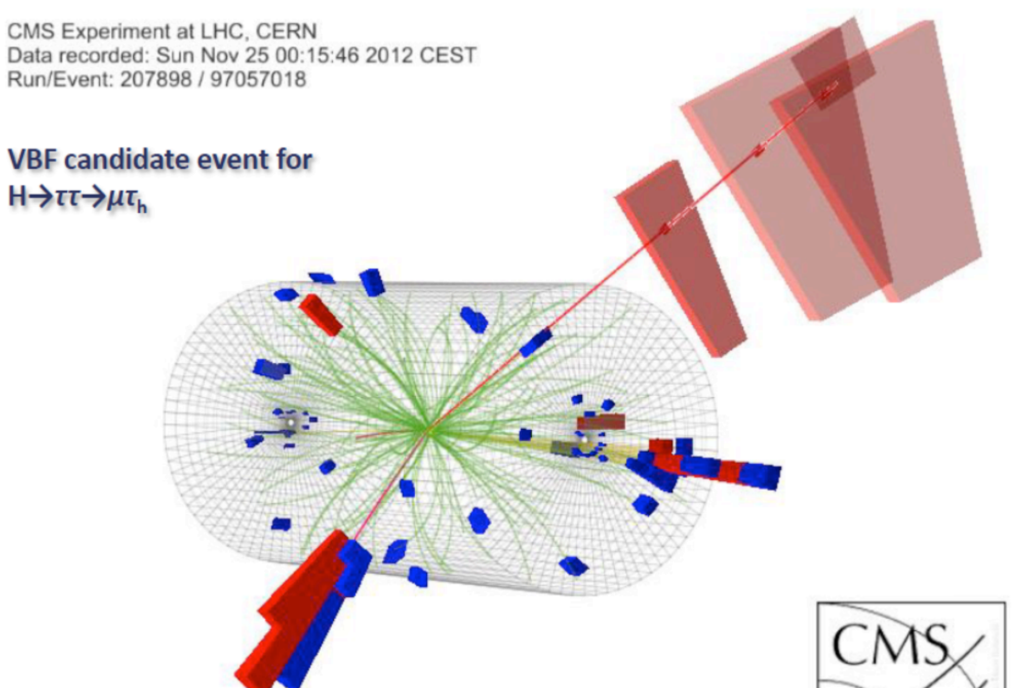
What have we learned at the Energy Frontier ?



M. E. Peskin
DPF 2013 Plenary
August 2013

These two plenary days of the DPF meeting are an attempt to gather "reminiscences of Snowmass".

The official summary report of the Energy Frontier at Snowmass is given in Chip Brock's talk, which you will find at:

https://indico.fnal.gov/conferenceTimeTable.py?confId=6890#20130806.detailed

This talk will include some slides from Chip's talk, together with my own introduction to the "Energy Frontier" perspective on the future of high energy physics.

Lang Lang - Liszt Reminiscences de Don Juan, S. 418

What is the purpose of Snowmass? Was it accomplished ?

Over the past few decades, the plan for the future of high energy physics has been accomplished in two stages. First, there is a “Snowmass meeting” to solicit community input and build consensus. Then, there is a HEPAP subpanel charged with producing a plan within defined budget scenarios.

This year, the problem of planning the future of HEP is more problematic than ever.

The total funding of high energy physics has declined significantly in the past decade.

The US is no longer hosting a frontier energy accelerator.

The “three frontiers” funding model used by the DOE makes it more difficult for us to talk as a community.

There is wide disagreement on where to look for physics beyond the Standard Model.

The most important goal of Snowmass was to have a unified discussion of the opportunities before us in high energy physics.

Broad coverage of opportunities at high-energy colliders, rare process searches, neutrinos, and cosmic probes.

Emphasis on long-term goals, and on planning in coordination with the HEP programs of Europe and Asia.

Emphasis on cross-frontier discussion -- on Higgs, dark matter, flavor violation ...
The Big Questions transcend the boundaries of the frontiers.

You will see these themes in all of the Snowmass presentations.

Now I would like to take up the perspective of the Energy Frontier.

We are at a pivotal moment in the history of high energy physics.

The discovery of the Higgs boson completes the particle spectrum of the Standard Model. This gives a theory that can be self-consistently extended to very high energies. For years, we have tested and verified the Standard Model. It is time for a new set of questions.

We are also (painfully) aware of the limitations of the Standard Model. The Standard Model cannot explain:

dark matter
baryogenesis
quantum numbers of quarks and leptons
neutrino mass
dark energy and cosmic inflation
...

All of these phenomena call for new particles and forces in nature.

For me, the central mystery is that of the Higgs boson itself.

Theorists and experimenters have been uncomfortable about the Higgs for a long time. Now it is reality.

Who gave us the Higgs field ? Why does it permeate the universe ?
Is there one Higgs, or this the first element of a larger structure ?

This question is important for two reasons.

First,

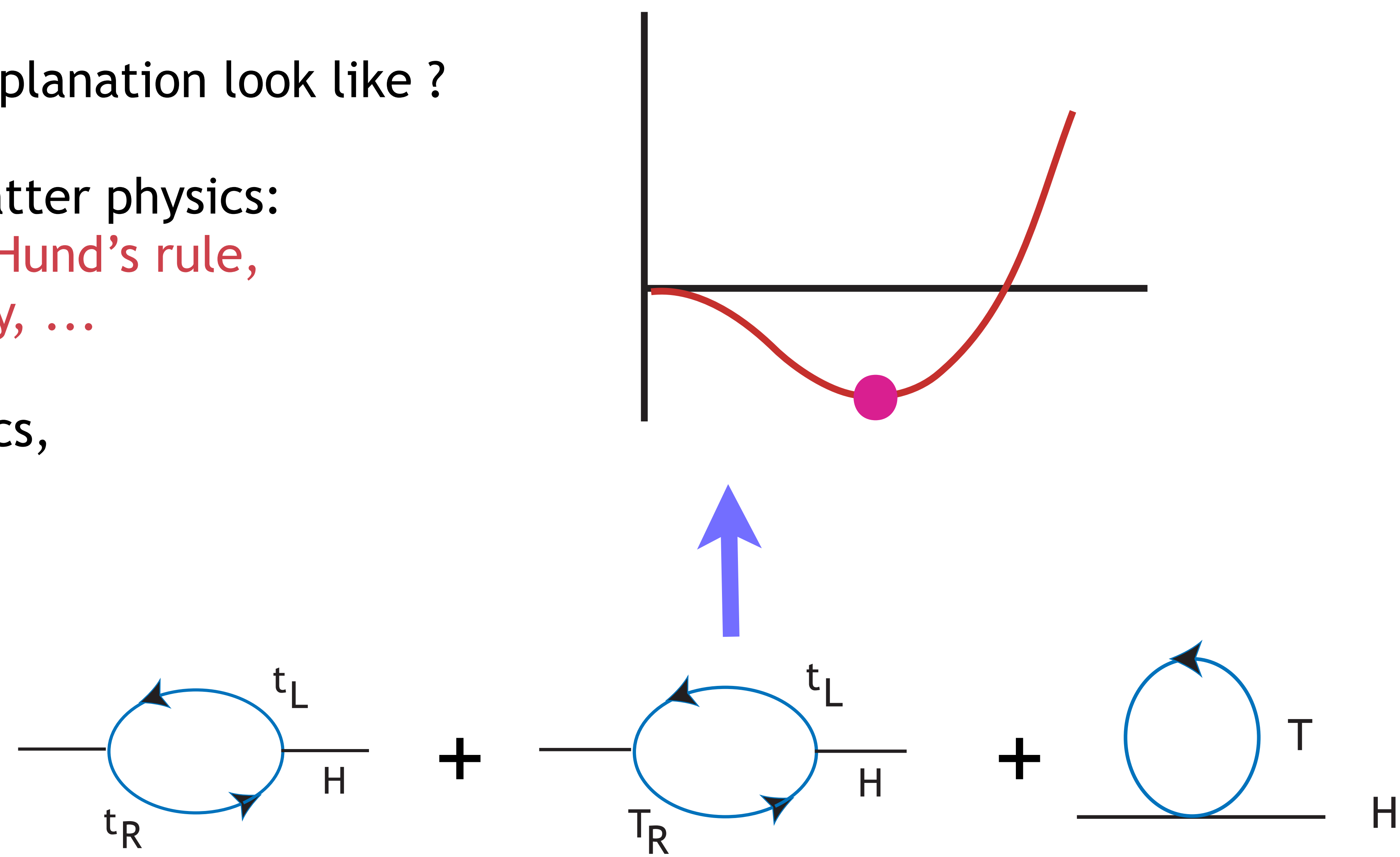
though we are accumulating evidence that the Higgs field acquires a nonzero value in the vacuum that gives mass to all quark, leptons, and gauge bosons,

we have no idea why this phenomenon occurs.

What does an explanation look like ?

In condensed matter physics:
Cooper pairing, Hund's rule,
Peierls instability, ...

In particle physics,



What are the new particles in these loop diagrams ? We do not know.

This brings us to the second motivation:

Theoretical models of the Higgs field suggest answers to other mysteries -- dark matter, unification, ...

Big ideas are proposed: supersymmetry, higher dimensions, Higgs compositeness. These give new -- perhaps essential -- building blocks of nature.

The solution of any problem posed at shorter distances -- flavor, neutrino mass, inflation, grand unification -- has to know about these building blocks: Do they exist ? Which are the correct ones ?

There are many ways to obtain information about these new particles, and they cross all of the frontiers. These particles might appear in dark matter searches, or in new flavor-violating processes.

However, the most direct method is to use the power of high energy accelerators. This is a 3-part program:

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

In the Energy Frontier study for Snowmass, we have considered experiments of these types against the future of energy frontier facilities:

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

We received technical assistance, in defining reference accelerator parameters and setting up simulations, from:

Mikael Berggren, Jeff Berryhill, Sergei Chekanov, Norman Graf, Markus Klute, Tom LeCompte, Akiya Miyamoto, Sanjay Padhi, Mark Palmer, Eric Prebys, Tor Raubenheimer, Eric Torrence

And, we thank the hundreds of physicists who contributed analyses, talks, and white papers to the study.

I will now show some slides from our conclusions, factorized first by working group and then by facility.

Chip Brock, in his inimitable style, supplied a color-code for easy reference:

Higgs
Electroweak
Top
QCD
New Particles and Forces (incl. Flavor)

Higgs: Themes

1. outline of a precision Higgs program

   mystery of Higgs, theoretical requirements

2. projections of Higgs coupling accuracy

   measurement potential at future colliders

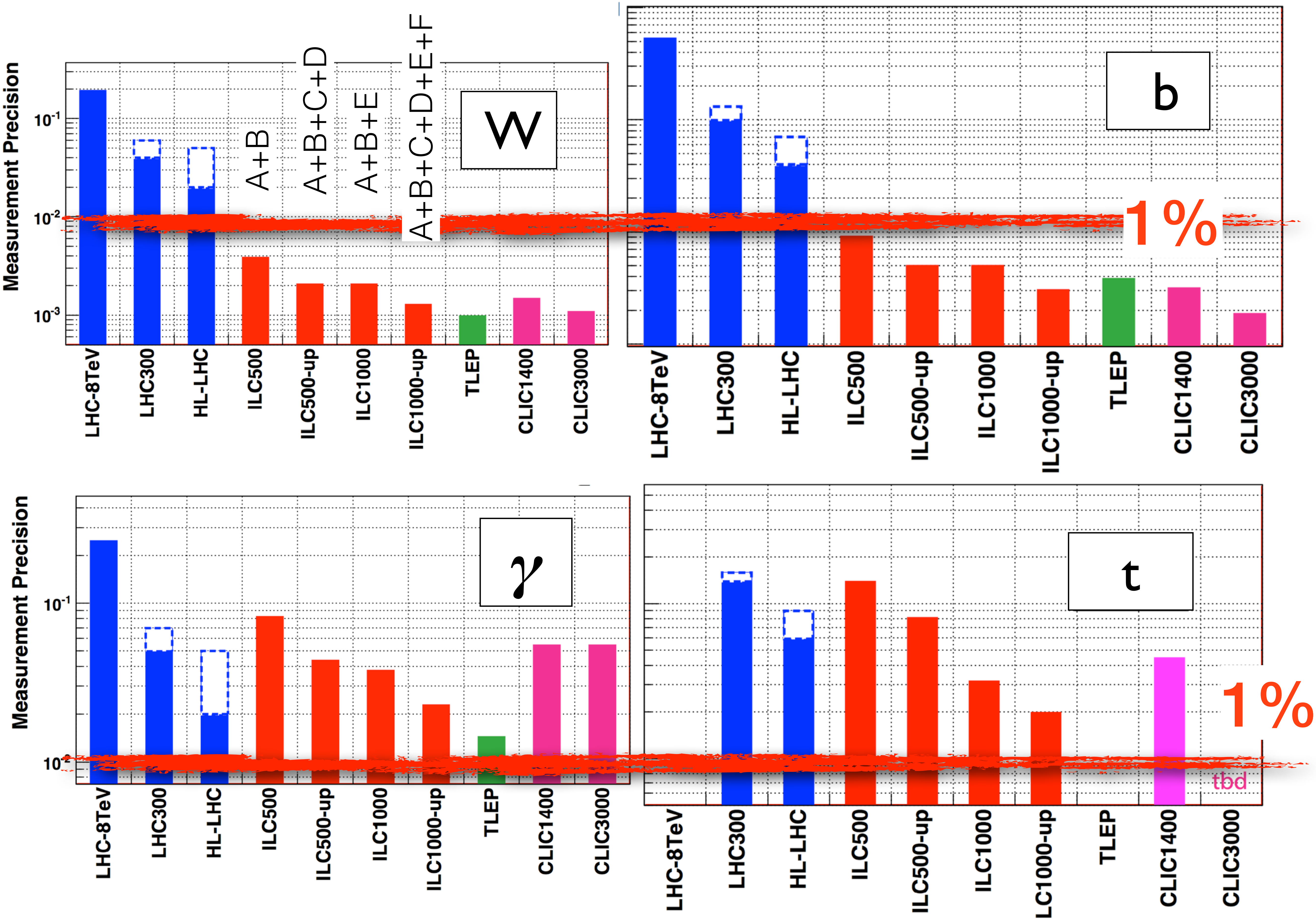
3. projections of Higgs property studies

   mass, spin-parity, CP mixture

4. extended Higgs boson sectors

   phenomenology and prospects for discovery

Precision in Higgs couplings by facility



The Higgs Boson message

1. Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.

   The light Higgs boson must be explained.

   An international research program focused on Higgs couplings to fermions and VBs to a precision of a few % or less is required in order to address its physics.

2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.

3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.

Origin of EWSB | **Origin of matter** | **Naturalness** | **Unification** | **New forces** | **Dark matter** | **Elementary?**

Electroweak: Themes

1. precision measurements:

- traditional electroweak observables: M_W, $\sin^2\theta_{\mathrm{eff}}$

  sensitive to new TeV particles in loops

2. studies of vector boson interactions

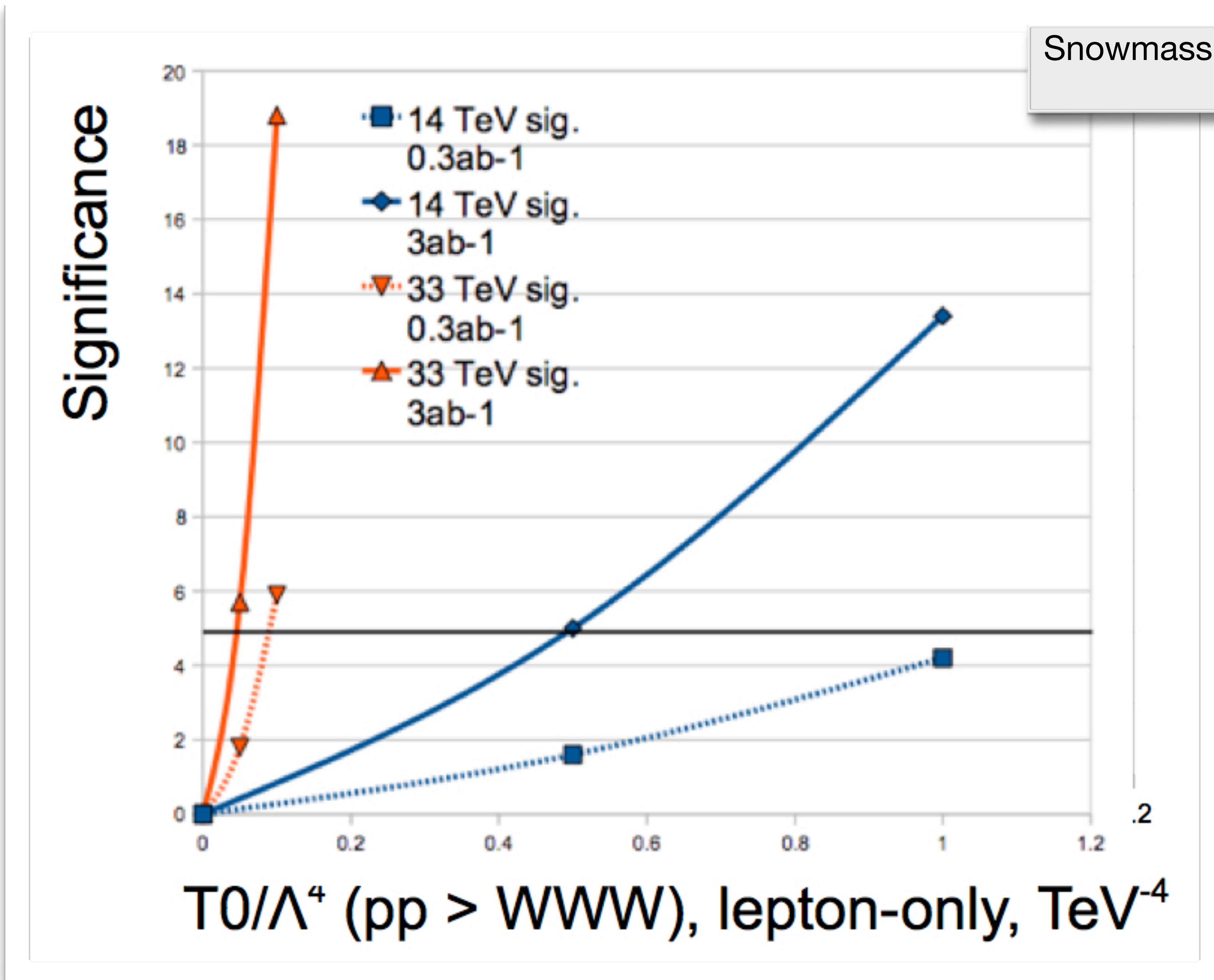
- triple VB couplings, VB scattering

  Effective Field Theory approaches

  sensitive to Higgs sector resonances

VB Scattering

Luminosity and Energy win.



Snowmass detector results

Brock/Peskin Snowmass 2013

The EW physics message

1. The precision physics of W's and Z's has the potential to probe indirectly for particles with TeV masses.

   This precision program is within the capability of LHC, linear colliders, TLEP.

2. Measurement of VB interactions probe for new dynamics in the Higgs sector.

   In such theories, expect correlated signals in triple and quartic gauge couplings.

Origin of EWSB **Naturalness** **New forces** **Unification** **Elementary?**

Top: Themes

1. Top Quark Mass
   - theory targets and capabilities
2. Top Quark Couplings
   - strong and electroweak couplings
3. Kinematics of Top Final States
   - top polarization observables and asymmetries
4. Top Quark Rare Decays
   - Giga-top program; connection to flavor studies
5. New Particles Connected to Top
   - crucial study for composite models of Higgs and top;
   - stop plays a central role in SUSY
6. Boosted-top observables

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

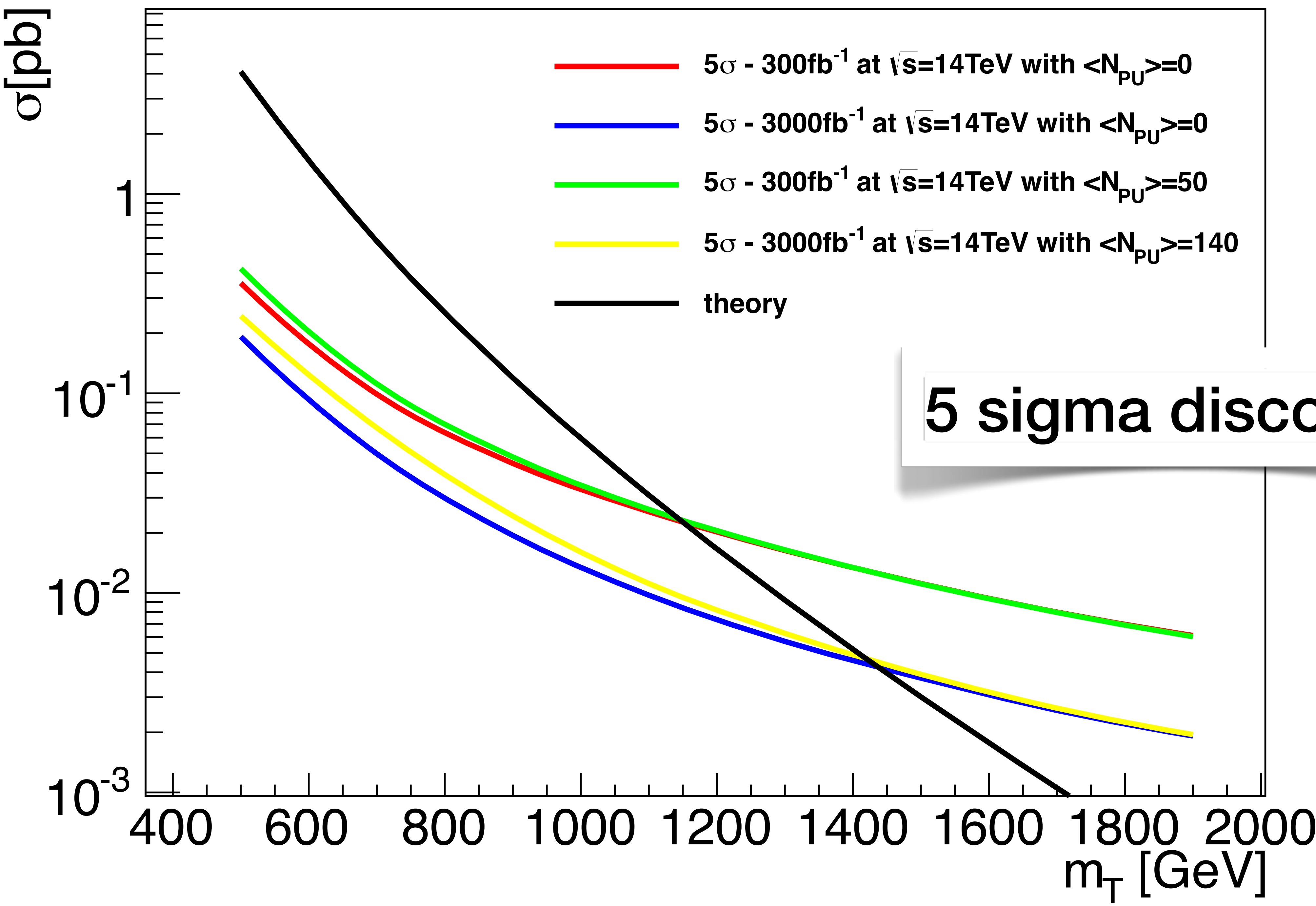
BSM: 2-10 %

LHC : few %

ILC/CLIC: sub-%

Direct search for top partner

search reach for vectorlike top partners at LHC 300 and 3000/fb



5 sigma discovery

The Top Quark physics message

1. Top is intimately tied to the problems of symmetry breaking and flavor
2. Precise and theoretically well-understood measurements of top quark masses are possible both at LHC and at e+e- colliders.
3. New top couplings and new particles decaying to top play a key role in models of Higgs symmetry breaking.

LHC will search for the particles;
Linear Colliders for coupling deviations.

Origin of EWSB | **Origin of flavor** | **Naturalness** | **New forces** | **Elementary?**

QCD: Themes

1. Improvement of PDFs and α_s
2. Event structure at hadron colliders
    - needed to enable all measurements
    - mitigation of problems from pileup at high luminosity
3. Improvement of the art in perturbative QCD
    - key role in LHC precision measurement, especially for Higgs

The QCD Physics Message

1. Improvements in PDF uncertainties are required.
   - There are strategies at LHC for these improvements.
   - QED and electroweak corrections must be included in PDFs and in perturbative calculations.
2. alphas error ~ 0.1% is achievable
   - lattice gauge theory + precision experiments
3. Advances in all collider experiments, especially on the Higgs boson, require continued advances in perturbative QCD.

Origin of matter **Unification** **Elementary?**

P1 precision program enabling the energy frontier

NP: Themes

1. Necessity for new particles at TeV mass

the questions of fine tuning and dark matter are still open

2. Candidate TeV particles

- weakly coupled: SUSY, Dark Matter, Long-lived
- strongly coupled/composite: Randall-Sundrum, KK and Z' resonances, long-lived particles
- evolution of robust search strategies

3. Connection to dark matter problem

4. Connection to flavor issues

SUSY at stages of LHC

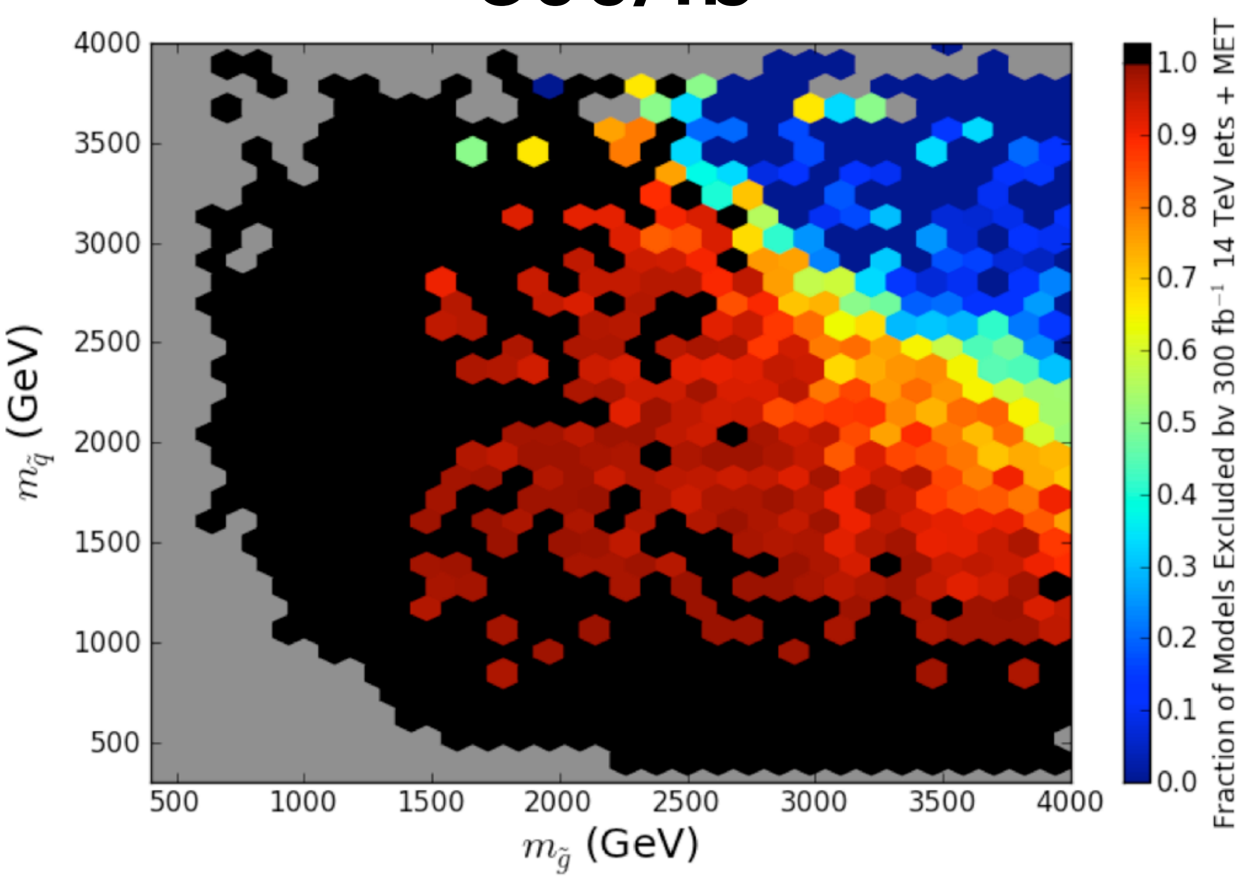
In the pMSSM survey of SUSY models

squark/gluino mass plane

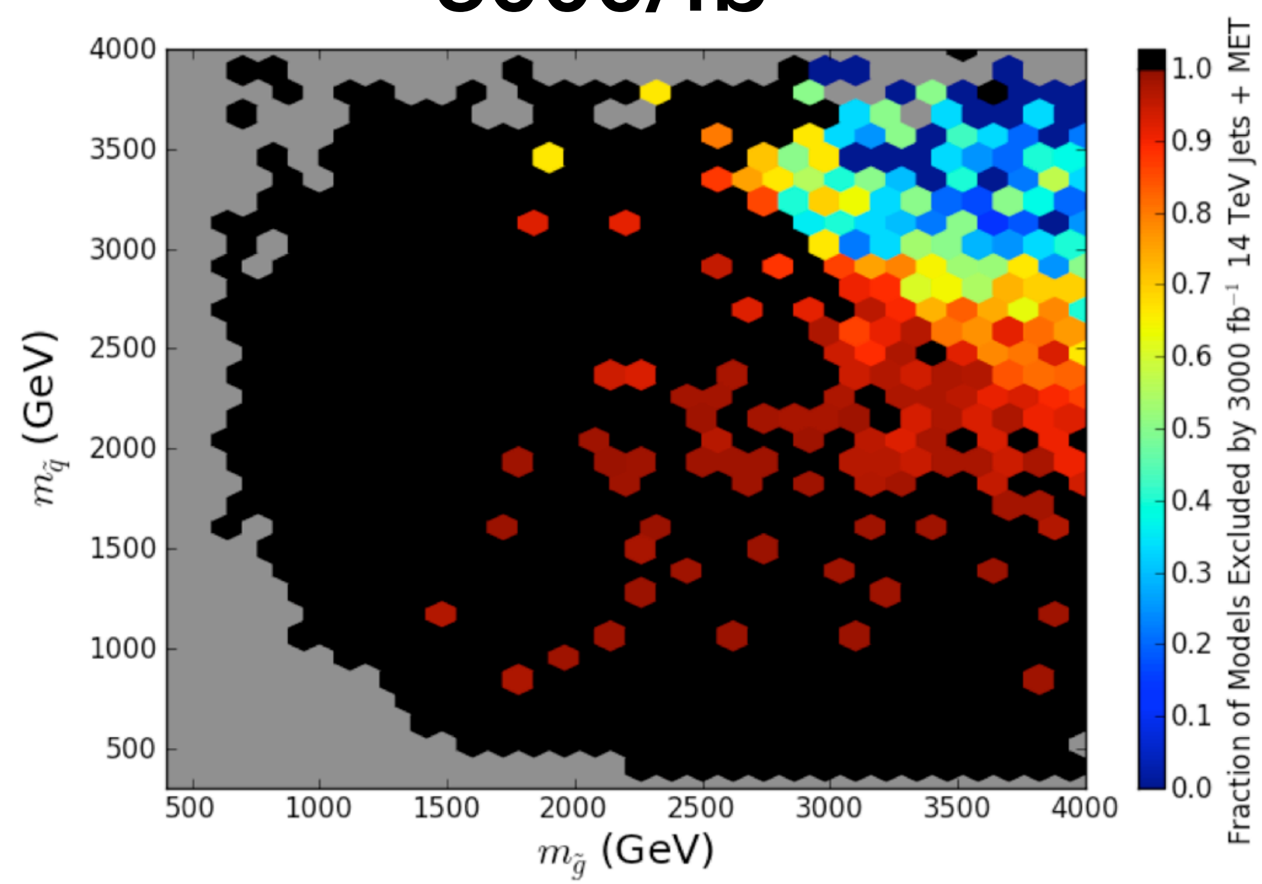
x2 from 8 TeV to 14 TeV (300/fb)

another ~ 30% to 3000/fb

300/fb



3000/fb



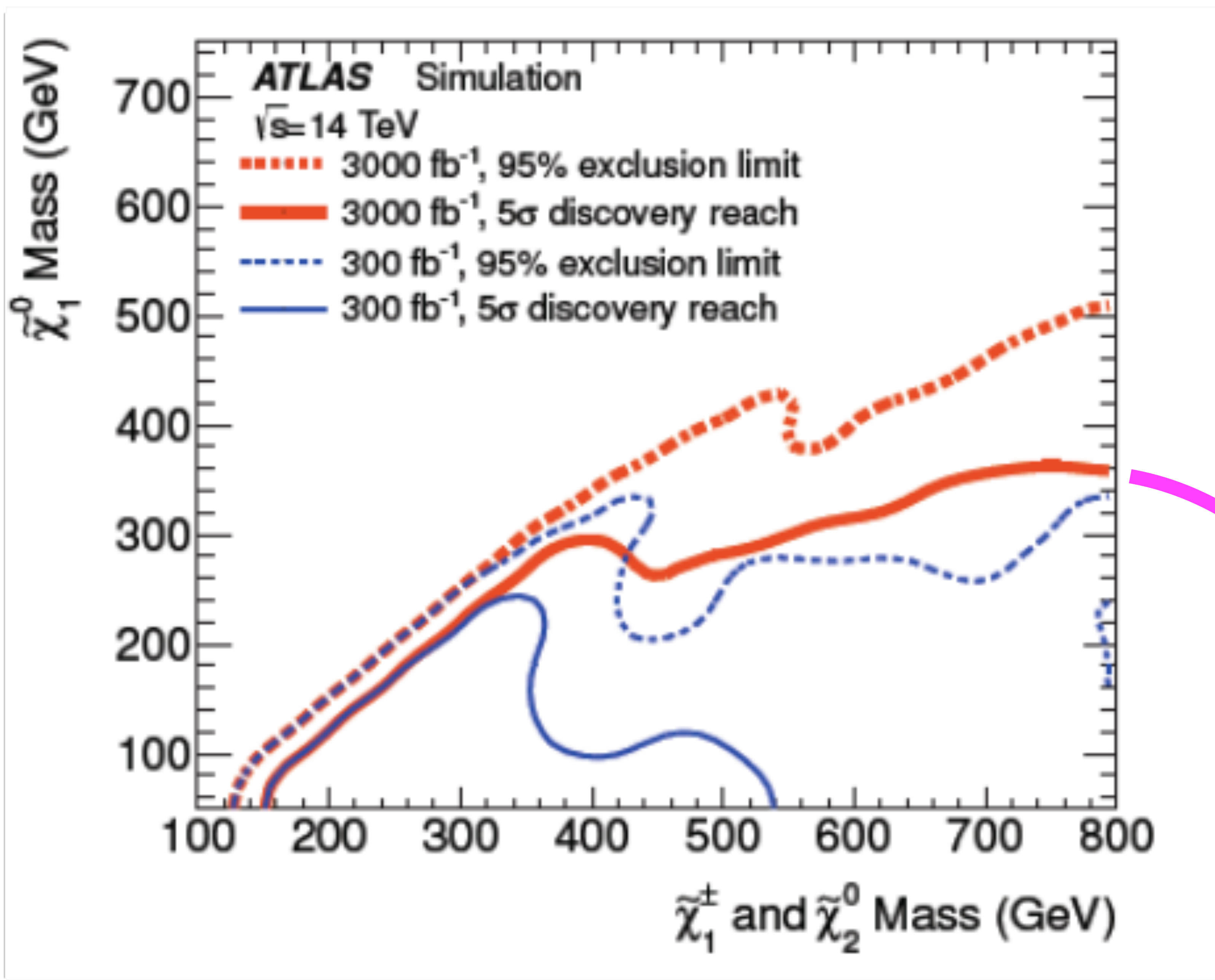
Note closing of loopholes in addition to increased energy reach.

Cahill-Rowley et al.

electroweakinos

× 2 again…300/fb to 3000/fb

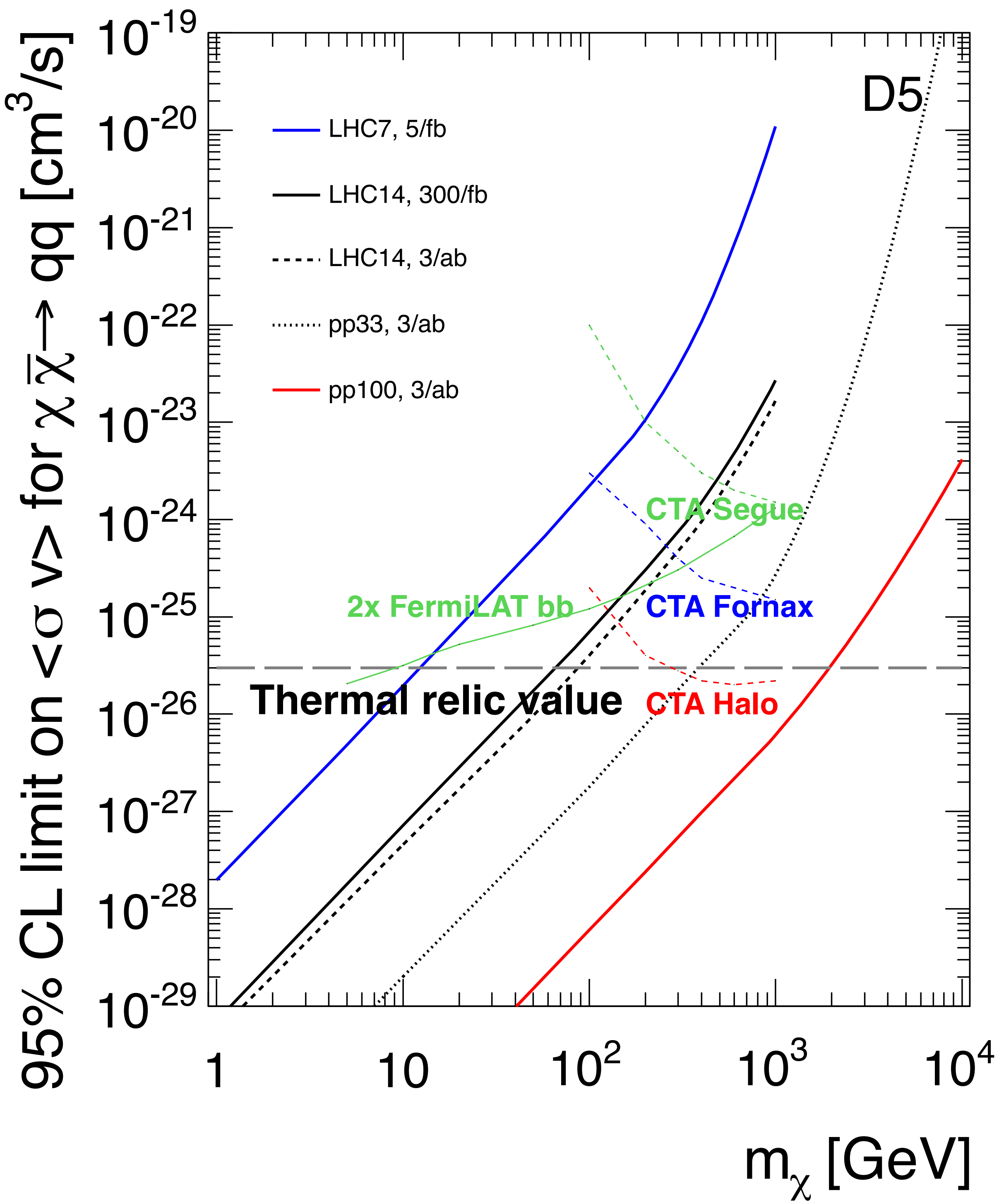
for lighter states with more difficult searches, in particular, states with only electroweak production at pp colliders.



famously ran out of MC ooph

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}

The NP Physics Message

1. TeV mass particles are needed in essentially all models of new physics. The search for them is imperative.
2. LHC and future colliders will give us impressive capabilities for this study.
3. This search is integrally connected to searches for dark matter and rare processes.
4. A discovery in any realm is the beginning of a story in which high energy colliders play a central role.

Origin of EWSB | Dark matter | Origin of matter | Naturalness | New spacetime | Unification

New forces | Elementary? | Origin of flavor | ν mass

Now, here are the conclusions again, written as opportunities for proposed facilities:

LHC, to 300 fb

LHC, to 3000 fb

ILC, to 500 GeV

ILC, to 1 TeV

CLIC, to 3 TeV

Muon Collider

Photon Collider

VLHC, to 33 or 100 TeV

LHC: 300 fb-1

Higgs EW Top QCD NP/flavor

1. **Clarification of Higgs couplings, mass, spin, CP to the 10% level.**
2. First direct measurement of top-Higgs couplings
3. Precision W mass below 10 MeV.
4. First measurements of VV scattering.
5. Theoretically and experimentally precise top quark mass to 600 MeV
6. Measurement of top quark couplings to gluons, Zs, Ws, photons with a precision potentially sensitive to new physics, a factor 2-5 better than today
7. **Search for top squarks and top partners and ttbar resonances predicted in models of composite top, Higgs.**
8. New generation of PDFs with improved g and antiquark distributions.
9. Precision study of electroweak cross sections in pp, including gamma PDF.
10. **x2 sensitivity to new particles: supersymmetry, Z', top partners – key ingredients for models of the Higgs potential – and the widest range of possible TeV-mass particles.**
11. Deep ISR-based searches for dark matter particles.

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., τ+τ-)
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

ILC 1 TeV

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 13% accuracy**
3. Model-independent search for extended Higgs states to 500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. **Model-independent search for new particles with coupling to gamma or Z to 500 GeV**
6. Search for Z' using e+e- -> $f \bar{f}$ to ~ 5 TeV, a reach comparable to LHC for similar models. Multiple observables for Z' diagnostics.
7. **Any discovery of new particles dictates a lepton collider program**:

   search for EW partners, 1% precision mass measurement, the complete decay profile, model-independent measurement of cross sections, BRs and couplings with polarization observables, search for flavor and CP-violating interactions

Higgs EW Top QCD NP/flavor

CLIC: 350 GeV, 1 TeV, 3 TeV

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 10%**
3. Model-independent search for extended Higgs states to 1500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. Precise measurement of VV scattering, sensitive to Higgs sector resonances.
6. **Model-independent search for new particles with coupling to gamma or Z to 1500 GeV: the expected range of masses for electroweakinos and WIMPs.**
7. Search for Z' using e+e- -> f $\bar{f}$ above 10 TeV
8. **Any discovery of new particles dictates a lepton collider program** as with the 1TeV ILC

Higgs EW Top QCD NP/flavor

muon collider: 125 GeV, 350 GeV, 1.5 TeV, 3 TeV

1. Similar capabilities to e+e- colliders described above. (Still need to prove by physics simulation that this is robust against machine backgrounds.)
2. **Ability to produce the Higgs boson, and possible heavy Higgs bosons, as s-channel resonances. This allows sub-MeV Higgs mass measurement and direct Higgs width measurement.**

Higgs EW Top QCD NP/flavor

photon collider

1. An ee collider can be converted to a photon-photon collider at ~ 80% of the CM energy. This allows production of Higgs or extended Higgs bosons as s-channel resonances, offering percent-level accuracy in gamma gamma coupling.
2. **Ability to study CP mixture and violation in the Higgs sector using polarized photon beams.**

Higgs EW Top QCD NP/flavor

TLEP, circular e+e-

1. **Possibility of up to 10x higher luminosity than linear e+e- colliders at 250 GeV. Higgs couplings measurements might still be statistics-limited at this level.** (Note: luminosity is a steeply falling function of energy.)
2. Precision electroweak programs that could improve on ILC by a factor 4 in sstw, factor 4 in mW, factor 10 in mZ.
3. Search for rare top couplings in e+e- -> $t \bar{c}$, $t \bar{u}$ at 250 GeV.
4. Possible improvement in alphas by a factor 5 over Giga-Z, to 0.1% precision.

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

Higgs EW Top QCD NP/flavor

With the discovery of the Higgs boson and the “completion” of the Standard Model,

we believe it is more important than ever to continue the search for new particles at the highest energy colliders.

There remain big questions in fundamental physics that require new particles and forces.

Any discovery of new physics -- as dark matter, in rare processes, or in direct searches -- implies a program of the discovery and elucidation of new particles in which high-energy colliders will play a central role.

Thanks to all of hard-working Energy Frontier conveners, and thanks to all participants in the study.

Special thanks to Chip Brock. It has been a pleasure working with you over the past year.