Some Guidance for Muon Smashers

Tim Cohen (U Oregon)

Snowmass Muon Collider Forum, April 14

How do we find BSM physics?

What experiment should we build?

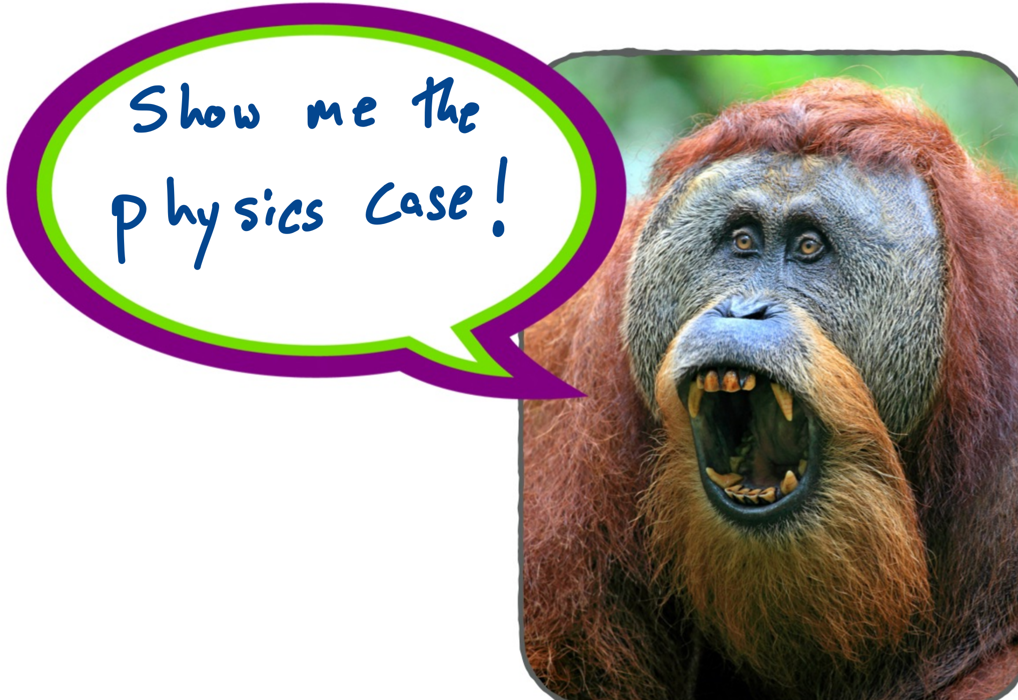
Assume we have one of these...

What experiment should we build?

and as
many ideas
as we need...

What experiment should we build?

So we can focus on...



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]

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arXiv: 2103.14043

Outline

I. Why Collide Muons?

II. Physics

III. Outlook

The Muon Smasher's Guide

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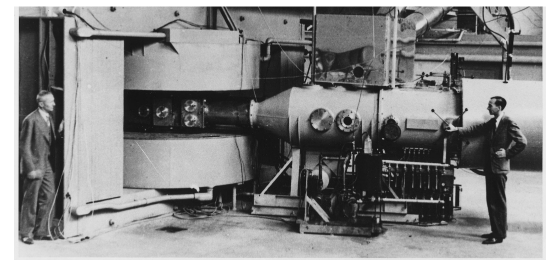
Contents

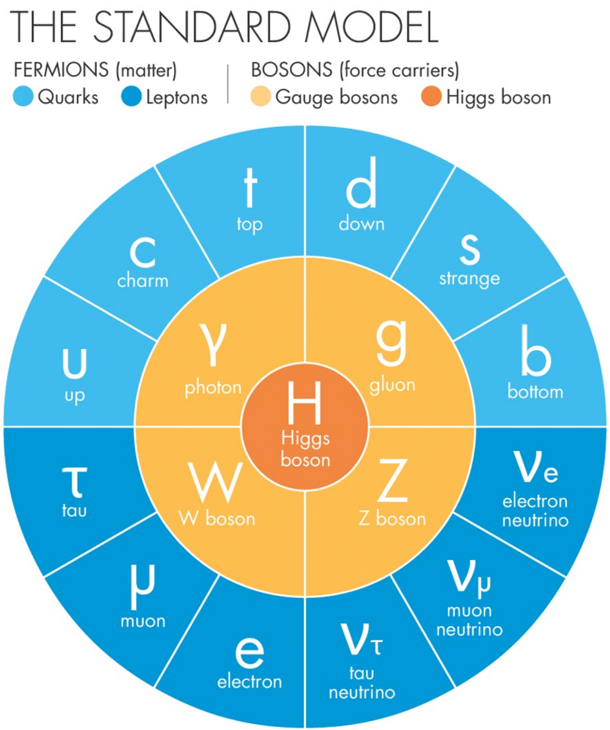
I. Why Collide Muons?

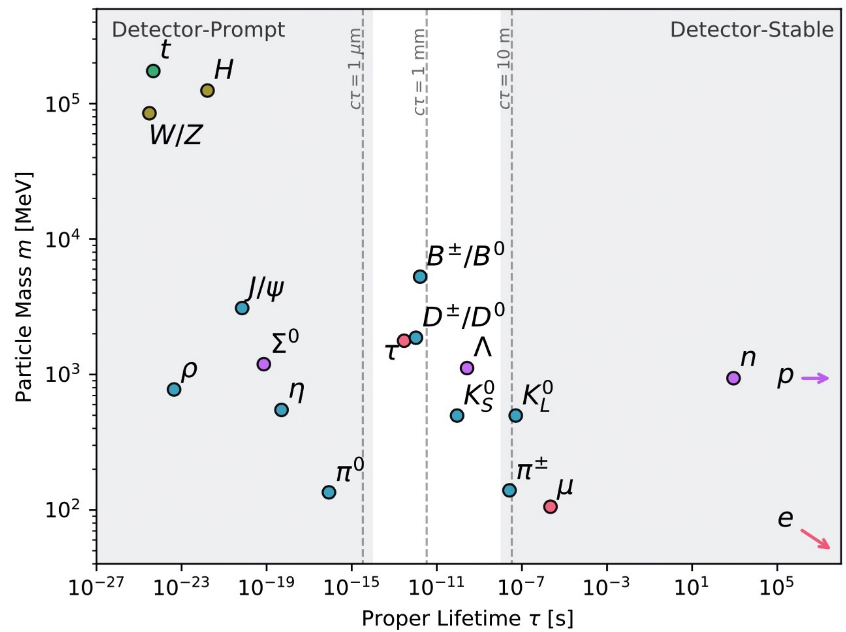
Evolution of the microscope



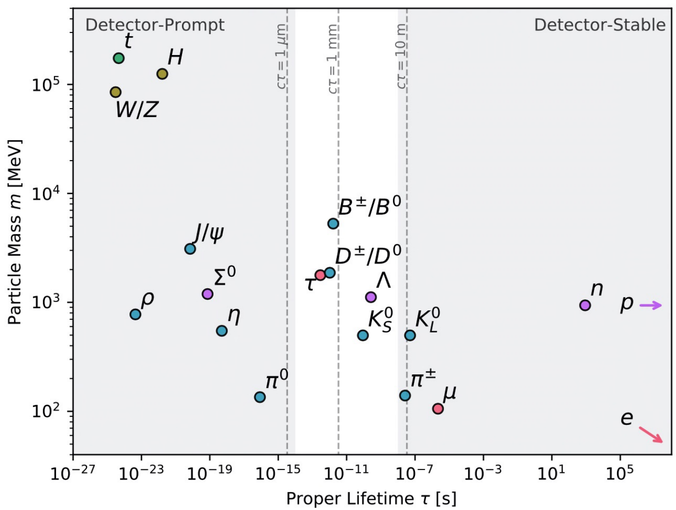
Muon collider??

What to collide?



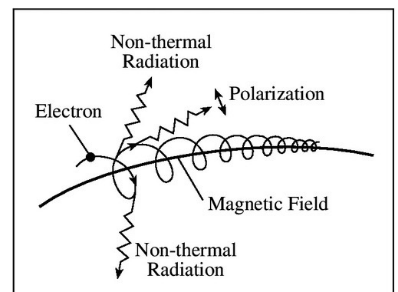


What to collide?



- Charged

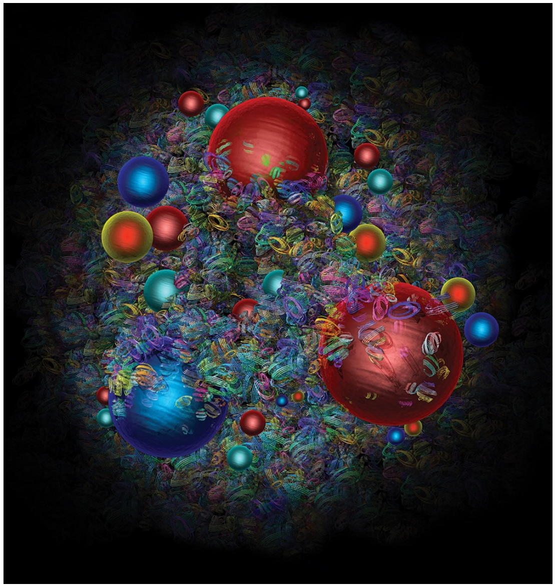
- Heavier is better



$$P_{sync} \sim \frac{1}{m^4}$$

- Stable(ish)

But fundamental is nice too...



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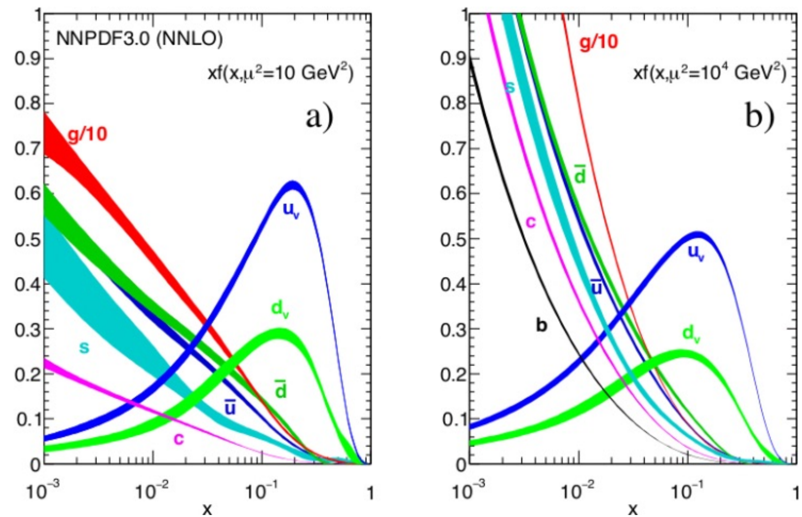

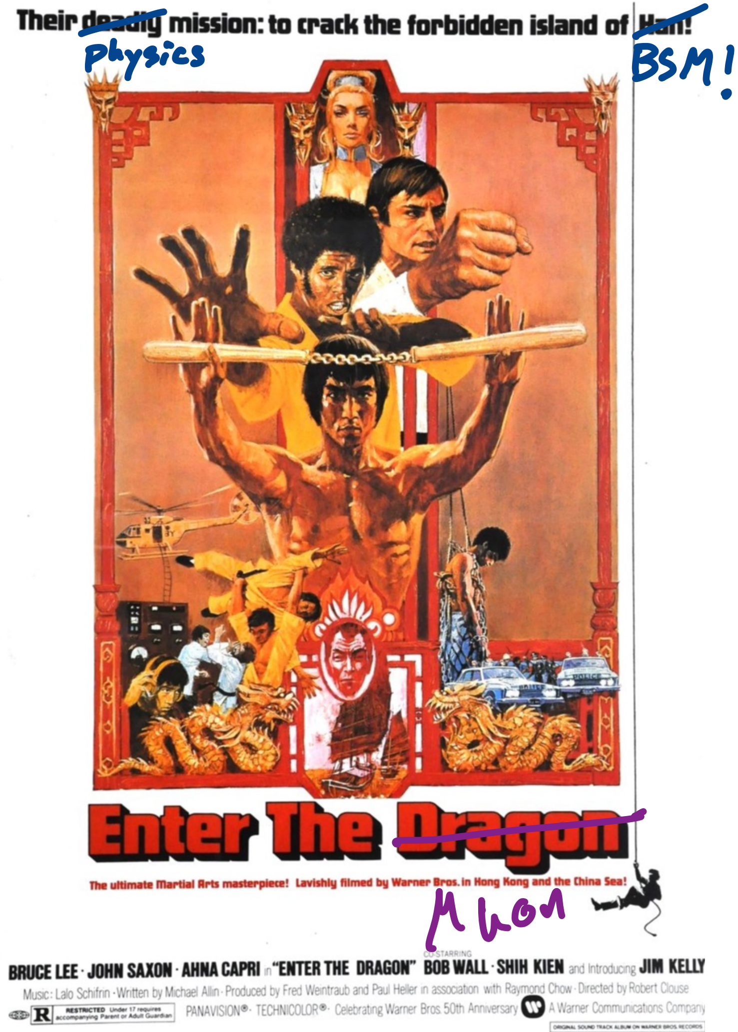

Their ~~deadly~~ Physics mission: to crack the forbidden island of ~~Han!~~ BSM!
Enter The ~~Dragon~~ Muon
The ultimate Martial Arts masterpiece! Lavishly filmed by Warner Bros. in Hong Kong and the China Sea!
CO-STARRING
BRUCE LEE · JOHN SAXON · AHNA CAPRI in "ENTER THE DRAGON" BOB WALL · SHIH KIEN and Introducing JIM KELLY
Music: Lalo Schifrin · Written by Michael Allin · Produced by Fred Weintraub and Paul Heller in association with Raymond Chow · Directed by Robert Clouse
R RESTRICTED Under 17 requires accompanying Parent or Adult Guardian
PANAVISION® · TECHNICOLOR® · Celebrating Warner Bros. 50th Anniversary
A Warner Communications Company
ORIGINAL SOUND TRACK ALBUM ON WARNER BROS. RECORDS

The muon is trending

A Tiny Particle's Wobble Could Upend the Known Laws of Physics

Experiments with particles known as muons suggest that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

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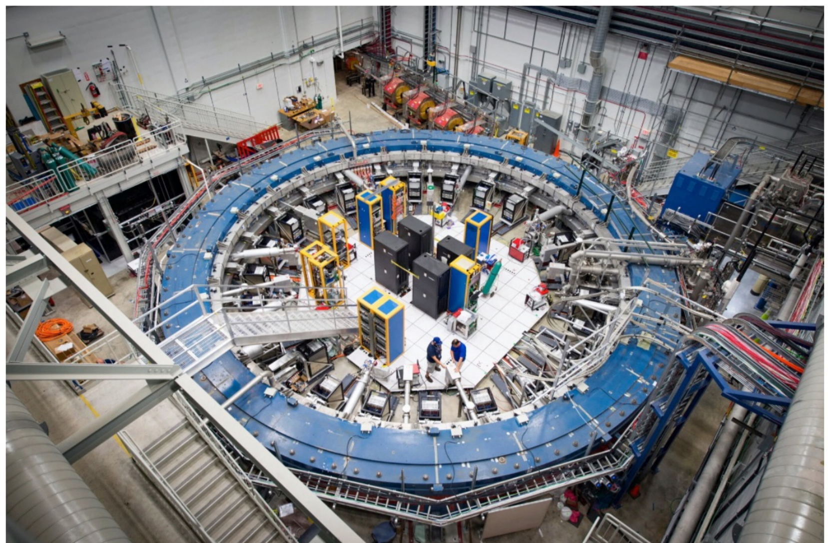


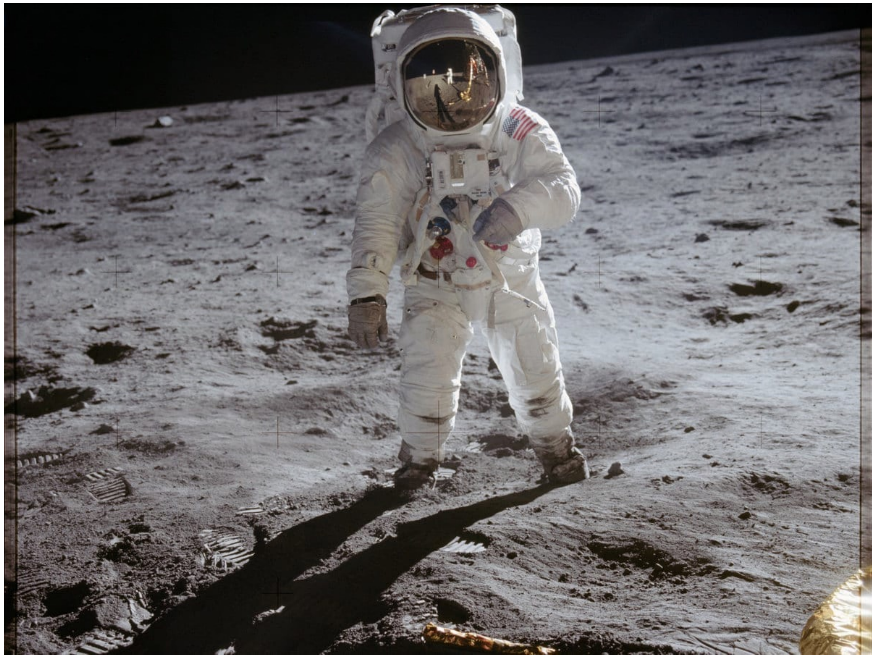
The Muon g-2 ring, at the Fermi National Accelerator Laboratory in Batavia, Ill., operates at minus 450 degrees Fahrenheit and studies the wobble of muons as they travel through the magnetic field. Reidar Hahn/Fermilab, via U.S. Department of Energy

But muons decay...

Poses many experimental challenges

Beam induced background ⇒ $\eta \lesssim 2.5$

Let's be "reasonable"



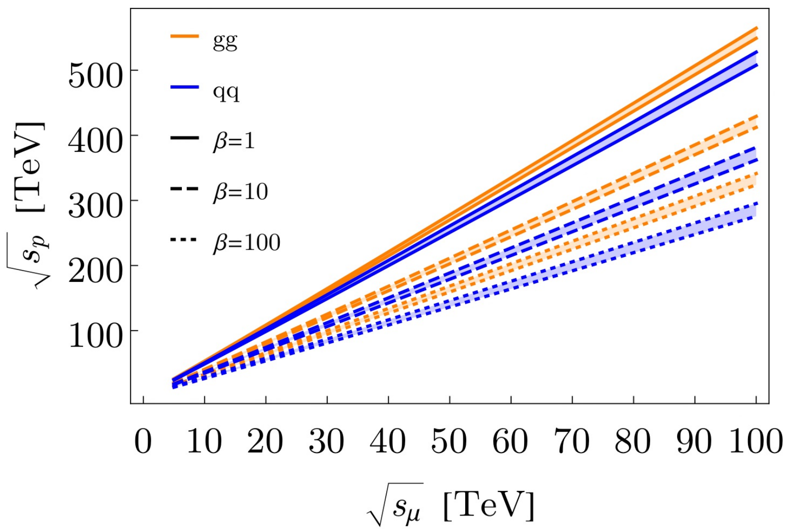
Next generation experiment at Fermilab and before we retire

$\Rightarrow \sqrt{s} \lesssim 10$ TeV

What is the physics case?

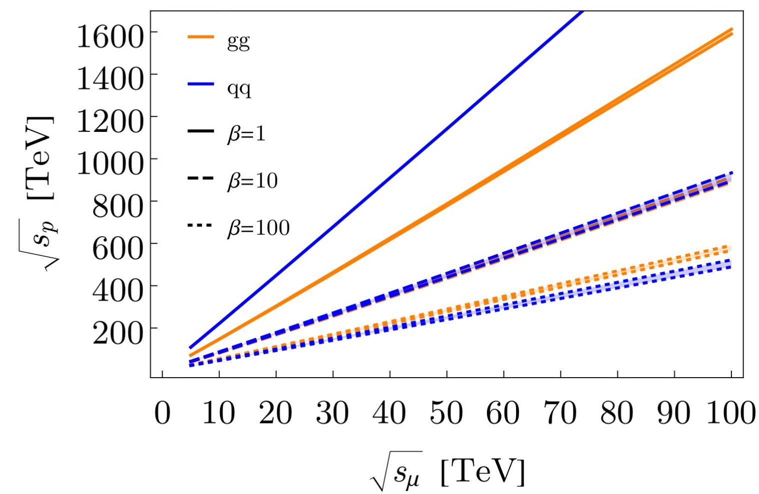
Muons vs. Protons

2 → 1



Curves of equivalent σ

2 → 2

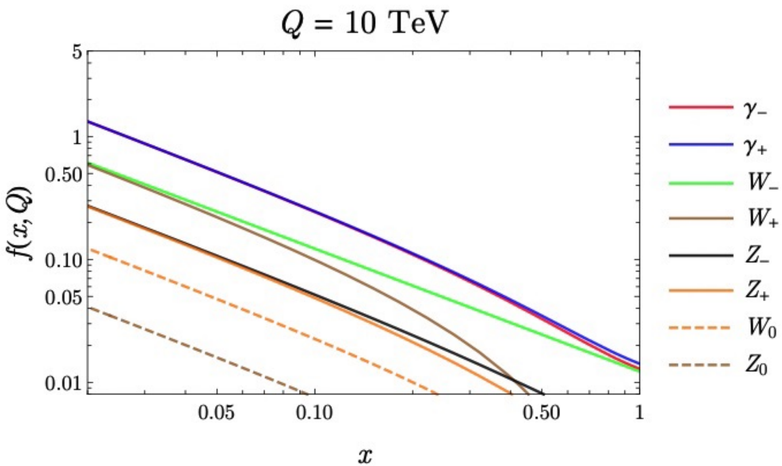


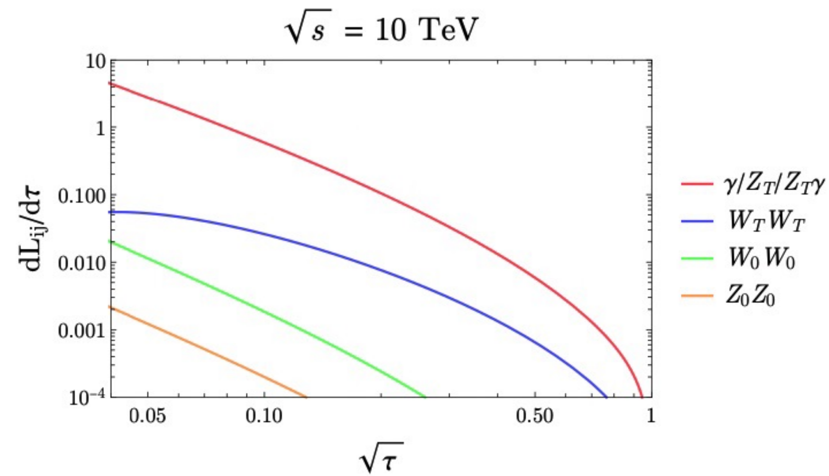
$$\beta = \frac{[\hat{\sigma}_p]}{[\hat{\sigma}_\mu]}$$

$$\frac{QCD}{EW} \Rightarrow \beta \sim 10$$

Muons have PDFs too!

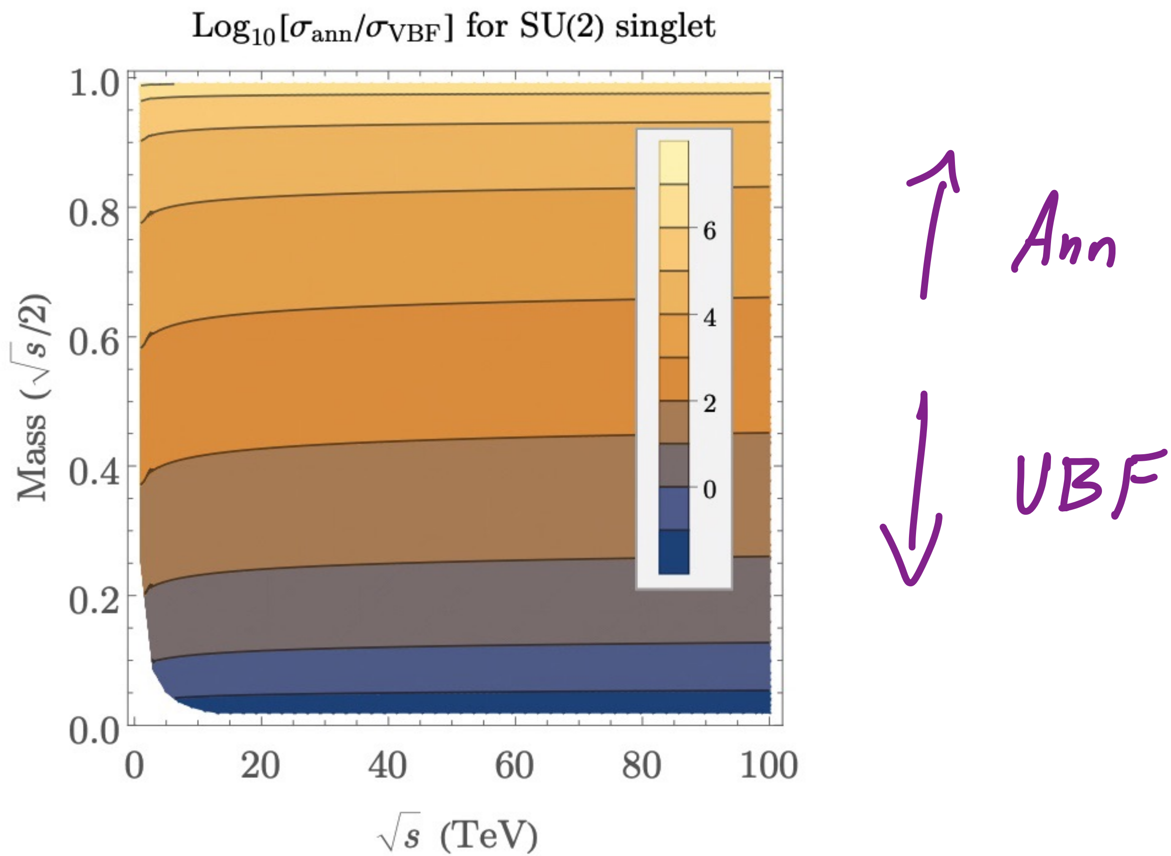
$$\sqrt{s} \gg m_W \gg m_\mu$$





Parton luminosity
$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_\tau^1 \frac{dx}{x} \left[f_i(x)\, f_j(\tau/x) + (i \leftrightarrow j) \right]$$

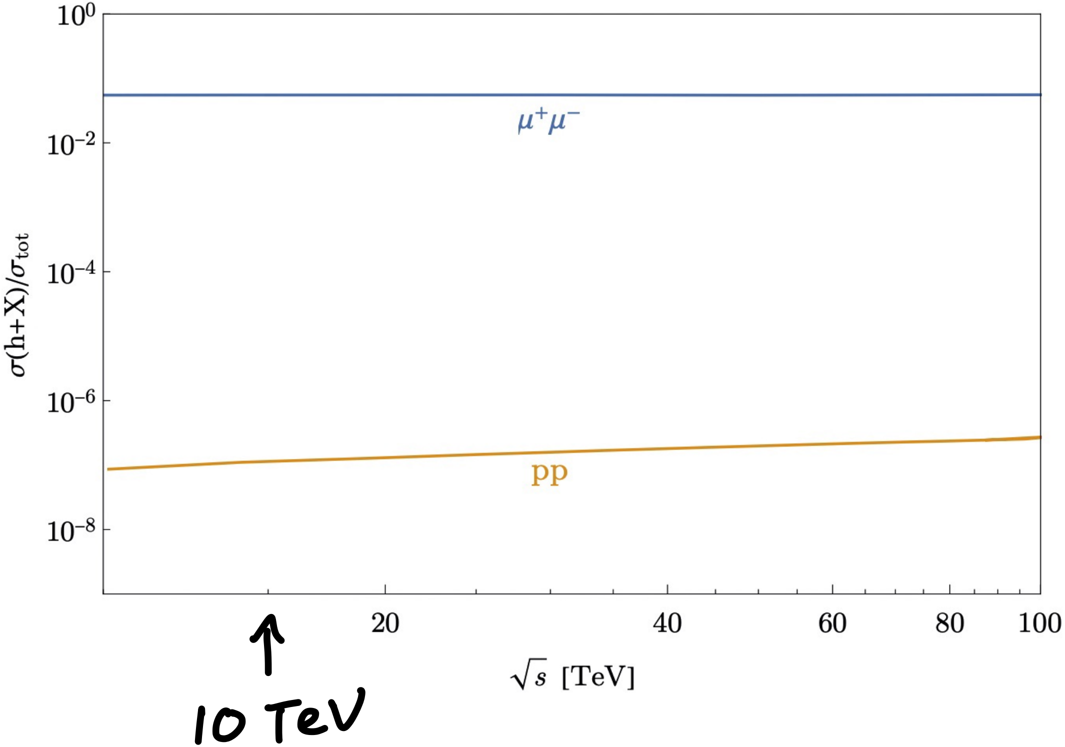
Annihilation vs. VBF



II. Physics

- Higgs/EW
- Dark Matter
- SUSY

Higgs production



Muon

$\sigma_h : \mu^+\mu^- \to h\nu\bar{\nu}$

$\sigma_{tot} : \mu^+\mu^- \to \bar{V}$

Proton

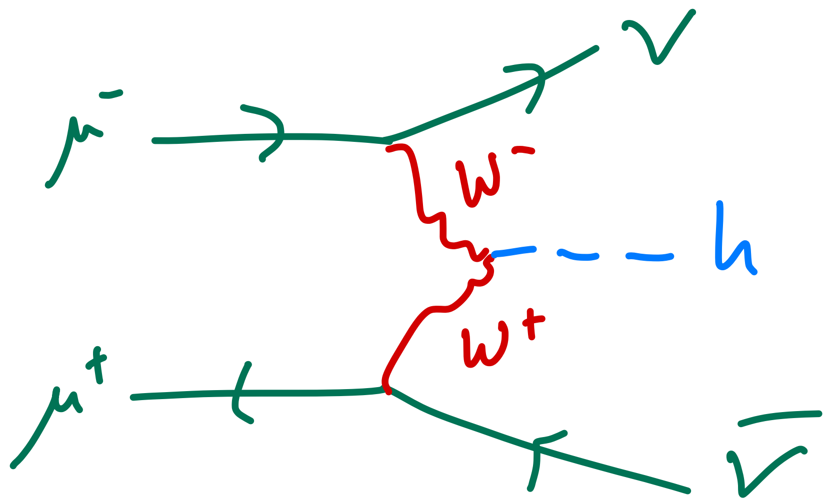
$\sigma_h : gg \to h$

$\sigma_{tot} : pp \to b\bar{b}$

Higgs Production

$\sqrt{s} = 10$ TeV $\Rightarrow$ $\mathcal{O}(10^7)$ single Higgs events

$\mathcal{L} = 10$ ab^{-1} $\quad$ $\mathcal{O}(10^4)$ di-Higgs events



Higgs Production

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

Signal only selection

Higgs Production

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

κ framework
signal only

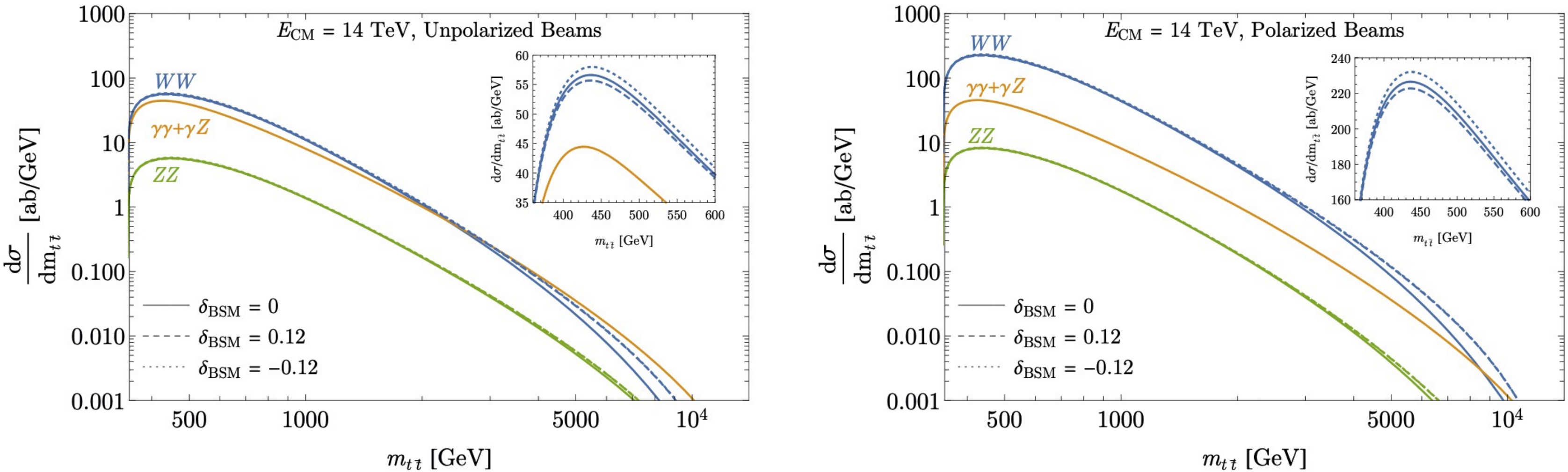
Higgs Production

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

(Not fair to compare with our signal only analysis)

Modified Top Yukawa

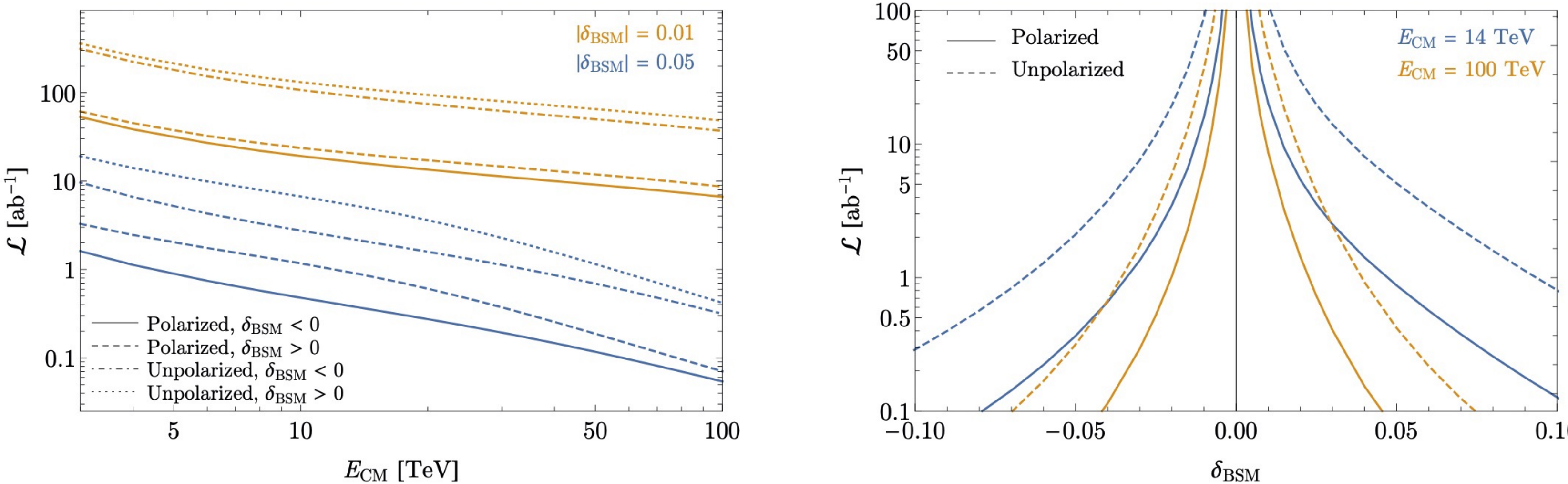
$$y_t \to y_t(1+\delta_{BSM})$$



$$\mathcal{M}(W_L^+W_L^- \to t\bar{t}) \simeq -\frac{m_t}{v^2}\delta_{BSM}\sqrt{\hat{s}} \quad \text{w/ } \hat{s} \gg m_t$$

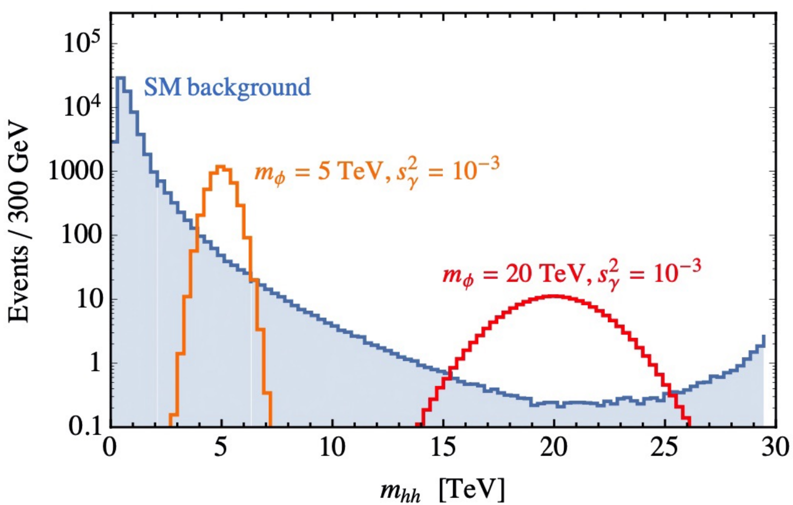
Modified Top Yukawa

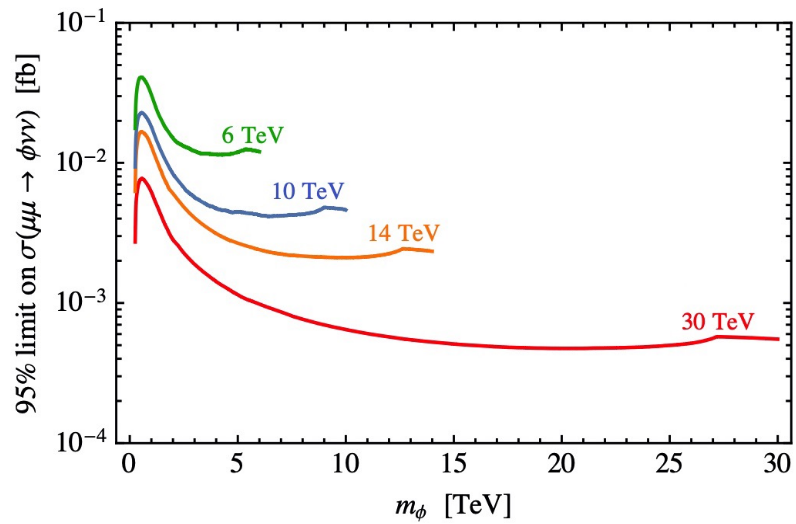
$$y_t \rightarrow y_t(1+\delta_{BSM})$$



Extra Higgs Bosons

$\mu^+\mu^- \to \phi\, \nu\bar{\nu} \to hh\, \nu\bar{\nu}$

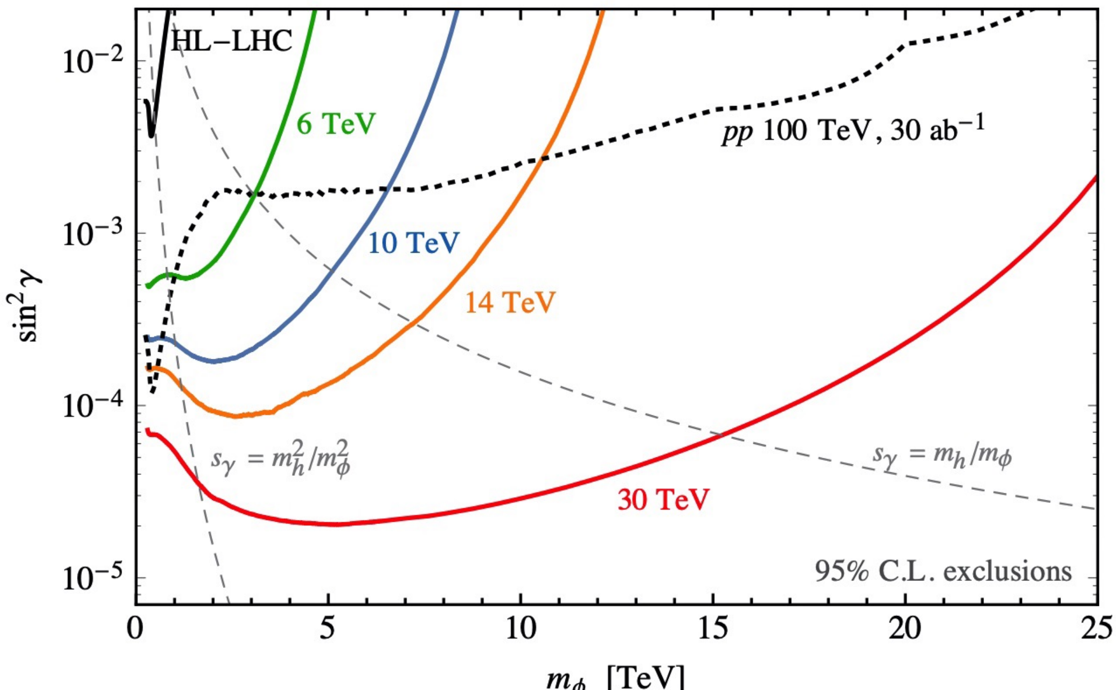




For di-Higgs 2HDM study, see arXiv: 2102.08386

Extra Higgs Bosons

$\mu^+\mu^- \to \phi\, \nu\bar{\nu} \to h h \nu\bar{\nu}$



WIMP Dark Matter

Models considered

Model (color, n, Y)		Thermal target	5σ discovery coverage (TeV)			
			mono-γ	mono-μ	di-μ's	disp. tracks
(1,2,½)	Dirac	1.1 TeV	—	2.8	—	1.8 - 3.7
(1,3,0)	Majorana	2.8 TeV	—	3.7	—	13 - 14
(1,3,ϵ)	Dirac	2.0 TeV	0.9	4.6	—	13 - 14
(1,5,0)	Majorana	14 TeV	3.1	7.0	3.1	10 - 14
(1,5,ϵ)	Dirac	6.6 TeV	6.9	7.8	4.2	11 - 14
(1,7,0)	Majorana	23 TeV	14	8.6	6.1	8.1 - 12
(1,7,ϵ)	Dirac	16 TeV	13	9.2	7.4	8.6 - 13

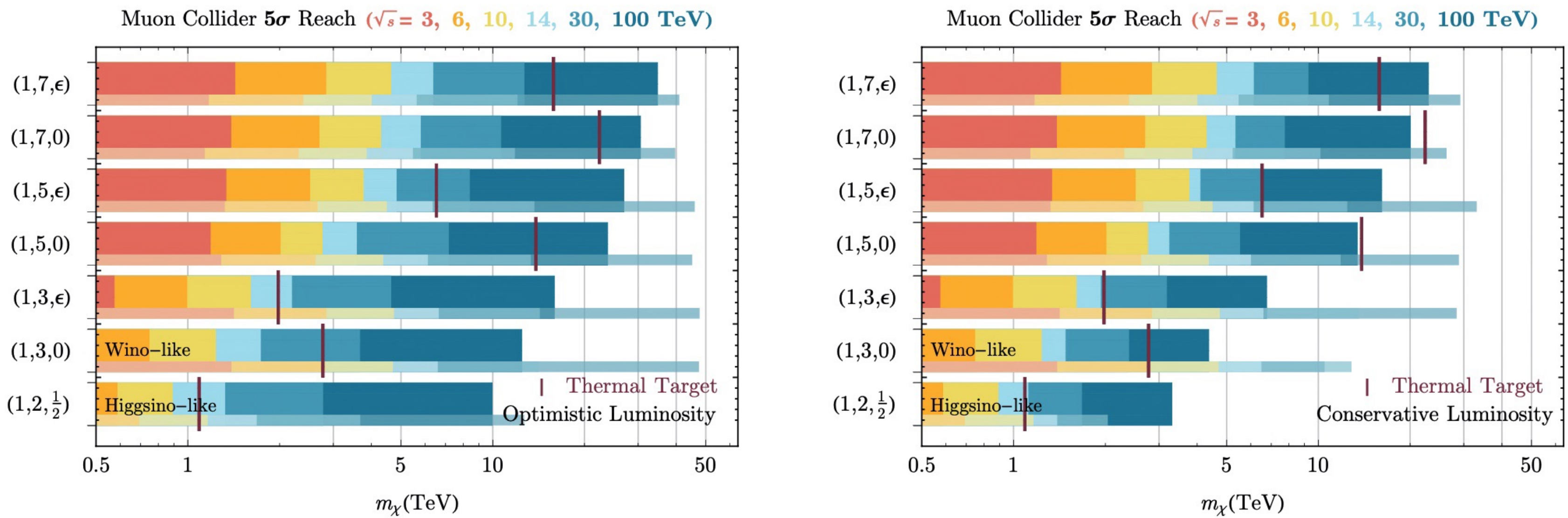
see arXiv: 2009.11287

WIMP Dark Matter

Strategies

- Mono-muon
- Mono-photon
- Di-muon
- Disappearing tracks

WIMP Dark Matter

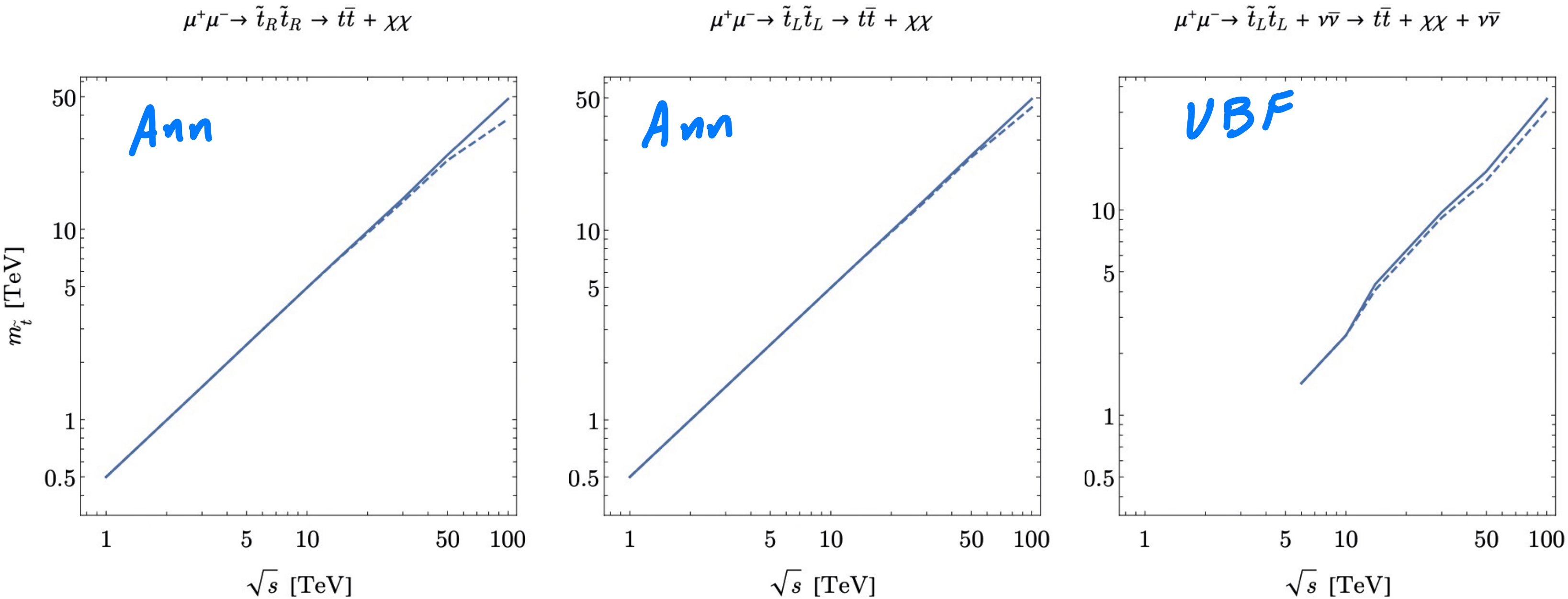


Narrow bars include dissappearing tracks

SUSY

Stop-neutralino simplified model

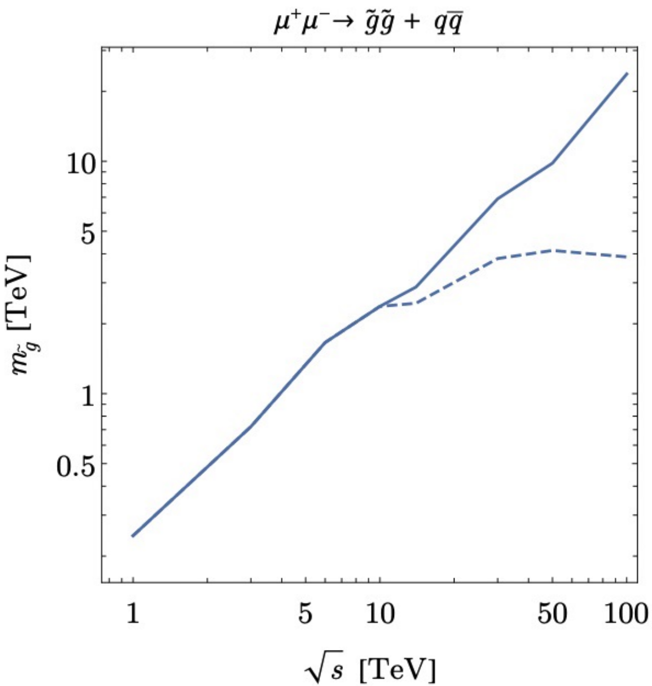
Exclusions



$m_\chi = 1$ GeV

SUSY

Gluino - neutralino simplified model



$m_\chi = 1$ GeV

III. Outlook

Outlook

10 TeV muon collider would qualitatively impact Higgs and WIMP dark matter pheno.

Would provide incremental progress for SUSY (heavy BSM) unless we get more $\sqrt{s}$.

Outlook

A naive comparison for single Higgs production

- Polarization $\Rightarrow$ factor of 2
- Log growth of rate from 3 TeV $\to$ 10 TeV $\Rightarrow$ factor of 2

$\Rightarrow$ 3 TeV CLIC w/ pol $\sim$ 10 TeV $\mu^+\mu^-$

and muon collider has more hh production

Outlook

Many fascinating accelerator and detector design questions!!

- Timing and tagging
- Polarization vs Luminosity
- $|\eta| < 2.5$ improved?
- What $\sqrt{s}$?

Outlook

A 10 TeV muon collider is viable and exciting opportunity for future US HEP program!!