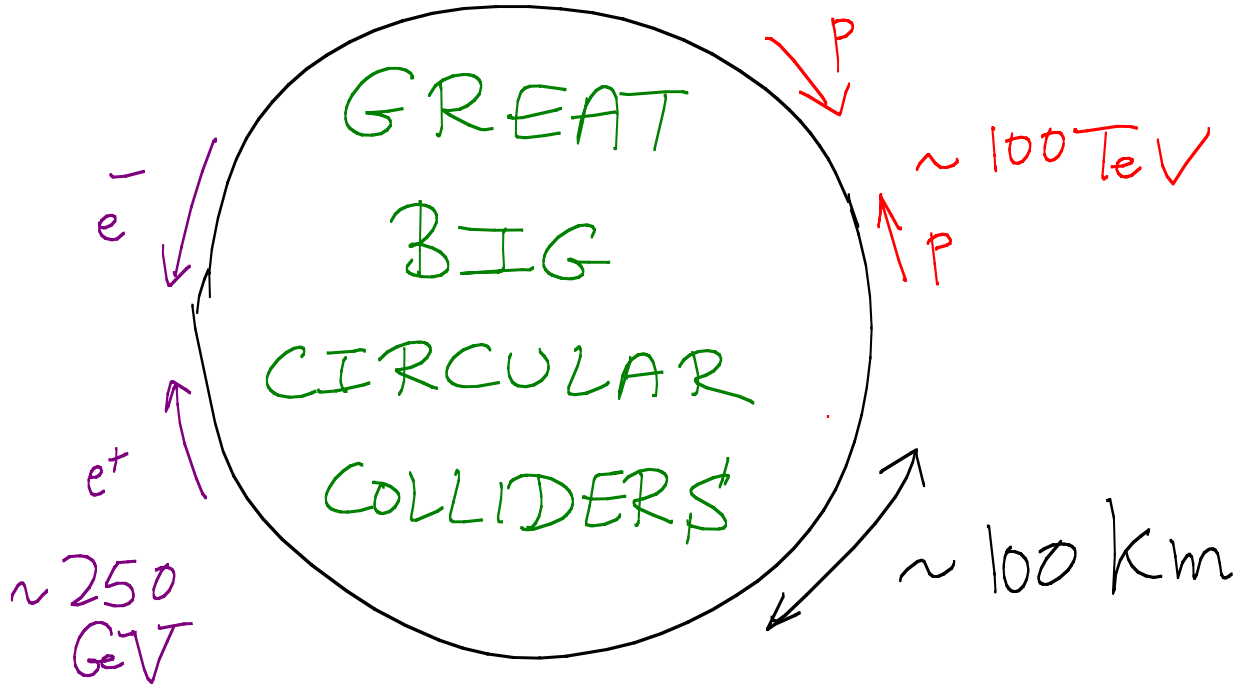
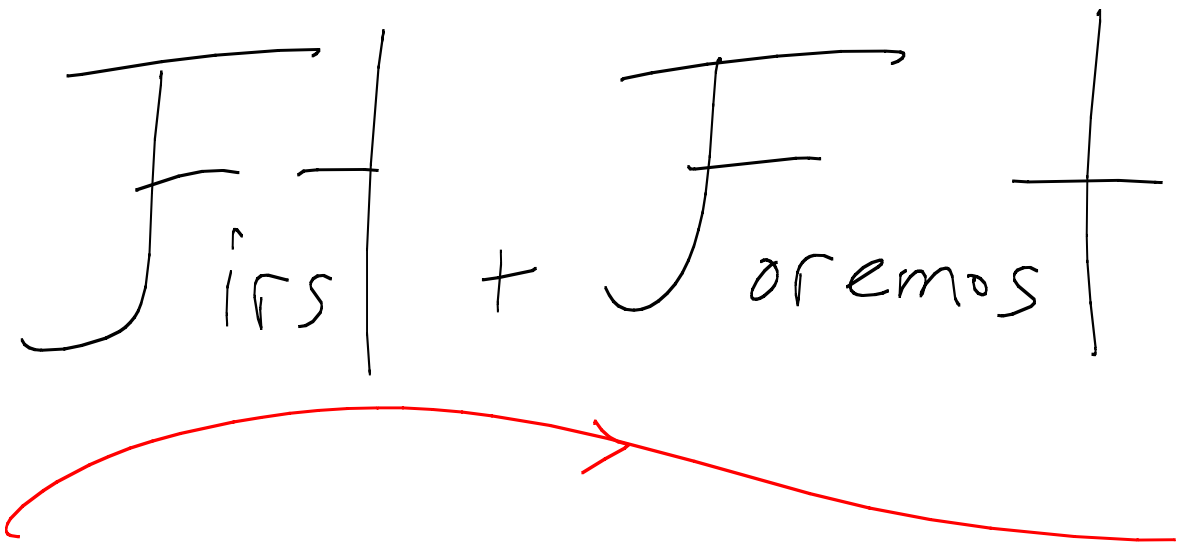
Motivations For




First + Foremost

* It's the OBVIOUS FUTURE

* BIG machines

BIG physics ideas

Lifeblood of The Field

Clearly, 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

* End of 20th Century

[1895 – 2012]

* Dawn of a New Era in Fundamental Physics

With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

The central questions today are not about details, but concern much deeper, structural issues:

Origin of Space-Time + our MACROSCOPIC universe

Higgs Discovery Crucial

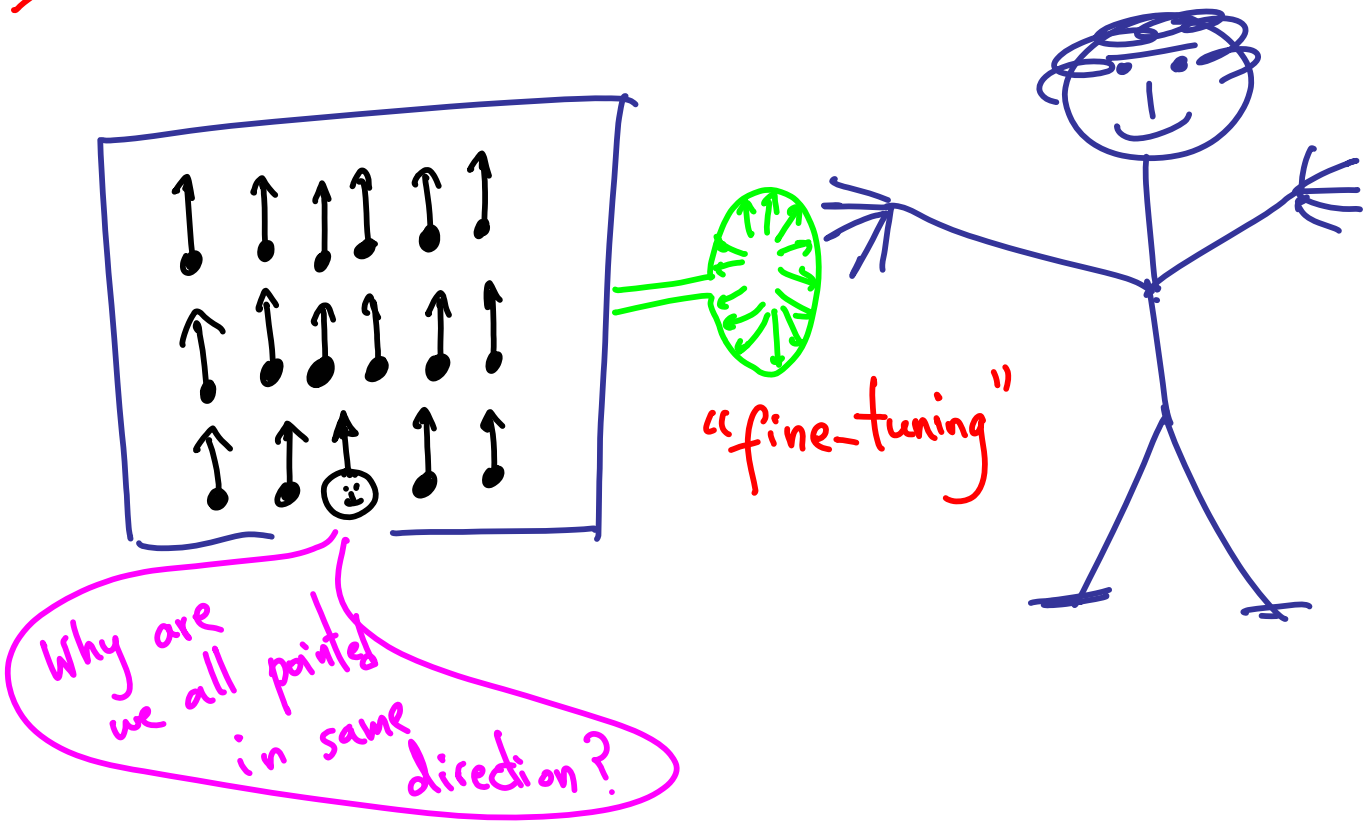
Light Higgs

↓

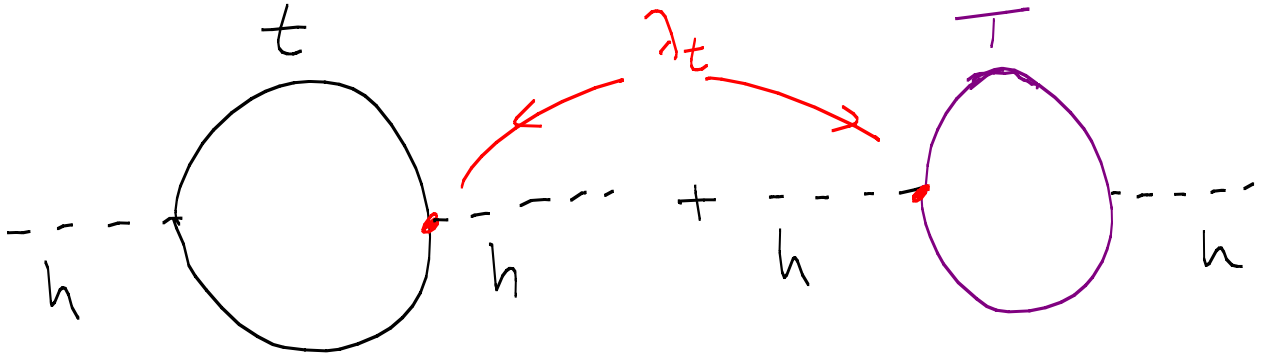
Our Vacuum is Qualitatively Different than Random C.M. System

[AKA "Random Metal"]

Never seen before in "state of nature"



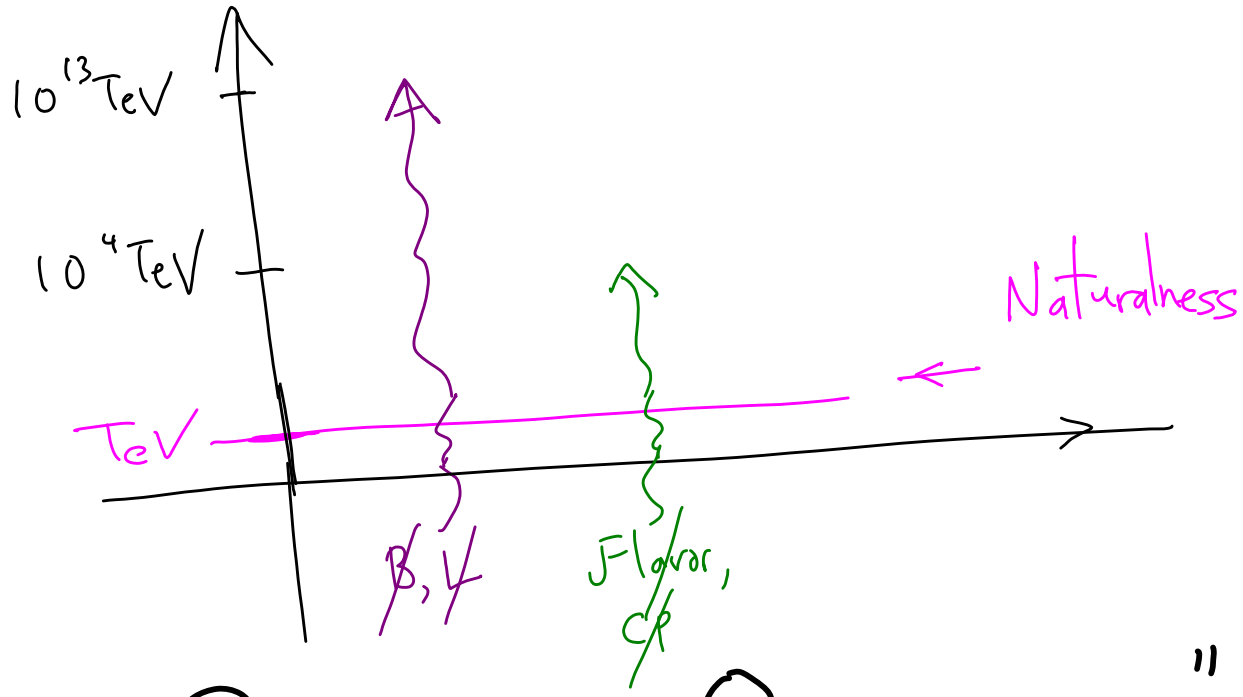
Ultimate Fate of Naturalness



T colored, $\Delta^{\text{tuning}} \sim \text{few} \times \left(\frac{400\,\text{GeV}}{m_T}\right)^2$


But Where Is Everybody?

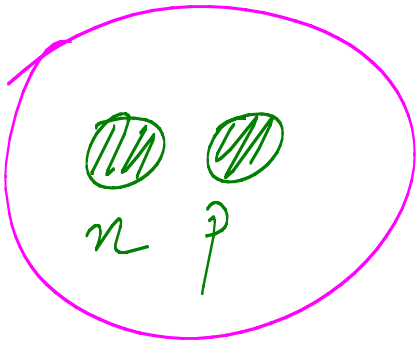
Tension Driving BSM Physics For 30 yrs



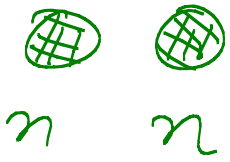
"Not Problems – Opportunities"

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

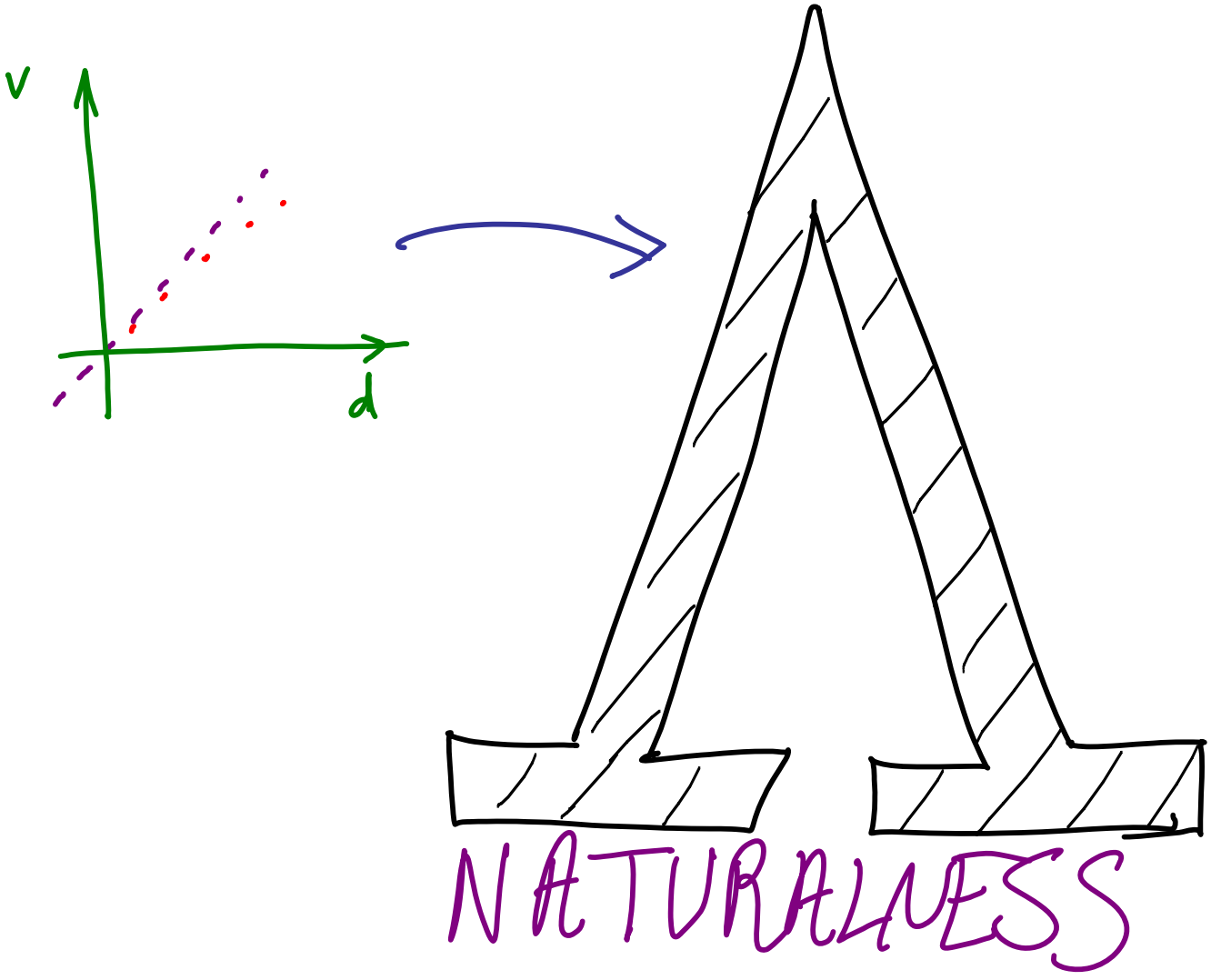
Nucl. Phys. is Confusing Because it's Tuned!



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



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

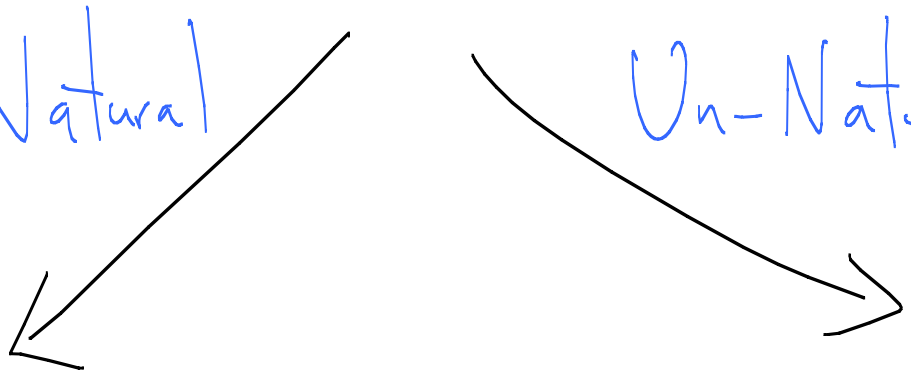

v
d
NATURALNESS

Is Weak Scale Natural?

HUGE STAKES

Not just this or that particle — deep, structural issue in QFT

Crucial Fork in the Road



BIG NEW PRINCIPLES

EVEN BIGGER PARADIGM SHIFT

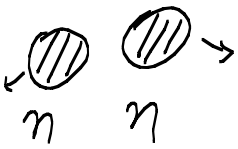
Like CC?

HOW TUNED?

Higgs + Nothing Else@LHC?

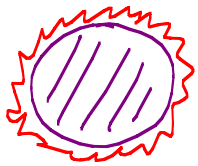
A Fine-tuning of at least 1% for weak scale CONVINCING?

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 - NEW.

CAN'T SHRUG SHOULDERS

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

MORTAL BLOW TO NATURALNESS

This alone fully justifies the march to 100 TeV

* Circular e^+e^- machine

Higgs Factory plays very important, complementary role

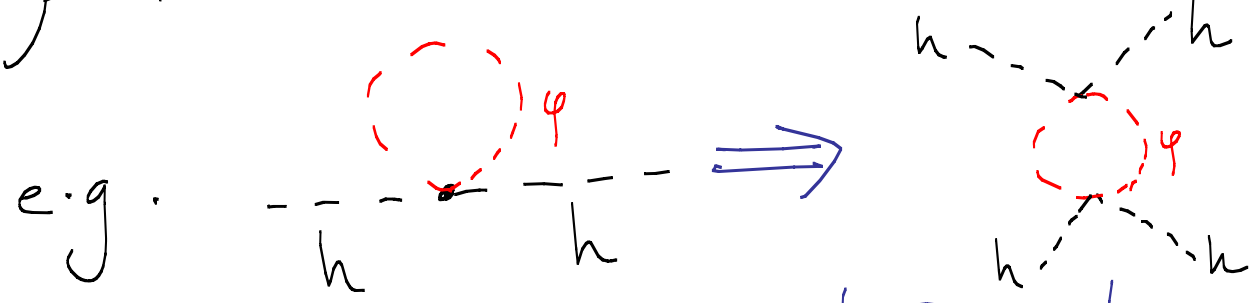
Looking for $\frac{h^\dagger h (h \bar{Q} b^c)}{\Lambda^2}$, $\frac{(h^\dagger D_\mu h)^2}{\Lambda^2}$, ...

* Tera-Z particularly exciting + powerful probe!

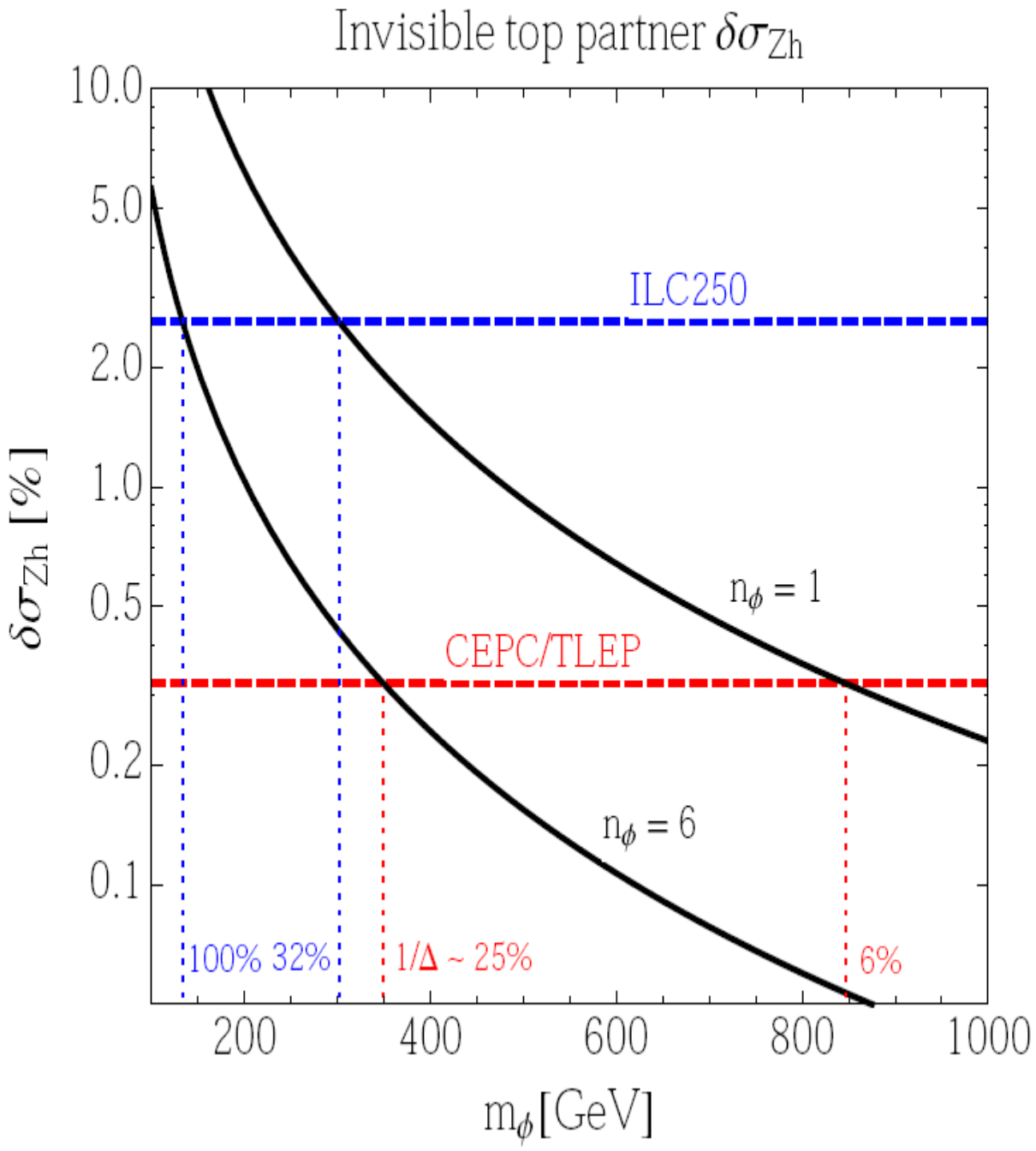
Also: naturalness "no lose theorem"

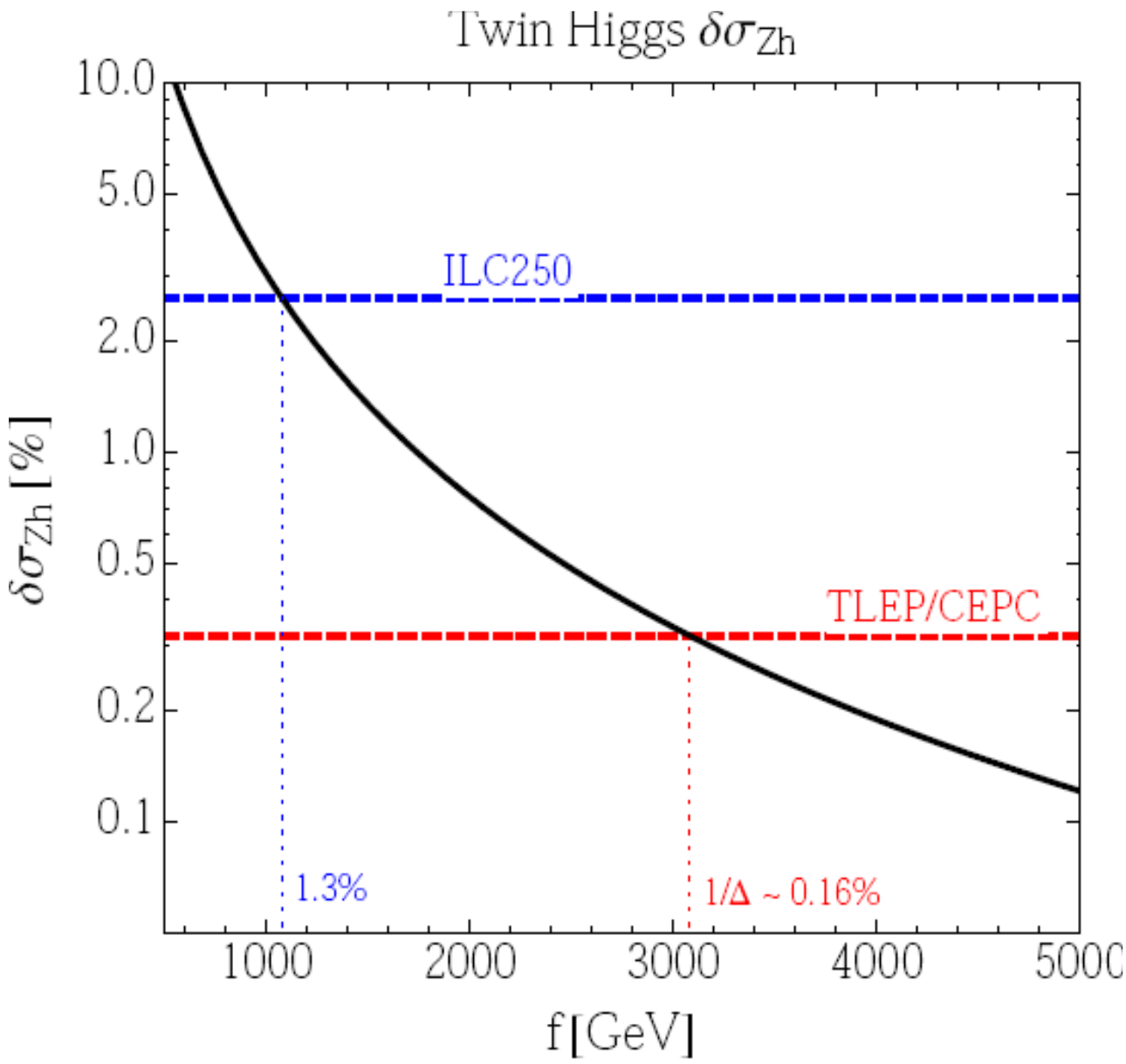
[Craig et. al.]

Perhaps higgs is natural, but top partners are not colored?

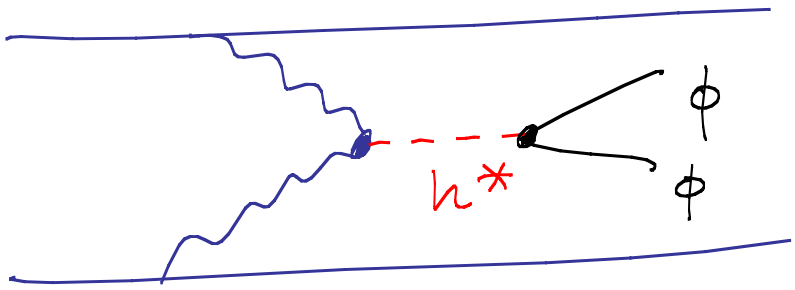
e.g. 

$\Rightarrow \sim 1\%$ mod to hZ coupling

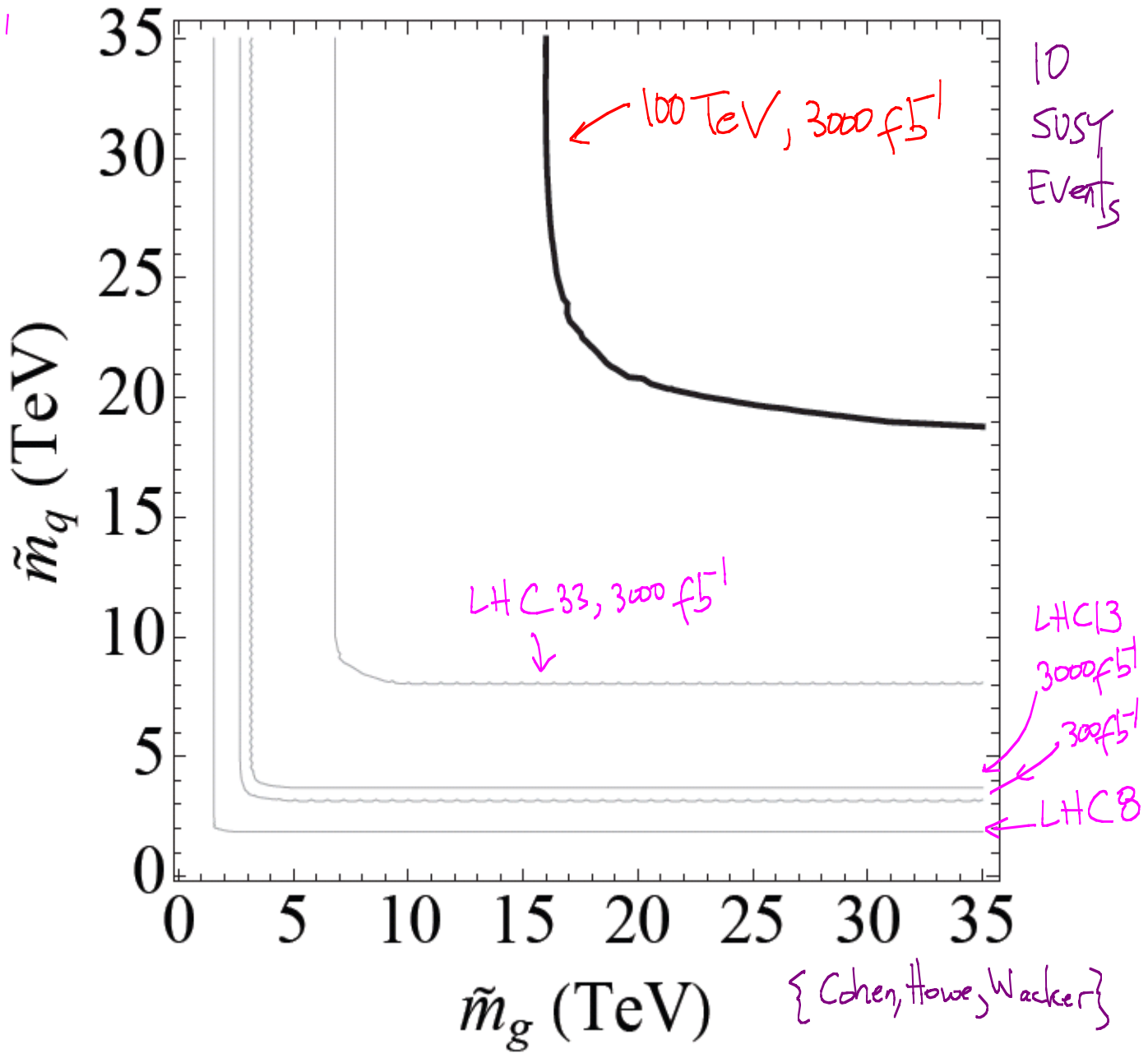

Invisible top partner $\delta\sigma_{Zh}$
10.0
5.0
2.0
1.0
0.5
0.2
0.1
$\delta\sigma_{Zh}$ [%]
ILC250
CEPC/TLEP
$n_\phi = 1$
$n_\phi = 6$
100% 32%
1/Δ ~ 25%
6%
200
400
600
800
1000
m_ϕ[GeV]


Twin Higgs $\delta\sigma_{Zh}$
10.0
5.0
2.0
1.0
0.5
0.2
0.1
$\delta\sigma_{Zh}$ [%]
ILC250
TLEP/CEPC
1.3%
1/Δ ~ 0.16%
1000
2000
3000
4000
5000
f[GeV]

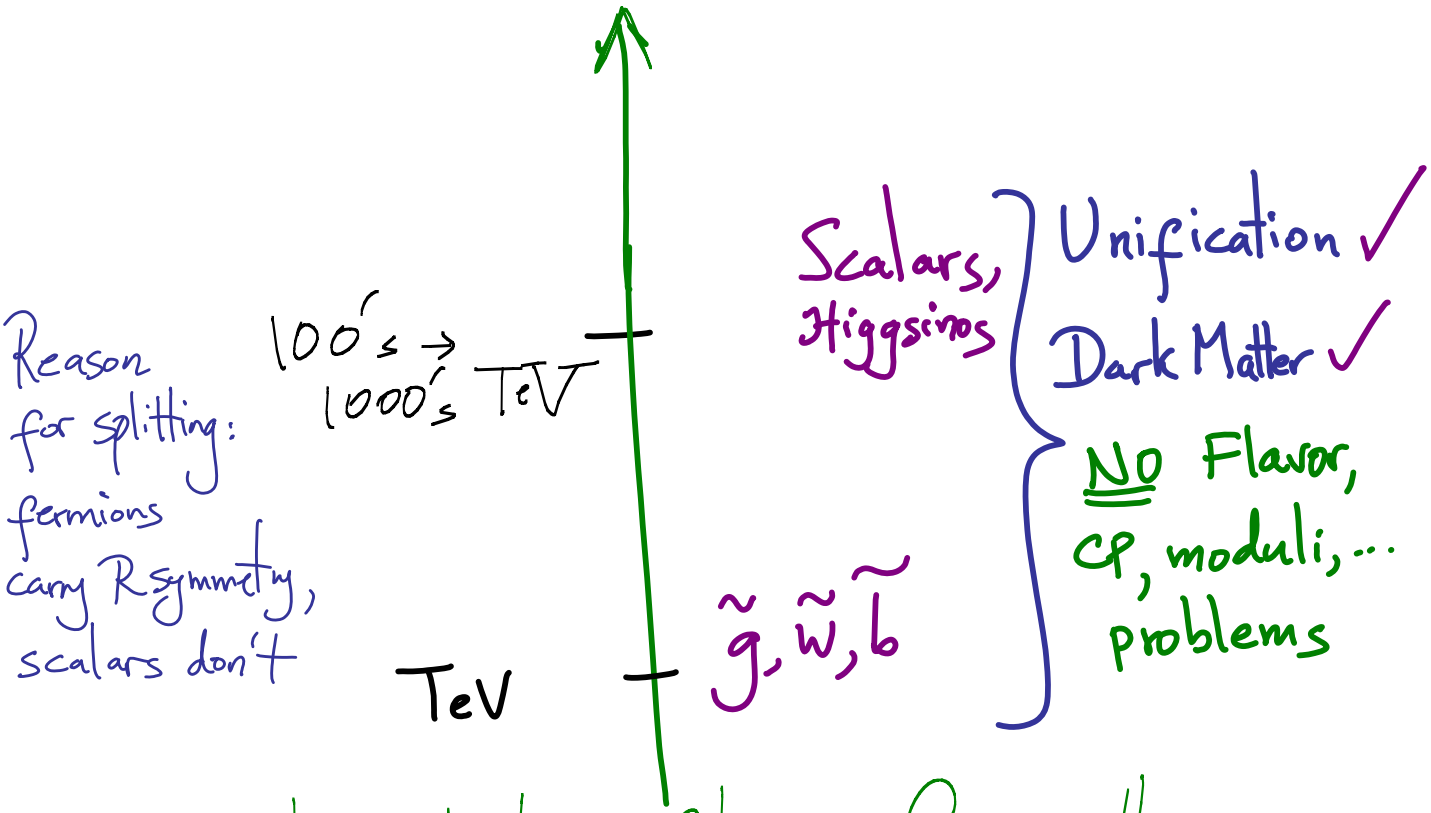
+ Obvious follow-up in pp collisions :



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

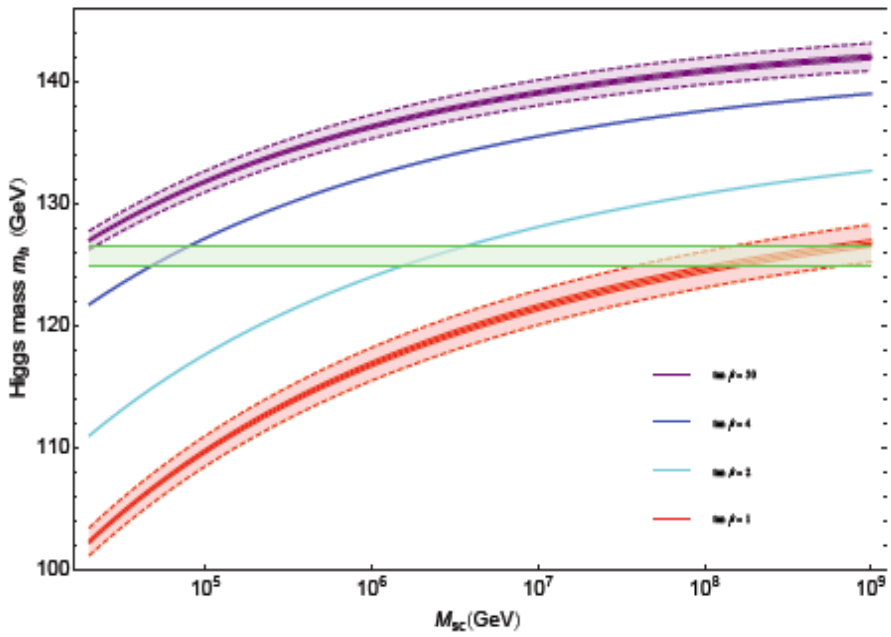

35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
$\tilde{m}_q$ (TeV)
$\tilde{m}_g$ (TeV)
100 TeV, 3000 fb^{-1}
10 SUSY Events
LHC33, 3000 fb^{-1}
LHC13
3000 fb^{-1}
300 fb^{-1}
LHC8
{Cohen, Howe, Wacker}

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;

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

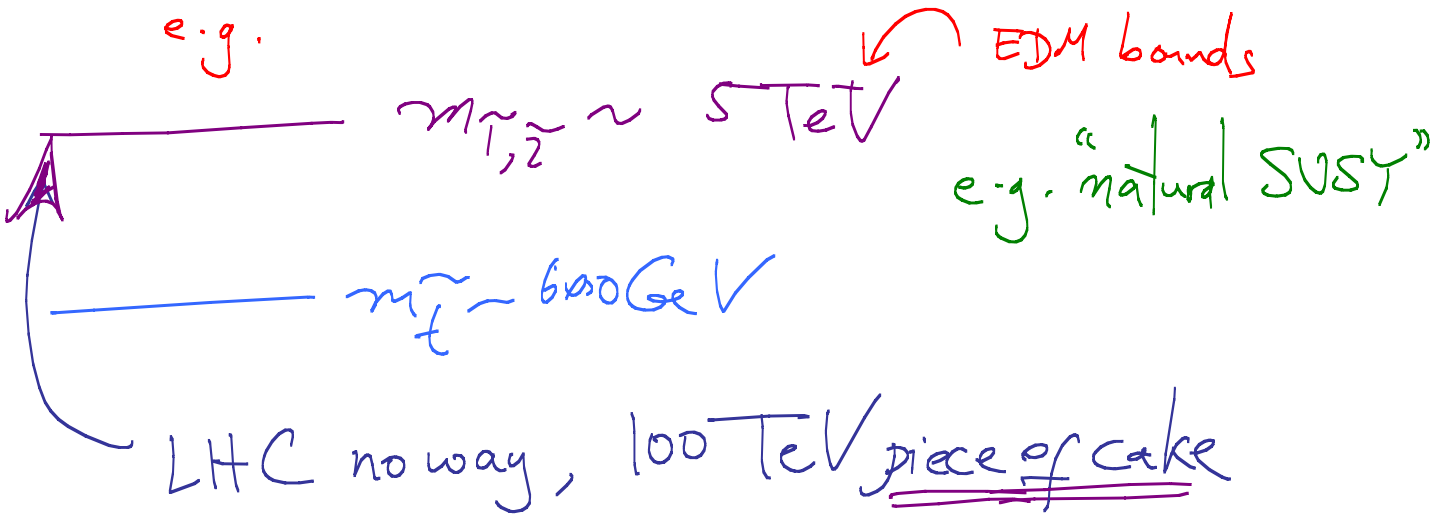
What if L.H.C discovers

(relatively) Natural Spectrum?

It's not 1995....

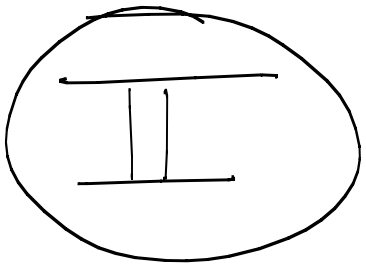
"Discover SUSY @ LHC,
precision study @ 500 GeV
ILC"

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



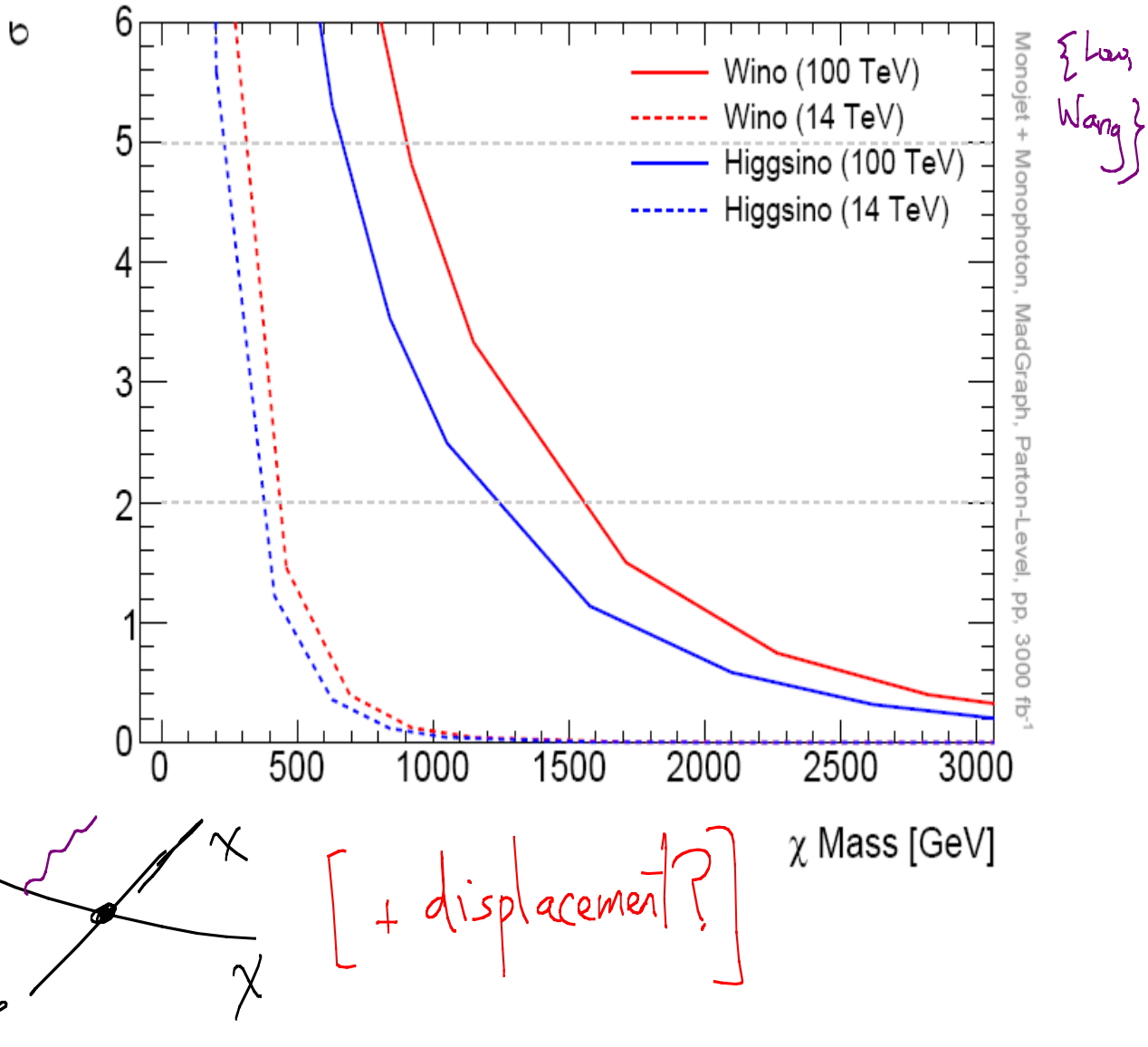
More generally, we will want a factory for new colored particles, to study how they make higgs Natural [e.g. SUSY coupling relations] $\longrightarrow$ RATE $\propto E_{CM}^{5 \to 6}$

$\sim 10^3$ gain @ 100 TeV



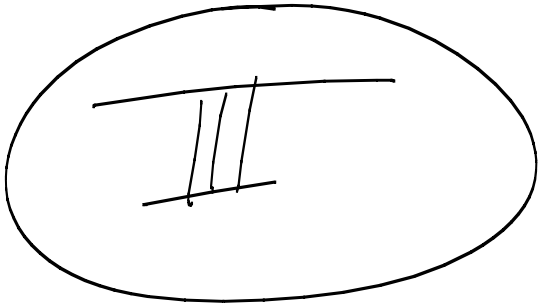
Robust probe of up to ~ few TeV electroweak particles.

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



{Low, Wang}

[+ displacement?]

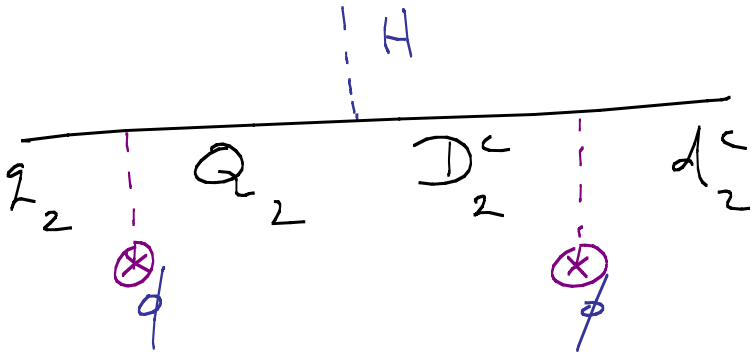


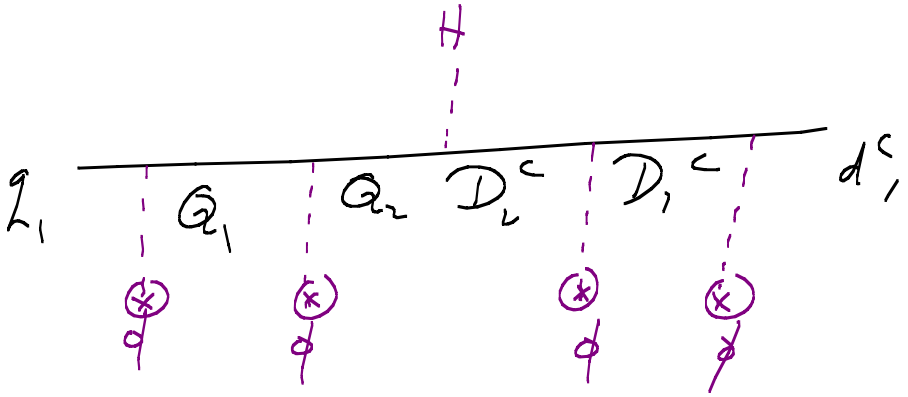
For the first time, rich + alive possibilities for Collider Flavor Physics

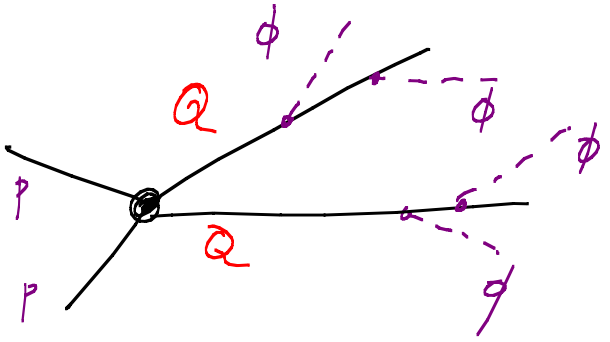
* Not possible to generate flavor @ ~ TeV scale + not be dead by FCNC's ⟹ no flavor collider physics @ LHC.

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

e.g.





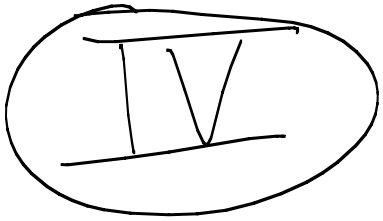


Long cascade decays w/ fingerprint of flavor symmetry structure.

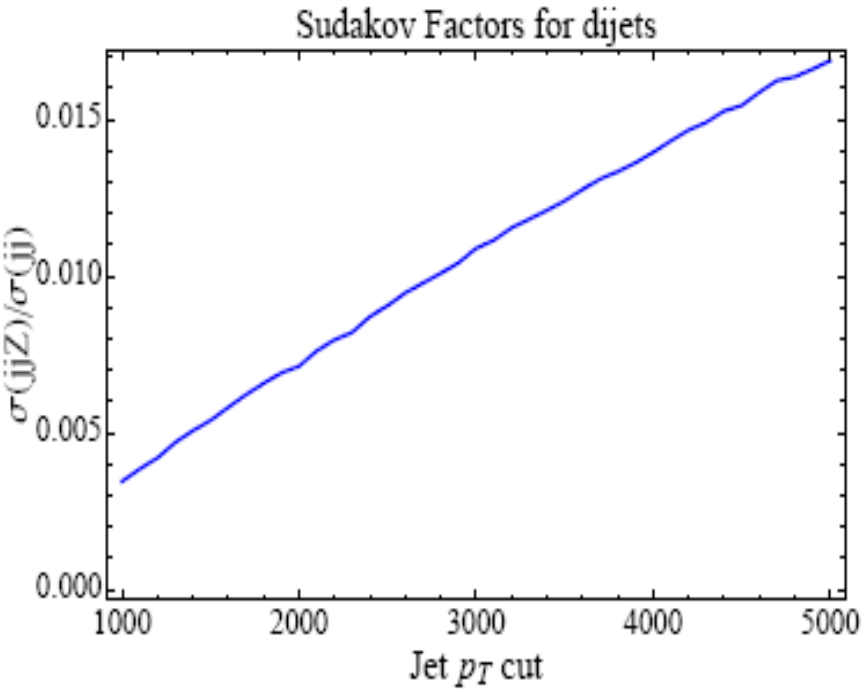
* ~ 10^{11} tops — we can start probing interesting levels of top flavor

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

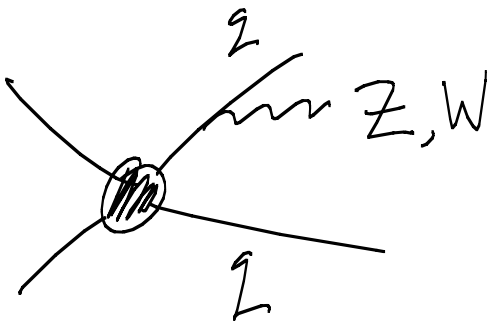
Any positive signal must come from new physics @ 10–100 TeV scale, can expose it directly with 100 TeV machine



Some qualitatively new aspects of 100 TeV collisions — e.g. $SU(2) \times U(1)$ finally looks unbroken! W/Z "radiation" significant — ν's + DM more "visible" [Hook, Katz]

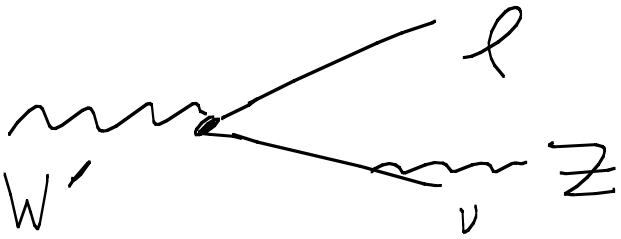


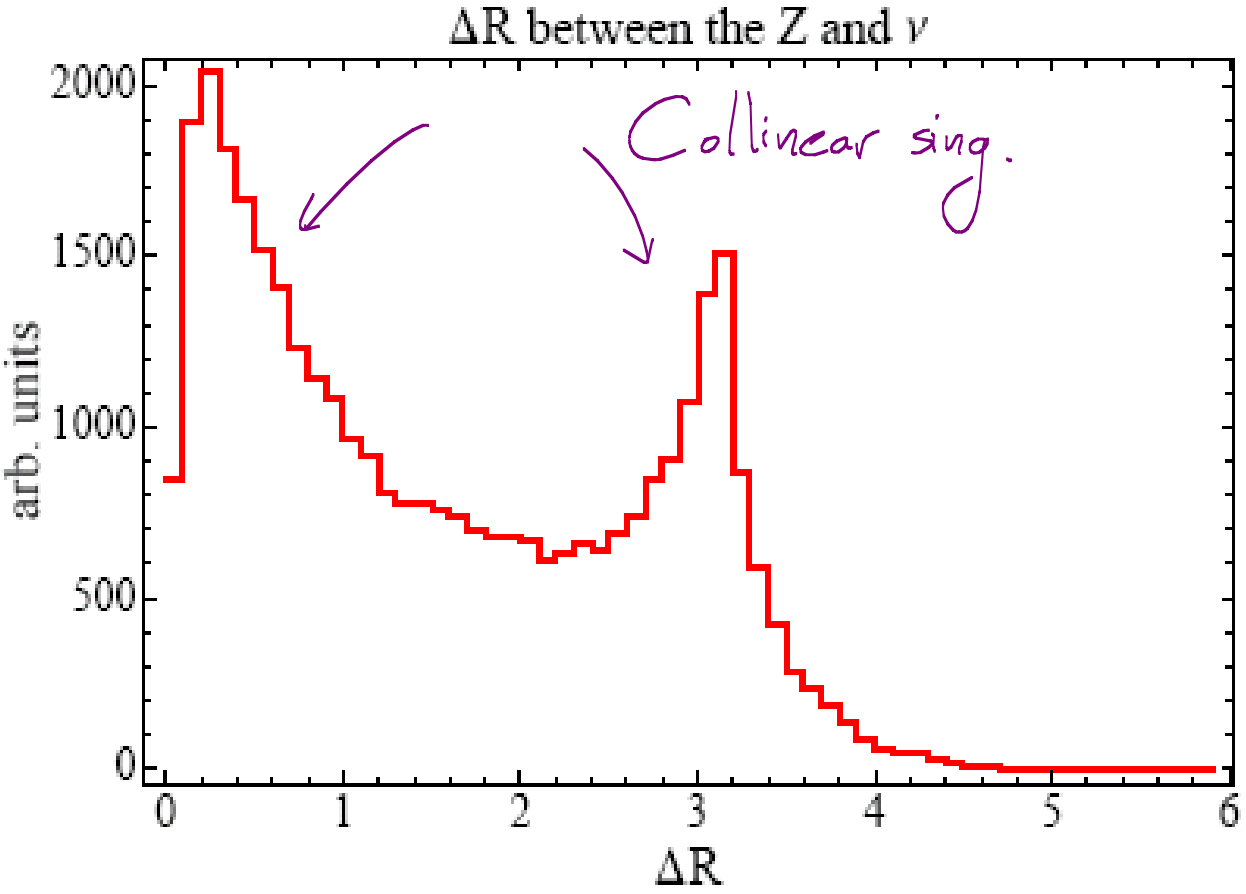
~10% of dijets @ 10TeV have W/Z's!

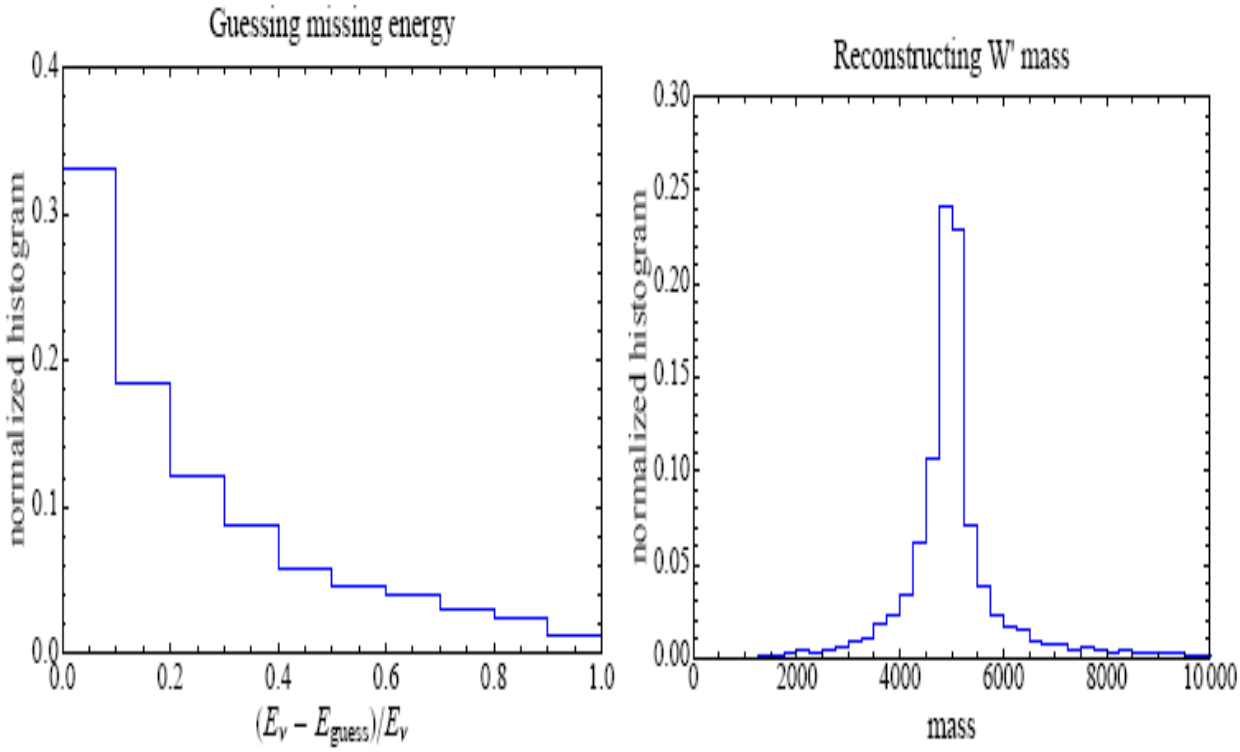


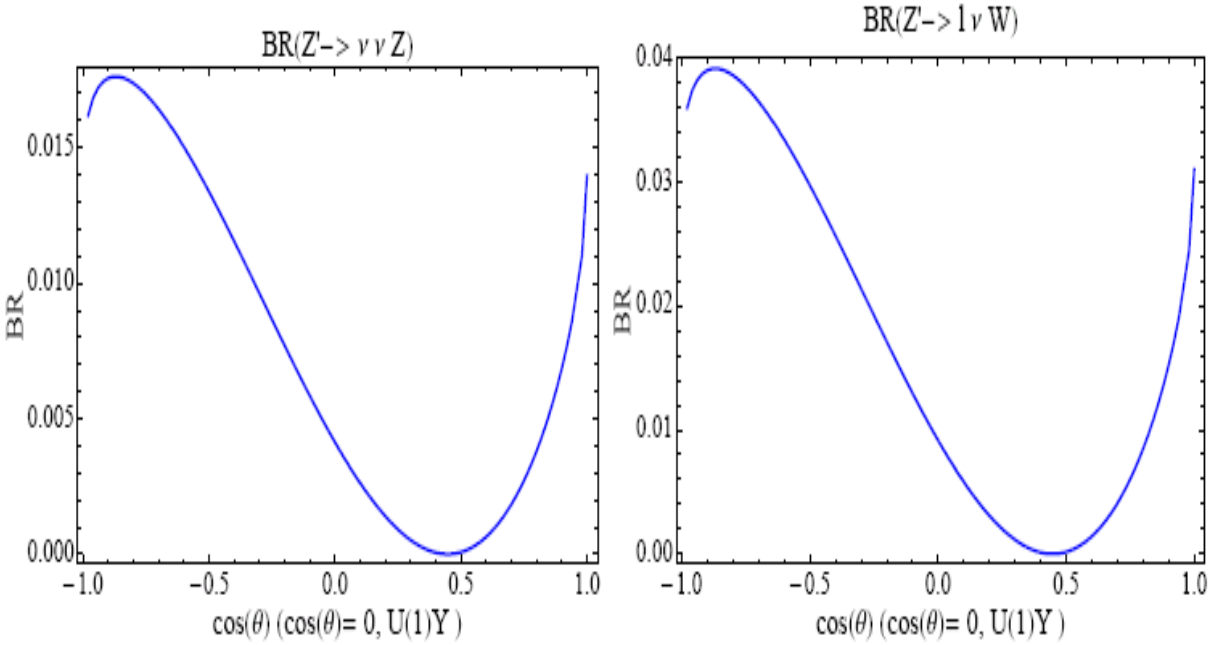
$$\frac{4\alpha_2}{\pi}\log^2\left(\frac{5\,\text{TeV}}{m_Z}\right)$$

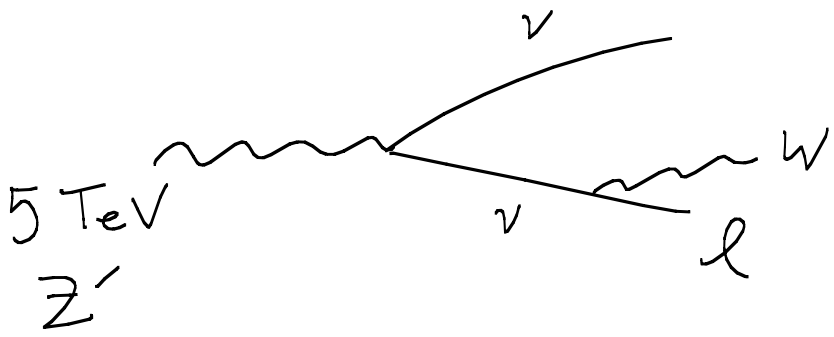
not small!


ℓ
W′
Z
ν

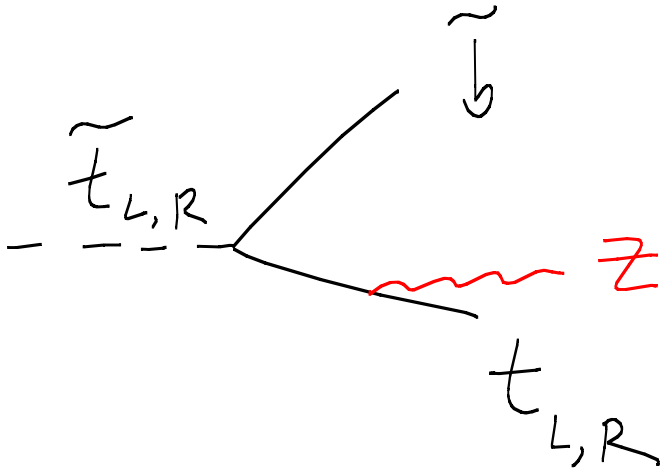

ΔR between the Z and ν
Collinear sing.
arb. units
2000
1500
1000
500
0
0
1
2
3
4
5
6
ΔR


Guessing missing energy
normalized histogram
0.0
0.1
0.2
0.3
0.4
0.0
0.2
0.4
0.6
0.8
1.0
$(E_\nu - E_{guess})/E_\nu$
Reconstructing W' mass
normalized histogram
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
2000
4000
6000
8000
10000
mass


BR(Z'-> ν ν Z)
BR
0.015
0.010
0.005
0.000
−1.0
−0.5
0.0
0.5
1.0
cos(θ) (cos(θ)= 0, U(1)Y)
BR(Z'-> l ν W)
BR
0.04
0.03
0.02
0.01
0.00
−1.0
−0.5
0.0
0.5
1.0
cos(θ) (cos(θ)= 0, U(1)Y)

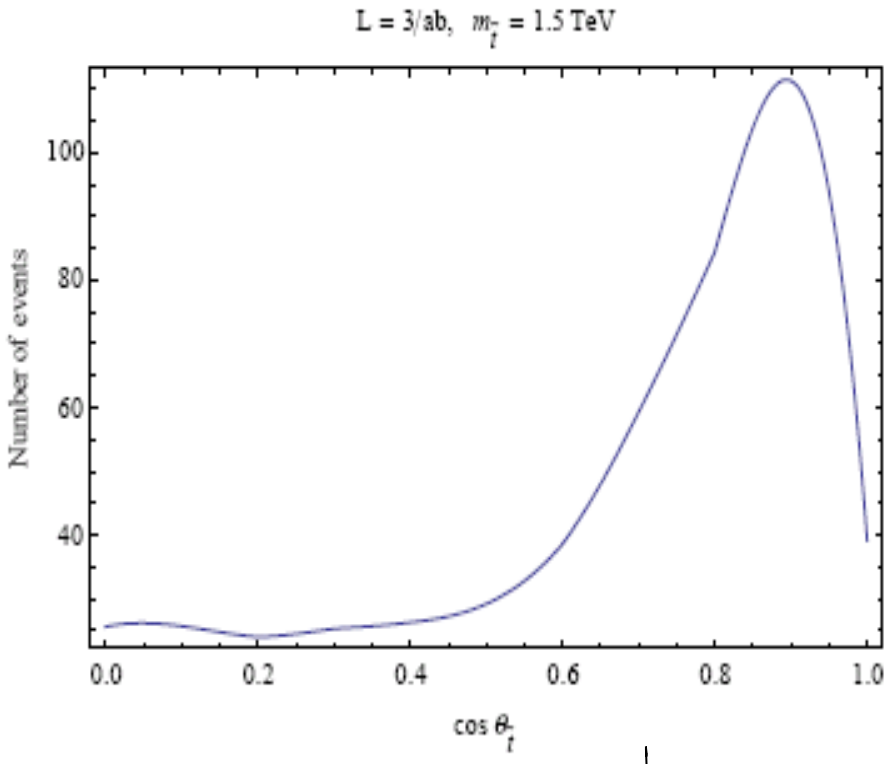

ν
W
5 TeV
ν
l
Z'

Are stops L or R ?



$\Longleftarrow$ probes

L/R mixture

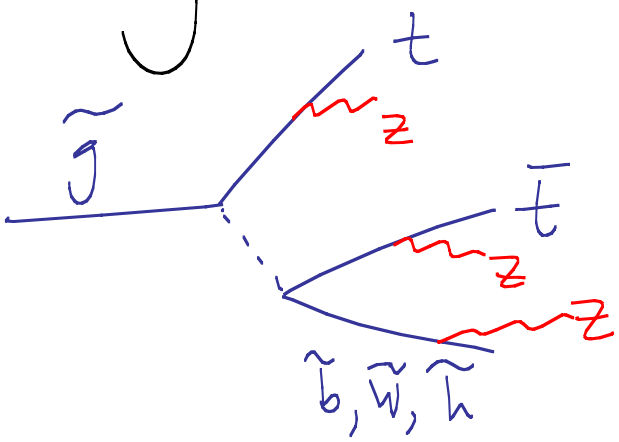


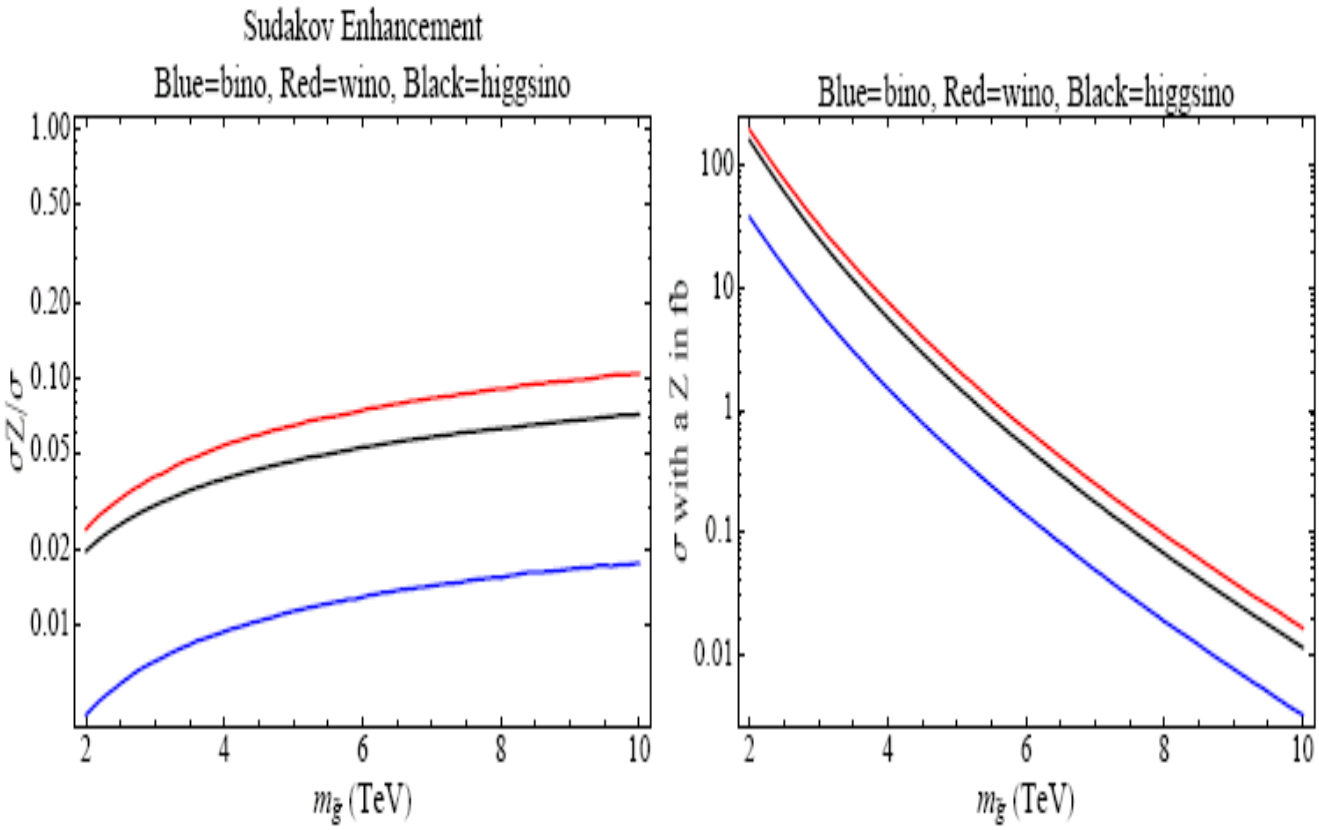
1.5 TeV stops not accessible @ LHC

Not only can see it @ 100 TeV —

determine L/R!

Is bottom of spectrum EW charged or neutral?




Sudakov Enhancement
Blue=bino, Red=wino, Black=higgsino
σZ/σ
1.00
0.50
0.20
0.10
0.05
0.02
0.01
2
4
6
8
10
$m_{\tilde{g}}$ (TeV)
Blue=bino, Red=wino, Black=higgsino
σ with a Z in fb
100
10
1
0.1
0.01
2
4
6
8
10
$m_{\tilde{g}}$ (TeV)

Large # of other big physics:

* WW scattering (!)

* Probe of Ewk phase transition

  + Ewk Baryogen [Meade]

(Again: Complem. between e^+e^- + pp modes)

⋮

* It's the OBVIOUS FUTURE

* BIG machines

BIG physics ideas

Lifeblood of The Field

ASK NOT WHAT BIG CIRCULAR COLLIDERS CAN DO FOR YOU, ASK WHAT YOU CAN DO FOR BIG CIRCULAR COLLIDERS!

Please join in the ongoing efforts @ CERN, and our new initiative @ IHEP,

Center For Future HEP

THE TIME IS NOW