Discussions on future circular colliders

Lian-Tao Wang
University of Chicago

MITP workshop, July 15, 2014

This talk

- Physics case.
- Some status
  - Mostly about the Chinese effort.
- Focusing more on 100 TeV pp collider.
  - Will mention lepton collider.

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However, I think this is the wrong question to ask.

Asking the right question

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Science is about exploring the unknown in nature. We want our future colliders to lead the way, to expand our horizon.

Moreover, the Standard Model left open a lot of open questions. There have been many ideas proposed to address them. We want our future colliders to help us test these ideas, and find new ones.

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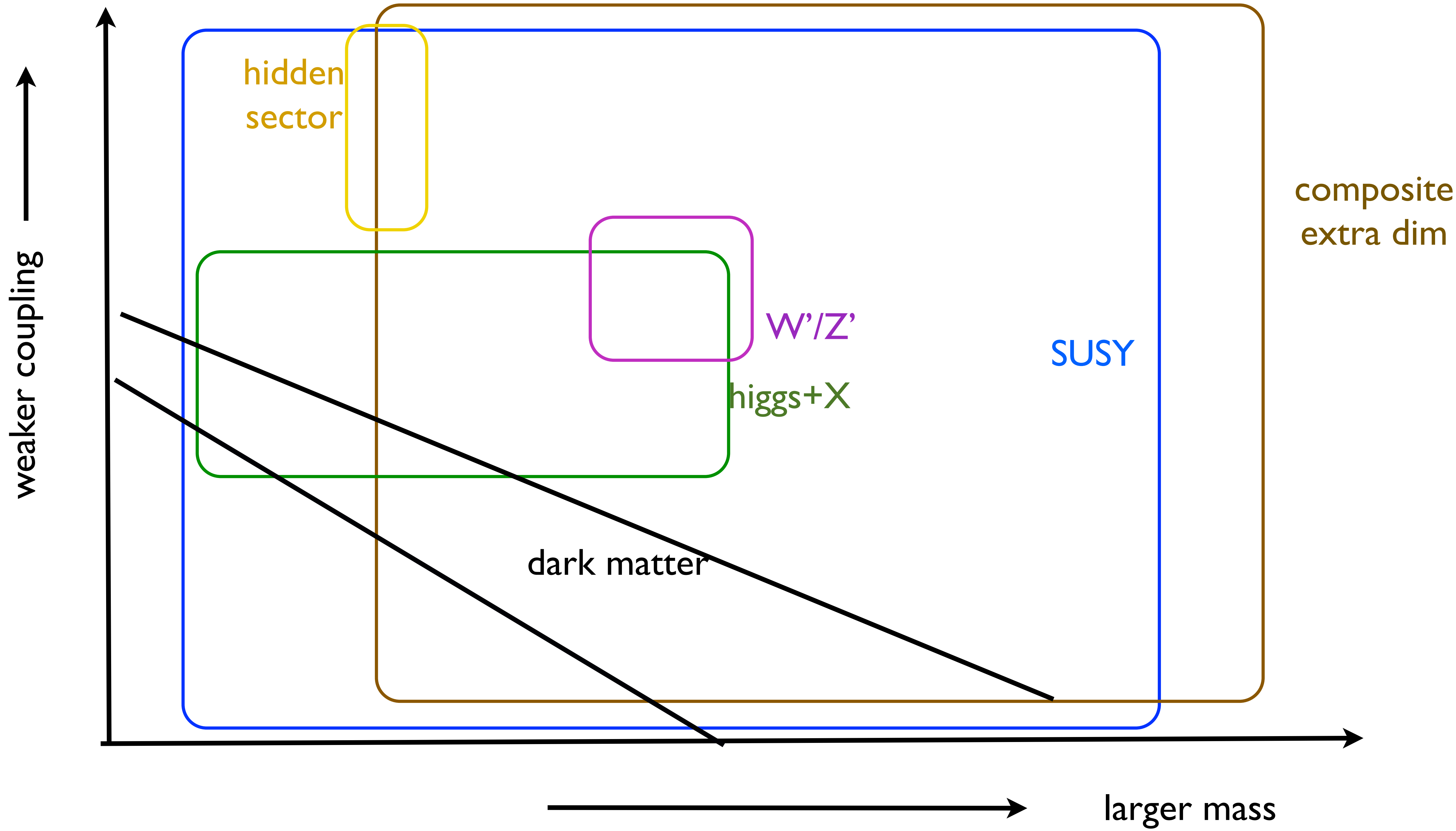
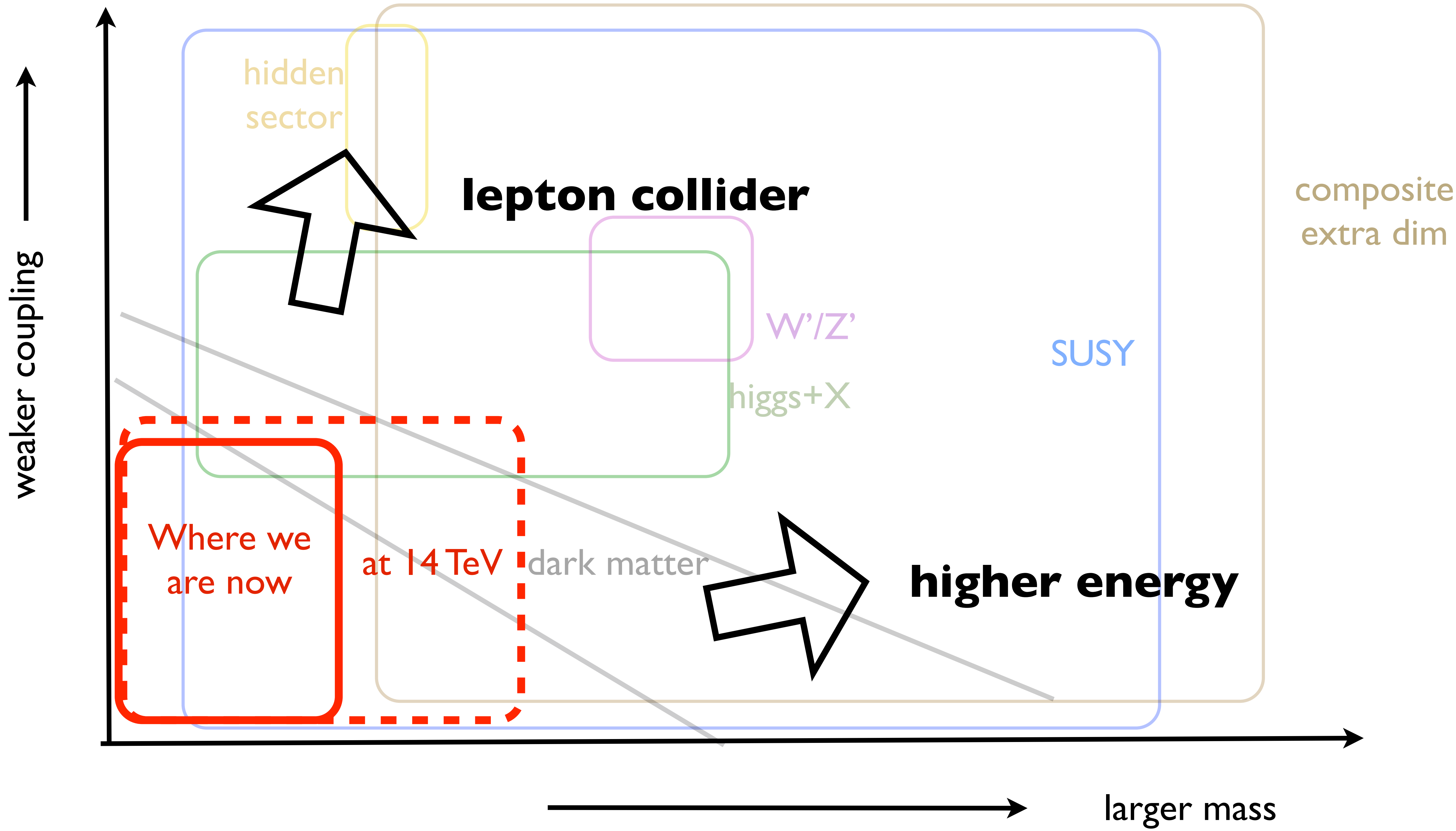
Here: future circular collider

Exploring the space of possibilities



Circular collider, ee+pp, offers a powerful combination

Exploring the space of possibilities



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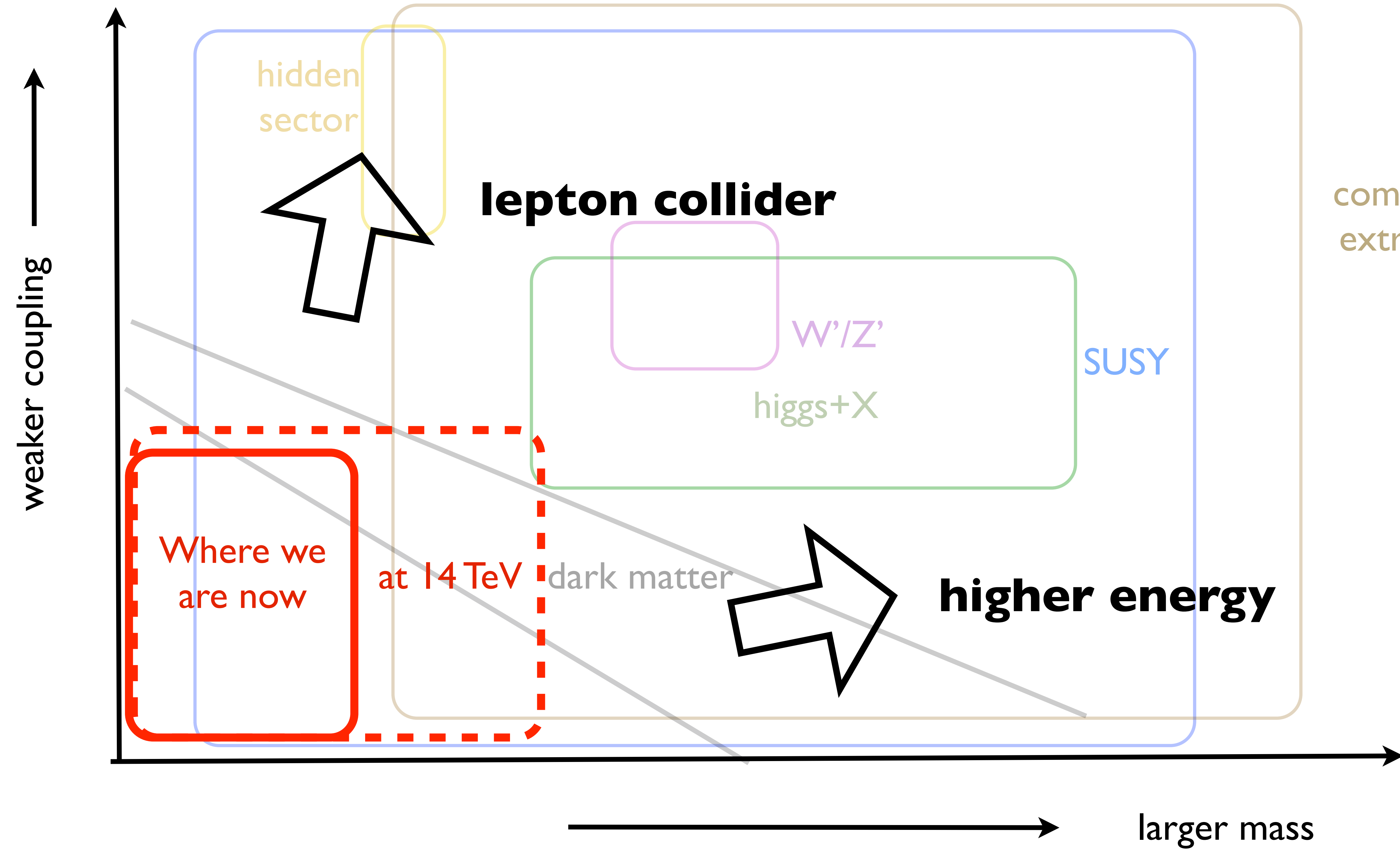
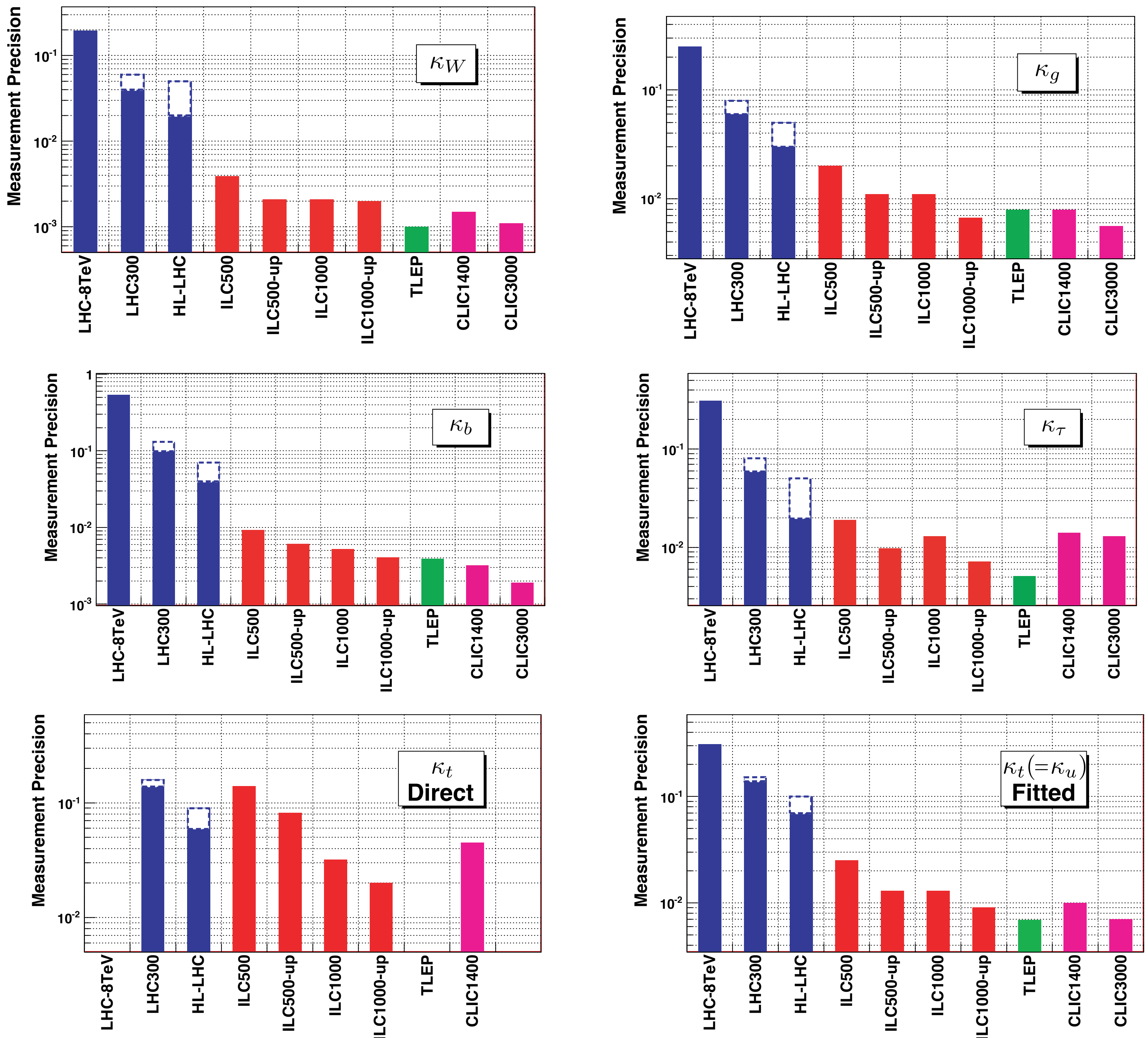


Circular collider, ee+pp, offers a powerful combination

Circular $e^+ e^-$ colliders

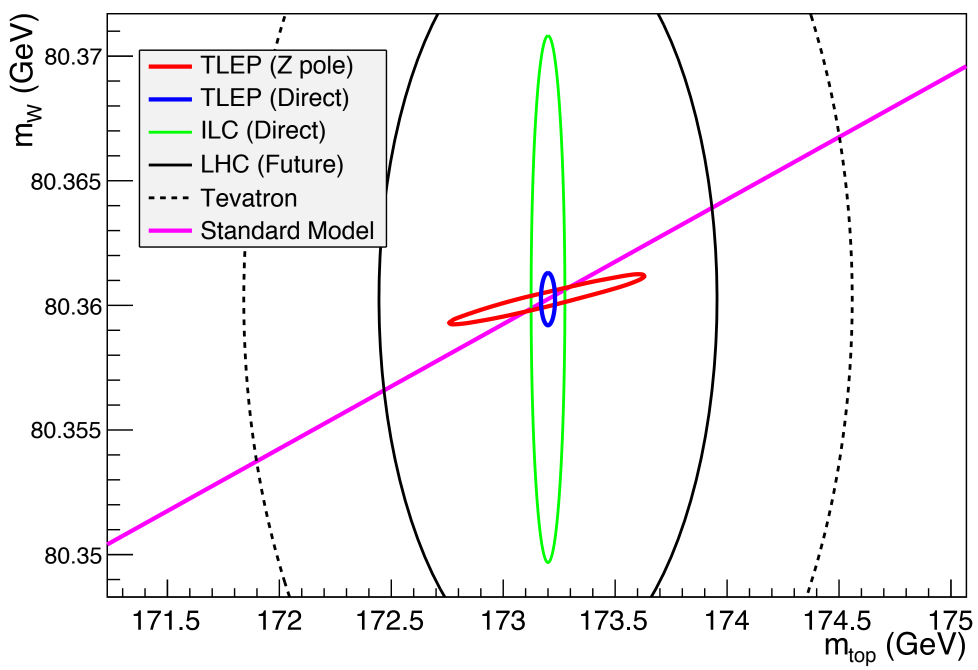
- CERN: Future Circular Collider - ee (FCC-ee)
- China: Circular Electron Positron Collider (CEPC)
- Higgs factory, of course.
- Other options, such as TeraZ, also being considered.

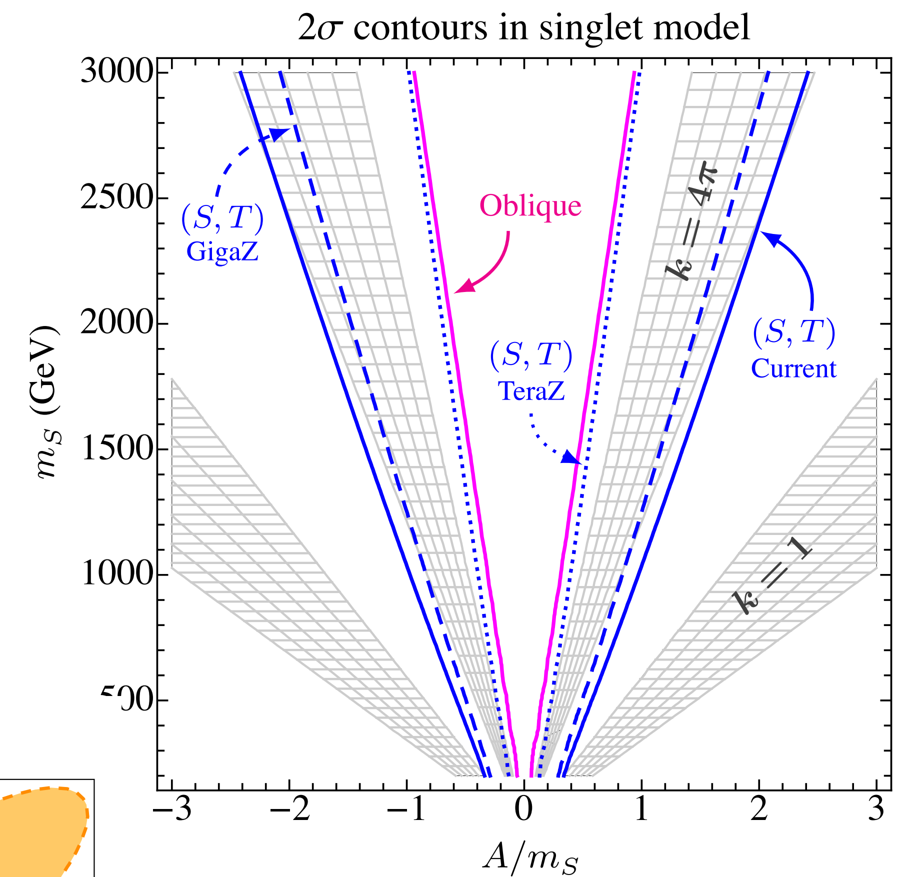
Higgs coupling



Snowmass Higgs working group report

Precision EW

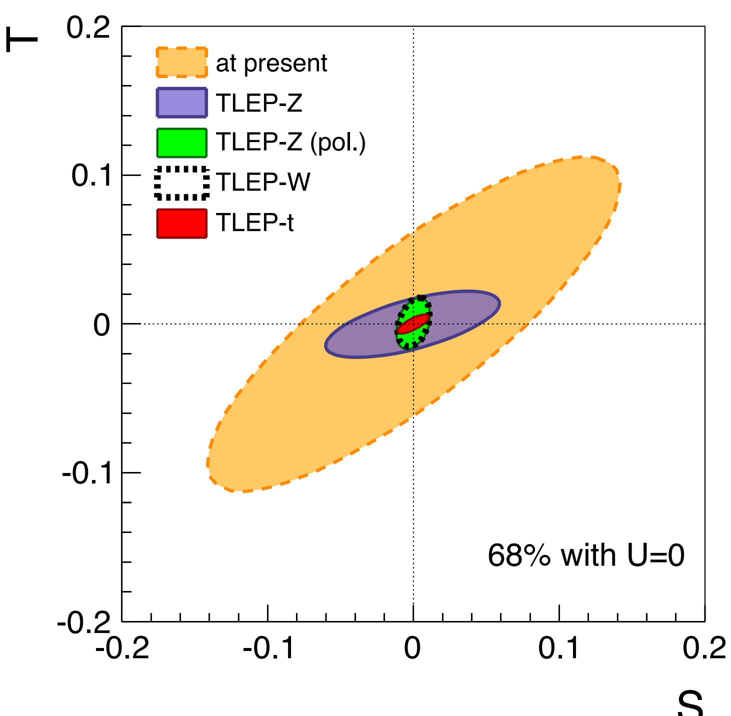




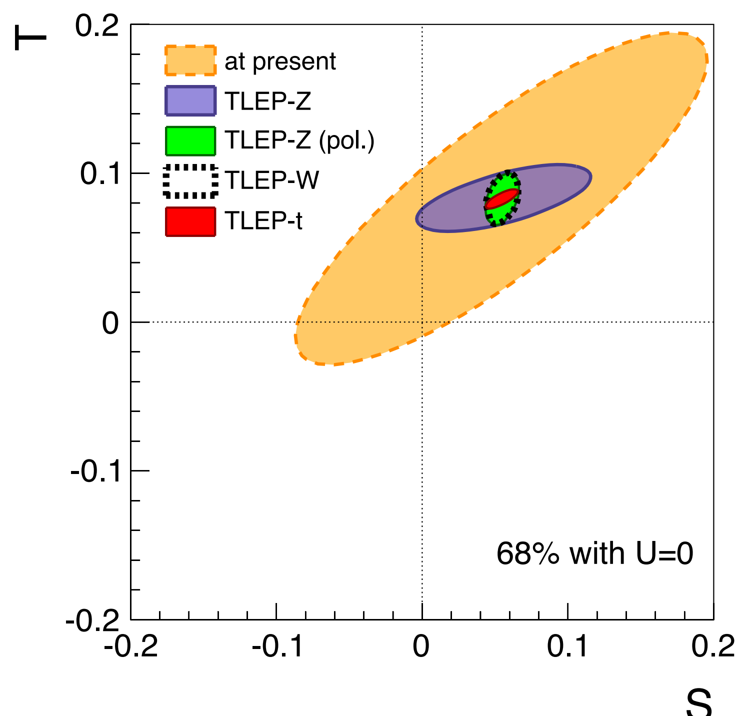
Higgs + singlet model

Henning, Lu and Murayama, 2014

SM scenario



NP scenario



S. Mishima, 6th TLEP workshop

Circular pp colliders

- A natural next step after the ee program (just like LEP ⇒ LHC)

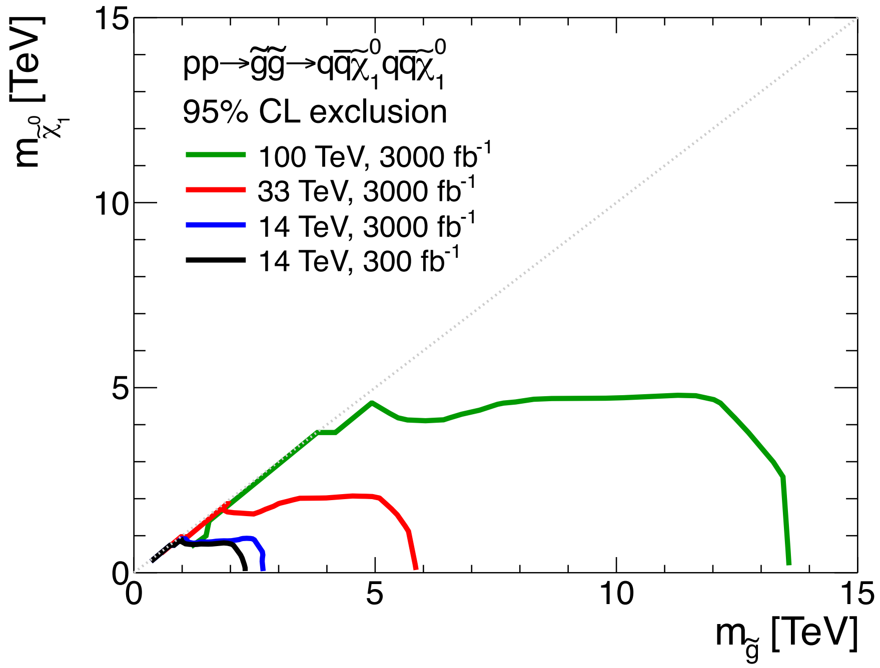
- The physics case is "obvious", it is the energy frontier. The next big step forward.

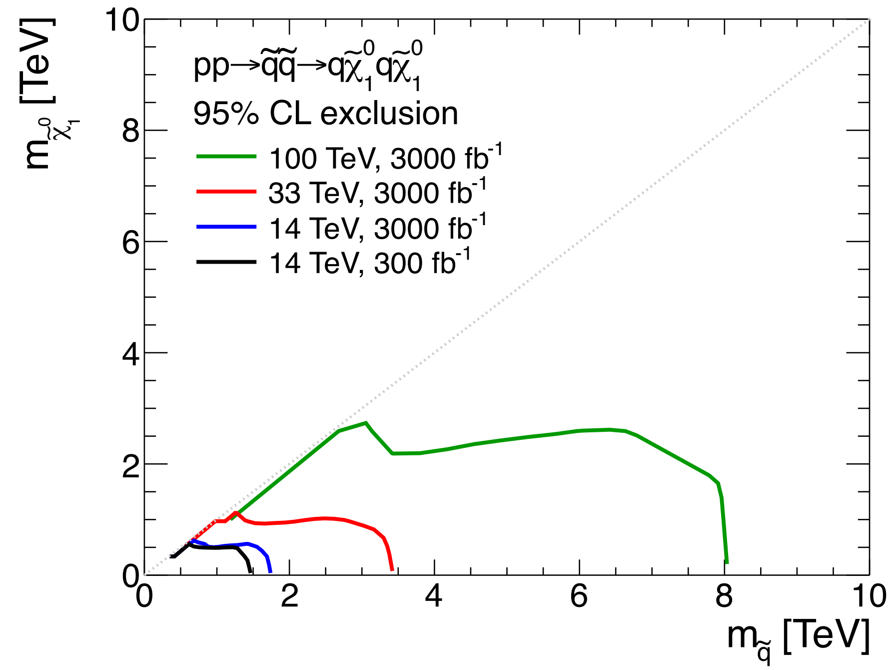
- CERN: FCC-hh

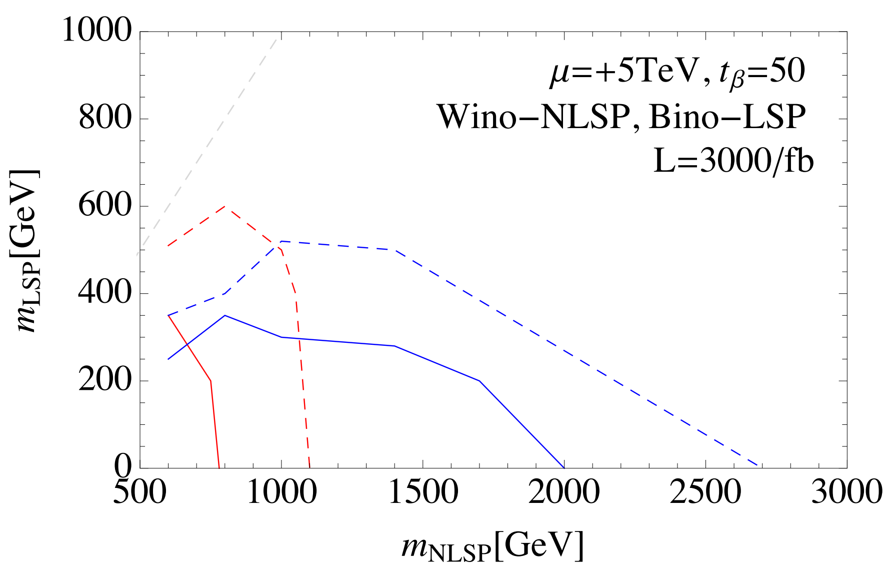
- China: Super p p Collider (SppC).

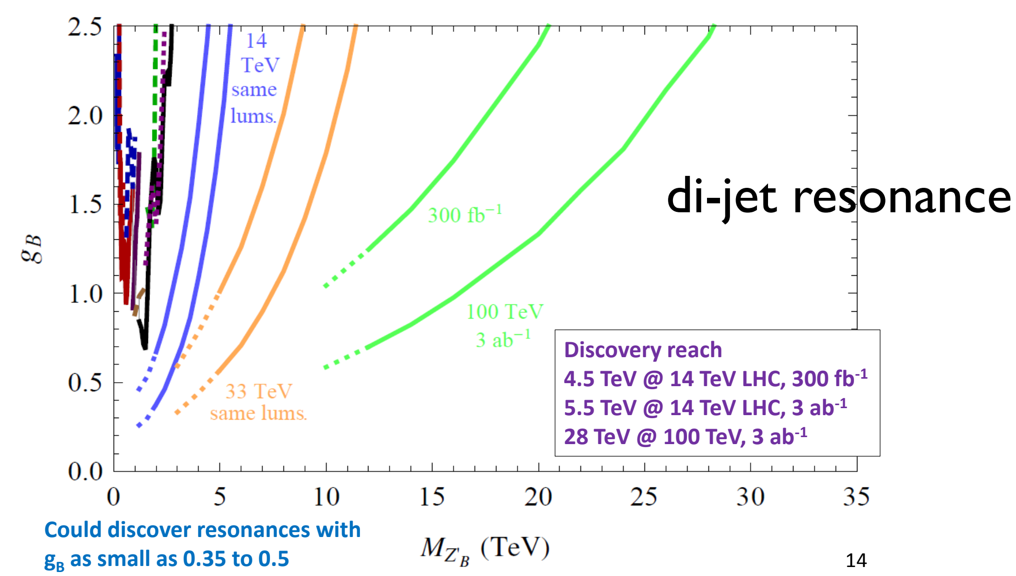
Big step forward

Cohen et al, 2013







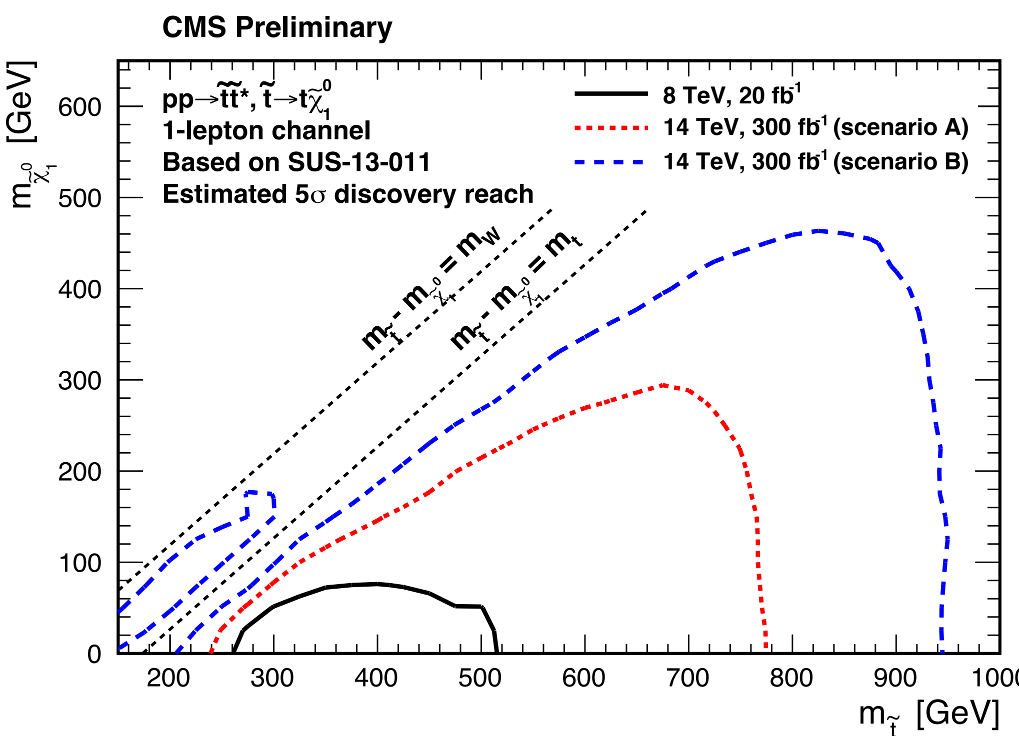


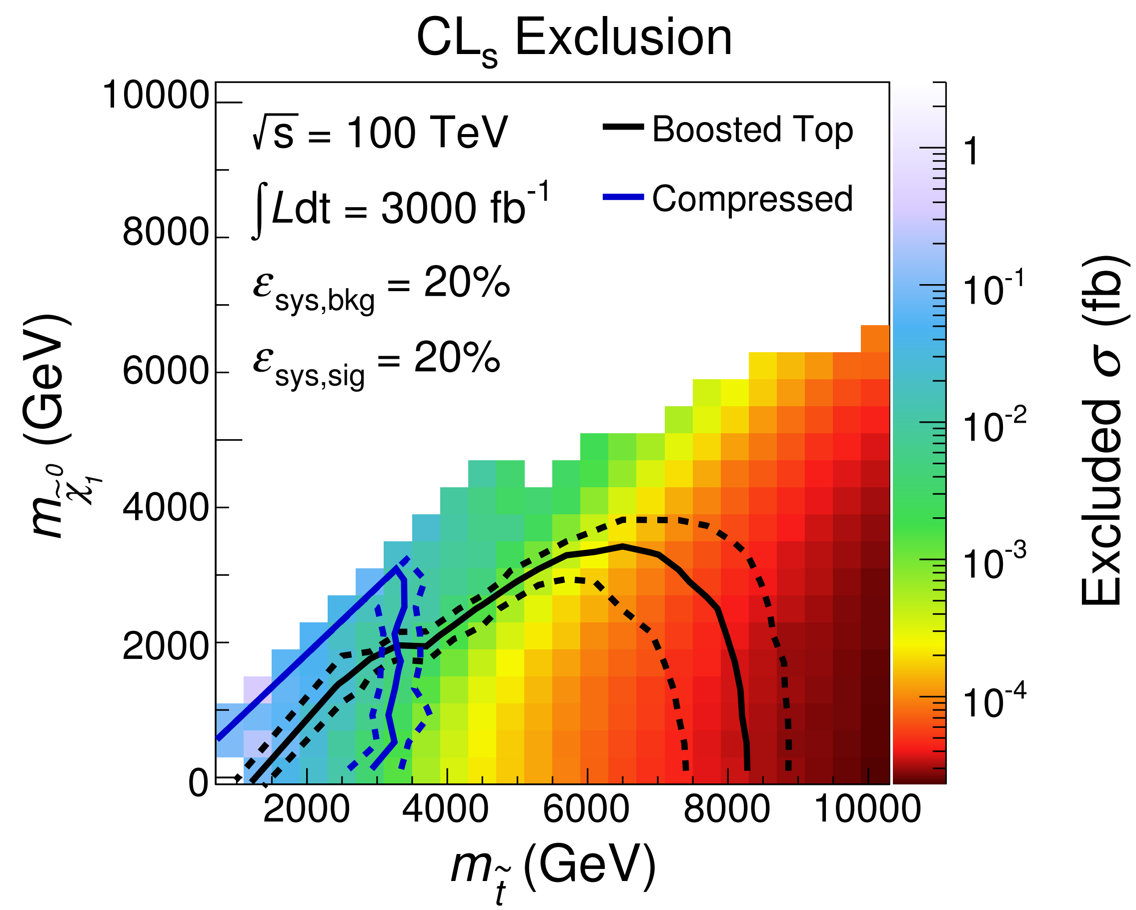
Gori, Jung, LTW, Wells, in prep

Felix Yu, 2013

Naturalness

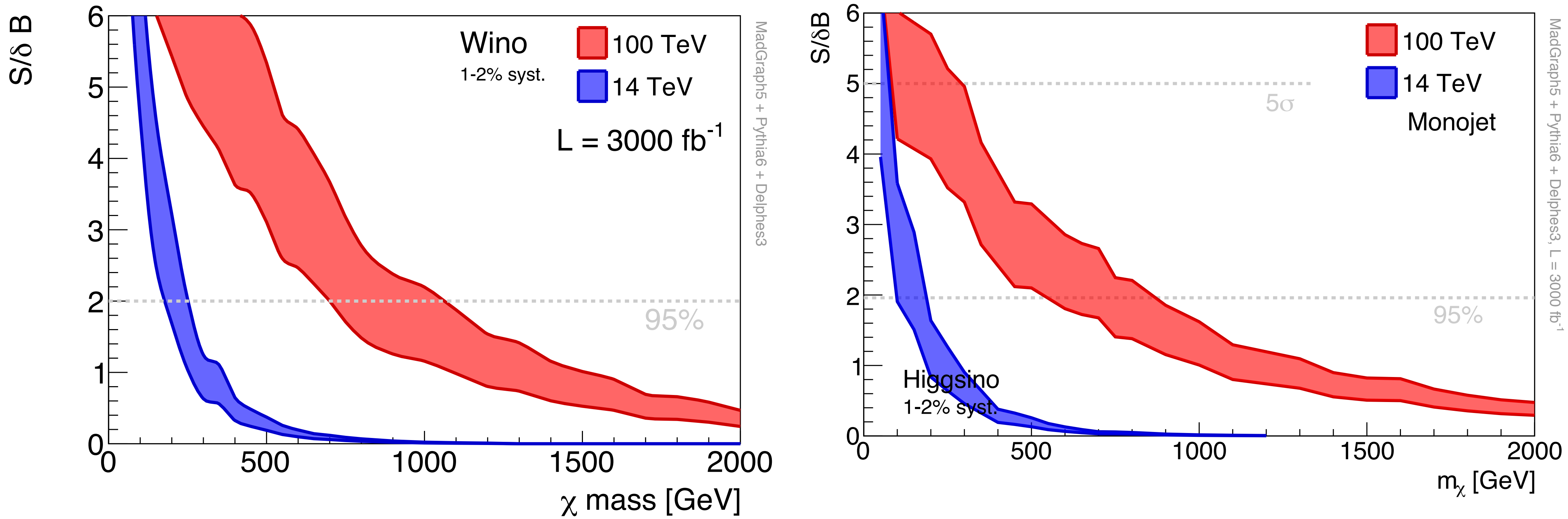
Cohen et. al., 2014





- tune proportional to $(m_{stop})^2$.
  - A gain of 2 orders of magnitude!
  - A 6 TeV stop can be discovered!

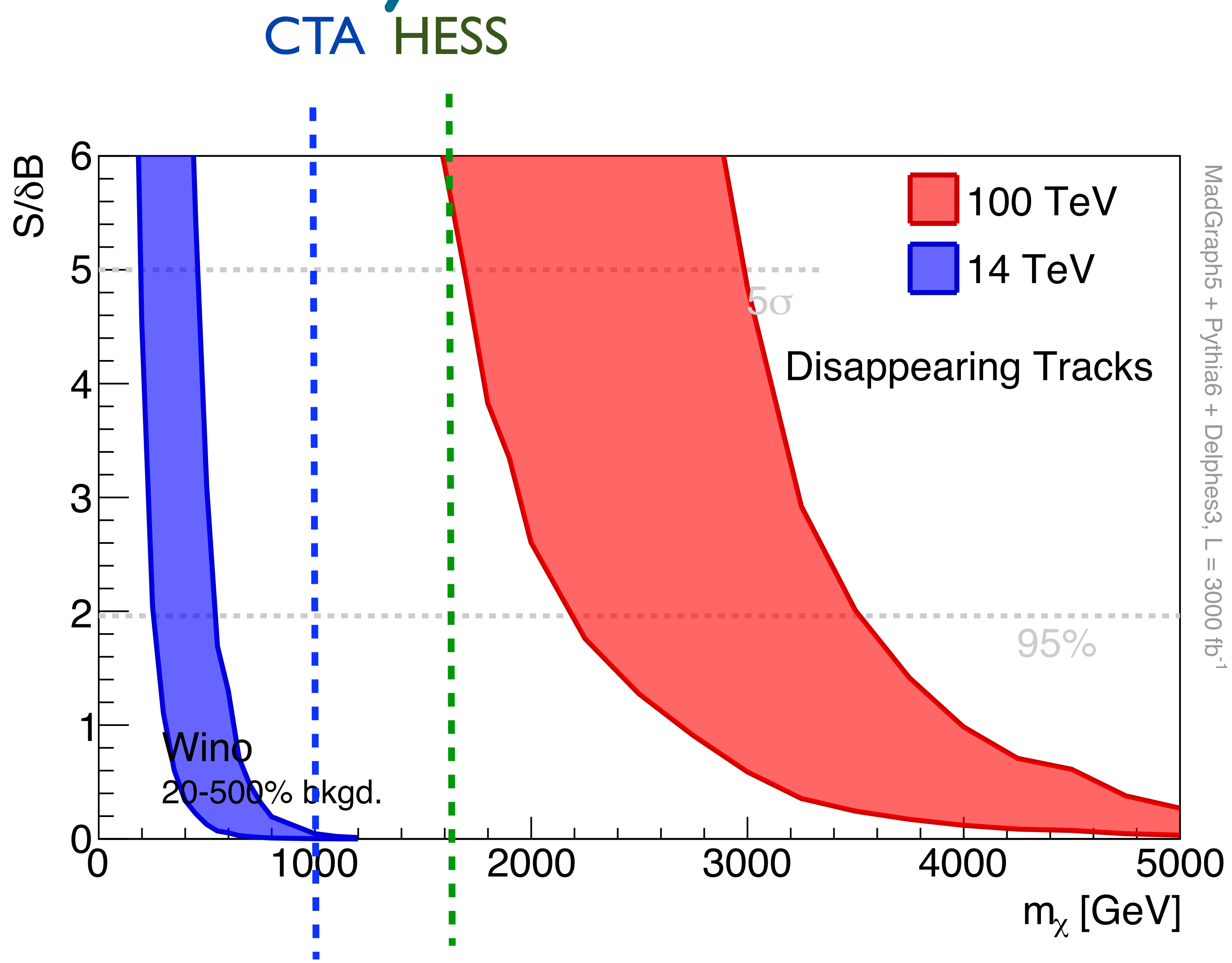
Dark matter (mono-jet)



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

- Large improvement beyond the LHC.
- Probing the "bulk" of WIMP parameter space.

Wino summary



- There is hope to "completely cover" the wino parameter space.

Many on-going studies.

- New physics and electroweak phase transition.
- Vector boson fusion for composite resonances.
- Z'.
- 10 TeV flavor physics.
- Fermionic top partner
- Top quark in PDF and other SM issues...
- Suggestions for more studies to be done?

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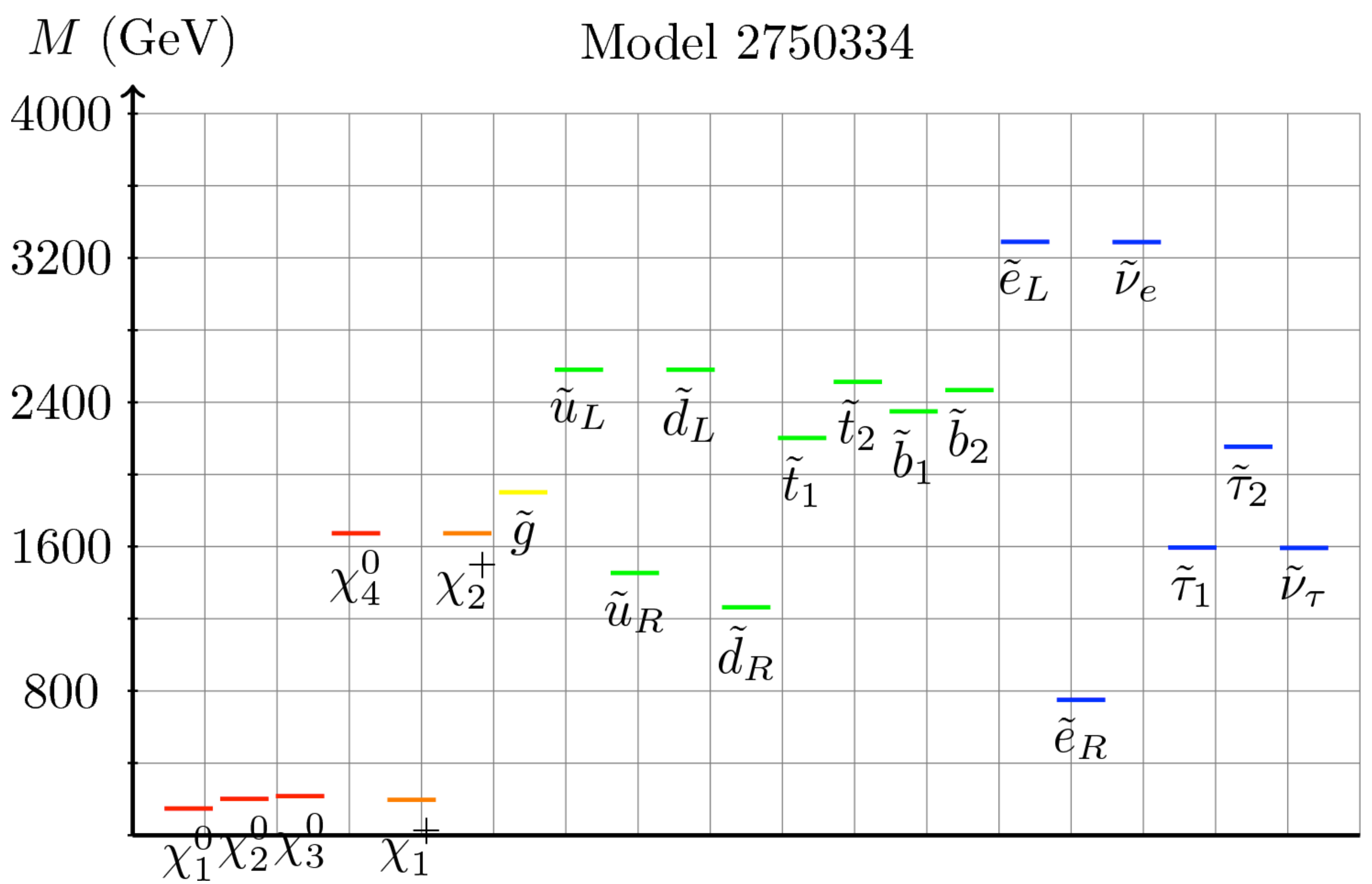
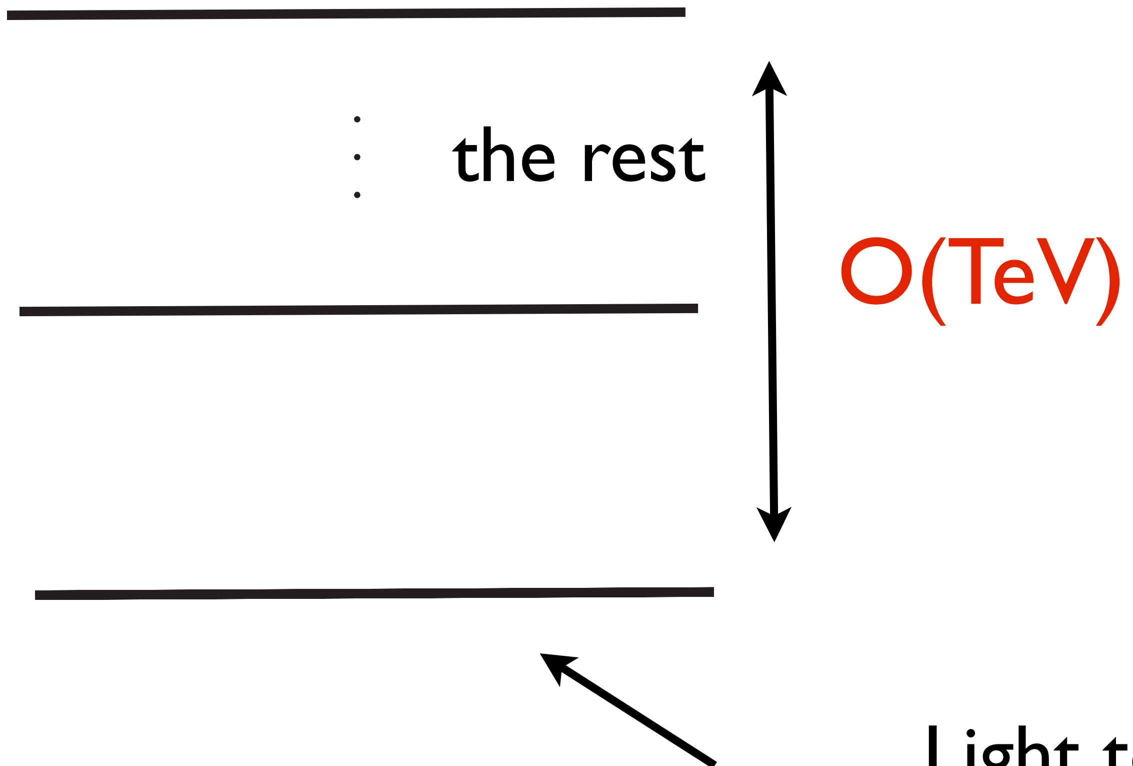
- Typically, going from 8 TeV to 14 TeV increase the reach by a factor of 2.
- However, many models feature particles with masses spread at least factor of several apart.
- Won't be able to see everything.
- LHC discovery will set the stage for our next exploration. Such as at a future 100 TeV pp collider.

Example: SUSY



- Run 2 may be able to see gluino, light neutralinos and charginos, some squarks, but not the rest.

Similar story in composite Higgs



Hard to see the full spectrum with the increase of reach from 8 to 14 TeV

Light top partner
“As natural as possible”

No discovery?

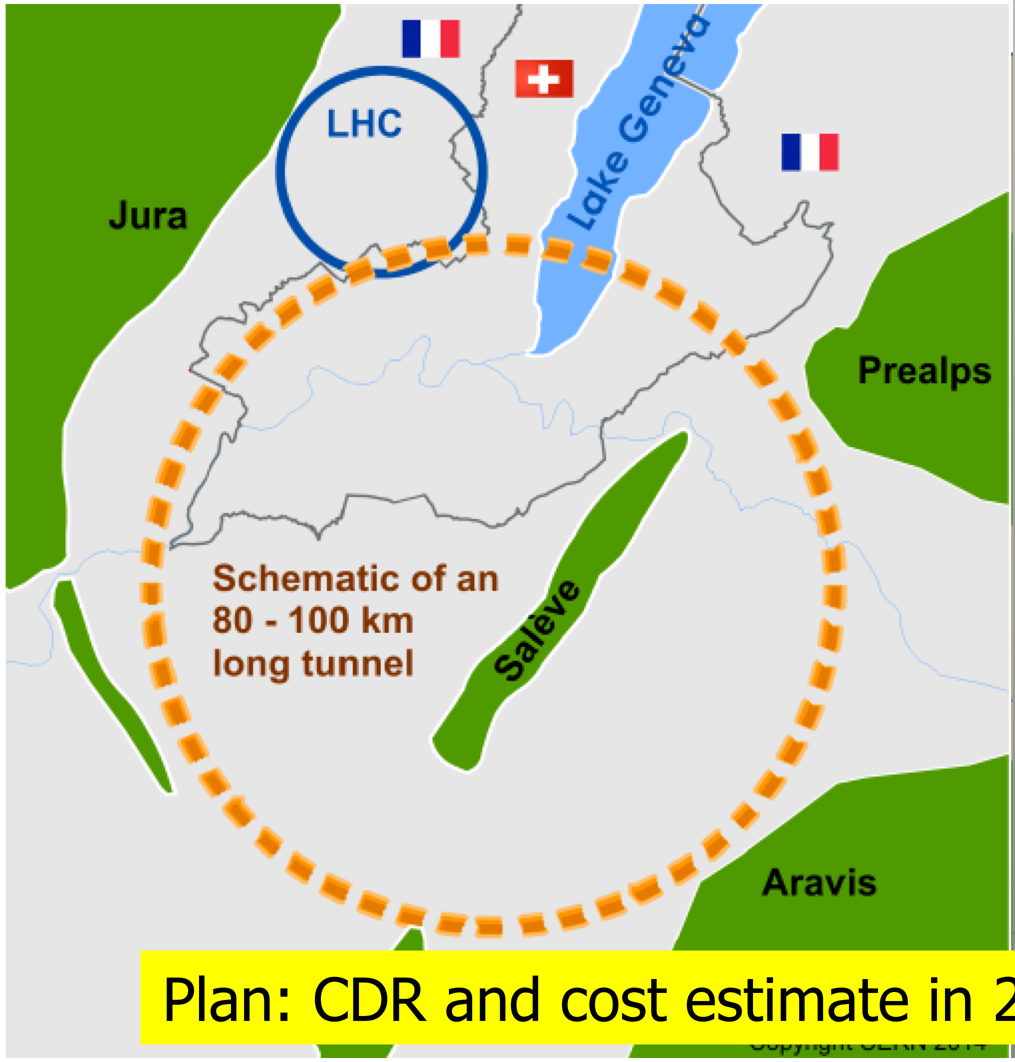
- Run 2 won't have the final word on many questions.
  - Won't nail the Higgs properties.
  - Not enough for naturalness yet (for me).
  - Not even close for WIMP dark matter.
- We should certainly go further.

CERN FCC

Recent CERN Initiative: FCC

Future Circular Colliders:

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh)
with possibility of e+-e- (FCC-ee) and p-e (FCC-he)



Plan: CDR and cost estimate in 2018

Albert De Roeck, at Astrophysics 2014

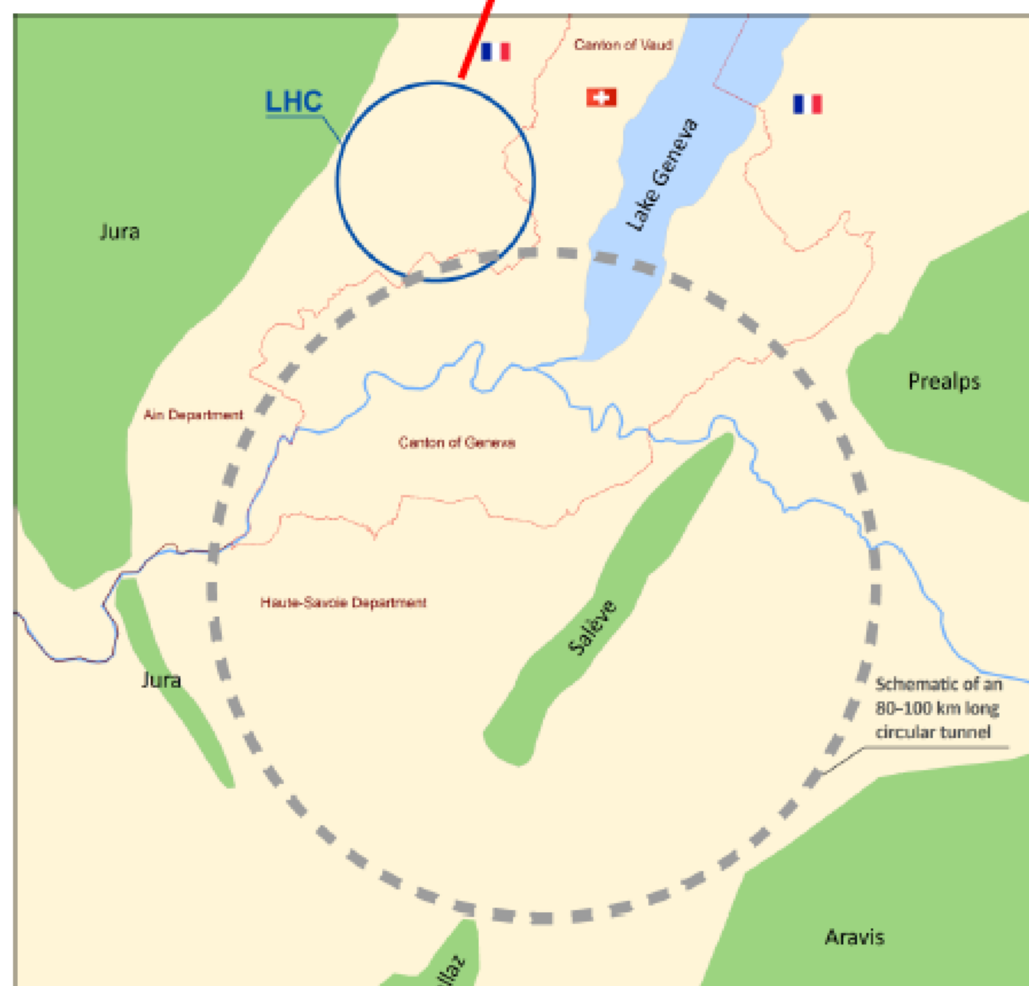
FCC-hh: a Proton-Proton Collider

"High Energy LHC"

HE-LHC :33 TeV with 20T magnets

First studies on a new 80 km tunnel in the Geneva area

- 42 TeV with 8.3 T using present LHC dipoles
- 80 TeV with 16 T based on Nb_3Sn dipoles
- 100 TeV with 20 T based on HTS dipoles



Albert De Roeck, at Astrophysics 2014

FCC-ee: the Electron-Positron Option

- In July 2011 a proposal was made to (re)install a 120 GeV / beam e^+e^- collider in the LEP-LHC tunnel – named LEP3. Work on LEP3 started in a series of workshops.
- The 80 km TLEP machine appeared in 2012 in parallel with the feasibility study for a 80 km ring for a future hadron collider around CERN. TLEP and LEP3 were presented in September 2012 at the European Strategy meeting in Krakow.
- In October 2013 TLEP was integrated into the FCC study and is now known as FCC-ee.

Circular e+e- collider with √s energy in the range of 90-350 GeV

Can serve 4 experiments simultaneously!

Challenging but no showstoppers!! (2 rings)
Energy loss/turn ~ 11 GeV

√s (GeV)	<L >(ab-1/year)*	Rate (Hz) ee—>hadrons	Years	Statistics
90	5.6	$2\ 10^4$	1	$2\ 10^{11}$ Z decays
160	1.6	25	1-2	$2\ 10^7$ W pairs
240	0.5	3	5	$5\ 10^5$ HZ events
350	0.13	1	5	$2\ 10^5$ ttbar

* each interaction point

Tera-Z, Giga-W, Mega-H, Mega-top

The Physics Case includes

- Precise measurement (0.1% to 1%) of the Higgs Couplings
- Improve precision (statistics x 10^5) on the measurements of the Z parameters [M_Z, Γ_Z , R_ℓ, R_b, R_c, Asymmetries & weak mixing angle]. Z rare decays.
- Scan W threshold (aiming at 0.5 MeV precision). W rear decays
- Scan ttbar threshold (aiming at 10 MeV)

Albert De Roeck, at Astrophysics 2014

What's happening in China

In the last 1.5+ years

- Started "talking about it" in 2012.
- Workshop in August 2013, a road map started to emerge.
- Things are happening fast since then
  - Several meetings, workshops.
  - Working groups, studies being organized in China.
  - Established Center for Future High Energy Physics (CFHEP): international collaboration in the study of physics case.
  - Broad conversation happening within Chinese physics community.

Tuesday, 18 March 2014

18:30 - 21:00 CEPC-SppC Steering Committee & Conveners Meeting 2h30' (B410)

Wednesday, 19 March 2014

08:30 - 09:00 Registration 30'

09:00 - 10:15 Opening Session
Convener: Prof. Xinchou Lou (IHEP, Beijing)

09:00 **Welcome and Introduction** 30'
Speaker: Prof. Yifang Wang (IHEP)

09:30 **Global Efforts for High Energy Accelerators** 45'
Speaker: Dr. Weiren Chou (FNAL)

10:15 - 10:35 Photo session and coffee break

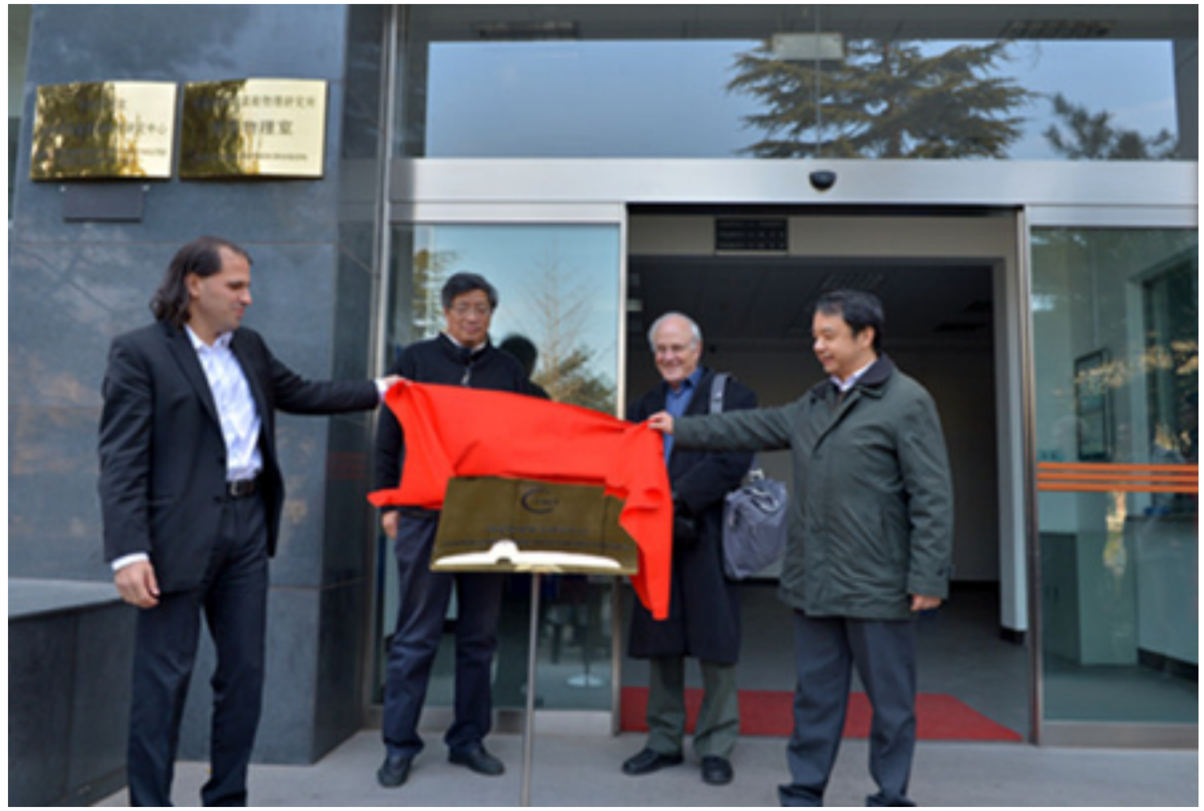
10:35 - 12:15 Accelerator Session
Convener: Dr. Qing QIN (Institute of High Energy Physics)

10:35 **Lattice design for CEPC** 20'
Speaker: Ms. Huiping Geng (Institute of High Energy Physics)
Material: Slides

10:55 **Final focus design for CEPC** 20'
Speaker: Dr. Dou Wang (IHEP)
Material: Slides

11:15 **Beam-beam simulations for CEPC** 20'
Speaker: Mr. Yuan Zhang (IHEP, Beijing)
Material: Slides

Center for Future High Energy Physics



- Coordinate studies of physics case.
- Coordinate international collaboration:
  - Currently, 5-10 intl. visitors every week.
  - Please come help us!

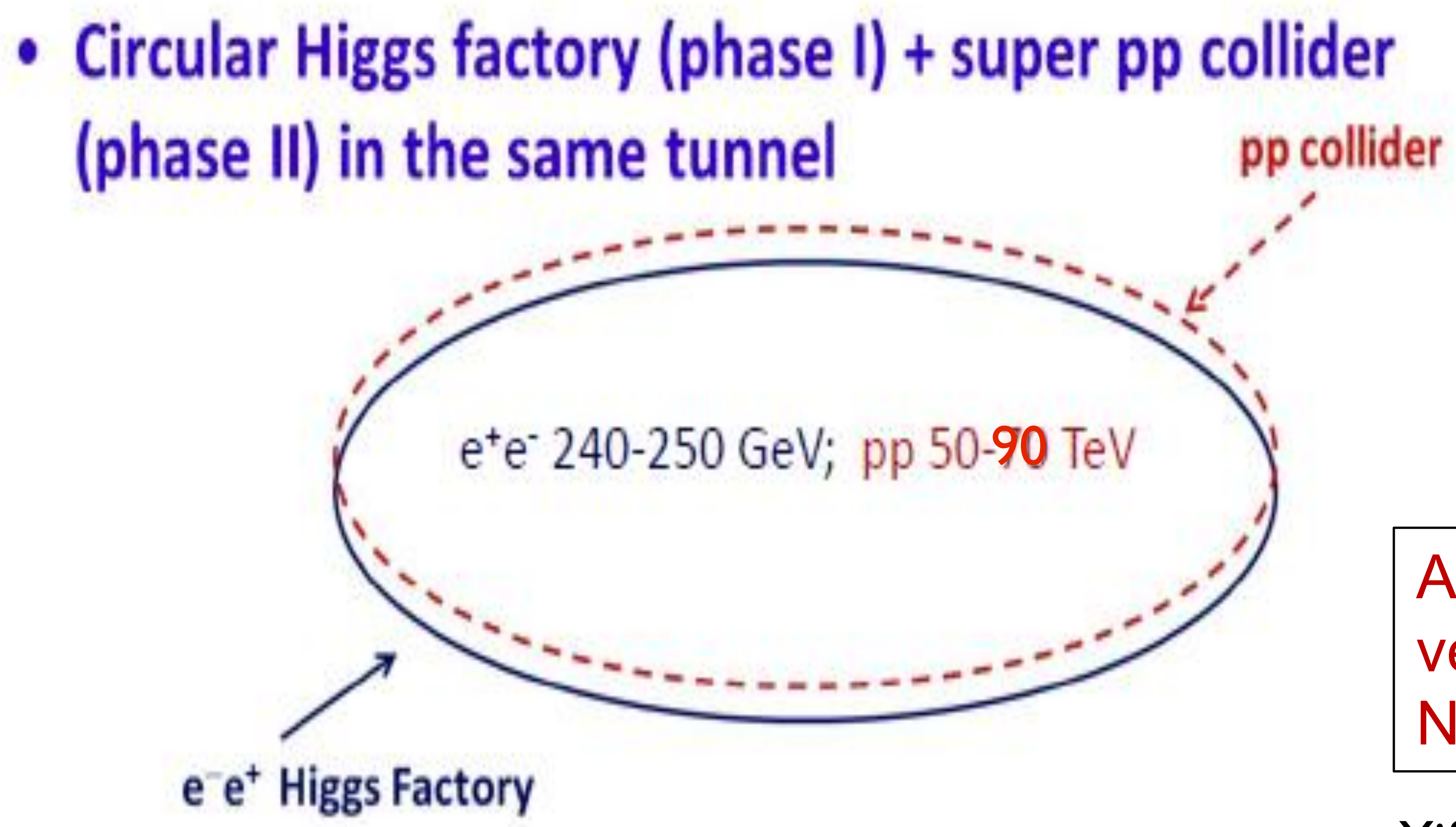
http://cfhep.ihep.ac.cn/

http://beijingcenterfuturecollider.wikispaces.com/

- Writing pre-CDR by the end of this year.

Under consideration now:

- Circular Electron Positron Collider (CEPC).
- Super Proton Proton Collider (SPPC)



A 50-70 km tunnel is very affordable in China NOW

Yifang Wang, director of IHEP

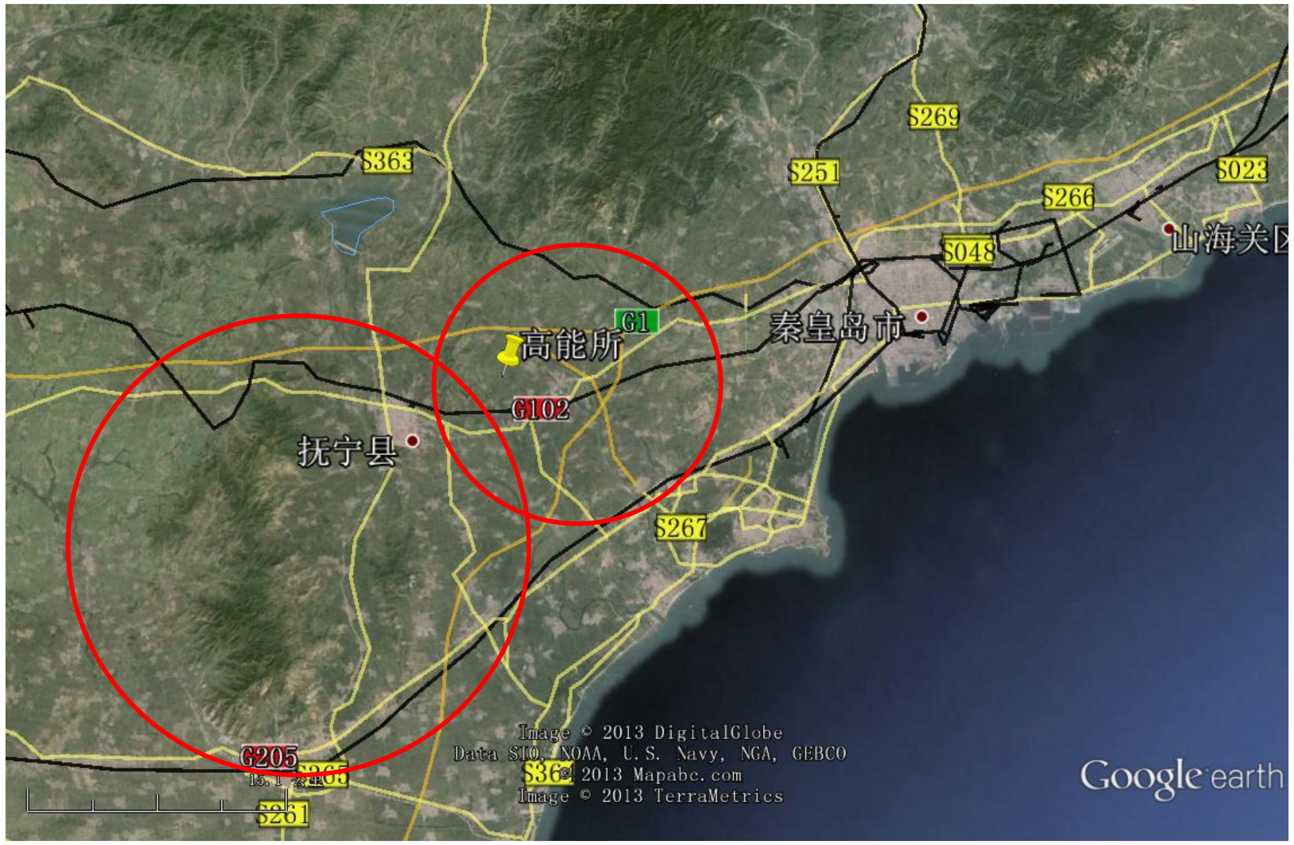
Main parameters of CEPC at 50km

Parameter	Unit	Value	Parameter	Unit	Value
Bean Energy	GeV	120	Circumference	km	50
Number of IP		2	L_0/IP (10^{34})	$cm^{-2}s^{-1}$	2.62
No. of Higgs/year/IP		1E+05	Power(wall)	MW	200
e+ polarization		0	e- polarization		0
Bending radius	km	6.2	N_e/bunch	1E10	35.2
N_b/beam		50	Beam current	mA	16.9
SR loss	(GeV/turn)	2.96	SR power/beam	MW	50
Critical energy of SR	MeV	0.6	ε_x,n	mm-mrad	1.57E+06
ε_y,n	mm-mrad	7.75E+03	β_{IP} (x/y)	mm	200/1
Trans. size (x/y)	µm	36.6/0.18	Bunch length	mm	3
Energy spread SR	%	0.13	Full crossing angle	mrad	0
Lifetime due to Bhabha	sec	930	Damping part. No. (x/y/z)		1/1/2
b-b tune shift x/y		0.1/0.1	Syn. Osci. tune		0.13
RF voltage V_{rf}	GV	4.2	Mom. compaction	1E-4	0.4
Long. Damping time	turns	40.5	Ave. No. of photons		0.59
dB beam-beam	%	0.014			

Main Parameters of SppC

Parameter	SppC-1	SppC-2
Beam energy (TeV)	25	45
Circumference (km)	49.78	69.88
Number of IPs	2	2
SR loss/turn (keV)	440	4090
N_p/bunch (10^{11})	1.3	0.98
Bunch number	3000	6000
Beam current (mA)	0.5	0.405
SR power /ring (MW)	0.22	1.66
B_0 (T)	12	19.24
Bending radius (km)	6.9	7.8
Momentum compaction (10^{-4})	3.5	2.5
β_{IP} x/y (m)	0.1/0.1	0.1/0.1
Norm. trans. emit. x/y (μm·rad)	4	3
ξ_y/IP	0.004	0.004
Geo. luminosity reduction factor F	0.8	0.9
Luminosity /IP ($10^{35}cm^{-2}s^{-1}$)	2.15	2.85

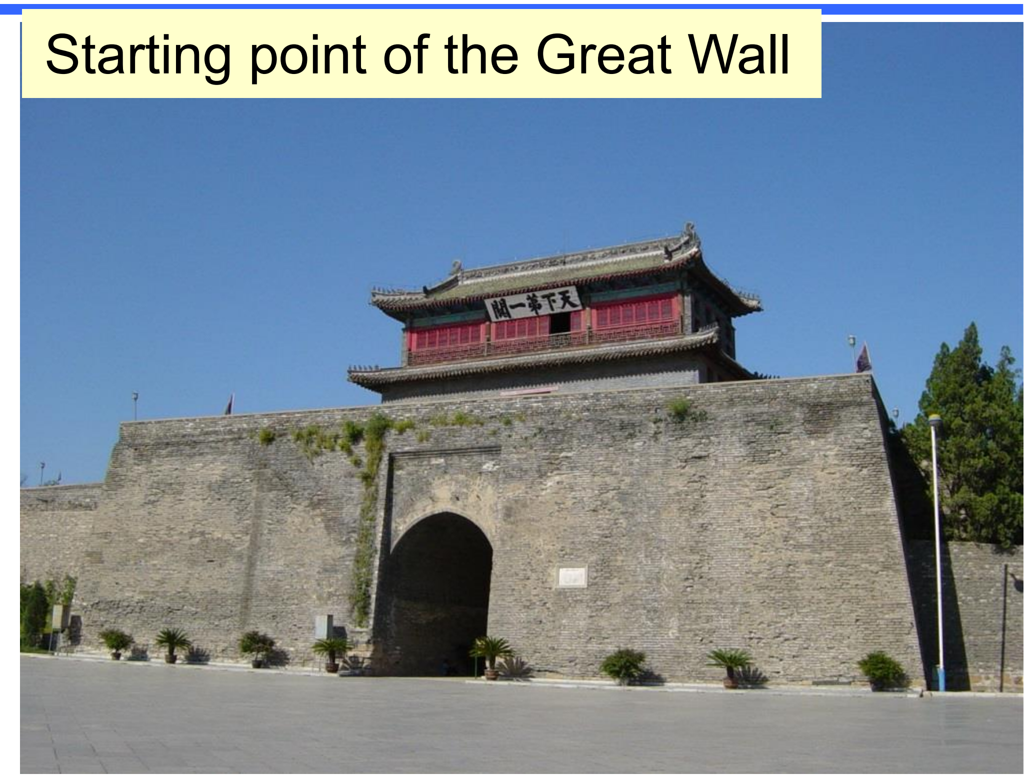
The circle is on the map



- A likely site: QinHuangDao (秦皇岛), 300 km from Beijing, 1hr by train.
- Good geological condition.
- Strong local support. Thinking about building a science city around it.

Beautiful Place for a Science Center

Best beach & cleanest air
Summer capital of China



Starting point of the Great Wall

Wine yard

The Chinese Dream

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR by the end of 2014 for R&D funding request**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2028-2035
- **SppC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2035-2042
  - Data taking: 2042 -

Yifang Wang at FCC kick off meeting

They say:

- Very long road, very difficult, but extremely exciting.
- Within China:
    - Good timing: BEPC to end in 2020. Time to plan the future. And in general, even at top levels, “in the mood” for something big.
    - Need to reach consensus (this year).
        - Not guaranteed, but excitements are building (and faster than expected)
    - A lot of money, but maybe affordable.
    - Many technological hurdles, but it is not impossible.
    - Need many more (and new) people.
        - So far, young people seem to be fired up.

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- It has to be completely international.
  - Will reply heavily on international collaboration for technology, man power...
  - Play an active role in global efforts: FCC and ILC.
  - Competing proposals and multiple machines are healthy ingredients of our community.
  - Even if this does not happen in China, the effort will help.

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  - Play an active role in global efforts: FCC and ILC.
  - Competing proposals and multiple machines are healthy ingredients of our community.
  - Even if this does not happen in China, the effort will help.
- This is part of the global effort to ensure a bright future for high energy physics.

Optimistic?

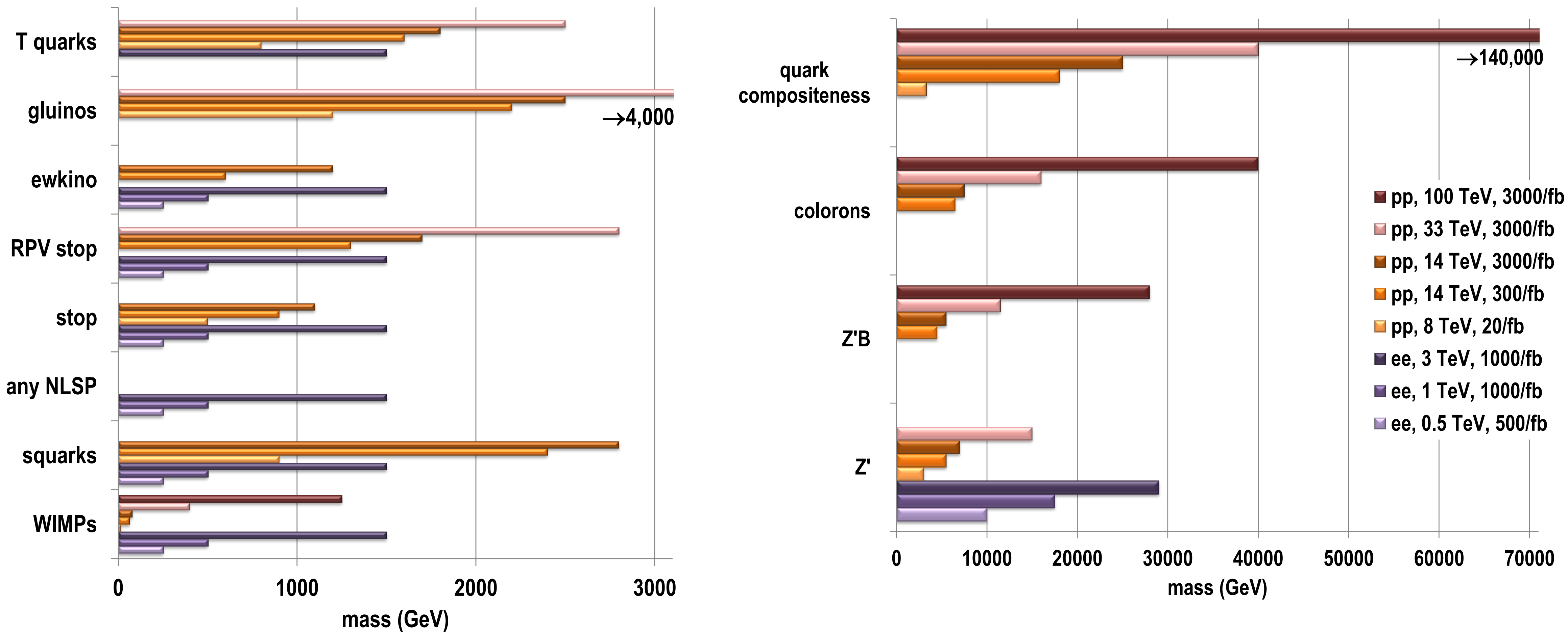
- Very long/difficult road, of course.
- So far, faster and better than I expected.
- May real test still to come
- I am optimistic. We have to try.

Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
$BR_{\rm inv}$	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_{Z} (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV	E_{beam} calibration	QED corrections
Γ_{Z} (keV)	$\Delta\rho$ (not $\Delta\alpha_{\mathrm{had}}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV	E_{beam} calibration	QED corrections
R_ℓ	$\alpha_{\mathrm{s}}, \delta_{\mathrm{b}}$	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004		Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	Zγ, 161 GeV	0.0010 (12)	< 0.001	Statistics	
R_{b}	δ_{b}	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{\mathrm{had}}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_{W} (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{\mathrm{had}}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV	E_{beam}, Statistics	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$\mathrm{t\bar{t}}$ threshold scan	10 (12) MeV	< 10 MeV	Statistics	Theory interpretation

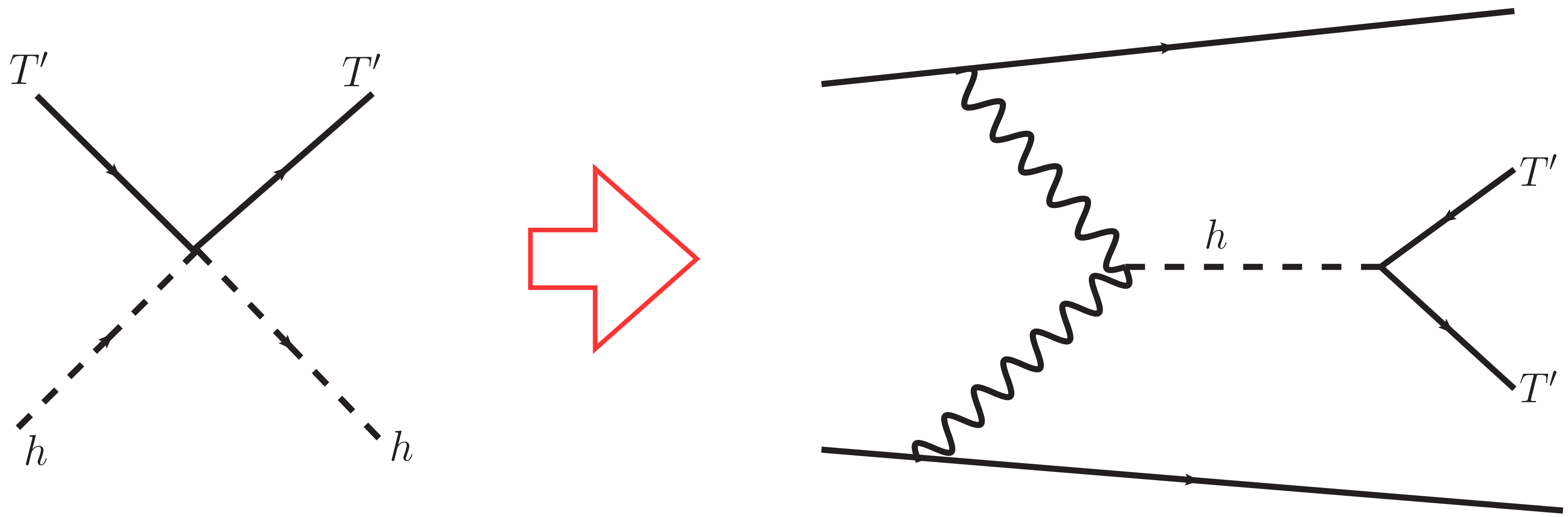
Summary figure from Snowmass



- However, just looking at the length of the bars could be misleading.

- More details needed to understand what lepton collider can do.

We can hide T′ very well.



- Top partner not colored.
  - Twin Higgs. Chacko, Harnik, et al
  - General Higgs portal.
- Study to be done!
  - Reach probably very limited, 100s GeV (my guess)