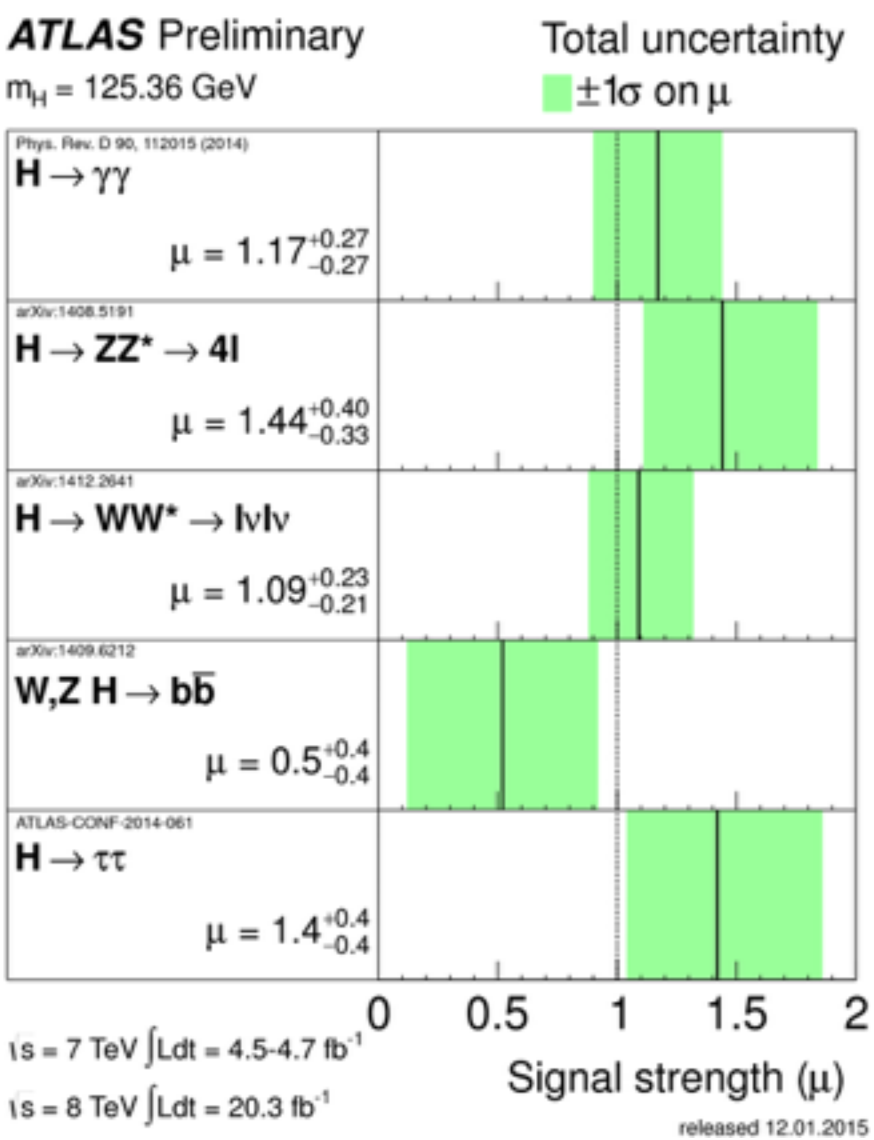
Physics opportunities at Hadron colliders, LHC and beyond

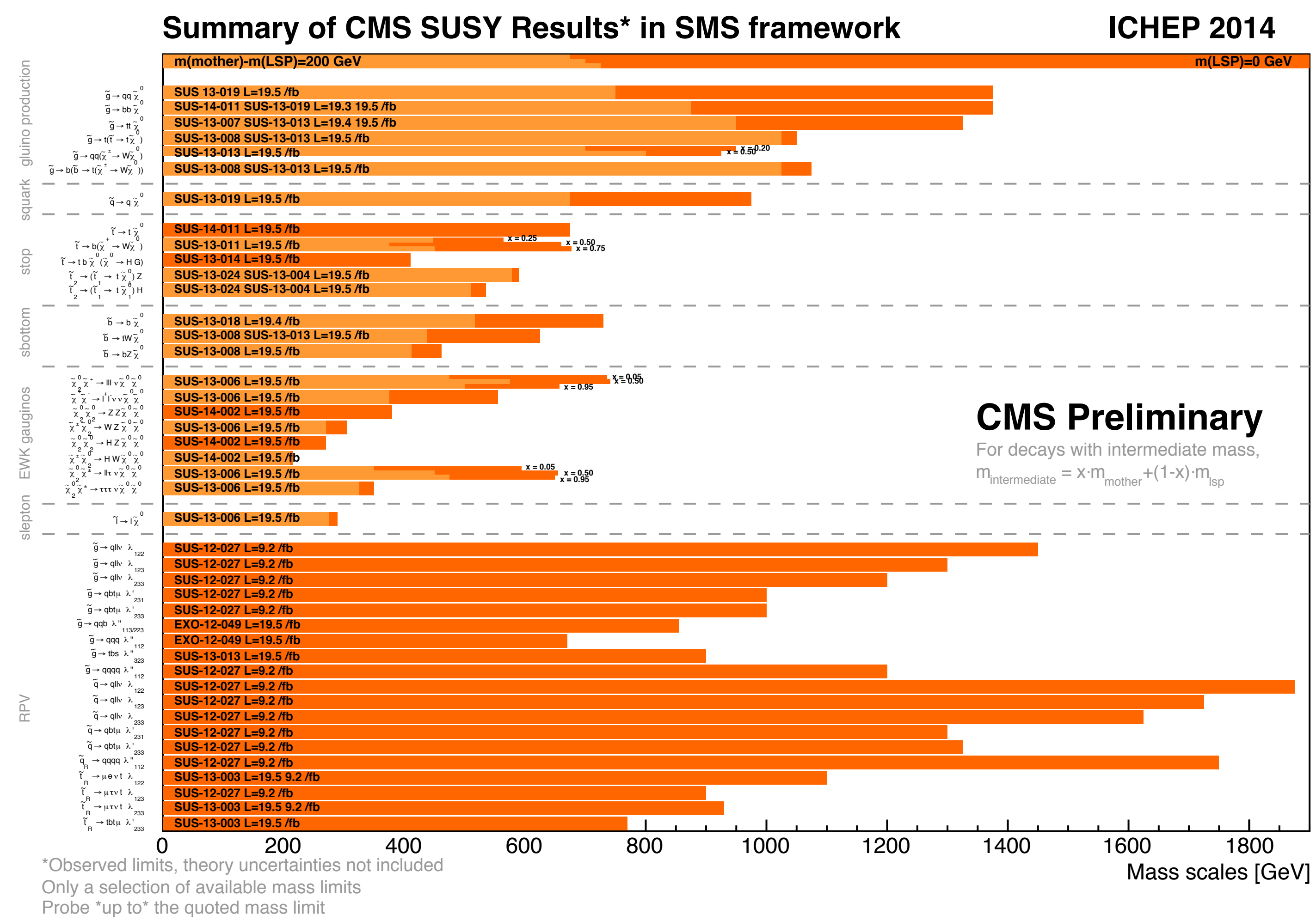
LianTao Wang
University of Chicago

SUSY 2015. Lake Tahoe. August 29, 2015

Current status

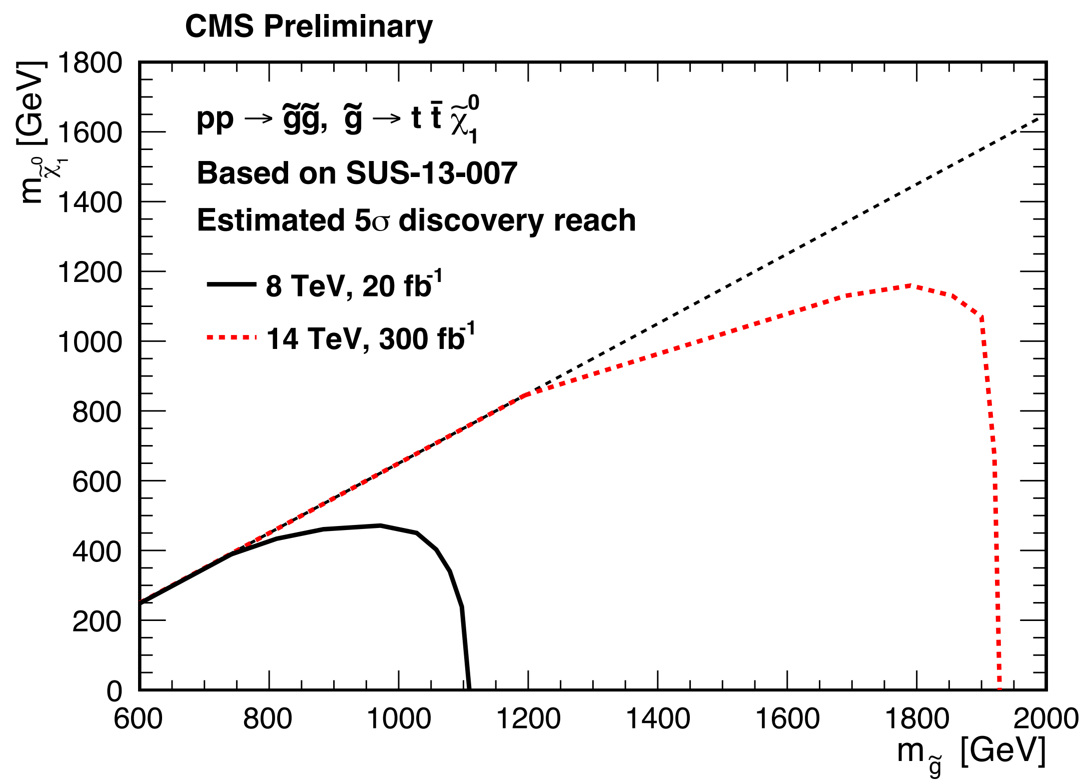


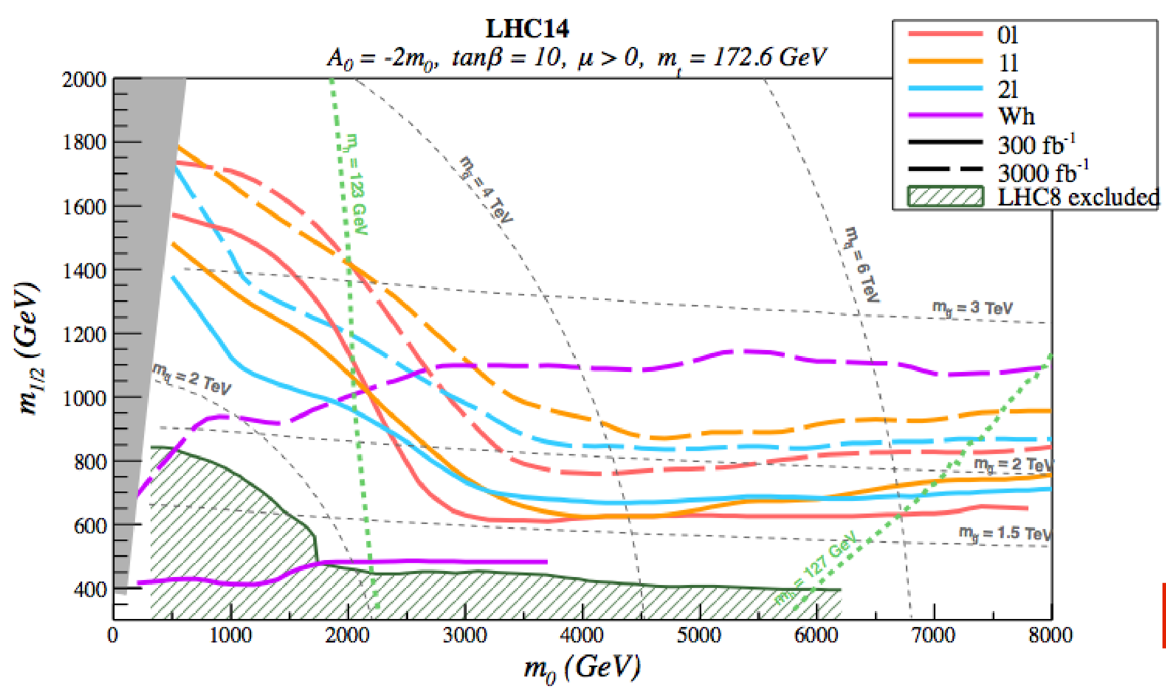
Found Higgs

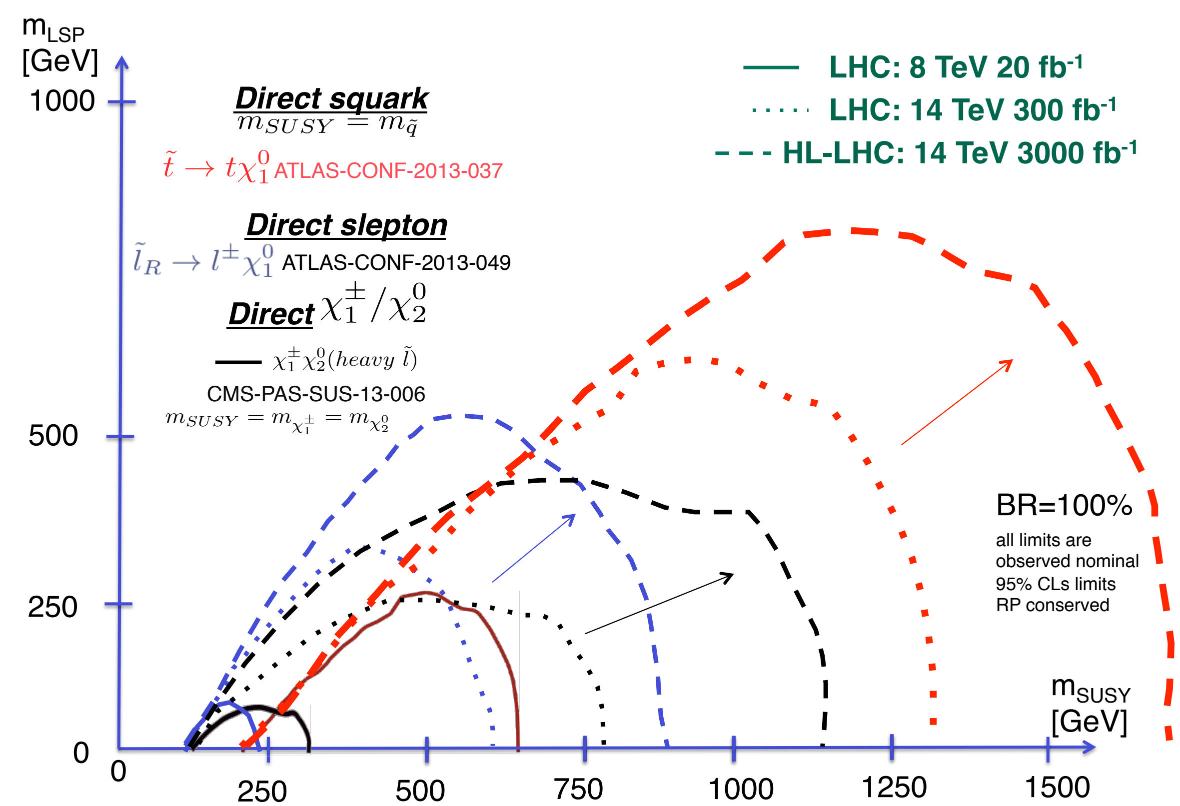


None observation of other new physics

LHC run 2+, higher energy, more data





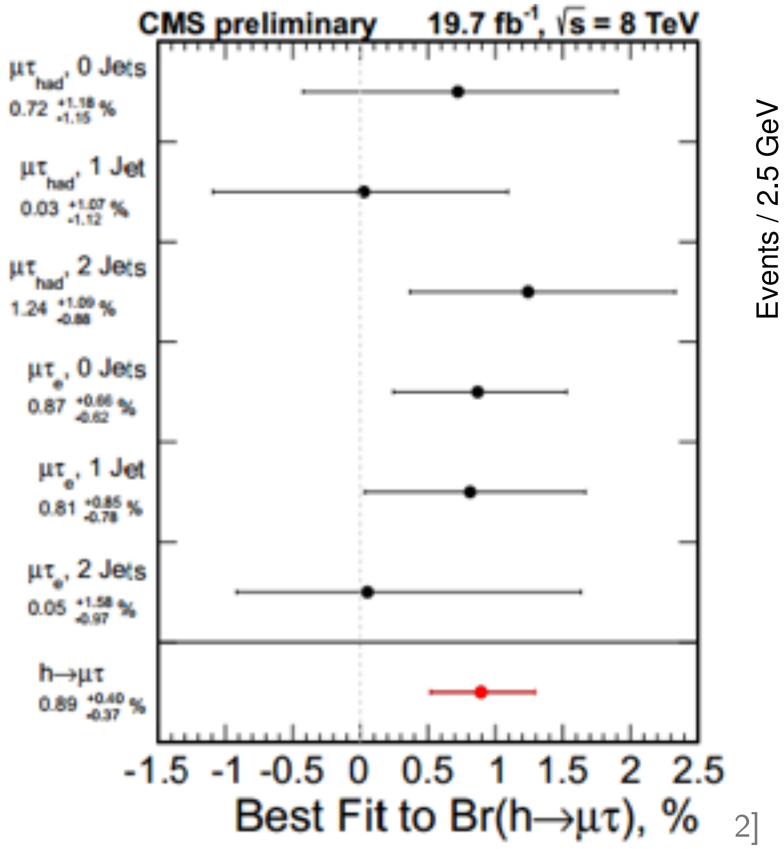


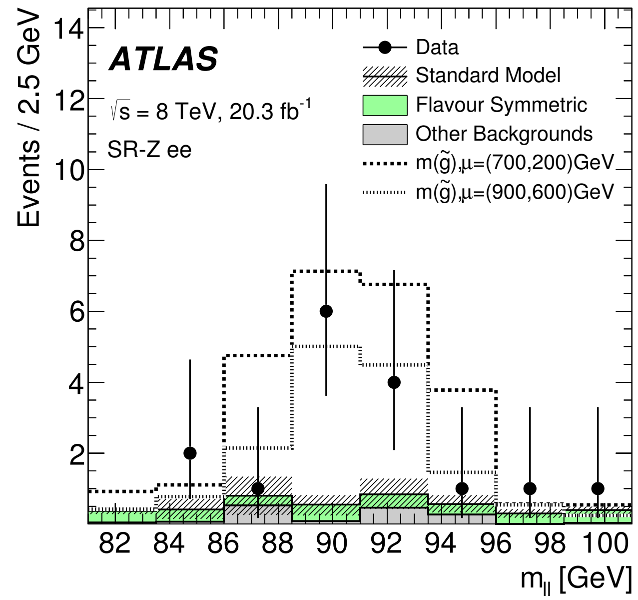
Virdee, LHCP 2014

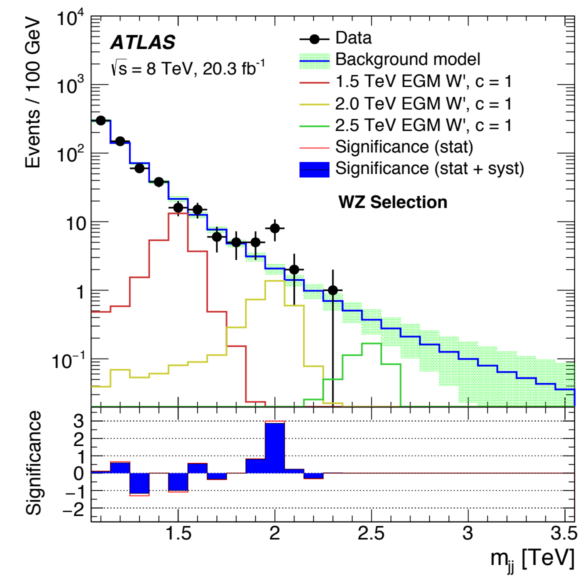
Will turn a big corner.

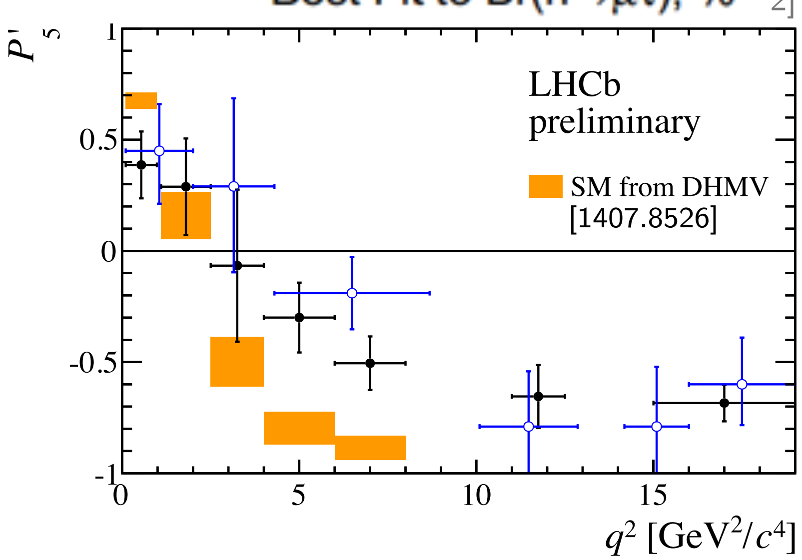
New physics could be right there!

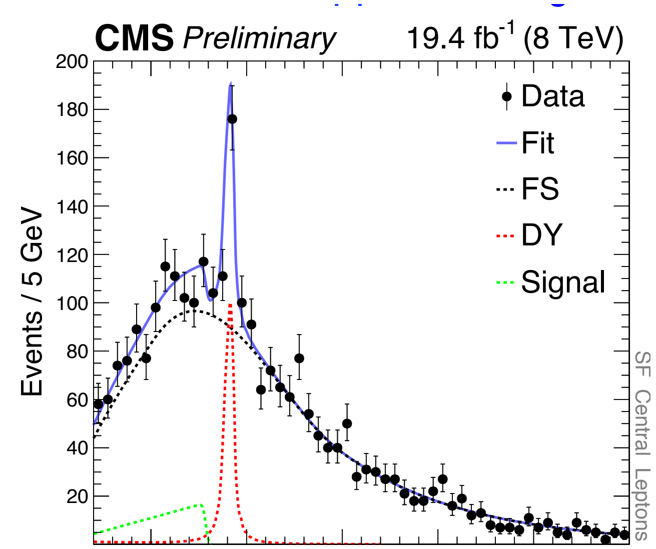
Maybe one of these?

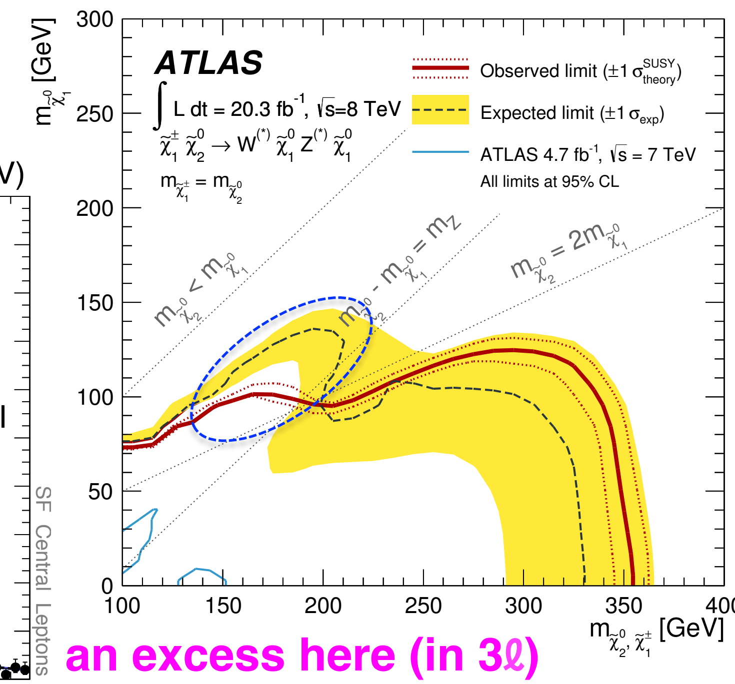








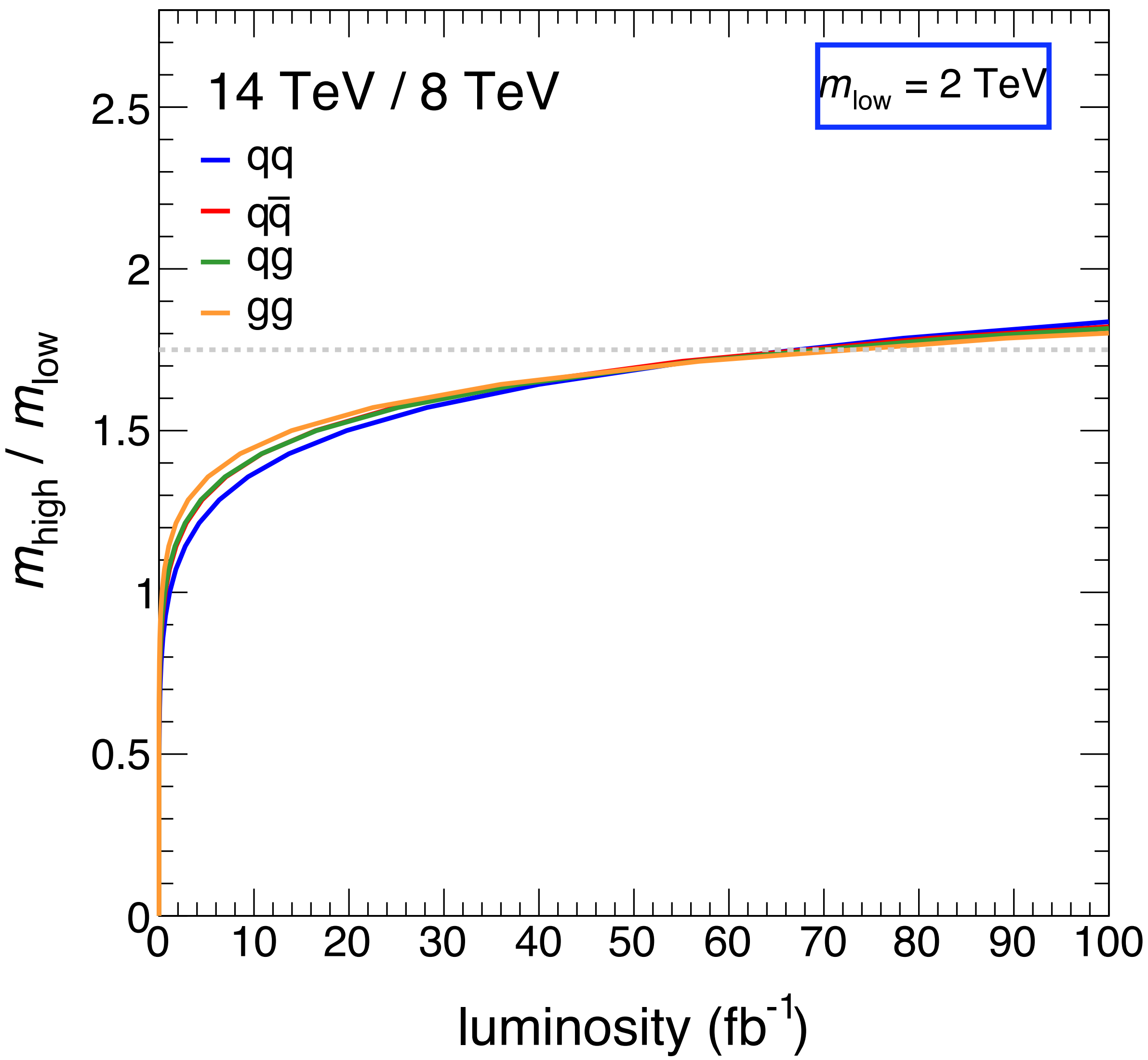




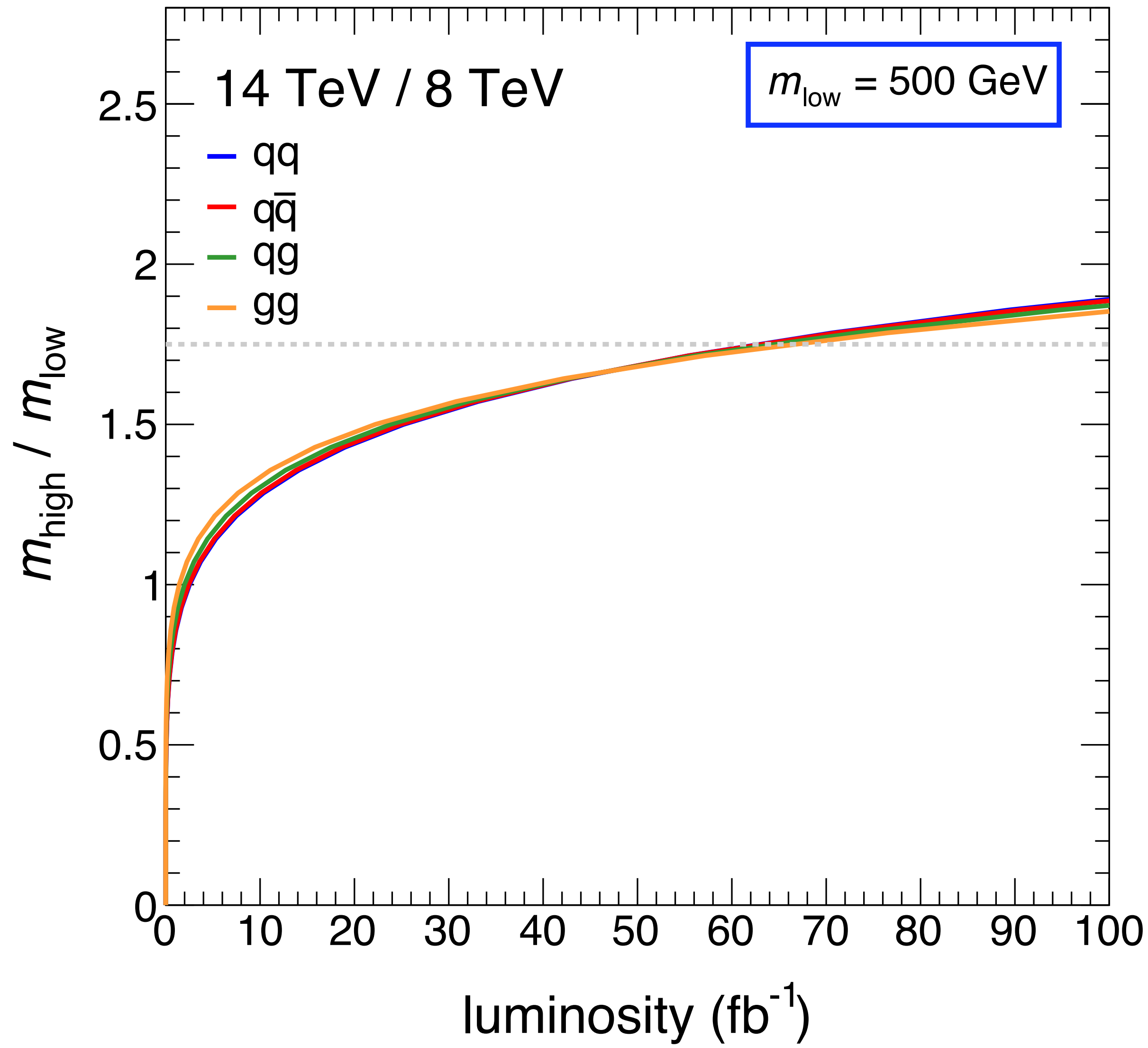
Or something else just around the corner?
Spectacular early discovery!

As data accumulates

Run 1 limit   2 TeV, e.g. pair of 1 TeV gluino.



500 GeV, e.g. pair of 250 GeV electroweak-ino



Steep falling PDF ➡ Rapid gain initial 10 fb^{-1}, slow improvements afterwards.

LHC Run 2 will continue to pursue a broad physics and successful program.

Of course, there are gaps in to be filled, new signals to be looked at.

Such as Softer, compressed, displaced, more hadronic ... many discussions.

My general impression:

Experimental collaborations are on top of most of these things.

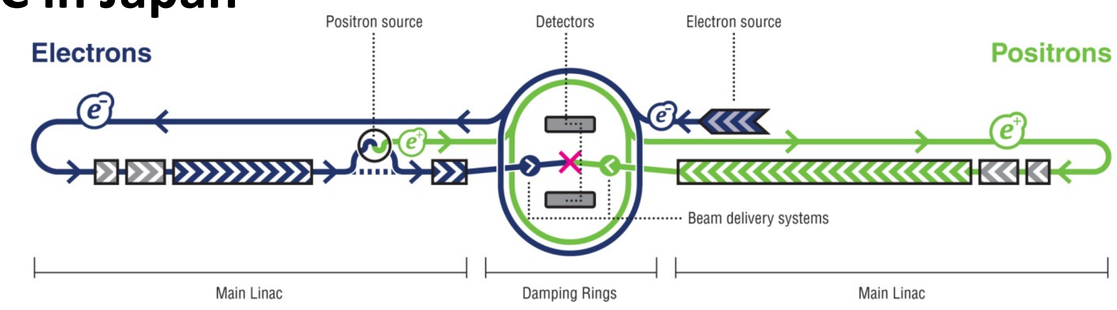
Open questions beyond LHC

- Nature of electroweak symmetry breaking.
- Naturalness.
- Dark matter.
- A discovery at the LHC is unlikely to be complete.
- ....

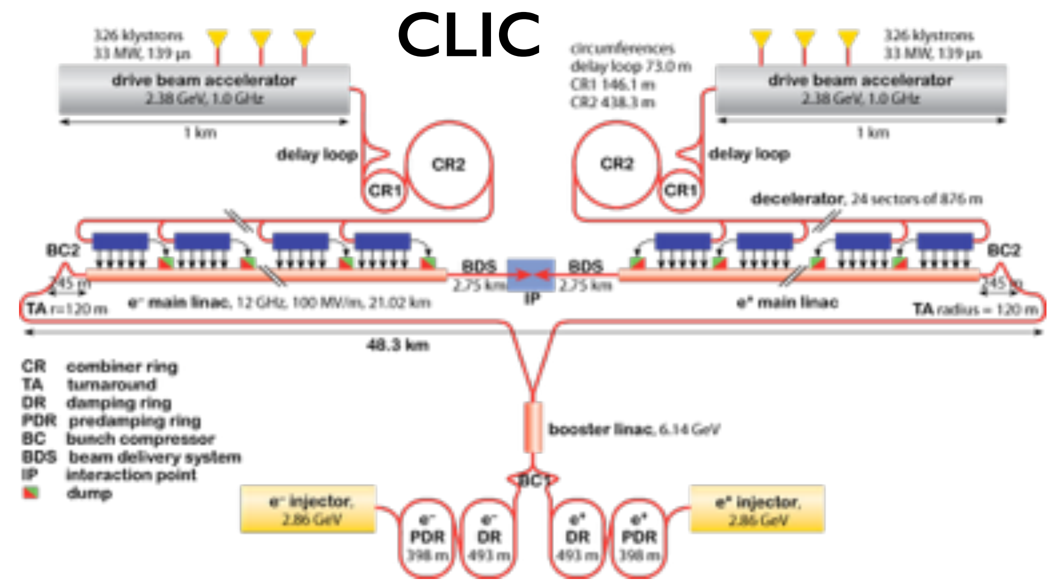
Need to go beyond

Beyond the LHC, future facilities

ILC in Japan



CLIC

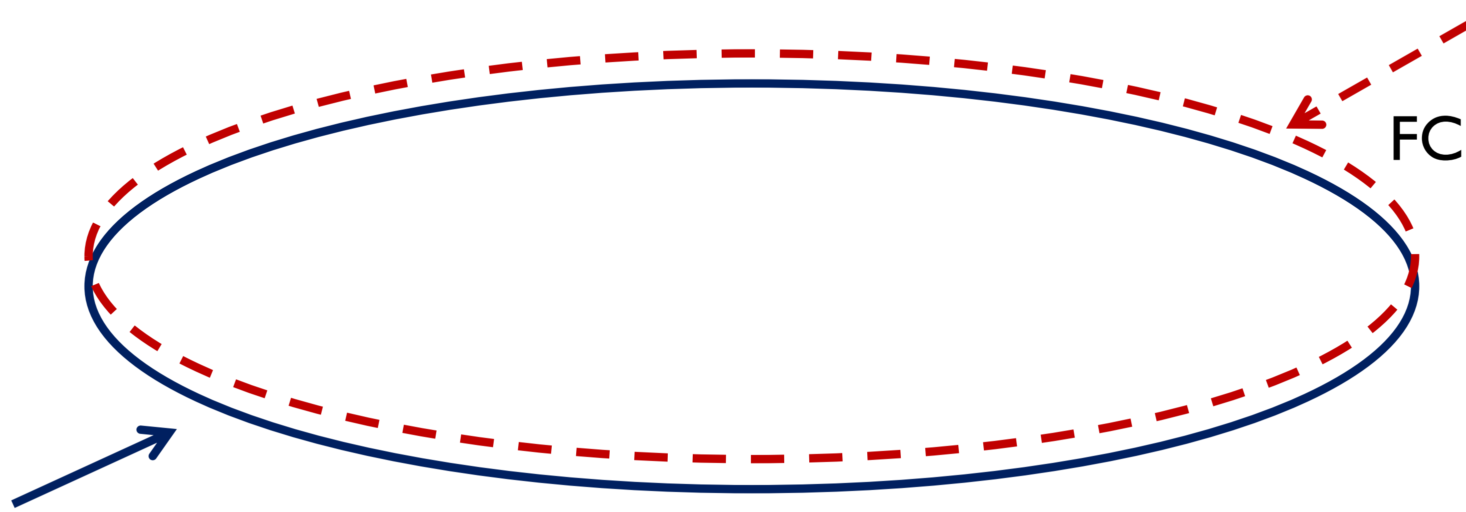


Circular. “Scale up” LEP+LHC

~100 TeV

pp collider

FCC-hh (CERN), SppC(China)



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

FCC-ee (CERN), CEPC(China)

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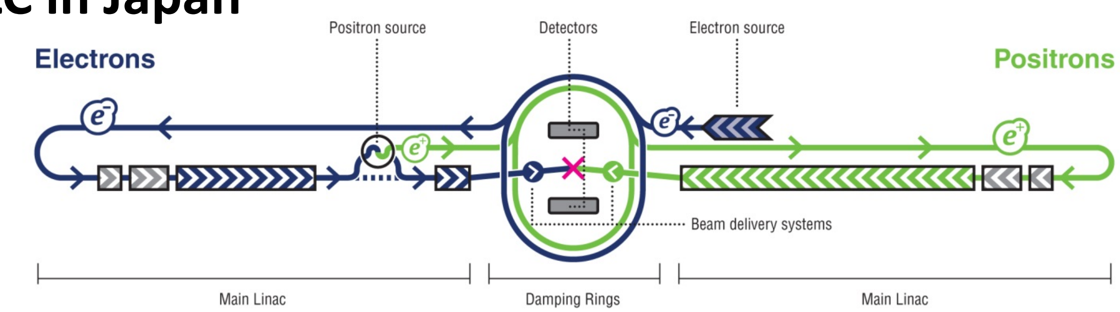

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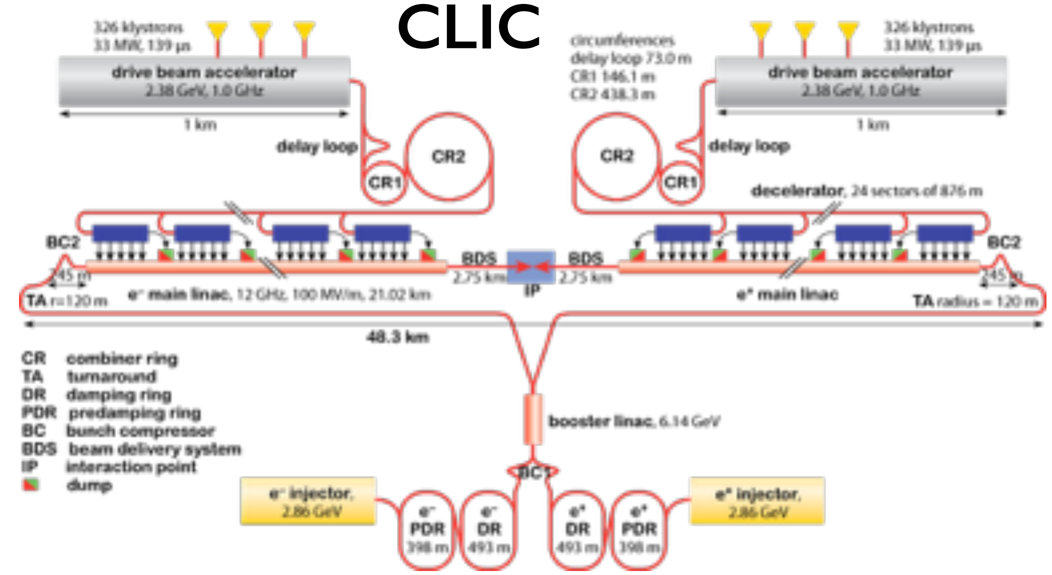

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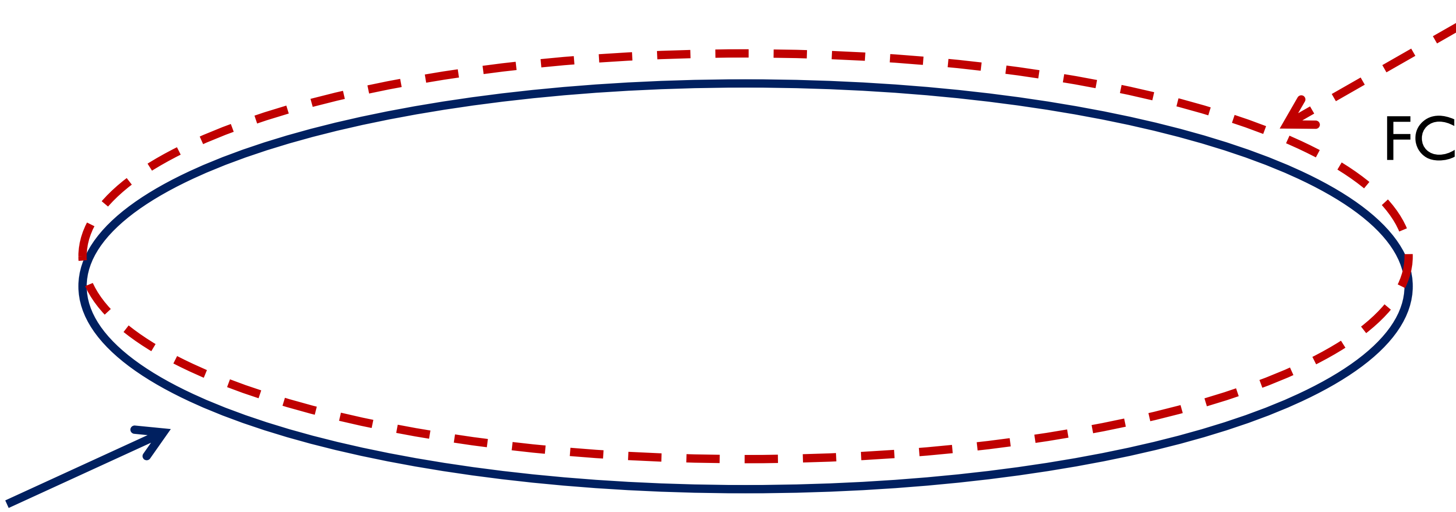

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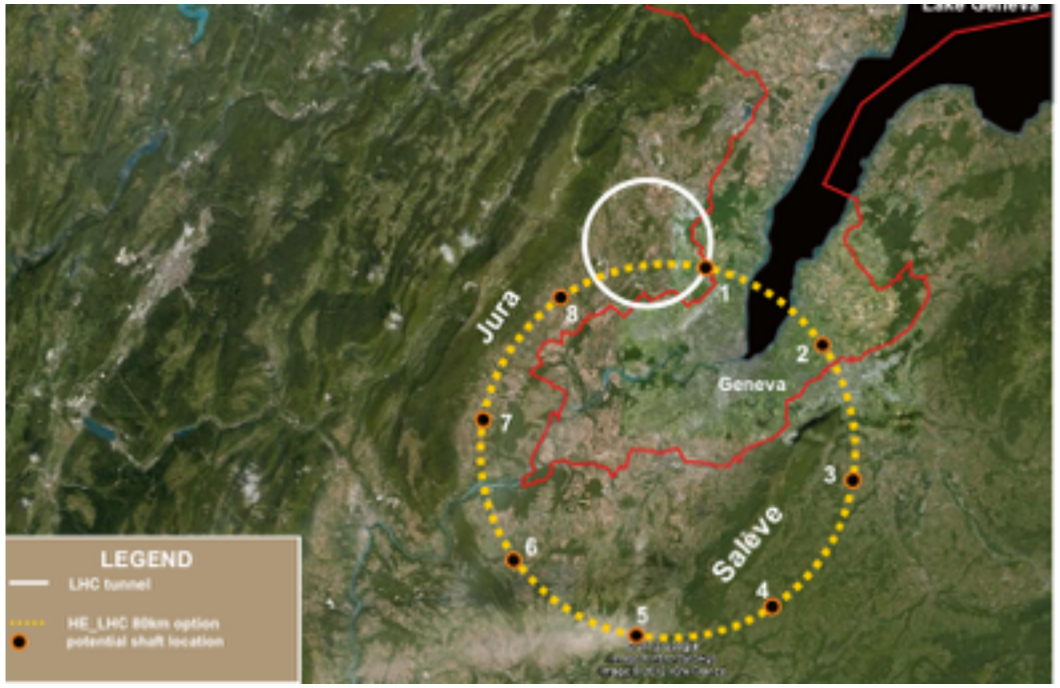
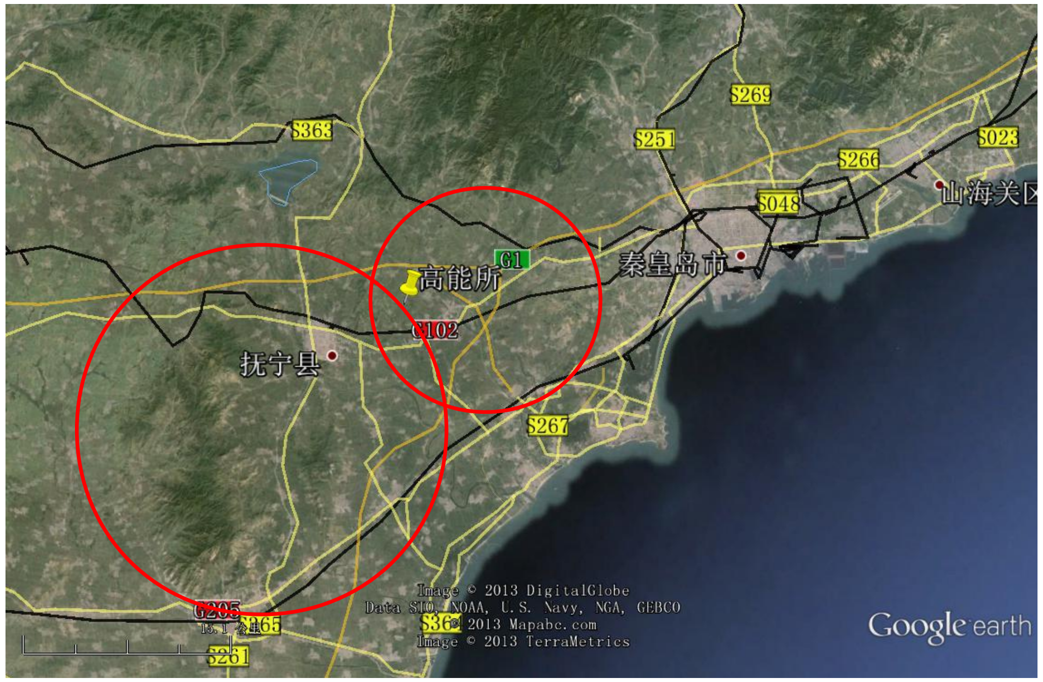
I will focus on the circular (hadron) colliders in this talk

Future circular colliders



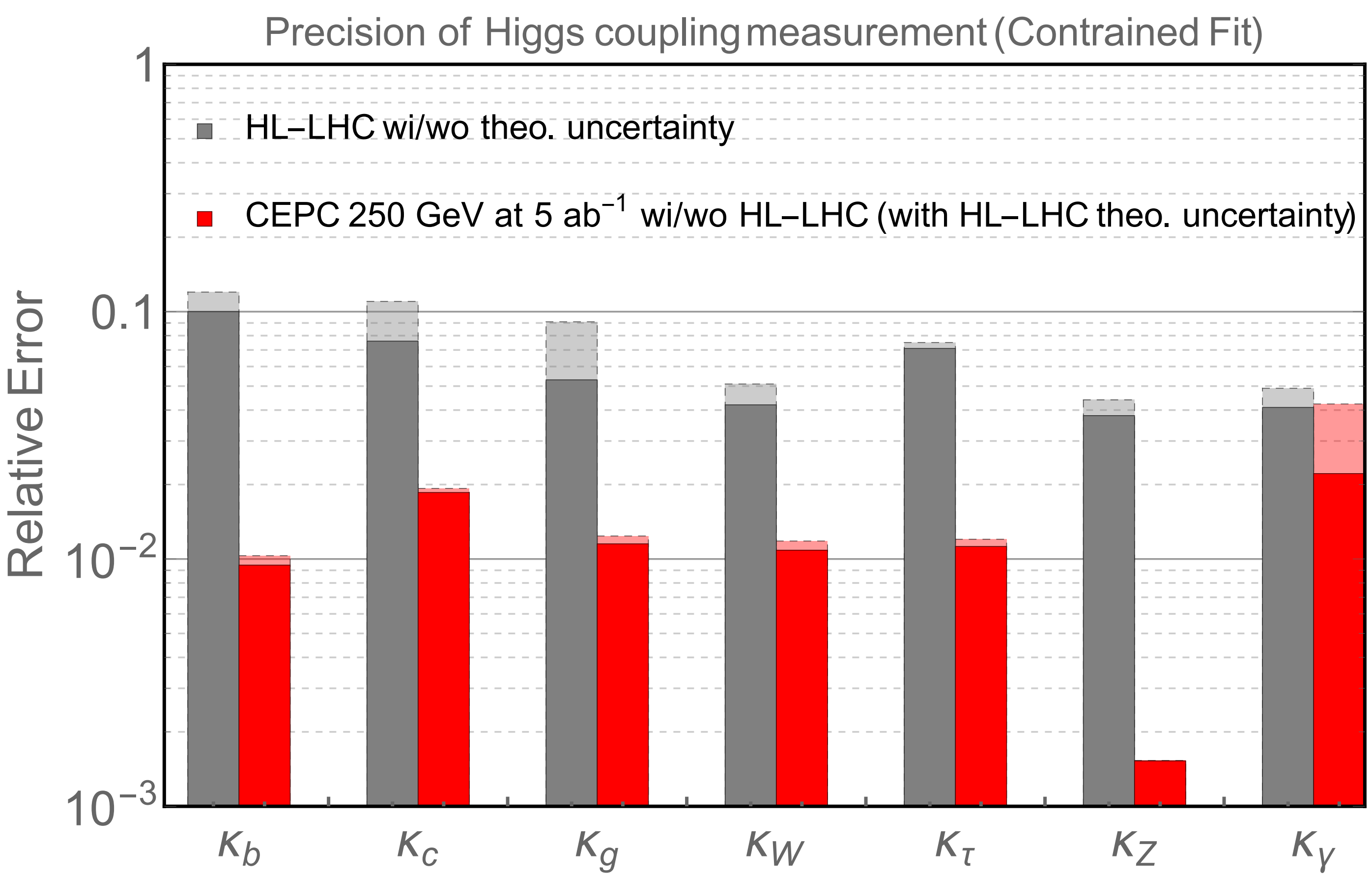
CERN
Higgs factory: FCC-ee
pp Collider: FCC-hh



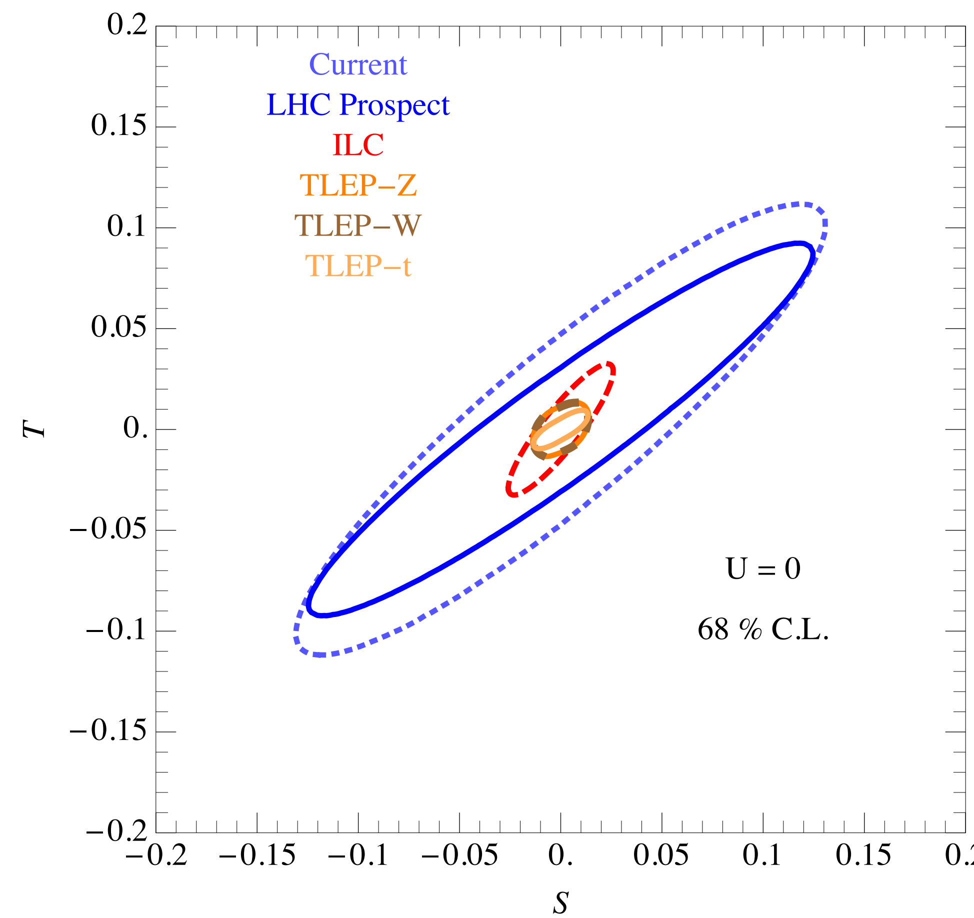
China.
Higgs factory: CEPC
pp Collider: SppC

Capabilities of future colliders

Precision measurements at lepton colliders

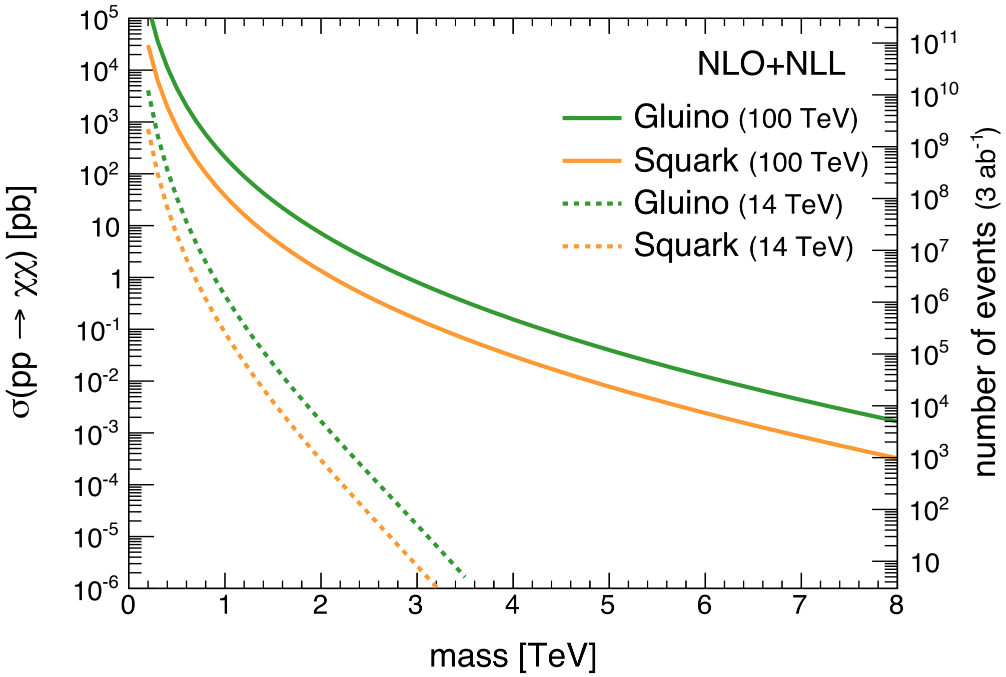


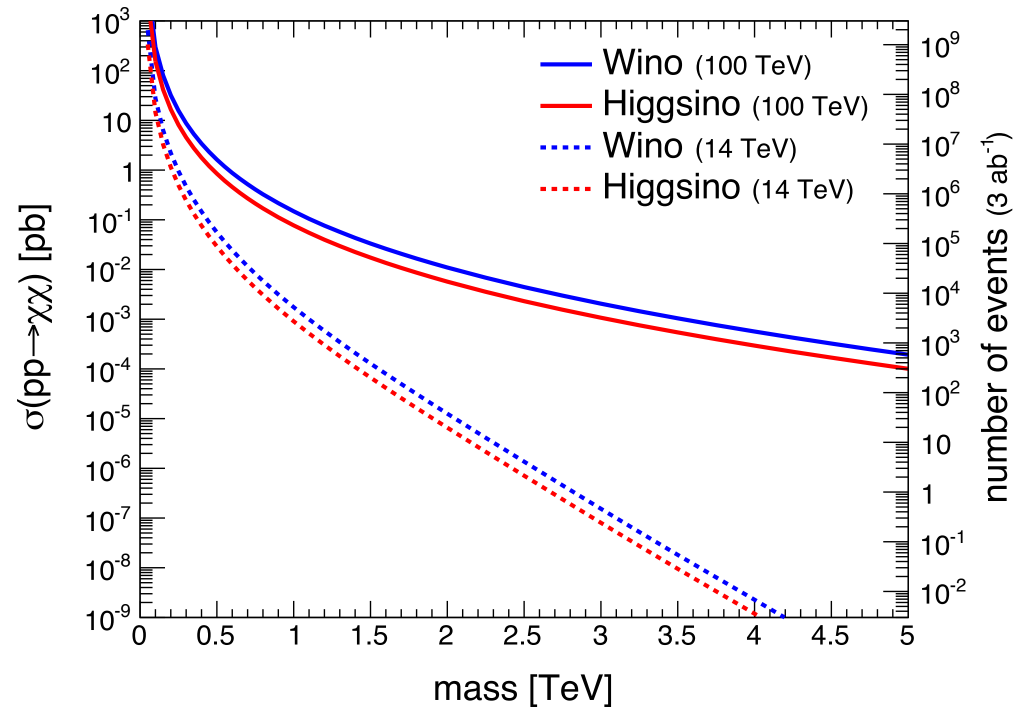
Higgs coupling

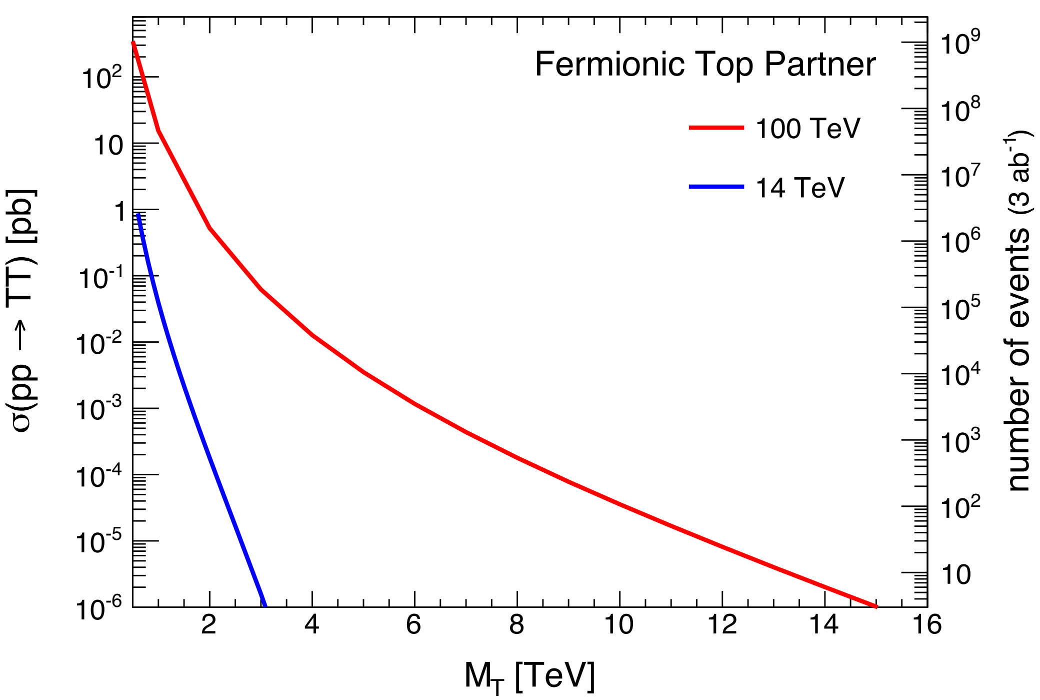


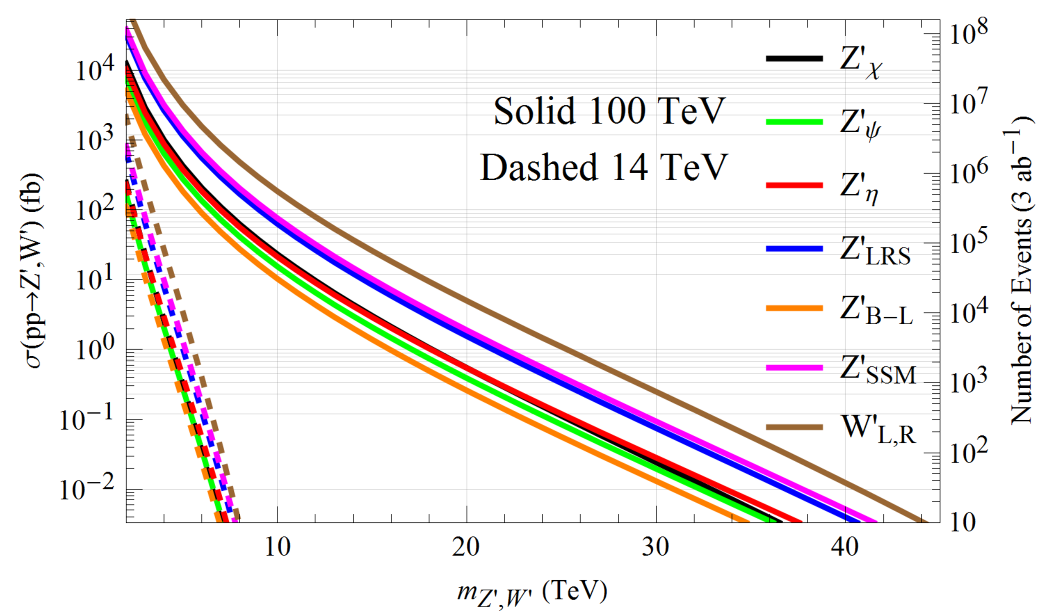
EWPT

100 TeV pp collider, a big step in energy









Status of circular collider studies

- In the past 2 years, many studies of the physics reaches of the circular colliders have been carried out.
  - On both FCC and CEPC/SppC.
- Demonstrated amazing capabilities.
- Preliminary designs made.
- Active efforts in trying to make it happen. Prospect will be clearer in the coming several years.

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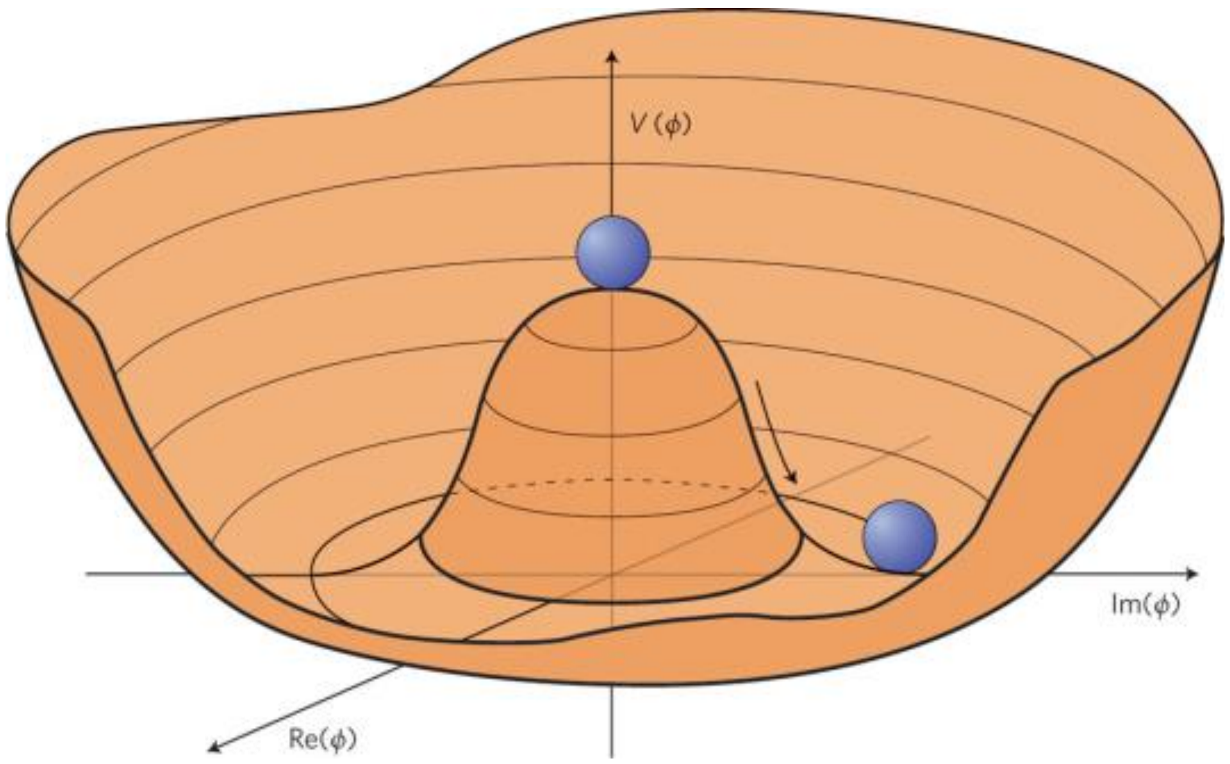
What can we learn?

Nature of electroweak symmetry breaking

“Simple” picture: Mexican hat

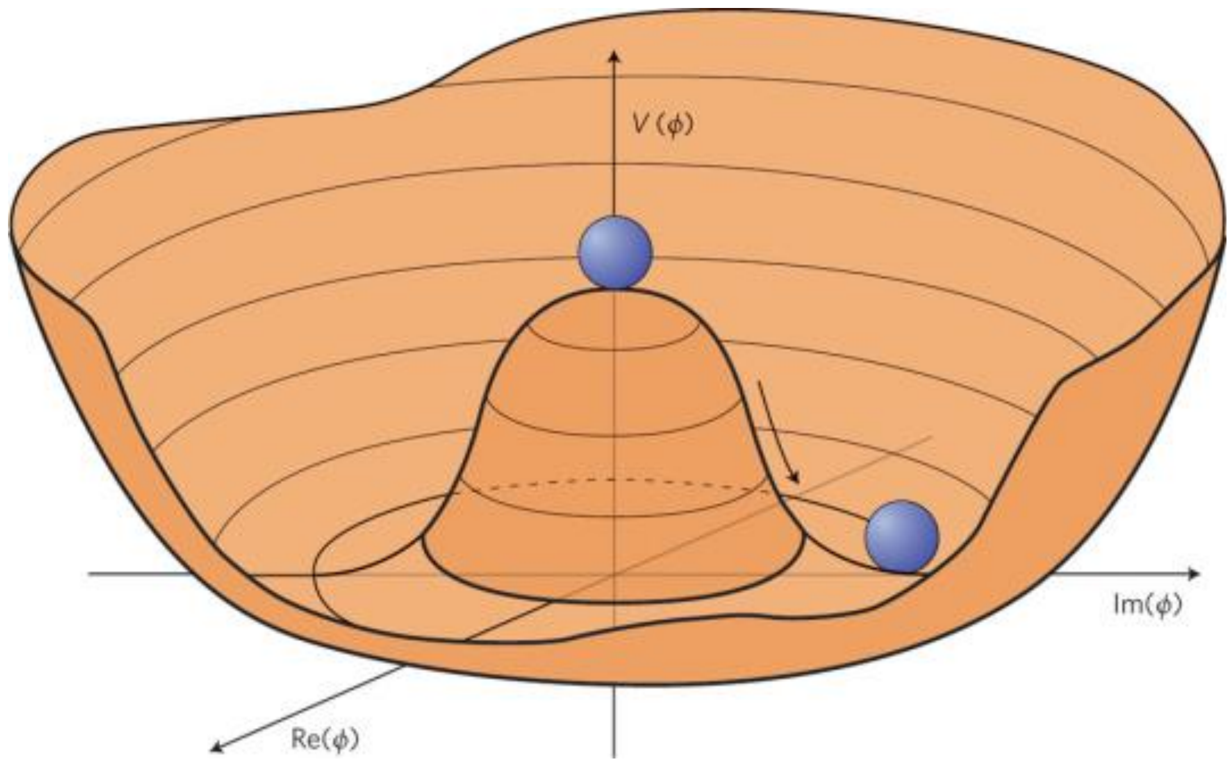


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

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

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

“Simple” picture: Mexican hat



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

However, this simplicity is deceiving.
Parameters not predicted by theory. Need new physics

Probing NP with precision measurements

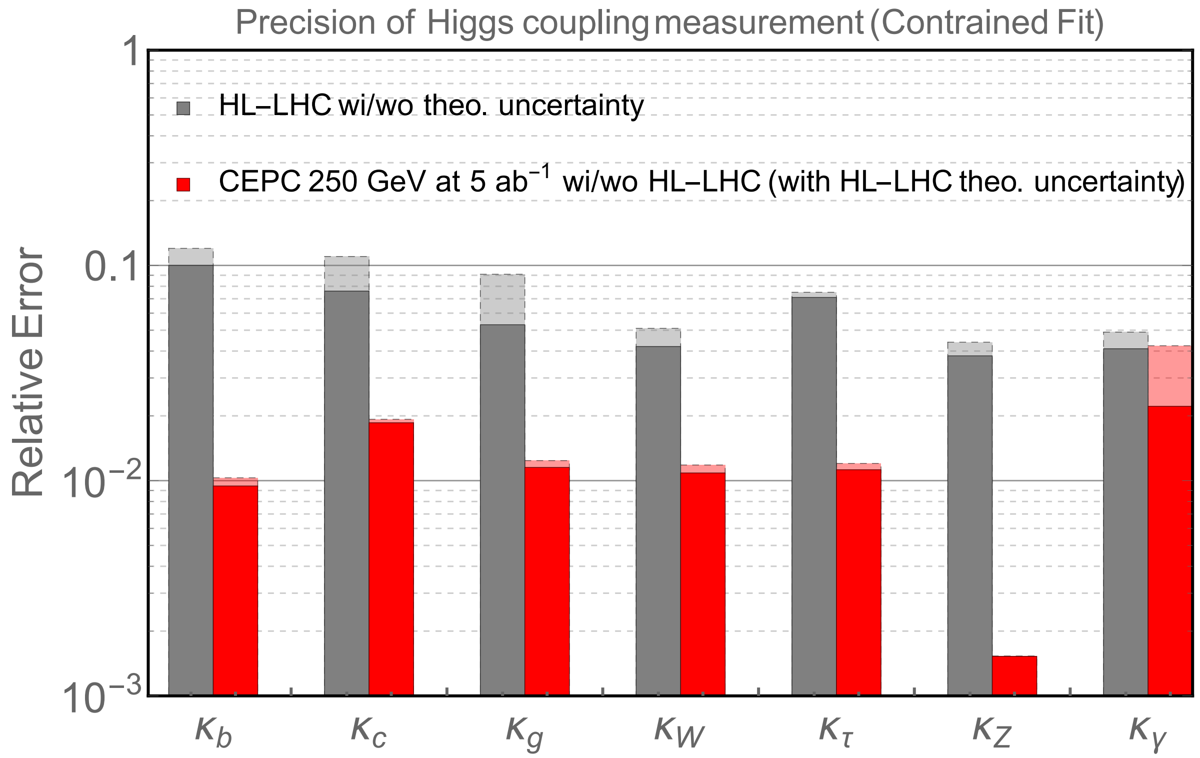
- $e^+ e^-$ Higgs factories: clean environment, good for precision.
- We are going after deviations of the form

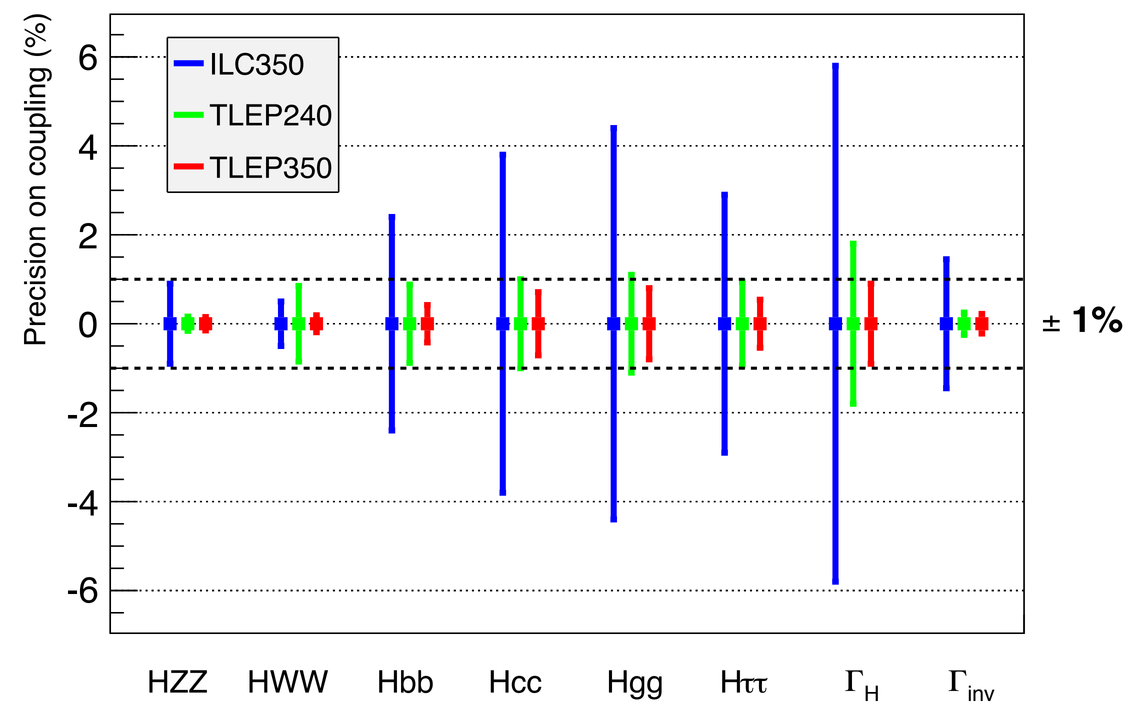
$$\delta \simeq c \frac{v^2}{M_{\mathrm{NP}}^2}$$

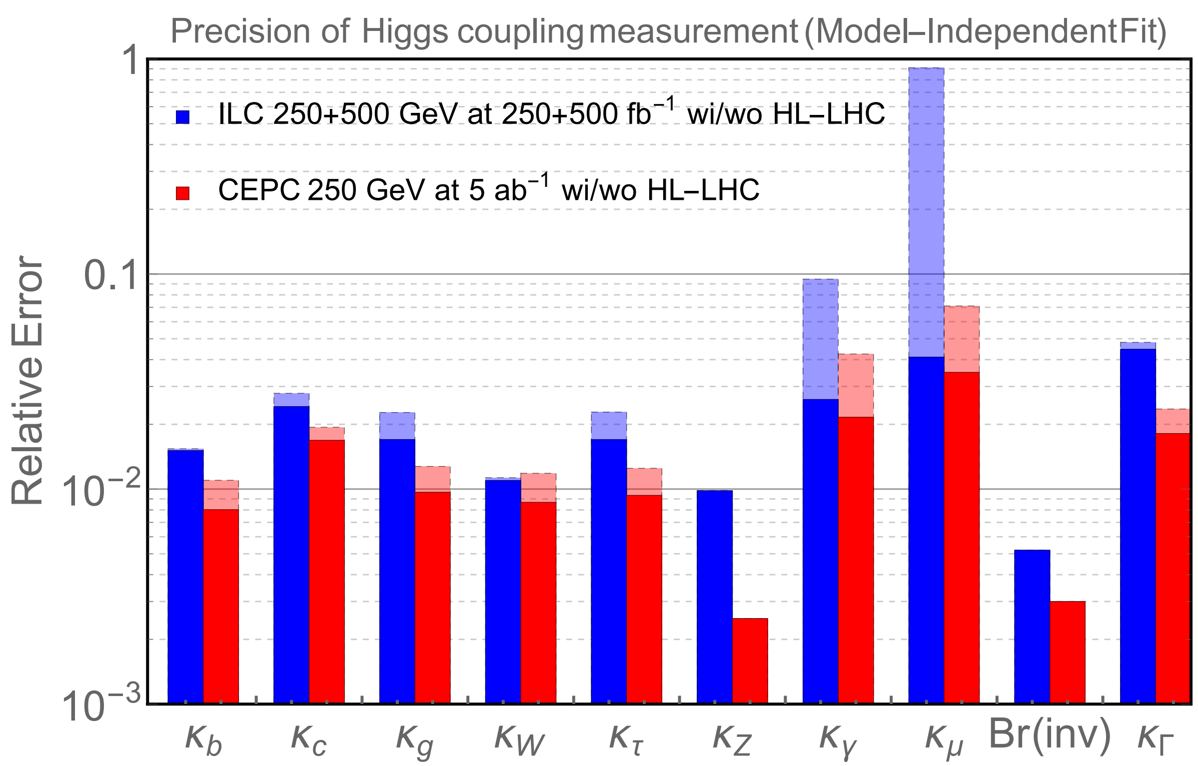
M_{NP} : mass of new physics
c: $O(1)$ coefficient

- Take for example the Higgs coupling.
  - LHC precision: a few-10% ⇒ sensitive to $M_{NP} < \mathrm{TeV}$
  - However, $M_{NP} < \mathrm{TeV}$ also probed by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

Measuring Higgs very well at Higgs factories

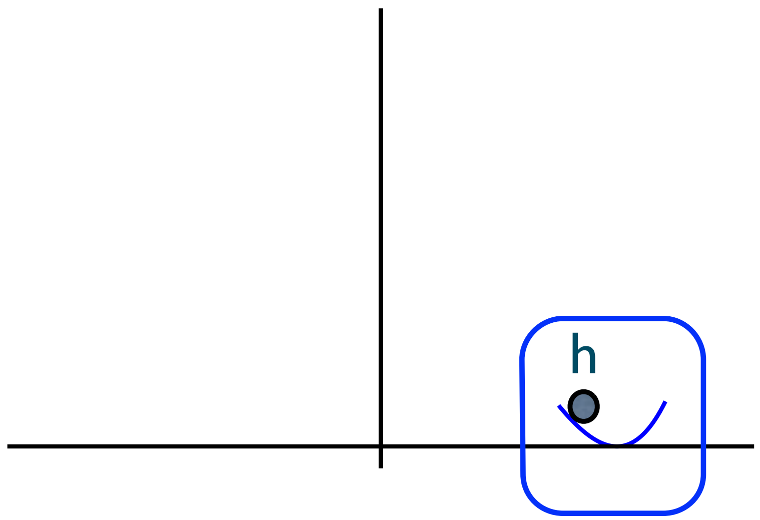






Total width.
HZ coupling to sub-percent level.
Many couplings to percent level.

Not even sure about "Mexican hat".



What we know now

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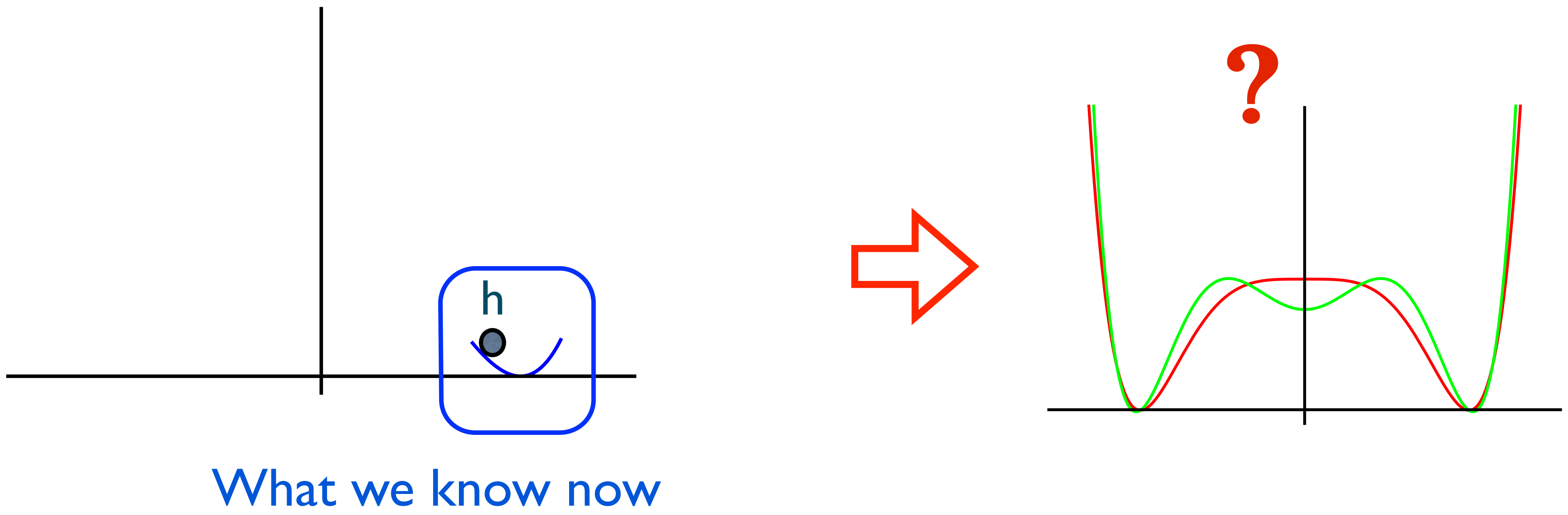
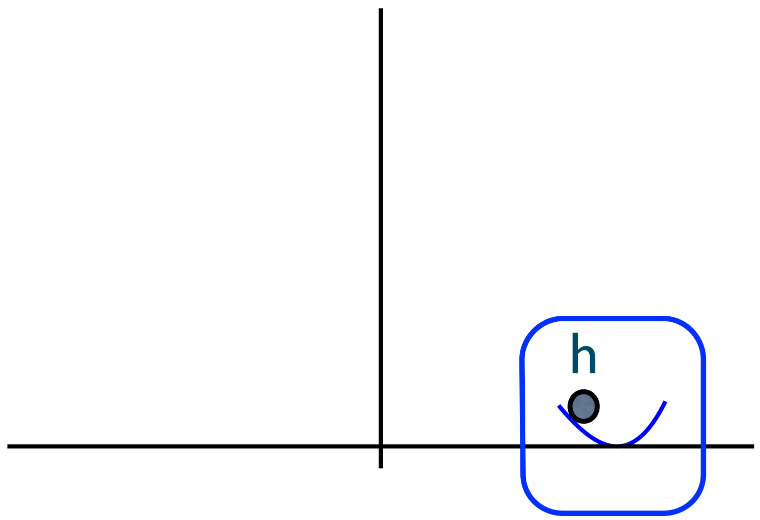


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Is the EW phase transition first order?

Not even sure about "Mexican hat".



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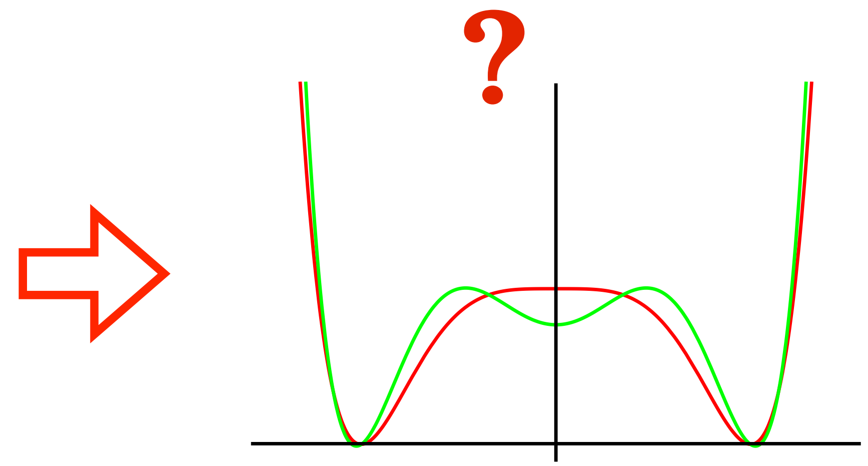

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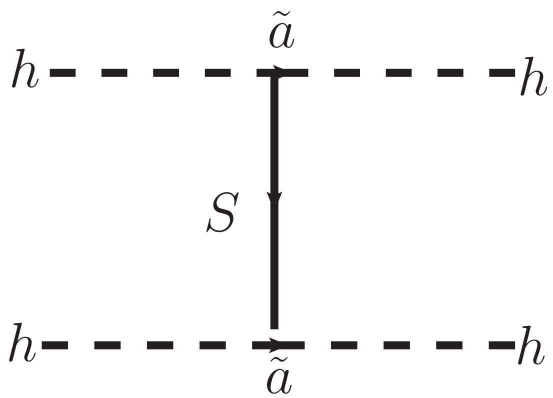
Is the EW phase transition first order?

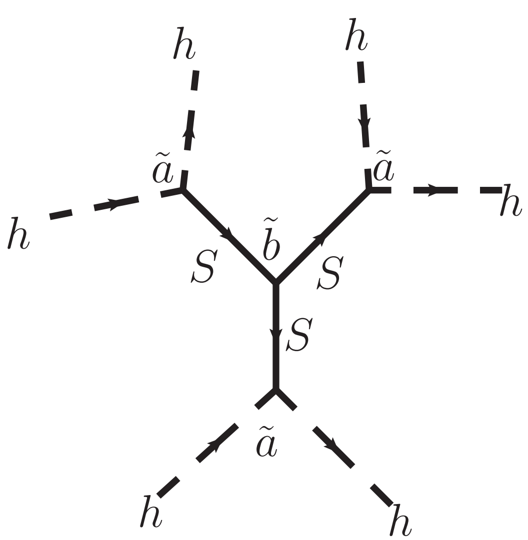
LHC can not distinguish these definitively.

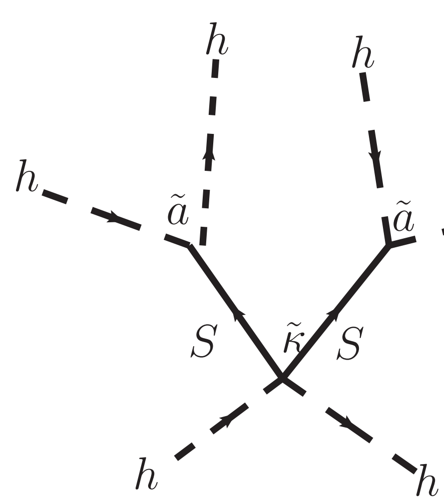
Simple example: Generic singlet model

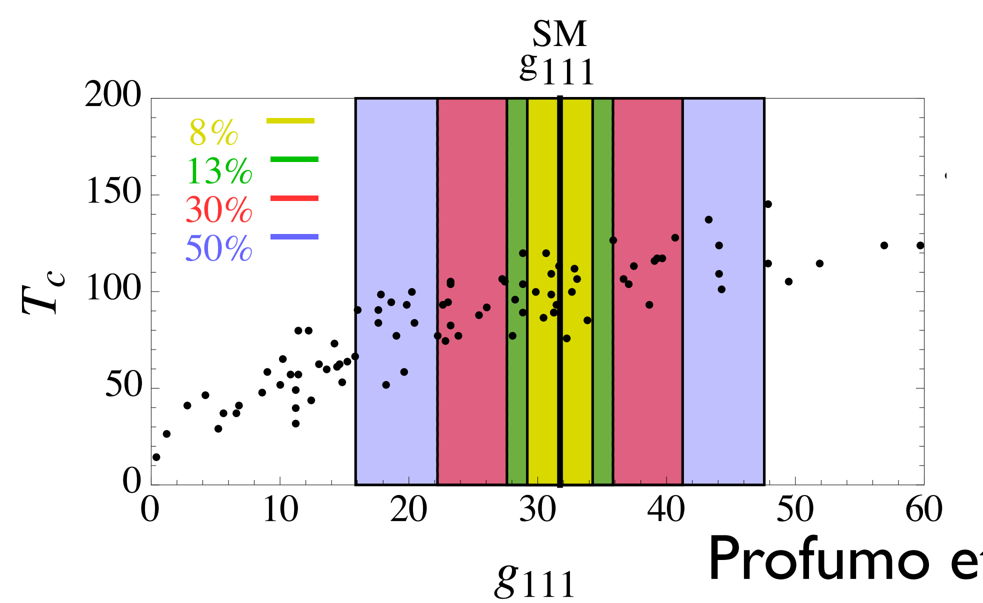
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



shift in h-Z coupling > 0.5%



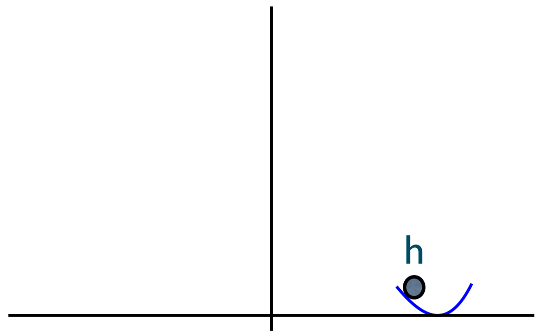


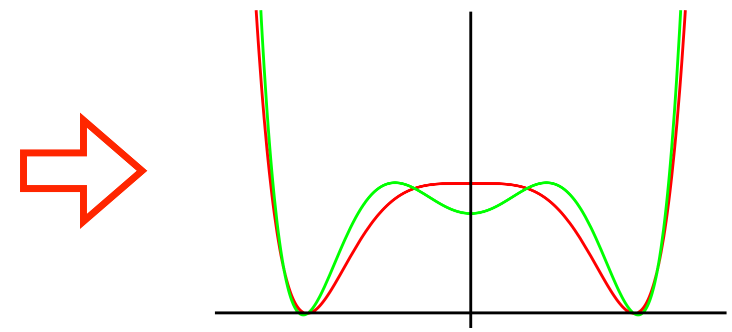


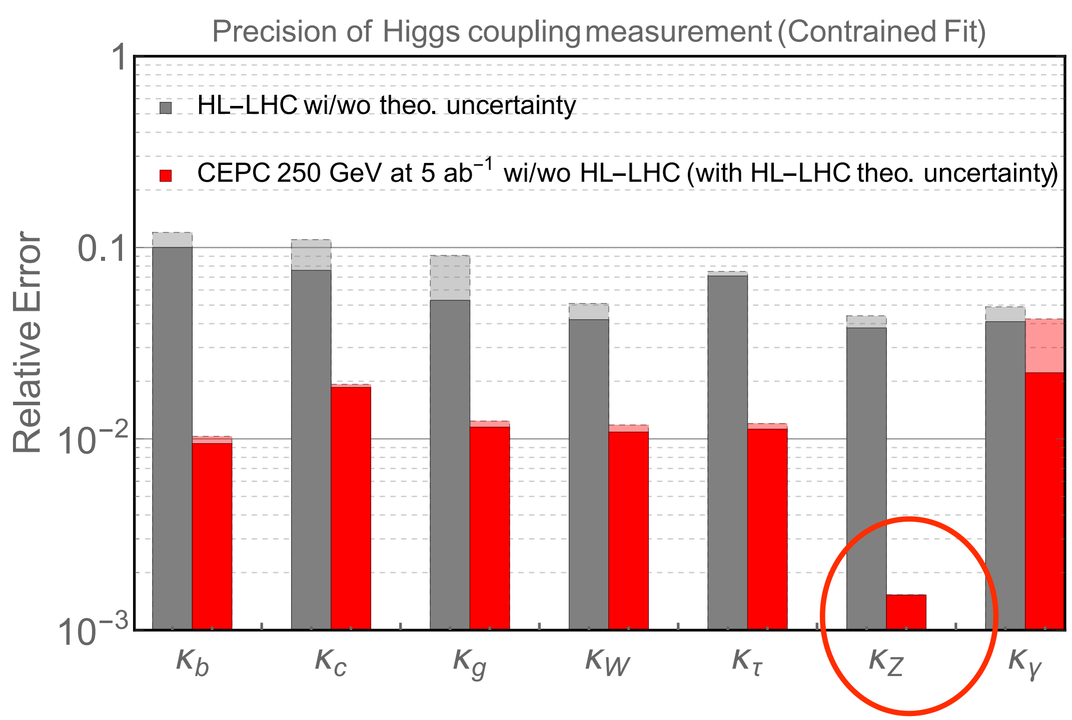
Profumo et al

O(1) devidation in triple Higgs coupling

Nature of EW phase transition







Triple Higgs coupling at 100 TeV pp collider
30 ab^{-1}

$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh+\text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh+\text{jet} \end{cases}$$

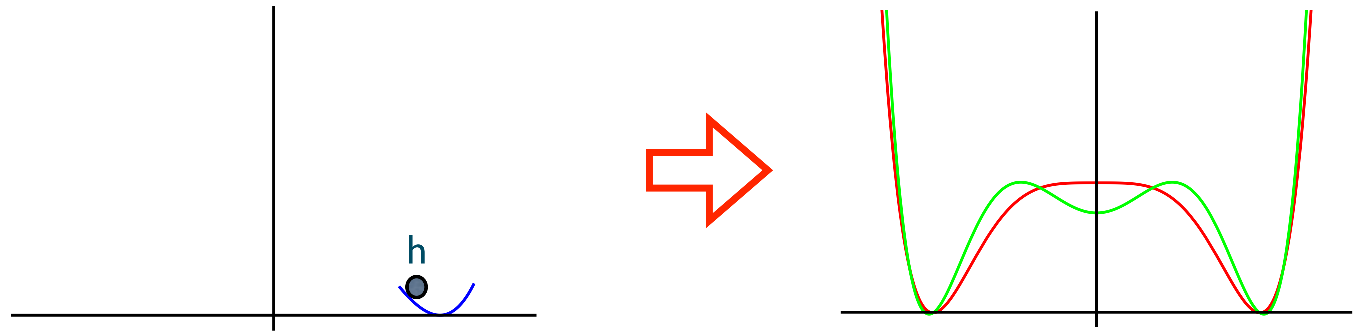
Barr, Dolan, Englert, de Lima, Spannowsky

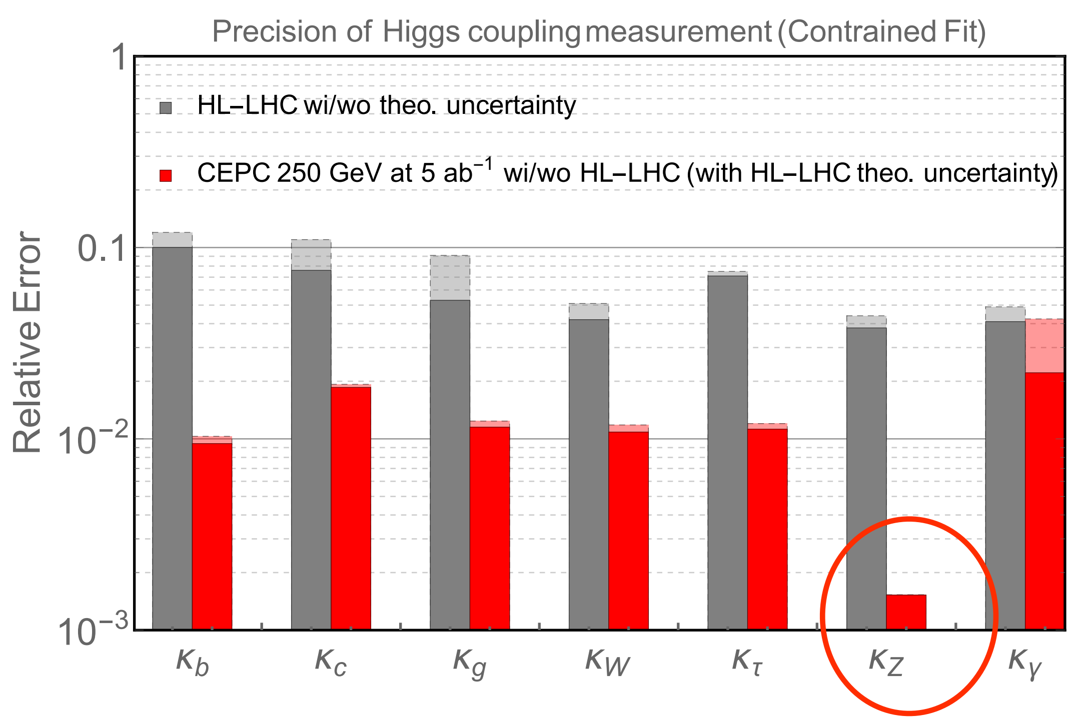
Shift in h-Z coupling > 0.5%

Order 1 deviation in triple Higgs

} Both within the reach

Nature of EW phase transition





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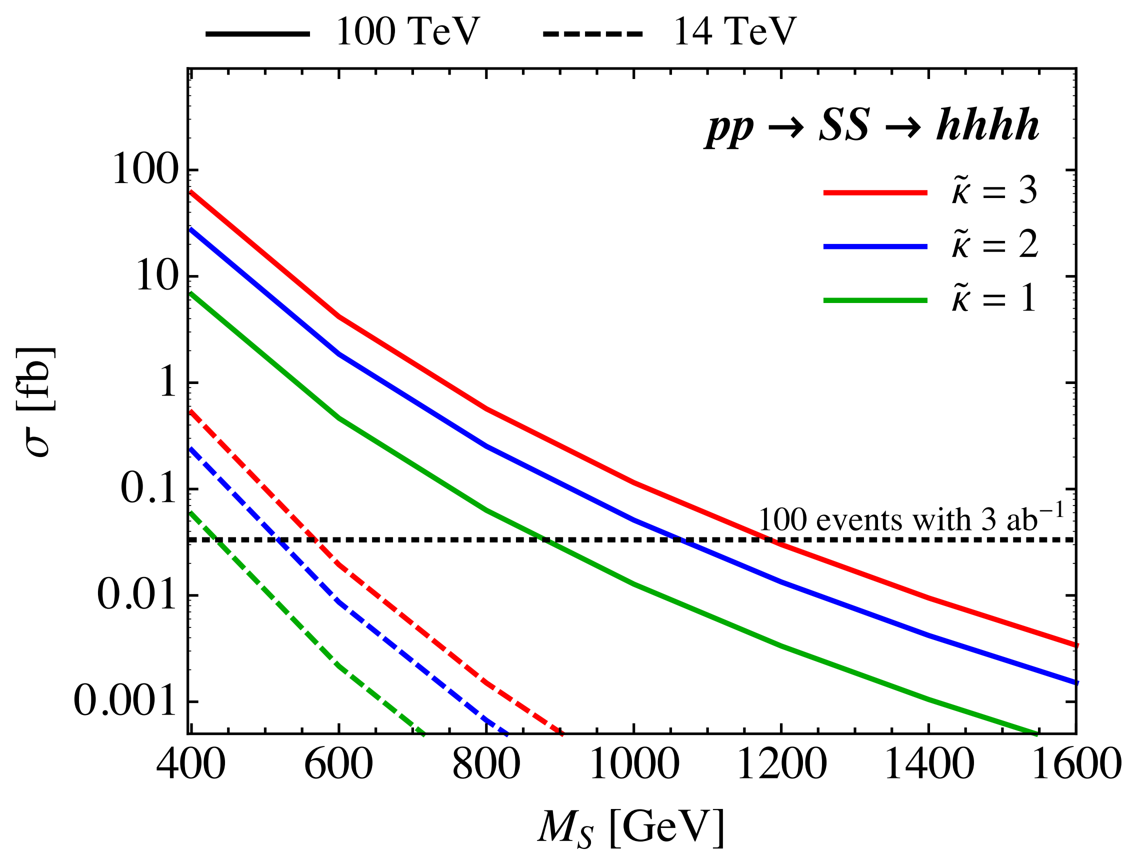
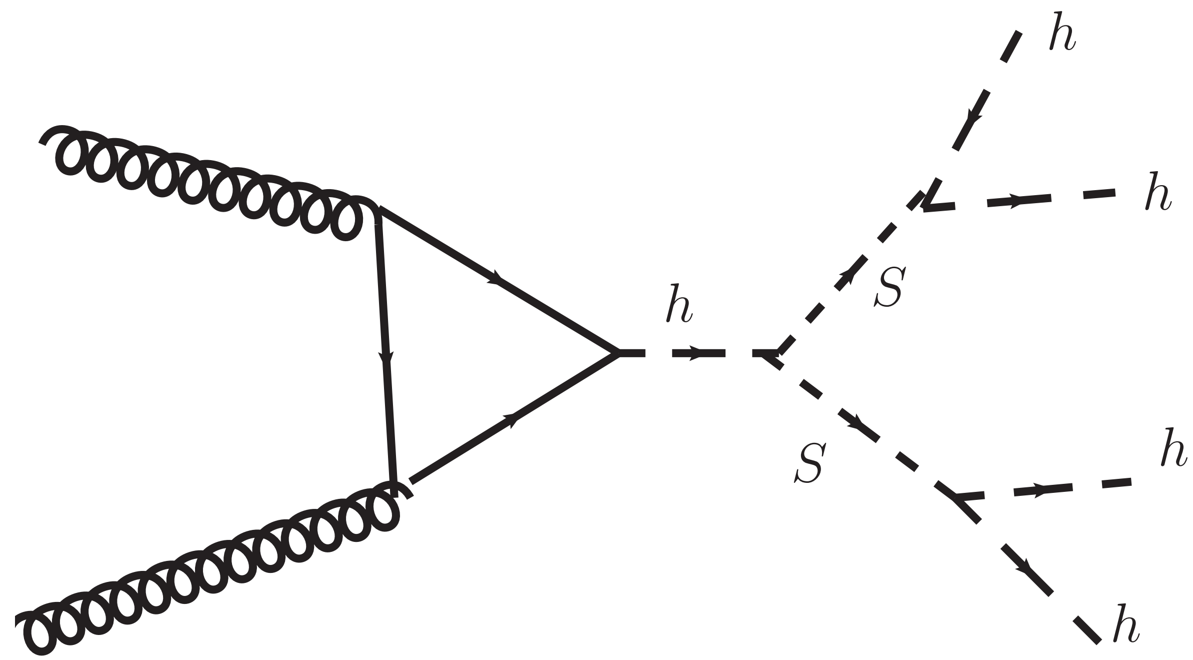
Singlet search at 100 TeV

See Andrea Tesi's talk





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

Singlet search at 100 TeV

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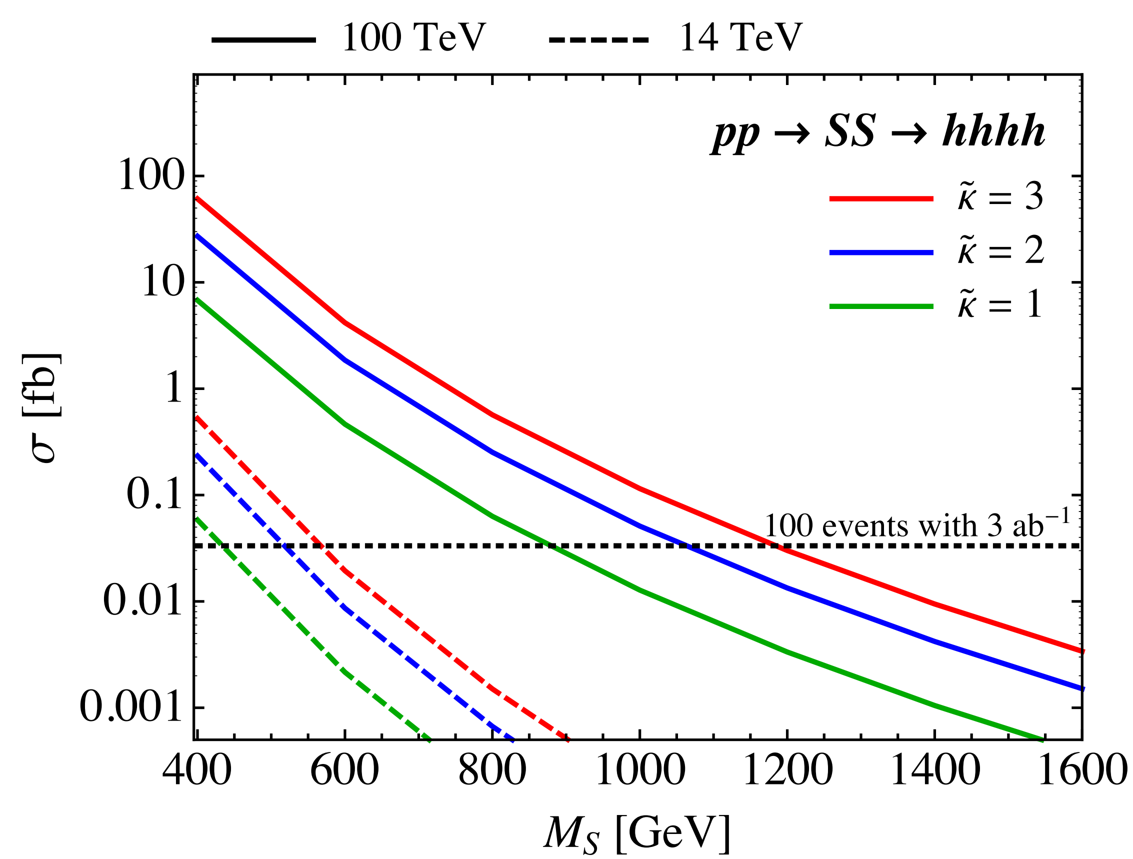
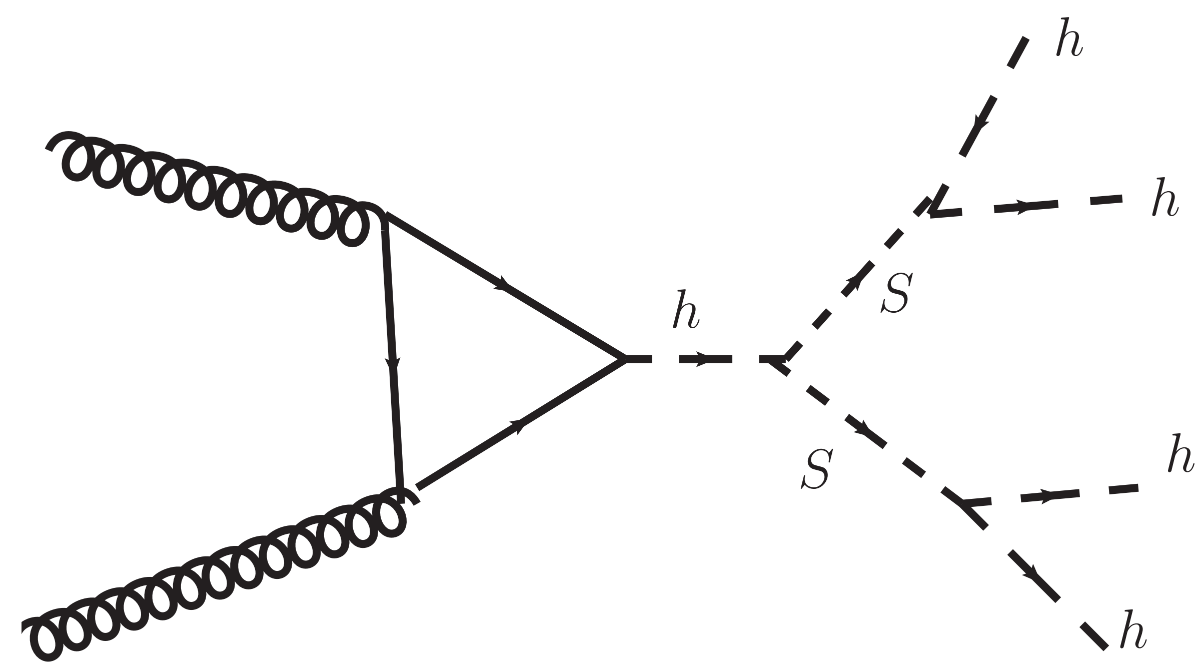


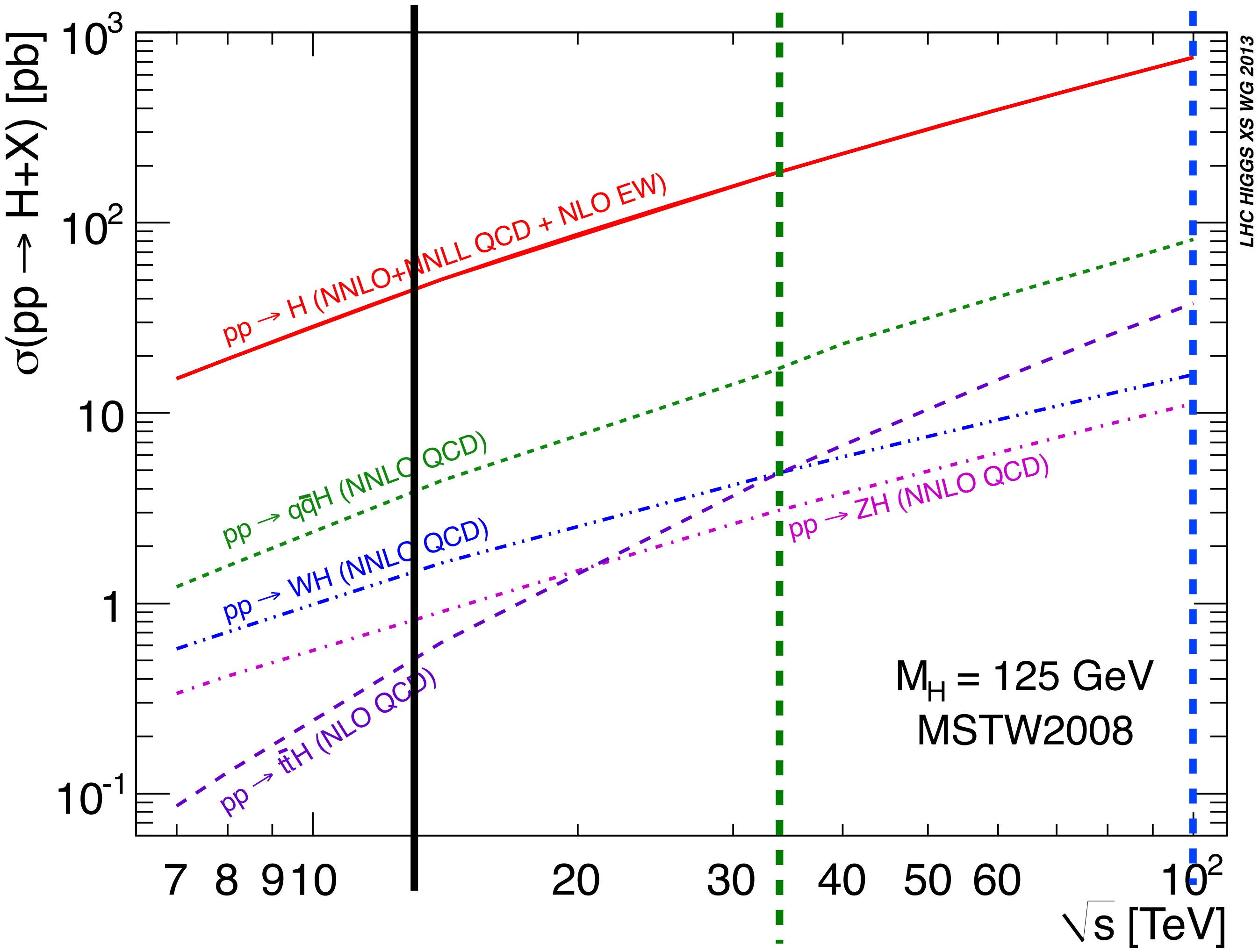


- 4 Higgs final state with decent rate.

- Good discovery potential.

Combination of Higgs factory and 100 TeV pp collider can go very long way in understanding EWSB

More Higgs physics at hadron collider



# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

33 TeV > 500 million

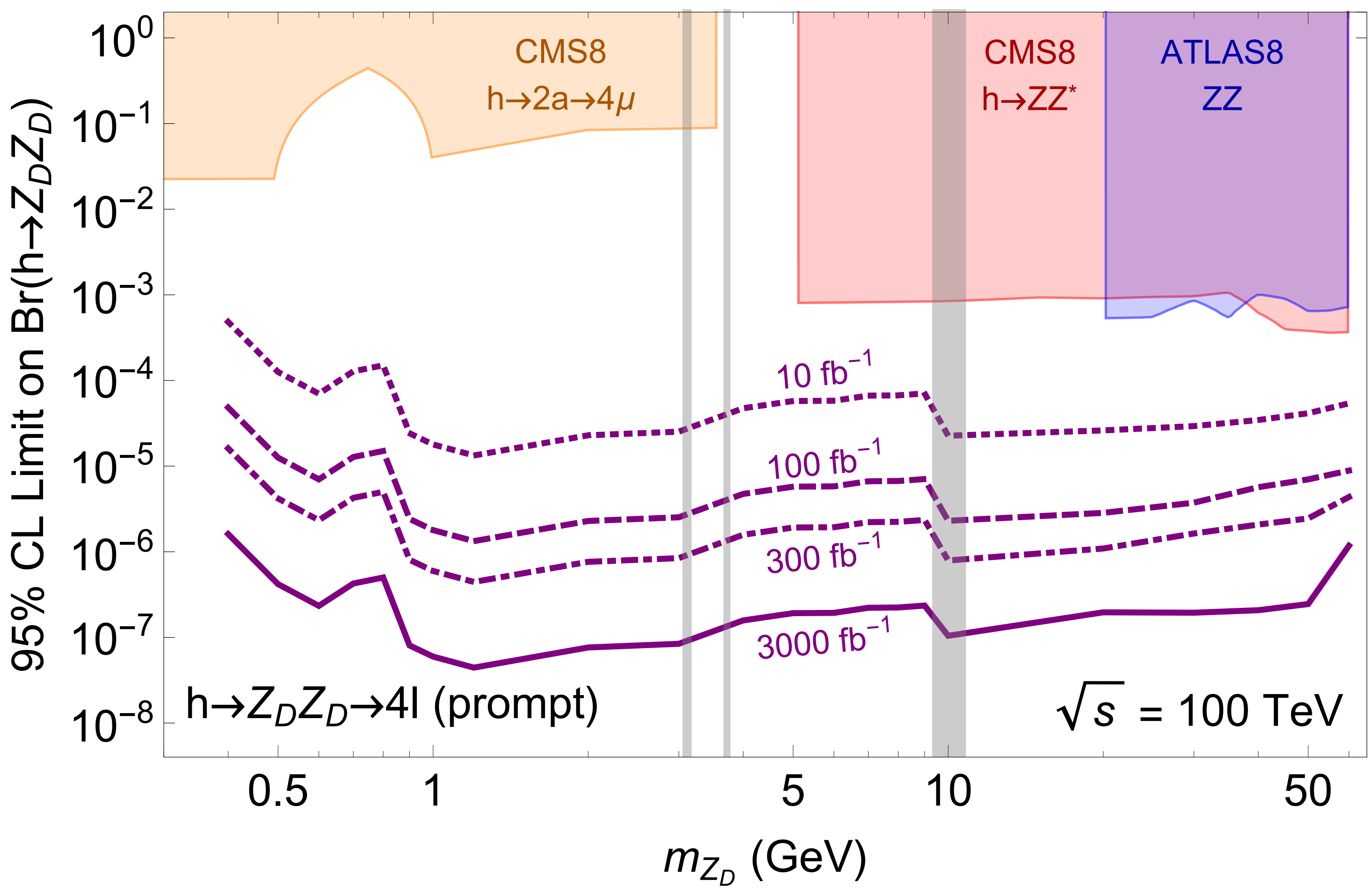
14 TeV > 150 million

In comparison, O(million) Higgs at Higgs factories

Can look for very rare and distinct Higgs signal.

New physics Higgs rare decays

dark photon



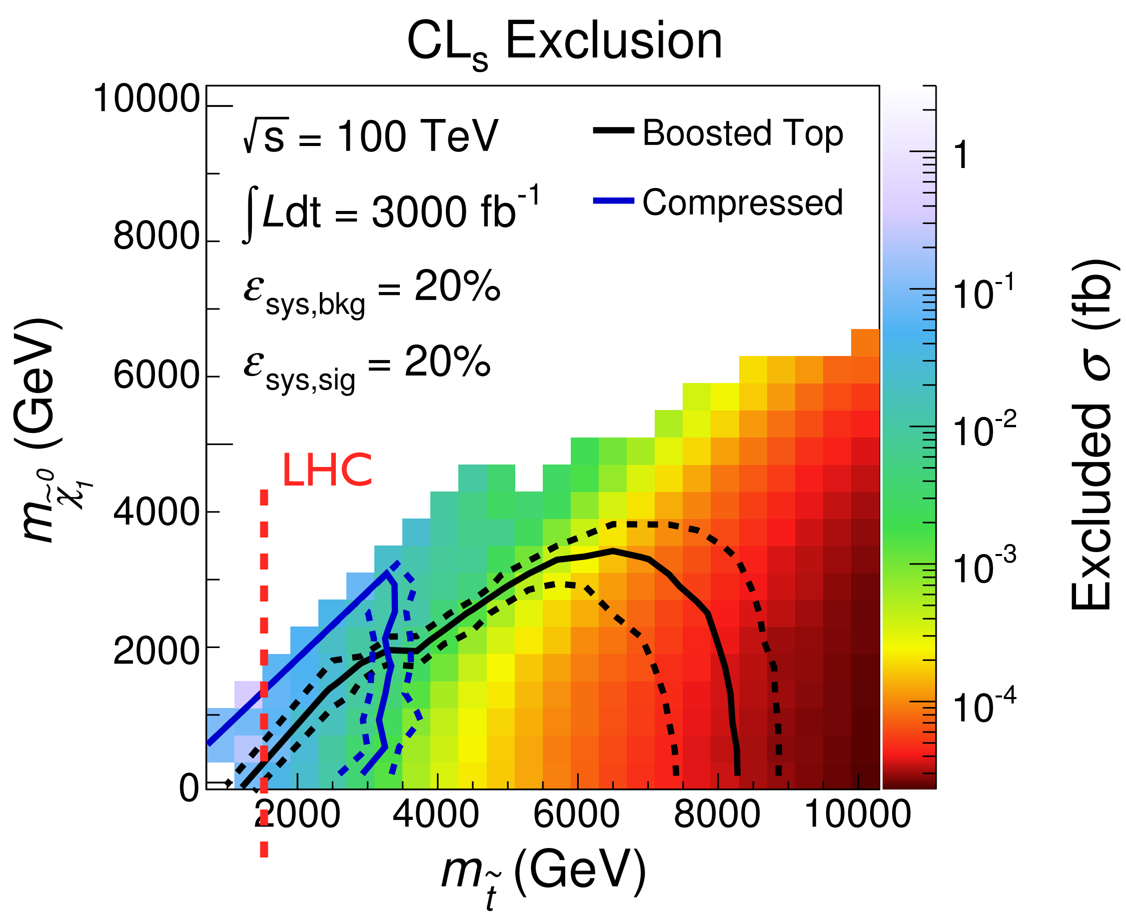
Curtin, Gori, Shelton

Certainly, there are more examples.

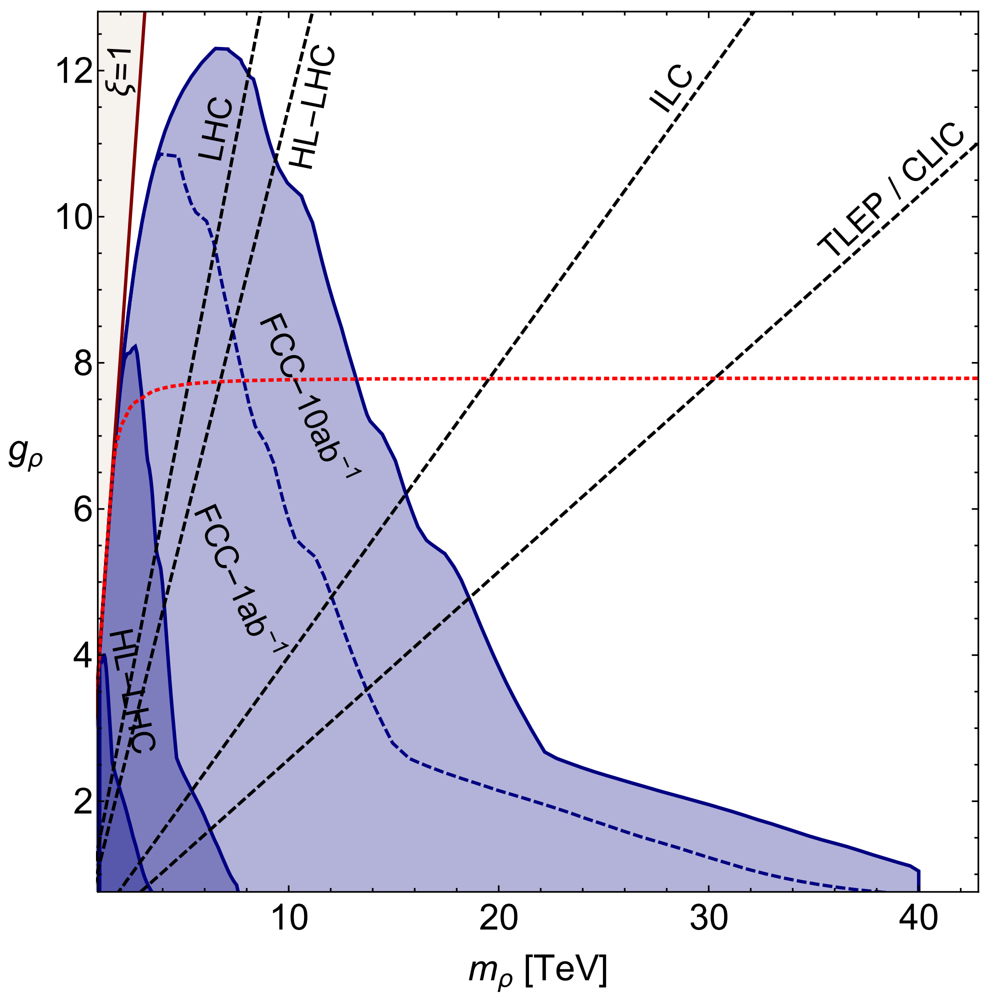
Naturalness

Test naturalness at 100 TeV collider

Cohen et. al., 2014



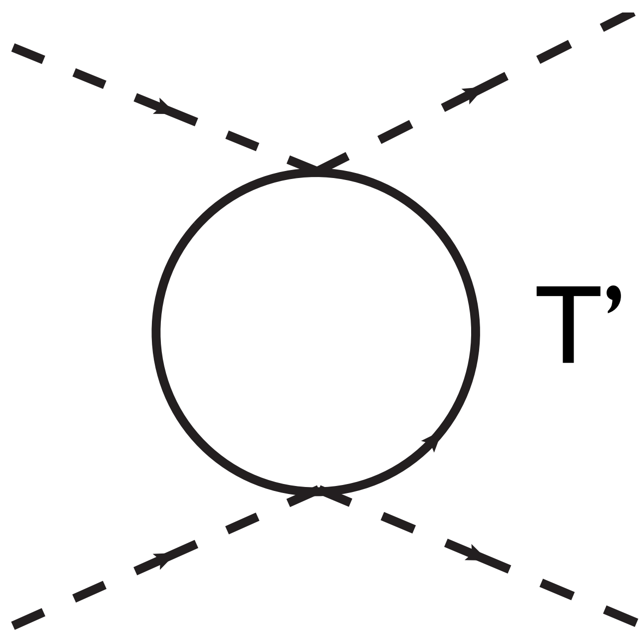
Pappadopulo, Thamm, Torre, Wulzer, 2014



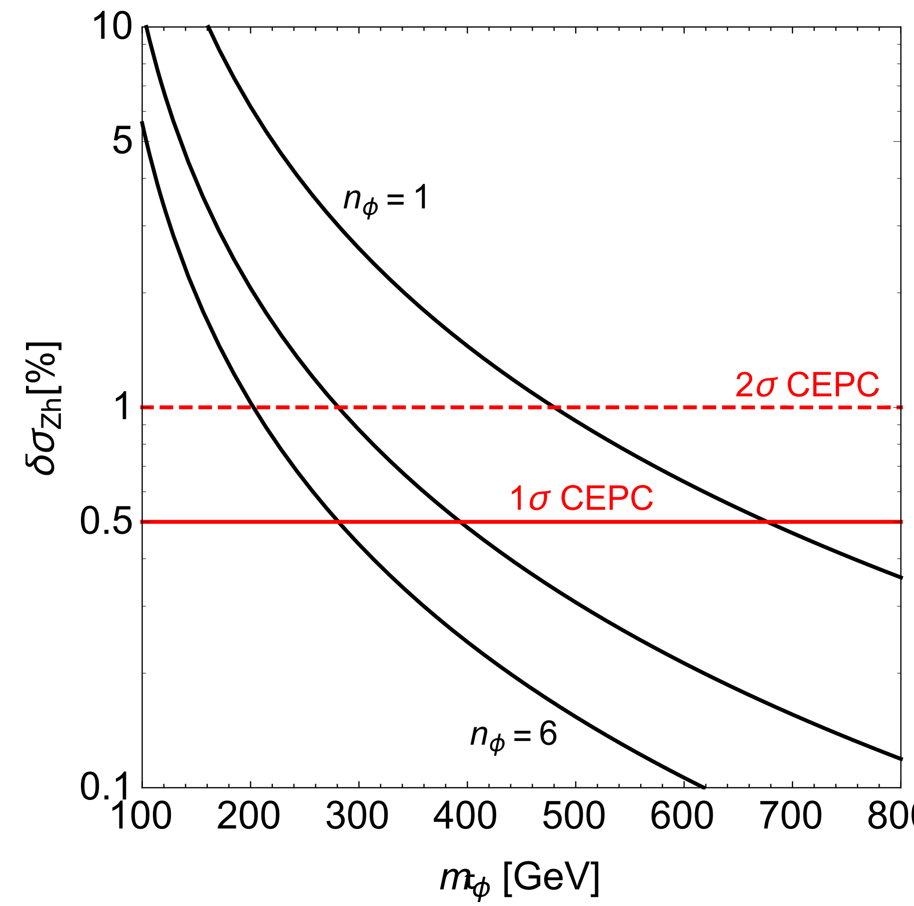
- tune proportional to $(m_{NP})^2$.
  - Much better test than LHC, by orders of magnitude!
  - Potential for discovery (would be a victory for naturalness).

Neutral naturalness

Twin Higgs. Chacko et al. Talk by Craig



Top partner only couple to Higgs.
Wavefunction renormalization
Induce shift in Higgs coupling.



Craig, Englert, McCullough, 2013

- LHC reach poor. Theory can be completely natural.
- Higgs factory can test this.

Need to consider UV completions for neutral top partners

- Induce measurable shifts in Higgs couplings, precision observables.
- UV completions can be directly probed at 100 TeV.
- Combination of precision measurement and direct search at 100 TeV pp collider can test naturalness.

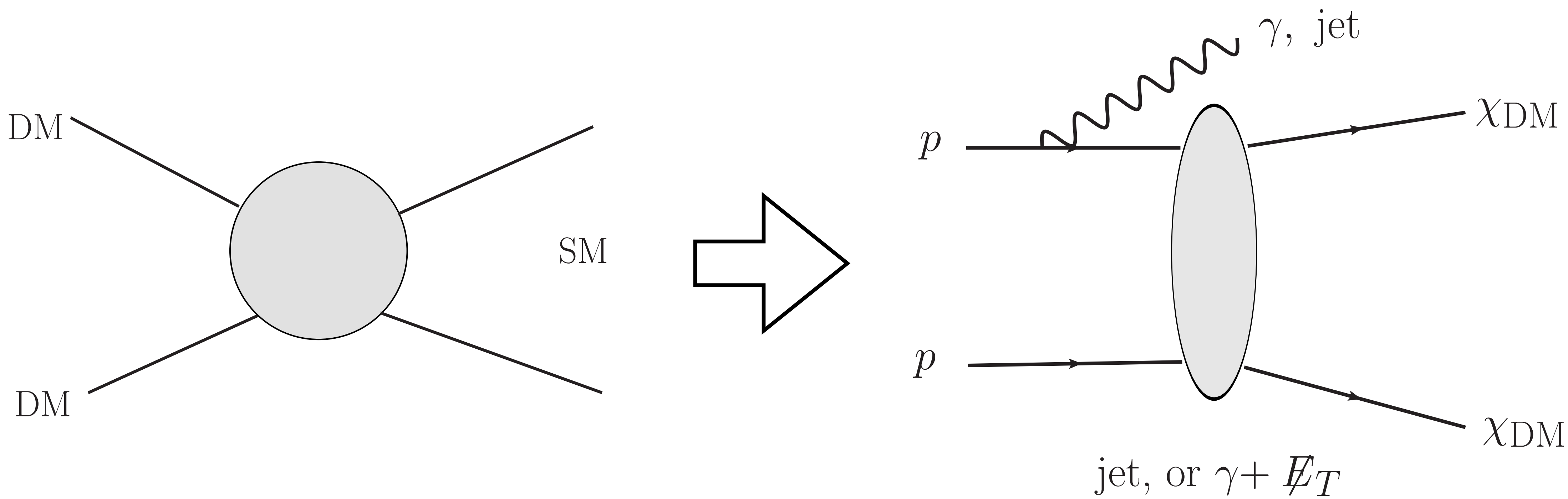
Talk by David Curtin

Testing WIMP Dark Matter

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

Basic channel

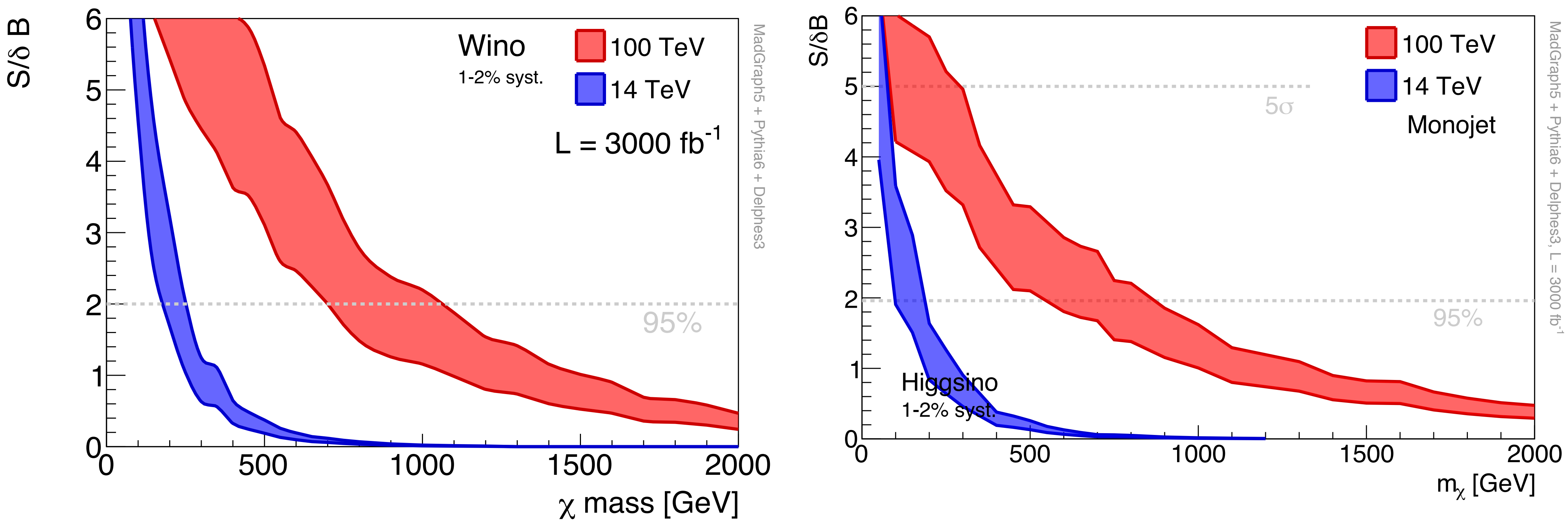
- pair production + additional radiation.



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

- Have become "Standard" LHC searches.

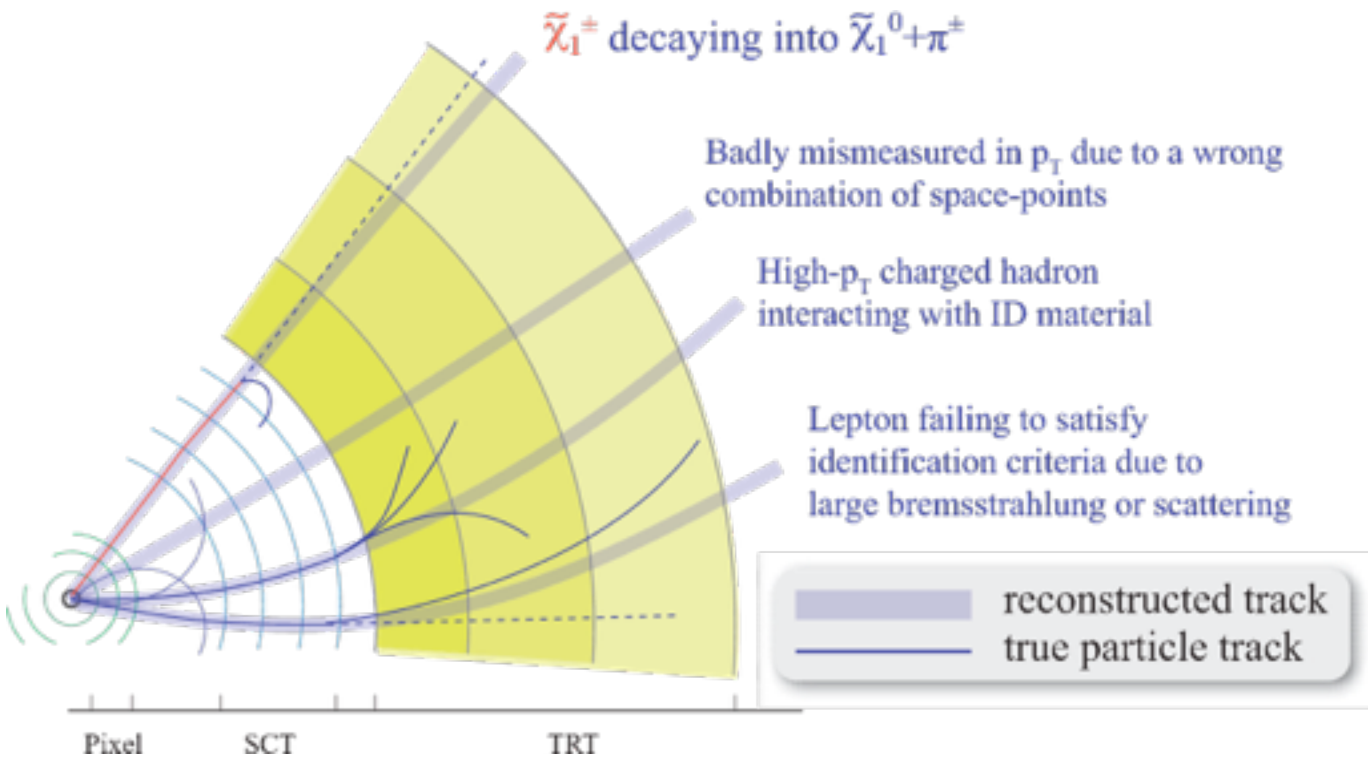
Dark matter (mono-jet)



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

- LHC only coverage very limited. Rate, systematics...
- 100 TeV pp collider can probe the “bulk” of WIMP parameter space.

Very degenerate, disappearing track.



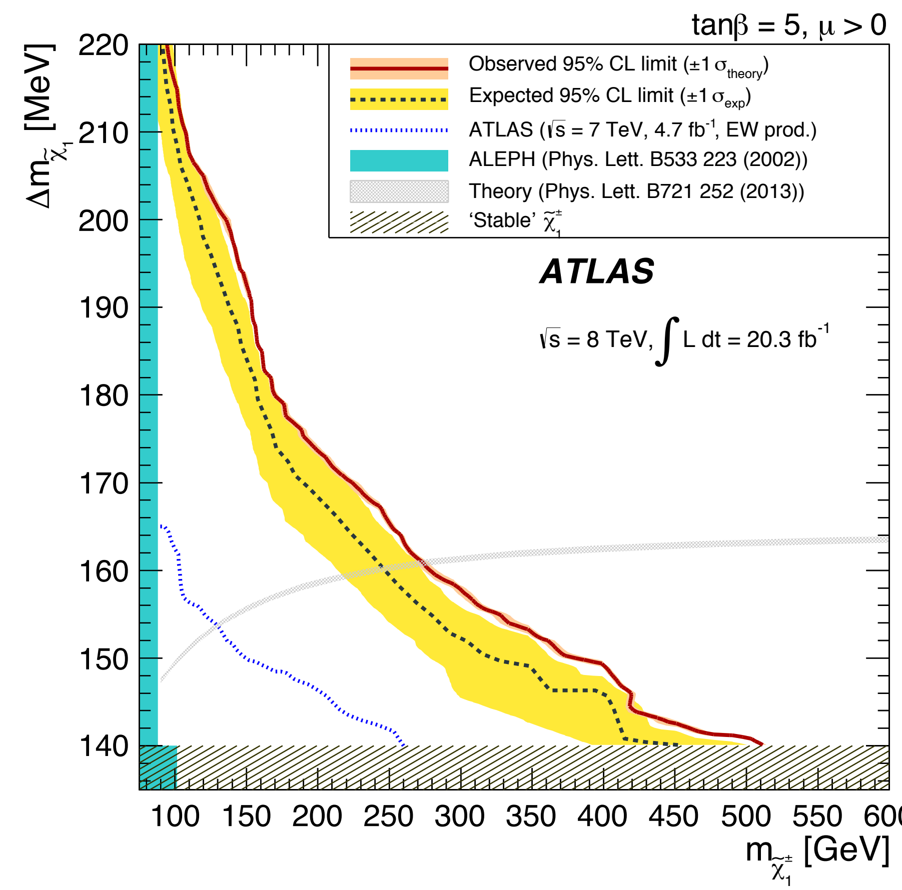
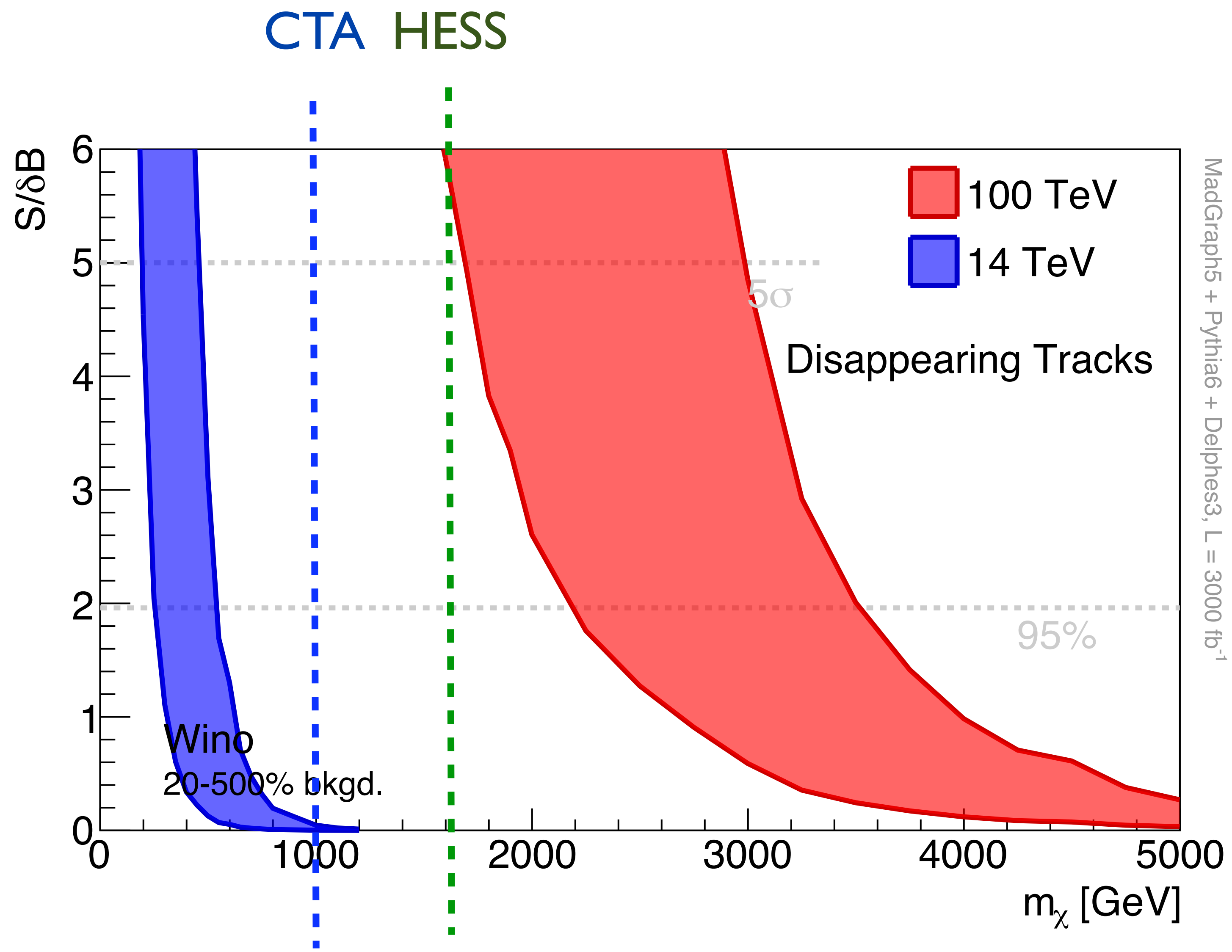


Figure from ATLAS disappearing track search twiki

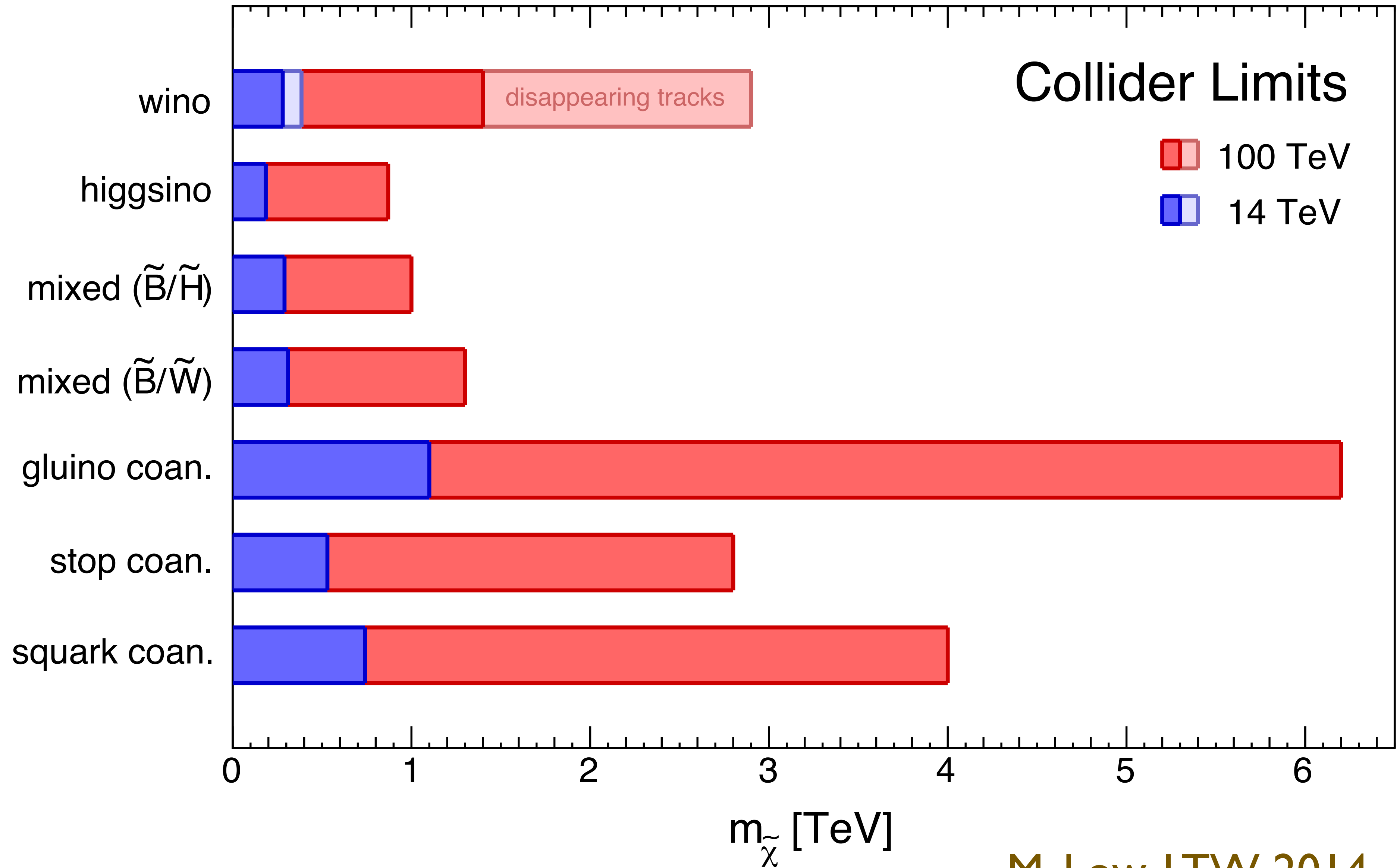
- Main decay mode $\chi^{\pm} \to \pi^{\pm} + \chi^{0}$.
- Charge track ≈ 10(s) cm
- Impressive limit at the LHC already.

Wino



– “Completely cover” the wino parameter space.

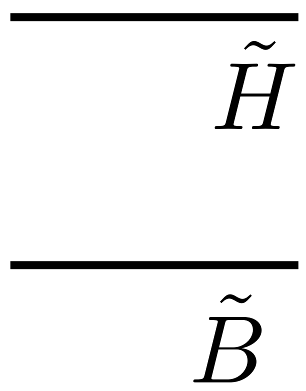
Mono-jet

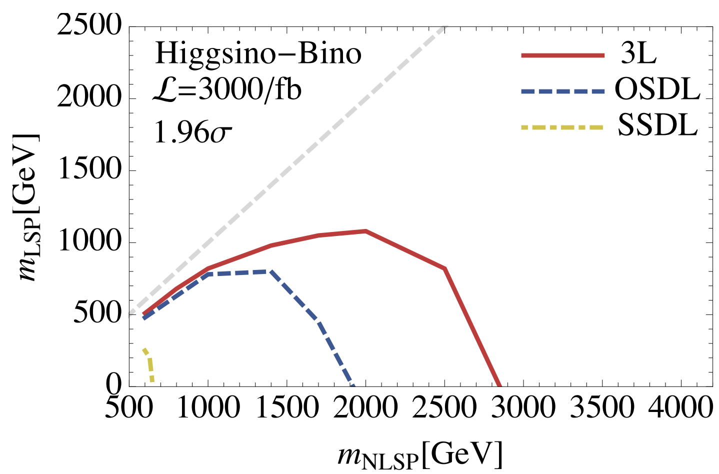


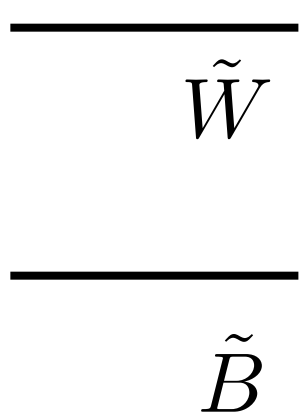
M. Low, LTW 2014

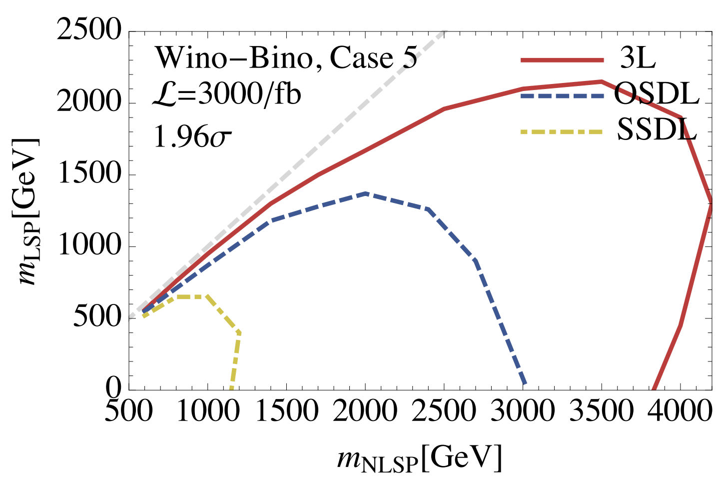
$$M_{\rm WIMP} \leq 1.8\ {\rm TeV}\ \left(\frac{g^2}{0.3}\right)$$

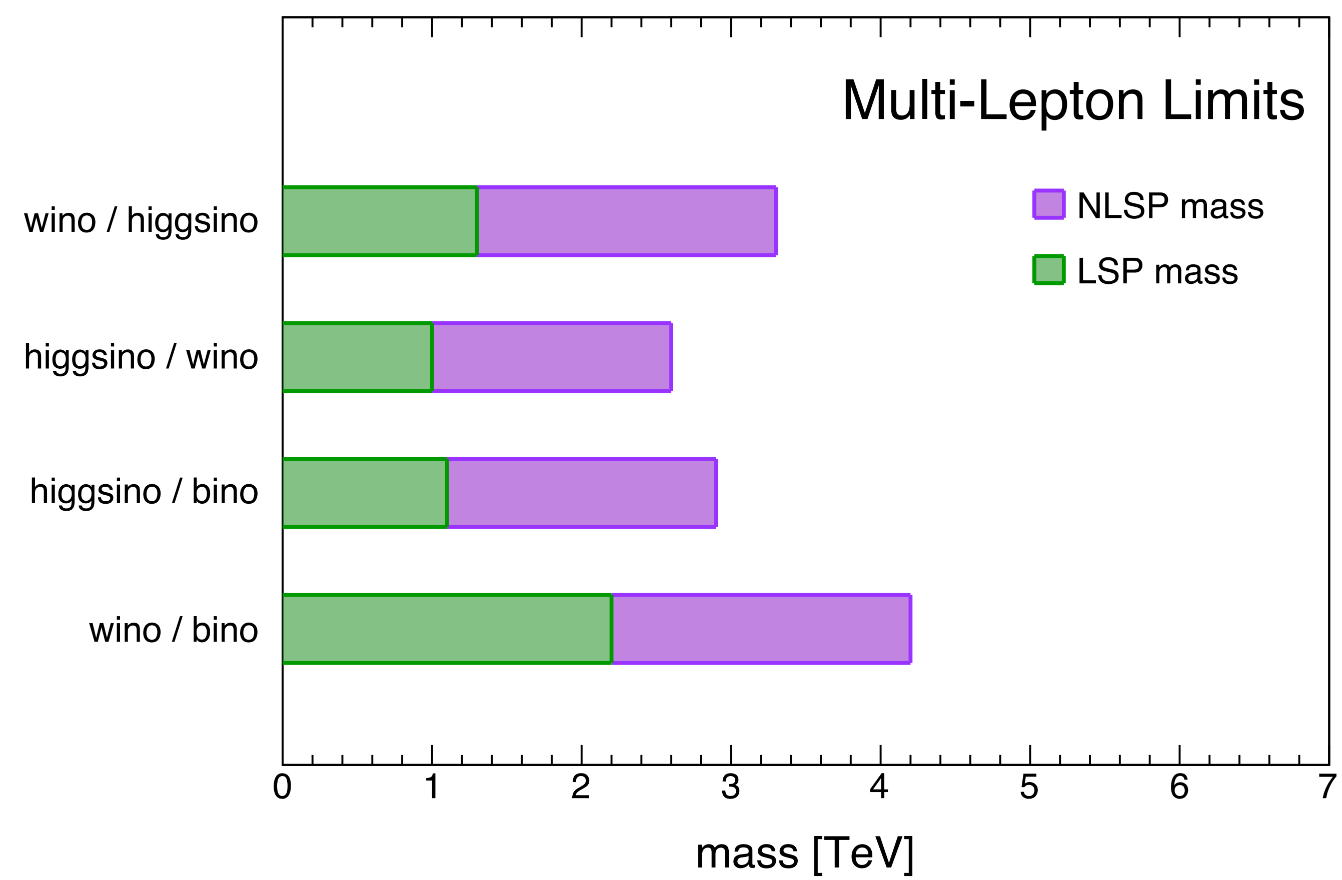
With cascade decays









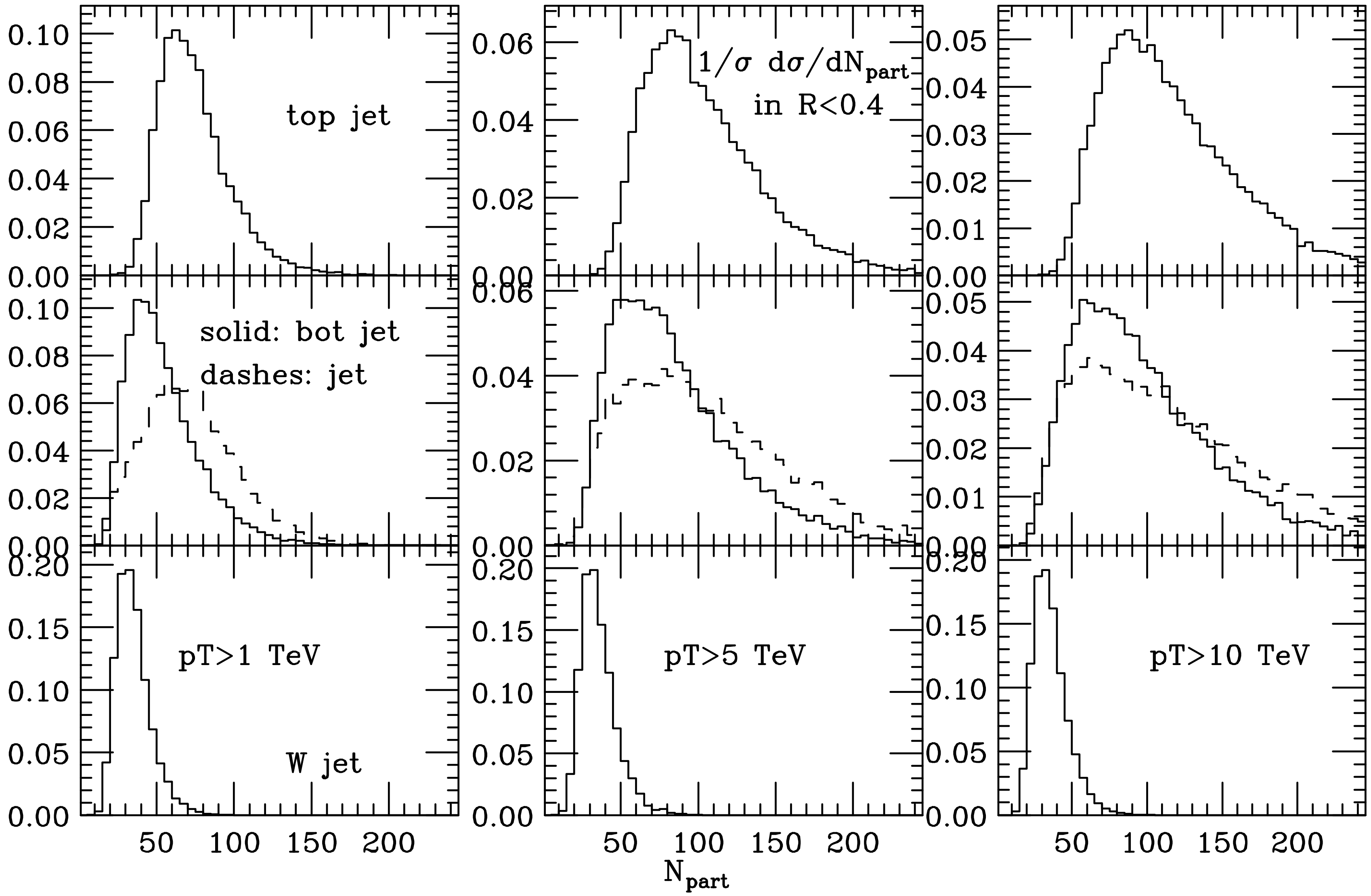


Gori, Jung, Wang, Wells, 2014

Decay ⇒ leptons ⇒ stronger limits

More novelties at a 100 TeV collider

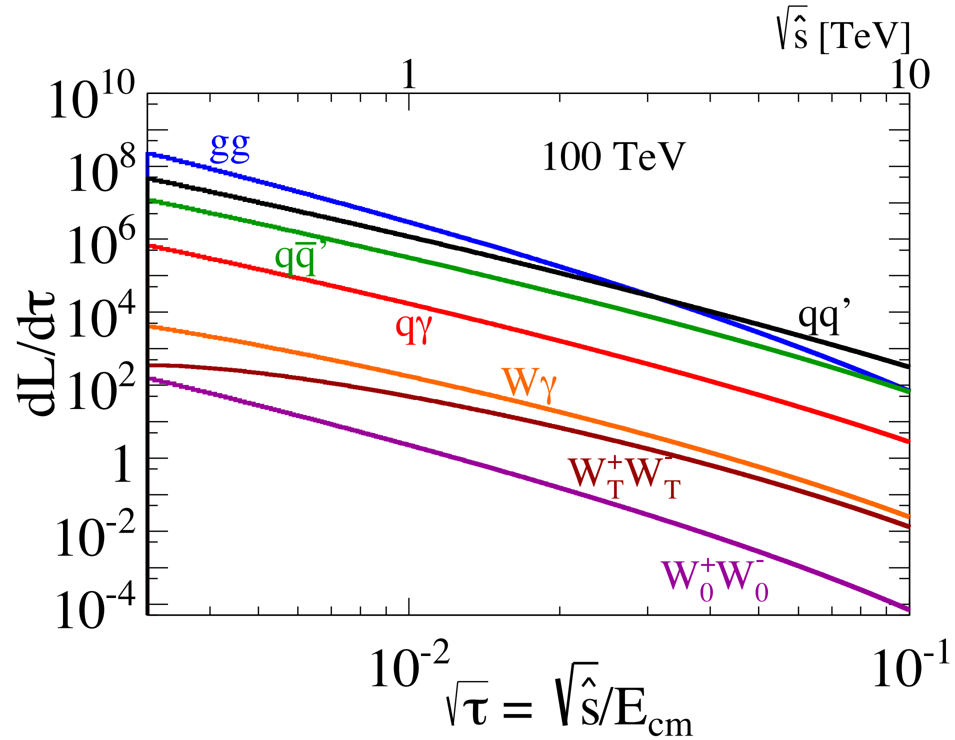
- Bigger, messier jets.

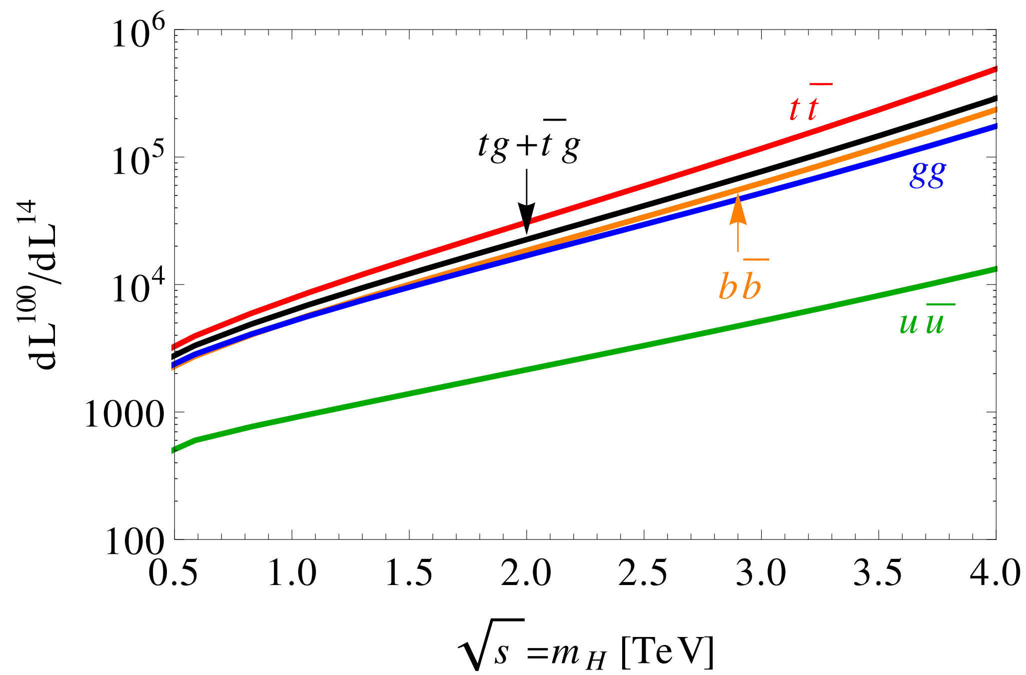


LHC triggered a revolution in jet technology.
100 TeV pp collider demands more!

More novelties at a 100 TeV collider

- SM EW scale particles become very like.
- W/Z/t/h
  - Treating them as part of the "PDF".





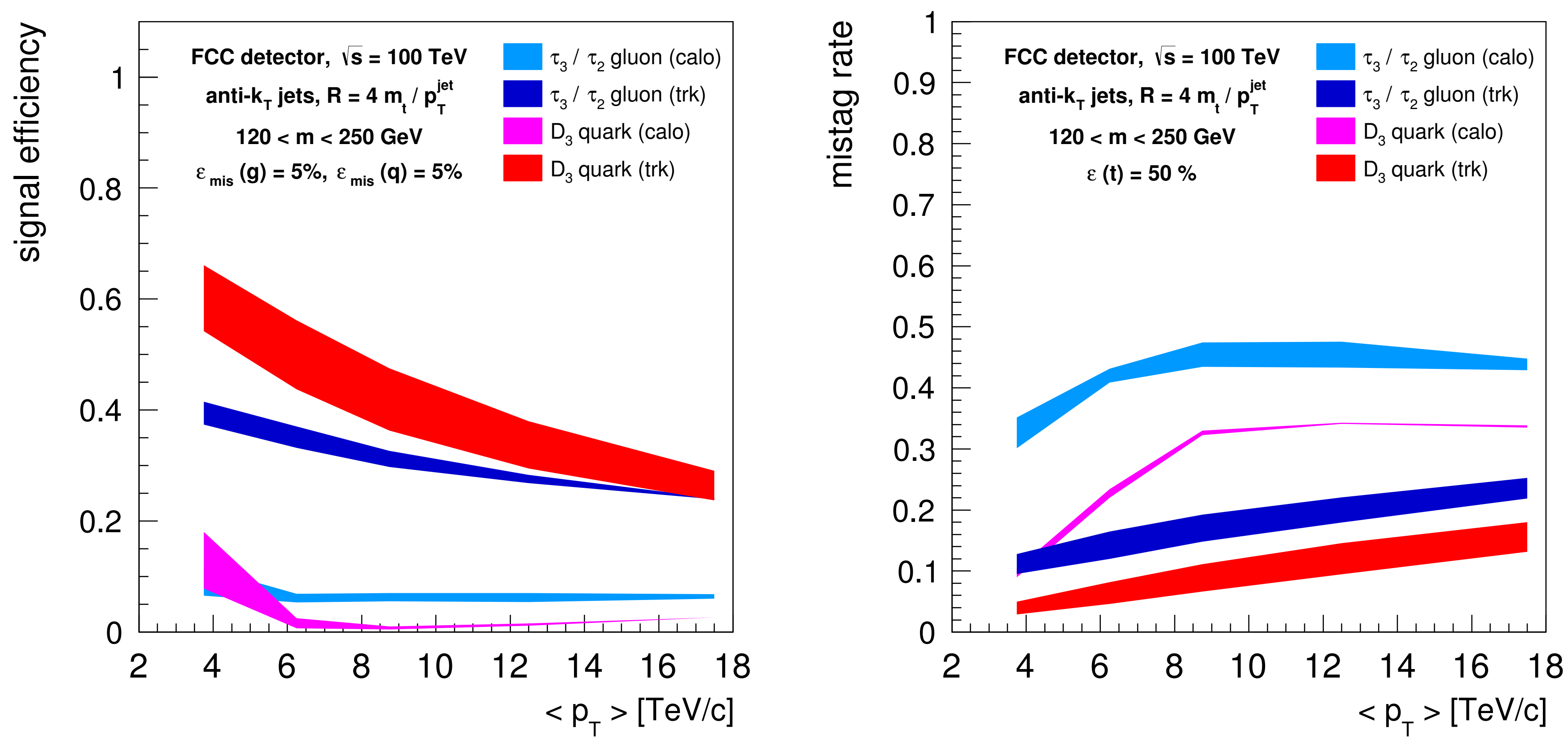
We learned a lot about going from 4 ➜ 5 flavors (doing bottom quark properly).

Similar strategy here (?)

More novelties at a 100 TeV collider

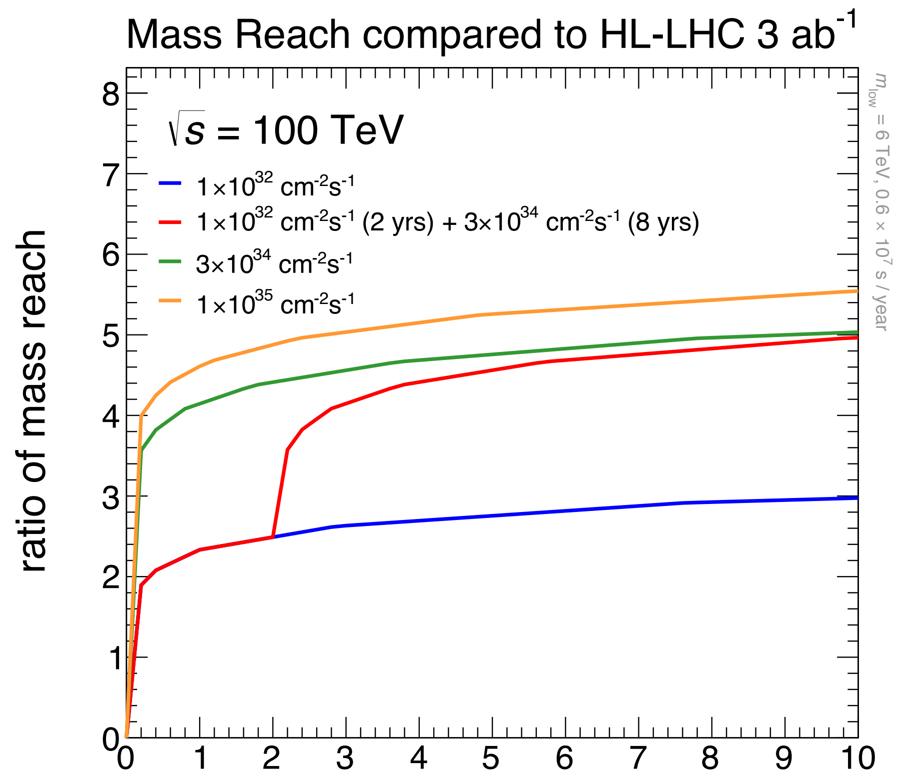
- SM EW scale particles become very like.
- Tagging W/Z/t/h as “fat” jets
  - Not so fat any more, using tracks.

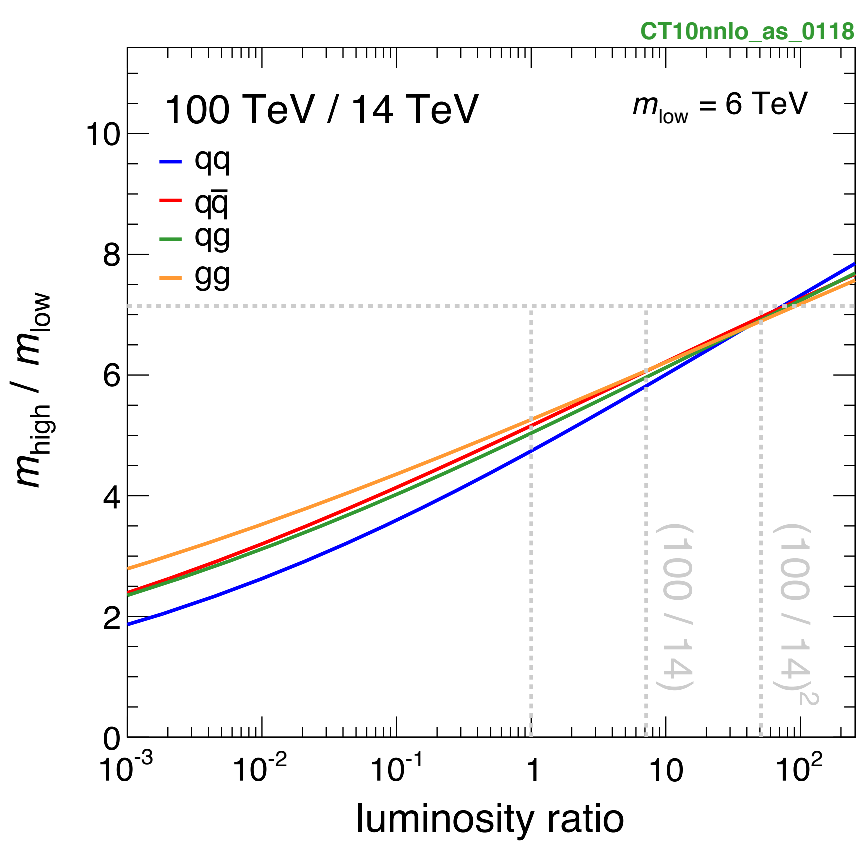
Larkoski, Maltoni, Selvaggi, 2015



New strategies?

Luminosity target of 100 TeV pp collider





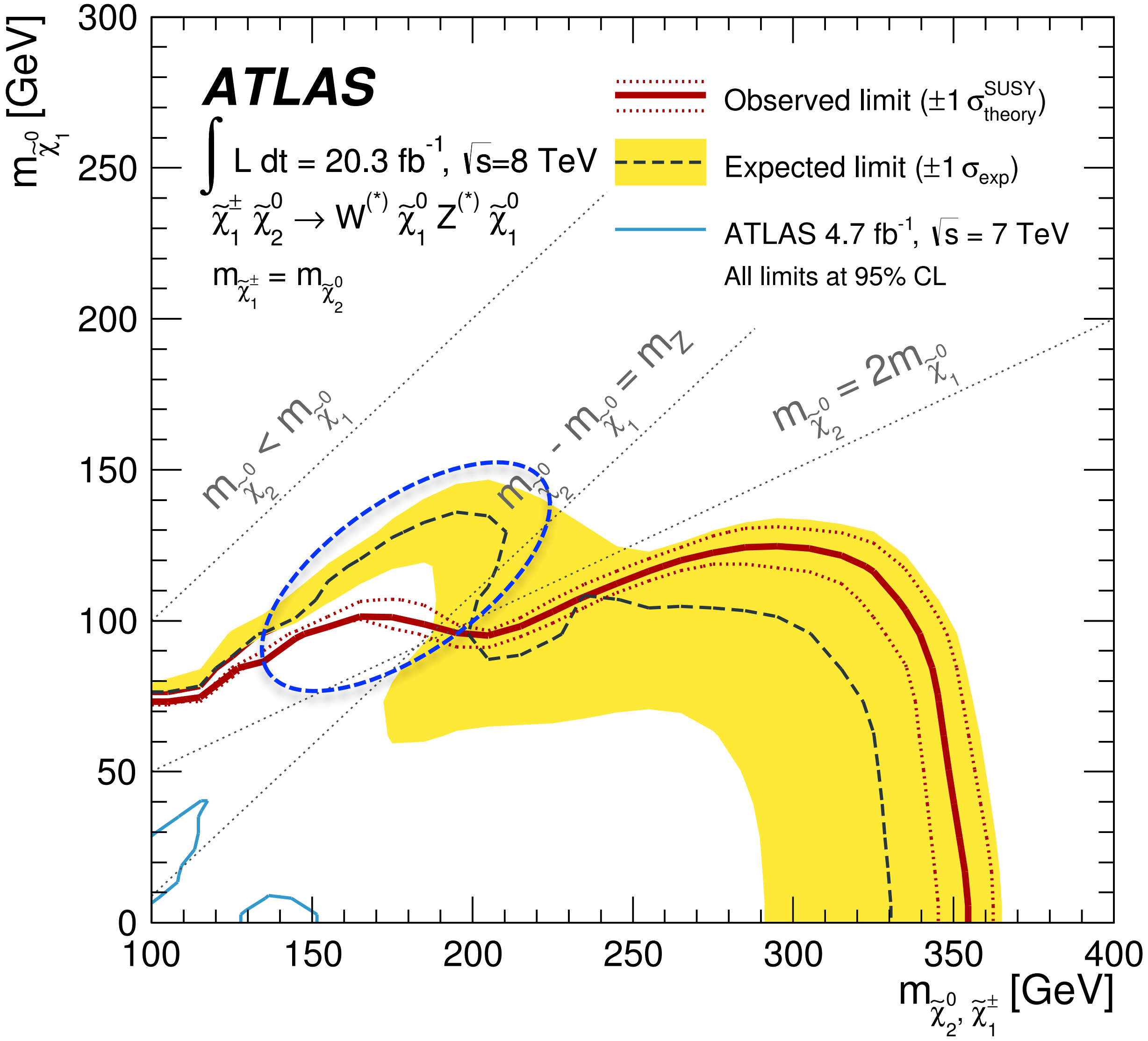
- Reach gain a factor of 5 for first 3 ab^{-1} , increase slowly after that.
- High lumi more important for light weakly coupled NP.
- Can start at lower instantaneous lumi.
- 10-20 ab^{-1} per experiment seems to be adequate.

Hinchliffe, Kotwal, Mangano, Quigg, LTW

If we made a discovery at run 2

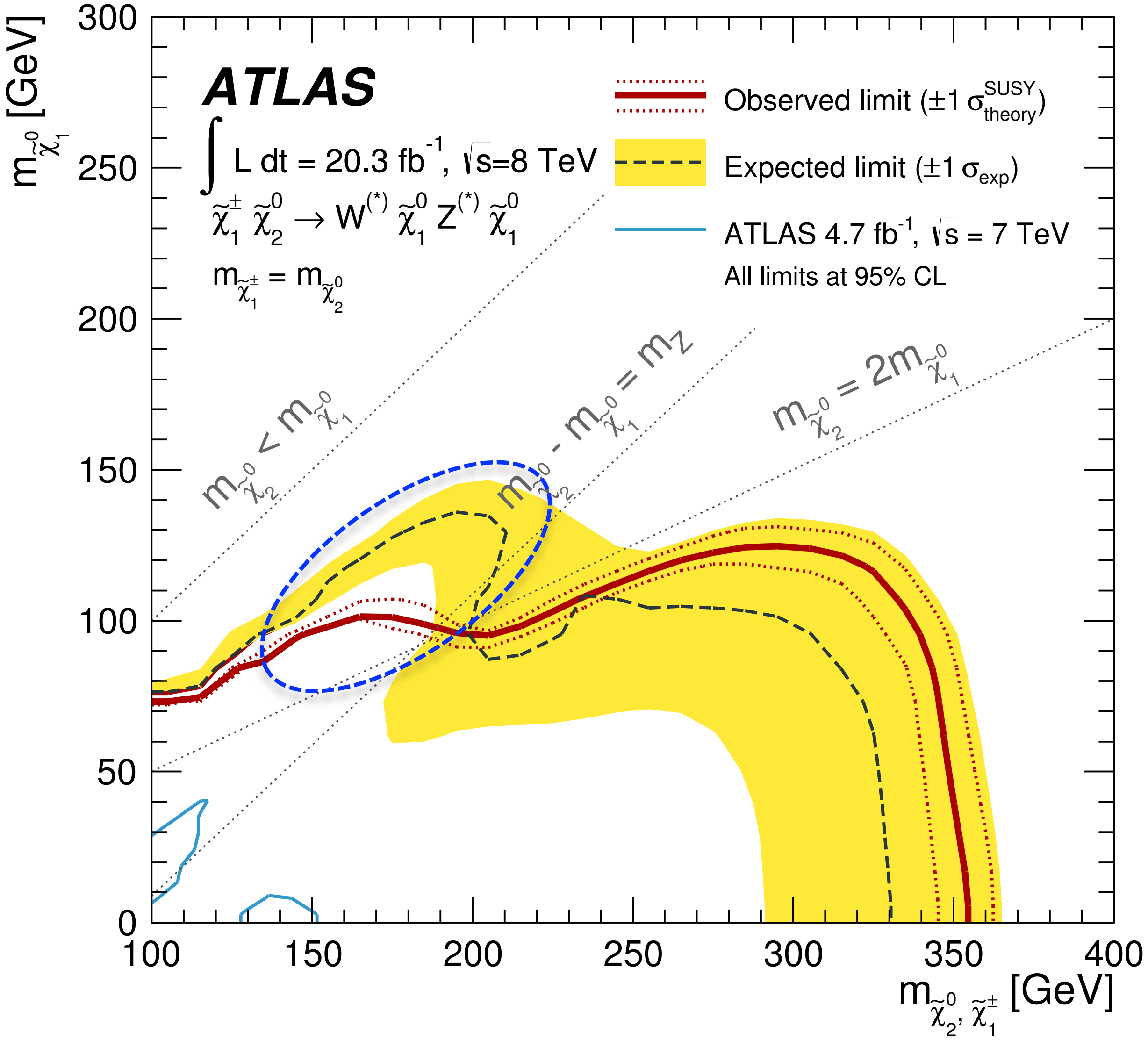
- Beginning of a new era. Seeing the first sign of a new layer of new physics.
- However, it is unlikely to discover the full set of the particles, since we have not see anything yet.
- Typically, going from 8 TeV to 14 TeV increase the reach at most by a factor of 2.
- However, many models feature particles 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, in particular at a 100 TeV pp collider.

What if?



ATLAS
$\int L\,dt = 20.3\ fb^{-1}$, $\sqrt{s}$=8 TeV
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W^{(*)}\tilde{\chi}_1^0 Z^{(*)}\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
Observed limit ($\pm 1\ \sigma_{theory}^{SUSY}$)
Expected limit ($\pm 1\ \sigma_{exp}$)
ATLAS 4.7 fb^{-1}, $\sqrt{s}$ = 7 TeV
All limits at 95% CL
$m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = m_Z$
$m_{\tilde{\chi}_2^0} = 2m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}}$ [GeV]

What if?



ATLAS
$\int L\,dt = 20.3\ fb^{-1}, \sqrt{s}=8$ TeV
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^0 Z^{(*)}\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
Observed limit ($\pm1\ \sigma^{SUSY}_{theory}$)
Expected limit ($\pm1\ \sigma_{exp}$)
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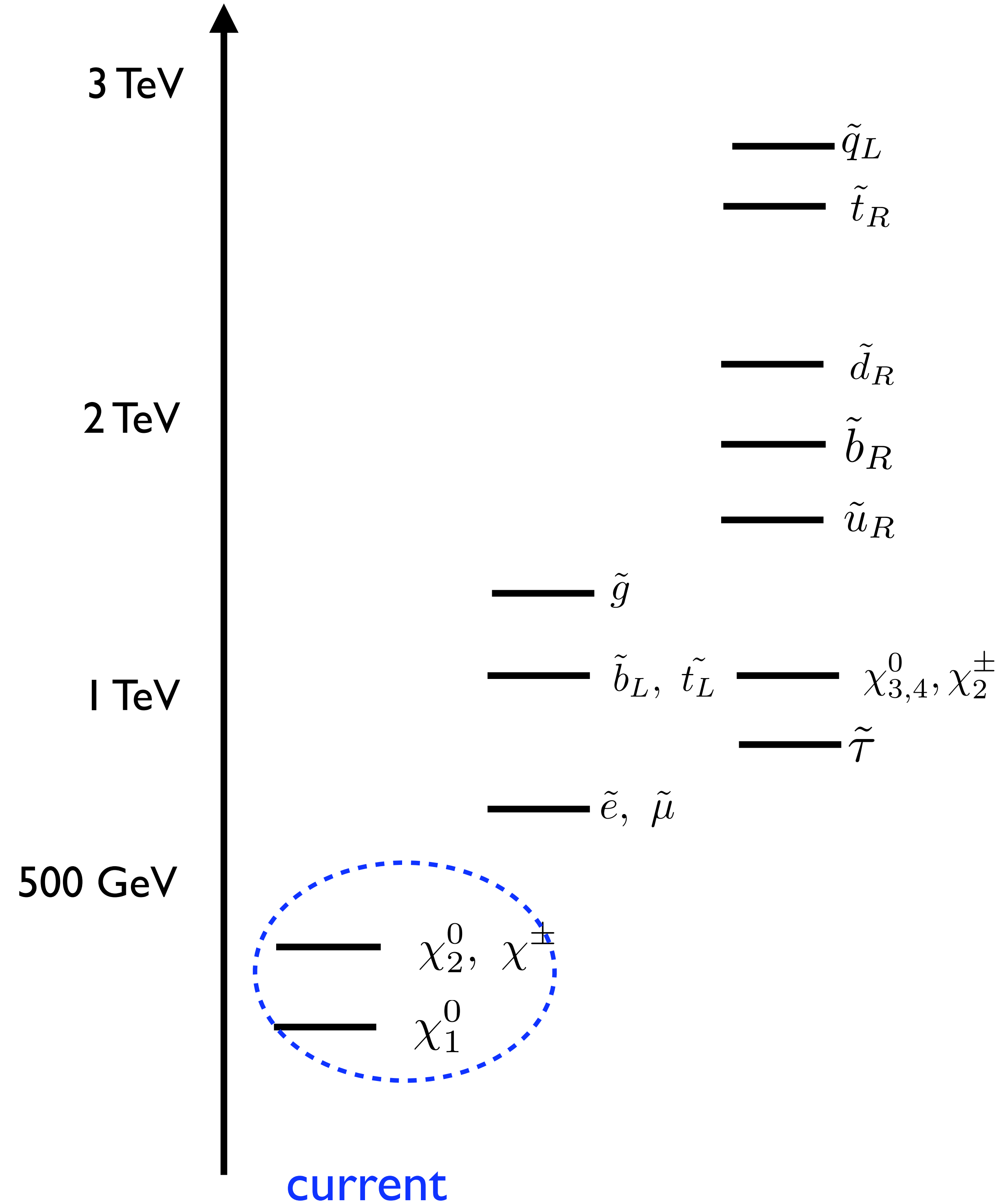
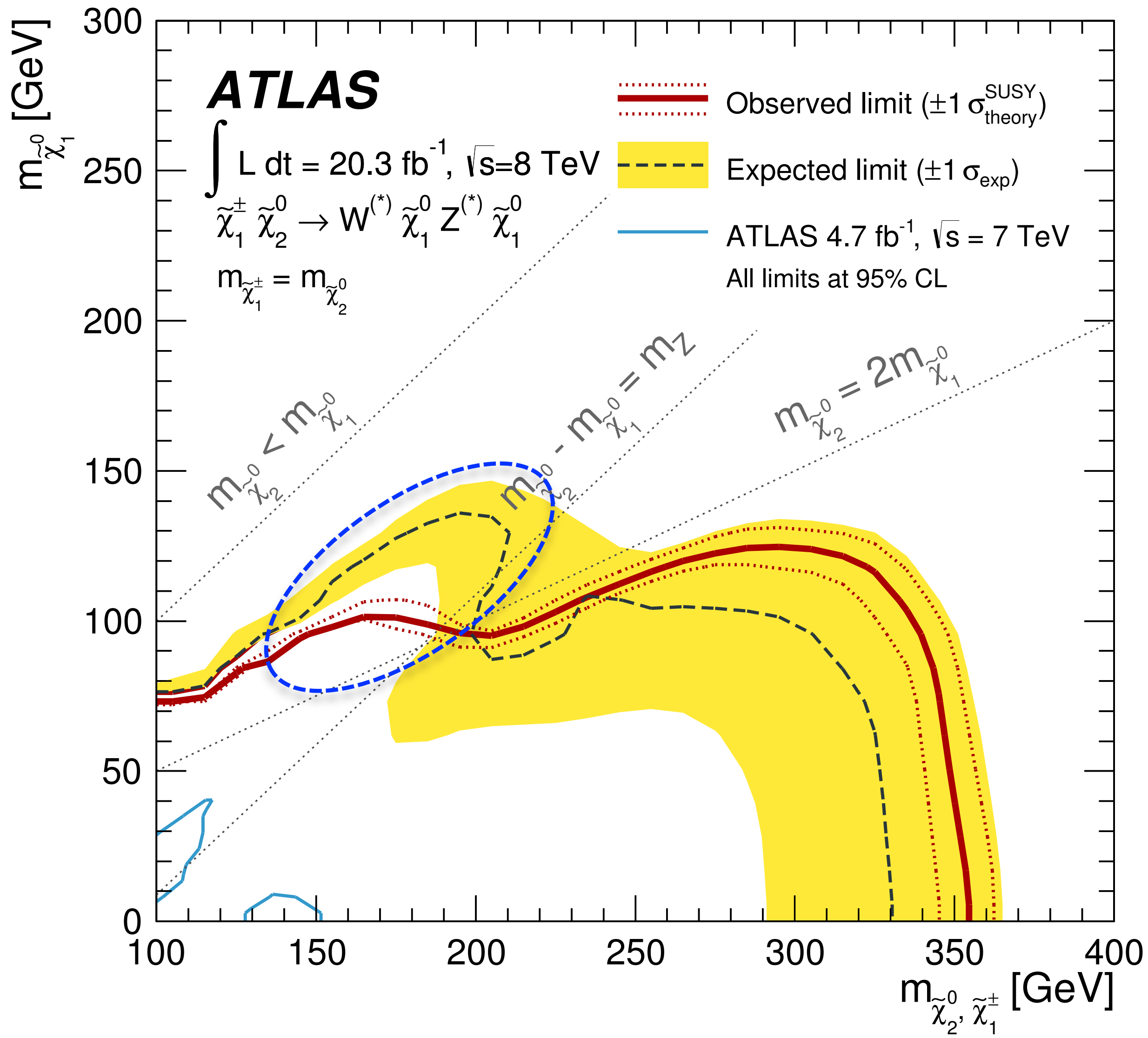


3 TeV
2 TeV
1 TeV
500 GeV
$\tilde{q}_L$
$\tilde{t}_R$
$\tilde{d}_R$
$\tilde{b}_R$
$\tilde{u}_R$
$\tilde{g}$
$\tilde{b}_L,\ \tilde{t}_L$
$\chi^0_{3,4}, \chi^\pm_2$
$\tilde{\tau}$
$\tilde{e},\ \tilde{\mu}$
$\chi^0_2,\ \chi^\pm$
χ^0_1
current

What if?



ATLAS
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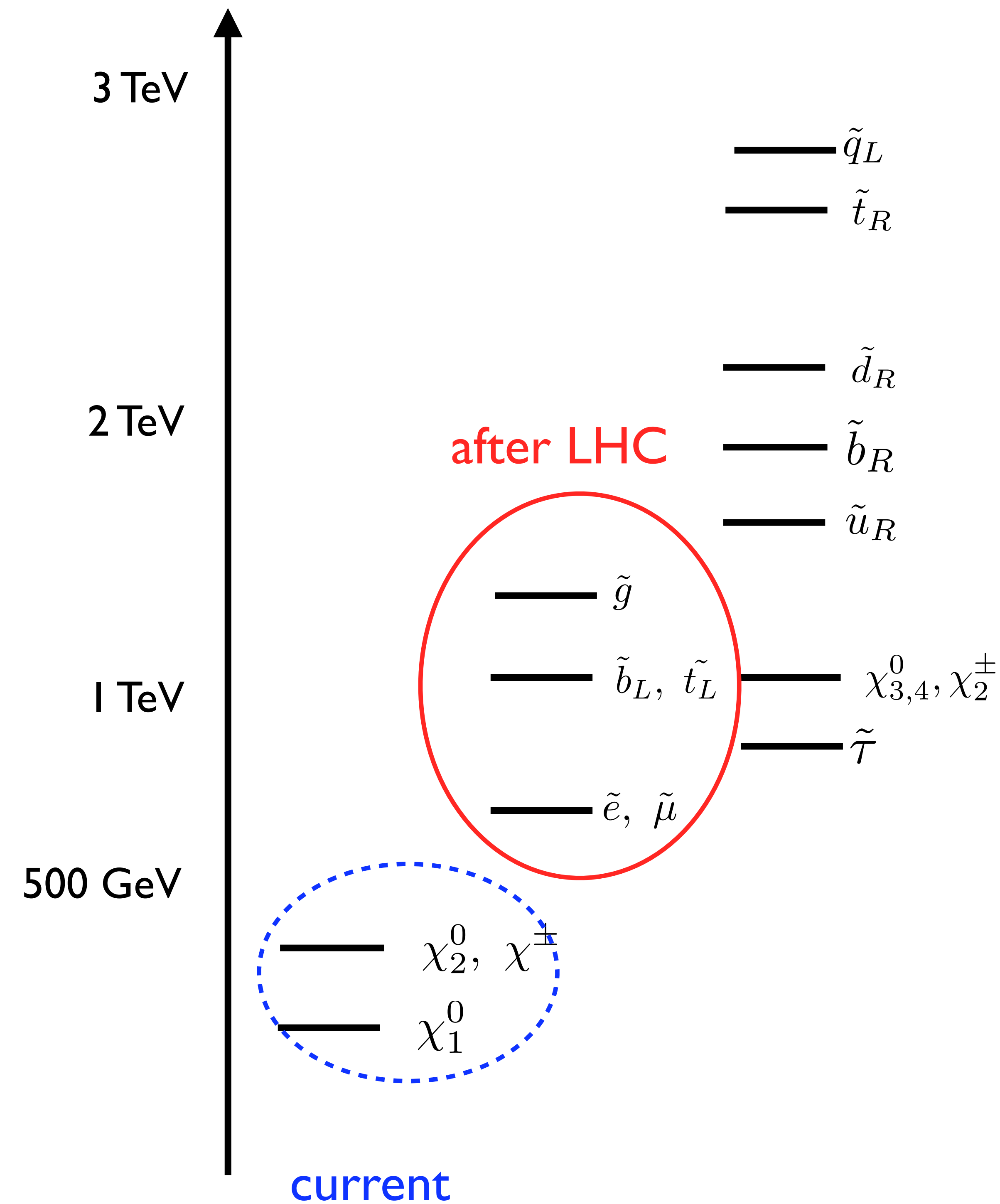
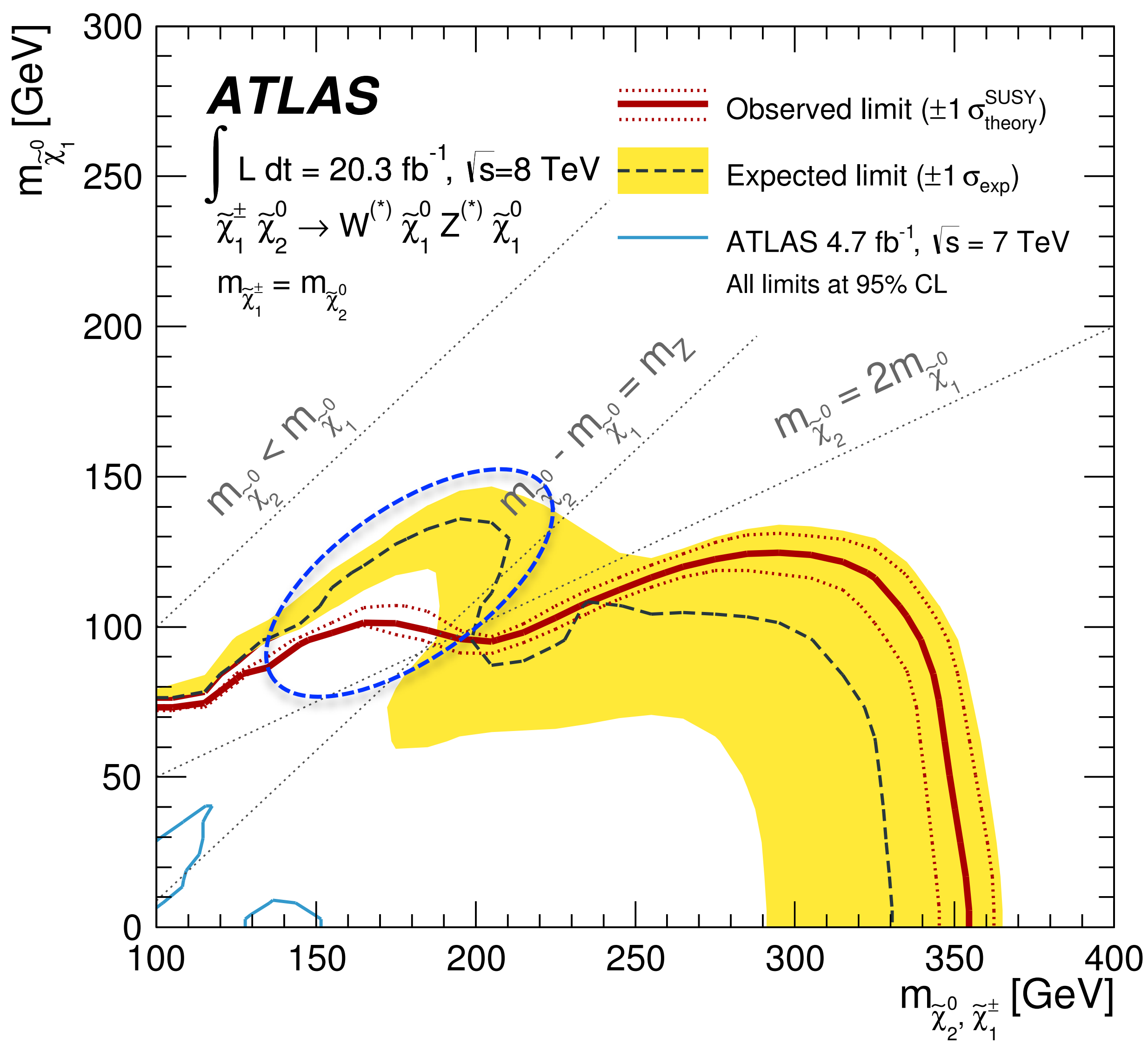
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0,\tilde{\chi}_1^{\pm}}$ [GeV]



3 TeV
2 TeV
1 TeV
500 GeV
after LHC
current
$\tilde{q}_L$
$\tilde{t}_R$
$\tilde{d}_R$
$\tilde{b}_R$
$\tilde{u}_R$
$\tilde{g}$
$\tilde{b}_L,\ \tilde{t}_L$
$\chi^0_{3,4}, \chi^{\pm}_2$
$\tilde{\tau}$
$\tilde{e},\ \tilde{\mu}$
$\chi^0_2,\ \chi^{\pm}$
χ^0_1

What if?



ATLAS
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$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
ATLAS 4.7 fb^{-1}, $\sqrt{s}$ = 7 TeV
All limits at 95% CL
$m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = m_Z$
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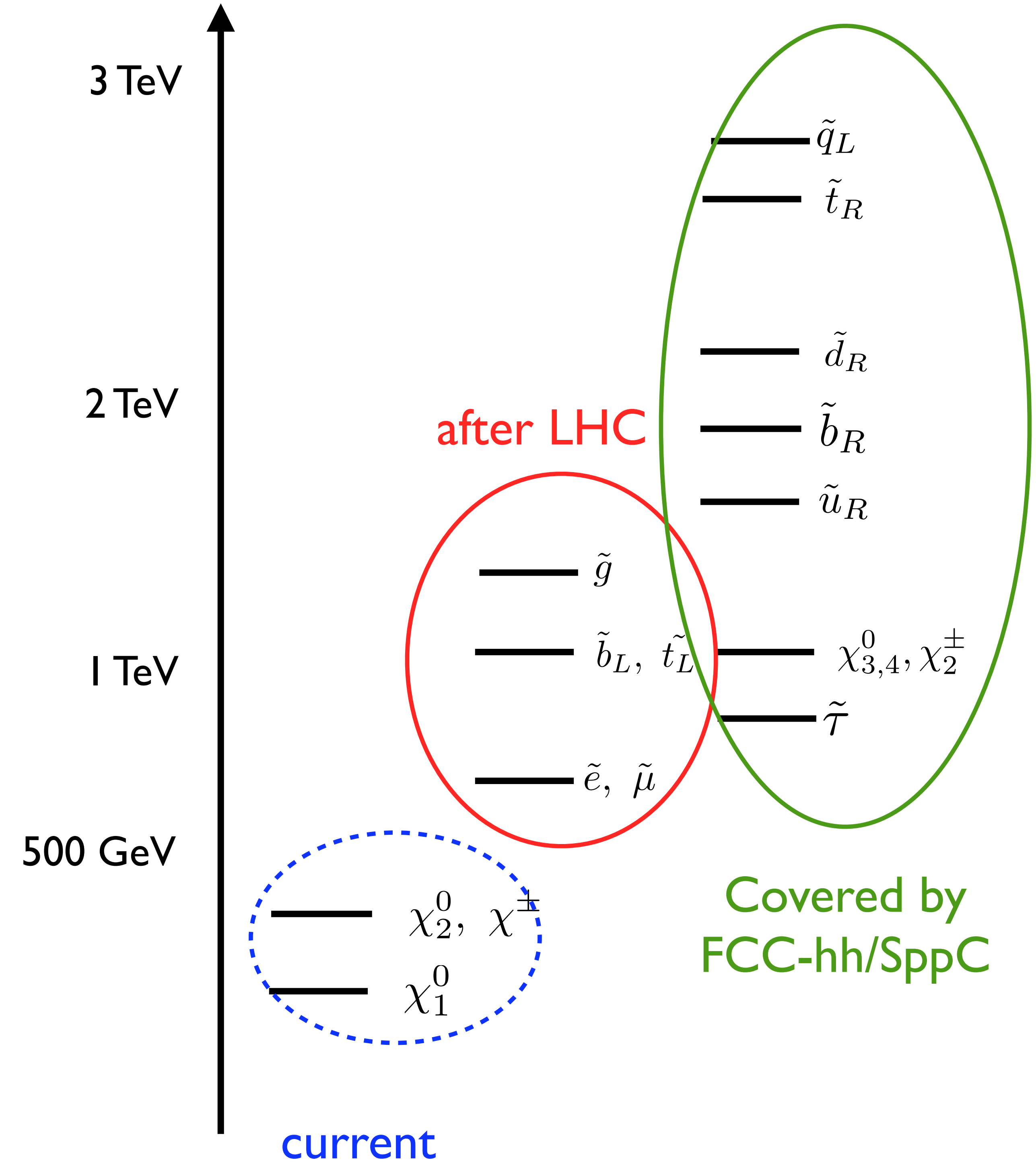
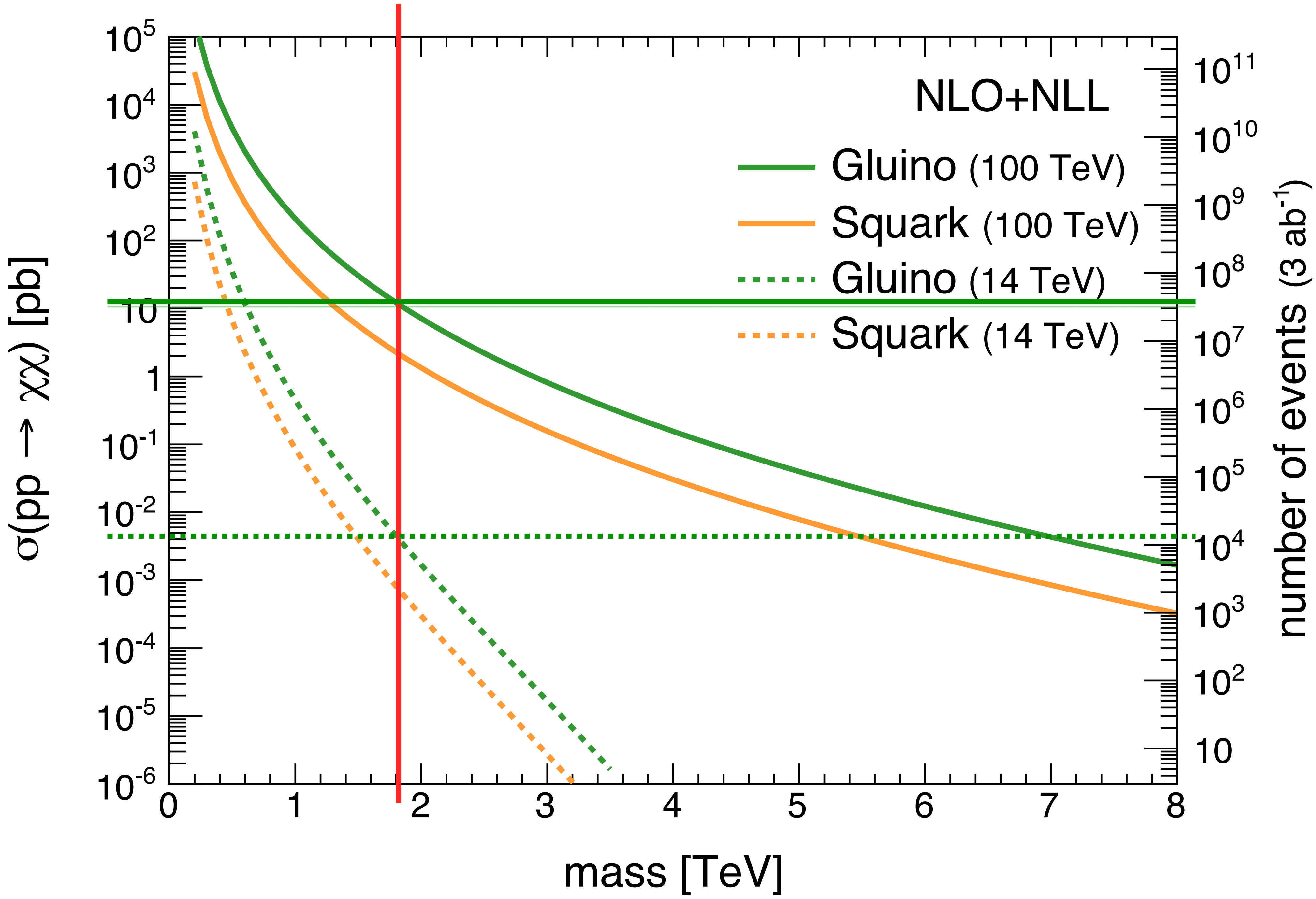


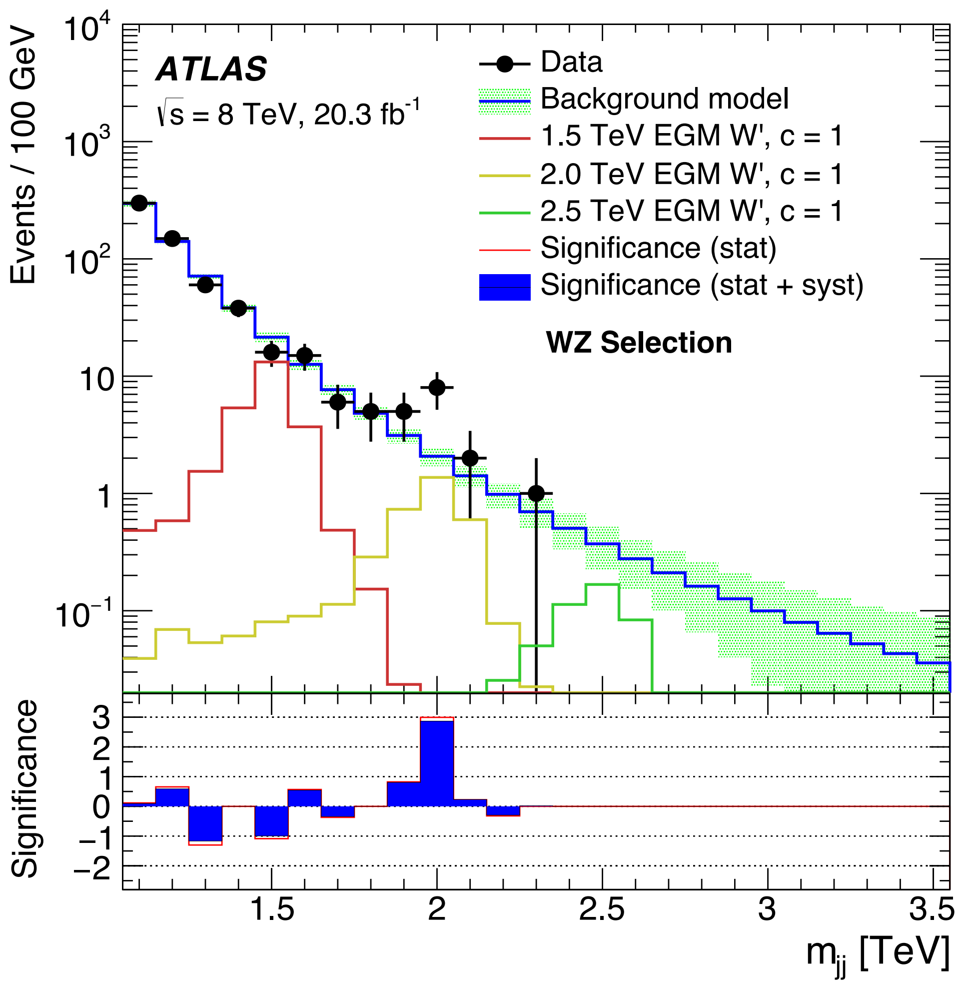
3 TeV
2 TeV
1 TeV
500 GeV
$\tilde{q}_L$
$\tilde{t}_R$
$\tilde{d}_R$
$\tilde{b}_R$
$\tilde{u}_R$
after LHC
$\tilde{g}$
$\tilde{b}_L,\ \tilde{t}_L$
$\chi^0_{3,4}, \chi^{\pm}_2$
$\tilde{\tau}$
$\tilde{e},\ \tilde{\mu}$
$\chi^0_2,\ \chi^{\pm}$
χ^0_1
Covered by FCC-hh/SppC
current

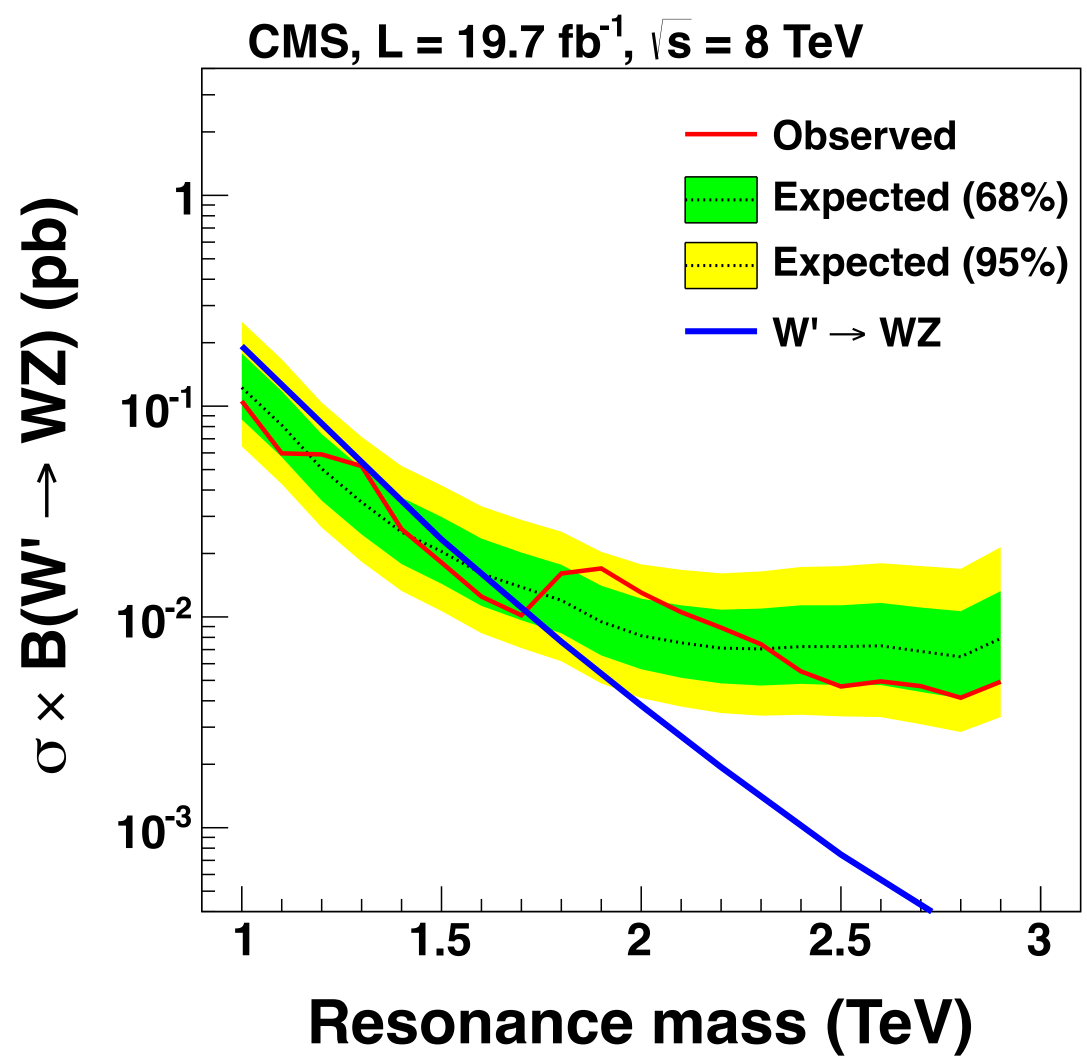
Gluino factory at 100 TeV



$> 10^3$ more gluino produced at 100 TeV collider

What if?

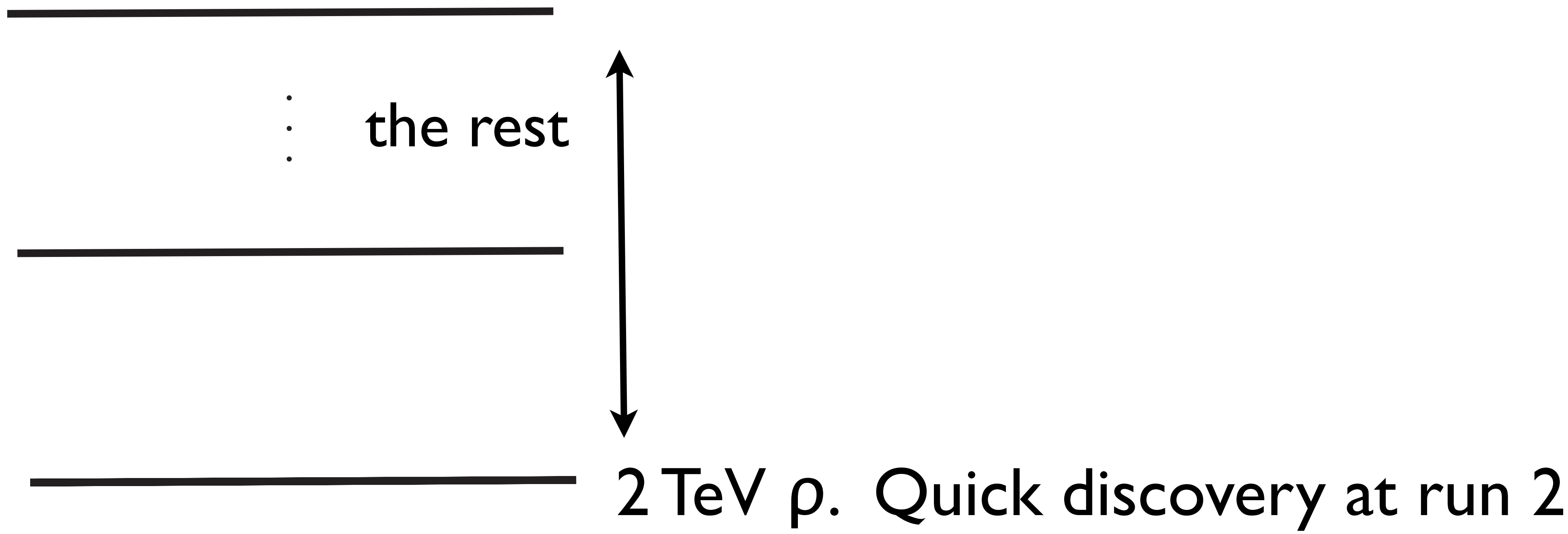




Composite spin-1 vector?

Thamm, Torre, Wulzer
Bian, Liu, Shu
Low, Tesi, LTW
…

Composite Higgs



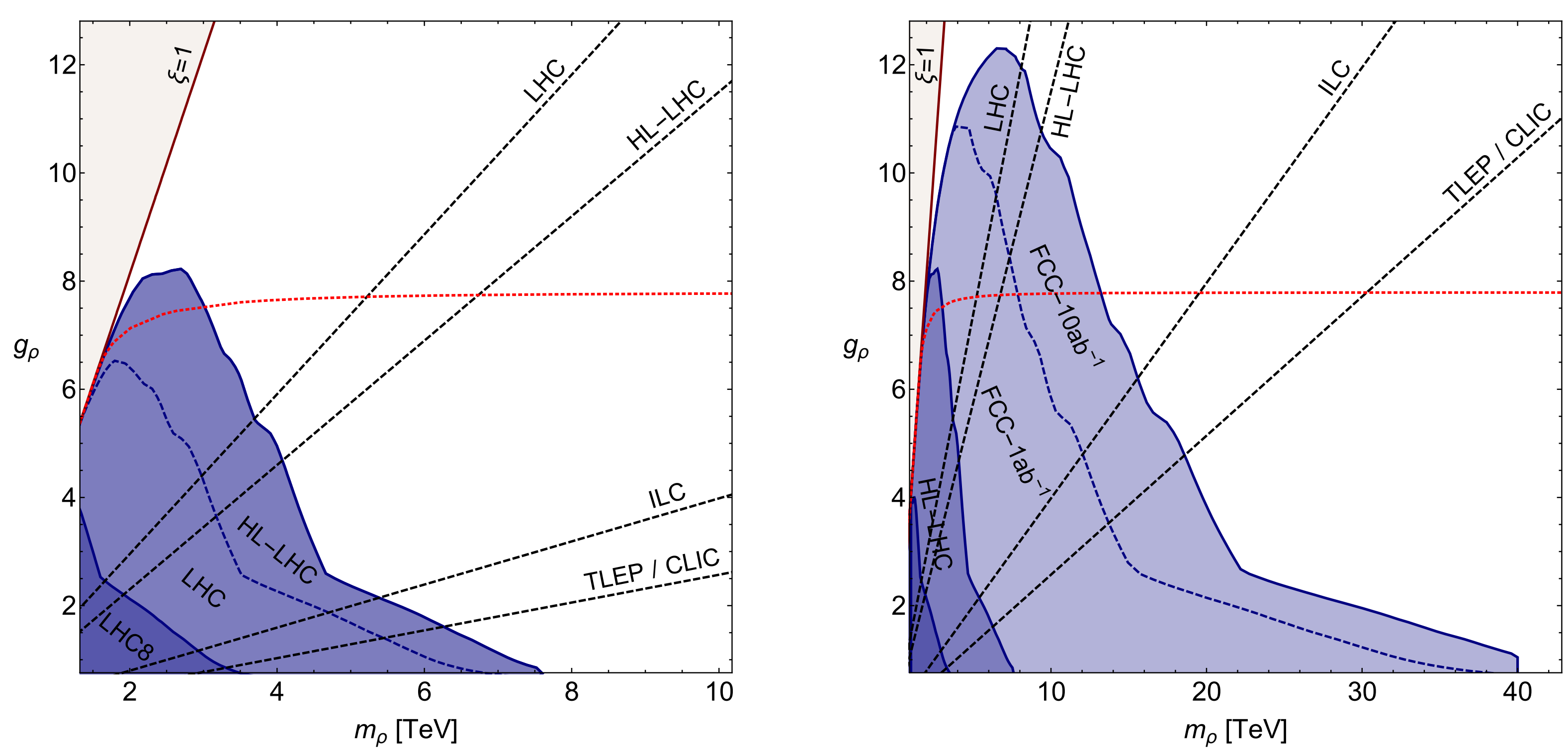
Composite Higgs

the rest

O(10 TeV)

2 TeV ρ. Quick discovery at run 2

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



More opportunities and challenges

- Better SM theory calculation needed for taking full advantage of energy and luminosity.
- Many more NP channels, e.g. flavor (violating) physics at 10s TeV?
- Full set of Higgs measurements at 100 TeV, both inclusive and energy dependence.
- Physics driven (such as dark matter search) novel detector designs.
- We will do much better than we know now in a couple of decades. cf. LHC vs SppS.

Conclusions

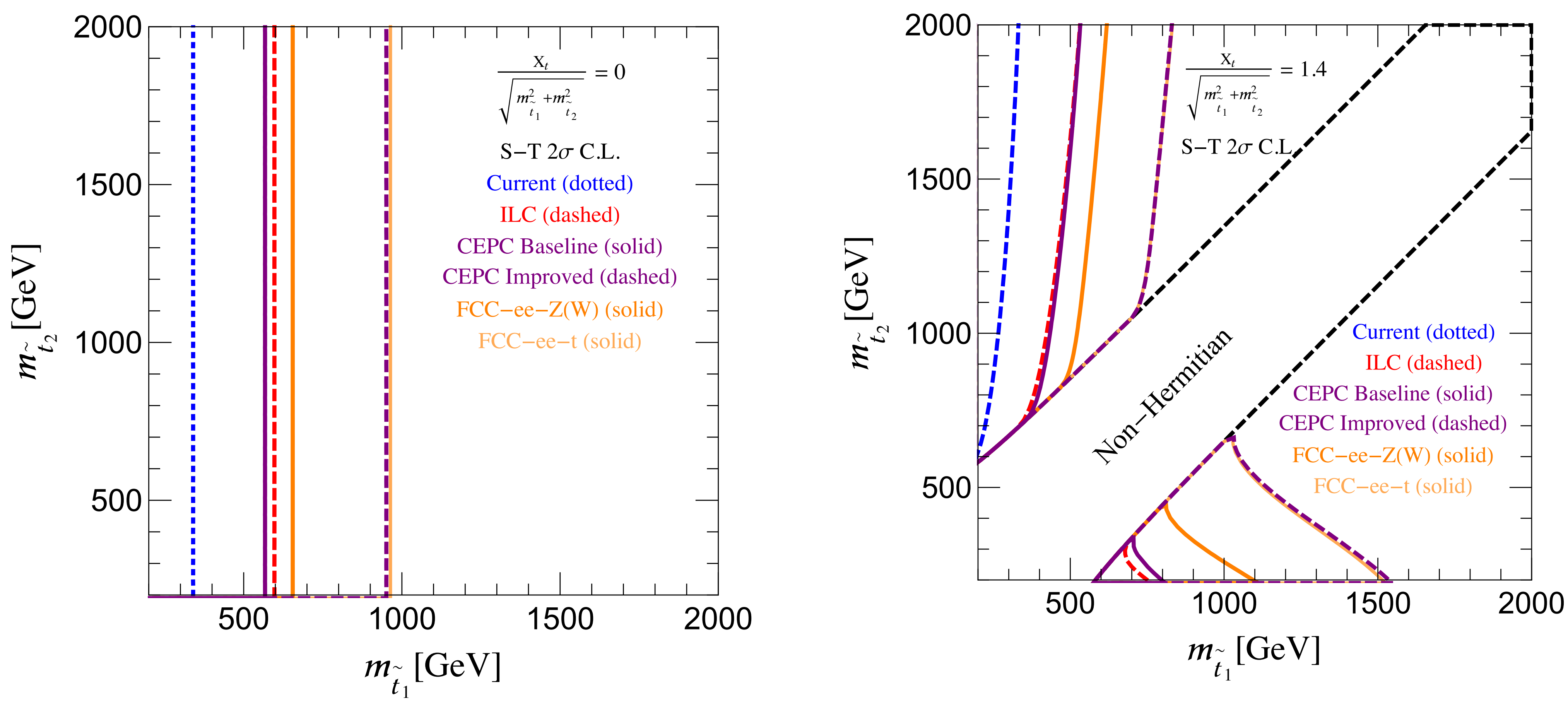
- LHC run 2+ will further probe new physics, interesting gain in reach.
- Several fundamental questions in particle physics will not be answered (fully) by the LHC.
  - Understanding EWSB, naturalness, dark matter, etc.
- Going beyond the LHC, circular colliders
  - Higgs factory + high energy pp collider.
  - Many activities, particularly the last couple of years.
  - Great physics case.
  - Effort underway to make it happen.

A lot to look forward to!

extras

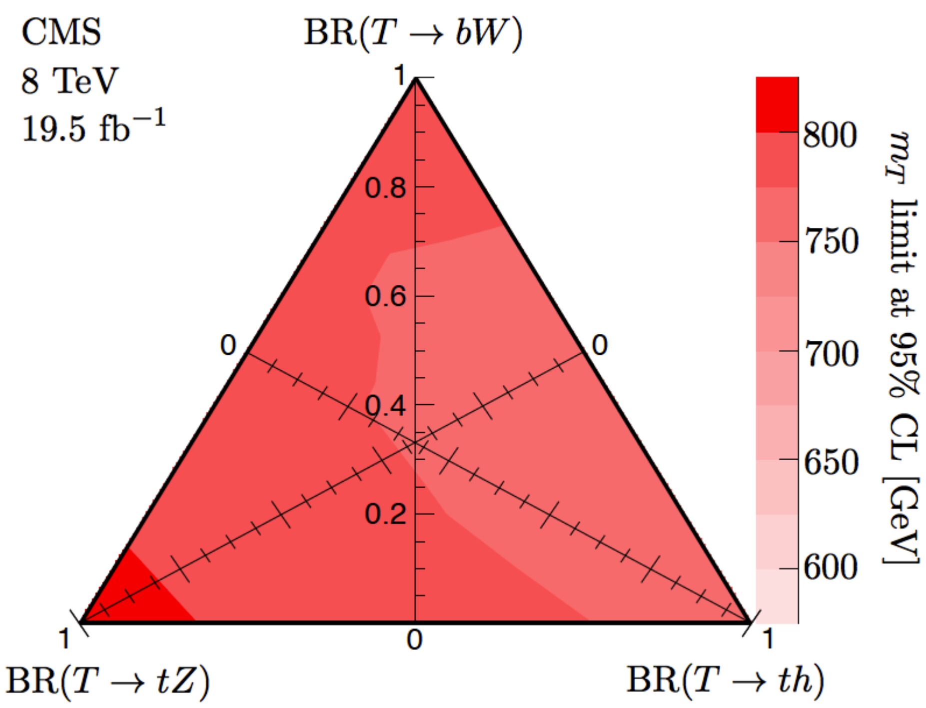
Folded SUSY

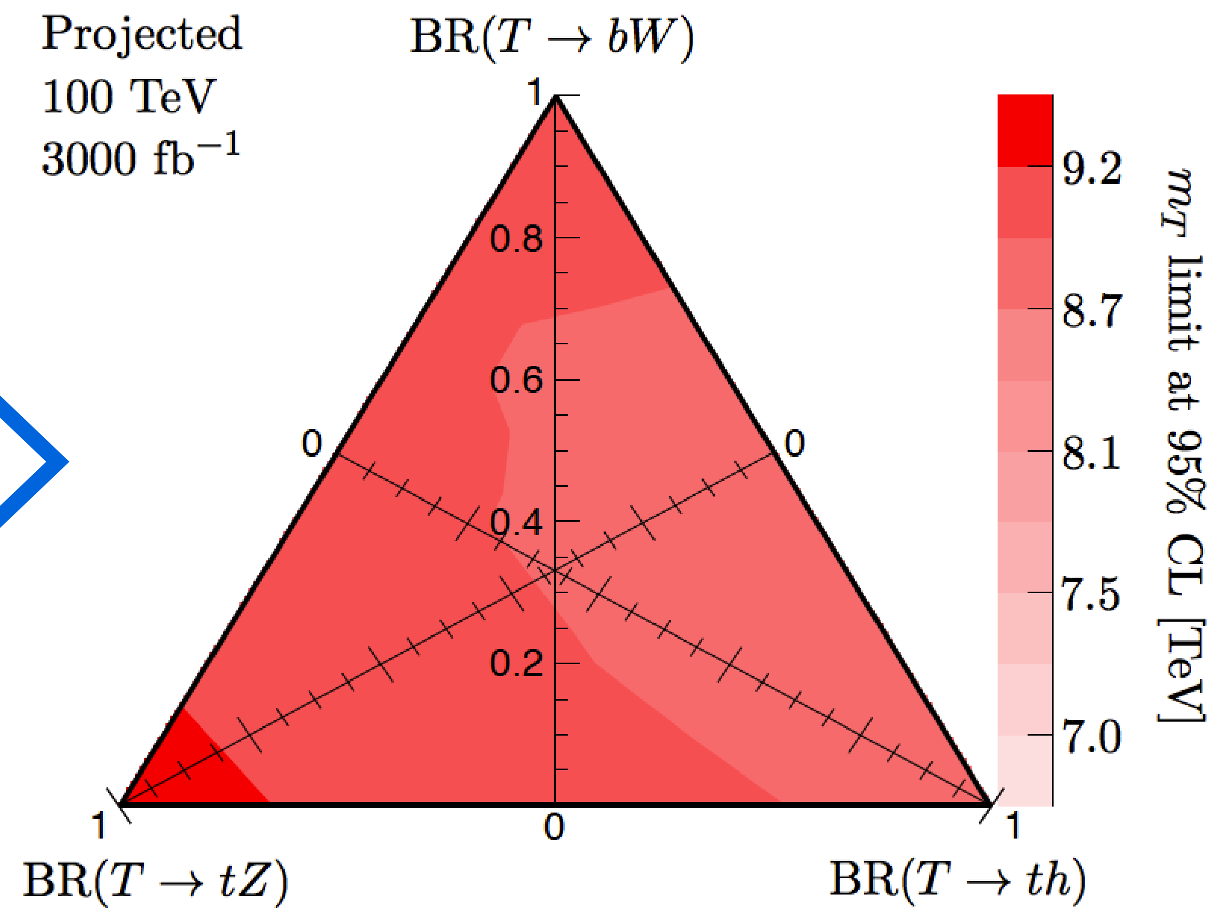
- They do introduce correction in EW precision observables.
- Strong limit from Z-pole measurement.



J. Fan, M. Reece, LTW, 1412.3107

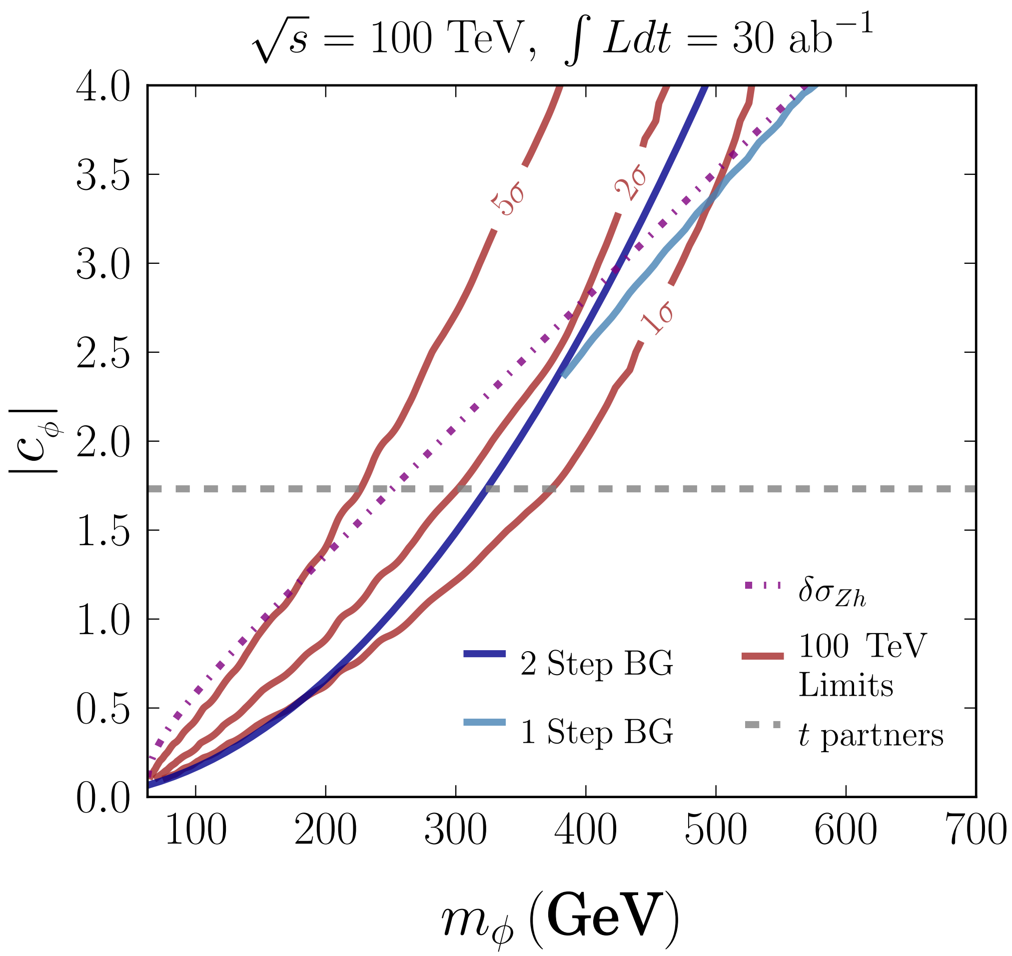
Going up to 100 TeV

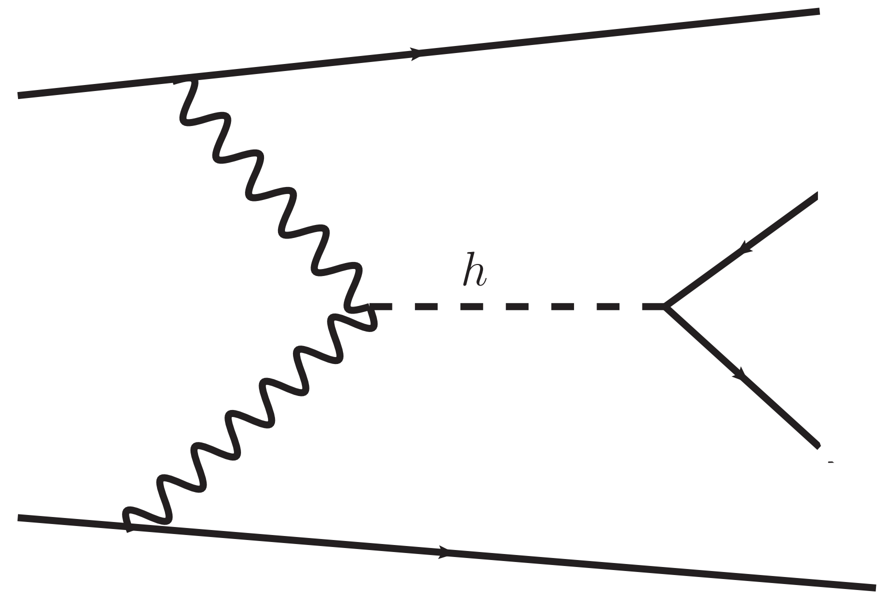




- Room for improvement by using single production, boosted technique, etc.

More difficult model, singlet with Z_2

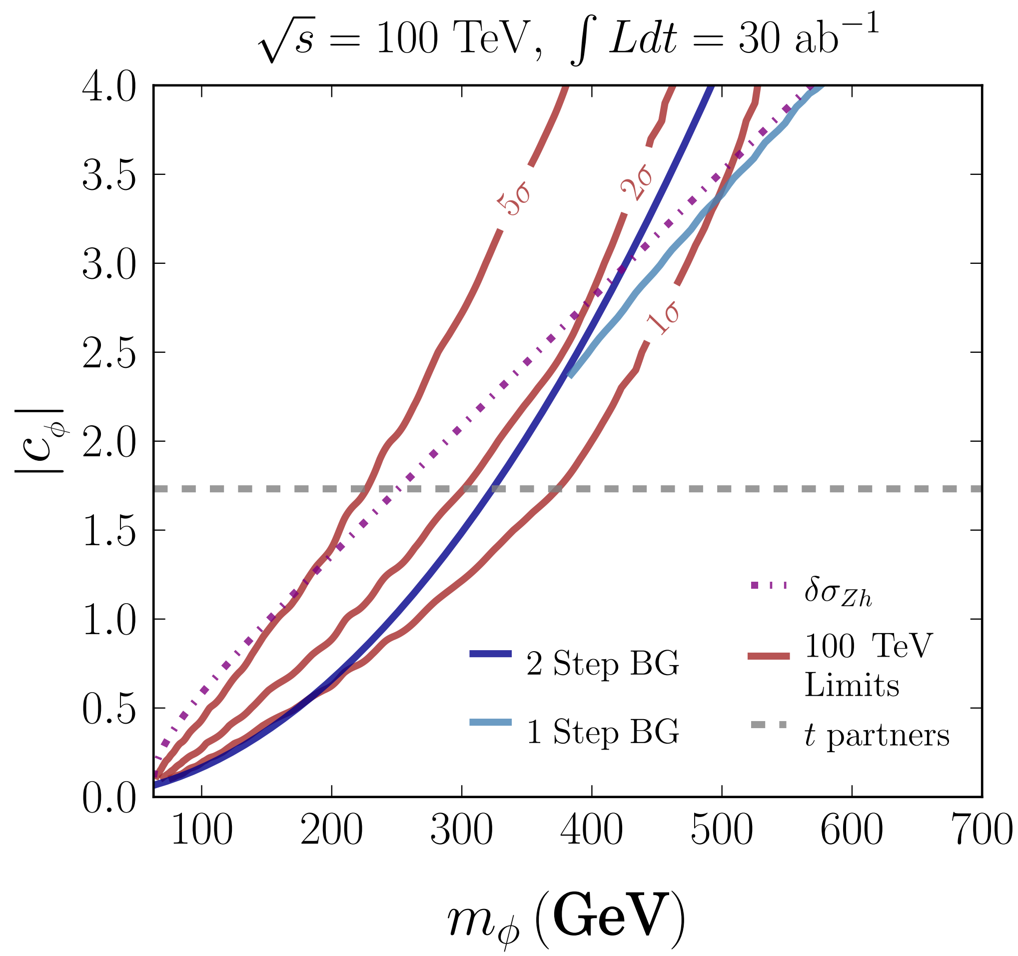


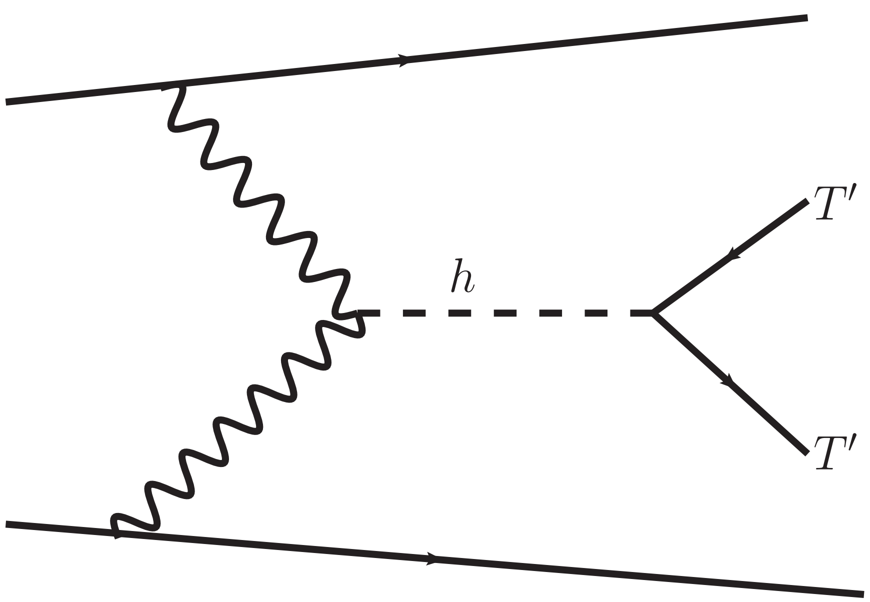


Craig, Lou, McCullough, Thalapillil

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

More difficult model, singlet with Z_2

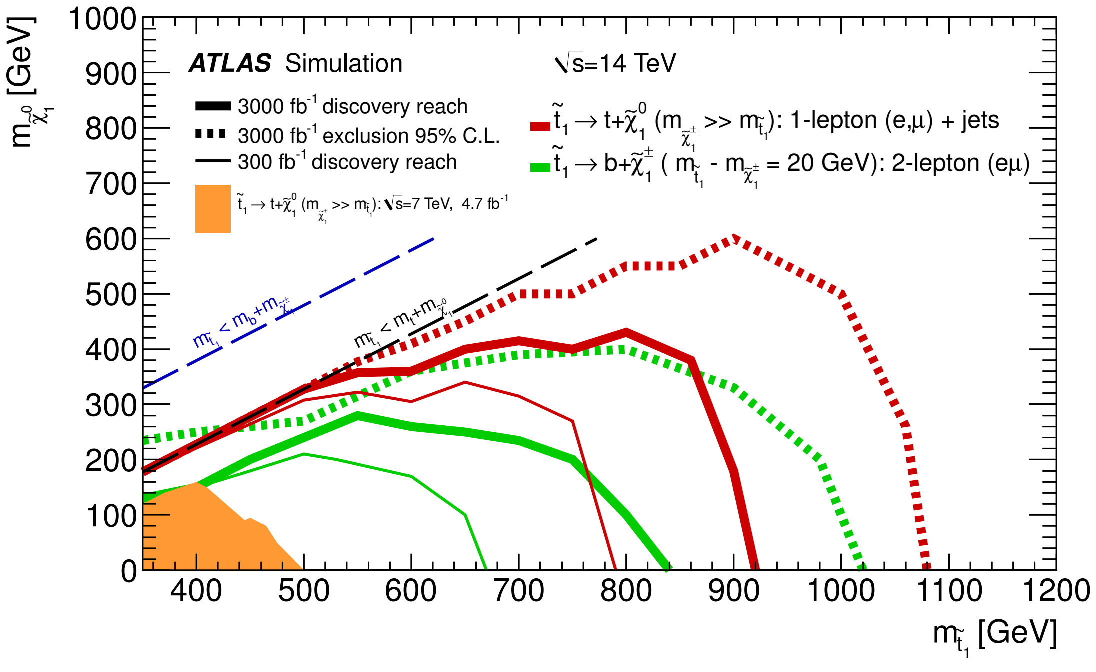


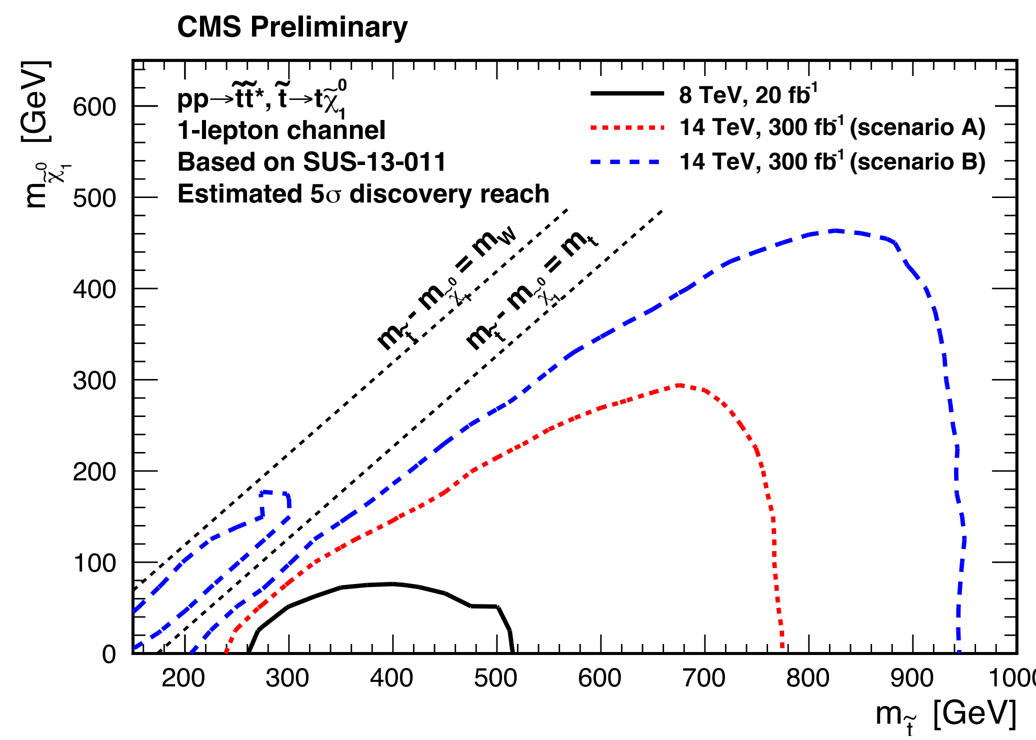


Craig, Lou, McCullough, Thalapillil

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

Highlight: top partner (SUSY)

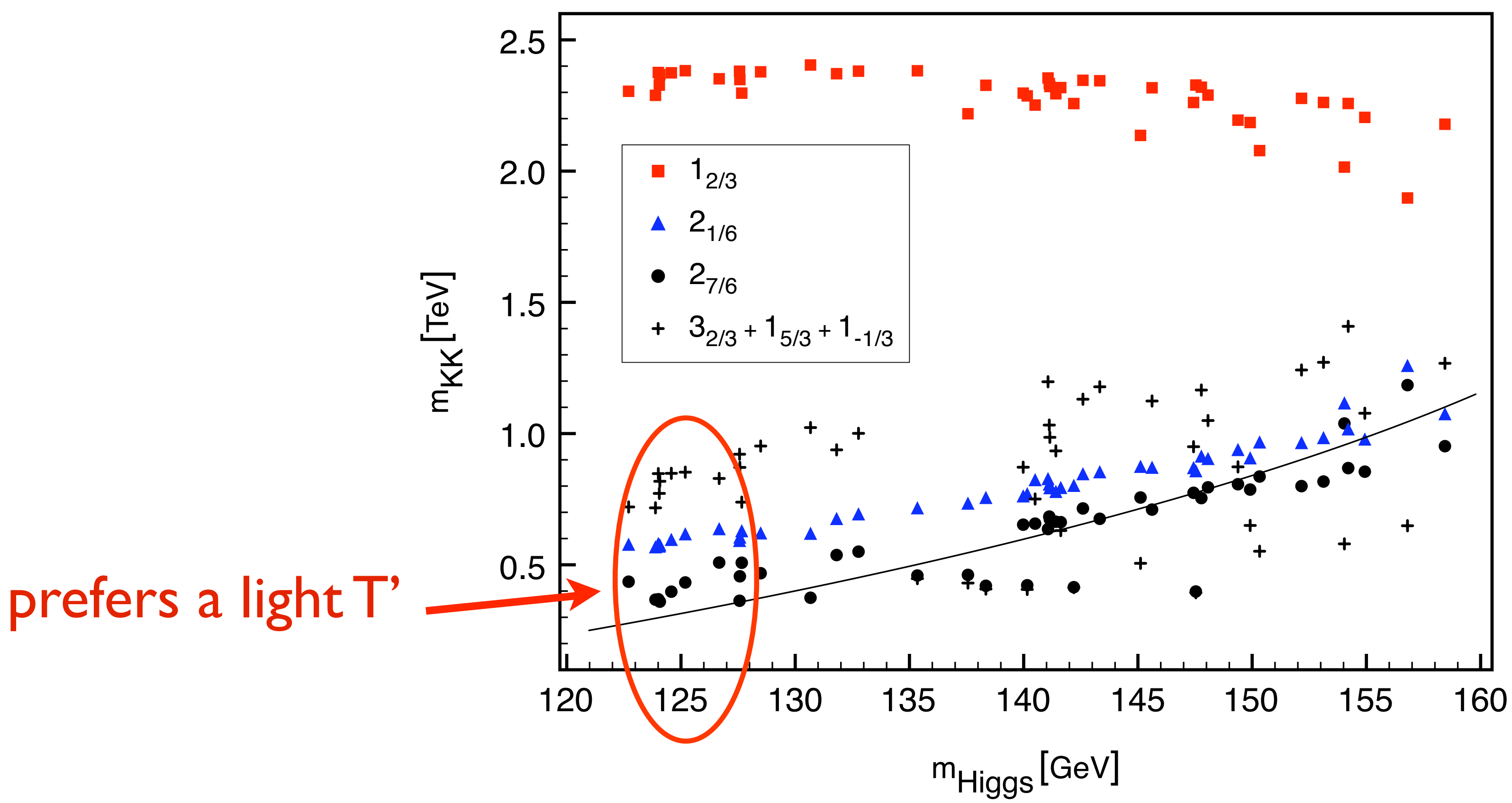




- Naturalness ∝ m_{stop}^2
- Discovery of top partner at Run 2 is a stunning success of naturalness.
- None discovery push fine-tuning to at least 1%

Compositeness and top partner

Wulzer's talk

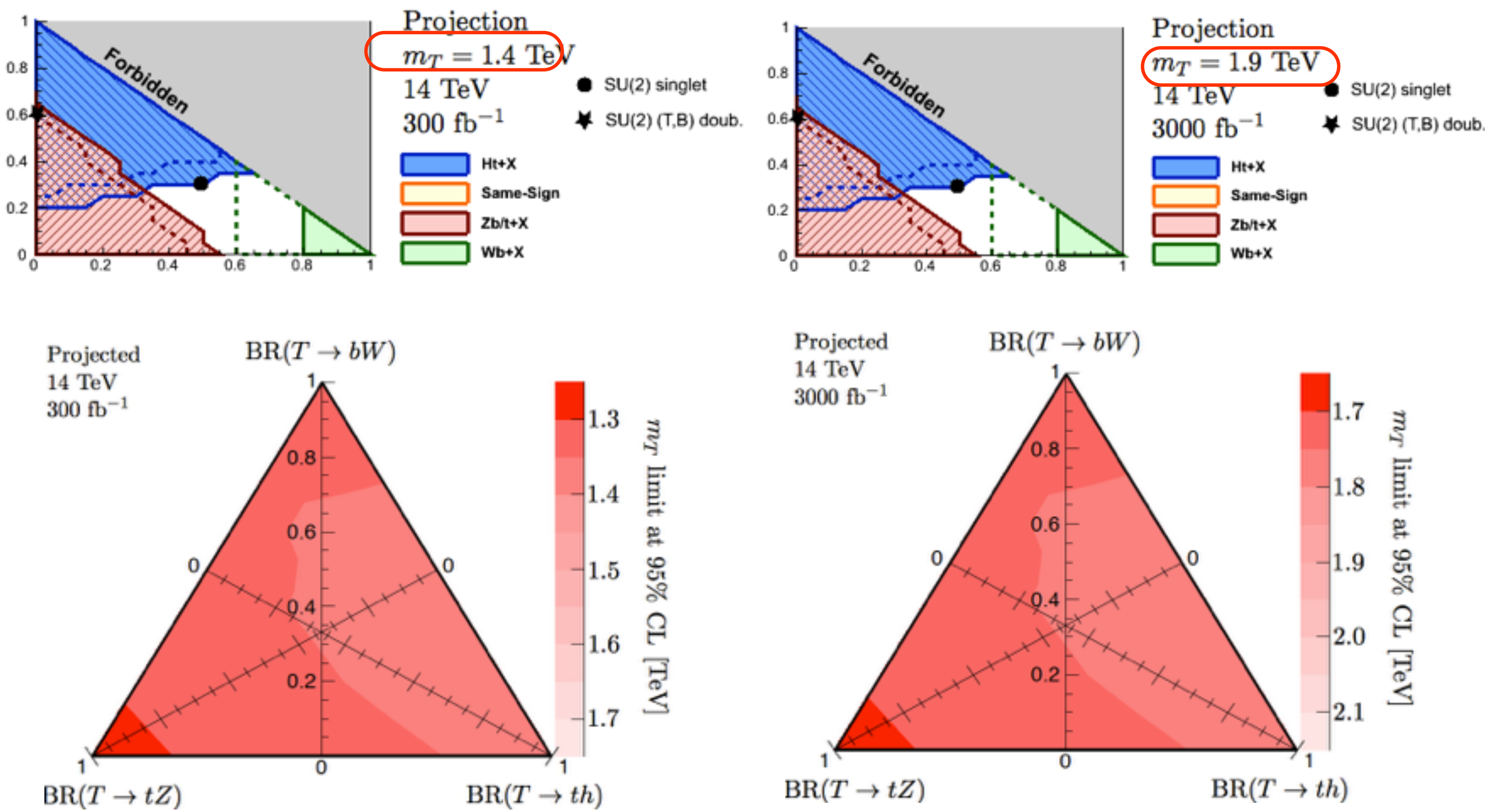


Contino, Da Rold, Pomarol, 2006

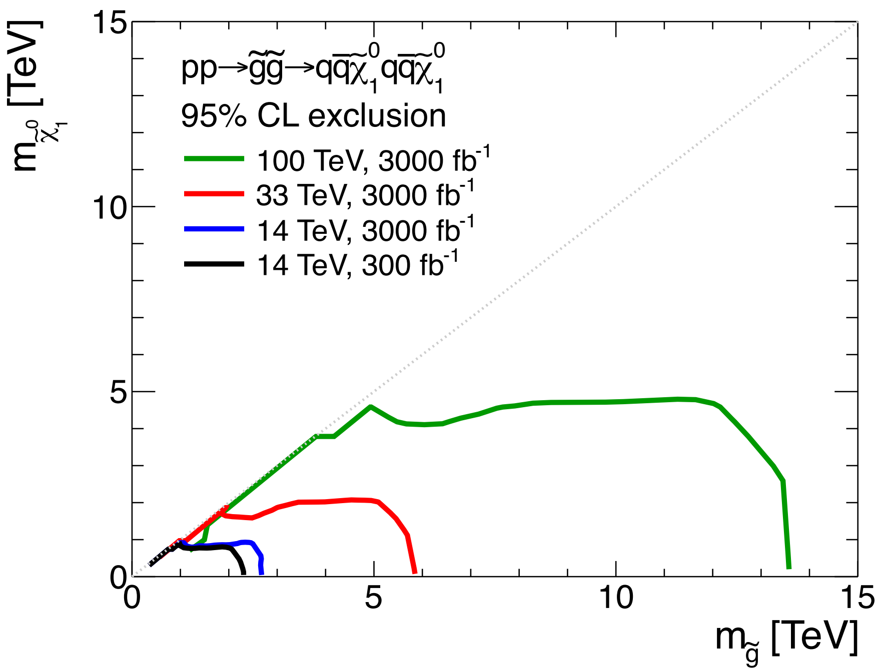
- Plays a crucial role in EWSB.

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

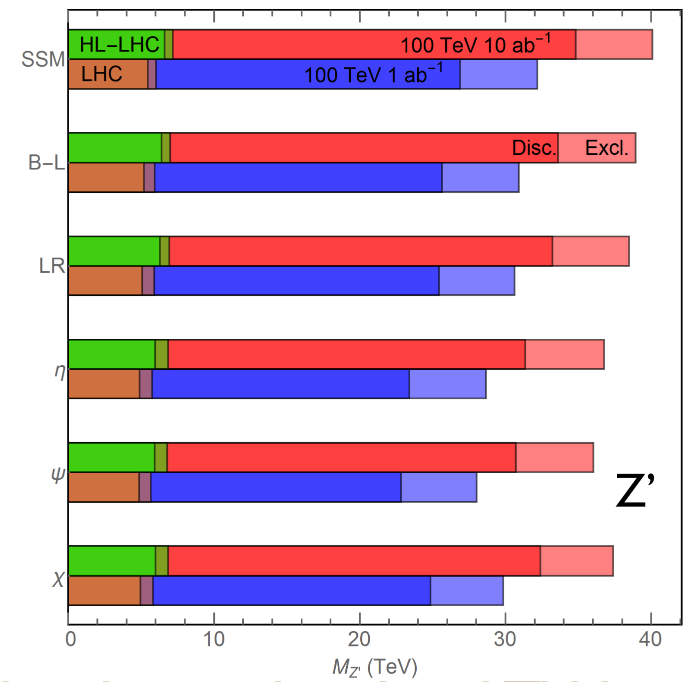
LHC 14 should cover (most of) it.



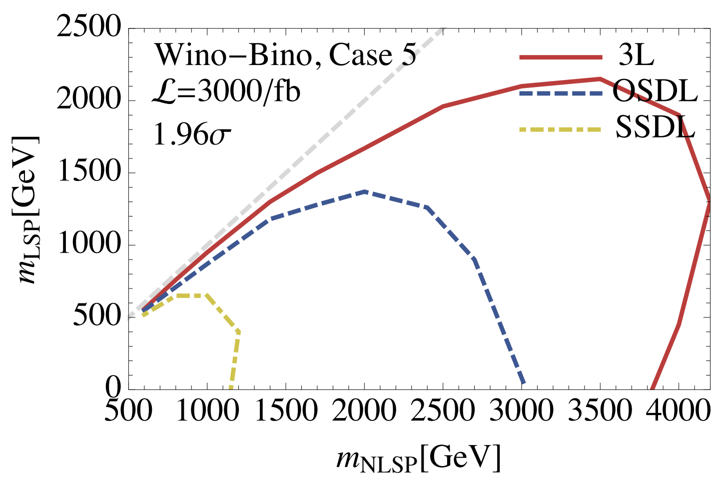
A big step forward in the energy frontier



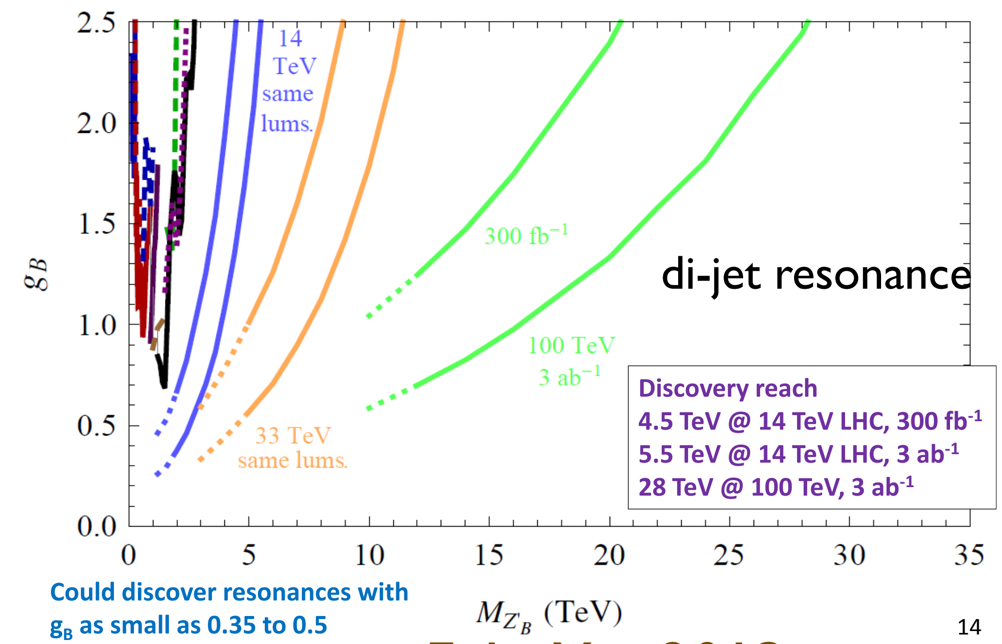
Cohen et al, 2013



Han, Langacker, Liu, LTW, to appear



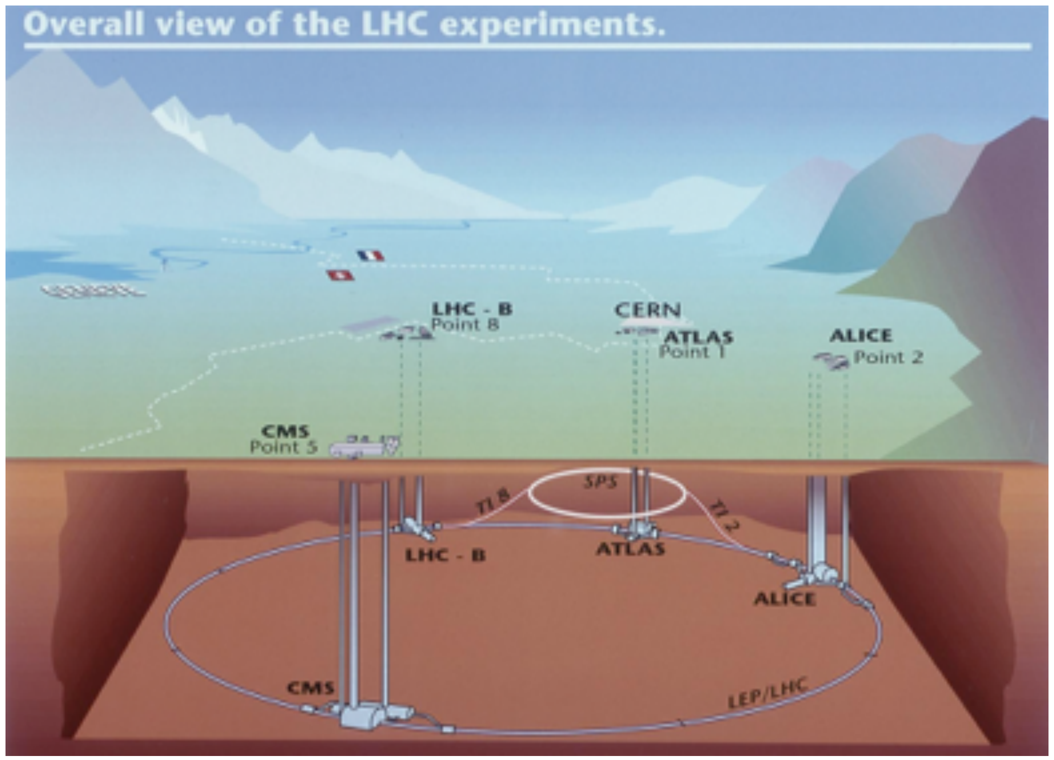
Gori, Jung, LTW, Wells, 2014

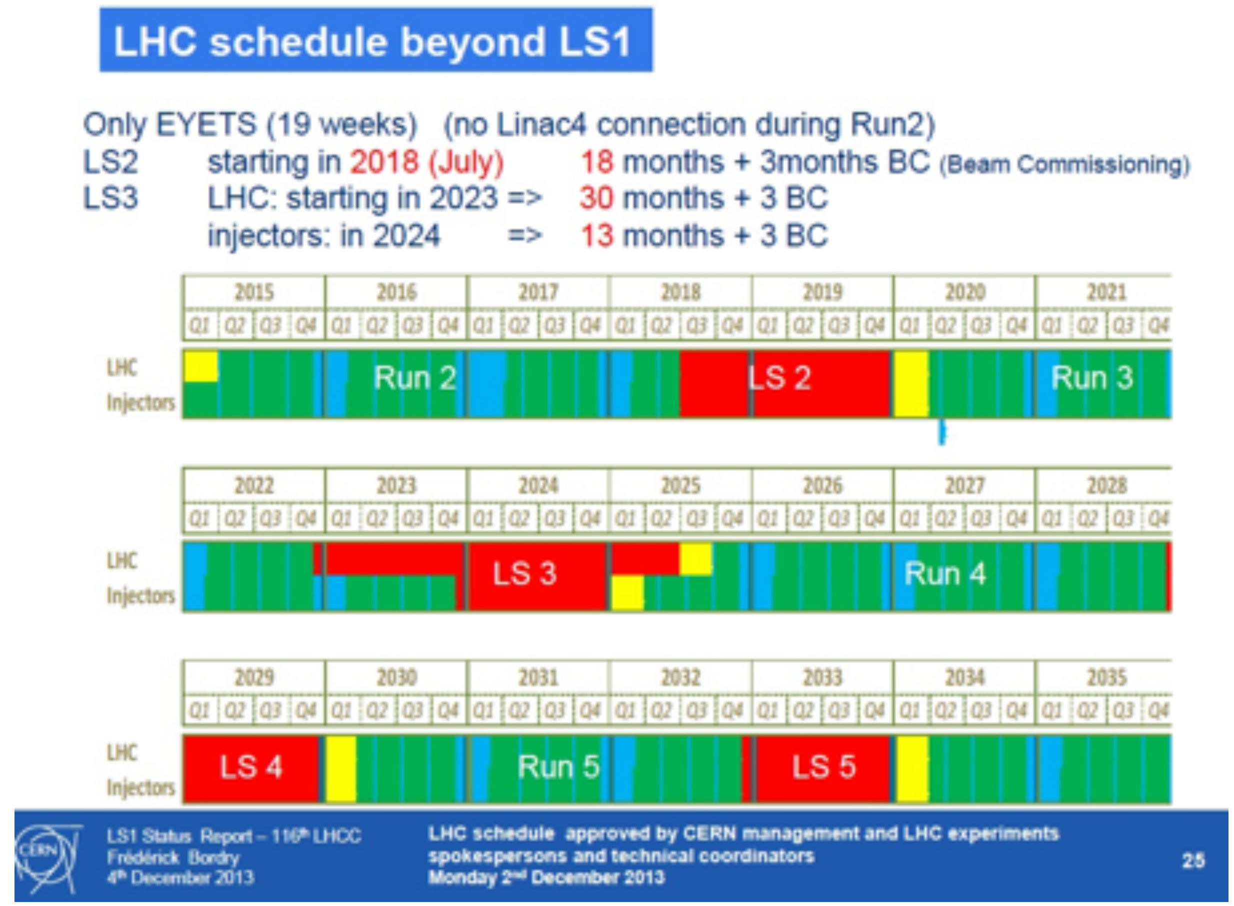


Felix Yu, 2013

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

Immediate future: LHC run 2 - run 5





- Restarted, at higher energy and intensity
  - E_{cm} = 13-14 TeV.
  - 10s and ultimately 100+ more data.