The Physics Case for Particle Colliders at Energies Beyond LHC

Snowmass 2013

Markus Luty
University of California Davis

Conclusions

- What unites us: focus on <u>discovery</u>

- Lepton and proton colliders are remarkably complementary

- A choice between unknowns

Conclusions (cont'd)

100 TeV pp machine:

- Unprecedented reach for new physics, but there are low-energy loopholes

- Best guess: most sensitive probe of tuning in SUSY

High energy lepton machines:

- Less energy reach, essentially no loopholes

- Precision program (Higgs, top)

- Best guess: most sensitive probe of tuning in composite Higgs models

The Standard Model

With the discovery of the Higgs, we have experimentally established a theory that can be consistently extrapolated to the Planck scale.

There is no guarantee of discovery.
We are exploring the unknown.

Can we justify continued exploration with expensive particle colliders?

Unanswered Questions

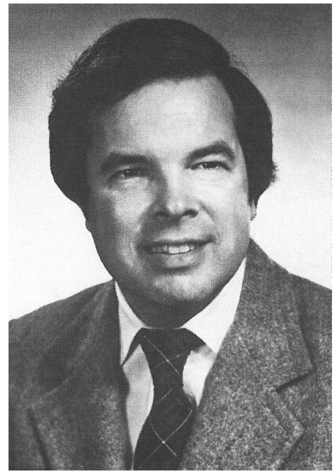
- Naturalness
- Dark matter

→ New physics at TeV scale

- Origin of masses and mixings
- Matter-antimatter asymmetry
- Inflation
- Unification

⋮

Naturalness



K. Wilson

Elementary scalars are unnatural

$$126^2 = 175992038487088835203904637364744757$$

$$- 175992038487088835203904637364728881$$

Two Ideas

SUSY

Compositeness

(includes extra dimensions)

$$m_{\mathrm{NP}} \lesssim \frac{\mathrm{TeV}}{\epsilon^{1/2}}$$

$\epsilon =$ tuning

$\sim 10^{-30}$ in standard model

SUSY

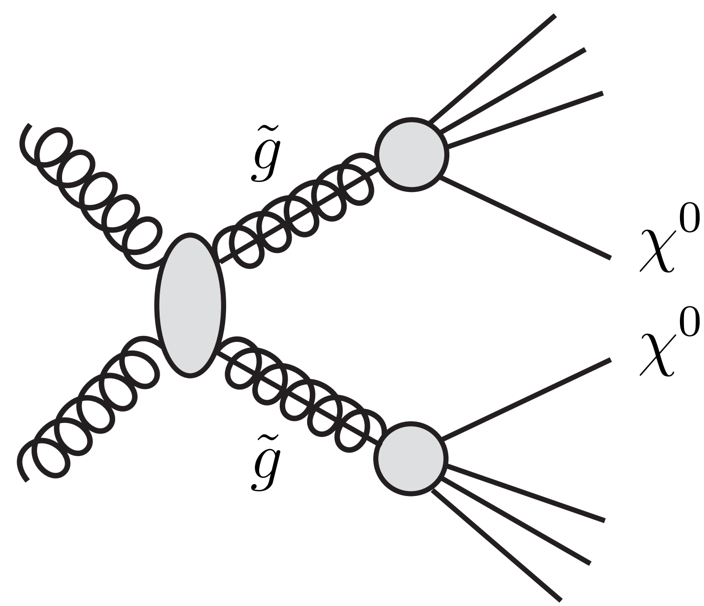
The most successful paradigm for physics beyond the standard model

Most general feature of spectrum: $\frac{m_{\tilde{g}}}{m_{\chi^0}} \sim \frac{N_c \alpha_3}{\alpha_W} \sim 6$

High scale SUSY breaking: RGE + unification

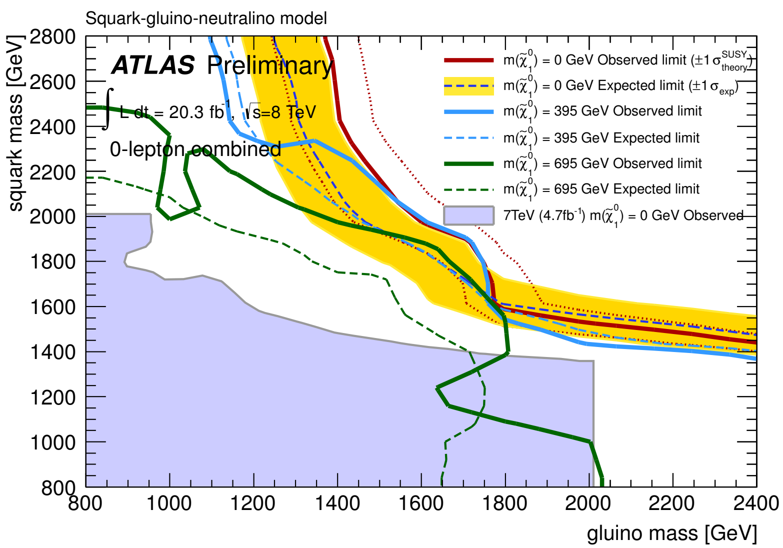
Low scale SUSY breaking: gauge mediation

$\Rightarrow$ jets + MET signature



SUSY at LHC

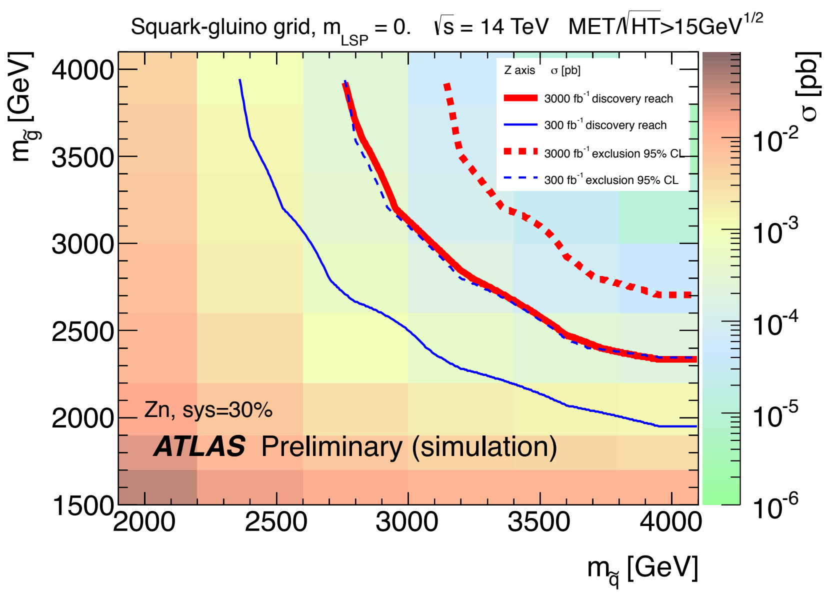
LHC run 1 searches: no sign of SUSY

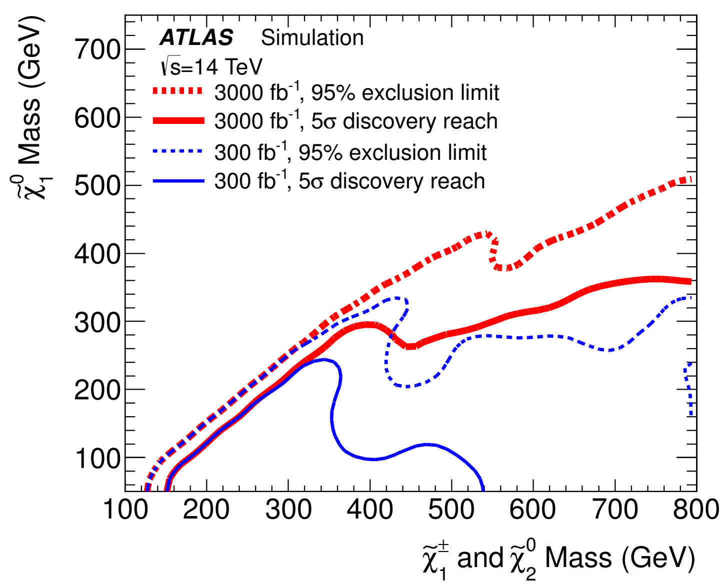


$$m_{\tilde{Q}} \gtrsim 1500 \text{ GeV}$$

$$m_{\tilde{g}} \gtrsim 1200 \text{ GeV}$$

LHC run 2 & HL-LHC: tremendous increase in reach

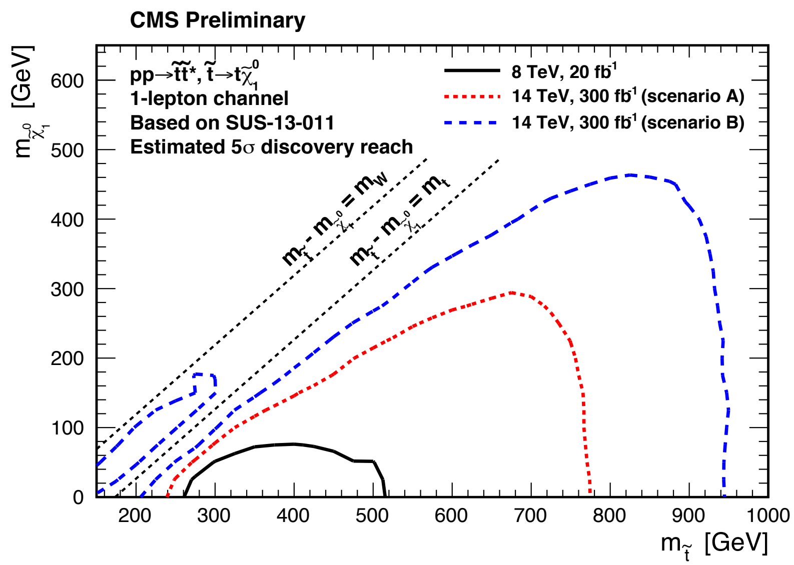


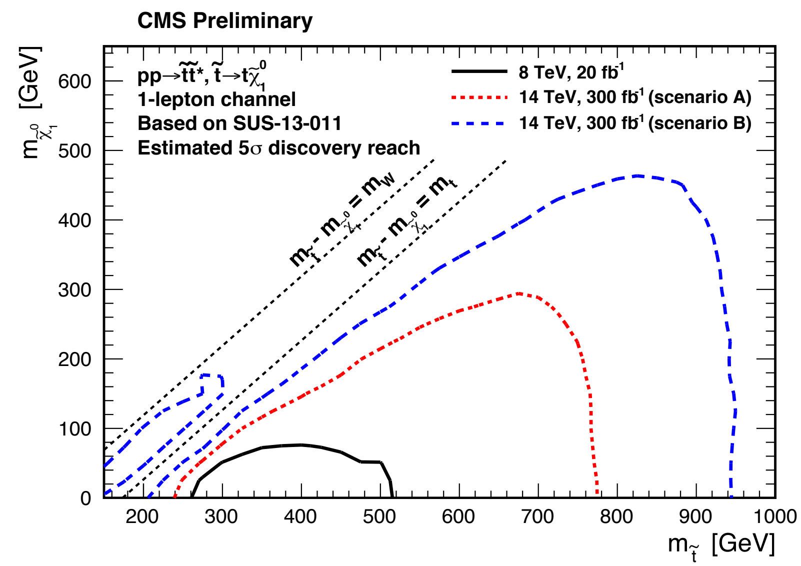


SUSY Naturalness?

Tuning: $\Delta m_H^2 \sim m_{\tilde{t}}^2 \quad \Rightarrow \quad \epsilon \sim 0.01 \left(\frac{m_{\tilde{t}}}{1 \text{ TeV}} \right)^{-2}$

Many sensitive stop searches...





My rough summary:

- LHC run 1: probes 10% tuning
- LHC run 2: 1% tuning
- HL-LHC: another factor of 4

Scenarios

Discovery: we know what to do...

- Drink champagne
- “We told you so”
- Study the %#**! out of the signal
- Assess what future facilities best leverage discovery

No discovery:

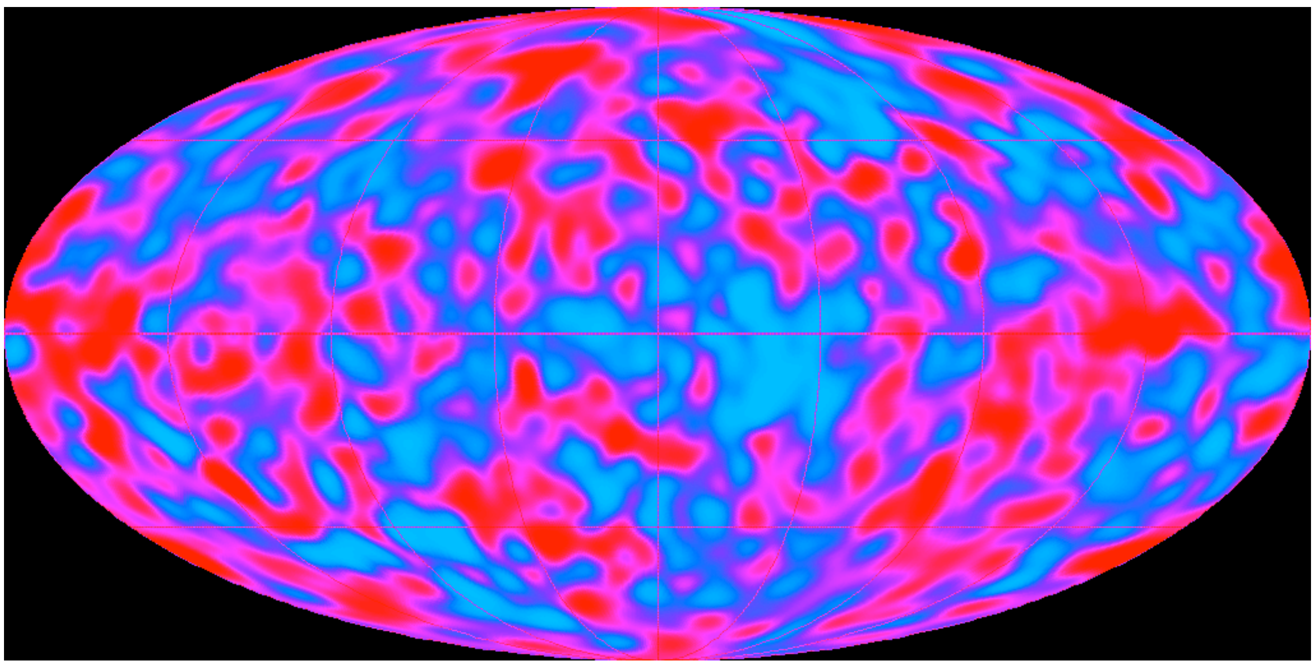
Do we keep going?

Cosmic Mysteries

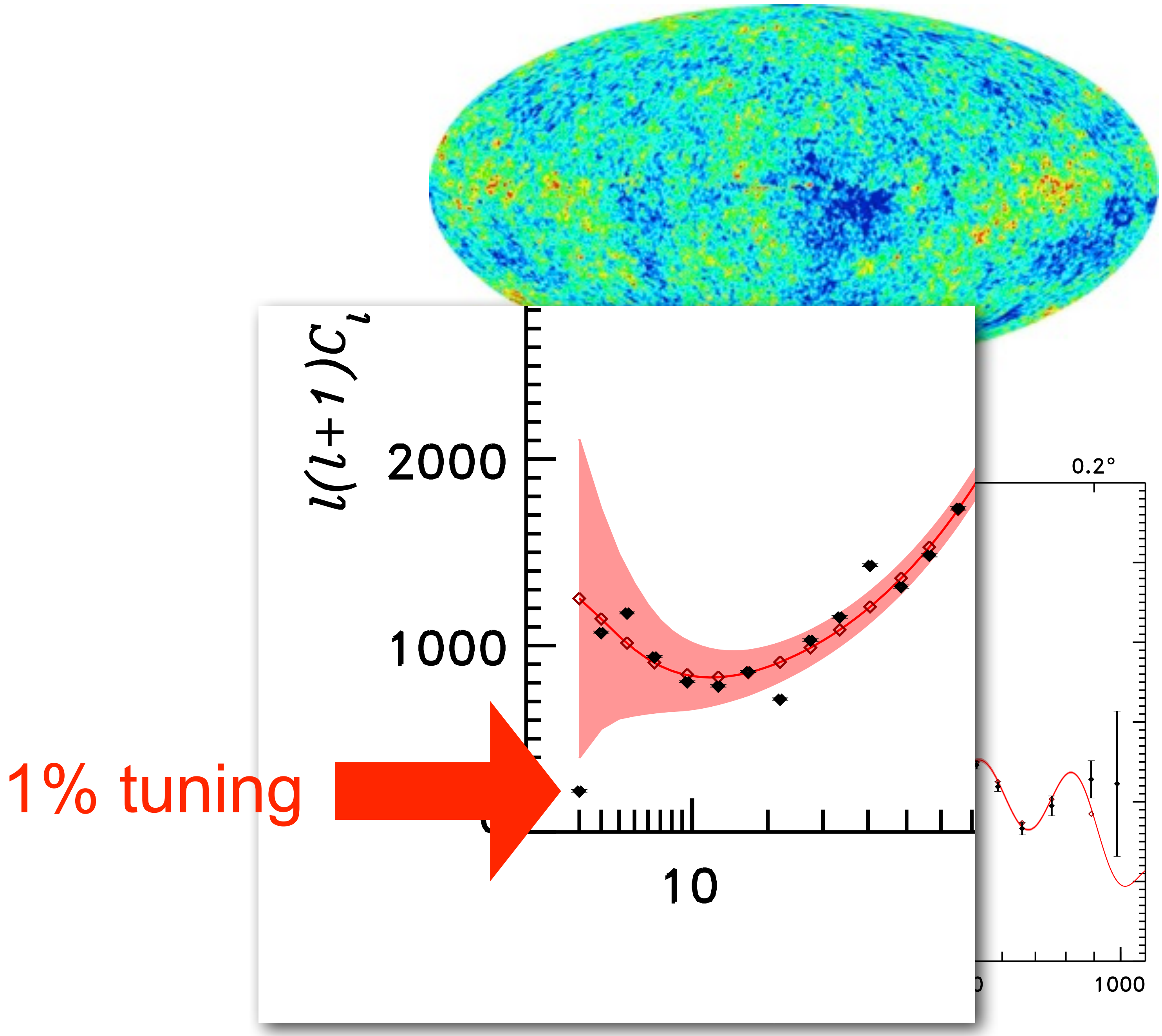
[H. Murayama Lepton-Photon 2013]

1991: Limits on the cosmic microwave anisotropy were pushing the limits of cold dark matter cosmology...

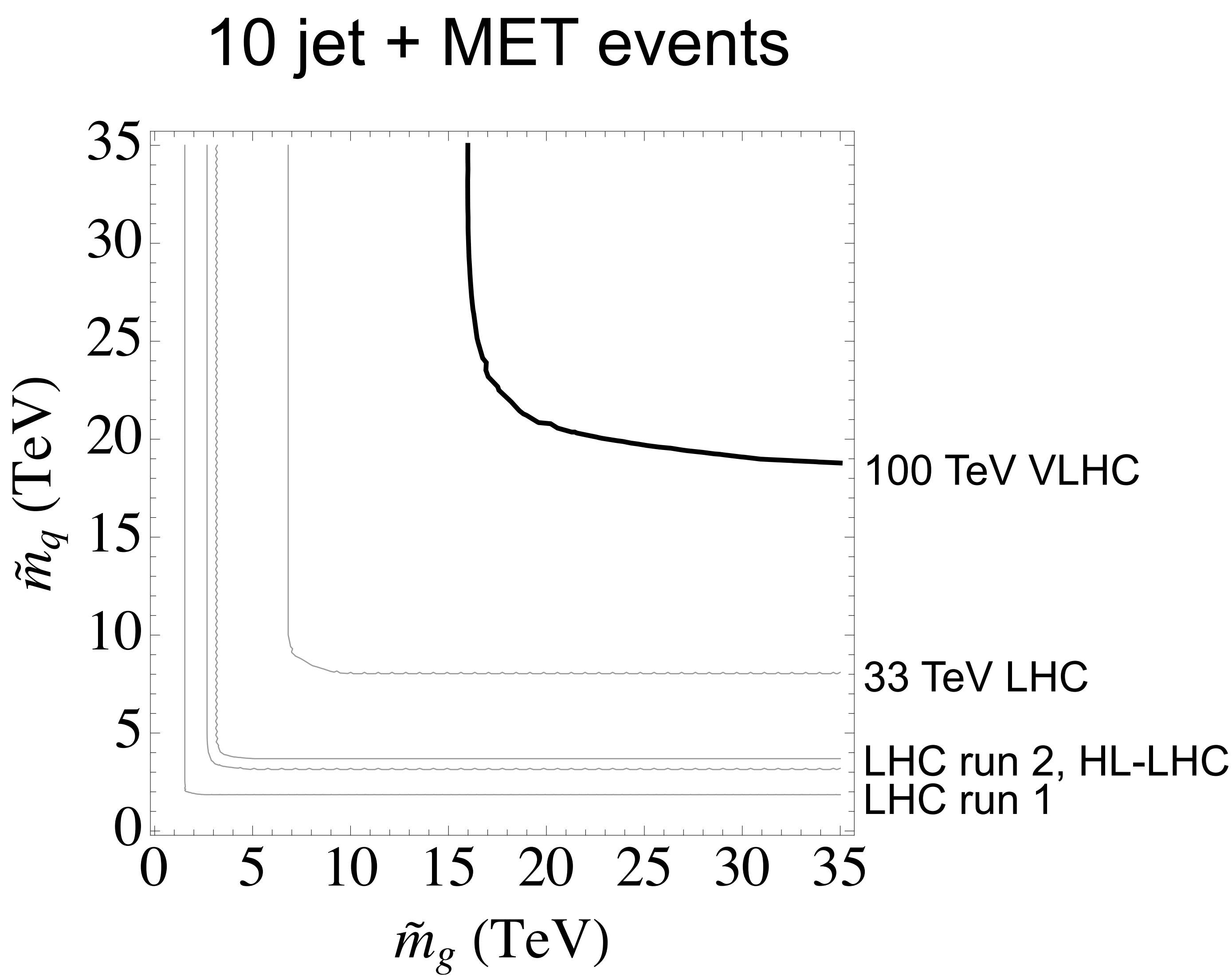
COBE:



Fine Tuning!



SUSY at 100 TeV pp



T. Cohen, K. Howe, J. Wacker

SUSY at e^+e^- Colliders

$\Delta m_H^2 \sim m_{\tilde{H}}^2$ $\quad\quad$ $\chi^0_{1,\ldots,4},\ \chi^\pm_{1,2} \longleftrightarrow \tilde{B}, \tilde{W}, \tilde{H}$

Tuning: $\epsilon \sim \left(\frac{125\ \mathrm{GeV}}{m_{\tilde{H}}}\right)^2$

Energy reach: $m_\chi \simeq \frac{1}{2} E_{\mathrm{cm}}$

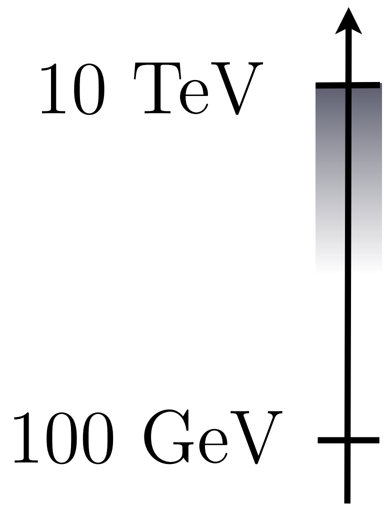
$m_{\tilde{H}} \sim 1.5\ \mathrm{TeV} \quad \Rightarrow \quad \epsilon \sim 1\%$

- Hermetic “EW-ino scan”
- Masses measured to 1%
- Similar for sleptons

Best hope for making <u>quantitative</u> connection between collider MET and DM

Compositeness

Version 2.0: Higgs as pseudo Nambu-Goldstone boson



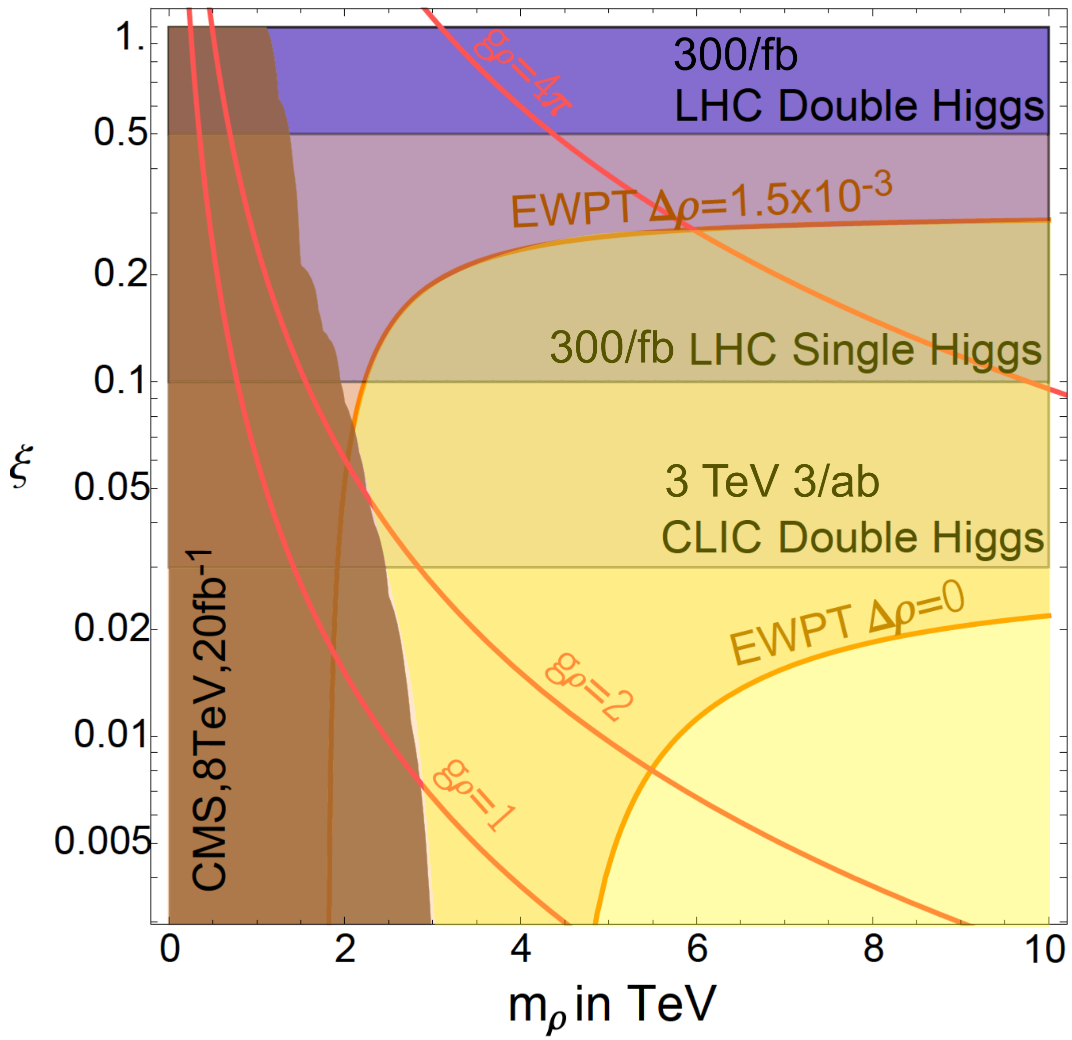
$$G \xrightarrow{f} H \supset SU(2)_W \times U(1)_Y$$

$$SU(2)_W \times U(1)_Y \xrightarrow{v} U(1)_{\mathrm{EM}}$$

Tuning: $\epsilon \sim \left(\frac{v}{f}\right)^2 \lesssim 10\%$ from Higgs couplings and precision EW

How far can we probe?

Compositeness at Colliders



VLHC can discover resonances to ???

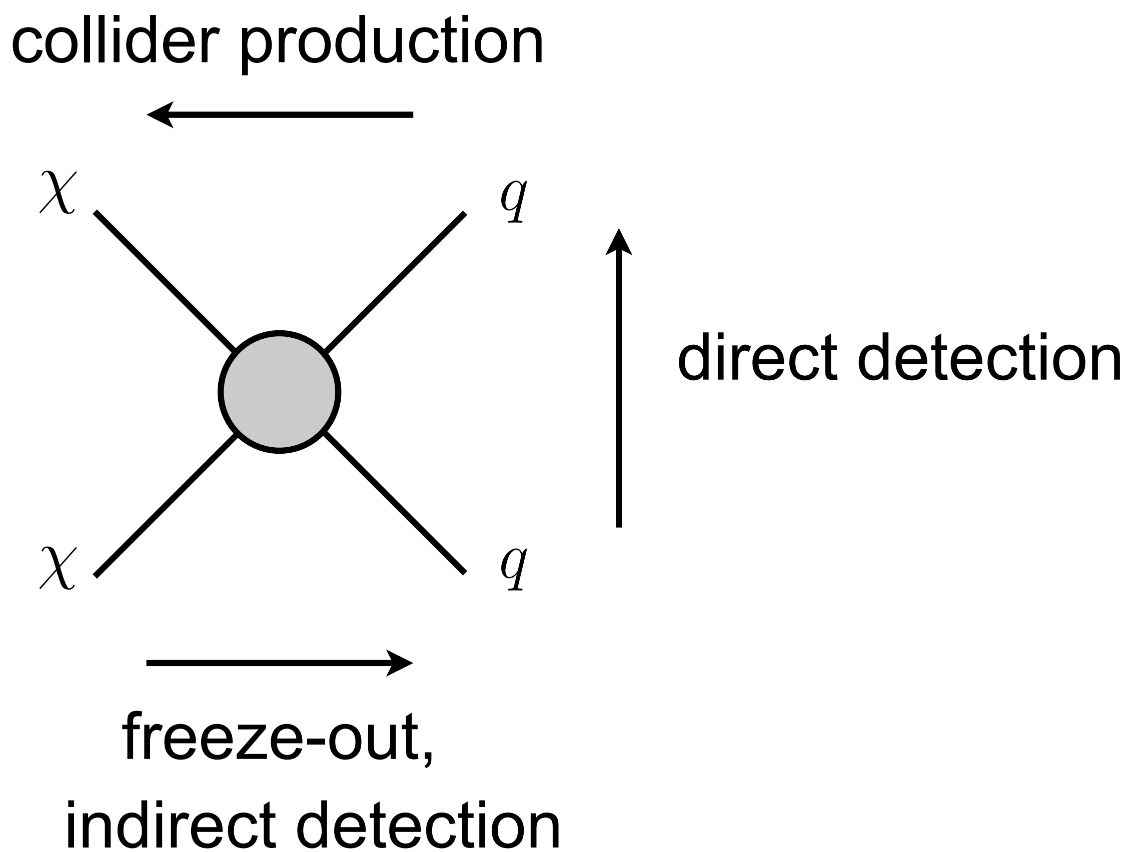
Probes naturalness only indirectly

Dark Matter

Thermal relic ⇒ $\Omega h^2 \sim$ observed value

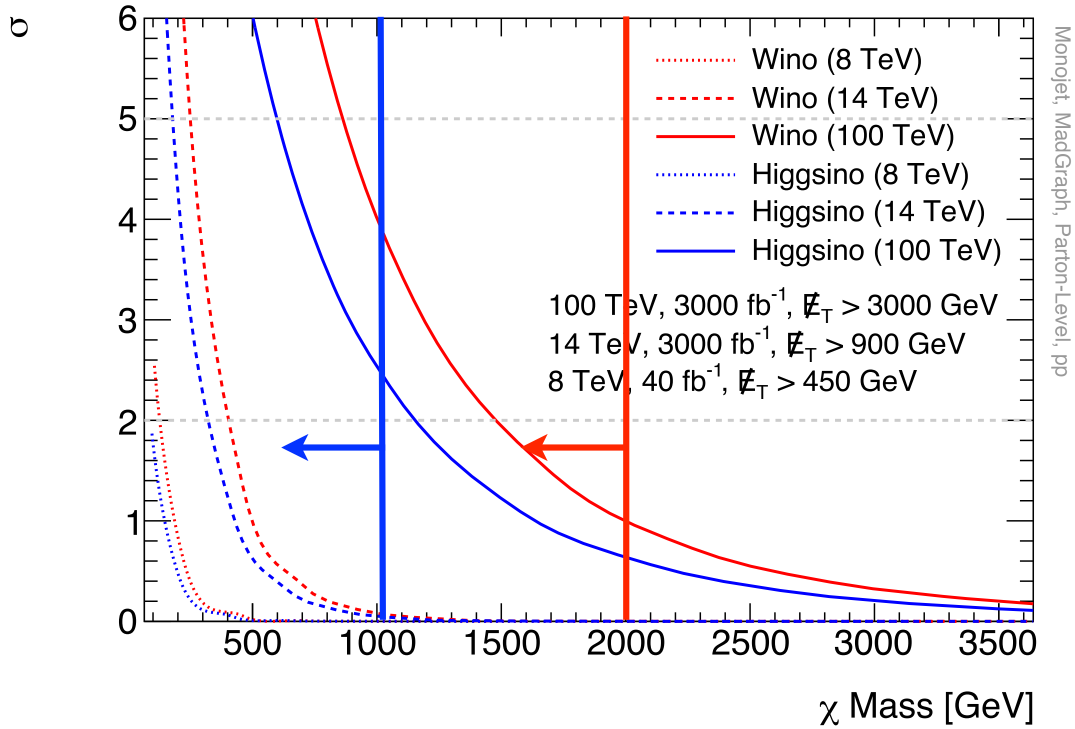
for $\langle \sigma_{\rm ann} v \rangle \sim {\rm pb}$

Motivates dark matter at TeV scale

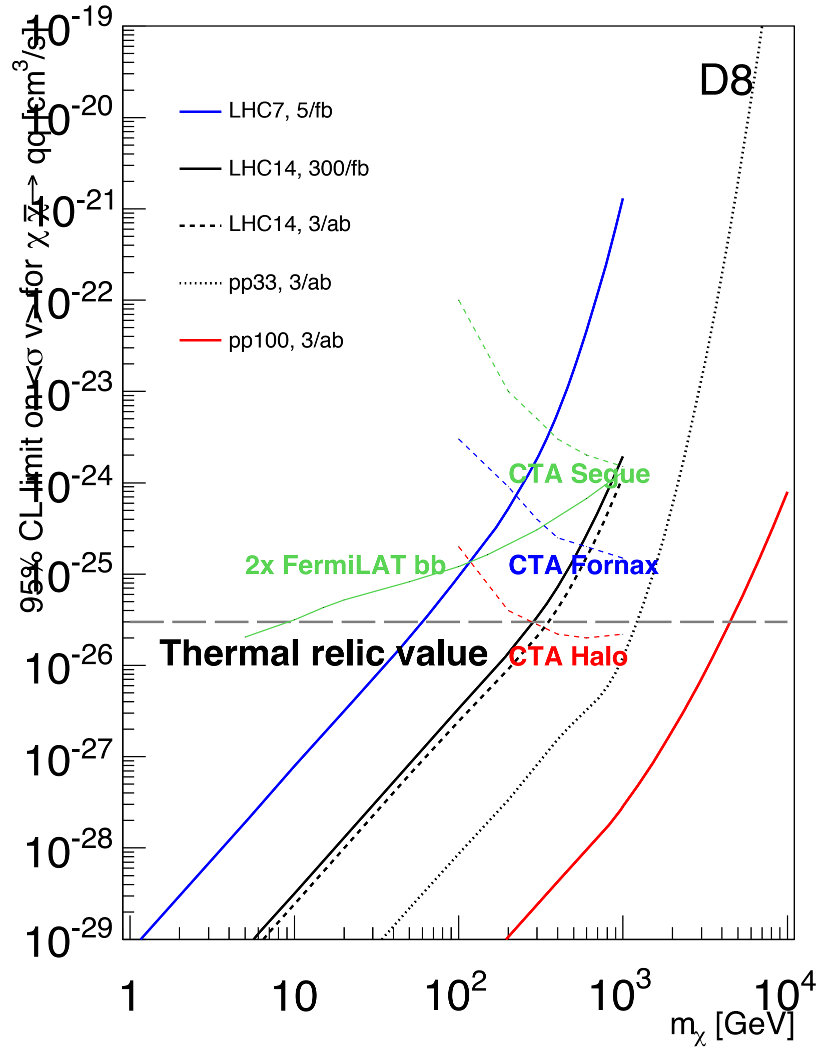


DM at 100 TeV pp

SUSY WIMP

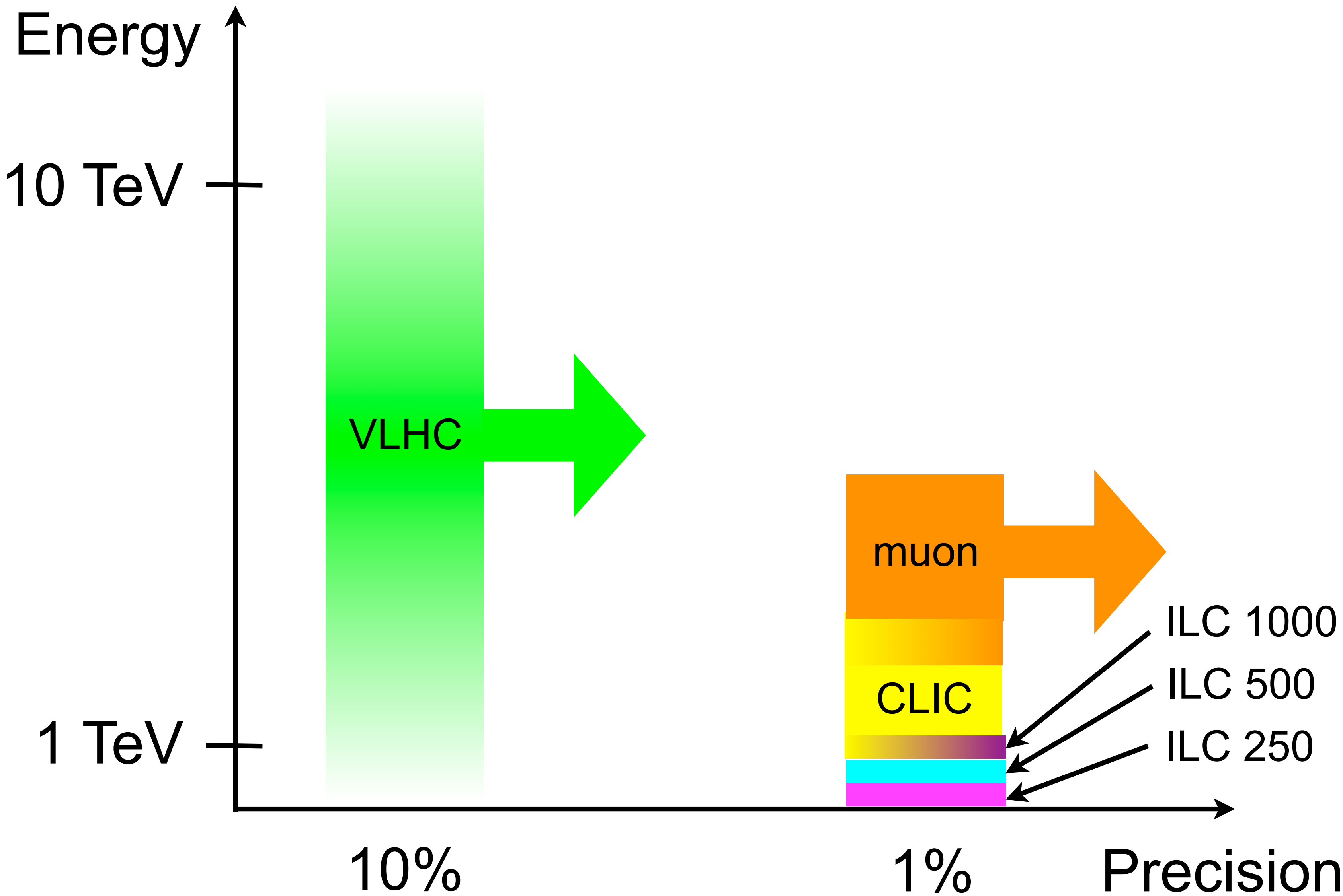


M. Low, L. Wang [preliminary]

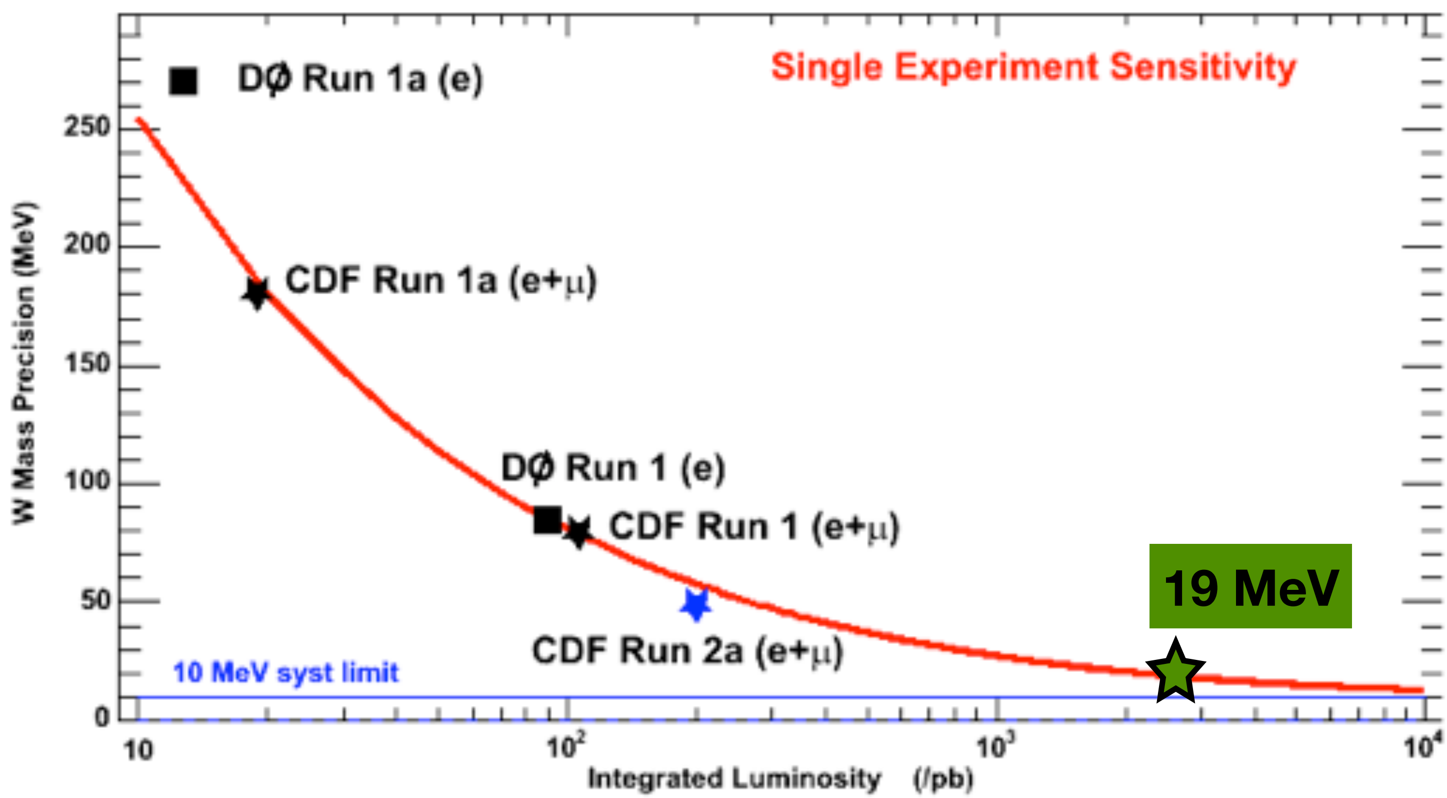


Effective DM

Leptons vs. Hadrons



Data Makes us Smarter



$$\text{systematics} \sim \frac{1}{\sqrt{\mathcal{L}}}$$

More Study Needed!

The ILC community has set the gold standard for documenting their machine and its physics reach.

CLIC is also in good shape, but there are few studies for VLHC and muon collider.

More such studies are needed as input to the decision about the next big step forward in the energy frontier.

How do we Decide?

“Guaranteed discovery” is guaranteed mediocrity

High energy lepton and proton colliders are extremely complementary

Neither has a guarantee of discovery

We have to decide.

If X finishes its run and we have seen nothing beyond the measurements that are guaranteed, I will say: “We did the right thing.”