Higgs Physics at High Energy Muon Colliders

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The Muon Smasher's Pirate Ship

The Muon Smasher's Guide

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dario Buttazzo[3], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid Ekhterachian[5], JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9], Seth Koren[10], Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Alberto Mariotti[13], Amara McCune[1], Patrick Meade[7], Isobel Ojalvo[14], Umut Oktem[1], Diego Redigolo[15,16], Matthew Reece[9], Filippo Sala[17], Raman Sundrum[5], Dave Sutherland[18], Andrea Tesi[16,19], Timothy Trott[1], Chris Tully[14], Lian-Tao Wang[10], and Menghang Wang[1]

Dario and Raman gave great general physics overviews including the Higgs already…

So we could take the canonical approach to "Higgs" at colliders

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
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
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
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
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
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
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41
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

Higgs Boson studies at future particle colliders

J. de Blas[1,2], M. Cepeda[3], J. D'Hondt[4], R. K. Ellis[5], C. Grojean[6,7], B. Heinemann[6,8], F. Maltoni[9,10], A. Nisati[11,*], E. Petit[12], R. Rattazzi[13], and W. Verkerke[14]

Slightly fancier (but still same spirit), SMEFT approach

	HL-LHC	LHeC	HE-LHC S_2	HE-LHC S_2'	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
		HL-LHC +												
$\frac{c_\phi}{\Lambda^2}[\mathrm{TeV}^{-2}]$	0.53 (0.28)†	0.15 (0.11)	0.43 (0.21)†	0.31 (0.16)†	0.13 (0.061)	0.057 (0.041)	0.038 (0.033)	0.14 (0.076)	0.049 (0.04)	0.033 (0.027)	0.14 (0.038)	0.15 (0.044)	0.1 (0.038)	0.036 (0.029)
$\frac{c_T}{\Lambda^2}[\mathrm{TeV}^{-2}]$	0.0056 (0.002)	0.0056 (0.002)	0.0056 (0.002)	0.0055 (0.002)	0.0018 (0.0013)	0.0016 (0.0011)	0.0016 (0.001)	0.0029 (0.001)	0.0025 (0.001)	0.0023 (0.001)	0.00097 (0.0008)	0.0007 (0.0007)	0.0004 (0.0002)	0.0003 (0.0002)
[illegible] $[\mathrm{TeV}^{-2}]$	0.33 (0.022)	0.28 (0.022)	0.24 (0.0098)	0.19 (0.0098)	0.06 (0.011)	0.046 (0.0073)	0.037 (0.004)	0.065 (0.011)	0.042 (0.0037)	0.035 (0.0015)	0.092 (0.0076)	0.11 (0.0051)	0.072 (0.0036)	0.032 (0.0029)
[illegible] $[\mathrm{TeV}^{-2}]$	0.32 (0.028)	0.27 (0.028)	0.24 (0.028)	0.19 (0.028)	0.057 (0.011)	0.045 (0.0084)	0.037 (0.0053)	0.066 (0.013)	0.048 (0.0079)	0.041 (0.0035)	0.088 (0.0081)	0.11 (0.005)	0.069 (0.0035)	0.031 (0.0035)
[illegible] $[\mathrm{TeV}^{-2}]$	0.32 (0.034)	0.27 (0.033)	0.24 (0.01)	0.19 (0.01)	0.07 (0.026)	0.058 (0.012)	0.041 (0.0047)	0.078 (0.02)	0.044 (0.0039)	0.036 (0.0014)	0.086 (0.021)	0.11 (0.021)	0.08 (0.015)	0.032 (0.0043)
[illegible] $[\mathrm{TeV}^{-2}]$	0.32 (0.18)	0.28 (0.18)	0.24 (0.099)	0.19 (0.067)	0.086 (0.048)	0.054 (0.016)	0.039 (0.0066)	0.093 (0.035)	0.05 (0.0092)	0.04 (0.0034)	0.086 (0.062)	0.11 (0.066)	0.086 (0.042)	0.031 (0.011)
[illegible] $[\mathrm{TeV}^{-2}]$	0.0052 (0.004)	0.0049 (0.004)	0.0042 (0.0031)	0.0026 (0.0021)	0.0043 (0.0039)	0.004 (0.0038)	0.0035 (0.0033)	0.0048 (0.004)	0.0042 (0.0039)	0.0036 (0.0035)	0.004 (0.0038)	0.0041 (0.0039)	0.004 (0.0038)	0.0012 (0.0010)
[illegible] $[\mathrm{TeV}^{-2}]$	0.0012 (0.0005)	0.0009 (0.0005)	0.001 (0.0004)	0.0006 (0.0003)	0.0006 (0.0004)	0.0005 (0.0003)	0.0003 (0.0002)	0.001 (0.0004)	0.0006 (0.0003)	0.0005 (0.0002)	0.0006 (0.0002)	0.0005 (0.0003)	0.0005 (0.0003)	0.0003 (0.0001)
[illegible] $[\mathrm{TeV}^{-2}]$	0.25 (0.2)	0.23 (0.18)	0.18 (0.13)	0.11 (0.091)	0.14 (0.096)	0.097 (0.079)	0.079 (0.07)	0.21 (0.17)	0.15 (0.13)	0.11 (0.1)	0.1 (0.072)	0.11 (0.078)	0.094 (0.071)	0.052 (0.044)
[illegible] $[\mathrm{TeV}^{-2}]$	0.57 (0.24)	0.42 (0.19)	0.44 (0.19)	0.26 (0.12)	0.26 (0.14)	0.19 (0.099)	0.12 (0.072)	0.42 (0.16)	0.23 (0.11)	0.19 (0.085)	0.25 (0.091)	0.2 (0.11)	0.19 (0.099)	0.11 (0.052)
[illegible] $[\mathrm{TeV}^{-2}]$	0.46 (0.25)	0.23 (0.13)	0.37 (0.19)	0.26 (0.14)	0.13 (0.084)	0.088 (0.066)	0.071 (0.059)	0.18 (0.098)	0.077 (0.063)	0.059 (0.055)	0.091 (0.064)	0.1 (0.068)	0.092 (0.064)	0.071 (0.057)
[illegible] $[\mathrm{TeV}^{-2}]$	0.08 (0.069)	0.08 (0.069)	0.028† (0.013)	0.028† (0.013)	0.025 (0.023)	0.0083 (0.0078)	0.0029 (0.0027)	0.031 (0.028)	0.0064 (0.0059)	0.0023 (0.0021)	0.042 (0.034)	0.042 (0.029)	0.028 (0.021)	0.0034 (0.0034)
[illegible] $[\mathrm{TeV}^{-2}]$	0.008 (0.0069)	0.008 (0.0069)	0.0053† (0.0024)†	0.0053† (0.0024)†	0.0062 (0.0058)	0.0032 (0.003)	0.0012 (0.0011)	0.0062 (0.0058)	0.0016 (0.0014)	0.0006 (0.0005)	0.0069 (0.0062)	0.0062 (0.0057)	0.0056 (0.0049)	0.0003 (0.0003)
[illegible] $[\mathrm{TeV}^{-2}]$	1.7 (1.6)	1.6 (1.6)	1.6 (1.6)	1.6 (1.6)	0.023 (0.022)	0.011 (0.011)	0.0076 (0.0075)	0.024 (0.024)	0.0031 (0.0031)	0.001 (0.001)	0.036 (0.02)	0.034 (0.019)	0.026 (0.015)	0.021 (0.015)
[illegible] $[\mathrm{TeV}^{-2}]$	8.4 (7.8)	8.1 (7.7)	2.5 (2.4)	2.4 (2.3)	8.1 (4.7)	3.5 (3.1)	1.5 (1.4)	8.1 (7.7)	4.8 (4.5)	1.8 (1.7)	8. (2.8)	8. (3.2)	5.3 (3.1)	0.81 (0.79)

A Muon Collider is great!

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

Di-Higgs too!

Double Higgs production

- Reach on Higgs trilinear coupling: hh → 4b

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{rec}	$\delta\sigma \sim N_{\text{rec}}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%

A muon collider is great for the Higgs!
The End.

Plan for the rest of the talk...

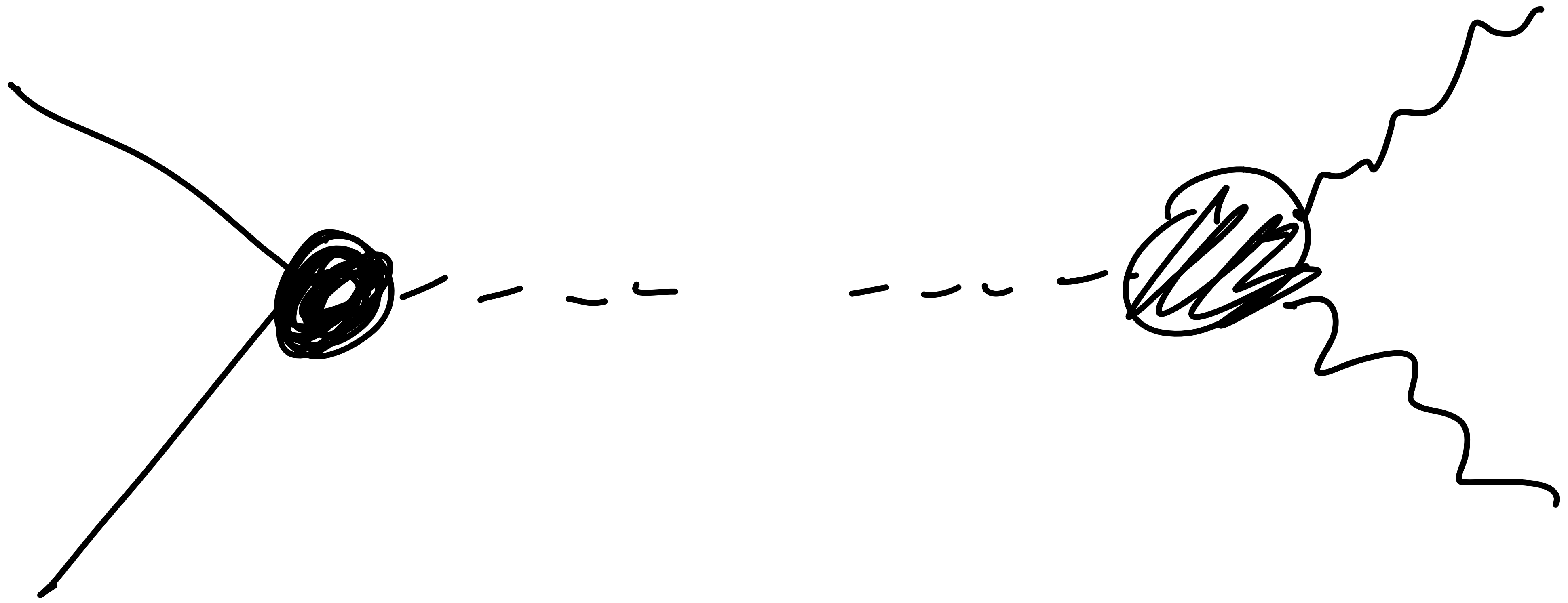
Where do these numbers come/
Why is a muon collider so good?

What do these numbers mean?
Are there important targets?
Are there novel features available with the muon collider?

Various levels of sophistication that went into this table

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

Looking for ***on-shell*** Higgs production deviations



production

decay

$$\mu_{if} = \frac{\sigma_{i\to h}\, B_{h\to f}}{\text{SM value}}$$

$$\kappa_i = \frac{\text{coupling to Higgs of } i}{\text{SM value}}$$

Need as *many* Higgs that decay into a particular final state as possible for smallest statistical error!

More Higgses are better!

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-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

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

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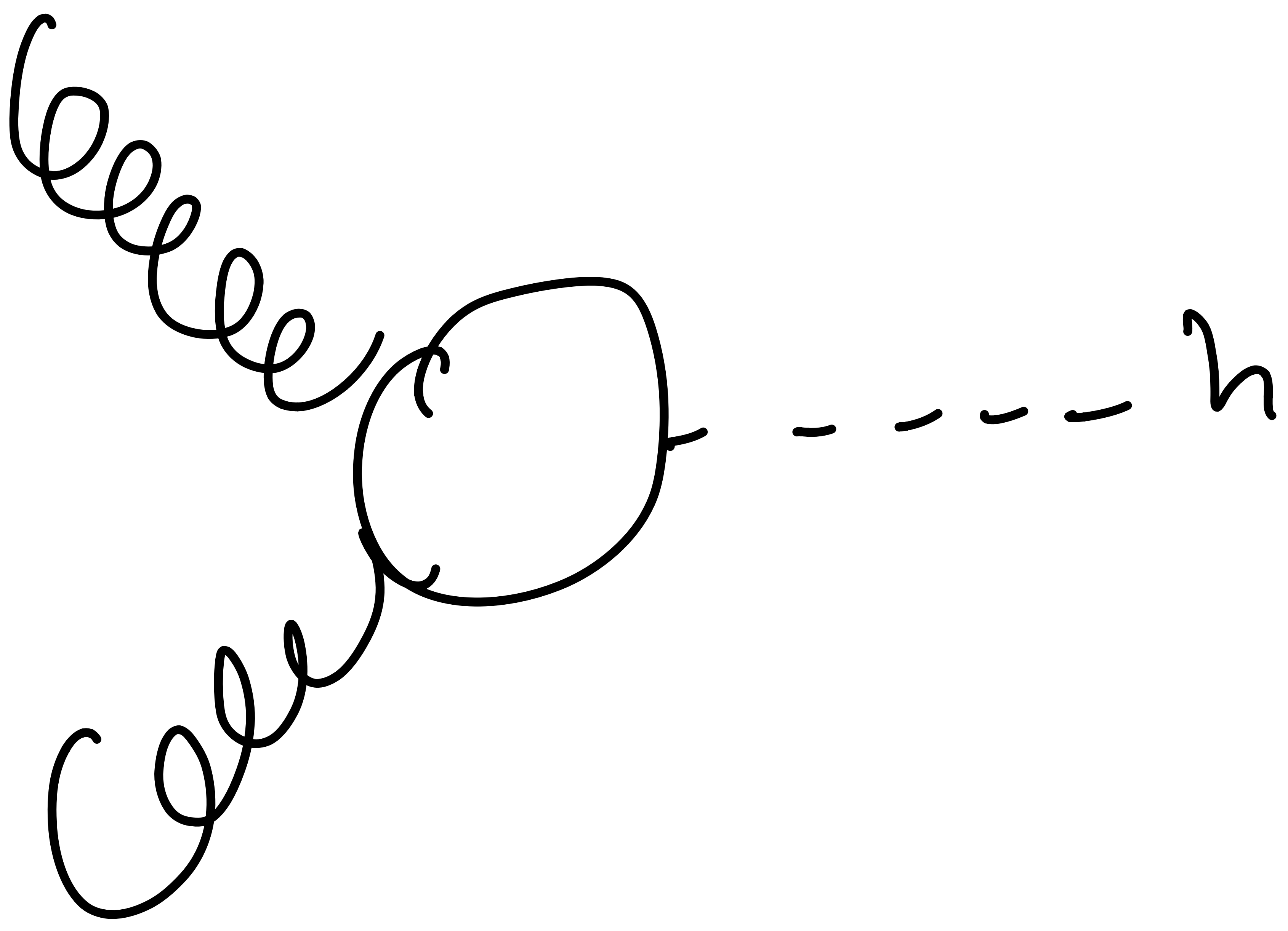
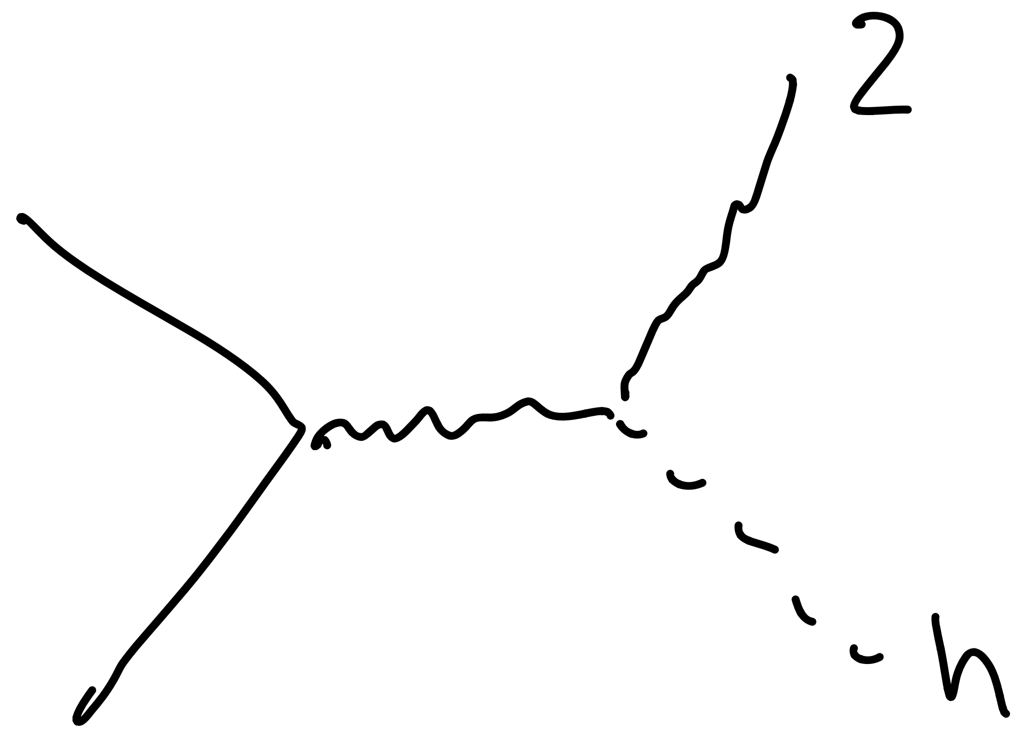
More energy = More Higgs
(*IF* you can provide the luminosity)

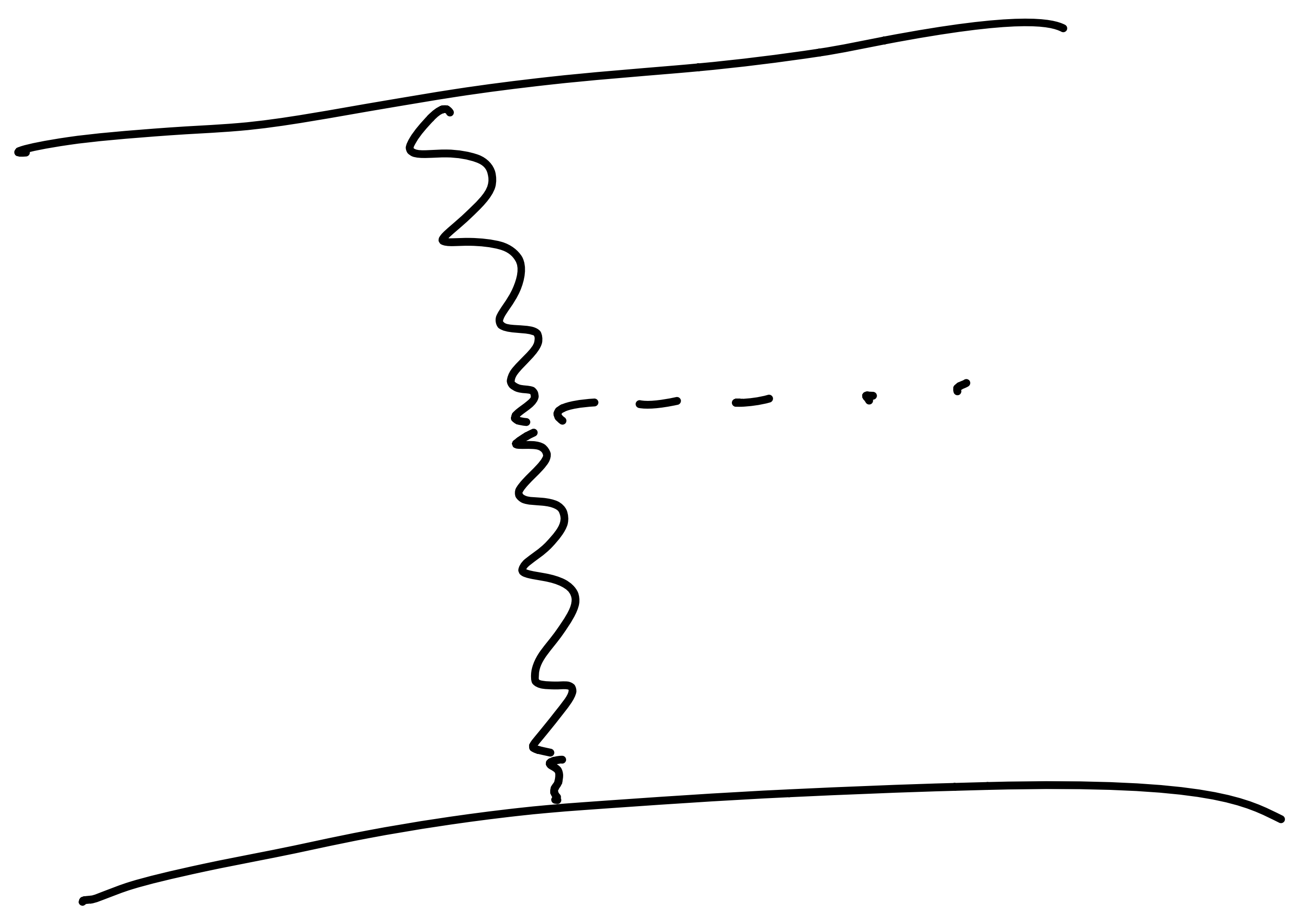


more gluons at low x

More energy = More Higgs
(*IF* you can provide the luminosity)

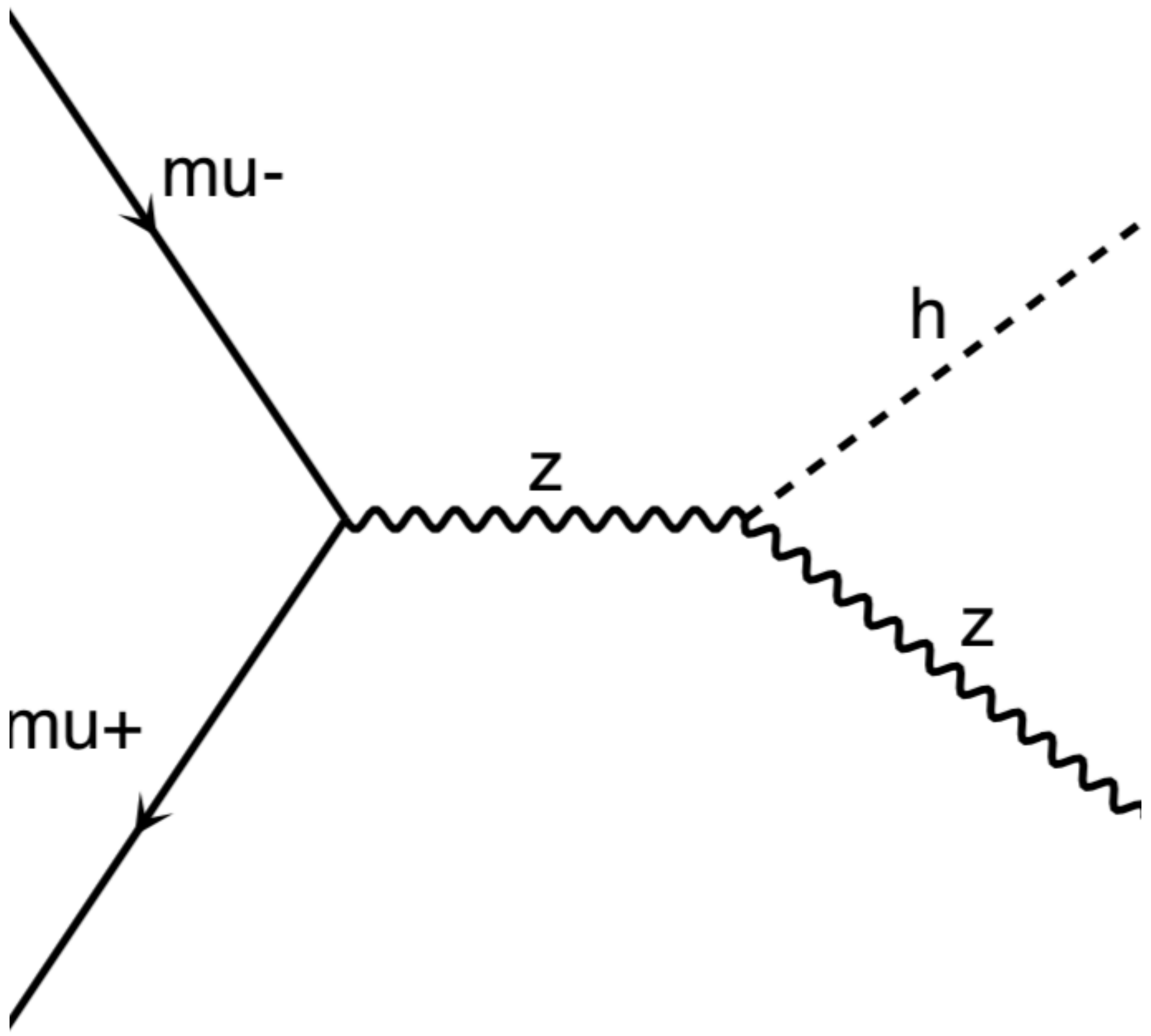


Versus

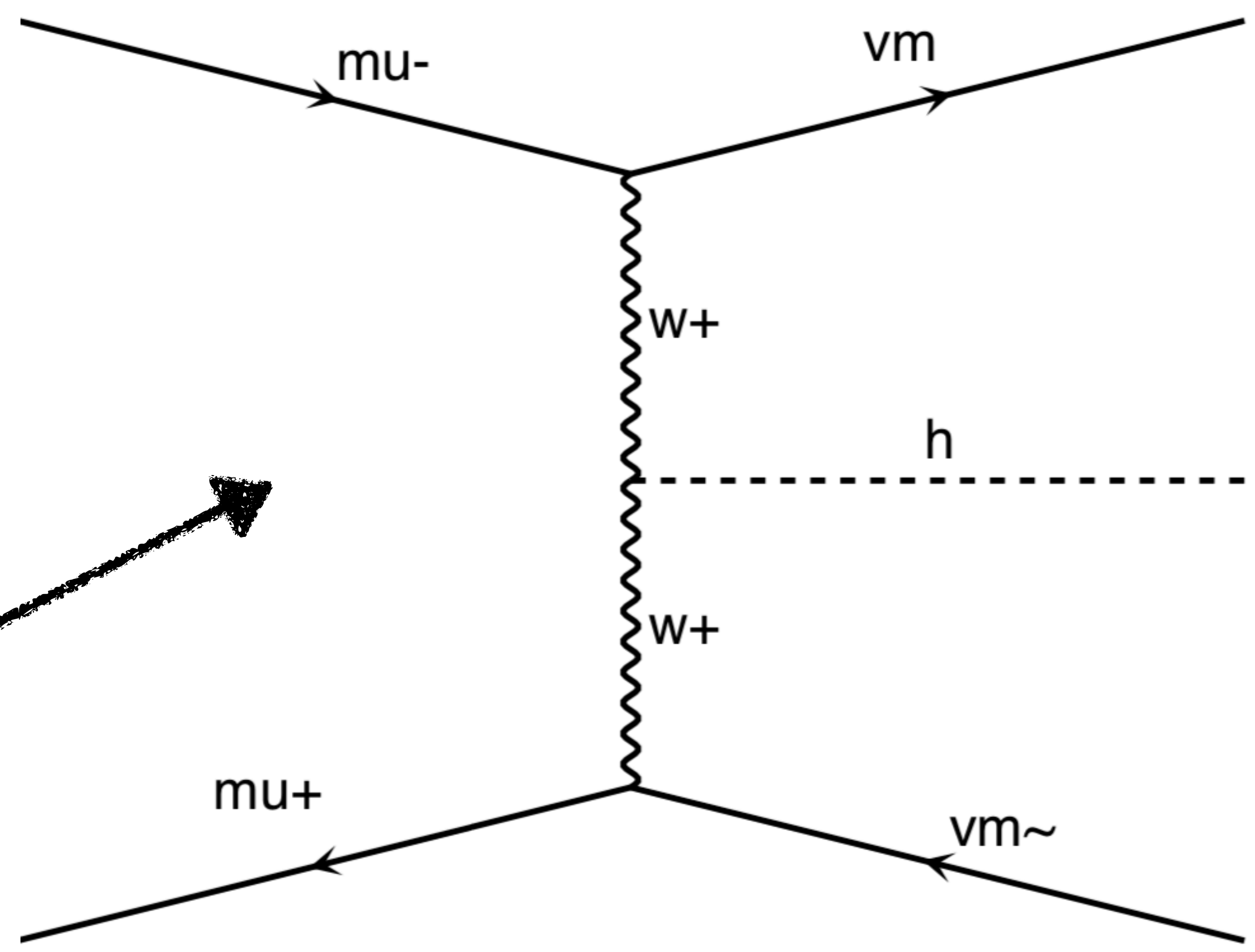


Same lesson holds for electron/muon colliders

Muon colliders are gauge boson colliders



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

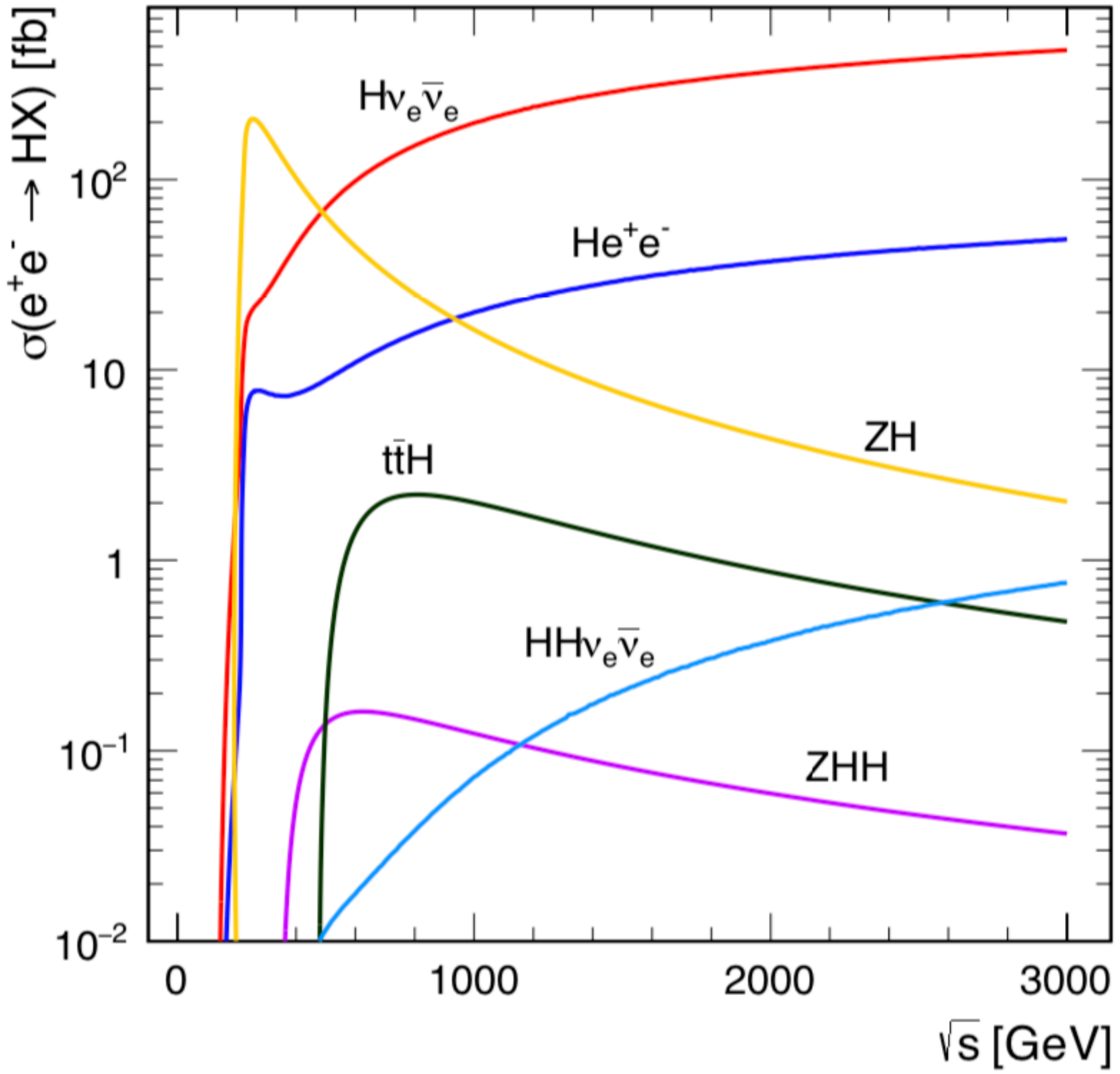


$$\sim \log E^2$$

Winner at moderate energies!

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

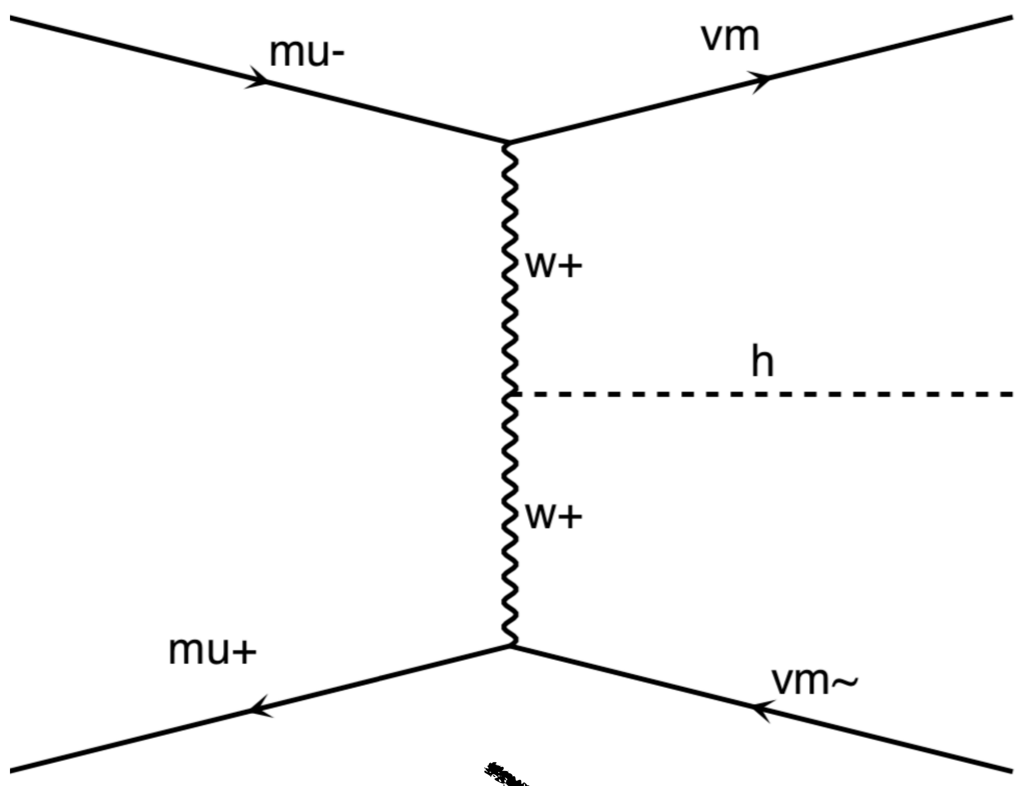
More energy = More Higgs
(*IF* you can provide the luminosity)

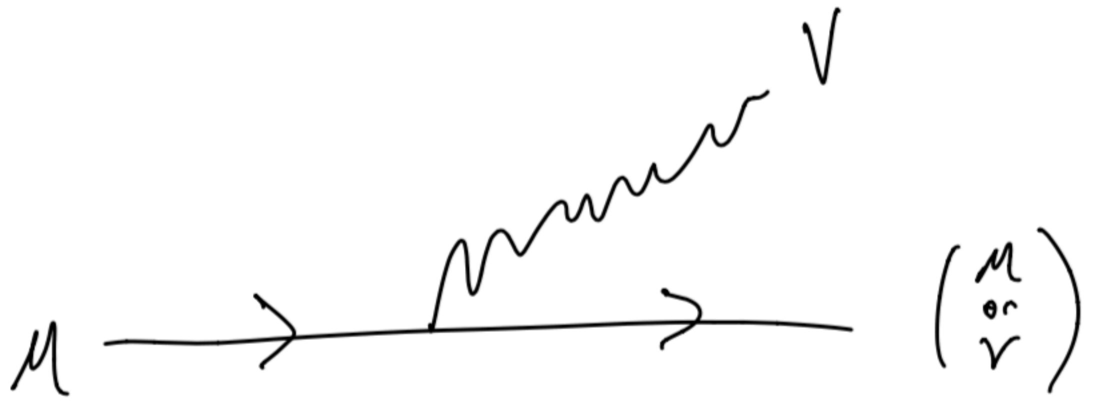


Same lesson holds for electron/muon colliders

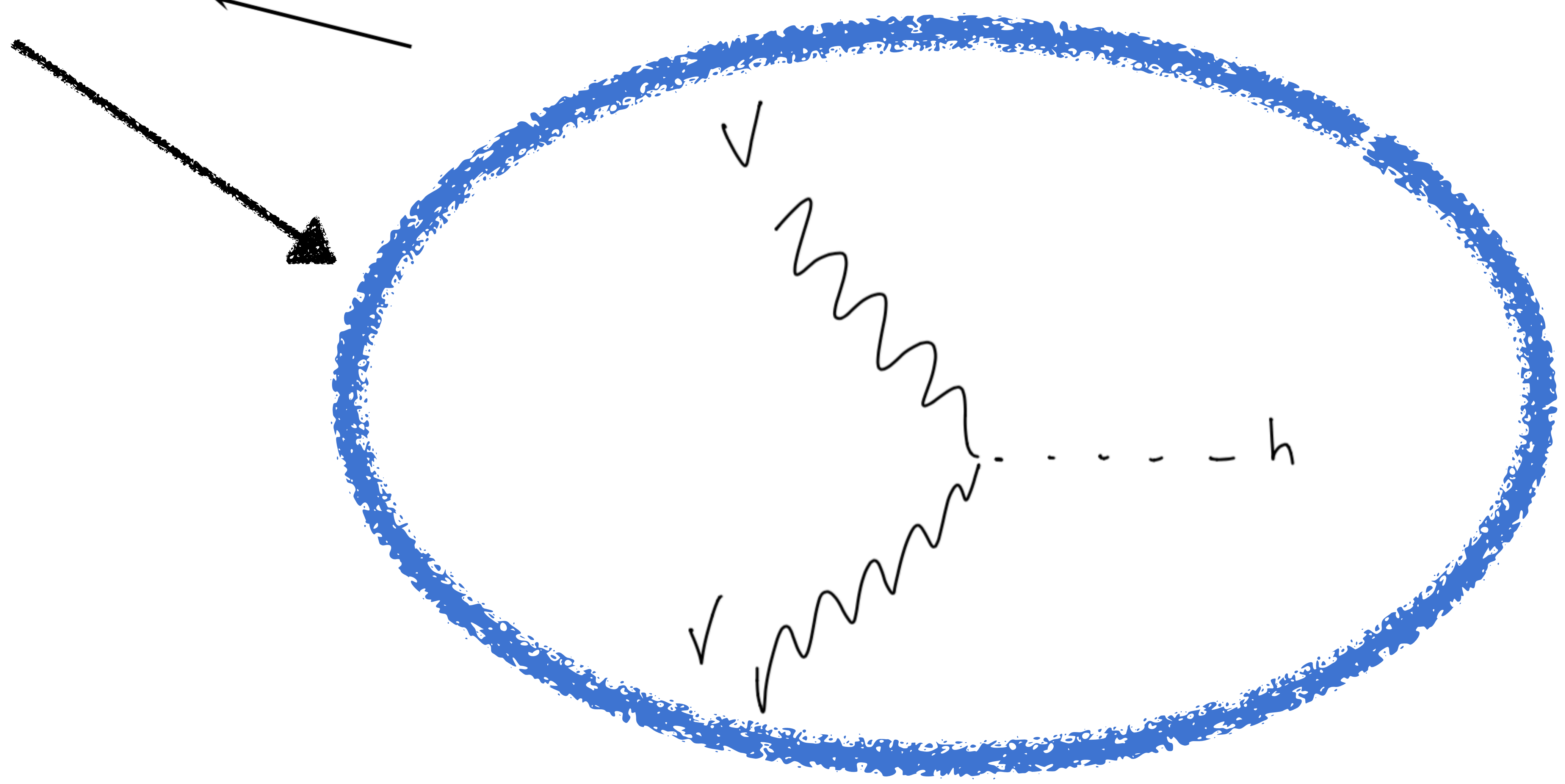
This can be extended to thinking of gauge bosons as *constituents* of muons!

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





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



So what does this get you?

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-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!

With a million Higgses…

Statistically you get .1% at best

Not crazy for Higgs factories…

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

Why does it fail so badly for LHC and FCC-hh?

Backgrounds!

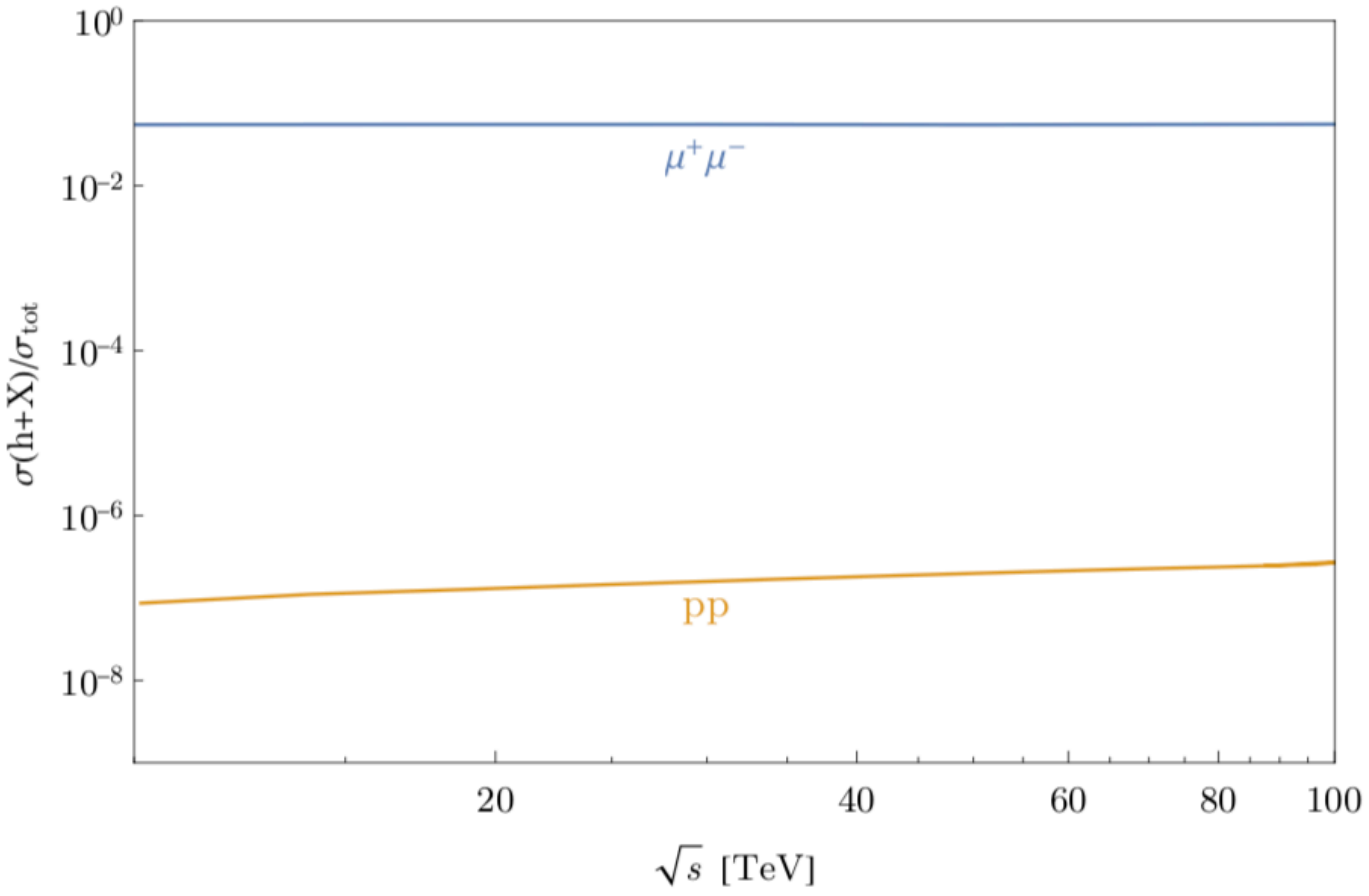


Figure 4: Higgs production cross section $\sigma(h+X)$ as a fraction of a representative "total" cross section σ_{tot} for $\mu^+\mu^-$ and pp colliders. For $\mu^+\mu^-$ colliders, we compute Higgs production using the LO cross section for $\mu^+\mu^- \to h + \nu\bar{\nu}$, while the "total" cross section σ_{tot} is taken to be the rate for single electroweak boson production, which is dominated by VBF production of W, Z, h, γ at these energies. For pp colliders we take the Higgs production cross section to be the N3LO cross section for $gg \to h$ [50] presented in [51], while the "total" cross section σ_{tot} is taken to be the $pp \to b\bar{b}$ cross section computed by MCFM [52].

As a first example of a general Higgs physics program

10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
W-fusion	bb	490	7.4	0.17
	cc	24	1.4	1.7
	jj	72	37	0.19
	$\tau^+\tau^-$	53	6.5	0.54
	$WW^*(jj\ell\nu)$	53	21	0.30
	$WW^*(4j)$	86	4.9	0.49
	$ZZ^*(4\ell)$	0.1	6.6	12
	$ZZ^*(jj\ell^+\ell^-)$	2.1	8.9	2.3
	$ZZ^*(4j)$	11	4.6	1.4
	$\gamma\gamma$	1.9	33	1.3
	$Z(jj)\gamma$	0.9	27	2.0
	$\mu^+\mu^-$	0.2	37	0.37
Z-fusion	bb	51	8.1	0.49
	$WW^*(4j)$	8.9	6.2	1.3
W-fusion tth	bb	0.06	12	12

Table 2: Signal rates and efficiencies for selected Higgs production channels at a 10 TeV muon collider using signal-only selection and the DELPHES muon collider fast simulation.

SIGNAL ONLY **+ DELPHES**

$$N_{Higgs} = (\sigma\, BF)\, \mathcal{L} \longrightarrow N_{Higgs} = (\sigma\, BF)\, \mathcal{L} \times (\varepsilon A)$$

As a first example of a general Higgs physics program

Fit Result [%]

	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

Adding other colliders to the fit...

As a first example of a general Higgs physics program

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

Completely unfair comparison... but still interesting nonetheless!

Throw in di-Higgs

Double Higgs production

- Reach on Higgs trilinear coupling: hh → 4b

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{rec}	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%

A muon collider could *potentially* be an all in one wonder for the Higgs

But why do we care so much about these numbers and what do they mean? And where do they come from!?

Building our Foundational Physics Potential Cases

Building our Four … cs Potential Cases

Building our Foundational Physics Potential Cases

BSM/UNKNOWN

Gauranteed returns are hard!

So it seems these numbers matter a lot!

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$\star$	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	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
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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 in many ways they matter even more than a “guaranteed” return

But in many ways they matter even more than a "guaranteed" return

HIGGS PHYSICS
IS
BSM PHYSICS

Connections to the Higgs!

OUTLINE

Higgs-ploration

Composite Resonances

Gravitational Waves from Cosmological Phase Transitions

WIMP Dark Matter

Matter-Antimatter Asymmetry

Long-Lived Particles

Supersymmetry

The Little Hierarchy Problem & the Anthropic Principle

Ghost ("dark") Sectors

Higgs Portal

Hidden Naturalness

4

How do we turn this into a BSM understanding? Is this(or SMEFT version) good enough?

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
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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
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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
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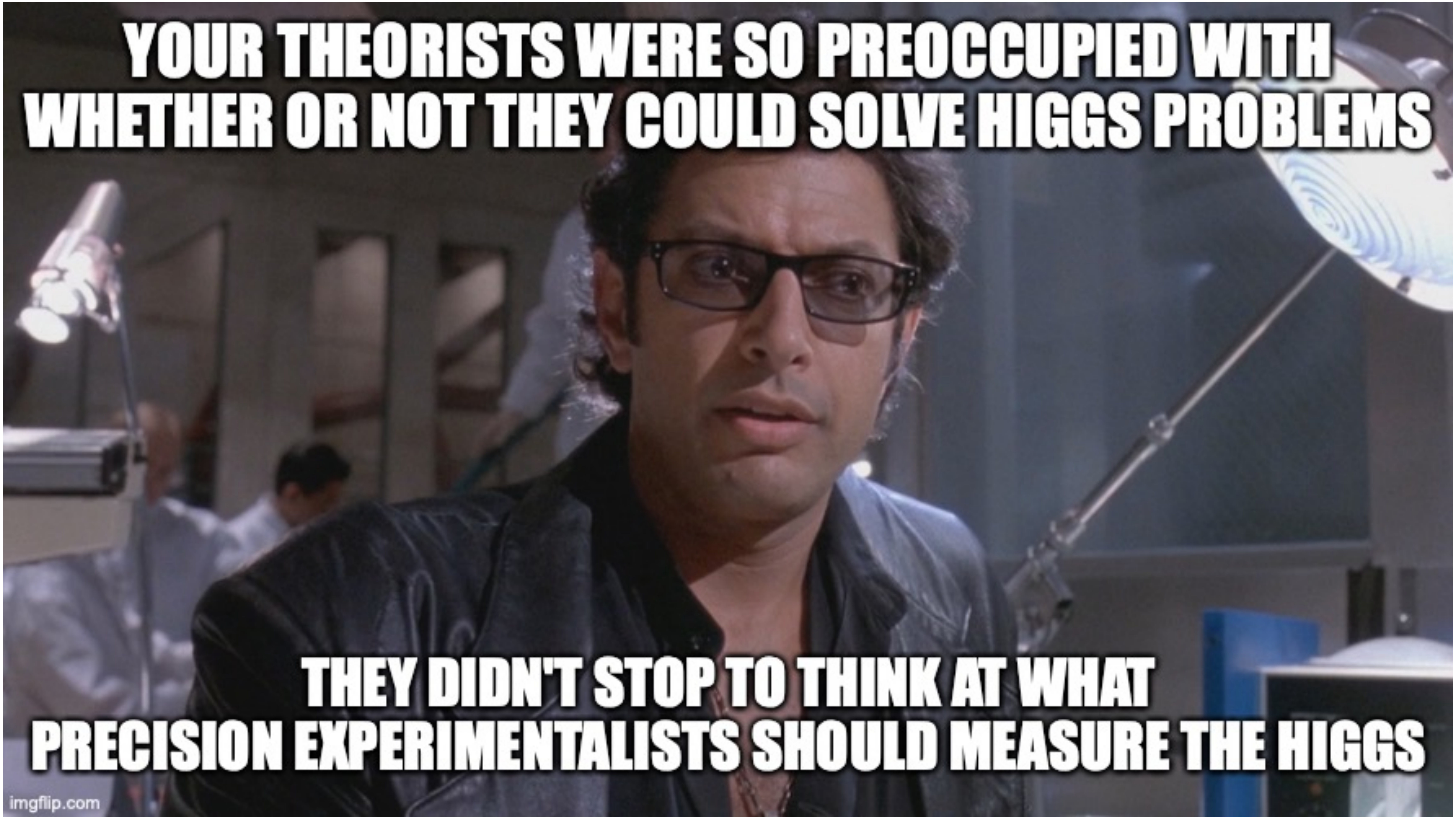
YOUR THEORISTS WERE SO PREOCCUPIED WITH WHETHER OR NOT THEY COULD SOLVE HIGGS PROBLEMS
THEY DIDN'T STOP TO THINK AT WHAT PRECISION EXPERIMENTALISTS SHOULD MEASURE THE HIGGS
imgflip.com

Luckily the fancy theories can be replaced by very *simple* questions about the Higgs…

- Why did Electroweak Symmetry Breaking occur?
- Why is the weak scale what it is?
- Why is there an apparent light spin 0 particle?
- What is the Higgs potential?
- What role did the Higgs have in the early universe?
- Is there a “scalar equivalence principle”?
- What is causing flavor/CPV as we see it?
- Is the Higgs a portal to other sectors?

So what do we want to glean from this table and specifically about the potential for a muon collider?

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
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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
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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
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So what do we want to glean from this table and specifically about the potential for a muon collider?

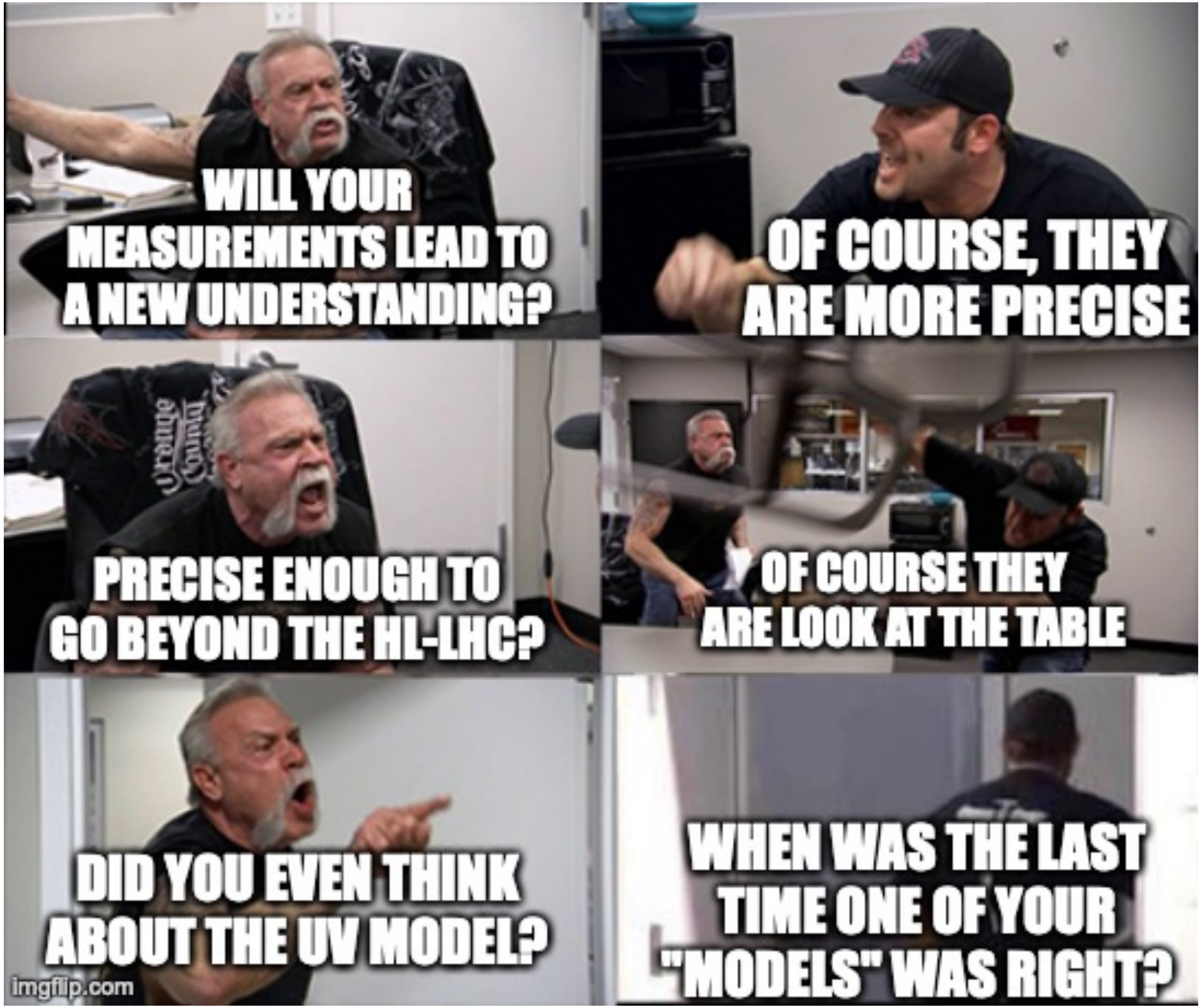
- When do these numbers tell us something about the fundamental questions we're stuck with now that we've seen the "Higgs"?

- Is there a particular set of experiments that are more interesting than others?

- Is this deviation parametrization framework useful and when do we actually go beyond the HL-LHC since new physics doesn't have to *only* show up in the Higgs?

- What are we missing and what are the studies left to be done? What new types of measurements are available at high energies!

Theorist vs. Experimentalist



So I’ve already shown where the muon collider is potentially great… but let me also throw out a few slides dreaming bigger

Where does the HL-LHC leave us with the least understanding about the Higgs?

So I've already shown where the muon collider is potentially great… but let me also throw out a few slides dreaming bigger

Where does the HL-LHC leave us with the least understanding about the Higgs?

Higgs self interactions

Light Fermions

Higgs self interactions

Double Higgs production

- Reach on Higgs trilinear coupling: hh → 4b

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

E [TeV]	$\mathscr{L}$ [ab^{-1}]	$N_{\rm rec}$	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%

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

What's the aspirational target?

Double Higgs production

- Reach on Higgs trilinear coupling: hh → 4b

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

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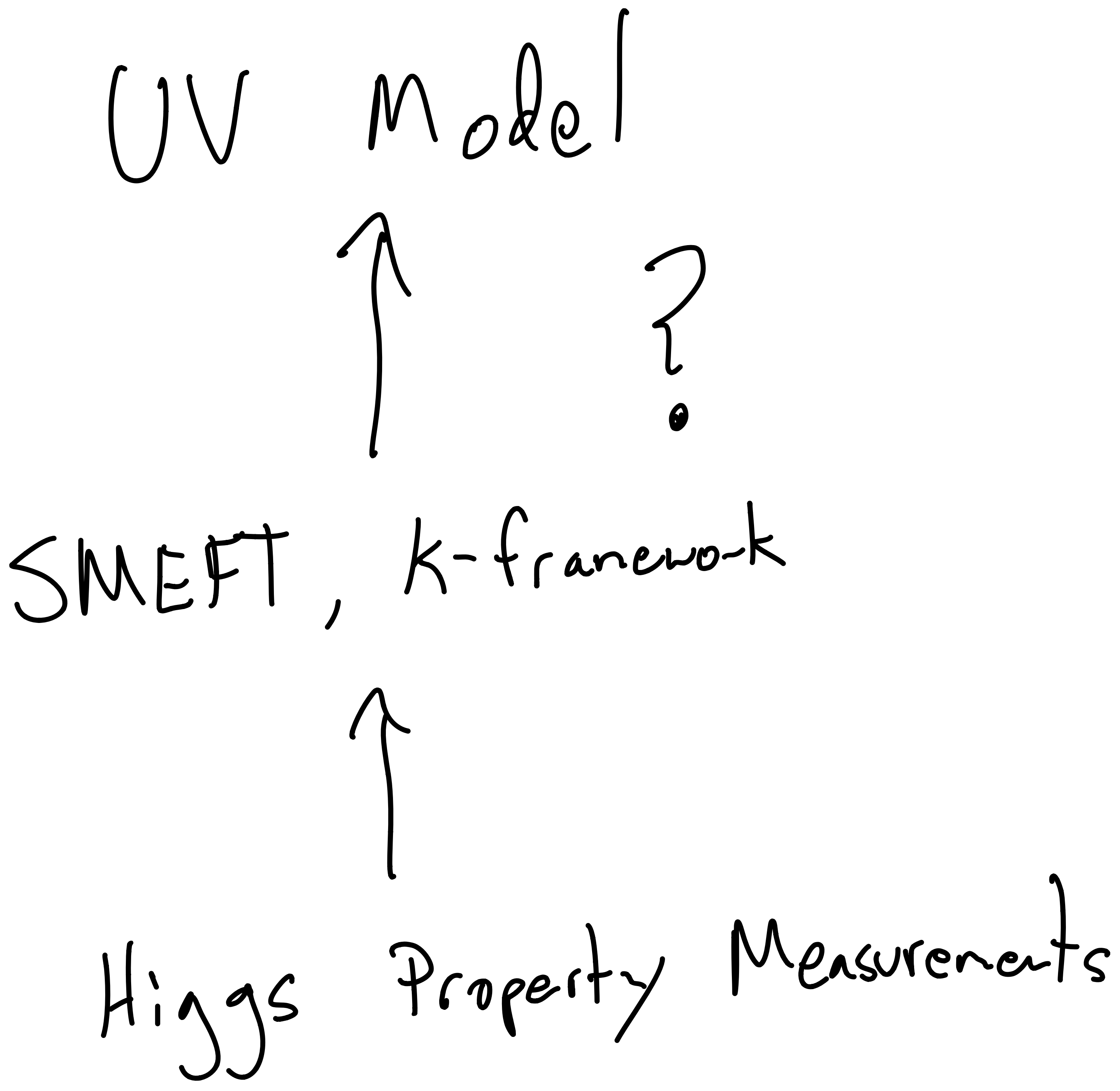
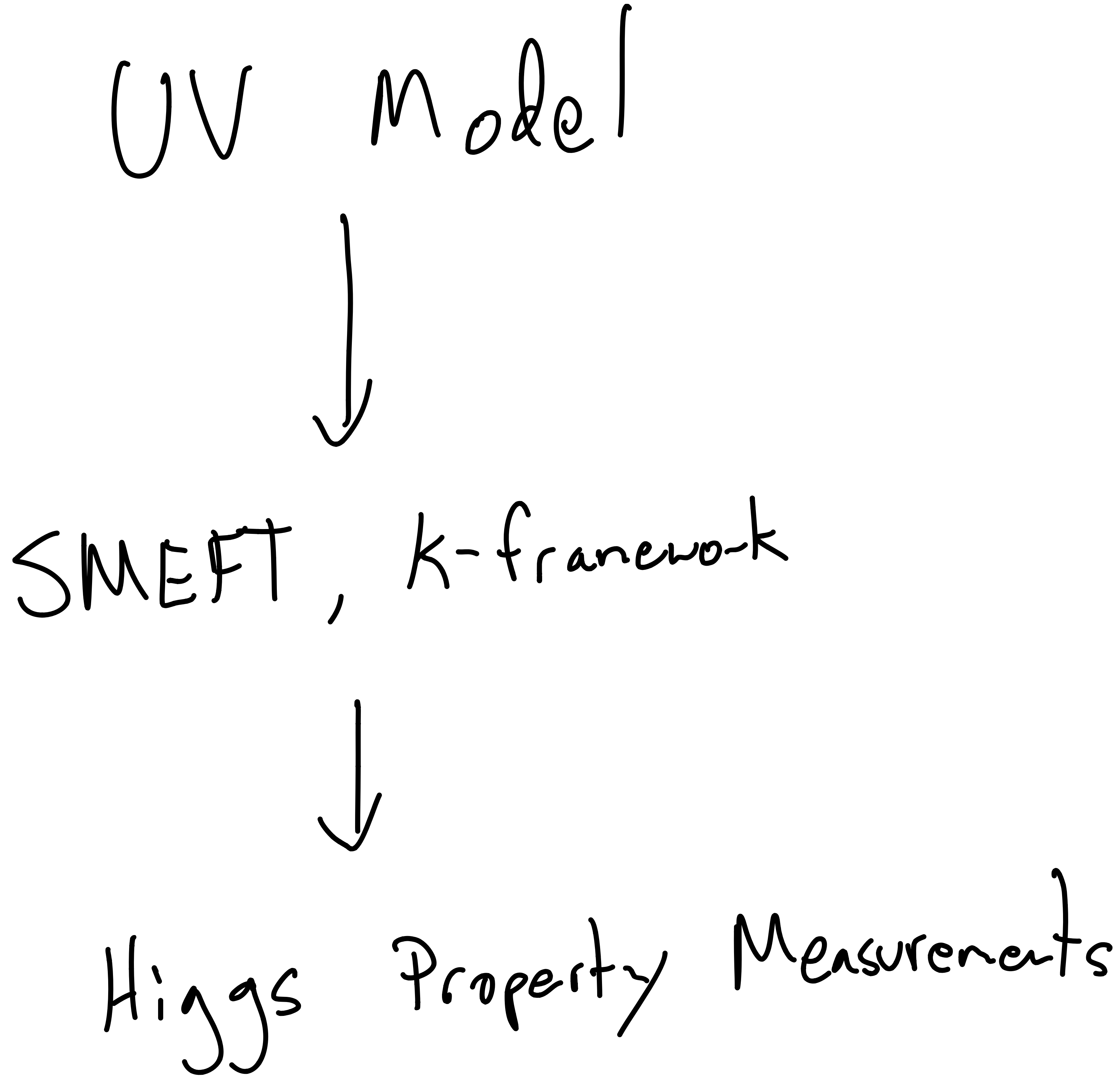
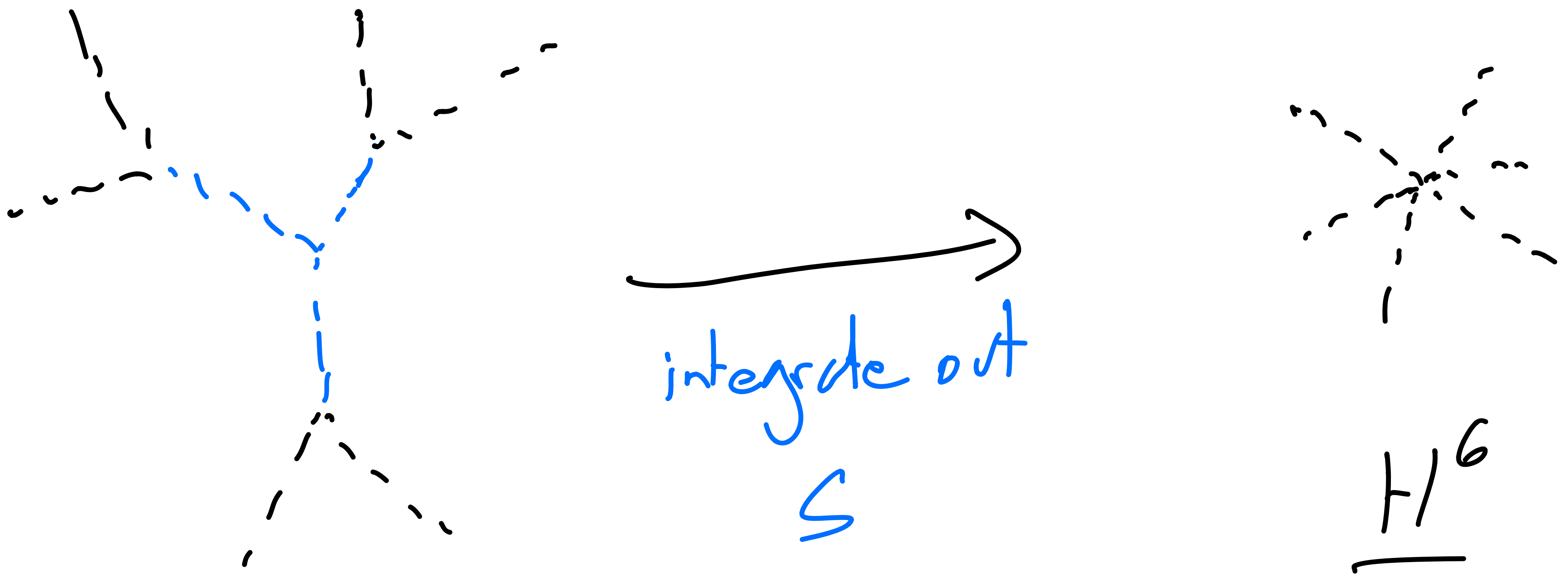
Or $\frac{H^6}{\Lambda^2}$

New physics is needed to *generate* these effects





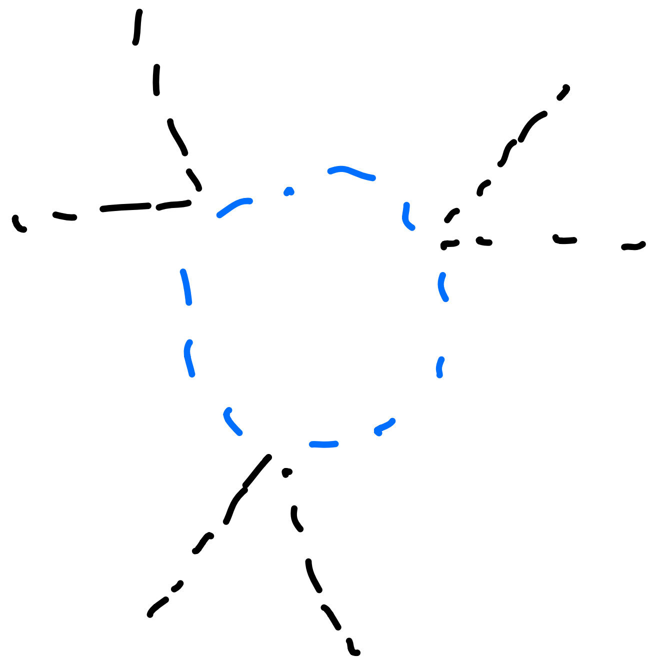


$$\frac{H^6}{\Lambda^2}$$

What is reach beyond LHC?

$H^2 S^2$ $\quad S^3$

$H^2 S$ $\quad S^4$



$H^2 S^2$

Loop-level

E.g. quartic we "know"

$$\delta\kappa_\lambda \sim 10^{-3}$$

Higgs Self Couplings
How well do we need to measure?

Strong First Order Phase Transition

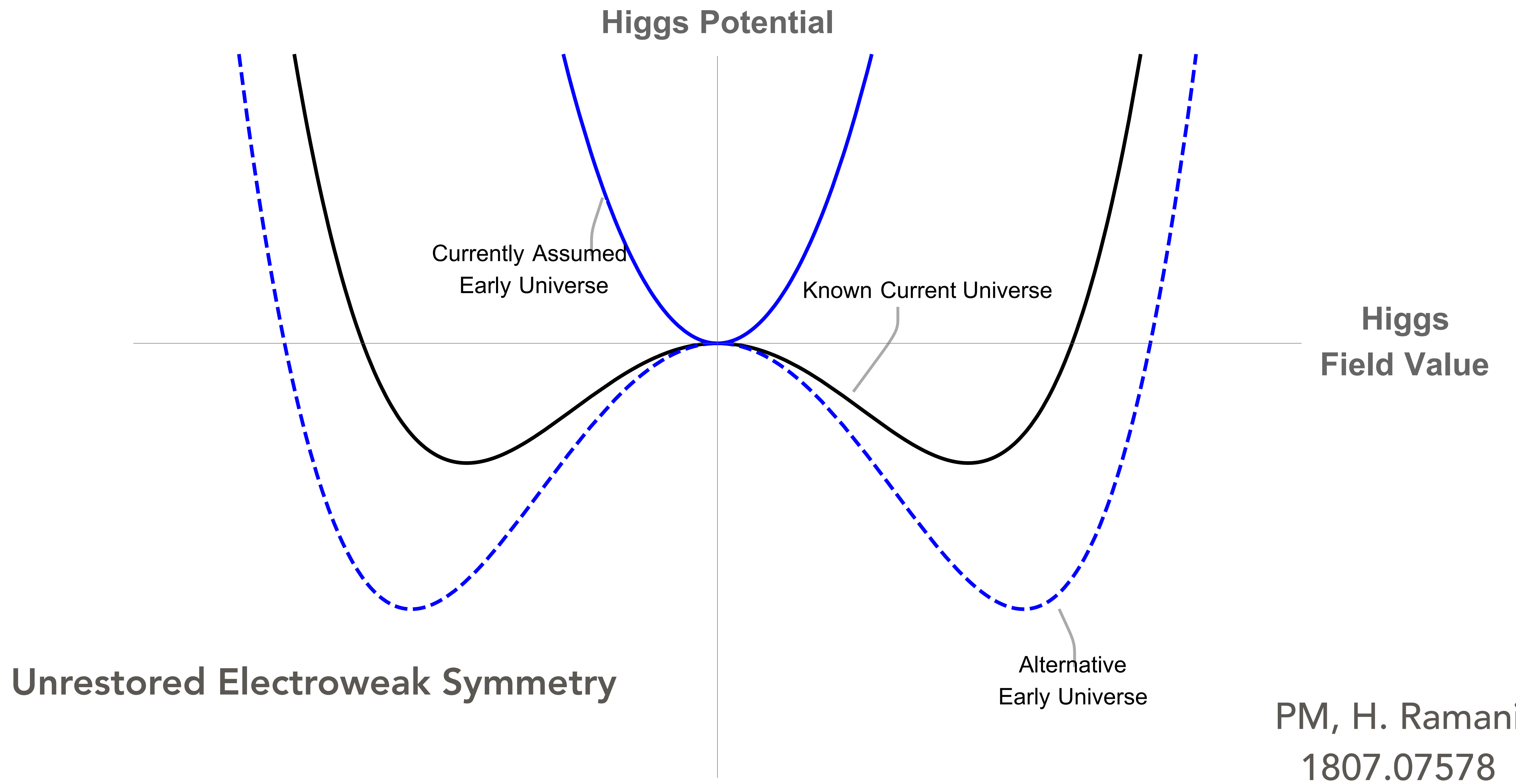
$$\delta\lambda_3 \gtrsim 10\%$$

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

SCALAR "EQUIVALENCE PRINCIPLE" (EP):

COUPLING ∝ MASS

to Higgs boson

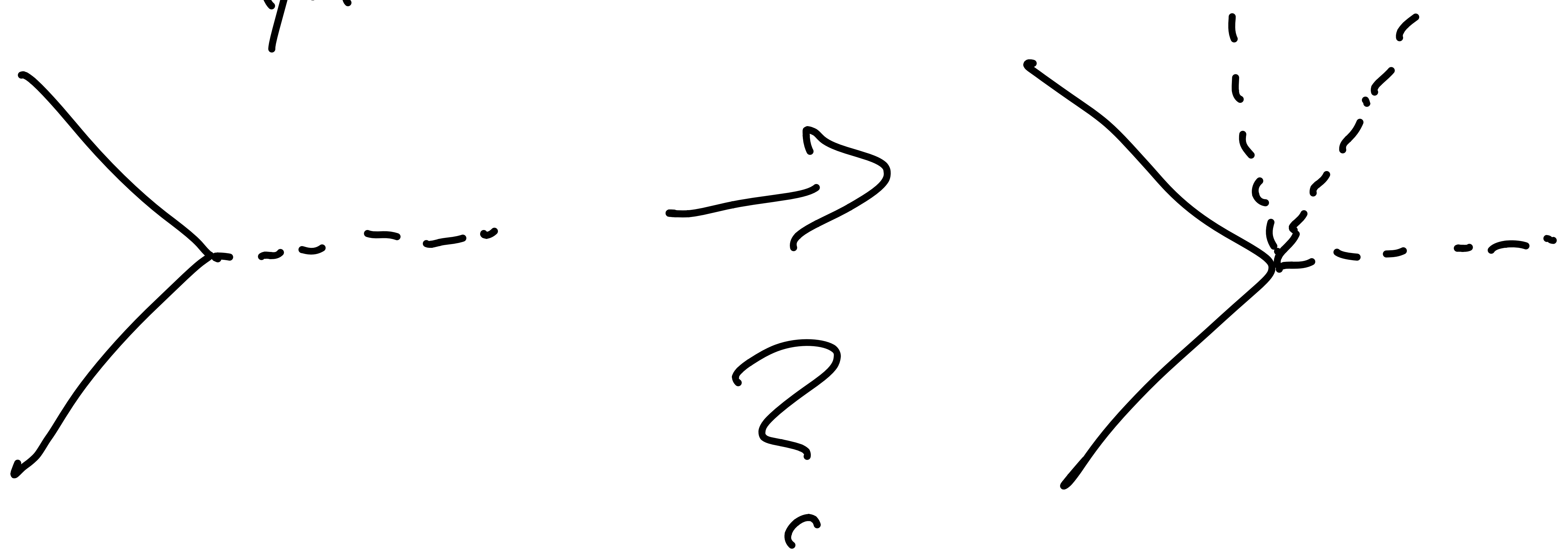
from Higgs Mechanism

+ QUANTUM CORRECTIONS

Really hard in 1st and 2nd gen

$H^2 Q H U$

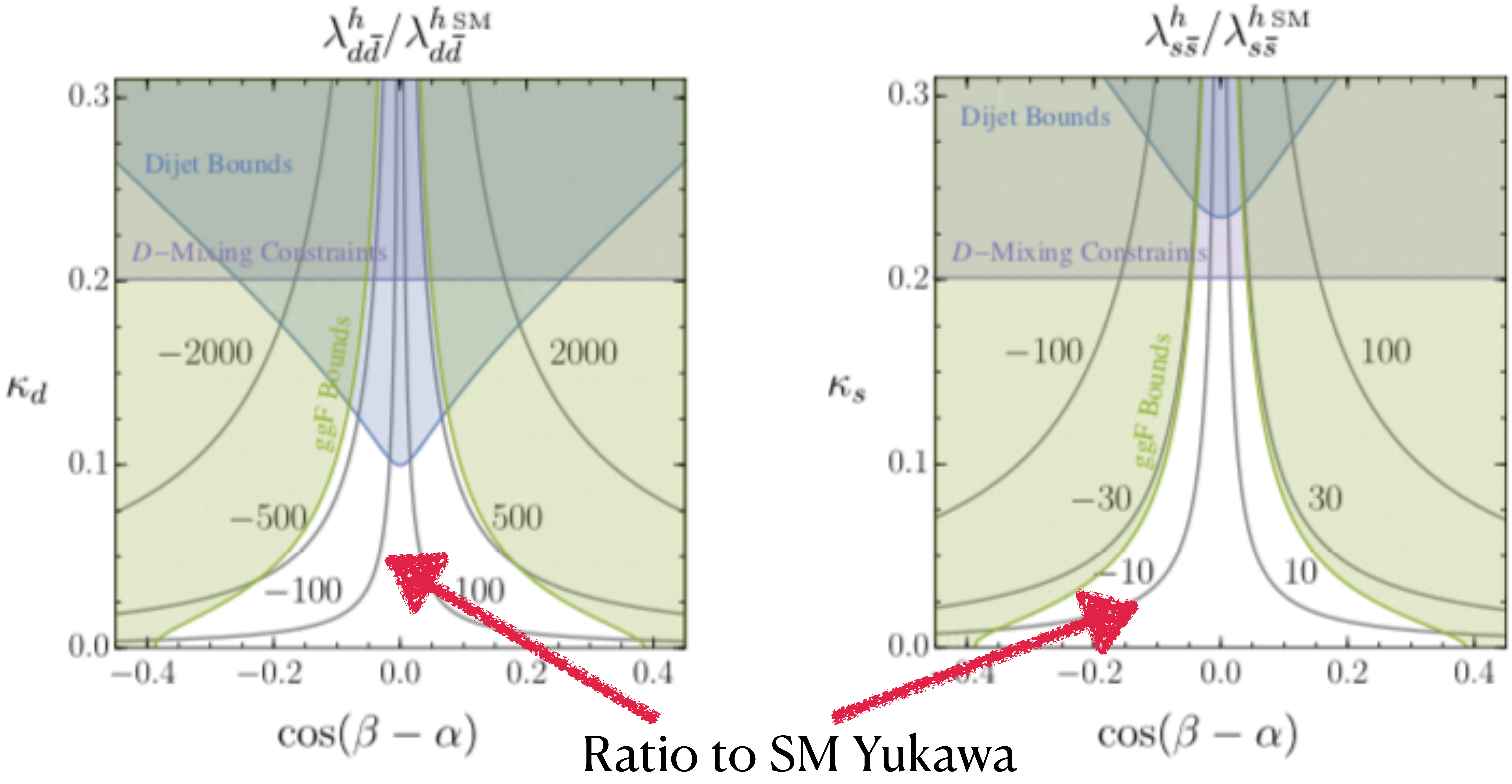
Yukawa



$H H'^3$ $H^3 H'$ $H' Q U$

1st and 2nd Gen Yukawa

Very difficult to measure but clean environment with lots of Higgses are what is needed!



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

But… There are now models with sizable enhancements!

Aspirational targets

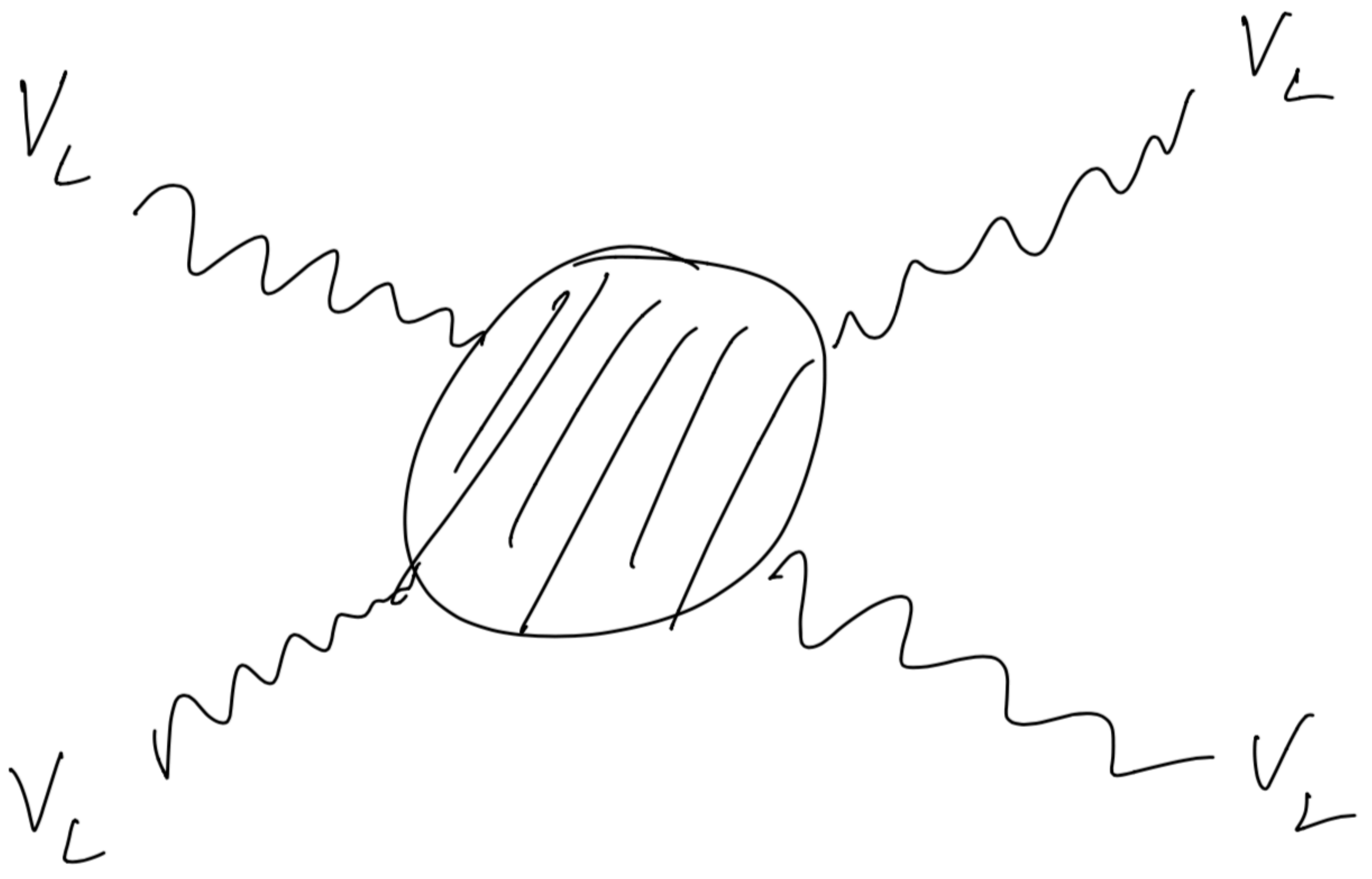
Observable/ Physics Driver/ Complementary Frontier Experiments	Scale or Precision Needed
EW Phase Transition	$\delta\lambda_3 \ll 1\%$
Higgs and Flavor	$\delta(y_u, y_d, y_s, y_e) \lesssim \mathcal{O}(1)$

Easiest place to get beyond LHC but also how far can the muon collider go?

Last but not least what can you do with high energies that is novel?

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... $y_t \mapsto y_t(1+\delta_{\rm BSM})$

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

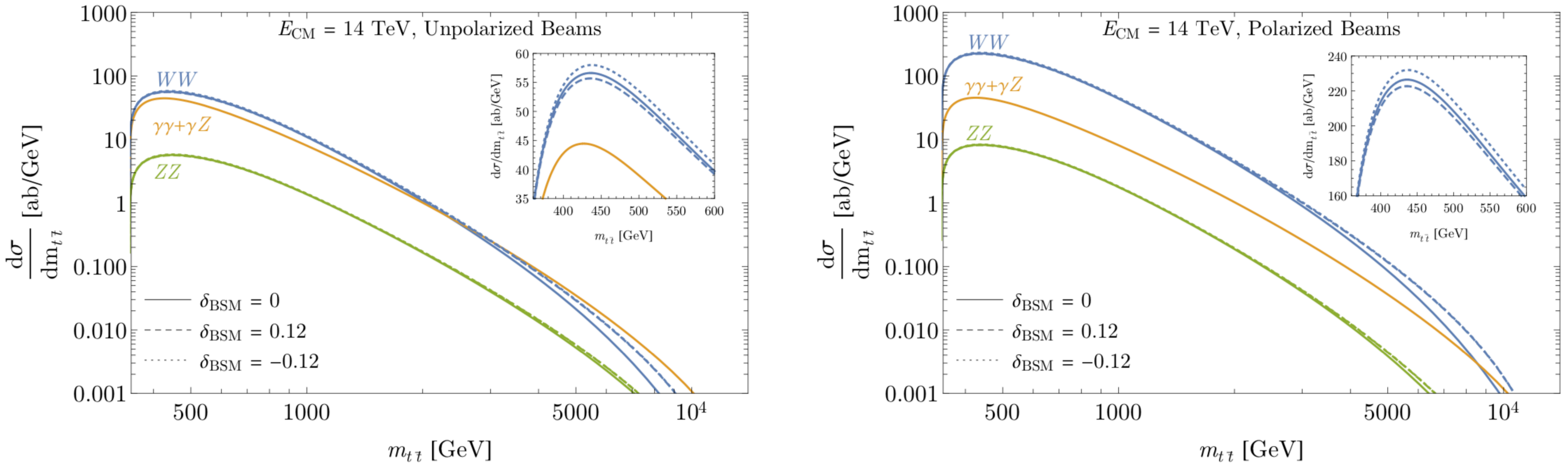


Figure 7: Differential cross section for $\mu^+\mu^- \to t\bar{t} + X$ from different gauge boson fusion processes at a 14 TeV muon collider, with unpolarized beams (left) or fully polarized (left-handed μ^- and right-handed μ^+) beams (right). At high energies, a deviation from the Standard Model top 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...

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

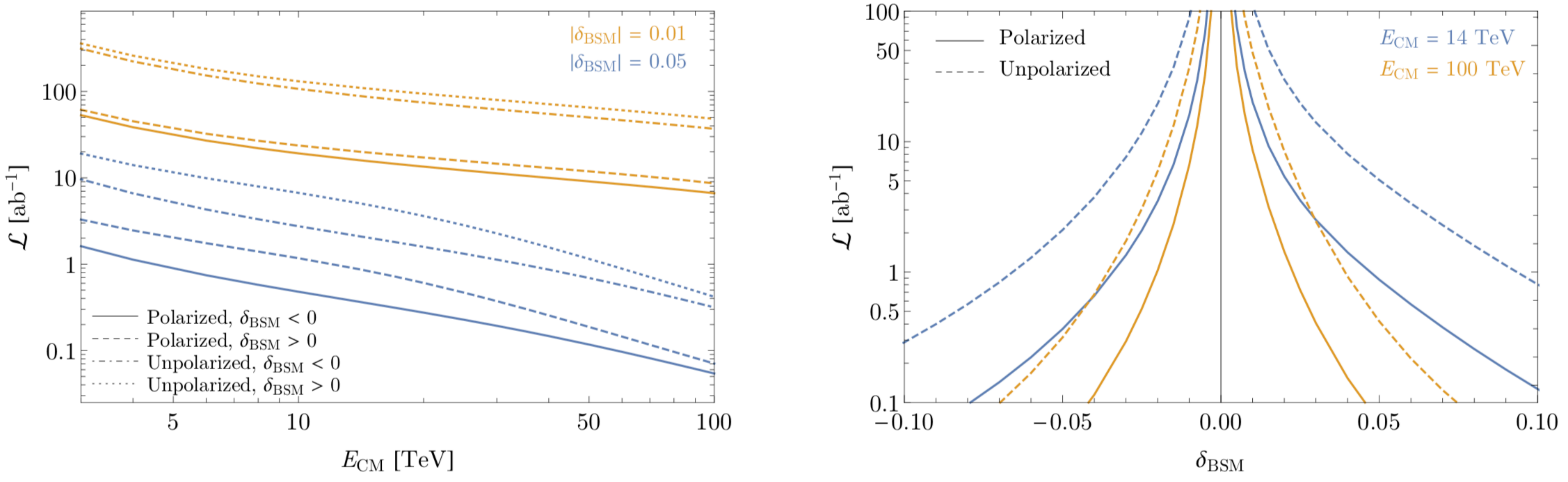


Figure 8: Luminosity needed to distinguish a modified top Yukawa coupling δ_{BSM} from the Standard Model at 2σ confidence, through the differential rate $d\sigma/dm^2_{t\bar{t}}$ of the process $\mu^+\mu^- \to t\bar{t} + X$.

Ok I’ll stop here but I’ve only scratched the surface, and remember the Higgs is the key!

Naturalness, EWSB, EWPT, future of universe, Flavor - all come back to Higgs!

Conclusions

- The muon collider is an incredible option for the Higgs
- What needs to be done
  - Backgrounds, Backgrounds, Backgrounds (PDFs)
  - Novel new studies available for off-shell properties, high p_T physics
- How much can the detector be optimized to really get flavor tagging down for light quarks?
- How much can the luminosity be increased?
- Can the muon collider be an all in one Higgs machine *or* is there a stronger case for ILC + muC in analogy with FCC ee/hh? Is there a better option Higgs physics wise?
- How do we actually finish measuring all the properties of the Higgs sufficiently for *current BSM theory? A: I have no clue…*