Motivations For Future Colliders

Particle Physics

|| ?

Study of Building Blocks of Matter

Particle Physics

≠ [At least not merely]

Study of Building Blocks of Matter

Particle Physics

||

Study of Fundamental Laws of Nature,

governed by still-mysterious union of

Space-Time + Quantum Mechanics

New Physics ? New Particles

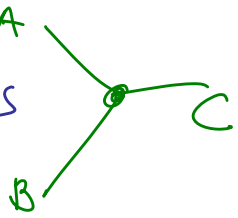
New Physics ≠ New Particles

New Physics = New Phenomena

New Physics = New Principles

Whatever the Ultimate Theory

Relativity ↓ Quantum Mechanics

At "Long" distances, particles interacting as 

with spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$. ← unique, "gravity"

Belief in Principles Paid Off

$$0, \frac{1}{2}, 1, \frac{3}{2}, 2$$

Higgs is first "really new" particle we've seen!

$$\left(\frac{E}{V}\right) = \int d^3k \; \frac{1}{2}\sqrt{k^2 + m_B^2} - \frac{1}{2}\sqrt{k^2 + m_F^2}$$

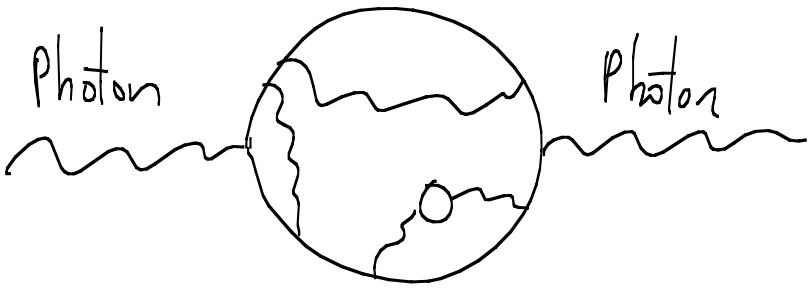
$m_B^2 \to g^2|h|^2$, $m_F^2 \to \lambda^2|h|^2$

$$= \Lambda_{UV}^4 + (g^2 - \lambda^2)\Lambda_{UV}^2 |h|^2 + \cdots$$

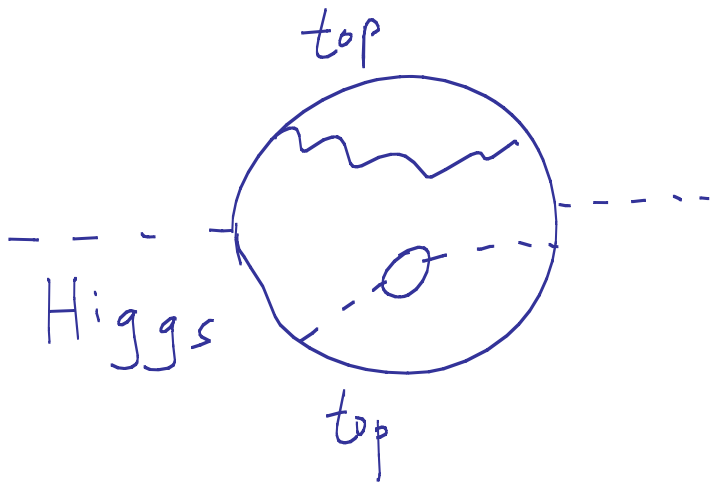
Λ_{UV}^4 : Cosmological Constant Problem

Λ_{UV}^2 : Hierarchy Problem

WHY IS THERE A MACROSCOPIC UNIVERSE?



Massless: $2 \neq 3$!



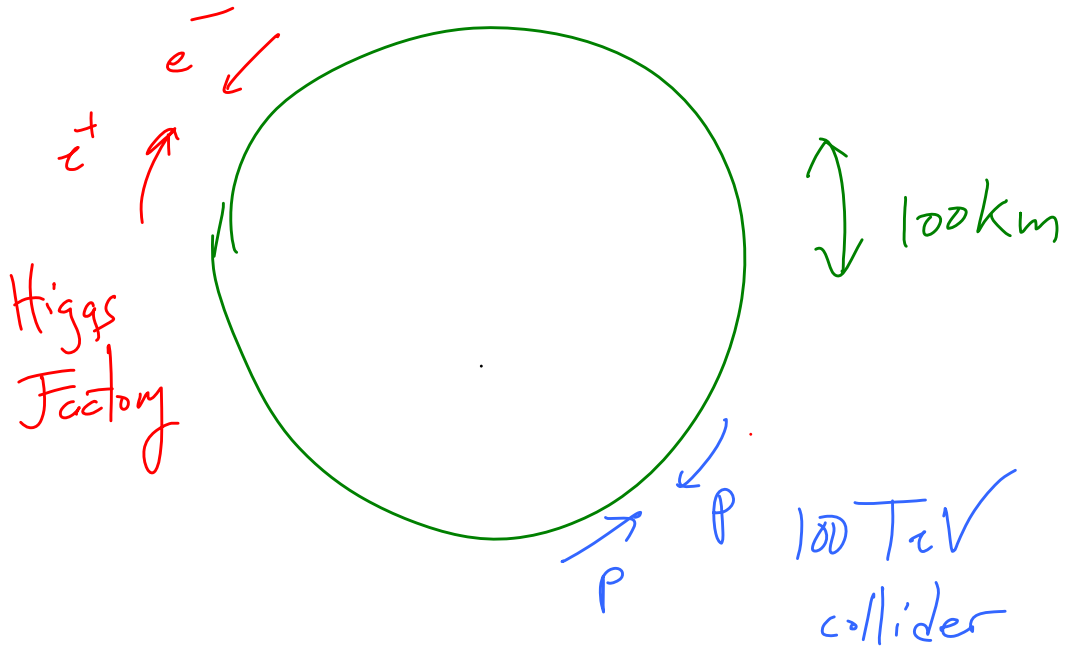
UltraMassive,

$1 = 1$!

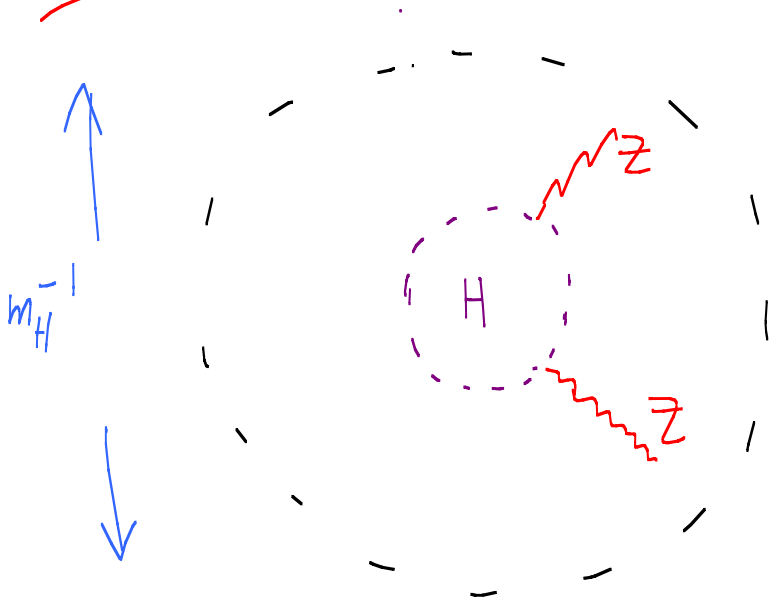
Higgs is Really New Physics!

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

* Linear Colliders

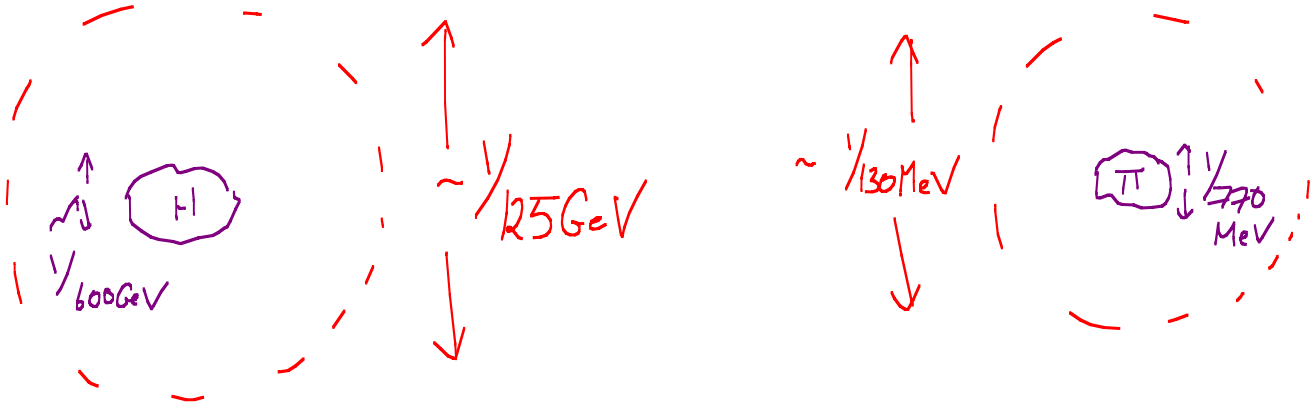


Never Seen Point-Like Scalar

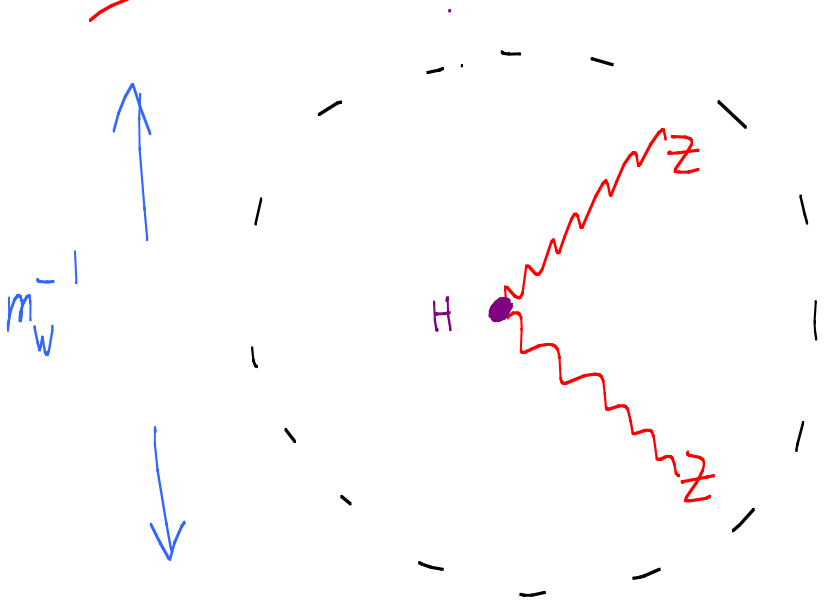


So, how pointlike is it?

But with LHC resolution, Higgs could be about as elementary as a "pion":



Never Seen Point-Like Scalar

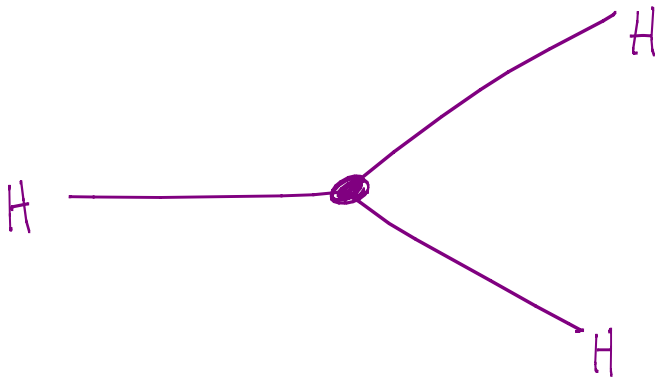


Higgs Factory

+

We will know FOR SURE if it is "a pion"

Never Seen Self-Interacting Fundamental Particles



100 TeV Collider

Measured to ~ 5-10% level!

Also, 100 TeV collider

blasts into the high energy

frontier. New particles ~ 10 X LHC reach.

Probes vacuum quantum fluctuations

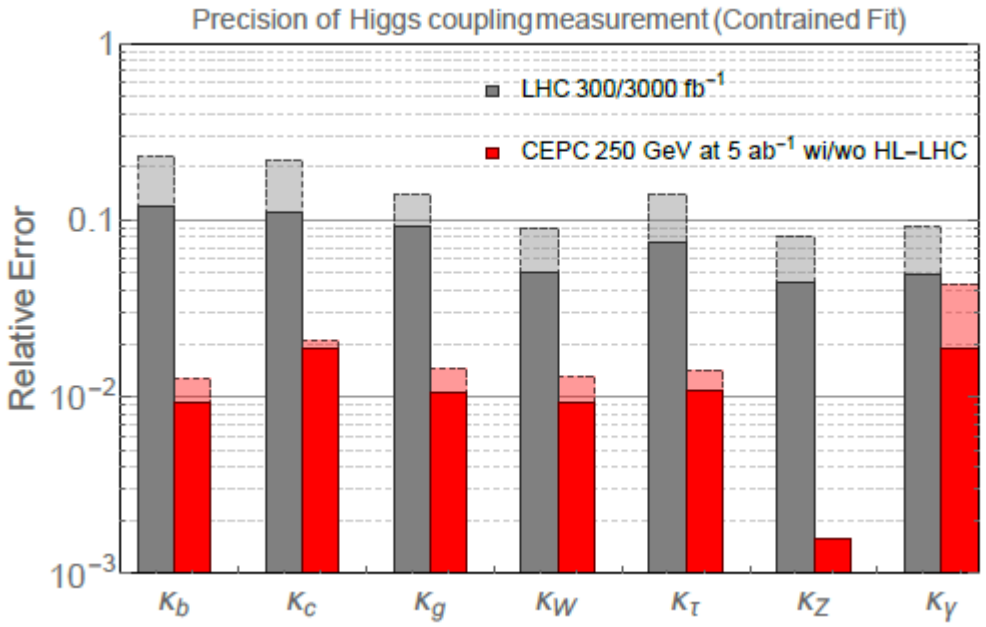
with power 100 X LHC

Charting The Unknown

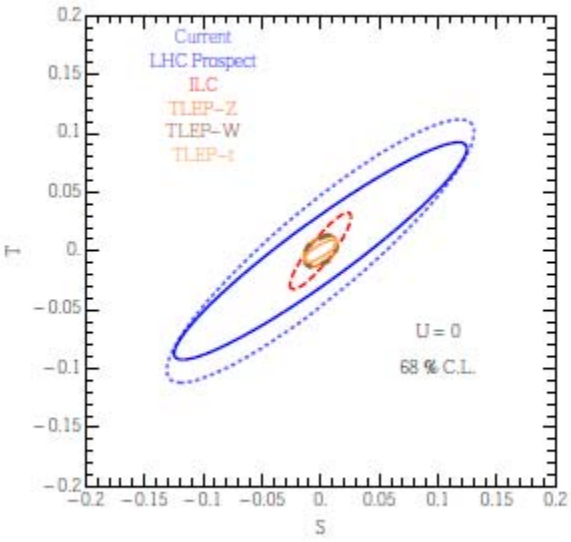
* Can any of our deepest questions be robustly probed with this level of precision + energy, and not (say) 10 x higher precision/energy?

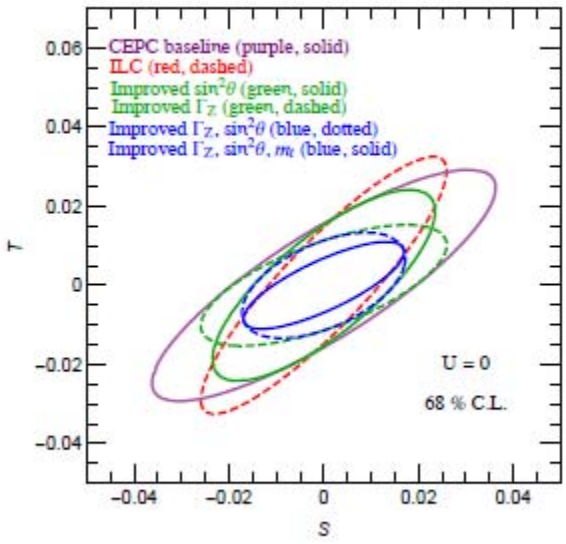
[YES]

Higgs / Z factory Leap in Precision



Higgs / Z factory Leap in Precision





CEPC + FCC-ee

* Main difference: FCC target $\mathcal{L}$ higher (10 vs. 5 ab^{-1})
  * Higgs coupling precision $\propto \frac{1}{\sqrt{\mathcal{L}}}$
  * Not much impact on precision EW (better for rare Z decays)
* Also plans to go to $t\bar{t}$ threshold

CEPC + FCC-ee / ILC

* Lower $\sqrt{s}$ in early (250–500) stage – not as good in Higgs couplings
* $t\bar{t}$ threshold
* Measure of $t\bar{t}H$ coupling @ 15%–7% [500→550]
  HHH " " @ 30%–10% [500→1000]
* Production of "ewk-ino" states
* Very nicely complementary

[* Nothing Better Geopolitically than for ILC to move forward — competition is GOOD!]

* Powerful + Complementary probes of Higgs couplings

$[\Lambda^2 \mathcal{L}_6]$: $[\partial (h^\dagger h)]^2$, $h^\dagger h\, h f f^c$, $h^\dagger h F^2$ ← Higgs Factory

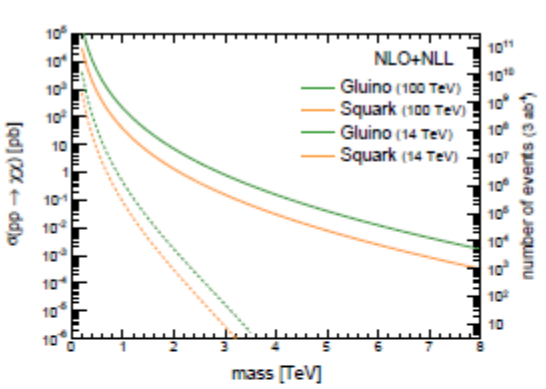
$(h^\dagger h)^3$ ← 100 TeV } Totally Generic

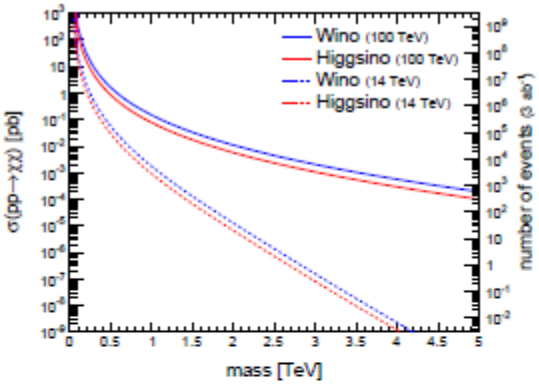
$(h^\dagger D^\mu h)^2$, $h^\dagger W^{\mu\nu} B_{\mu\nu} h$, $h^\dagger \overleftrightarrow{D}_\mu h\, f \bar{f}$

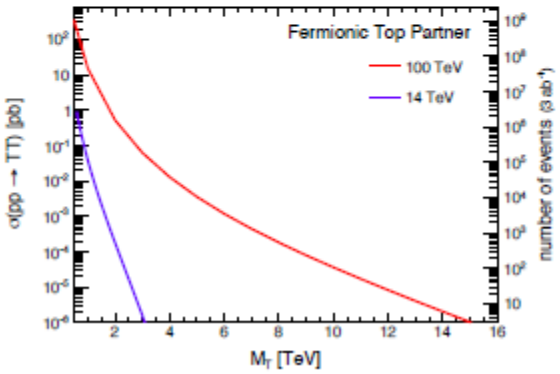
↑ Z factory

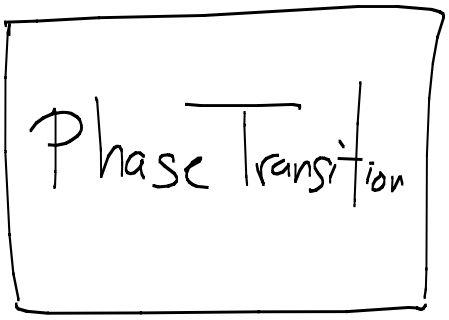
Λ probed to (multi-) TeV scale

100 TeV Leap

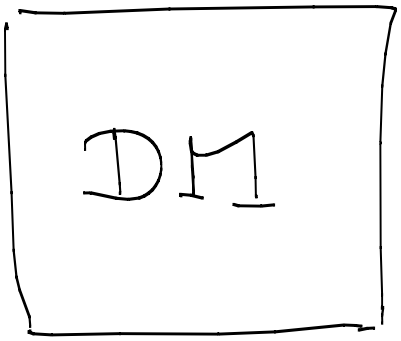

NLO+NLL
Gluino (100 TeV)
Squark (100 TeV)
Gluino (14 TeV)
Squark (14 TeV)
σ(pp → χχ) [pb]
number of events (3 ab⁻¹)
mass [TeV]


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]



"No Lose"



See or Rule out
Simplest possibilities

NO LOSE

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!

($O(1)$ Deviations in HHH coupling)

How is Electroweak Symmetry Restored?

Was Transition 1st or 2nd Order?

LHC Won't Come Close to Settling This

PERFECT TARGET FOR HIGGS FACTORY+

And Follow-Up With 100 TeV

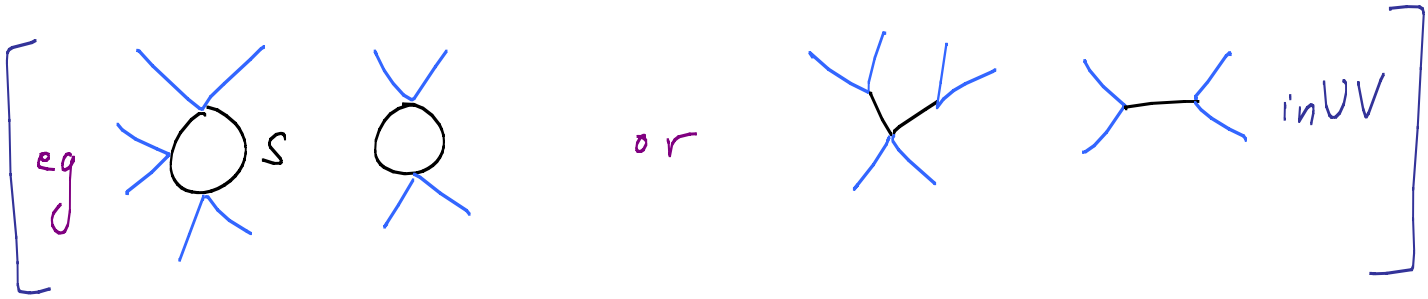
$$\star \quad \Delta\mathcal{L} = \frac{(h^\dagger h)^3}{\Lambda^2} + \frac{(\partial\, h^\dagger h)^2}{\Lambda^2} + \dots$$

directly affects transition (h^3 coupling)

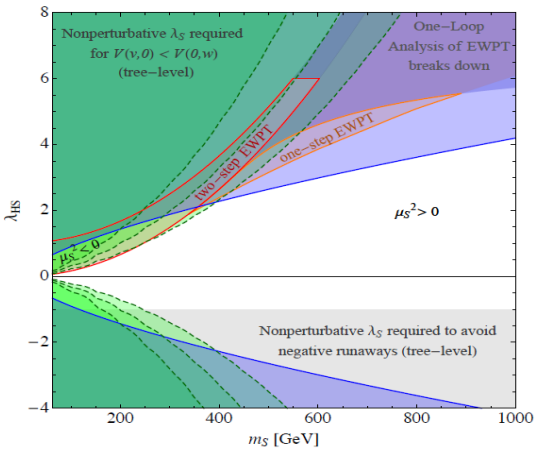
100 TeV/Higgs Factory

identical symmetries ($\mathbb{Z}_2$)

Higgs Factory

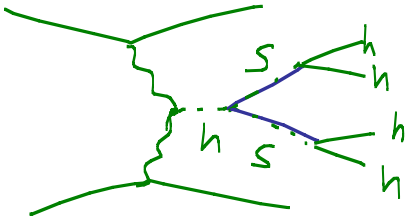


Even Hardest Scenario

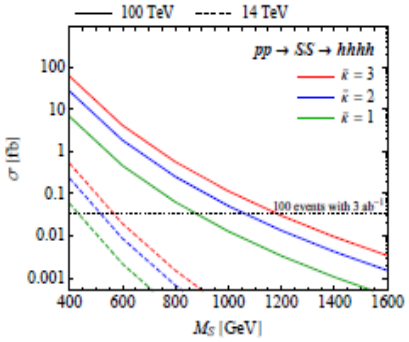


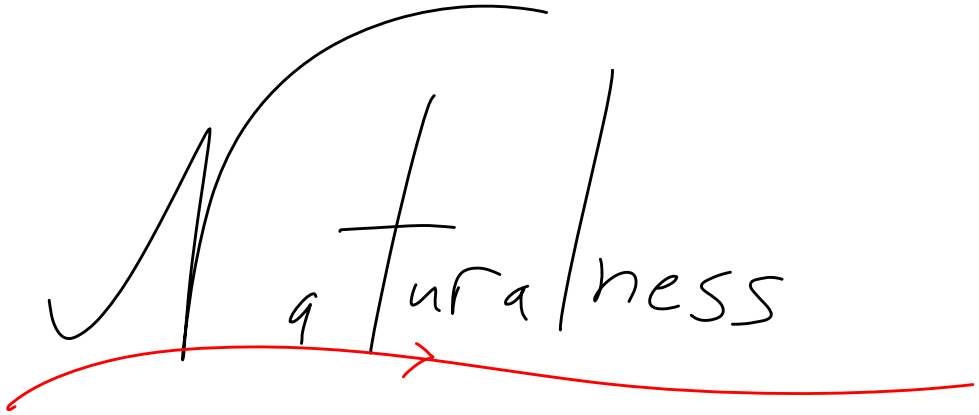
Can be Seen!

S - decays

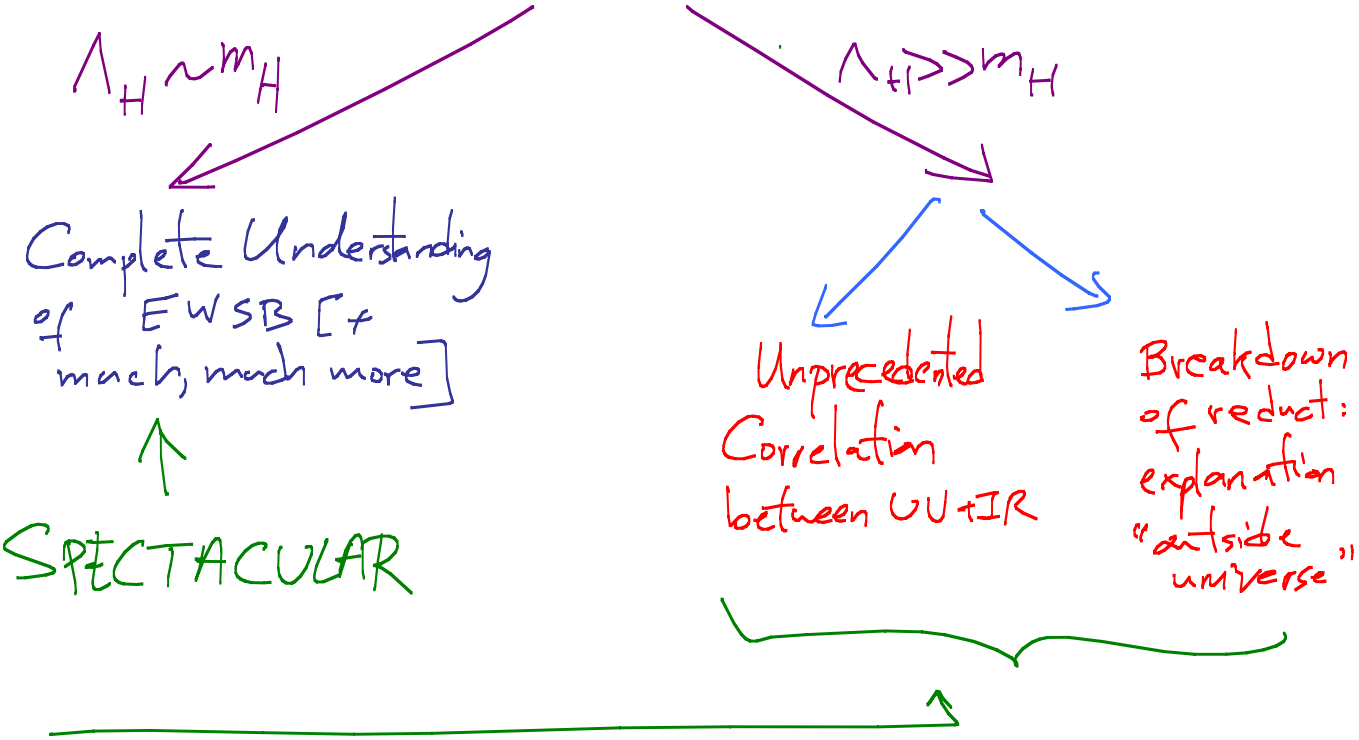


Spectacular Signal!



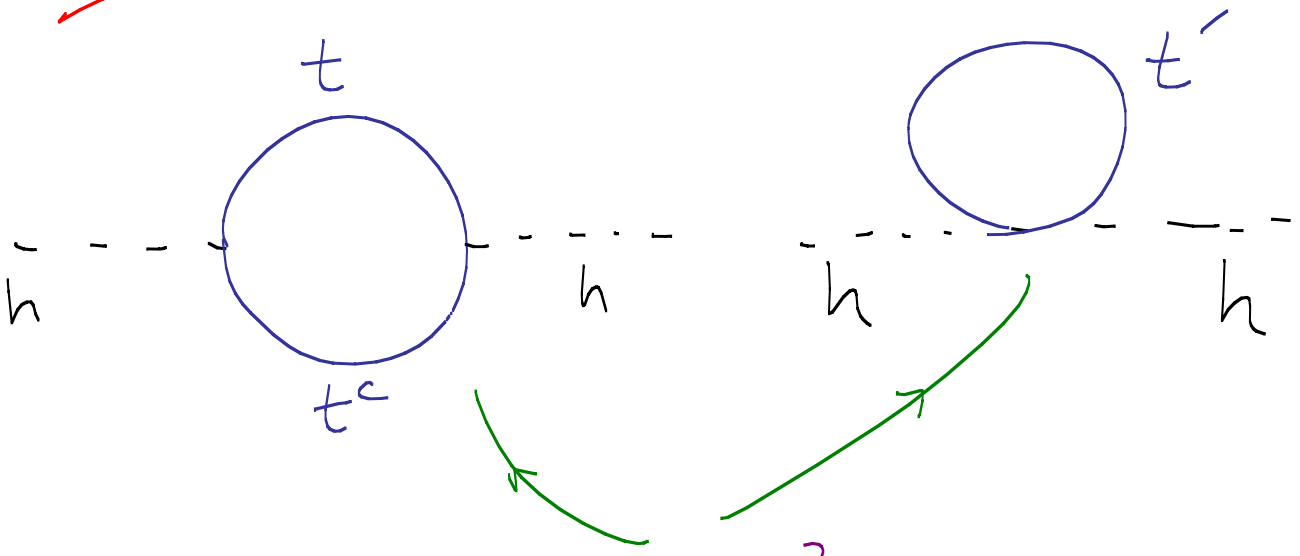

Naturalness

WIN-WIN-WIN



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

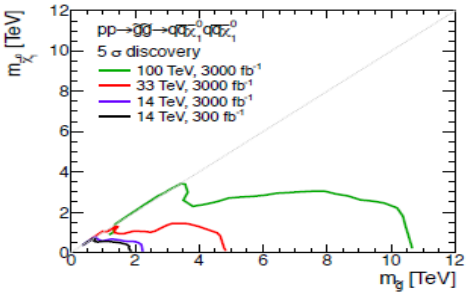
Expectation of New Part. At LHC

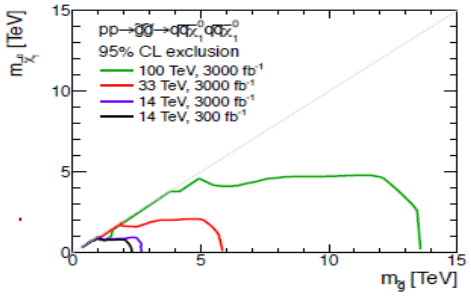


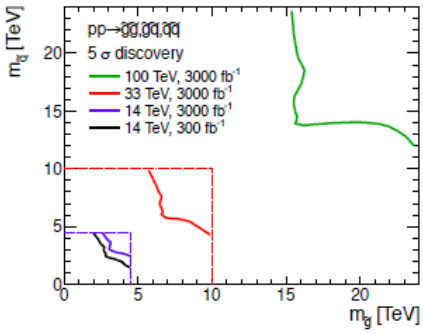
$$\delta m_h^2 = \frac{3\lambda_t^2}{8\pi^2}\Lambda^2$$

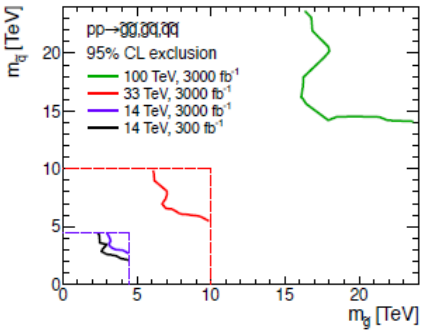
COLORED top partners $\lesssim 400\,GeV$

100 TeV Collider Reach For e.g. SUSY



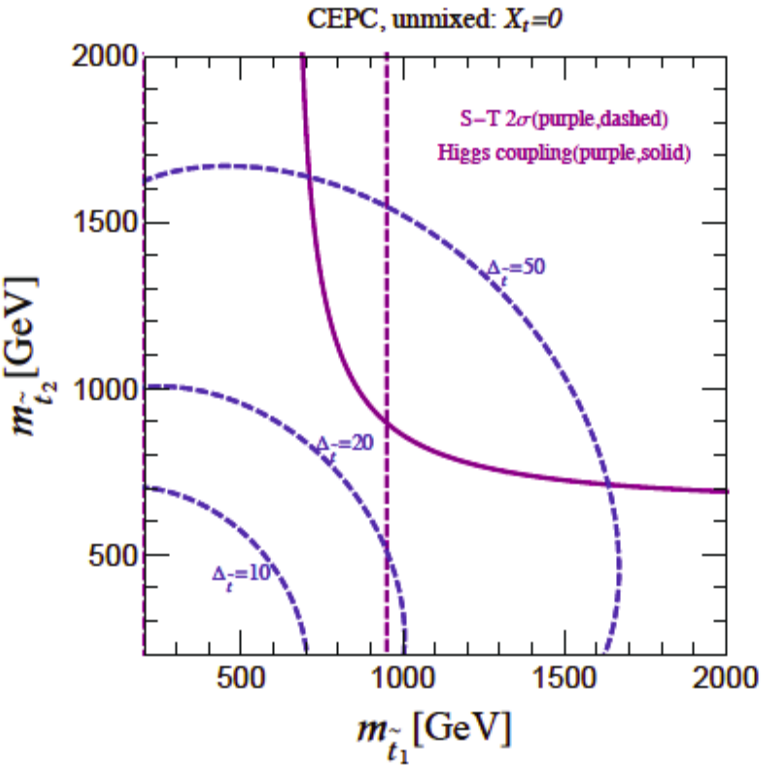






But "Hadronic Muck Gaps" possible...

Stops have nowhere to Hide!



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

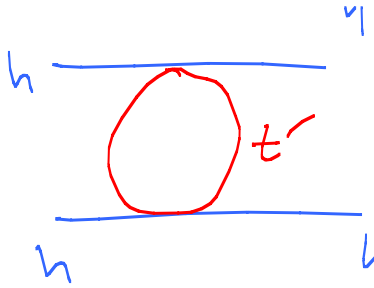
* Of course if we do see new particles @ LHC [e.g. 1.5 TeV $\tilde{g}$'s], we won't produce with enough rate to learn what they are trying to tell us!

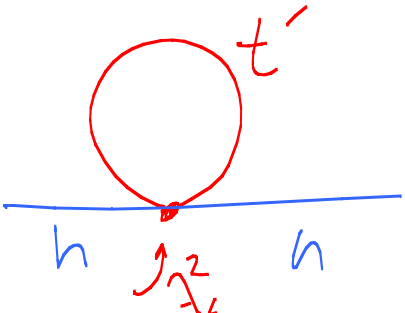
[e.g. is it a gluino?]

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

Neutral Naturalness

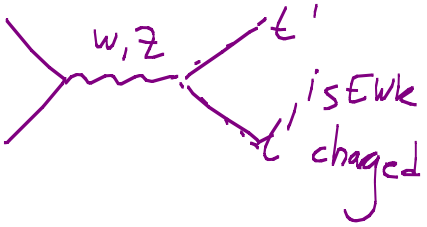
"Twin Higgs"
"Folded SUSY"



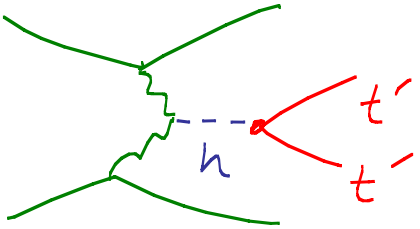


Uncolored top partners, "3" from partner to $SU(3)_{color}$

EWk charged

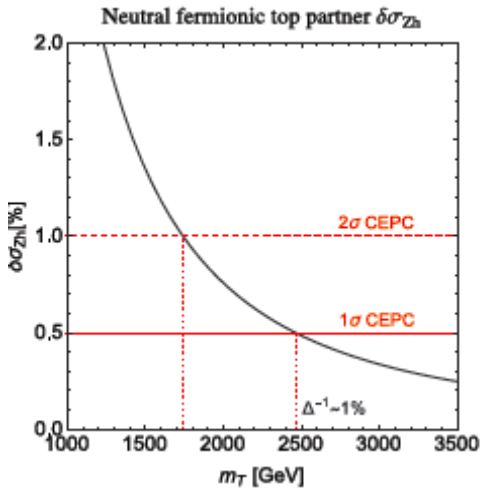


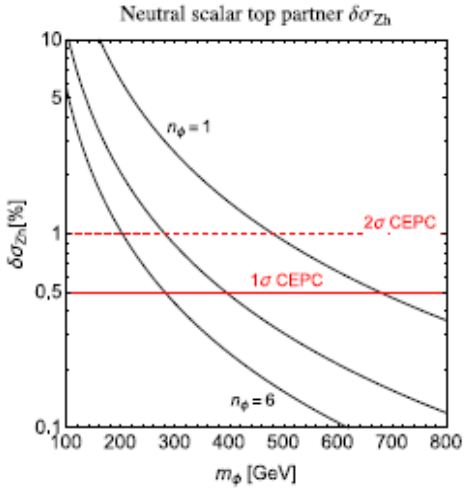
is EWk chaged

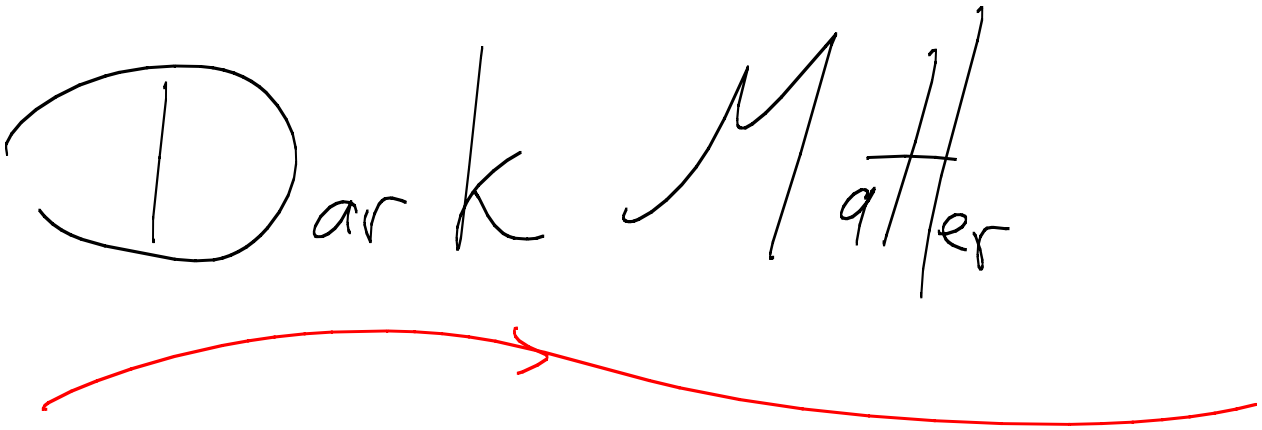


production @ 100 TeV

Naturalness "No-Lose" Thm

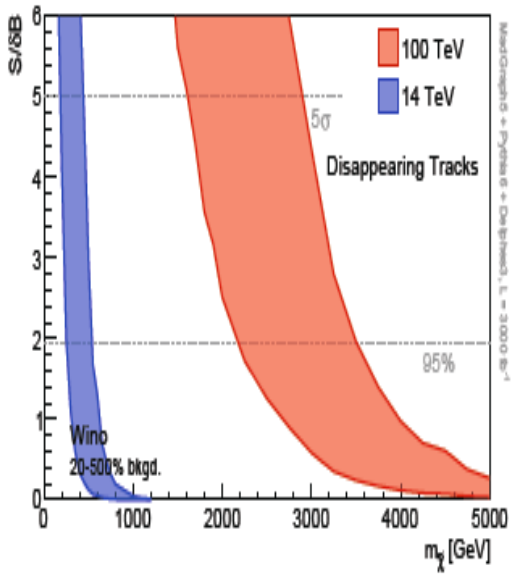


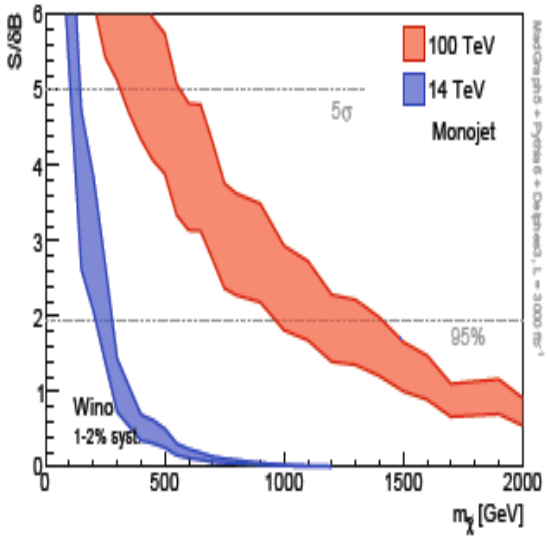



Dark Matter

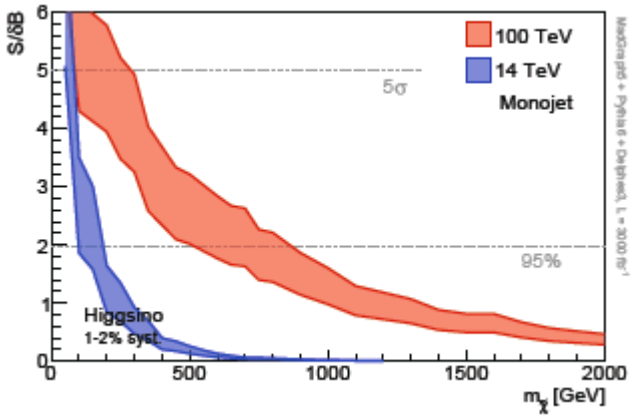
- WIMPS are, still, the only calculable models of dark matter we have
- If "W" = "elWeak" — could easily be ~ few TeV, + inaccessible @ LHC. [Even more likely now, after LHC 8]

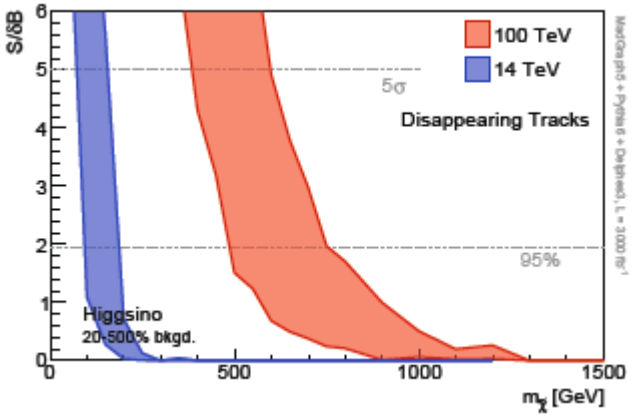
"Winos"

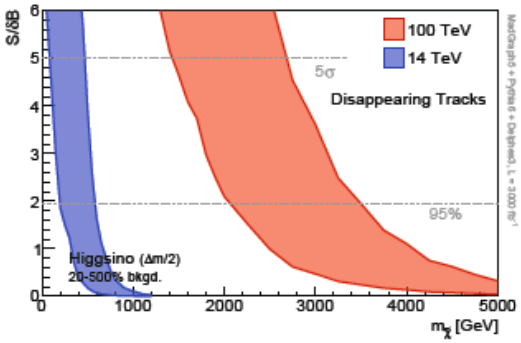

S/δB
100 TeV
14 TeV
5σ
Disappearing Tracks
95%
Wino
20-500% bkgd.
0
1000
2000
3000
4000
5000
m_χ [GeV]


S/δB
100 TeV
14 TeV
5σ
Monojet
95%
Wino
1-2% syst.
0
500
1000
1500
2000
m_χ [GeV]

"Higgsinos"

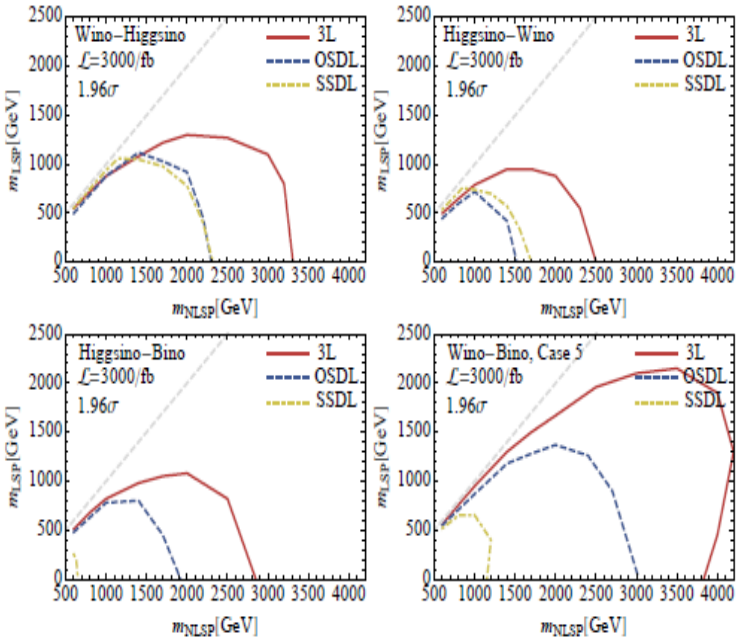

S/δB
100 TeV
14 TeV
Monojet
5σ
95%
Higgsino
1-2% syst.
m_χ [GeV]

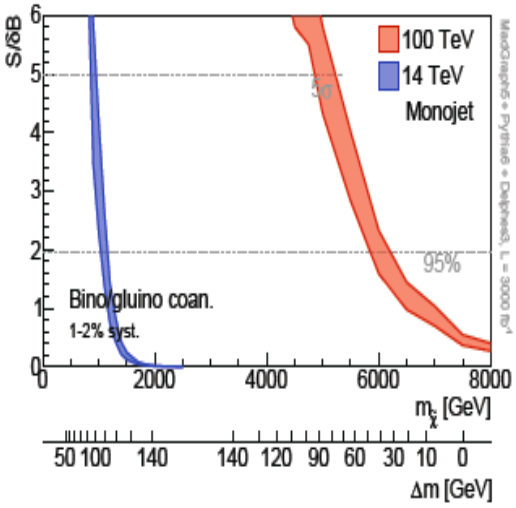

S/δB
100 TeV
14 TeV
Disappearing Tracks
5σ
95%
Higgsino
20-500% bkgd.
m_χ [GeV]


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

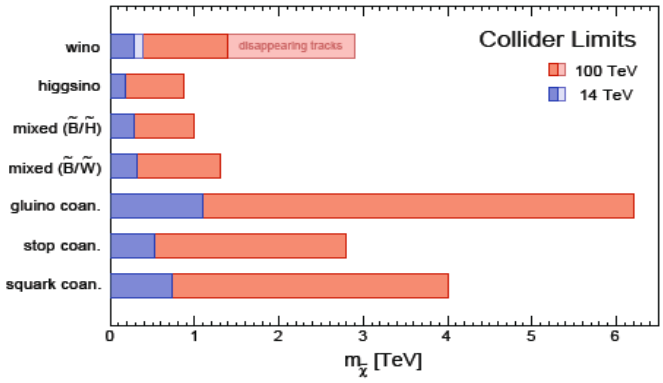
Electroweak Cascades

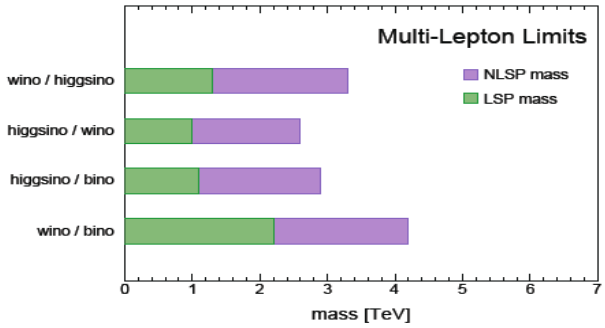
Co-Annihilation

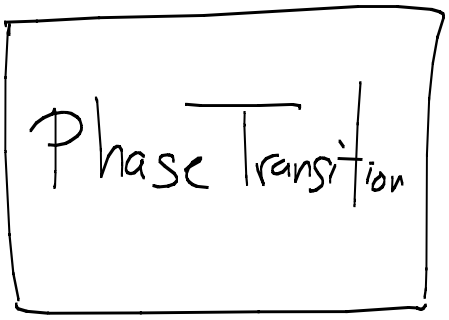




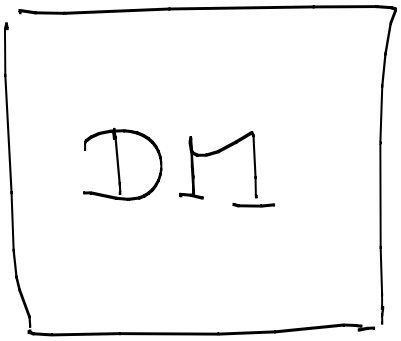
Robust Coverage For WIMPs







"No Lose"



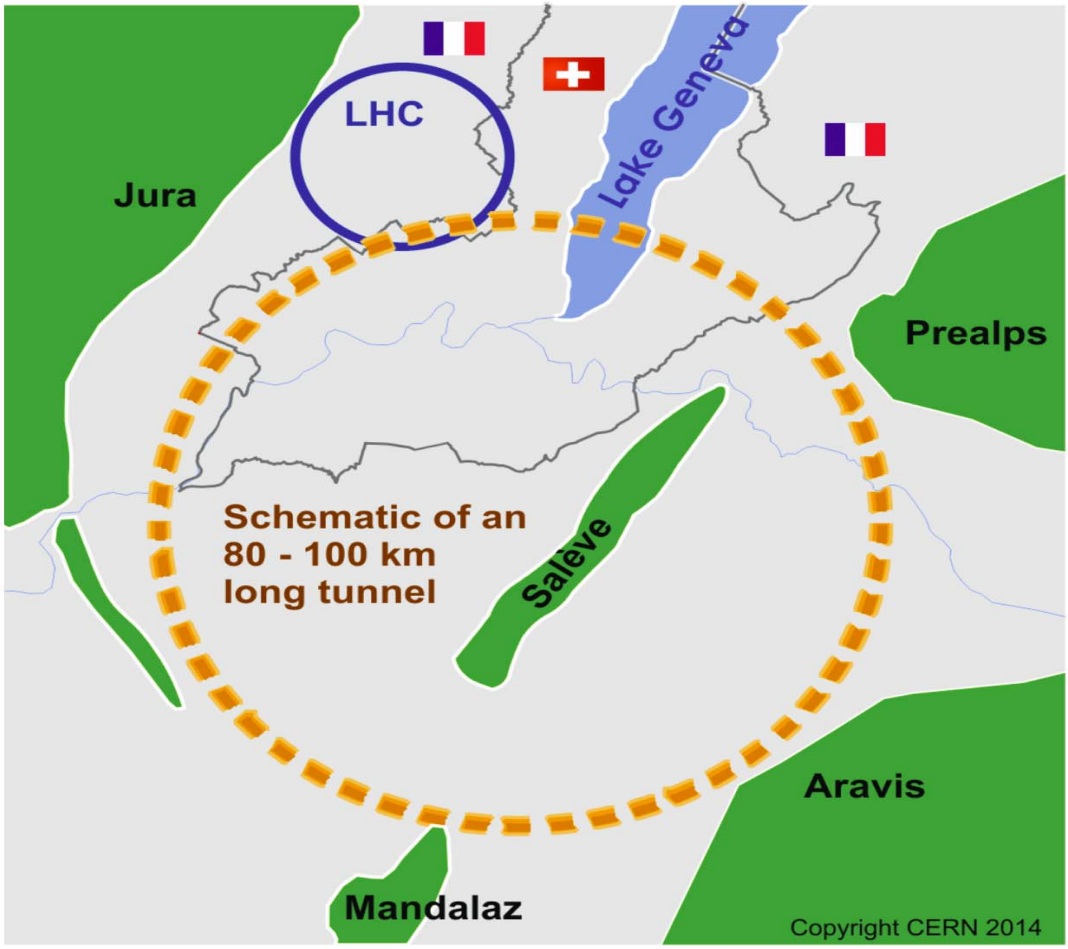
See or Rule out
Simplest possibilities

NO LOSE

We're entering most exciting phase of LHC!

But NOMATTER WHAT we see from LHC, case for proceeding to circular coll. is rock-solid.

* Nothing but Higgs? ⟹ Study Higgs, only fuzzy from LHC
* See new particles e.g. "stops" – not high enough rate @ LHC to know what it is! Higgs fact. confirms coupling to higgs(!), 100 TeV for the "factory"


LHC
Jura
Lake Geneva
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis
Mandalaz
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Site

- Preliminary selected: Qinhuangdao (秦皇岛)
- Strong support by the local government

10 Billion in Your Favorite Units

- Practical issues: too costly ?
  - BEPC cost/4 y/GDP of China in 1984 ≈ 0.0001
  - SSC cost/10y/GDP of US in 1992 ≈ 0.0001
  - LEP cost/8y/GDP of EU in 1984 ≈ 0.0002
  - LHC cost/10y/GDP of EU in 2004 ≈ 0.0003
  - ILC cost/8y/GDP of Japan in 2018 ≈ 0.0002
  - CEPC cost/6y/GDP of China in 2020 ≈ 0.00005
  - SPPC cost/6y/GDP of China in 2036 ≈ 0.0001

Outlook

In (not just) my view, the scientific issues we face today are the most difficult + profound ones our field has seen since the 1930's

The questions raised by the accelerating universe, and the higgs discovery, both go to the heart of our understanding of the nature of spacetime, quantum mechanics + the vacuum.

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