What Happened at Snowmass ?

Energy Frontier

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Crucial issues for the Snowmass Energy Frontier study:

The Higgs is discovered. What comes next ? What do we have yet to learn about the Higgs boson ?

Where is the TeV new particle spectroscopy ?

How do these issues provide opportunities for collider experiments ?

To address the mystery of the Higgs and possible TeV spectrum, we need a 3-prong program at colliders:

Direct searches for new heavy particles.
Searches for the imprint of new physics on W, Z, top quark
Searches for the imprint of new physics on the Higgs boson

I. What scientific targets can be achieved at the LHC with 300 fb^{-1} ?

II. What are the science cases that motivate the High Luminosity LHC ?

III. Is there a scientific necessity for a precision Higgs program ?

IV. Is there a scientific case today for experiments at higher energies beyond 2030 ?

Chip Brock and I, the conveners of the Energy Frontier study, set up 6 working groups. We recruited a truly exceptional set of conveners for these groups:

1. The Higgs Boson
Sally Dawson , Andrei Gritsan , Heather Logan, Jianming Qian , Chris Tully , Rick Van Kooten

2. Precision Study of Electroweak Interactions
Ashutosh Kotwal, Michael Schmitt, Doreen Wackeroth

3. Fully Understanding the Top Quark
Kaustubh Agashe, Robin Erbacher, Cecilia Gerber, Kirill Melnikov, Reinhard Schwienhorst

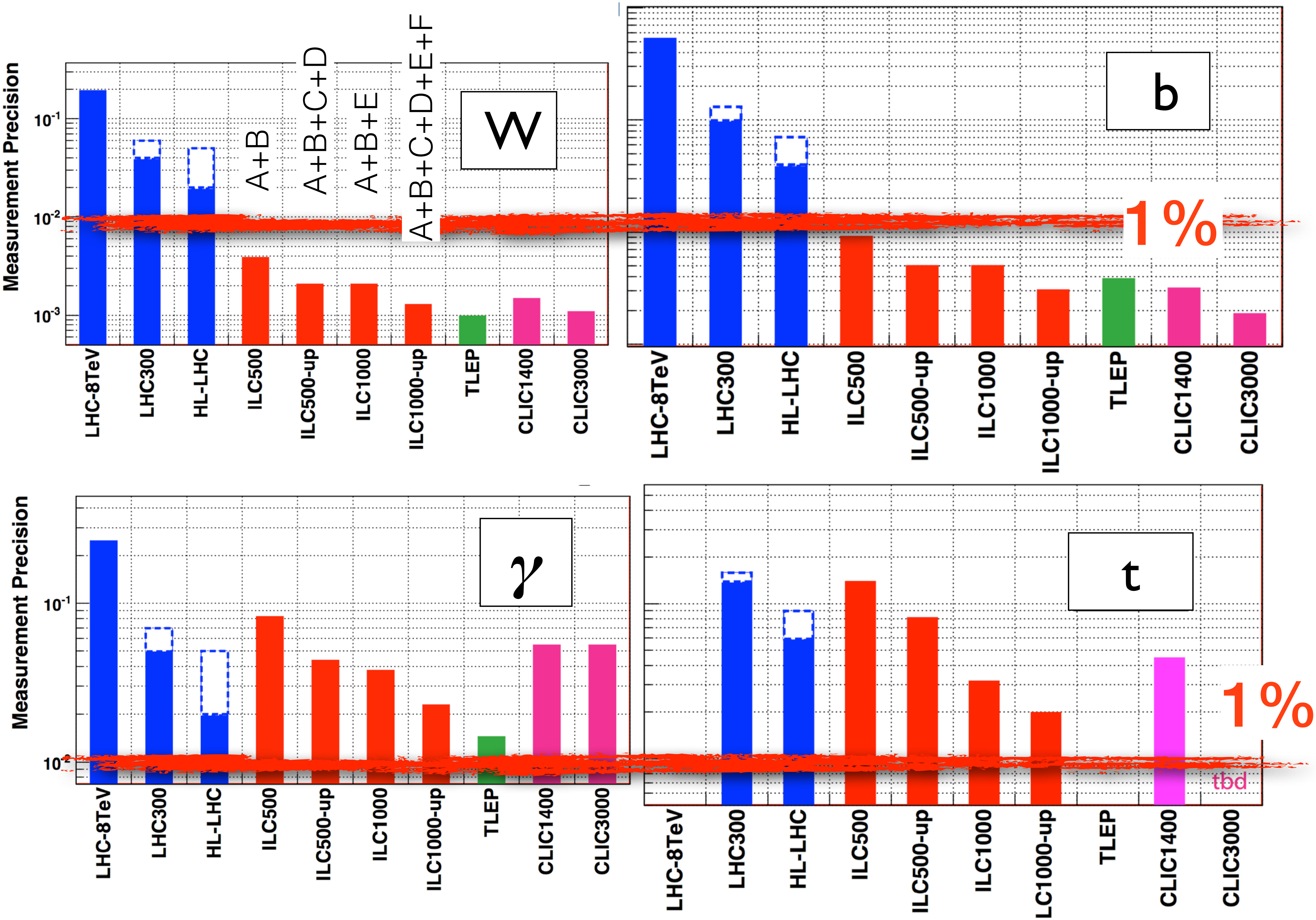
4. The Path Beyond the Standard Model - New Particles, Forces, and Dimensions
Yuri Gershtein, Markus Luty, Meenakshi Narain, Liantao Wang, Daniel Whiteson

5. Quantum Chromodynamics and the Strong Force
John Campbell, Kenichi Hatakayama, Joey Huston, Frank Petriello

6. Flavor Mixing and CP Violation at High Energy
Marina Artuso, Michele Papucci, Soeren Prell

Here are a few snapshots from the study:

Higgs couplings: Precision in kappa by facility



EW top-Neutral VB couplings

projected precision of $t-\gamma$, $t-Z^0$ couplings

Collider	LHC		ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity [fb^{-1}]	300	3000	500
SM Couplings			
photon, F_{1V}^{γ} (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^{Z} (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^{Z} (0.6)	0.058	?	0.005
Non-SM couplings			
photon, F_{1A}^{γ}	0.05	?	?
photon, F_{2V}^{γ}	0.037	0.025	0.003
photon, F_{2A}^{γ}	0.017	0.011	0.007
Z boson, F_{2V}^{Z}	0.25	0.17	0.006
Z boson, ReF_{2A}^{Z}	0.35	0.25	0.008
Z boson, ImF_{2A}^{Z}	0.035	0.025	0.015

BSM: 2-10 %

LHC : few %

ILC/CLIC: sub-%

Flavor-changing top decay

10^{-4} level probes BSM top decay models

projected limits for FCNC top decay processes

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[136]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[136]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[137]
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[137]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	[136]
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	[136]
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	[137]
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	[137]

Brock/Peskin Snowmass 2013

SUSY at stages of LHC

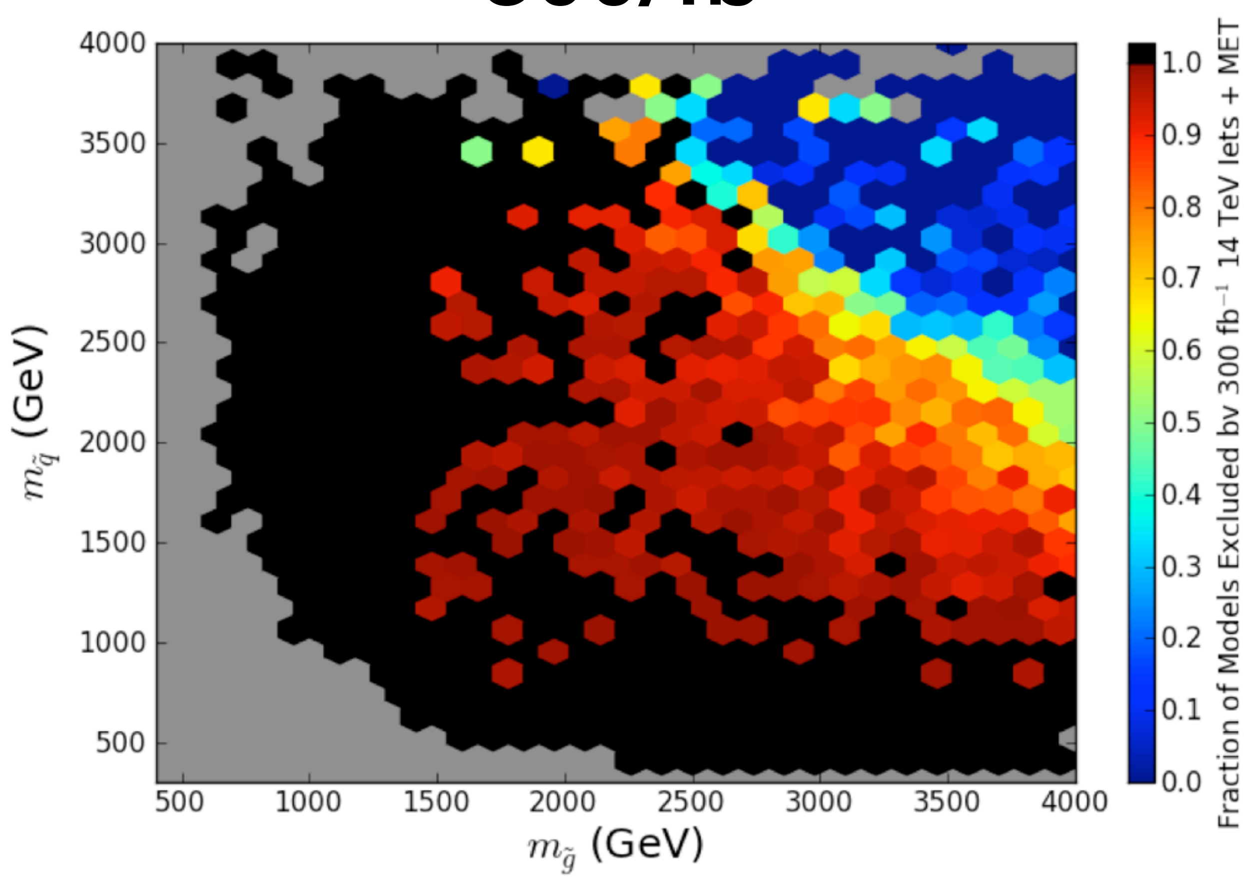
In the pMSSM survey of SUSY models

squark/gluino mass plane

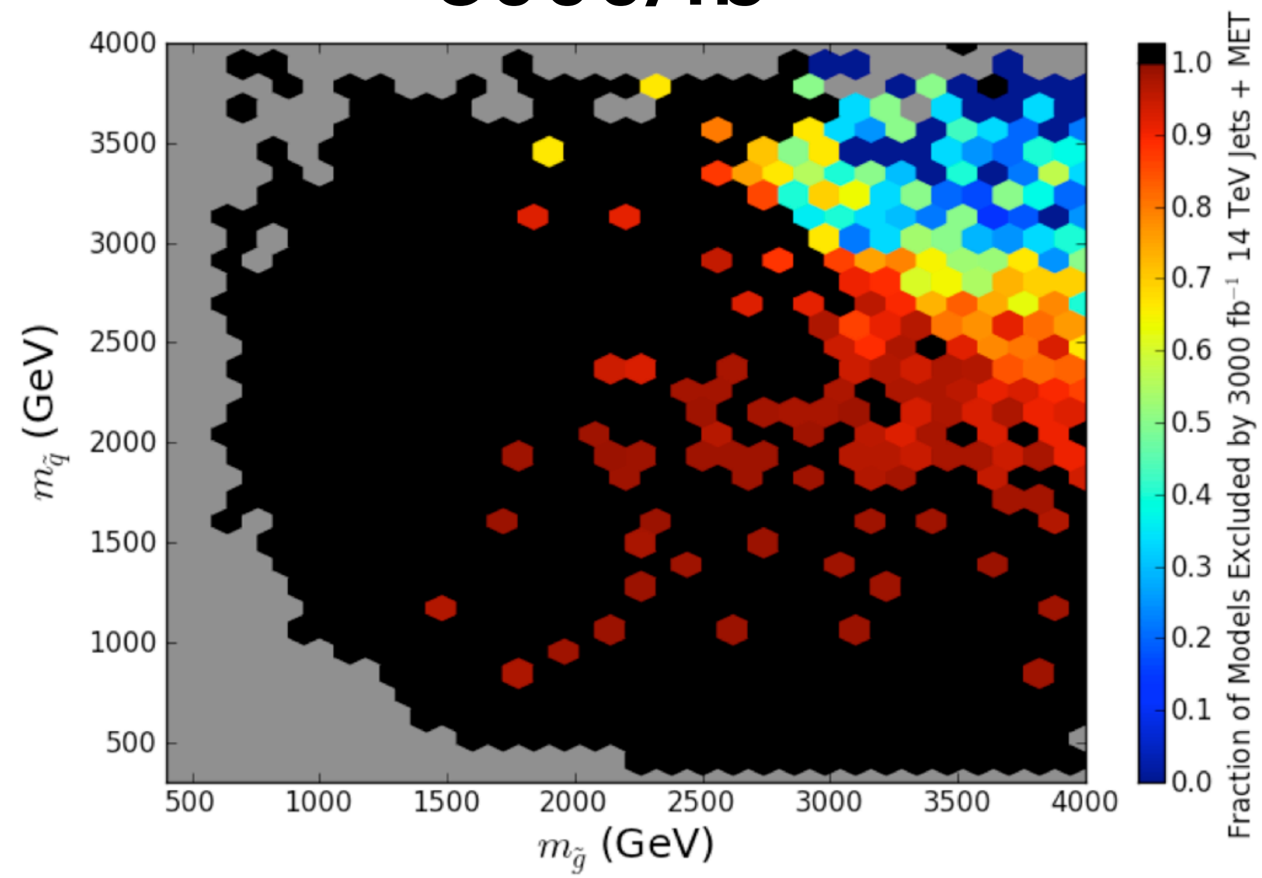
x2 from 8 TeV to 14 TeV (300/fb)

another ~ 30% to 3000/fb

300/fb



3000/fb

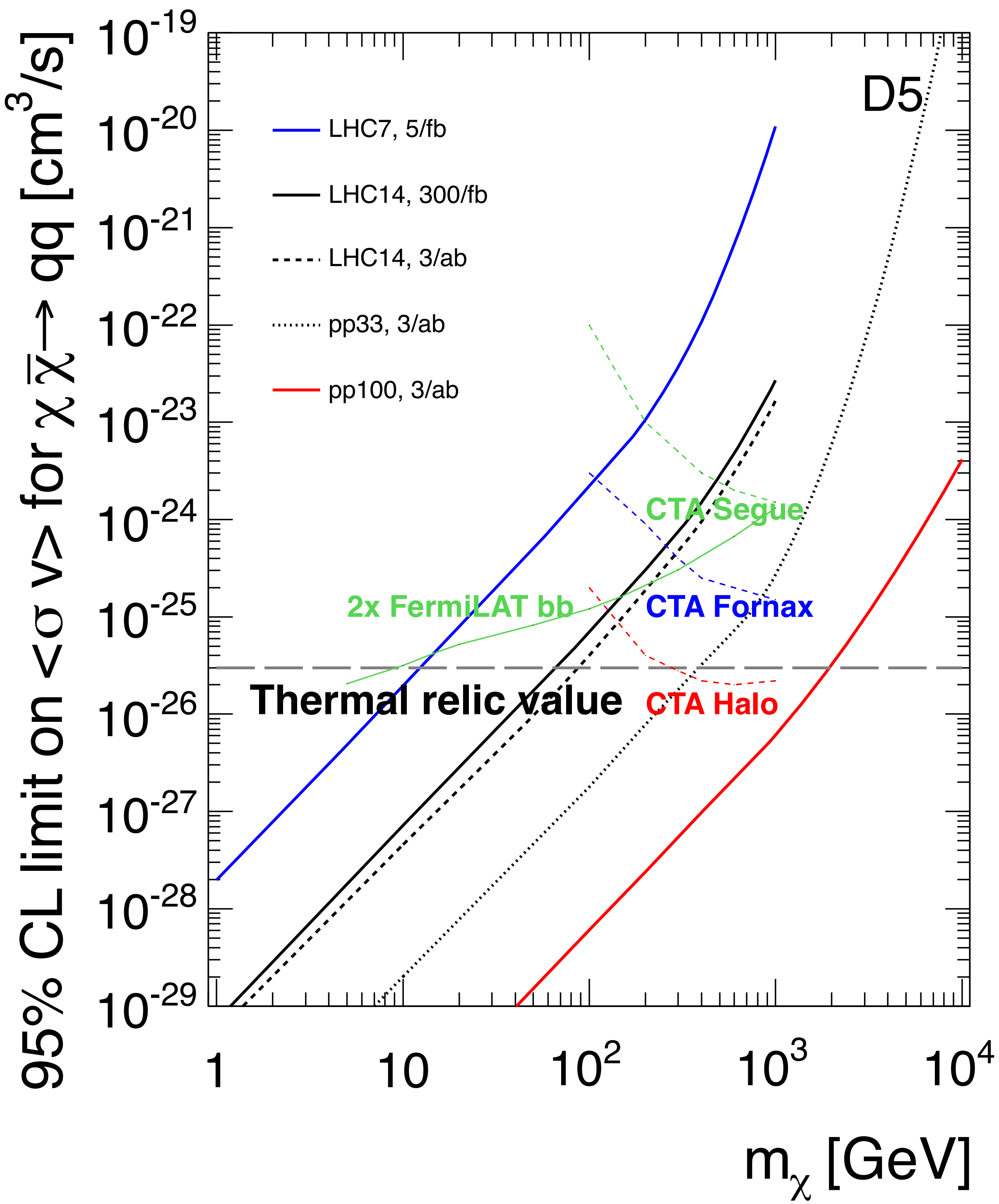


Note closing of loopholes in addition to increased energy reach.

Cahill-Rowley et al.

Dark Matter Connection

close the thermal relic range?



progressive increase in sensitivity

VLHC (100 TeV) exhausts the thermal WIMP region

Likewise, VLHC closes the fine tuning requirement to 10^{-4}

We listed physics cases for 9 different colliders, beginning with the LHC with 300 fb^{-1}.

Here are the three most important.

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **The precision era in Higgs couplings: couplings to 2-10% accuracy, 1% for the ratio gamma gamma/ZZ.**
2. Measurement of rare Higgs decays: mu mu, Z gamma with 100 M Higgs.
3. **First measurement of Higgs self-coupling.**
4. Deep searches for extended Higgs bosons
5. Precision W mass to 5 MeV
6. **Precise measurements of VV scattering; access to Higgs sector resonances**
7. Precision top mass to 500 MeV
8. Deep study of rare, flavor-changing, top couplings with 10 G tops.
9. Search for top squarks & partners in models of composite top, Higgs in the expected range of masses.
10. Further improvement of q, g, gamma PDFs to higher x, Q^2
11. A 20-40% increase in mass reach for generic new particle searches - can be 1 TeV step in mass reach
12. **EW particle reach increase by factor 2 for TeV masses.**
13. Any discovery at LHC–or in dark matter or flavor searches–can be **followed up**

ILC, up to 500 GeV

1. **Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs Γ, direct study of invisible & exotic Higgs decays**
2. **Model-independent Higgs couplings with % accuracy, great statistical & systematic sensitivity to theories.**
3. Higgs CP studies in fermionic channels (e.g., $\tau^+\tau^-$)
4. **Giga-Z program for EW precision, W mass to 4 MeV and beyond.**
5. Improvement of triple VB couplings by a factor 10, to accuracy below expectations for Higgs sector resonances.
6. Theoretically and experimentally precise top quark mass to 100 MeV.
7. **Sub-% measurement of top couplings to gamma & Z, accuracy well below expectations in models of composite top and Higgs**
8. Search for rare top couplings in e+e- -> $t\,\bar{c}$, $t\,\bar{u}$.
9. Improvement of α_S from Giga-Z
10. No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter

Higgs EW Top QCD NP/flavor

pp Collider: 33/100 TeV

1. High rates for double Higgs production; measurement of triple Higgs couplings to 8%.
2. Deep searches, beyond 1 TeV, for extended Higgs states.
3. Dramatically improved sensitivity to VB scattering and multiple vector boson production.
4. Searches for top squarks and top partners and resonances in the multi-TeV region.
5. **Increased search reach over LHC, proportional to the energy increase, for all varieties of new particles (if increasingly high luminosity is available). Stringent constraints on "naturalness".**
6. **Ability to search for electroweak WIMPs (e.g. Higgsino, wino) over the full allowed mass range.**
7. Any discovery at LHC -- or in dark matter or flavor searches -- can be followed up by measurement of subdominant decay processes, search for higher mass partners. Both luminosity and energy are crucial here.

Higgs EW Top QCD NP/flavor