AF ⇔ theory

LianTao Wang
University of Chicago

Snowmass Theory Frontier Workshop. KITP, Santa Barbara. Feb 24, 2022

AF–TF connection

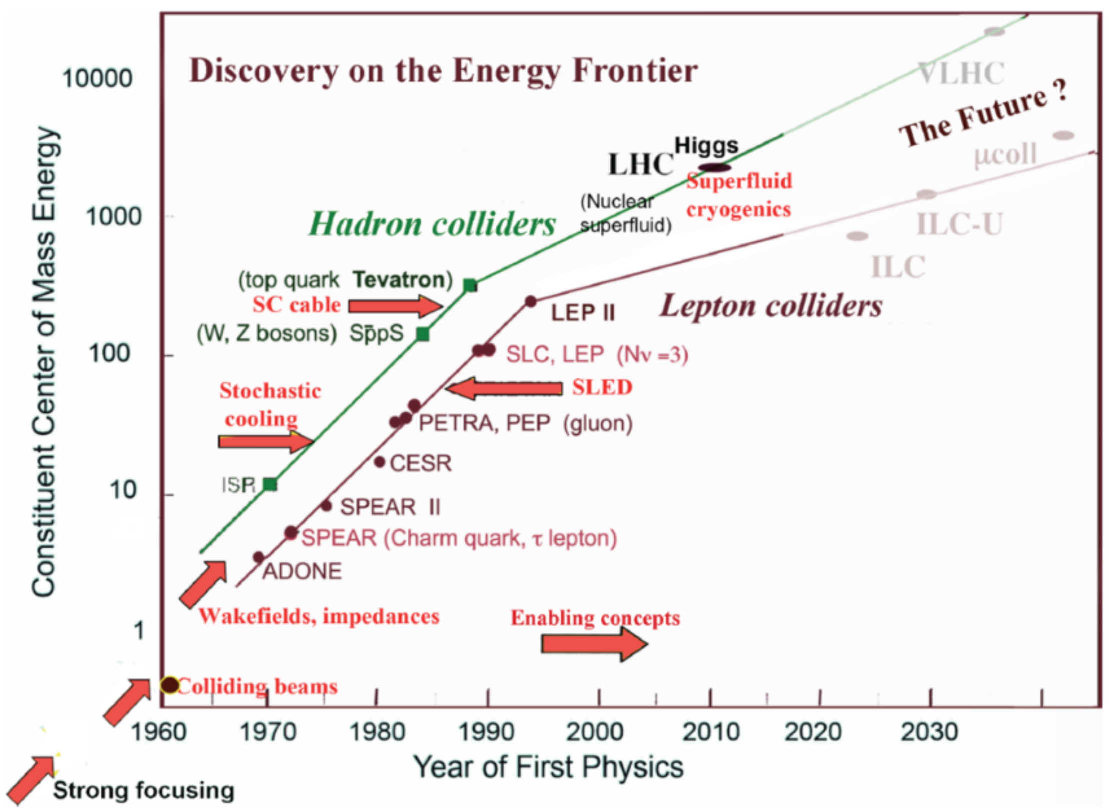
TF: theory advances $\Rightarrow$ fundamental questions

AF-TF connection

TF: theory advances ⇒ fundamental questions

⇕

- Physics is an experimental science.
  - Big accelerator facilities have been and will continue to be front and center for the future advances.
  - Testing theory ideas, discoveries lead to new theories.



AF-TF connection

TF: theory advances $\Rightarrow$ fundamental questions

$$\Updownarrow$$

- Physics is an experimental science.
  - Big accelerator facilities have been and will continue to be front and center for the future advances.
  - Testing theory ideas, discoveries lead to new theories.

$$\Updownarrow$$

AF: accelerators design, feasibility, cost, ...

Accelerator Frontier

Frontier Conveners

Name	Institution	email
Steve Gourlay	Lawrence Berkeley National Laboratory	sagourlay[at]lbl.gov
Tor Raubenheimer	SLAC National Accelerator Laboratory	tor[at]slac.stanford.edu
Vladimir Shiltsev	Fermi National Accelerator Laboratory	shiltsev[at]fnal.gov

Description

The Accelerator Frontier activities include discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for the "Physics Beyond Colliders", accelerator technologies, science, education and outreach as well as the progress of core accelerator technology, including RF, magnets, targets and sources. Participants will submit LoI, contributed papers, take part in corresponding workshops and events, contribute to writing summaries and take part in the general Snowmass'21 events.

Each AF Working group will address the overall questions:
1. What is needed to advance the physics?
2. What is currently available (state of the art) around the world?
3. What new accelerator facilities could be available on the next decade (or next next decade)?
4. What R&D would enable these future opportunities?
5. What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facility?

Topical groups, Group Conveners, and Liasons

- **AF1: Beam Physics and Accelerator Education**
- **AF2: Accelerators for Neutrinos**
- **AF3: Accelerators for EW/Higgs**
- **AF4: Multi-TeV Colliders**
- **AF5: Accelerators for PBC and Rare Processes**
- **AF6: Advanced Accelerator Concepts**
- **AF7: Accelerator Technology R&D**
  - AF7-RF : RF Accelerator Technology R&D

+ implementation task force (ITF)

White papers in TF in this area

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	
Opportunities for theory studies with public collider	
Fully differential likelihood techniques	
BSM Signatures	
Ultra-exotics and forgotten signatures at colliders N	
Model dependent vs. model independent approach	

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

i	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	

Focus: theoretical techniques

Full list of white papers

Theory and future collider

- No dedicated discussion on the experimental (accelerator) facilities within the TF.
  - More in the energy frontier.

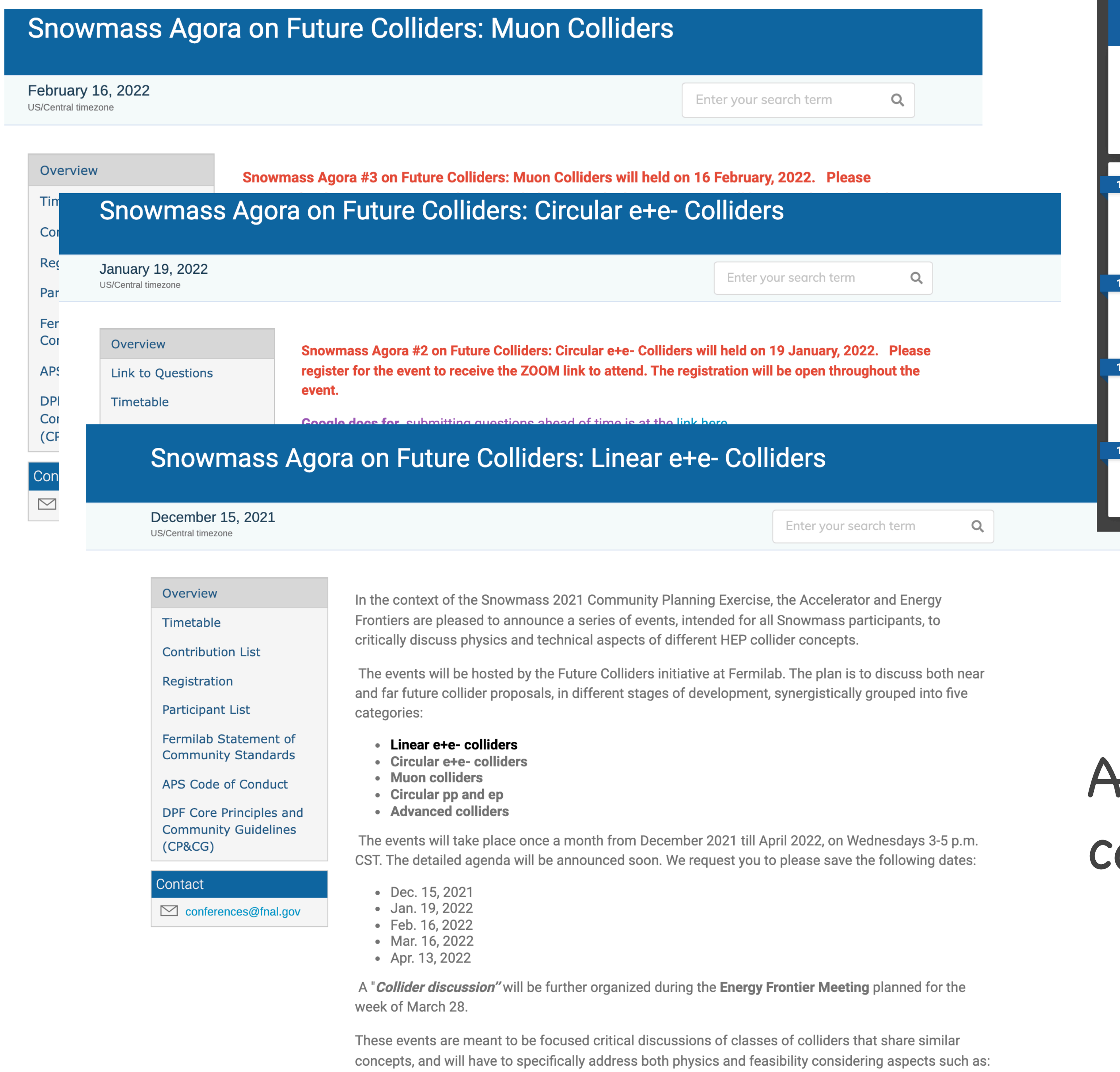
Involvement of theory

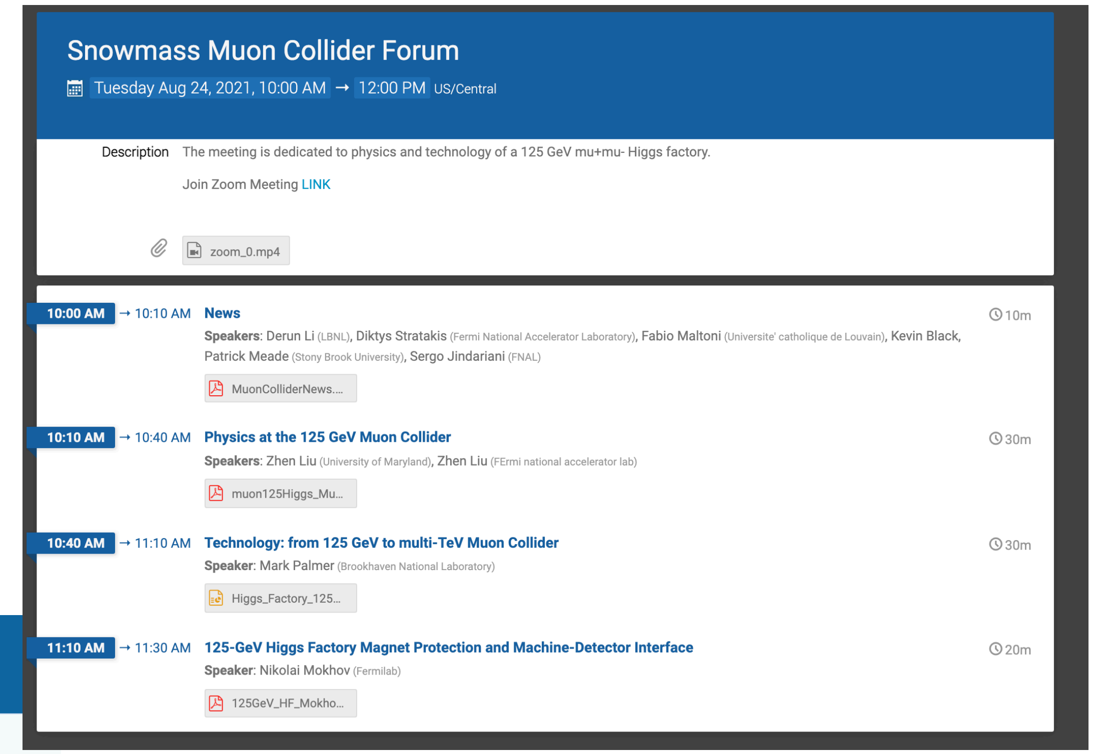
- No dedicated discussion on the experimental (accelerator) facilities within the TF.
  - More in the energy frontier.

At the same time:

- Future collider has been a focus for many theorists.

Many accelerator related activities in Snowmass 21





Active participation and contribution from many theorists

Theorists -> AF: physics studies

- Theorists contribute: first looks, estimates, pheno studies.
- Available studies.
  - European Strategy updates
  - CDR/TDR: ILC/CLIC/CEPC-SppC/FCC(hh, ee, eh)
  - muon collider forum + studies
- Still needed to do more.
  - photon collider, ep…

The rest of my talk

- Review the collider options which have been put forward.

- Briefly summarizes the physics cases have been laid out (so far).

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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
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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
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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
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T. Roser. Implementation Task Force

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Low energy lepton colliders
Higgs (Z) factories.
Also physics of WW, ttbar

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High energy lepton (photon) colliders
Mutli- to 10s TeV.

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pp collider, 100-ish TeV

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.

ITF will present

Possible Higgs factory comparison table

Proposal Name	Nominal COM energy (Range) [TeV]	Luminosity per IP at nominal COM energy [10^{34} cm^{-2} s^{-1}]	Years of pre-construction R&D required	Construction cost range, including explicit labor [2021 MUS$]	Estimated operating electric power consumption [MW]
FCC-ee	0.24 (0.09 - 0.37)	8.5			
CEPC	0.24 (0.09 - 0.24)	2.9			
ILC (Higgs factory)	0.25 (0.09 - 3)	1.35			
CCC (Cryo Cooled Collider)	0.25 (0.25 - 0.55)	1.3			
CLIC (Higgs factory)	0.38 (0.09 - 0.38)	1.5			
CERC (ERL ee collider)	0.24 (0.09 - 0.6)	78			
ReLiC (Linear ERL Collider)	0.24 (0.09 - 1.0)	115			
ERLC (ERL Linear Collider)	0.25	100			
XCC FEL-based $\gamma\gamma$ Collider	0.125 (0.125 - 0.14)	0.1			
Circular ee Fermi site filler	0.24	1.2			
TWLC Fermi site filler	0.25	1.4			
MC (Higgs factory)	0.13	0.01			

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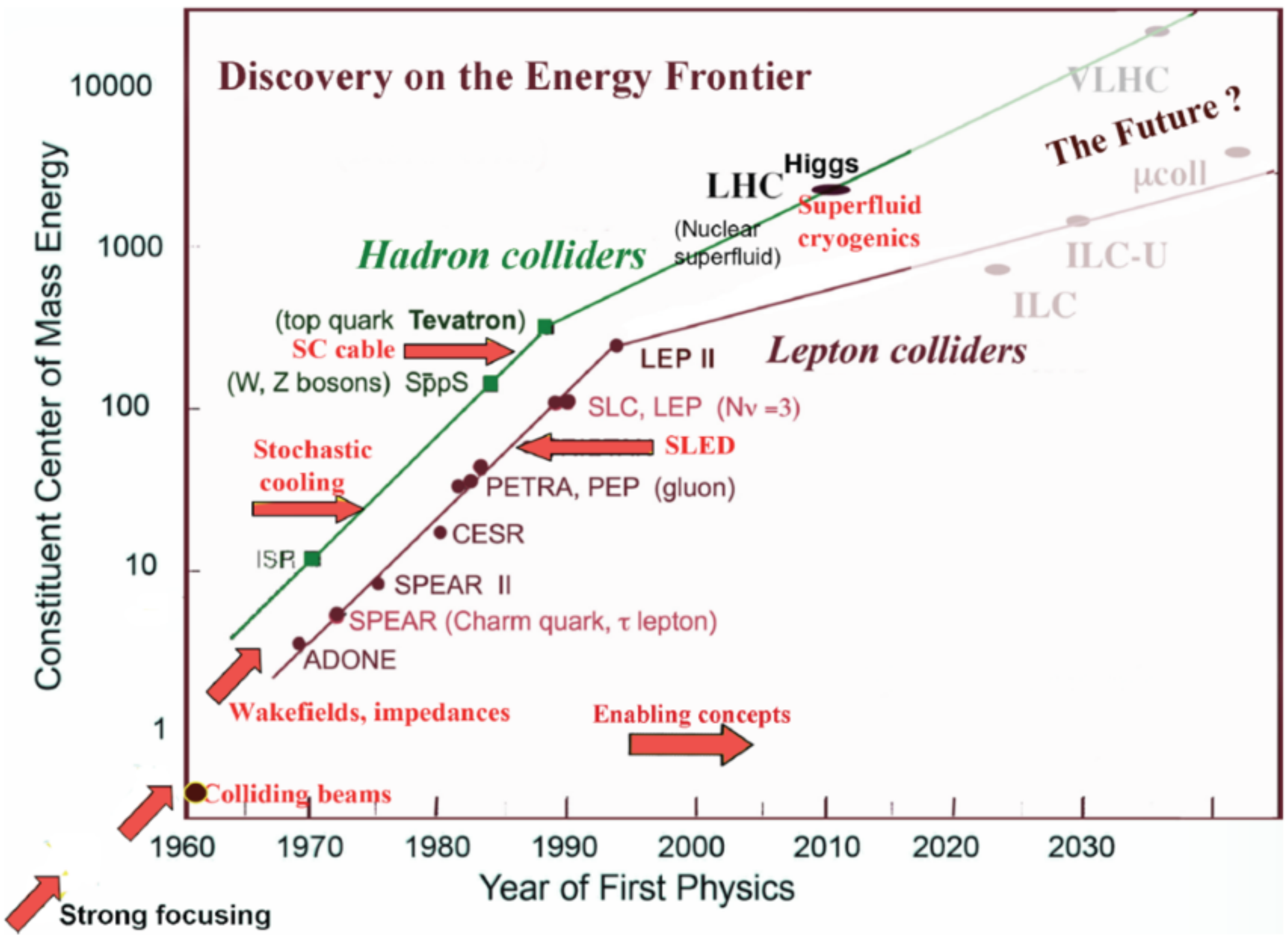
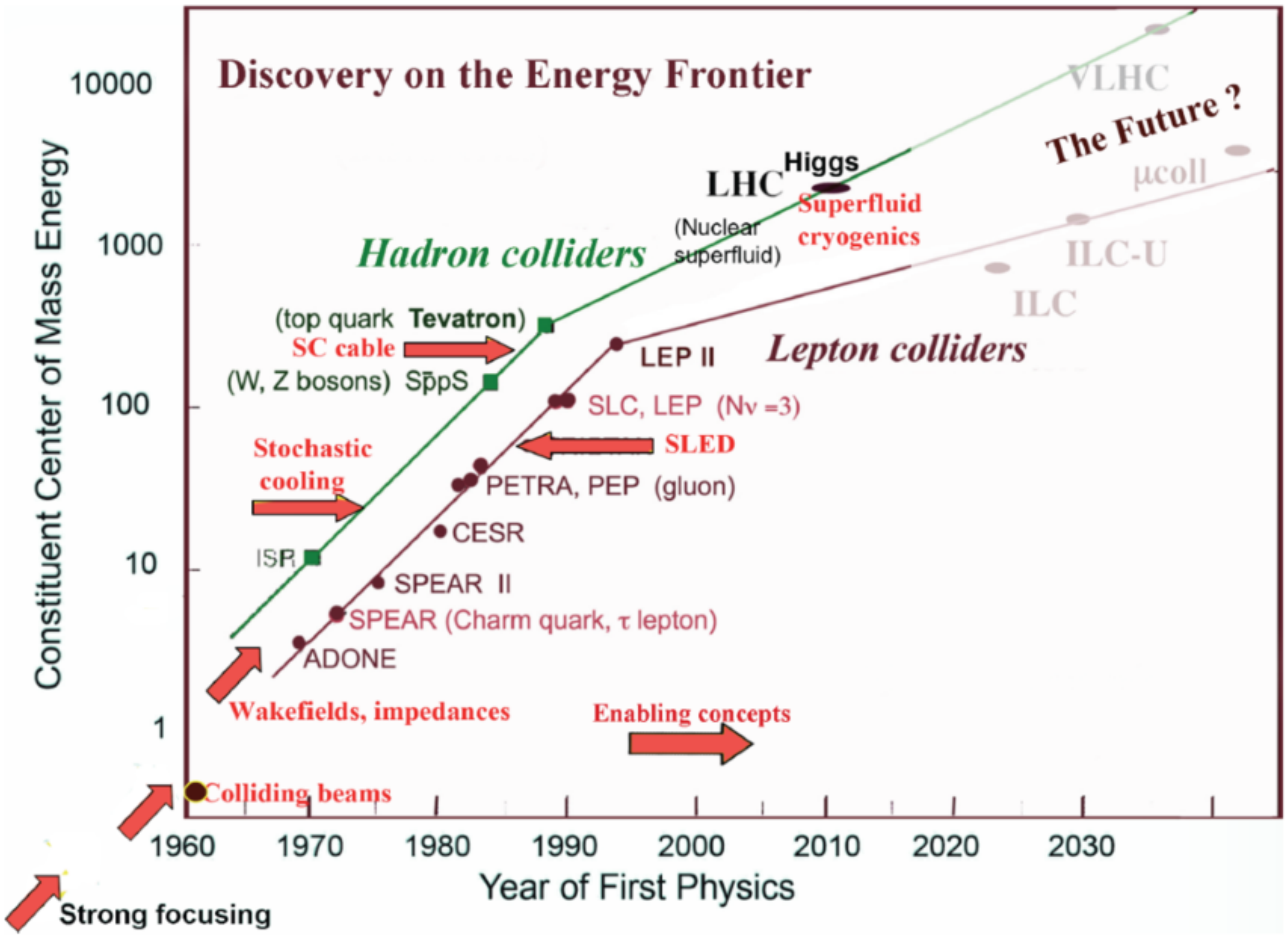
- Briefly summarizes the physics cases have been laid out (so far).

Frontiers: smaller distances



Tao Han: everything has a factory, Higgs needs one too!

Frontiers: smaller distances



Tao Han: everything has a factory, Higgs needs one too!

We all agree.
At the same time, useful to say more about the physics questions we would like these facilities to address.

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
- Rich physics program: portals, flavor physics, QCD, QFT tests, ...

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No guarantee to discover new particles, of course.
But, we will learn a lot.

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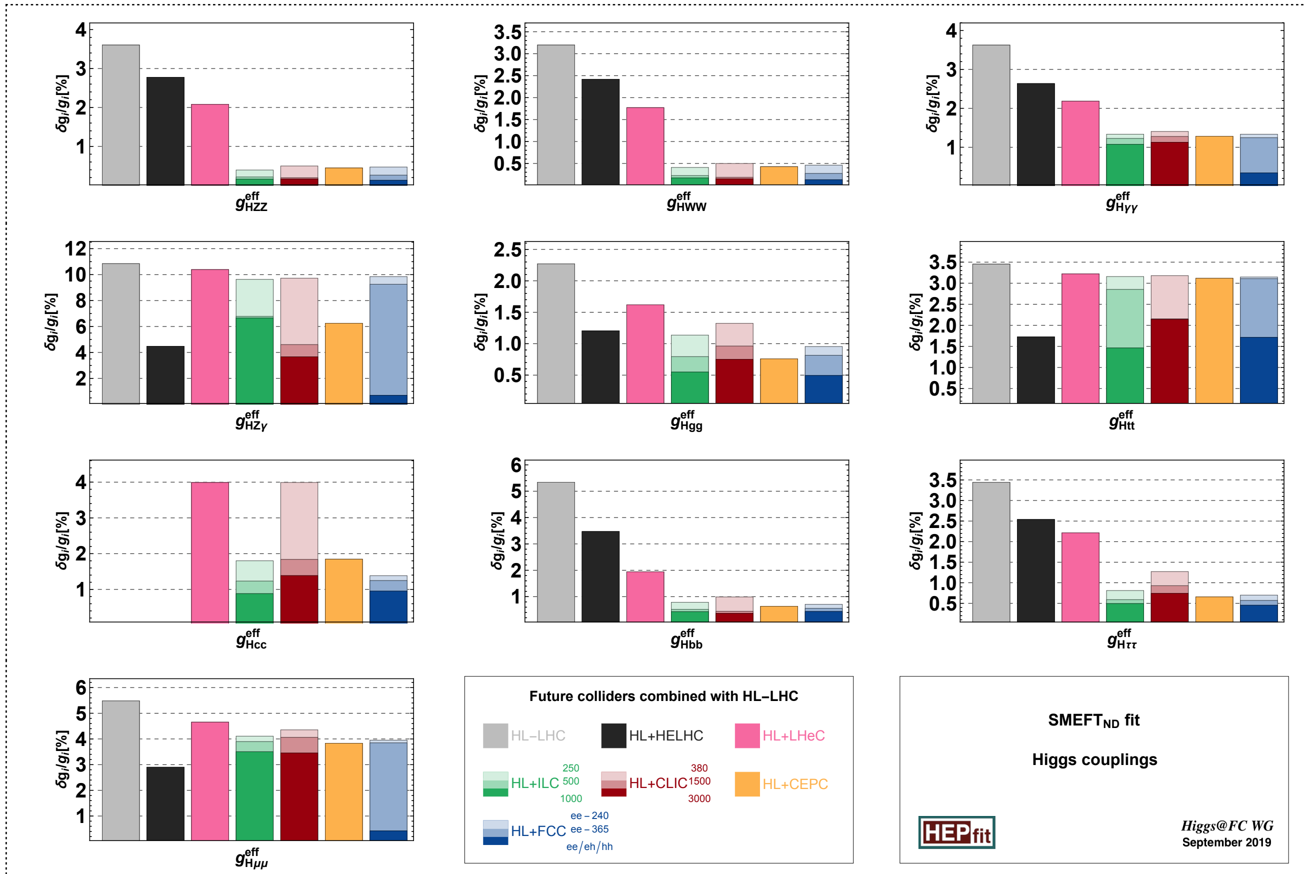
Higgs coupling

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

Higgs coupling

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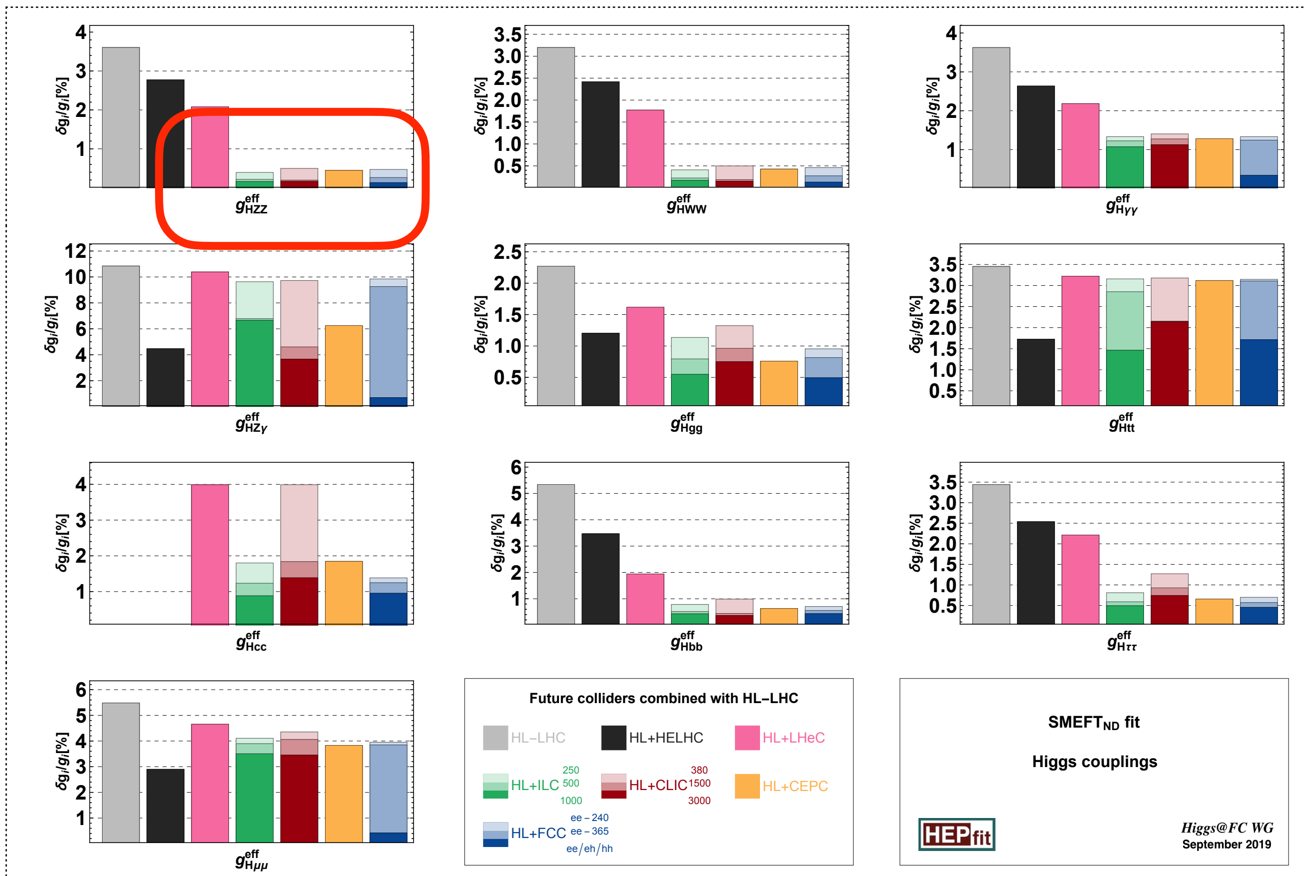

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10^{-3} or better possible

Higgs coupling

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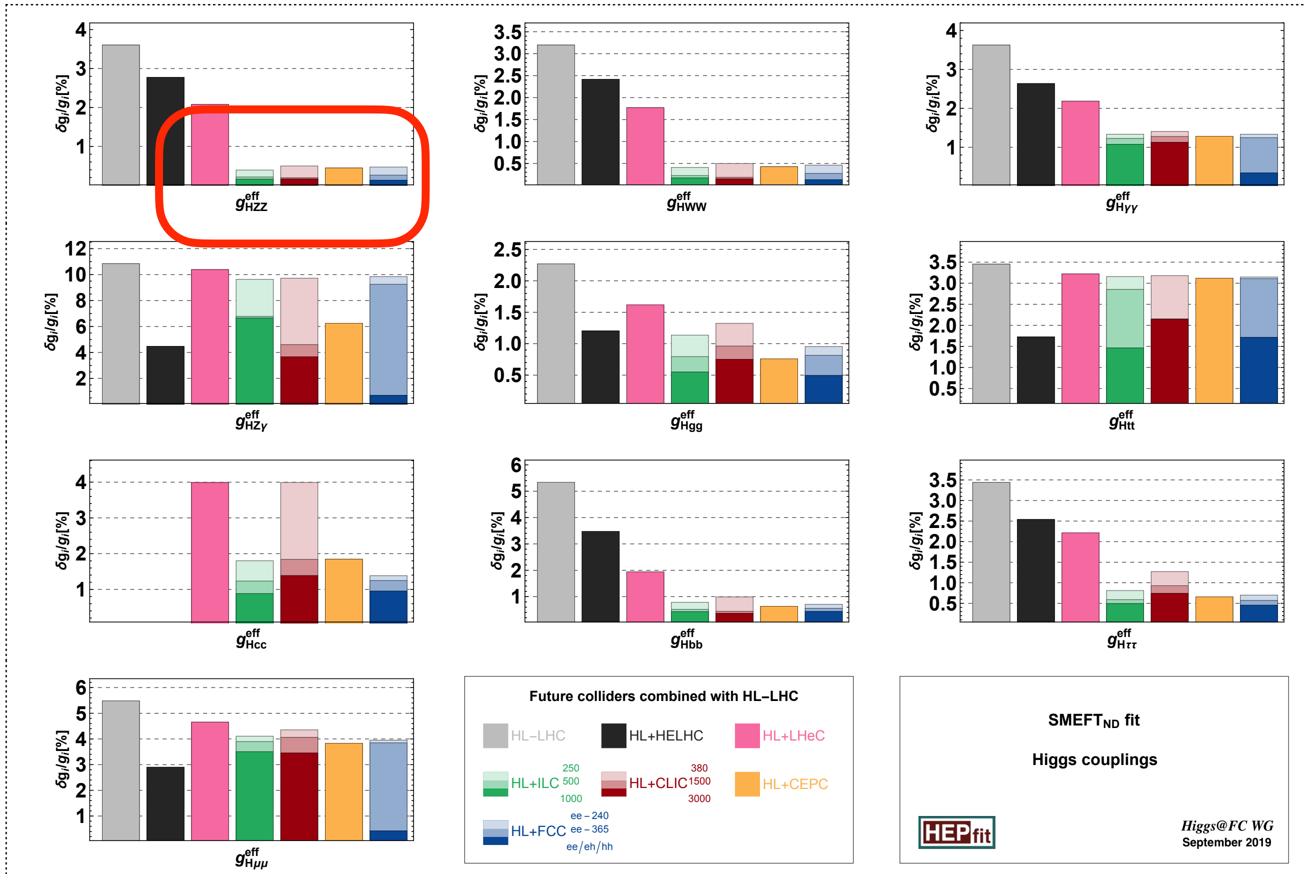

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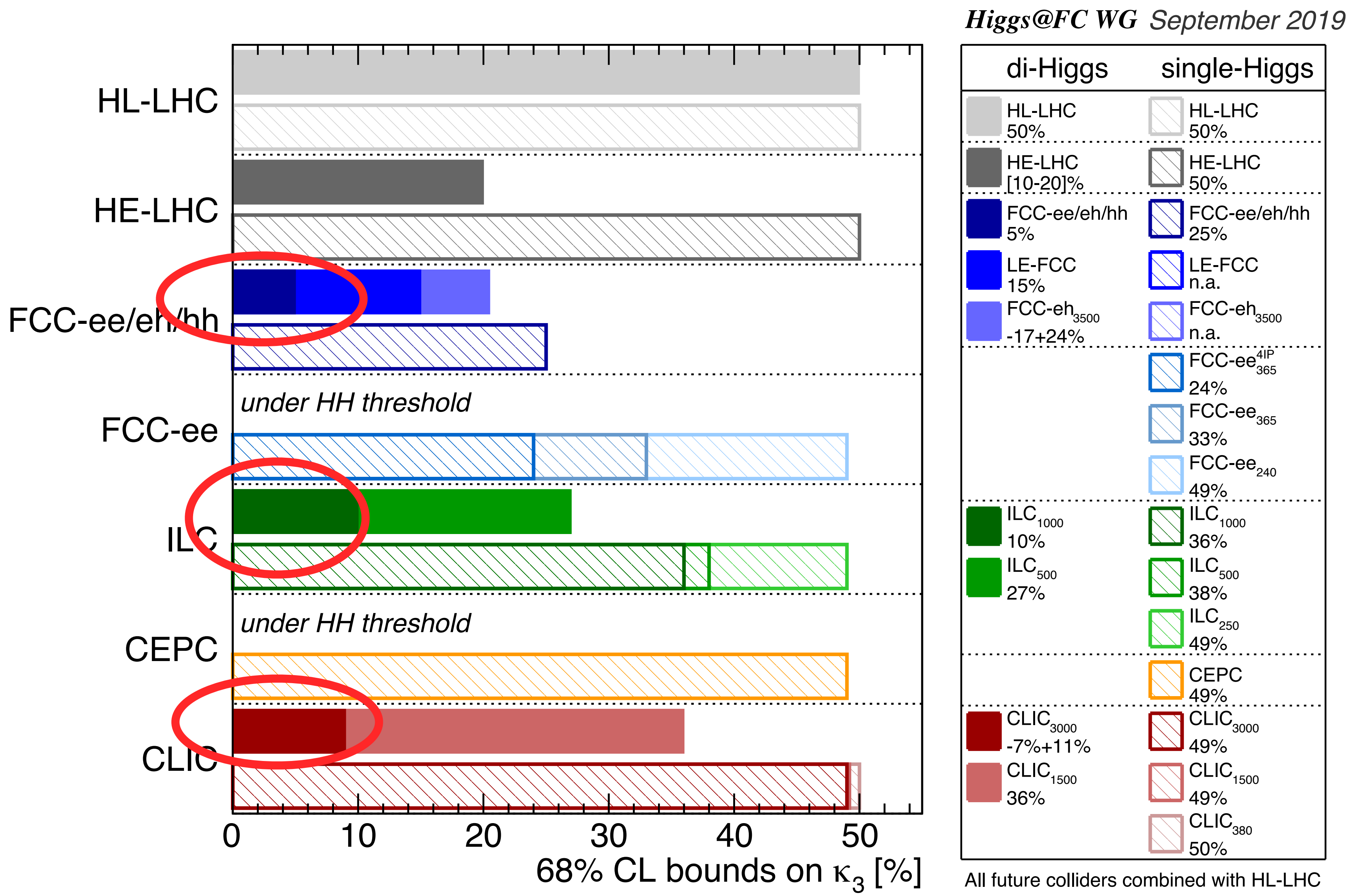
10^{-3} or better possible

At Higgs factories: Precision scale (very 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



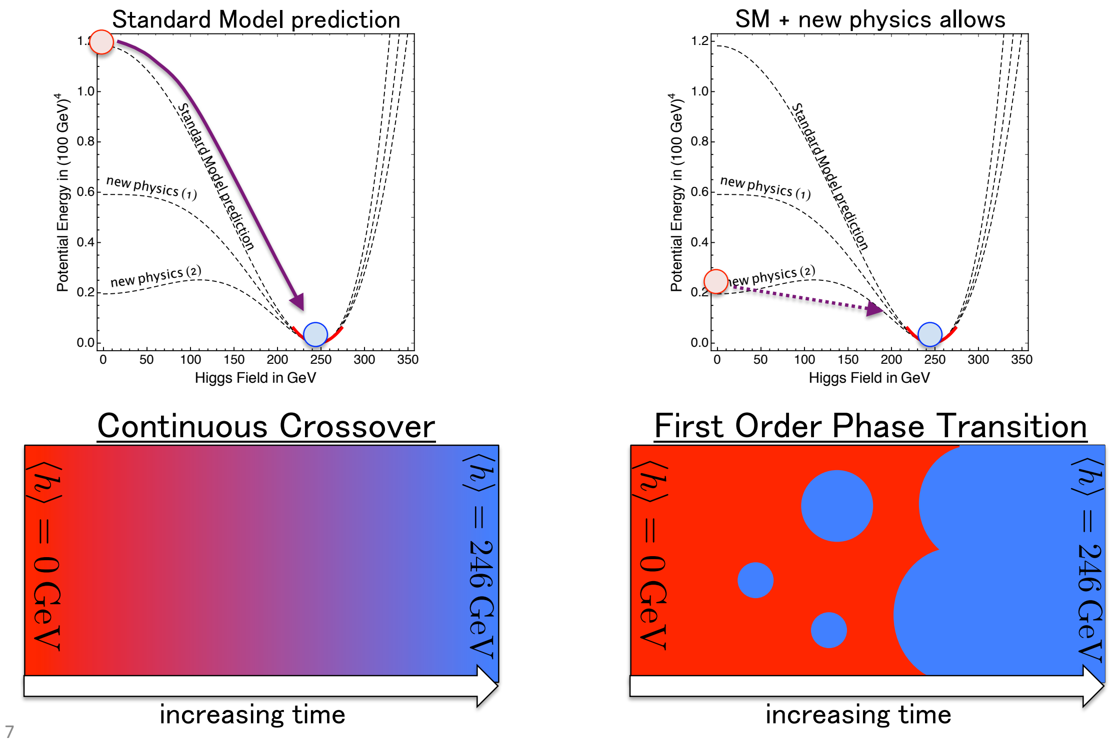
A few percent accuracy would cover most of the ground.

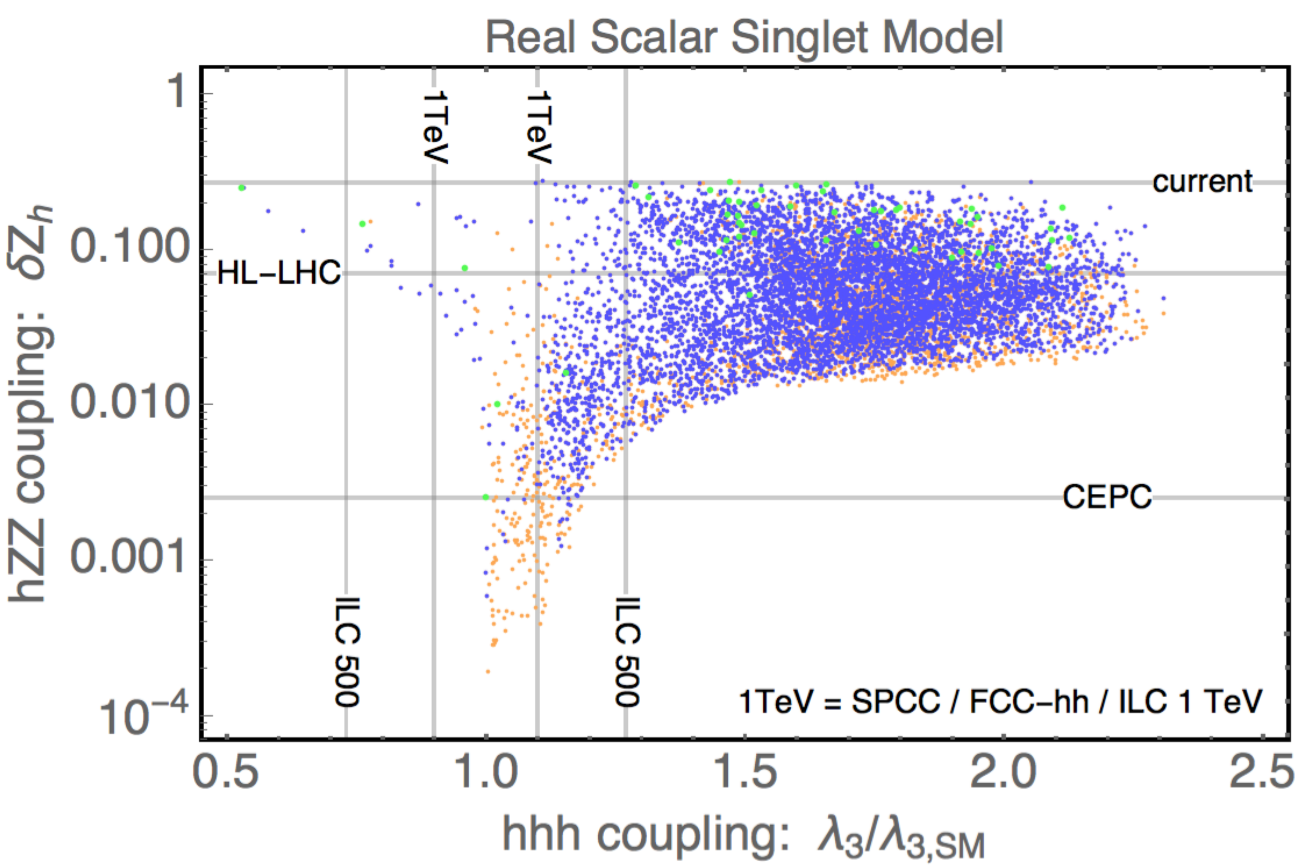
Higher energy collider needed:

TeV lepton collider, 100 TeV pp collider

Lesson: nature of EW phase transition

Which one is the right picture?

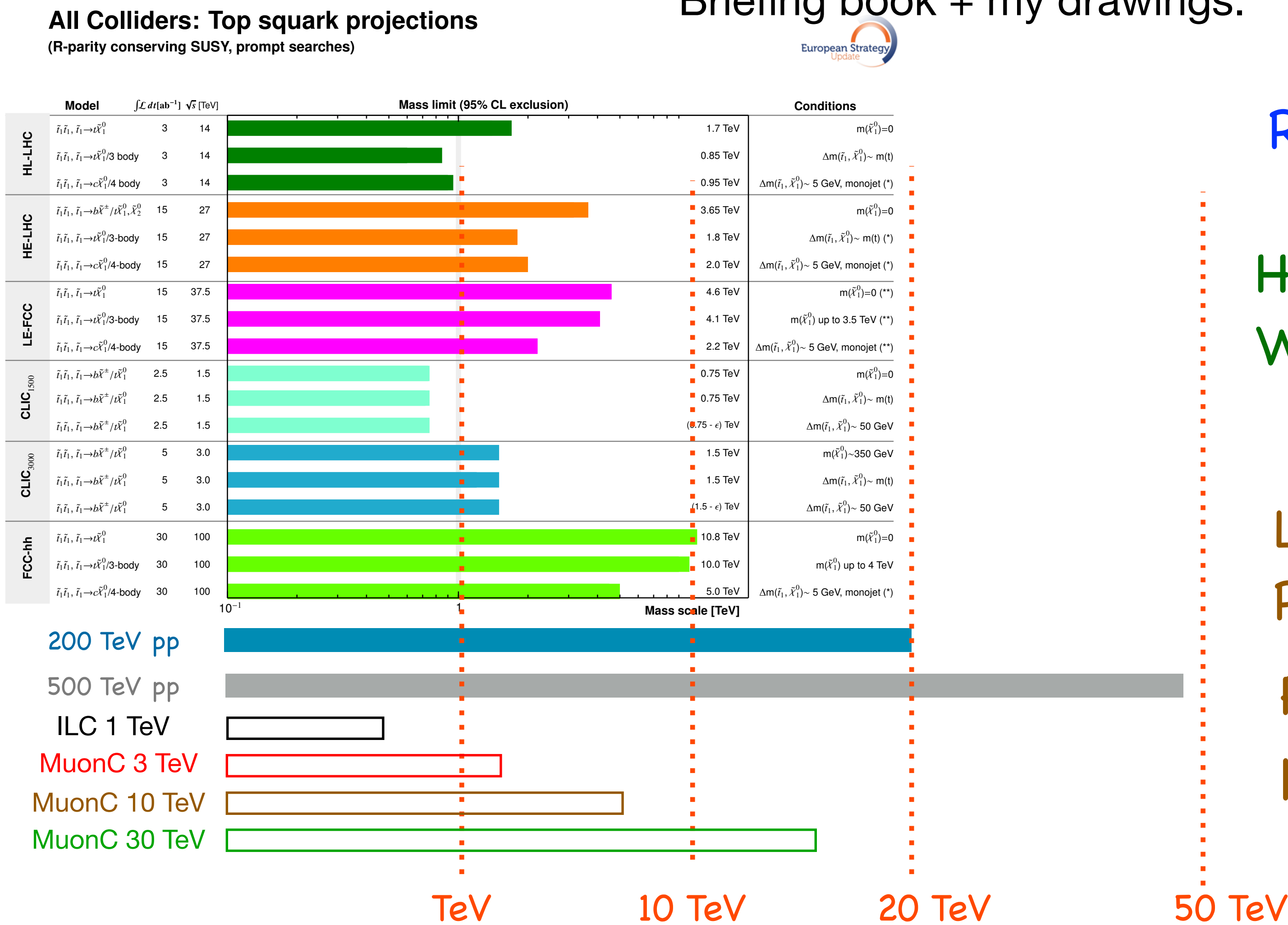




Precision Higgs measurements can reveal a lot

Reach of the top partners

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.

Motivated by the naturalness puzzle

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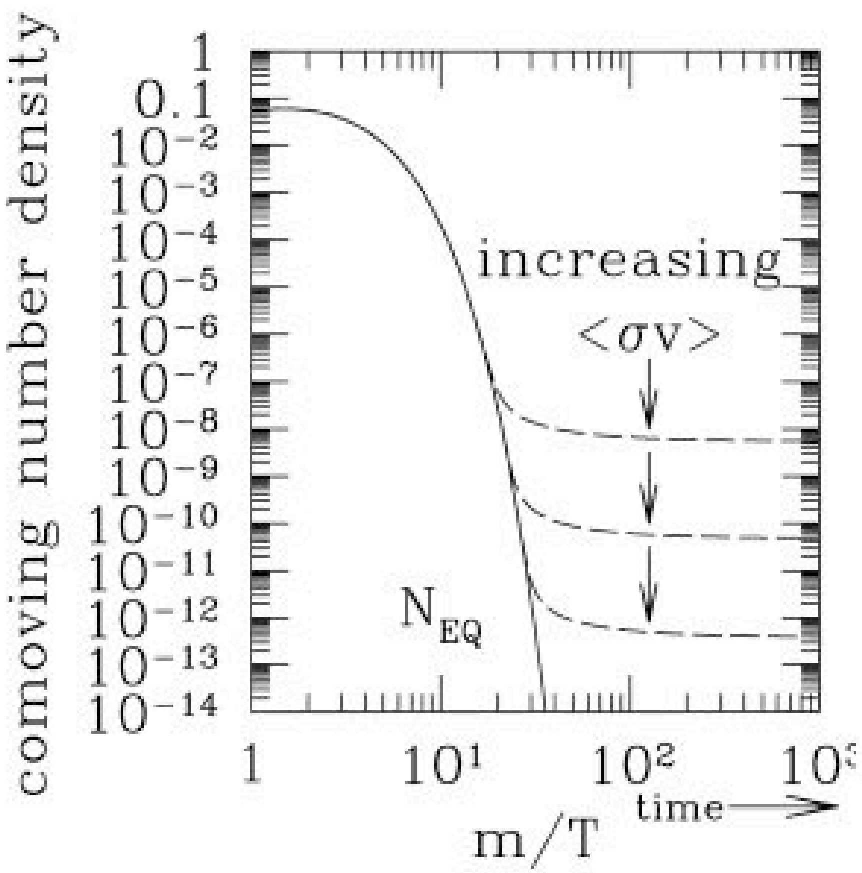
WIMP Dark matter

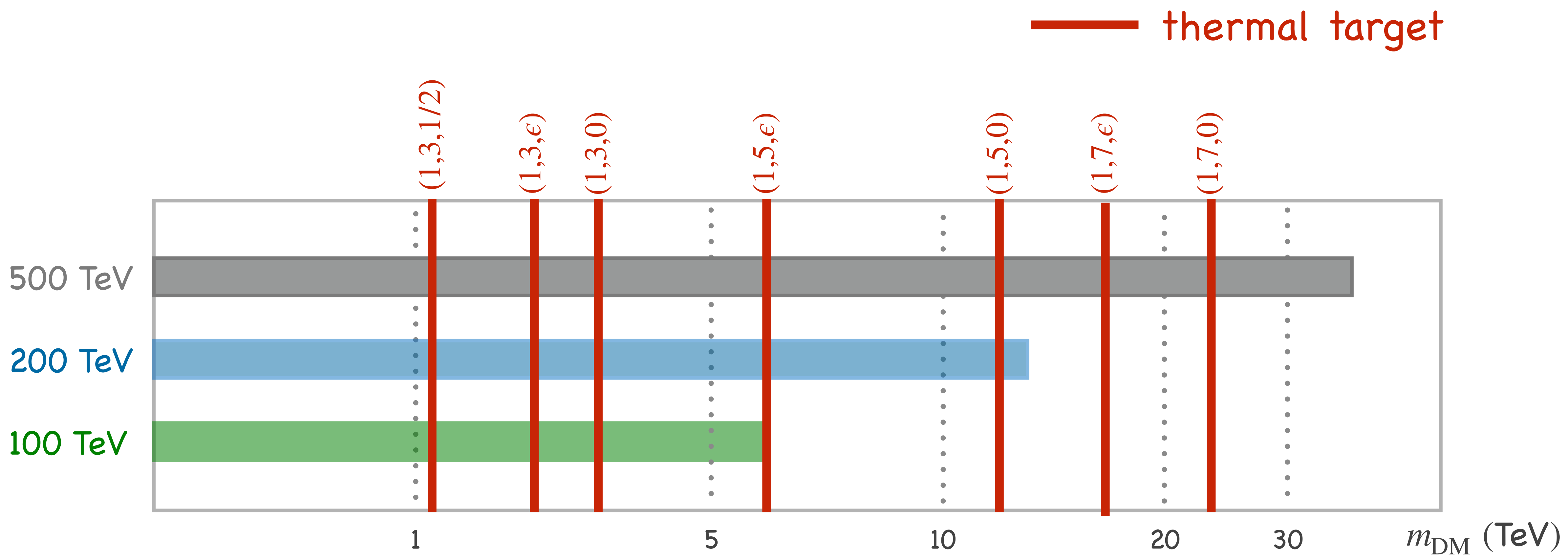


Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	11 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

The simplest WIMP model: DM part of EW multiplet.

Interaction: Standard Model gauge interactions.

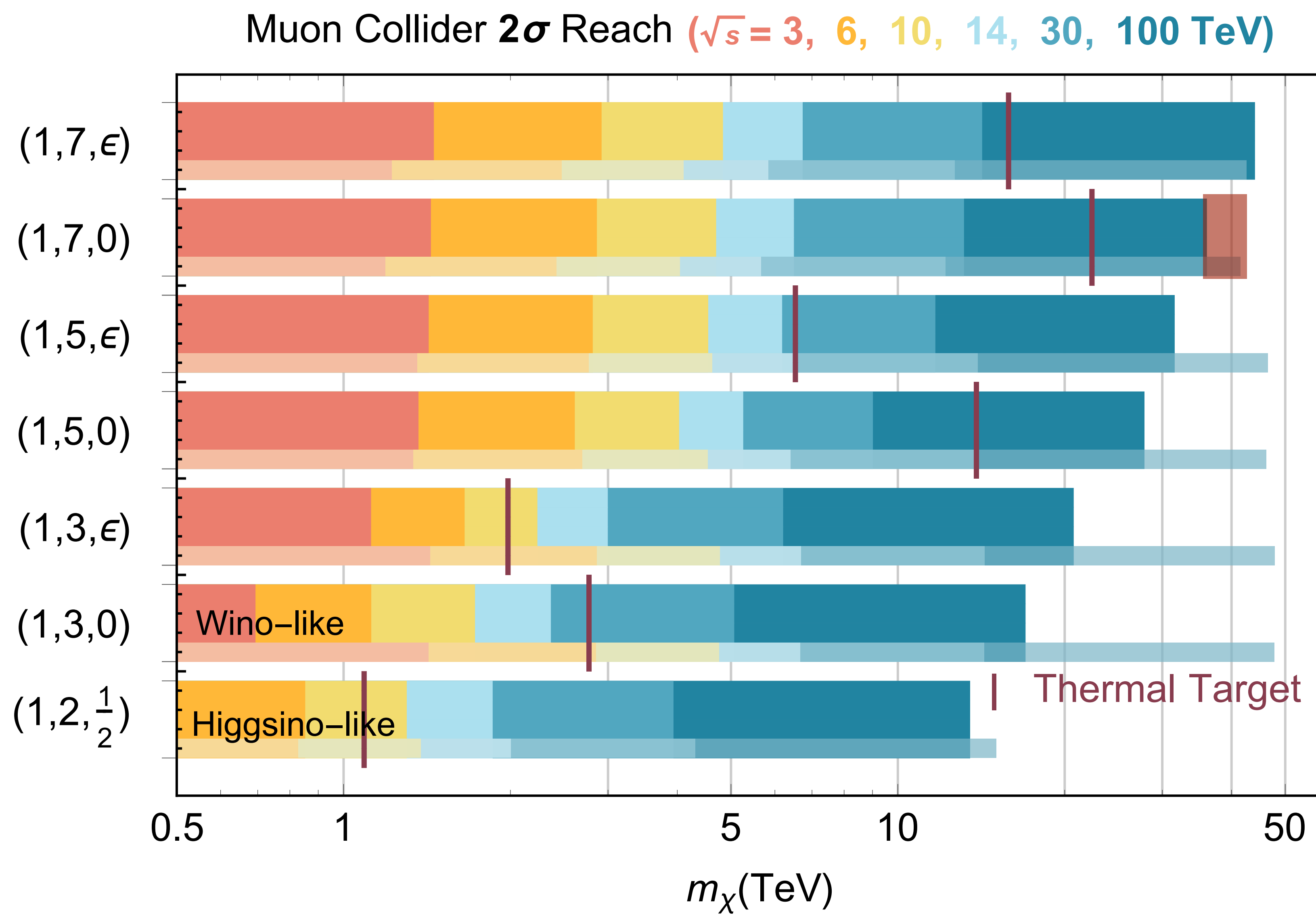
EW Dark matter reach: pp collider



Higher energy needed to cover higher dimensional multiplets.

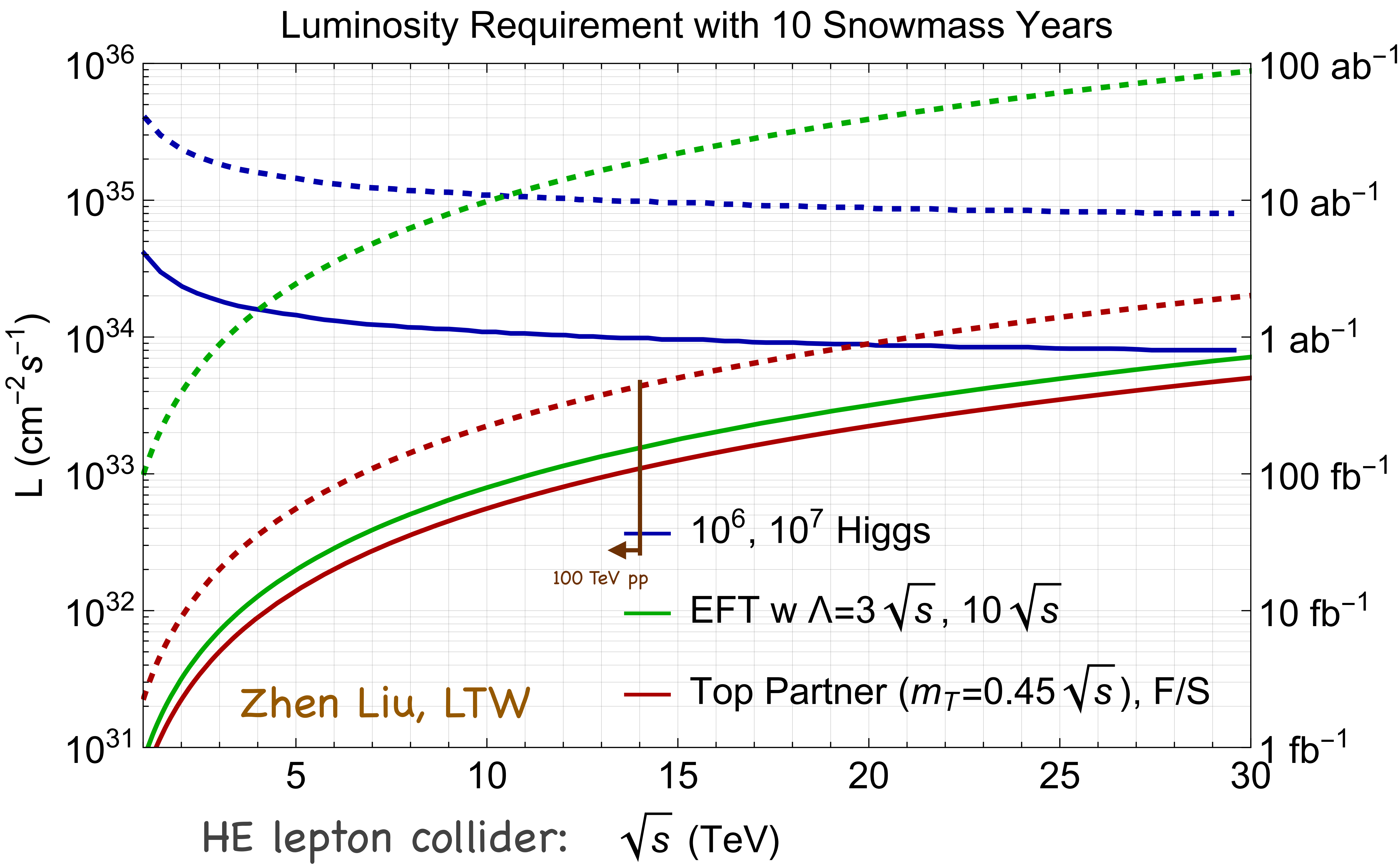
Either discovery or exclusion, we can make a clear statement of this very compelling WIMP DM scenario.

High energy muon collider



High energy muon collider can play
a decisive role in probing WIMP dark matter!

Another example of th input: luminosity needs and physics goals



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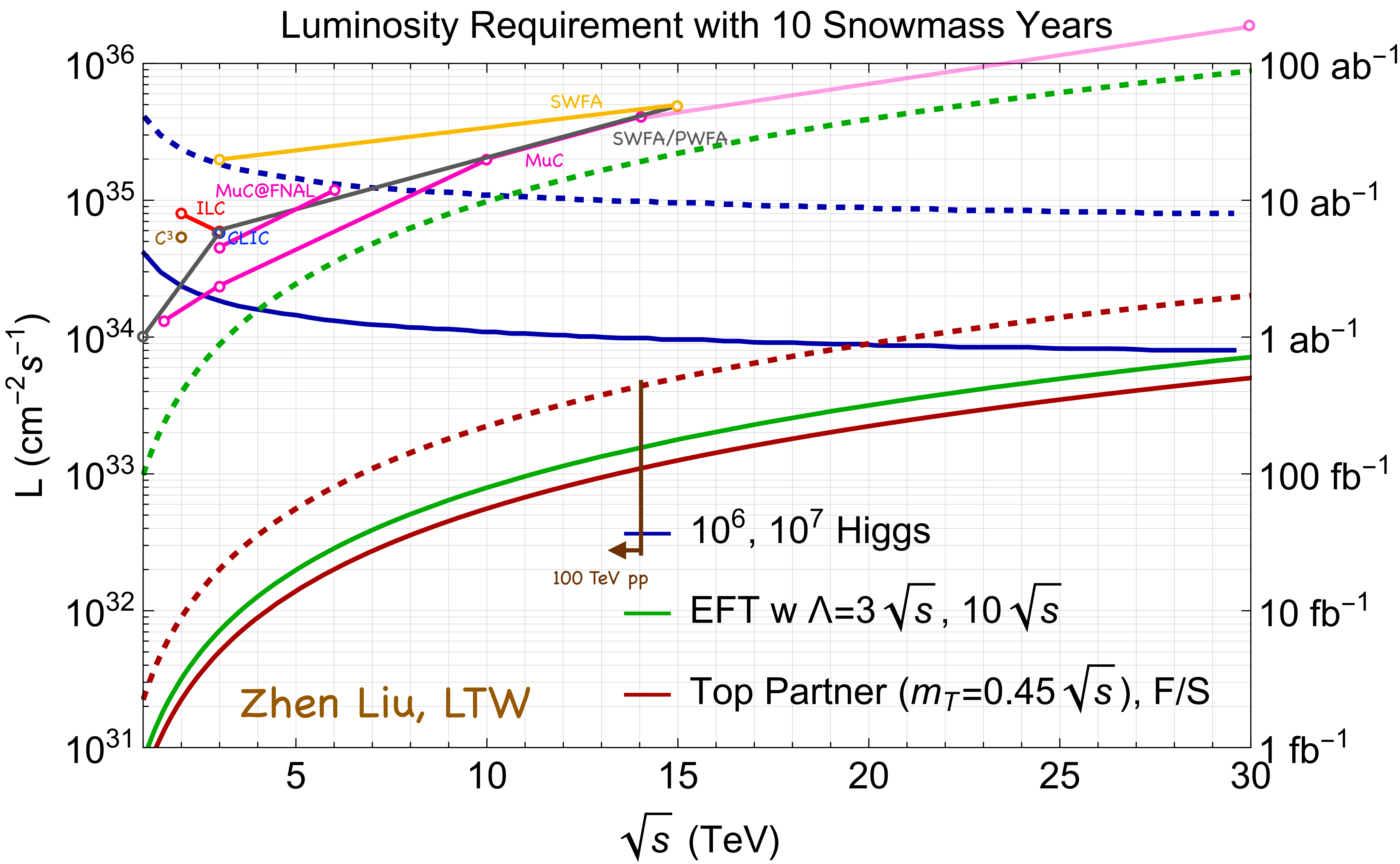

wimp DM: about the muon collider line and E_{CM} > 3 TeV.

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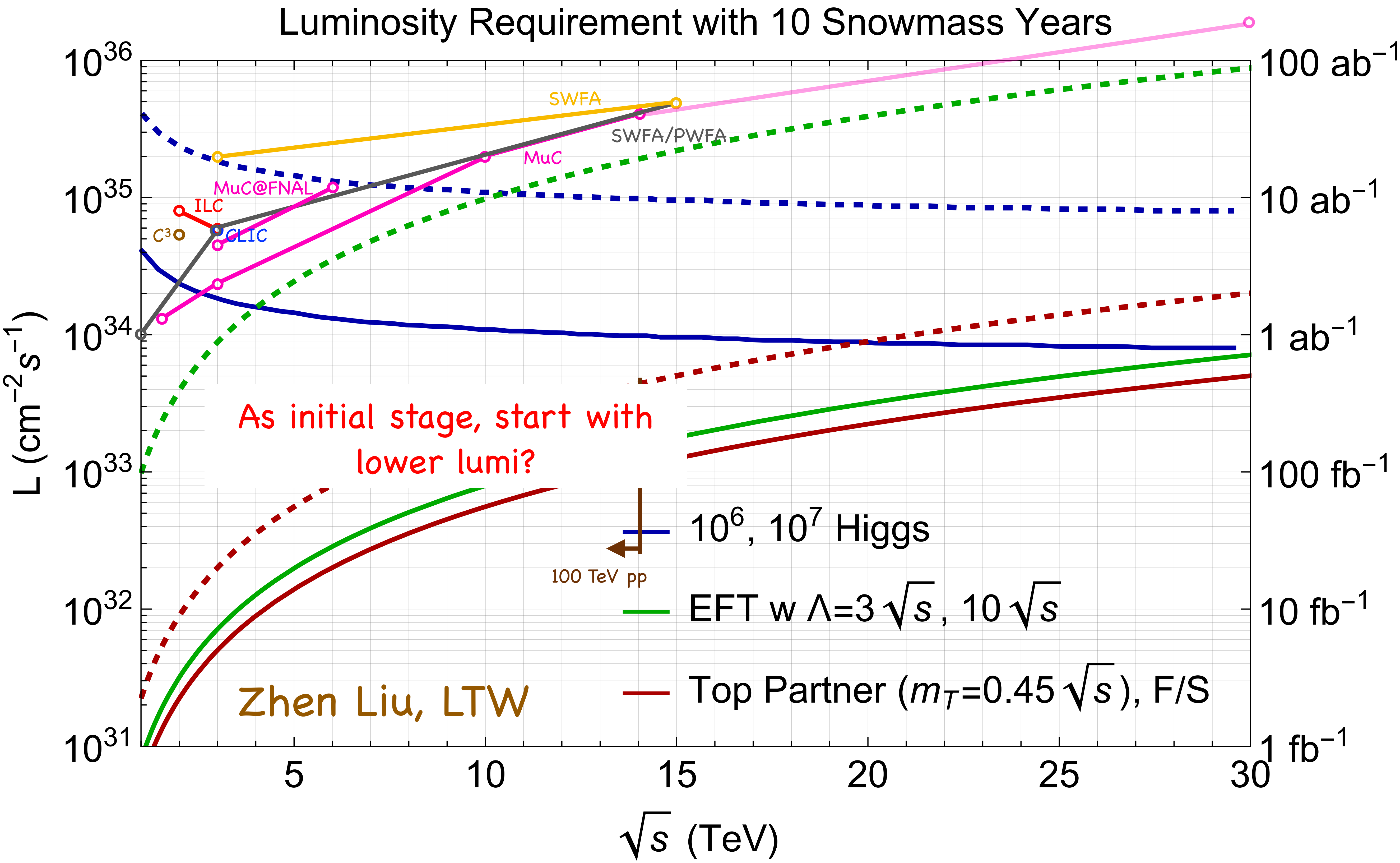


wimp DM: about the muon collider line and E_{CM} > 3 TeV.

Not covered in this talk

Topical groups, Group Conveners, and Liasons

- **AF1: Beam Physics and Accelerator Education**
- **AF2: Accelerators for Neutrinos**
- **AF3: Accelerators for EW/Higgs**
- **AF4: Multi-TeV Colliders**
- **AF5: Accelerators for PBC and Rare Processes**
- **AF6: Advanced Accelerator Concepts**
- **AF7: Accelerator Technology R&D**
  - AF7-RF : RF Accelerator Technology R&D

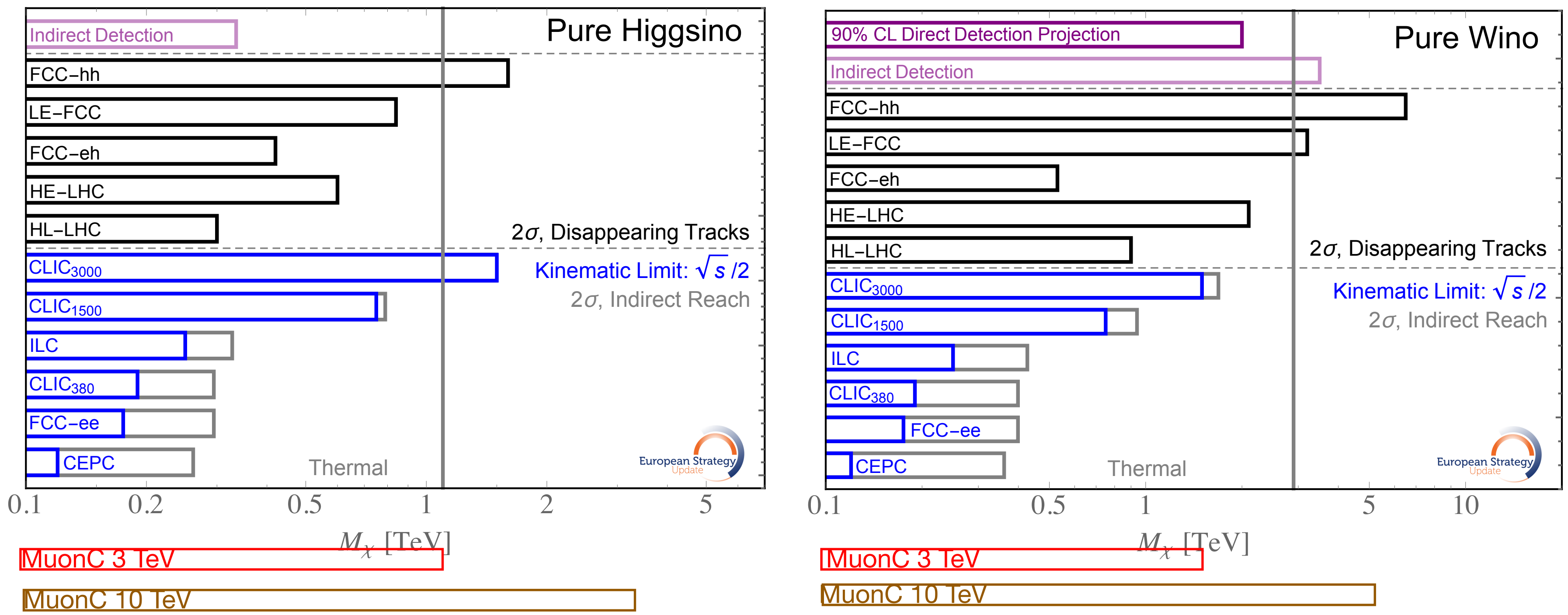
More details at AF page

Looking forward

- Theorists have been, and will continue to be, at the forefront of high energy physics.
  - Identifying questions.
  - Suggesting solutions.
  - Proposing ways of testing ideas.
- Laying the foundation of the planning for future accelerator facilities.
- With the future at stake, we need to think harder.
  - Anything big we have missed?

Extra

Dark matter reach

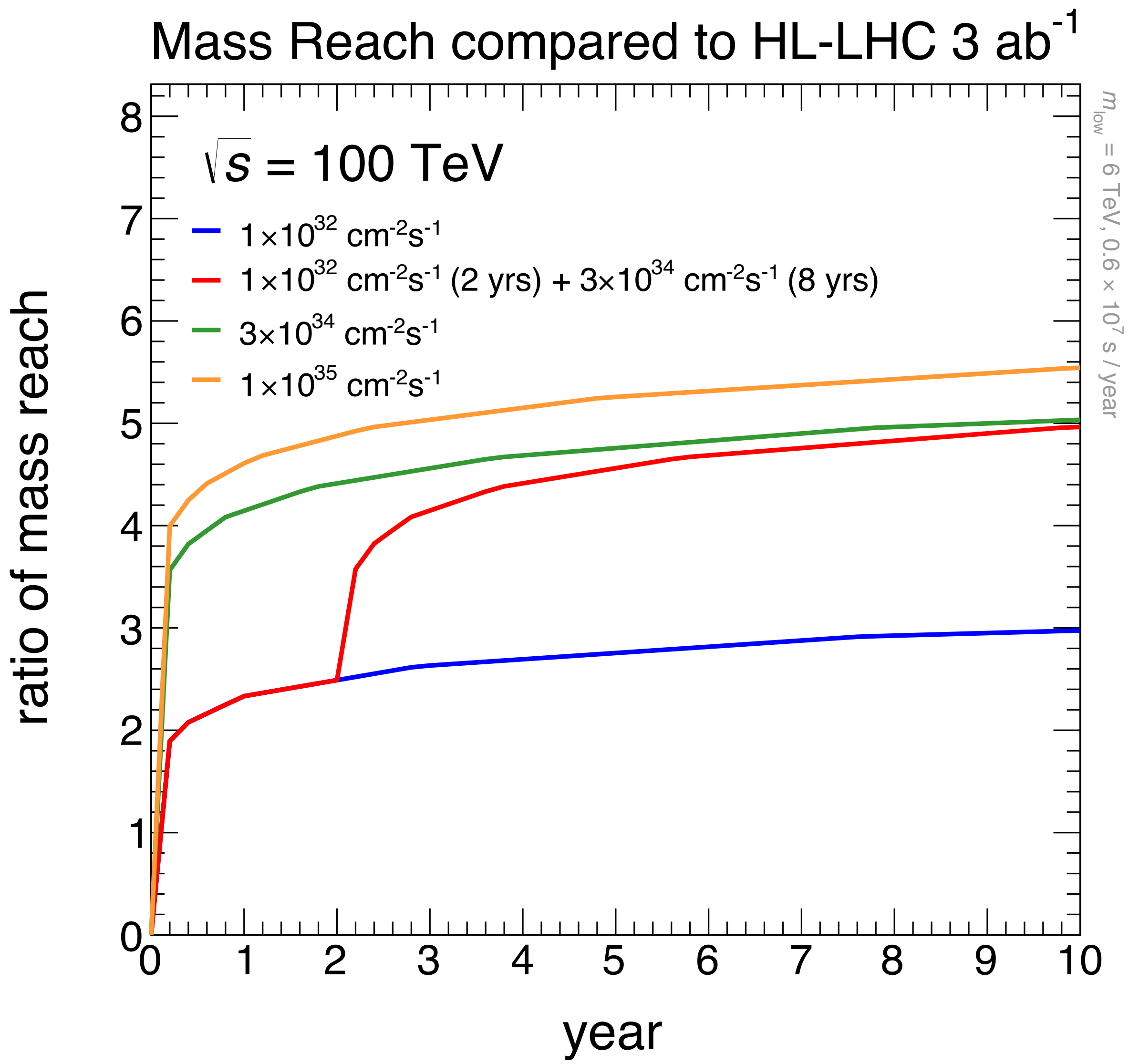


briefing book + my drawings for muon (or lepton) colliders.

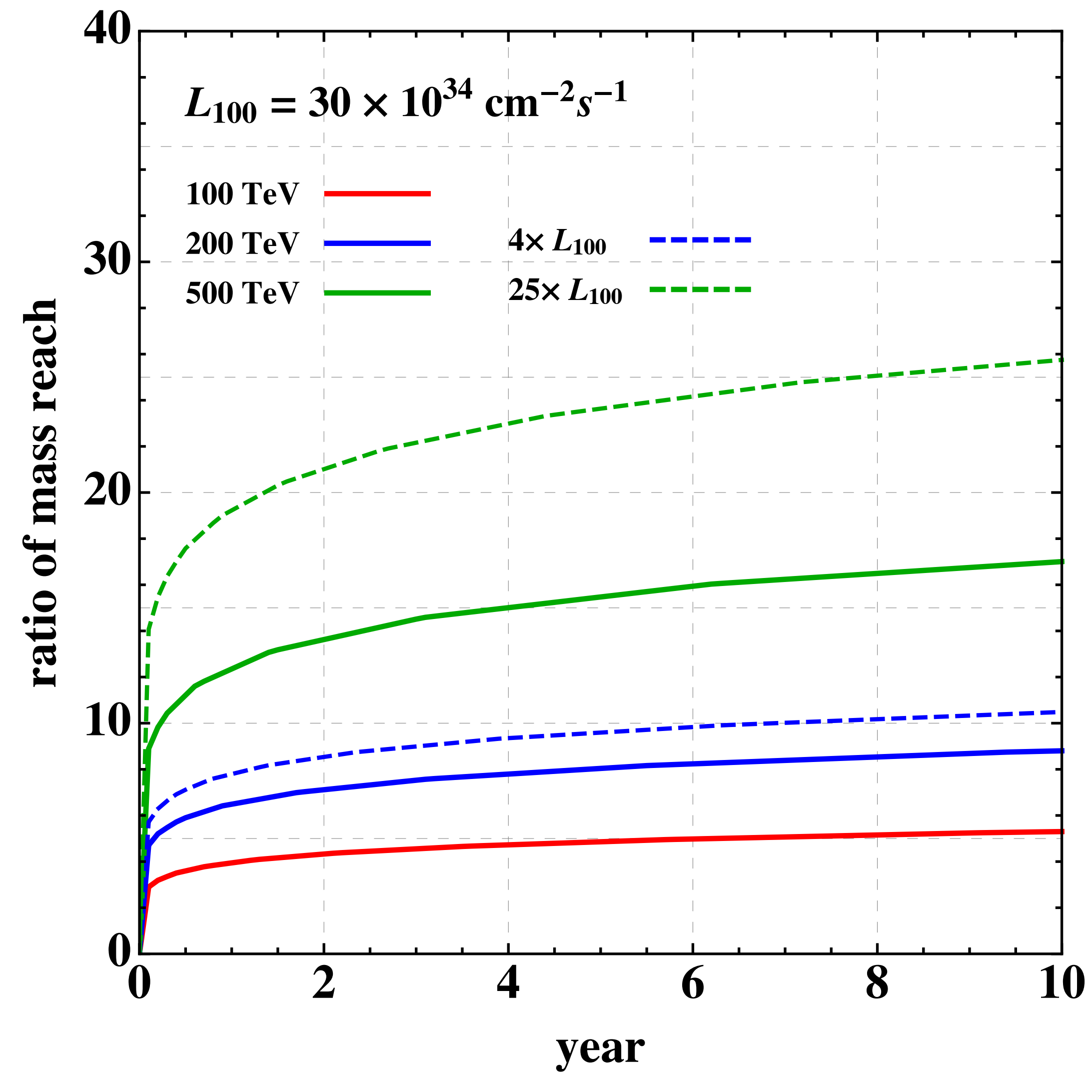
Simplest WIMP model, very predictive, definitive target mass ≈ TeVs.
Out of reach for LHC, difficult for direct detection.

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

Hadron collider scenarios



M. Low



Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Hadron collider scenarios

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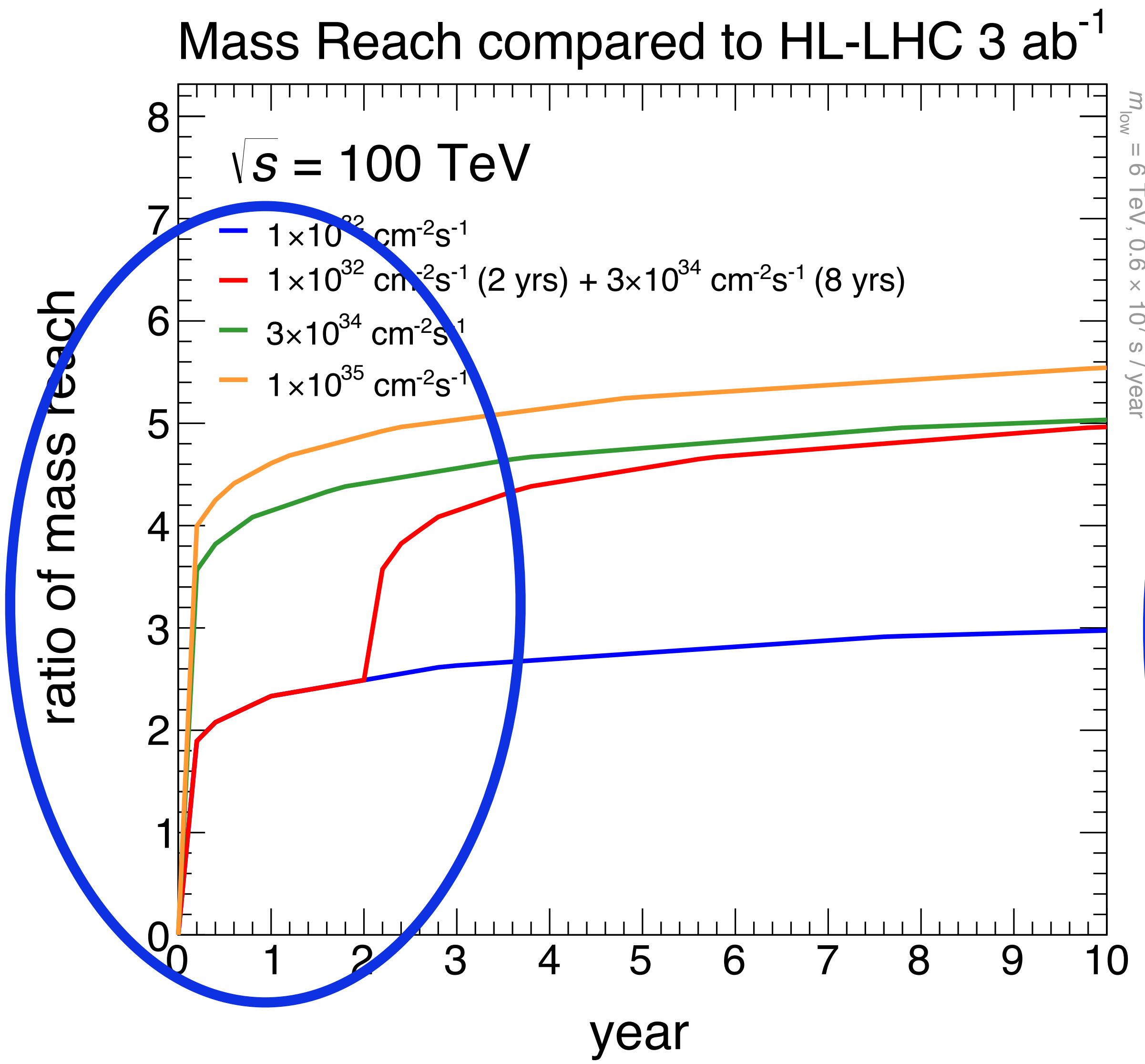
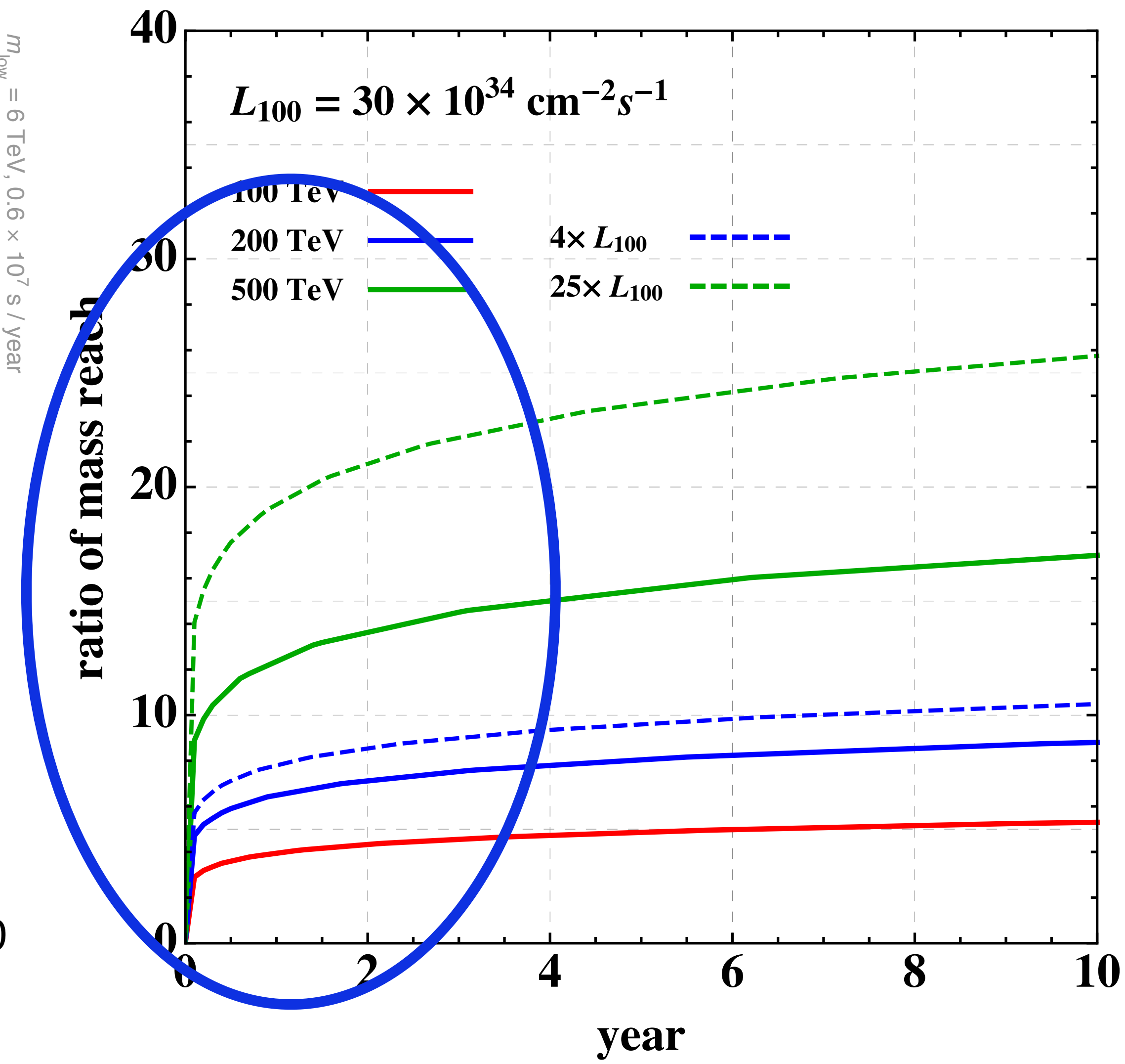
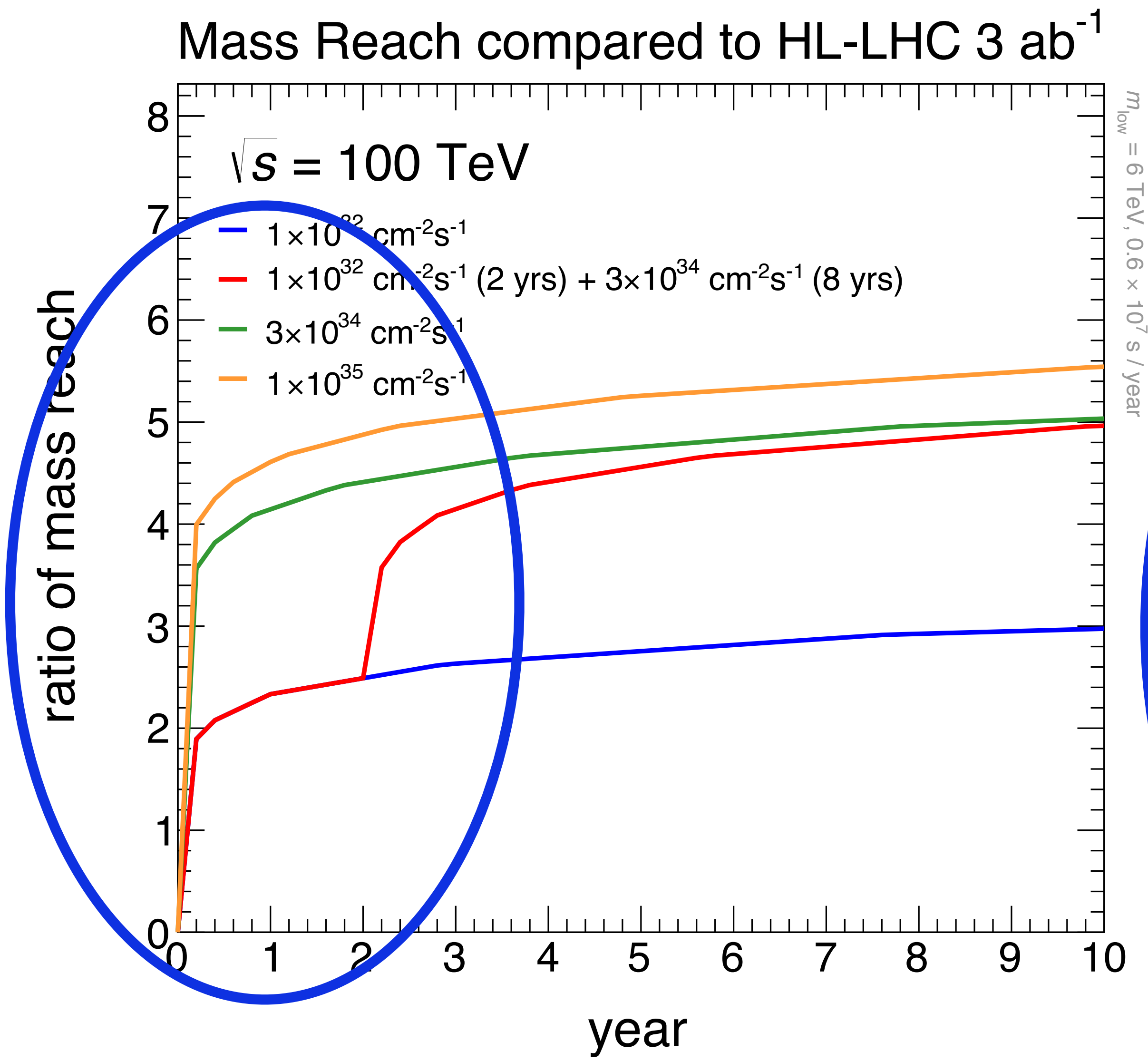




Rapid gain in mass reach

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Hadron collider scenarios



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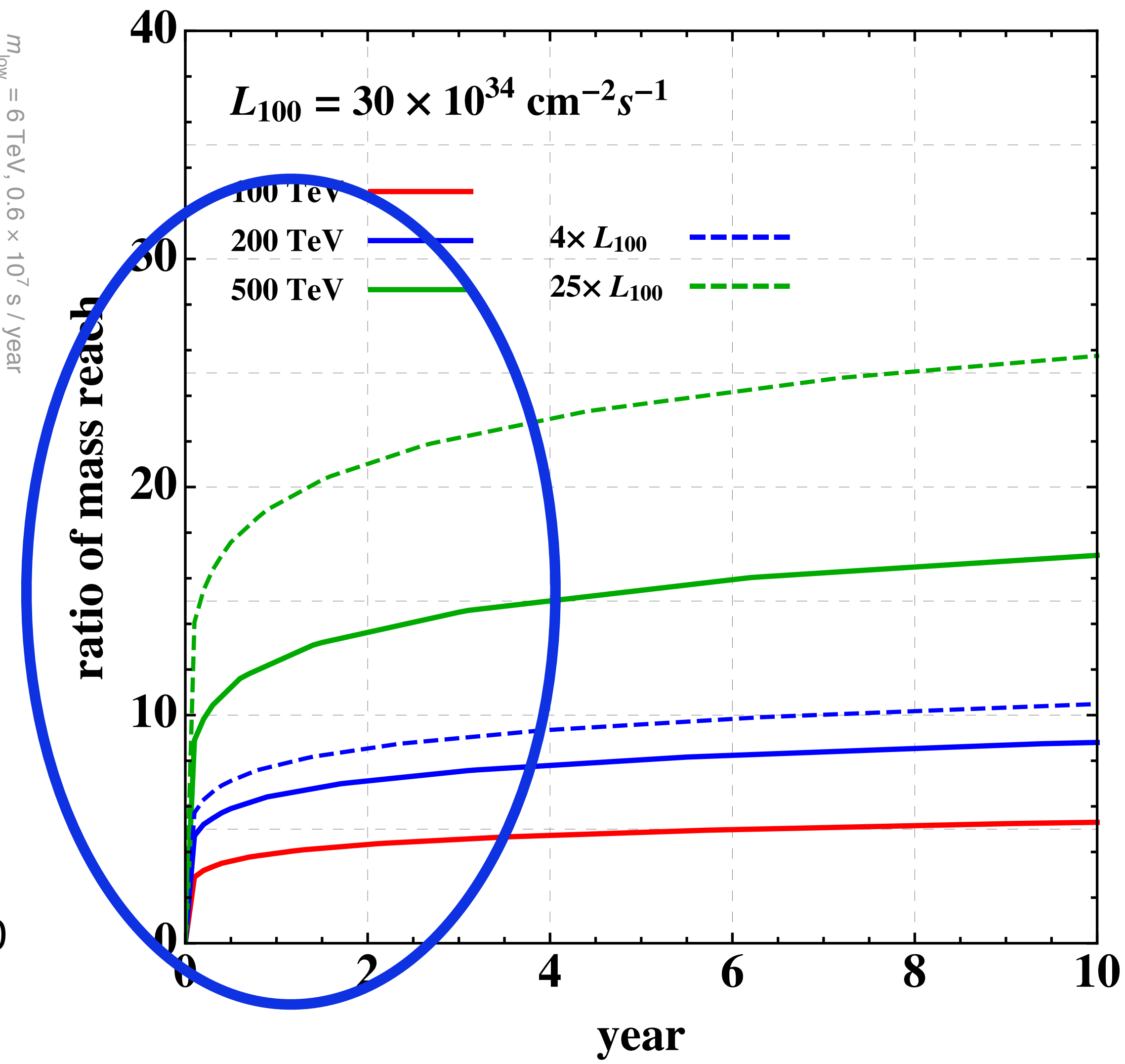


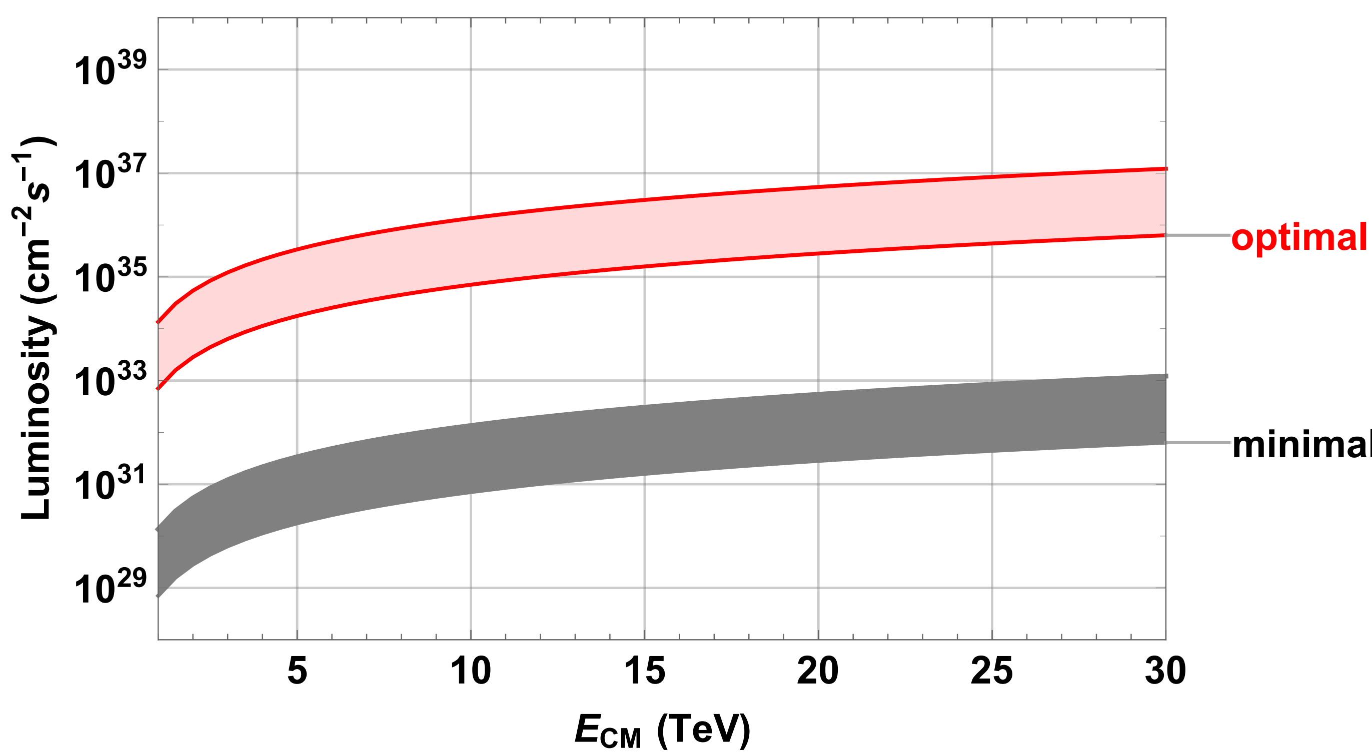
Rapid gain in mass reach

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

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