Physics Motivations

for

100 TeV Colliders

First + Foremost

* It's the OBVIOUS FUTURE

* BIG machines

BIG physics ideas

Lifeblood of The Field

Clearly, how to proceed will depend on first LHC13 results.

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

Higgs Discovery Crucial

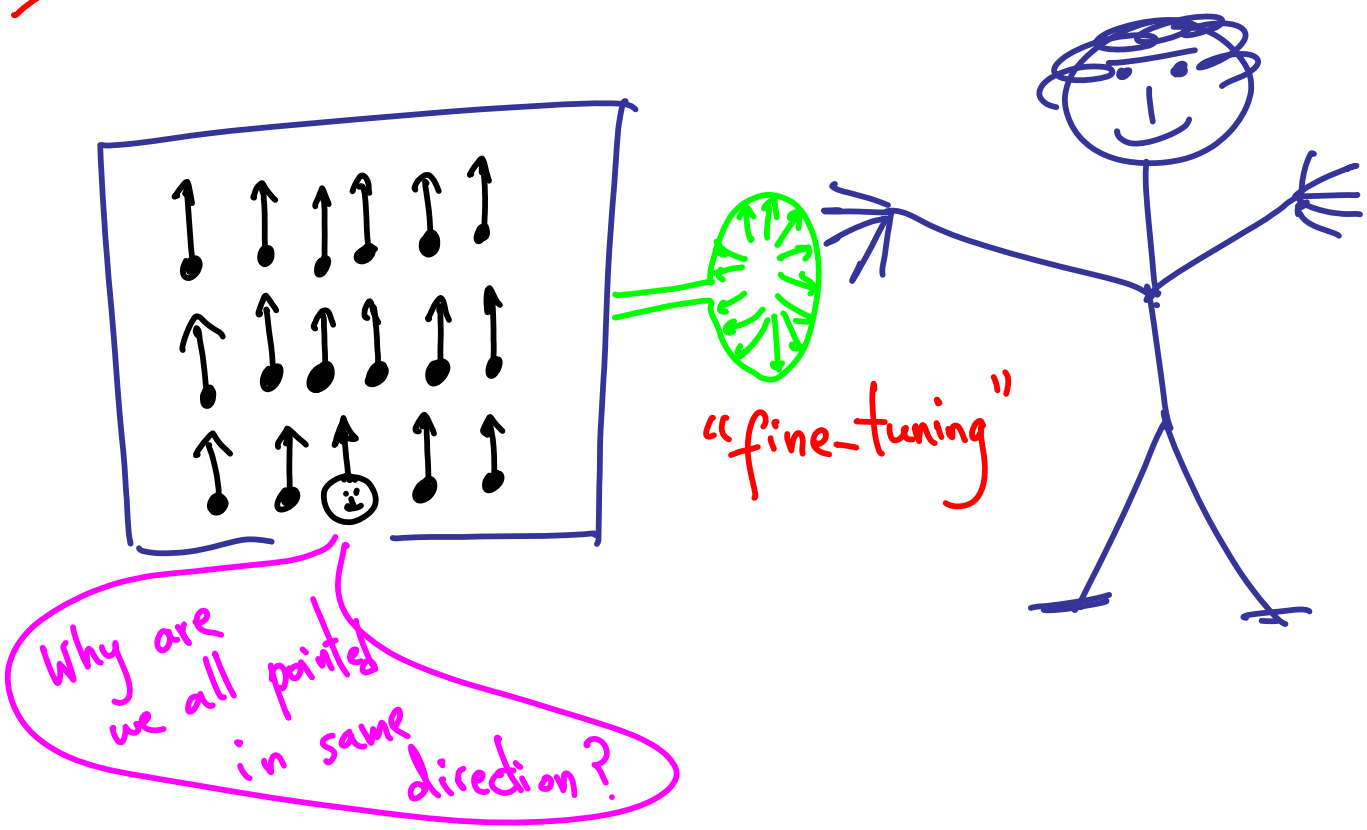
Light Higgs

↓

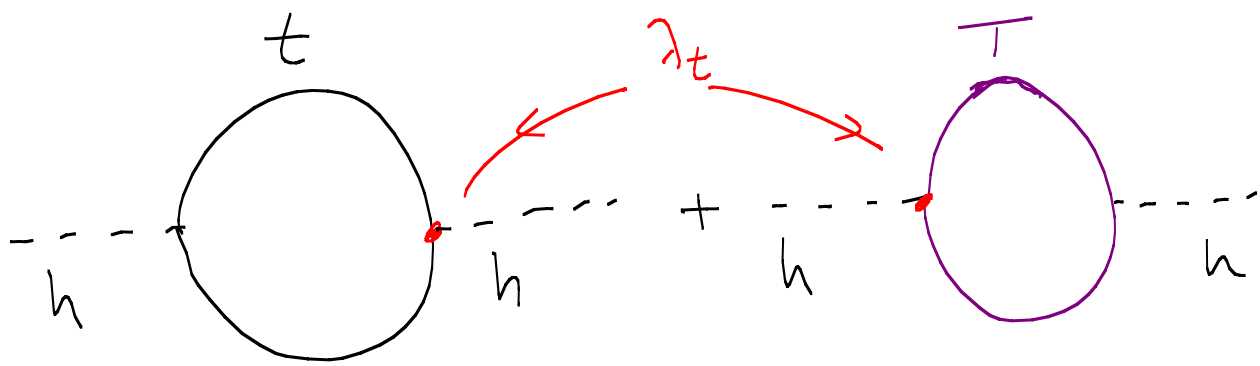
Our Vacuum is Qualitatively Different than Random C.M. System

[AKA "Random Metal"]

Never seen before in "state of nature"



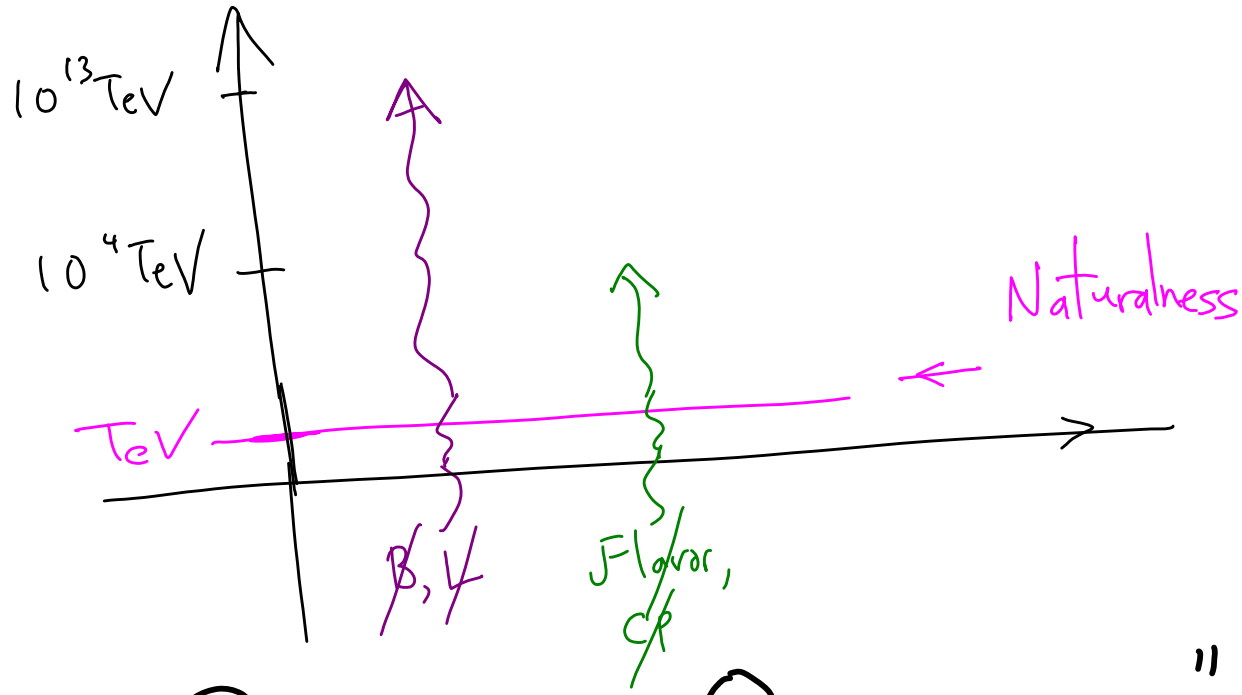
Ultimate Fate of Naturalness



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

But Where Is Everybody?

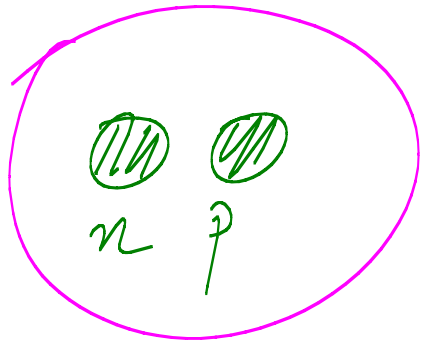
Tension Driving BSM Physics For 30 yrs



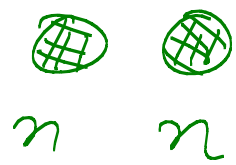
"NOT PROBLEMS – OPPORTUNITIES"

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

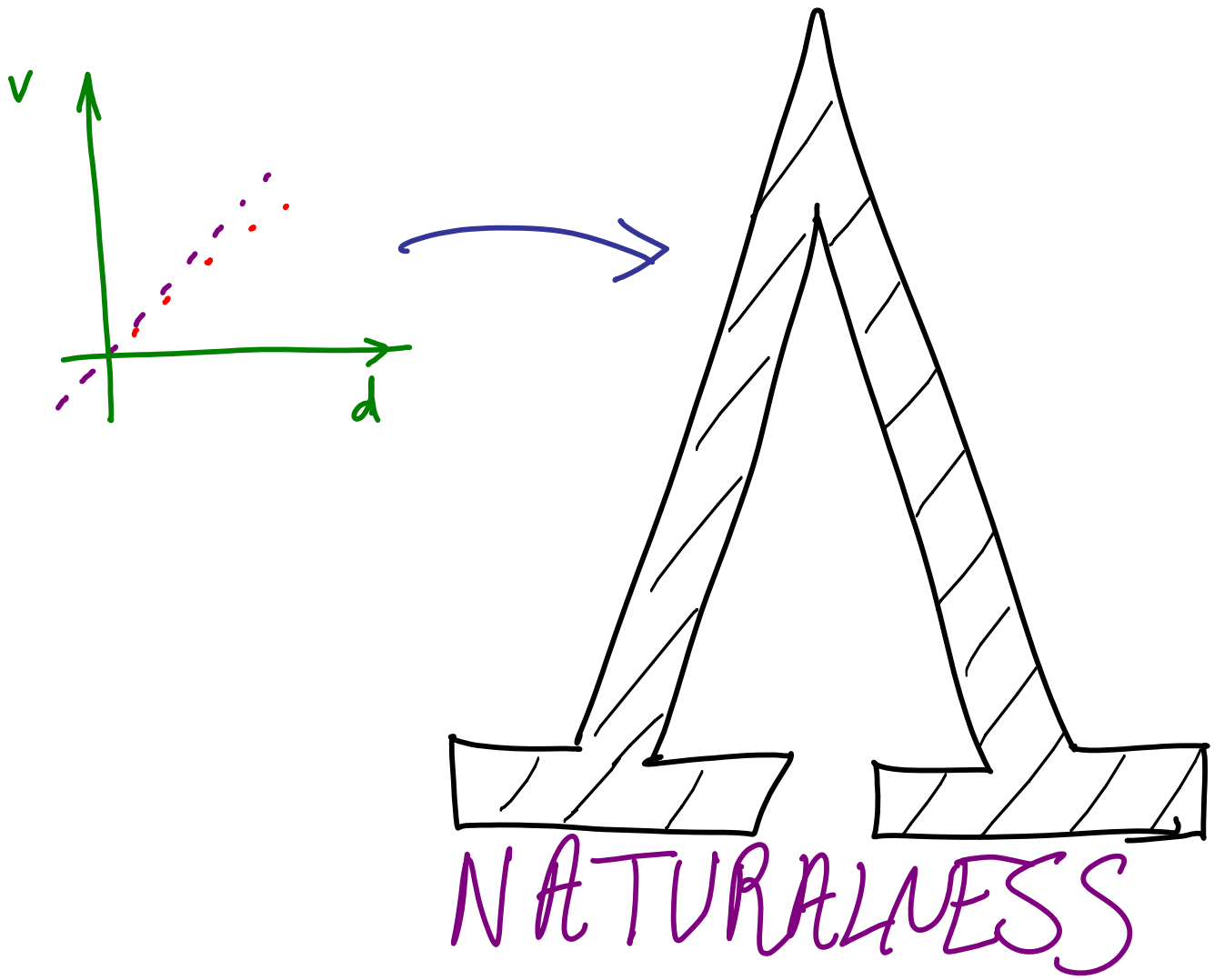
Nucl. Phys. is Confusing Because it's Tuned!



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



Not bound by
60 keV(!),
$\lesssim 1\%$ accident


v
d
NATURALNESS

Crucial Fork in the Road

Natural

Un-Natural

BIG NEW PRINCIPLES

EVEN BIGGER PARADIGM SHIFT

Like CCP

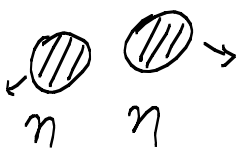
HOW TUNED?

Higgs + Nothing Else@LHC?

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

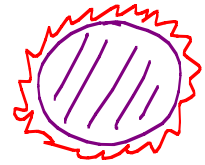
CONVINCING?

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 $\propto E_{machine}^{2}$
- 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 $\frac{h^\dagger h (h Q b^c)}{\Lambda^2}$, $\frac{(h^\dagger D_\mu h)^2}{\Lambda^2}$, ...

* Tera-Z particularly exciting + powerful probe!

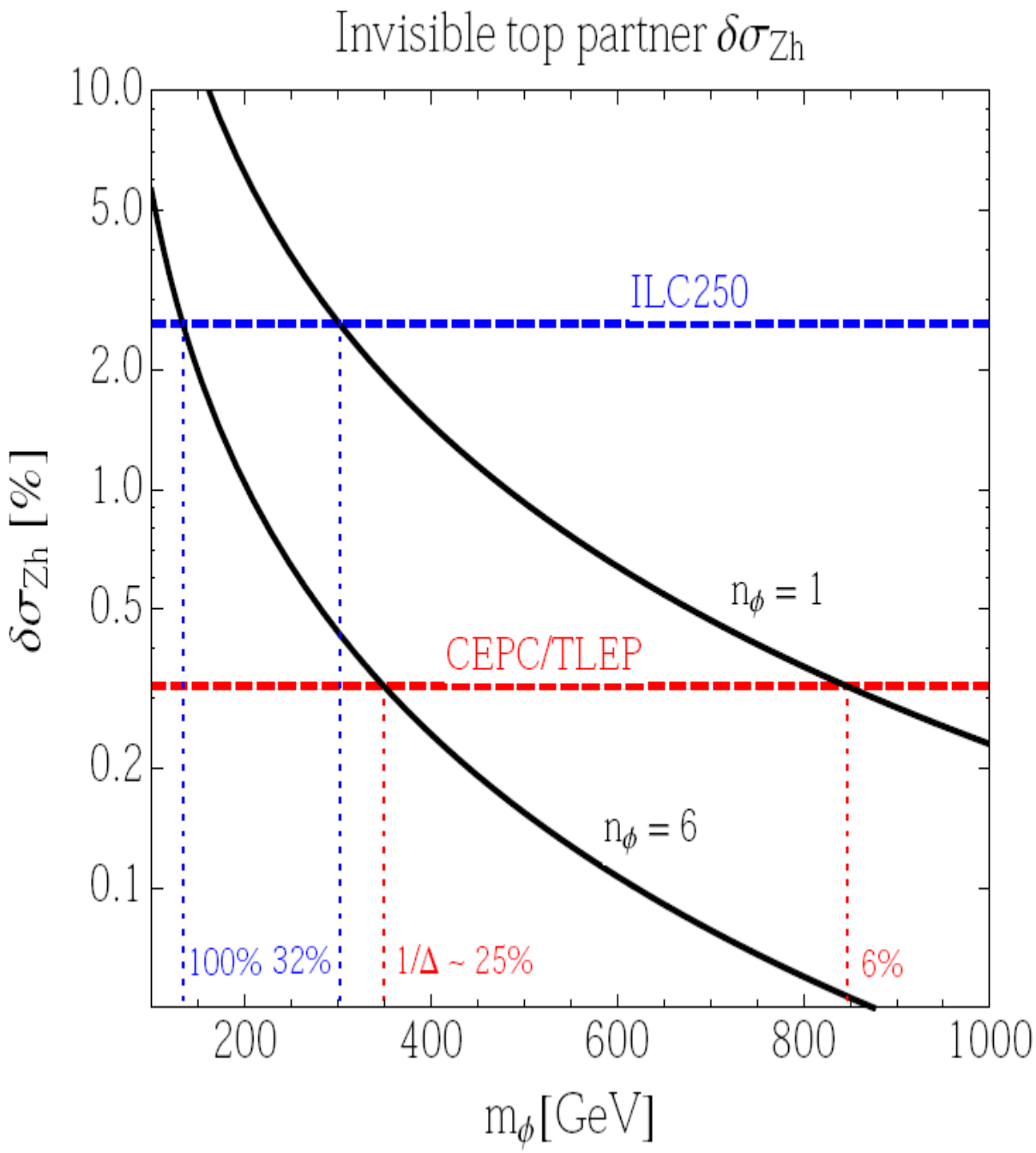
Also: naturalness "no lose theorem"

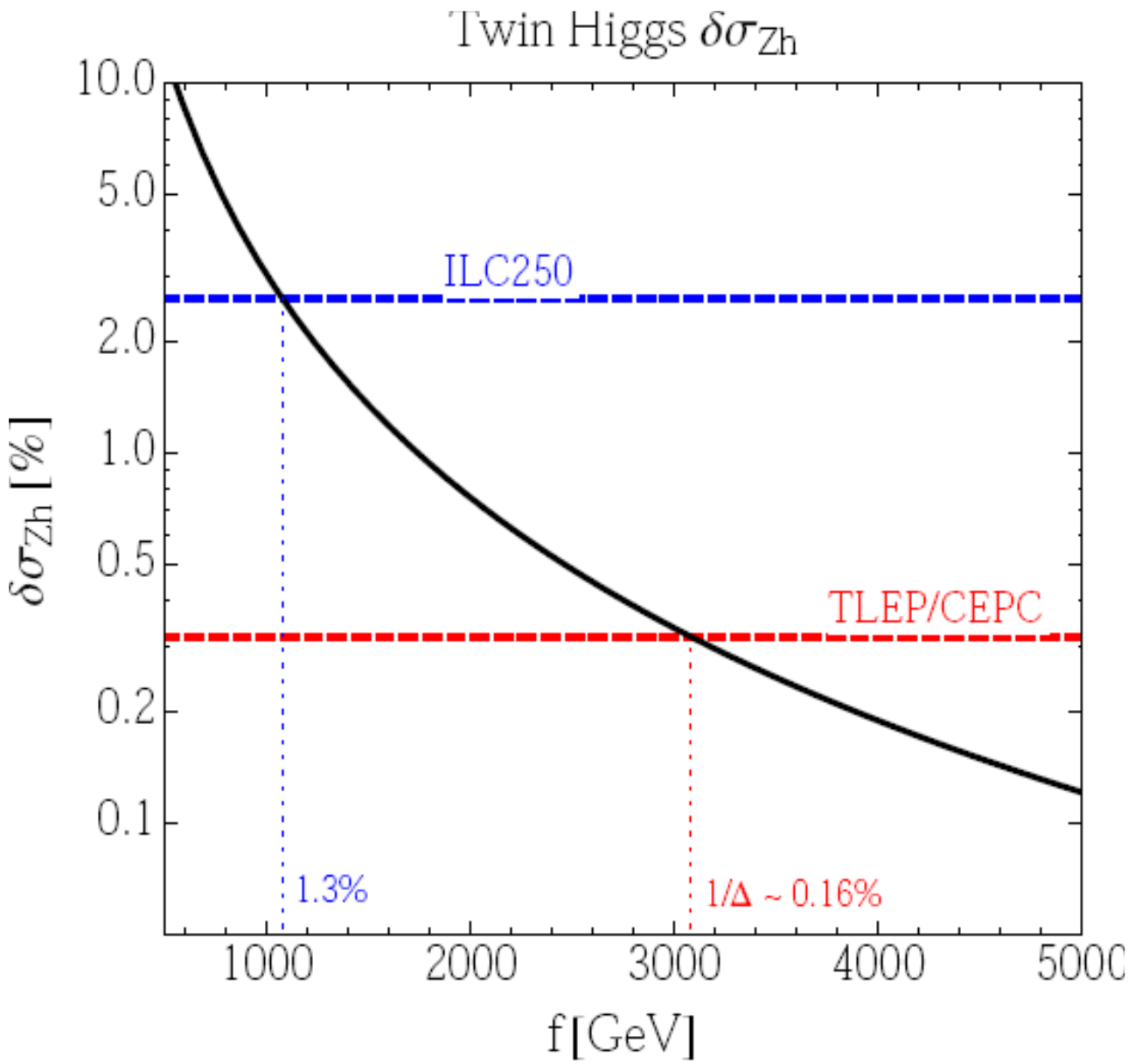
[Craig et. al.]

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

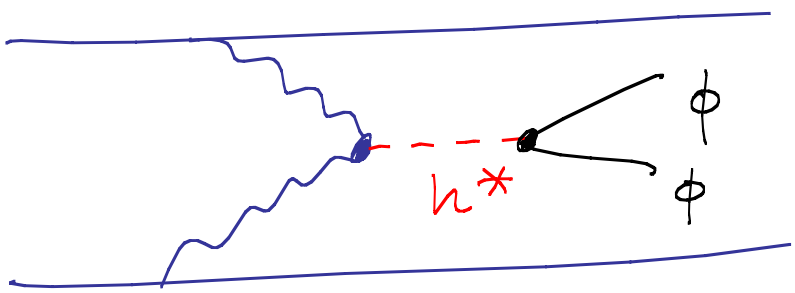
e.g.

$\Longrightarrow$ ~ 1% mod to hZ coupling

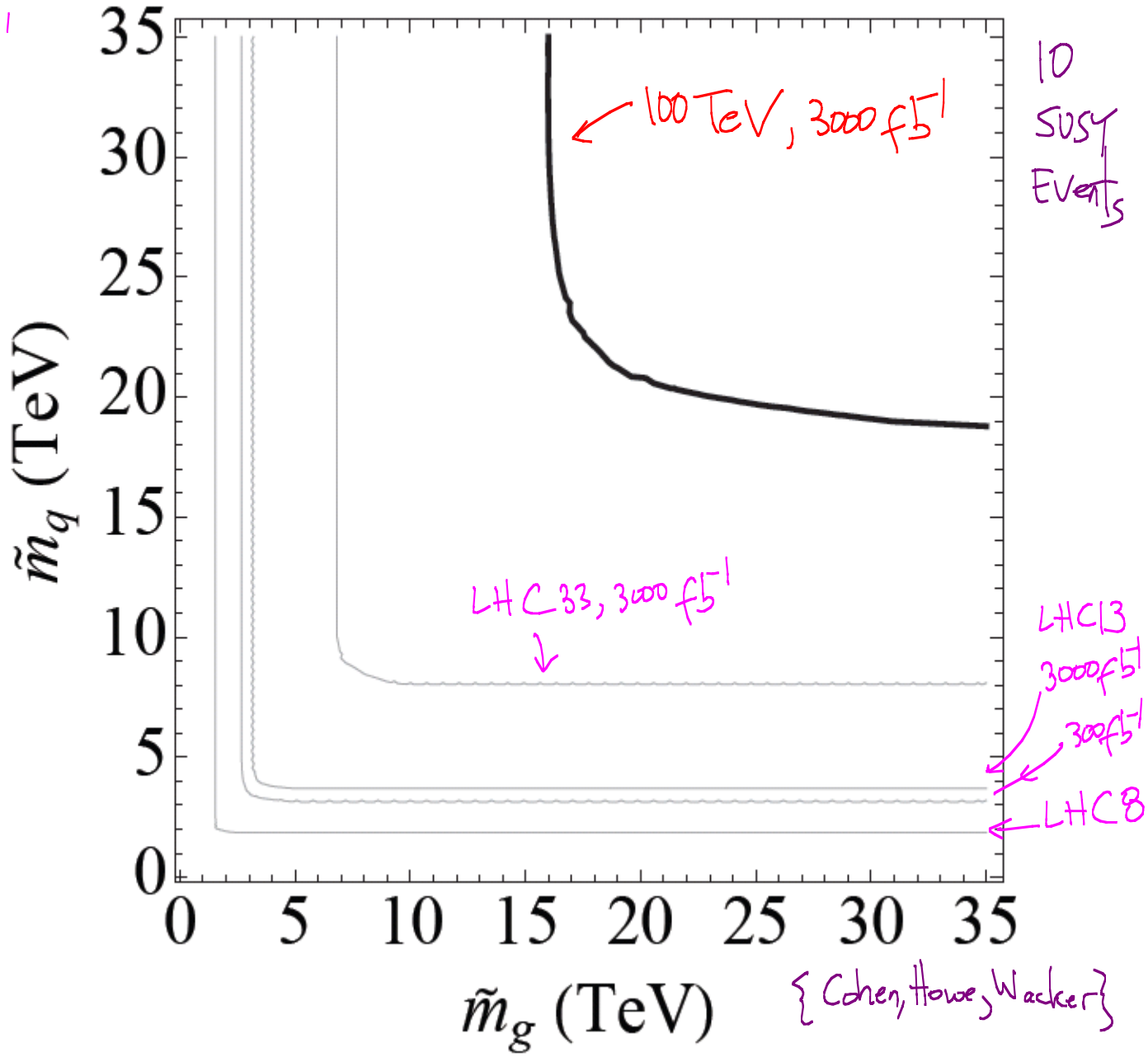

Invisible top partner $\delta\sigma_{Zh}$
10.0
5.0
2.0
1.0
0.5
0.2
0.1
$\delta\sigma_{Zh}$ [%]
ILC250
CEPC/TLEP
$n_\phi = 1$
$n_\phi = 6$
100% 32%
1/Δ ~ 25%
6%
200
400
600
800
1000
m_ϕ[GeV]


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}
LHC33, 3000 fb^{-1}
10 SUSY Events
LHC13 3000 fb^{-1}
300 fb^{-1}
LHC8
{Cohen, Howe, Wacker}

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:

e.g.

$m_{\tilde{1},\tilde{2}} \sim 5\,\text{TeV}$ EDM bounds

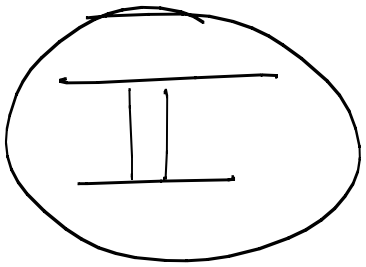
e.g. "natural SUSY"

$m_{\tilde{t}} \sim 600\,\text{GeV}$

LHC no way, 100 TeV piece of cake

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



← Lian-Tao's Talk

Robust probe of up to ~ few TeV electroweak particles.

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

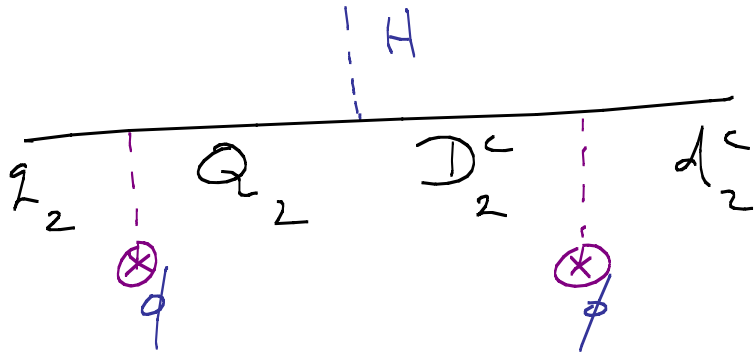
III

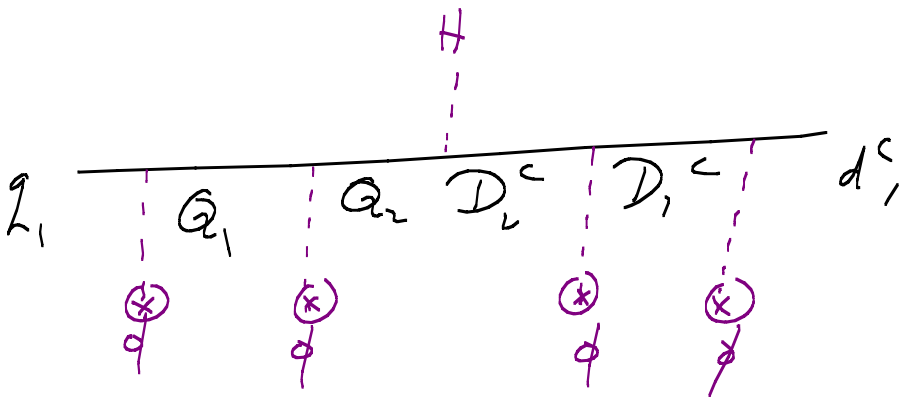
For the first time, rich + alive possibilities for Collider Flavor Physics

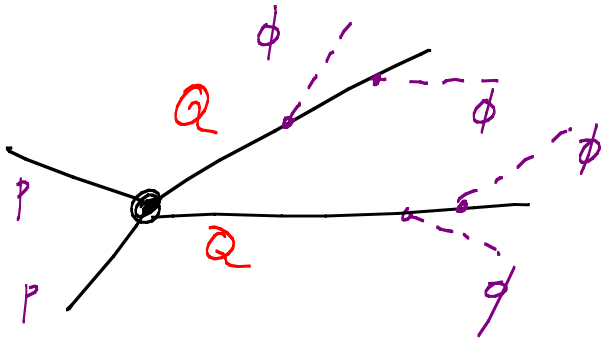
* Not possible to generate flavor @ ~ TeV scale + not be dead by FCNC's $\Longrightarrow$ no flavor collider physics @ LHC.

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

e.g.







Long cascade decays w/ fingerprint of flavor symmetry structure.

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

Also, we have ongoing probes of $\not{C}\not{P}$ and $\not{F}$lavor, e.g. electron EDM's, $\mu \leftrightarrow e$ conversion, ...

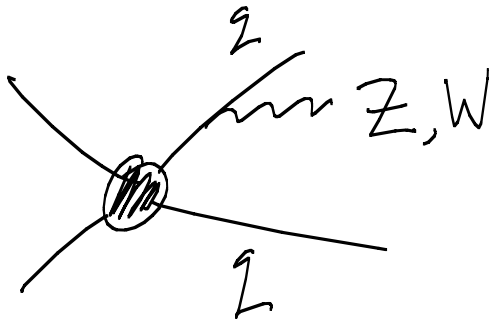
Any positive signal must come from new physics @ 10–100 TeV scale, can expose it directly with 100 TeV machine

IV

Some qualitatively new aspects of 100 TeV collisions —

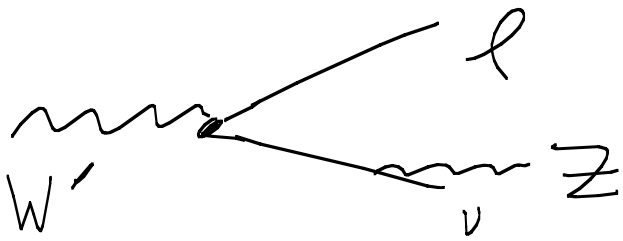
e.g. $SU(2) \times U(1)$ finally looks unbroken! W/Z "radiation" significant — ν's + DM more "visible" [Hook, Katz]

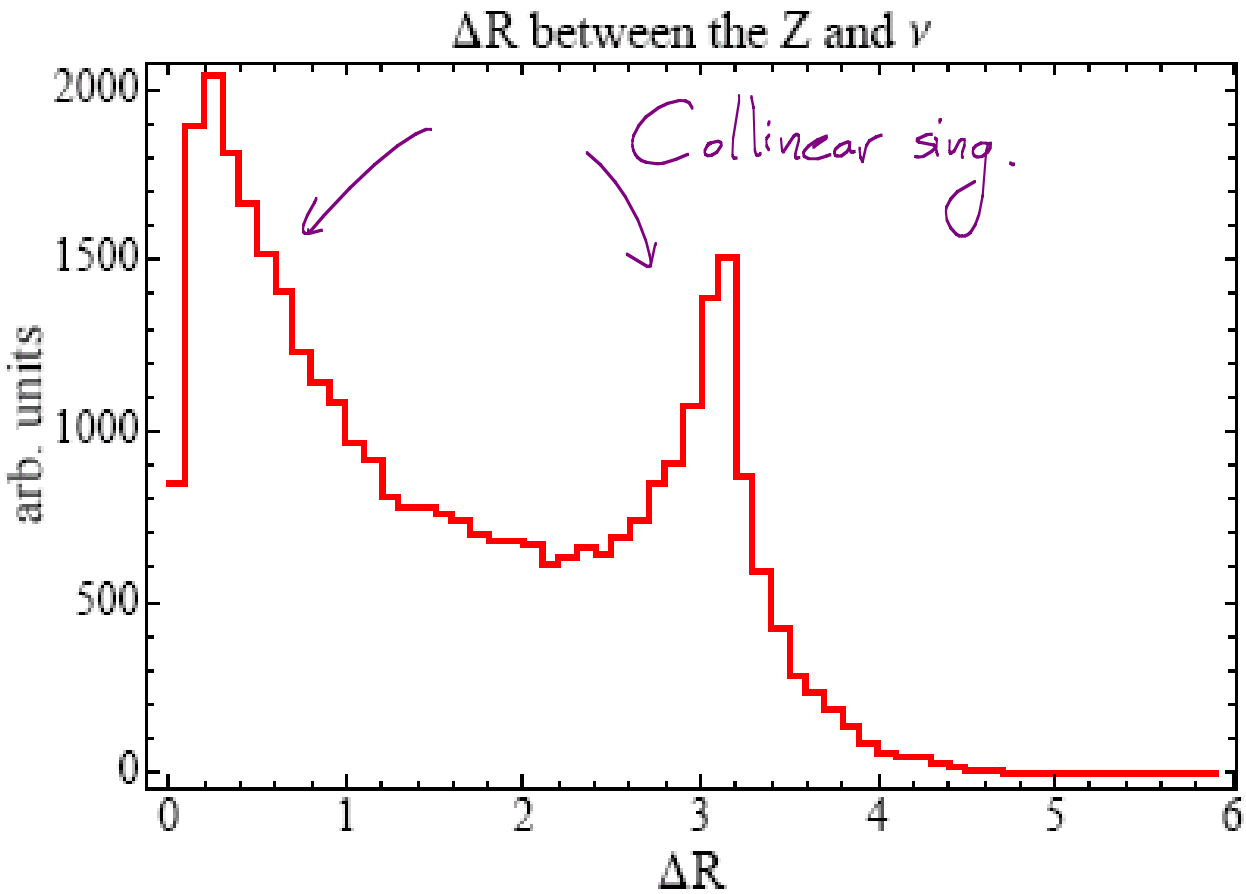
~10% of dijets @ 10TeV have W/Z's!

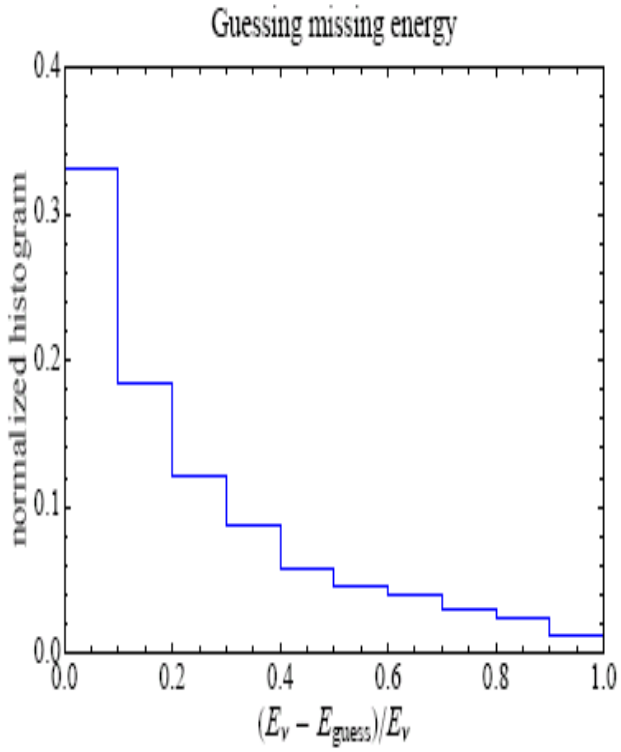


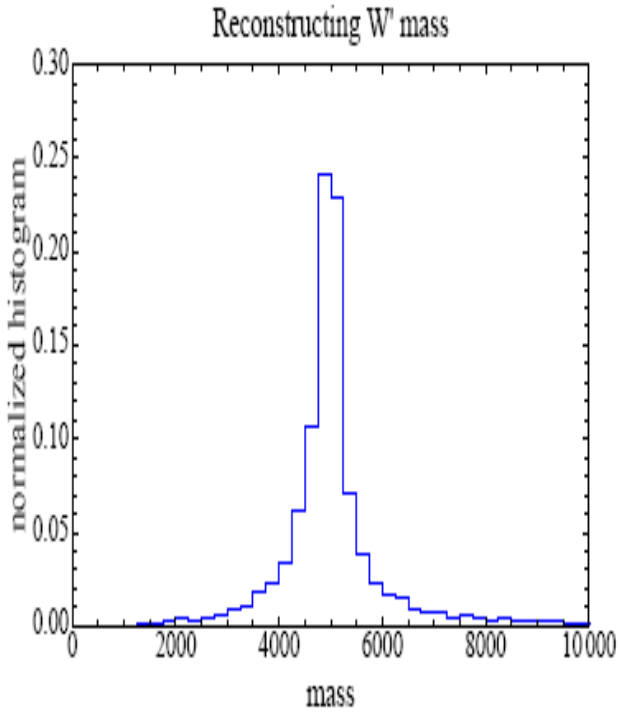
$$\frac{4\alpha_2}{\pi} \log^2\left(\frac{5\,\text{TeV}}{m_Z}\right)$$

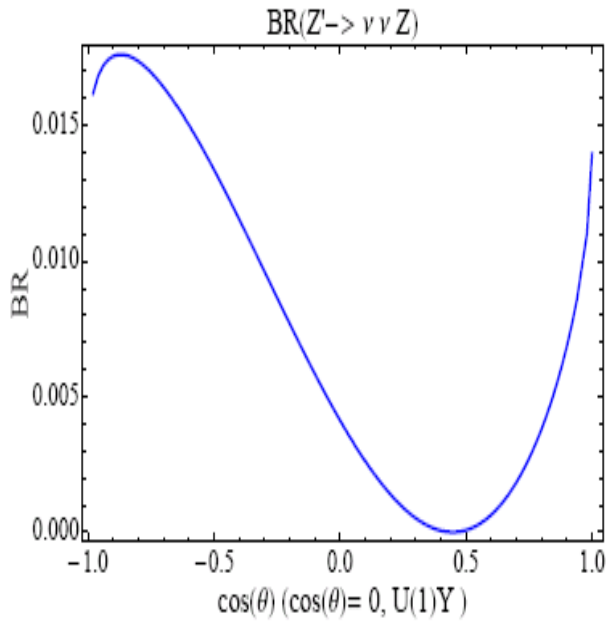
not small!

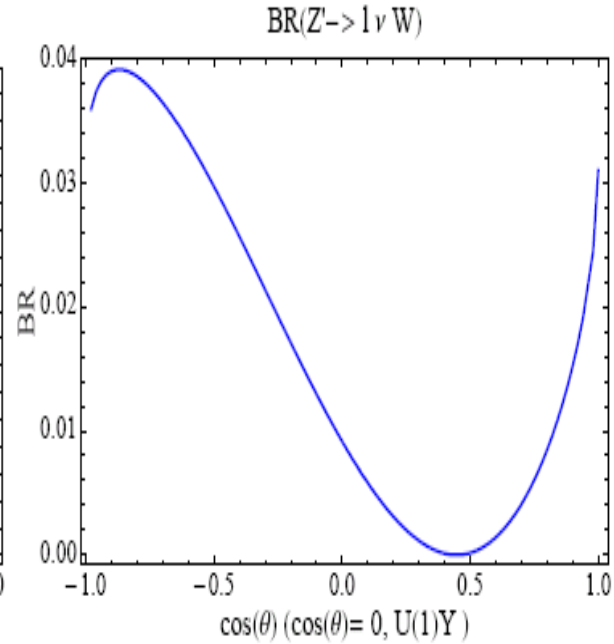

W'
ℓ
ν
Z

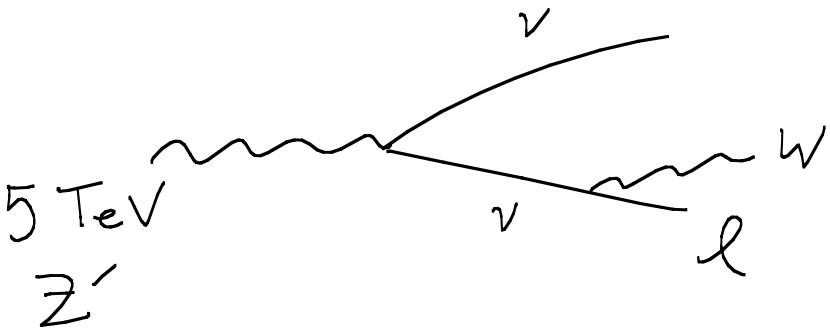

ΔR between the Z and ν
arb. units
ΔR
Collinear sing.
0
500
1000
1500
2000
0
1
2
3
4
5
6


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
$(E_\nu - E_{\text{guess}})/E_\nu$


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
Z'
ν
ℓ

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

Kickoff Mtg: Feb 23-25

Fermilab has

a CRITICAL

role in this endeavour

[Accelerator/HighFieldMagnets/Physics...]