# Snowmass 2013, Energy Frontier Division

**Chip Brock**
*Michigan State University*
**Michael Peskin**
*SLAC*


*Minneapolis, MN*
*August 6, 2013*

# contents

# Introduction

# we don't work at the

level

# we work at the

level

# let's briefly think about the

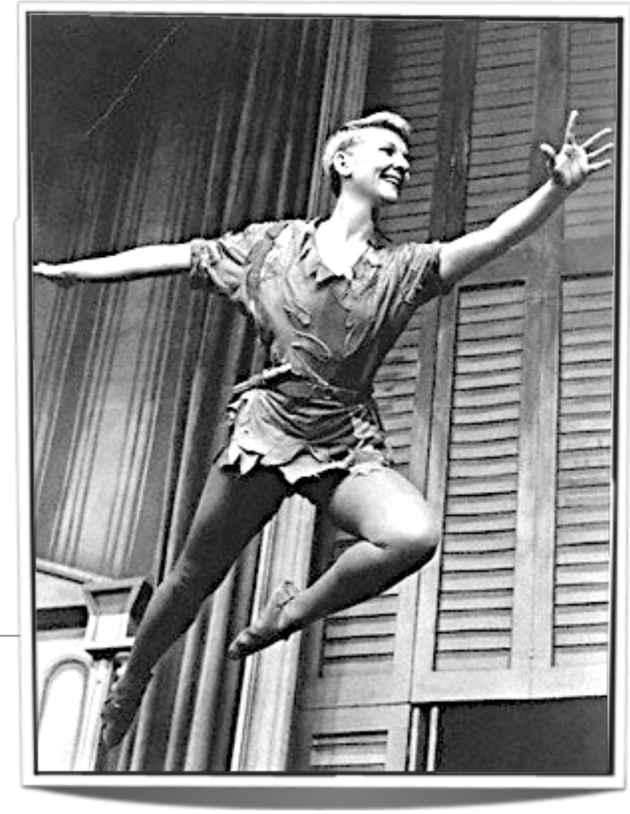
# if you watched this lady

**on your black and white TV**

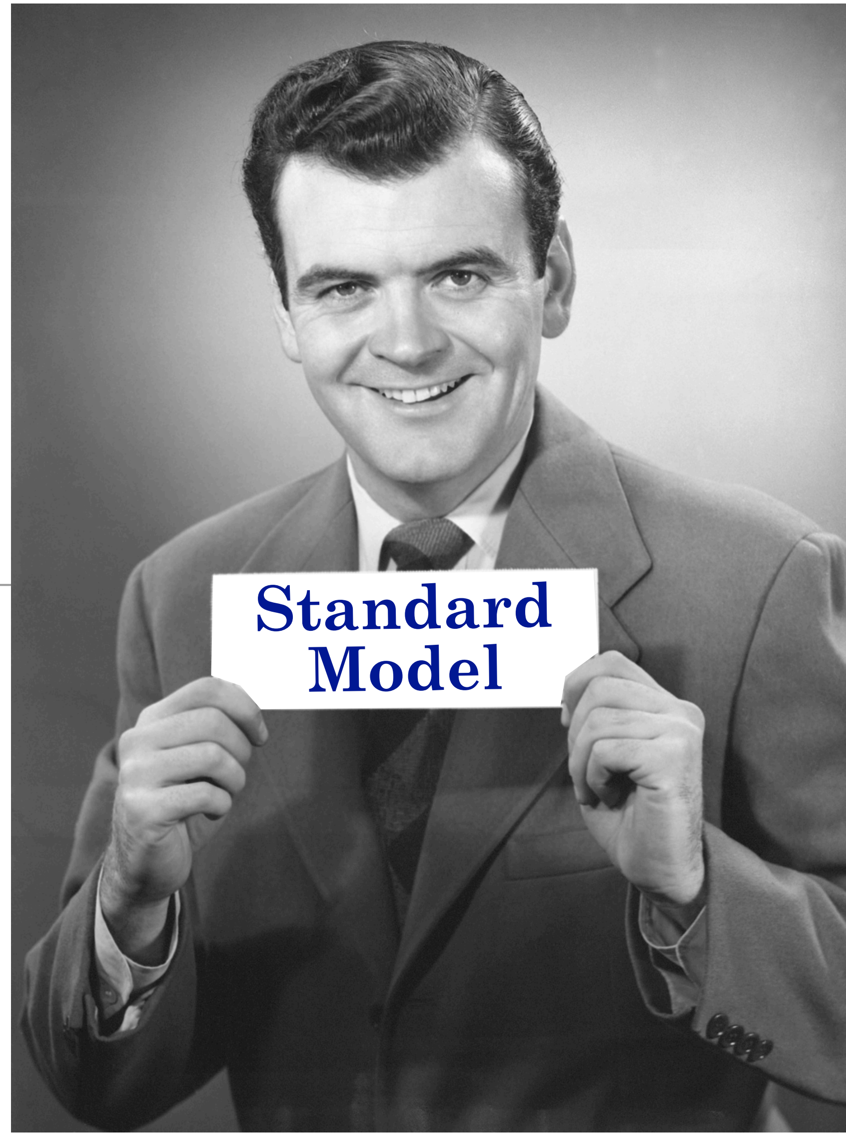
***then you***

and everyone younger that you

**share a common, professional bond**

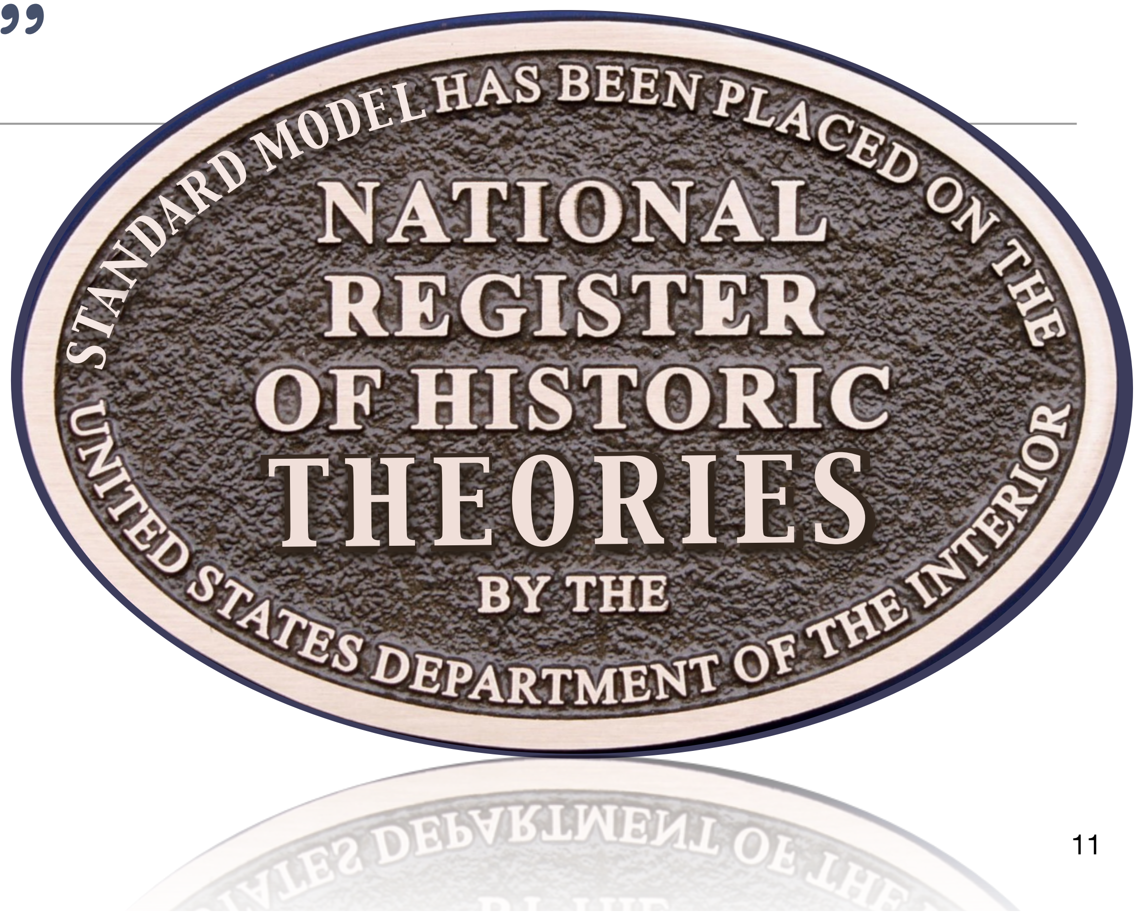


“Second star to the right and straight on 'til morning. ”


Standard
Model

# translation of "Standard"

**The SM is remarkably precise!**



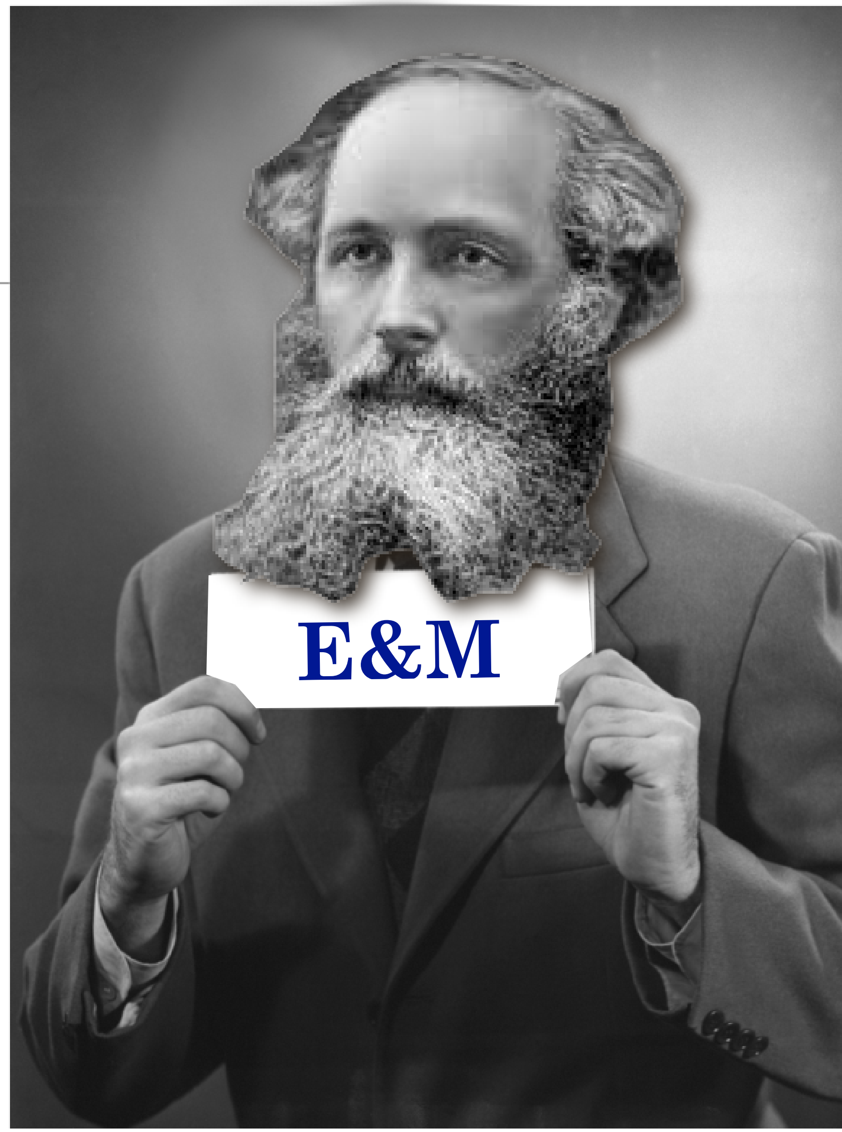
# translation
# of
# "Model"

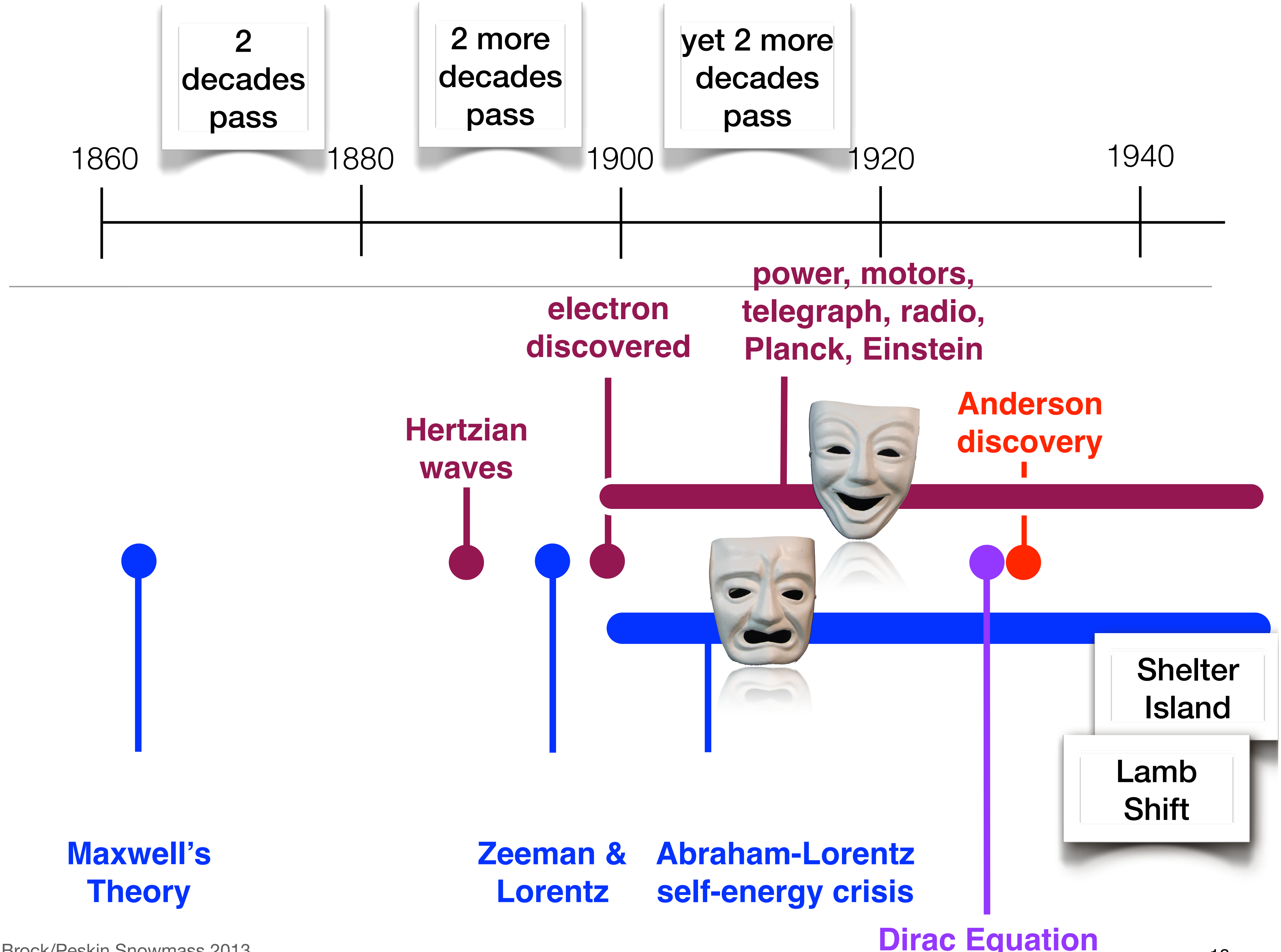
The SM is remarkably precise!

**It's not the whole story**

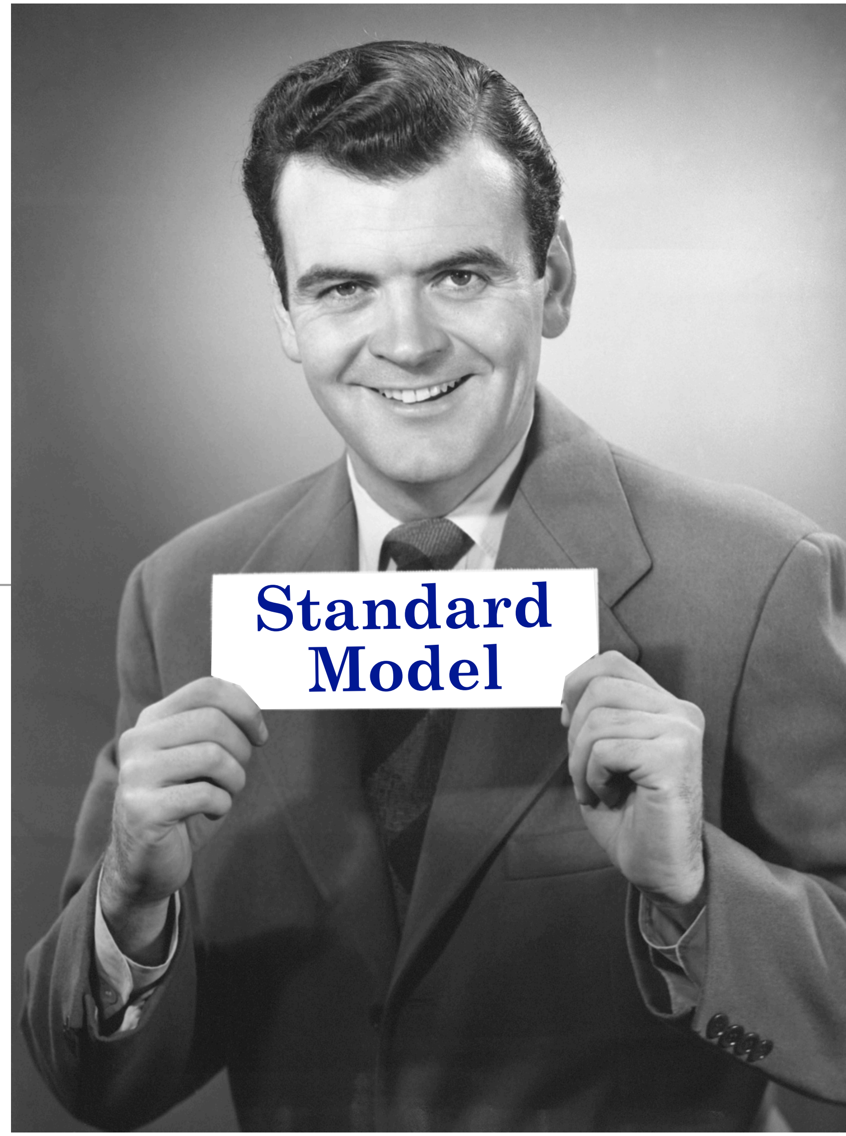
# AN HISTORIC

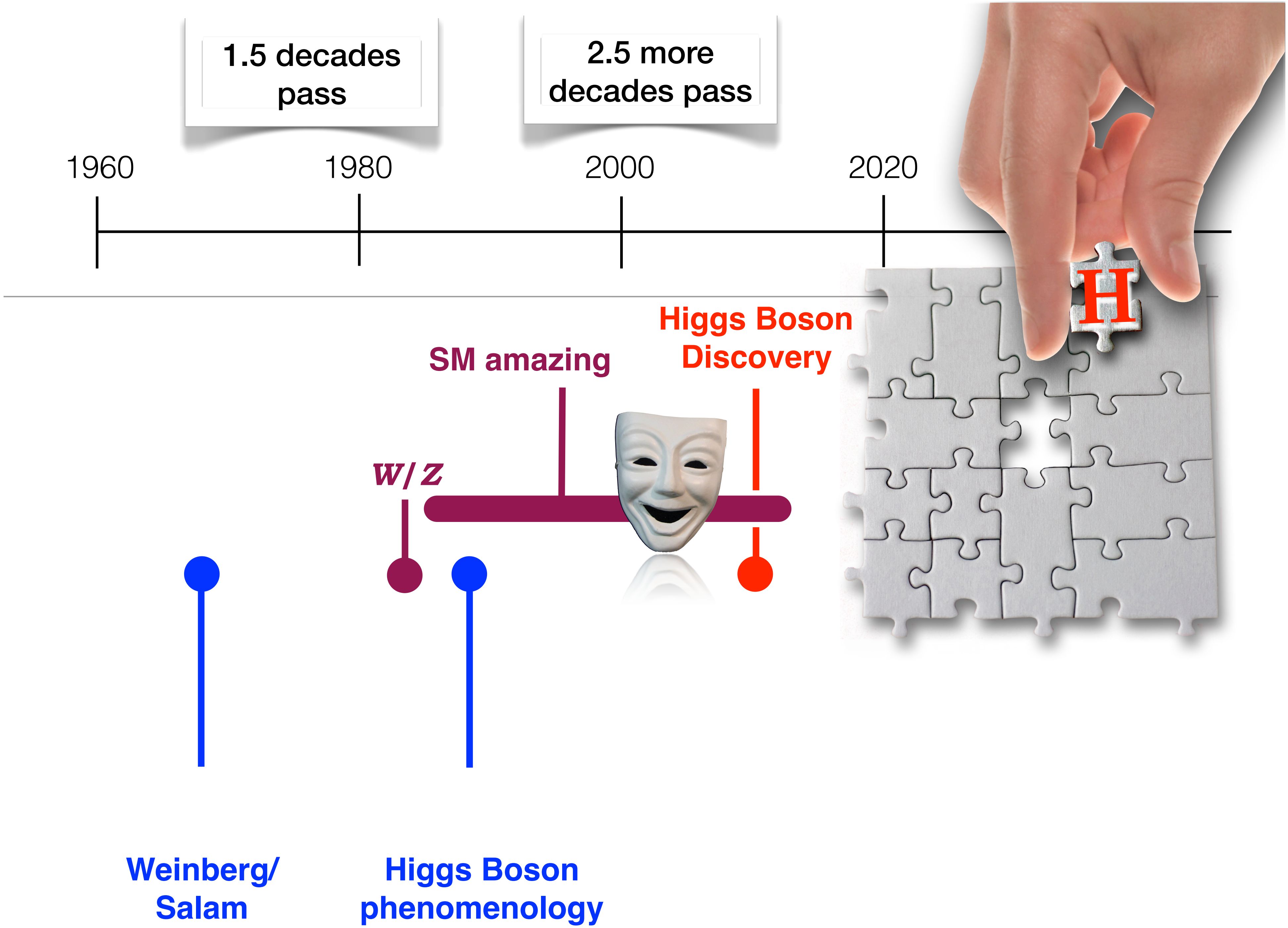
# TIME

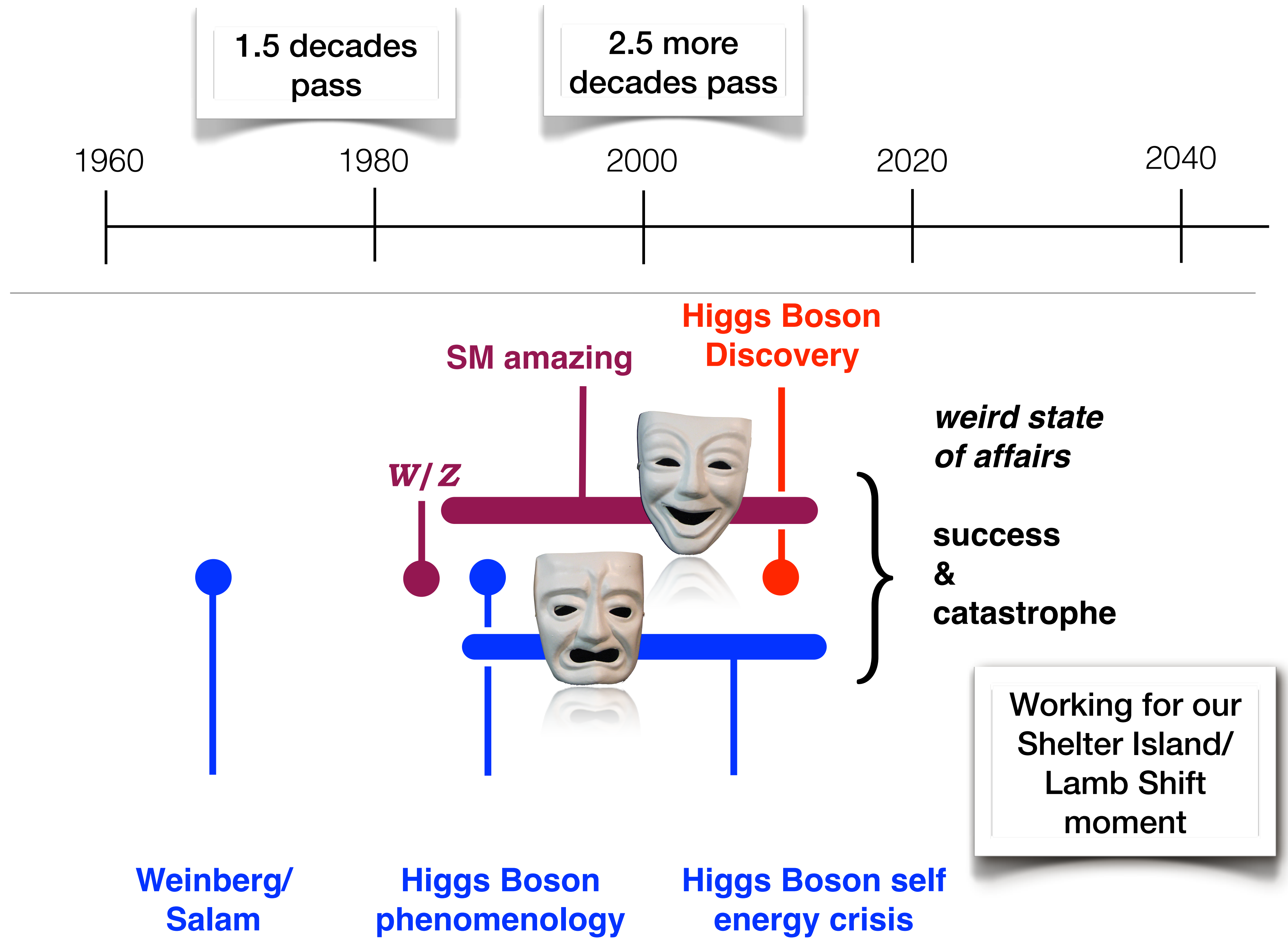

E&M



2 decades pass
2 more decades pass
yet 2 more decades pass
1860
1880
1900
1920
1940
power, motors, telegraph, radio, Planck, Einstein
electron discovered
Hertzian waves
Anderson discovery
Shelter Island
Lamb Shift
Maxwell’s Theory
Zeeman & Lorentz
Abraham-Lorentz self-energy crisis
Dirac Equation


Standard
Model


1.5 decades pass
2.5 more decades pass
1960
1980
2000
2020
H
Higgs Boson Discovery
SM amazing
W/Z
Weinberg/ Salam
Higgs Boson phenomenology


1.5 decades pass
2.5 more decades pass
1960
1980
2000
2020
2040
Higgs Boson Discovery
SM amazing
W/Z
weird state of affairs
success & catastrophe
Working for our Shelter Island/ Lamb Shift moment
Weinberg/ Salam
Higgs Boson phenomenology
Higgs Boson self energy crisis

# particle physics


HIGGS
HIGGS
ticl
phys

# strange and exciting

**state of affairs**

**3 sets of hints provided by:**

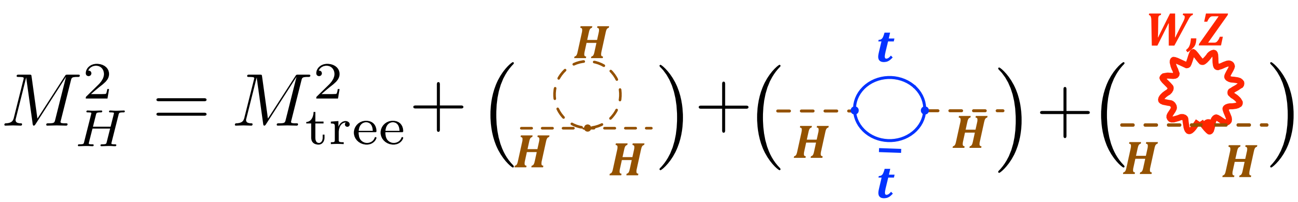
***elementary scalar particle***

***experiment***

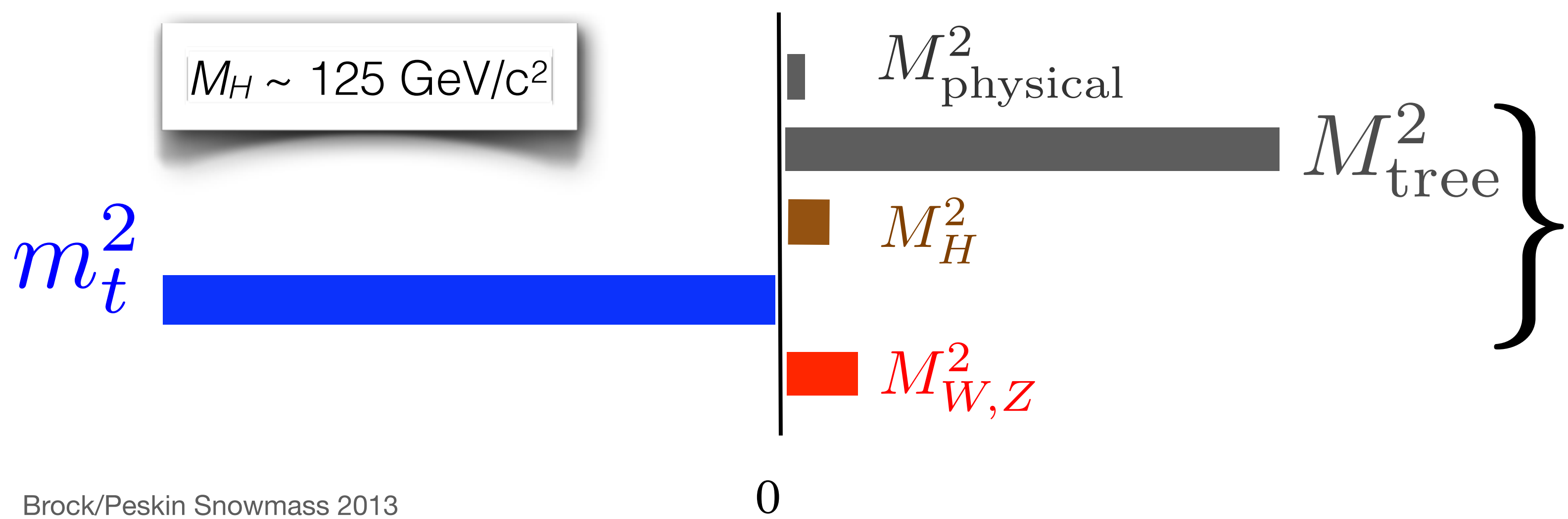
***history***

# Light scalar?
# mass confusion

## additive, quadratic cut-offs...




$M_H \sim 125$ GeV/c$^2$




un-fine tuning?

# “coincidence”

**is not a scientific term of art**

If the next mass scale up from $M_H$ is $\Lambda_{\text{Planck}}$

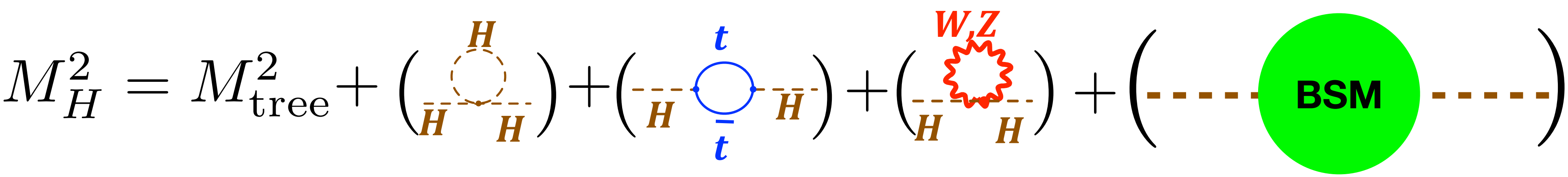
The corrections and tree must cancel:

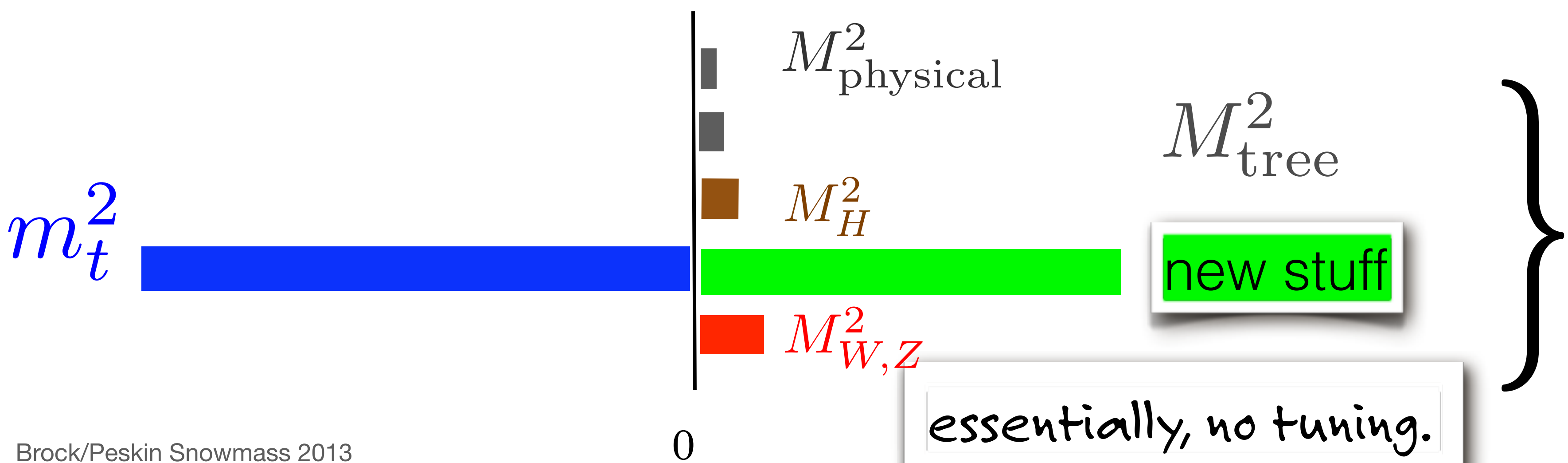
$$M_H^2 = \mathbf{nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ n60{,}000}$$
$$- \mathbf{nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ nnn,\ n44{,}375}$$

# a huge hint

## of something “BSM”?

*plenty of ideas*

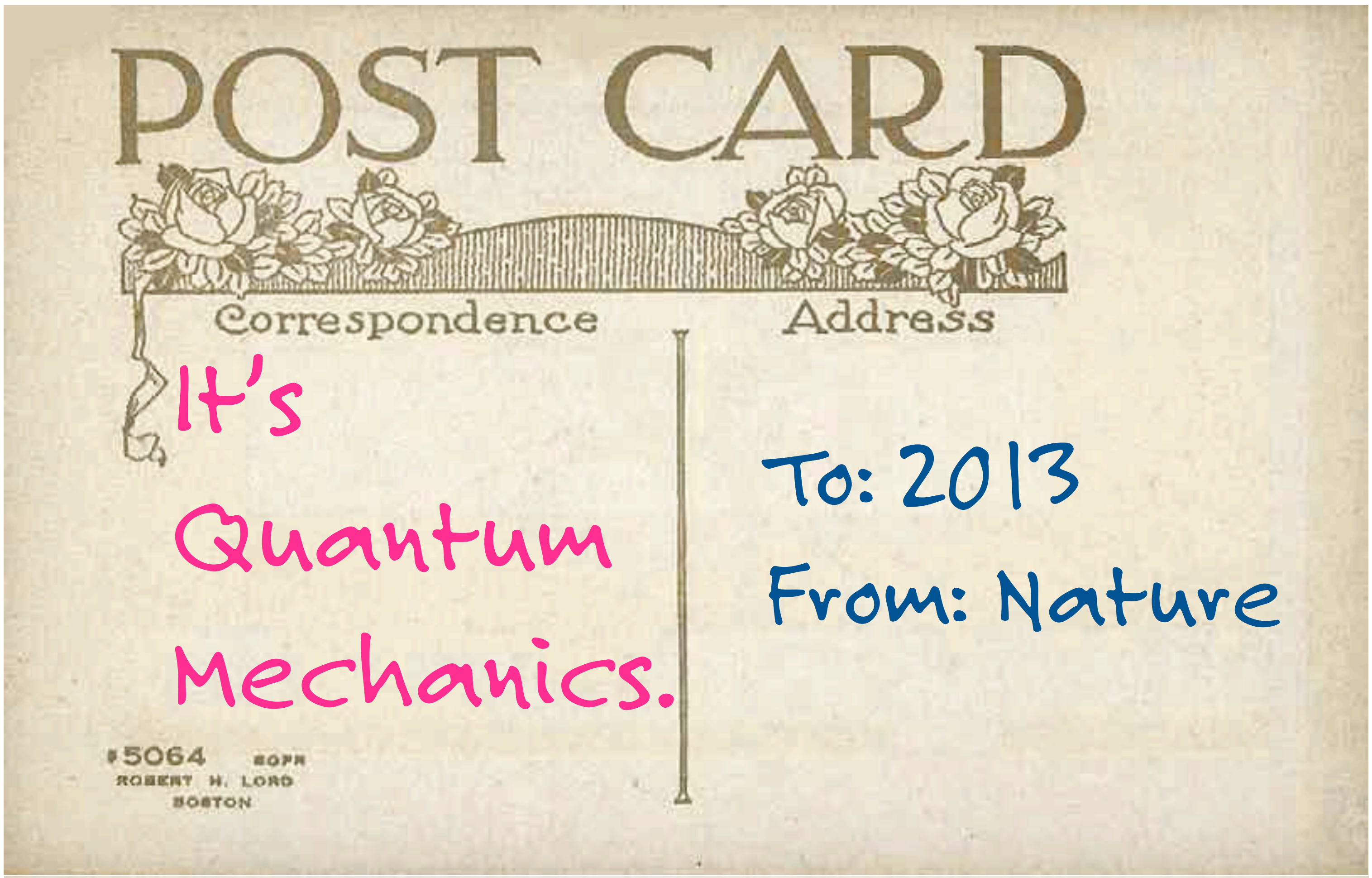


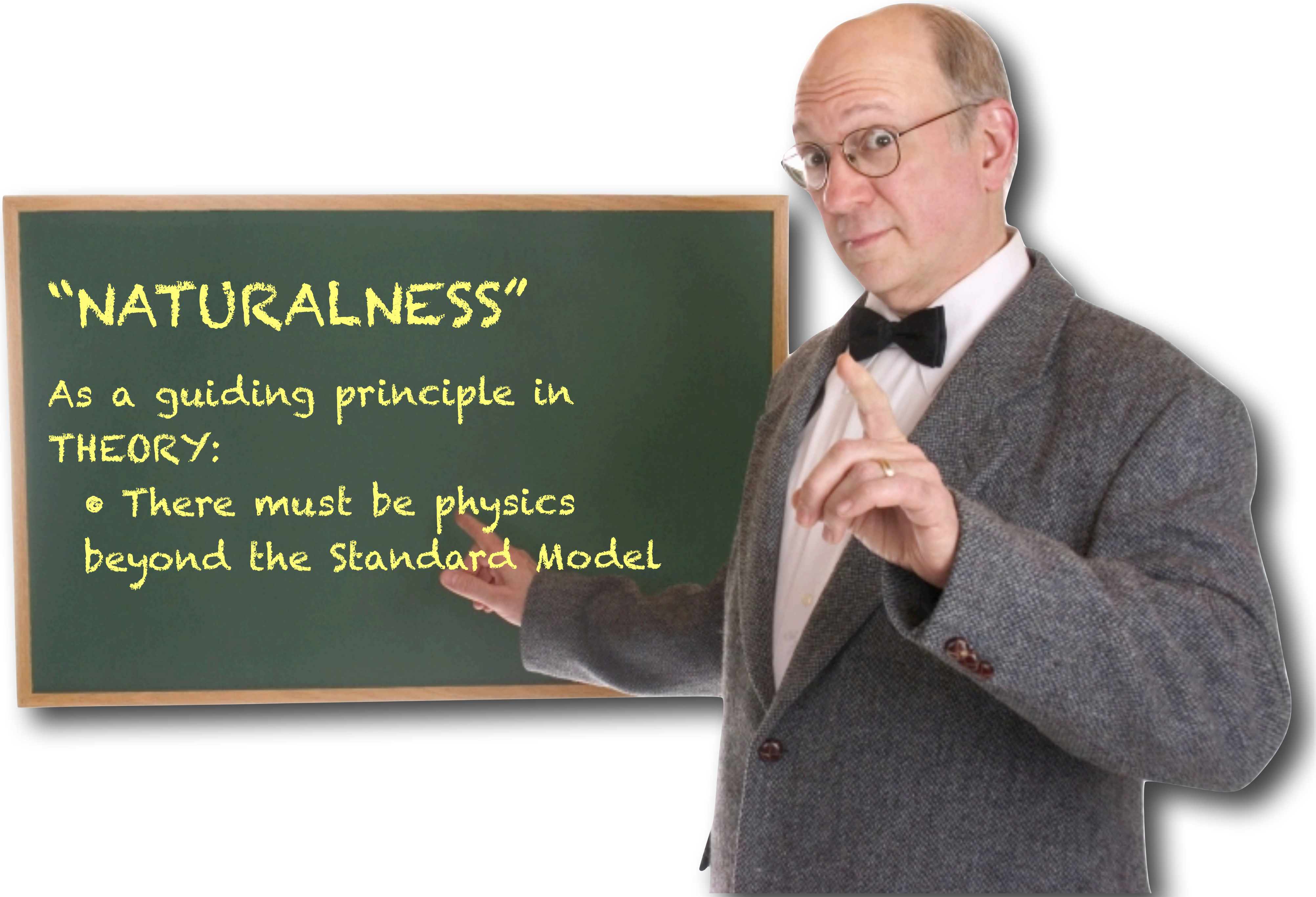




essentially, no tuning.

# goes by many names:

## The Hierarchy Problem, The Naturalness Problem




"NATURALNESS"
As a guiding principle in THEORY:
• There must be physics beyond the Standard Model

# major theoretical motivation

gotta find that **new stuff**

## Broadly speaking, of four sorts:

*Supersymmetric theories - a Boson-like top*

*Little Higgs-like theories - a Vector-like top*

*Composite Higgs - like a Cooper Pair*

*Extra dimensional theories - a 5th D gauge field component*

**or we tend to default to ideas like:**

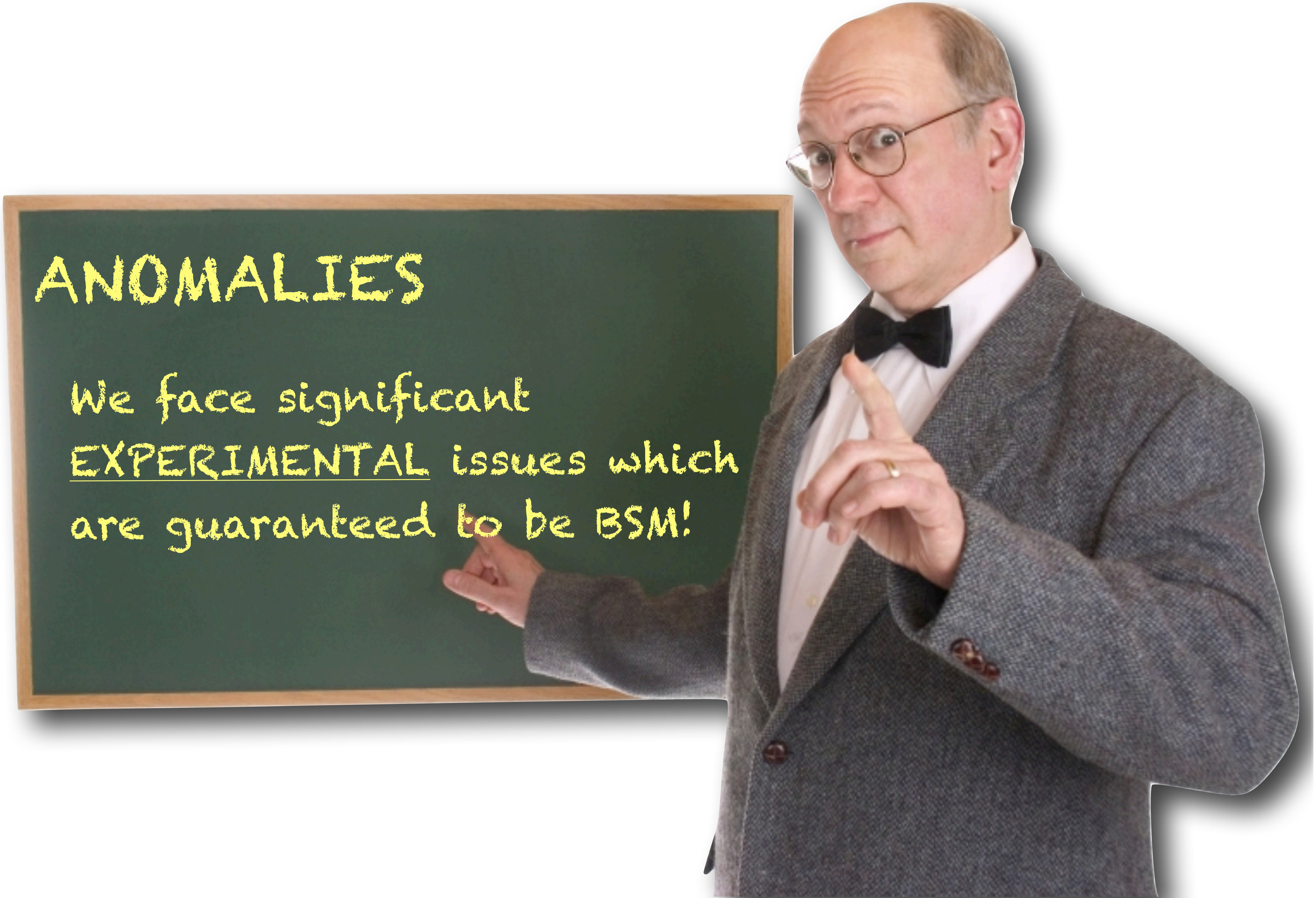
*the multiverse*

*anthropomorphism...fine tuning leading us away from Science*

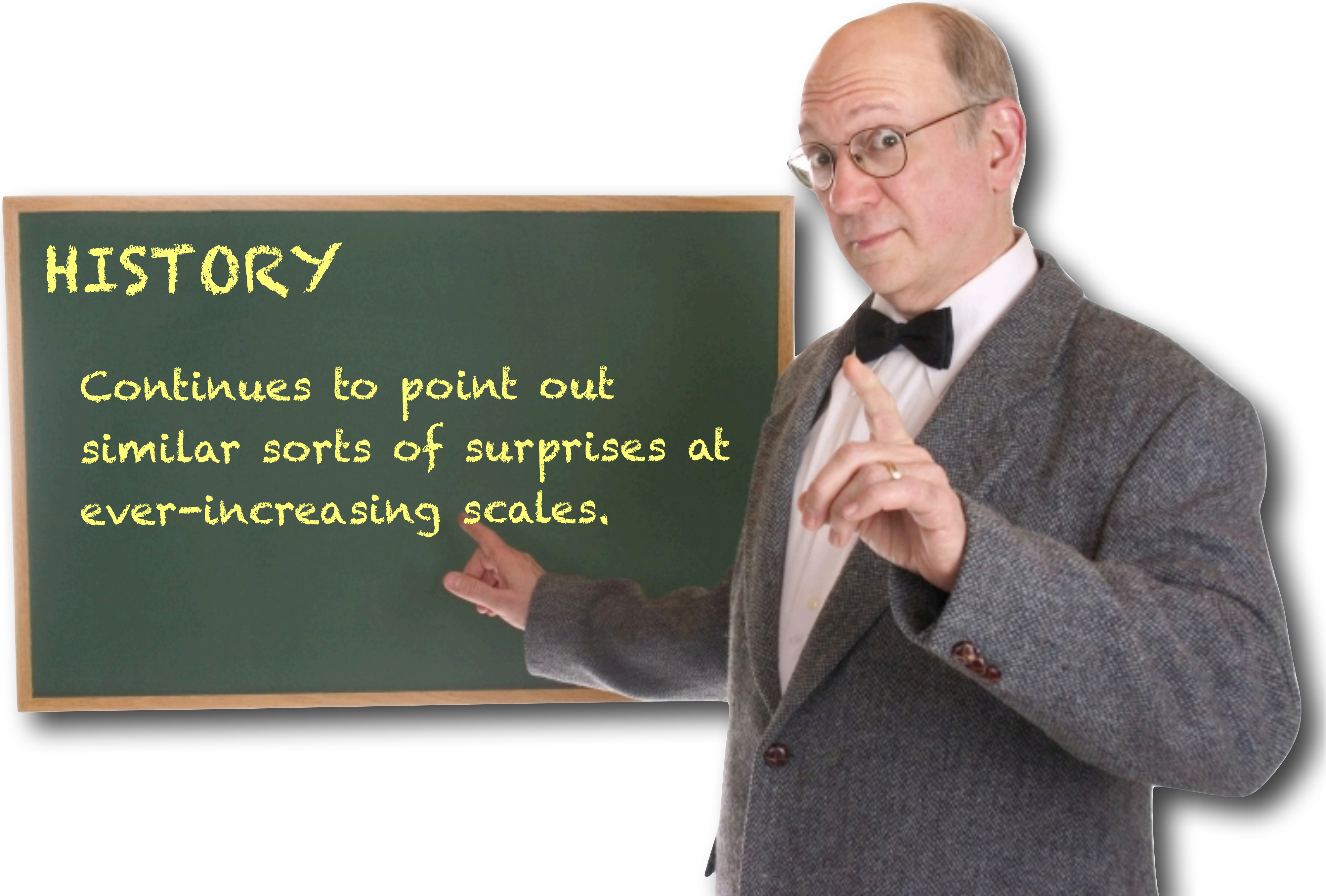

# No! That's not all there is!

# There are serious experimental anomalies = BSM

*The Higgs Boson mass is small.*
*ν's flavor, mass, symmetry properties outside of SM.*
*Dark Matter needs a quantum.*
*Primordial antimatter needs an explanation.*
***$(g\text{-}2)_\mu$ needs confirmation or disconfirmation***


ANOMALIES
We face significant
EXPERIMENTAL issues which
are guaranteed to be BSM!


Symmetry violations
Gauge group ⬆
Compositeness
History?
→ Big Surprises Themes
http://turningplace.files.wordpress.com/2013/01/aaaa.jpg


HISTORY
Continues to point out similar sorts of surprises at ever-increasing scales.

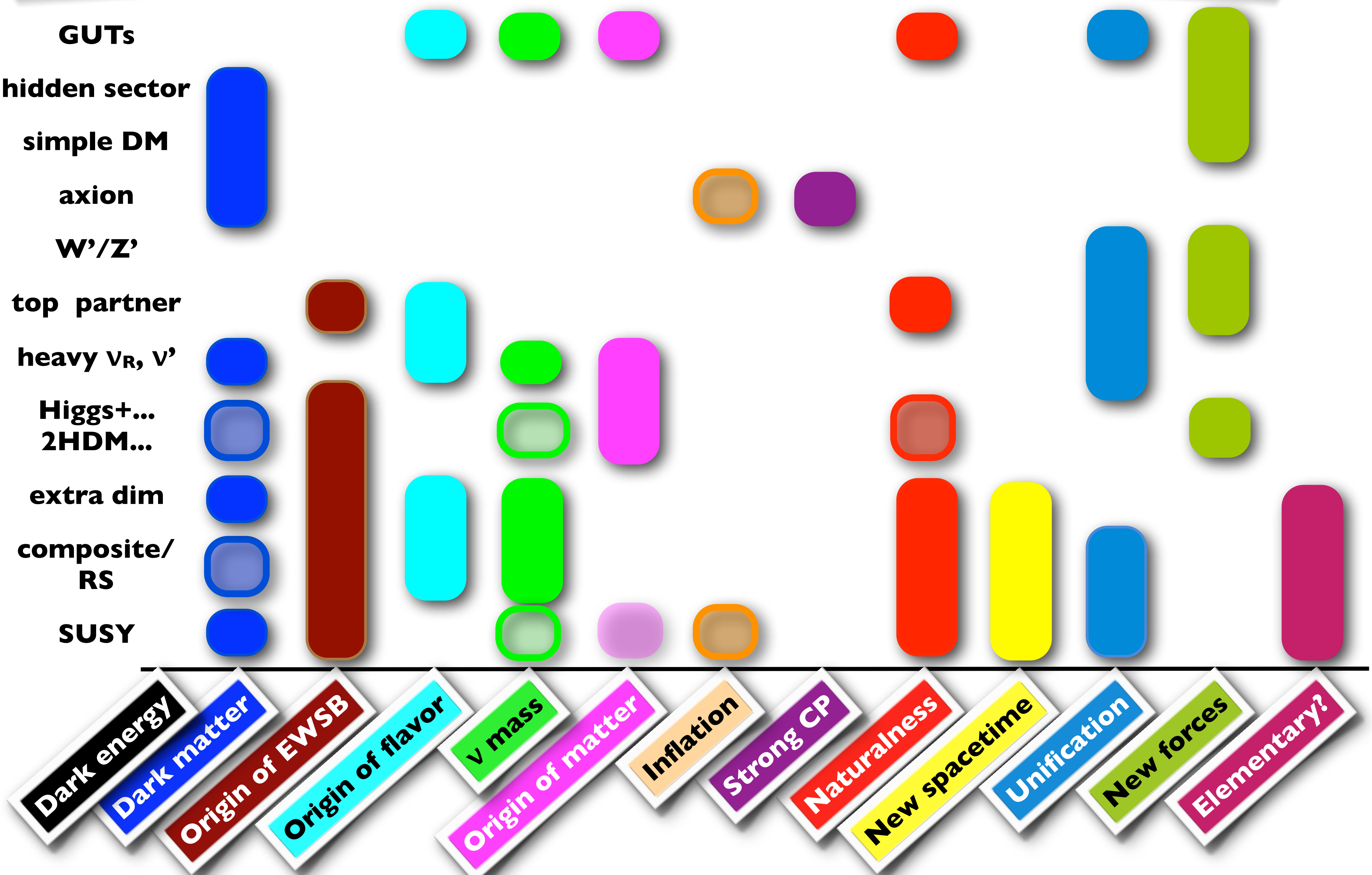
# The events of 2012

***The Higgs Boson discovery***
***The determination of $\theta_{13}$***

**Lead us to think anew about the**

**Big Questions of Particle Physics**

# New Particles Group: Answers vs Questions



# back to the

# The Snowmass Energy Frontier Process

# 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**

Michael Schmitt (Northwestern), 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)

# Organization:

## Created necessary correlations among groups

Technical groups, accelerators, simulations

Explicit liaisons between EF and other frontiers

## *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*

# Energy Frontier Goals:

## Concrete Goals: the science cases

I. **What are the scientific cases which motivate HL LHC running:**

*"Phase 1": circa 2022 with $\int \mathcal{L}\, dt$ of approximately 300 fb $^{-1}$*

*"Phase 2": circa 2030 with $\int \mathcal{L}\, dt$ of approximately 3000 fb $^{-1}$*

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

II. **Is there a scientific necessity for a precision Higgs Boson program?**

III. **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?

# Snowmass 2013: the allovertheplace workshop

snowmass@Batavia (3)

snowmass@Princeton

snowmass@Irvine

snowmass@Durham

snowmass@Brookhaven

snowmass@Dallas

snowmass@SantaBarbara

snowmass@Boston

snowmass@Boulder

snowmass@Tallahassee

snowmass@Seattle

snowmass@ Minneapolis

snowmass@Geneva!


# candidate accelerator parameterizations

***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 Hadron Collider simulation tools

## *A DELPHES 3 "Snowmass detector"**

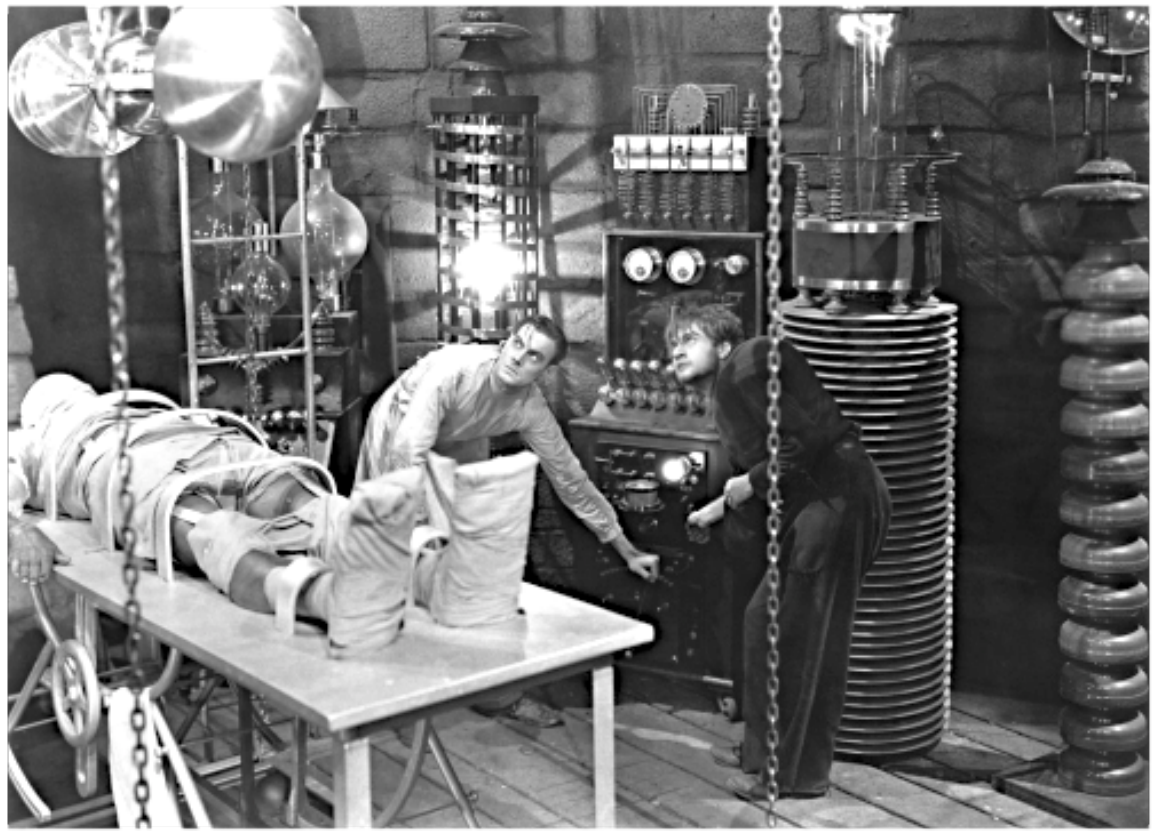
### *Extensive background simulations*

Thanks to

Sanjay Padhi,
Sergei Chekanov,

Ken Bloom,

CMS T1, ATLAS T1



*"Snowmass Energy Frontier Simulations for Hadron Colliders", A. Avetisyan et. al. arXiv:1307.XXX, July 2013

# ILC Simulations

## The LC community

***engaged in Snowmass-specific analyses beyond the CLIC CDR & ILC TDR/DBD.***

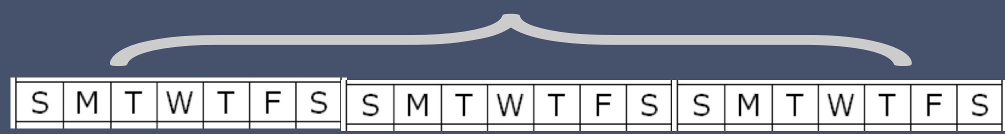
- Signal & complete SMbackground samples were generated at 250, 350 and 500GeV
- common set of tools.

***Supplemental agency funding supported Snowmass-specific infrastructure***

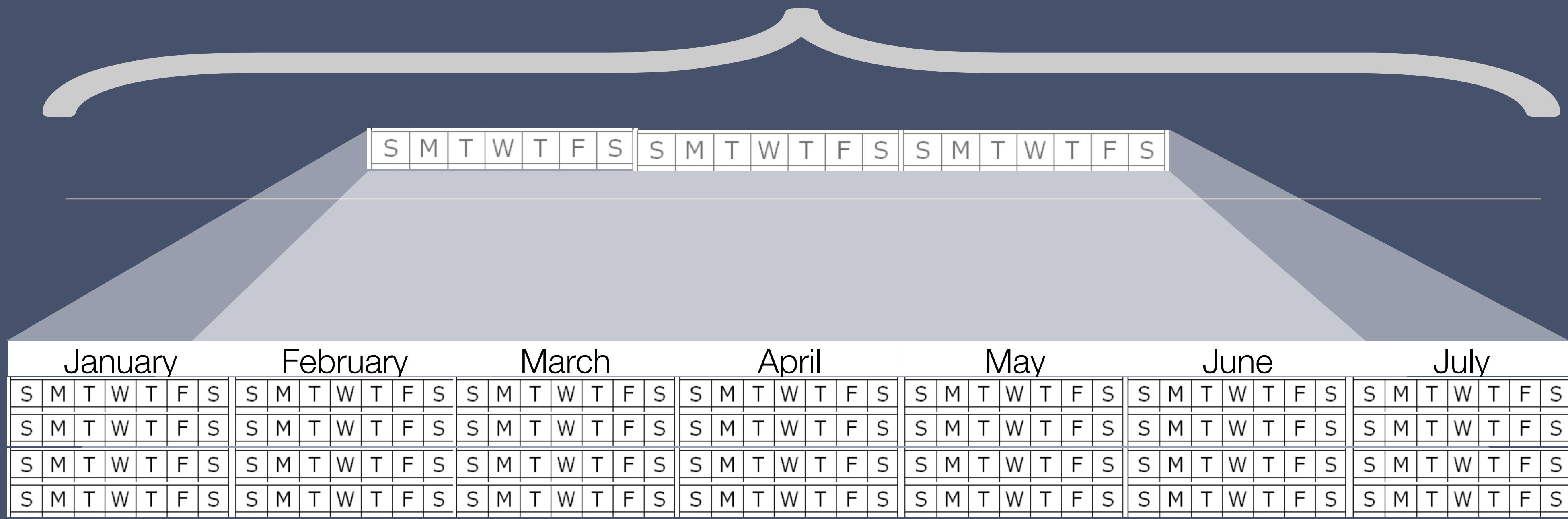
# BTW:
# a typical 3 week Snowmass?

**working time**

(hiking time, eating time, day-trip time, wine time, shopping time...Aspen Time)



# our Snowmass




**Irritating, sure.**

**But IMO there’s more depth in Snowmass2013 than in previous times.**

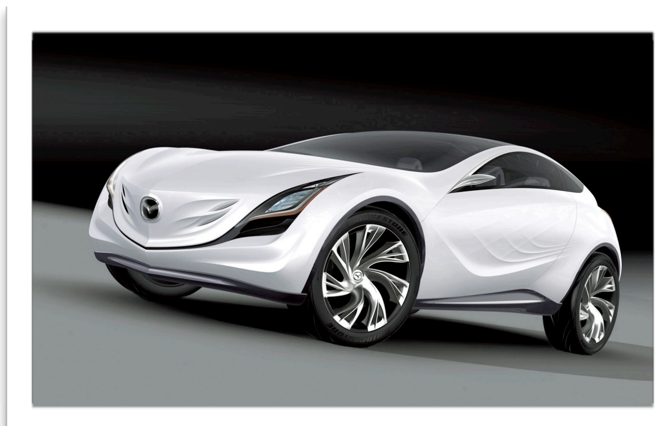
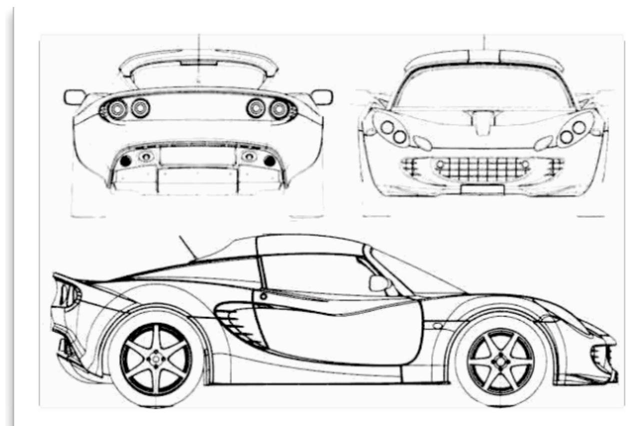
# Working Group Results

# Study the reports!

**~300 pages**
**reading which will bring tears to your eyes**

# the Proposal Frontier

| 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 | | | |

# The Higgs Boson

# The Documentation Frontier

## Higgs Boson:
## Statement of Work

1. Spin 0
2. P+
3. The Higgs is elementary.
4. The Higgs production cross sections are as predicted.
5. Field gives mass to fermions.
   a) Higgs couples to fermions as proportional to mass.
6. Primordial partners give mass to W/Z.
   a) Higgs couples W and Z with strengths mass squared.
7. Couples to self.
8. The width of the Higgs is as predicted.

## Higgs Boson:
## Statement of Work

Oversight essential!

1. Spin 0
2. P+
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8. The width of the Higgs is as predicted.

**Any behavior not according to spec...means BSM physics.**

# 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***

# Higgs: Couplings

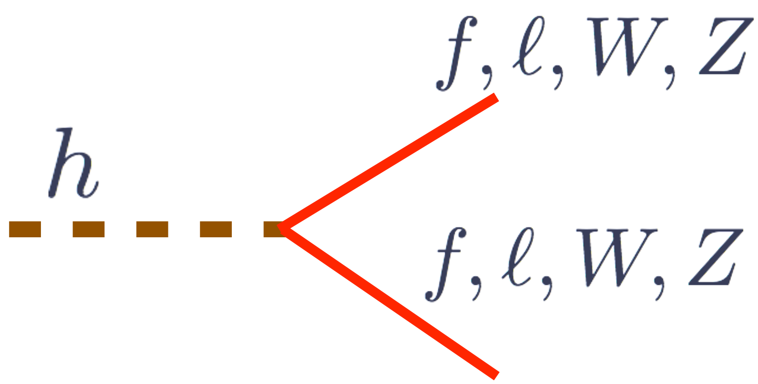
1. Models with new TeV particles give corrections to Higgs couplings of a few %.
2. An experimental program to determine these couplings is achievable.
   - LHC is the facility to study Higgs in the next decade
   - Interesting precision begins with the 300/fb running
   - Success requires considerable theoretical effort
3. Lepton colliders are required in order to measure sub-% precision in couplings in a model-independent fashion.
   - with access to invisible and exotic decay modes

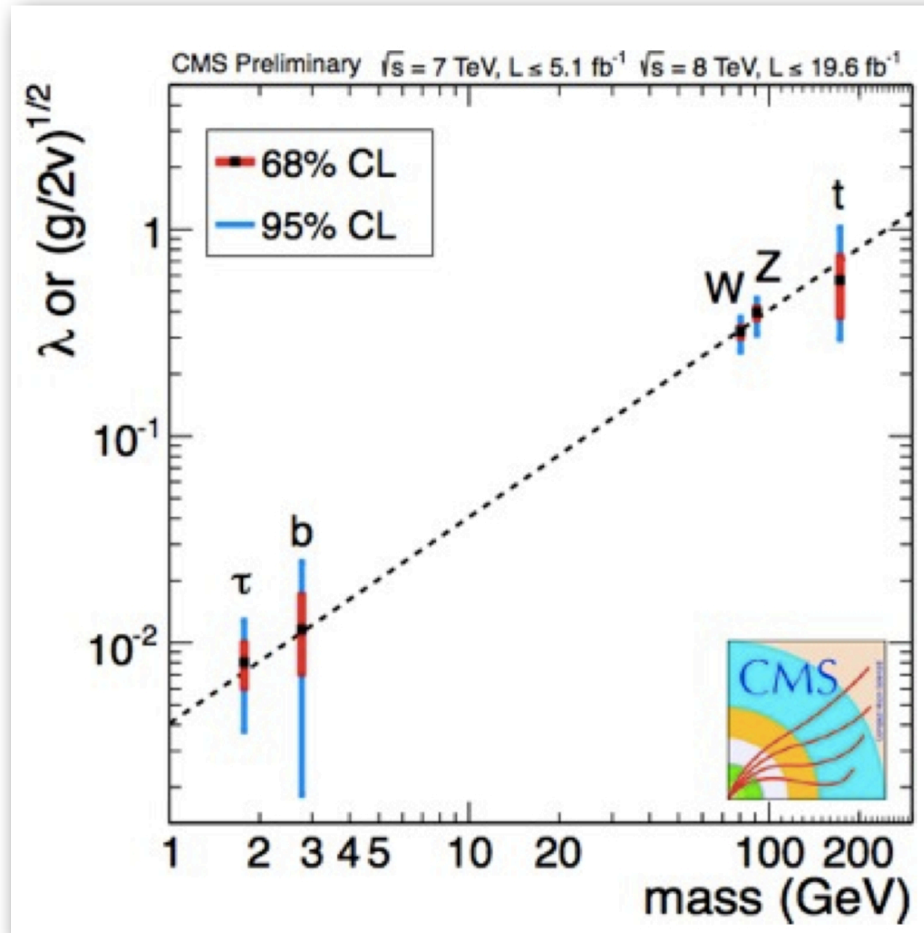
# couplings

## 1. Higgs discovery spawned an industry

***precision fitting of couplings***

$$\mathcal{L} \propto \sum_i \kappa_i SM\left[h\bar{\psi}_i\psi_i\right]$$



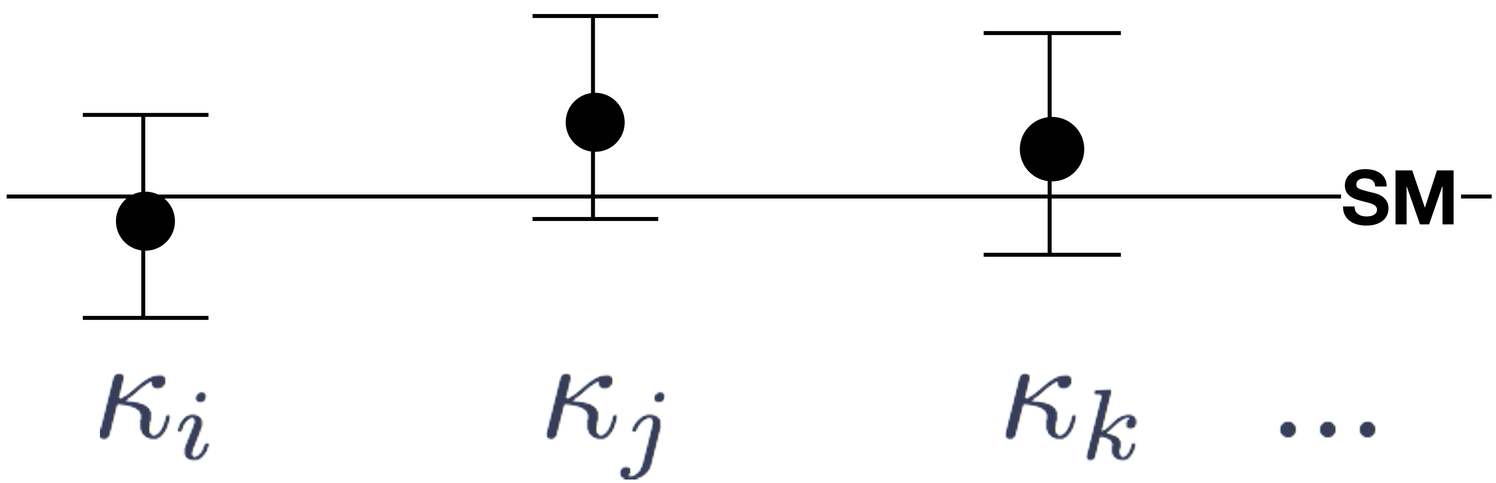



# how well?

## Higgs group evaluated models

- when new particles are ~1TeV:

| | $\kappa_V$ | $\kappa_b$ | $\kappa_\gamma$ |
|---|---|---|---|
| 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 | $\sim -2\%$ | $\sim -2\%$ | $\sim -3\%$ |

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# precision for precision's sake?

## No - this is a discovery search

| | $\kappa_V$ | $\kappa_b$ | $\kappa_\gamma$ |
|---|---|---|---|
| Singlet Mixing | $\sim 6\%$ | $\sim 6\%$ | $\sim 6\%$ |
| 2HDM | $\sim 1\%$ | $\sim 10\%$ | $\sim 1\%$ |
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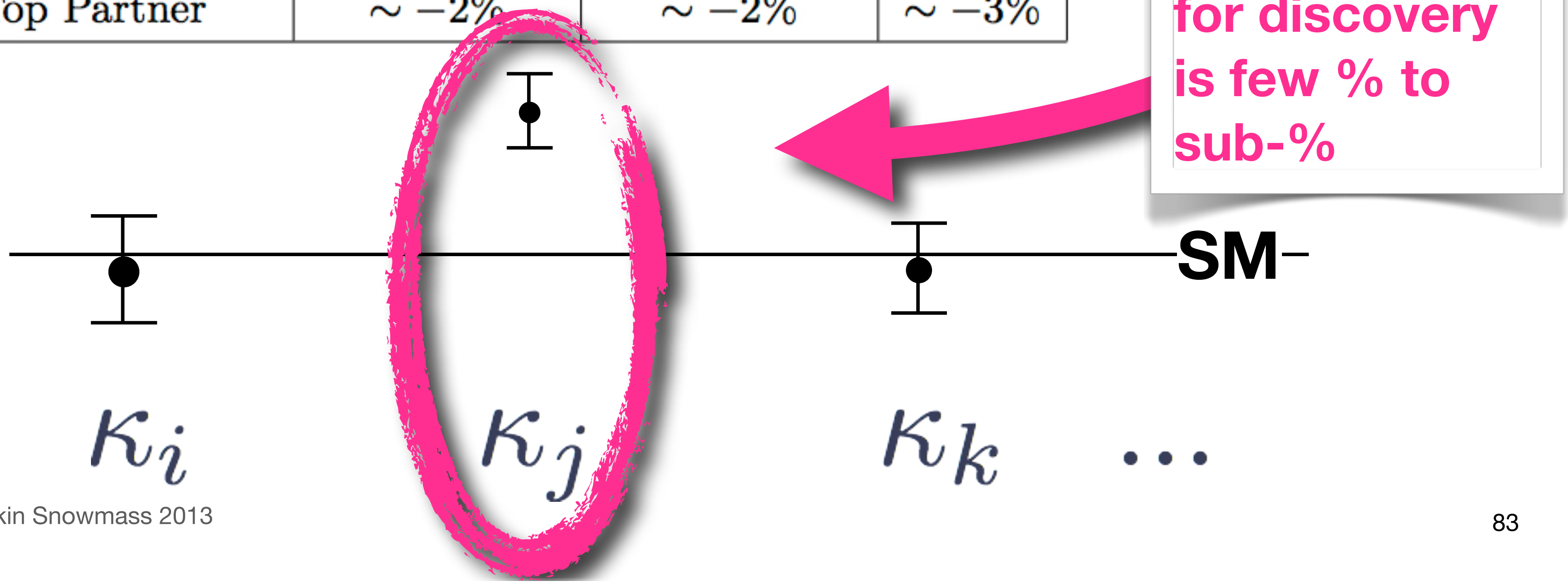


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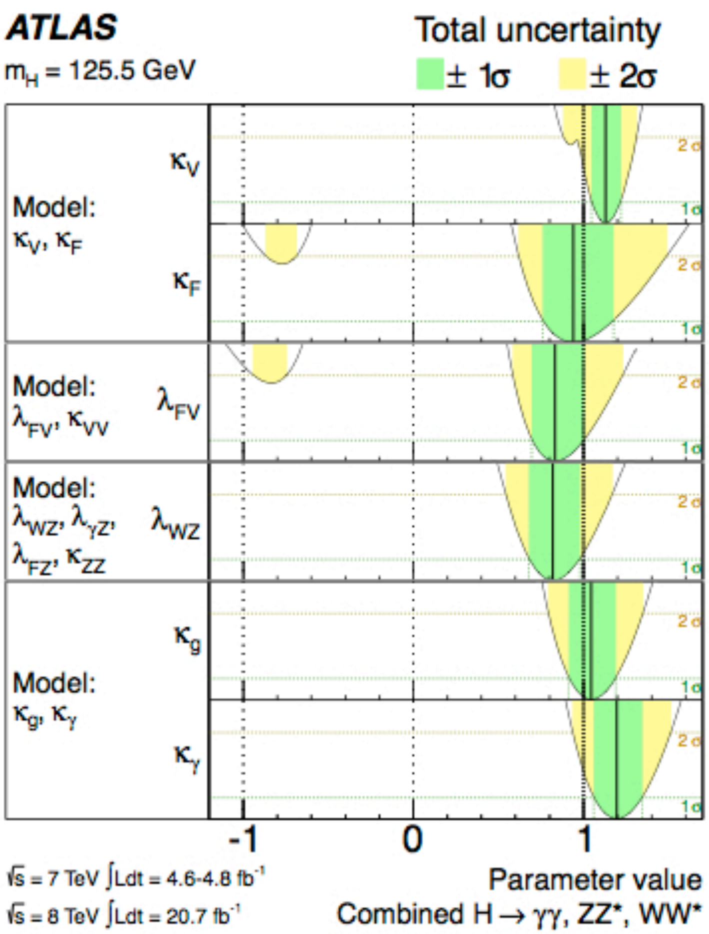
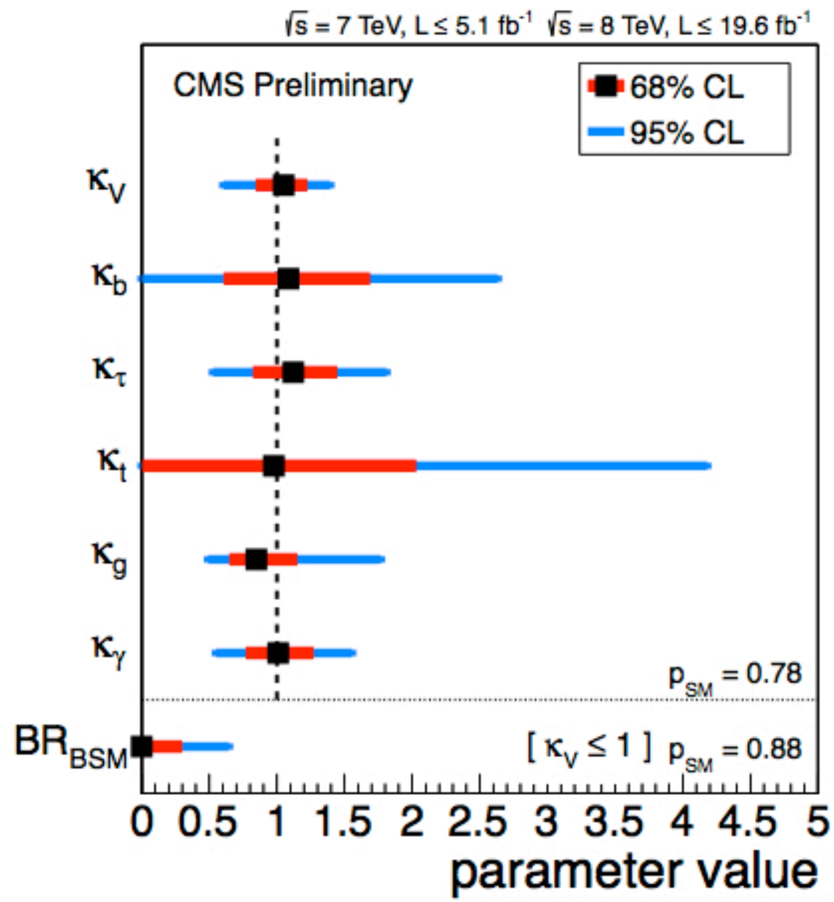
# to date:


ATLAS
m_H = 125.5 GeV
Total uncertainty
± 1σ ± 2σ
Model: κV, κF
κV
κF
Model: λFV, κVV
λFV
Model: λWZ, λγZ, λFZ, κZZ
λWZ
Model: κg, κγ
κg
κγ
-1 0 1
Parameter value
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Combined H → γγ, ZZ*, WW*


√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
CMS Preliminary
68% CL
95% CL
κV
κb
κτ
κt
κg
κγ
p_SM = 0.78
BR_BSM
[ κV ≤ 1 ] p_SM = 0.88
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
parameter value

# couplings by facility

## Extrapolating LHC requires a strategy

**2 numbers shown:**
**optimistic* – conservative**

| 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 |
| $\kappa_\gamma$ | $5-7\%$ | $2-5\%$ | 8.3% | 4.4% | 3.8% | 2.3% | $-/5.5/<5.5\%$ | 1.45% |
| $\kappa_g$ | $6-8\%$ | $3-5\%$ | 2.0% | 1.1% | 1.1% | 0.67% | 3.6/0.79/0.56% | 0.79% |
| $\kappa_W$ | $4-6\%$ | $2-5\%$ | 0.39% | 0.21% | 0.21% | 0.13% | 1.5/0.15/0.11% | 0.10% |
| $\kappa_Z$ | $4-6\%$ | $2-4\%$ | 0.49% | 0.24% | 0.44% | 0.22% | 0.49/0.33/0.24% | 0.05% |
| $\kappa_\ell$ | $6-8\%$ | $2-5\%$ | 1.9% | 0.98% | 1.3% | 0.72% | $3.5/1.4/<1.3\%$ | 0.51% |
| $\kappa_d$ | $10-13\%$ | $4-7\%$ | 0.93% | 0.51% | 0.51% | 0.31% | 1.7/0.32/0.19% | 0.39% |
| $\kappa_u$ | $14-15\%$ | $7-10\%$ | 2.5% | 1.3% | 1.3% | 0.76% | 3.1/1.0/0.7% | 0.69% |

$$^*\ \delta(\text{sys}) \propto \frac{1}{\sqrt{\mathcal{L}}} \quad \& \quad \delta(\text{theory}) \downarrow 1/2$$

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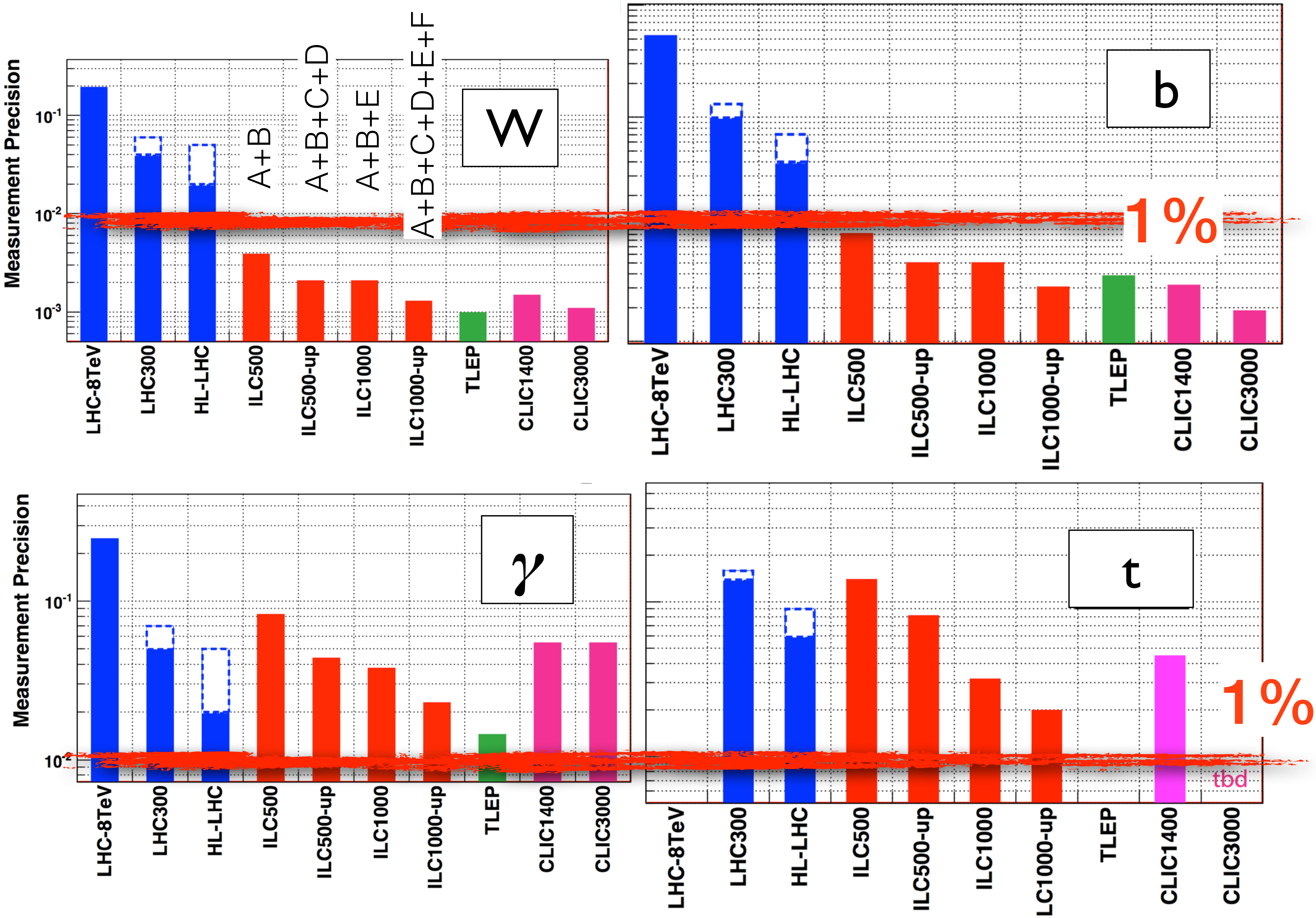
# Precision in kappa by facility

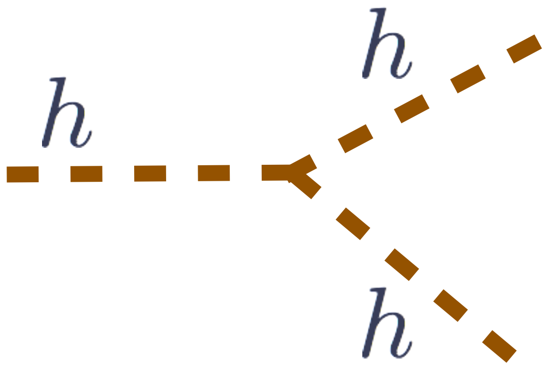


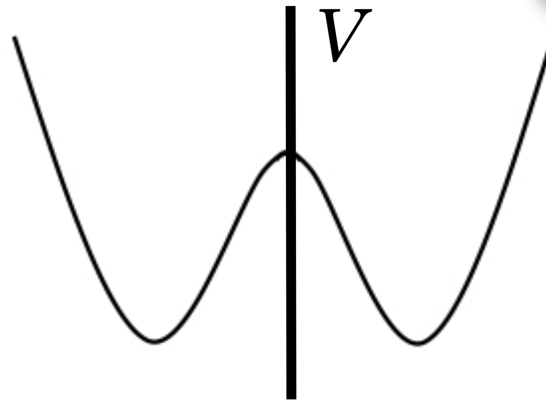
# Higgs Self-Coupling

## Critical feature of SM

- extremely challenging

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$




| | 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$^\ddagger$ | 500/1000 | 1600/2500$^\ddagger$ | 1500 | +2000 | 3000 | 3000 |
| $\lambda$ | 50% | 83% | 46% | 21% | 13% | 21% | 10% | 20% | 8% |

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

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# Mass and Width

## Mass

- LHC: 50 MeV/c2
- ILC: 35 MeV/c2

## Total Width

- LHC limits on $\Gamma$
- ILC: model-independent
- MC: direct

**Table 1-26.** *Summary of the Higgs mass and total width measurement precisions of various facilities. "Full ILC" is 250+500+1000 GeV with 250+500+1000 fb$^{-1}$, while "ILC LumUp" is 1150+1600+2500 fb$^{-1}$ at the same collision energies.*

| Facility | LHC | HL-LHC | ILC500 | ILC1000 | ILC1000-up | CLIC | TLEP (4 IP) | $\mu$C |
|---|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ (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 |
| $\Gamma_H$ | – | – | 5.9% | 5.6% | 2.7% | 8.4% | 0.6% | 1.7–17% |

few %

Brock/Peskin Snowmass 2013

# Higgs Properties & extensions

## 2. SM Higgs J will be constrained by LHC

## 3. 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.*

# Precision Study of Electroweak Physics

# Electroweak: Themes

## 1. precision measurements:

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

  *sensitive to new TeV particles in loops*

## 2. studies of vector boson interactions

- triple VB couplings, VB scattering

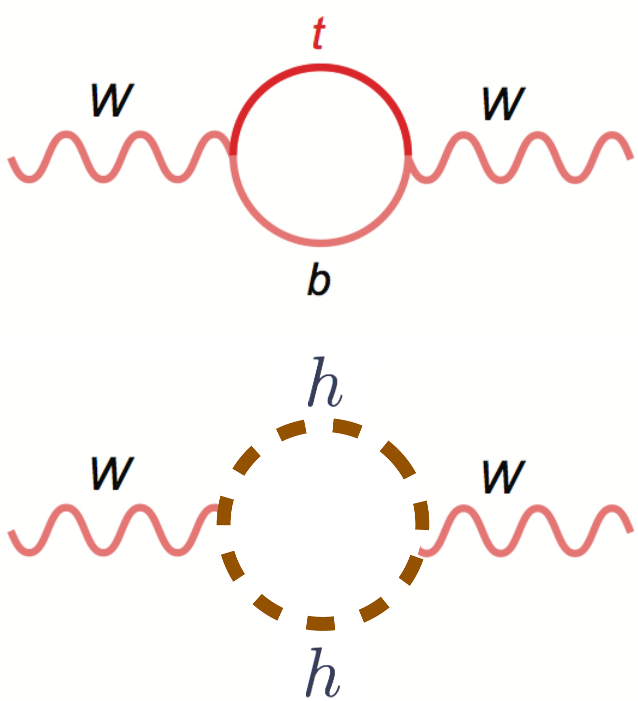
  *Effective Field Theory approaches*

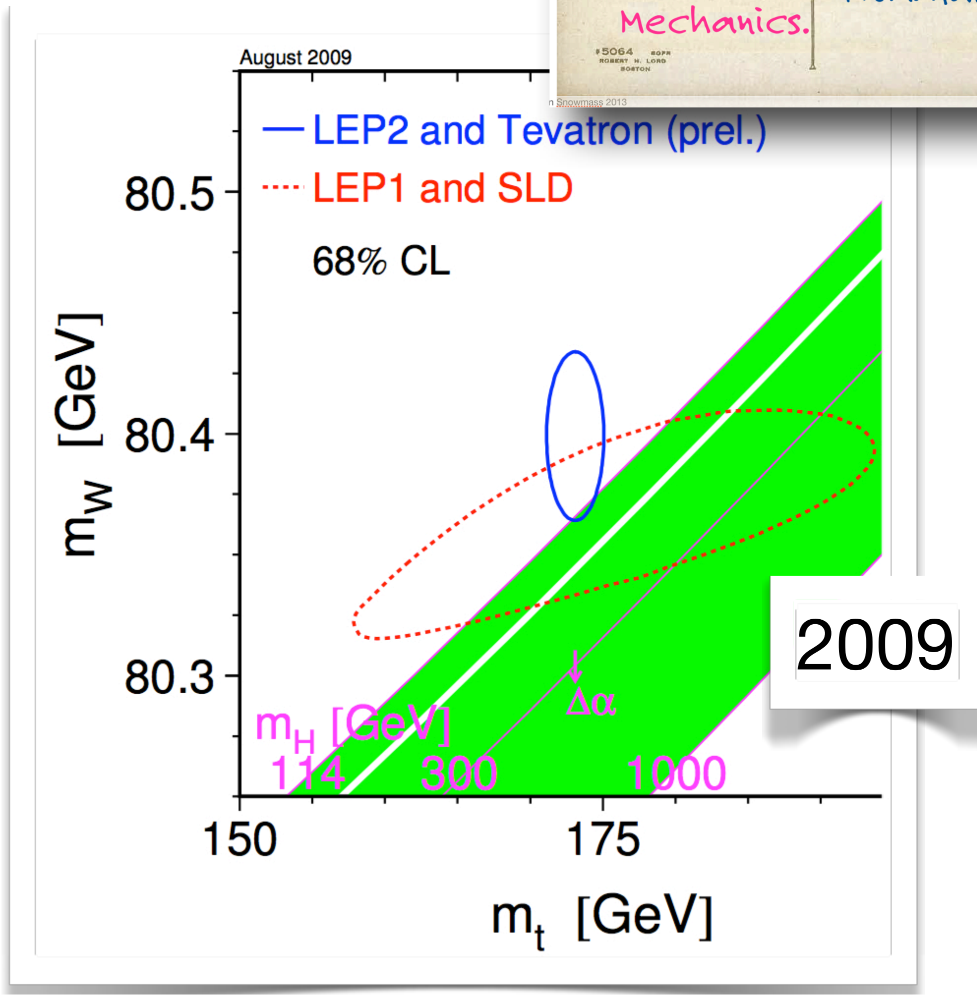
  *sensitive to Higgs sector resonances*

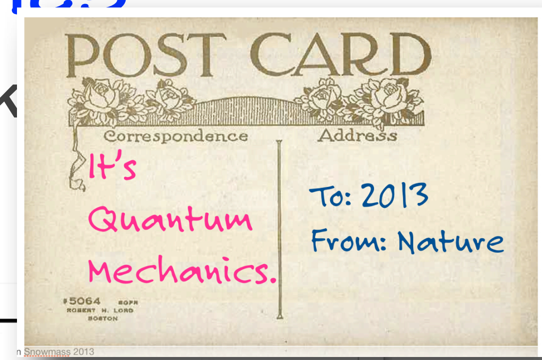
# EWPOs

## Electroweak Precision Observables

- We knew where to look for the Top Quark
- We knew where to look for the Higgs




**EWPOs are a well-trusted probe**

# Now...a new target: BSM

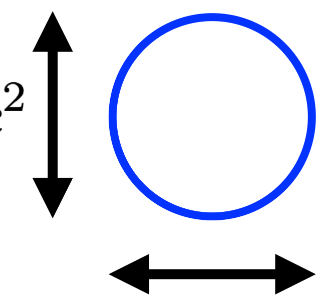
## Premium on $M_W$

This is now a BSM search

Now fits include $M_h$

$\delta M_W$

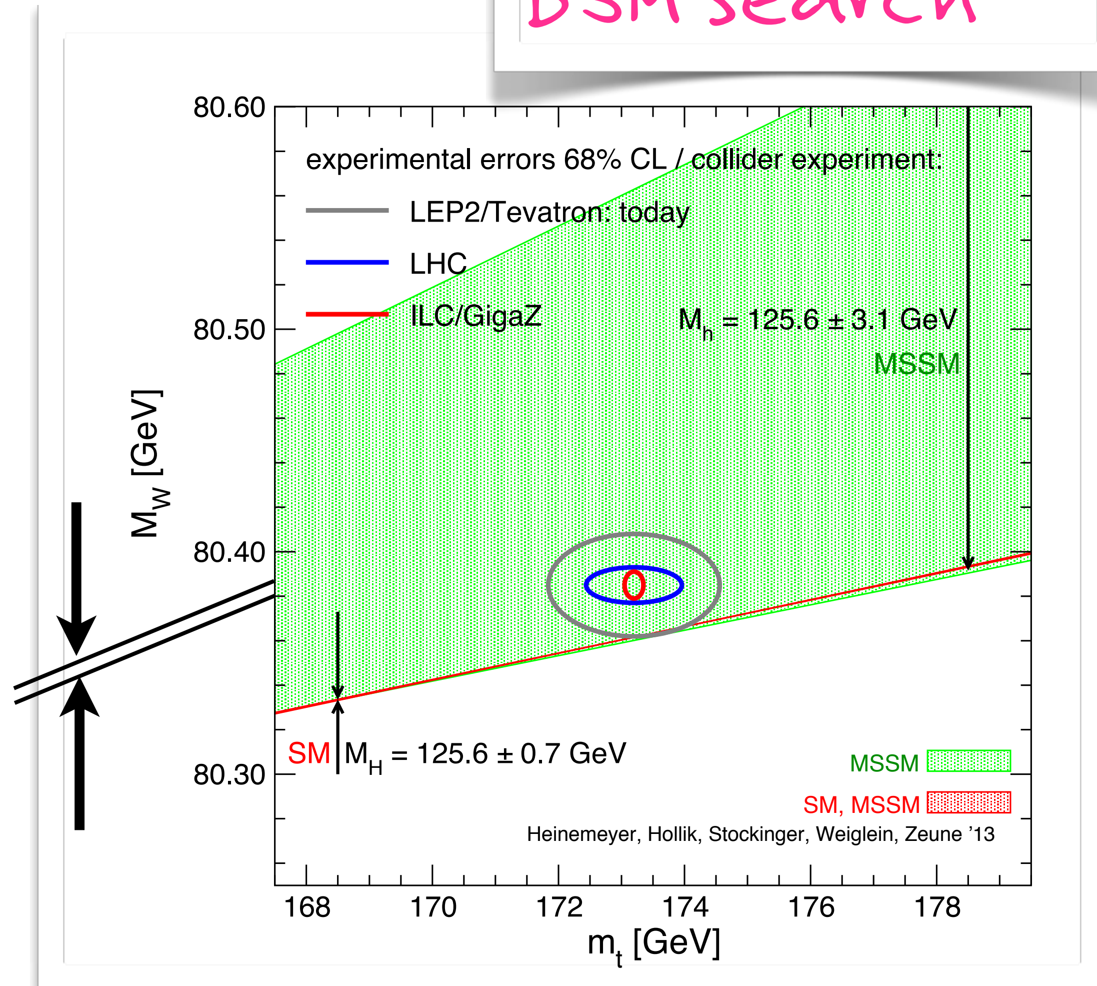
$\sim 5 \text{ MeV}/c^2$



$\sim 500 \text{ MeV}/c^2$

$\delta m_t$

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



# $M_W$ precision

## $M_W$ at the LHC

- $\delta M_W$ ~ 5 MeV requires x7 improvement in PDF uncertainty

  *a critical need*

## $M_W$ at the lepton colliders

- A *WW* threshold program can achieve 2.5 – 4 MeV at ILC, sub-MeV at TLEP.

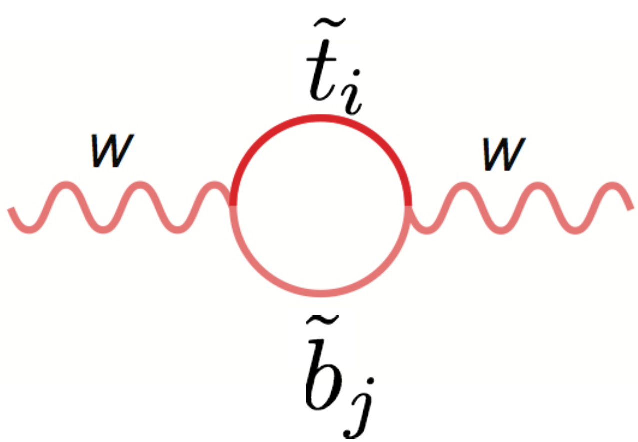
## Furthermore: $\sin^2\theta_{eff}$

- Running at the Z at ILC (Giga-Z) can improve $\sin^2\theta_{\rm eff}$ by a factor 10 over LEP/SLC;
- TLEP might provide another factor 4.

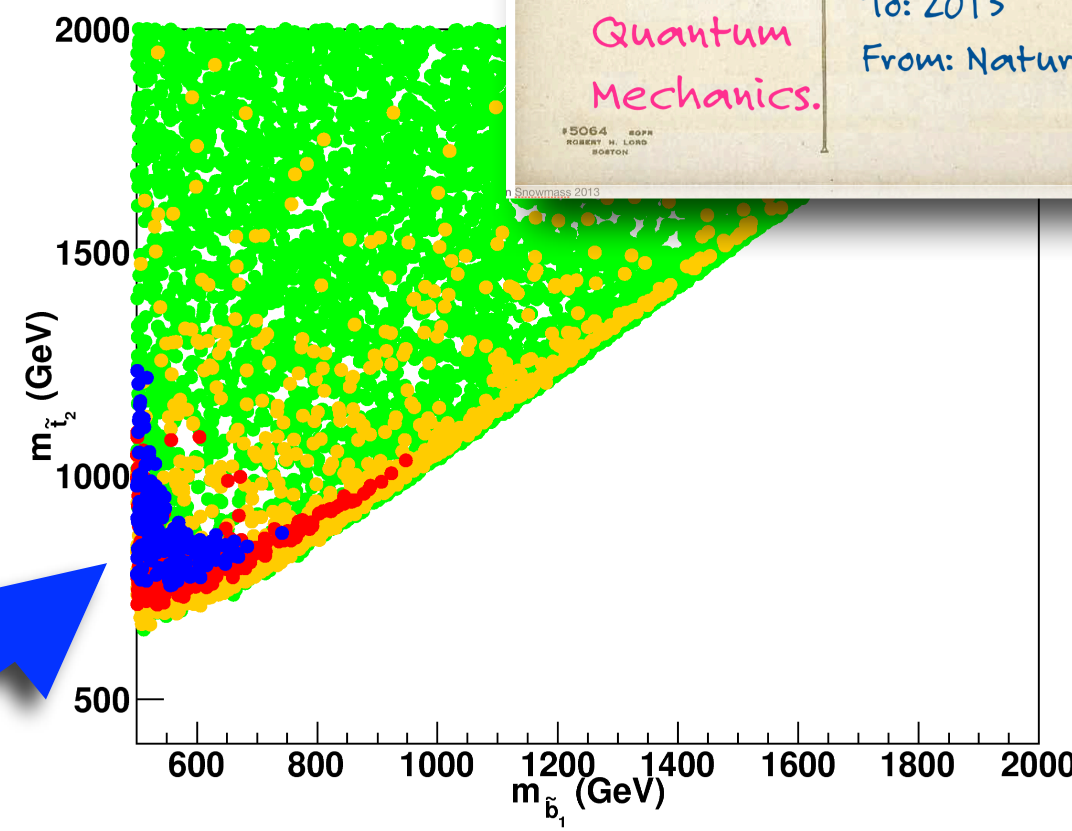
# $M_W$, the old fashioned way

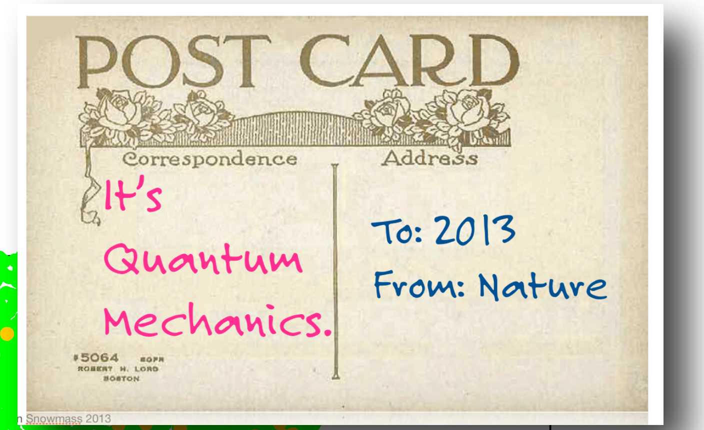
Imagine we knew:

- the stop1 mass, and $M_W$ to 5 MeV




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



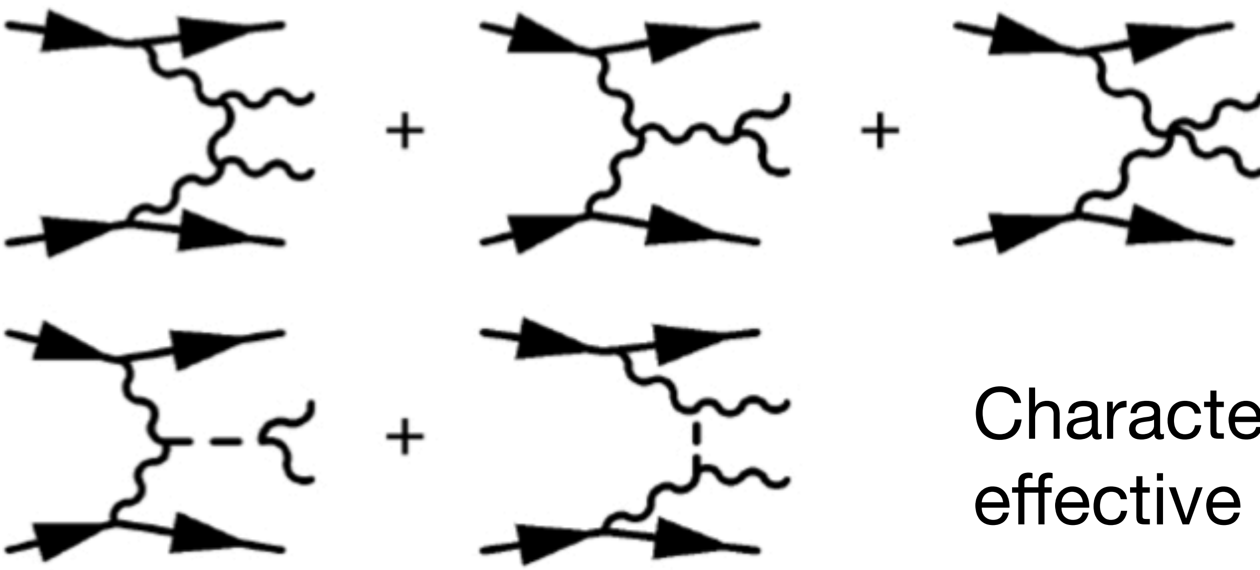



# EW scale - TeV?

**Originally, EW theory broke down at TeV scale**

- Higgs tames this...in theory

  *now a test*



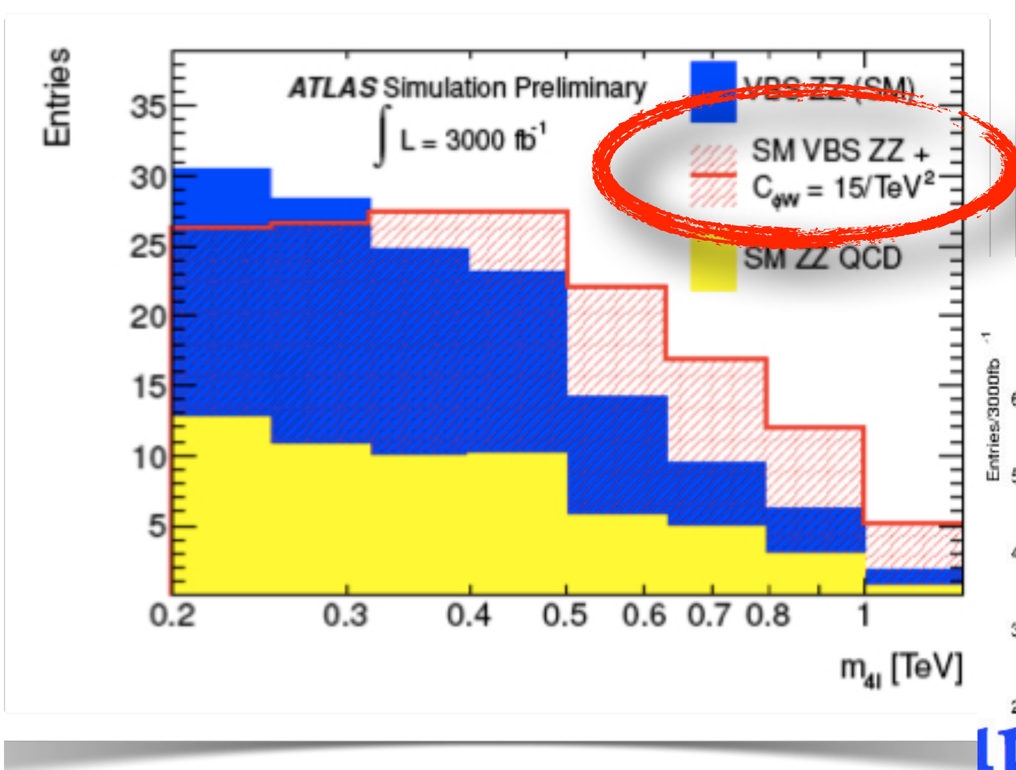
Characterize as a general effective operator

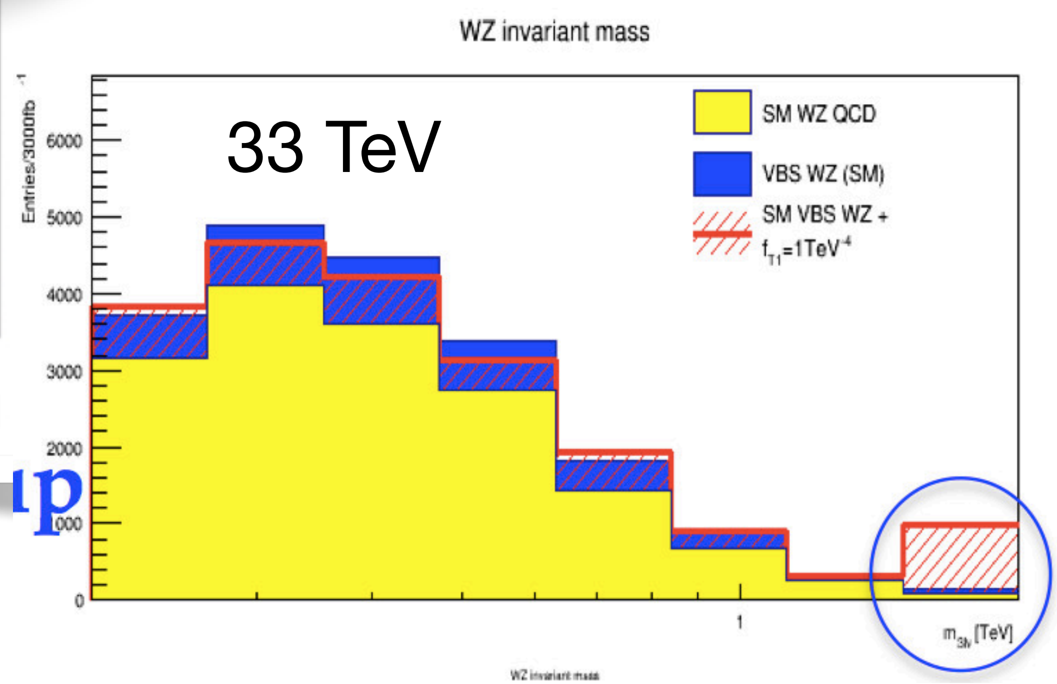
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_i \frac{f_j}{\Lambda^4}\mathcal{O}_j + \cdots$$

# VB Scattering

## Effective Operator Machinery built into Madgraph for Snowmass

- Sensitivity to non-standard gauge interactions

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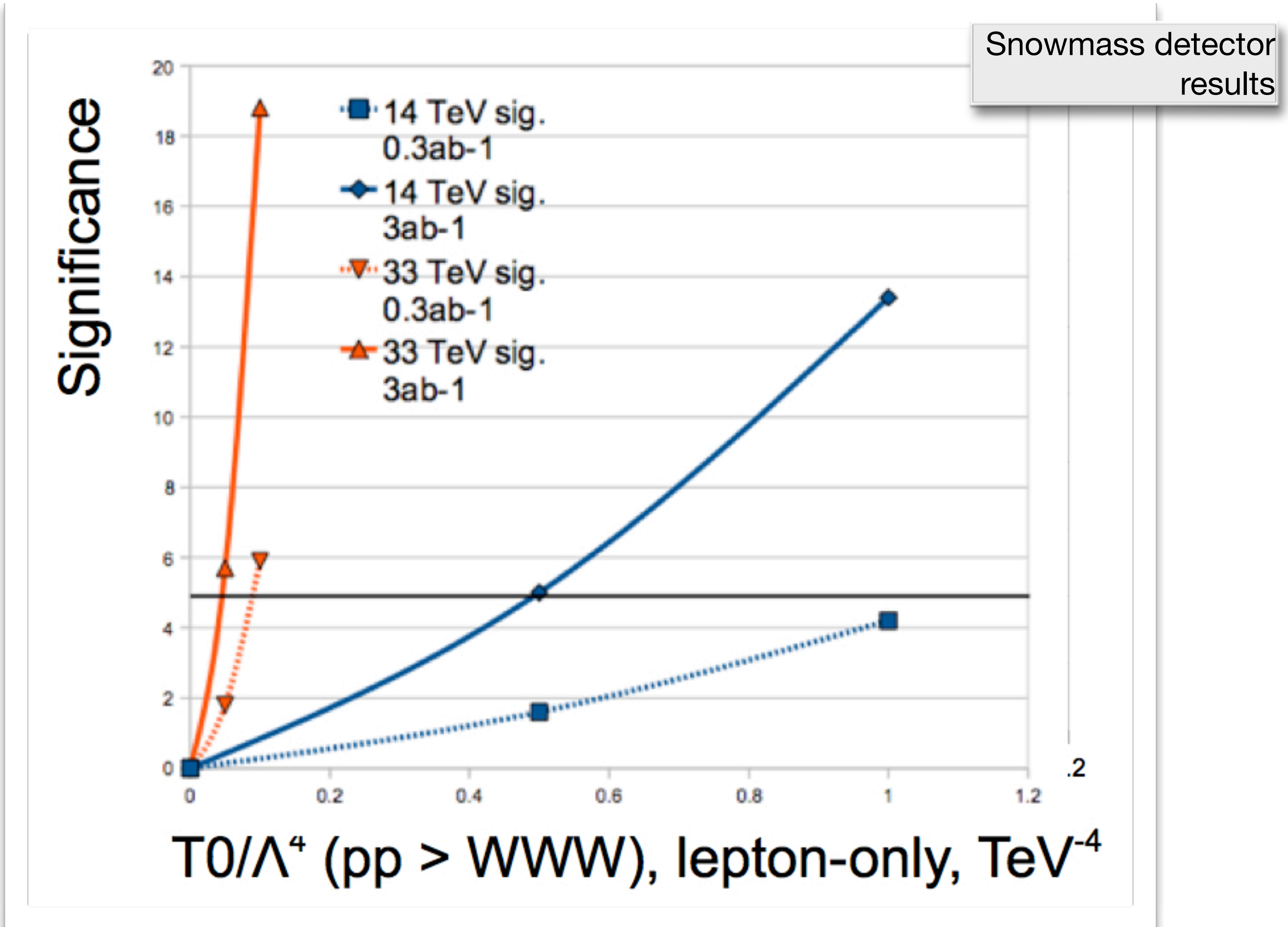
# VB Scattering

Luminosity and Energy win.

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# Fully Understanding the Top Quark

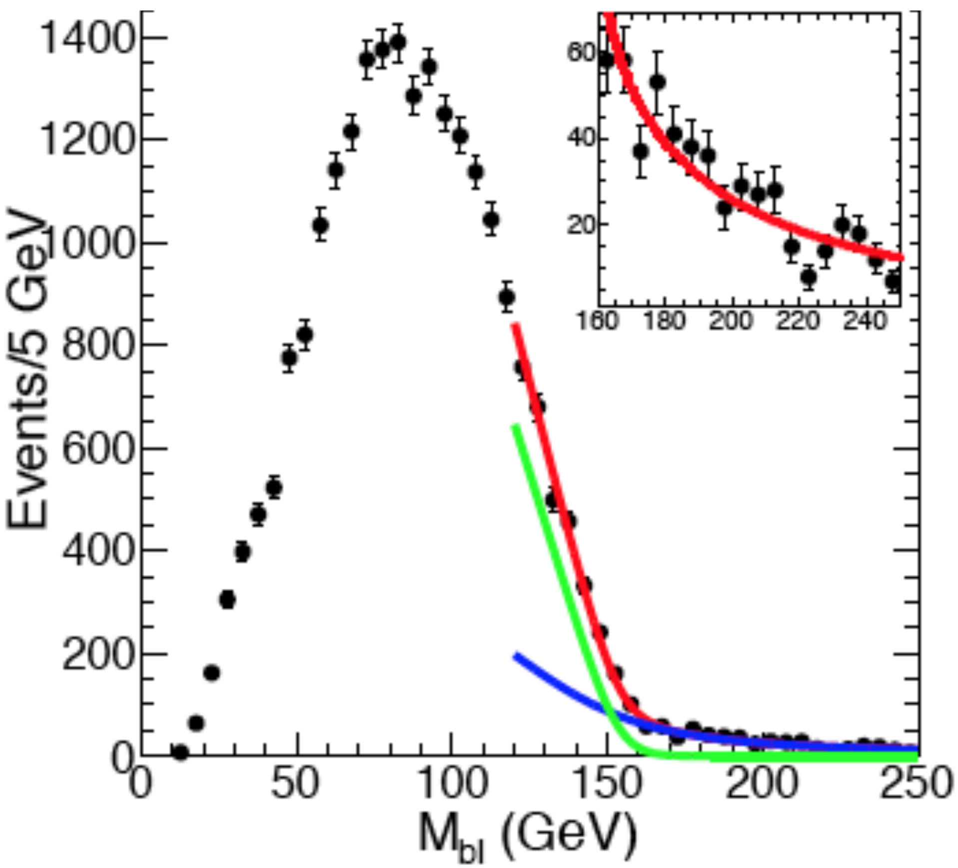
# Top: Themes

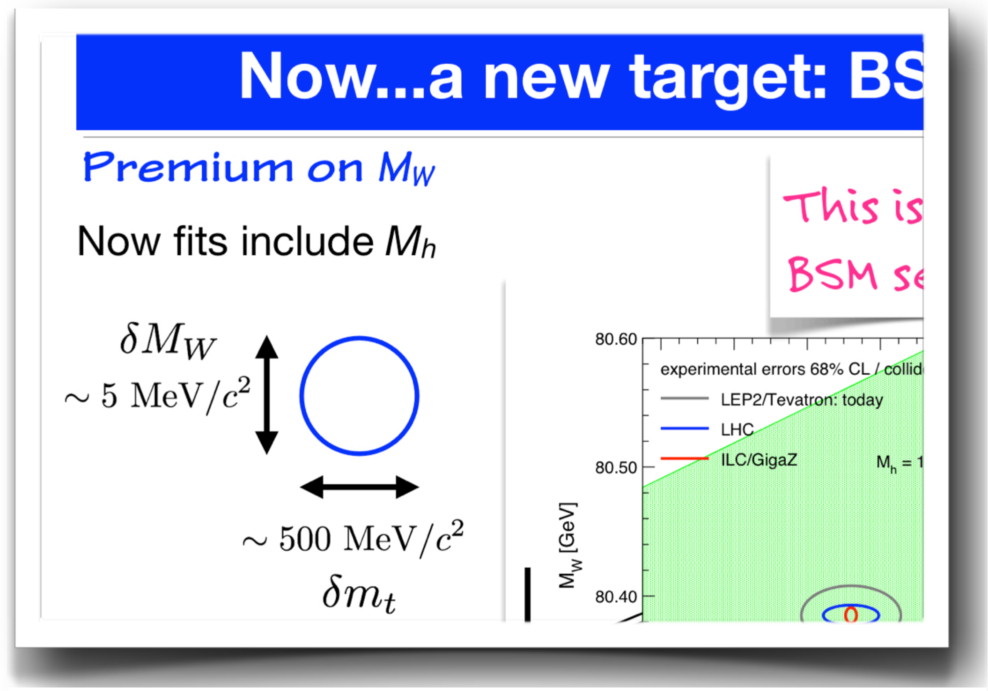
1. Top Quark Mass
    - theory targets and capabilities
2. Top Quark Couplings
    - strong and electroweak couplings
3. Kinematics of Top Final States
    - top polarization observables and asymmetries
4. Top Quark Rare Decays
    - Giga-top program; connection to flavor studies
5. New Particles Connected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

# Precision mt at LHC

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

Theoretically understood $m_t$ definition;
500 MeV accuracy at HL-LHC

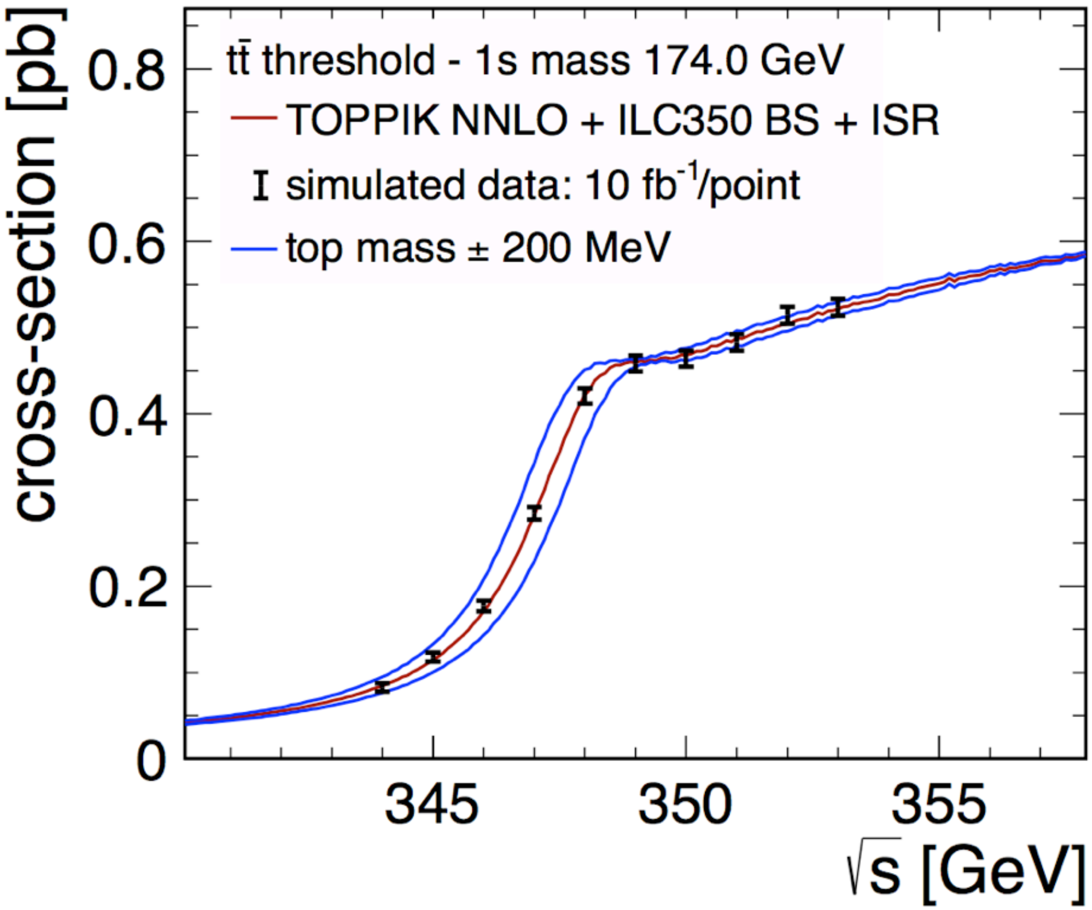



matching the 5 MeV precision goal of $M_W$

# 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



# 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, $F_{1V}^{\gamma}$ (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, $F_{1A}^{\gamma}$ | 0.05 | ? | ? |
| photon, $F_{2V}^{\gamma}$ | 0.037 | 0.025 | 0.003 |
| photon, $F_{2A}^{\gamma}$ | 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 %**

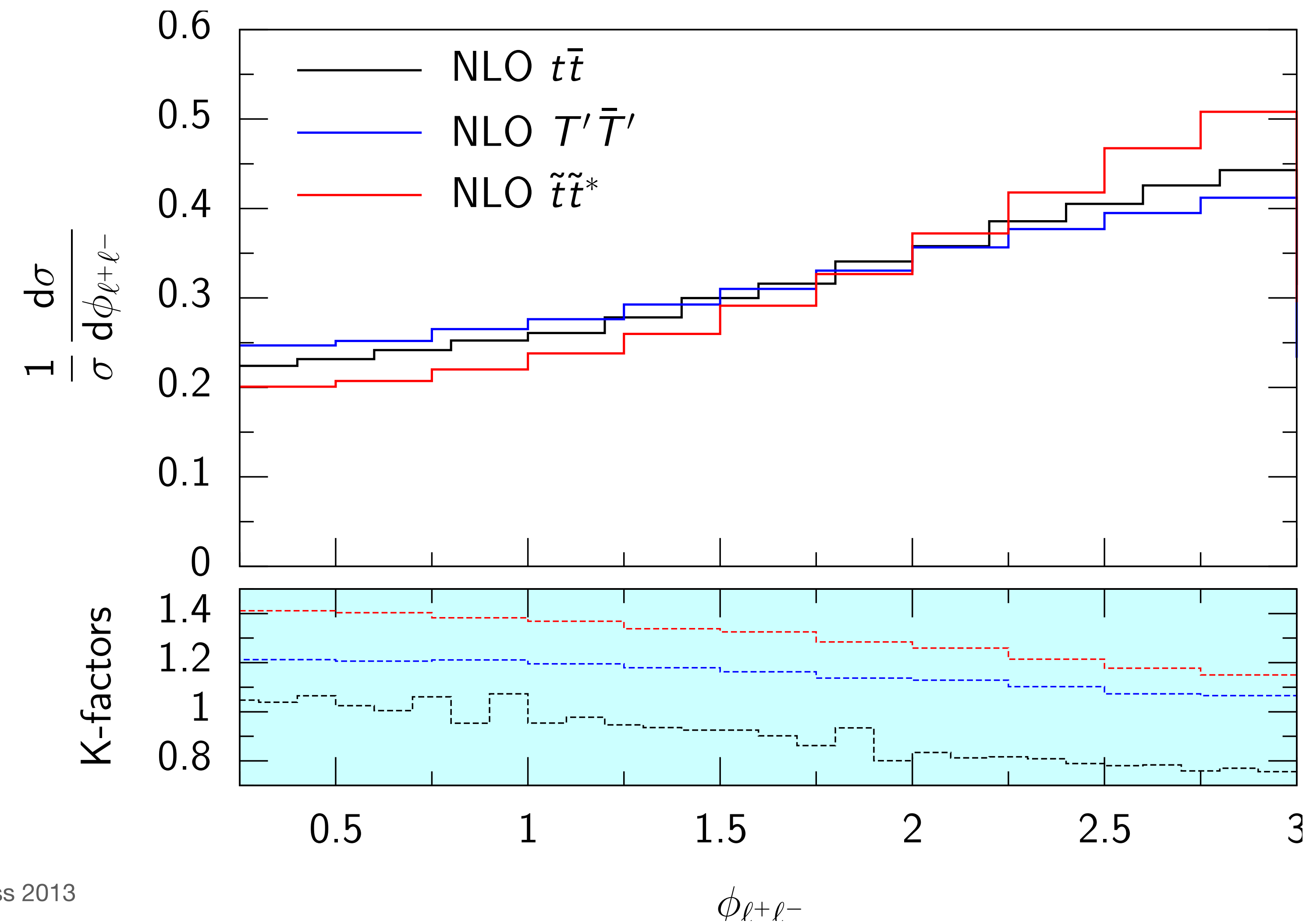
**LHC : few %**

**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

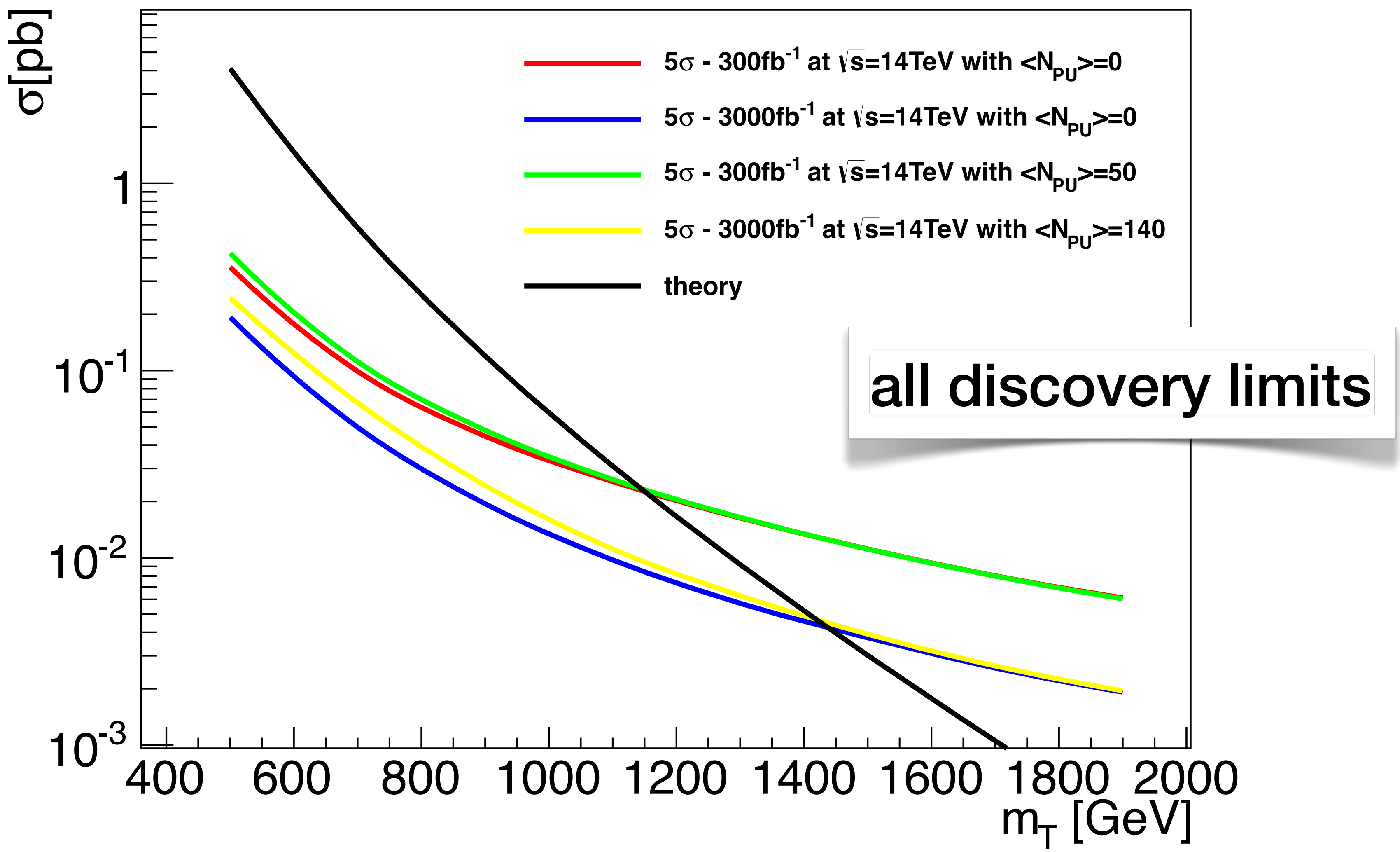
projected limits for FCNC top decay processes

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

Brock/Peskin Snowmass 2013

# Direct search for top partner

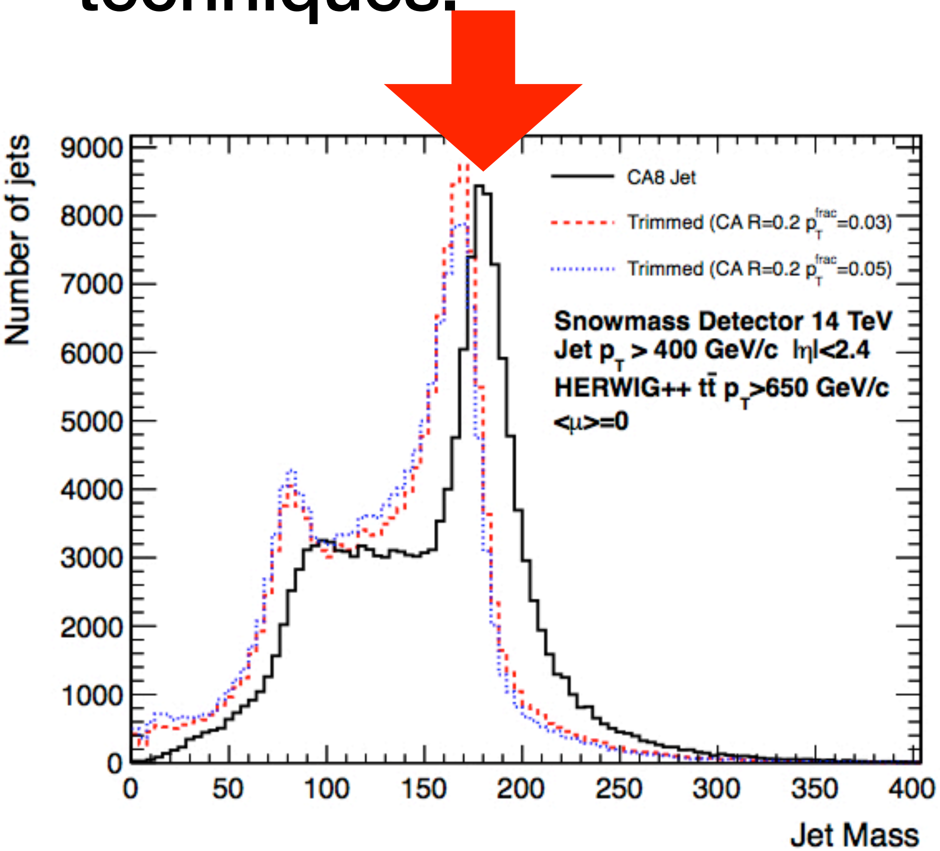
## search reach for vectorlike top partners at LHC 300 and 3000/fb

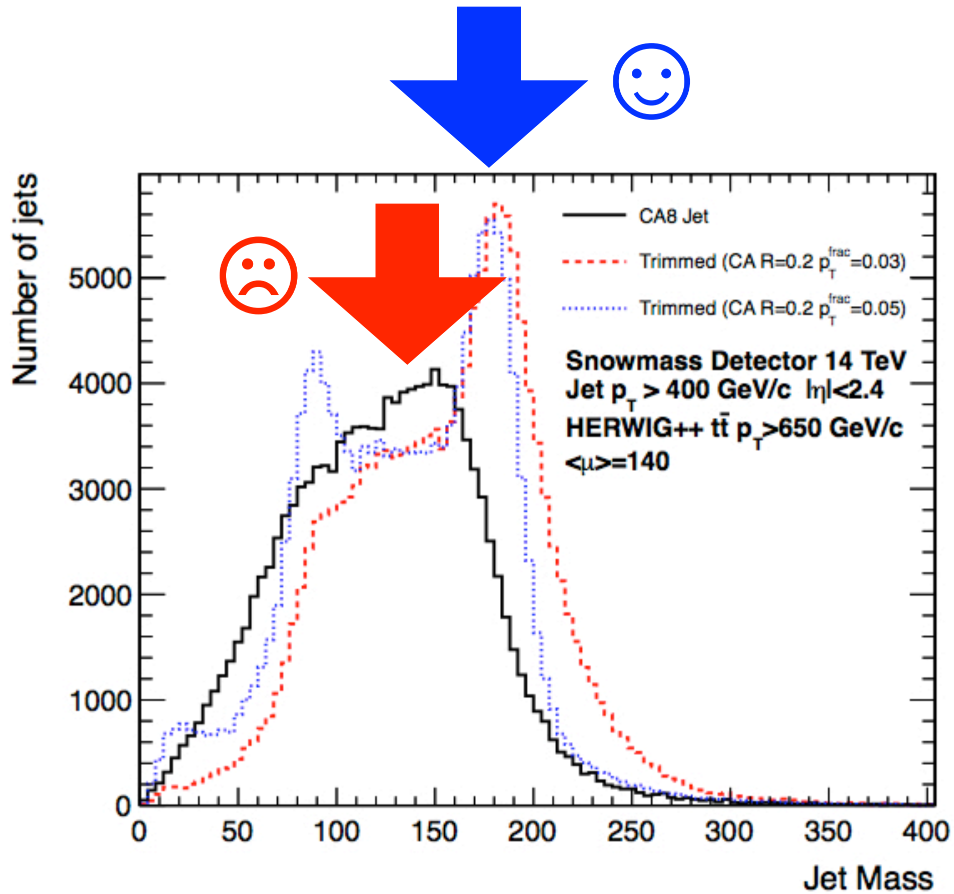


# boosted top technique

## Top quark finding deteriorates at high pileup.

Restore the performance with grooming and trimming techniques.




pileup = 0 140

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# Quantum Chromodynamics and the Strong Force

# QCD: Themes

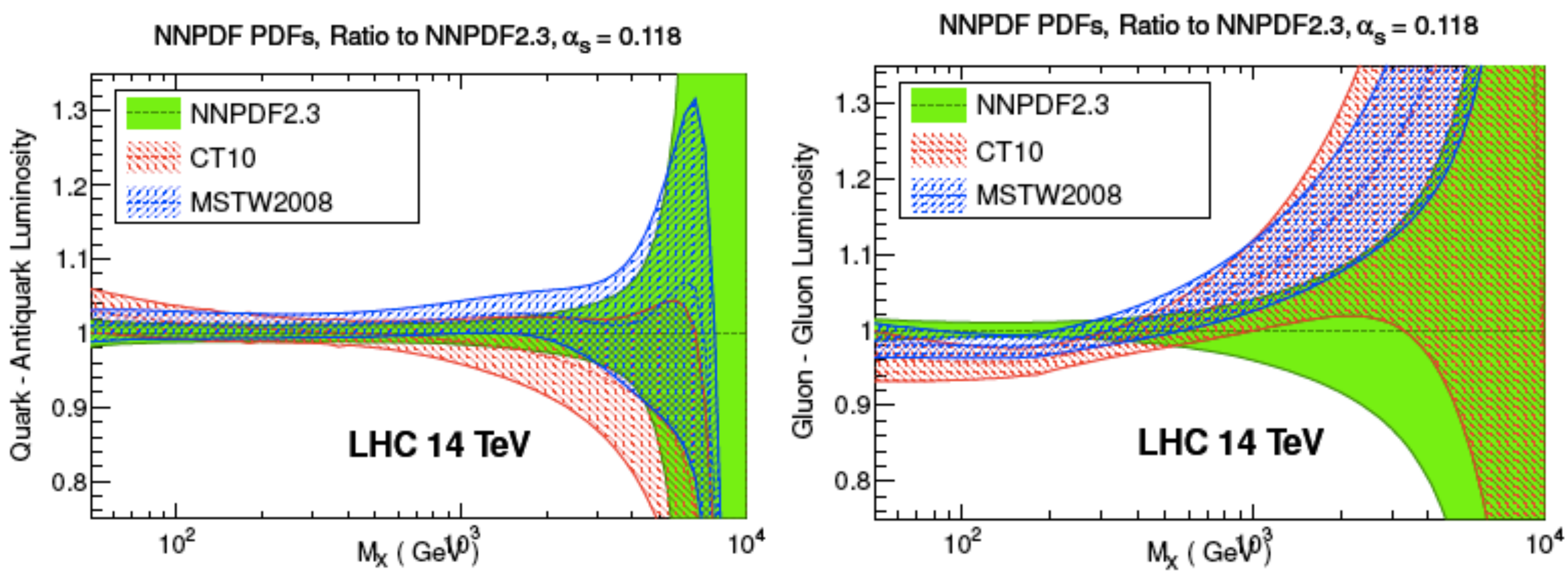
1. Improvement of PDFs and $\alpha_S$

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

# PDFs

## significant PDF uncertainties in regions relevant to Higgs, new particle searches

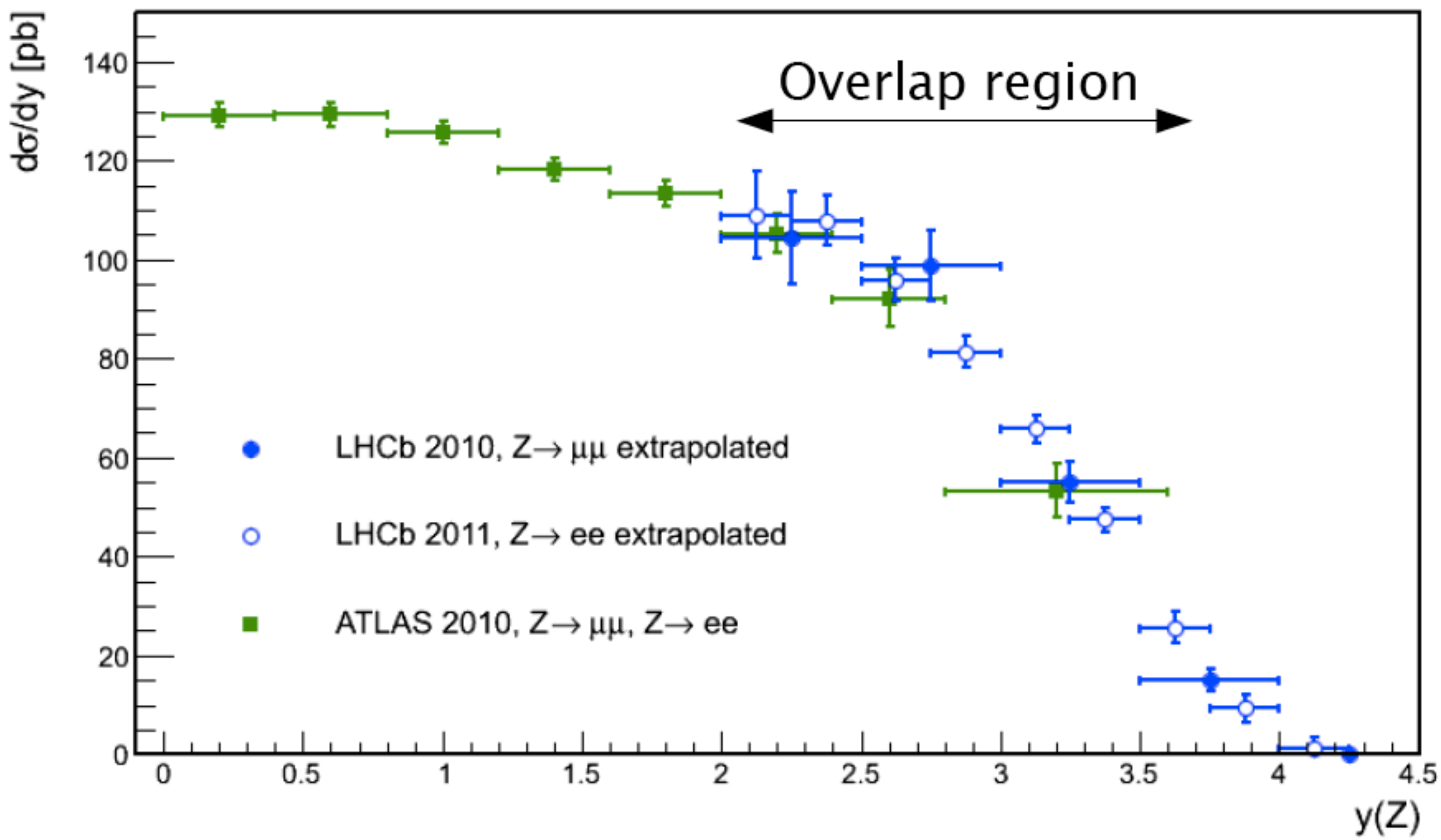



Juan Rojo

Improve at LHC with W, Z, top rapidity distributions

# full rapidity coverage required

## complementary role of ATLAS,CMS and LHCb

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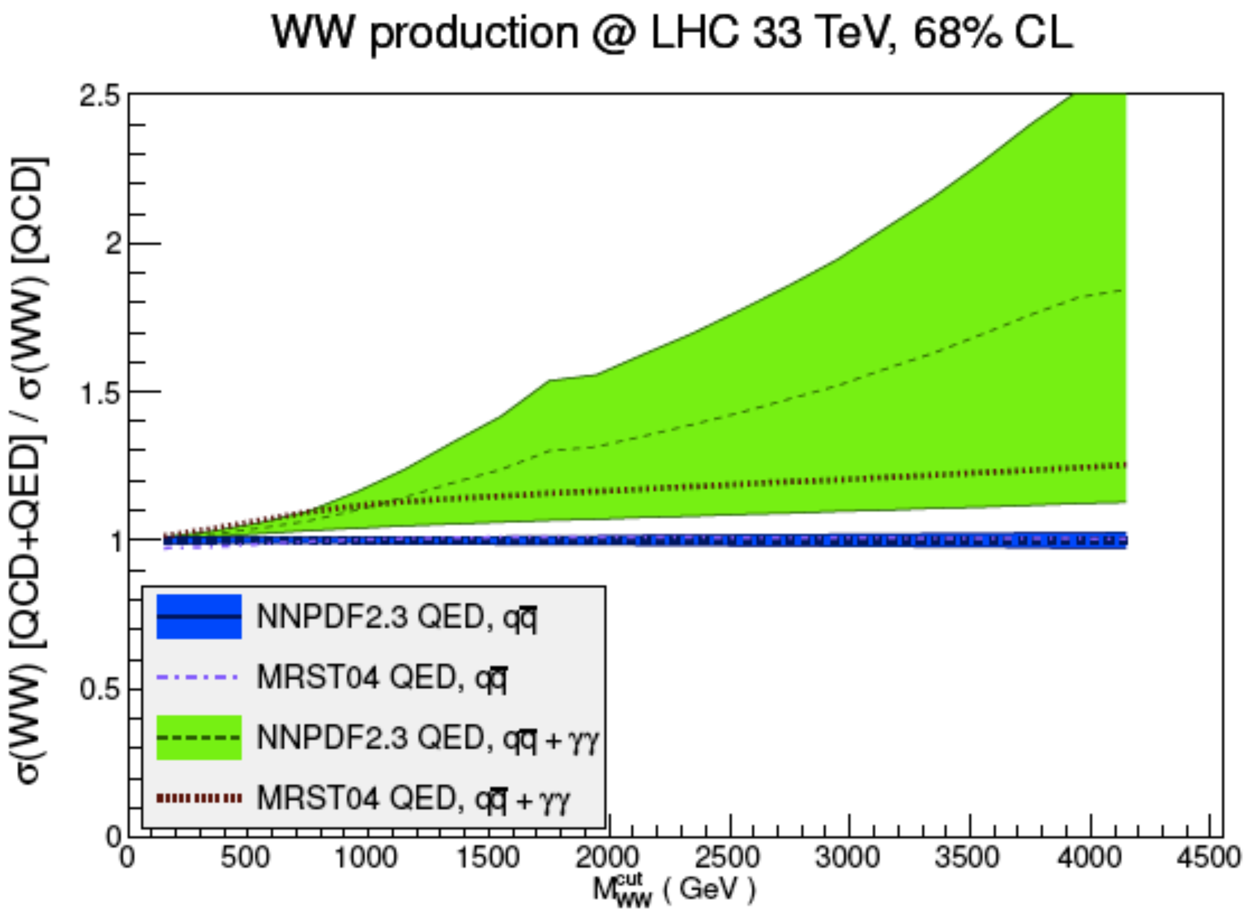
# Photon PDF and QED

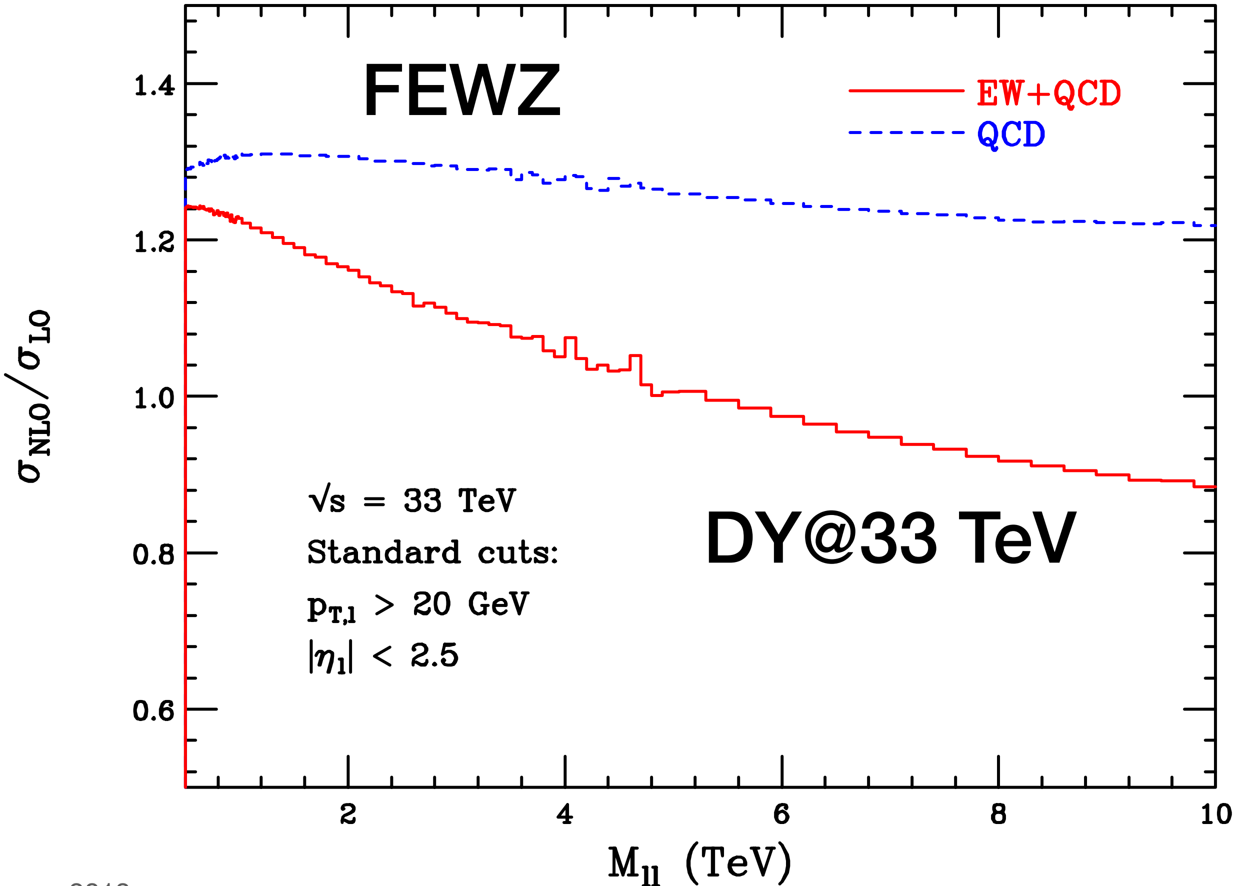
Photon-induced processes are increasingly important; need to extend the current state of the art in PDFs to QED.




Juan Rojo

# Electroweak Sudakov

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

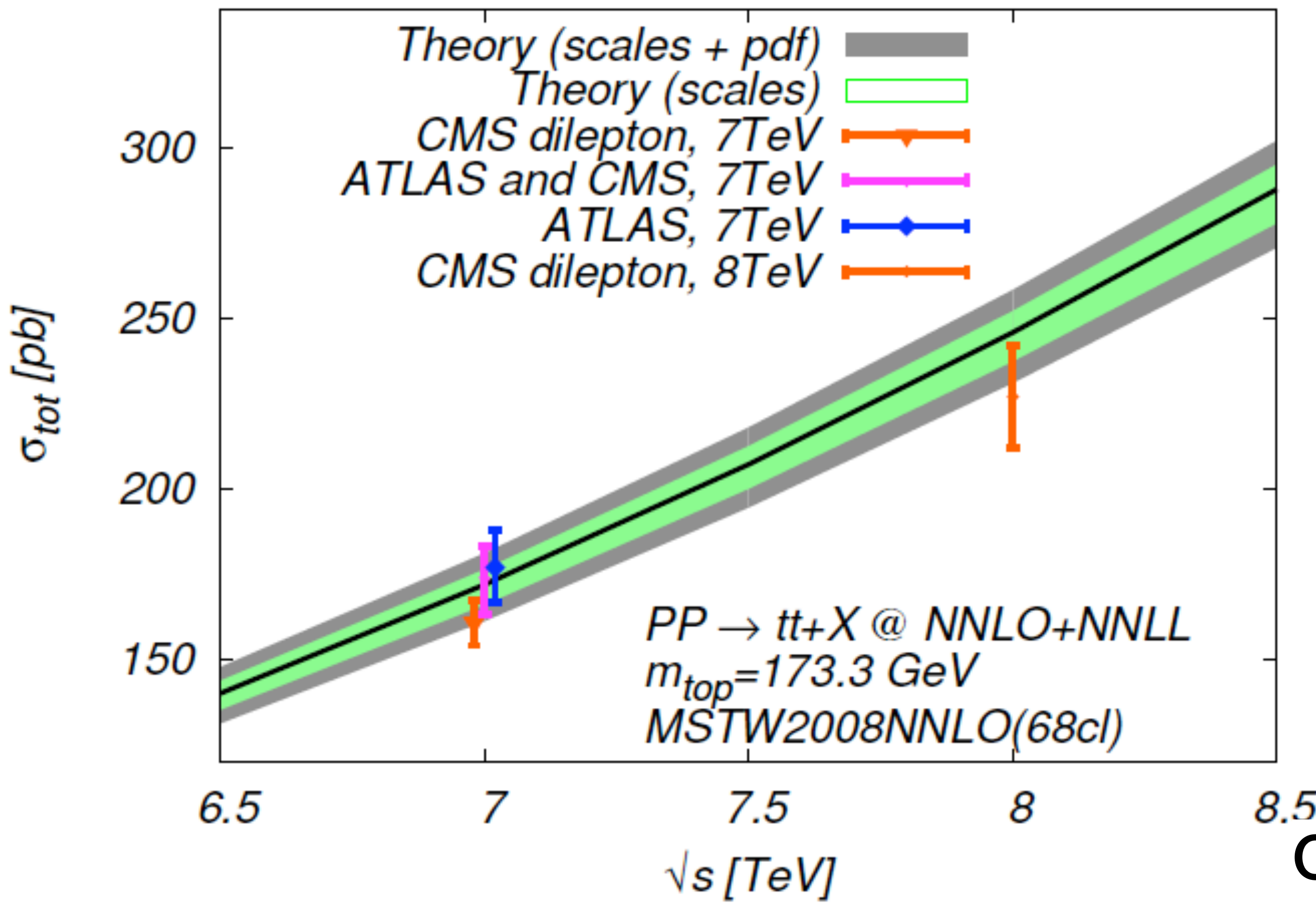



Kaland Mishra

# NNLO

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

NNLO will soon be available for 2->2 and some 2->3 processes. It is needed for Higgs studies and many other LHC analyses.






Czakon-Mitov

# 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] |
| $\delta m_c$ (GeV) | 0.03 | 0.025 | 0.013 [31] | 0.006 [24] | 0.004 | - |
| $\delta m_b$ (GeV) | 0.06 | 0.03 | 0.016 [31] | 0.023 [24] | 0.011 | - |

Paul Mackenzie,
Snowmass QCD report

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

## and, Extensions with New Flavor and CP dynamics

# 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

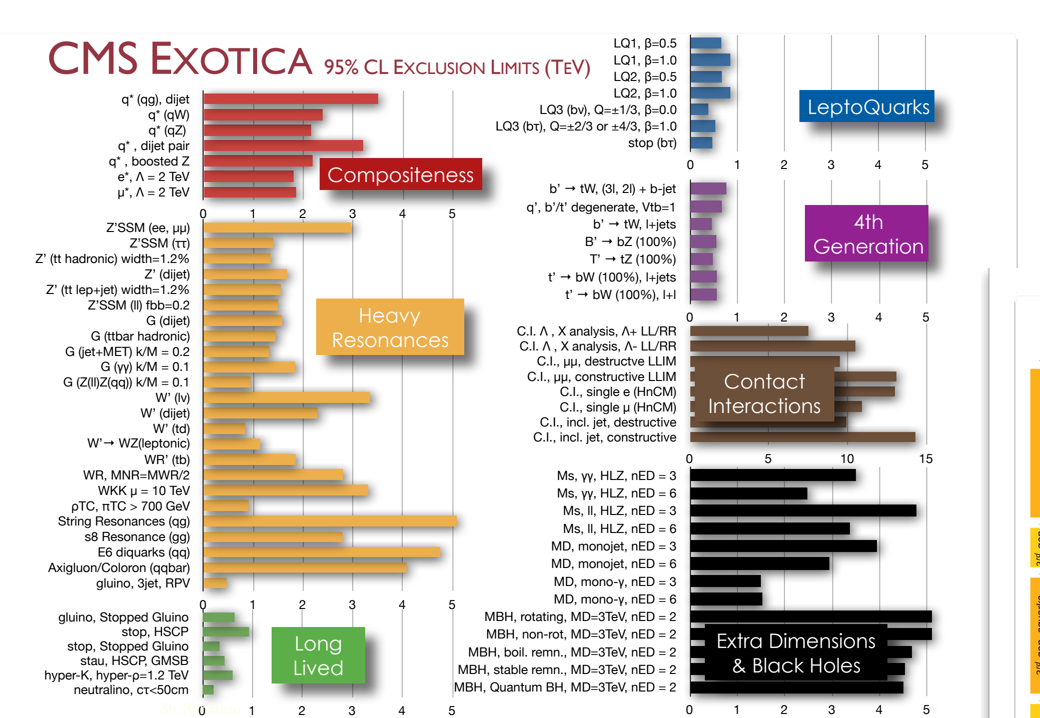
- weakly coupled: SUSY, Dark Matter, Long-lived
- strongly coupled/composite: Randall-Sundrum, KK and Z' resonances, long-lived particles
- evolution of robust search strategies

## 3. Connection to dark matter problem

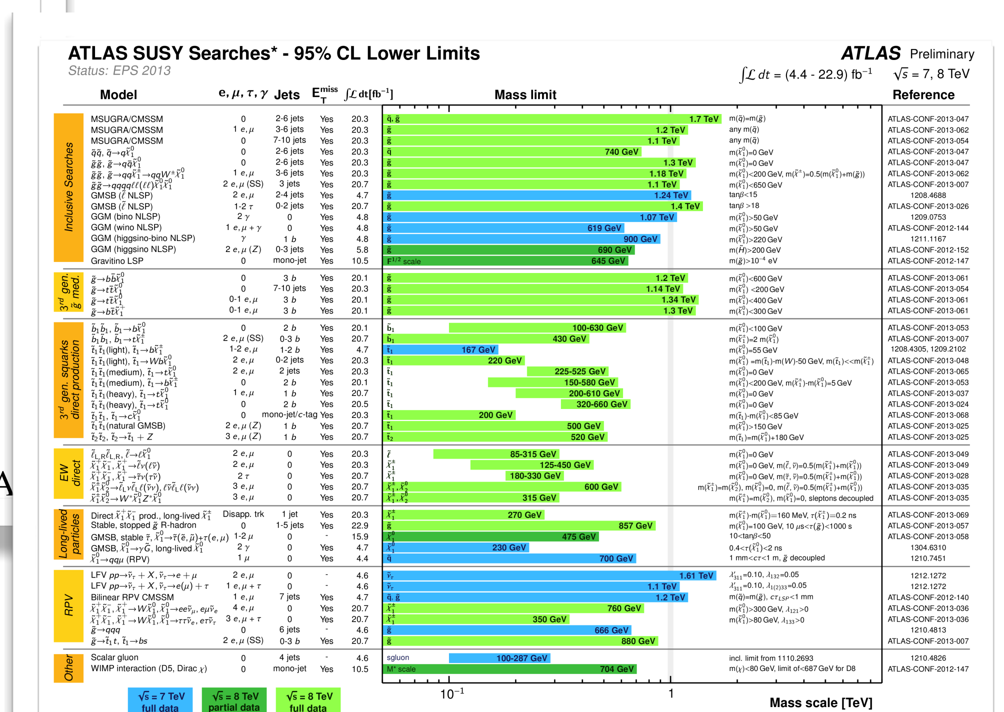
## 4. Connection to flavor issues

# current LHC searches

## New particle searches at the current LHC.



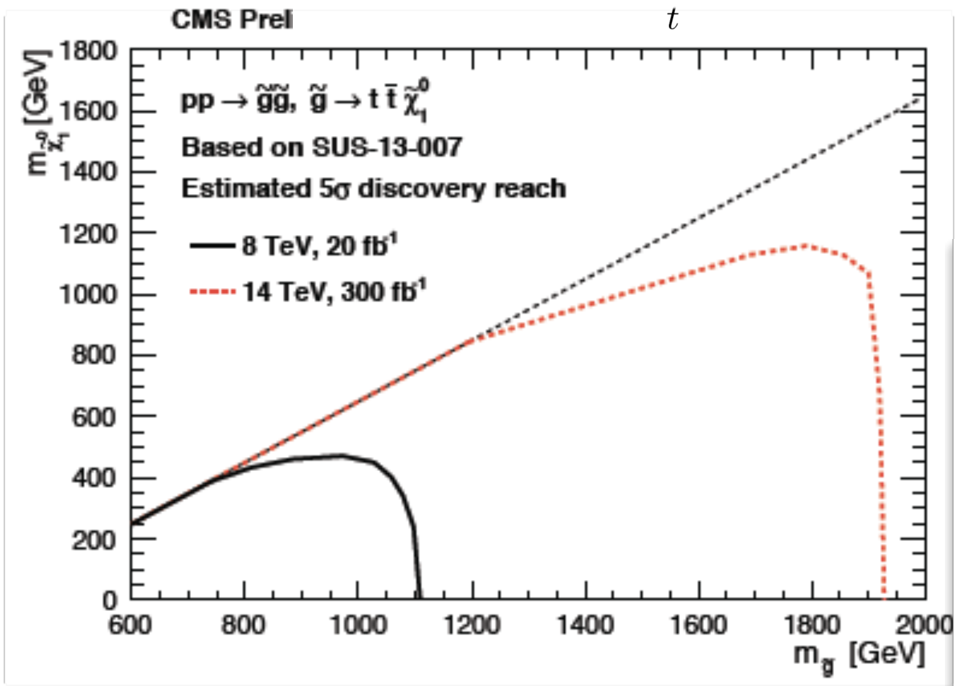

*similar results obtained by ATLAS

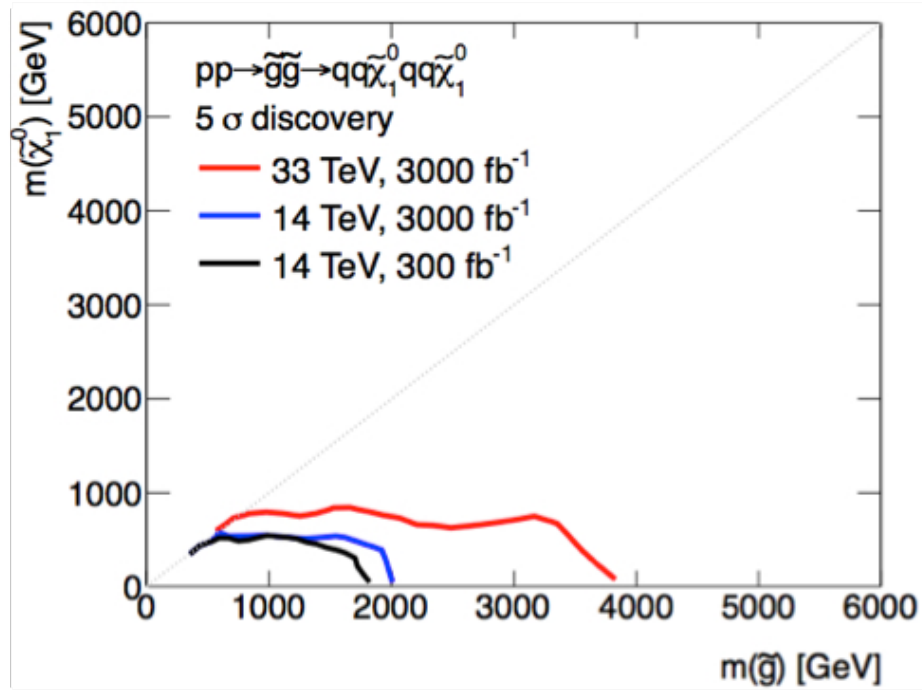



*similar results obtained by CMS

# gain from now to 300/fb & beyond

x2 in gluino mass reach 8-14 TeV,
& more 14-33 TeV



# SUSY at stages of LHC

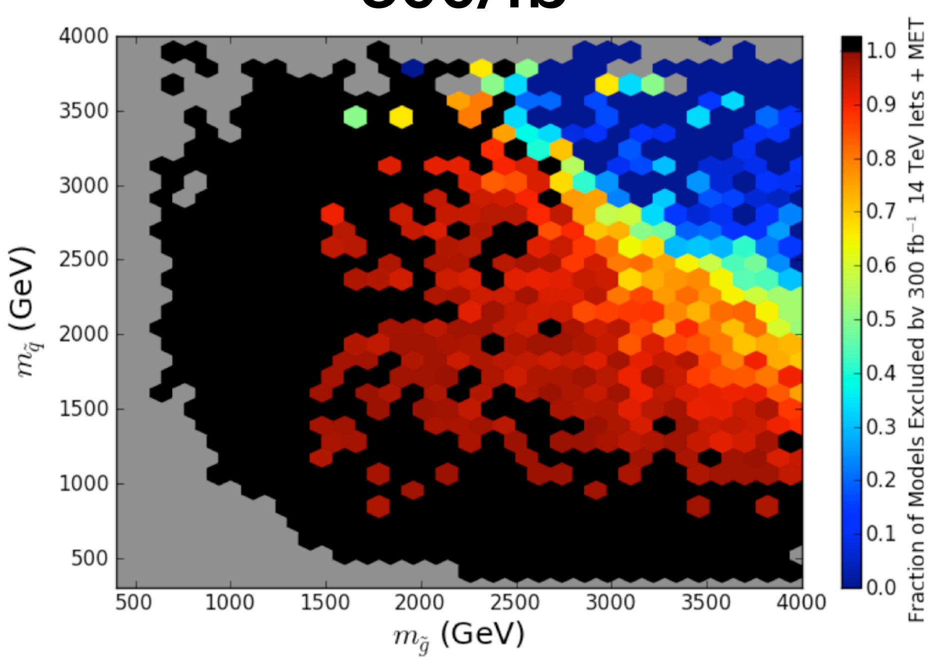
## In the pMSSM survey of SUSY models

squark/gluino mass plane

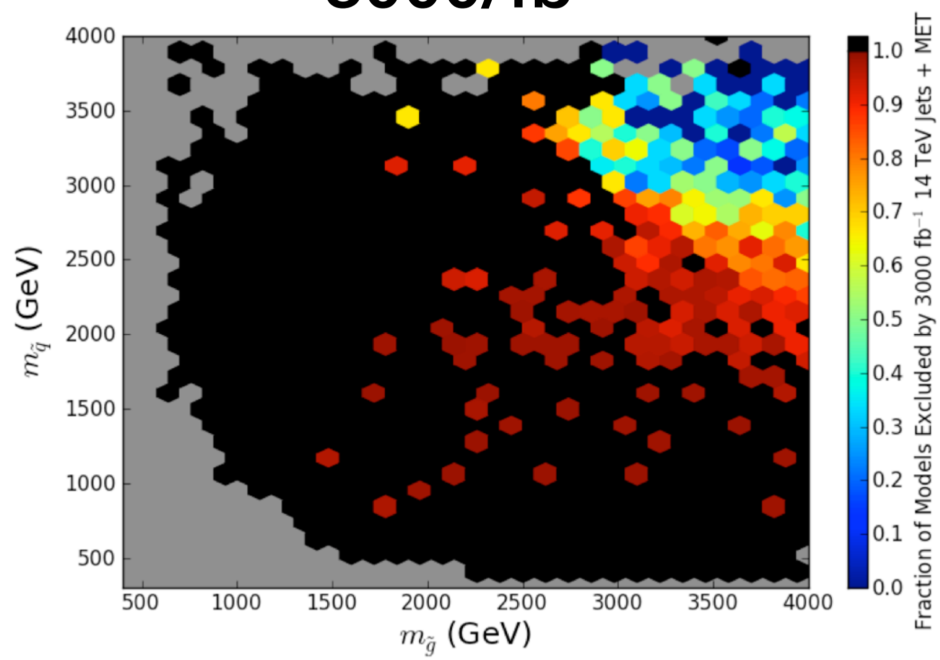
x2 from 8 TeV to 14 TeV (300/fb)

another ~ 30% to 3000/fb

300/fb




3000/fb

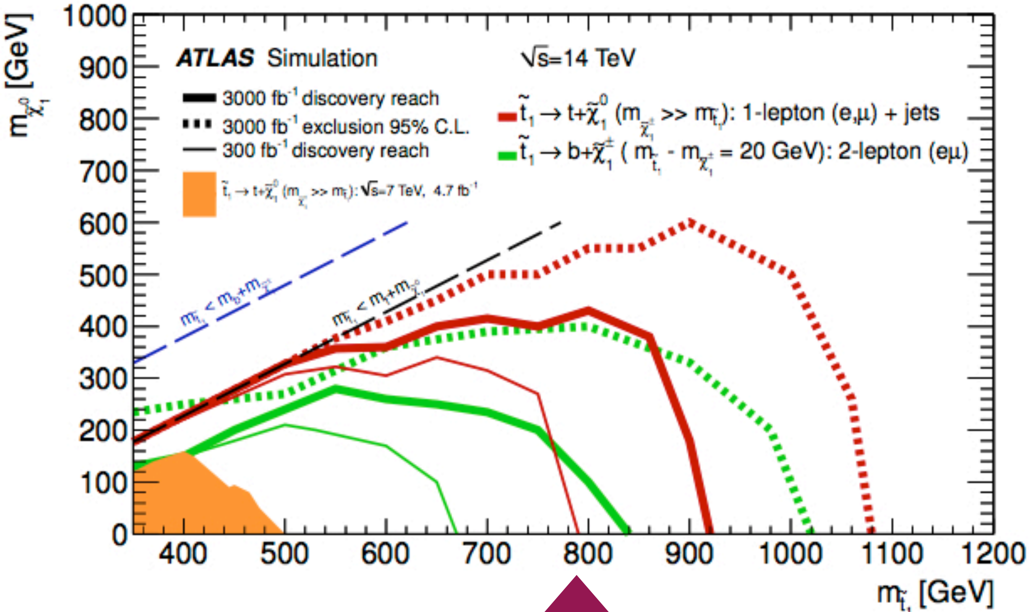


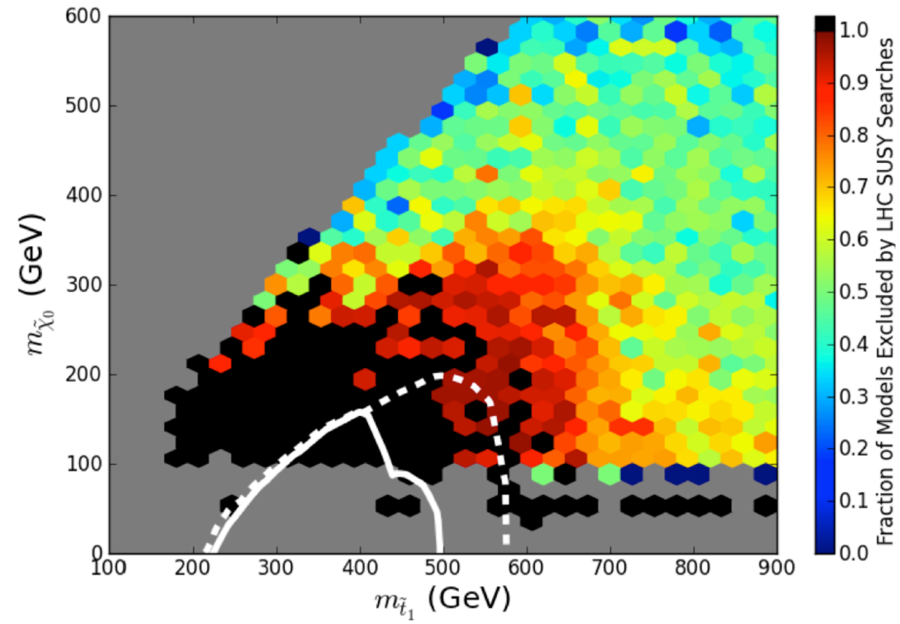

Note closing of loopholes in addition to increased energy reach.

Cahill-Rowley et al.

# stop in the name of love

## a full factor 2 in mass reach is expected




300/fb reach
stop-> t + neutralino

3000/fb reach
stop-> t + neutralino

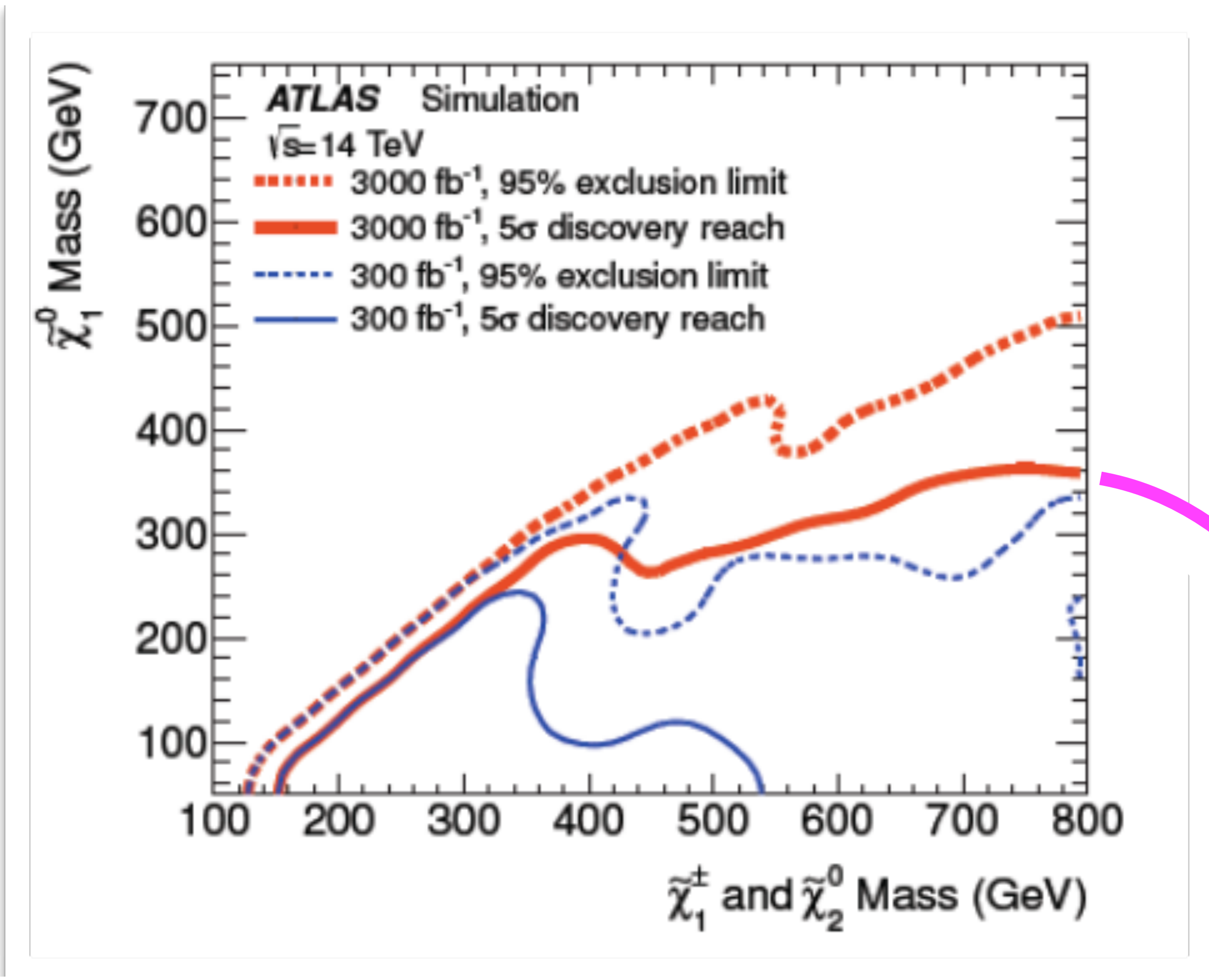
Brock/Peskin Snowmass 2013

Cahill-Rowley et al.

# electroweakinos

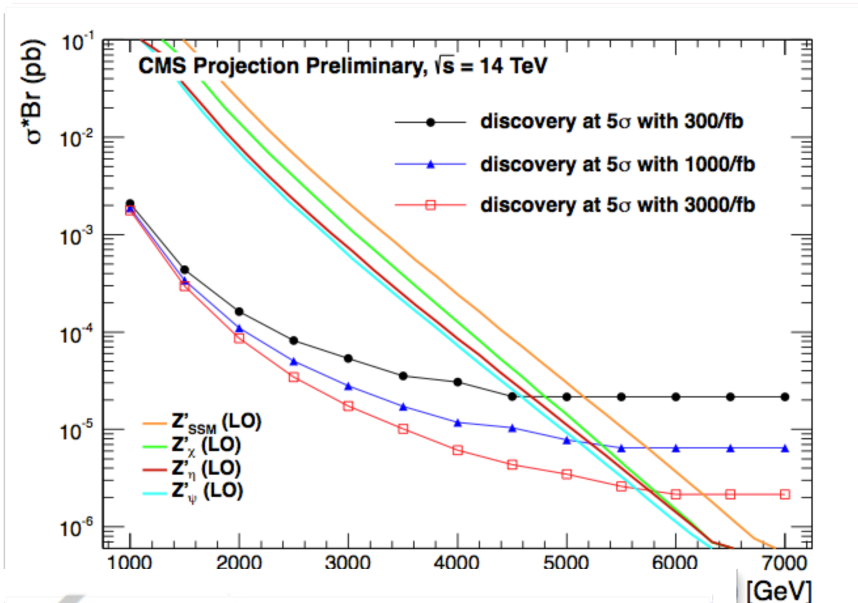
× 2 again...300/fb to 3000/fb

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

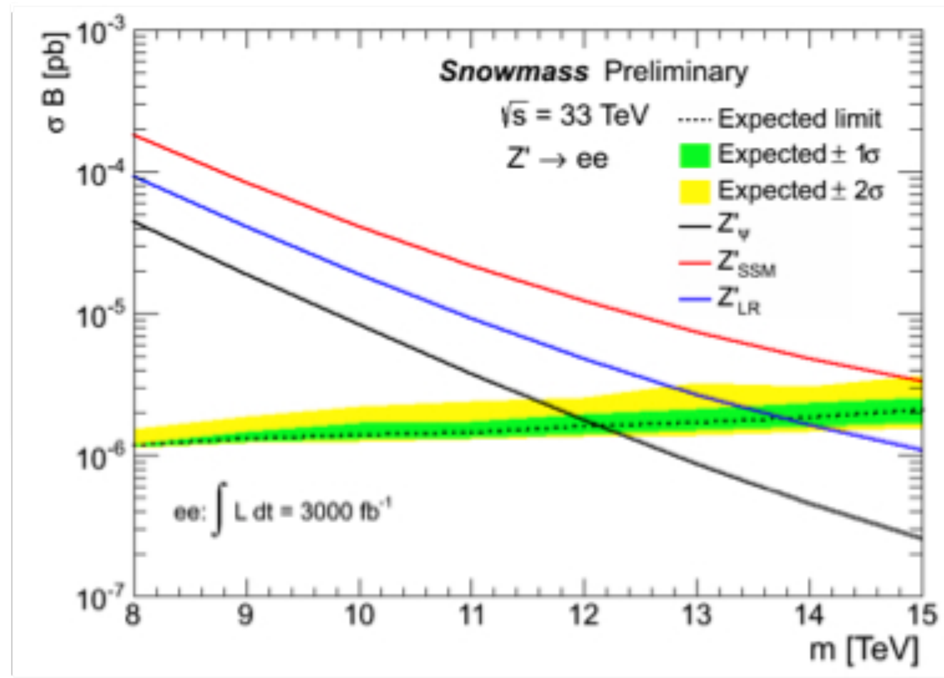



famously ran out of MC ooph

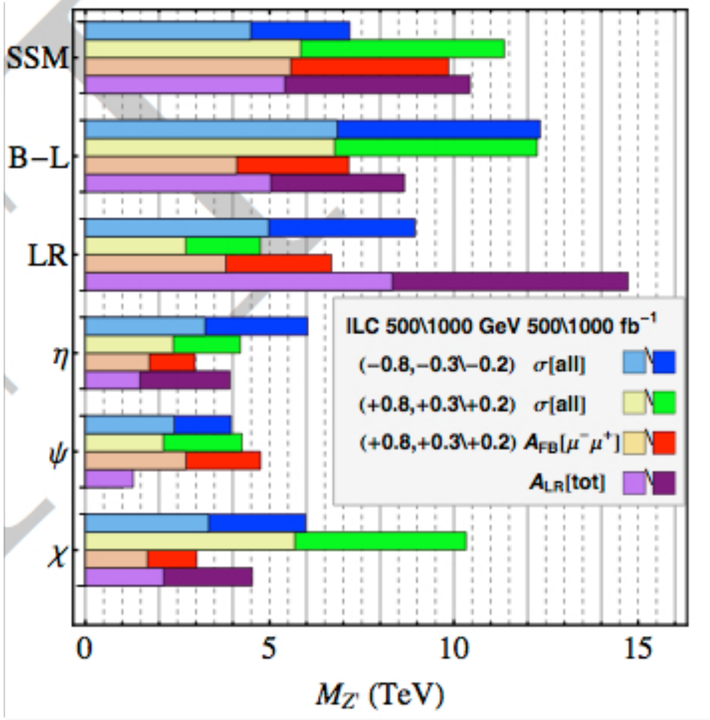
# Z' sensitivity




5-6+ TeV Discovery range at 14 TeV LHC



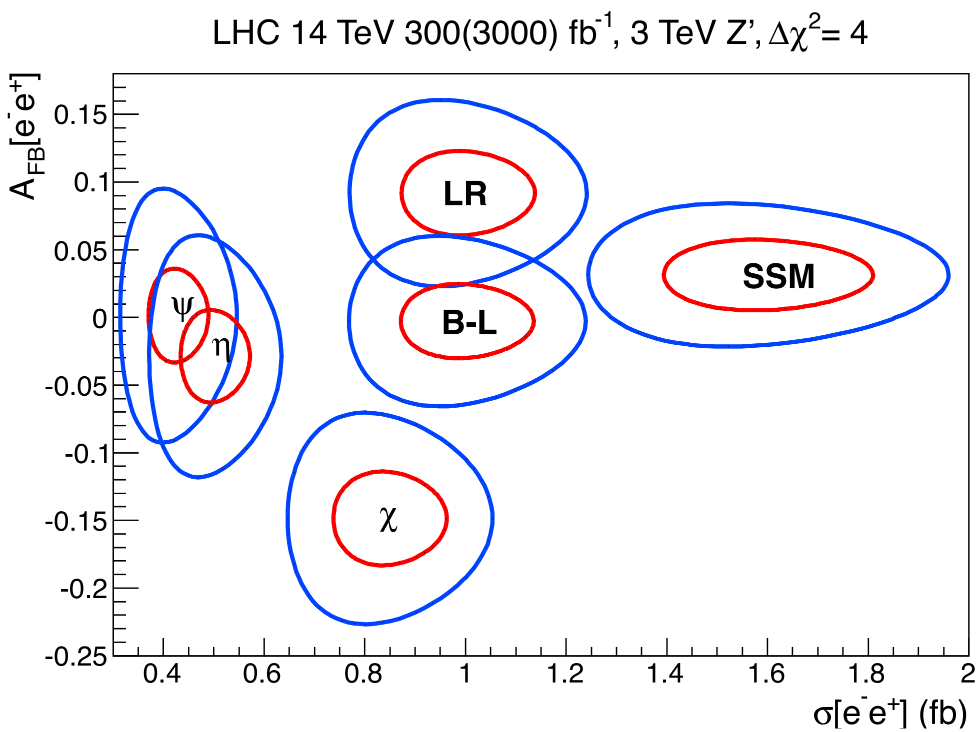

12-15 TeV limit range at 33 TeV pp



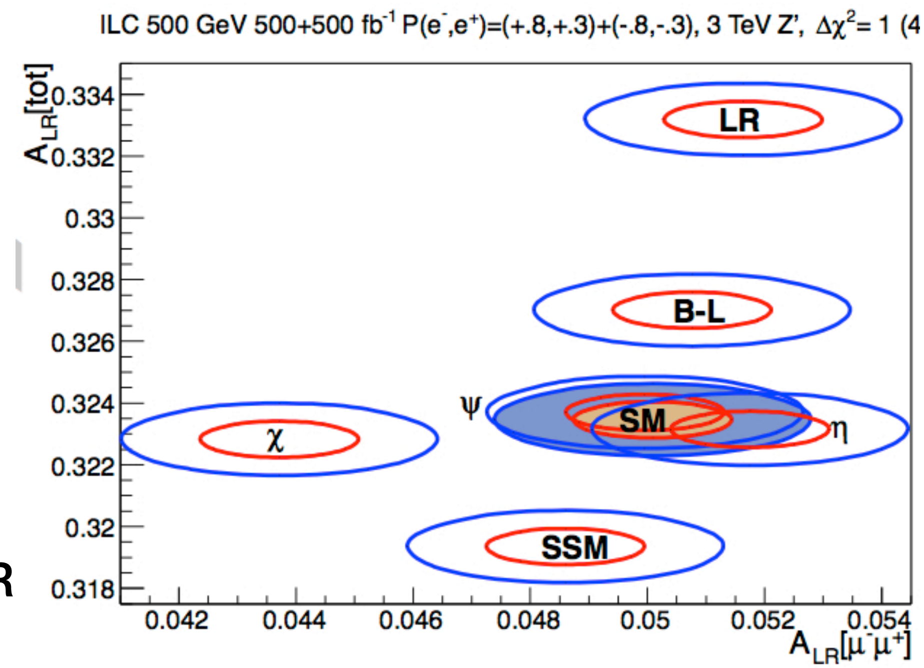

ILC asymmetry interference, beyond LHC

# 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 $A_{LR}$

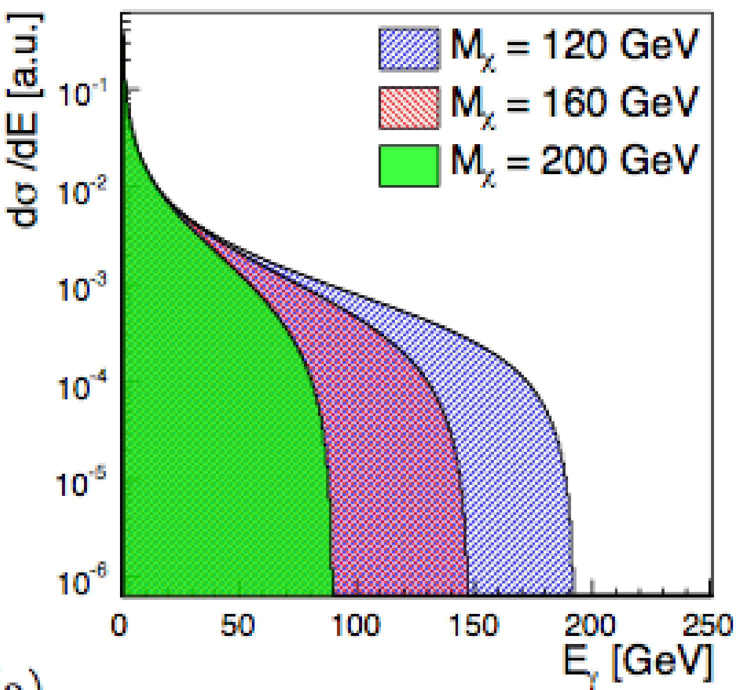
Brock/Peskin Snowmass 2013

# Dark matter connection

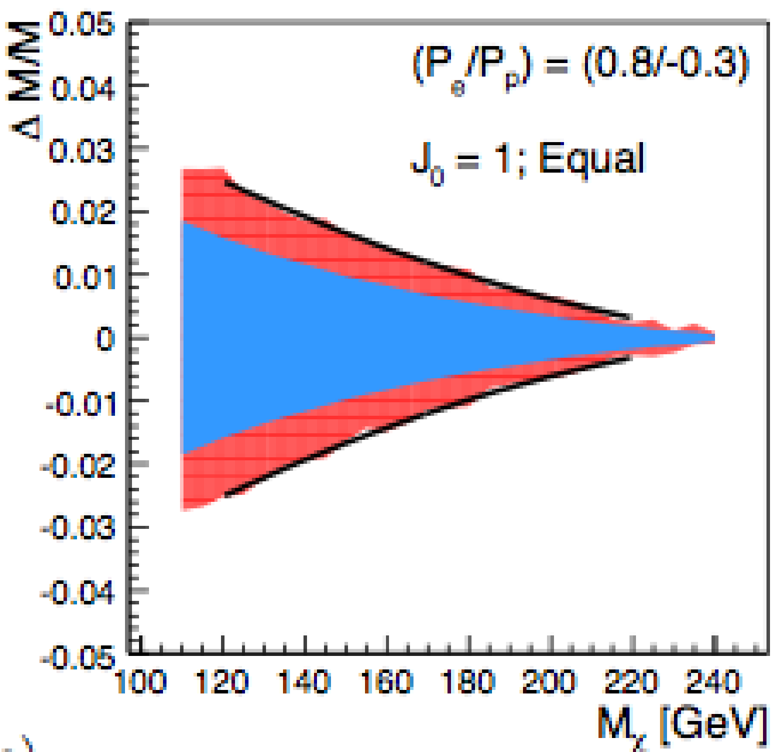
WIMP search at ILC in

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

polarization significant in controlling backgrounds



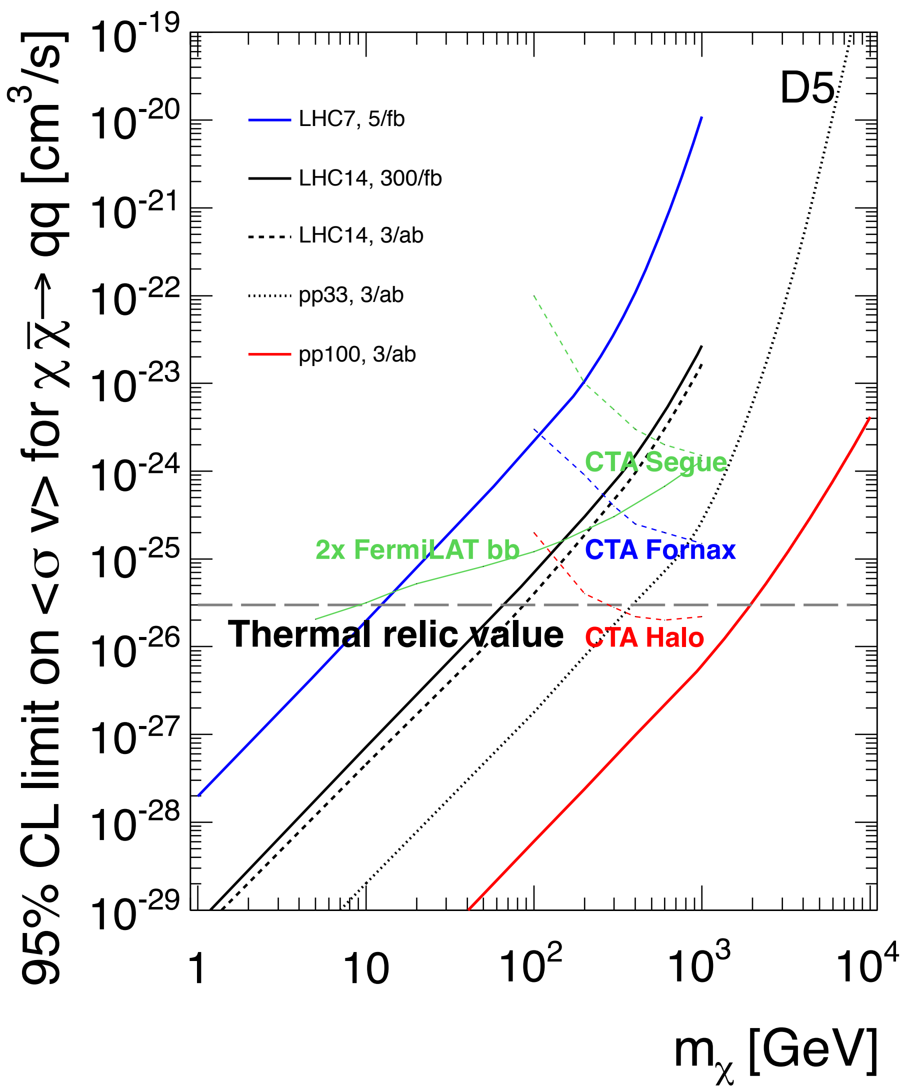
(a)



(a)

# Dark Matter Connection

## close the thermal relic range?



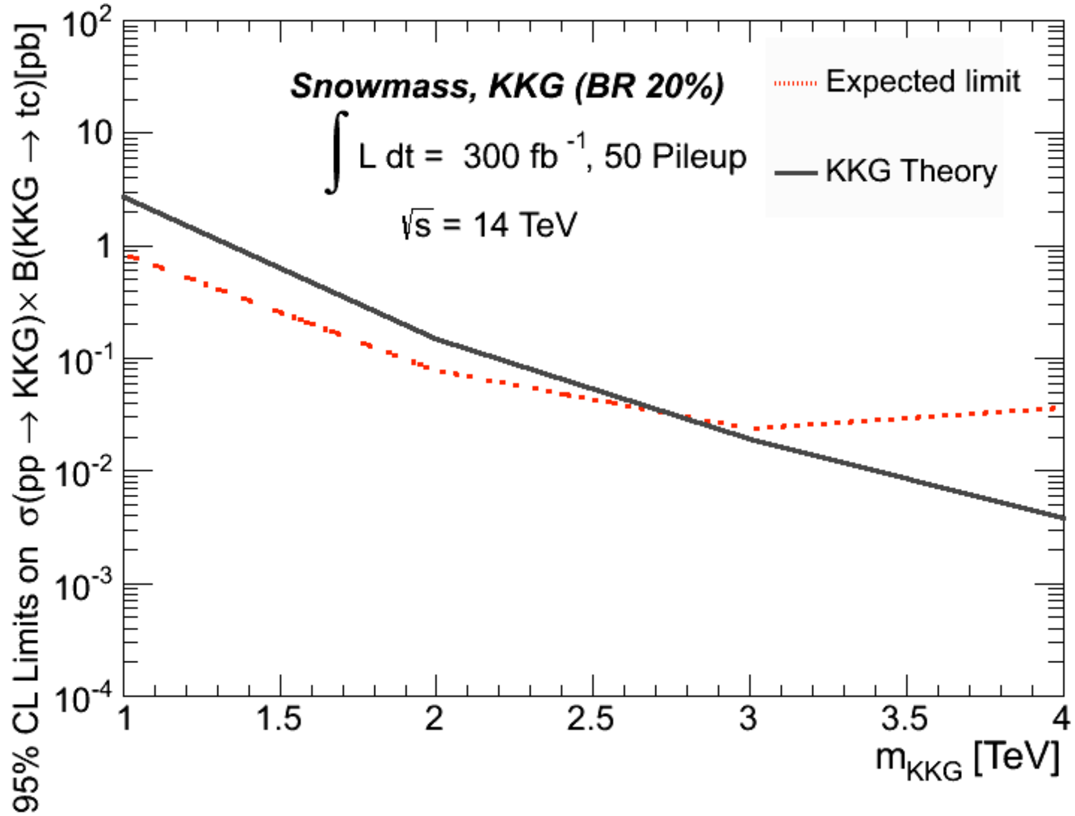

progressive increase in sensitivity

VLHC (100 TeV) exhausts the thermal WIMP region

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

# Flavor connection

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



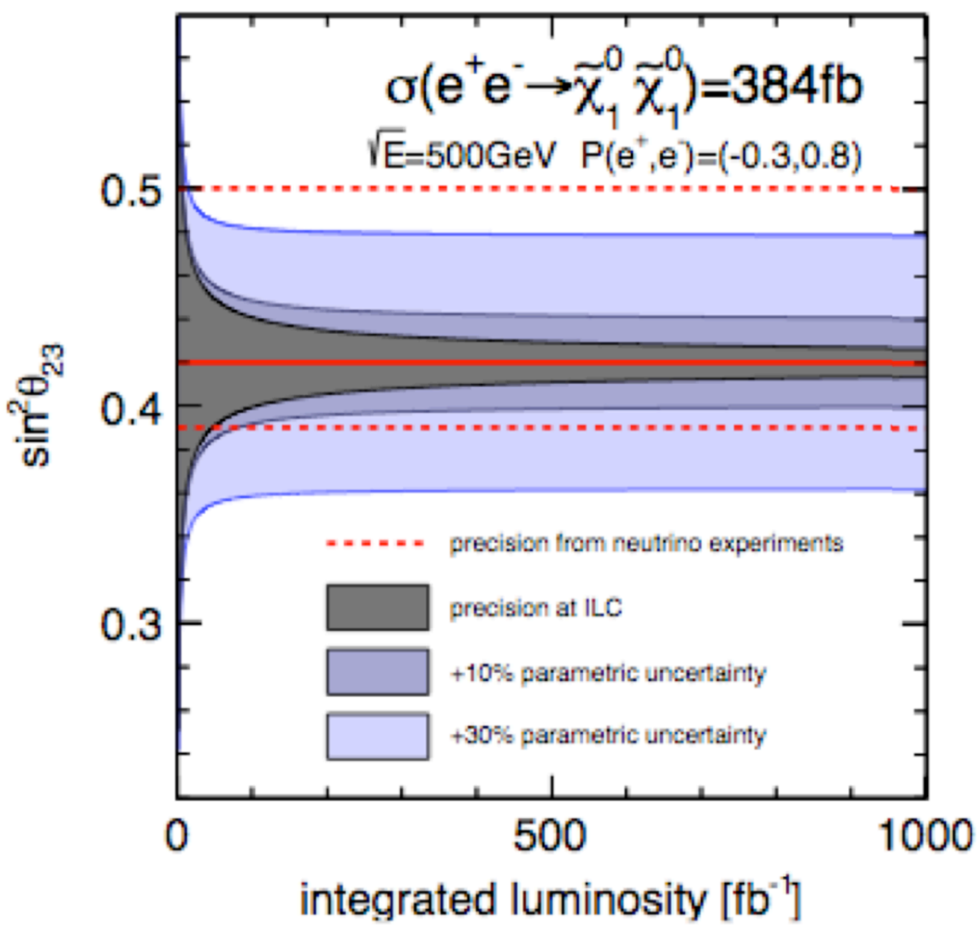

Schoenrock, Drueke, Alavarez-Gonzalez, Schwienhorst

# Neutrino connection

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 $\theta_{23}$ 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.

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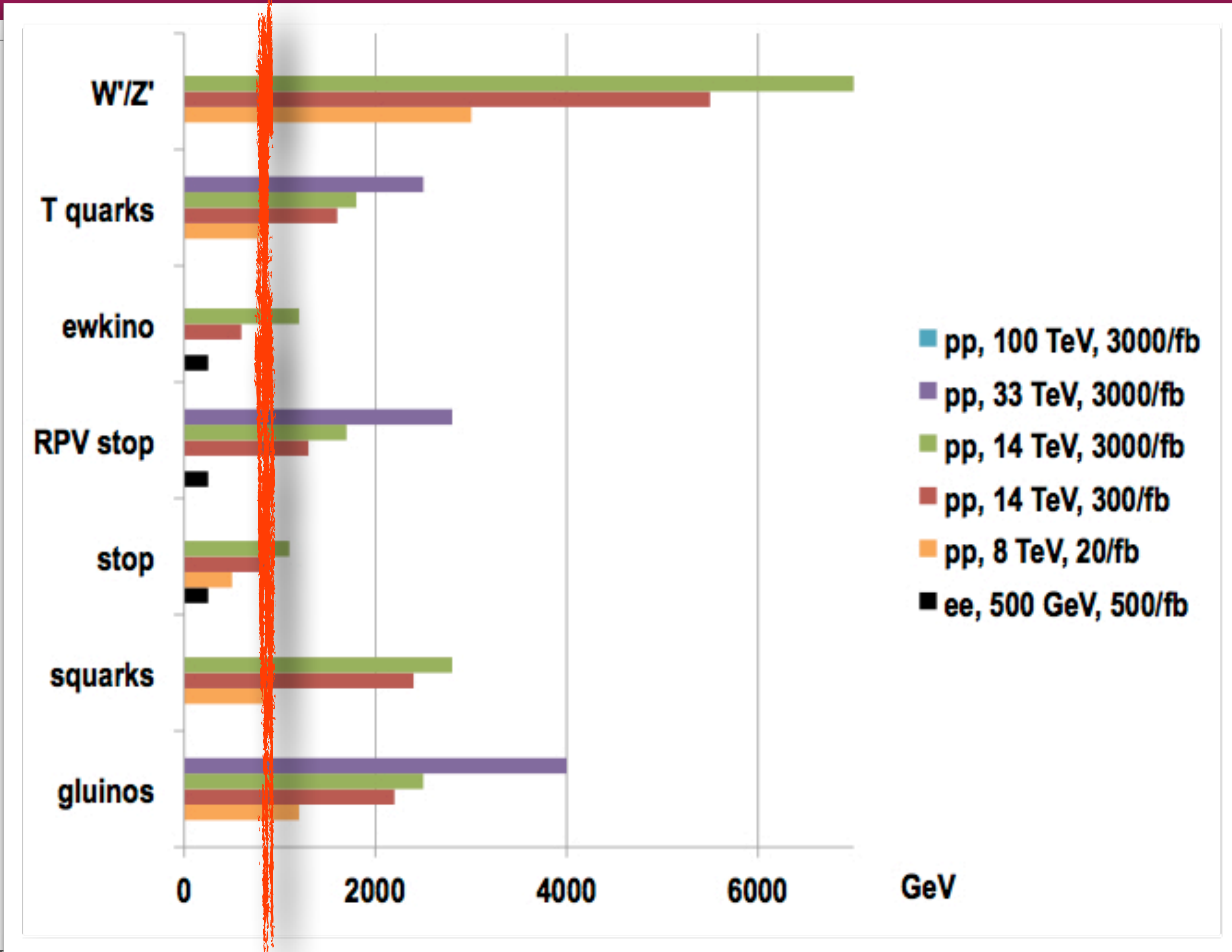
# the TeV scale is in sight

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# Reprise of the Physics Messages
# &
# The Scientific Cases for:

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## LHC upgrades: 300, 3000 fb$^{-1}$

## 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

# 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?**

# 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 probes for Higgs sector resonances.

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

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

# 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?**

# 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

# 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

# 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**

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# ILC, up to 500 GeV

1. **Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs $\Gamma$, 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 $\alpha_S$ 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 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

**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 fbar 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 cbar, tubar 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**

# Conclusions

# NOW, LOOK.

# MASS

## We collider types say we know about Mass.

# Really?

**as long as we know**

***nothing about the electrically neutral fermions***

**&**

***nothing about 1/4 of the universe***

**We don't know the whole Mass story.**

## On Electroweak Symmetry Breaking

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC and charged-lepton flavor violation may provide more information.

Searches for nucleon decay provide the only handle on a new energy scale (3) if

## On Electroweak Symmetry Breaking

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**Beautiful NOvA and LBNE programs might very well influence the Higgs Program.**

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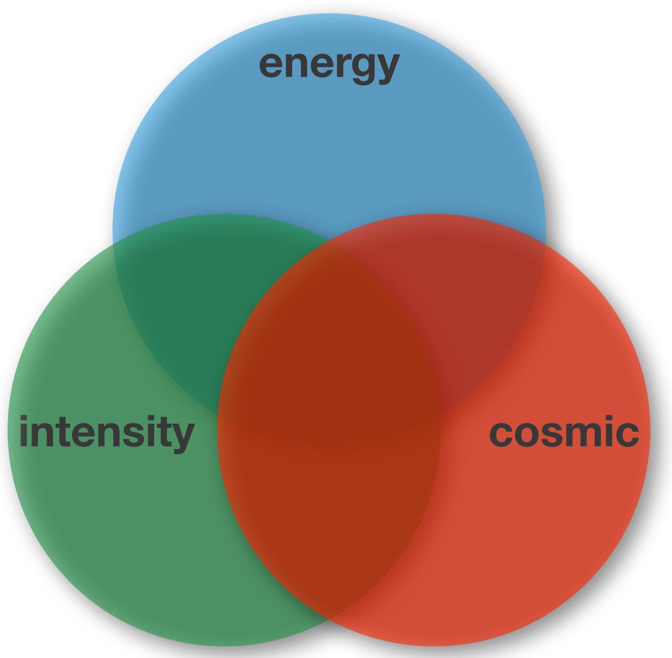
Three Frontiers

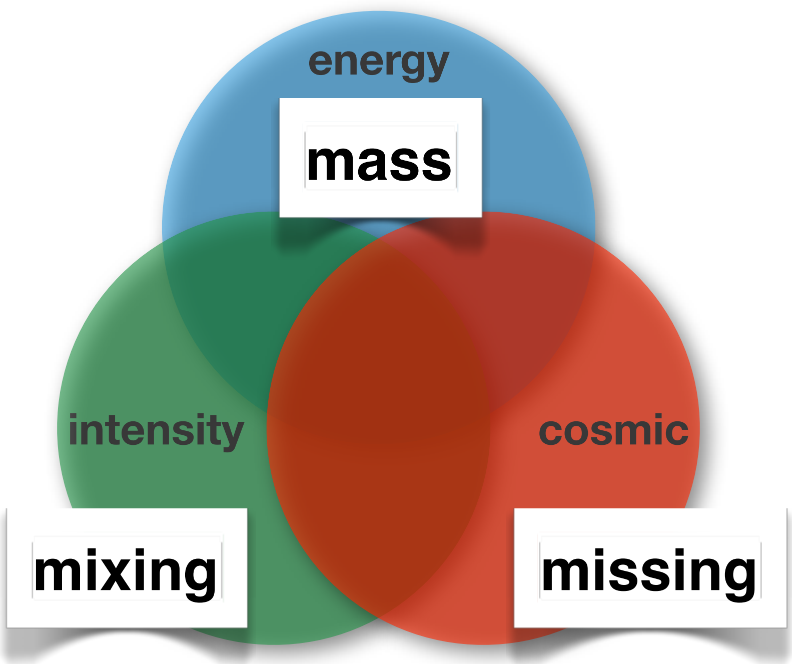
# those circles are pithy

## but they force us to be tribal



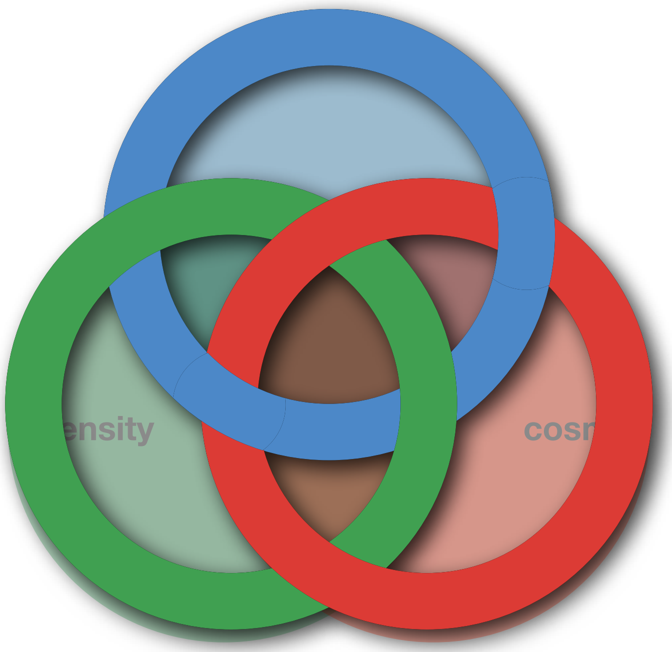
# those circles are pithy

## and encourage silly things like:



# scientific reality

## is more complex

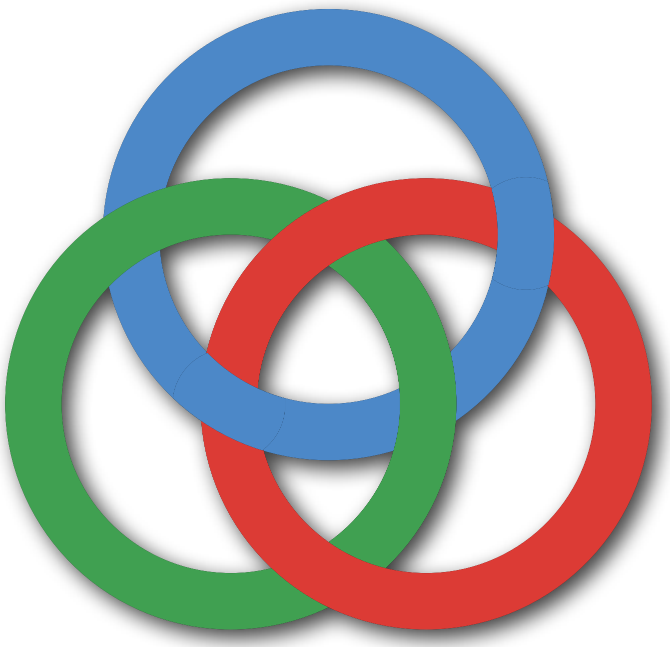





idea stolen from Sasha Vaniachine

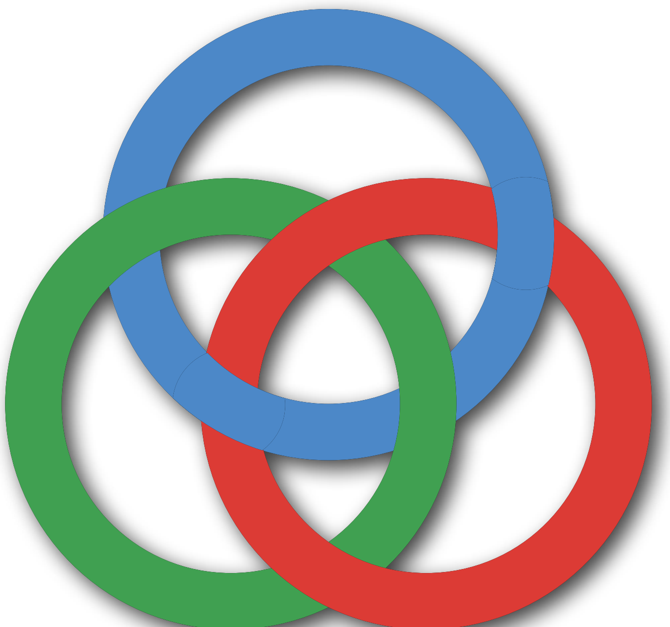
# scientific reality

## is more complex



# a great scientific nation

## plans for balance:



*precision experiments --->*
discovery through inducing quantum loops

*neutrino experiments --->*
discovery by inducing quantum mixing

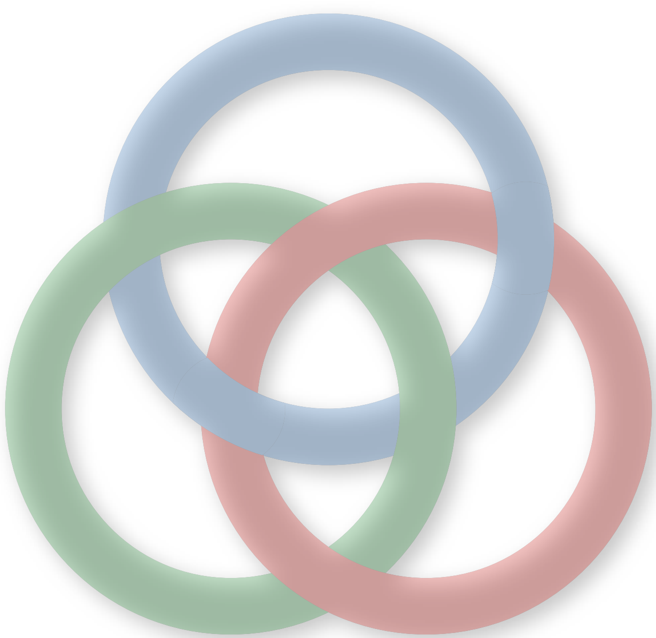
*astrophysical experiments --->*
discovery by capturing cosmic quanta

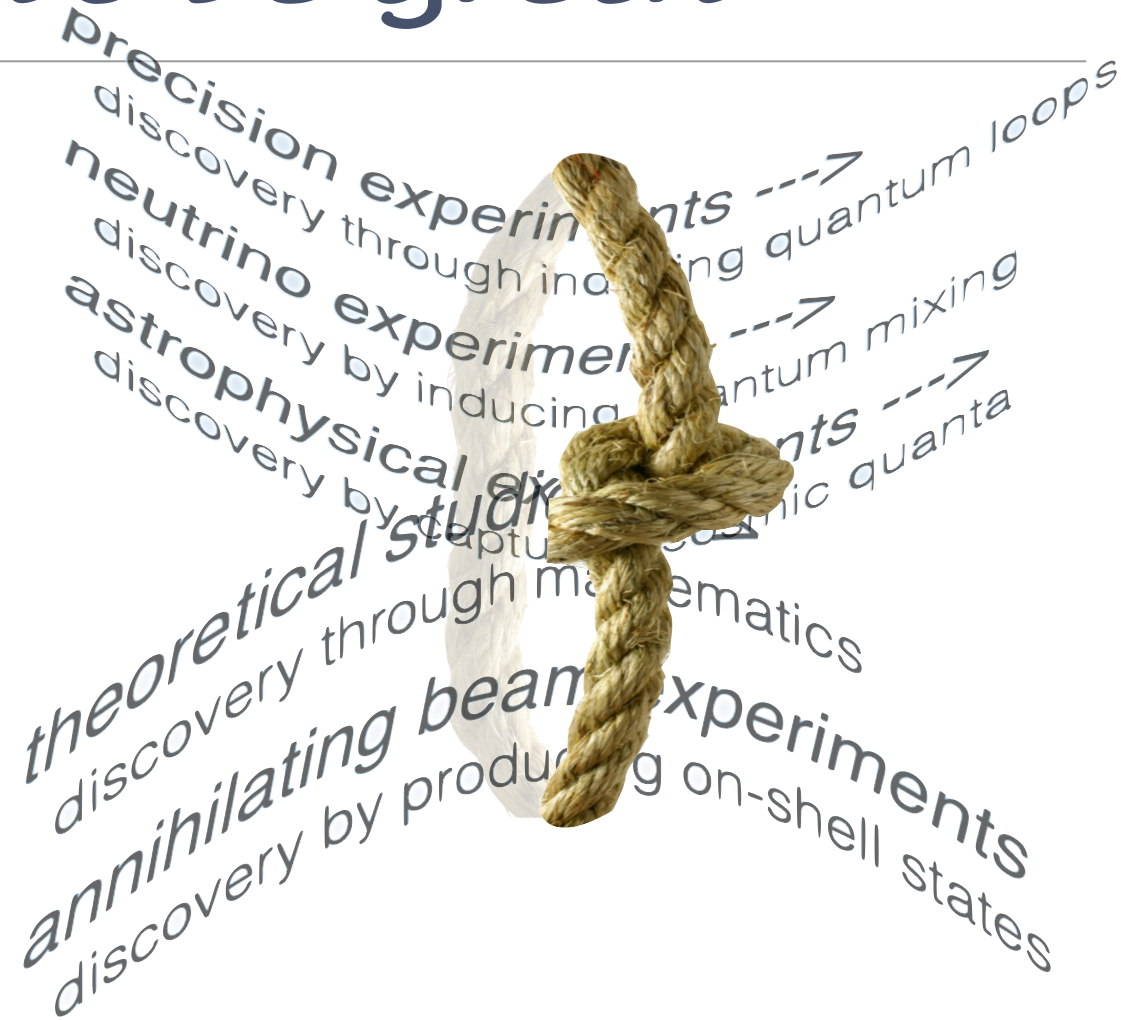
*theoretical studies --->*
discovery through mathematics

*annihilating beam experiments*
discovery by producing on-shell states

# a great scientific nation in order to be great

## plans for balance:





# bottom line

**This Higgs Boson changes everything.**

**We're obligated to understand it using all tools.**

# Thanks to:

## Our Conveners

whose efforts were above & beyond the call of duty

## Jon Rosner and the DPF Executive Committee

Snowmass is special.

## Dan and his Gophers

too bad about the 2014 basketball season

## Thanks, Michael!