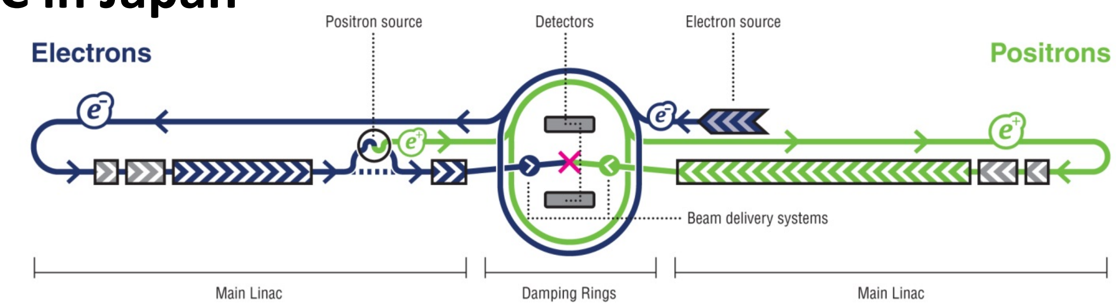
The Physics Potential at future HEP colliders

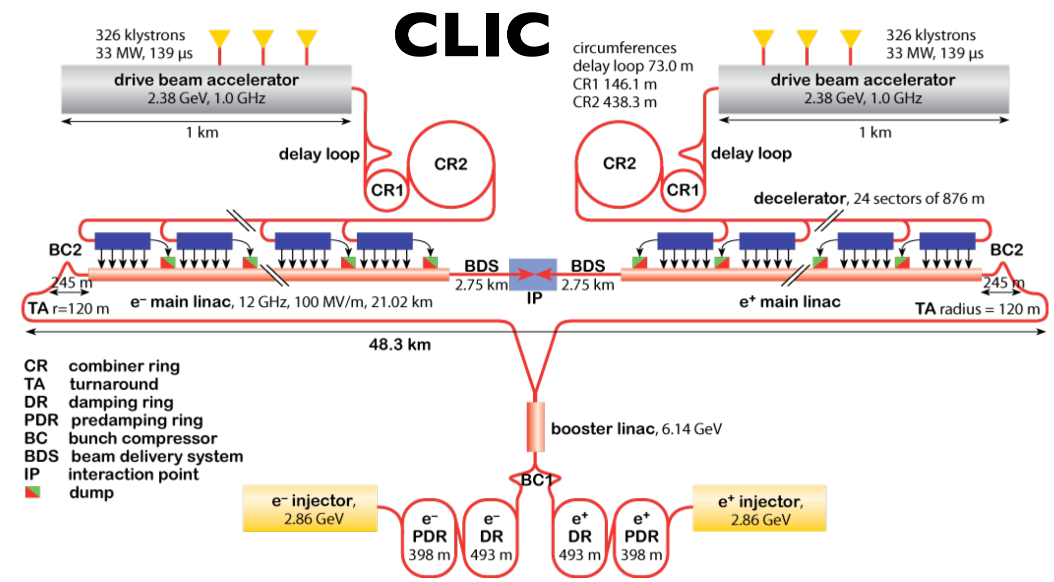
LianTao Wang
University of Chicago

Gordon Research Conference
HKUST July 3, 2019

Future Colliders

ILC in Japan



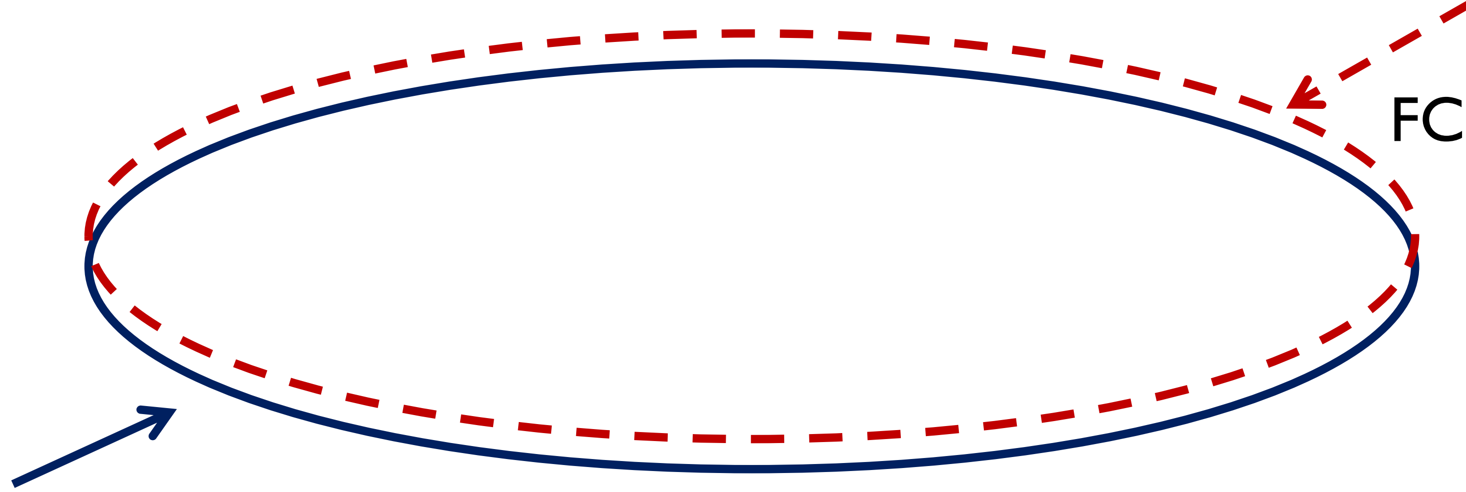


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

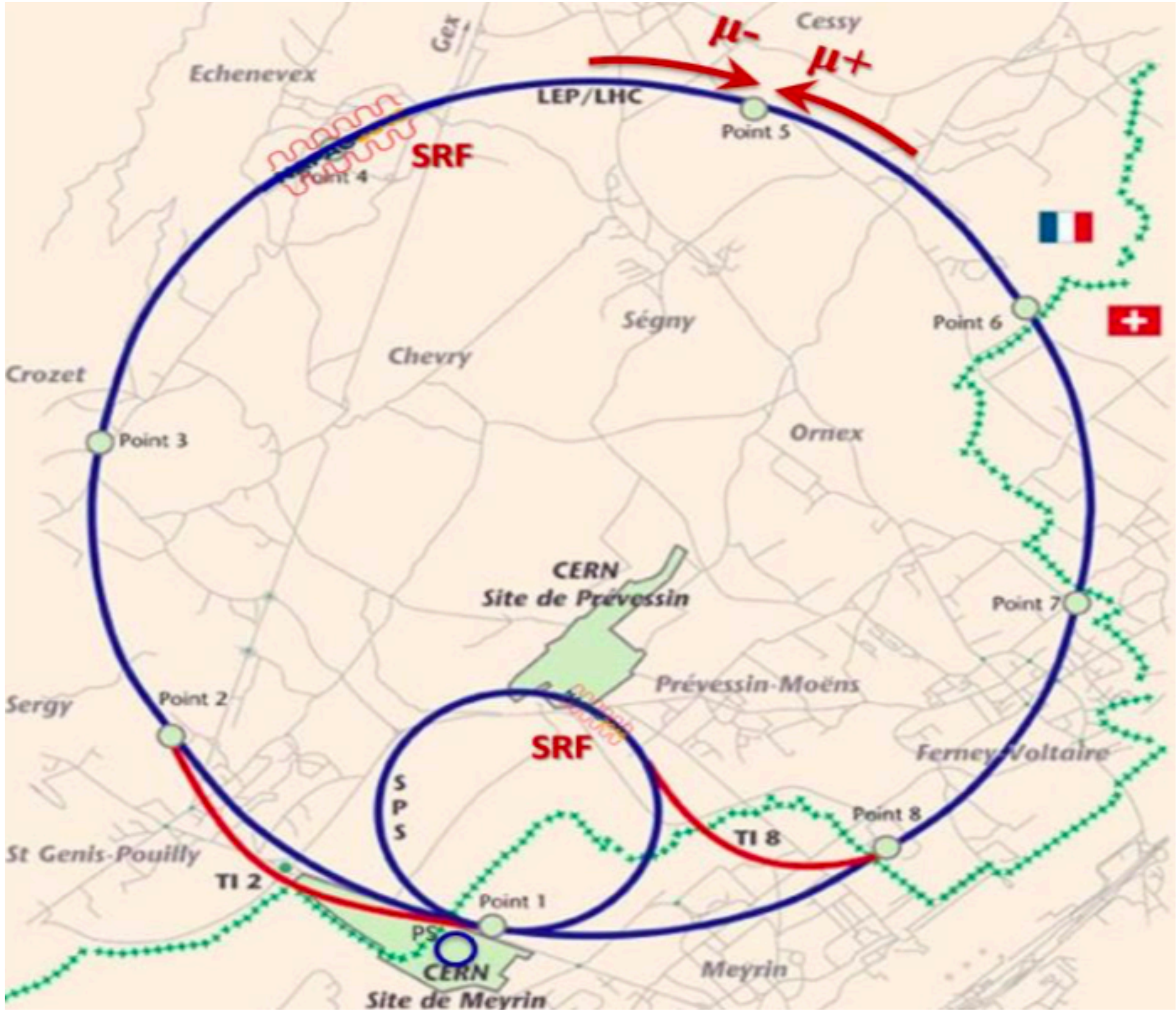
FCC-hh (CERN), SppC(China)

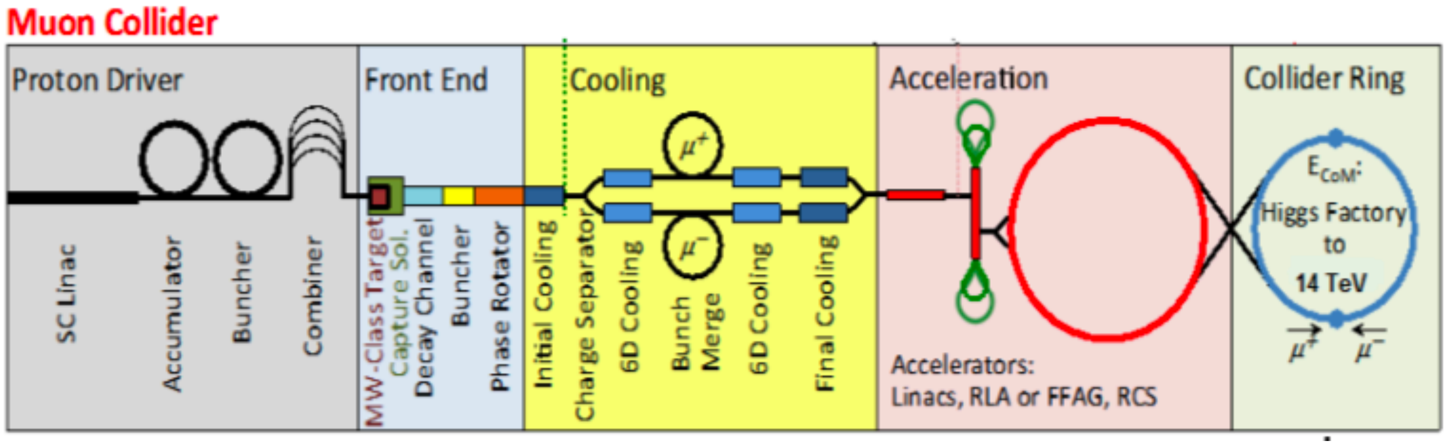


250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

muon collider





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?

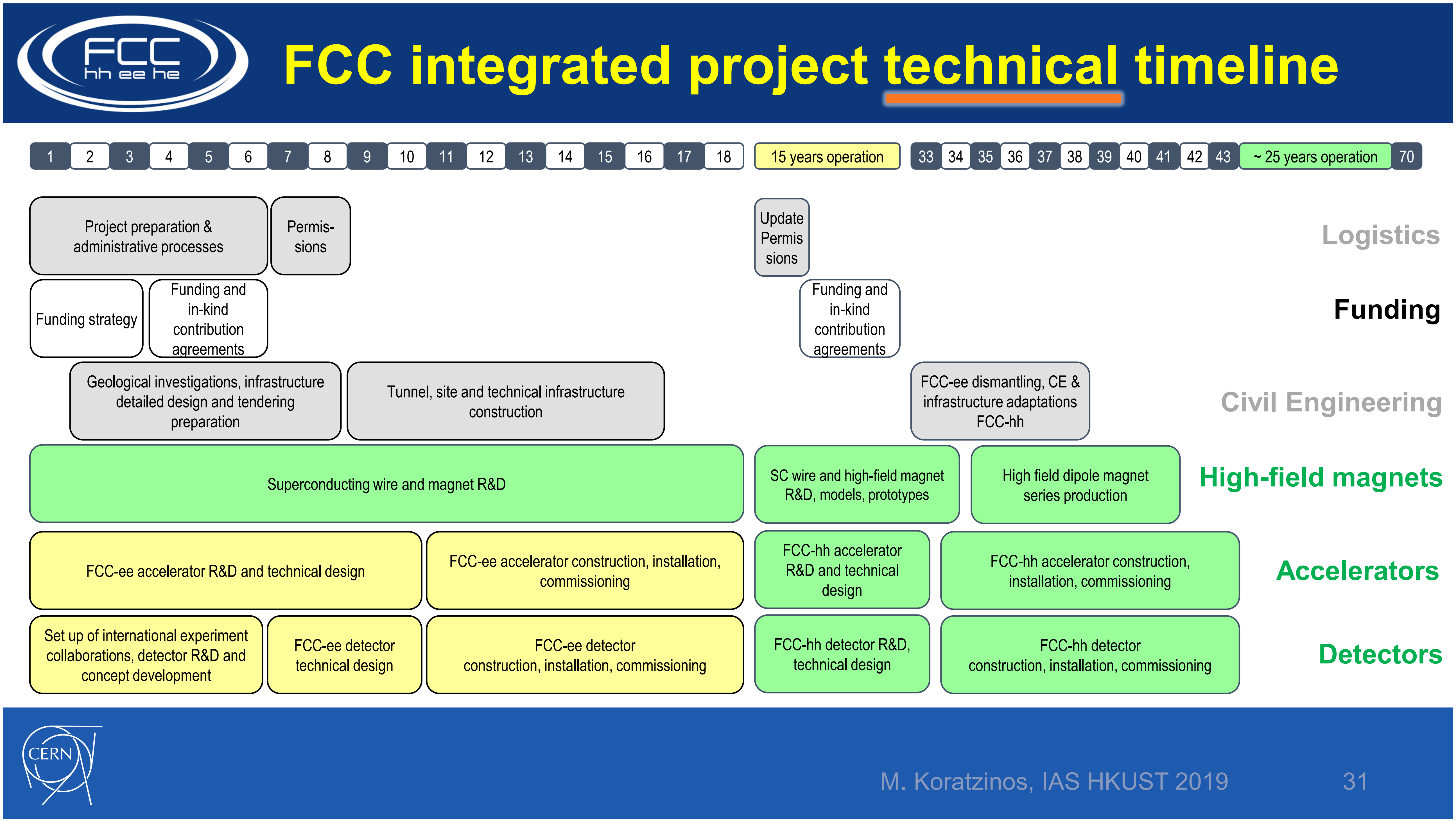
• • •

My focus here

- More "near future".
- Circular: FCC-ee/FCC-hh, CEPC/SppC
- Linear: ILC, CLIC

My apologies for using more CEPC plots.
Qualitatively similar capabilities at other Higgs factories.
Will comment on the difference.

FCC time line



FCC-ee: ～2039, FCC-hh: ~2060s

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**

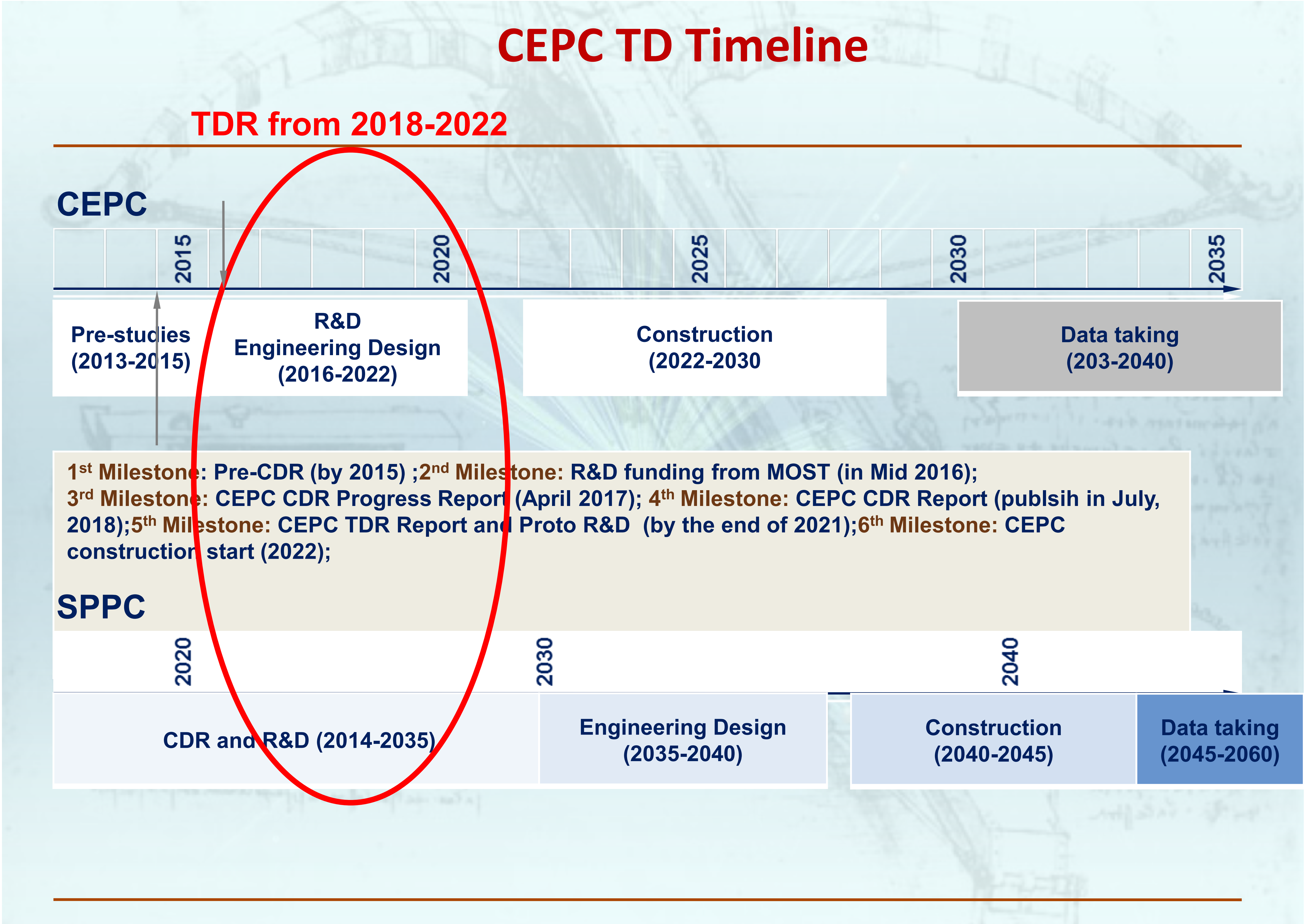
$$\sim 10^6 \text{ Higgses}, \ \sim 10^{13} \text{ Zs}, \ldots$$

13 yr run plan: 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



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

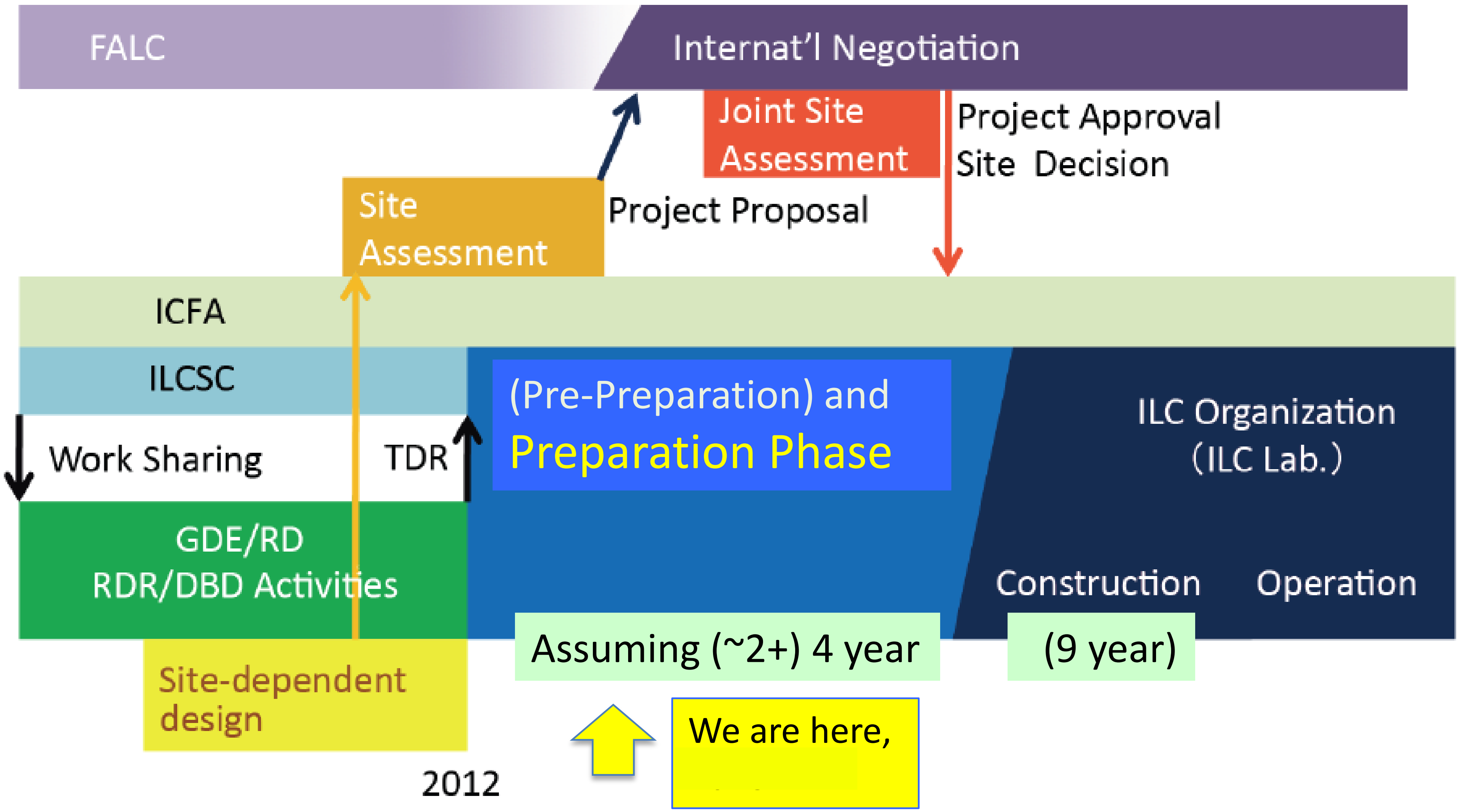
CEPC yearly run time assumption:

- 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

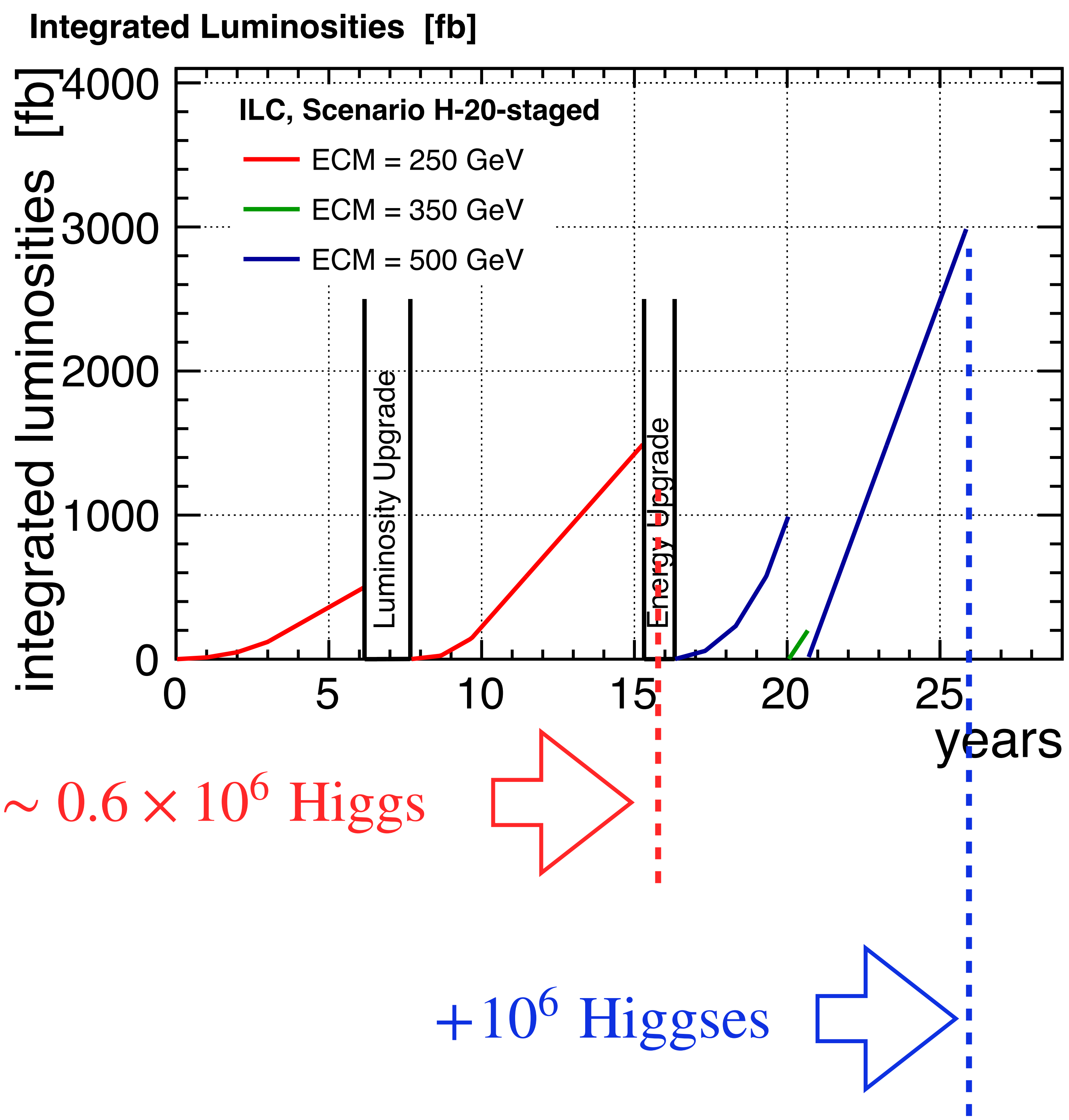
ILC Time Line: Progress and Prospect



Shin Michizono, HK IAS conference 2018 and 2019

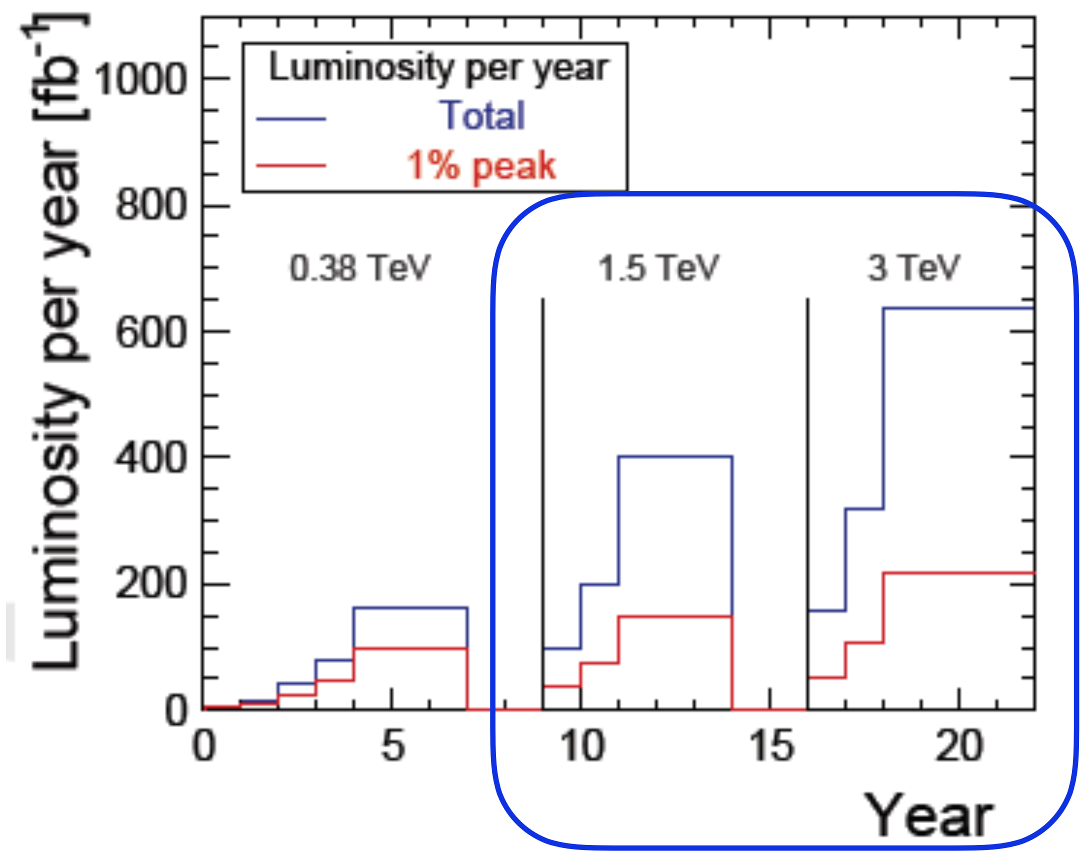
Next key step: European strategy 2020

ILC run plan



No Z-pole or WW run planned

CLIC



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

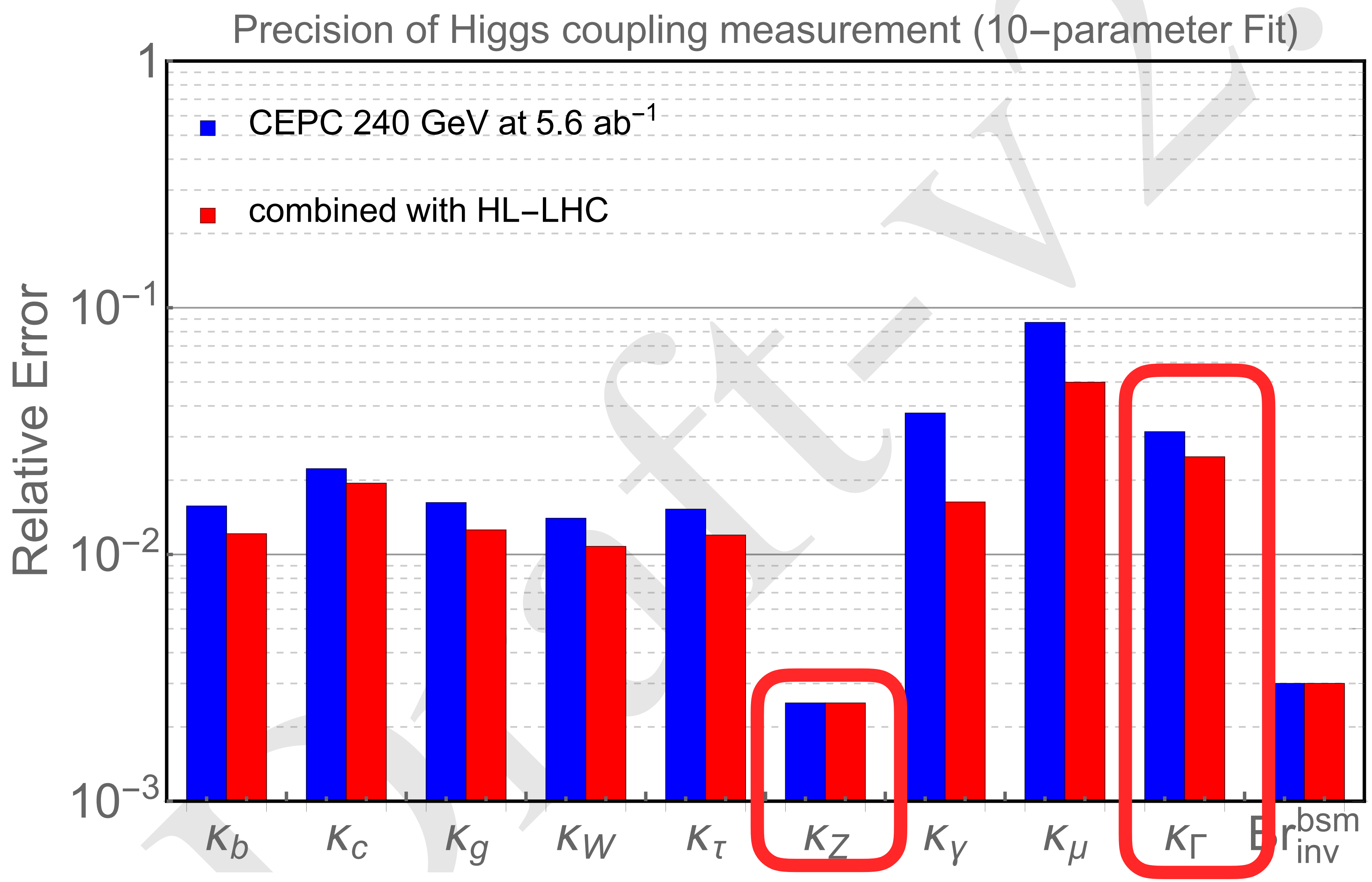
$\sim 2 \times 10^5$ Higgs

higher energies!

Physics potential for future collider

- Basic physics studies have been finished
  - ILC physics case well studied.
  - CDR for CEPC and FCC published recently.
  - A clear picture has emerged.
- I will give an overview of the main results.
- Assumption: LHC will not make discovery of new physics.
  - Otherwise, great!!!.
  - We need to completely re-think.

Measurements at Higgs factories



Allows model independent determination of Higgs width and Higgs-Z coupling

Comments on Higgs measurement

- The most important measurement is the hZ coupling.
  - Most precise Higgs coupling measurement at e+e-.
  - Key component of the physics case.
- Several other BR measurements and rare decay searches can also be powerful tools.
- Statistics limited. Clear advantageous to have more Higgs bosons!

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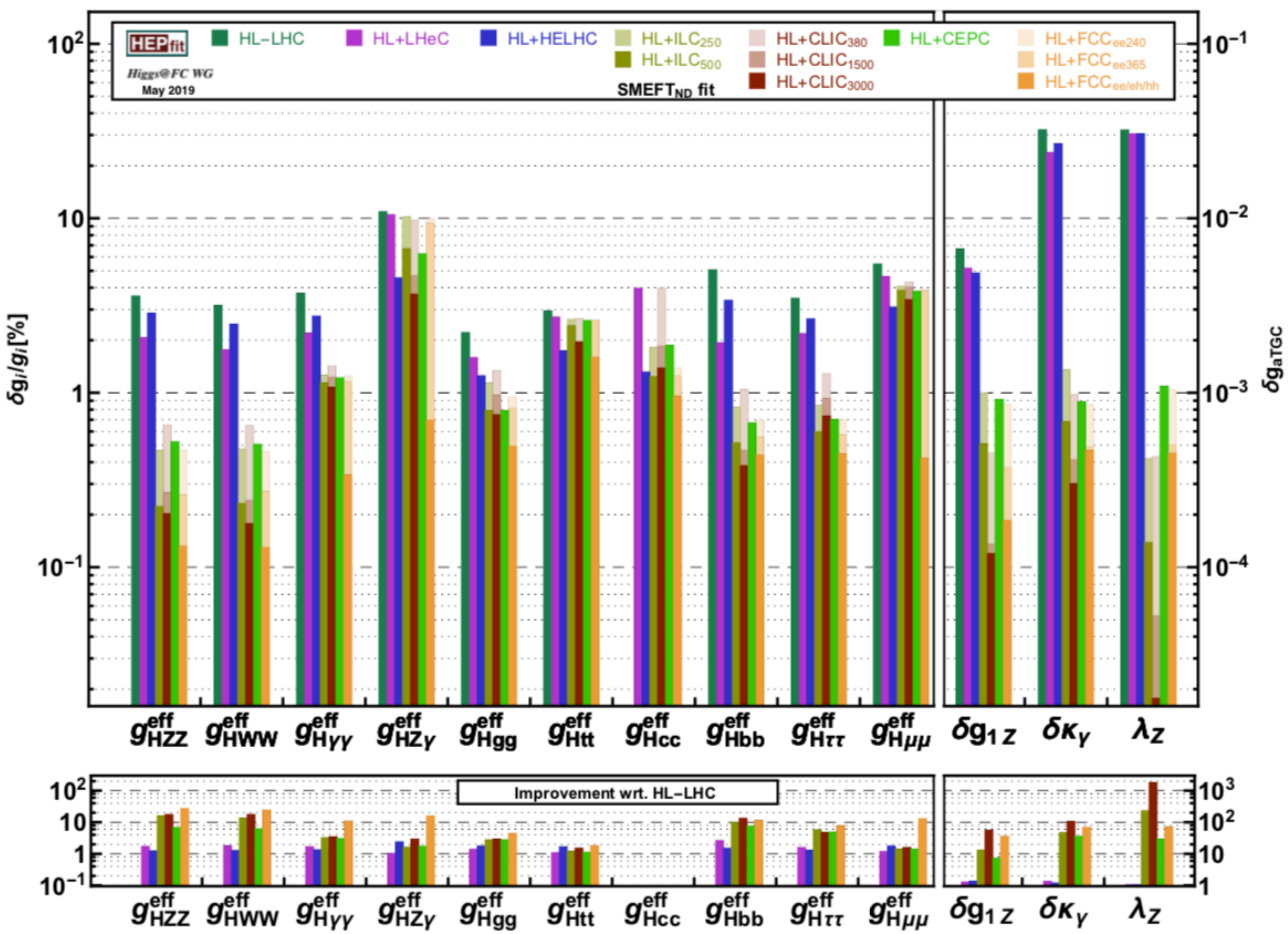
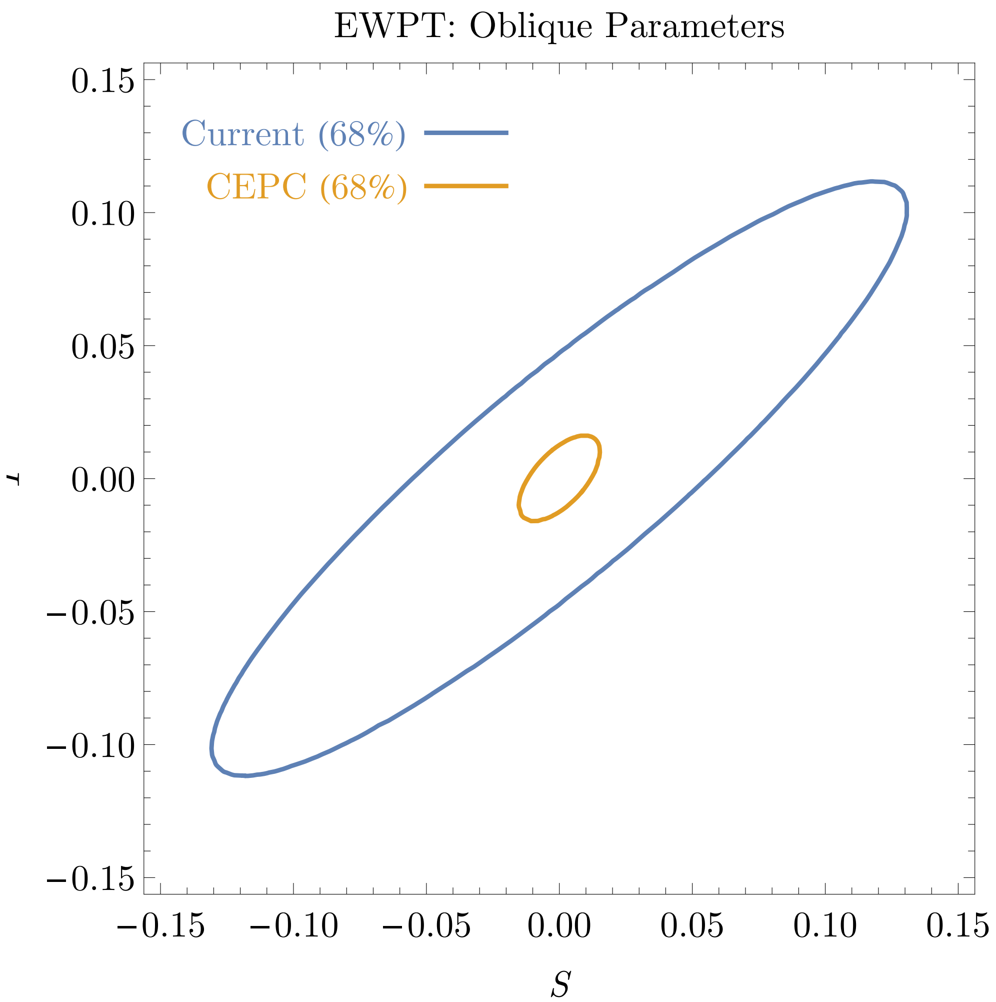
- Several other BR measurements and rare decay searches can also be powerful tools.
- Statistics limited. Clear advantageous to have more Higgs bosons!
- Model independent determination of the Higgs width is powerful in search for new physics.

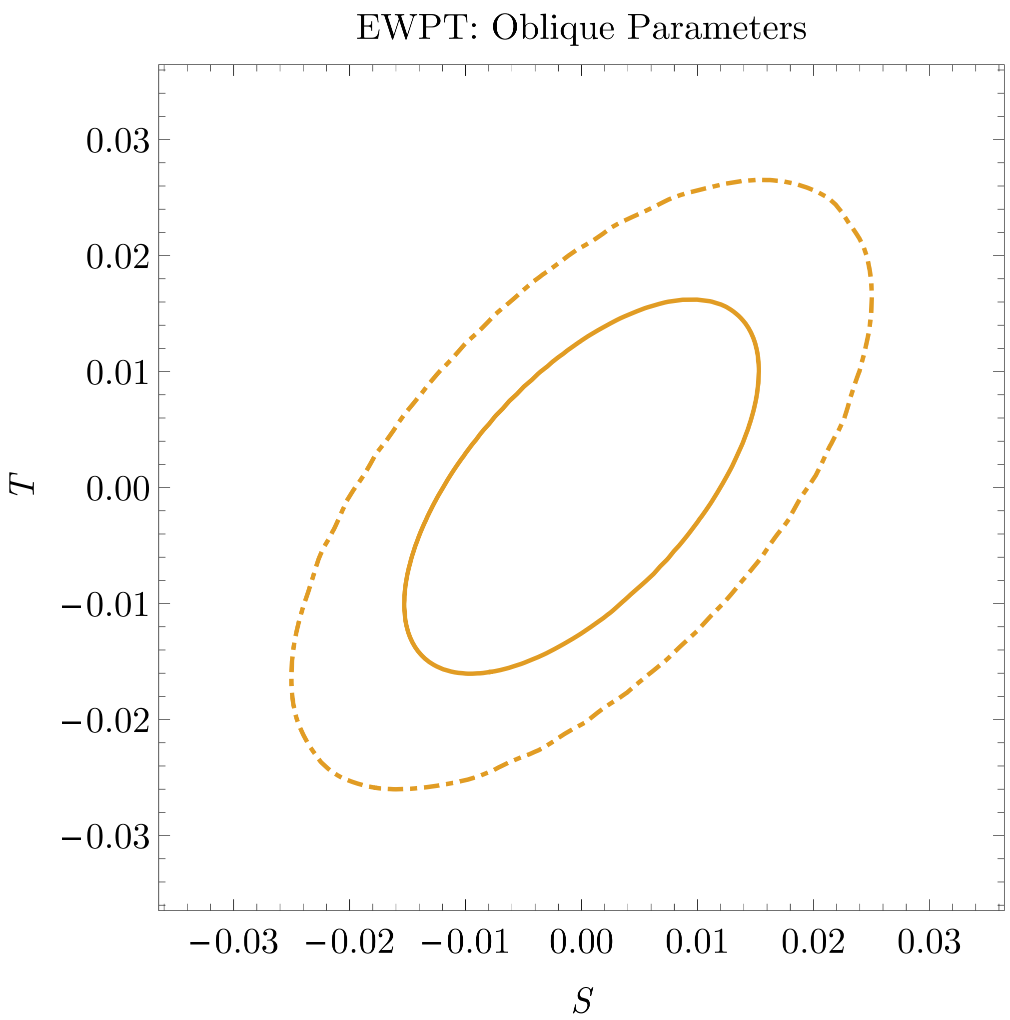
Comments Higgs measurement

- Higher energies can help.
- Additional handle such as polarization helps with distinguish different new physics effects.



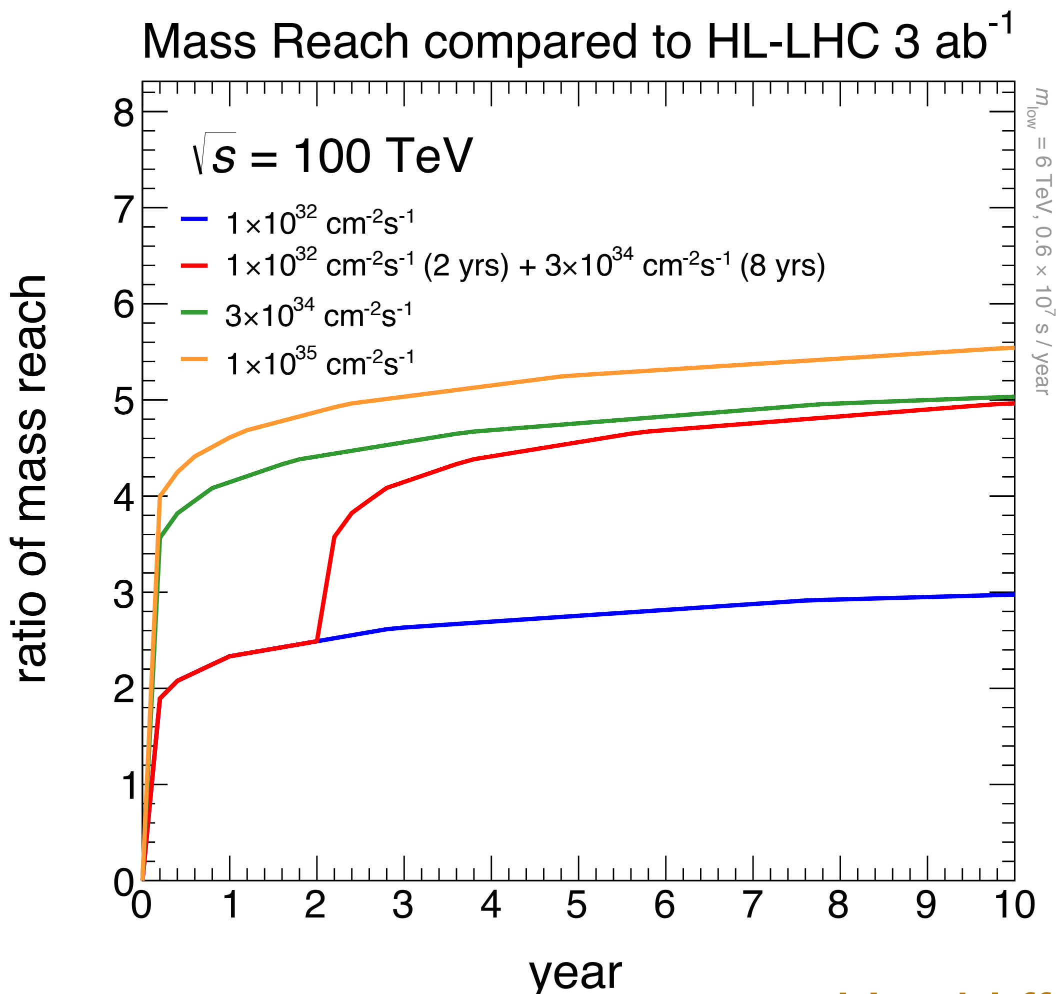
Big step in Electroweak precision





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

100-ish TeV pp collider

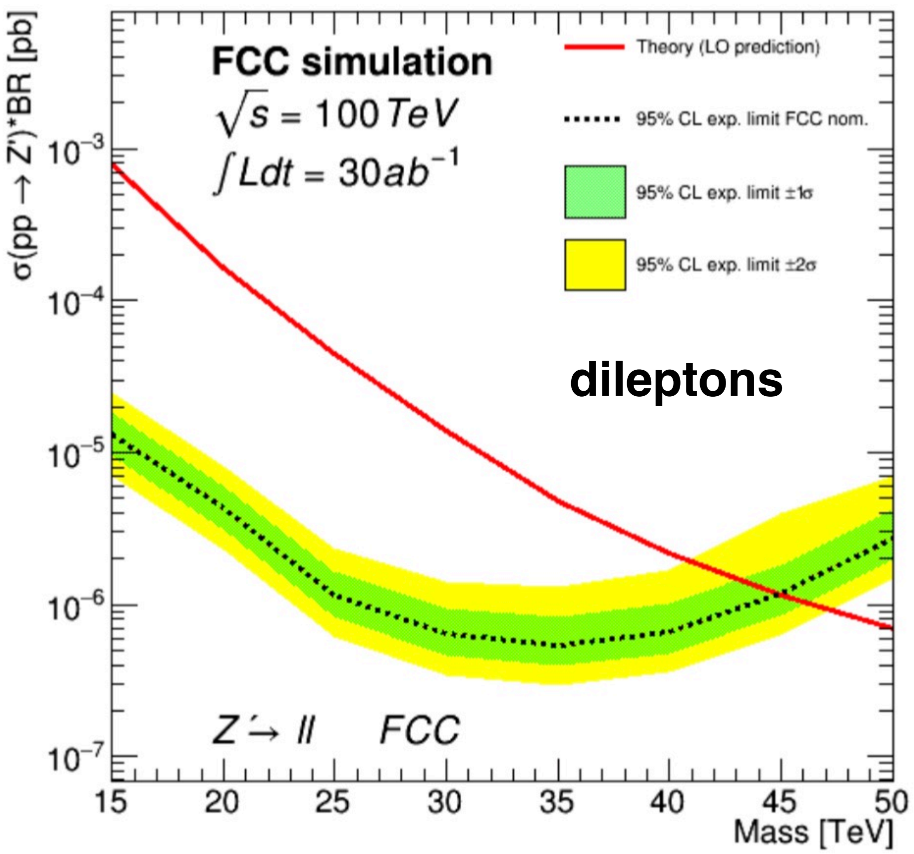


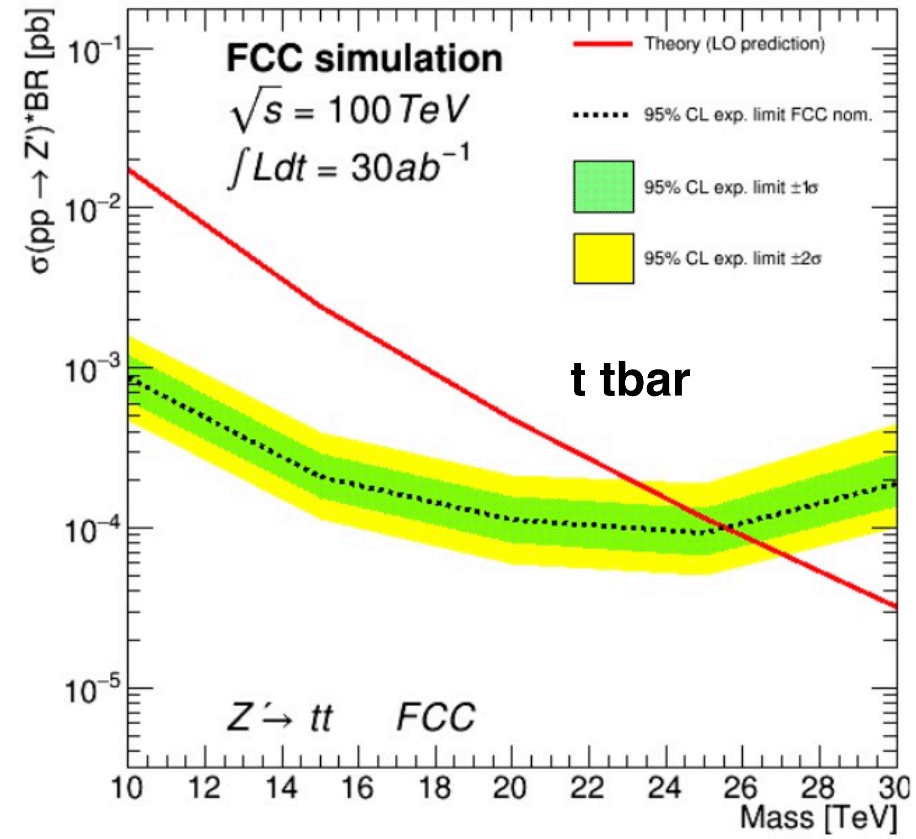
Hinchliffe, Kotwal, Mangano, Quigg, LTW

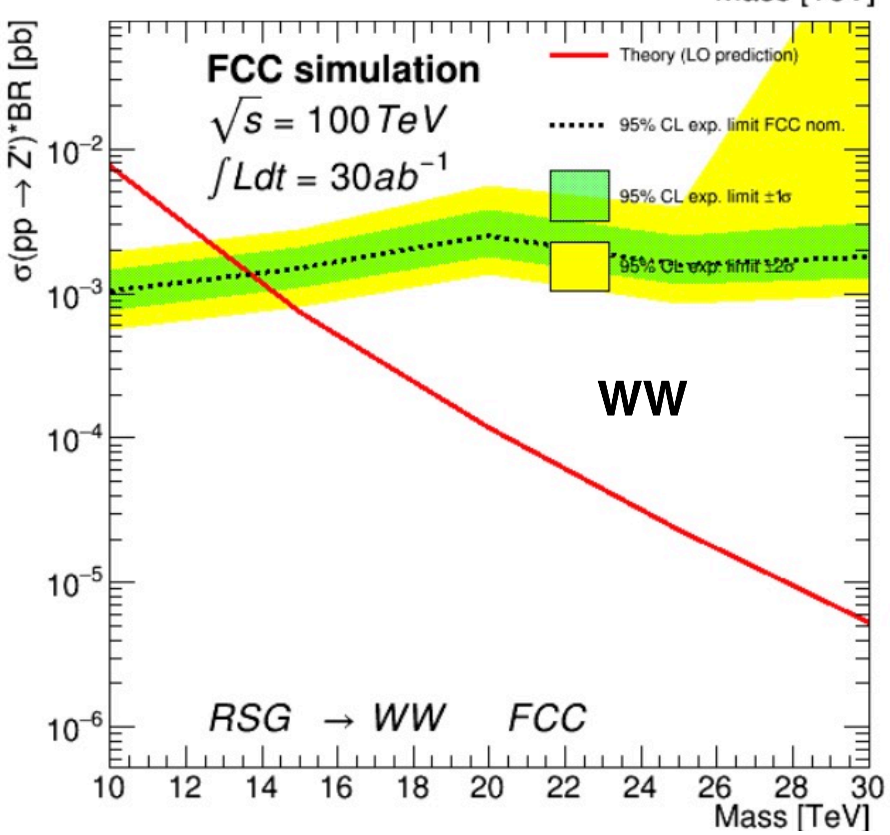
A factor of at least 5 increase in reach beyond the LHC, with modest luminosity

New physics reach: 10s TeV

Resonances: SSM Z'



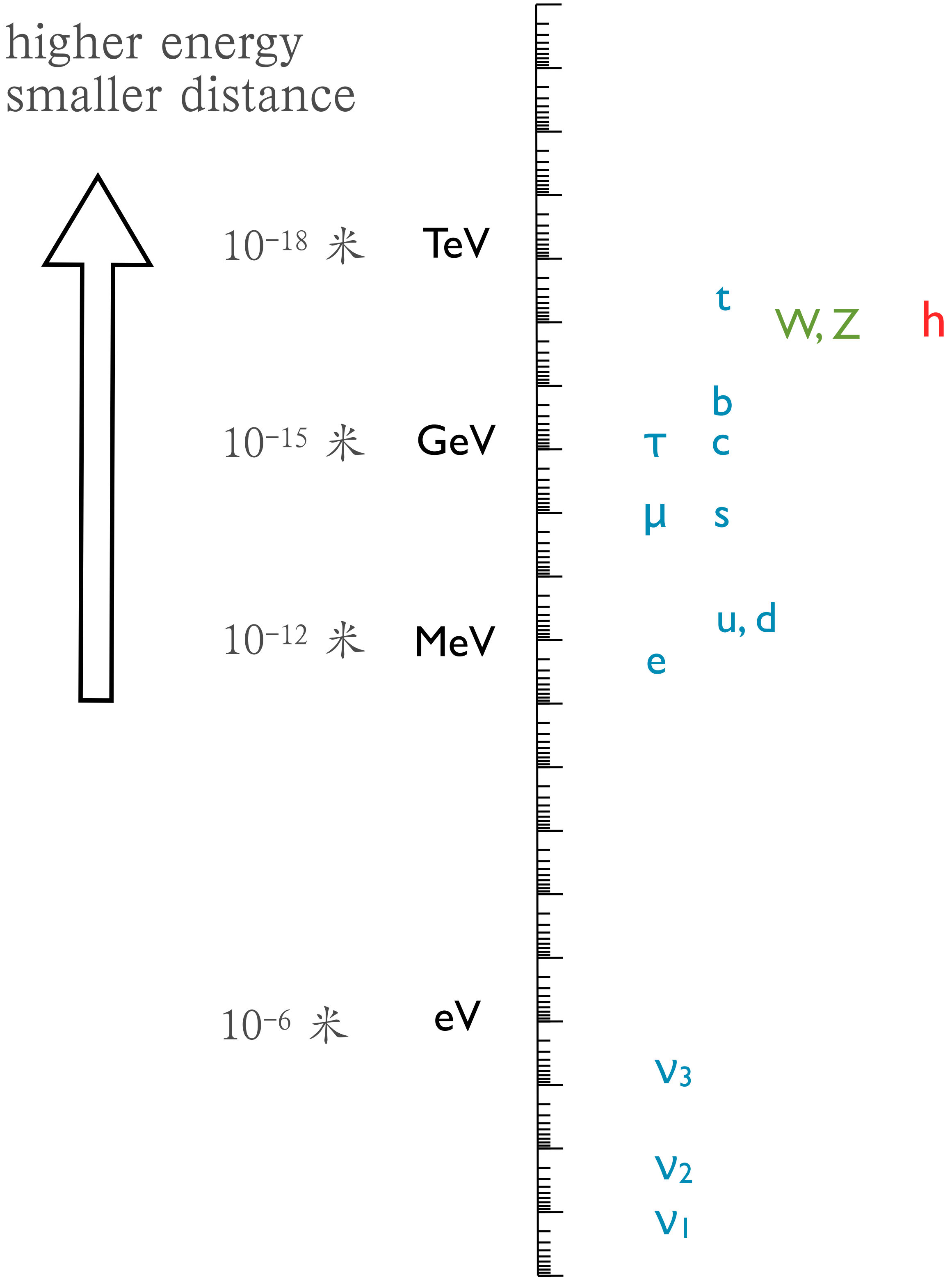




C. Helsens & M. Selvaggi + Summer students
Rachel Smith UIUC and Ine Arts UA

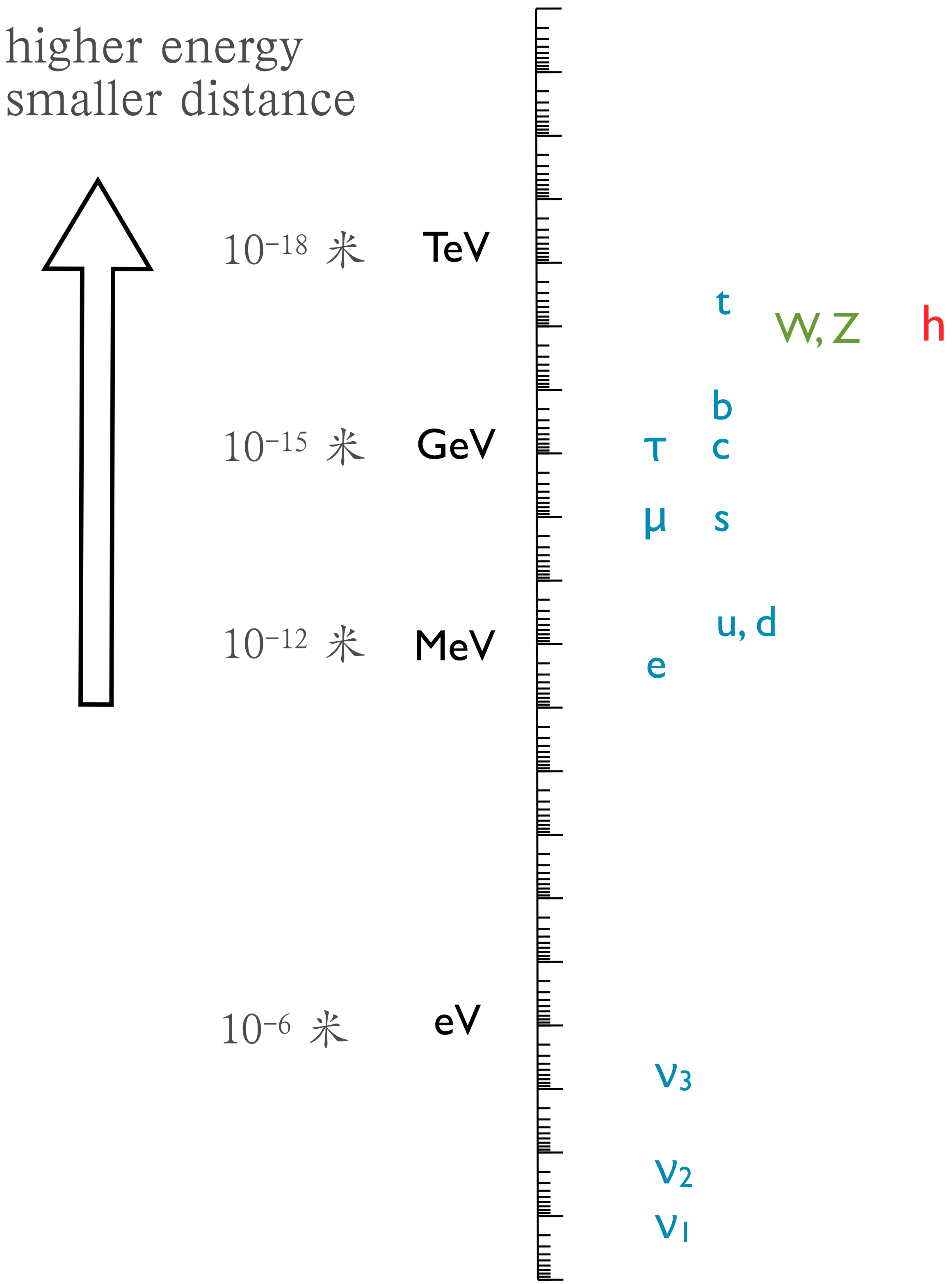
What are we looking for?

Standard Model



Amazing progresses in the last ~100 years

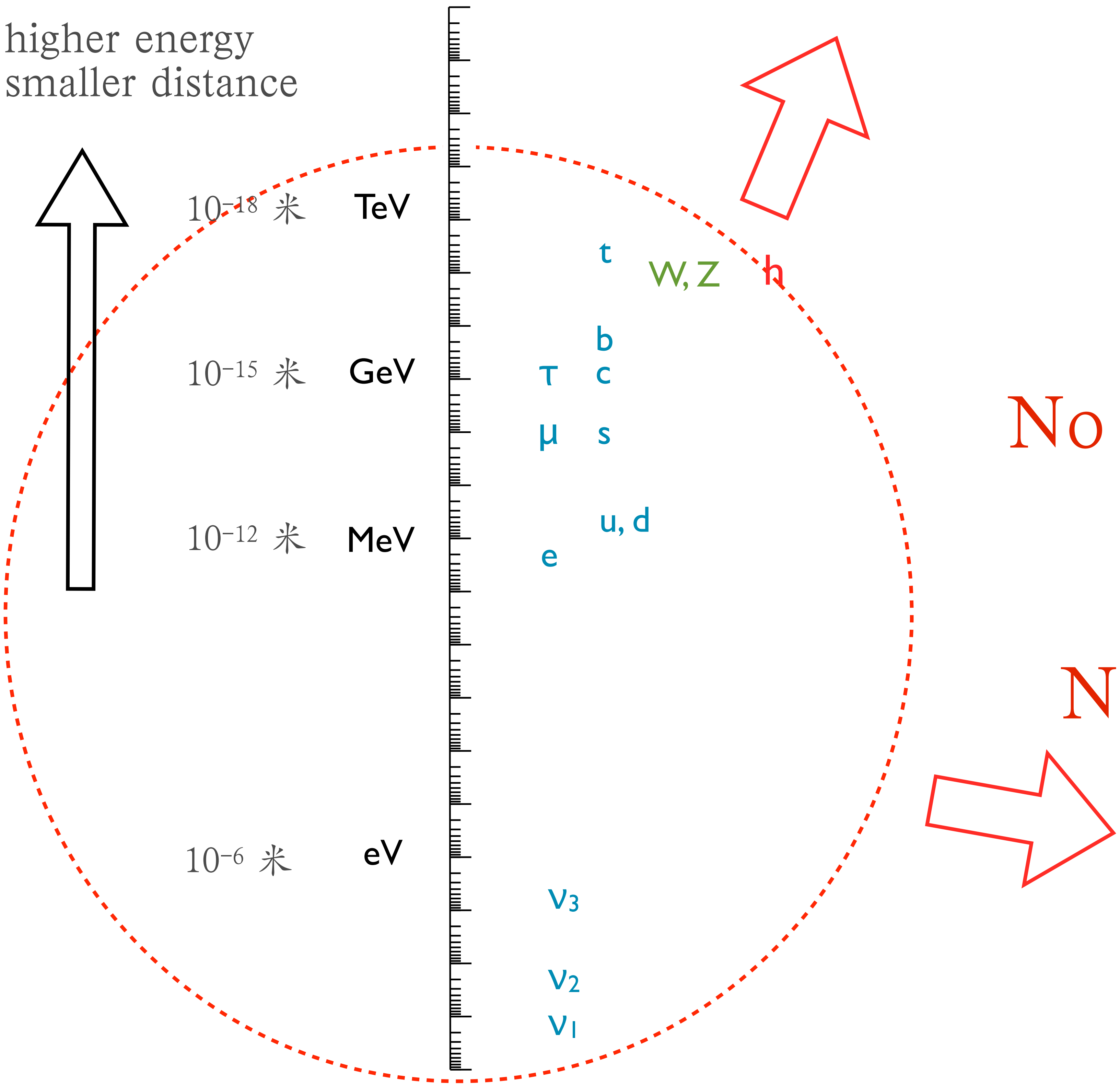
Guidance for the journey



Almost at each step, exp+theoretical consistency told us there must be something new, and how to find them.

We are getting (too) used to it.

Beginning of an new era



unknown

No exp and theoretical inconsistency

No no−lose theorem

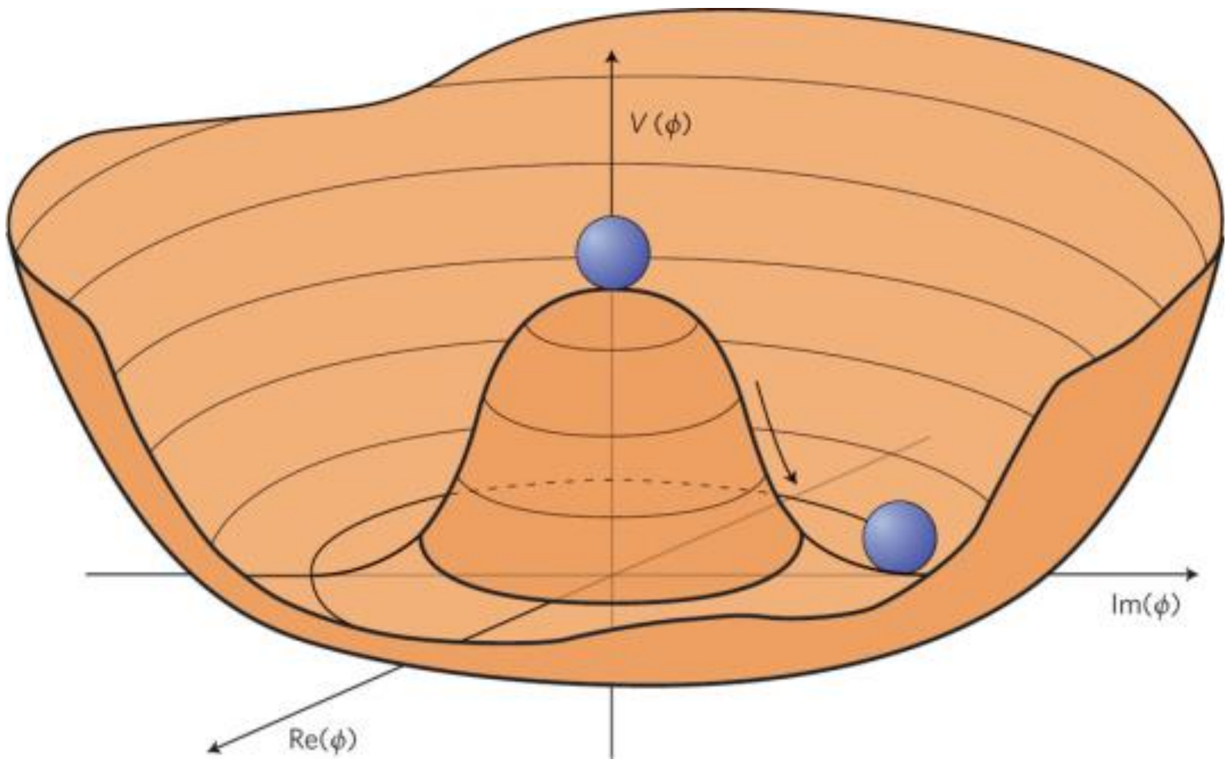
Open questions in particle physics

- Electroweak symmetry breaking.
- Dark matter.
- Matter anti-matter asymmetry of the universe
- Neutrino mass
- Origin of flavor structure
- CP violation
- ...

Electroweak symmetry breaking

The main physics goal of the lepton colliders

“Simple” picture:

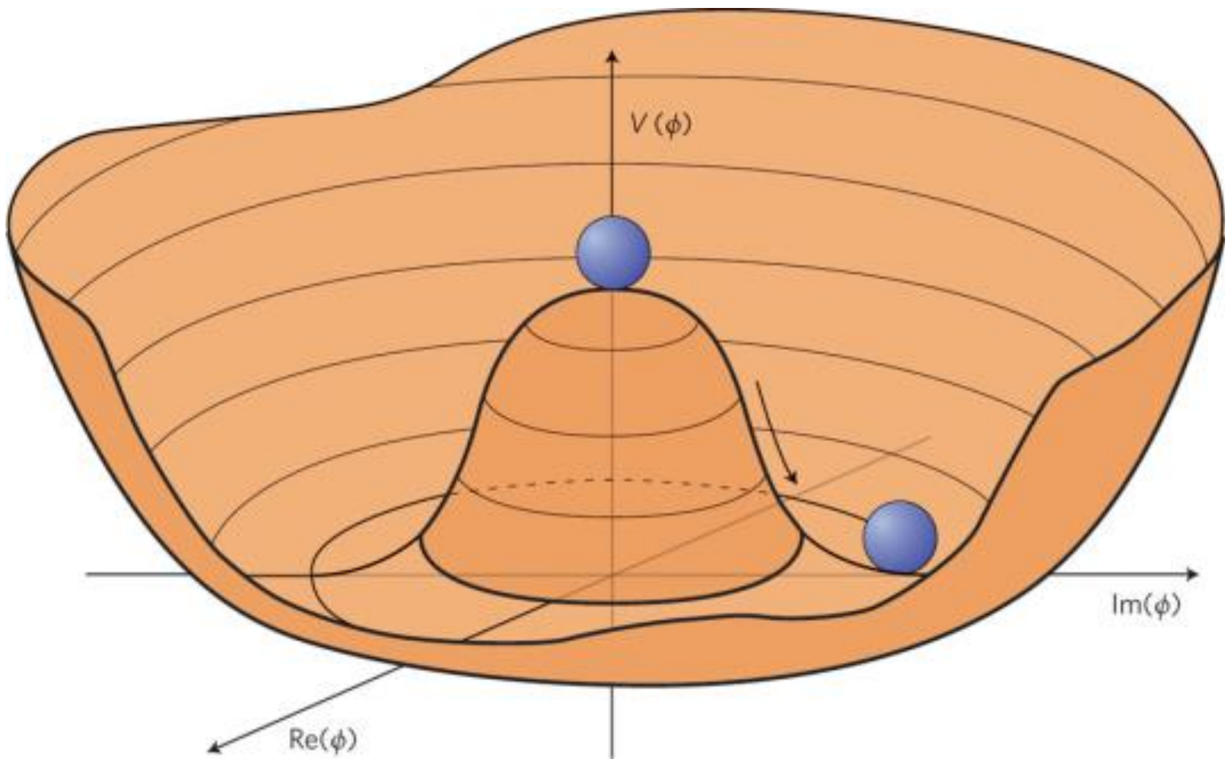


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

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

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

“Simple” picture:



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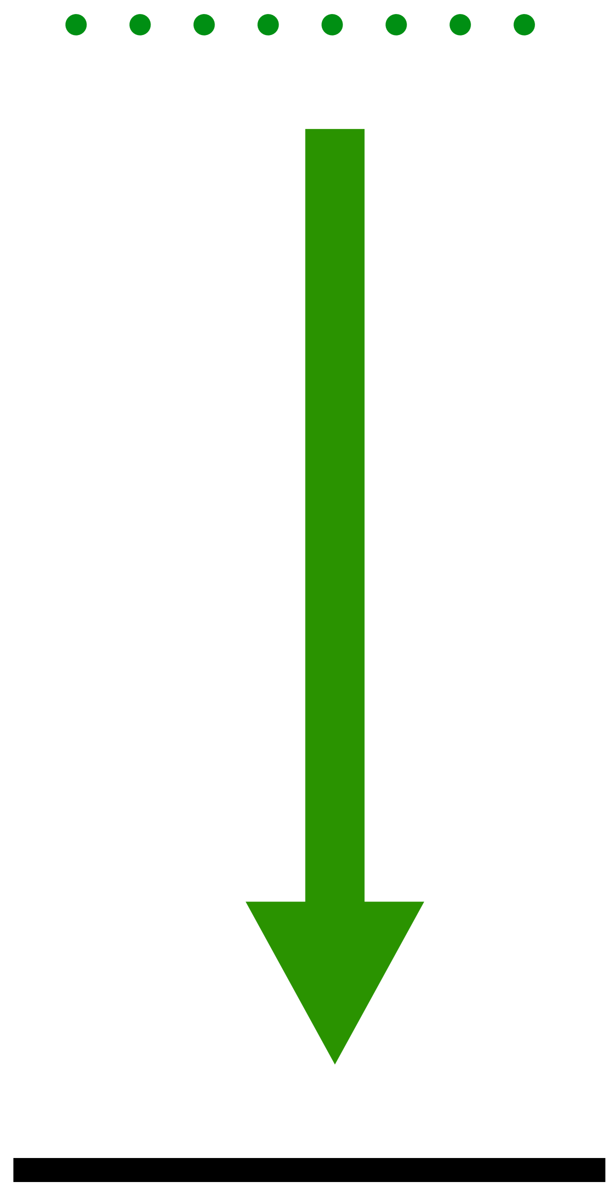
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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

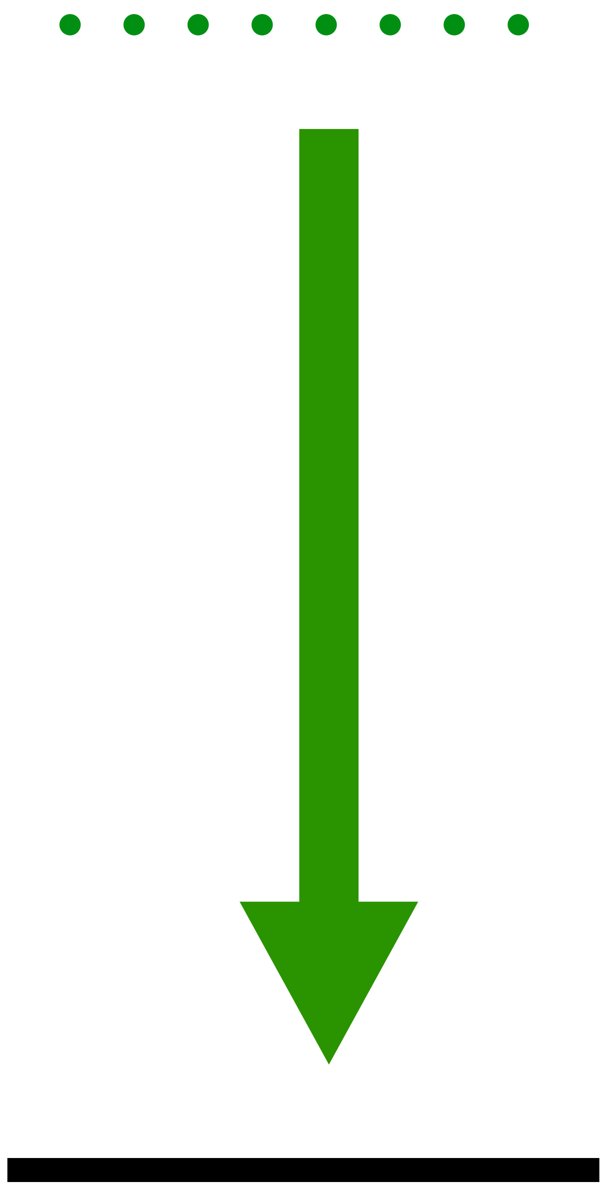
How to predict Higgs mass?



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 hierarchy problem.

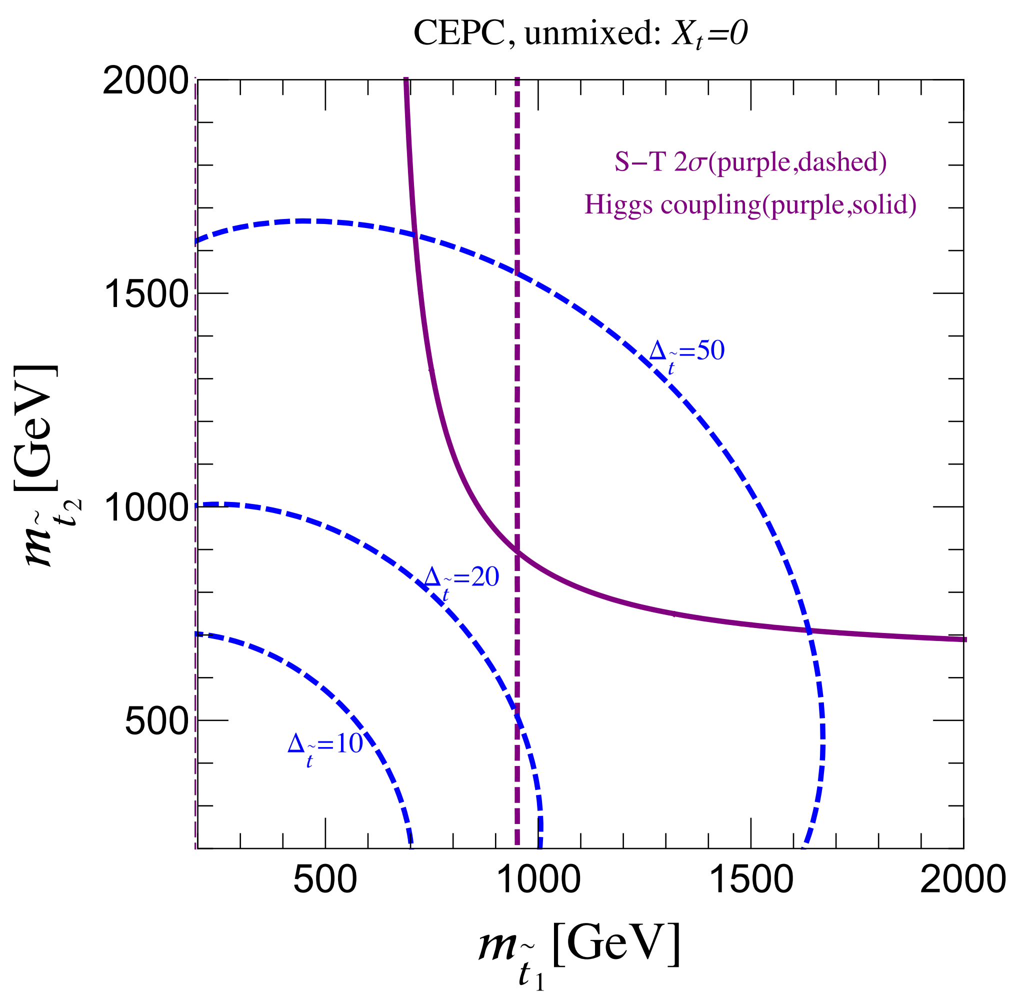
Electroweak scale, 100 GeV.
m_h , m_W …

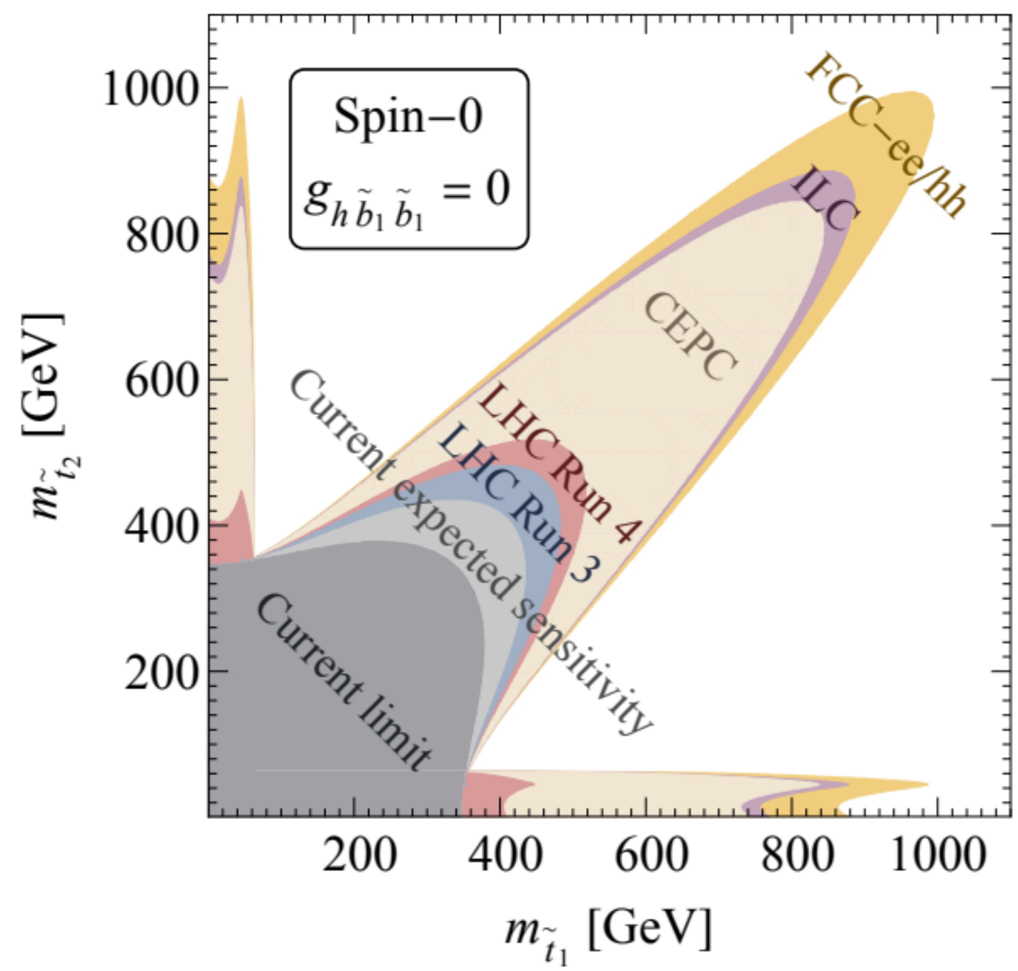
Why is Higgs measurement crucial?

- Hierarchy (naturalness, fine-tuning) problem is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- No confirmation of any of the proposed models.
- We may not have the right idea. 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.

Naturalness in SUSY

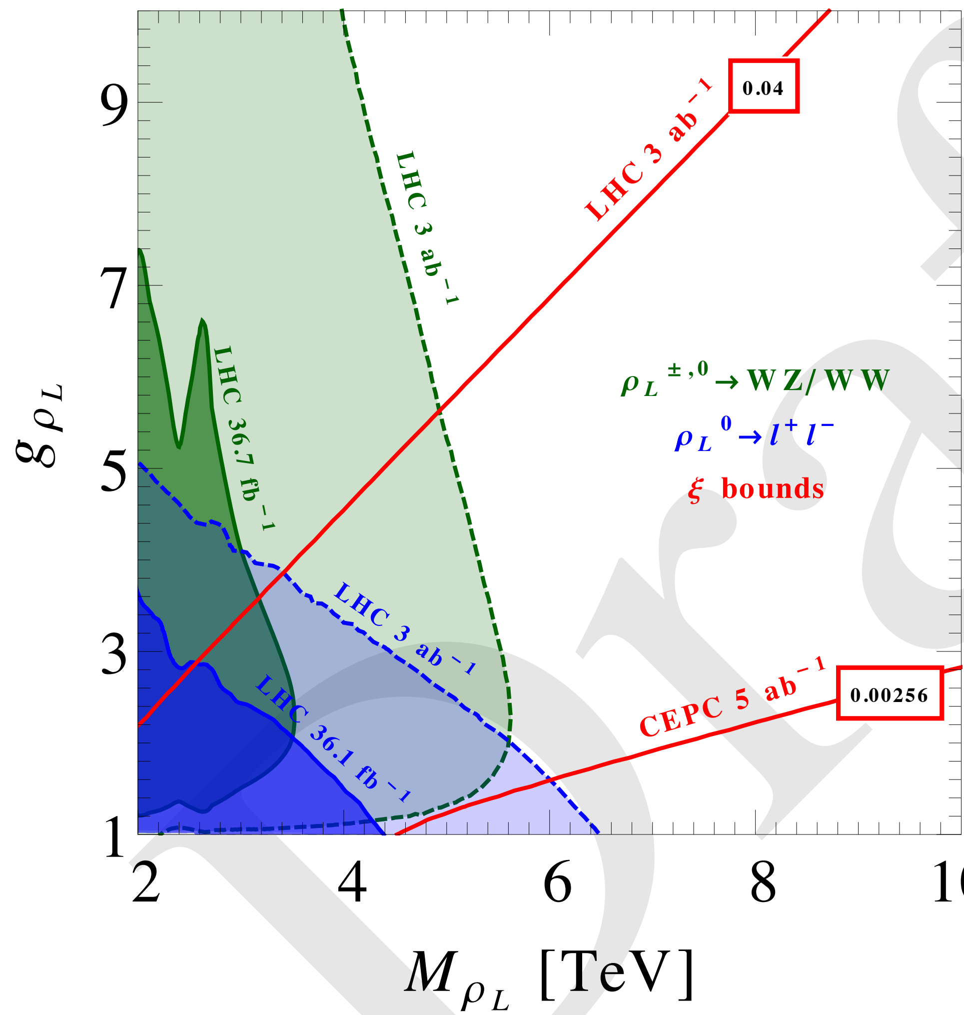
- LHC searches model dependent, many blind spots.

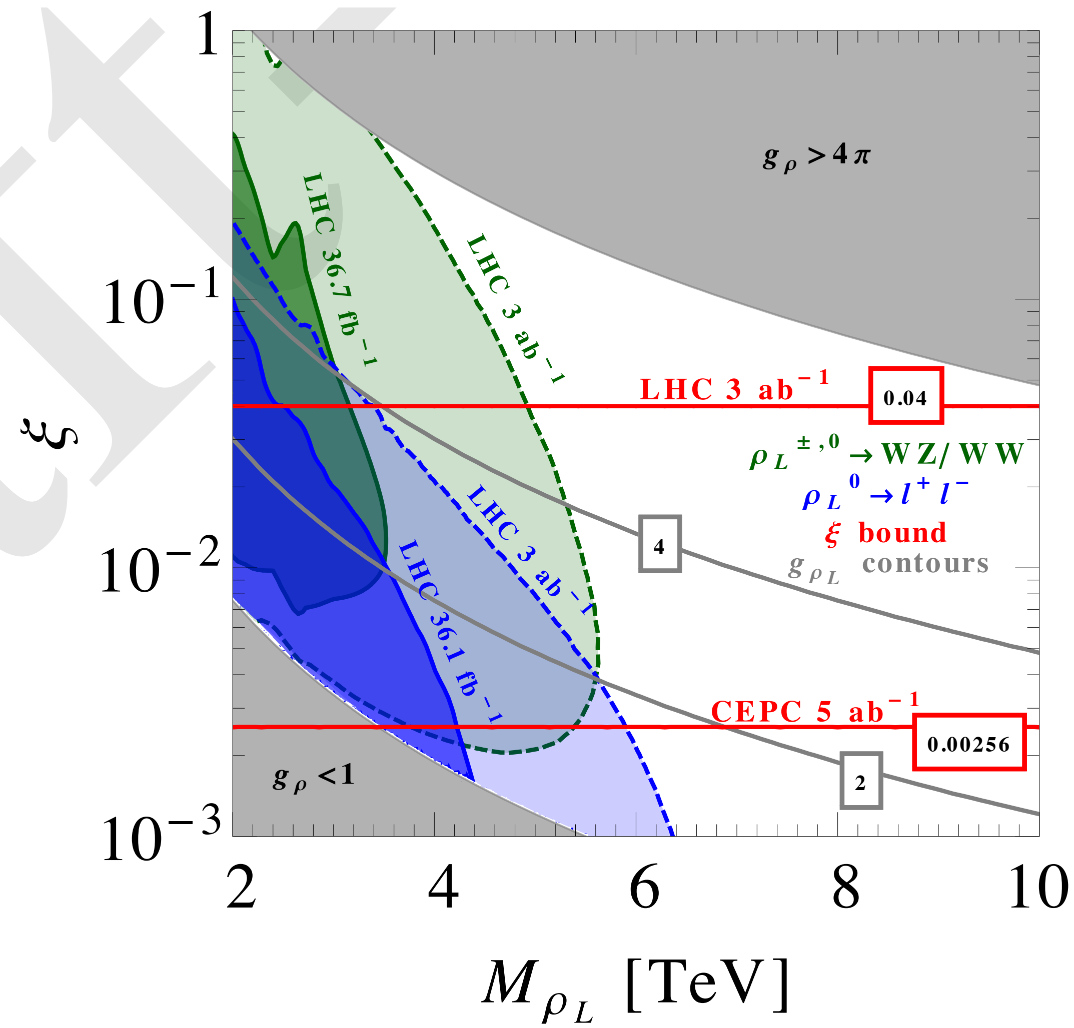




- Testing fine-tuning down to percent level.

Composite Higgs

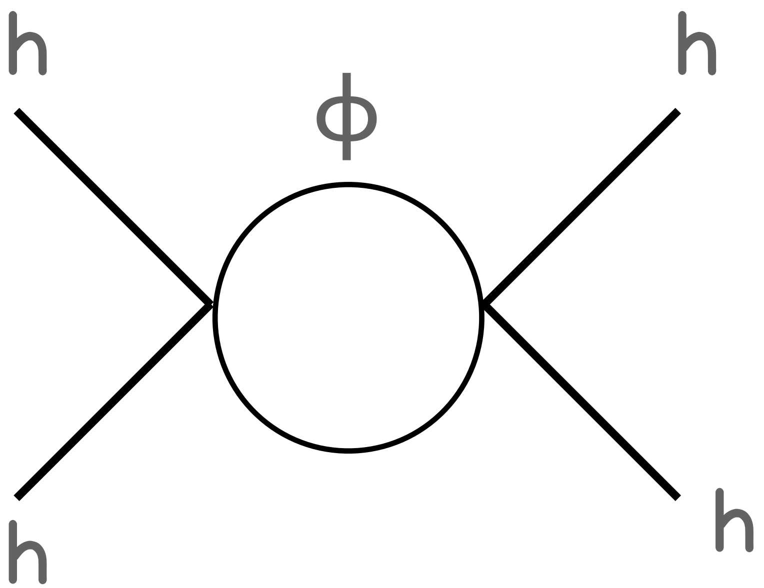


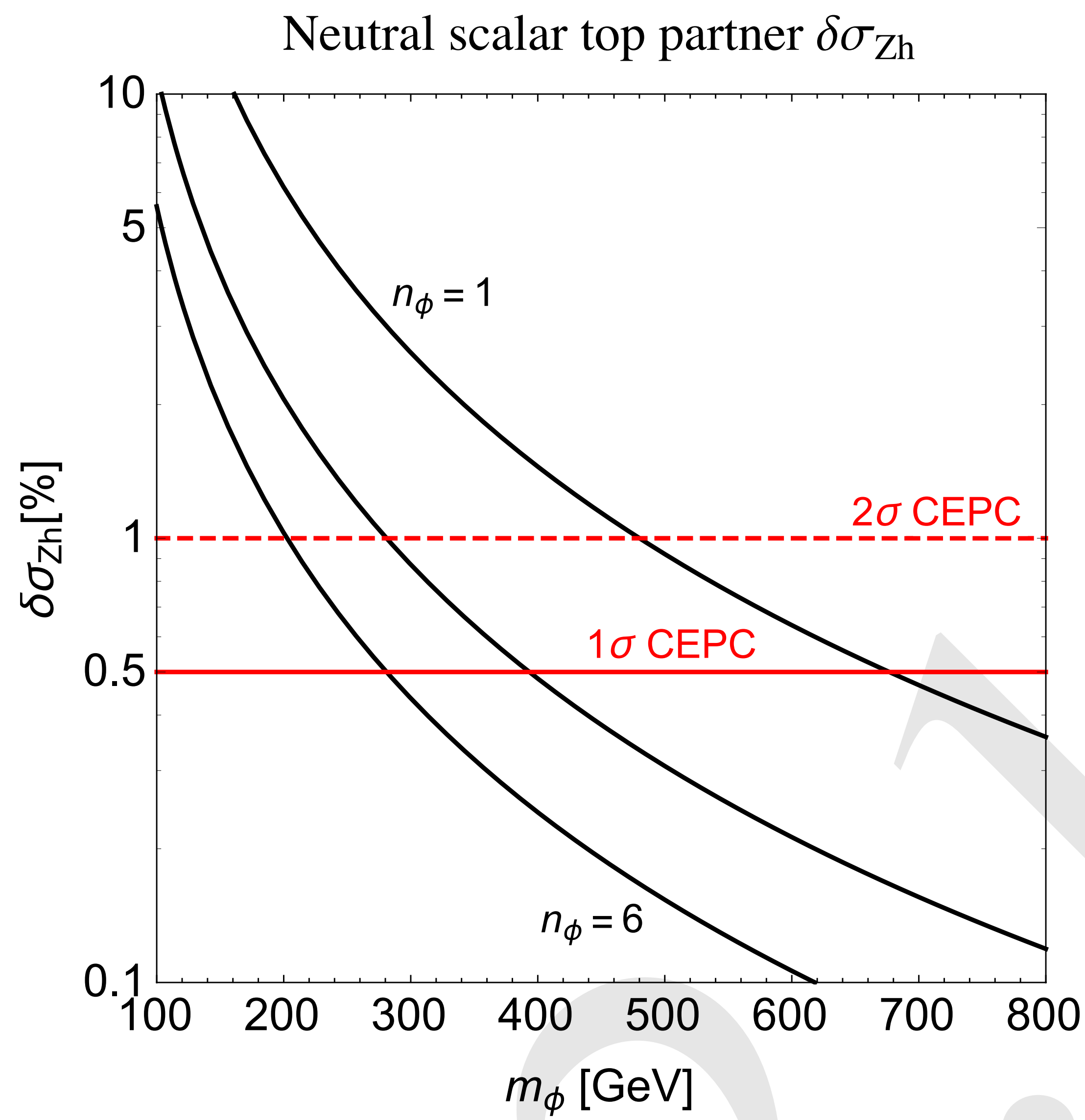


$$\text{fine} - \text{tuning} \propto \xi = \frac{v^2}{f^2} \qquad\qquad \delta_{Zh} \simeq 1 - \xi$$

Higgs coupling: good test of fine-tuning

Neutral naturalness.



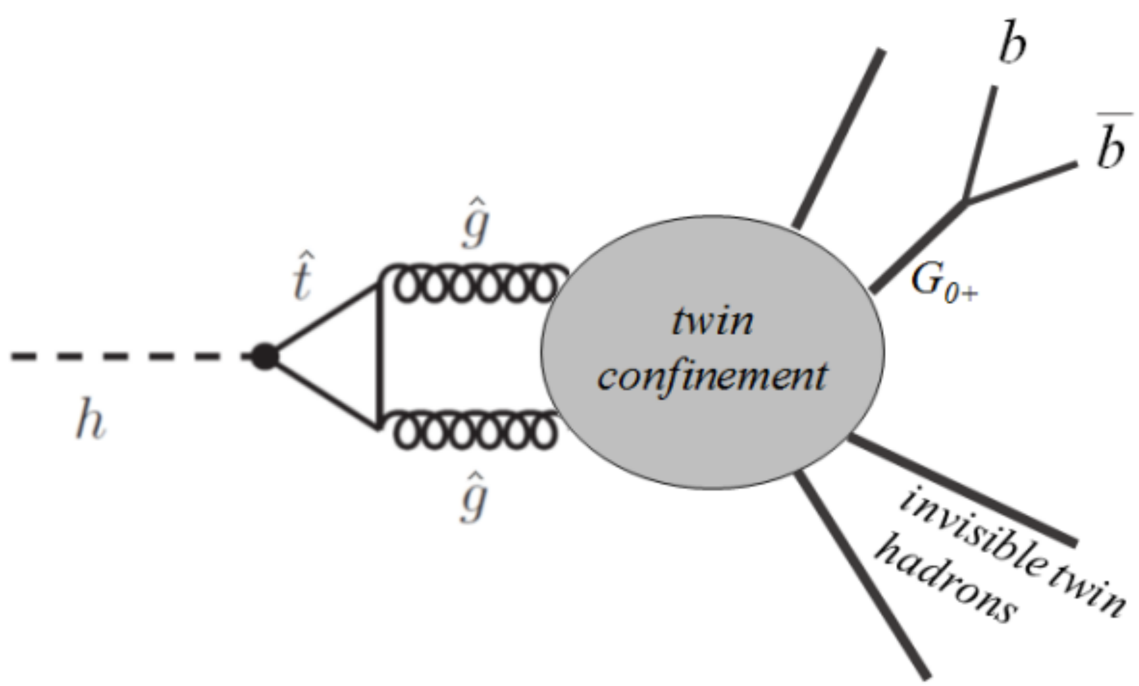


Top partner not colored. Probed through loop correction to h-Z coupling.

Stealthy top partner. "twin"

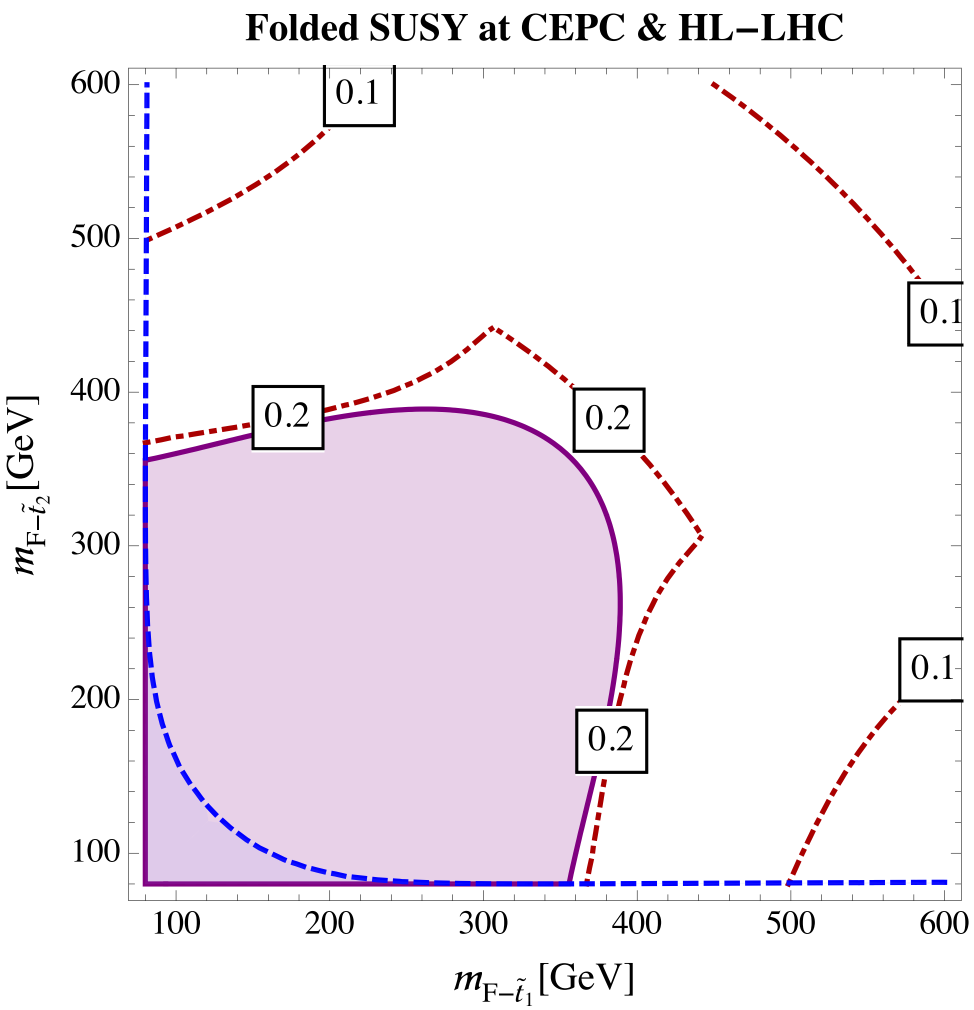
Chacko, Goh, Harnik

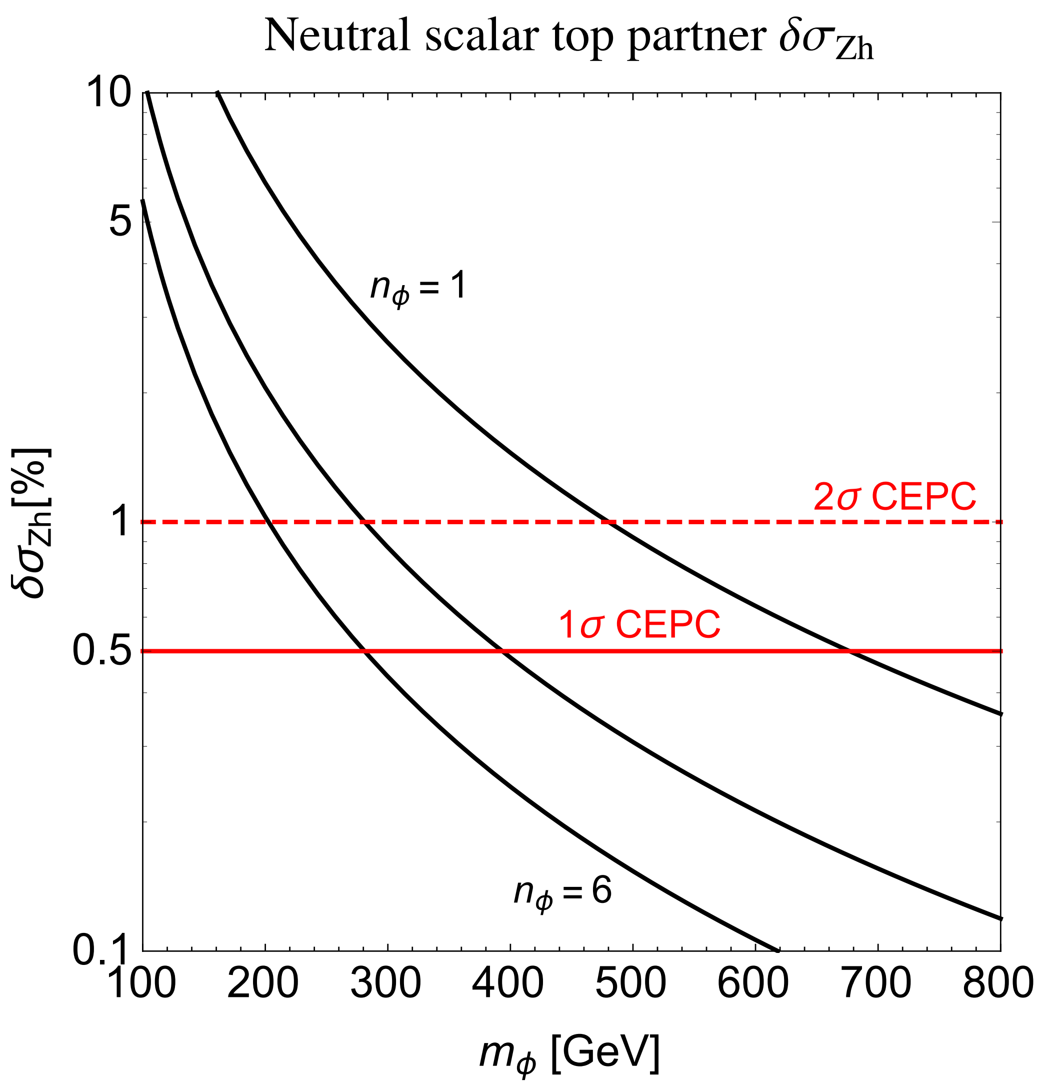
Craig, Katz, Strassler, Sundrum



- Top partner not colored. Higgs decay through hidden world and back.
- Can lead to Higgs rare decays.

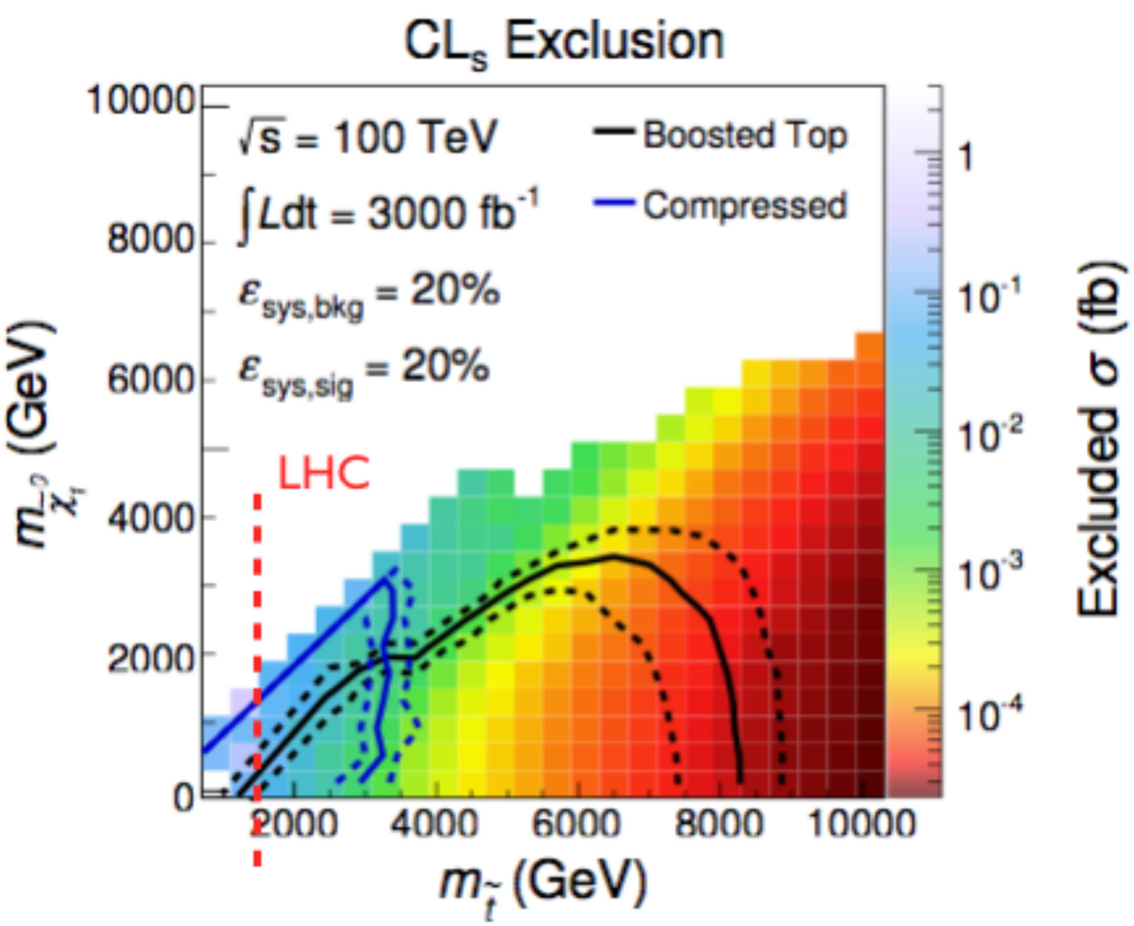
Scalar top partner:



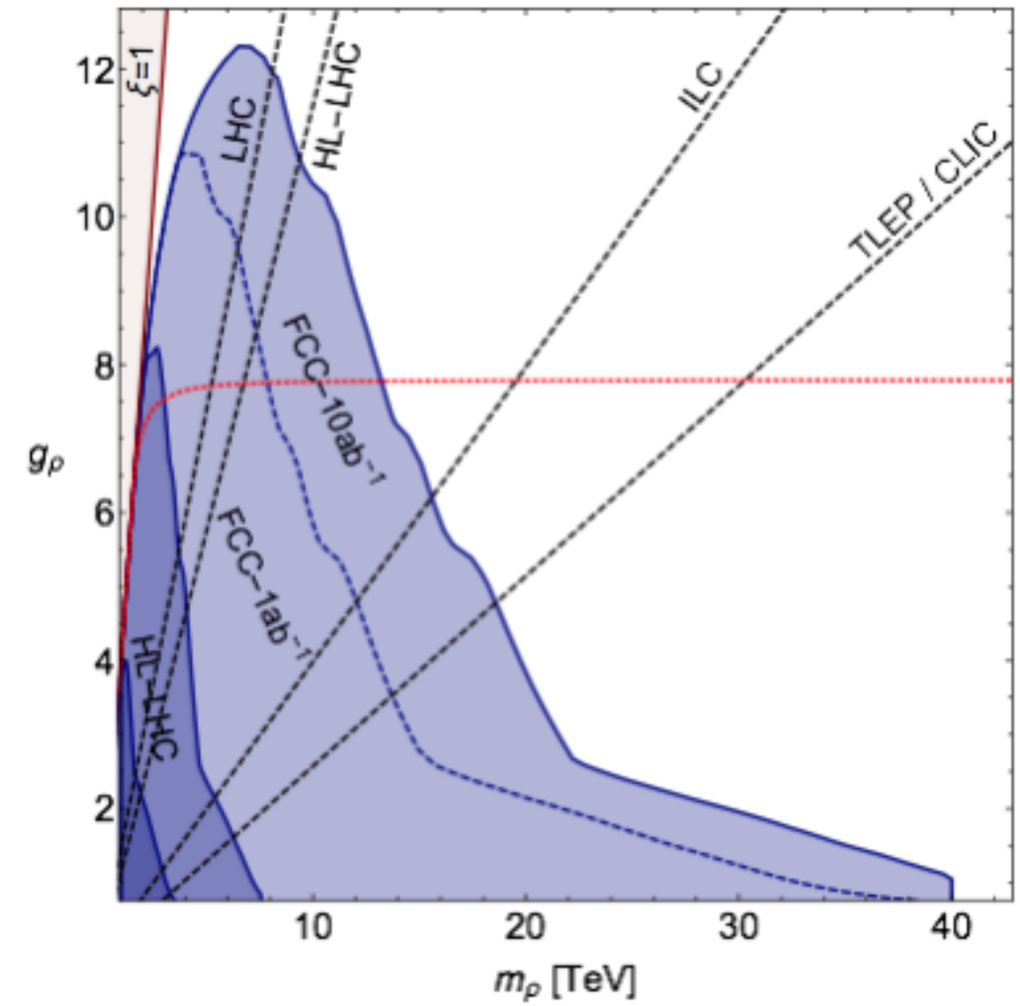


Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



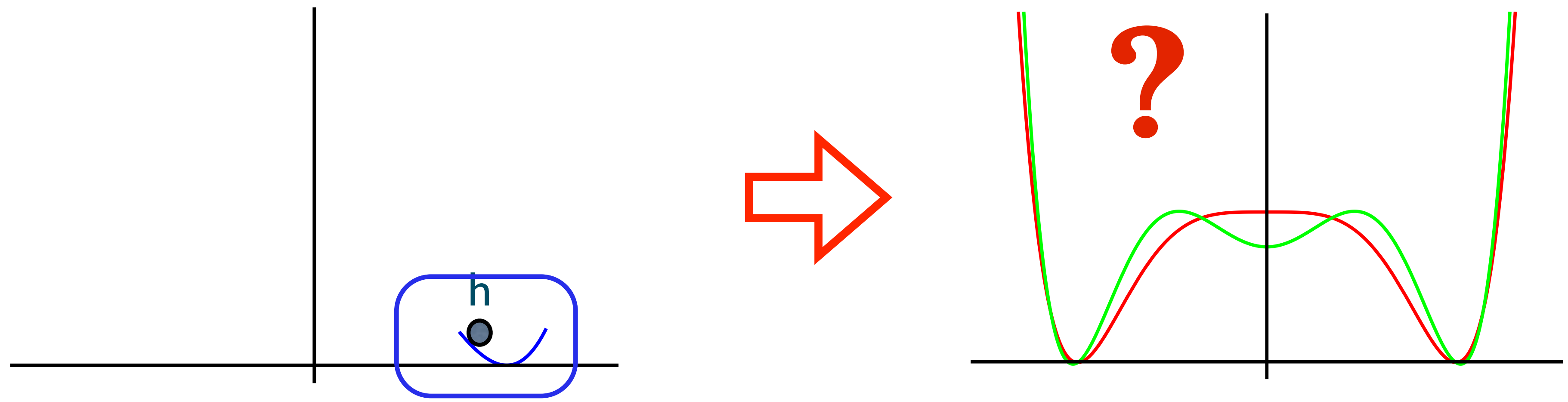
Pappadopulo, Thamm, Torre, Wulzer, 2014



Fine tuning $\propto M_{\rm NP}^2$

Go much beyond the LHC.

Nature of EW phase transition



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

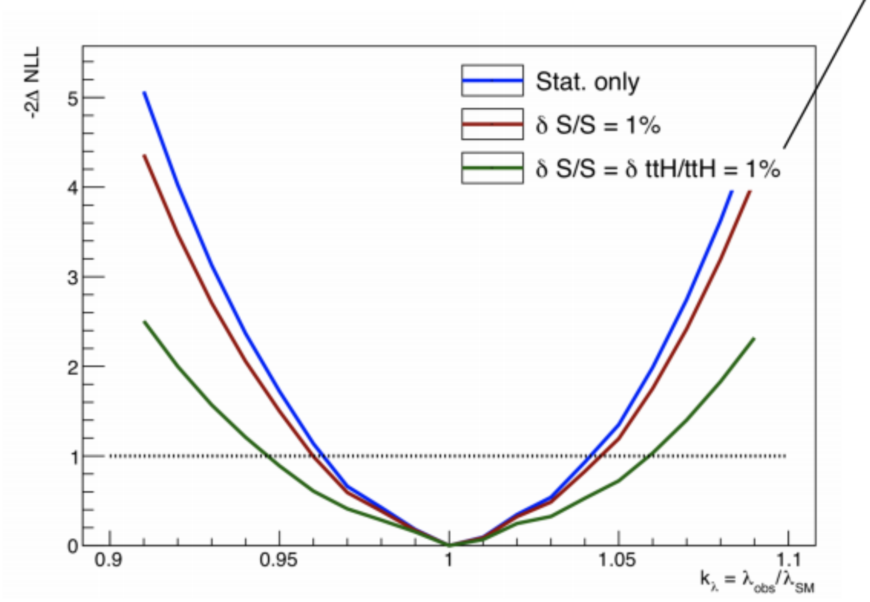
"wiggles" in Higgs potential

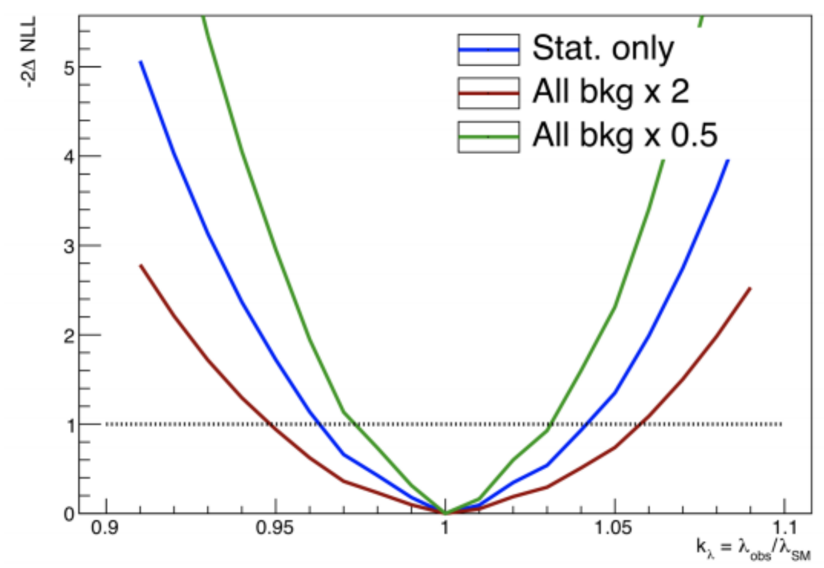
Big difference in triple Higgs coupling

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

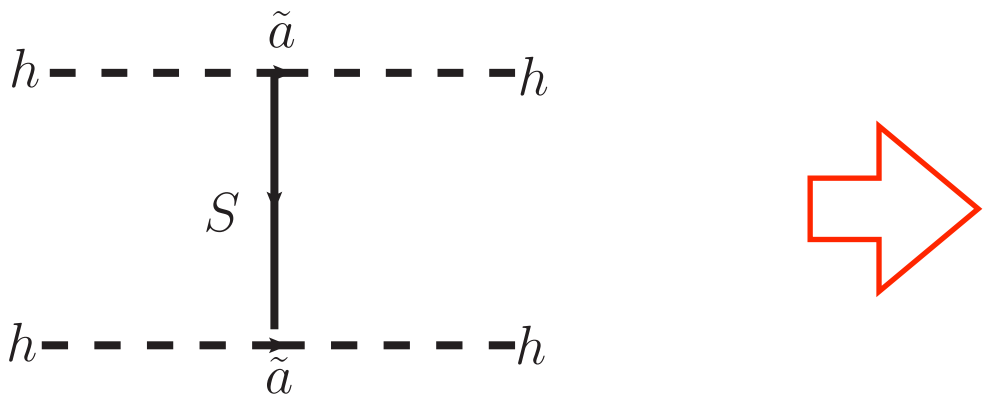
But, there should be more

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

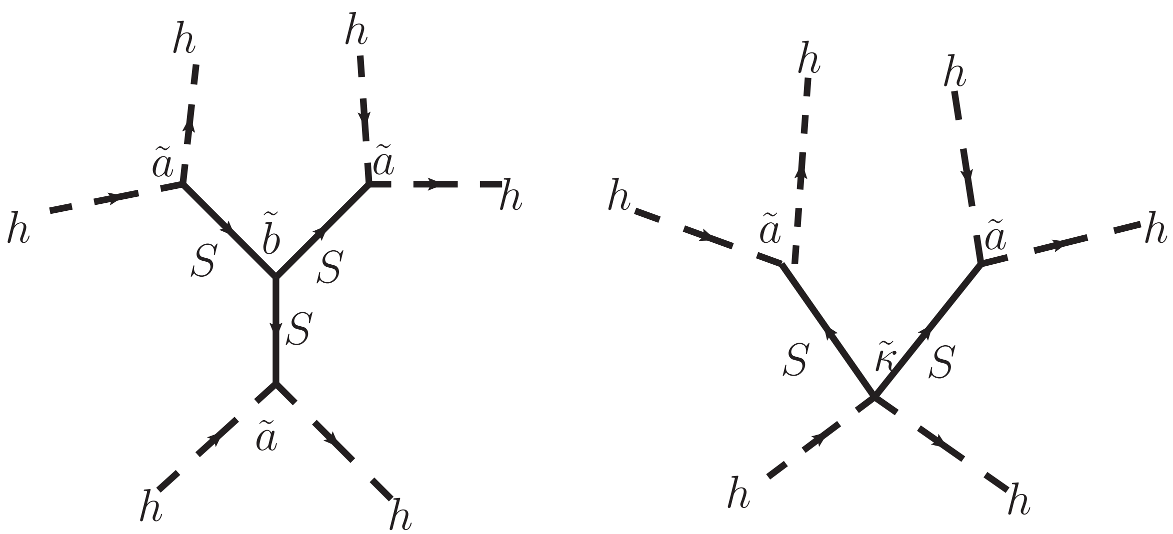
- 1st order EW phase transition means there is new physics close to the weak scale.
- We can look for them at high energy colliders. (More studies needed)
- Generically, will leave more signature in Higgs coupling, in addition to the triple Higgs coupling.

For example

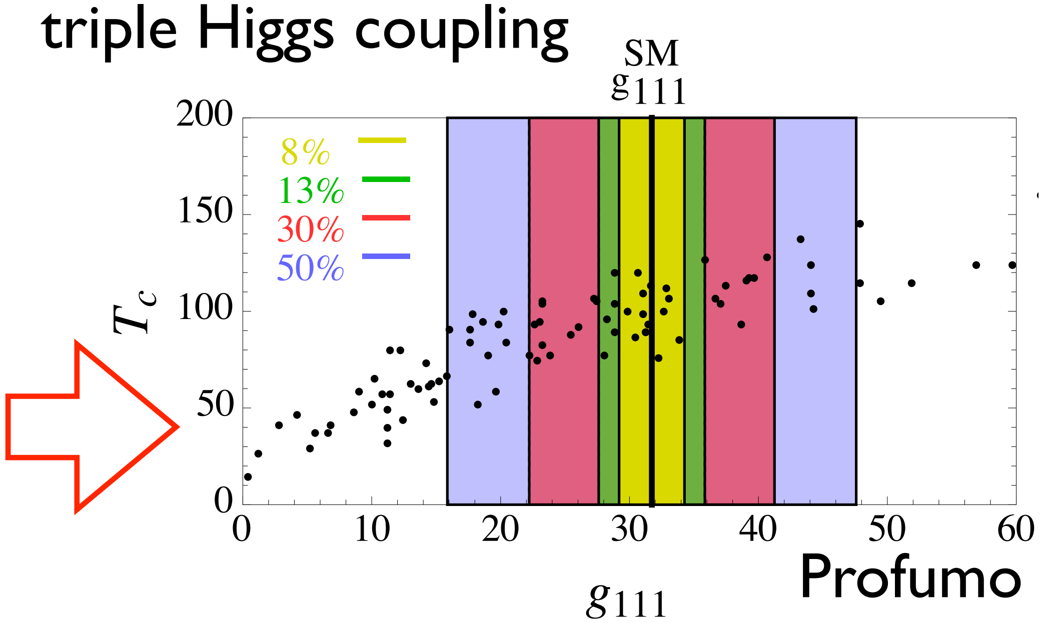
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



shift in h-Z coupling



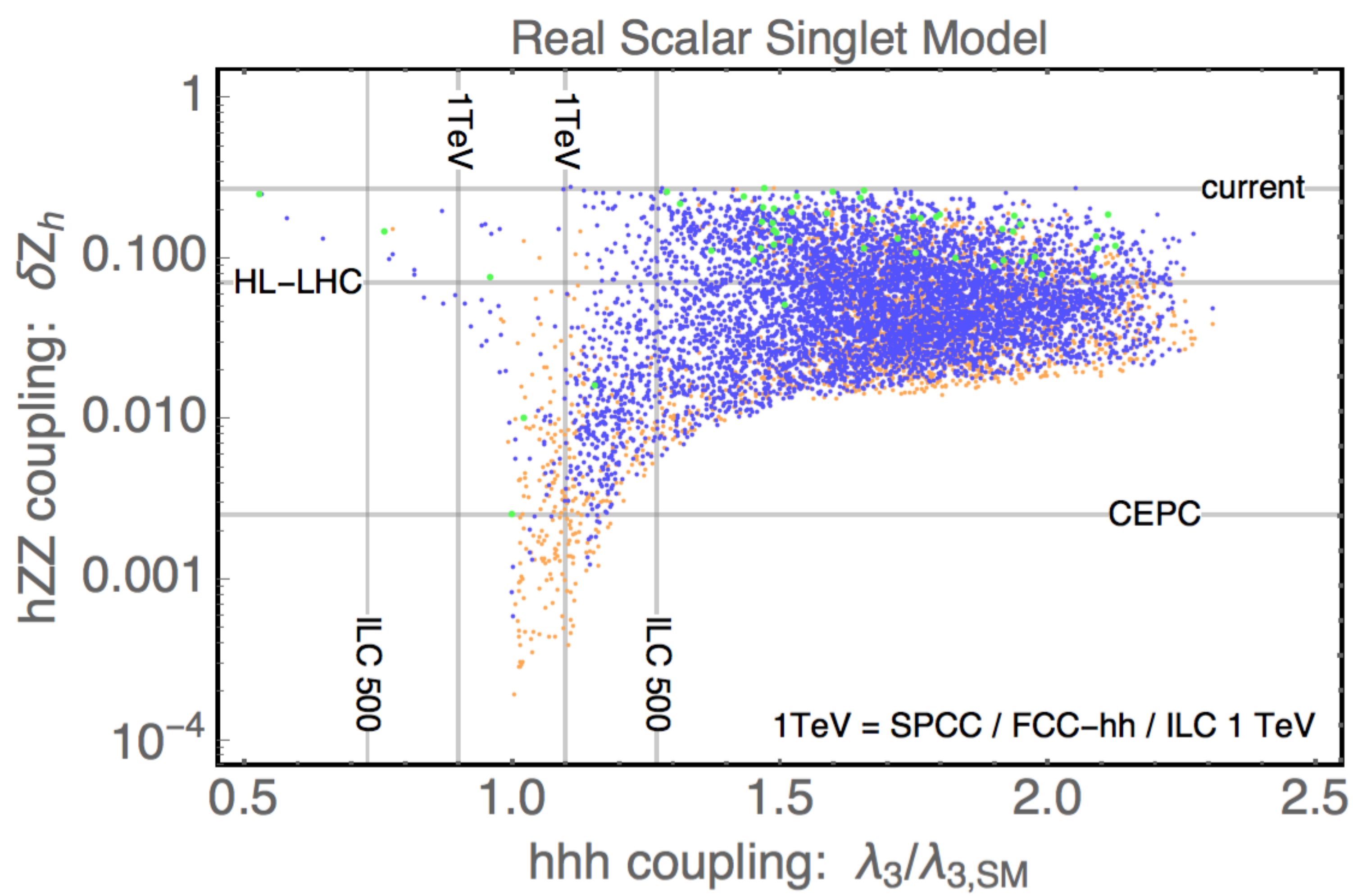
triple Higgs coupling



Profumo et al

– Both within the reach of the Higgs factories.

Probing EWSB at higgs factories

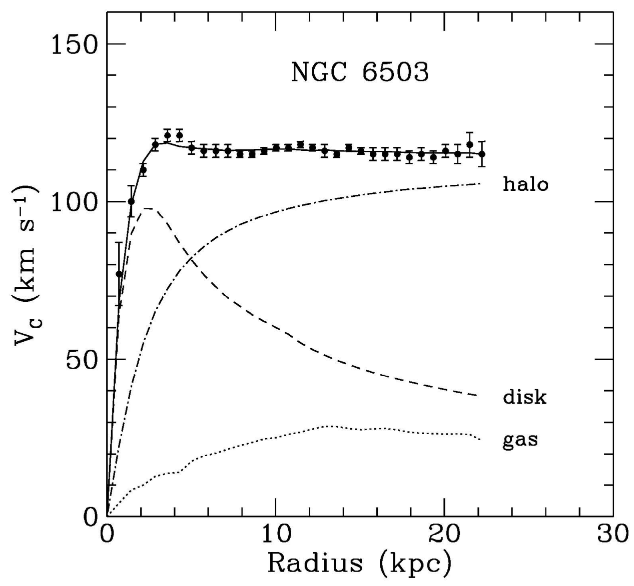


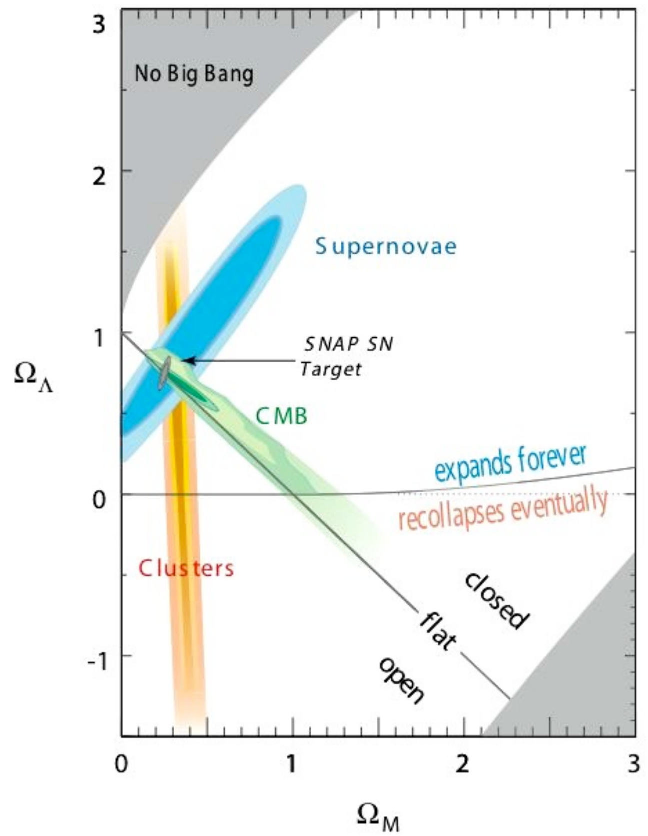
Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

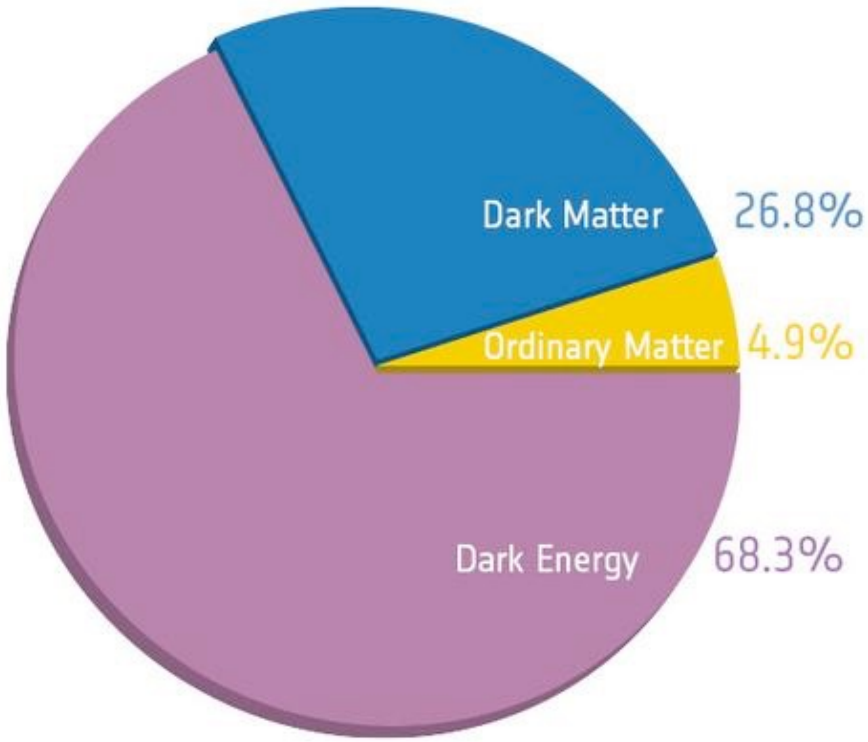
Huang, Long, LTW, 1608.06619

Good coverage in model space

Dark matter



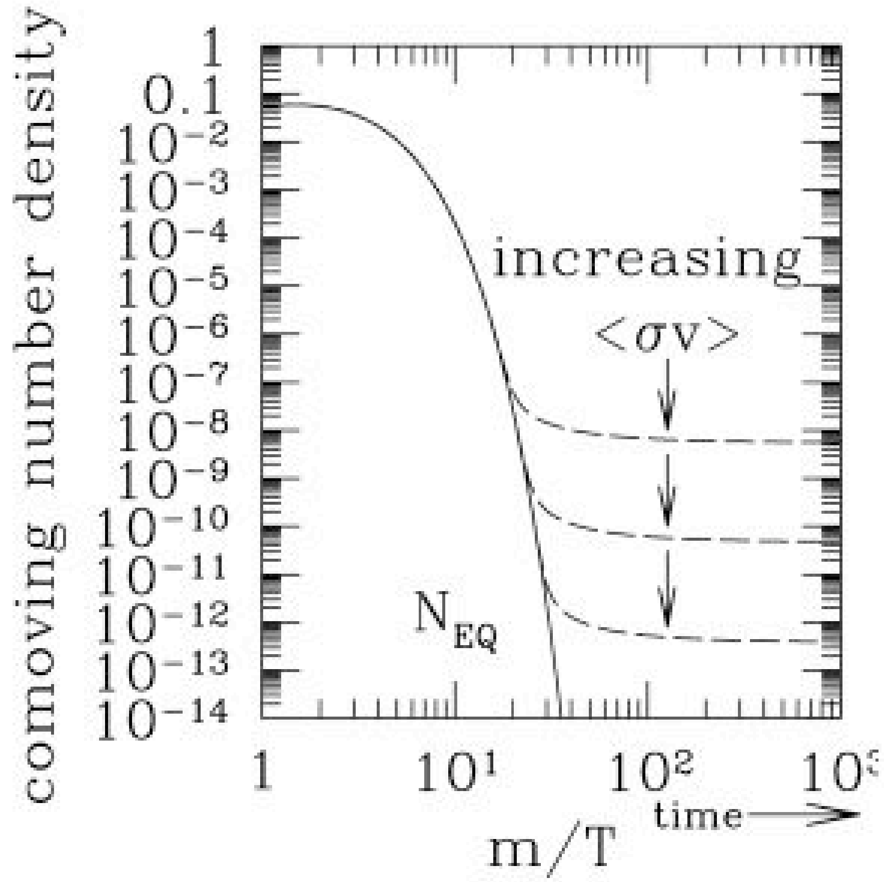


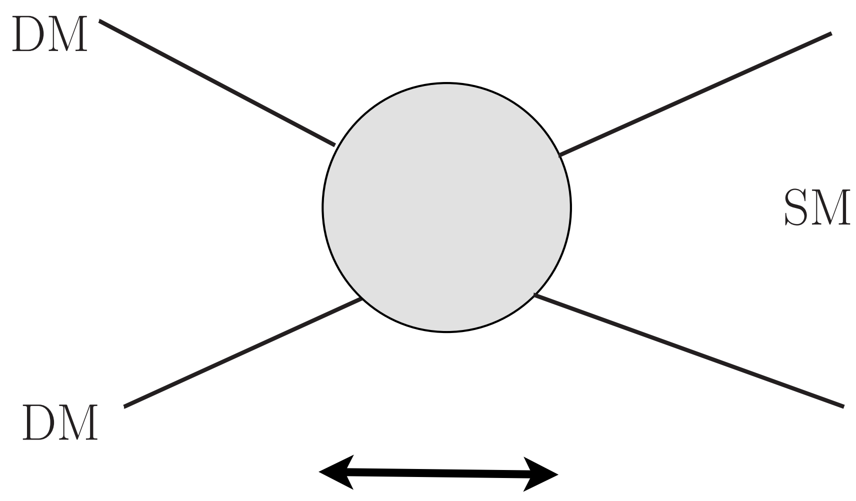


It is there.
Only seen its gravitational interaction.

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

WIMP mass





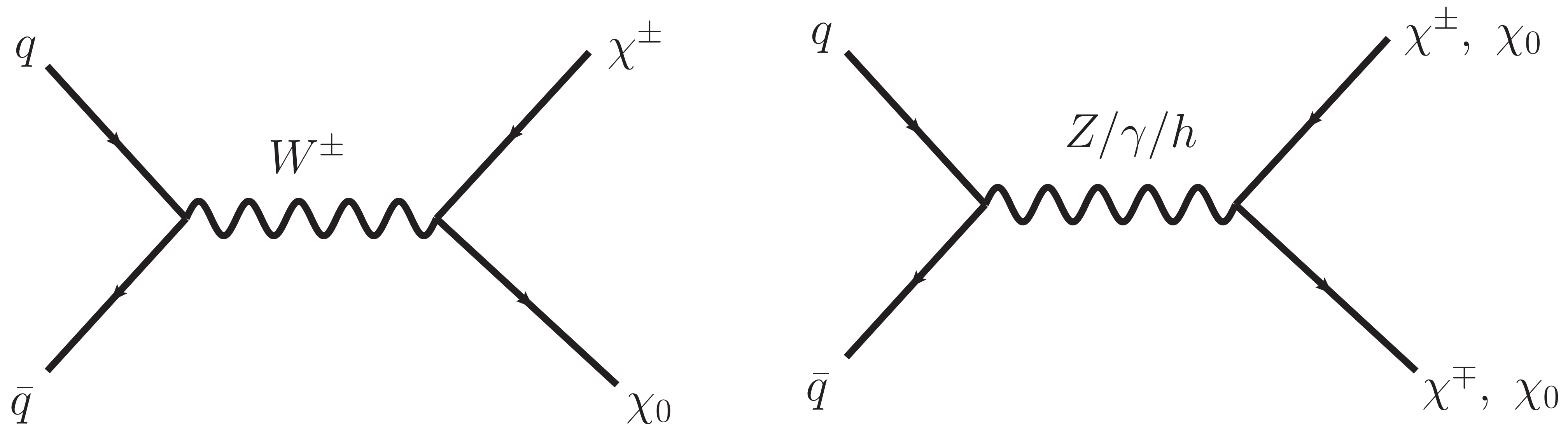
$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- More precisely, to get the correct relic abundance

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

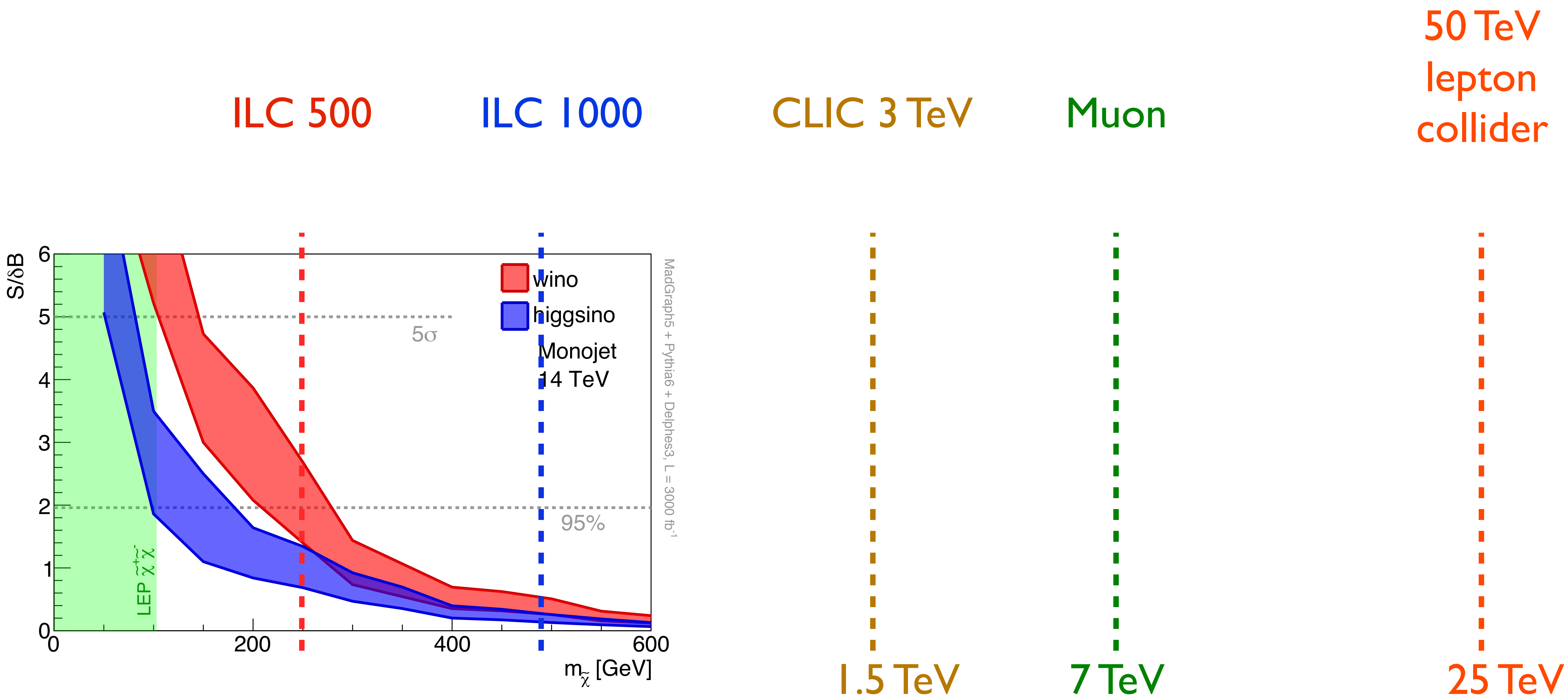
TeV-ish in simplest models

Simplest WIMP: part of weak multiplet



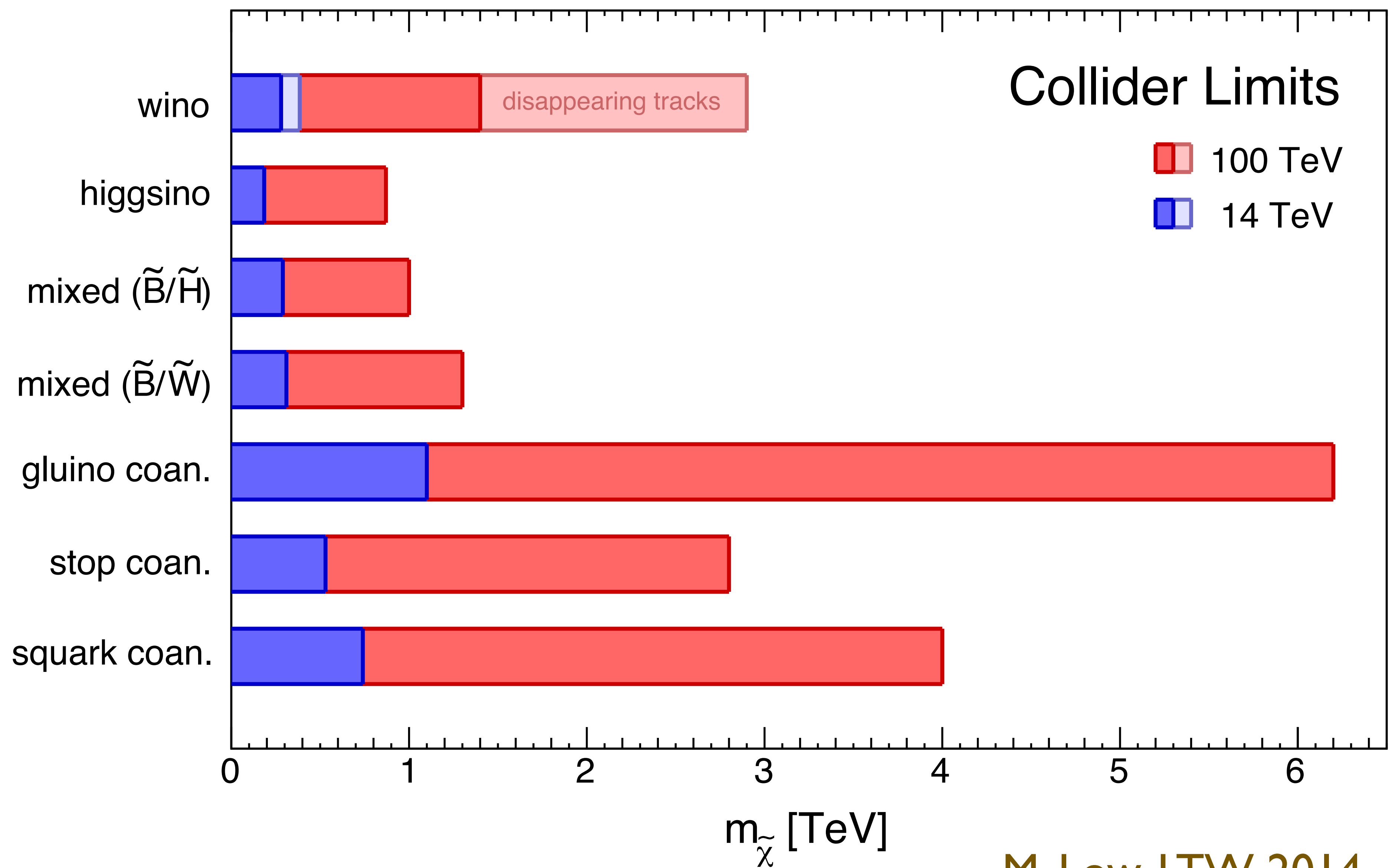
- Mediated by W/Z/h.
- Predictive, no unkown particle as mediator.
- The original WIMP proposal.

Mono-X



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

Dark matter with Mono-jet



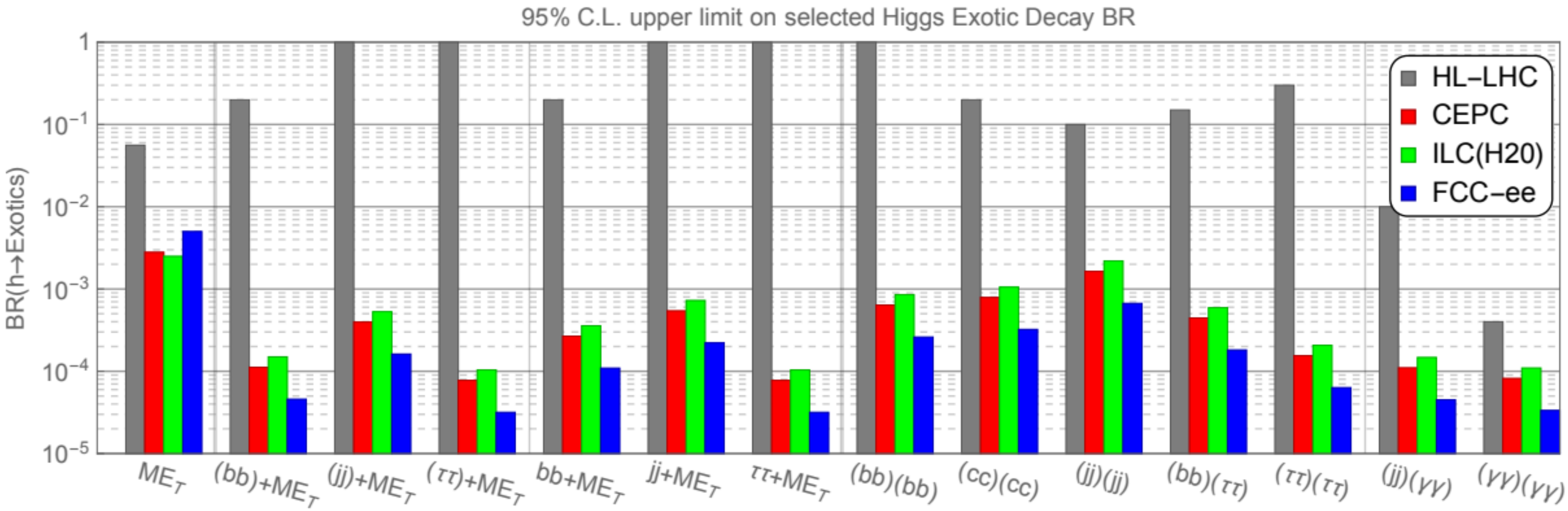
M. Low, LTW 2014

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

More exotic searches

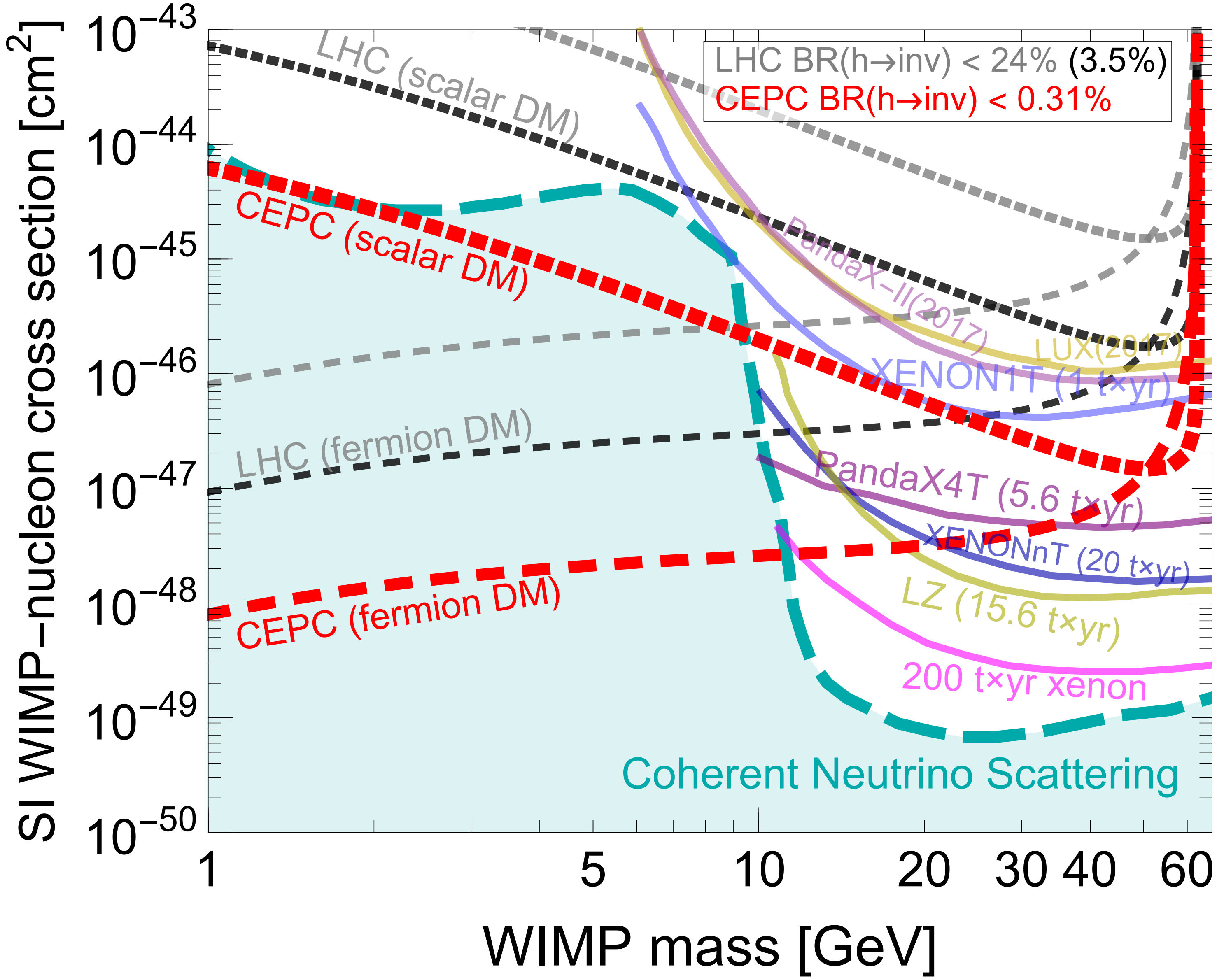
A long list, enriching the future collider physics program

Higgs exotic decay

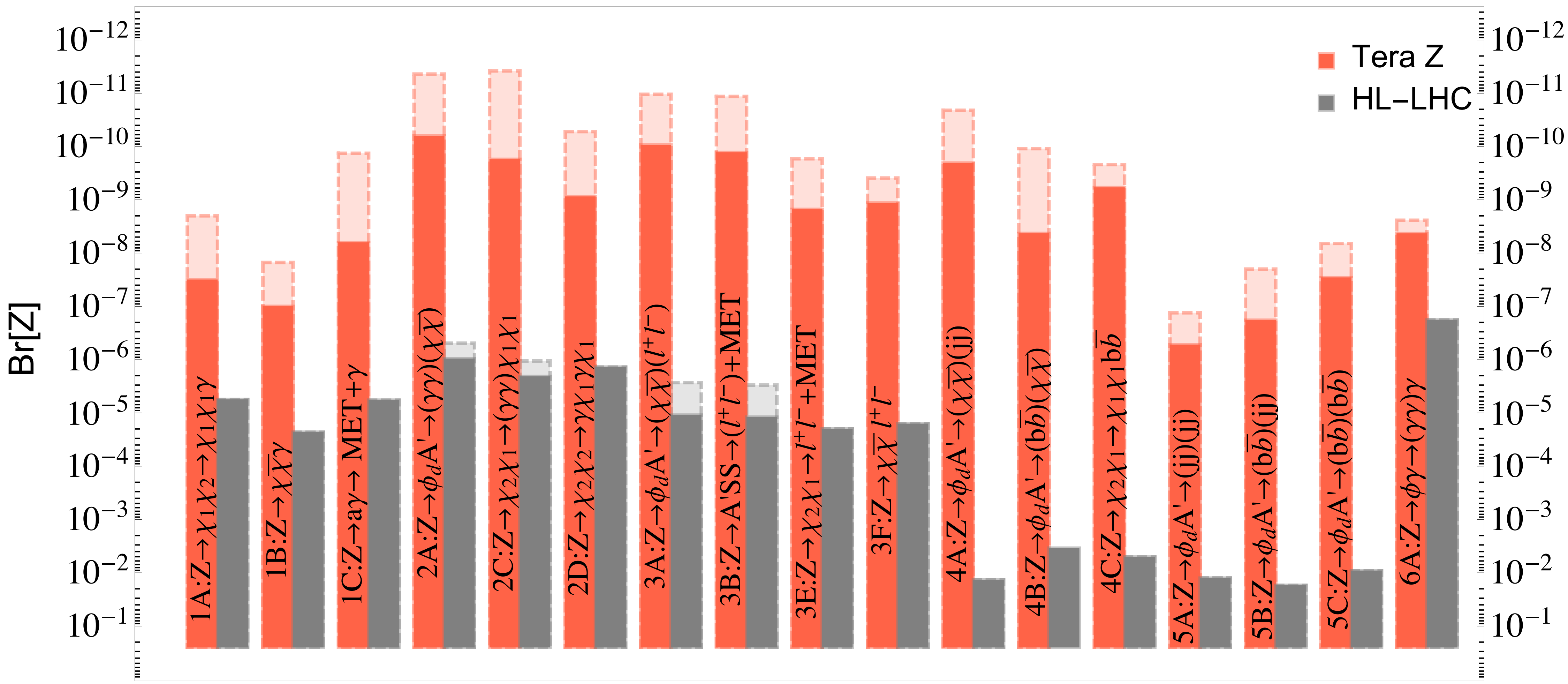


Complementary to hadron collider searches

Higgs portal dark matter

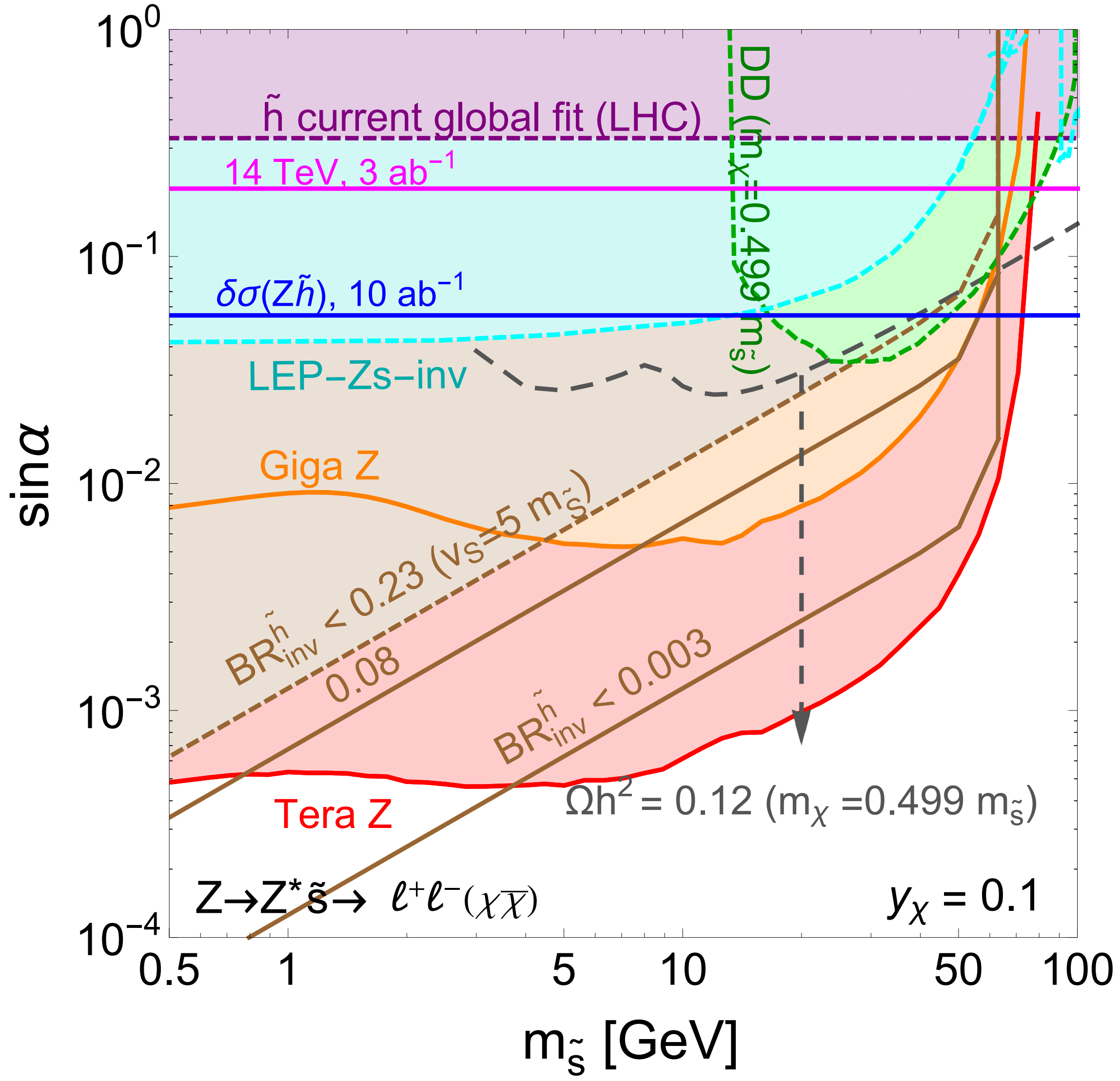


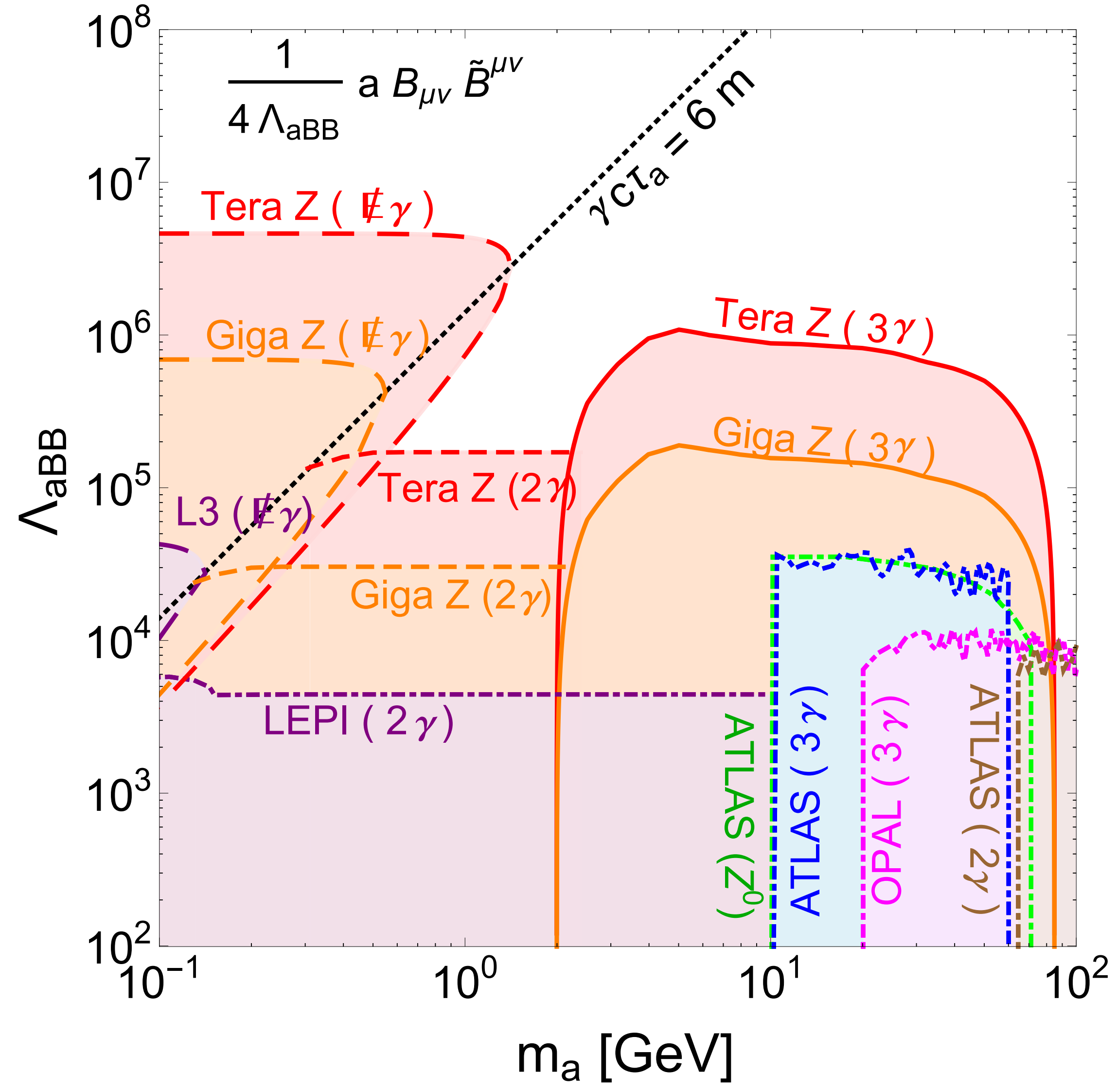
Rare Z decay



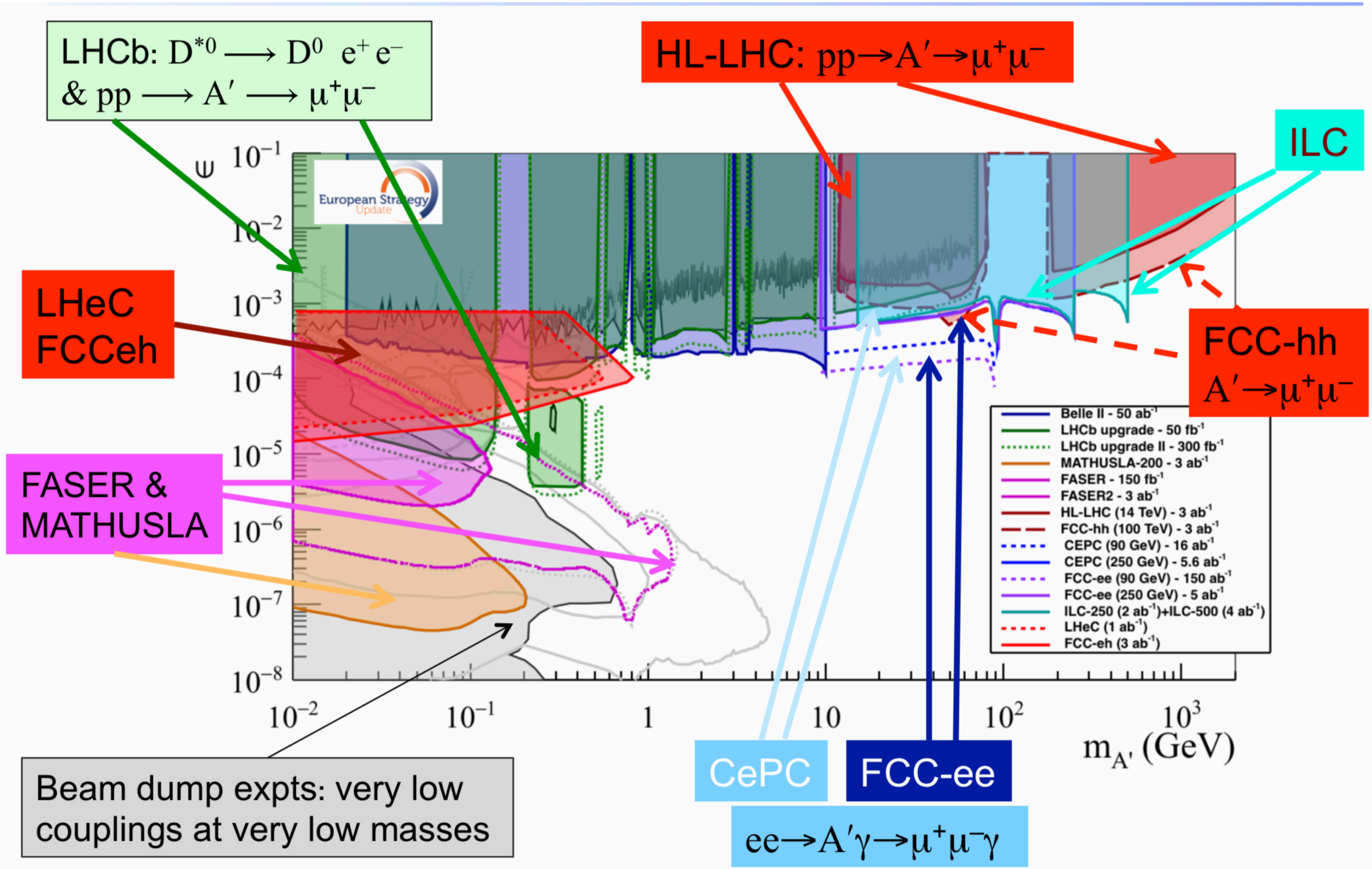
Tera Z
HL−LHC
Br[Z]
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1A:Z→$\chi_1\chi_2\to\chi_1\chi_1\gamma$
1B:Z→$\chi\bar{\chi}\gamma$
1C:Z→$a\gamma\to$ MET+γ
2A:Z→ϕ_dA'→$(\gamma\gamma)(\chi\bar{\chi})$
2C:Z→$\chi_2\chi_1\to(\gamma\gamma)\chi_1\chi_1$
2D:Z→$\chi_2\chi_2\to\gamma\chi_1\gamma\chi_1$
3A:Z→ϕ_dA'→$(\chi\bar{\chi})(l^+l^-)$
3B:Z→A'SS→(l^+l^-)+MET
3E:Z→$\chi_2\chi_1\to l^+l^-$+MET
3F:Z→$\chi\bar{\chi}\,l^+l^-$
4A:Z→ϕ_dA'→$(\chi\bar{\chi})$(jj)
4B:Z→ϕ_dA'→$(b\bar{b})(\chi\bar{\chi})$
4C:Z→$\chi_2\chi_1\to\chi_1\chi_1 b\bar{b}$
5A:Z→ϕ_dA'→(jj)(jj)
5B:Z→ϕ_dA'→$(b\bar{b})$(jj)
5C:Z→ϕ_dA'→$(b\bar{b})(b\bar{b})$
6A:Z→$\phi\gamma\to(\gamma\gamma)\gamma$

Dark sector at Z factory



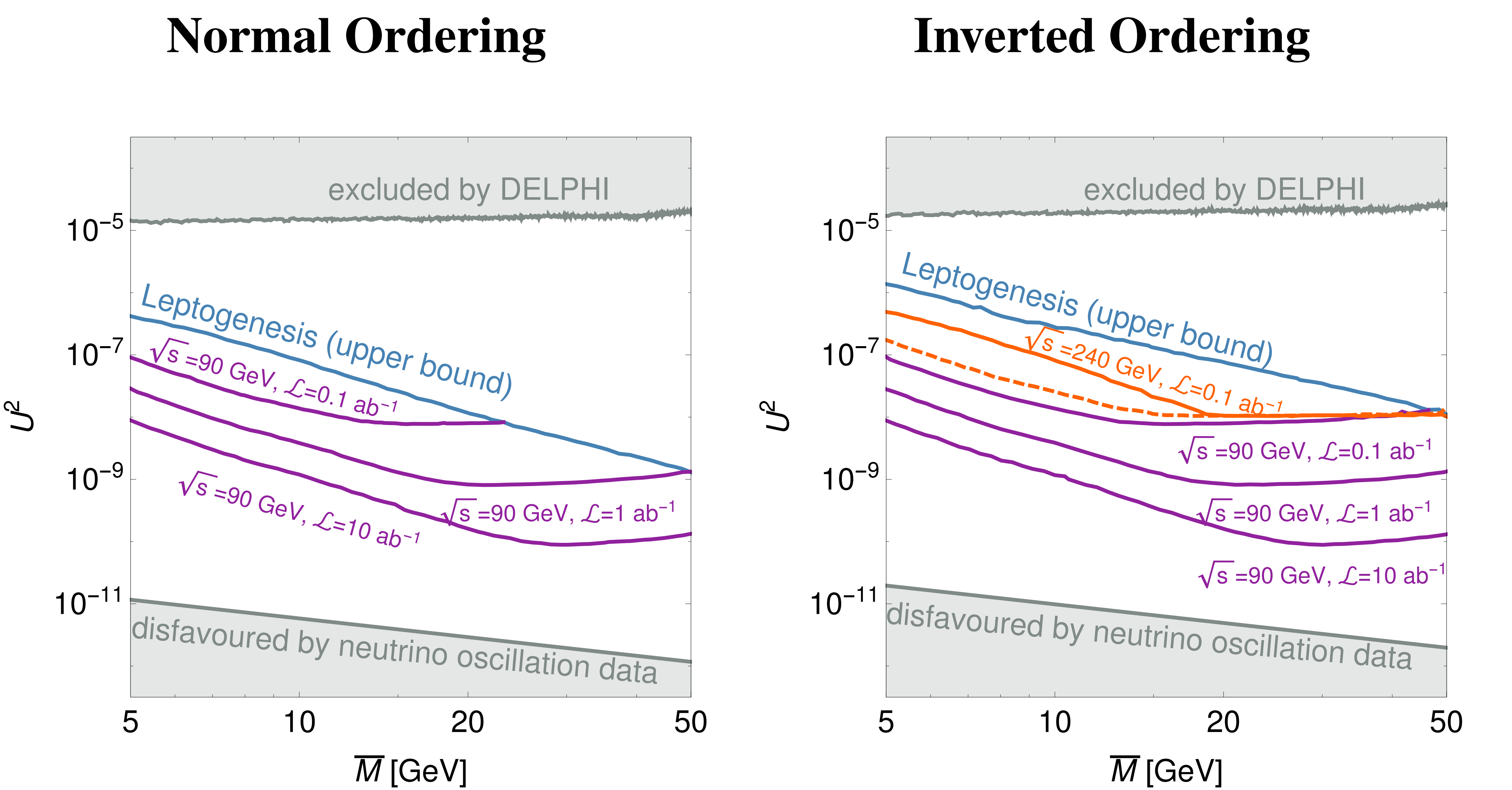


Dark sector



LHCb: D*0 ⟶ D0 e+ e−
& pp ⟶ A′ ⟶ μ+μ−
HL-LHC: pp→A′→μ+μ−
ILC
LHeC
FCCeh
FASER &
MATHUSLA
FCC-hh
A′→μ+μ−
European Strategy Update
ε
10−1
10−2
10−3
10−4
10−5
10−6
10−7
10−8
10−2
10−1
1
10
102
103
mA′ (GeV)
Belle II - 50 ab-1
LHCb upgrade - 50 fb-1
LHCb upgrade II - 300 fb-1
MATHUSLA-200 - 3 ab-1
FASER - 150 fb-1
FASER2 - 3 ab-1
HL-LHC (14 TeV) - 3 ab-1
FCC-hh (100 TeV) - 3 ab-1
CEPC (90 GeV) - 16 ab-1
CEPC (250 GeV) - 5.6 ab-1
FCC-ee (90 GeV) - 150 ab-1
FCC-ee (250 GeV) - 5 ab-1
ILC-250 (2 ab-1)+ILC-500 (4 ab-1)
LHeC (1 ab-1)
FCC-eh (3 ab-1)
CePC
FCC-ee
ee→A′γ→μ+μ−γ
Beam dump expts: very low
couplings at very low masses

Sterile neutrino



low scale see-saw models

Flavor

Particle production

Particle	@ Tera-Z	@ Belle II		@ LHCb
b hadrons				
B^+	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}
c hadrons				
D^0	2×10^{11}			
D^+	6×10^{10}			
D_s^+	3×10^{10}			
Λ_c^+	2×10^{10}			
τ^+	3×10^{10}	5×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	

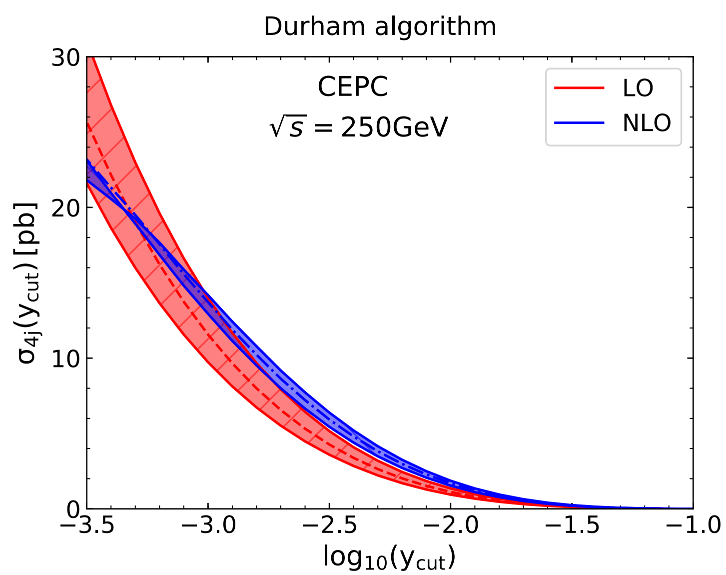
From CEPC's CDR using fragmentation ratios from Amhis et al, 17

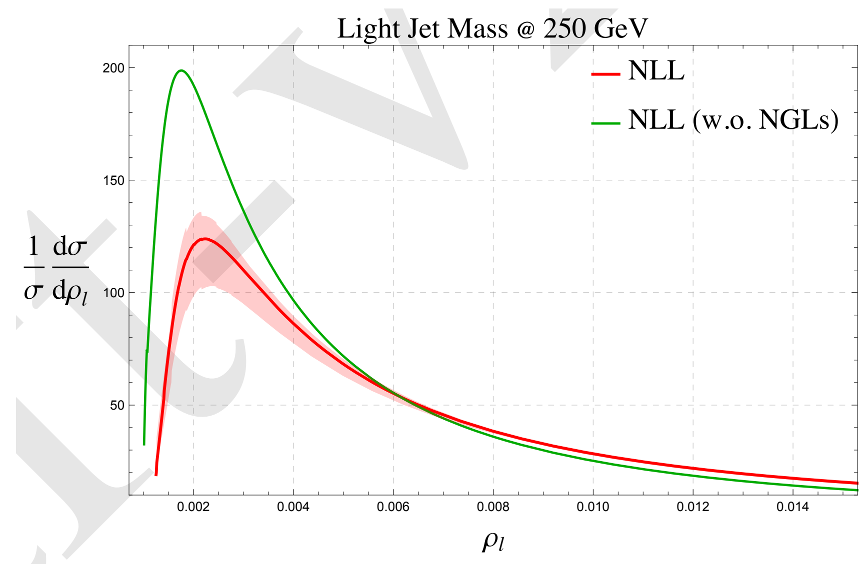
- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and CEPC
- Two order of magnitude more B_s at CEPC wrt to Belle 2
- b-baryon physics possible at the CEPC
- Limited possibilities for charm physics at Belle 2

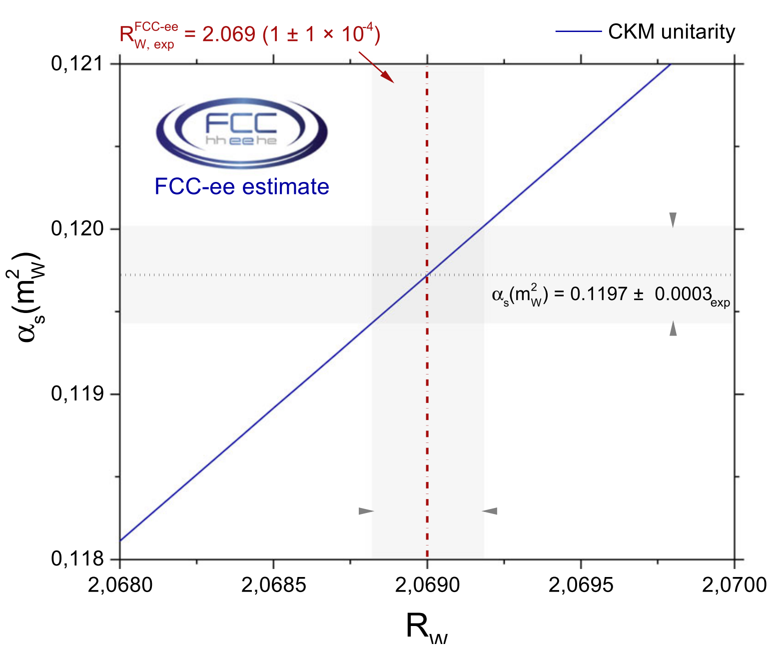
More detailed study needed to understand its full potential

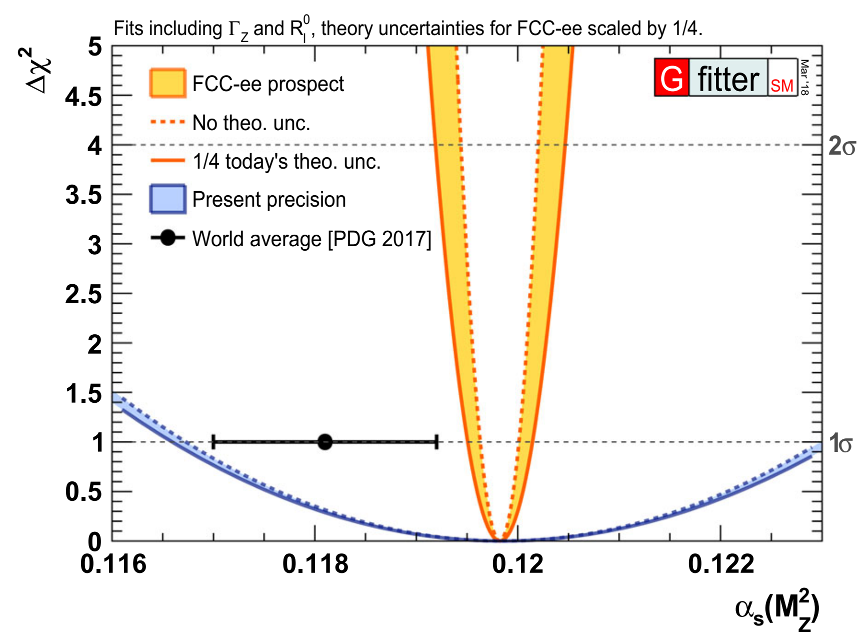
Precision QCD at e+e- collider

- Similar to LEP, but at much higher statistics, higher energy, better detector.





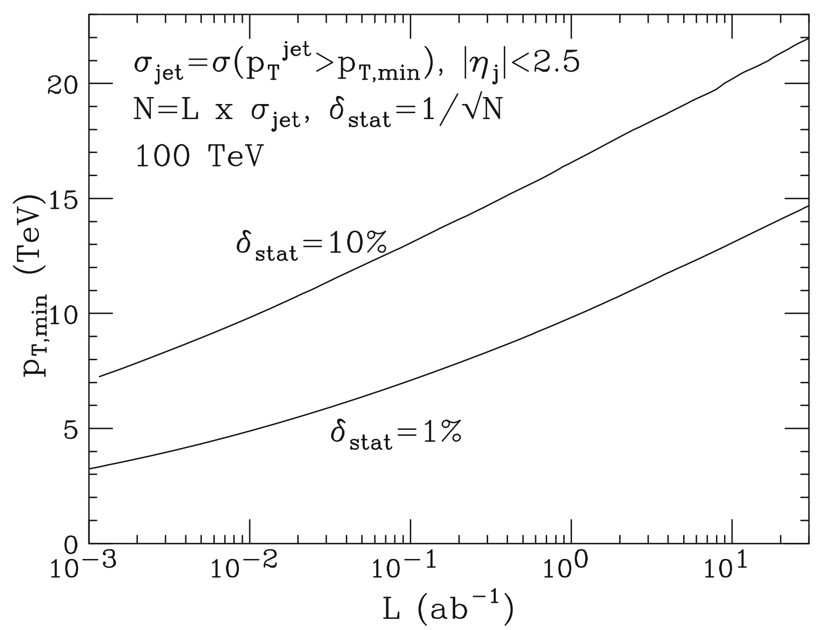




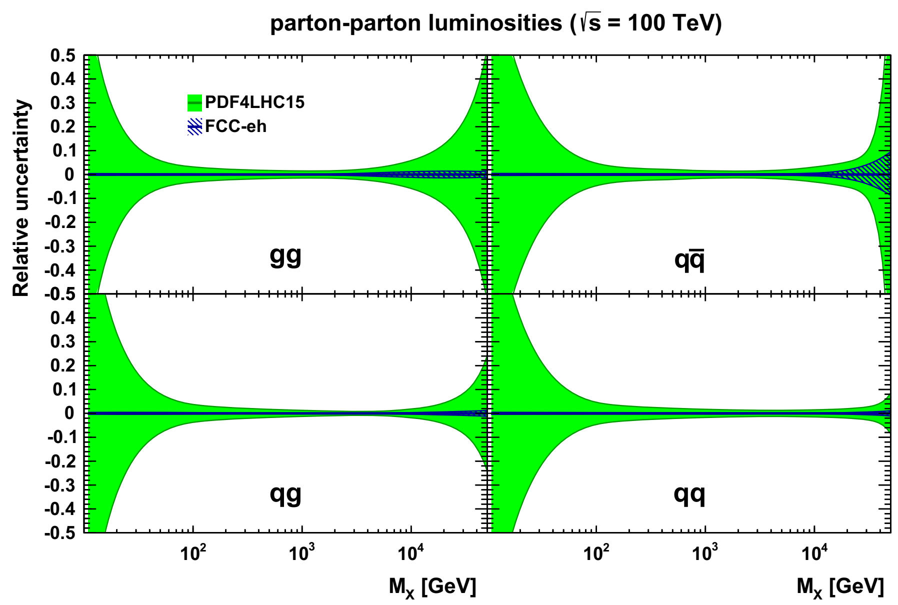
sub-percent measurement of α_S

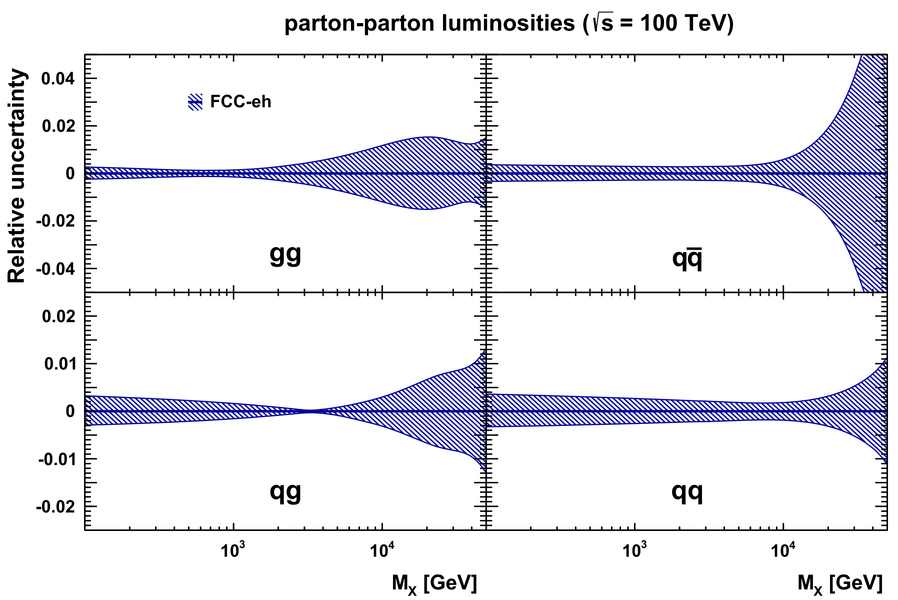
QCD at 100 TeV Hadron collider

FCC CDR



Systematics under better control,
can be at percent level for jets up to 10 TeV





PDF measurement to percent (or better) from FCC-eh

Strong tools for discovery at 100 TeV pp collider!

Some my personal thoughts

Lepton collider: 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
- In an ideal world, good to have both!

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.

40 TeV?

- Worse than 100, by a factor of 40/100.
- Better than the LHC, by a factor of 40/14.
- Good to have of course.
- Is this the most cost effective way of going forward?

Based on national inputs.

Open symposium on European strategy update. Bethke

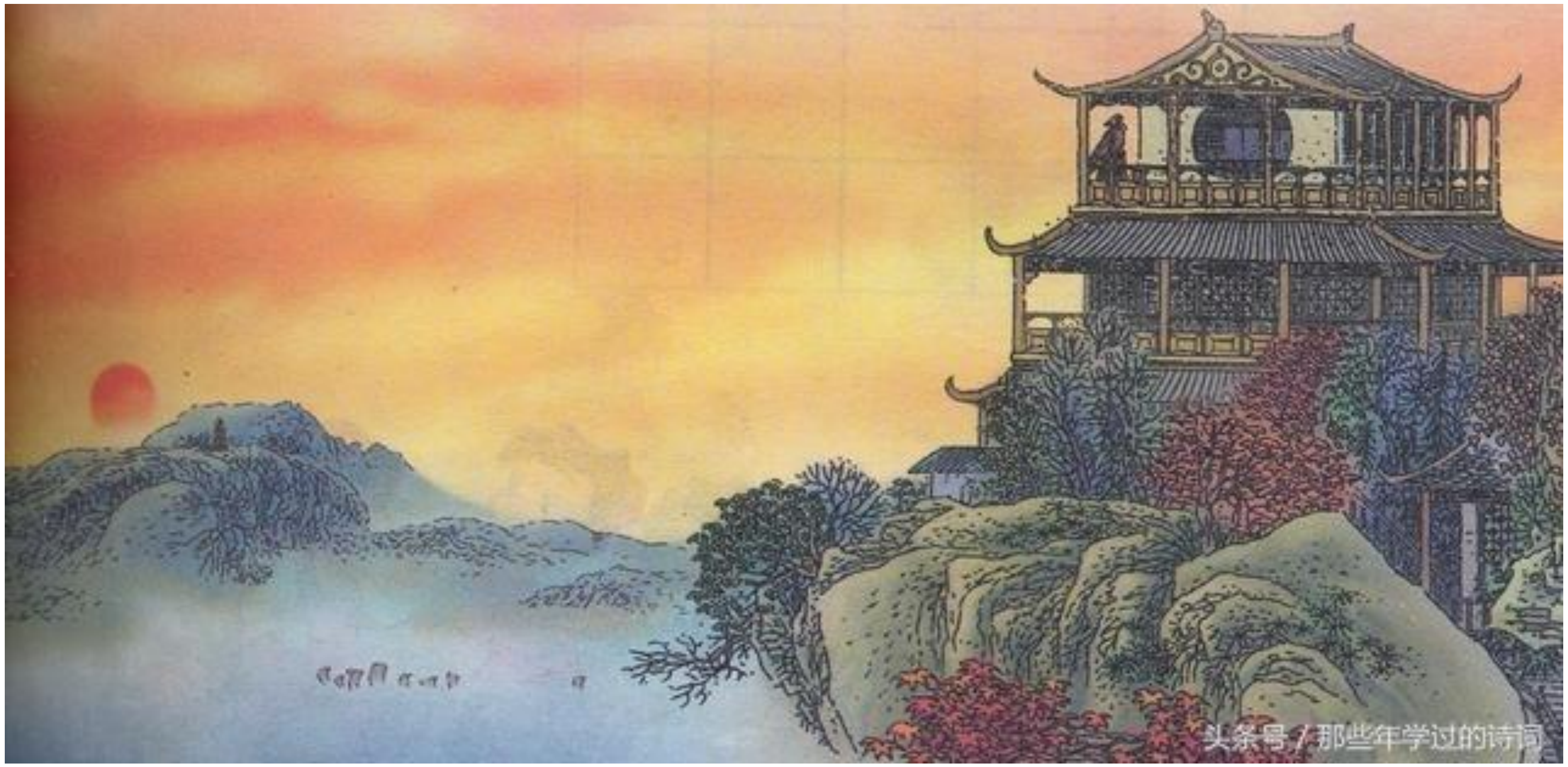
summary:

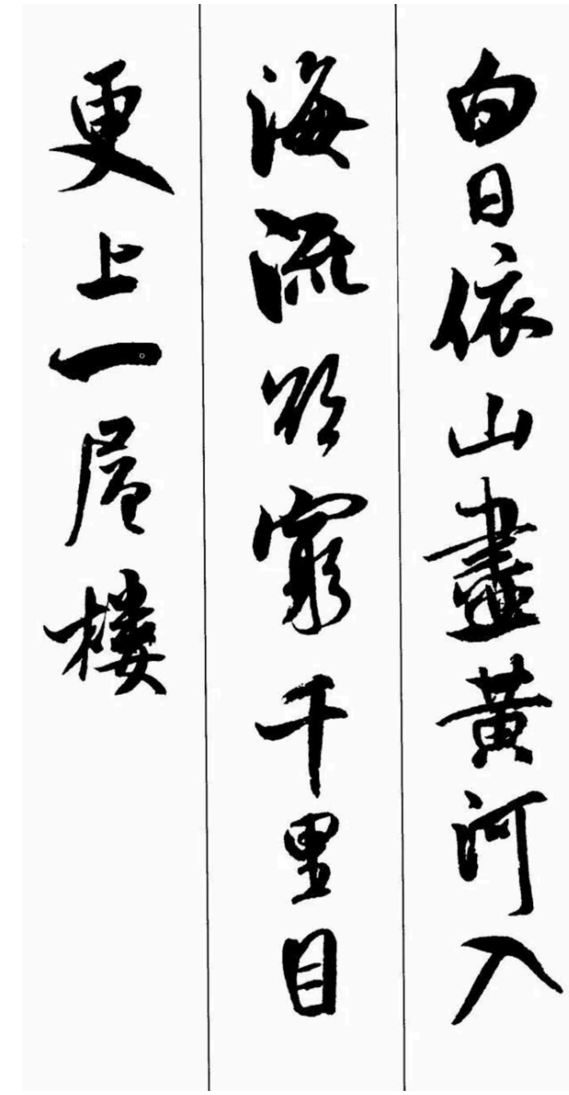
- clear preference for an e^+e^- collider as the next h.e. collider:
  - as H-factory and for precision e.w. measurements (ILC, CEPC, FCC-ee, CLIC)
  - significant demands for upgradeability to access $t\bar{t}$ (ILC, CEPC, FCC-ee, CLIC) and also HH and ttH final states (ILC+; CLIC)
- second priority: R&D for future h.e. collider: h.f. s.c. magnets for hadron colliders, and also novel accelerator techniques (PWA, μ-collider)
- third priority: future hadron collider beyond LHC (FCC-hh; fewer demands for he-LHC and eh-collider)
- large diversity of other, “smaller” projects (PBC, neutrino, DM searches, precision/intensity frontier, astro-particle, …

I agree with these preferences.

Conclusion

- We are at a special historical juncture. About to make the next step beyond the Standard Model.
- International effort in realizing the future collider(s).
  - European strategy next year (FCC, ILC, CLIC...)
  - CEPC decision early 2020s.
- Hope we have the wisdom and good fortune to converge on the right path.





登鸛雀楼，王之涣

To enjoy a grander view
Go to a higher level

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

Probing NP with precision measurements

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

  clean environment, good for precision.

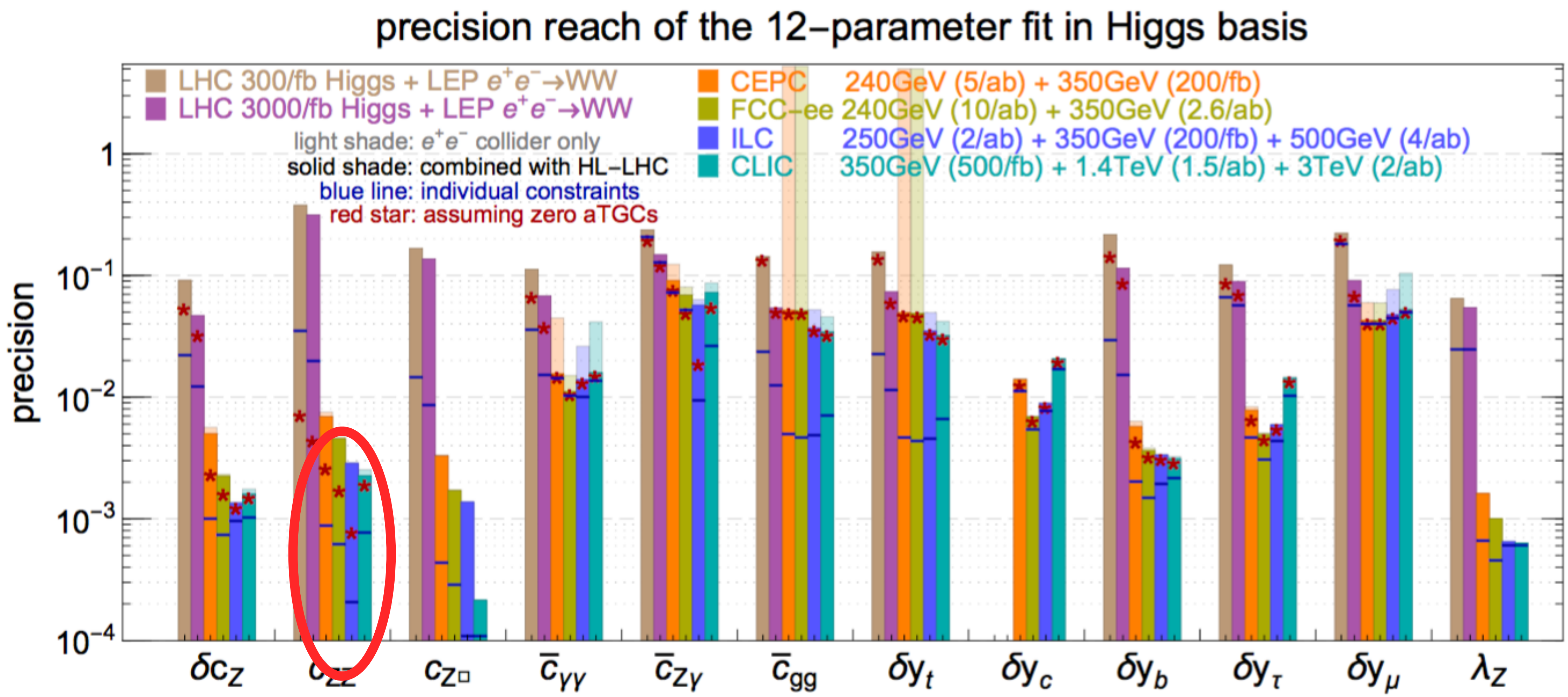
- We are going after deviations of the form

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

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.

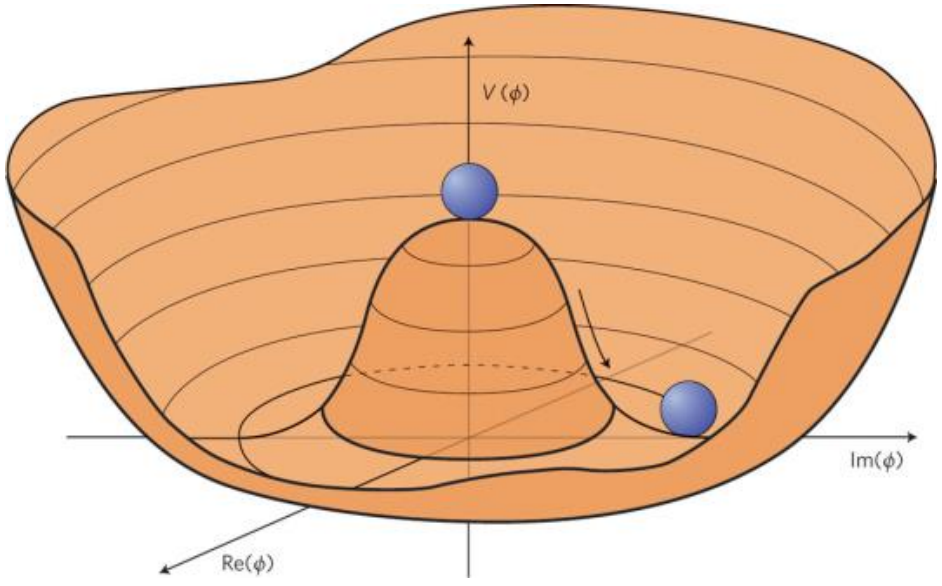
Lepton colliders and precision measurements



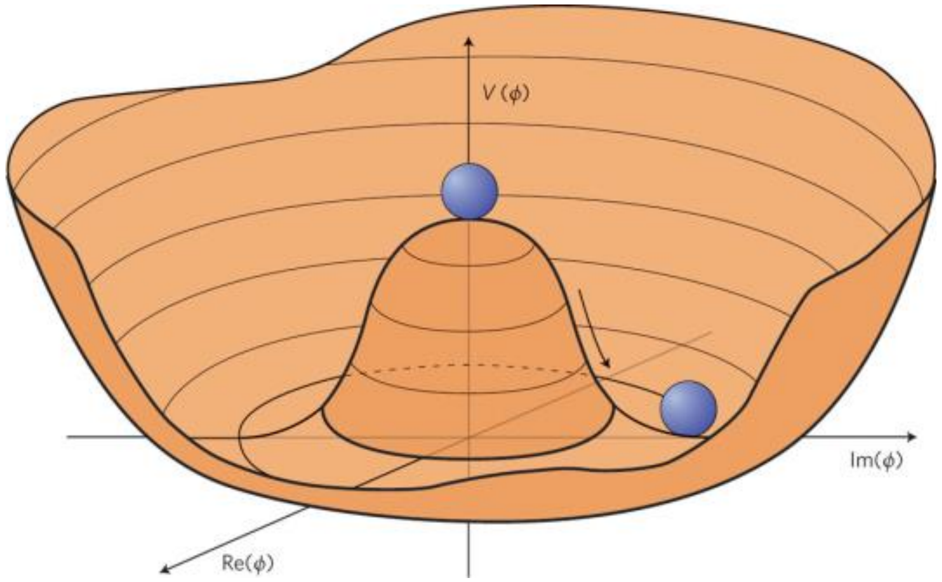
Grojean et al. 1704.02333

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

Mysteries of the electroweak scale.

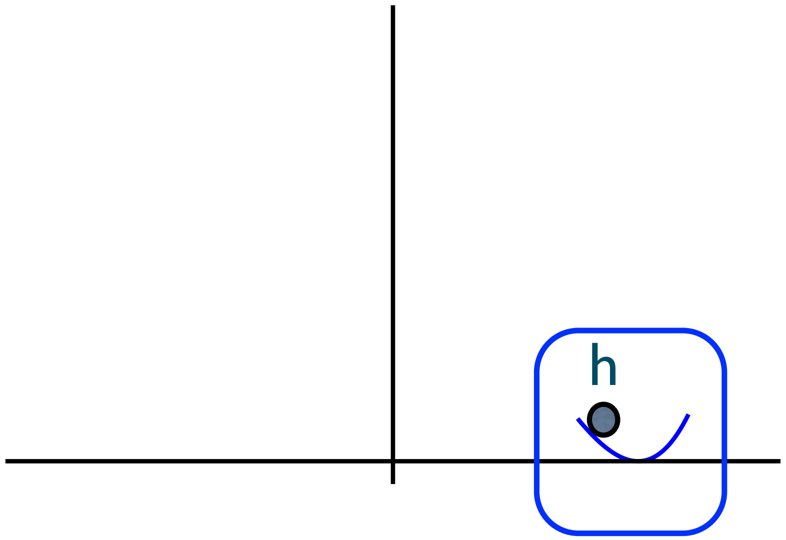


Mysteries of the electroweak scale.



- How to predict/calculate Higgs mass? Naturalness

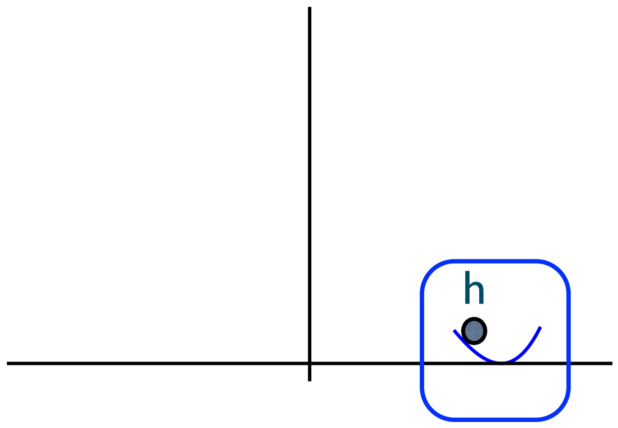
Mysteries of the electroweak scale.



What we know now

- Full Higgs potential?
  - Order of electroweak phase transition
  - Connection with matter anti-matter asymmetry?

Mysteries of the electroweak scale.



What we know now

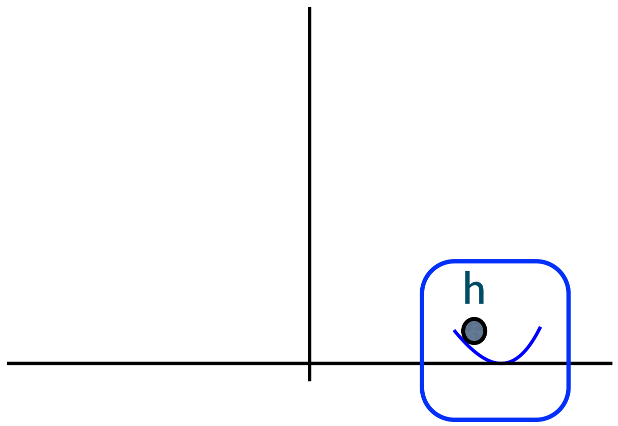
- How to predict/calculate Higgs mass?
- How does electroweak phase transition happen?
- Is it connected to the matter anti-matter asymmetry?

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 only as a second step of a circular Higgs factory in longer term.

Mysteries of the electroweak scale.

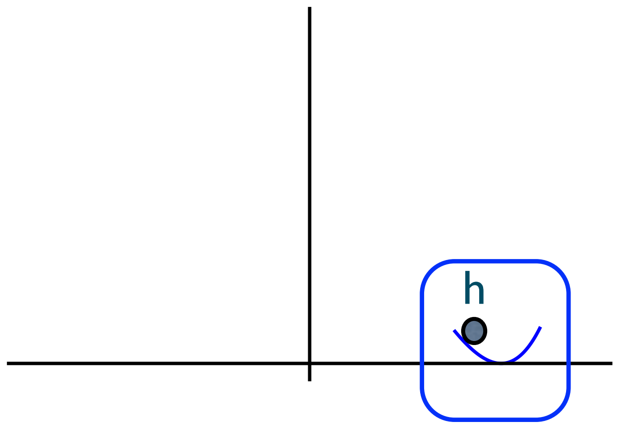
Mysteries of the electroweak scale.



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?

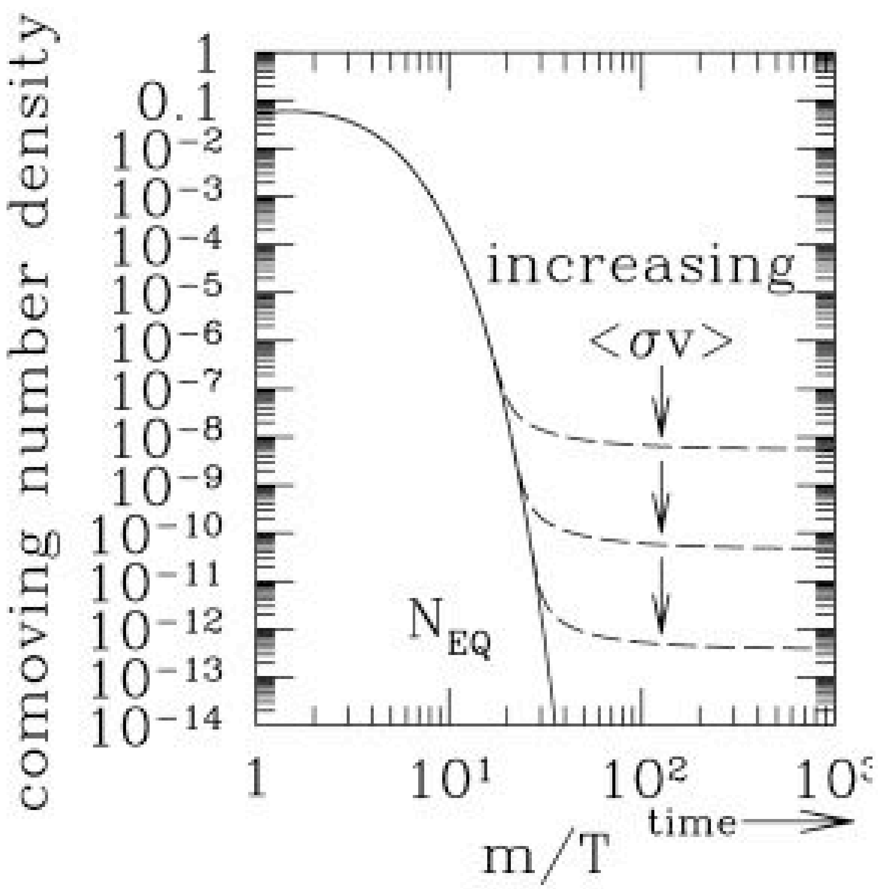
Mysteries of the electroweak scale.

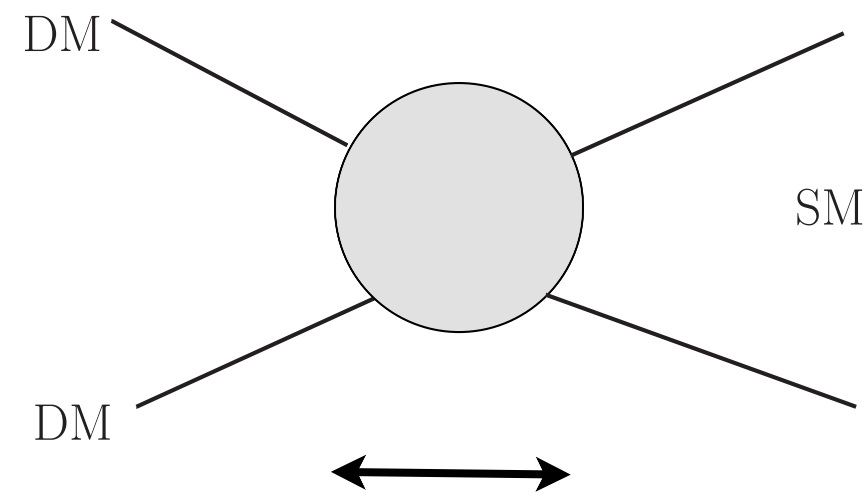


What we know now

- 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?

WIMP miracle

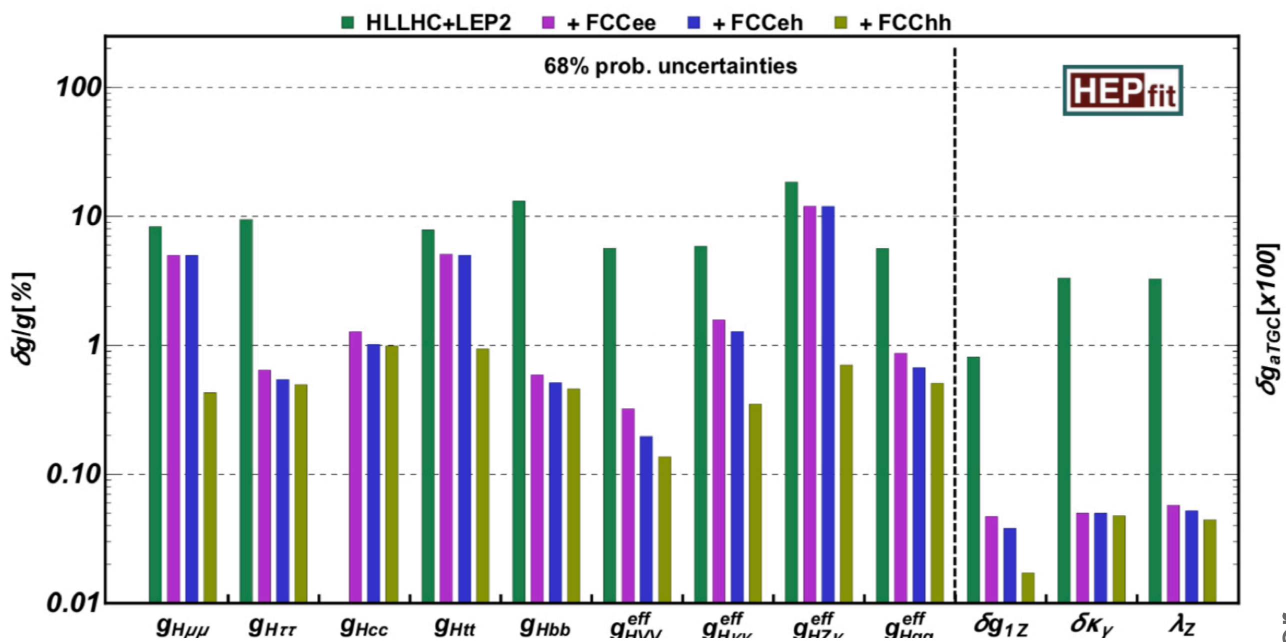


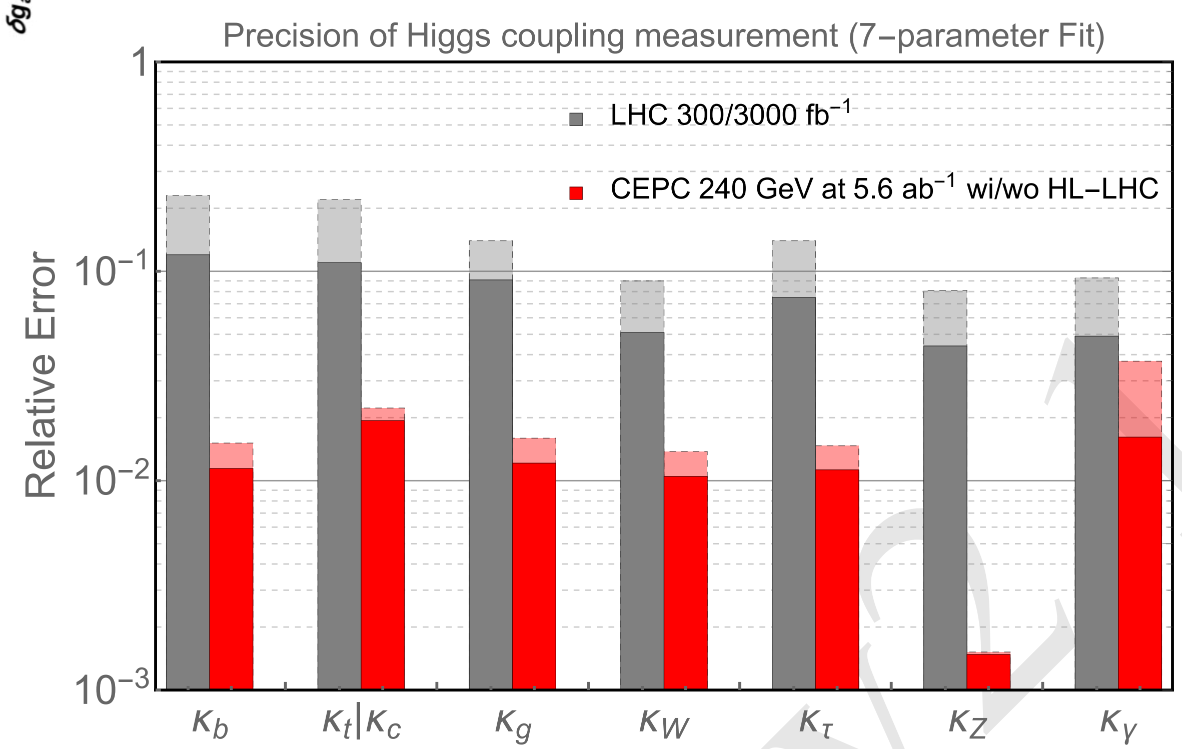


$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- 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!

Higgs coupling at future colliders

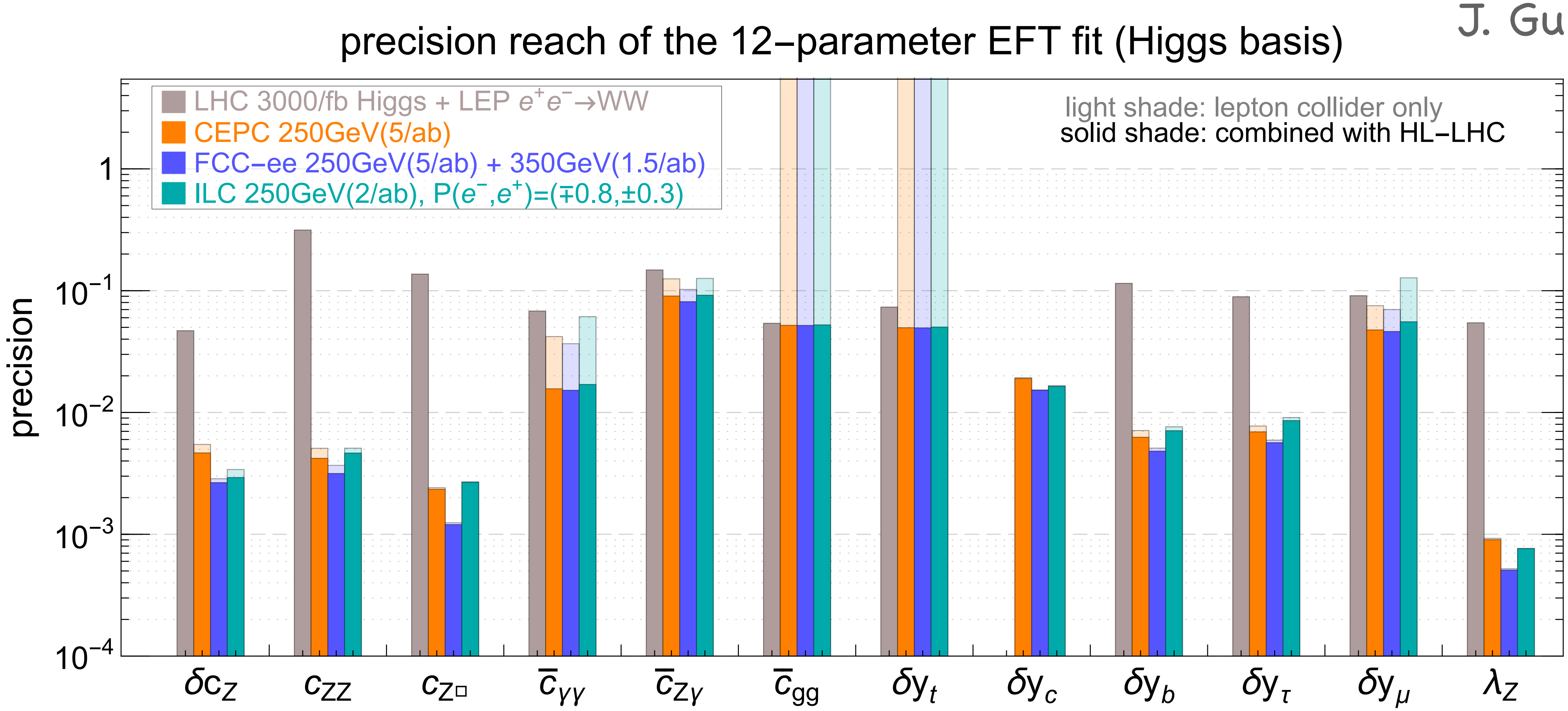




- A large step beyond the HL-LHC.
  - Can achieve per-mil level measurement.
  - Determination of the Higgs width.

Higgs measurement in EFT

J. Gu



- Both 350 and polarization could help.

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!