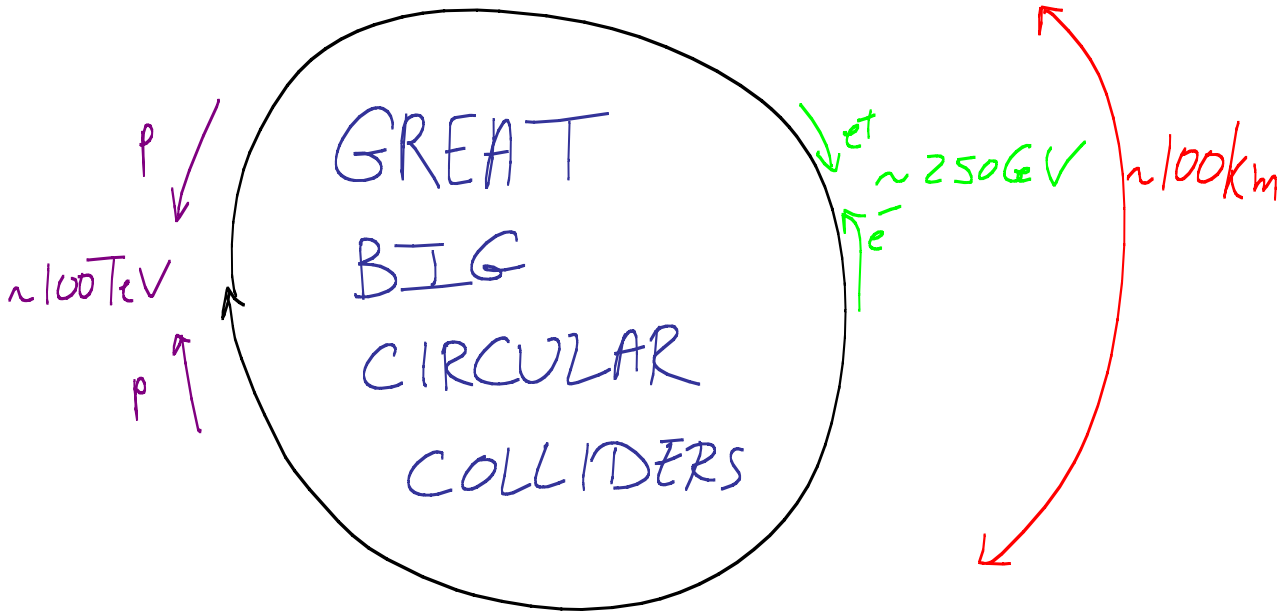
Motivations For



OBVIOUS FUTURE

BIG MACHINES,
BIG PHYSICS IDEAS

LIFEBLOOD OF
FUNDAMENTAL PHYSICS

Triumph of 20th Century

* Relativity + QM, dictate structure of long-distance physics

* Discovery of Higgs completes story:

smoothly extrapolate IR $\longrightarrow$ UV

massive massless

21st Century Challenges

* Spacetime is doomed — what replaces it?
* How is a macro-universe compatible with violent micro-quantum fluctuations?

Higgs Stars in This One!

New Physics $\stackrel{?}{=}$ New Particles

New Physics $\neq$ New Particles

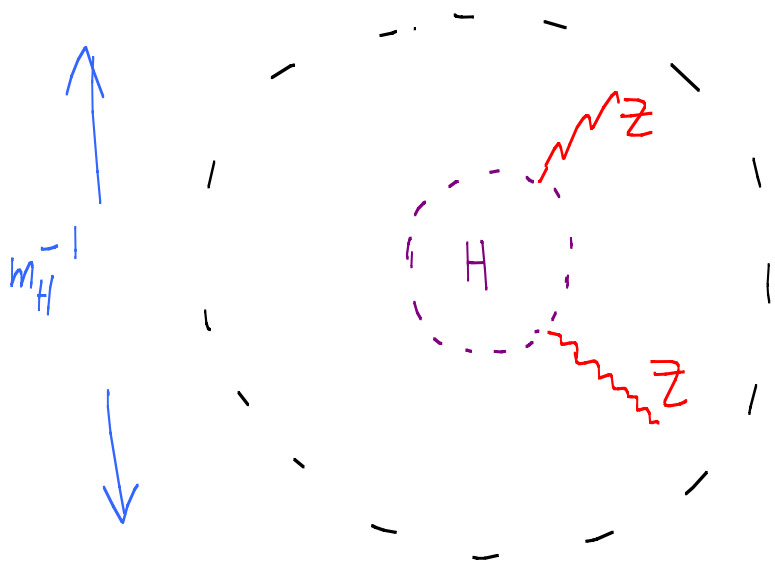
New Physics = New Phenomena

New Physics = New Principles

Higgs is Really New Physics!

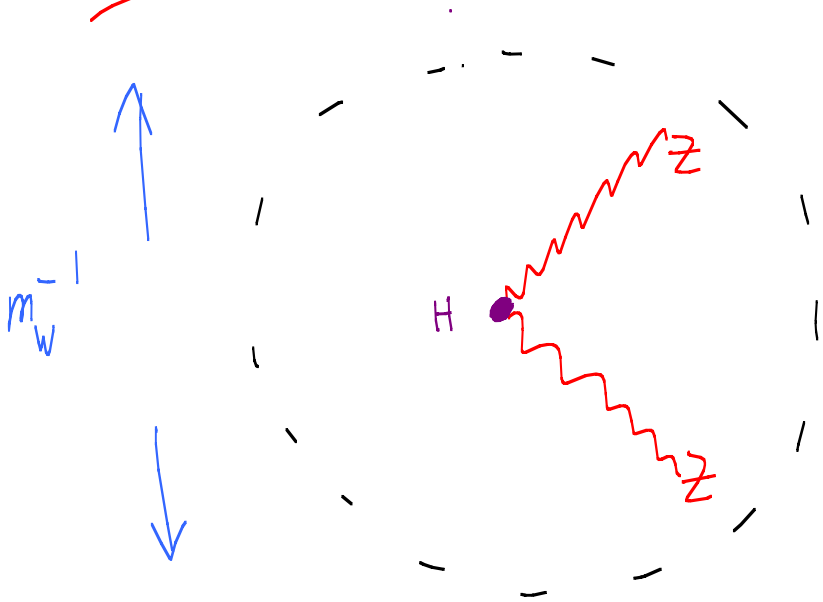
* We've never seen anything like it
* Harbinger of profound New Principles at work in quantum vacuum
* MUST LOOK AT IT CLOSELY

Never Seen Point-Like Scalar



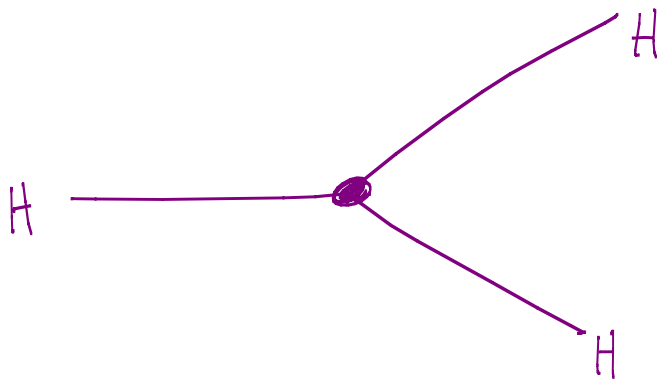
So, how pointlike is it?

Never Seen Point-Like Scalar



Higgs Factory

Never Seen Self-Interacting Fundamental Particles



100 TeV Collider

Charting The Unknown

* What are the raw capabilities of these machines?

[Spectacular]

Charting The Unknown

* Can any of our deepest questions be robustly probed with this level of precision + energy, and not (say) 10 x higher precision/energy?

[YES]

Phase Transition

"No Lose"

DM

See or Rule out
Simplest possibilities

Naturalness

NO LOSE

(0) New Machines for a New Frontier

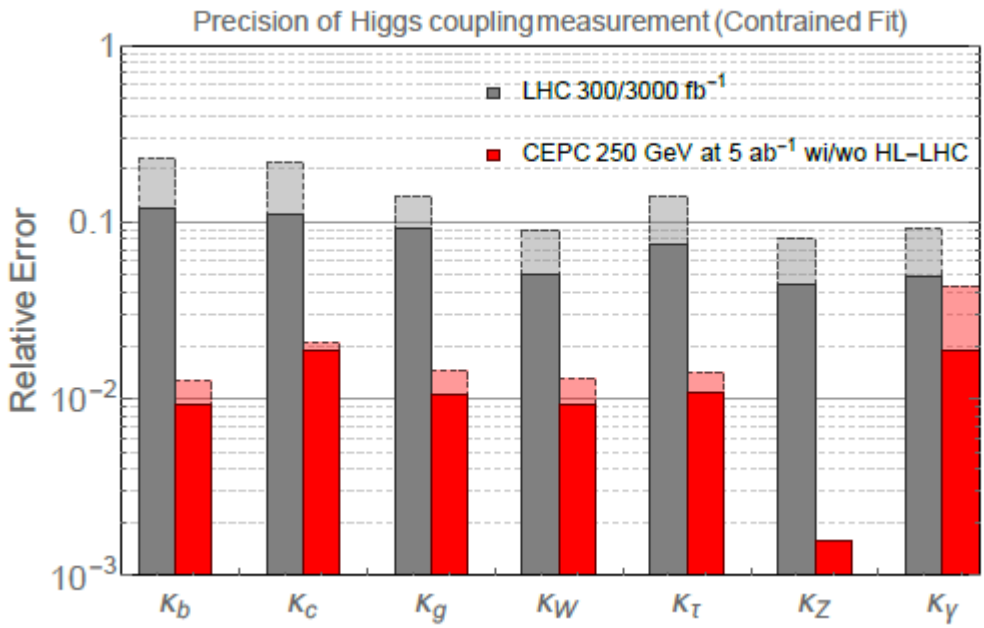
(1) The EWK Phase Transition

(2) Naturalness + deep origin of EWSB

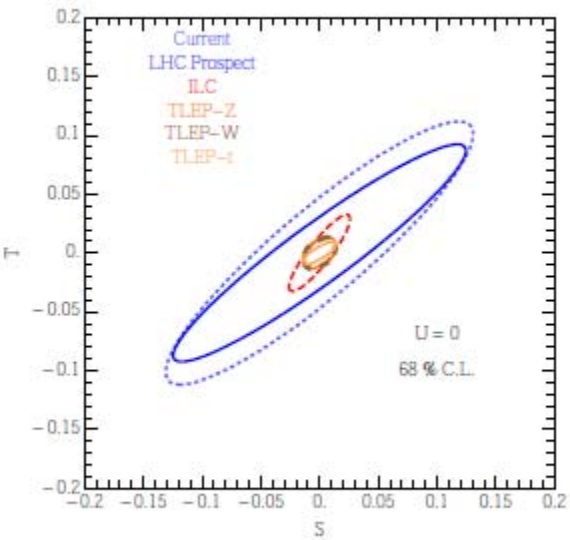
(3) Dark Matter(s)

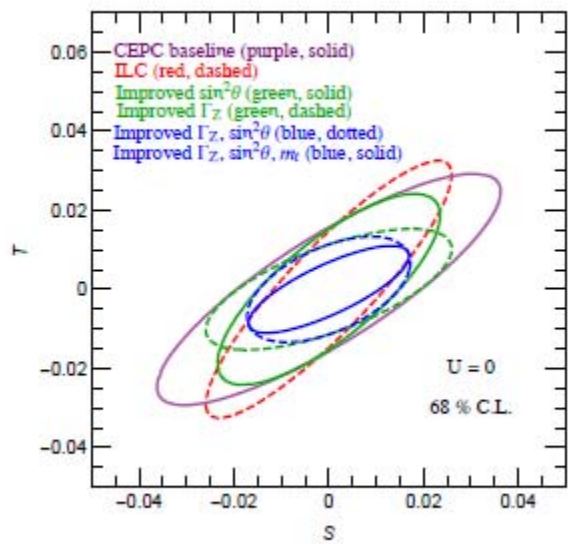
[(4) New world of Flavor + CP]

Higgs/Z factory Leap in Precision

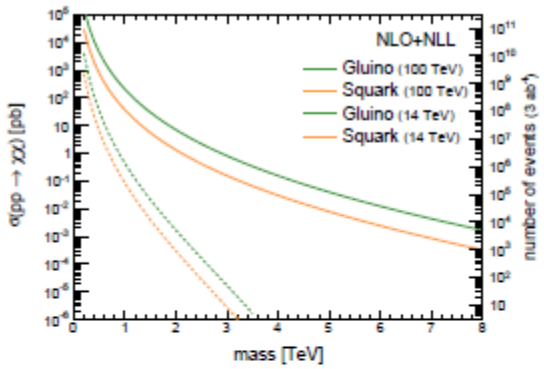


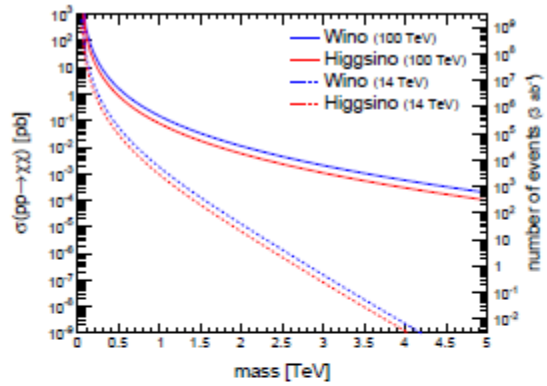
Higgs/Z factory Leap in Precision

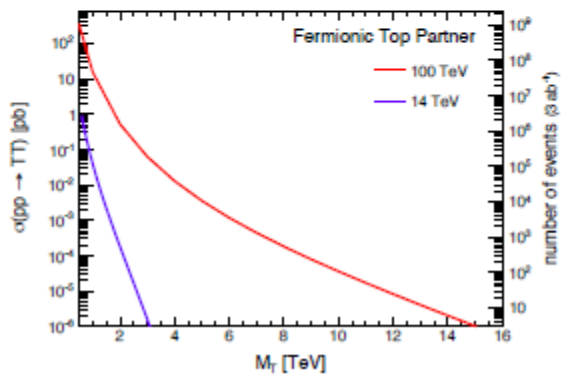


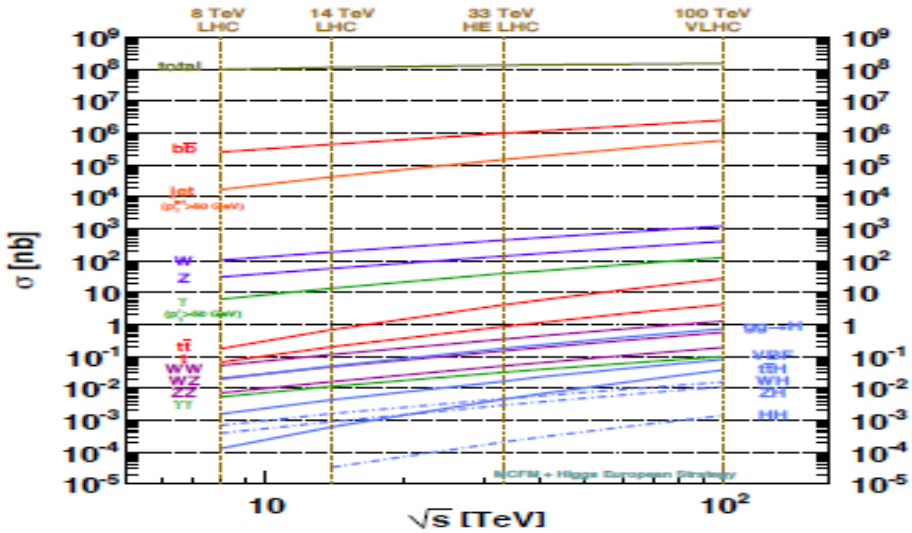


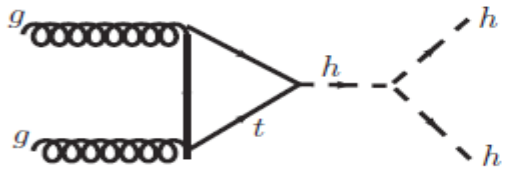
100 TeV Leap

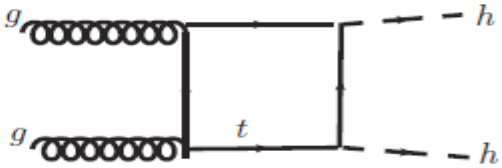

NLO+NLL
Gluino (100 TeV)
Squark (100 TeV)
Gluino (14 TeV)
Squark (14 TeV)
σ(pp → χχ) [pb]
number of events (3 ab⁻¹)
mass [TeV]


Wino (100 TeV)
Higgsino (100 TeV)
Wino (14 TeV)
Higgsino (14 TeV)
σ(pp→χχ) [pb]
number of events (3 ab⁻¹)
mass [TeV]


Fermionic Top Partner
100 TeV
14 TeV
σ(pp → TT) [pb]
number of events (3 ab⁻¹)
M_T [TeV]


8 TeV LHC
14 TeV LHC
33 TeV HE LHC
100 TeV VLHC
total
bb̄
jet
W
Z
γ
tt̄
t
WW
WZ
ZZ
γγ
gg→H
VBF
tt̄H
WH
ZH
HH
σ [nb]
√s [TeV]


g
g
t
h
h
h


g
g
t
h
h

* Powerful + Complementary probes of Higgs couplings

$[\Lambda^2 \alpha_6]$: $[\partial h^\dagger h]^2$, $h^\dagger h\, h f f^c$, $h^\dagger h F^2$ ← Higgs Factory

$(h^\dagger h)^3$ ← 100 TeV

Totally Generic

$(h^\dagger D^\mu h)^2$, $h^\dagger W^{\mu\nu} B_{\mu\nu} h$, $h^\dagger \overleftrightarrow{D}_\mu h\, \bar{f} \bar{\sigma}_\mu f$

↑ .1 Tera Z

Λ probed to (multi-) TeV scale

The Electroweak Transition

What is Shape of Potential?

$$V(h) \longrightarrow m^2 h^\dagger h + \lambda (h^\dagger h)^2$$

Landau-Ginzburg ...

NOT INNOCUOS!

$$V(h) \xrightarrow{?} \lambda (h^\dagger h)^2 + \frac{1}{\Lambda^2}(h^\dagger h)^3$$

$$V(h) \xrightarrow{?} \lambda (h^\dagger h)^2 \log \frac{h^\dagger h}{\Lambda^2}$$

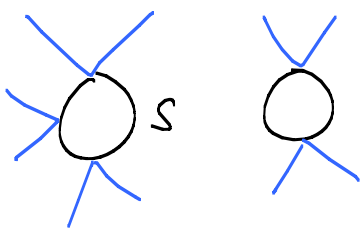
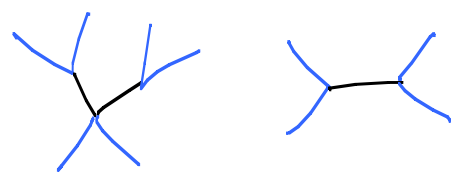
LHC won't tell us!

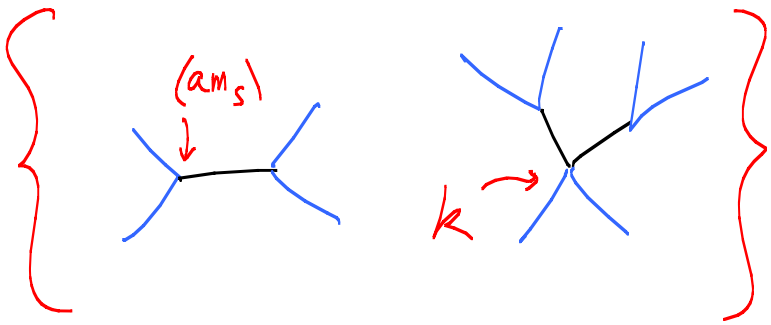
How is Electroweak Symmetry Restored?

Was Transition 1st or 2nd Order?

PERFECT TARGET FOR HIGGS FACTORY/
100 TeV

$$* \quad \Delta\mathcal{L} = \underbrace{\frac{(h^\dagger h)^3}{\Lambda^2}}_{\substack{\text{directly affects transition} \\ (h^3 \text{ coupling}) \\ \text{100 TeV/Higgs Factory}}} + \underbrace{\frac{(\partial\, h^\dagger h)^2}{\Lambda^2}}_{\substack{\text{identical symmetries} \\ (\mathbb{Z}_2) \\ \text{Higgs Factory}}} + \cdots$$

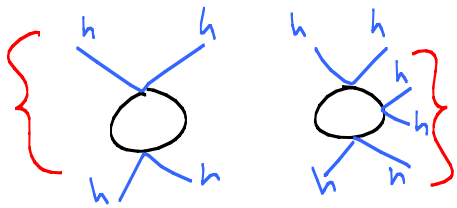
[eg  s or  in UV]



$$\lambda (h^\dagger h)^2 + \frac{K a^2}{m_s^2} (h^\dagger h)^3 + \frac{a^2}{m_s^2} (\partial_\mu h^\dagger h)^2$$

$$\Downarrow$$

$$\delta Z_h \sim \frac{\lambda}{K} \gtrsim \frac{\sqrt{\lambda}}{4\pi} \sim 0.3, \quad m_s \lesssim 4\pi V \sim 2\,\text{TeV}!$$


h
h
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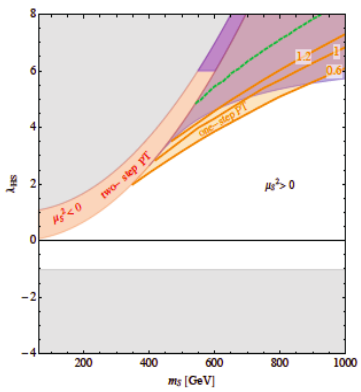
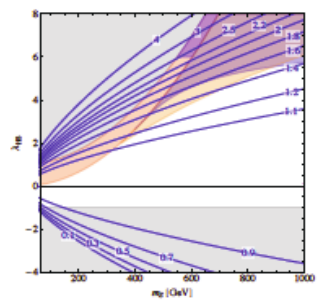
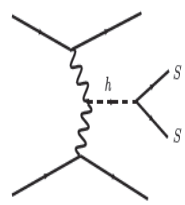
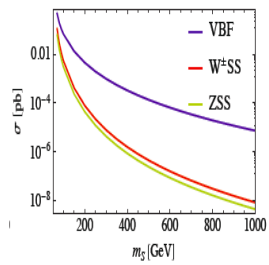
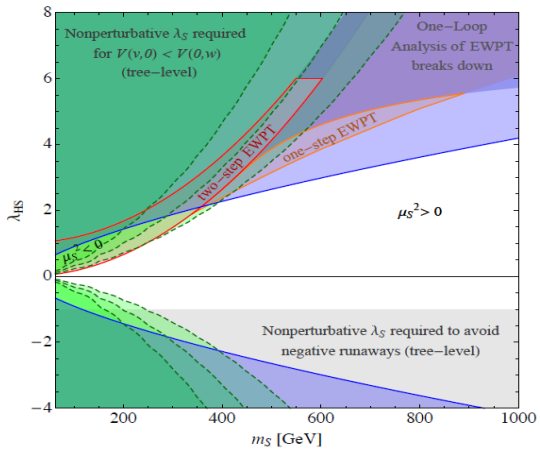

λ_{HS}
m_S [GeV]
two-step PT
one-step PT
$\mu_S^2 < 0$
$\mu_S^2 > 0$
1.2
1.1
0.6


λ_{HS}
m_S [GeV]


h
S
S

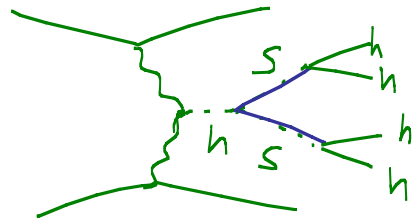

VBF
$W^{\pm}SS$
ZSS
σ [pb]
m_S [GeV]

Even Hardest Scenario



Can be Seen!

S - decays

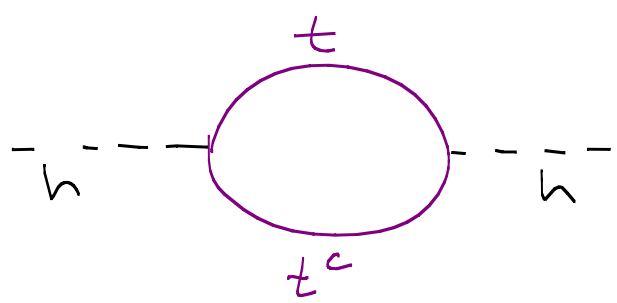


Spectacular Signal!

Origin + Naturalness of Electroweak Scale

The Standard Model is aptly named... it is a phenomenological MODEL, not a deep THEORY of EWSB.

M_h^2 is a parameter, not predicted, but fitted by experiment!



$$\propto \left(\frac{3\lambda_t^2}{8\pi^2}\right)\Lambda^2$$

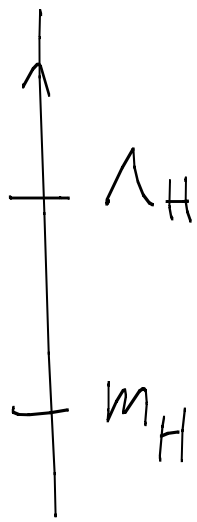
model, not theory

* Higgs is SIMPLEST PARTICLE we've ever seen

* $m_H^2 H^\dagger H$ is SIMPLEST PARAMETER in particle physics, and the most relevant @ low E!

* Quest for THEORY starts here — especially since it turns out to be the most mysterious of all of them!

[400-Yr] Reductionist Paradigm



scale where Higgs THEORY is revealed, m_H becomes calculable

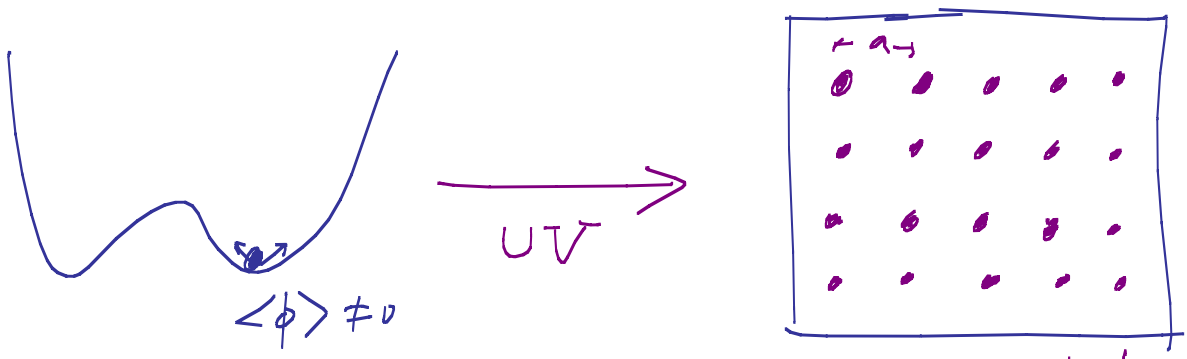
$$m_H^2 = a\,\Lambda_H^2 + b\left(\frac{3\lambda_t^2}{8\pi^2}\right)\Lambda_H^2 + \cdots$$

$\Lambda_H \sim m_H$: "Natural"
Complete Understanding

$\Lambda_H \gg m_H$: Needs extreme correlation between UV + IR physics (POSSIBLE, NEVER SEEN BEFORE)

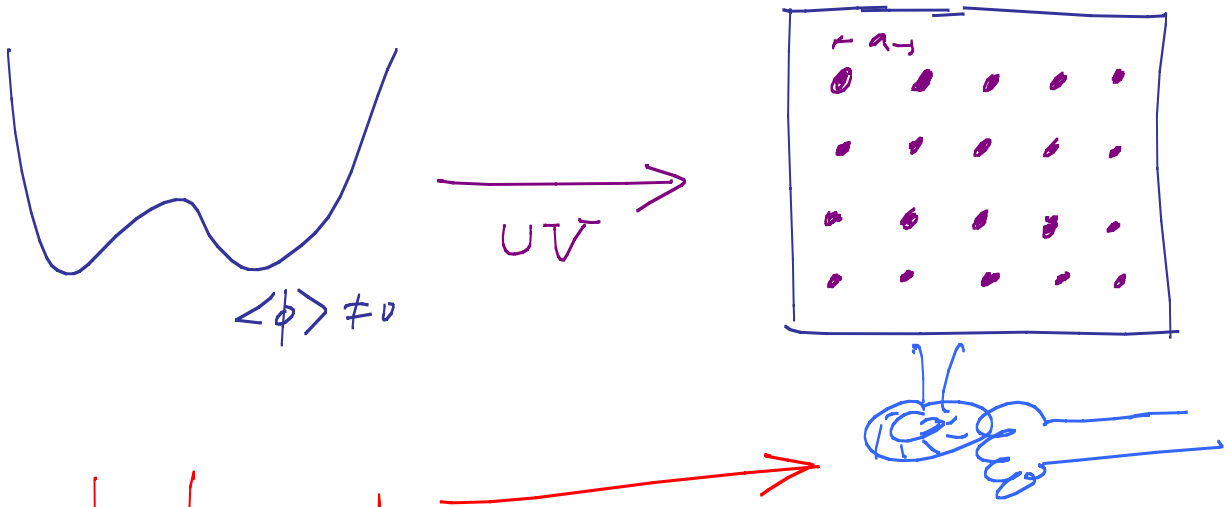
Borne out by all known examples, both theoretically, as well as experimentally!

A Famous Example



Still no understanding of $m_\psi^2 \ll 1/a^2$!

A Famous Example



Explanation not in UV, but OUTSIDE SYSTEM!

* Here: "fine-tuning"
* Breakdown of reductionism for this system!

WIN-WIN-WIN

$\Lambda_H \sim m_H$

Complete Understanding of EWSB [+ much, much more]

SPECTACULAR

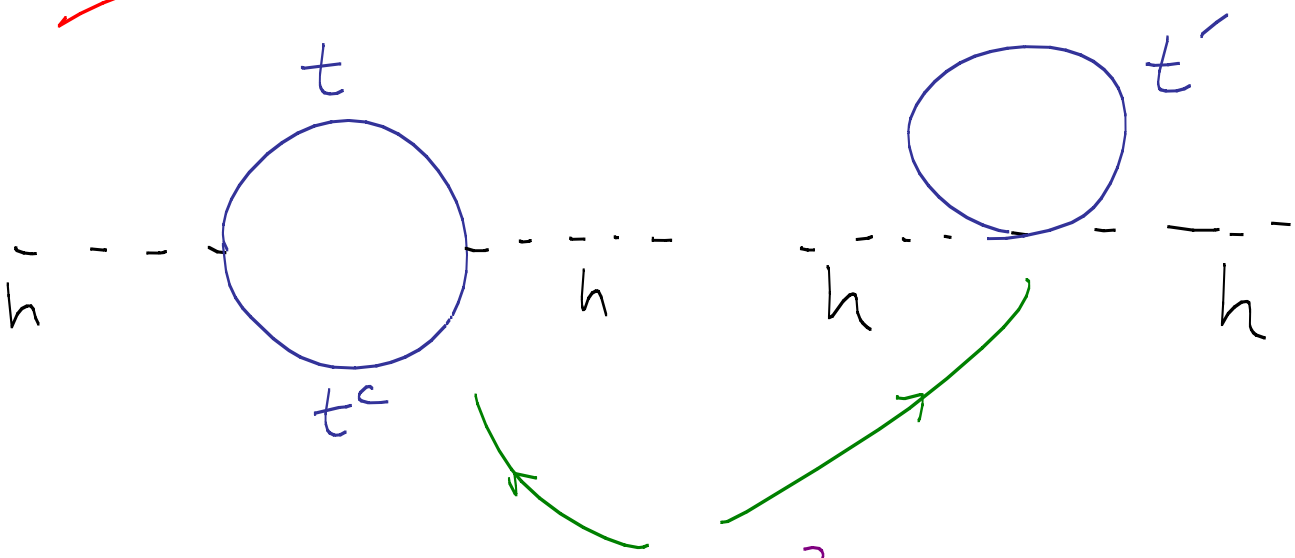
$\Lambda_{HI} \gg m_H$

Unprecedented Correlation between UV + IR

Breakdown of reduct: explanation "outside universe"

Won't know which, but, REVOLUTIONARY either way.
Epochal change in direction of Fundamental Physics

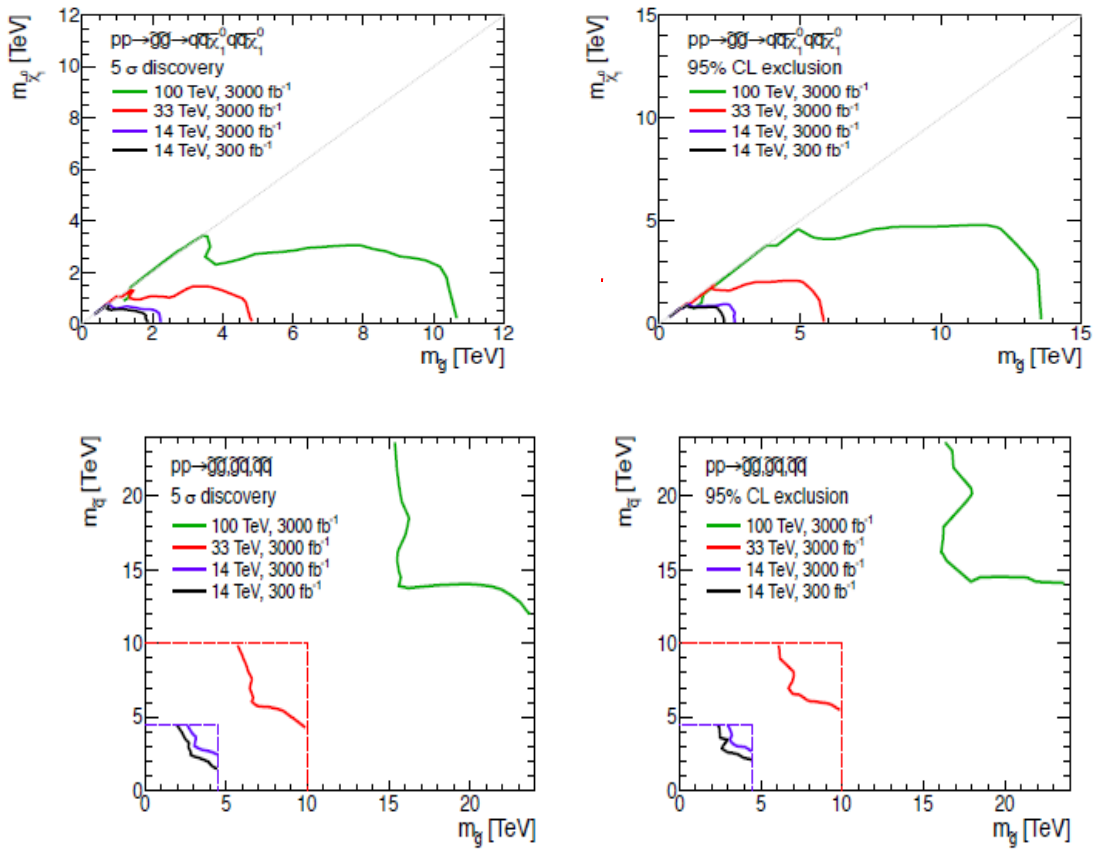
Expectation of New Part. At LHC



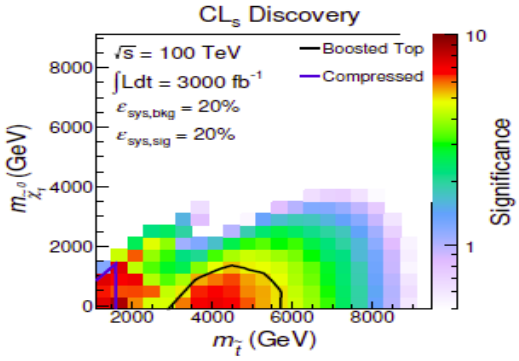
$$\delta m_h^2 = \frac{3\lambda_t^2}{8\pi^2}\Lambda^2$$

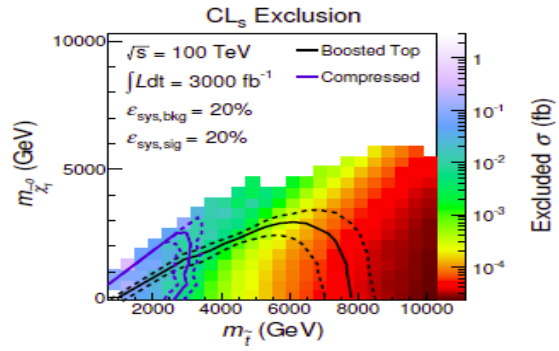
COLORED top partners $\lesssim$ 400 GeV

Meso-Tuned SUSY?

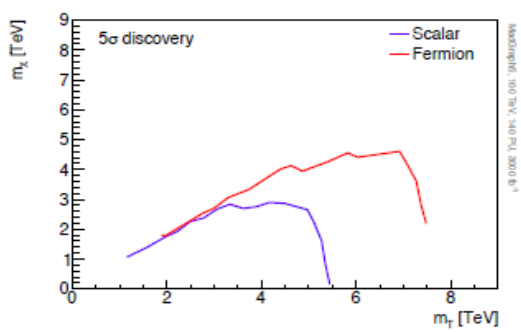


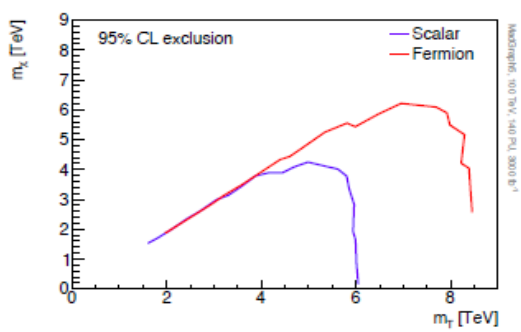
Stops





Top Partners



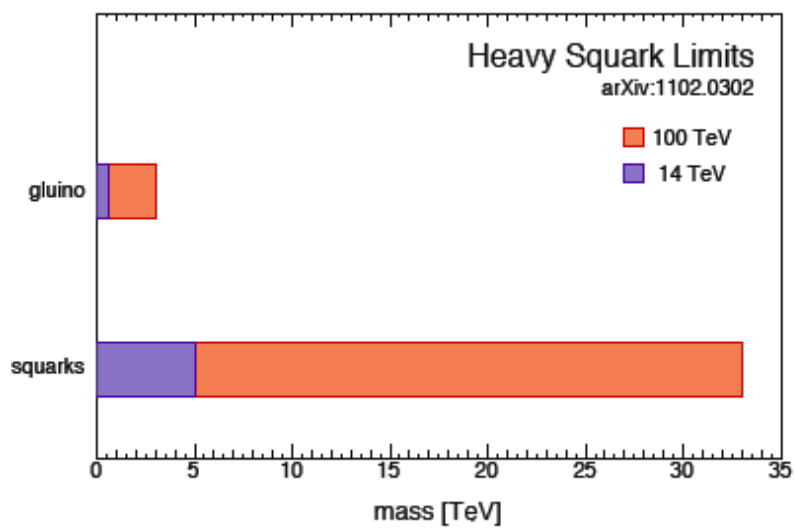


* Of course if we <u>do</u> see new physics @ LHC [e.g. 2 TeV $\tilde{g}$'s], we won't produce with enough rate to learn what they are trying to tell us!

[e.g. is it a gluino?]

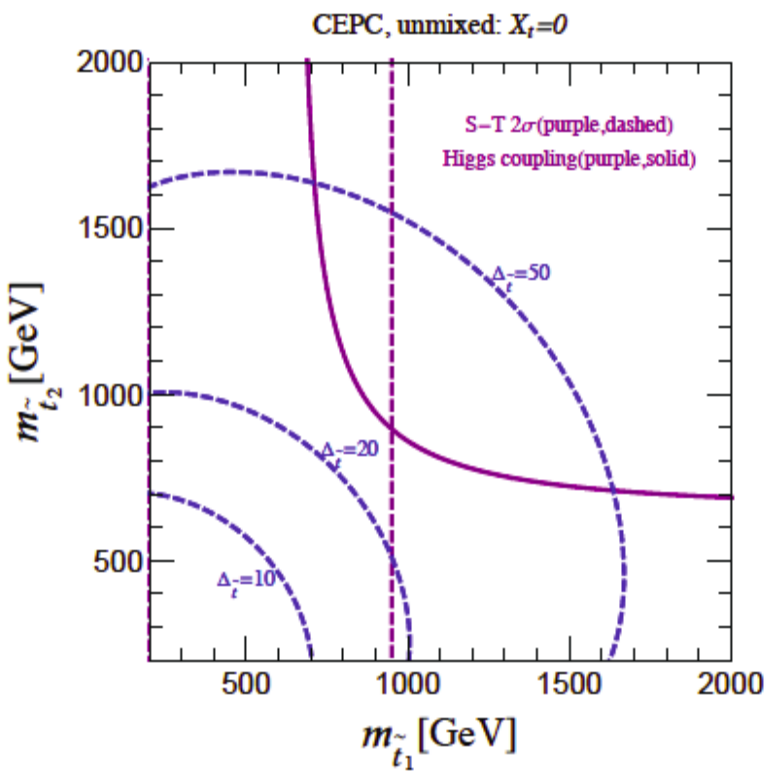
Unlikely To See Full Spectrum

E.g. "natural SUSY", $\tilde{q}_{1,2}$ could be ~20 TeV!



Assoc. Production w/ light gluino up to ~35 TeV!

Stops have nowhere to Hide!



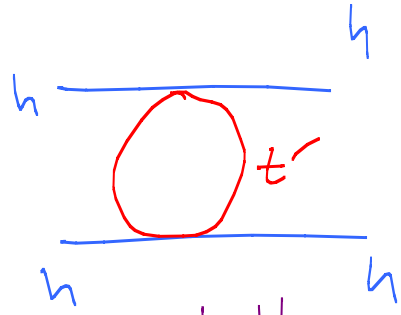
higgs/Z coupling shifts, Can't be hidden in hadronic muck

It's 2020, no new particles @ LHC... aren't we crying over spilled milk with naturalness? Won't we already know it's wrong? Do we need colliders to further beat an already dead horse?

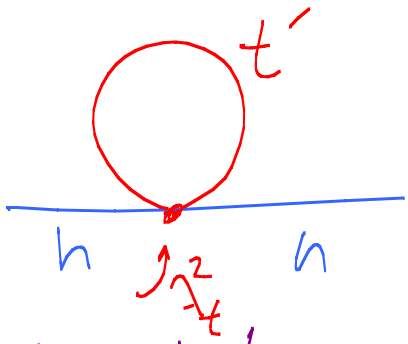
No

Neutral Naturalness

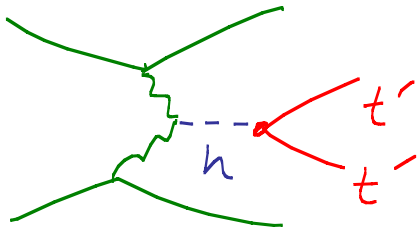
"Twin Higgs"
"Folded SUSY"



inevitable
Z-h shift

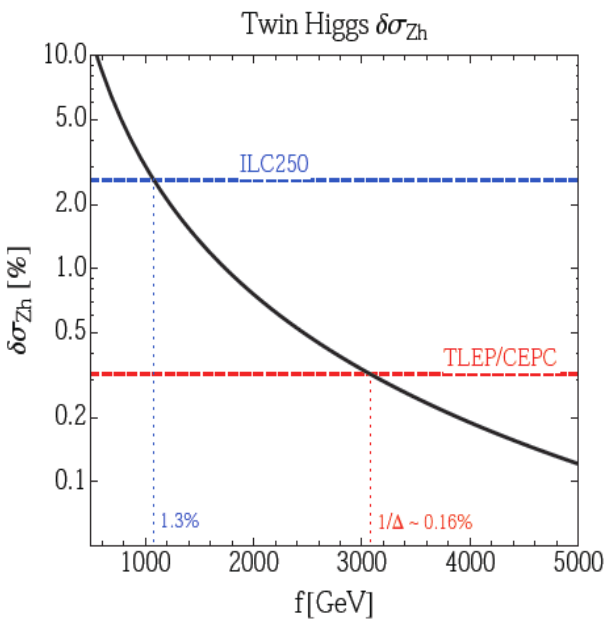


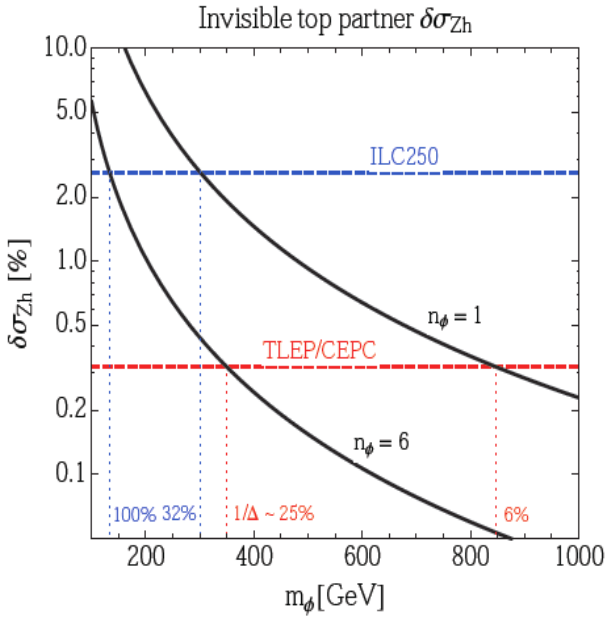
Uncolored top partners,
"3" from partner to $SU(3)_{color}$



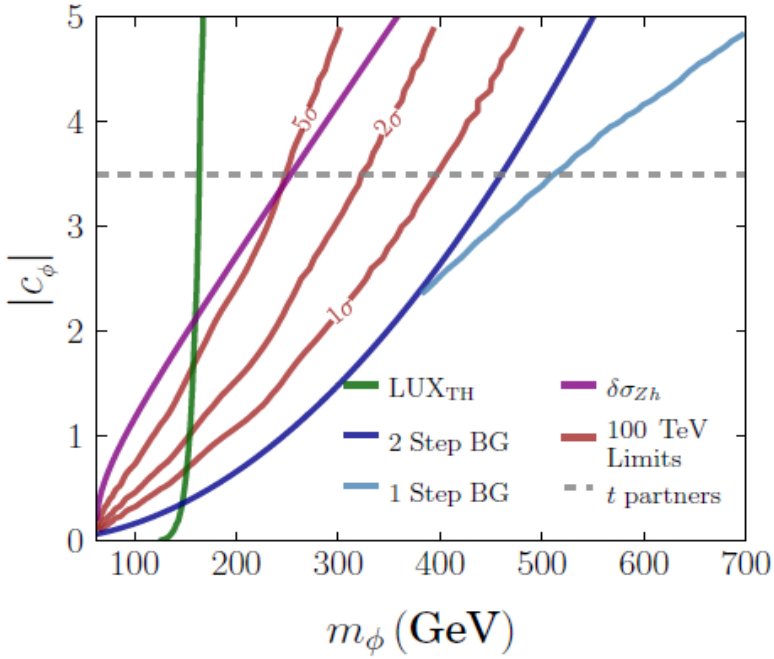
production
@ 100 TeV

Naturalness "No-Lose" Thm



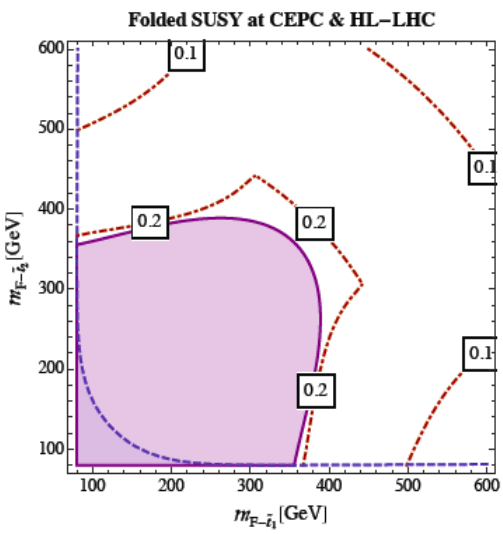


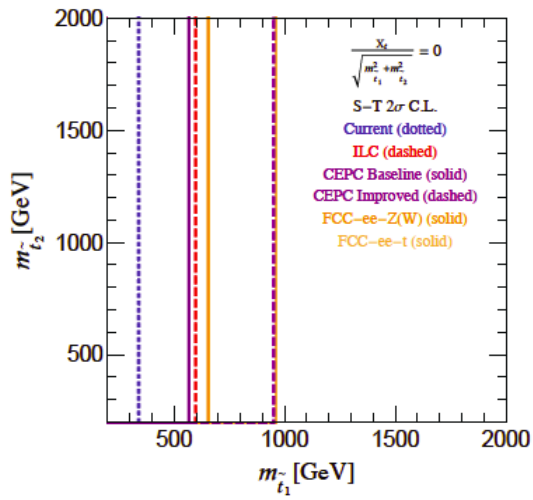
And Look For VBF t's prod. @ 100 TeV



2 sigma δZ_{higgs} $\Longrightarrow$ 5 TeV discovery @ 100 TeV

Electroweak Charged $\tilde{t}$'s





{ Stronger Probe @ Higgs Factory! }

WIN-WIN-WIN

$\Lambda_H \sim m_H$

Complete Understanding of EWSB [+ much, much more]

SPECTACULAR

$\Lambda_{HI} \gg m_H$

Unprecedented Correlation between UV+IR

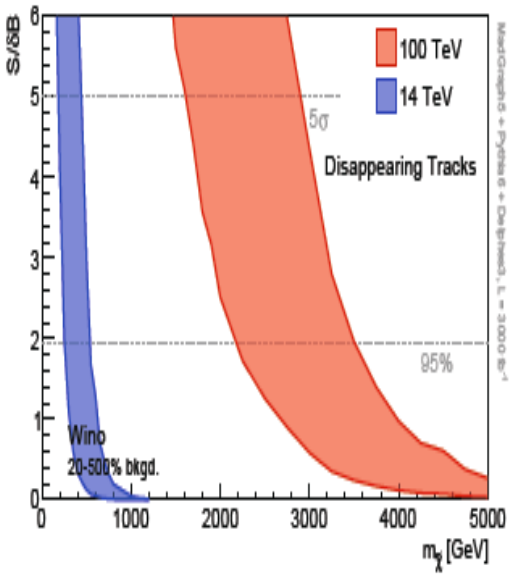
Breakdown of reduct: explanation "outside universe"

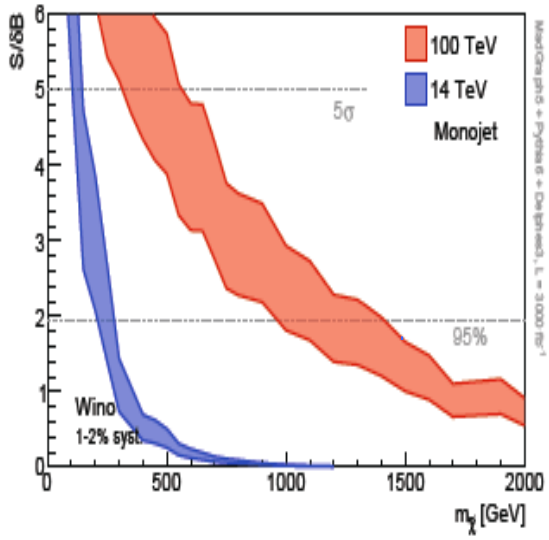
Won't know which, but, REVOLUTIONARY either way.
Epochal change in direction of Fundamental Physics

Dark Matter

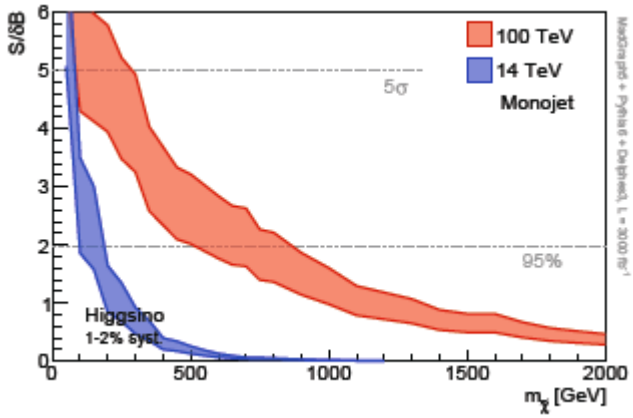
- WIMPS are, still, the only calculable models of dark matter we have
- If "W" = "elWeak" — could easily be ~ few TeV, + inaccessible @ LHC. [Even more likely now, after LHC 8]

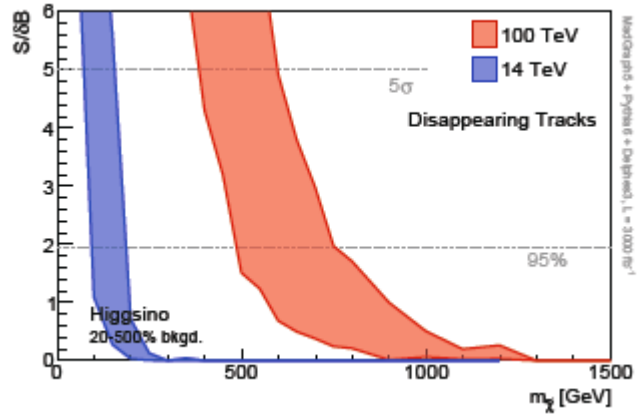
"Winos"

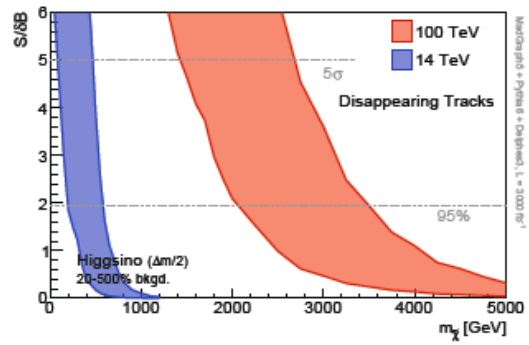

S/δB
100 TeV
14 TeV
5σ
Disappearing Tracks
95%
Wino
20-500% bkgd.
m_χ [GeV]


S/δB
100 TeV
14 TeV
5σ
Monojet
95%
Wino
1-2% syst.
m_χ [GeV]

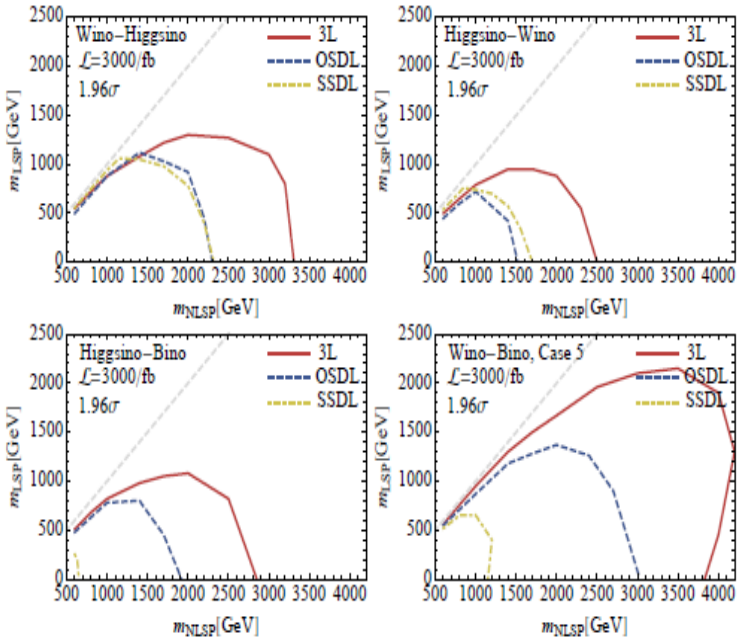
"Higgsinos"


S/δB
100 TeV
14 TeV
Monojet
5σ
95%
Higgsino
1-2% syst.
m_χ [GeV]

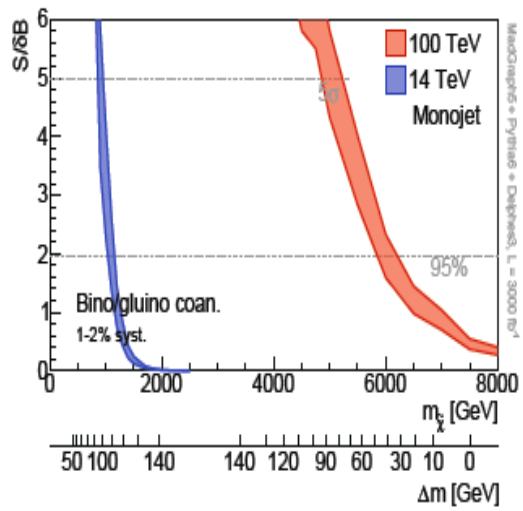

S/δB
100 TeV
14 TeV
Disappearing Tracks
5σ
95%
Higgsino
20-500% bkgd.
m_χ [GeV]


S/δB
100 TeV
14 TeV
Disappearing Tracks
5σ
95%
Higgsino (Δm/2)
20-500% bkgd.
m_χ [GeV]

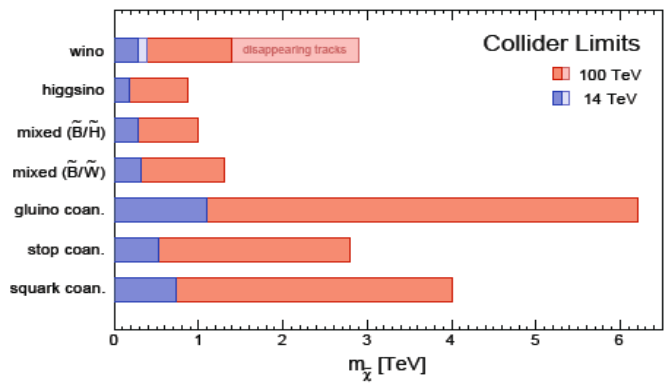
Electroweak Cascades

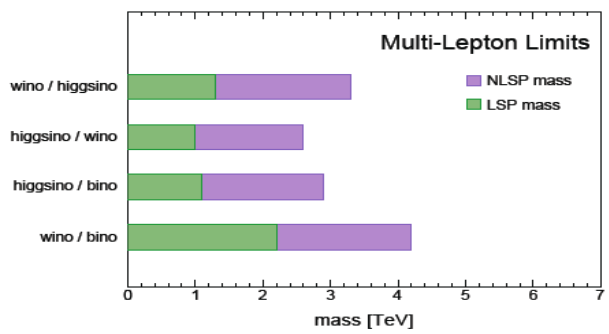


Co-Annihilation



Robust Coverage For WIMPS





Phase Transition

"No Lose"

DM

See or Rule out
Simplest possibilities

Naturalness

NO LOSE

[Countering]

Common Objections

"There's no point to planning ahead before we get LHC14 results"

"If only Higgs @ LHC,
we can't guarantee
discoveries, won't convince
politicians to build machines"

"If Higgs Factory/100 TeV
doesn't see new physics,
it will be a big
waste/failure"

"Instead of building bigger accelerators, shouldn't we wait to develop revolutionary new methods + do it cheap?"

"What About The ILCP"

Case is Amazingly Strong

+

Easy to Explain

The scientific issues at stake are the most difficult + profound ones we have faced since 1930's

The scale of our vision + ambition must be commensurate with what the science demands: BE MORE, NOT LESS AGGRESSIVE IN PURSUING IT!