Overview of Physics Opportunities at 100 TeV pp colliders

Lian-Tao Wang
University of Chicago

Flavor @ 100 TeV workshop, March 4, 2015

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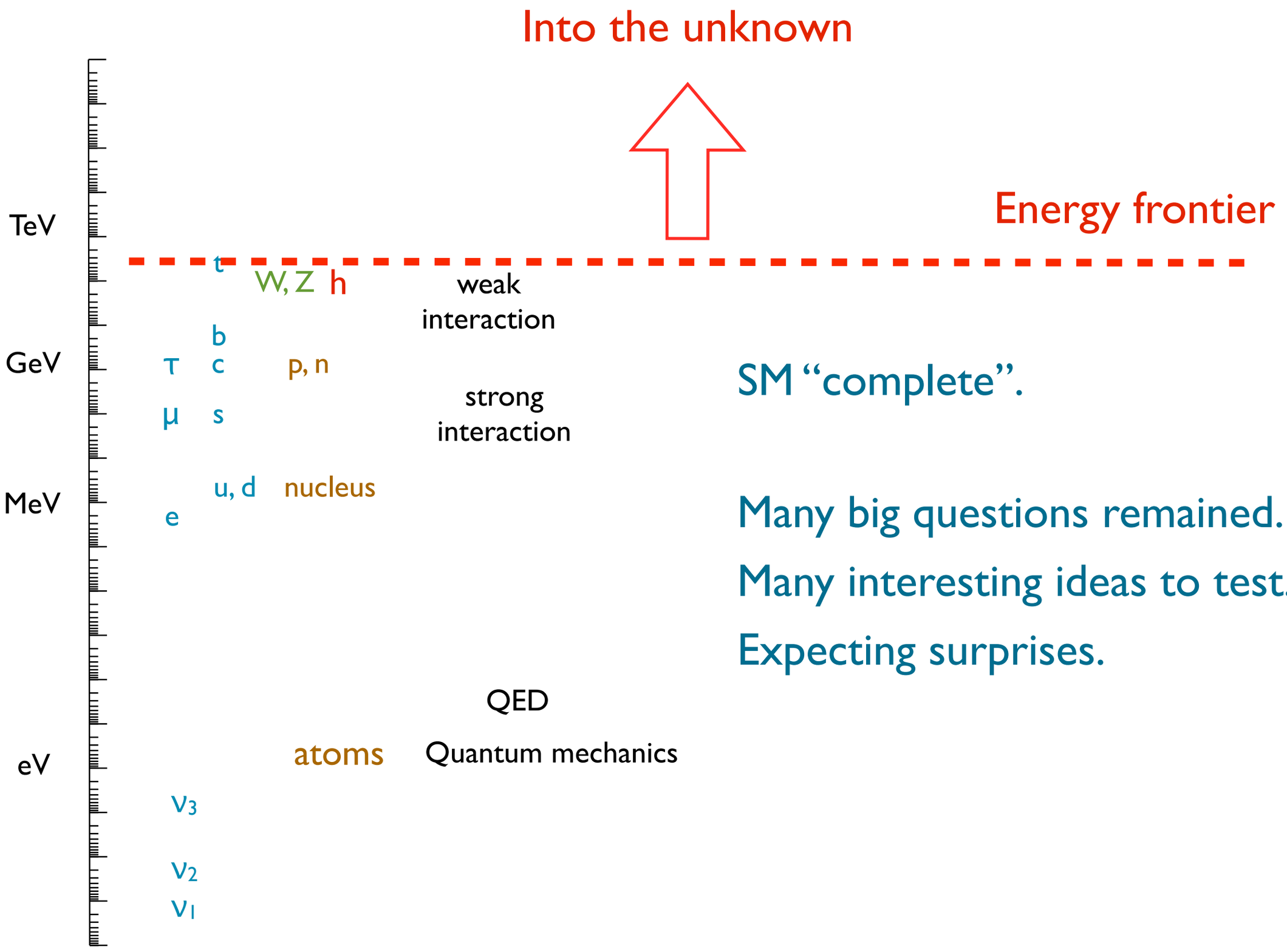
However, I think we have to go further.

A critical and historical juncture.



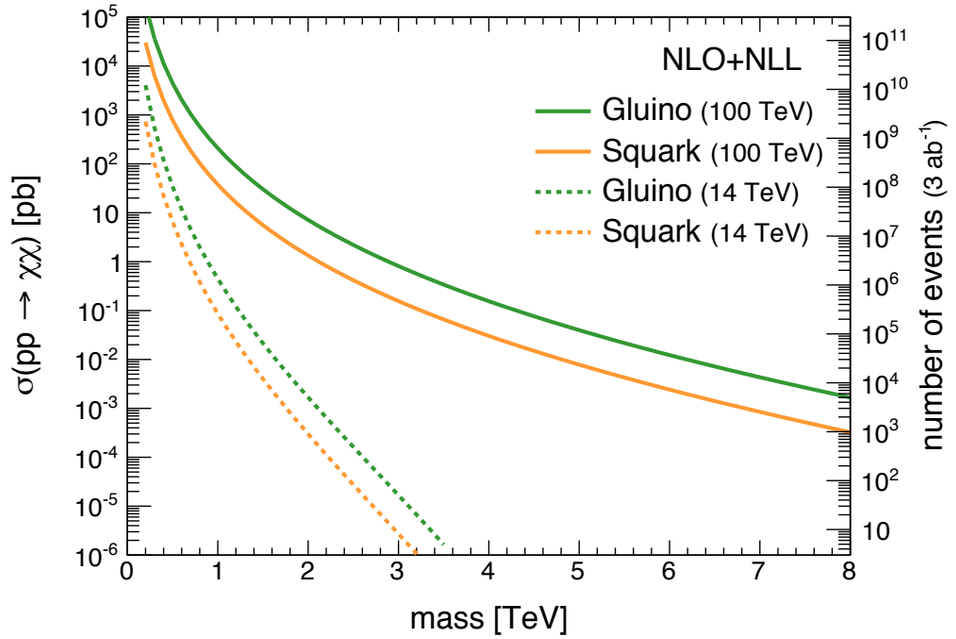
SM "complete".

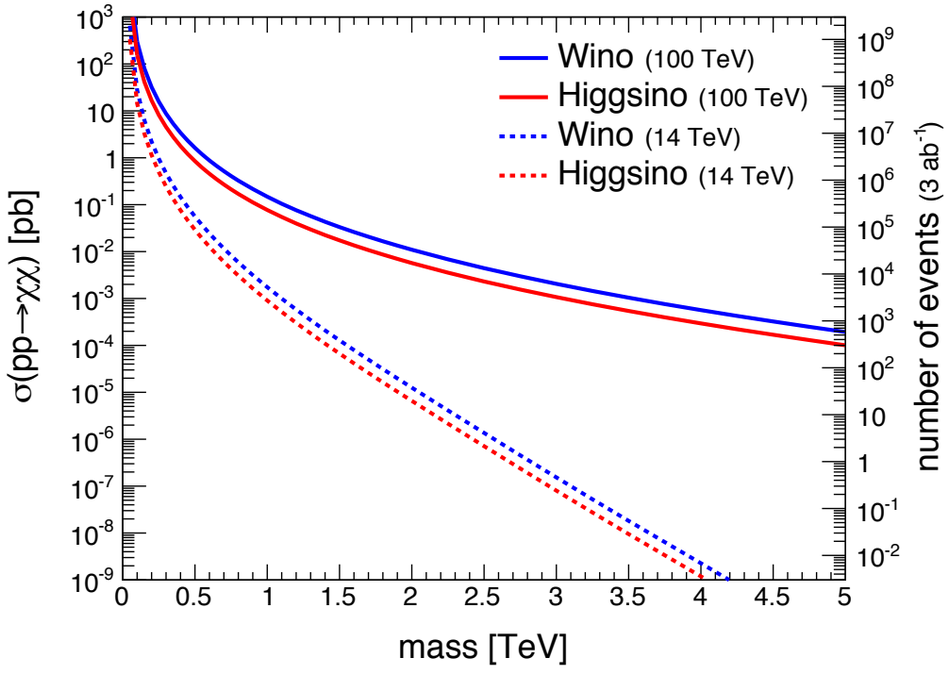
Many big questions remained.

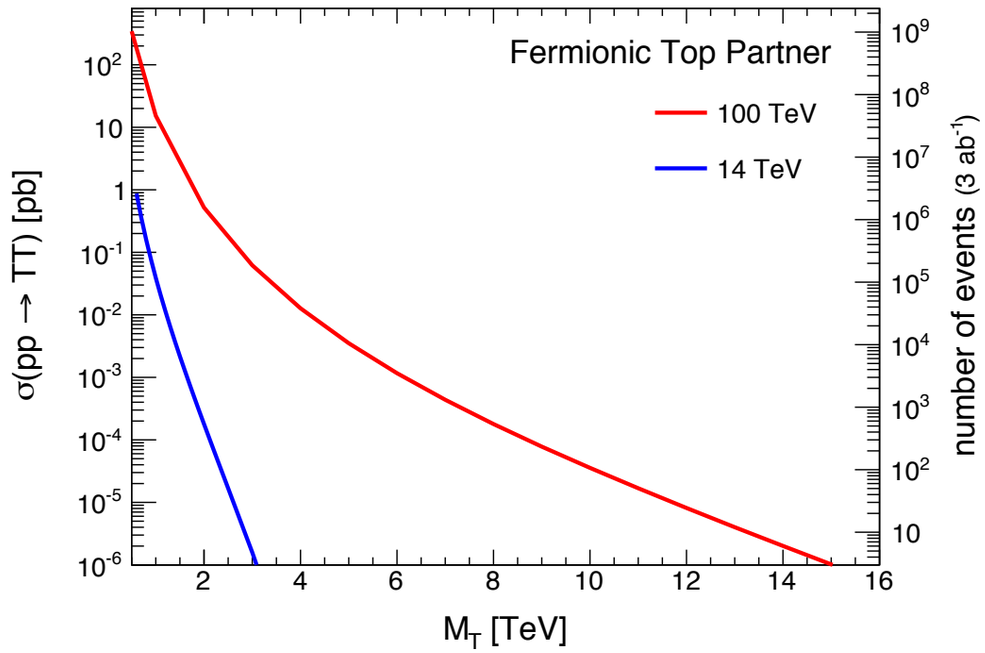
Many interesting ideas to test.

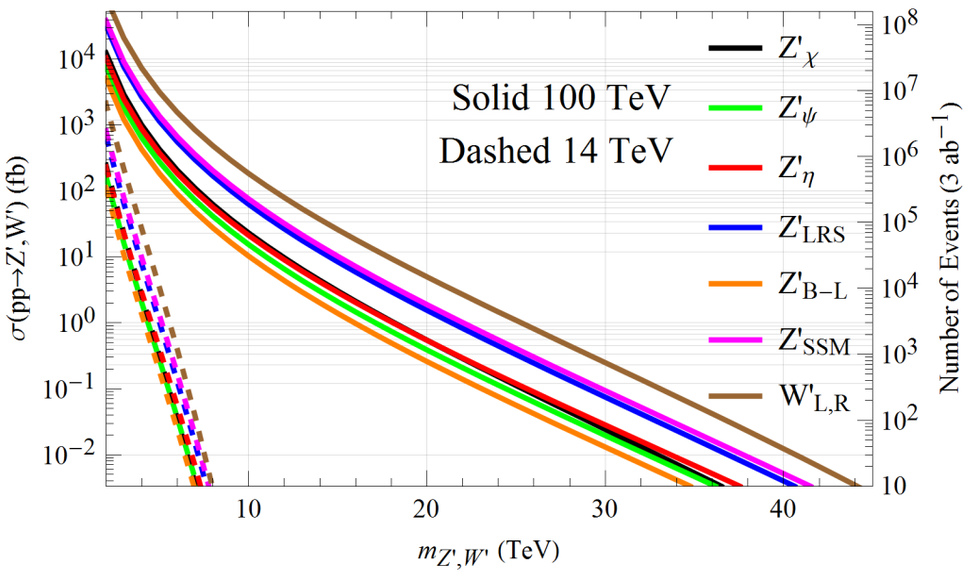
Expecting surprises.

A big step forward

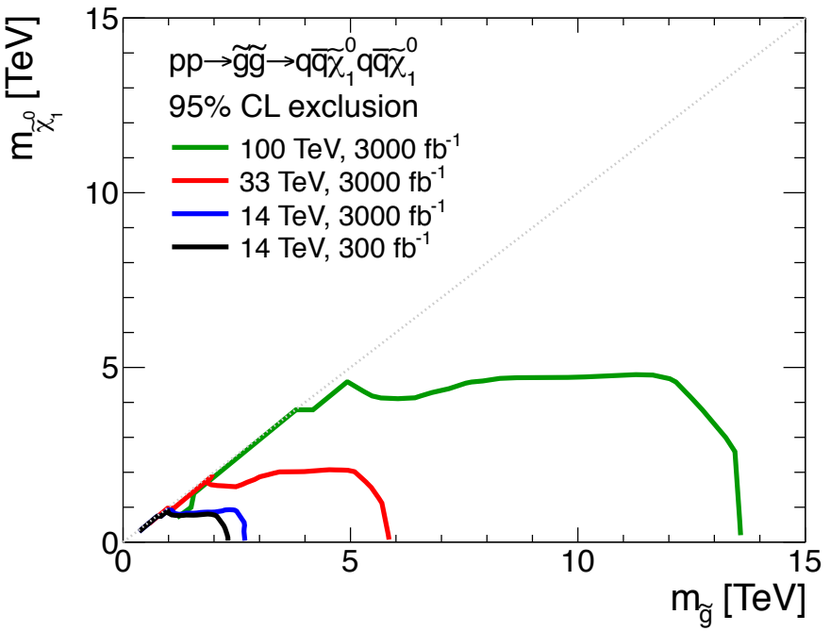




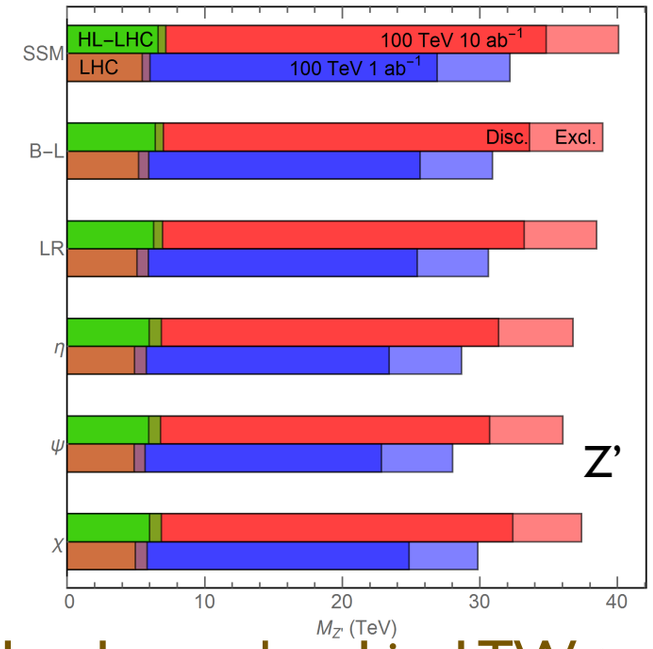




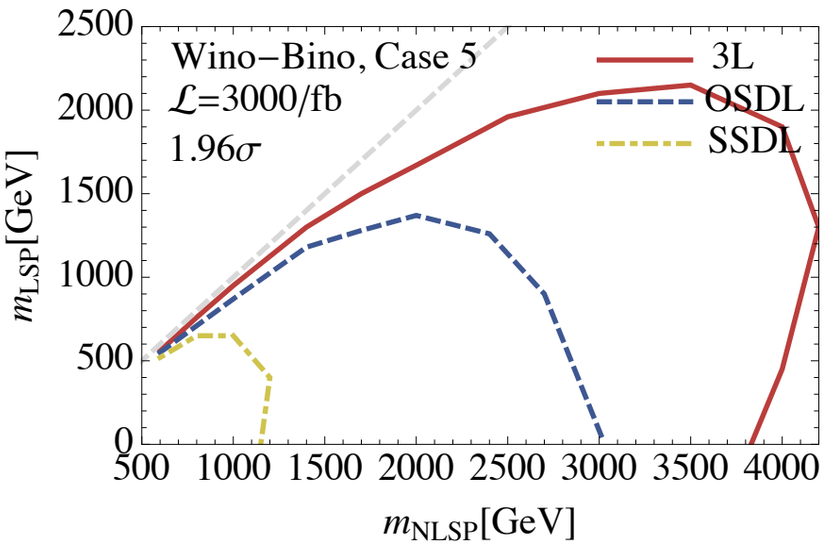
The simplest and strongest justification.



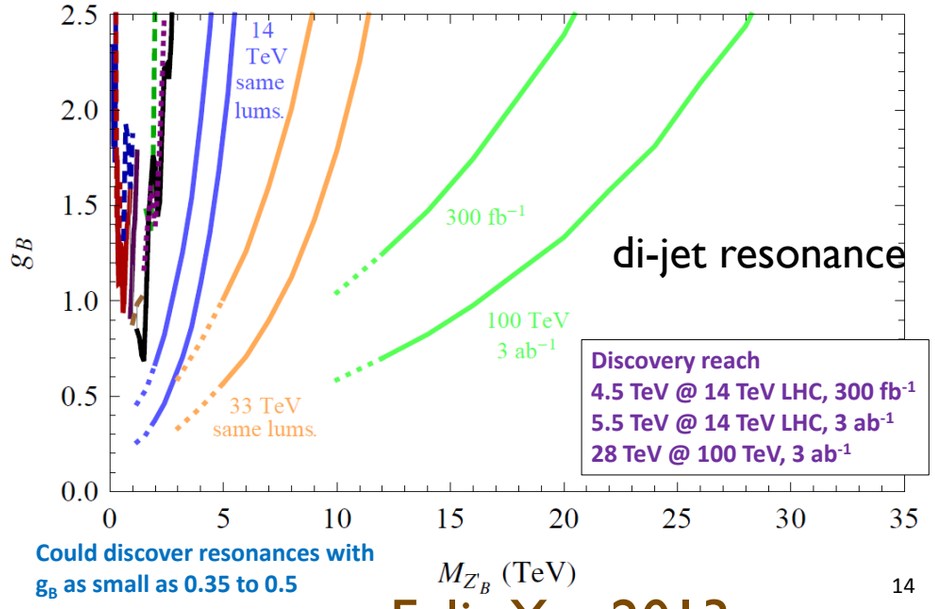
Cohen et al, 2013



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

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

To answer these questions

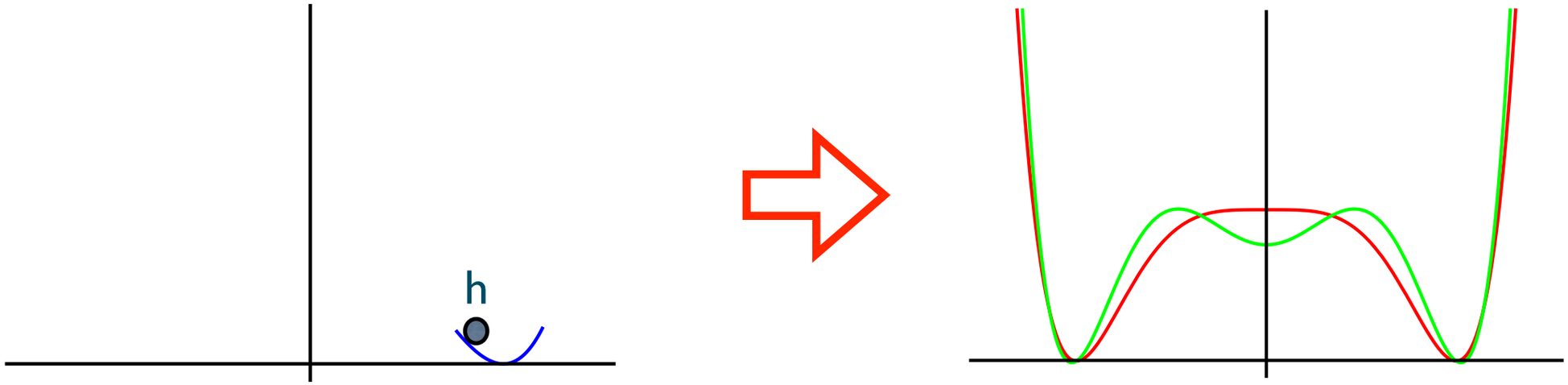
- Going further in the energy frontier is necessary.

- 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.

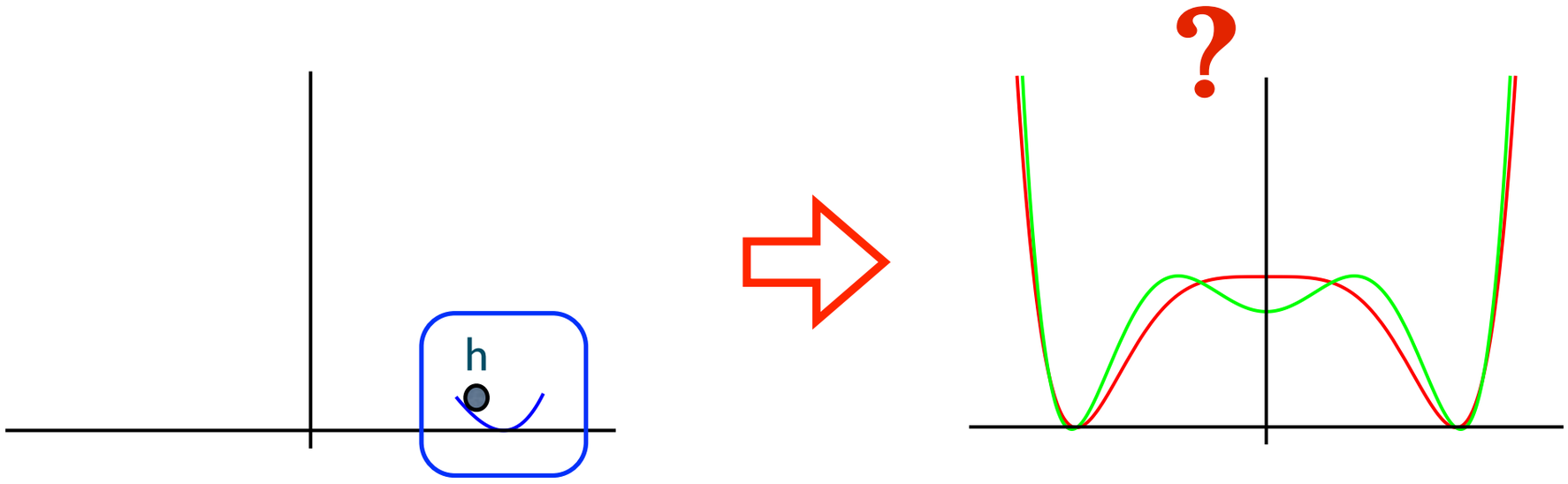
Nature of EW phase transition



current state of knowledge

We know very little about Higgs,
not even sure about "Mexican hat".

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4}h^4 + \frac{1}{\Lambda^2}h^6$$

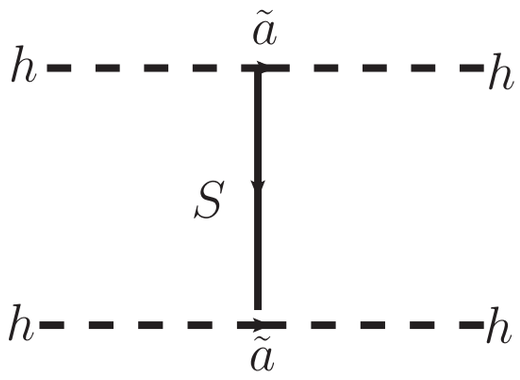


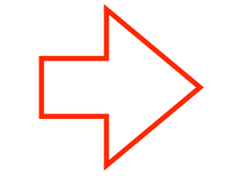
What we know now

Is the EW phase transition first order?

Generic singlet model

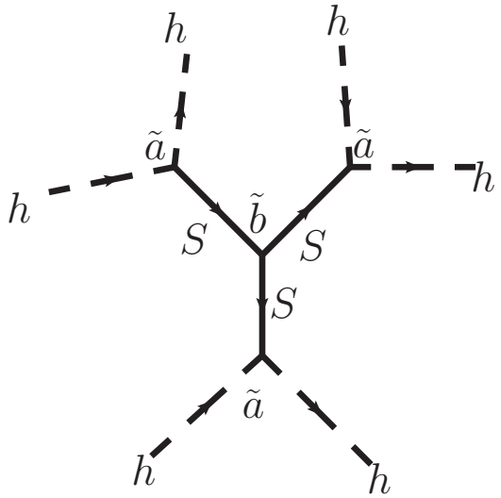
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$

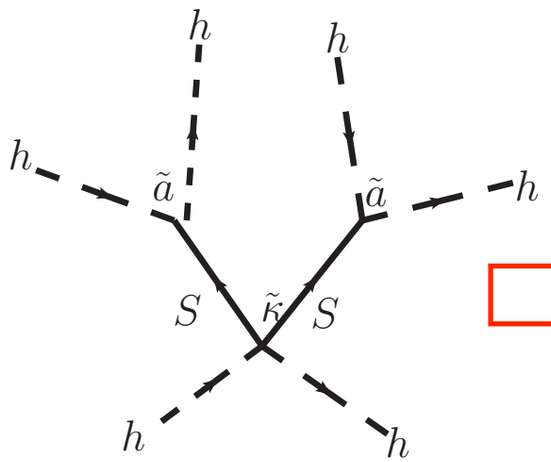


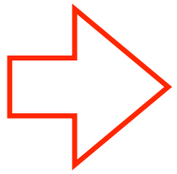


shift in h-Z coupling > 0.5%

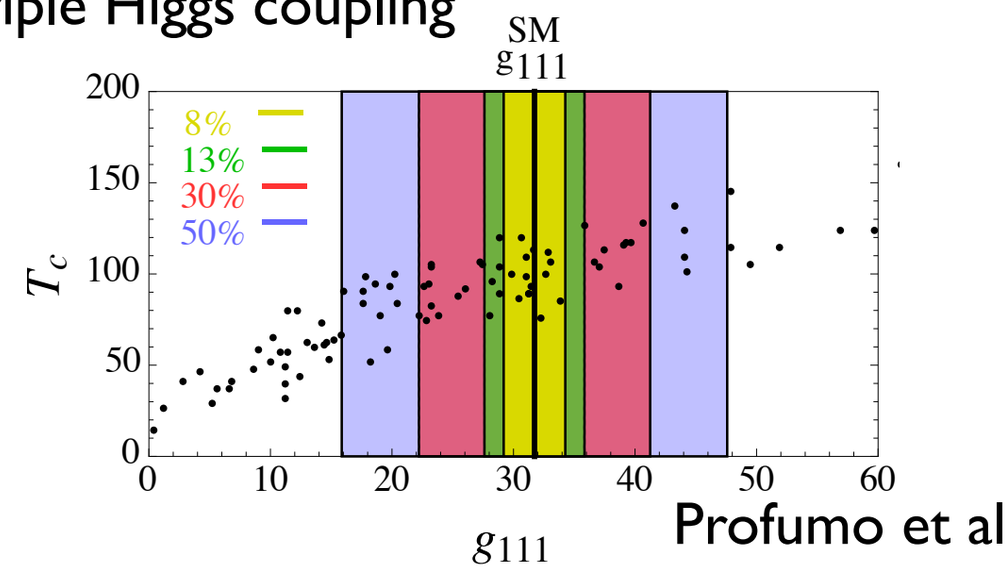
Within the reach of Higgs factories





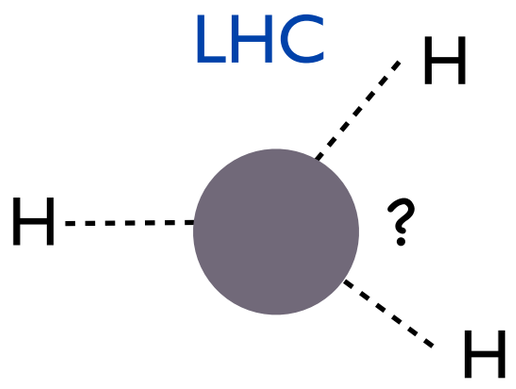


triple Higgs coupling



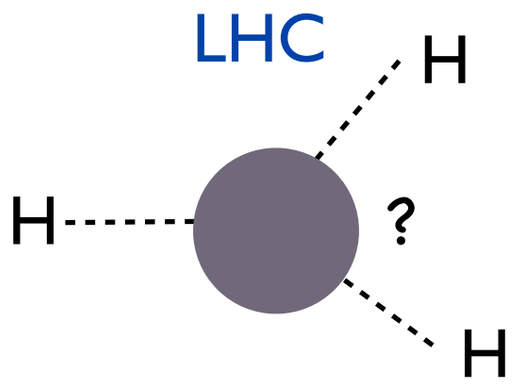
Profumo et al

Self coupling



Unique type of coupling for spin-0 scalars
Not seen before in nature!

Self coupling



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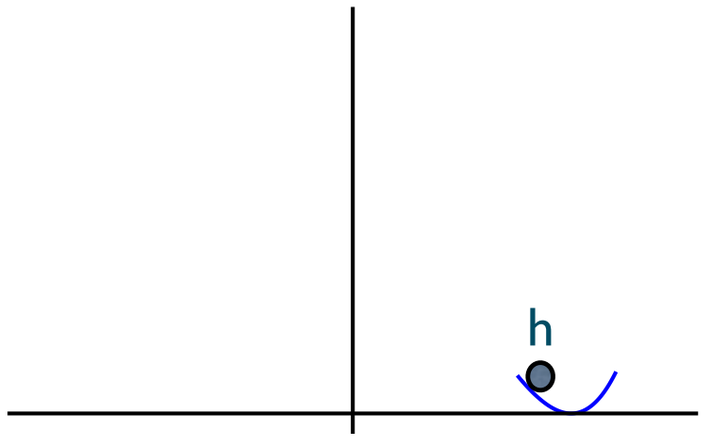
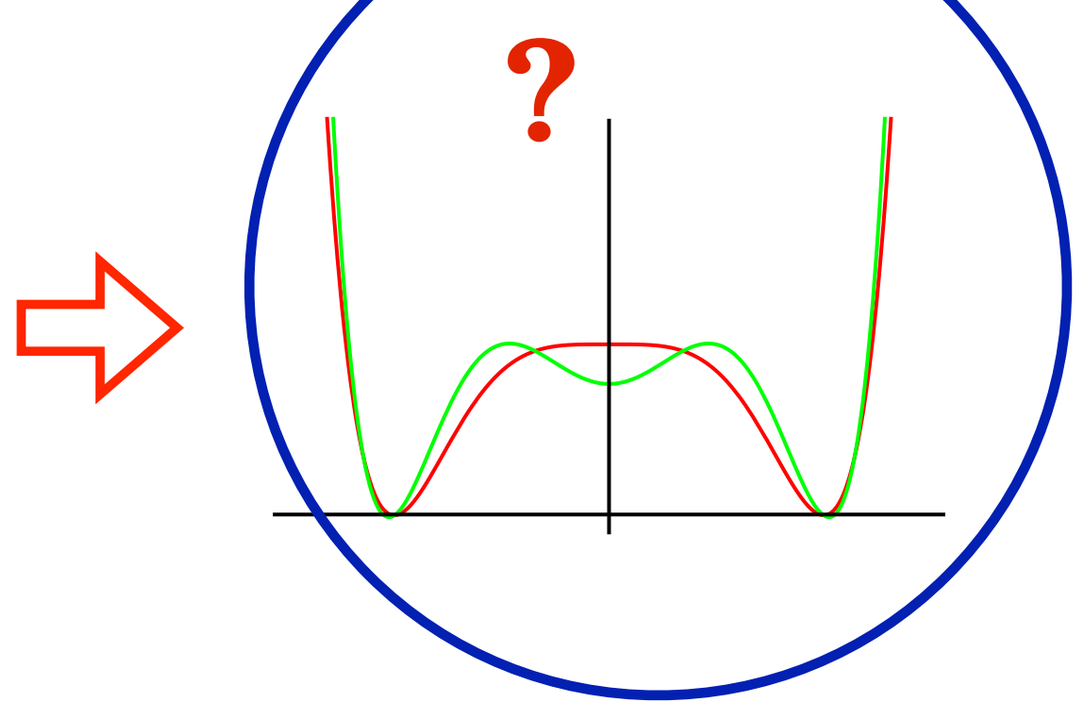
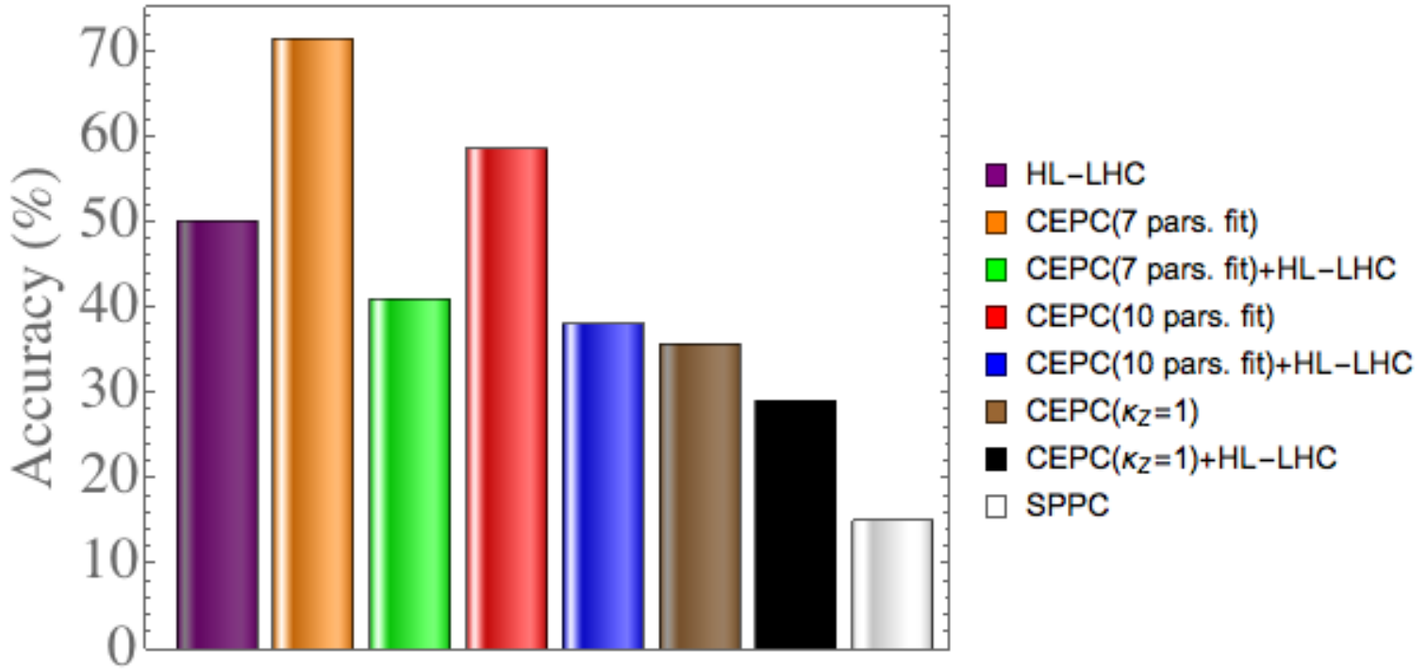
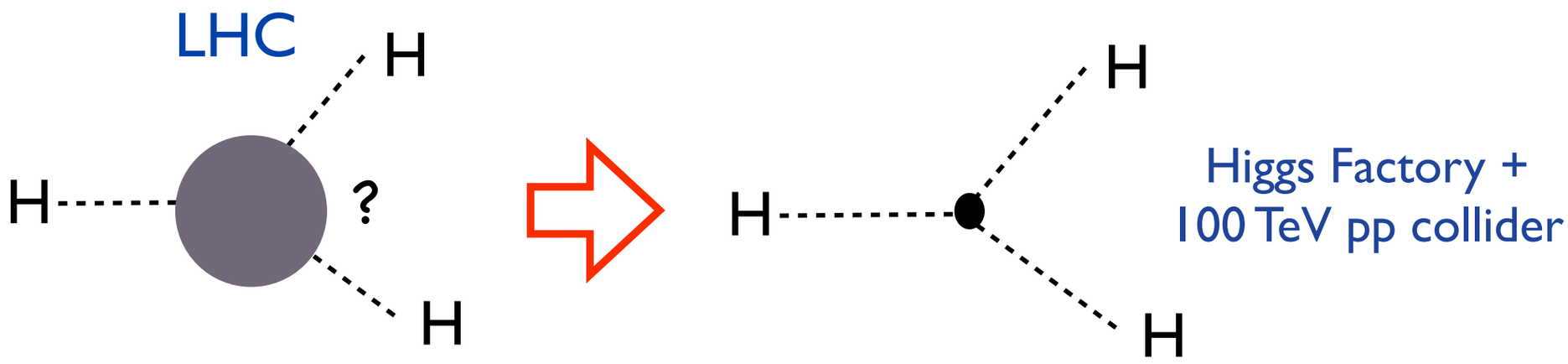
Measuring it well is crucial to answer this question.





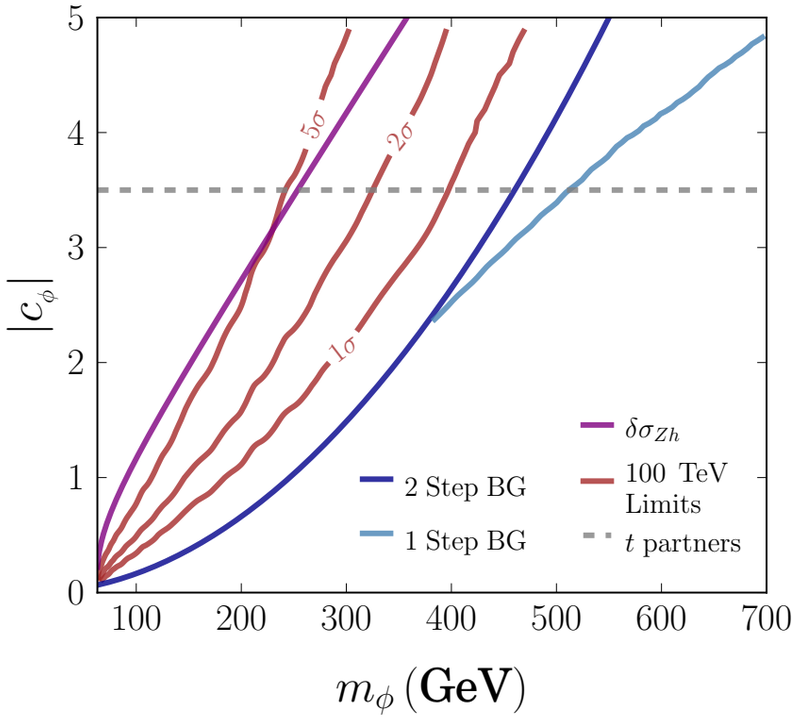
Measuring Higgs self coupling

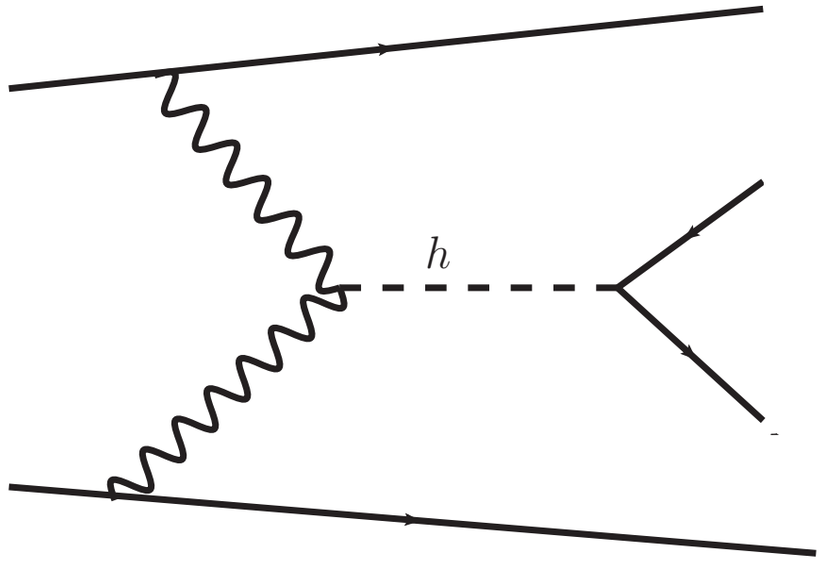




Difficult, but doable.

Direct production of singlet at 100 TeV





Craig, Lou, McCullough, Thalapillil

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

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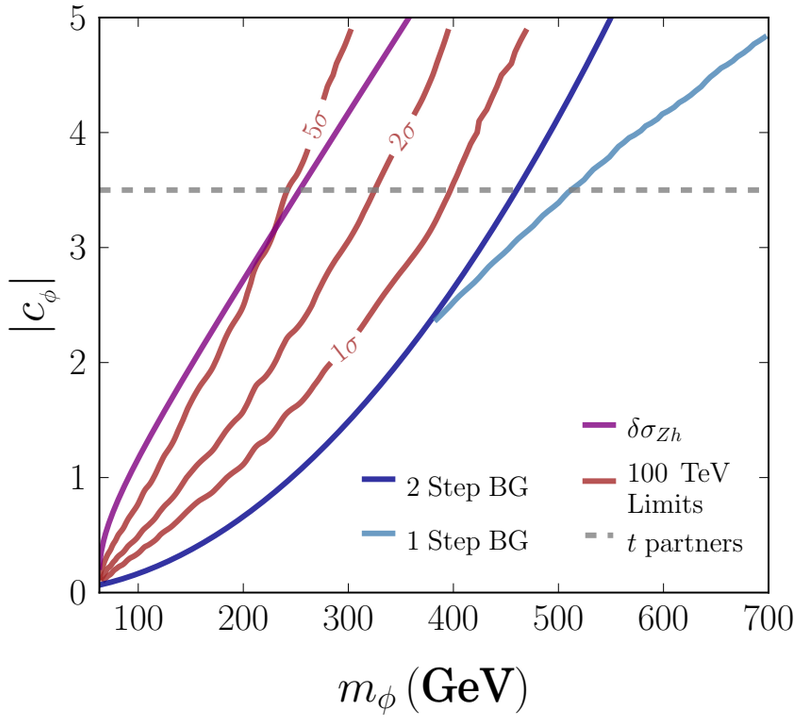

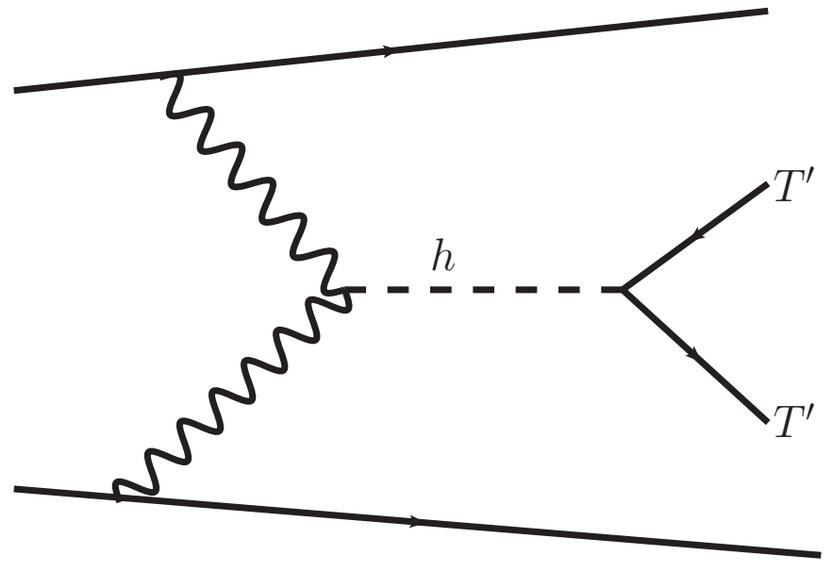

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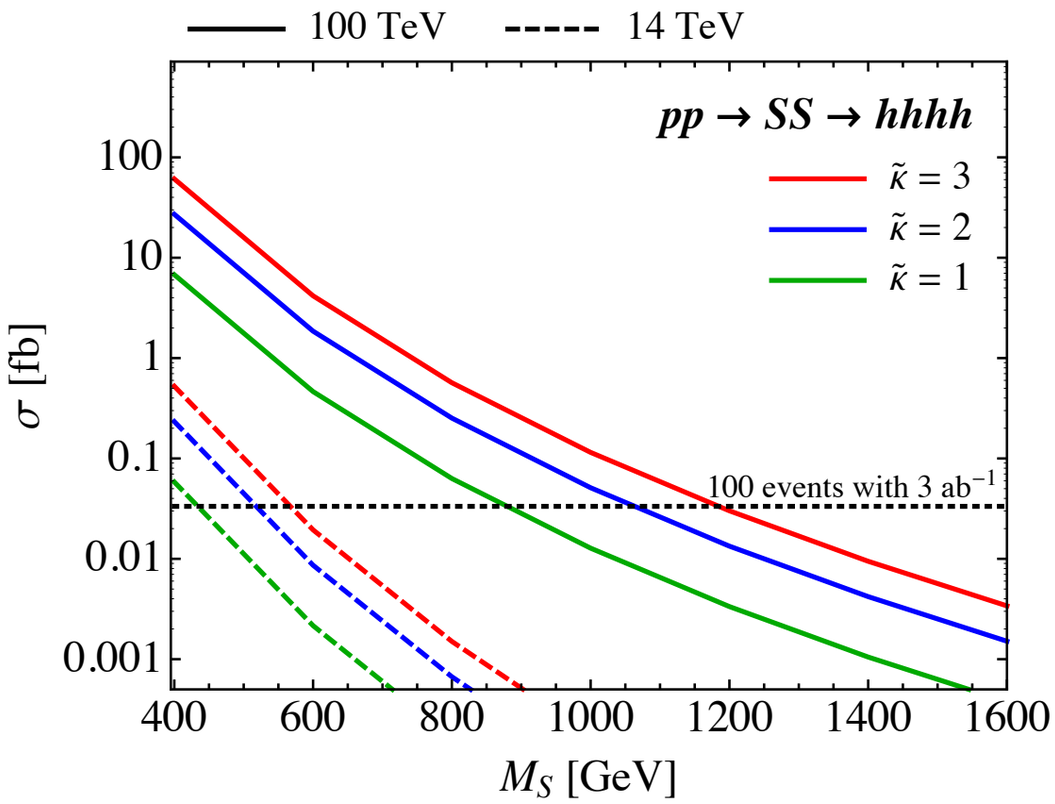
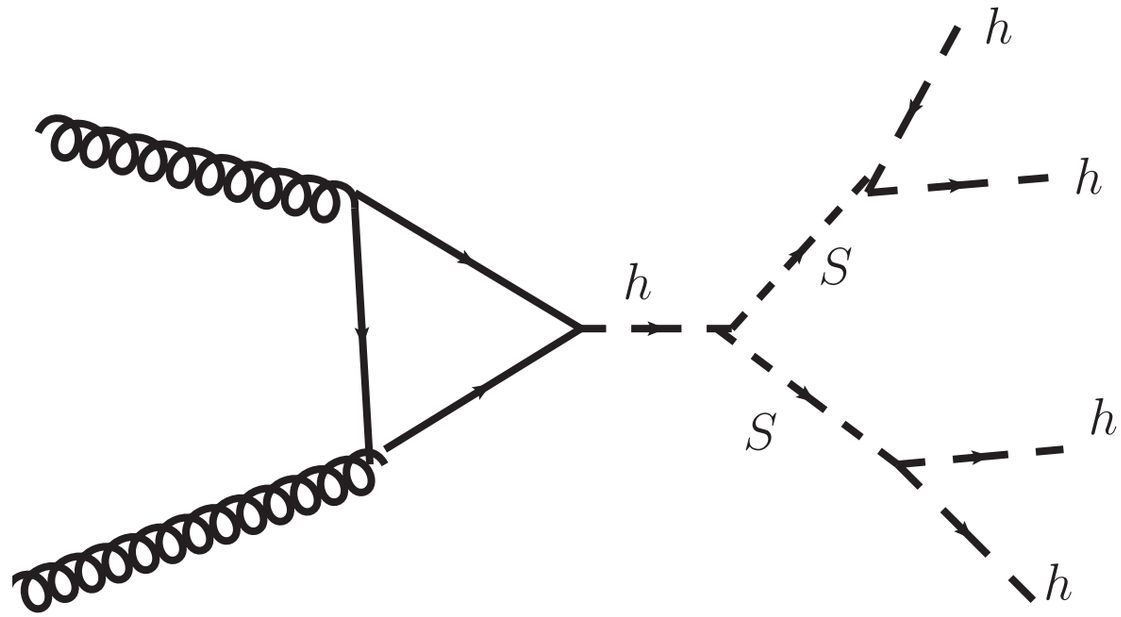
Singlet search at 100 TeV

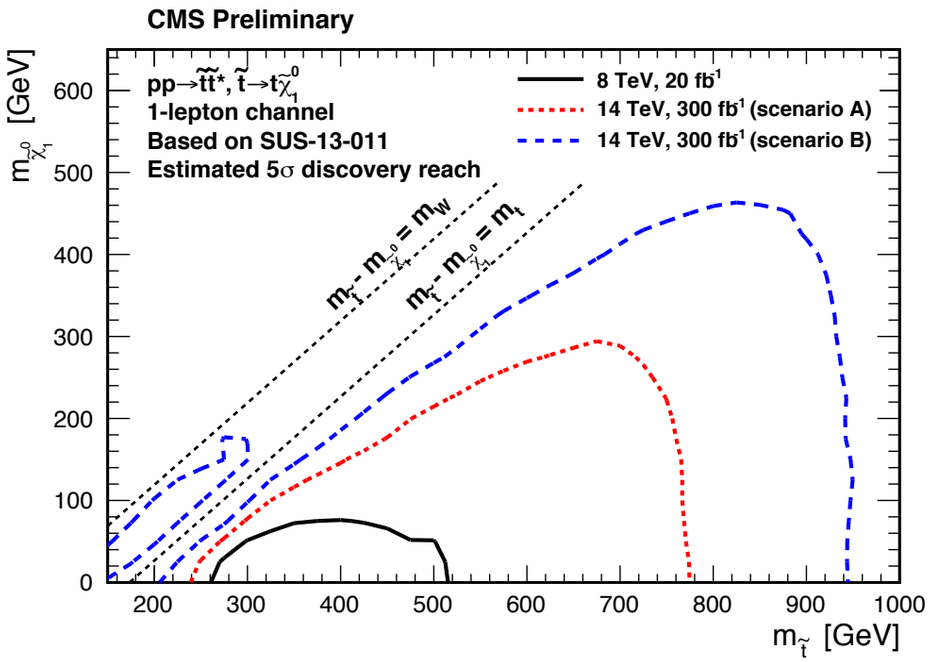




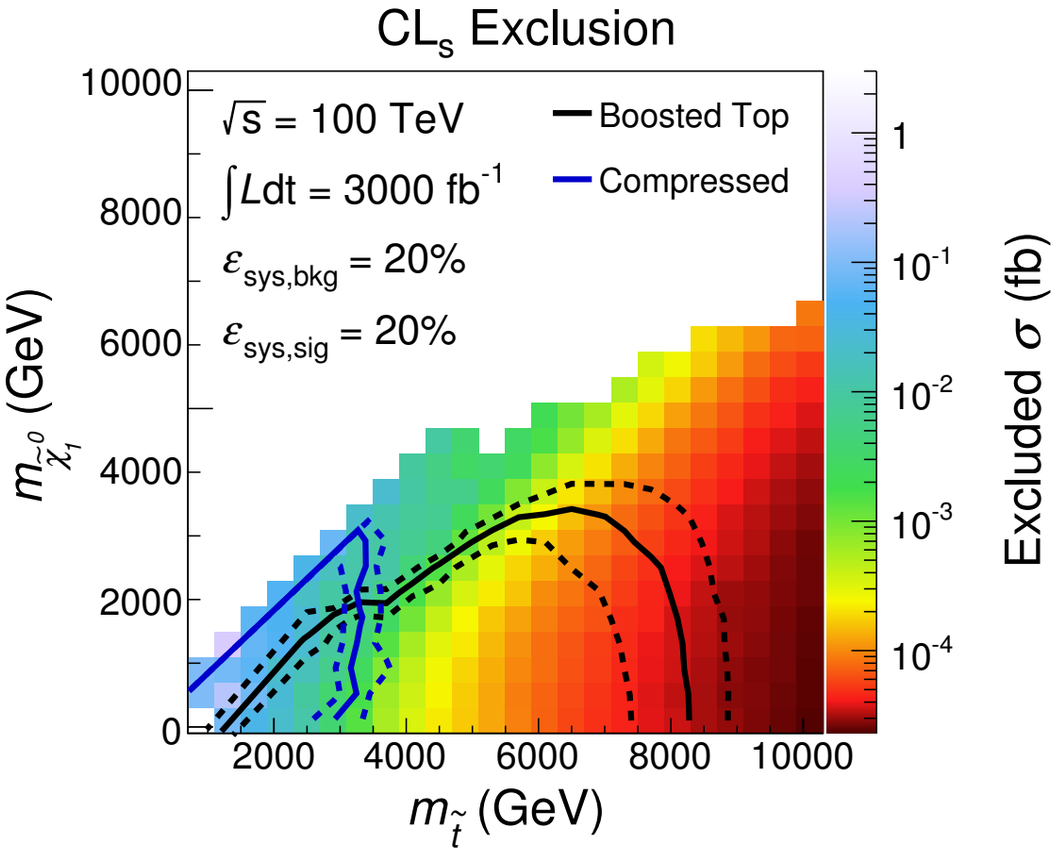
- 4 Higgs final state with decent rate.
- Good discovery potential.

Naturalness

Naturalness

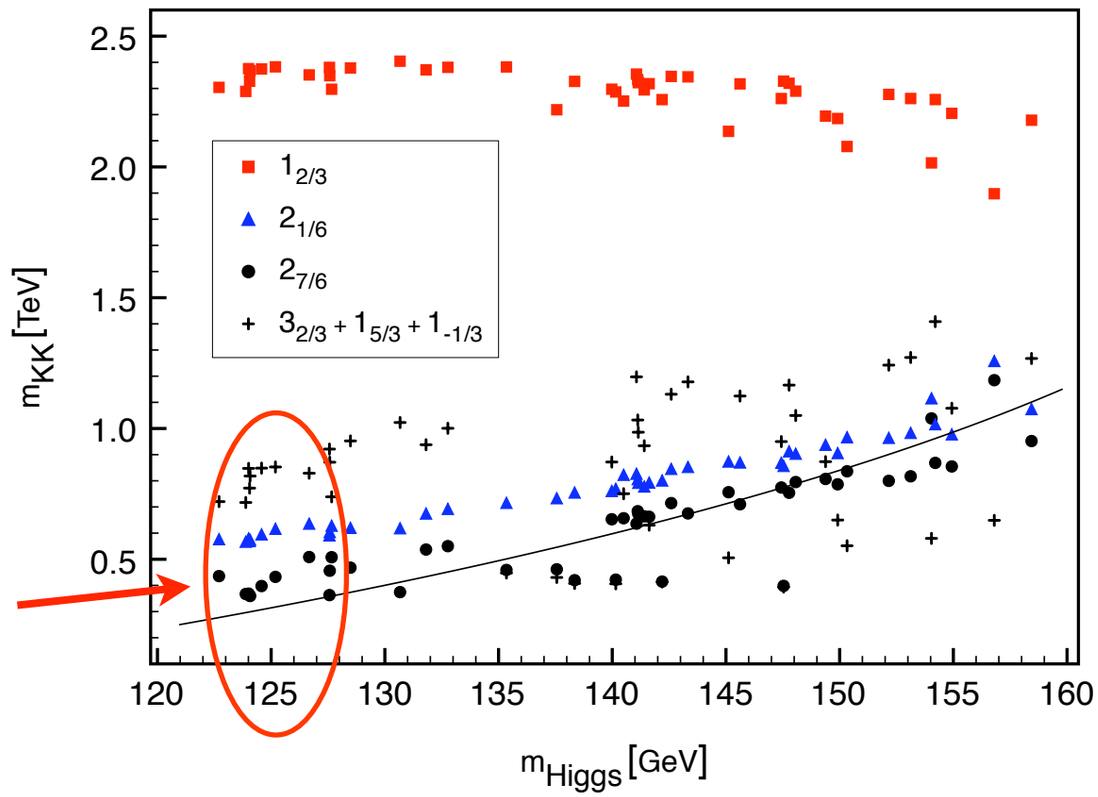


Cohen et. al., 2014



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

Compositeness and top partner



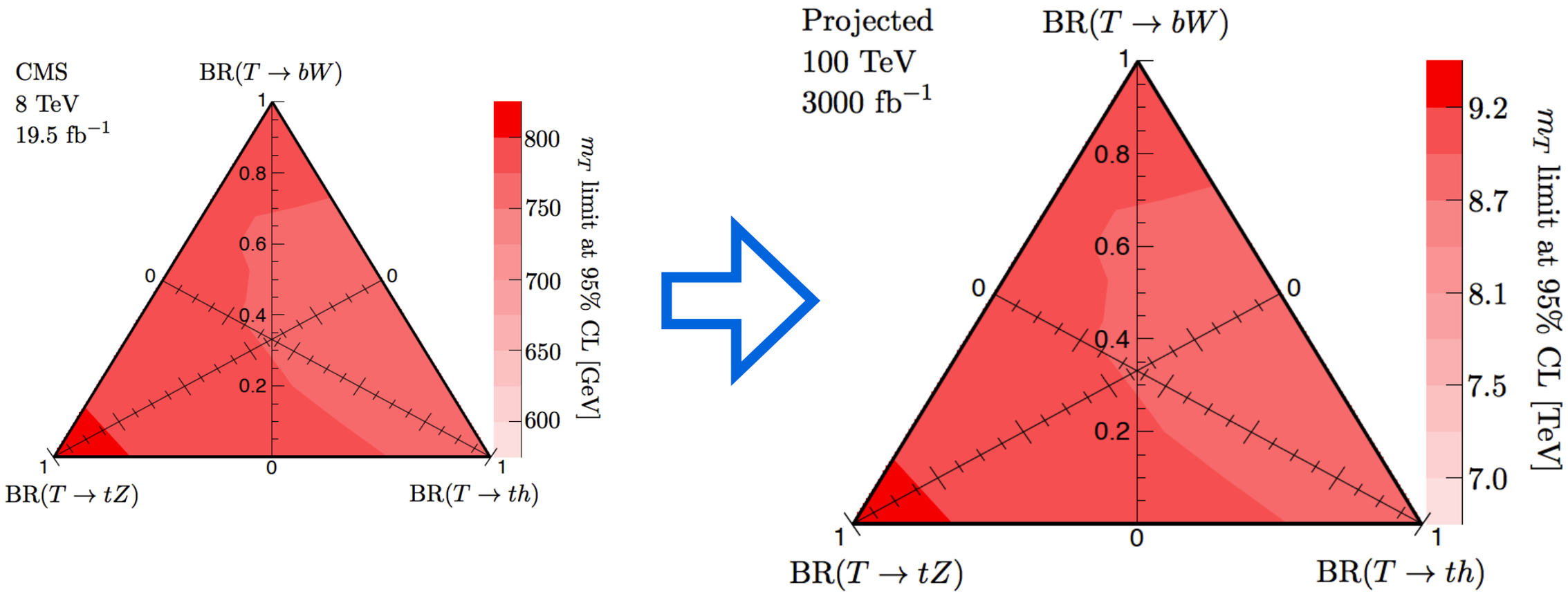
prefers a light T'

Contino, Da Rold, Pomarol, 2006

- Plays a crucial role in EWSB.

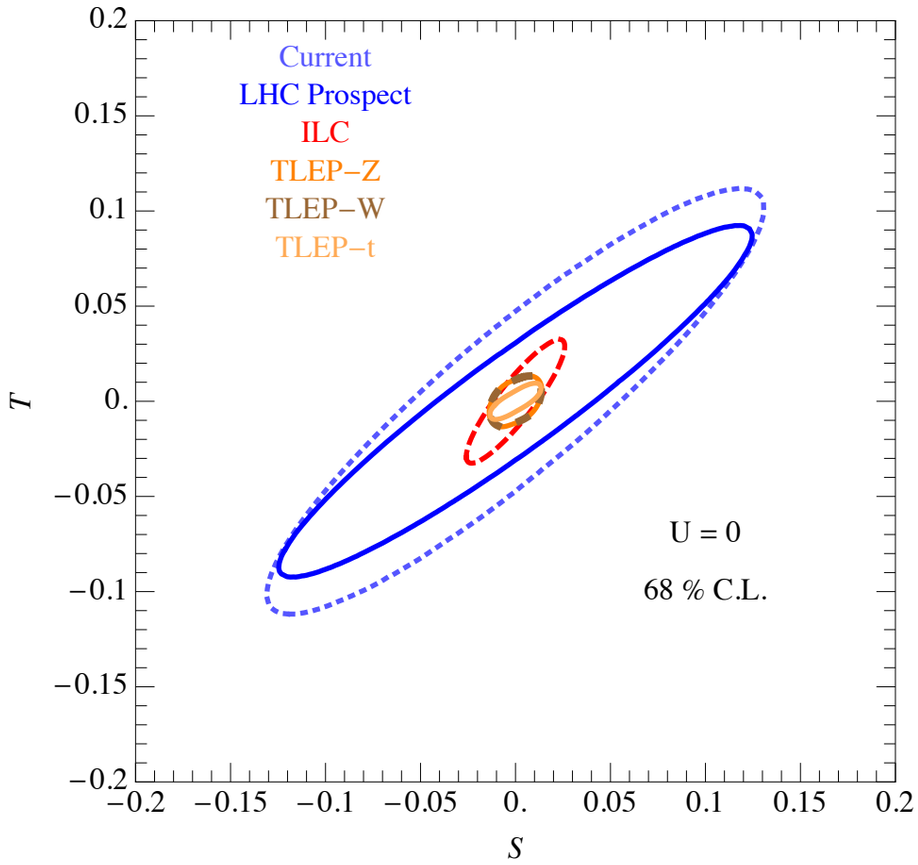
For a comprehensive discussion, see
De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663

Going up to 100 TeV

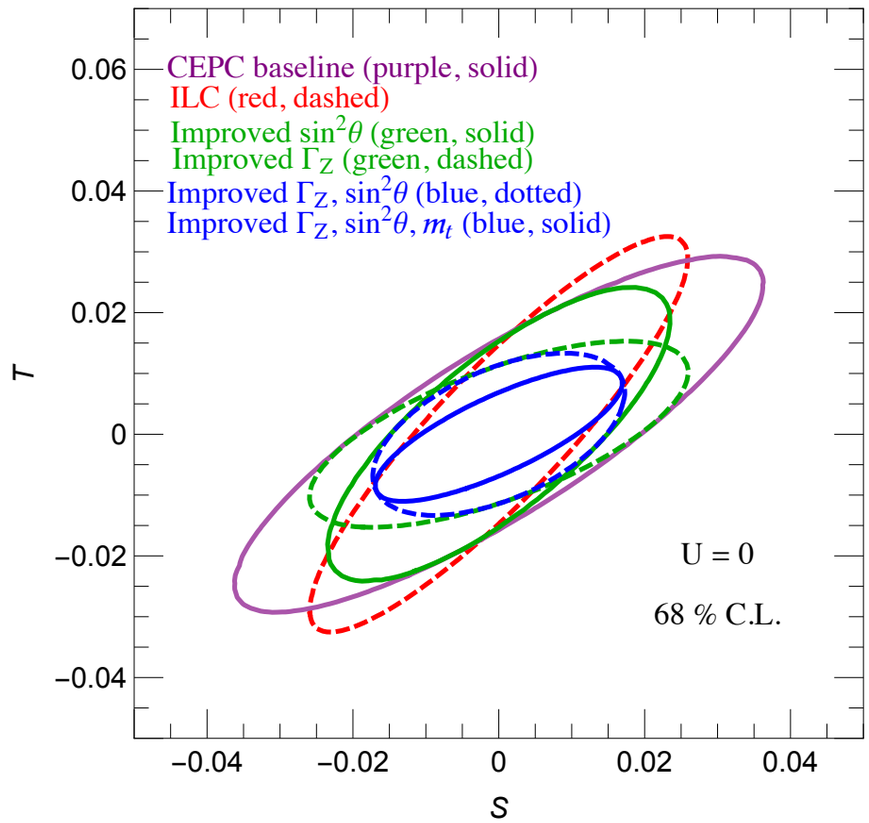


- Room for improvement by using single production, boosted technique, etc.

From precision measurements



Fan, Reece, LTW



- Lepton colliders ⇒ 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

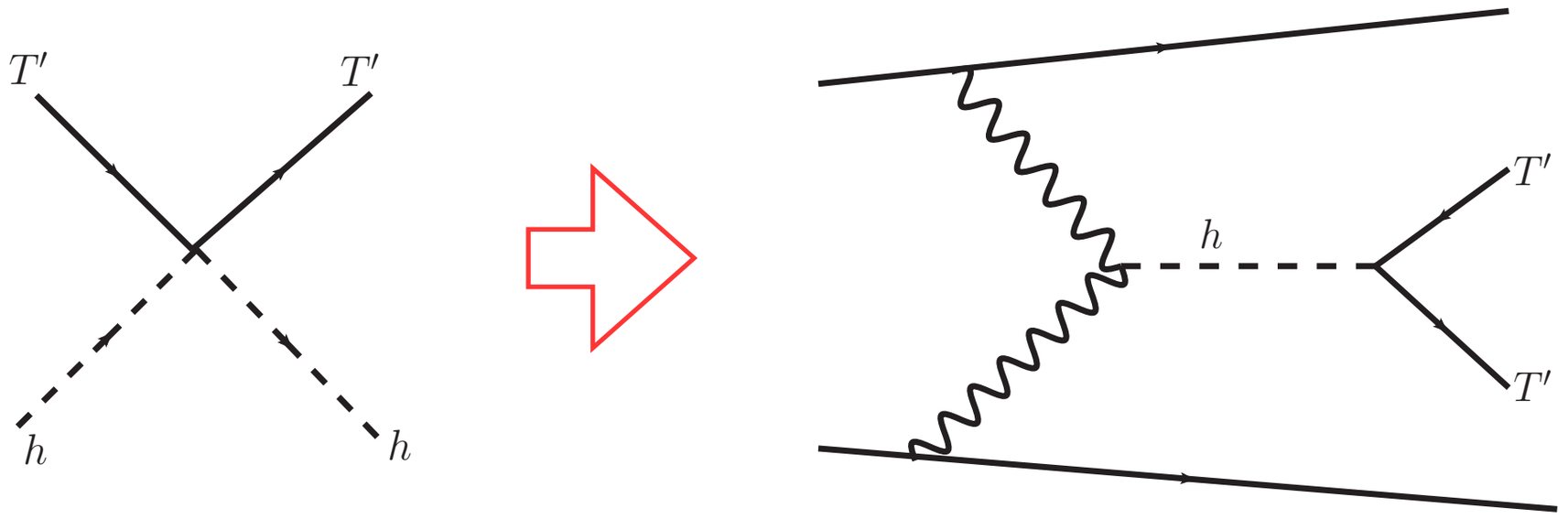
Experiment	S (68%)	f (GeV)	T (68%)	$m_{\tilde{t}_L}$ (GeV)
ILC	0.012	1.1 TeV	0.015	890 GeV
CEPC (opt.)	0.02	880 GeV	0.016	870 GeV
CEPC (imp.)	0.014	1.0 TeV	0.011	1.1 GeV
TLEP-Z	0.013	1.1 TeV	0.012	1.0 TeV
TLEP-t	0.009	1.3 TeV	0.006	1.5 TeV

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

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

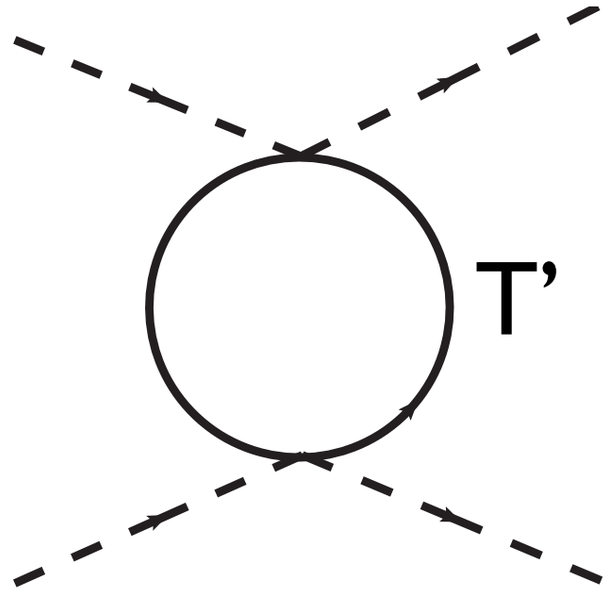
- This is complementary to the direct collider searches.
  - Independent of decay modes and kinematics.

We can hide T' very well.

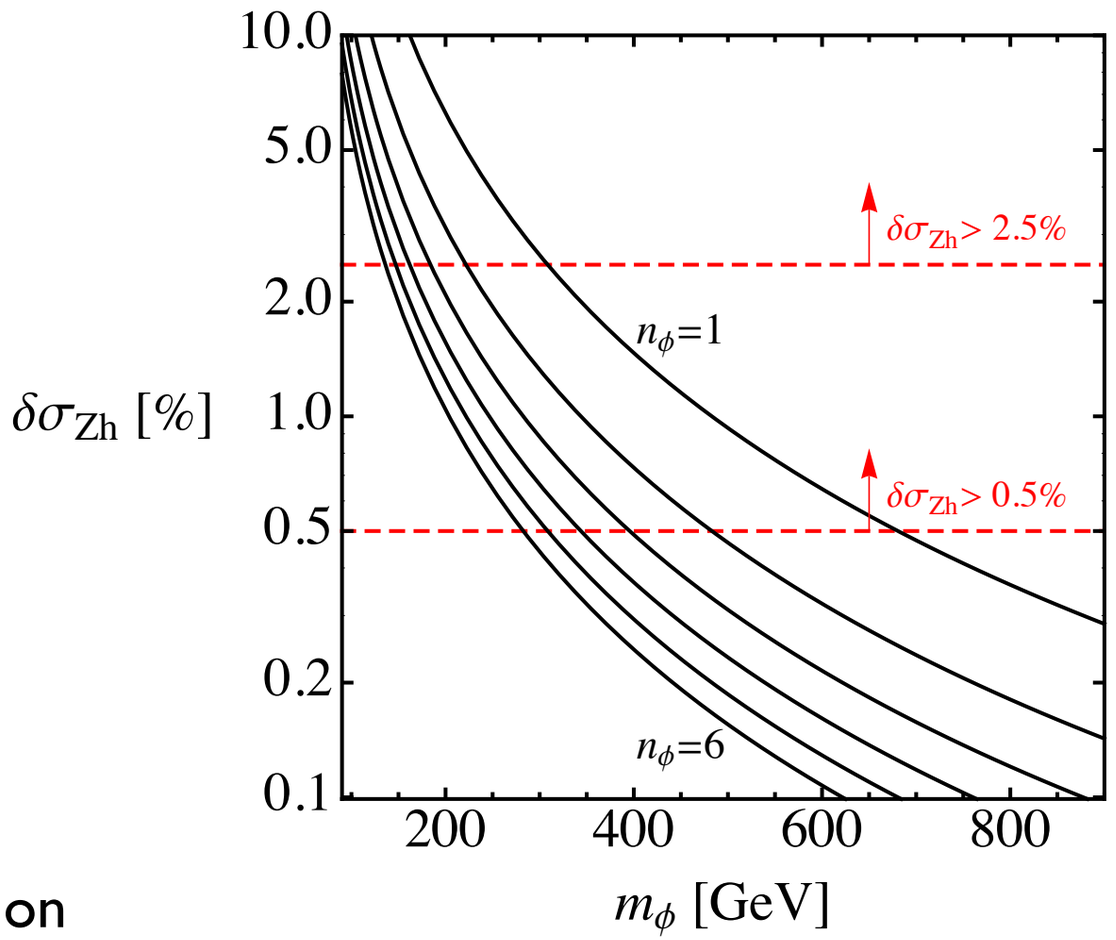


- Top partner not colored.
  - Twin Higgs. Chacko, Harnik, et al Craig et. al.
- Reach probably very limited, 100s GeV.

Anything else we can do?



Wavefunction renormalization
Induce shift in Higgs coupling.

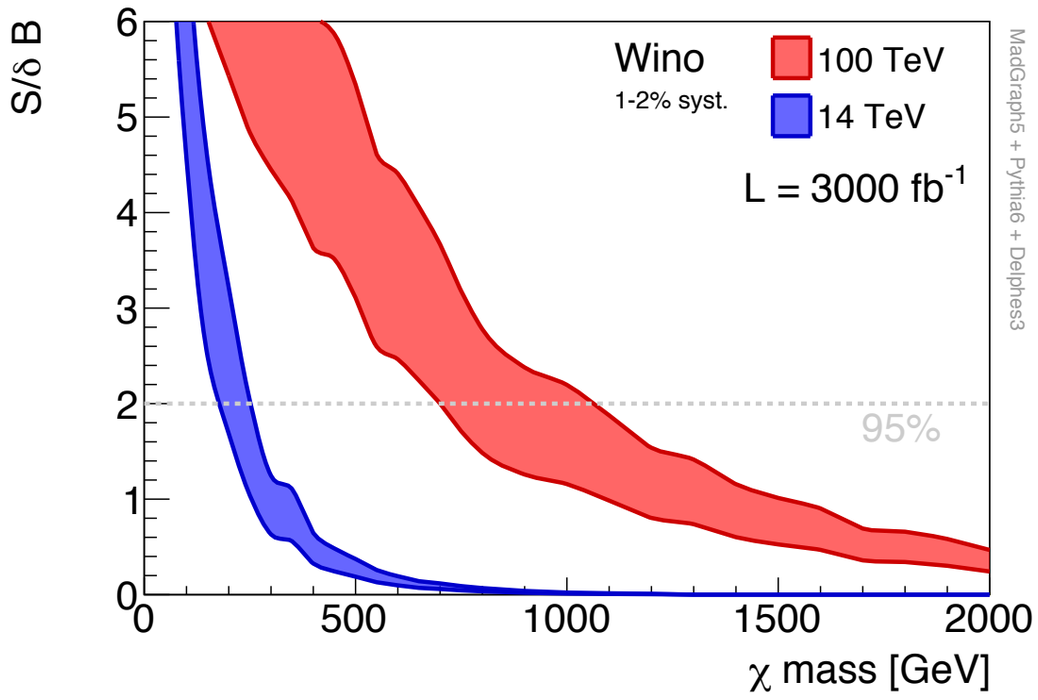


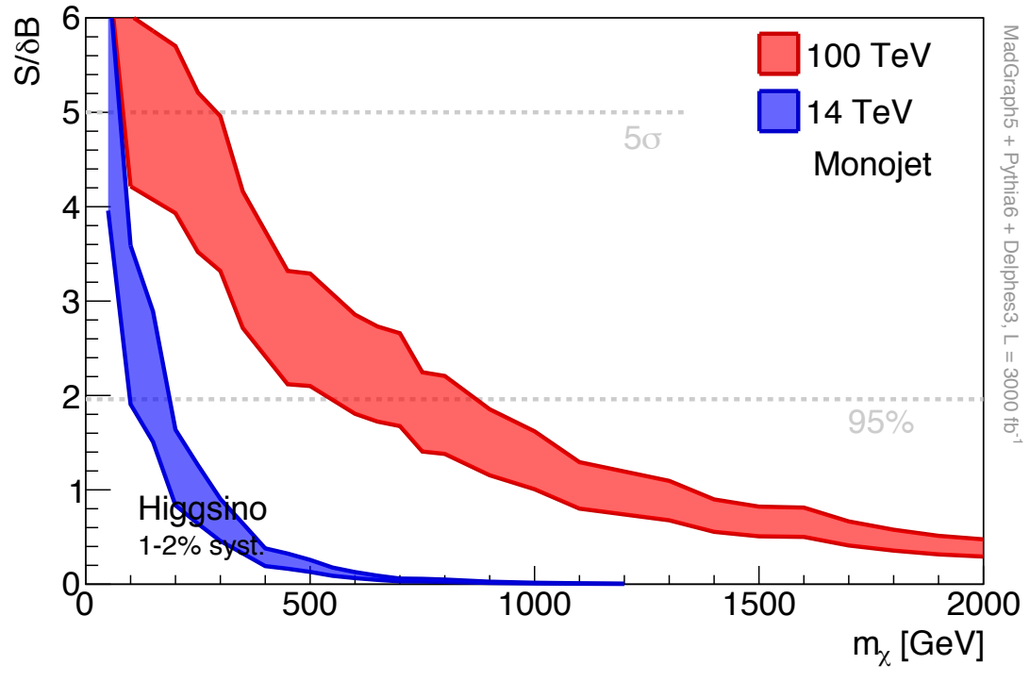
Craig, Englert, McCullough, 2013

- Higgs factory provides a solid probe.

Dark Matter

Dark matter (mono-jet)

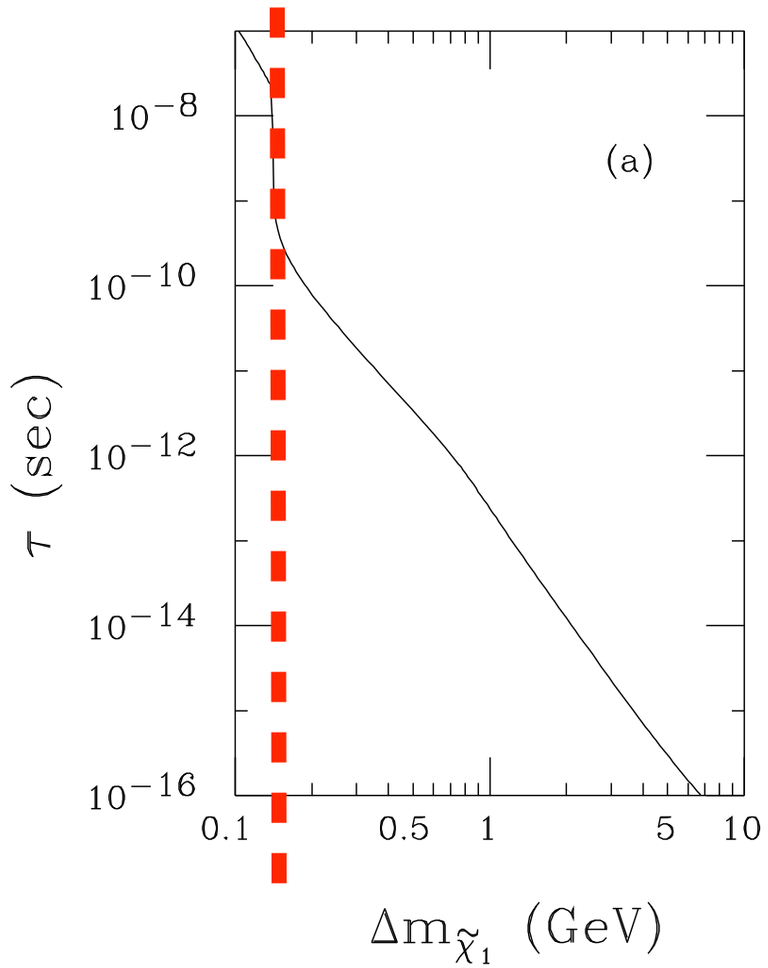




$$M_{\rm WIMP} \leq 1.8 \text{ TeV } \left(\frac{g^2}{0.3}\right)$$

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

Disappearing track



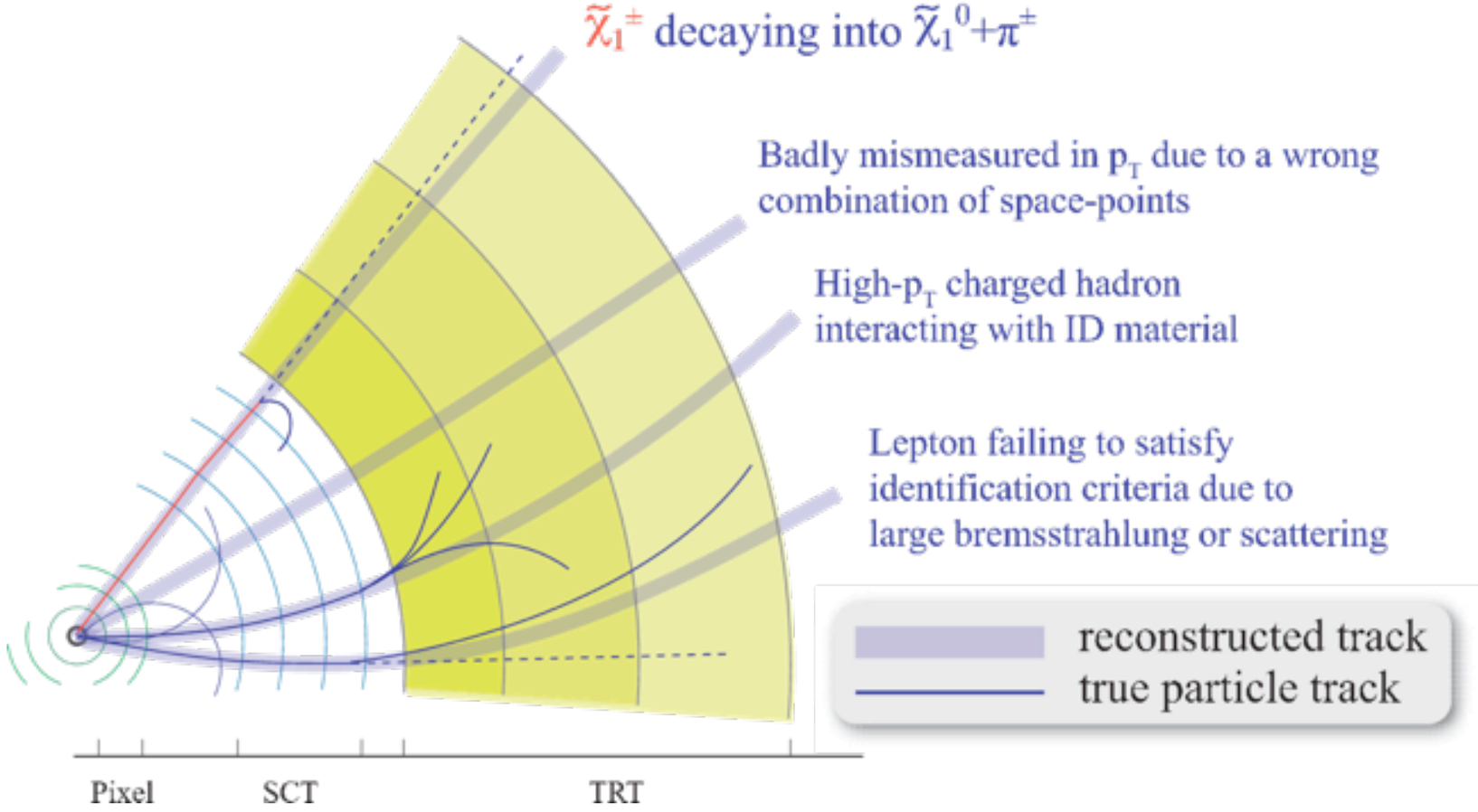
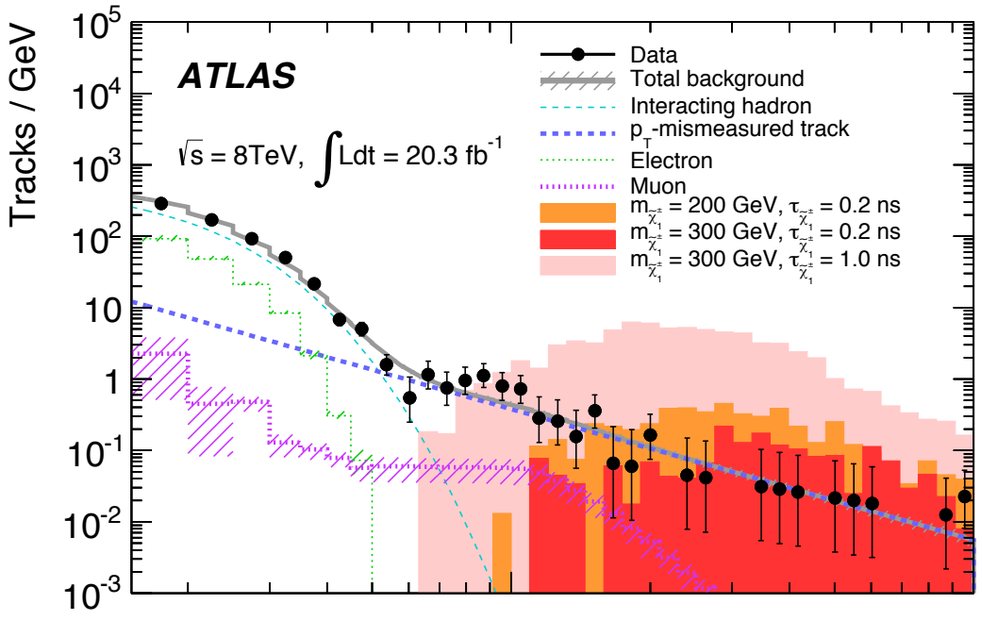


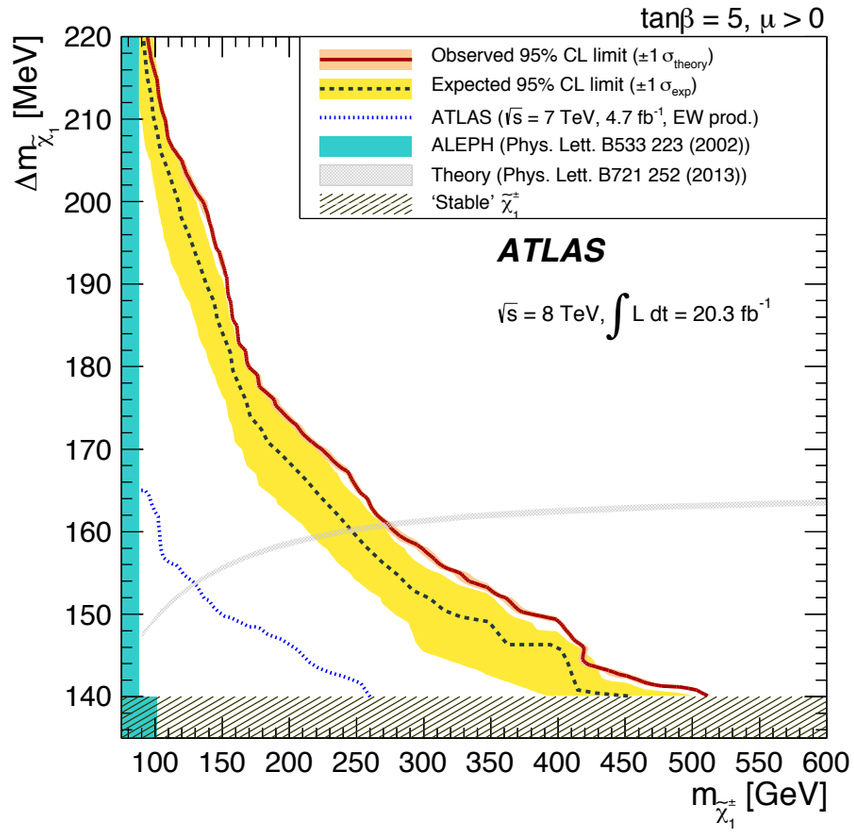
Figure from ATLAS disappearing track search twiki

- Main decay mode $\chi^{\pm} \rightarrow \pi^{\pm} + \chi^{0}$
- Charge track ≈ 10(s) cm

ATLAS search

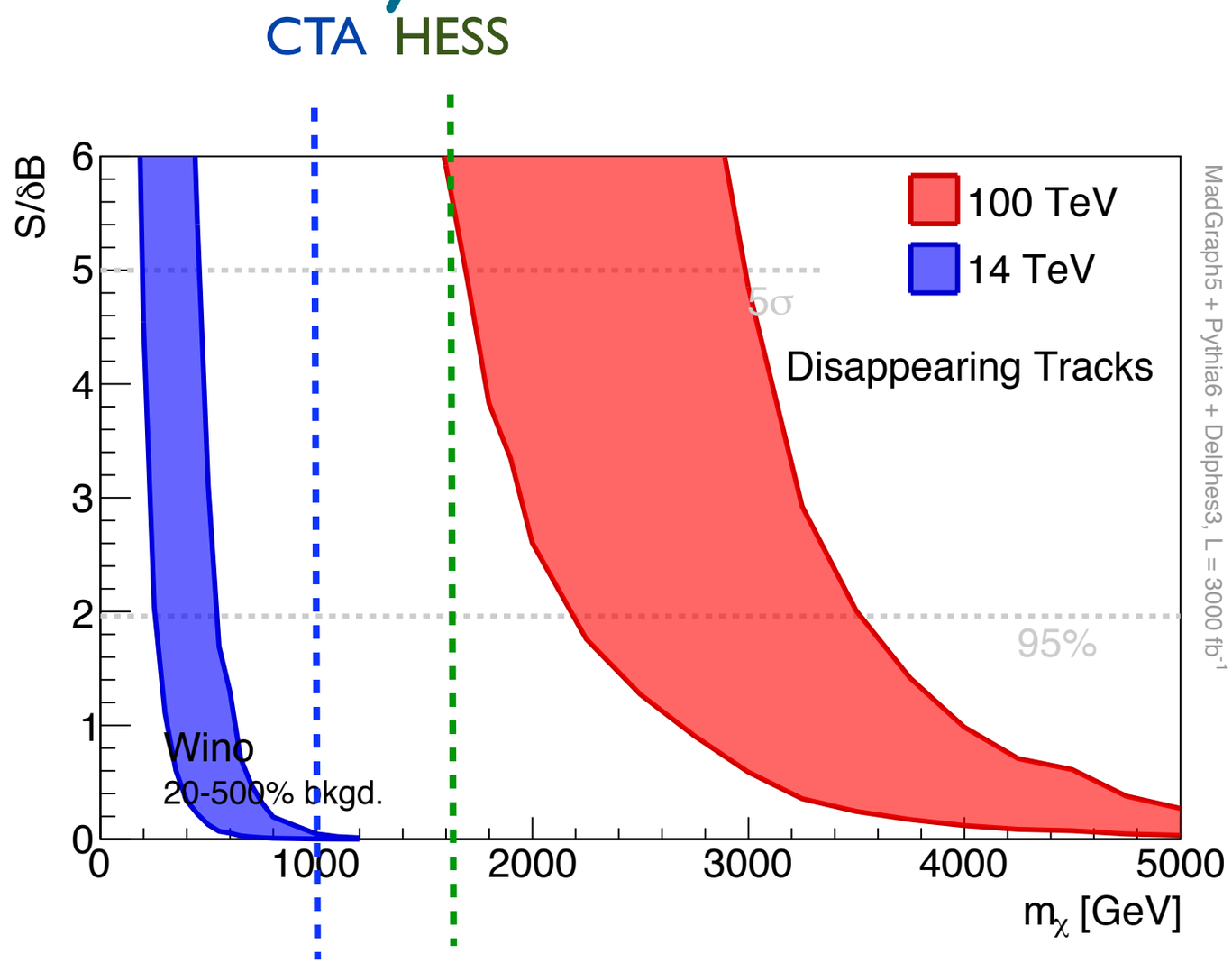
ATLAS, 1310.3675





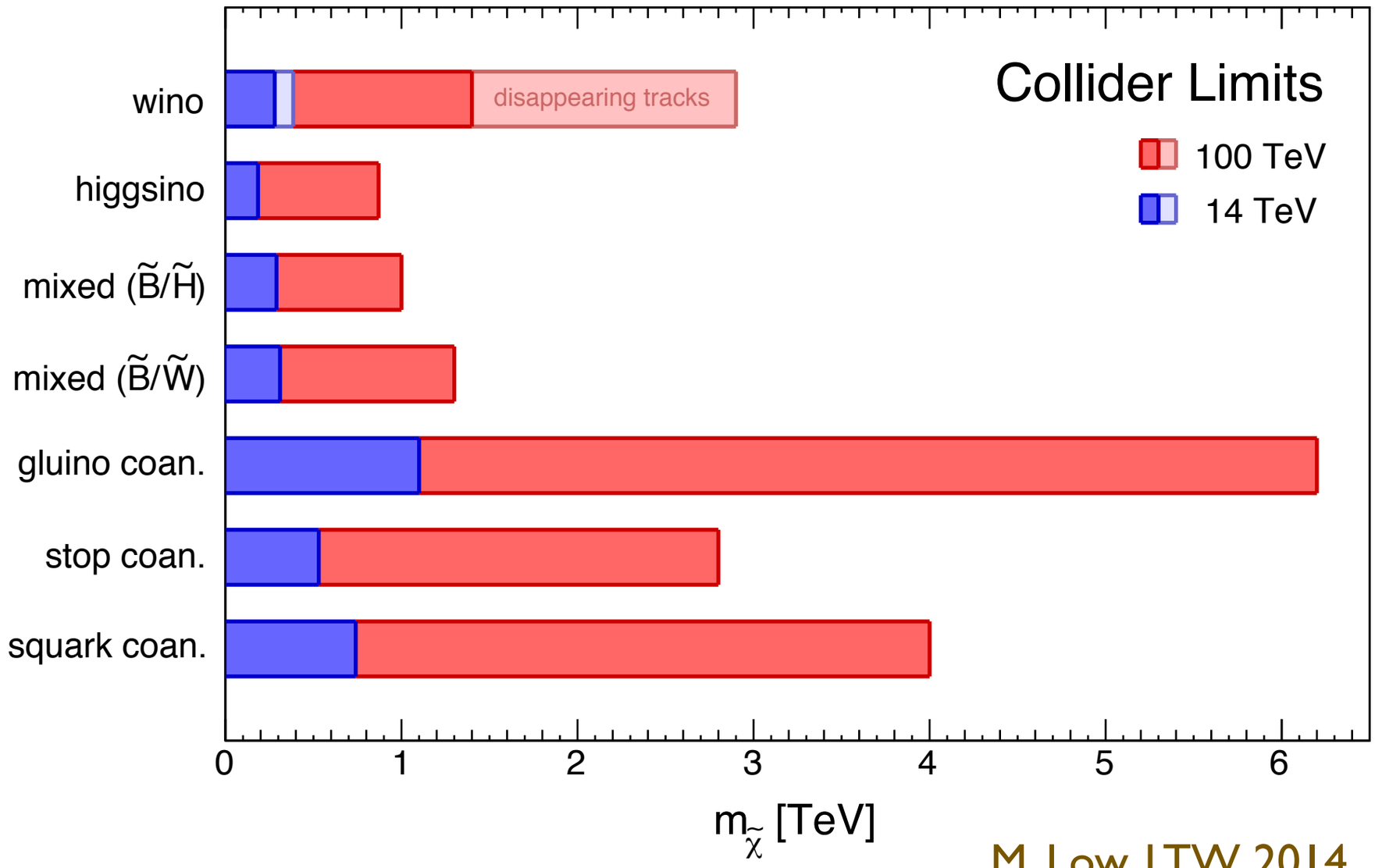
- Essentially free of physics background.
- Dominated by p_T mis-measured tracks.
- Very promising reach, much better than mono-jet

Wino summary



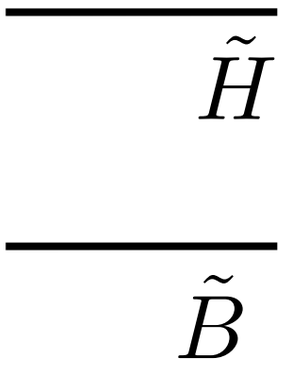
- There is hope to "completely cover" the wino parameter space.

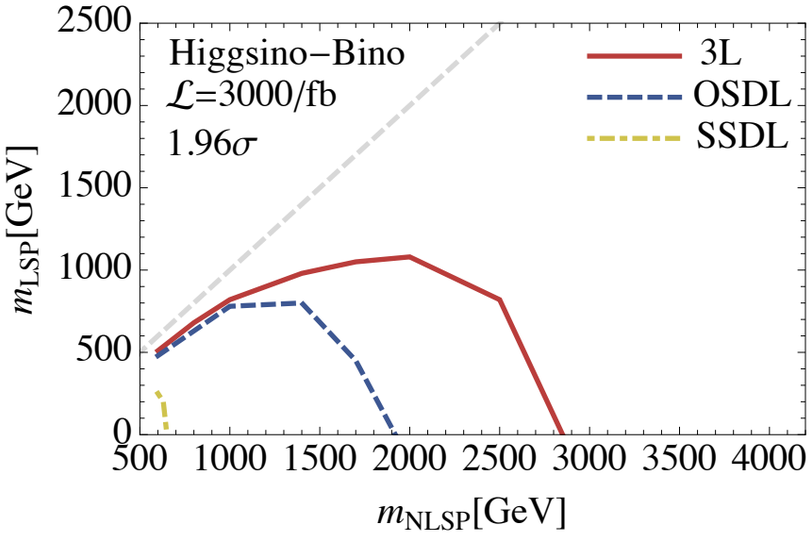
Mono-jet

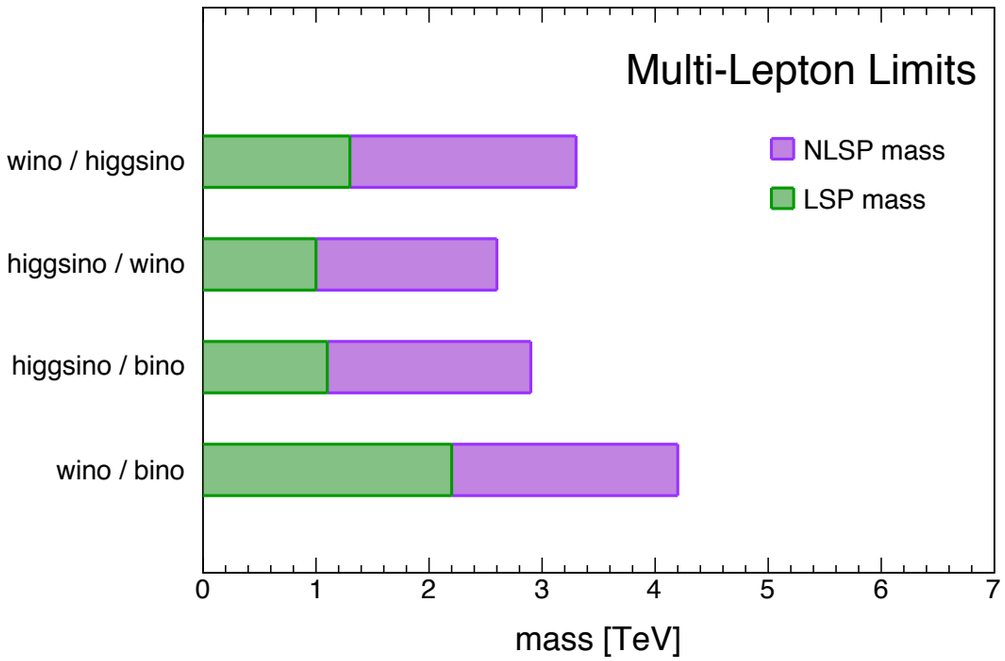


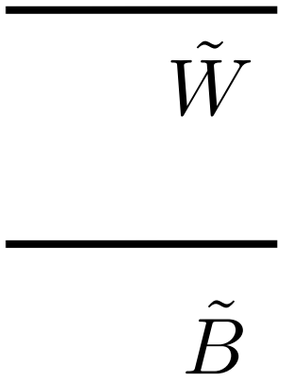
M. Low, LTW 2014

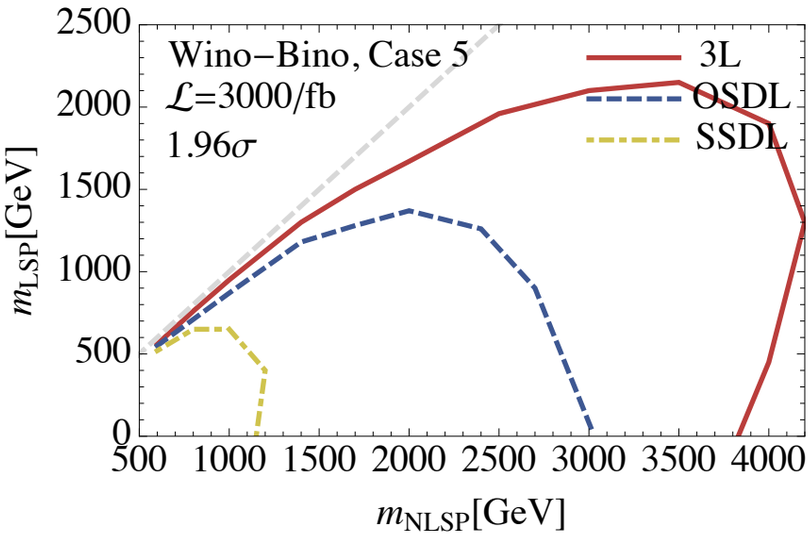
Cascade











Decay ⇒ leptons ⇒ stronger limits

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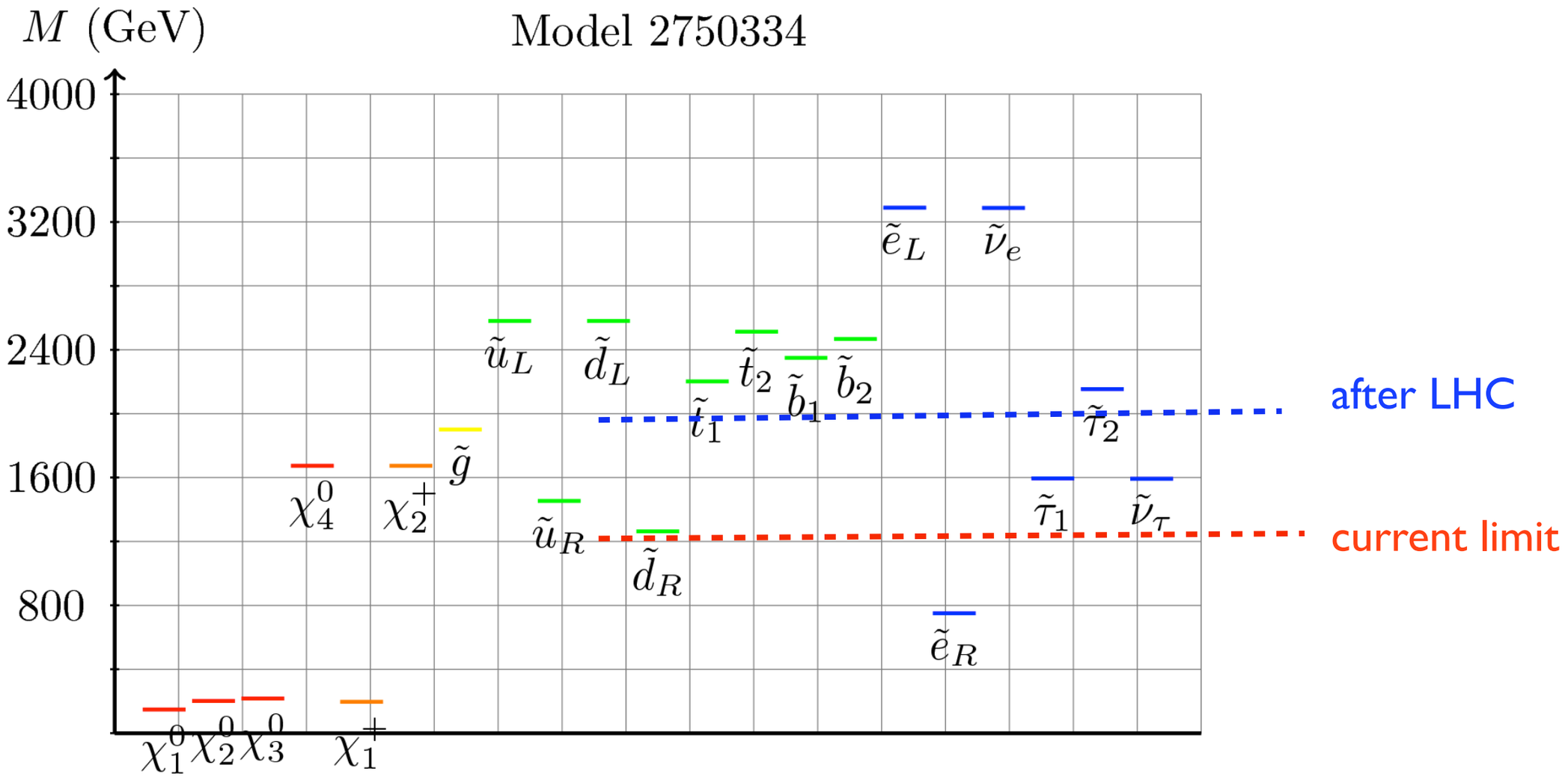
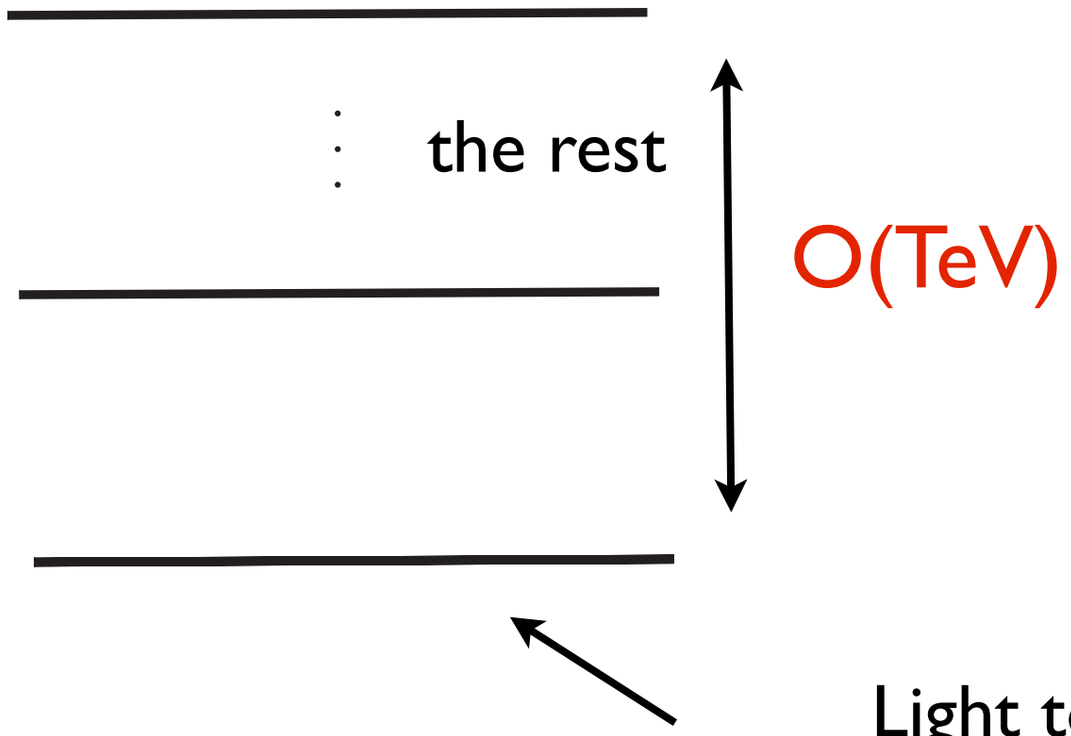
- However, many models feature particles with masses spread at least factor of several apart.
- Won't be able to see everything.
- LHC discovery will set the stage for our next exploration. Such as at a future 100 TeV pp collider.

Example: SUSY (a random model)



- 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.

Many new and on-going studies.

- Vector boson fusion for composite resonances.
- Z'.
- flavor @ 100 TeV (the rest of this workshop!).
- Fermionic top partner
- Suggestions for more studies to be done?

More excitements to come...

Under consideration now:

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

- **Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel**

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

Yifang Wang, director of IHEP