AF ⇔ theory

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Snowmass restart Sept. 24, 2021

Theory frontier activities

- Activities restarted. Convener-liaison meeting on Sept 9.
- Santa Barbara meeting Feb 23-25 2022.
- Collected/solicited white papers, will begin to process them.
- More updates here.

White papers in TF

TF7: collider phenomenology

TOPIC	AUTHORS
Observables	
Geometric strategies for collider data analysis	Jesse Thaler (MIT)
Theoretical perspective on machine learning for data a	Andrew Larkoski (Reed)
New developments in kinematic observables	Doojin Kim (Texas A&M)
New kinematic representations of jets and events	Tao Liu (HKUST)
Calculations	
Interface of theory calculations with experimental met	Simone Marzani (Genova)
Electroweak at very high energy and EW parton show	Tao Han (Pittsburg)
Needs and trends in QED resummation	Stefano Frixione (Genova), Eric Laenen (NIKHEF)
Factorization	George Sterman (Stony Brook)
Higher order QCD calculations inspired by aspects of	No coordinator identified yet
Generators	
NNLO+NNLL event generators	Giulia Zanderighi (Munich)
First-principles simulations with machine learning	Tilman Plehn (Heidelberg)
Interpretation	
Anomaly detection with machine learning	David Shih (Rutgers)
Opportunities for theory studies with public collider da	Matt Bellis (Siena)
Fully differential likelihood techniques	
BSM Signatures	
Ultra-exotics and forgotten signatures at colliders No	
Model dependent vs. model independent approaches	

TF2: EFT techniques

TOPIC	AUTHORS
Constraints on IR physics from UV consistency	Matt Reece
EFT of dark matter	Mikhail Solon
HEP/CMT connections	Riccardo Penco
Naturalness	Nathaniel Craig
EFTs of gravity	Walter Goldberger
SMEFT	Will Shepherd
EFT of cosmology (with TF09)	Mehrdad Mirbabayi and Marko Simonovic

TF8: model building

	AUTHORS	TITL
Early Universe Model-Building (with TF09)	David Curtin, Eric Kuflik, Yonit Hochberg, Neal Weiner, and Keisuke Harigaya	
Weak Gravity Conjecture, Swampland and Implications for Theory	Patrick Draper, Isabel Garcia-Garcia, Matthew Reece	
Flavor Model Building (with TF06)	Wolfgang Altmannshofer, Jure Zupan	
Neutral Naturalness	Brian Batell, Chris Verhaaren	
Strong Coupling, Model Building, and Lattice	Graham Kribs, Ethan Neil	
Axion Model Building	Prateek Agrawal, JiJi Fan, Anson Hook, Junwu Huang, Gustavo Marques Tavares	
Neutrino Model Building [tentative] (with TF11)	Kaladi Babu, Marco Drewes, Julia Gehrlein (?)	
Models of Baryogenesis	Gilly Elor, Seyda Ipek	
Relaxion/Clockwork [tentative]	Claudia Frugiuele, Gilad Perez	

TF6: theory techniques for precision physics

TOPIC	Author	TITLE
The path to N3LO precision	Fabrizio Caola, Claude Duhr, Xiaohui Liu, Frank Petriello, Stefan Weinzierl	
Future prospects for parton showers	Simone Alioli, Zoltan Nagy, Dave Soper, Bryan Webber	
Theoretical developments in the SMEFT at dimension-8 and beyond	Alioli, Durieux, Martin, Melia, Mereghetti, Murayama, Murphy, Petriello, Shadmi, Shepherd et al	
Proton structure at the precision frontier (with EF06)	Alekhin, Ball, Blumlein, Cooper-Sarkar, Forte, Nadolsky, Thorne, Ubiali, Yuan, et al	
Resummation for future colliders	Thomas Becher, Andrea Ferroglia, Xiaohui Liu, Alexandre Penin, Felix Ringer, Robert Szafron et al	
Flavor model building (with TF08)	Wolfgang Altmannshofer, Jure Zupan	

Full list of white papers

TF in connection with AF

- The goal of TF.
  - Focusing on theoretical techniques needed for making progresses.
    - Techniques for doing calculations, making models.
- No dedicated discussion on the experimental (accelerator) facilities needed to achieve physics goals.
  - More in the energy frontier working group.
- Although there are certainly overlaps and hard to separate these two focuses.

Future collider is a central focus of many theorists

Connecting theory community with AF is the focus of my work as a liaison.

List of proposals

Name	Details	POC	AF Group
CepC	e+e-, $\sqrt{s}$ = 0.24 TeV, L= 3.0 $\times 10^{34}$	Jie Gao (gaoj@ihep.ac.cn)	AF3
CLIC (Higgs factory)	e+e-, $\sqrt{s}$ = 0.38 TeV, L= 1.5 $\times 10^{34}$	Steinar Stapnes (Steinar.Stapnes@cern.ch)	AF3
Circular ERL ee collider	e+e-, $\sqrt{s}$ = 0.24 TeV, L= 73 $\times 10^{34}$	Thomas Roser (roser@bnl.gov)	AF3
FCC-ee	e+e-, $\sqrt{s}$ = 0.24 TeV, L= 17 $\times 10^{34}$	Katsunobu Oide (katsunobu.oide@ern.ch)	AF3
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider	Tim Barklow (timb@slac.stanford.edu)	AF3
ILC (Higgs factory)	e+e-, $\sqrt{s}$ = 0.25 TeV, L= 1.4 $\times 10^{34}$	Shin-ichi Michizono (shinichiro.michizono@kek.jp	AF3
LHeC	ep, $\sqrt{s}$ = 1.3 TeV, L= 0.1 $\times 10^{34}$	Oliver Bruening (oliver.bruening@cern.ch)	AF3
MC (Higgs factory)	$\mu\mu$, $\sqrt{s}$ = 0.13 TeV, L= 0.01 $\times 10^{34}$	Mark Palmer (mpalmer@bnl.gov)	AF3
Cryo-Cooled Copper (C^3) linac	e+e-, $\sqrt{s}$ = 2 TeV, L= 4.5 $\times 10^{34}$	Emilio Nanni (nanni@slac.Stanford.edu)	AF3
High Energy CLIC	e+e-, $\sqrt{s}$ = 1.5 –3 TeV, L= 5.9 $\times 10^{34}$	S.Stapnes (steinar.stapnes@cern.ch)	AF4
High Energy ILC	e+e-, $\sqrt{s}$ = 1 –3 TeV	Hassan Padamsee (hsp3@cornell.edu)	AF4
FCC-hh	pp, $\sqrt{s}$ = 100 TeV, L= 30 $\times 10^{34}$	M.Benedikt (Michael.Benedikt@cern.ch)	AF4
SPPC	pp, $\sqrt{s}$ = 75/150 TeV, L= 10 $\times 10^{34}$	J.Tang (tangjy@ihep.ac.cn)	AF4
Collider-in-Sea	pp, $\sqrt{s}$ = 500 TeV, L= 50 $\times 10^{34}$	P.McIntyre mcintyre@physics.tamu.edu	AF4
Gamma-gamma	??	W.Krasny (mieczyslaw.witold.krasny@cern.ch)	AF4
LHeC	ep, $\sqrt{s}$ = 1.3 TeV, L= 1 $\times 10^{34}$	Oliver Bruening (oliver.bruening@cern.ch)	AF4
FCC-eh	ep, $\sqrt{s}$ = 3.5 TeV, L= 1 $\times 10^{34}$	Oliver Bruening (oliver.bruening@cern.ch)	AF4
CEPC-SPPpC-eh	ep, $\sqrt{s}$ = 6 TeV, L= 4.5 $\times 10^{33}$	Y.Zhang (yzhang@jlab.org)	AF4
VHE-ep	ep, $\sqrt{s}$ = 9 TeV		AF4
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s}$ = 1.5 TeV, L= 1 $\times 10^{34}$	D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s}$ = 3 TeV, L= 2 $\times 10^{34}$	D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s}$ = 10 – 14 TeV, L= 20 $\times 10^{34}$	D.Schulte (daniel.schulte@cern.ch)	AF4
MC – Positron Driver	$\mu\mu$, $\sqrt{s}$ = 10 – 14 TeV, L= 20 $\times 10^{34}$	D.Schulte (daniel.schulte@cern.ch)	AF4
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven plasmas; e+e-, $\sqrt{s}$ = 1 – 30 TeV	Carl Schroeder (CBSchroeder@lbl.gov)	AF6
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven plasmas; e+e-, $\sqrt{s}$ = 1 – 30 TeV	Gessner, Spencer J. (sgess@slac.edu)	AF6
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s}$ = 1 – 30 TeV	Chunguang Jing (jingchg@anl.gov)	AF6

T. Roser. Implementation Task Force

Snowmass 2021: EF Benchmark Scenarios

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
		1.5 TeV	$\pm80/0$	2.5
		3.0 TeV	$\pm80/0$	5
CEPC	ee	M_Z		16
		$2M_W$		2.6
		240 GeV		5.6
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Muon collider at a very high energy (>30 TeV?)[Need to consolidate g list of c.o.m. energies]
- FCC pp >200 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- Other emerging ideas: γ-γ collider, C^3 e^+e^- collider [C3=Cool Copper Collider]

M. Narain. Energy frontier restart workshop.

Questions: Theorists <-> AF

- T->A:
    - The more (larger) the better.
    - But obviously there are constraints.
    - What is even remotely possible?
    - What's promising?
- A->T: What's needed? (more on this)

Theorists -> AF: physics goals

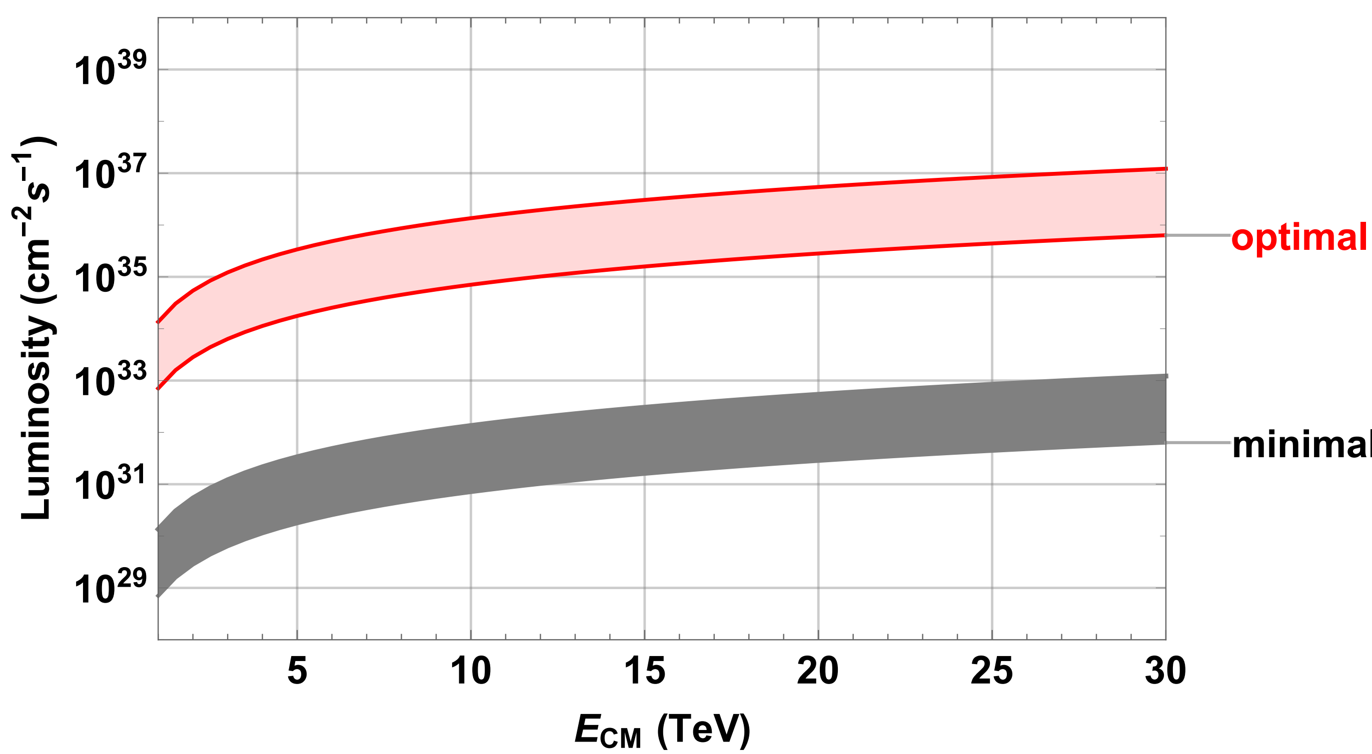
- Good consensus in the community.
  - Main physics drivers: Higgs, dark matter.
- Higgs.
  - couplings: precision measurement
  - naturalness: direct production (higher energy)
- Dark matter
  - WIMP: higher energy
  - dark sector: intensity
- Others: flavor physics, QCD, ...

Theorists -> AF: physics studies

- Theorists can contribute: first looks, estimates, quick pheno studies.
- Available studies.
  - European Strategy updates
  - CDR/TDR: ILC/CLIC/CEPC-SppC/FCC(hh, ee, eh)
  - muon collider forum + studies
- Still needed to get started.
  - high energy pp, photon collider.

Theorists -> AF:
physics goals vs luminosity (polarization…)

- Different physics goals need different machine parameters
  - For example: at high energy lepton colliders:
    - Discovery of heavy new physics particles and Higgs coupling measurements can require very different luminosities.



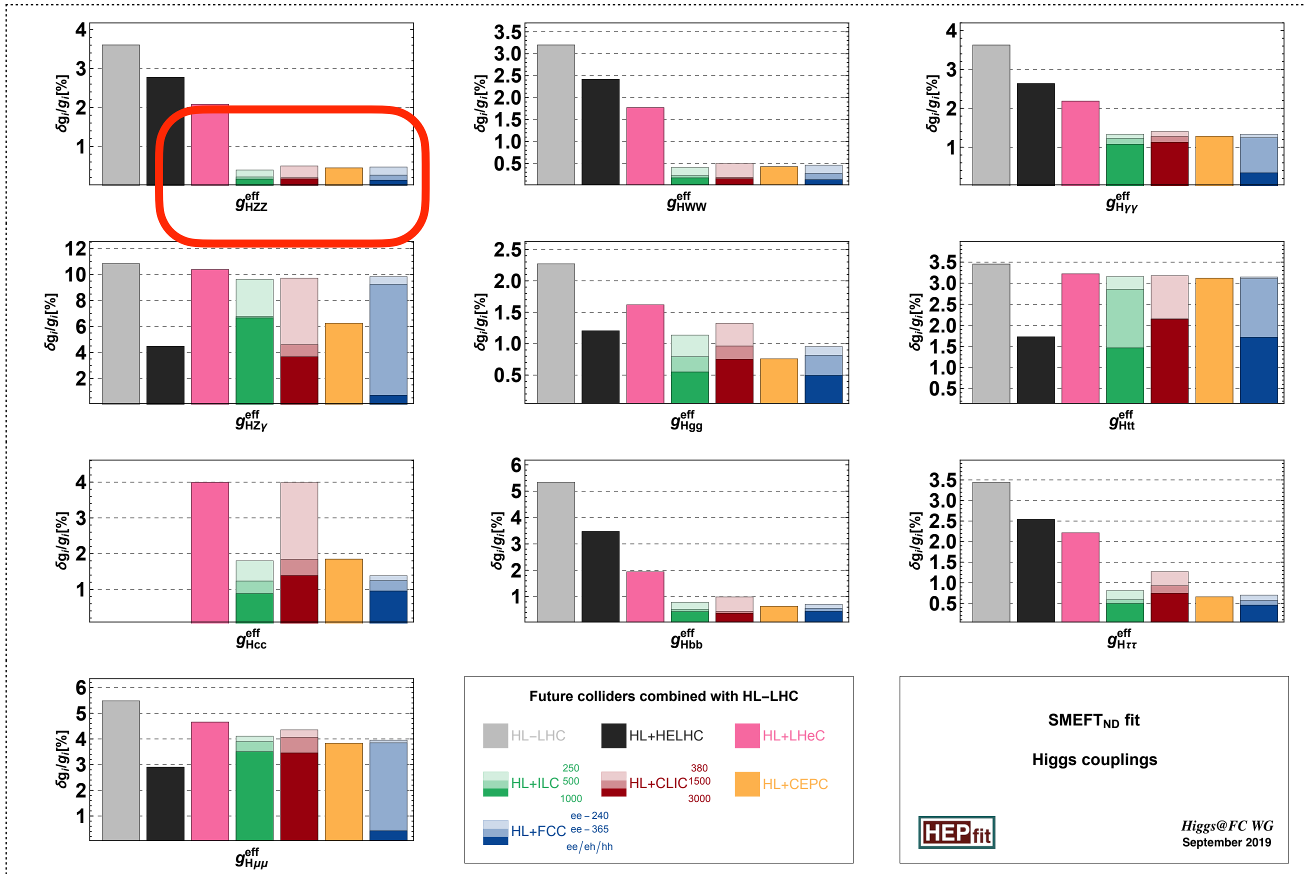
Clarifying further such trade-offs can be very beneficial

Comments, questions, requests?

Extra

Higgs coupling

European Strategy Physics Briefing book



Muon smasher's guide

	Fit Result [%]	
	10 TeV Muon Collider	with HL-LHC
κ_W	0.06	0.06
κ_Z	0.23	0.22
κ_g	0.15	0.15
κ_γ	0.64	0.57
$\kappa_{Z\gamma}$	1.0	1.0
κ_c	0.89	0.89
κ_t	6.0	2.8
κ_b	0.16	0.16
κ_μ	2.0	1.8
κ_τ	0.31	0.30

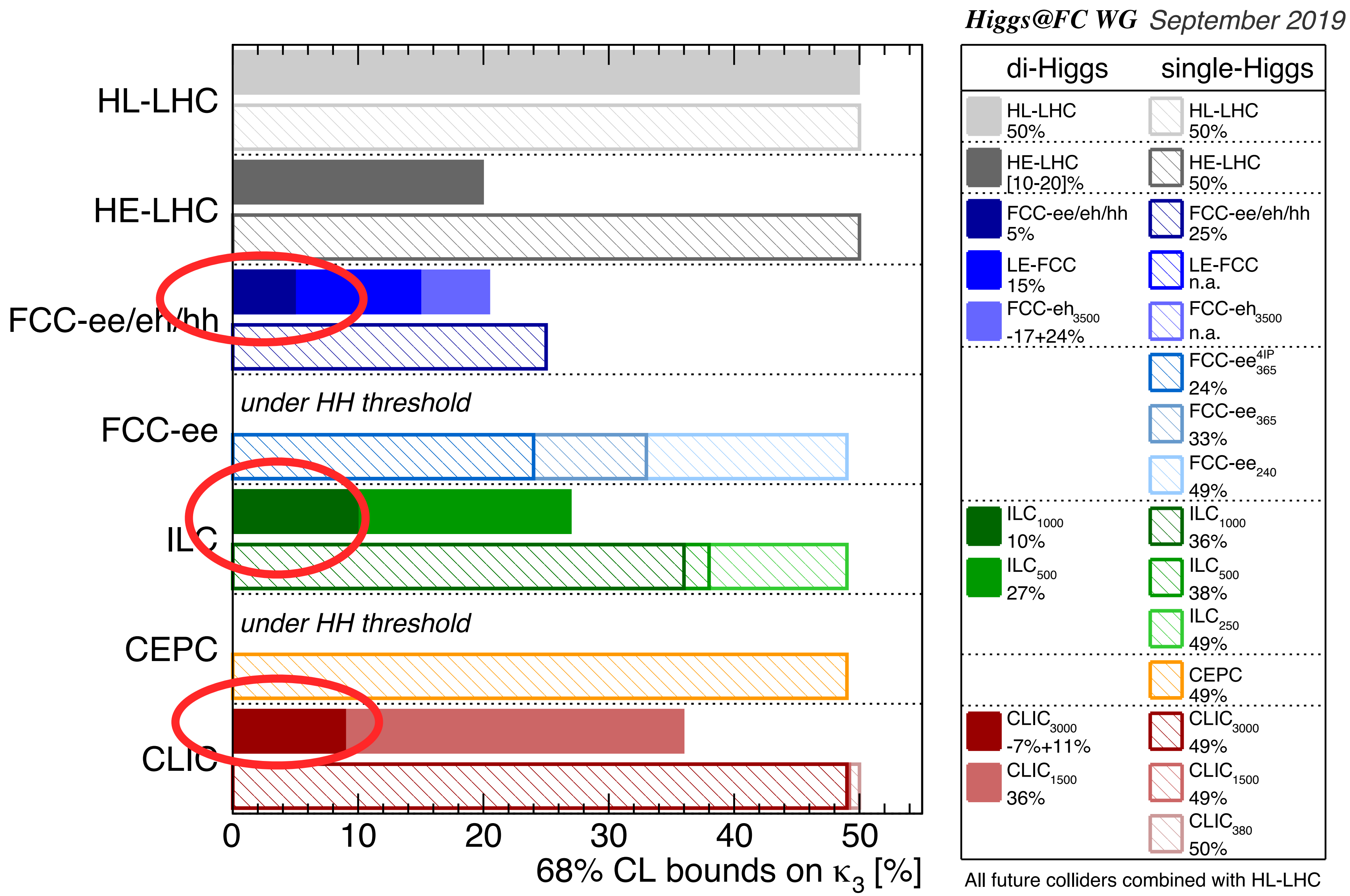
10^{-3} or better possible

Precision scale (roughly) with (# of Higgs)$^{-1/2}$

Low energy Higgs factories (Zh)
High energy (> 600 GeV) lepton colliders (WW fusion)
Sensitive to different couplings.

Measurement at lepton collider more model independent: width, Zh coupling, ...
Tera Z (and ttbar threshold) can improve significantly other EW precision measurements.

Higgs self-coupling

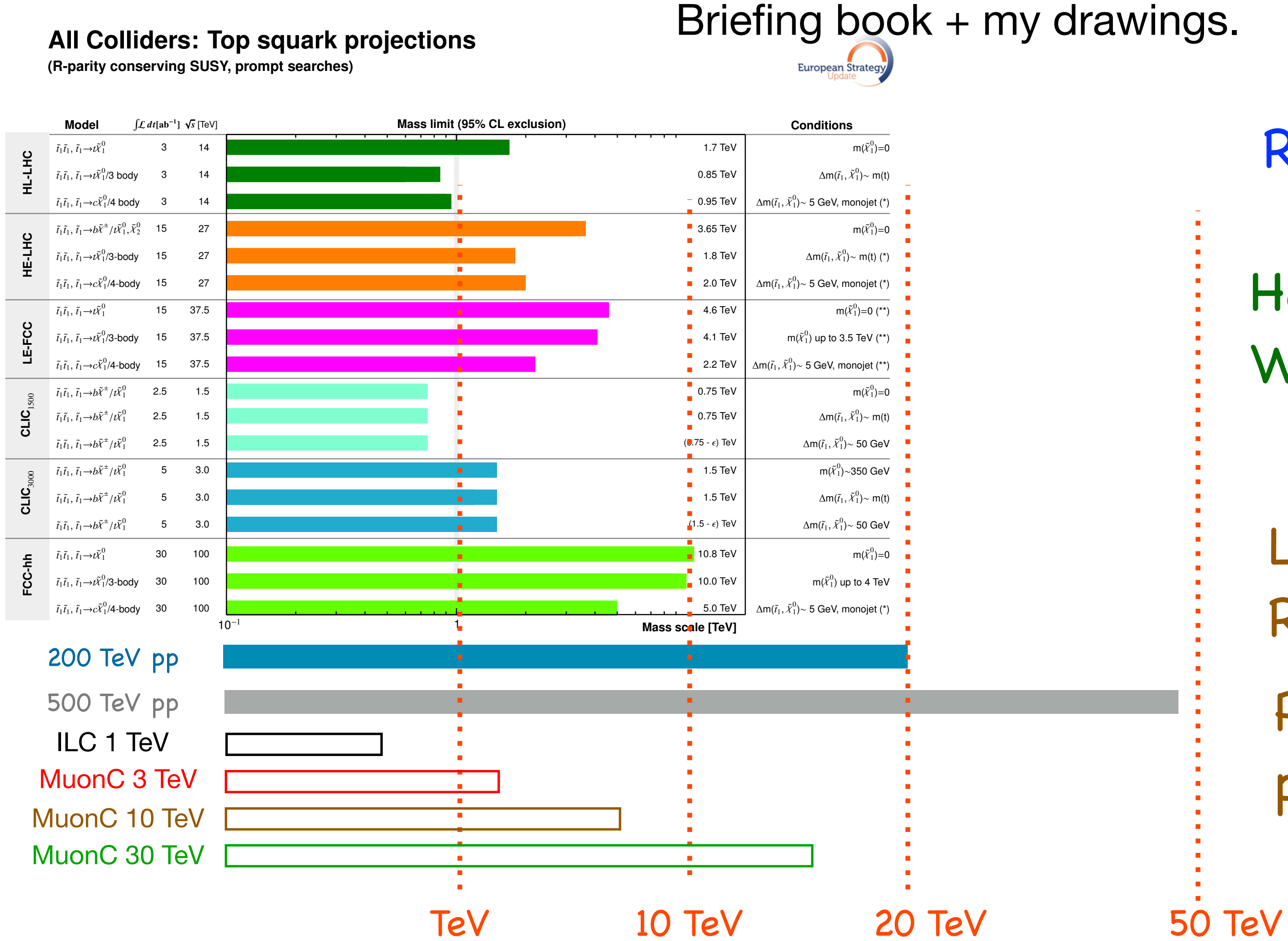


A few percent accuracy would cover most of the ground.

Higher energy collider needed:
TeV lepton collider, 100 TeV pp collider

Reach of SUSY stop

Briefing book + my drawings.



Reach for other top partners similar

Hadron collider reach ≈ 10% of E_{CM}

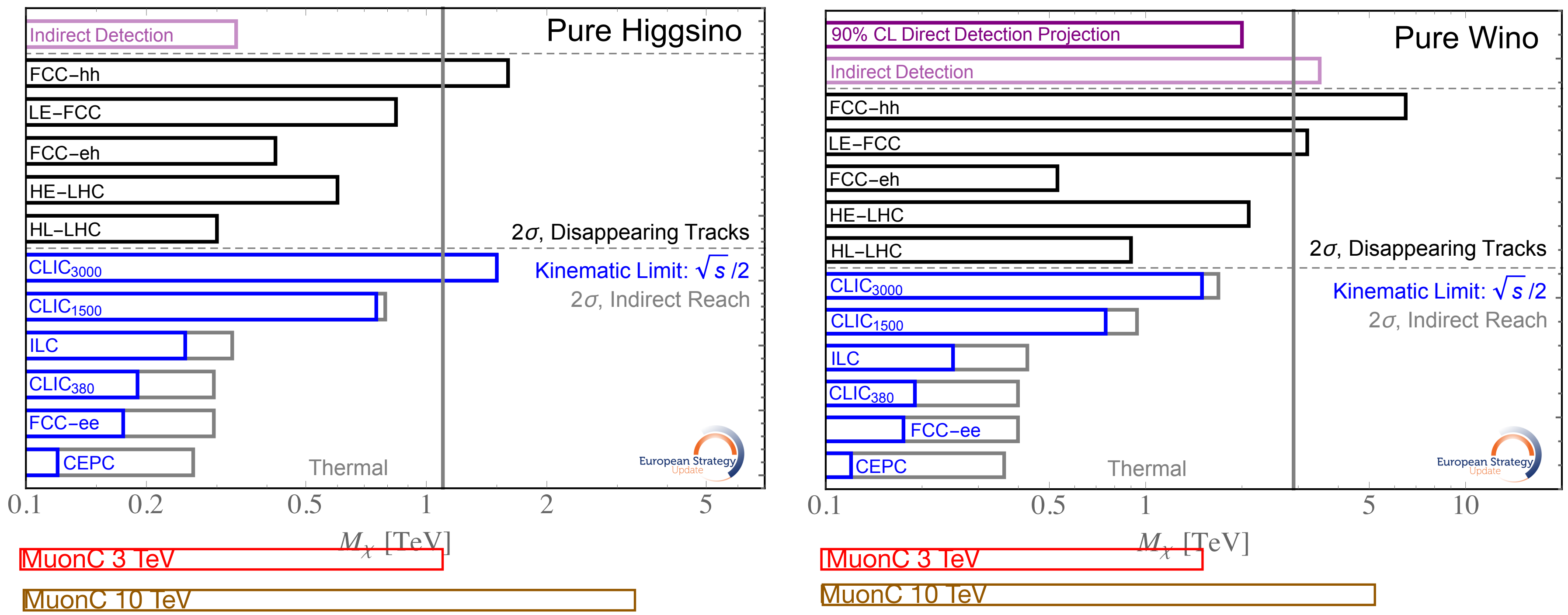
Weaker if new physics without strong int.

Lepton collider reach ≈ $0.5 \times E_{CM}$

Reach for other new physics similar.

Photon collider similar, but only for produce charged particles.

Dark matter reach



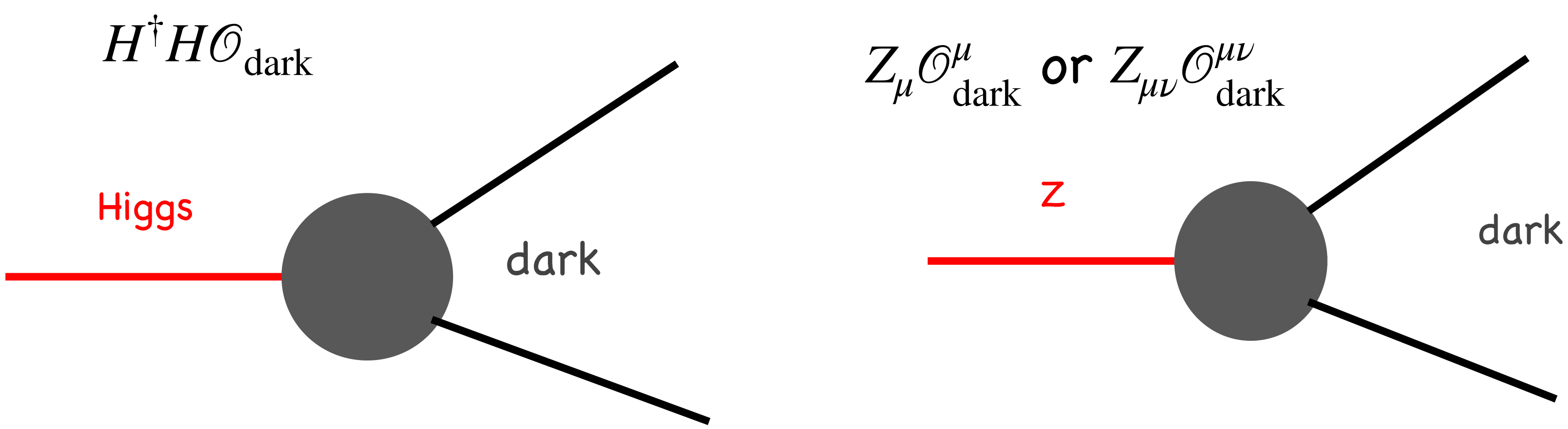
briefing book + my drawings for muon (or lepton) colliders.

Simplest WIMP model, very predictive, definitive target mass ≈ TeVs.
Out of reach for LHC, difficult for direct detection.

Lepton collider reach close to $0.5 \times E_{CM}$ (a little less), need 10(s) TeV and hi lumi
Hadron collider ≈ a few percent × E_{CM} , need 100 (or more) TeV

Windows into dark sector: portals

- SM particle can in principle have small couplings to dark matter/ dark sector. In particular:



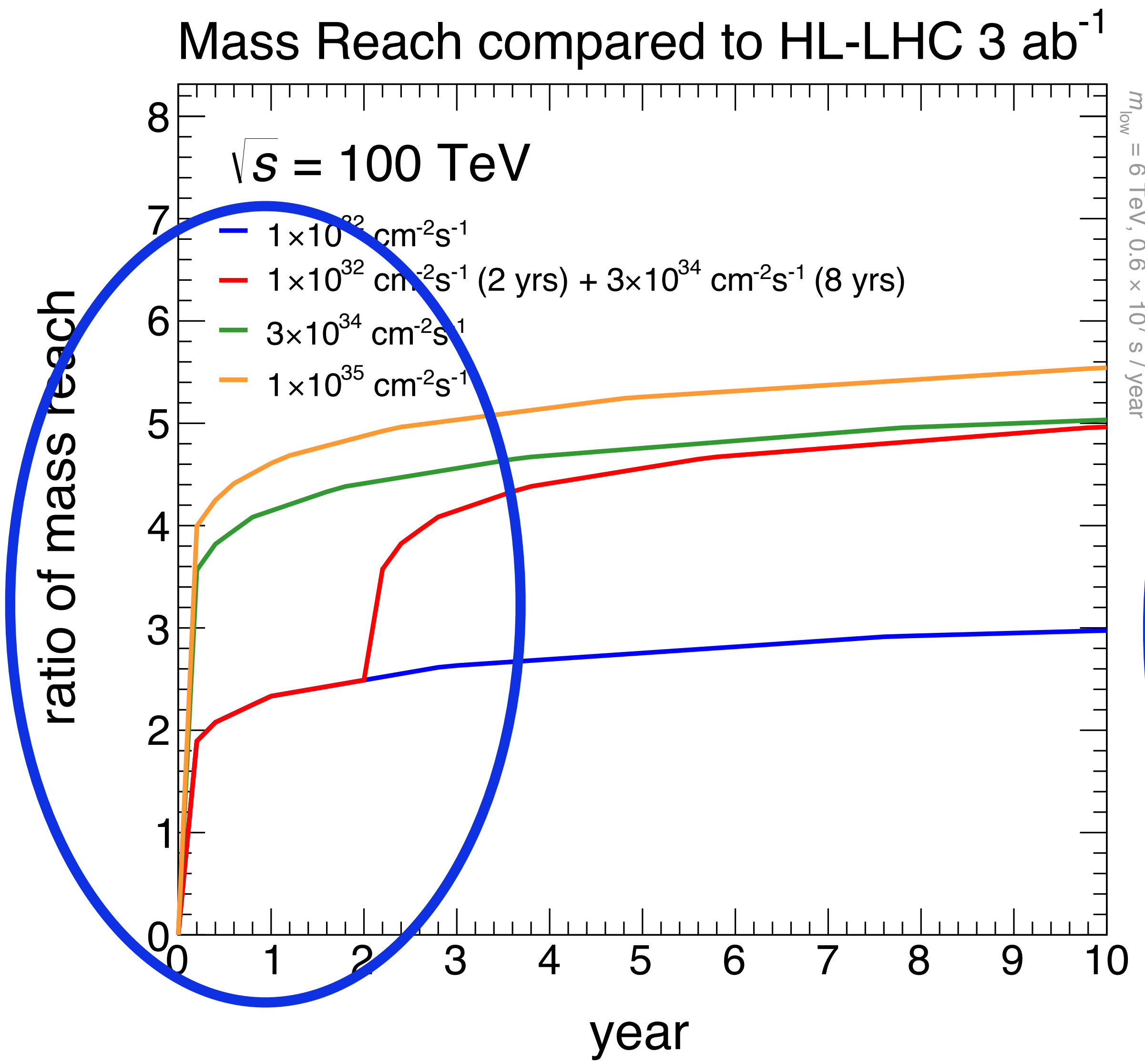
Higgs/Z factories, sensitivity to Higgs/Z rare decays determined by the number of Higgs/Z produced.

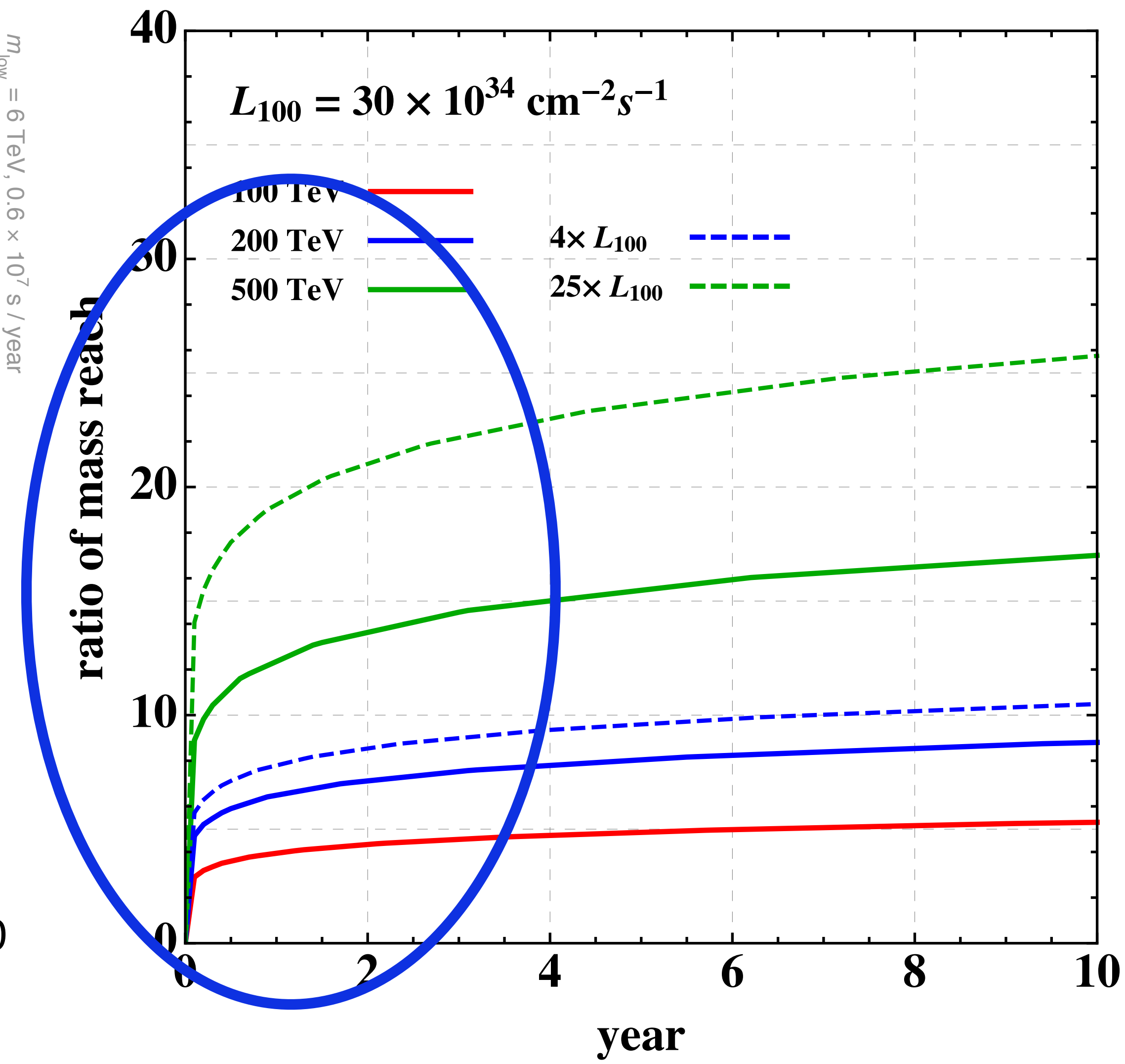
Rough estimates, if interaction is mediated by some 10(s) TeV new physics

Br(h→dark) $\sim 10^{-2}$ to 10^{-3}. Higgs factory sensitivity up to 10^{-5}. Hadron collider produces much more Higgses (better potential if decay distinct).

Br(Z→dark) $\sim 10^{-4}$ to 10^{-5}. Tera-Z sensitivity up to 10^{-11} .

Hadron collider scenarios





Rapid gain in mass reach

10^{34} cm^{-2}s^{-1} doing a reasonable job for 100 TeV.

Need higher luminosity for Higgs self-coupling.

10^{35}–10^{36} cm^{-2}s^{-1} may be needed for higher energies.

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Lepton collider scenarios

A possible minimal scenario: can produce at least 10 signal event for weak scale cross section. Can do "basic" new physics searches and cover interesting scenarios.

Will miss some important physics. Maybe only a good starting point.

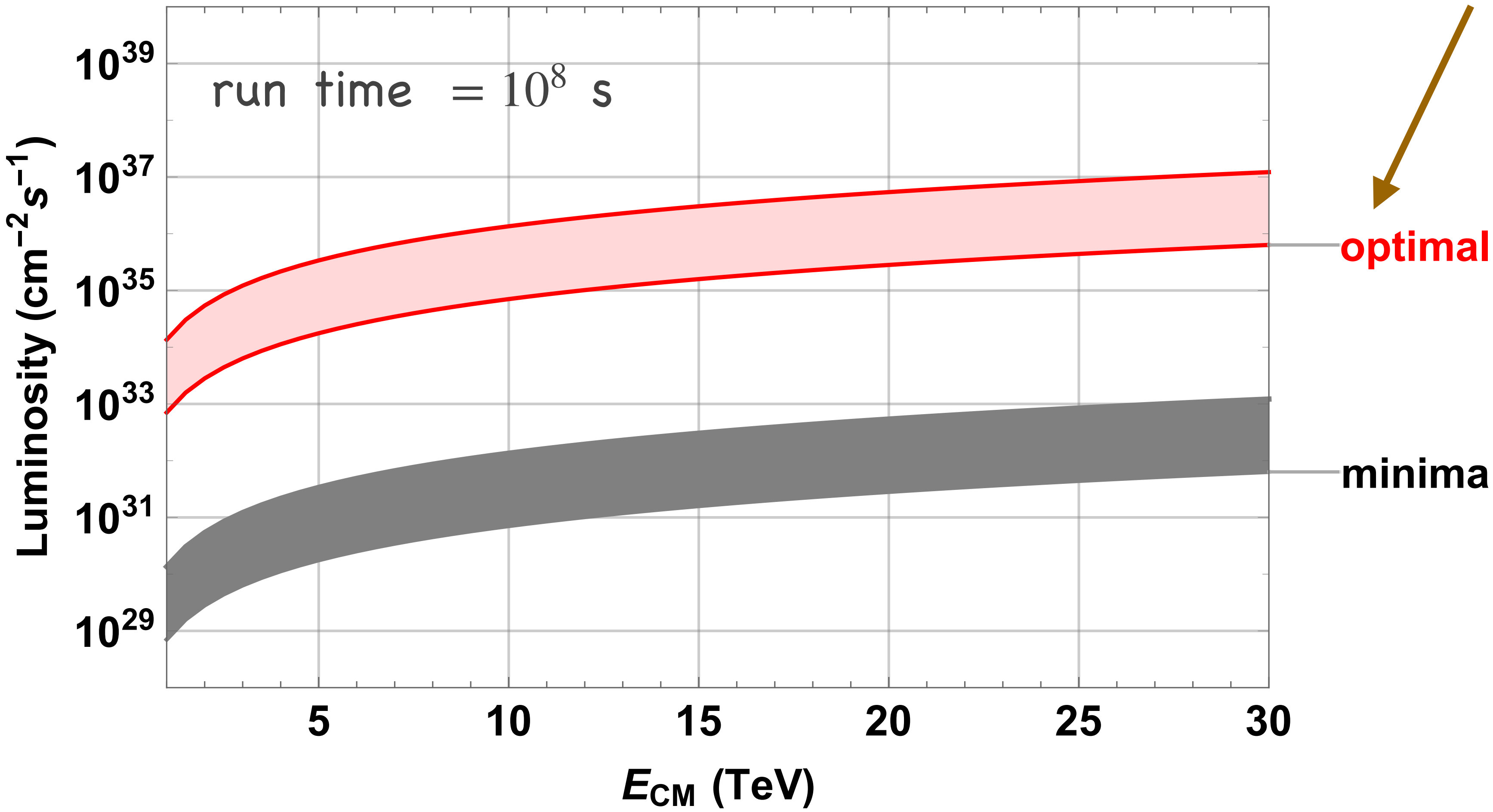
"Optimal" scenario: can cover as many difficult cases as possible, such as the dark matter searches.

Some choices needed here, but the basic wishlist is quite commonly accepted.

Lepton collider luminosities

- For both muon and electron (photon collider similar)

Based on electroweak cross section.
Bands represent O(10) variation in signal rate



$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2 \times 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$$

Both scales as $\mathscr{L} \propto E_{\text{CM}}^2$, minimal $\sim 10^{-4} \times$ optimal

Summary

Higgs:

Precision measurement: 10^6 Higgs at lepton collider or above need to achieve 10^{-3} accuracy.
Tera-Z (also ttbar) can help a lot.

Self coupling, percent measurement.
TeV lepton collider, 100 TeV pp collider

New physics, aiming at 10s TeV.
10(s) TeV lepton collider and/or 100(s) TeV pp collider

Dark matter:

WIMP, target mass TeV(s)
10(s) TeV lepton collider, 100(s) TeV pp collider

Dark sector.
rare decay of Higgs (br $< 10^{-3}$) and Z (br $< 10^{-4}$).
Sensitivity proportional to # of Higgs/Z produced.
Higgs factories, Tera Z, and hadron colliders