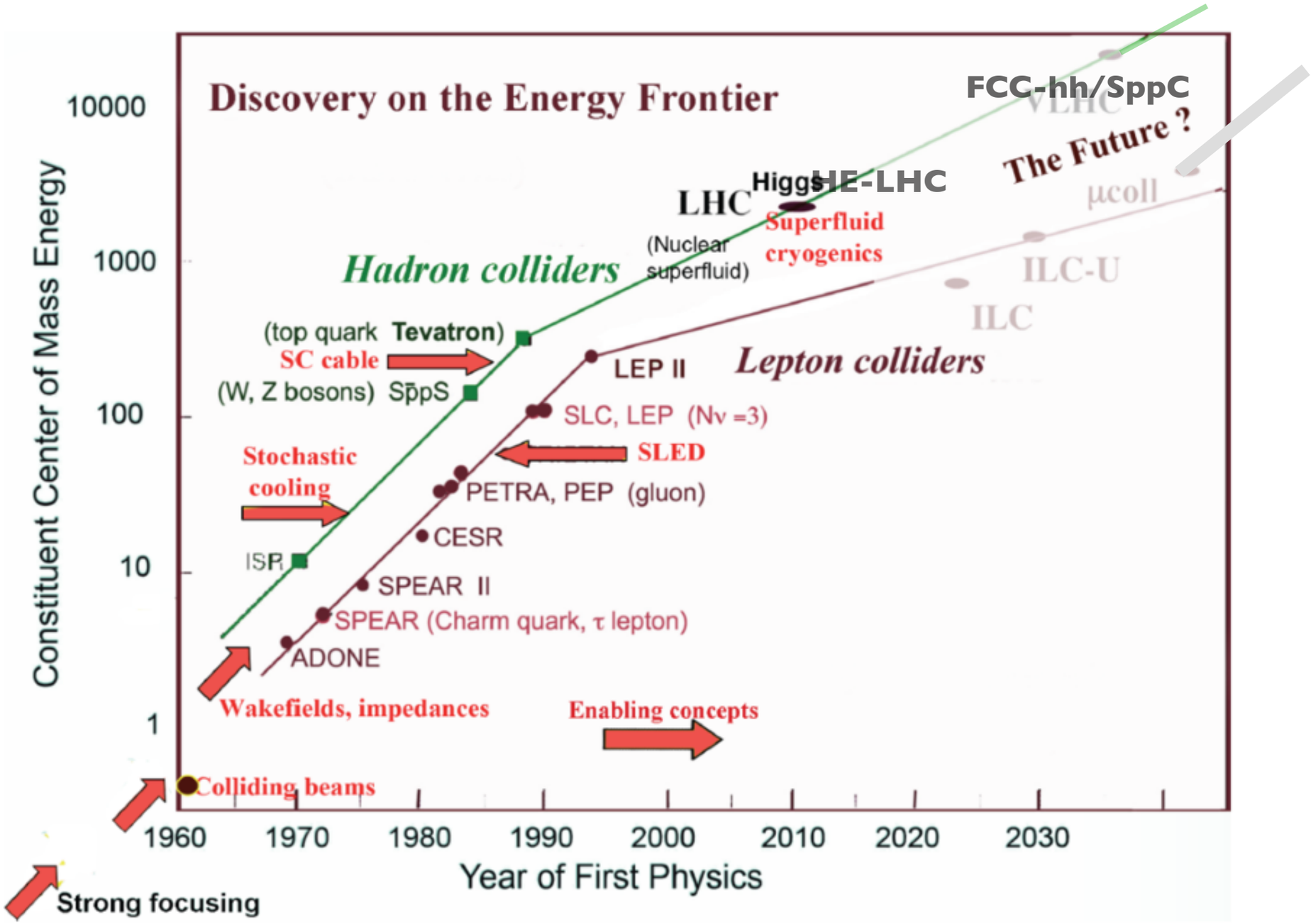
Physics potential of high energy pp (ep) colliders

LianTao Wang
University of Chicago

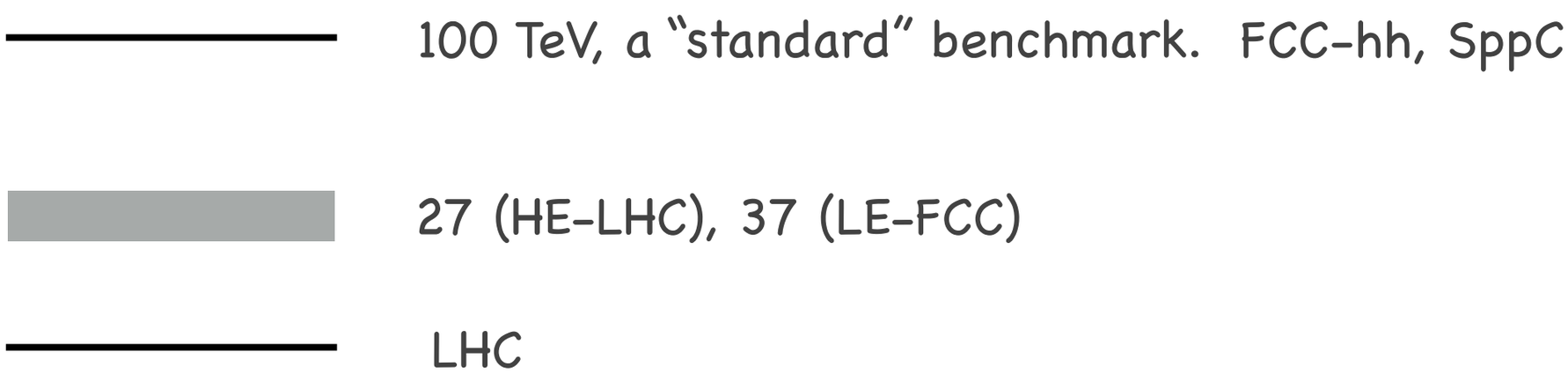
Snowmass21 Community Planning Meeting. Oct. 6, 2020

Why hadron collider?



Highest energies achieved in the lab.
Offers a first direct glance at shortest distances.

LHC and recent proposals



Physics case for 27, 37, and 100 TeV have been studied.

Beyond the known options

higher?

500

200

A goal post beyond 100 TeV?

100 TeV, a "standard" benchmark. FCC-hh, SppC

27 (HE-LHC), 37 (LE-FCC)

LHC

another benchmark?

My talk

- Go over the physics potential of high energy pp colliders.
  - A broad brushed picture of physics at > 100 TeV pp collider (based on simple extrapolations)

- My thoughts on the benchmarks.

Hadron collider reach

Cross section at hadron collider, for producing heavy new physics with mass M.

$$\sigma \sim L_p \cdot \hat{\sigma} \propto \frac{1}{M^{2a}} \hat{\sigma} \qquad \hat{\sigma} \propto \frac{1}{M^2}$$

Sharp falling Parton Luminosity $L_p \longleftrightarrow a \gg 1$

Hadron collider reach

Cross section at hadron collider, for producing heavy new physics with mass M.

$$\sigma \sim L_p \cdot \hat{\sigma} \propto \frac{1}{M^{2a}} \hat{\sigma} \qquad \hat{\sigma} \propto \frac{1}{M^2}$$

Sharp falling Parton Luminosity $L_p \longrightarrow a \gg 1$

For two colliders with different energy and luminosity

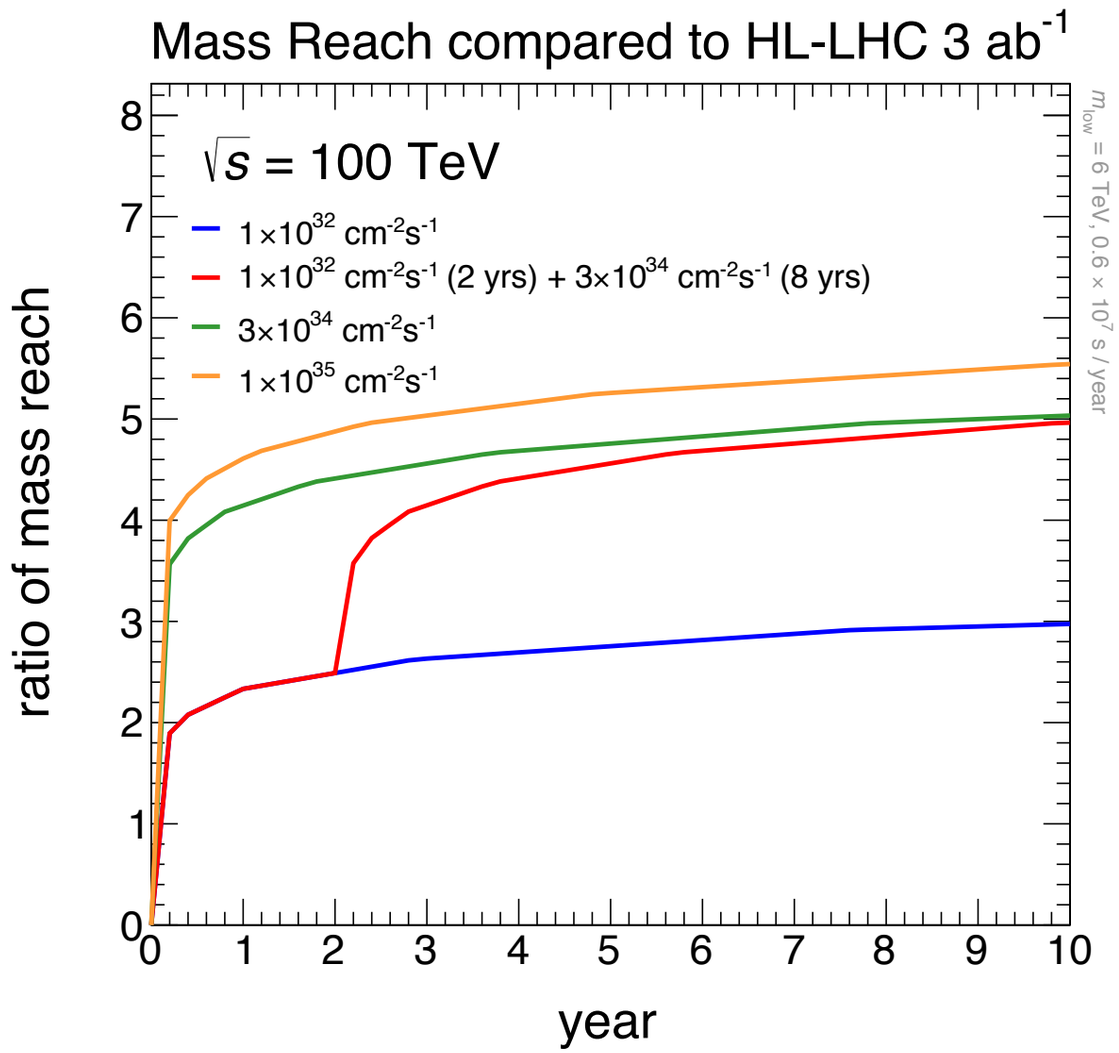
$E_1, \mathscr{L}_1$ and $E_2, \mathscr{L}_2$

Reach in new physics mass, M_1 and M_2 scales as

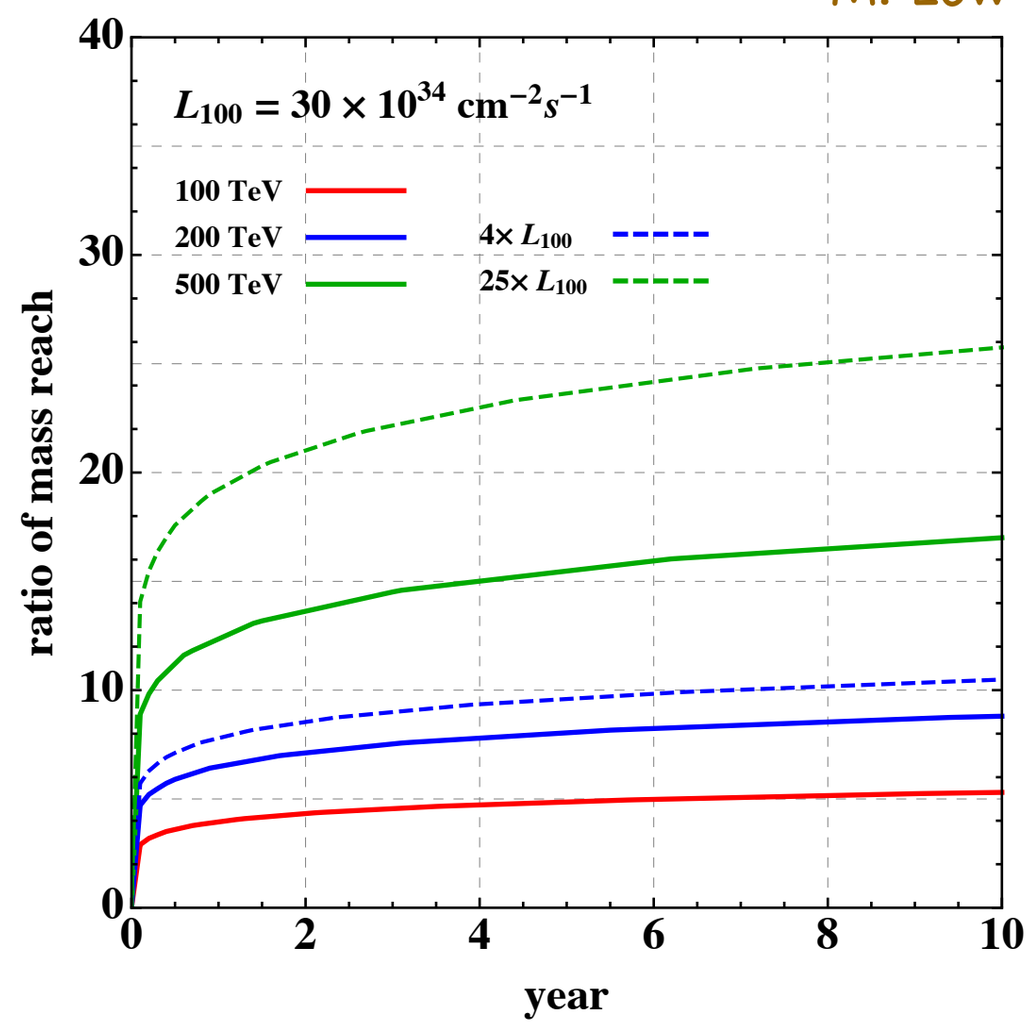
$$\frac{M_1}{M_2} = \left(\frac{E_1}{E_2}\right)^{\frac{a}{a+1}} \left(\frac{\mathscr{L}_1}{\mathscr{L}_2}\right)^{\frac{1}{2a+2}}$$

Reach scale with energy.
With a weaker dependence on luminosity

Physics program at hadron collider

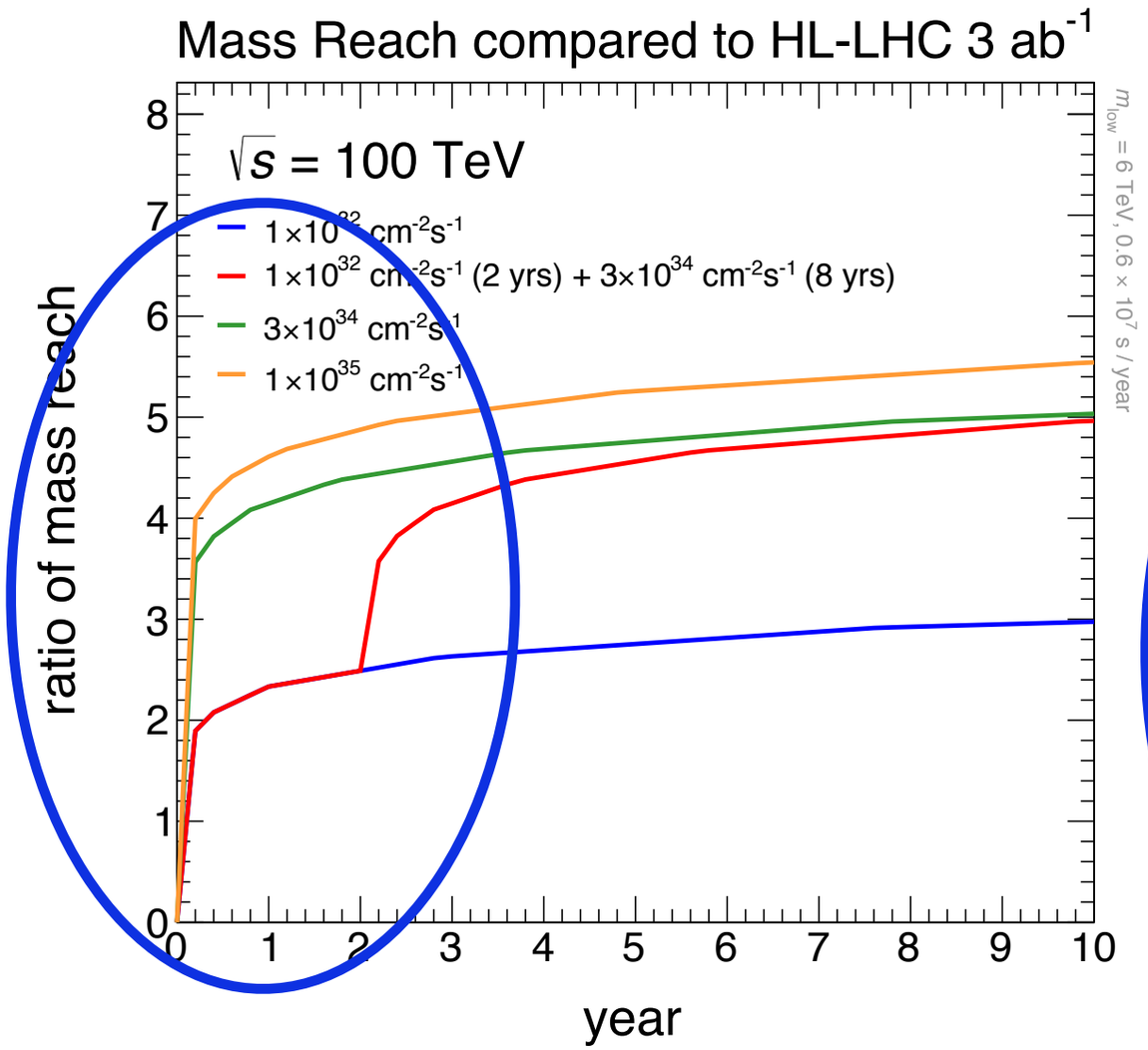


M. Low

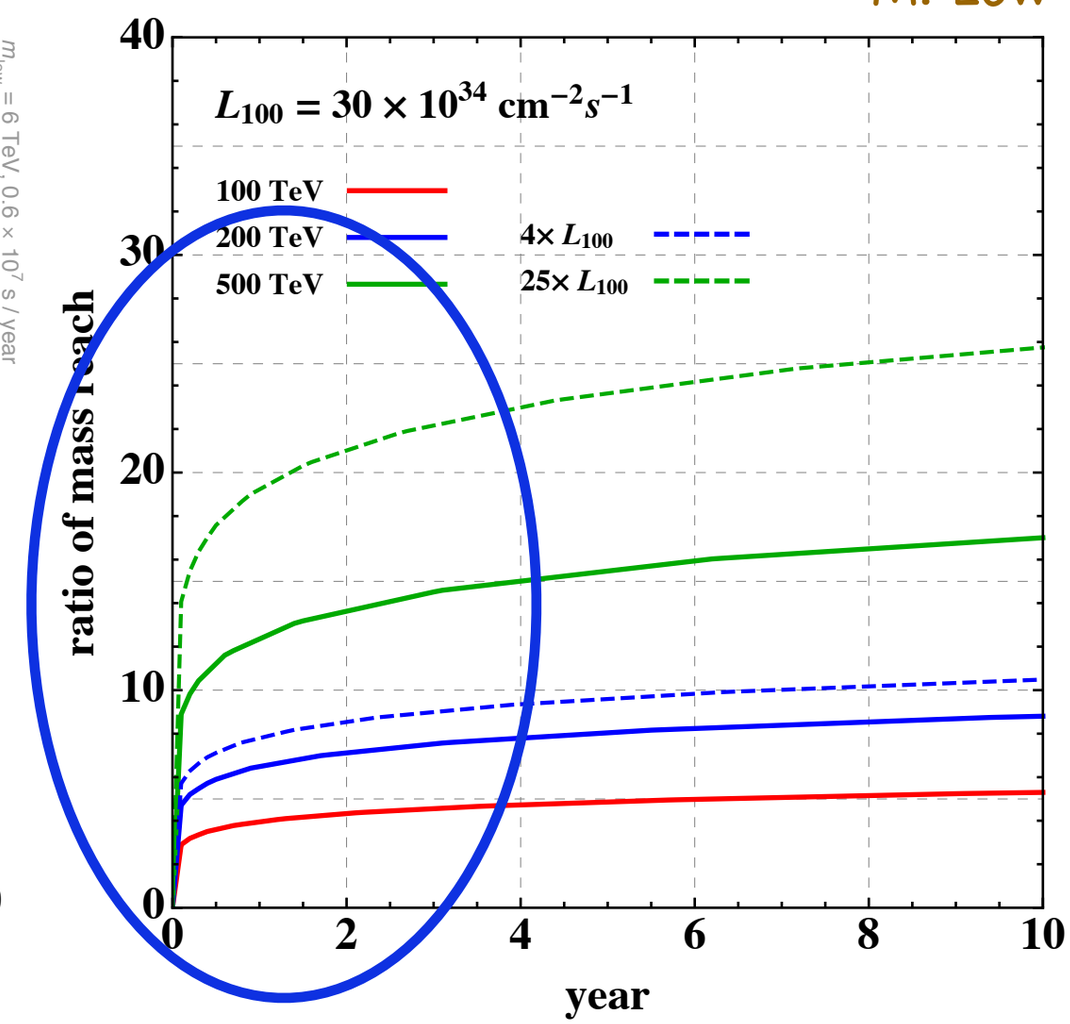


Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Physics program at hadron collider



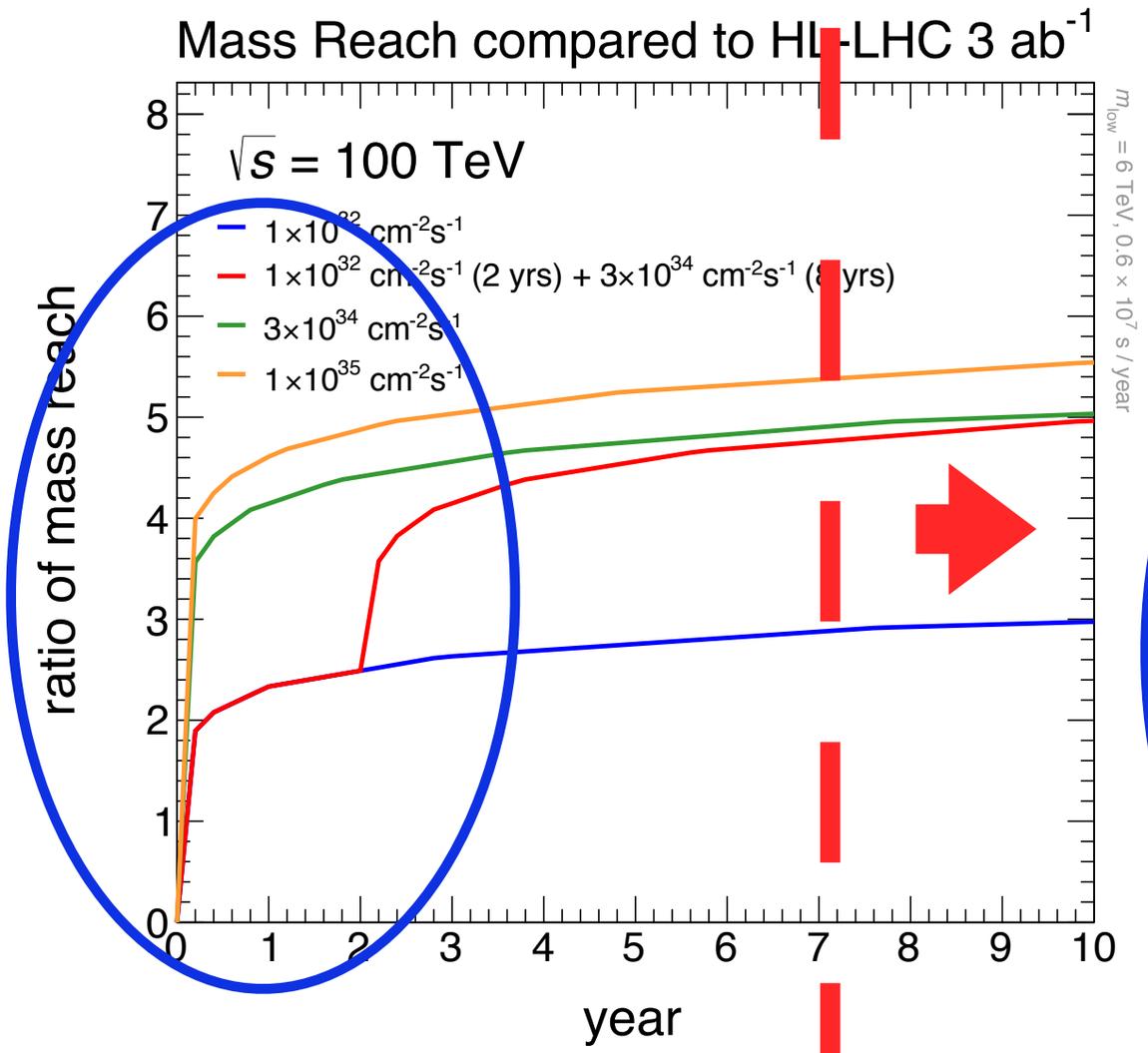
M. Low

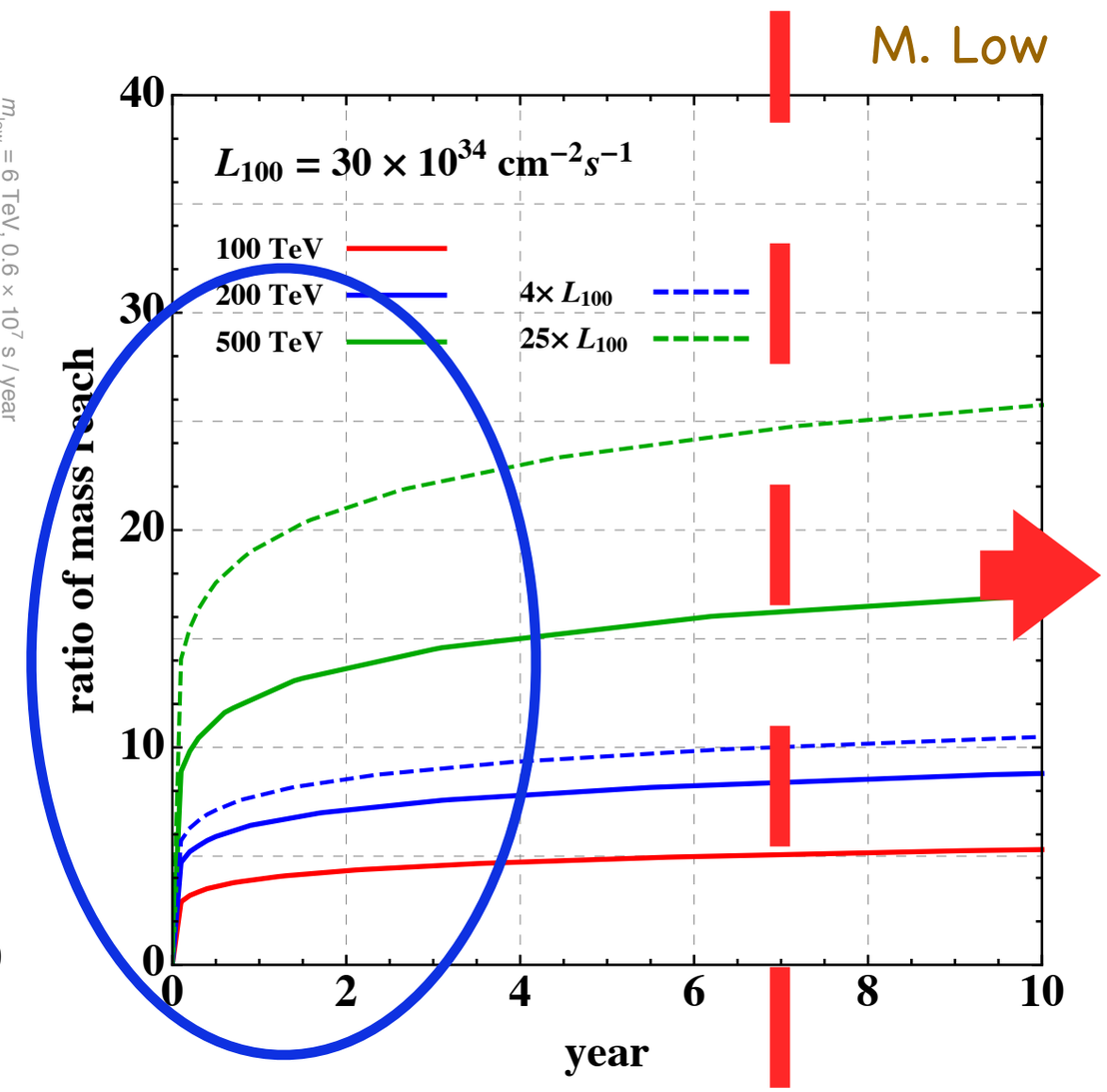


Rapid gain in mass reach

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

Physics program at hadron collider



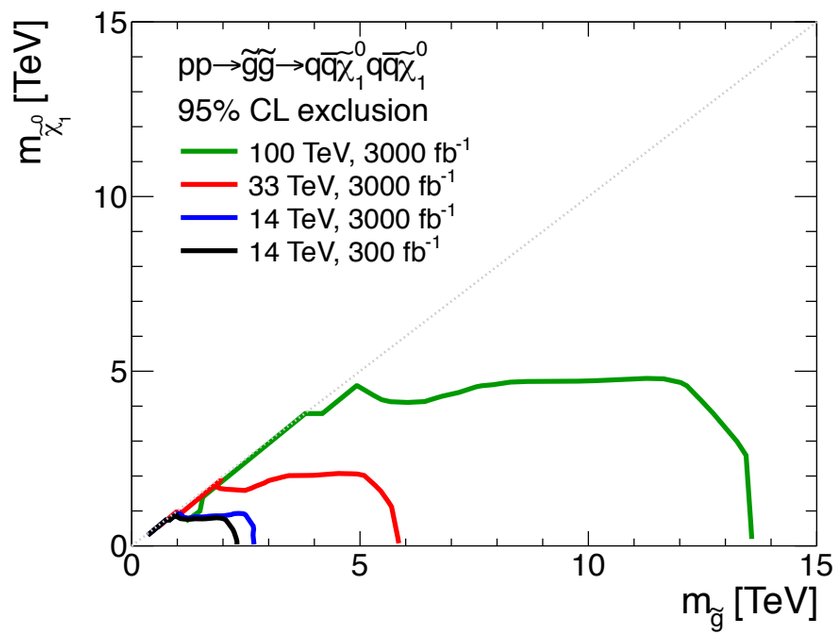


Rapid gain in mass reach

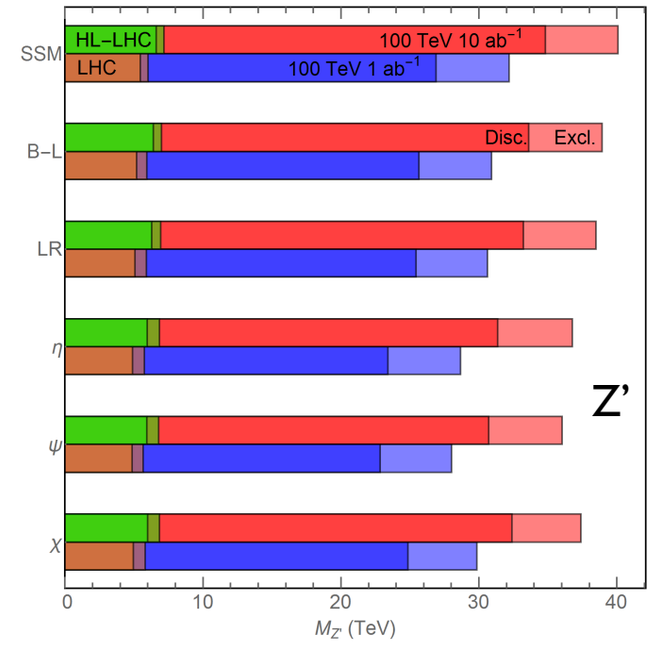
Precision measurement becomes possible

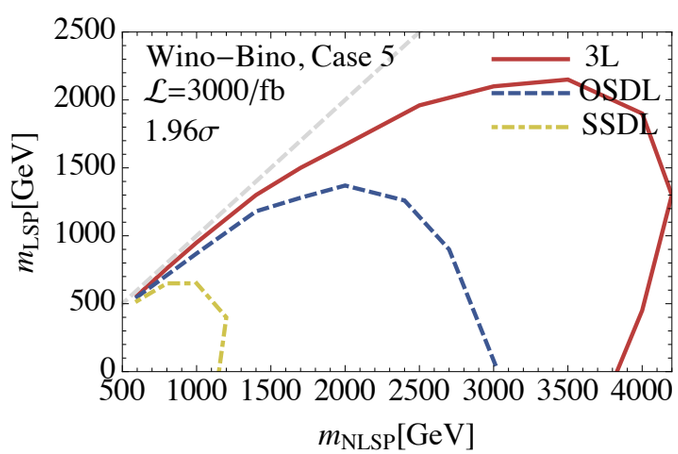
Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

A big step on energy frontier

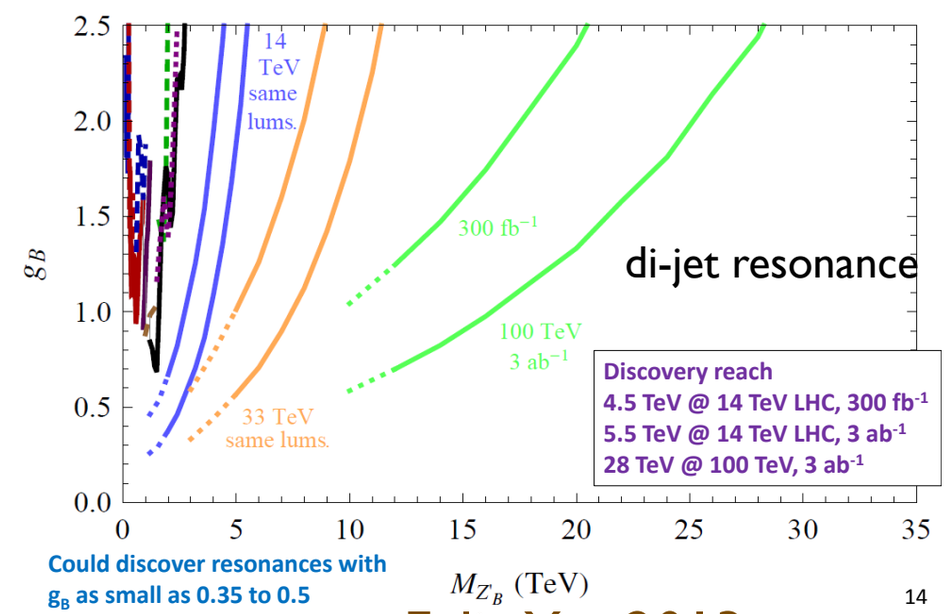


Cohen et al, 2013





Gori, Jung, LTW, Wells, 2014



Felix Yu, 2013

e.g. 100 TeV: x 5(more) improvement, into (10)TeV regime

Precision measurements

- Maybe the new physics scale is above 10^2 TeV.
- The NP effect can be parameterized by EFT operators

$$\frac{1}{\Lambda^2}\mathcal{O}^{(6)},\ \frac{1}{\Lambda^4}\mathcal{O}^{(8)},\ldots \qquad \Lambda \sim \text{scale of new physics}$$

- Can only probe through precision measurements.

Energy = precision

At FCC-ee/CEPC/ILC

$$(\delta\sigma/\sigma)_{ee} \sim \frac{m_W^2}{\Lambda^2} \sim (10^{-3})_{\rm exp}$$

At hadron collider

$$(\delta\sigma/\sigma)_{\rm had} \sim \frac{E^2}{\Lambda^2}$$

Effects larger at higher energies!

E = parton energy ≈ 0.1 E_{CM}

Can probe: $\Lambda \sim 0.1 \times E_{\rm CM} (\delta\sigma/\sigma)^{-1/2}_{\rm exp.error}$

For example: $(\delta\sigma/\sigma)_{\rm exp.error} \sim 10\,\%$, $\Lambda \sim 30$ TeV with $E_{\rm CM} = 100$ TeV

What are we looking for?

No lose theorem?

- Are we guaranteed to discover X (e.g. X=SUSY)?
  - No.
- Standard Model can be consistent up to the Planck scale.
- At the same time, we do have questions to answer, models to test. We need to go forward.

Physics targets

- Origin of the Electroweak scale.
- Understanding the Higgs better.
- Dark Matter
- Flavor/CP
- Matter anti-matter asymmetry.
- ...

Physics targets

- Origin of the Electroweak scale.
- Understanding the Higgs better.
- Dark Matter
- Flavor/CP
- Matter anti-matter asymmetry.
- ...

Origin of the weak scale

For a detailed discussion: See V. Cavaliere and M. Reece, Session 126

Electroweak scale, 100 GeV.

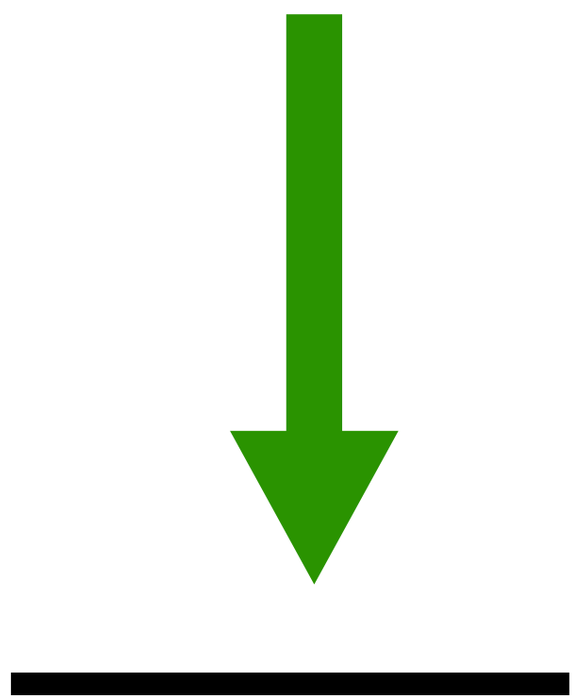
m_h , m_W …

Weak scale not fundamental!

Origin of the weak scale

The energy scale of new physics responsible for the weak scale

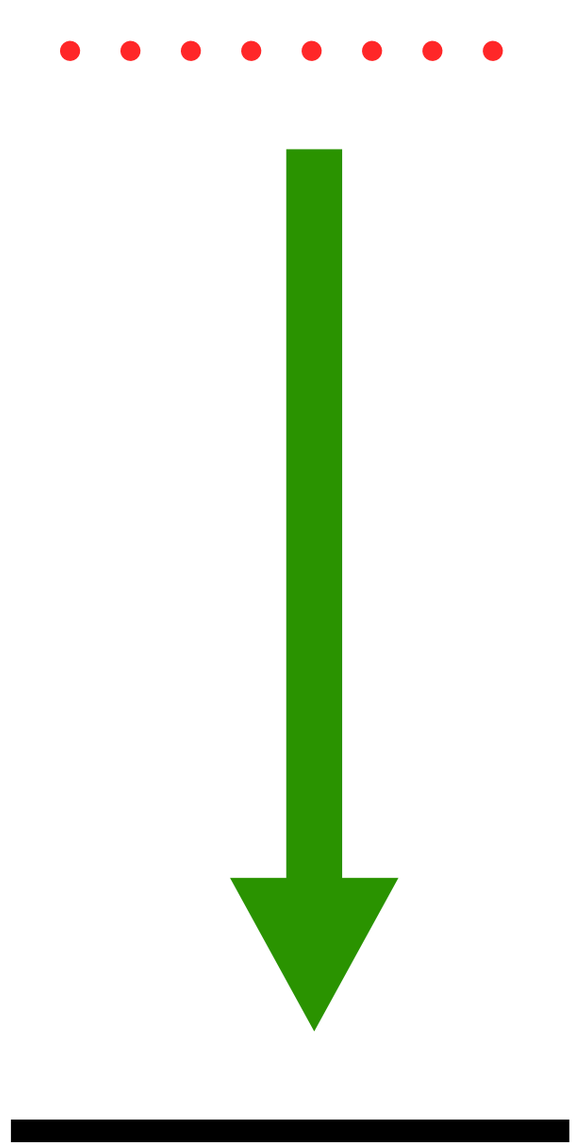
Question: where this scale is?



Electroweak scale, 100 GeV.

m_h , m_W …

Origin of the weak scale

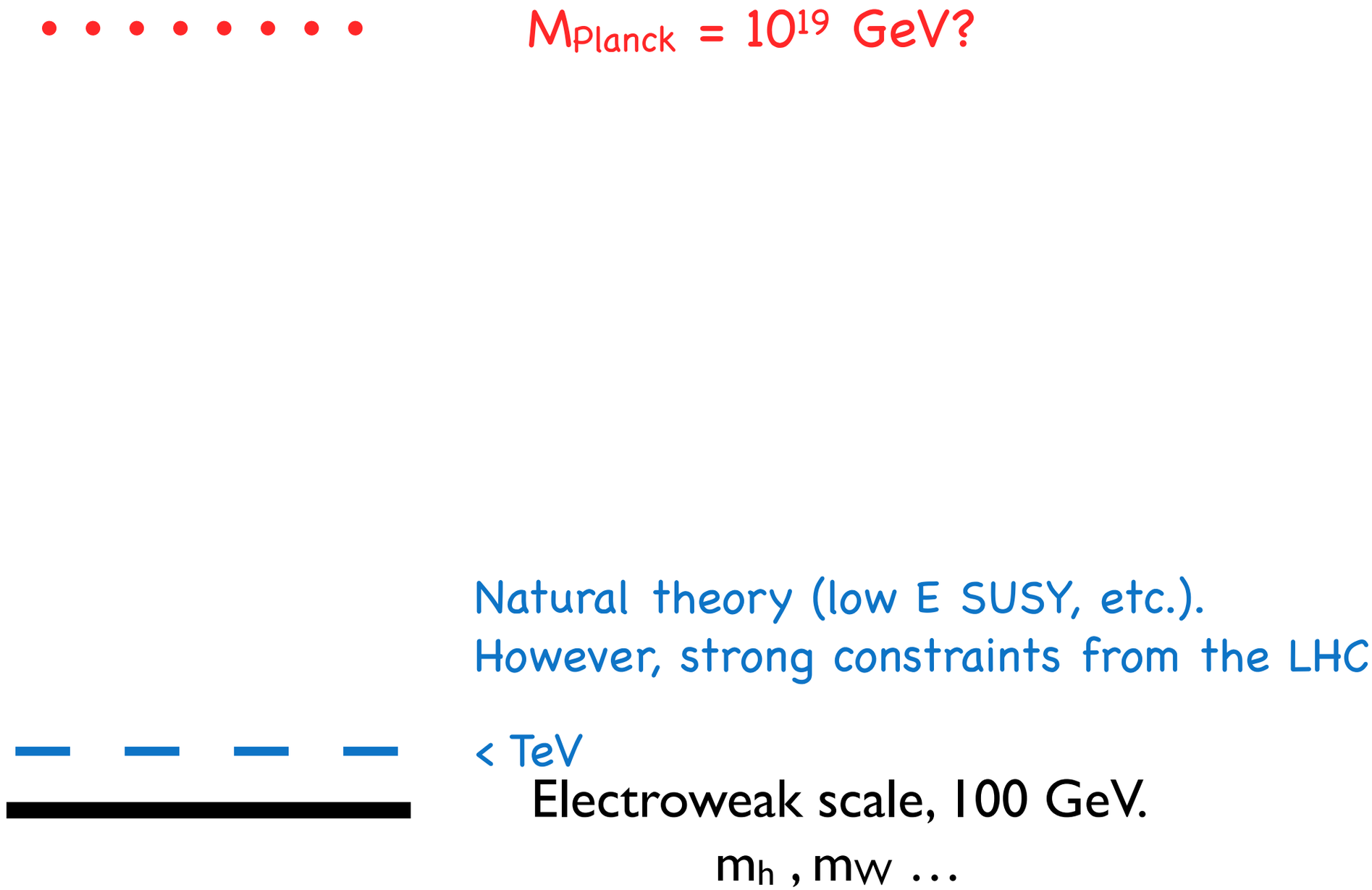


$M_{Planck} = 10^{19}$ GeV ?

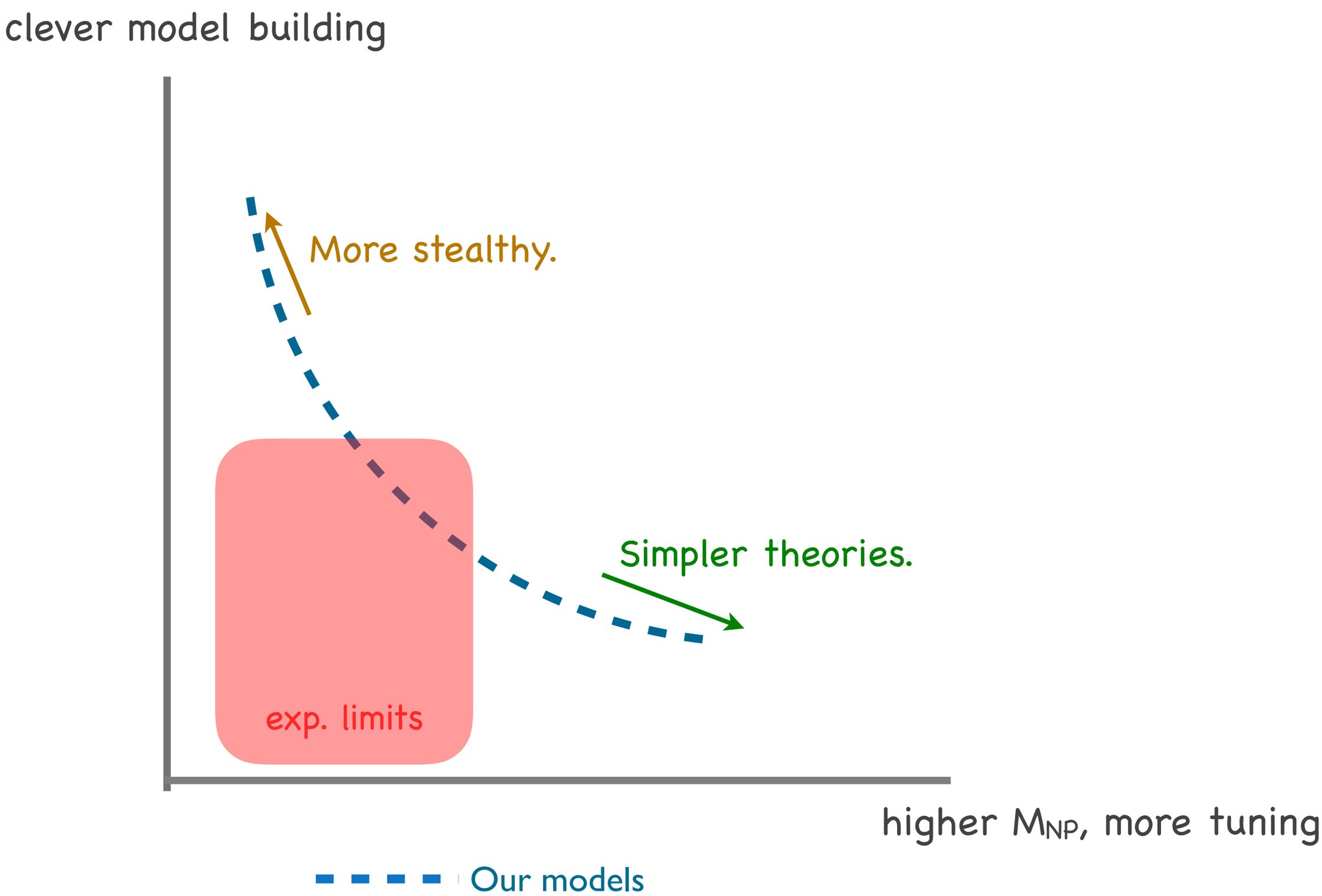
If so, why is so different from 100 GeV?
Hierarchy problem.

Electroweak scale, 100 GeV.
m_h , m_W …

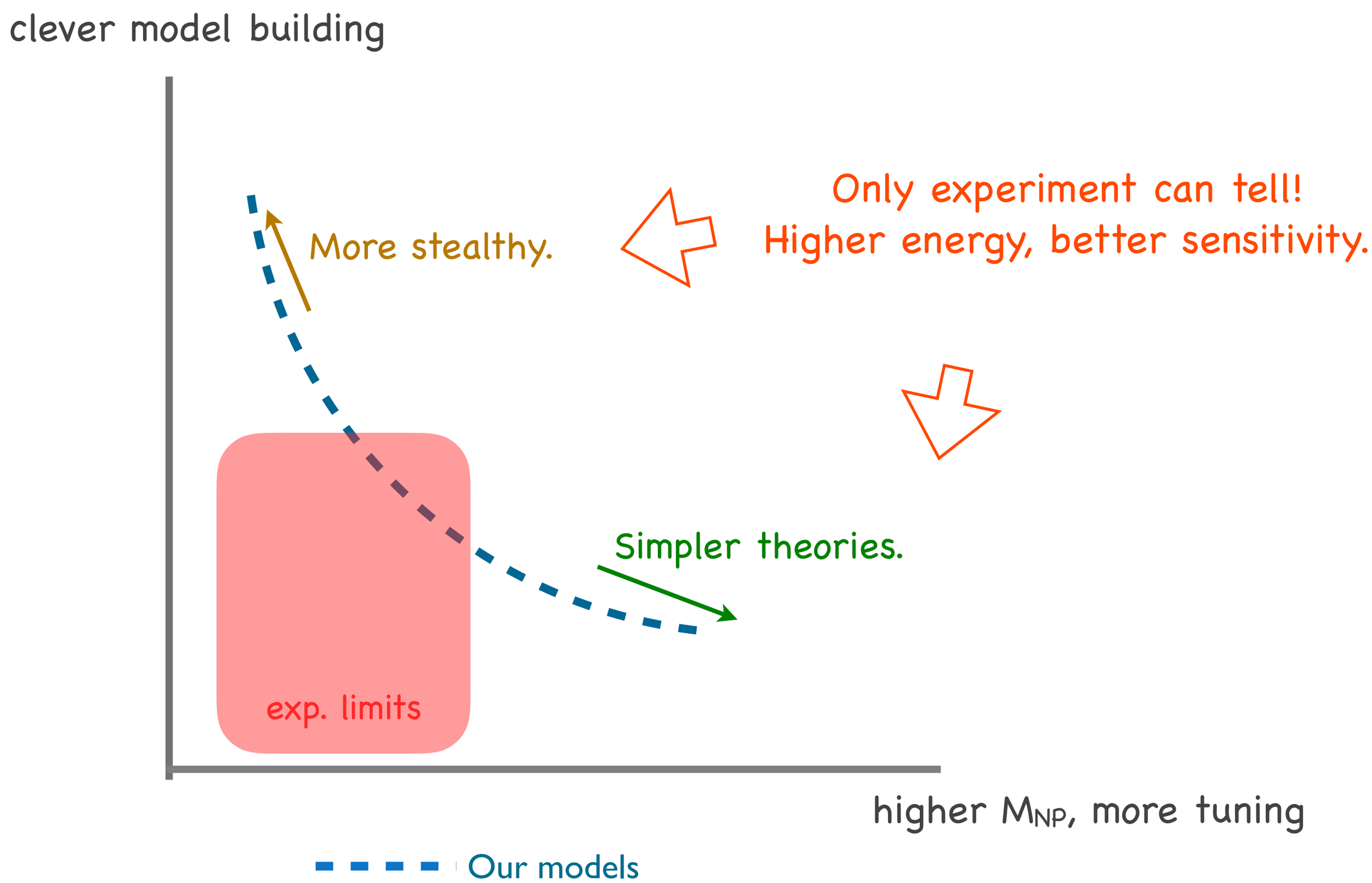
Origin of the weak scale



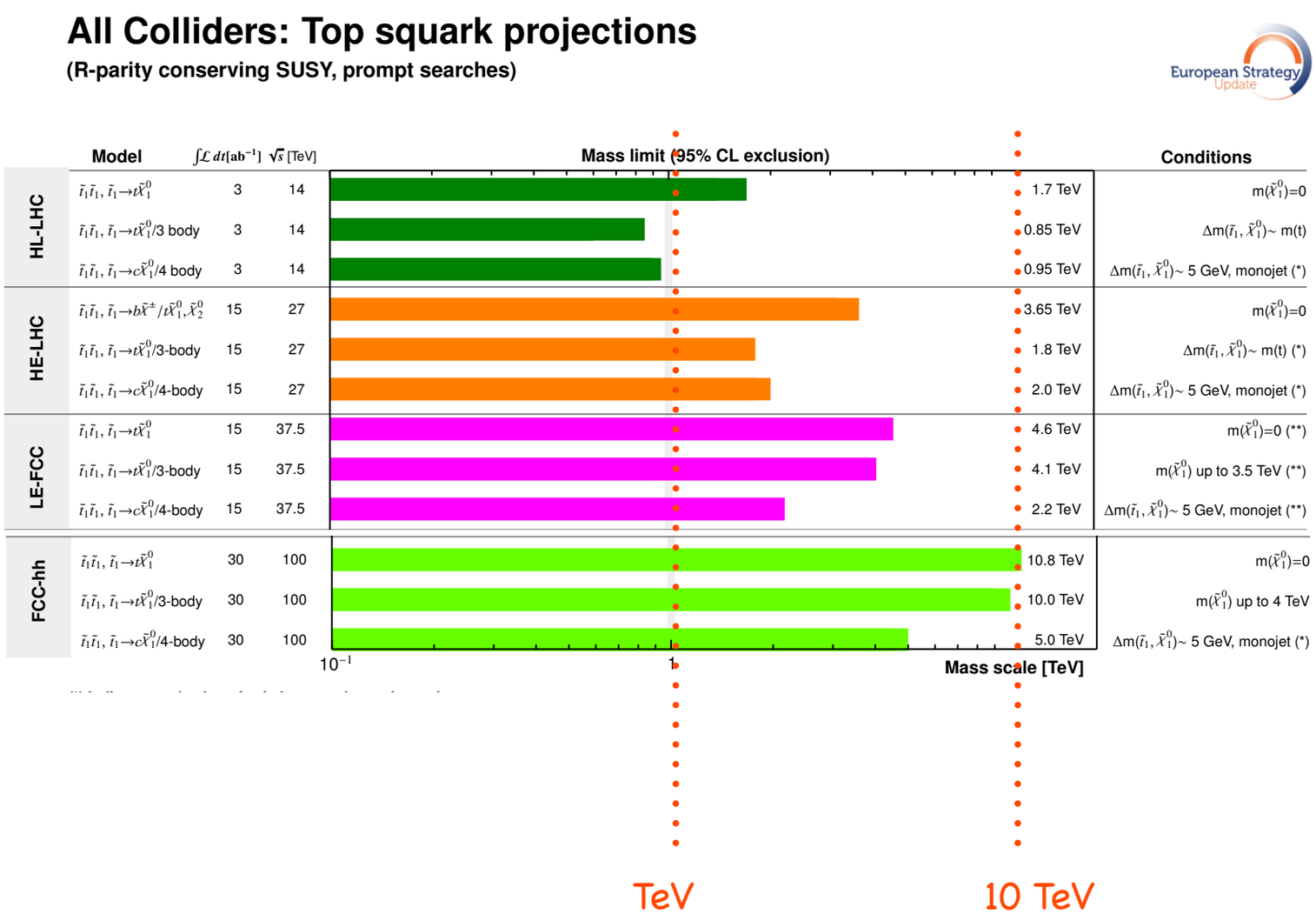
Which direction to go?



Which direction to go?

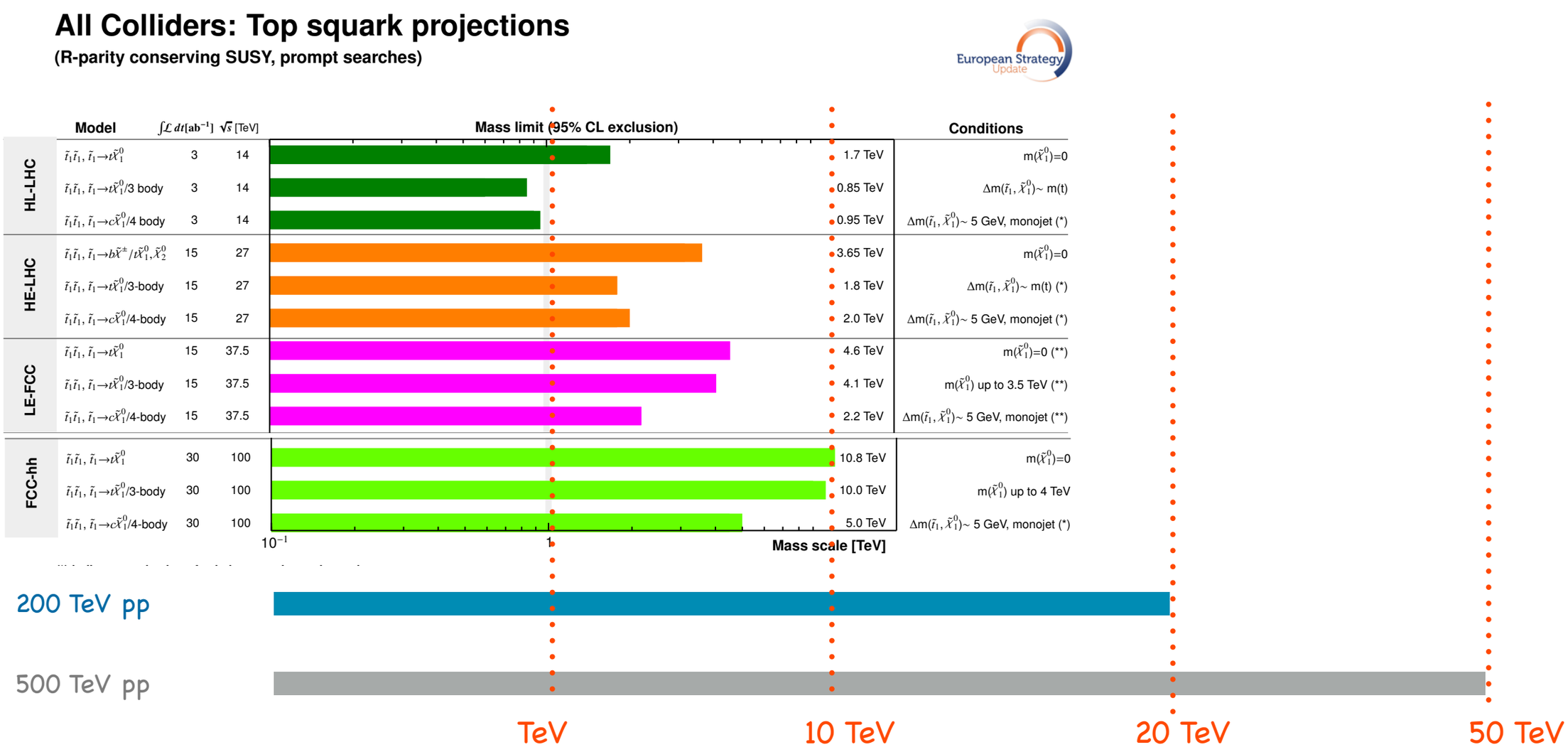


Pushing ahead with hadron collider



fine-tuning = $\frac{1}{16\pi^2}m_{\mathrm{T}}^2 \quad vs \quad m_h^2 = (125\ \mathrm{GeV})^2$

Pushing ahead with hadron collider

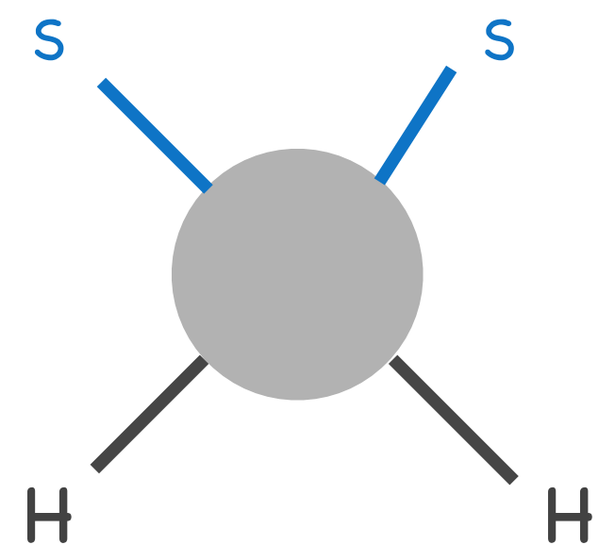


fine-tuning = $\frac{1}{16\pi^2}m_{\mathrm{T}}^2 \quad vs \quad m_h^2 = (125\ \mathrm{GeV})^2$

Clever model: Neutral naturalness

S: States "protect" the weak scale
Standard Model singlet.
Part of a hidden sector.
Not easily produced at colliders.

- Still, S (must) couples to the Higgs.
  - Signal: modifying Higgs coupling.
  - Signal: pp→h→SS.
  - Signal: h decay into lighter states in the S-sector



$m_S \sim \sqrt{1/\epsilon} \cdot 500$ GeV

$\epsilon \simeq$ level of tuning

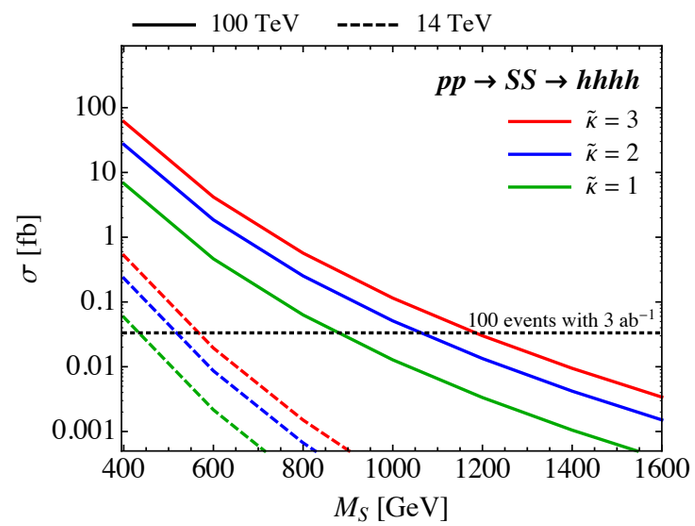
No tuning → $m_S \sim$ TeV

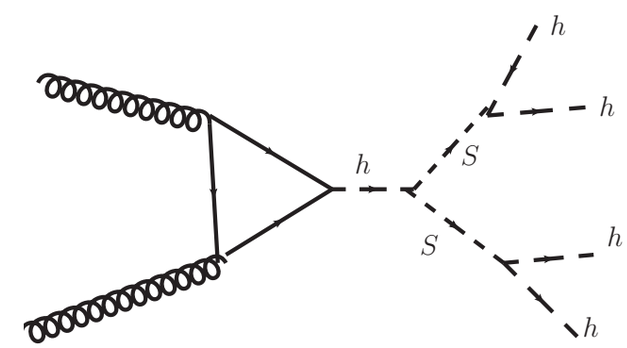
Probing neutral naturalness

100 TeV Testing tuning to 10%

200(500) push down to several %

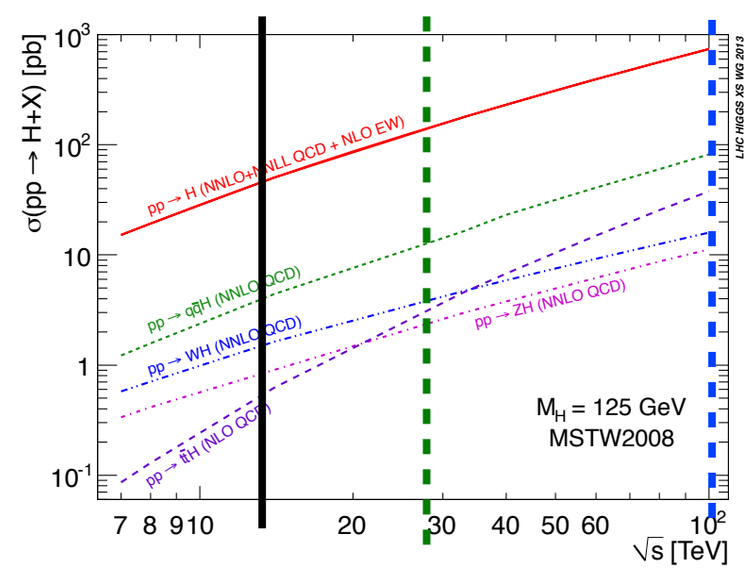
Probing m_S > TeV





h→ dark sector
(LLP, ...)

100 TeV collider can improve at least a factor of 10 beyond the LHC.



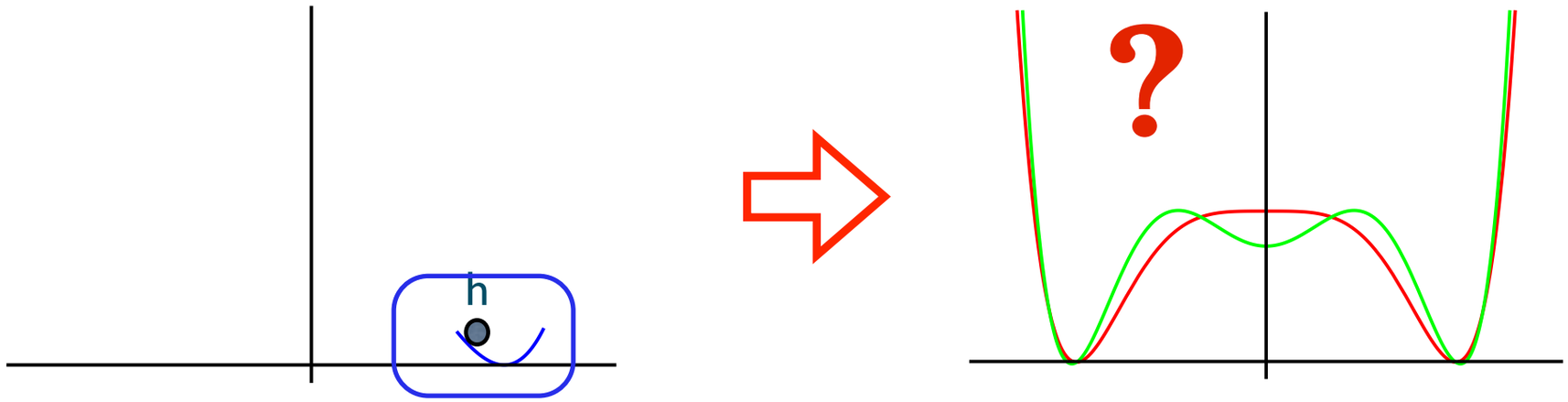
# of Higgses

100 TeV > 10 billion

27 TeV > 2 billion

14 TeV > 150 million

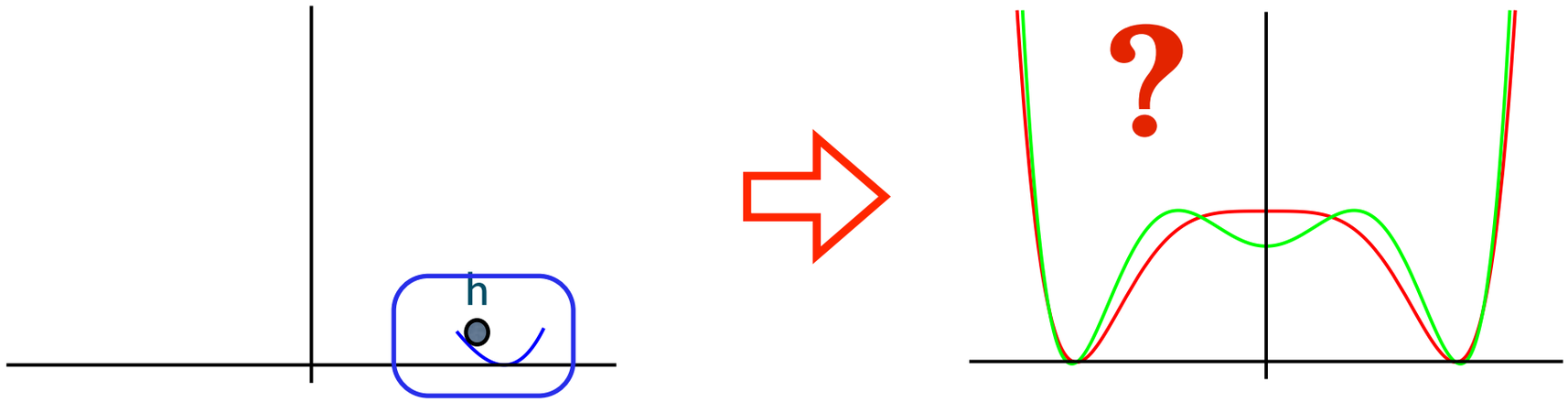
Understanding the Higgs better



What we know from LHC
LHC upgrades won't go much further

Addition info on Higgs measurements at pp collider:
European strategy physics briefing book, 1910.11775

Understanding the Higgs better



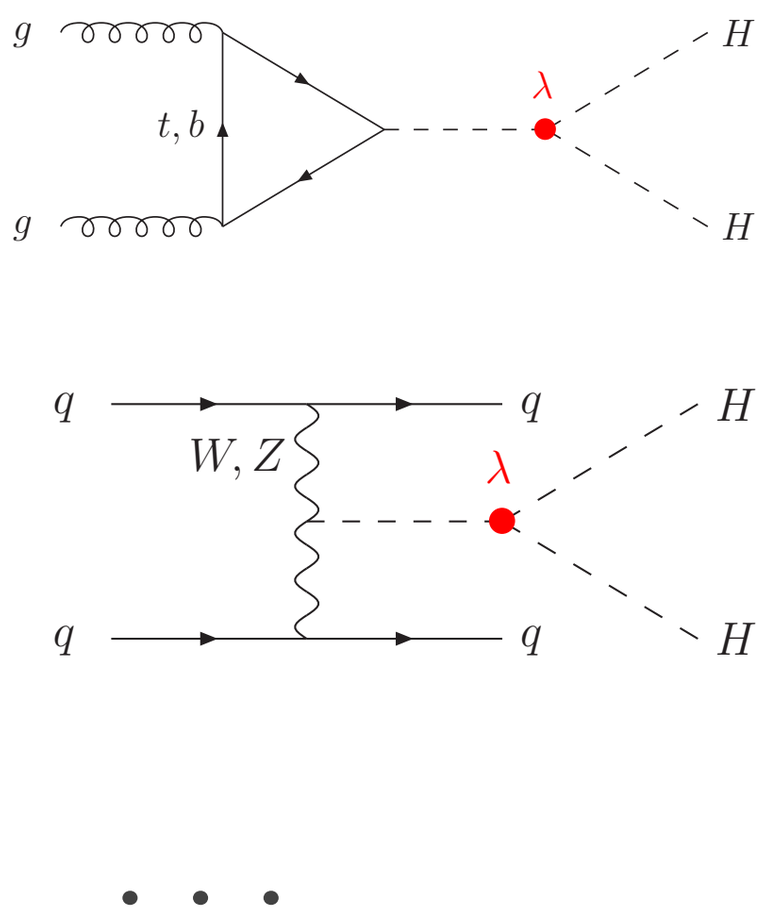
What we know from LHC
LHC upgrades won't go much further

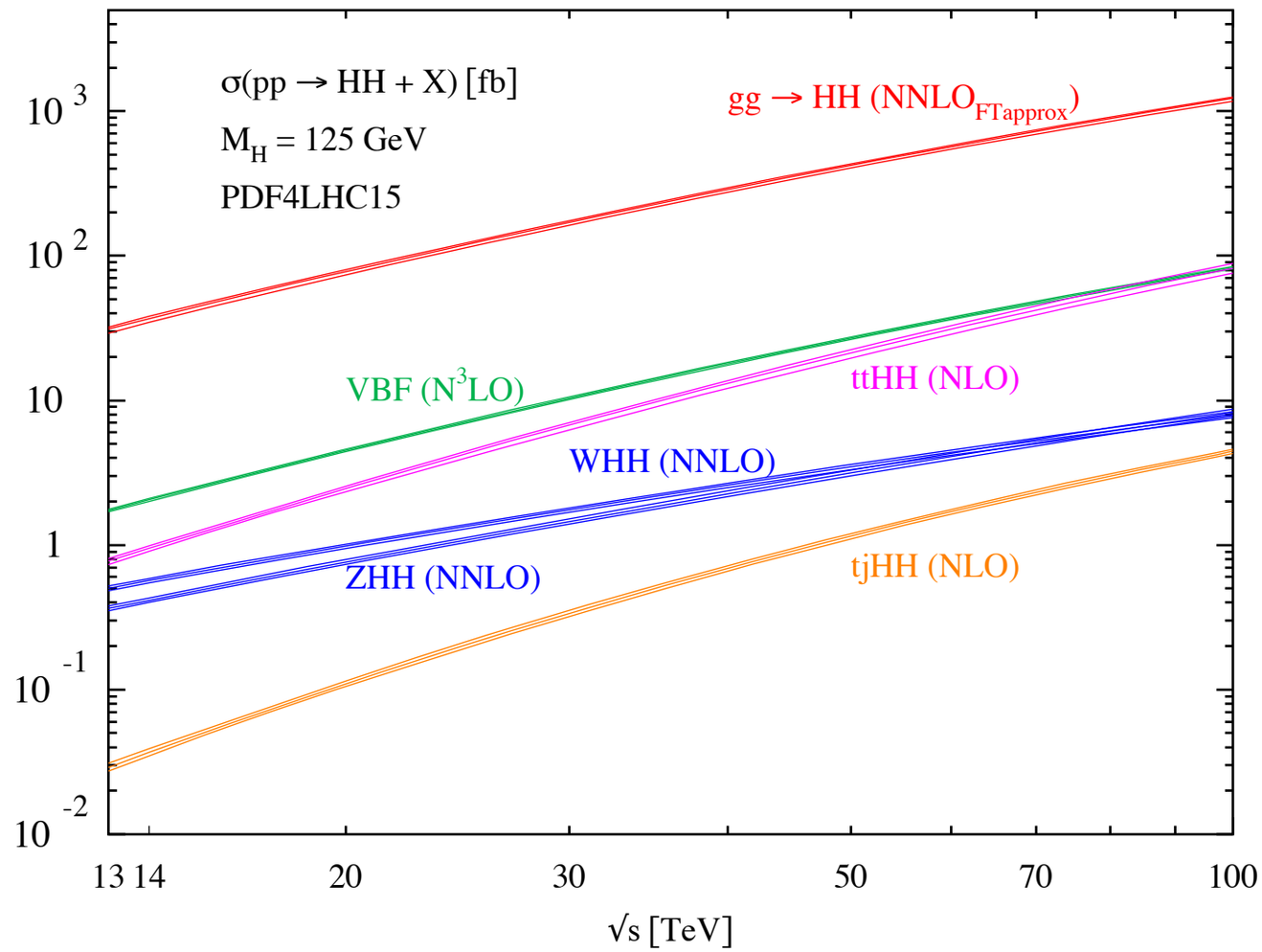
"wiggles" in Higgs potential

Big difference in triple Higgs coupling

Addition info on Higgs measurements at pp collider:
European strategy physics briefing book, 1910.11775

Larger statistics at higher energies

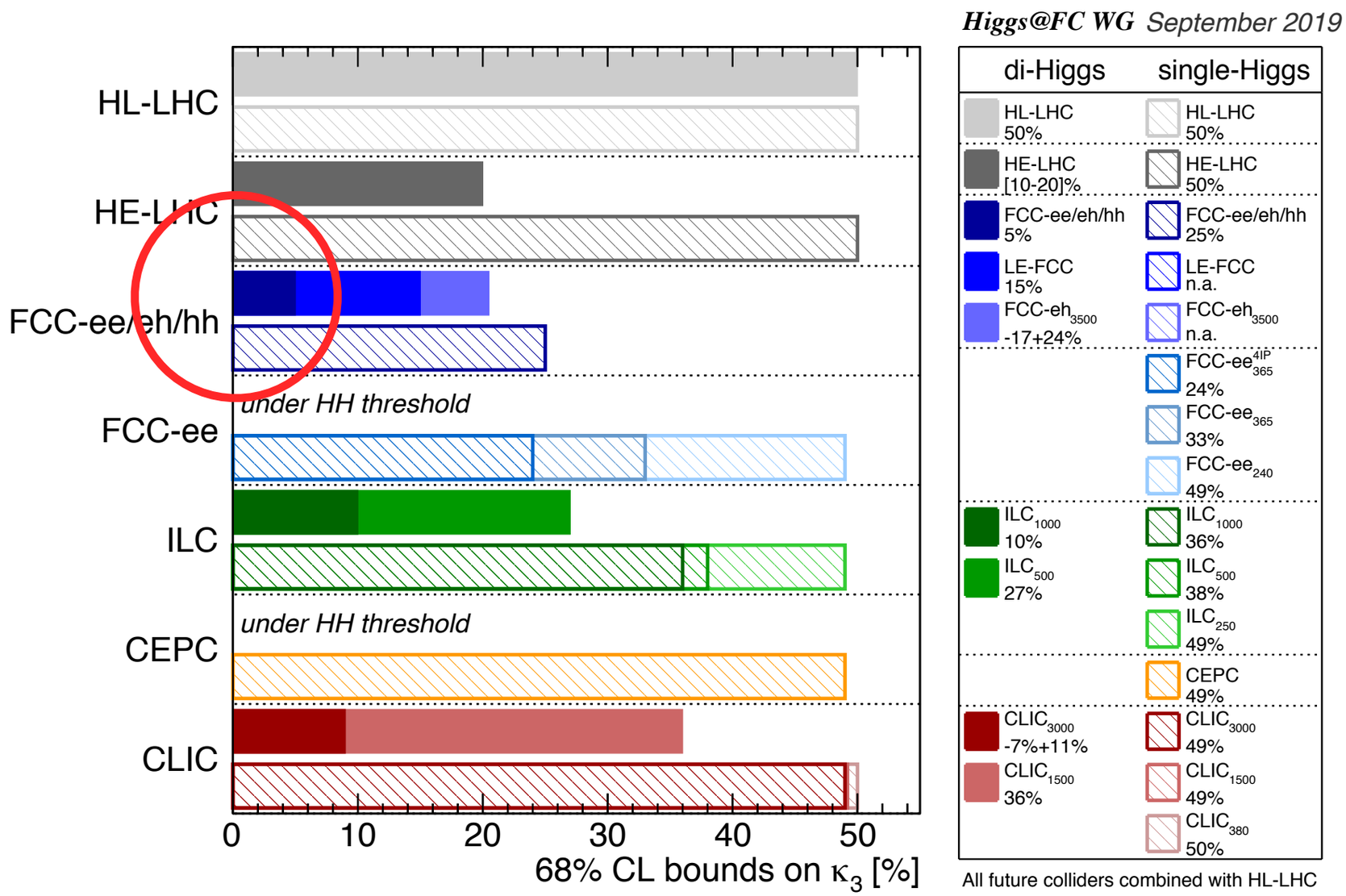




1910.00012

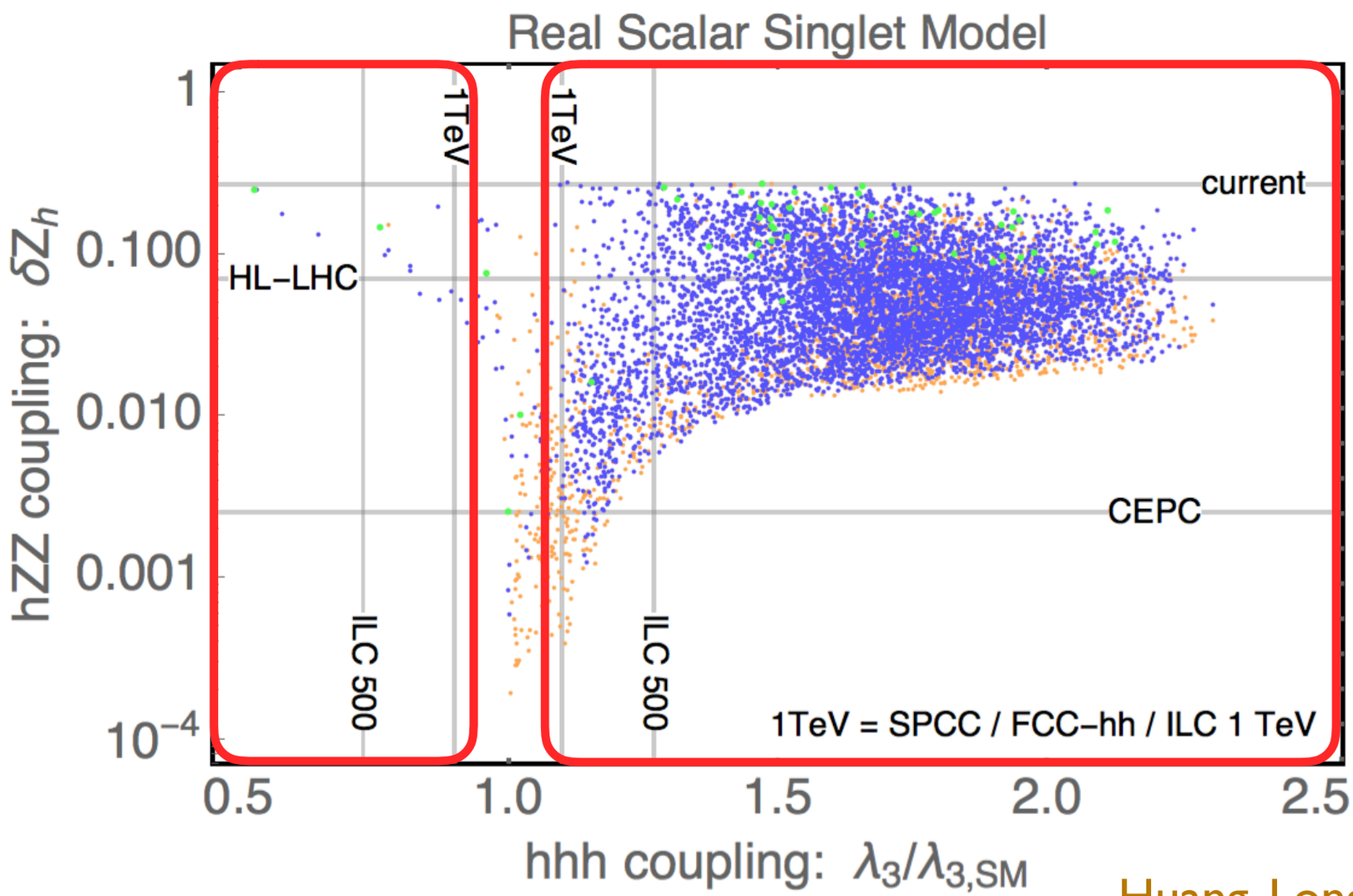
At 100 TeV, rate 40 times the LHC

Higgs potential



Extrapolating to higher energies more difficult.
We should expect a factor of a few improvement.

Probing EW phase transition

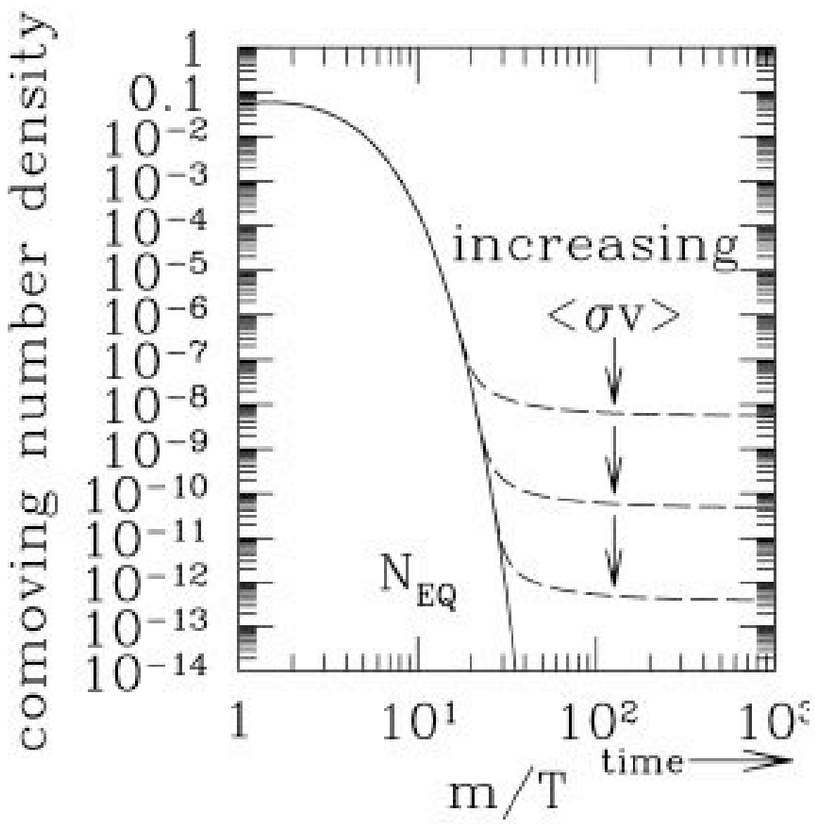


FCC-hh/SppC

Huang, Long, LTW, 1608.06619

Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

WIMP Dark matter

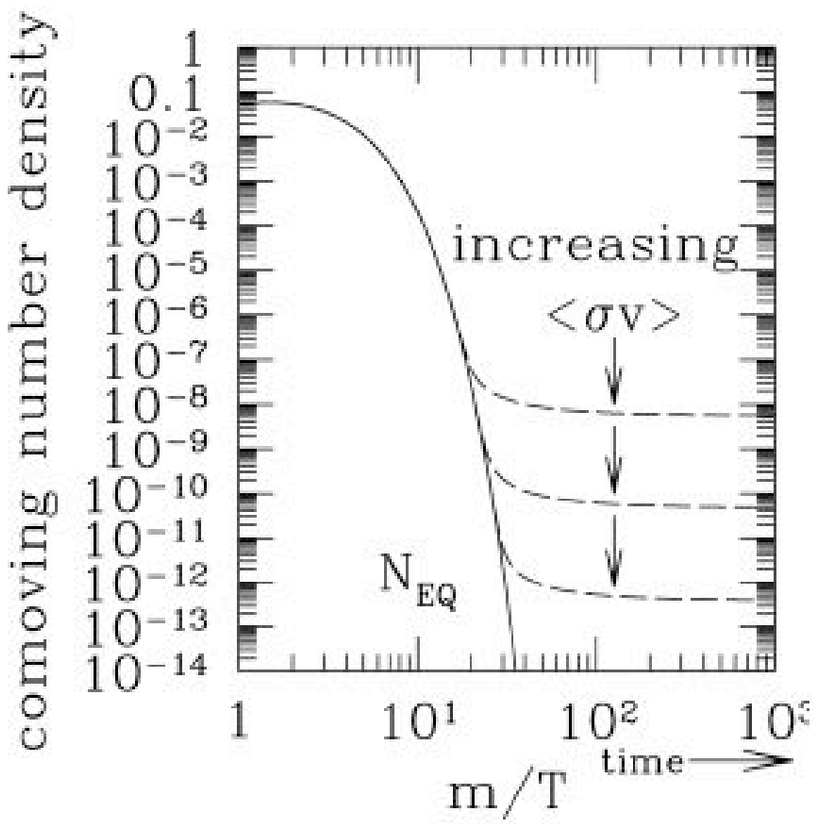


Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	11 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

The simplest WIMP model: DM part of EW multiplet.

Interaction: Standard Model gauge interactions.

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

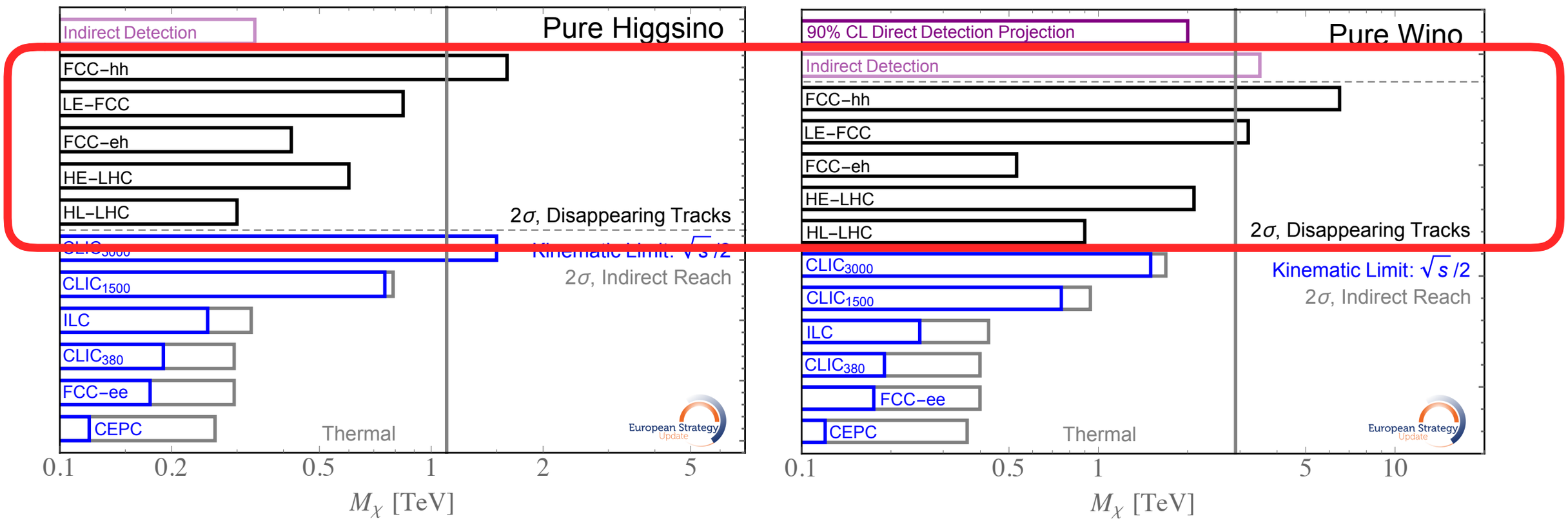
The simplest WIMP model: DM part of EW multiplet.

Interaction: Standard Model gauge interactions.

Very predictive. Thermal relic abundance $\rightarrow$ m_{DM} > TeV

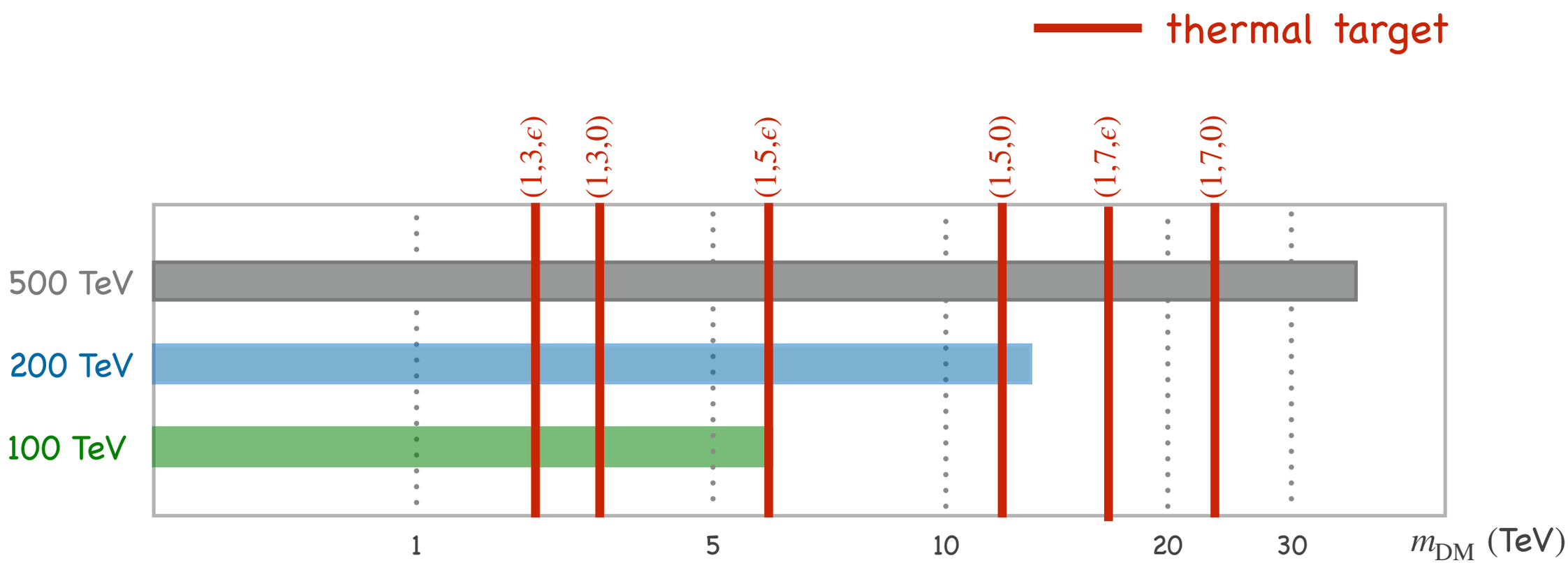
Really need (very) high energy colliders!

Dark matter reach



100 TeV pp collider is needed
to cover the EW doublet (Higgsino) and triplet (wino) DM.

EW Dark matter reach

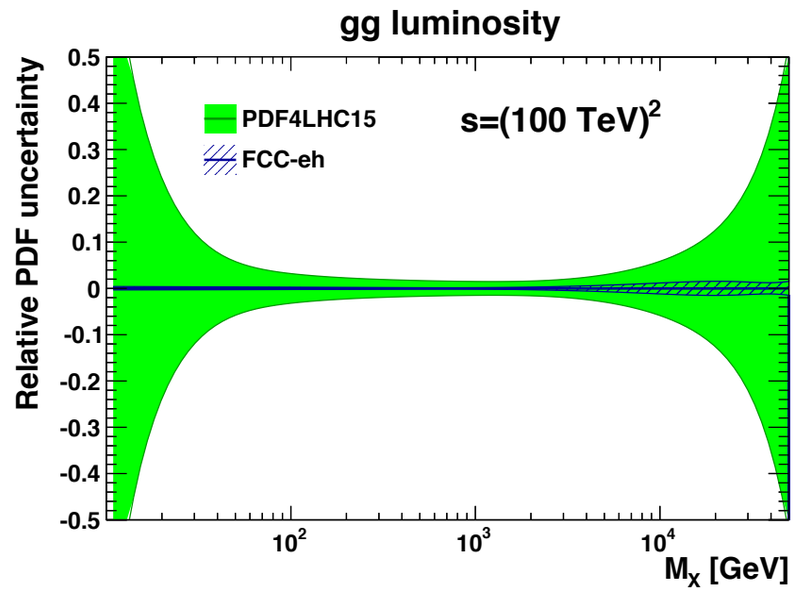


Higher energy needed to cover higher dimensional multiplets.

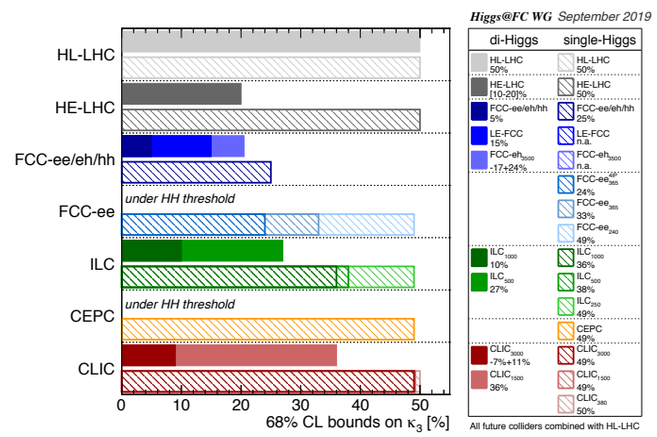
Either discovery or exclusion, we can make a clear statement of this very compelling WIMP DM scenario.

ep collider

Strong in PDF and related measurements

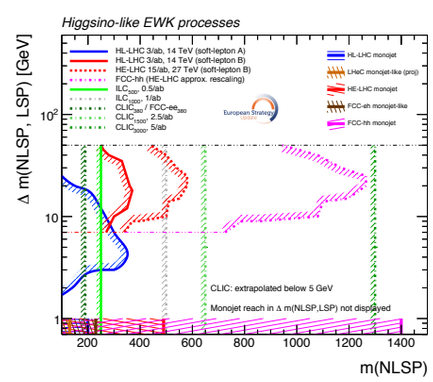


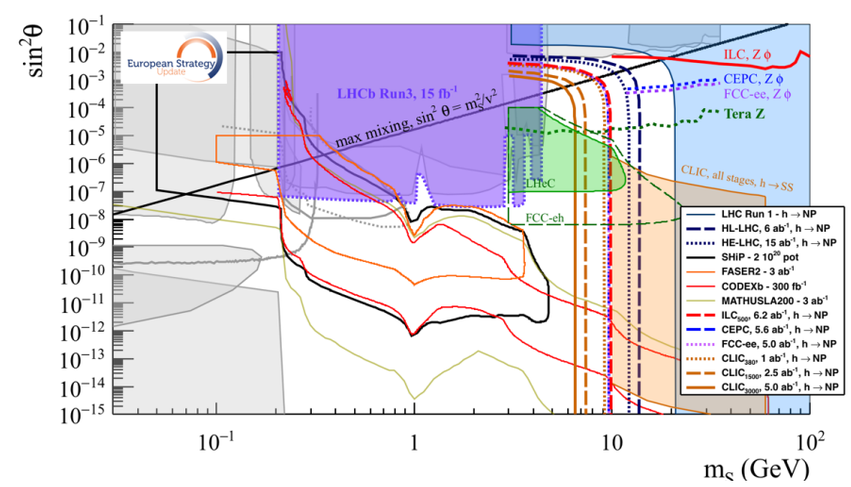
Helpful in Higgs measurements



+ higgs coupling such as κ_W

Sensitive to NP.





A good complement to a pp program.

Hadron vs lepton (intuition)

pp collider

- Higher energy.
- Messier, noisier.
- Probing more interactions, Stronger if NP has strong interaction.

lepton collider

- Lower energy.
- Cleaner environment, better sensitivity, precision.
- Stronger for electroweak states.

Hadron vs lepton (intuition)

pp collider

- Higher energy.
- Messier, noisier.
- Probing more interactions, Stronger if NP has strong interaction.

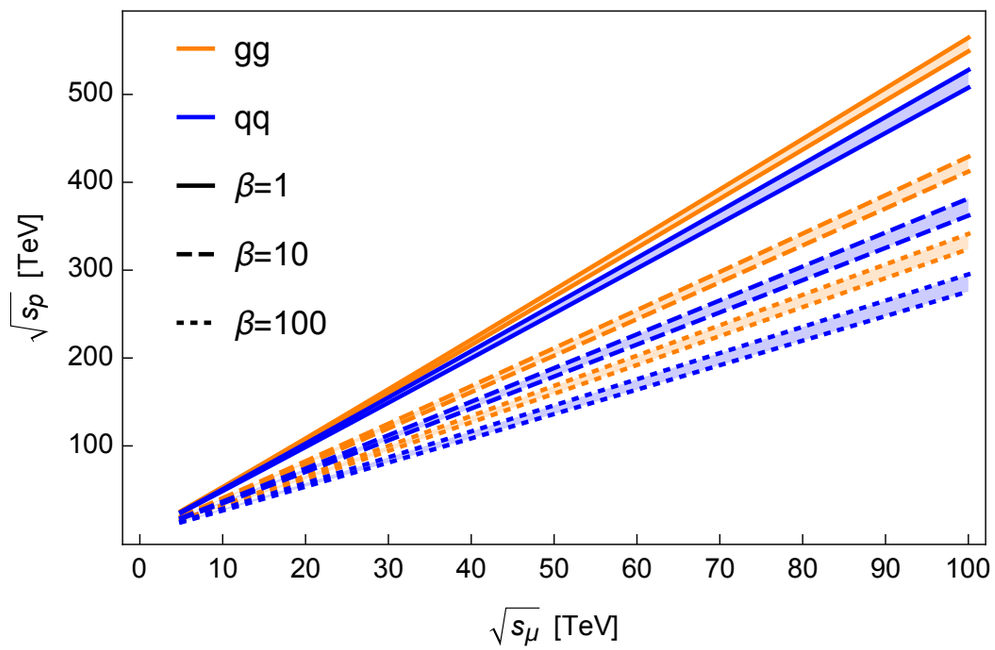
lepton collider

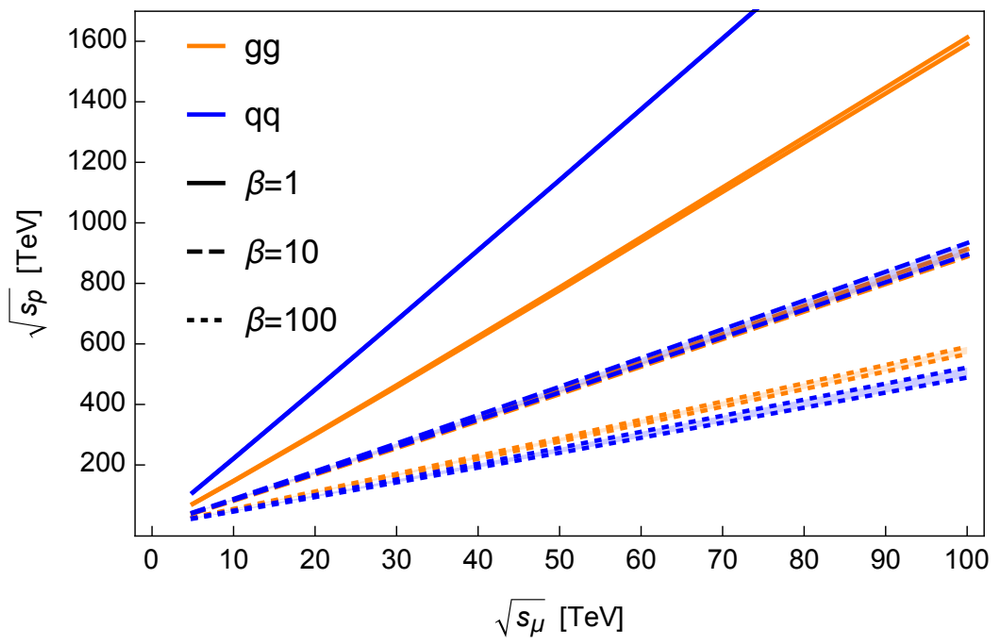
- Lower energy.
- Cleaner environment, better sensitivity, precision.
- Stronger for electroweak states.

However, this comparison really depends on what is achievable.

Hadron vs lepton

See P. Meade's talk in this session.





We "know" how to make hadron colliders.

But, we also need it to be much (O(10)) bigger.

What is our best route to (super) high energies?

Thoughts on benchmarks

higher?

500

200

A goal post beyond 100 TeV?

100 TeV, a "standard" benchmark. FCC-hh, SppC

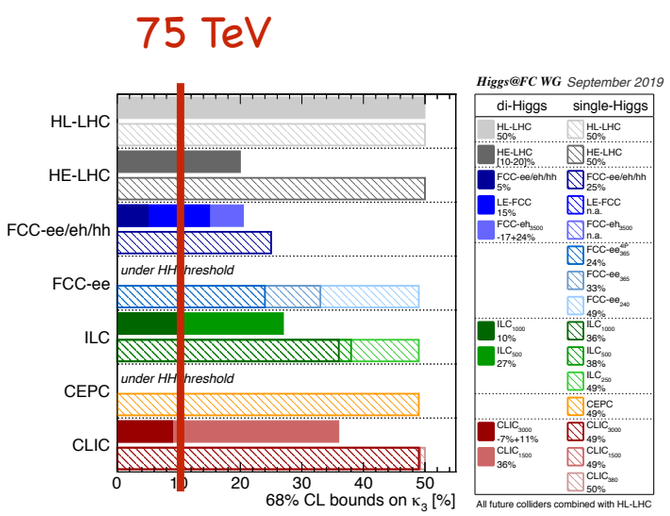
27 (HE-LHC), 37 (LE-FCC)

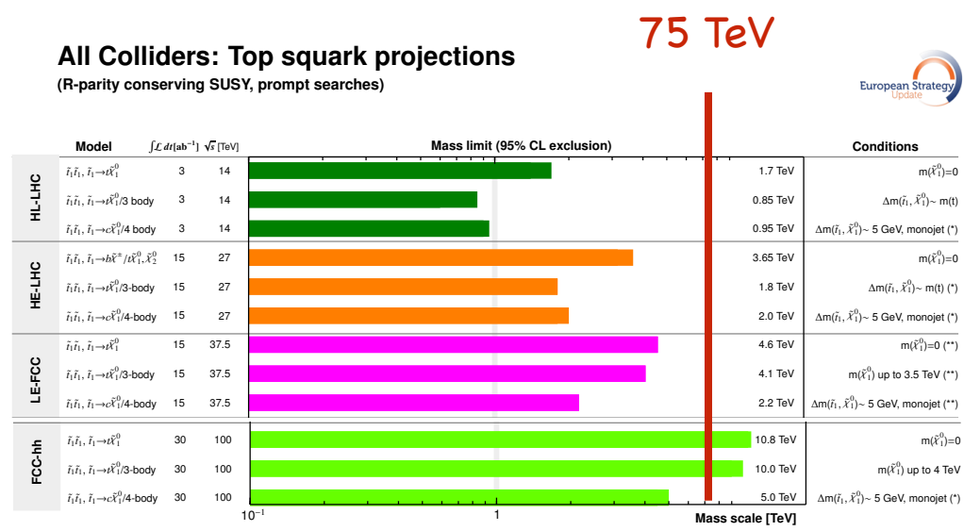
LHC

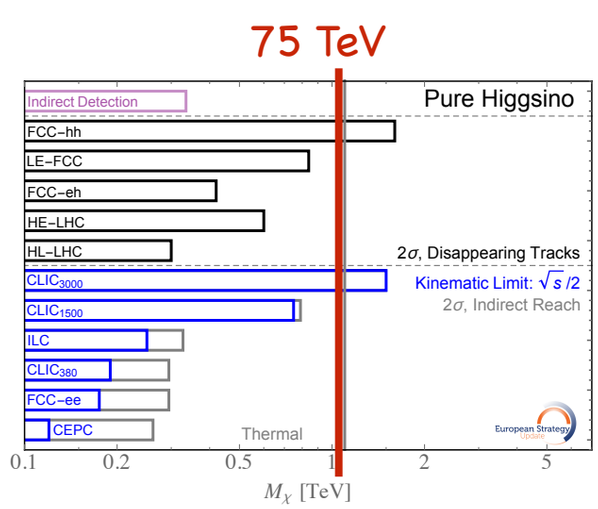
another benchmark?

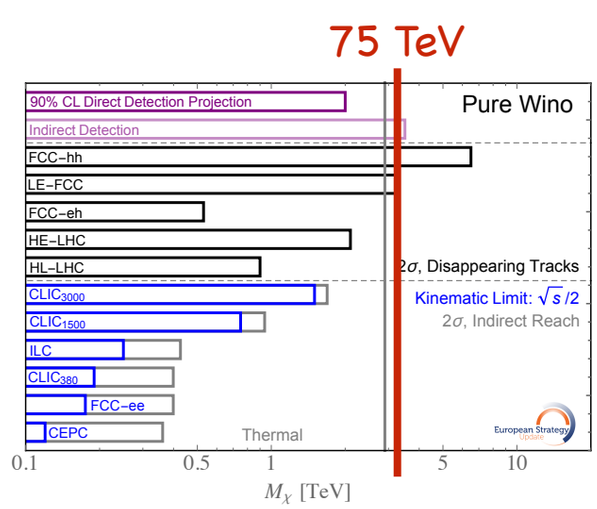
Below 100.

- Physics at 27, 37, as well 100 has been studied.
  - Physics potential in between bracketed.
  - For example, 75 TeV would be also a good step above the LHC.





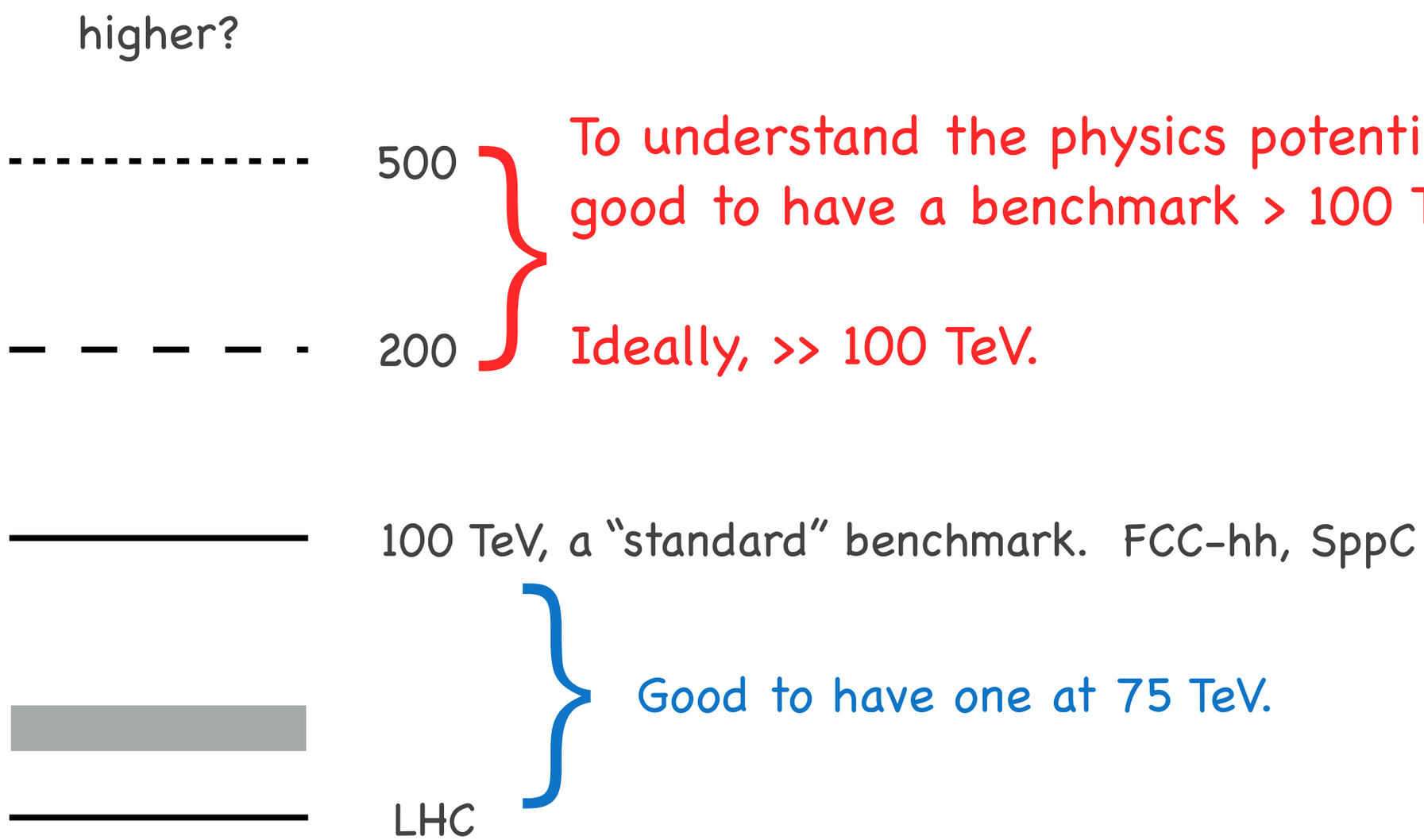




Above 100.

- Beyond 100, need to be as different as possible.
  - 150 won't be too different than 100. Would be 50% better than 100.
  - 200?
  - 500???
- Important to understand where the upper limit is.

Conclusion: benchmark for physics studies



What is a reasonable upper limit?

extras

Some Future Hadron collider proposals

ESG request for parameters of a lower-energy hadron collider

parameter	FCC-hh		FCC-hh-6T	HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		37.5	27	14	14
dipole field [T]	16		6	16	8.33	8.33
beam current [A]	0.5		0.6	1.1	1.1	0.58
synchr. rad. power/ring [kW]	2400		57	101	7.3	3.6
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	10 (lev.)	16	5 (lev.)	1
events/bunch crossing	170	1000	~300	460	132	27
stored energy/beam [GJ]	8.4		3.75	1.4	0.7	0.36

- **NbTi technology from LHC, magnet with single-layer coil providing 6 T at 1.9 K:**
  - → Corresponding beam energy 18.75 TeV or 37.5 TeV c.m.
  - → Significant reduction of synchrotron radiation wrt FCC-hh (factor 50) and corresponding cryogenic system requirements.
- **Luminosity goal 10 ab^{-1} over 20 years or 0.5 ab^{-1} annual luminosity:**
  - → Beam current 0.6 A or 20% higher than for FCC-hh, 1.2E11 ppb (FCC-hh: 1.0 ppb).
  - → Stored beam energy 3.75 GJ vs 8.4 GJ for FCC-hh.
- **Analysis of physics potential, technology requirements and cost ongoing.**

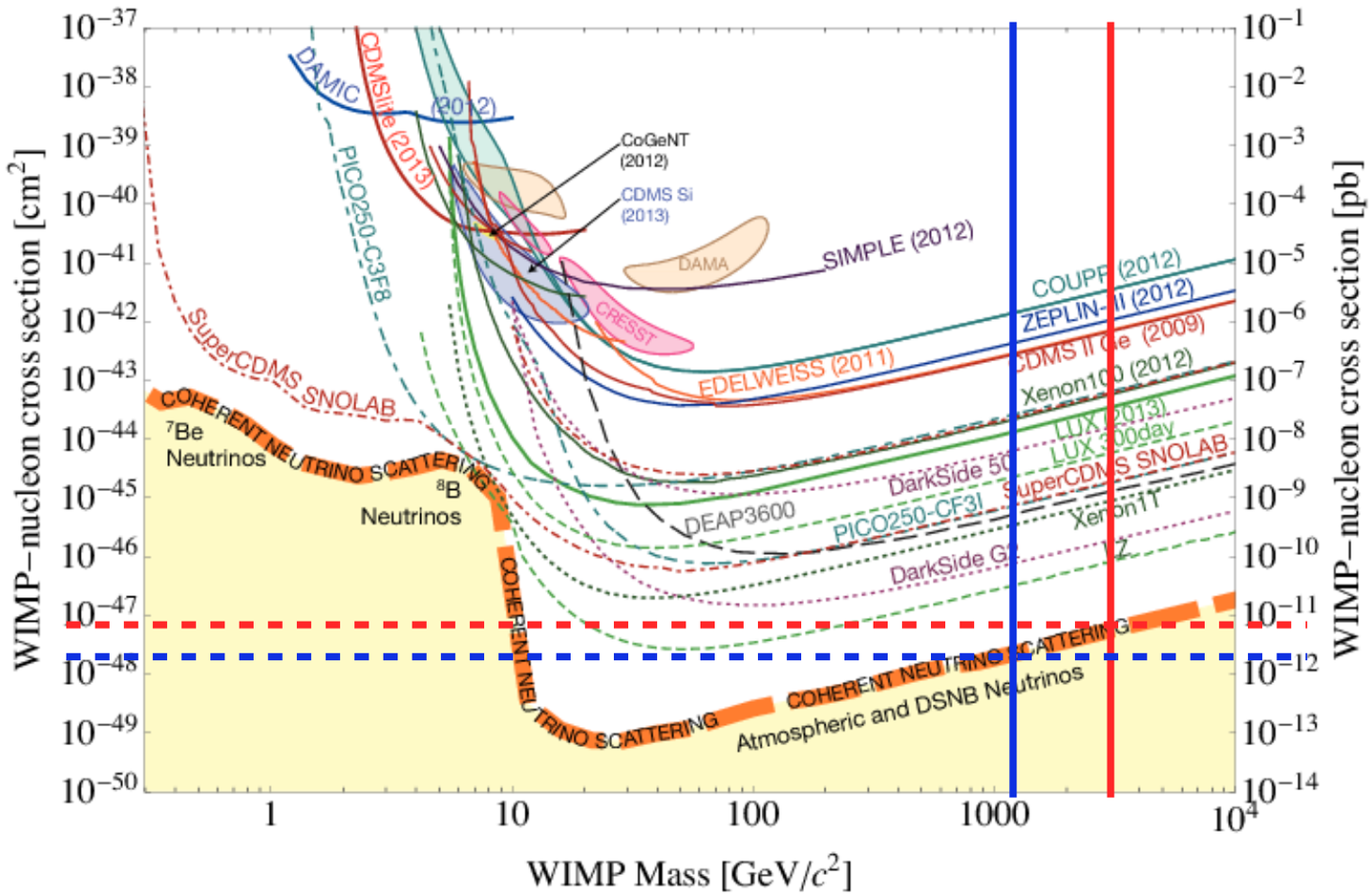
M. Benedikt and F. Zimmermann, FCC week

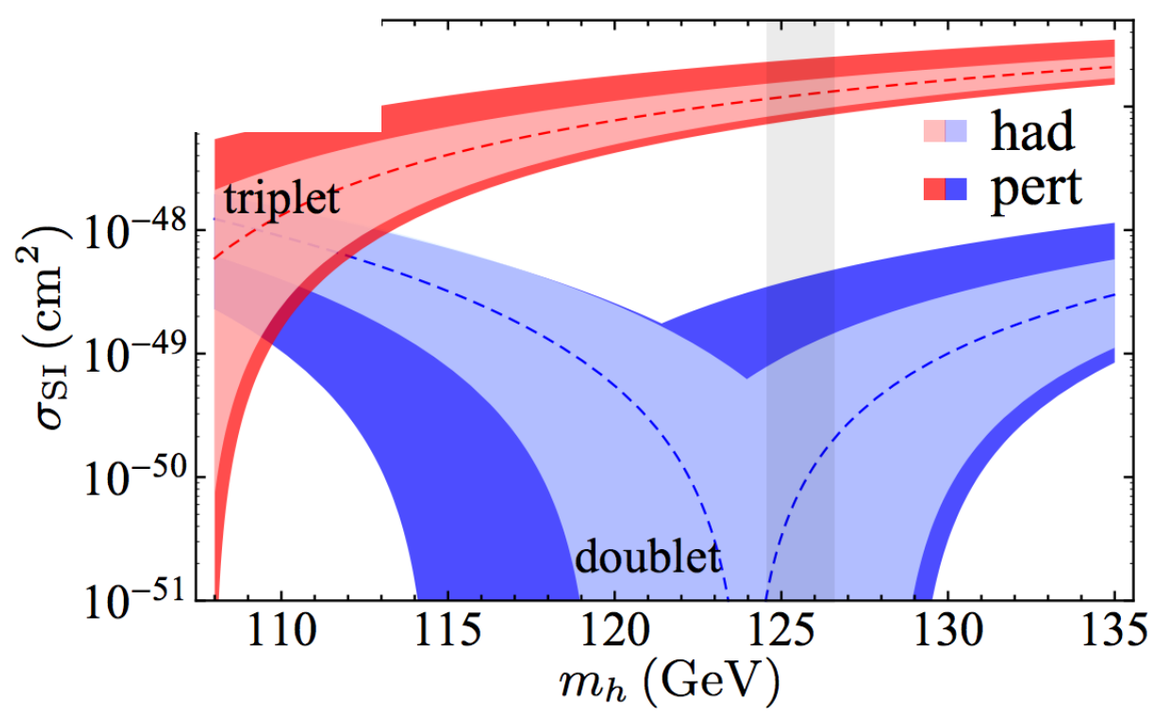
Future Hadron colliders

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

target luminosity HL-LHC: 3 ab^{-1} , HE-LHC and FCC-hh: 20-30 ab^{-1}

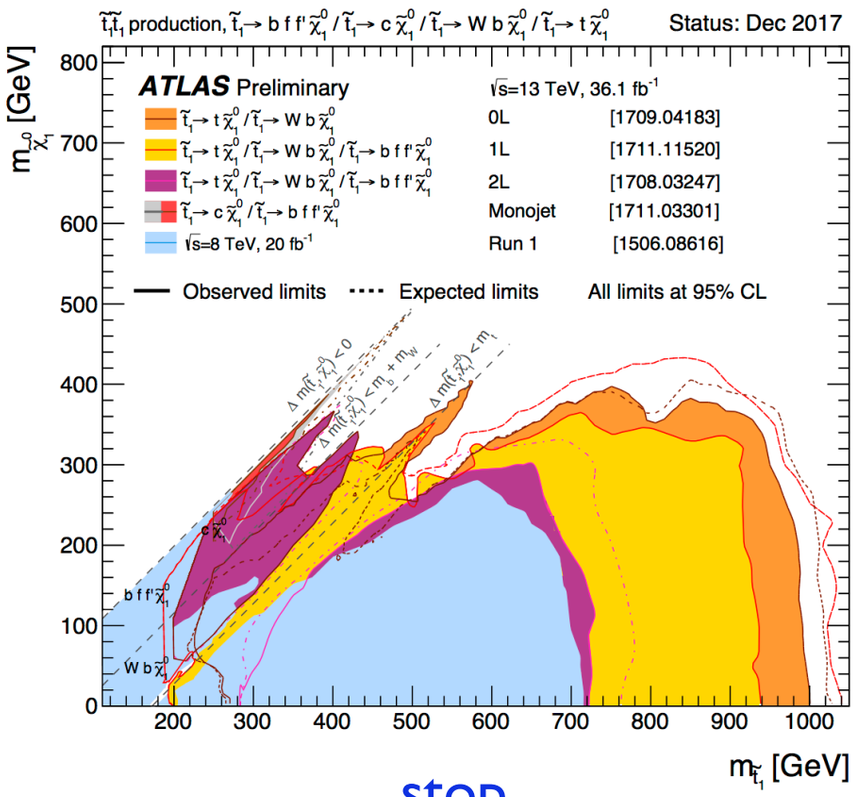




Hill and Solon, 2014

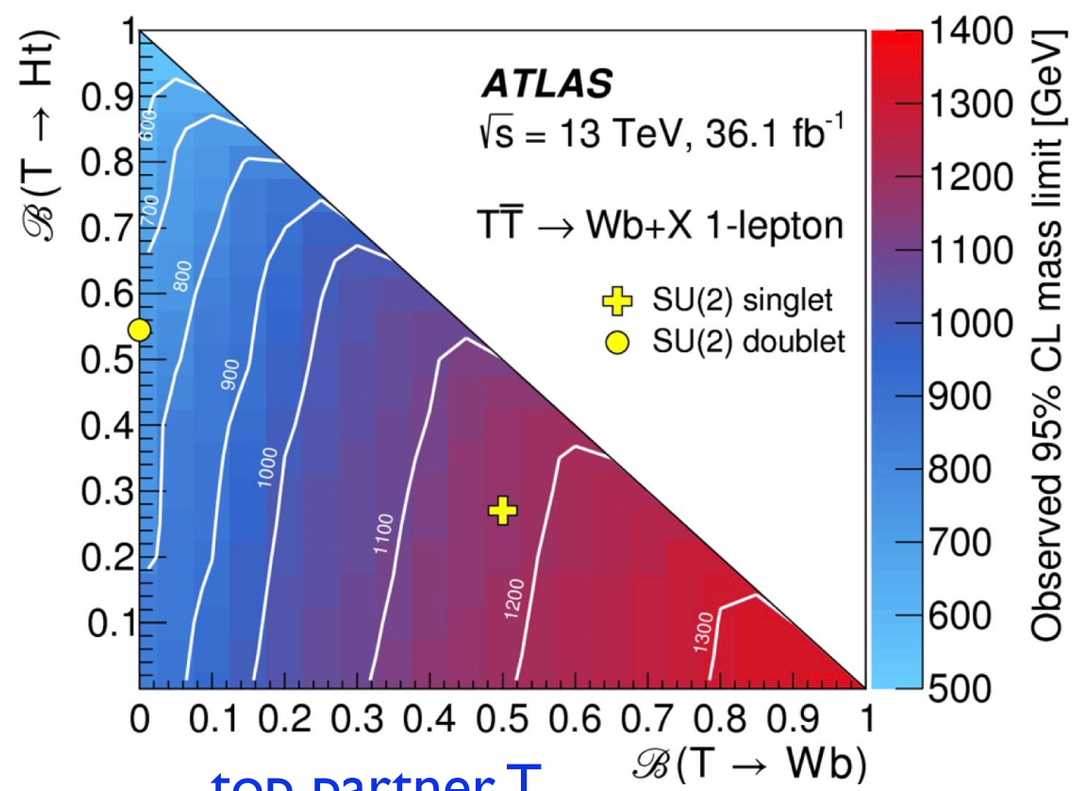
However, didn't quite pan out

Supersymmetry



stop

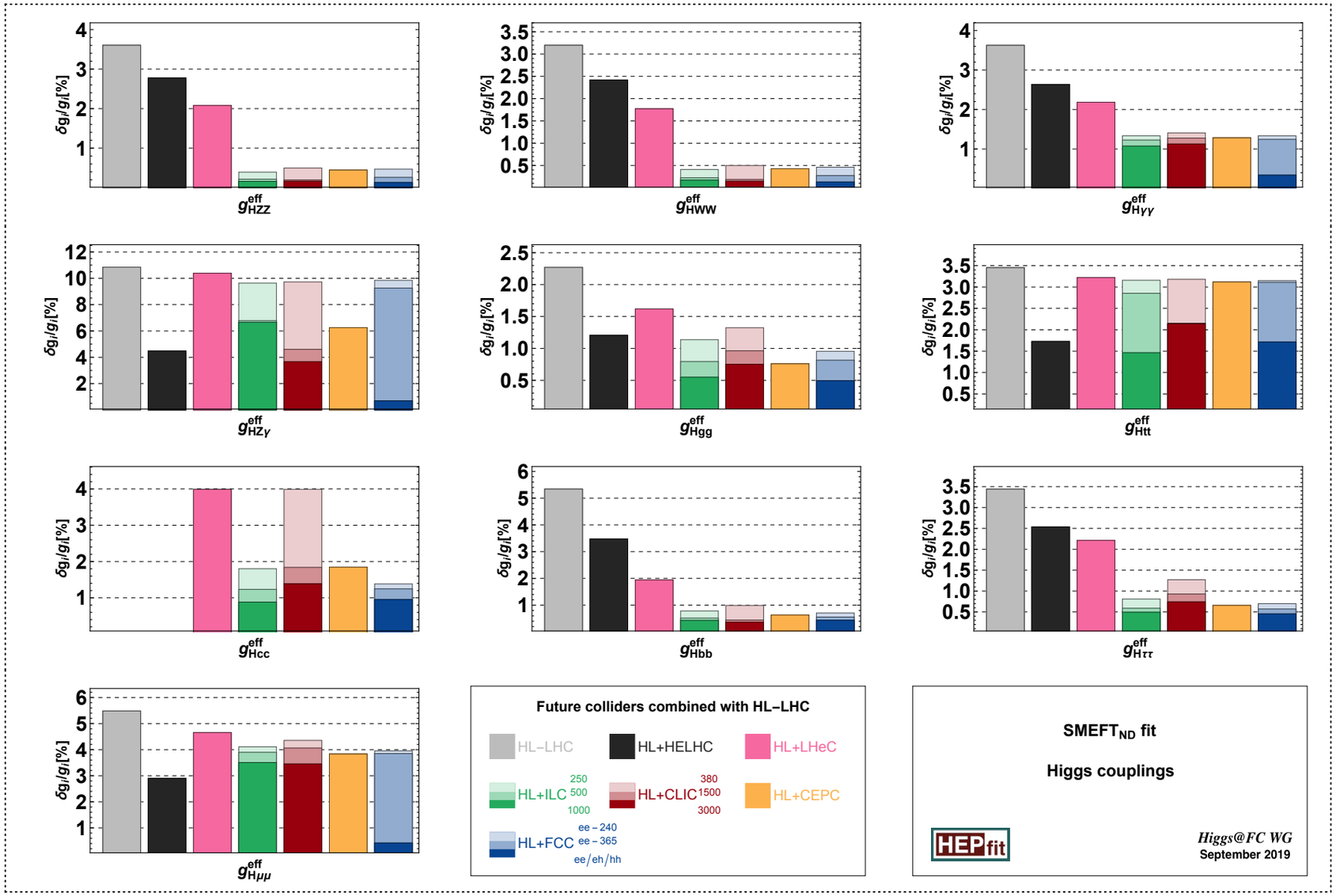
Composite Higgs



top partner, T

fine-tuning = comparison $\frac{1}{16\pi^2} m_{\mathrm{T}}^2 \quad vs \quad m_h^2 = (125\ \mathrm{GeV})^2$

current limit: $m_{\mathrm{T}} \sim 1\ \mathrm{TeV}$


$\delta g_i/g_i[\%]$
g^{eff}_{HZZ}
g^{eff}_{HWW}
$g^{eff}_{H\gamma\gamma}$
$g^{eff}_{HZ\gamma}$
g^{eff}_{Hgg}
g^{eff}_{Htt}
g^{eff}_{Hcc}
g^{eff}_{Hbb}
$g^{eff}_{H\tau\tau}$
$g^{eff}_{H\mu\mu}$
Future colliders combined with HL−LHC
HL−LHC
HL+HELHC
HL+LHeC
HL+ILC 250 500 1000
HL+CLIC 380 1500 3000
HL+CEPC
HL+FCC ee−240 ee−365 ee/eh/hh
SMEFT$_{ND}$ fit
Higgs couplings
HEPfit
Higgs@FC WG
September 2019

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] [e^-/e^+]	$N_{\rm Det}$	$\mathscr{L}_{\rm inst}$/Det. [10^{34}cm^{-2}s^{-1}]	$\mathscr{L}$ [ab^{-1}]	Time [years]	Ref.
HL-LHC	pp	14 TeV	–	2	5	6.0	12	[23]
HE-LHC	pp	27 TeV	–	2	16	15.0	20	[23]
FCC-hh	pp	100 TeV	–	2	30	30.0	25	[637]
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[637]
		$2M_W$	0/0	2	25	10	1-2	
		240 GeV	0/0	2	7	5	3	
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5	
		(1y SD before $2m_{top}$ run)					(+1)	
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[342]
		350 GeV	±80/±30	1	1.6	0.2	1	[346]
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5	
		(1y SD after 250 GeV run)					(+1)	
CEPC	ee	M_Z	0/0	2	17/32	16	2	[509]
		$2M_W$	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	[638]
		1.5 TeV	±80/0	1	3.7	2.5	7	
		3.0 TeV	±80/0	1	6.0	5.0	8	
		(2y SDs between energy stages)					(+4)	
LHeC	ep	1.3 TeV	–	1	0.8	1.0	15	[636]
HE-LHeC	ep	1.8 TeV	–	1	1.5	2.0	20	[637]
FCC-eh	ep	3.5 TeV	–	1	1.5	2.0	25	[637]