Future Hadron Colliders

Lian-Tao Wang
University of Chicago

BSM Higgs Workshop @ LPC Nov. 4, 2014

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Translation:

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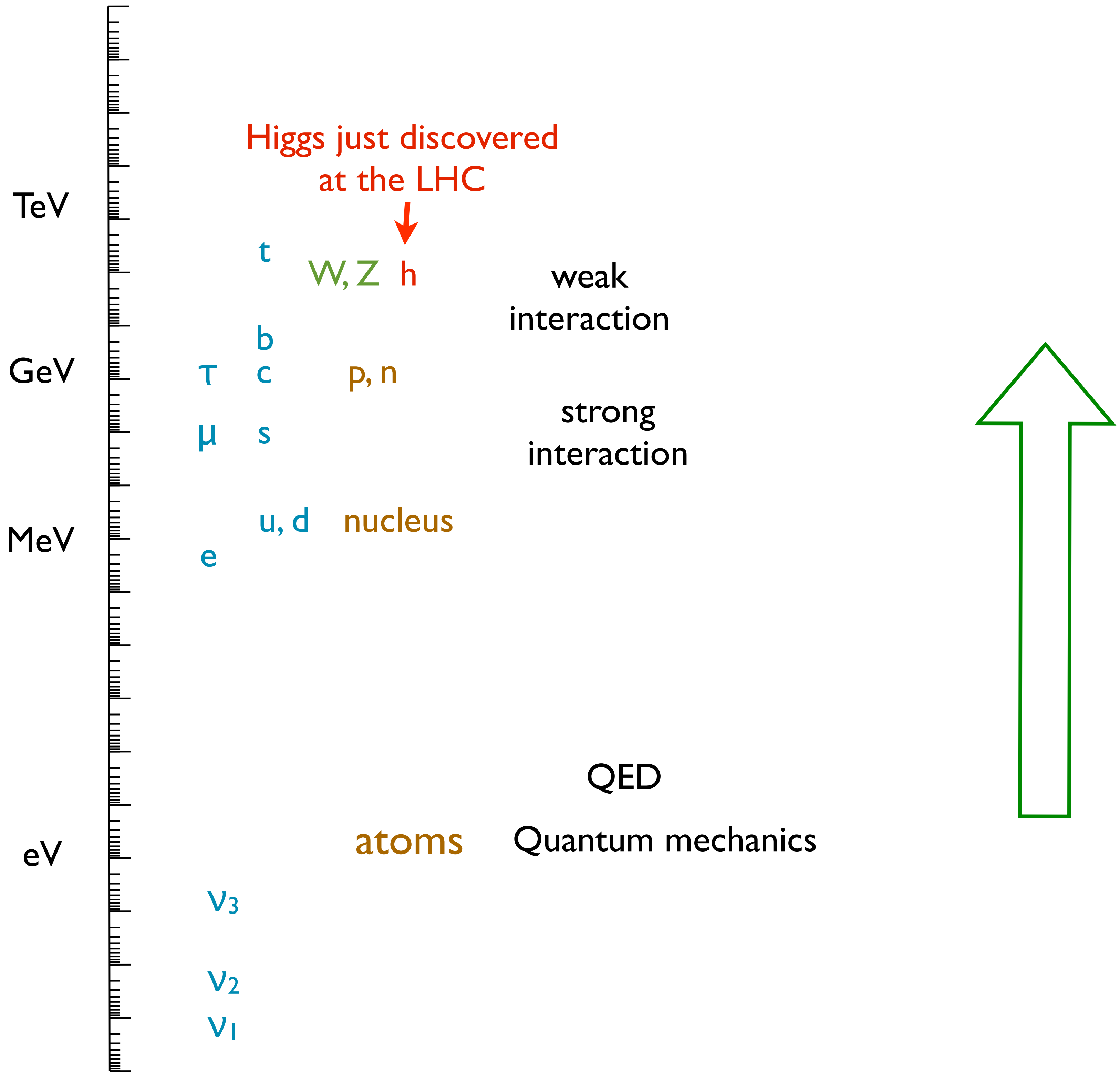
However, I think we have to go further.

Following the historically successful path



A long journey,
many discoveries
along the way.

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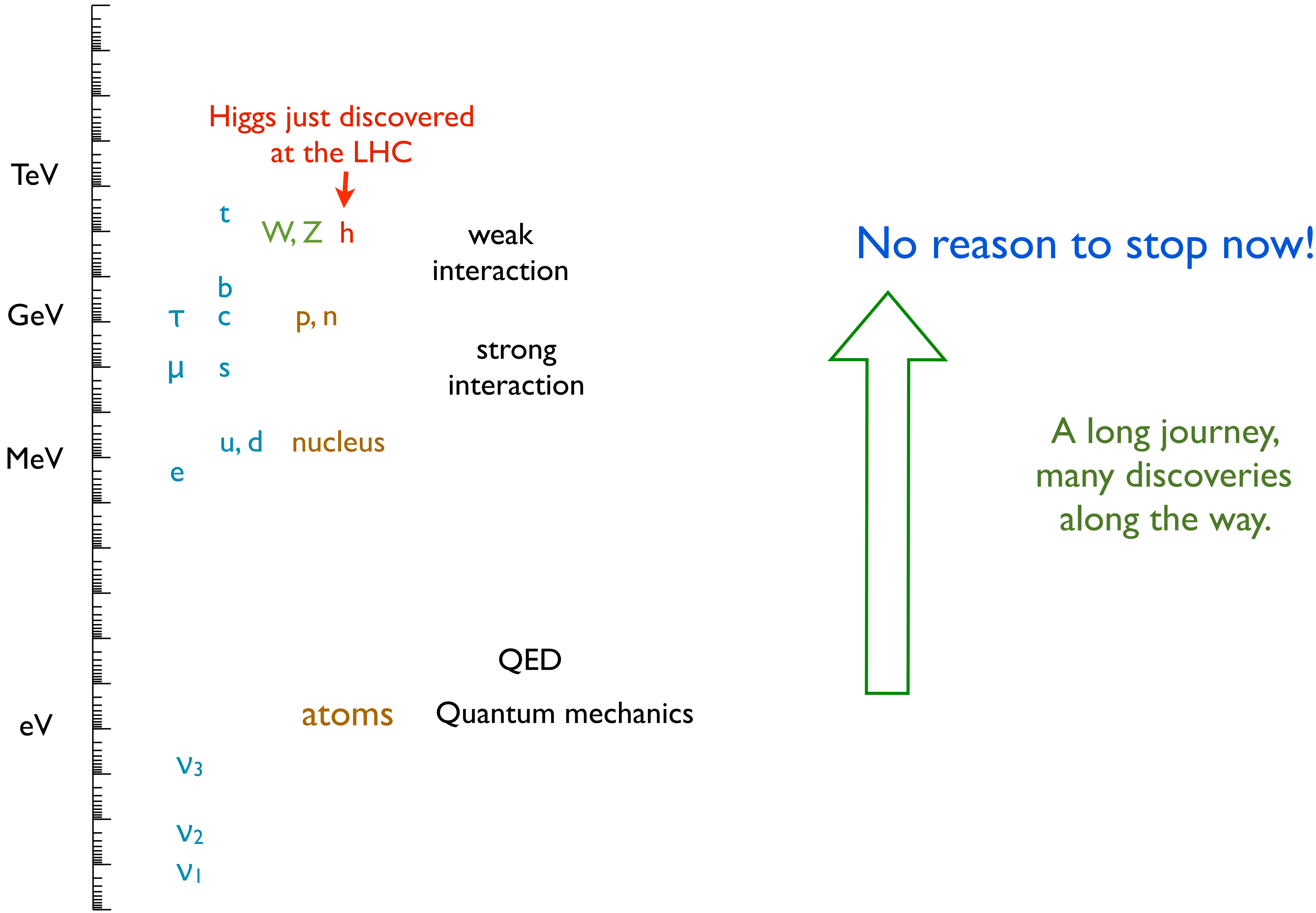

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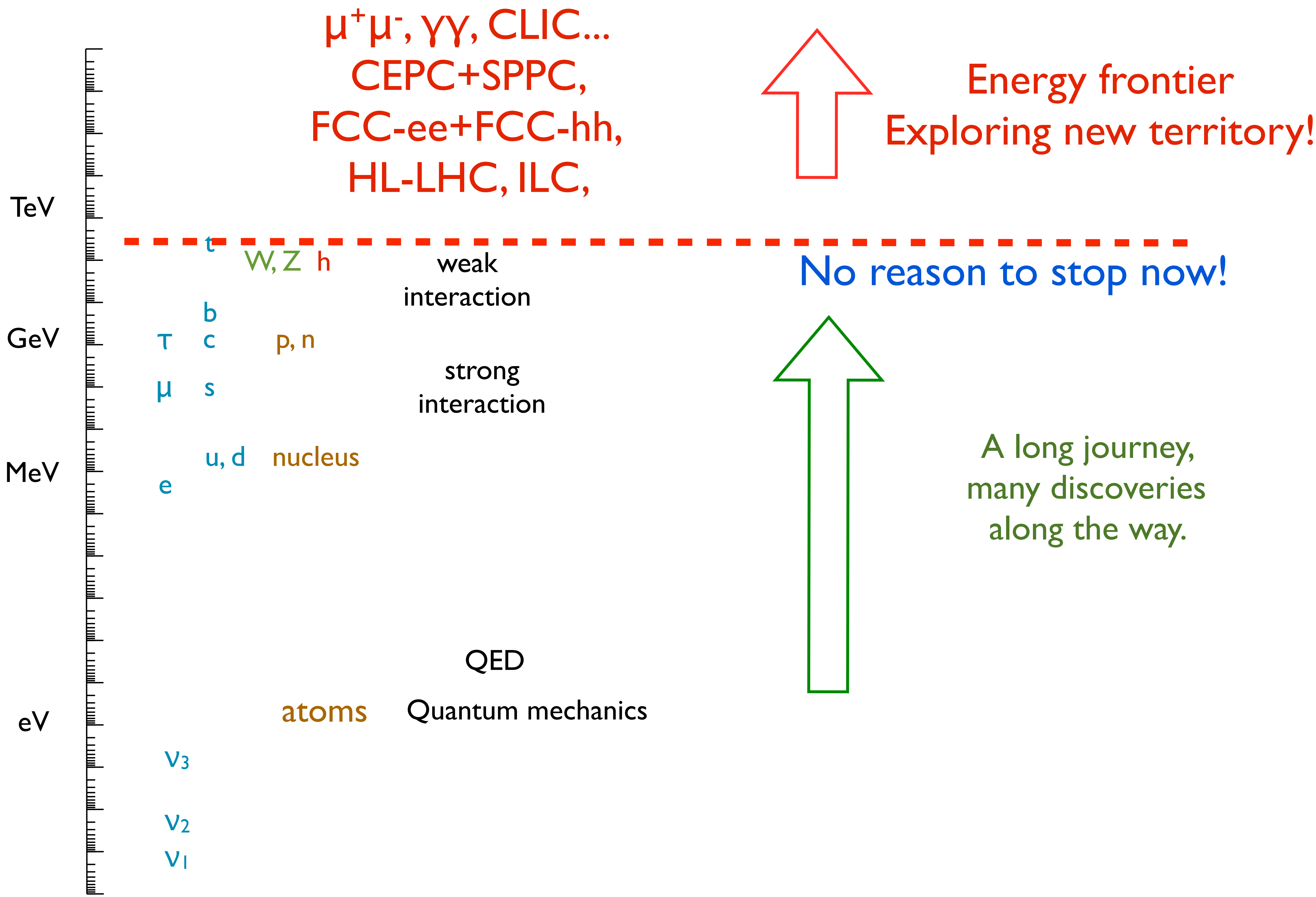

Many open questions

Discovery of a SM-like Higgs boson
"completes" SM with the following Higgs potential

$$V(H) = -\mu^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$

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Naturalness, ...

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Naturalness, ...

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Other open questions:
dark matter, matter-antimatter asymm....

To answer these questions

- Going further in the energy frontier is necessary.
- Will focus on future hadron collider in this talk.
- A natural next step after the ee program (just like LEP ⇒ LHC)
    - CERN: FCC-hh
    - China: Super p p Collider (SppC).
    - Will mention ee program at places.

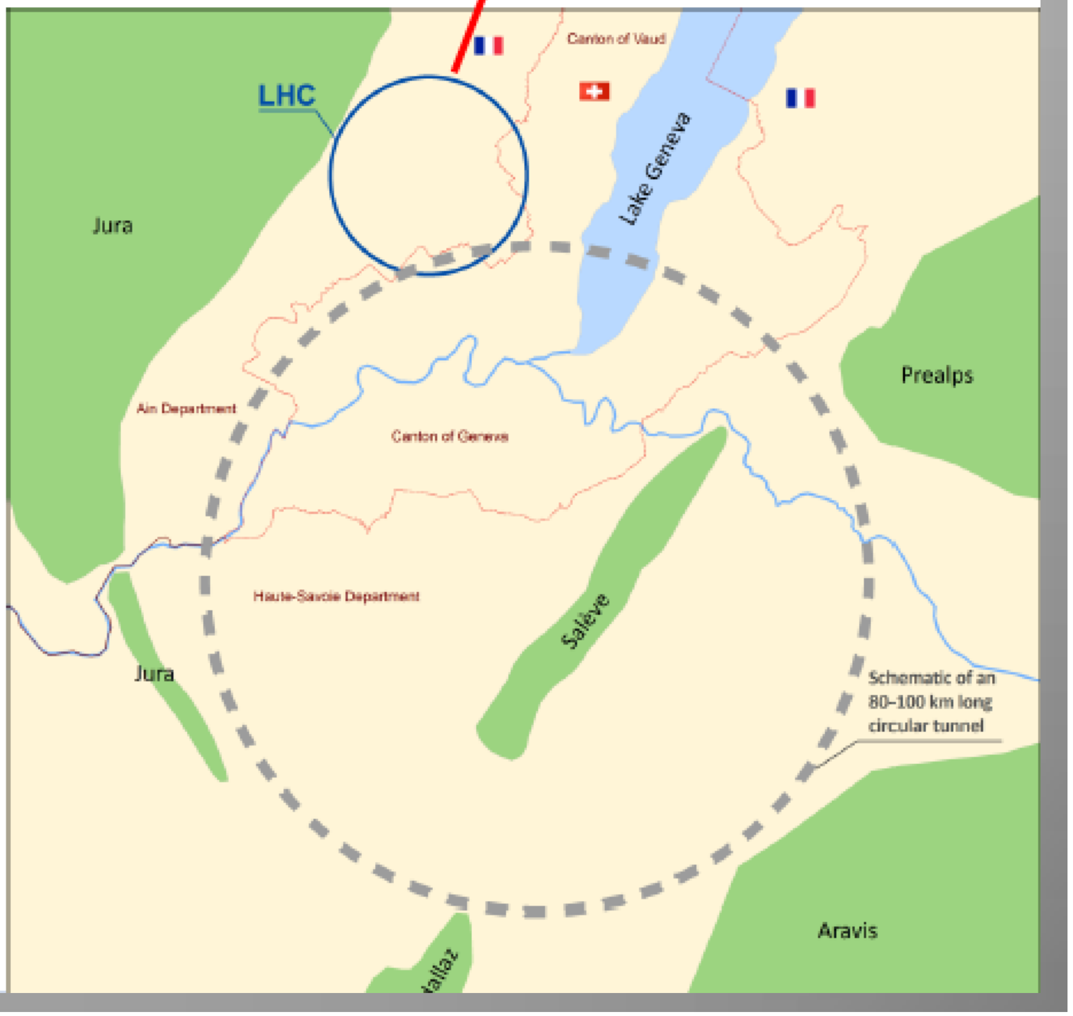
FCC-hh: a Proton-Proton Collider

"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

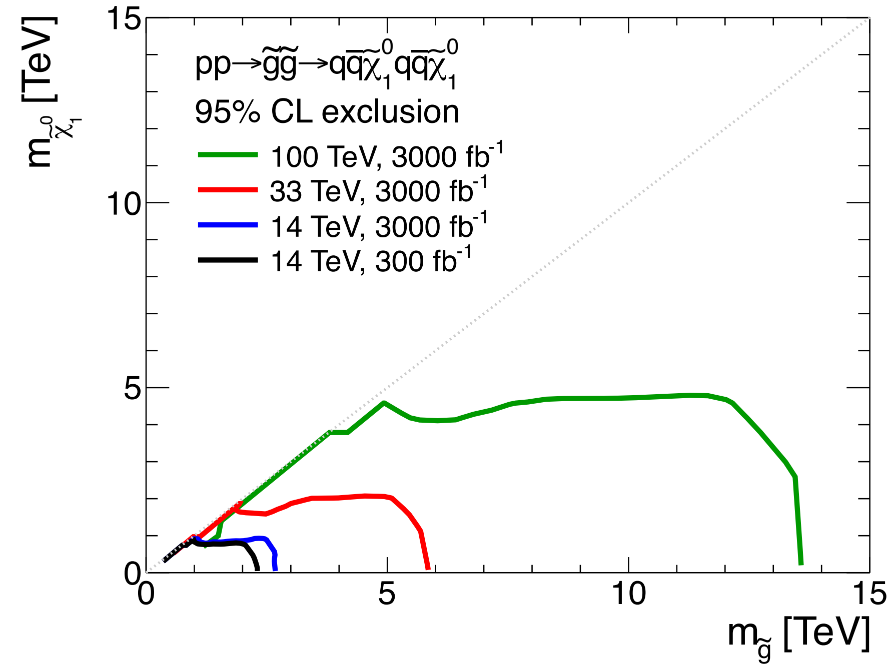


Albert De Roeck, at Astrophysics 2014

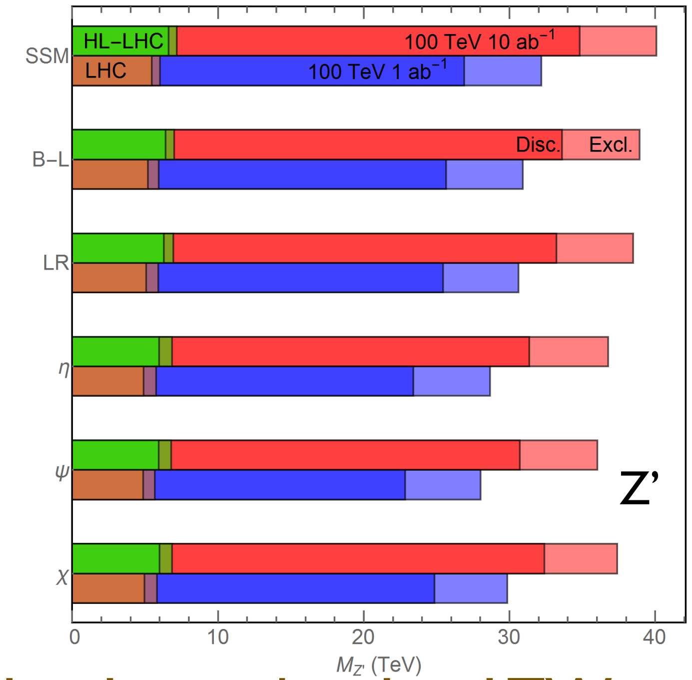
Main Parameters of SppC

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

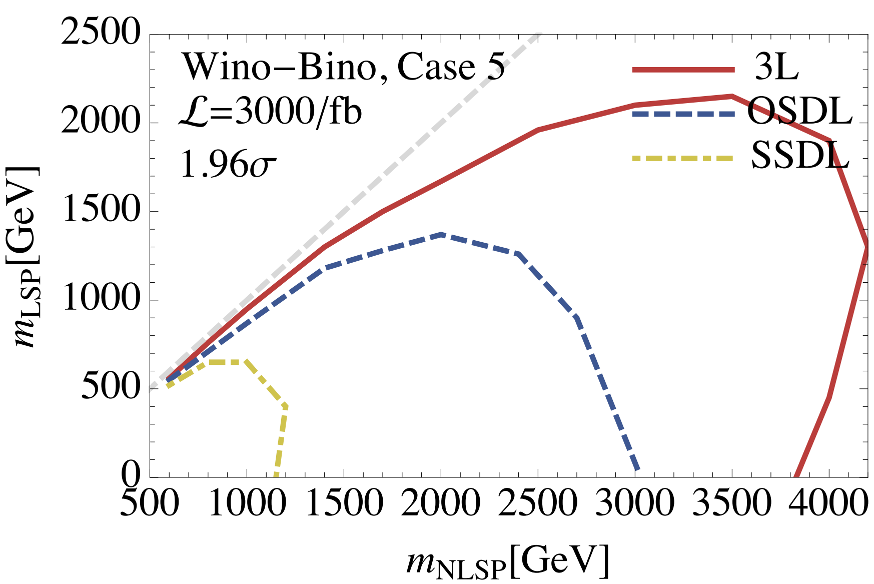
Big step forward



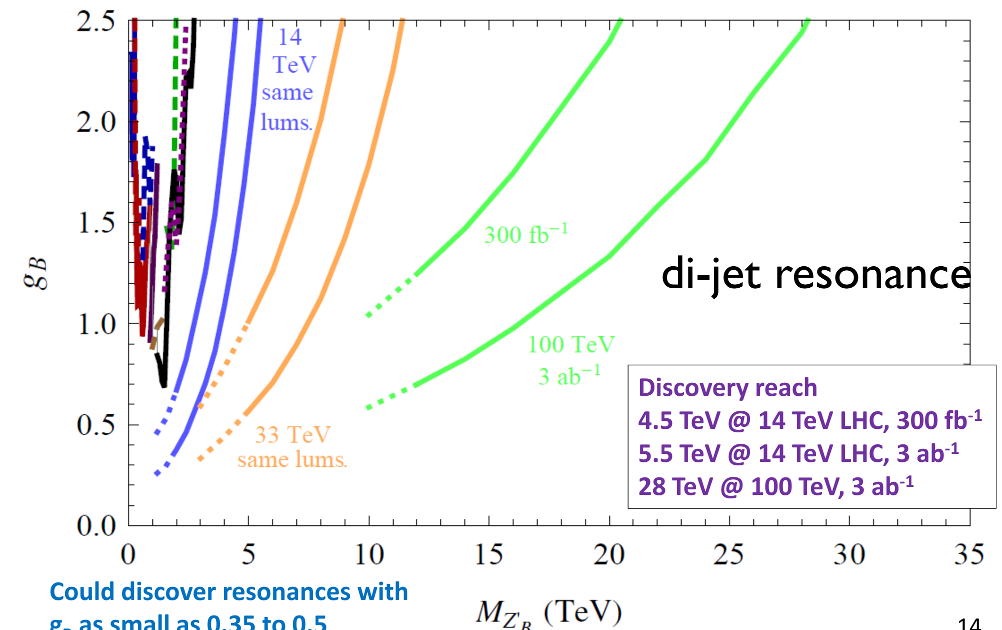
Cohen et al, 2013



Han, Langacker, Liu, LTW, to appear



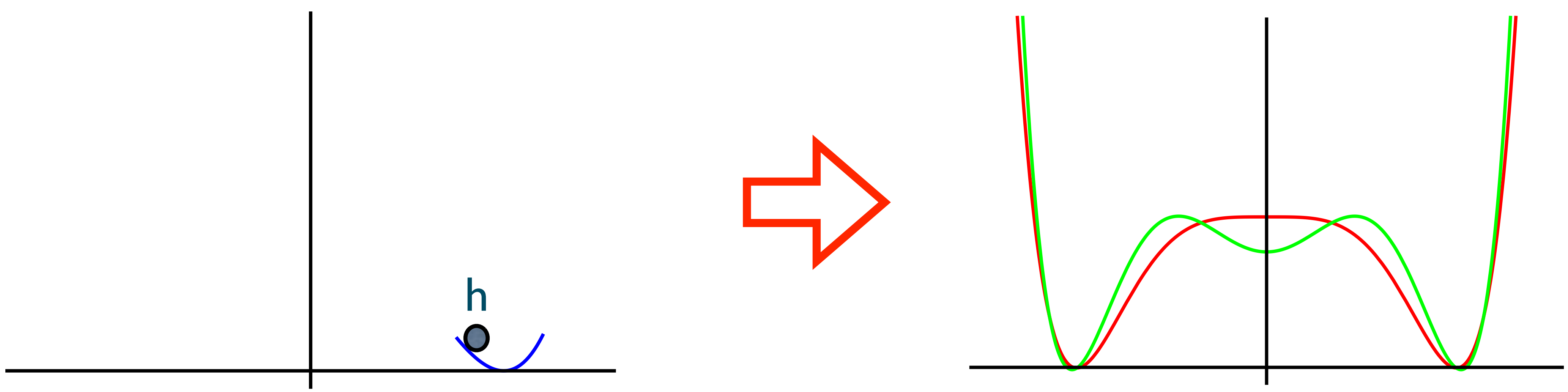
Gori, Jung, LTW, Wells, 2014



Felix Yu, 2013

cross the board: x 5(more) improvement, into (10)TeV regime

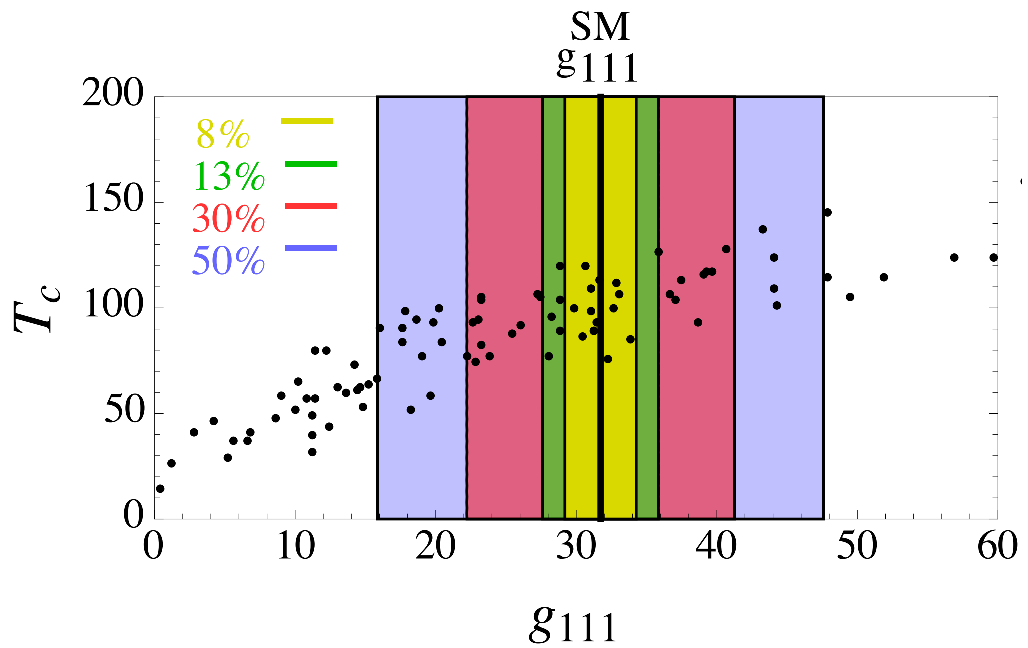
Nature of EW phase transition



current state of knowledge

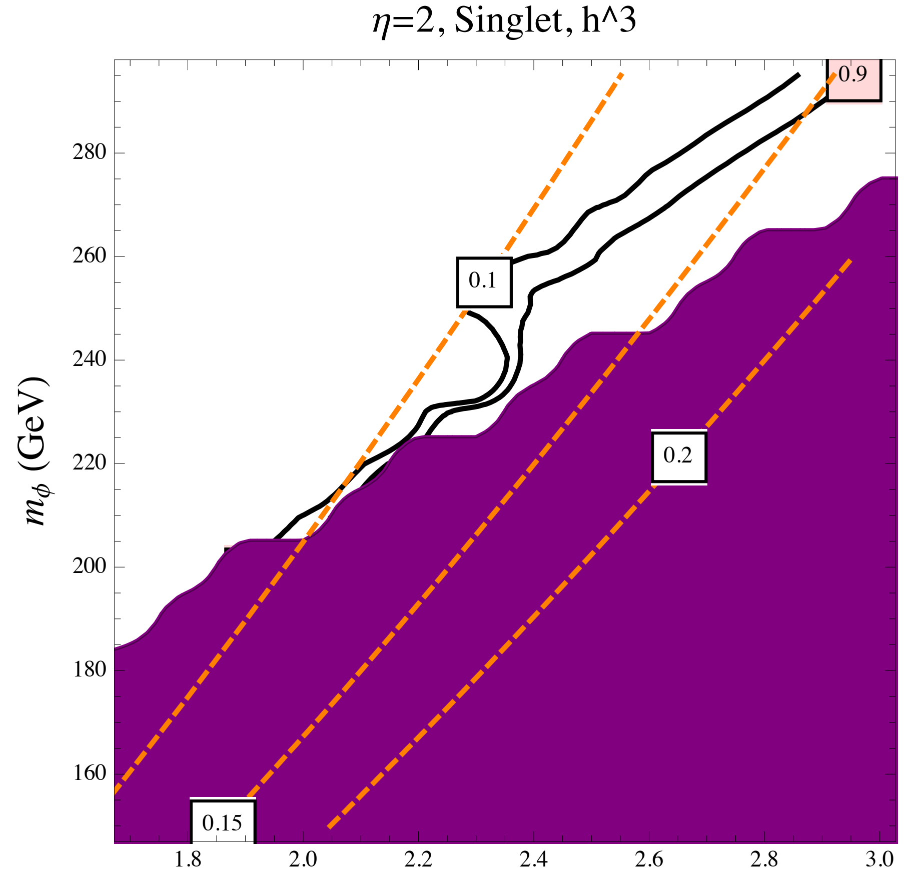
See M. Perelstein's talk

Triple Higgs coupling



Generic singlet model

Profumo et al, 2014



Singlet with Z_2

Katz, Perelstein, 2014

See also Curtin, Meade and Yu, 2014

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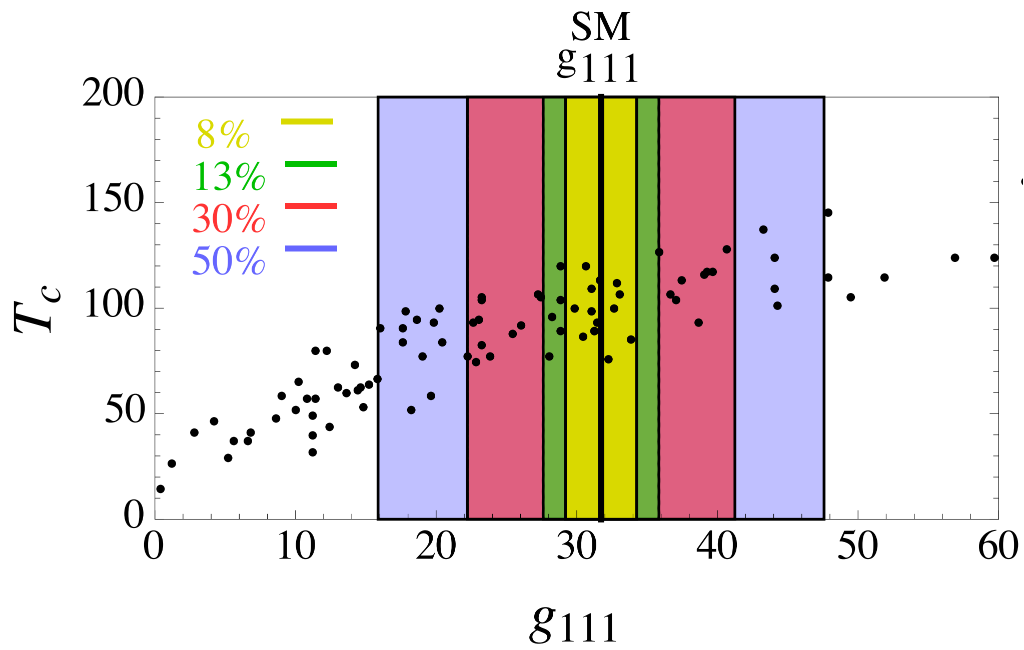

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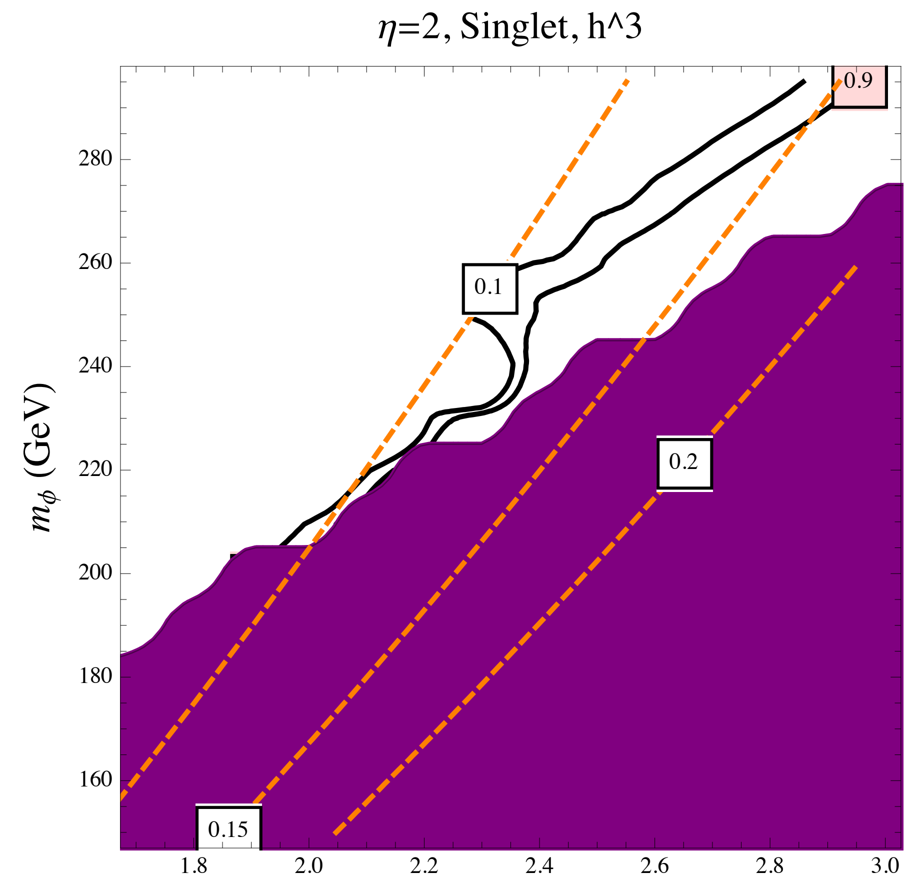

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- Simplest model for 1st order phase transition, introducing a singlet.
  - Also the toughest to discover.

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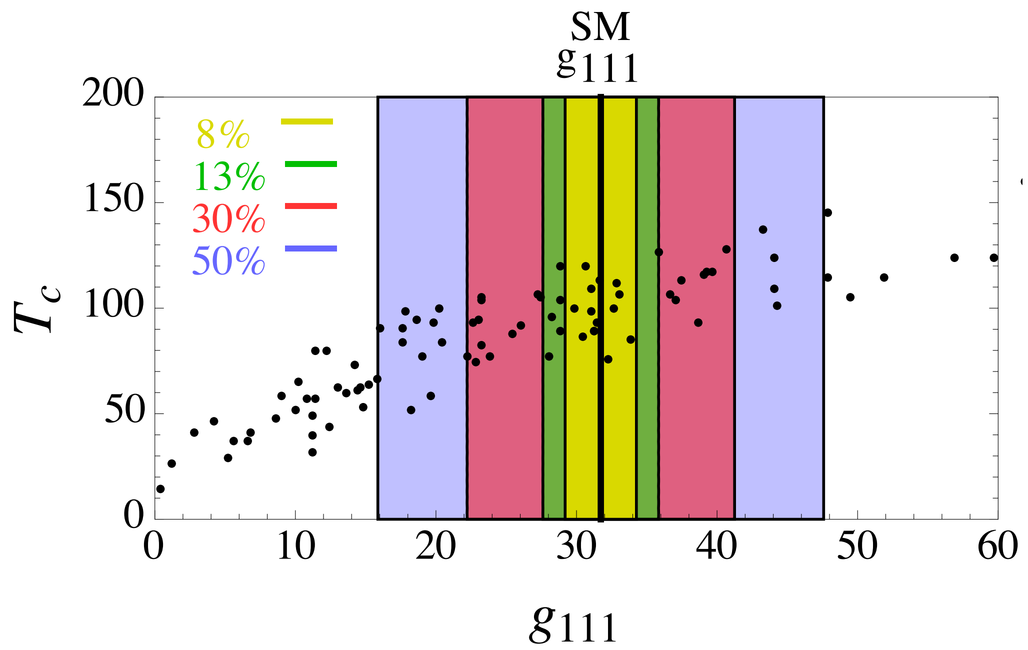

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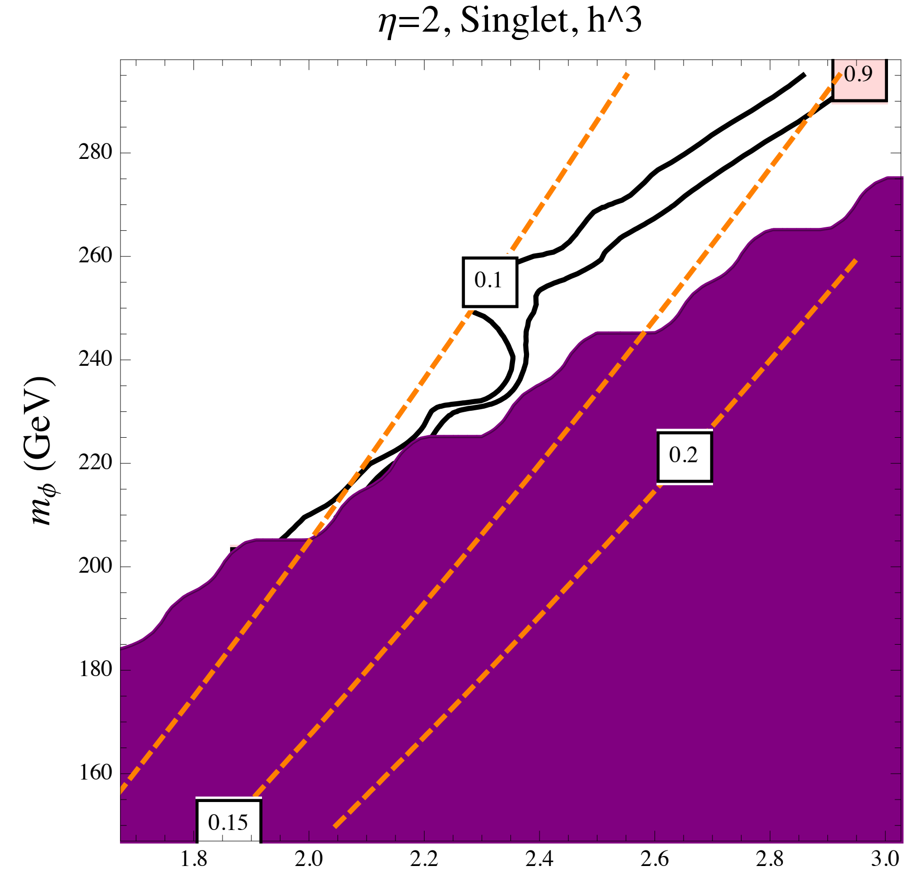


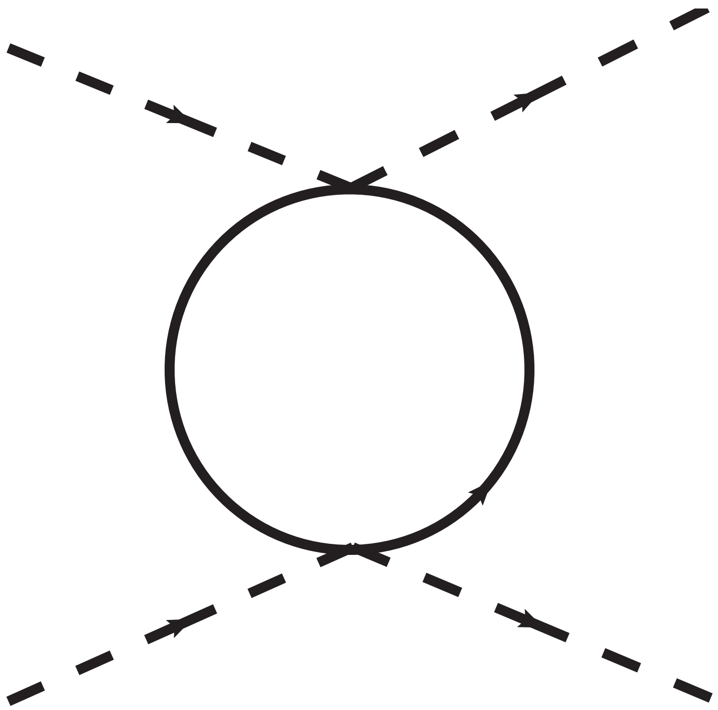
Singlet with Z_2

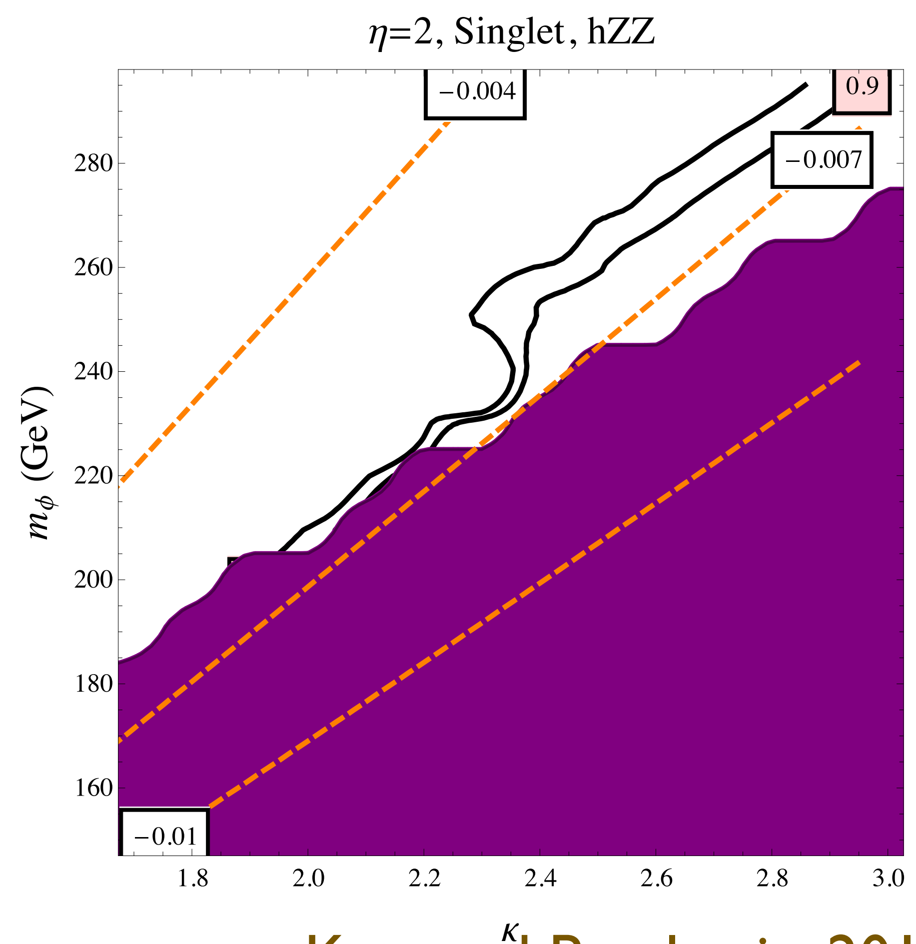
Katz, Perelstein, 2014

See also Curtin, Meade and Yu, 2014

- Simplest model for 1st order phase transition, introducing a singlet.
  - Also the toughest to discover.
- HL-LHC 30% - 50%?, Higgs factory: 20%, 100 TeV: 8%-15%?
  - Generic model, large deviation. "Completely" covered.
  - Model with Z_2 , harder, perhaps an evidence at HF or 100 TeV.

Also shifts the Zh coupling

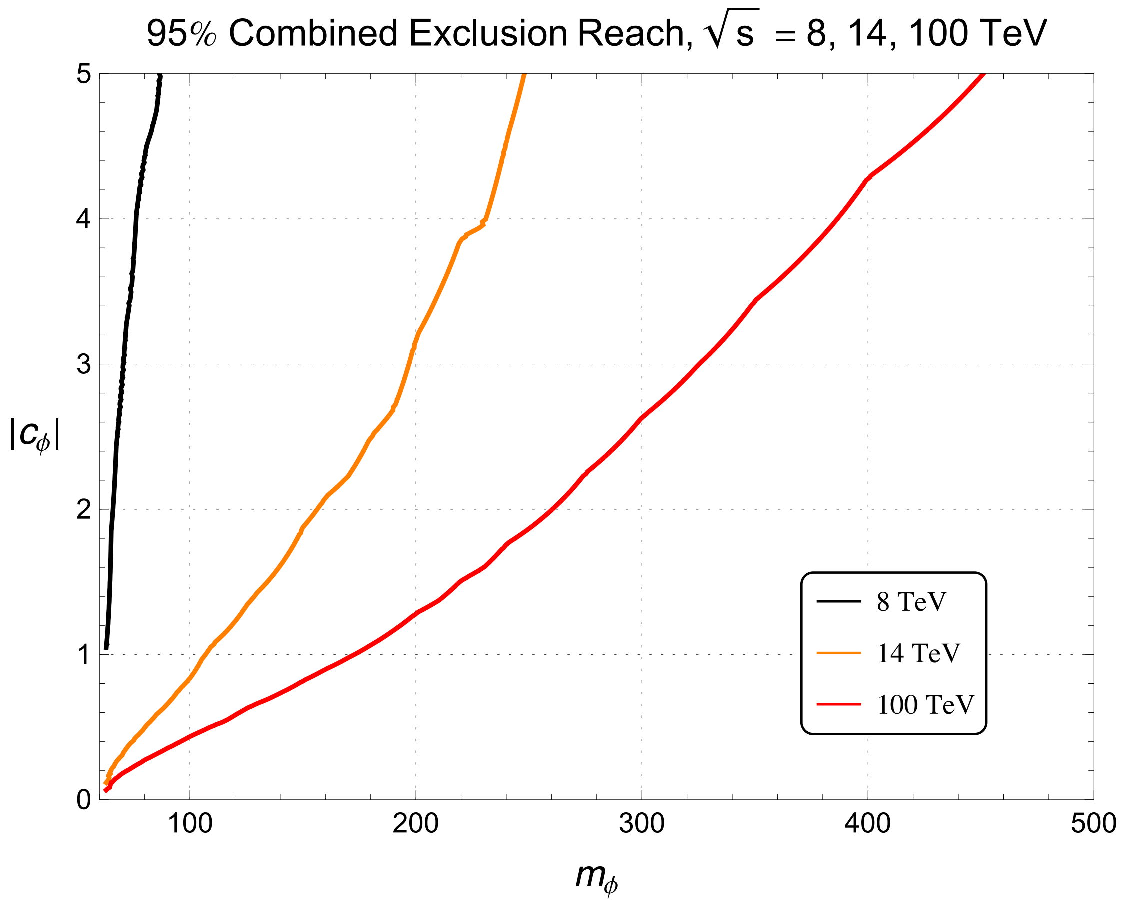


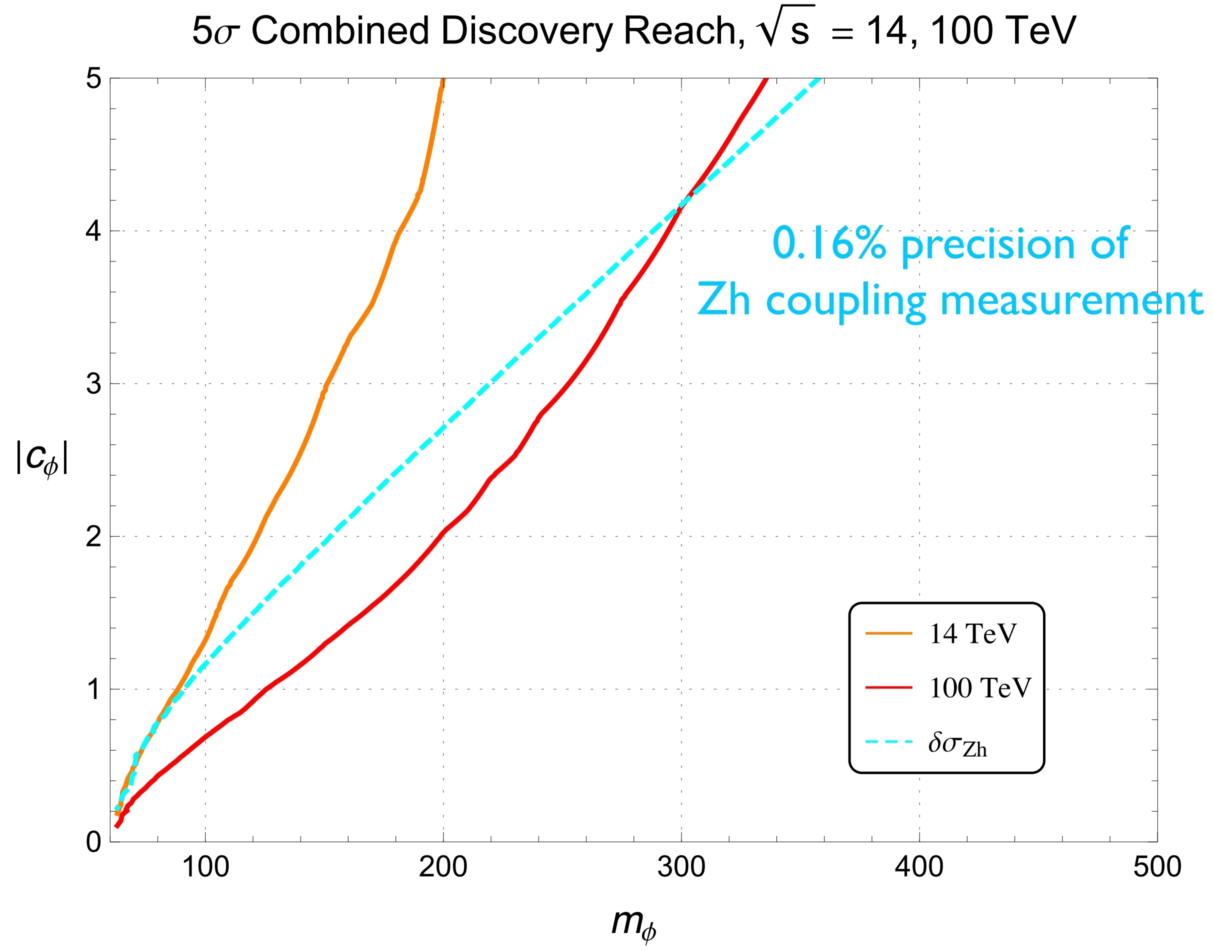


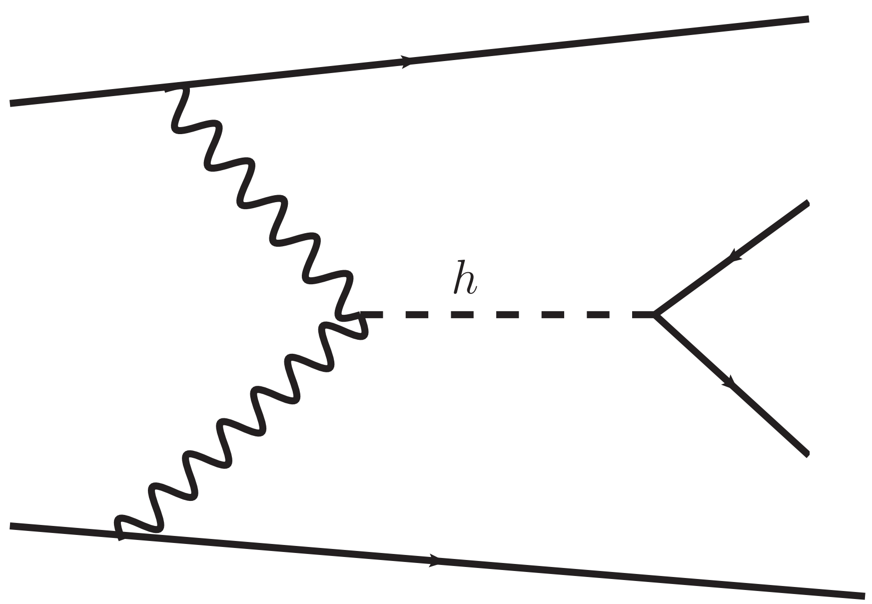
Katz and Perelstein, 2014

- At the 0.5-06% level.
- Higgs factory will have a chance > 2σ

Better chance: direct production of singlet at 100 TeV







Craig, Lou, McCullough, Thalapillil, to appear

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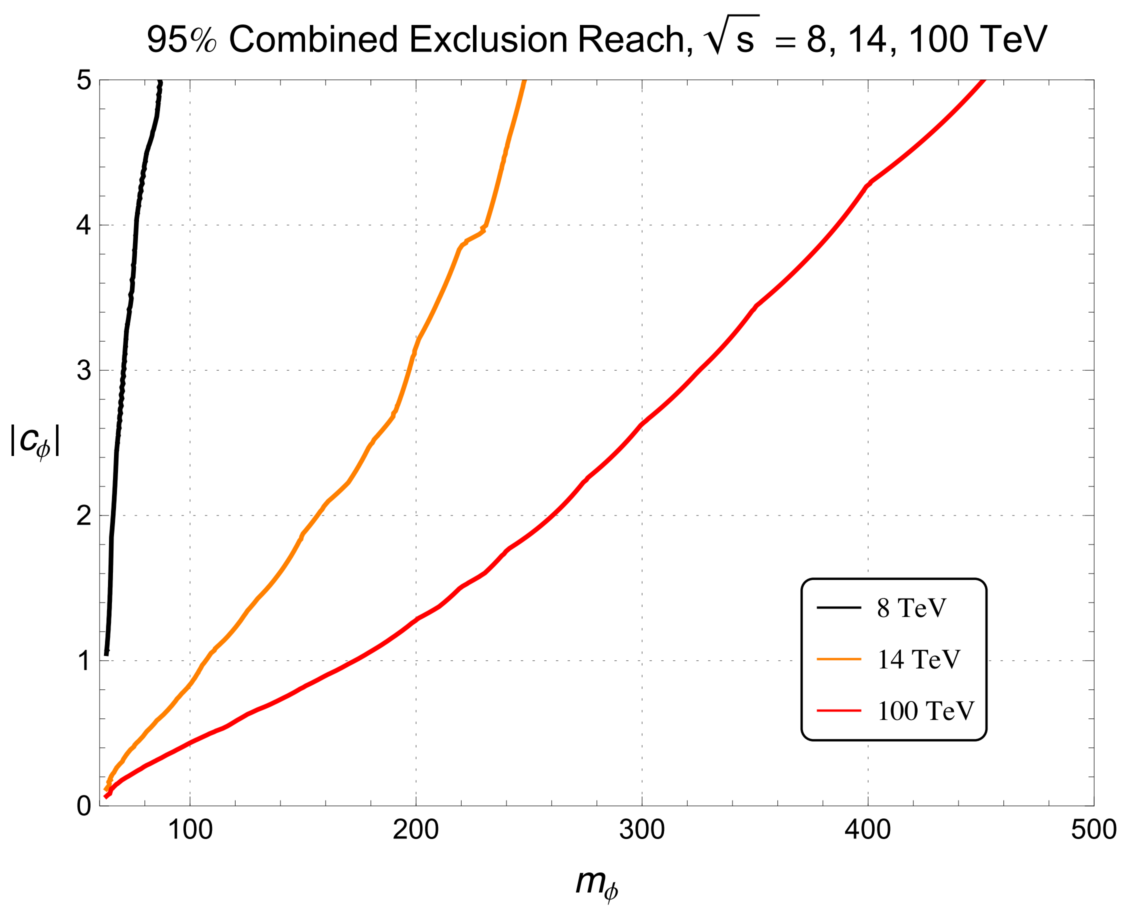
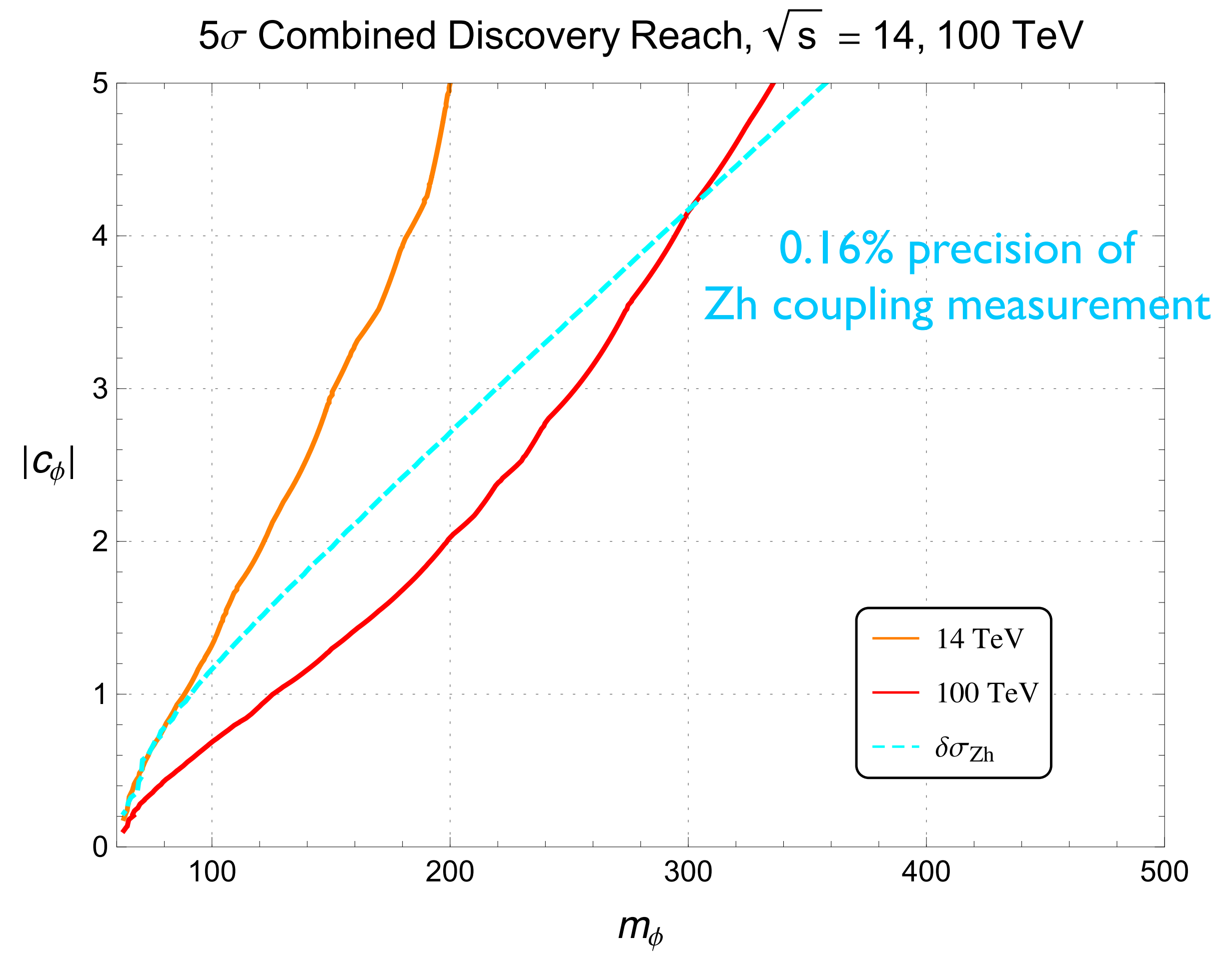




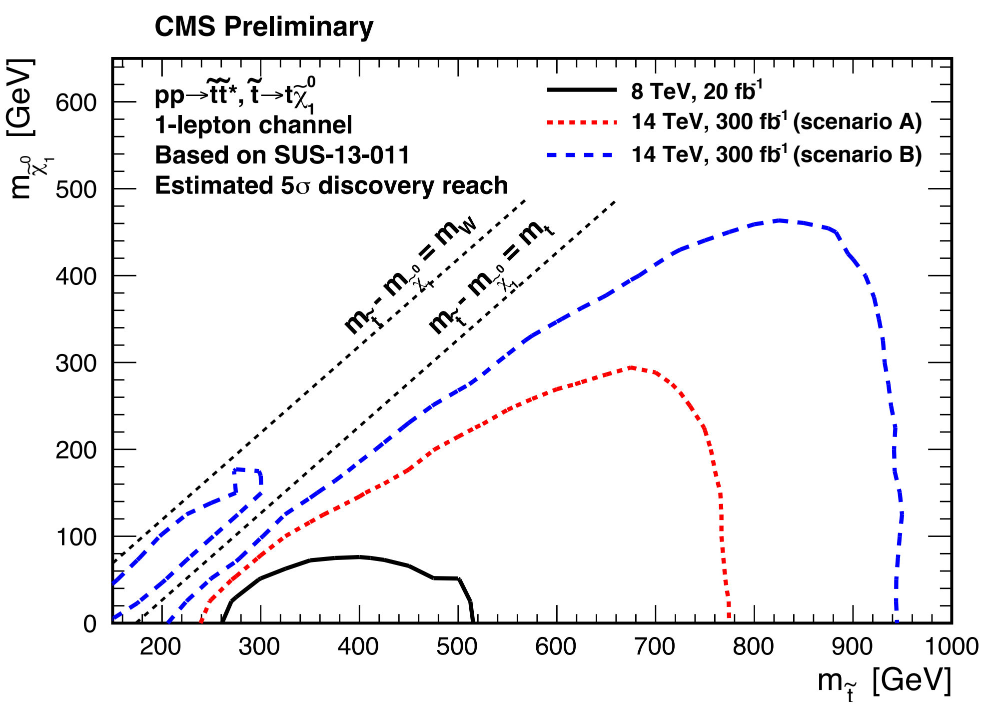
Craig, Lou, McCullough, Thalapillil, to appear

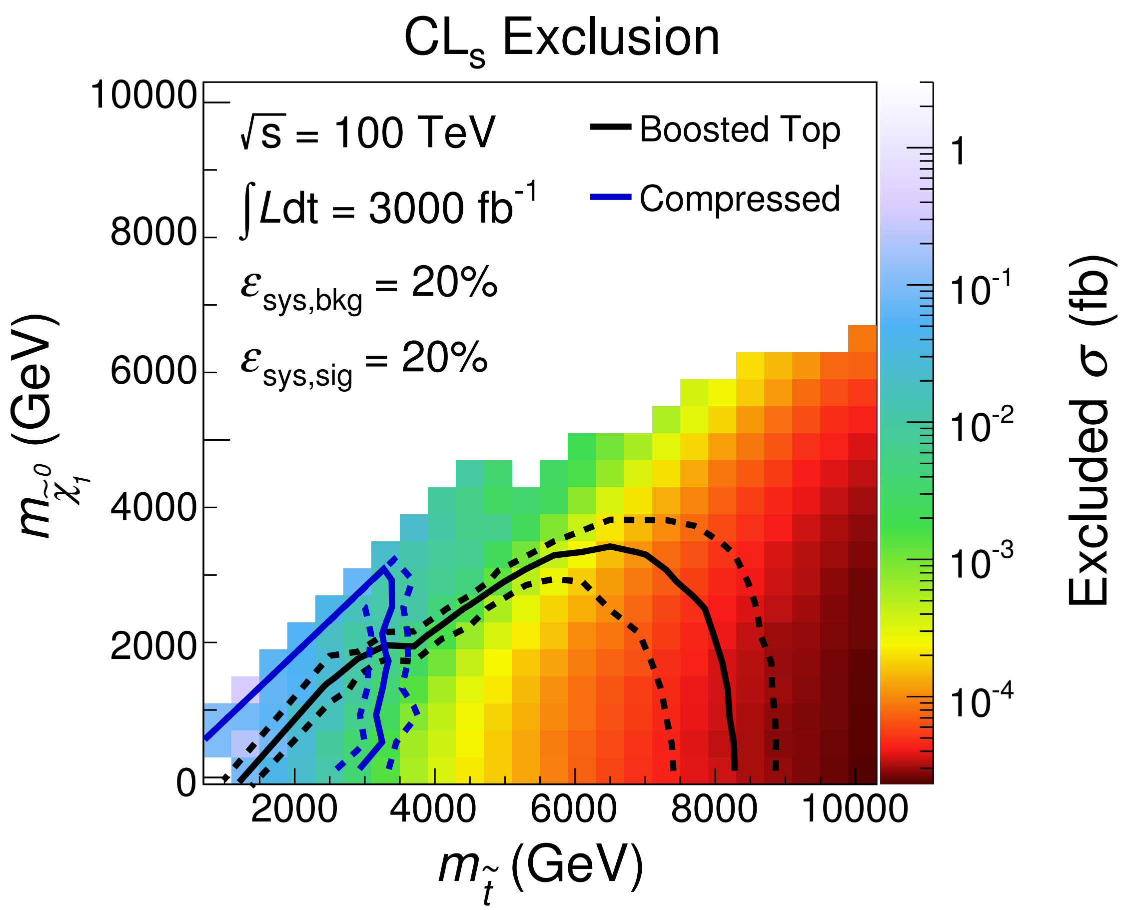
- Is EW phase transition 1st order?
  - Combination of Higgs factory and 100 TeV pp collider will go (very) long way!

Naturalness

Naturalness

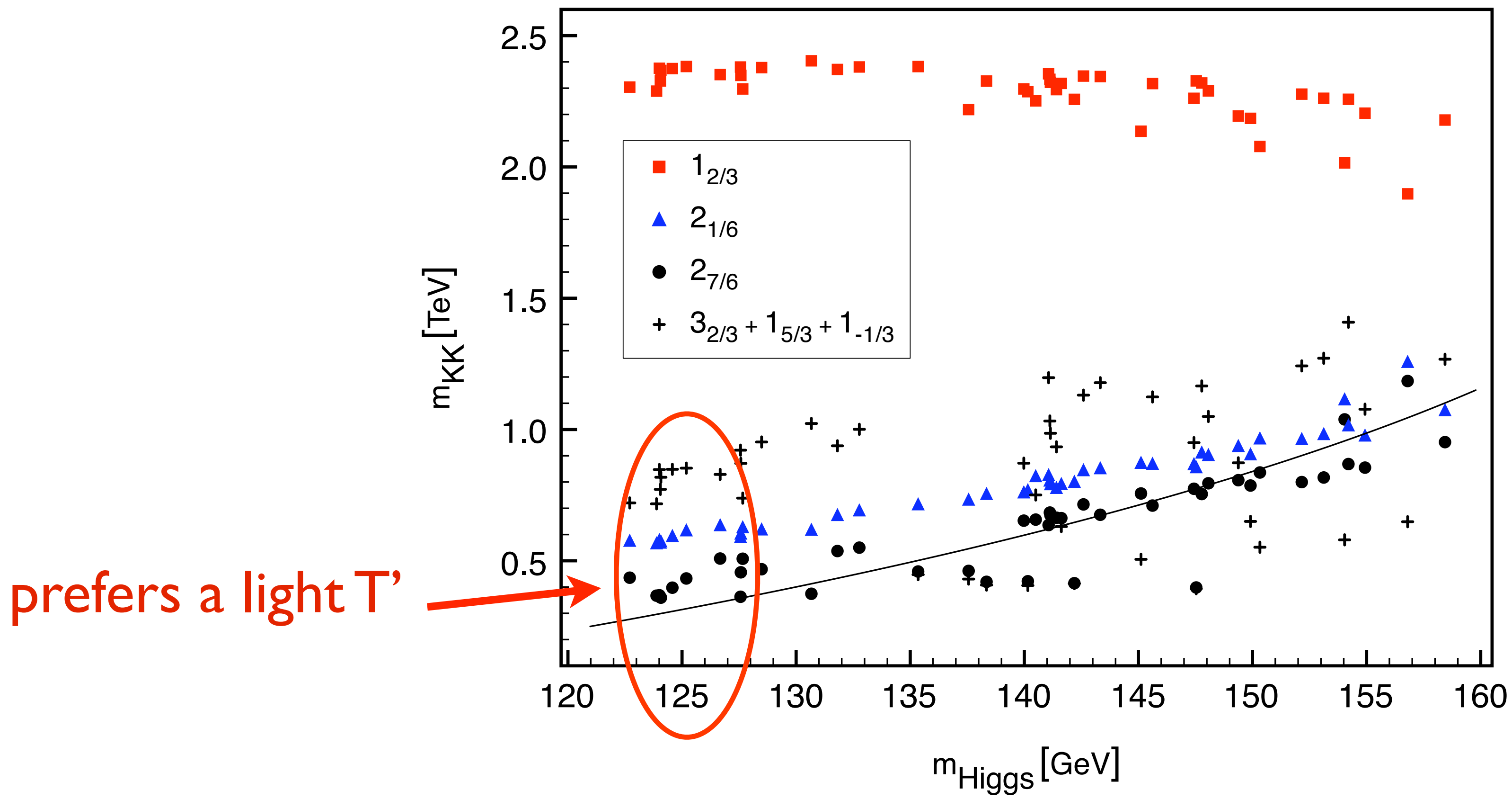
Cohen et. al., 2014





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

Compositeness and top partner

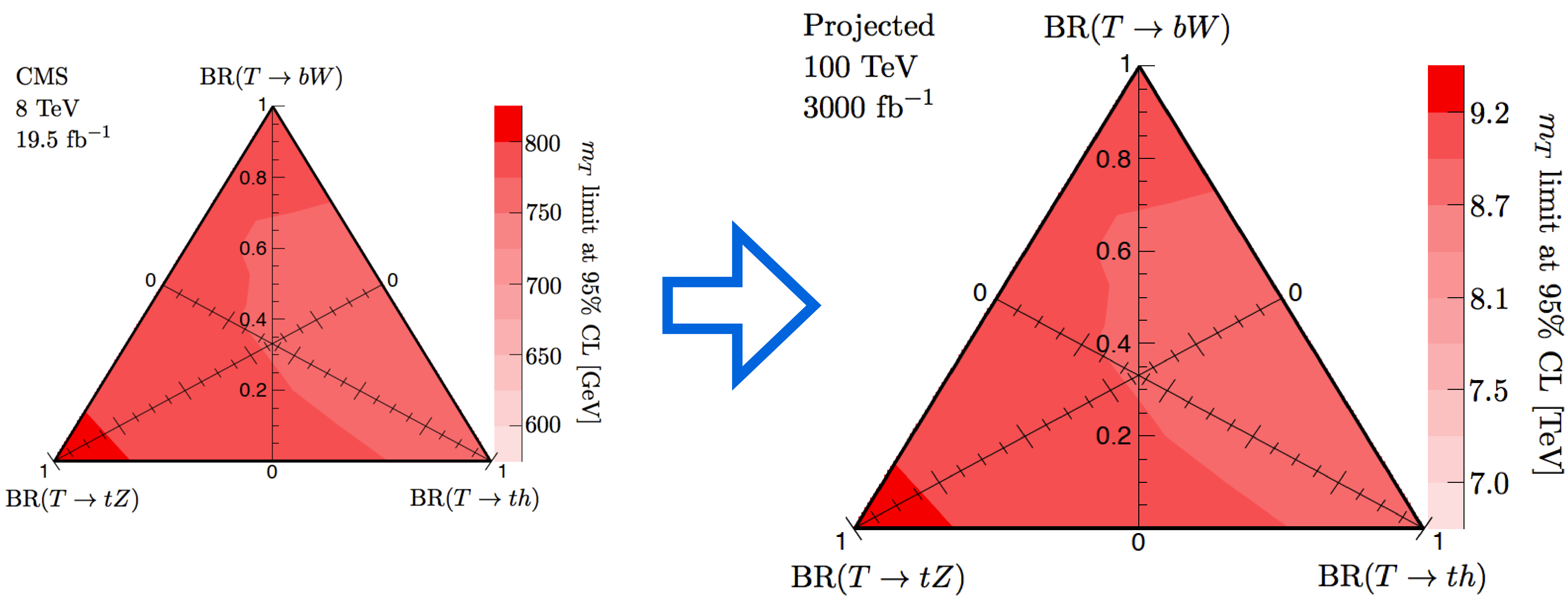


Contino, Da Rold, Pomarol, 2006

- Plays a crucial role in EWSB.

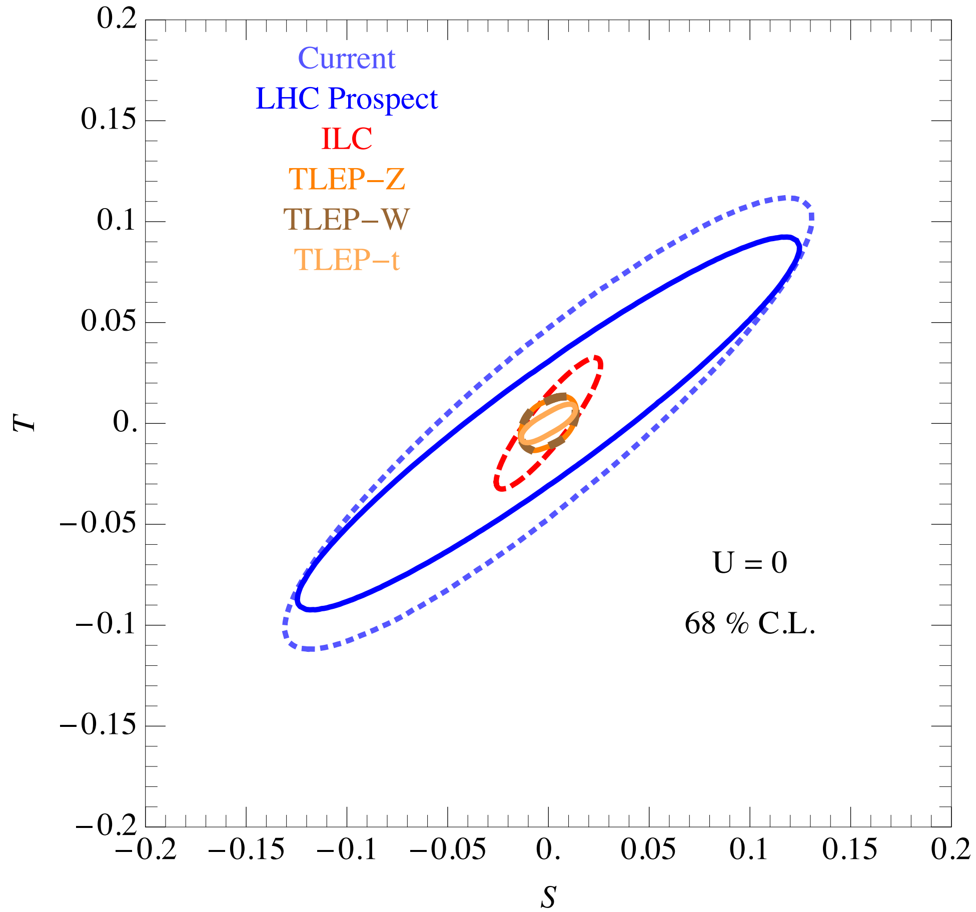
For a comprehensive discussion, see
De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663

Going up to 100 TeV

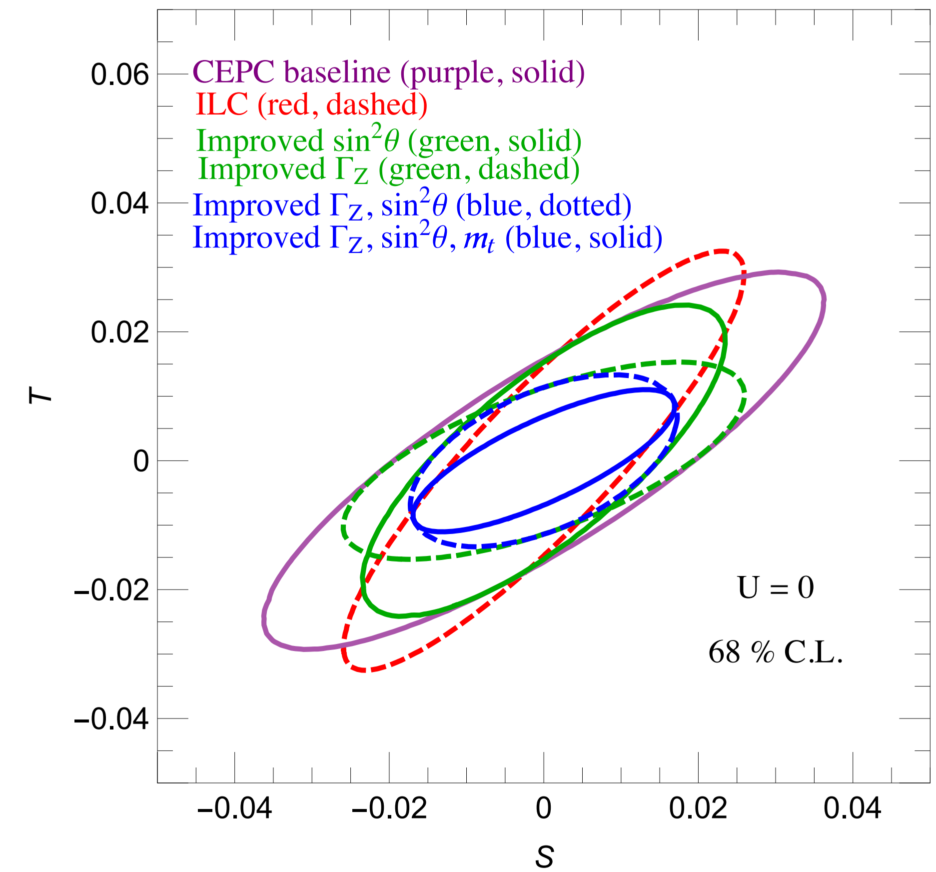


- Again, room for improvement by using single production, boosted technique, etc.

From precision measurements



Fan, Reece, LTW



- Lepton colliders $\Rightarrow$ new era in EW precision.
  - A factor of 10 improvement on S and T
- LEP+SLD taught us a lot, we will learn much more with these facilities.

Probing compositeness/SUSY scales

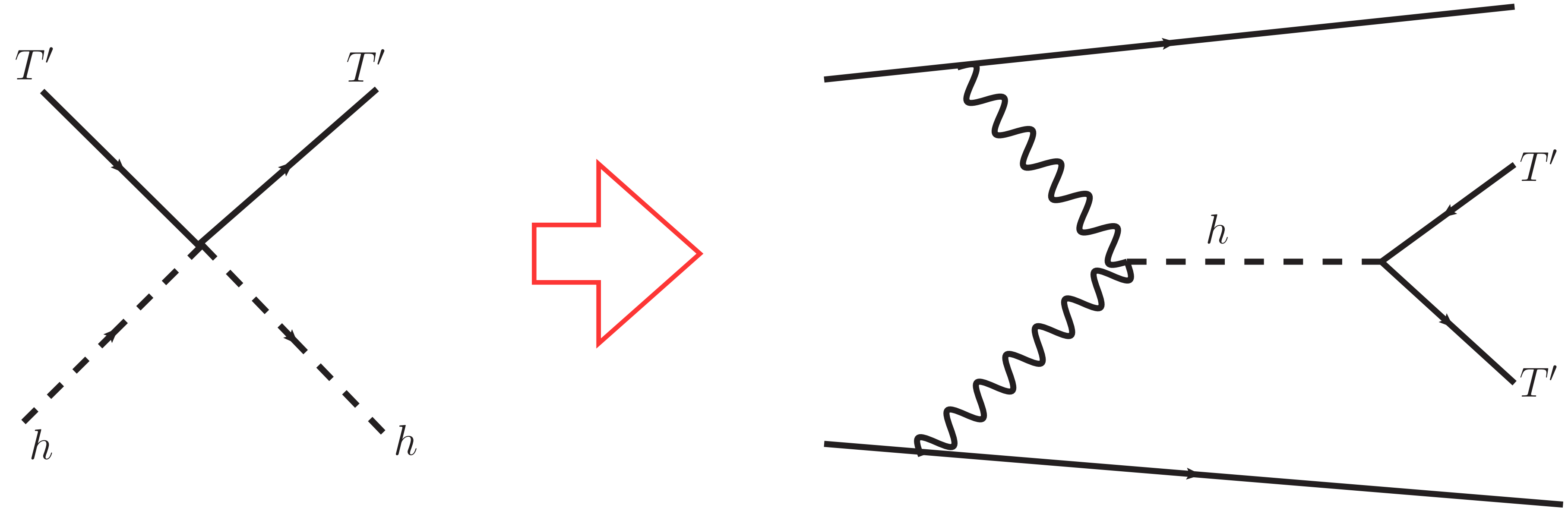
Experiment	S (68%)	f (GeV)	T (68%)	$m_{\tilde{t}_L}$ (GeV)
ILC	0.012	1.1 TeV	0.015	890 GeV
CEPC (opt.)	0.02	880 GeV	0.016	870 GeV
CEPC (imp.)	0.014	1.0 TeV	0.011	1.1 GeV
TLEP-Z	0.013	1.1 TeV	0.012	1.0 TeV
TLEP-t	0.009	1.3 TeV	0.006	1.5 TeV

Compositeness: $S \sim \frac{4\pi v^2}{m_\rho^2} \sim \frac{N}{4\pi}\frac{v^2}{f^2}$

SUSY: $T \approx \frac{m_t^4}{16\pi \sin^2\theta_W m_W^2 m_{\tilde{t}_L}^2}$

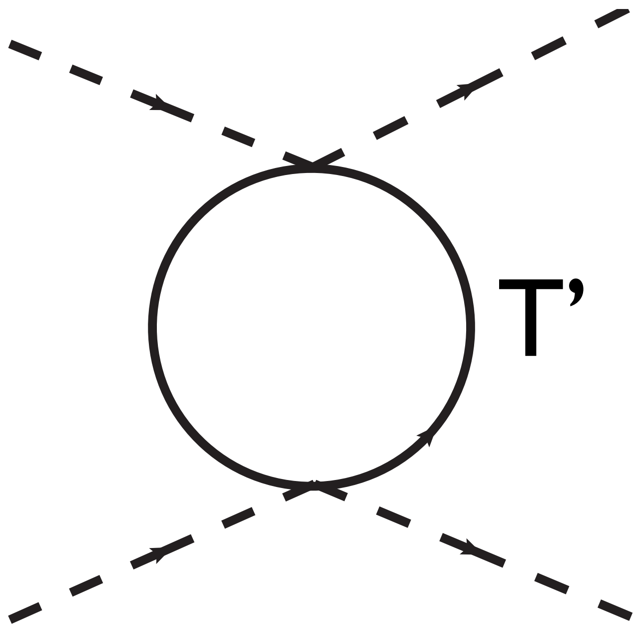
- This is complementary to the direct collider searches.
  - Independent of decay modes and kinematics.

We can hide T′ very well.

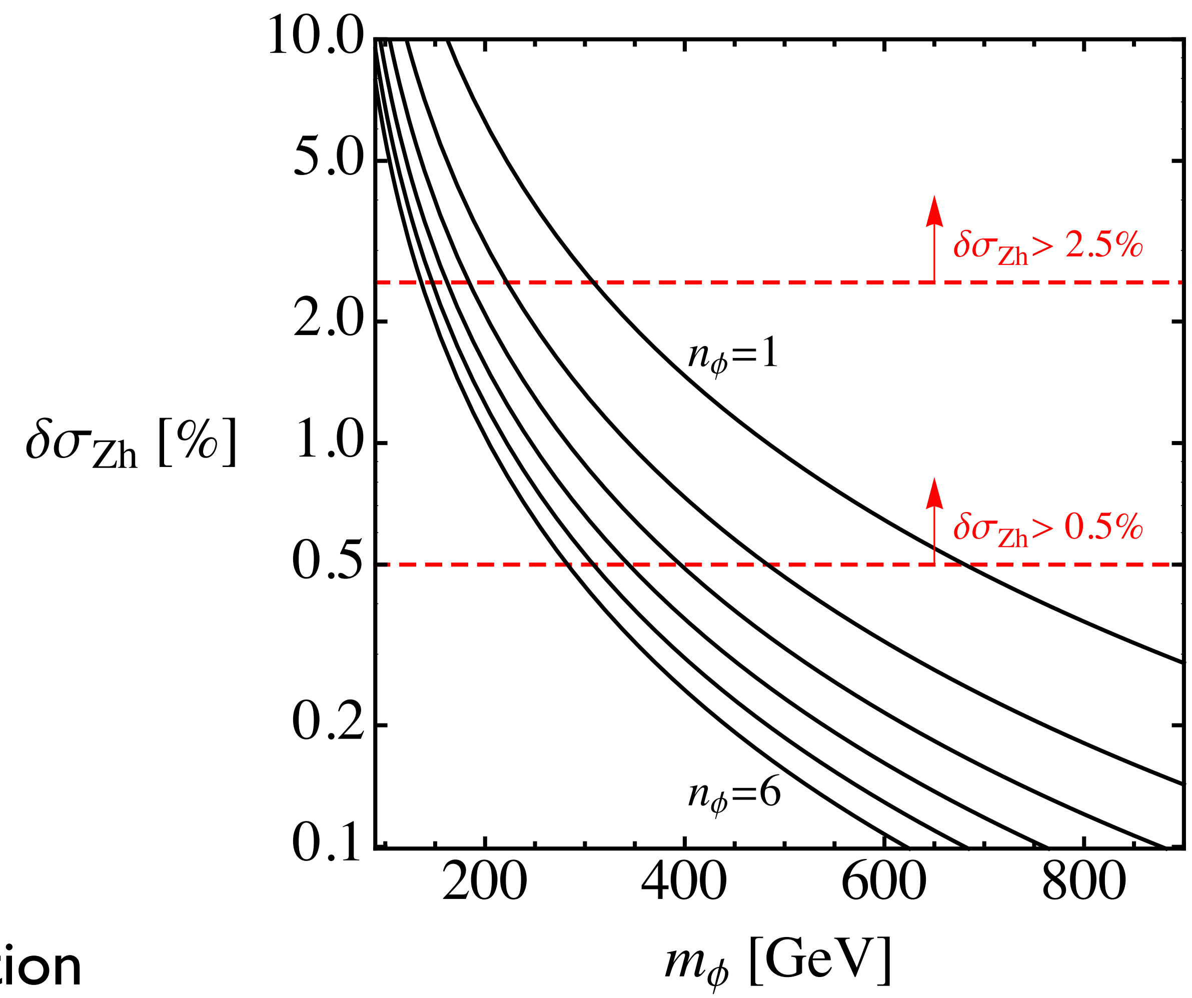


- Top partner not colored.
  - Twin Higgs. Chacko, Harnik, et al Craig et. al.
- Reach probably very limited, 100s GeV.

Anything else we can do?



Wavefunction renormalization
Induce shift in Higgs coupling.

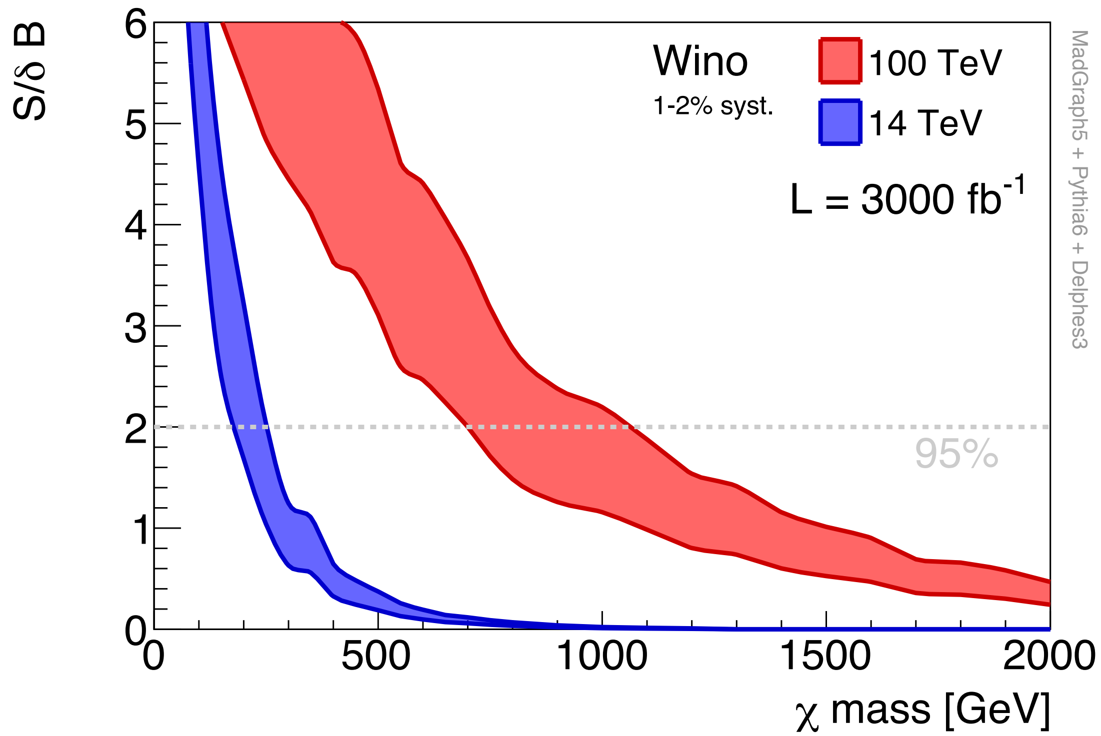


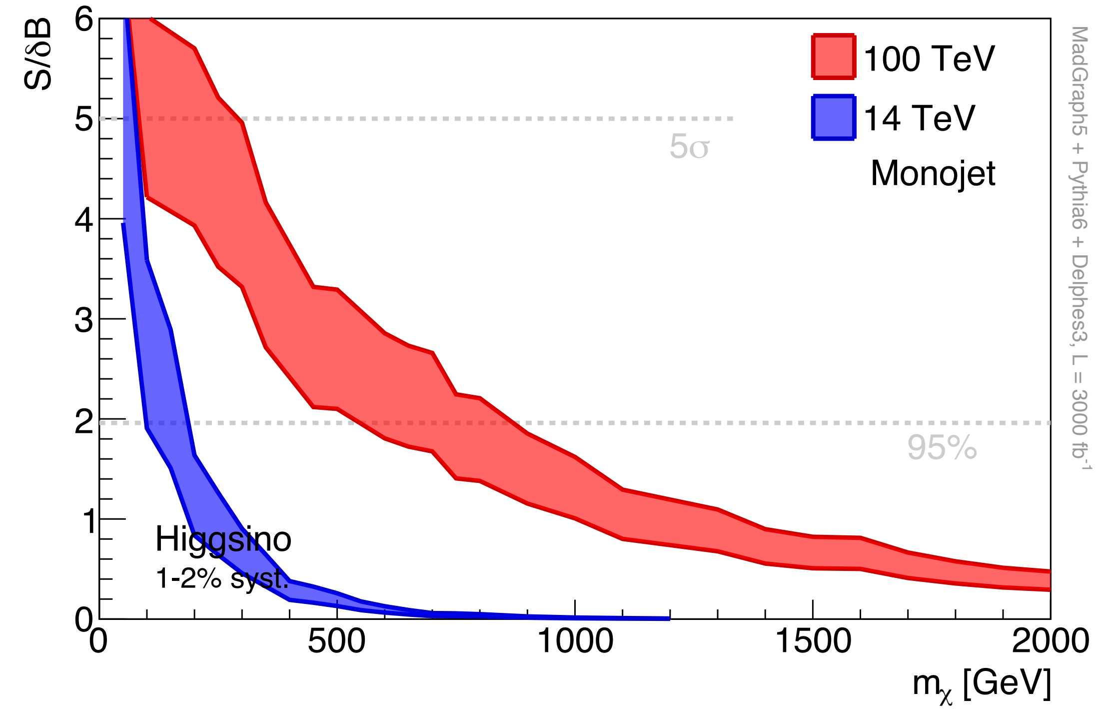
Craig, Englert, McCullough, 2013

– Higgs factory provides a solid probe.

Dark Matter

Dark matter (mono-jet)

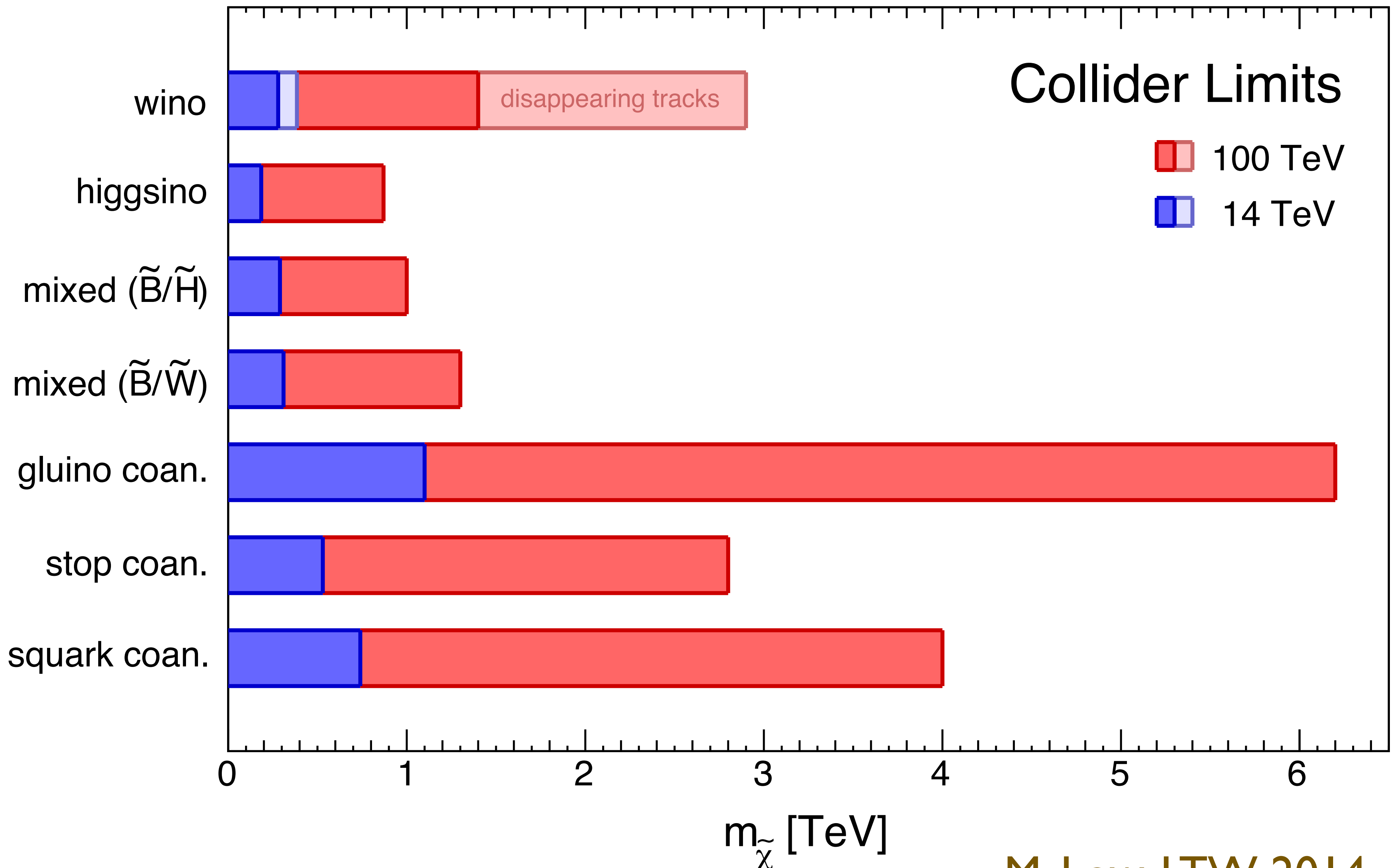




$$M_{\text{WIMP}} \leq 1.8\ \text{TeV}\ \left(\frac{g^2}{0.3}\right)$$

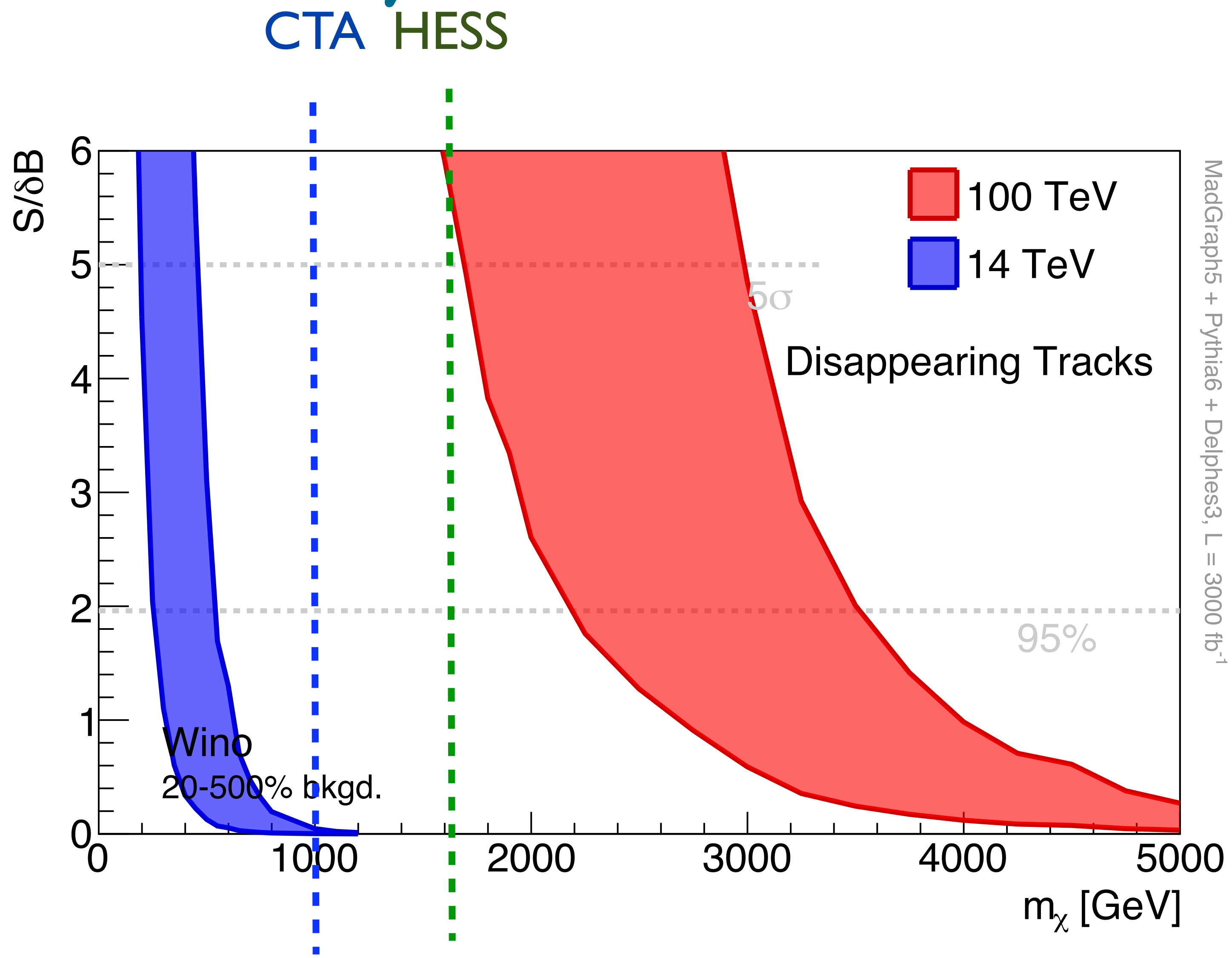
- LHC only coverage very limited.
- Probing the "bulk" of WIMP parameter space.

Mono-jet



M. Low, LTW 2014

Wino summary



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

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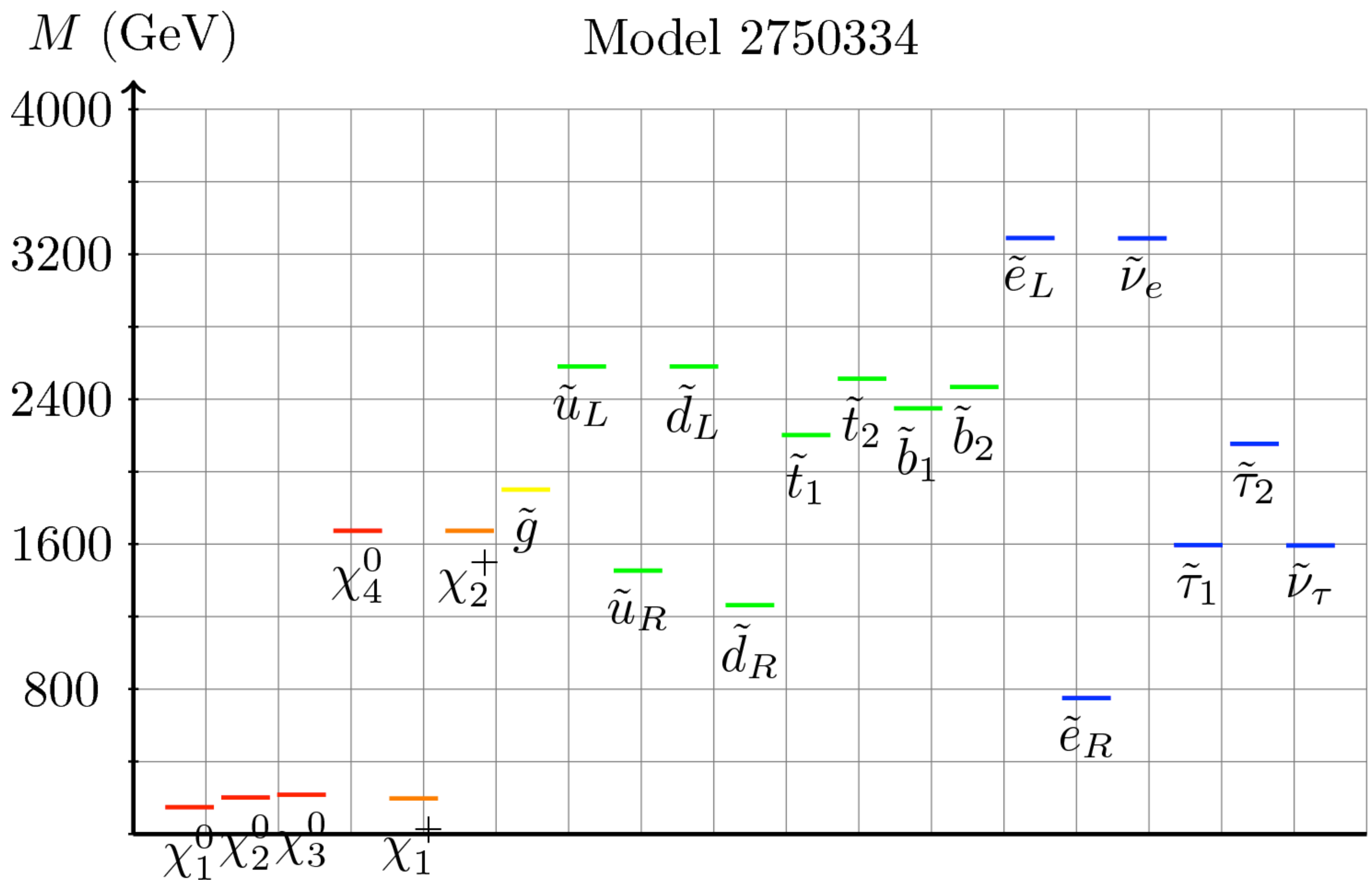
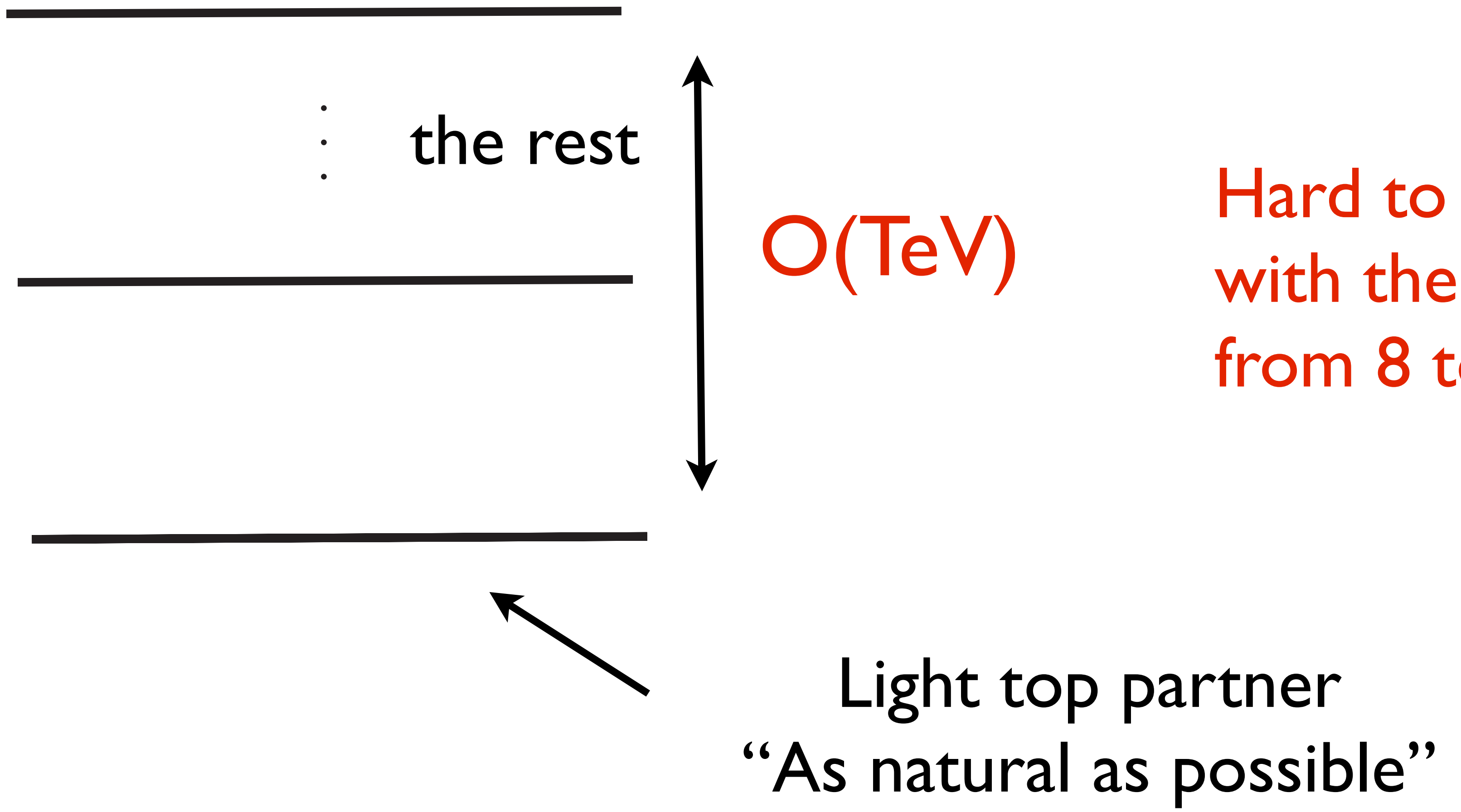
- However, many models feature particles with masses spread at least factor of several apart.
- Won't be able to see everything.
- LHC discovery will set the stage for our next exploration. Such as at a future 100 TeV pp collider.

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

No discovery?

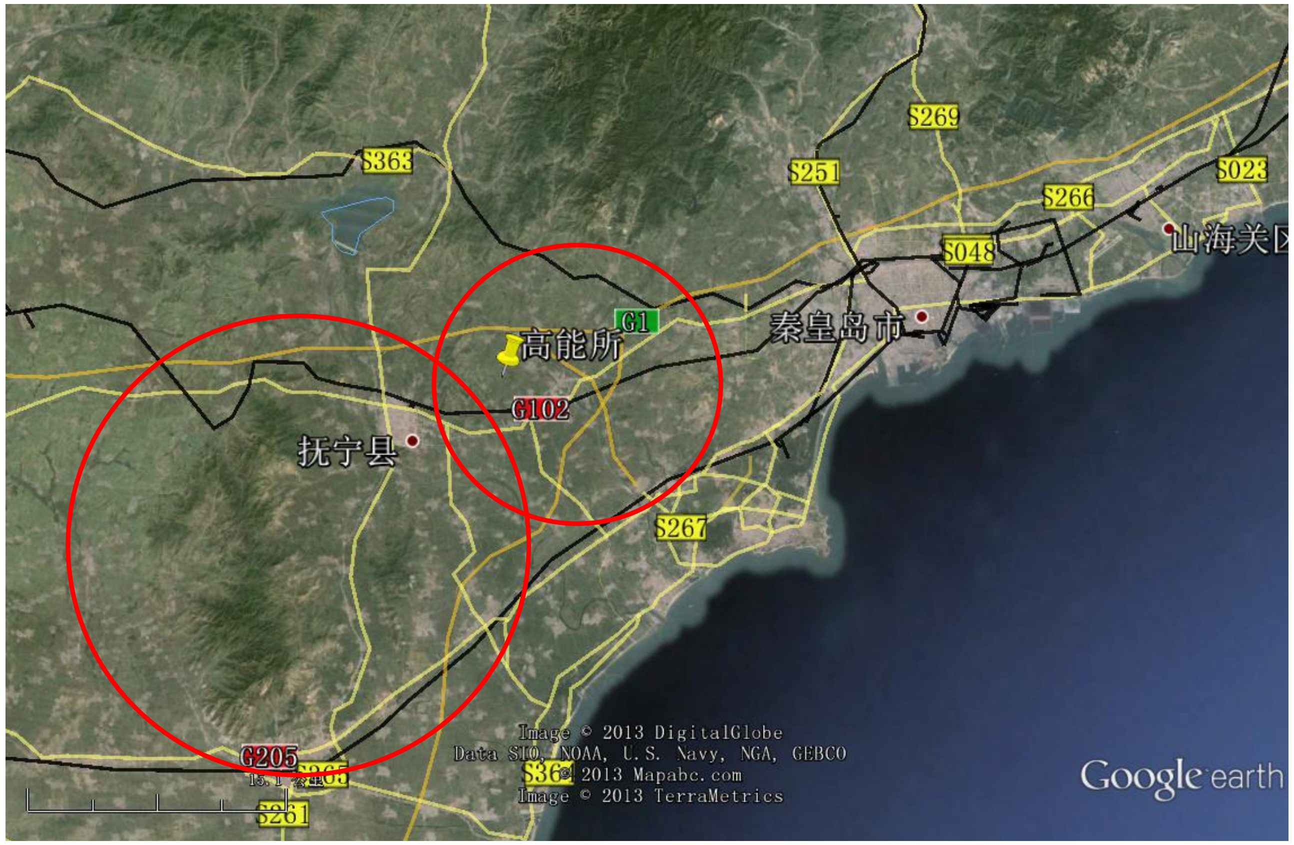
- Run 2 won't have the final word on many questions.
  - Won't nail the Higgs properties.
  - Not enough for naturalness yet (for me).
  - Not even close for WIMP dark matter.
- We should certainly go further.

Many new and on-going studies.

- Vector boson fusion for composite resonances.
- Z'.
- 10 TeV flavor physics.
- Fermionic top partner
- Top quark in PDF.
- Suggestions for more studies to be done?

What's happening in China

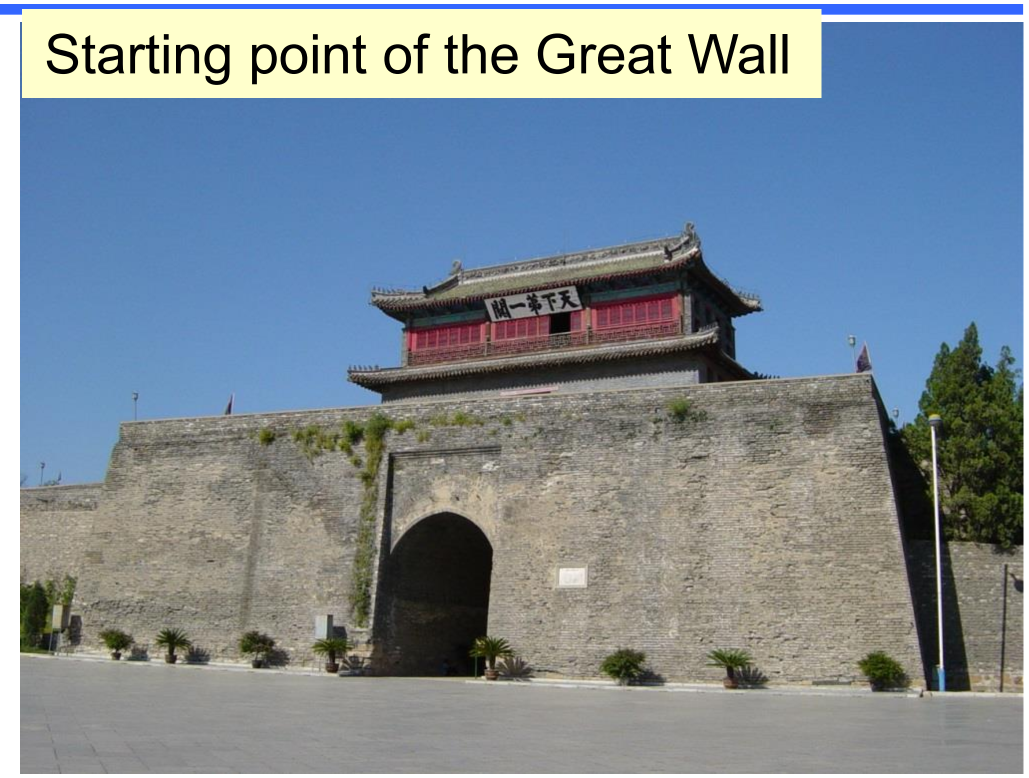
The circle is on the map



- 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

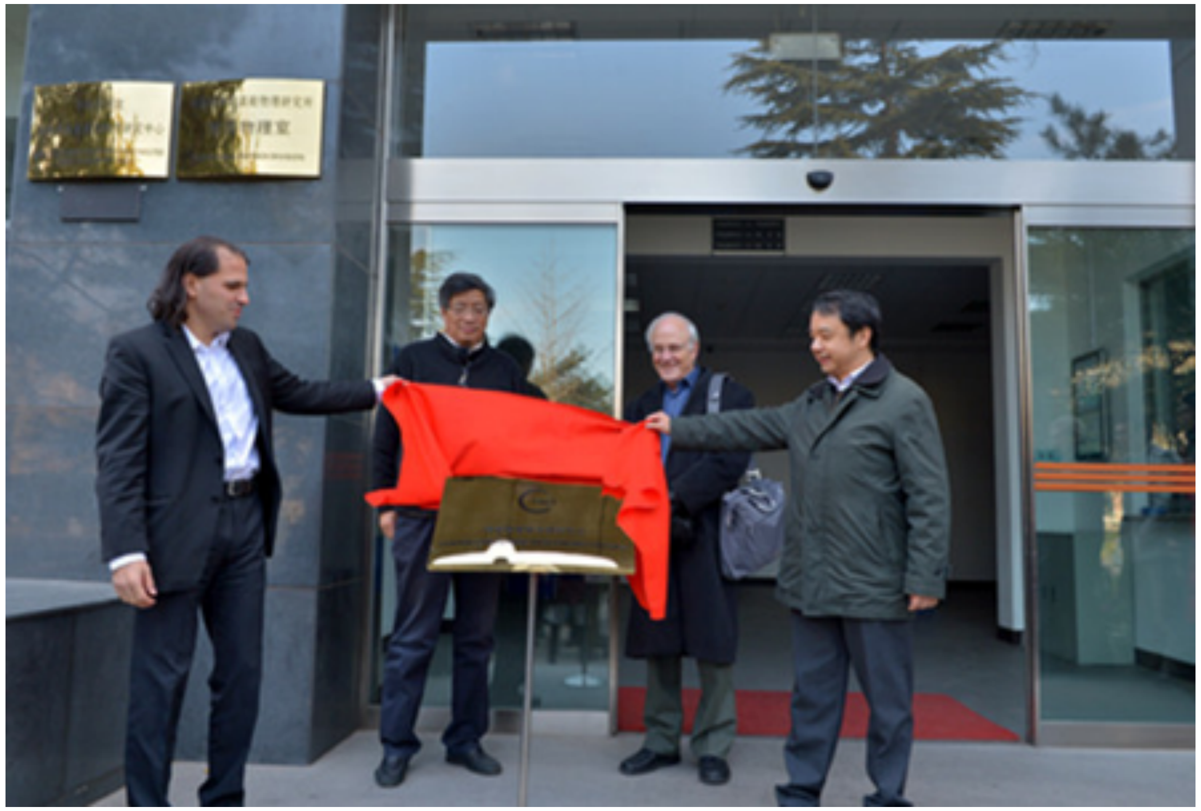
Wine yard

In the last 2 years

- Started “talking about it” in 2012.

- 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.
- PreCDR by the end of this year.
- R/D money decision (likely) 2015.

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.

The Chinese Dream

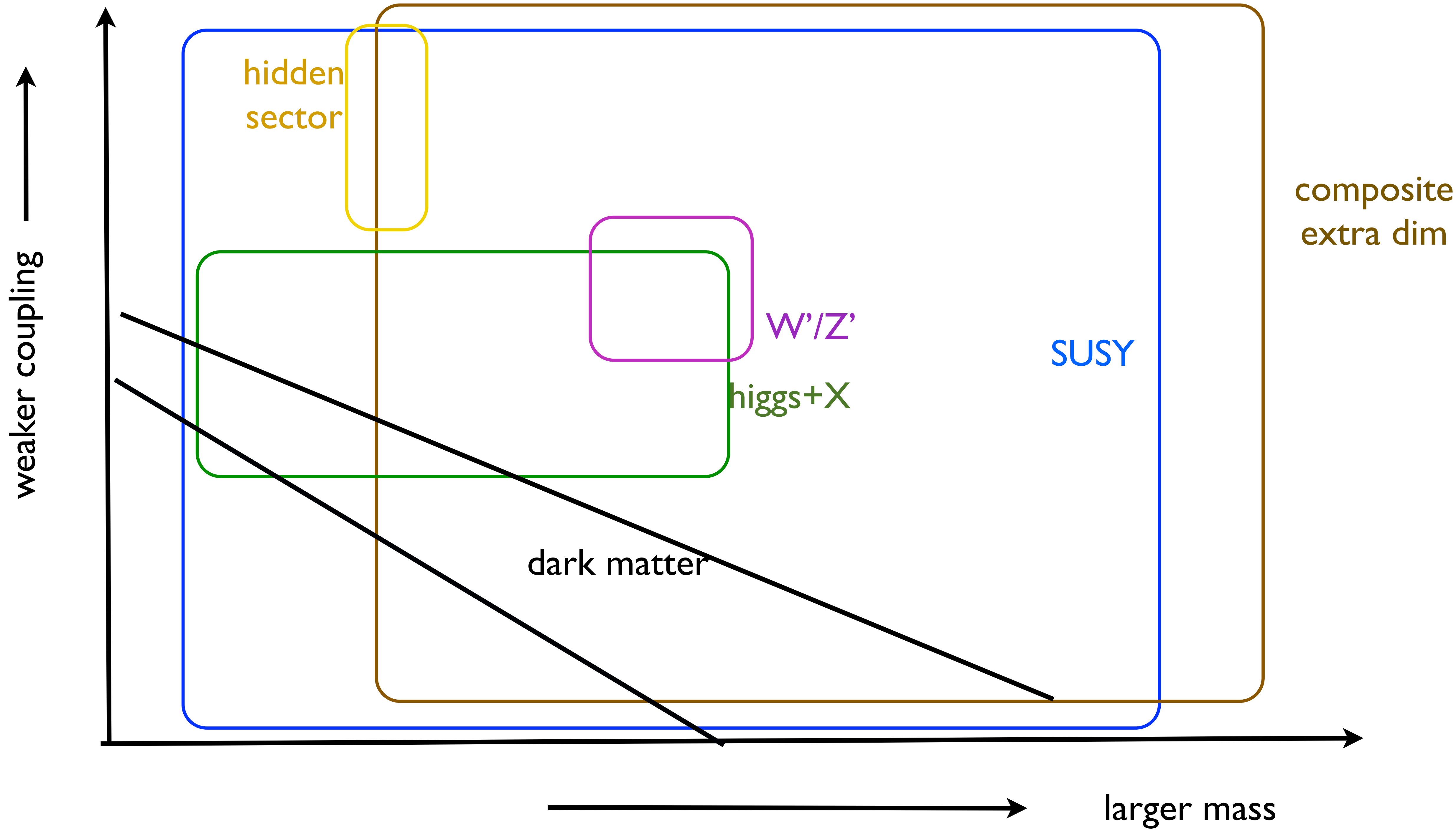
- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR by the end of 2014 for R&D funding request**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2028-2035
- **SppC**
  - Pre-study, R&D and preparation work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

Optimistic?

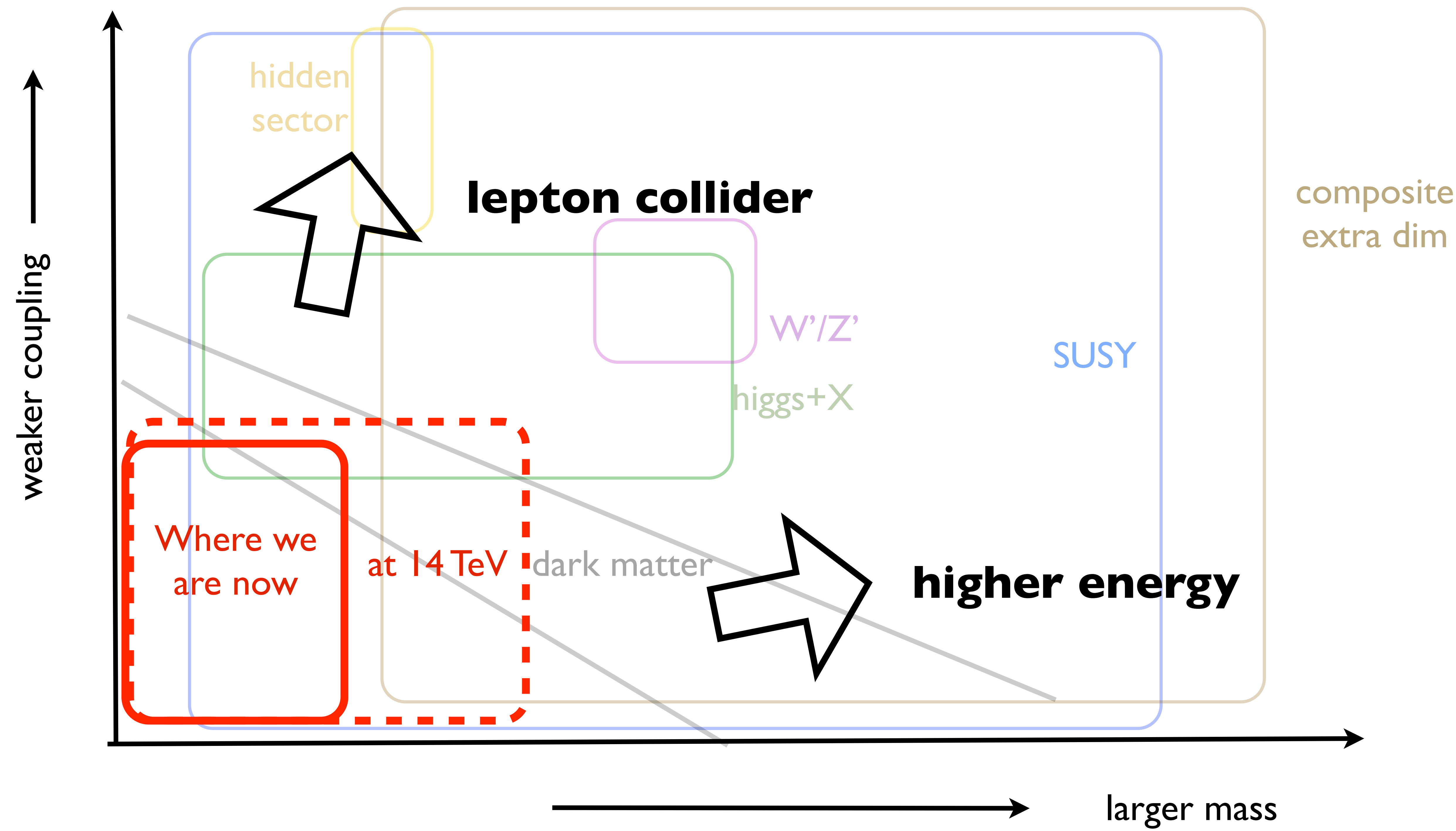
- Very long/difficult road, of course.
- So far, faster and better than I expected.
- I am optimistic. We have to try.

Exploring the space of possibilities



Circular collider, ee+pp, offers a powerful combination

Exploring the space of possibilities



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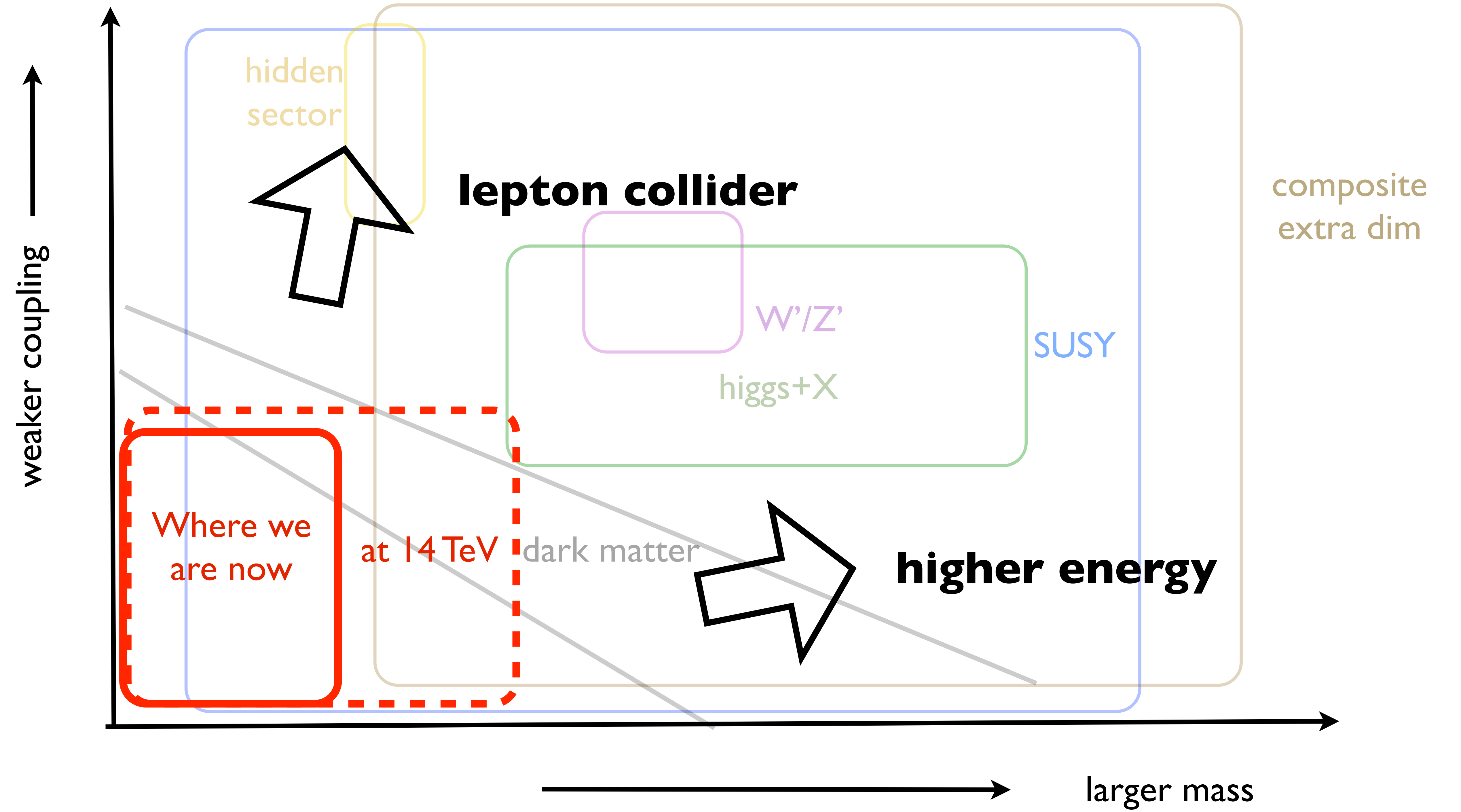
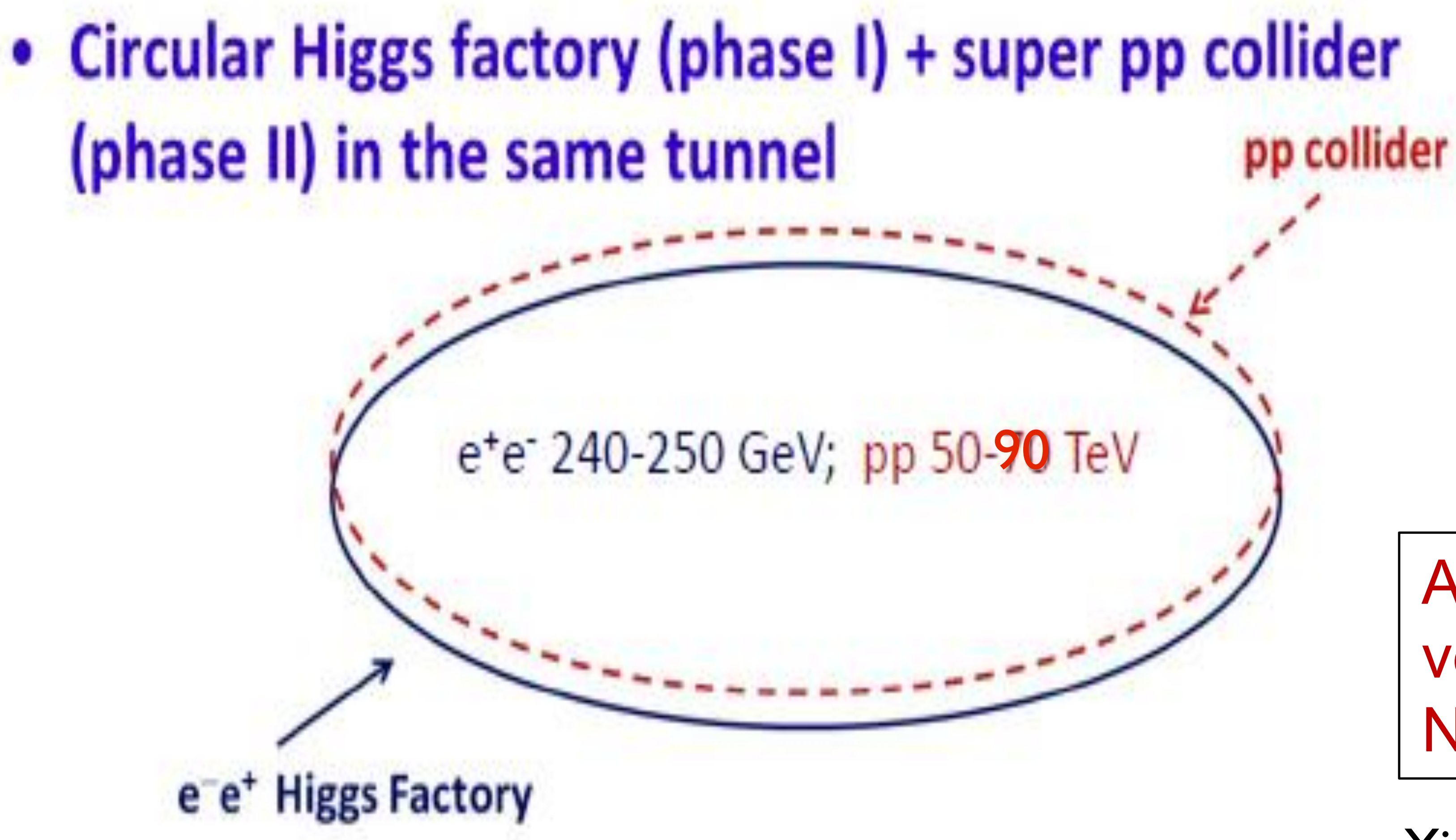


Circular collider, ee+pp, offers a powerful combination

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