Desired ultimate beams for Probing BSM at colliders: Luminosity vs energy

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Physics limits of ultimate beams workshop, Dec. 18

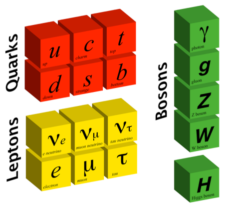
This talk

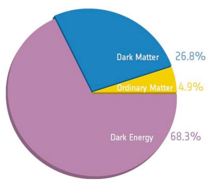
- Focus on high energy colliders.
- Mainly order of magnitude estimates and scaling.
  - Focus on broad classes of signals, not special models. (There is not a model much more compelling than this others.)
- Both the bare minimal requirement, and what's needed for a more comprehensive program.

Many more detailed studies still needed to be done.
I hope to give the impression of the order of magnitude here.

Where we are

- We have a good picture of the universe, including its basic content and the interactions.
  - Standard Model of particle physics
  - Dark matter + dark energy



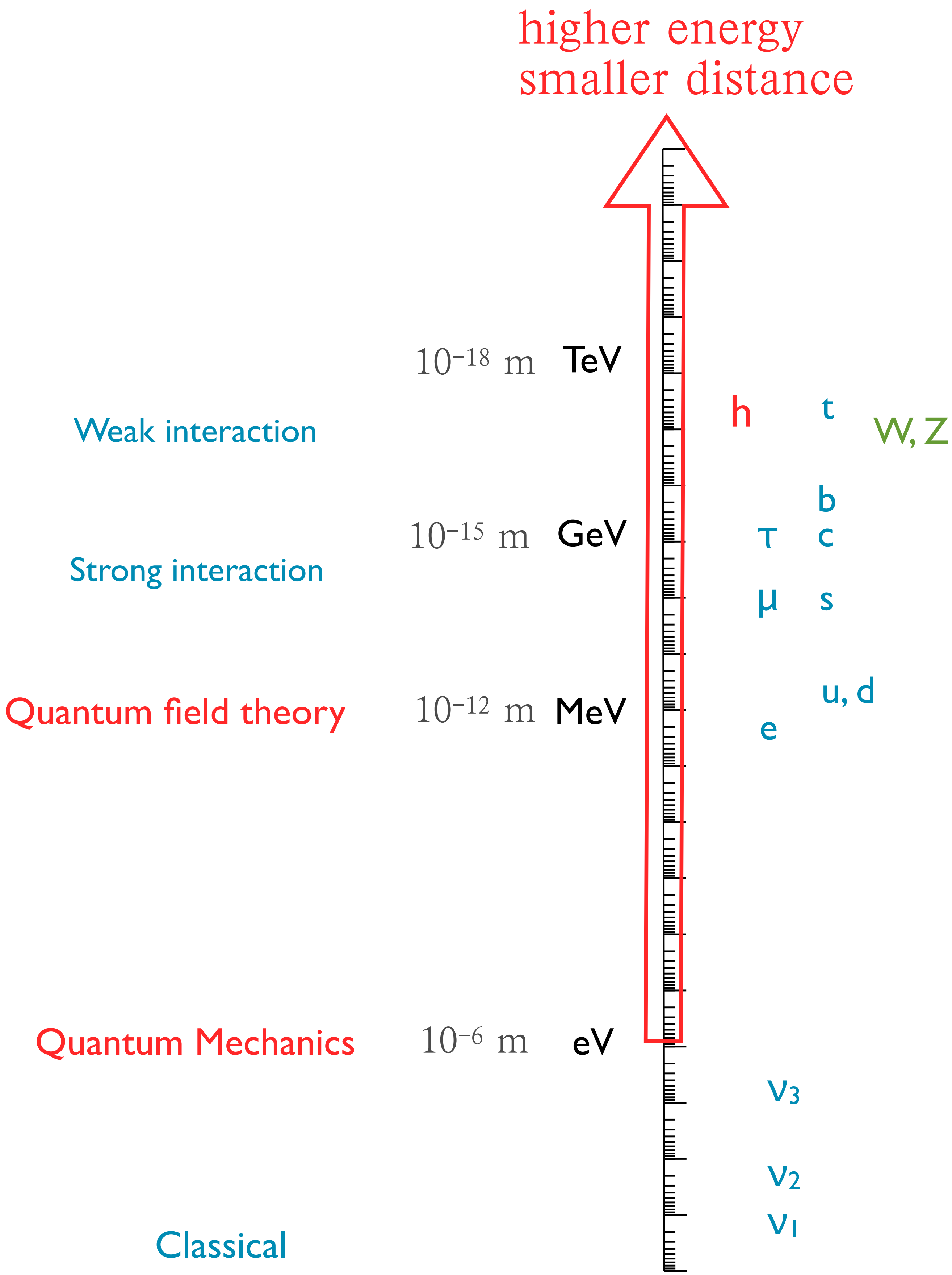


- However, we are missing the underlying principles of this picture.

Many remaining puzzles

- Origin of the Electroweak scale.
- What is Dark Matter
- What is the origin of Flavor/CP
- Matter anti-matter asymmetry.
- Dark energy?
- ...

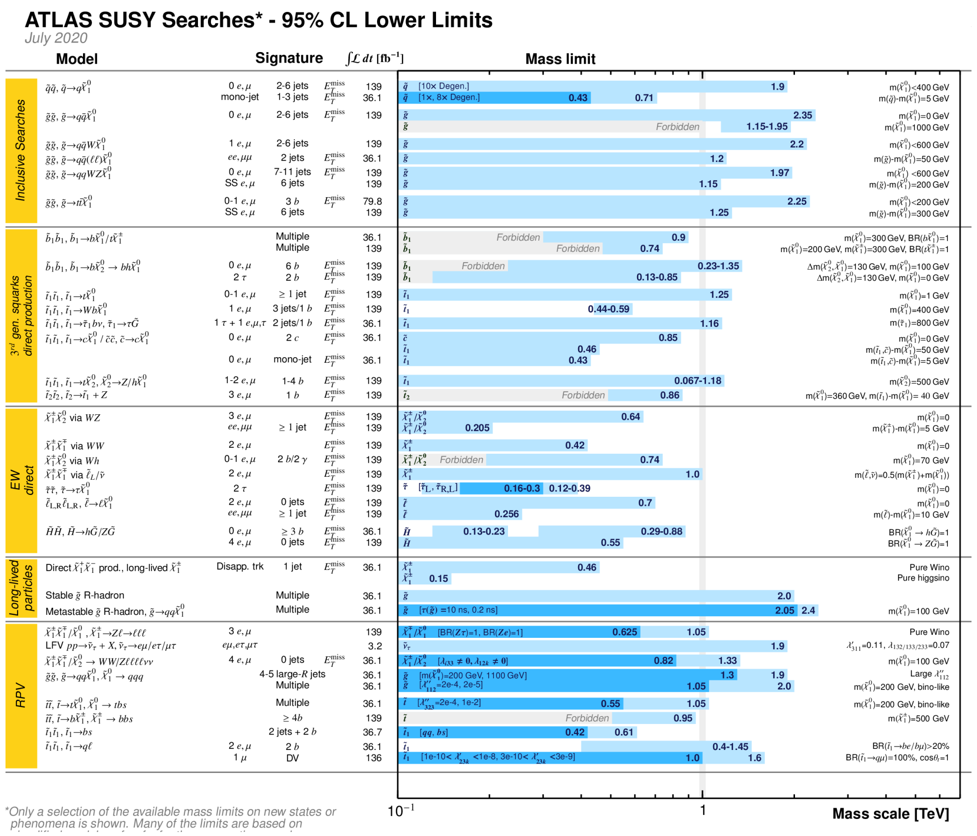
We believe that going to higher energy (shorter distance) will give us answers.

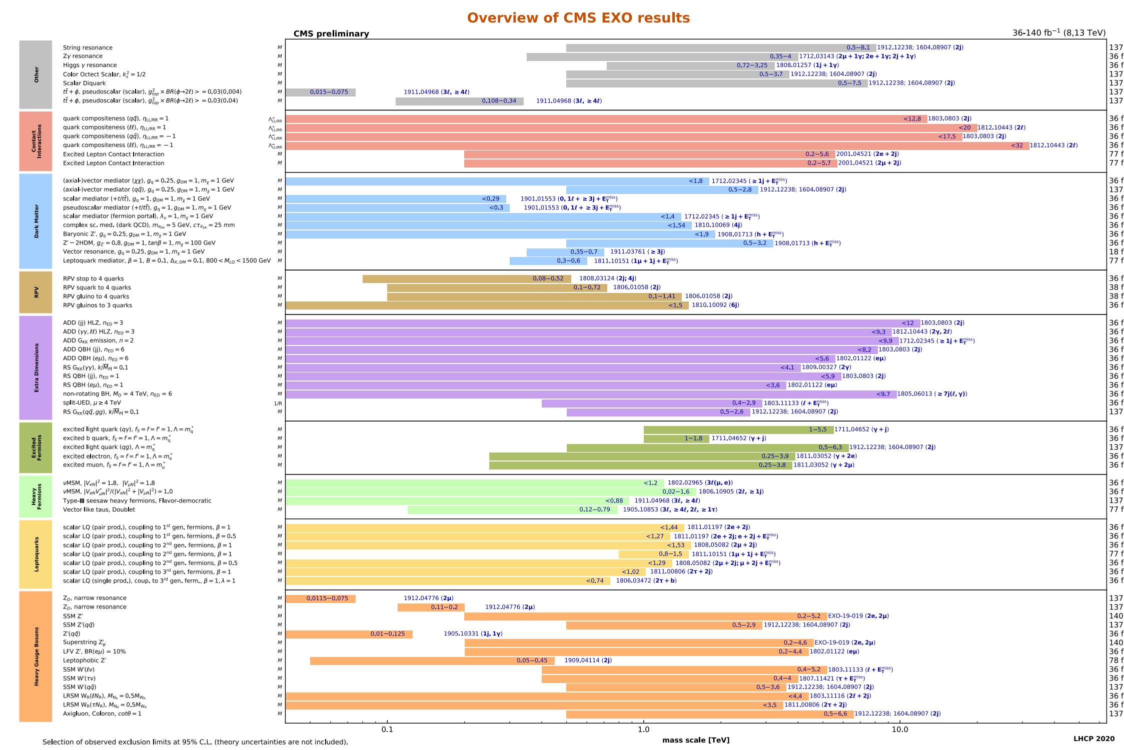


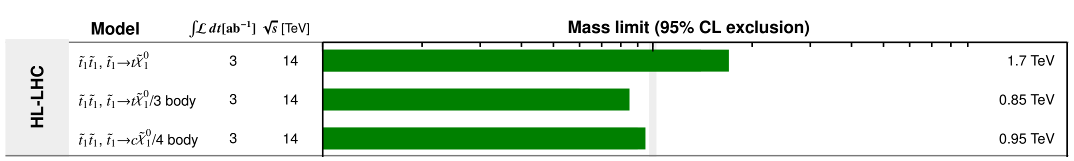
Amazing progresses made in the last century by marching towards higher energies (~12 orders of magnitudes).

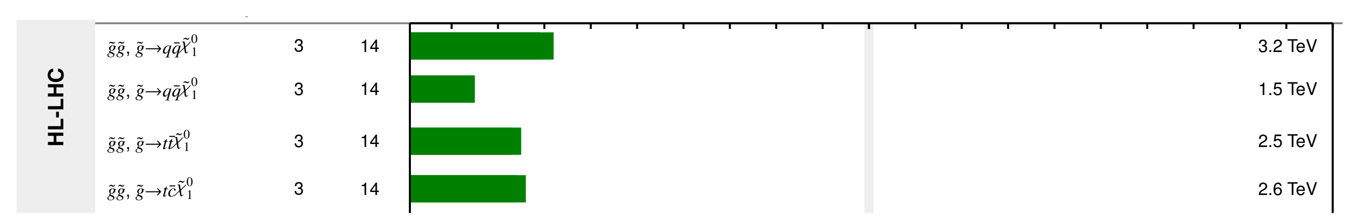
We certainly should continue!

Current status and next decade



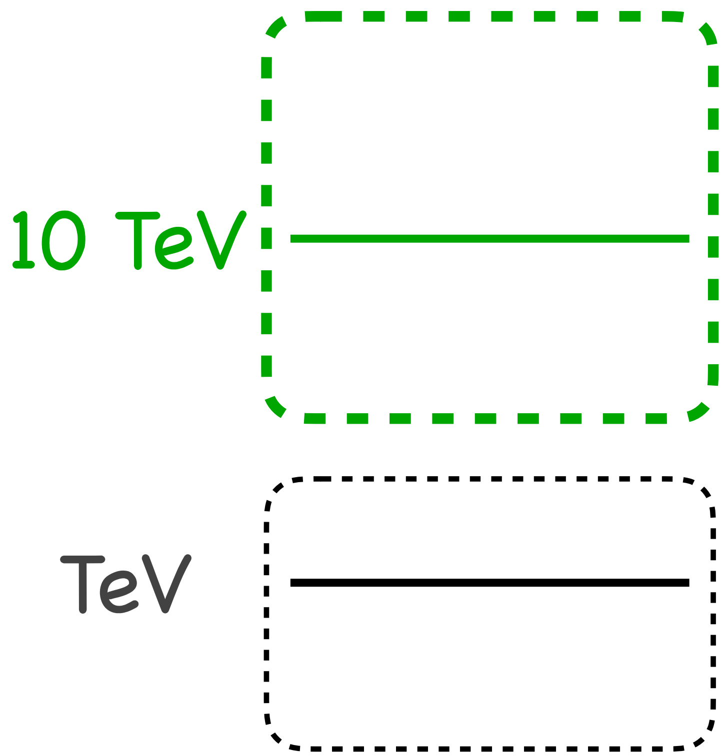






- TeVs explored, coverage will improve at the HL-LHC (by about 50-100%).

The next frontier

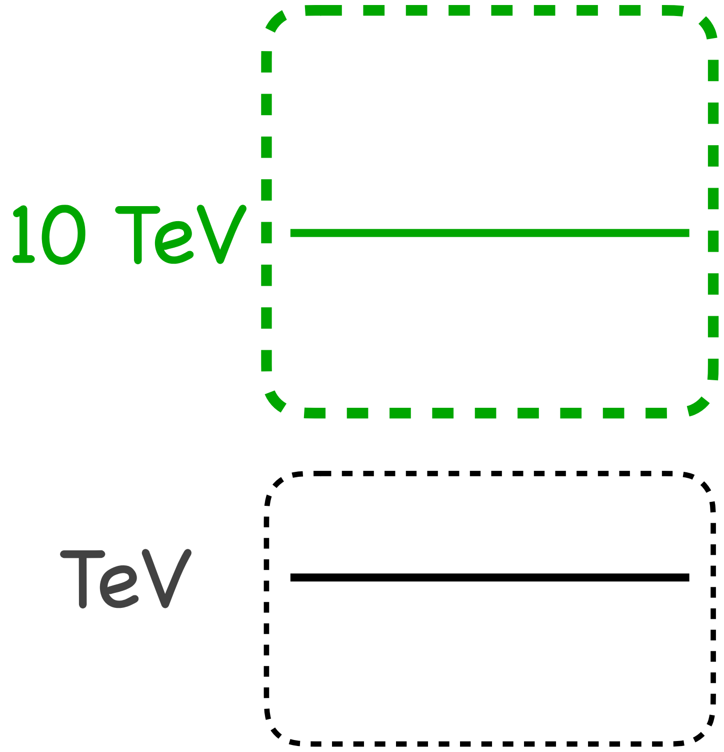


Our next goalpost should be 10(s) of TeV.

LEP, Tevatron, LHC covered from weak scale to TeV

What could be there?

- Naturalness



For decades, we hope naturalness should give us new physics below or around TeV scale.

Could still be there, just harder to discover.
Gaps/difficult spots in searches: twin Higgs, ...

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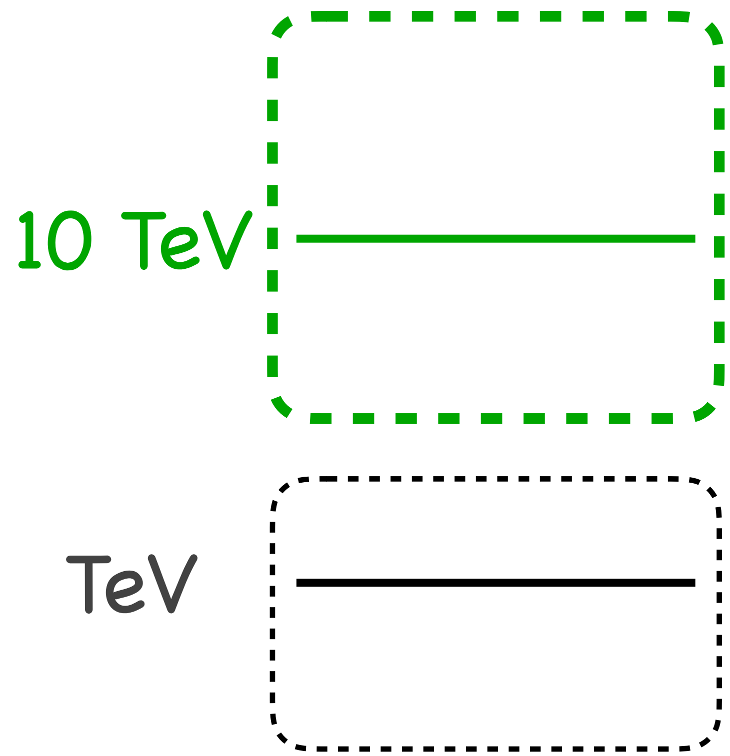

Plausible scenarios have emerged for new physics to be here.
mini-split SUSY, meso-tuned, ...

Also possible that first hint at TeV, but more interesting dynamics here.
Compositeness, ...

Higher rates, helps cover difficult spots in TeV searches.

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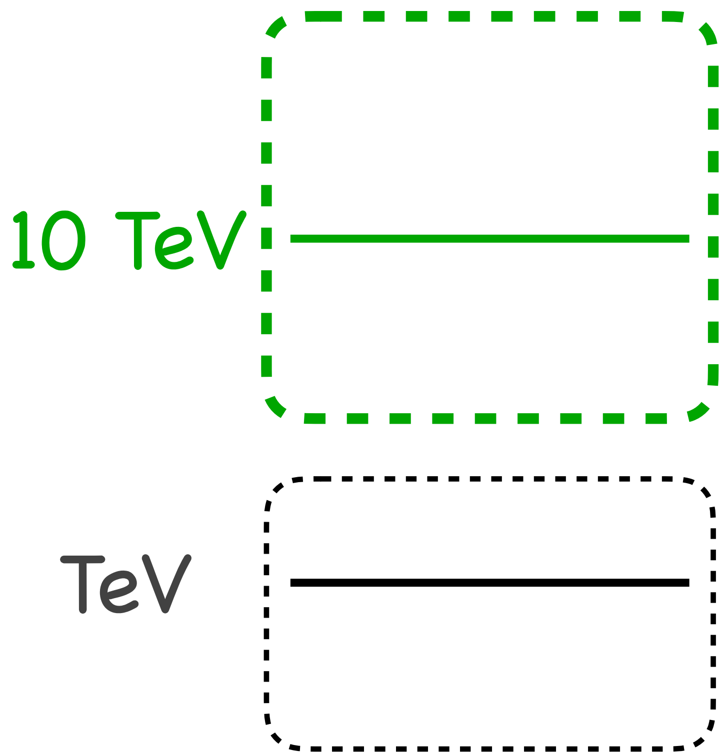

Simplest WIMP dark matter models:

dark matter part of a EW multiplet

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	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
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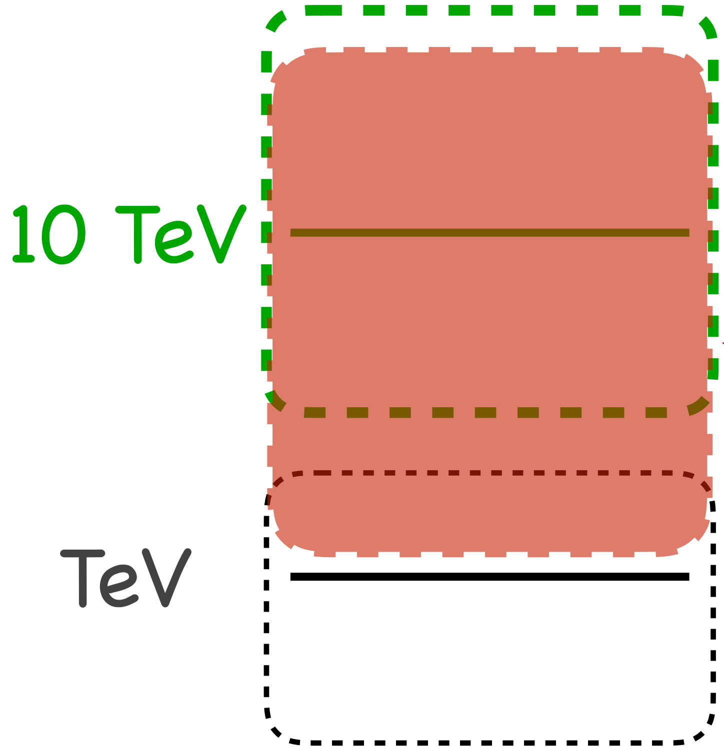

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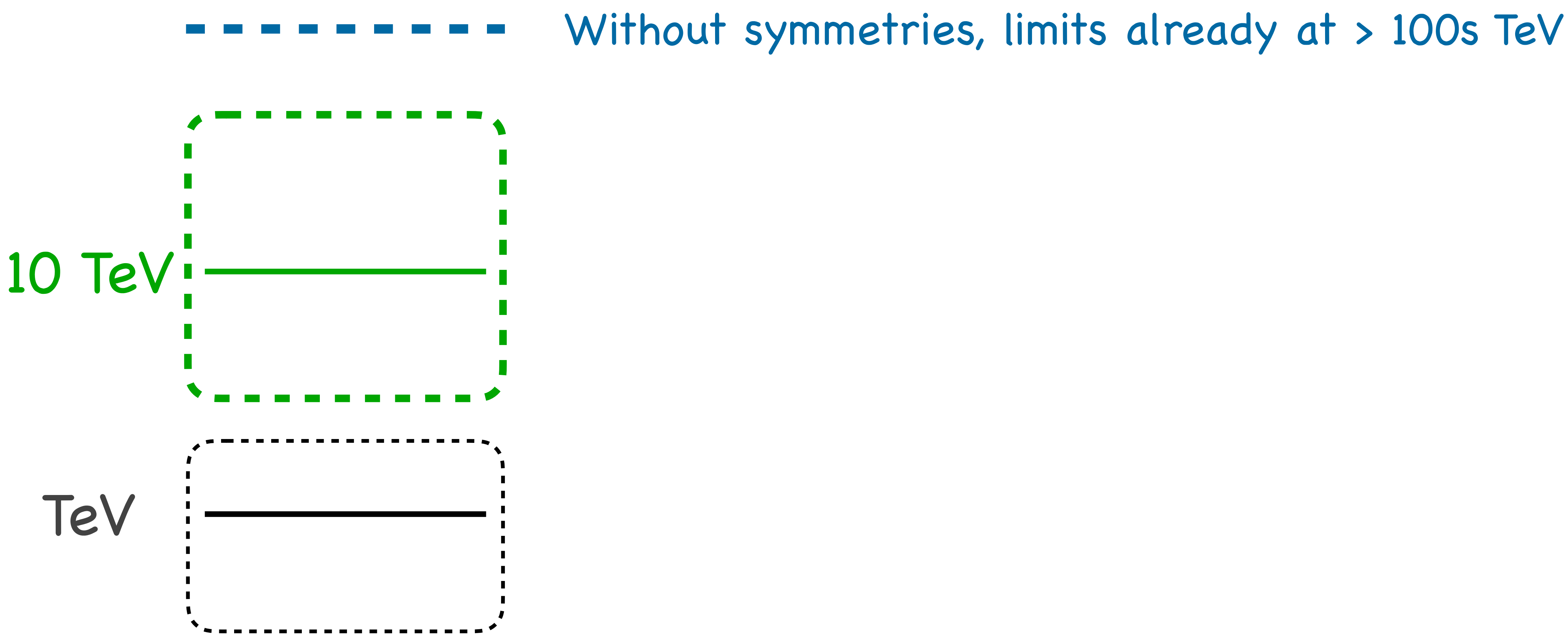

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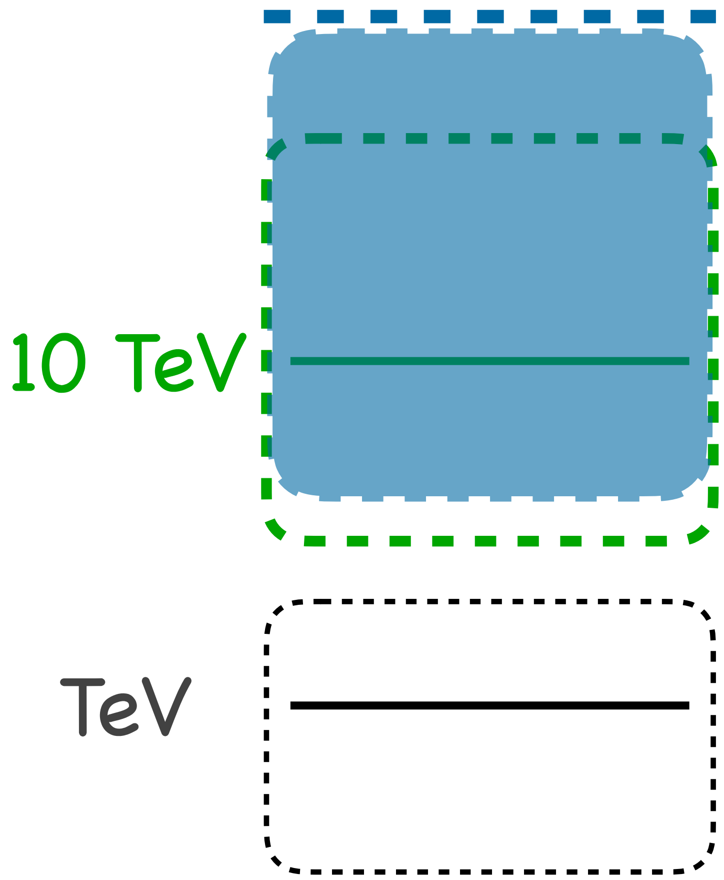


Without symmetries, limits already at > 100s TeV

Many scenarios with new flavor physics at 10s TeV.
Partial compositeness, some flavor symmetries...

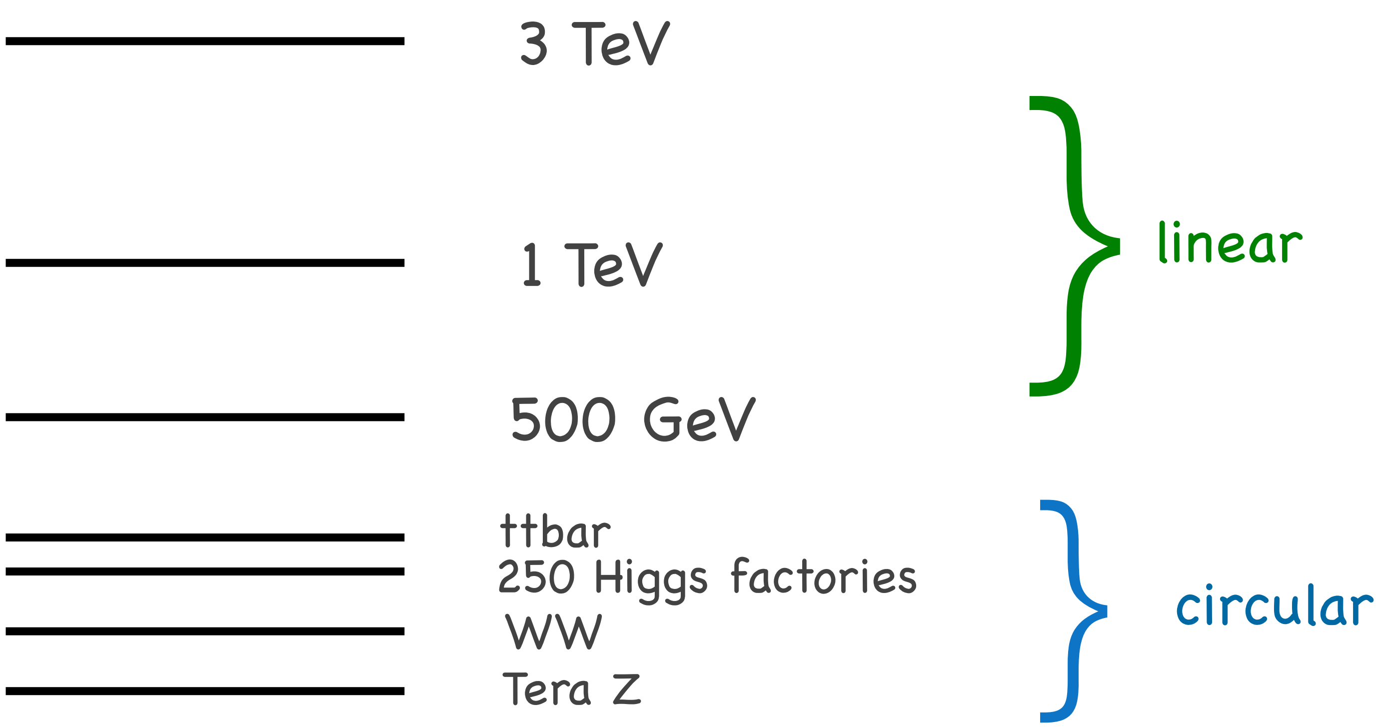
How to get there

- Two possible routes
  - Lepton: e^+e^-, $\mu^+ \mu^-$
    - $\gamma\gamma$ similar, but somewhat narrower physics program.
  - Hadron, pp.
- Two approaches
  - Direct production of new physics particles.
  - Precision measurement. Can be sensitive to even higher energy scales.

Lepton collider

e^+e^-, $\mu^+ \mu^-$

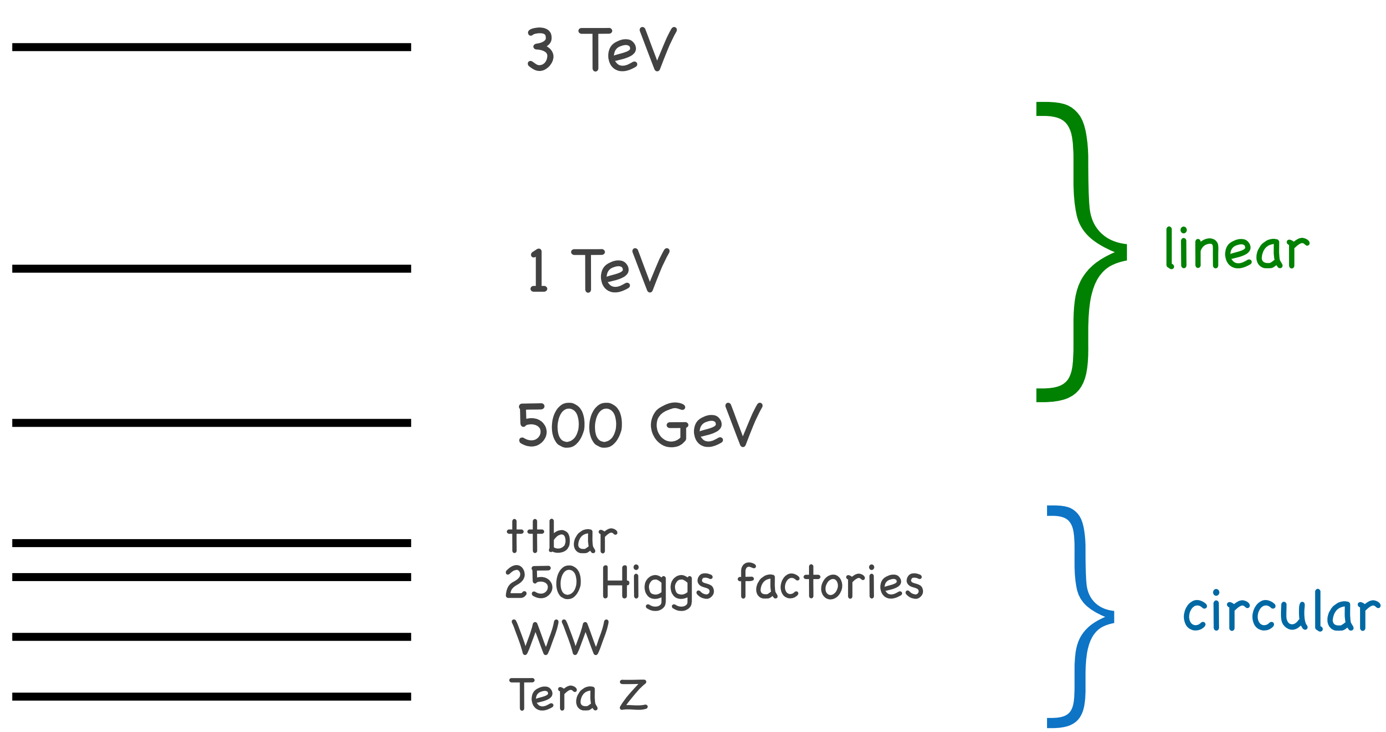
Recent proposals



Physics cases have been studied.

Recent proposals

Beyond this, higher energies? muon collider? $\gamma\gamma$?...
What is needed?



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Direct production

For letpon colliders: $M_{\mathrm{NP}} \sim E_{\mathrm{CM}}$

in principle no parton distribution suppression,
can produce new physics with mass up to beam energy.

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New physics production cross section:

$$\sigma \sim \pi\alpha_W^2 \frac{1}{E_{\rm CM}^2}, \quad \alpha_W \sim 10^{-2}$$

Signal $= \mathscr{L} \cdot \sigma, \quad \mathscr{L}$: luminosity

Fixing signal strength: $\rightarrow \mathscr{L} \propto E_{\rm CM}^2$

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For higher energies, maybe we just take LEP luminosity and scale up?

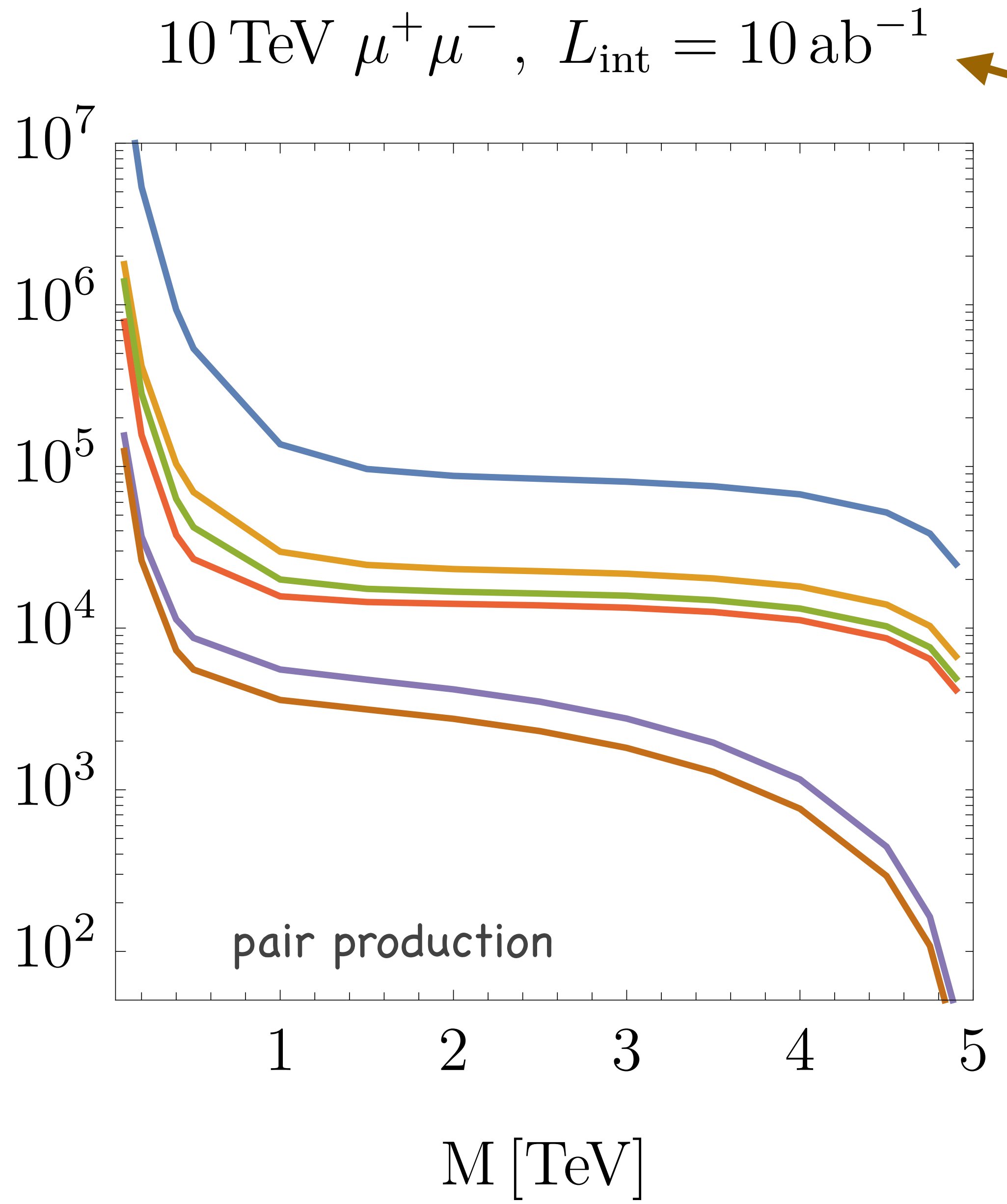
More careful consideration

- Discoveries are simpler in general at lepton colliders.
  - New physics give energetic final states.
  - Low background (comparable to signal).
  - May need only O(10s) signal events.
    - Different from the need to produce thousands and millions particles (such as Z boson at LEP) to study them in detail.
- Of course, there are also difficult scenarios to cover.

Top partner search.

A benchmark for muon collider

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



Good production rate up to : $2M \sim E_{\mathrm{CM}}$

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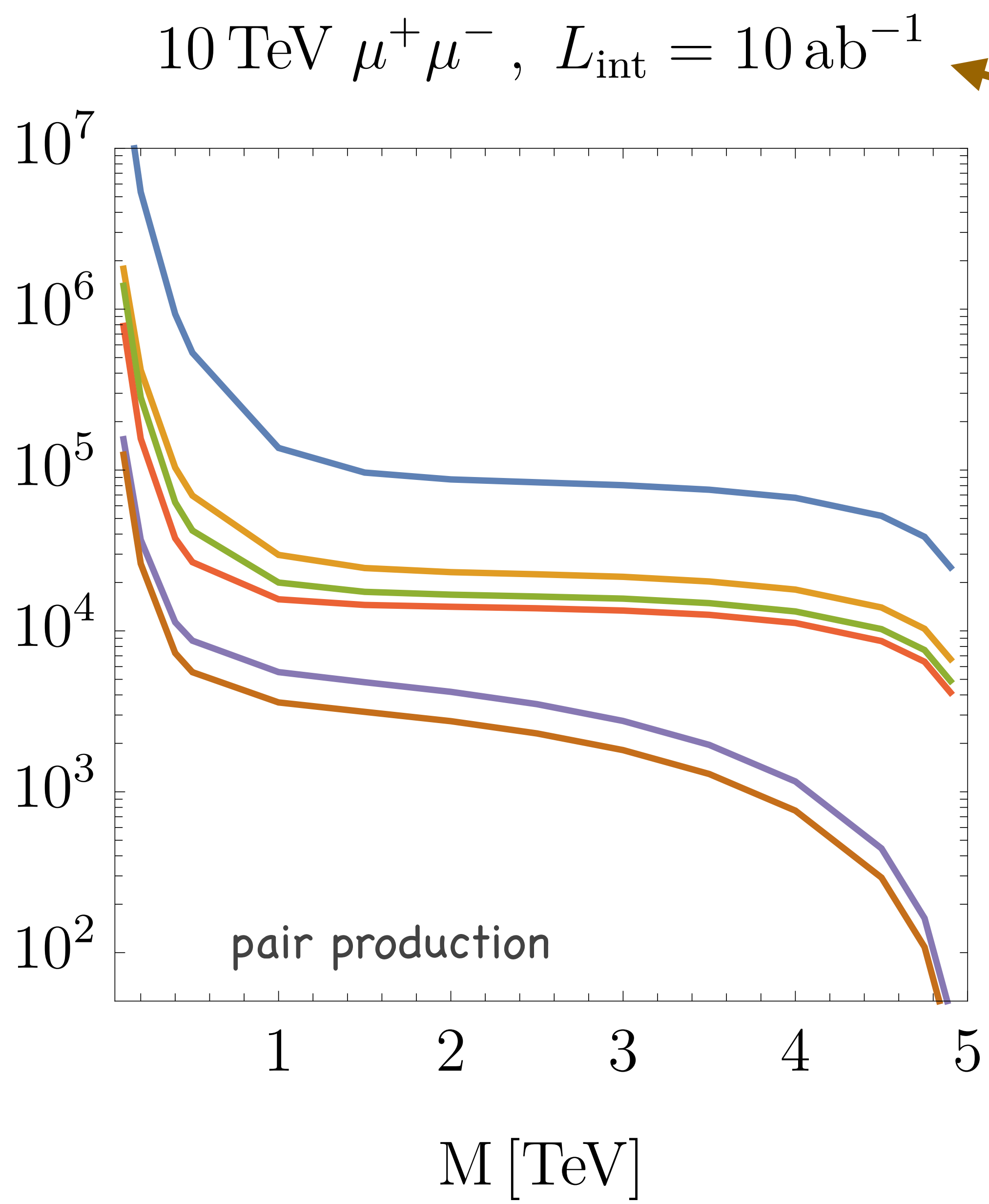


Good production rate up to : $2M \sim E_{\mathrm{CM}}$

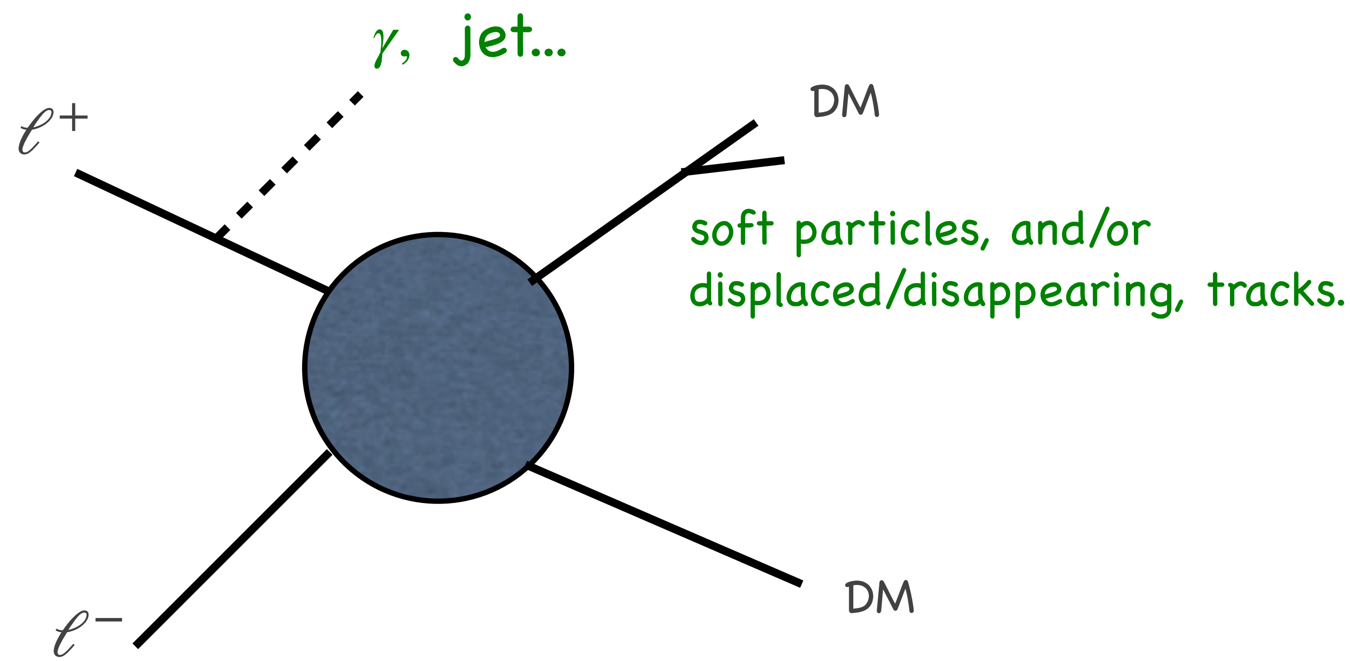
Can have > 10^5 events

However, for 5 TeV T′ with

$$T' \to tZ,\ th,\ bW$$

10s signal events (L=10^{32} cm^{-2} s^{-1}) should be enough.

Harder case, dark matter

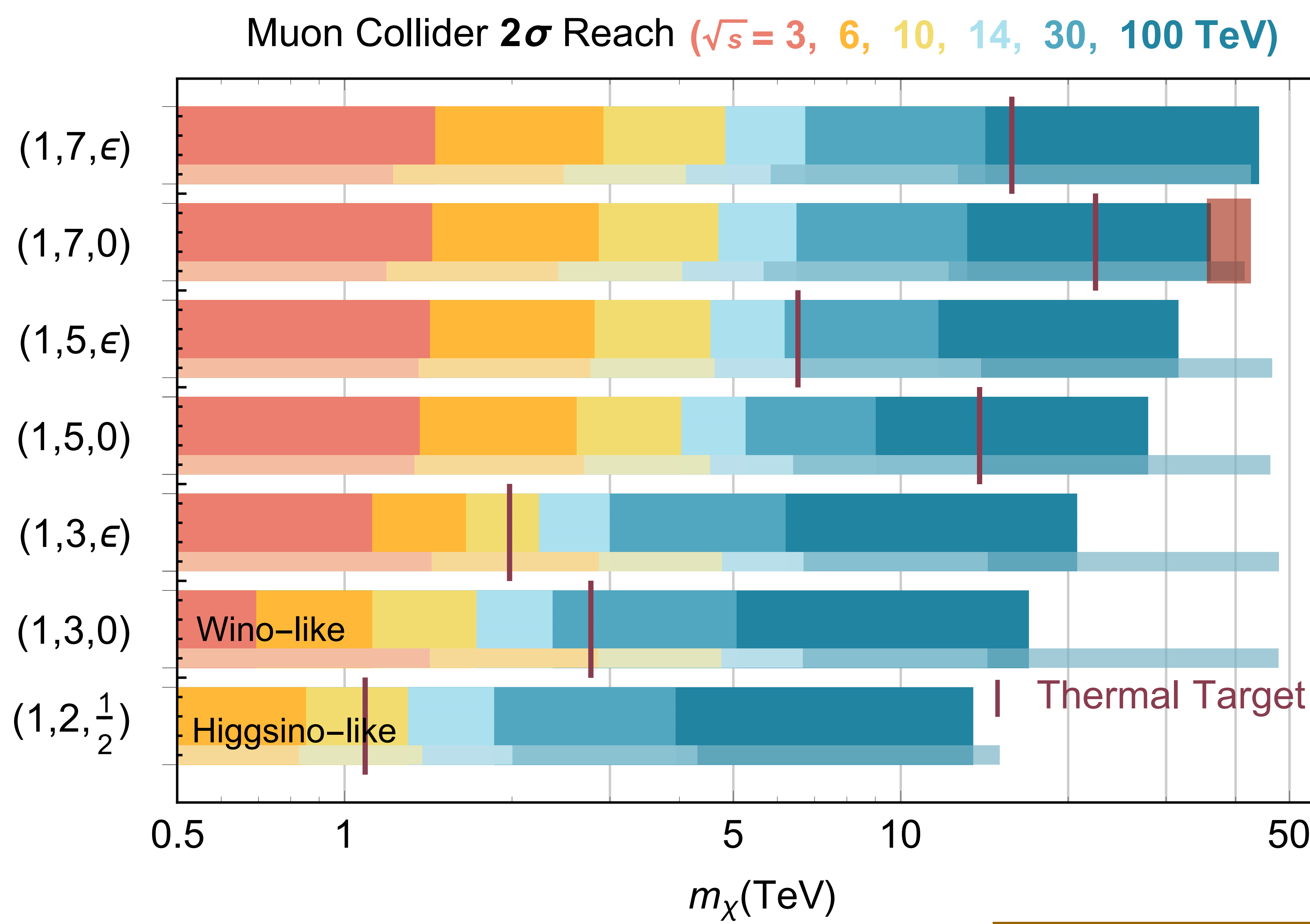


Most energy goes into making the heavy dark matter particle.

The remaining objects, such as photon, jet, soft.

Large background! More difficult.

Harder case, dark matter



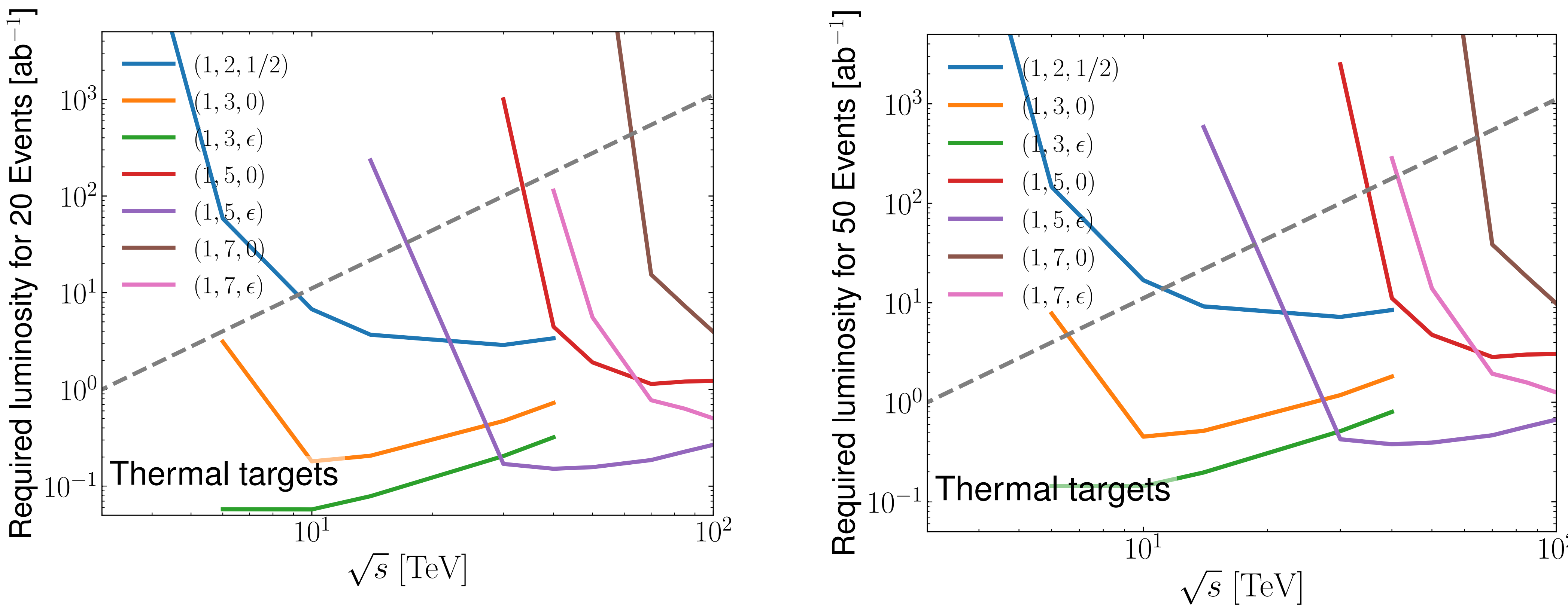
assumed luminosity:

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

Really need the large luminosity to get there.

Dark matter: E vs L, some trade off

Disappearing track searches



Some examples

doublet: 10 ab^{-1} at 10 TeV or 3 ab^{-1} at 20 TeV

Dirac triplet: < 0.1 ab^{-1} at 6 TeV

Majorana 5-plet: 100 ab^{-1} at 30 TeV or 1 ab^{-1} at 100 TeV

Dirac 7-plet: 100 ab^{-1} at 40 TeV or 10 ab^{-1} at 50 TeV

Minimal and optimal scenarios

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

Bare minimum. 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.

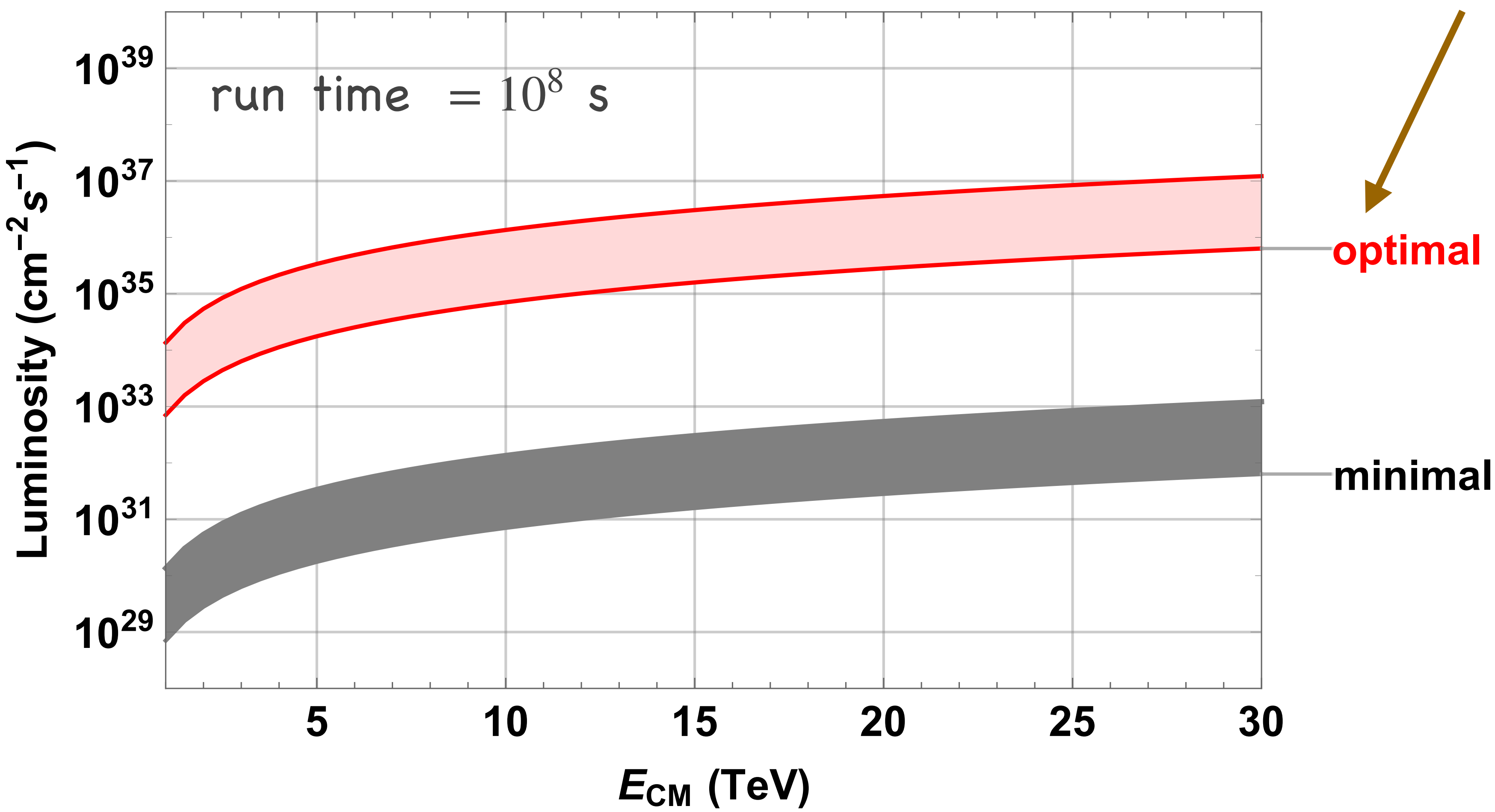
Some choices needed here, but the basic wishlist is quite commonly accepted.

Lepton collider luminosities

- For both muon and electron

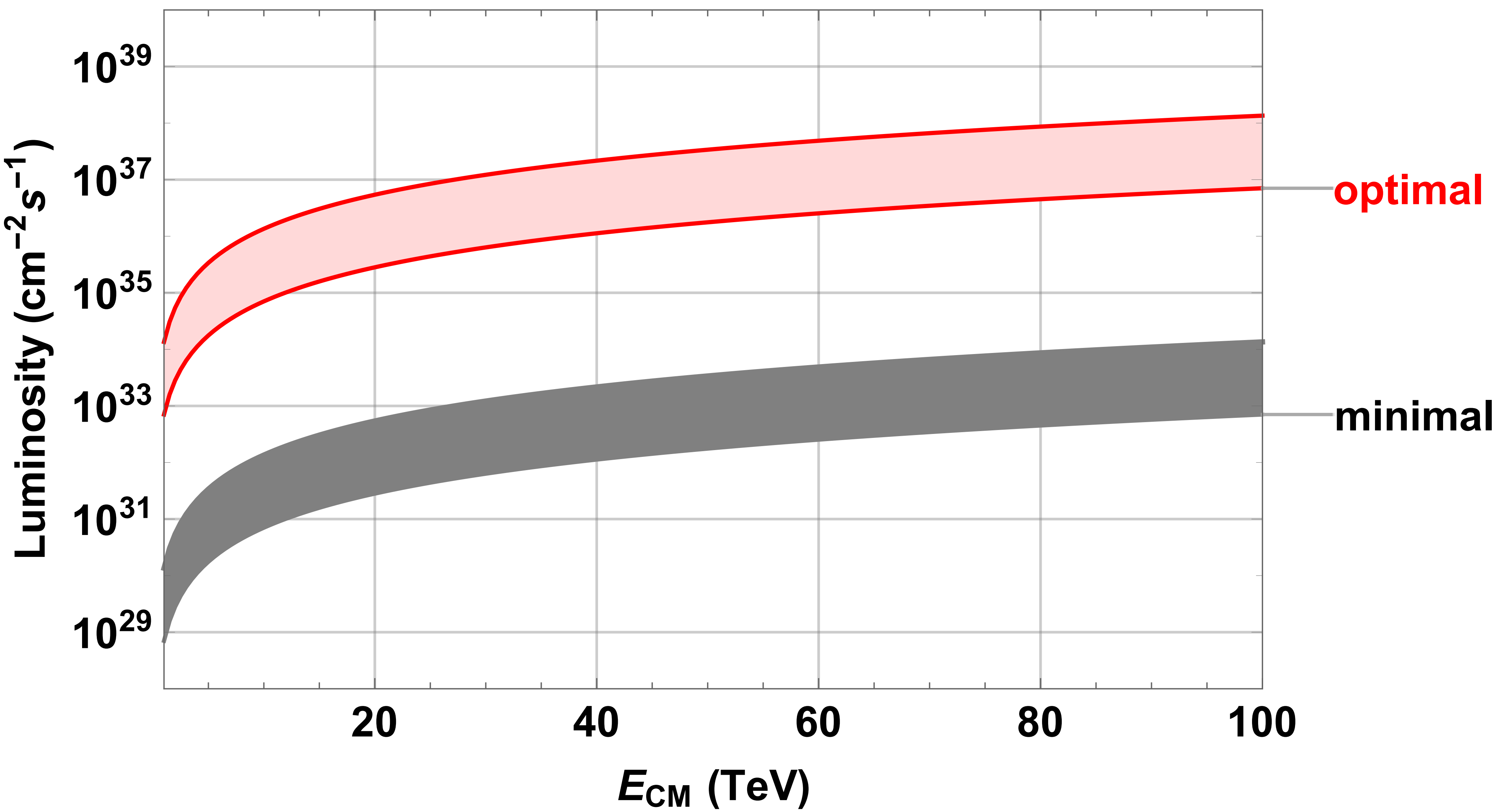
$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

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

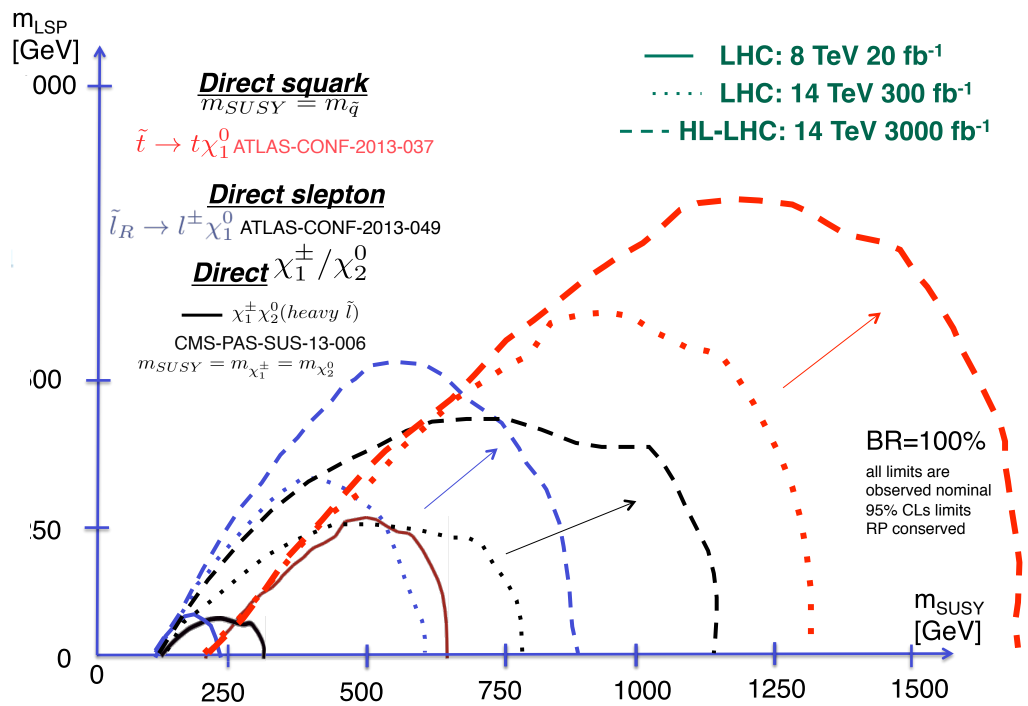


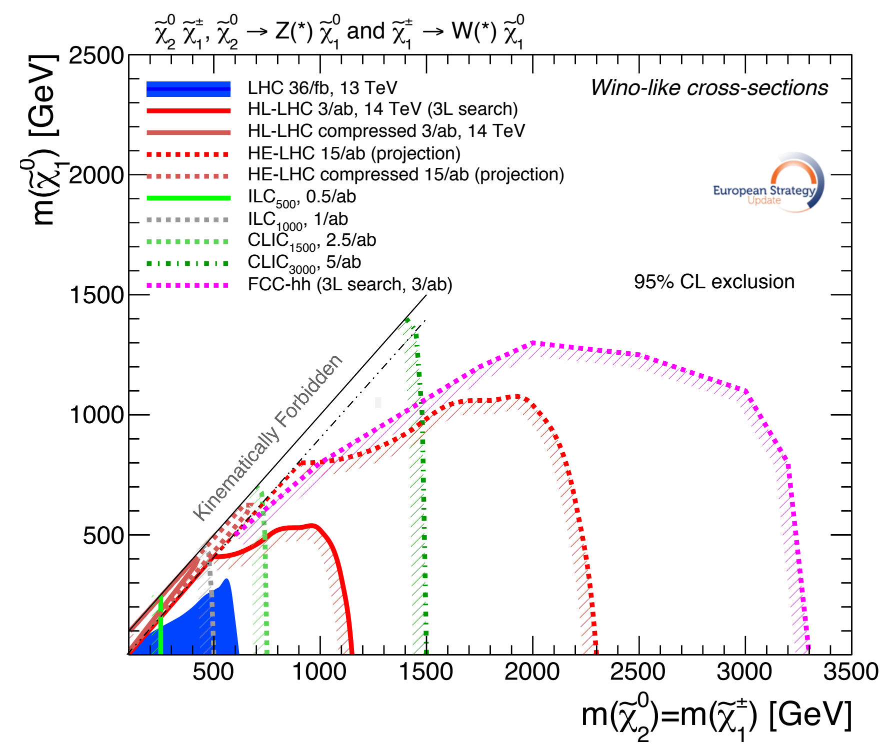
Both scales as $\mathscr{L} \propto E_{\rm CM}^2$, minimal $\sim 10^{-4} \times$ optimal

Even higher energies



Intermediate energy range 1-10 TeV





For particles without strong interaction, HL-LHC barely covers up to TeV, with gaps in parameter space

Lepton collider can cover up to E_{CM} very well.

Lepton collider below 10 TeV can still improve a lot beyond the LHC.

Precision measurements

- Maybe the new physics scale is above E_{CM}.
- 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.
- Naturally, can be a later part of the physics program.

Precision measurement

Deviation from SM coupling $\delta \sim c\frac{m_W^2}{\Lambda^2}, \quad c \sim \mathcal{O}(1)$

LHC: $\delta \sim$ a few $\% \to \Lambda \sim$ TeV

$\delta \sim \mathcal{O}(10^{-3})$ (per mil) needed to reach up to $\Lambda \sim 10$ TeV

Statistics limited: $\delta \propto \frac{1}{\mathcal{L}^{1/2}}$

Higgs coupling measurement needs 10^6 Higgs at proposed Higgs factories

Energy = precision

For heavy new physics parameterized by

$$\frac{1}{\Lambda^2}\mathcal{O}^{(6)}, \ \frac{1}{\Lambda^4}\mathcal{O}^{(8)}, \ldots$$

Effect of new physics larger at higher energy scales

$$(\delta\sigma/\sigma)_{\text{higher E}} \sim \frac{E^2}{\Lambda^2},$$ $\delta\sigma$ deviation due to $\mathcal{O}^{(6)}$

Don't need to do as precise a measurement if we can measure the process at higher energies.

Energy = precision

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

For example:

At 250 GeV Higgs factories with 10^6 events

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

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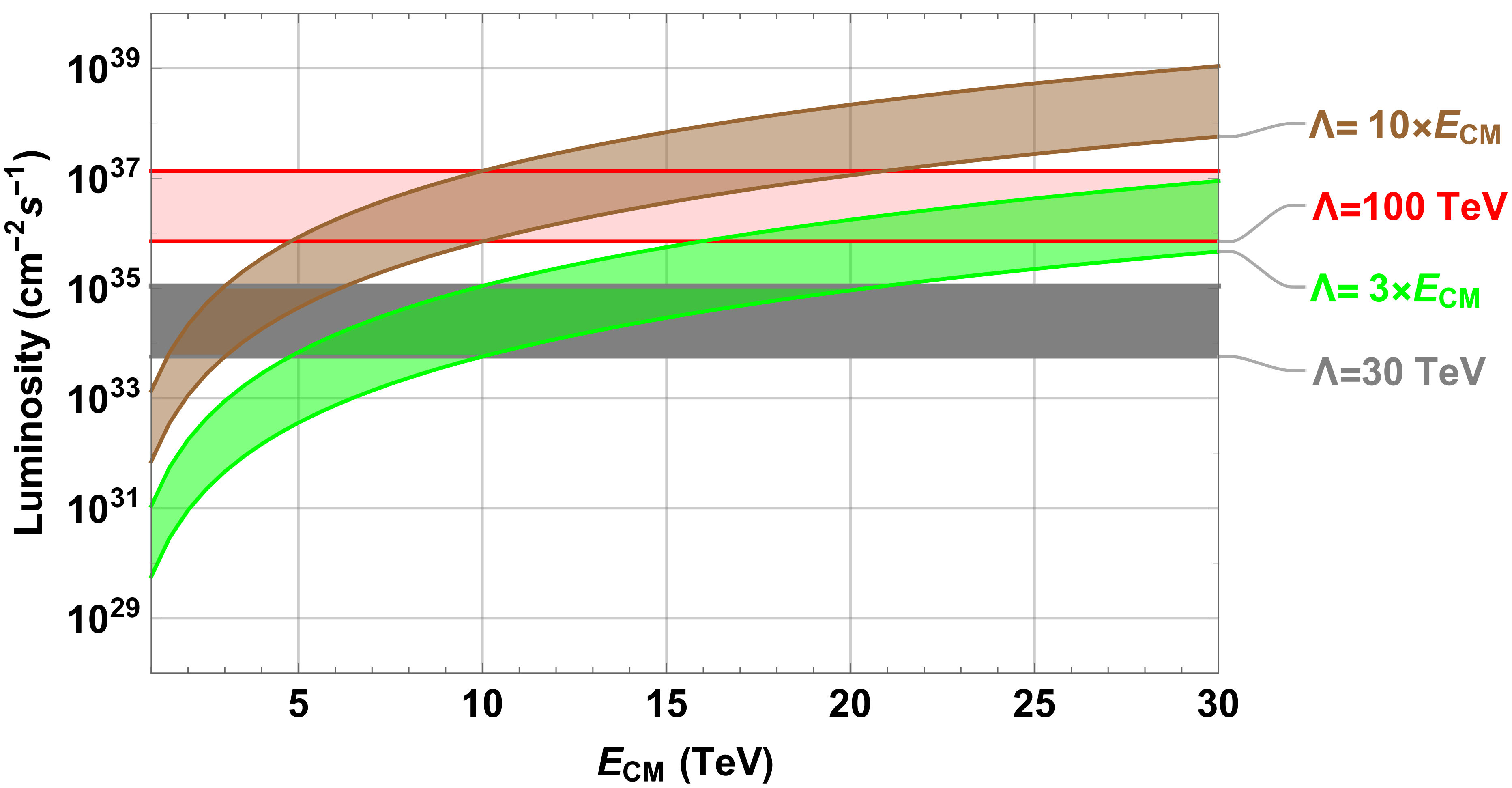
For example, $E = 1$ TeV, need an accuracy of $10\,\%$

$\rightarrow \sim 100$ events will do.

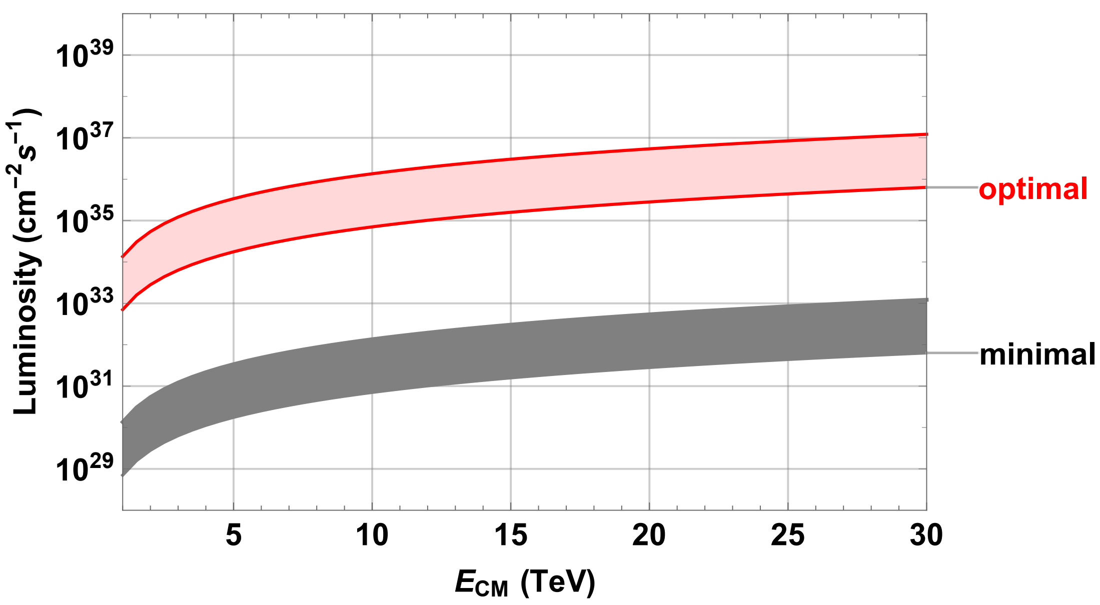
Luminosity need for precision

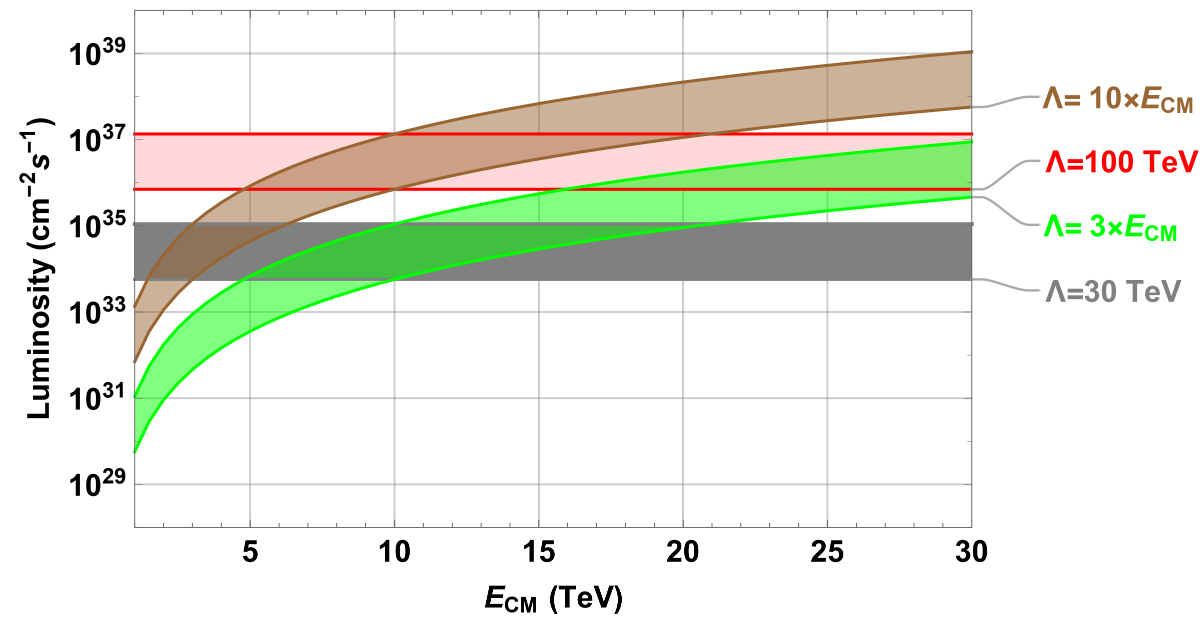


Minimally, we hope to reach new physics scale $\Lambda \approx 3\ E_{CM}$

Optimally, we would like to reach new physics scale $\Lambda \approx 10\ E_{CM}$
Also cover potential difficult cases.

Lepton collider summary





Luminosity cm^{-2} s^{-1}	1.5 TeV	3 TeV	6 TeV	10 TeV	14 TeV	30 TeV	100 TeV
Direct search minimal	3×10^{29}	10^{30}	5×10^{30}	2×10^{31}	5×10^{31}	2×10^{32}	2×10^{33}
Direct search optimal	3×10^{33}	10^{34}	5×10^{34}	2×10^{35}	5×10^{35}	2×10^{36}	2×10^{37}
Precision minimal	3×10^{30}	8×10^{31}	2×10^{33}	10^{34}	5×10^{34}	10^{36}	2×10^{37}
Precision optimal	7×10^{32}	10^{34}	2×10^{35}	2×10^{36}	5×10^{36}	10^{38}	2×10^{39}

Hadron colliders

LHC and recent proposals

100 TeV, a “standard” benchmark. FCC-hh, SppC

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

LHC

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

LHC and recent proposals

A goal post beyond 100 TeV?

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

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

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

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 $L_p \longleftrightarrow a \gg 1$

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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

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

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

Reach scale with energy, weaker dependence on luminosity

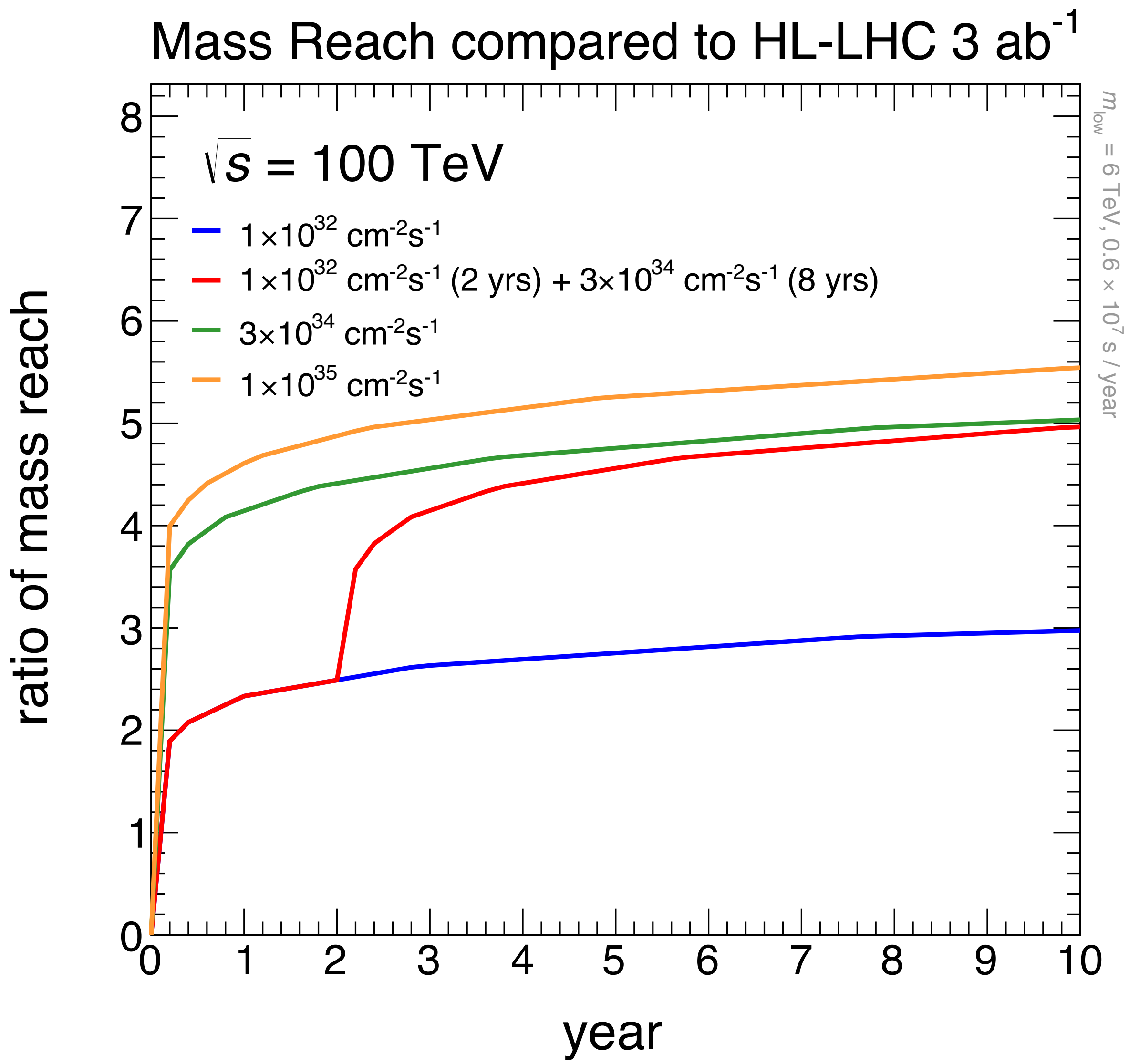
Rapid gain in mass reach after turning on.

Gain slowing down as luminosity increases.

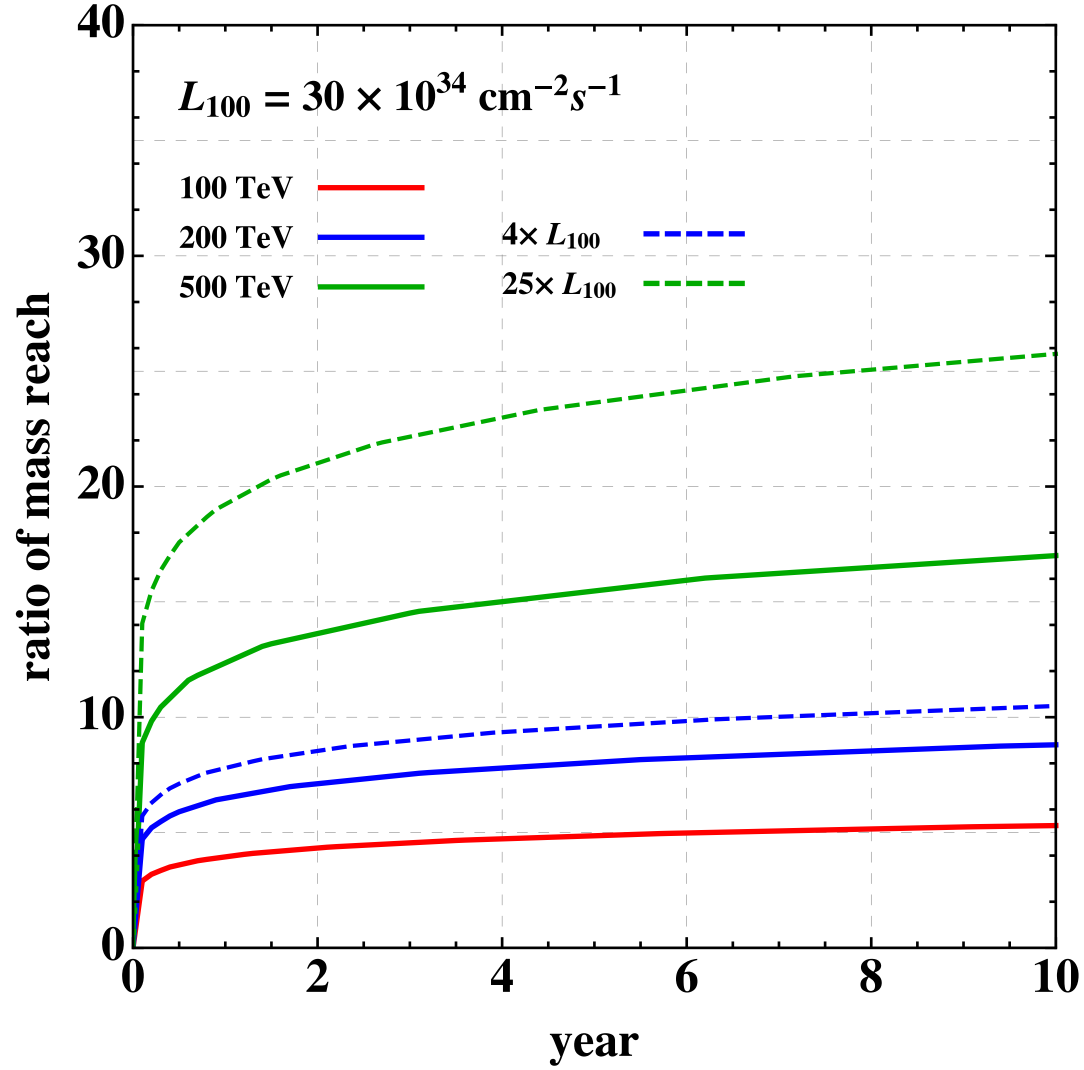
Eventually, $\frac{\mathscr{L}_1}{\mathscr{L}_2} = \frac{E_1^2}{E_2^2}, \quad \frac{M_1}{M_2} \to \frac{E_1}{E_2}$

However, most of the gain come much earlier. Lower luminosity can do a lot already.

Physics program at hadron collider



M. Low



Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

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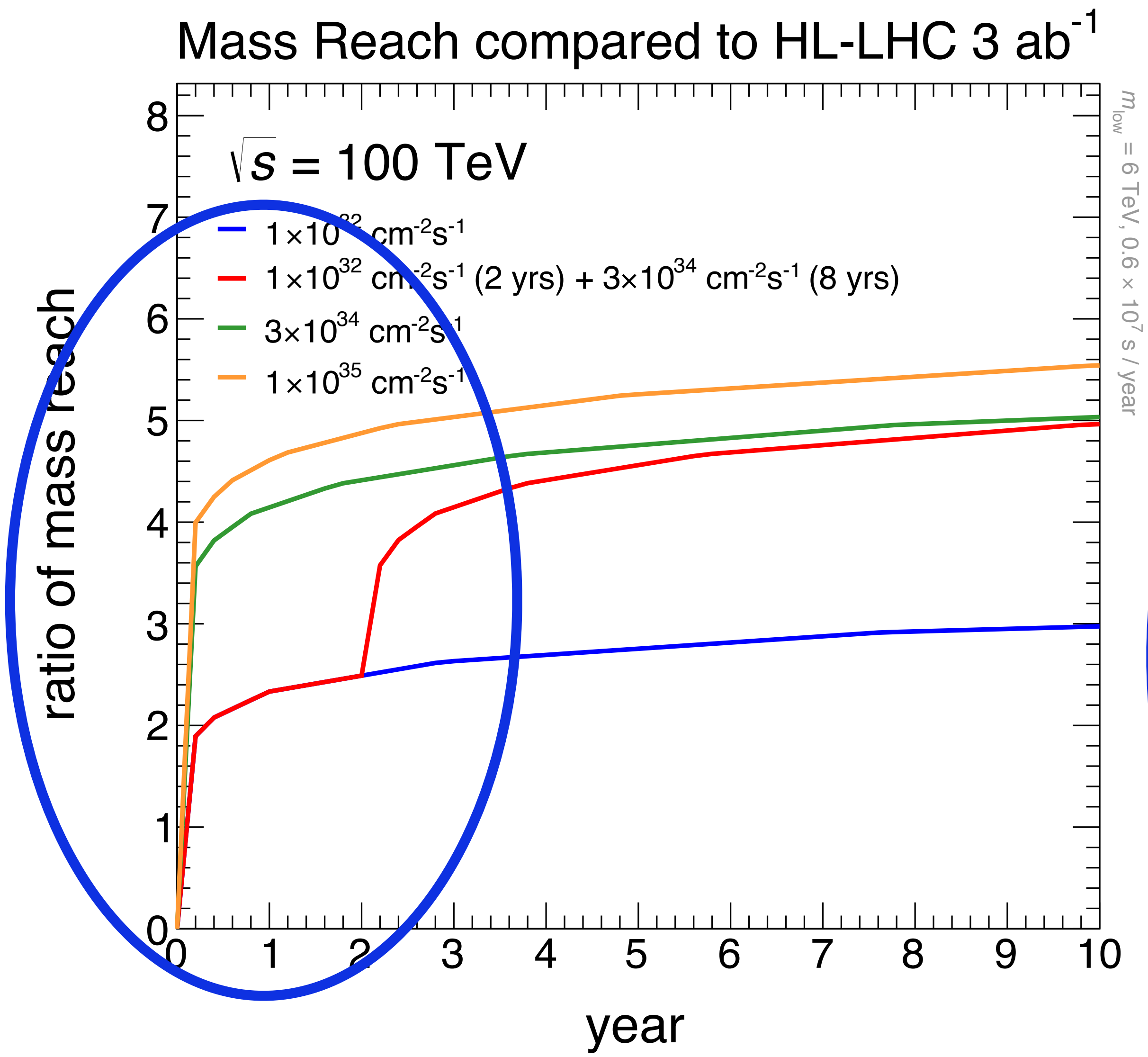
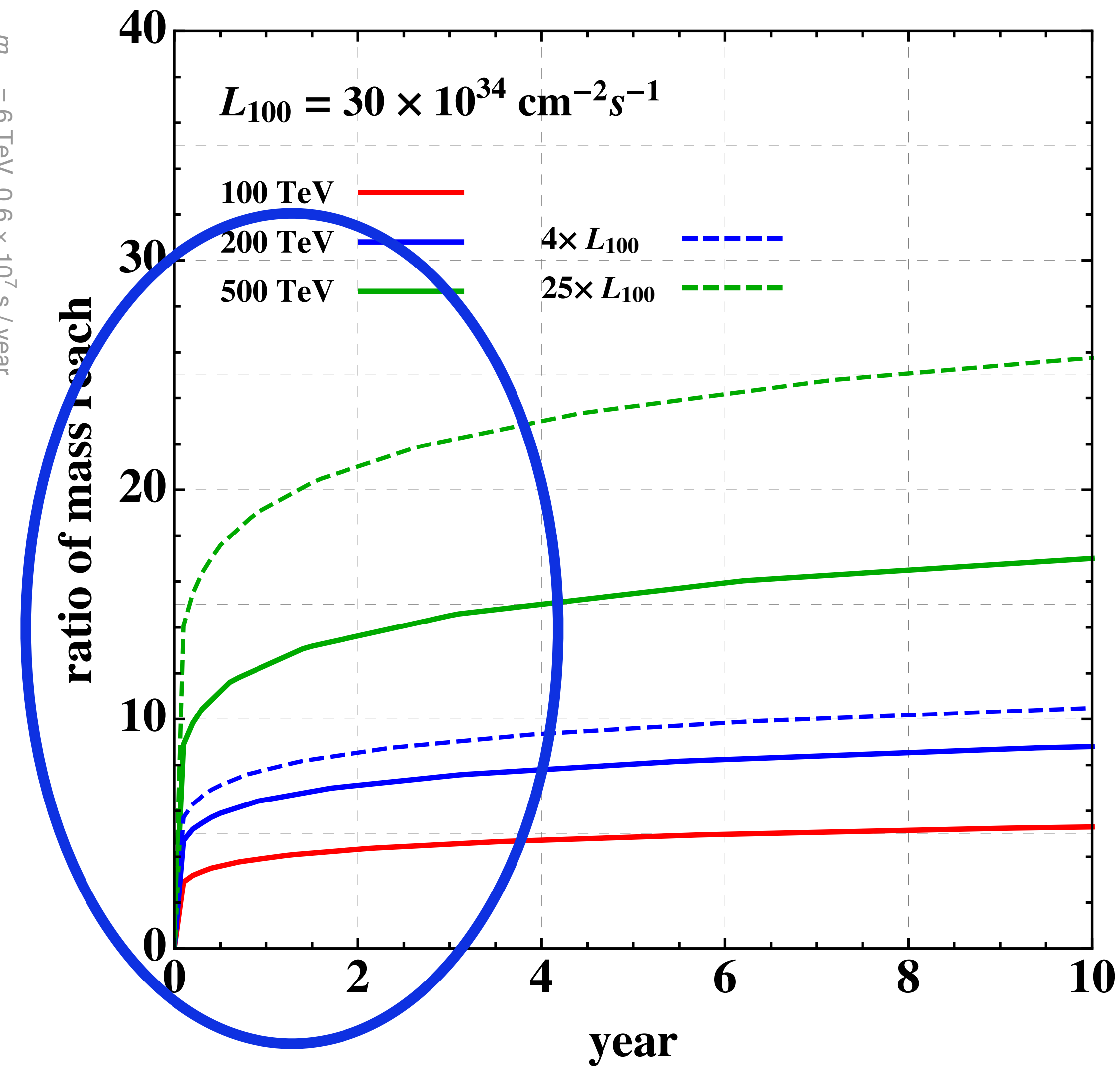




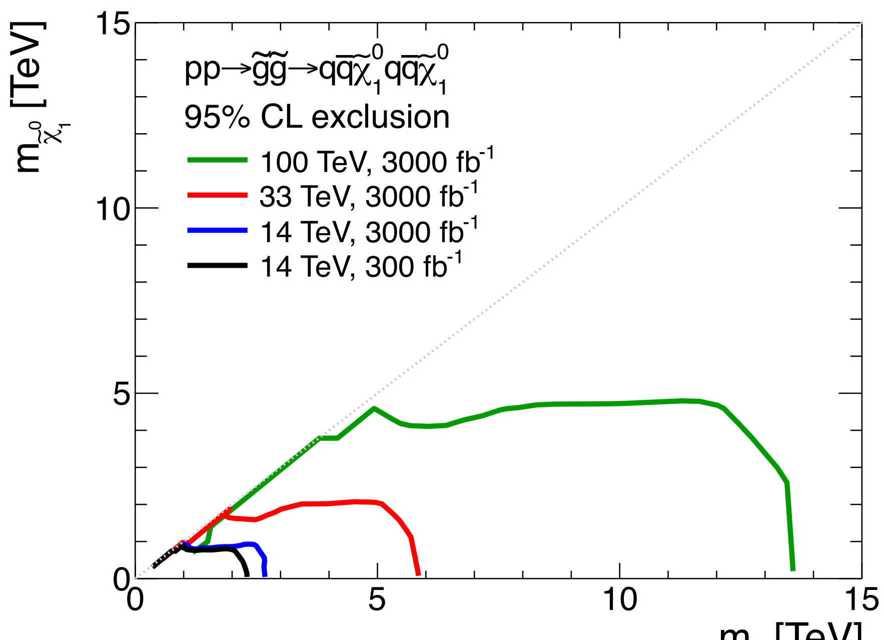
Rapid gain in mass reach

10^{35}–10^{36} cm^{-2}s^{-1} doing a good job already.

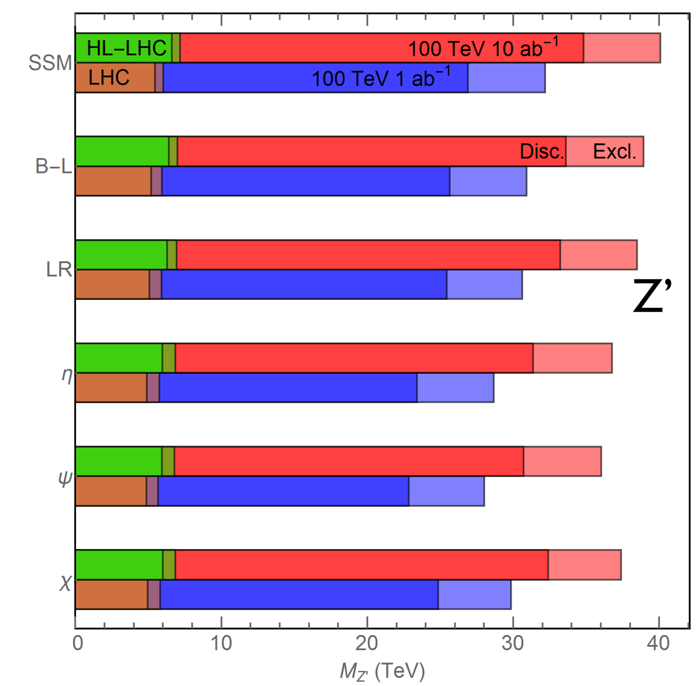
Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

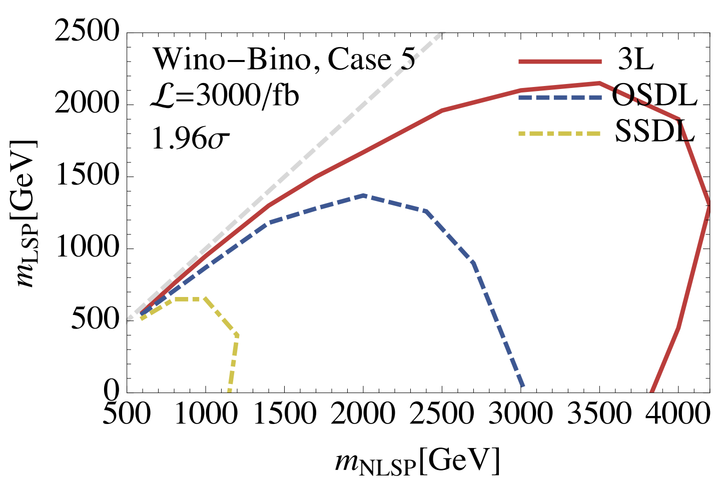
Examples:

100 TeV: x 5(more) improvement with same lumi as HL-LHC

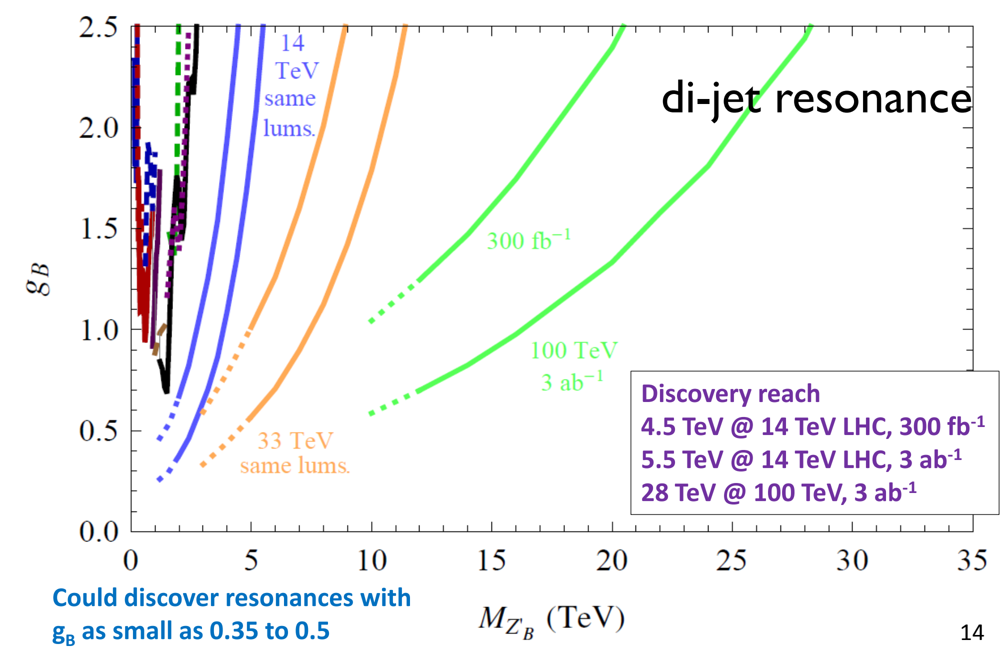


Cohen et al, 2013



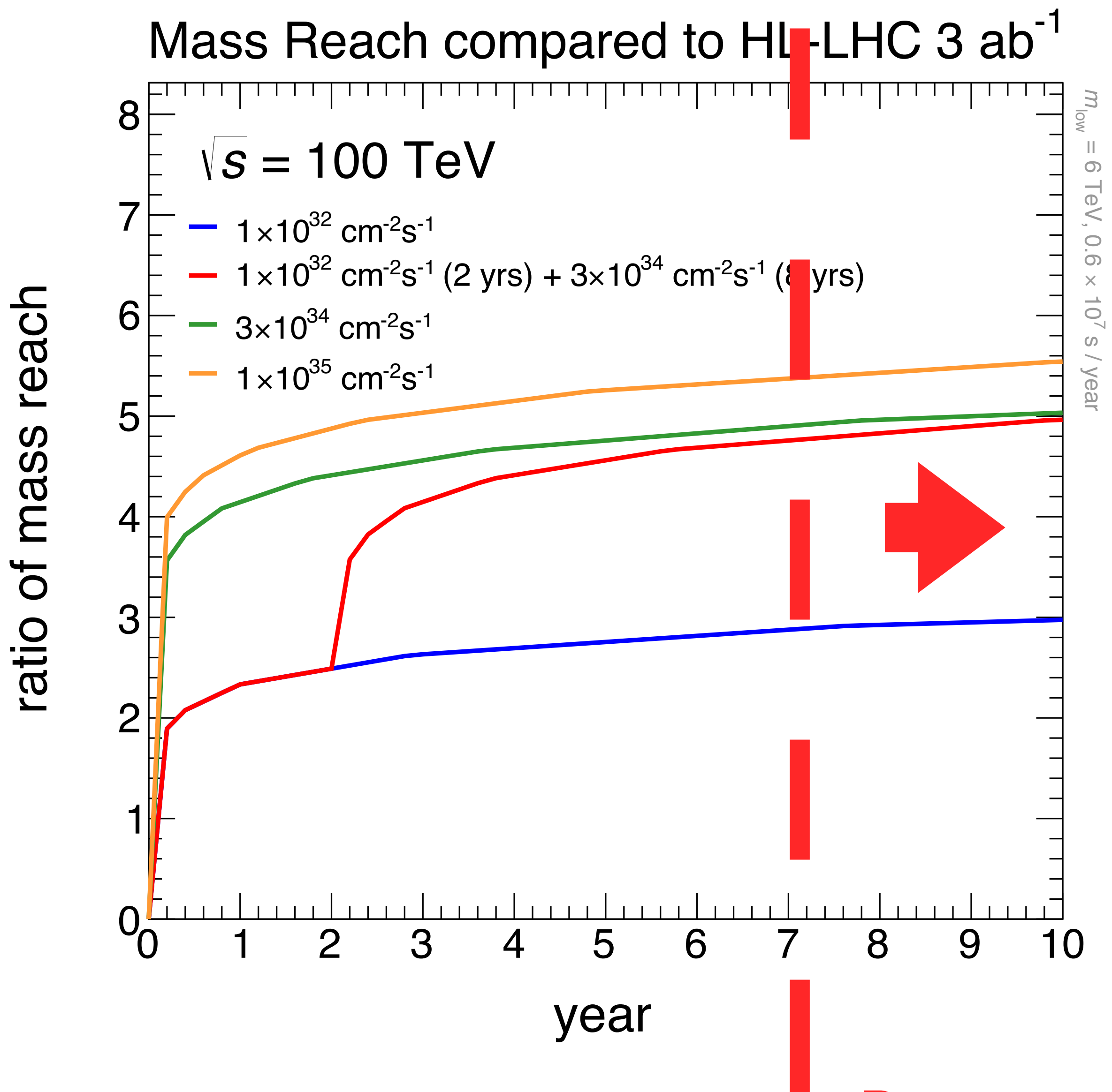


Gori, Jung, LTW, Wells, 2014



Felix Yu, 2013

Physics program at hadron collider



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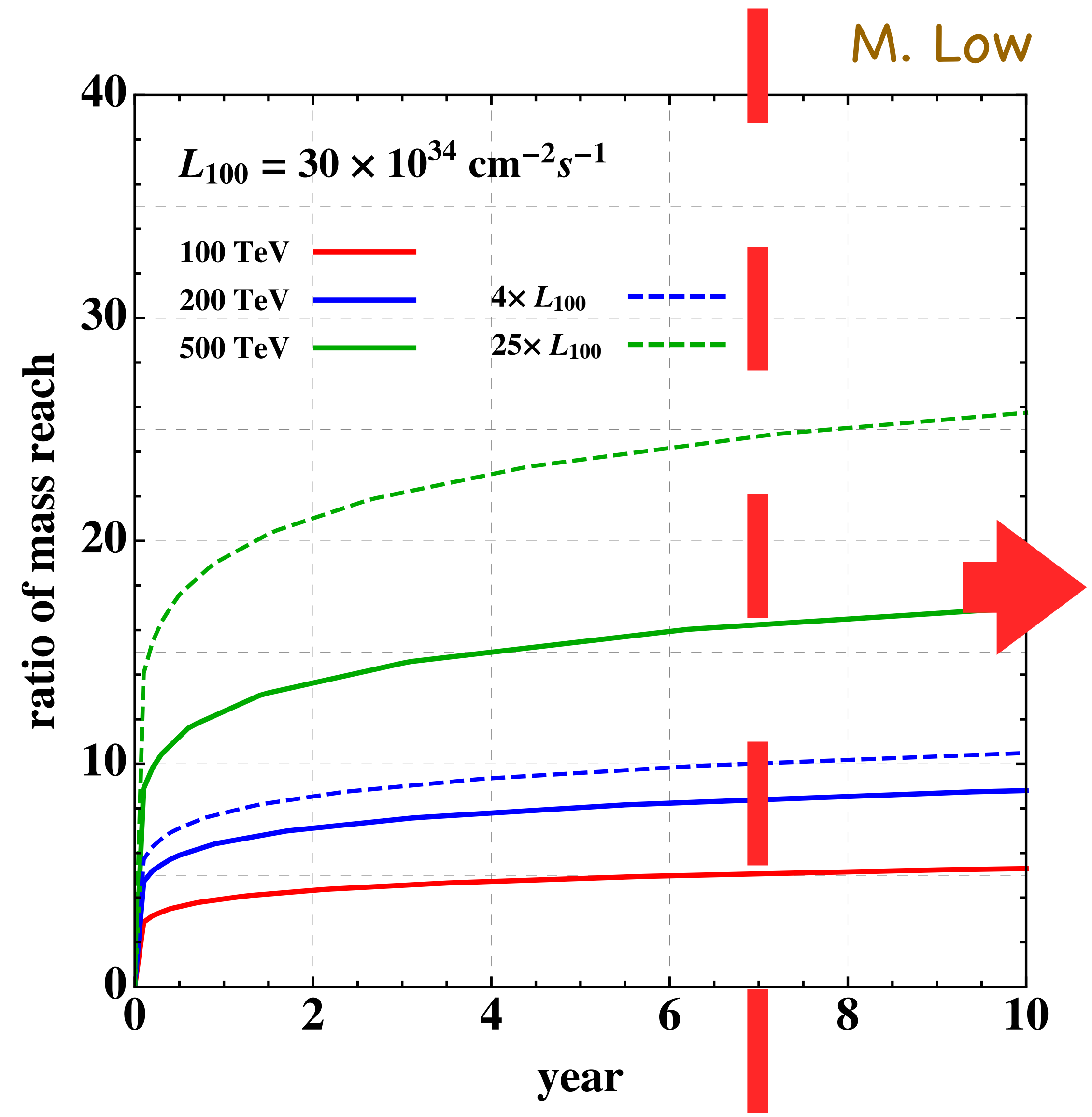

Precision measurement
becomes possible

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108

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

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

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At the same time, the error at hadron colliders typically dominated by systematics, less direct dependence on luminosity.

Based on available studies, 10-30 ab^{-1} seems to do an adequate job.

Benchmarks beyond known options

higher?

500

200

benchmarks beyond 100 TeV

100 TeV, FCC-hh, SppC

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

LHC

Benchmarks beyond known options

higher?

500

200

benchmarks beyond 100 TeV

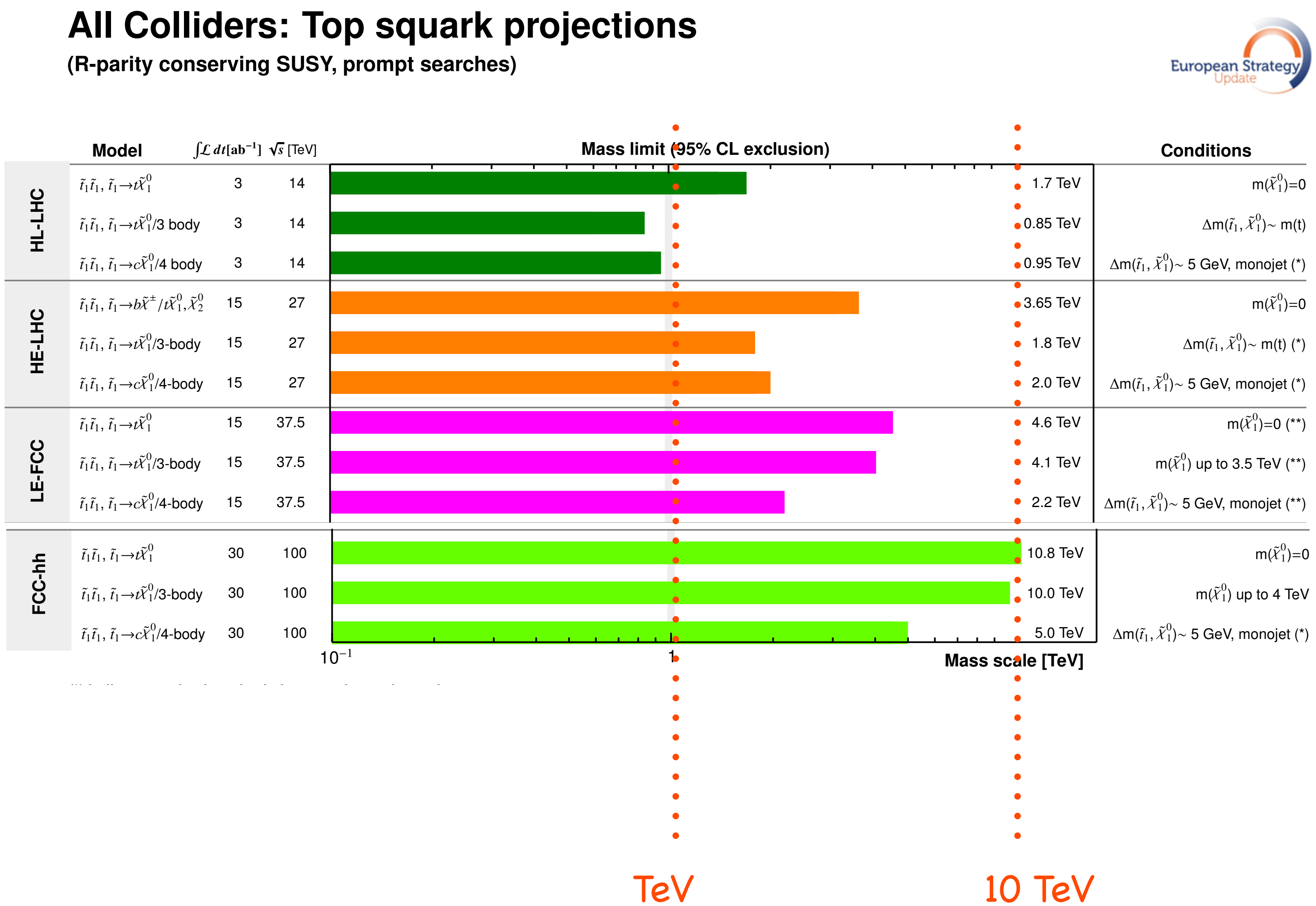
100 TeV, FCC-hh, SppC

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

LHC

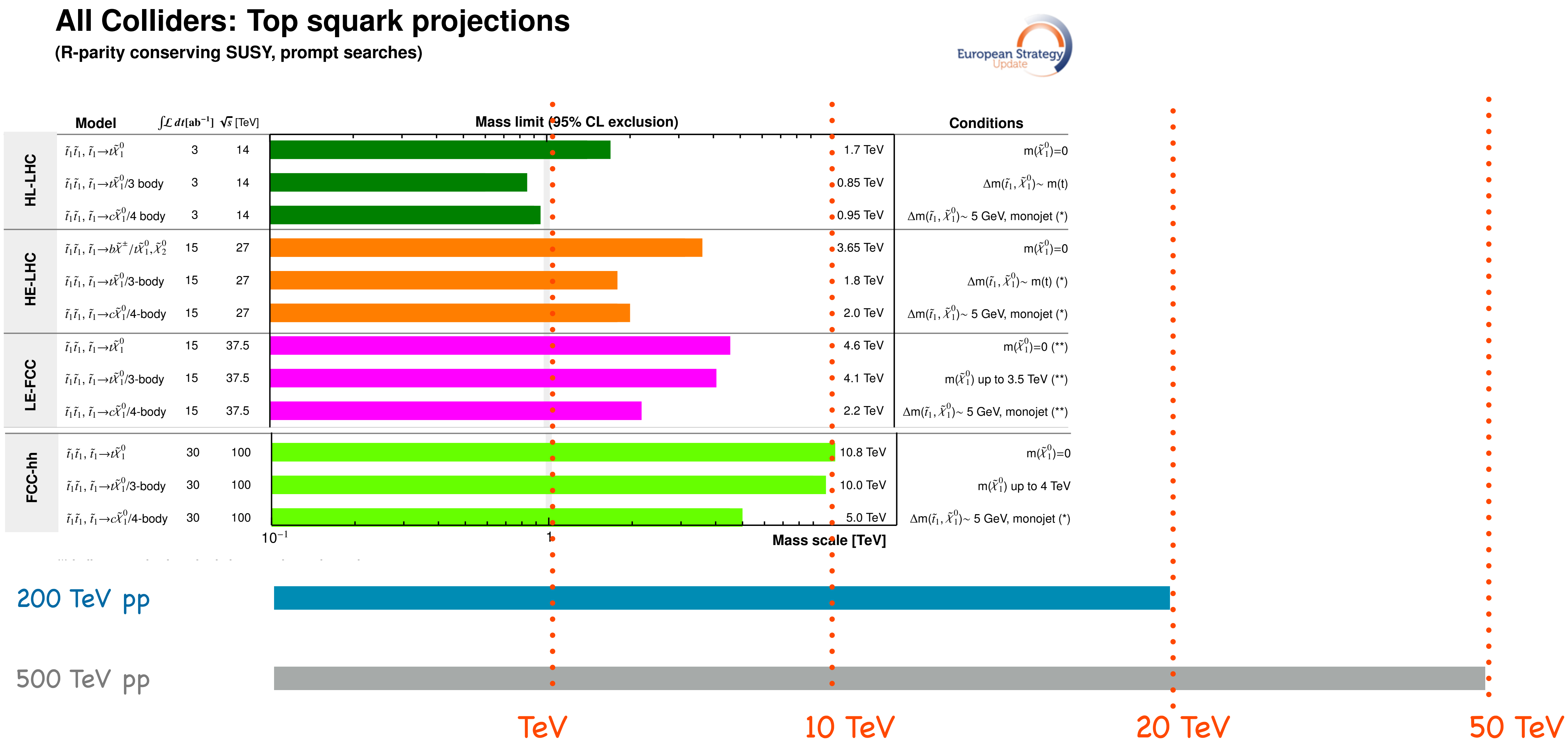
Luminosity: 10^{35}–10^{36} cm^{-2} s^{-1}

Example: Naturalness



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

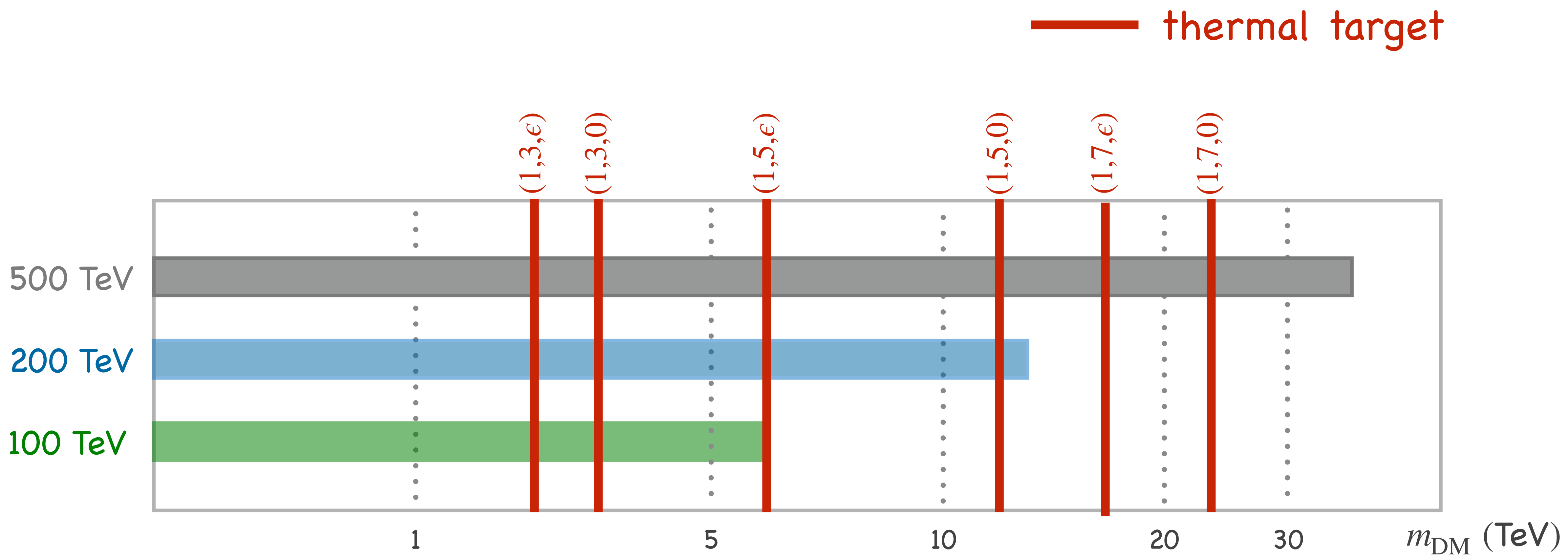
Pushing ahead with hadron collider



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

Comparing with 100 TeV, gaining a factor of 4(25) at 200(500) TeV pp

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.

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.

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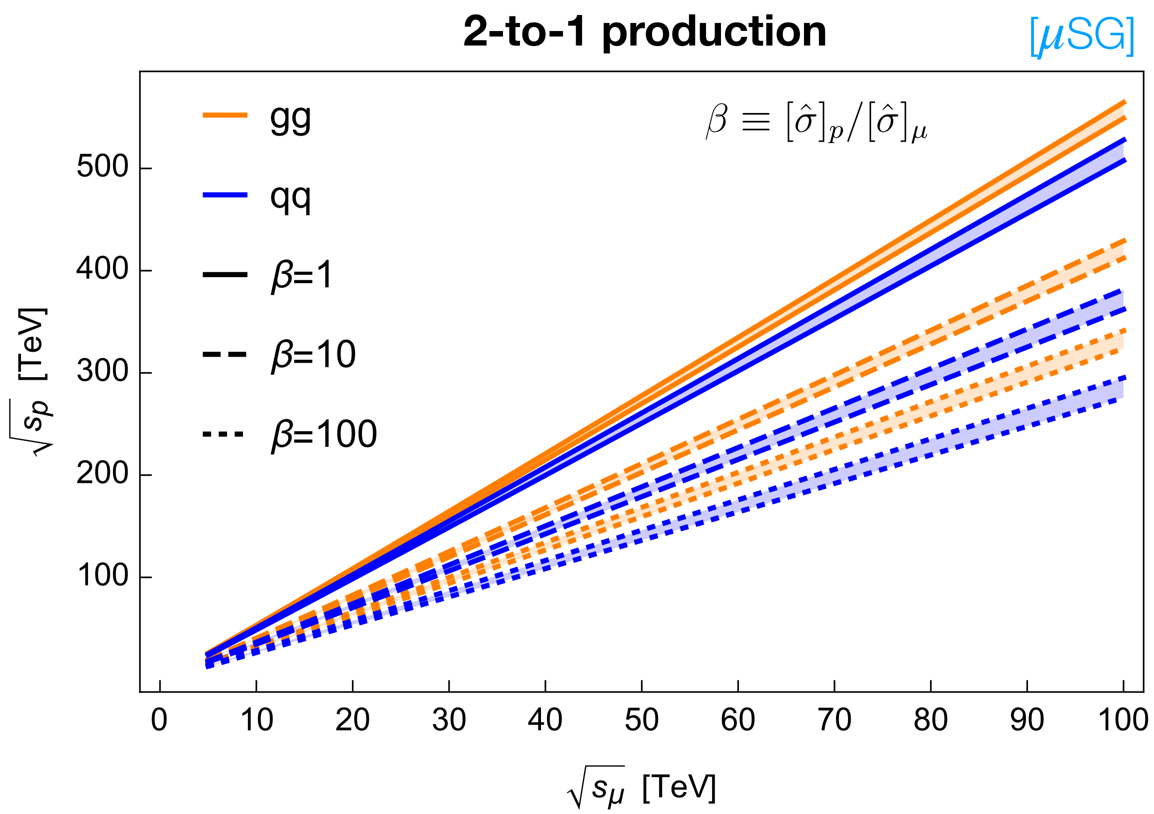
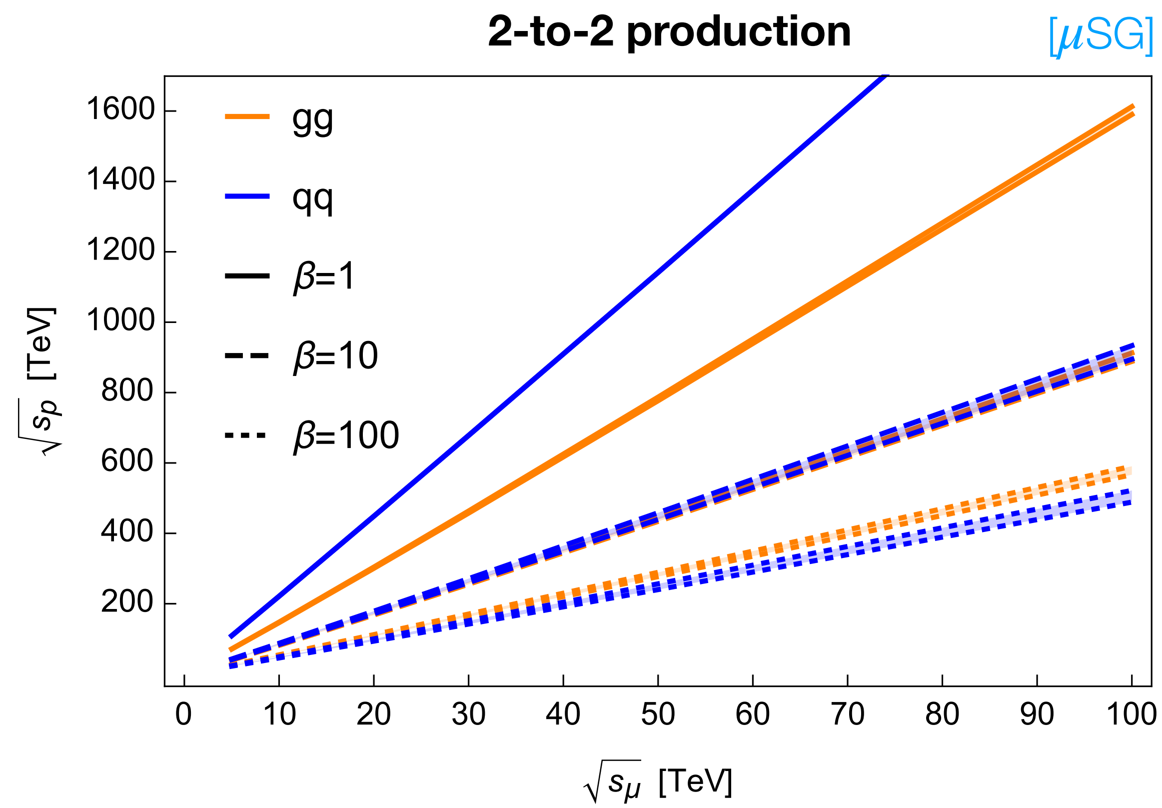
- Stronger for electroweak states.

However, this comparison really depends on what is achievable.

Hadron vs lepton



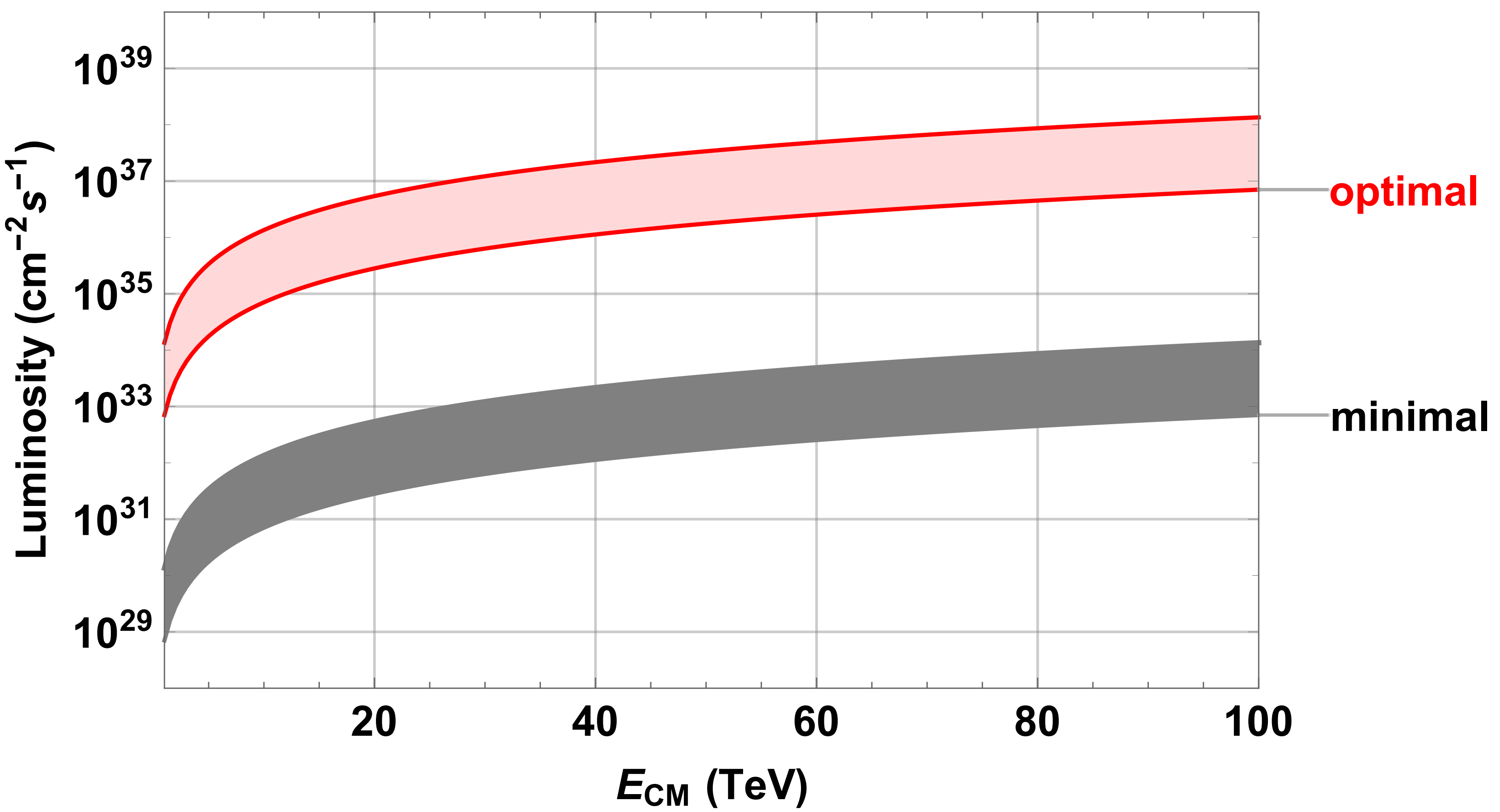


We "know" how to make hadron colliders.

But, we also need it to be at much (O(10)) higher E_{CM}.

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

Conclusion: Lepton collider



Beyond the proposed Higgs factories, high energy lepton colliders from TeV to 10s TeV extremely interesting!

A bare minimal scenario with much less lumi can already do some interesting searches.

Conclusion: Lepton collider

Luminosity $cm^{-2}\ s^{-1}$	1.5 TeV	3 TeV	6 TeV	10 TeV	14 TeV	30 TeV	100 TeV
Direct search minimal	3×10^{29}	10^{30}	5×10^{30}	2×10^{31}	5×10^{31}	2×10^{32}	2×10^{33}
Direct search optimal	3×10^{33}	10^{34}	5×10^{34}	2×10^{35}	5×10^{35}	2×10^{36}	2×10^{37}
Precision minimal	3×10^{30}	8×10^{31}	2×10^{33}	10^{34}	5×10^{34}	10^{36}	2×10^{37}
Precision optimal	7×10^{32}	10^{34}	2×10^{35}	2×10^{36}	5×10^{36}	10^{38}	2×10^{39}

A bare minimal scenario with much less lumi can already do some interesting searches.

Upgrades towards optimal scenarios highly desired, covering interesting cases such as dark matter, and allow precision measurements to reach its full potential.

Conclusion: hadron collider

higher?

500

To understand the physics potential, good to have a benchmark > 100 TeV.

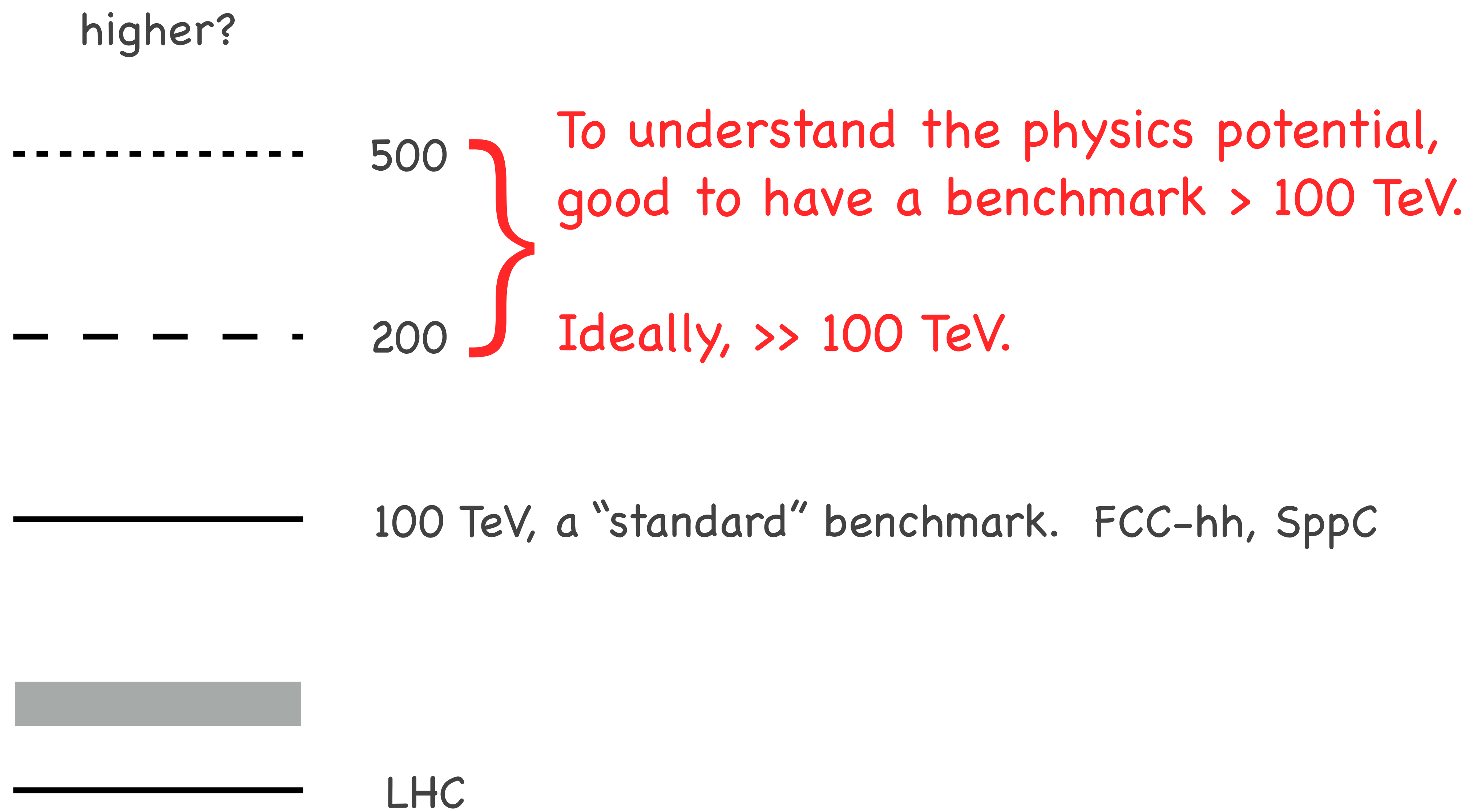
200

Ideally, >> 100 TeV.

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

LHC

Conclusion: hadron collider



Luminosity at HL-LHC level can already have interesting sensitivity.

Higher luminosity at 10^{35}–10^{36} cm^{-2} s^{-1} can realize full physics potential.

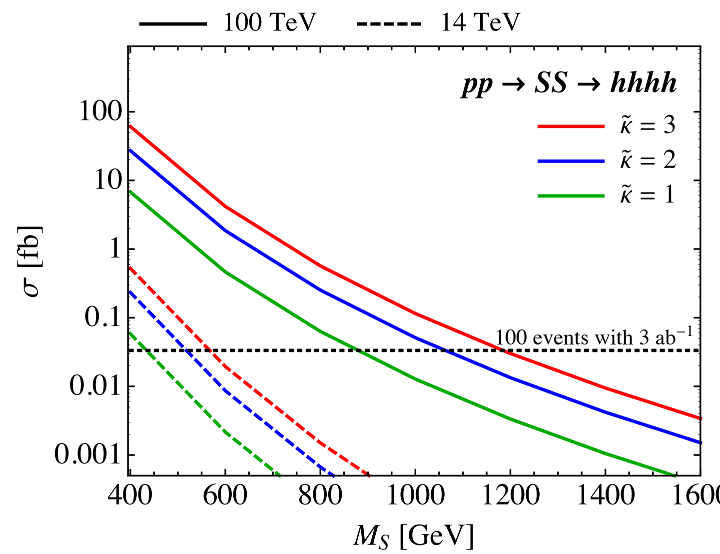
extras

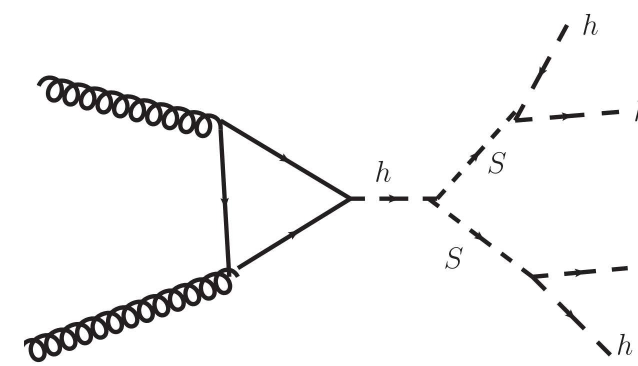
Probing neutral naturalness

100 TeV Testing tuning to 10%

200(500) push down to several %

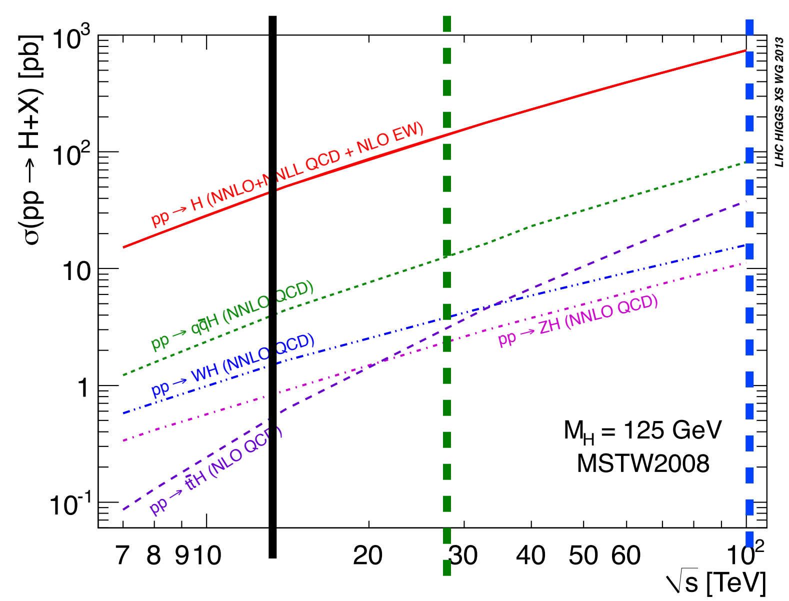
Probing m_S > TeV





h→ dark sector
(LLP, ...)

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



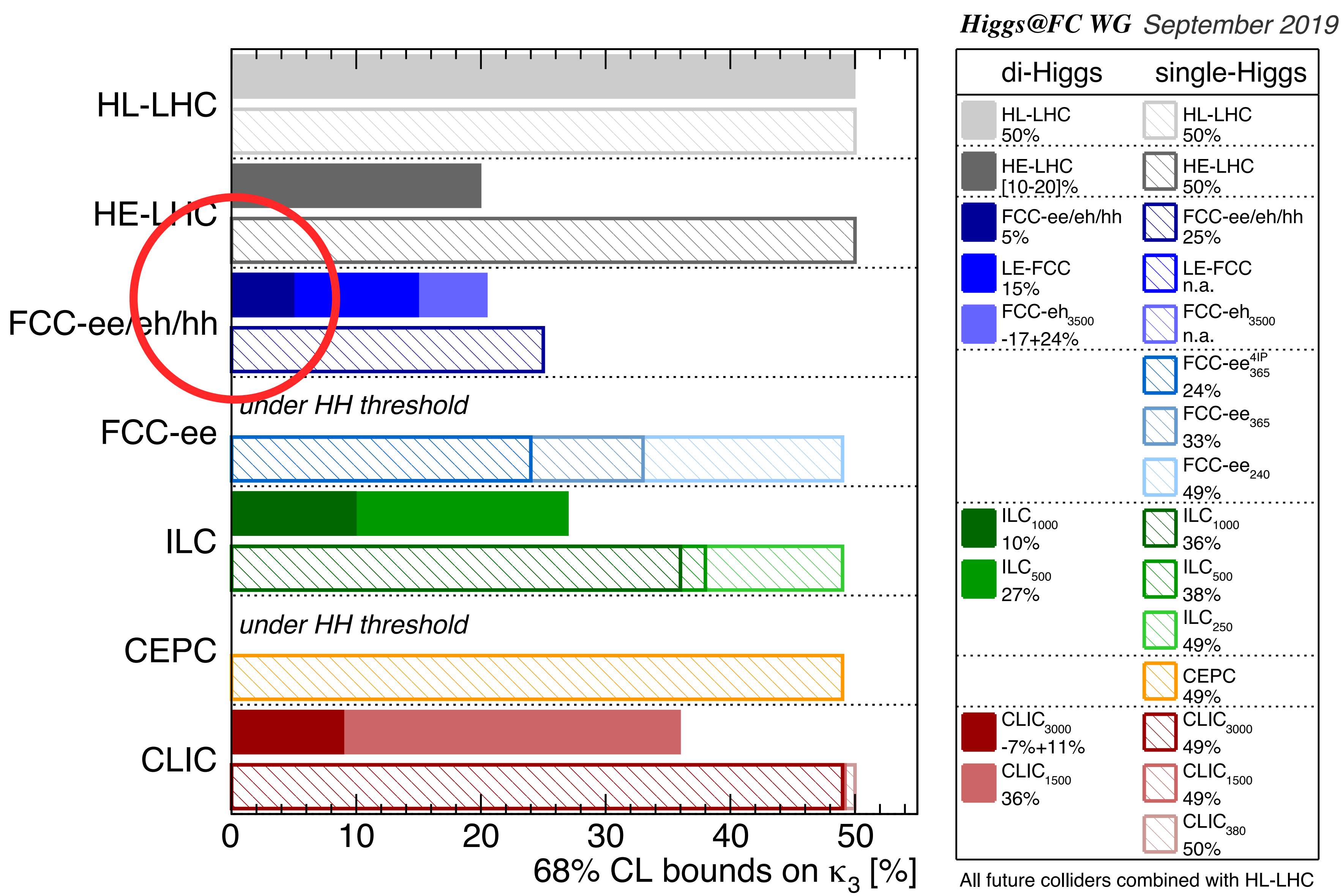
# of Higgses

100 TeV > 10 billion

27 TeV > 2 billion

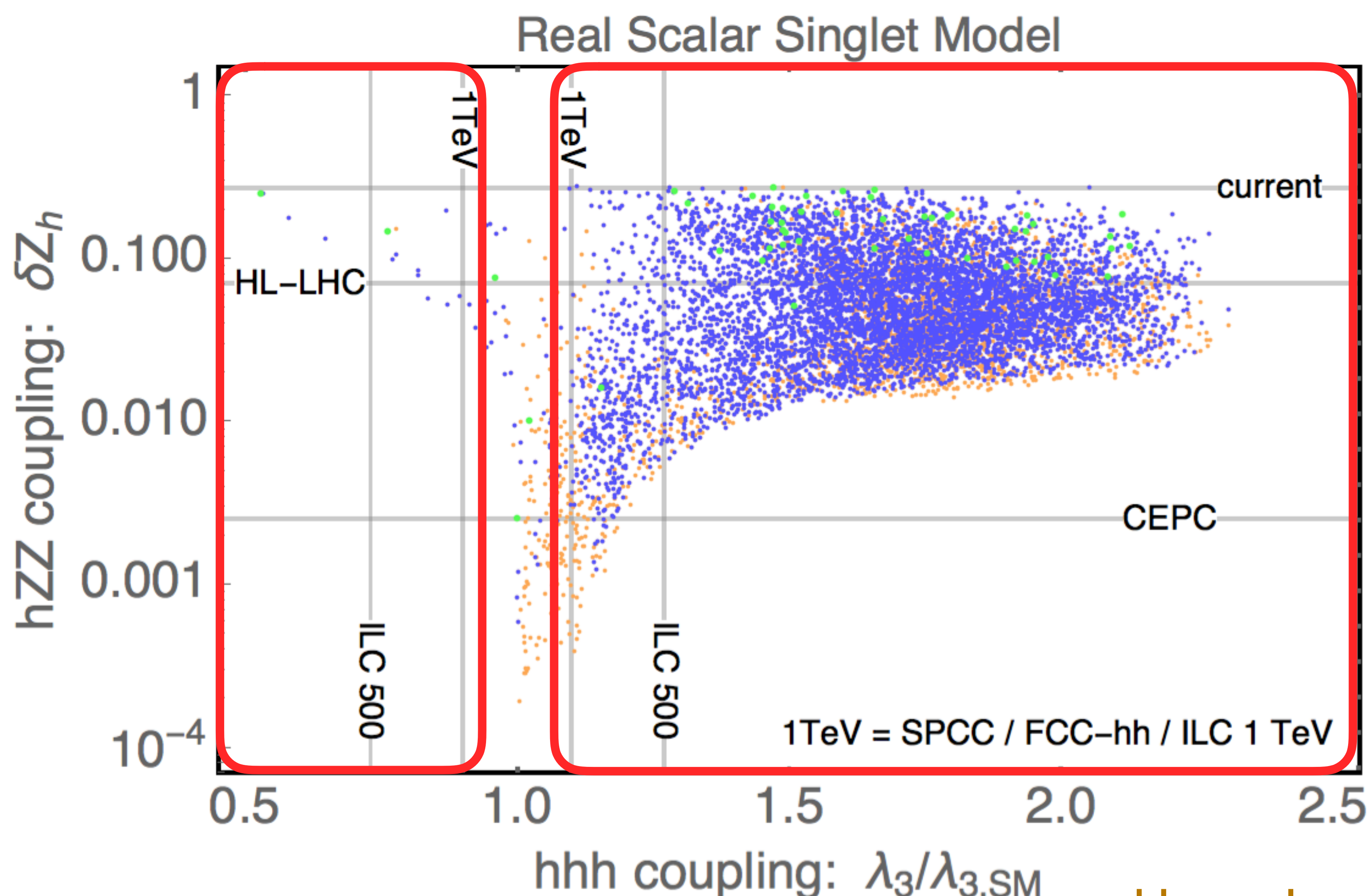
14 TeV > 150 million

Higgs potential



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

Probing EW phase transition

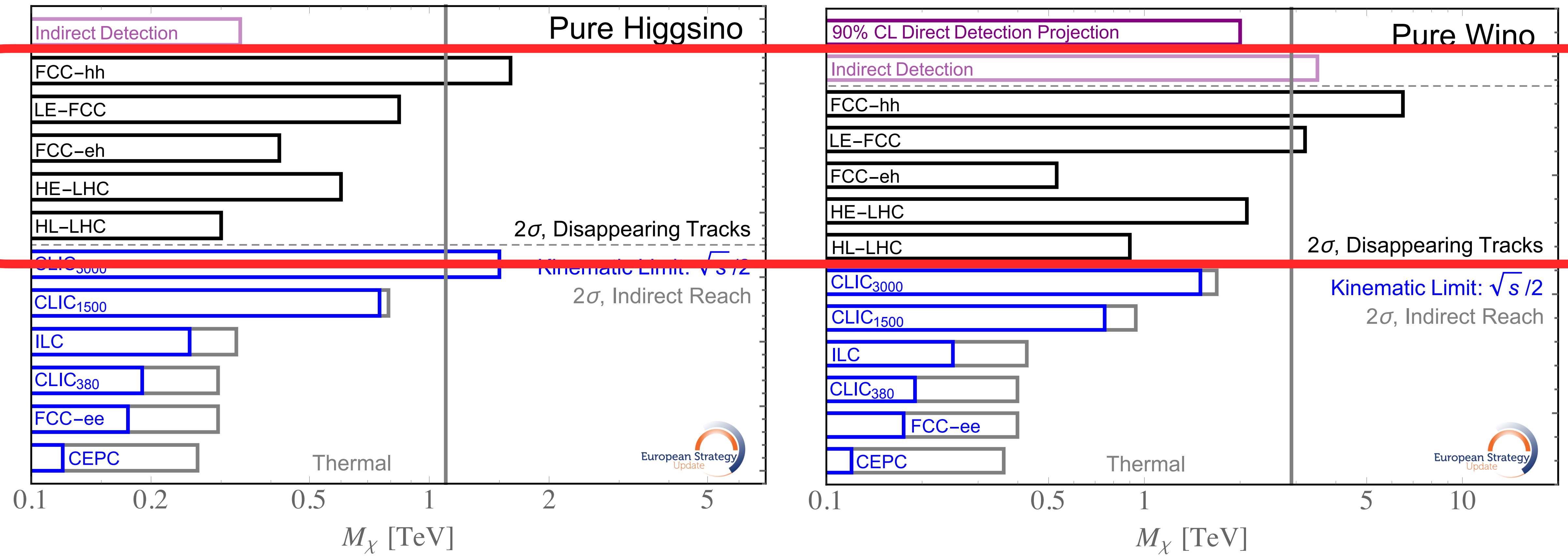


FCC-hh/SppC

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

Dark matter reach



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

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

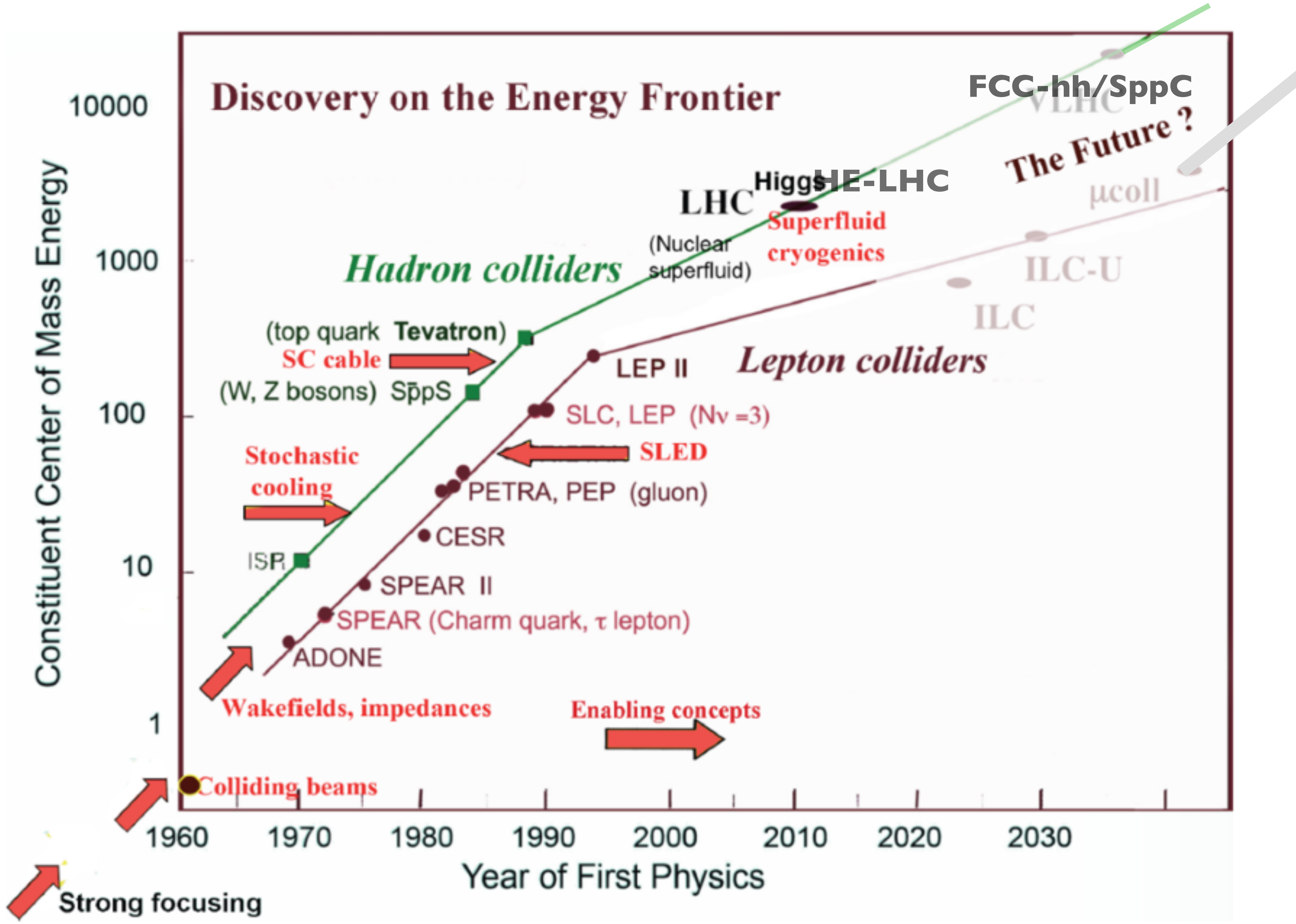
Hadron collider parameters (*pp*)

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}

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	$N_{\rm Det}$	$\mathscr{L}_{\rm inst}$/Det. $[10^{34}\rm cm^{-2}s^{-1}]$	$\mathscr{L}$ $[\rm ab^{-1}]$	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	$\pm$80/$\pm$30	1	1.35/2.7	2.0	11.5	[342]
		350 GeV	$\pm$80/$\pm$30	1	1.6	0.2	1	[346]
		500 GeV	$\pm$80/$\pm$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	$\pm$80/0	1	1.5	1.0	8	[638]
		1.5 TeV	$\pm$80/0	1	3.7	2.5	7	
		3.0 TeV	$\pm$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]

Why hadron collider?



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