
SEEK
The
TRUTH
COMMON
HOTEL

Snowmass 2013, Energy Frontier Division

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Michigan State University
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SLAC

Minneapolis, MN
August 6, 2013

contents

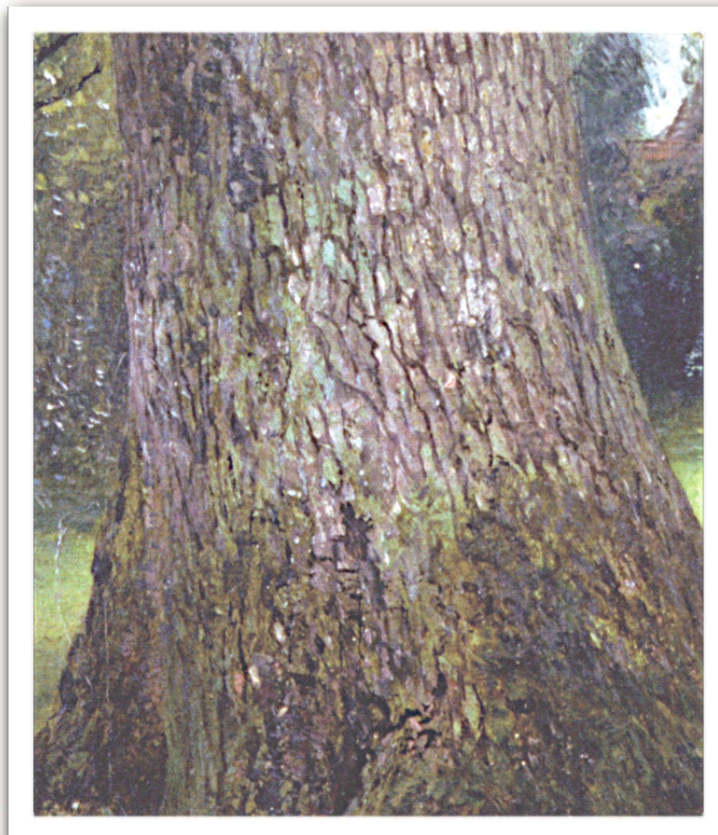
INTRODUCTION: why we're excited
ENERGY FRONTIER PROCESS: why we're tired
HIGHLIGHTS OF RESULTS: why we're eager
CONCLUSIONS: why we're here

Introduction

we don’t work at the

level

we work at the



level

let's briefly think about the

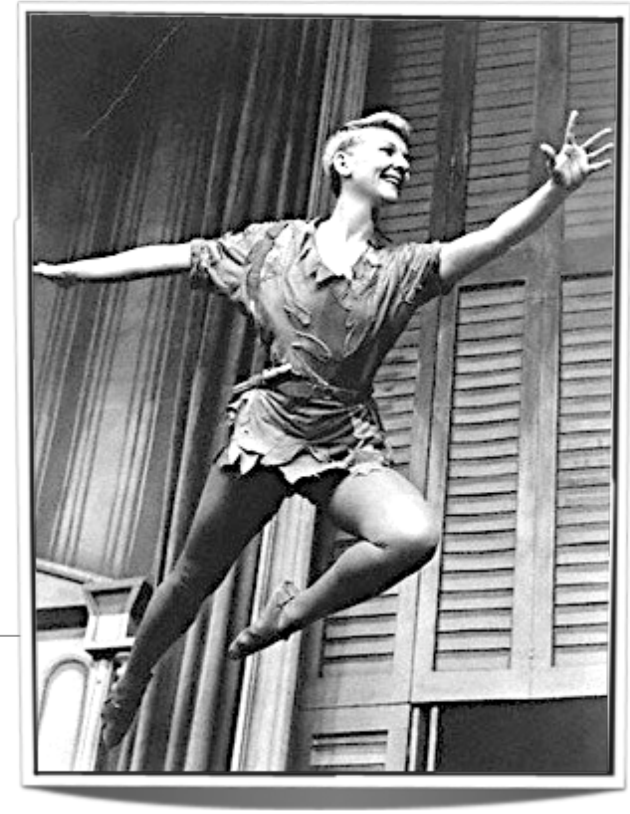
if you watched this lady

on your black and white TV

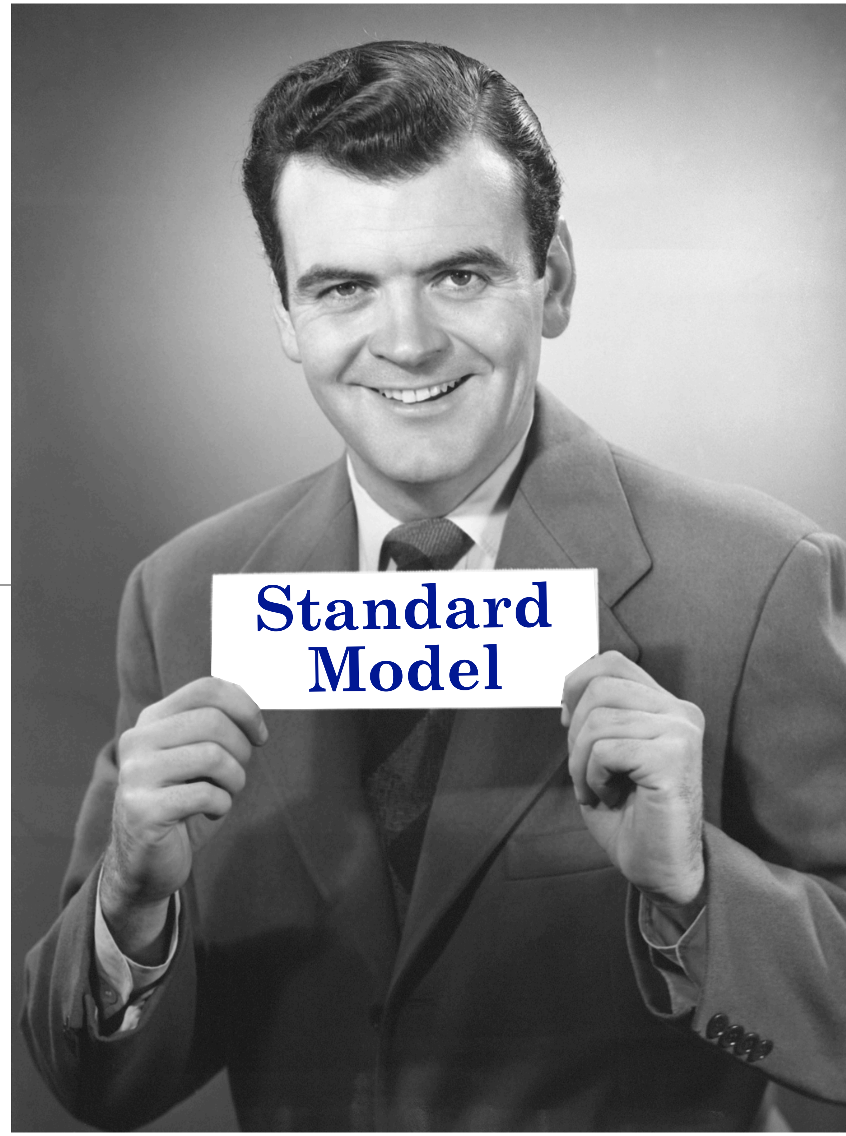
then you

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"

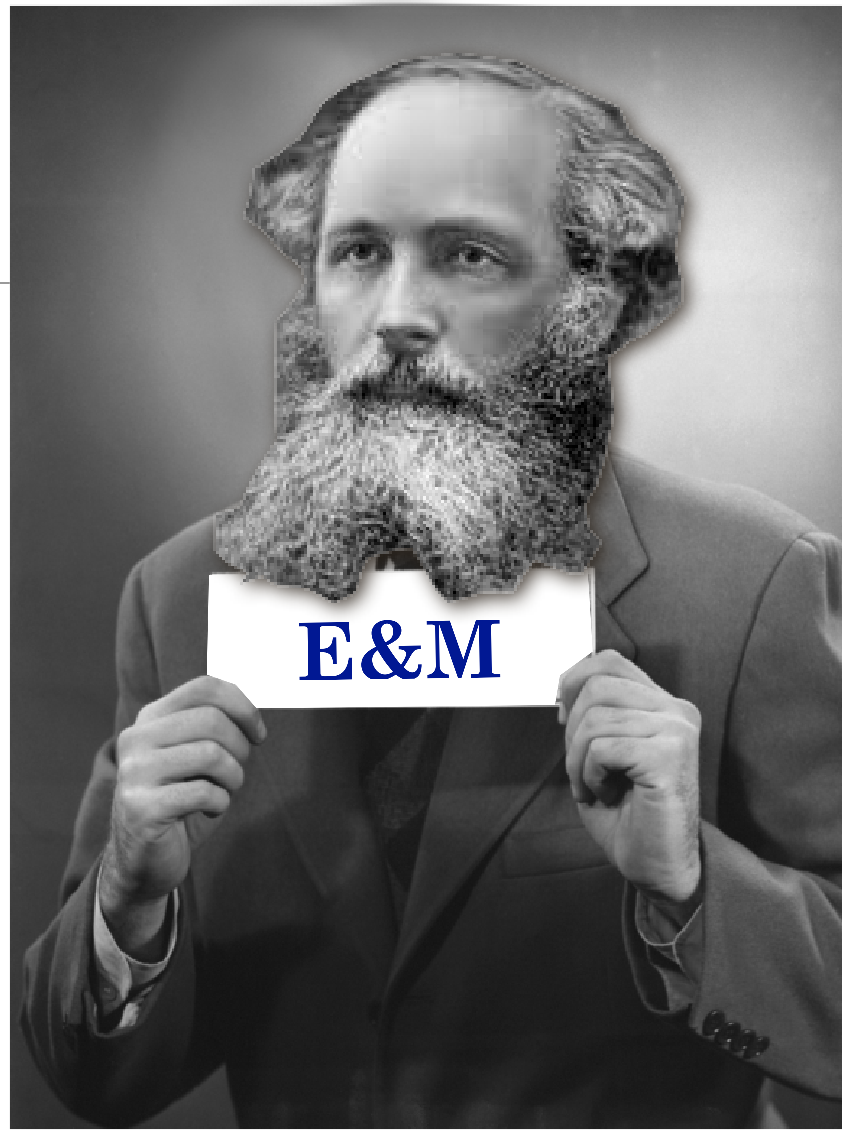
The SM is remarkably precise!

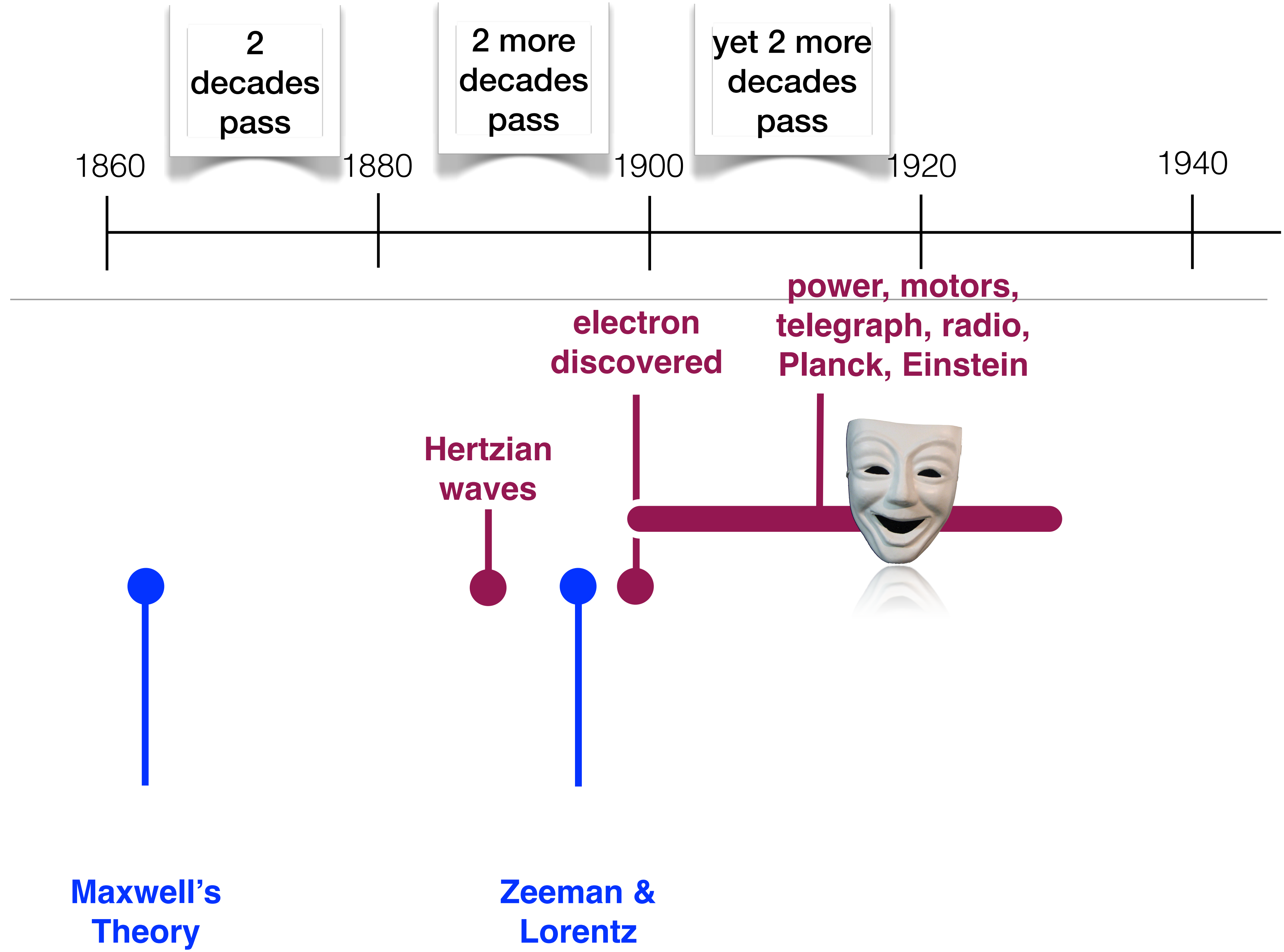
translation of "Model"

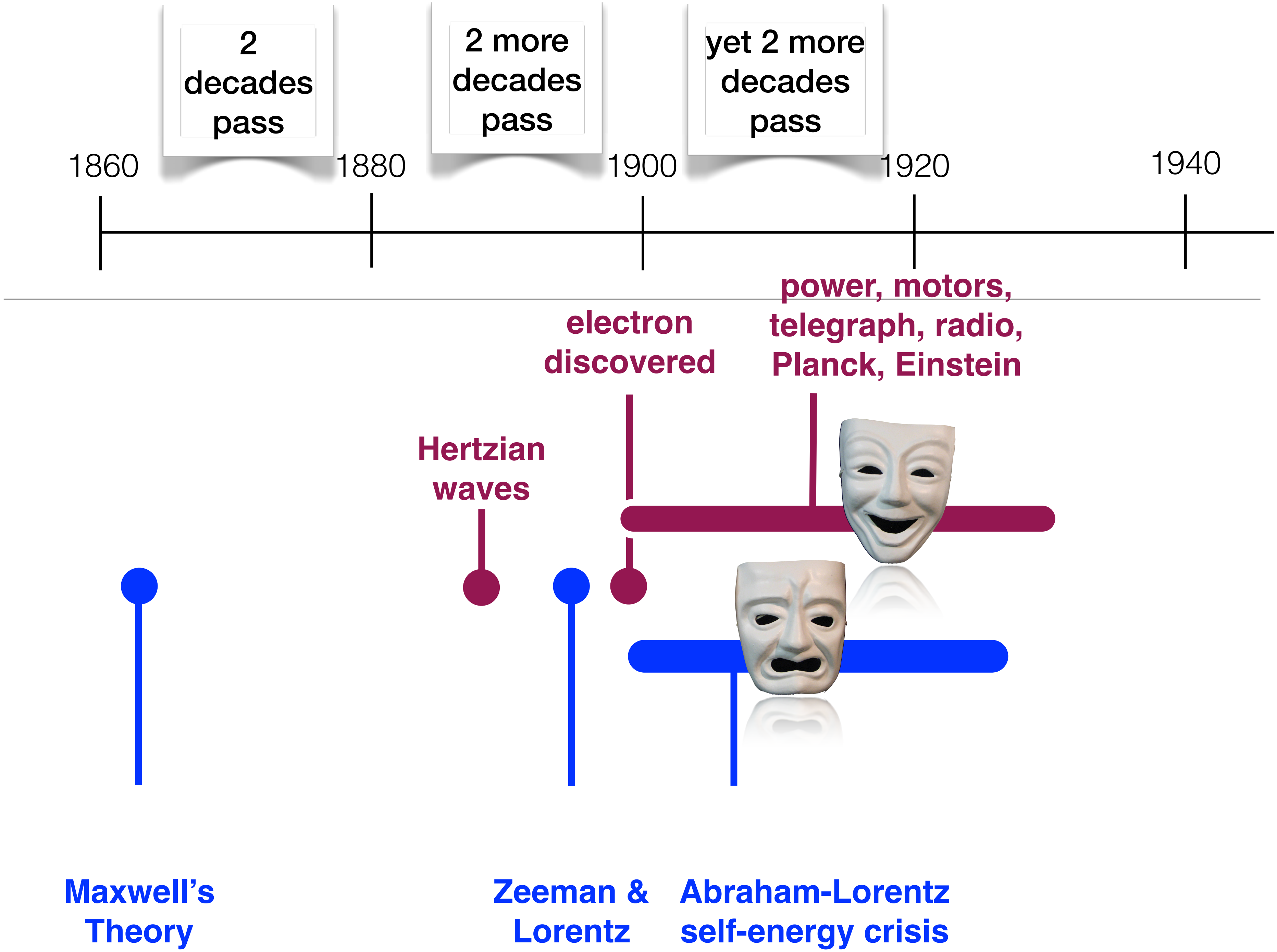
The SM is remarkably precise!

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
Maxwell's Theory
Zeeman & Lorentz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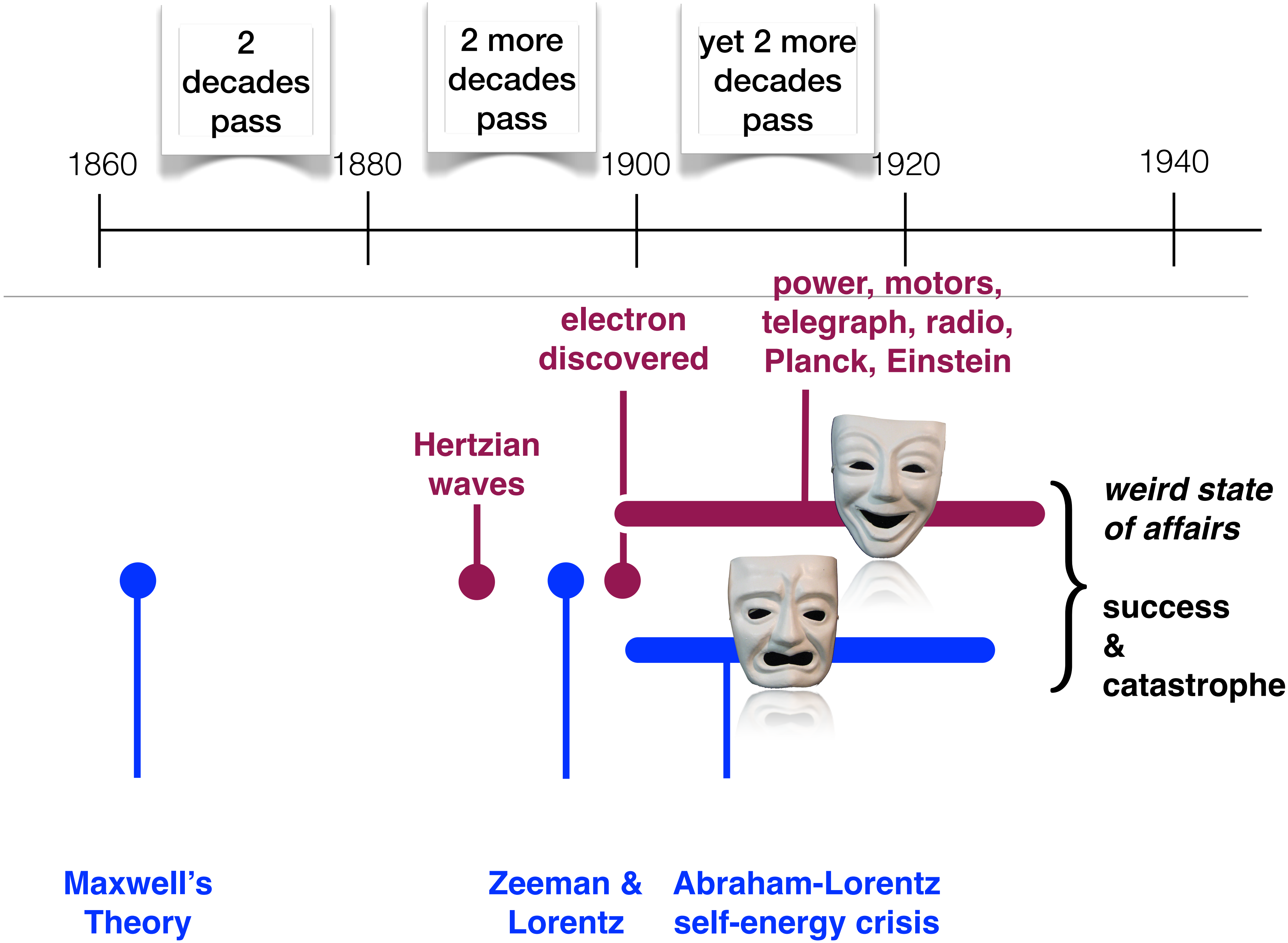
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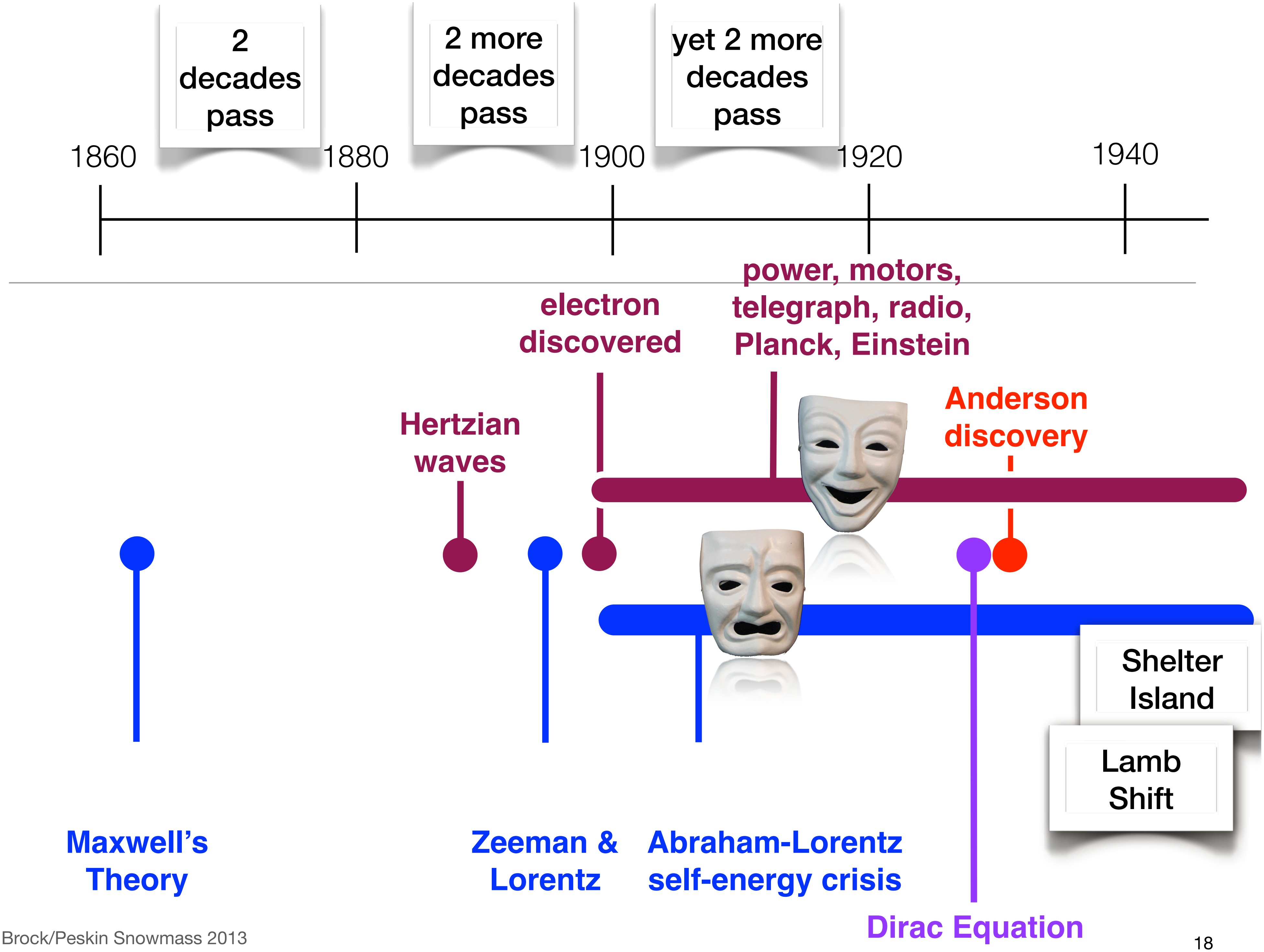

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Shelter Island
Lamb Shift
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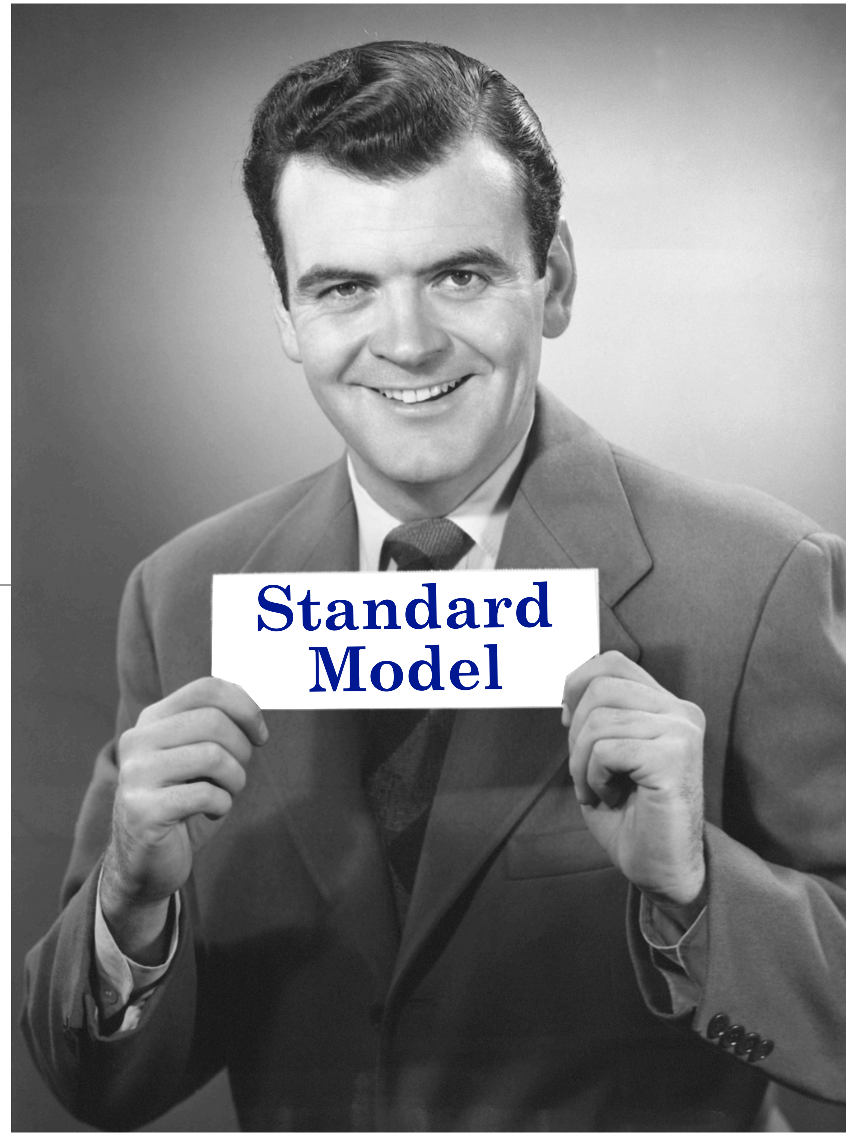
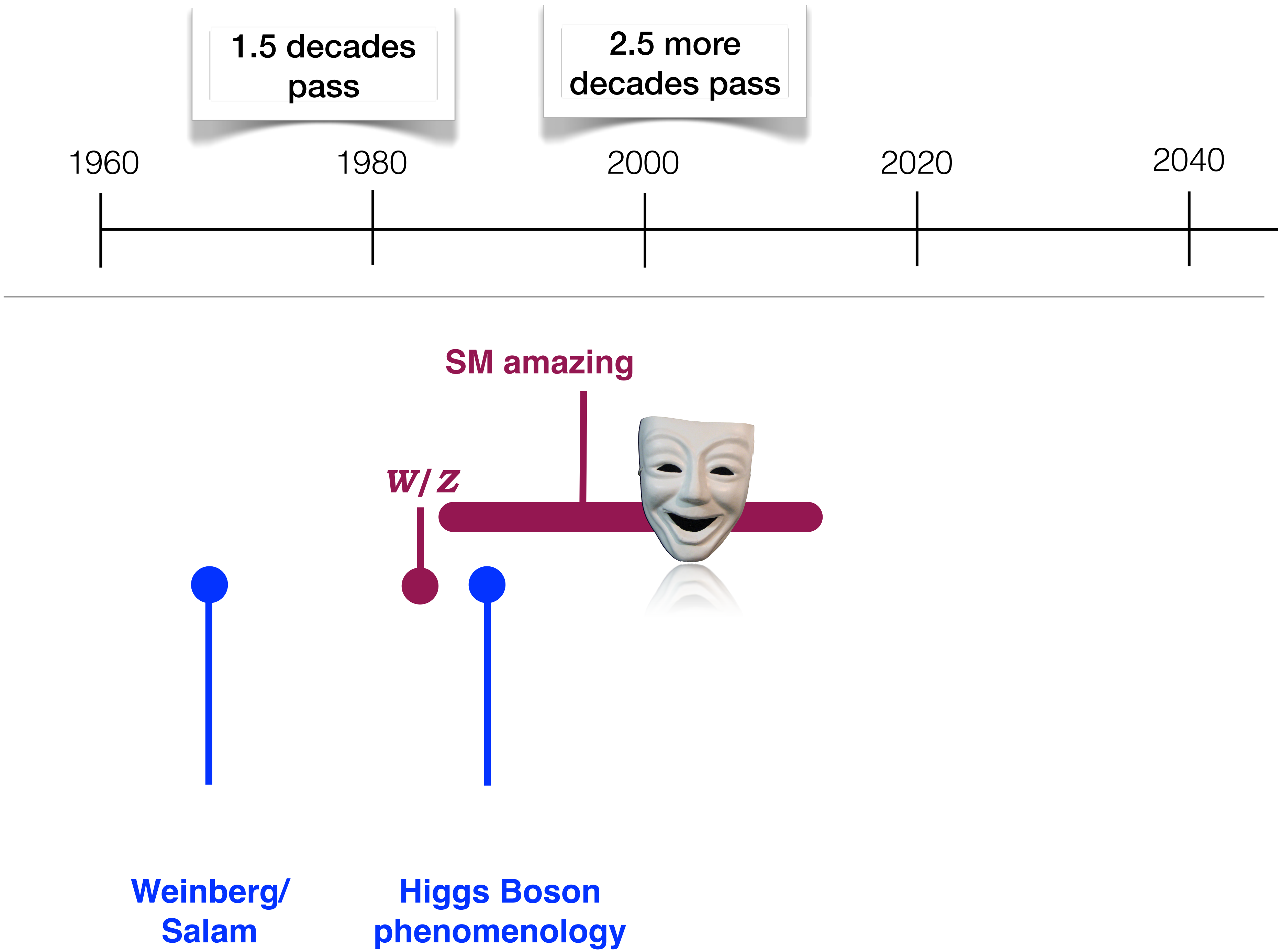
Zeeman & Lorentz
Abraham-Lorentz self-energy crisis
Dirac Equation


Standard
Model


1.5 decades pass
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1960
1980
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2020
2040
SM amazing
W/ Z
Weinberg/ Salam
Higgs Boson phenomenology

1.5 decades pass

2.5 more decades pass

1960 1980 2000 2020 2040

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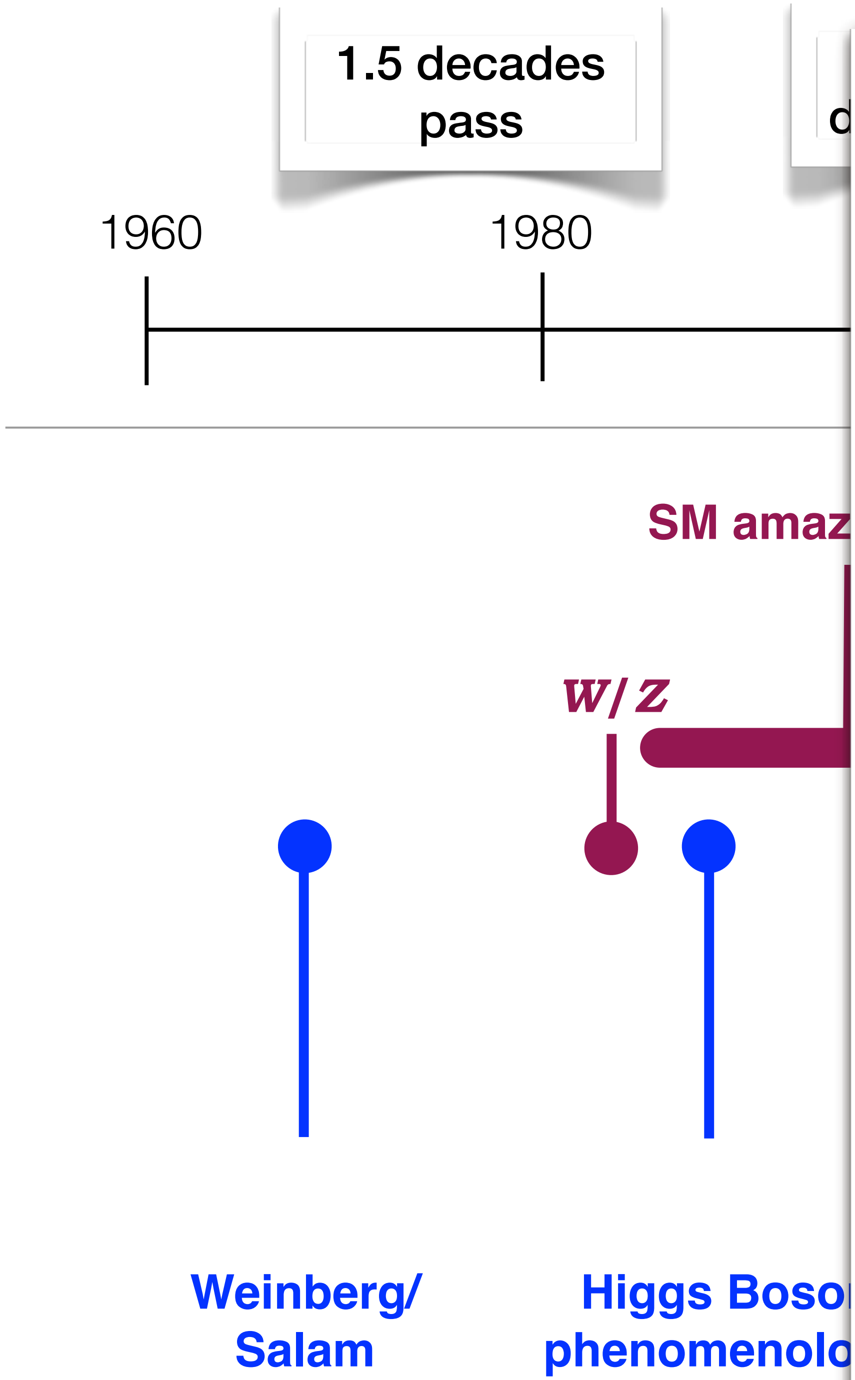
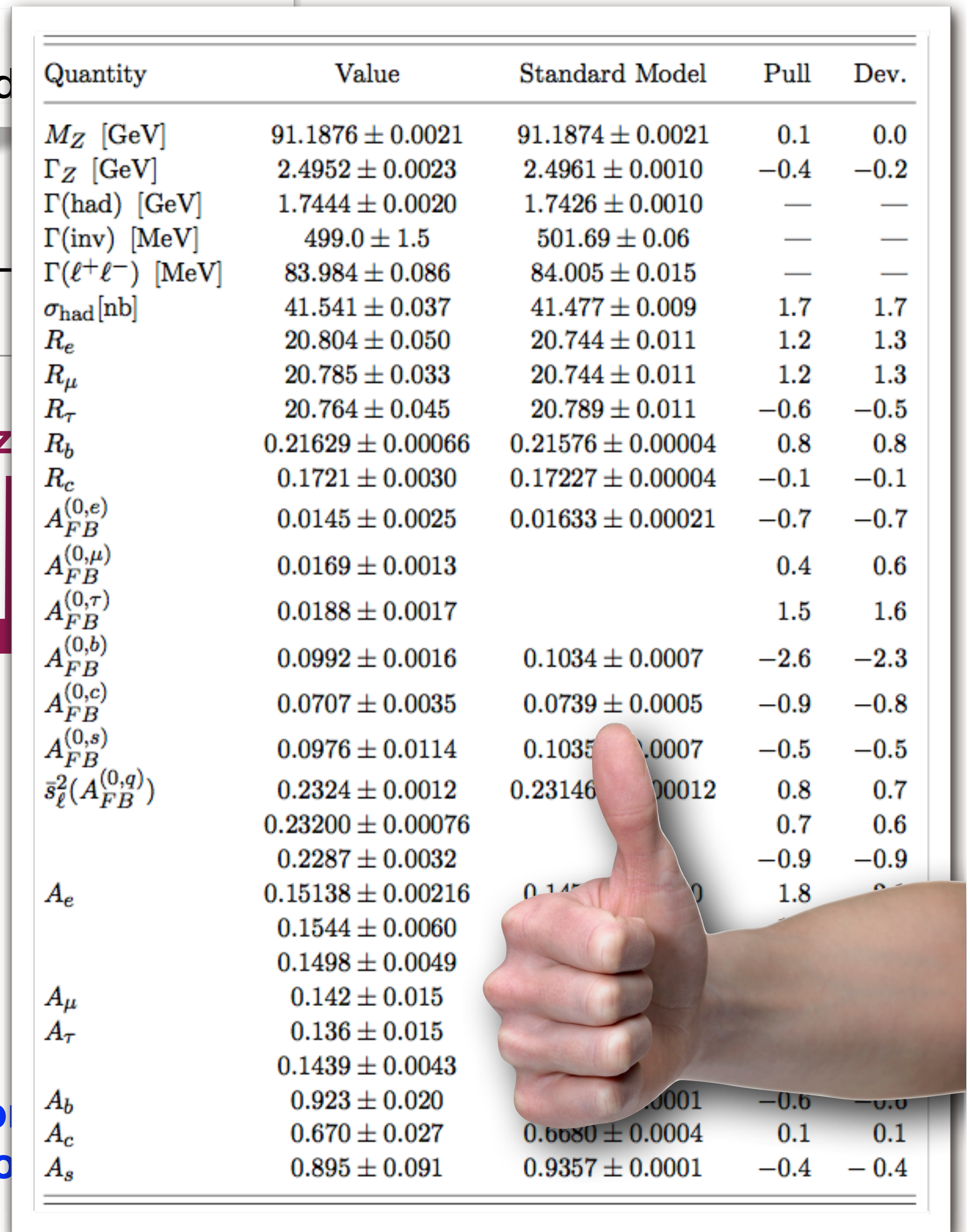
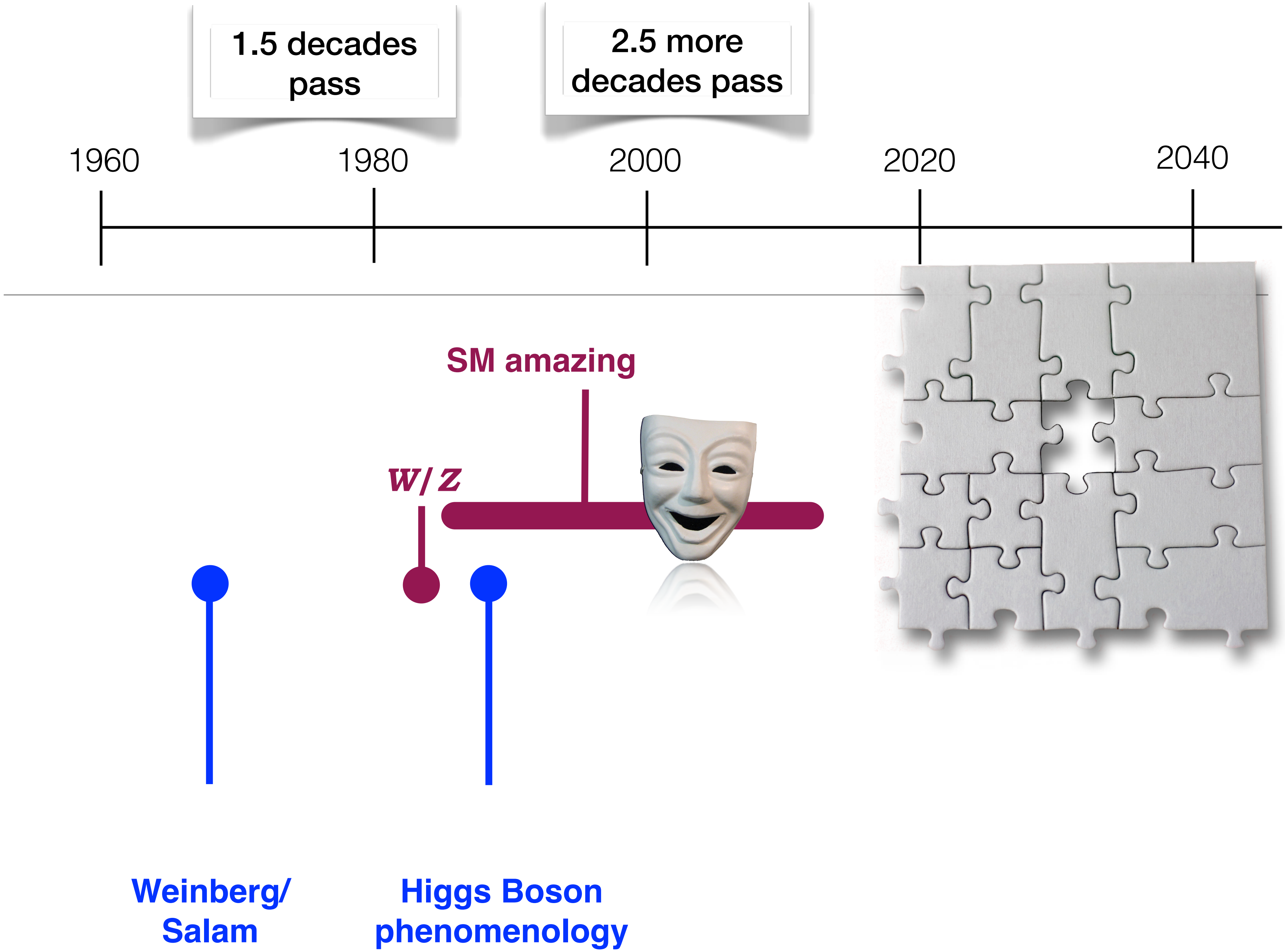




Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	−0.4	−0.2
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had} [nb]	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_μ	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_τ	20.764 ± 0.045	20.789 ± 0.011	−0.6	−0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.0030	0.17227 ± 0.00004	−0.1	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.6	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035[illegible].0007	−0.5	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146[illegible]00012	0.8	0.7
	0.23200 ± 0.00076		0.7	0.6
	0.2287 ± 0.0032		−0.9	−0.9
A_e	0.15138 ± 0.00216	[illegible]	1.8	[illegible]
	0.1544 ± 0.0060	[illegible]	[illegible]	[illegible]
	0.1498 ± 0.0049	[illegible]	[illegible]	[illegible]
A_μ	0.142 ± 0.015	[illegible]	[illegible]	[illegible]
A_τ	0.136 ± 0.015	[illegible]	[illegible]	[illegible]
	0.1439 ± 0.0043	[illegible]	[illegible]	[illegible]
A_b	0.923 ± 0.020	[illegible]0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	−0.4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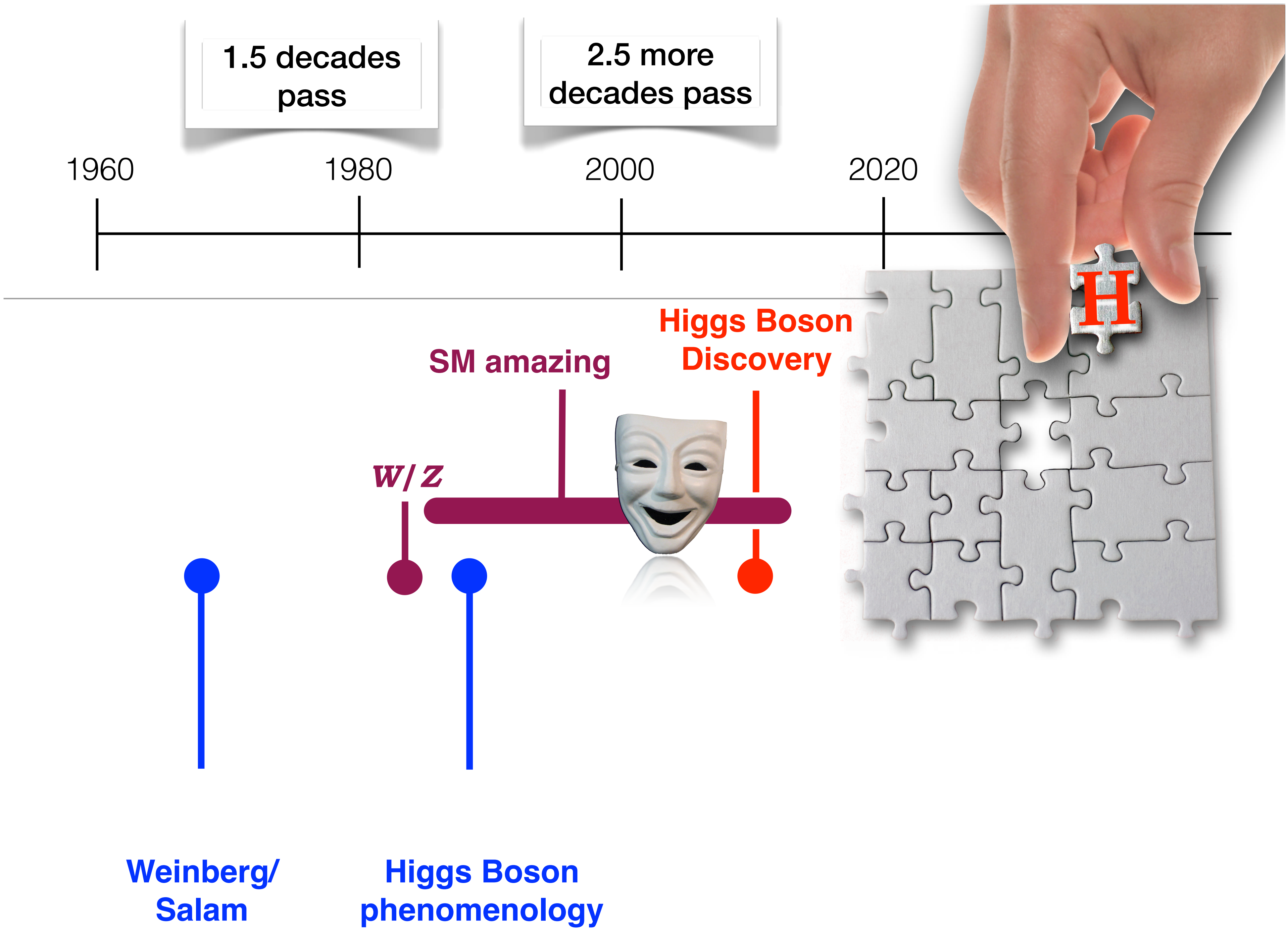
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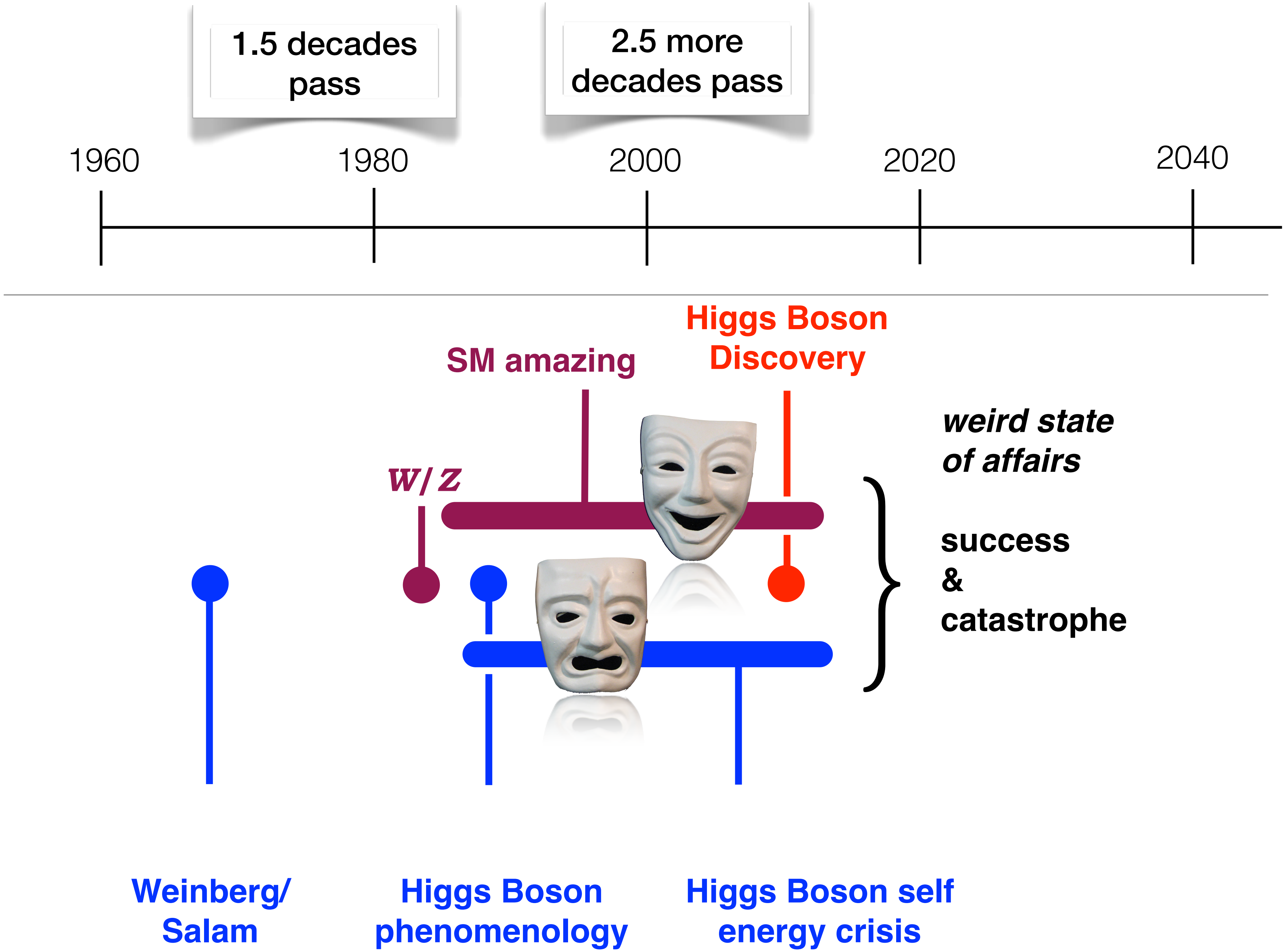
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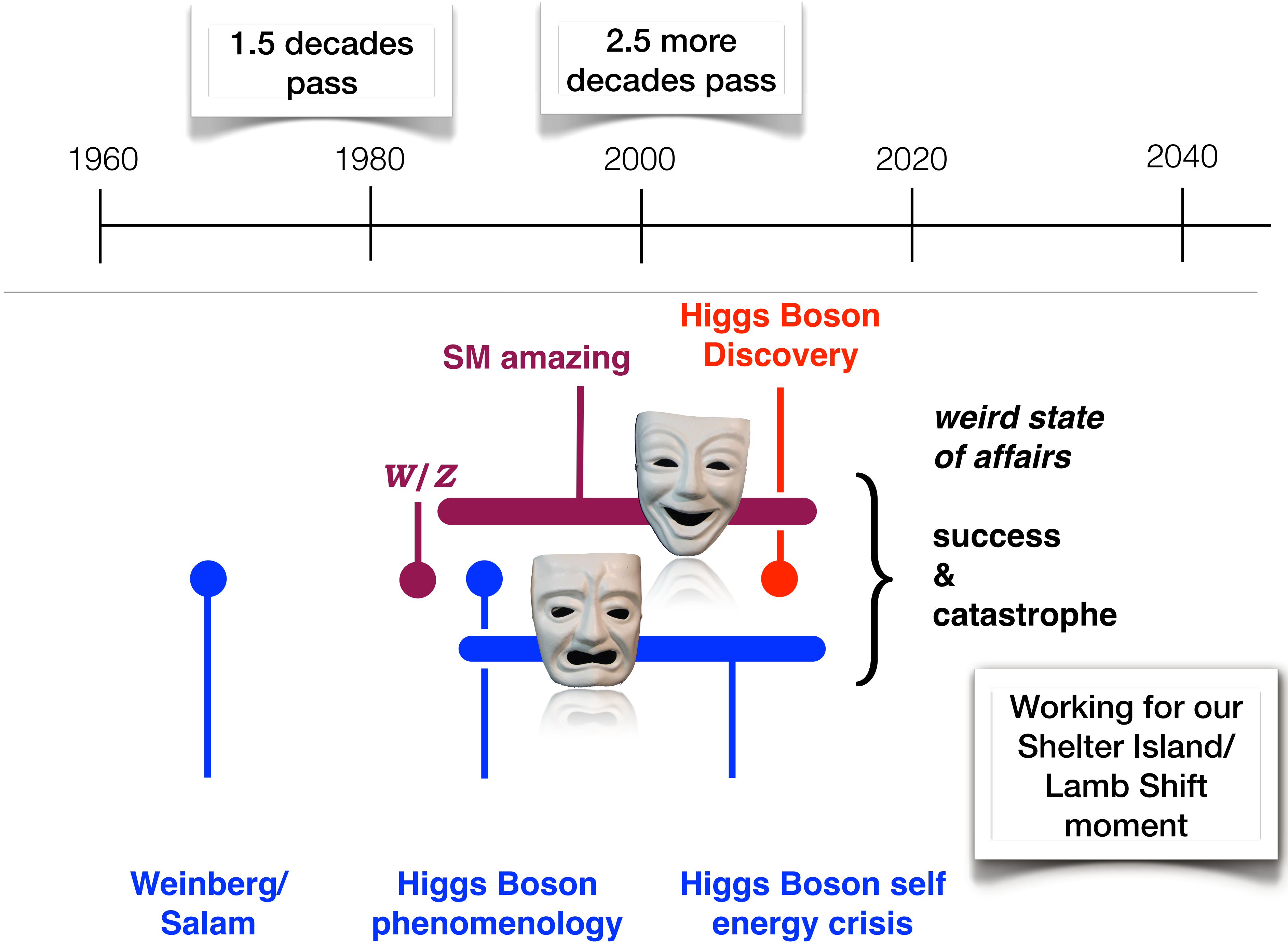
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Working for our Shelter Island/ Lamb Shift moment
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particle physics


HIGGS
ticl
e p
phys
HIGGS

strange and exciting

state of affairs

strange and exciting

state of affairs

3 sets of hints provided by:

strange and exciting

state of affairs

3 sets of hints provided by:

elementary scalar particle

experiment

history

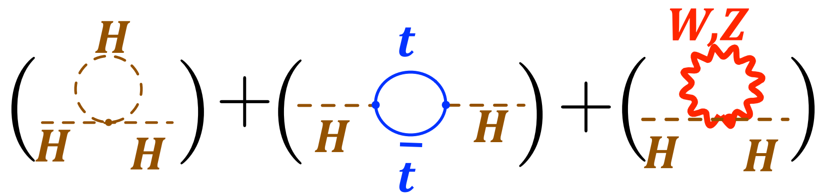
Light scalar?
mass confusion

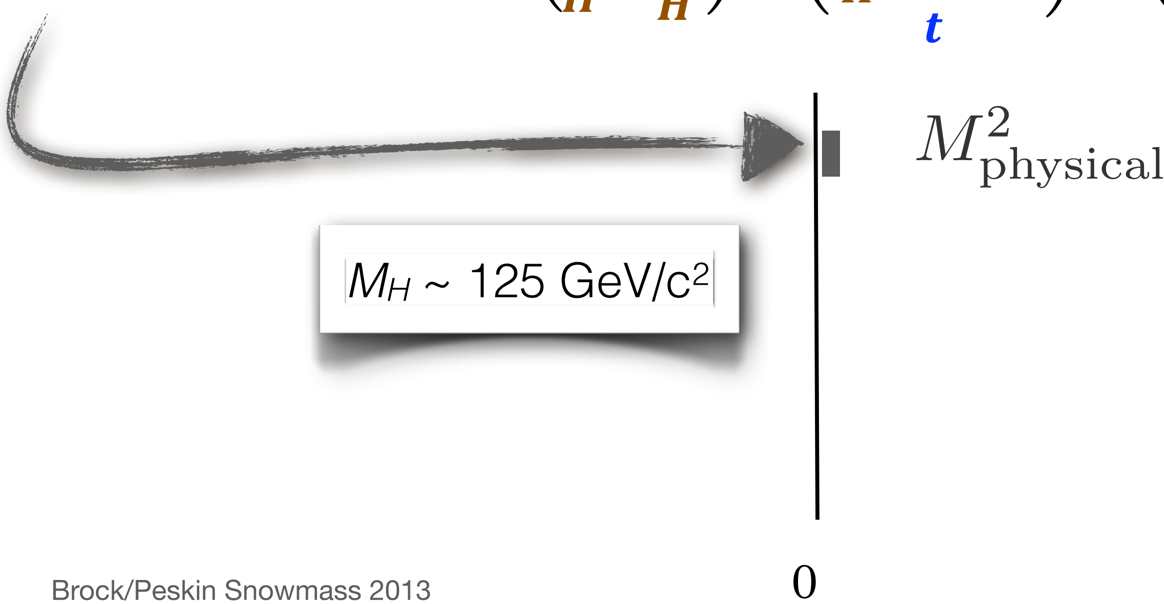
$$M_H^2 = M_{\rm tree}^2 +$$

Light scalar?
mass confusion

additive, quadratic cut-offs...

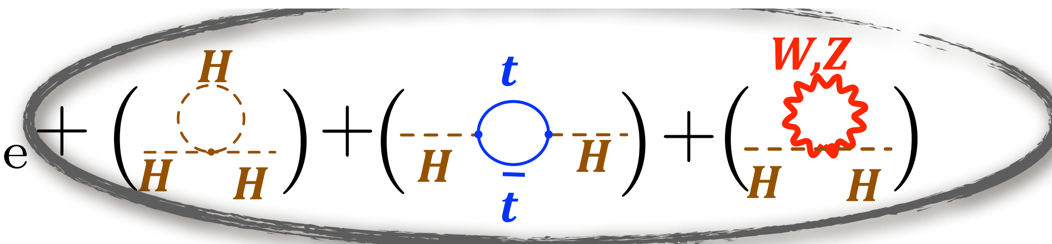
$$M_H^2 = M_{\text{tree}}^2 + \left(\;\cdot\;\right) + \left(\;\cdot\;\right) + \left(\;\cdot\;\right)$$

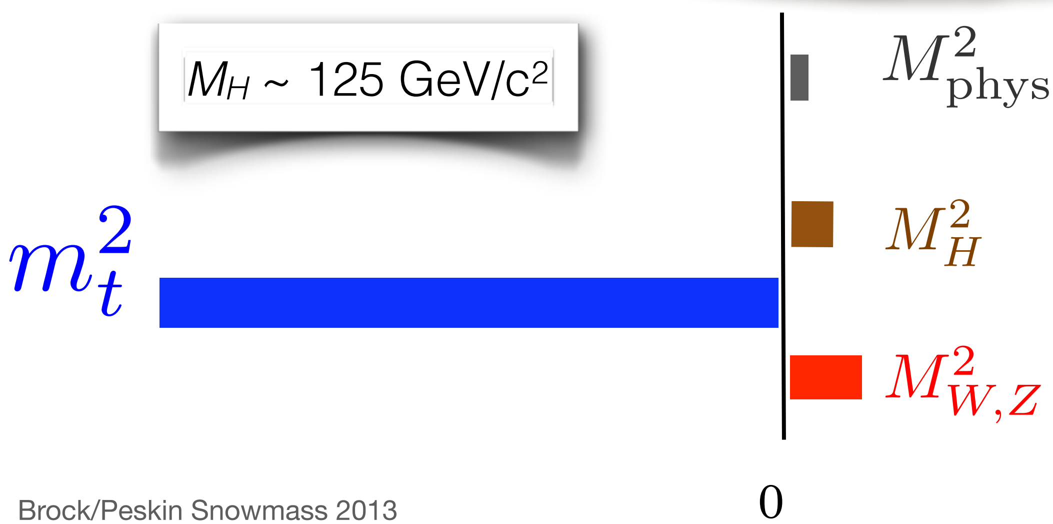




Light scalar?
mass confusion

additive, quadratic cut-offs...

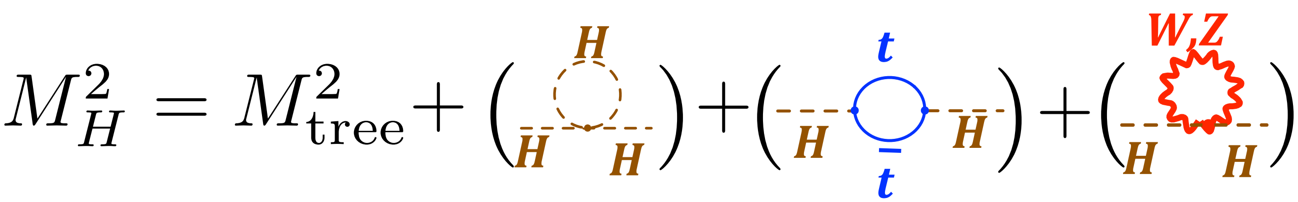
$M_H^2 = M_{\text{tree}}^2 +$ 

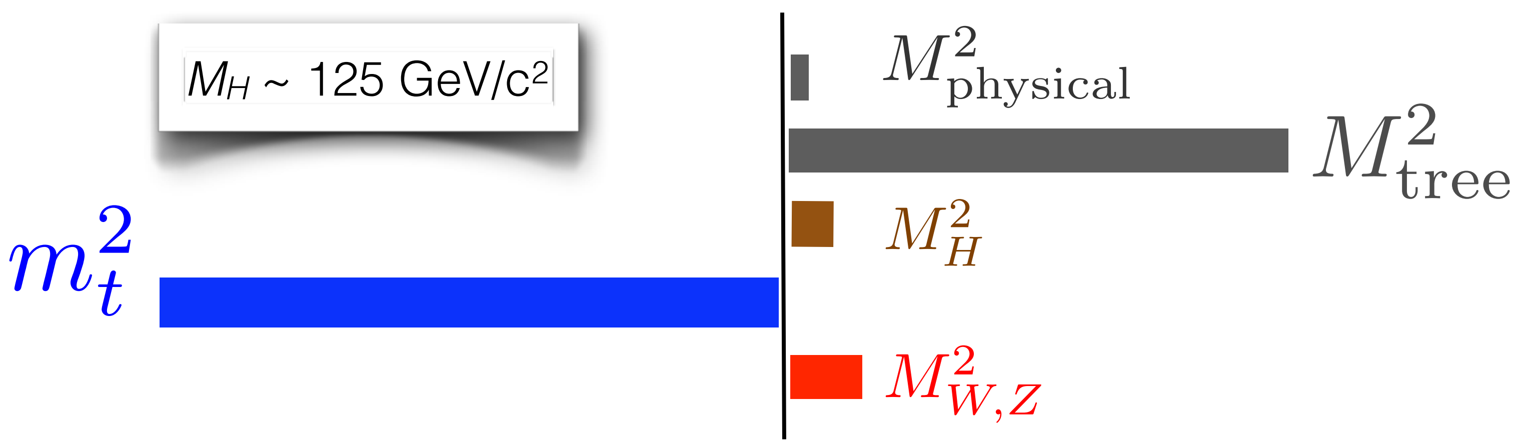


$$\delta M^2 \propto \frac{c}{16\pi^2} g^2 \Lambda^2$$

Light scalar? mass confusion

additive, quadratic cut-offs...





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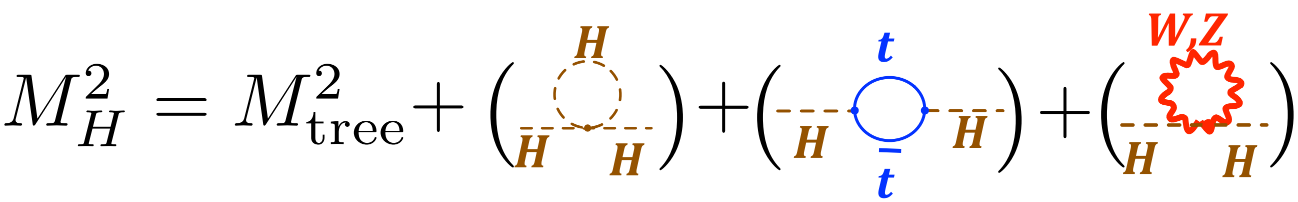

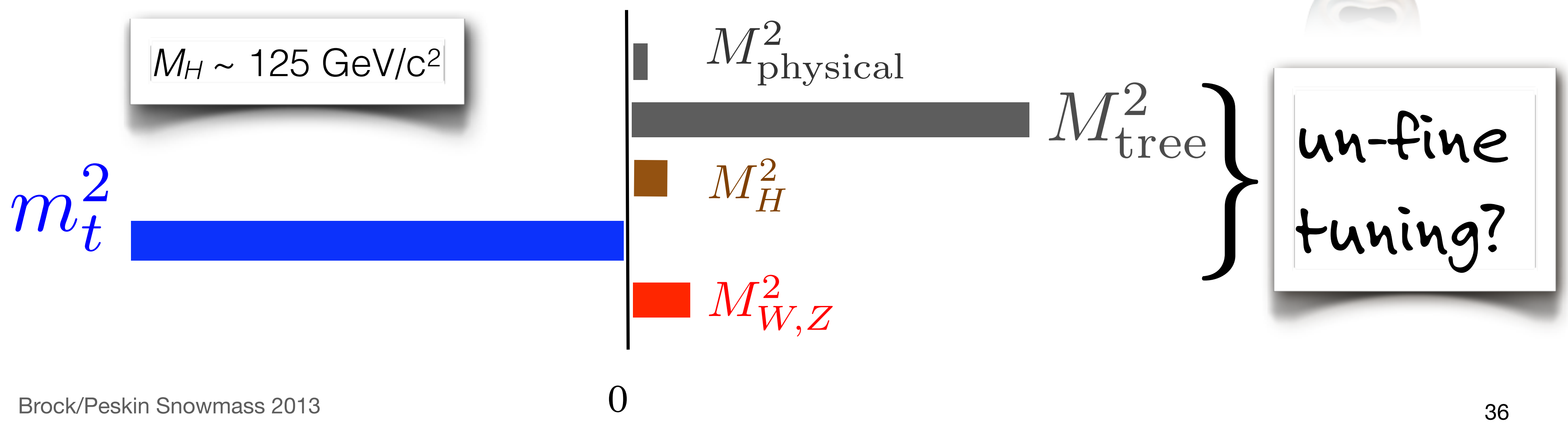

“coincidence”

is not a scientific term of art

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is not a scientific term of art

If the next mass scale up from M_H is Λ_{Planck}

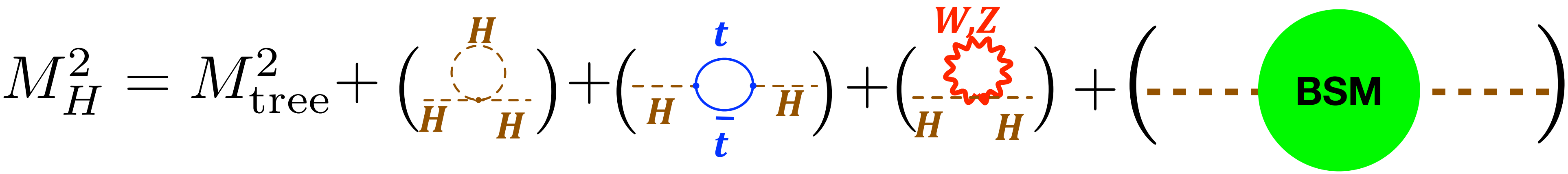
The corrections and tree must cancel:

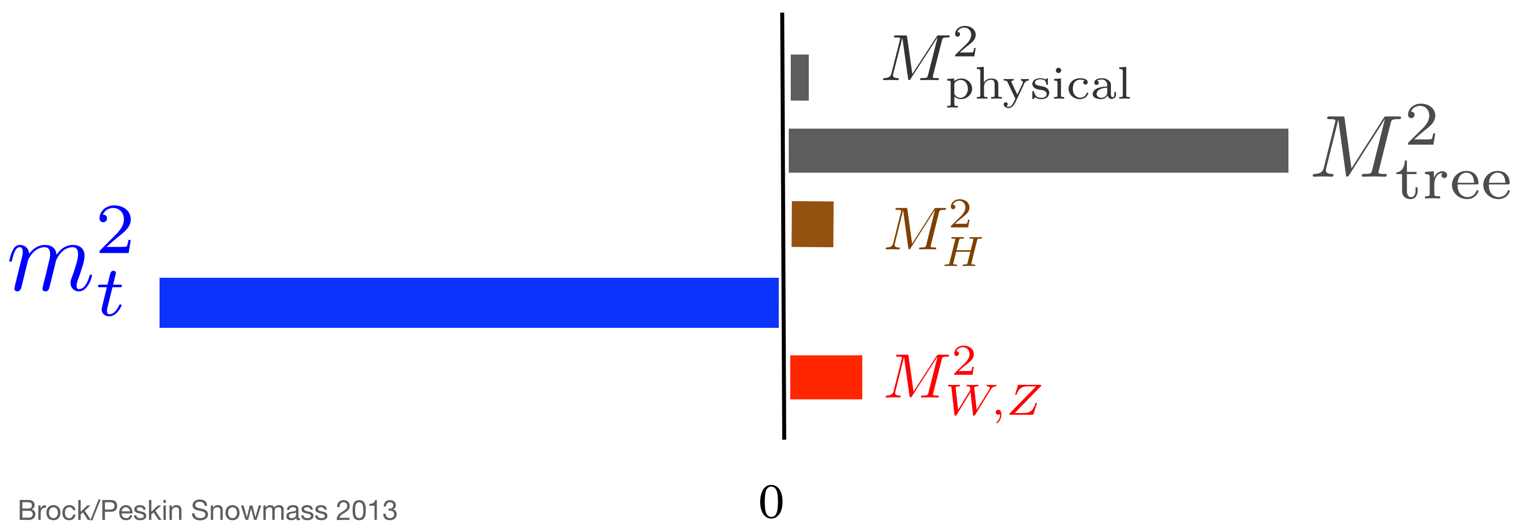
$$M_H^2 = \text{nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n60,000}$$
$$- \text{nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n44,375}$$

a huge hint

of something "BSM"?

plenty of ideas





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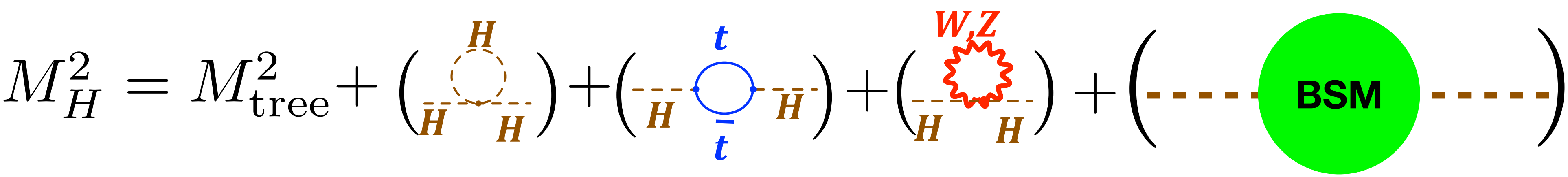

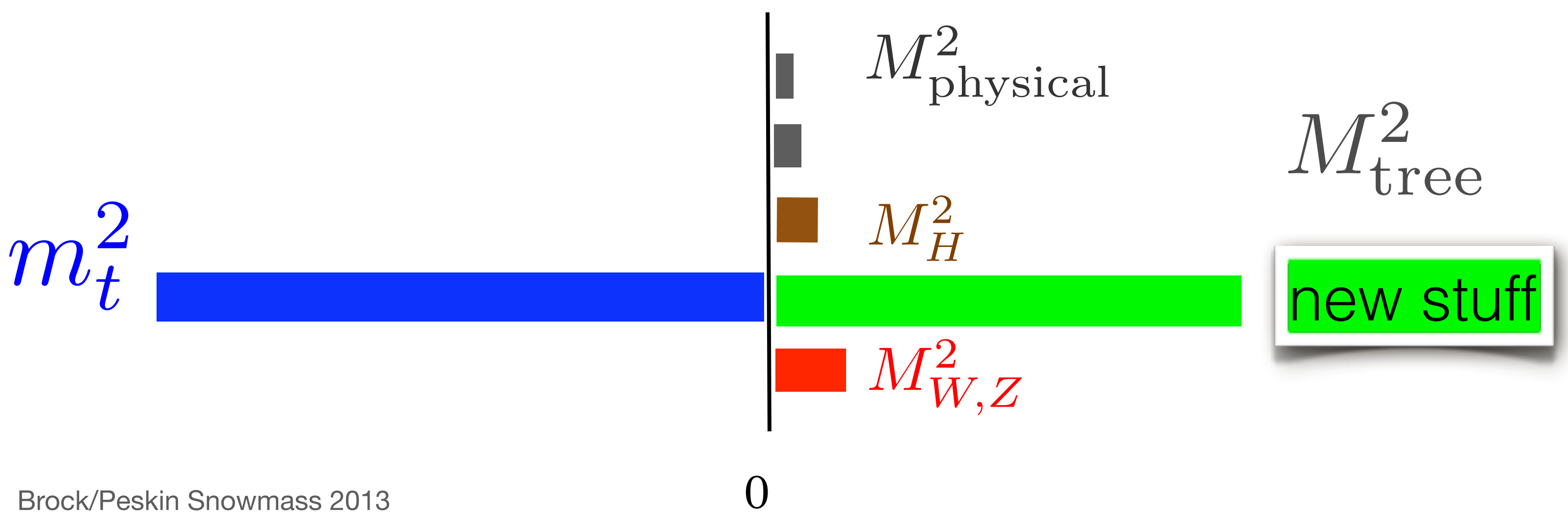

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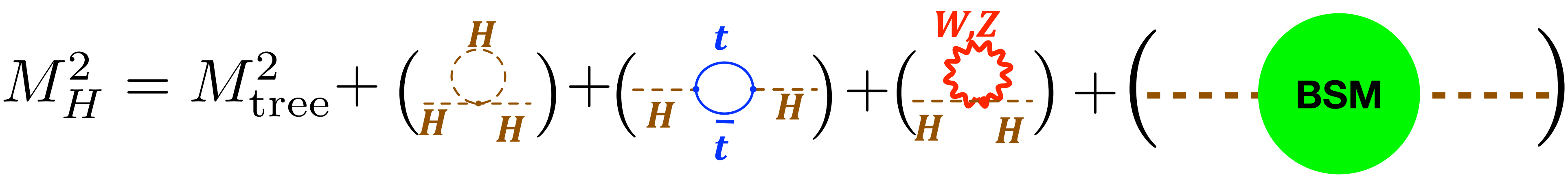

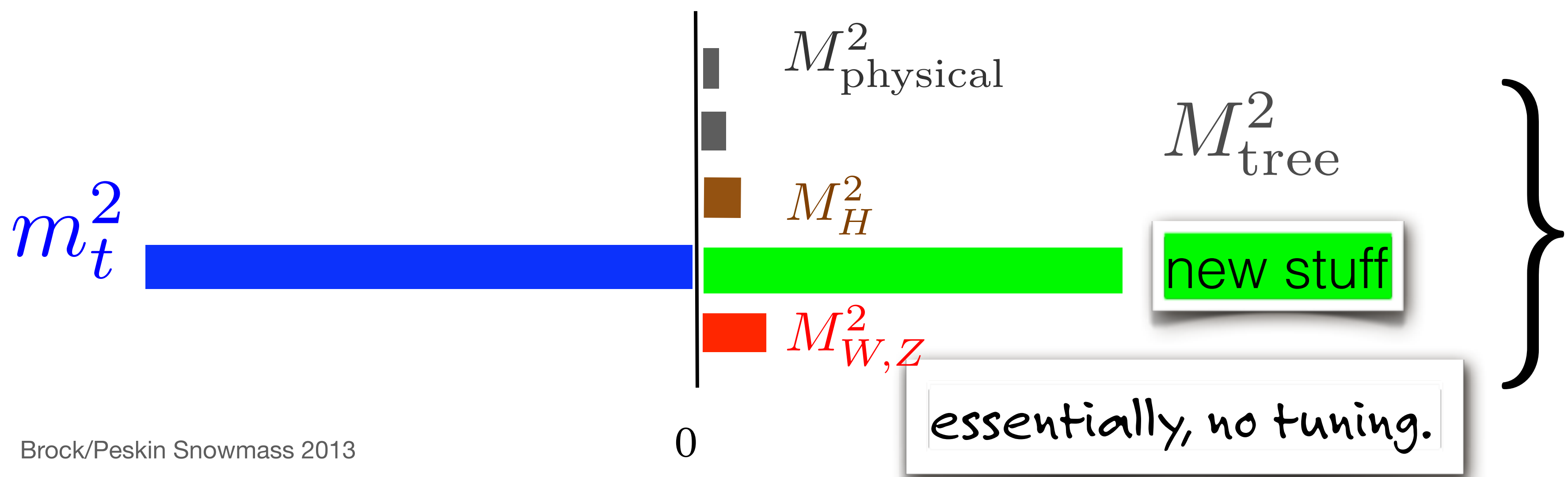

goes by many names:

The Hierarchy Problem, The Naturalness Problem

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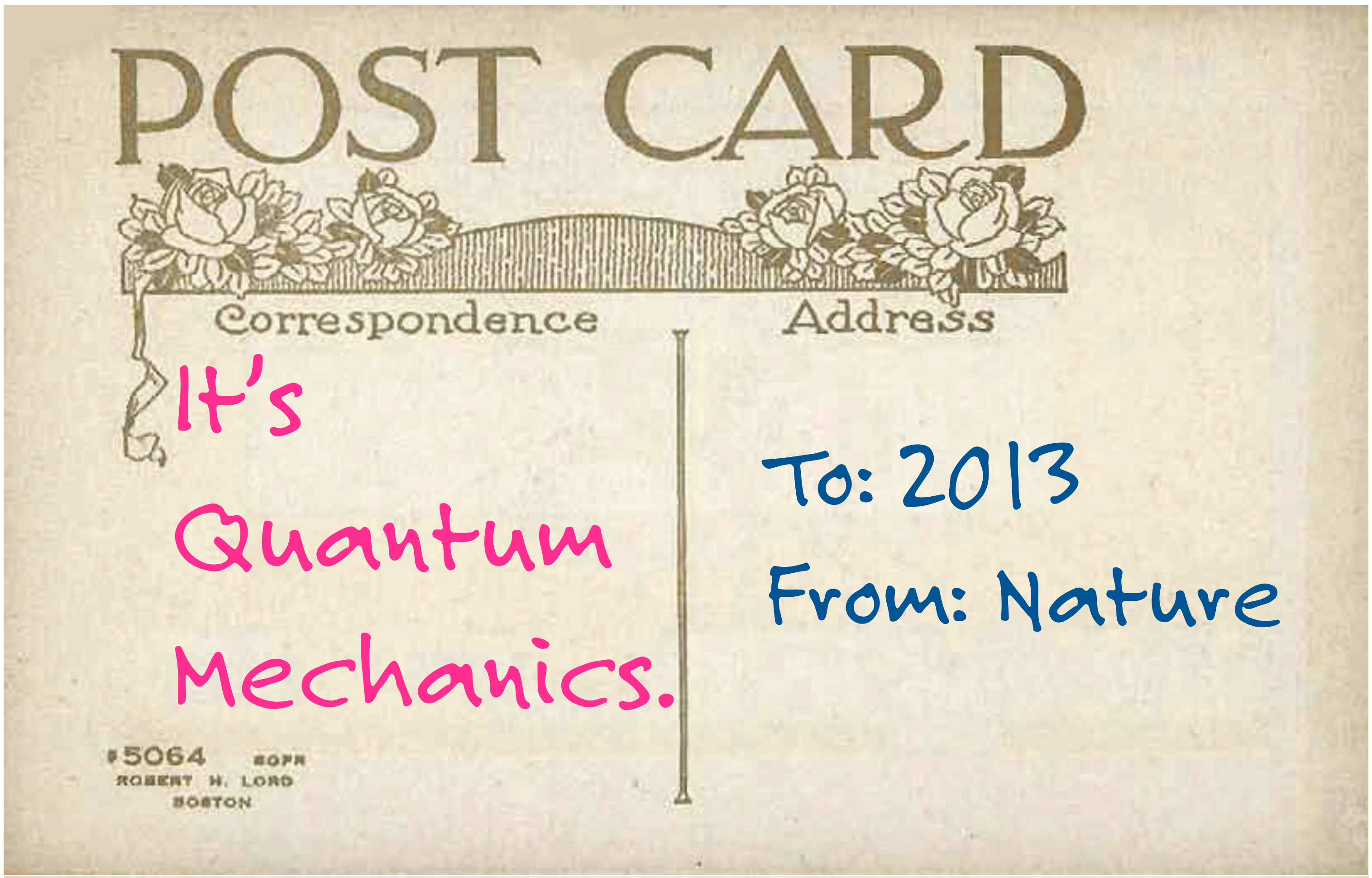

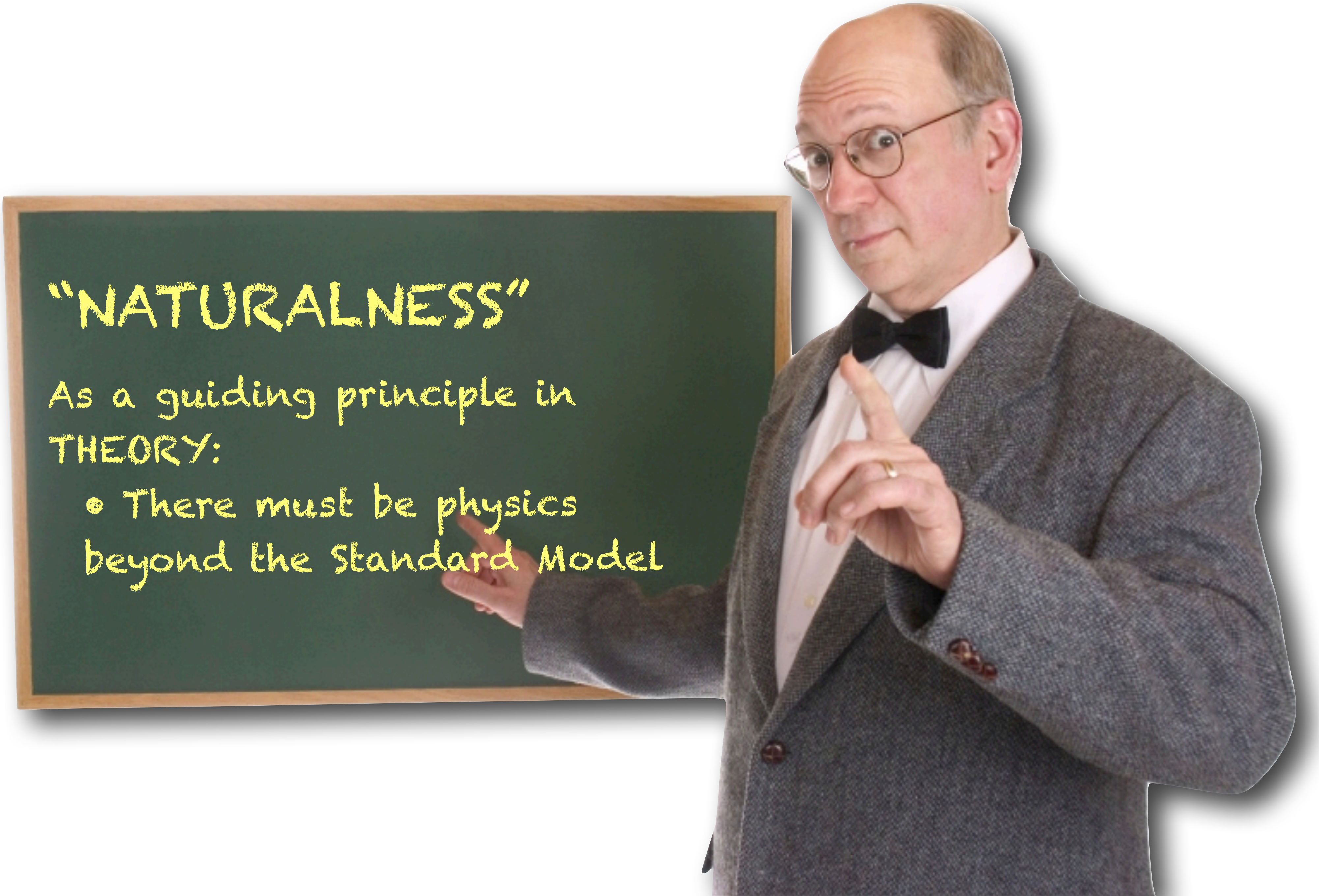
"NATURALNESS"
As a guiding principle in THEORY:
• There must be physics beyond the Standard Model

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

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Supersymmetric theories - a Boson-like top

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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

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The Higgs Boson mass is small.

There are serious experimental anomalies = BSM

The Higgs Boson mass is small.

ν's flavor, mass, symmetry properties outside of SM.

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Dark Matter needs a quantum.

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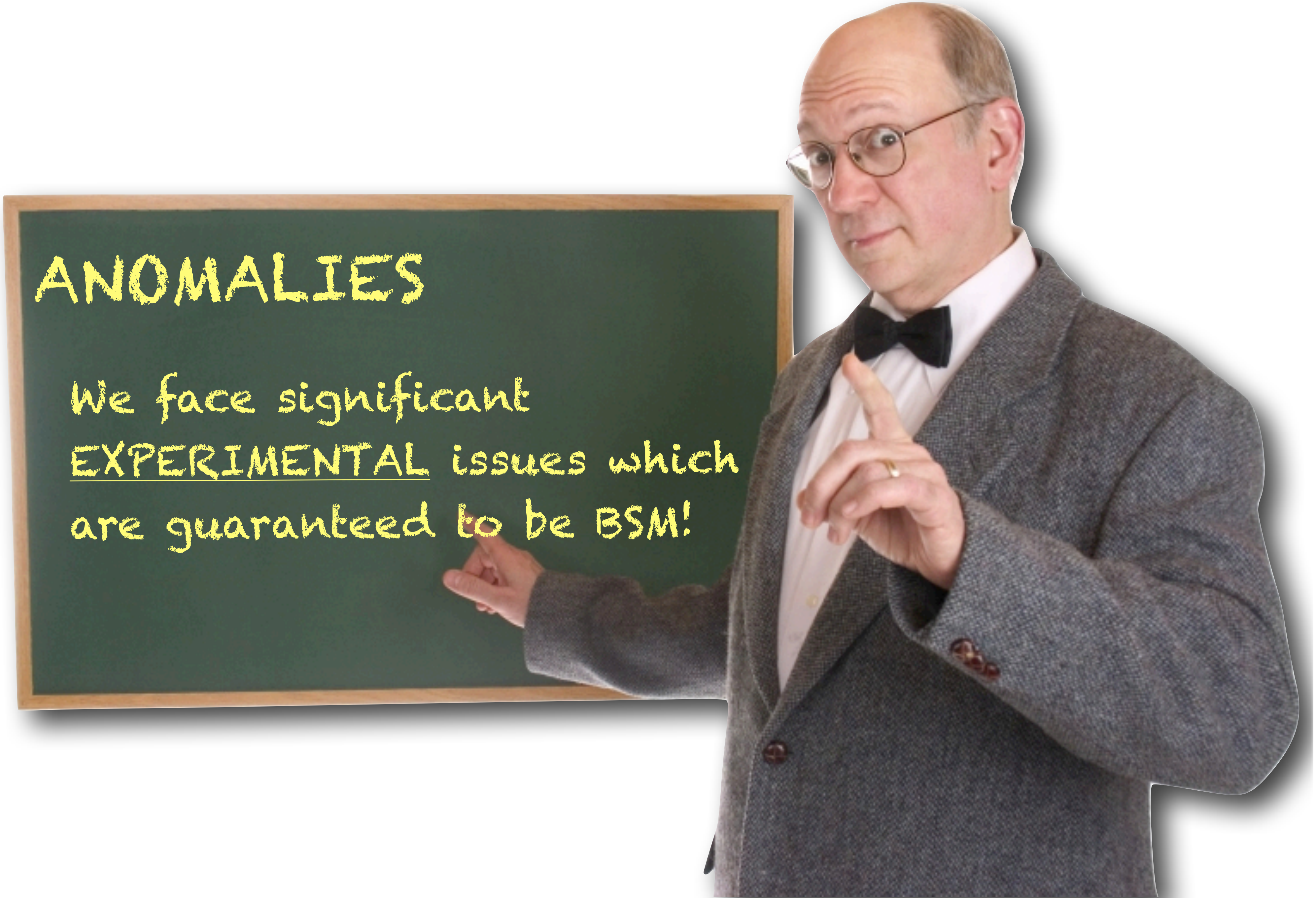
Primordial antimatter needs an explanation.

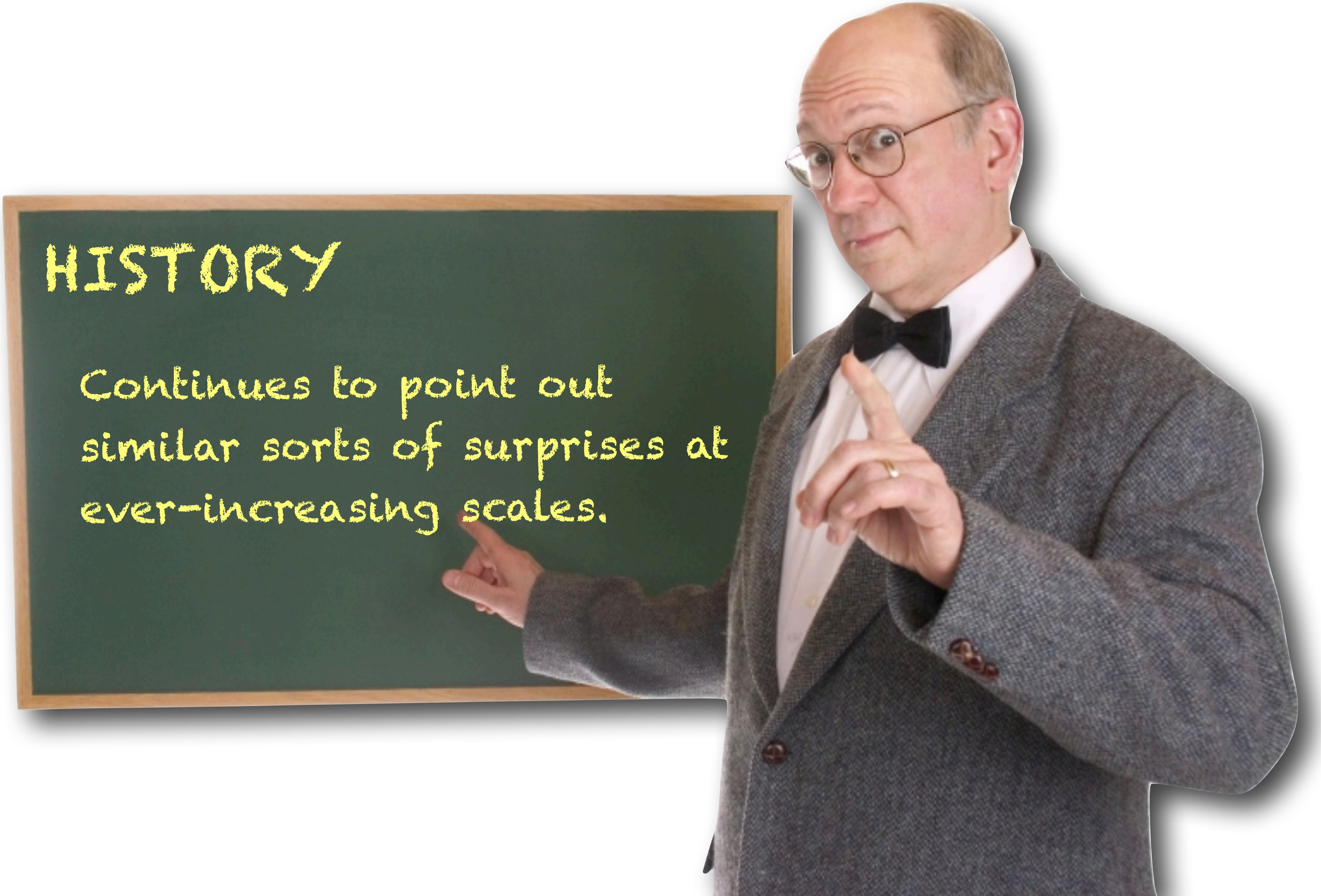
There are serious experimental anomalies = BSM

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.
$(g-2)_\mu$ needs confirmation or disconfirmation


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

http://turningplace.files.wordpress.com/2013/01/aaaa.jpg


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.

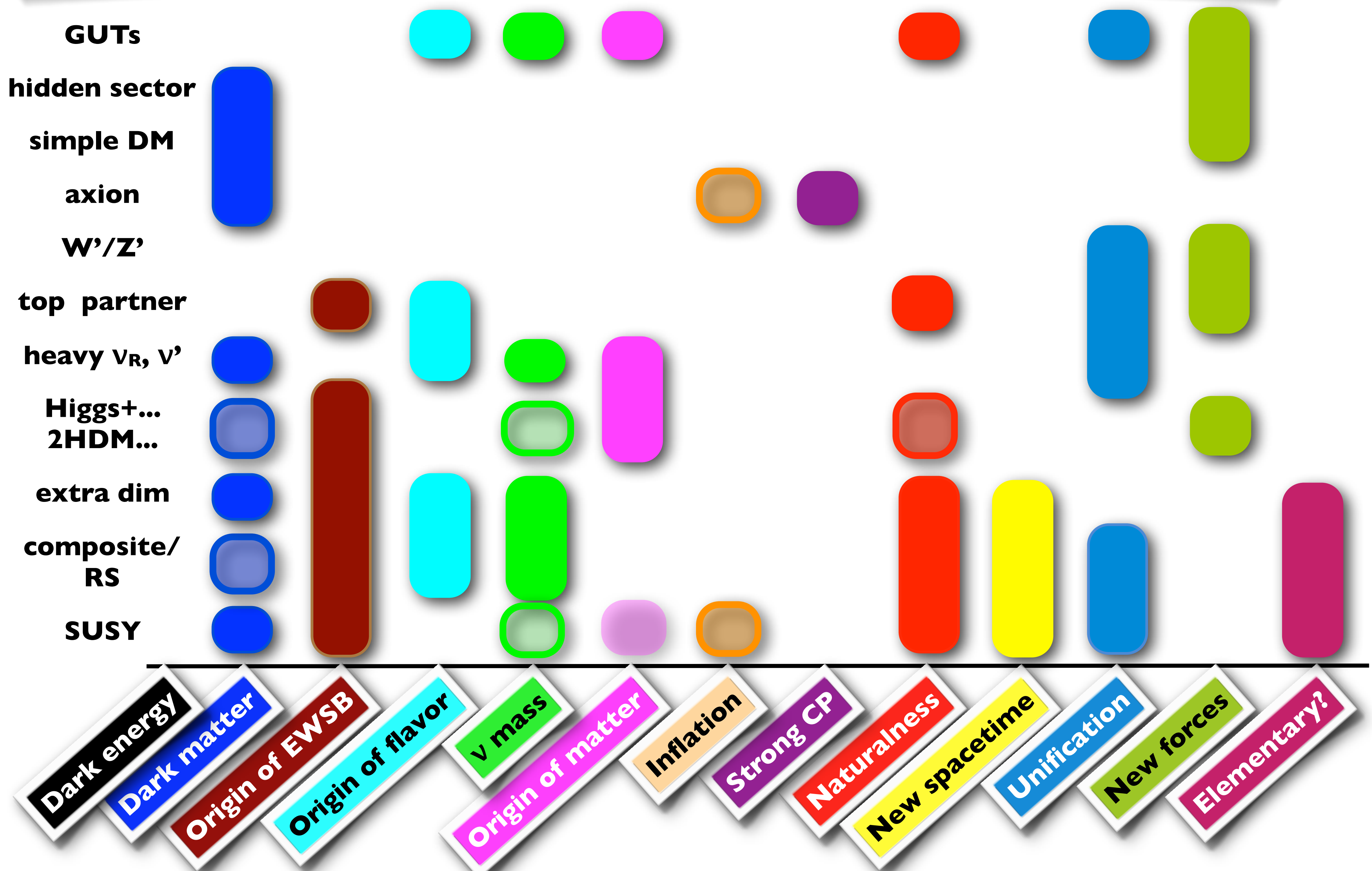
The events of 2012

The Higgs Boson discovery
The determination of θ_{13}

Lead us to think anew about the

Big Questions of Particle Physics

New Particles Group: Answers vs Questions



So.
This is the Energy Frontier

Colliding beam experiments
at the highest constituent energies

So.
This is the Energy Frontier

Colliding beam experiments
at the highest constituent energies

Distinct as an experimental technique which:

Directly probes these questions.

Directly produces new states.

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}

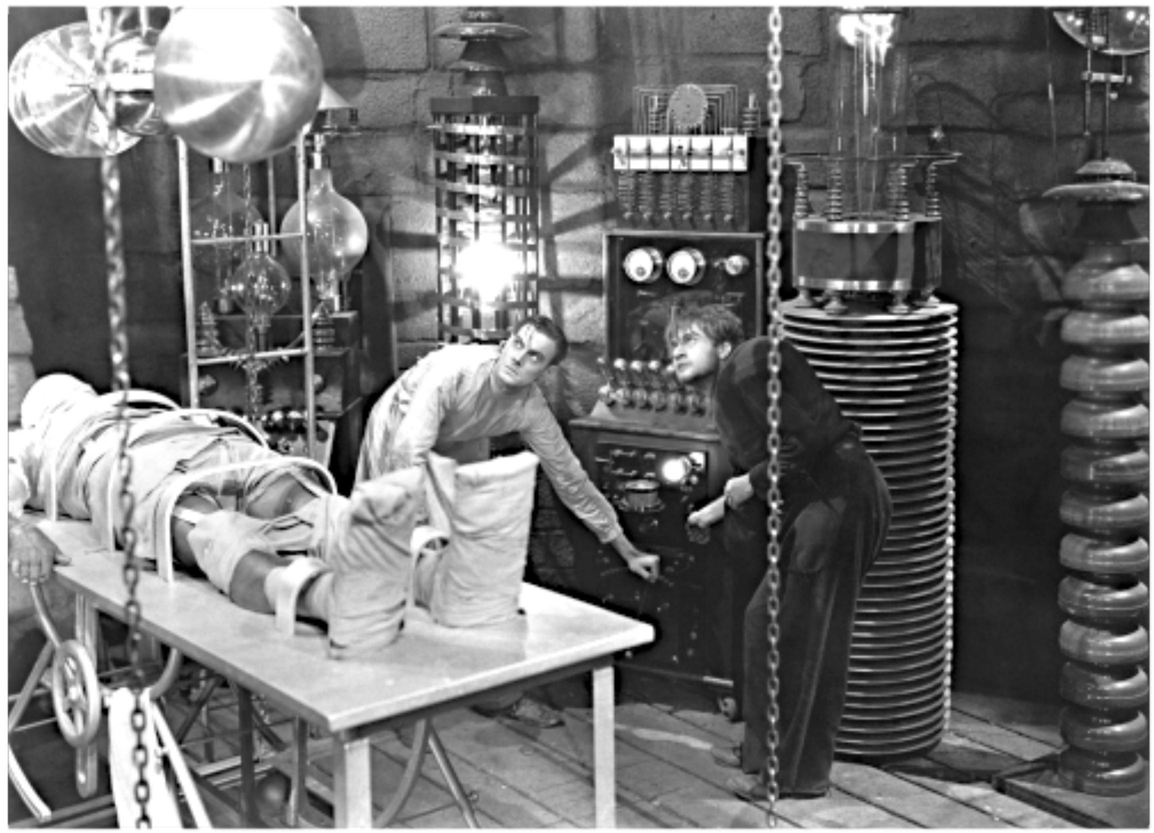
1 ep collider, ***(E_{cms};*** $\int \mathcal{L}dt$ ***)*** = e/p: (60/7000; 50) GeV / GeV, fb^{-1}

* 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

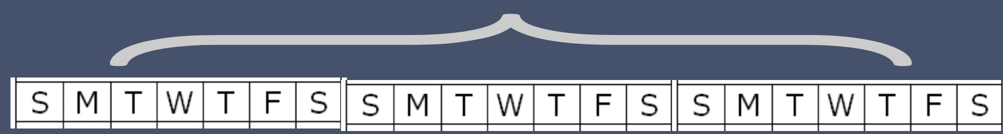
common set of tools.

Supplemental agency funding supported Snowmass-specific infrastructure

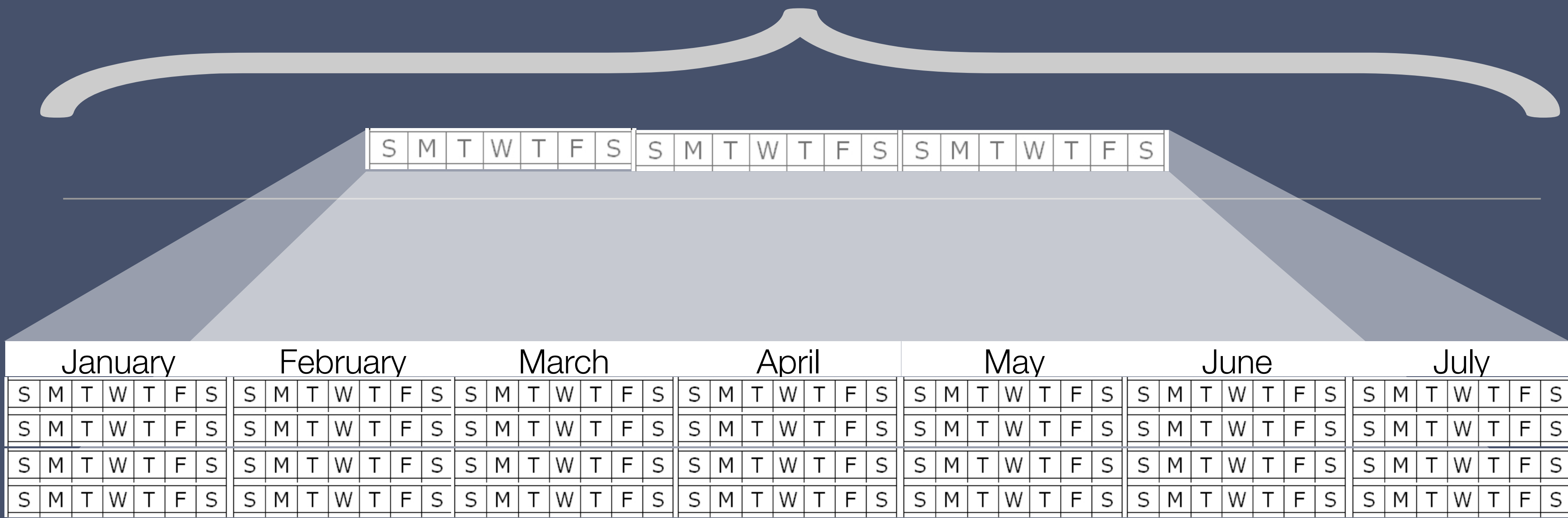
BTW:
a typical 3 week Snowmass?

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.

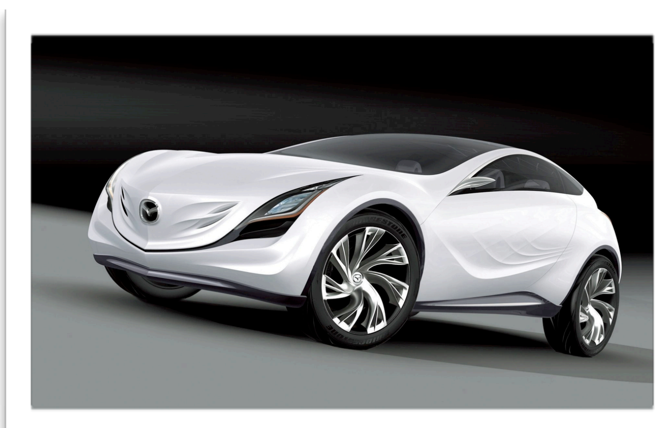
Working Group Results

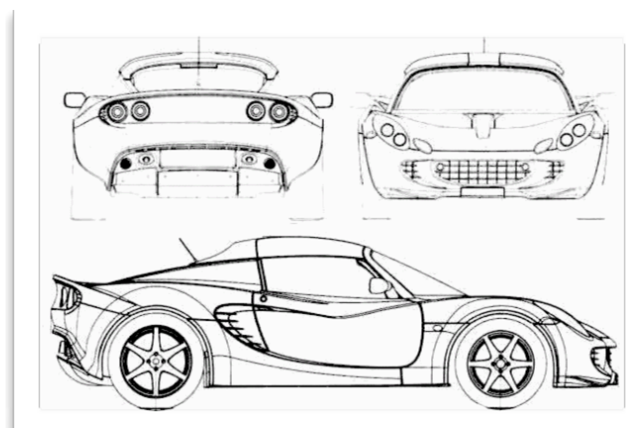
Study the reports!

~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+
3. The Higgs is elementary.
4. The Higgs production cross sections are as predicted.
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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.

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

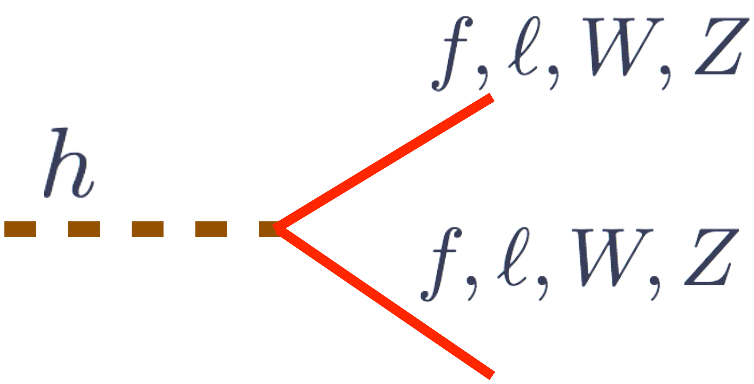
1. Models with new TeV particles give corrections to Higgs couplings of a few %.
2. An experimental program to determine these couplings is achievable.
   - LHC is the facility to study Higgs in the next decade
   - Interesting precision begins with the 300/fb running
   - Success requires considerable 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

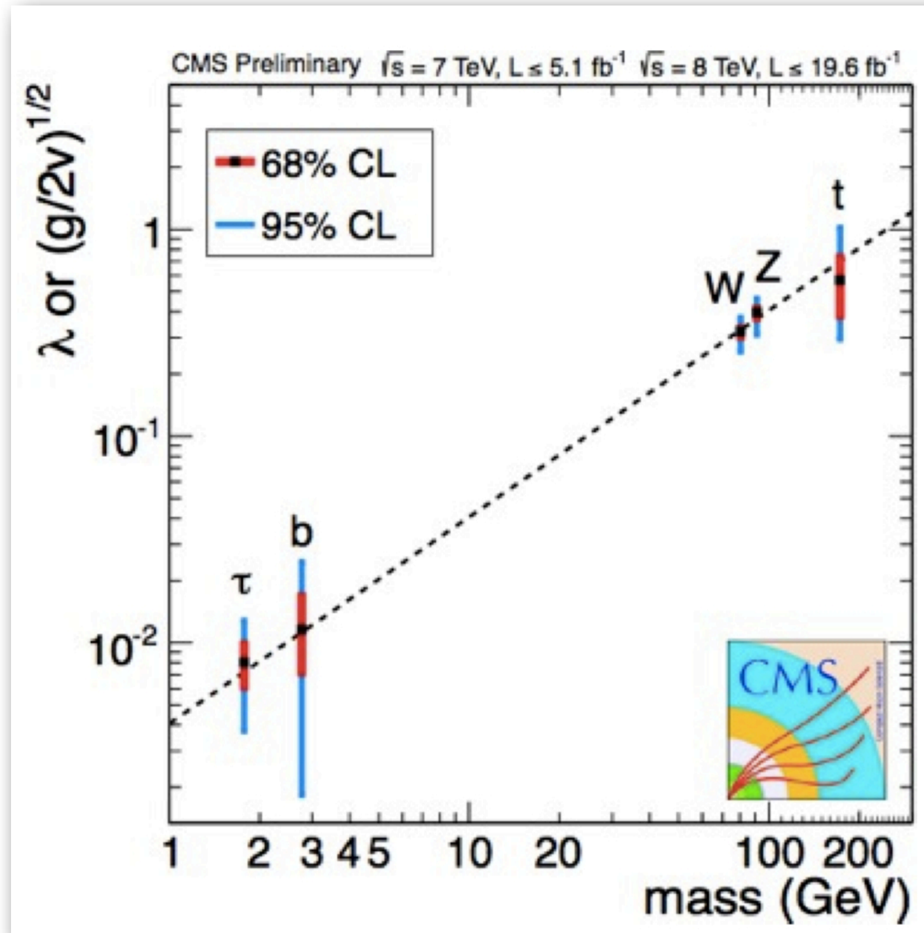
couplings

1. Higgs discovery spawned an industry

precision fitting of couplings

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



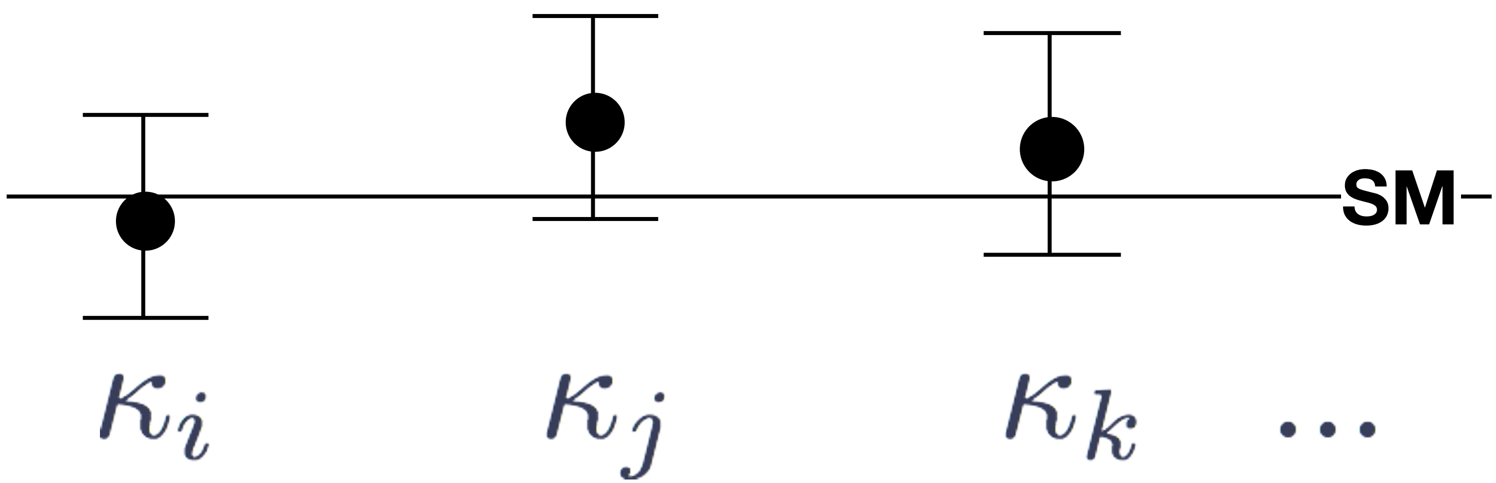


how well?

Higgs group evaluated models

- when new particles are ~1TeV:

	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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



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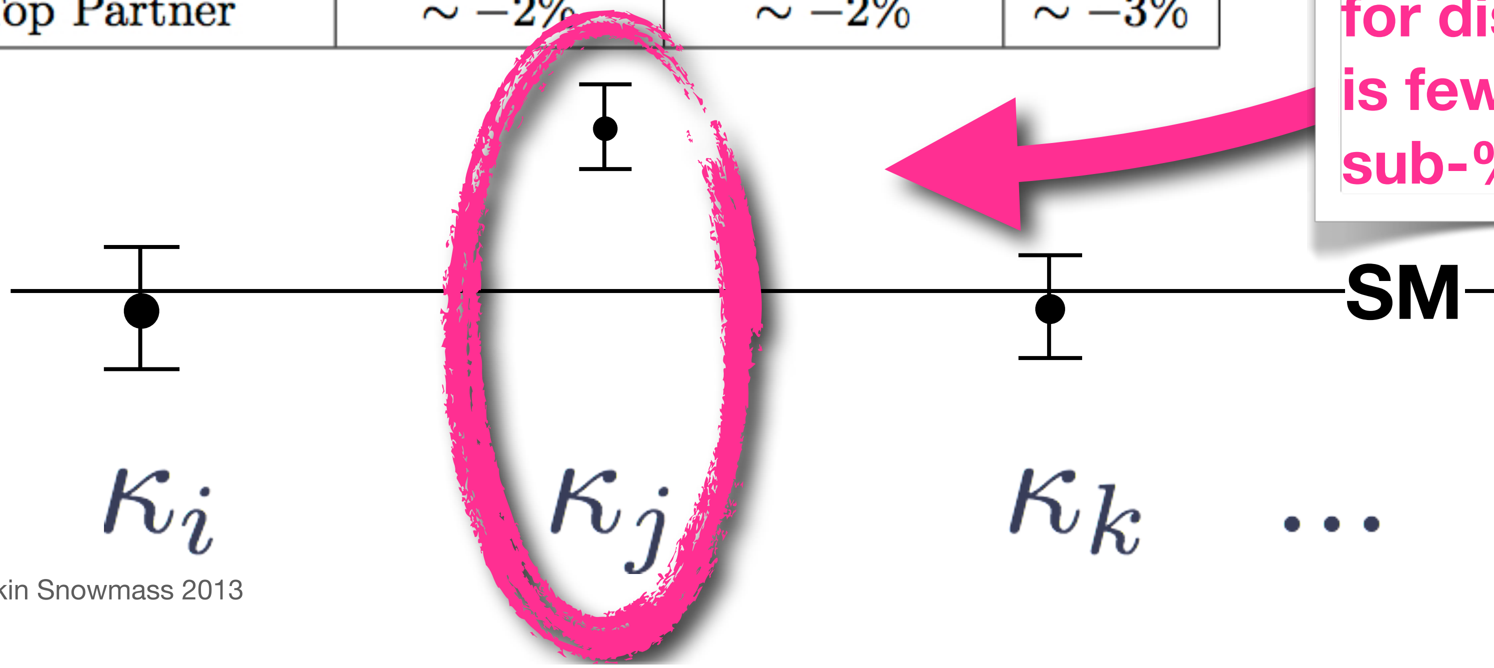
precision for precision's sake?

No - this is a discovery search

	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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Benchmark for discovery is few % to sub-%



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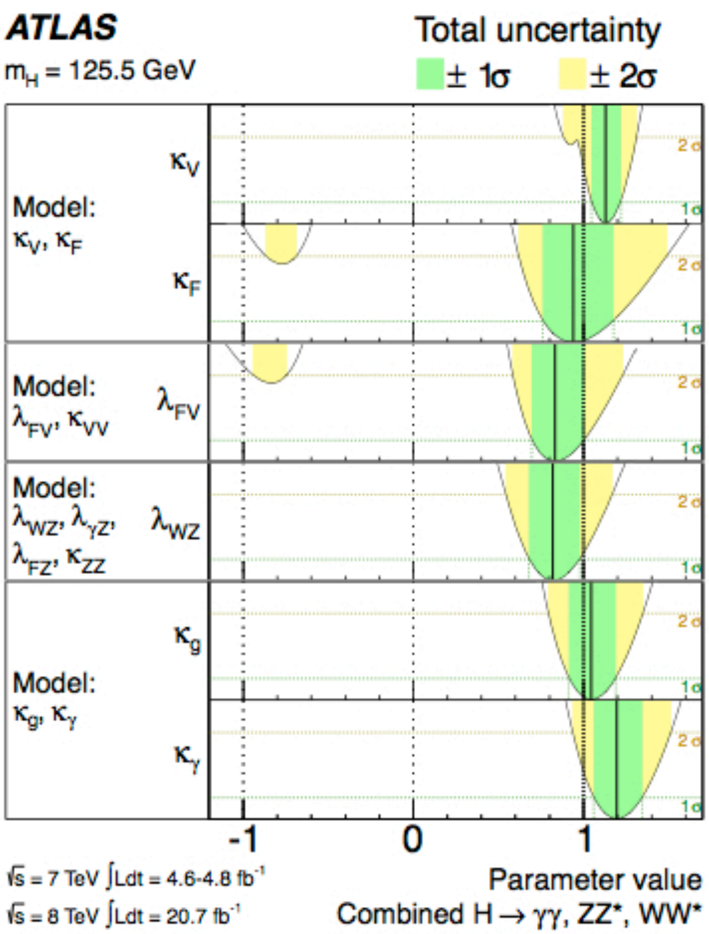
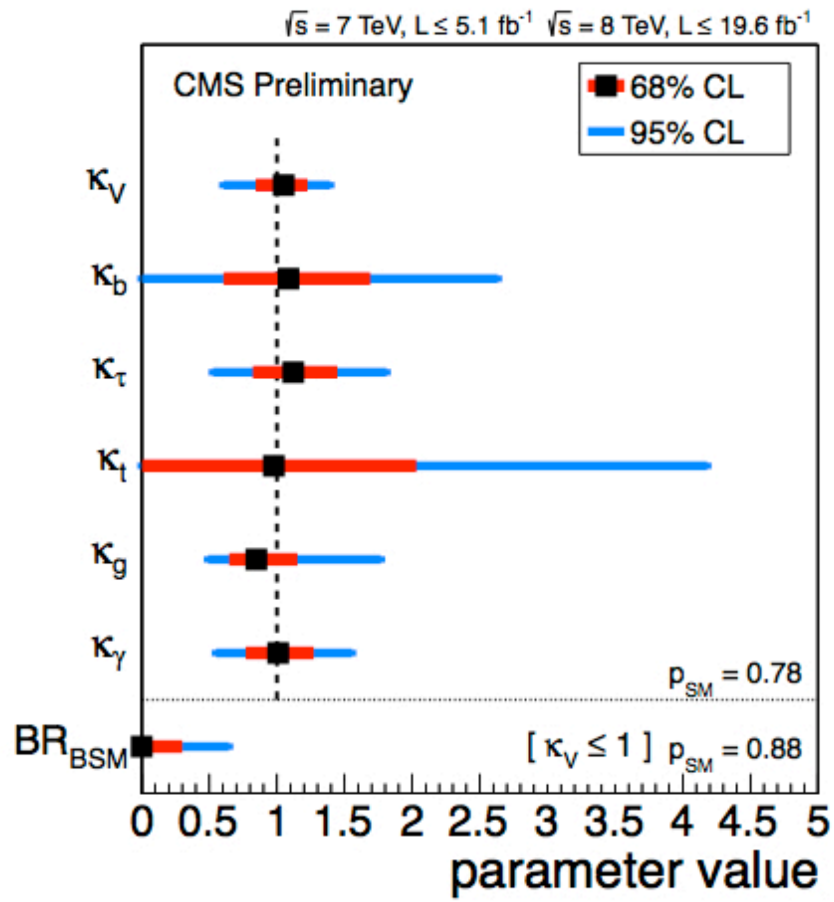
to date:



ATLAS
m_H = 125.5 GeV
Total uncertainty
± 1σ ± 2σ
Model: κ_V, κ_F
κ_V
κ_F
Model: λ_{FV}, κ_{VV}
λ_{FV}
Model: λ_{WZ}, $\lambda_{\gamma Z}$, λ_{FZ}, κ_{ZZ}
λ_{WZ}
Model: κ_g, κ_γ
κ_g
κ_γ
-1 0 1
Parameter value
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
Combined $H \rightarrow \gamma\gamma$, ZZ^*, WW^*



$\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L ≤ 19.6 fb^{-1}
CMS Preliminary
68% CL
95% CL
κ_V
κ_b
κ_τ
κ_t
κ_g
κ_γ
p_{SM} = 0.78
BR_{BSM}
[$\kappa_V \leq 1$] 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
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%

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

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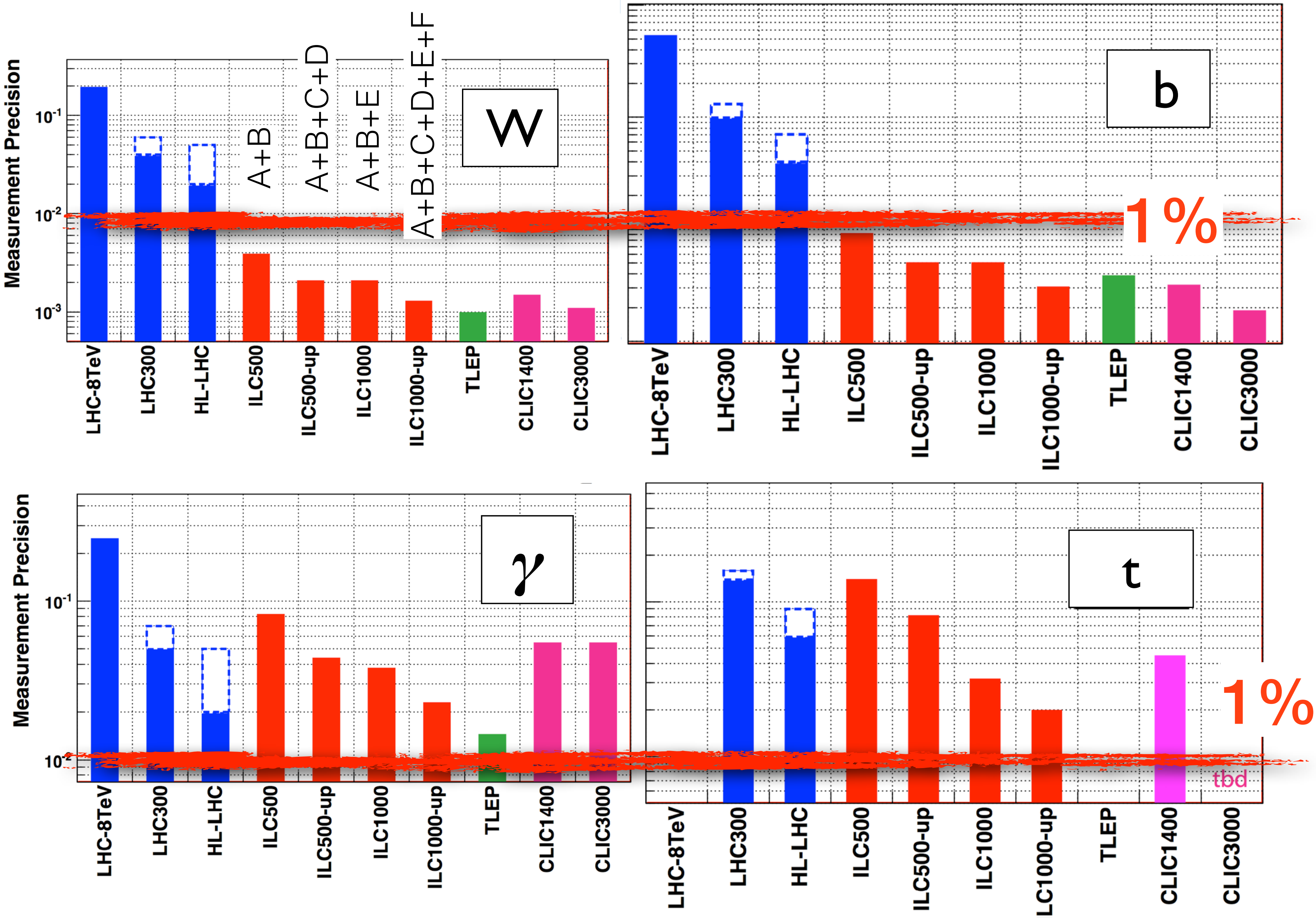
Precision in kappa by facility

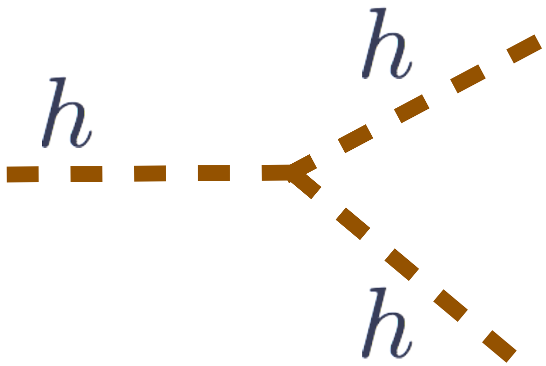


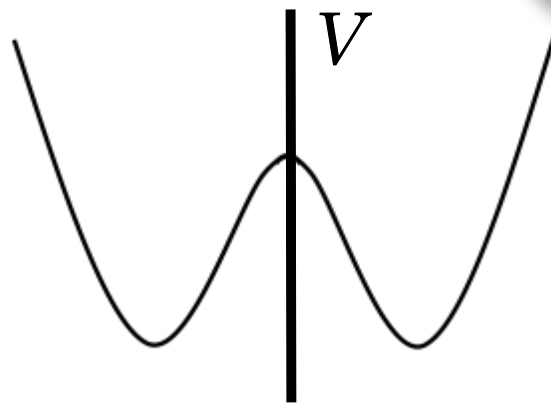
Higgs Self-Coupling

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‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	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 Γ
- 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)	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%

few %

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.*

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?**

Precision Study of Electroweak Physics

Electroweak: Themes

1. precision measurements:

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

  sensitive to new TeV particles in loops

2. studies of vector boson interactions

- triple VB couplings, VB scattering

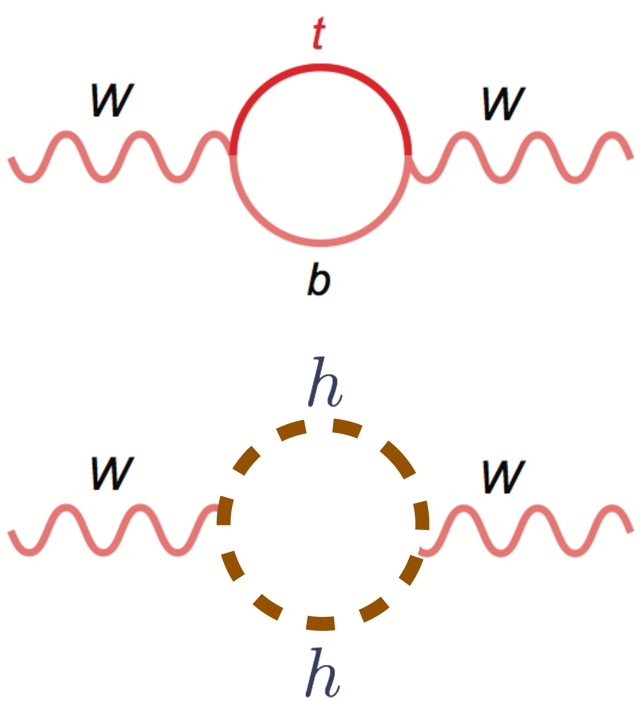
  Effective Field Theory approaches

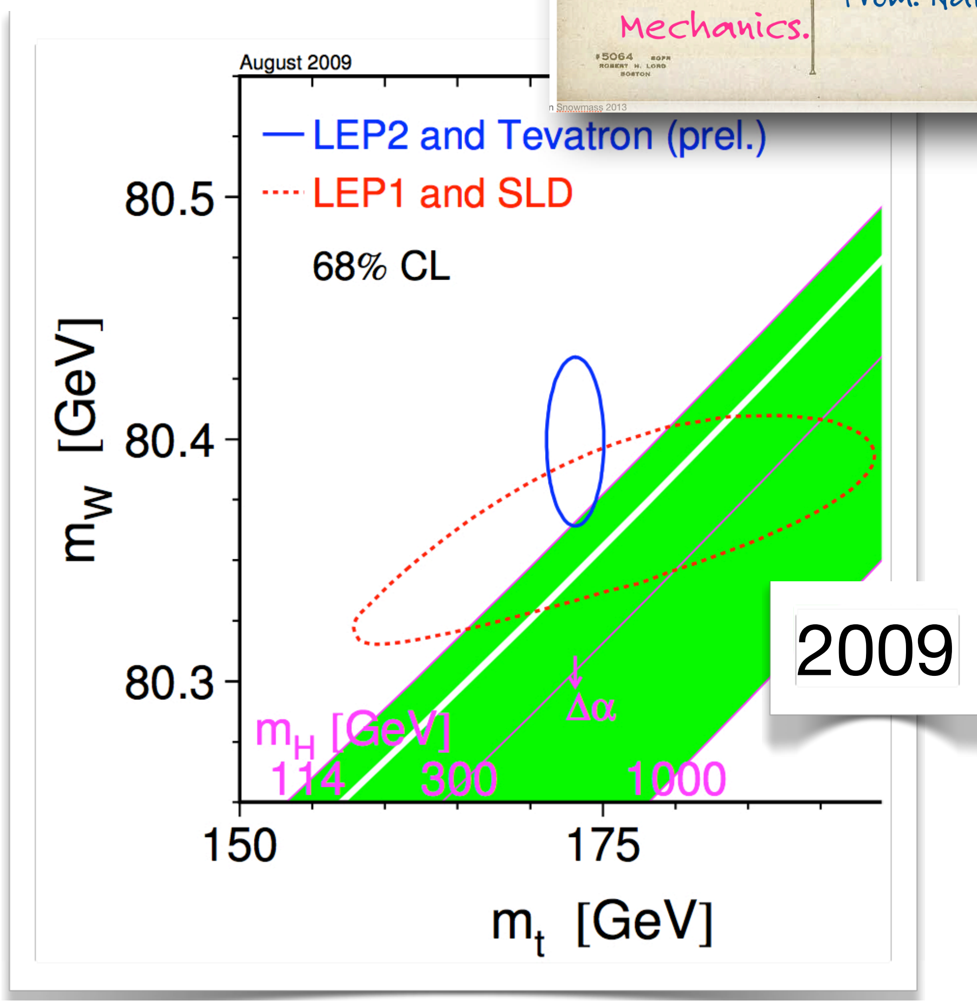
  sensitive to Higgs sector resonances

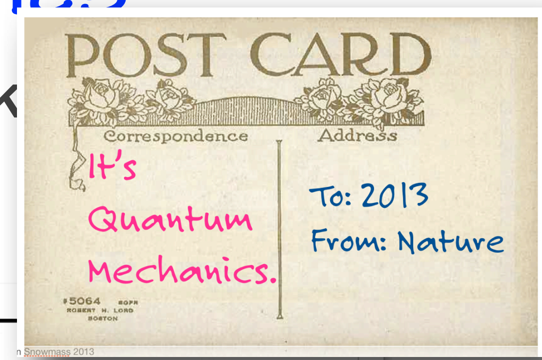
EWPOs

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

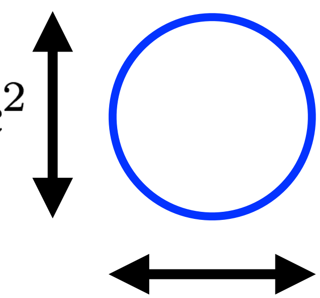
Premium on M_W

Now fits include M_h

This is now a BSM search

δM_W

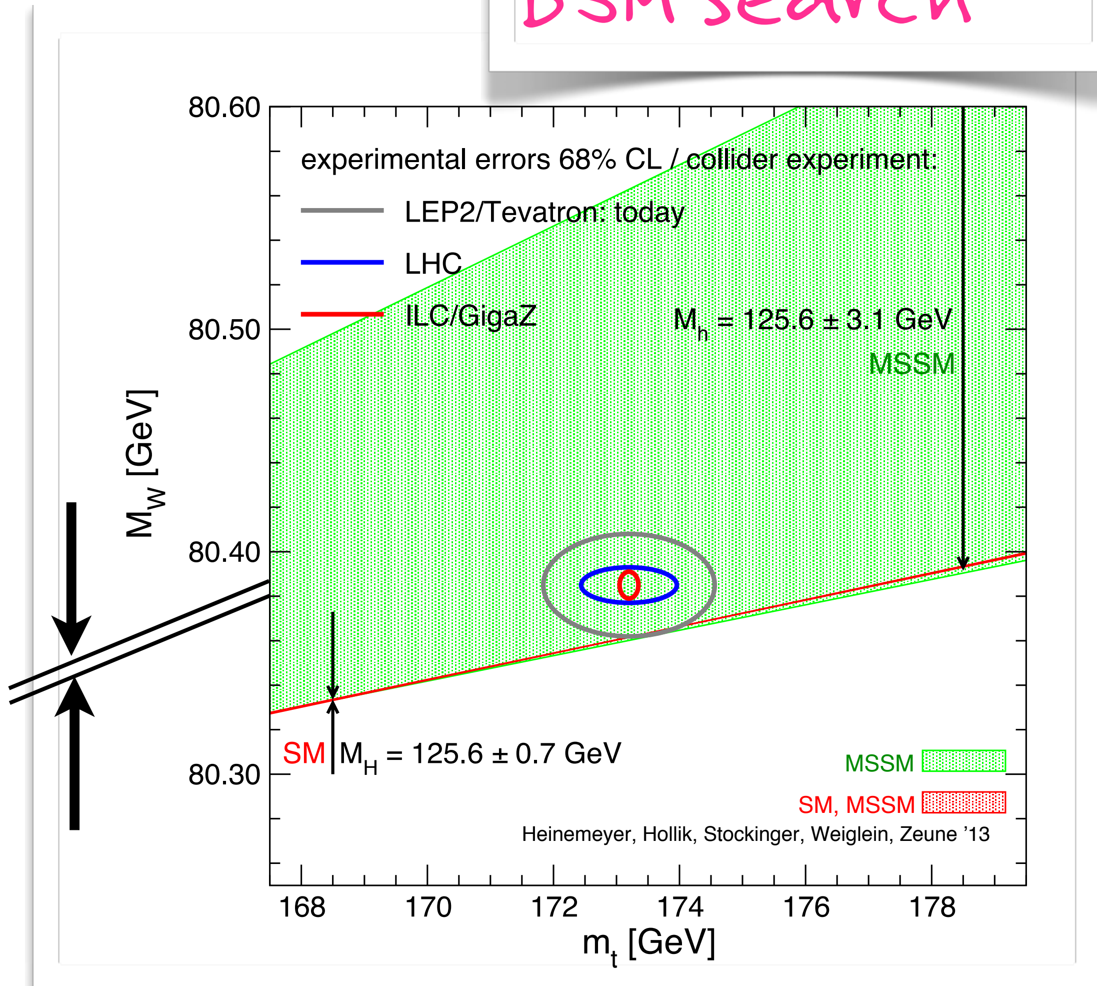
$\sim 5\ \mathrm{MeV}/c^2$



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

δm_t

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



M_W precision

M_W at the LHC

- δM_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.

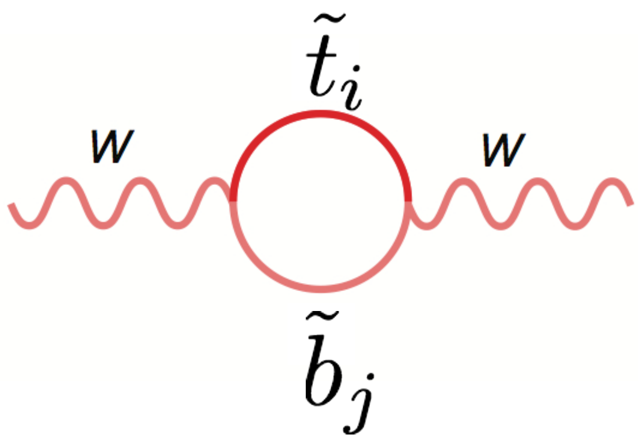
Furthermore: $\sin^2\theta_{eff}$

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

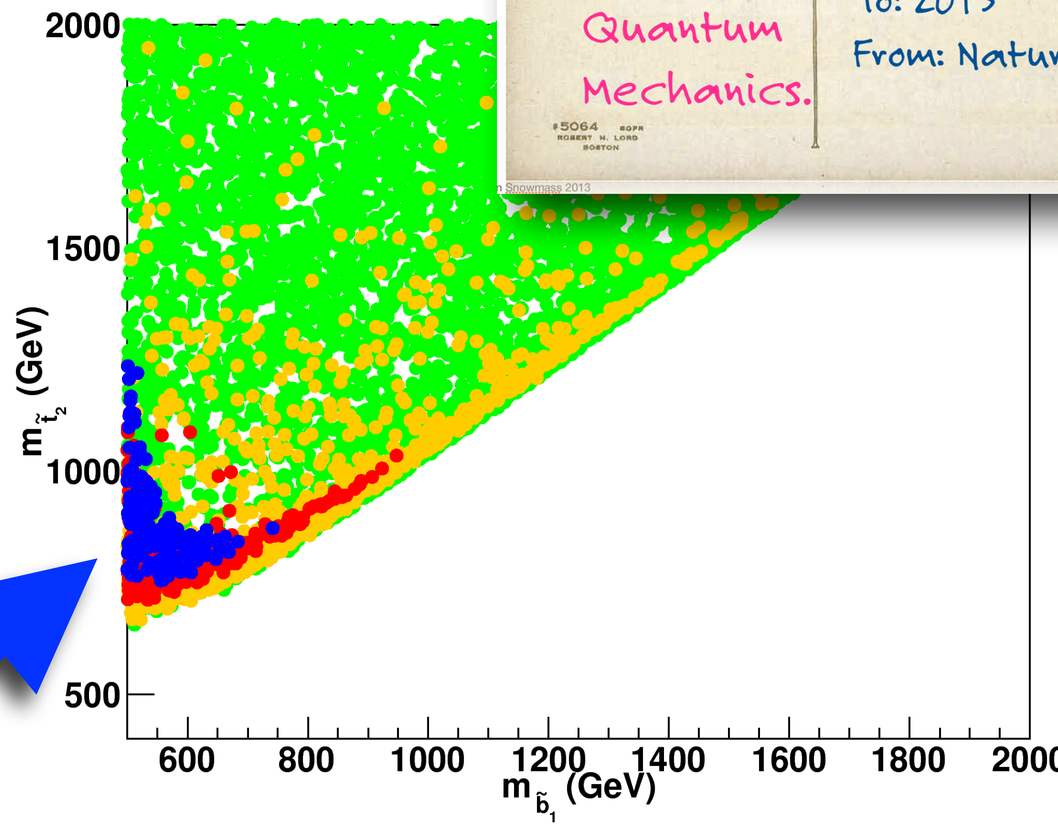
M_W, the old fashioned way

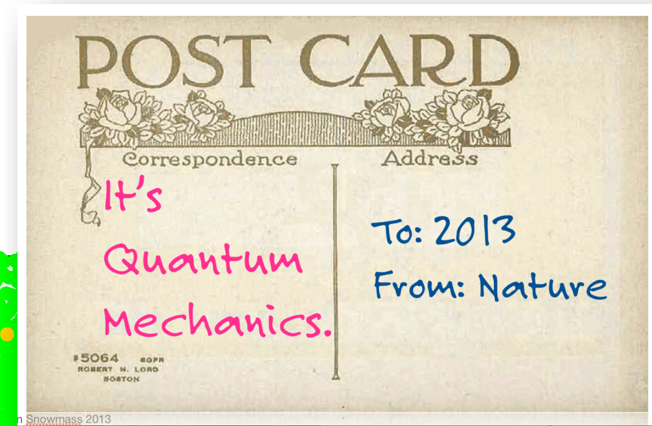
Imagine we knew:

- the stop1 mass, and M_W to 5 MeV



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



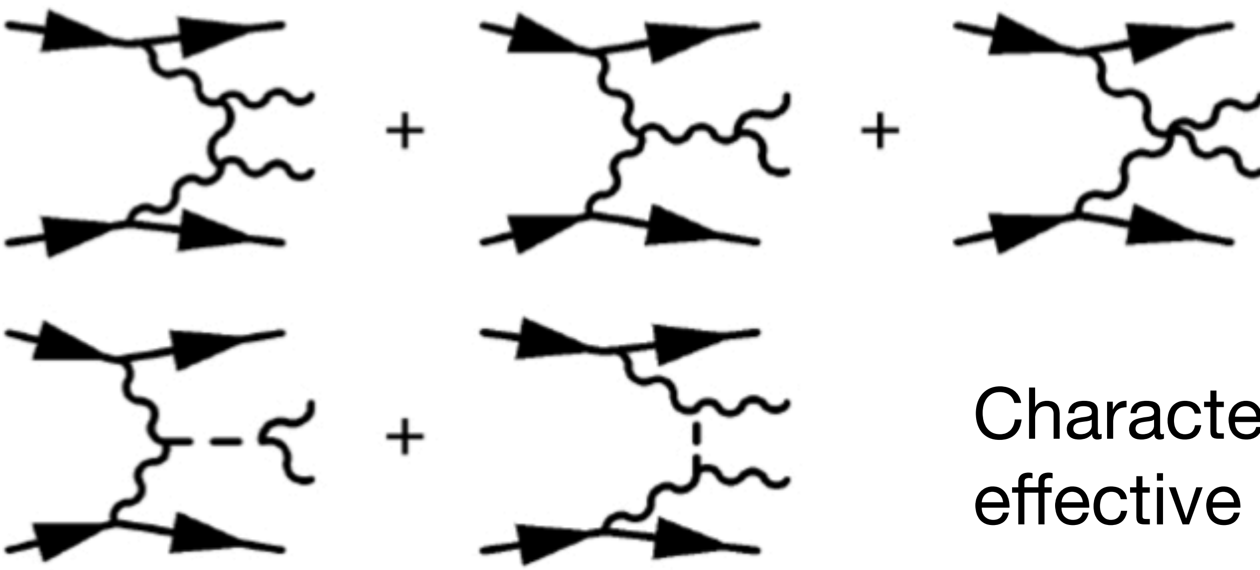


EW scale - TeV?

Originally, EW theory broke down at TeV scale

- Higgs tames this...in theory

  now a test



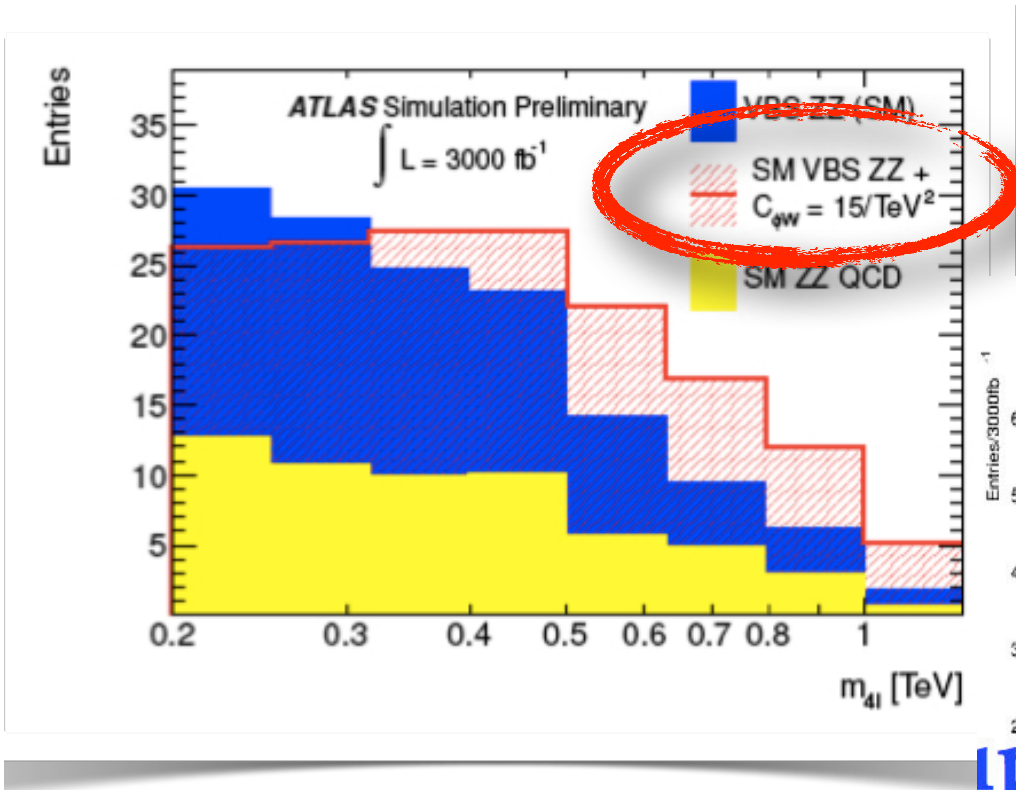
Characterize as a general effective operator

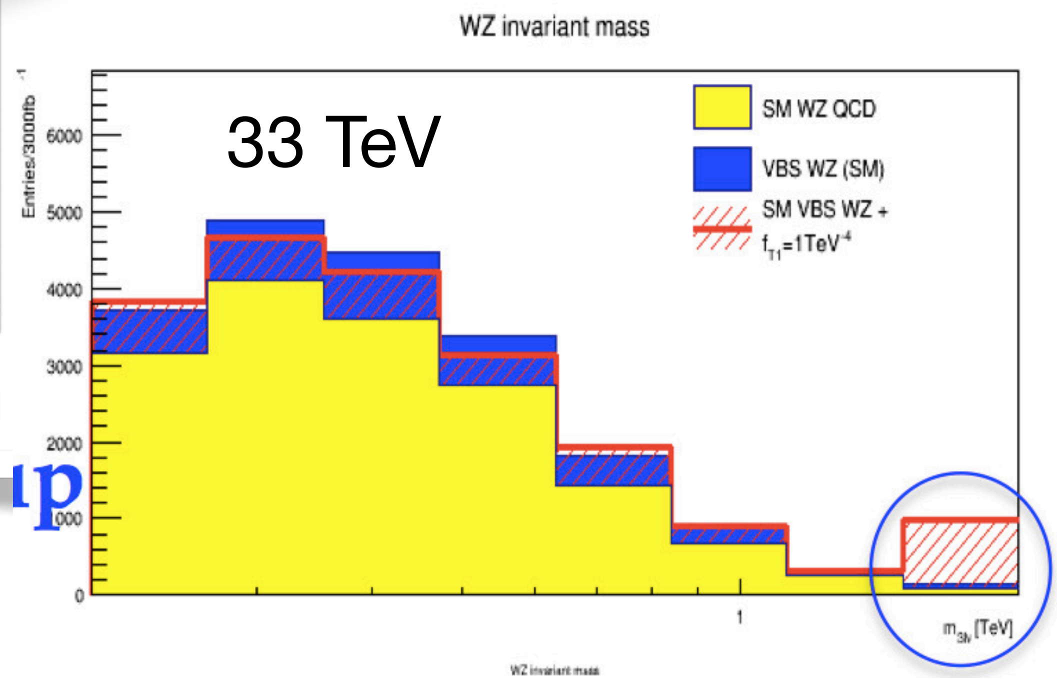
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_i \frac{f_j}{\Lambda^4}\mathcal{O}_j + \cdots$$

VB Scattering

Effective Operator Machinery built into Madgraph for Snowmass

- Sensitivity to non-standard gauge interactions





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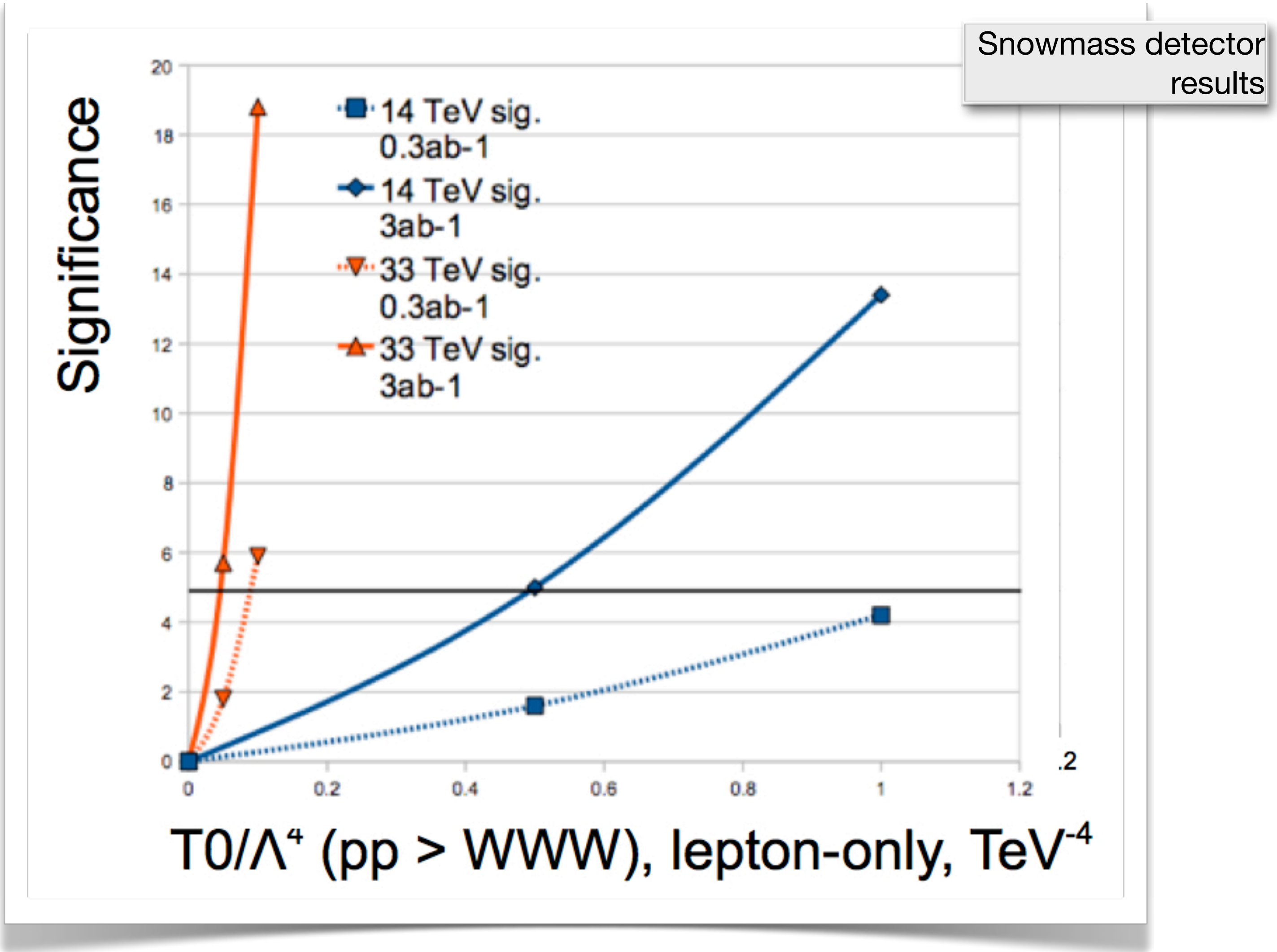
VB Scattering

Luminosity and Energy win.



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The EW physics message

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

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

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

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

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

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

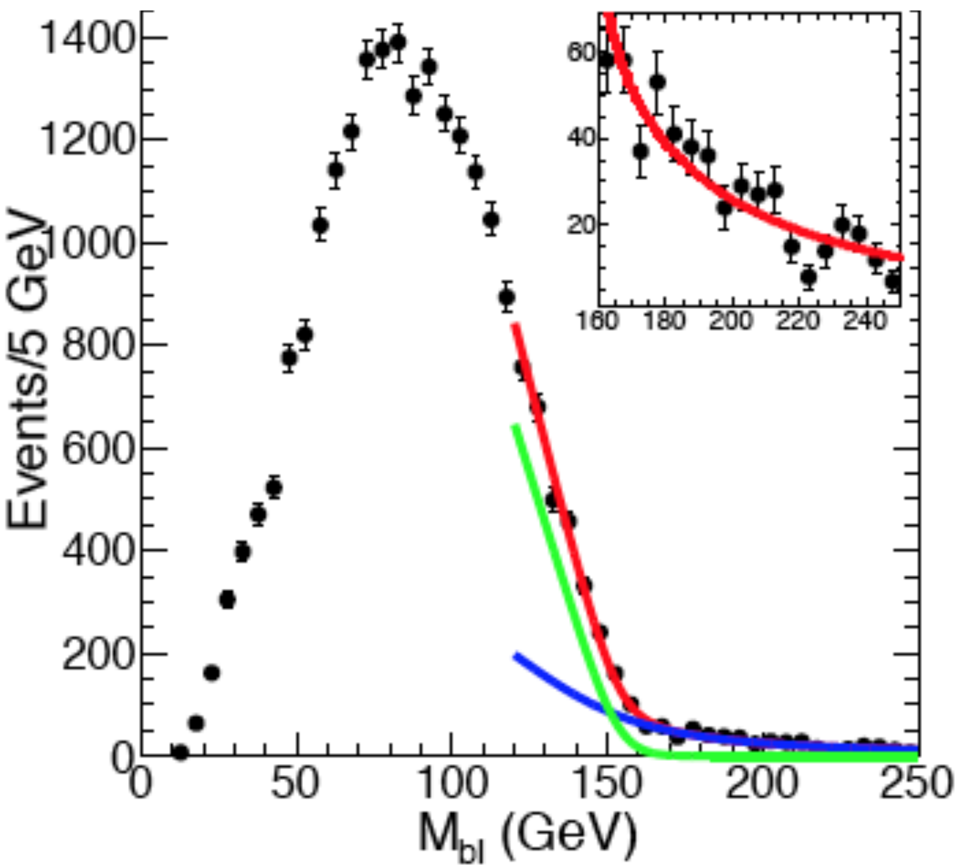
- crucial study for composite models of Higgs and top;
- stop plays a central role in SUSY

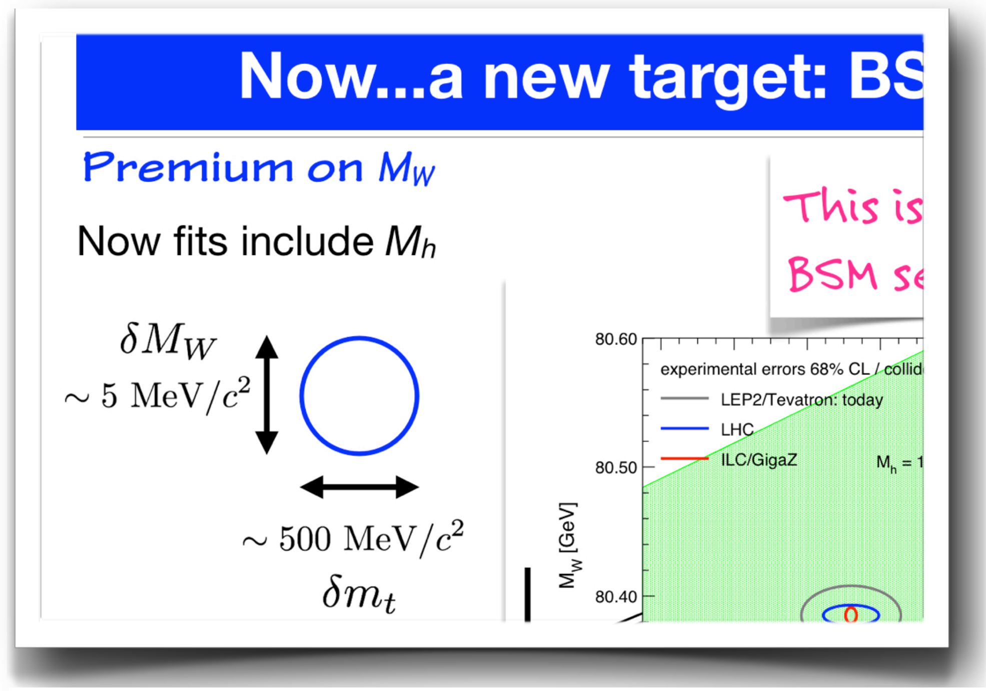
6. Boosted-top observables

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

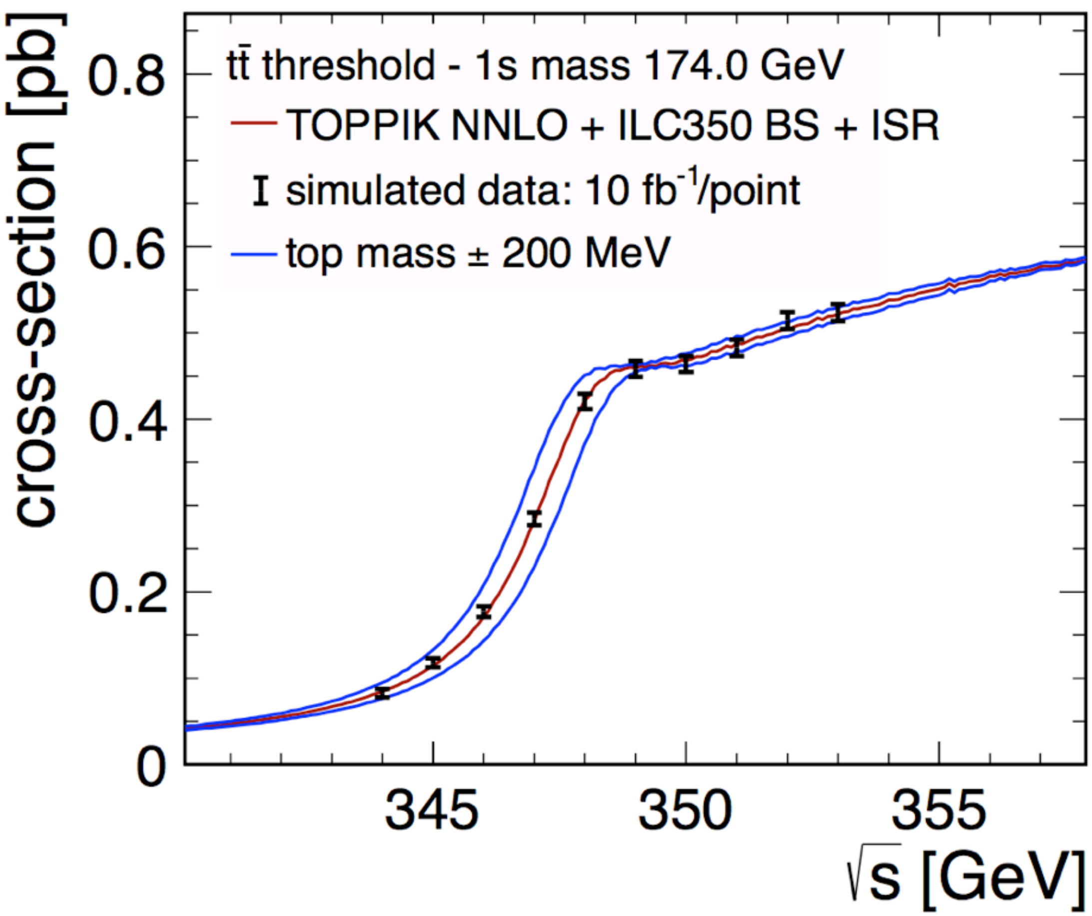




matching the 5 MeV precision goal of M_W

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}^{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 %

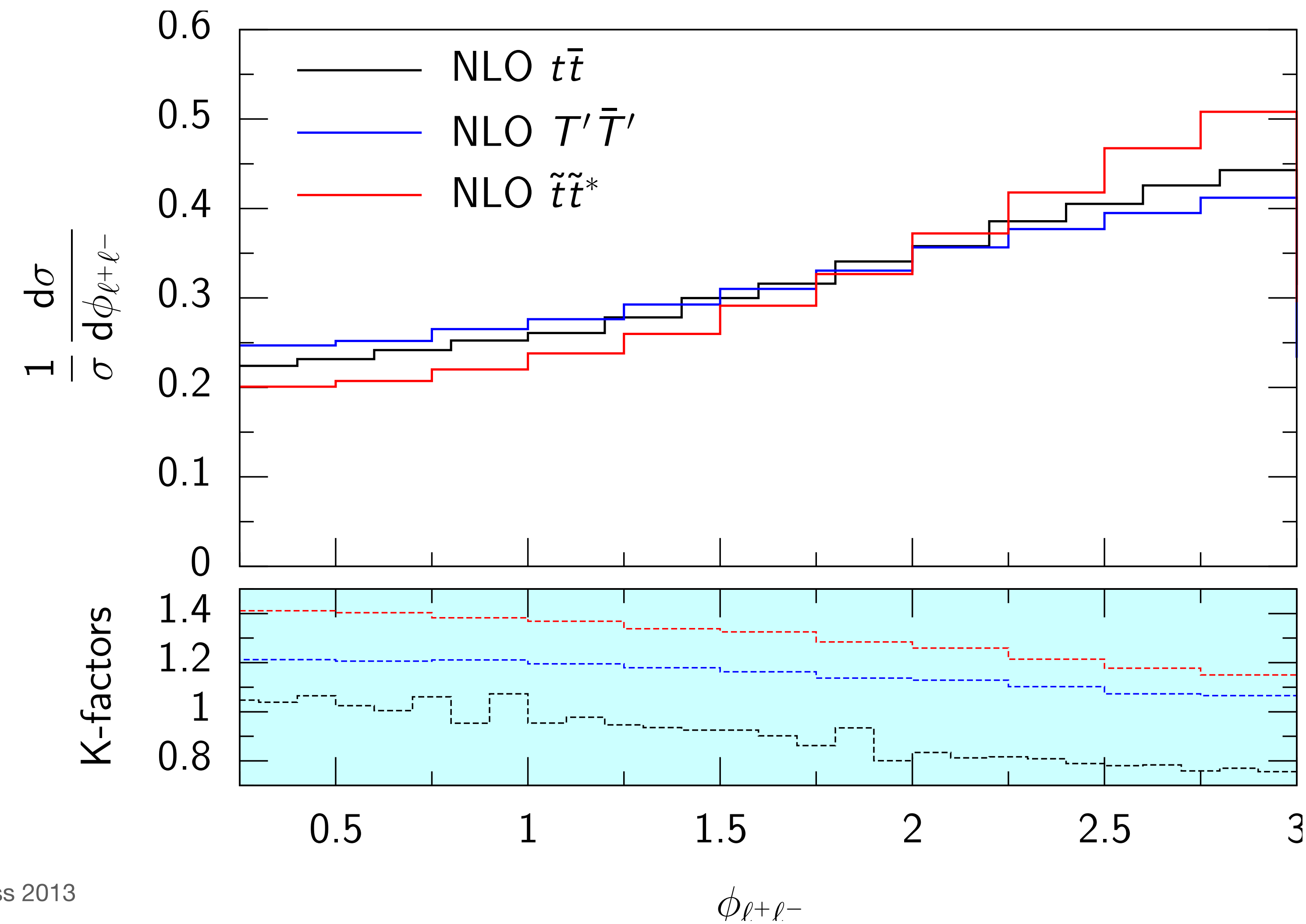
LHC : few %

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]

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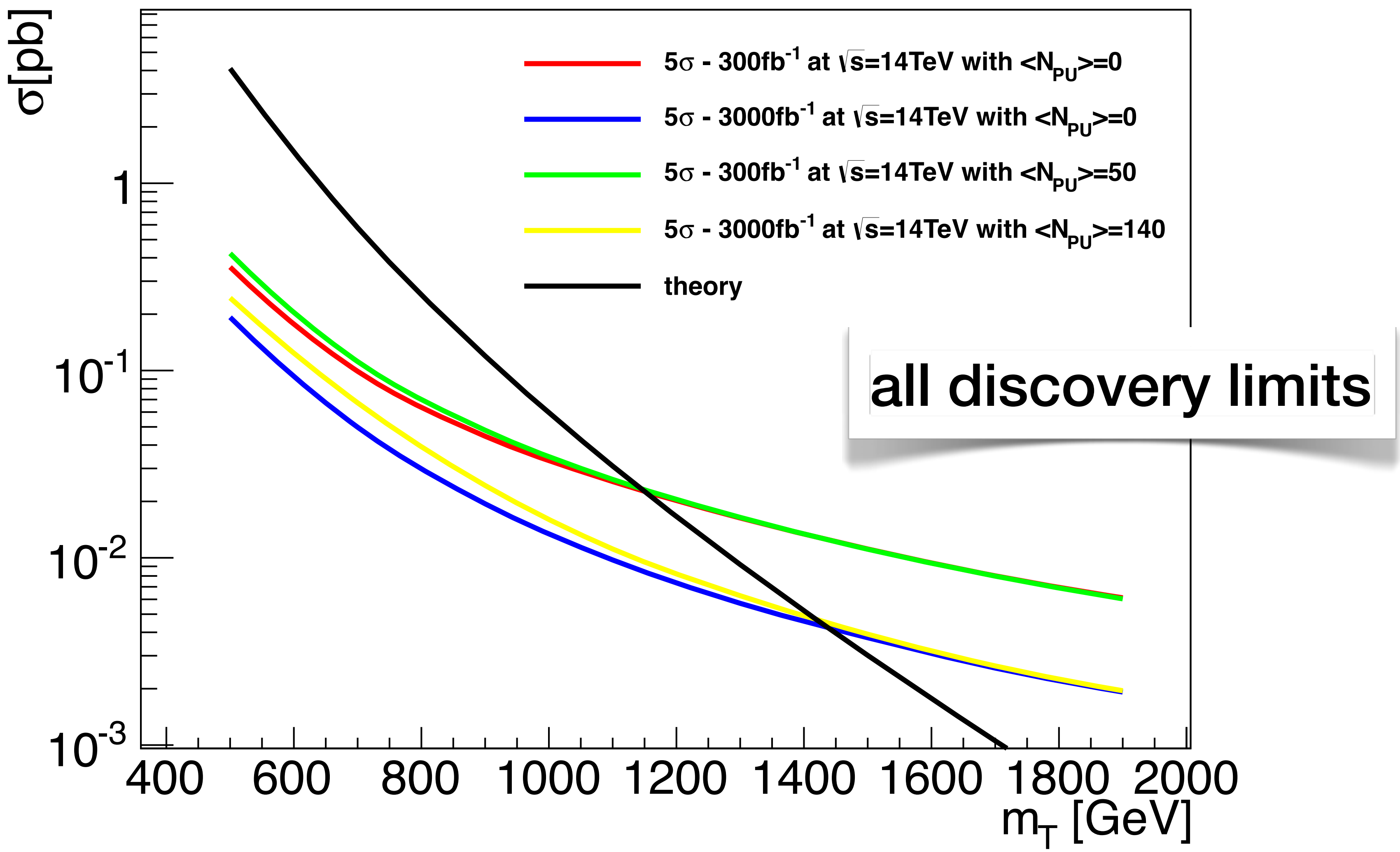
Direct search for top partner

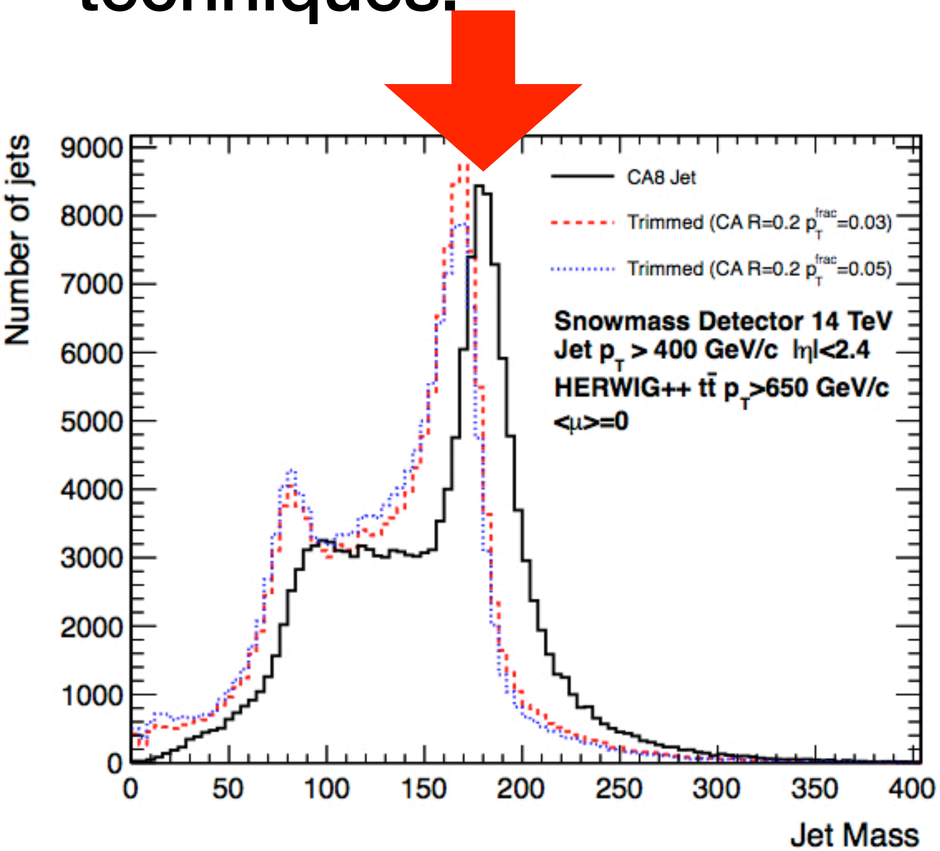
search reach for vectorlike top partners at LHC 300 and 3000/fb

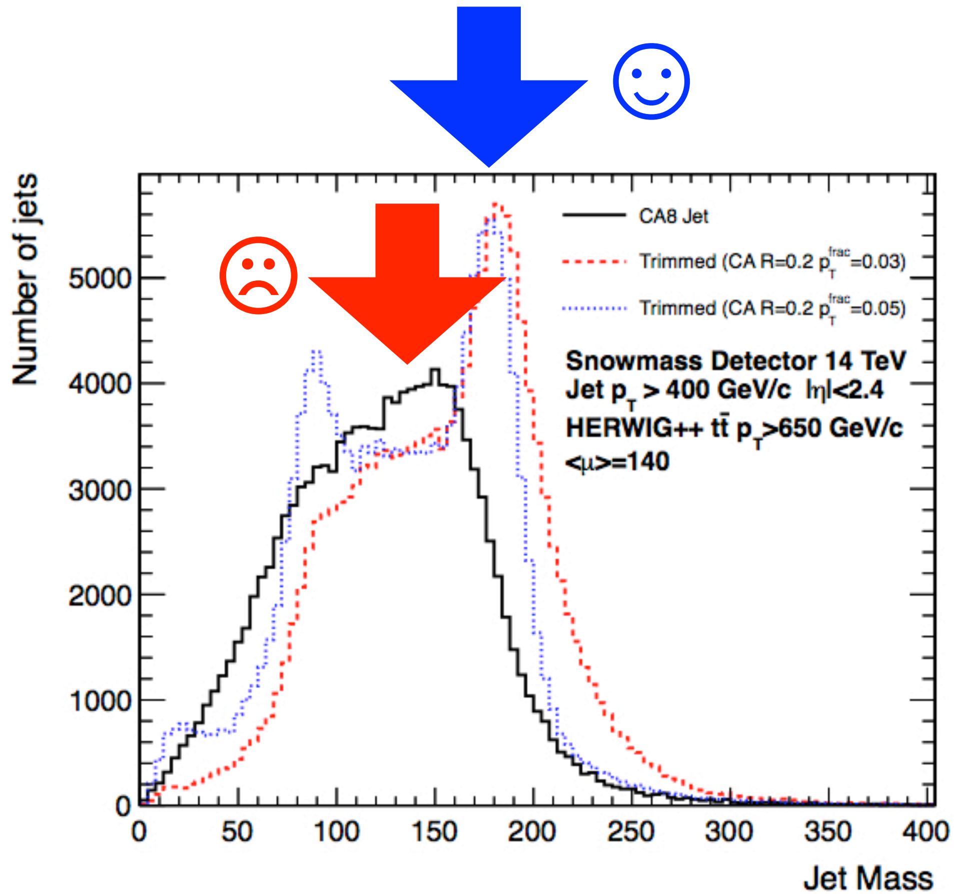


boosted top technique

Top quark finding deteriorates at high pileup.

Restore the performance with grooming and trimming techniques.





pileup = 0 140

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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?**

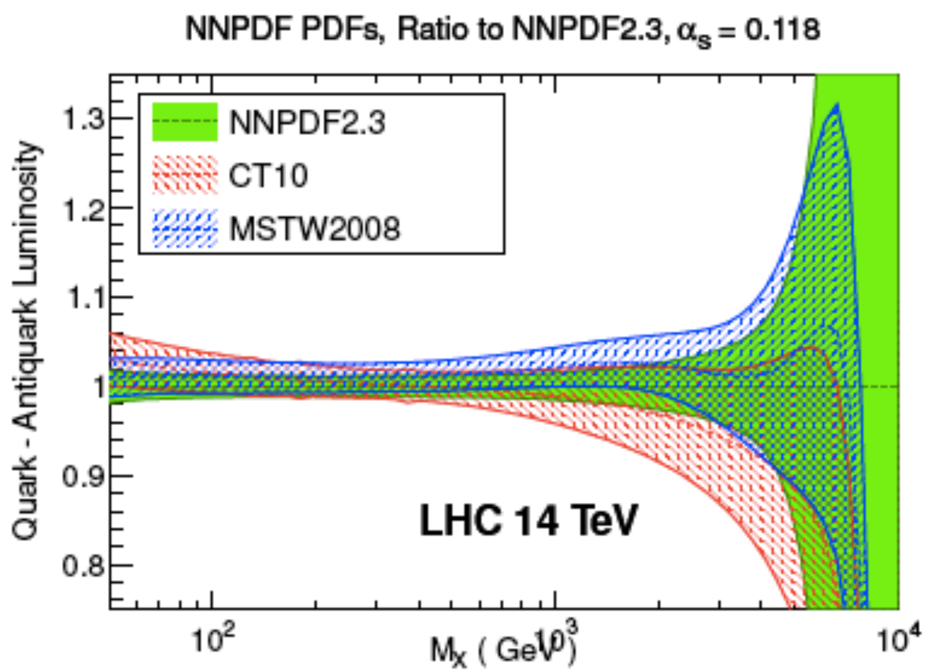
Quantum Chromodynamics and the Strong Force

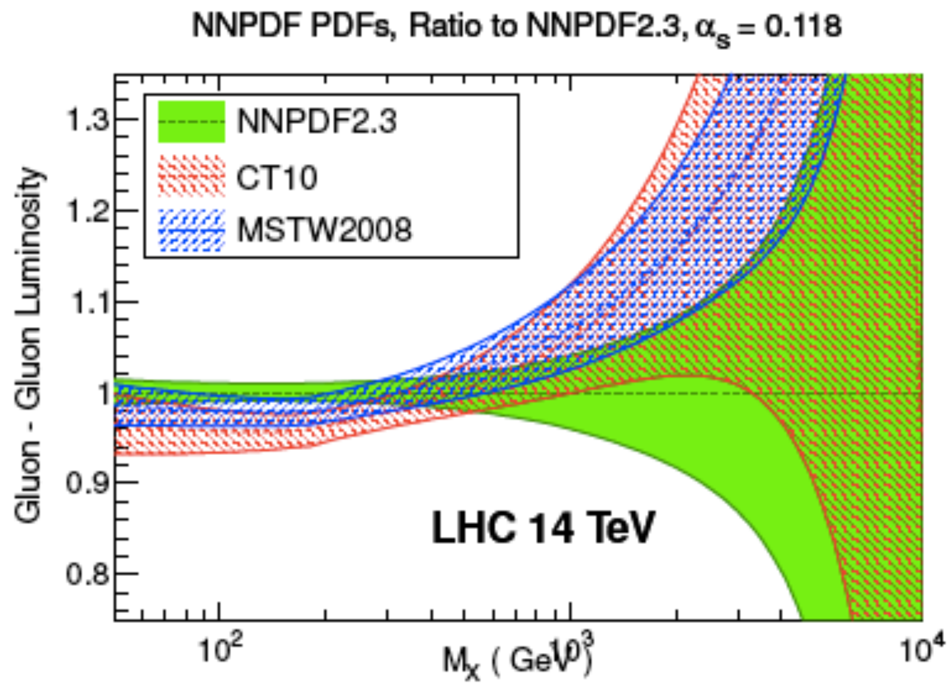
QCD: Themes

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

PDFs

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



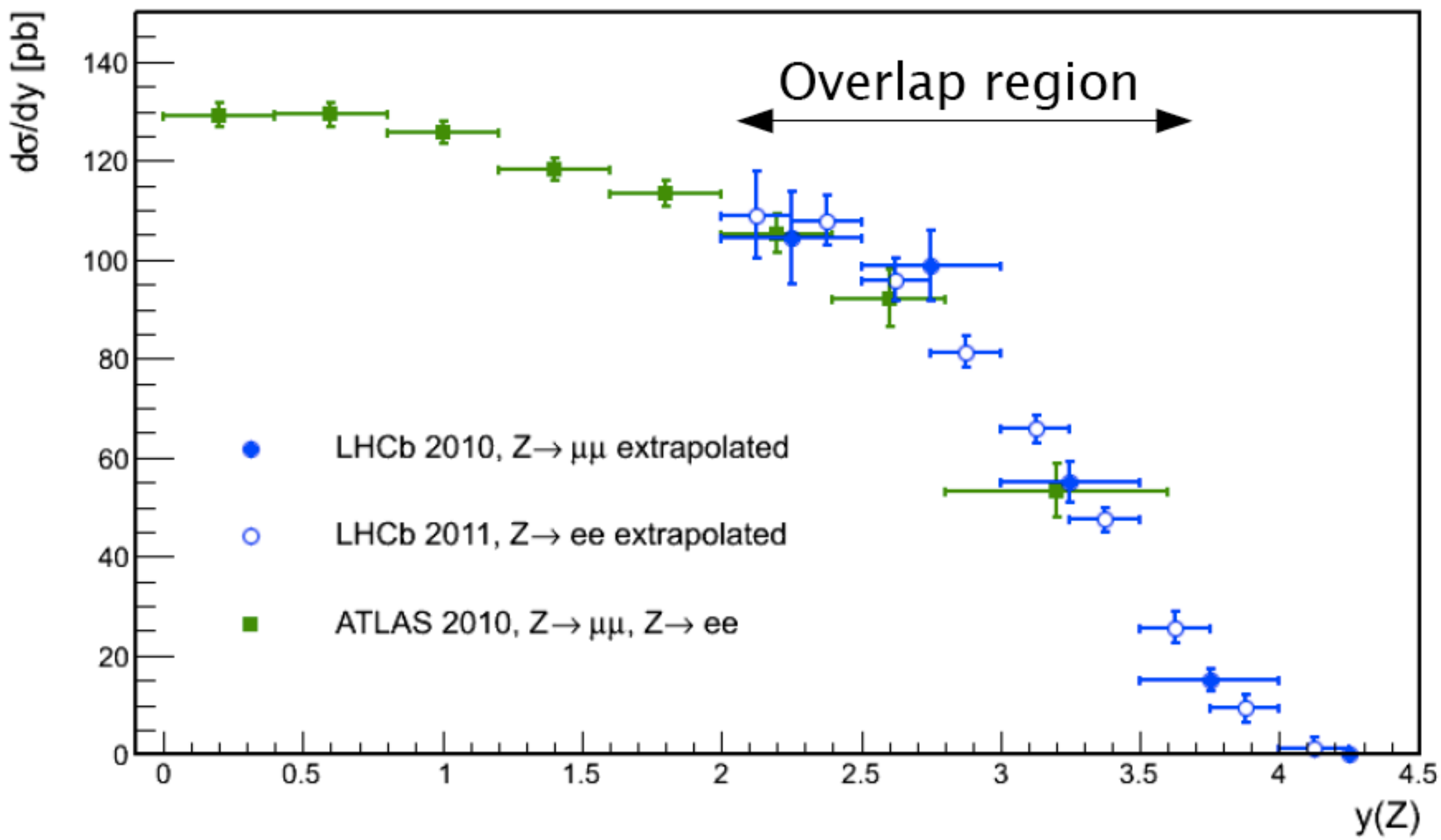


Juan Rojo

Improve at LHC with W, Z, top rapidity distributions

full rapidity coverage required

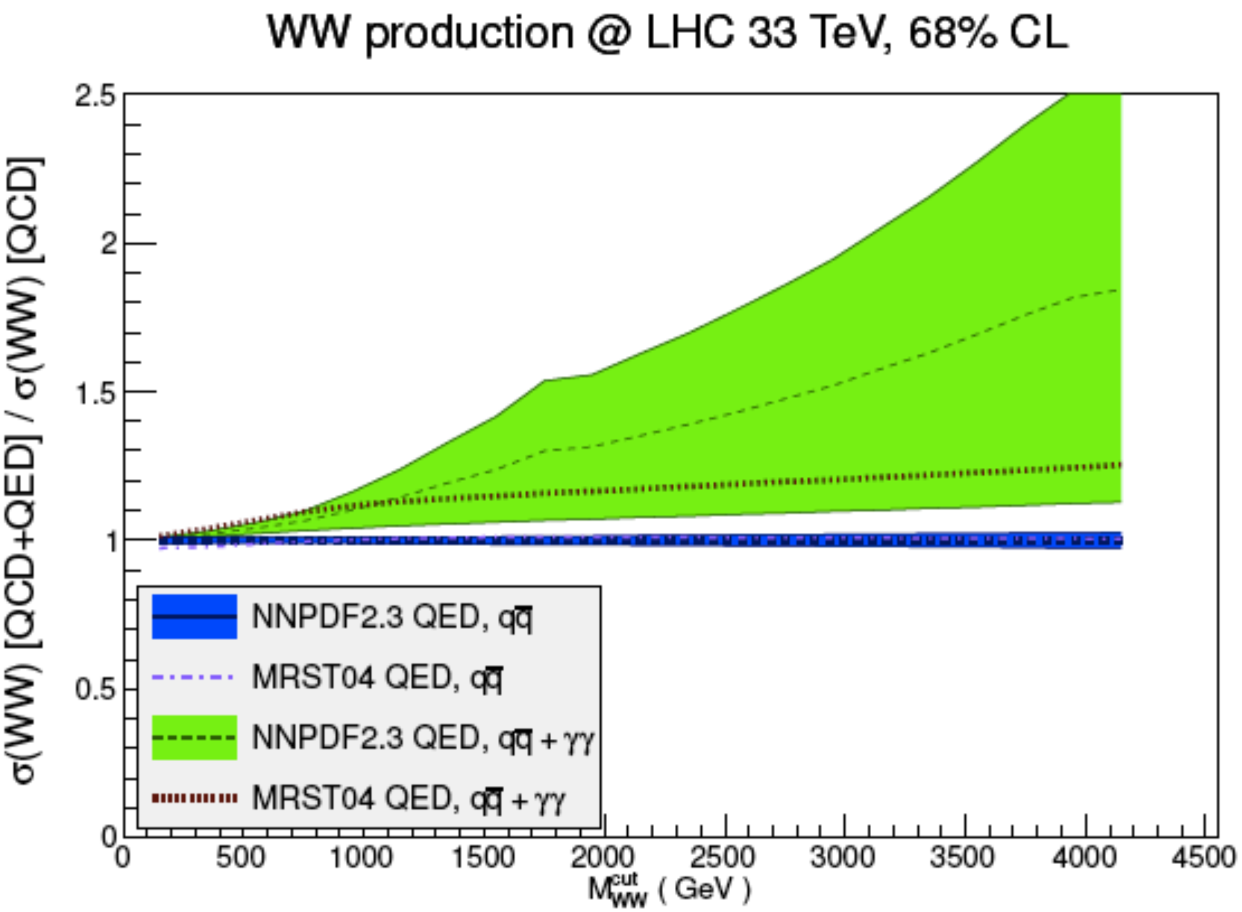
complementary role of ATLAS,CMS and LHCb



Brock/Peskin Snowmass 2013

Photon PDF and QED

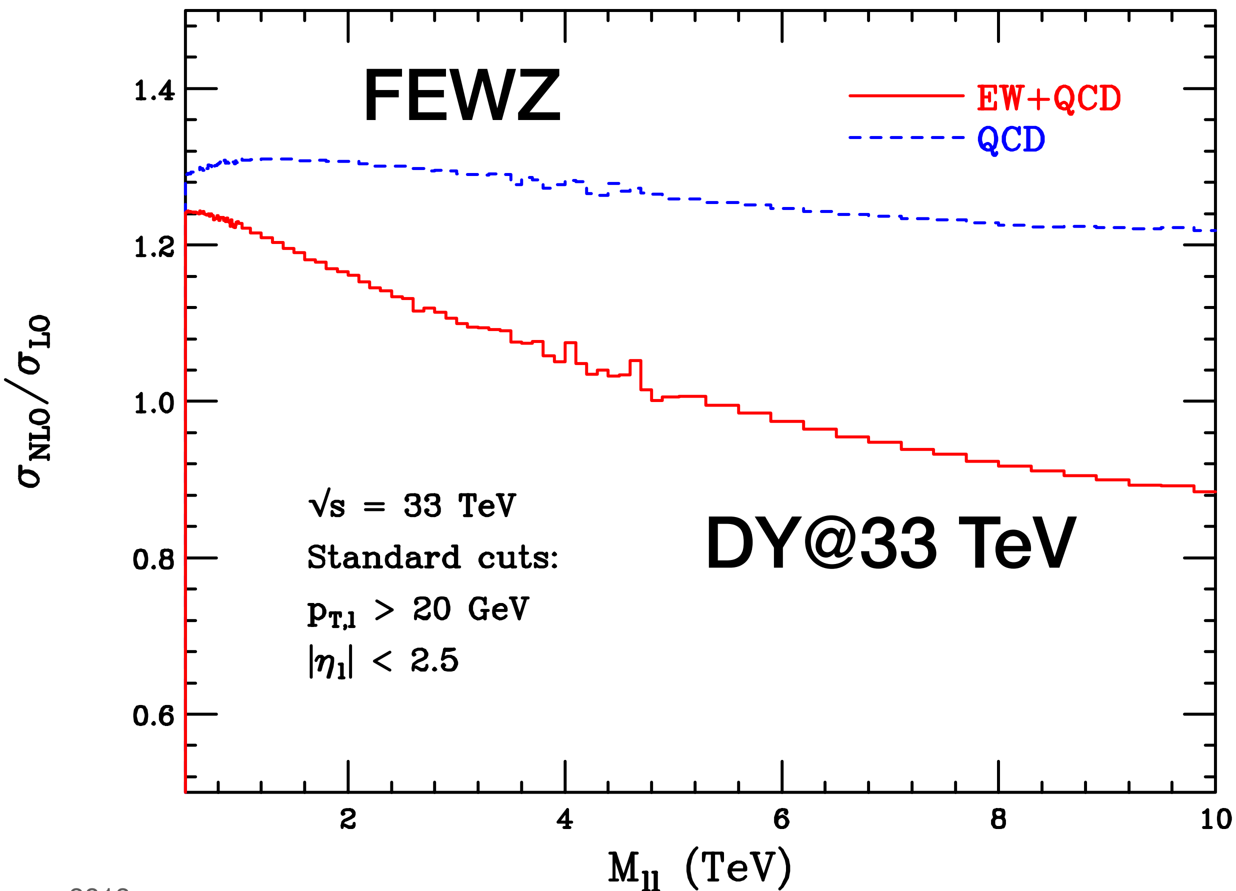
Photon-induced processes are increasingly important; need to extend the current state of the art in PDFs to QED.



Juan Rojo

Electroweak Sudakov

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

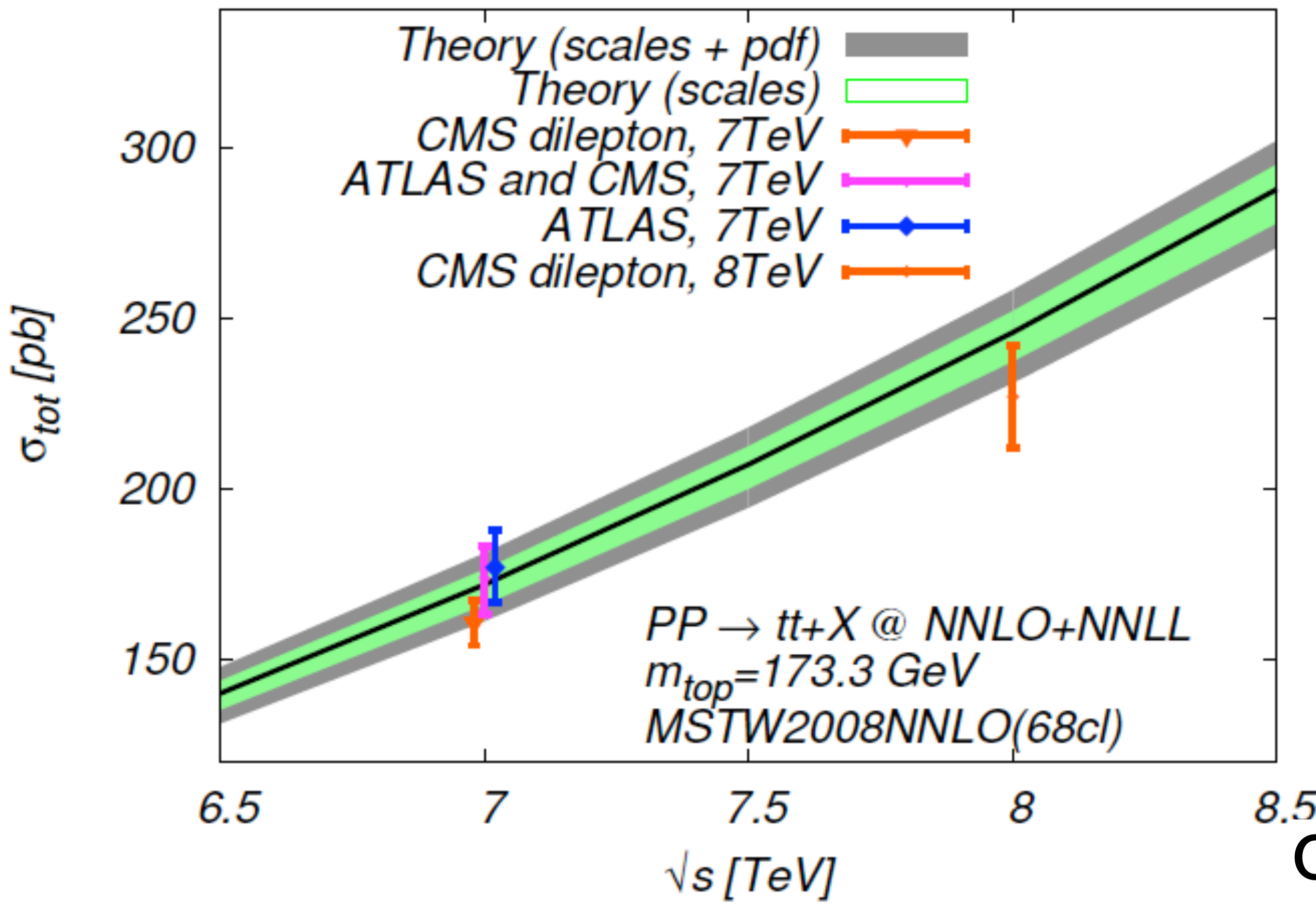


Kaland Mishra

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]
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

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 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

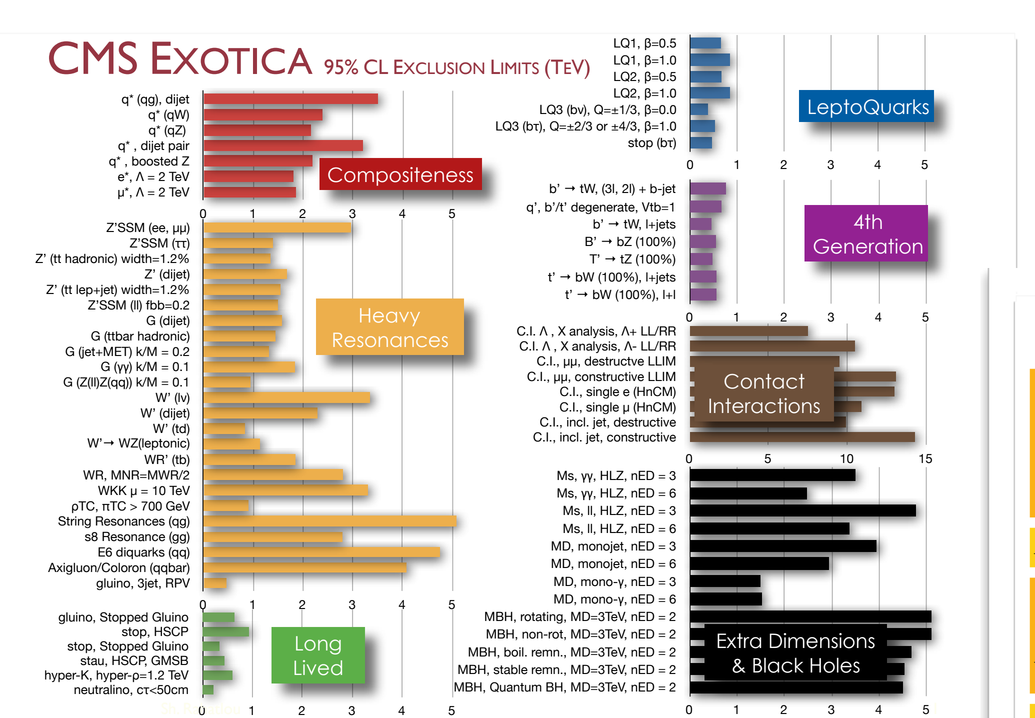
- weakly coupled: SUSY, Dark Matter, Long-lived
- strongly coupled/composite: Randall-Sundrum, KK and Z' resonances, long-lived particles
- evolution of robust search strategies

3. Connection to dark matter problem

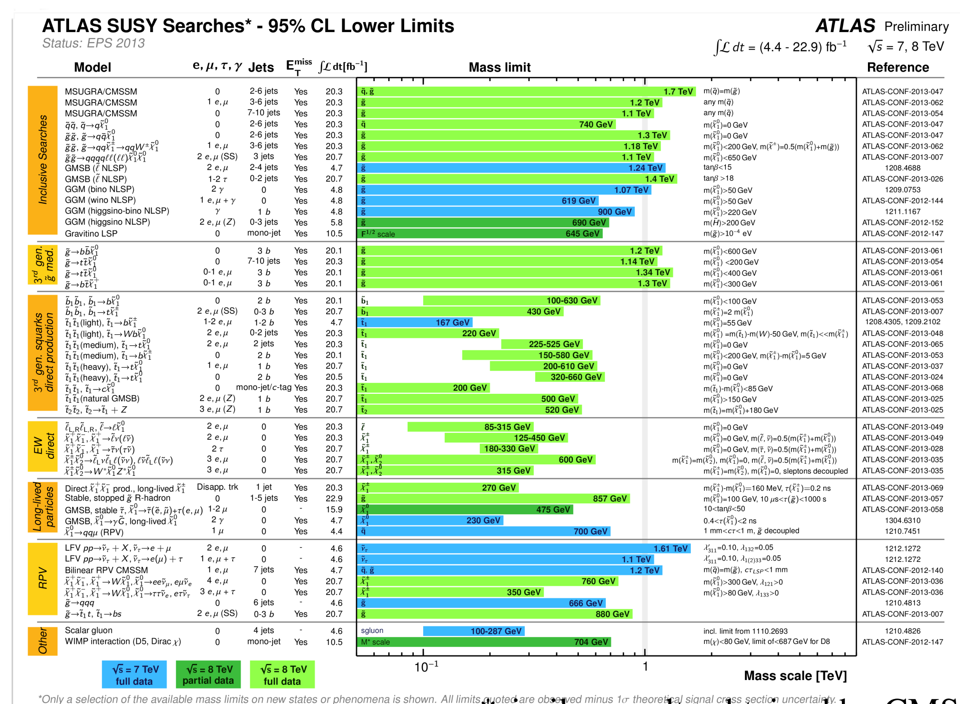
4. Connection to flavor issues

current LHC searches

New particle searches at the current LHC.



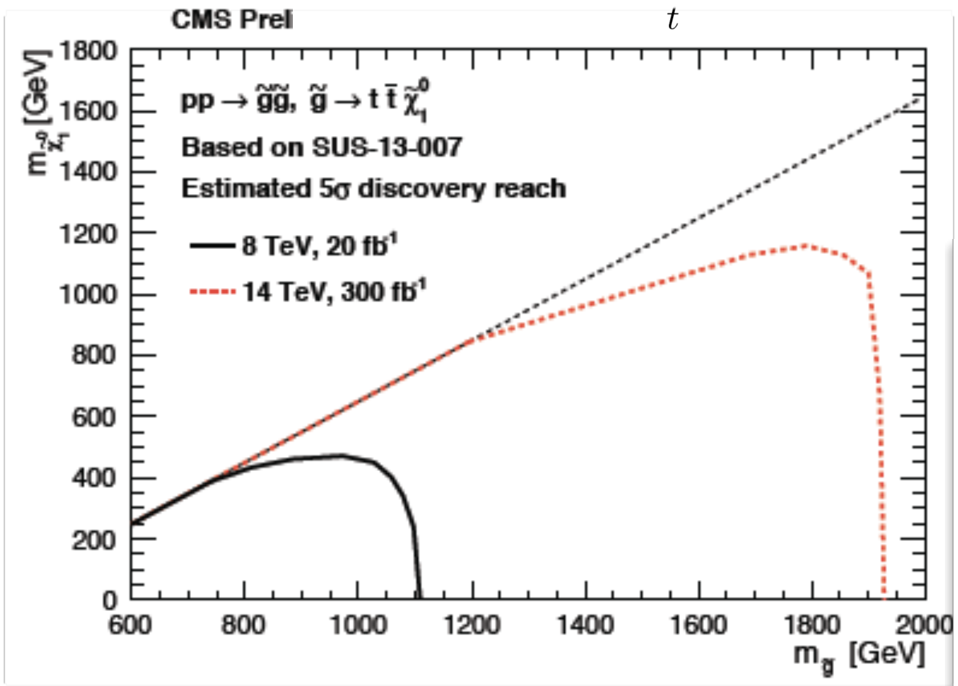
*similar results obtained by ATLA

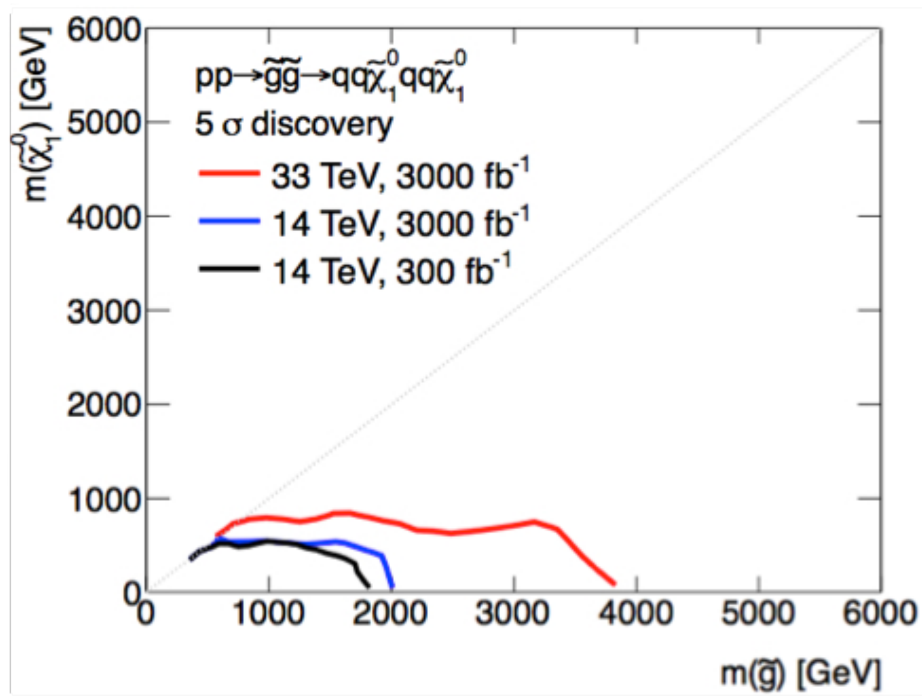


*similar results obtained by CMS

gain from now to 300/fb & beyond

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





SUSY at stages of LHC

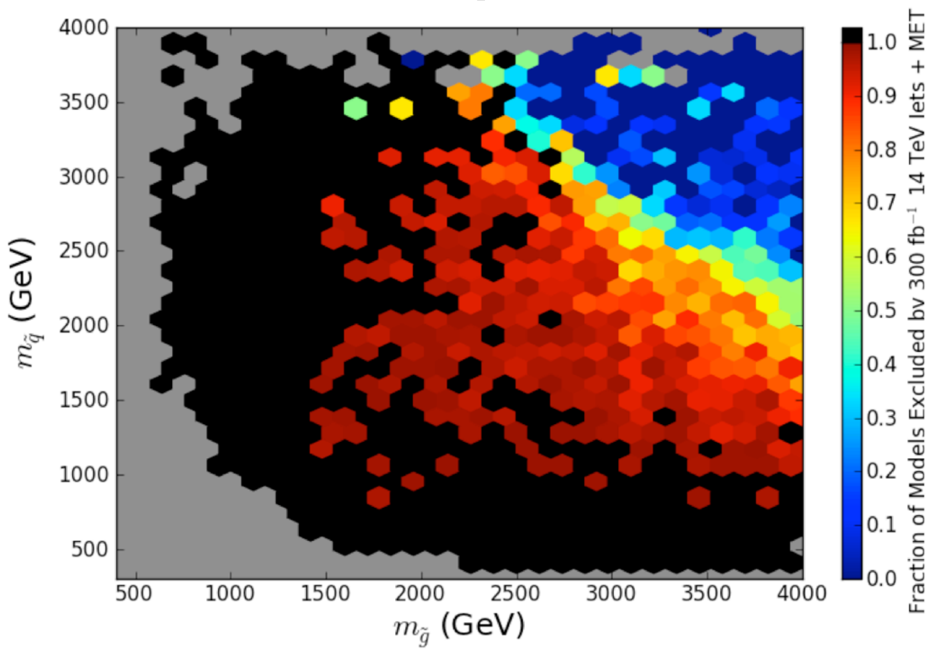
In the pMSSM survey of SUSY models

squark/gluino mass plane

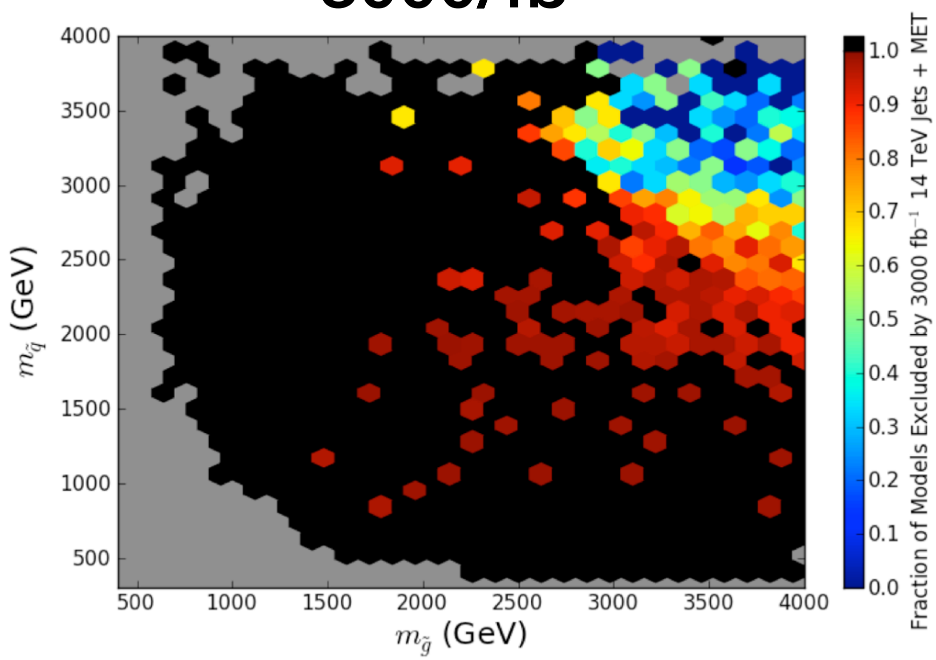
x2 from 8 TeV to 14 TeV (300/fb)

another ~ 30% to 3000/fb

300/fb



3000/fb

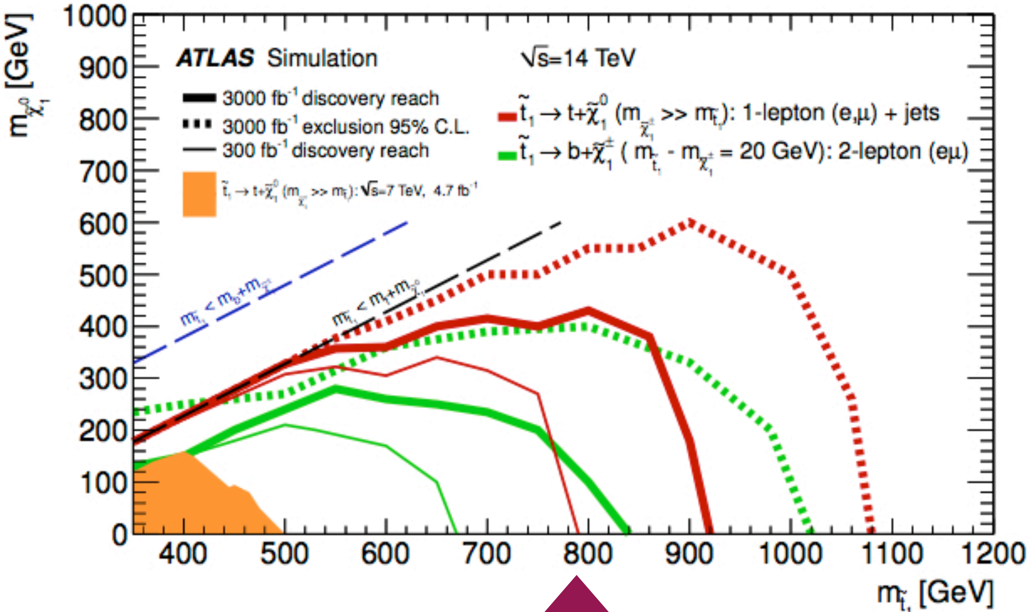


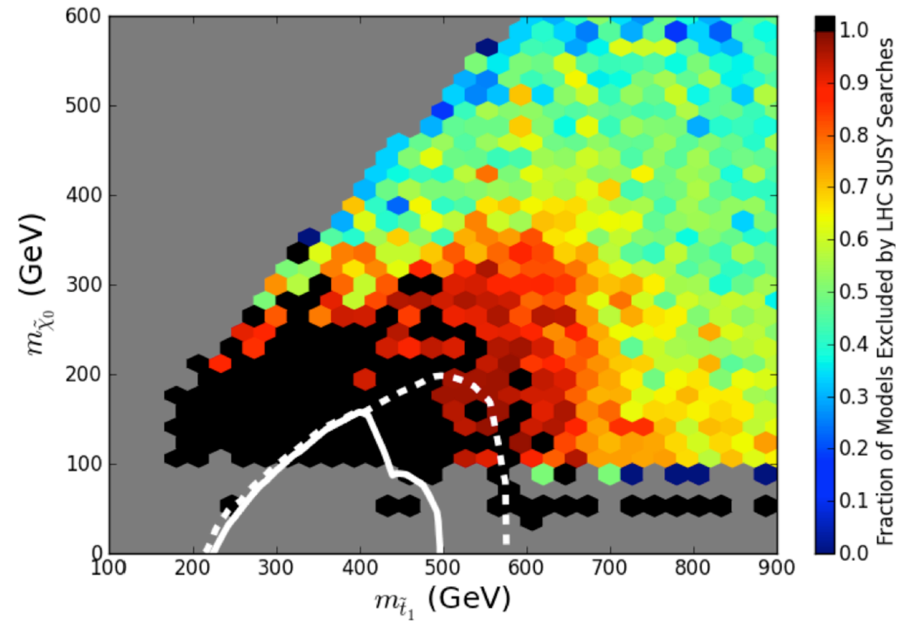
Note closing of loopholes in addition to increased energy reach.

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

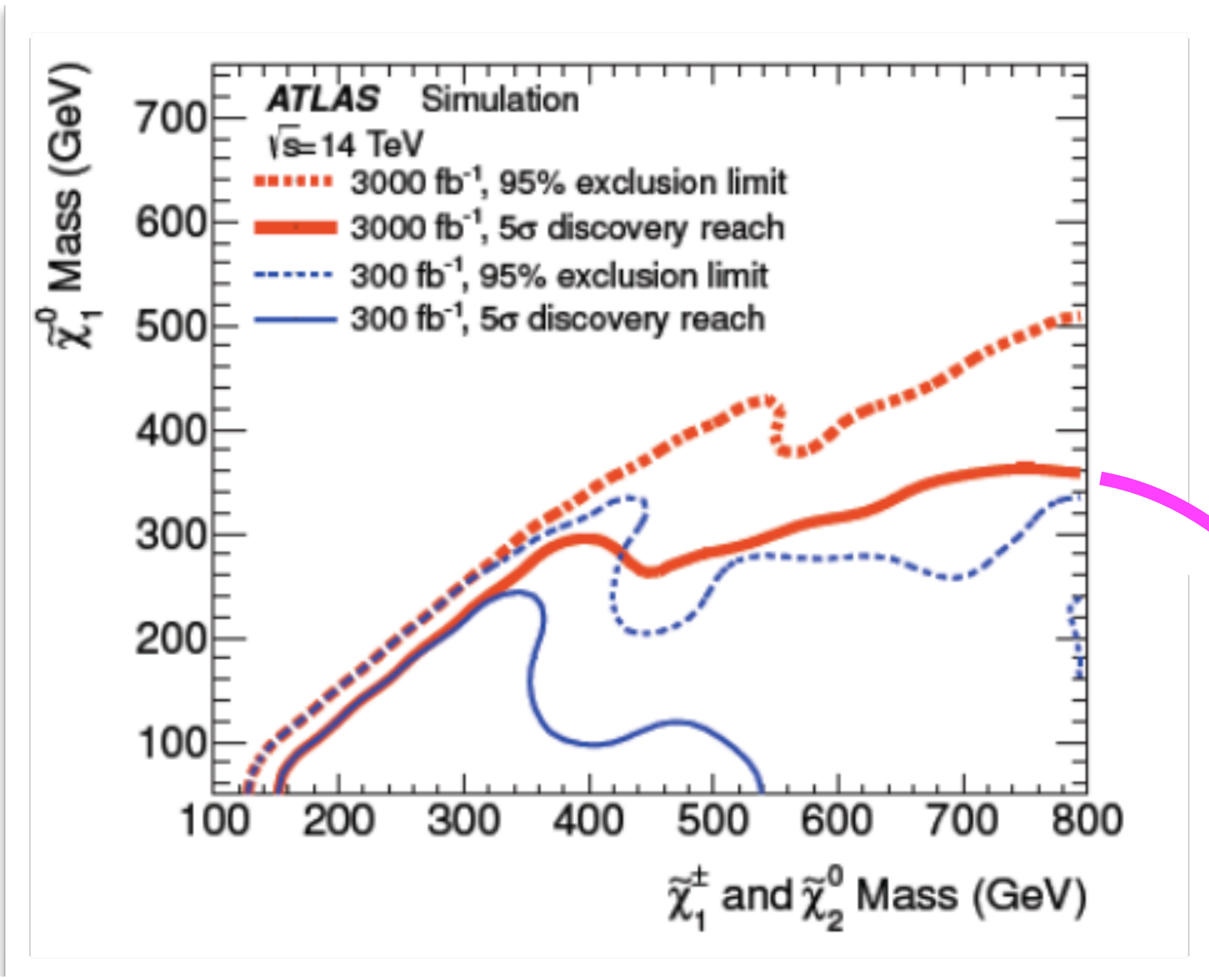
3000/fb reach
stop-> t + neutralino

Cahill-Rowley et al.

electroweakinos

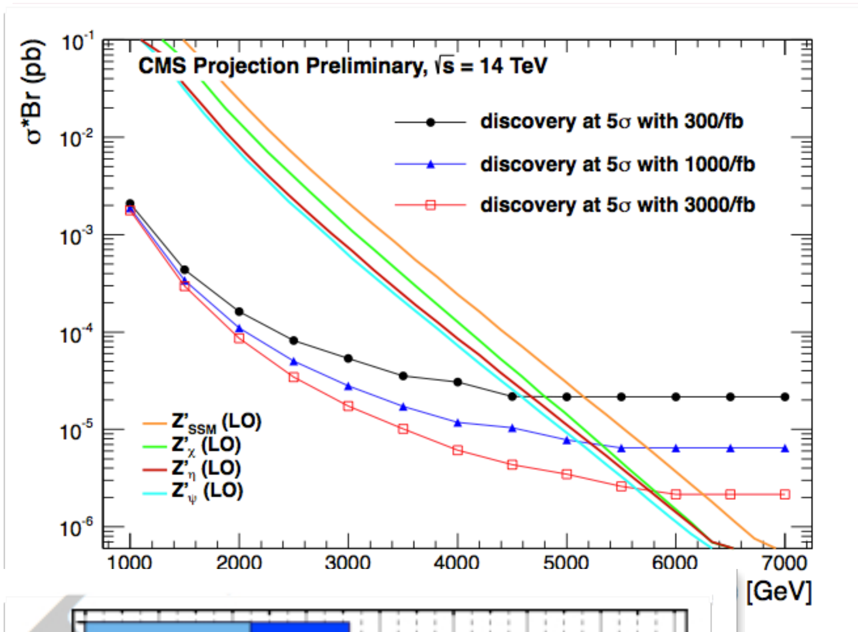
× 2 again...300/fb to 3000/fb

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

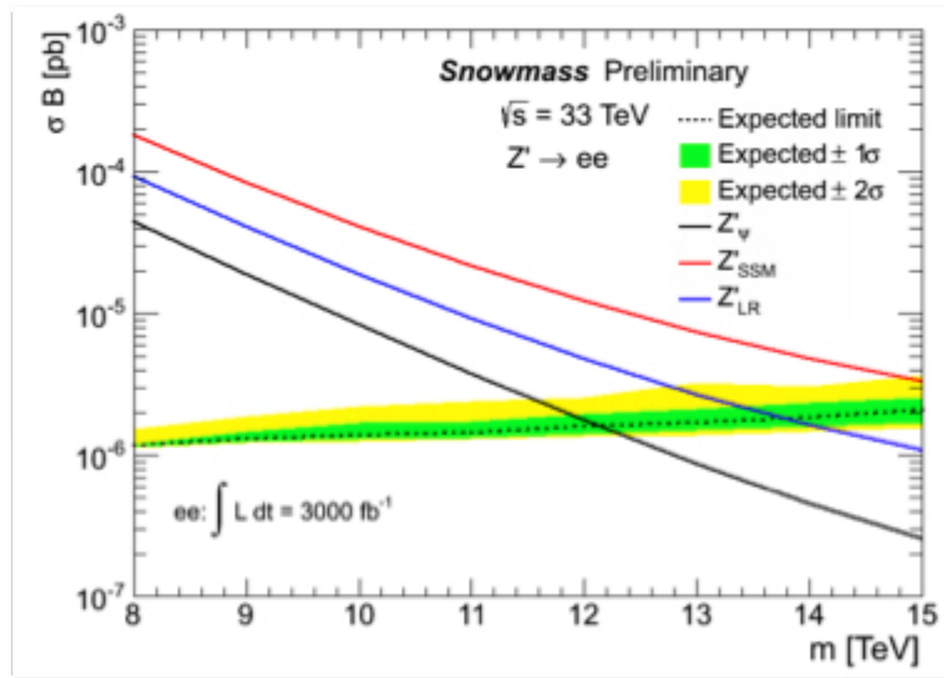


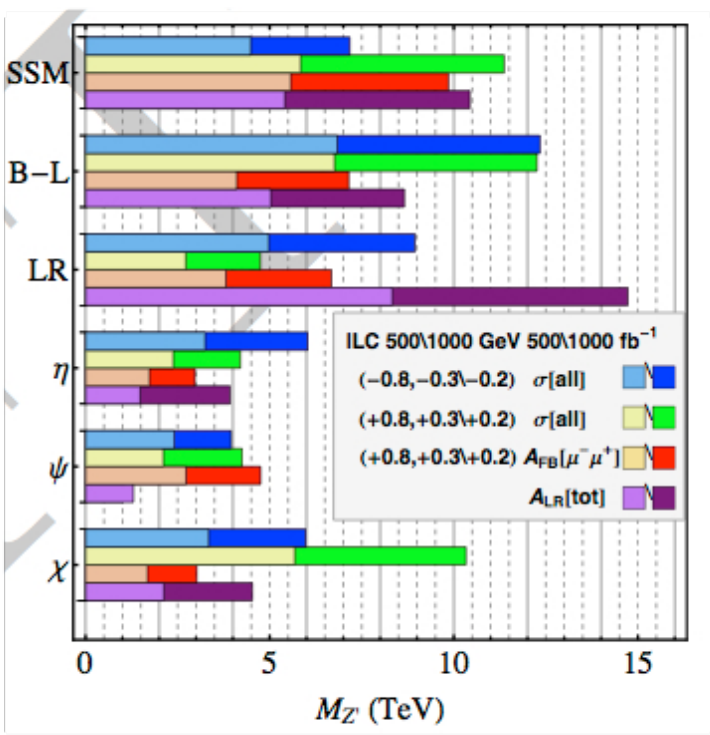
famously ran out of MC ooph

Z' sensitivity



5-6+ TeV Discovery range at 14 TeV LHC



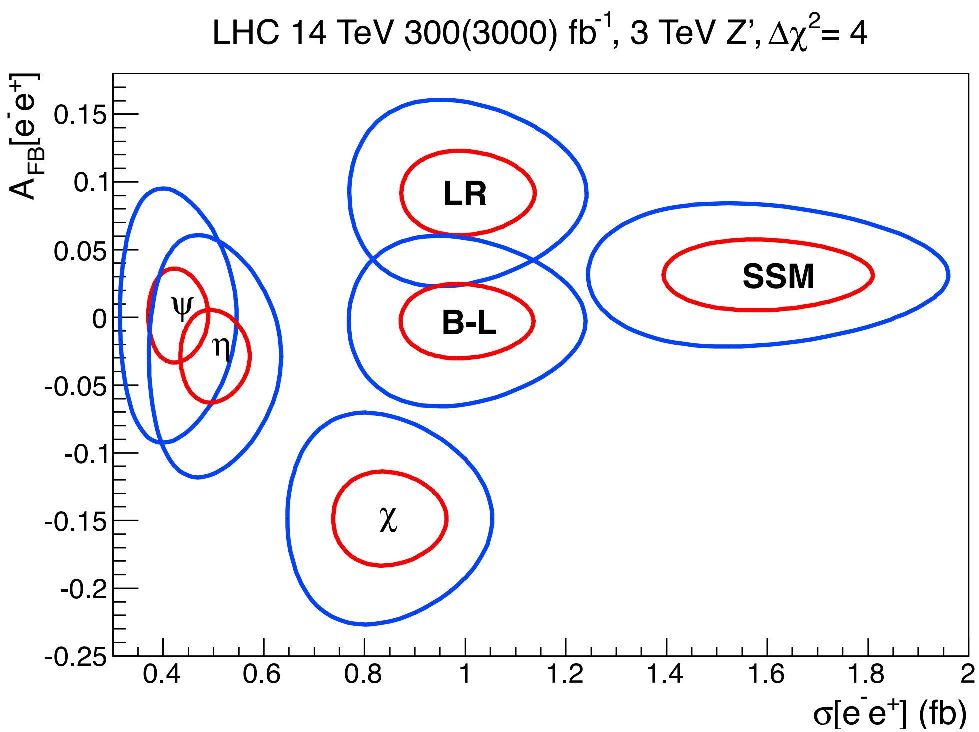


12-15 TeV limit range at 33 TeV pp

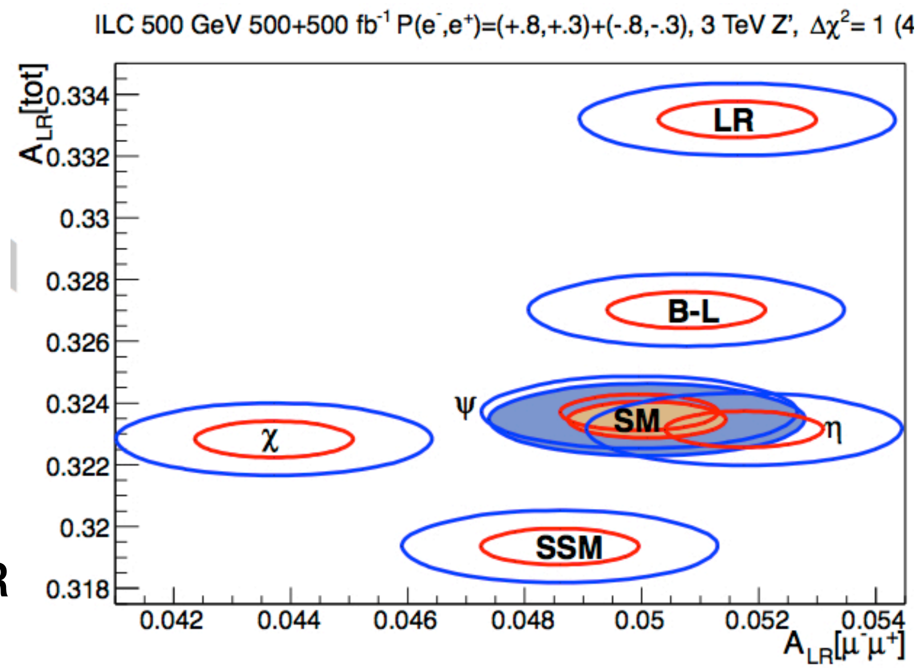
ILC asymmetry interference, beyond LHC

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}

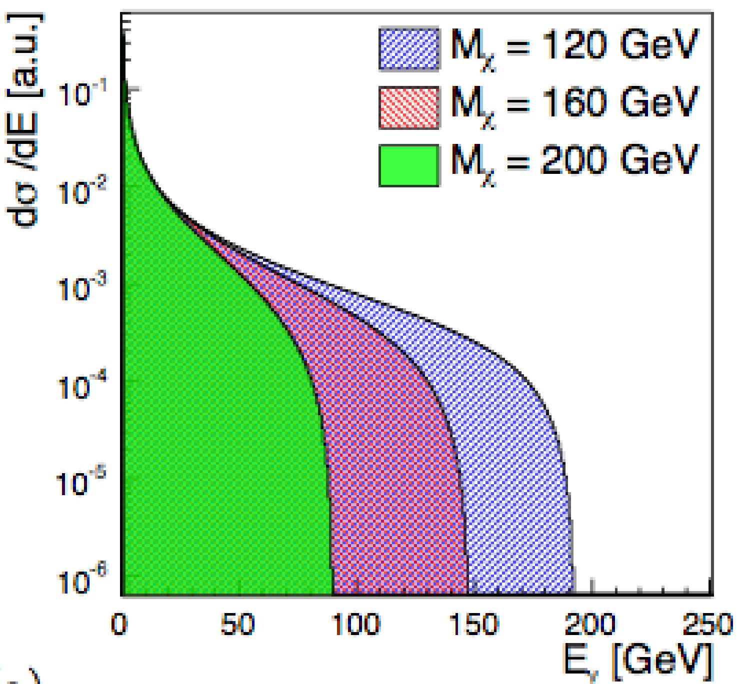
Brock/Peskin Snowmass 2013

Dark matter connection

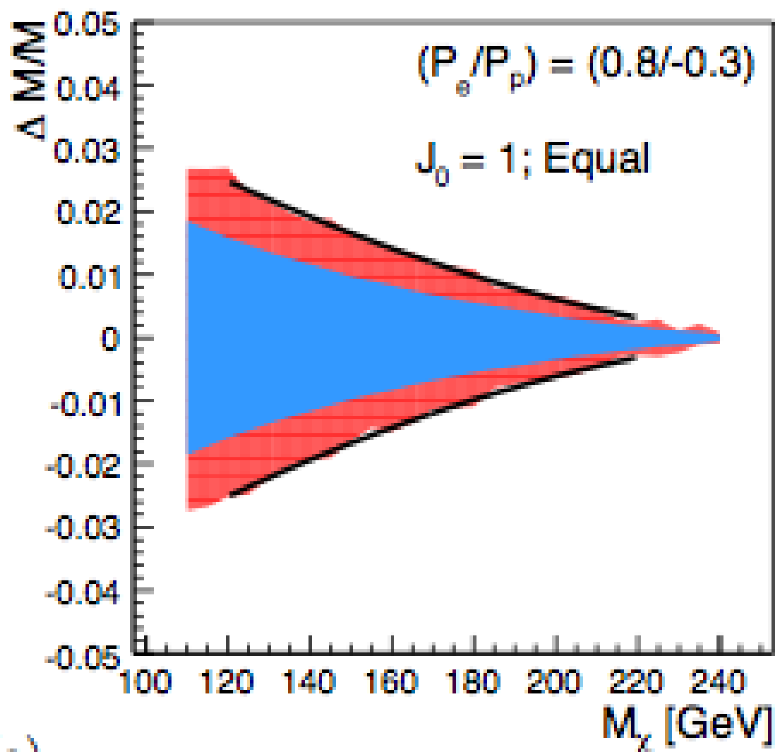
WIMP search at ILC in

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

polarization significant in controlling backgrounds



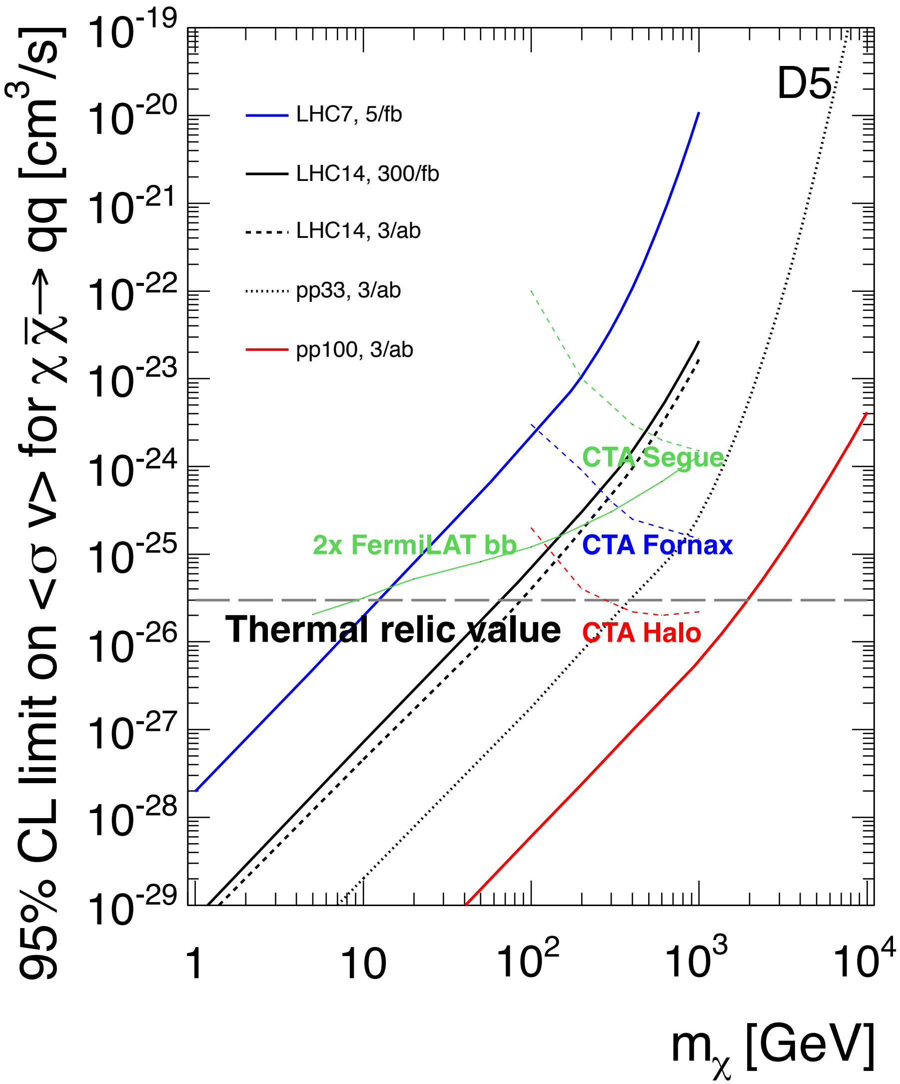
(a)



(a)

Dark Matter Connection

close the thermal relic range?



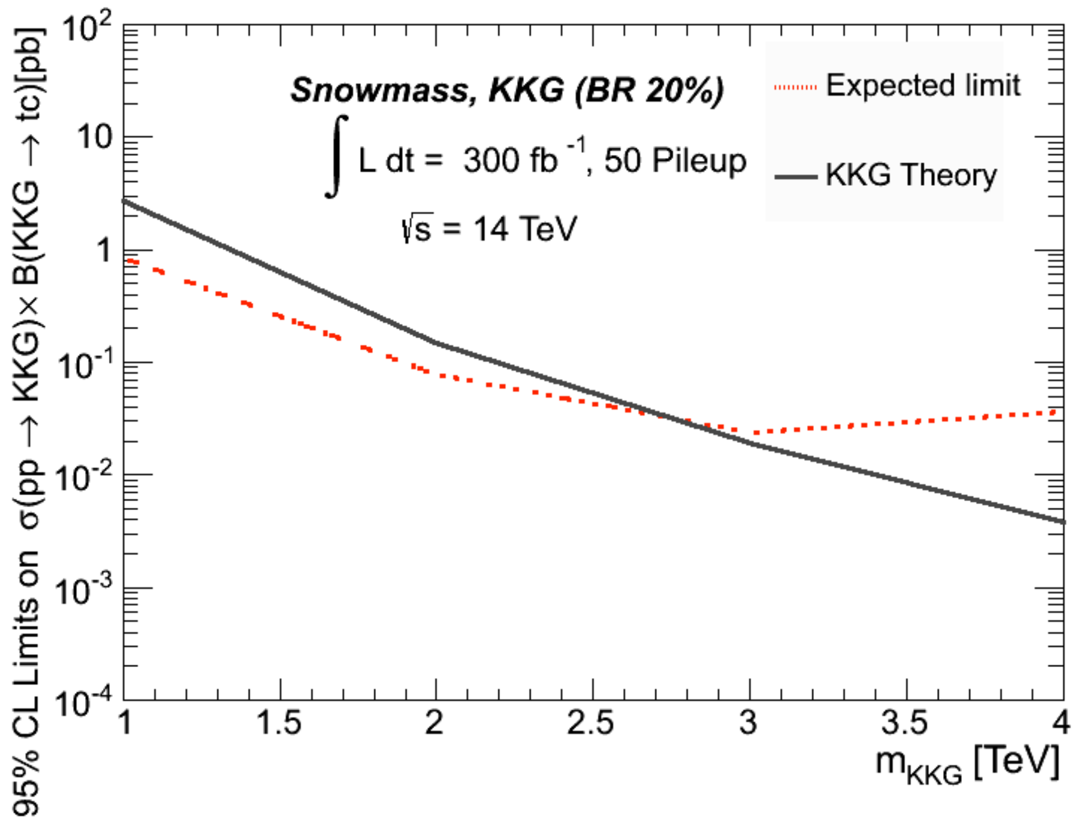
progressive increase in sensitivity

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

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

Flavor connection

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



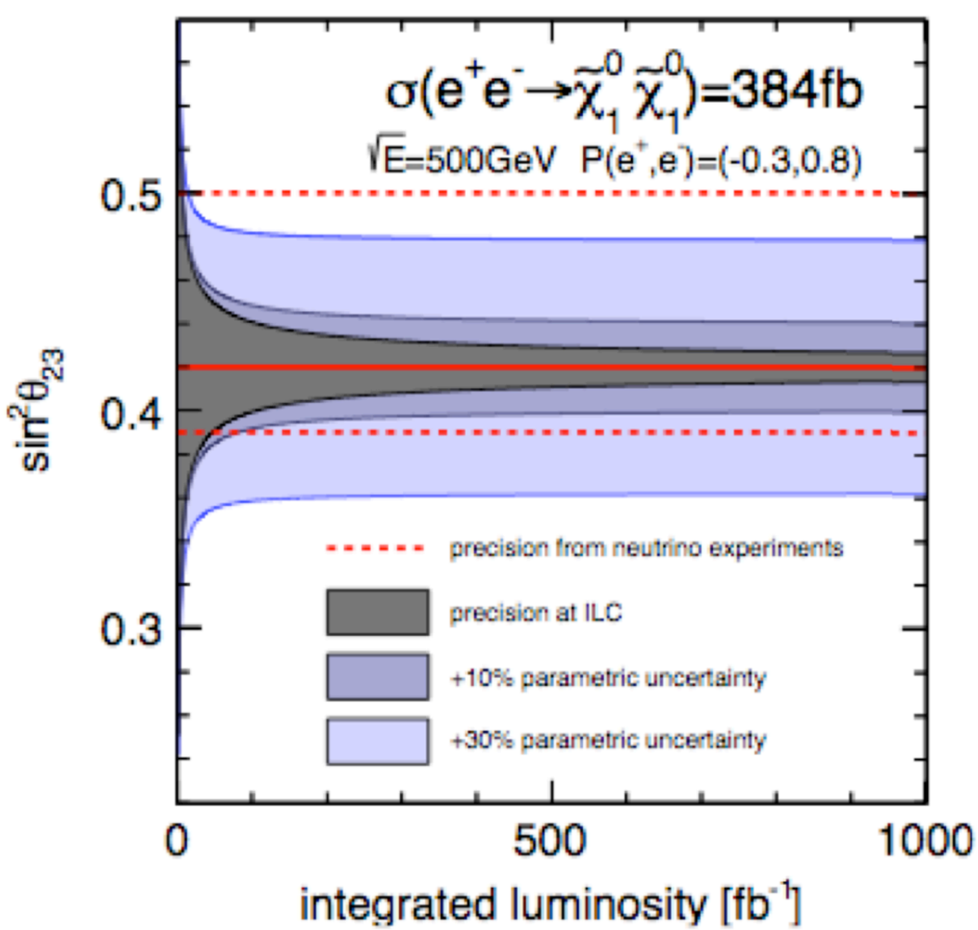
Schoenrock, Drueke, Alavarez-Gonzalez, Schwienhorst

Neutrino connection

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

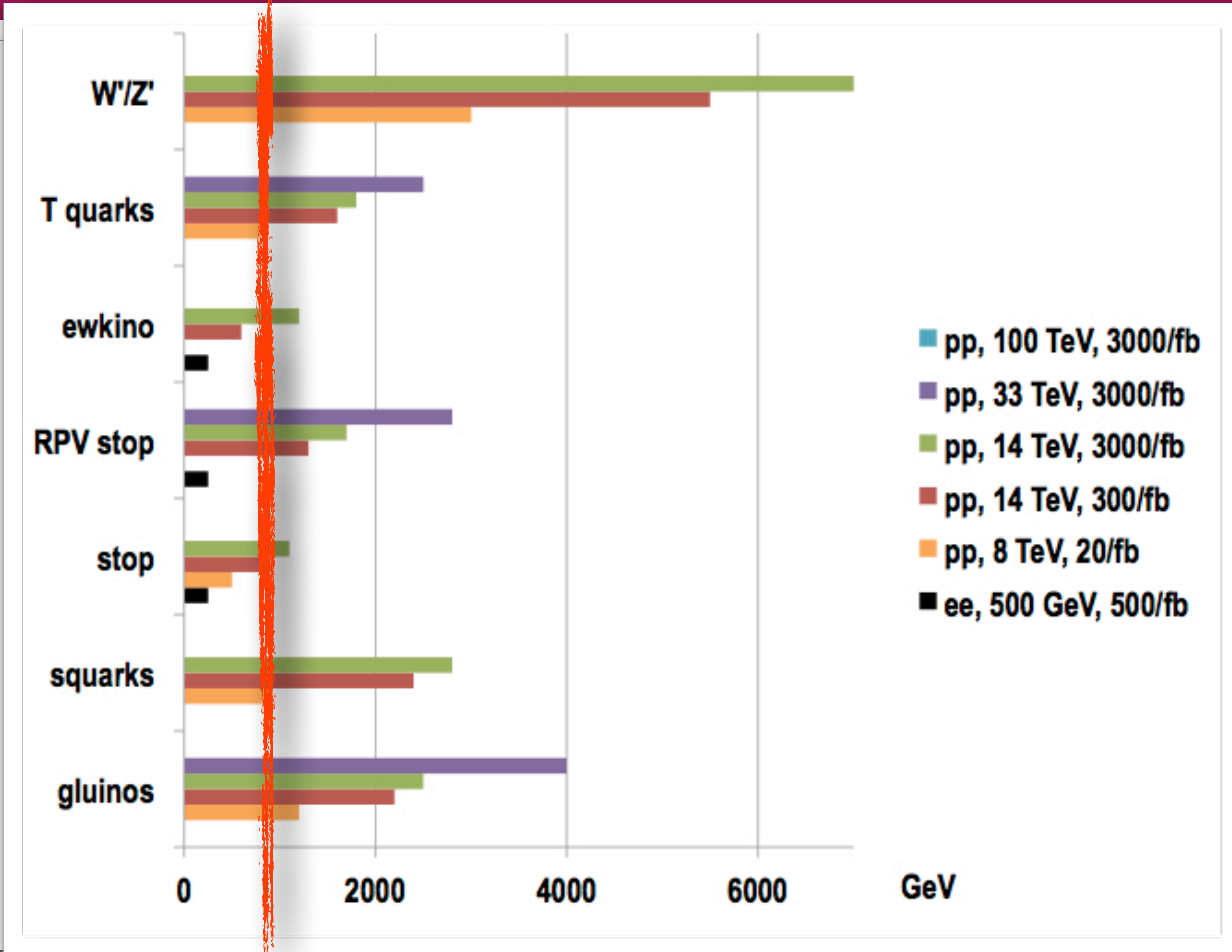
In "Type III seesaw," the θ_{23} controls the rate of the subleading decay $\tilde{\chi}_1^0 \to W + \mu$

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



Brock/Peskin Snowmass 2013

the TeV scale is in sight



Brock/Peskin Snowmass 2013

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

Reprise of the Physics Messages
&
The Scientific Cases for:

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?

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   - There are strategies at LHC for these improvements.
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2. alphas error ~ 0.1% is achievable
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Origin of matter

Unification

Elementary?

P1 precision program enabling the energy frontier

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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**

ILC, up to 500 GeV

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

Higgs EW Top QCD NP/flavor

ILC 1 TeV

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 13% accuracy**
3. Model-independent search for extended Higgs states to 500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. **Model-independent search for new particles with coupling to gamma or Z to 500 GeV**
6. Search for Z' using e+e- -> f 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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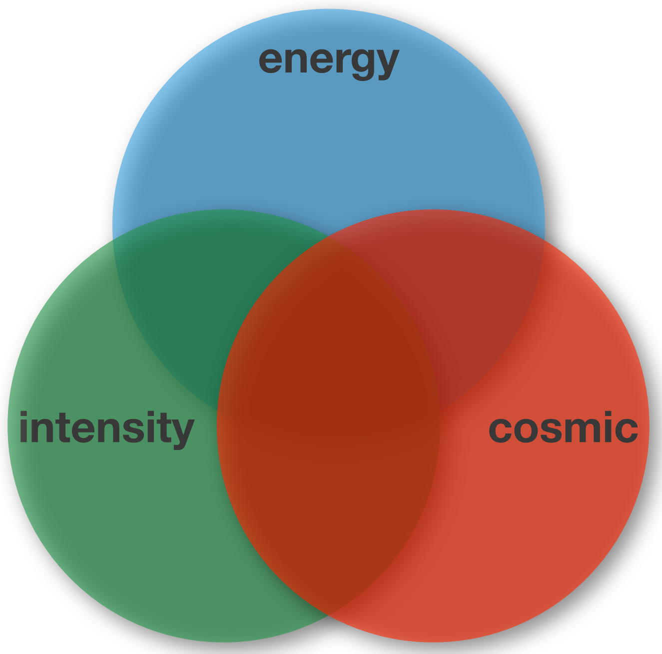
Three Frontiers

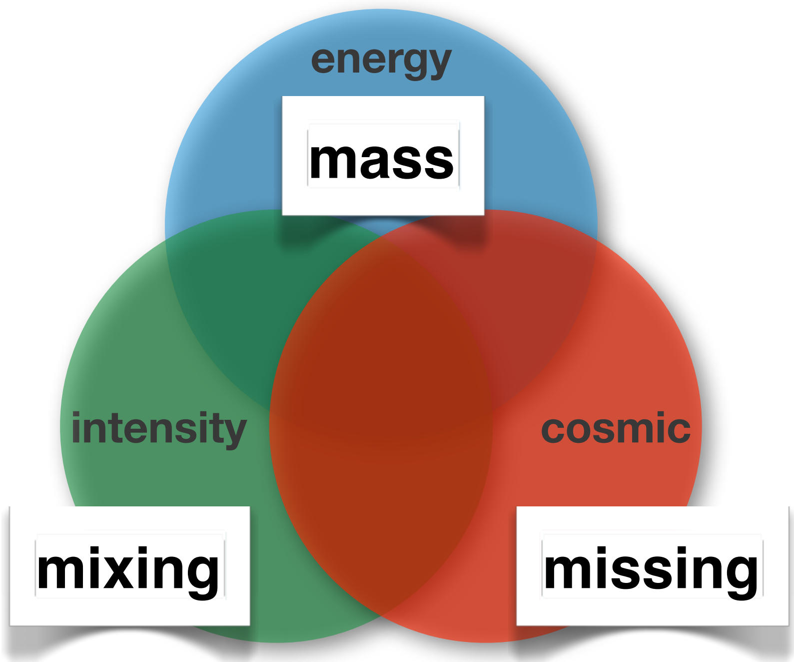
those circles are pithy

but they force us to be tribal



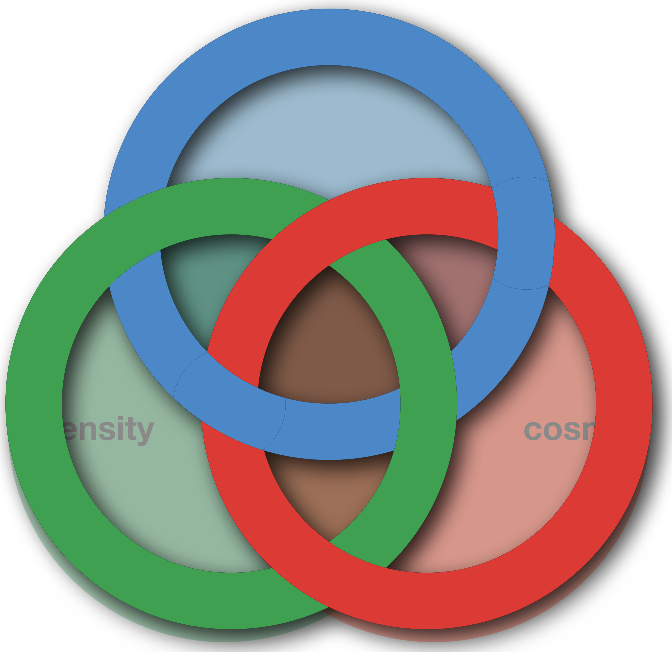
those circles are pithy

and encourage silly things like:



scientific reality

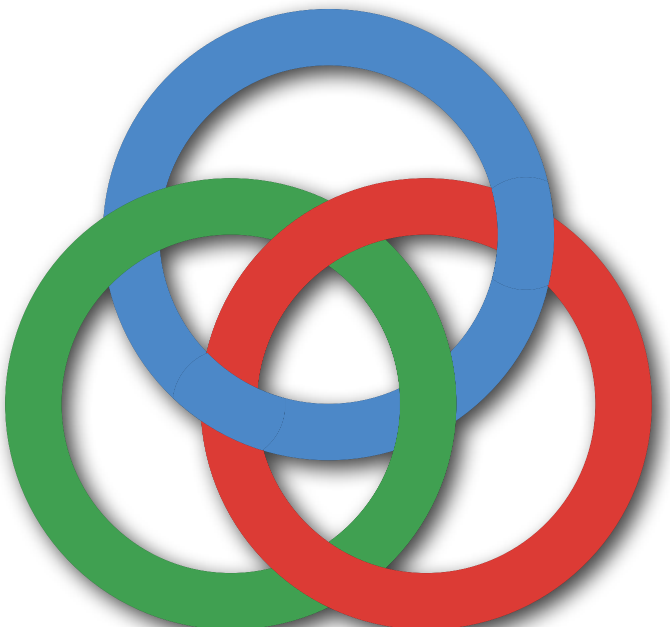
is more complex



idea stolen from Sasha Vaniachine

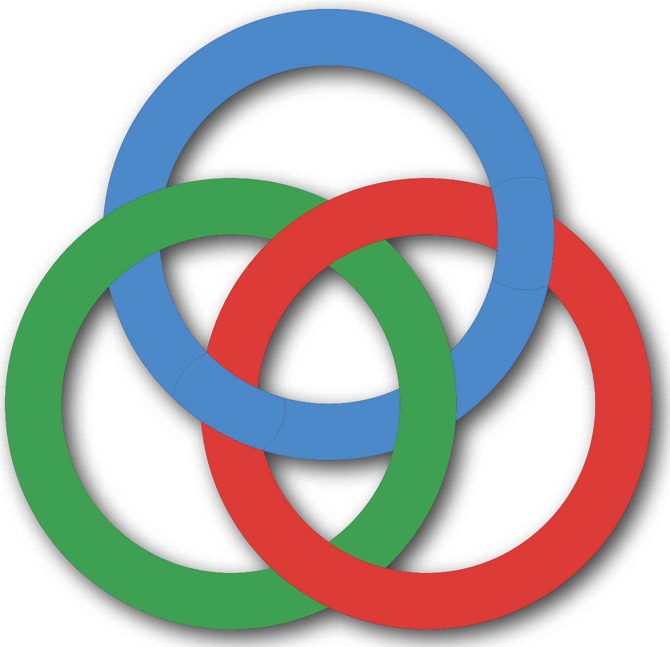
scientific reality

is more complex



a great scientific nation

plans for balance:



precision experiments --->
discovery through inducing quantum loops

neutrino experiments --->
discovery by inducing quantum mixing

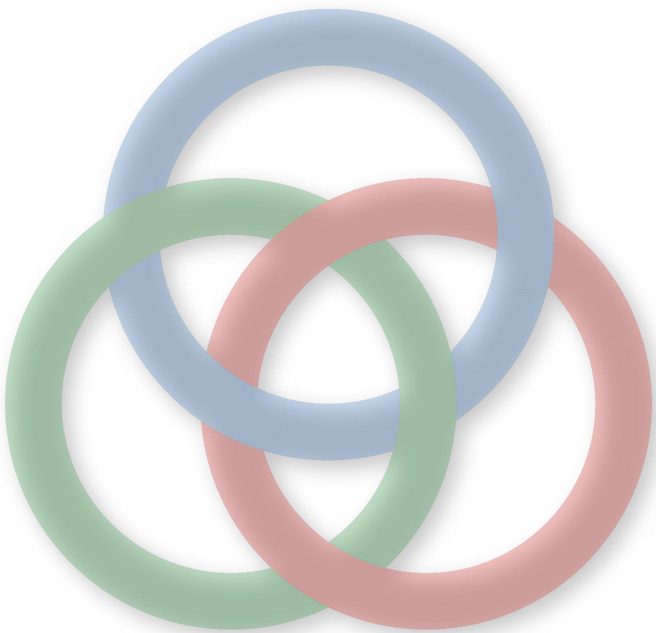
astrophysical experiments --->
discovery by capturing cosmic quanta

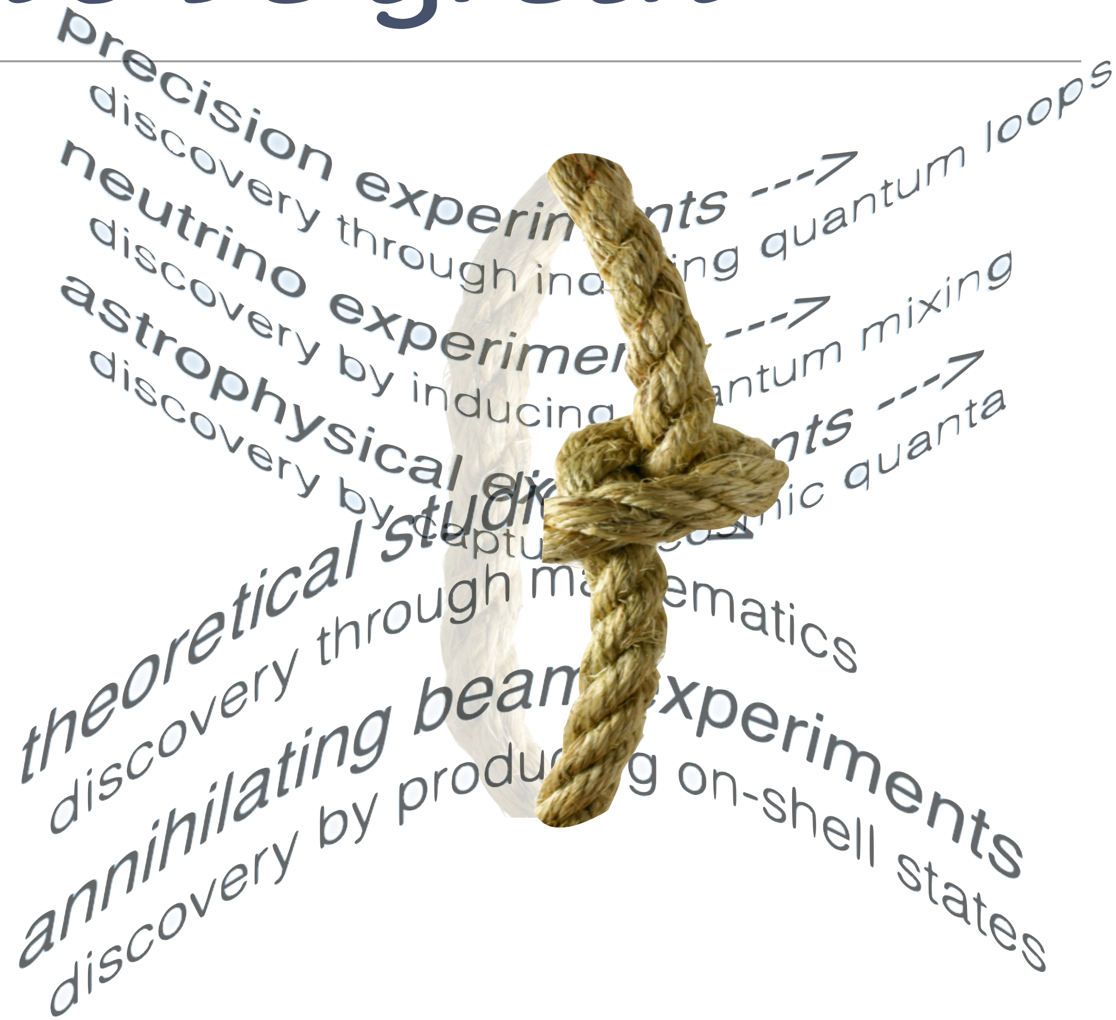
theoretical studies --->
discovery through mathematics

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

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Jon Rosner and the DPF Executive Committee

Snowmass is special.

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too bad about the 2014 basketball season

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Thanks, Michael!

Snowmass ILC running

sorry.

TDR = A+B+E

SNOWMASS = A+B+C+D & A+B+C+D+F