Muon

Colliders

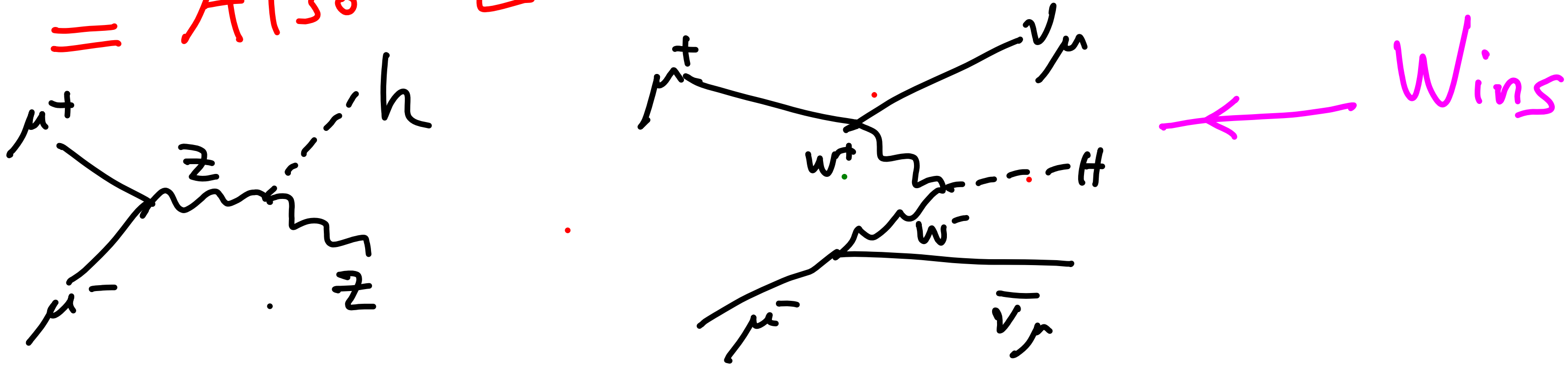
Rock!

* $E_{CM} \sim 3\,\text{TeV} - 100\,\text{TeV}$

* $\mathcal{L} \to 1 \to 10^{1\to 2}\,\text{ab}^{-1}$

* $\frac{\alpha_W}{\pi} \log^2 \frac{E}{m_\mu} \sim 1 \Longrightarrow$ "Muon" Collider

= Also EWK Vector Boson Collider



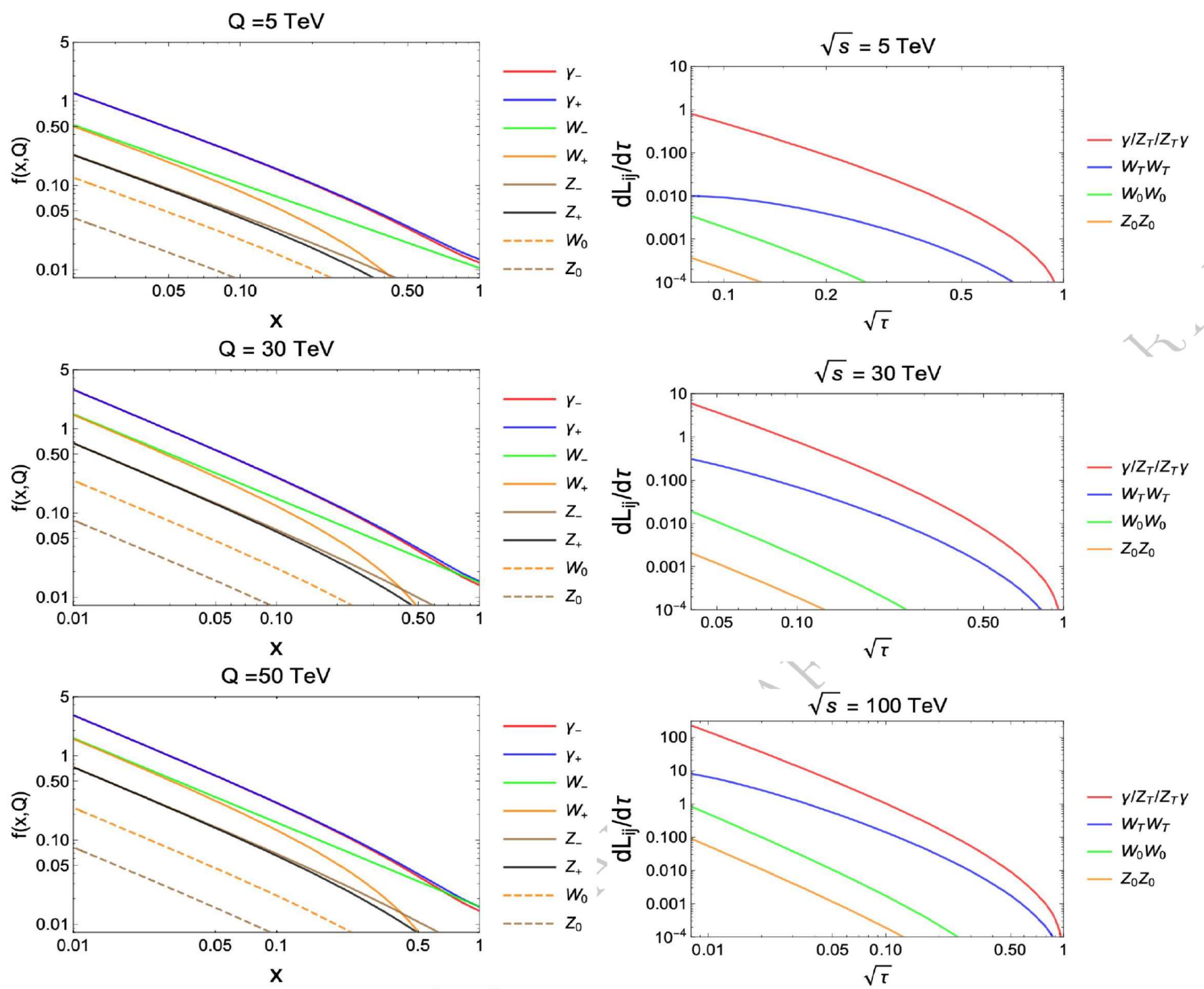


Figure 3: The left column shows the polarized PDF $f_i(x, Q)$ for gauge bosons separated b
helicity. The right column shows the parton luminosity functions $\mathrm{d}L_{ij}/\mathrm{d}\tau(\tau, Q = \sqrt{\tau s}/2$
for gauge bosons separated by helicity.

High PRECISION

(e.g. $\sim 10^{6-8}$ Higgses)

High ENERGY

(e.g. EWK charged part. reach $\sim E_{CM}/2$)

Shouldn't We

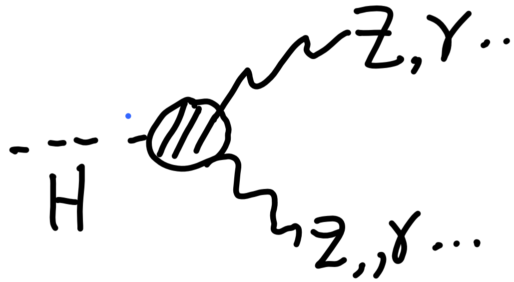
Take Our Ball

And Go Home?

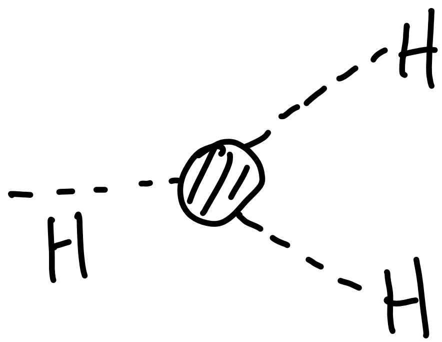
* No Guarantee of New Particles

* Study the Higgs to Death

All usual Higgs Factory + 100 TeV pp. also apply to Muon collider, + more....

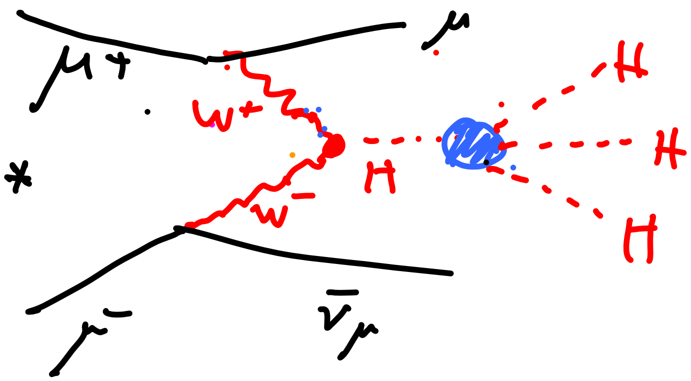


~ 10^6 Clean Higges @ Higgs Factory

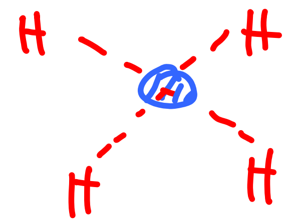


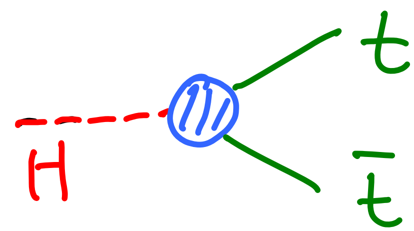
~ 10^{10} Messier Higgses @ 100 TeV pp collider

Can hope for ~ 10^8 Clean Higgses @ muon collider...

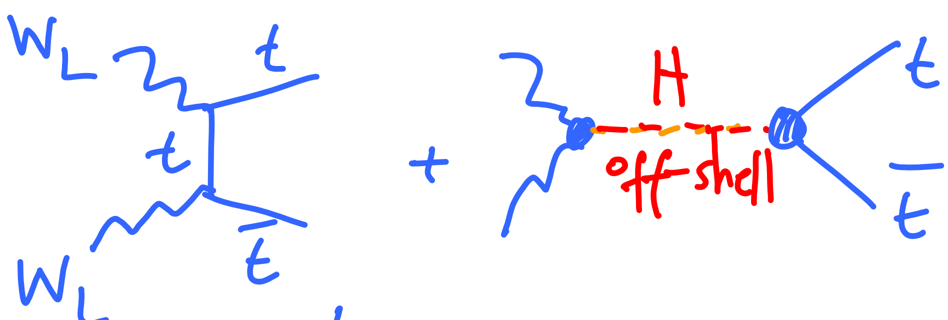
* 

Possible Clean Probe of

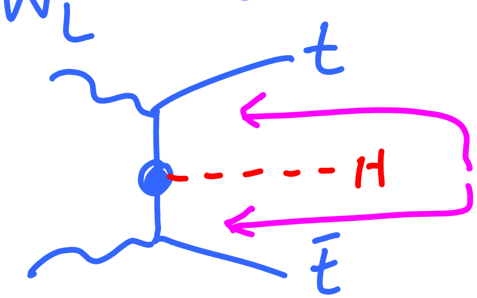


* Crucial to probe 

off-shell...

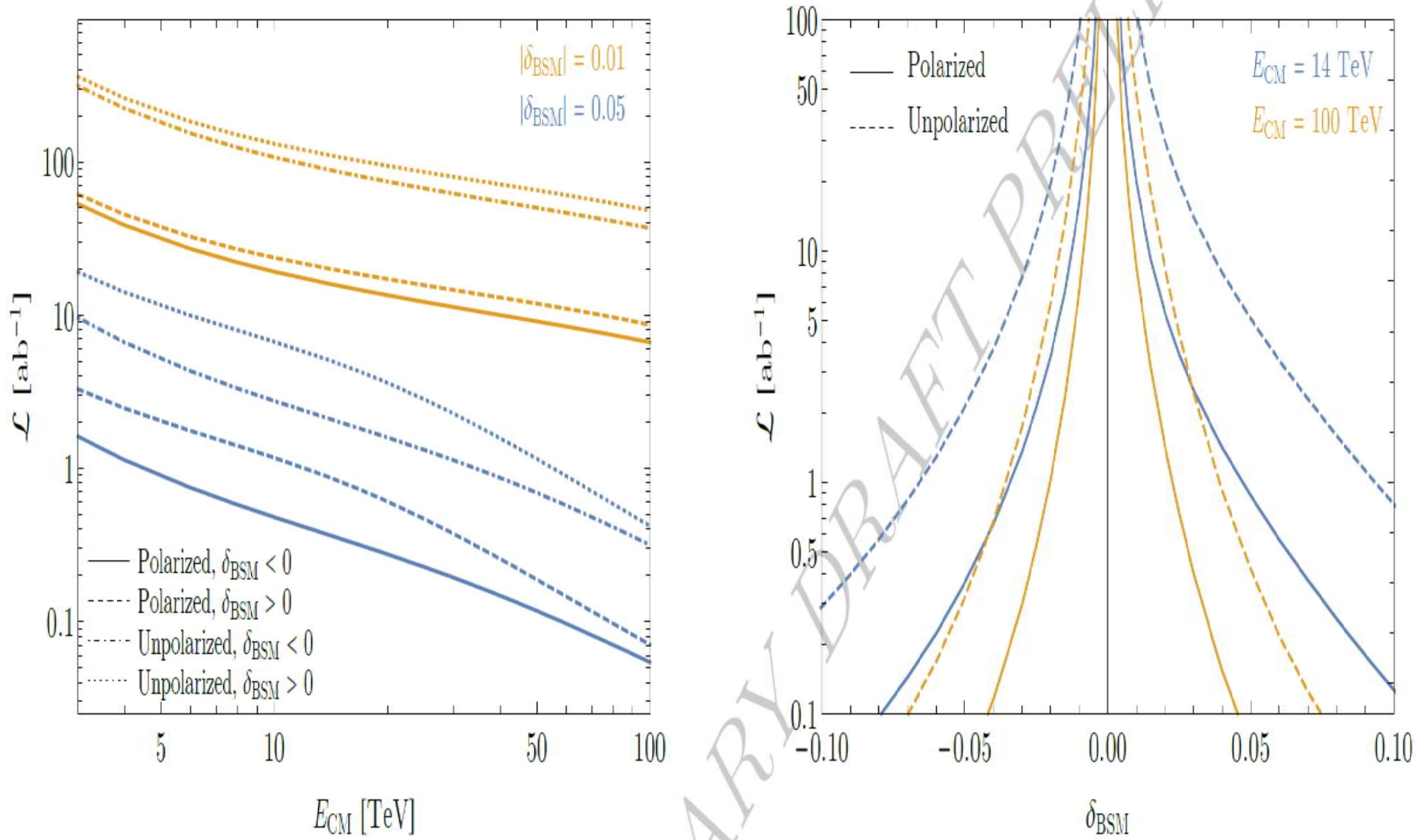
* 

Direct Probe of Unit. of $W_L W_L \to t\bar{t}$!

* 

$t\bar{t}$ off-shell

Ultimate model-indep. probe of naturalness



$|\delta_{BSM}| = 0.01$
$|\delta_{BSM}| = 0.05$
Polarized, $\delta_{BSM} < 0$
Polarized, $\delta_{BSM} > 0$
Unpolarized, $\delta_{BSM} < 0$
Unpolarized, $\delta_{BSM} > 0$
$\mathcal{L}$ [ab^{-1}]
E_{CM} [TeV]
Polarized
Unpolarized
E_{CM} = 14 TeV
E_{CM} = 100 TeV
δ_{BSM}

* No Guarantee of New Particles

... But perfectly reasonable theories — actively discussed long before LHC! — where we <u>wouldn't</u> see new particles @ LHC but <u>would</u> at ~ few → 10's of TeV!

SIMPLEST WIMP

DM ALIVE + WELL

(The Baroque but "natural" versions have been ruled out by direct detection + LHC...)

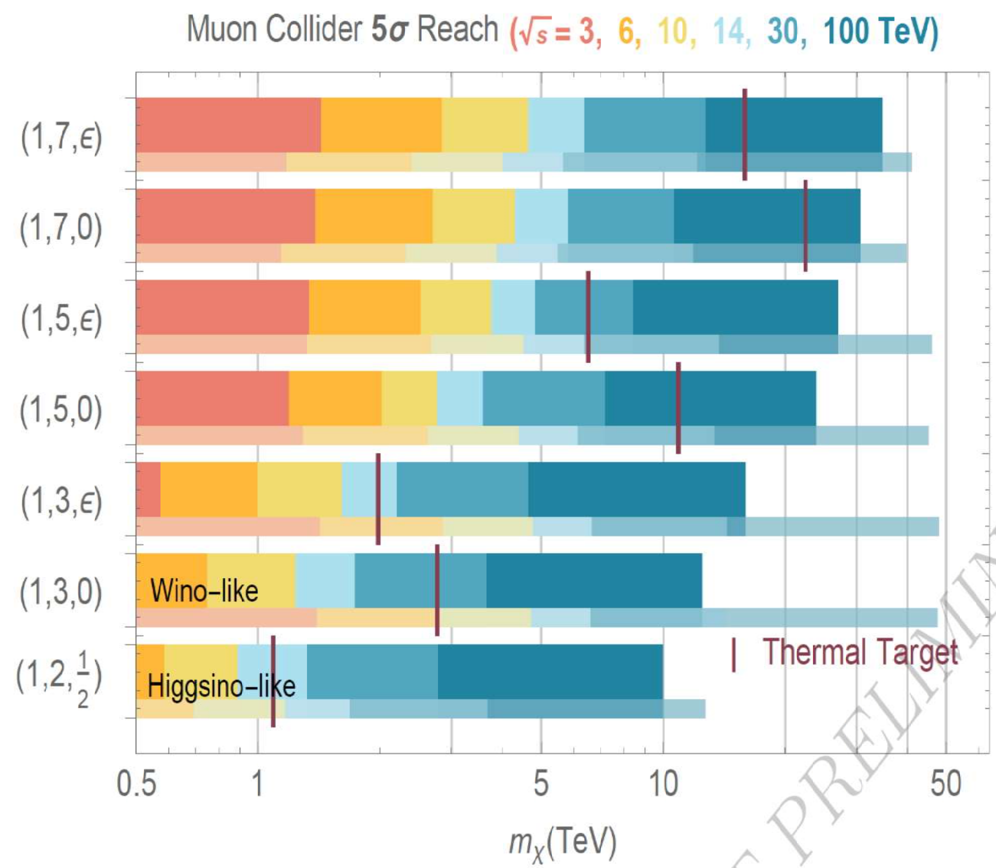


Figure 10: Summary of the discovery reaches of various muon collider running scenarios. The thicker bars represent the combined reach from missing mass searches through mono-photon, mono-muon, and VBF di-muon channels. The thinner and faint bars are our estimates of the mono-photon plus one disappearing track search. The burgundy vertical bars represent the thermal target for a given EW-multiplet model. More details, including the detailed reaches for each channels and different muon collider energies, can be found in Ref. [22].

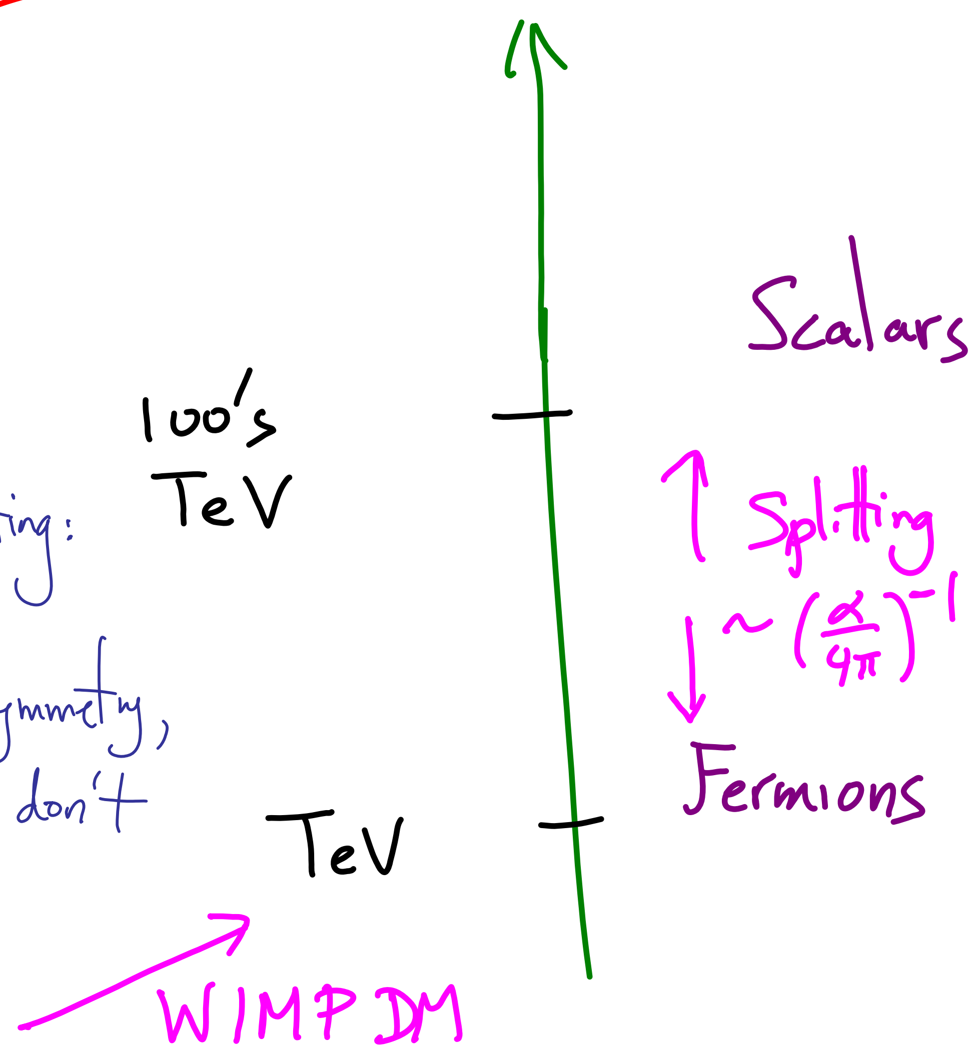
My Own Best Bet

(Since ~ 2004/2005)

Minimal Split SUSY

Minimal Split SUSY

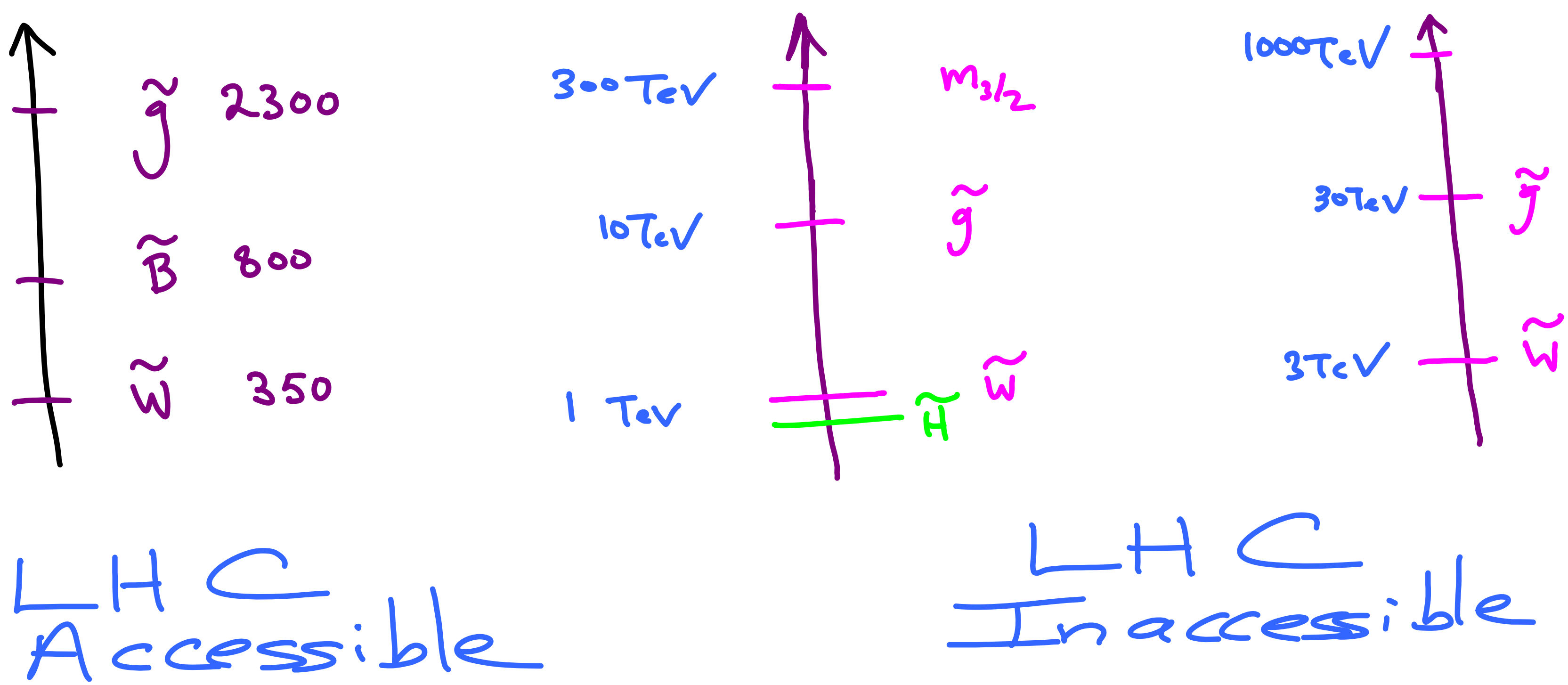
Reason for splitting: fermions carry R symmetry, scalars don't



Unification ✓

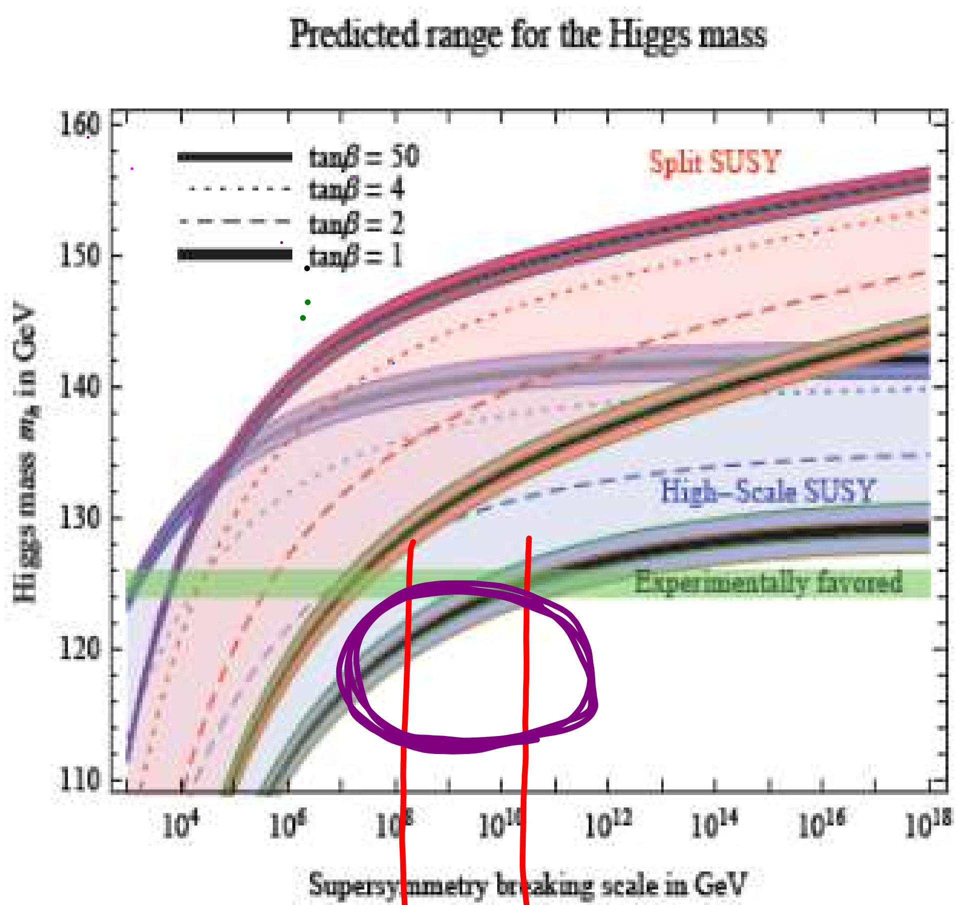
Dark Matter ✓

<u>NO</u> Flavor, CP, moduli, ... problems



Finally, we want to remark that the supersymmetric dark-matter impasse, discussed in sect. 1, does not immediately apply to Split Supersymmetry, since values of μ of about 1 TeV or M_2 of about 2.5 TeV are perfectly acceptable, once we abandon the naturalness criterion. Why then should we expect to have an extra tuning to get well-tempered neutralinos? It is difficult to answer this question without having a more precise notion of what the physical measure of tuning actually is, but we can at least identify a competition between two factors. If we scale up the Wino to 2.5 TeV as the LSP, so there is no tuning for dark matter, we are making the scalars heavier too, which makes electroweak breaking more tuned. If we leave Winos in the hundreds of GeV range, the scalars are lighter and electroweak breaking is less tuned but there is more tuning to get the dark matter. At any rate, a 2.5 TeV Wino make Split Supersymmetry invisible at the LHC (for conventional gaugino mass relations).

(Jan 2006)



Prediction: $120\,GeV \lesssim m_h \lesssim 135\,GeV$

$m_h = 125\,GeV$

$\Downarrow$

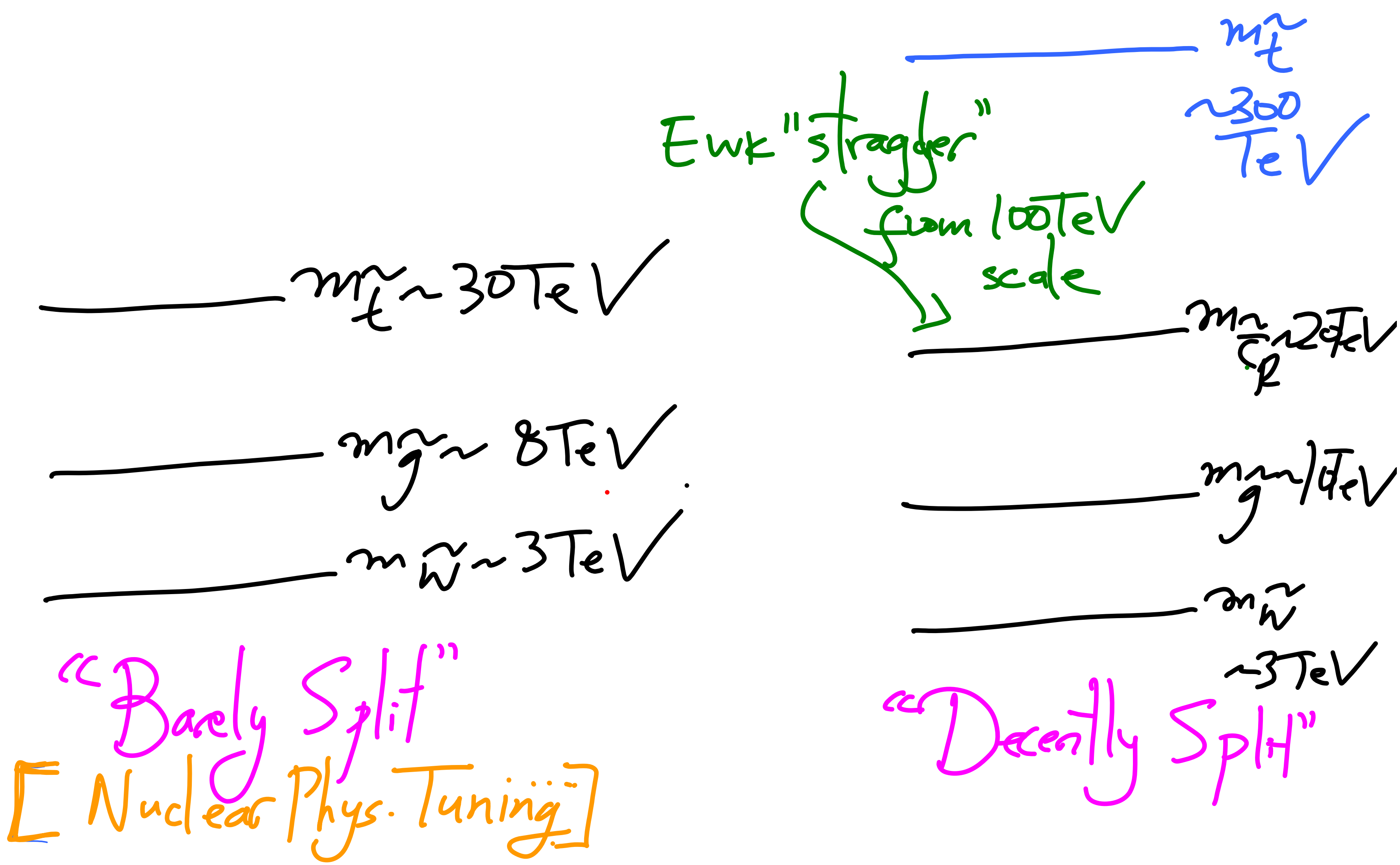
$10\,TeV \lesssim m_{\tilde{t}} \lesssim 10^{2-3}\,TeV$

$\Downarrow$

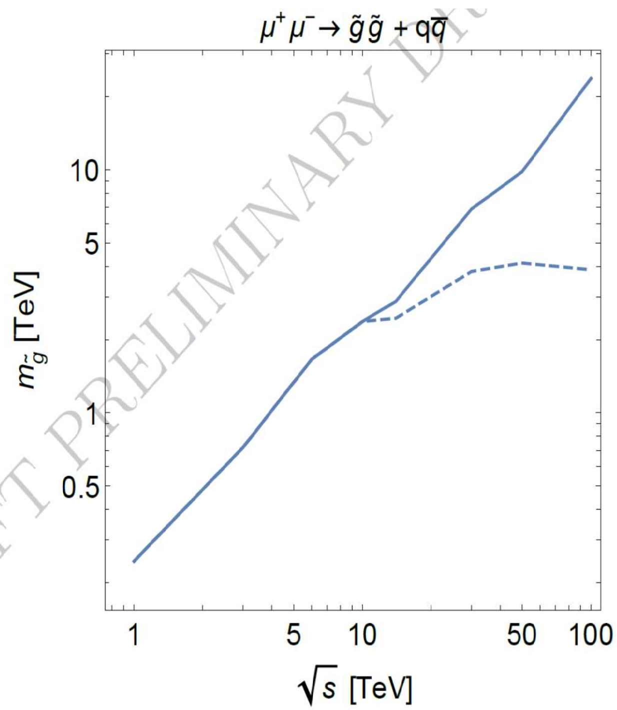
$m_{\tilde{g}} \lesssim 10'\text{s}\,TeV$

EWK-ino's, $\tilde{g}$, + possibly stops, ewk scalar "stragglers", @ $\lesssim 10'\text{s}\,TeV$

Reasonable Top-Down Spectra



Reach For Gluino ~ $E_{cm}/5$



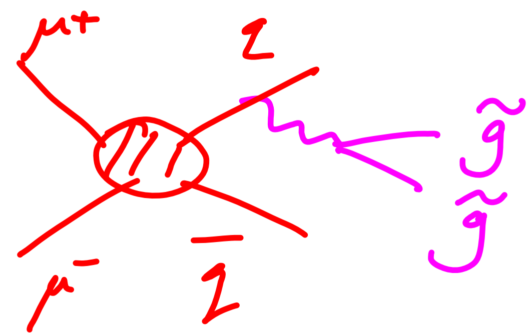


Figure 9: Gluino discovery reach from $\mu^+\mu^- \to \tilde{g}\tilde{g} + q\bar{q}$ as a function of $\sqrt{s}$, assuming "optimistic" (solid) and "conservative" (dashed) integrated luminosity scaling as detailed in the body of the text.

Coming Expt. hints for ~$10^{1\to 2}$ TeV scale NP?

* Electron EDM : $d_e/e \sim \left(\frac{\alpha}{4\pi}\right)^2 \frac{m_e}{M^2}\theta_{\phi} \sim 10^{-31}\,\text{cm}\cdot\left(\frac{10\,\text{TeV}}{M}\right)^2$

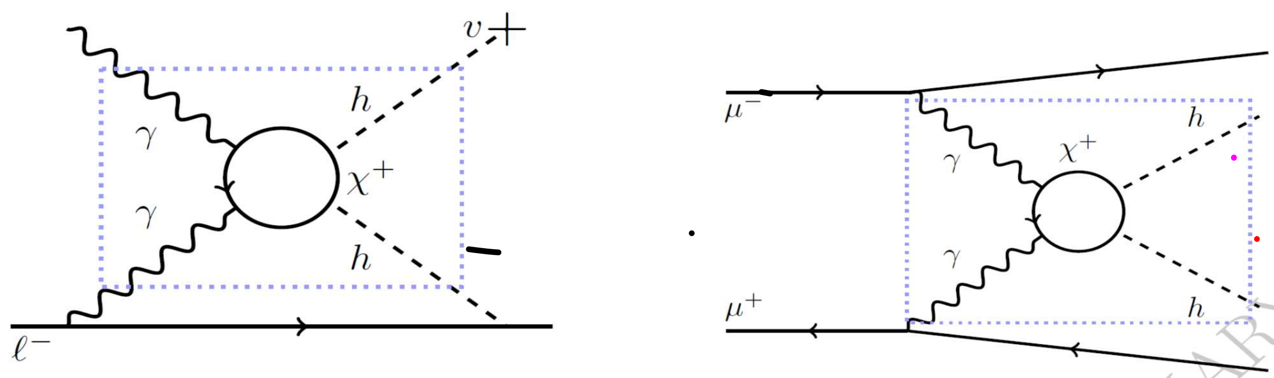


Figure 11: One possibility for testing the physics associated with a Barr-Zee type contribution to a lepton EDM at a future muon collider. At left: the two-loop Barr-Zee contribution to a lepton EDM. At right: a $\gamma\gamma \to hh$ process at a muon collider, sensitive to loops of charged particles coupled to the Higgs. The dotted blue box shows that both processes probe the same underlying physics.

Current ACME $(d_e/e) \sim 10^{-29}$ cm (!!)

$\xrightarrow{10\,\text{yrs}}$ $(d_e/e) \sim 10^{-32}$ cm (!!!!)

Coming Expt. hints for $\sim 10^{1\to 2}$ TeV scale NP?

* Lepton Flavor Physics

$\tau \to 3\mu$

Belle II $Br \lesssim 10^{-10} \sim \left(\frac{1}{30\,TeV}\right)^2$

$\mu^+\mu^- \to \tau^\pm \mu^\mp$

Directly Probed

$\sigma \propto s \left(\sim 10\,fb \text{ for } (1/30\,TeV)^2\right)$

$\mu \to 3e$

Mu3e $\to Br \lesssim 10^{-16} \sim \left(\frac{1}{3000\,TeV}\right)^2$

Relative size depends on Flavor Model...

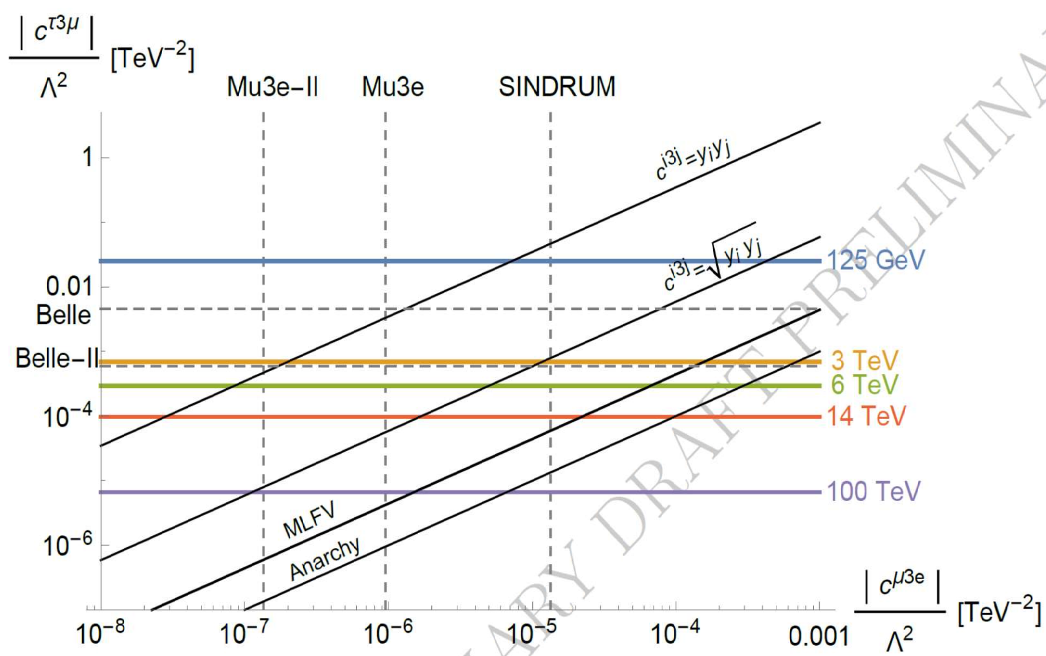


Figure 12: Summary of muon collider and precision constraints on flavor-violating 3-body decays. The colored horizontal lines show the sensitivity to the $\tau 3\mu$ operator at various energies, all assuming $1\,\text{ab}^{-1}$ of data. The dashed horizontal (vertical) lines show the current or expected sensitivity from $\tau \to 3\mu$ ($\mu \to 3e$) decays for comparison. The diagonal black lines show the expected relationship between the different Wilson coefficients with various ansatz for the scaling of the flavor-violating operators (e.g., "Anarchy" assumes that all Wilson coefficients are $\mathcal{O}(1)$).

Muon Collider is EXCITING, AMBITIOUS + SUPER-COOL

EASY TO SHARE EXCITEMENT WITH PROFESSIONALS + LAYPEOPLE ALIKE!

PERFECT LONG-TERM GOAL FOR HEP—ESPECIALLY IN US!