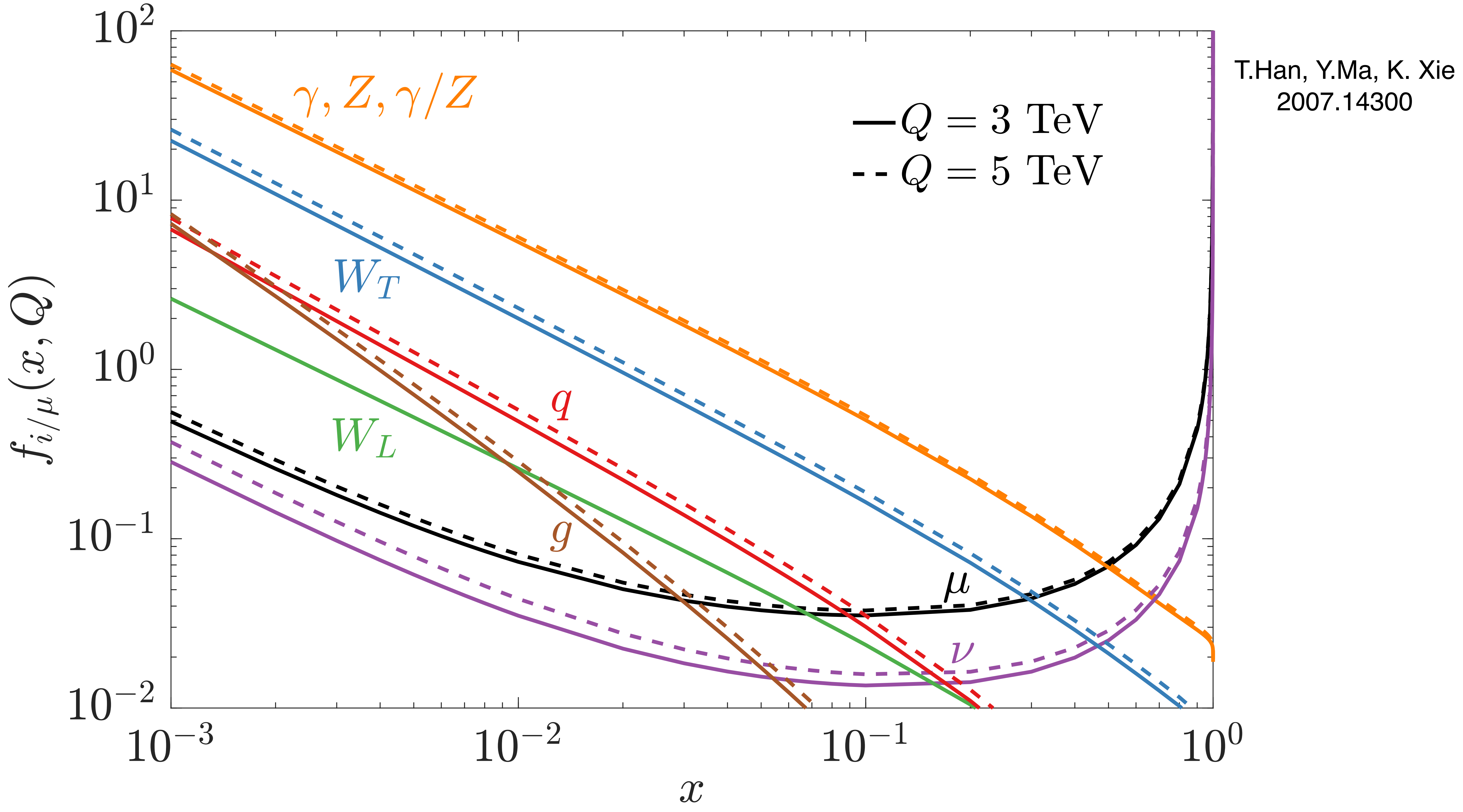


Protons
valence peaks at x~.2
sea of quarks and gluons below

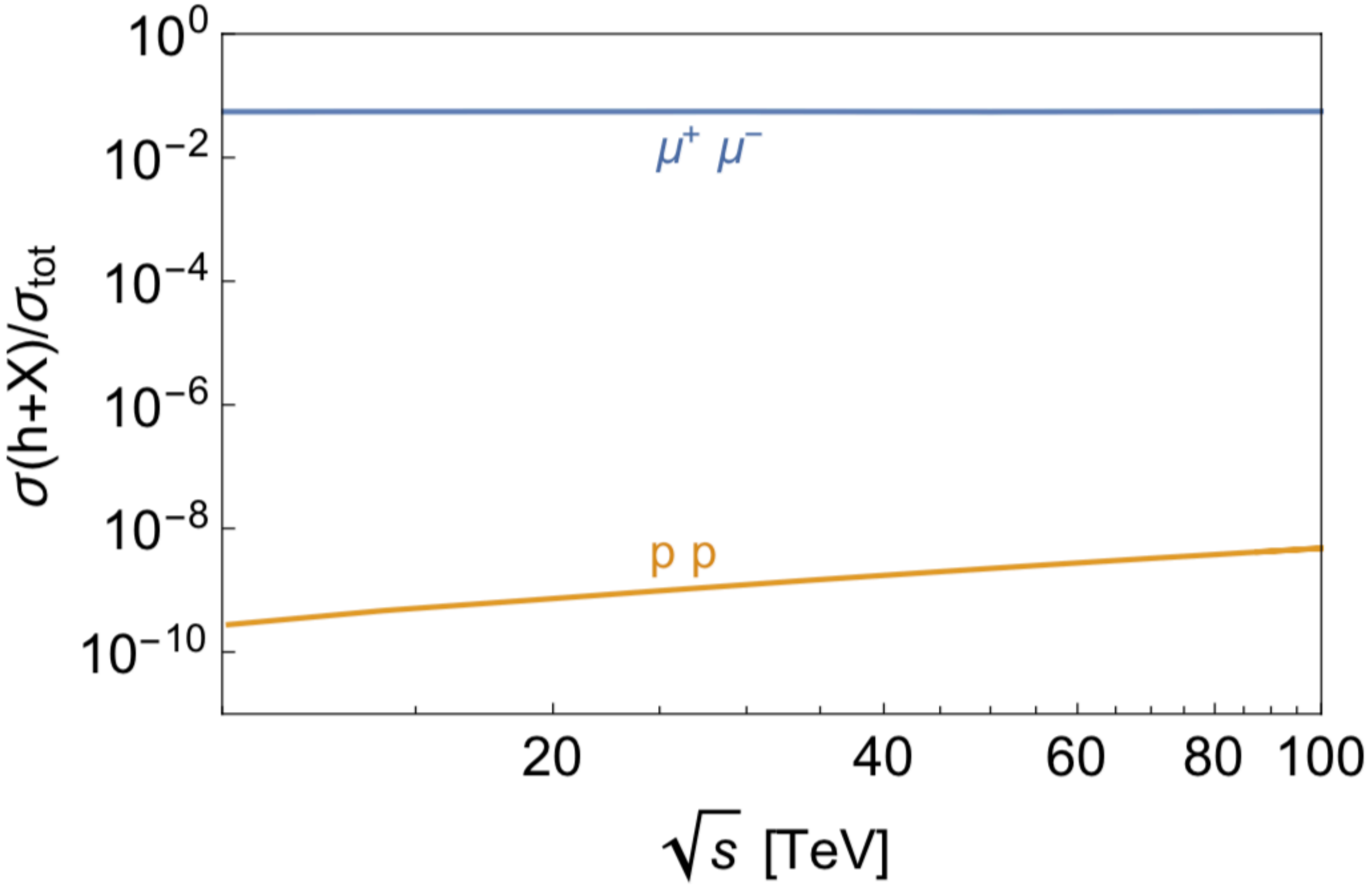


Muons
muons and neutrinos peak at x~1
EW + more sea

Both FCC-hh and μCol have a robust low-x (SM) program - not just absolute reach

Last but not least, backgrounds!

"Hard" physics backgrounds



Muons as fundamental particles start from reduced backgrounds compared to protons

Collider specific backgrounds

FCC-hh	**μCol**
Pileup	**BIB**
~1000 events/ crossing	**Large flux from μ-decays**

These will be discussed more in the next talks and help drive R&D

So what do these colliders give you in terms of the physics discussed?

Higgs Precision Physics

European strategy update
de Blas et al
1905.03764

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 10000
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.45
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	5.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	1.8
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	1.4
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.24
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.59

Rapid progress, μCol numbers didn't *exist* at the time of last European Strategy Update

M. Forslund et al. 2203.09425+WIP
M. Chen, D. Liu 2212.11067
Z. Liu et al WIP

High energy improves Higgs precision

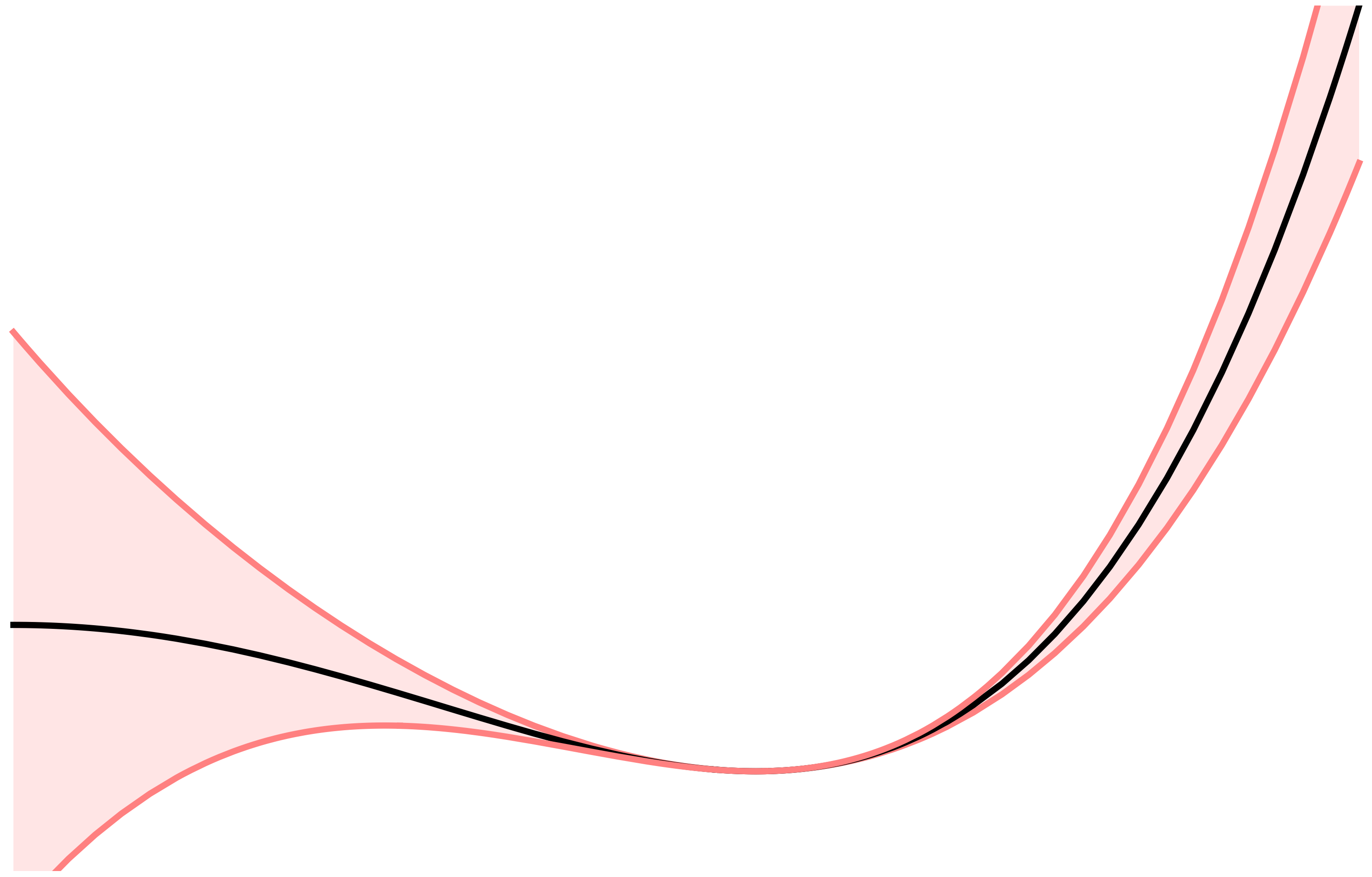
Precision implies a scale

$$\sim \frac{v^2}{M_{NP}^2}$$

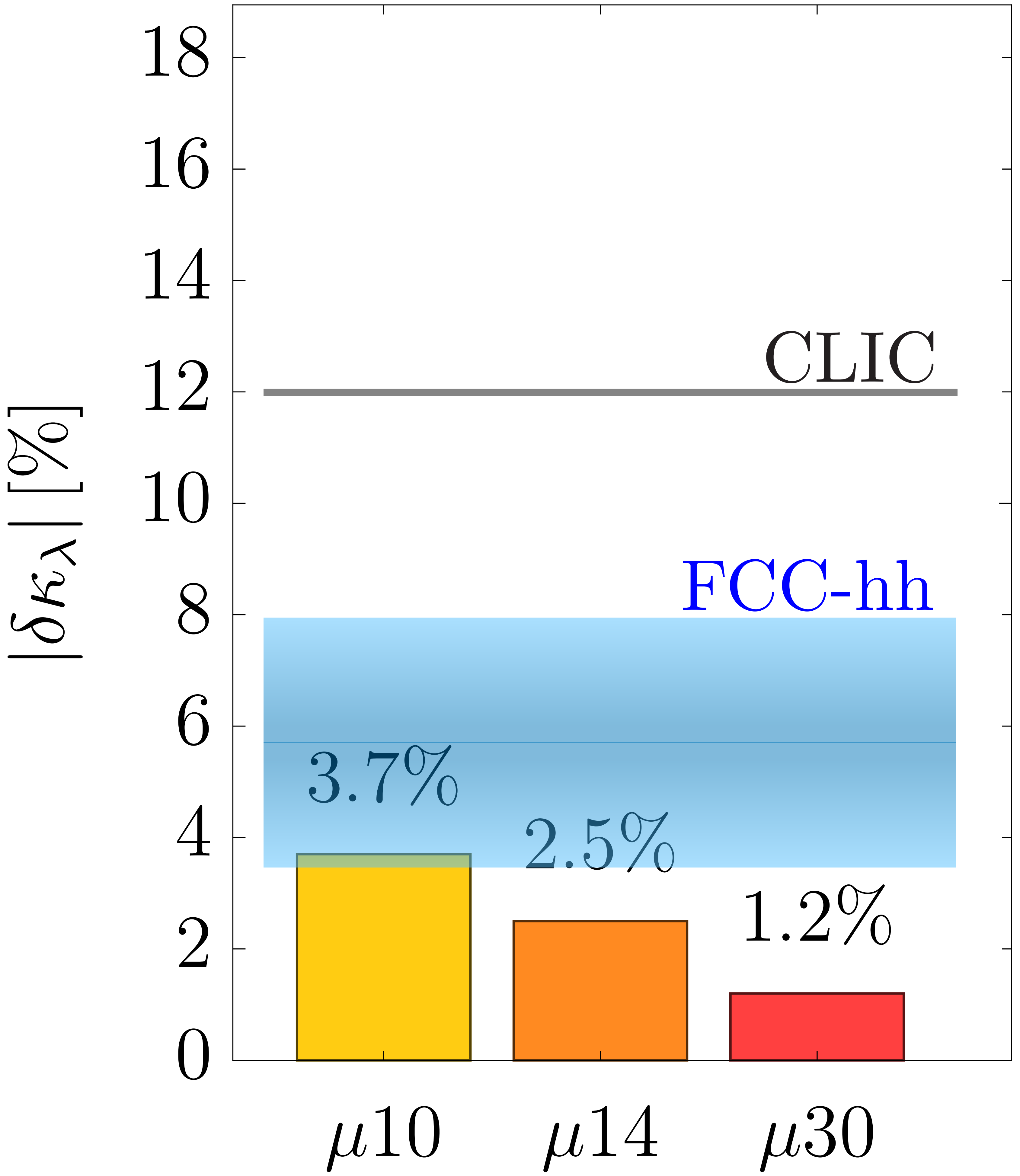
$$1\,\% \implies M_{NP} \sim 1\,\text{TeV}$$

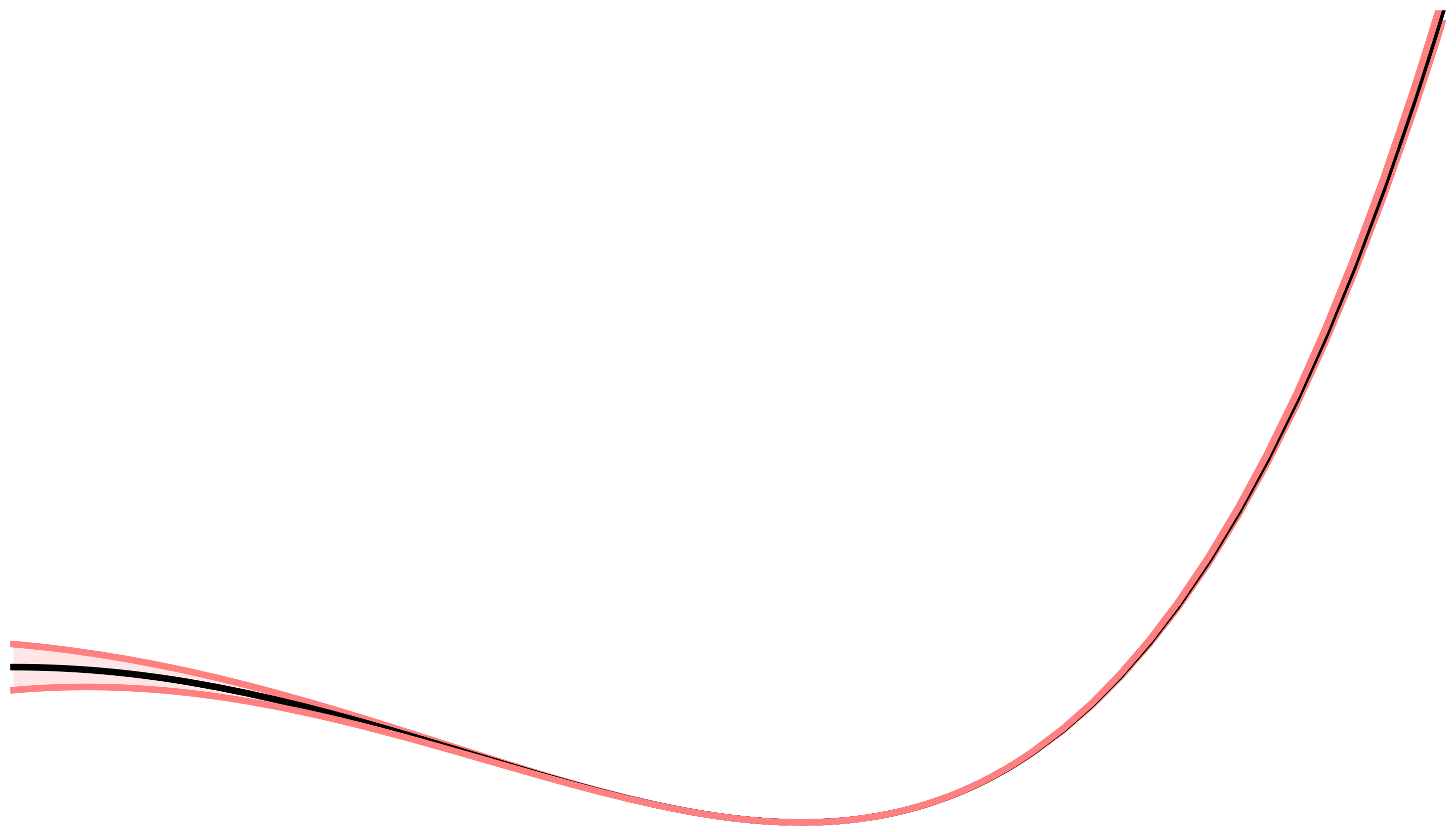
High energy also implies one can *also* test origin of deviations simultaneously - new formalism needed

High energy lets us finally improve on Higgs Potential



HL-LHC

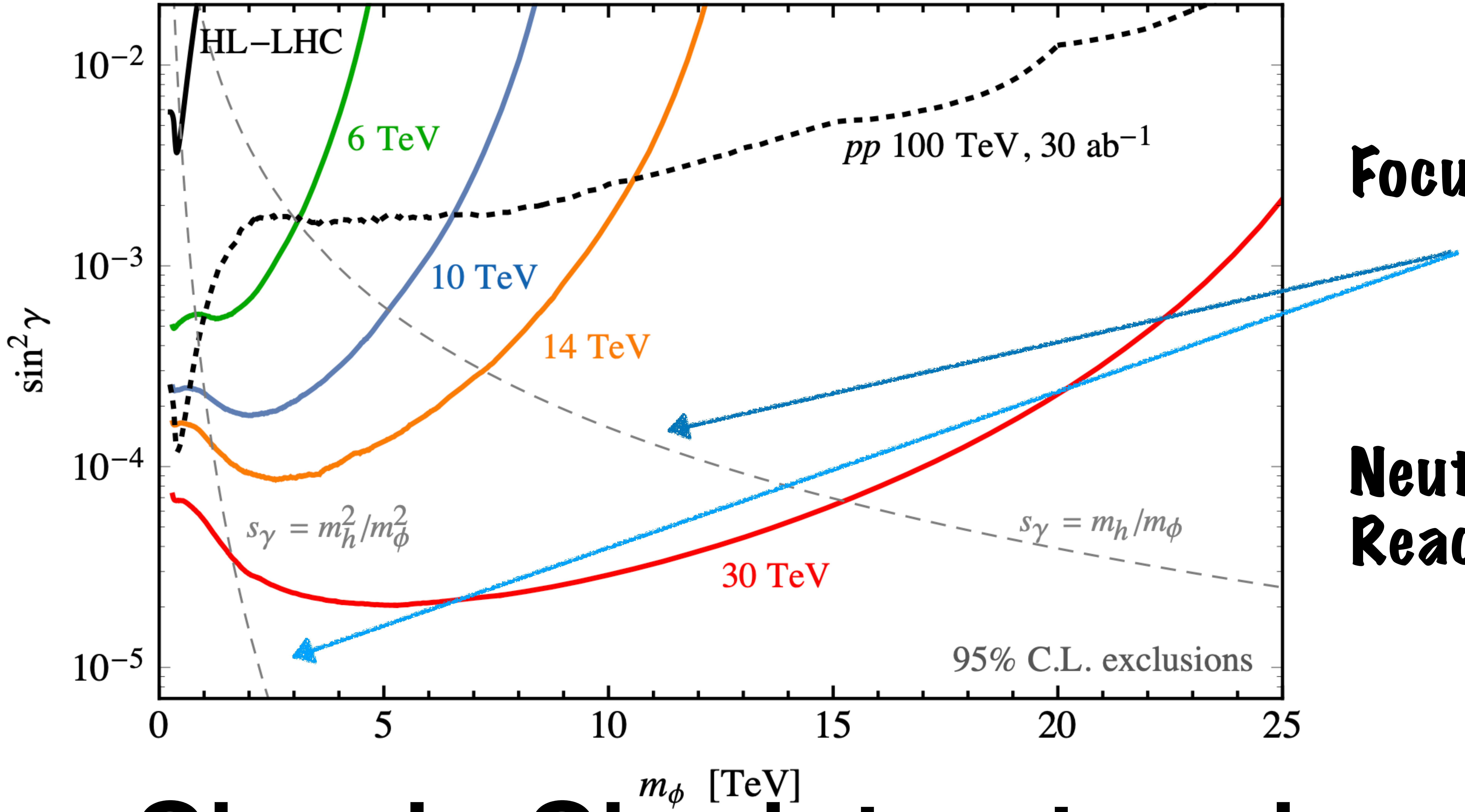




10 TeV μCol

Note that we can get to threshold for EW phase transition at EW scale with FCC-hh and μCol

Higgs portal/EW phase transition

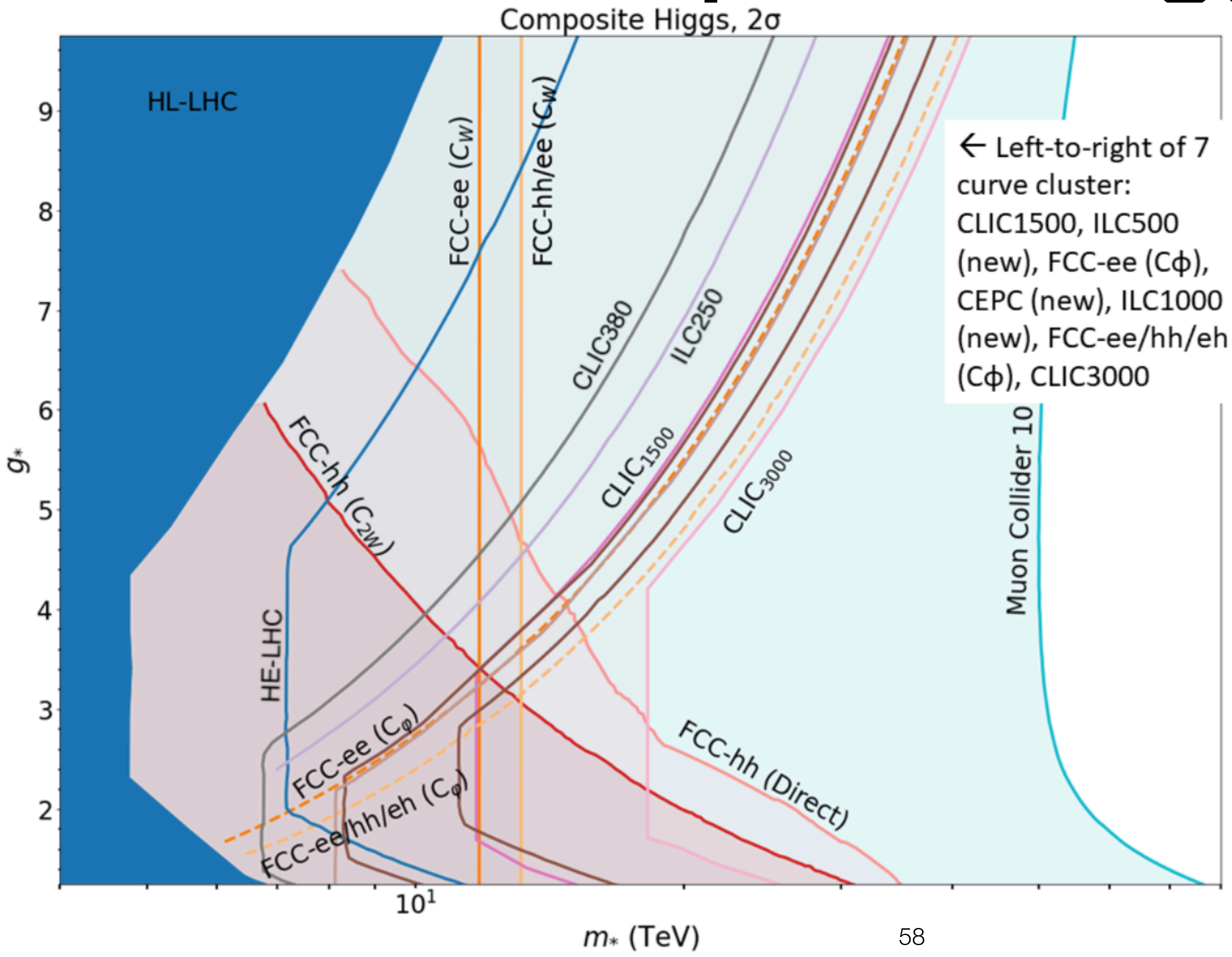


Focus on model lines

Can map to Neutral Naturalness Reach/Dark Sectors

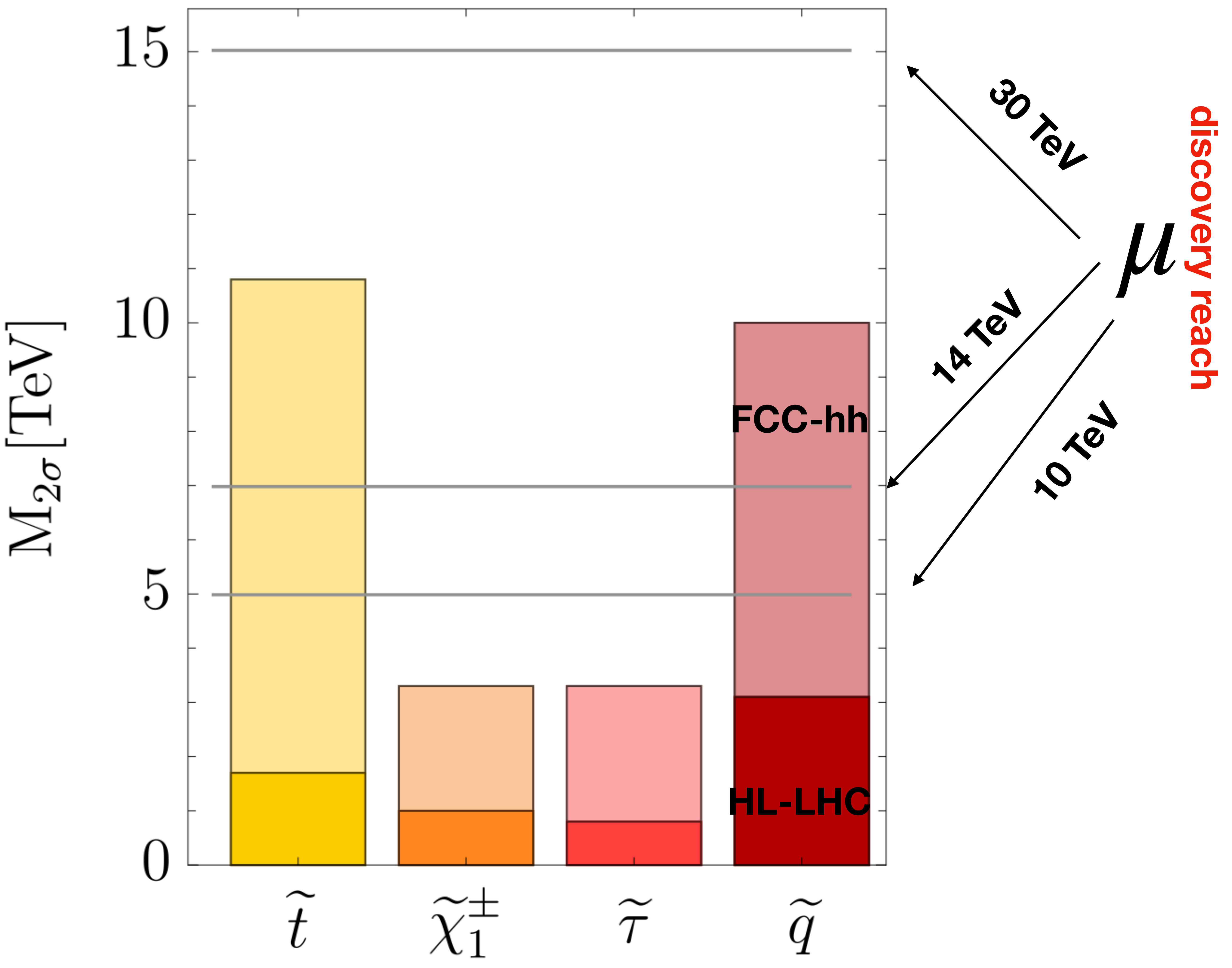
Simple Singlet extension of SM

Composite Higgs



Muon colliders are particular suited to testing possible Higgs Compositeness

Naturalness and Supersymmetry Example



The Higgs at 125 GeV already suggested the SUSY scale was high, e.g. Stops ~ 10 TeV

FCC-hh is superior to 10 TeV muon collider for Stop Searches, given colored particle nature

In realistic models - EWinos/ Sleptons tend to be TeV scale which is within reach of a 10 TeV muon collider

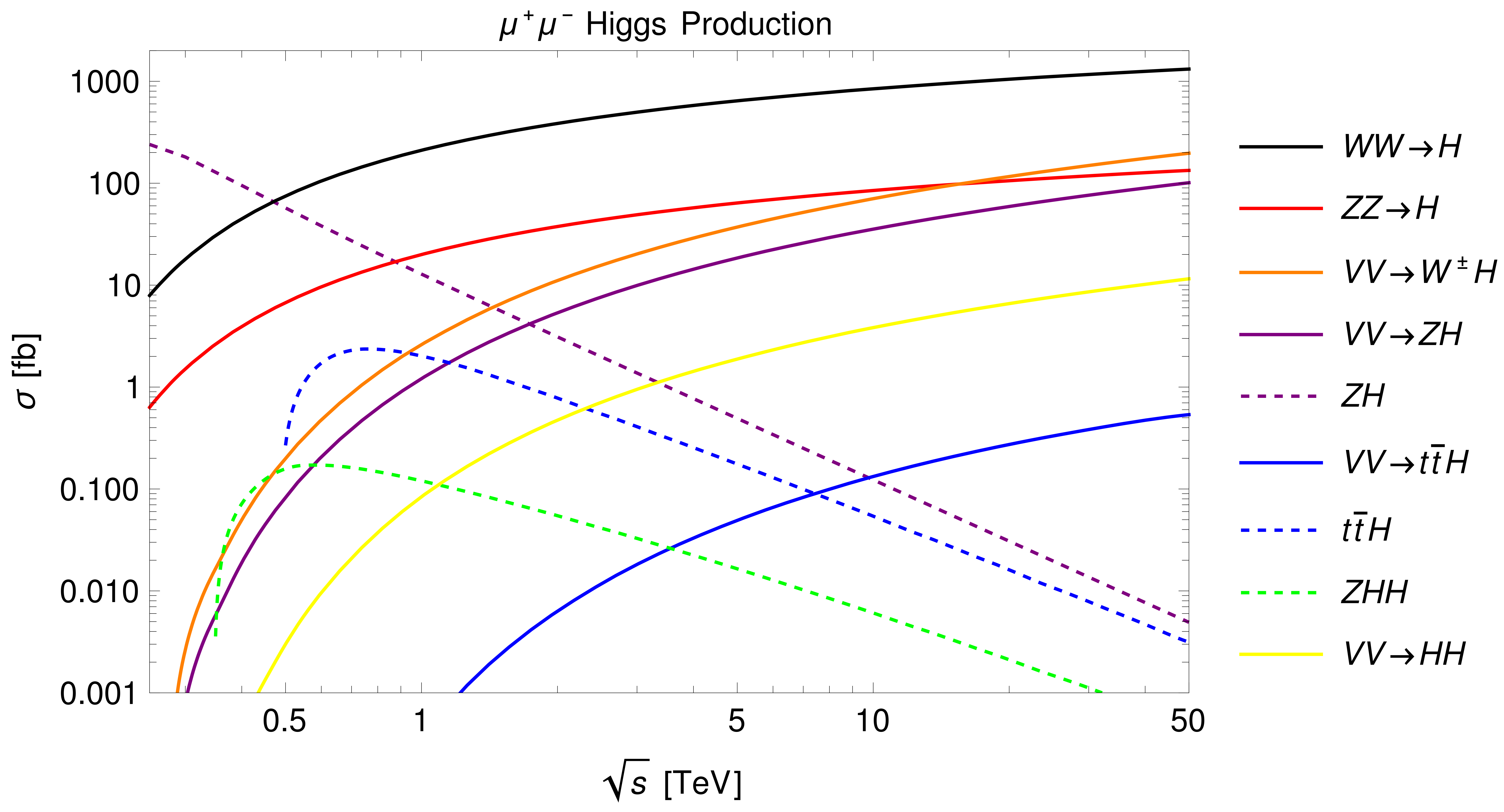
Testing the simplest WIMPs

FCC-hh or a μCol is needed!

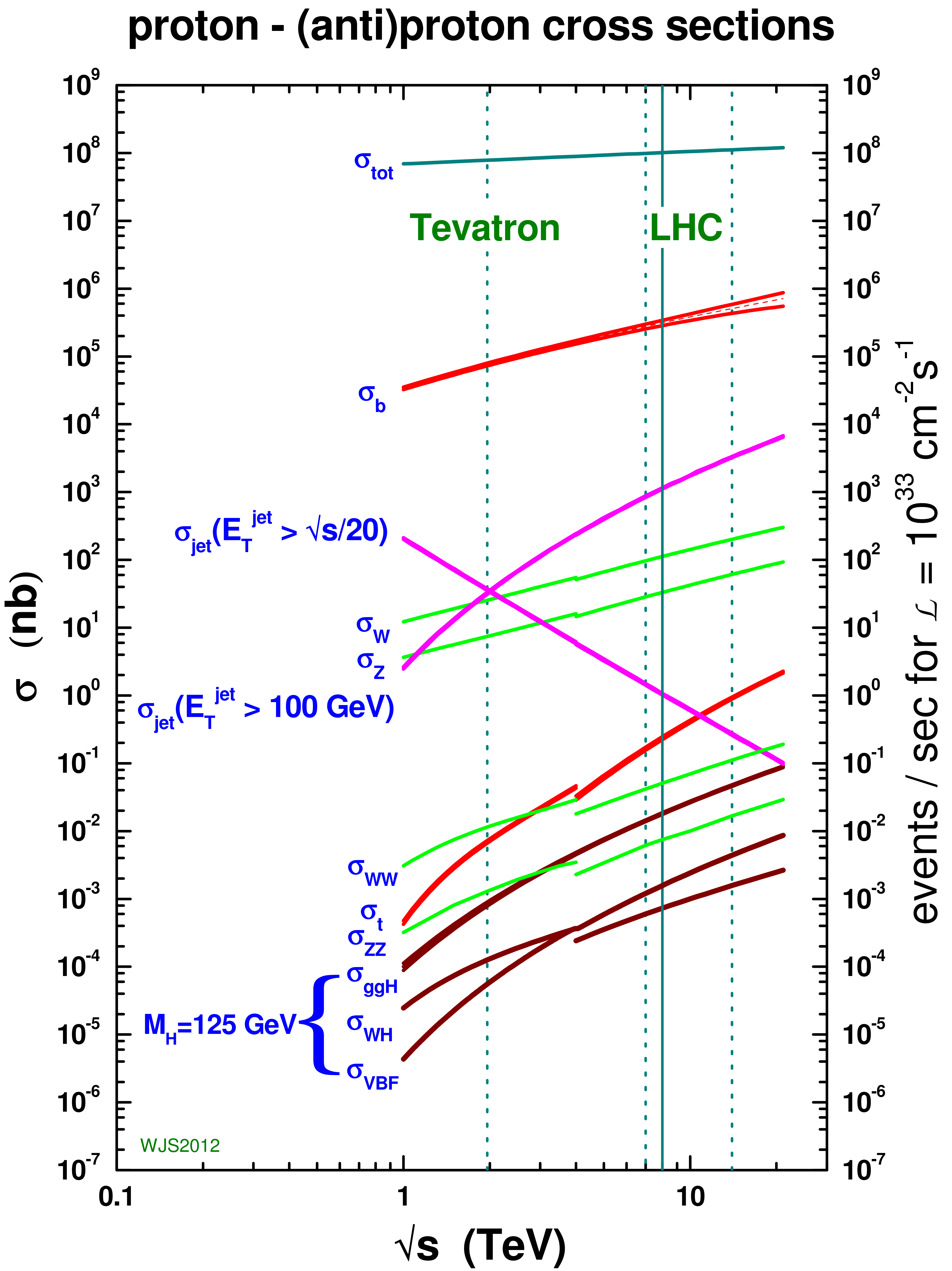
Conclusions

- **There is an urgency for High Energy colliders already**
  - Being prepared to reach beyond the picture painted by the LHC so far
  - Probing the Higgs potential and the origin and fate of the universe, understanding the origin of all of us through EWSB
  - Dark Matter - the simplest motivated possibilities still persist and are testable
  - *More possibilities in the Snowmass reports* (an enormous amount of work went into them)
- **These colliders of course have further synergies/staging I haven't touched here**
- **The 10 TeV scale let's us attack fundamentally new questions and answers, the only drawback is we can't get there *yet***
  - We must invest in our future to bring this to a reality ASAP
  - <u>We must invest in robust R&D toward ***multiple*** approaches in order to ensure we get there</u>

Backup



$\mu^+\mu^-$ Higgs Production
1000
100
10
1
0.100
0.010
0.001
σ [fb]
0.5
1
5
10
50
$\sqrt{s}$ [TeV]
$WW \to H$
$ZZ \to H$
$VV \to W^{\pm} H$
$VV \to ZH$
ZH
$VV \to t\bar{t}H$
$t\bar{t}H$
ZHH
$VV \to HH$


proton - (anti)proton cross sections
σ (nb)
events / sec for ℒ = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10
Tevatron
LHC
σtot
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σWW
σt
σZZ
σggH
σWH
σVBF
MH=125 GeV
WJS2012

These questions are not all independent, but I hope to give you some sense of what they are and how to test them to motivate future colliders