Physics potential of lepton and γ colliders with energies above 3 TeV

Patrick Meade
YITP Stony Brook

An overview where everyone joining from AF, EF, IF, and TF can understand

An overview where everyone joining from AF, EF, IF, and TF can understand

In other words a talk sure to disappoint all, but it does give me license to go even more meme heavy...

Lots of very respectable collider talks so far

Session

129. Higgs Factories

Oct 6, 2020, 12:30 PM
Zoom 1

Session

183. Intermediate lepton collision energies between 500 GeV and 3 TeV

Oct 6, 2020, 4:00 PM
Zoom 21

Session

26. Energy Frontier discovery machines

Oct 7, 2020, 2:00 PM
Virtual

Lots of very respectable collider talks so far

14:00	**Introduction**	*Zoom 1*	*Dmitri Denisov*	14:00 - 14:05
	Hadron and lepton-hadron colliders with energies above 3 TeV	*Zoom 1*	*Frank Zimmermann*	14:05 - 14:22
	Physics potential of hadron and hadron-lepton colliders with energies above 3 TeV	*Zoom 1*	*Liantao Wang*	14:22 - 14:42
	Lepton and gg colliders with energies above 3 TeV	*Zoom 1*	*Daniel Schulte*	14:42 - 15:00
15:00	**Physics potential of lepton and gg colliders with energies above 3 TeV**	*Zoom 1*	*Patrick Meade*	15:00 - 15:20
	Summary and plans for 2021 Snowmass meeting	*Zoom 1*	*Meenakshi Narain*	15:20 - 15:30

And then finally we reach the last talk…
(other than the summary)

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

Wait a minute… that wasn’t in the last P5 right?

Last P5

Report of the Particle Physics Project Prioritization Panel (P5) May 2014

Last P5

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.

Report of the Particle Physics Project Prioritization Panel (P5) May 2014

Last P5

Table 1
Summary of Scenarios

	Scenarios		
	Scenario A	Scenario B	Scenario C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y
MAP	N	N	N

No lepton colliders >3 TeV and muon collider is persona non grata

Where has the recent interest in high energy lepton colliders come from?
Especially for muon colliders

Q & A

A Call for Courage as Physicists Confront Collider Dilemma

11

Carlo Rubbia, leader of the bold collider experiment that in 1983 discovered the W and Z bosons, thinks particle physicists should now smash muons together in an innovative "Higgs factory."

August 2019

Courage, Ambition, something else??

More recent physics efforts *just* since the pandemic…

Measuring the quartic Higgs self-coupling at a multi-TeV muon collider

Mauro Chiesa (Annecy, LAPTH), Fabio Maltoni (Louvain U., CP3 and U. Bologna, DIFA and INFN, Bologna), Luca Mantani (Louvain U., CP3 and U. Heidelberg, ITP), Barbara Mele (INFN, Rome), Fulvio Piccinini (INFN, Pavia) et al. (Mar 30 2020)

Published in: *JHEP* 09 (2020) 098 • e-Print: 2003.13628 [hep-ph]

High Energy Leptonic Collisions and Electroweak Parton Distribution Functions

Tao Han (Pittsburgh U.), Yang Ma (Pittsburgh U.), Keping Xie (Pittsburgh U.) (Jul 28, 2020)

e-Print: 2007.14300 [hep-ph]

Vector boson fusion at multi-TeV muon colliders

Antonio Costantini (INFN, Bologna), Federico De Lillo (Louvain U., CP3), Fabio Maltoni (Louvain U., CP3 and Bologna U. an INFN, Bologna), Luca Mantani (Louvain U., CP3 and U. Heidelberg, ITP), Olivier Mattelaer (Louvain U., CP3) et al. (May 20, 2020)

Published in: *JHEP* 09 (2020) 080 • e-Print: 2005.10289 [hep-ph]

Electroweak Couplings of the Higgs Boson at a Multi-TeV Muon Collider

Tao Han (Pittsburgh U.), Da Liu (UC, Davis, QMAP), Ian Low (Northwestern U. and Argonne), Xing Wang (UC, San Diego) (Aug 27, 2020)

e-Print: 2008.12204 [hep-ph]

A Guaranteed Discovery at Future Muon Colliders

Rodolfo Capdevilla (Toronto U. and Perimeter Inst. Theor. Phys.), David Curtin (Toronto U.), Yonatan Kahn (Illinois U., Urbana), Gordan Krnjaic (Fermilab) (Jun 29, 2020)

e-Print: 2006.16277 [hep-ph]

WIMPs at High Energy Muon Colliders

Tao Han (Pittsburgh U.), Zhen Liu (Maryland U.), Lian-Tao Wang (Chicago U., EFI and Chicago U., KICP), Xing Wang (UC, San Diego) (Sep 23, 2020)

e-Print: 2009.11287 [hep-ph]

Many LOIs

More recent physics efforts just since the pandemic…

There's even an international Muon collider collaboration

2020)
Published in: *JHEP* 09 (2020) 098 • e-Print: 2003.13628 [hep-ph]

e-Print: 2007.14300 [hep-ph]

Vecto
Antoni
INFN, E
2020)
Publish

San Diego)

A Guar
Rodolfo
Urbana)
e-Print:

Wang (UC,

Muon Collider Collaboration Meeting

Friday 3 Jul 2020, 14:00 → 18:40 Europe/Zurich

Description The Update of the European Strategy for Particle Physics demands an international design study for a muon collider. This is the first meeting to start the preparation of such a collaboration.

The goal is to start identifying the community interest in a muon collider. To this end, we call the community to let us know if they are potentially interested to contribute to a design study and in which field of expertise. This information should help to facility the formation of the collaboration by assuring that all potential partners are included but it is not even morally committing.

Please prepare a slide or two indicating your interest and, in case you already know, the fields in which you would consider contributing. It would be good, but not mandatory, to contact daniel.schulte@cern.ch in advance so that we can put this on the agenda.

Why am I giving this talk?

It all started with some research into the ***first*** snowmass and some memes

HADRON HADRON COLLIDER GROUP*

R. Palmer
Brookhaven National Laboratory, Upton, New York 11973

J. Peoples
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

C. Ankenbrandt, FNAL
C. Baltay, Columbia U.
R. Diebold, ANL
E. Eichten, FNAL
H. Gordon, BNL
P. Grannis, SUNY at Stony Brook
R. Lanou, Brown U.
J. Leveille, U. Michigan
L. Littenberg, BNL
F. Paige, BNL
E. Platner, BNL
H. Sticker, Rockefeller U.
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

We're *still* trying to implement these

PHYSICS WITH LINEAR COLLIDERS IN THE TEV CM ENERGY REGION

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

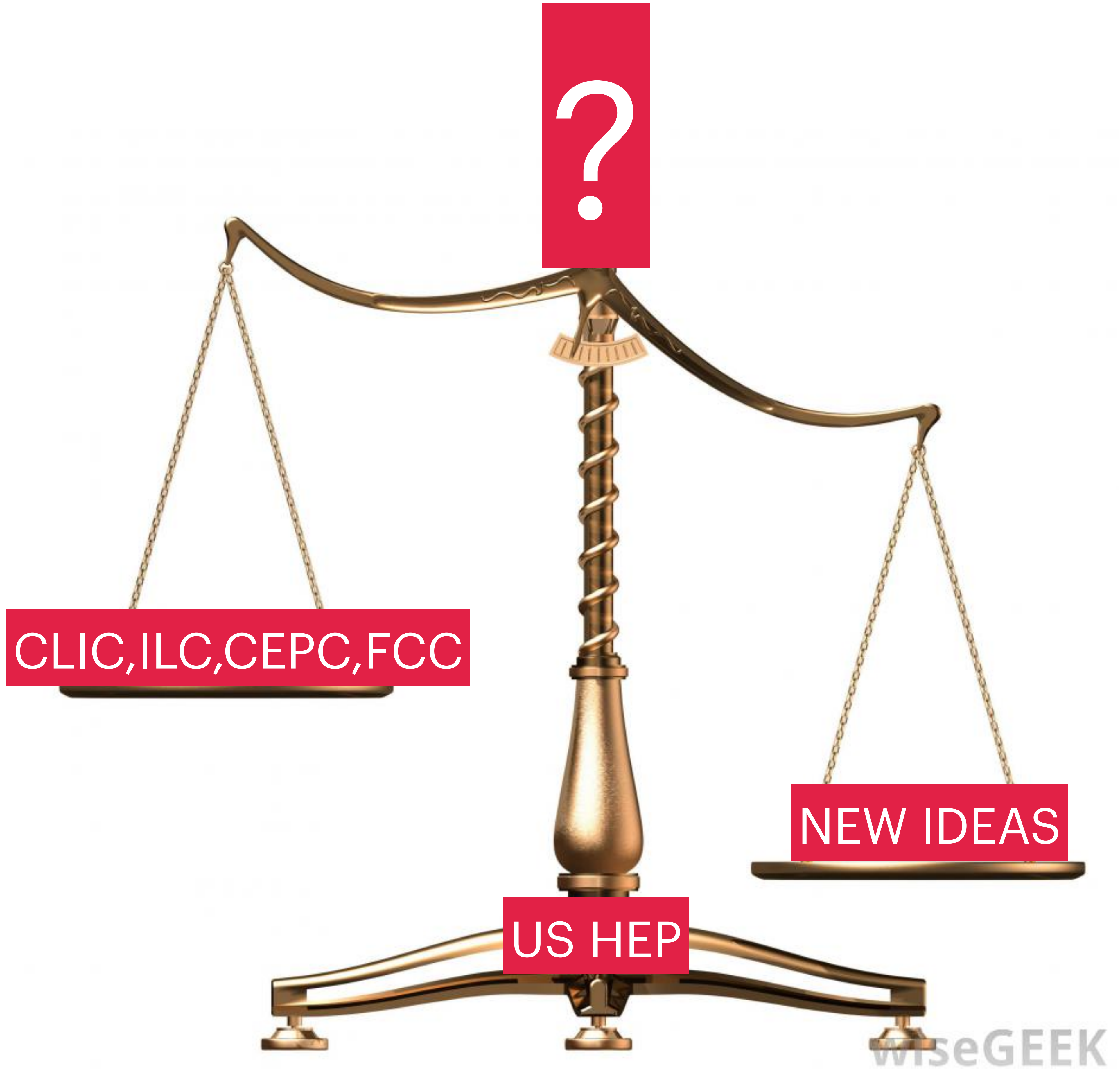
Design Goals

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

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

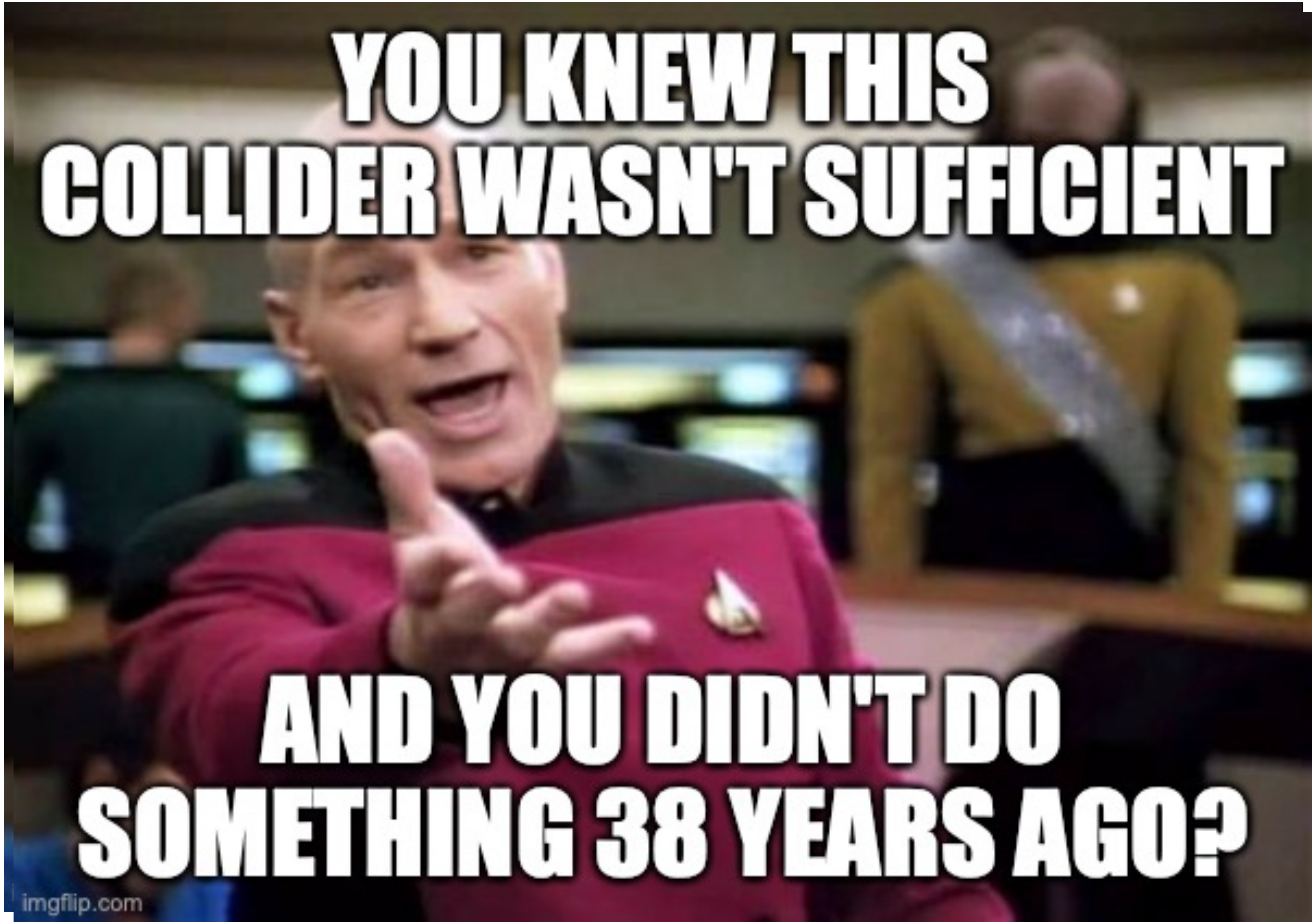
Snowmass 1982

US has no official HEP collider planned

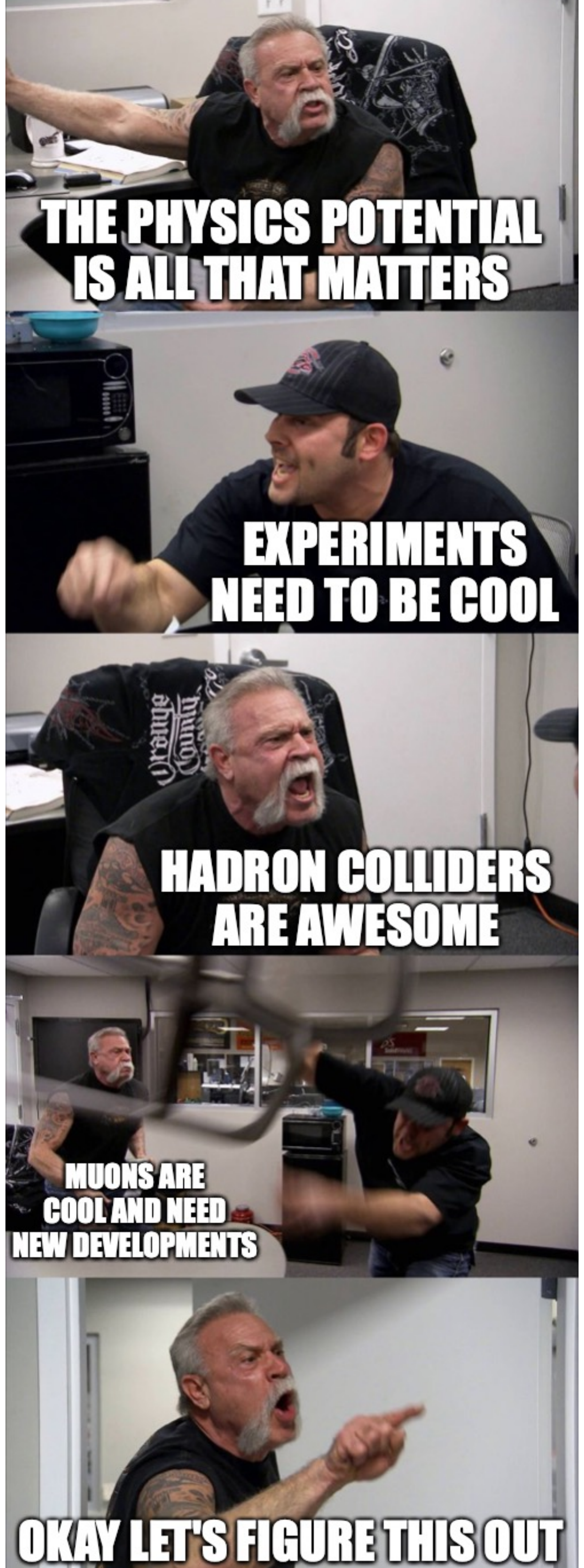


Obviously we want to help guide prioritization of projects through lens of BSM/Higgs

However… nothing stops you from dreaming big and **theory** and **experiment** have both evolved since 1982

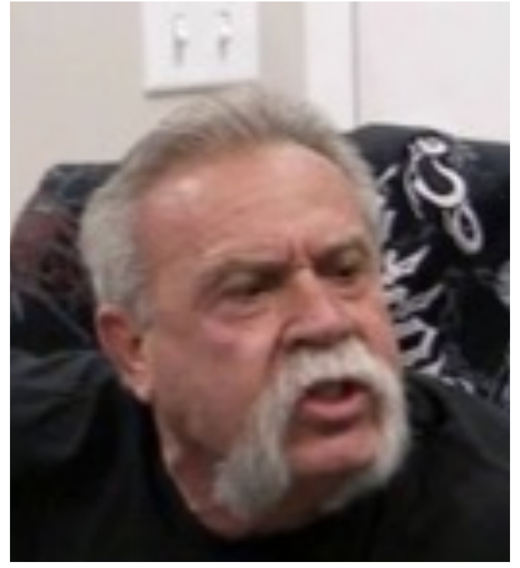


#Snowmass1982 #Snowmass2058



Why am I giving this talk?

Paraphrasing a conversation between EF02 conveners months ago



= Me (Theorist who doesn't sufficiently appreciate all the work that goes into an experiment)

= Isobel Ojalvo (Experimentalist AKA voice of reason)

Which led to the infamous figure

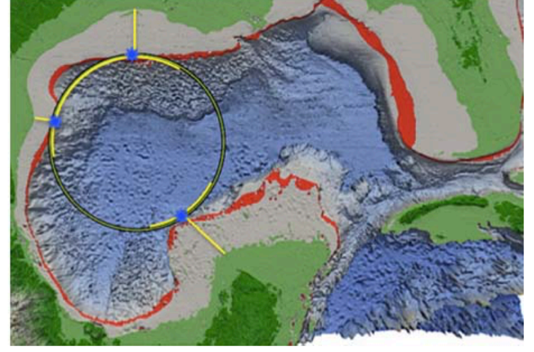


Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron

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

?

μ -collider e w/PWFA 30 TeV

FCC-hh/SPPC

μ-collider 14 TeV

Physics

Potential

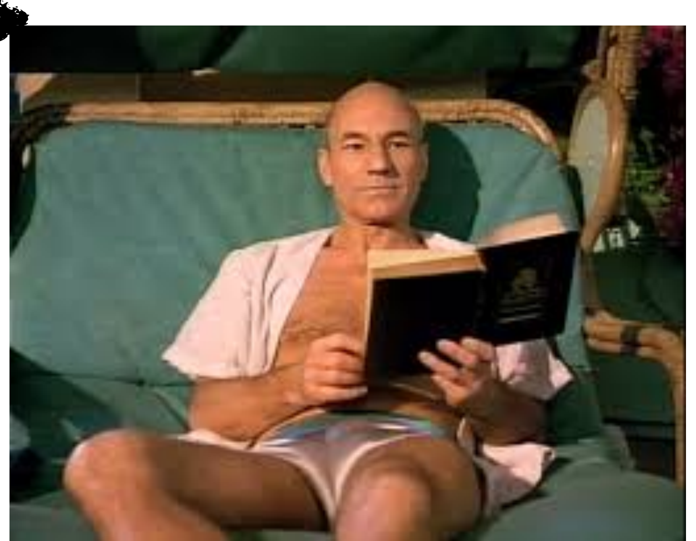
CLIC

FCC-ee/CEPC

ILC

μ-collider 125

R&D attractiveness



And then Nathaniel said…

And then Nathaniel said...

And then Nathaniel said…

The Muon-Smasher's Guide [Working Title]

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[3], Nathaniel Craig[1], JiJi Fan[4], Isabel Garcia Garcia[5], Samuel Homiller[6], Seth Koren[7], Giacomo Koszegi[1], Zhen Liu[8], Qianshu Lu[6], Kunfeng Lyu[9], Amara McCune[1], Patrick Meade[10], Isobel Ojalvo[11], Umut Oktem[1], Matthew Reece[6], Raman Sundrum[8], Dave Sutherland[12], Timothy Trott[1], Chris Tully[11], Ken Van Tilburg[5], Lian-Tao Wang[7], and Menghang Wang[1]

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[4] *Department of Physics, Brown University, Providence, RI 02912*
[5] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106*
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[7] *Department of Physics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*
[8] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742*
[9] *Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong S.A.R., P.R.C*
[10] *C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794*
[11] *Princeton University, Princeton, NJ 08540*
[12] *INFN Sezione di Trieste, via Bonomea 265, 34136 Trieste, Italy*

So with this + literature I'll discuss physics case for e, μ, γ

Why new colliders?

To boldly go where no one has gone before

Isn’t it just the energy?

Why new colliders?

To boldly go where no one has gone before

Costs a lot...

Joint AF-EF Meeting on Future coliders : Day 1

Wednesday Jun 24, 2020, 9:00 AM → 10:00 PM US/Central

Dmitri Denisov (Fermilab), Meenakshi Narain (Brown University), Vladimir Shiltsev (FNAL)

Energy Frontier

- EF science goals currently envision two types of future colliders (in arbitrary order)
  - Higgs (and other known elementary particles) factory
  - Next high energy frontier machine
- Discoveries at the Energy Frontier are intricately linked to the progress in accelerators.

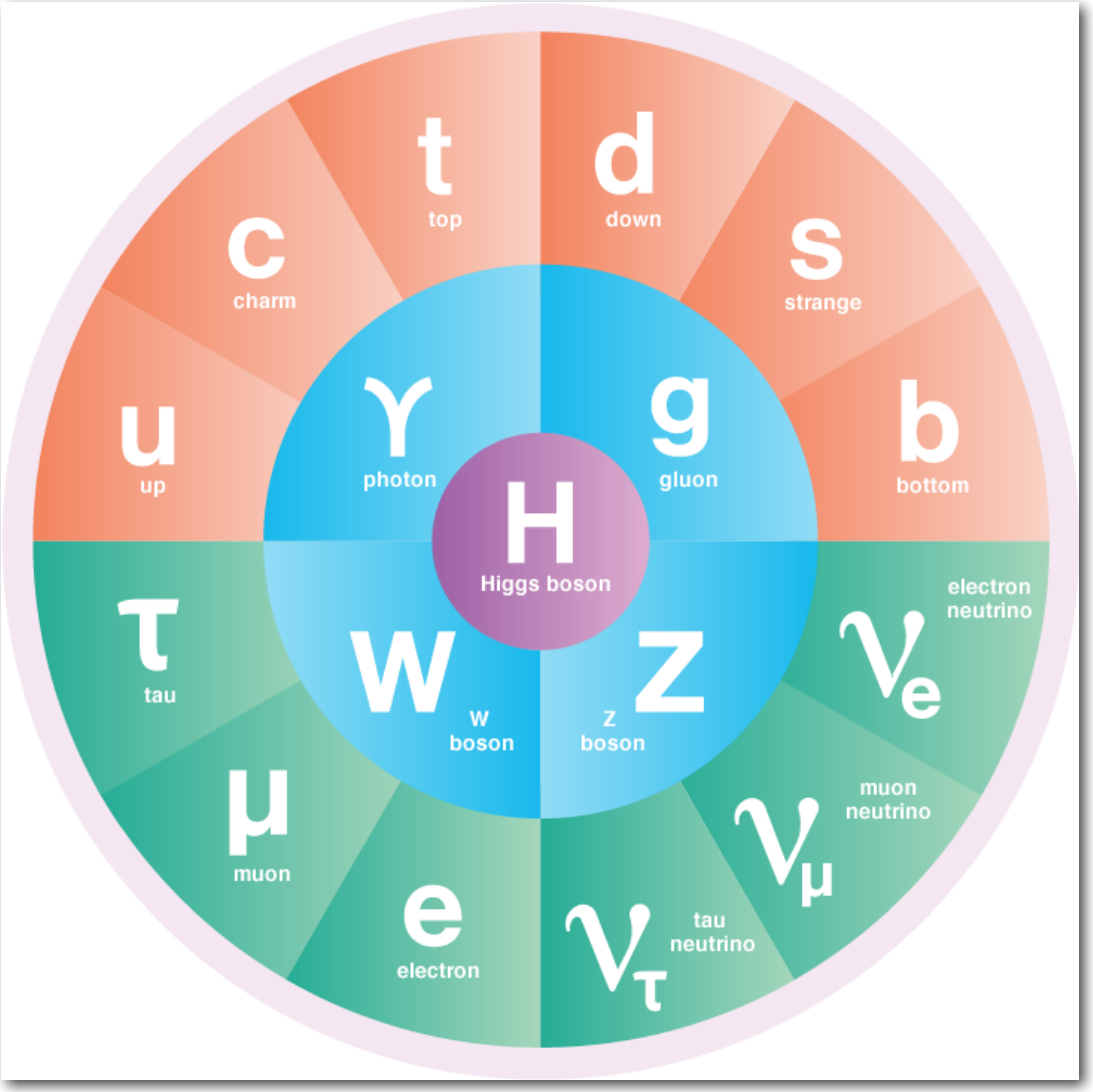
Meshes well with *last* P5 science drivers

- 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

Foundational Physics Potential Cases

Foundational Physics Potential Cases

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



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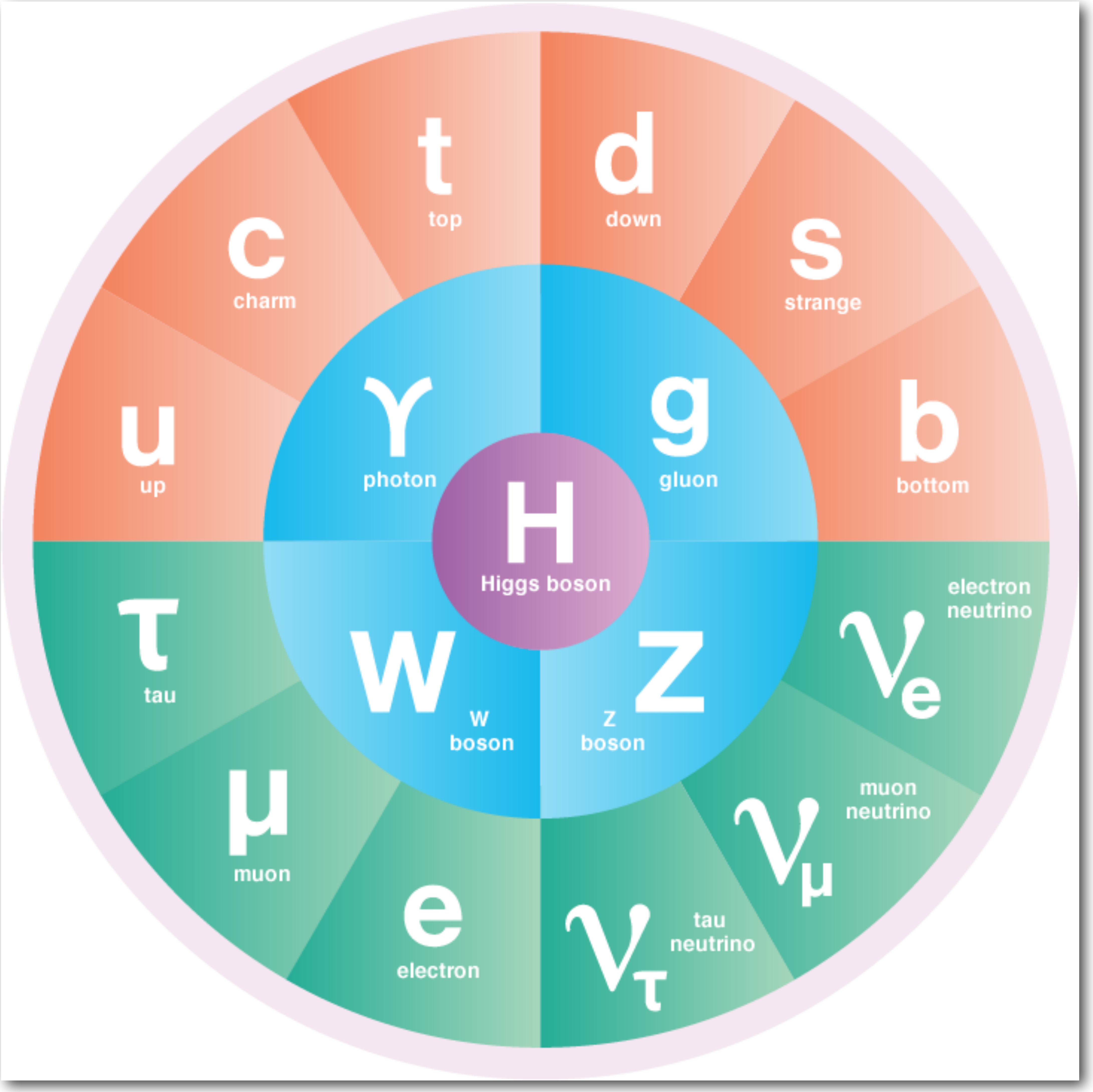
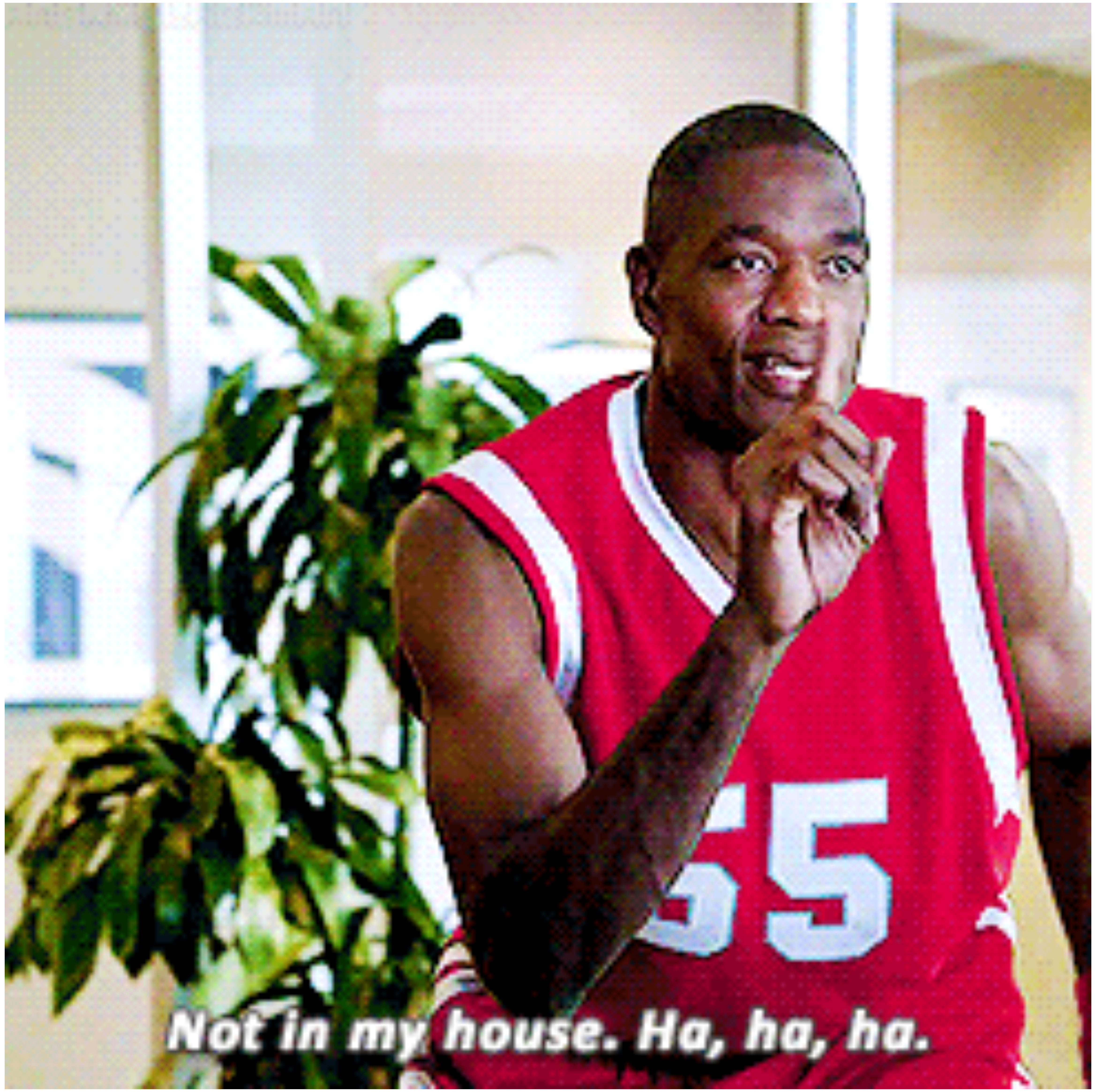
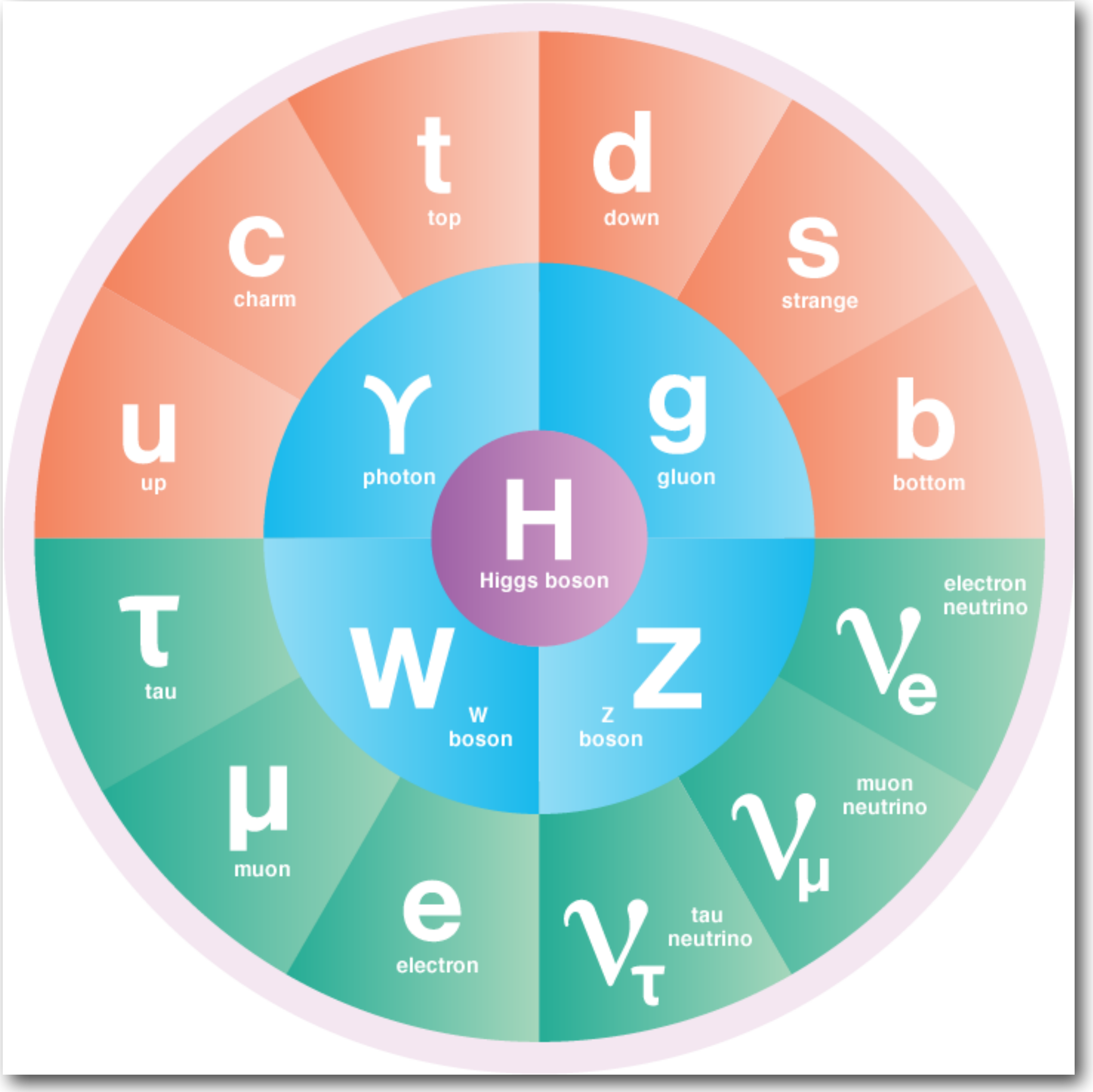


We found the last ingredient, particle physics is done but a bow on it...



We found the last ingredient, particle physics is done but a bow on it...

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

We are just scratching the surface of the Higgs!

Obviously we want precision in *all* couplings

Lots of historical precedent where precision leads to discovery!

Neptune discovery -> Perturbation theory combined w/ data leads to prediction

Hubble and expansion of universe -> SN and *accelerated expansion*

Precision can lead to ***revolutionary changes***

COMPLETE THE SM!

Higgs

BSM

Biggest open areas post HL-LHC

Self couplings!

Needs Energy

Light Flavor!

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.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ 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-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-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...

ESG run plans 1905.03764

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		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
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		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
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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

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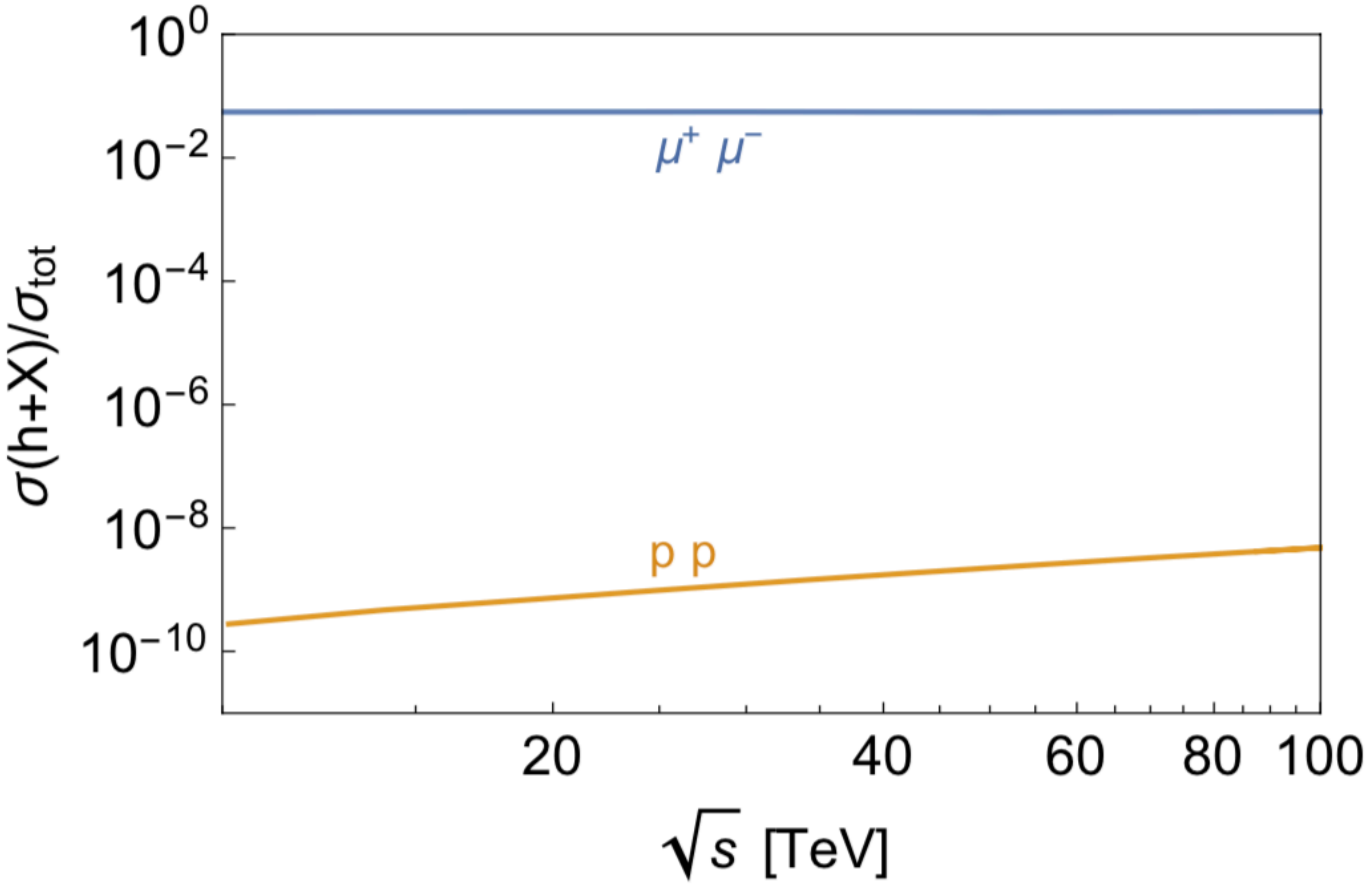
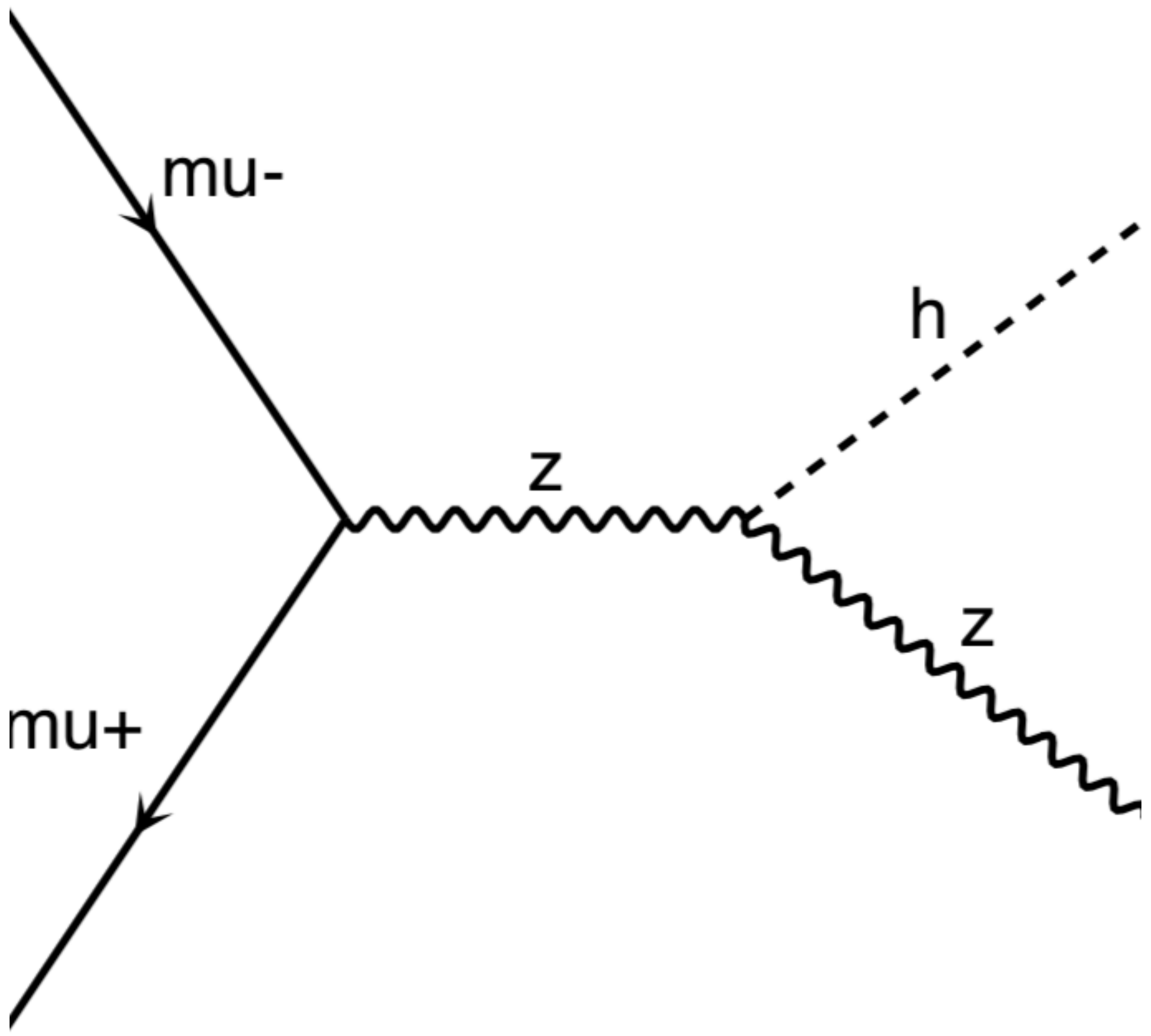


Precision needs precision (Higgs factories yesterday), but leptons give you a head start!

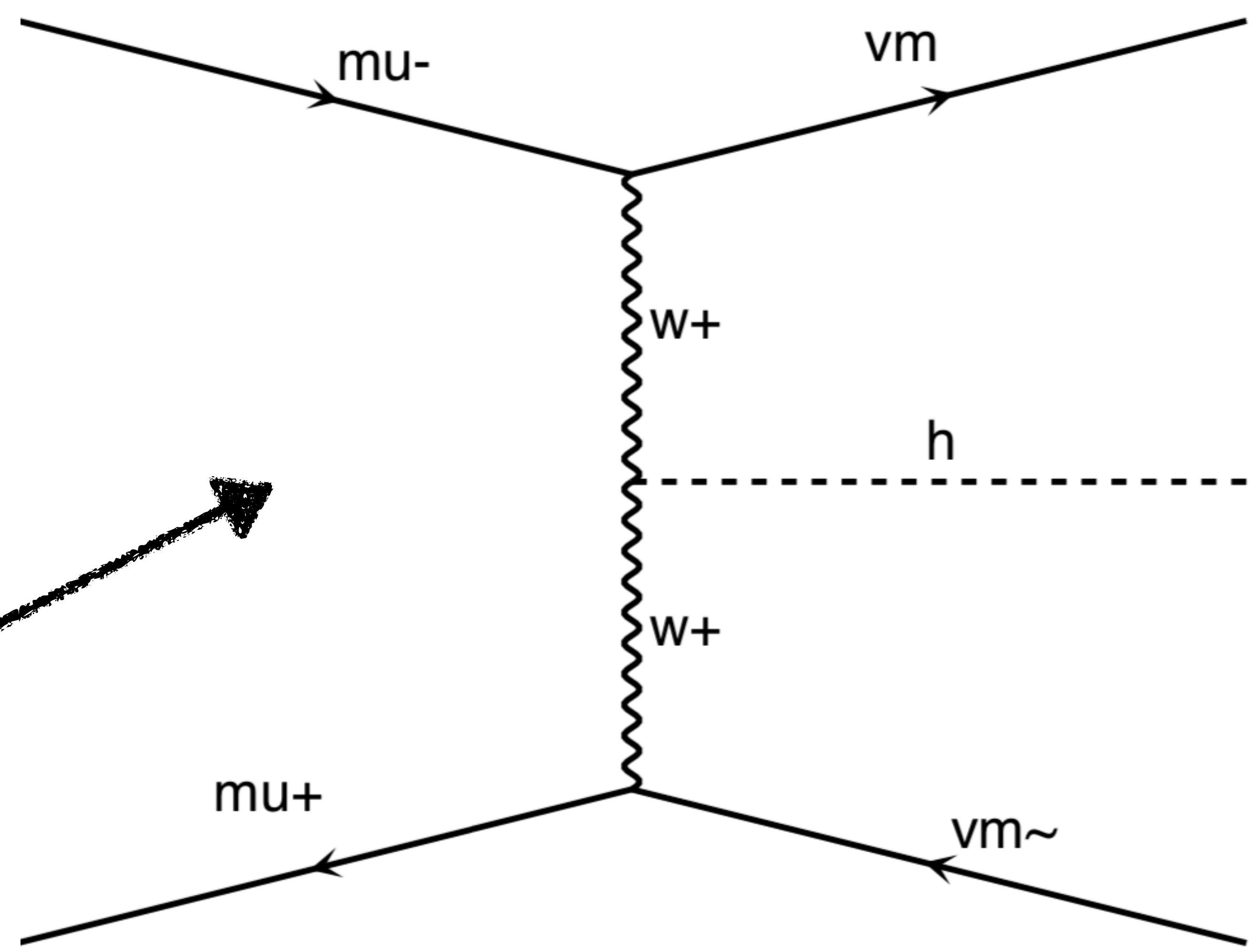
Why do high energy leptons produce so many Higgs particles?

Muon colliders are gauge boson colliders

That's why a lot of this physics case ports directly to high energy e, mu, gamma colliders



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



$$\sim \log E^2$$

Winner at moderate energies!

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

Muon colliders are gauge boson colliders

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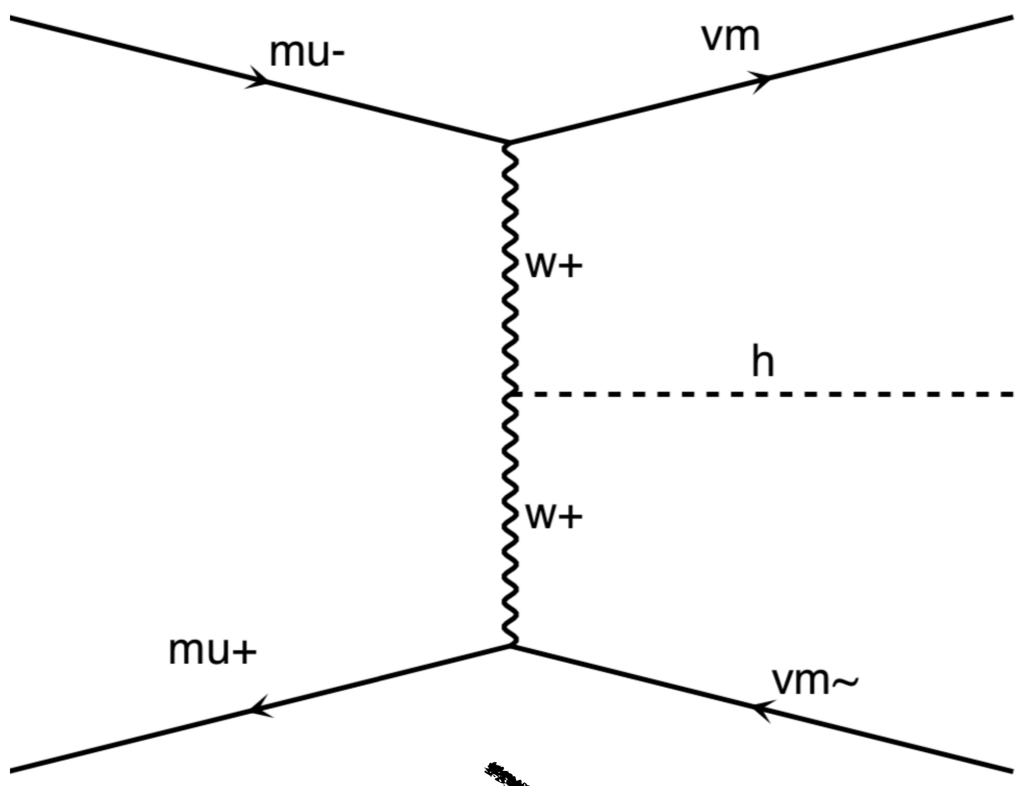
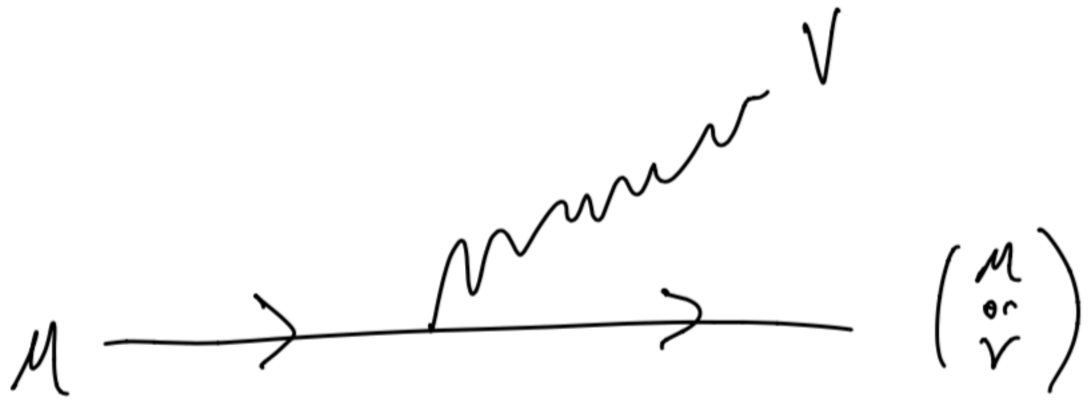
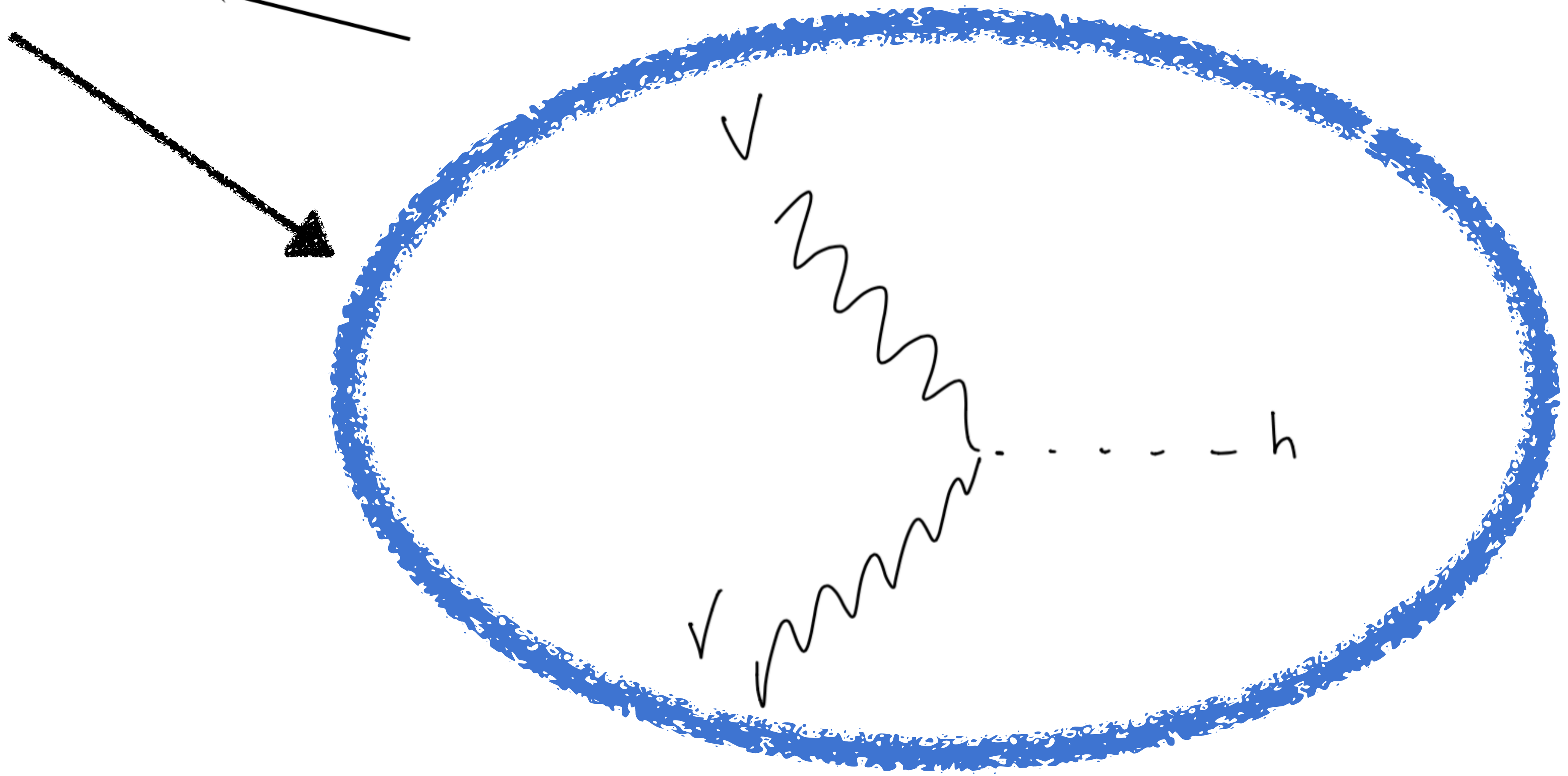




Vector Boson really wants to be soft or collinear....



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

$\sqrt{s}$ (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 (δ_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

HE lepton collider = Precision + Energy?

Is that it?

Just potentially amazing all in one Higgs?

Since so much of my time is otherwise occupied

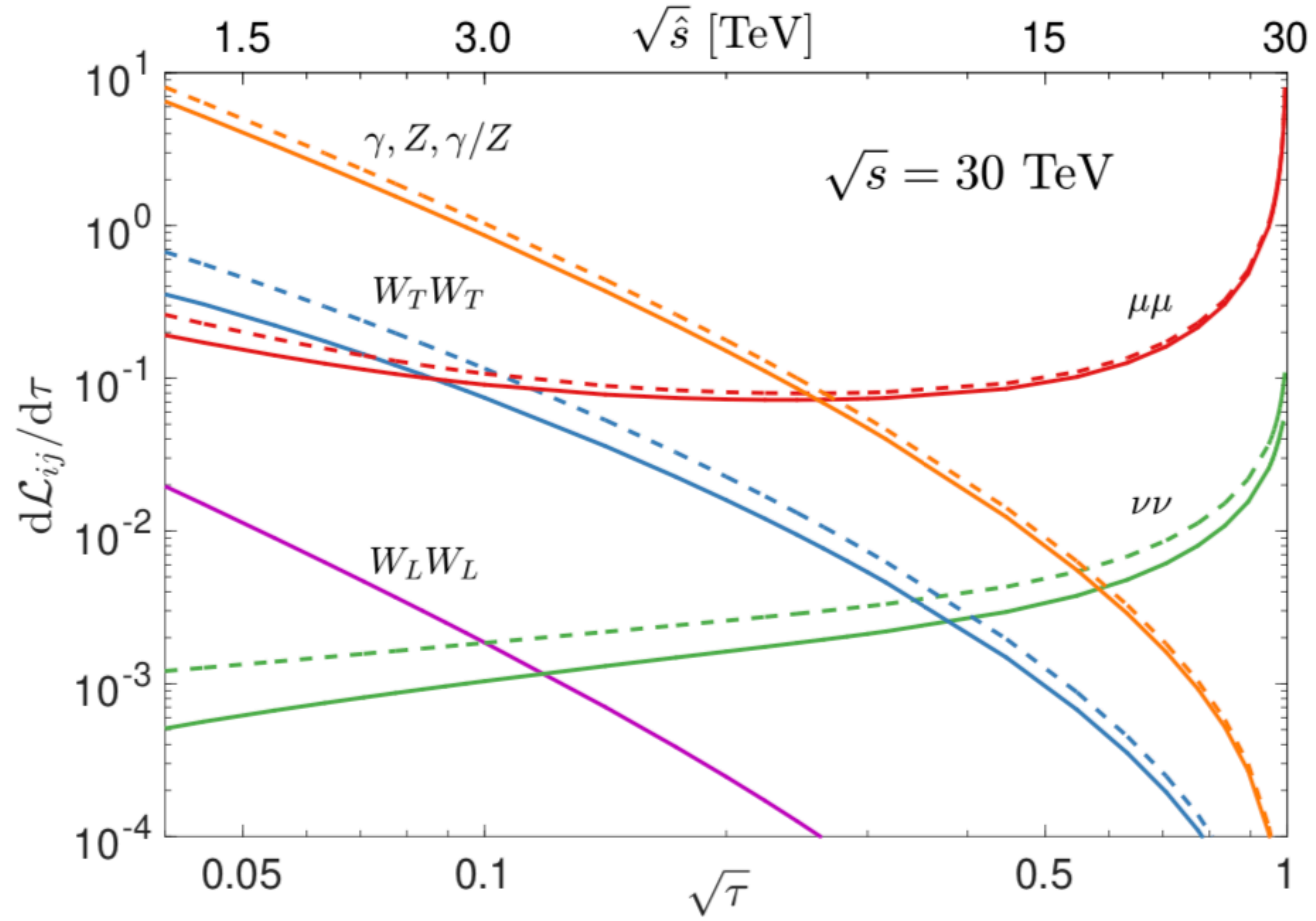
I thought a relevant segue was...

but that is not ALL i can do! said the cat...

But that is not ALL I can do! Said the high-energy lepton collider...

Muon colliders are *more than* gauge boson colliders

That's why not everything ports to gamma colliders, but still e and mu are good



2007.14300 T. Han, Y. Ma, K. Xie

FIG. 2. Distributions for (a) EW PDFs $f_i(x)$ and, (b) parton luminosities $dL_{ij}/d\tau$ versus $\sqrt{\tau}$ for $\sqrt{s} = 30$ TeV with a factorization scale $Q = \sqrt{\hat{s}}/2$ (solid) and $\sqrt{\hat{s}}$ (dashed).

You get tons of Gauge Bosons at low x - like gluons at a Hadron collider

BUT

you **ALSO** get muons peaking at x~1 *unlike* quarks at hadron colliders!!

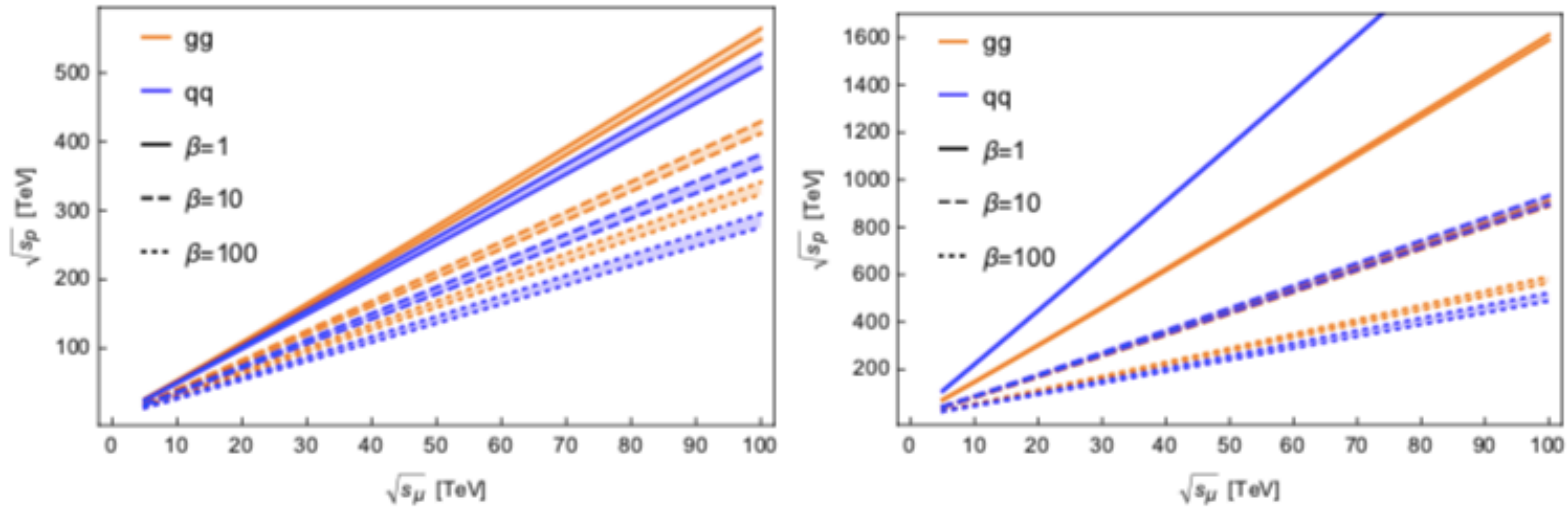
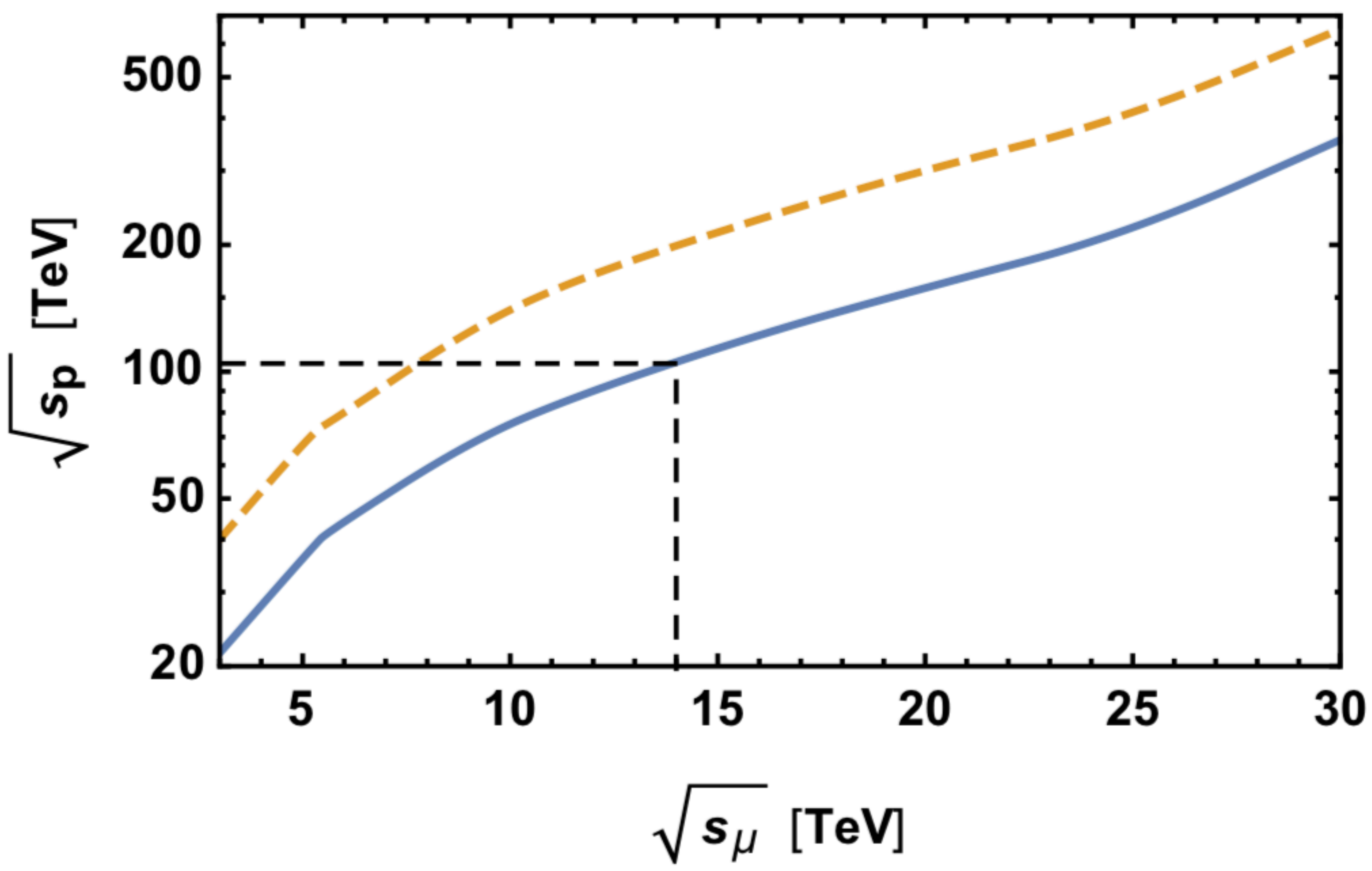
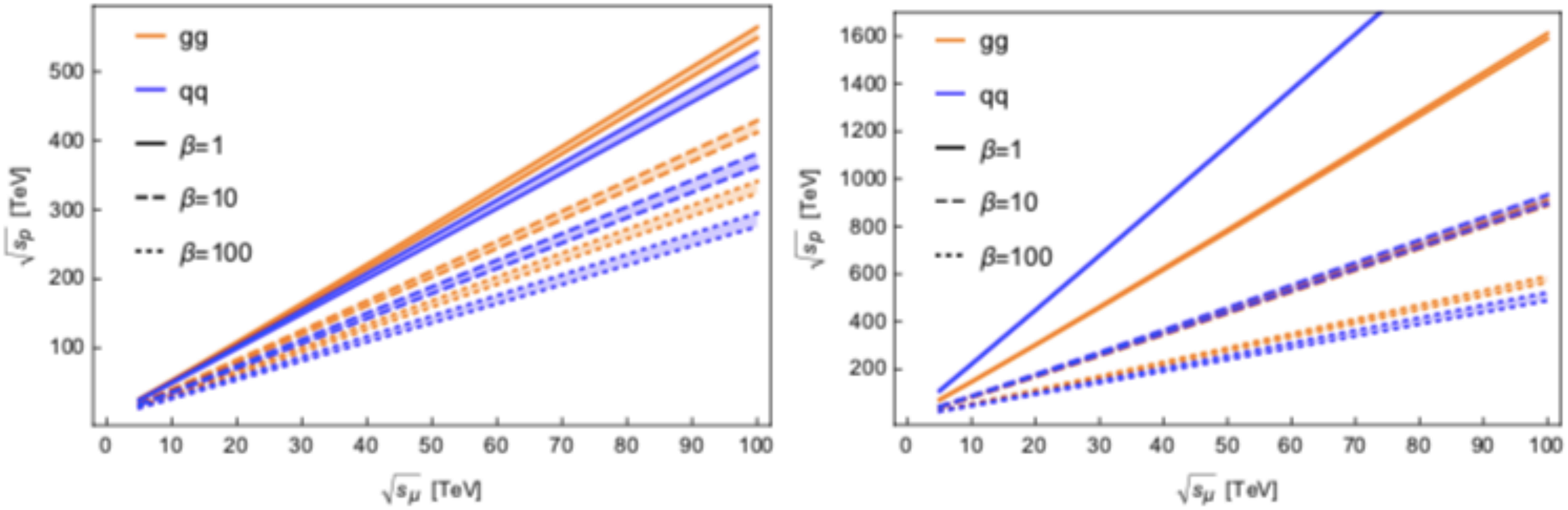


Figure 1: The c.m. energy $\sqrt{s_p}$ in TeV at a proton-proton collider versus $\sqrt{s_\mu}$ in TeV at a muon collider, which yield equivalent cross sections. Curves correspond to production via a gg (orange) or $q\bar{q}$ (blue) initial state at the proton-proton collider, while production at the 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.



Similar to what's in 1901.06150 Delahaye et al



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Roughly there is equivalence to a 100 TeV pp collider for

$2 \to 1$ | $2 \to 2$

$\sqrt{s_\mu} \sim 20\,\mathrm{TeV}$ | $\sqrt{s_\mu} \sim 5 - 7\,\mathrm{TeV}$

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

Lots of BSM Targets

Naturalness

Dark Matter

Electroweak Symmetry Breaking
Electroweak Phase Transition
Electroweak Baryogenesis
Flavor

Complementarity

Complementarity with other Frontiers

While slow at the start, the energy frontier is ultimately needed to "win the race"

Nevertheless if we get indirect hints from existing

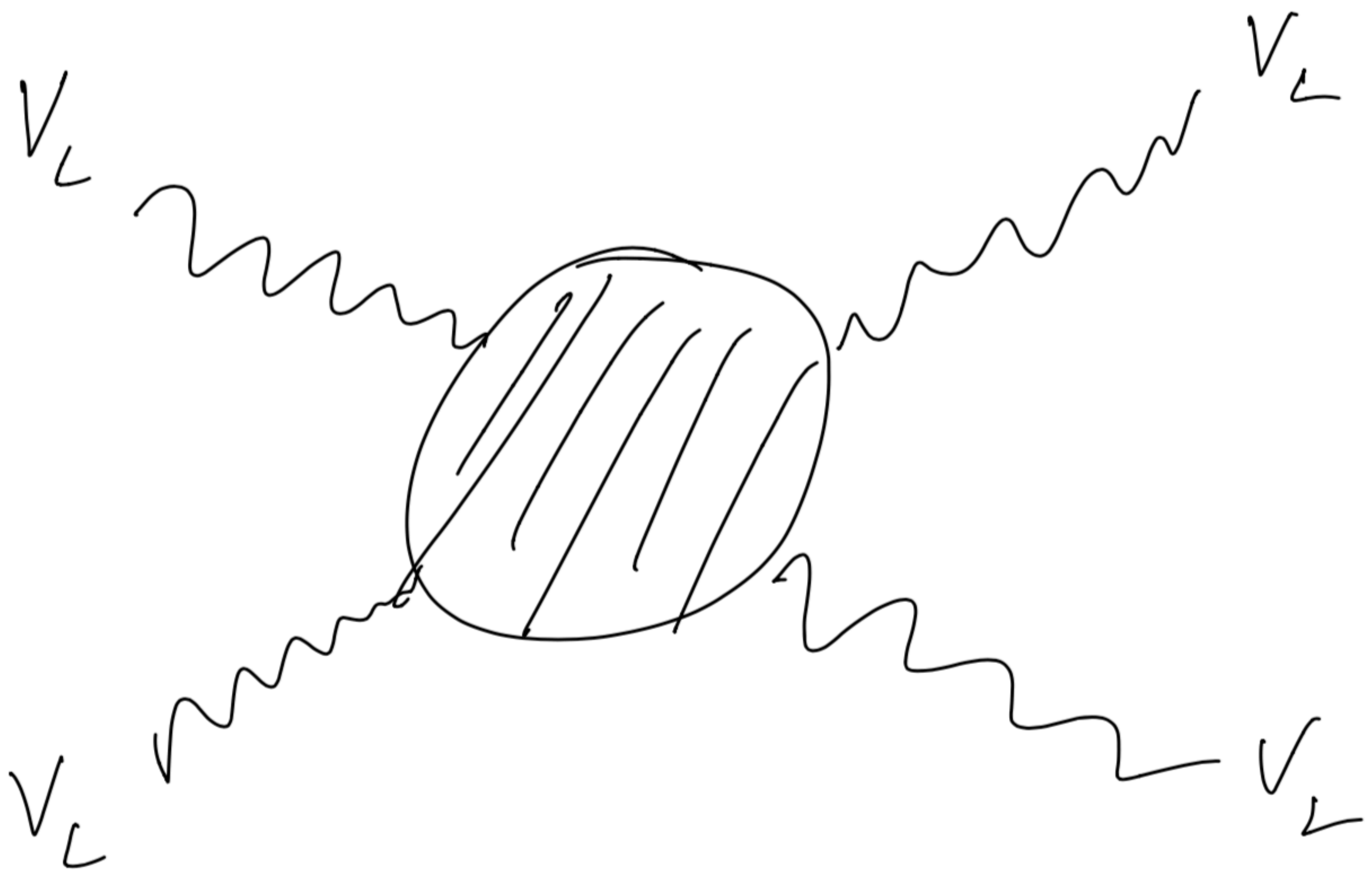
or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

What can you do with energy and EWSB?

Perturbative Unitarity Bounds!

Lee-Quigg-Thacker Higgs mass bound



$m_h \lesssim 1\,\text{TeV}$

The SM Higgs

- These properties are very delicate

What can you do with energy and EWSB?

These delicate cancellations persist all over the place!

For example a modified Top Yukawa...

$$\mathcal{M}(W_L^+ W_L^- \to t\bar{t})$$

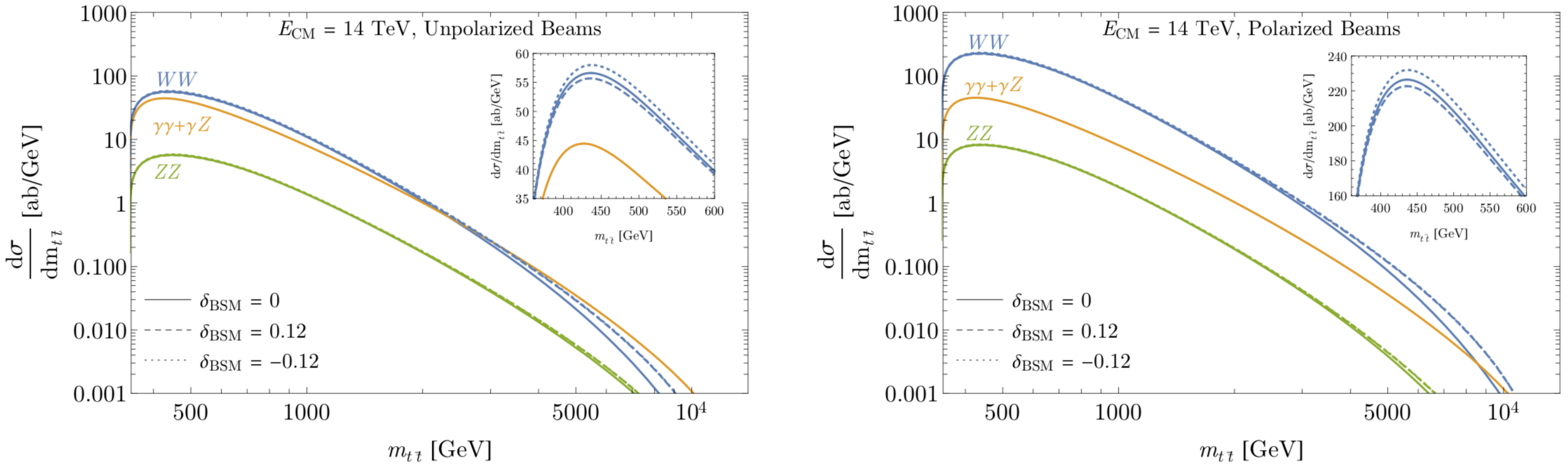


Figure 7: Differential cross section for $\mu^+\mu^- \to t\bar{t} + X$ from different gauge boson fusion processes at a 14 TeV muon collider, with unpolarized beams (left) or fully polarized (left-handed μ^- and right-handed μ^+) beams (right). At high energies, a deviation from the Standard Model top Yukawa leads to a significant increase in the rates for the $W_L W_L \to t\bar{t}$ process. At low energies (visible in the insets), it produces either destructive interference ($\delta_{\rm BSM} > 0$) or constructive interference ($\delta_{\rm BSM} < 0$).

What can you do with energy and EWSB?

These delicate cancellations persist all over the place!

For example a modified Top Yukawa...

$$\mathcal{M}(W_L^+ W_L^- \to t\bar{t})$$

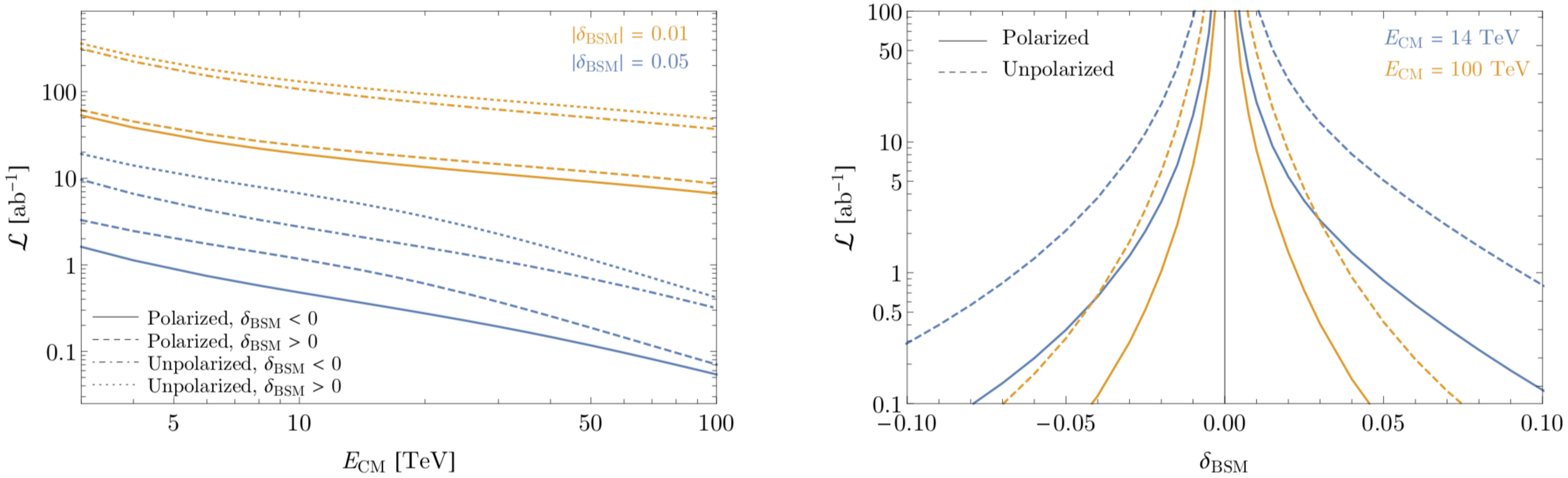
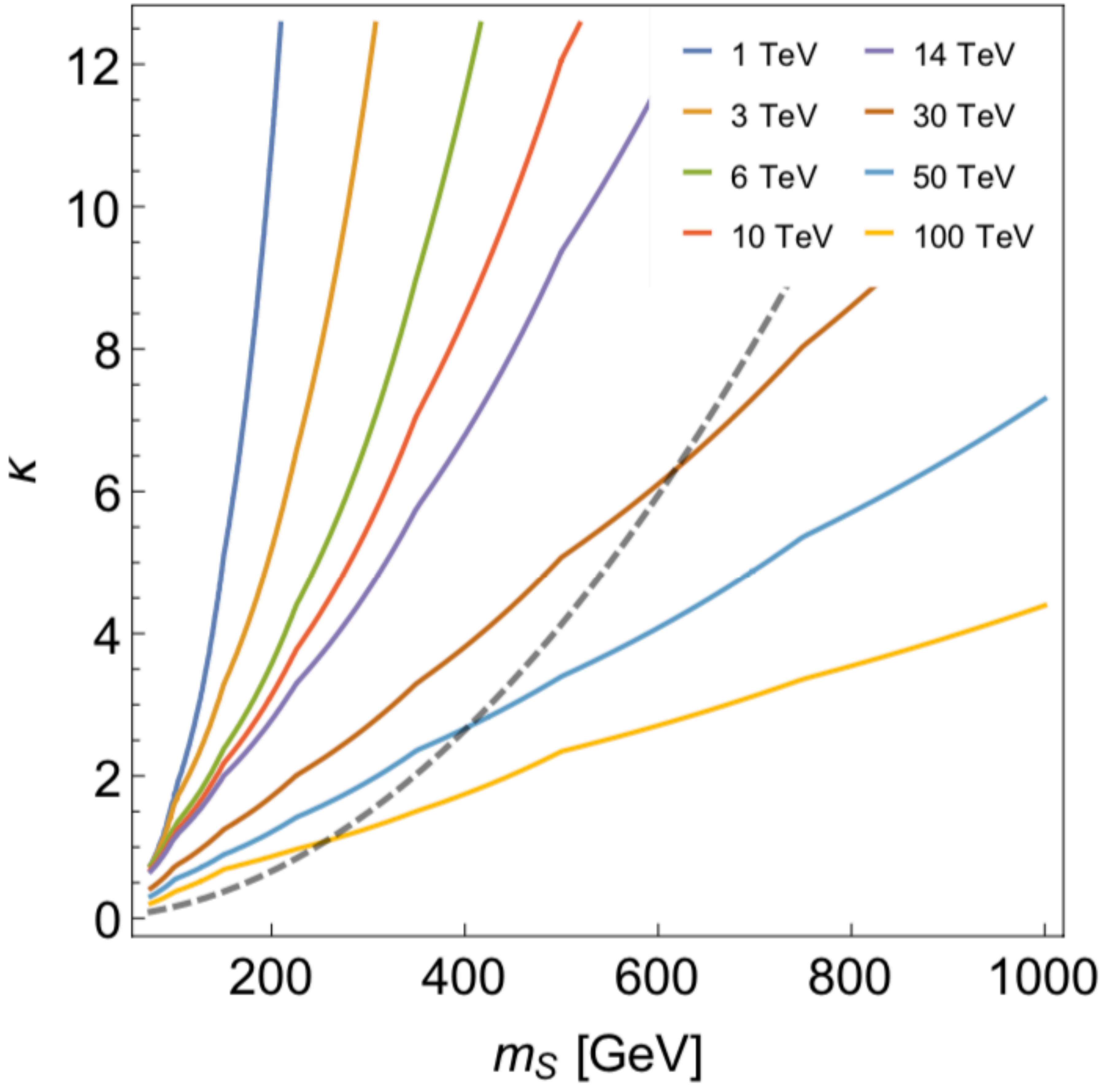


Figure 8: Luminosity needed to distinguish a modified top Yukawa coupling $\delta_{\rm BSM}$ from the Standard Model at 2σ confidence, through the differential rate $d\sigma/dm^2_{t\bar{t}}$ of the process $\mu^+\mu^- \to t\bar{t} + X$.

The Nightmare Higgs Portal Scenario

EWPT and Neutral Naturalness Prototype

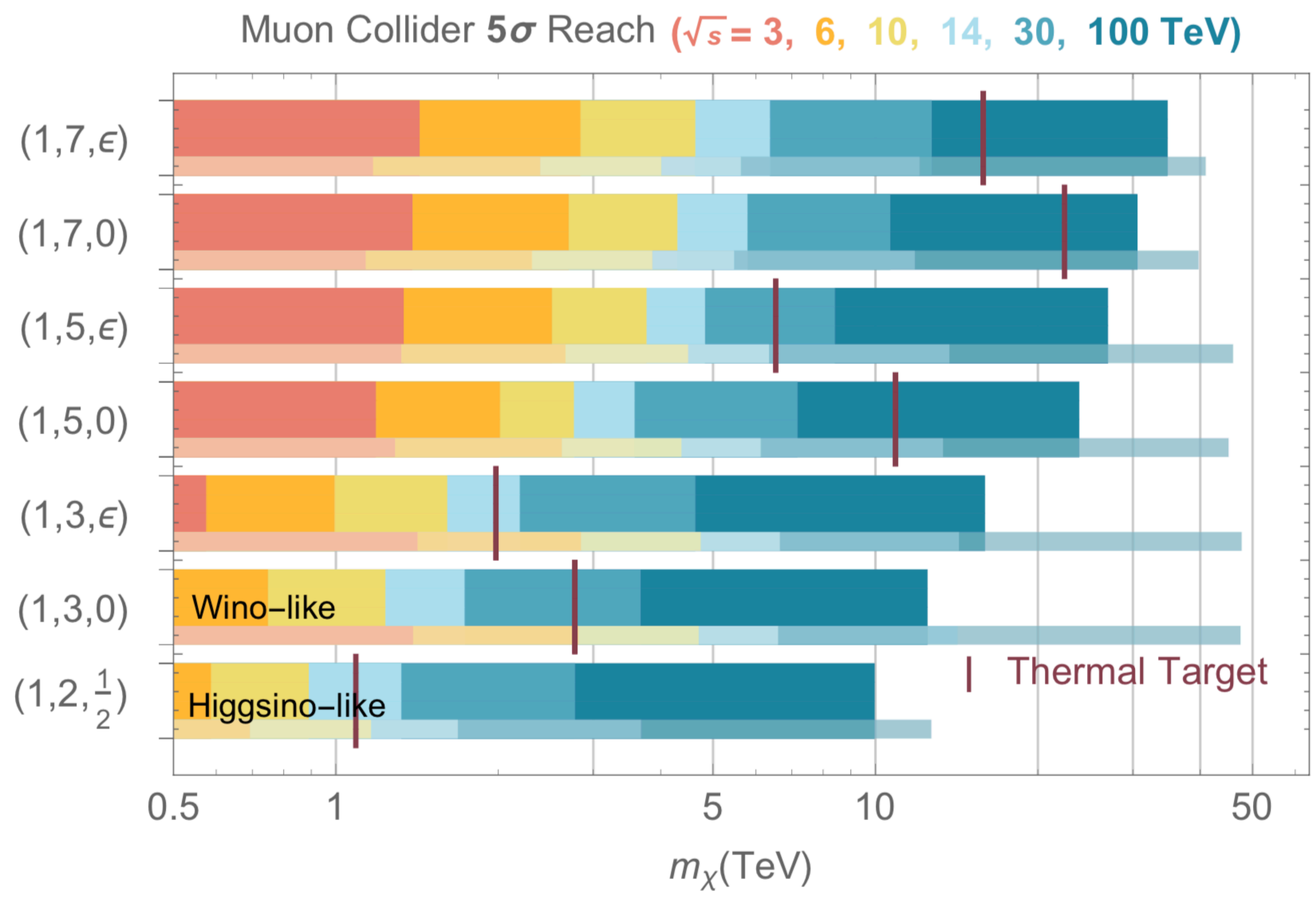
$$\mathcal{L} = \frac{1}{2}(\partial S)^2 - \frac{1}{2}M_S^2 S^2 - \kappa\, S^2 |H|^2$$



Takeaway - even the hardest things are doable!

Dark Matter

The WIMP *still* can be the DM



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].

Naturalness Example

Stop mass reach

rough background assumptions
for collider up to 100 TeV

$$m_{\tilde{t}} \sim .9\frac{\sqrt{s}}{2}$$

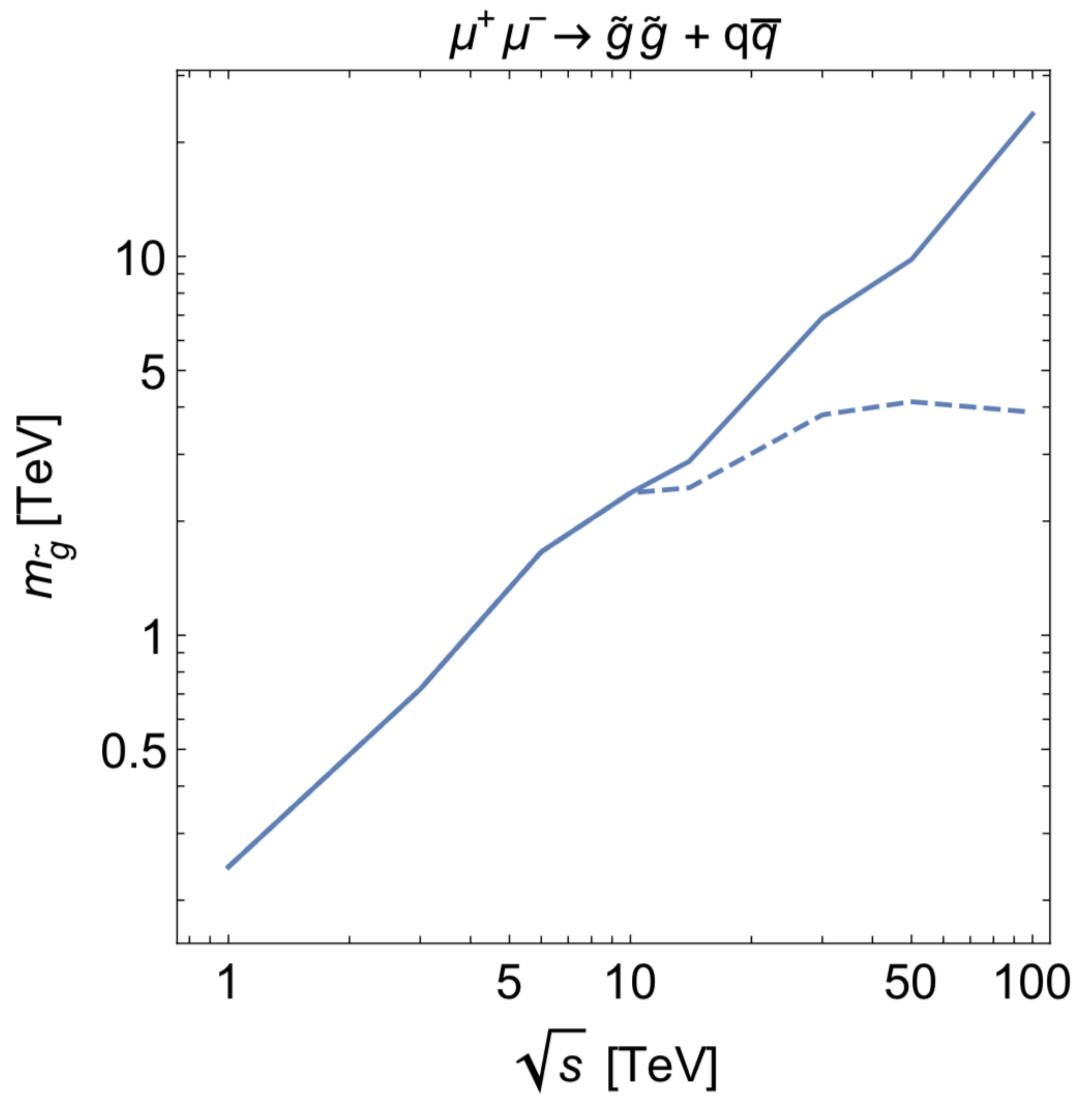


Figure 9: Gluino discovery reach from $\mu^+\mu^- \to \tilde{g}\tilde{g} + q\bar{q}$ as a function of $\sqrt{s}$, assuming "optimistic" (solid) and "conservative" (dashed) integrated luminosity scaling as detailed in the body of the text.

Can even do gluinos at a lepton collider!

These were just a few physics examples but hopefully it gives you a taste of what can be done…

Sloganeering time

Replace muon with electron as you see fit

High energy muon collider= Precision + Energy

End the energy/precision dichotomy

A muon collider is a vector boson collider

A muon collider is *more* than just a vector boson collider

A muon collider is like a hadron collider only better (j/k)

Optimal one project?

Complete the SM and large reach

What's the takeaway from this talk?
That ***potentially*** there is…

Who knows what the future holds?

#2020

Even back at the first Snowmass in 1982 they understood…

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.

Who knows what the future holds?

AKA Why now?

- We don't know if ILC , FCC, CEPC/SPPC will go forwards
- It's hard to imagine more than one mega project gets a greenlight soon…
- **IF** a high energy lepton collider *could* be an all-in-one collider we need to demonstrate it **now** as an alternative
    - There is work to be done on the Accelerator side - muons maybe closer? But we need something concrete and $\gtrsim \mathcal{O}(10)$ TeV!
    - New detector technologies to deal with backgrounds, nuts and bolts estimates to show whether precision means precision
    - R&D for this can be good for all, timing, trigger, radiation mitigation for detector, magnets etc. so investing this effort isn't taking away from something else

“Snowmass - Let a thousand flowers bloom”

J. Siegrist - Monday

Conclusion

The physics case for a high energy lepton collider is strong and exciting across fields!

Lots of exciting work to do for AF, EF, TF, IF!

This is not just scaling up what we've done before, exciting opportunity to launch a wide range of R&D projects with specific research goals

Please join these efforts since we are at a rare point in our field!