Physics Opportunities at Future Colliders

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A minimally-organized collection of theory thoughts + Muon collider updates for Snowmass

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Based on conversations w/N. Arkani-Hamed, N. Craig, M. Reece, R. Sundrum and some insights from the "Muon Smasher's Guide" 2103.14043 w/many authors

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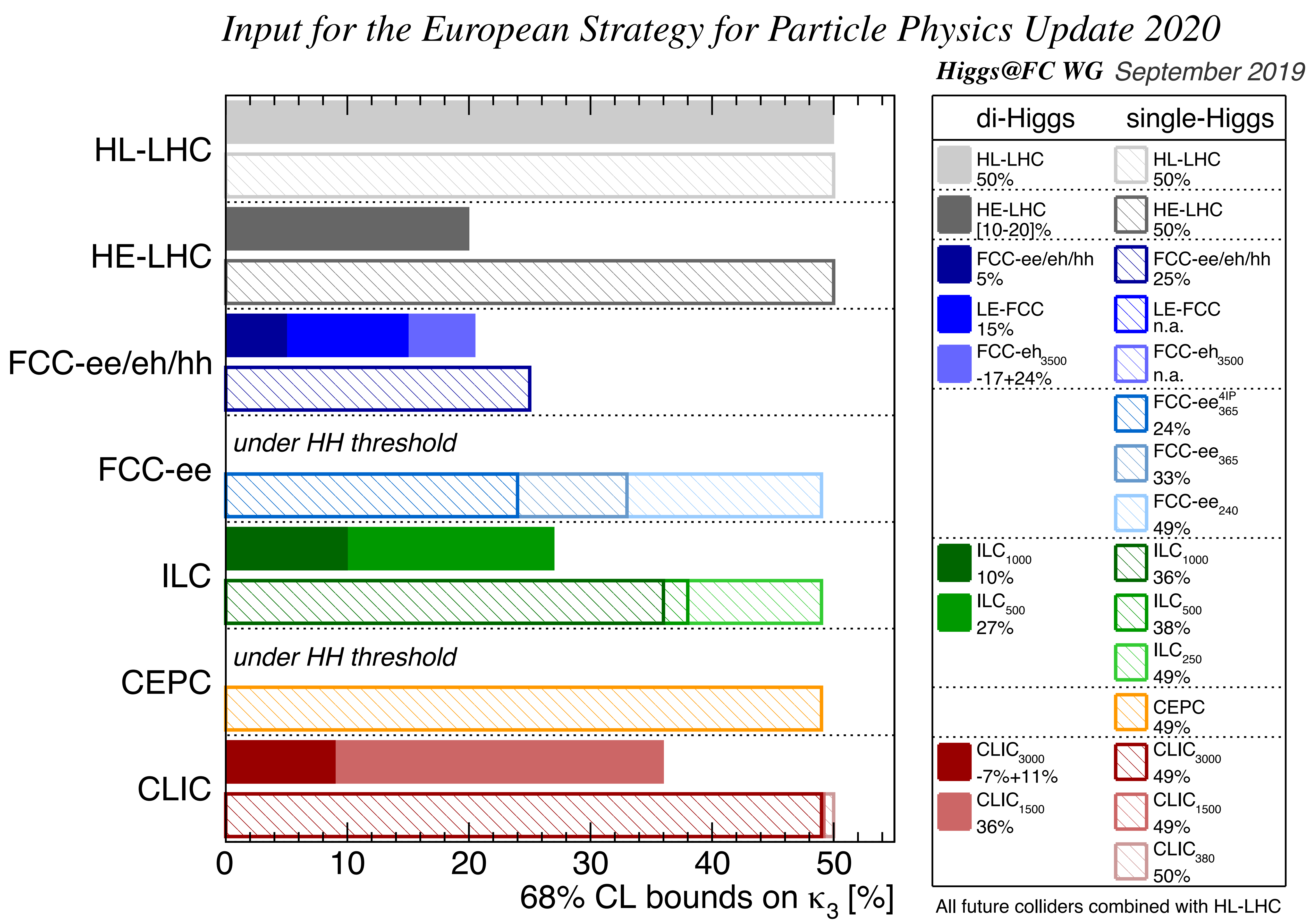
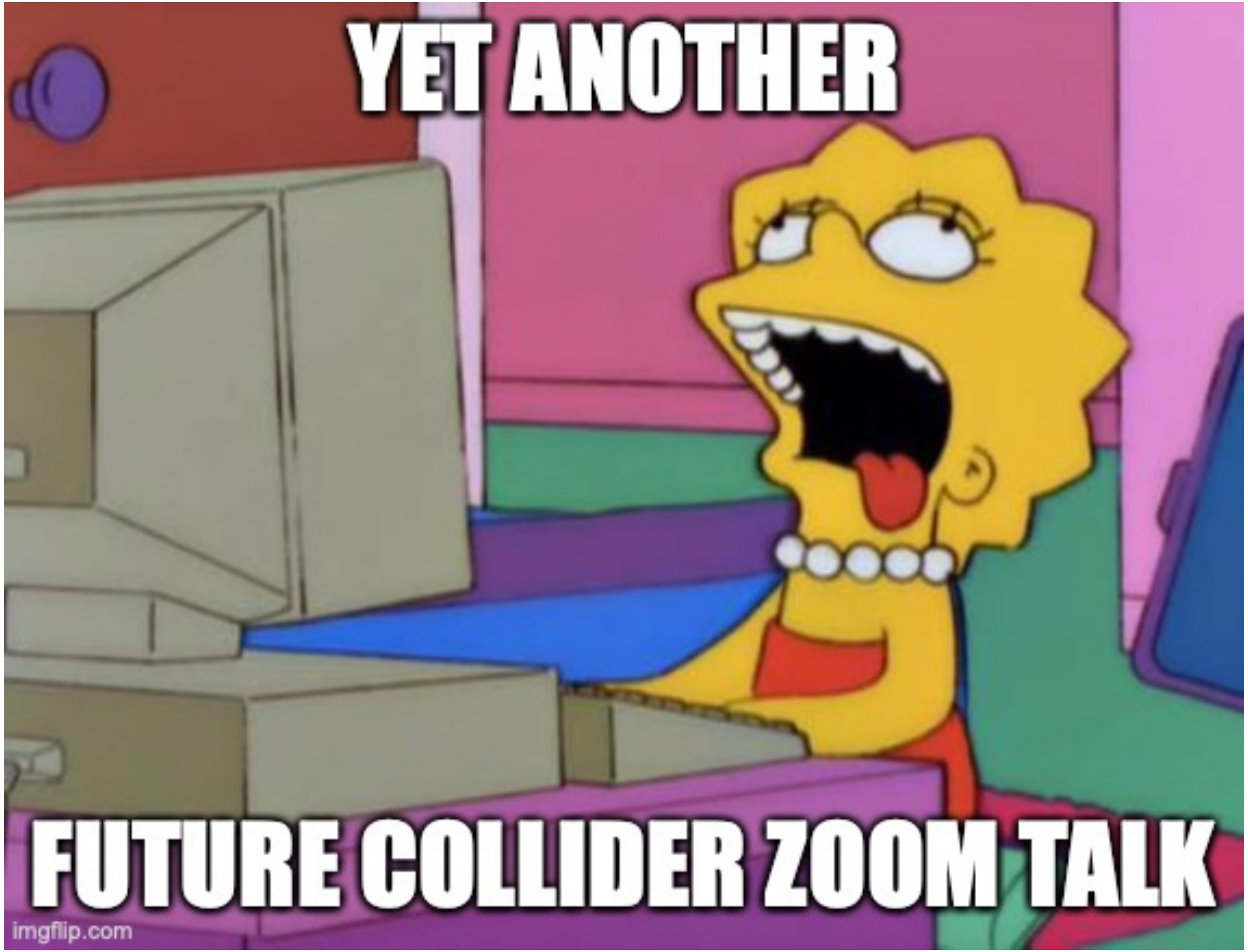
This could be a standard talk…

Physics Briefing Book



An *enormous* amount of work has gone into **Euro Strategy Update** and now **Snowmass**, and some collider proposals have been around quite a long time!


YET ANOTHER
FUTURE COLLIDER ZOOM TALK
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What kinds of opportunities are there?

Physics Opportunities at Future Colliders

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What kinds of opportunities are there?

Physics Opportunities at Future Colliders

What are the options?

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Which goes first?

Future Colliders → Physics Opportunities

ILC
FCC-ee/CEPC
CLIC
FCC-hh/SPPC

→

Physics
Reach

Basic collider options well known

Electrons

Linear | **Circular**

Energy limited (practically)
“cleaner” events - fundamental particle

Protons

Higher Energy
“dirtier” events
Composite particle

Basic collider options well known

Electrons

Linear | **Circular**

Energy limited (practically)
"cleaner" events - fundamental particle

Protons

Higher Energy
"dirtier" events
Composite particle

Muons

Best of both worlds? - Never been done before…


ONE COLLIDER
TO RULE THEM ALL
imgflip.com

ILC
FCC-ee/CEPC
CLIC
FCC-hh/SPPC
Muon Collider
?

→

Physics
Reach

Future Colliders ← ? Physics Opportunities

"Never, ever, think outside the box."

A more concrete version

ILC
FCC-ee/CEPC
CLIC
FCC-hh/SPPC
Muon Collider
?

←

Physics
Reach
Goals

Are there quantitative differences that lead to qualitative differences in our understanding?

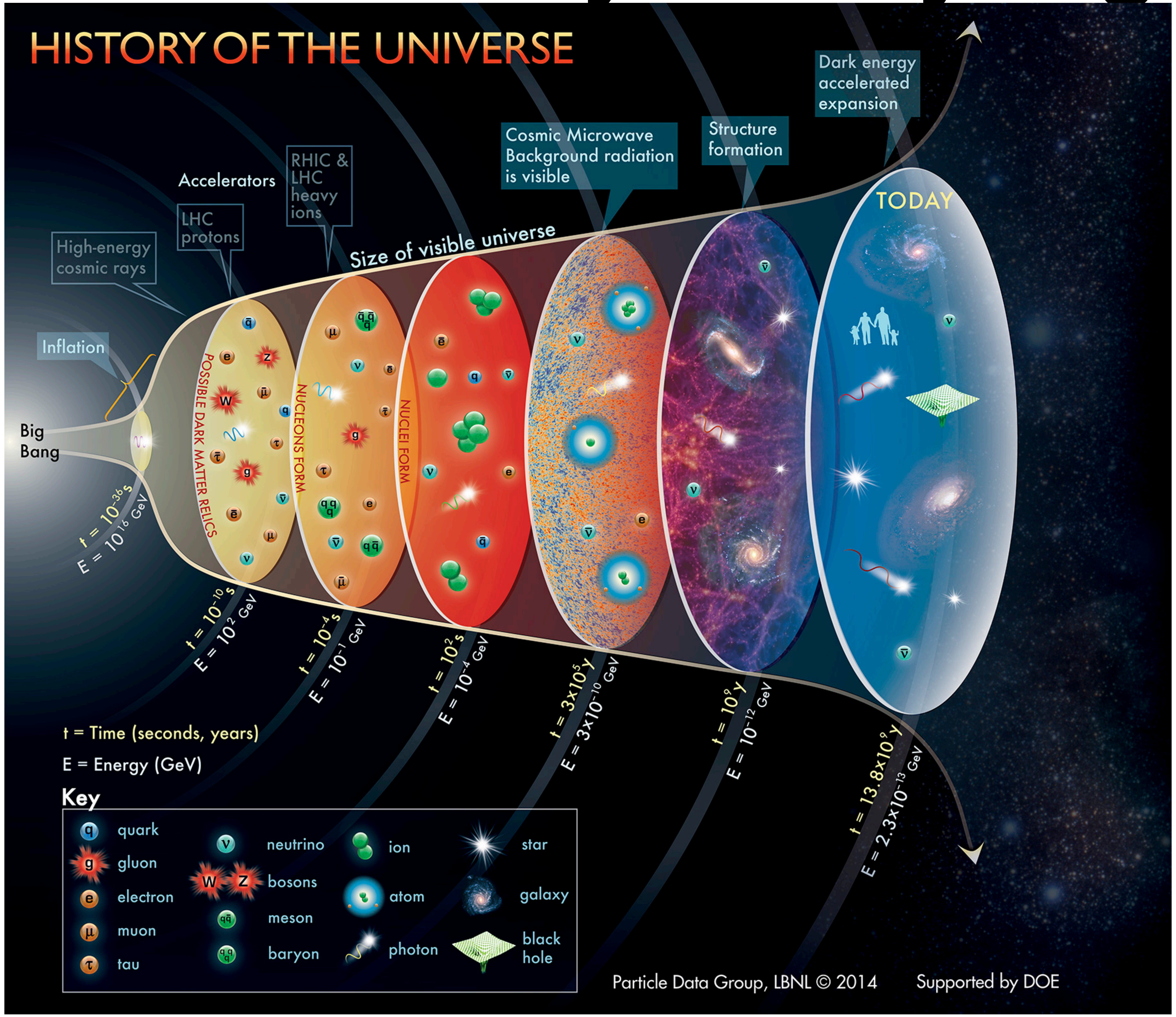
My aim is not going to be a particular conclusion… but more along the lines of food for thought and an incomplete BSM wishlist

Future Colliders ← ? Physics Opportunities

Simplest version of this is obvious…

Highest Energy Possible!

You don’t need fancy theory arguments



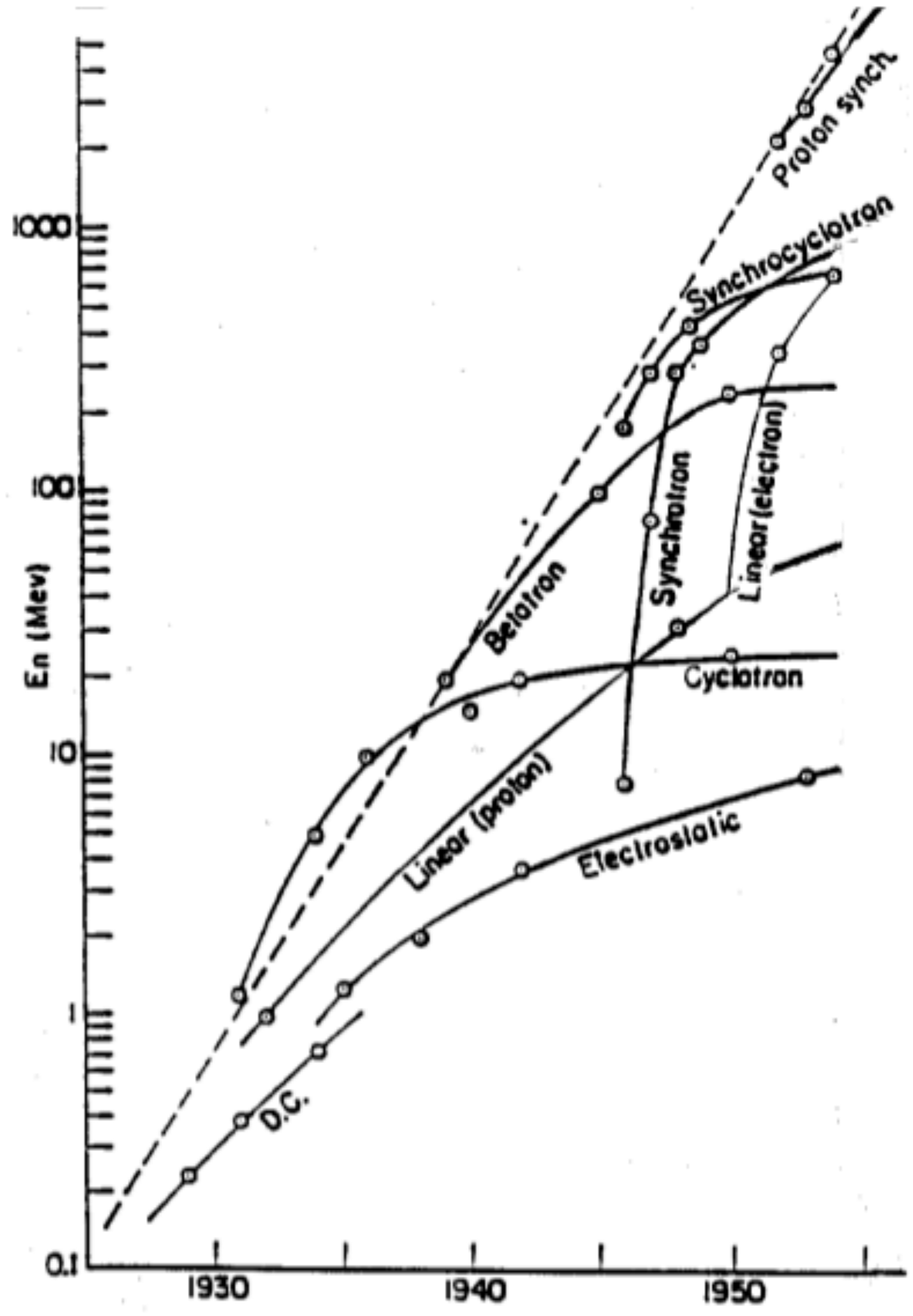
We all know the basic picture

Moreover there's an ultimate goal

M_{Pl}

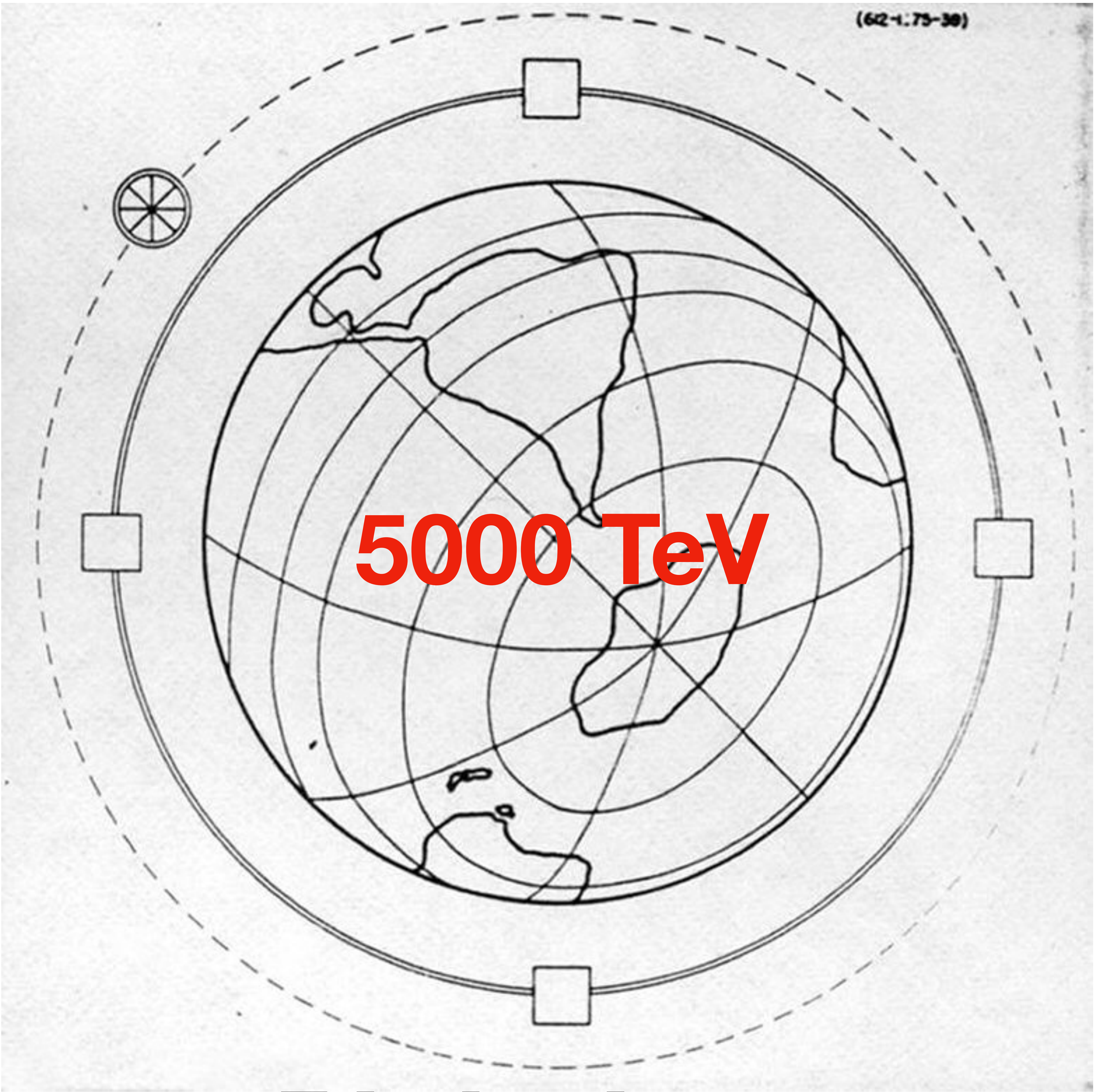
How close can we get?

Colliders used to have their version of a Moore's law

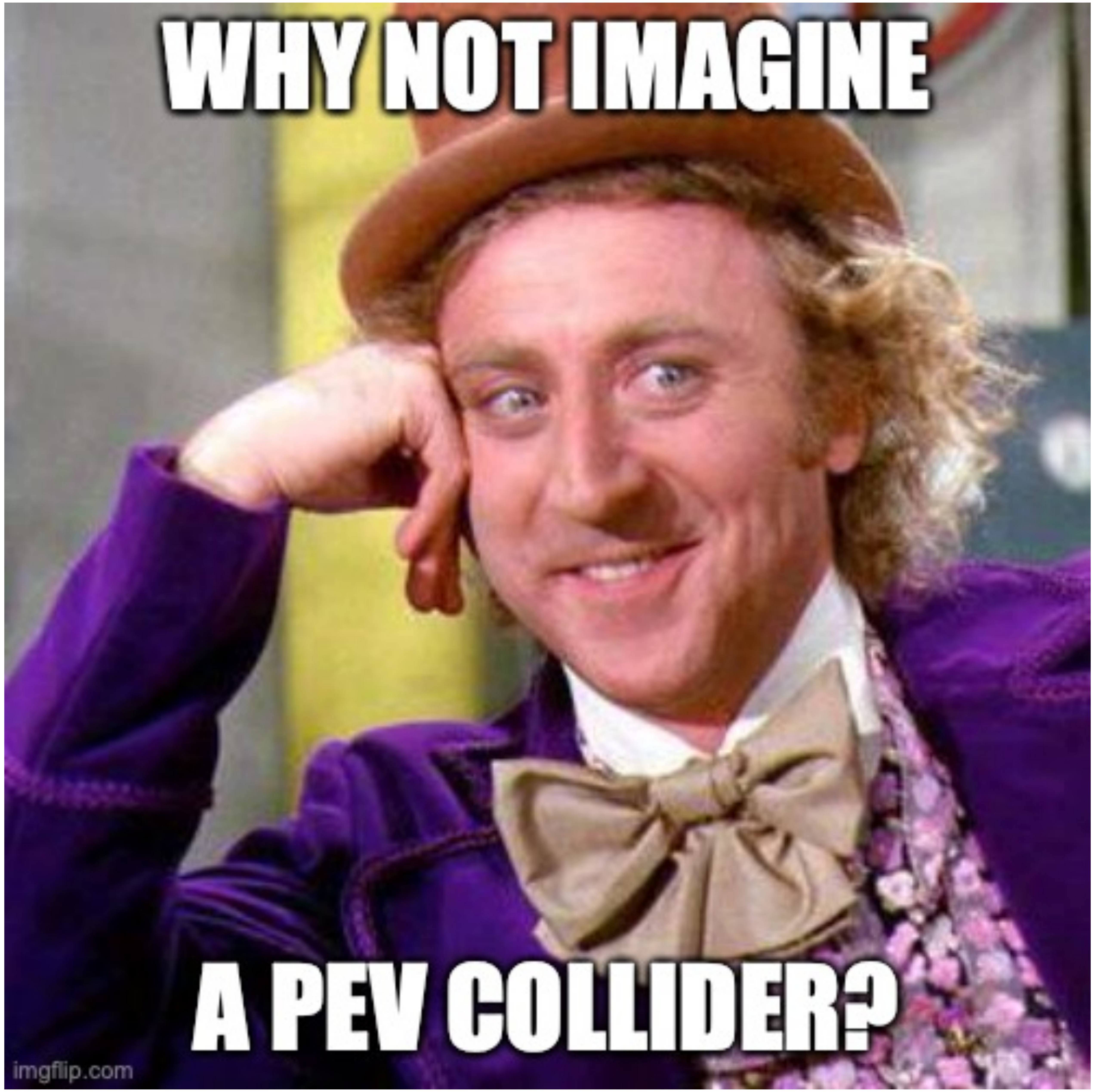


Livingston's Law - Doubling of energy every six years

This allowed Fermi to speculate 50 years in the future



Globaltron

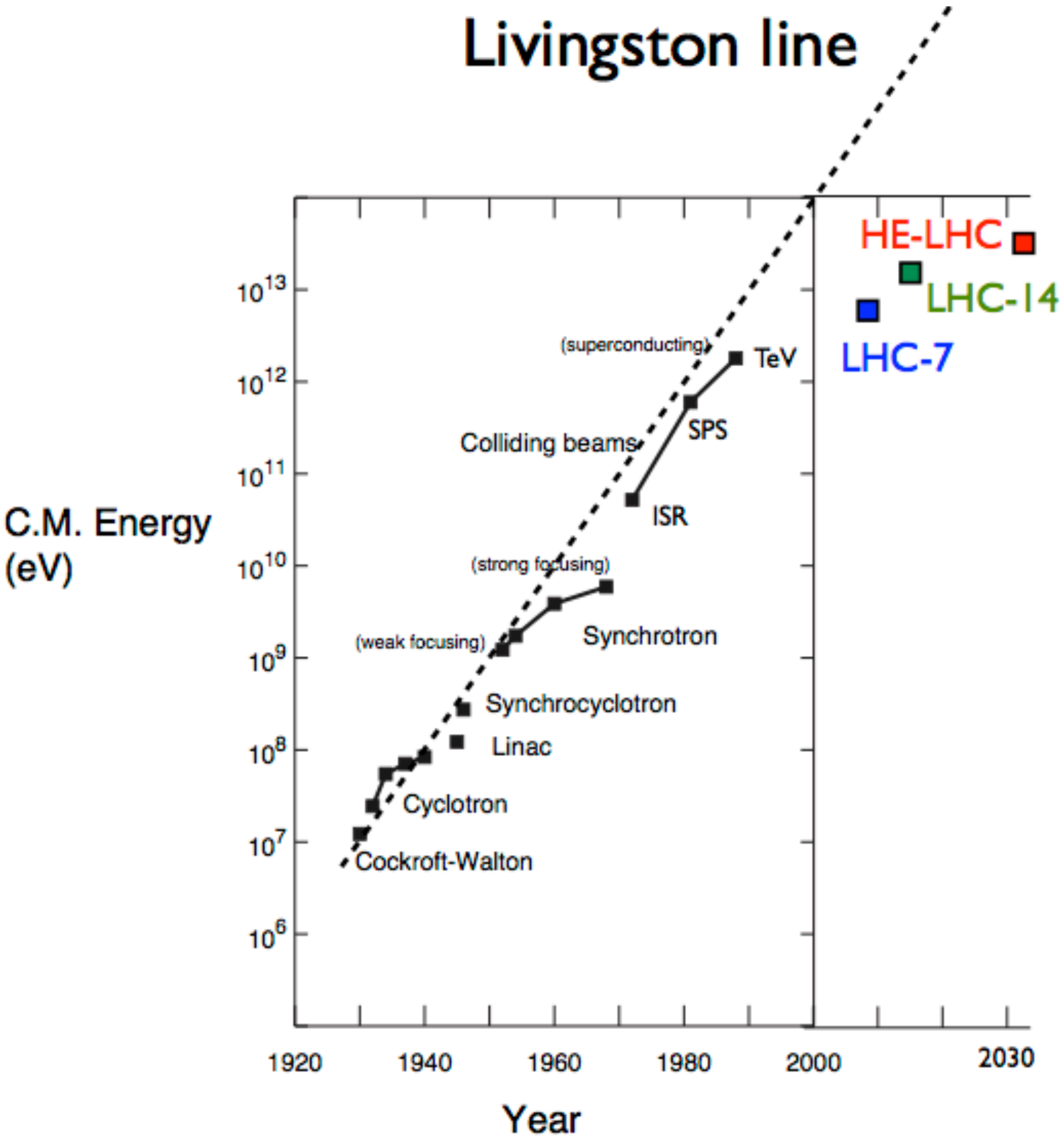


Probably the only thing I can say I have in common with Fermi other than general field of study…

Alas it’s probably out of reach anytime soon…

Alas it's probably out of reach anytime soon…

The law is already broken!

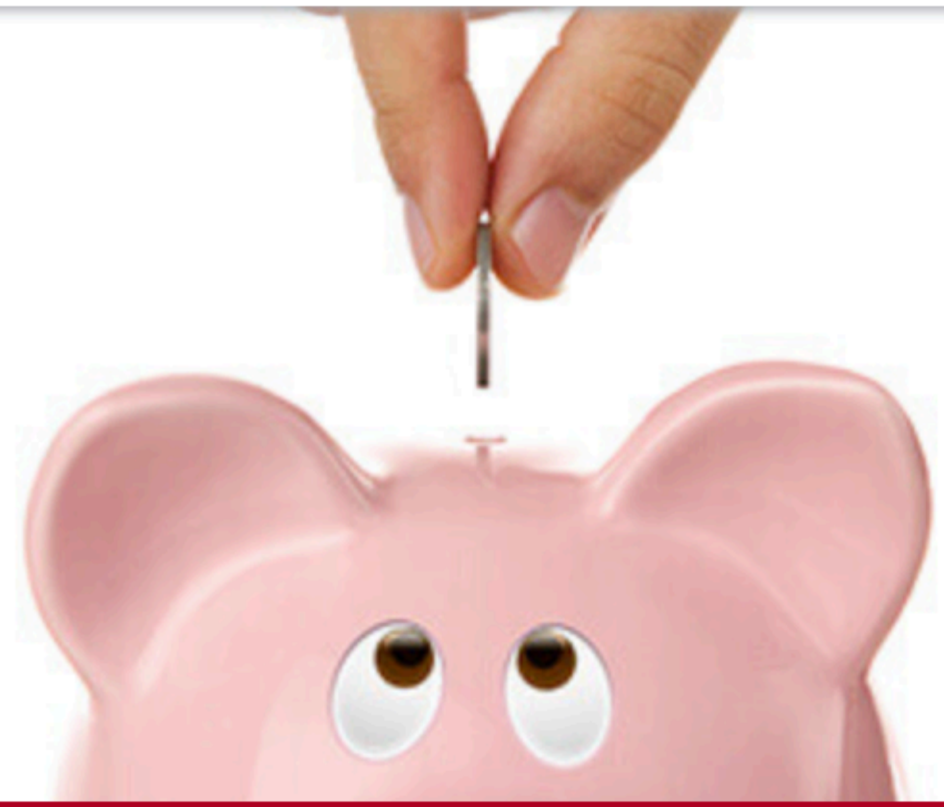


J. Rohlf "Modern Physics from a to Z"

First entry for reality check on Google:

TEXAS
Reality Check

FAQ Feedback



Will you be able to afford the lifestyle you want?

It's difficult to predict the future, but it's never too early to start planning for it. Texas Reality Check will show you how much your living expenses will cost, and the amount of money you will need to earn to pay for them.

It's time for a Reality Check.

First entry for reality check on Google:

TEXAS
Reality Check

FAQ Feedback

Will you be able to afford the Collider you want?

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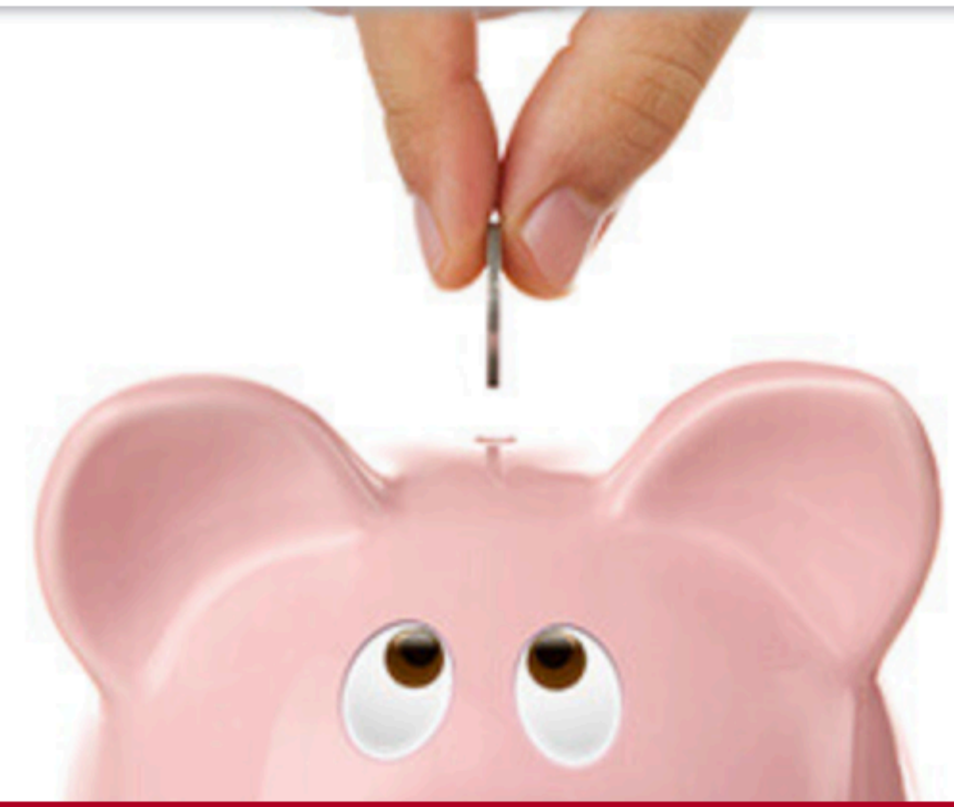
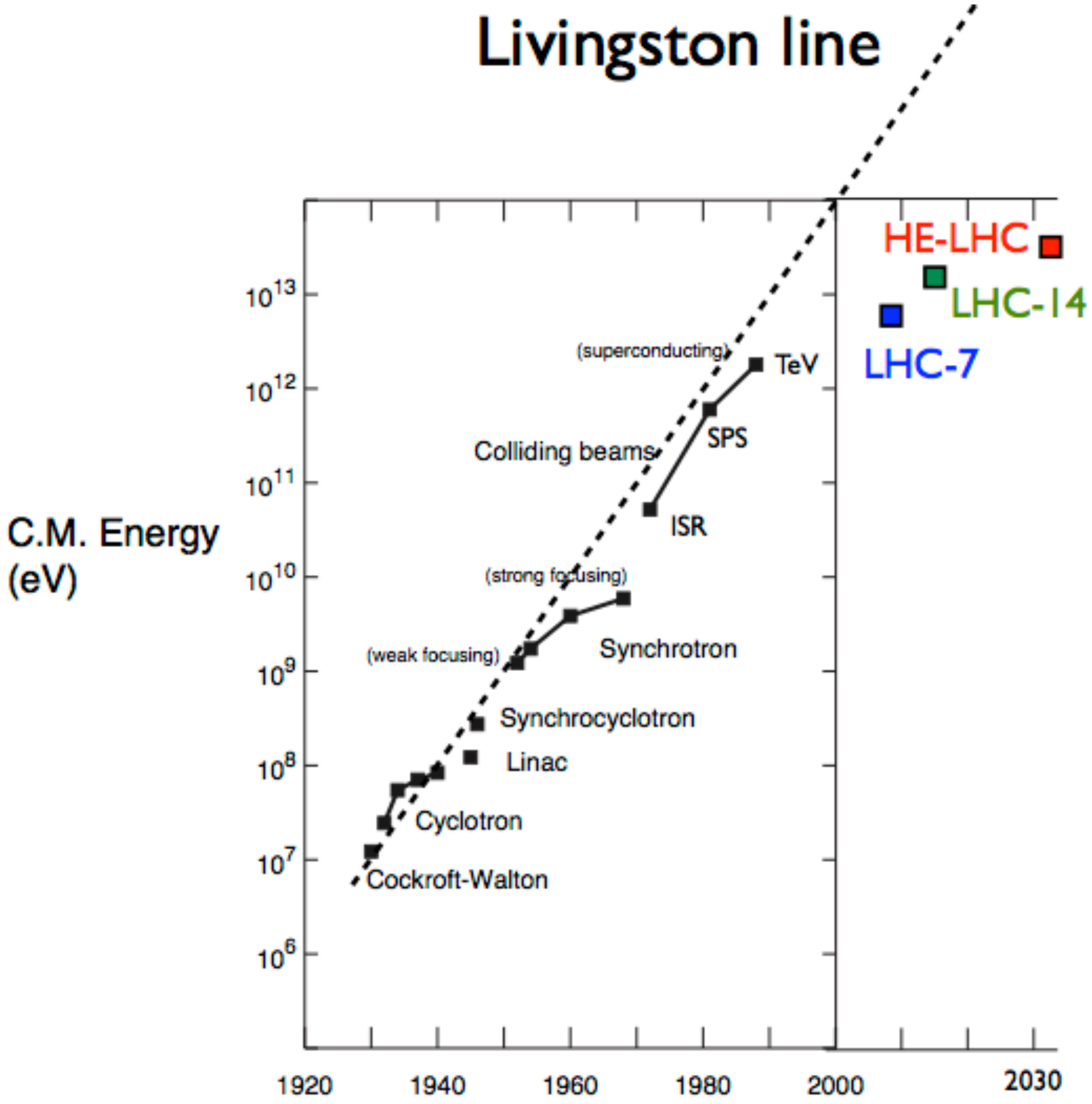


It's time for a Reality Check.

Complete accident that Texas was involved in this and no correlation to SSC

We've already seen the law breaking



Although SSC would have kept us on track…

J. Rohlf "Modern Physics from a to Z"

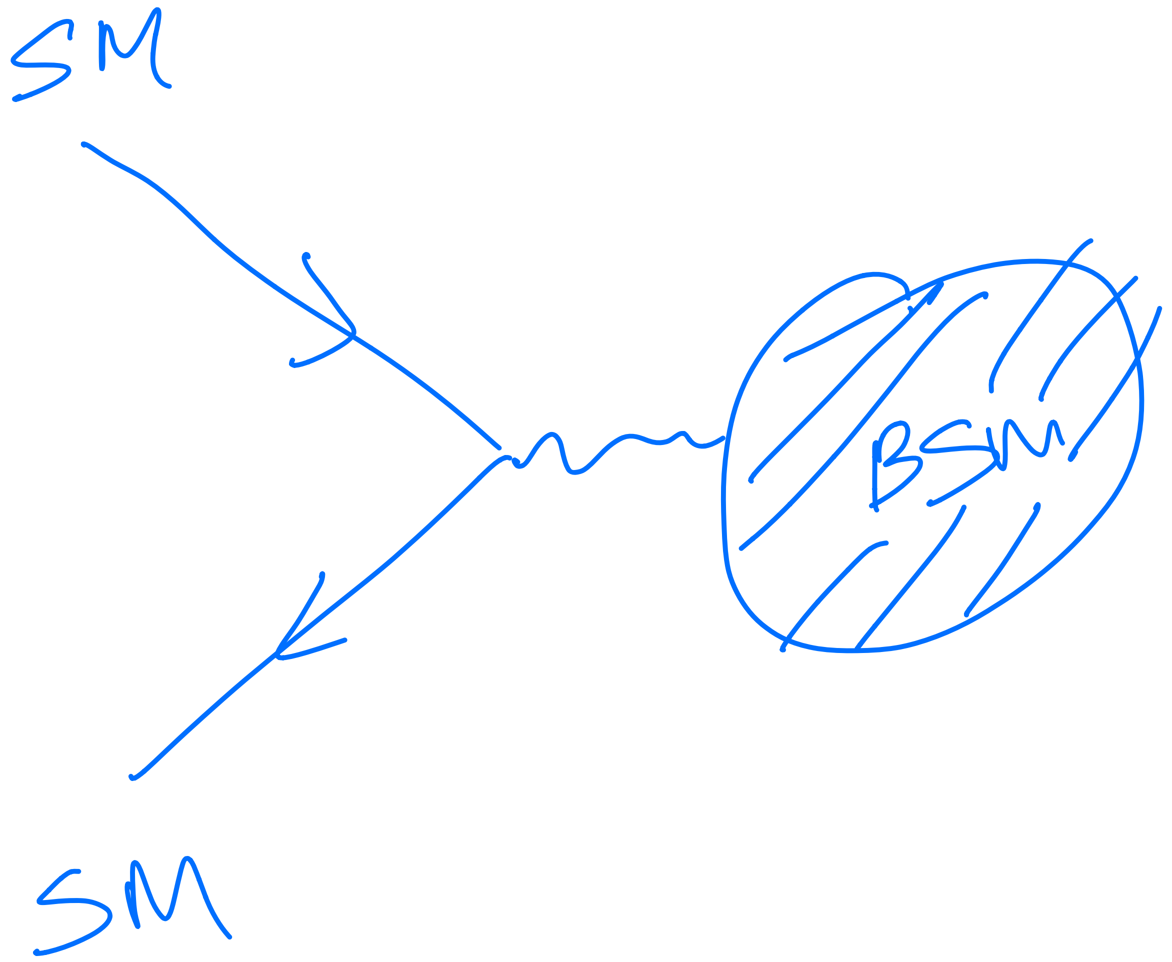
Many competing factors:

Time

Cost

Technology

It's also not *just* an Energy race



$$\sigma \sim \frac{1}{s}$$

$$N_{ev} \sim \sigma \mathcal{L}$$

$$\mathcal{L} \sim s$$

Yikes!

Many competing factors:

Time

Cost

Technology

Many competing factors:

At the first Snowmass in 1982 they felt compelled to write it up...

Planning is establishing the Facility and Resource Allocation direction of the field. Hopefully it is driven by the physics opportunities; in the real world this gets modified by these considerations:

- money
- pork barrel
- survival imperative (at both laboratory and university group level)
- competition
- geography
- and strong personalities.

So if we don’t make it here yet…

M_{Pl}

Are there some interesting signposts along the way? Are some existing collider options more exciting than others?

Physics Opportunities

Three main categories with lots of overlap

BSM Wishlist

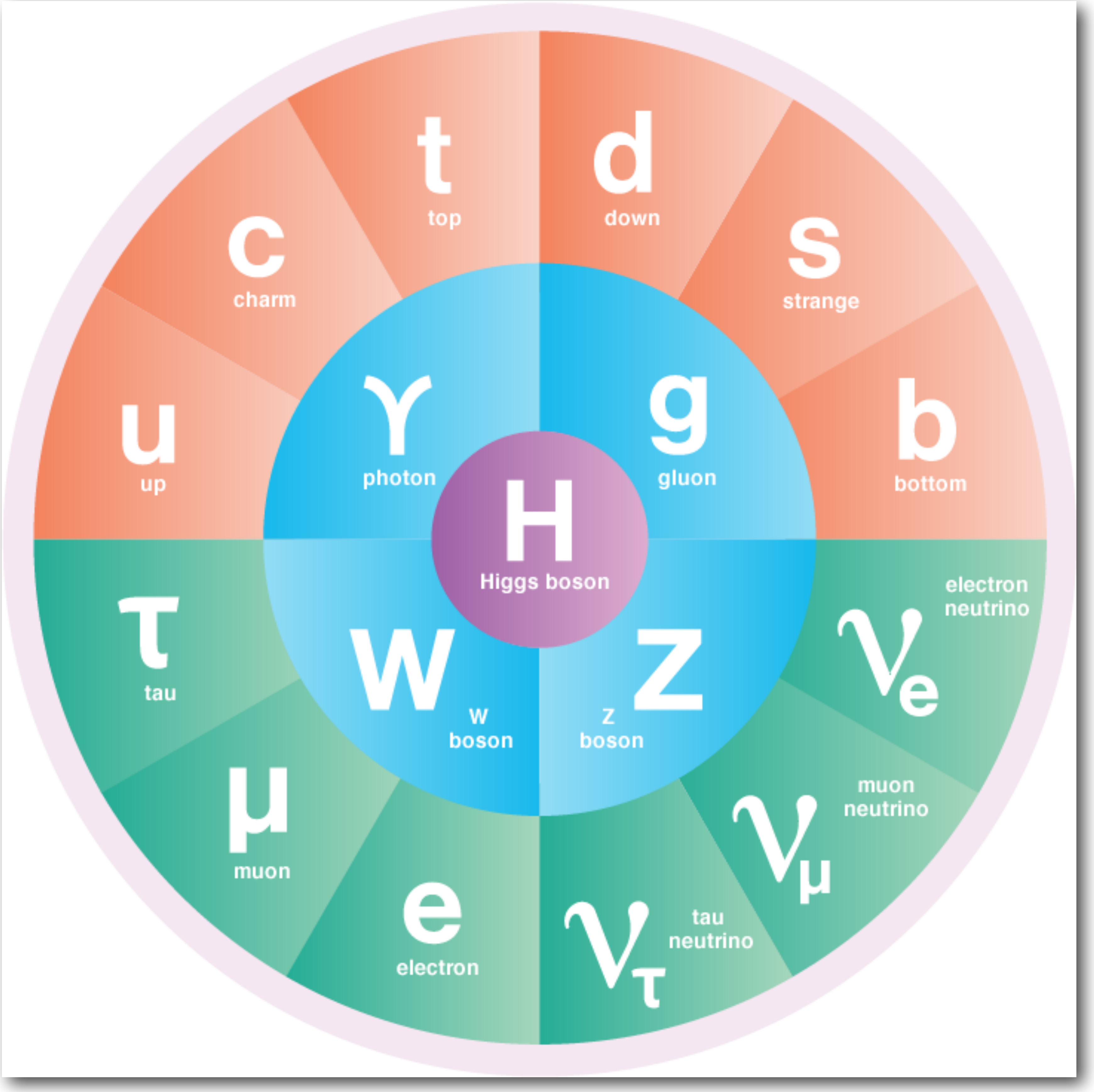
Even if you are this much of a curmudgeon…

Physics Opportunities

Three main categories with lots of overlap

BSM Wishlist

Completing the SM/measuring the Higgs



We often act as if the SM is complete, but we still haven't observed or measured many of the couplings at an O(1) precision!

Completing the SM/measuring the Higgs

- Why does EWSB occur?
- Naturalness?
- Higgs potential just the minimal one?
- Origin of flavor?
- Higgs and early universe role?
- …

Completing the SM/measuring the Higgs

Aren't the Higgs factories supposed to do this?

Completing the SM/measuring the Higgs

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	0.06
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	0.23
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	0.15
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	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
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	0.16
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
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	0.31

But what are the biggest missing pieces post HL-LHC?

Biggest missing Higgs pieces

Higgs self couplings

1st and 2nd Generation Yukawa Couplings

How well do we need to measure?

Higgs Self Couplings
How well do we need to measure?

Strong First Order Phase Transition

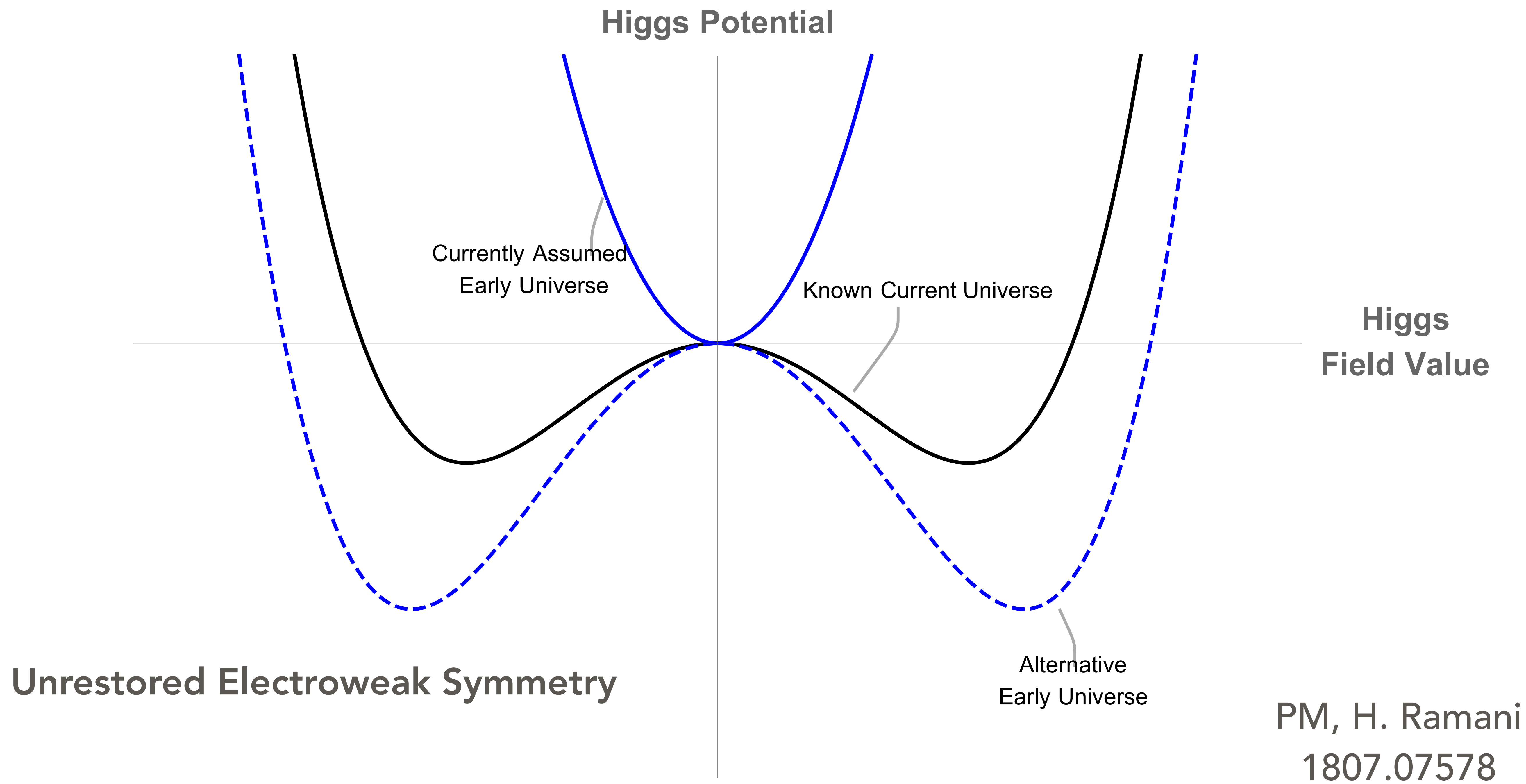
$$\delta\lambda_3 \gtrsim 10\%$$

SM Crossover

$$\delta\lambda_3 \sim 0\%$$

Lore - Easy to distinguish 2 possible early universes with Triple Higgs

Higgs Self Couplings
How well do we need to measure?



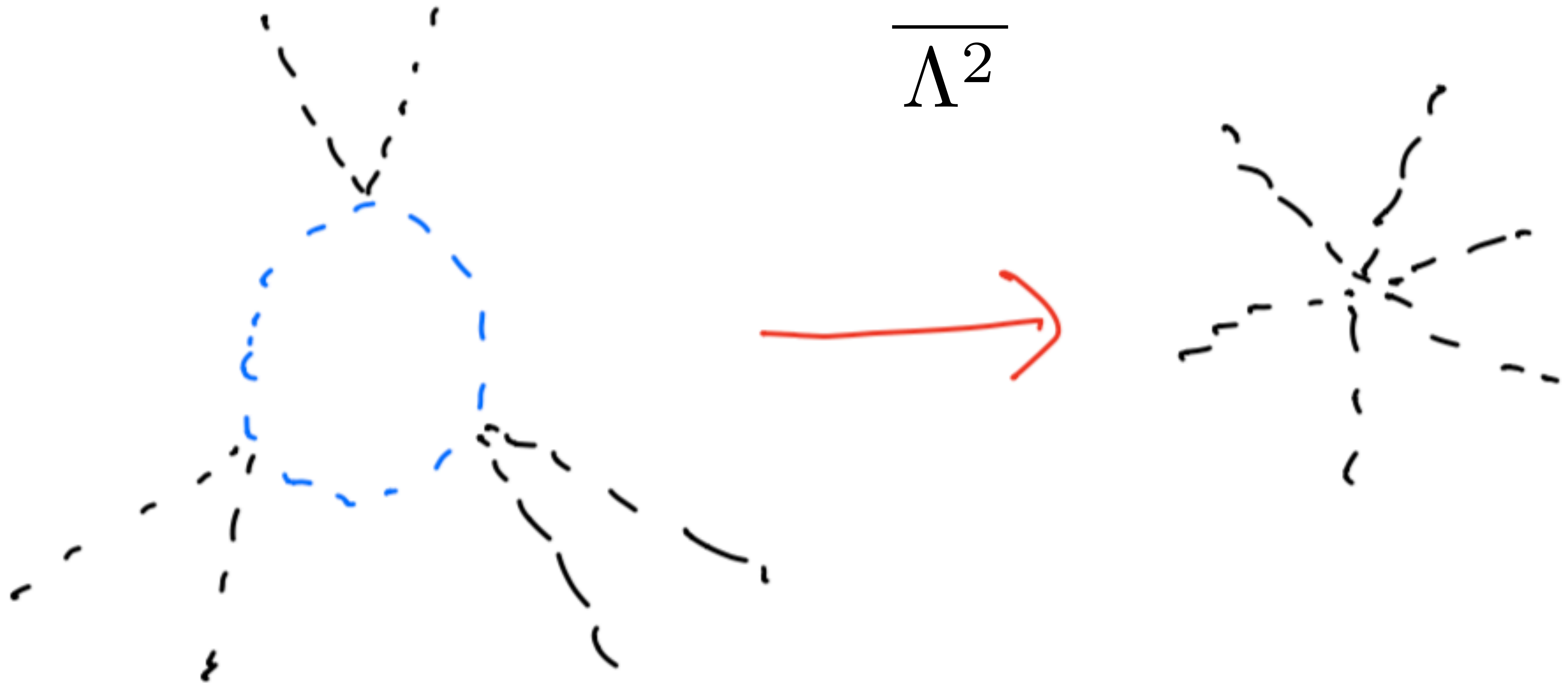
PM, H. Ramani
1807.07578

Three qualitatively DIFFERENT histories of our universe

In principle need $\delta\lambda_3 \ll 1\%$ to distinguish

Higgs Self Couplings
More generally - Higgs Portal

$$\frac{H^6}{\Lambda^2}$$

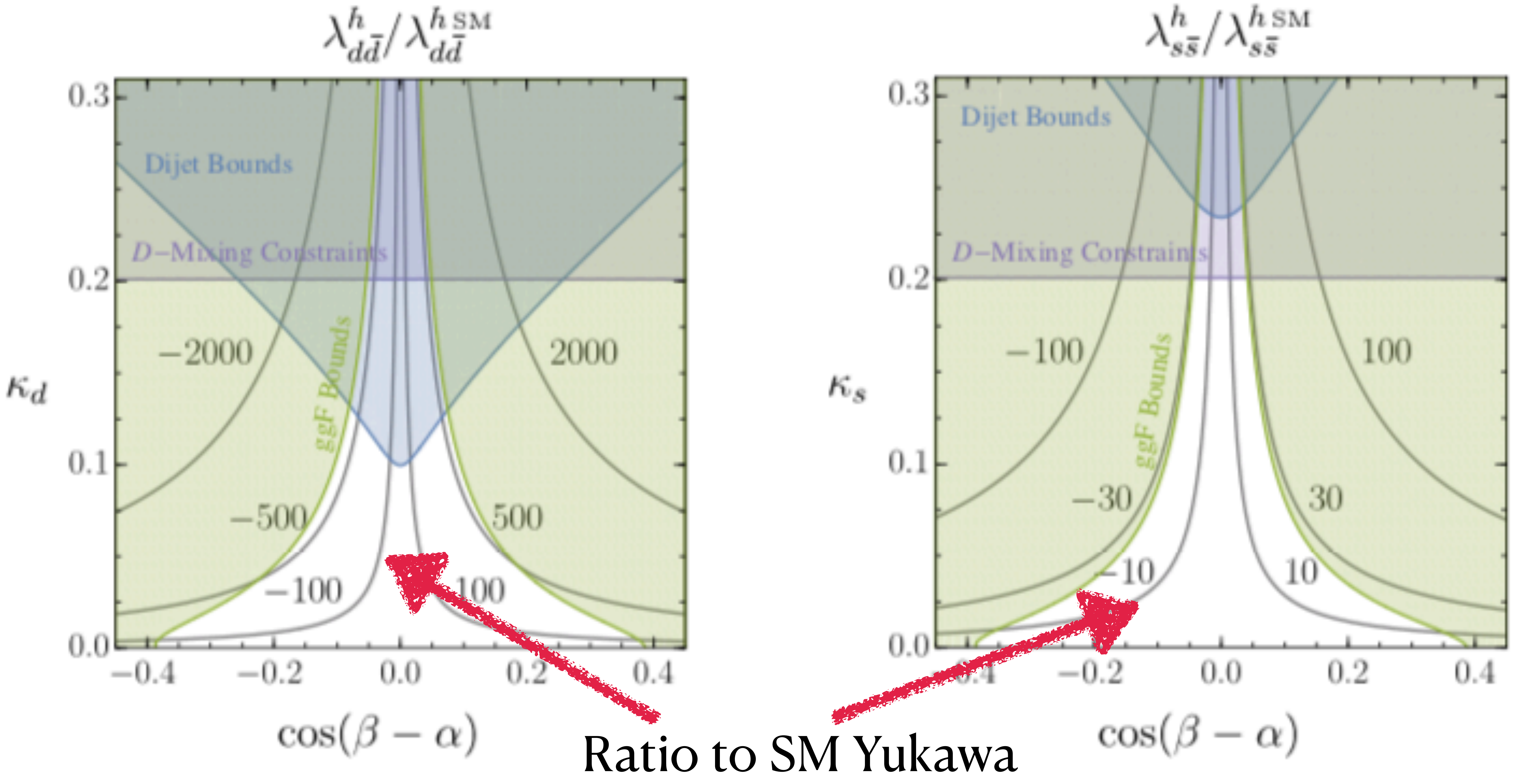


Loop-level

Using magnitude of only quartic we "know"

$$\delta\lambda_3 \sim 10^{-3}$$

1st and 2nd Gen Yukawa Very difficult to measure!



D. Egaña, S.Homiller, PM
1811.00017, 1908.11376,
2101.04119

But… There are now models with sizable enhancements!

Physics Opportunities

Three main categories with lots of overlap

BSM Wishlist

BSM Motivations

- Naturalness
  - Compositeness
  - SUSY
  - Neutral Naturalness
- Dark Matter
- Flavor, CPV
- Hidden Sectors
- Baryogenesis

The questions remain even with the success of LHC

some even more so than before

There are also new *potential* answers being developed

that have qualitatively and quantitatively different pheno

Naturalness

***The report of my death was an exaggeration*.**

Higgs makes it even a *more* alive problem!

What is dead is very natural elegant solutions…

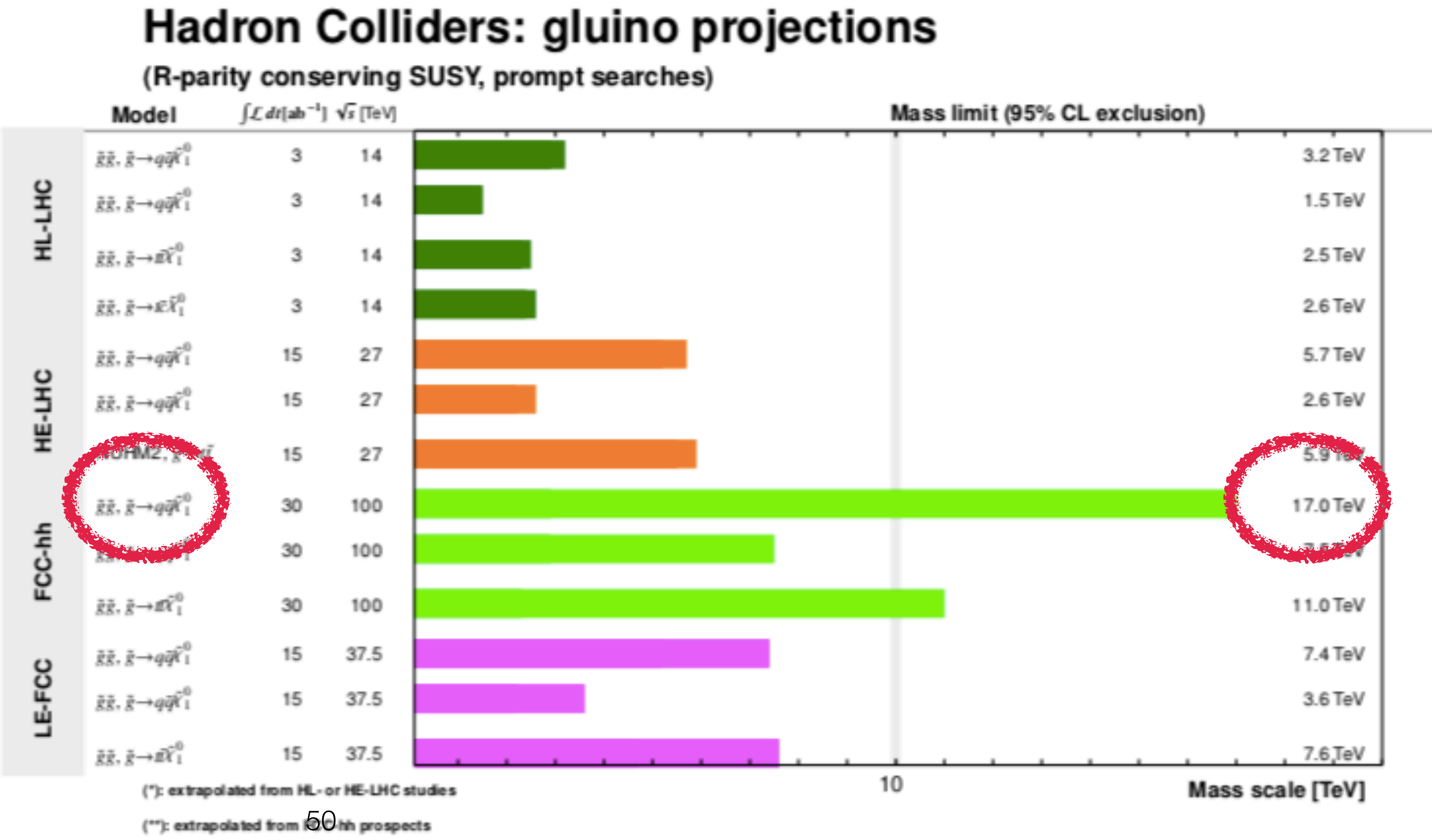
2 (or more) choices

Less natural, but simple

Less simple, but more natural

Motivated Natural Targets?

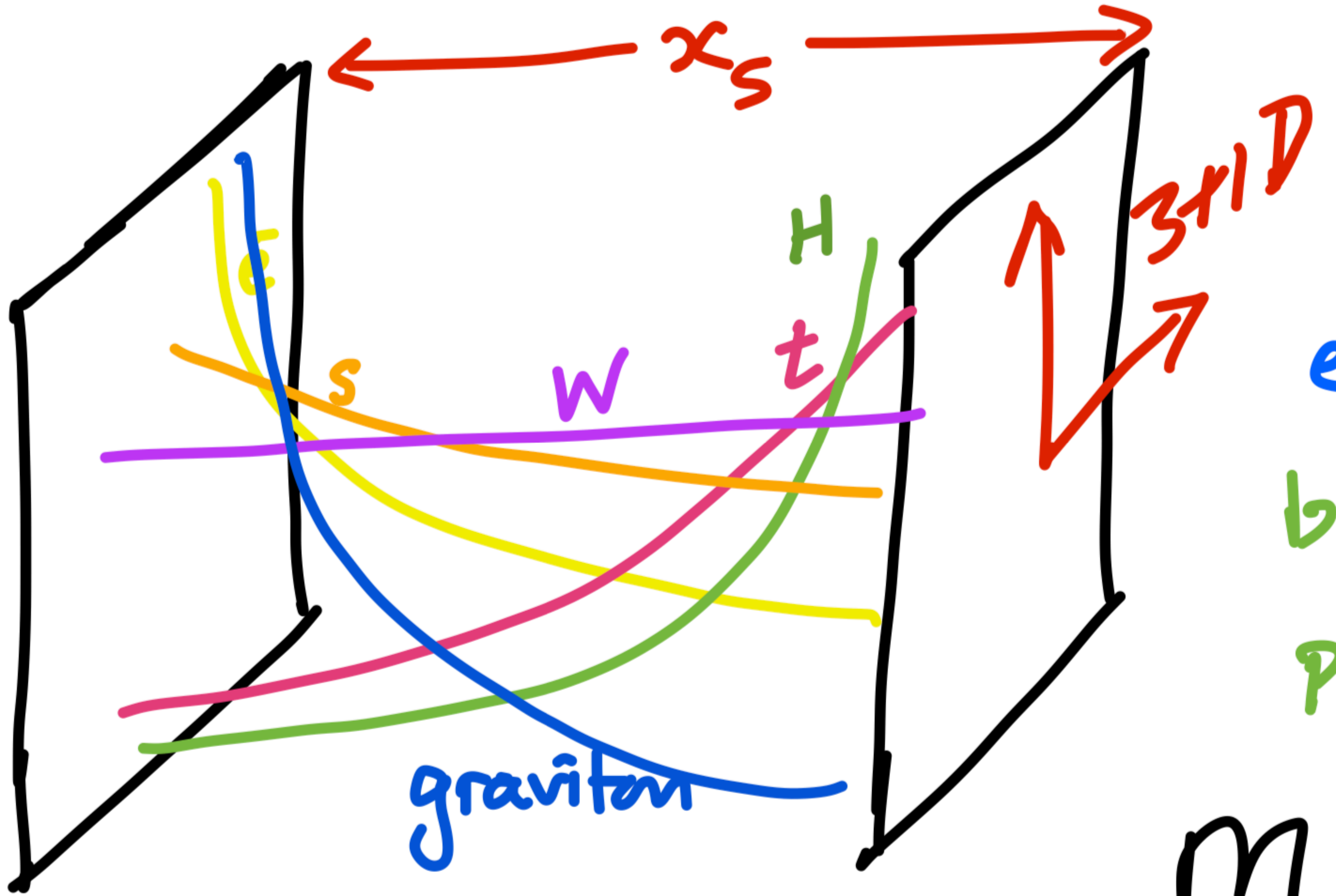
Simple option: Mini-Split
Wino as Thermal Relic implies ~ 30 TeV Gluino



Motivated Natural Targets?

COMPOSITE HIGGS

This strong-coupling problem can be geometrized via AdS/CFT into WARPED EXTRA DIMENSIONS

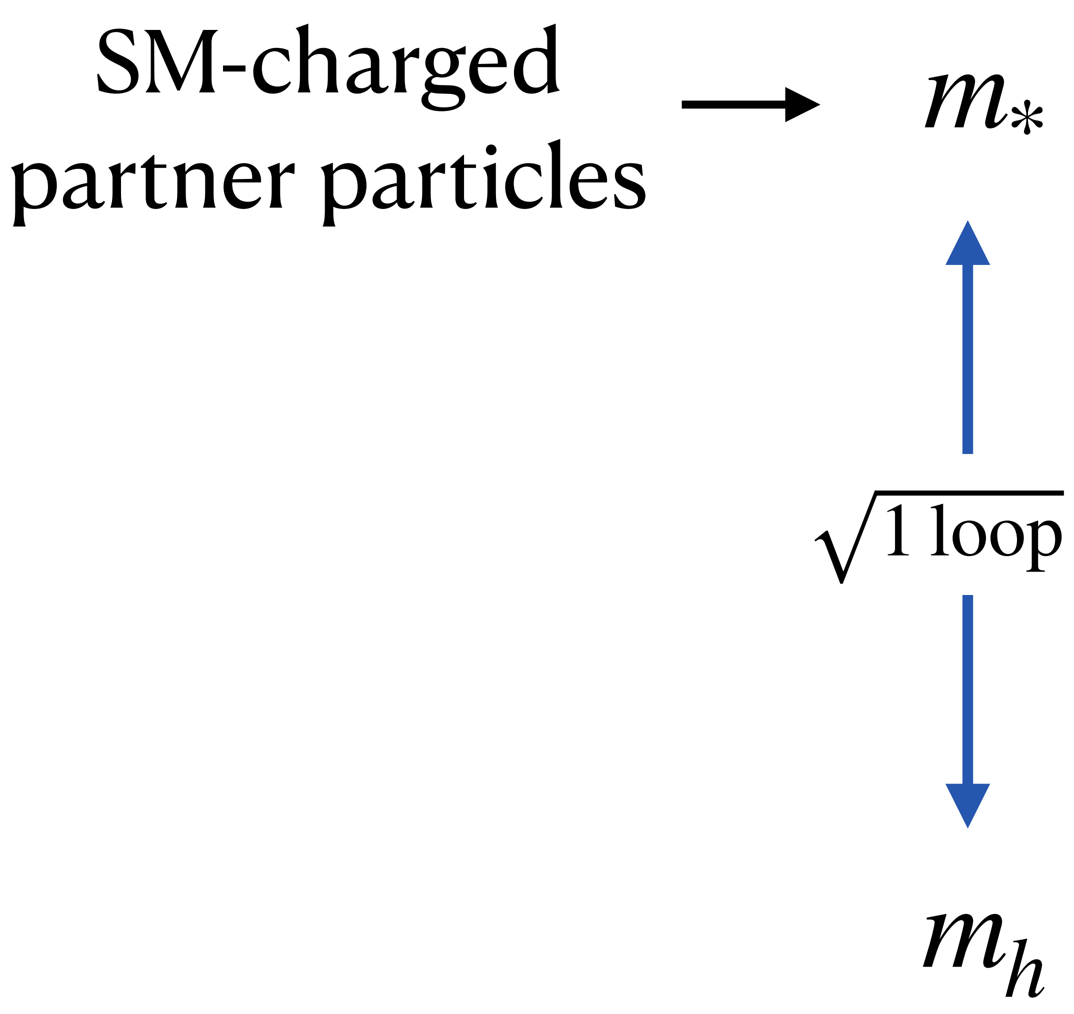


SIMPLEST MODELS (fewest theoretical epicycles) CONSTRAINED by ~~FLAVOR~~ ~~CP~~ PRECISION TESTS

$m_{\text{Kaluza-Klein excitations}} \gtrsim 10\text{s} - 100\ \text{TeV}$

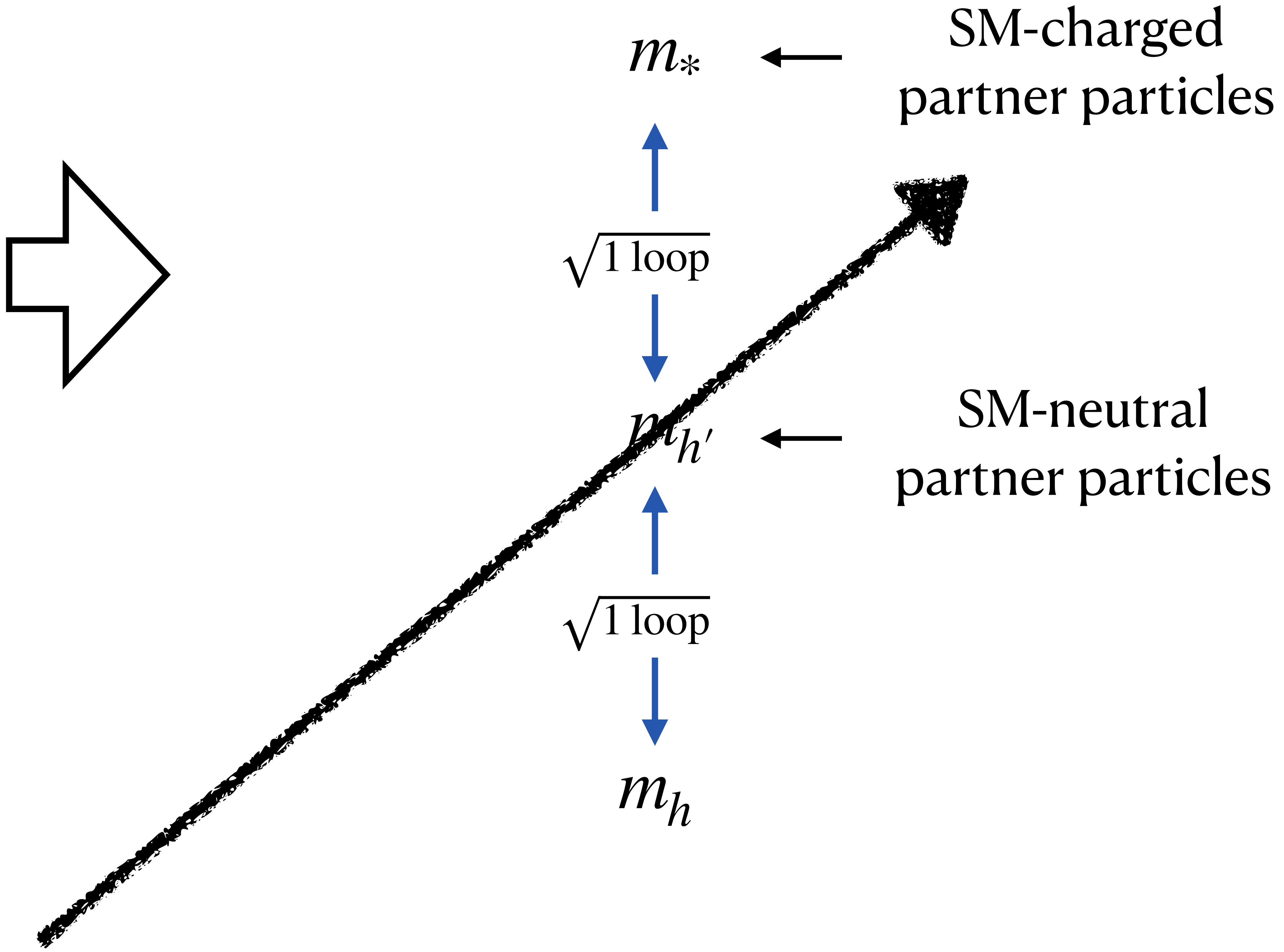
Neutral Naturalness

Conventional Naturalness



Natural scale of new SM-charged particles raised by ~ 4π

Neutral Naturalness (Twin Higgs, ...)



~20 TeV particles!

Physics Opportunities

Three main categories with lots of overlap

Complementarity with other measurements

There are multiple approaches to BSM physics at higher scales

Nevertheless if we get indirect hints from existing

or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes (EDM, LFV, g-2 etc)

Current complementarity…

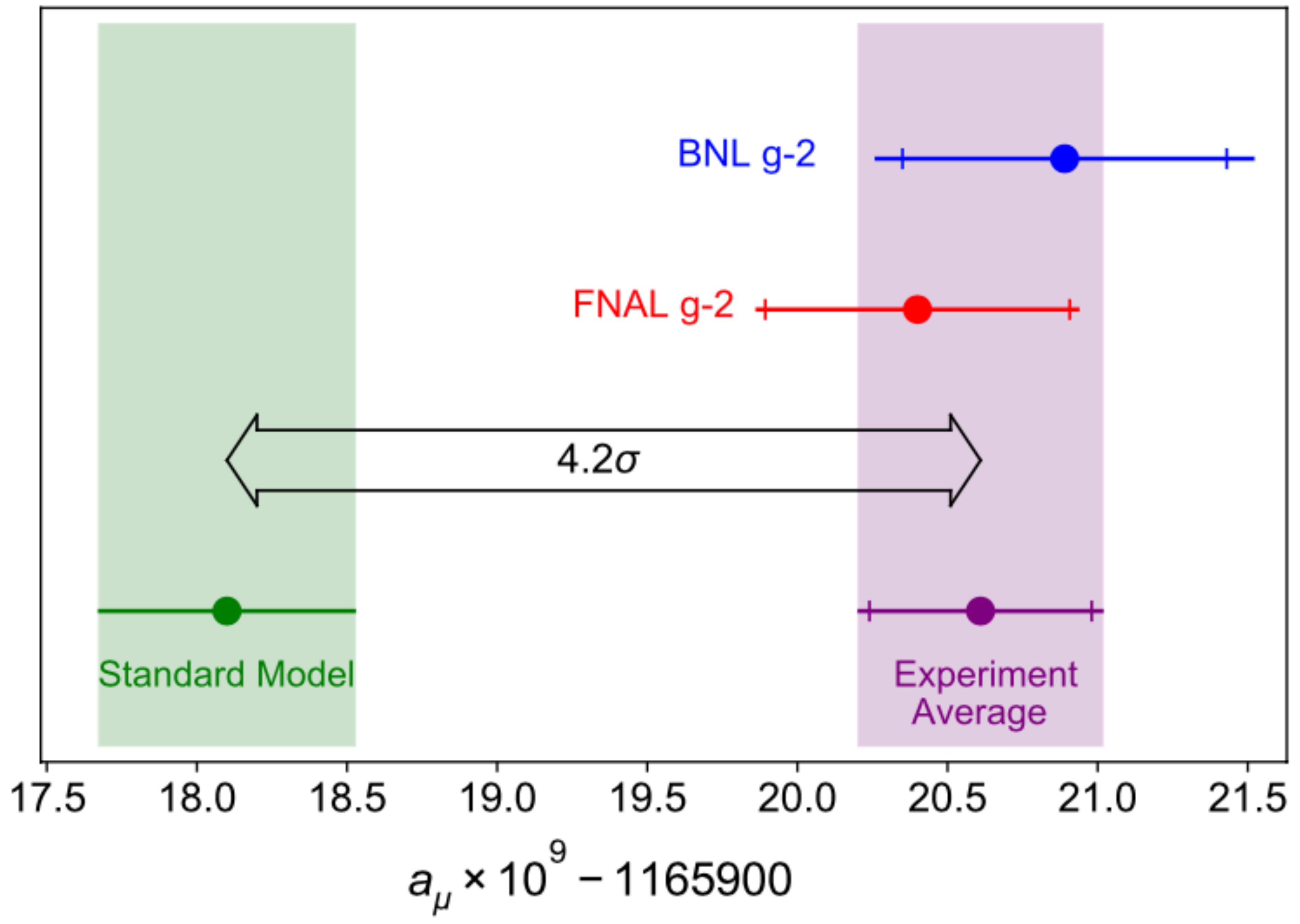


FIG. 4. From top to bottom: Experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the Standard Model is also shown.

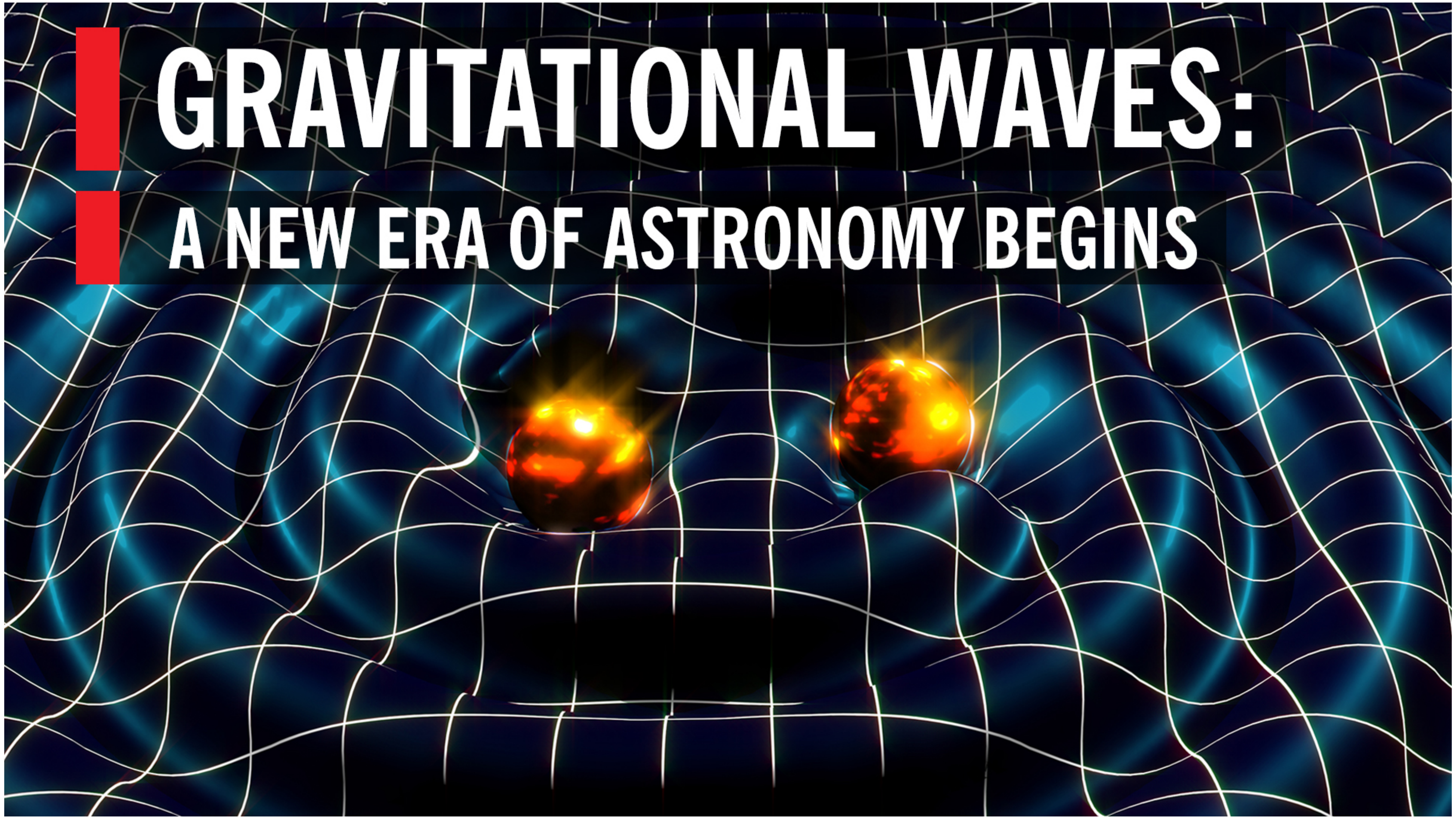
A No-Lose Theorem for Discovering the New Physics of $(g-2)_\mu$ at Muon Colliders

Rodolfo Capdevilla (Toronto U. and Perimeter Inst. Theor. Phys.), David Curtin (Toronto U.), Yonatan Kahn (Illinois U., Urbana, Astron. Dept.), Gordan Krnjaic (Fermilab and Chicago U., KICP)

30 TeV Muon Collider?

Gravitational Waves From Phase Transitions

Gravitational waves are a direct observational probe before CMB in Cosmology



AND THEY ARE HERE!!

Gravitational Waves From Phase Transitions

Gravitational waves are a direct observational probe before the CMB in Cosmology

Search for the isotropic stochastic background using data from Advanced LIGO's second observing run

The LIGO Scientific Collaboration and The Virgo Collaboration
(Dated: September 9, 2019)

The stochastic gravitational-wave background is a superposition of sources that are either too weak or too numerous to detect individually. In this study we present the results from a cross-correlation analysis on data from Advanced LIGO's second observing run (O2), which we combine with the results of the first observing run (O1). We do not find evidence for a stochastic background, so we place upper limits on the normalized energy density in gravitational waves at the 95% credible level of $\Omega_{GW} < 6.0 \times 10^{-8}$ for a frequency-independent (flat) background and $\Omega_{GW} < 4.8 \times 10^{-8}$ at 25 Hz for a background of compact binary coalescences. The upper limit improves over the O1

Stochastic Gravitational Wave Signal is Very Hard (and astrophysics constributions!)-

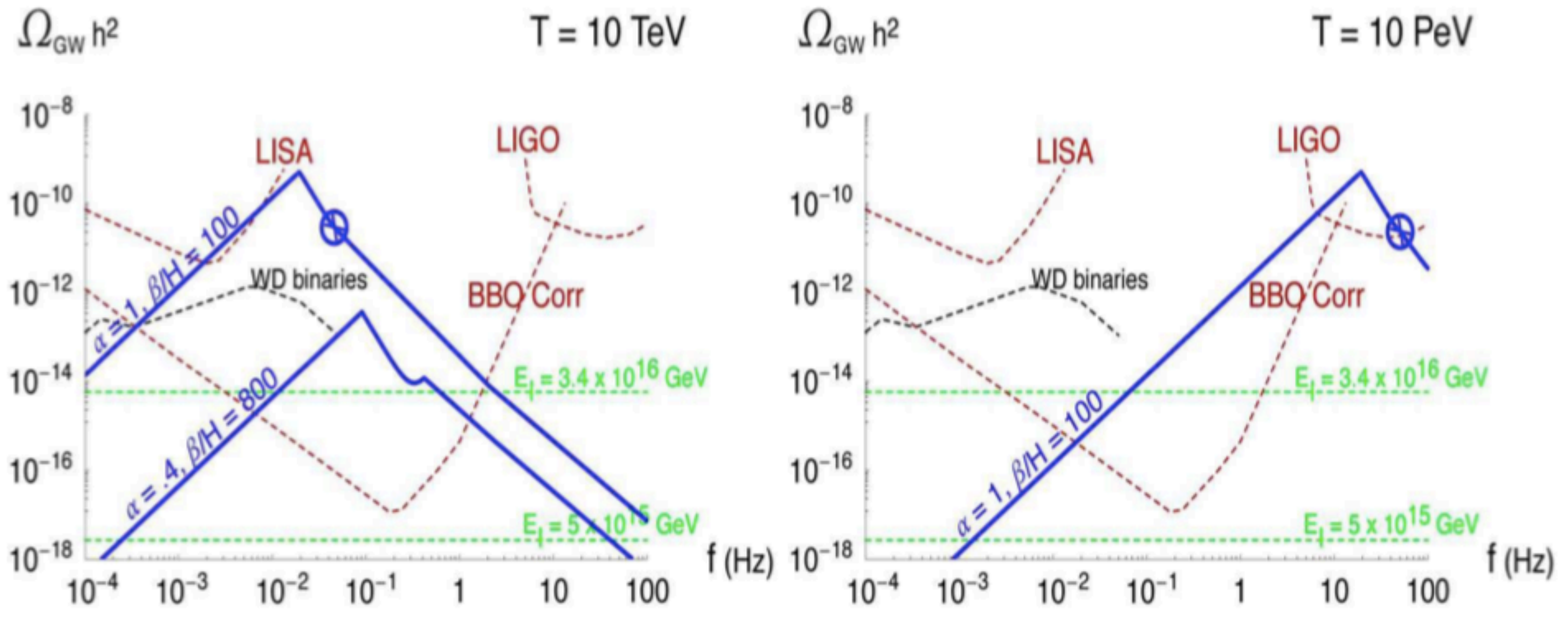
Would it be trusted as signal for BSM without complementary measurements?

Gravitational Waves From Phase Transitions

Stochastic Gravitational Wave Signal is Very Hard - Would it be trusted as signal for BSM?

LIGO frequency band $f \sim \mathcal{O}(10^2)\text{Hz}$

LISA frequency band $f \sim \mathcal{O}(10^{-3})\text{Hz}$



Therefore if something is *observed* with future LIGO runs it points to high (PeV) scales!

LISA 2030s timescale fills in to lower, but still favors higher scales

What *assumptions* can we make about testability assuming thermal equilibrium etc

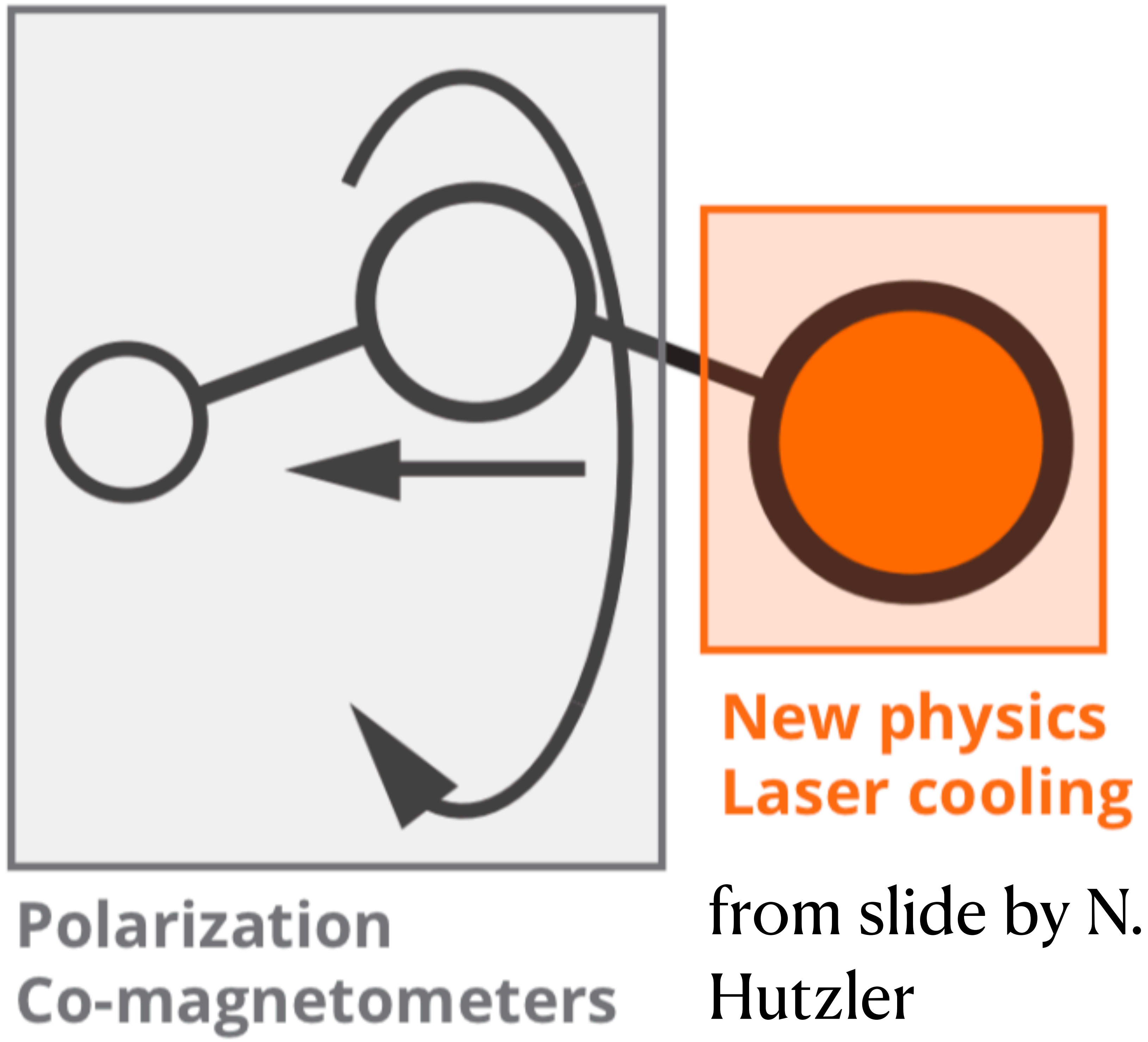
specialization to EW phase transitions tightens this up considerably

Complementarity: Electric Dipole Moments (EDMs)

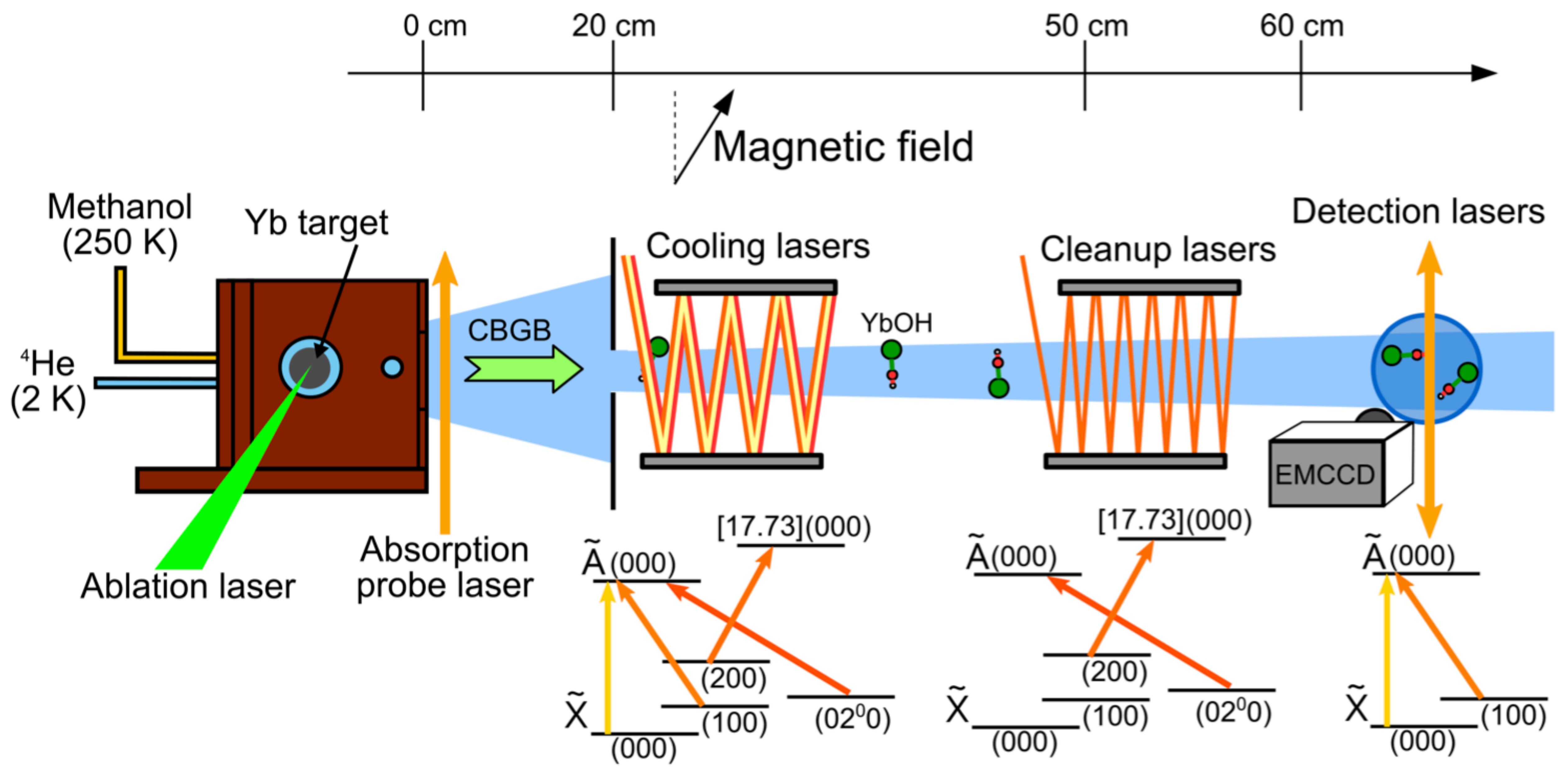
Precision on the Horizon

One of several parallel approaches:

Polyatomic Molecules (e.g., YbOH)
Hutzler, Kozyryev 1705.11020



from slide by N. Hutzler

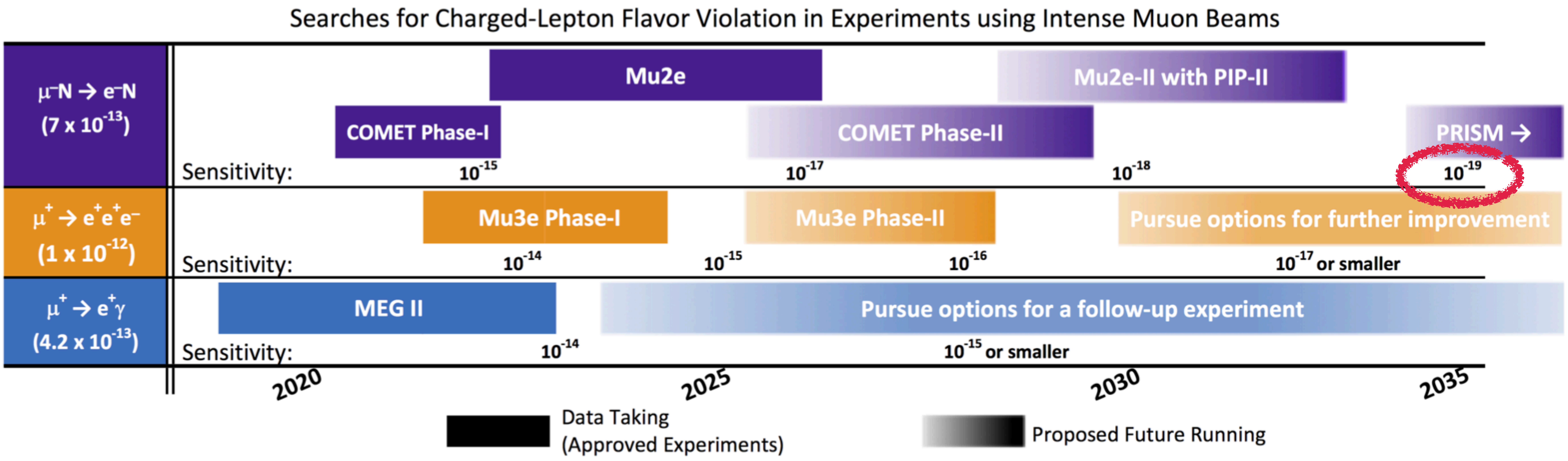


Laser cooling achieved (Augenbraun et al., 1910.11318)

Electron EDM: $10^{-29} e\,\text{cm} \longrightarrow 10^{-32} e\,\text{cm}$ **!**

Complementarity: Charged Lepton Flavor Violation (CLFV)

Precision on the Horizon



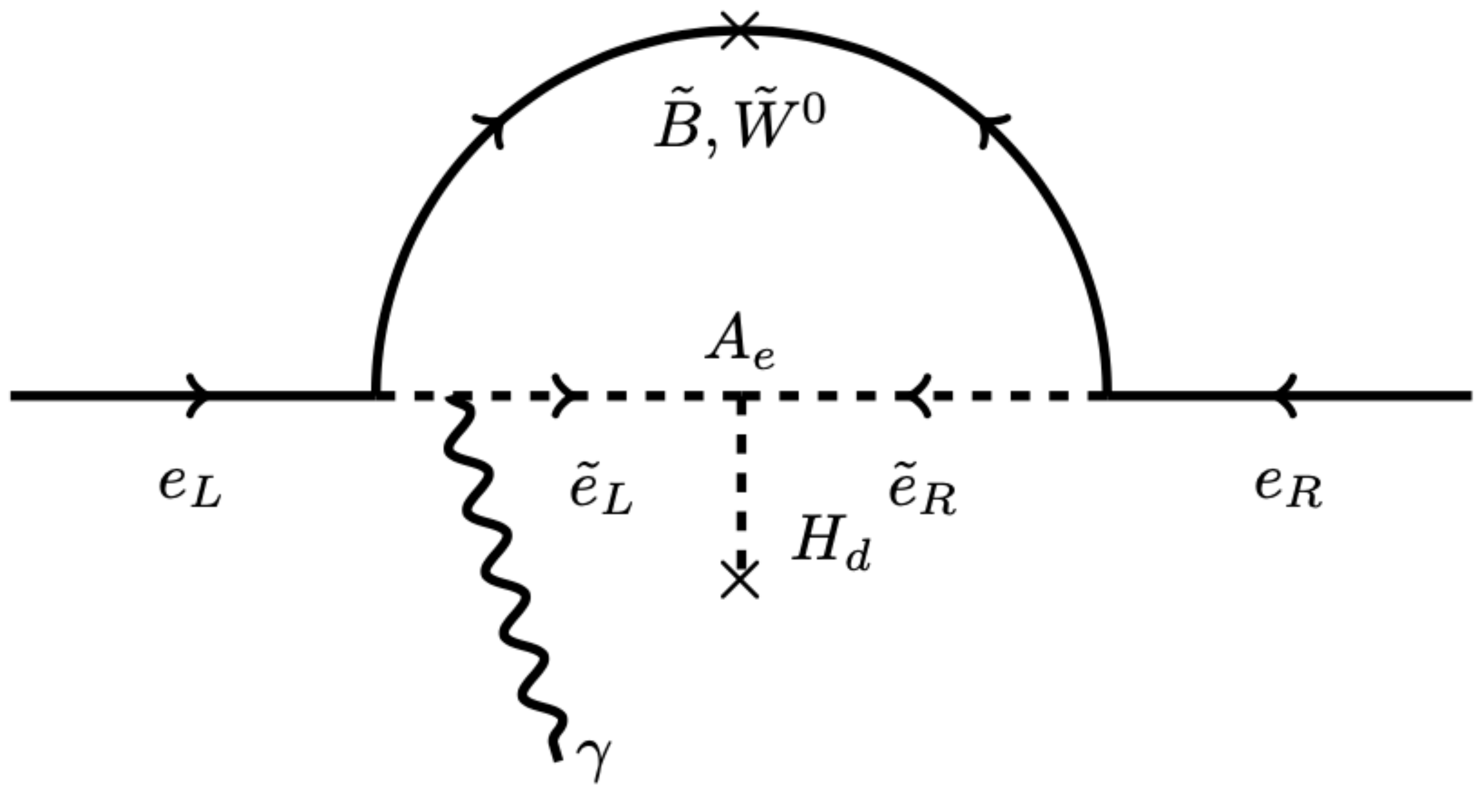
Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations

Complementarity: Physics Reach

The Bottom Line: Probe 10s of TeV to PeV Energy Scales!

EDM, 1-loop

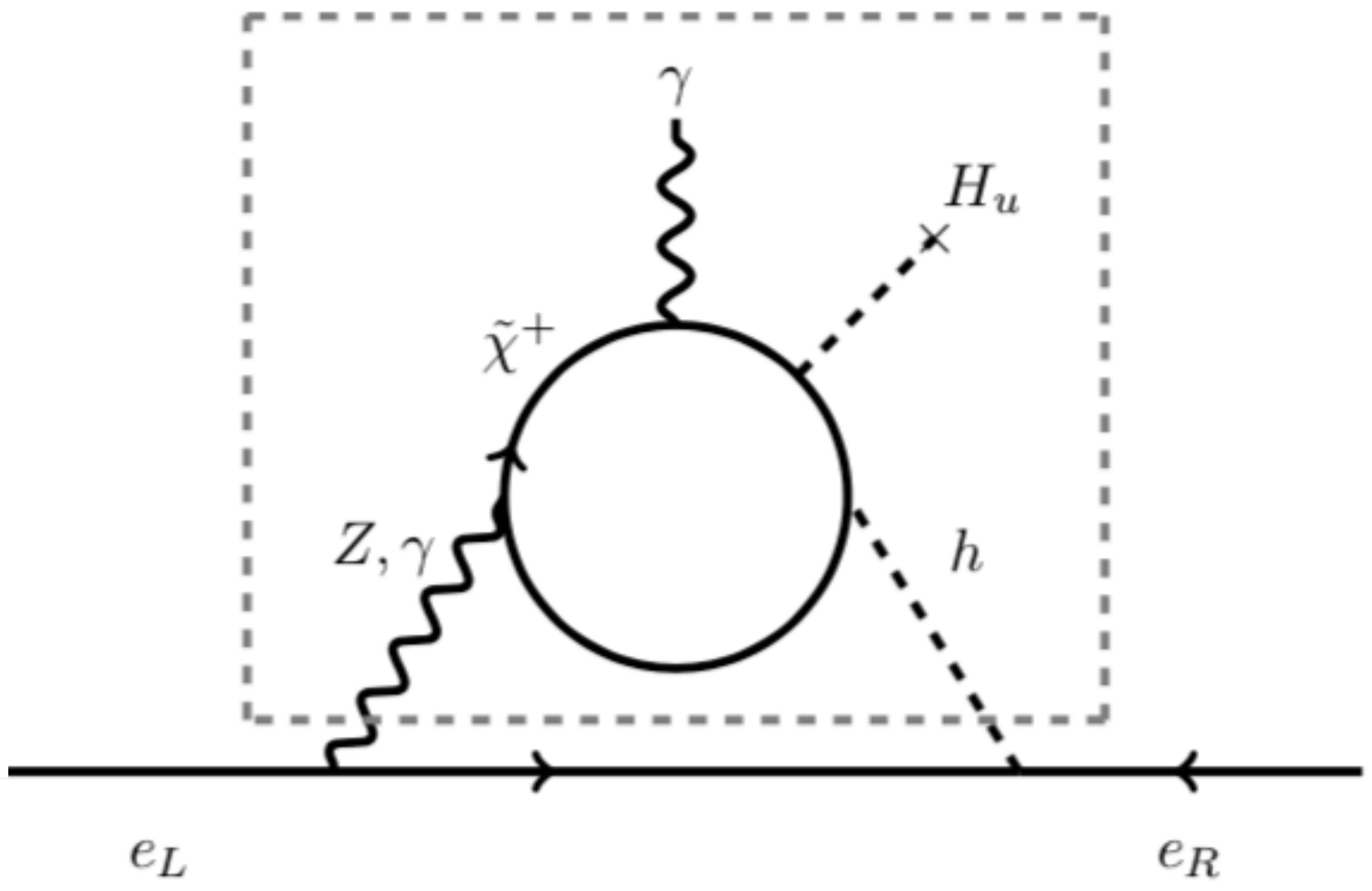
electron-flavored



10^{-32} *e* cm $\Longrightarrow$ ~ **1 PeV (!)**

EDM, 2-loop Barr-Zee

Anything Higgs+EWK



10^{-32} *e* cm $\Longrightarrow$ ~ **50 TeV (!)**

μ→*e*, 1-loop, flavor violating

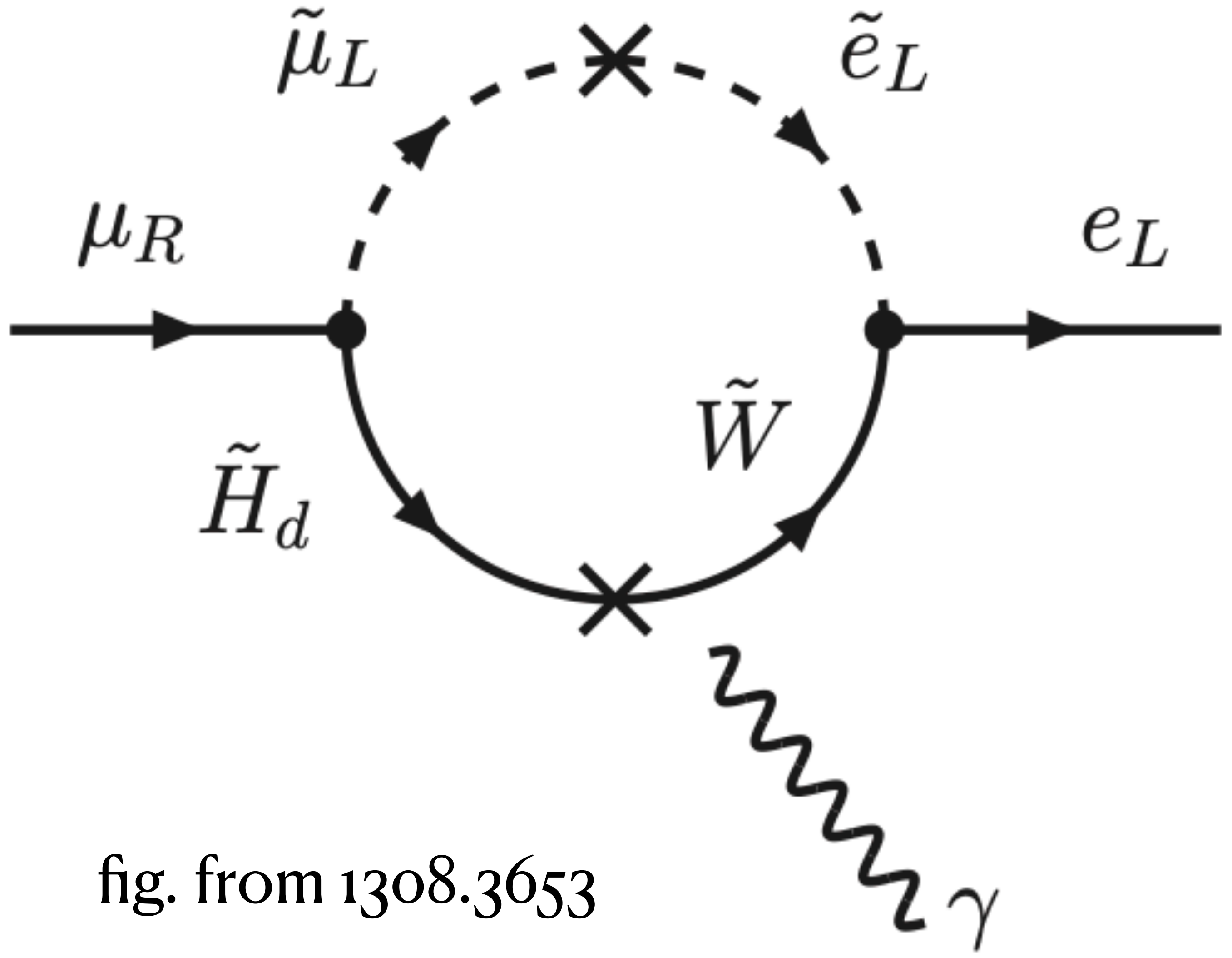


fig. from 1308.3653

Altmannshofer, Harnik, Zupan

10^{-19} on Al $\Longrightarrow$ ~ **50+ TeV (!)**

(w/ electron Yukawa spurions on all diagrams)

Incomplete BSM wishlist…

Observable/ Physics Driver/ Complementary Frontier Experiments	Scale or Precision Needed
EW Phase Transition	$\delta\lambda_3 \ll 1\%$
Higgs and Flavor	$\delta(y_u, y_d, y_s, y_e) \lesssim \mathcal{O}(1)$
Compositeness-Mesotuning	KK scale 10-100 TeV
Supersymmetry/Dark Matter-Mini Split SUSY	Nail the simplest WIMP 3 TeV Wino WIMP DM Mini-split implies 30 TeV gluino
Neutral Naturalness	Probe SM charged partner states at 20 TeV (naively implying 300 TeV pp collider)
Gravitational Waves/Phase Transitions	1-10 PeV LIGO 100 GeV-Tev LISA
Electron EDM rapid improvement 2-3 orders of mag in next decade or so	1 PeV - electron flavored 50 TeV - Higgs or EW Barr-Zee
Charged Lepton Flavor Violation 4 orders of mag in mu to e by 2035	50 TeV 1 loop CLVF

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Charged Lepton Flavor Violation 4 orders of mag in mu to e by 2035	50 TeV 1 loop CLVF

?

→ **Ultimate Collider(s)**

Most all of *this* wishlist needs Energy

Motivated targets extending from tens of TeV to PeV scale!

Realistic options for this are muons or protons

For 1st/2nd gen Higgs physics -

low energy lepton collider w/highest lumi possible is probably needed
+ detectors that can do incredible particle ID

FCC/CEPC/ILC or even newer ideas e.g. 1807.10195?

Maybe this sounds crazy to dream beyond FCC-hh and SPPC but…

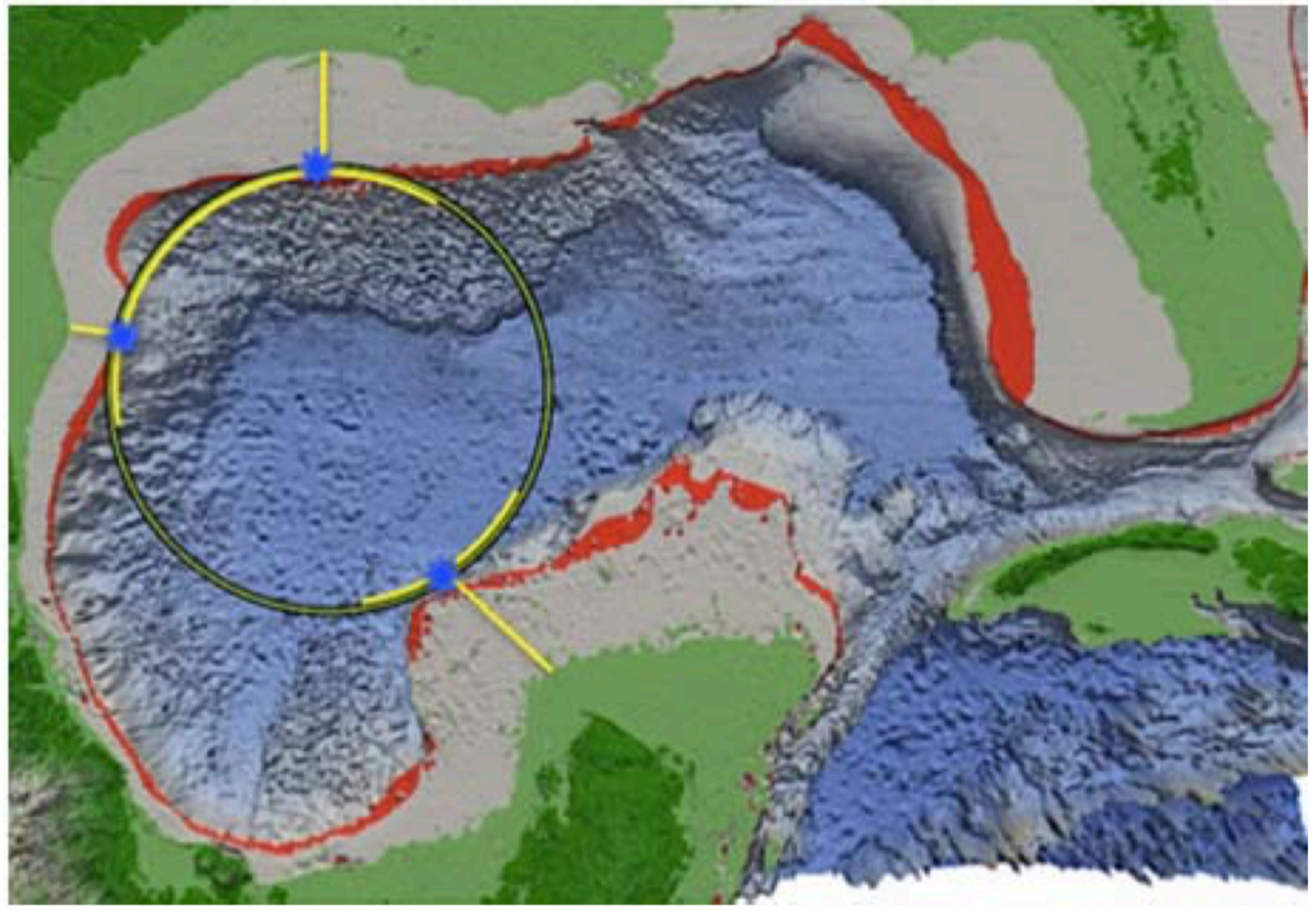


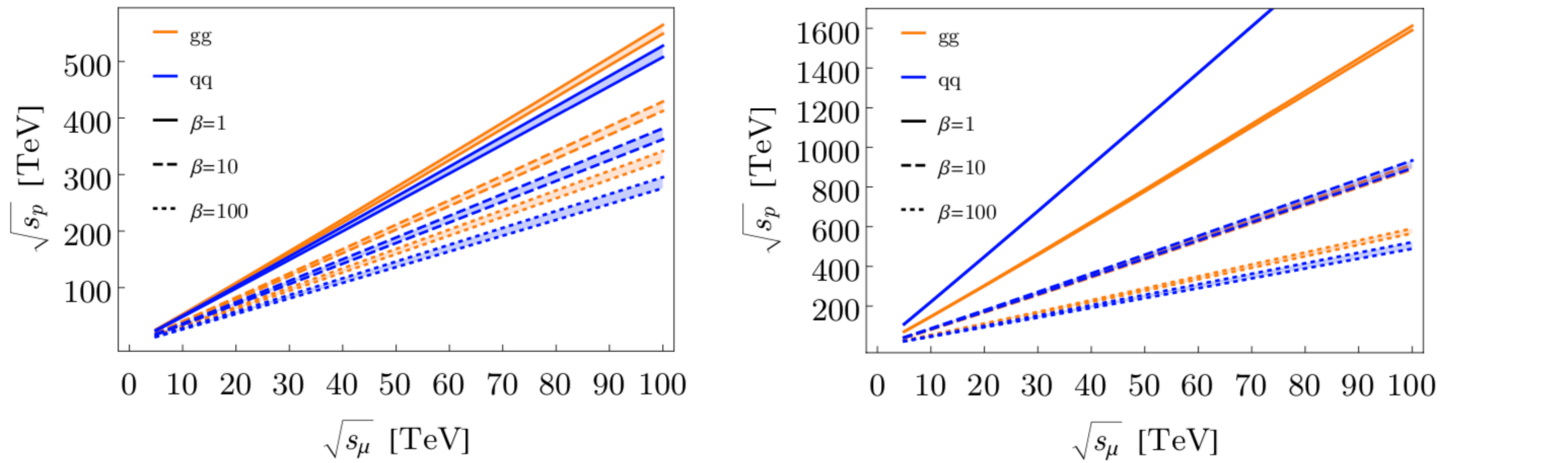
Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron collider. Red =100➔200 m isobaths; gray = 0-100 m isobaths; blue = detectors; green = surface topography.

Collider in the Sea: Vision for a 500 TeV World Laboratory

Proceedings, 2nd North American Particle Accelerator Conference (NAPAC2016), P. McIntyre et al

There could be proton options before Globaltron…

I’m even more excited by muons!



2103.14043

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 [32]) and CT18NNLO. The left (right) panel is for $2 \to 1$ ($2 \to 2$) scattering.

Roughly there is equivalence to a 100 TeV pp collider for

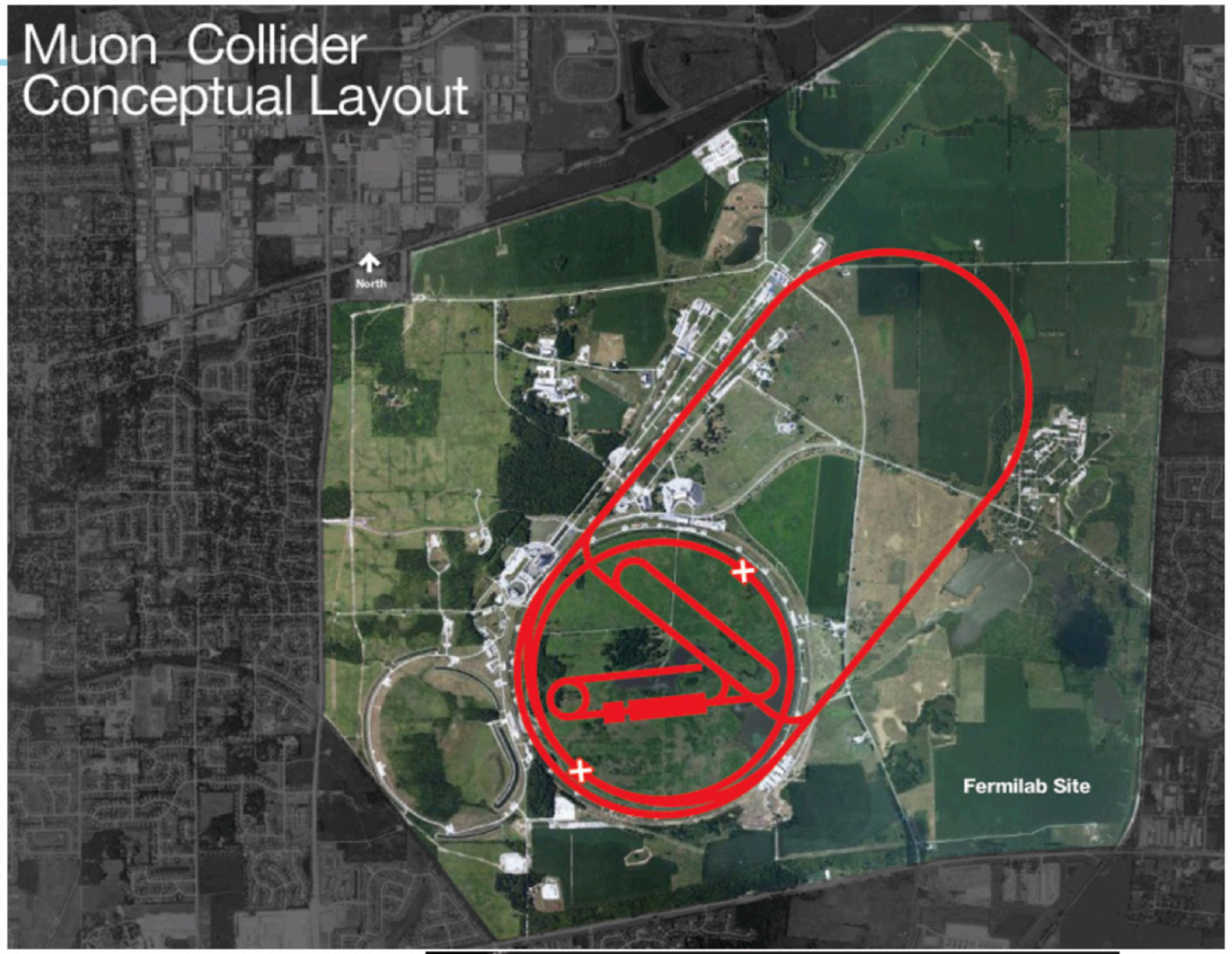
$2 \to 1$	$2 \to 2$
$\sqrt{s_\mu} \sim 20\,\text{TeV}$	$\sqrt{s_\mu} \sim 5-7\,\text{TeV}$

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

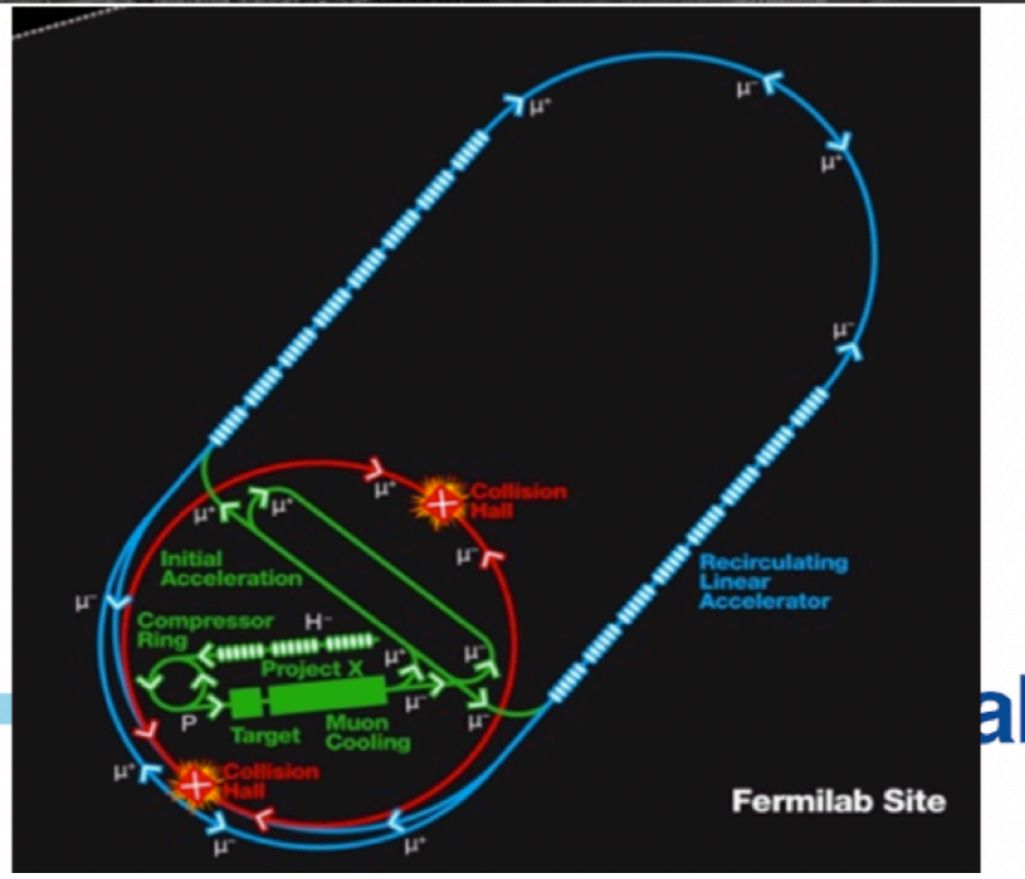
10 TeV Muon Collider on Fermilab campus?

~4 TeV (2 x 2) Muon Collider (~2005)

D. Neuffer



- **Muon Collider**
  - **2 TeV ring (~8T magnets)**
  - **RLA accelerator**
    - **~18 turns**
      2km linacs -50 GeV each
      ~30 MV/m rf
      Arcs are ~8T magnets each
- **Not quite site filler**
  - **Easily expand to 2.5x2.5**
  - **(5 TeV)**
- **Double gradients, B_{max}**
  - **10 TeV (5 x 5) – (16 T – 60 MV/m)**



Extreme acceleration?

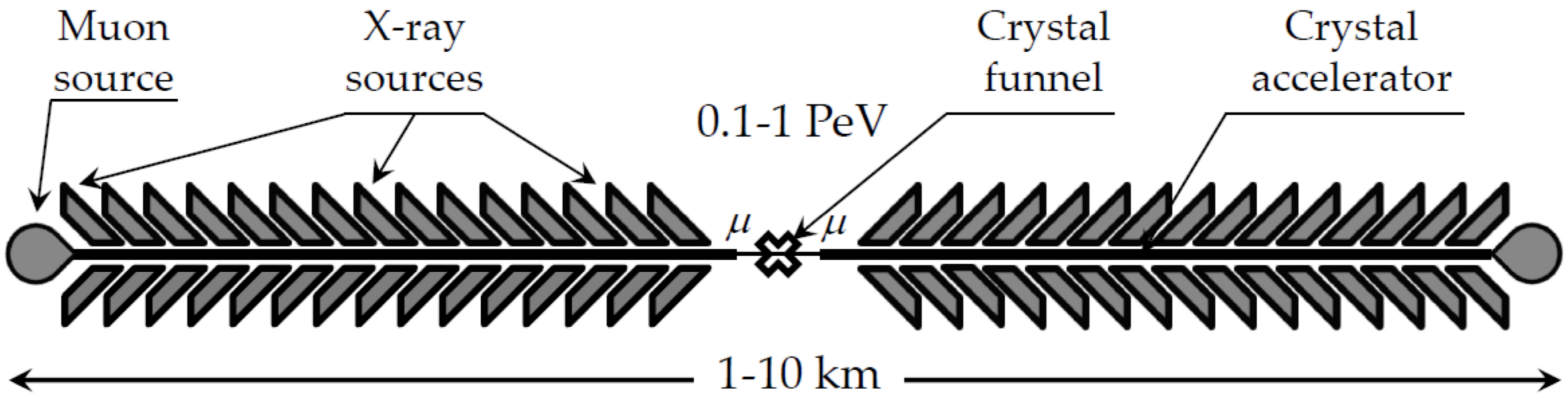


Figure 7: Concept of a linear X-ray crystal muon collider.

V. Shiltsev - 1205.3087

There *are* physics opportunities and potential paths for future colliders!

What’s the best next collider?

What’s the best next collider?

As we’ve learned through the pandemic and from our epidemiologist friends - what’s the best vaccine? The first one you can get.

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The first collider the community rallies around and is funded!

What’s the best next collider?

As we’ve learned through the pandemic and from our epidemiologist friends - what’s the best vaccine? The first one you can get.

The first collider the community rallies around and is funded!

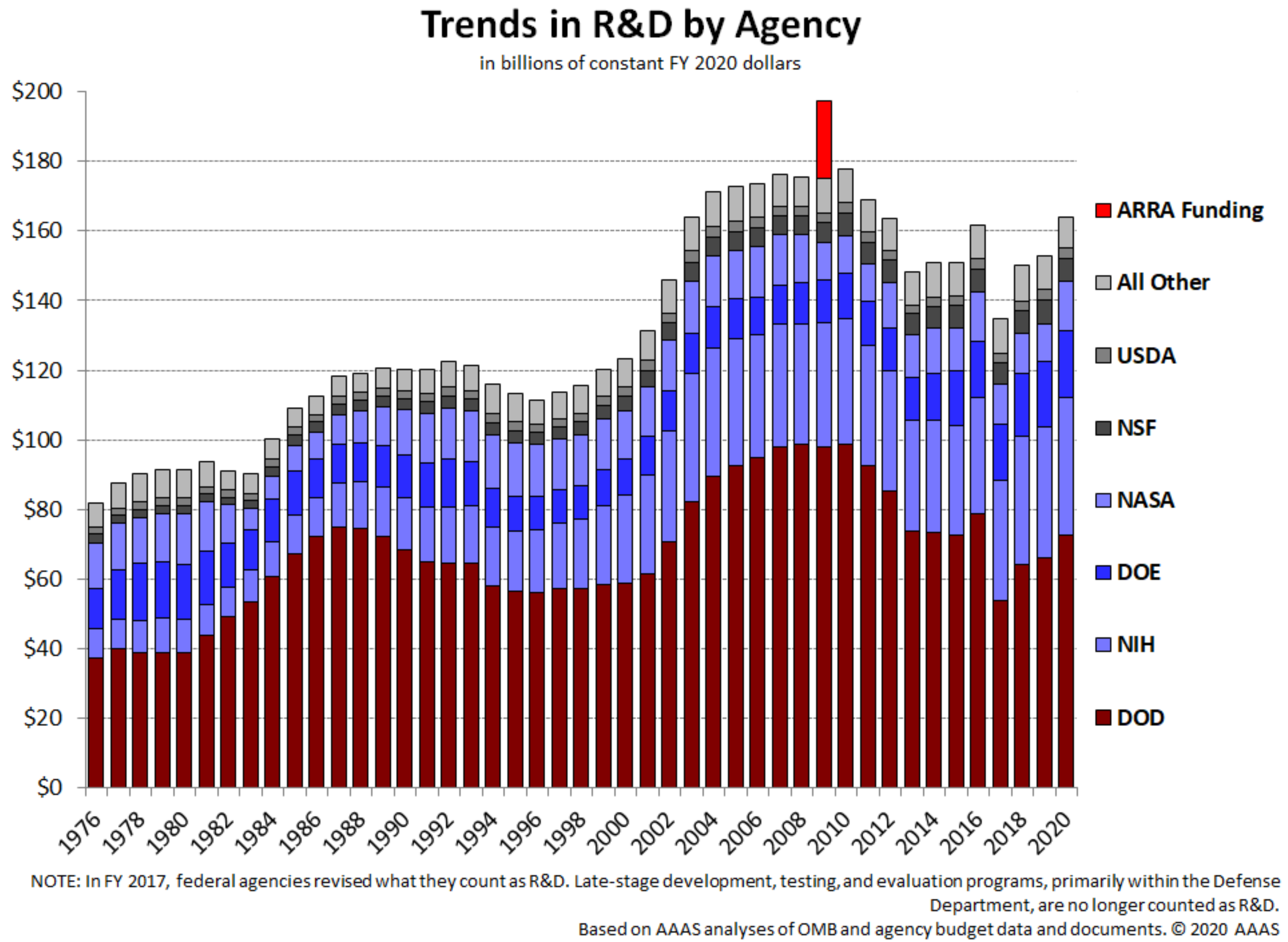
But don’t forget to dream bigger!

Since Pheno 2021 is at Pitt… we can use the cathedral of learning as motivation!

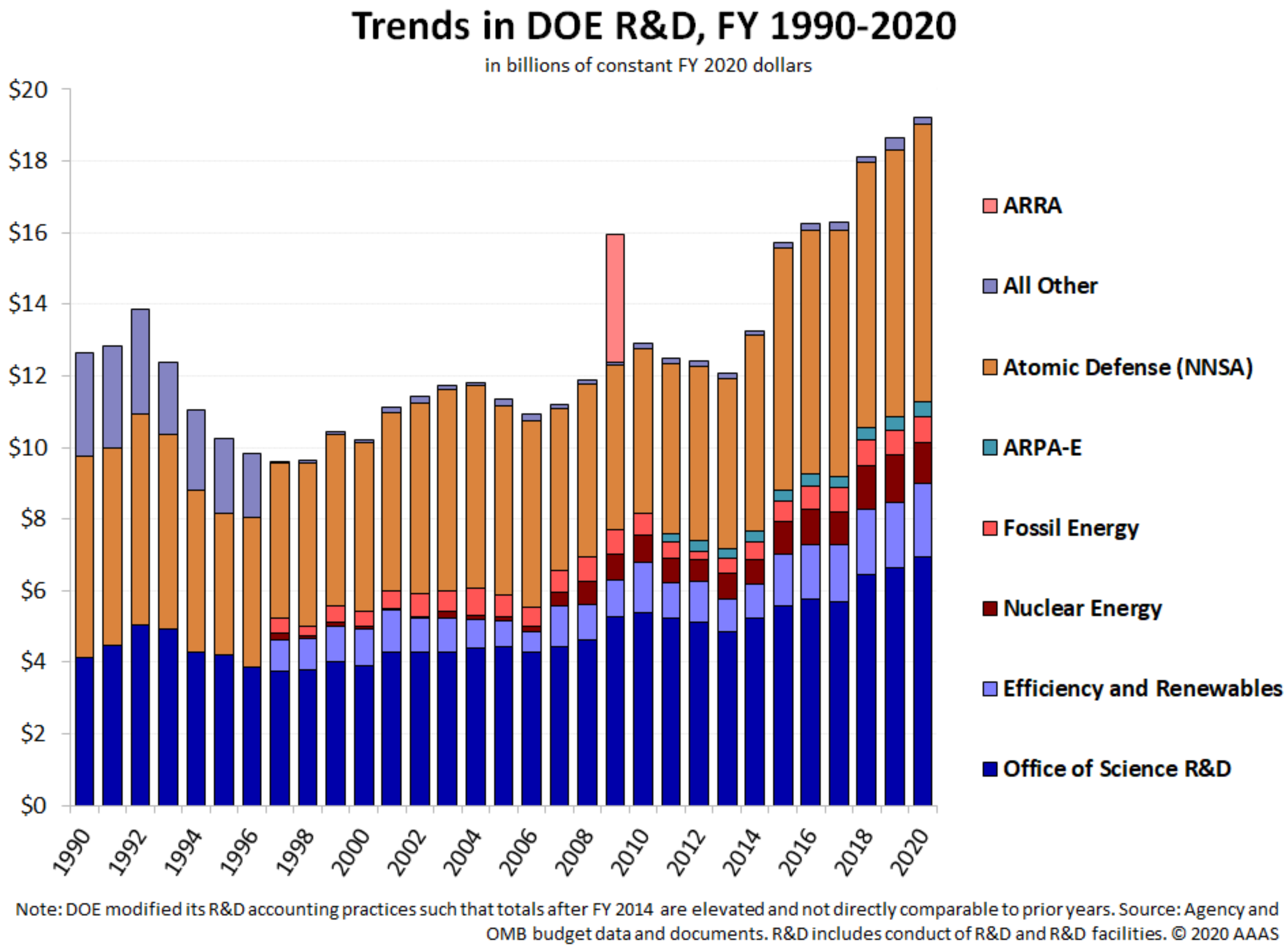
Since Pheno 2021 is at Pitt… we can use the cathedral of learning as motivation!

Is it too expensive?

Remember Science Funding isn't a zero sum game!



Science Funding isn't a zero sum game!



Science Funding isn't political!

Endless Frontier Act (old name)

A U.S. Senate committee voted 24-4 to pass a compromise measure authorizing more than $110 billion for basic and advanced technology research over five years

May 12, 2021 Reuters

We live with the tragedy of the SSC… BUT

U.S. Department of Energy
and the
National Science Foundation

P5 charge

Professor Andrew Lankford
Chair, HEPAP
University of California at Irvine
4129H Frederick Reines Hall
Irvine, CA 92697

Dear Professor Lankford:

Much has changed since the last long-range
was endorsed by HEPAP (the Particle Physi
submitted in 2008). It is therefore an opport
and the NSF. To that end, we ask that you co
updated strategic plan for U.S. high energy p
timescale, in the context of a 20-year global

Your report should provide recommendations on the priorities for an optimized high energy physics program over the next ten years (FY 2014-2023), under the following three scenarios:

- a constant level of funding for three years, followed by increases of 2.0% per year with respect to the appropriated FY 2013 budget for HEP; and
- a constant level of funding for three years, followed by increases of 3.0% per year with respect to the FY 2014 President's Budget Request for HEP; and
- unconstrained budget. For this scenario, please list, in priority order, specific activities, beyond those mentioned in the previous budget scenario, that are needed to mount a leadership program addressing the scientific opportunities identified by the research community.

We live with the tragedy of the SSC… BUT

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It's up to us to make the case to the world!

Historical Perspective

HADRON HADRON COLLIDER GROUP*

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M. Tannenbaum, BNL
H. Williams, U. Penn.
R. Wilson, Columbia U.

I. Introduction

The objective of this group was to make a rough assessment of the characteristics of a hadron-hadron collider which could make it possible to study the 1 TeV mass scale. Since there is very little theoretical guidance for the type of experimental measurements which could illuminate this mass scale, we chose to extend the types of experiments which have been done at the ISR, and which are in progress at the SPS collider to these higher energies. Initially we chose to call these experiments "bellwether experiments" for reasons of convenience. In the absence of any alternative predictions we assumed that the cross sections for these standard experiments could be obtained either by extrapolating perturbative QCD models of hadrons to center of mass energies of 40 TeV or by extrapolating phenomenological parameterization of data obtained from experiments done in the center of mass energy range of 20 to 60 GeV to 40 TeV. For each bellwether we asked up to what mass (or momentum transfer Q) could a significant (> 100) number of events be seen in 10^7 seconds. While it is unlikely

Snowmass 1982

PHYSICS WITH LINEAR COLLIDERS IN THE TEV CM ENERGY REGION

F. Bulos†, V. Cook*, I. Hinchliffe**, K. Lane††,
D. Pellet⊗, M. Perl†, A. Seiden∆, H. Wiedemann†

Design Goals

The physics as described in previous sections calls for maximum center-of-mass energies of at least 1000 GeV and possibly above. We will therefore explore the parameters of linear colliders from about 400 GeV up to 2000 GeV. As we mentioned before, the luminosity is limited by the electrical power available to the collider. In this study we have arbitrarily assumed a maximum electrical power of

$$P_{AC} = 100 \text{ MW} \qquad \text{(VII.1)}$$

Snowmass 1982

We were thinking about things similar to current proposals 40 years ago, physics has changed in between - let’s dream bigger together for the future!

The end.