Is there a No-lose theorem for future colliders?

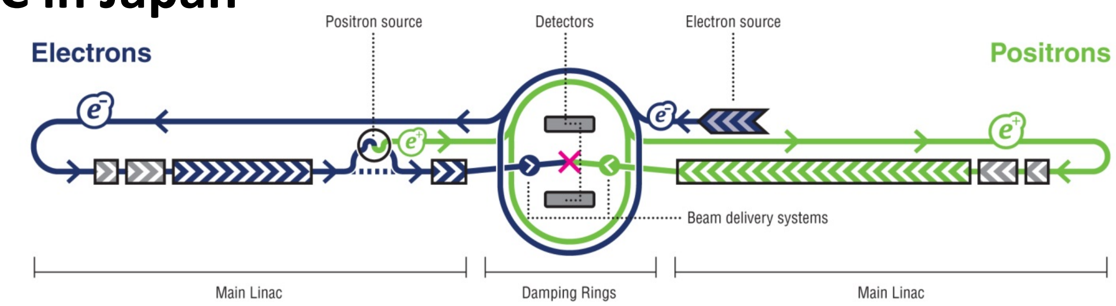
LianTao Wang
University of Chicago

SLAC Summer Institute, August 10 2018

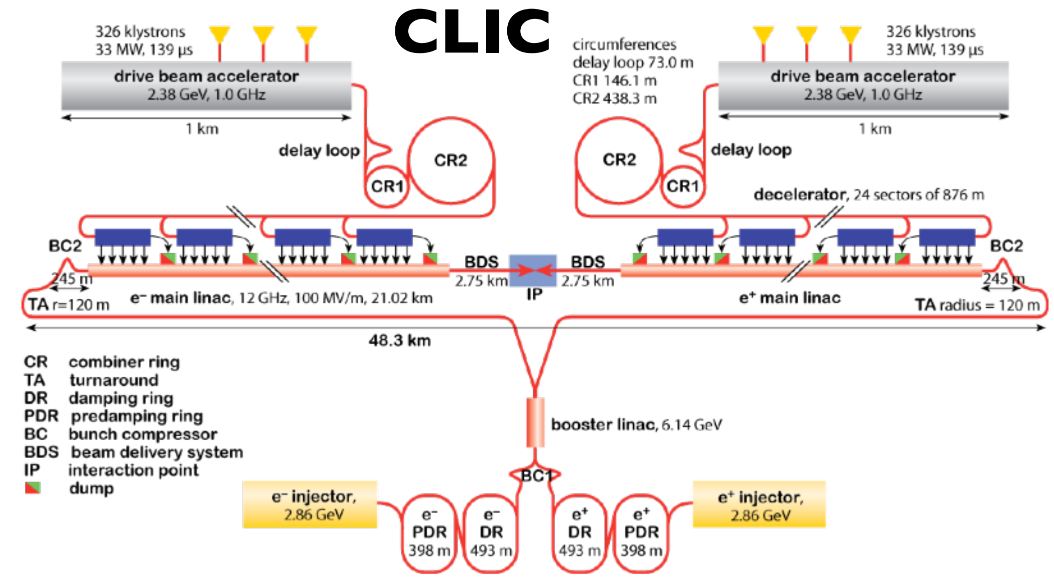
Simple answer: No! So what?

Future Colliders

ILC in Japan



CLIC

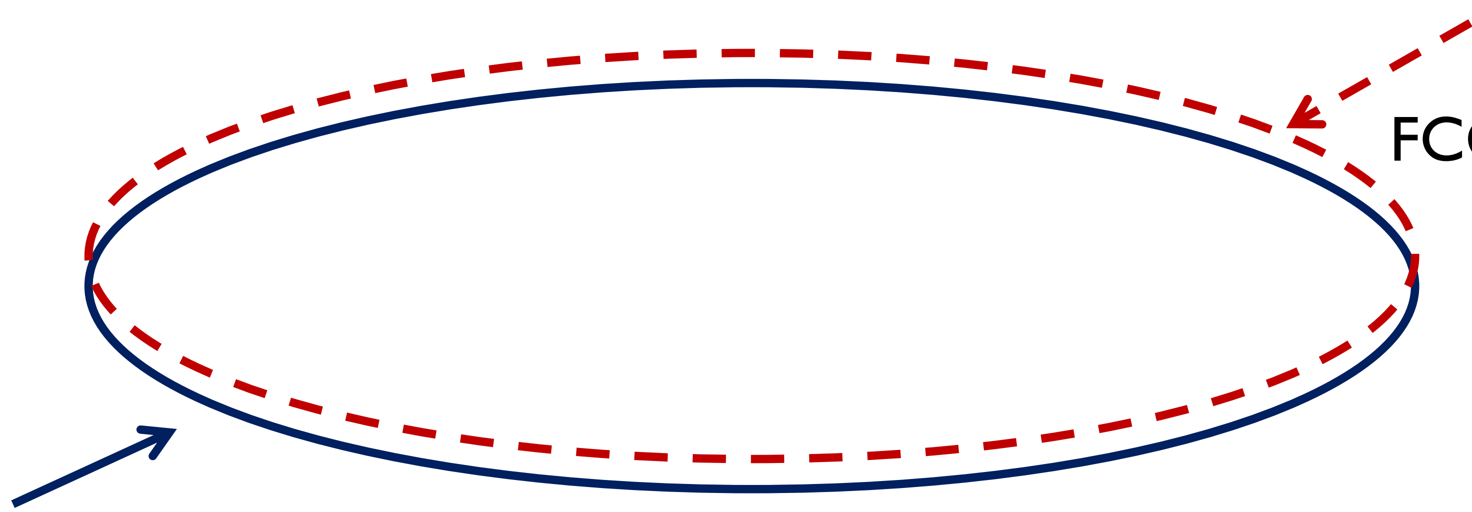


Circular. “Scale up” LEP+LHC

~100 TeV

pp collider

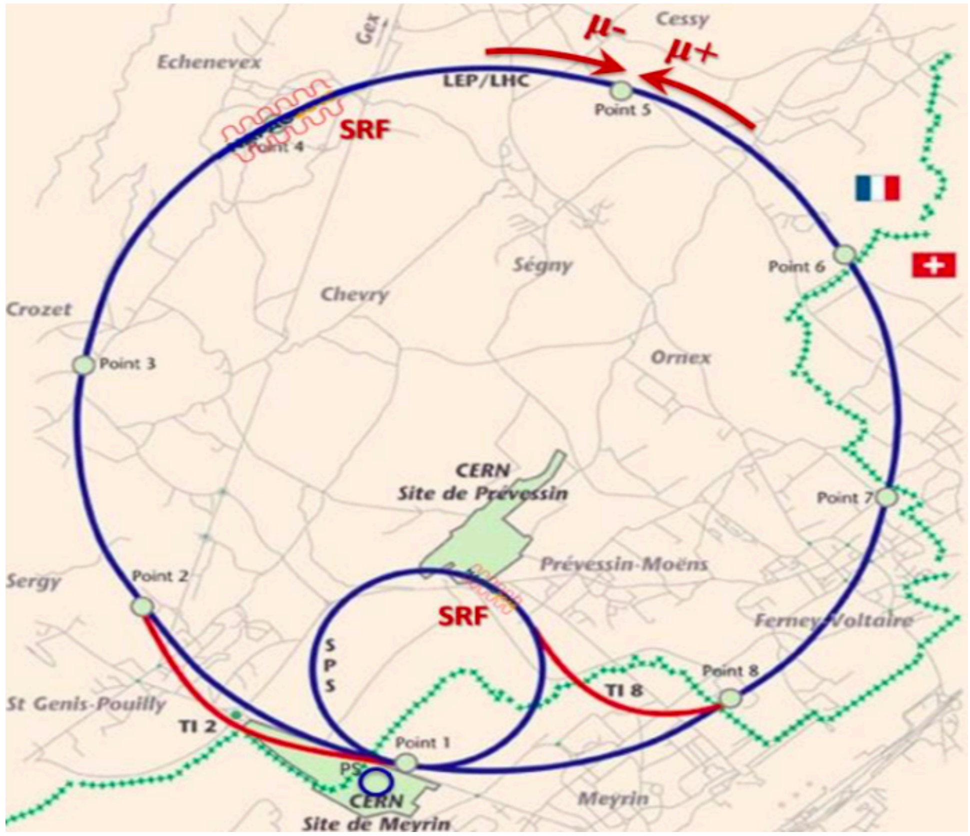
FCC-hh (CERN), SppC(China)

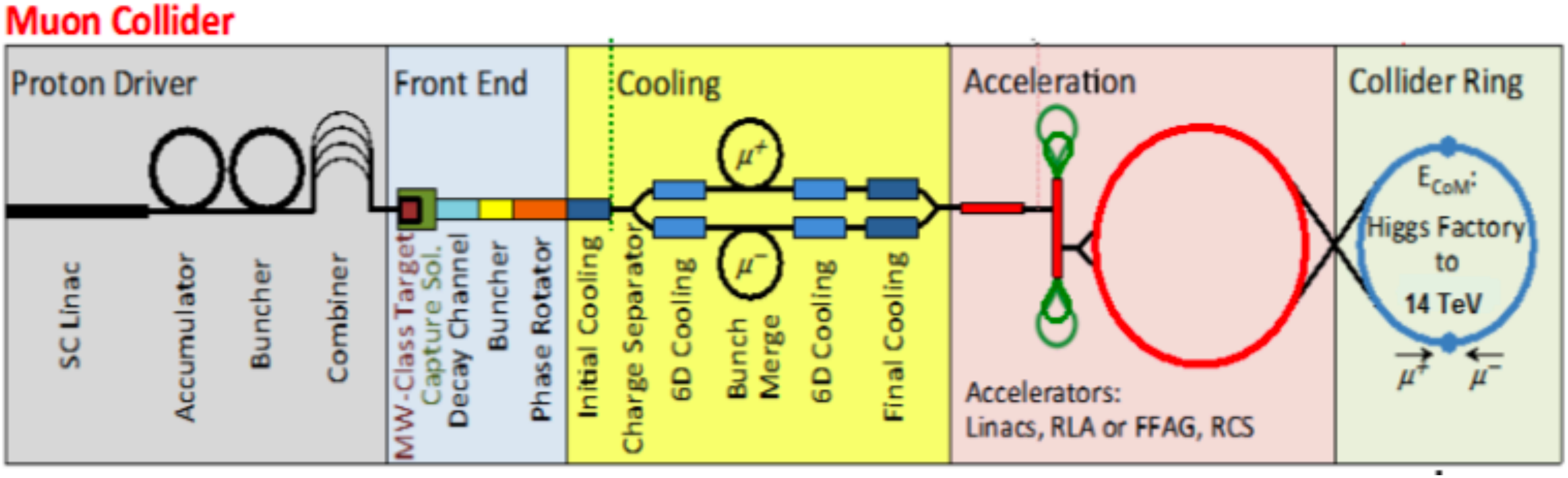


250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

Muon collider





Even more exciting

From: "Peskin, Michael E." <mpeskin@slac.stanford.edu>
Subject: lepton collider physics at 10- 50 TeV

Dear Colleague,

I am starting a new community study in particle theory. I hope you will be interested in it, and it would be great if you would participate. There is a serious purpose, but, for the moment, it is an excuse to have fun

• • •

5 GeV/m is SLAC in 10m. In a 10 km accelerator, such as one might envision for a new global facility in the 2040's, it would give a 50 TeV beam energy.

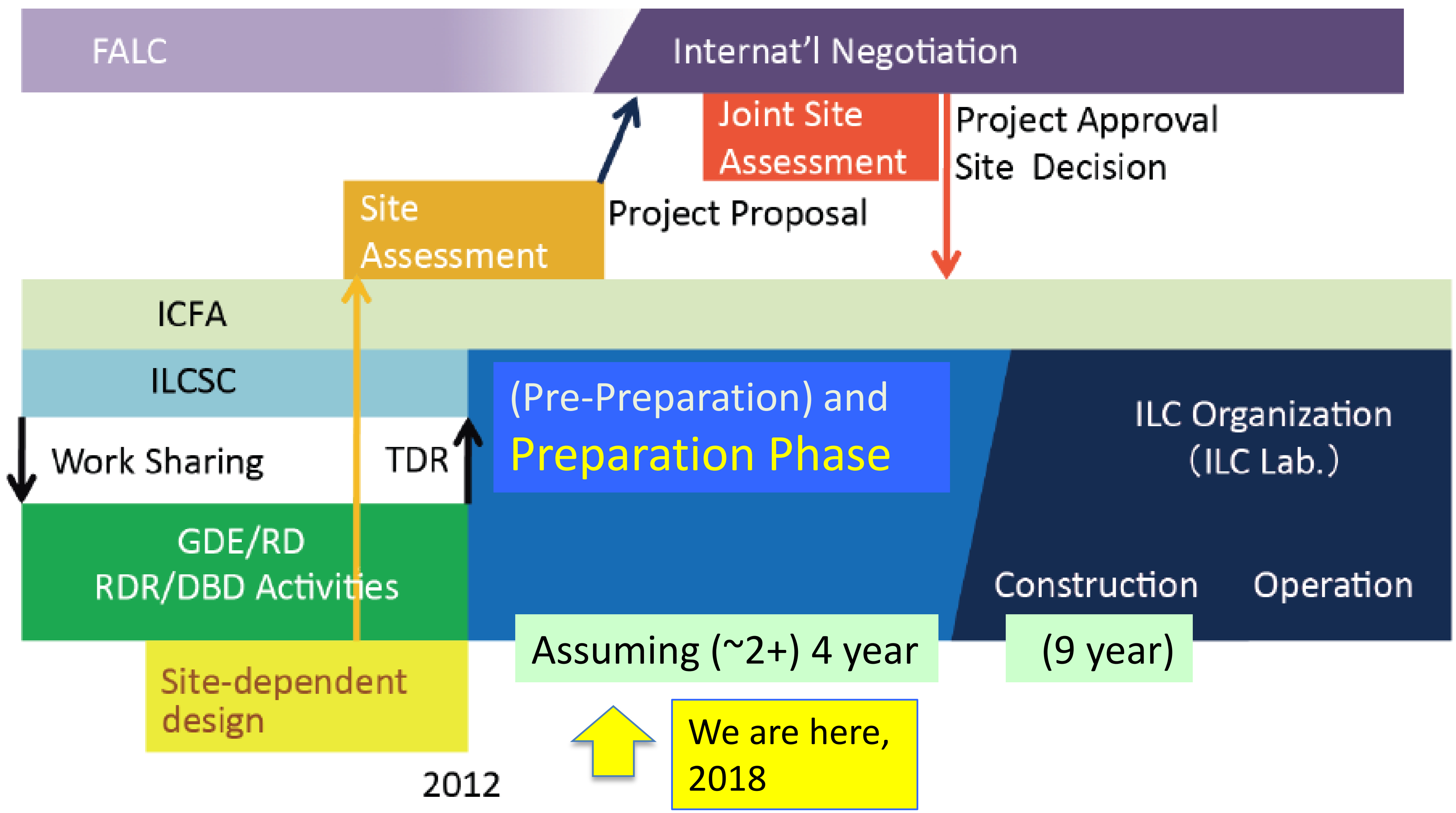
I think it is important that the development of these technologies should be pushed by theorists. To motivate this program, we need to answer the question: What would we learn from an electron accelerator of energy 10 - 50 TeV? This question is also relevant for thinking about future muon colliders and hadron colliders. We have studied the TeV range of energies for a long time, but future facilities might vault us into the tens of TeV. What then?

• • •

My focus here

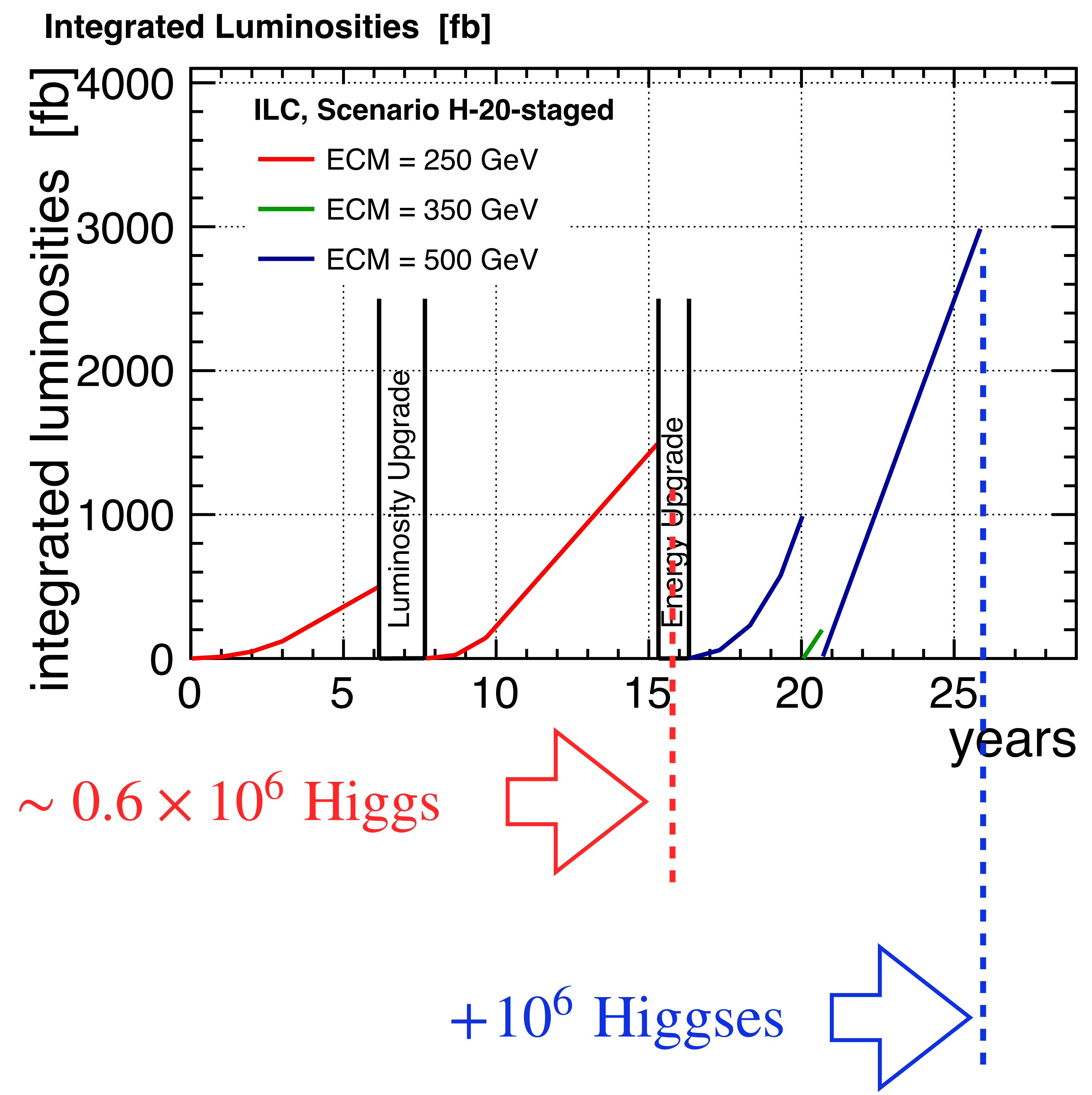
- Circular: FCC-ee/FCC-hh, CEPC/SppC
- Linear: ILC, CLIC
- Very brief comment on higher energy lepton colliders

ILC Time Line: Progress and Prospect



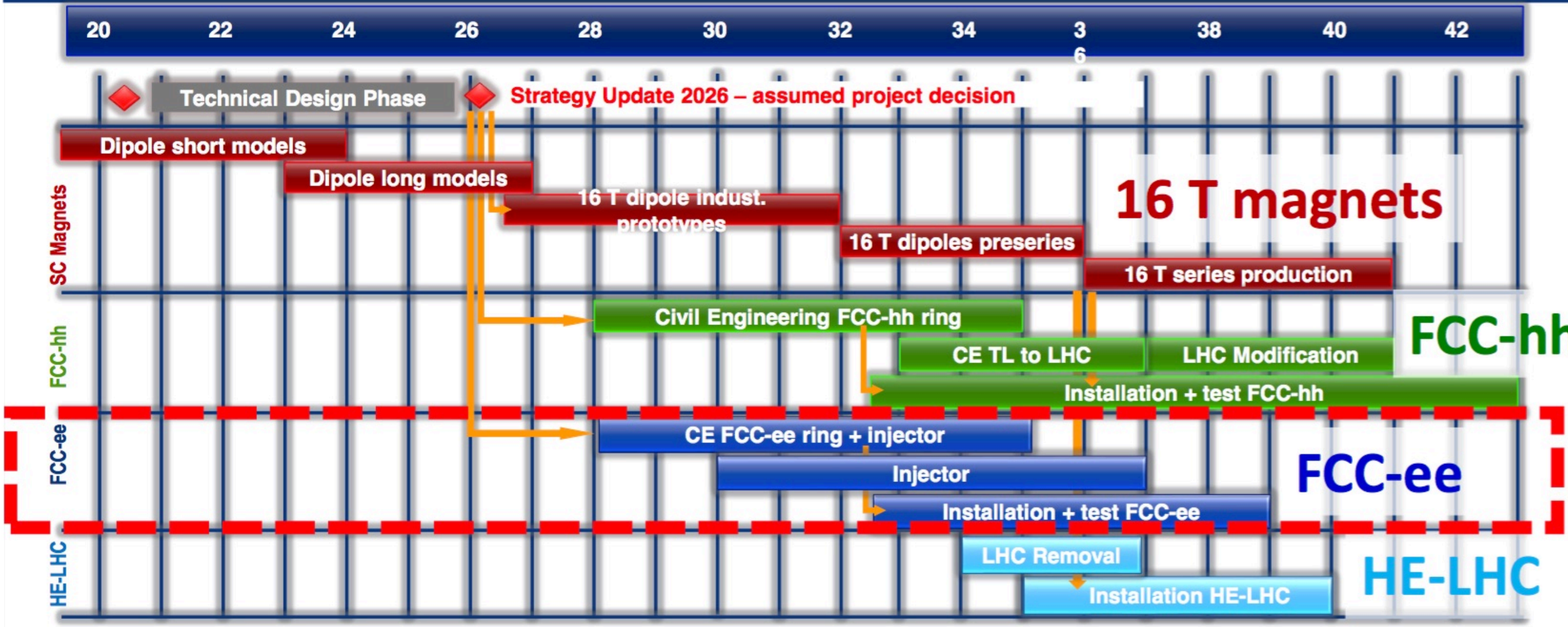
Shin Michizono, HK IAS conference 2018

A possible ILC run plan



Will scan top threshold. No Z-pole or WW run planned

Technical Schedule for each the 3 Options



schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

M. Benedikt

FCC-ee machine parameters - Dec 2017

	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
emittance hor/vert [nm]/[pm]	0.27/1.0	0.28/1.0	0.63/1.3	1.46/2.9
beta* horiz/vertical [m]/[mm]	0.15/.8	0.2/1	0.3/1	1/2
total RF voltage [GV]	0.10	0.4	2.0	10
energy acceptance [%]	±1.3	±1.3	±1.5	-2.8+2.4
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25
bunch intensity [10^{11}]	1.7	2.3	1.8	3.3
no. of bunches / beam	16640	1300	328	33
beam current [mA]	1390	147	29	5.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	**>200**	**>30**	**>7**	**>1.5**
luminosity lifetime [min]	70	30	20	20
allowable asymmetry [%]	±5	±3	±3	±3

An ambitious program

FCC-ee:

FCC-ee possible operation model

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	32	8.3 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.5	0.38 ab^{-1}/year	**1.5 ab^{-1}**	**4**

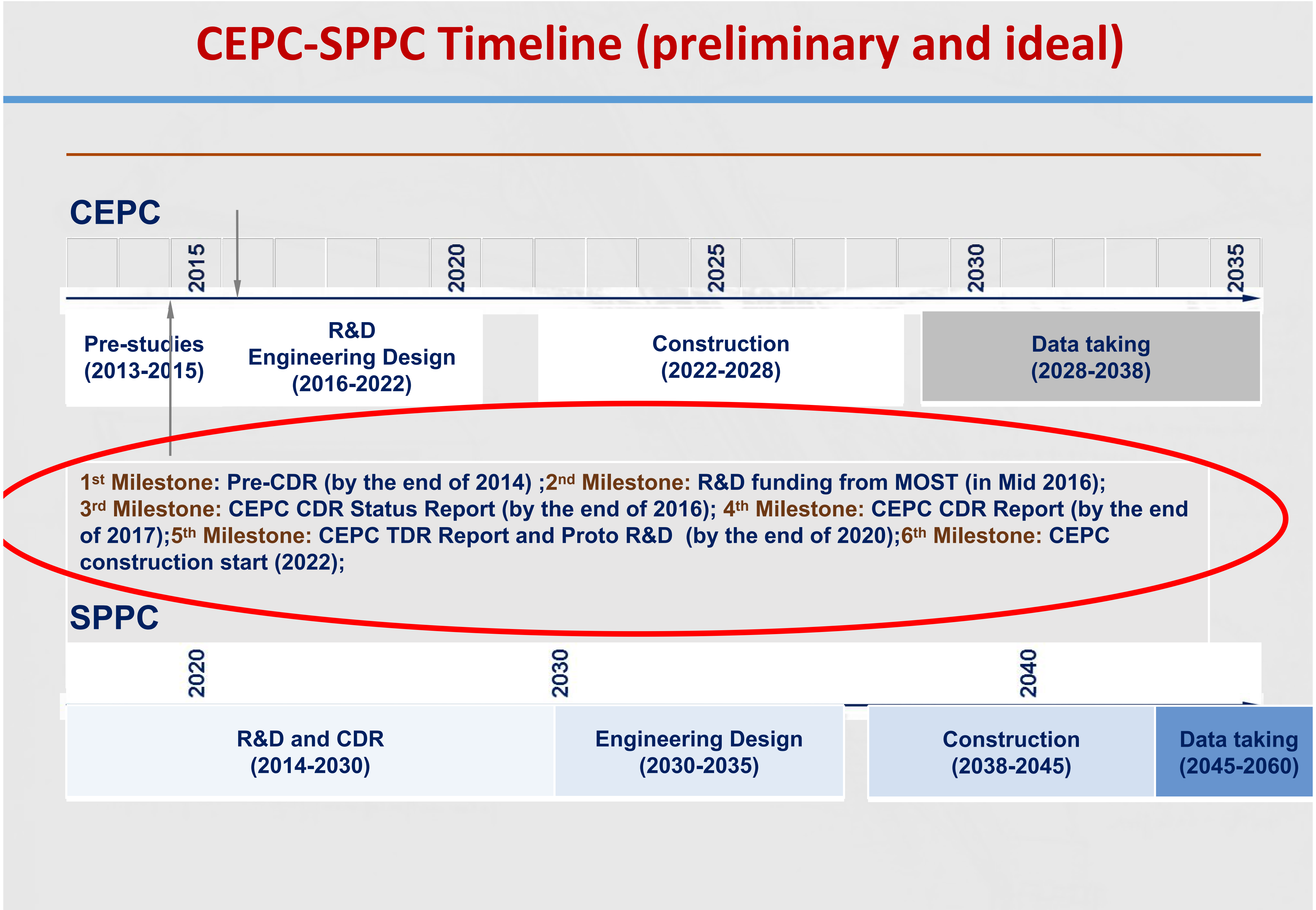
$$\sim 10^6 \text{ Higgses}, \ \sim 10^{13} \text{ Zs}, \ldots$$

13 years: Higgs=3 yr, Z=4 yr, top=5 yr, W=1 yr

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

Goal: 20-30 ab^{-1} during the collider lifetime



Current design effort focusing on CEPC

CEPC Operation Plan

Particle type	Energy (c.m.) (GeV)	Luminosity per IP (10^{34} cm^{-2}s^{-1})	Luminosity per year (ab^{-1}, 2 IPs)	Years	Total luminosity (ab^{-1}, 2 IPs)	Total number of particles
H	240	3	0.8	**7**	5.6	1×10^6
Z	91	32	8	**2**	16	7×10^{11}
W	160	10	2.6	**1**	2.6	8×10^6

CEPC yearly run time assumption:

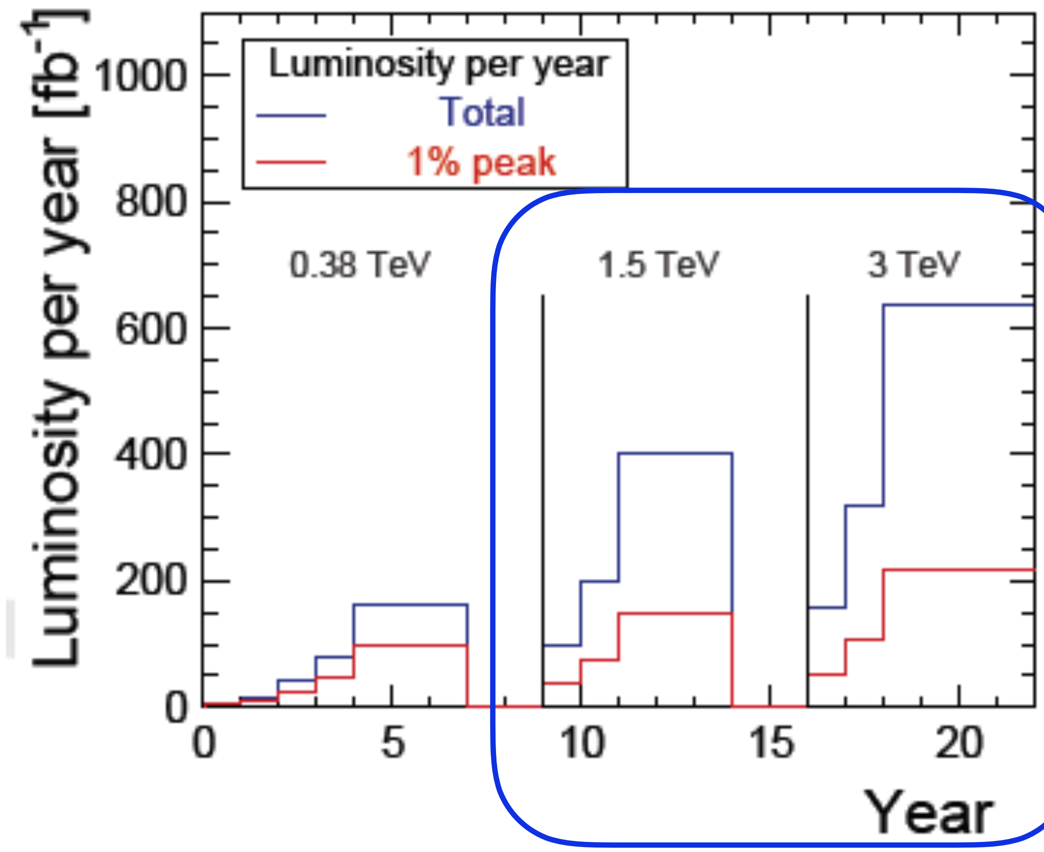
- Operation – 8 months, or 250 days, or 6,000 hrs
- Physics (60%) – 5 months, or 150 days, or **3,600 hrs**, or 1.3 Snowmass Unit.

CEPC

staging scheme	physics focus
7 year at Higgs **~1M events** 240 GeV (initial stage)	H indir. BSM
2 years at Z **upto 10^{12} events** 1 year at WW **~20M events**	Z, W EW Physics

No top threshold scan planned

CLIC

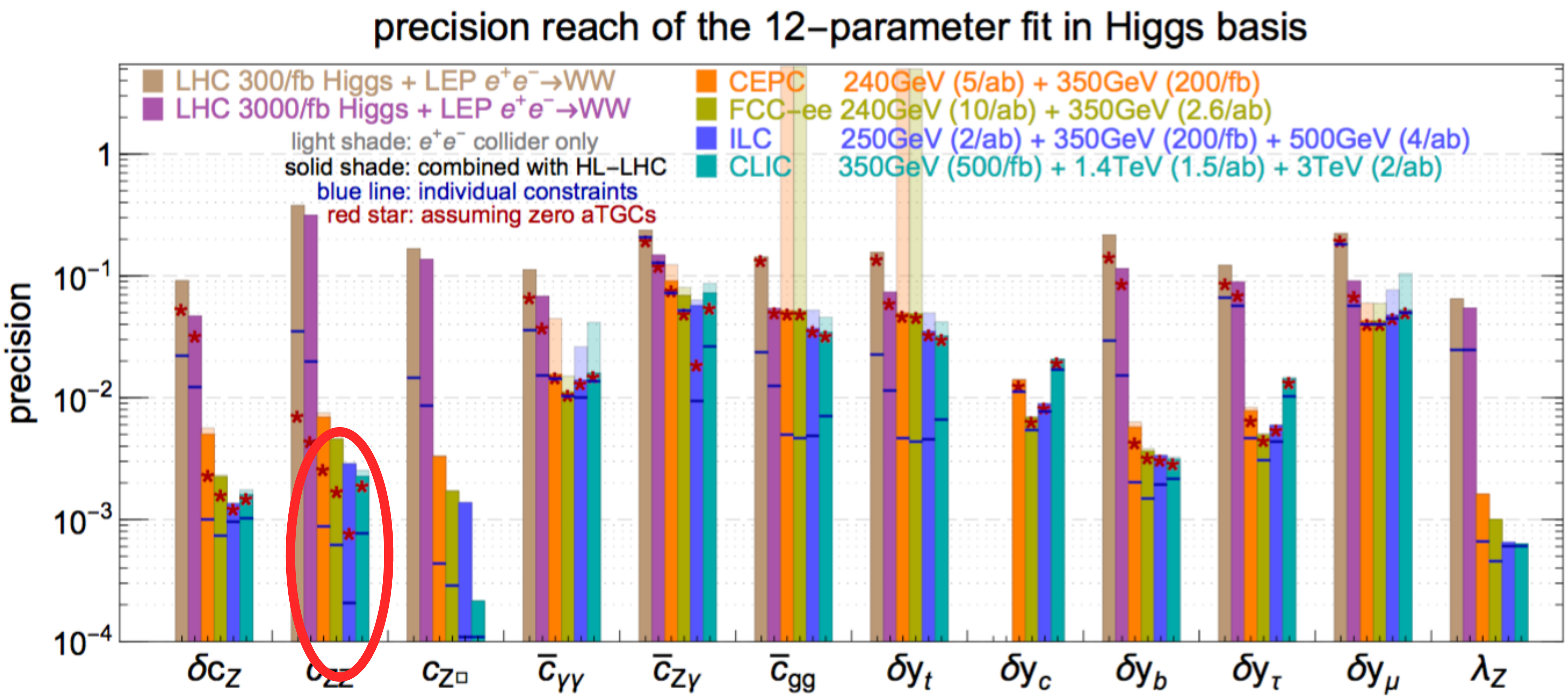


Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

$\sim 2 \times 10^5$ Higgs

higher energies

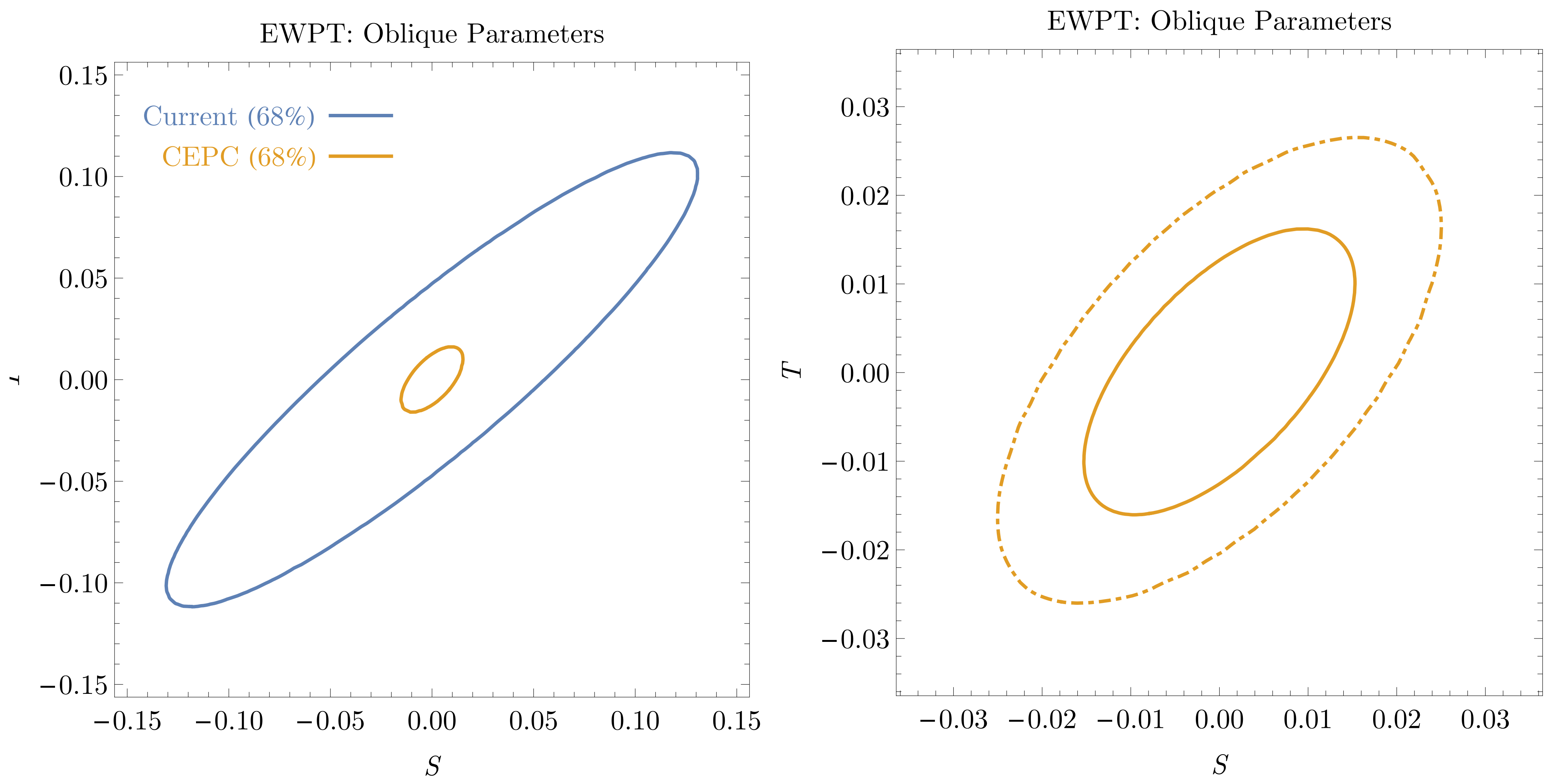
Lepton colliders and precision measurements



Grojean et al. 1704.02333

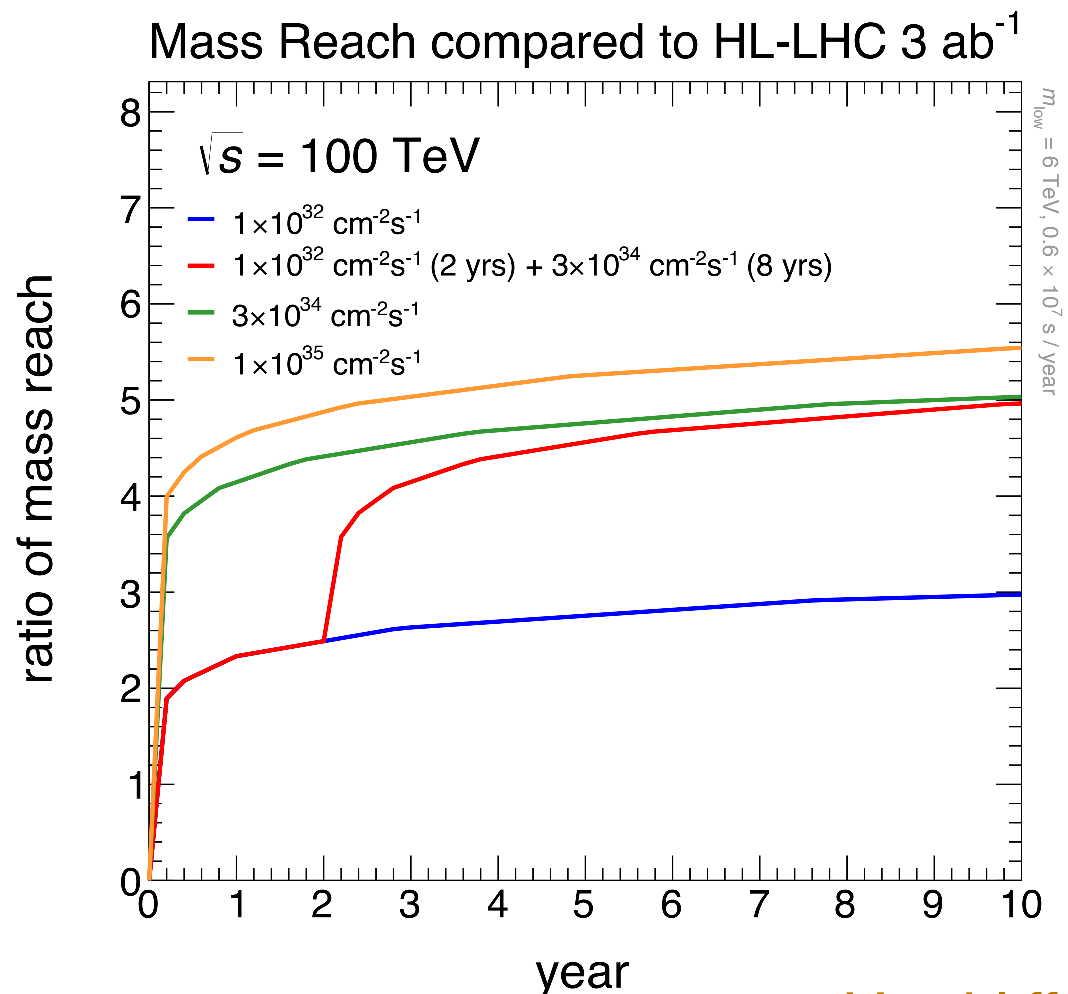
Sub percent precision, reach to new physics at multi-TeV scale.
Far beyond the reach of LHC.

Electroweak precision



FCC can do even better (by a factor of a few)

100-ish TeV pp collider

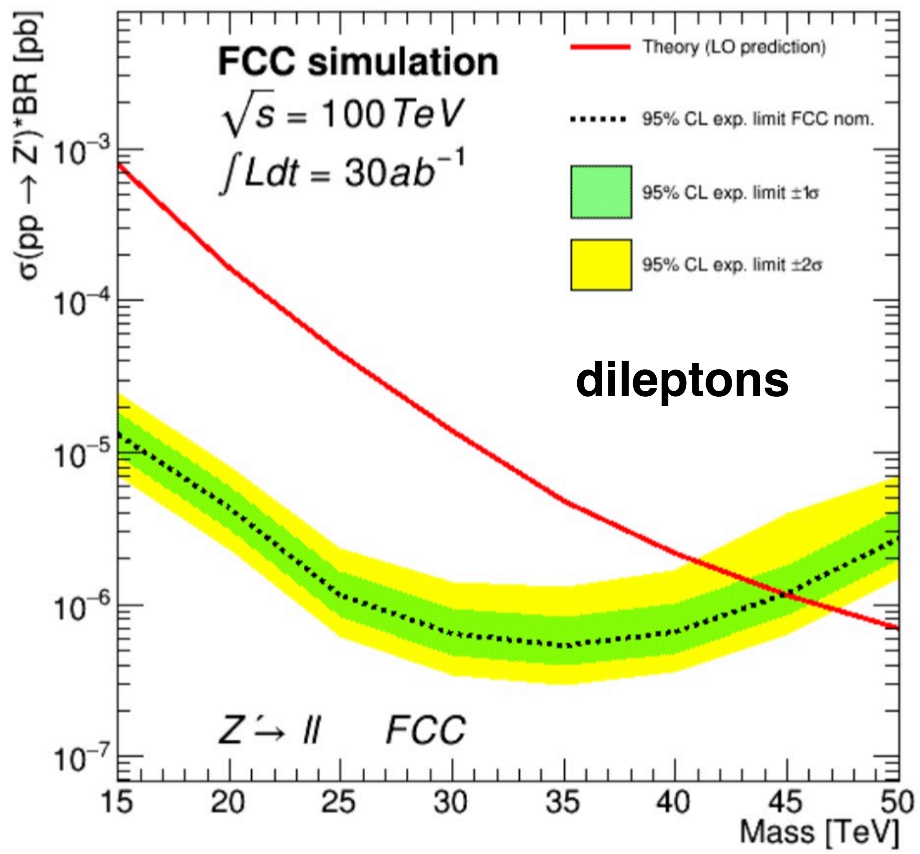


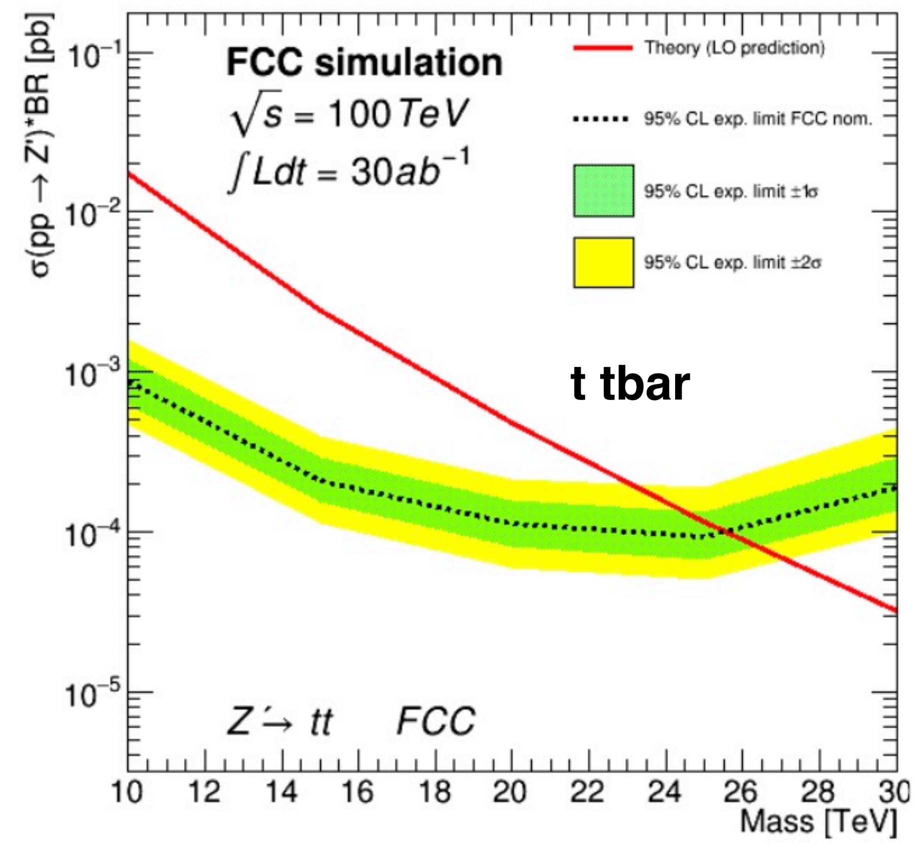
Hinchliffe, Kotwal, Mangano, Quigg, LTW

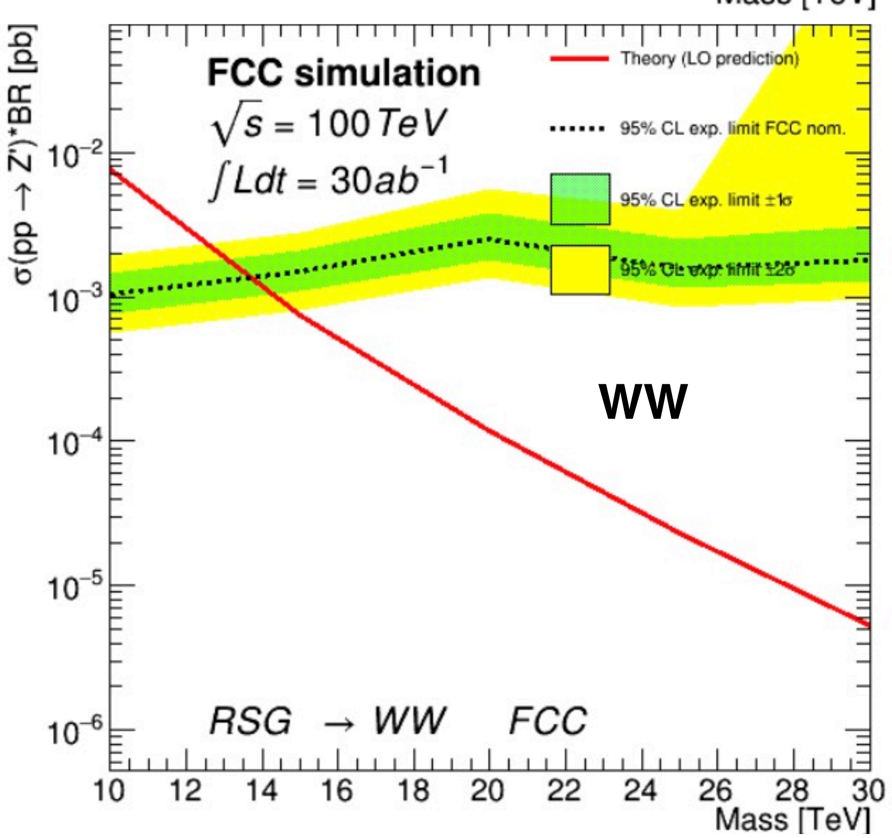
A factor of at least 5 increase in reach beyond the LHC, with modest luminosity

New physics reach: 10s TeV

Resonances: SSM Z'







C. Helsens & M. Selvaggi + Summer students
Rachel Smith UIUC and Ine Arts UA

No-lose theorem

- Often understood as a guarantee of discovering new particles, or detect deviations from the SM.

- For physics case of future colliders, it is tempting to construct No-lose theorems.
  - Sometimes viewed as necessary for successful proposal of the project.

No-lose theorem

- We can learn a lot even if there is no new particle discovered.
  - For example, if collider searches can rule out an idea, a paradigm, or a very broad class of models.
- Therefore, the definition of a No-lose Theorem should include this case as well.

No-lose theorem

- Can't be based on particular models.
  - Take any more, multiply mass scale by a factor of x, with $x < 10$
  - Model does not change (much).
  - Yet, this can very well be the difference between visible and invisible at a collider.

No-lose theorem

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [37]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [38]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [38]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [38]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [39]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [40]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [41]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [42]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [43]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Such deviations can be detected at Higgs factories

Demonstrates Higgs measurement lepton collider can probe a broad range of models.

No-lose theorem

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [37]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [38]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [38]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [38]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [39]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [40]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [41]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [42]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [43]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

However, these are not no lose theorems. Can change model parameters to make these deviations small, invisible to Higgs coupling measurements.

No-lose theorem

- There are important physics questions which are pointing to new physics at lower mass scales.
  - We can try to attempt to establish no-lose theorem in this case.
- Model dependence unavoidable.
- Loop-holes are usually there. "nightmare" scenarios.
- An "almost" or pseudo No-lose Theorem with some nightmare scenario is a place we can make a lot of progresses.

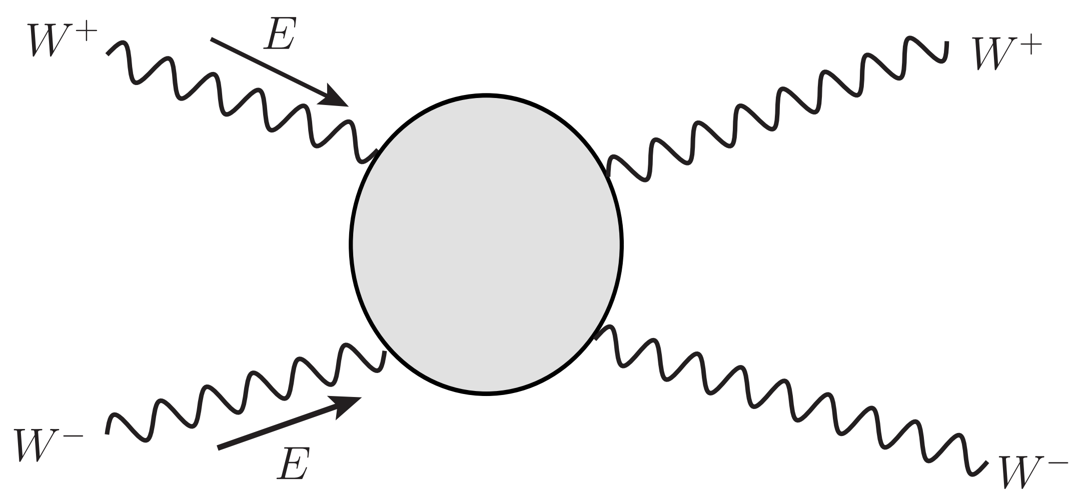
There is no general no-lose theorem.

It is fine to have nightmare scenarios.
There is risk in any scientific exploration. Should not abandon them just because of the risks.

We will make significant progresses on important questions at future colliders!

A no lose theorem before 2012

Consider:

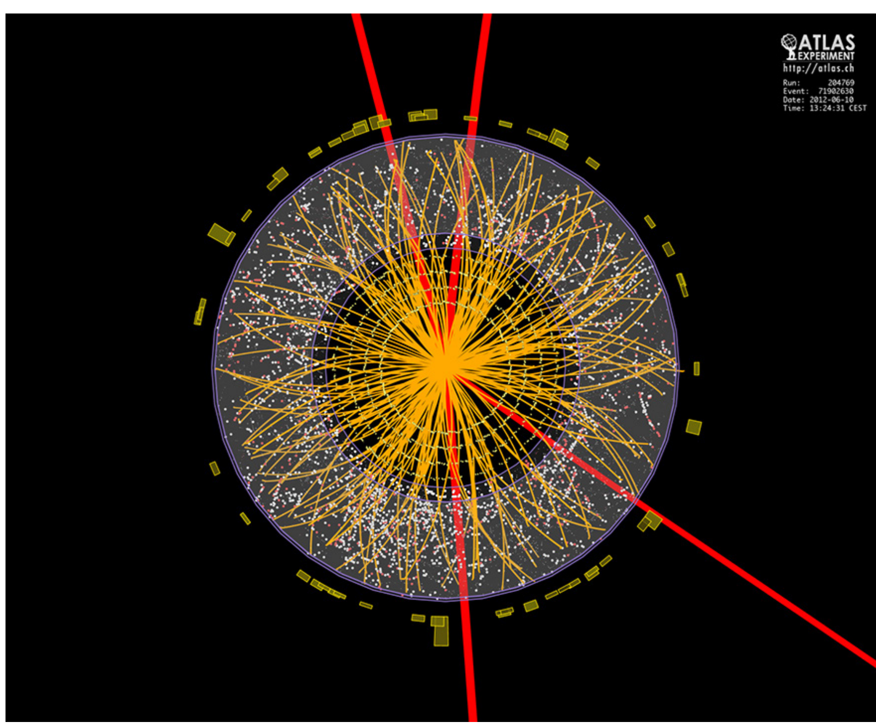


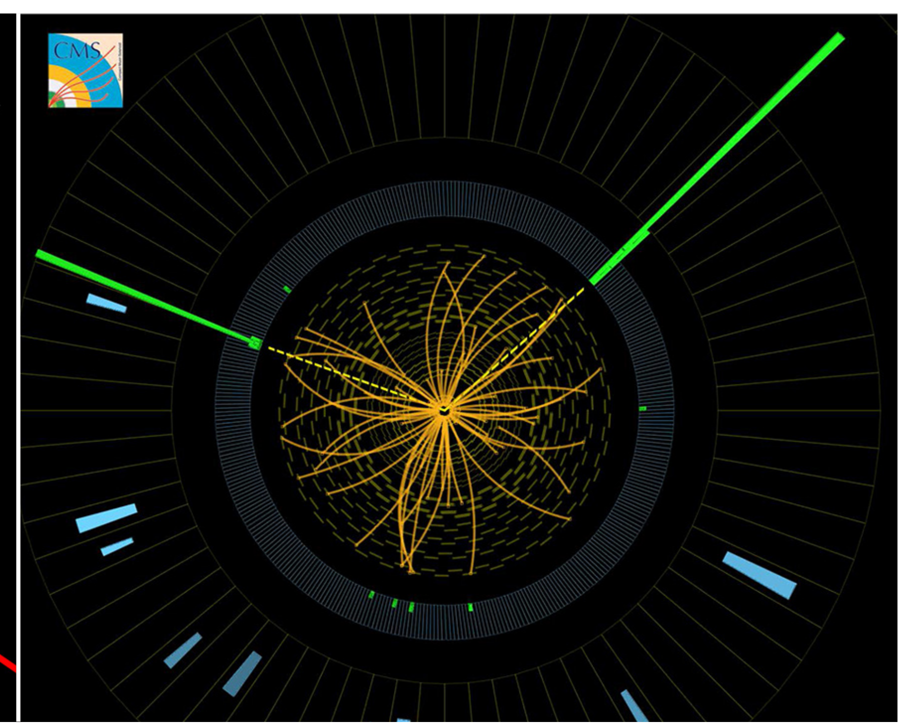
$$\text{Amplitude} \approx g_{\mathrm{W}}^2 \frac{E^2}{m_{\mathrm{W}}^2}$$

Growing stronger at higher energy.
Perturbative unitarity breaks down.

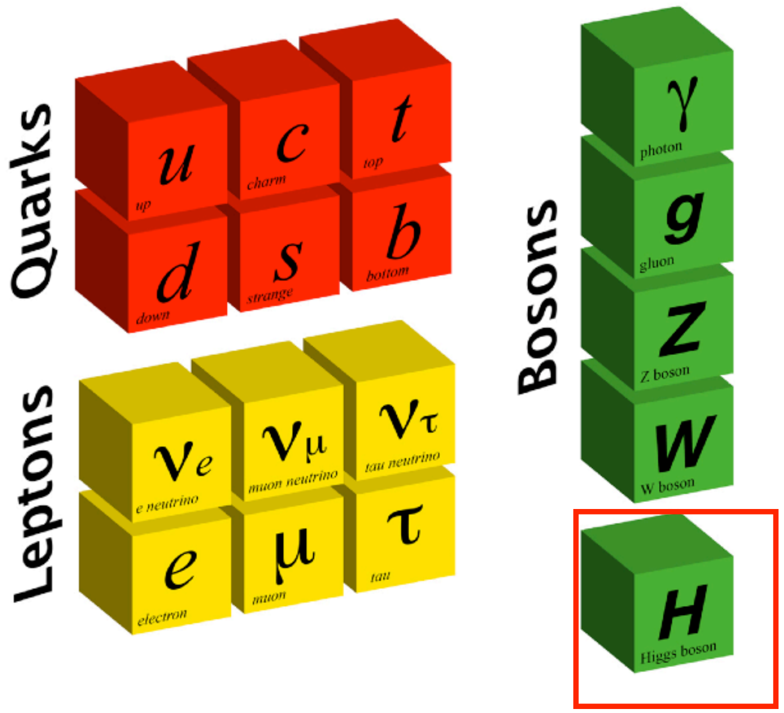
- Therefore, this picture is not valid at $E \sim 4\pi m_{\mathrm{W}}/g_{\mathrm{W}} \simeq$ TeV
- Something new must happen before TeV scale.

A spectacular discovery!





Simplest answer



- The Higgs boson.
  - Spin 0 (scalar)

- Higgs field gives masses to electrons, W/Z....

SM: complete yet incomplete

- Complete: could be a consistent theory valid up to the Planck scale.

- Incomplete: many open questions
  - Origin of electroweak scale
  - Dark matter
  - Origin of CP, flavor
  - ...

- Future collider will help us make progress in addressing these open questions.

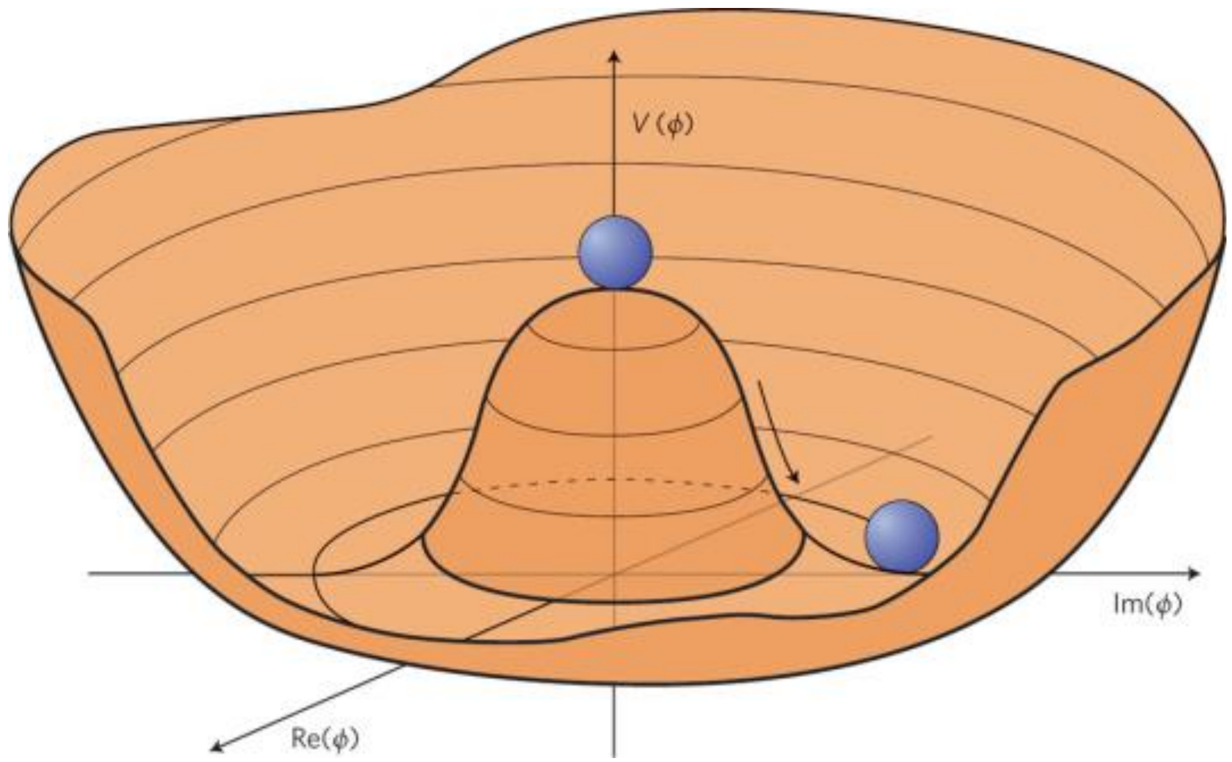
Several examples

pseudo no lose theorems and nightmare scenarios

a.k.a places we can make a lot of progresses

Electroweak symmetry breaking

“Simple” picture: Mexican hat

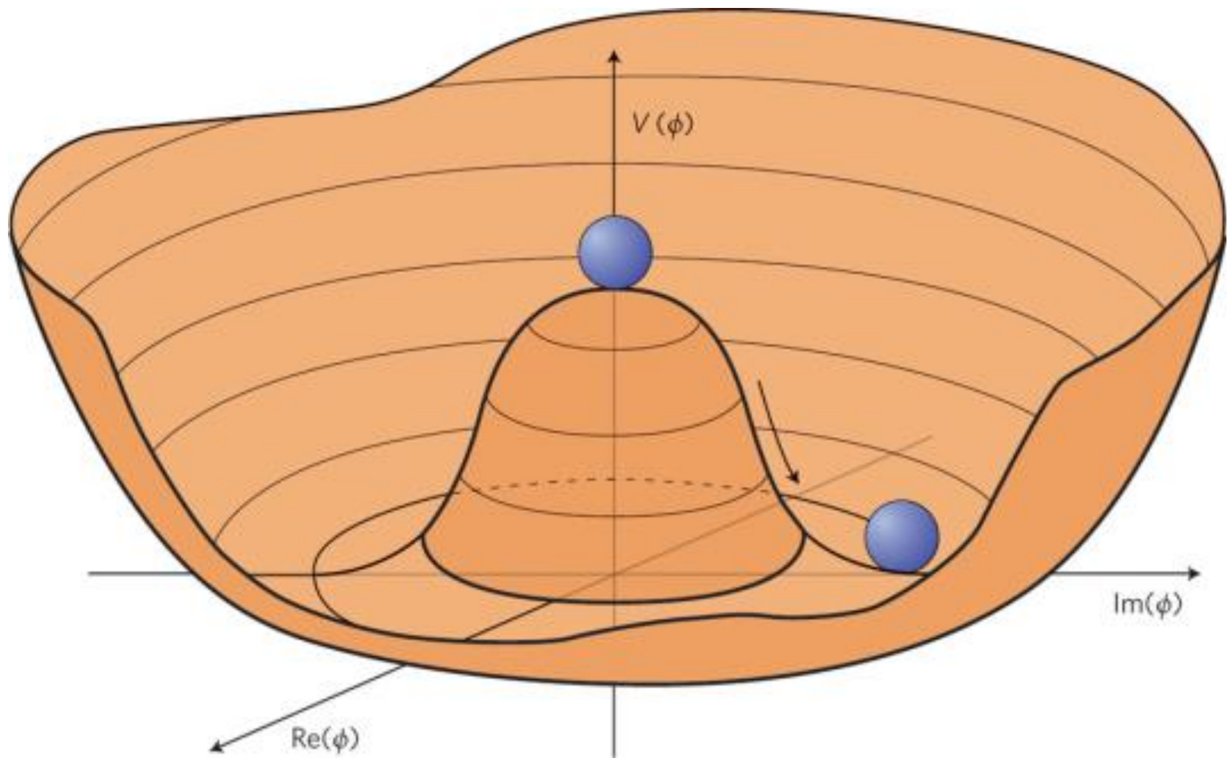


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \ \rightarrow \ m_W = g_W \frac{v}{2}$$

Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

“Simple” picture: Mexican hat



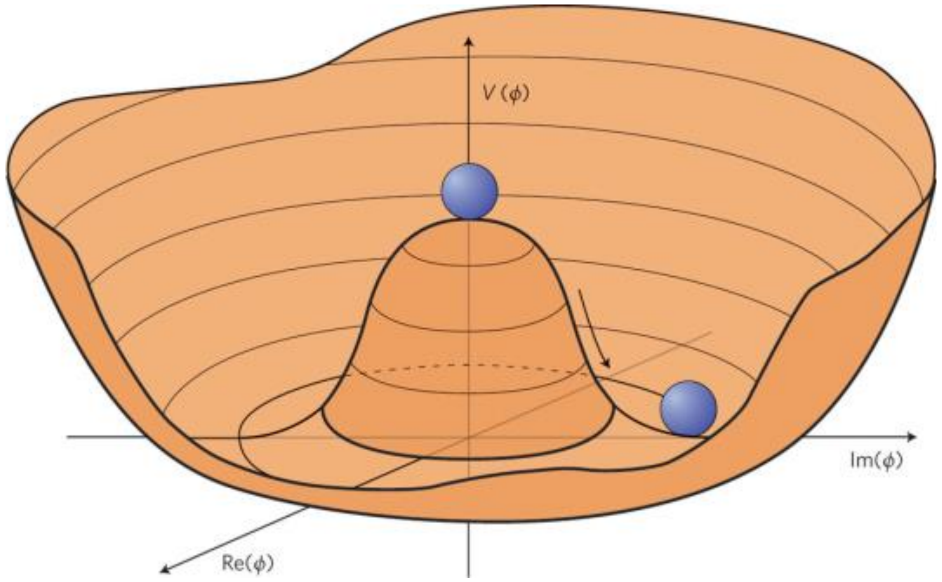
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

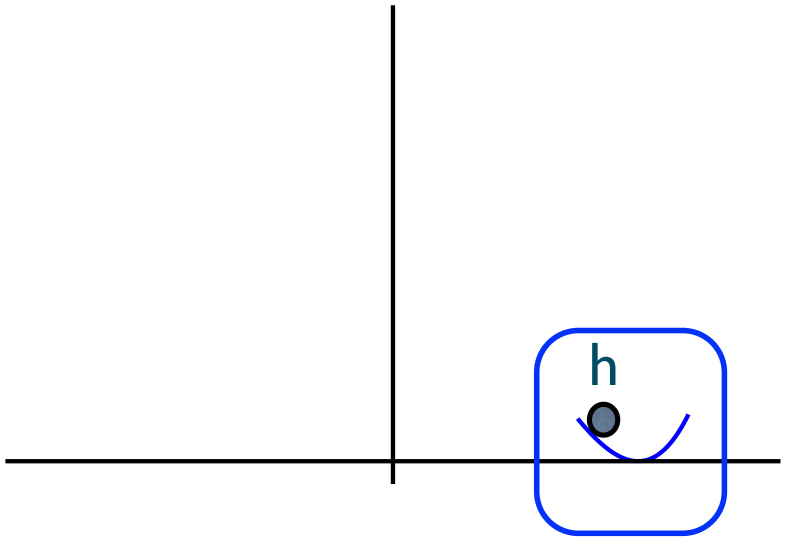
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

However, this simplicity is deceiving.
Parameters not predicted by theory. Can not be the complete picture.

Mysteries of the electroweak scale.

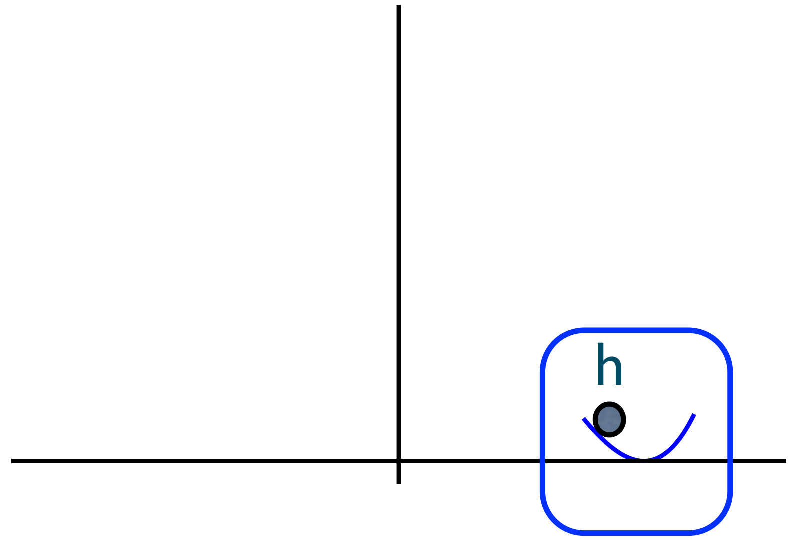


Mysteries of the electroweak scale.



What we know now

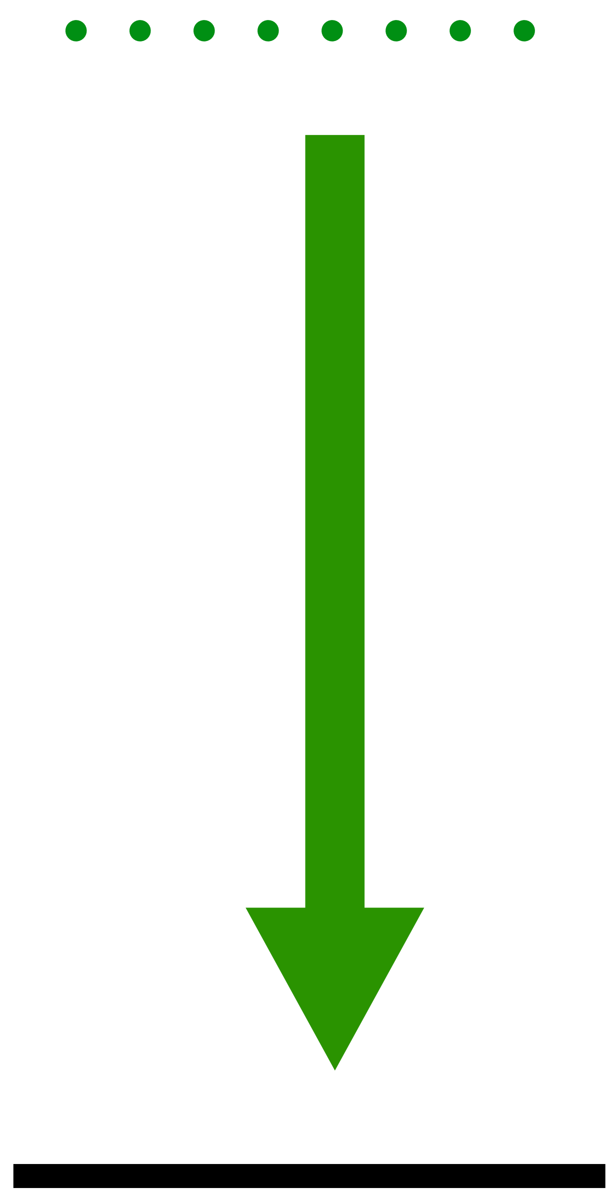
Mysteries of the electroweak scale.



What we know now

- How to predict/calculate Higgs mass? Naturalness
- Full Higgs potential?
    - Order of electroweak phase transition

How to predict Higgs mass?

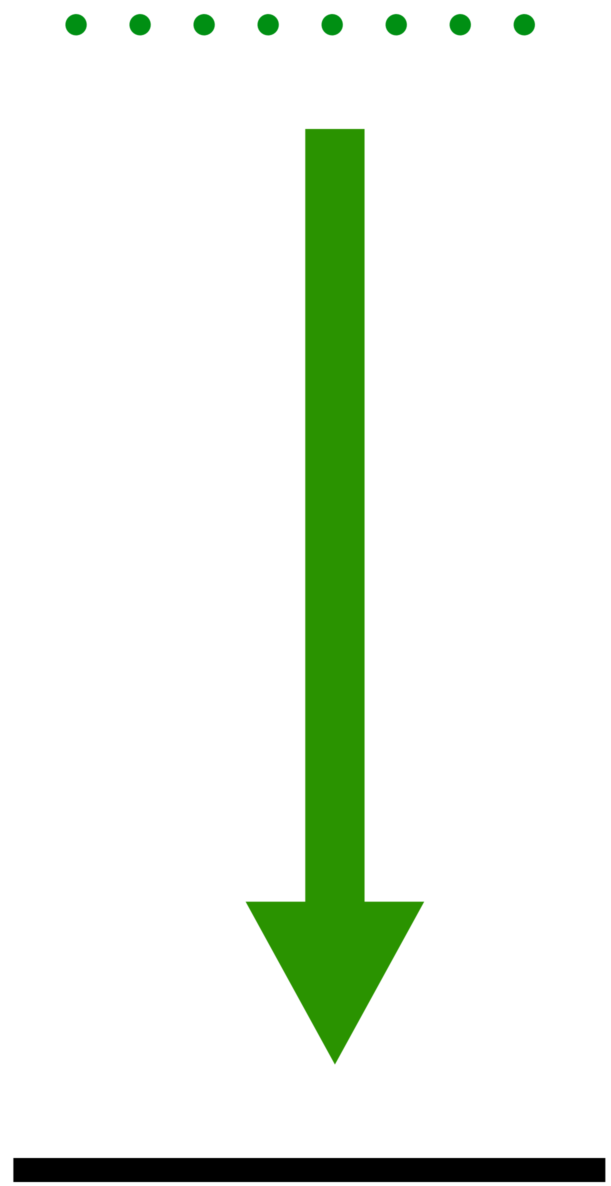


The energy scale of new physics responsible for EWSB

Electroweak scale, 100 GeV.

m_h , m_W ...

How to predict Higgs mass?



The energy scale of new physics
responsible for EWSB

What is this energy scale?
$M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?
The so called naturalness problem

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness of electroweak symmetry breaking

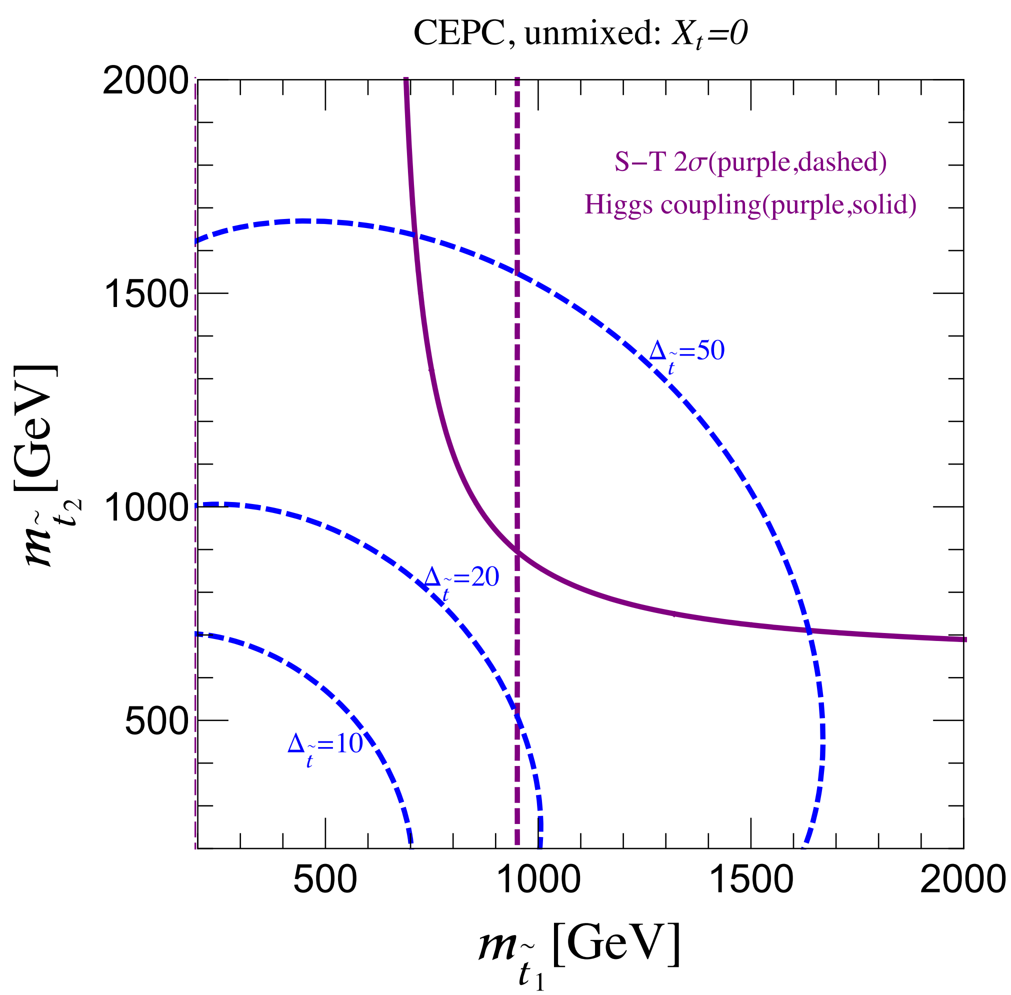
The energy scale of new physics
responsible for EWSB

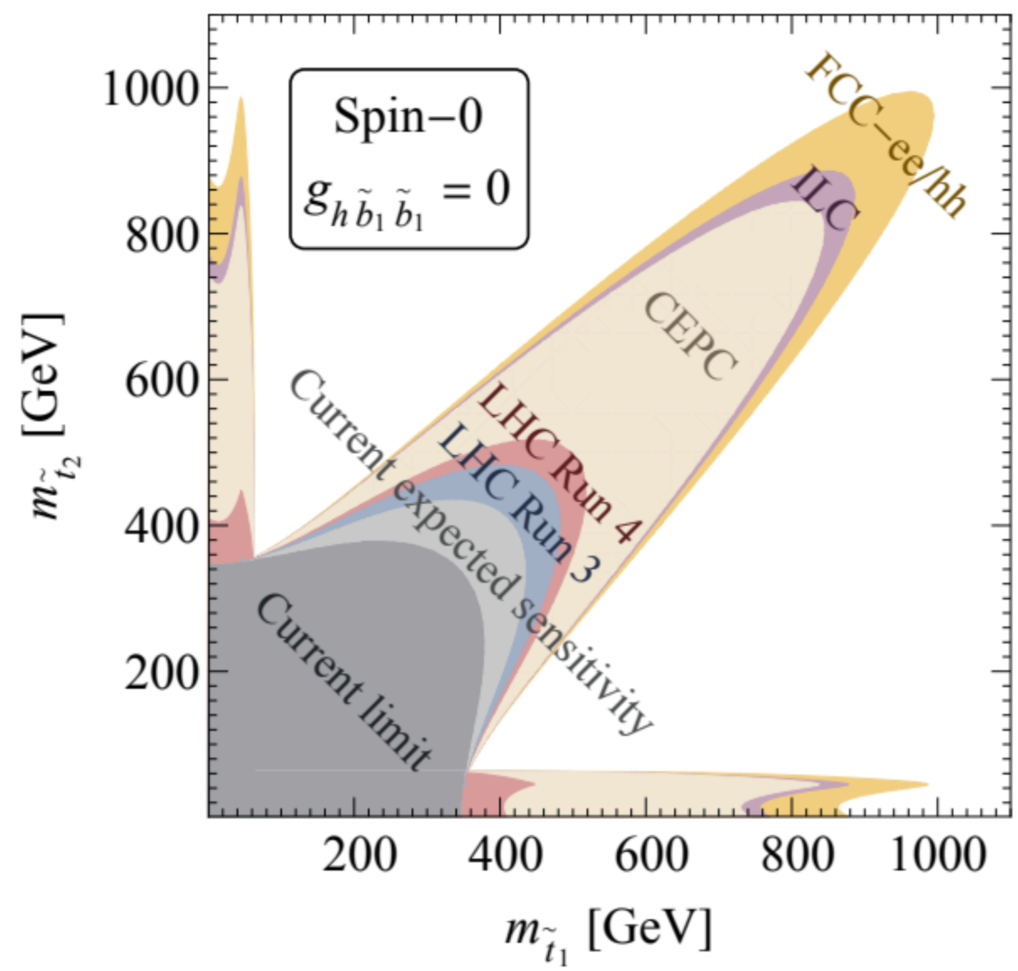
TeV new physics.
Naturalness motivated
Many models, ideas.

Electroweak scale, 100 GeV.
m_h , m_W ...

Naturalness in SUSY

- LHC searches model dependent, many blind spots.

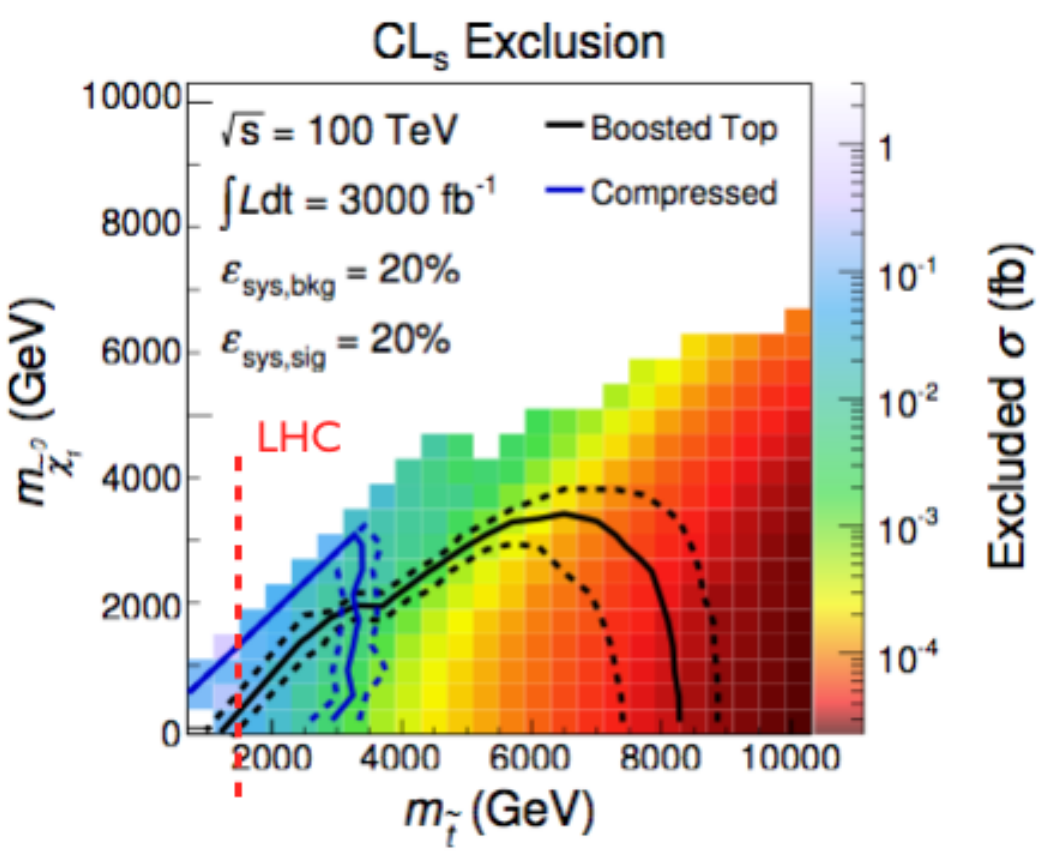




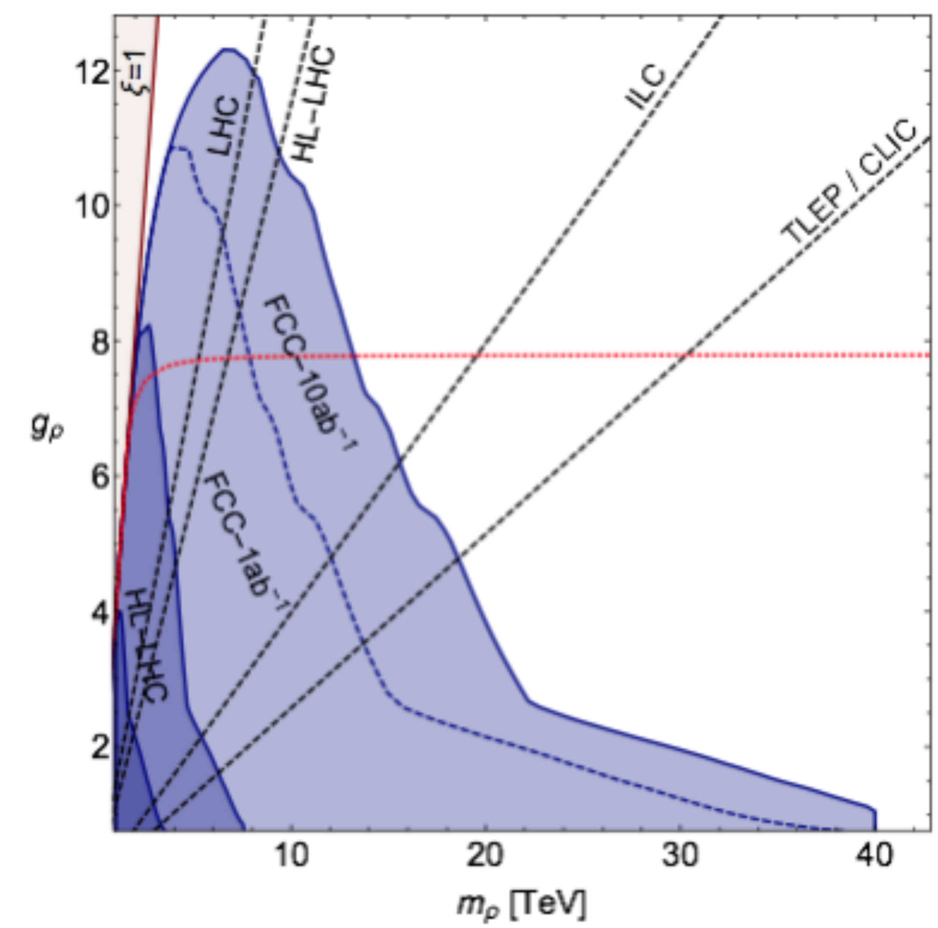
- Testing fine-tuning down to percent level.

Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014

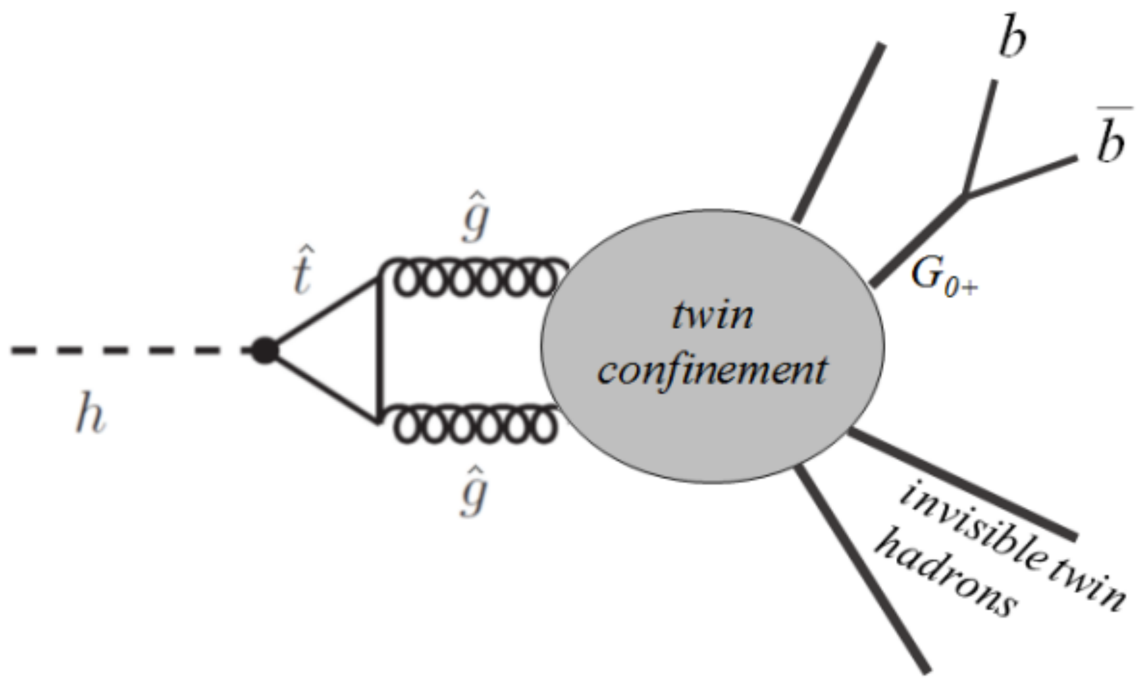


Fine tuning: $(M_{NP})^{-2}$

“nightmare” scenario

Chacko, Goh, Harnik

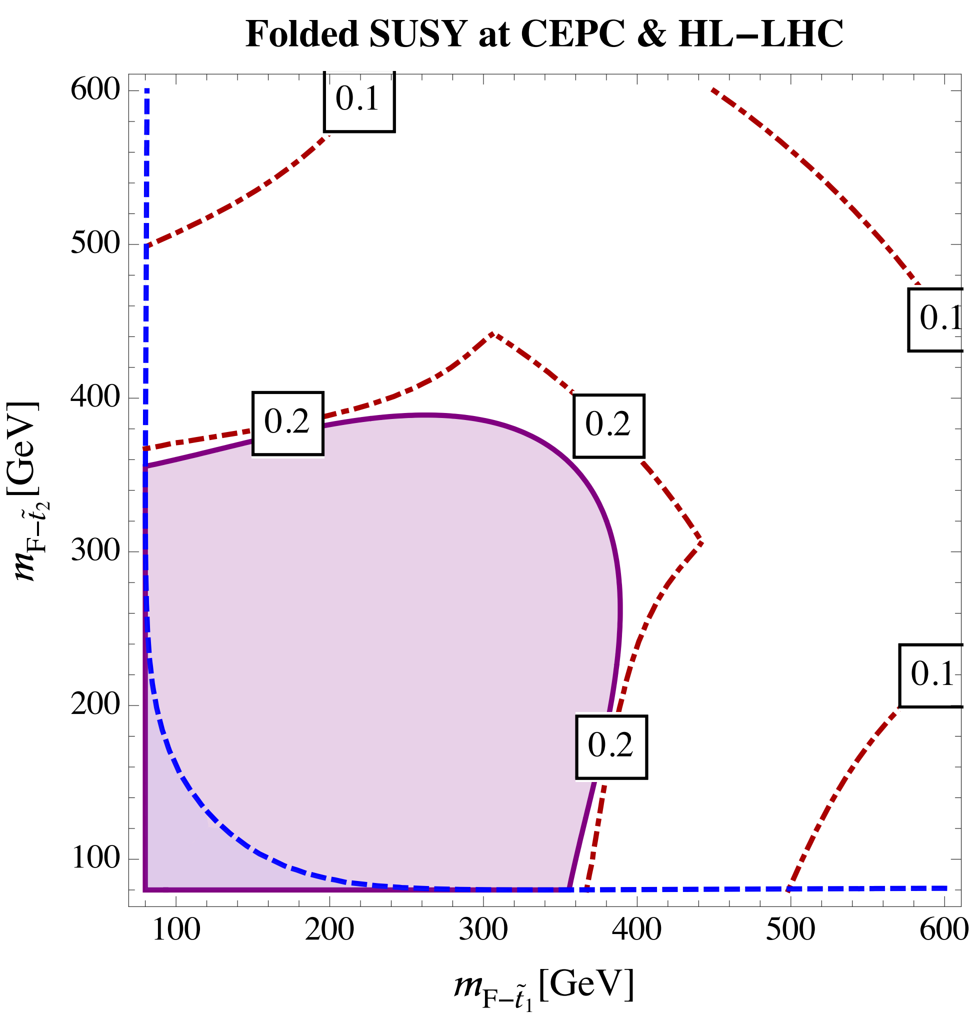
Craig, Katz, Strassler, Sundrum

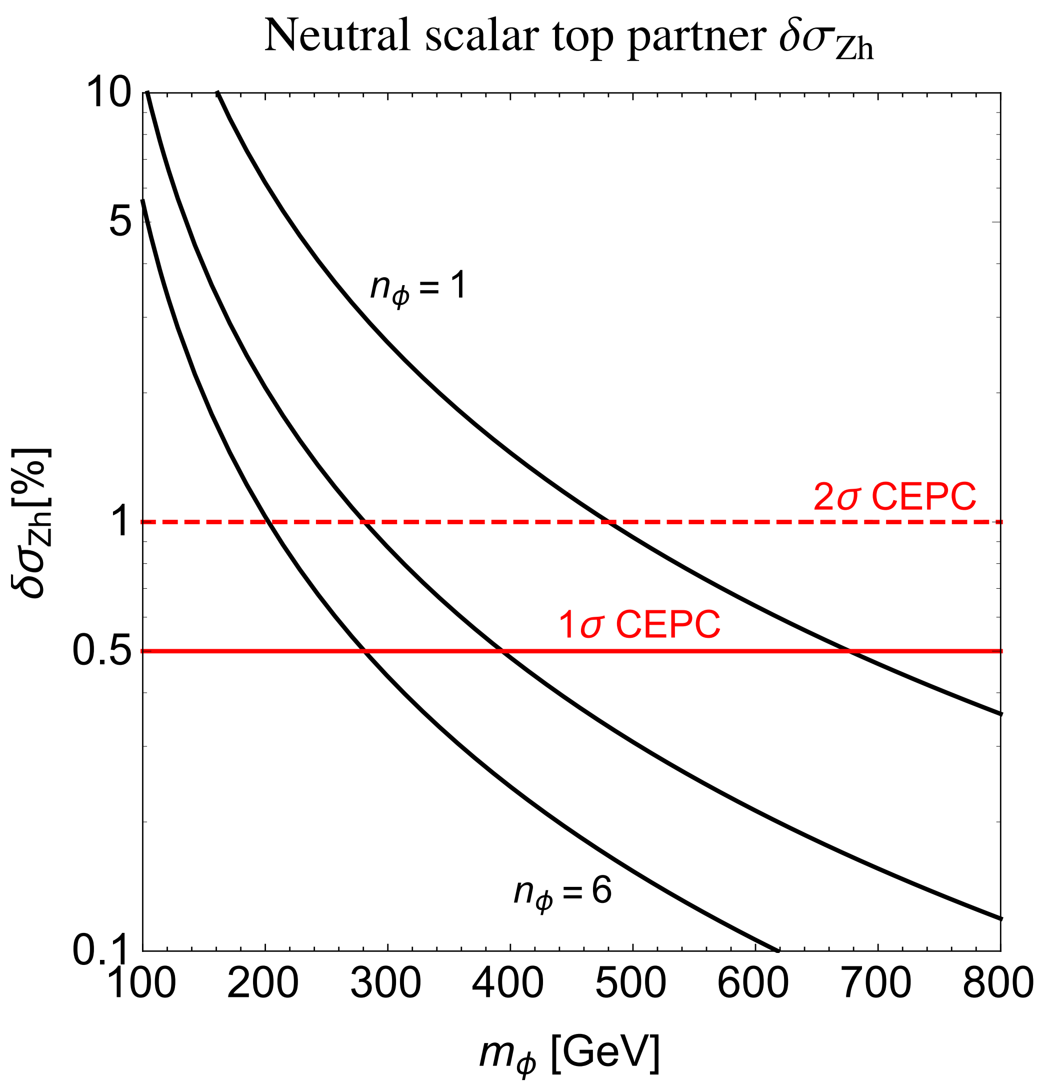


- Top partner not colored. Higgs decay through hidden world and back.

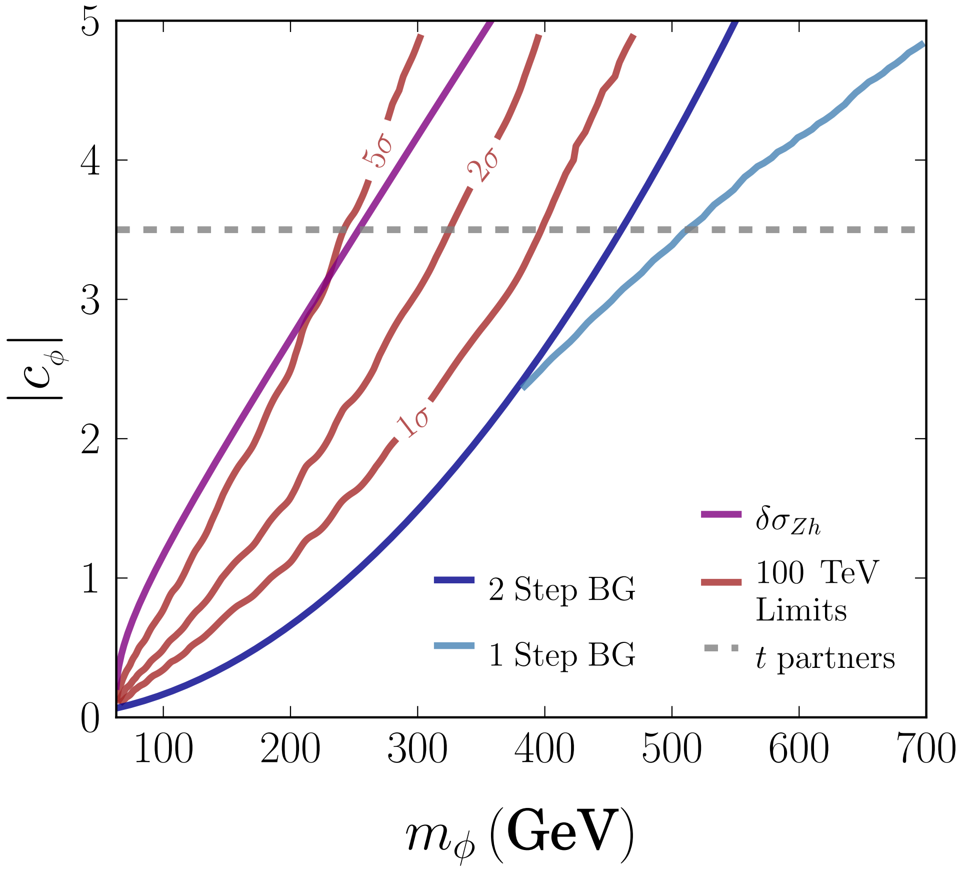
- Can lead to Higgs rare decays.

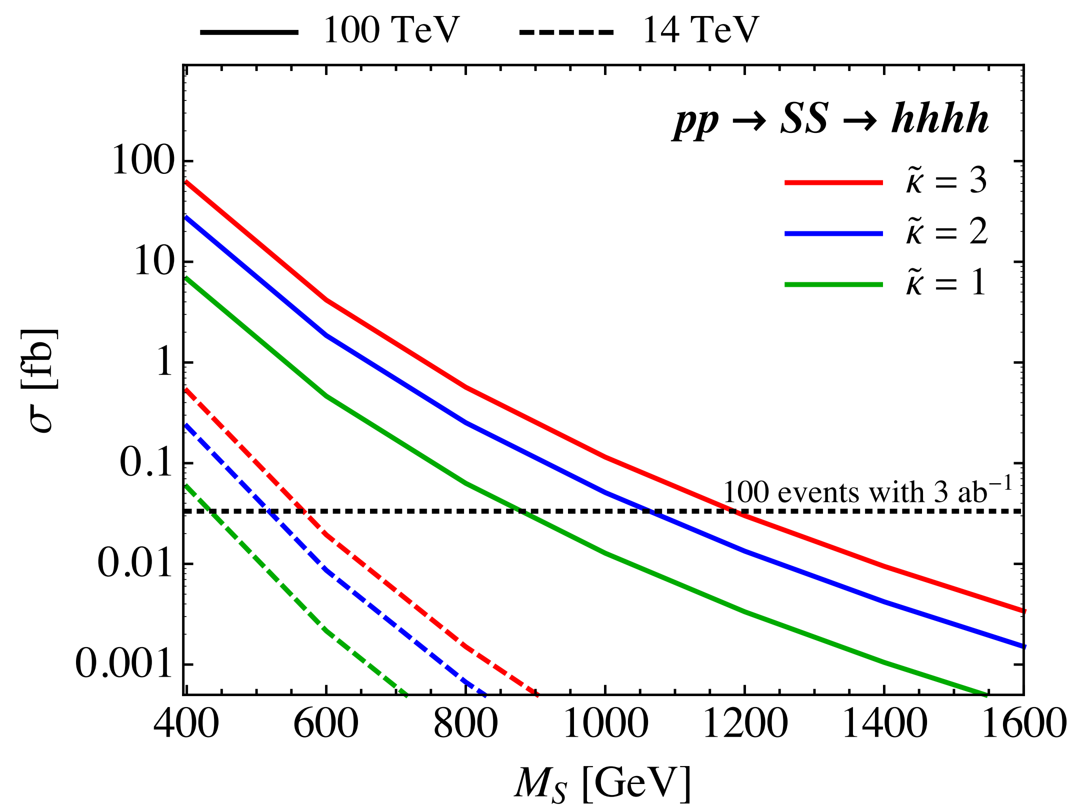
Signal of top partner:





At 100 TeV pp collider





Difficult search, especially if the top partner has a Z_2 symmetry (thus stable)

A No-lose theorem?

Towards a No-Lose Theorem for Naturalness

David Curtin[1,*] and Prashant Saraswat[1,2,†]

[1] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742*
[2] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

We derive a phenomenological no-lose theorem for naturalness up to the TeV scale, which applies when quantum corrections to the Higgs mass from top quarks are canceled by perturbative BSM particles (top partners) of similar multiplicity due to to some symmetry. Null results from LHC searches already seem to disfavor such partners if they are colored. Any partners with SM charges and $\sim$ TeV masses will be exhaustively probed by the LHC and a future 100 TeV collider. Therefore, we focus on neutral top partners. While these arise in Twin Higgs theories, we analyze neutral top partners as model-independently as possible using EFT and Simplified Model methods. We classify all perturbative neutral top partner structures in order to compute their irreducible low-energy signatures at proposed future lepton and hadron colliders, as well as the irreducible tunings suffered in each scenario. Central to our theorem is the assumption that SM-charged BSM states appear in the UV completion of neutral naturalness, which is the case in all known examples. Direct production at the 100 TeV collider then allows this scale to be probed at the $\sim$10 TeV level. We find that proposed future colliders probe any such scenario of naturalness with tuning of 10% or better.

A No-lose theorem?

Towards a No-Lose Theorem for Naturalness

David Curtin[1,*] and Prashant Saraswat[1,2,†]

[1] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742*
[2] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

We derive a phenomenological no-lose theorem for naturalness up to the TeV scale, which applies when quantum corrections to the Higgs mass from top quarks are canceled by perturbative BSM particles (top partners) of similar multiplicity due to to some symmetry. Null results from LHC searches already seem to disfavor such partners if they are colored. Any partners with SM charges and $\sim$ TeV masses will be exhaustively probed by the LHC and a future 100 TeV collider. Therefore, we focus on neutral top partners. While these arise in Twin Higgs theories, we analyze neutral top partners as model-independently as possible using EFT and Simplified Model methods. We classify all perturbative neutral top partner structures in order to compute their irreducible low-energy signatures at proposed future lepton and hadron colliders, as well as the irreducible tunings suffered in each scenario. Central to our theorem is the assumption that SM-charged BSM states appear in the UV completion of neutral naturalness, which is the case in all known examples. Direct production at the 100 TeV collider then allows this scale to be probed at the $\sim$10 TeV level. We find that proposed future colliders probe any such scenario of naturalness with tuning of 10% or better.

A No-lose theorem?

Towards a No-Lose Theorem for Naturalness

David Curtin[1,*] and Prashant Saraswat[1,2,†]

[1] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742*
[2] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

We derive a phenomenological no-lose theorem for naturalness up to the TeV scale, which applies when quantum corrections to the Higgs mass from top quarks are canceled by perturbative BSM particles (top partners) of similar multiplicity due to to some symmetry. Null results from LHC searches already seem to disfavor such partners if they are colored. Any partners with SM charges and $\sim$ TeV masses will be exhaustively probed by the LHC and a future 100 TeV collider. Therefore, we focus on neutral top partners. While these arise in Twin Higgs theories, we analyze neutral top partners as model-independently as possible using EFT and Simplified Model methods. We classify all perturbative neutral top partner structures in order to compute their irreducible low-energy signatures at proposed future lepton and hadron colliders, as well as the irreducible tunings suffered in each scenario. Central to our theorem is the assumption that SM-charged BSM states appear in the UV completion of neutral naturalness, which is the case in all known examples. Direct production at the 100 TeV collider then allows this scale to be probed at the $\sim$10 TeV level. We find that proposed future colliders probe any such scenario of naturalness with tuning of 10% or better.

Nightmare scenario:

There are certainly (contrived) ways of hide 10(s) TeV new physics in at Higgs factories, 100 TeV pp colliders.

A No-lose theorem?

Towards a No-Lose Theorem for Naturalness

David Curtin[1,*] and Prashant Saraswat[1,2,†]

[1] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742*
[2] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

We derive a phenomenological no-lose theorem for naturalness up to the TeV scale, which applies when quantum corrections to the Higgs mass from top quarks are canceled by perturbative BSM particles (top partners) of similar multiplicity due to to some symmetry. Null results from LHC searches already seem to disfavor such partners if they are colored. Any partners with SM charges and $\sim$ TeV masses will be exhaustively probed by the LHC and a future 100 TeV collider. Therefore, we focus on neutral top partners. While these arise in Twin Higgs theories, we analyze neutral top partners as model-independently as possible using EFT and Simplified Model methods. We classify all perturbative neutral top partner structures in order to compute their irreducible low-energy signatures at proposed future lepton and hadron colliders, as well as the irreducible tunings suffered in each scenario. Central to our theorem is the assumption that SM-charged BSM states appear in the UV completion of neutral naturalness, which is the case in all known examples. Direct production at the 100 TeV collider then allows this scale to be probed at the $\sim$10 TeV level. We find that proposed future colliders probe any such scenario of naturalness with tuning of 10% or better.

A No-lose theorem?

Towards a No-Lose Theorem for Naturalness

David Curtin[1,*] and Prashant Saraswat[1,2,†]

[1] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742*
[2] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

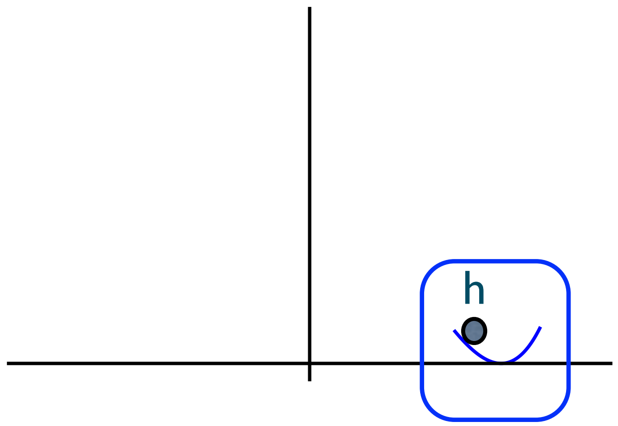
We derive a phenomenological no-lose theorem for naturalness up to the TeV scale, which applies when quantum corrections to the Higgs mass from top quarks are canceled by perturbative BSM particles (top partners) of similar multiplicity due to to some symmetry. Null results from LHC searches already seem to disfavor such partners if they are colored. Any partners with SM charges and $\sim$ TeV masses will be exhaustively probed by the LHC and a future 100 TeV collider. Therefore, we focus on neutral top partners. While these arise in Twin Higgs theories, we analyze neutral top partners as model-independently as possible using EFT and Simplified Model methods. We classify all perturbative neutral top partner structures in order to compute their irreducible low-energy signatures at proposed future lepton and hadron colliders, as well as the irreducible tunings suffered in each scenario. Central to our theorem is the assumption that SM-charged BSM states appear in the UV completion of neutral naturalness, which is the case in all known examples. Direct production at the 100 TeV collider then allows this scale to be probed at the $\sim$10 TeV level. We find that proposed future colliders probe any such scenario of naturalness with tuning of 10% or better.

Coverage probably better for
lepton collider which can probe 10s of TeV.

But can't prove a No-lose theorem

Mysteries of the electroweak scale.

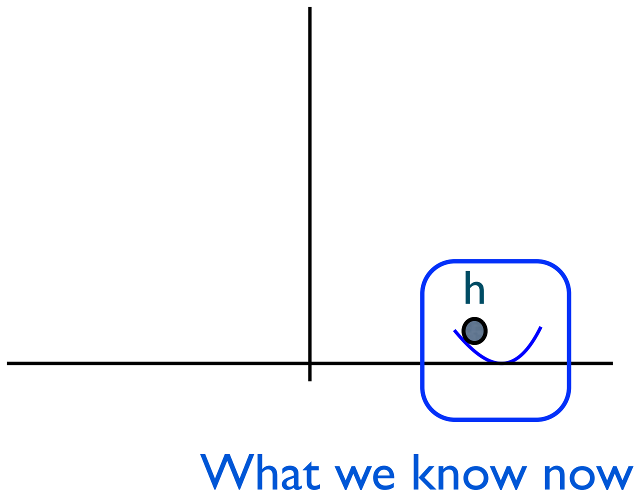
Mysteries of the electroweak scale.



What we know now

- How to predict/calculate Higgs mass?
- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.
- Is it connected to the matter anti-matter asymmetry?

Mysteries of the electroweak scale.

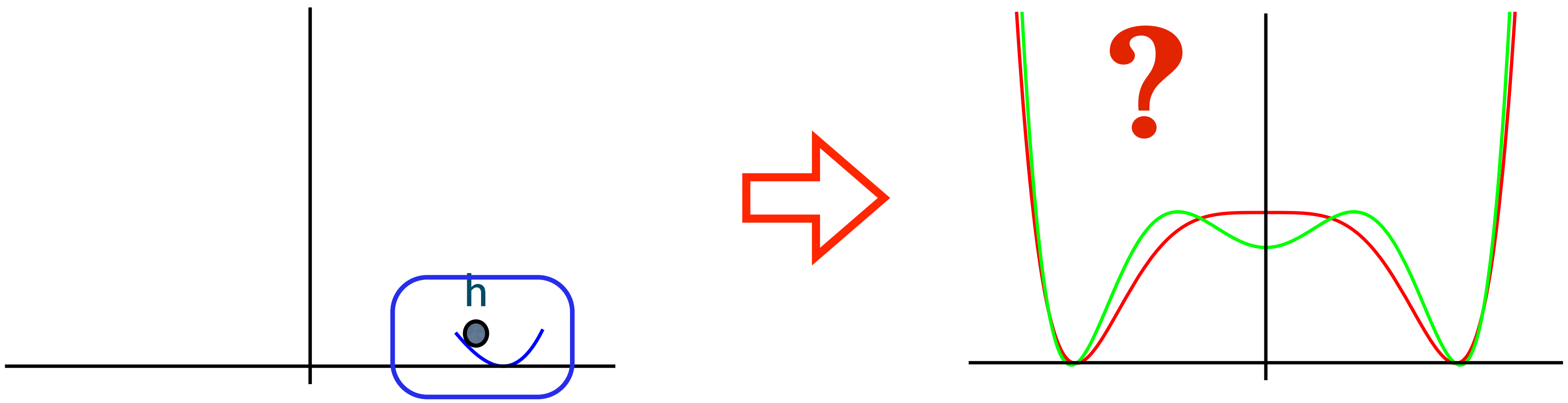


- How to predict/calculate Higgs mass?

- What does the rest of the Higgs potential look like?   Nature of electroweak phase transition.

- Is it connected to the matter anti-matter asymmetry?

Nature of EW phase transition



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

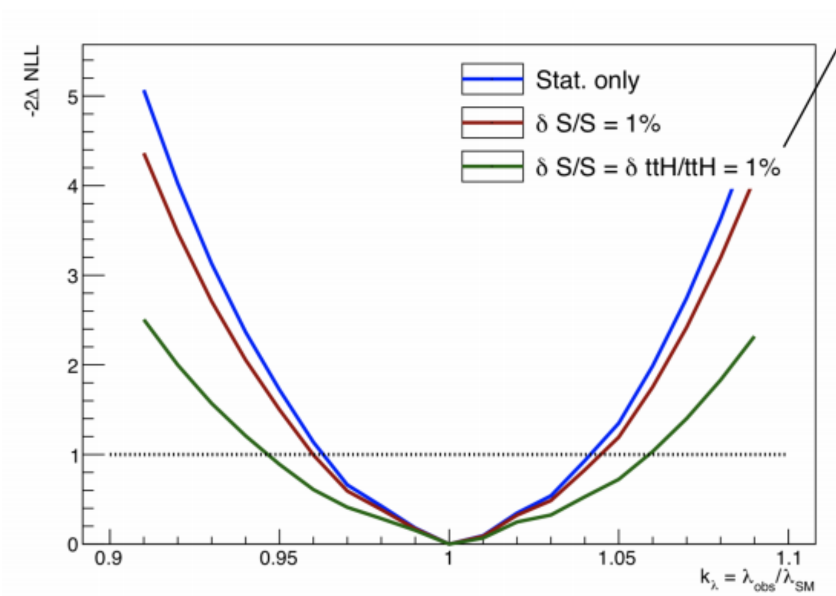
"wiggles" in Higgs potential

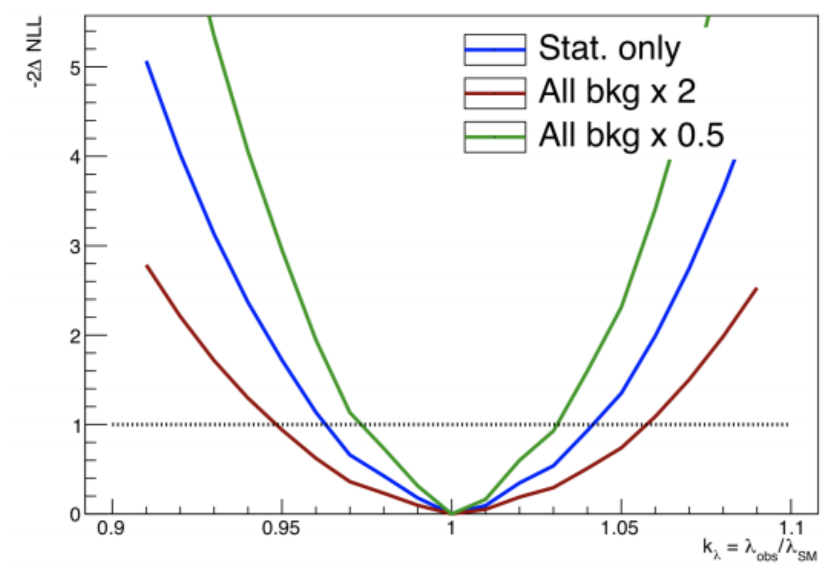
Big difference in triple Higgs coupling

Triple Higgs coupling at 100 TeV collider

Precision on the self-coupling

assuming QCD can be measured from sidebands





nominal background yields:

$\delta\kappa_\lambda$(stat) ≈ 3.5 %
$\delta\kappa_\lambda$(stat + syst) ≈ 6 %

varying (0.5x-2x) background yields:

$\delta\kappa_\lambda$(stat) ≈ 3 - 5 %

Talk by Michele Selvaggi at 2nd FCC physics workshop

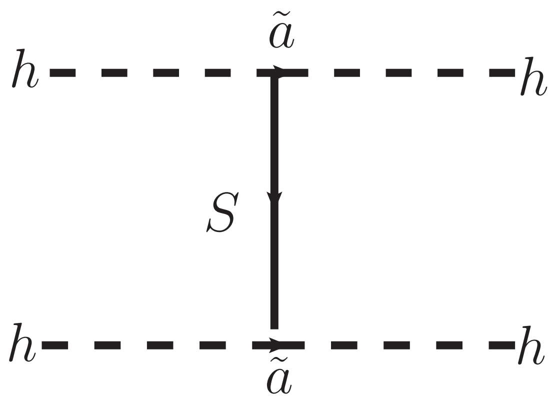
But, there should be more

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \ldots$$

- 1st order EW phase transition means there is new physics close to the weak scale.
- Can be difficult to discover at the LHC.
- Will leave more signature in Higgs coupling.

For example

$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



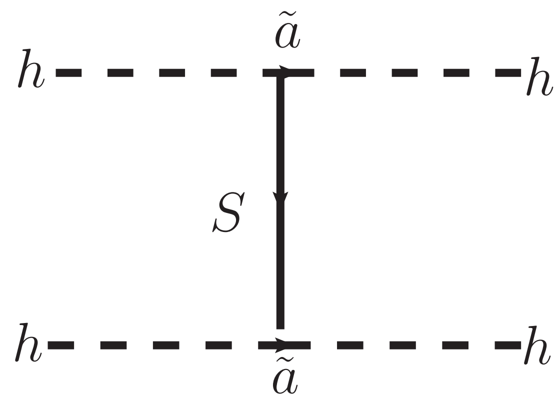
$$\frac{c}{m_S^2}\left(h^\dagger \partial h\right)^2$$

shift in h-Z coupling

$$\delta_{Zh} \sim c\frac{v^2}{m_S^2}$$

For example

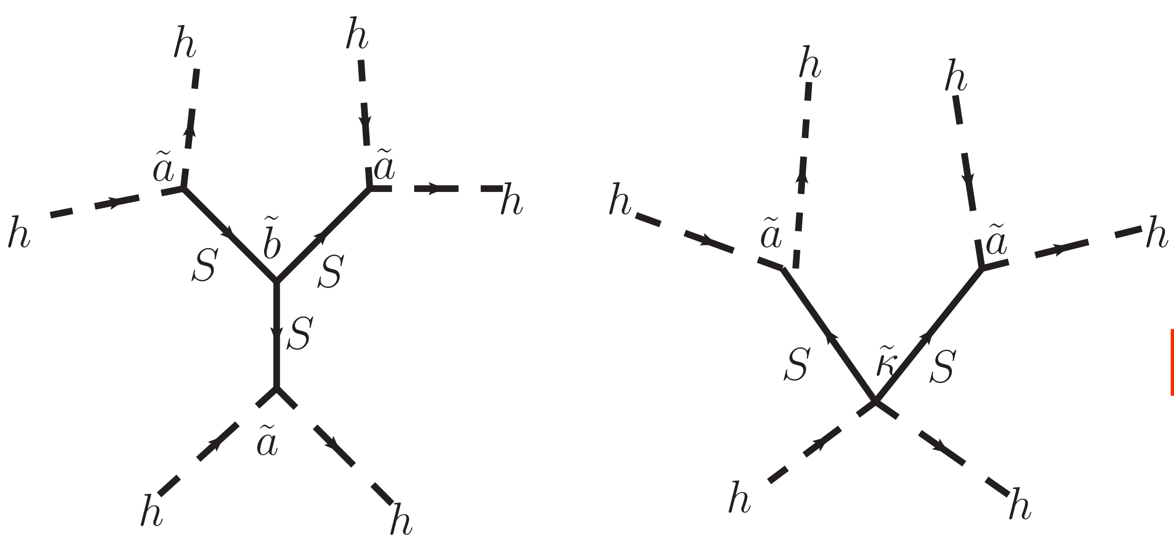
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$

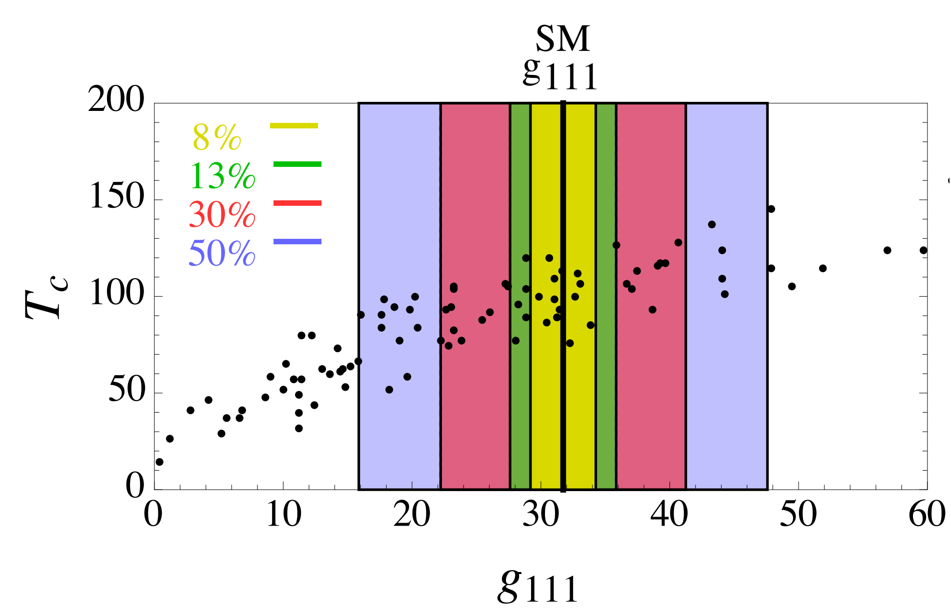


$$\frac{c}{m_S^2}\left(h^\dagger \partial h\right)^2$$

shift in h-Z coupling

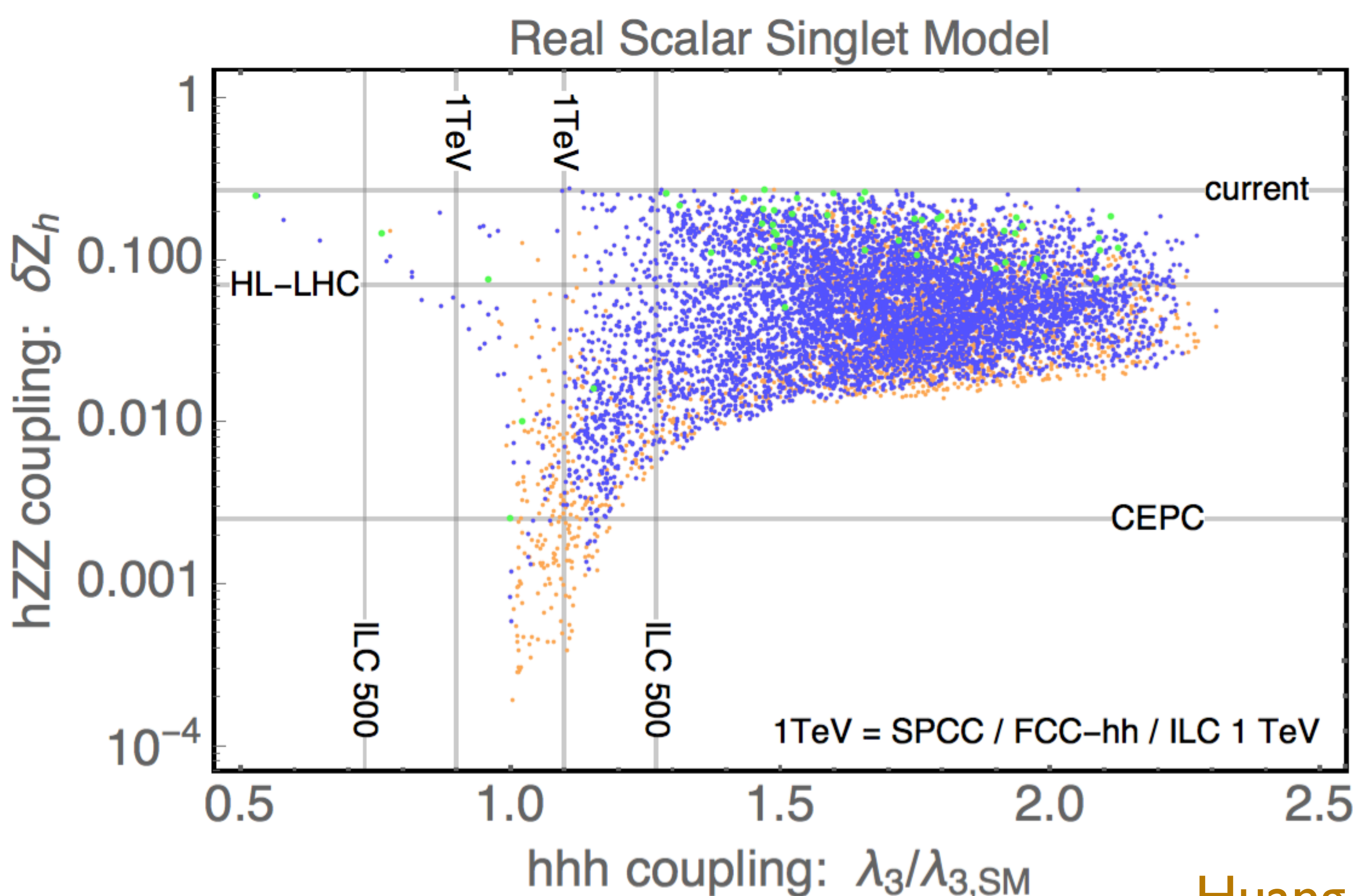
$$\delta_{Zh} \sim c\frac{v^2}{m_S^2}$$





triple Higgs coupling

Probing EWSB at higgs factories



Huang, Long, LTW, 1608.06619

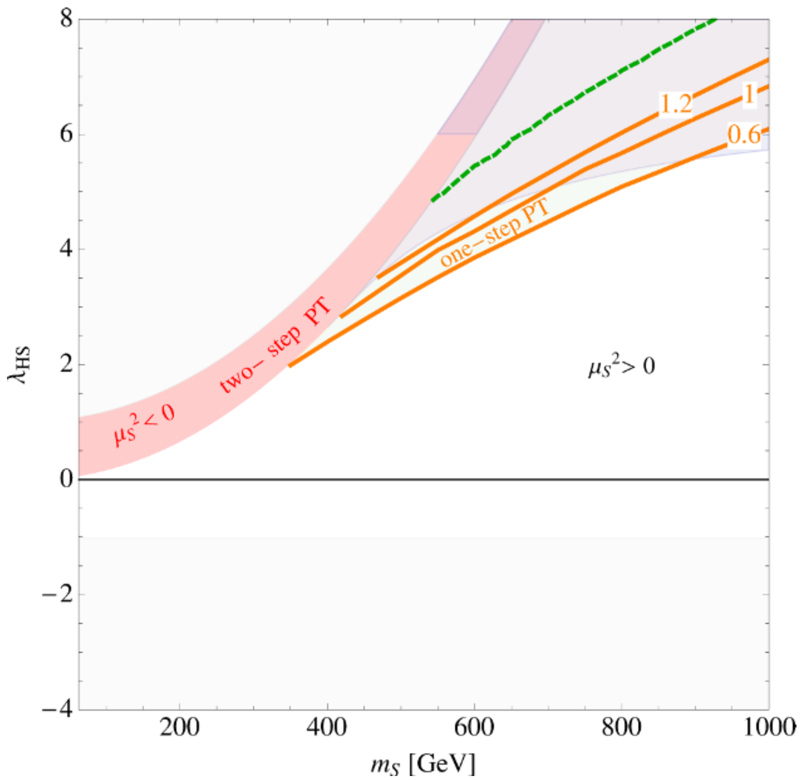
Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = “strongly” first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

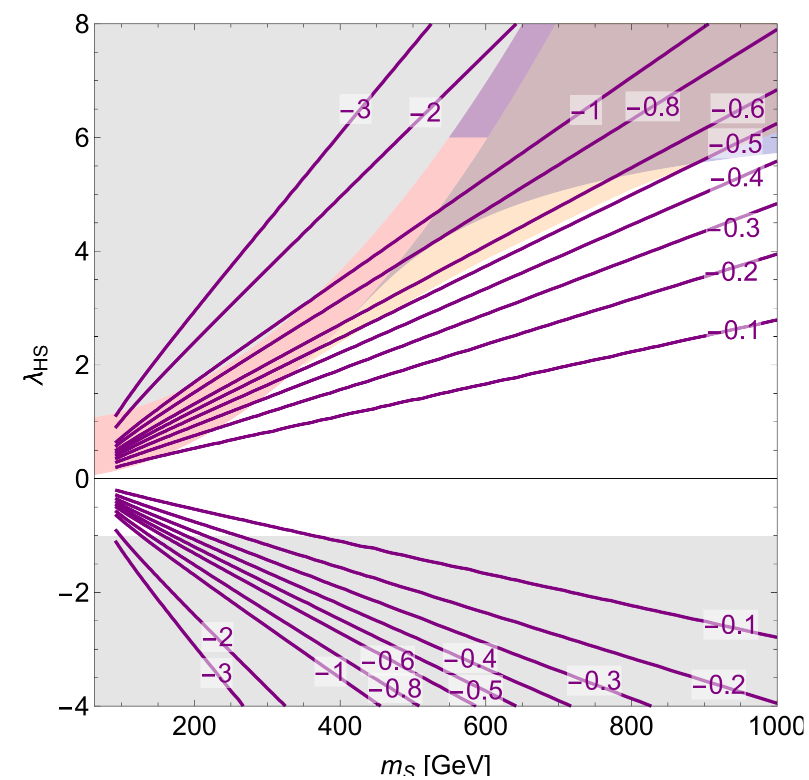
Good coverage in model space

Nightmare scenario:

Meade et al

Singlet model with a Z2 $S \to -S$

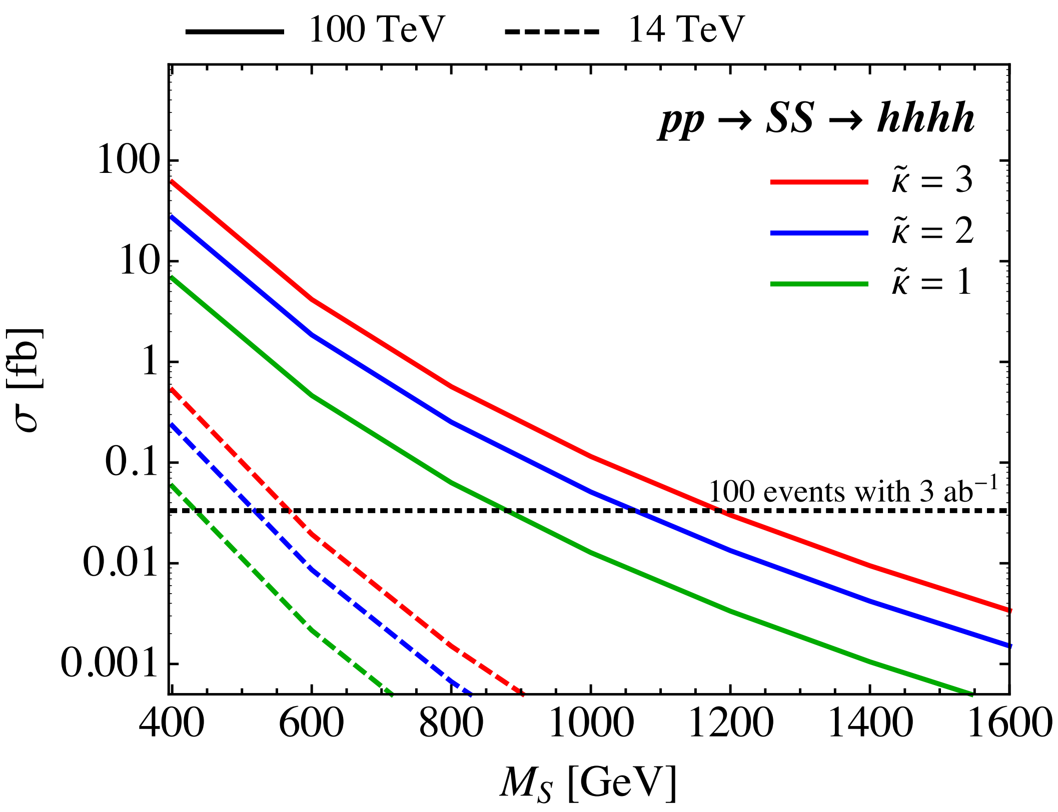


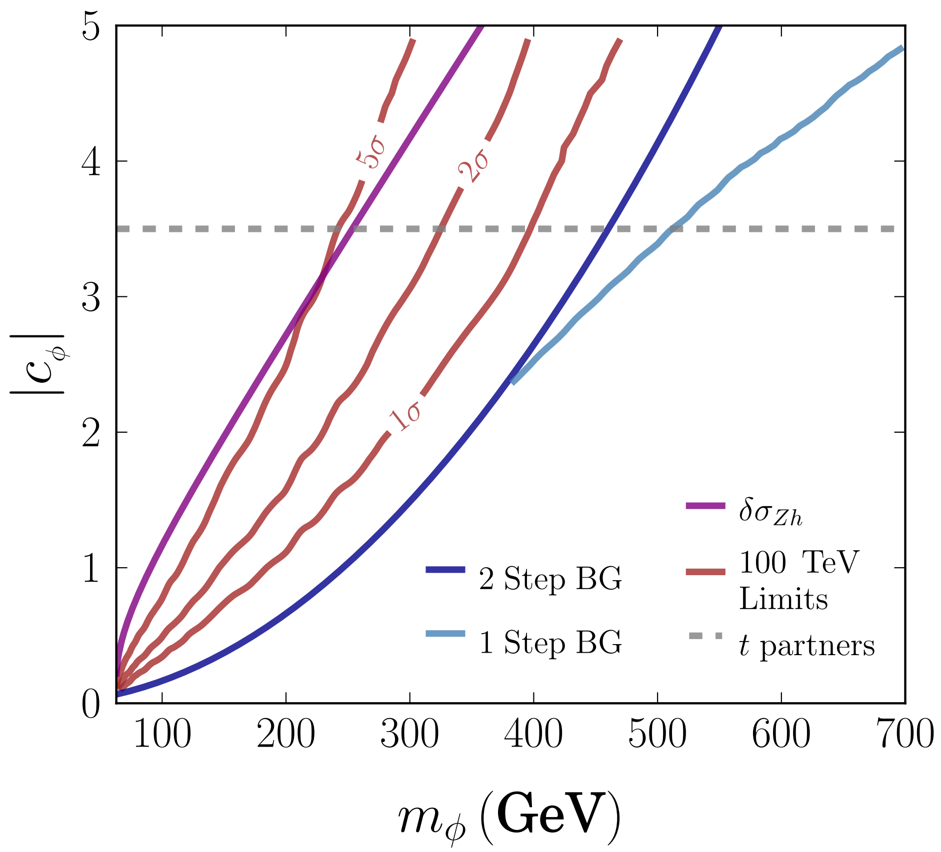


h^6 term generated at 1-loop order

Only marginally visible.

Nightmare scenario

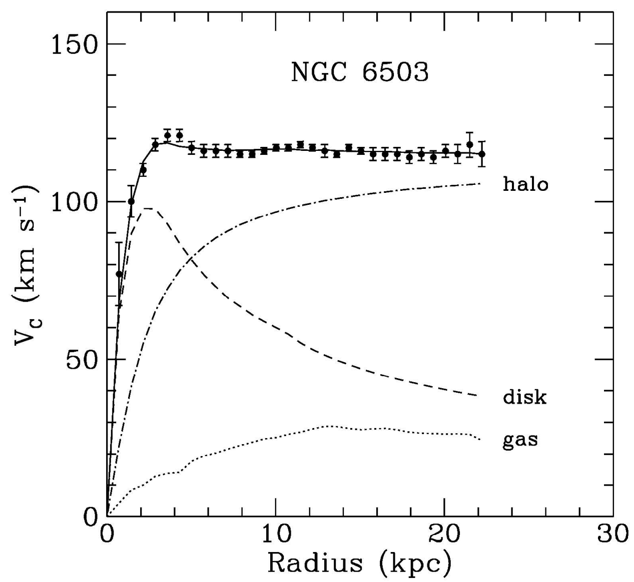


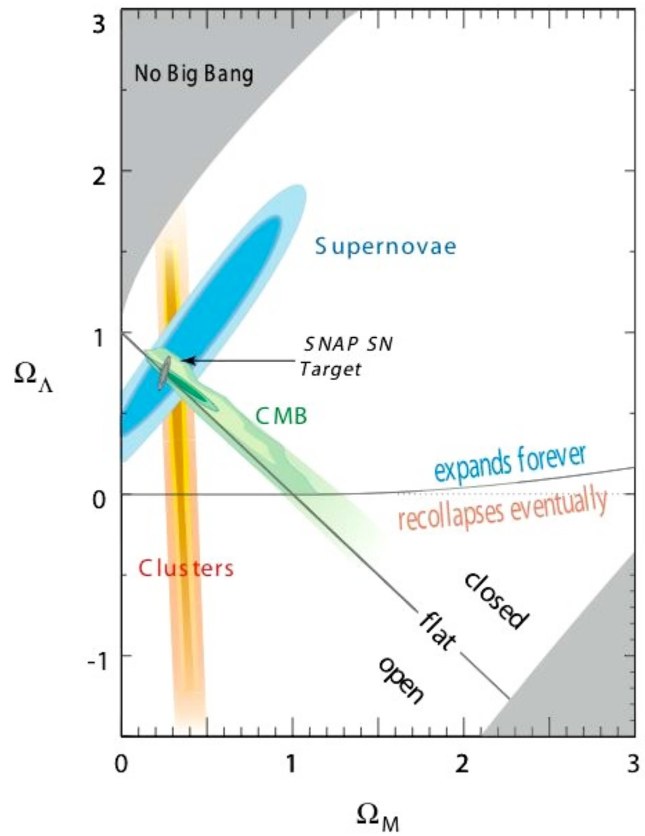


Can be probed at 100 TeV pp collider if Z_2 is broken (even if only slightly) .

More difficult if Z_2 is exact.

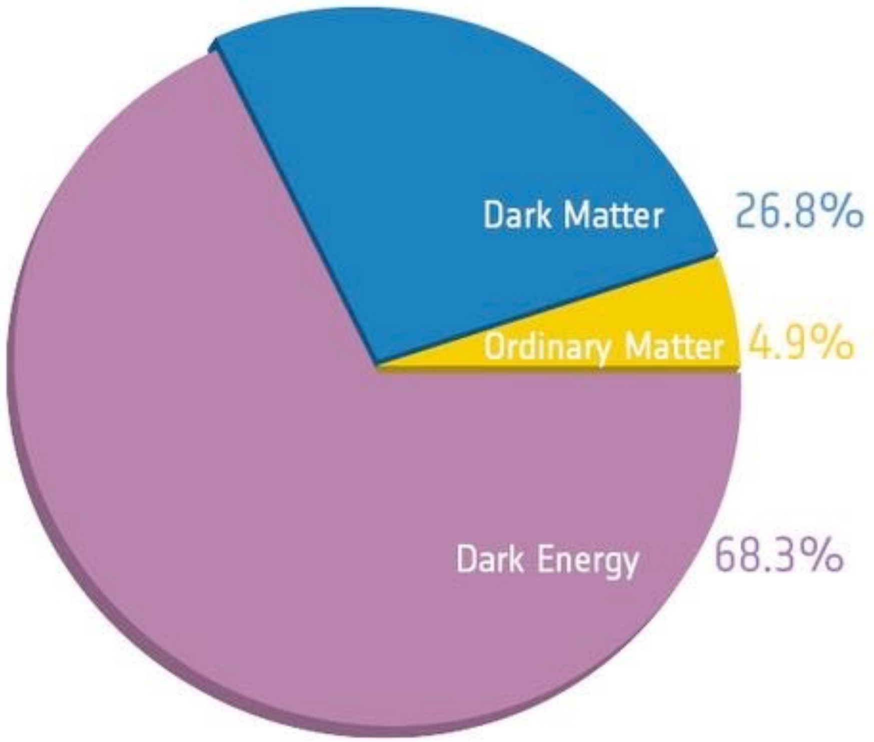
Dark matter



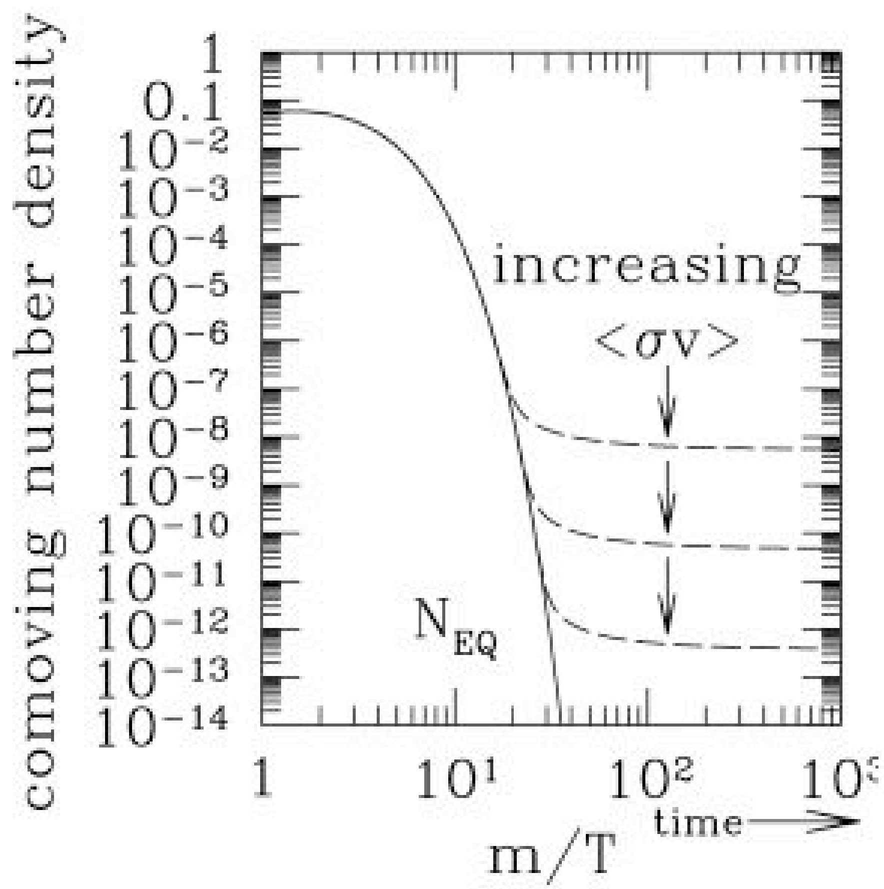


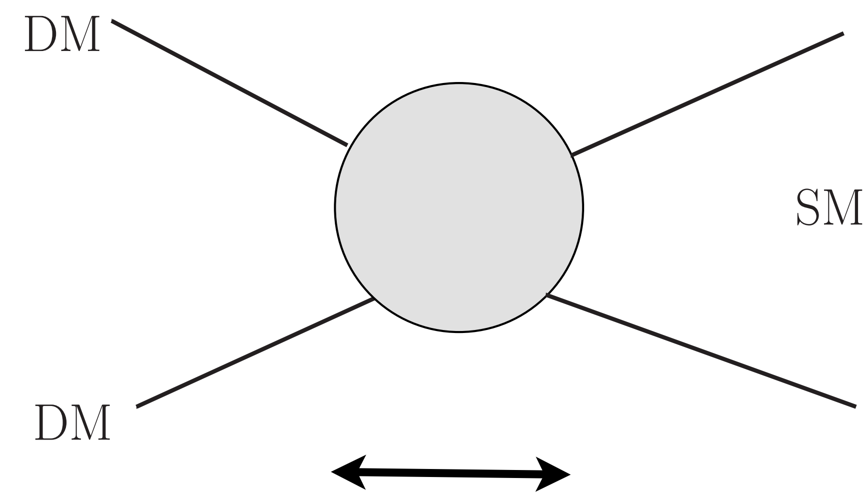
It is there.
Only seen its gravitational interaction.

We have to understand them better.
Collider search is a key approach.



WIMP miracle

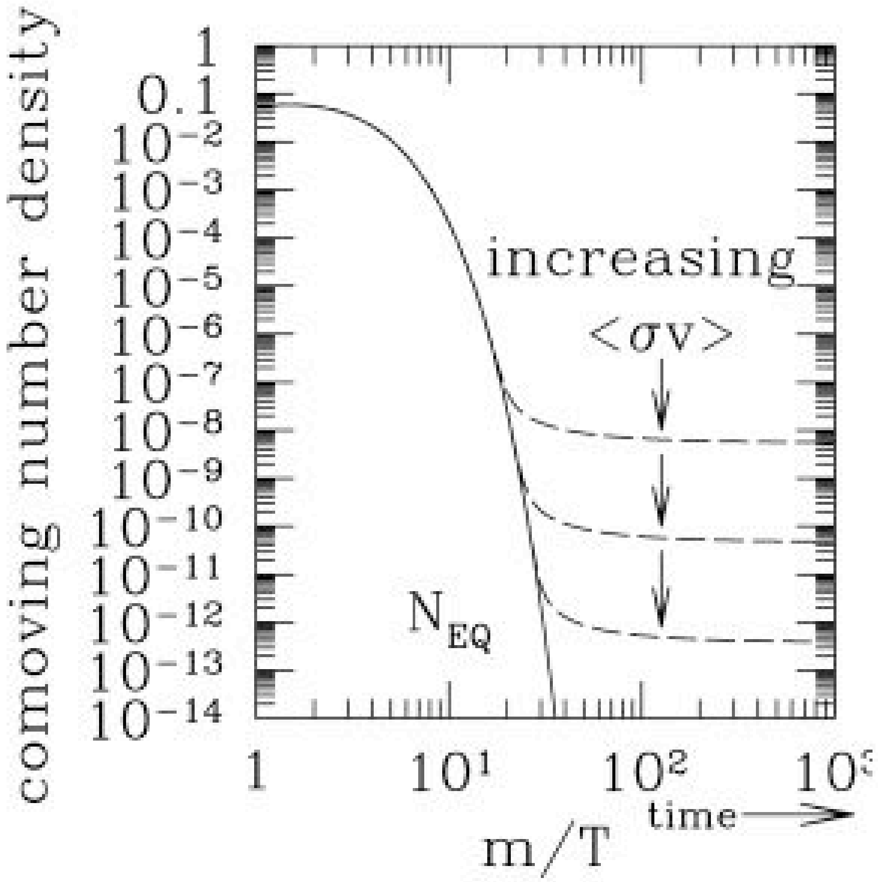


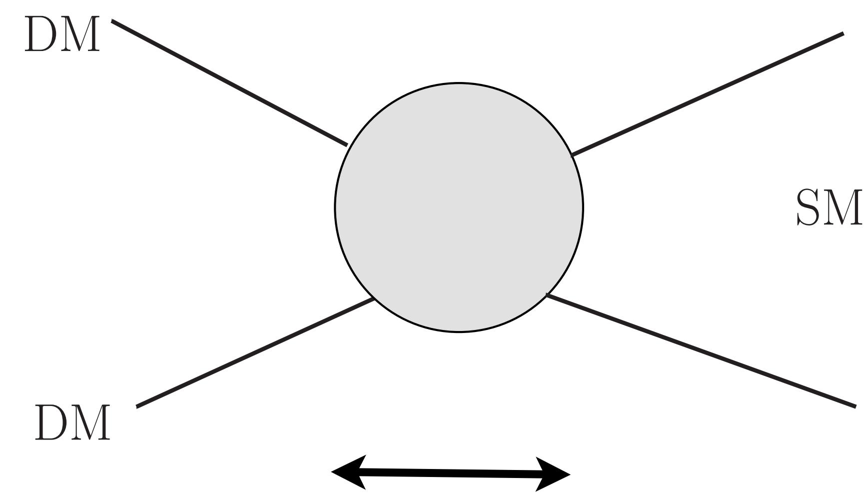


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- Thermal equilibrium in the early universe.
- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- Major hint for weak scale new physics!

WIMP mass



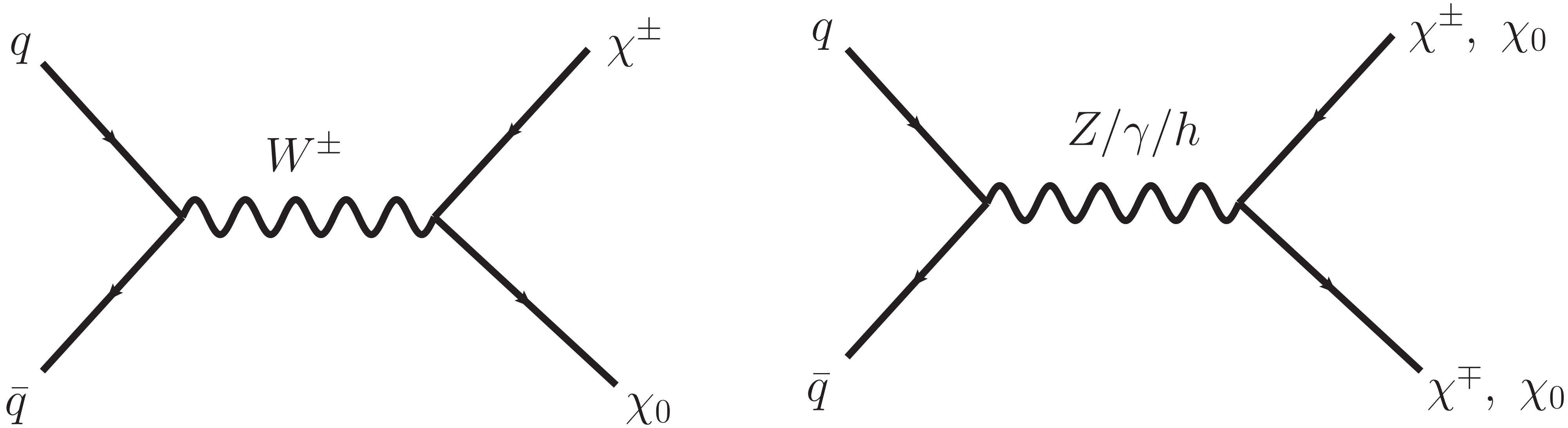


$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

– More precisely, to get the correct relic abundance

$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3} \right)$$

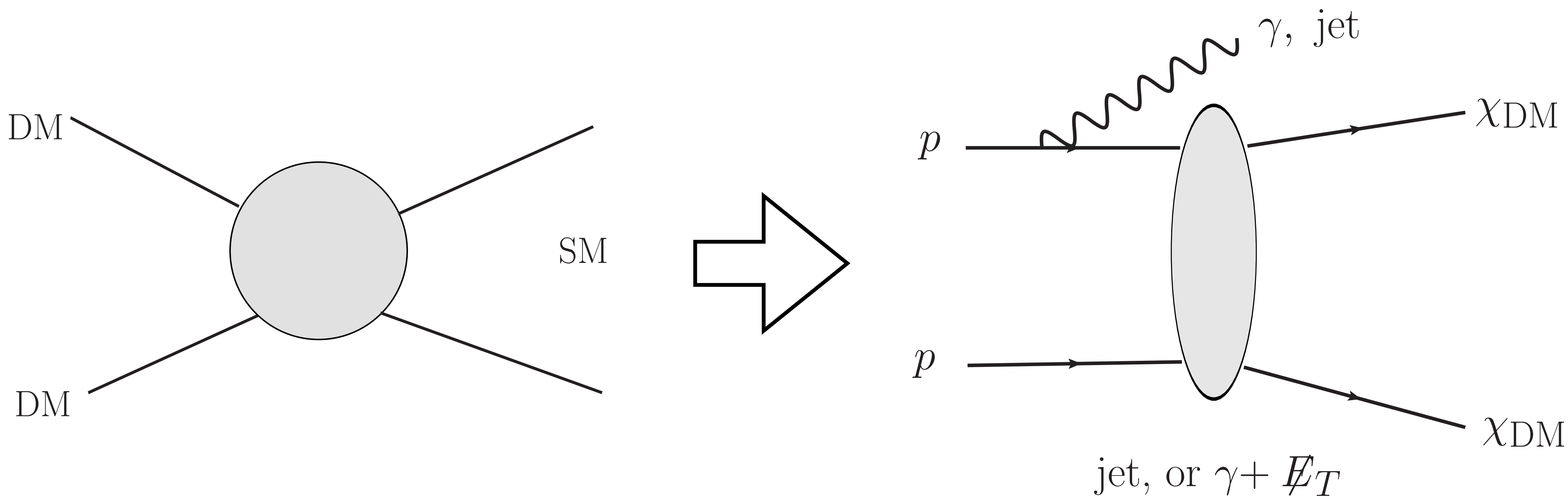
Simplest WIMP: part of weak multiplet



- Mediated by W/Z/h.
- Predictive, no unkown particle as mediator.
- The original WIMP proposal.

Basic channel

- pair production + additional radiation.

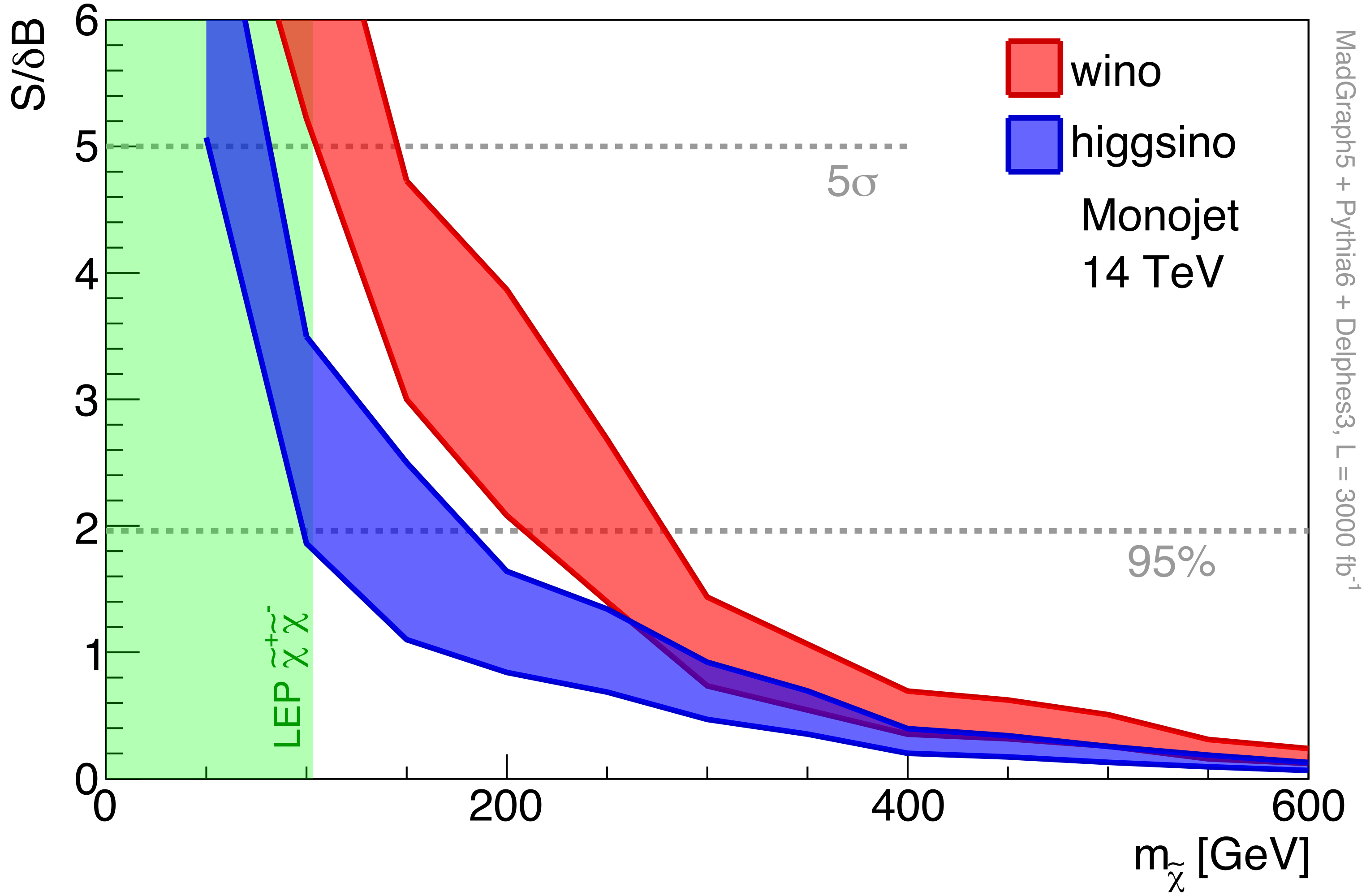


- Mono-jet, mono-photon, mono-...

- Have become "Standard" LHC searches.

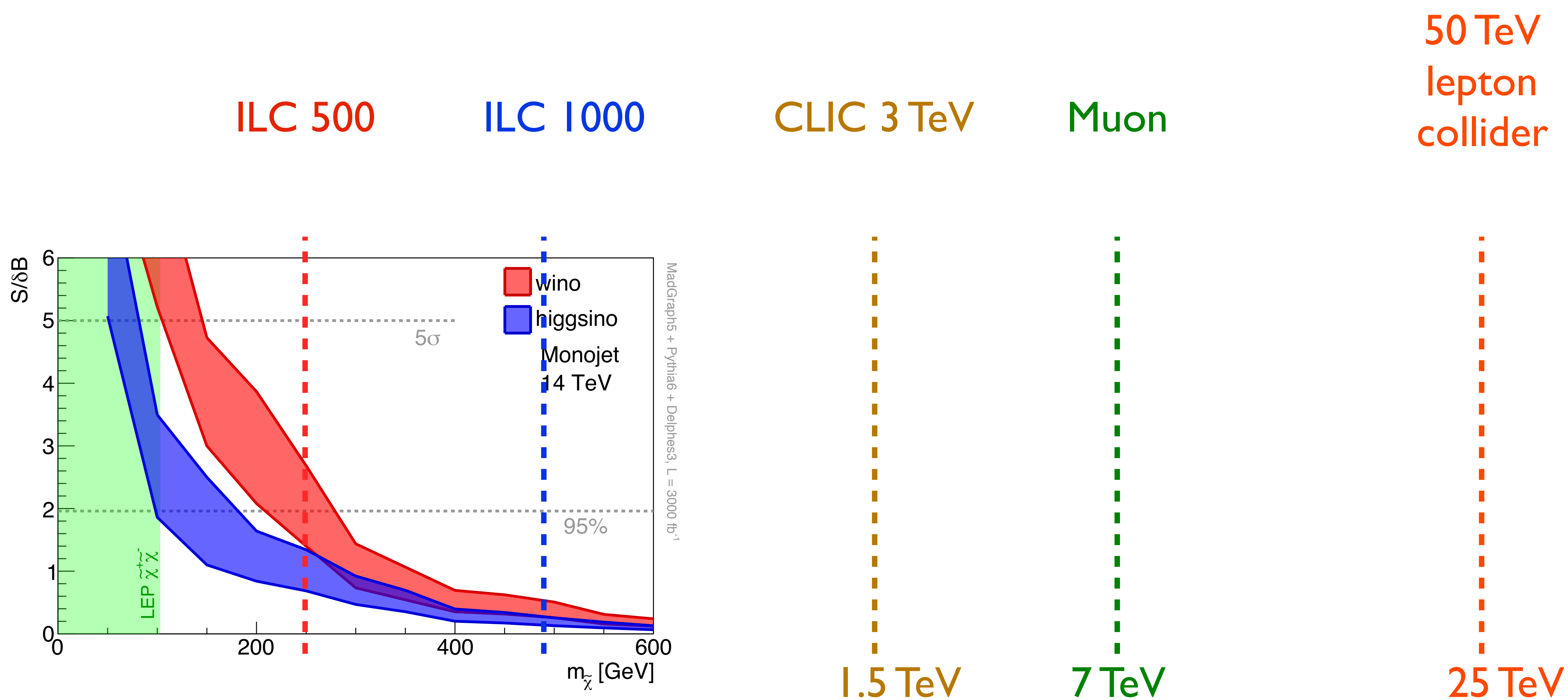
- Very challenging, systematics dominated

Mono-X



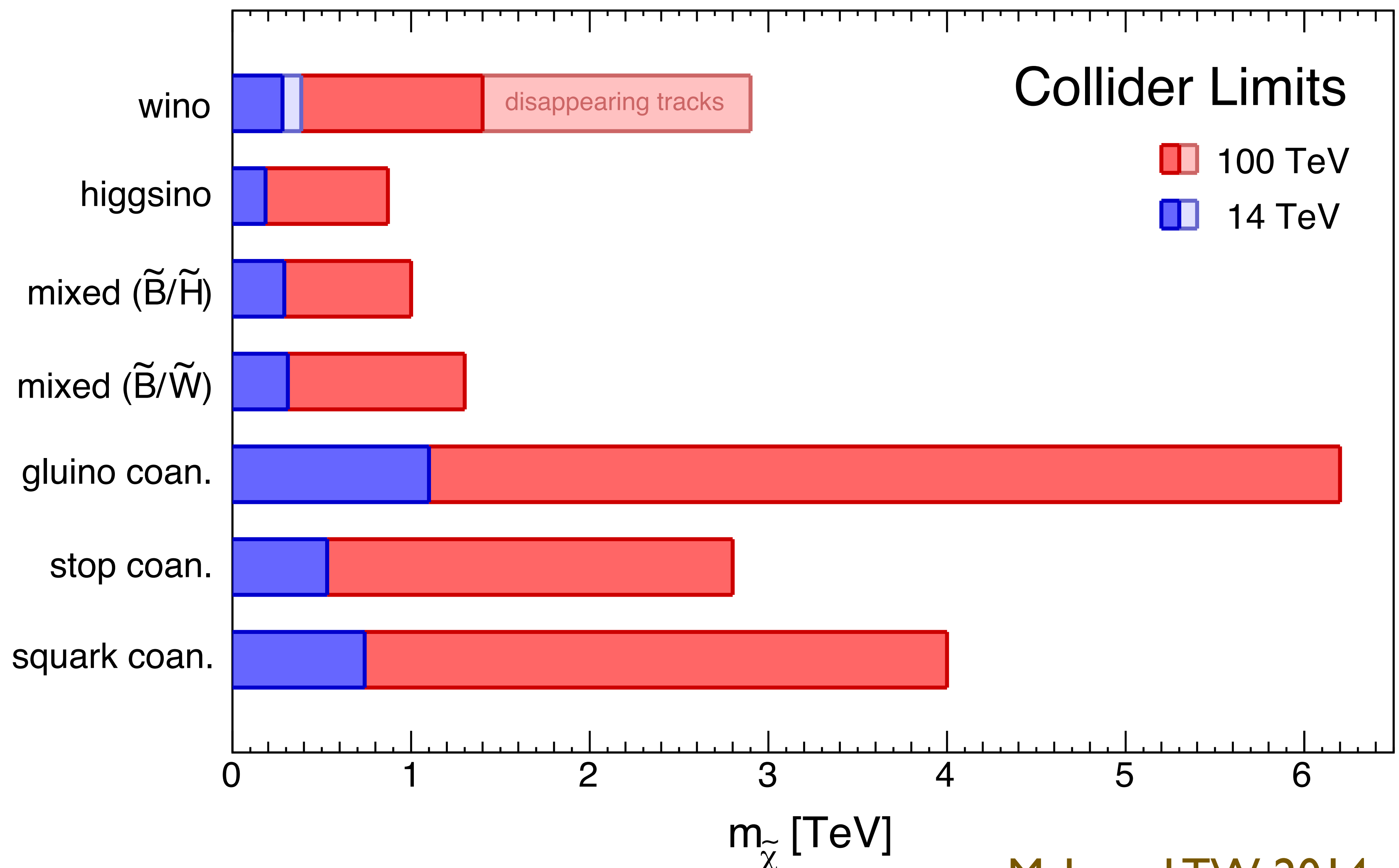
- Very challenging. Systematics dominated
  - No limit from the 8 TeV run.
  - Very weak discovery reach at 14 TeV, 3 ab^{-1} .

Mono-X



- Reach at lepton collider, about 1/2 E_{CM}.

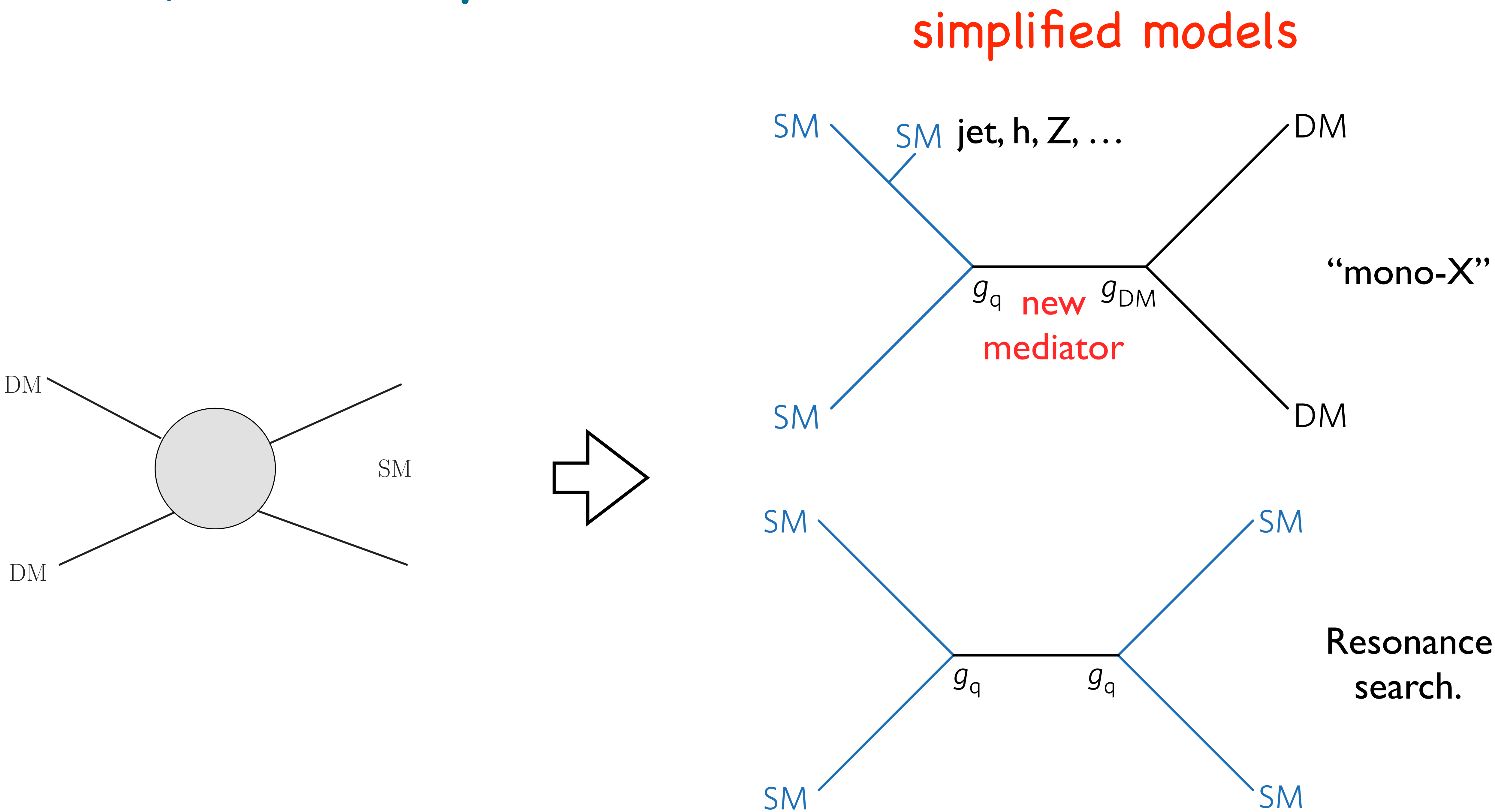
Dark matter with Mono-jet



M. Low, LTW 2014

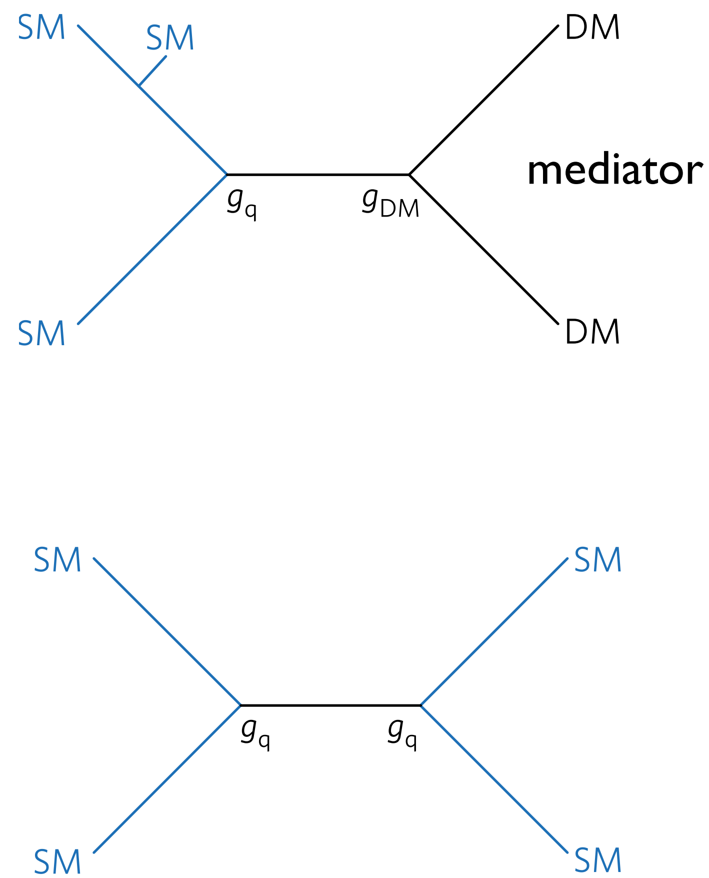
$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

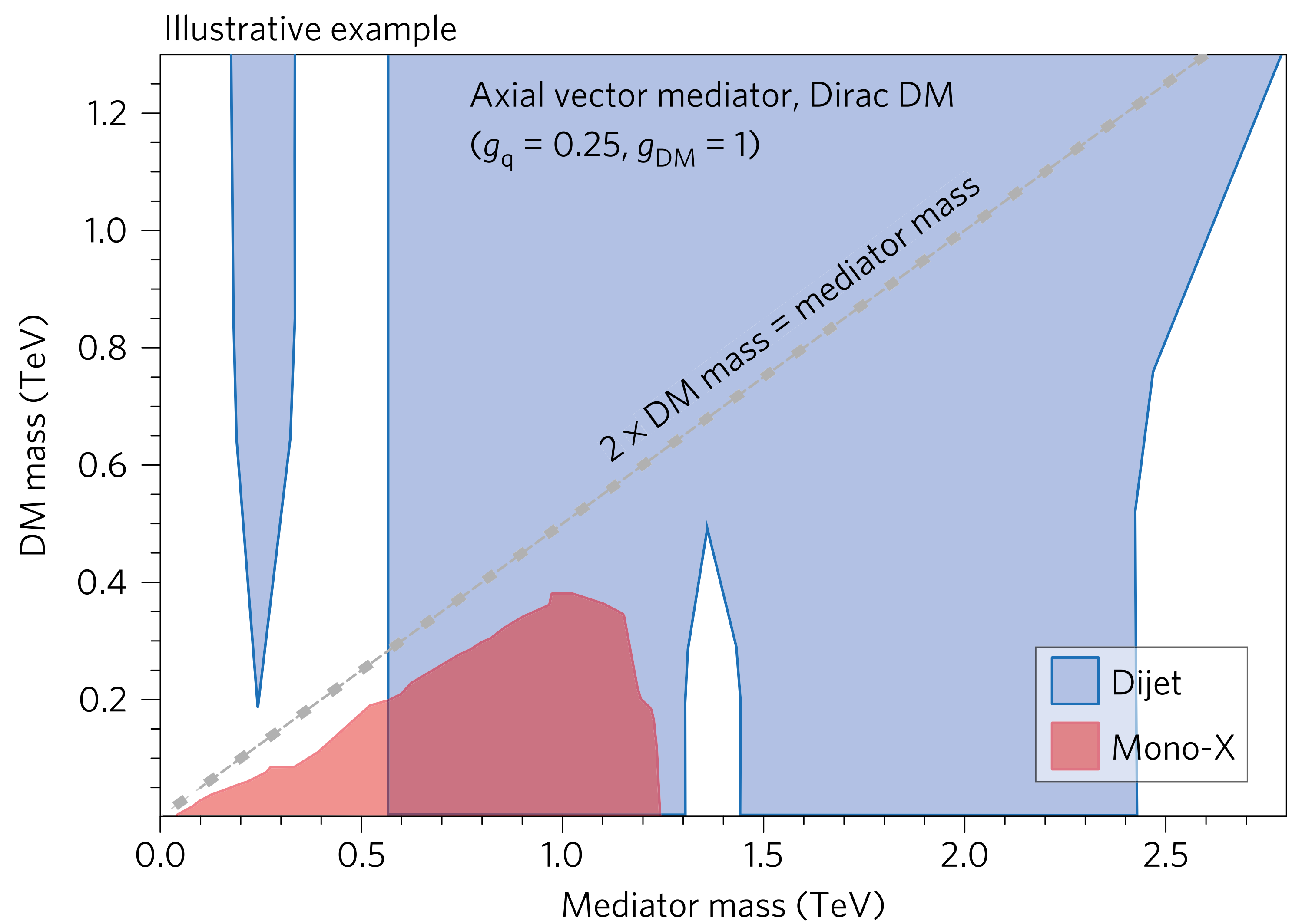
Beyond simplest WIMP



- Both became standard LHC searches.

Simplified models





- Mediator search is generically more sensitive
- Same holds for 100 TeV pp colliders.

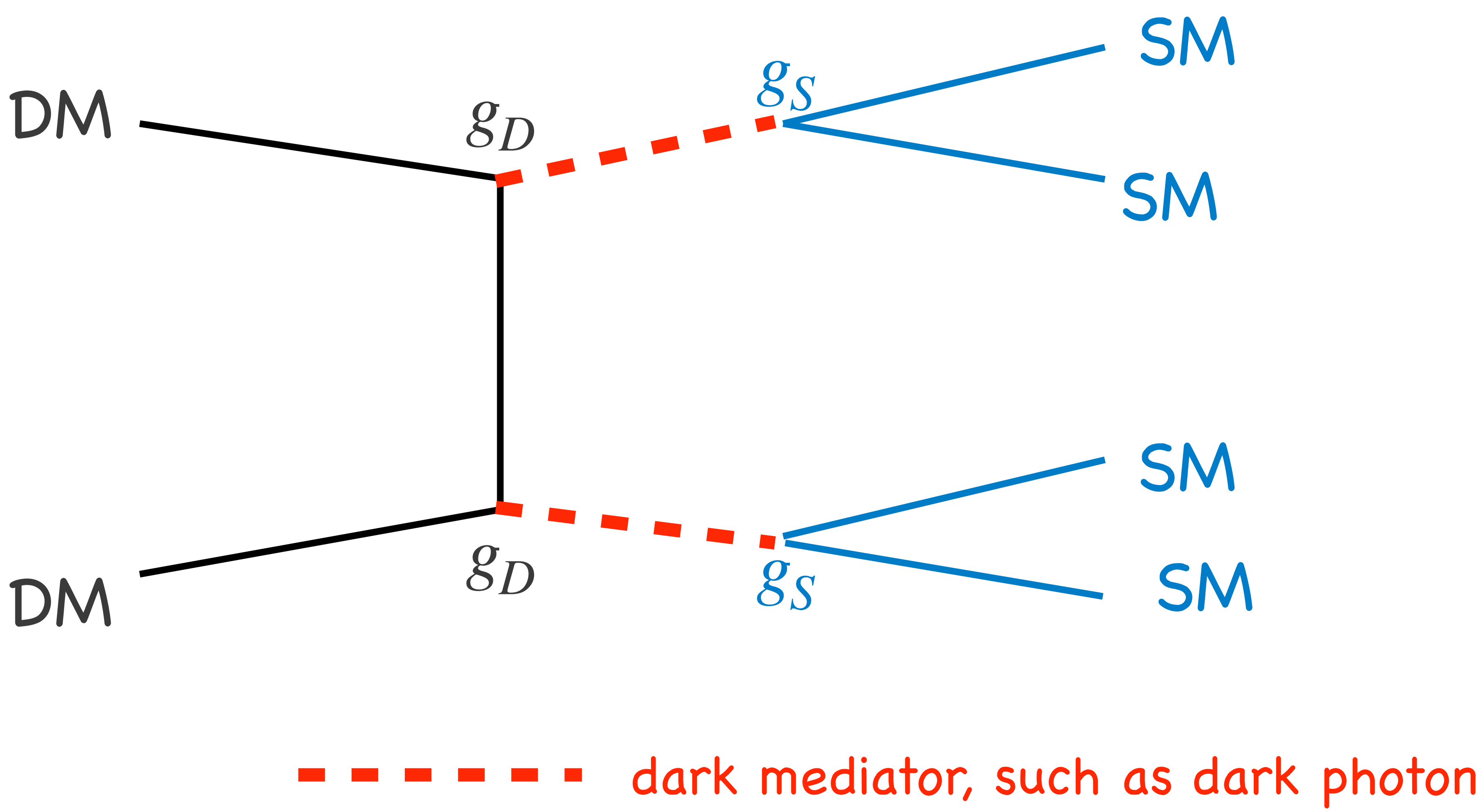
Nightmare scenario

$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

Strongly coupled: g $\sim 4\pi$

$M_{\mathrm{DM}} \sim 100s$ GeV

Nightmare scenario



g_S can be very small, still maintain thermal eq. among SM and dark sector

Very hard to produce DM at detectors.

Conclusions

- There is not a “rigorous” no lose theorem. We should not pretend there is one.
- At the same time, future colliders have great physics potential.
    - Nightmare scenarios should not prevent us from building them.

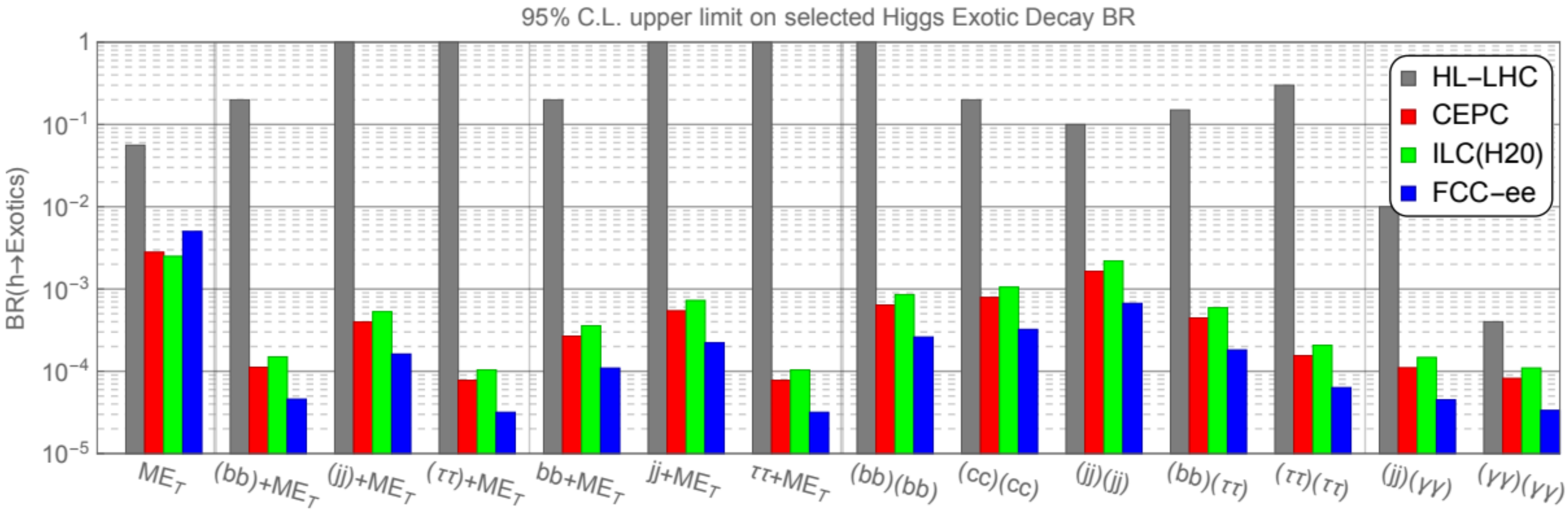
extra

Why is Higgs measurement crucial?

- Naturalness is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We may not have the right idea. No confirmation of any of the proposed models.
- Need experiment!
- Fortunately, with Higgs, we know where to look.
- And, the clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

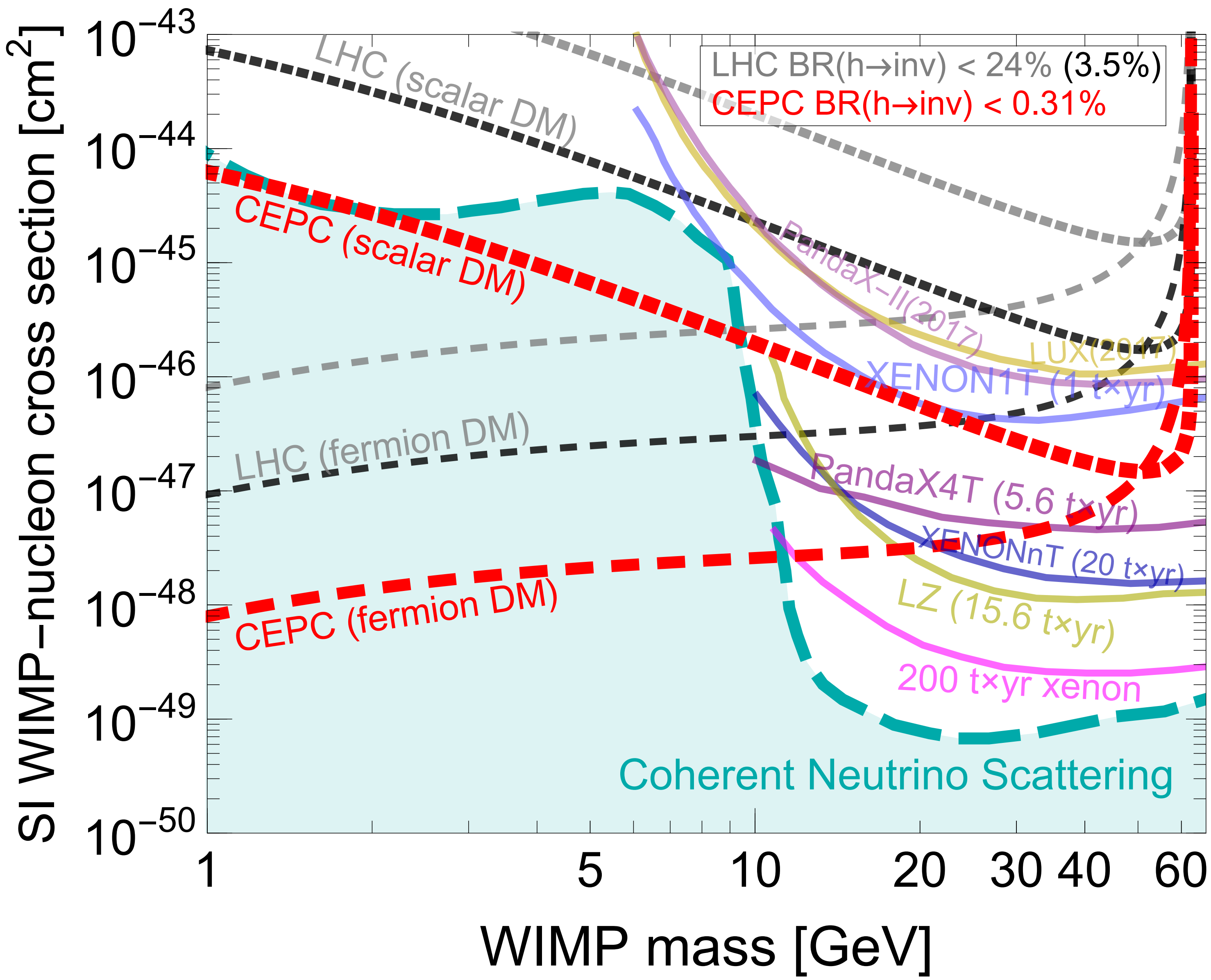
More exotic searches

Higgs exotic decay

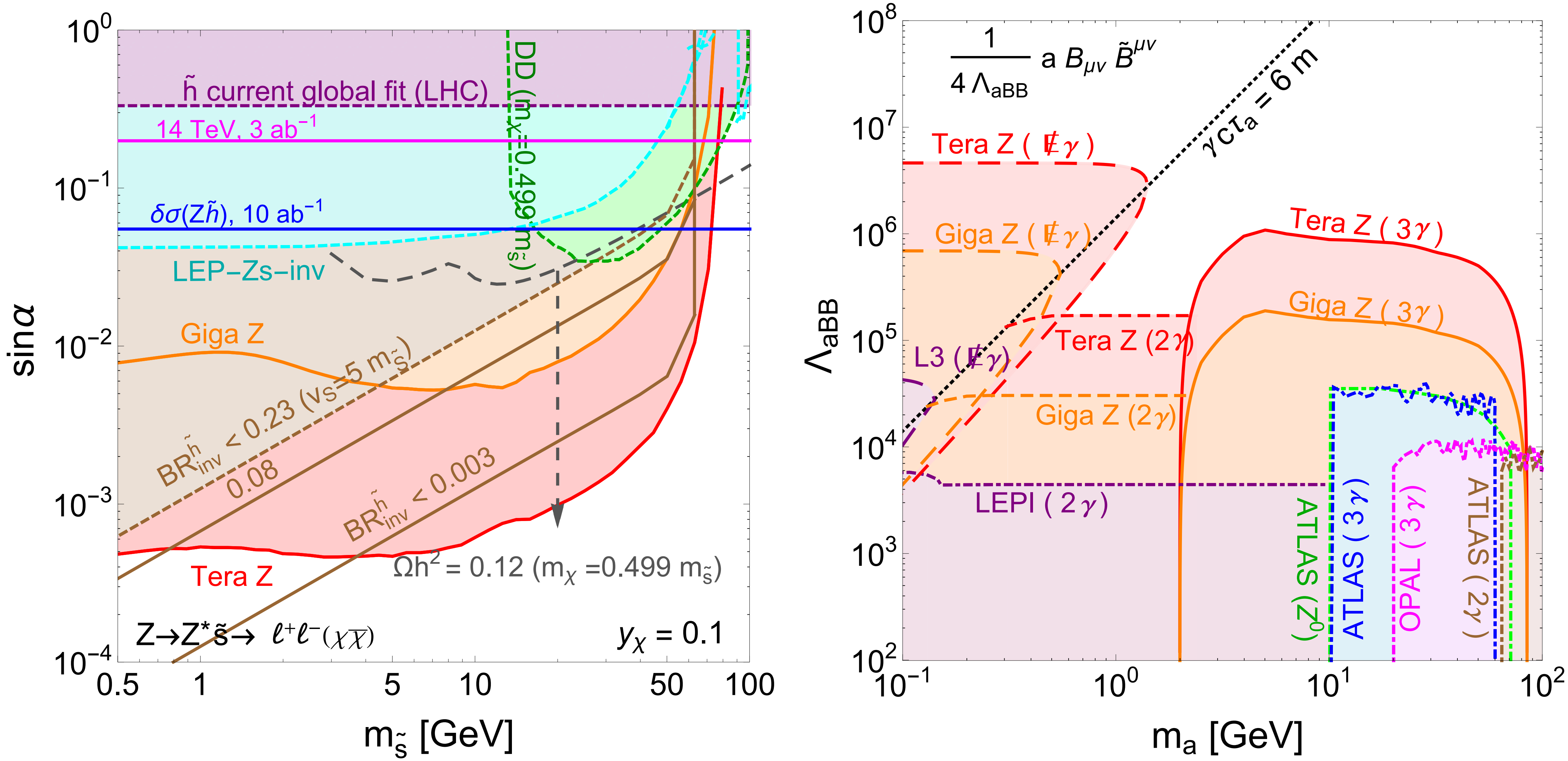


Complementary to hadron collider searches

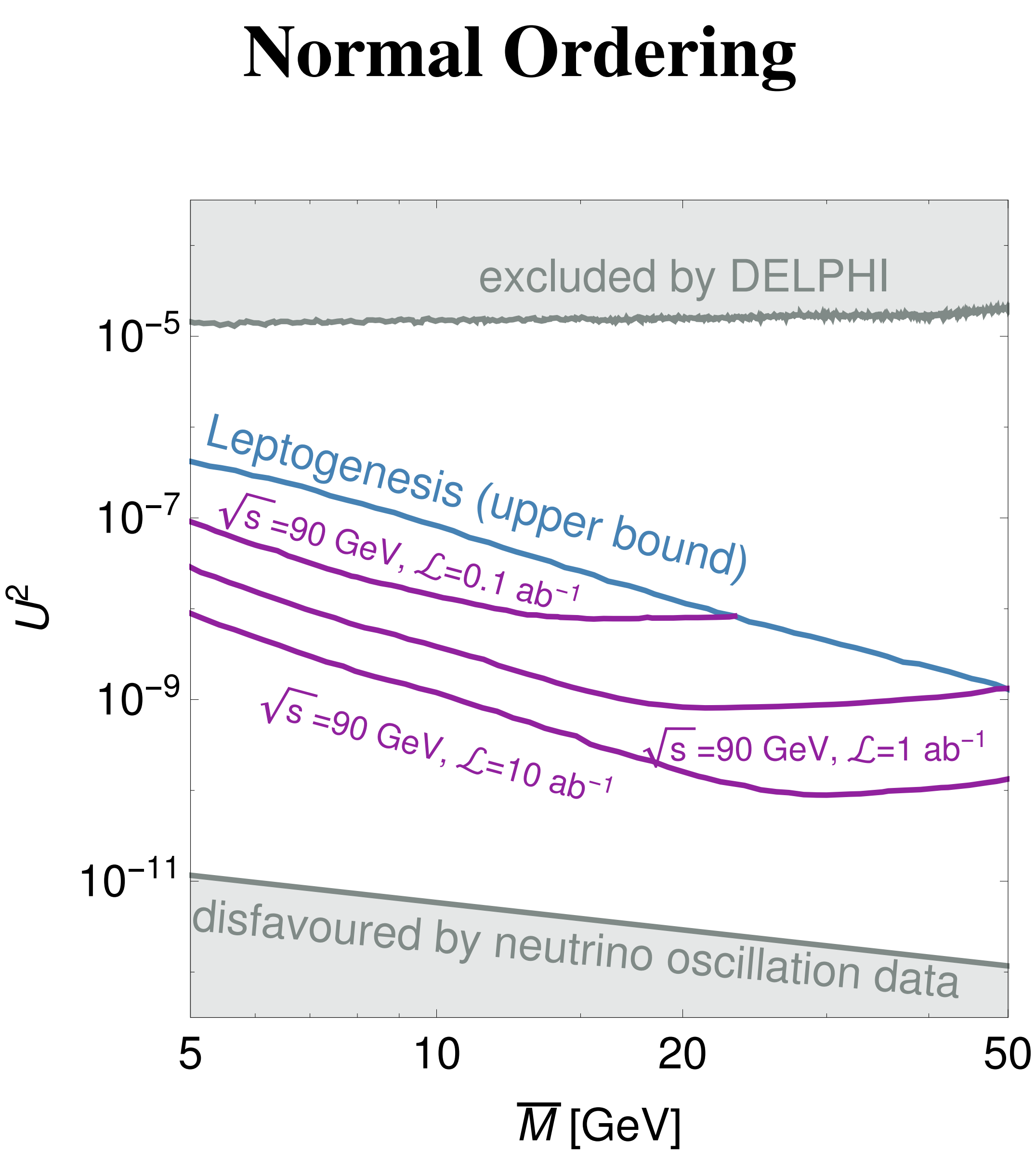
Higgs portal dark matter

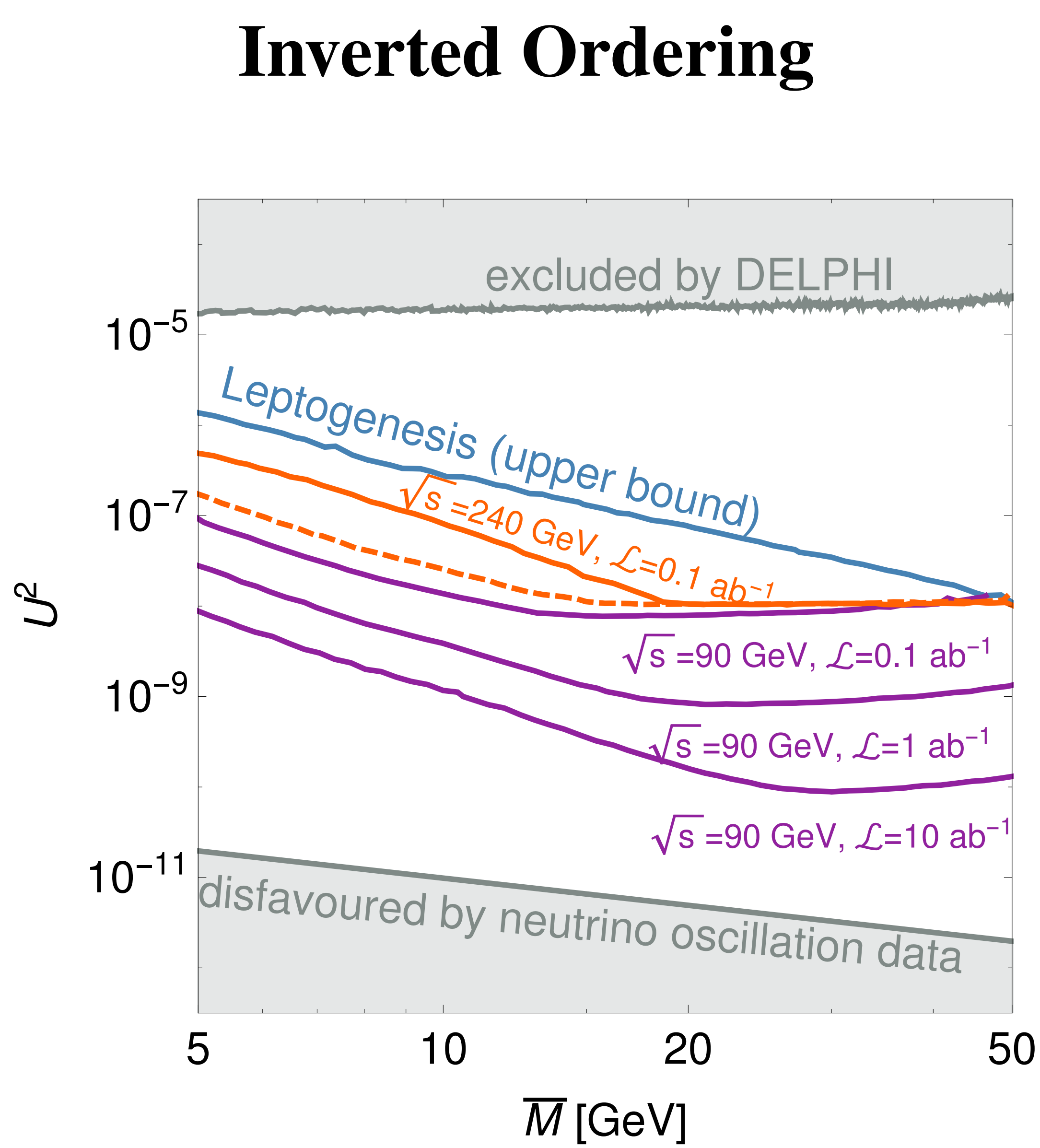


Dark sector at Z factory



Sterile neutrino





low scale see-saw models

Open questions and some thoughts

Circular vs linear

- Circular.
  - Higher luminosity. More statistics.
  - "Easier" to build
  - 1st stage of a big hadron collider.
- Linear
  - Can get to higher energy.
  - Polarization useful tool to discern new physics.
  - Newer technology
- Good to have both! We will hear about ILC soon.

On future hadron colliders

- Physics case "obvious". The energy frontier.

- Without LHC discovery.
  - Physics case for a 100 TeV pp collider stronger than HE-LHC at 28 TeV.
  - Cost+technological challenge. Perhaps easier to "sell" only as a second step of a circular Higgs factory in longer term.

Why 100 TeV?

- Higher is better.

- This is fixed by reasonable expectation of technology, resource, etc.

- A significant step, factor of 100/14, above LHC.

- Interesting test of naturalness, WIMP dark matter.

HE-LHC

- Considering the limitation of resource, may be the only realistic way forward.

- Magnet useful for 100 TeV collider down the road.

- A factor 27/14 better than the LHC. Factor of 100/27 worse than the 100 TeV pp collider.

- Still, good to have it!

CEPC CDR Baseline Parameters (Jan. 2018)

D. Wang

	Higgs	*W*	*Z*
Number of IPs		2	
Energy (GeV)	120	80	45.5
Circumference (km)		100	
SR loss/turn (GeV)	1.73	0.34	0.036
Half crossing angle (mrad)		16.5	
Piwinski angle	2.58	4.29	16.4
N_e/bunch (10^{10})	15	5.4	4.0
Bunch number (bunch spacing)	242 (0.68us)	3390 (98ns)	8332 (40ns)
Beam current (mA)	17.4	88.0	160
SR power /beam (MW)	30	30	5.73
Bending radius (km)		10.6	
Momentum compaction (10^{-5})		1.11	
β_{IP} x/y (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015
Emittance x/y (nm)	1.21/0.0031	0.54/0.0016	0.17/0.004
Transverse σ_{IP} (um)	20.9/0.068	13.9/0.049	5.9/0.078
ξ_x/ξ_y/IP	0.031/0.109	0.0148/0.076	0.0043/0.04
V_{RF} (GV)	2.17	0.47	0.054
f_{RF} (MHz) (harmonic)		650 (216816)	
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.26	3.62	6.0
HOM power/cavity (kw)	0.54 (2cell)	0.47(2cell)	0.49(2cell)
Energy spread (%)	0.1	0.066	0.038
Energy acceptance requirement (%)	1.52		
Energy acceptance by RF (%)	2.06	1.47	0.76
Photon number due to beamstrahlung	0.29	0.16	0.28
Lifetime due to beamstrahlung (hour)	1.0		
Lifetime (hour)	0.67 (40 min)	2	4
F (hour glass)	0.89	0.94	0.99
L_{max}/IP (10^{34}cm^{-2}s^{-1})	**2.93**	**7.31**	**4.1**

J. Gao, IAS2018

without bootstrapping

Inputs for the further study

Baseline option

	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [17]	$\pm 1.0 \times 10^{-4}$ [18]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [19]	$\pm 4.7 \times 10^{-5}$ [20]
m_Z [GeV]	91.1875 ± 0.0021 [21]	$\pm \mathbf{0.0005}$
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [22] $\pm 0.5_{\rm th}$ [20]	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$ [20]
m_h [GeV]	125.14 ± 0.24 [20]	$< \pm 0.1$ [20]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [17]$\pm 0.004_{\rm th}$ [23]	$(\pm \mathbf{3}_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [23]
$\sin^2\theta_{\rm eff}^{\ell}$	$(23153 \pm 16) \times 10^{-5}$ [21]	$(\pm \mathbf{4.6}_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [24]
Γ_Z [GeV]	2.4952 ± 0.0023 [21]	$(\pm \mathbf{5}_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [25]
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.21629 ± 0.00066 [21]	$\pm \mathbf{1.7} \times 10^{-4}$
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.767 ± 0.025 [21]	$\pm \mathbf{0.007}$

With possible improvements.

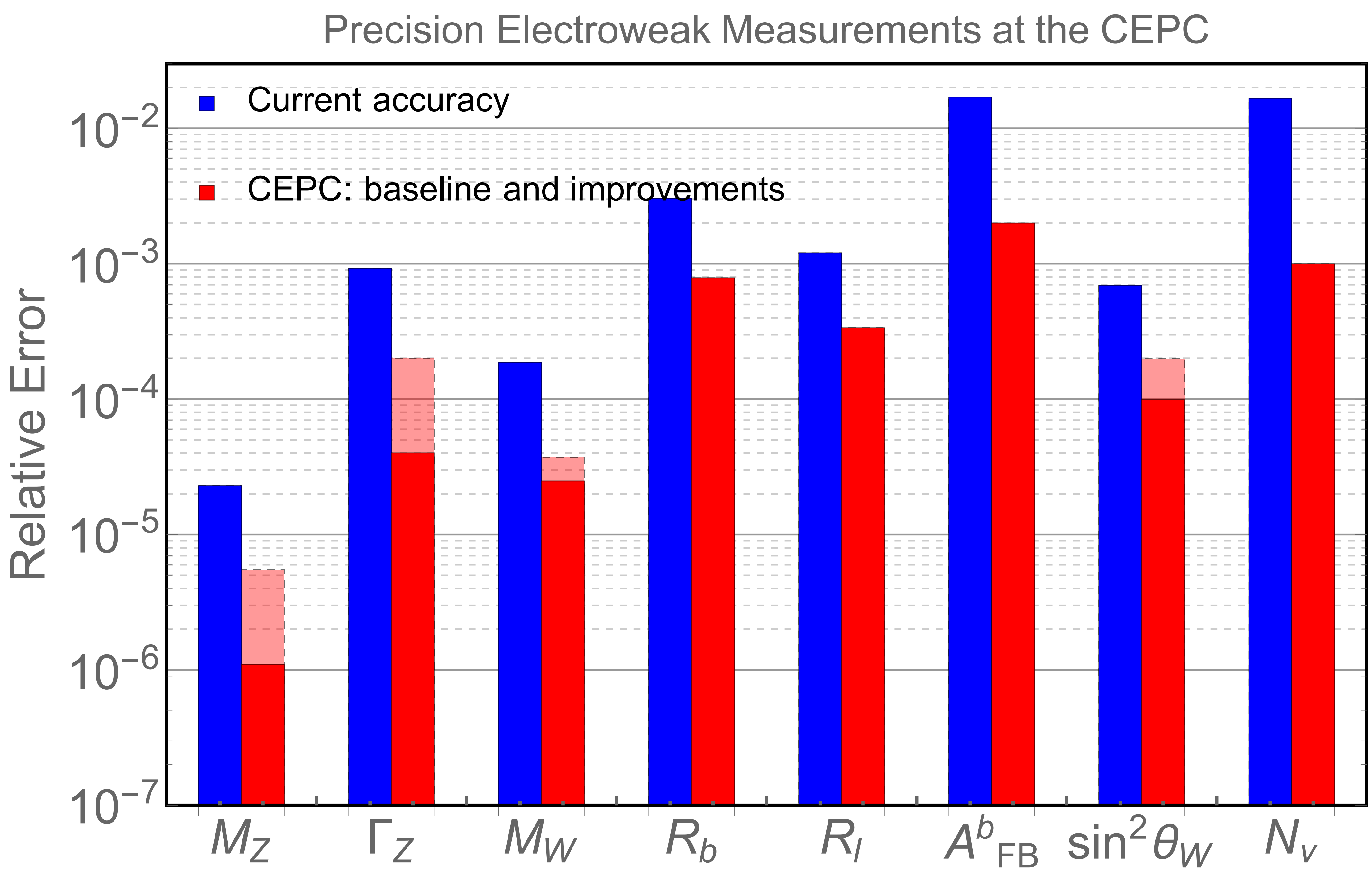
CEPC	$\sin^2\theta_{\rm eff}^{\ell}$	Γ_Z [GeV]	m_t [GeV]
Improved Error	$(\pm 2.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$

x4 statistics off Z-pole

energy calibration

ILC?

Big advance in electroweak precision



Large improvements across the board

Probing NP with precision measurements

- Lepton colliders: ILC, FCC-ee, CEPC, CLIC

  clean environment, good for precision.

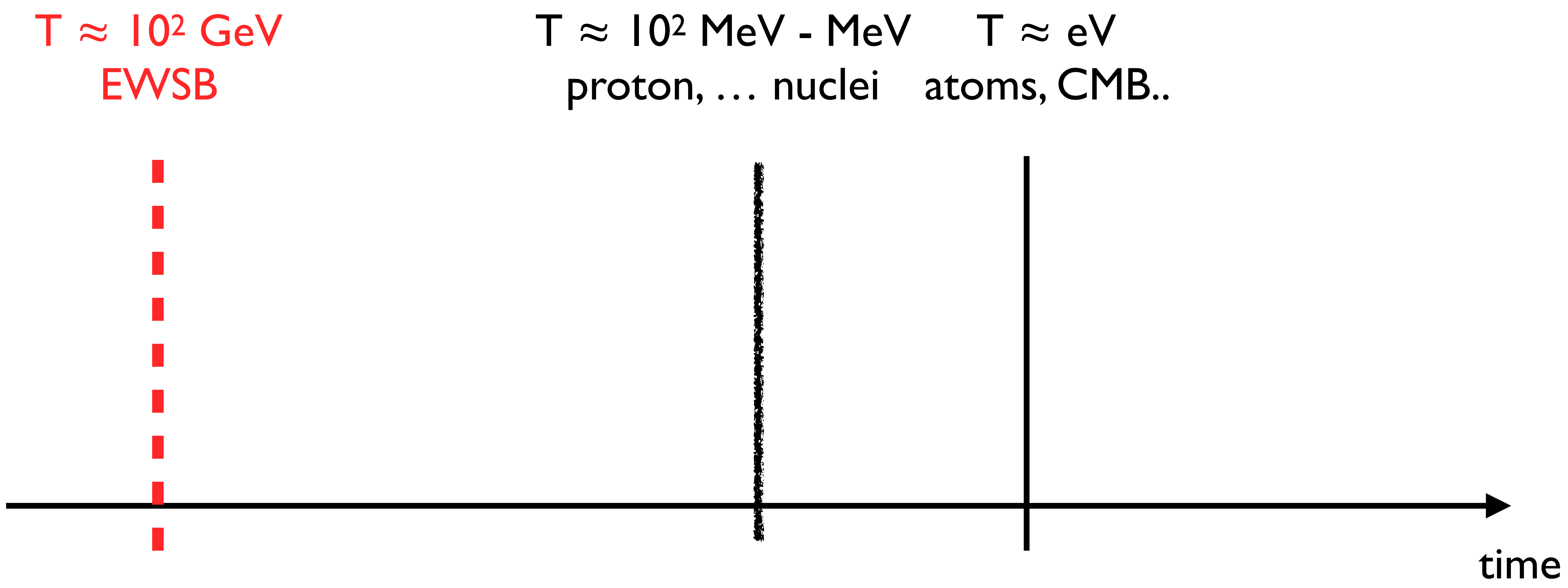
- We are going after deviations of the form

$$\delta \simeq c\frac{v^2}{M_{\rm NP}^2}$$

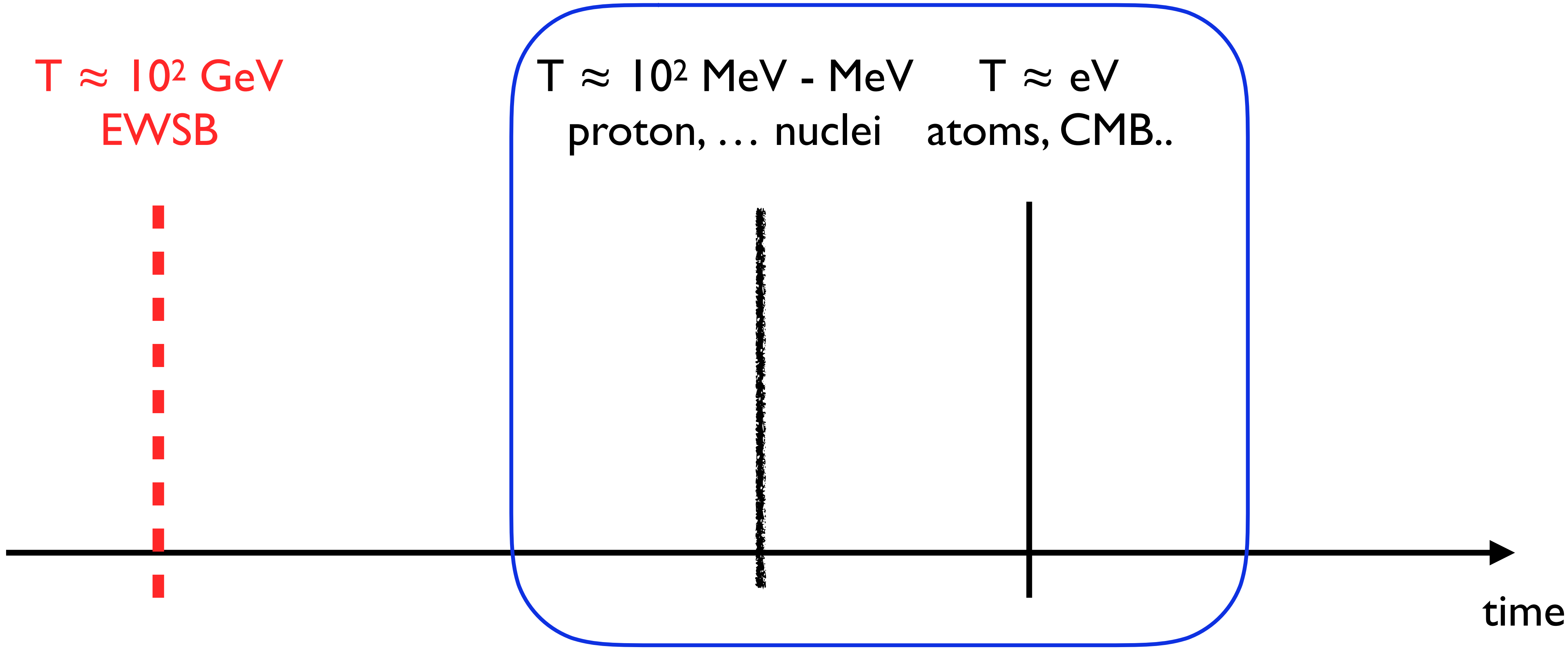
M_{NP} : mass of new physics
c: $O(1)$ coefficient

- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

Milestones in cosmology



Milestones in cosmology



Well understood through both astrophysical observation and laboratory measurements of particle properties.

Lead to the establishment of modern cosmology

Composite Higgs at lepton collider

Higgs is not (quite) elementary, will have deviations in Higgs couplings.

$$\delta W_h \sim \delta Z_h \sim \frac{v^2}{f^2}$$

Composite resonances couples to W and Z. Will give rise to deviation in EW precision observables.

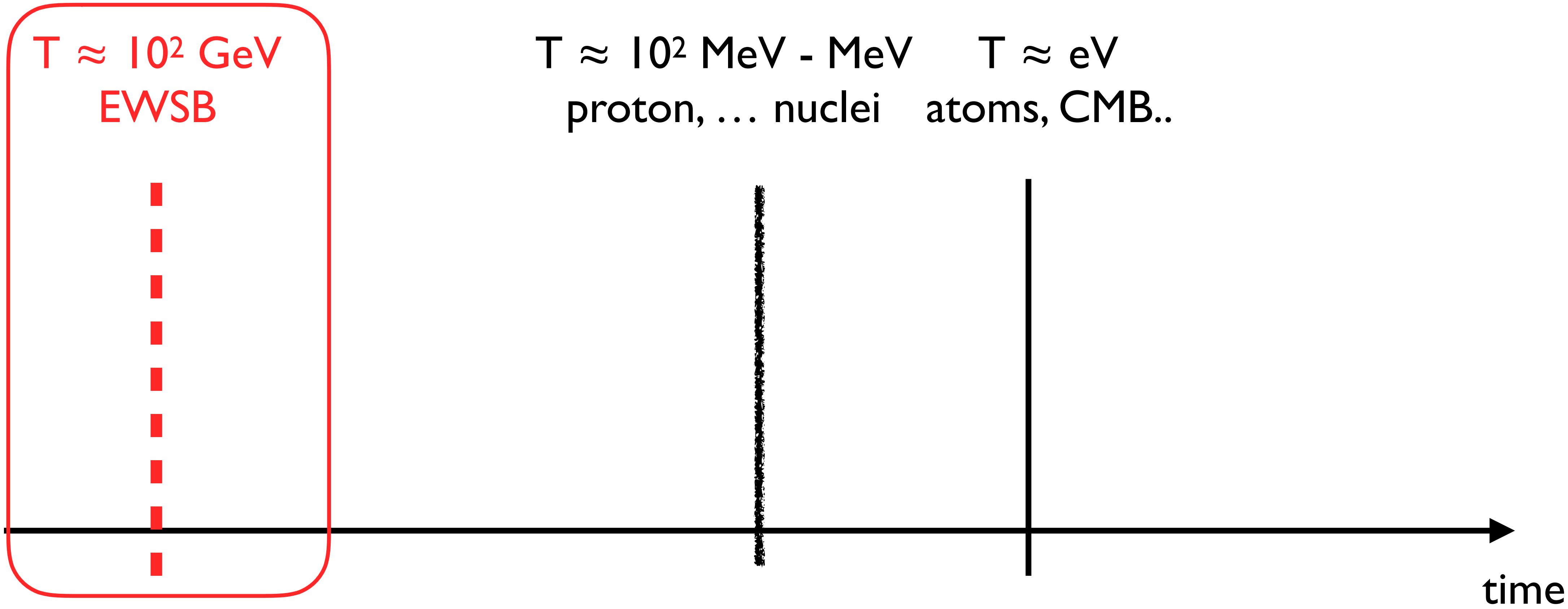
$$S \simeq \frac{N}{4\pi}\frac{v^2}{f^2}$$

Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

Lesson: when both type of corrections generated at the same order, Higgs coupling measurement is typically stronger.

Milestones in cosmology



A monumental event. Set stage for later evolution.
W/Z/h and SM matter acquire masses.

Phase transition can lead to matter anti-matter asymmetry.

Yet, our experimental probe has just begun.
Lab measurement of Higgs properties instrumental.

Fundamental interactions in the SM

Electromagnetism: Coulomb $\sim \dfrac{\alpha}{r}$

QCD: confinement $\sim r$

Weak interaction: Higgs $\sim \dfrac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

Fundamental interactions in the SM

Electromagnetism: Coulomb $\sim \dfrac{\alpha}{r}$

QCD: confinement $\sim r$

Well understood with many decades of exp study.

Lead to numerous breakthroughs, including the establishing QM and QFT

Weak interaction: Higgs $\sim \dfrac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

Fundamental interactions in the SM

Electromagnetism: Coulomb $\sim \dfrac{\alpha}{r}$

QCD: confinement $\sim r$

Well understood with many decades of exp study.

Lead to numerous breakthroughs, including the establishing QM and QFT

Weak interaction: Higgs $\sim \dfrac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

A very different type of interaction.
With a spin-0 Higgs boson, different from all other particles.
We have just barely started to study it, much to learn.