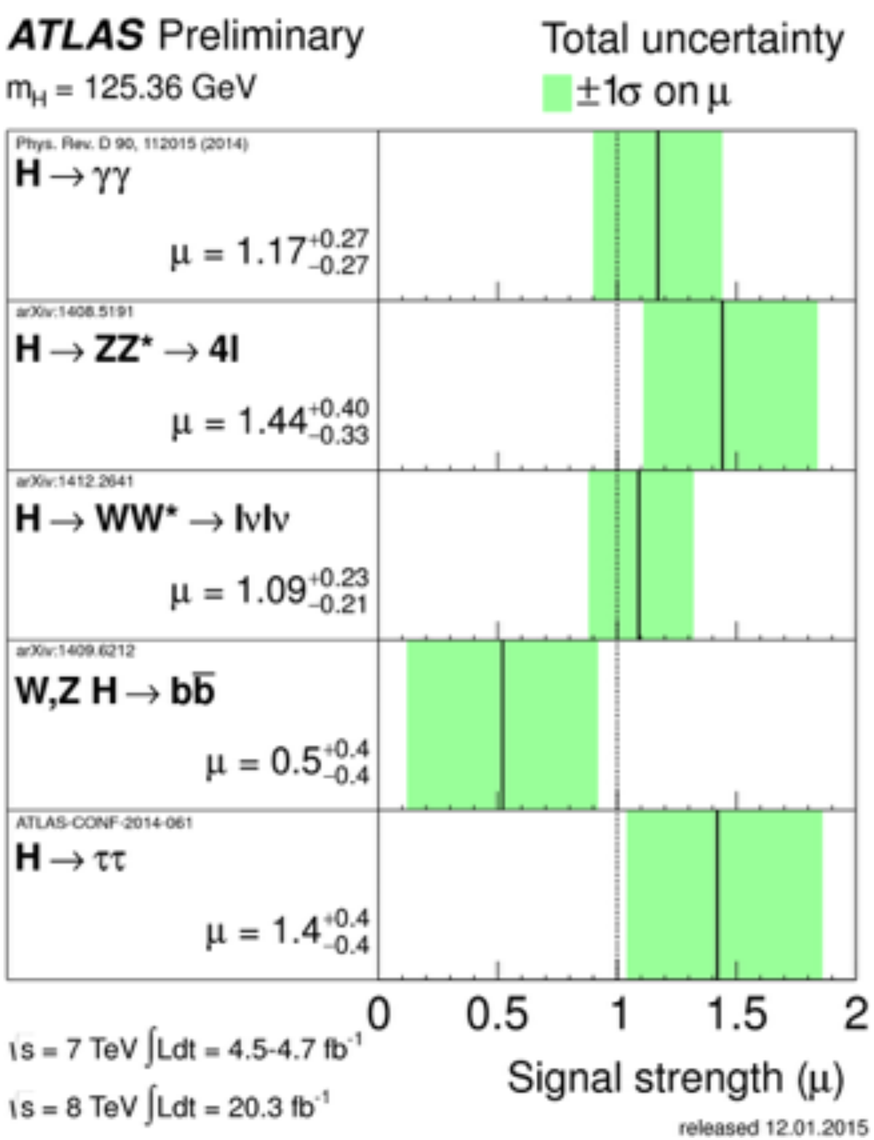
Physics of next colliders: Theory perspective

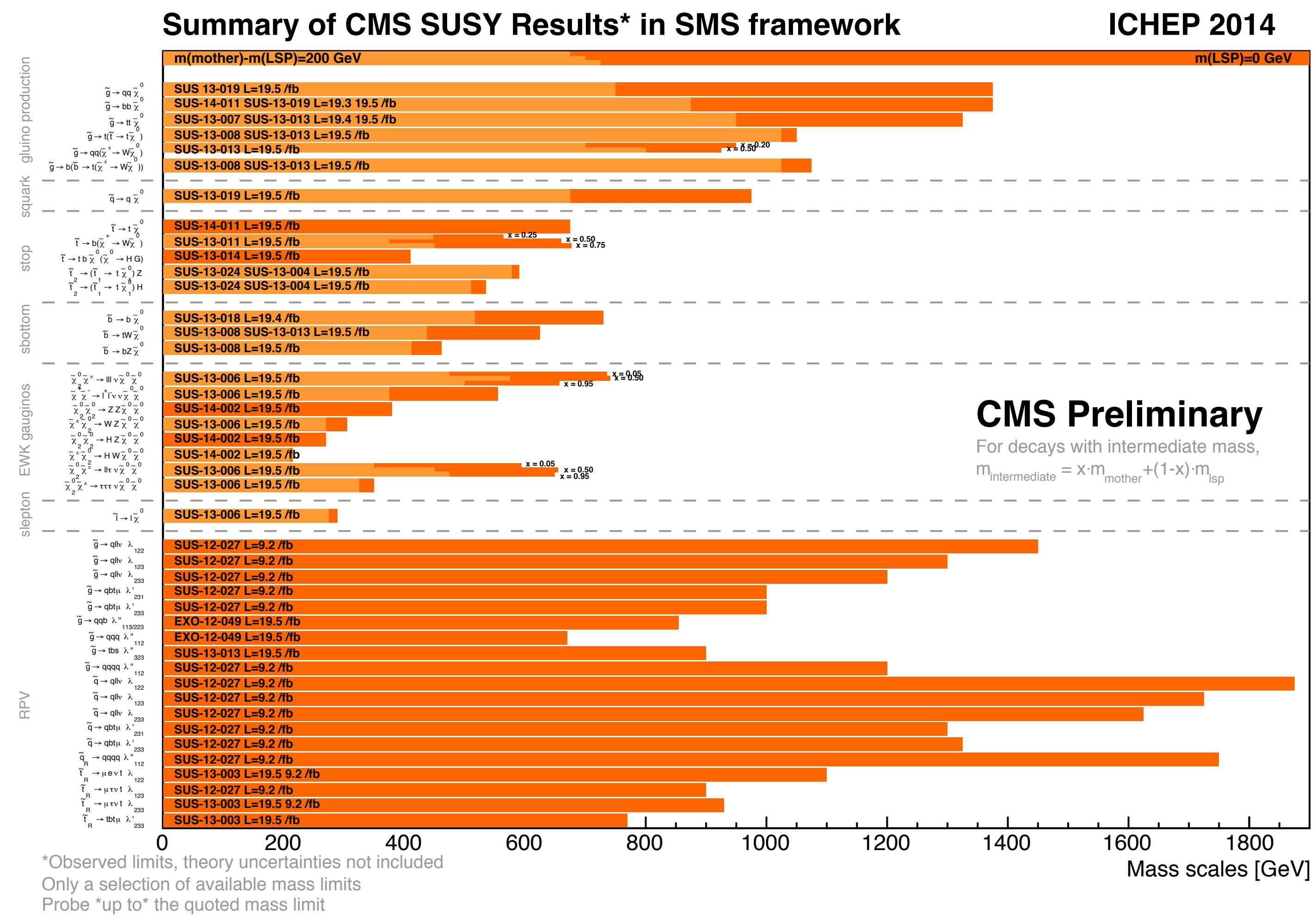
LianTao Wang
University of Chicago

Higgs Hunting 2015. LAL, France. Aug. 1, 2015

Learned a lot from LHC Run I!

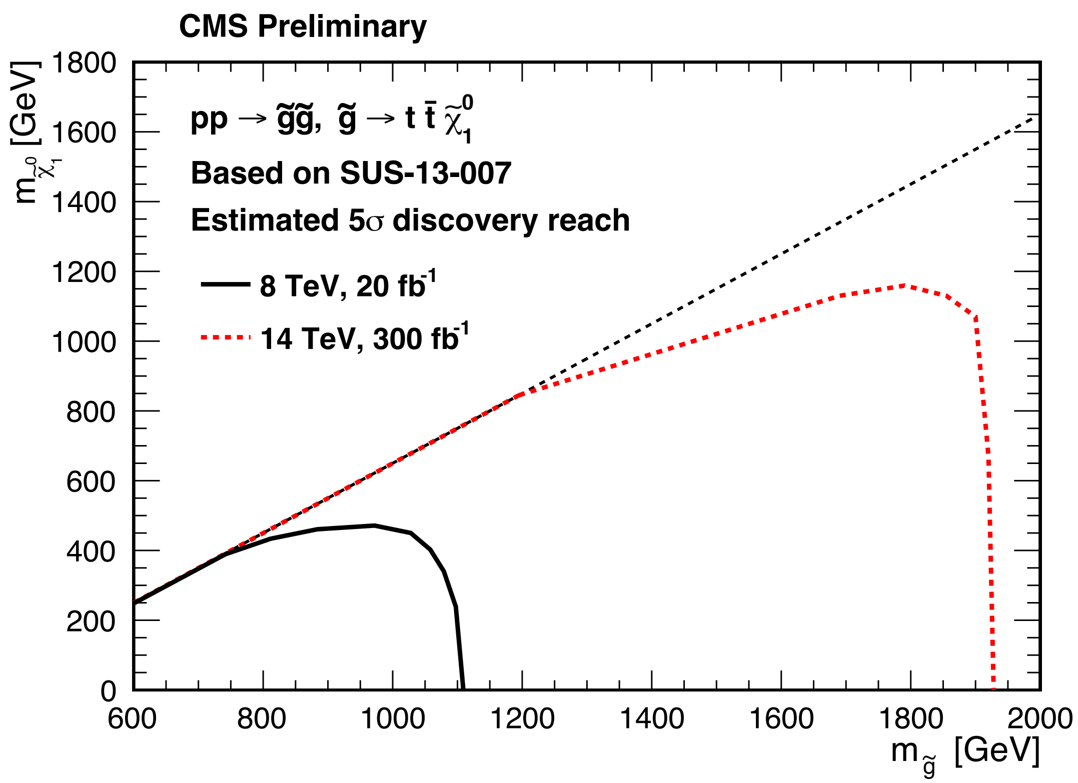


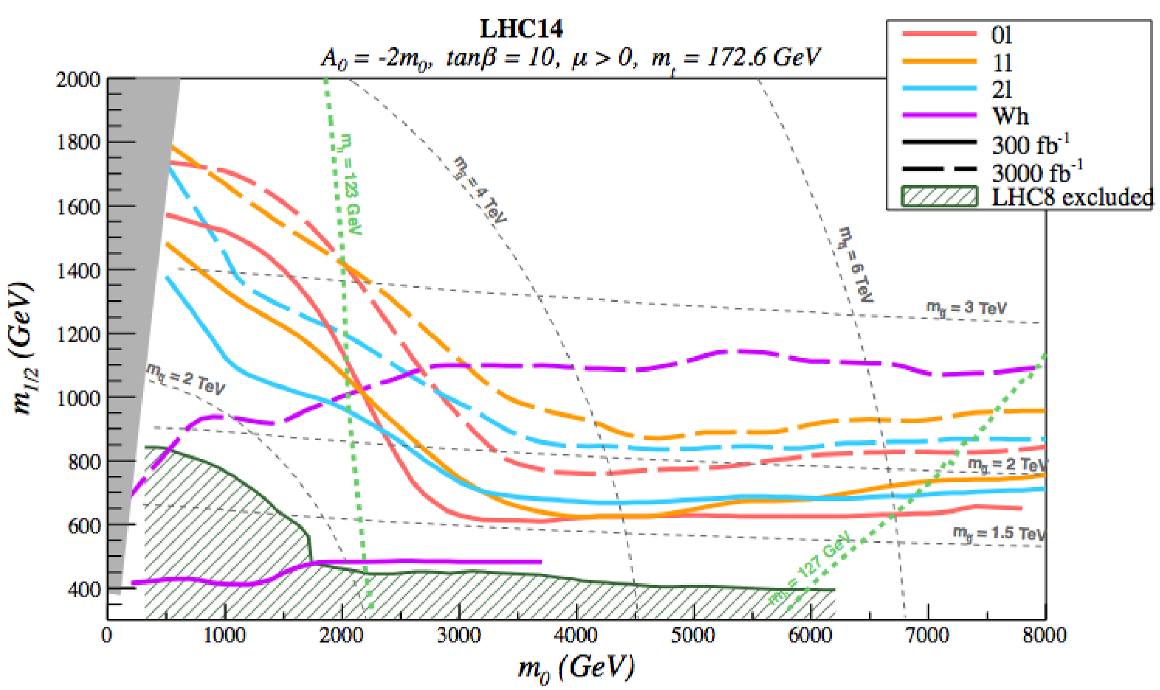
Found Higgs

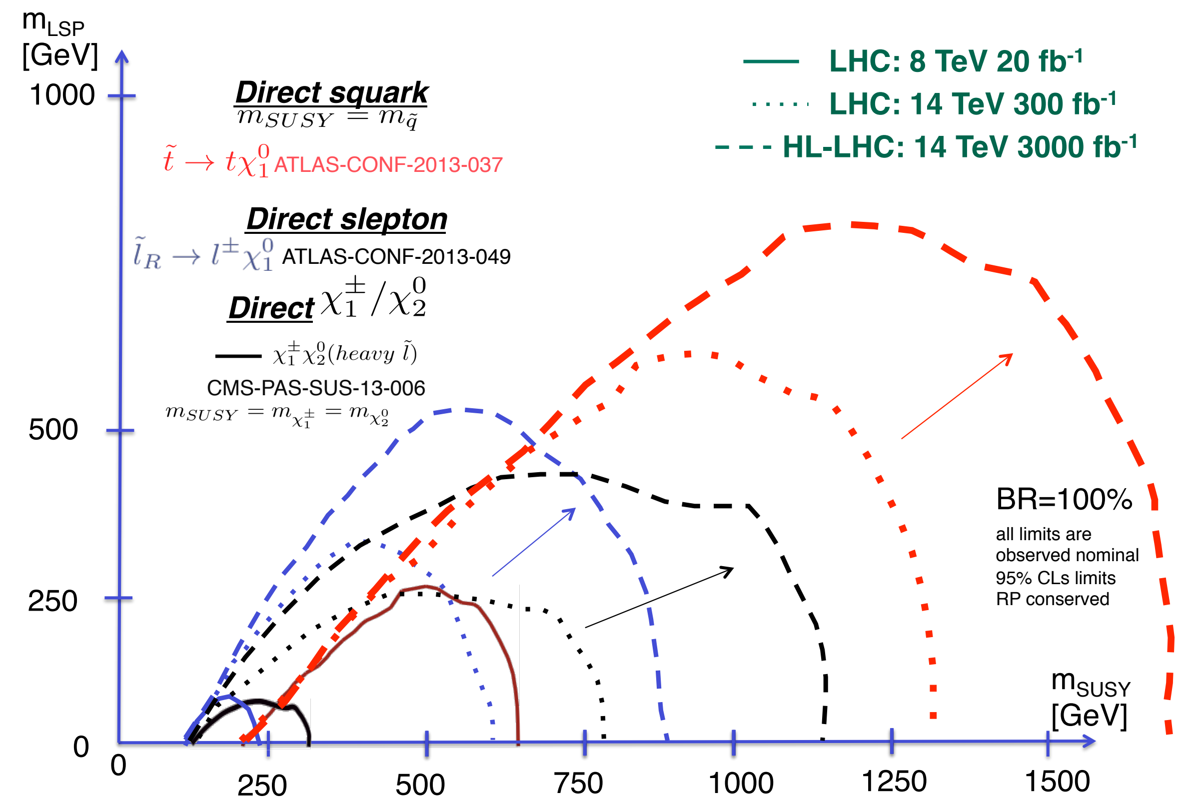


None observation of other new physics

Run II will turn a big corner







Virdee, LHCP 2014

New physics could be right there!

Finer details of the Higgs

channel	Prec. (%) 100 fb^{-1}	Prec. (%) 300 fb^{-1}		Prec. (%) 3000 fb^{-1}	
ttH $H \rightarrow \gamma\gamma$	~65	38	36	17	12
ttH $H \rightarrow ZZ^* \rightarrow 4l$	~85	49	48	20	16
VBF $H \rightarrow \gamma\gamma$	~80	47	43	22	15
VBF $H \rightarrow ZZ^* \rightarrow 4l$	~60	36	33	21	16
$H \rightarrow \mu\mu$	~70	39	38	16	12
$H \rightarrow \tau\tau$	~18	14	8	8	5
$H \rightarrow bb$	~20	14	11	7	5
$H \rightarrow \gamma\gamma$	~15	12	6	8	4
$H \rightarrow 4l$	~15	11	7	9	4
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$H\to 4l$	~15	11	7	9	4
$H\to 4l$	~15	11	7	7	4

Higgs Hunting → Higgs gathering, or "tasting"

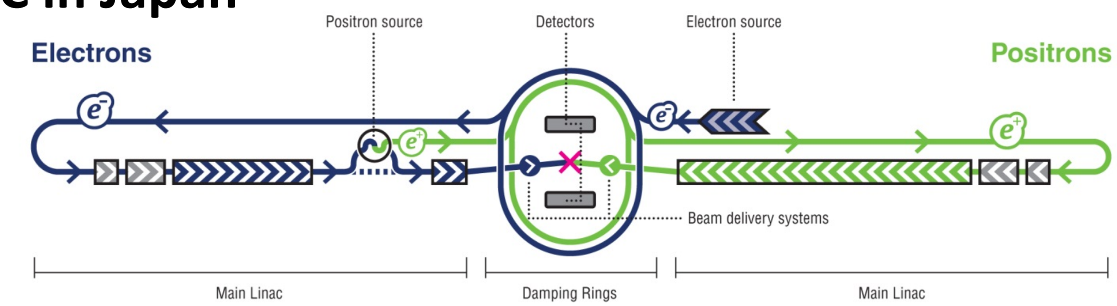
Open questions beyond LHC

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

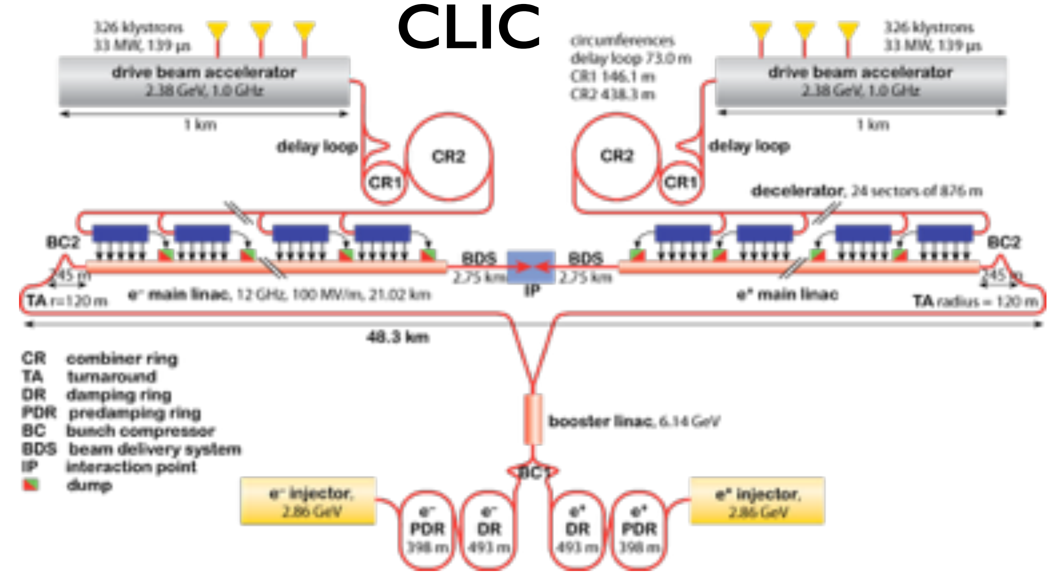
Need to go beyond

Beyond the LHC, future facilities

ILC in Japan



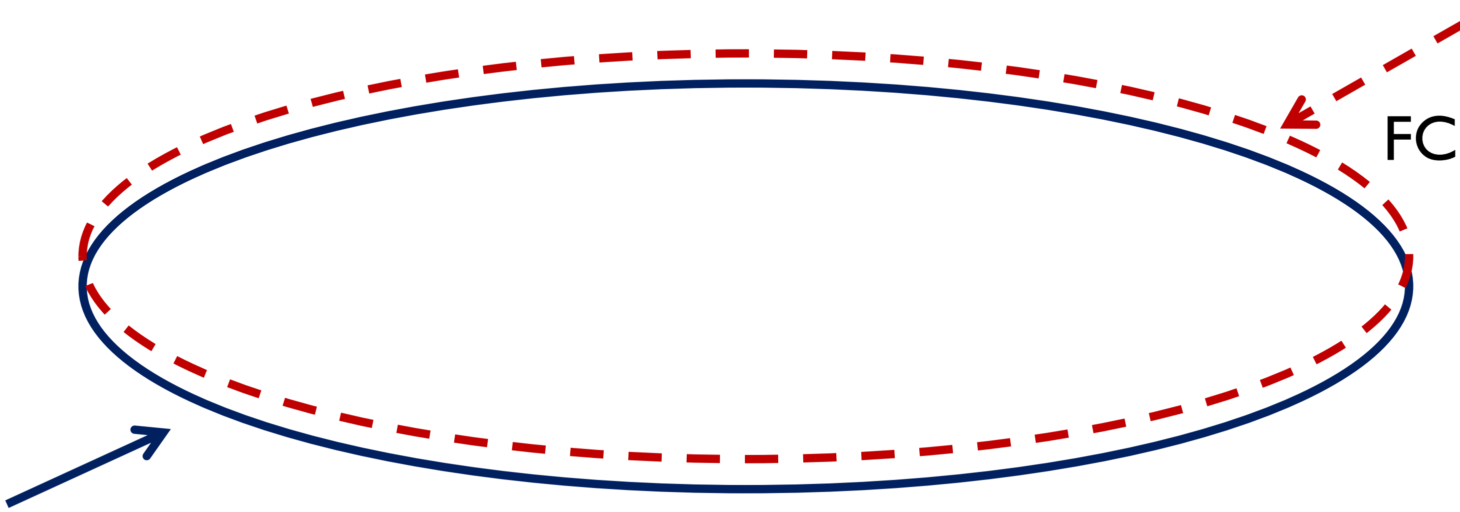
CLIC



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)

Beyond the LHC, future facilities

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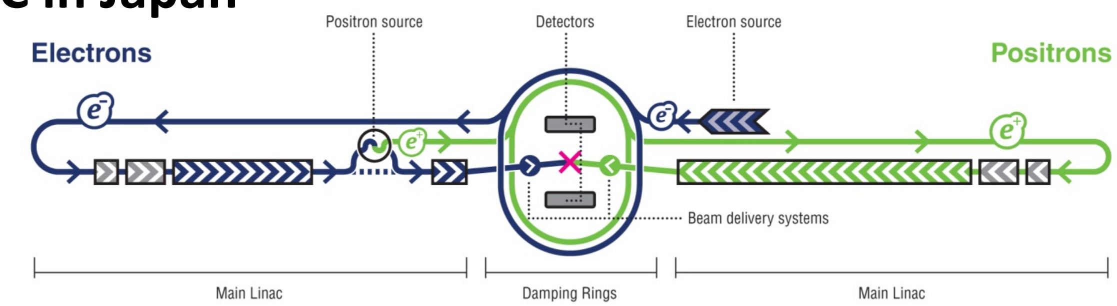

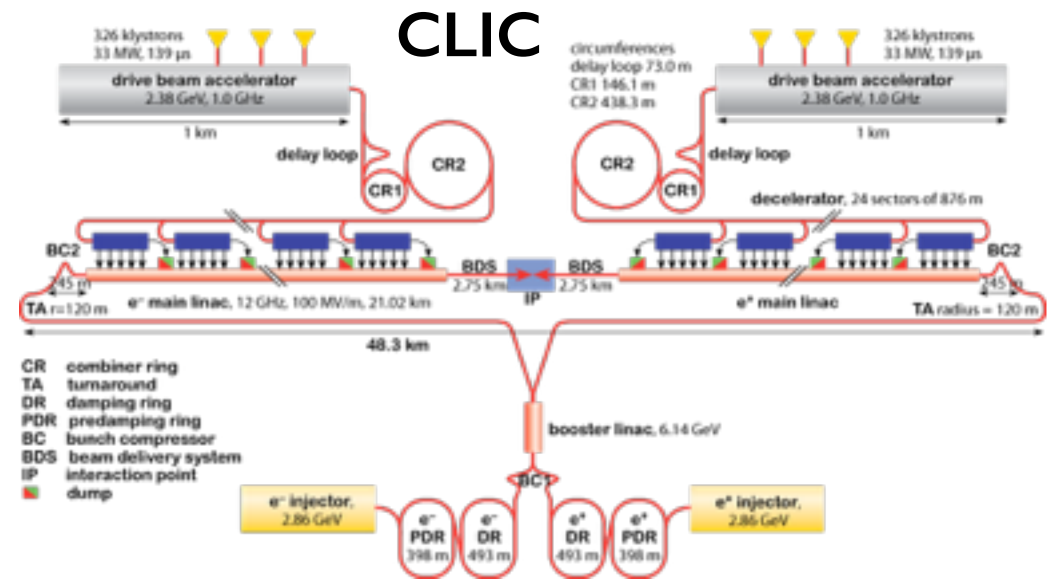

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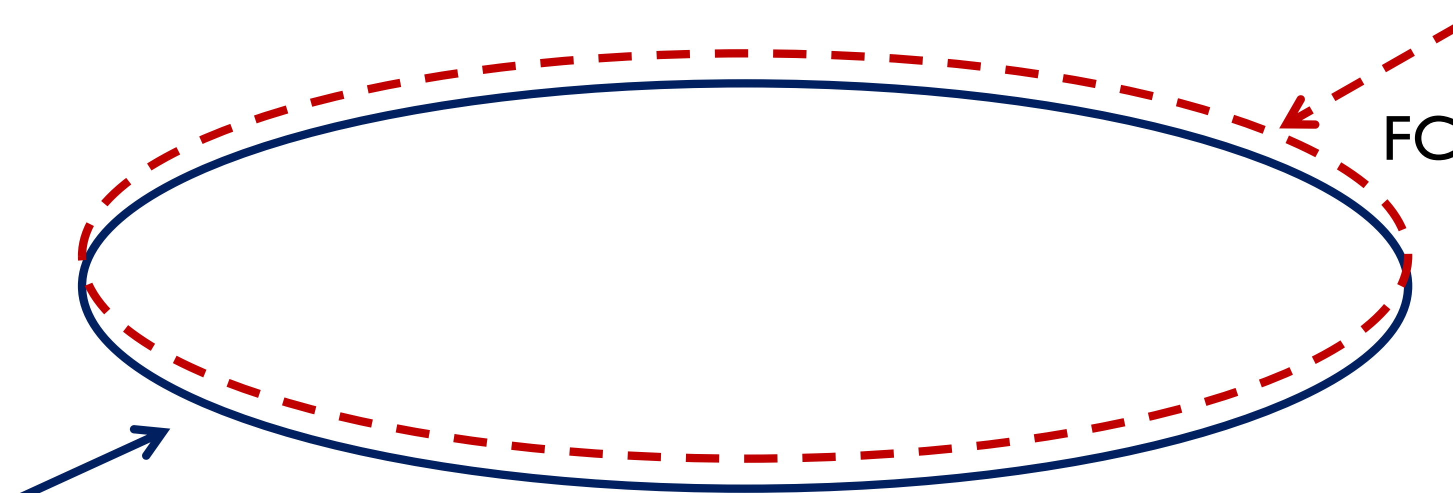
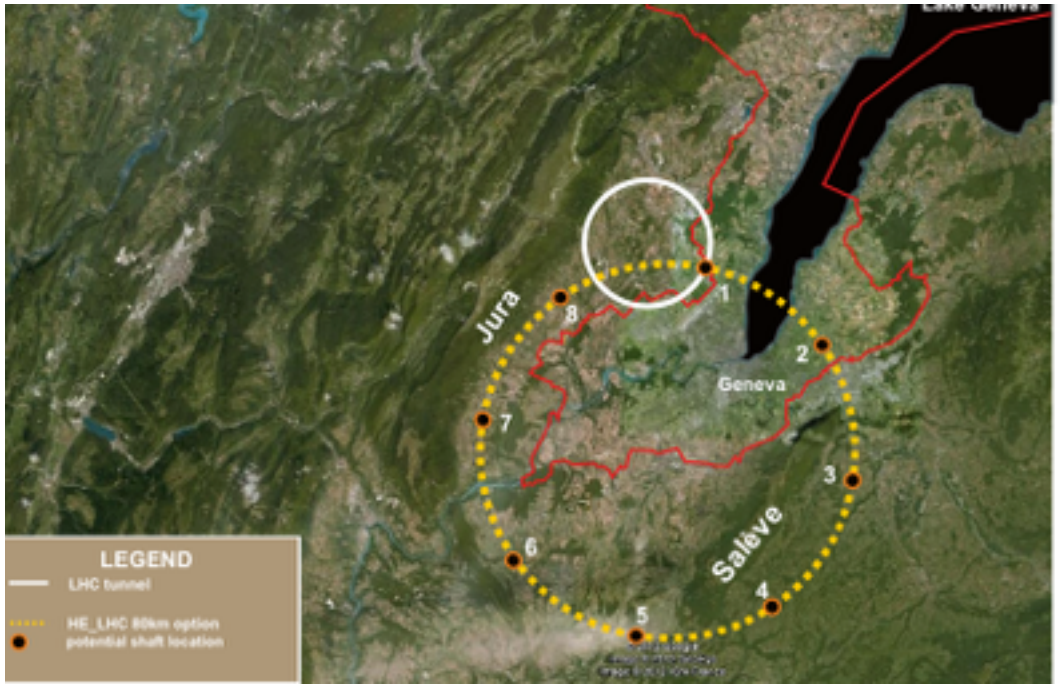


250 GeV **e^-e^+ Higgs Factory**

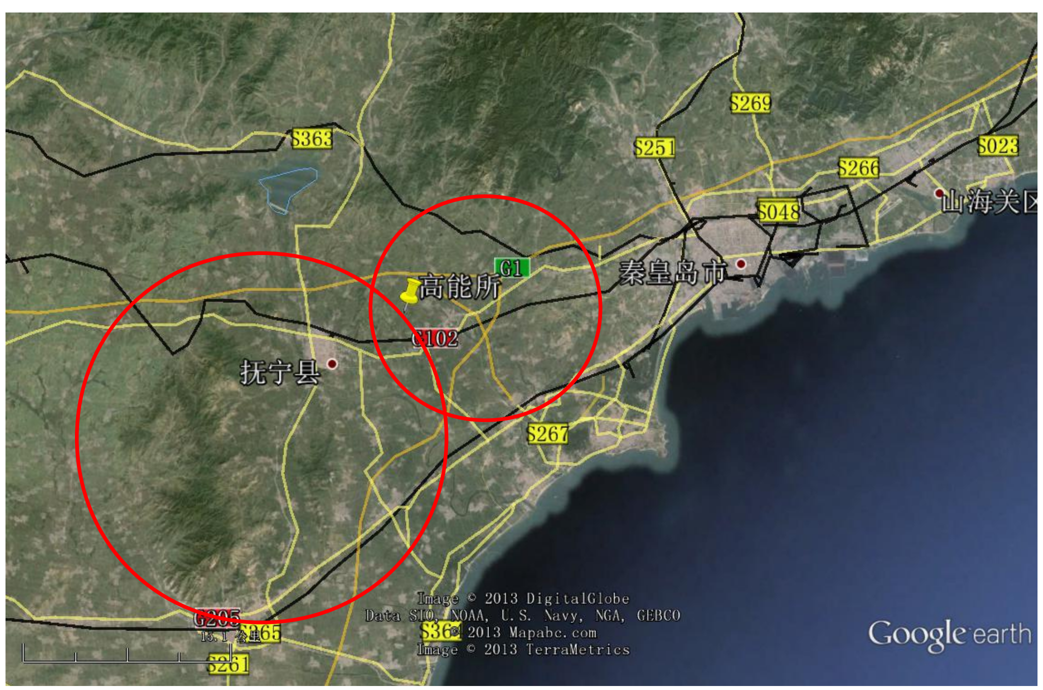
FCC-ee (CERN), CEPC(China)

I will focus on
the circular colliders
in this talk

Future circular colliders



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



China.
Higgs factory: CEPC
pp Collider: SppC

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.
- However, still just scratched surface.
  - Focused on most “obvious” cases.
  - Need to go deeper, address many open questions.
  - What should be done theoretically to take full advantages of the next generation circular colliders?

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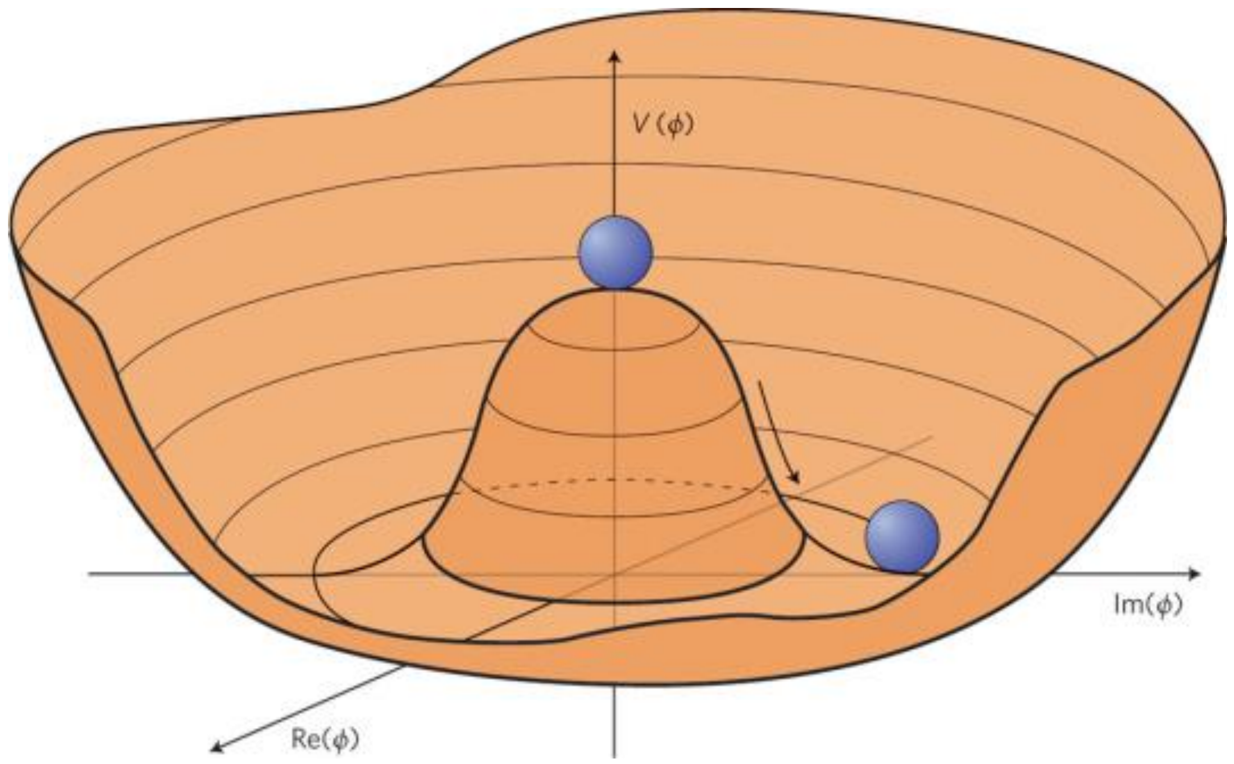
this talk

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.

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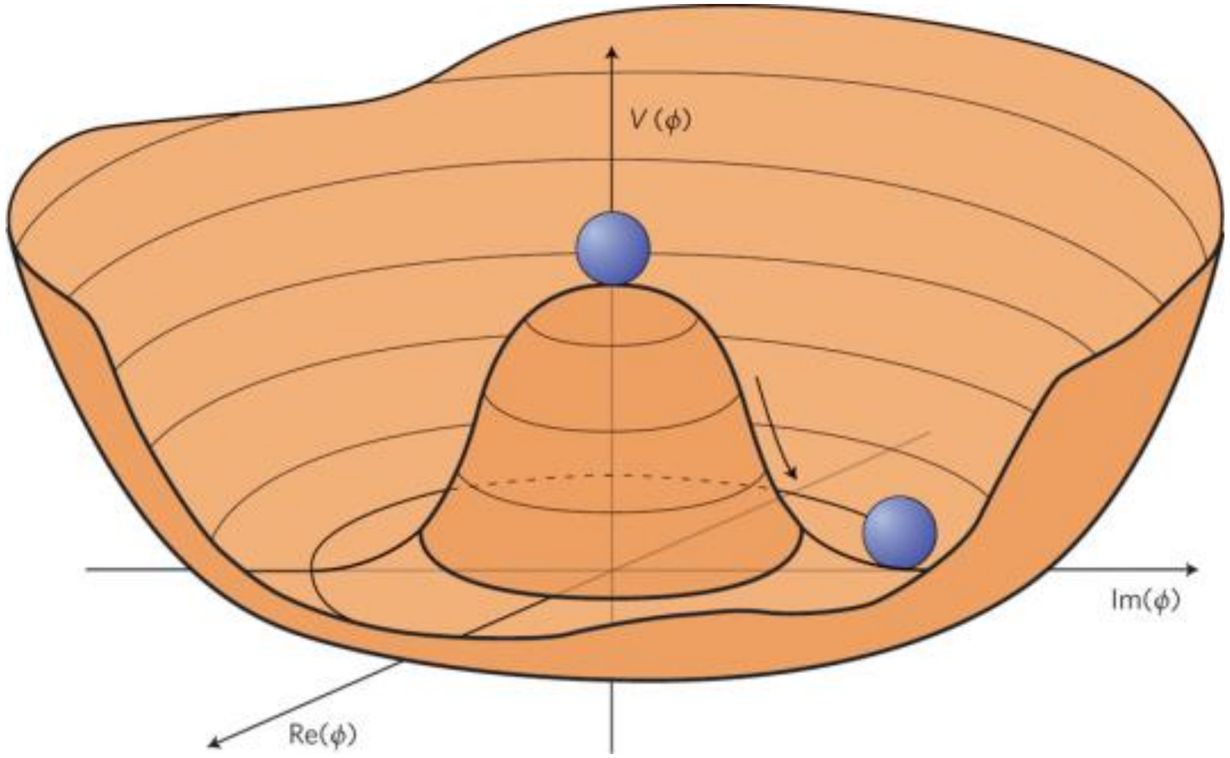

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Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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.

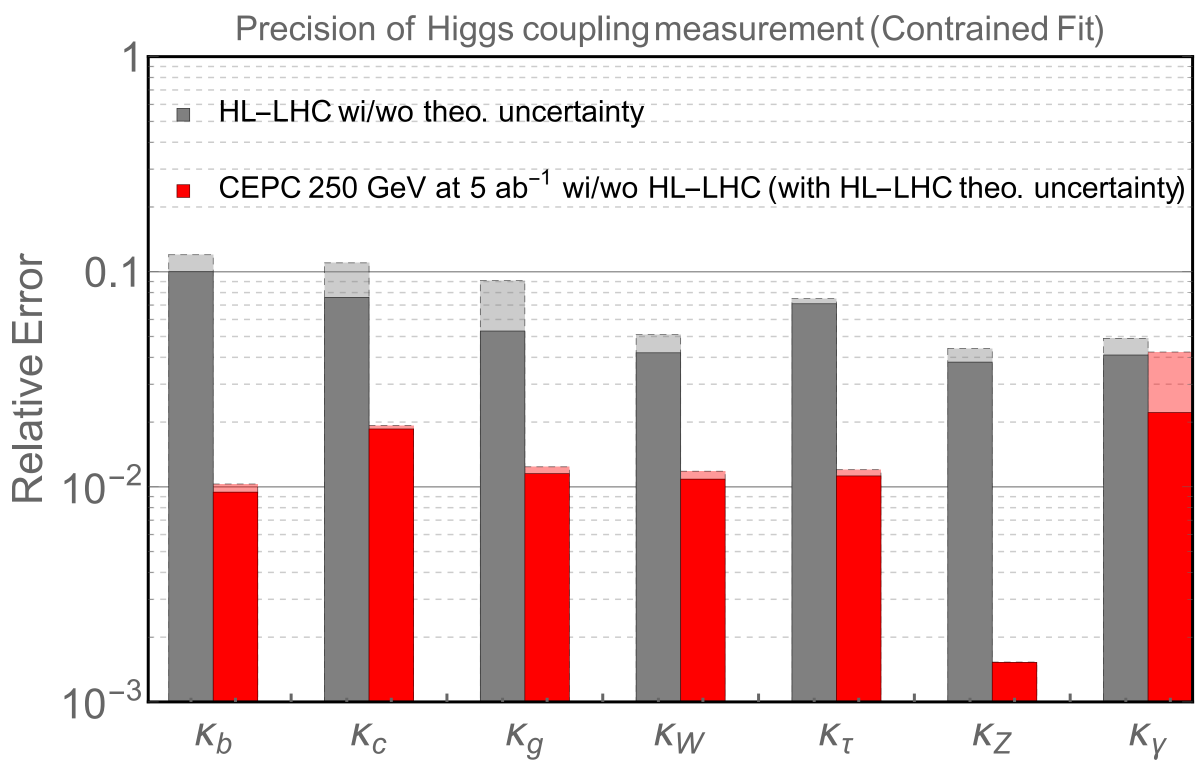
- We are going after deviations of the form

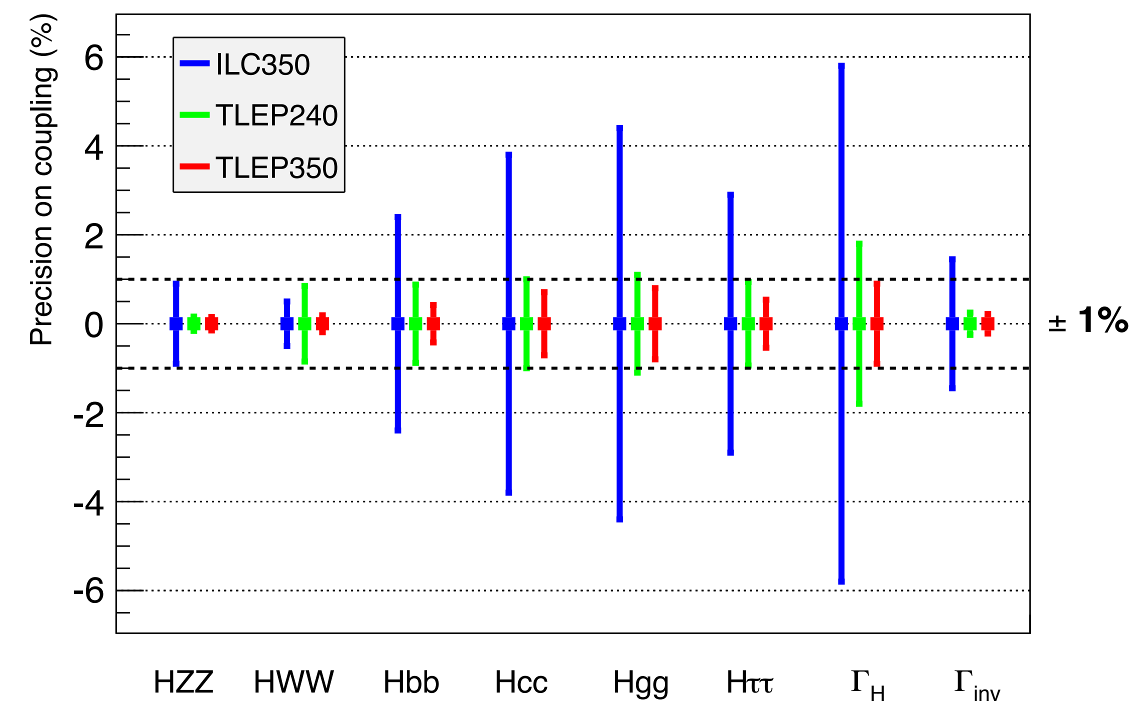
$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

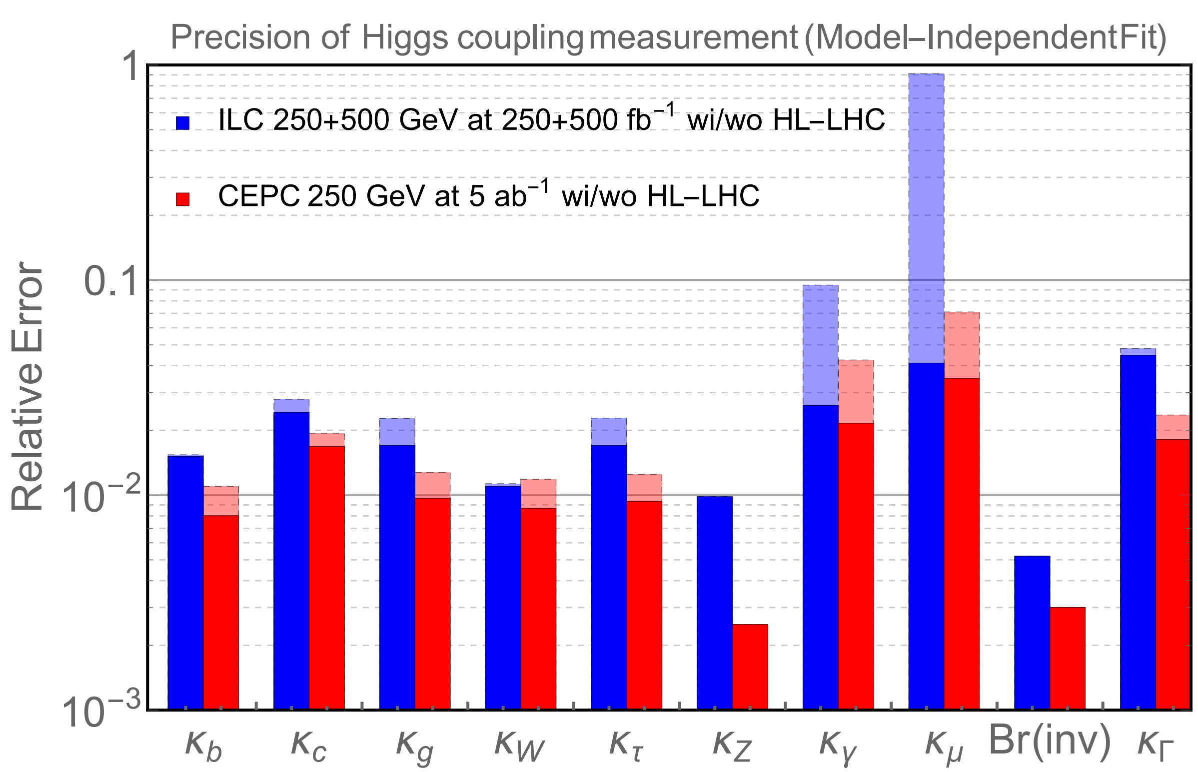
M_{NP} : mass of new physics
c: $O(1)$ coefficient

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

Higgs factories can do it.

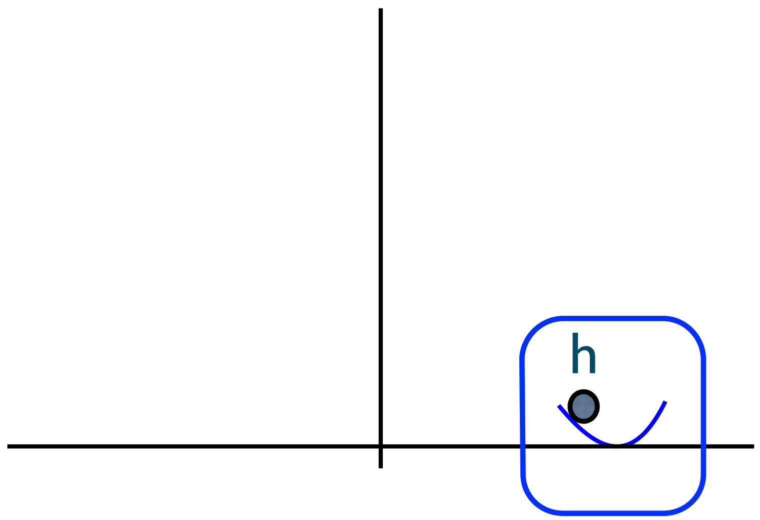






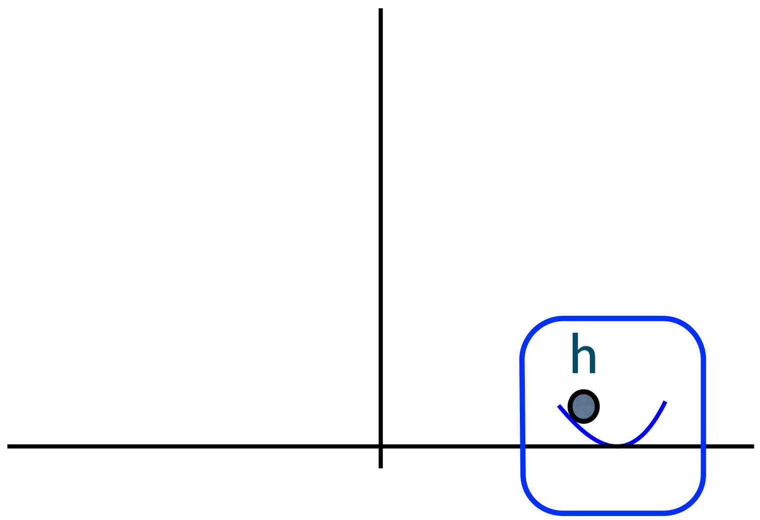
Total width.
HZ coupling to sub-percent level.
Many couplings to percent level.

Not even sure about "Mexican hat".



What we know now

Not even sure about "Mexican hat".



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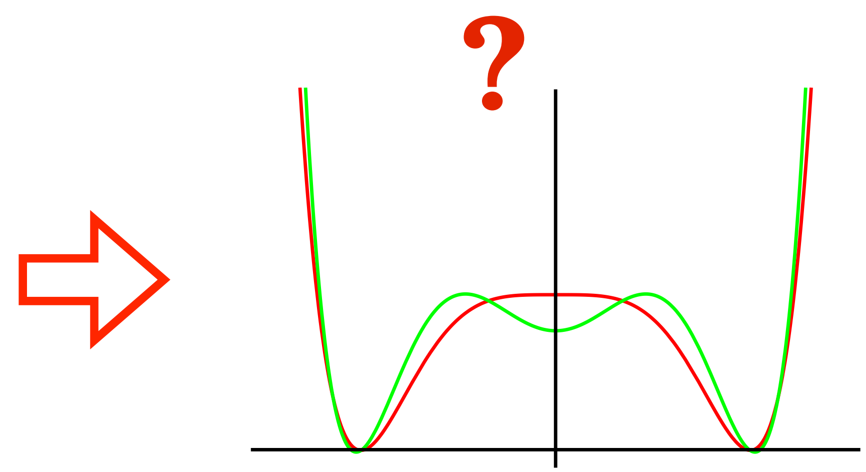
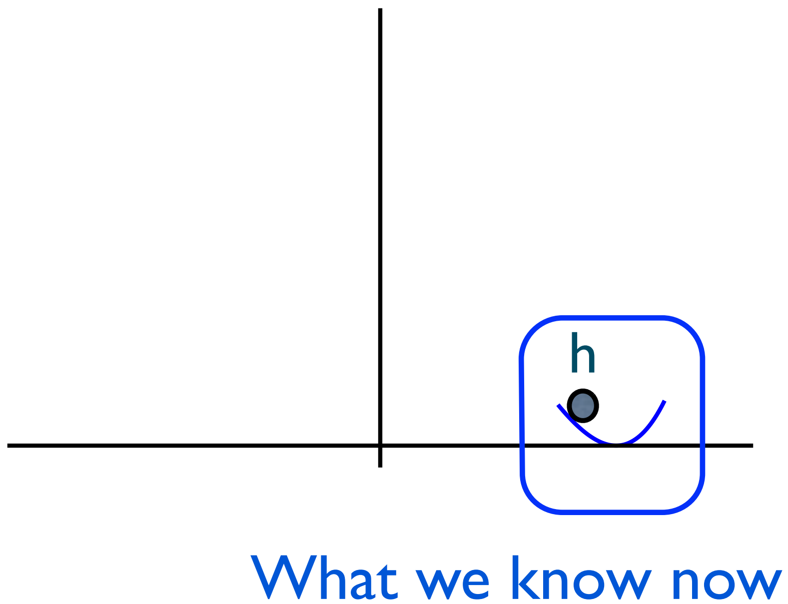
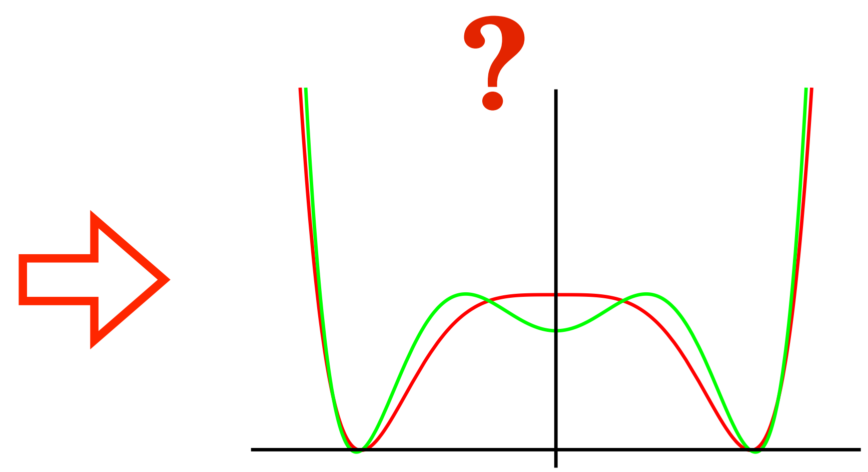


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Is the EW phase transition first order?

Not even sure about “Mexican hat”.





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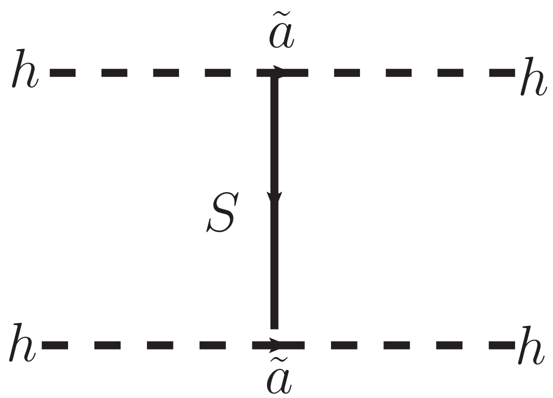
Is the EW phase transition first order?

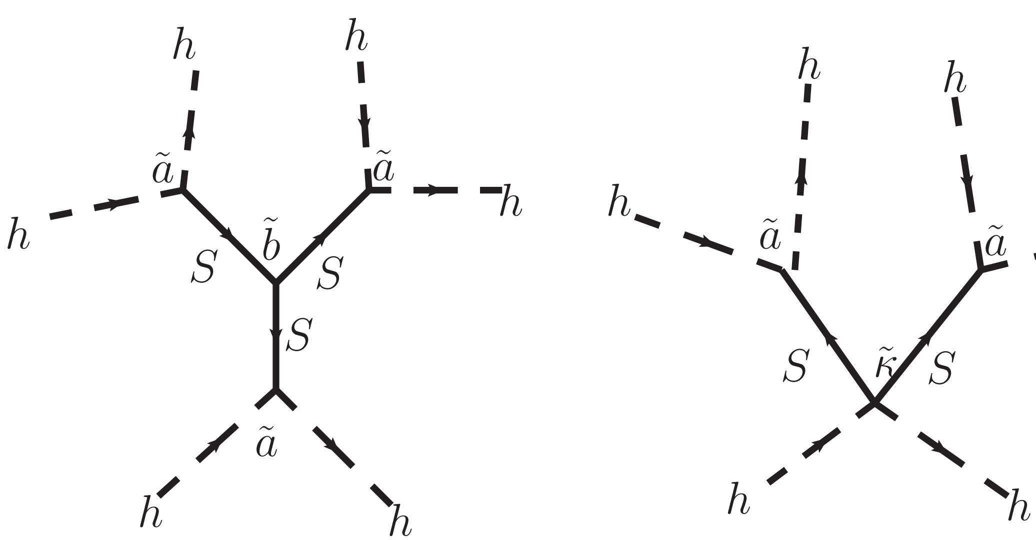
LHC can not distinguish these definitively.

Simple example: Generic singlet model

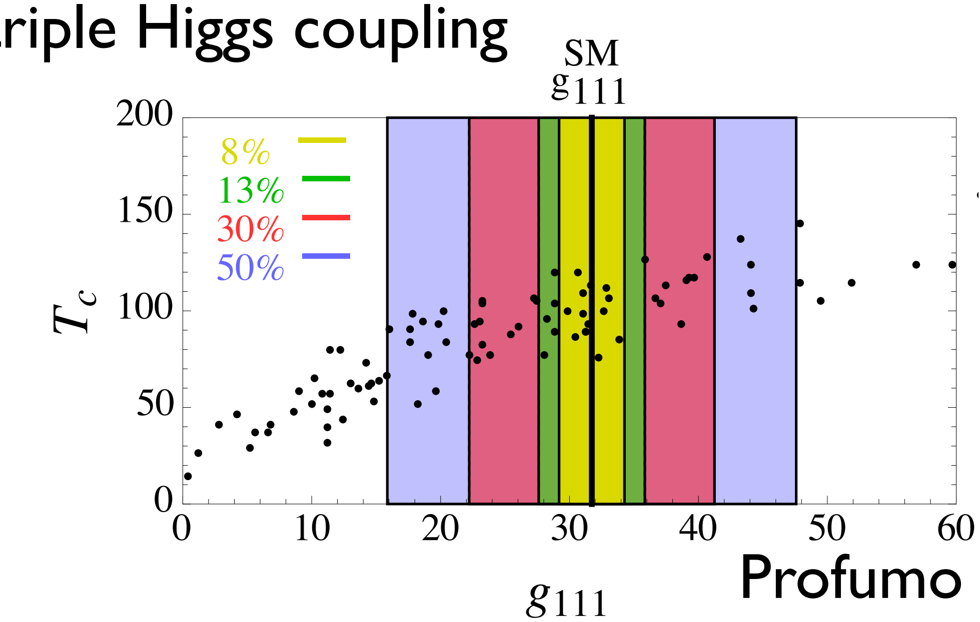
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



shift in h-Z coupling > 0.5%

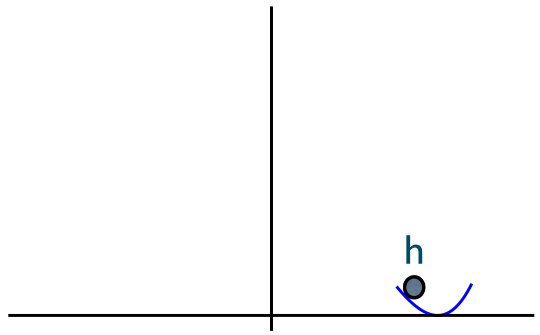


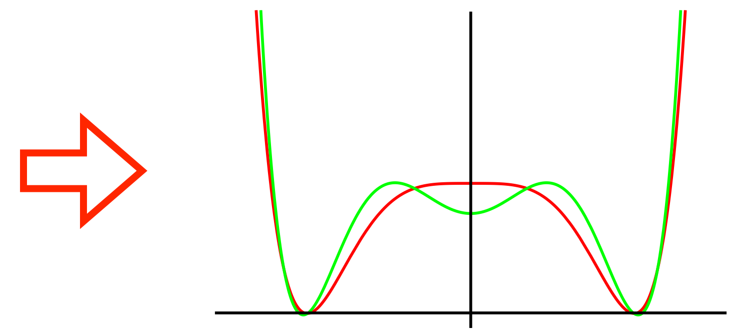
triple Higgs coupling

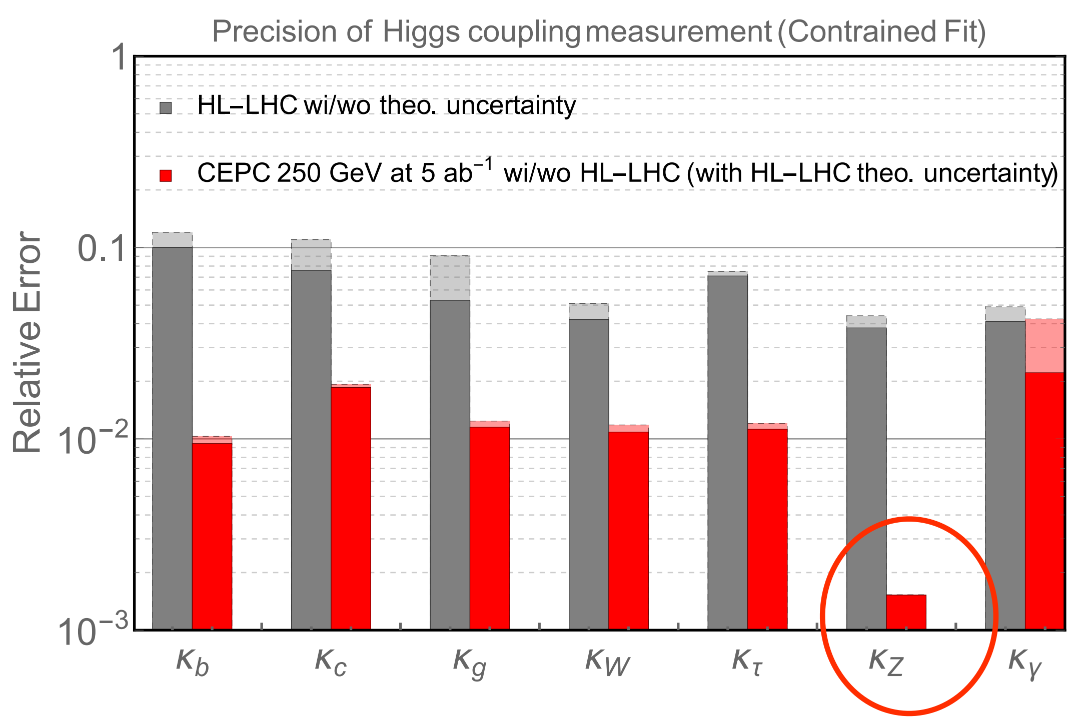


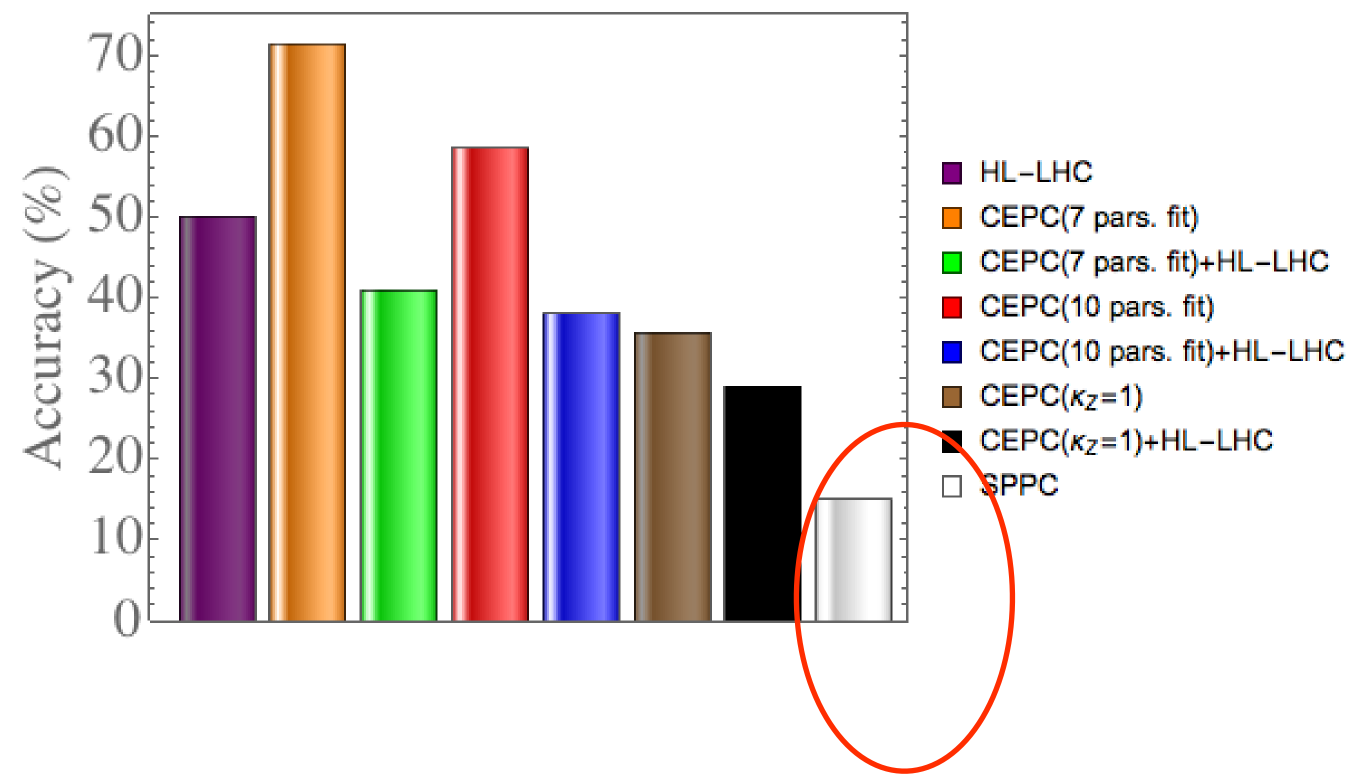
Profumo et al

Nature of EW phase transition

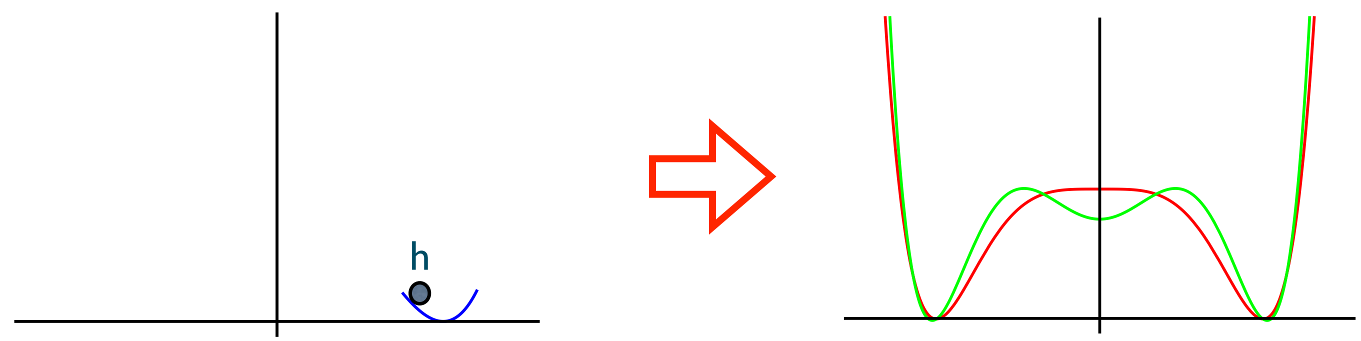


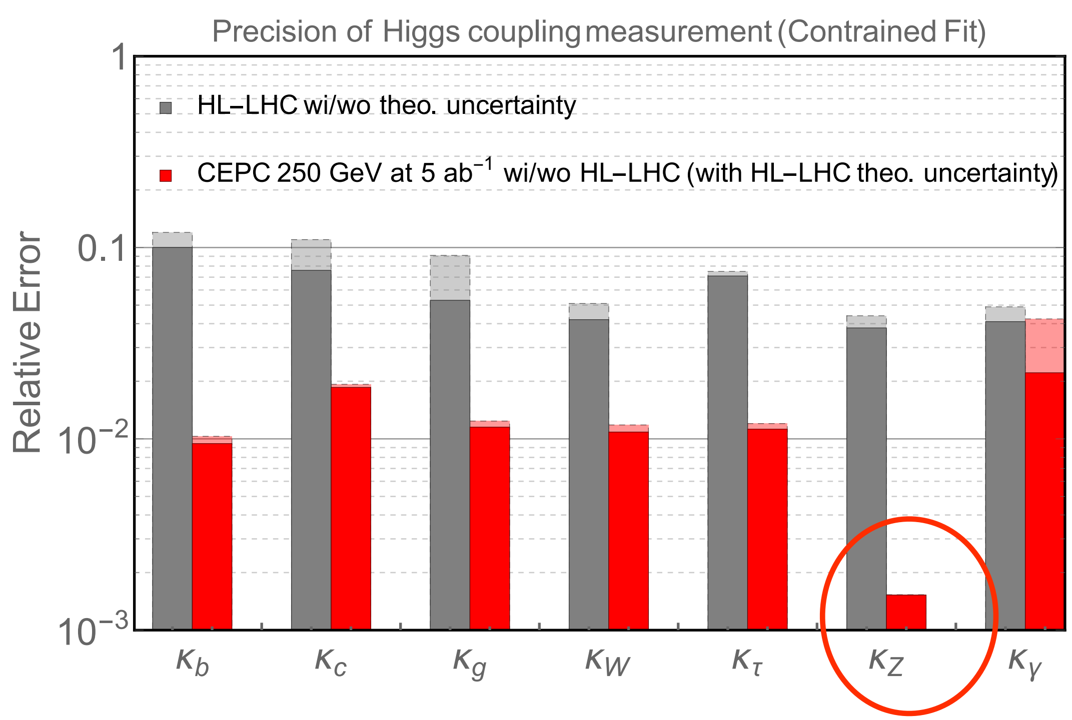


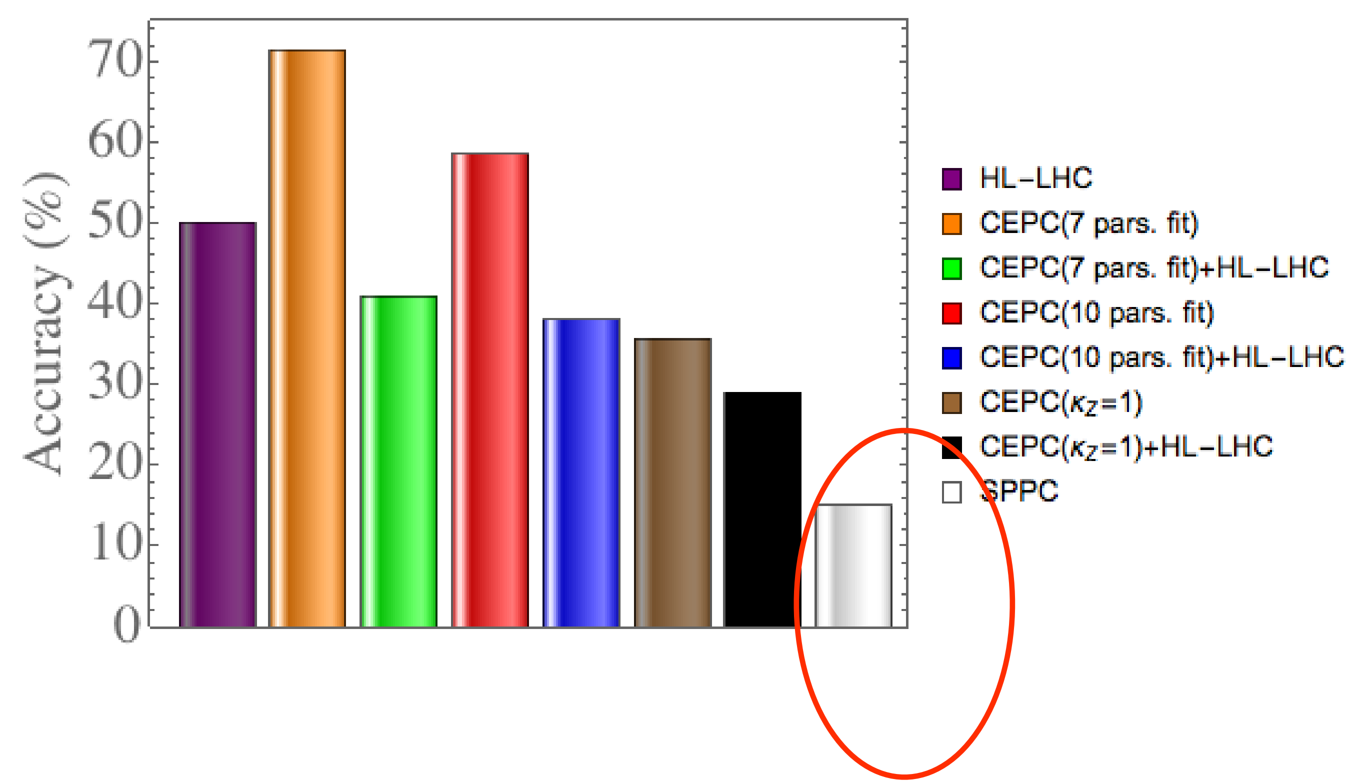




Nature of EW phase transition





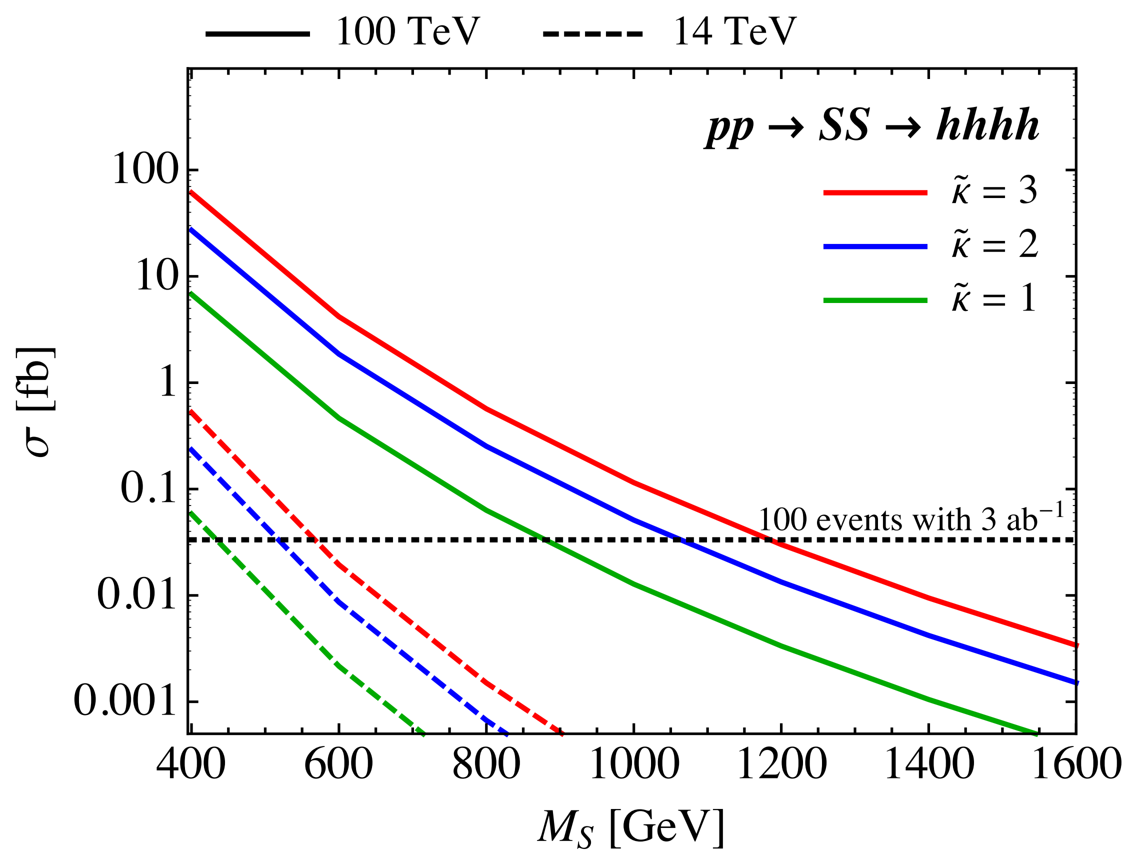


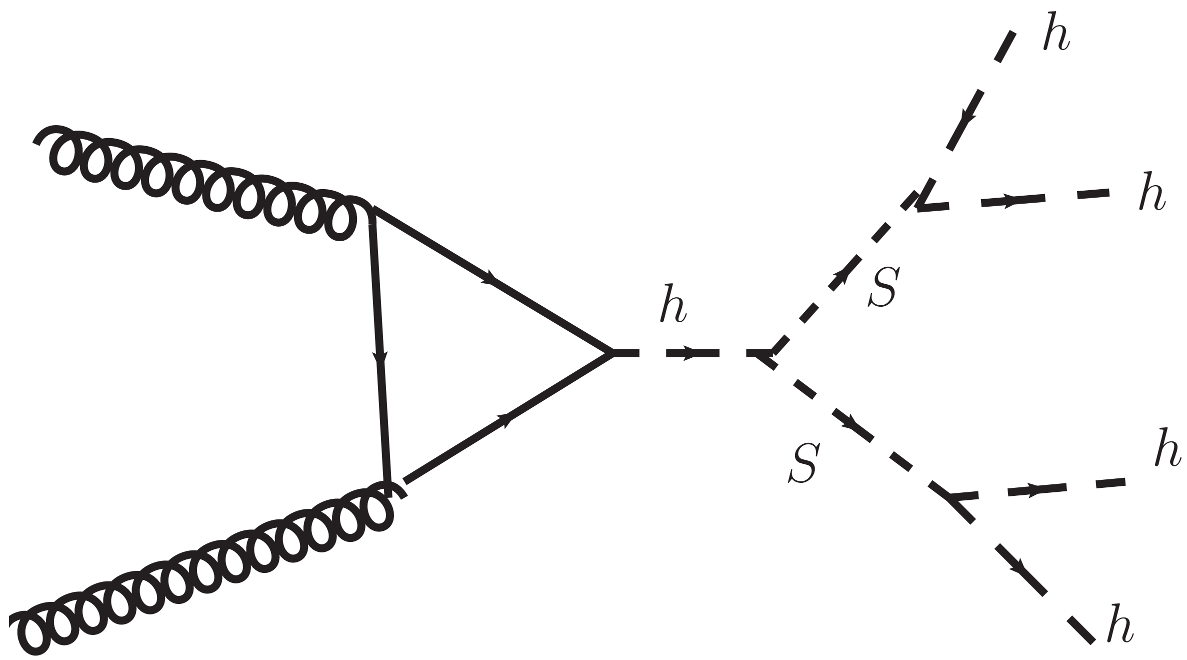
Shift in h-Z coupling > 0.5%

Order 1 deviation in triple Higgs

Both within the reach

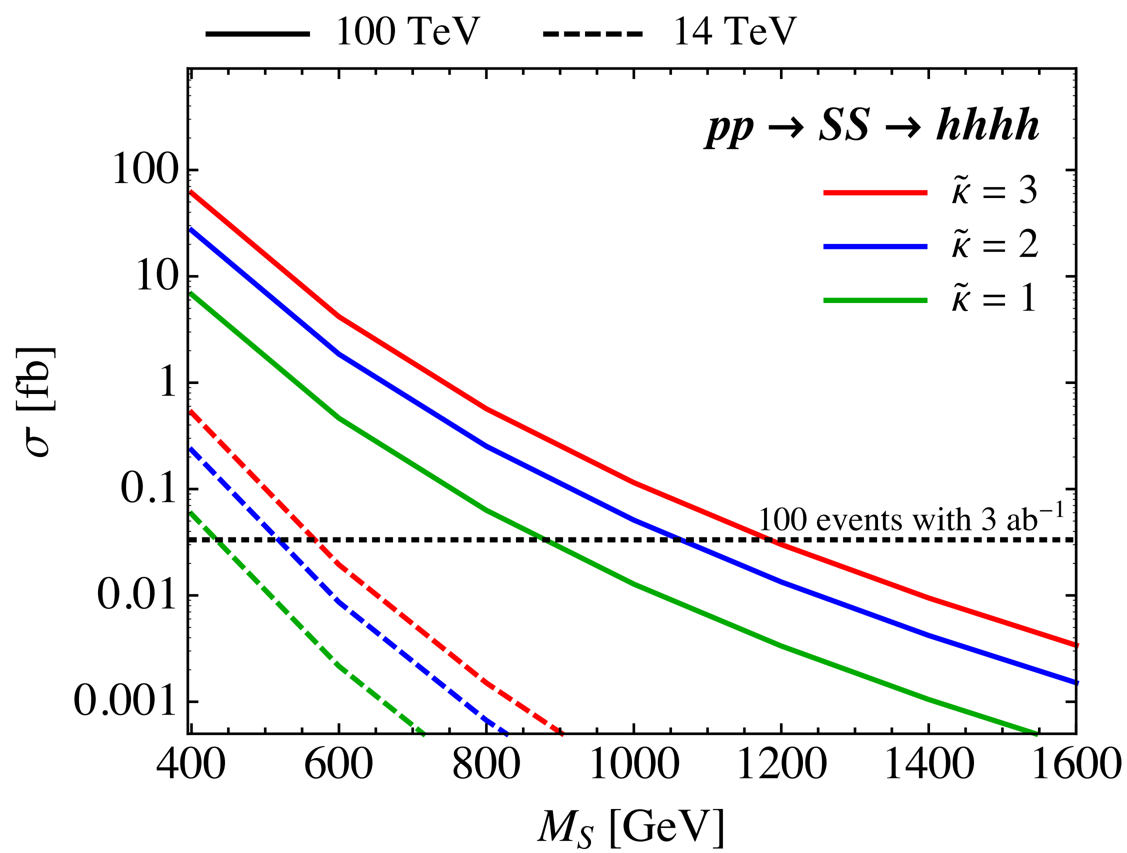
Singlet search at 100 TeV

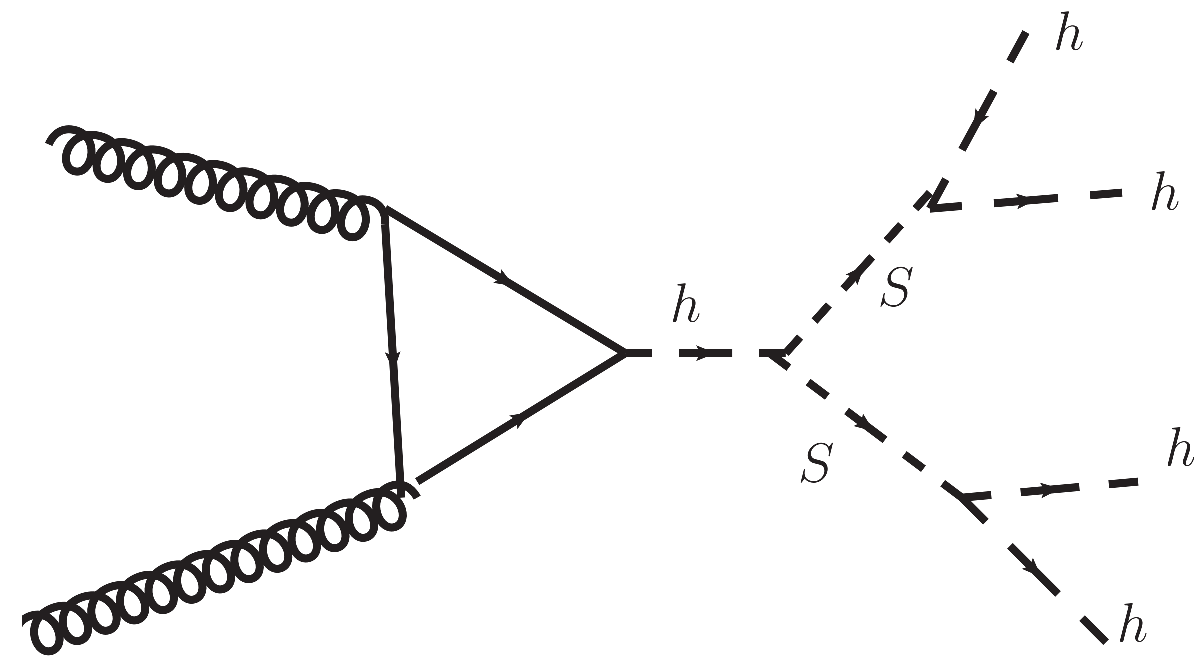




- 4 Higgs final state with decent rate.
- Good discovery potential.

Singlet search at 100 TeV





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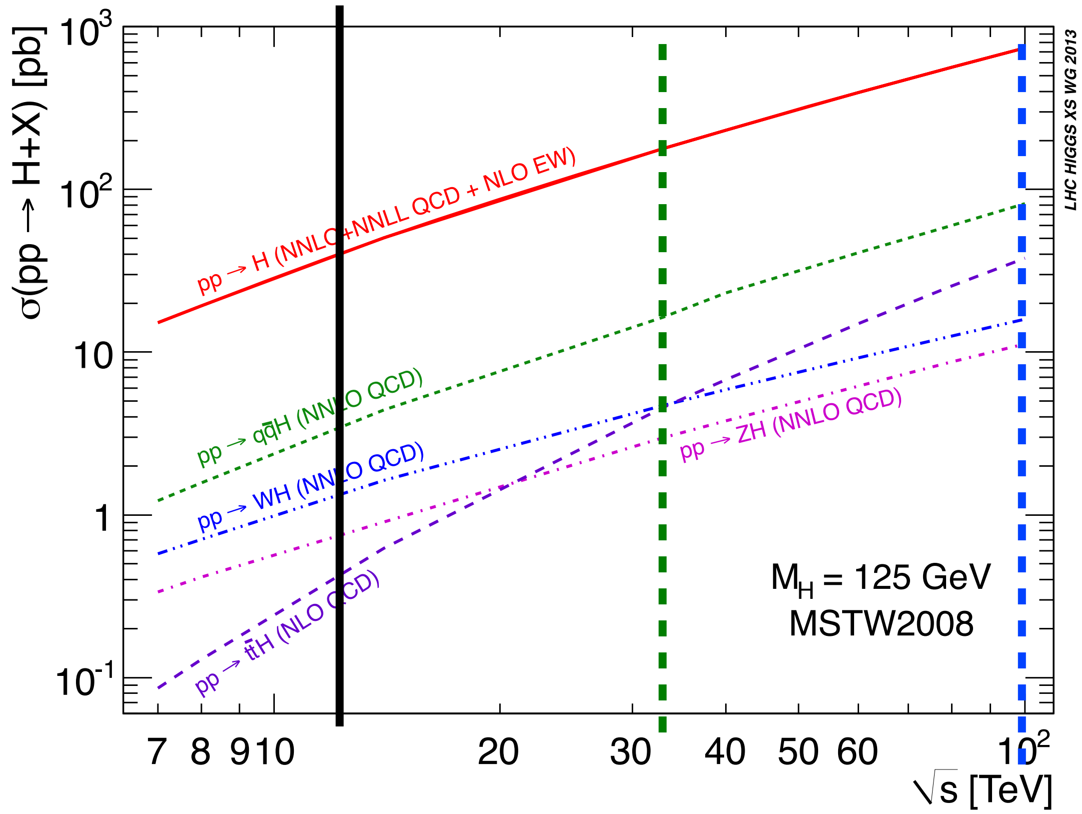
Combination of Higgs factory and 100 TeV pp collider can go very long way in understanding EWSB

More Higgs physics at hadron collider

- The ultimate Higgs factories



\# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

33 TeV > 500 million

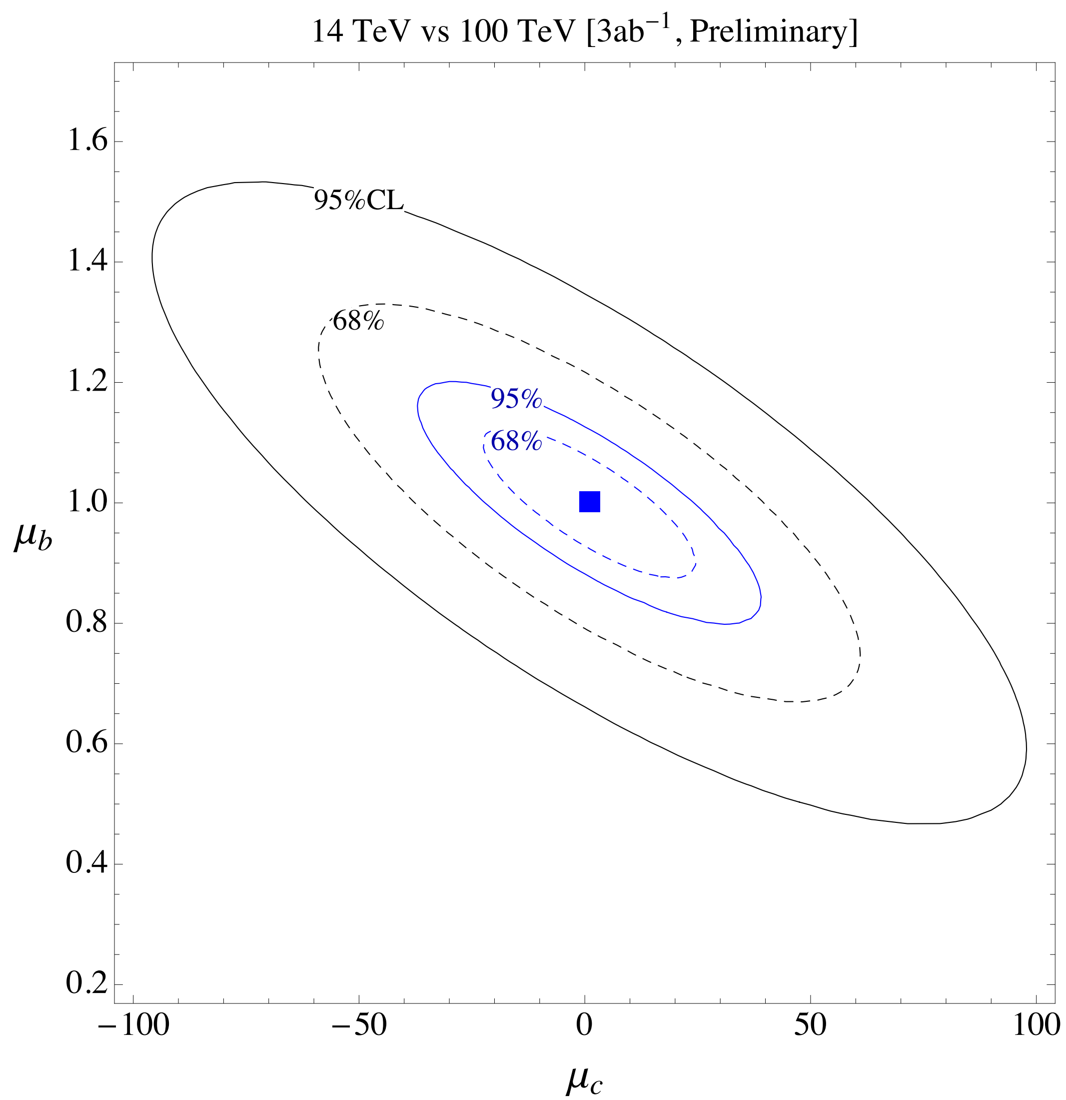
14 TeV > 150 million

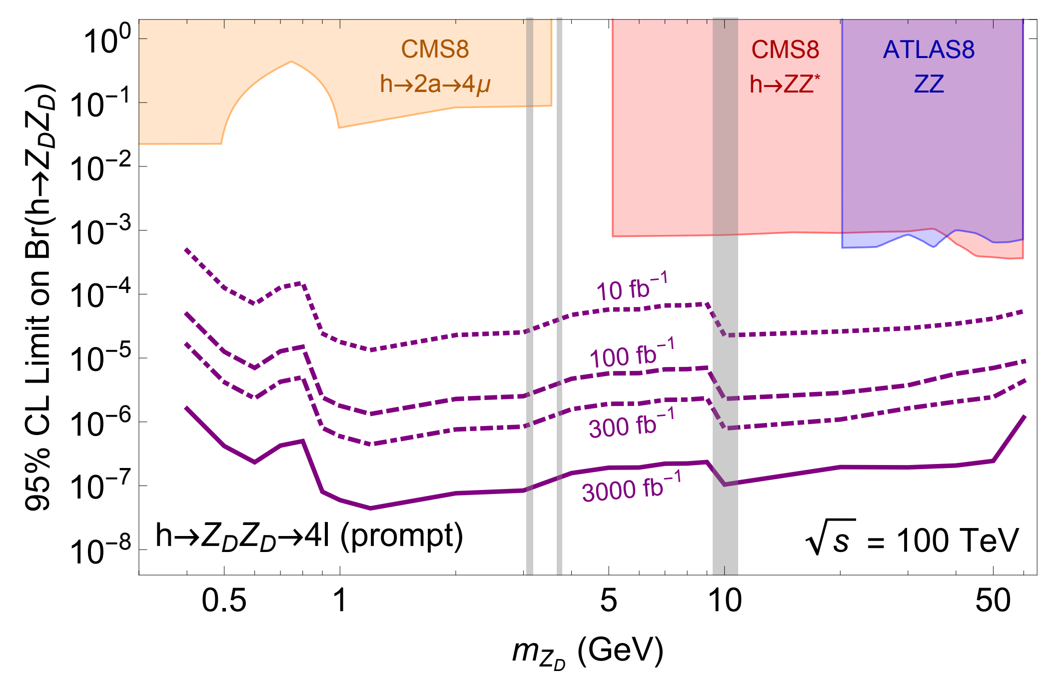
Precision calculations needed to take full advantage of this!

Amazing progress in the past couple of decades. We should be confident!

Talks by Duhr and Forte in this workshop

New physics Higgs rare decays





Higgs-coupling to charm

Perez, Soreq, Stamou, Tobioka

dark photon

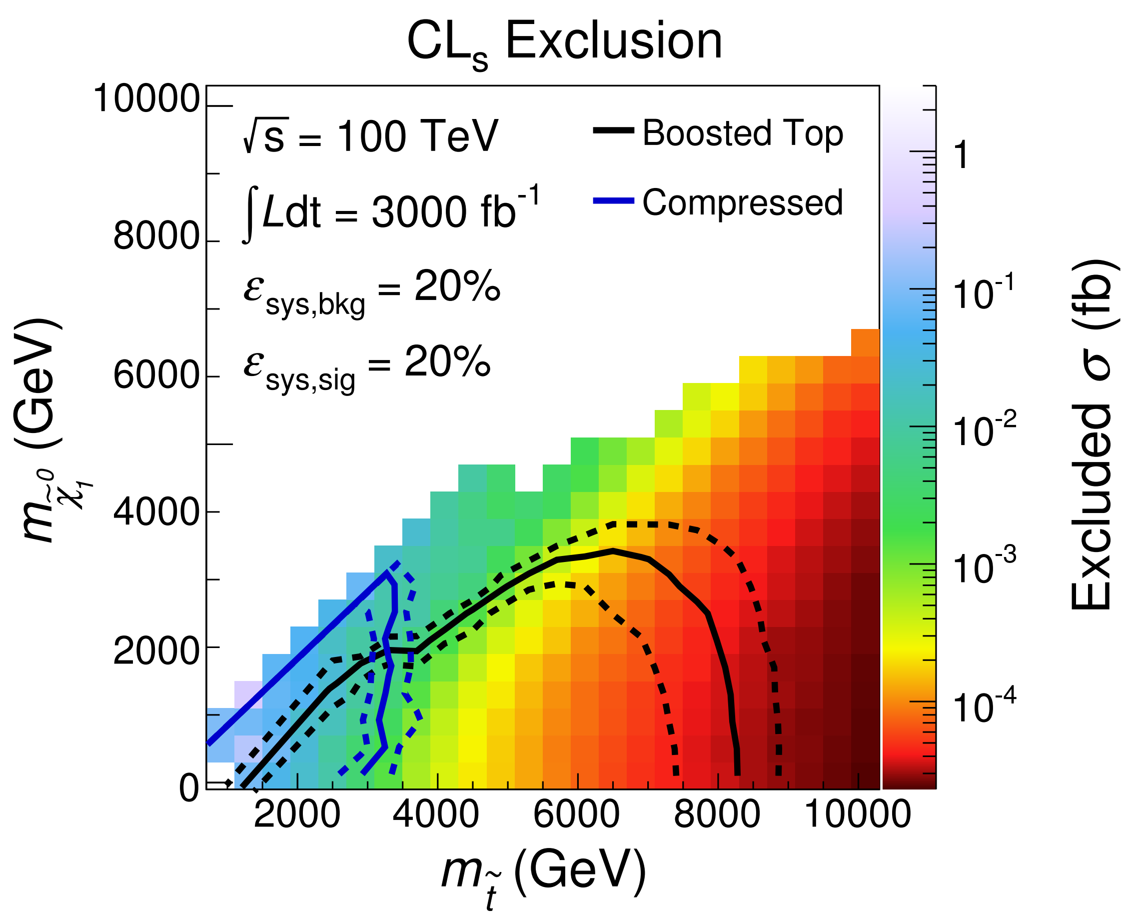
Curtin, Gori, Shelton

More examples?

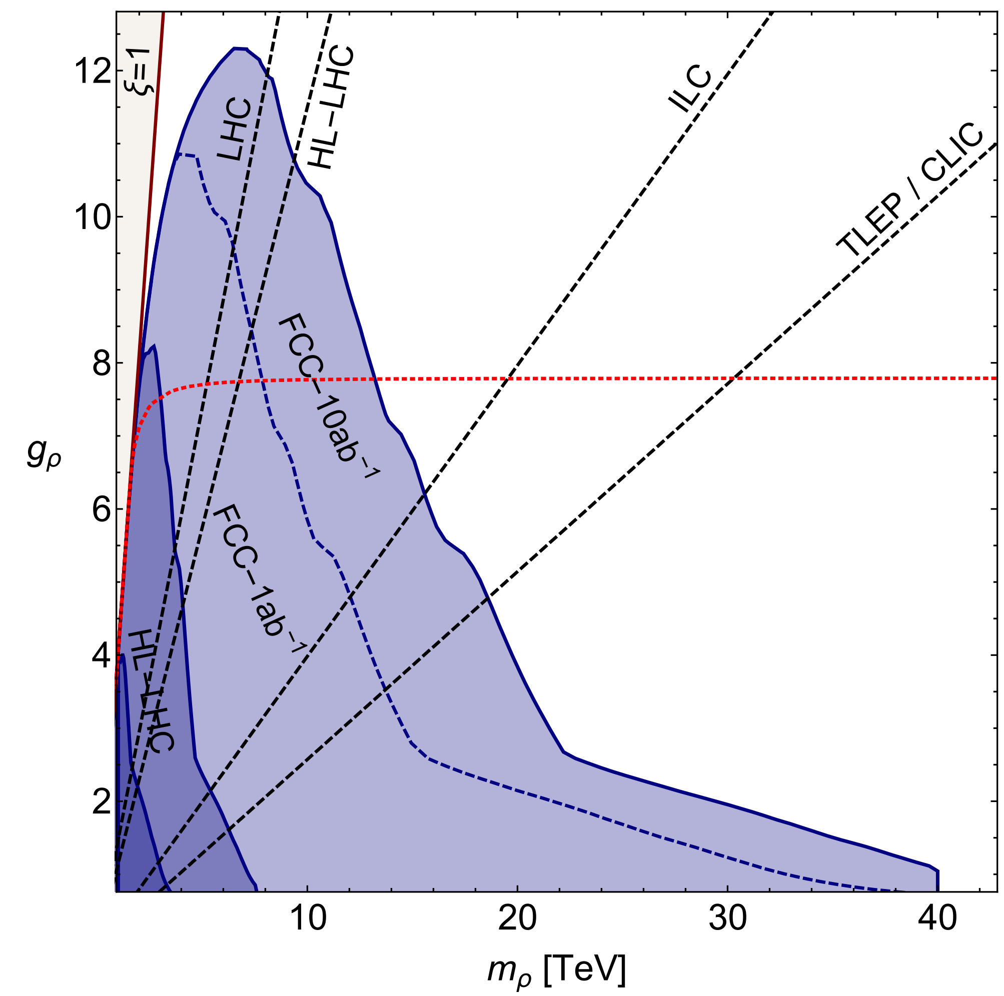
Naturalness

Naturalness at 100 TeV collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014



– tune proportional to $(m_{NP})^2$.

- A gain of 2 orders of magnitude!
- A 6 TeV stop can be discovered!

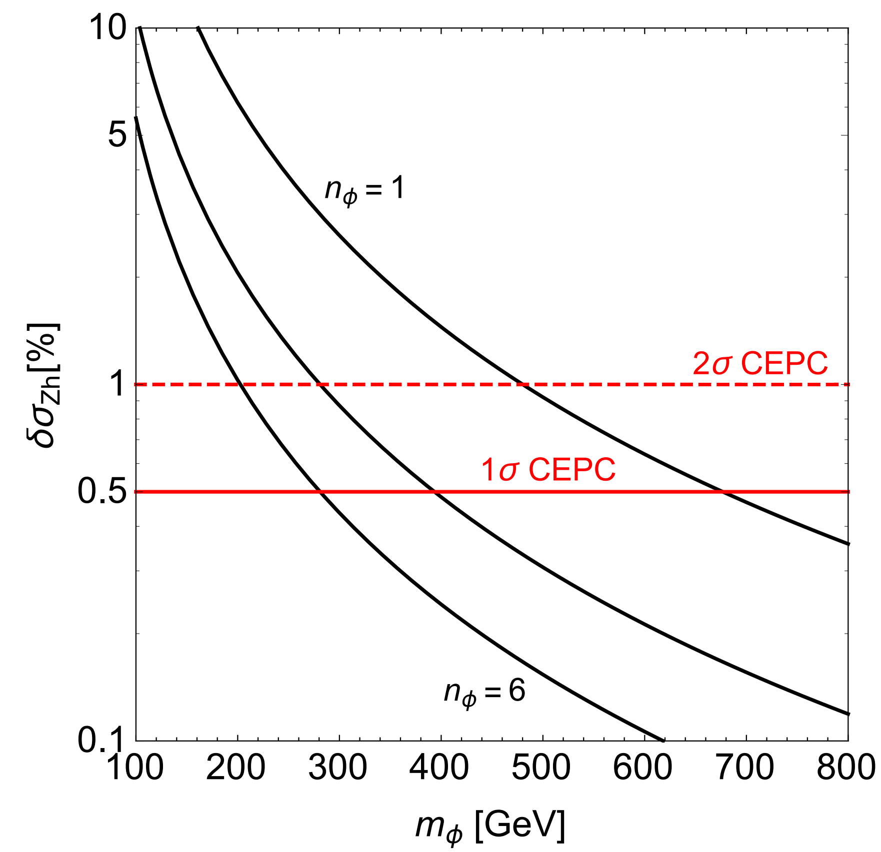
Naturalness at Higgs factories.

Fan, Reece, Wang, 2014

Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

composite Higgs

Craig, Englert, McCullough, 2013



"neutral naturalness"
neutral top partner
twin Higgs

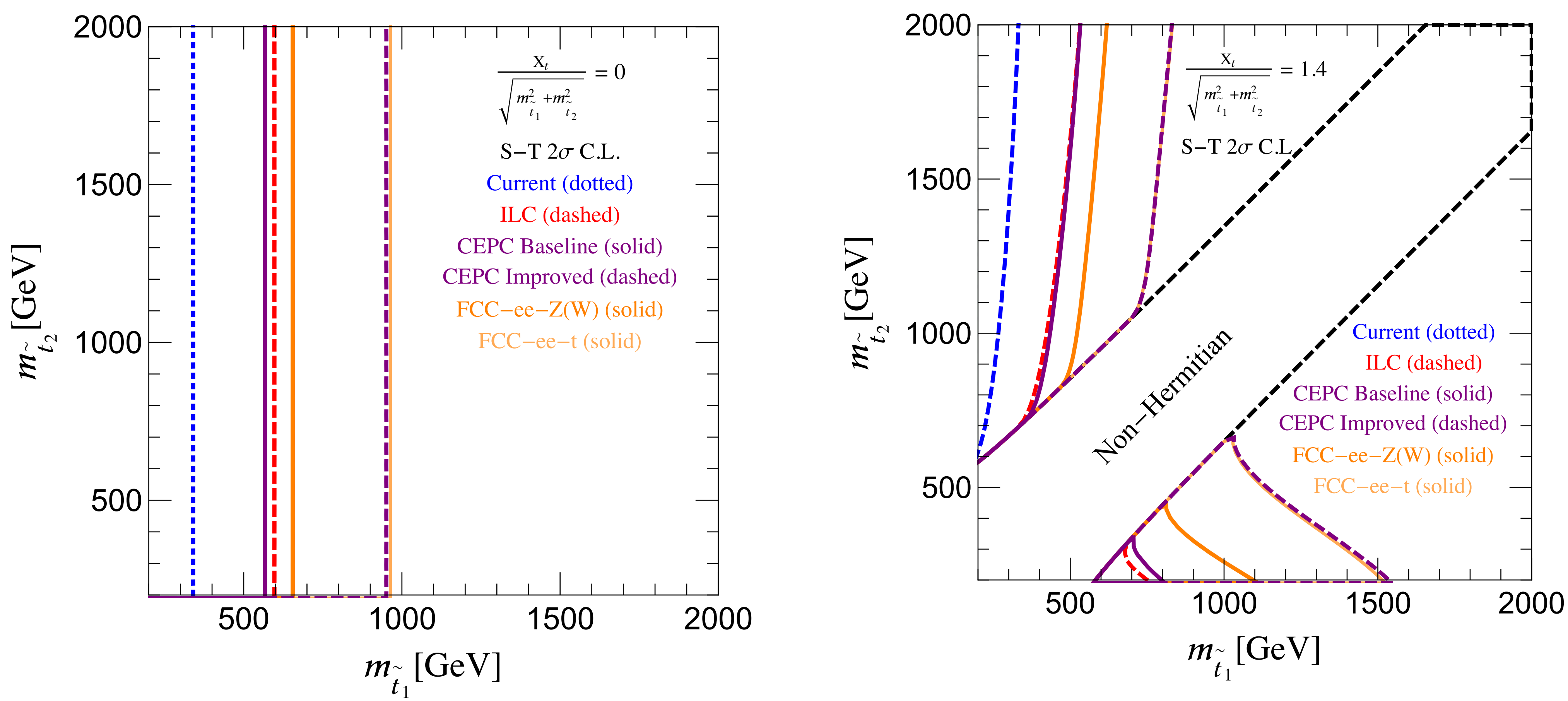
Solid test of naturalness.
Complementary to direct searches
at hadron colliders.

Folded SUSY

Burdman, Chacko, Harnik

- Top partner with EW charge only. They do introduce correction in EW precision observables.

- Strong limit from Z-pole measurement.



J. Fan, M. Reece, LTW, 2014

Pushing the boundary of naturalness

- Is the "neutral naturalness" convincing?
  - Naturalness is a question about UV theories.
  - Can neutral naturalness have nice UV framework?
  - More signals in testing them?

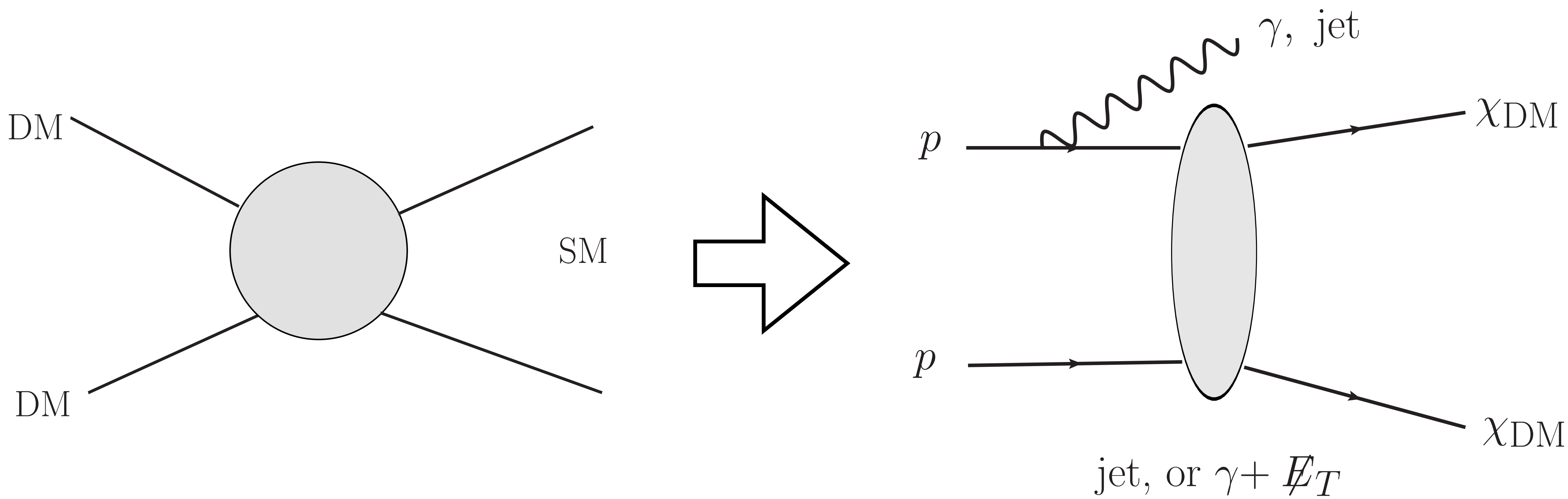
- How much can we cover all the grounds?
  - Special features in detector designed to tease out natural physics?
    - Top bottom rich?
    - Higgs portal like.
    - ...

Testing WIMP Dark Matter

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

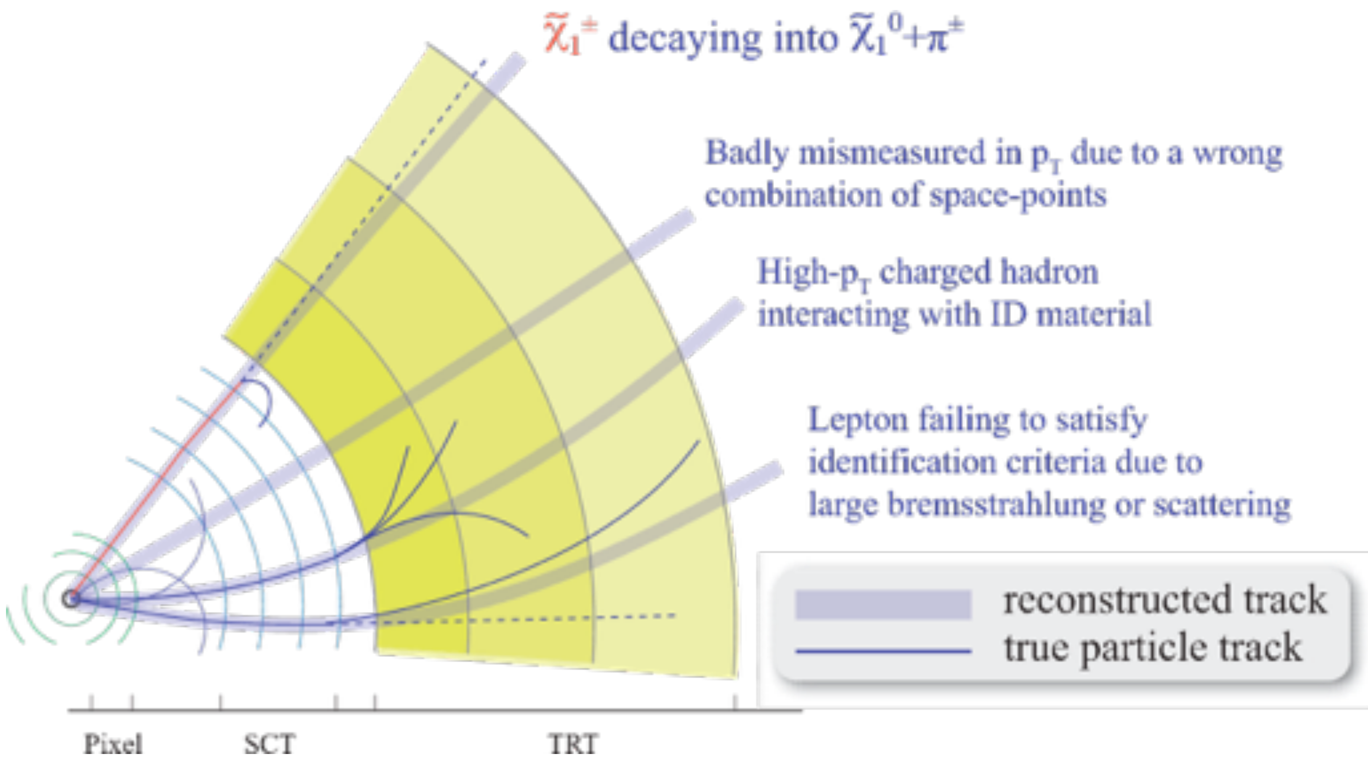
Basic channel

- pair production + additional radiation.



- Mono-jet, mono-photon, mono-...
- Have become "Standard" LHC searches.

Very degenerate, disappearing track



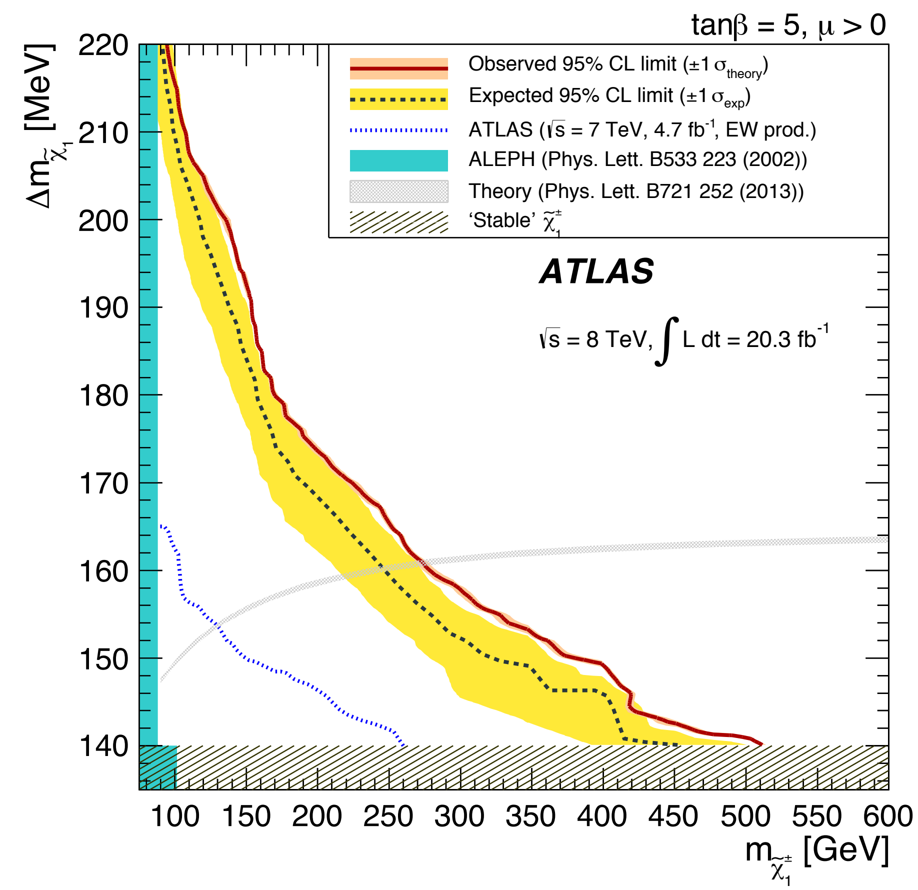
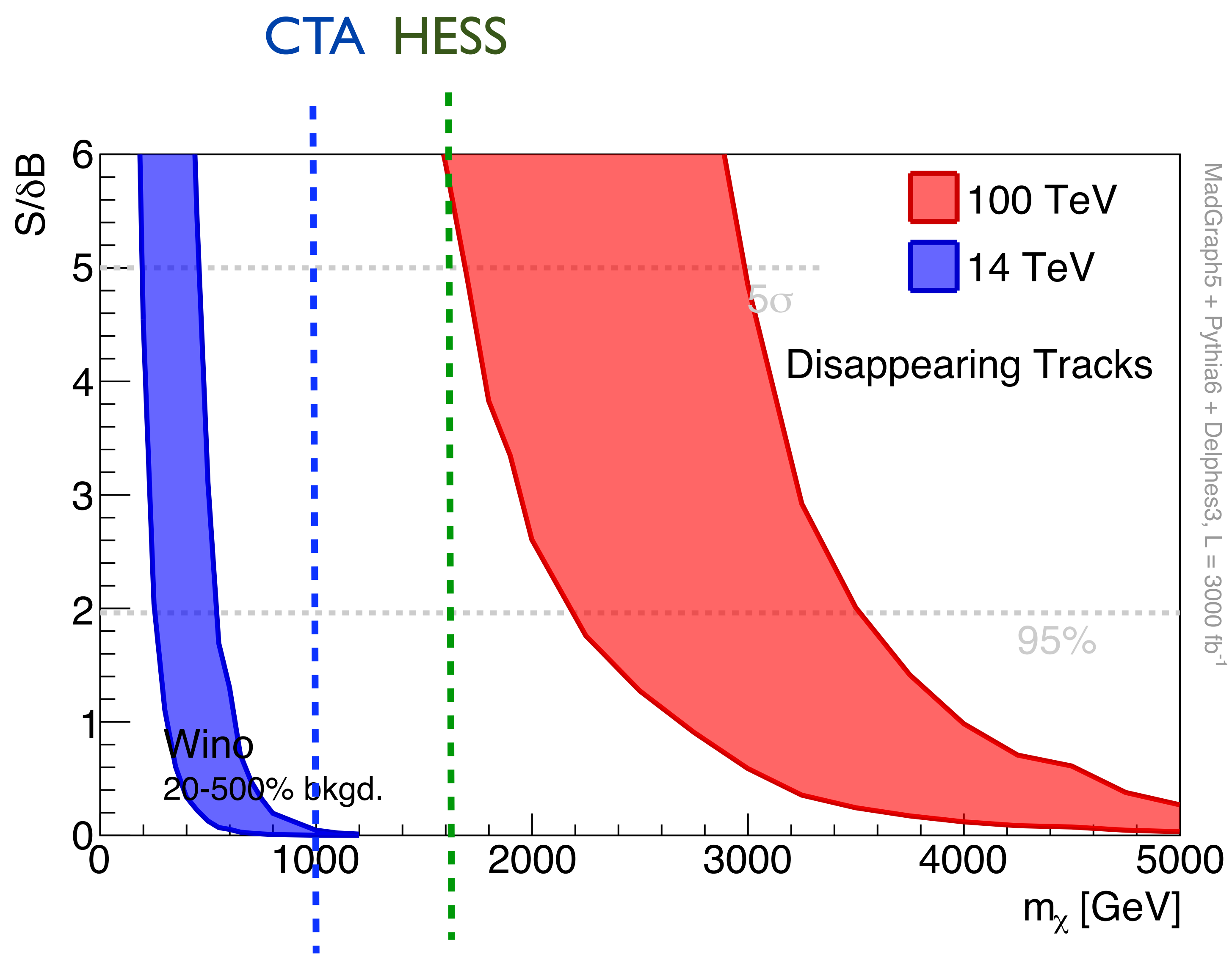


Figure from ATLAS disappearing track search twiki

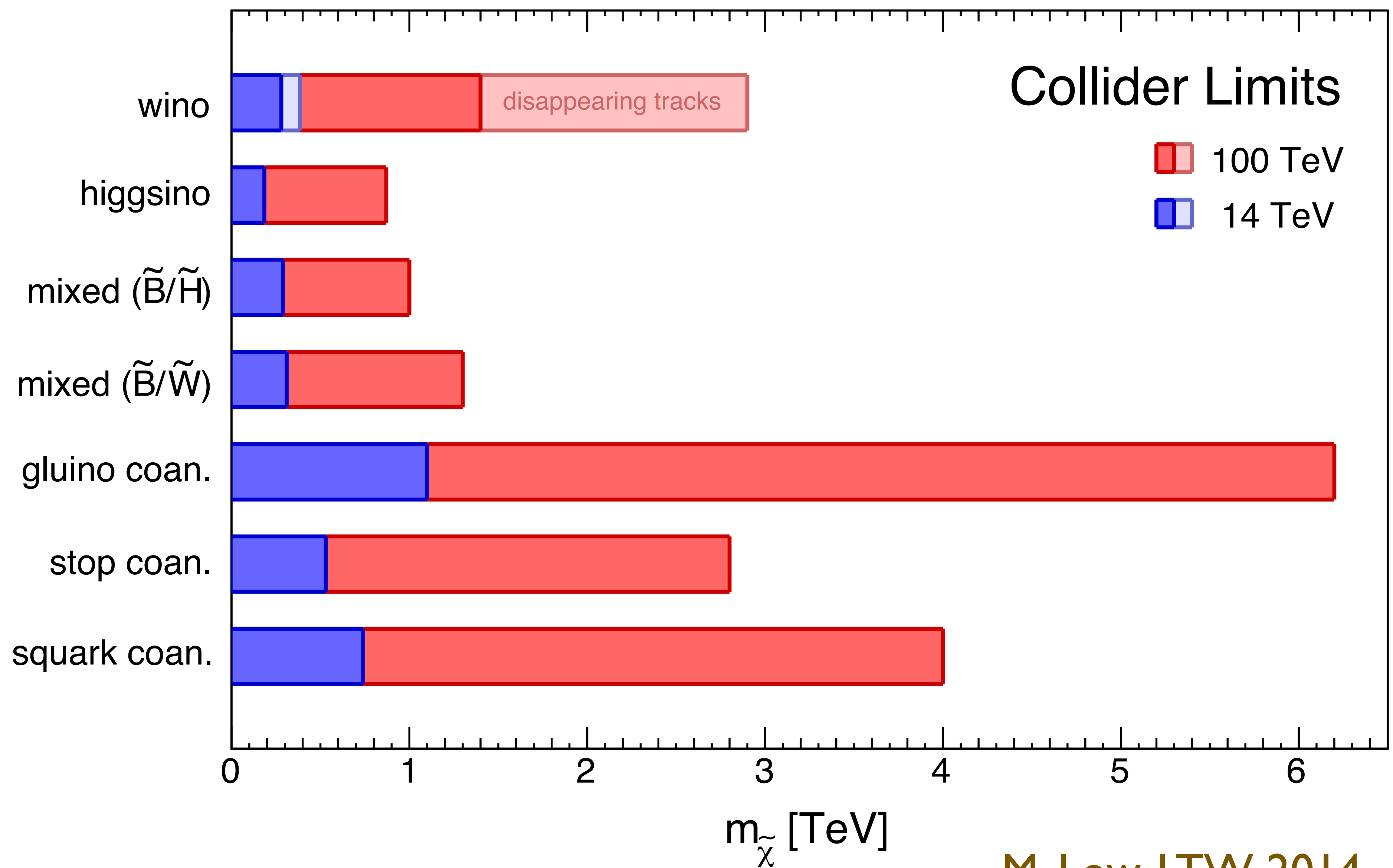
- Main decay mode $\chi^{\pm} \to \pi^{\pm} + \chi^0$.
- Charge track ≈ 10(s) cm
- Impressive limit at the LHC already.

Wino



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

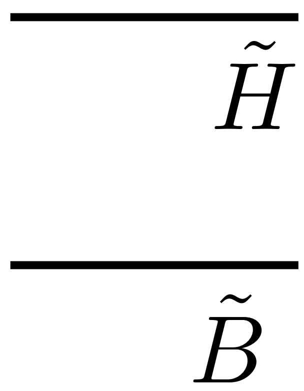
Mono-jet

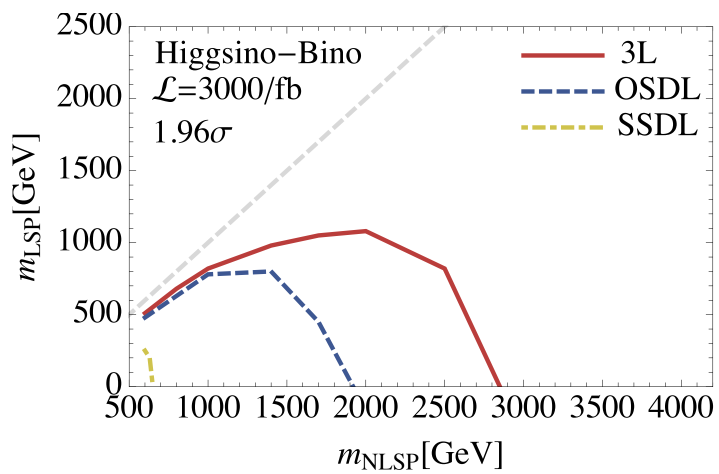


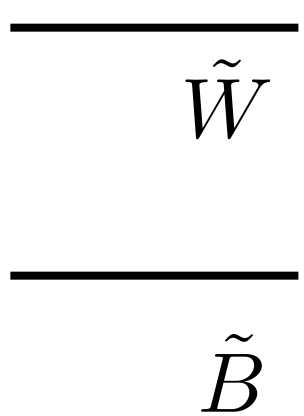
M. Low, LTW 2014

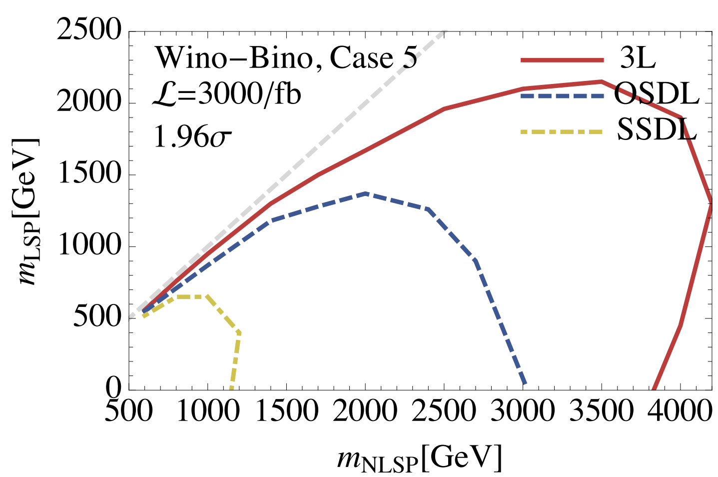
$$M_{\rm WIMP} \leq 1.8\ \text{TeV} \left(\frac{g^2}{0.3}\right)$$

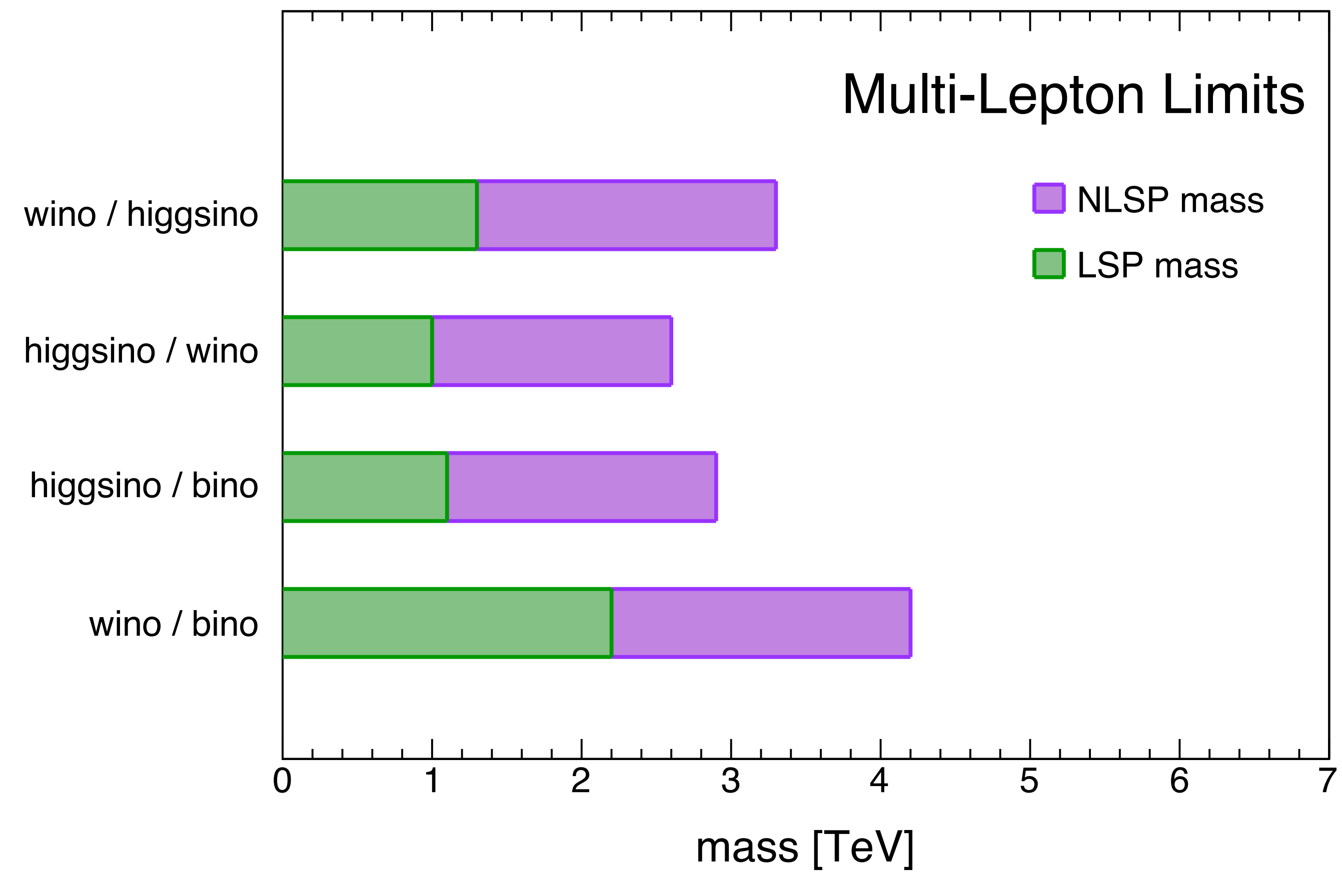
With cascade decays









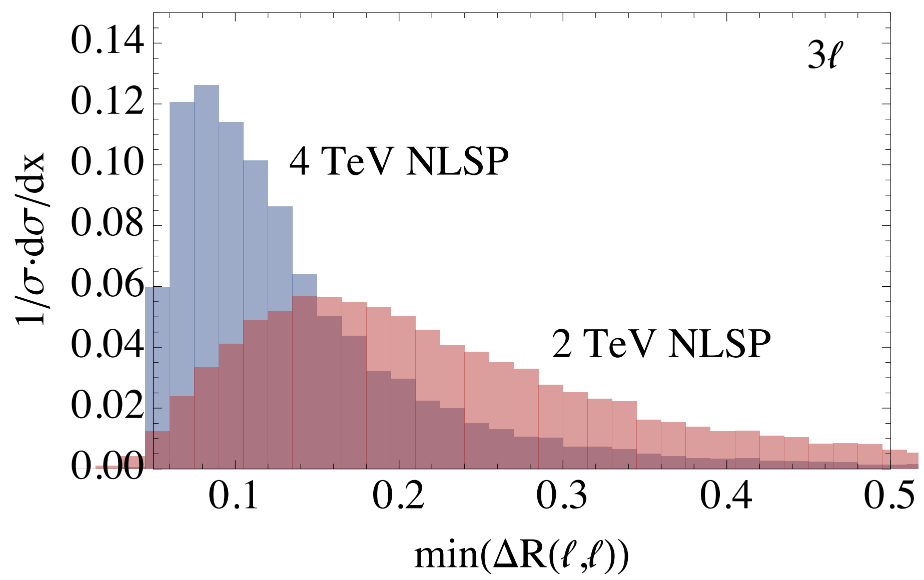


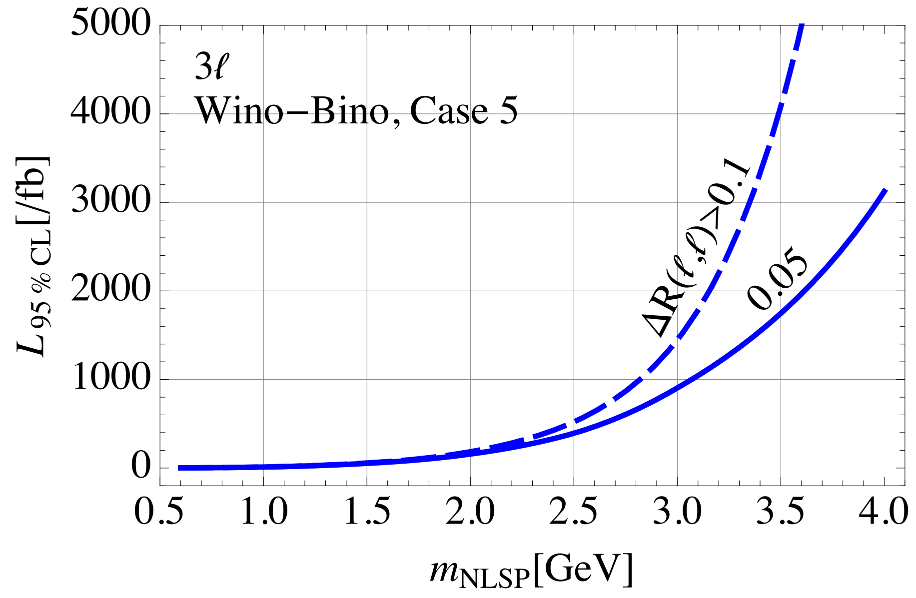
Gori, Jung, Wang, Wells, 2014

Decay ⇒ leptons ⇒ stronger limits

Food for thought

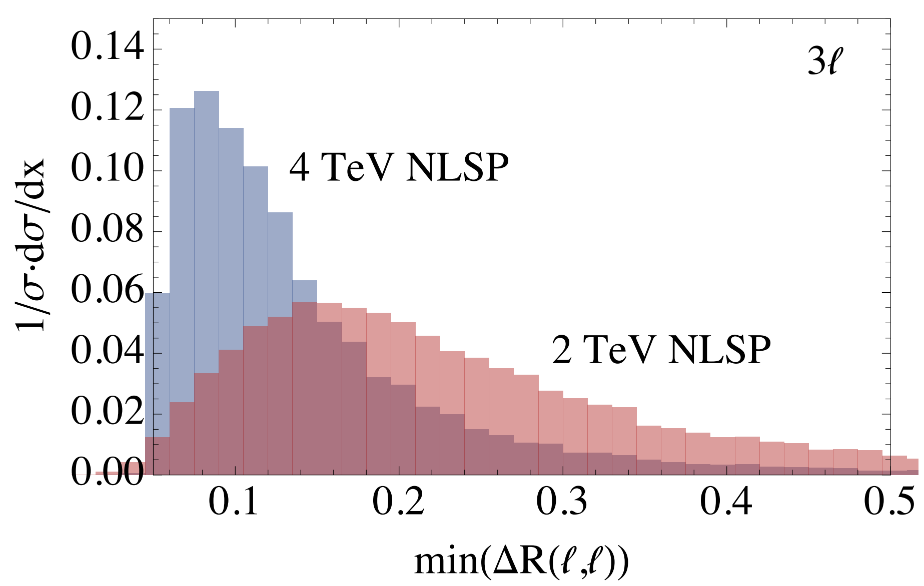
Boosted W/Zs. High resolution, less stringent lepton isolation.

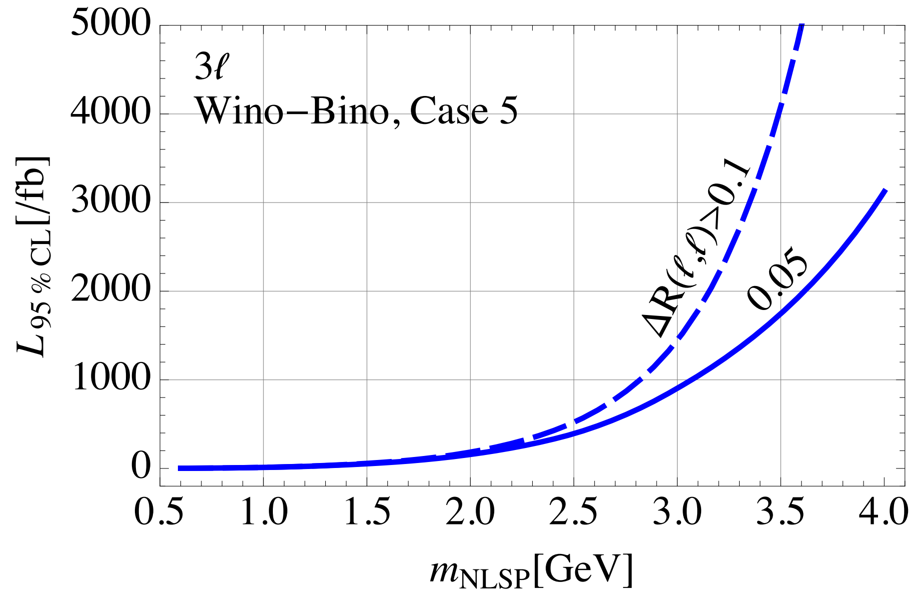




Food for thought

Boosted W/Zs. High resolution, less stringent lepton isolation.

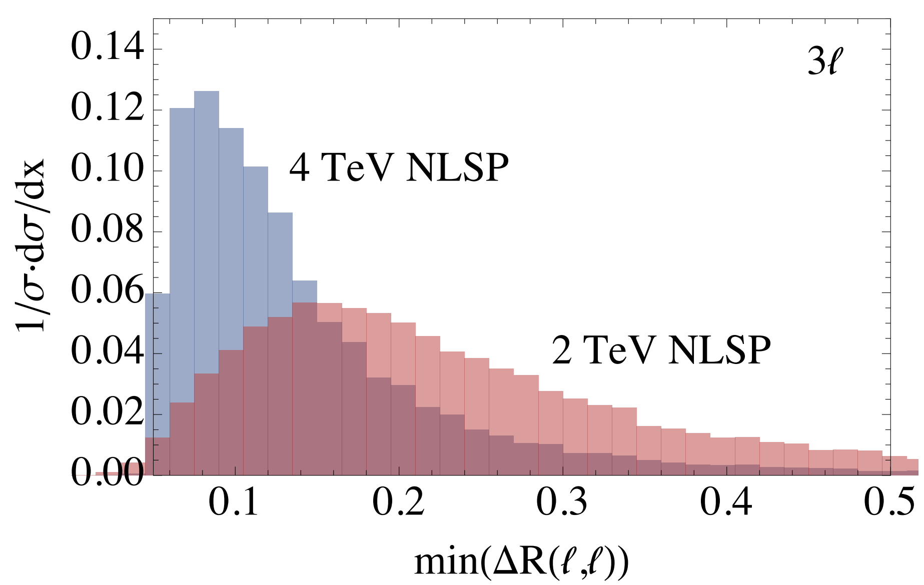


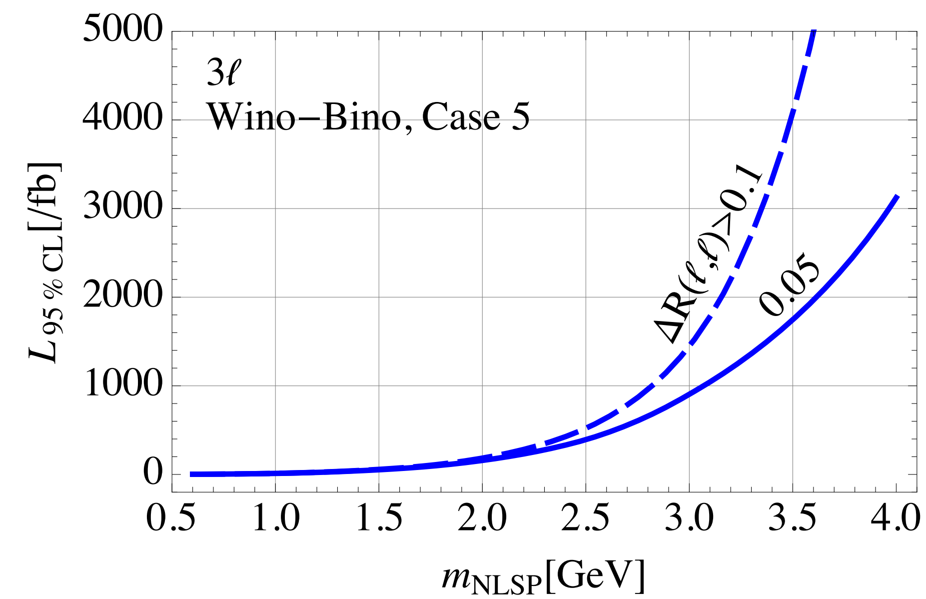


Compressed spectrum generic.
Dedicated detector to id soft lepton, displaced tracks better?

Food for thought

Boosted W/Zs. High resolution, less stringent lepton isolation.





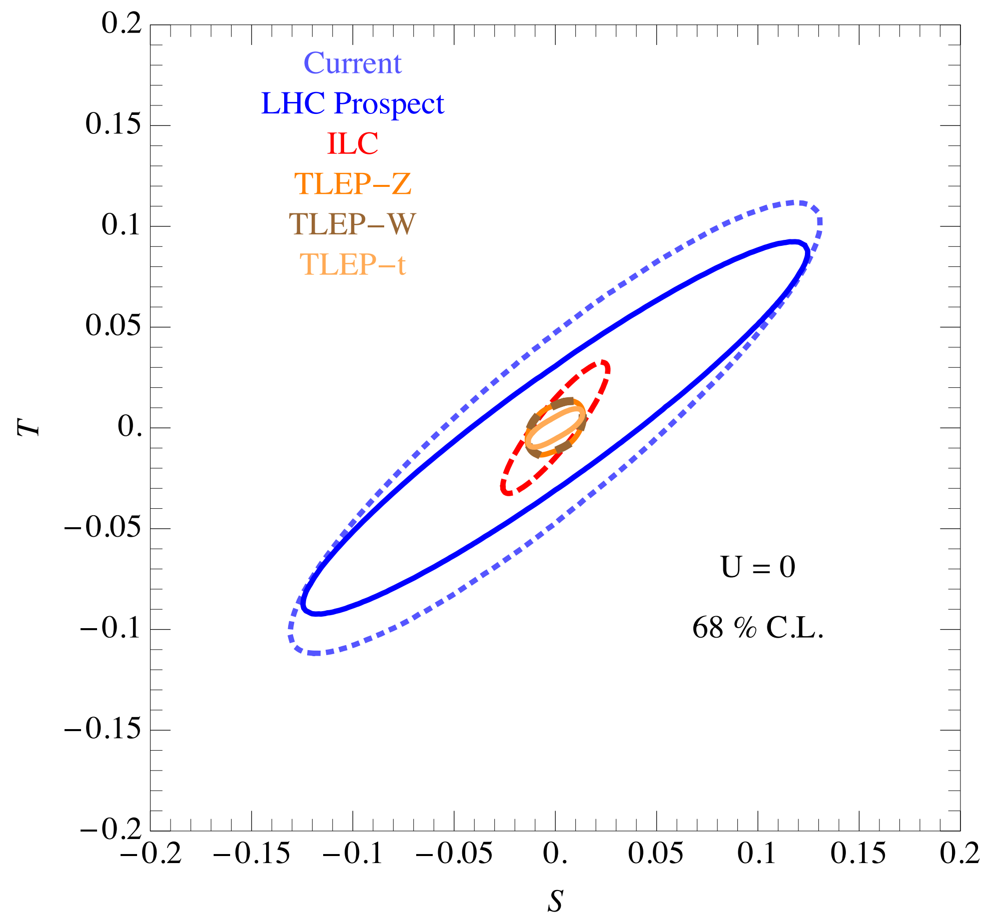
Compressed spectrum generic.
Dedicated detector to id soft lepton, displaced tracks better?

Dark matter signal simpler. Typically no/low jet activities.
Lepton optimized detector?
Write less to tape, trigger more?

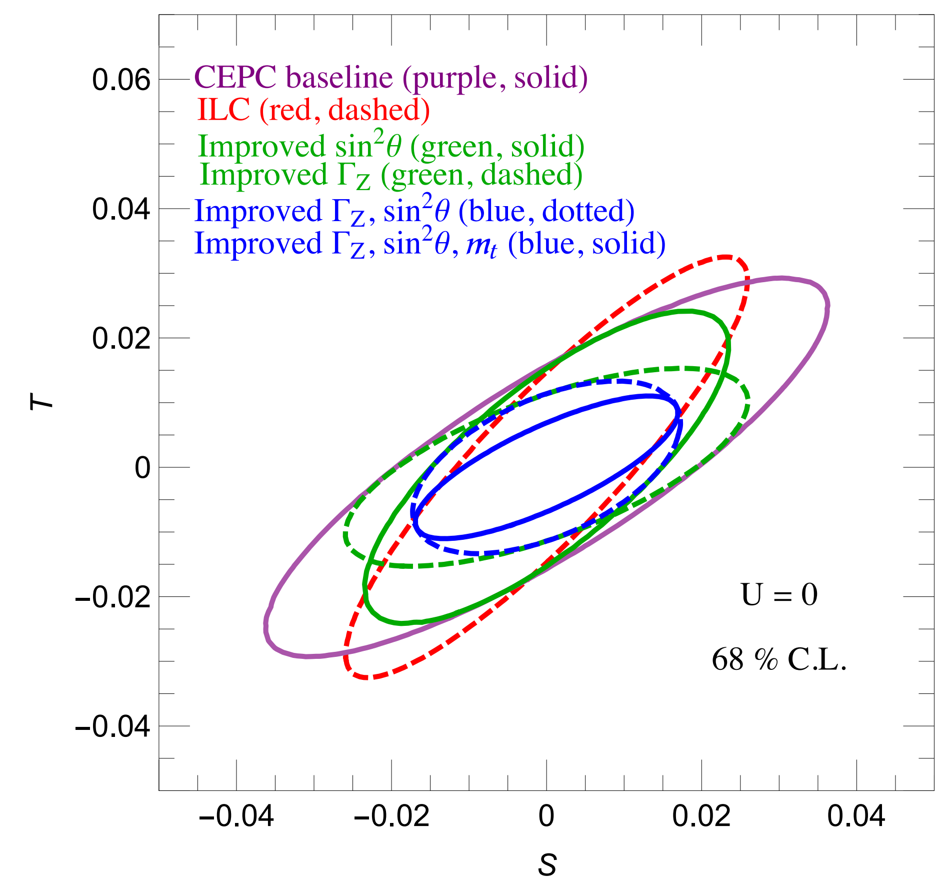
And, there are much more...

For example,

EW precision measurements

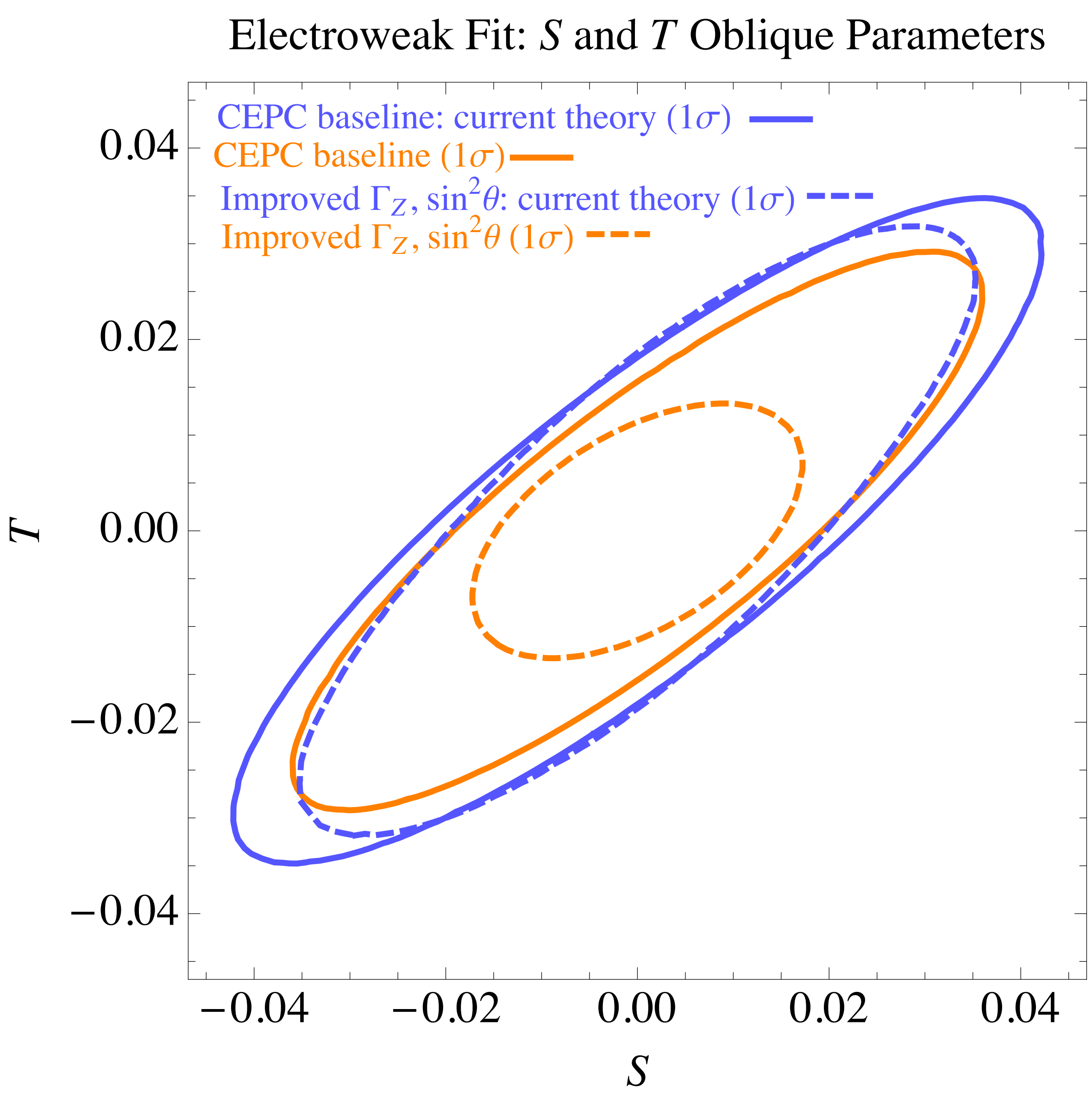


Fan, Reece, LTW



- Lepton colliders $\Rightarrow$ new era in EW precision.
  - A factor of 10 improvement on S and T
- LEP 1+SLD taught us a lot, we will learn much more with these facilities.

Challenge (opportunity) for theorists



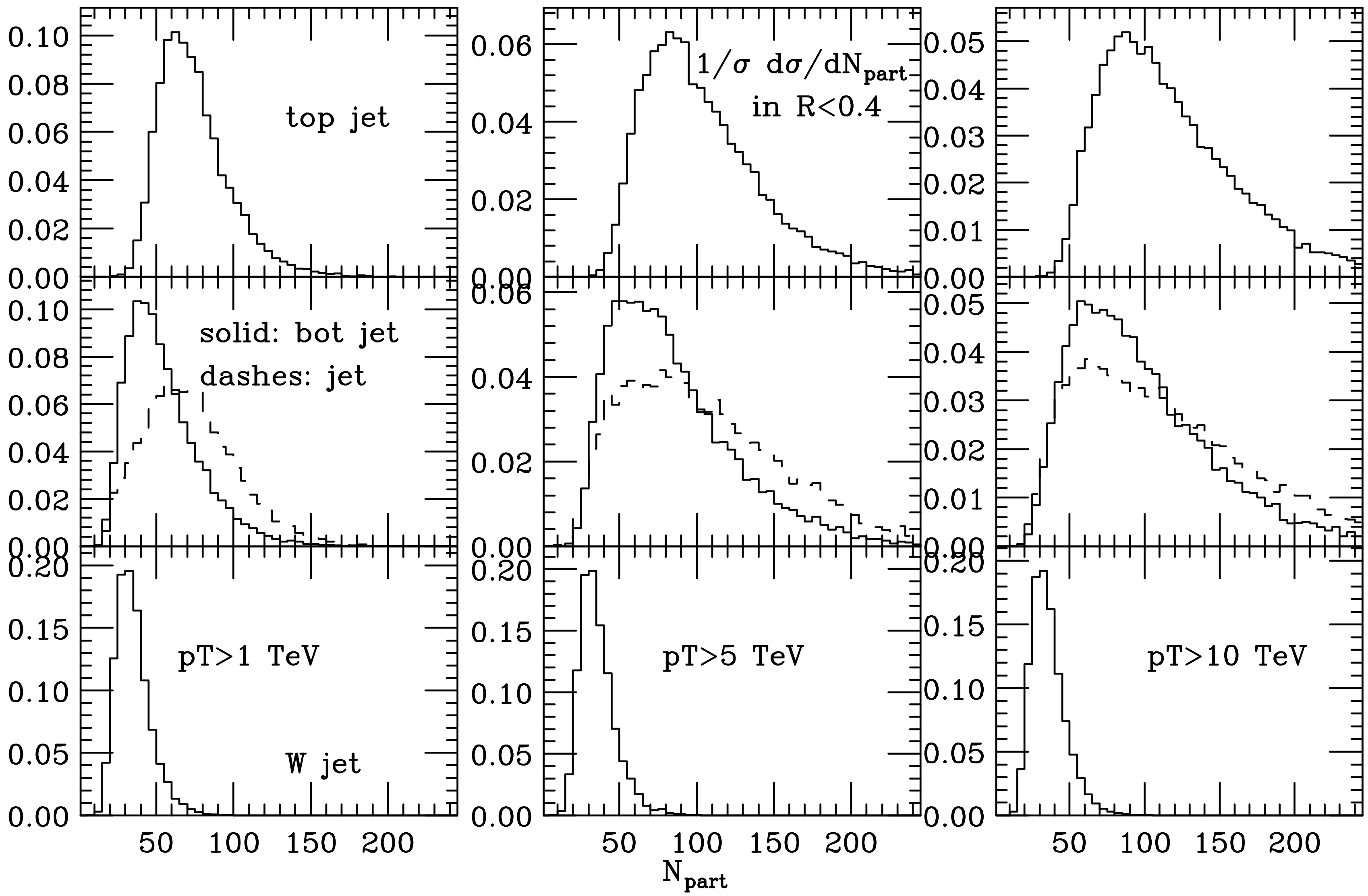
Our main result (orange contour) assumes completion of most electroweak 3 loop calculations.

Pushing beyond current status by at least one order is crucial.

See also talk by Kogler

More novelties at a 100 TeV collider

- Bigger, messier jets.

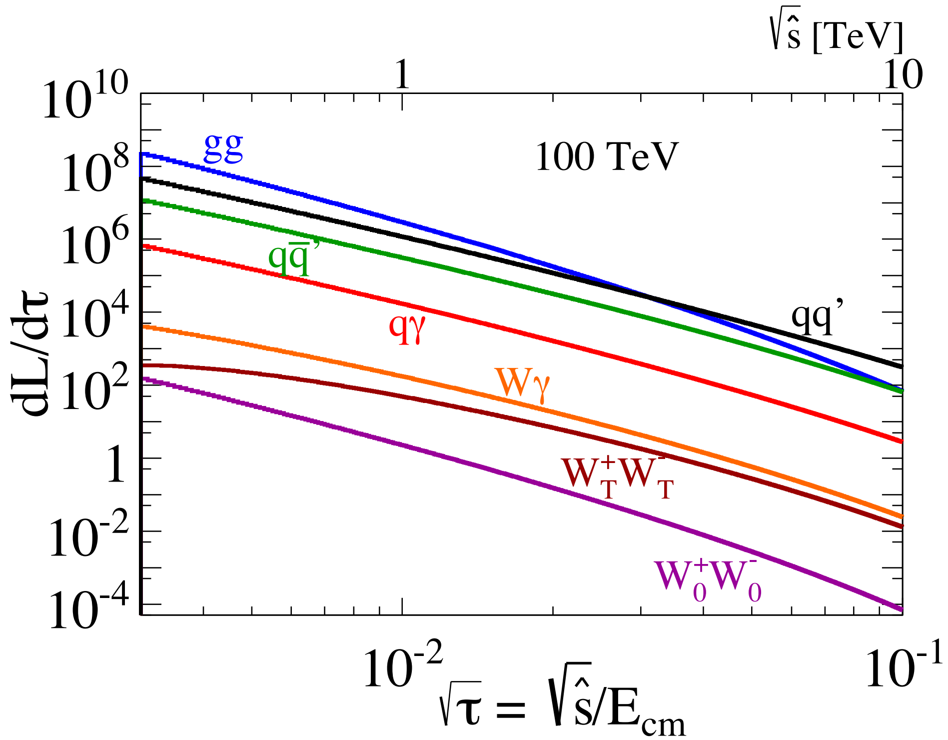


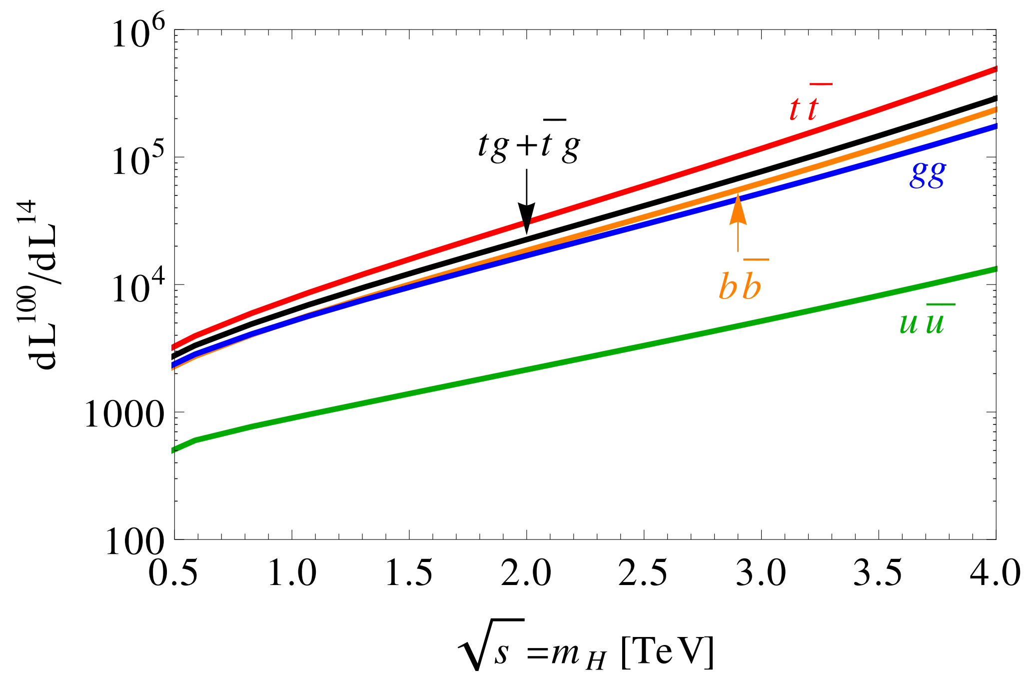
LHC triggered a revolution in jet technology.

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".





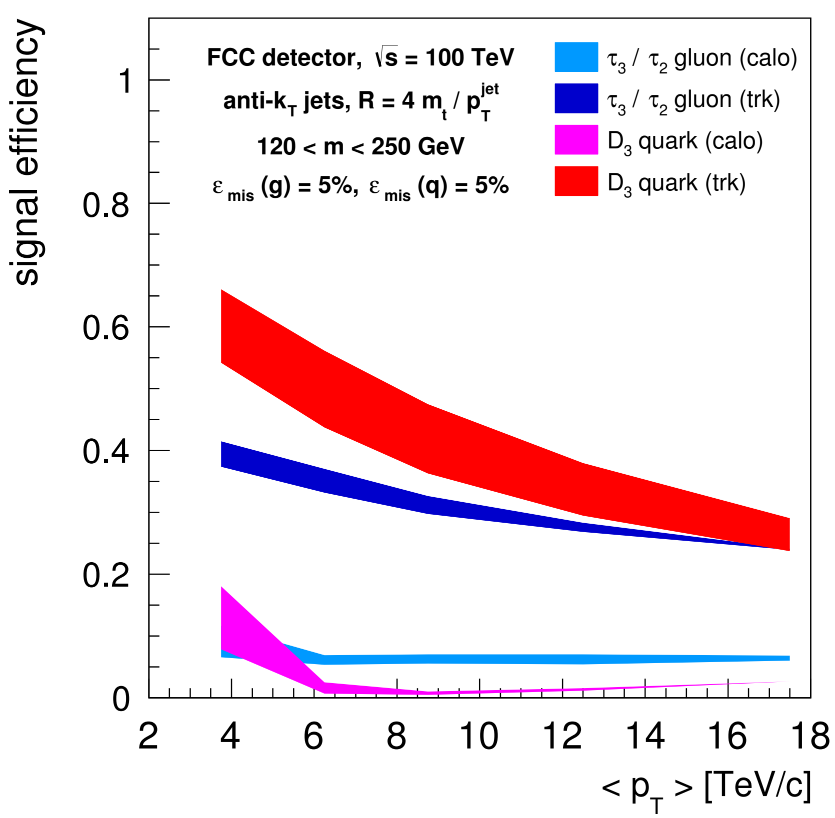
We learned a lot about going from 4 ➜ 5 flavors (doing bottom quark properly).

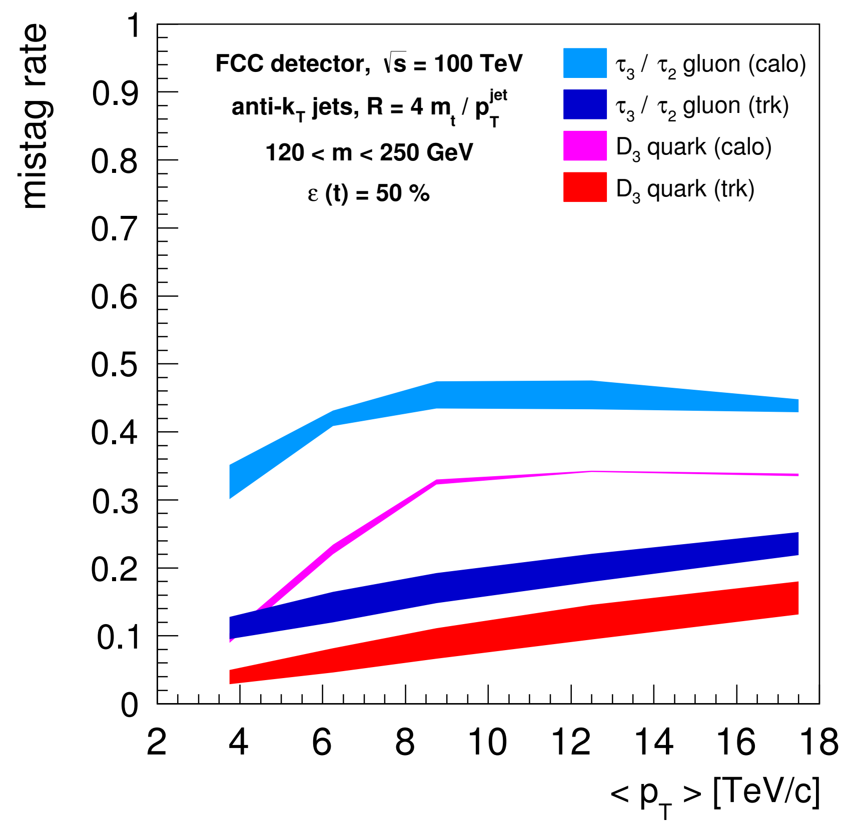
Similar strategy here (?)

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



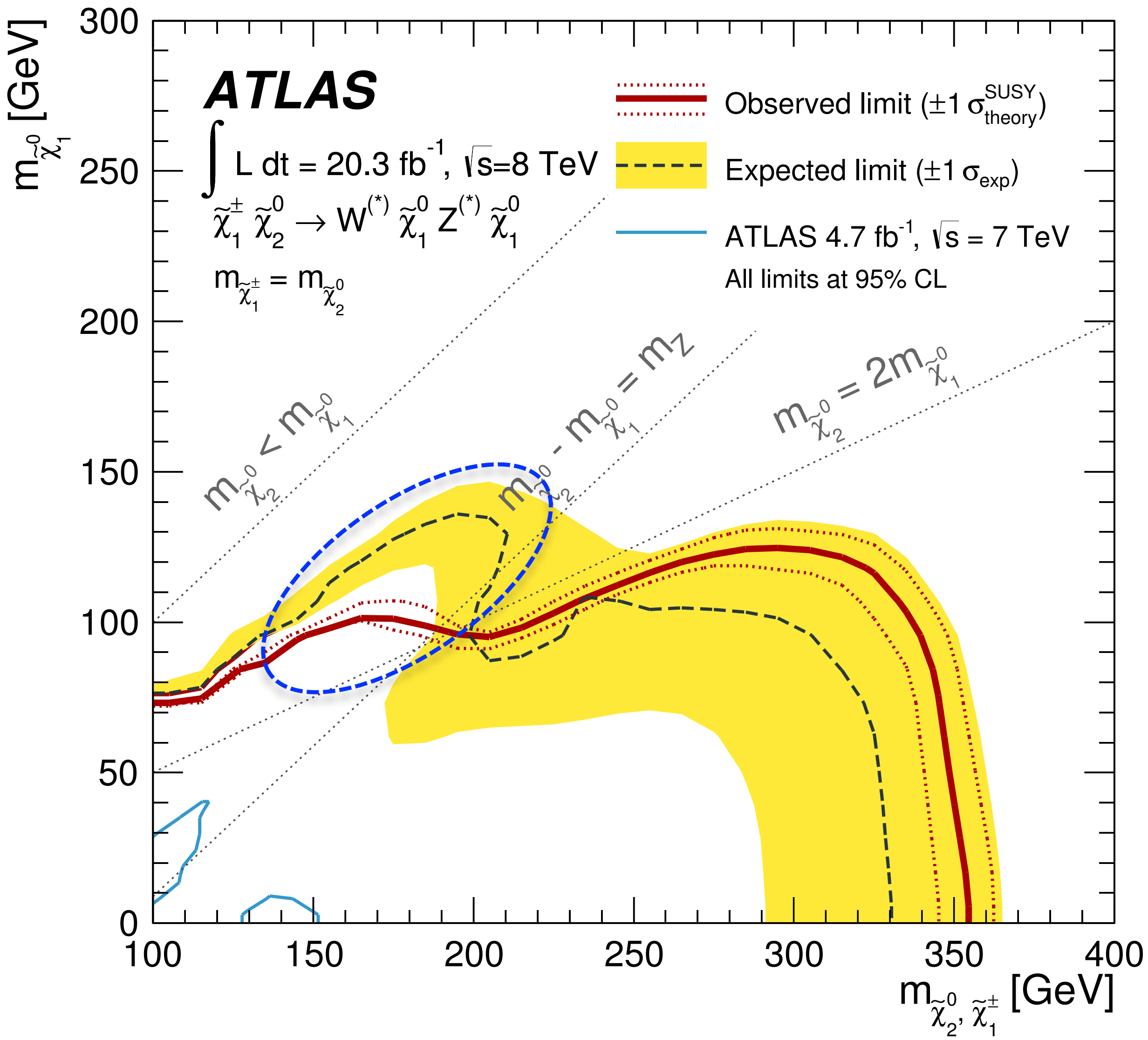


New strategies? detector design?

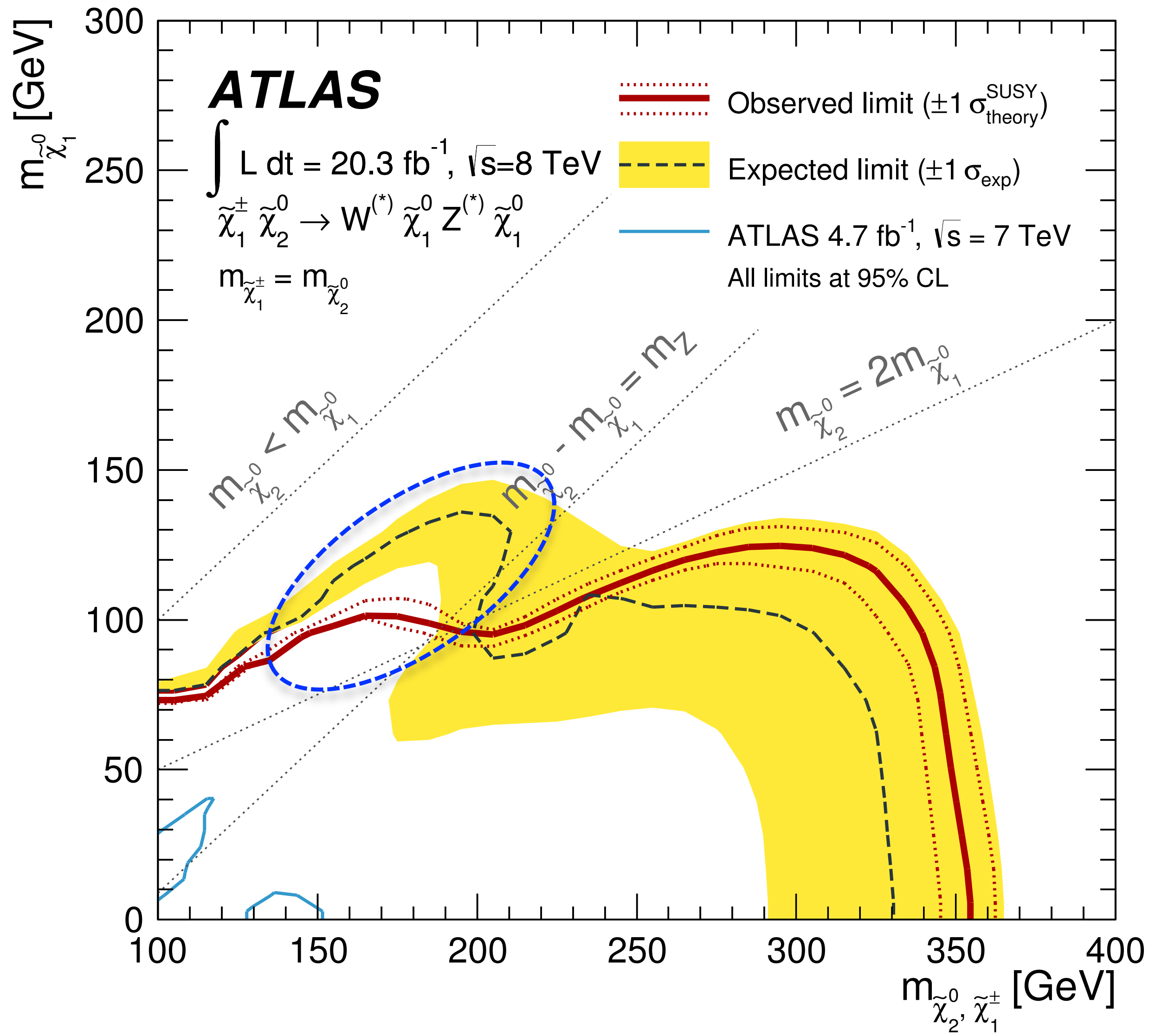
If we made a discovery at run 2

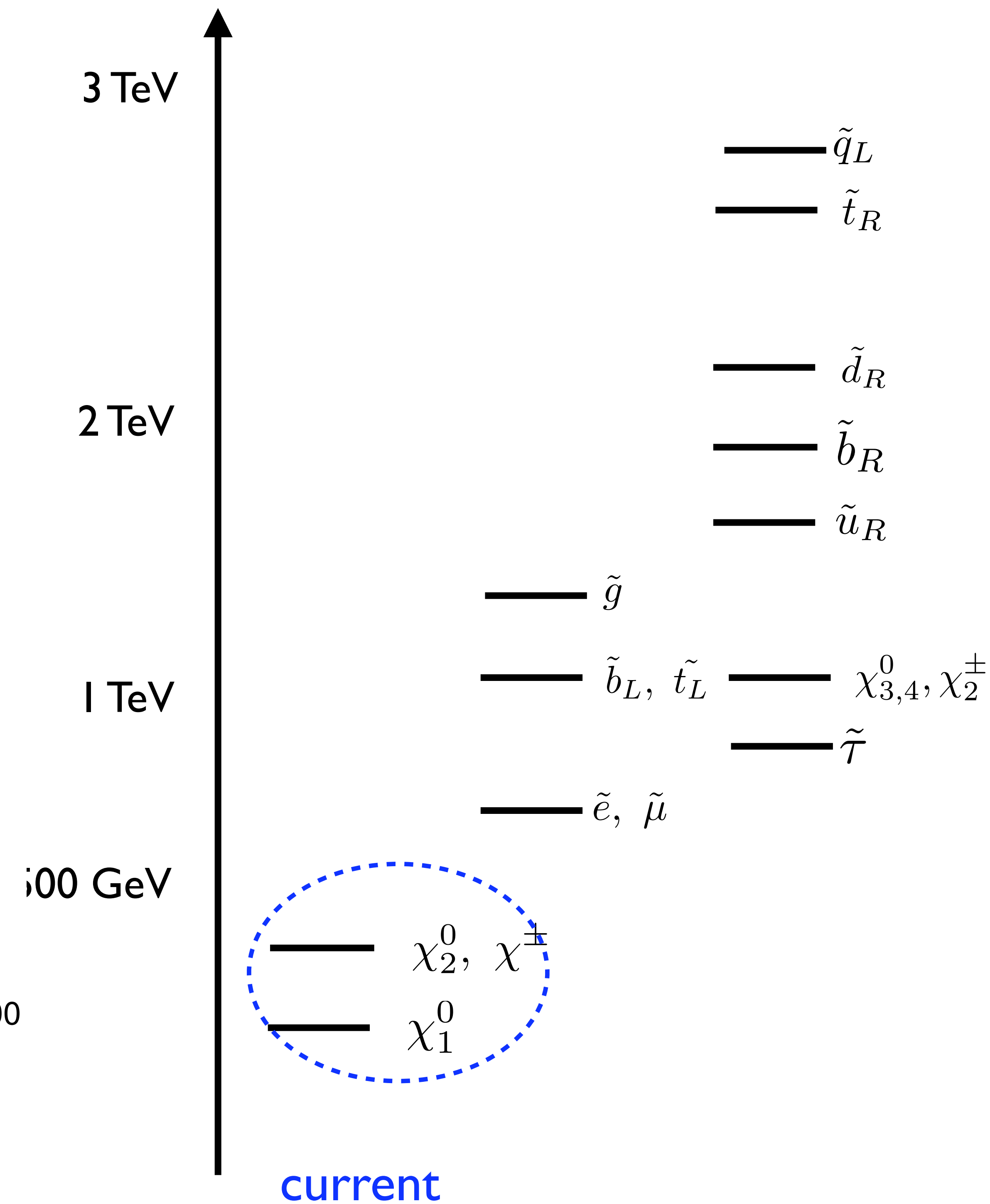
- Beginning of a new era. Seeing the first sign of a new layer of new physics.
- However, it is unlikely to discover the full set of the particles, since we have not see anything yet.
- Typically, going from 8 TeV to 14 TeV increase the reach at most by a factor of 2.
- However, many models feature particles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

What if?

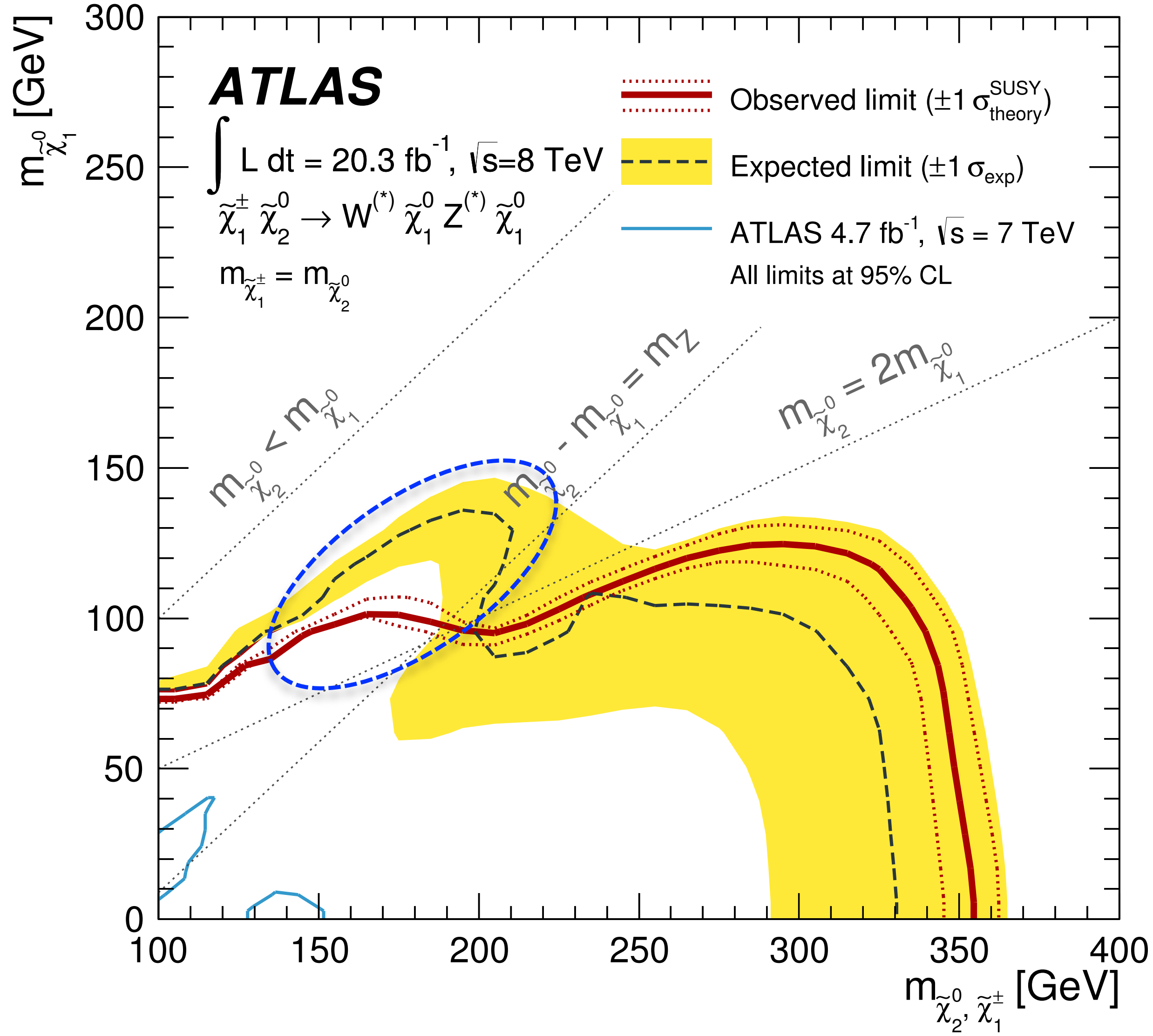

ATLAS
$\int L\,dt = 20.3\ fb^{-1}$, $\sqrt{s}$=8 TeV
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W^{(*)}\tilde{\chi}_1^0 Z^{(*)}\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
Observed limit ($\pm 1\ \sigma_{theory}^{SUSY}$)
Expected limit ($\pm 1\ \sigma_{exp}$)
ATLAS 4.7 fb^{-1}, $\sqrt{s}$ = 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]
0
50
100
150
200
250
300
100
150
200
250
300
350
400

What if?

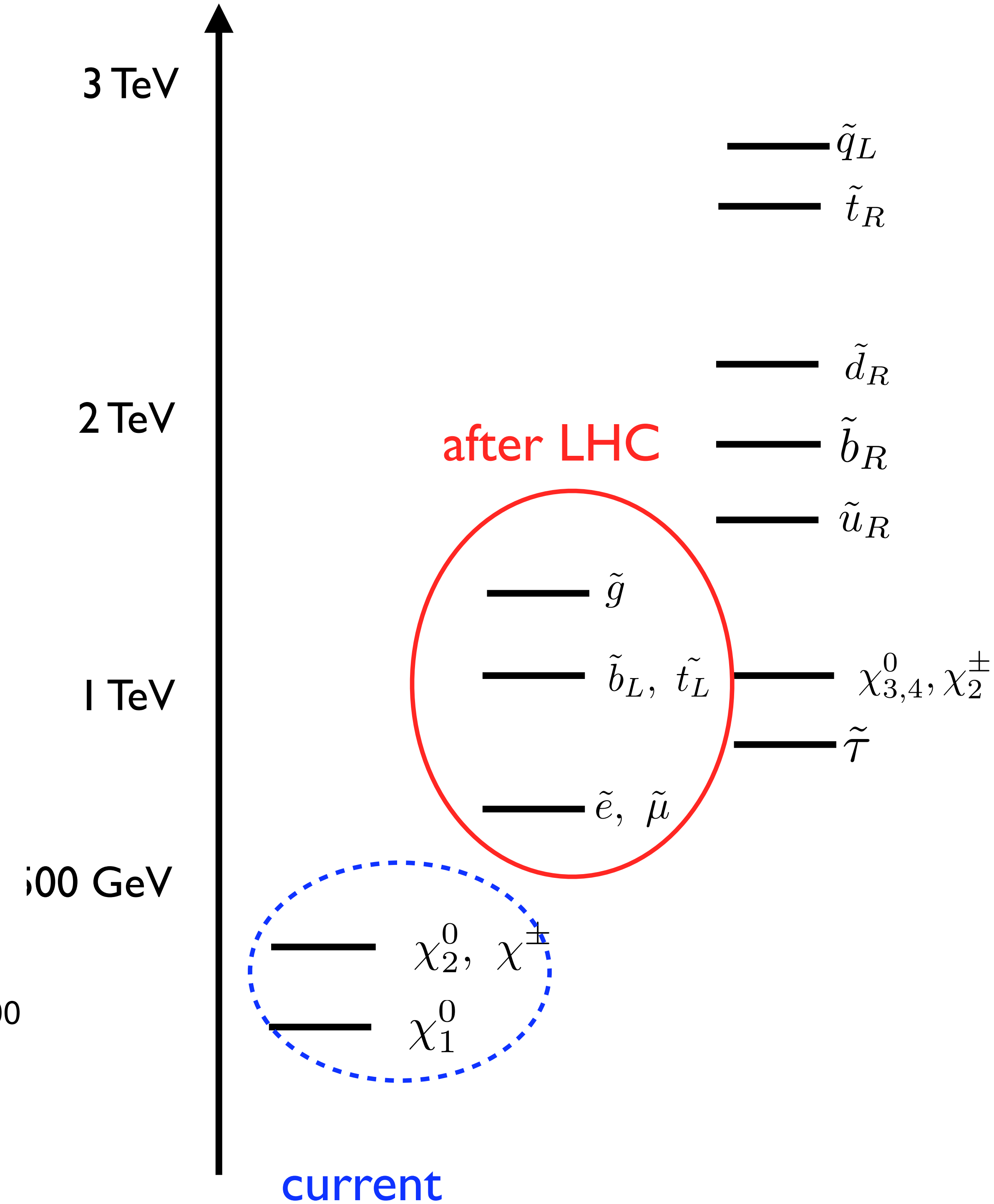

ATLAS
$\int$ L dt = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV
$\tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0 \rightarrow W^{(*)}\,\tilde{\chi}_1^0\,Z^{(*)}\,\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
ATLAS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


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?

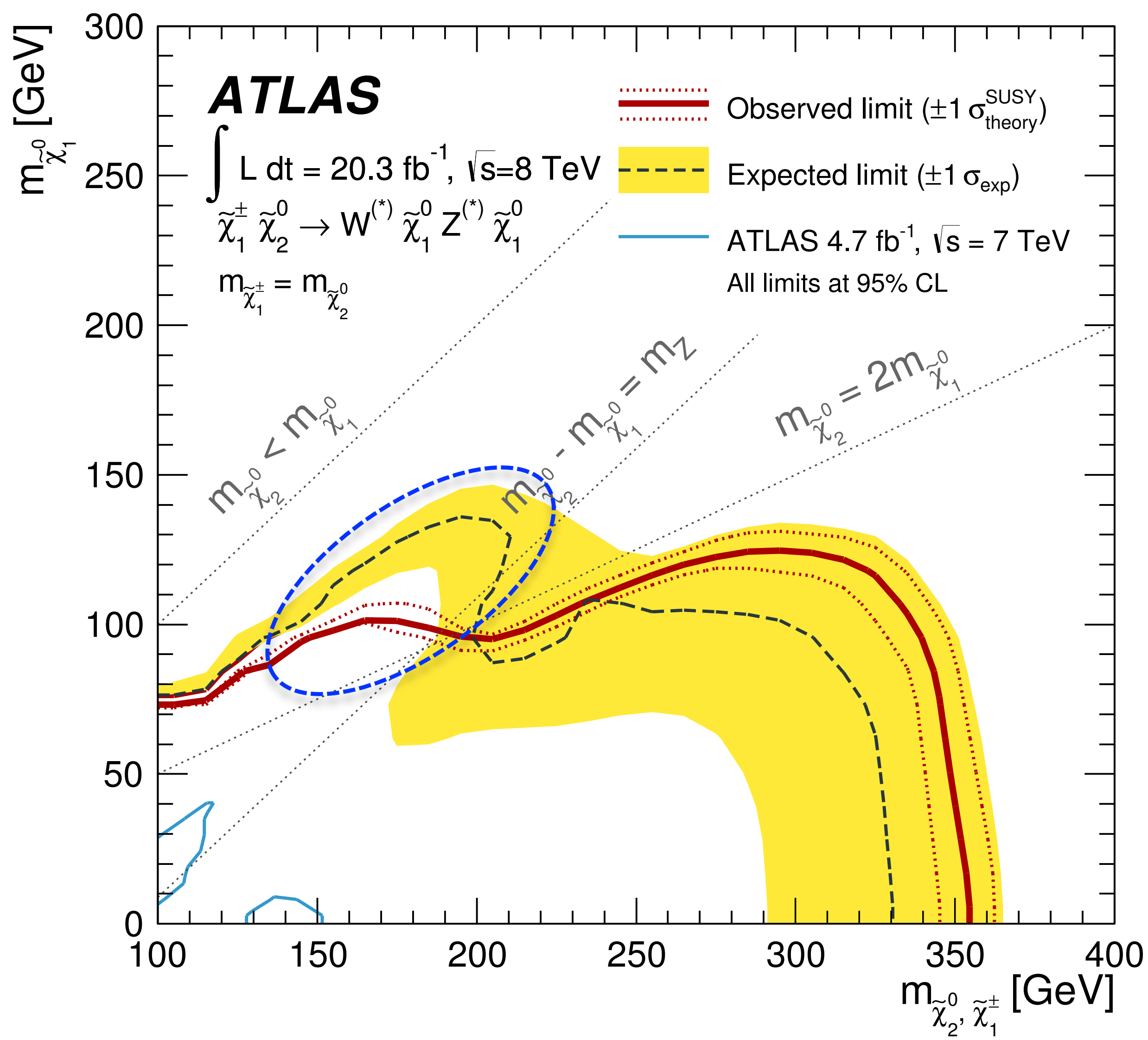


ATLAS
$\int L\,dt$ = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W^{(*)} \tilde{\chi}_1^0 Z^{(*)} \tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$
Observed limit (±1 σ^{SUSY}_{theory})
Expected limit (±1 σ_{exp})
ATLAS 4.7 fb^{-1}, $\sqrt{s}$ = 7 TeV
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]

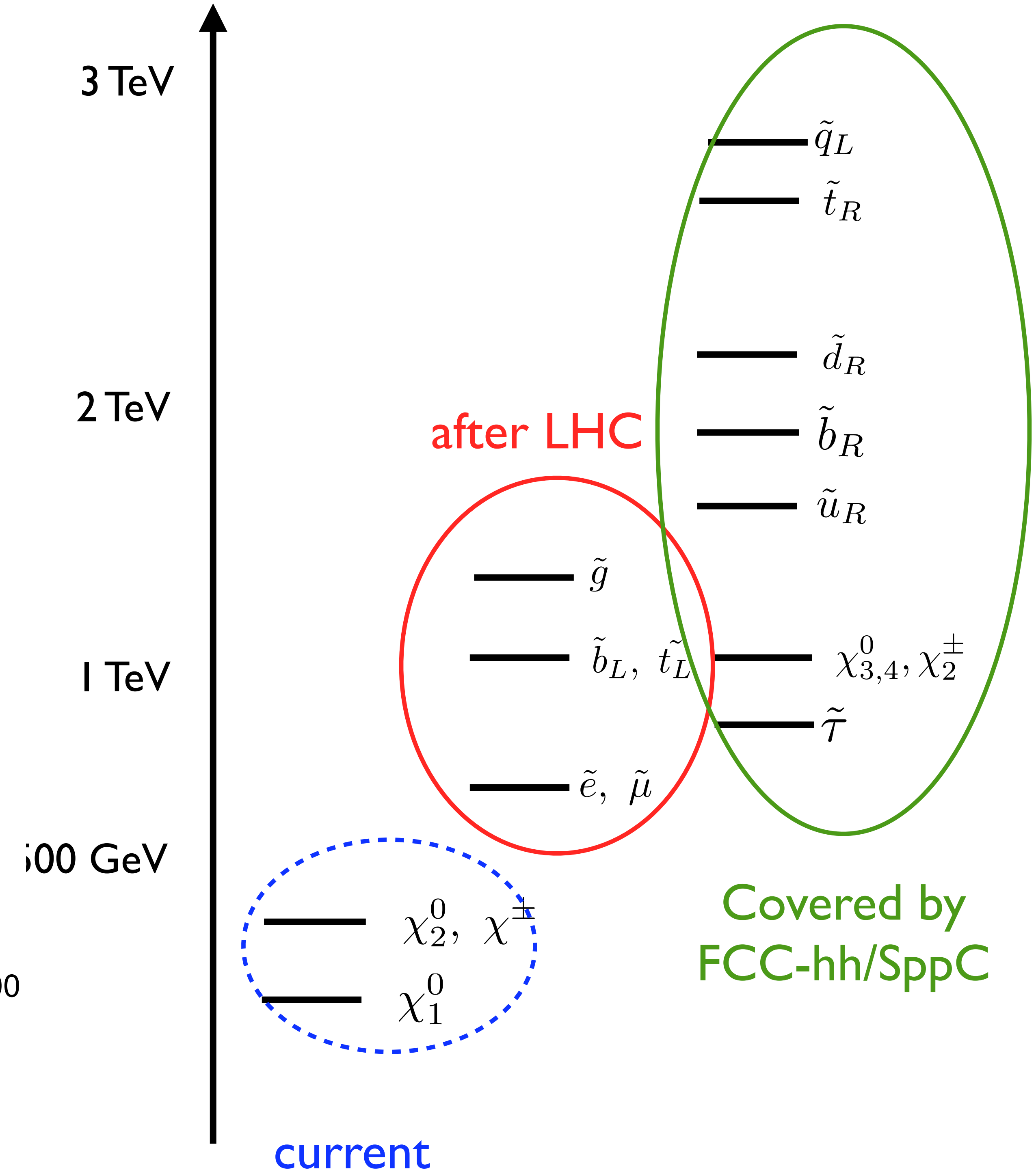


3 TeV
2 TeV
1 TeV
500 GeV
$\tilde{q}_L$
$\tilde{t}_R$
$\tilde{d}_R$
$\tilde{b}_R$
$\tilde{u}_R$
after LHC
$\tilde{g}$
$\tilde{b}_L,\ \tilde{t}_L$
$\chi^0_{3,4}, \chi^\pm_2$
$\tilde{\tau}$
$\tilde{e},\ \tilde{\mu}$
$\chi^0_2,\ \chi^\pm$
χ^0_1
current

What if?

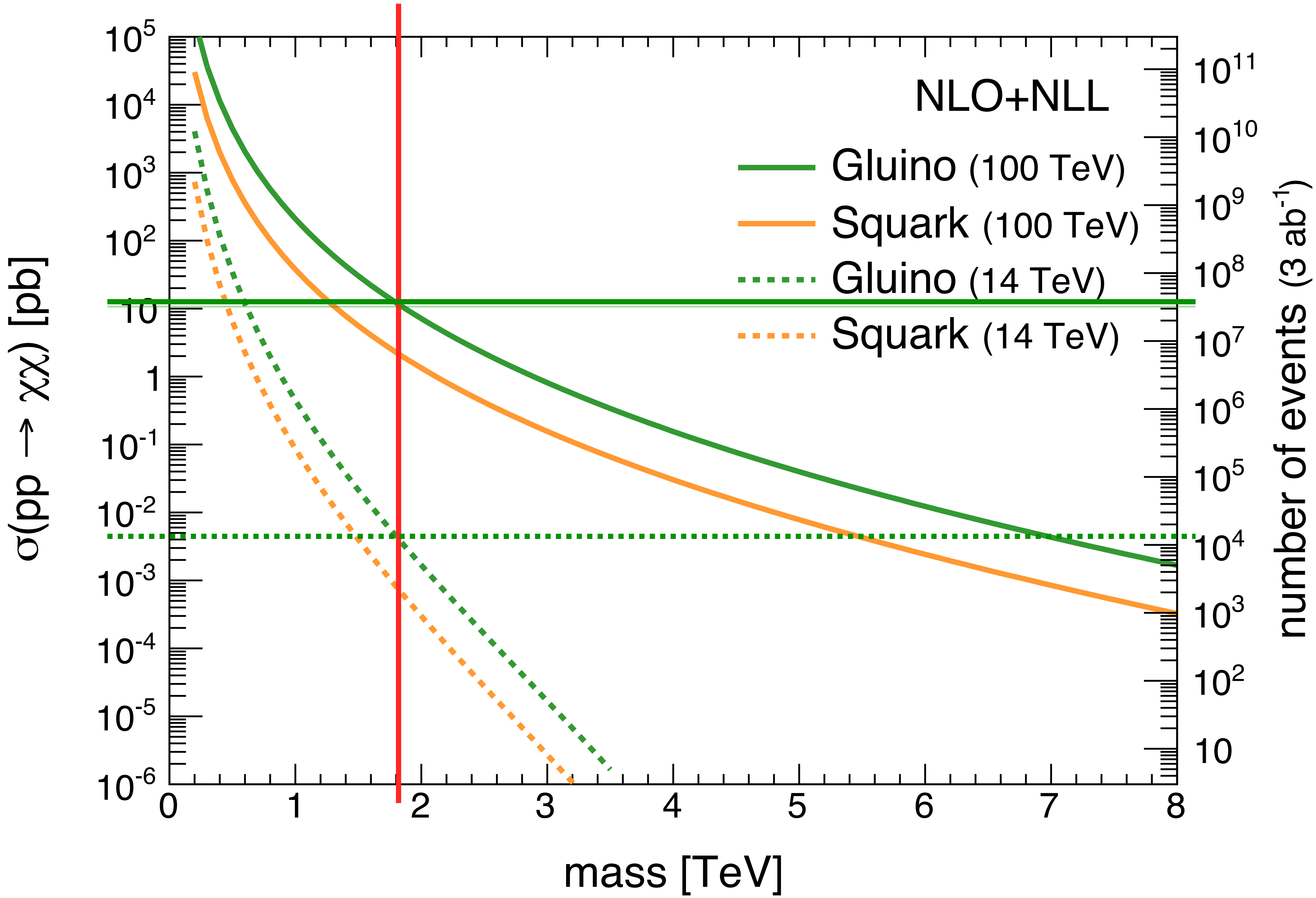


ATLAS
$\int L\,dt = 20.3\ \mathrm{fb}^{-1}$, $\sqrt{s}$=8 TeV
$\tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0 \rightarrow W^{(*)}\,\tilde{\chi}_1^0\,Z^{(*)}\,\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
Observed limit ($\pm1\,\sigma^{\mathrm{SUSY}}_{\mathrm{theory}}$)
Expected limit ($\pm1\,\sigma_{\mathrm{exp}}$)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



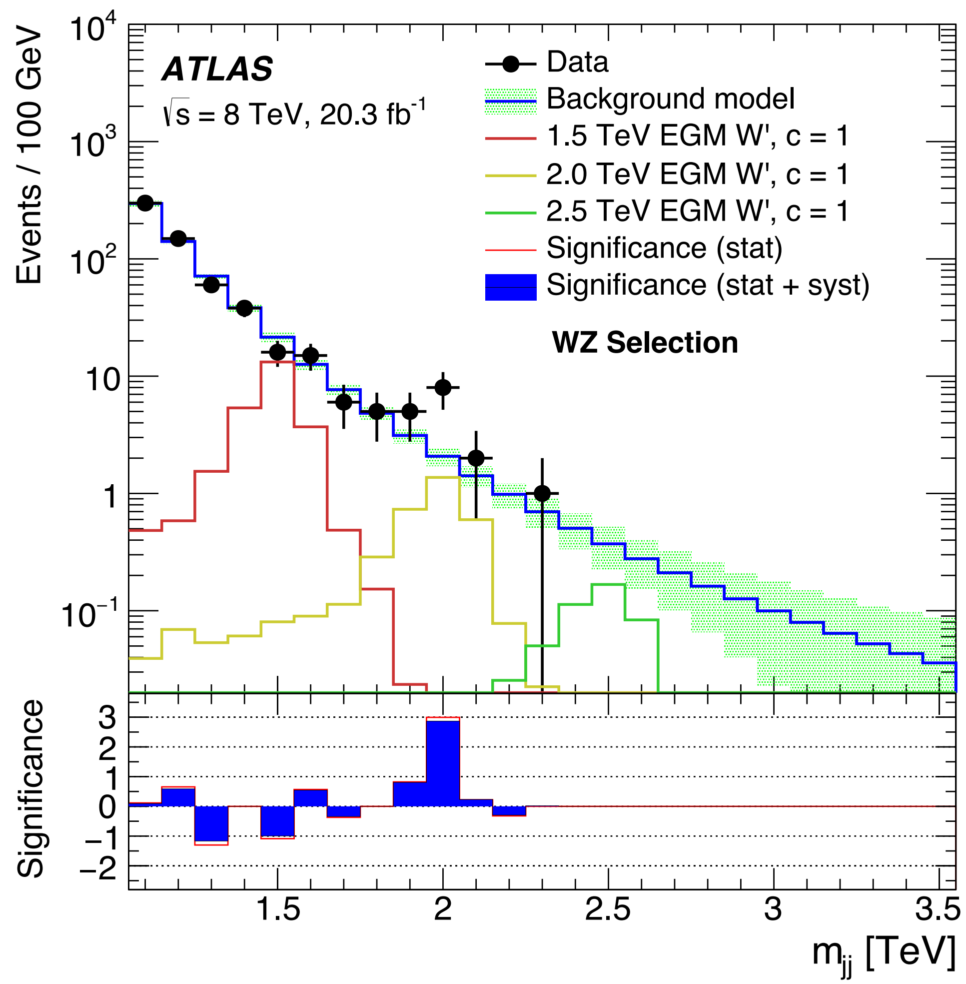
3 TeV
2 TeV
1 TeV
00 GeV
$\tilde{q}_L$
$\tilde{t}_R$
$\tilde{d}_R$
$\tilde{b}_R$
$\tilde{u}_R$
$\tilde{g}$
$\tilde{b}_L,\ \tilde{t}_L$
$\chi^0_{3,4}, \chi^{\pm}_2$
$\tilde{\tau}$
$\tilde{e},\ \tilde{\mu}$
$\chi^0_2,\ \chi^{\pm}$
χ^0_1
after LHC
Covered by
FCC-hh/SppC
current

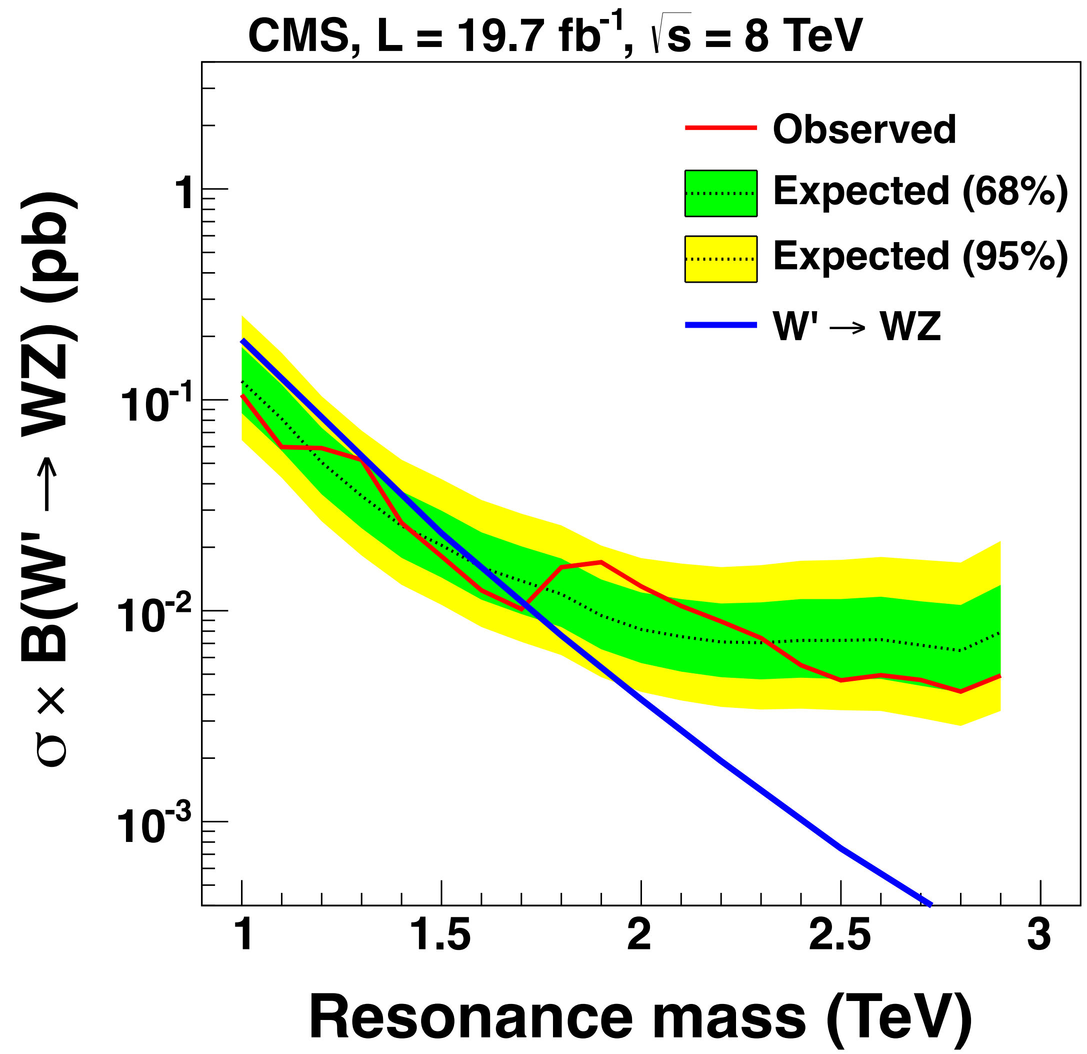
Gluino factory at 100 TeV



> 10^3 more gluino produced at 100 TeV collider

What if?





Composite spin-1 vector?

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

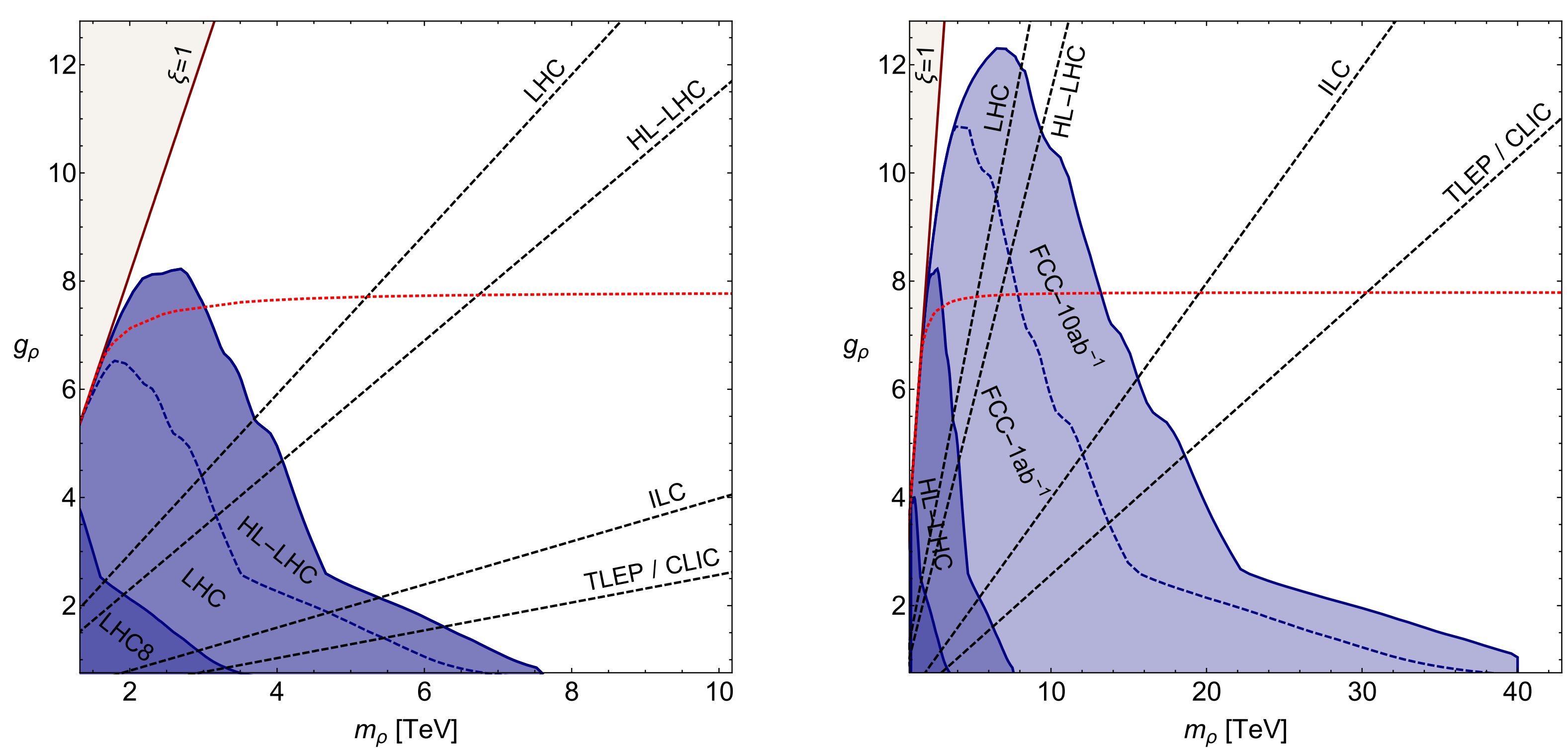
Composite Higgs

the rest

O(TeVs)

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

2 TeV ρ. Quick discovery at run 2



Conclusions

- LHC run 2+ will further probe new physics. However, several fundamental questions in particle physics will not be answered (fully) by the LHC.
  - Understanding EWSB, naturalness, dark matter, etc.
- Next generation Circular colliders, a promising step beyond the LHC.
  - Many activities, particularly the last couple of years.
  - Great physics case.

Conclusions

- Still just scratched the surface.
- Many work needs to be carried out to make sure circular colliders can reach its full physics potential.
- A lot of room for innovation.
  - New signals.
  - Improving precision SM calculations.
  - New collider physics studies.
  - New detector designs.

A lot to look forward to!

extras

Improve the precision

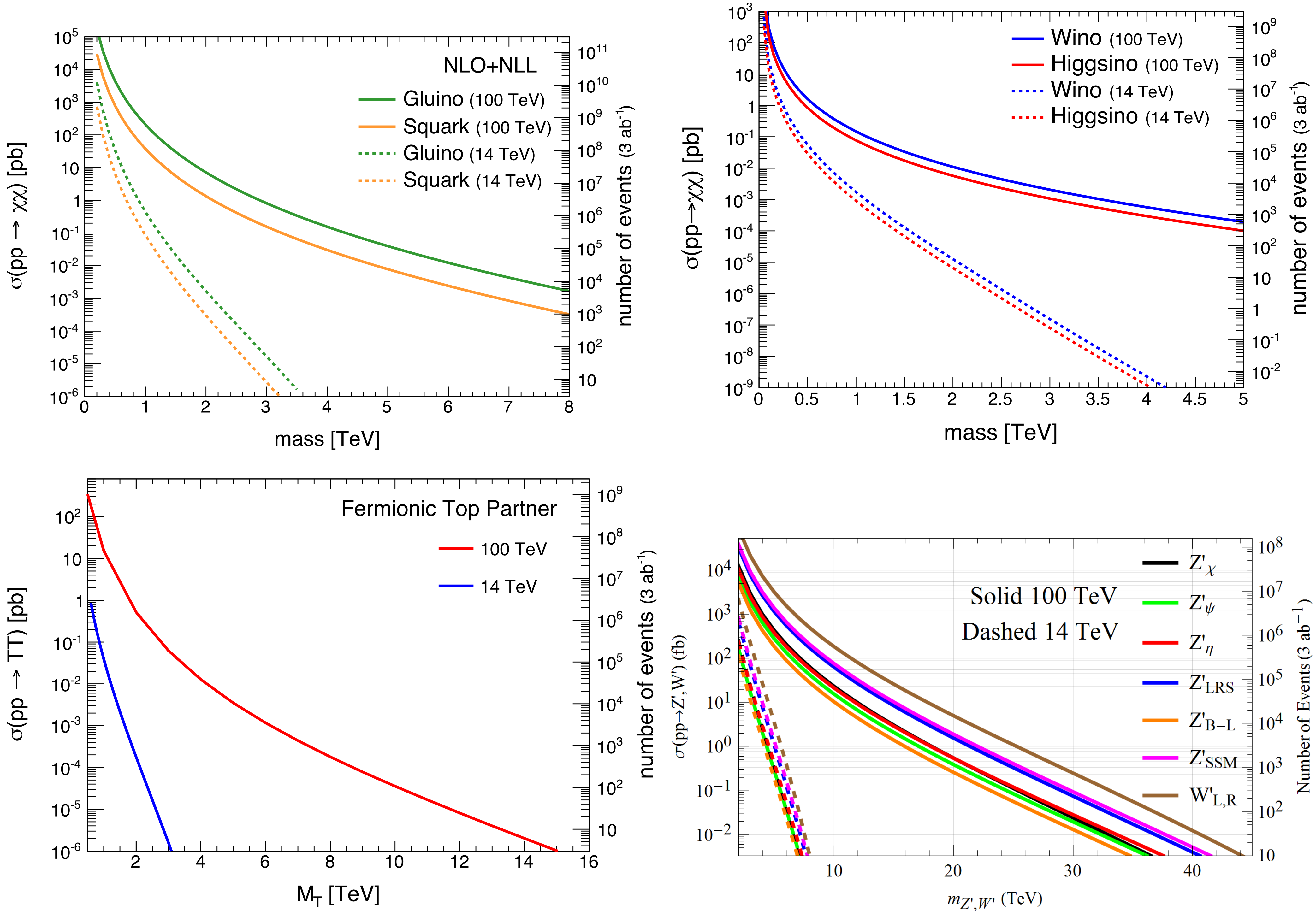
	TLEP-Z	TLEP-W	TLEP-t
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$ [35]	$\pm 1.0 \times 10^{-4}$ [35]	$\pm 1.0 \times 10^{-4}$ [35]
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$
m_Z [GeV]	$\pm 0.0001_{\text{exp}}$ [2]	$\pm 0.0001_{\text{exp}}$ [2]	$\pm 0.0001_{\text{exp}}$ [2]
m_t [GeV] (pole)	$\pm 0.6_{\text{exp}} \pm 0.25_{\text{th}}$ [23]	$\pm 0.6_{\text{exp}} \pm 0.25_{\text{th}}$ [23]	$\pm 0.02_{\text{exp}} \pm 0.1_{\text{th}}$ [2, 23]
m_h [GeV]	$< \pm 0.1$	$< \pm 0.1$	$< \pm 0.1$
m_W [GeV]	$(\pm 8_{\text{exp}} \pm 1_{\text{th}}) \times 10^{-3}$ [23, 38]	$(\pm 1.2_{\text{exp}} \pm 1_{\text{th}}) \times 10^{-3}$ [20, 38]	$(\pm 1.2_{\text{exp}} \pm 1_{\text{th}}) \times 10^{-3}$ [20, 38]
$\sin^2\theta_{\text{eff}}^{\ell}$	$(\pm 0.3_{\text{exp}} \pm 1.5_{\text{th}}) \times 10^{-5}$ [20, 38]	$(\pm 0.3_{\text{exp}} \pm 1.5_{\text{th}}) \times 10^{-5}$ [20, 38]	$(\pm 0.3_{\text{exp}} \pm 1.5_{\text{th}}) \times 10^{-5}$ [20, 38]
Γ_Z [GeV]	$(\pm 1_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-4}$ [2, 26]	$(\pm 1_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-4}$ [2, 26]	$(\pm 1_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-4}$ [2, 26]

Too optimistic?

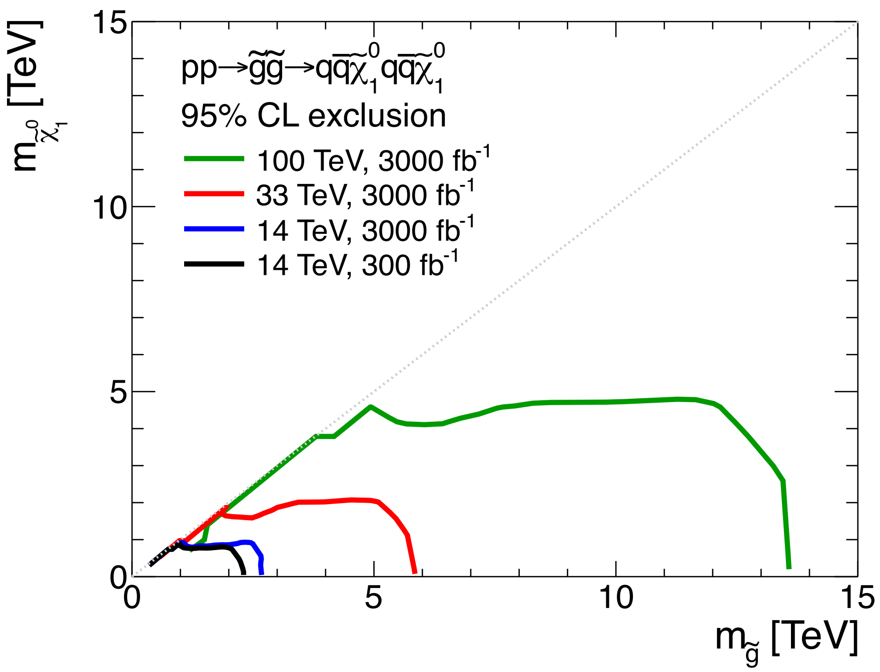
Dominated by systematics, such as $\Delta\alpha$

Need to improve theory error.

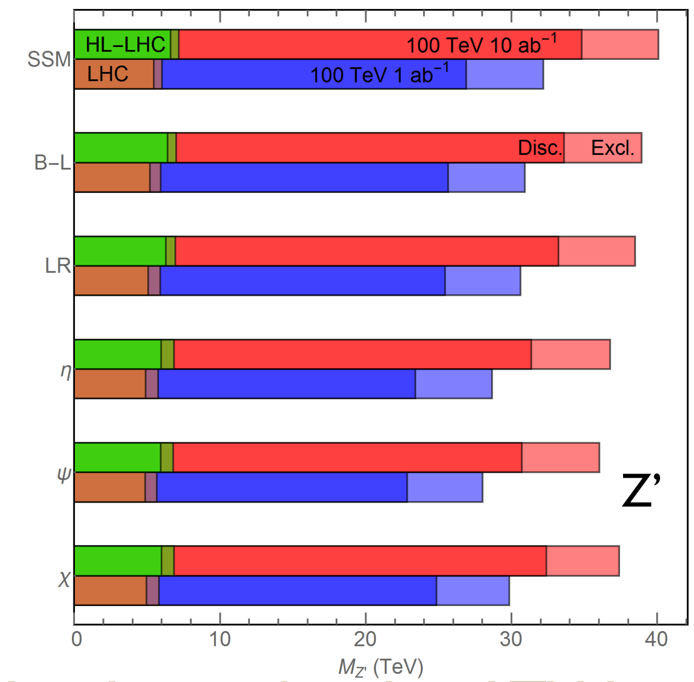
100 TeV pp collider, a big step



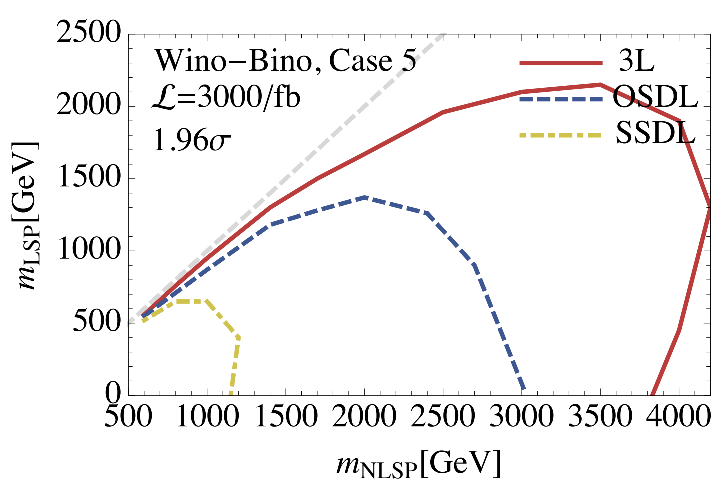
A big step forward in the energy frontier



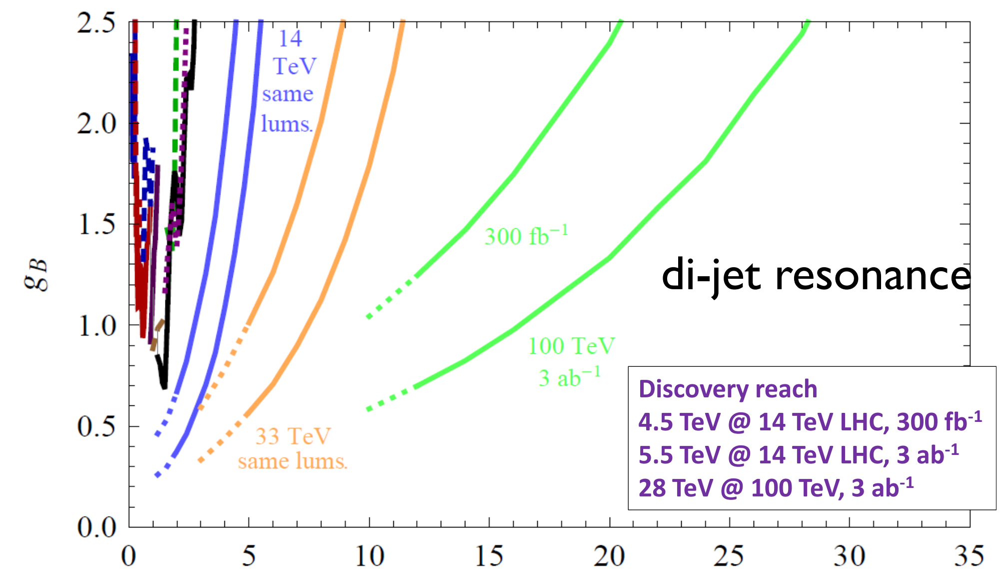
Cohen et al, 2013



Han, Langacker, Liu, LTW, to appear



Gori, Jung, LTW, Wells, 2014

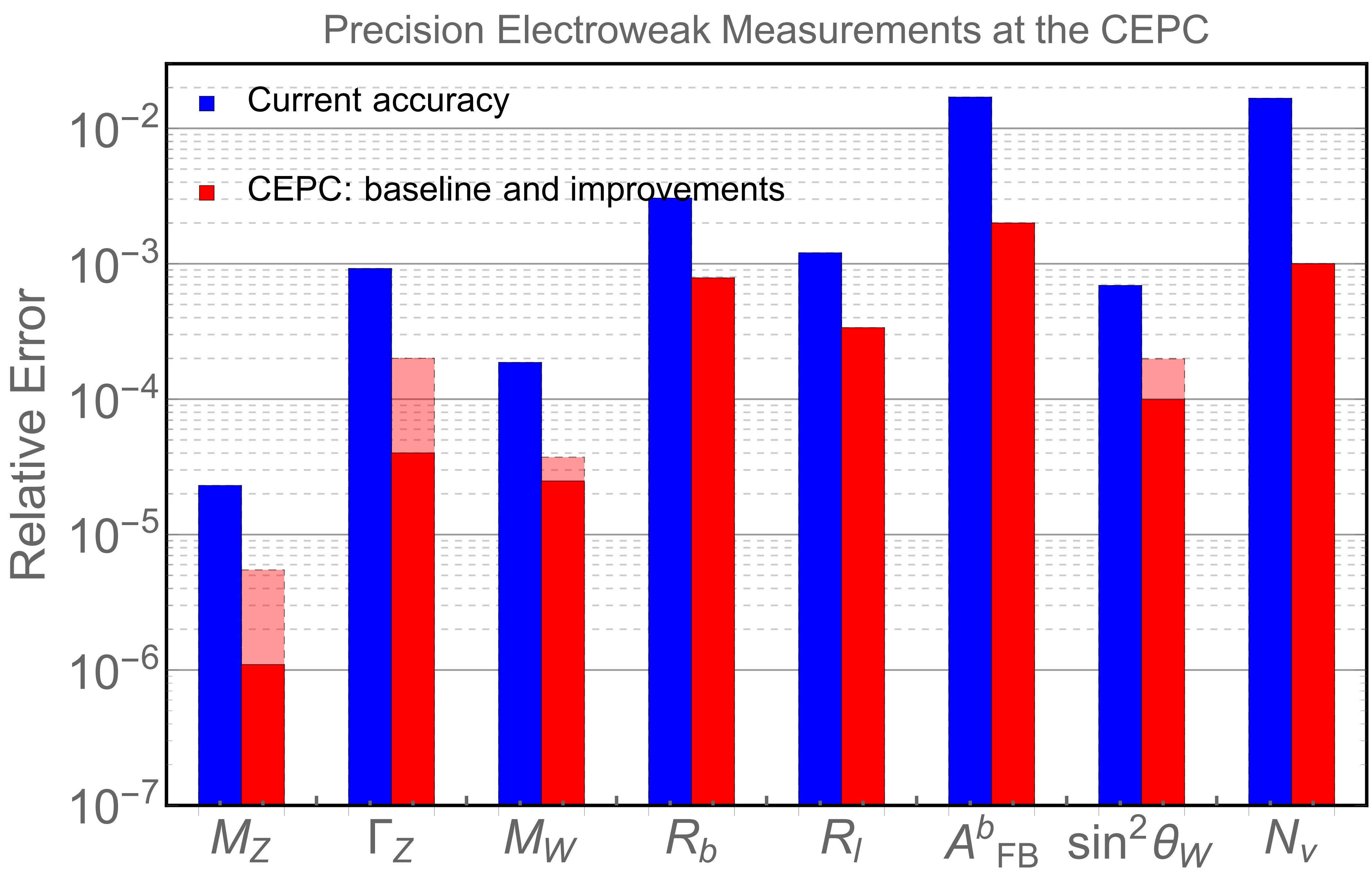


Could discover resonances with g_B as small as 0.35 to 0.5

Felix Yu, 2013

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

Precision EW at Higgs factory



Large improvements across the board

Summary of LHC Experimental Anomalies

B. Hooberman'15

Search	Dataset	**Max Significance**	Reference
Dilepton mass edge	CMS 8 TeV	**2.6σ**	CMS-PAS-SUS-12-019
WW cross section	CMS 7 TeV	**1.0σ**	EPJC 73 2610 (2013)
WW cross section	CMS 8 TeV	**1.7σ**	PLB 721 (2013)
$3\ell+E_T^{miss}$ electroweak SUSY	CMS 8 TeV	**~2σ**	EPJC 74 (2014) 3036
$4\ell+E_T^{miss}$ electroweak SUSY (see backup)	CMS 8 TeV	**~3σ**	PRD 90, 032006 (2014)
Higgs$\longrightarrow\mu\tau$ (lepton flavor violation)	CMS 8 TeV	**2.5σ**	CMS-PAS-HIG-14-005
1st generation leptoquarks (evjj channel)	CMS 8 TeV	**2.6σ**	CMS-PAS-EXO-12-041
ttH with same-sign muons	CMS 8 TeV	$\mu_{ttH} = 8.5^{+3.5}_{-2.7}$	arXiv:1408.1682v1 [hep-ex]
Dijet resonance search	CMS 8 TeV	**~2σ**	arXiv:1501.04198 [hep-ex]
$3\ell+E_T^{miss}$ electroweak SUSY	ATLAS 8 TeV	**2.2σ**	PRD 90, 052001 (2014)
Soft $2\ell+E_T^{miss}$ strong SUSY	ATLAS 8 TeV	**2.3σ**	ATLAS-CONF-2013-062
WW cross section	ATLAS 7 TeV	**1.4σ**	PRD 87, 112001 (2013)
WW cross section	ATLAS 8 TeV	**2.0σ**	ATLAS-CONF-2014-033
Monojet search	ATLAS 8 TeV	**1.7σ**	arXiv:1502.01518 [hep-x]
H→h(bb)h(γγ)	ATLAS 8 TeV	**2.4σ**	arXiv:1406.5053 [hep-ex]