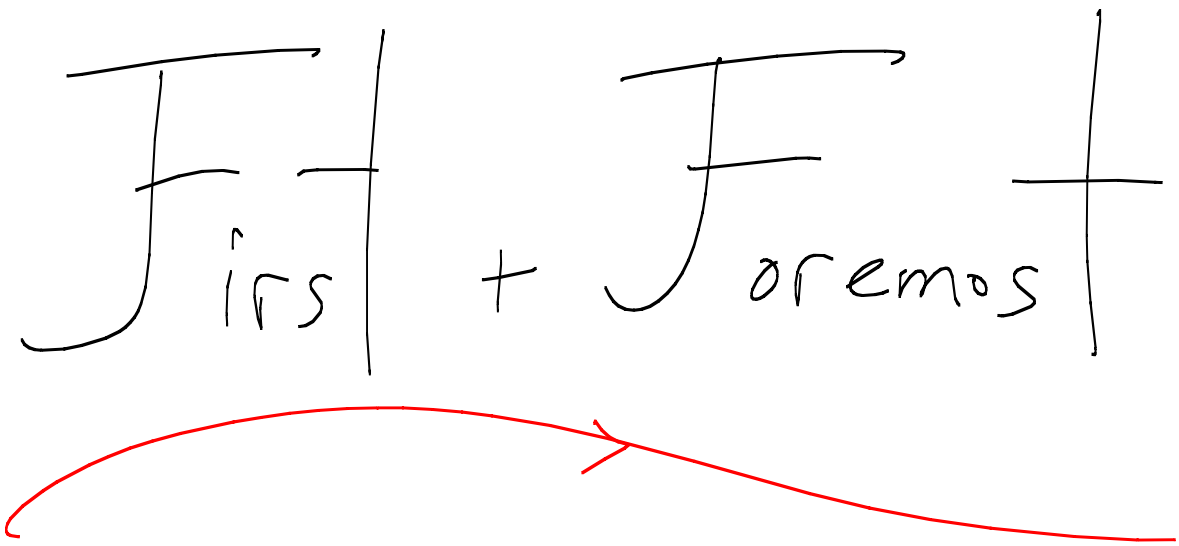
SUSY

2033

OR...

Motivations For a

100 TeV pp - collider

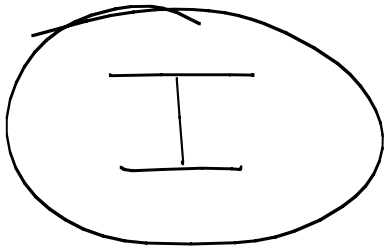

First + Foremost

* It's the OBVIOUS FUTURE

* BIG physics ideas, BIG ambitions and BIG machines are the lifeblood of our field. It's how we've attracted the best minds on the planet to work on the hardest, most fundamental, most long-term problems in all of Science.

Obviously, how to proceed will depend on first LHC 13 results.

But in every scenario I can imagine, we will need the 100 TeV pp machine



Ultimate Fate of Naturalness

Higgs Discovery Crucial

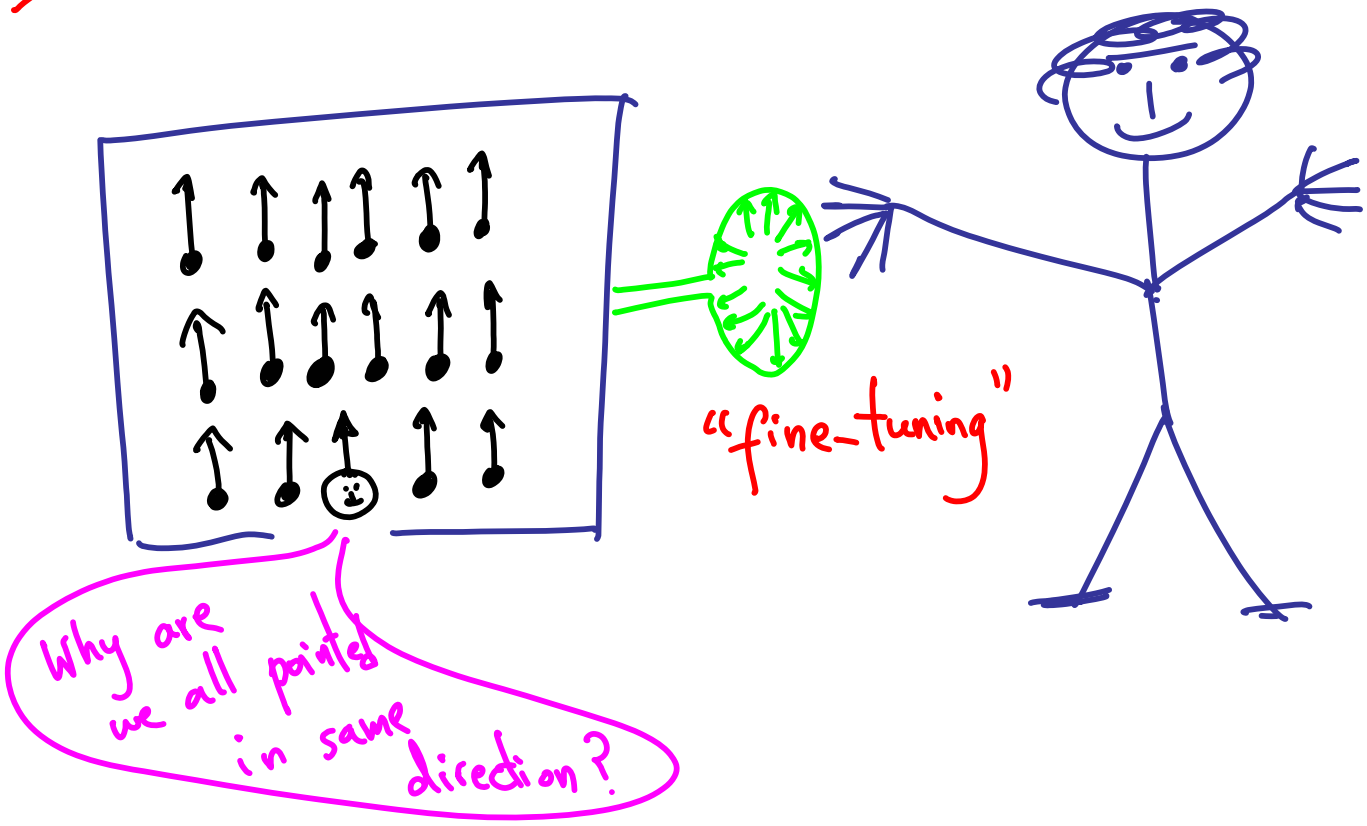
Light Higgs

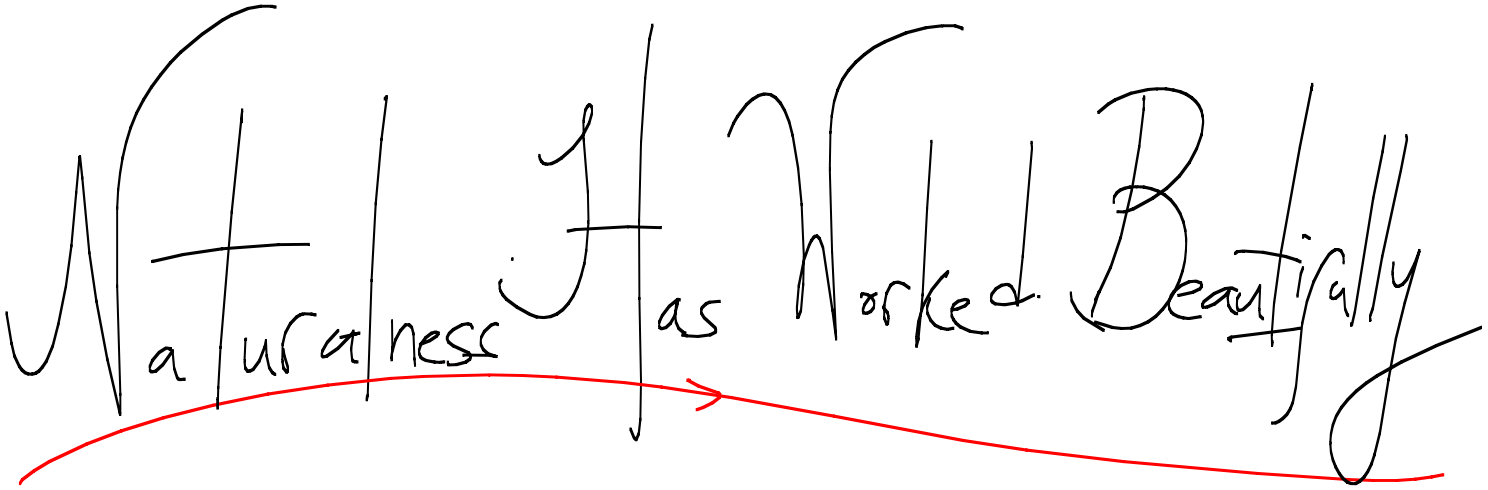
↓

Our Vacuum is Qualitatively Different than Random C.M. System

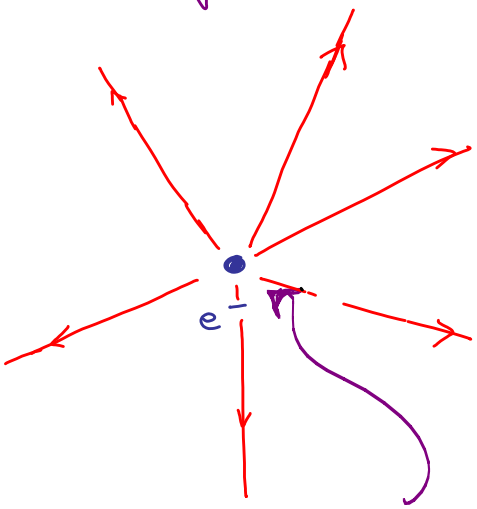
[AKA "Random Metal"]

Never seen before in "state of nature"

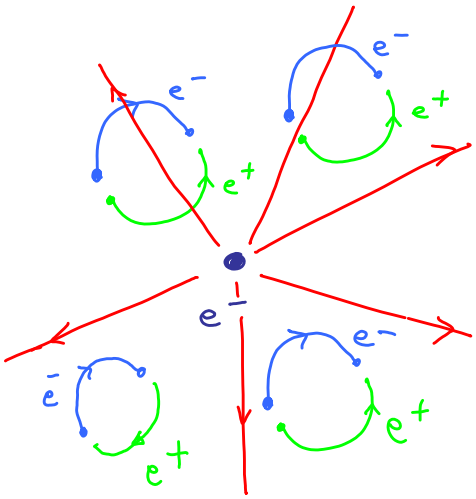



Naturalness Has Worked Beautifully

Infinite Energy In Electric Field



Q.M.
Rel.

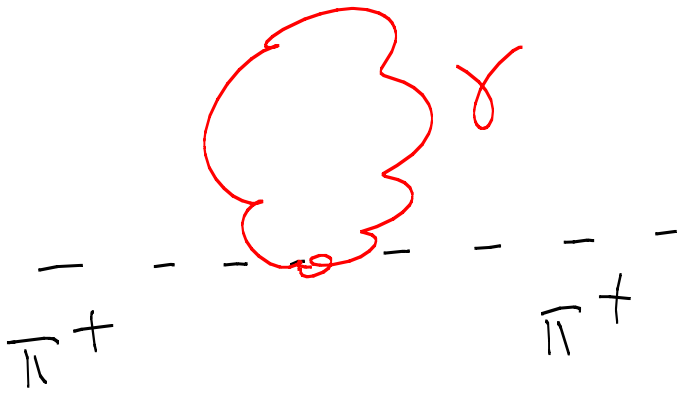


$$\frac{e^2}{4\pi a_{cl}} \sim m_e c^2 \Rightarrow a_{cl} \sim \frac{e^2}{4\pi m_e c^2}$$

$$a_{compton} \sim \frac{\hbar}{m_e c}$$

$$\sim \left[\frac{e^2}{4\pi\hbar c}\right]^{-1} \times a_{cl} \; !$$

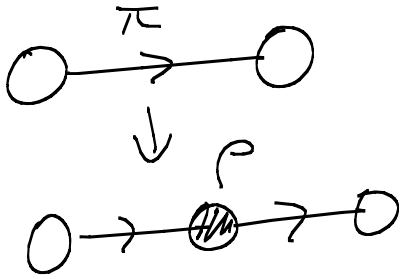
cut off α^{-1} earlier than needed

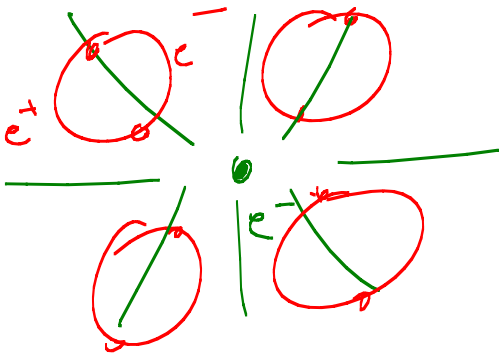


$$\delta m_\pi^2 \sim \frac{e^2}{16\pi^2}\Lambda^2 \Rightarrow \Lambda \lesssim 1\,\text{GeV}$$

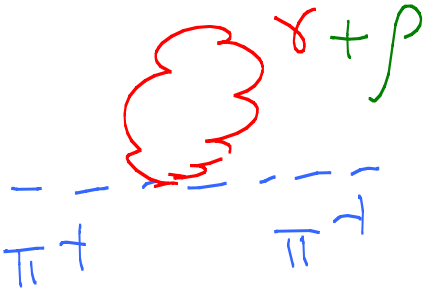
ρ meson cuts it off

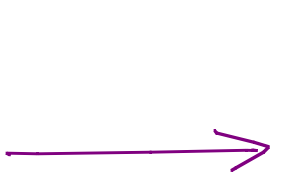
$\sim \frac{1}{\sqrt{N}}$ earlier than needed





SUSY



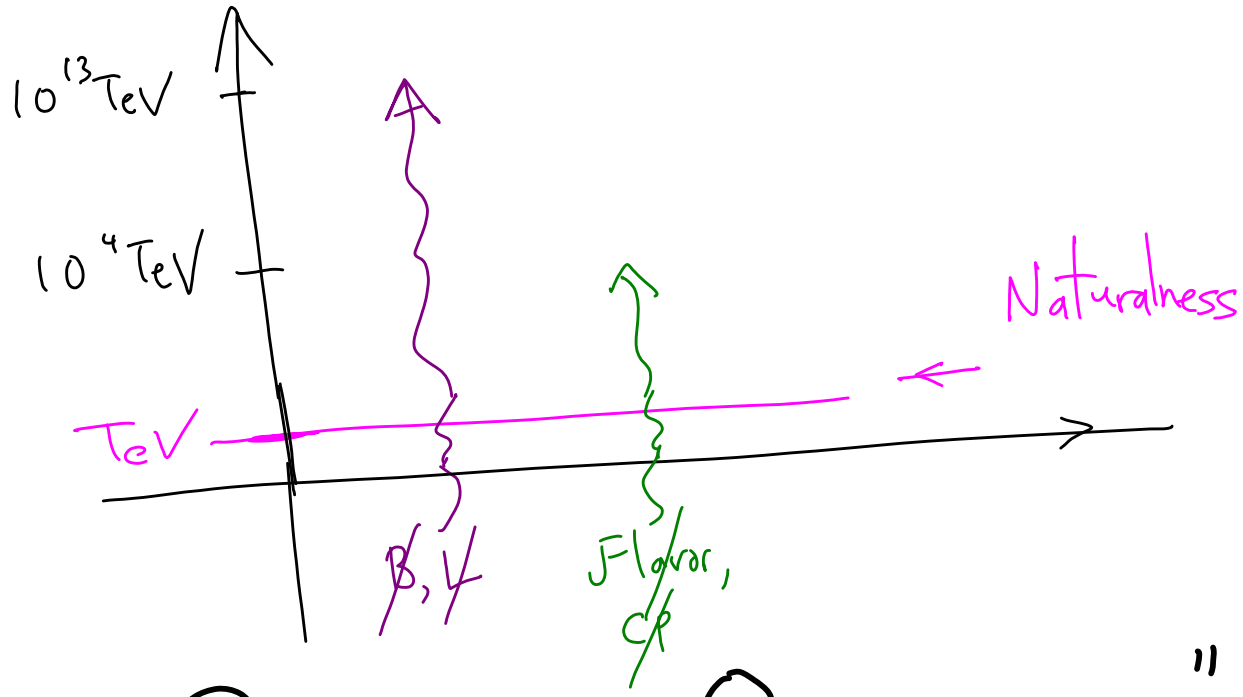


Pseudo Goldstone

Higgs


But Where Is Everybody?

Tension Driving BSM Physics For 30 yrs

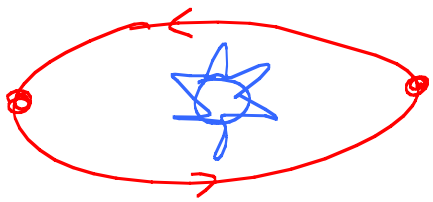


"Not Problems – Opportunities"

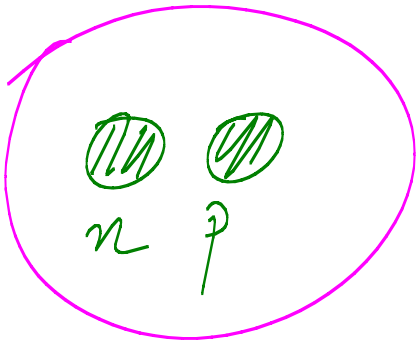
No new physics so far @ LHC is putting broad idea of Naturalness under somewhat more pressure


Naturalness has Failed Dramatically

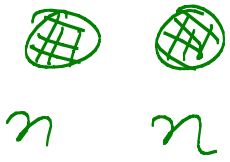
- Aristarchos had heliocentric model of solar system – rejected because parallax not seen – CRAZY that stars should be so far away!



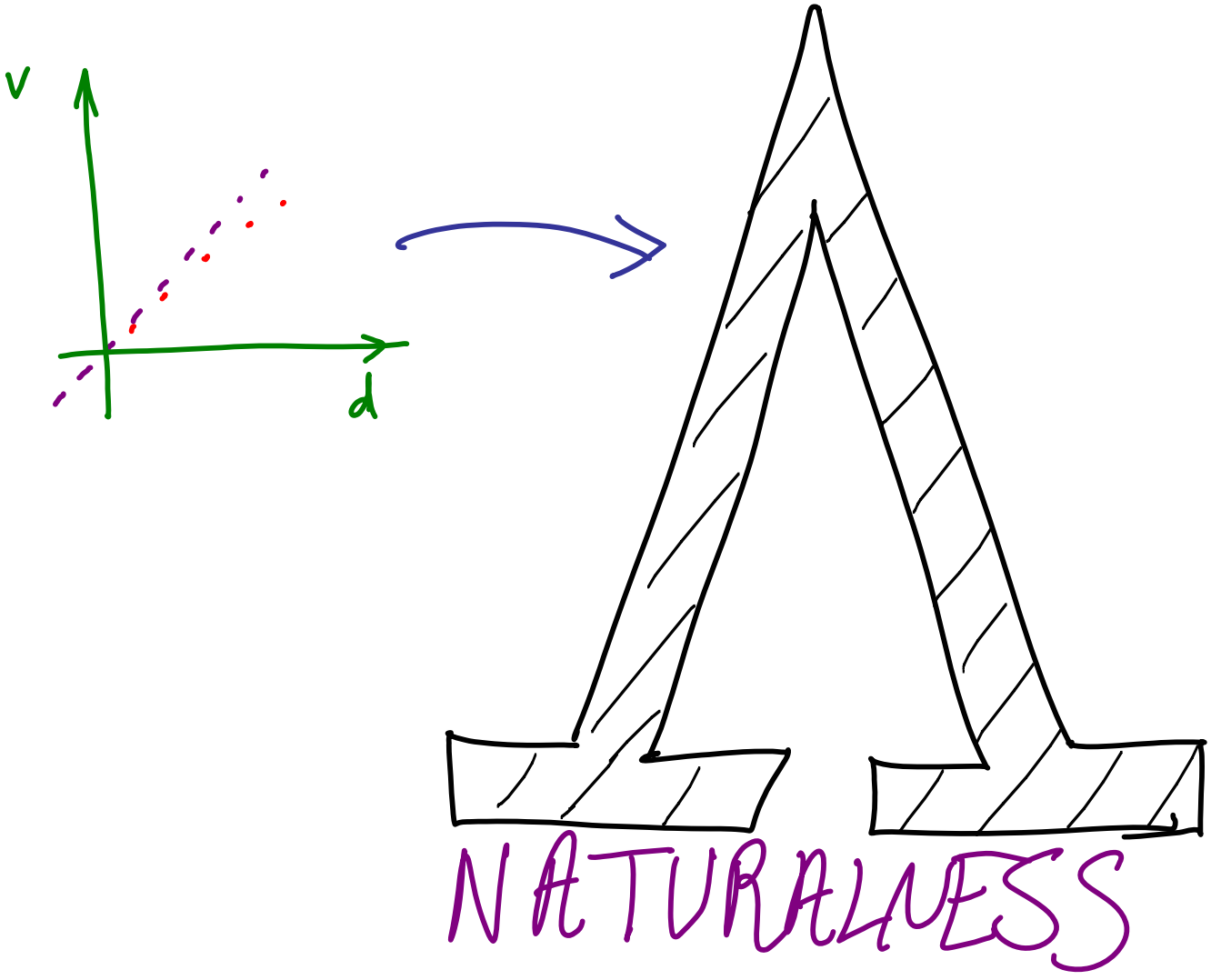
Nucl. Phys. is Confusing Because it's Tuned!

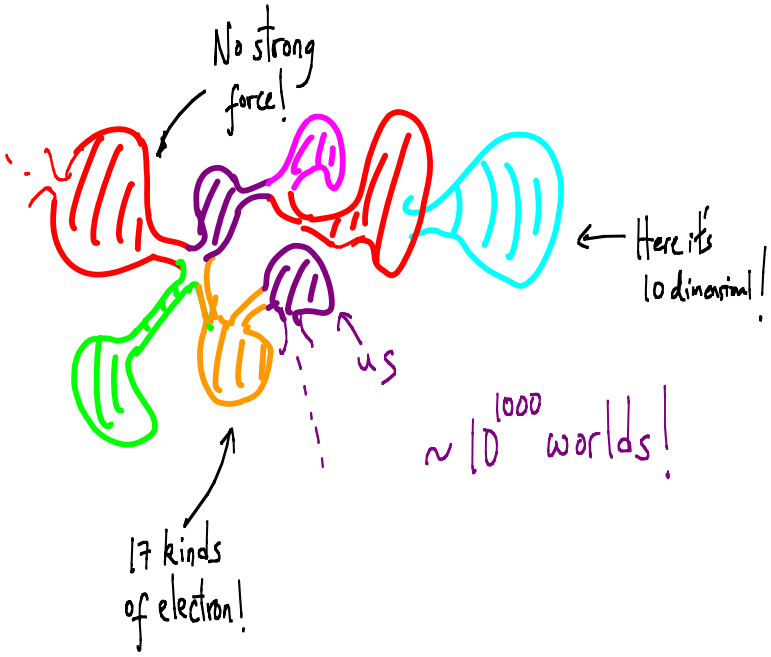


Binding Energy
$\sim$ 2 MeV
$\sim$ 20% accident

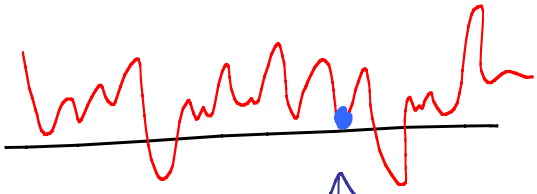


^{2}H bound by
60 keV(!),
$\lesssim$ 1% accident


v
d
NATURALNESS



$\sim 10^{1000}$ worlds!



Everywhere Lethal + Empty except ...

Here, accidentally, Universe not empty

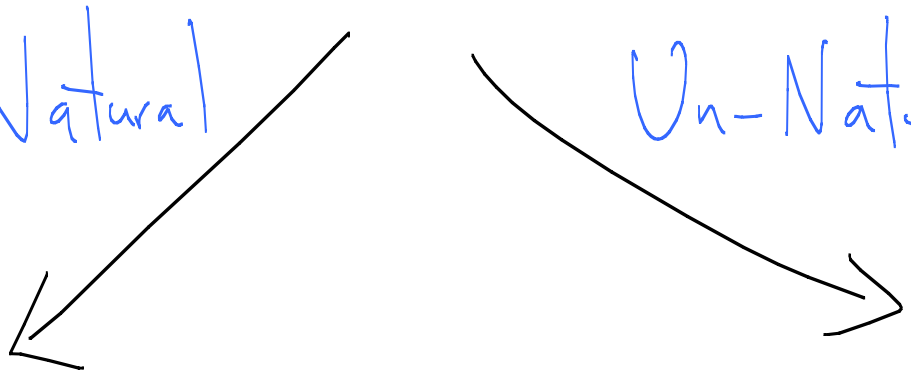
We could be getting circumstantial evidence, + more of a push towards this radical picture

Is Weak Scale Natural?

HUGE STAKES

Not just this or that particle— deep, structural issue at the foundational heart of fundamental physics

Crucial Fork in the Road



BIG NEW PRINCIPLES

EVEN BIGGER PARADIGM SHIFT

Like CC?

HOW TUNED?

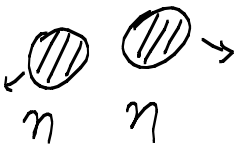
Higgs + Nothing Else@LHC?

A Fine-tuning of at least 1% for weak scale

CONVINCING?

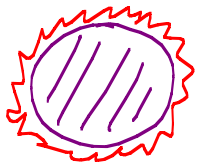
[I'LL need more evidence!]

There are many ~1% level "accidents"



Two neutrons not bound by 60 keV!

Low Quadrupole of CMB power



Moon eclipsing the sun

Adding "EWSB" to this list from L.H.C would be fascinating, but not KNOCKOUT

How will we know?

- Higher Energy!!
  - * Find Something! → End of discussion!
  - * Find Nothing → Tuning $\propto E^{2}_{machine}$
- Rare processes
- Precision measurements

} Indirect, Linear gain in tuning

* tuning probe $\propto E_{CM}^2$

* Higgs + nothing else @ 100 TeV

$\Longrightarrow \sim 10^{-4}$ tuning!

* Never seen this level of tuning in particle physics - Dramatically new

* In my view, even this "worst-case scenario" would be ~ 100 X more shocking + dramatic than nothing but Higgs@LHC

NAIL IN COFFIN OF NATURALNESS

This alone fully justifies the march to 100 TeV

* Circular e^+e^- machine

Higgs Factory plays very important, complementary role

Looking for $\frac{h^\dagger h (h \bar{Q} b^c)}{\Lambda^2}$, $\frac{(h^\dagger D_\mu h)^2}{\Lambda^2}$, ...

* Tera-Z particularly exciting + powerful probe!

Even more surprising things could be found:

——— ~10 TeV scale

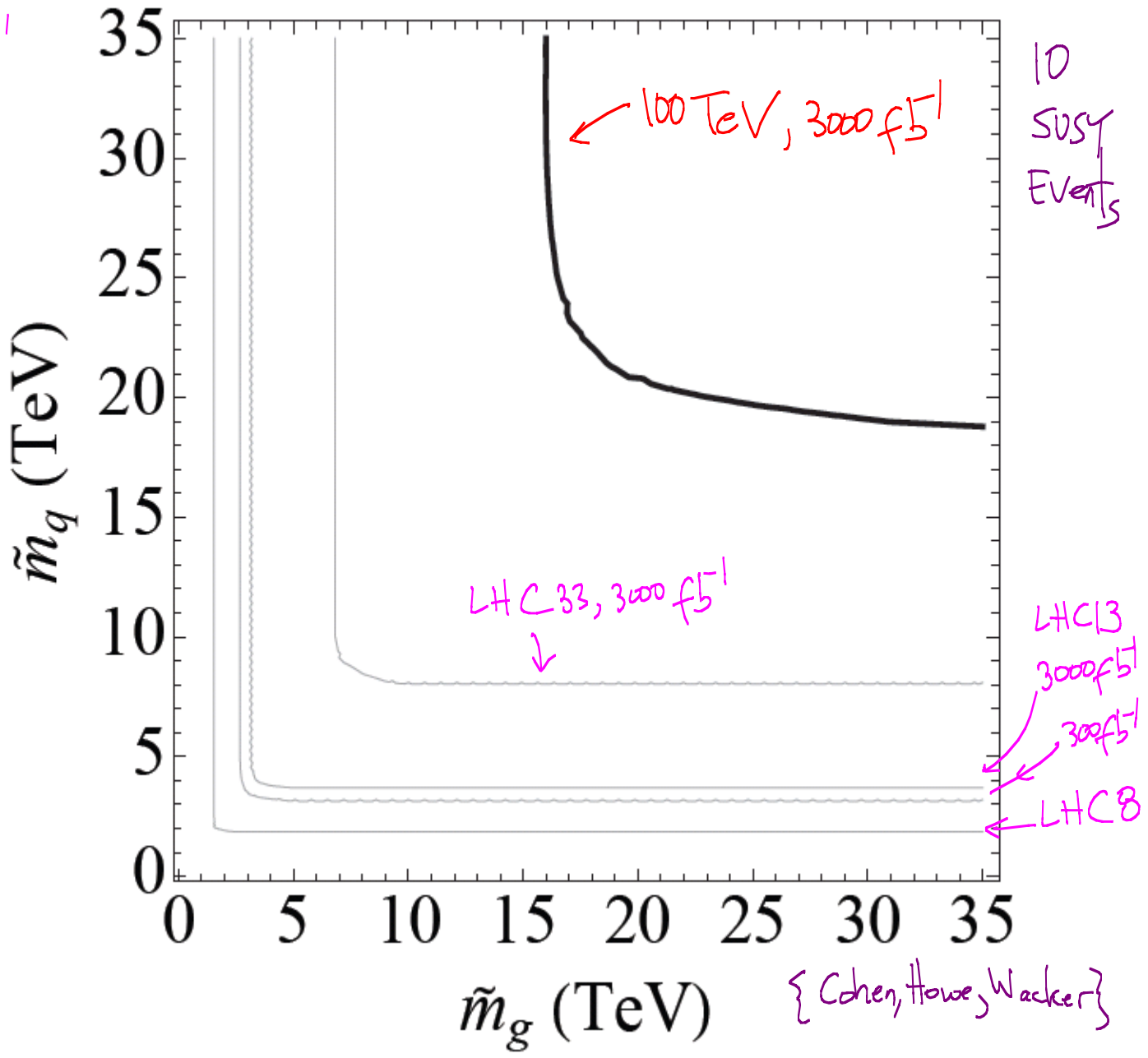
——— $H_2 \sim 1$ TeV

——— $H_1 \sim 125$ GeV

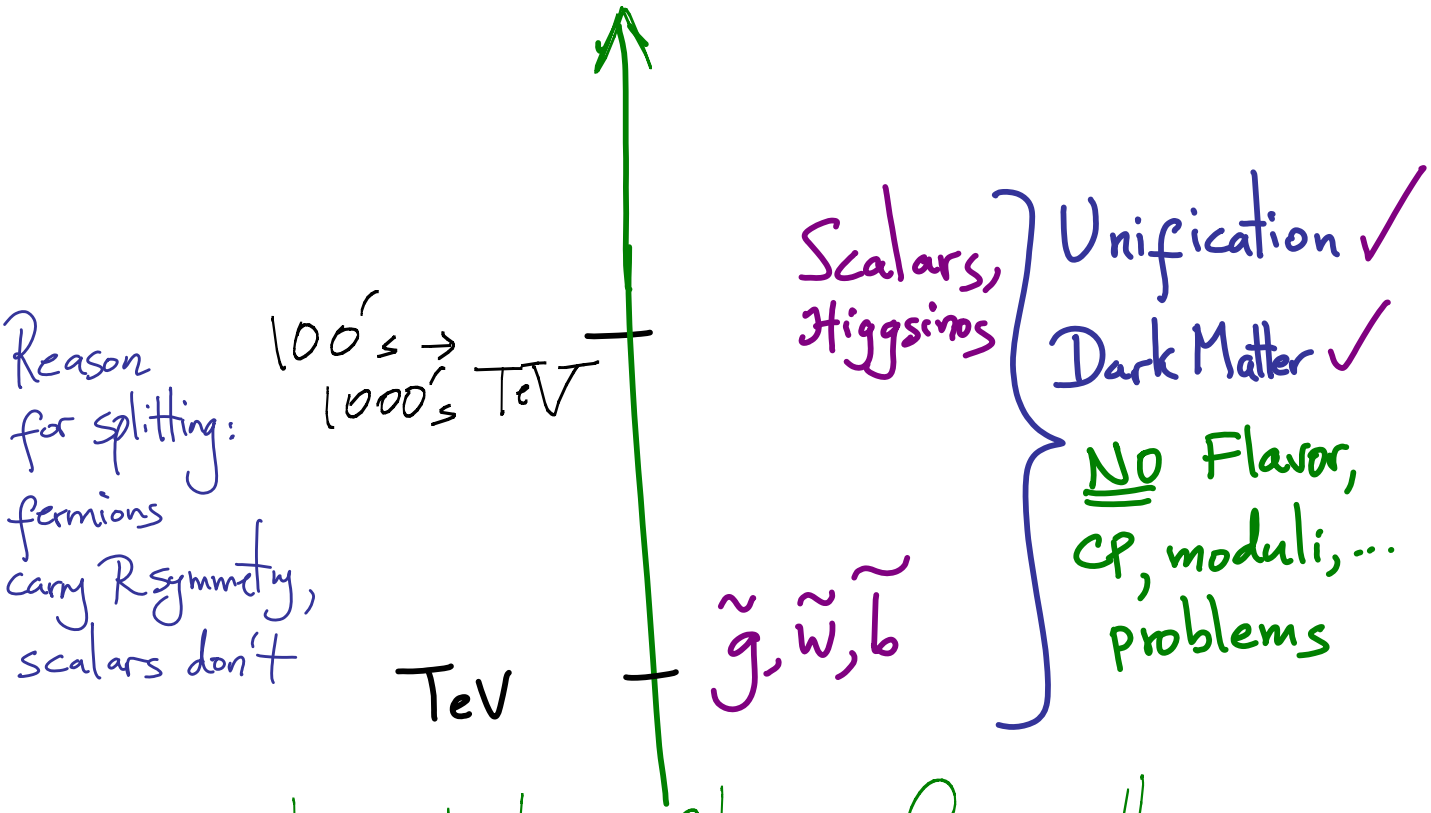
* Tuning $\sim (10^{-4}) \times (10^{-2}) \sim 10^{-6}$!

* kills all anthropic explanations

- If instead, we are "just" ~1% unlucky, LHC could still miss everything, but 100 TeV pp will catch the new physics

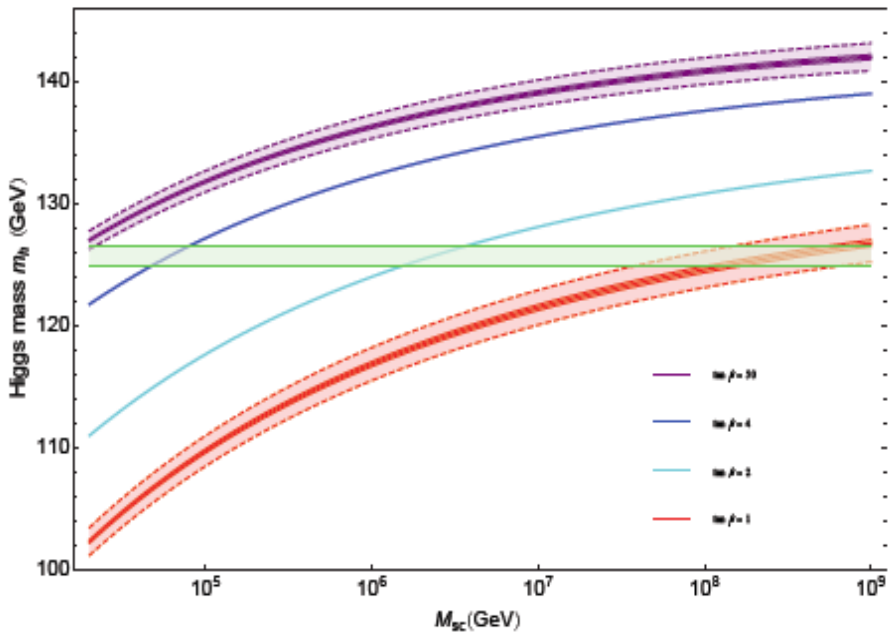

35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
$\tilde{m}_q$ (TeV)
$\tilde{m}_g$ (TeV)
100 TeV, 3000 fb^{-1}
10 SUSY Events
LHC33, 3000 fb^{-1}
LHC13
3000 fb^{-1}
300 fb^{-1}
LHC8
{Cohen, Howe, Wacker}

Minimally Split SUSY



$\sim \alpha^{-1}$ Splitting Happens Generically

Higgs Mass



$\tilde{g}$ 6TeV
$\tilde{W}$ 3TeV
$\tilde{h}$ 1TeV

Could easily have 3TeV $\lesssim m_{\tilde{g}} \lesssim$ 20TeV, compatible with DM, out of LHC reach, accessible to 100TeV;

With $\tilde{g}, \tilde{W}, \tilde{b}$ as only new particles – their decays can only proceed through higher-dimension operators!

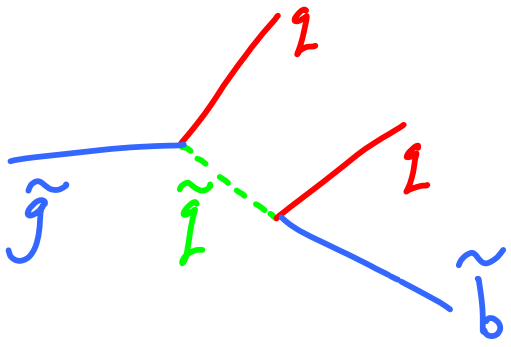
Inside detector $\longrightarrow$ scale $\gtrsim 10^2$ TeV!

LOOK FOR MODERATE DISPLACED DECAYS

Gluino Decays

$$\frac{\bar{q}\,\tilde{g}\,q\,\tilde{b}}{M^2}$$

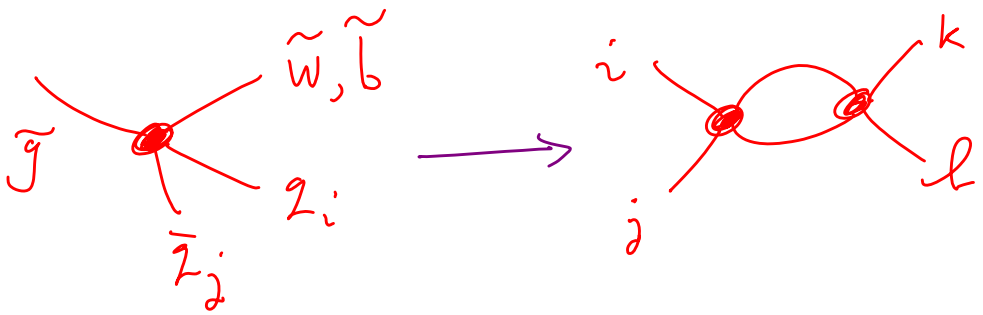
$$\frac{\bar{q}\,\tilde{g}\,q\,\tilde{W}}{M^2}$$



$\sim$ mm displ. for

$$m_{\tilde{q}} \gtrsim (300\,\text{TeV}) \left(\frac{\Delta m}{\text{TeV}}\right)^{5/4}$$

Flavor-violation in gluino decays



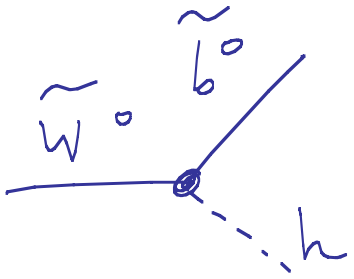
Unless Operator is suppressed by

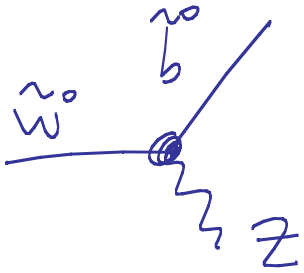
$\sim 100 - 1000$ TeV

Need $\tilde{g}$ Factory

* Say we produce ~ 3 TeV gluino in LHC ; 100 TeV is gluino factory, precision on decay patterns + displacement, big clues/constraints on heavy scale

Direct probe of heavy higgsinos:

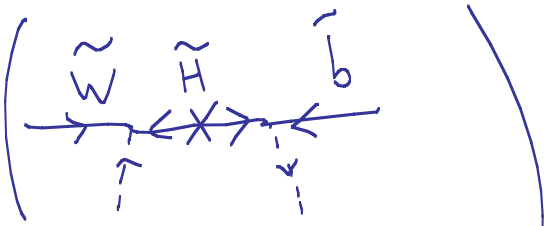




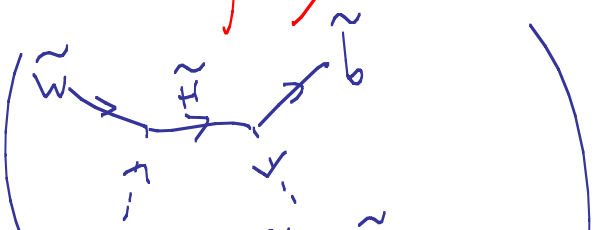
Need $\tilde{g}$ Factory

dominates

$Br \sim 10^{-4}$ for $\mu \sim 10$ TeV



$\frac{h^+ \tilde{W} h \tilde{b}}{\mu}$ dim 5



$\frac{h^+ D^\mu h \tilde{W} \sigma_\mu \tilde{b}}{\mu^2}$ dim 6

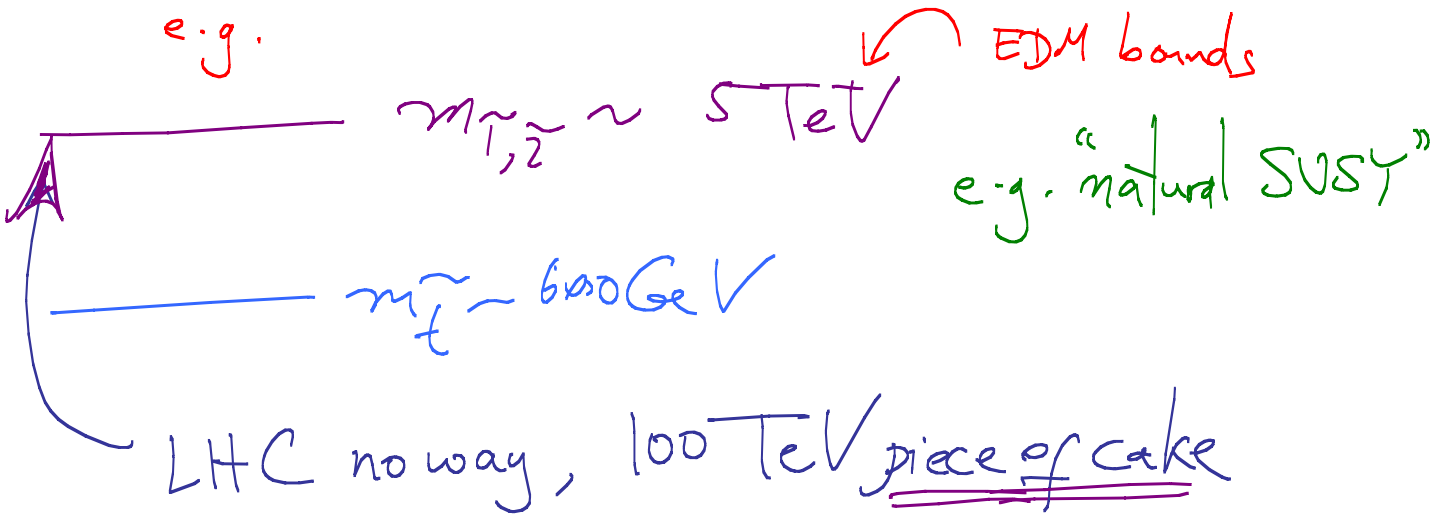
What if L.H.C discovers

(relatively) Natural Spectrum?

It's not 1995....

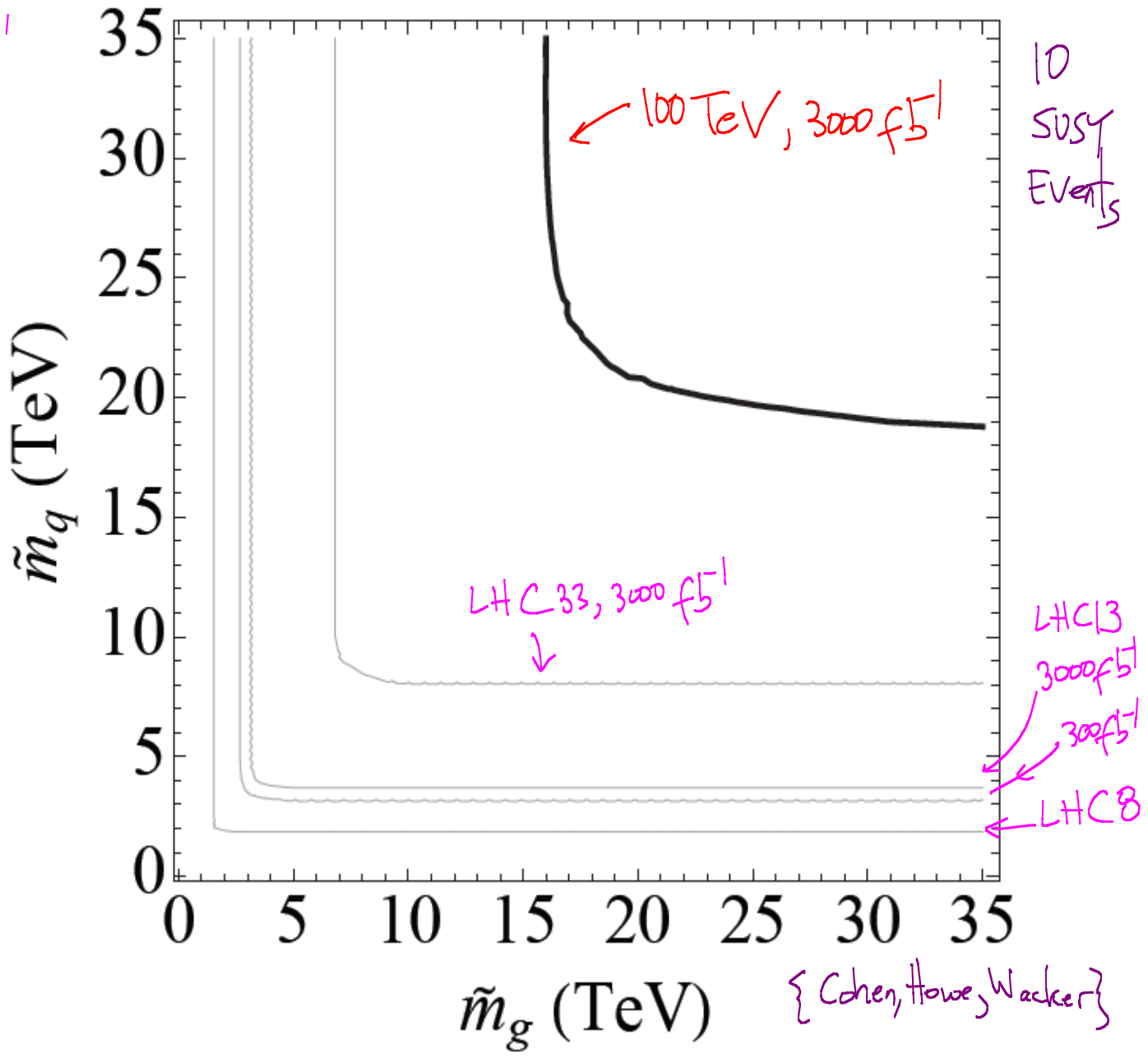
"Discover SUSY @ LHC,
precision study @ 500 GeV
ILC"

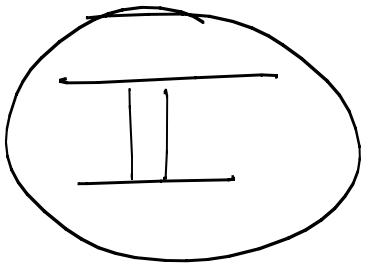
* What we already know from LHC makes it implausible that we'll see whole spectrum of new physics, even if its relatively natural:



More generally, we will want a factory for new colored particles, to study how they make higgs Natural [e.g. SUSY coupling relations] $\longrightarrow$ RATE $\propto E_{CM}^{5 \to 6}$

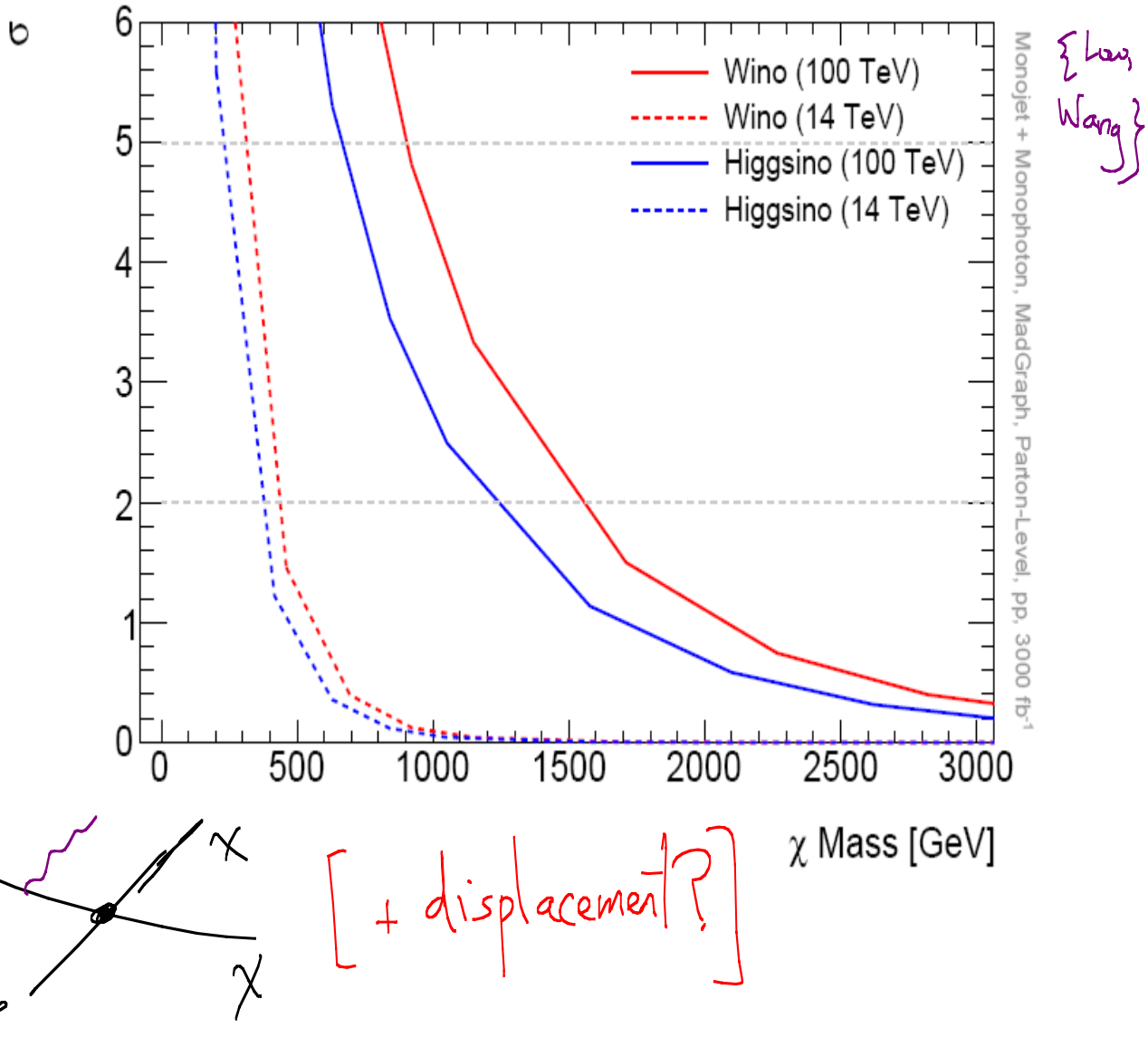
$\sim 10^3$ gain @ 100 TeV


35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
$\tilde{m}_q$ (TeV)
$\tilde{m}_g$ (TeV)
100 TeV, 3000 fb^{-1}
10 SUSY Events
LHC33, 3000 fb^{-1}
LHC13
3000 fb^{-1}
300 fb^{-1}
LHC8
{Cohen, Howe, Wacker}



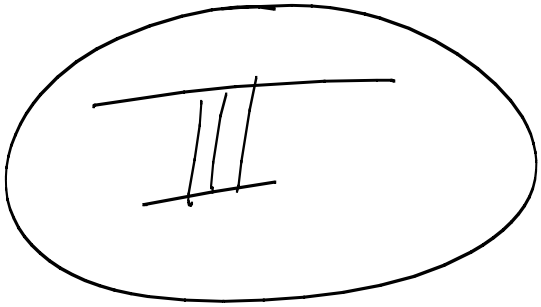
Robust probe of up to ~ few TeV electroweak particles.

{WIMPS could very easily be here — LHC not ideal "DM factory"}



{Low, Wang}

[+ displacement?]

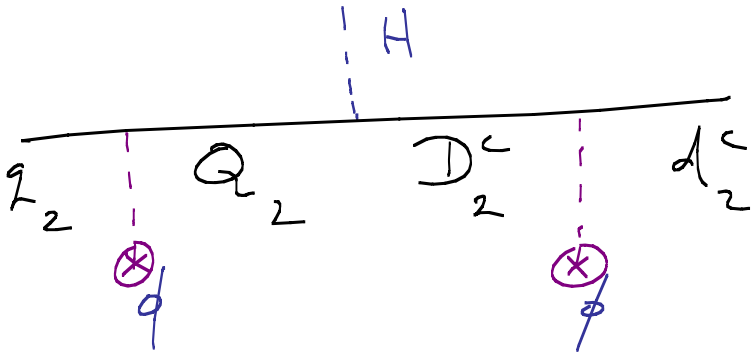


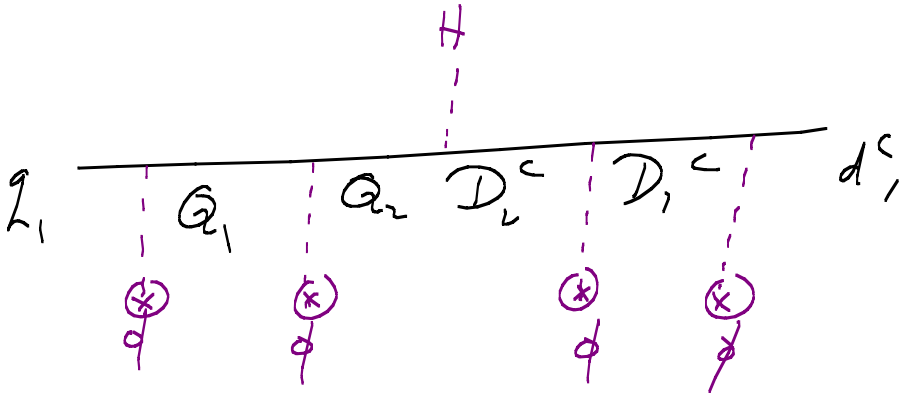
For the first time, rich + alive possibilities for Collider Flavor Physics

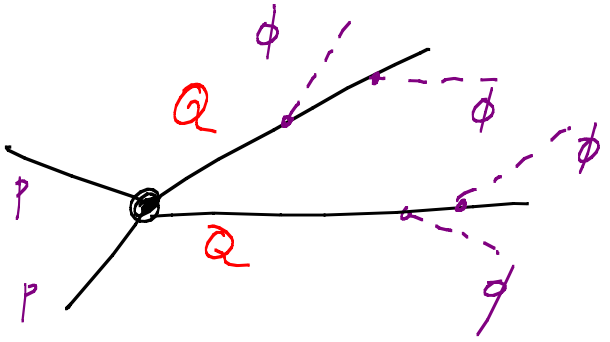
* Not possible to generate flavor @ ~ TeV scale + not be dead by FCNC's ⟹ no flavor collider physics @ LHC.

* Not so already if new physics @ 10 TeV...

e.g.







Long cascade decays w/ fingerprint of flavor symmetry structure.

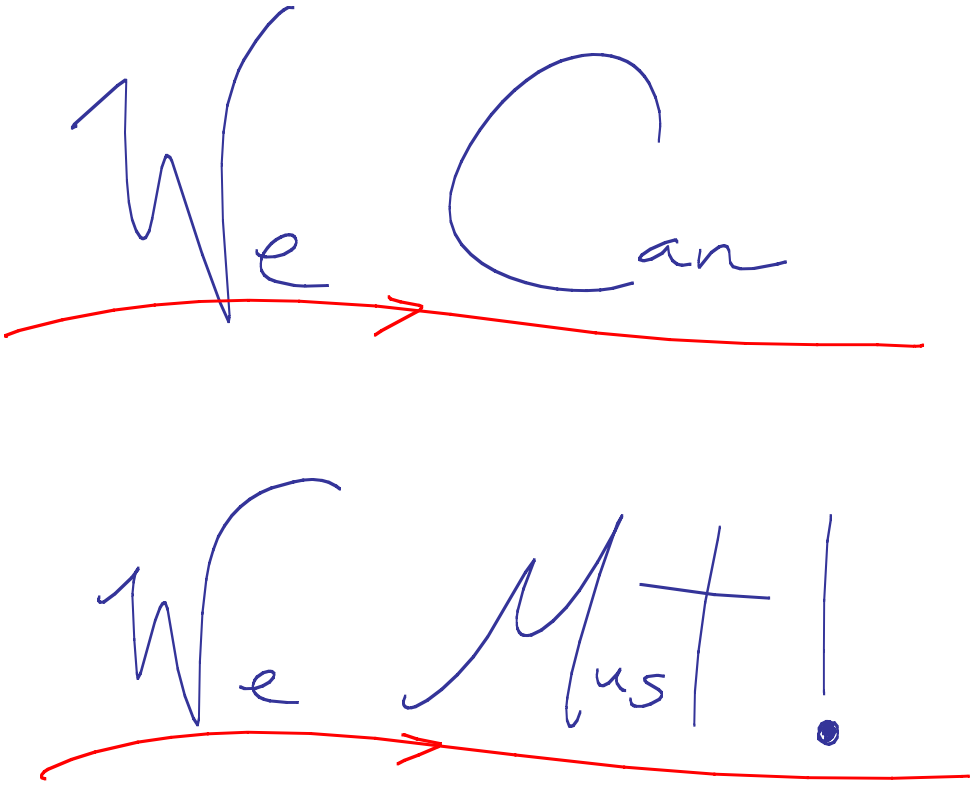
*So many tops, we can start probing interesting levels of top flavor

Also, we have ongoing probes of CP and Flavor, e.g. electron EDM's, $\mu \leftrightarrow e$ conversion, ...

Any positive signal must come from new physics @ 10–100 TeV scale, can expose it directly with 100 TeV machine

The Scientific Questions at Stake in our field are the deepest ones we have encountered in 50 years

*EVERY student/post-doc/ person with a pulse (esp. under 35) I know is EXTREMELY excited by the prospects of a 100 TeV collider, + enthusiastic to work on this physics.


We Can
We Must!