Higgs Couplings at a Muon Collider

Patrick Meade
YITP Stony Brook

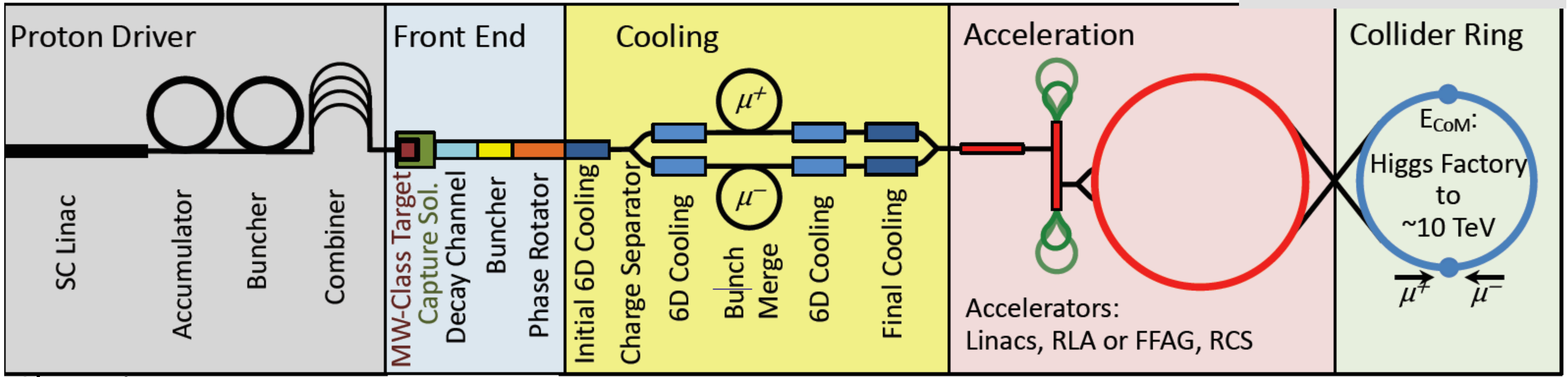
2203.09425, 2306.xxxxx w/ M. Forslund
IMCC + Snowmass Muon Collider Forum Reports

What is a Muon Collider?

Proton-driven Muon Collider Concept

Muon collider design is driven by finite muon lifetime

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Protons produce pions

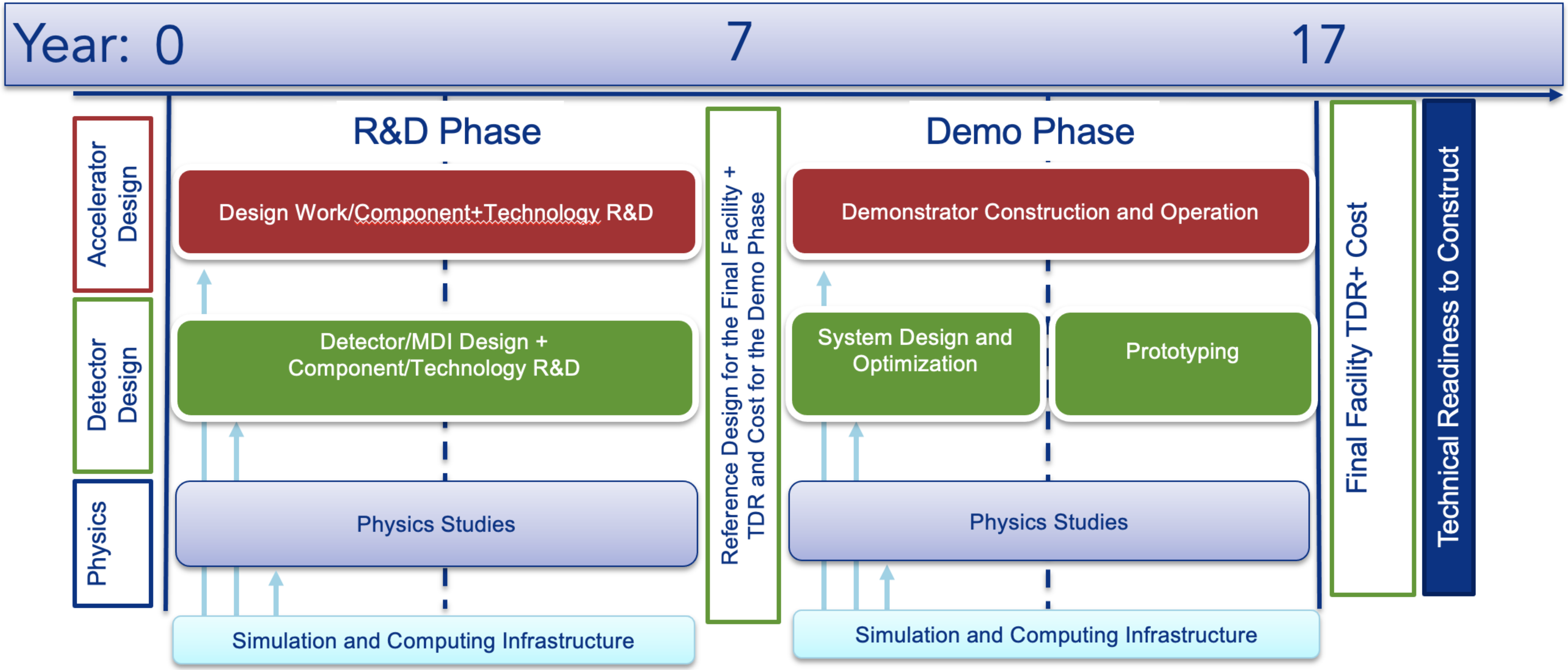
Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Collision

Collides fundamental particles, with high luminosity and high energy in the smallest footprint

Current Goal TDR by ~ 2040



Both CERN LDG and Snowmass process conclude *no show-stoppers* and this is doable with *sufficient* R&D funding (fingers crossed for P5 in US)

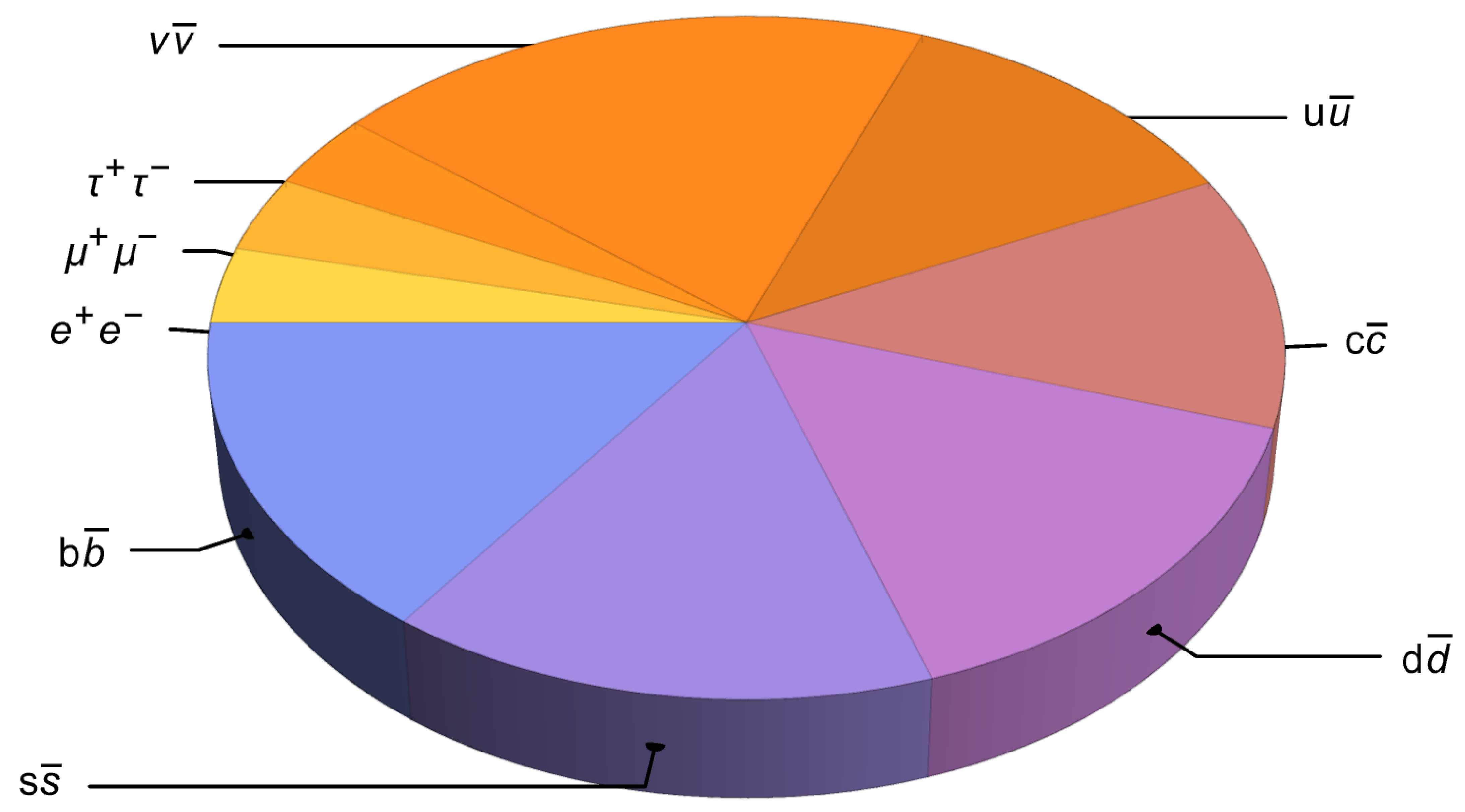
But why Muon Colliders and the Higgs? Don't we have perfectly good Higgs Factory proposals?

The SM Higgs is an unprecedented particle.

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

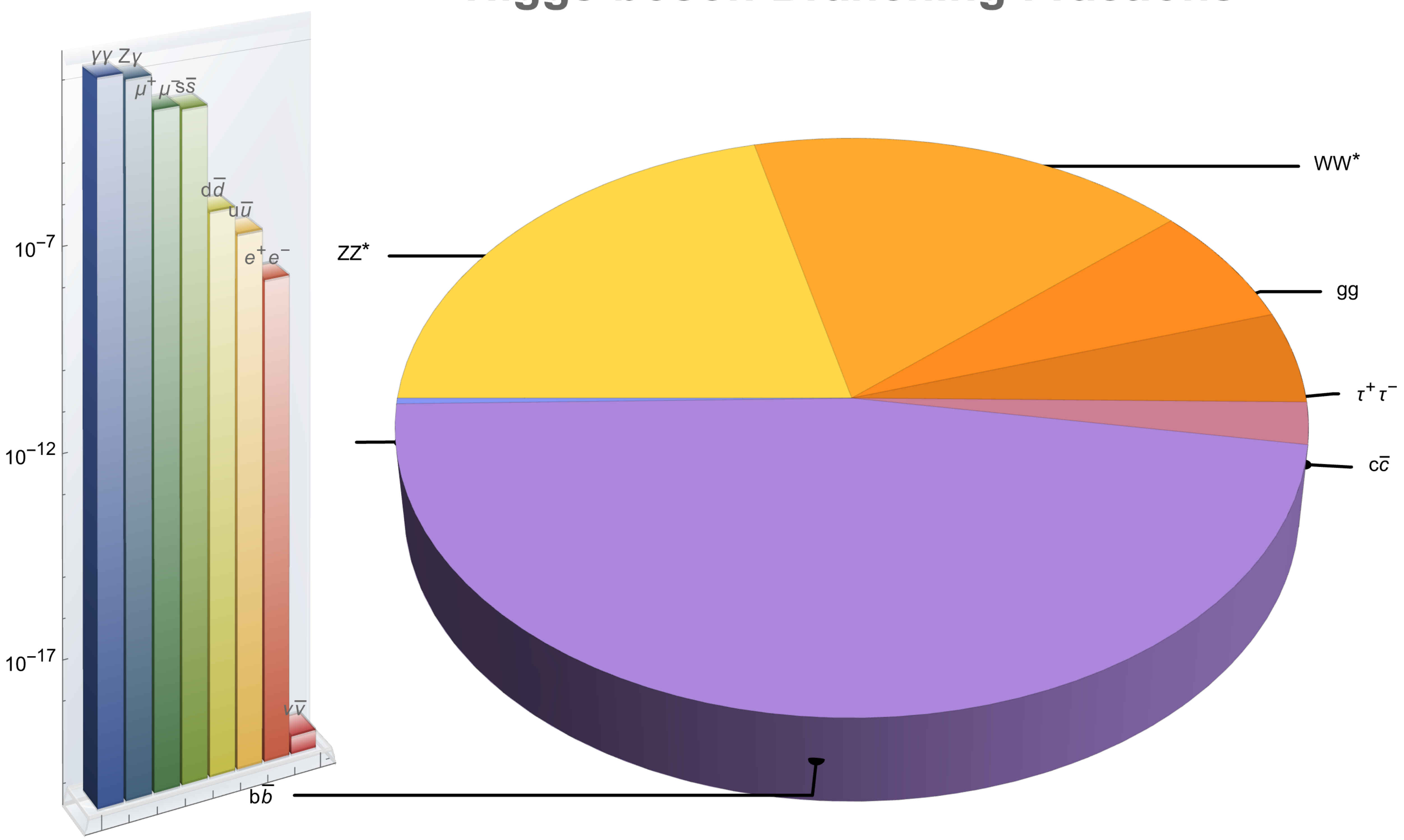
Higgs Factories produce ~ 1 Million Higgs bosons

Z boson Branching Fractions



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

Higgs boson Branching Fractions



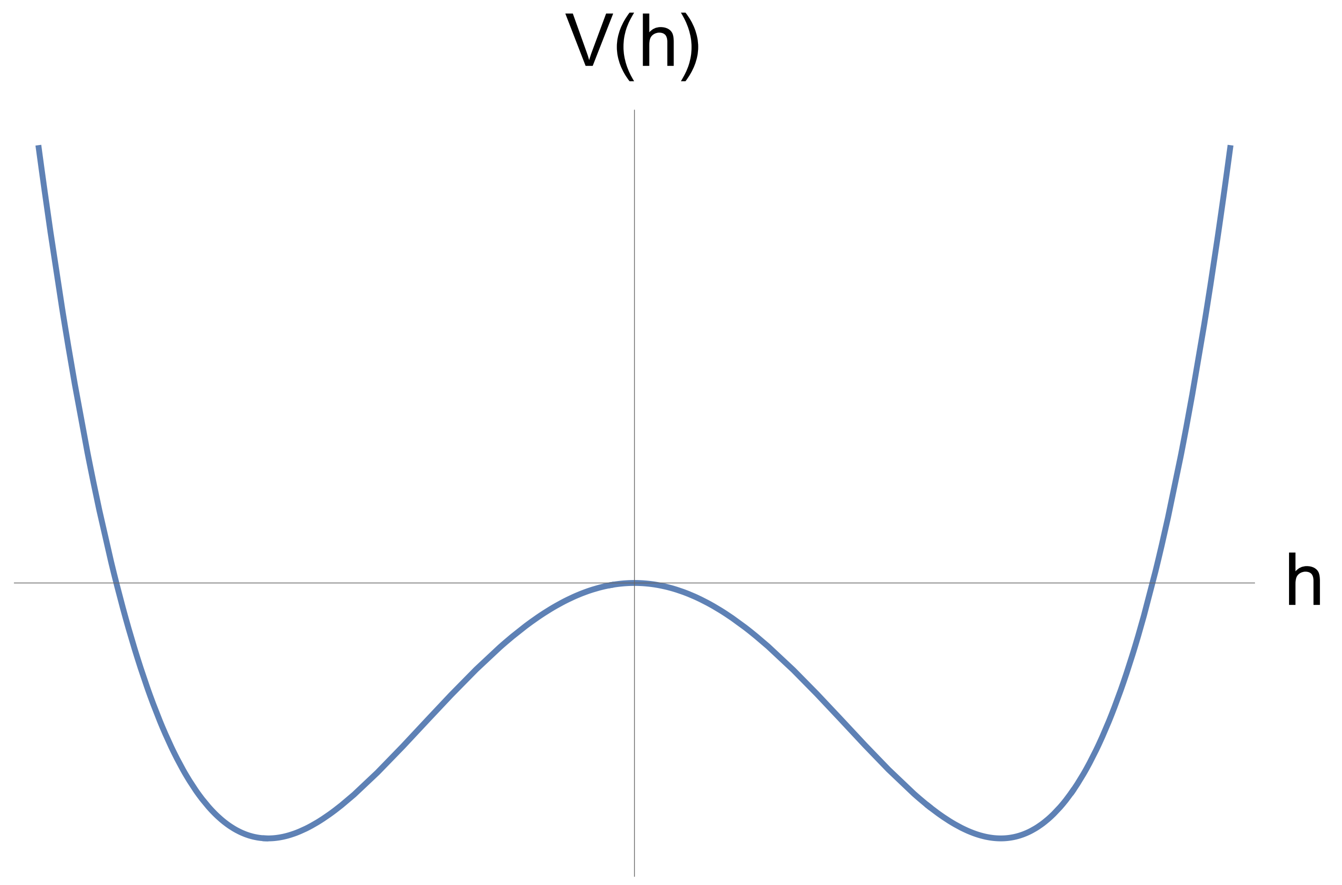
The *same* Higgs Branching Fractions span 8 to 20 ORDERS OF MAGNITUDE or more!

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!

Why does this matter?

Testing the Higgs potential experimentally



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

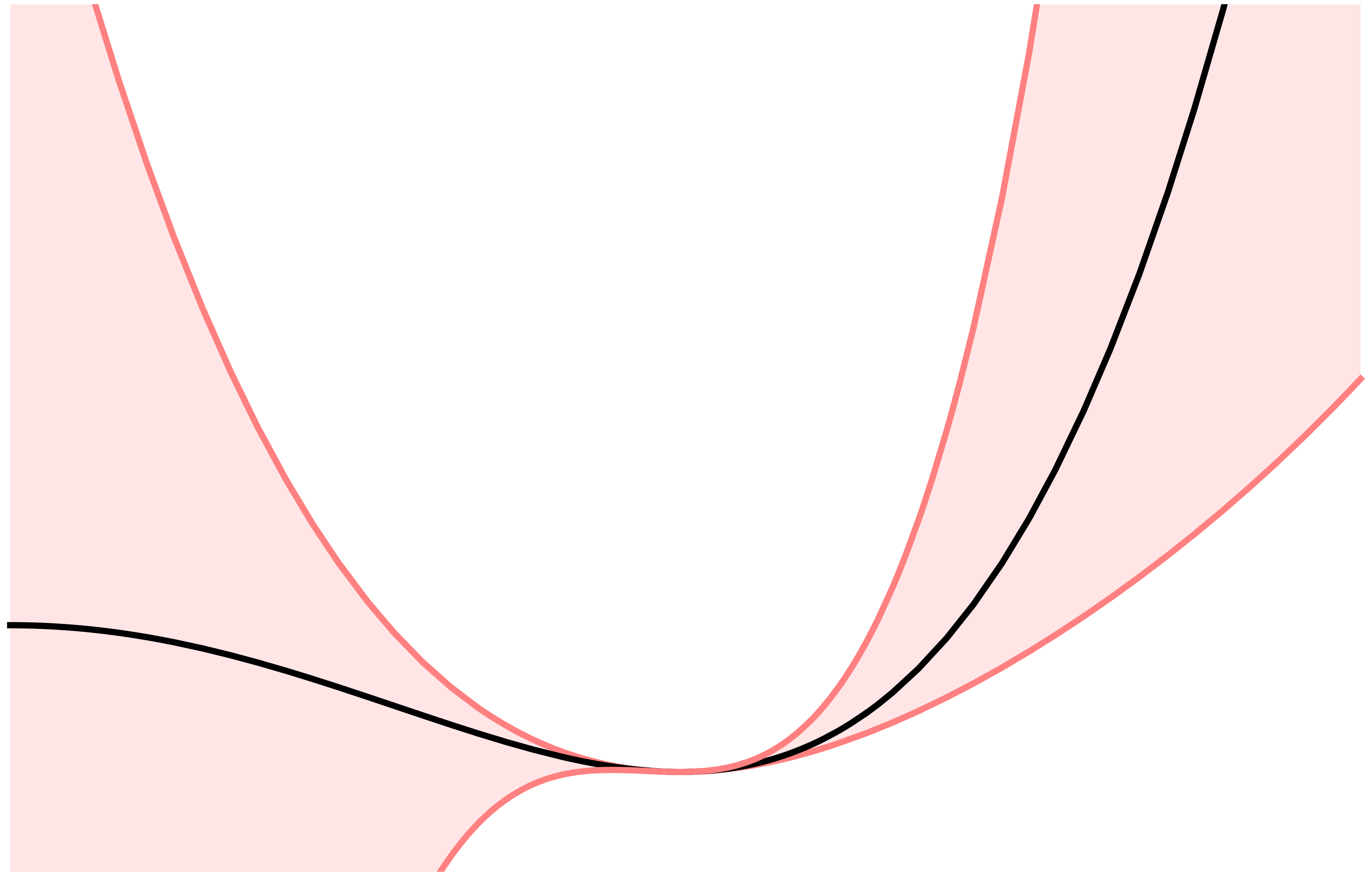
$$\left.\frac{\partial^2 V(h)}{\partial h^2}\right|_{h=v} = m_h^2$$

+ 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?

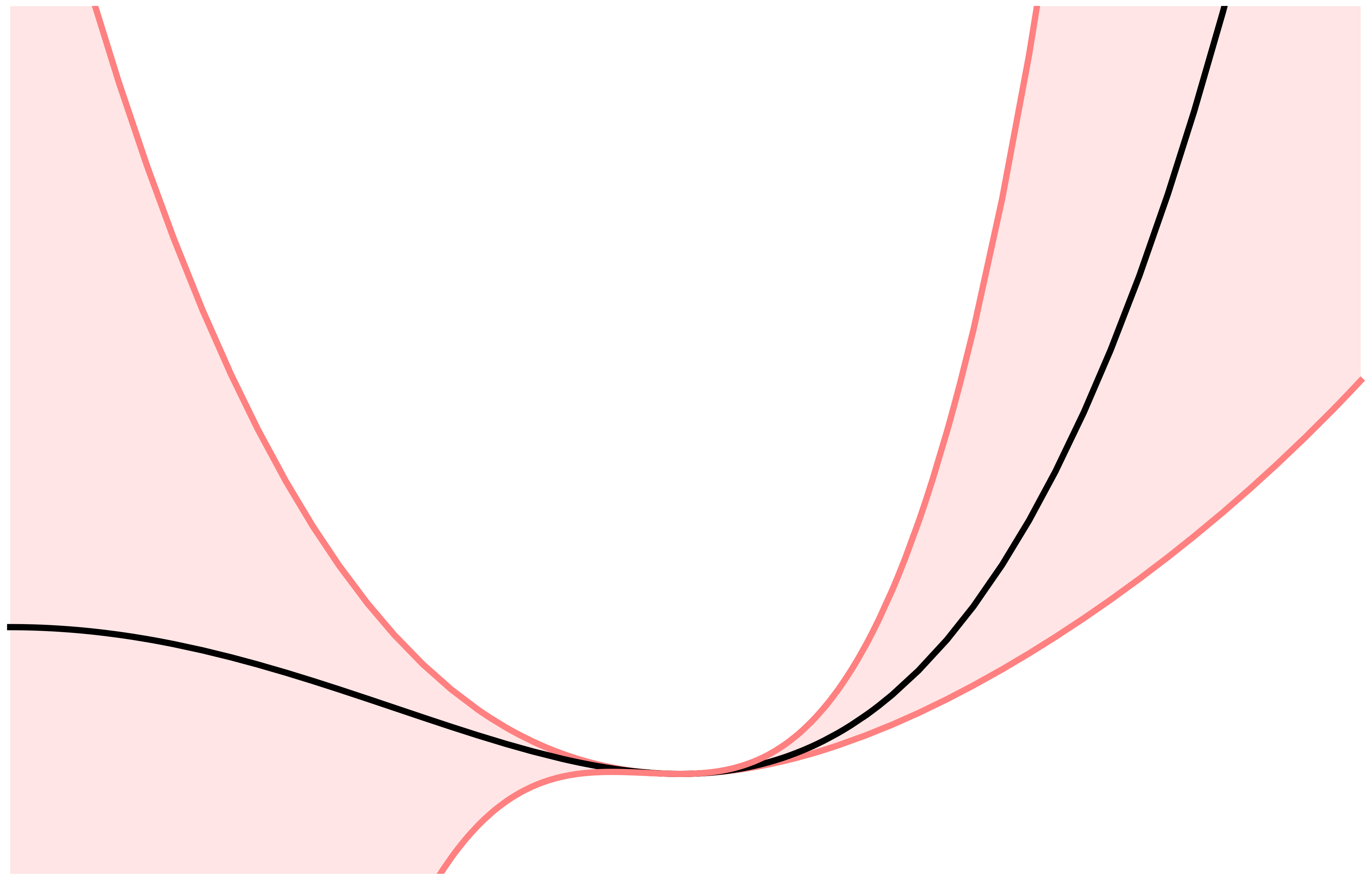


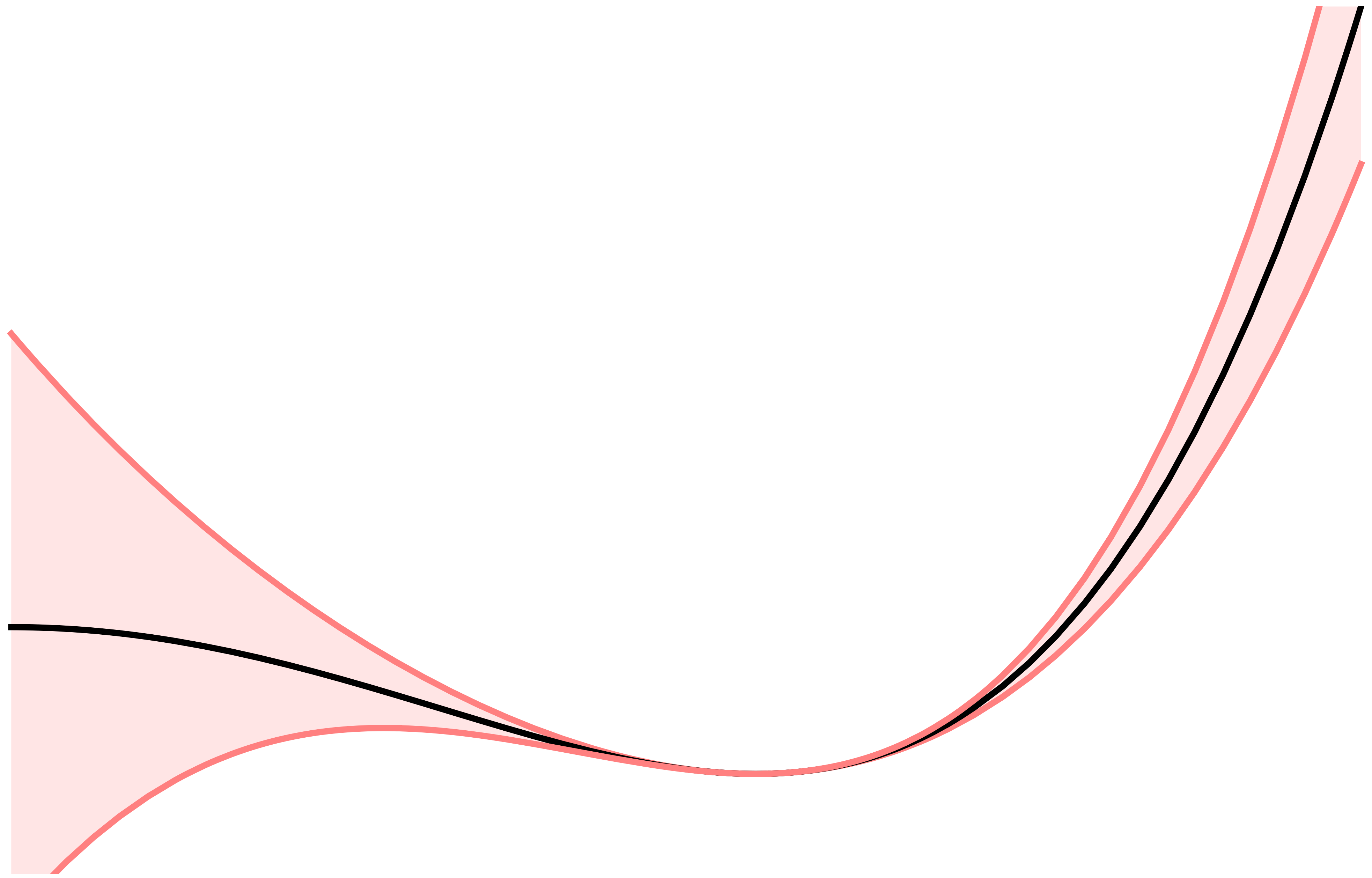
H/T N.Craig, R. Petrossian-Byrne

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

Current status of LHC Higgs Potential Measurements?





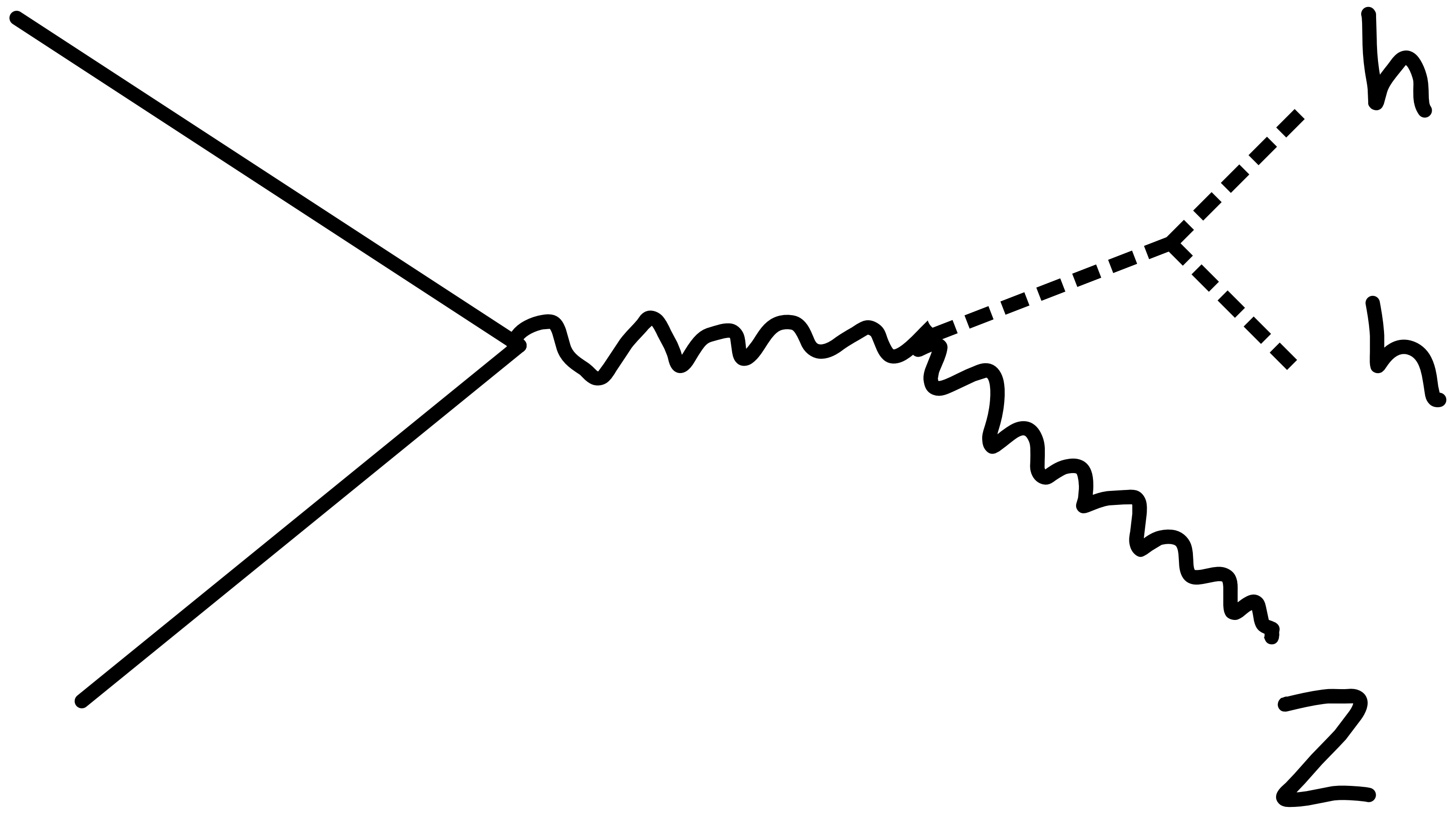
H/T N.Craig, R. Petrossian-Byrne

Current LHC → **HL-LHC**

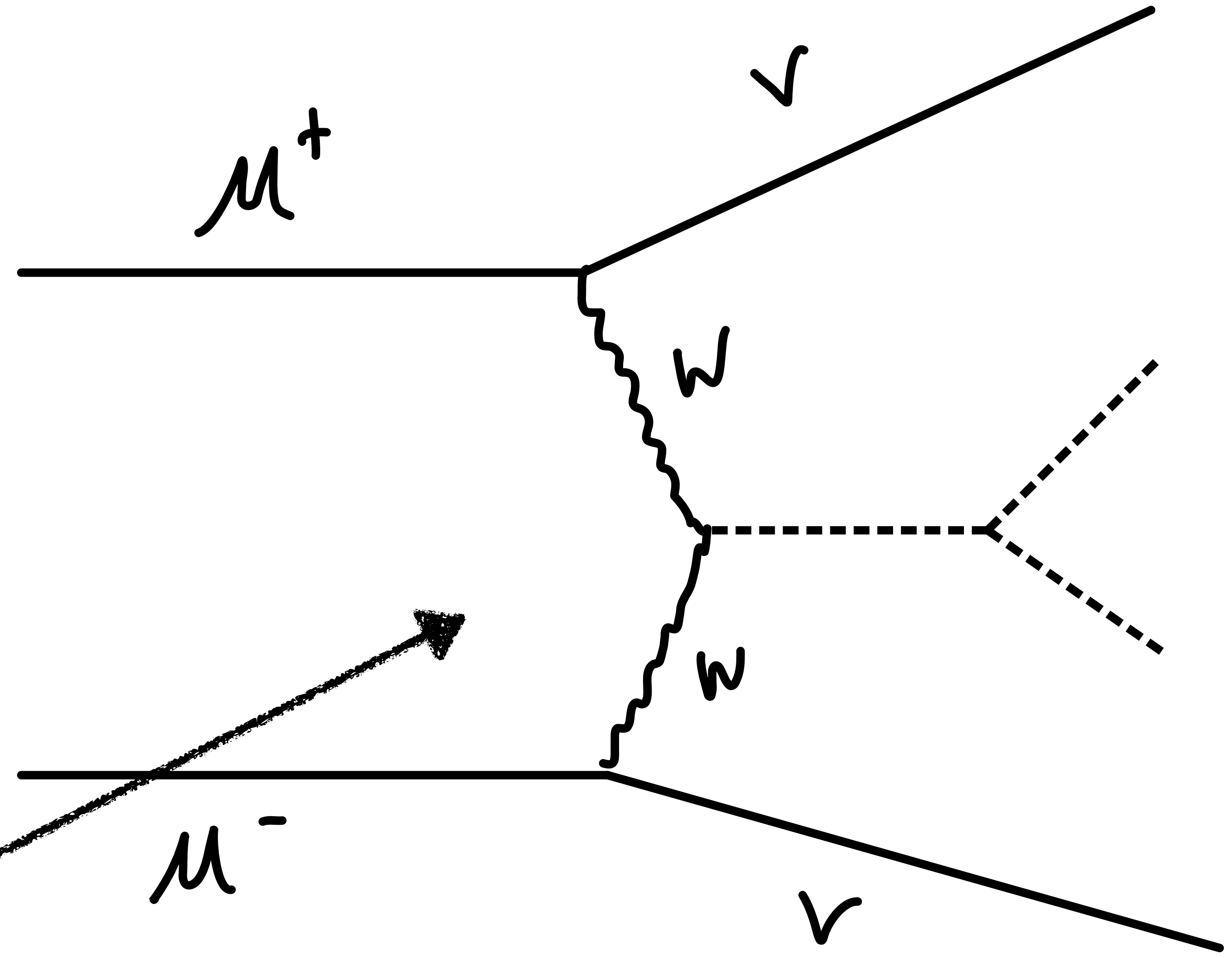
Why does Energy help with the Higgs?

First way:
Energy helps make more Higgs (and multi-Higgs)

Muon colliders are *also* gauge boson colliders!



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

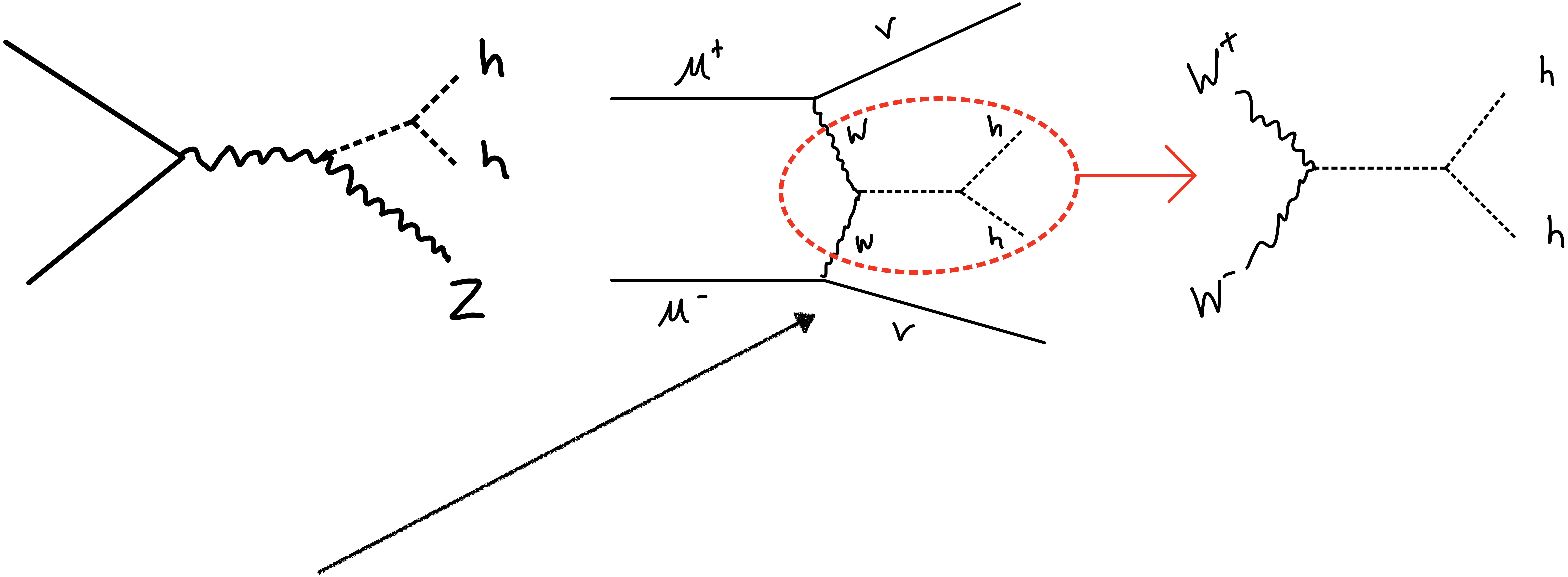


$\sim \log^2 E^2$

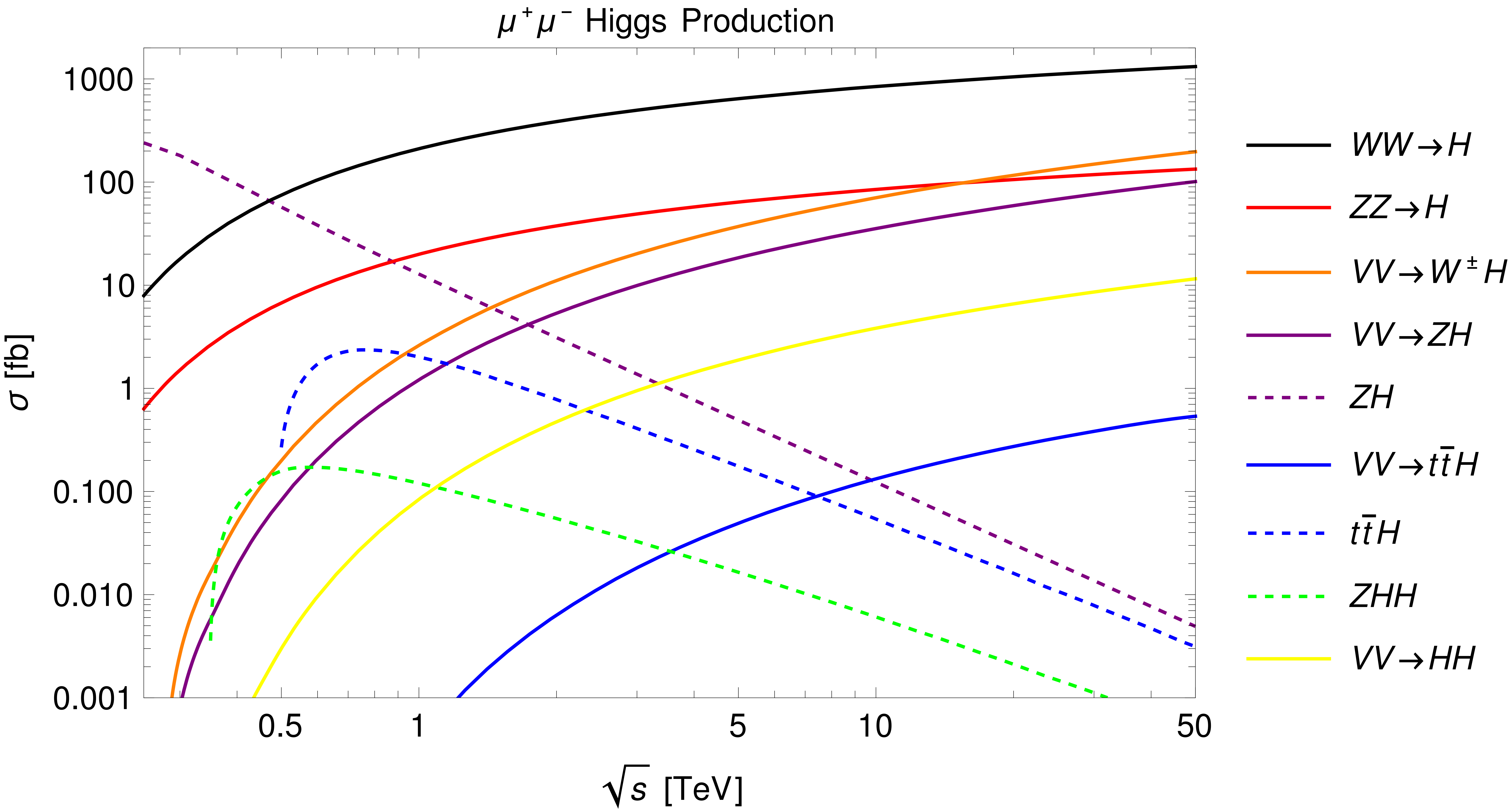
Winner at moderate energies!

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

Muon colliders are *also* gauge boson colliders!



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



Benchmarks in this talk will be using 10 TeV w 10/ab (5 yr run @ design luminosity)

How Many Higgs??

Take this with many grains of salt...

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 factorie
~ few million Higgs

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

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

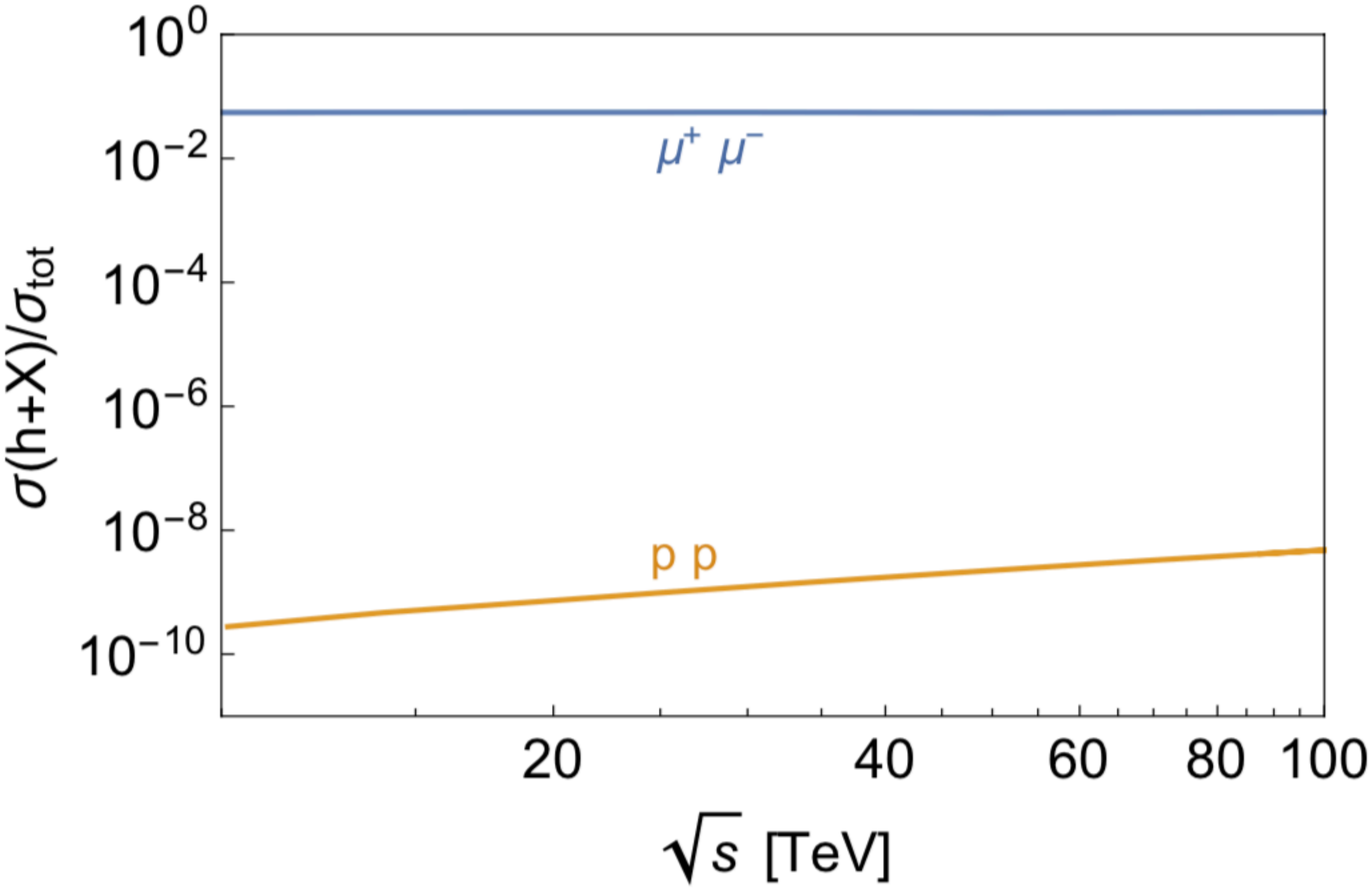
Muon Colliders

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 $\sim .18 \times 10^9$

10s to 100s of millions of Higgs

A Muon Collider gives a great balance of more Higgs, multi-Higgs *and* low backgrounds

If this enhancement is done with “fundamental” particles



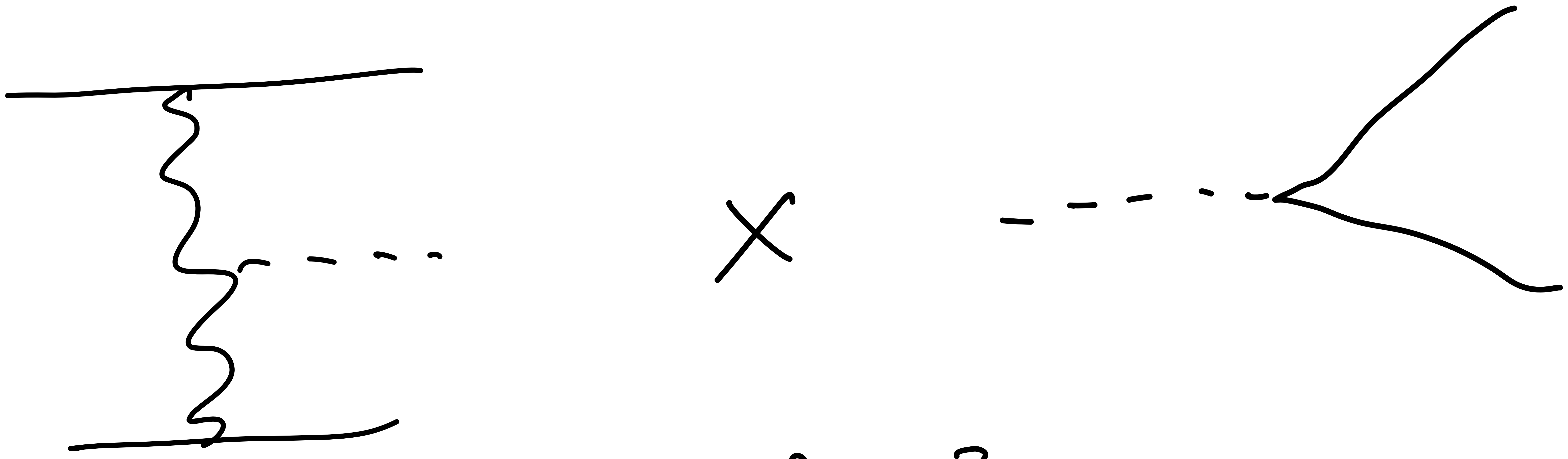
You can get an enhanced S/B too!

Blurring the Precision versus Energy Dichotomy!

Second way:
Energy allows one to probe the Higgs in *multiple* ways

How do we quantify Higgs precision

Kappa fits, EFTs, what else?



$$\sigma \cdot B \sim \kappa_W^2 \frac{\kappa_b^2}{\Gamma}$$

What precision we measure an individual channel in can then be combined *based on theoretical assumptions*

Typically results in things that look like this

ESG run plans 1905.03764

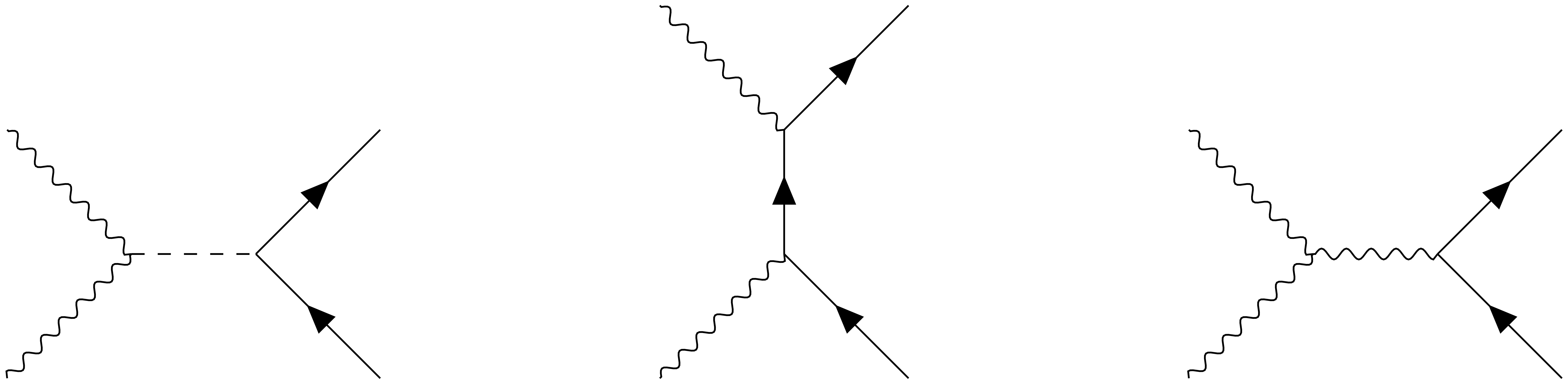
kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	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⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	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⋆	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

In this case the assumption is no *new* channels beyond the SM can contribute to the Higgs width

With Energy we get new observables

$$W^+W^- \to t\bar{t}$$

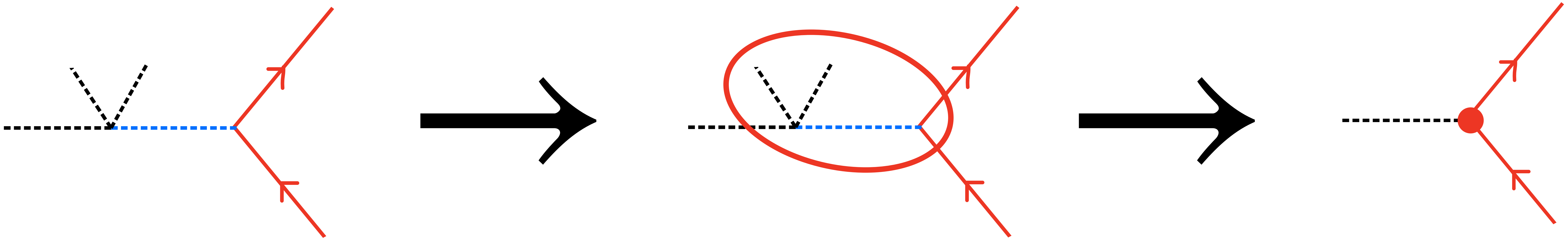
H. Al Ali et al 2103.14043
M. Chen, D. Liu 2212.11067
Z. Liu et al WIP



The SM is a *delicate* structure, modification of couplings leads to modifications of amplitudes with deviations that grow with energy

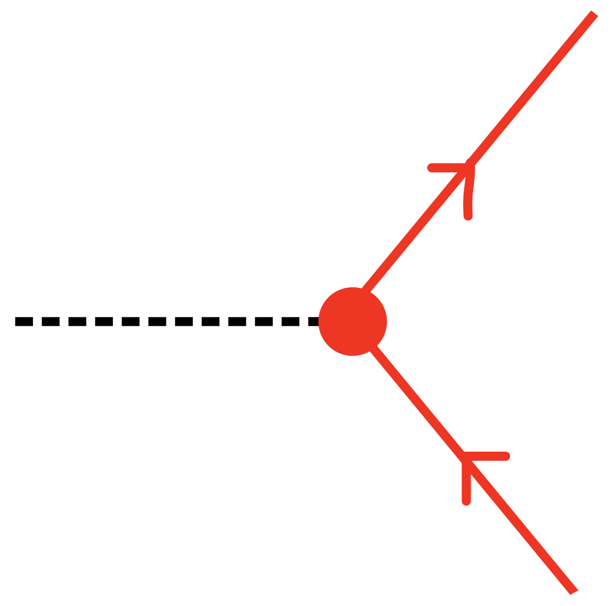
At a Muon Collider you can probe Higgs multiple ways with Energy!

Why do we care about precision? To *find* new physics



$$\text{UV model} \rightarrow \frac{1}{\Lambda^2}\bar{f}_L H f_R H^2 \rightarrow k_f \sim \frac{v^2}{M_{NP}^2}$$

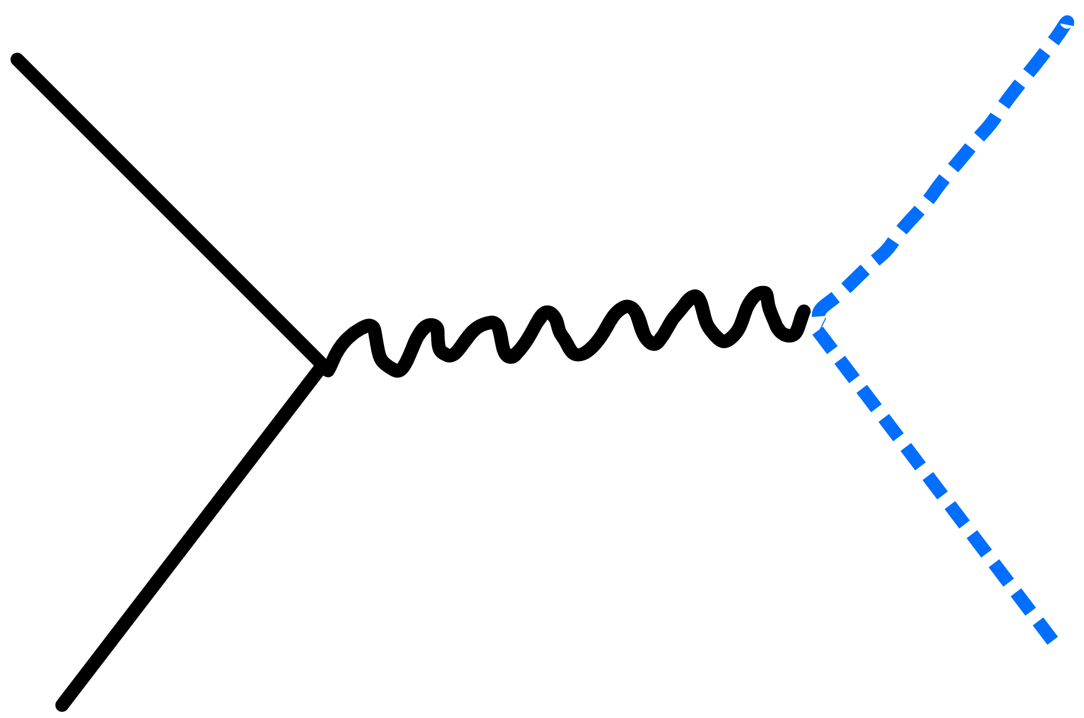
At a Muon Collider you can probe Higgs multiple ways with Energy!



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

$1\,\%$ Higgs Precision $\implies M_{NP} \lesssim 1$ TeV

Dimensionless couplings $\lesssim 1$



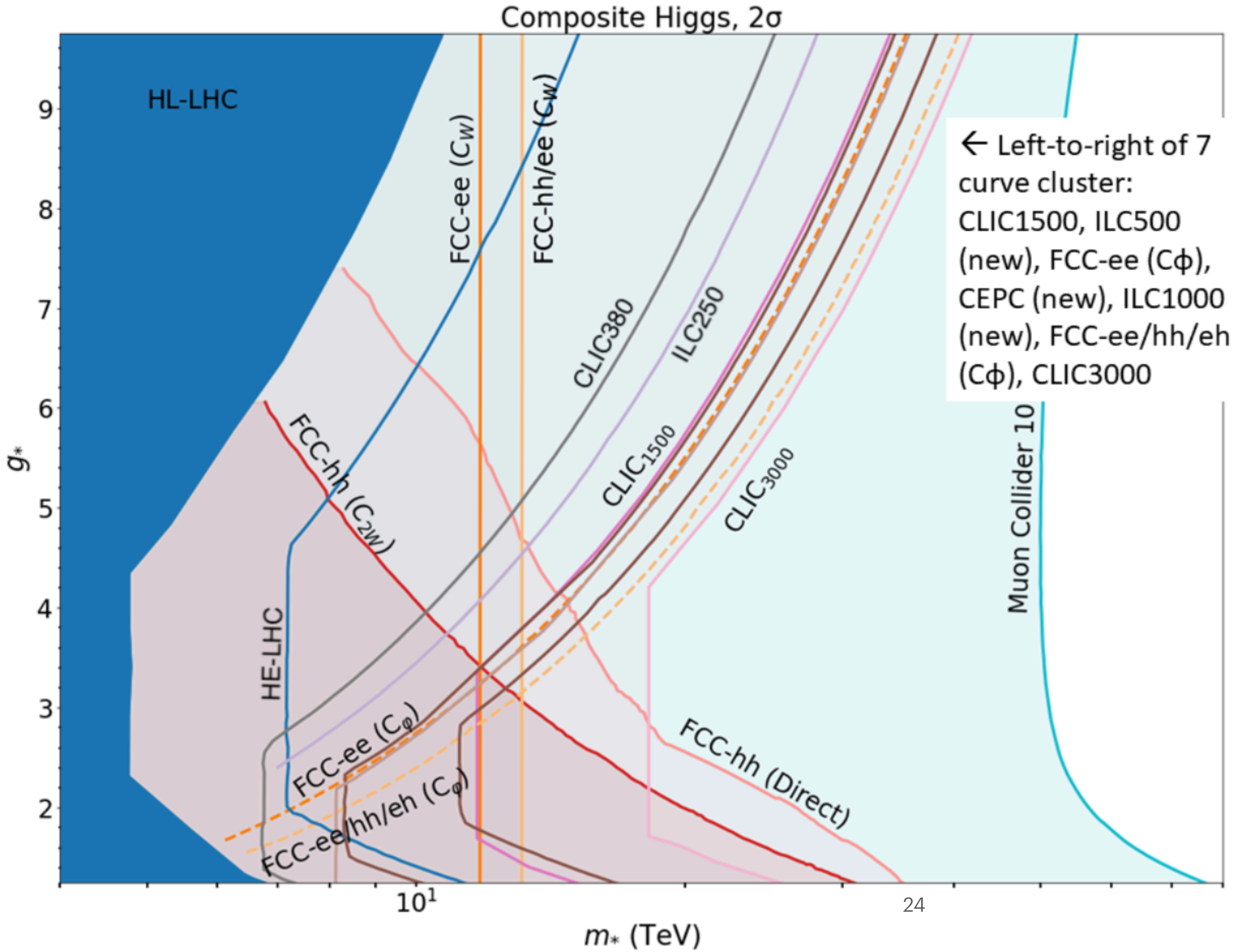
Produce the new states that can *cause* Higgs deviations at the same time!

No need to build separate colliders e.g.

Factory→Discovery machine

You *could* do it all in one with a Muon collider!

Can you escape this conclusion with strong coupling?



Sure… but a MuC turns out to be ideally suited to search for this as well!

So with all that being said, what do we get for Higgs precision at a Muon Collider?

What has gone into the studies

- Signal and Background fast simulation with muon collider DELPHES card
  - Hard Physics backgrounds - included
  - Beam in Beam (BIB) Background not included
    - DELPHES fast sim compared against full simulation with BIB at 3 TeV and found to give consistent results
  - Collinear backgrounds not fully included but small
  - Results I will show assume you can tag forward muons (to discriminate ZBF from WBF)
  - $WW \to t\bar{t}$ included for top Yukawa
- Signal strengths calculated and then various different theoretical interpretation run

European strategy update
de Blas et al
1905.03764

Higgs Precision Physics

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

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, *μ*Col numbers didn't *exist* at the time of last European Strategy Update

High energy implies one can *also* test origin of deviations simultaneously - new formalism needed and not fully exploited here

Other interpretations

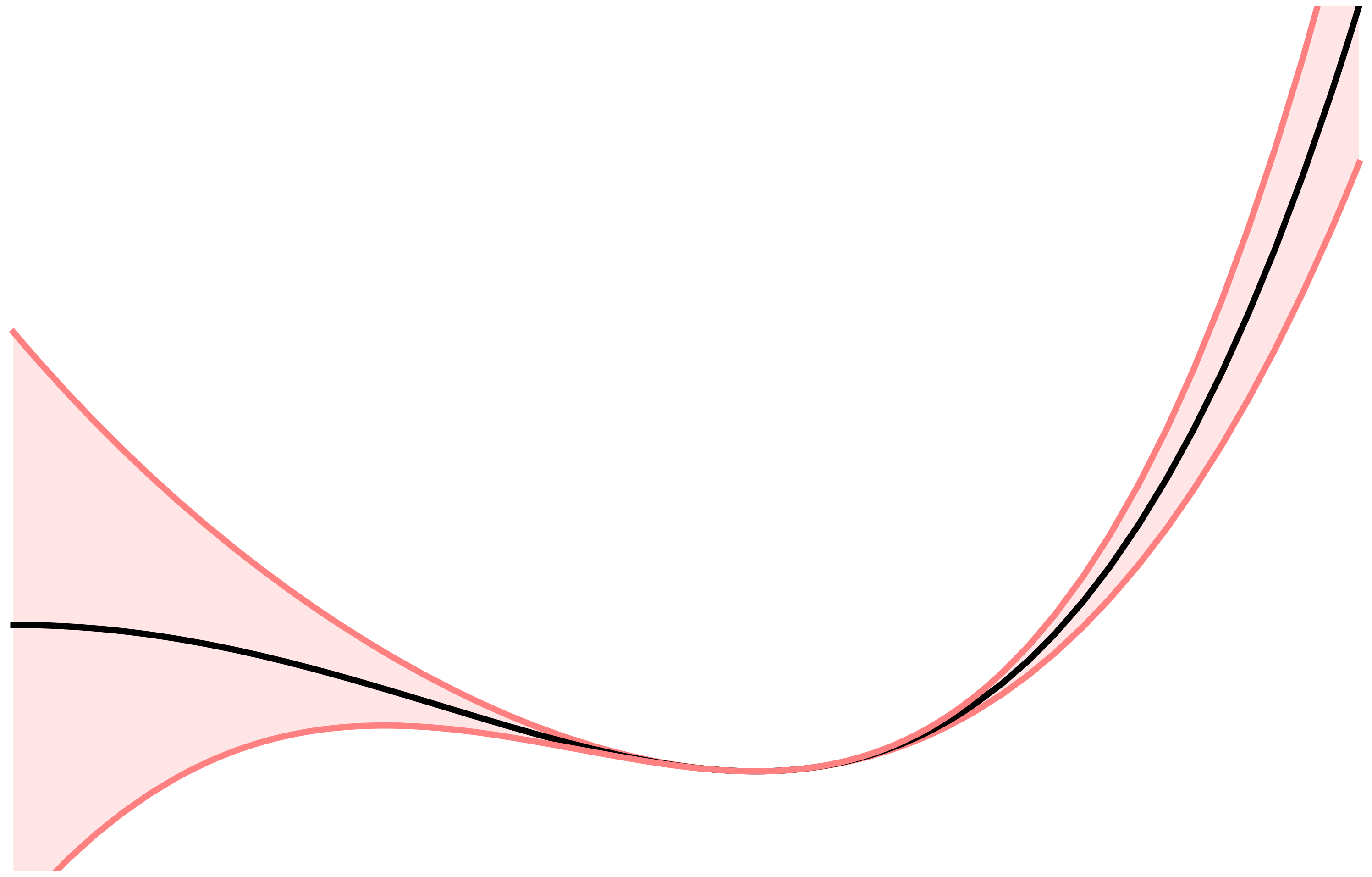
- Can of course be recast in terms of EFT coefficients (see IMCC and muC forum for slightly outdated plots)
- What about if you let the Higgs width vary?
  - Notorious flat direction by letting SM couplings increase and adding a new contribution to the Higgs width
    - Can break this degeneracy with an e+e- Higgs factory *or* a 125 GeV muC
    - Can *also* break this degeneracy with a 10 TeV muon collider exploiting $VV \to VV$ scattering and direct search constraints

M. Forslund, PM. 2306.XXXXX

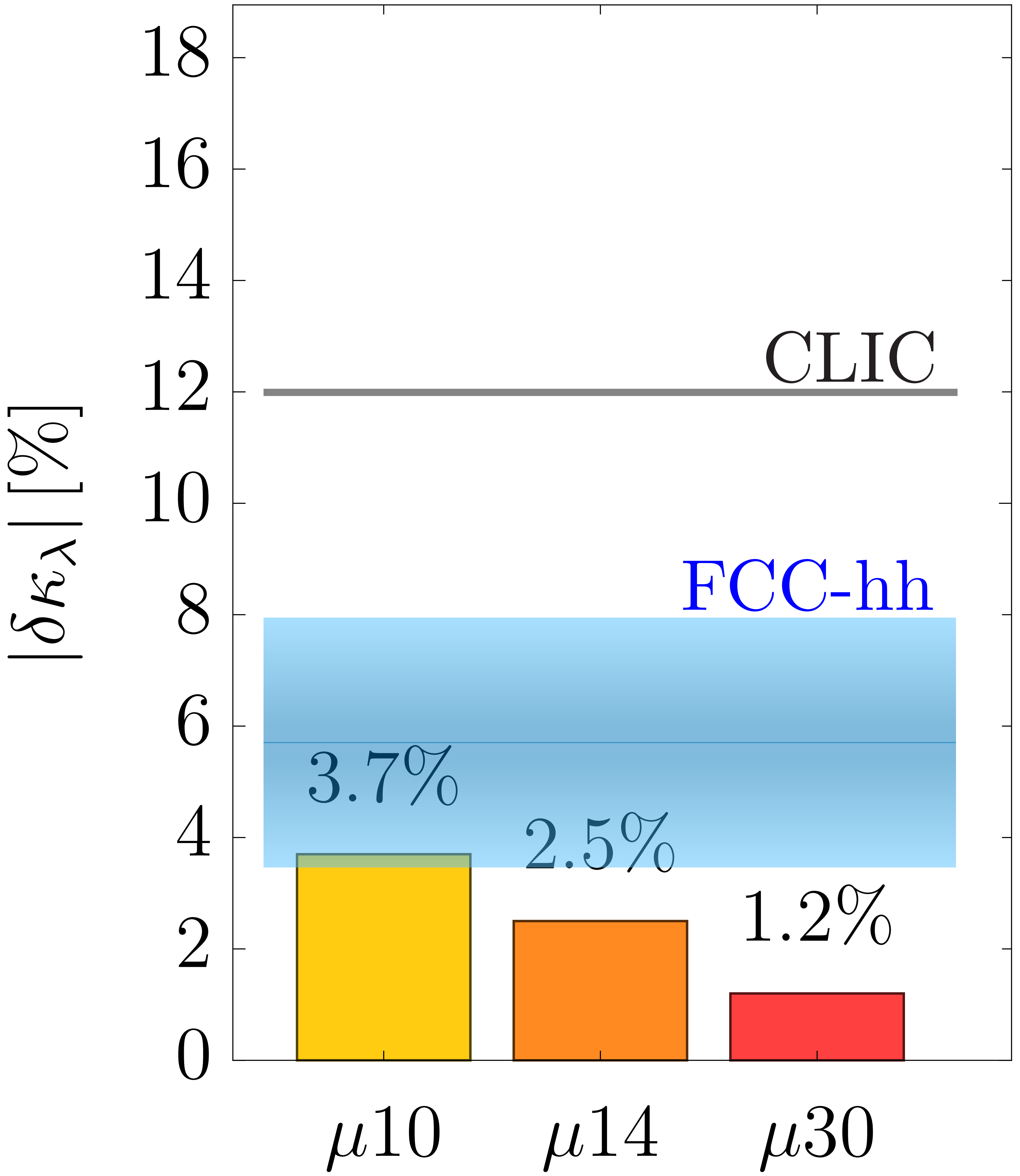
- Full exotic Higgs decay program still open to do, BR_{inv} preliminary results exist

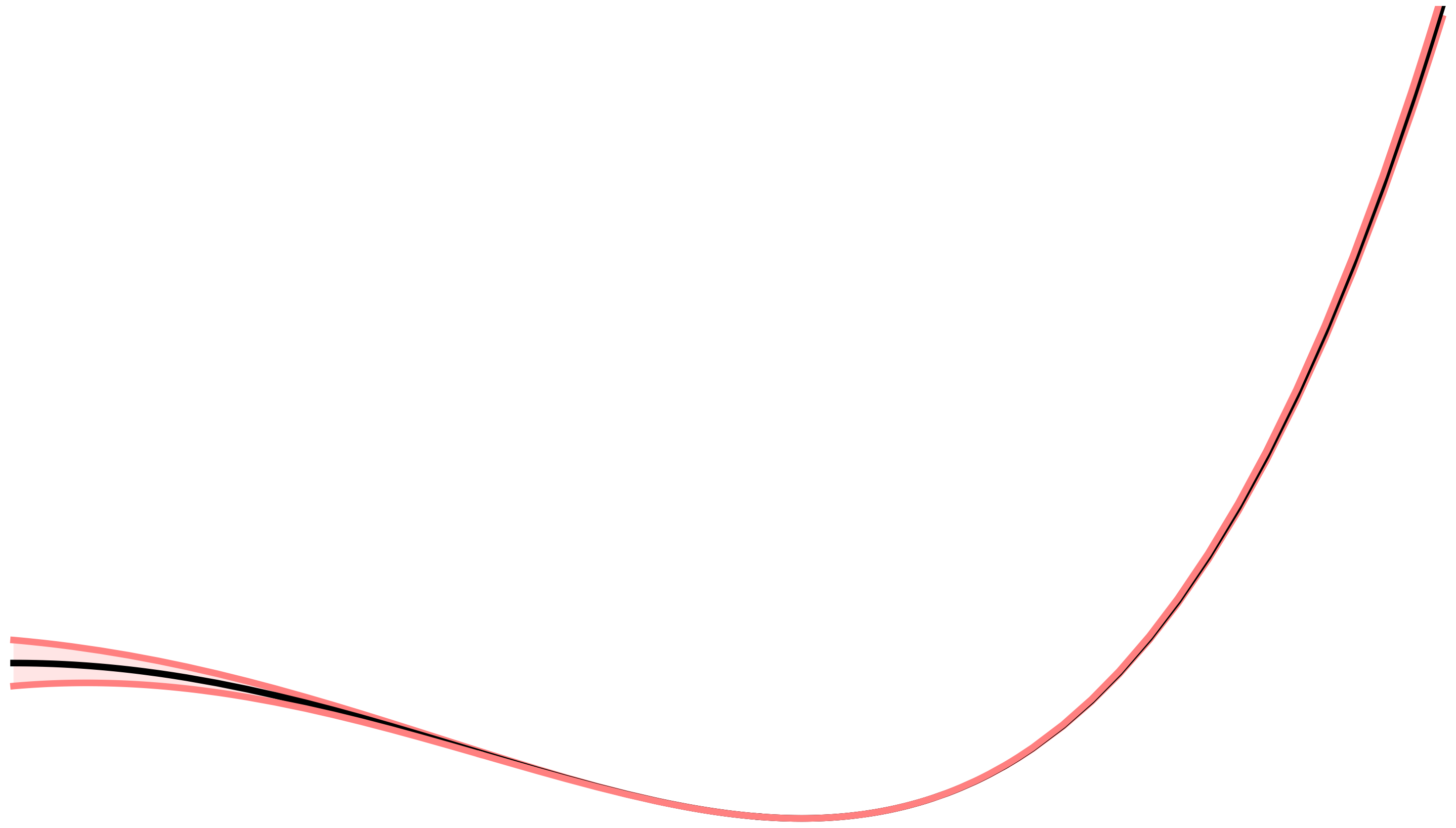
M. Ruhdorfer,E.Salvioni, A.Wulzer 2303.14202
M. Forslund, PM. 2306.XXXXX

Last but not least a muon collider lets us really improve on Higgs Potential



HL-LHC





10 TeV μCol

This is important for getting to the threshold for testing the EW phase transition at EW scale

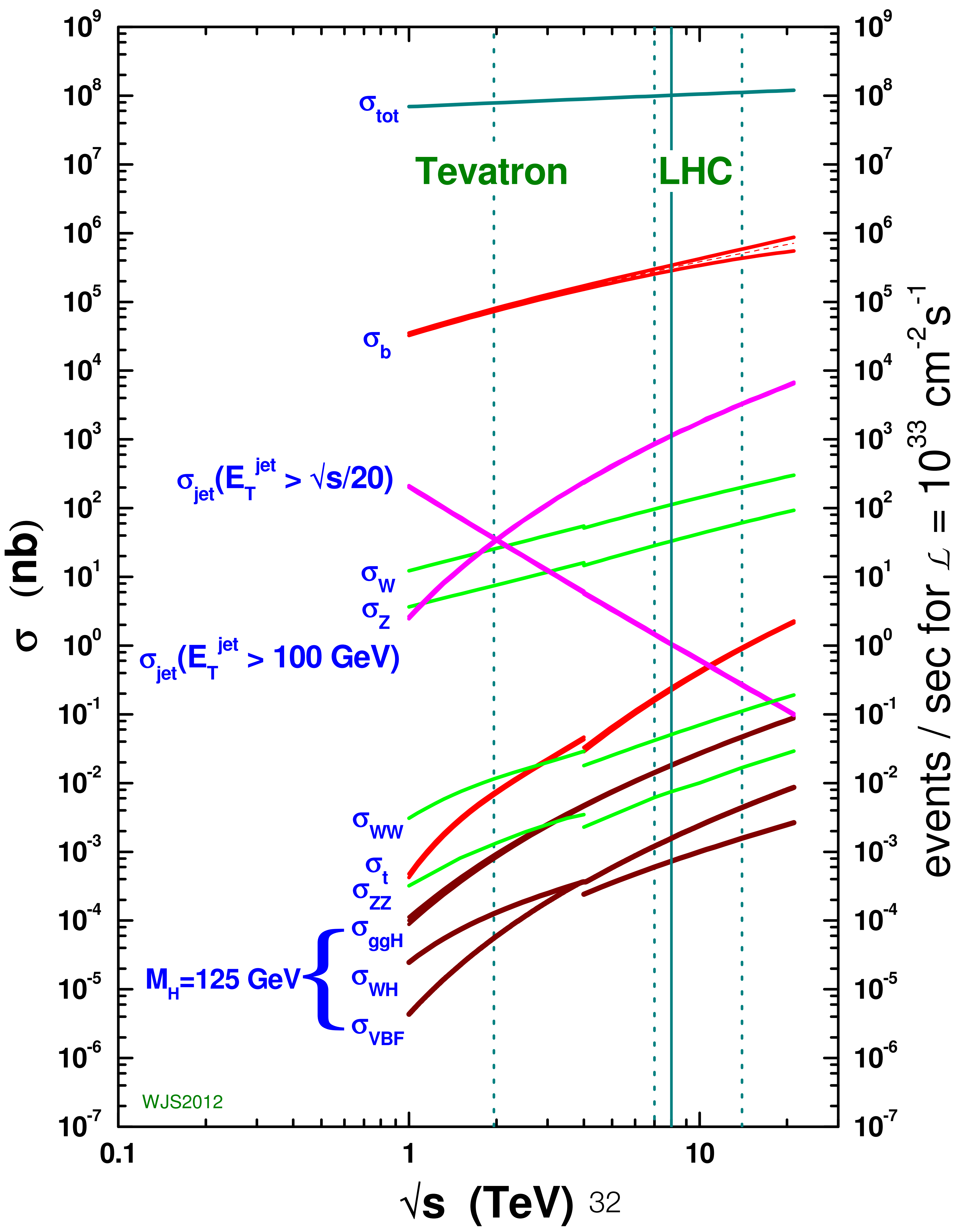
Conclusions

- A muon collider is an amazing option to study the fundamental questions that the LHC has explicitly presented us about Electroweak symmetry breaking
  - Single Higgs
  - Double Higgs
  - New differential observables
  - Ability to probe precision deviations and their origin in the *same collider*
- There is still more work to be done, and *hopefully* with the outcome of P5 in the US and continued/increased support in Europe/CERN we could realize this fundamentally new direction for our field
- If you want your own muon collider swag you can find it here:

  https://www.redbubble.com/people/muon-collider/

Backup

proton - (anti)proton cross sections



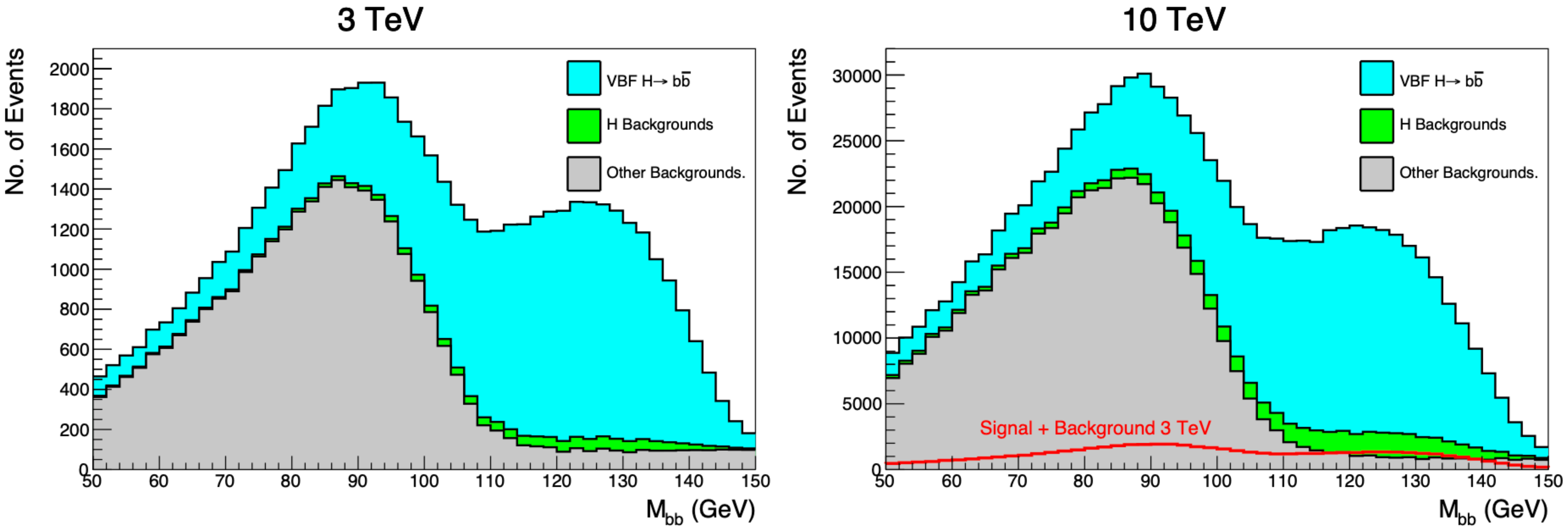
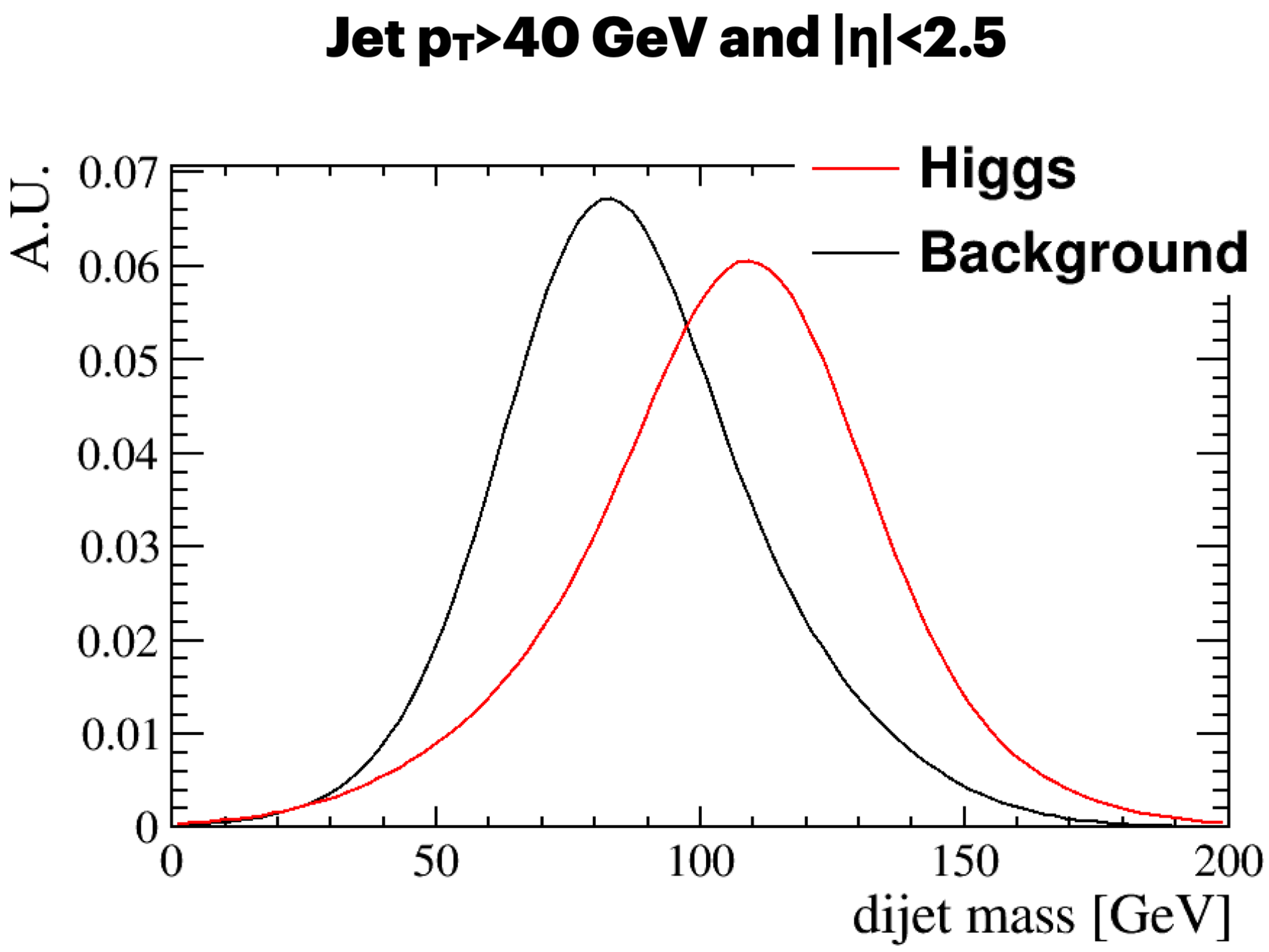


Figure 4. Stacked $b\bar{b}$ pair invariant mass histograms for the $H \to b\bar{b}$ analysis after p_T cuts and b-tagging at (left) 3 TeV and (right) 10 TeV. The sum of signal and background at 3 TeV is overlayed on the 10 TeV plot for ease of comparison.

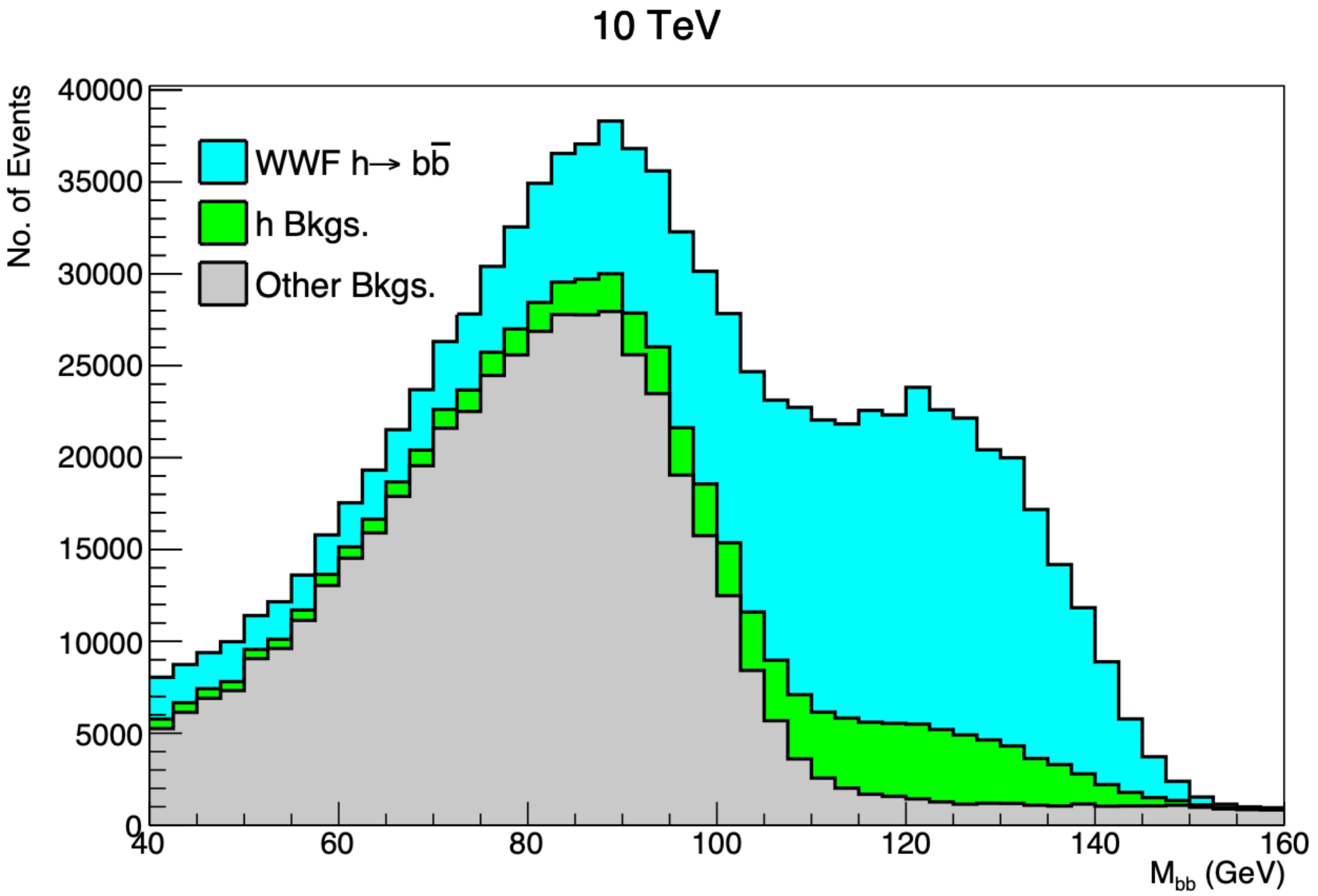
Process	Number of Events: 3 TeV			Number of Events: 10 TeV		
	$b\bar{b}$	$c\bar{c}$	gg	$b\bar{b}$	$c\bar{c}$	gg
$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu H;\ H \to X$	19000	154	8570	251000	2030	125000
$\mu^+\mu^- \to \mu^+\mu^- H;\ H \to X$	2000	16	951	26700	220	14300
$\mu^+\mu^- \to (\mu^+\mu^-, \nu_\mu \bar{\nu}_\mu) H;\ H \not\to X$	75	52	23400	1310	1040	339000
$\mu^+\mu^- \to (\mu^+\mu^-, \nu_\mu \bar{\nu}_\mu) jj$	2760	183	24900	34700	2300	355000
$\mu^+\mu^- \to \nu_\mu \mu^\pm jj$	3	20	18200	93	718	283000
Others	1440	70	21800	37000	1610	412000
Total Backgrounds	4280	325	88300	73200	5670	1390000

Table 1. Signal and some of the most important backgrounds for VBF $H \to X$, with X one of $(b\bar{b}, c\bar{c}, gg)$, after applying flavor tagging and analysis cuts. "Others" consists of s-channel and VBF diboson production, tb, and $t\bar{t}$.

Harder to separate hadronic final states

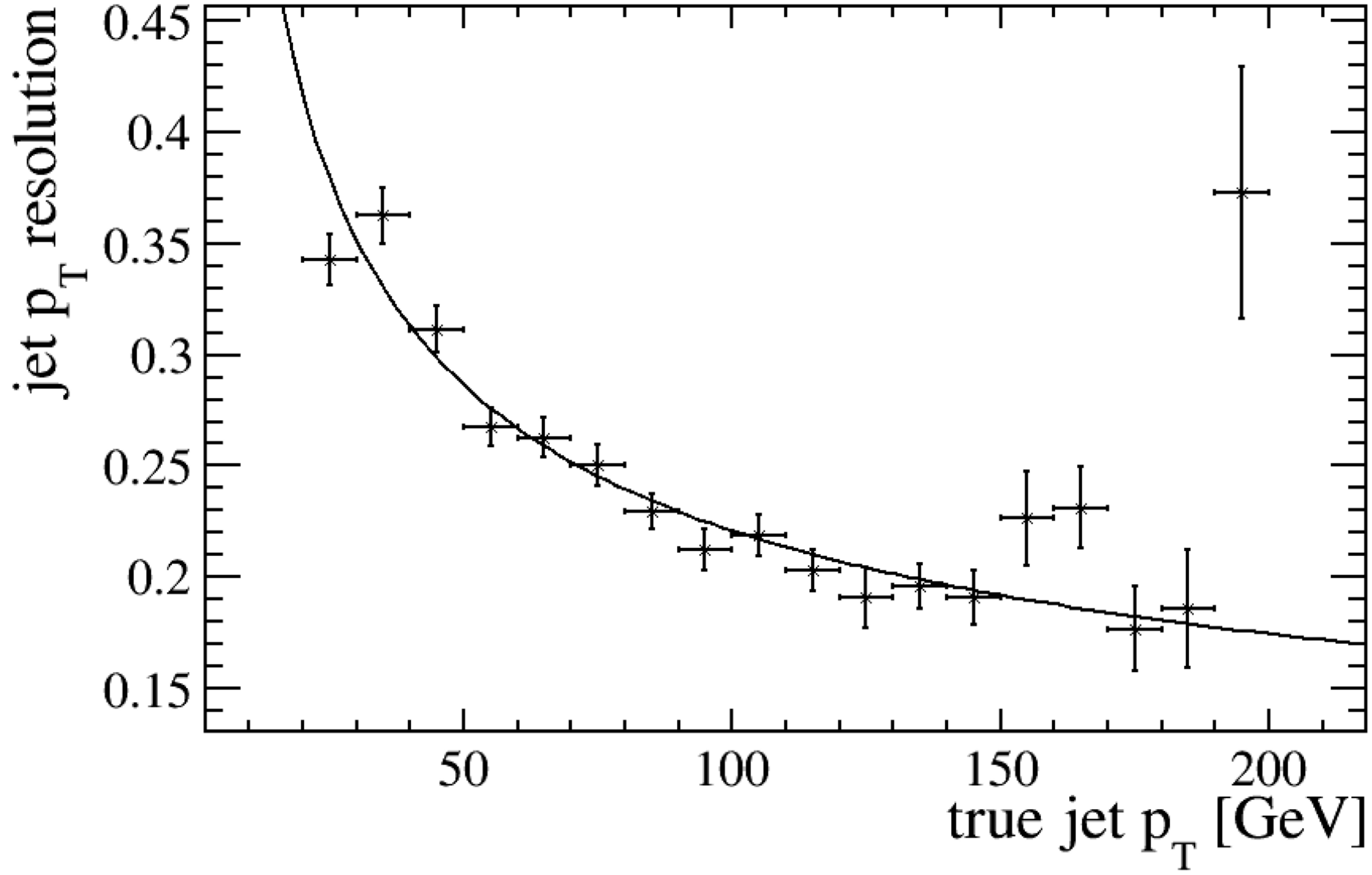


L. Sestini full sim + BIB

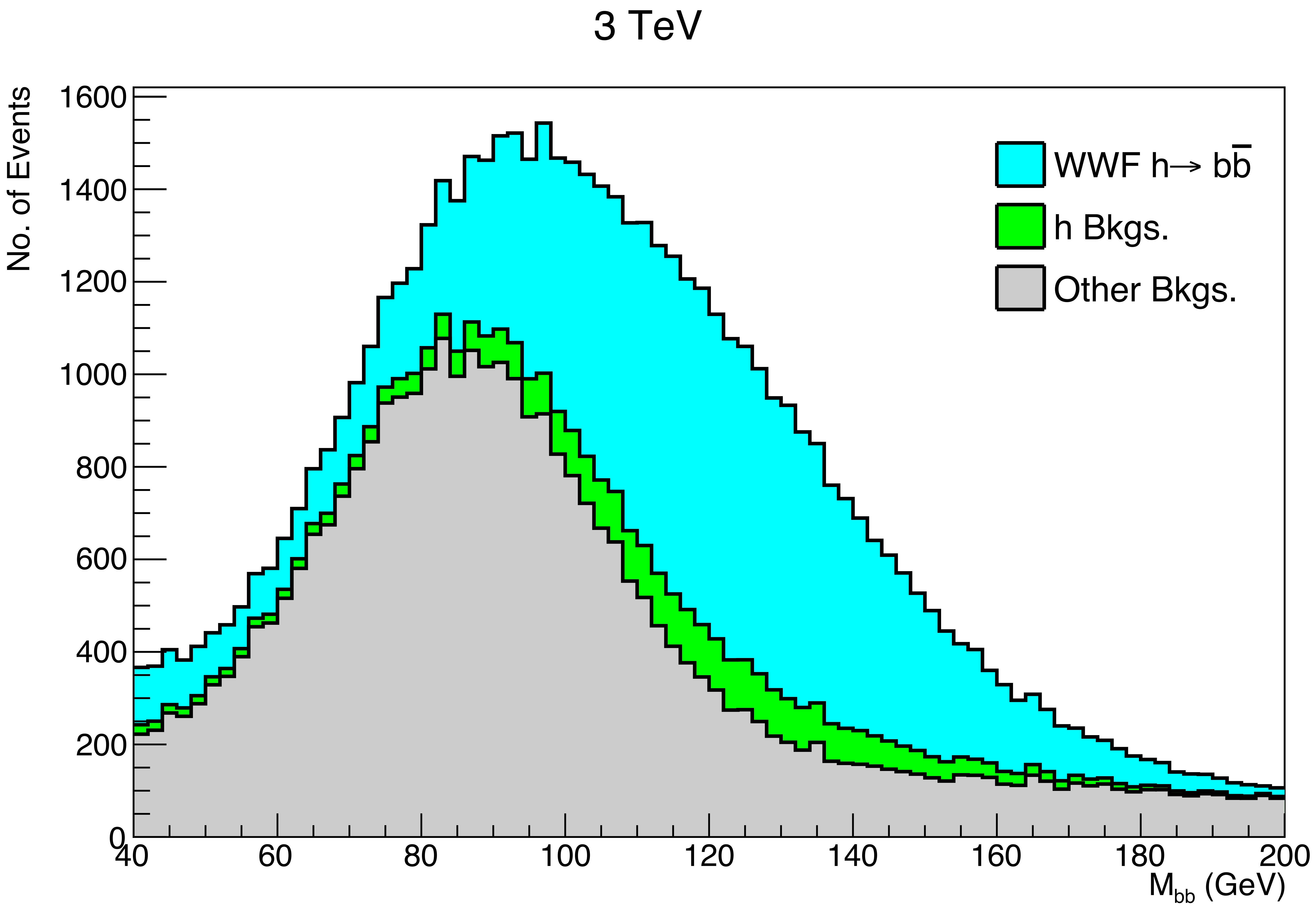


PM, M. Forslund Delphes

Full sim+ BIB JER about an order of magnitude worse than CLIC/Delphes

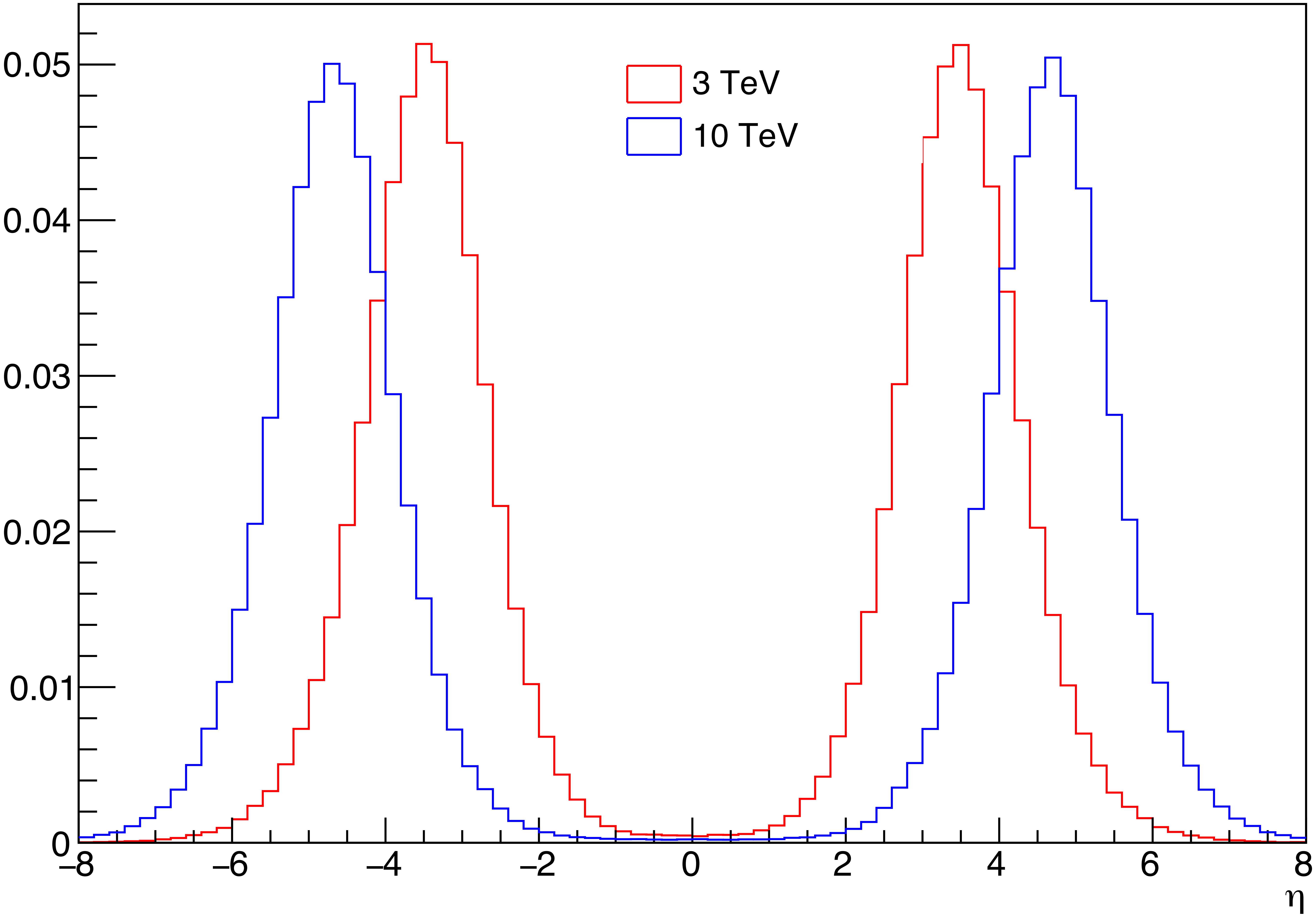


Nevertheless...



Modify Delphes JER to current full SIM + BIB, sensitivity goes from .84% to .95% for Delphes

Full sim closer to original Delphes due to shape test rather than cut and count



3 TeV
10 TeV
0.05
0.04
0.03
0.02
0.01
0
−8
−6
−4
−2
0
2
4
6
8
η