Snowmass 2013
Energy Frontier working group

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Michigan State University

HEPAP September 5, 2013

Comments:

This is a shorter version of the Snowmass Energy Frontier summary talk. All of the snowmass summaries can be found at:

`http://www.hep.umn.edu/css2013/streaming.html`

The EF wiki is:

`http://www.snowmass2013.org/tiki-index.php?page=Energy%20Frontier`

- the stakes
- the energy frontier process
- reports from the subgroups
  - themes
  - content
  - message
- cases for future programs

Comments:

Each physics group set includes their themes, illustrative figures and tables, and each group’s “message.”

These are all vetted and approved by the conveners.

For this summary, time constraints don’t allow for complete coverage. Some figures and tables will be in handouts, but not shown from the podium.

imagine a couple of years ago

Comments:

We used to talk about a Higgsless future possibility.

CERN was actively working on a writing effort to explain why no-Higgs would be even more exciting that the actual discovery!


H

now


STANDARD MODEL HAS BEEN PLACED ON THE
NATIONAL
REGISTER
OF HISTORIC
THEORIES
BY THE
UNITED STATES DEPARTMENT OF THE INTERIOR

Comments:

The Standard Model is unique in the history of physics. It is the most precisely confirmed theory of mankind but also simultaneously plagued with tricky formal problems.

It’s an odd schizophrenia: the best ever and yet mathematically compromised!

what embodies the

?

- the Gauge Principle

Comments:

The Gauge Principle is behind much of the numerical success of the SM.

It’s also a highly effective motivator for developing new theories. Nature seems to favor symmetry as a prior and the Gauge Principle allows us to link that to forces and gauge particles and even dynamics.

What’s odd about the Standard Model?

- the Potential.

  Much of our work is unpacking it:

$$V = V_0 - \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \left[y_{ij}\bar{f}_{Li}f_{Rj}\phi + HC\right]$$

vacuum energy

Higgs mass

instability?

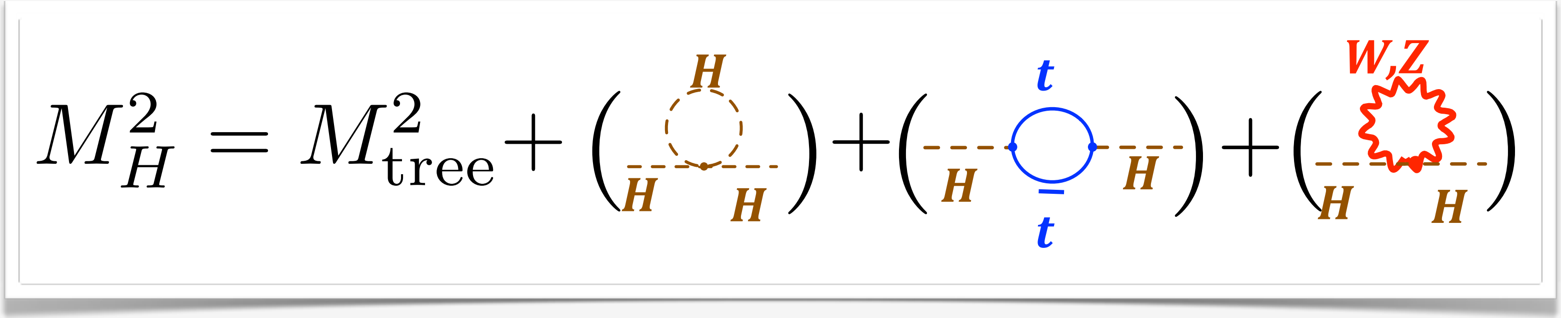
Yukawa couplings

particle physics


HIGGS
ticle phys
HIGGS

- We know of BSM physics.

First-ever spin 0 elementary particle.



- leads to perplexing quantum

  additive, quadratic cut-offs...

  in mass-squared, by the way

$$V(\text{Higgs}) = \boxed{-\mu^2\Phi^\dagger\Phi} + \lambda(\Phi^\dagger\Phi)^2$$

Comments:

Concern about this situation takes many forms and has many names.

It’s a quantum mechanical fact and relies on all of the machinery that we believed in to narrow the top quark mass window and the Higgs boson window.

But spin 0 fields are very different from any other and the consequences are for fundamentally problematic for some people.

to many

A Hint

To: 2013

From: Nature

Serious experimental anomalies

- The Higgs Boson mass is small.
- *ν*'s flavor, mass, symmetry properties not SM.
- Dark Matter needs a quantum.
- Primordial antimatter needs an explanation.
- (g-2)μ results need confirmation or disconfirmation

Serious experimental anomalies

- The Higgs Boson mass is small.
- *ν*’s flavor, symmetry properties not SM.
- Dark M uantum.
- Primordial a an explanation.
- (g-2)μ results need or disconfirmation

Dramatically influence the EF

Conclusions from the Energy Frontier

A three-pronged research program:

- Measure properties of the Higgs boson.
- Measure properties of the: *t*, *W*, and *Z*
- Search for TeV-scale particles

A three-pronged research program:

Mass, CP, and
especially
couplings

- Measure properties of the Higgs boson.
- Measure properties of the: *t*, *W*, and *Z*
- Search for TeV-scale particles

A three-pronged research program:

They talk to
the Higgs Field

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- Measure properties of the: t, W, and Z
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A three-pronged research program:

- Measure properties of the Higgs boson.
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Scale inspired by naturalness

🟩 The Snowmass Energy Frontier Process

Comments:

The EF organization started in June 2012 and kicked off at the CPM at Fermilab in October 2012.

From that point, conveners were in place and work began.

The first subgroup workshops began in January, 2013.

EF working groups

EF1: The Higgs Boson

- *Jianming Qian (Michigan), Andrei Gritsan (Johns Hopkins), Heather Logan (Carleton), Rick Van Kooten (Indiana), Chris Tully (Princeton), Sally Dawson (BNL)*

EF2: Precision Study of Electroweak Interactions

- *Doreen Wackeroth (Buffalo), Ashutosh Kotwal (Duke)*

EF3: Fully Understanding the Top Quark

- *Robin Erbacher (Davis), Reinhard Schwienhorst (MSU),Kirill Melnikov (Johns Hopkins), Cecilia Gerber (UIC), Kaustubh Agashe (Maryland)*

EF4: The Path Beyond the Standard Model–New Particles, Forces, and Dimensions

- *Daniel Whiteson (Irvine), Liantao Wang (Chicago), Yuri Gershtein (Rutgers), Meenakshi Narain (Brown), Markus Luty (UC Davis)*

EF5: Quantum Chromodynamics and the Strong Interactions

- *Ken Hatakeyama (Baylor), John Campbell (FNAL), Frank Petriello (Northwestern), Joey Huston (MSU)*

EF6: Flavor Physics and CP Violation at High Energy

- *Soeren Prell (ISU), Michele Papucci (LBNL), Marina Artuso (Syracuse)*

Comments:

This was an exhausting process.

The 25 conveners and hundreds of contributors worked hard – meeting weekly in some cases – for almost a year.

Snowmass has been a highly participatory and selfless activity by many particle physicists.

Organization:

Created necessary correlations among groups

- Technical groups, accelerators, simulations
    - *Eric Prebys, Eric Torrence, Tom LeCompte, Sanjay Padhi, Tor Raubenheimer, Jeff Berryhill, Markus Klute, and Mark Palmer*

Organization:

- Created necessary correlations among groups
  - Technical groups, accelerators, simulations
    - *Eric Prebys, Eric Torrence, Tom LeCompte, Sanjay Padhi, Tor Raubenheimer, Jeff Berryhill, Markus Klute, and Mark Palmer*
- Additional group “infrastructure”
  - established direct connection with the established collaborations:
    - *“Advisors”:*

      ATLAS: Ashutosh Kotwal; CMS: Jim Olsen; LHCb: Sheldon Stone; ILD: Graham Wilson; SiD: Andy White; CLIC: Mark Thomson; Muon Collider: Ron Lipton; VLHC: Dmitri Denisov

Energy Frontier Goals:

What are the scientific cases which motivate HL LHC running:

“Phase 1”: circa 2022 with ∫ L dt of approximately 300 fb -1

“Phase 2”: circa 2030 with ∫ L dt of approximately 3000 fb -1

- *How do the envisioned upgrade paths inform those goals?*
- *Specifically, to what extent is precision Higgs Boson physics possible?*

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Is there a scientific necessity for a precision Higgs Boson program?

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- *How do the envisioned upgrade paths inform those goals?*
- *Specifically, to what extent is precision Higgs Boson physics possible?*

Is there a scientific necessity for a precision Higgs Boson program?

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

- *High energy lepton collider?*
- *A high energy LHC?*
- *Lepton-hadron collider?*
- *VLHC?*

EF meetings:

the alloverthеplace workshop.

snowmass@Batavia

snowmass@Princeton

snowmass@Durham

snowmass@Brookhaven

snowmass@Dallas

snowmass@SantaBarbara

snowmass@Boston

snowmass@Tallahassee

snowmass@Boulder

snowmass@Geneva

snowmass@Seattle

snowmass@Minneapolis

We simulated against a defined set of accelerators

- This included:

LHC 14 TeV running at 300/fb and 3000/fb

LHC at 33 TeV

linear and circular e+e- colliders

muon collider

gamma-gamma colliders

pp collider at 100 TeV

Comments:

The full set of accelerators:

5 pp colliders, $(E_{cms};\int \mathcal{L}dt)$ =

pp(14; 300, 3000), (33; 3000), (100, 3000) TeV, fb^{-1}

9 lepton colliders, $(E_{cms};\int \mathcal{L}dt)$ =

Lin ee*: (250; 500), (500;500), (1000;1000) (1400;1400) GeV, fb^{-1}

Cir ee: (250; 2500), (350,350) GeV, fb^{-1}

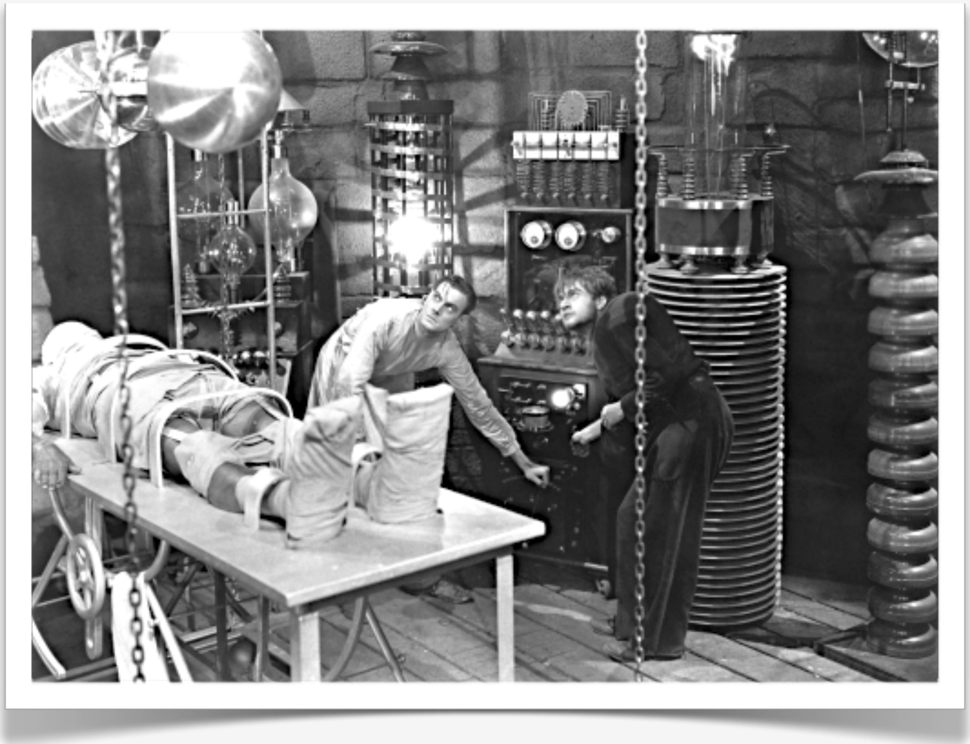
$\mu\mu$: (125; 2), (1500; 1000), (3000, 3000) GeV, fb^{-1}

$\gamma\gamma$: (125; 100), (200; 200), (800, 800) GeV, fb^{-1}

1 ep collider, $(E_{cms};\int \mathcal{L}dt)$ = e/p: (60/7000; 50) GeV / GeV, fb^{-1}

* incl polarization choices

Fast simulation tools



- LHC simulation strategies

  A Generic DELPHES 3 “Snowmass detector”

  Background simulations

- The LC community

  Snowmass-specific analyses beyond the CLIC CDR & ILC TDR.

  Signal & complete SM background samples

Comments:

A. Avetisyan et. al., “Methods and Results for Standard Model Event Generation at $\sqrt{s}$ = 14 TeV, 33 TeV and 100 TeV Proton Colliders (A Snowmass Whitepaper)”, arXiv:1308.1636, Aug. 2013 ,

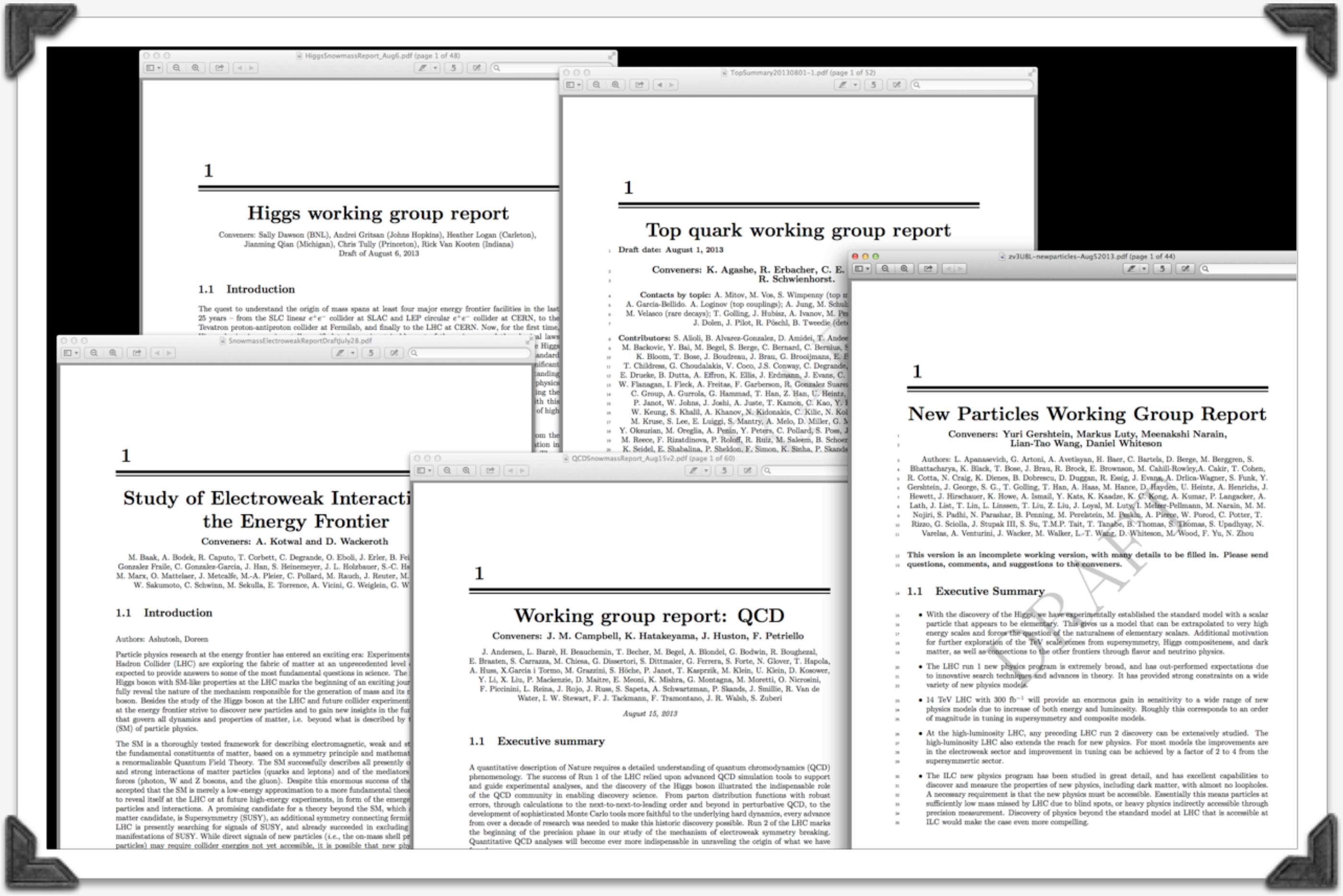
A. Avetisyan et. al., “Snowmass Energy Frontier Simulations using the Open Science Grid (A Snowmass 2013 whitepaper)”, arXiv:1308.0843, Aug. 2013 ,

A. Avetisyan et. al., “Snowmass Energy Frontier Simulations for Hadron Colliders ”, arXiv: 1308.XXX (Submitted) http://arxiv.org/submit/790246

Reports are being finished up

- 300 pages of technical detail

http://www.snowmass2013.org/tiki-index.php?page=Energy%20Frontier



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Higgs working group report

Conveners: Sally Dawson (BNL), Andrei Gritsan (Johns Hopkins), Heather Logan (Carleton),
Jianming Qian (Michigan), Chris Tully (Princeton), Rick Van Kooten (Indiana)
Draft of August 6, 2013

1.1 Introduction

The quest to understand the origin of mass spans at least four major energy frontier facilities in the last 25 years – from the SLC linear e^+e^- collider at SLAC and LEP circular e^+e^- collider at CERN, to the Tevatron proton-antiproton collider at Fermilab, and finally to the LHC at CERN. Now, for the first time,

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Top quark working group report

Draft date: August 1, 2013

Conveners: K. Agashe, R. Erbacher, C. E.
R. Schwienhorst.

Contacts by topic: A. Mitov, M. Vos, S. Wimpenny (top m
A. Garcia-Bellido. A. Loginov (top couplings); A. Jung, M. Schul
M. Velasco (rare decays); T. Golling, J. Hubisz, A. Ivanov, M. Pe
J. Dolen, J. Pilot, R. Pöschl, B. Tweedie (dete

Contributors: S. Alioli, B. Alvarez-Gonzalez, D. Amidei, T. Andee
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K. Bloom, T. Bose, J. Boudreau, J. Brau, G. Brooijmans, E. B
T. Childress, G. Choudalakis, V. Coco, J.S. Conway, C. Degrande,
E. Drueke, B. Dutta, A. Effron, K. Ellis, J. Erdmann, J. Evans, C.
W. Flanagan, I. Fleck, A. Freitas, F. Garberson, R. Gonzalez Suare
C. Group, A. Gurrola, G. Hammad, T. Han, Z. Han, U. Heintz,
P. Janot, W. Johns, J. Joshi, A. Juste, T. Kamon, C. Kao, Y. I
W. Keung, S. Khalil, A. Khanov, N. Kidonakis, C. Kilic, N. Kol
M. Kruse, S. Lee, E. Luiggi, S. Mantry, A. Melo, D. Miller, G. M
Y. Oksuzian, M. Oreglia, A. Penin, Y. Peters, C. Pollard, S. Poss, J
M. Reece, F. Rizatdinova, P. Roloff, R. Ruiz, M. Saleem, B. Schoer
K. Seidel, E. Shabalina, P. Sheldon, F. Simon, K. Sinha, P. Skands

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Study of Electroweak Interacti
the Energy Frontier

Conveners: A. Kotwal and D. Wackeroth

M. Baak, A. Bodek, R. Caputo, T. Corbett, C. Degrande, O. Eboli, J. Erler, B. Fei
Gonzalez Fraile, C. Gonzalez-Garcia, J. Han, S. Heinemeyer, J. L. Holzbauer, S.-C. Hs
M. Marx, O. Mattelaer, J. Metcalfe, M.-A. Pleier, C. Pollard, M. Rauch, J. Reuter, M.
W. Sakumoto, C. Schwinn, M. Sekulla, E. Torrence, A. Vicini, G. Weiglein, G. W

1.1 Introduction

Authors: Ashutosh, Doreen

Particle physics research at the energy frontier has entered an exciting era: Experiments
Hadron Collider (LHC) are exploring the fabric of matter at an unprecedented level
expected to provide answers to some of the most fundamental questions in science. The
Higgs boson with SM-like properties at the LHC marks the beginning of an exciting jour
fully reveal the nature of the mechanism responsible for the generation of mass and its
boson. Besides the study of the Higgs boson at the LHC and future collider experiment
at the energy frontier strive to discover new particles and to gain new insights in the fu
that govern all dynamics and properties of matter, i.e. beyond what is described by
(SM) of particle physics.

The SM is a thoroughly tested framework for describing electromagnetic, weak and st
the fundamental constituents of matter, based on a symmetry principle and mathemat
a renormalizable Quantum Field Theory. The SM successfully describes all presently
and strong interactions of matter particles (quarks and leptons) and of the mediators
forces (photon, W and Z bosons, and the gluon). Despite this enormous success of th
accepted that the SM is merely a low-energy approximation to a more fundamental theo
to reveal itself at the LHC or at future high-energy experiments, in form of the emerge
particles and interactions. A promising candidate for a theory beyond the SM, which
matter candidate, is Supersymmetry (SUSY), an additional symmetry connecting fermi
LHC is presently searching for signals of SUSY, and already succeeded in excluding
manifestations of SUSY. While direct signals of new particles (i.e., the on-mass shell p
particles) may require collider energies not yet accessible, it is possible that new ph

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Working group report: QCD

Conveners: J. M. Campbell, K. Hatakeyama, J. Huston, F. Petriello

J. Andersen, L. Barzè, H. Beauchemin, T. Becher, M. Begel, A. Blondel, G. Bodwin, R. Boughezal,
E. Braaten, S. Carrazza, M. Chiesa, G. Dissertori, S. Dittmaier, G. Ferrera, S. Forte, N. Glover, T. Hapola,
A. Huss, X.Garcia i Tormo, M. Grazzini, S. Höche, P. Janot, T. Kasprzik, M. Klein, U. Klein, D. Kosower,
Y. Li, X. Liu, P. Mackenzie, D. Maitre, E. Meoni, K. Mishra, G. Montagna, M. Moretti, O. Nicrosini,
F. Piccinini, L. Reina, J. Rojo, J. Russ, S. Sapeta, A. Schwartzman, P. Skands, J. Smillie, R. Van de
Water, I. W. Stewart, F. J. Tackmann, F. Tramontano, J. R. Walsh, S. Zuberi

August 15, 2013

1.1 Executive summary

A quantitative description of Nature requires a detailed understanding of quantum chromodynamics (QCD) phenomenology. The success of Run 1 of the LHC relied upon advanced QCD simulation tools to support and guide experimental analyses, and the discovery of the Higgs boson illustrated the indispensable role of the QCD community in enabling discovery science. From parton distribution functions with robust errors, through calculations to the next-to-next-to-leading order and beyond in perturbative QCD, to the development of sophisticated Monte Carlo tools more faithful to the underlying hard dynamics, every advance from over a decade of research was needed to make this historic discovery possible. Run 2 of the LHC marks the beginning of the precision phase in our study of the mechanism of electroweak symmetry breaking. Quantitative QCD analyses will become ever more indispensable in unraveling the origin of what we have

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New Particles Working Group Report

Conveners: Yuri Gershtein, Markus Luty, Meenakshi Narain,
Lian-Tao Wang, Daniel Whiteson

Authors: L. Apanasevich, G. Artoni, A. Avetisyan, H. Baer, C. Bartels, D. Berge, M. Berggren, S. Bhattacharya, K. Black, T. Bose, J. Brau, R. Brock, E. Brownson, M. Cahill-Rowley,A. Cakir, T. Cohen, R. Cotta, N. Craig, K. Dienes, B. Dobrescu, D. Duggan, R. Essig, J. Evans, A. Drlica-Wagner, S. Funk, Y. Gershtein, J. George, S. G., T. Golling, T. Han, A. Haas, M. Hance, D. Hayden, U. Heintz, A. Henrichs, J. Hewett, J. Hirschauer, K. Howe, A. Ismail, Y. Kats, K. Kaadze, K. C. Kong, A. Kumar, P. Langacker, A. Lath, J. List, T. Lin, L. Linssen, T. Liu, Z. Liu, J. Loyal, M. Luty, I. Melzer-Pellmann, M. Narain, M. M. Nojiri, S. Padhi, N. Parashar, B. Penning, M. Perelstein, M. Peskin, A. Pierce, W. Porod, C. Potter, T. Rizzo, G. Sciolla, J. Stupak III, S. Su, T.M.P. Tait, T. Tanabe, B. Thomas, S. Thomas, S. Upadhyay, N. Varelas, A. Venturini, J. Wacker, M. Walker, L.-T. Wang, D. Whiteson, M. Wood, F. Yu, N. Zhou

This version is an incomplete working version, with many details to be filled in. Please send questions, comments, and suggestions to the conveners.

1.1 Executive Summary

- With the discovery of the Higgs, we have experimentally established the standard model with a scalar particle that appears to be elementary. This gives us a model that can be extrapolated to very high energy scales and forces the question of the naturalness of elementary scalars. Additional motivation for further exploration of the TeV scale comes from supersymmetry, Higgs compositeness, and dark matter, as well as connections to the other frontiers through flavor and neutrino physics.
- The LHC run 1 new physics program is extremely broad, and has out-performed expectations due to innovative search techniques and advances in theory. It has provided strong constraints on a wide variety of new physics models.
- 14 TeV LHC with 300 fb^{-1} will provide an enormous gain in sensitivity to a wide range of new physics models due to increase of both energy and luminosity. Roughly this corresponds to an order of magnitude in tuning in supersymmetry and composite models.
- At the high-luminosity LHC, any preceding LHC run 2 discovery can be extensively studied. The high-luminosity LHC also extends the reach for new physics. For most models the improvements are in the electroweak sector and improvement in tuning can be achieved by a factor of 2 to 4 from the supersymmertic sector.
- The ILC new physics program has been studied in great detail, and has excellent capabilities to discover and measure the properties of new physics, including dark matter, with almost no loopholes. A necessary requirement is that the new physics must be accessible. Essentially this means particles at sufficiently low mass missed by LHC due to blind spots, or heavy physics indirectly accessible through precision measurement. Discovery of physics beyond the standard model at LHC that is accessible at ILC would make the case even more compelling.

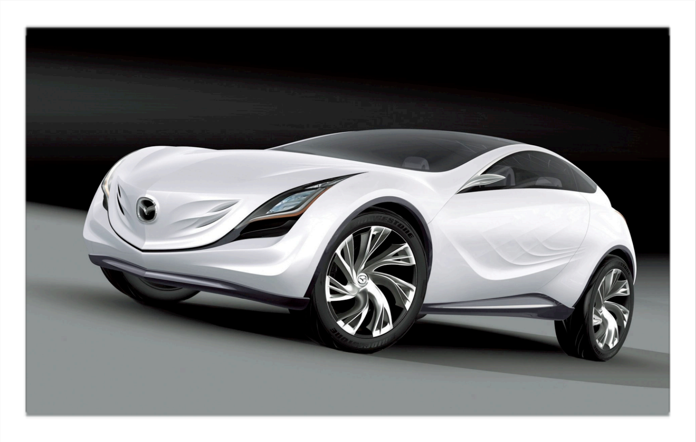
Comments:

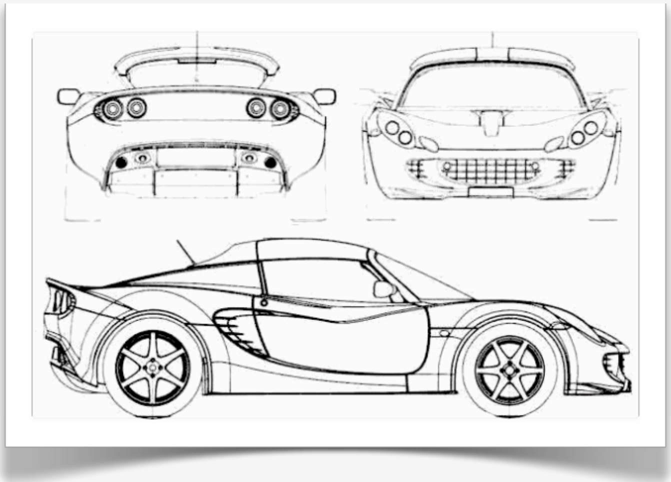
Some work is still going on.

End of September is the drop-dead date.

- two points

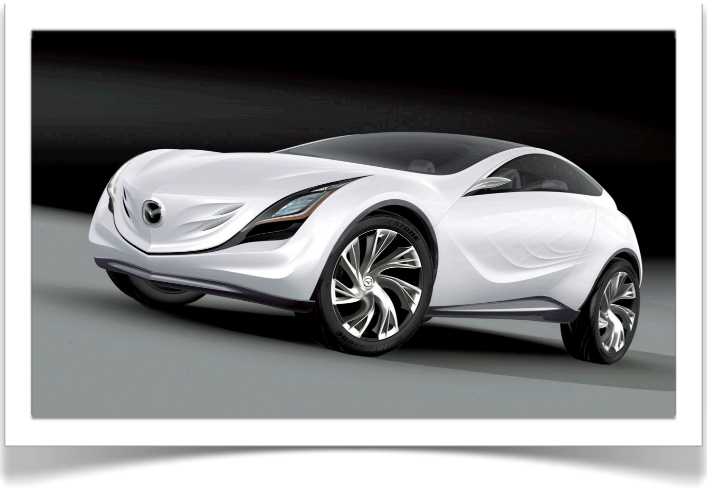
the Proposal Frontier

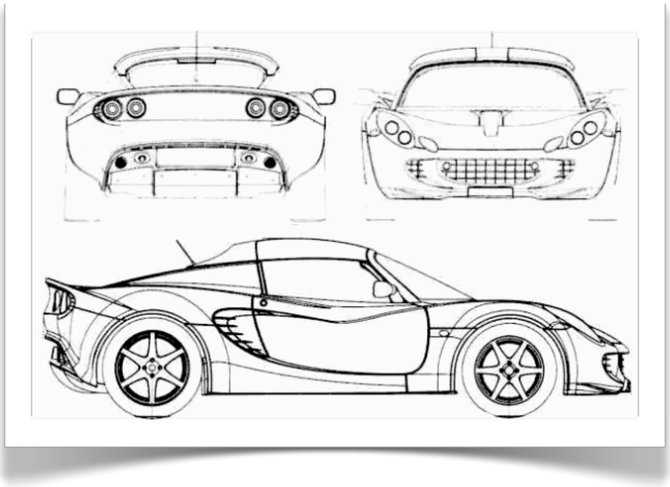




Comments:

LHC 100/fb	LHC 300/fb	LHC 3/ab	ILC 250-500GeV	ILC 1TeV	CLIC >1TeV	MC	TLEP	VLHC
years beyond TDR	TDR	LOI	TDR	TDR	CDR			





Comments:

The EF struggled with the differences among potential new facilities.

On the one hand, we felt an obligation to evaluate only physics potential without regard to “likelihood” of realization or a timeline.

On the other hand, there is a burden that the LHC experiments face by being “real.” They were ultimately reduced in scope for actual construction and budgets and contend with extrapolations based on existing detectors. This leads to conservatism.

And there is the extraordinary preparation behind an ILC program, unmatched by any other future facility.

Exclusion

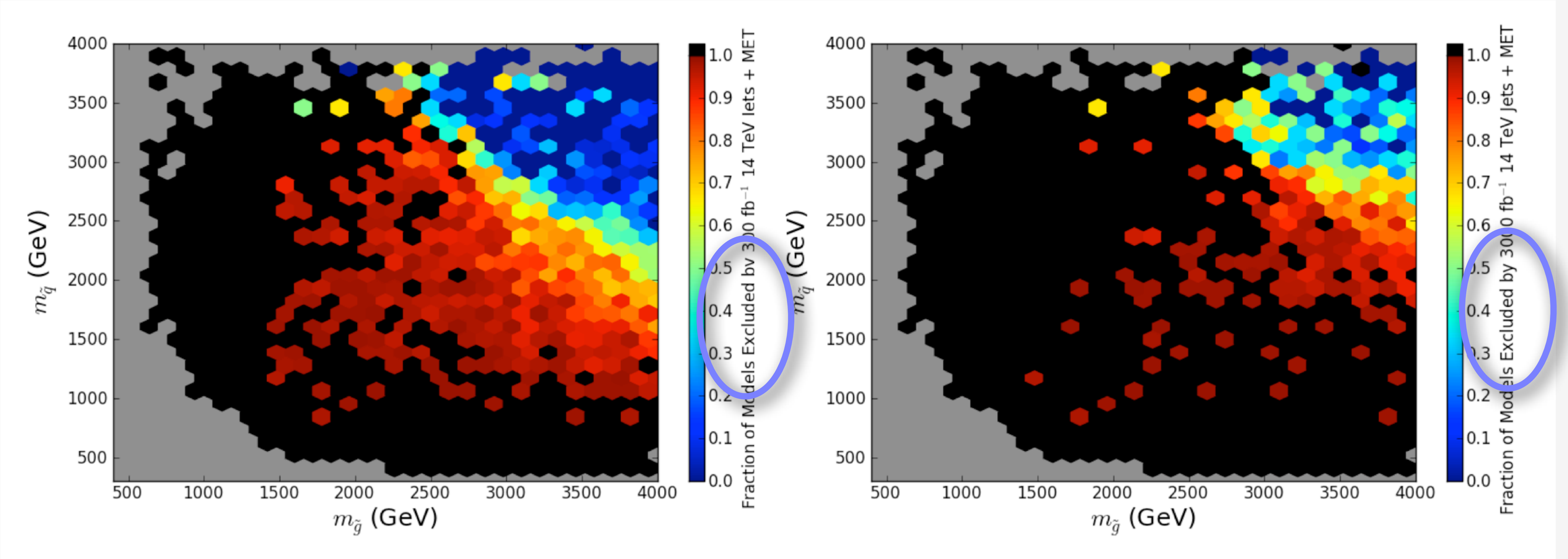
- we always speak of “exclusion plots”

  implying that the goal is to eliminate any place for new physics!

Not exclusion.

Discovery

- We’ve all seen these nice Cahill-Rowley, Hewett, Rizzo grids



300/fb

3000/fb

No exclusion.

Discovery

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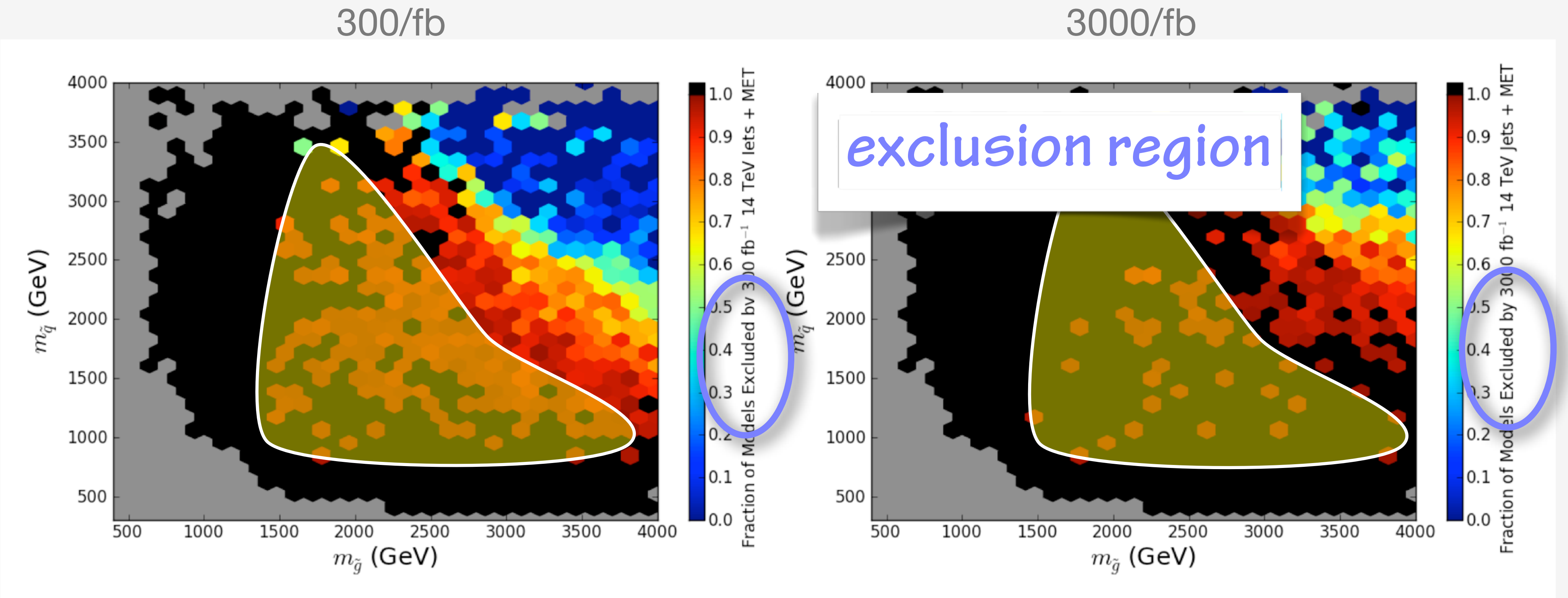

No exclusion.

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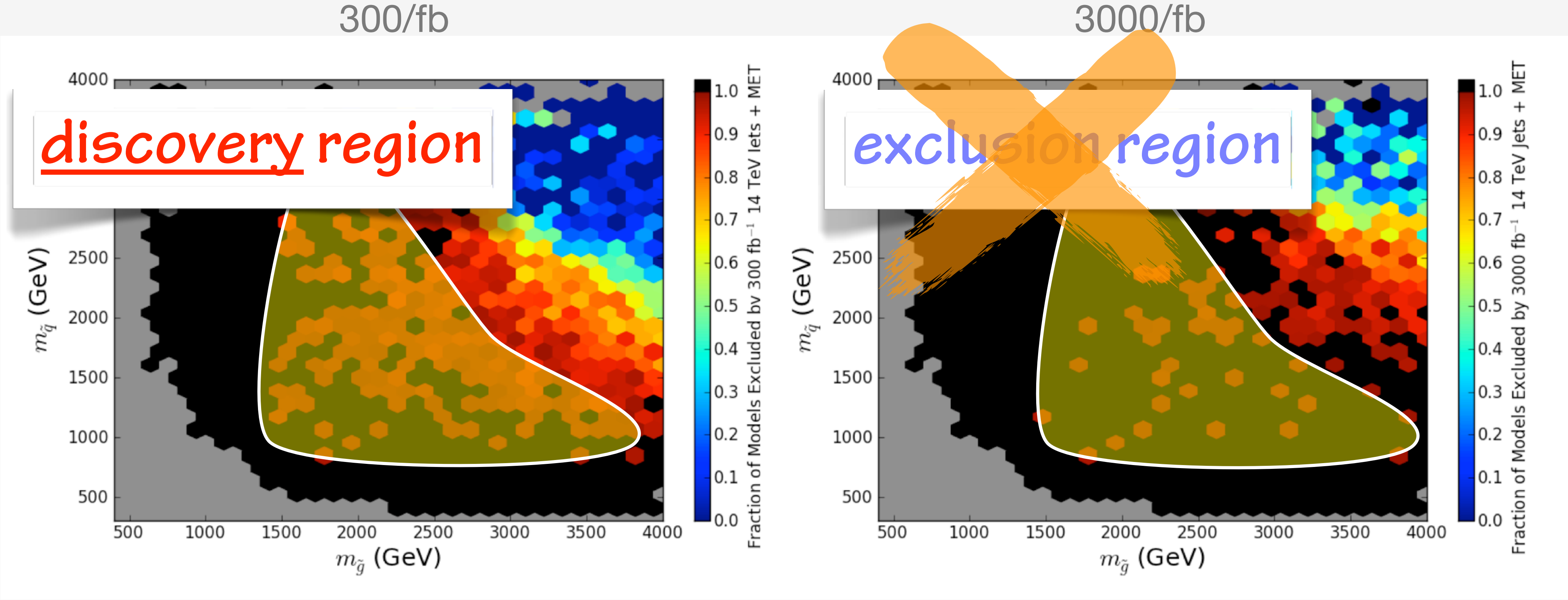


🟩 Working Group Results

Comments:

We asked for the following from each working group:

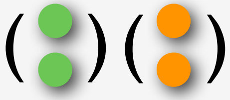
1. The few themes that guided their investigations.
2. The “take-away message” from their work.
3. The cases for each potential facility that come from their investigations.

The following will report in detail on 1,2, and 3 and inadequately report on bits of their actual results.

Big Questions

1. How do we understand the Higgs boson?

2. How do we understand the multiplicity of quarks and leptons?

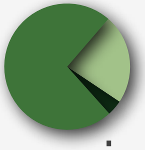


3. How do we understand the neutrinos?

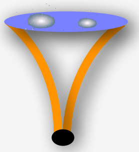
4. How do we understand the matter-antimatter asymmetry of the universe?

5. How do we understand the substance of dark matter?

6. How do we understand the dark energy?



7. How do we understand the origin of structure in the universe?



8. How do we understand the multiplicity of forces?

9. Are there new particles at the TeV energy scale?

10. Are there new particles that are light and extremely weakly interacting?

11. Are there extremely massive particles to which we can only couple indirectly at currently accessible energies?

Comments:

The Snowmass conveners have tried to come up with a set of Big Questions – not necessarily *Quantum Universe*, but "professional" questions that motivate research.

The following is the state of these at this time. They, along with questions from Instrumentation, Computing, Outreach, and Accelerators will be in the final report.

1. How do we understand the Higgs boson? What principle determines its couplings to quarks and leptons? Why does it condense and acquire a vacuum value throughout the universe? Is there one Higgs particle or many? Is the Higgs particle elementary or composite?

2. What principle determines the masses and mixings of quarks and leptons? Why is the mixing pattern apparently different for quarks and leptons? Why is the CKM CP phase nonzero? Is there CP violation in the lepton sector?

3. Why are neutrinos so light compared to other matter particles? Are neutrinos their own antiparticles? Are their small masses connected to the presence of a very high mass scale? Are there new interactions invisible except through their role in neutrino physics?

4. What mechanism produced the excess of matter over anti-matter that we see in the universe? Why are the interactions of particles and antiparticles not exactly mirror opposites?

5. Dark matter is the dominant component of mass in the universe. What is the dark matter made of? Is it composed of one type of new particle or several? What principle determined the current density of dark matter in the universe? Are the dark matter particles connected to the particles of the Standard Model, or are they part of an entirely new dark sector of particles?

6. What is dark energy? Is it a static energy per unit volume of the vacuum, or is it dynamical and evolving with the universe? What principle determines its value?

7. What did the universe look like in its earliest moments, and how did it evolve to contain the structures we observe today? The inflationary universe model requires new fields active in the early universe. Where did these come from, and how can we probe them today?

8. Are there additional forces that we have not yet observed? Are there additional quantum numbers associated with new fundamental symmetries? Are the four known forces unified at very short distances? What principles are involved in this unification?

9. Are there new particles at the TeV energy scale? Such particles are motivated by the problem of the Higgs boson, and by ideas about spacetime symmetry such as supersymmetry and extra dimensions. If they exist, how do they acquire mass, and what is their mass spectrum? Do they carry new sources of quark and lepton mixing and CP violation?

10. Are there new particles that are light and extremely weakly interacting? Such particles are motivated by many issues, including the strong CP problem, dark matter, dark energy, inflation, and attempts to unify the microscopic forces with gravity. What experiments can be used to find evidence for these particles?

11. Are there extremely massive particles to which we can only couple indirectly at currently accessible energies? Examples of such particles are seesaw heavy neutrinos or GUT scale particles mediating proton decay.

- The Higgs Boson

Higgs Boson Group Themes:

1. outline 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

couplings

$$V(\text{Yukawa}) = \left[\boxed{y_{ij}}\,\bar{f}_{Li} f_{Rj} \phi + HC\right]$$

Higgs discovery spawned an industry

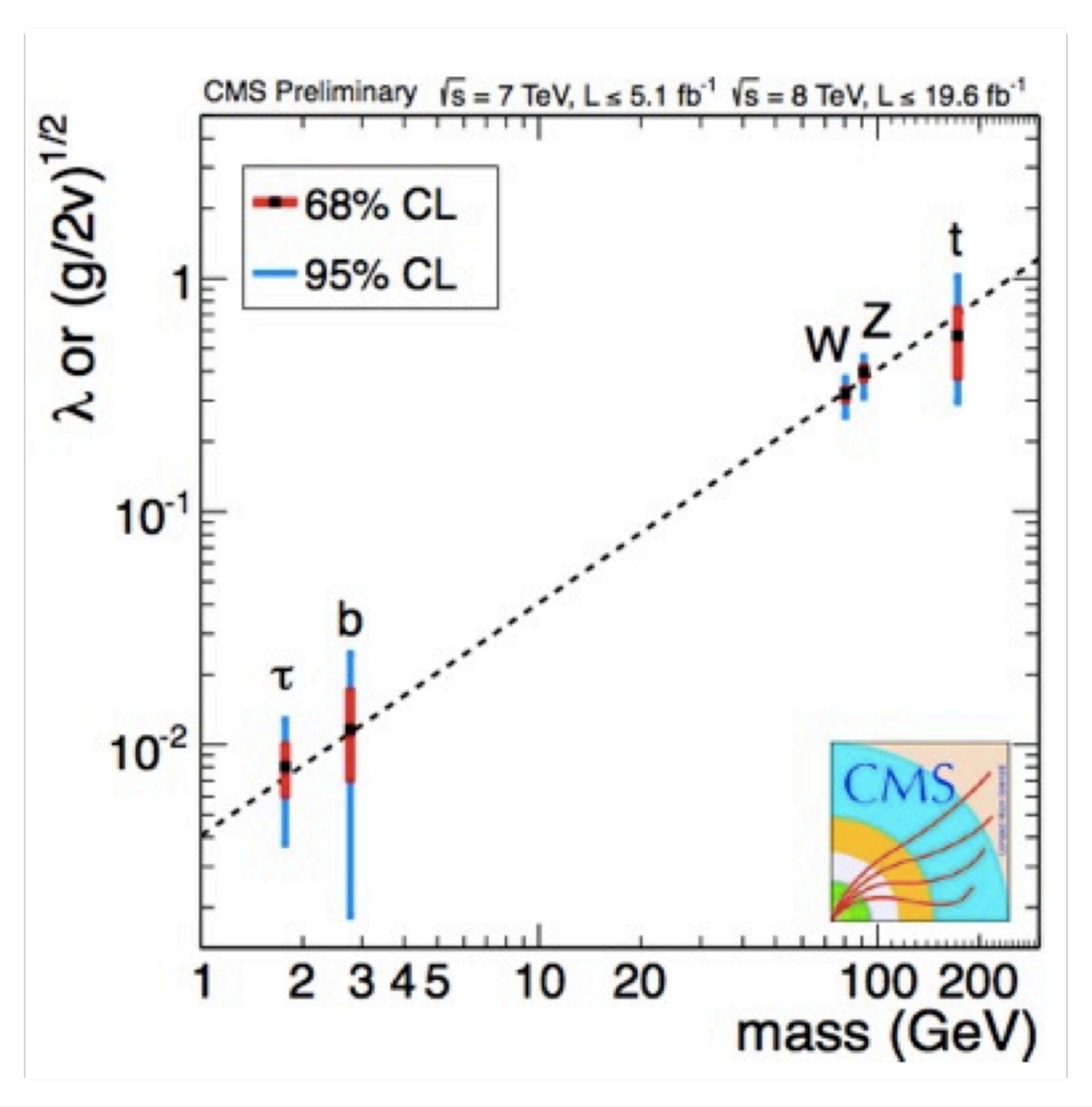
- precision fitting of couplings,

  eg for fermions

couplings

Early results are in line

- for fermions and VBs



couplings

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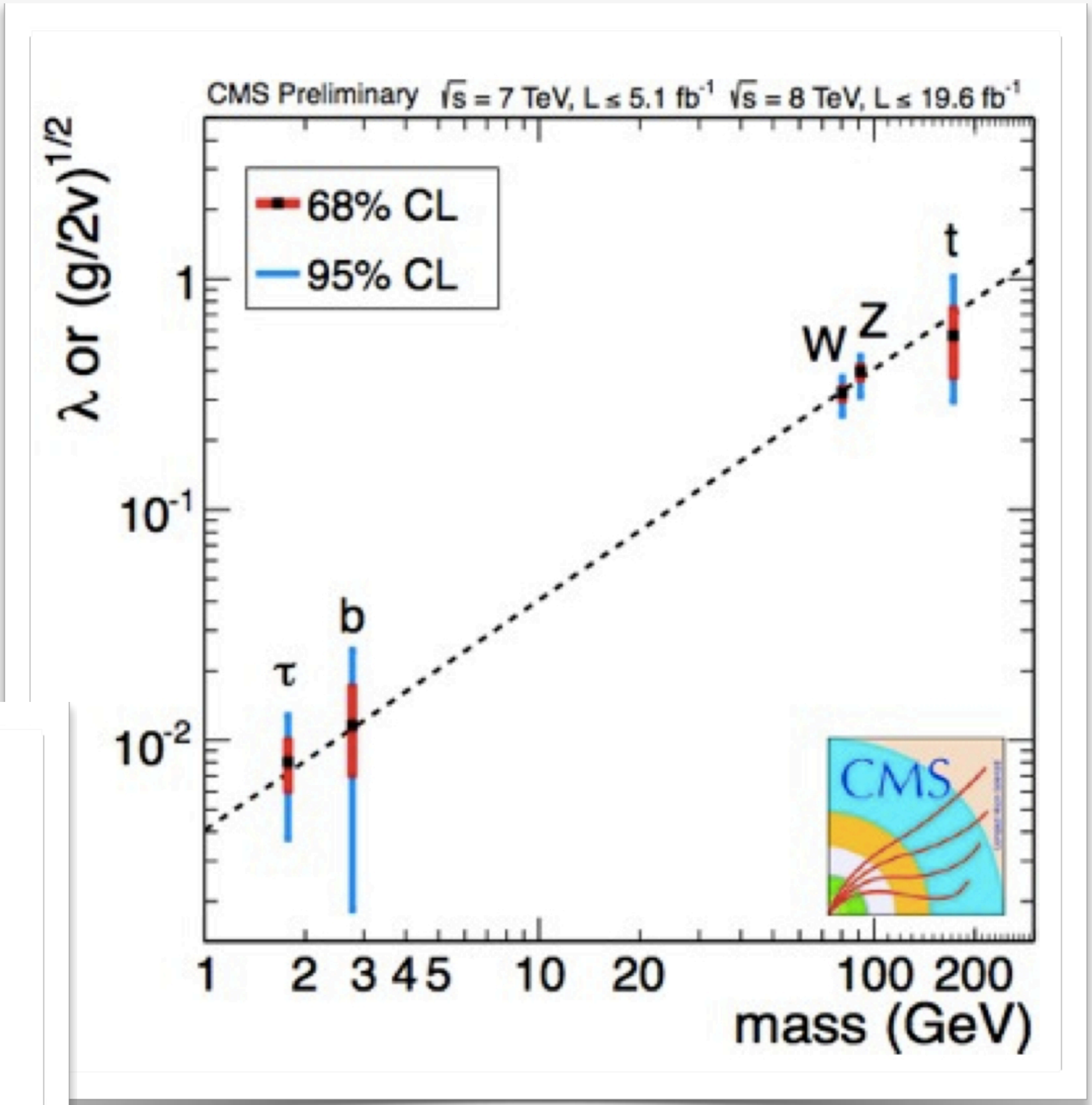
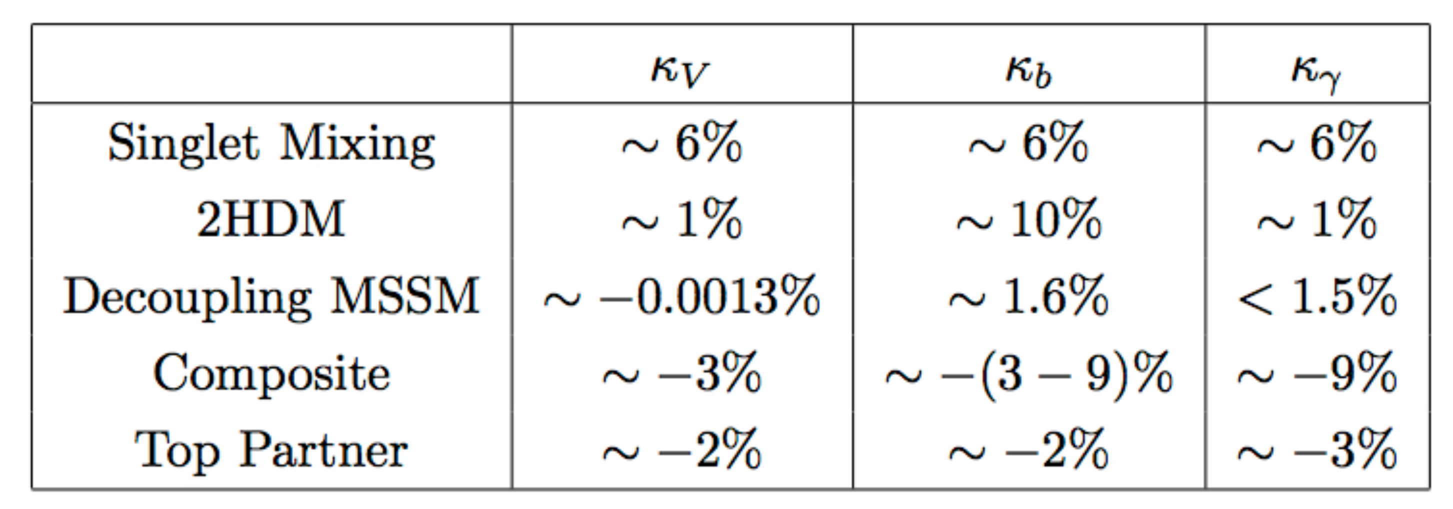


The precision Higgs boson program has begun.

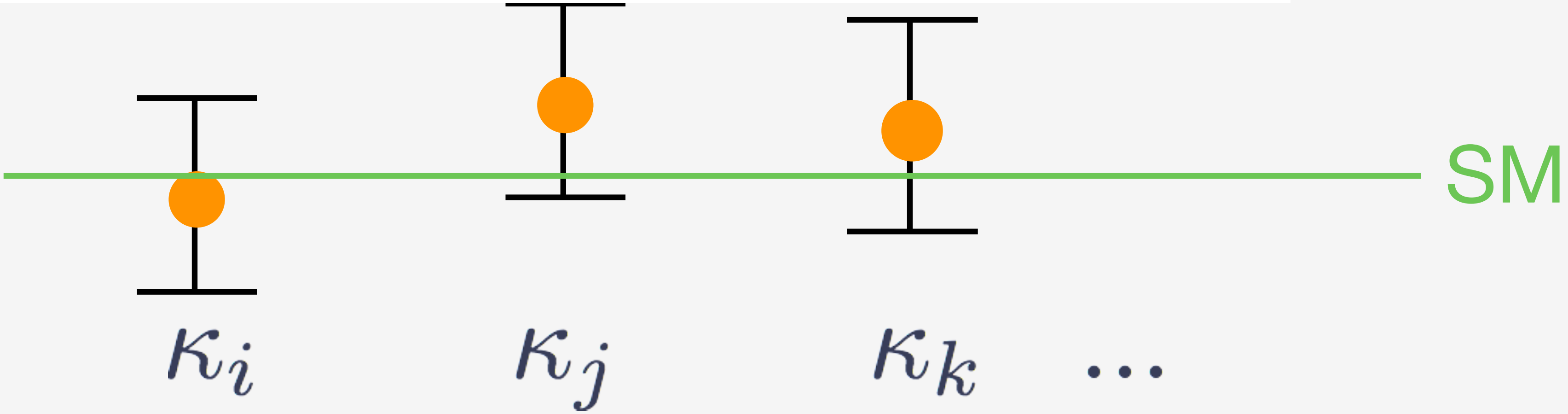
How well do we need to know couplings?

Higgs group evaluated models

- when new particles are ~1TeV:

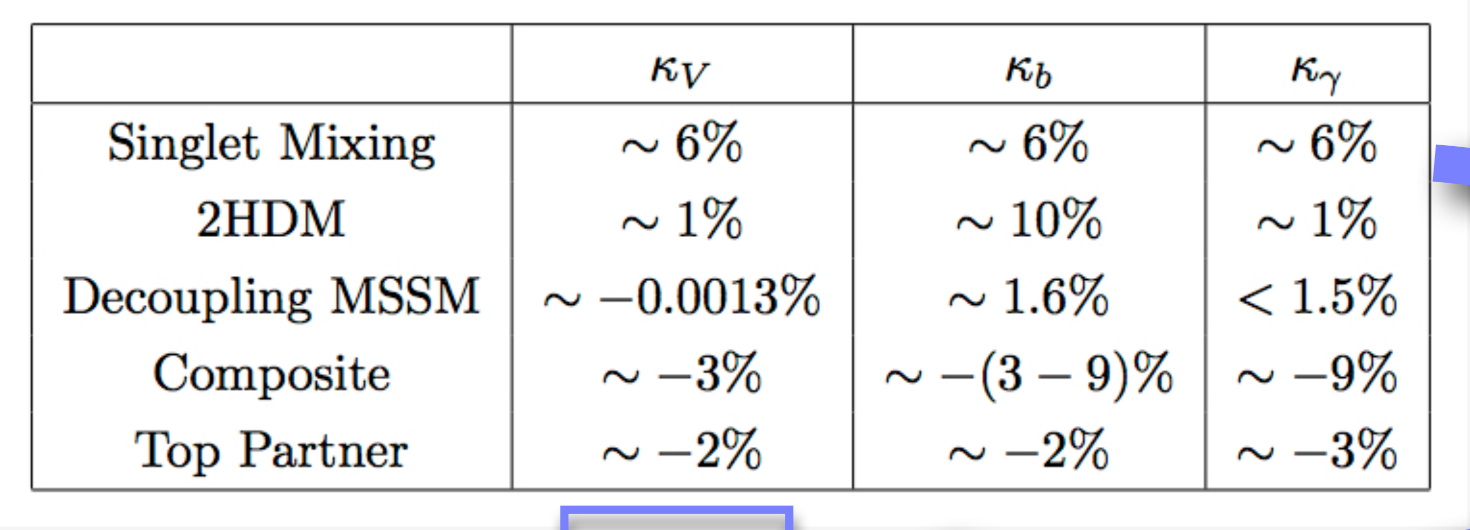


	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



precision for precision's sake?

No - this is a discovery search



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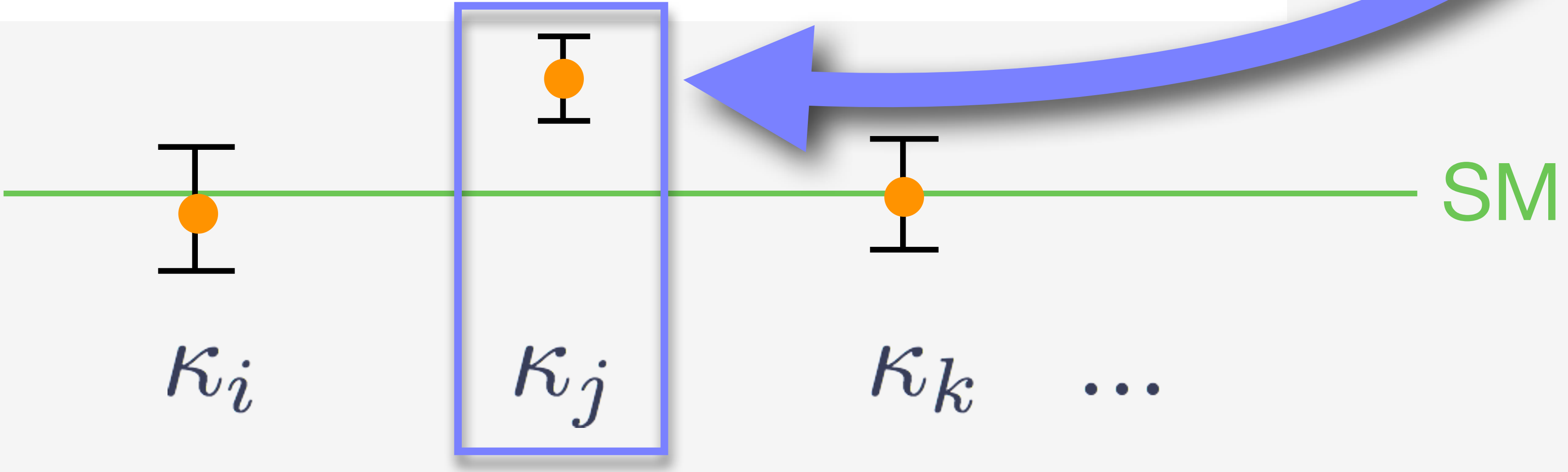
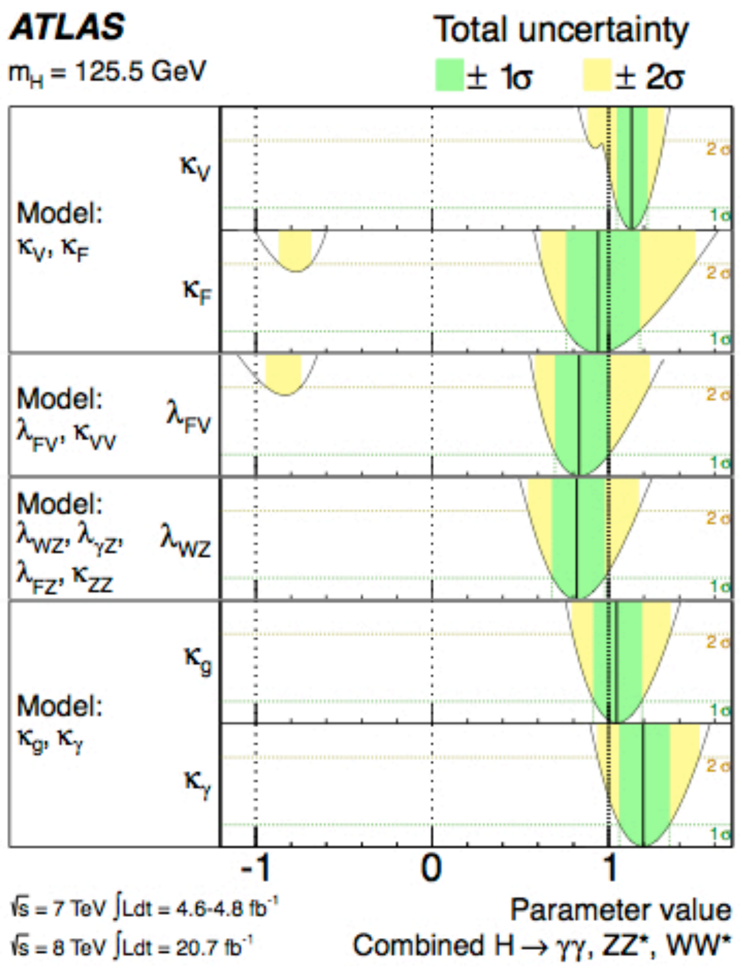
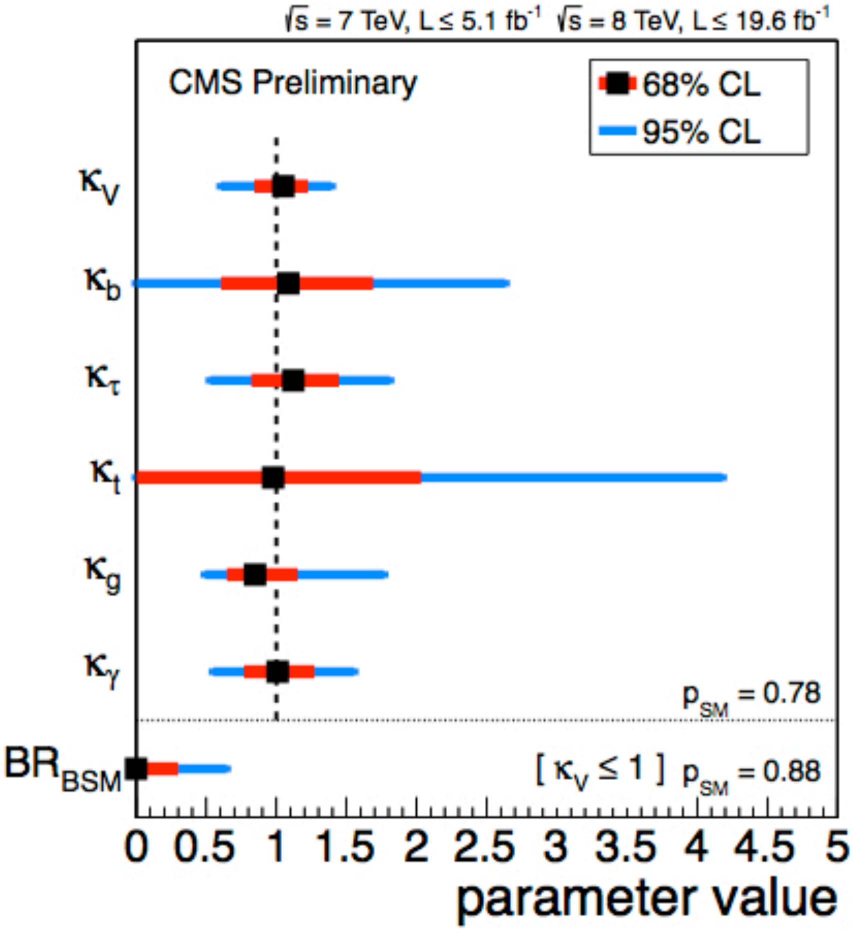
Benchmark for discovery is few % to sub-%



Current precision is multiple 10’s%.

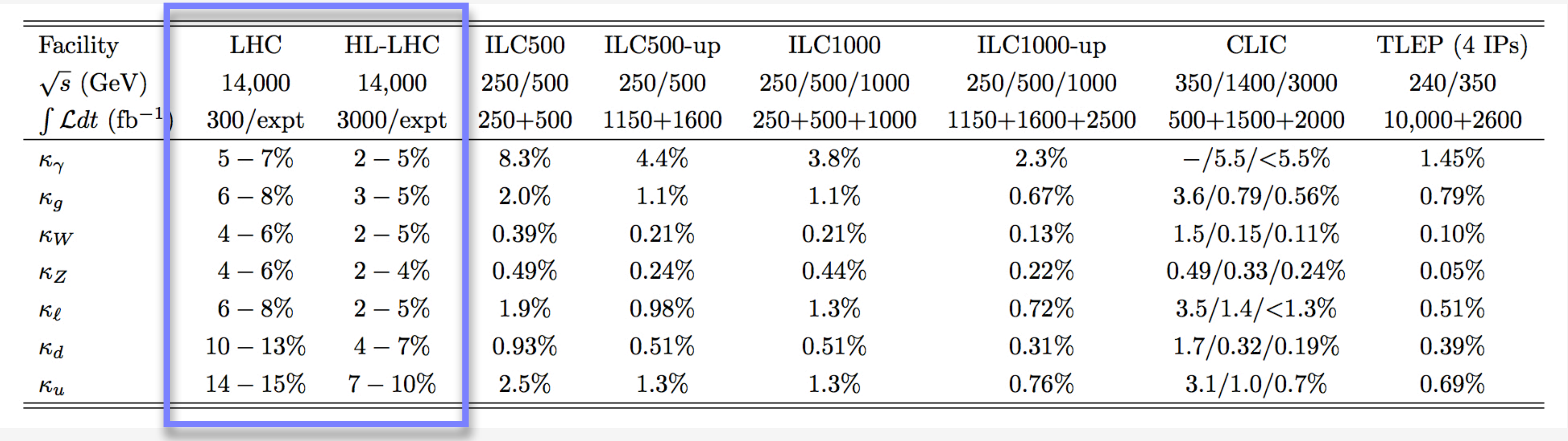




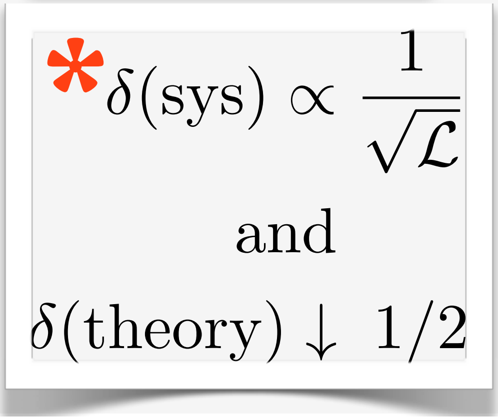
Evaluation of coupling extrapolations

Extrapolating LHC requires a strategy

- 2 numbers shown:*



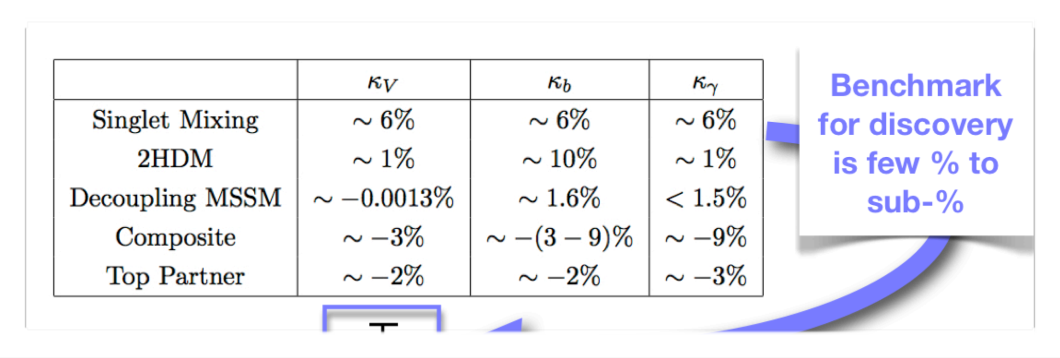
Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
κ_d	$10-13\%$	$4-7\%$	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%



$$*\delta(\text{sys}) \propto \frac{1}{\sqrt{\mathcal{L}}}$$

and

$$\delta(\text{theory}) \downarrow 1/2$$



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Benchmark for discovery is few % to sub-%

Comments:

caption for the table, including assumptions of polarizations and definitions:

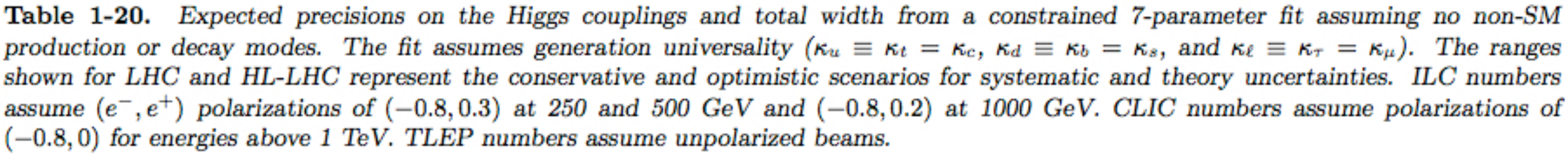
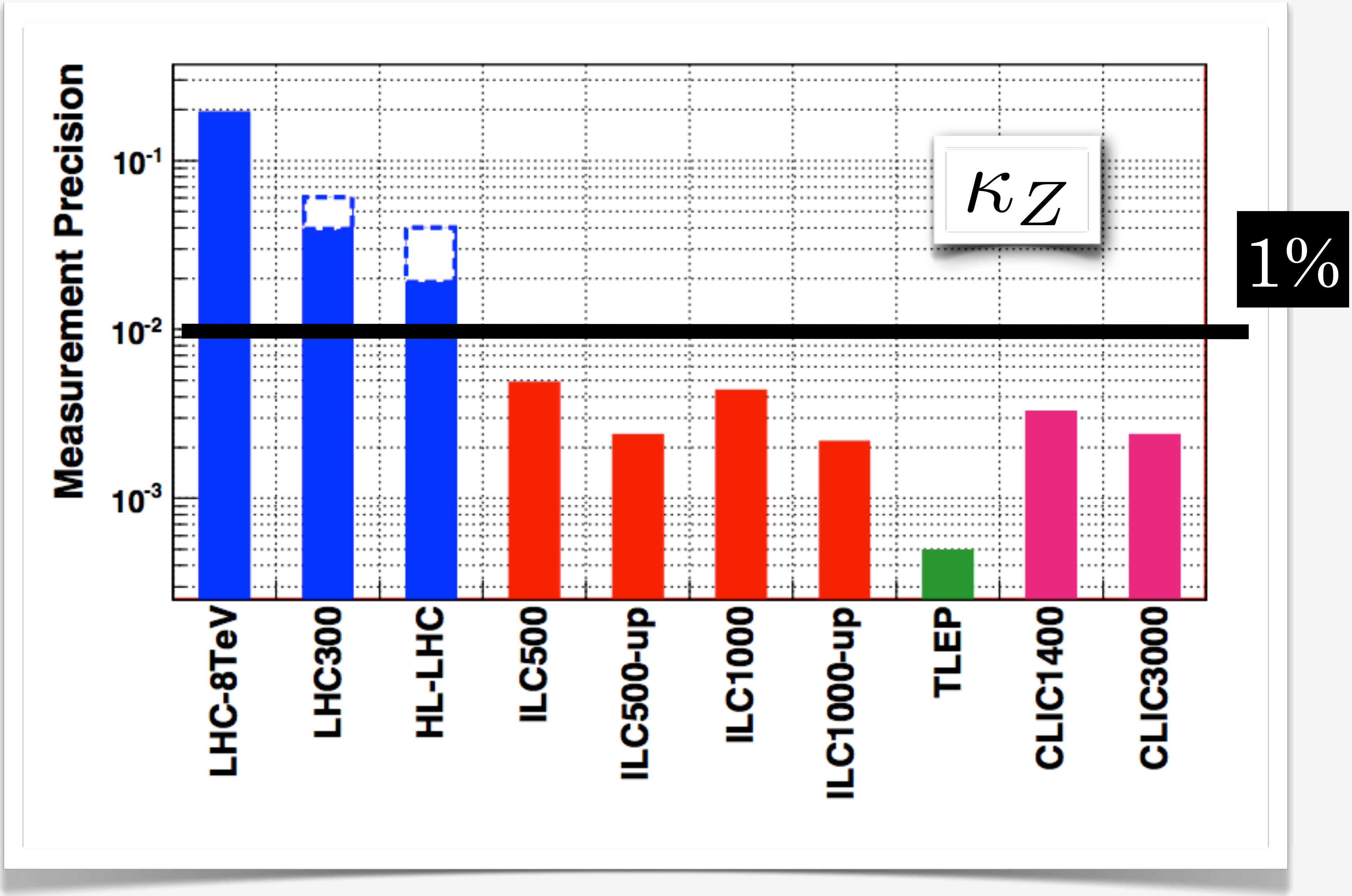


Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

example precision by facility

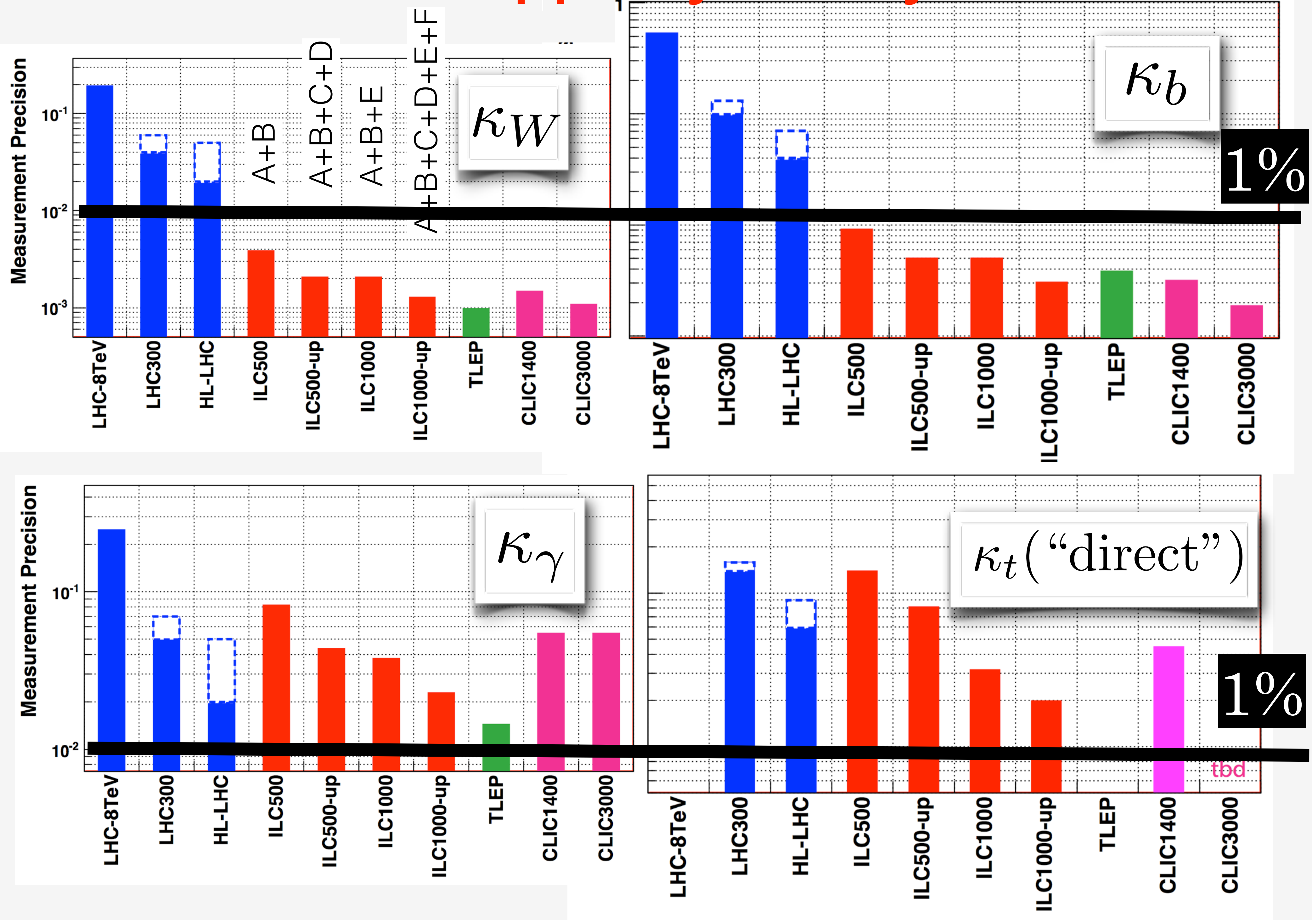


Comments:

The running scenarios assumed for an ILC are from the TDR

and are a little complicated.

Precision in kappa by facility



Comments:

“direct” *t* couplings refers to producing *ttbar* final states, for LHC in particular this was an analysis of $pp \to t\bar{t}H \to t\bar{t}WW$

Lepton colliders can perform a model-independent fitting of Higgs couplings. From the report:

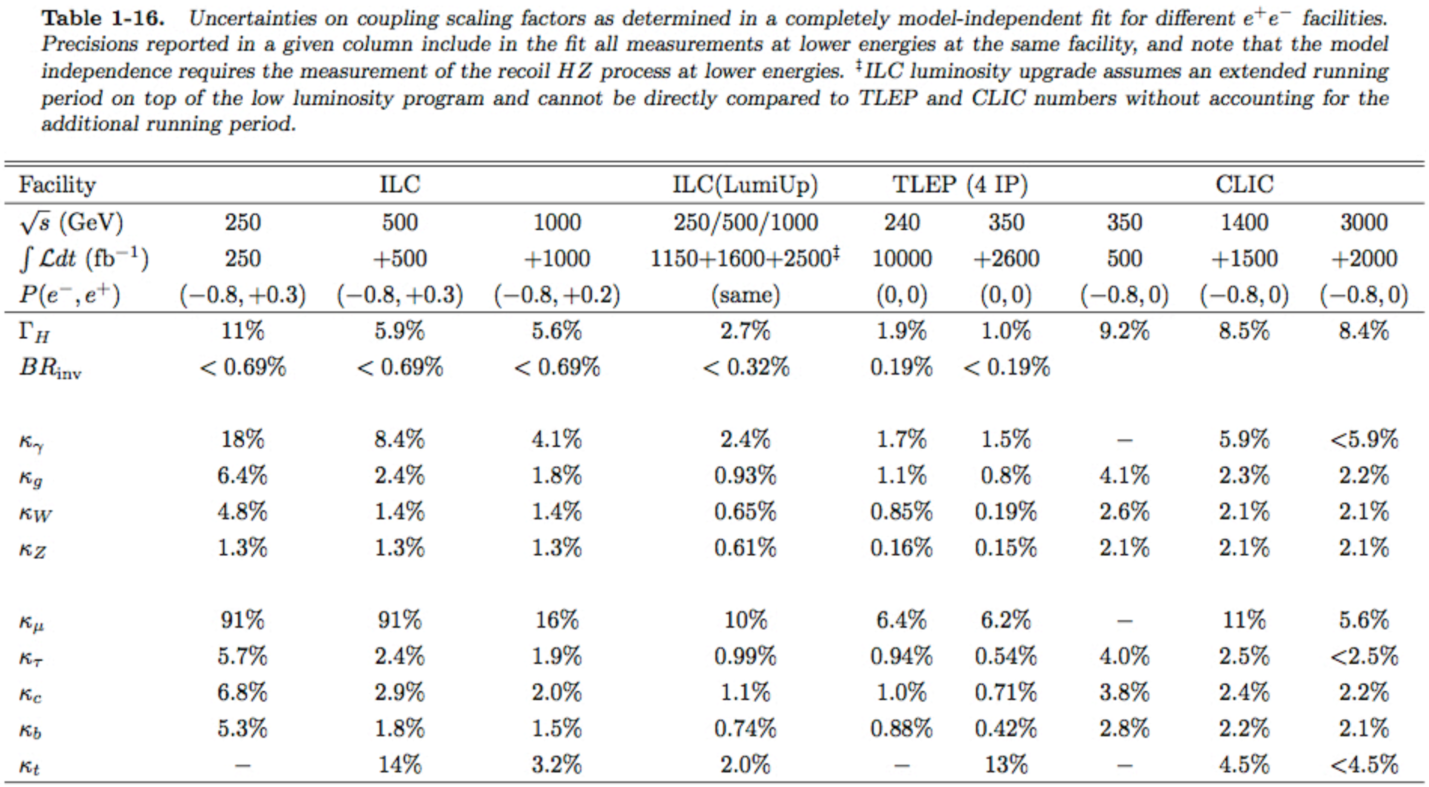


Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period.*

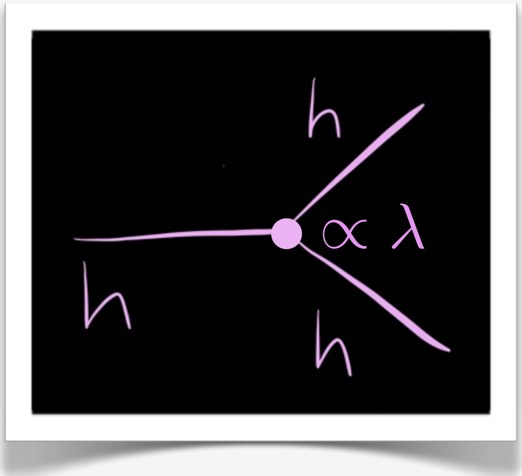
Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	11%	5.9%	5.6%	2.7%	1.9%	1.0%	9.2%	8.5%	8.4%
BR_{inv}	< 0.69%	< 0.69%	< 0.69%	< 0.32%	0.19%	< 0.19%			
κ_γ	18%	8.4%	4.1%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.4%	1.8%	0.93%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.8%	1.4%	1.4%	0.65%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.3%	1.3%	0.61%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.7%	2.4%	1.9%	0.99%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.9%	2.0%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.8%	1.5%	0.74%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%

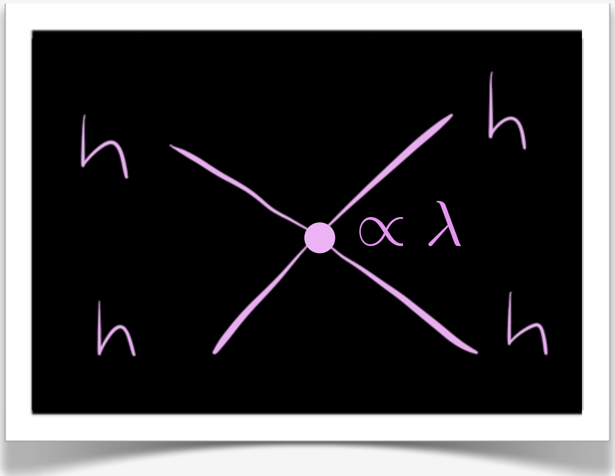
Higgs Self-Coupling

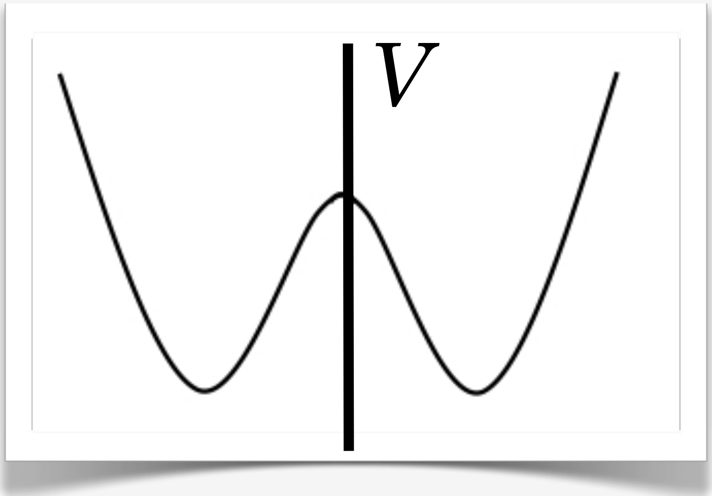
Critical feature of SM

$$V(\text{Higgs}) = -\mu^2\Phi^\dagger\Phi + \boxed{\lambda}(\Phi^\dagger\Phi)^2$$

- extremely challenging







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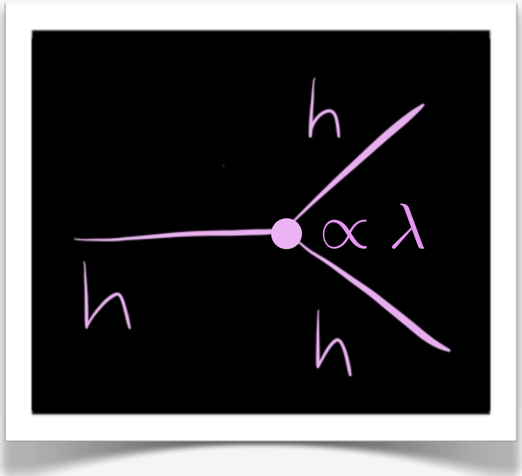

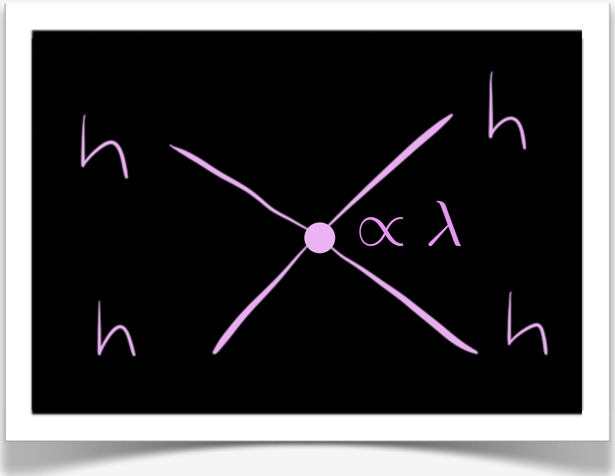

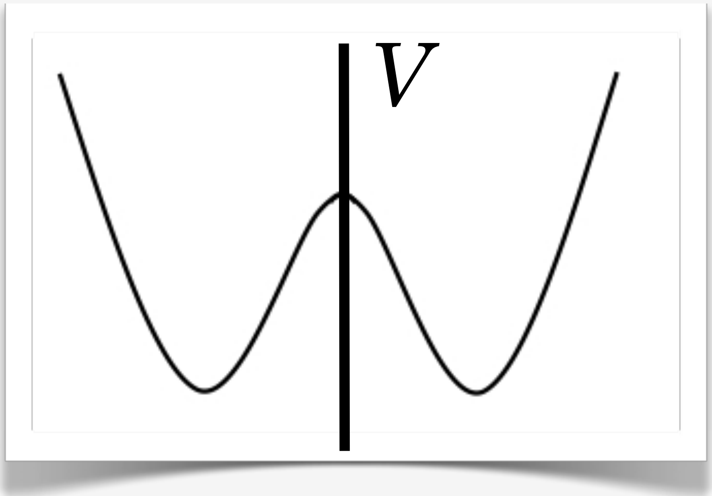

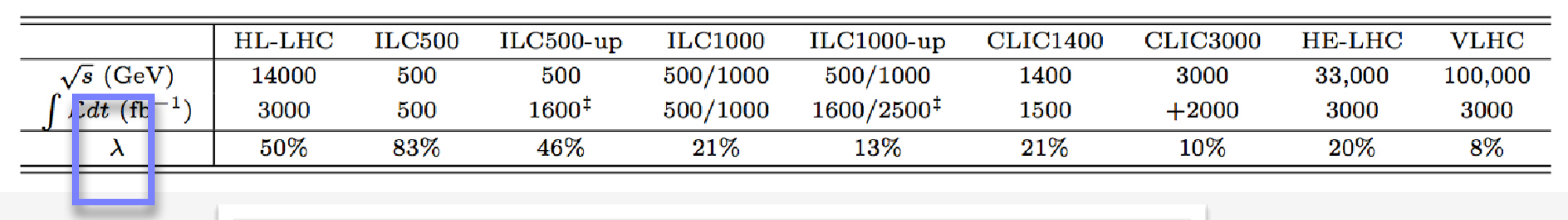

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
$\boxed{\lambda}$	50%	83%	46%	21%	13%	21%	10%	20%	8%

Higgs self-coupling is difficult to measure precisely at any facility.

m_H & Γ_H can be determined to a few %

Mass

- LHC: 50 MeV/c^2
- ILC: 35 MeV/c^2

m_H & Γ_H can be determined to a few %

Mass

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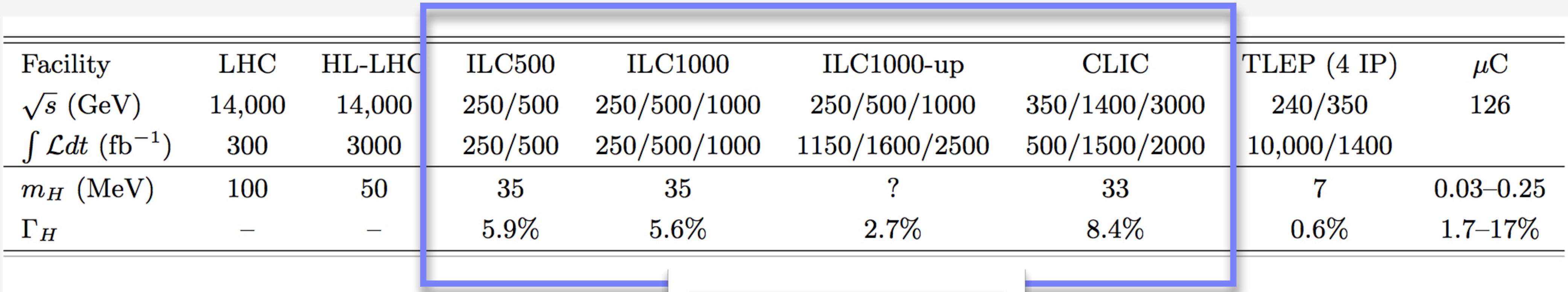
- ILC: 35 MeV/c^2

Total Width

- LHC: limits on Γ
- ILC: model-independent
- MC: direct



Facility	LHC	HL-LHC	ILC500	ILC1000	ILC1000-up	CLIC	TLEP (4 IP)	μC
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350	126
$\int \mathcal{L}dt$ (fb^{-1})	300	3000	250/500	250/500/1000	1150/1600/2500	500/1500/2000	10,000/1400	
m_H (MeV)	100	50	35	35	?	33	7	0.03–0.25
Γ_H	–	–	5.9%	5.6%	2.7%	8.4%	0.6%	1.7–17%

Γ_W to few %

Higgs Properties & extensions

1. SM Higgs spin will be constrained by LHC
2. Many models anticipate multiple Higgs’

   LHC has begun the direct search

   - *The LHC can reach to 1 TeV, with a gap in tan beta*
   - *Lepton colliders can reach to sqrt(s)/2 in a model-independent way.*

   Evidence for CP violation would signal and extended Higgs sector

   - *Specific decay modes can access CP admixtures.*
   - *An example is h-> tau tau at lepton colliders.*
   - *Photon colliders and possibly muon colliders can test CP of the Higgs CP as an s-channel resonance.*

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.

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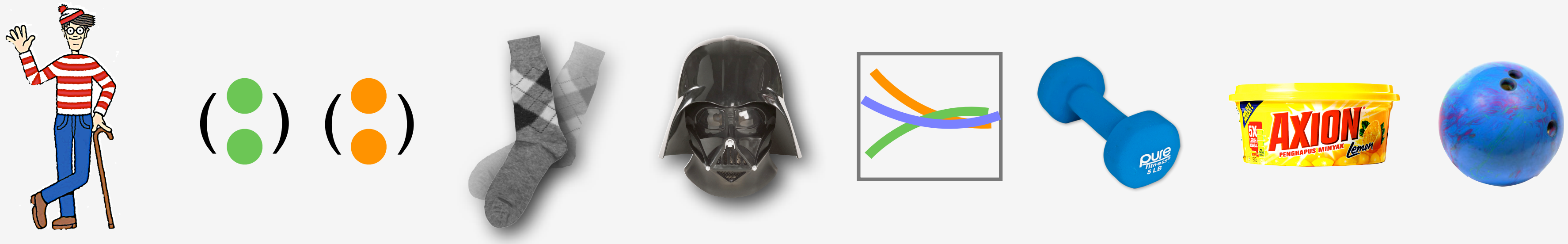
2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.
3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.



- Precision Study of Electroweak Physics

Electroweak: Themes

1. precision measurements:

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

   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*

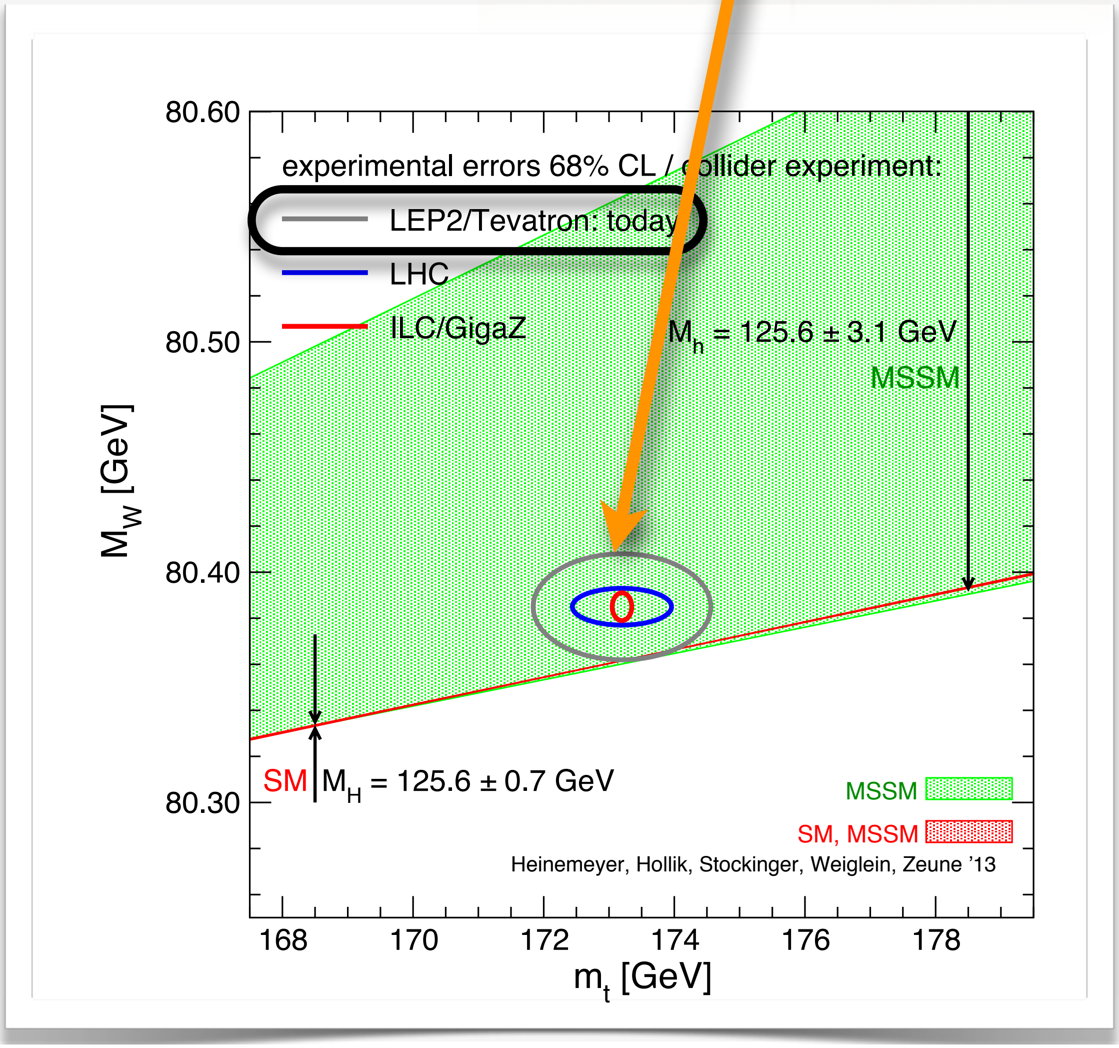
Now...a new target: BSM

Premium on M_W

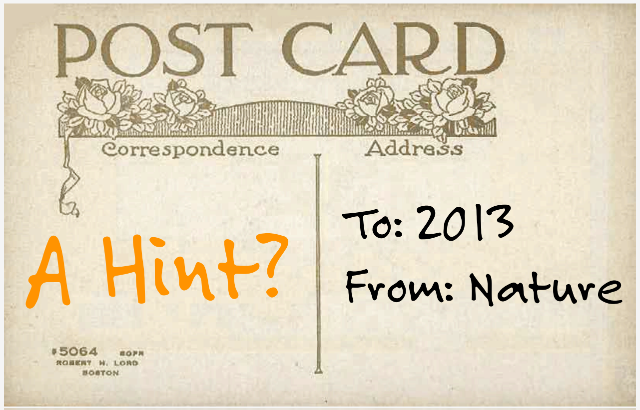
- Now fits include M_h

A Hint?

To: 2013
From: Nature

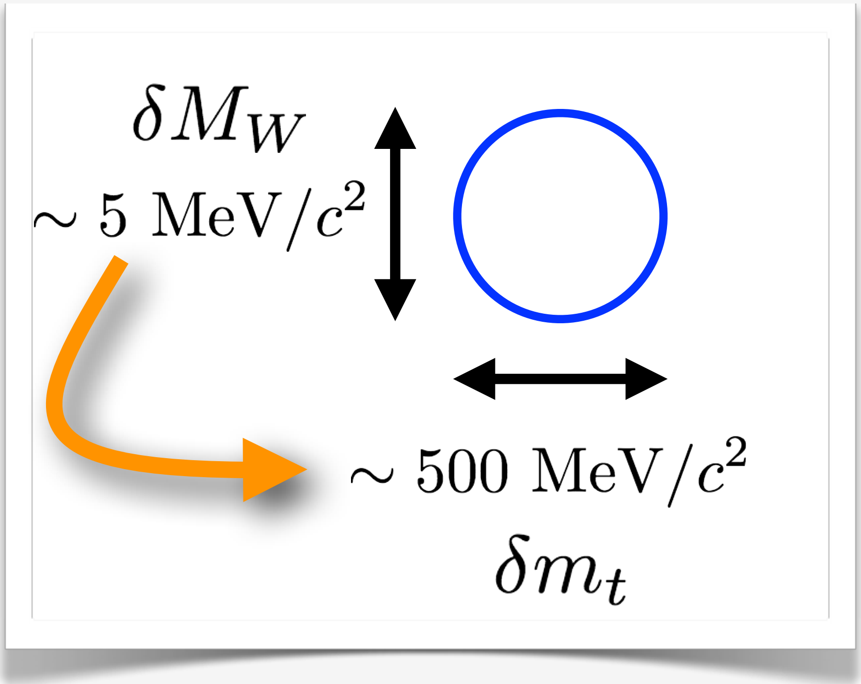


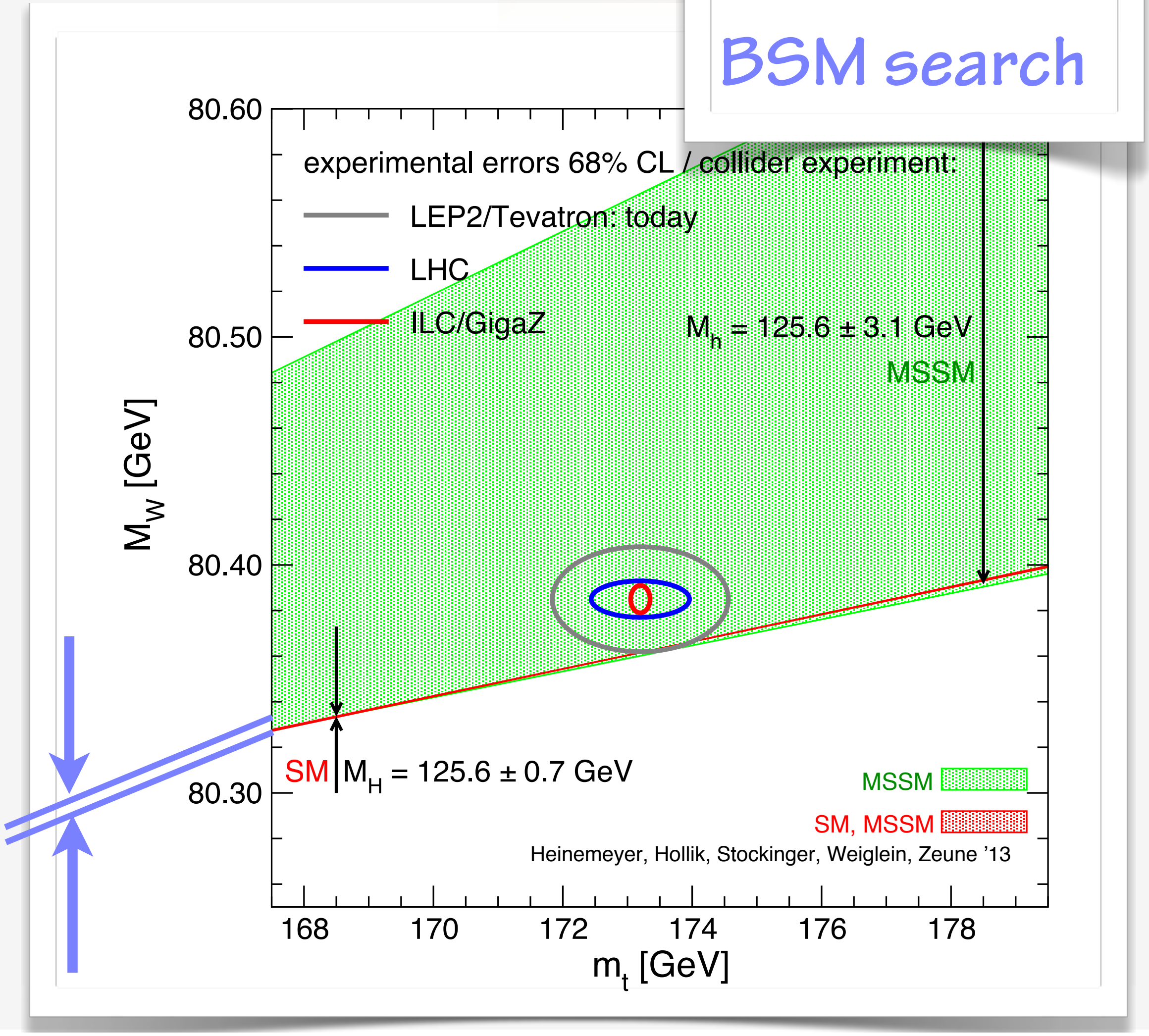
Now...a new target: BSM



Premium on M_W

- Systematics goal of $M_W = \pm\ 5\ \mathrm{MeV}/c^2$





This is now a BSM search

$\delta M_W \sim 5\ \mathrm{MeV}/c^2$

achievable M_W precision: few MeV/c^2

1. M_W at the LHC

   δM_W ~ 5 MeV requires x7 improvement in PDF uncertainty

   - *a critical need*

2. M_W at the lepton colliders

   A *WW* threshold program: δM_W ~ 2.5 – 4 MeV at ILC, sub-MeV at TLEP.

3. Furthermore: $\sin^2\theta_{\mathrm{eff}}$

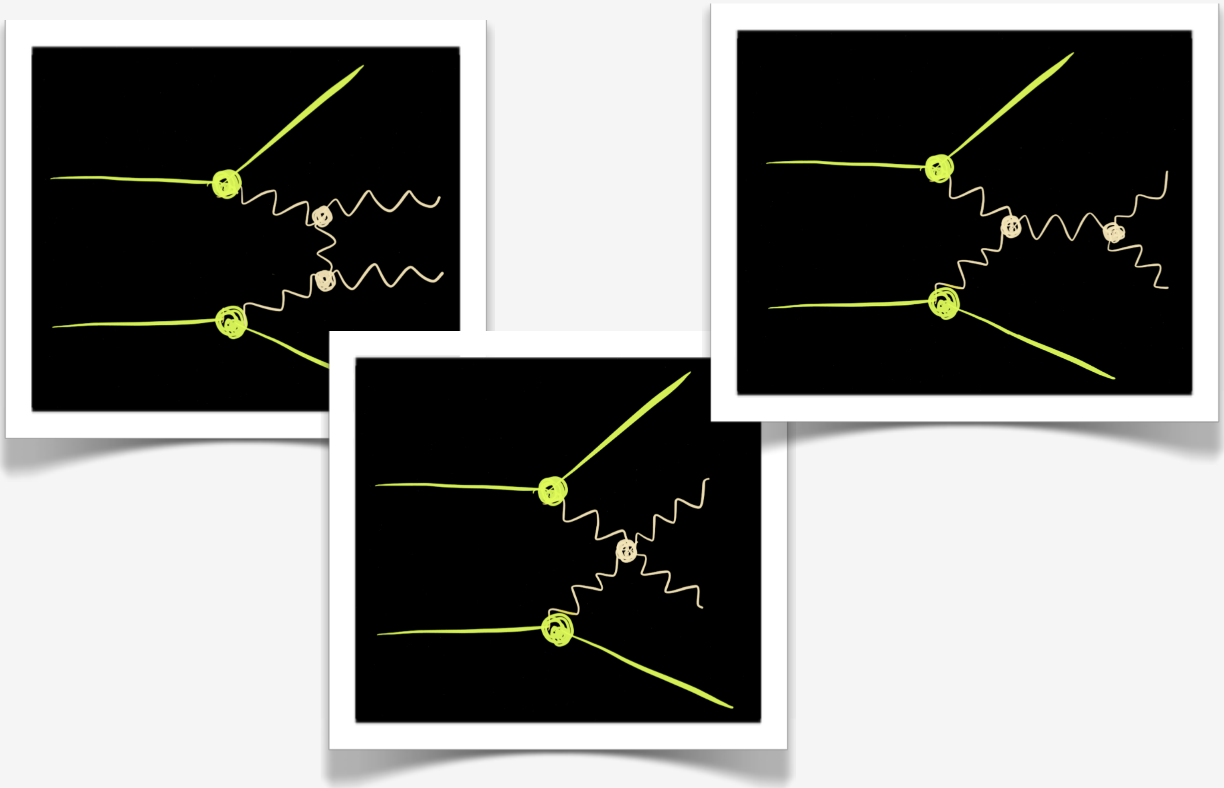
   Running at the *Z* at ILC (Giga-Z) can improve $\sin^2\theta_{\mathrm{ef}}$f by a factor 10 over LEP/SLC;

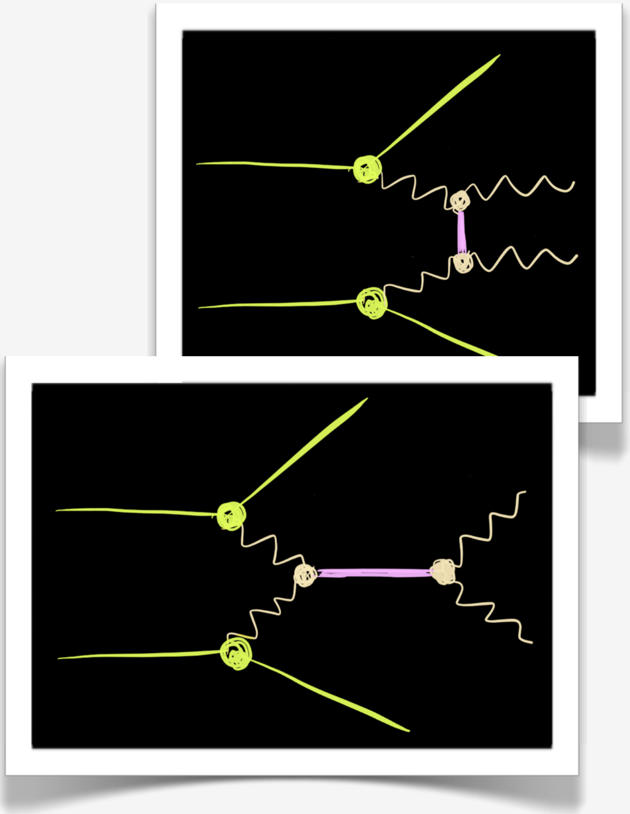
   - *TLEP might provide another factor 4.*

EW scale - TeV?

Weak Interaction theory broke down at TeV scale

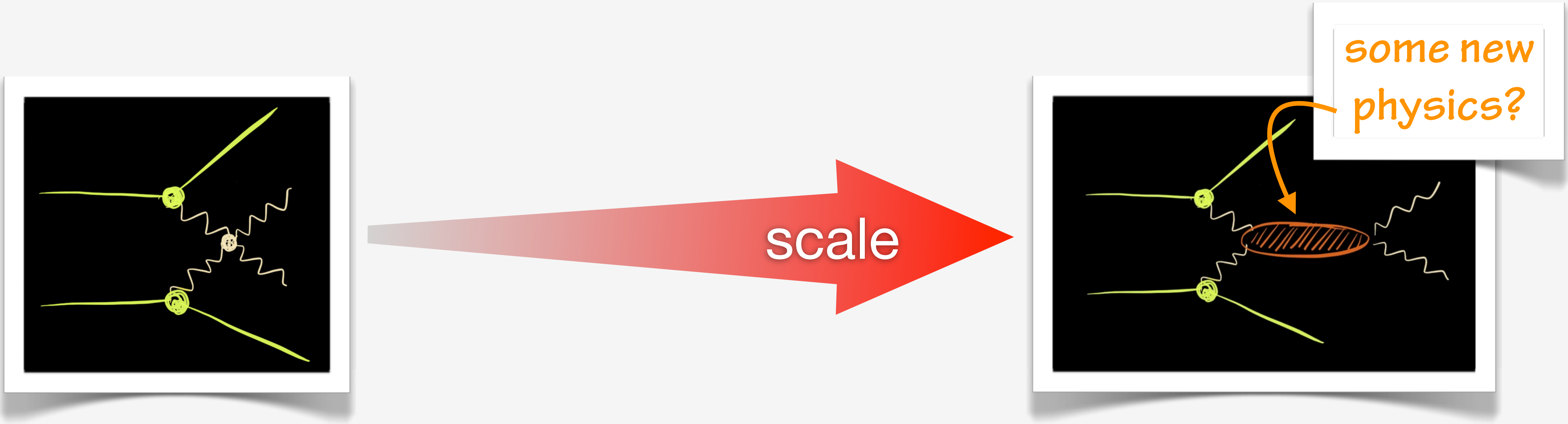
- Higgs tames this...one of its jobs





searching beyond: quartic VB scattering

- Effective Operator Machinery built into Madgraph specifically for the Snowmass EW group

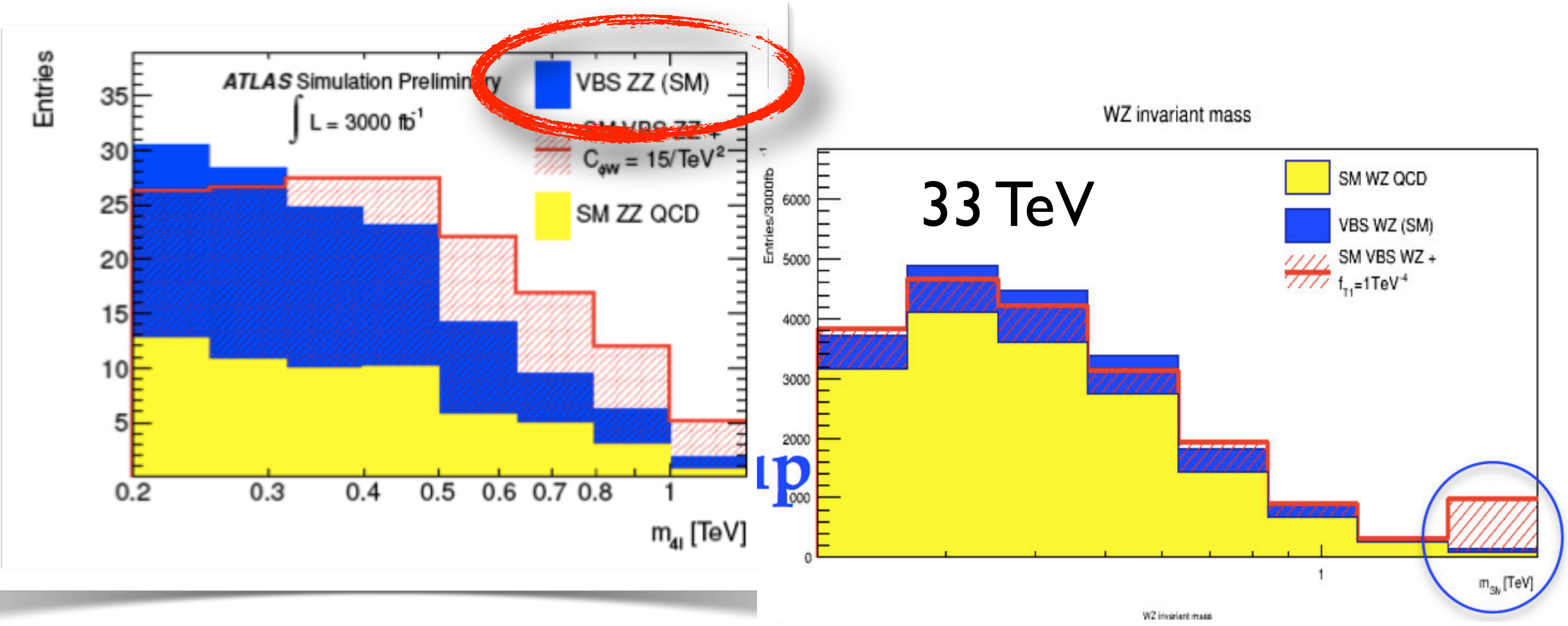


$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_i \frac{f_j}{\Lambda^4}\mathcal{O}_j + \cdots$$

Comments:

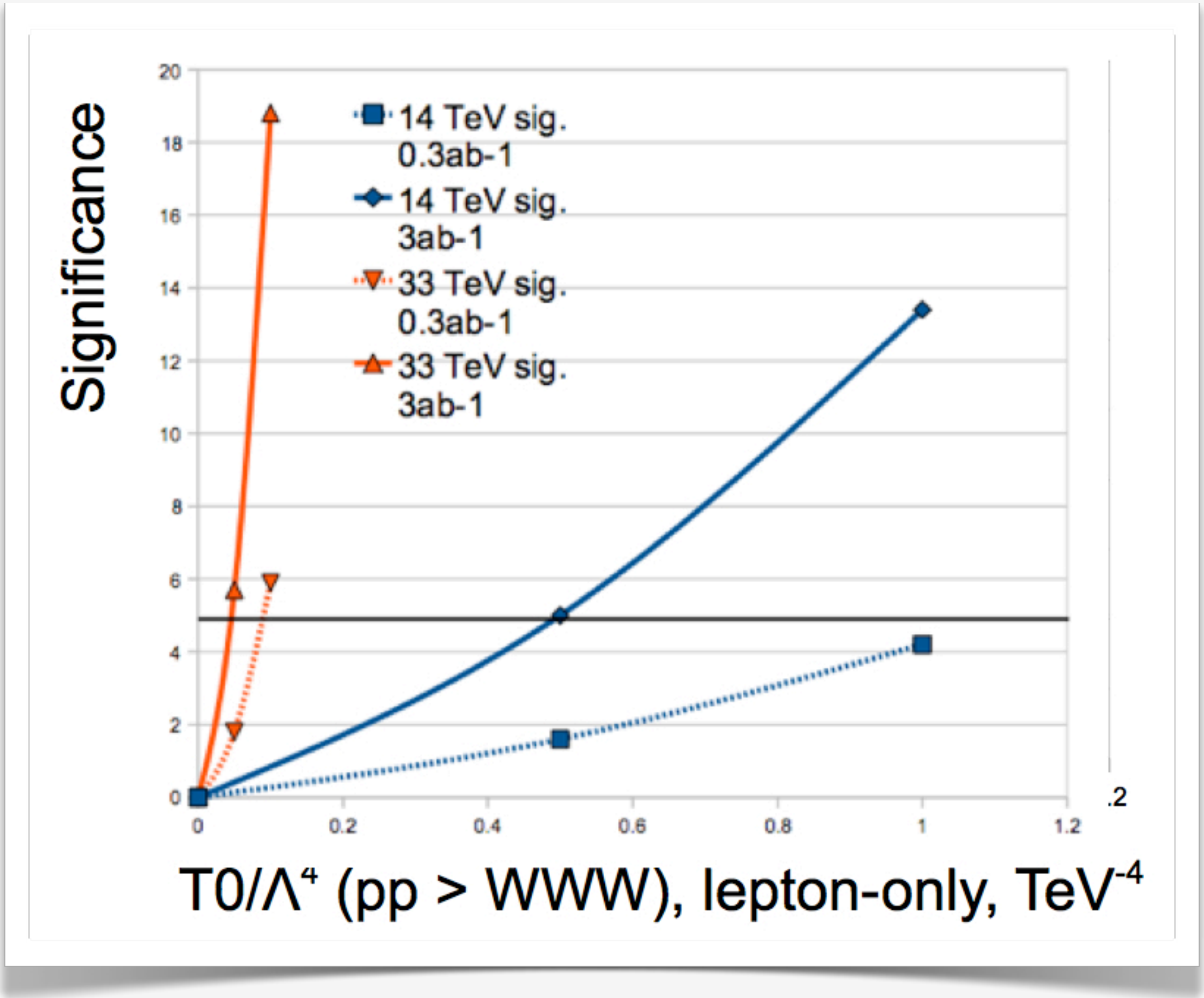
Effective Operator Machinery built into Madgraph for Snowmass

- Sensitivity to non-standard gauge interactions



VB Scattering

Luminosity and Energy win.



$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_i \frac{f_j}{\Lambda^4}\mathcal{O}_j + \cdots$$

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.

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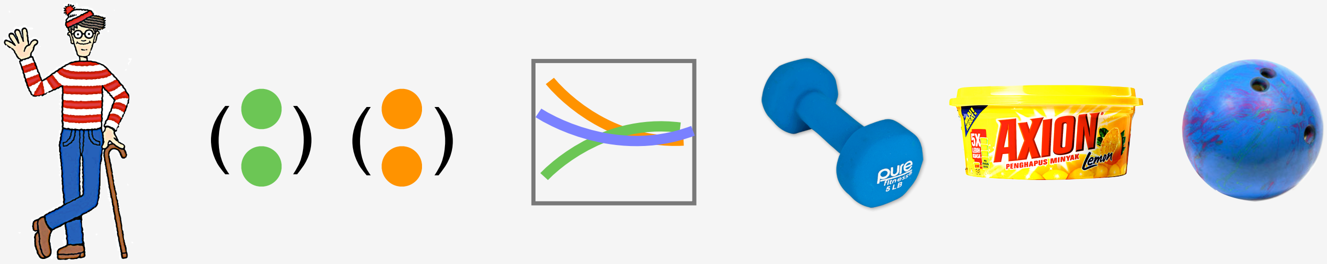
1. The precision physics of W’s and Z’s has the potential to probe indirectly for particles with TeV masses.

   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.



- Fully Understanding the Top Quark

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

Mass: why measure m_t precisely?

- EWPOs

  “keep up with” M_W precision

- fundamental parameter

  Yukawa coupling to Higgs

  close to weak scale

  stability argument sensitivity

why measure m_t precisely?

$$V(\mathrm{Higgs}) = -\mu^2\Phi^\dagger\Phi + \boxed{\lambda}(\Phi^\dagger\Phi)^2$$

- EWPOs

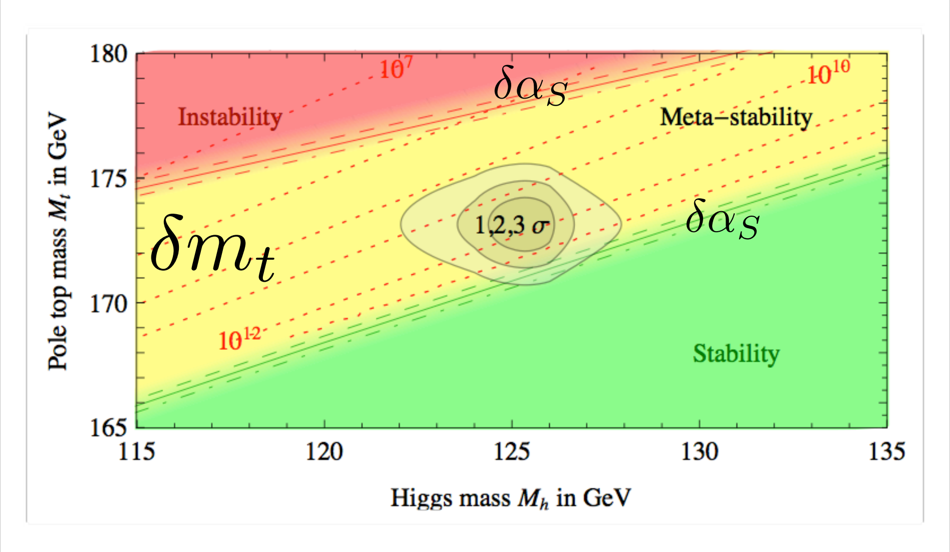
  keep up with M_W precision

- fundamental parameter

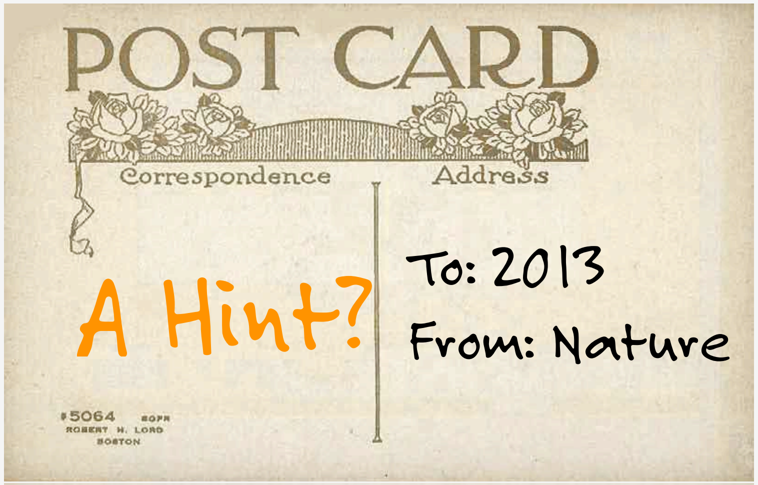
  Yukawa coupling to Higgs

  close to weak scale

  stability argument sensitivity



why measure m_t precisely?


POST CARD

Correspondence

Address

A Hint?

To: 2013

From: Nature

#5064

ROBERT H. LORD

BOSTON

$$V(\text{Higgs}) = -\mu^2\Phi^\dagger\Phi + \boxed{\lambda}(\Phi^\dagger\Phi)^2$$

- EWPOs

  keep up with M_W precision

- fundamental parameter

  Yukawa coupling to Higgs

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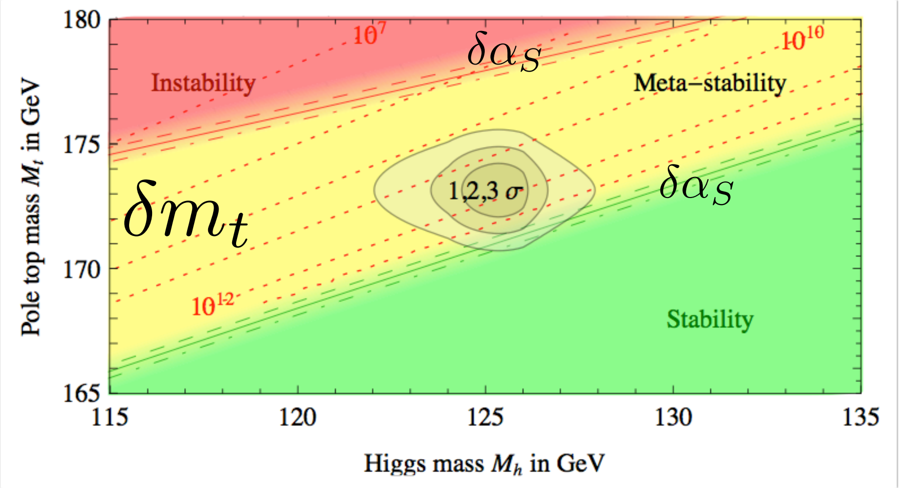
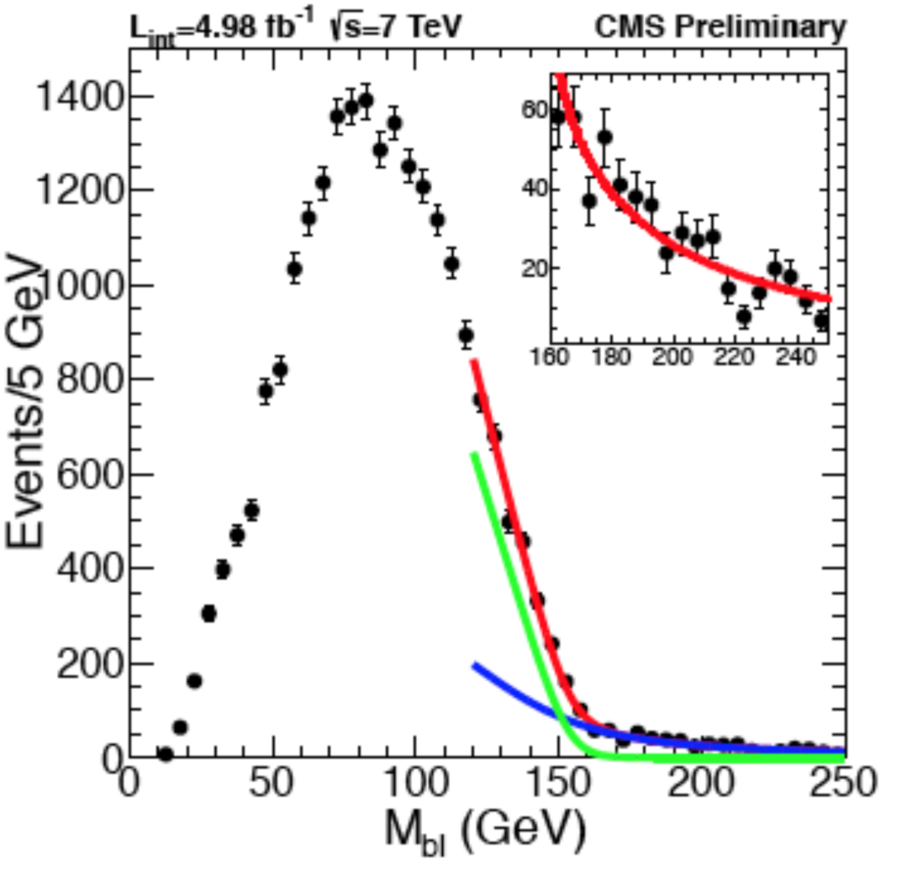


A precision, theoretically sound m_t is doable at LHC

$m(b\ell)$ endpoint method for m_t at LHC



- δm_t ~ 500 MeV/c^2 ultimately

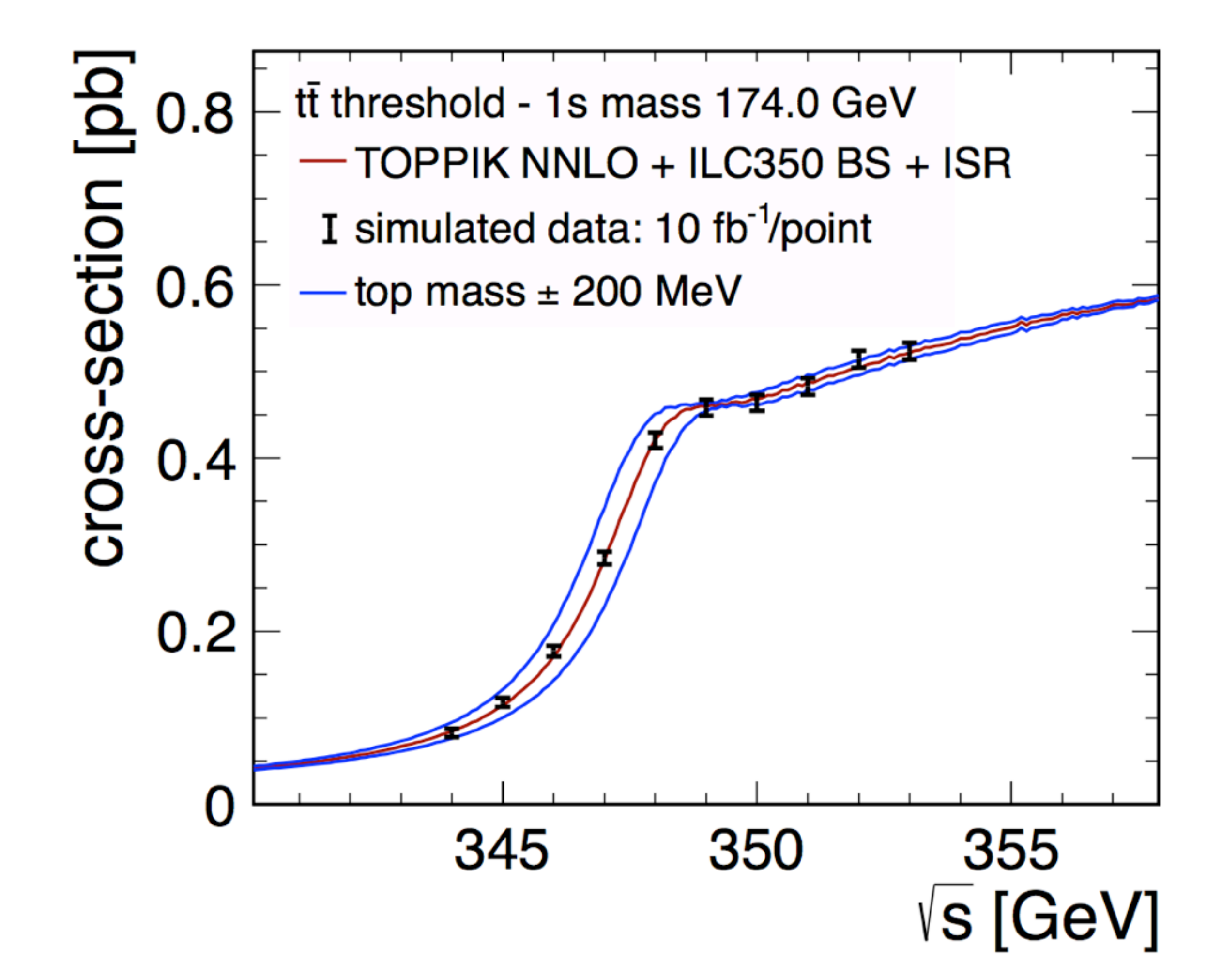
matching the 5 MeV/c^2 precision goal of MW

Comments:

The 500 MeV/c2 resolution is for the HL-LHC

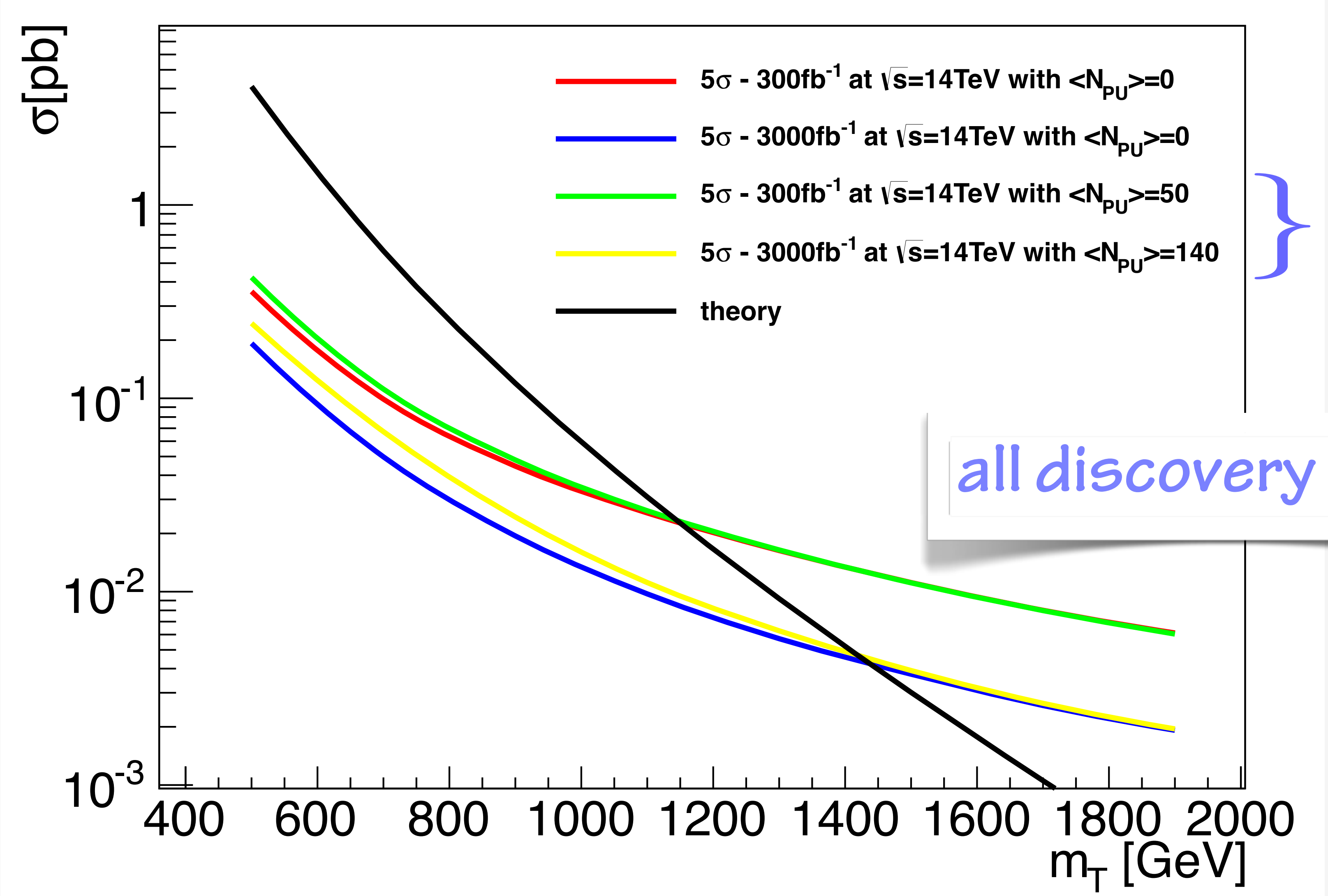
Precision m_t at Lepton Colliders

theoretically clean 100 MeV accuracy in $m_t(\overline{MS})$, matching the needs of Giga-Z precision electroweak fit



Top partner searches to 1.2-1.5 TeV

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



robust against pileup

all discovery limits

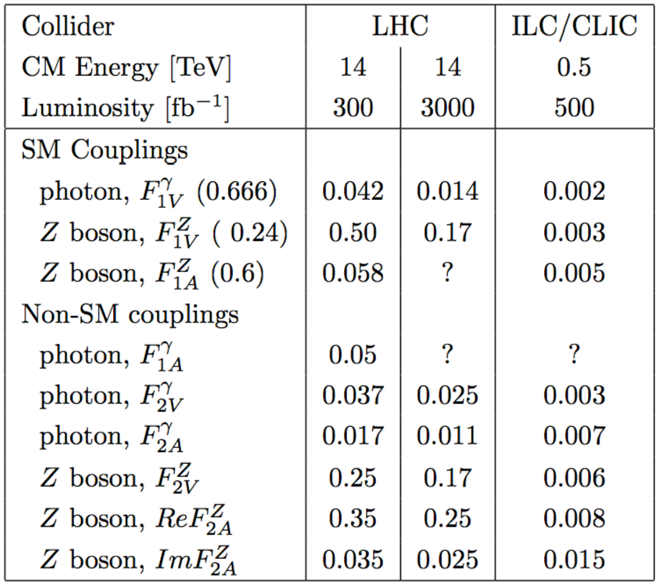
additionally

- EW top-Neutral VB couplings
- Top quark spin correlations
- Flavor-changing top decays

Comments:

projected precision of

$t-\gamma,\ t-Z^0$ couplings



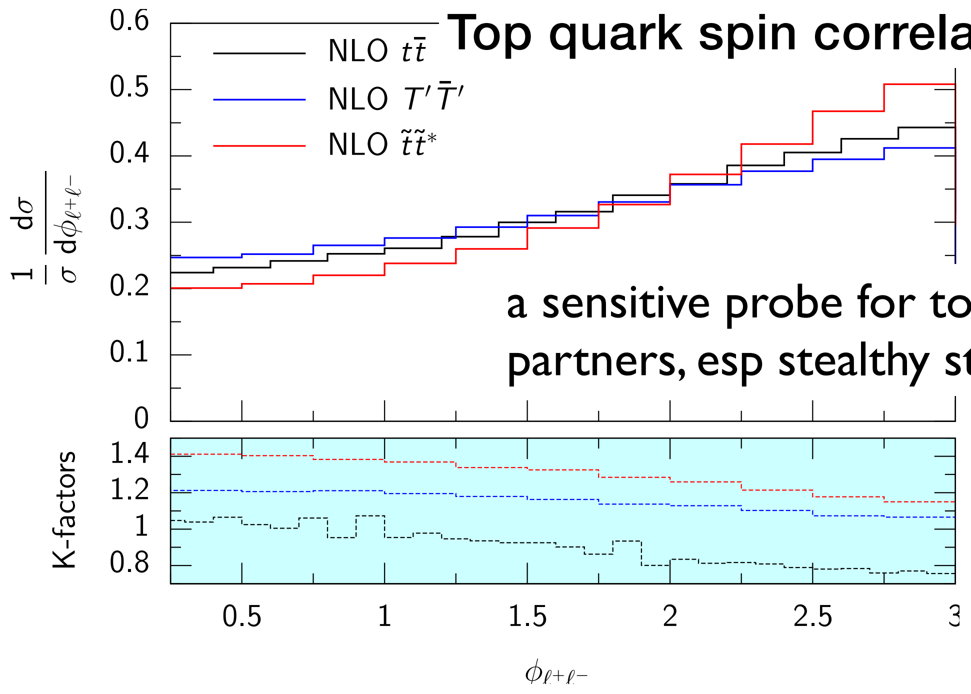
Collider	LHC		ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity [fb^{-1}]	300	3000	500
SM Couplings			
photon, F_{1V}^{γ} (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^{Z} (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^{Z} (0.6)	0.058	?	0.005
Non-SM couplings			
photon, F_{1A}^{γ}	0.05	?	?
photon, F_{2V}^{γ}	0.037	0.025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

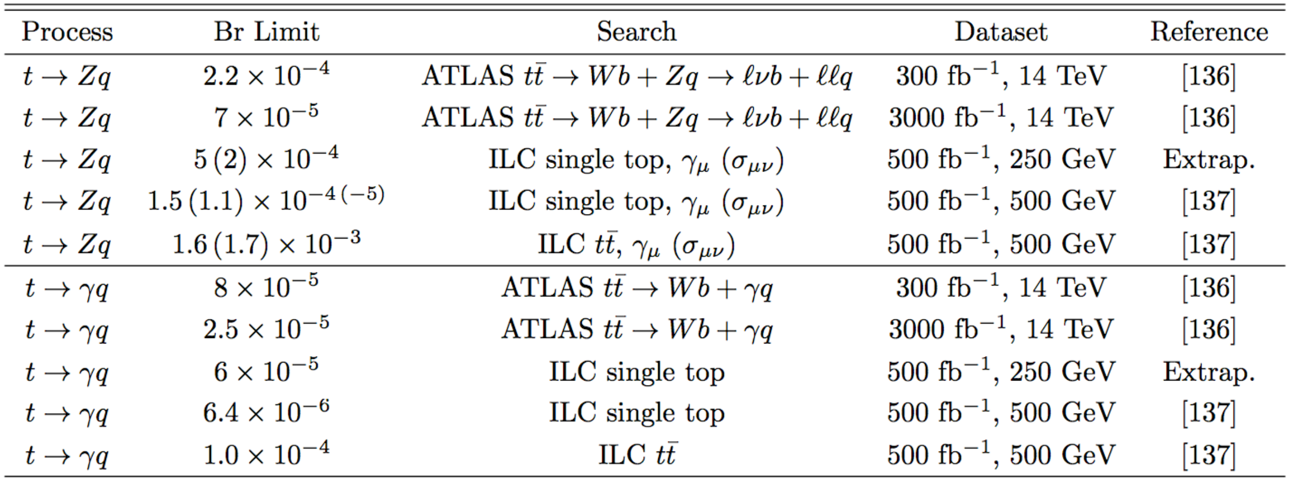
ILC/CLIC: sub-%

Top quark spin correlation



a sensitive probe for top partners, esp stealthy stop

Flavor-changing top decay

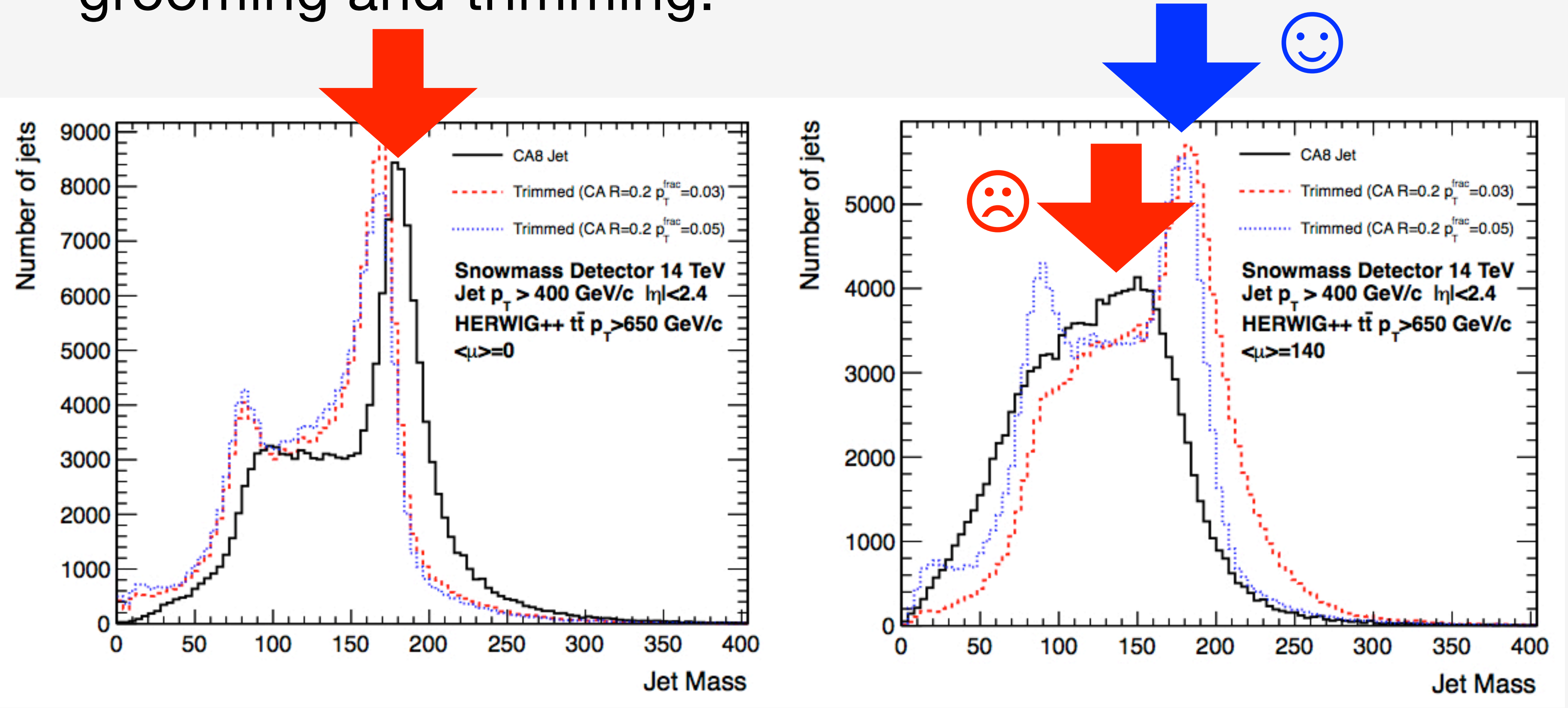


Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[136]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[136]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, 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]

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

Analysis techniques inoculate against pileup

Restore the performance with boosted techniques of grooming and trimming.



pileup = 0 = 140

The Top Quark physics message

1. Top is intimately tied to the problems of symmetry breaking and flavor

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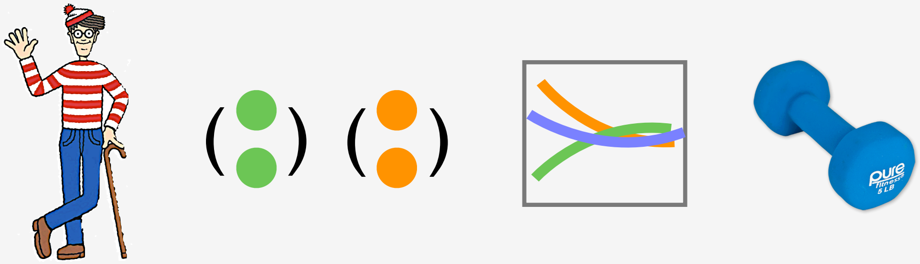
The Top Quark physics message

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.



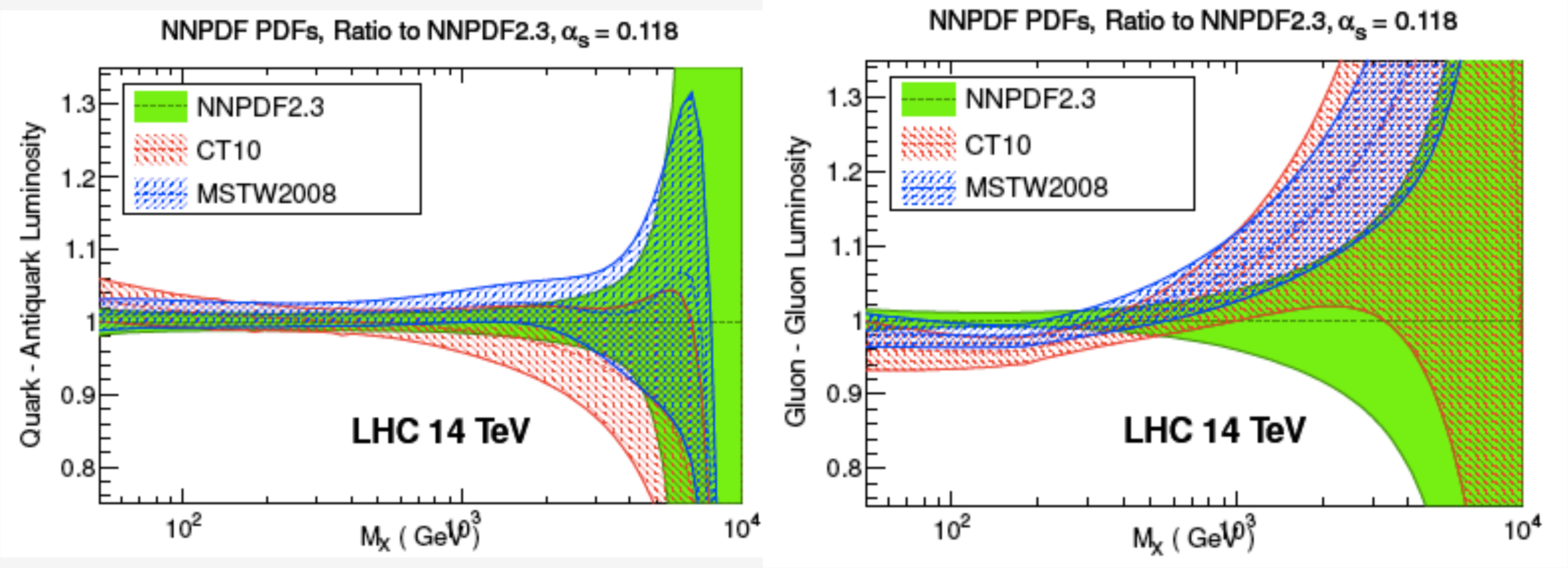
🟩 Quantum Chromodynamics and the Strong Force

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*

PDF uncertainties must improve

significant in regions relevant to Higgs, EWPOs, & new particle searches

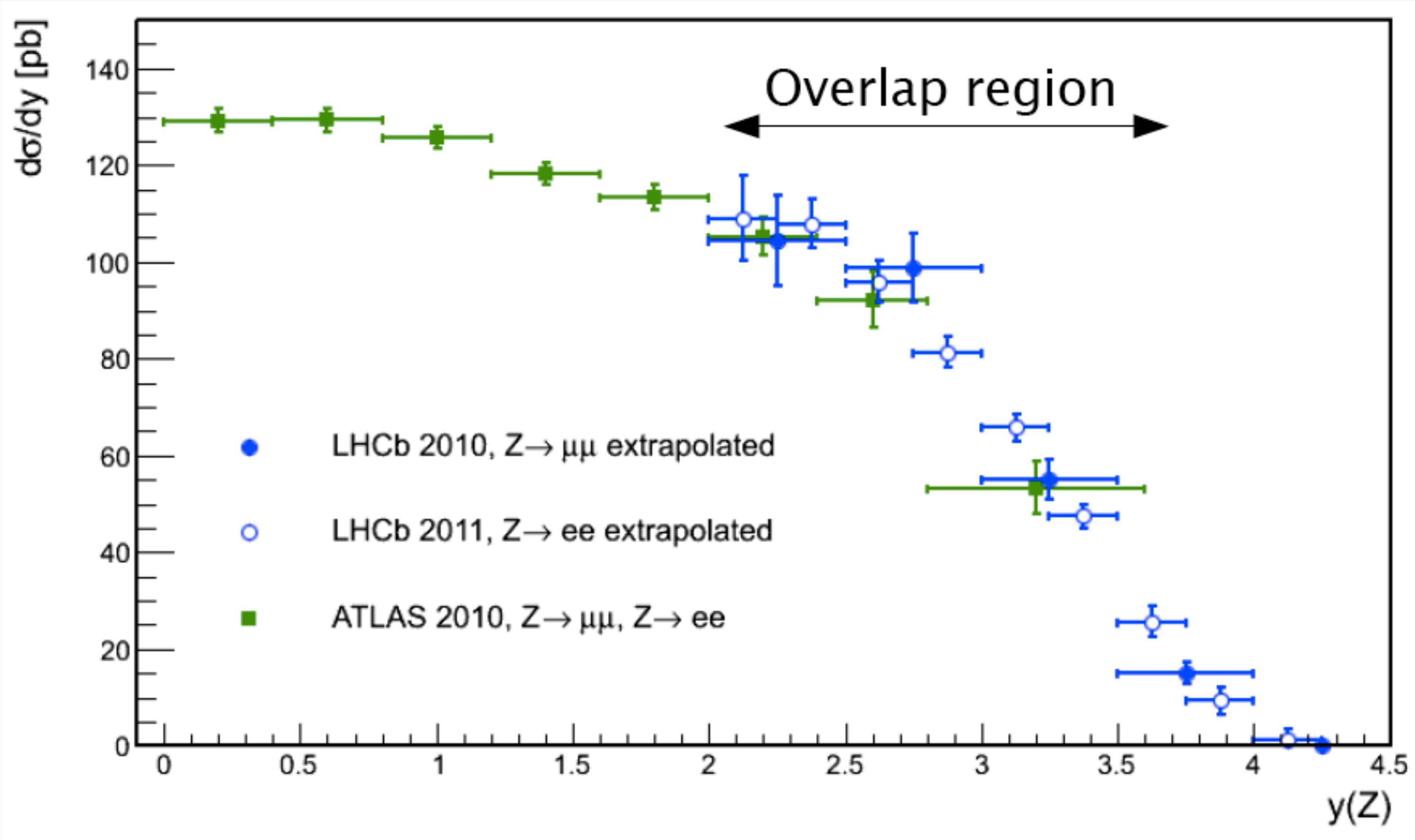


Juan Rojo

- Improve at LHC with W, Z, top rapidity distributions

full rapidity coverage required

complementary role of ATLAS,CMS and LHCb

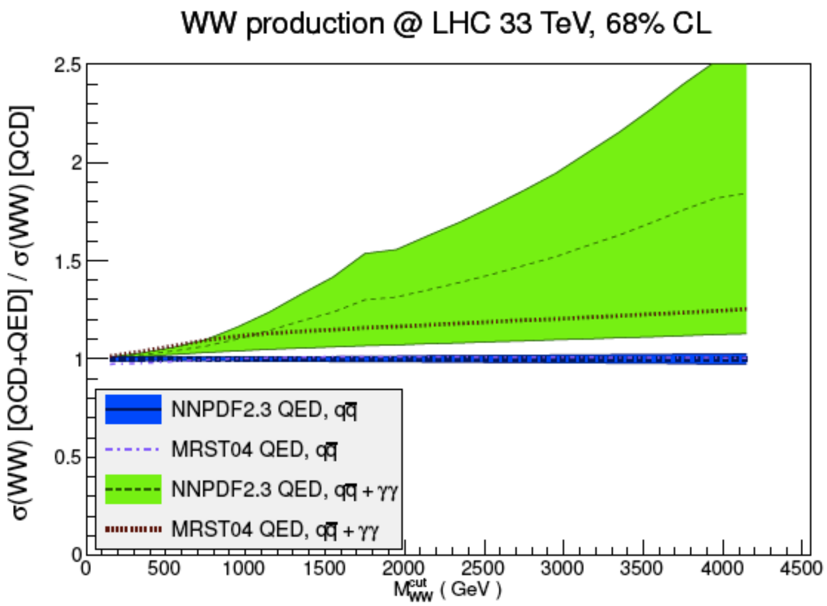


additionally

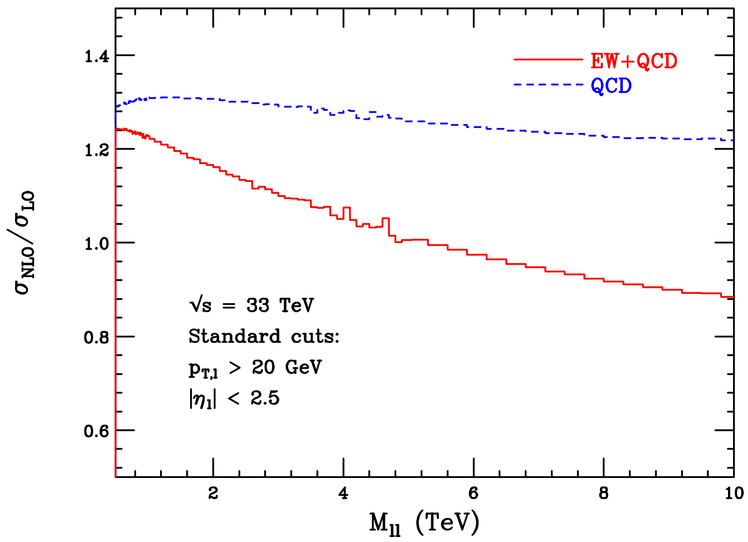
- importance of photon distribution function
- need to incorporate full EW resummation
- lattice contributions, esp aS

Comments:

Photon-induced processes are increasingly important; need to extend the current state of the art in PDFs to QED.



Electroweak corrections and Sudakov EW logs must be incorporated into event simulation.



Improvement in alphas and quark masses will come from lattice gauge theory.

- These are necessary inputs to precision Higgs theory and other precision programs.

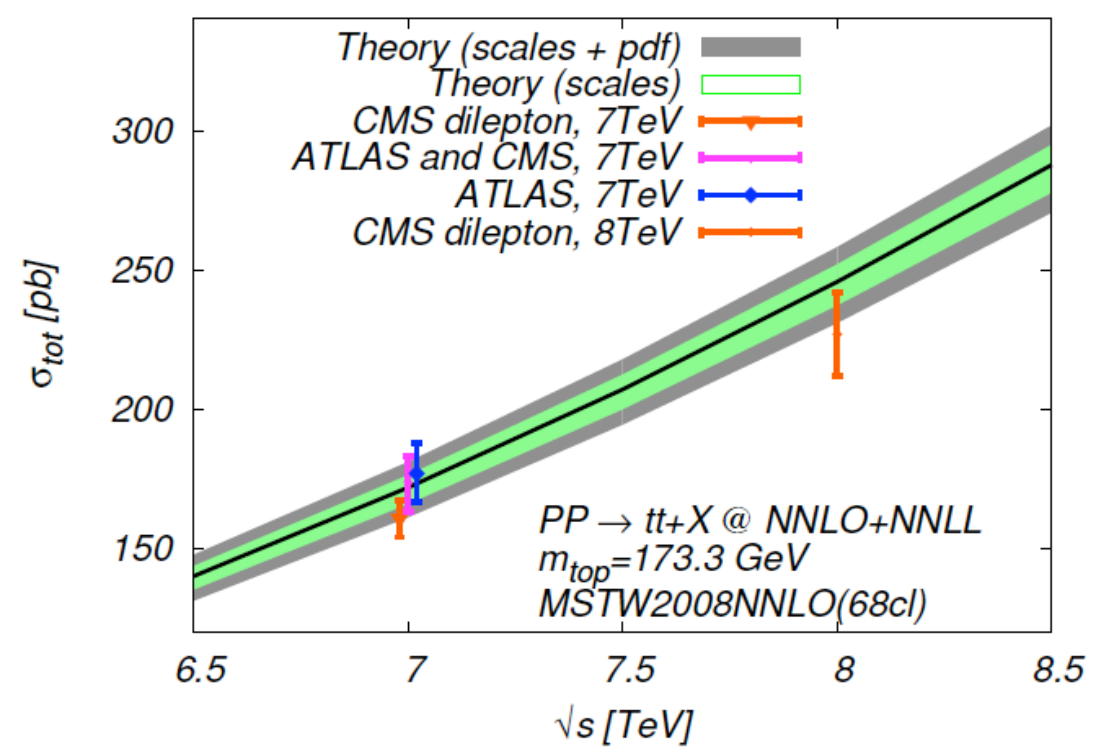
	Higgs X-section Working Group [34]	PDG[1]	Non-lattice	Lattice (2013)	Lattice (2018)	Prospects from ILC/TLEP/LHeC
$\delta\alpha_s$	0.002	0.0007	0.0012 [1]	0.0006 [24]	0.0004	0.0001–0.0006 [8, 27, 28]
δm_c (GeV)	0.03	0.025	0.013 [31]	0.006 [24]	0.004	-
δm_b (GeV)	0.06	0.03	0.016 [31]	0.023 [24]	0.011	-

NNLO

Landmark NNLO calculation of the top quark pair production cross section.

- Soon for 2->2 & some 2->3 processes.

  Higgs and many other LHC analyses.



Czakon-Mitov

The QCD Physics Message

1. Improvements in PDF uncertainties are achievable.
    - *There are strategies at LHC for these improvements.*
    - *QED and electroweak corrections must be included in PDFs and in perturbative calculations.*

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   - *lattice gauge theory + precision experiments*

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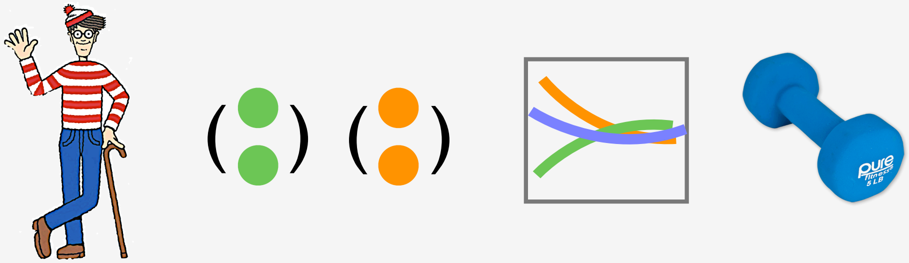
    - *QED and electroweak corrections must be included in PDFs and in perturbative calculations.*
2. alphas error ~ 0.1% is achievable
    - *lattice gauge theory + precision experiments*
3. Advances in all collider experiments, especially for Higgs boson physics & M_W

require continued advances in perturbative QCD.



- The Path Beyond the Standard Model – New Particles, Forces, and Dimensions

Comments:

Flavor group’s results are included in some of the NP group’s public reporting.

NP: Themes

1. Necessity for new particles at TeV mass

the questions of fine tuning and dark matter are still open

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    - *evolution of robust search strategies*

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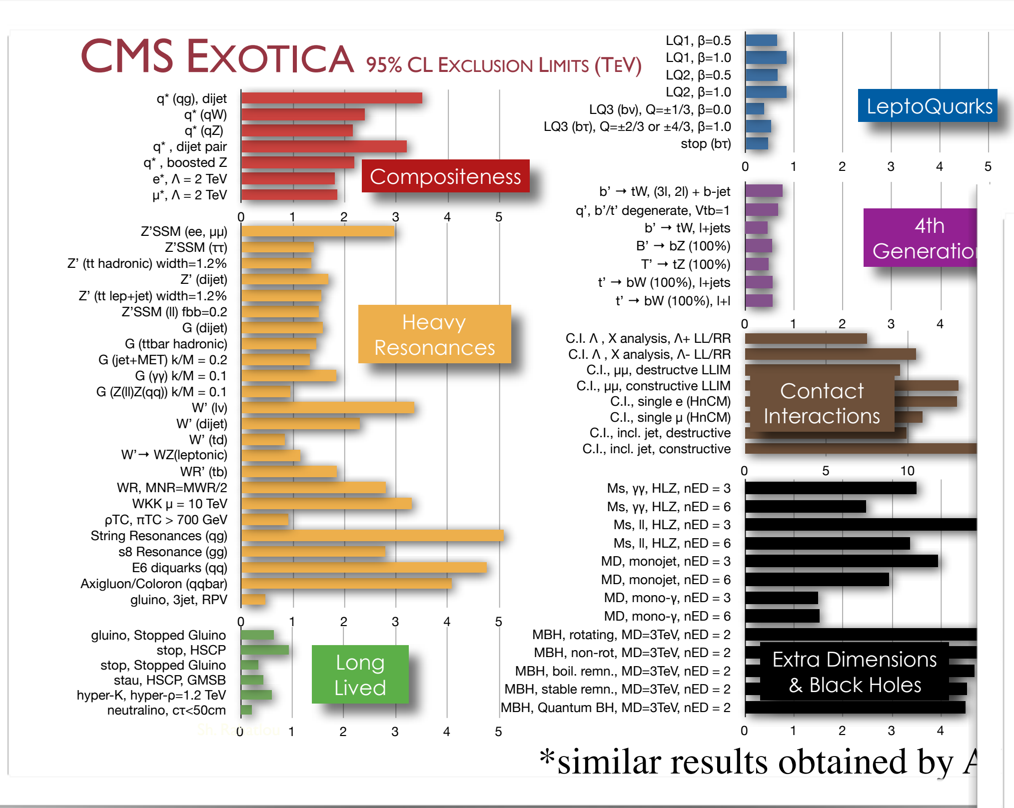
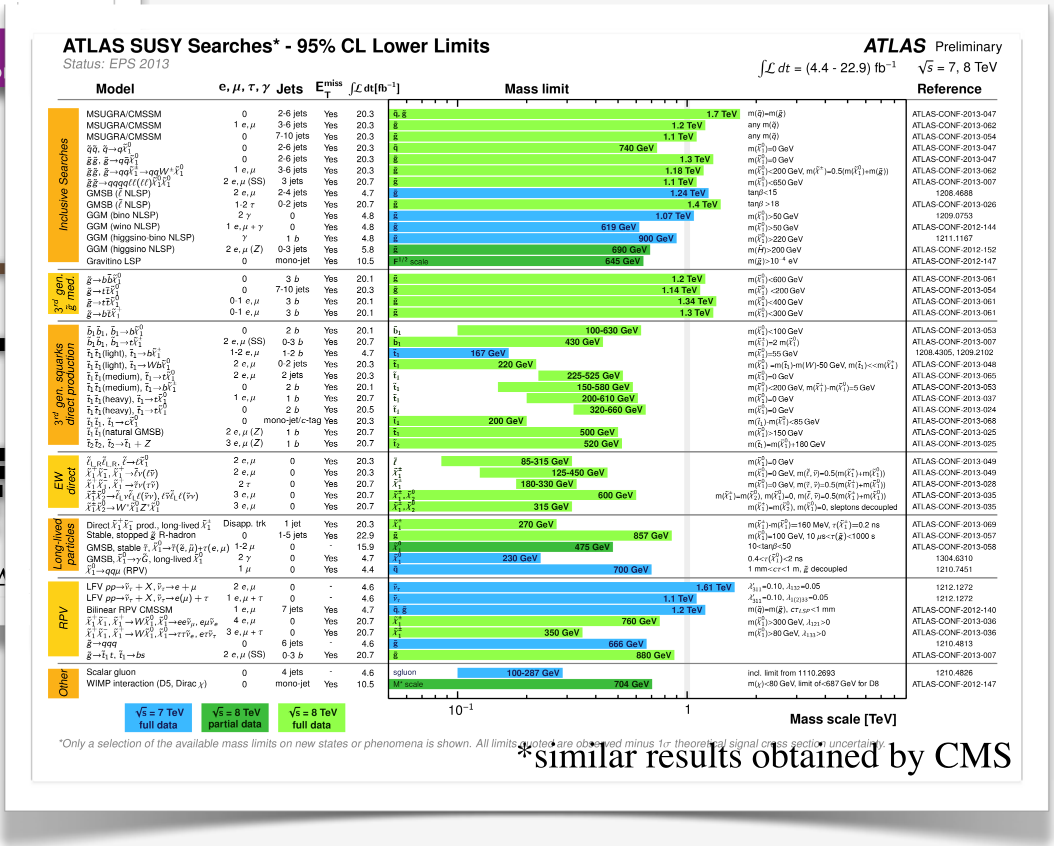
3. Connection to dark matter problem
4. Connection to flavor issues

current LHC searches

New particle searches at the current LHC.



*similar results obtained by A



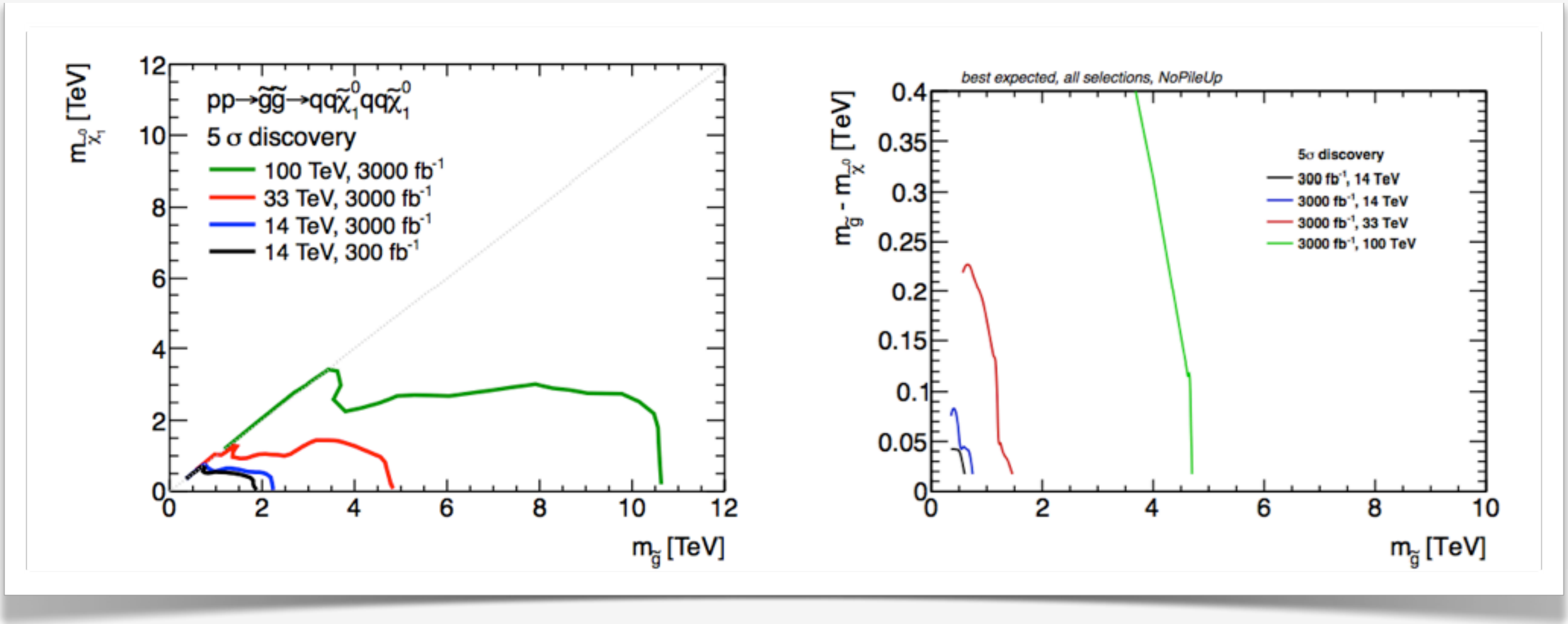
*similar results obtained by CMS

gain from now to 300/fb & beyond

x2 in gluino mass reach 8-14 TeV,

- 30% more with 300/fb - 3000/fb @14 TeV

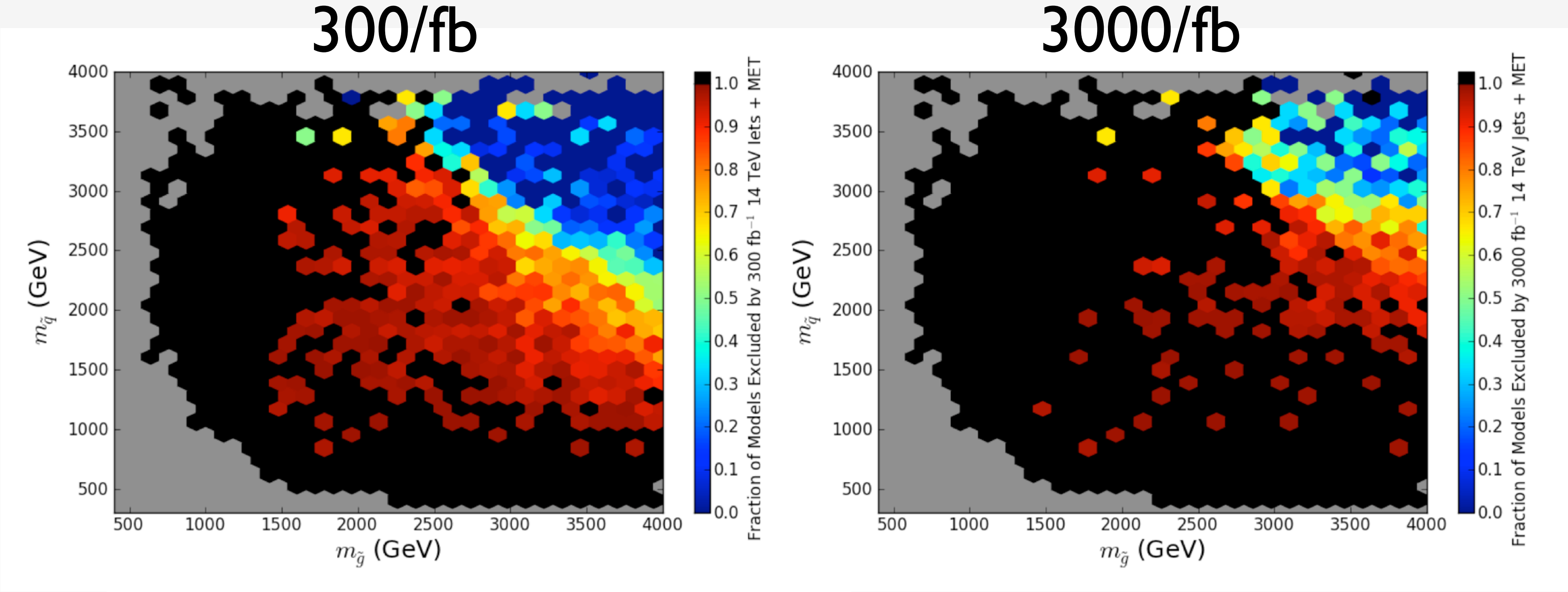
  factors of 2 for 33 TeV and 100 TeV



SUSY reach: x2 from E_{cm}, 1.3 in $\mathcal{L}$

In the pMSSM survey of SUSY models

- squark/gluino mass plane

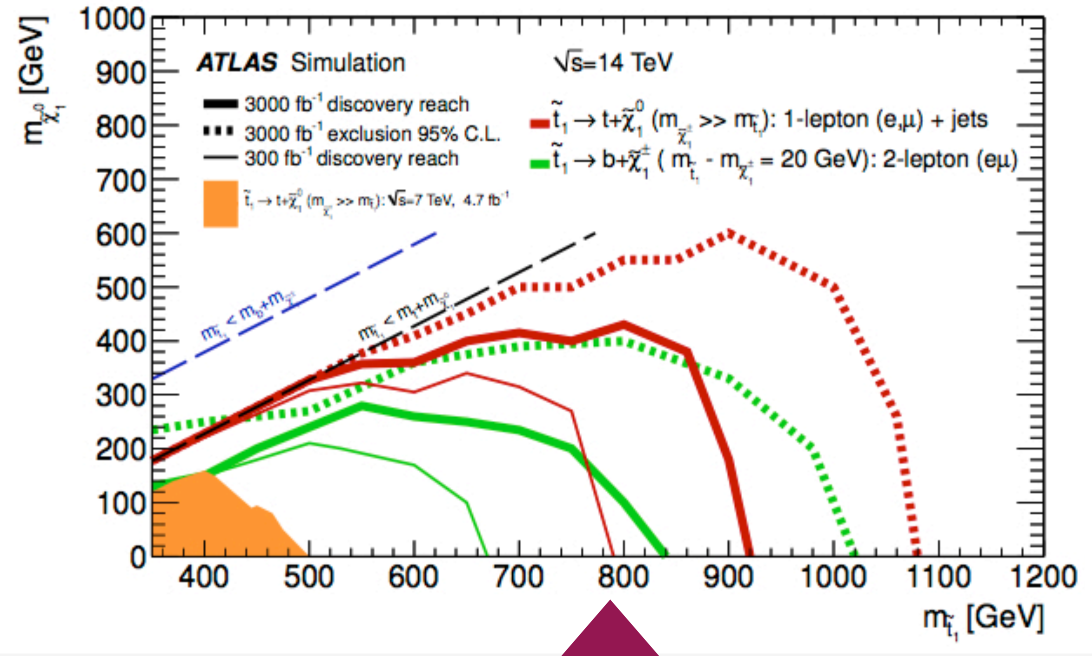

300/fb

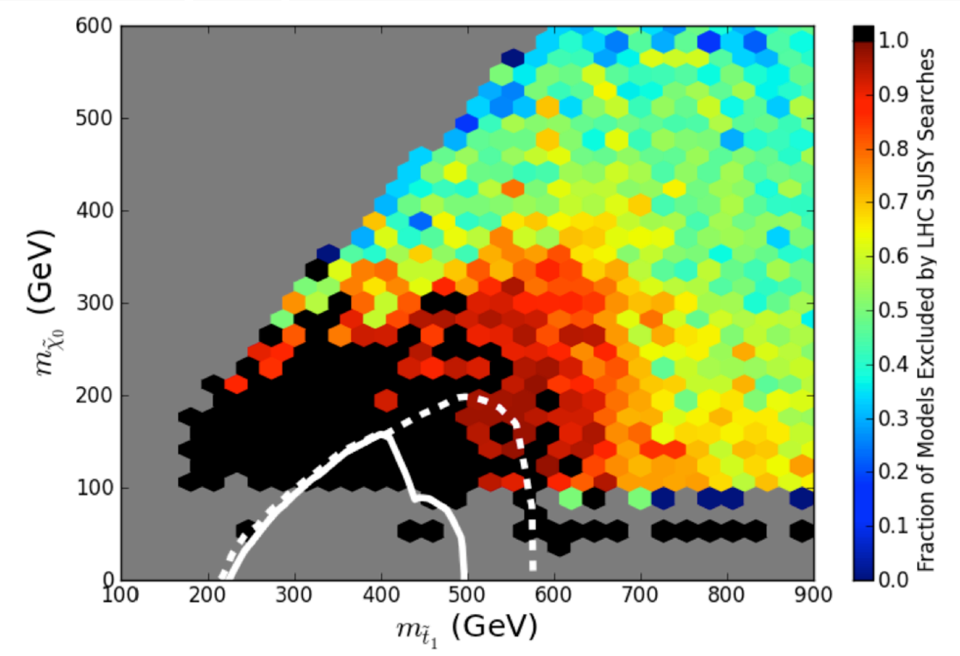
3000/fb

Note closing of loopholes in addition to increased energy reach.

Cahill-Rowley et al.

m_{stop} reach: ~50% from E_{cm}, 1.5 in $\mathcal{L}$



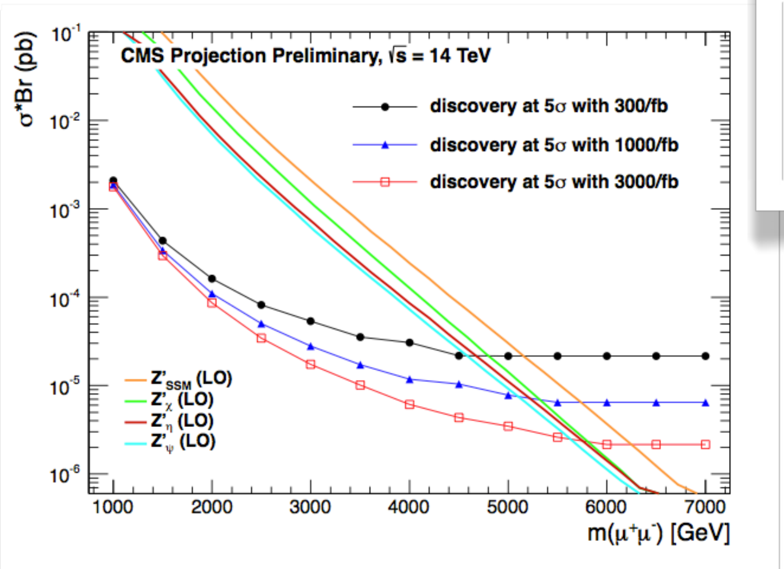


300/fb reach
stop-> t + neutralino

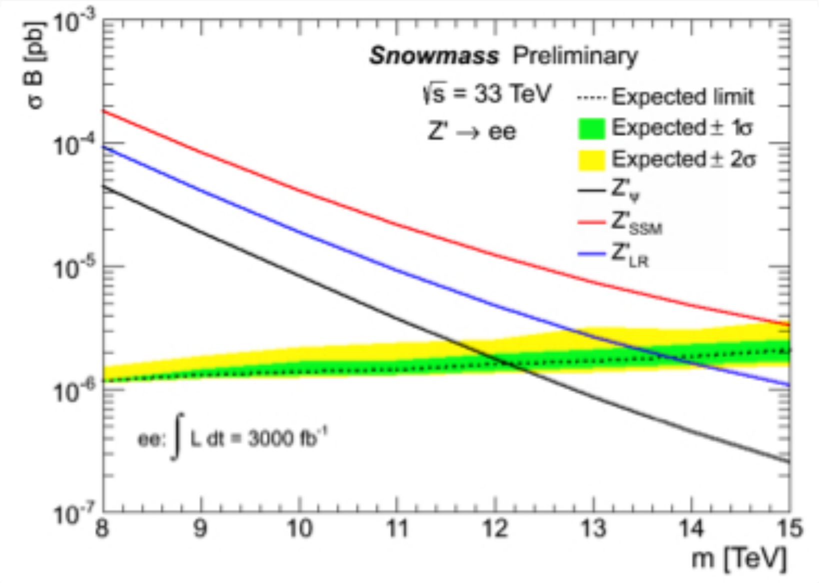
3000/fb reach
stop-> t + neutralino

Cahill-Rowley et al.

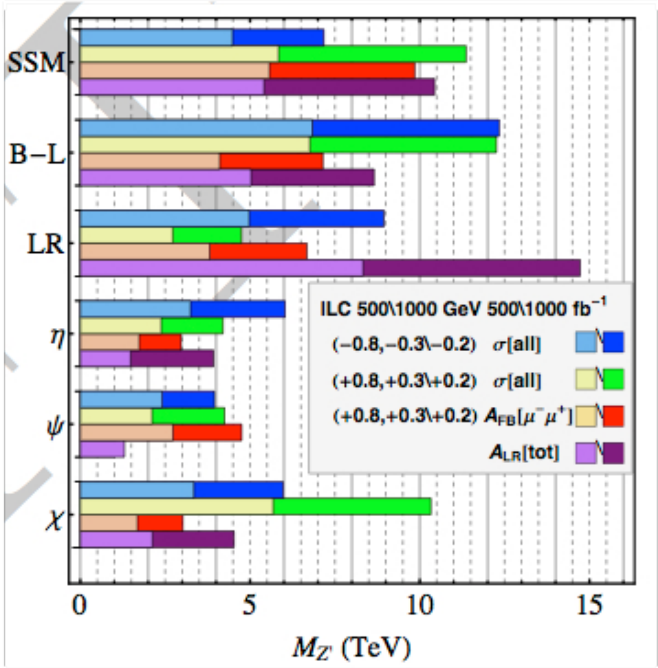
Z’ sensitivity



5-6+ TeV Discovery range at 14 TeV LHC



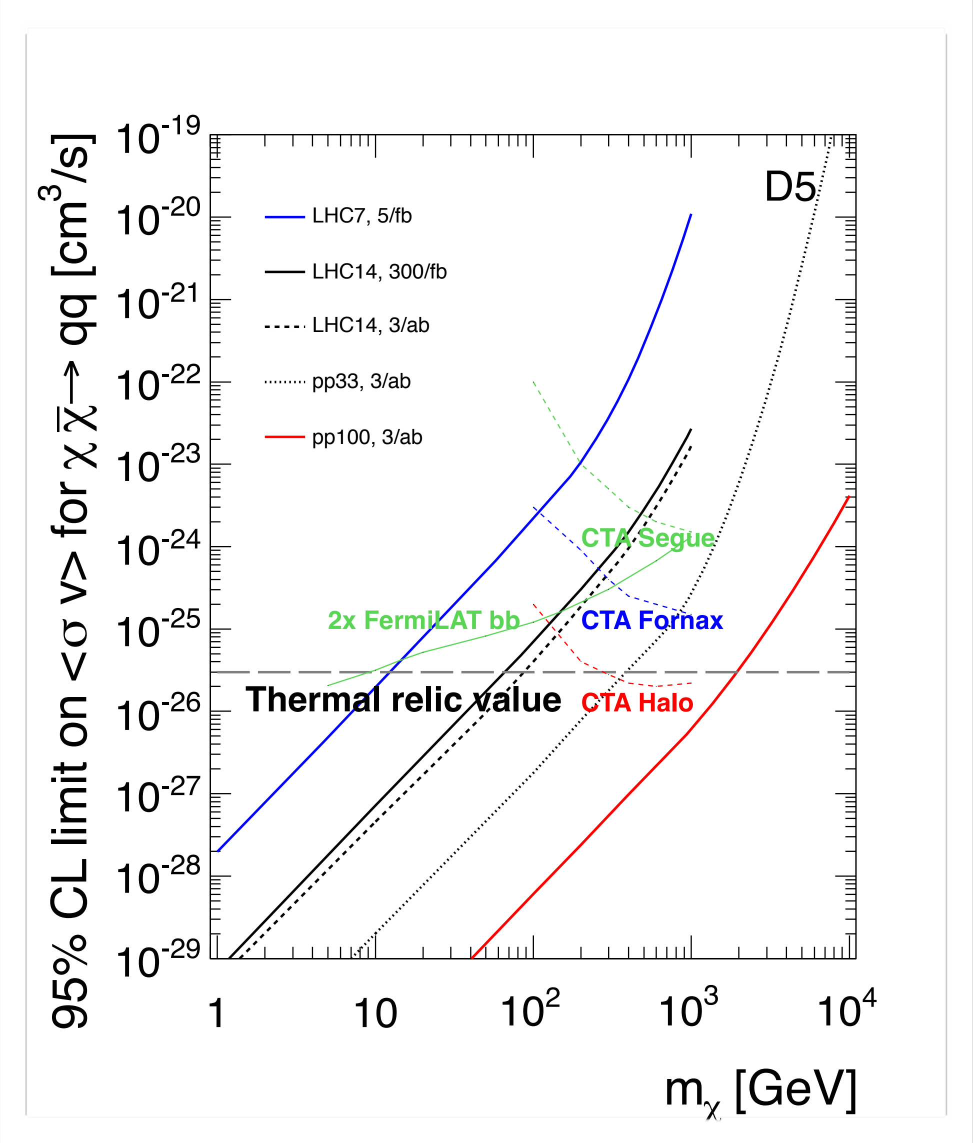
12-15 TeV limit range at 33 TeV pp



ILC asymmetry interference, beyond LHC

Dark Matter Connection

nearly close the thermal relic range?



progressive increase in sensitivity

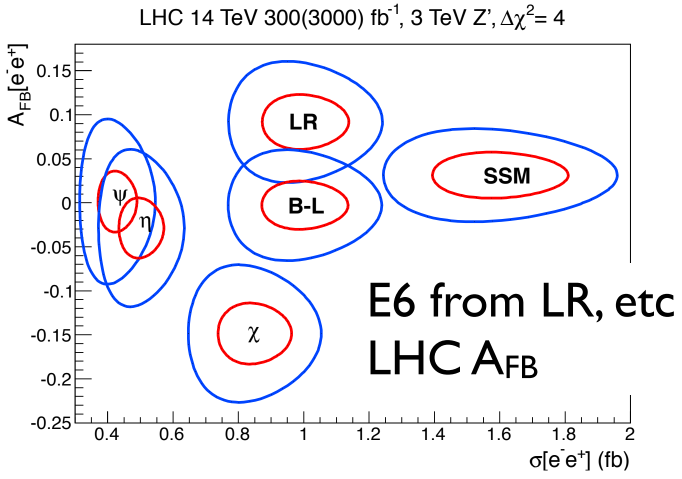
VLHC (100 TeV) can probe WIMP DM candidacy up to 1-2 TeV

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

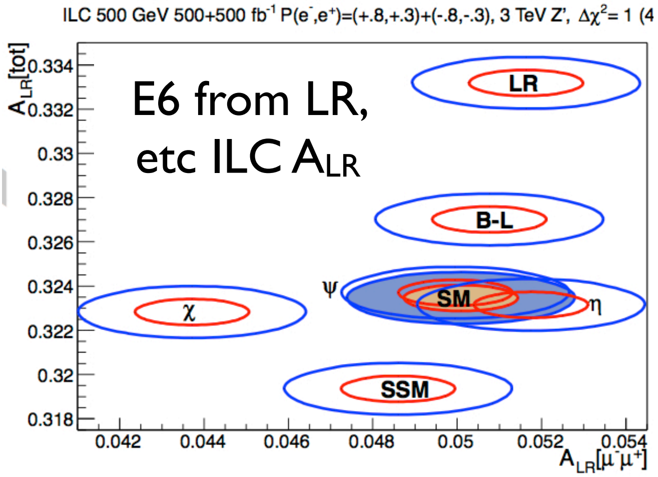
additionally

- model discrimination in Z' discovery
- WIMP sensitivity in ILC $e^+e^- \to \gamma + \chi + \chi$
- SUSY neutralino decaying $\tilde{\chi}_1^0 \to W + \tau$
- electroweak-inos, x2 sensitivity in 2015

Comments:



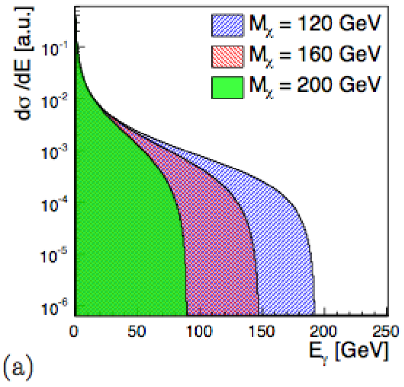
E6 from LR, etc LHC A_{FB}



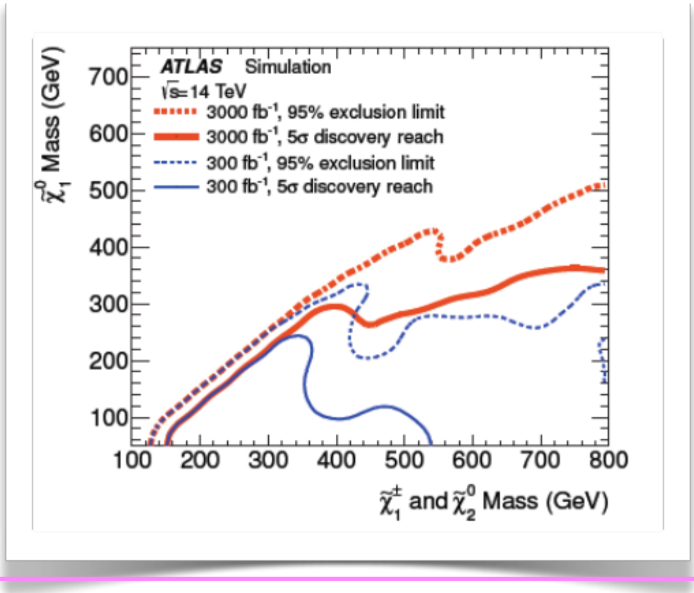
E6 from LR, etc ILC A_{LR}

WIMP search at ILC in

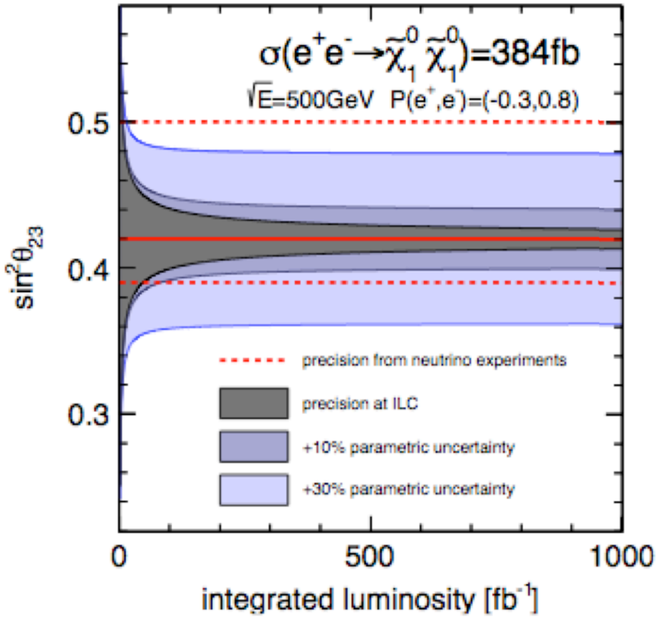
$$e^+e^- \to \gamma + \chi + \chi$$



electroweakinos



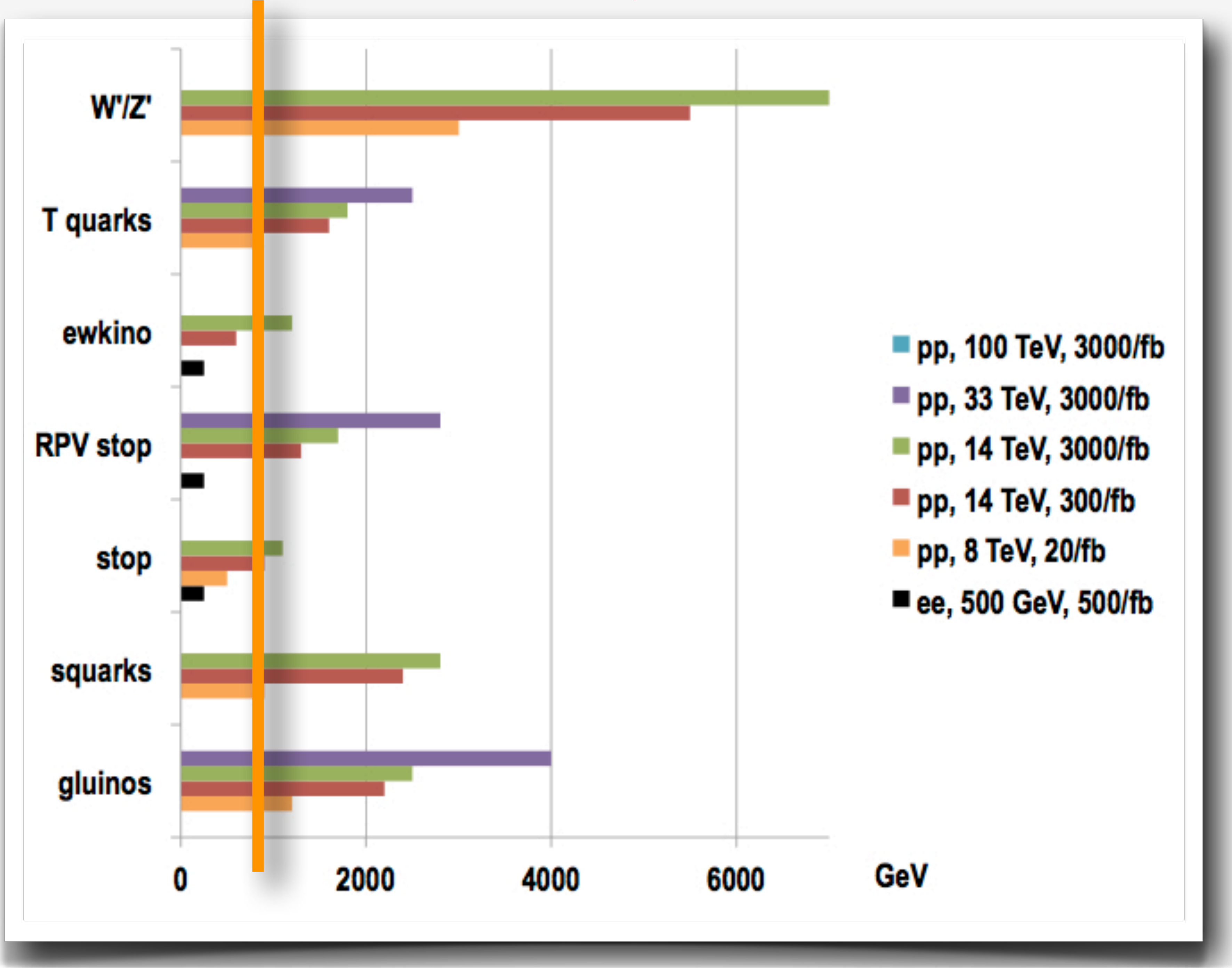
Discover the SUSY neutralino decaying via $\tilde{\chi}_1^0 \to W + \tau$ through the R-parity violating SUSY coupling.



In "Type III seesaw," the θ_{23} controls the rate of the subleading decay $\tilde{\chi}_1^0 \to W + \mu$

In this model, with neutralino accessible at ILC, this prediction is directly testable.

The TeV scale is in sight



The NP Physics Message

1. TeV mass particles are needed in essentially all models of new physics. The search for them is imperative.

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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.

- **Scientific Cases for:**

  LHC upgrades: 300, 3000/fb
  Linear ee collider: 250/500, 1000 GeV
  CLIC: CLIC: 350 GeV, 1 TeV, 3 TeV
  muon collider
  photon collider
  Circular ee collider: up to 350 GeV
  pp Collider: 33/100 TeV

- cases for machine B

  are usually written as if machine A found nothing.

an obvious point

an obvious point

- cases for machine B

  are usually written as if machine A found nothing.

- The most important cases for machine B?

  to study the discoveries of machine A with more precision.

  and to find additional particles or forces

LHC: 300 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **Clarification of Higgs couplings, mass, spin, CP to the 10% level.**

5. **Theoretically and experimentally precise top quark mass to 600 MeV**

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.**

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.

3. First measurement of Higgs self-coupling.

6. Precise measurements of VV scattering; access to Higgs sector resonances

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

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

Higgs EW Top QCD NP/flavor

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.**

4. **Giga-Z program for EW precision, W mass to 4 MeV and beyond.**

7. **Sub-% measurement of top couplings to gamma & Z, accuracy well below expectations in models of composite top and Higgs**

10. No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter

ILC, up to 500 GeV

Higgs EW Top QCD NP/flavor

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 cbar, t ubar.
9. Improvement of αS from Giga-Z
10. No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter

ILC 1 TeV

Higgs EW Top QCD NP/flavor

2. **Higgs self-coupling, 13% accuracy**

5. **Model-independent search for new particles with coupling to gamma or Z to 500 GeV**

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

ILC 1 TeV

Higgs EW Top QCD NP/flavor

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 fbar 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

CLIC: 350 GeV, 1 TeV,

Higgs EW Top QCD NP/flavor

2. Higgs self-coupling, 10%

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.

8. Any discovery of new particles dictates a lepton collider program as with the 1TeV ILC

CLIC: 350 GeV, 1 TeV,

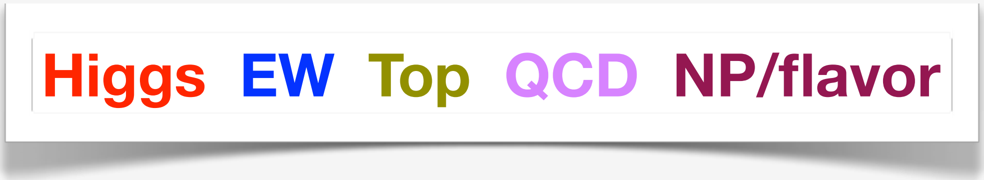
Higgs EW Top QCD NP/flavor

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 fbar above 10 TeV
8. **Any discovery of new particles dictates a lepton collider program as with the 1TeV ILC**

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

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**

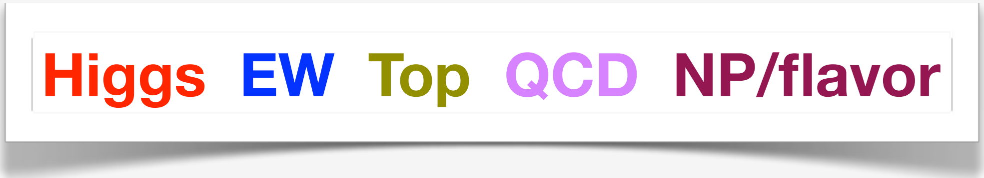
muon collider: 125 GeV, 350 GeV,1.5 TeV, 3 TeV

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

Higgs **EW** **Top** **QCD** **NP/flavor**

2. **Ability to study CP mixture and violation in the Higgs sector using polarized photon beams.**

photon collider

Higgs EW Top QCD NP/flavor

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.**

TLEP, circular e+e-

Higgs EW Top QCD NP/flavor

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.)

TLEP, circular e+e-

Higgs EW Top QCD NP/flavor

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 cbar, tubar at 250 GeV.
4. Possible improvement in alphas by a factor 5 over Giga-Z, to 0.1% precision.

pp Collider: 33/100 TeV

Higgs EW Top QCD NP/flavor

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.

pp Collider: 33/100 TeV

Higgs EW Top QCD NP/flavor

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.

- **Let’s be clear.**

  We collider types say we know about Mass.

Really?

- As long as we know

  nothing about the neutral fermions

  &

  nothing about 85% of the gravitating universe

- We don’t know the Mass story.

This is serious.

The very light neutrino mass **is BSM physics:**

- is it Dirac? – it's a tiny coupling to v
  - *then the Higgs sector could be expanded*
- is it Majorana? – it might talk to a different Higgs!
  - *then we have to find it*
- do they get mass differently... because it's tiny?
  - *neutral fermions and charged fermions with different mass generation? Completely bizarre*

Andre de Gouvea keeps making this point

This is serious.

The very light neutrino mass **is BSM physics:**

is it Dirac? – it’s a tiny coupling to v

- *then we need to find W and expand the Higgs sector*

is it Majorana? – it might talk to a different Higgs!

- *then we have to find it*

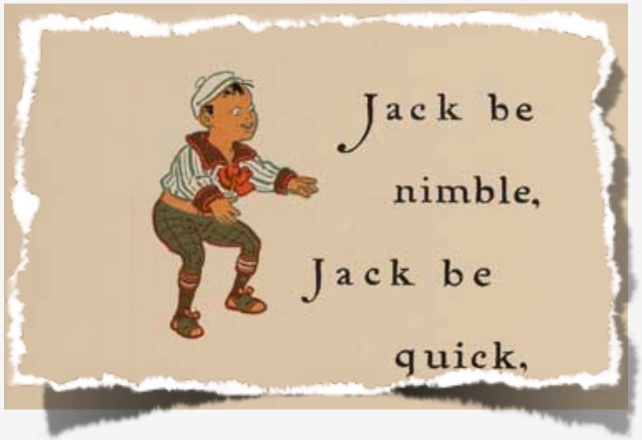
do they get mass differently... because it’s tiny?

- *neutral fermions and charged fermions with different mass generation? Completely bizarre*

Understanding Mass is still “all hands on deck” physics – EF, IF, and CF!

Andre de Gouvea keeps making this point

Energy Frontier: precision, mass reach, and surprise



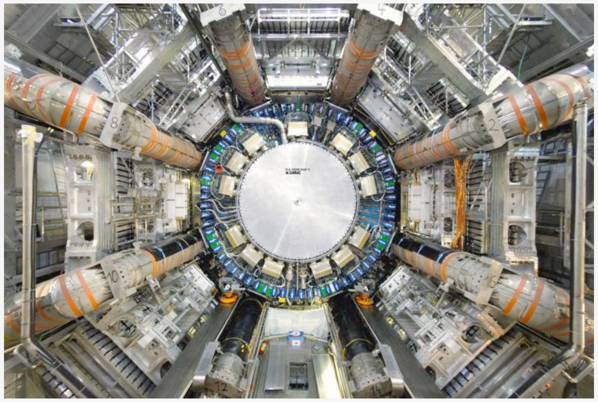
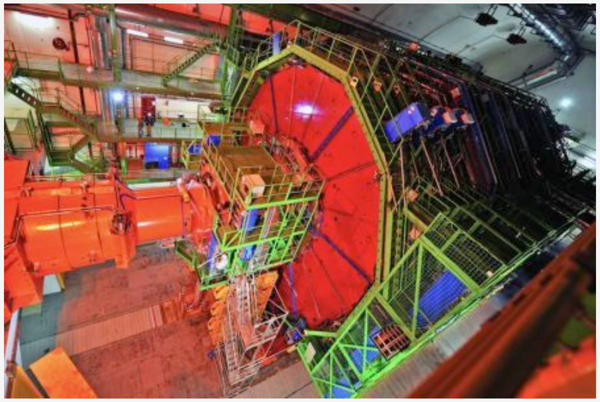
- LHC: exquisite instruments

  proven capability

  precision and surprise

- Will point to the EF future at

  ILC, Muon Collider, CLIC, TLep, $\gamma\gamma$, ep, or VLHC


by
incrementally:

- Measuring the properties of the Higgs boson.
- Measuring the properties of the: *t*, *W*, and *Z*
- Searching for TeV-scale particles

- The Higgs particle changes everything.

why?

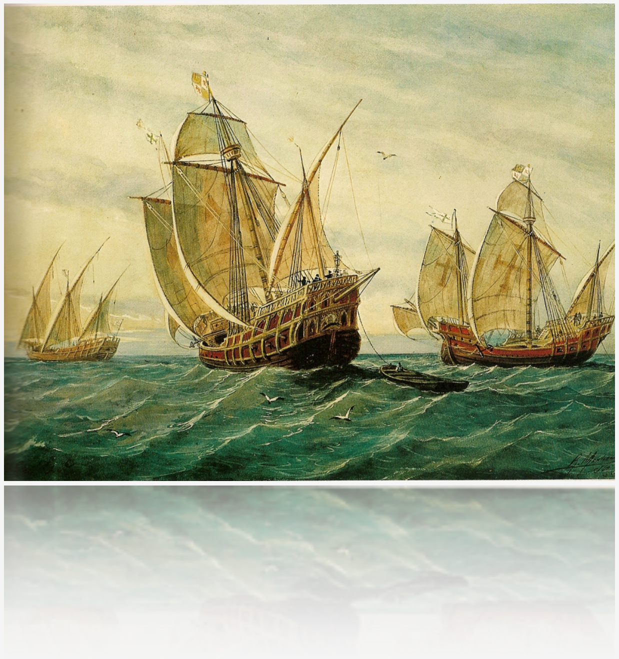
- Confirming the SM?

  No longer a goal

- Now we’re exploring.

  The real meaning of

“Frontier”



Comments:

1. How do we understand the Higgs boson?

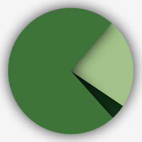
2. How do we understand the multiplicity of quarks and leptons?

3. How do we understand the neutrinos?

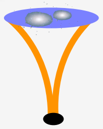
4. How do we understand the matter-antimatter asymmetry of the universe?

5. How do we understand the substance of dark matter?

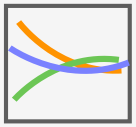
6. How do we understand the dark energy?



7. How do we understand the origin of structure in the universe?

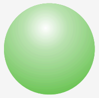


8. How do we understand the multiplicity of forces?



9. Are there new particles at the TeV energy scale?

10. Are there new particles at higher energies?

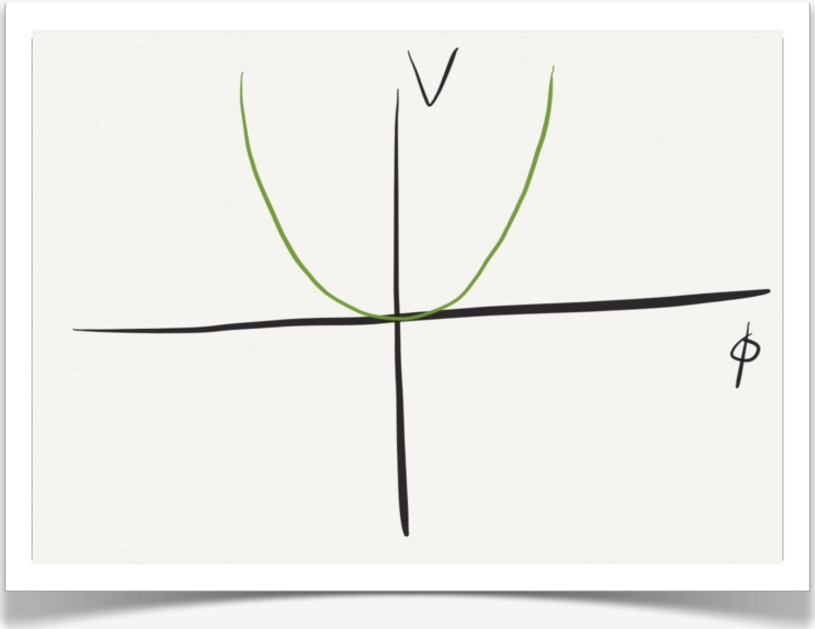


But we know that the Standard Model is

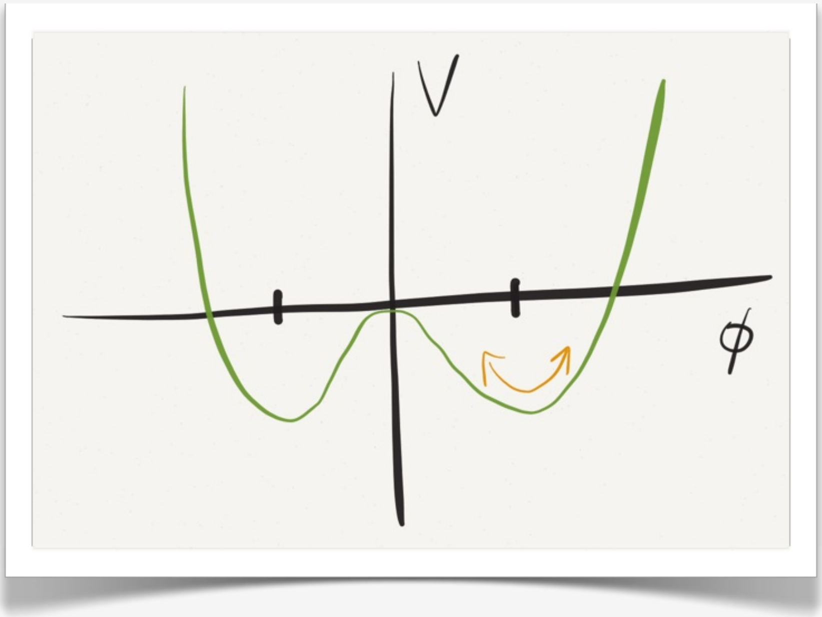
- It’s only an effective model

  It lacks dynamics to explain the change of potential

from this:

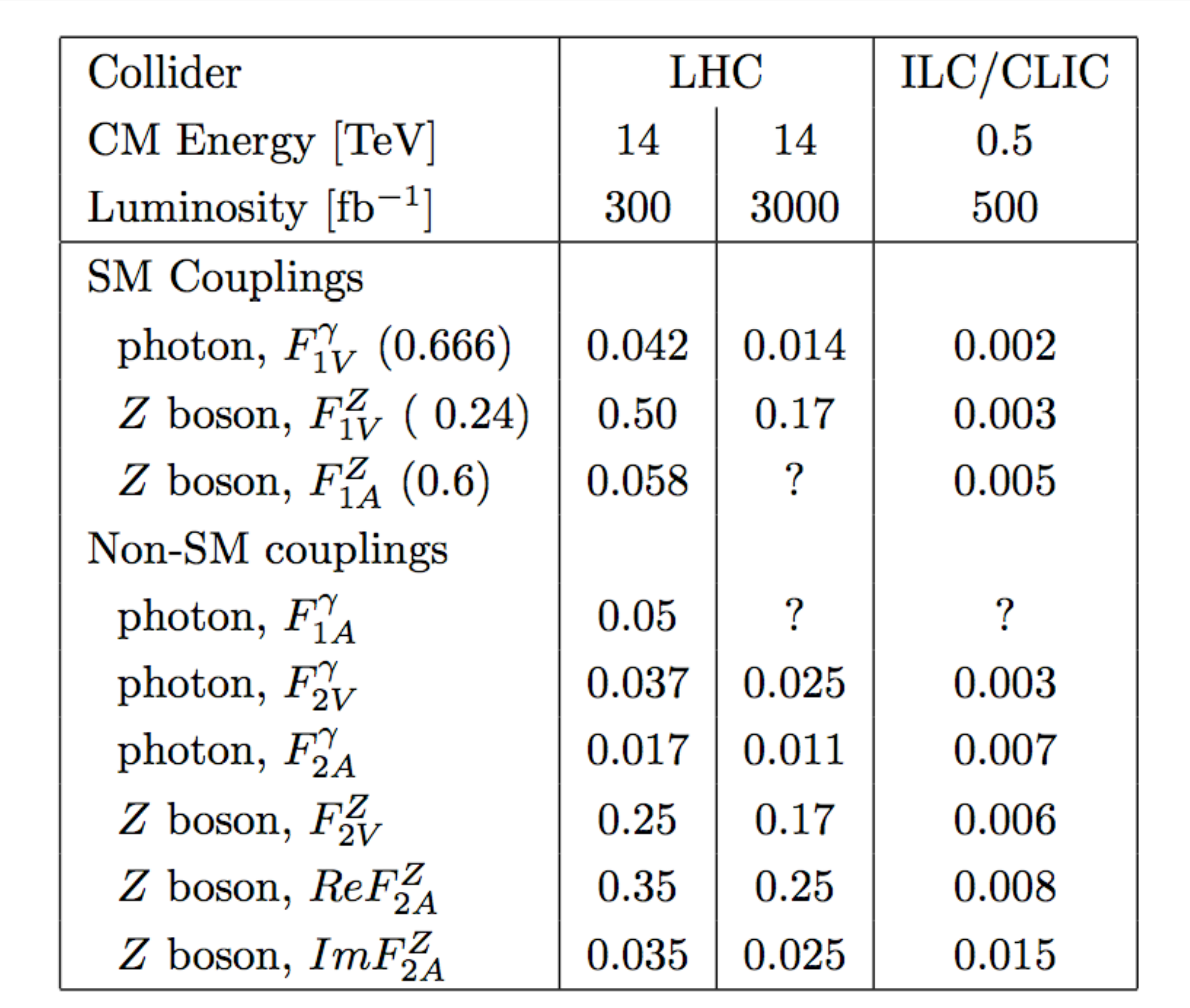


to this:



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

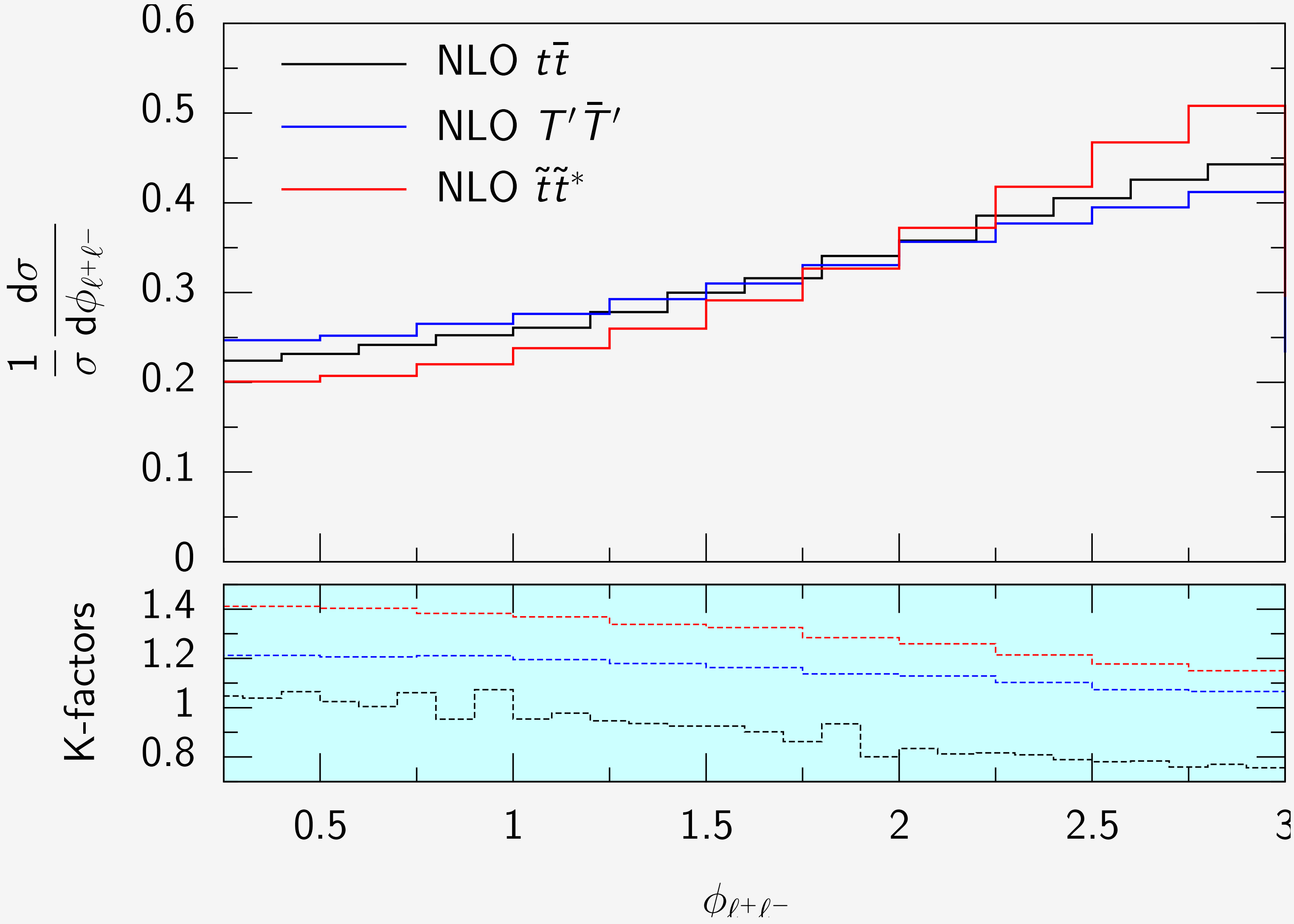
BSM: 2-10 %

LHC : few %

ILC/CLIC: sub-%

Top quark spin correlation

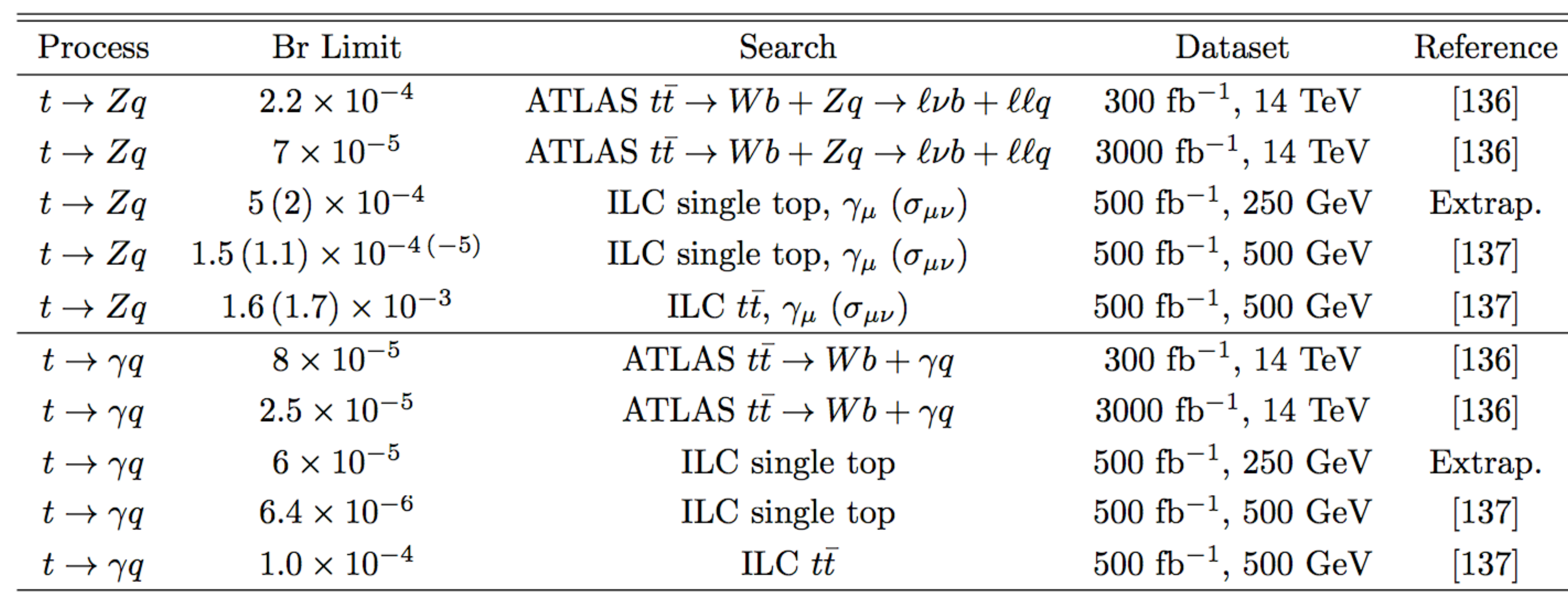
diagnostic of top polarization;
a sensitive probe for top partners, esp stealthy stop



Flavor-changing top decay

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

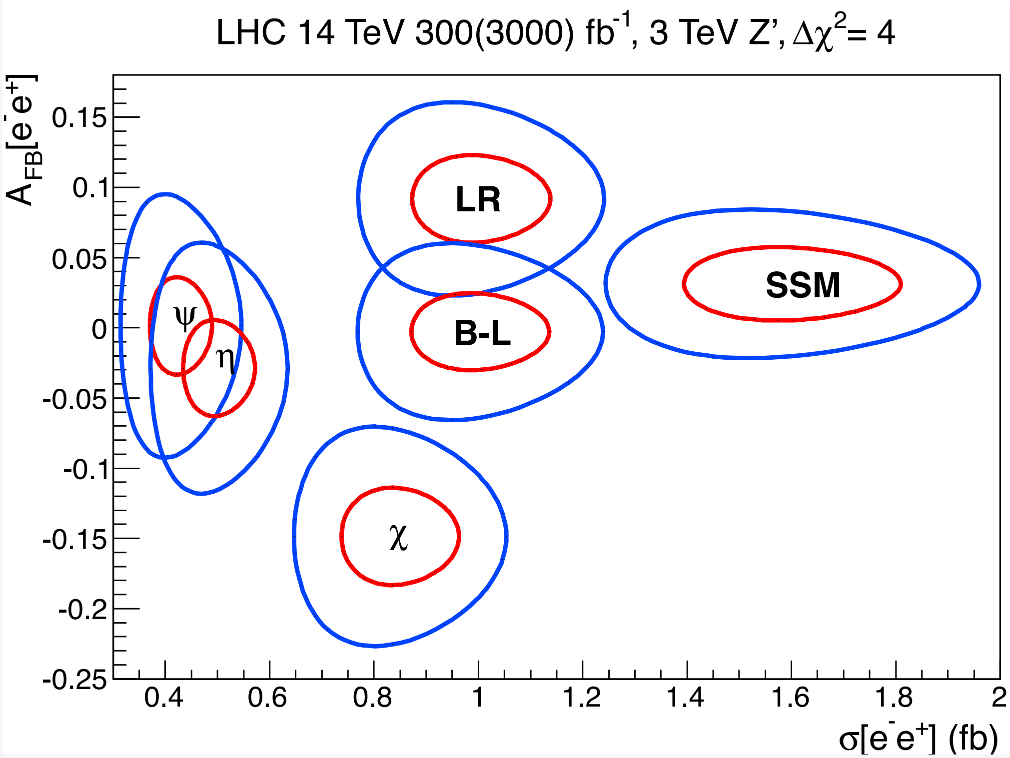
projected limits for FCNC top decay processes



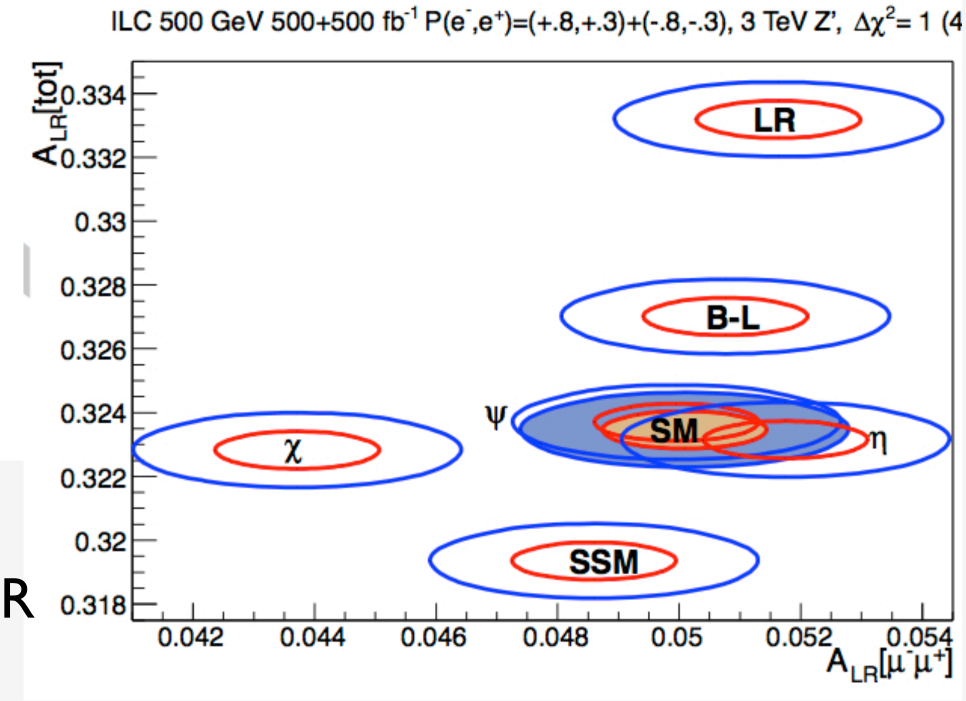
Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[136]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[136]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, 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]

Finding the identity of a Z’

Many more diagnostic observables are available in e+e-, similar reach.



E6 from LR, etc LHC A_{FB}

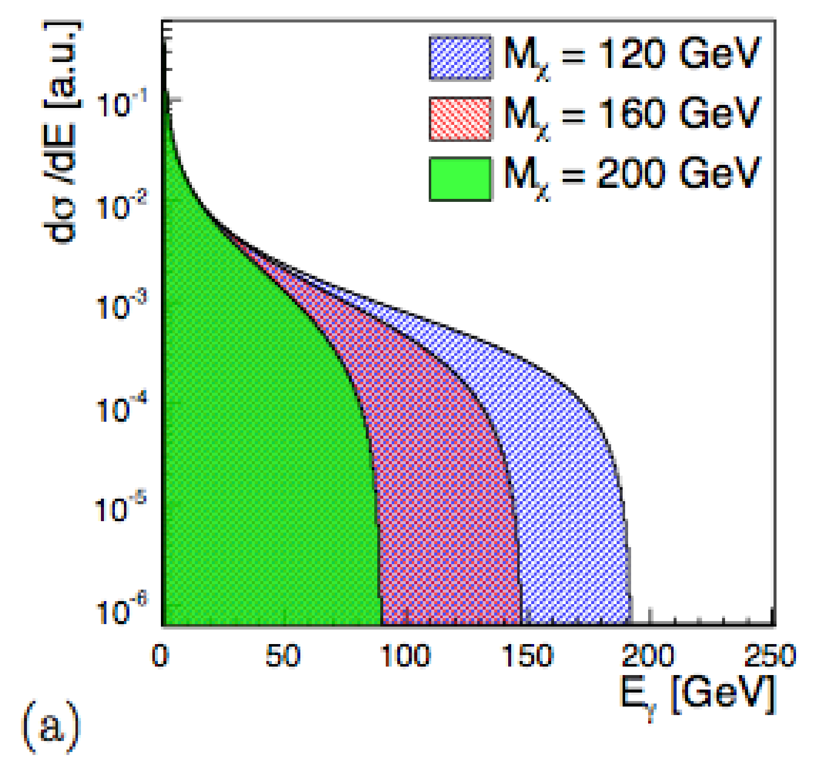


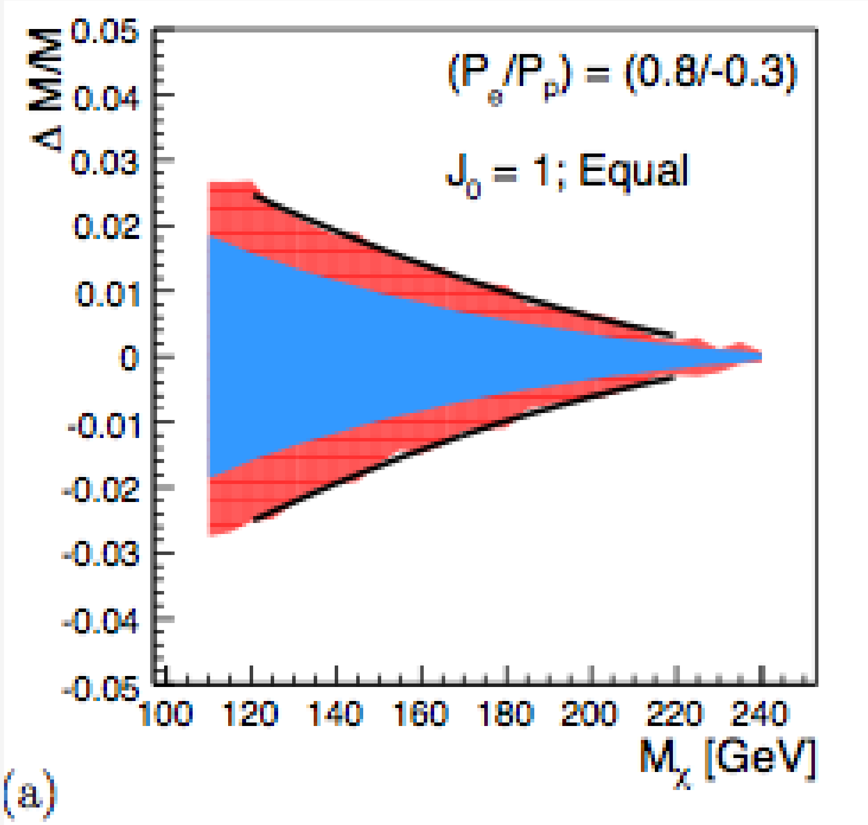
E6 from LR, etc ILC A_{LR}

Dark matter connection

WIMP search at ILC in $e^+e^- \rightarrow \gamma + \chi + \chi$

polarization significant in controlling backgrounds

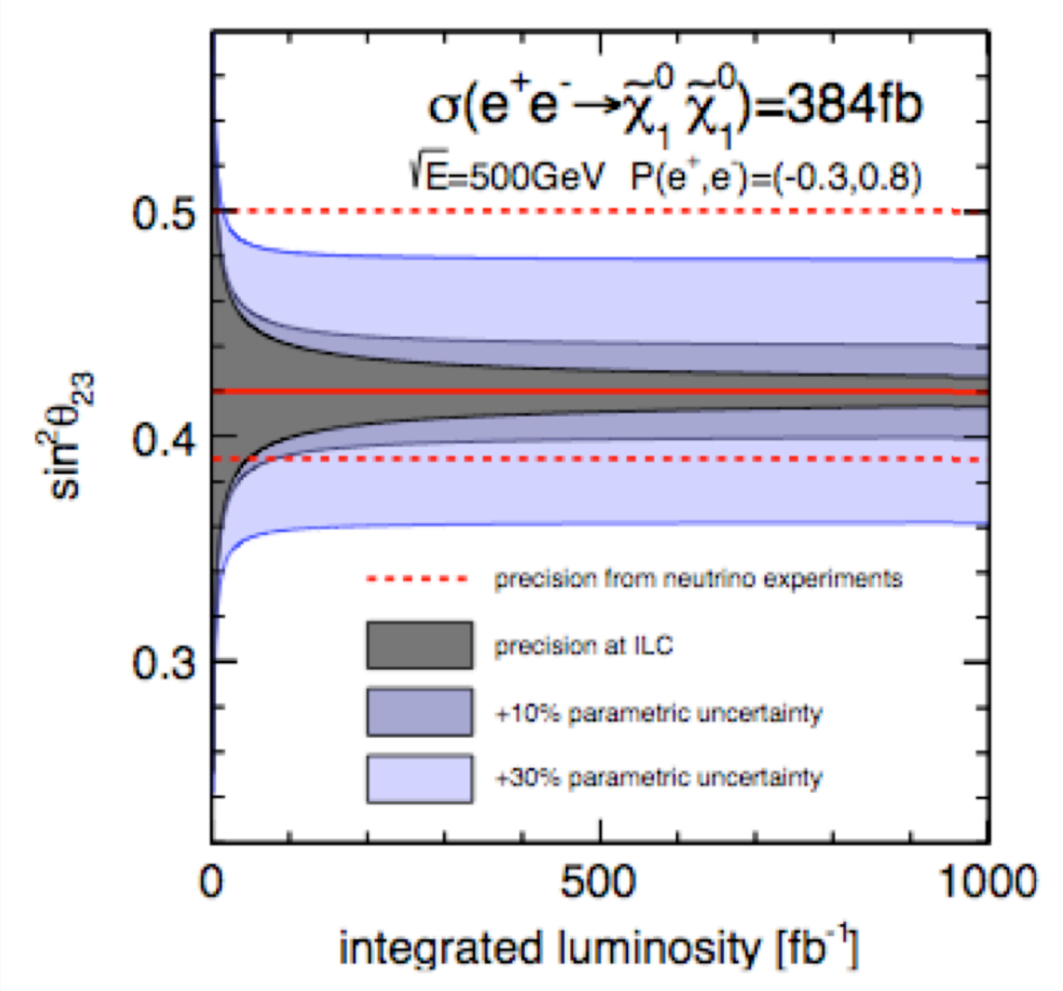




Neutrino connection

Discover the SUSY neutralino decaying $\tilde{\chi}_1^0 \to W + \tau$ via ....through the R-parity violating SUSY coupling.

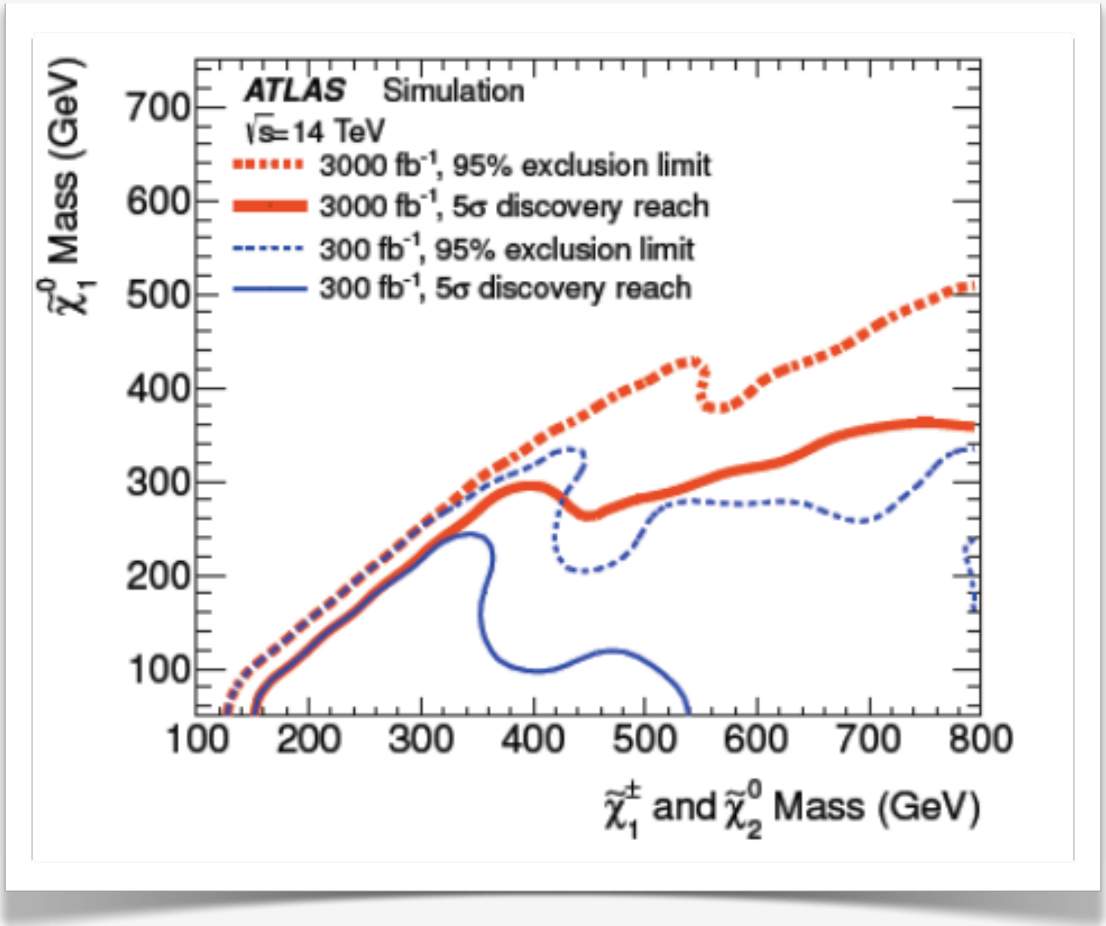
In “Type III seesaw,” the θ23 controls the rate of the subleading $\tilde{\chi}_1^0 \to W + \mu$ decay ....
In this model, with neutralino accessible at ILC, this prediction is directly testable.



electroweakinos

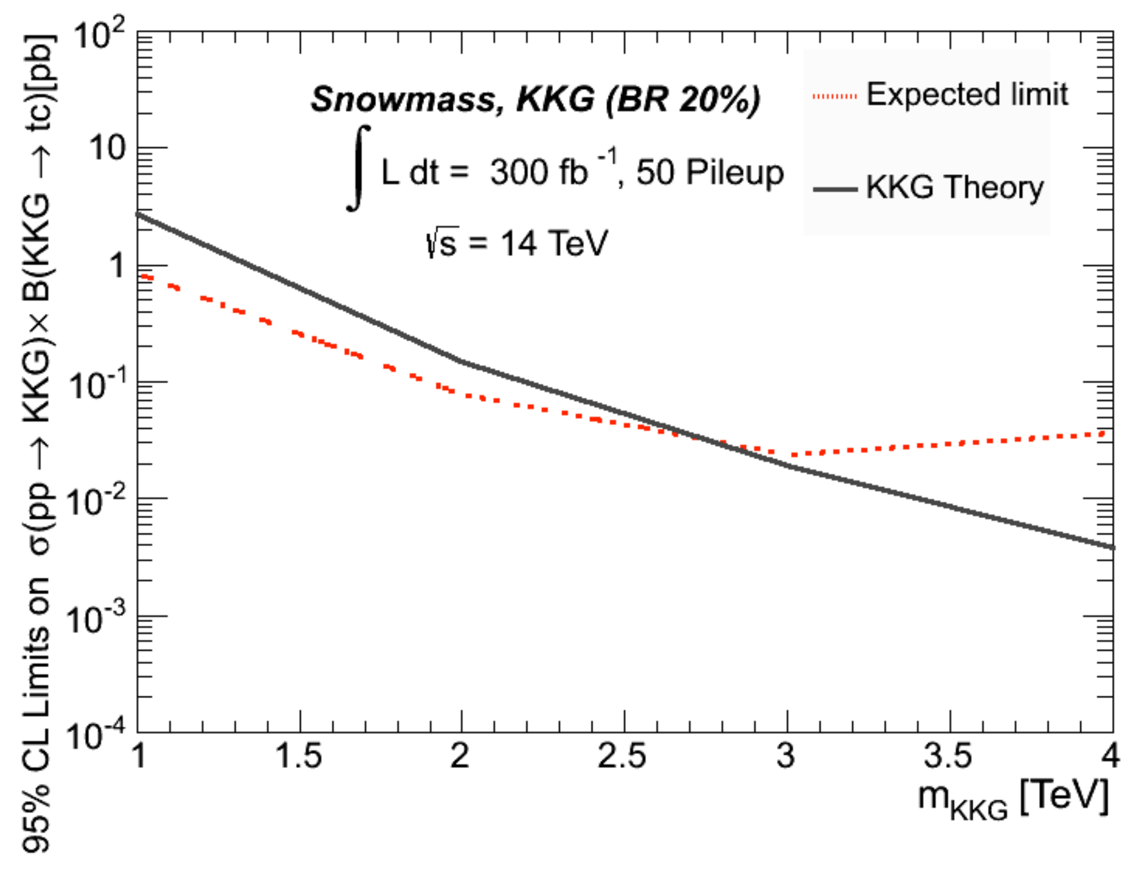
x 2 again...300/fb to 3000/fb

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



Flavor connection

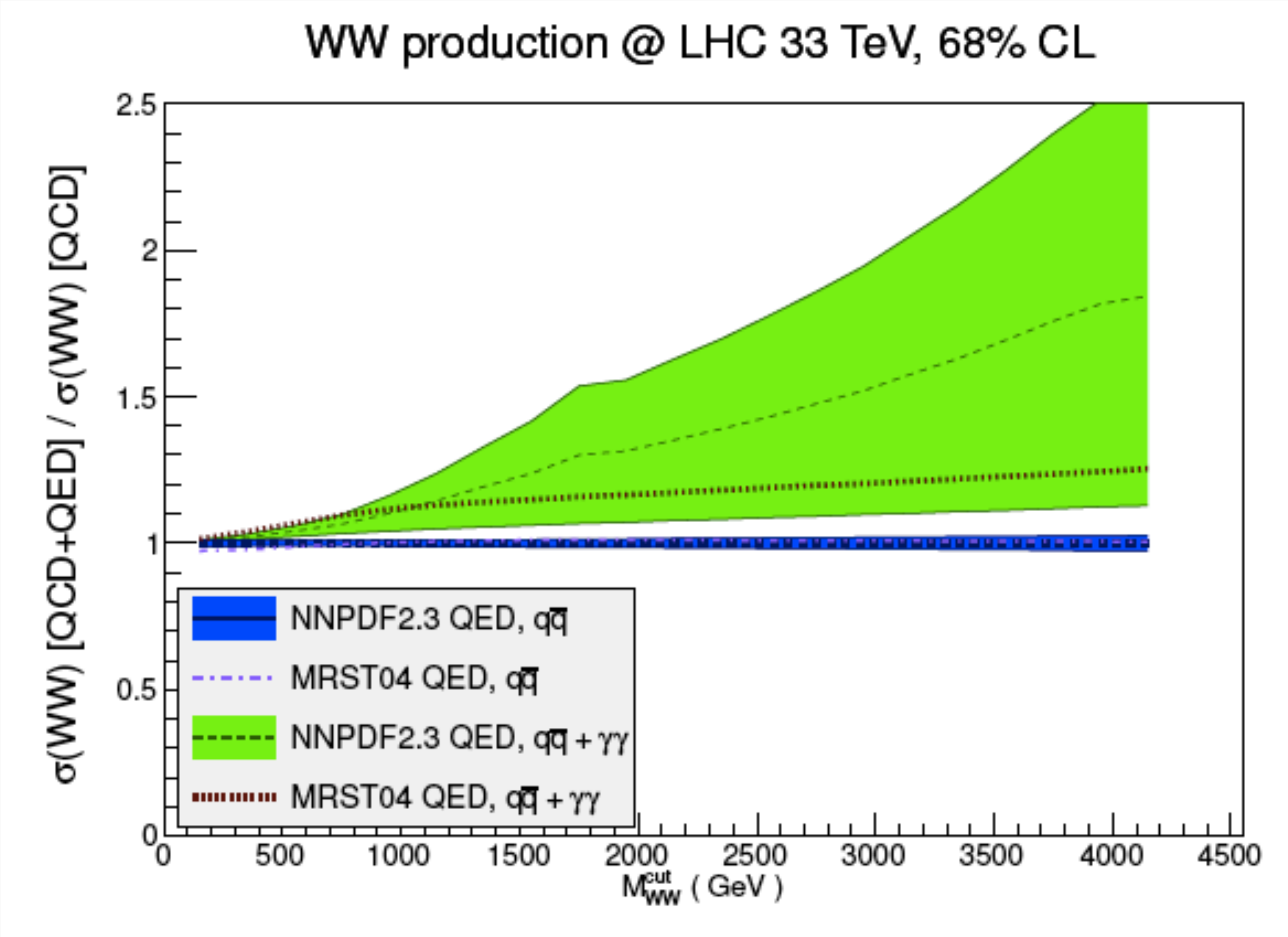
Discover KK resonance -> t tbar, search for decay to t cbar



Schoenrock, Drueke, Alavarez-Gonzalez, Schwienhorst

Photon PDF and QED

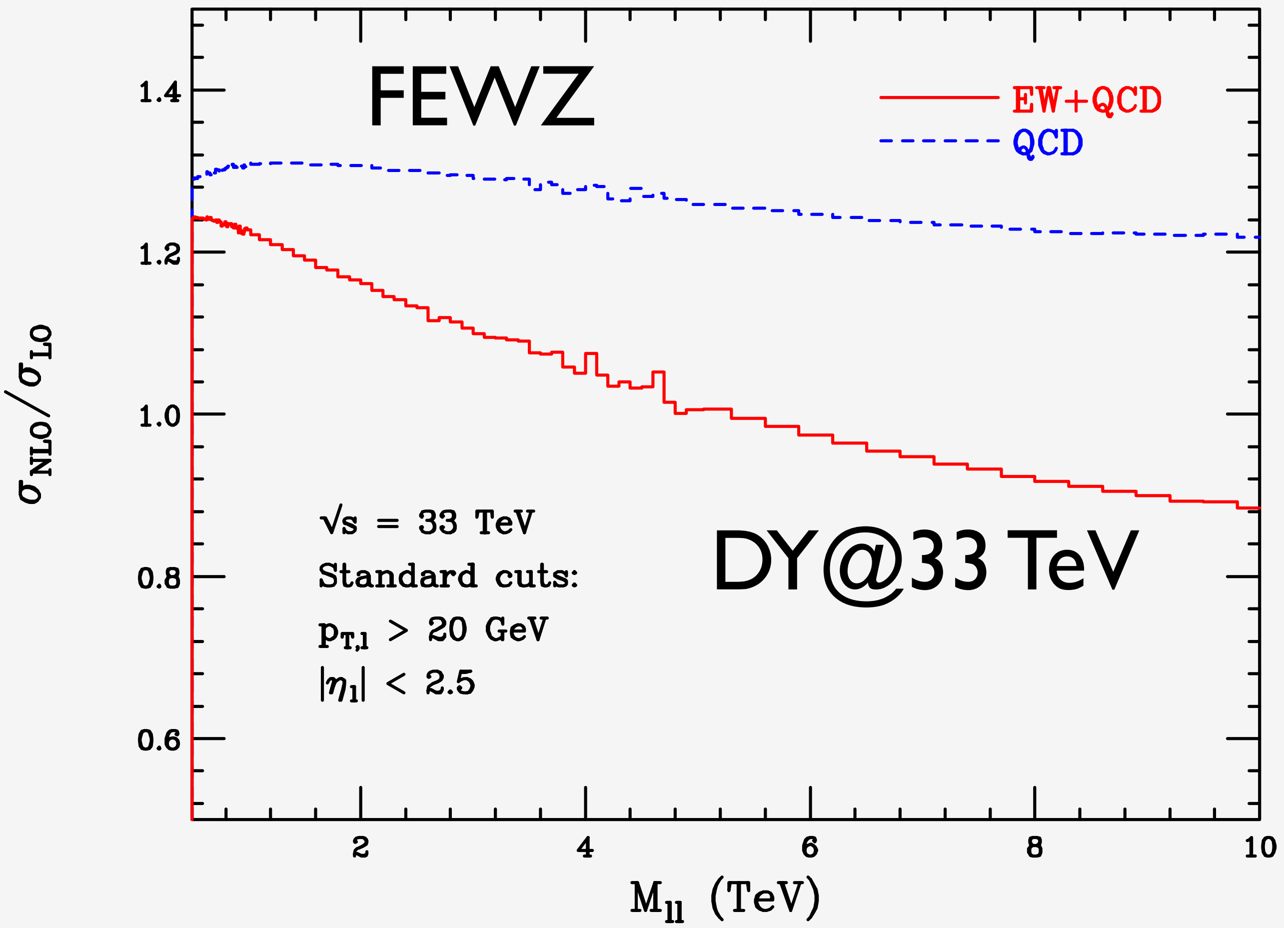
Photon-induced processes are increasingly important; need to extend the current state of the art in PDFs to QED.



Juan Rojo

Electroweak Sudakov

Electroweak corrections and Sudakov EW logs must be incorporated into event simulation.

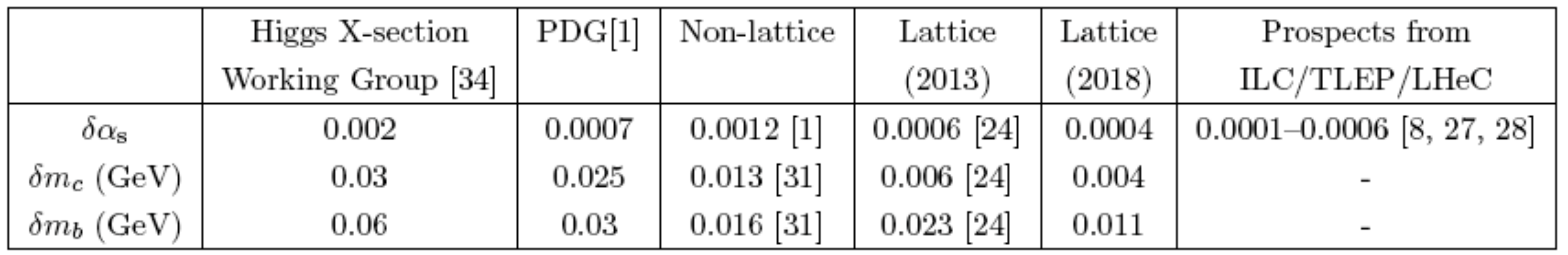


Kaland Mishra

Precision inputs from Lattice

Improvement in alphas and quark masses will come from lattice gauge theory.

- These are necessary inputs to precision Higgs theory and other precision programs.



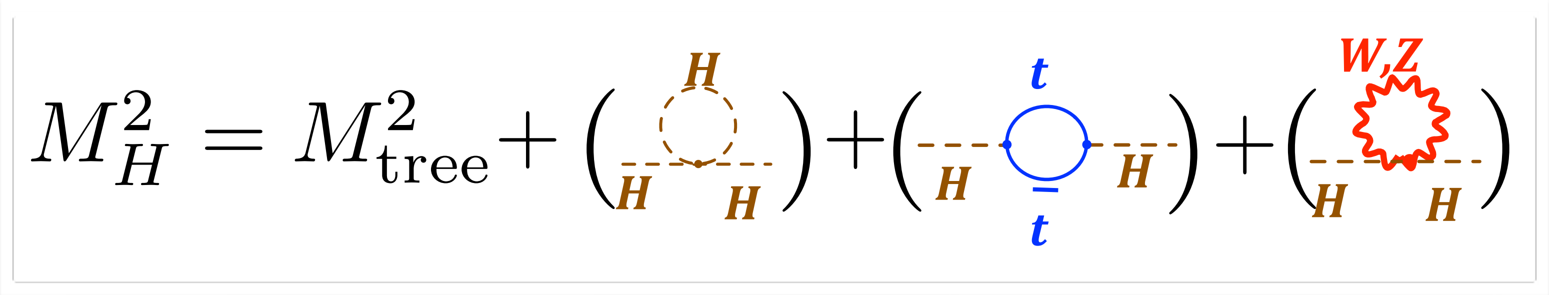
	Higgs X-section Working Group [34]	PDG[1]	Non-lattice	Lattice (2013)	Lattice (2018)	Prospects from ILC/TLEP/LHeC
$\delta\alpha_s$	0.002	0.0007	0.0012 [1]	0.0006 [24]	0.0004	0.0001–0.0006 [8, 27, 28]
δm_c (GeV)	0.03	0.025	0.013 [31]	0.006 [24]	0.004	-
δm_b (GeV)	0.06	0.03	0.016 [31]	0.023 [24]	0.011	-

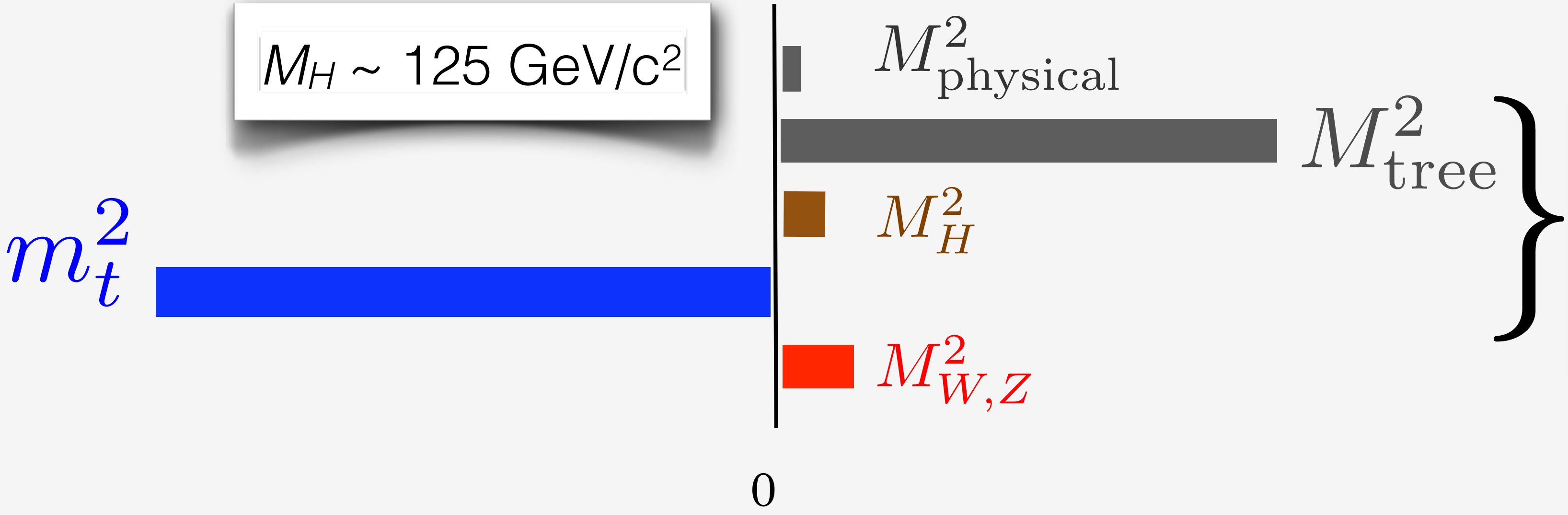
Paul Mackenzie,
Snowmass QCD report

Light scalar mass = mass confusion

“hierarchy” problem

additive, quadratic cut-offs...in mass-squared, by the way





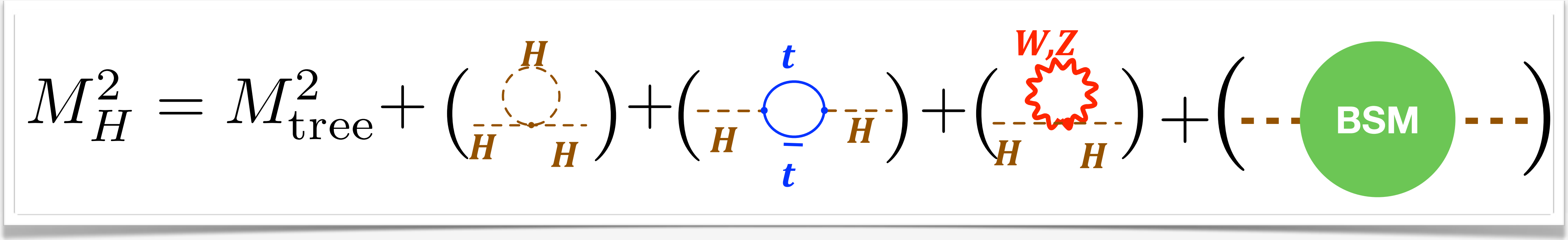
M_H ~ 125 GeV/c²

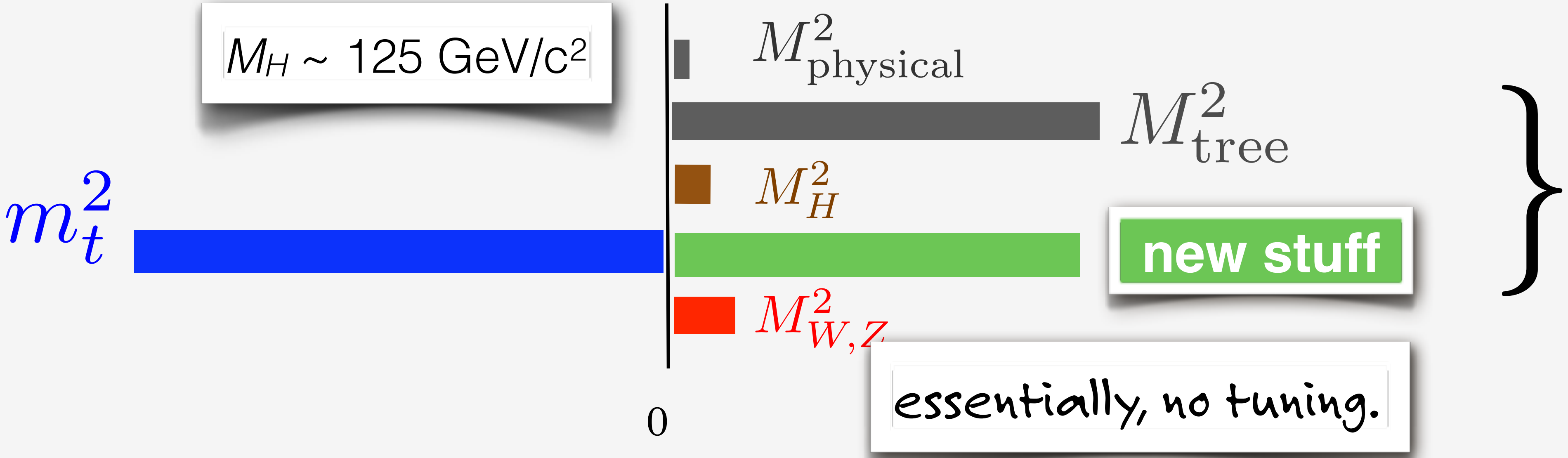
un-fine tuning?

Perhaps a huge hint?

of something "BSM"?

- no shortage of ideas





M_H ~ 125 GeV/c²

new stuff

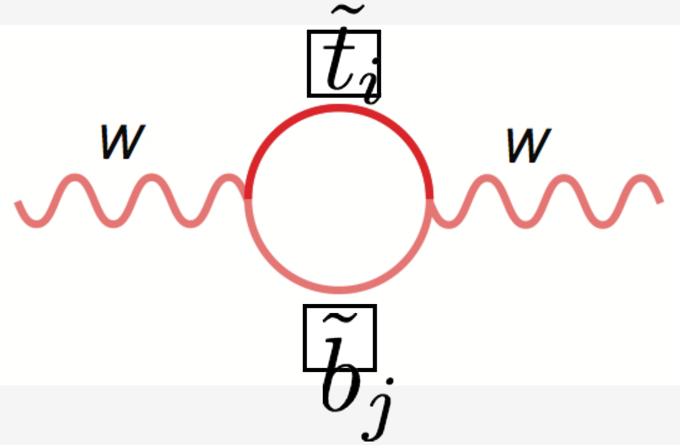
essentially, no tuning.

M_W, the old fashioned way

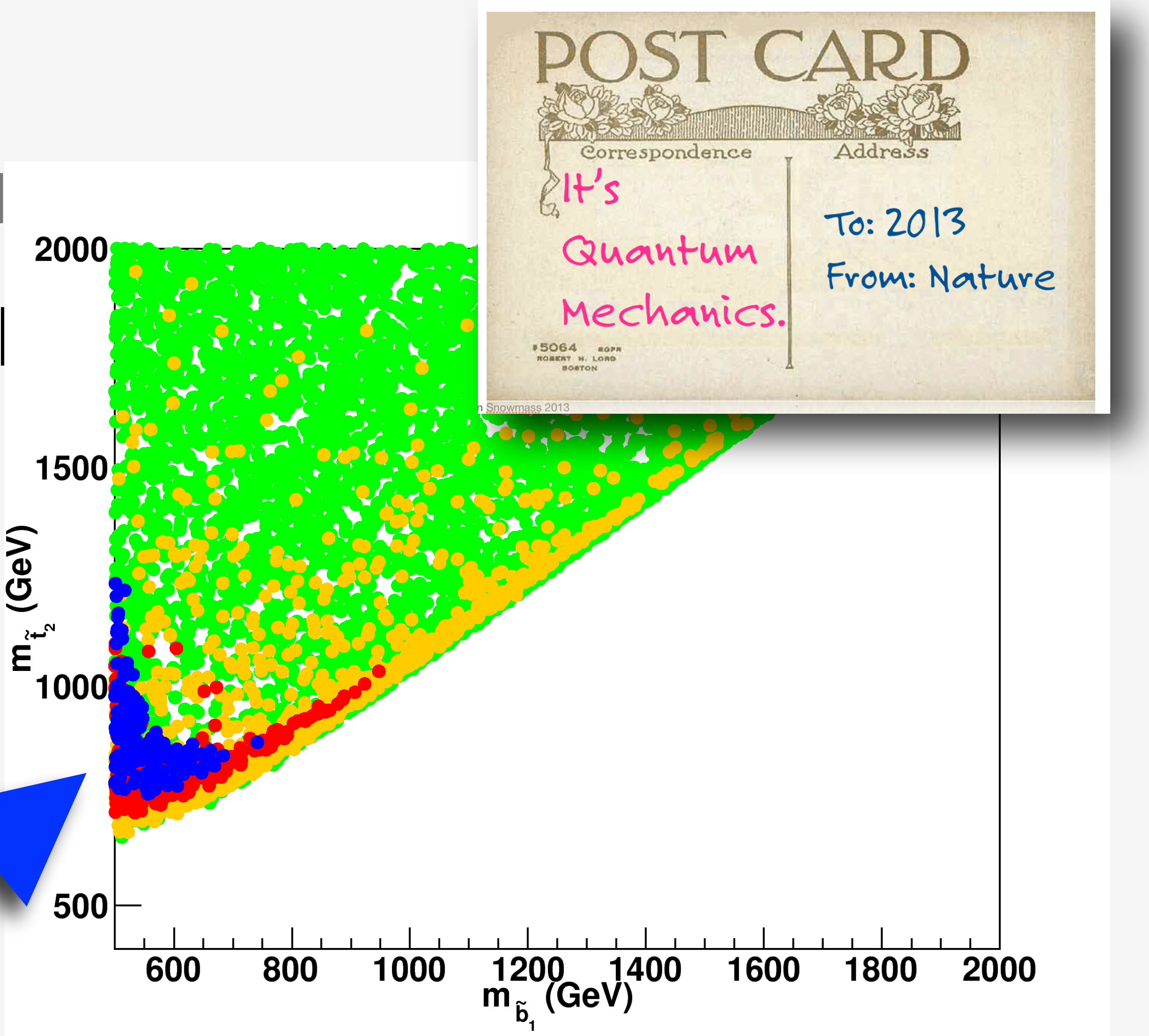
Imagine we knew:

- the stop1 mass, and

n tl



$$\delta M_W \sim 5\ \mathrm{MeV}/c^2$$



It's

Quantum

Mechanics.

To: 2013

From: Nature

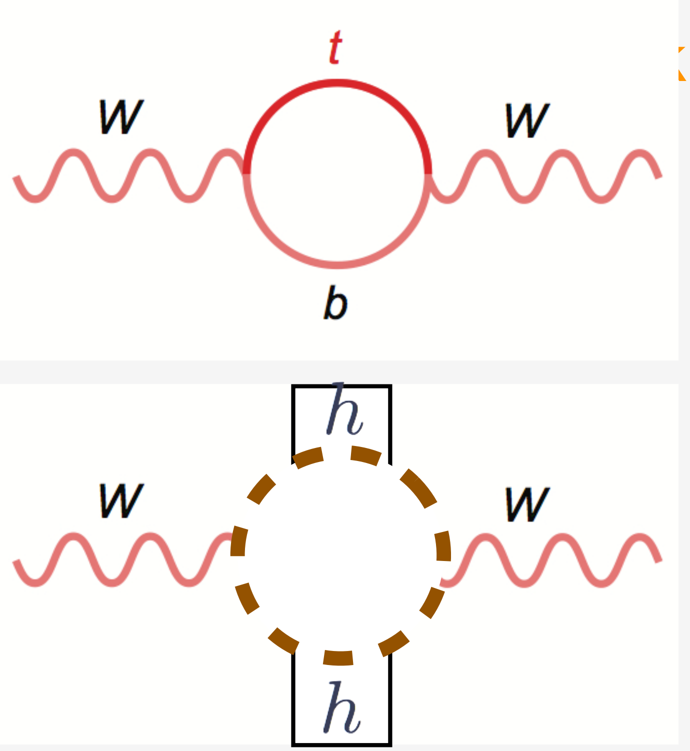
MSSM scenarios in mstop2 vs msbottom1 plane with

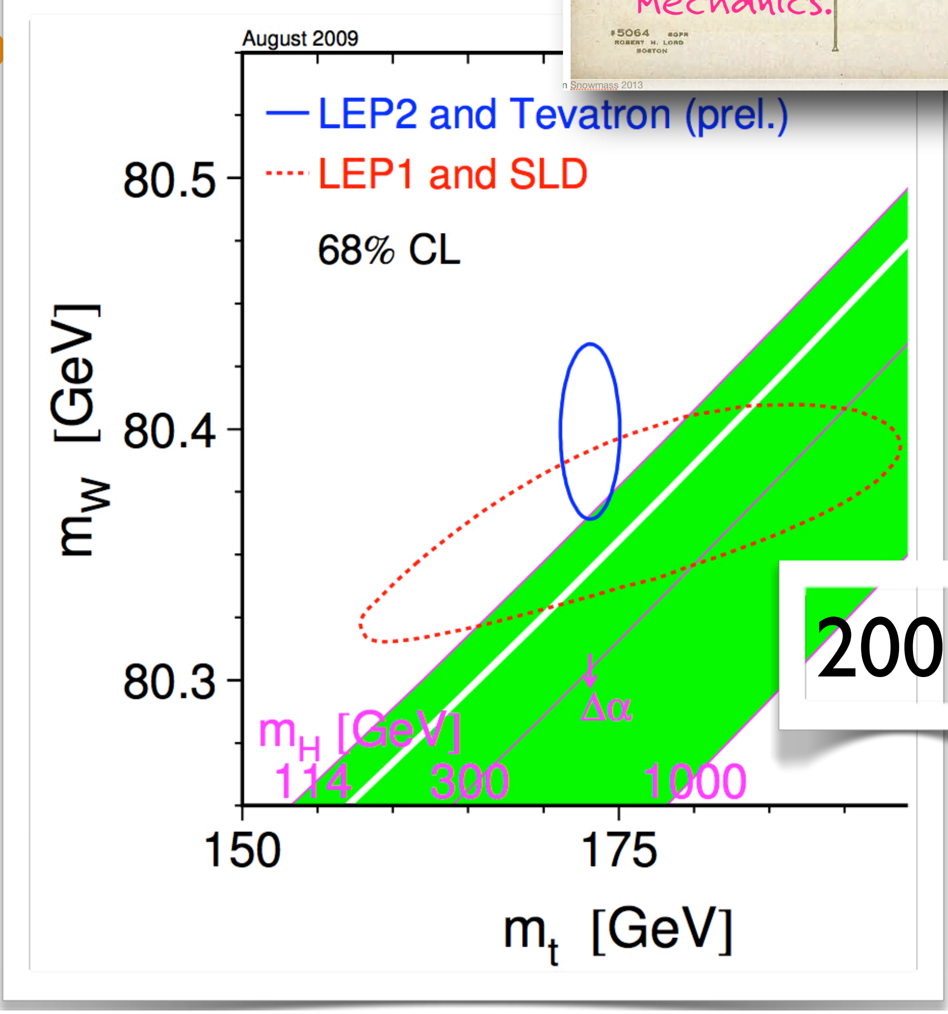
EWPOs

Electroweak Precision Observables

- We knew where to look for the Top Qua

W   fo





POST CARD

Correspondence

It's Quantum Mechanics.

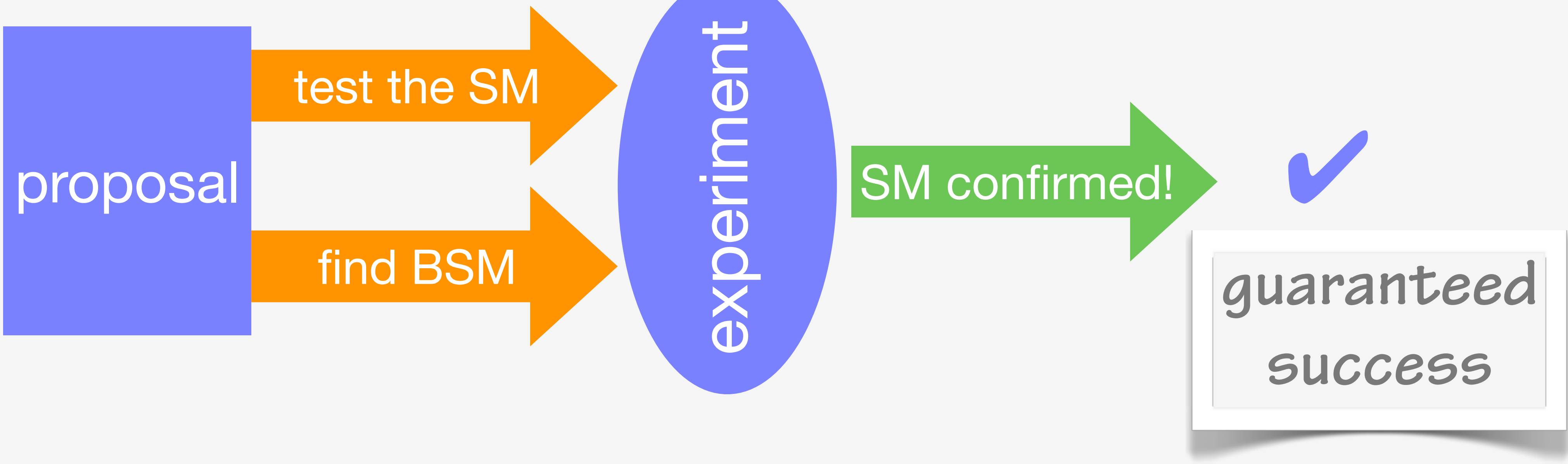
Address

To: 2013

From: Nature

EWPOs are a well
trusted probe

In the past:



proposal

test the SM

find BSM

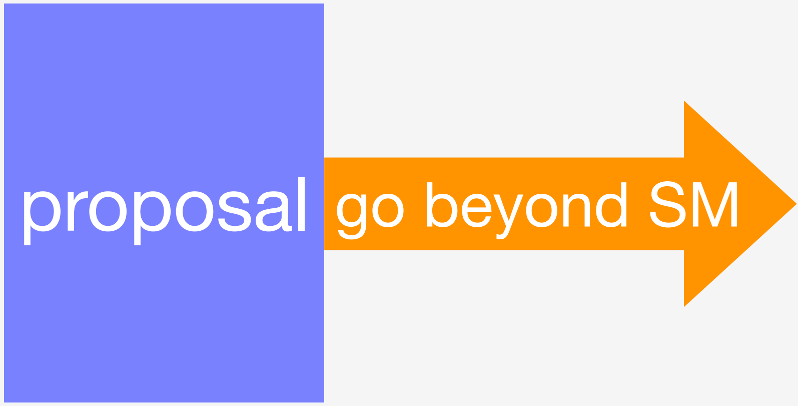
experiment

SM confirmed!

✓

guaranteed success

Now:



proposal

go beyond SM