Snowmass 2013

Energy Frontier

2013 US LHC Users Organization Annual Meeting
November 8, 2013

Chip Brock

Michigan State University

Snowmass 2013

Energy Frontier

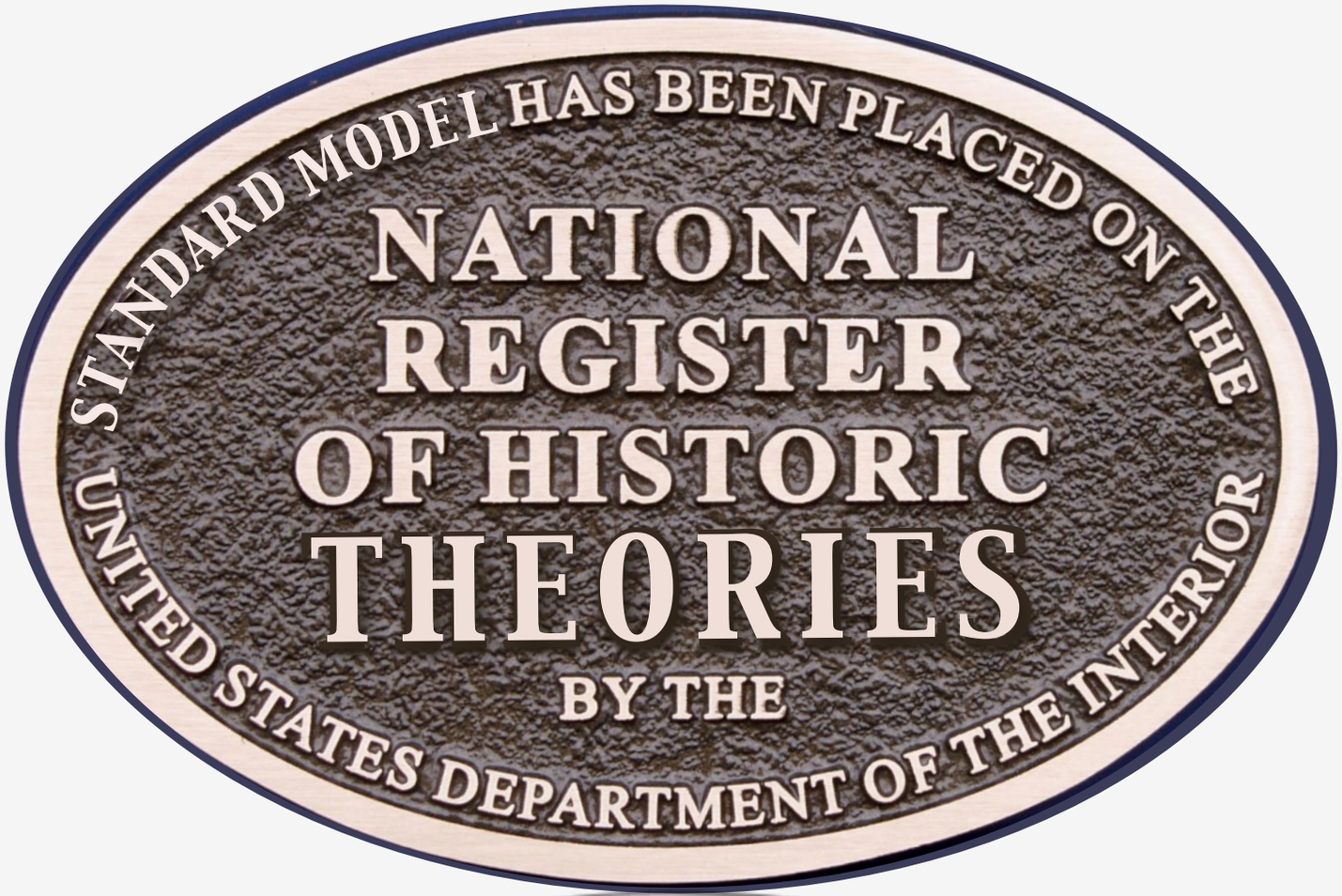
The Orthopedic Frontier

2013 US LHC Users Organization Annual Meeting
November 8, 2013

Chip Brock

Michigan State University

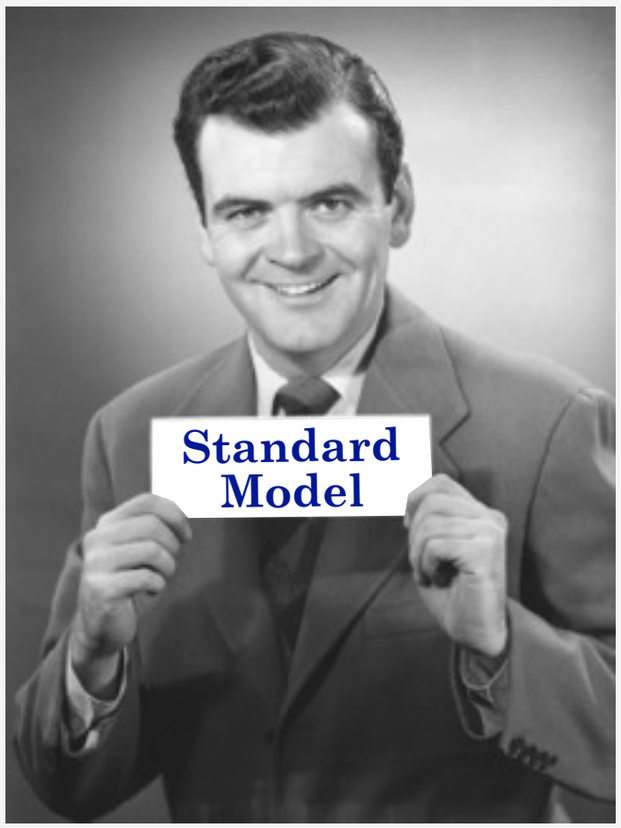
- 30,000 ft View
- the Snowmass Process
- The Energy Frontier process
- reports from the subgroups
  - themes
  - content
  - message
- cases for future programs


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

30,000 ft View

what's great

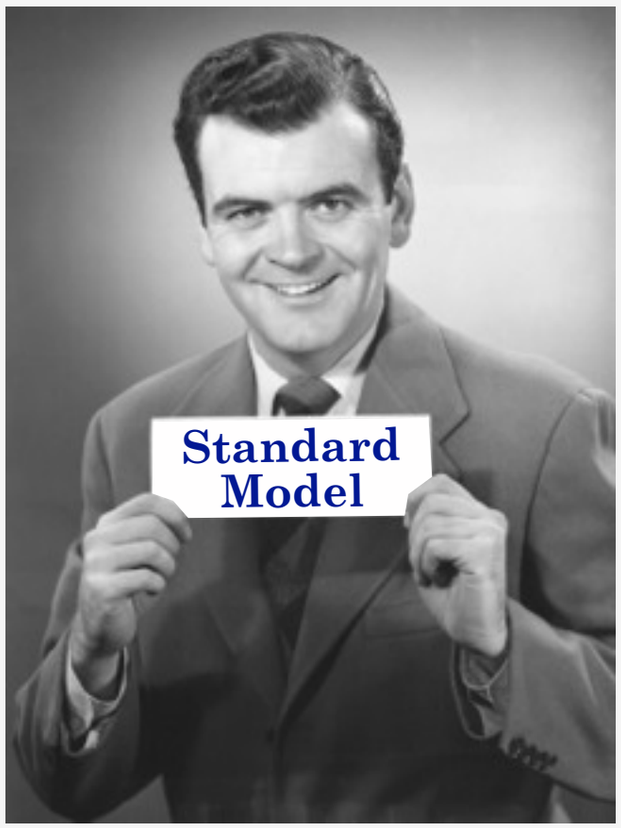
about the Standard Model?



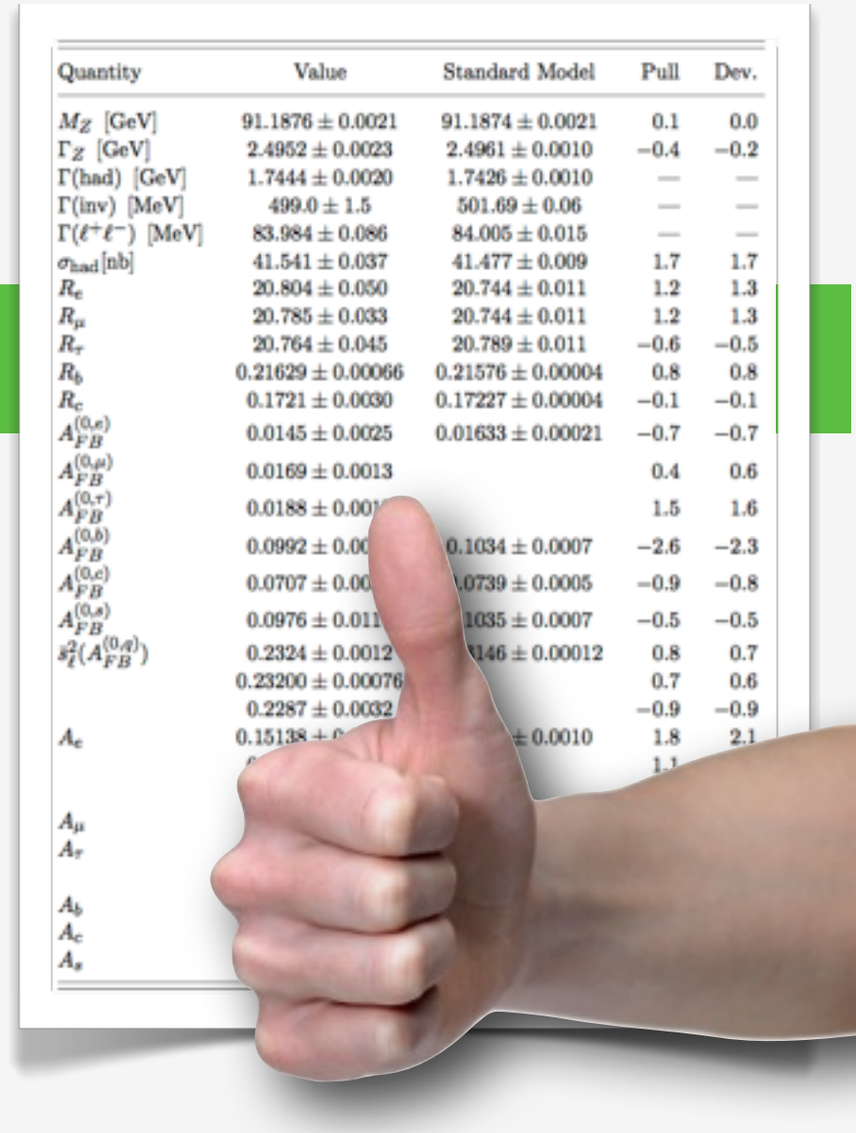
the Gauge Principle

what's great

about the Standard Model?



the Gauge Principle



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
Γ(had) [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
Γ(inv) [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
$\sigma_{\rm had}$ [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 ± 0.00		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.00	0.1034 ± 0.0007	−2.6	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.00	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.011	1035 ± 0.0007	−0.5	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	3146 ± 0.00012	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	± 0.0010	1.8	2.1
			1.1	
A_μ				
A_τ				
A_b				
A_c				
A_s				

The most accurate and precise scientific model in history

H

the Ot object is not your father's particle!

particle physics

HIGGs
HIGGS

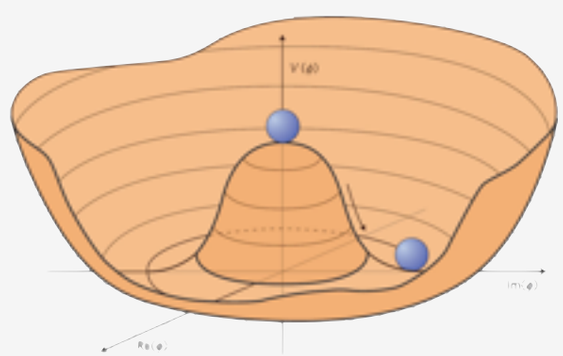
what's embarrassing

about the Standard Model?

- the nature of the Higgs particle

- the Higgs Story

$$\phi \rightarrow v + h$$



Deep Puzzles

known for a long time

theoretical puzzles...

experimental puzzles...

conceptual puzzles...

The Sociology Frontier

never theorize

hints welcome

theory guarantees new physics

never
theorize

hints
welcome

theory
guarantees
new physics

Higgs particle

- strange.

How many things are only one thing?

FAMILIES

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$W^{\pm}, Z^0, \gamma, g$$

an elementary *singelton*

singleton | ˈsiNGgəltən |

noun

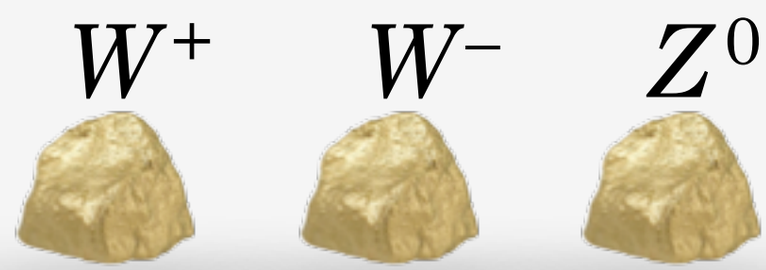
a single person or thing of the kind under consideration: *splitting the clumps of plants into singletons.*

- [often as modifier] a child or animal born singly, rather than one of a multiple birth: *singleton boys.*
- (in card games, esp. bridge) a card that is the only one of its suit in a hand.
- Mathematics & Logic a set that contains exactly one element.

ORIGIN late 19th cent.: from SINGLE, on the pattern of *simpleton* .

- quantum numbers of the vacuum

is it alone?



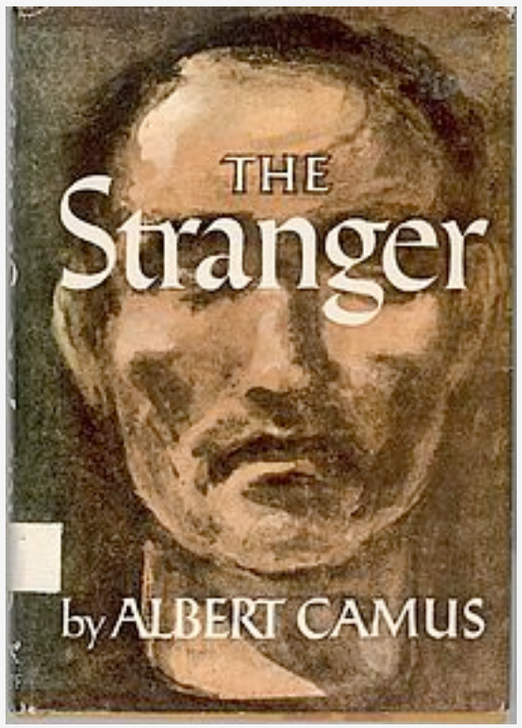
is it alone?

a part of a family?

different in tiny details?

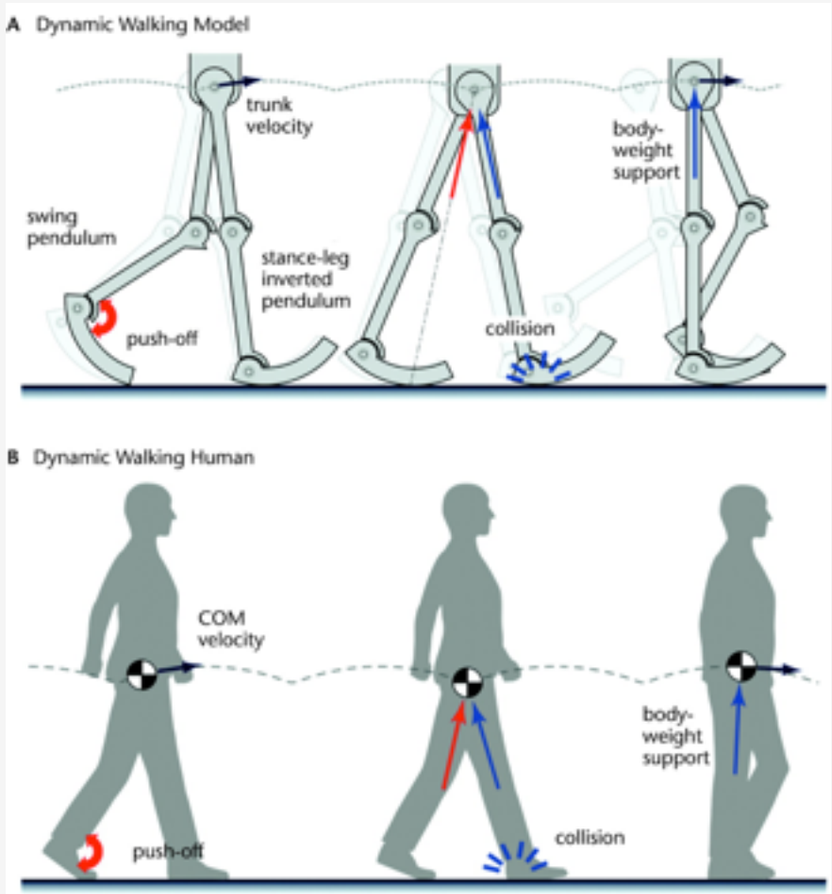
Higgs story

stranger.



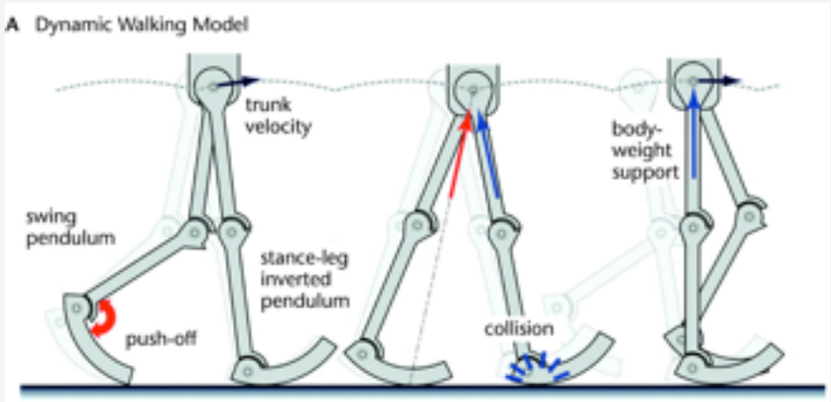
SM is an effective theory

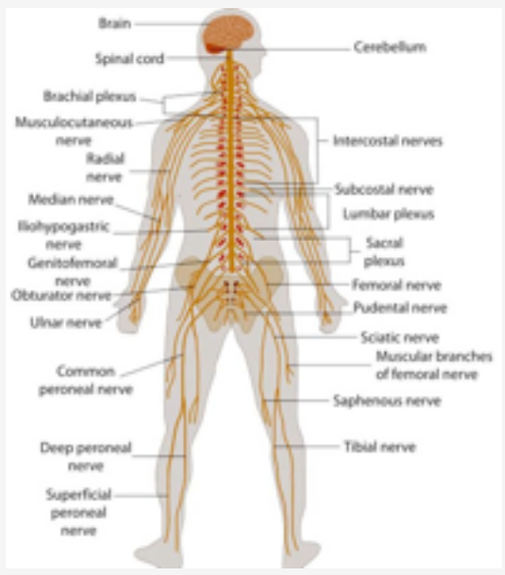
I can draw free-body diagrams and make a SM of walking

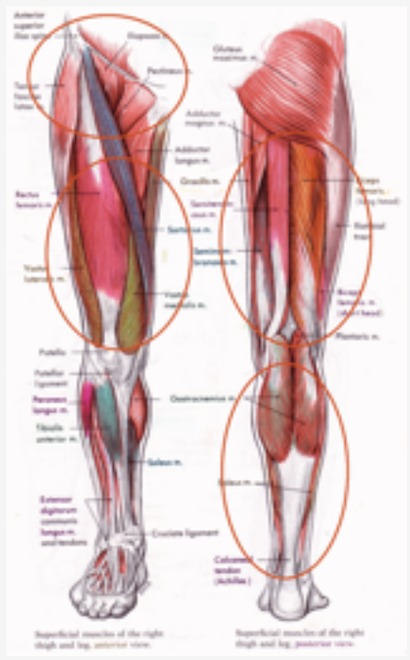


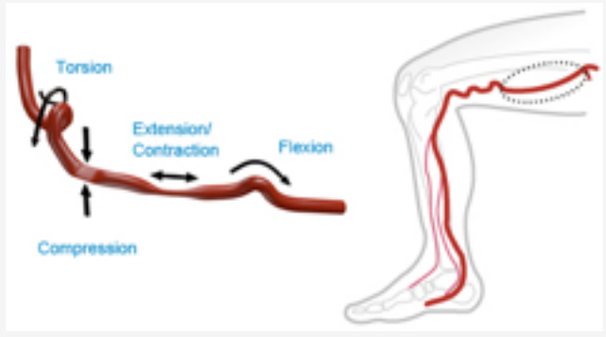
SM is not a dynamical explanation of anything

I can draw free-body diagrams and make a SM of walking









But it's not the actual physiology of walking!

Much confusion centers on

- the “Higgs” Potential.

  Much of our future work will be unpacking it:

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

vacuum energy

Higgs mass

instability?

Yukawa couplings

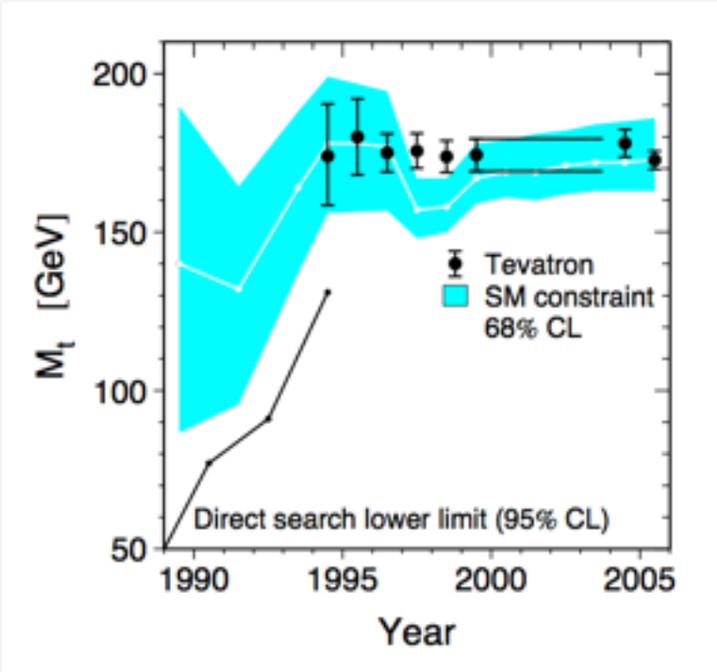
LOOPS

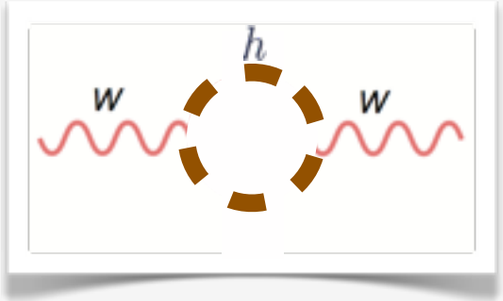
not mysticism

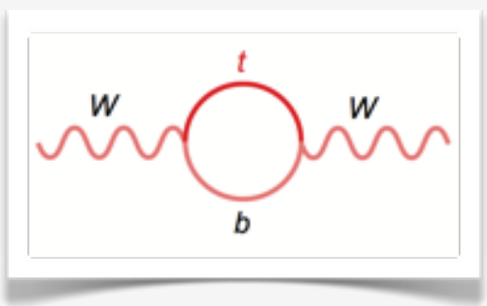
- “Loops” are at the core of our language

  traditionally highly predictive

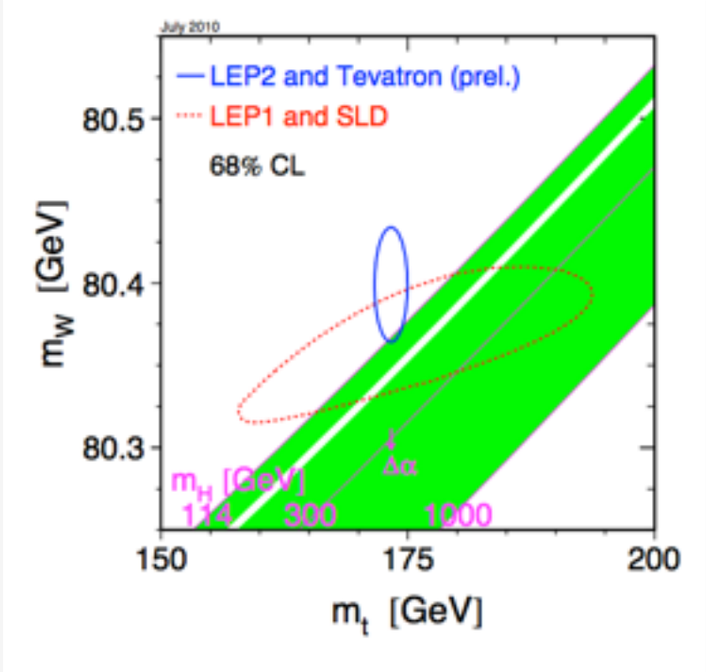
  highly accurate



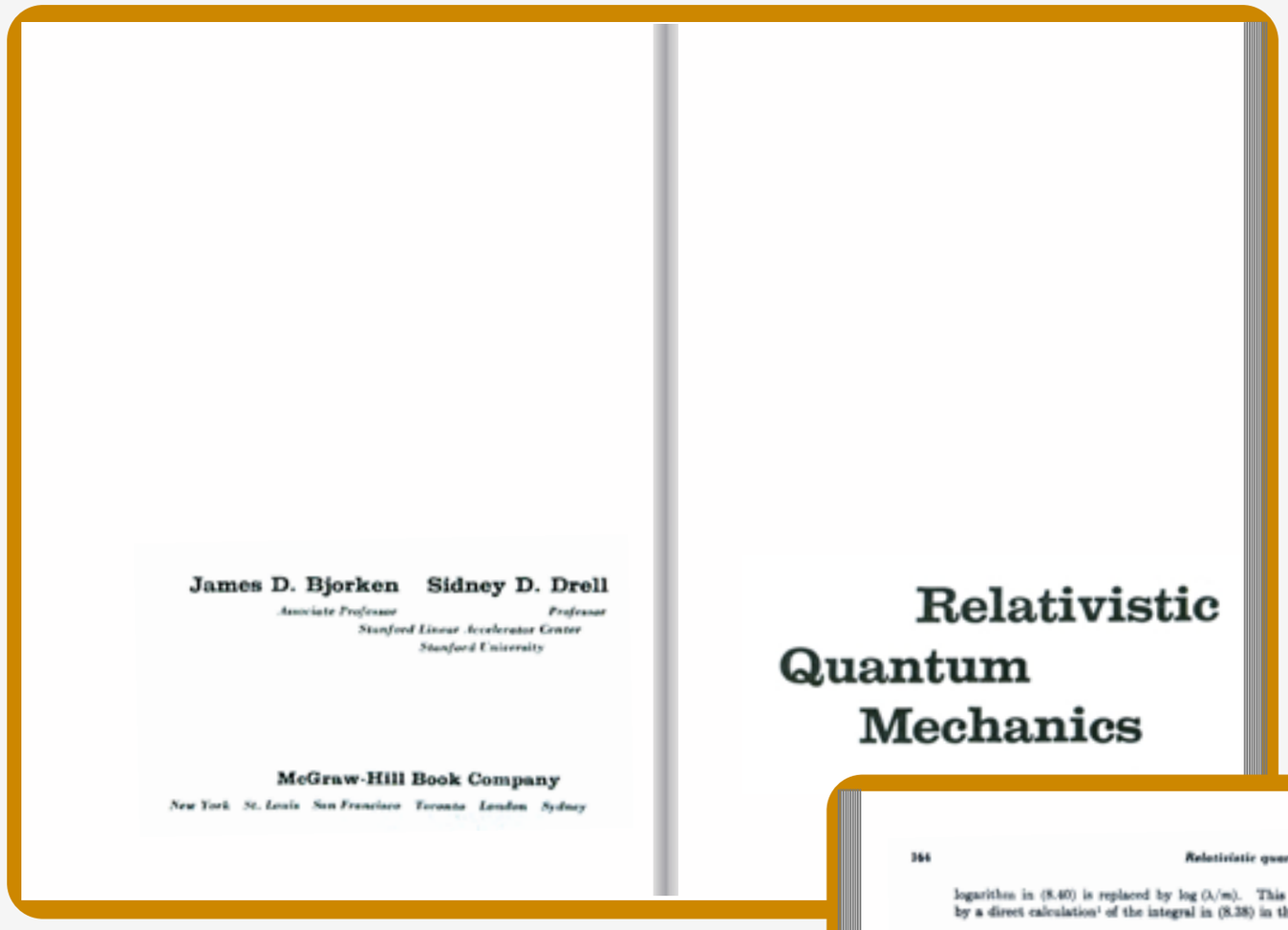




EW fits: top quark



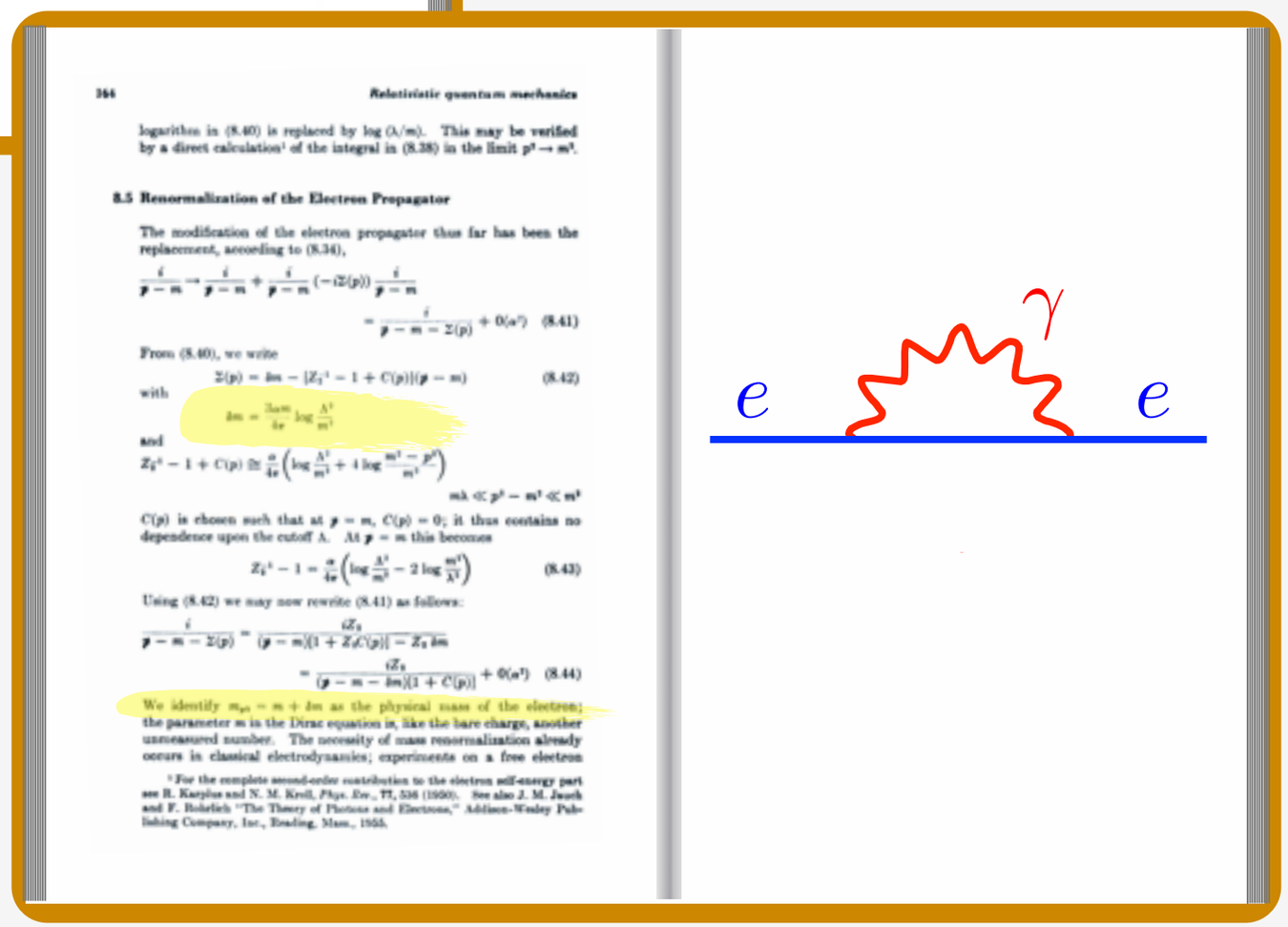
EW fits: Higgs boson



symmetry

dimensionless

$$\delta m = \frac{3\alpha m}{4\pi} \log\left(\frac{\Lambda^2}{m^2}\right)$$

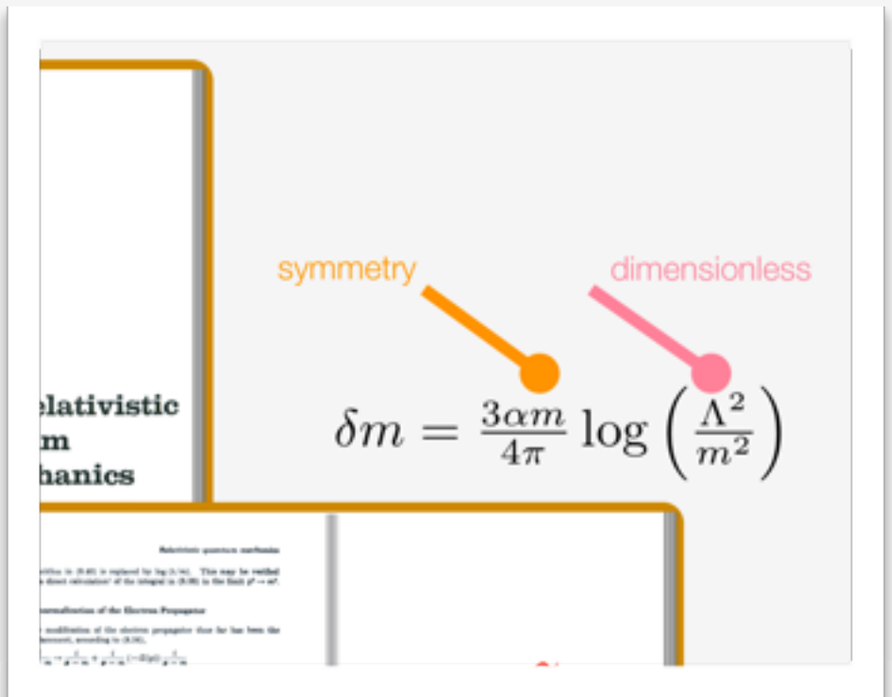


How about a spin 0, elementary particle?

- ϕ with mass μ

$$\mu^2 = \mu_0^2 + \left(\phi \quad \psi \quad \phi \right)$$

spin 0 loops:



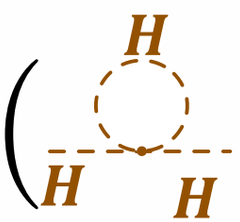
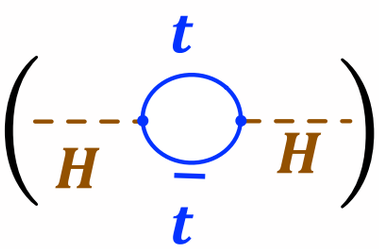
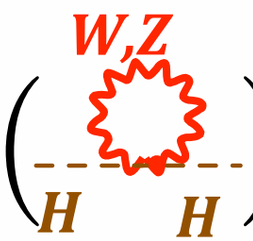
$$\mu^2 = \mu_0^2 \pm \left(\frac{\text{coupling}}{\text{number} \times \pi\text{'s}} \right) \Lambda^2$$

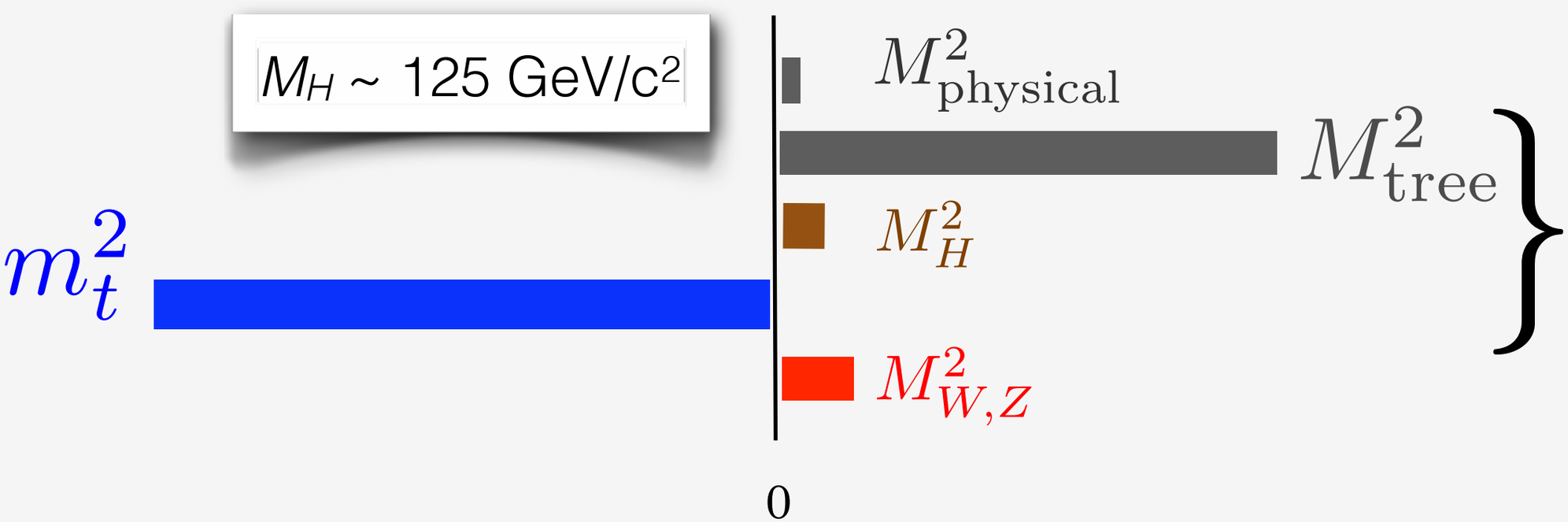
no mass factor

dimensionfull

An enormous fine-tuning

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

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



un-fine tuning?

if next scale is

■ the Planck Scale?

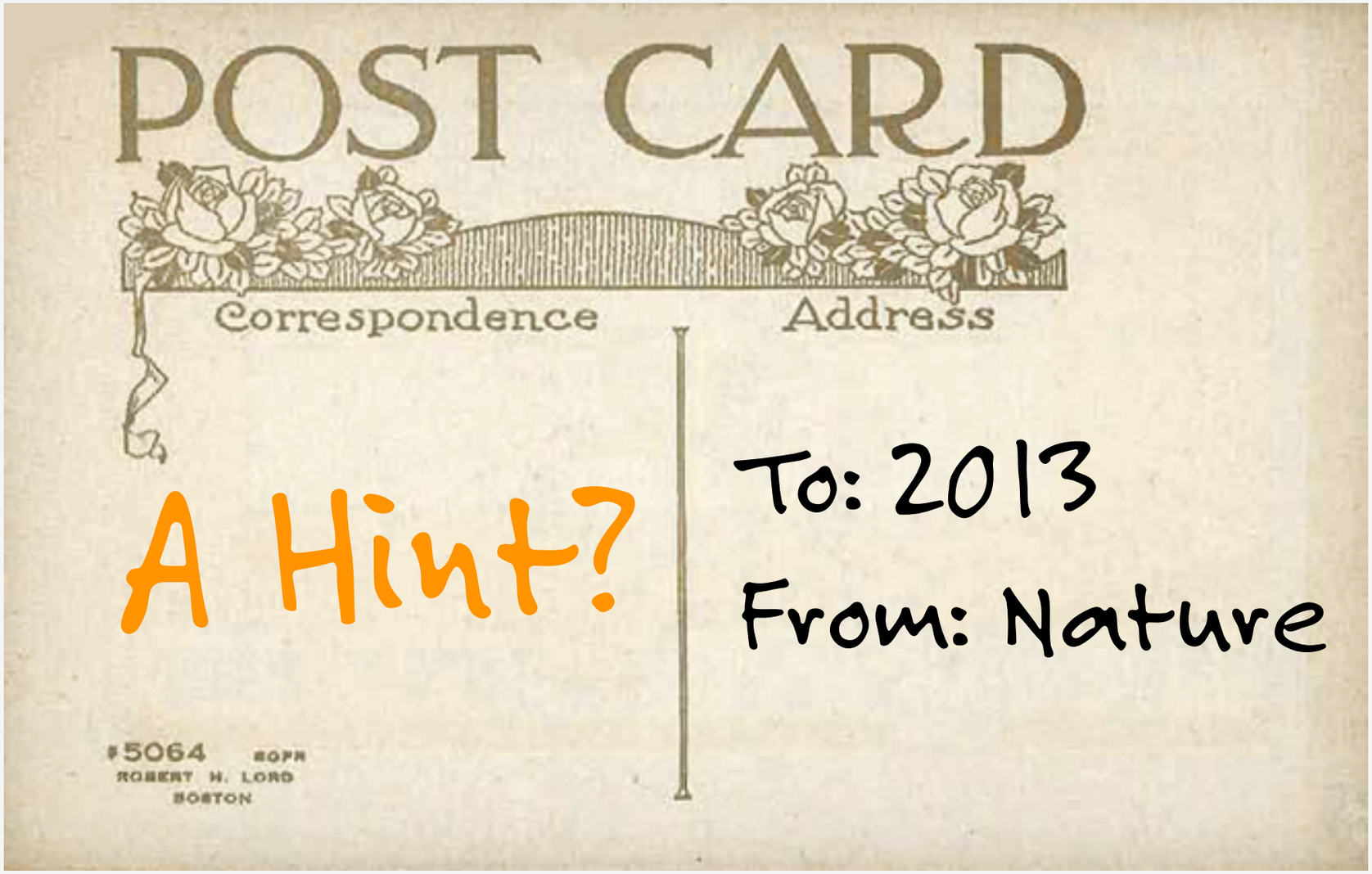
$$M_H^2 =$$

$$\mathbf{nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n60{,}000}$$

$$\mathbf{- nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n44{,}375}$$

$$M_H^2 = \mathbf{125^2}$$

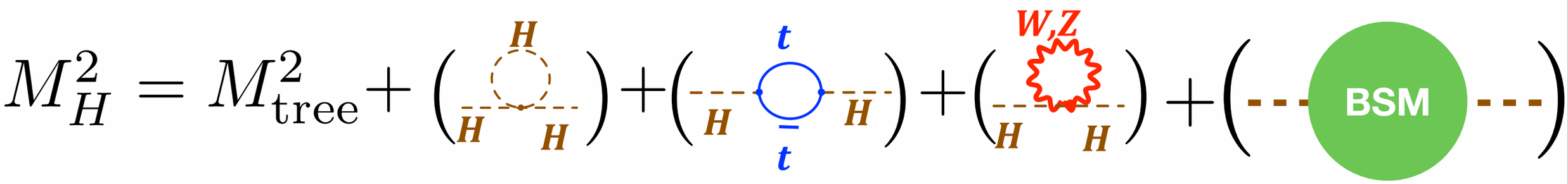
“coincidence”?

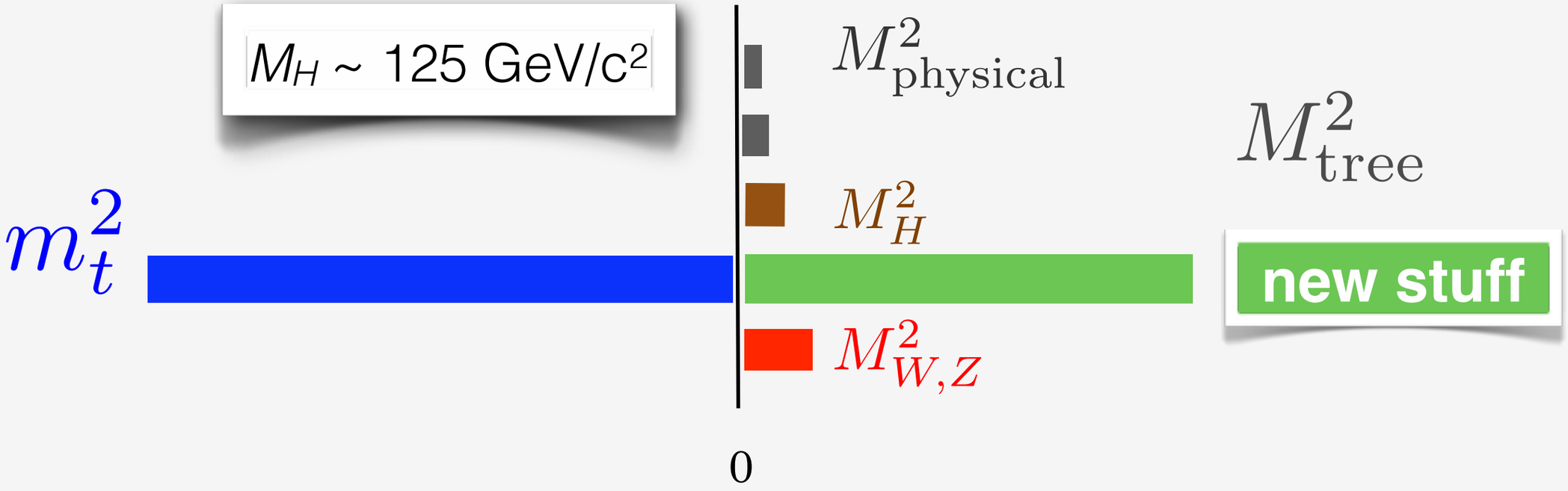

POST CARD
Correspondence
Address
A Hint?
To: 2013
From: Nature
#5064 EOPR
ROBERT H. LORD
BOSTON

Perhaps a huge hint?

of something “BSM”?

no shortage of ideas





gotta find that **new stuff**

Broadly speaking, of four sorts:

Supersymmetric theories – a Bose-like top

Little Higgs-like theories – a Vector-like top

Composite Higgs – a Cooper Pair-like H

Extra dimensional theories

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

  the multiverse or...

  anthropomorphism

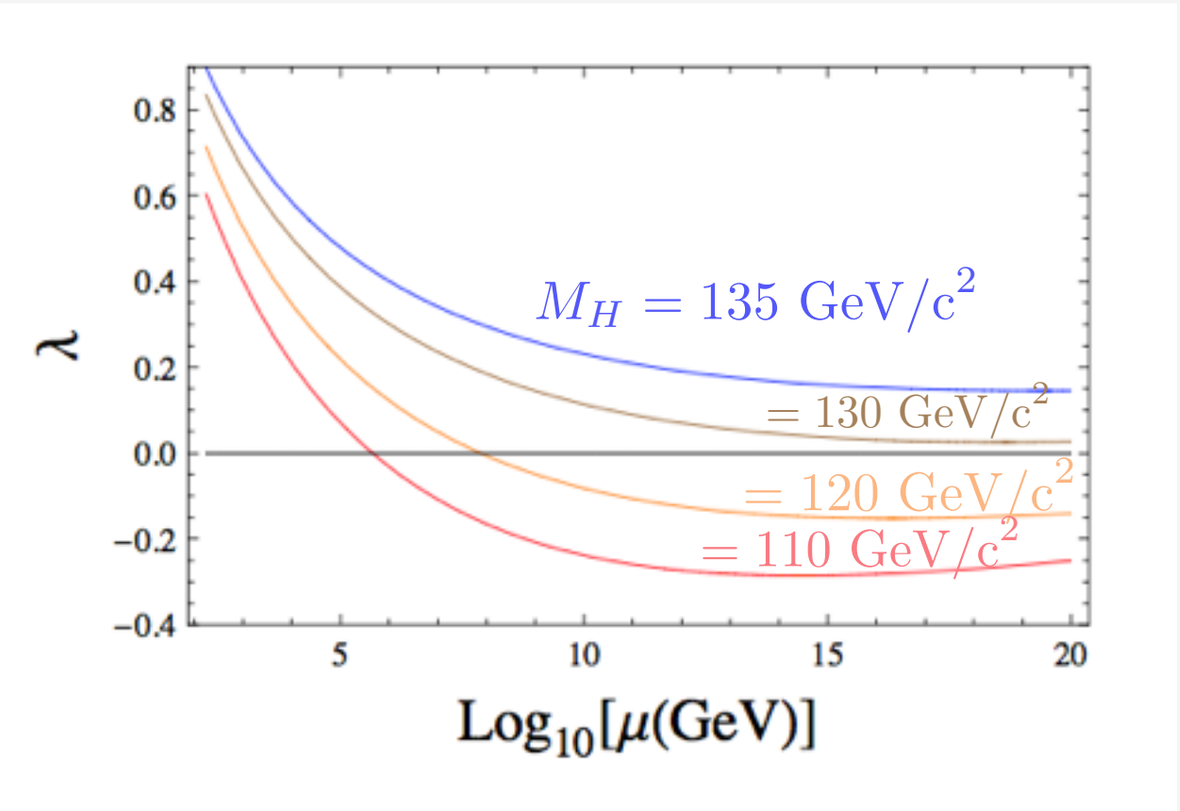
doom?

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

- the quartic coupling runs

  mixing up M_H and m_t

M_H is itself odd!



Nima Arkani-Hamed, et al. arXiv:0801.2399

So, where do you stand? :)

- The strangeness of the Higgs particle
- The fine-tuning required in the mass
- The lack of stability in the vacuum potential
- The lack of a dynamical explanation for the PT

never theorize

hints welcome

theory guarantees new physics

We know of *experimental* BSM physics.

Serious experimental anomalies

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

Serious experimental anomalies

- The [illegible]s is small.
- *ν*'s flav[illegible]roperties not SM.
- Dark Matter [illegible]
- Primordial antimat[illegible]tion.
- (g-2)μ results need con[illegible]sconfirmation

Dramatically influence the EF

Conclusions from the Energy Frontier

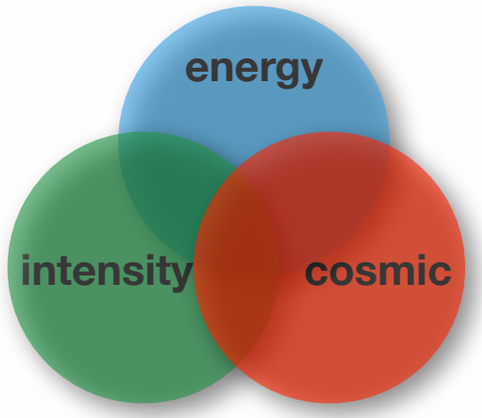
A three-pronged research program:

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

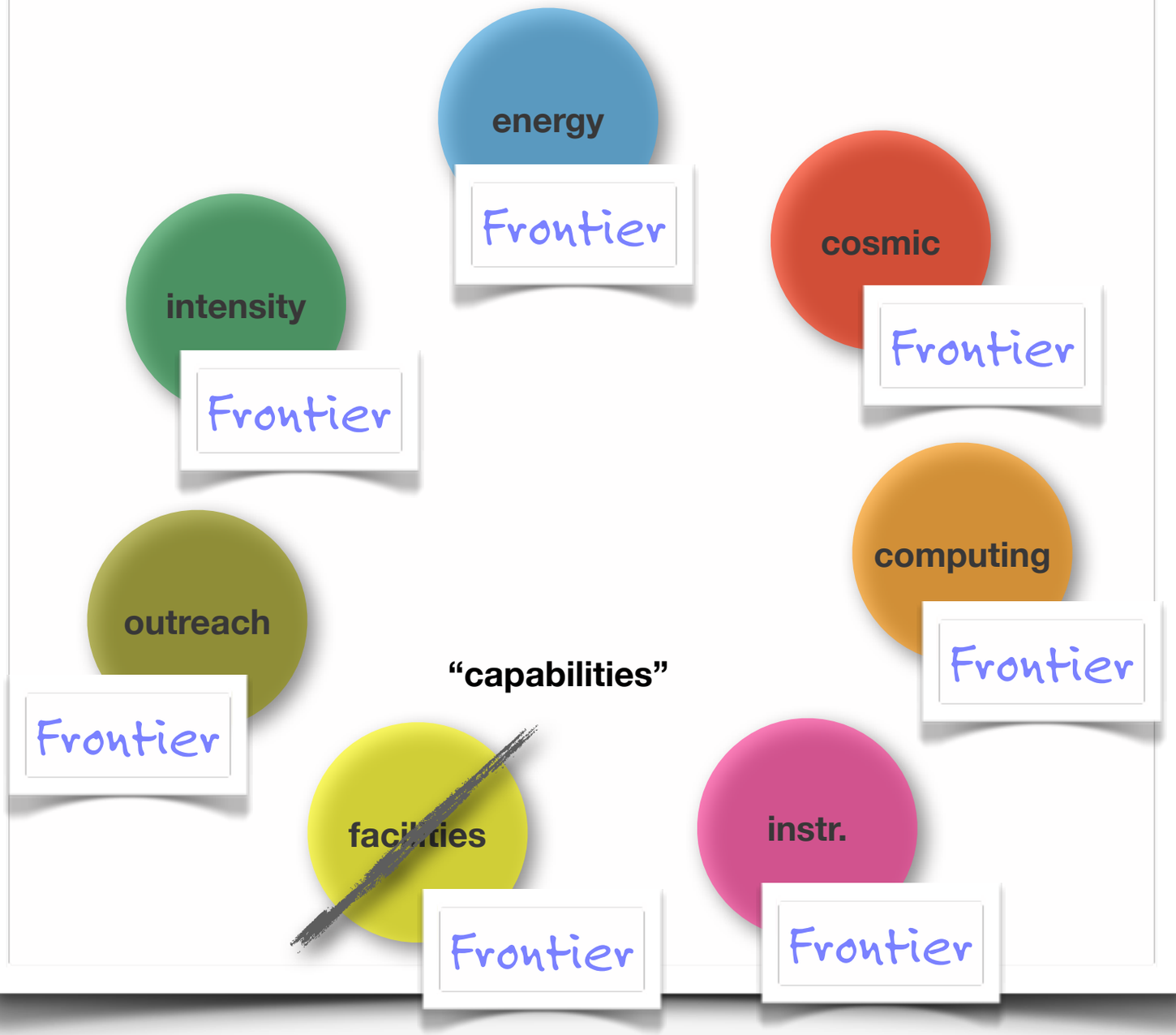
the Snowmass process

DPF 2010-2013 targeted summer 2013

This is our sentiment:



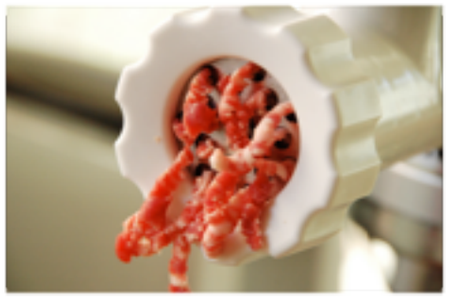
This was our organizational reality:

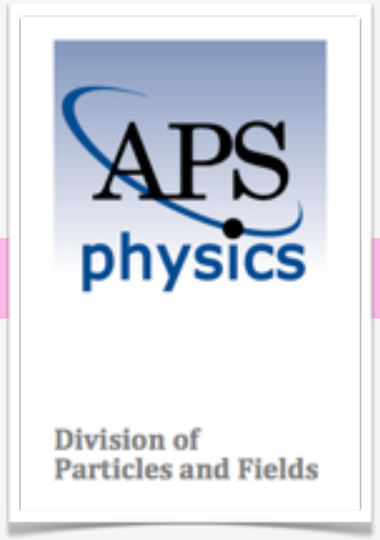


long process

August 2013

October 30





Oct 2012-July 2013

August 2013

long process

September 2013

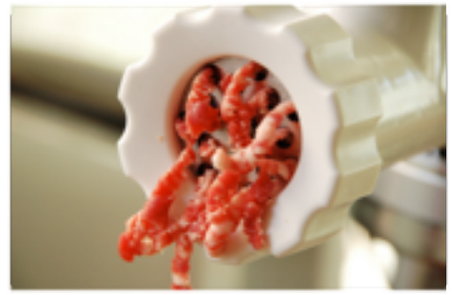
HEPAP

P5

March 2014

HEPAP

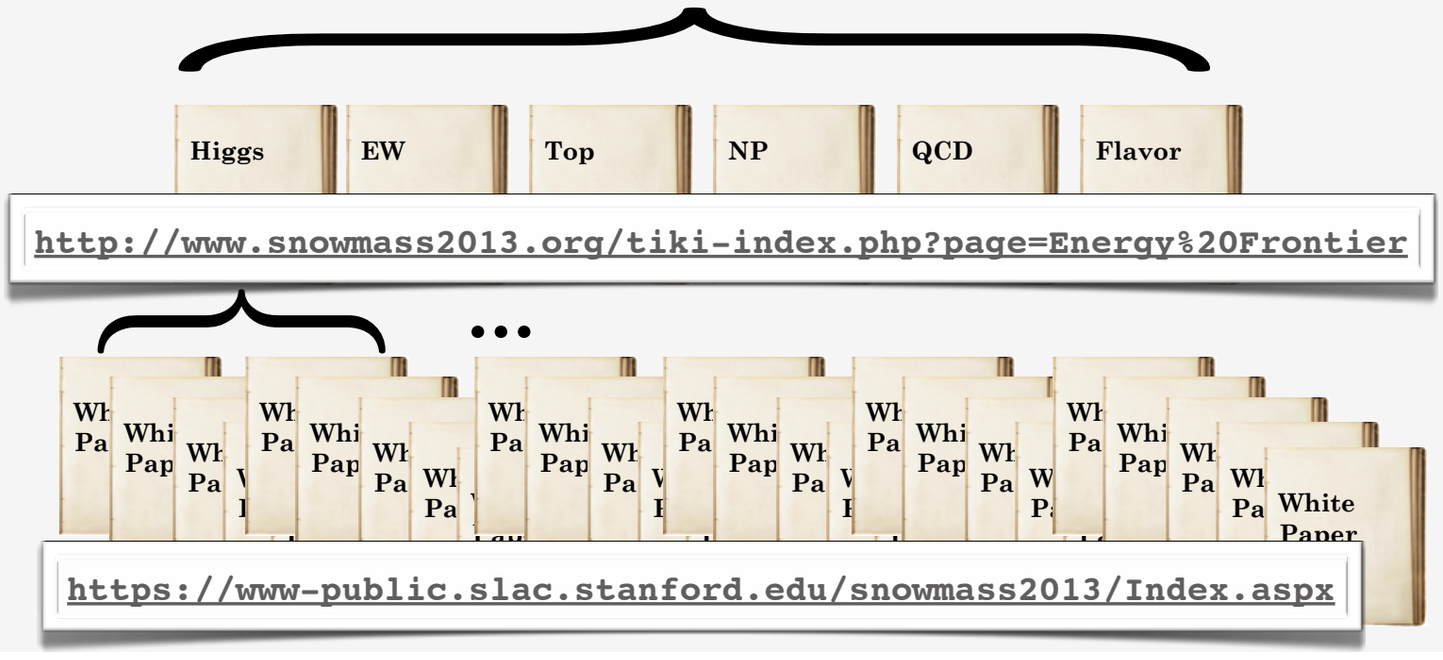
May 2014



http://usparticlephysics.org/p5

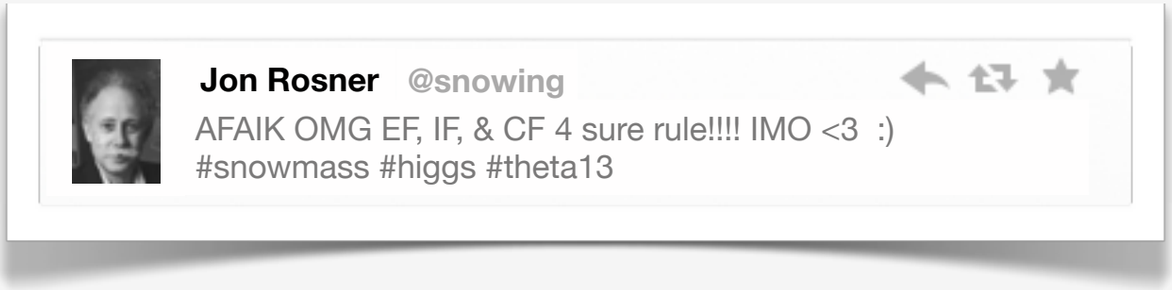
paper trail

paper, 30pp ea.



on-line, 30-80pp ea.

paper trail



executive tweet

one-page “3 fold”

Executive Summary, 7pp

the 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

- *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

Eric Prebys, Eric Torrence, Tom LeCompte, Sanjay Padhi, Tor Raubenheimer, Jeff Berryhill, Markus Klute, and Mark Palmer

Additional group “infrastructure”

established direct connection with the established collaborations:

“Advisors”:

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

Energy Frontier Goals:

What are the scientific cases which motivate HL LHC running:

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

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

How do the envisioned upgrade paths inform those goals?

Specifically, to what extent is precision Higgs Boson physics possible?

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

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

High energy lepton collider?

A high energy LHC?

Lepton-hadron collider?

VLHC?

EF meetings:

the alloverthe place workshop.

snowmass@Batavia

snowmass@Princeton

snowmass@Durham

snowmass@Brookhaven

snowmass@Dallas

snowmass@SantaBarbara

snowmass@Boston

snowmass@Tallahassee

snowmass@Boulder

snowmass@Geneva

snowmass@Seattle

snowmass@Minneapolis

We simulated against a defined set of accelerators

- This included:

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

  LHC at 33 TeV

  linear and circular e+e- colliders

  muon collider

  gamma-gamma colliders

  pp collider at 100 TeV

The full set of accelerators:

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

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

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

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

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

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

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

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

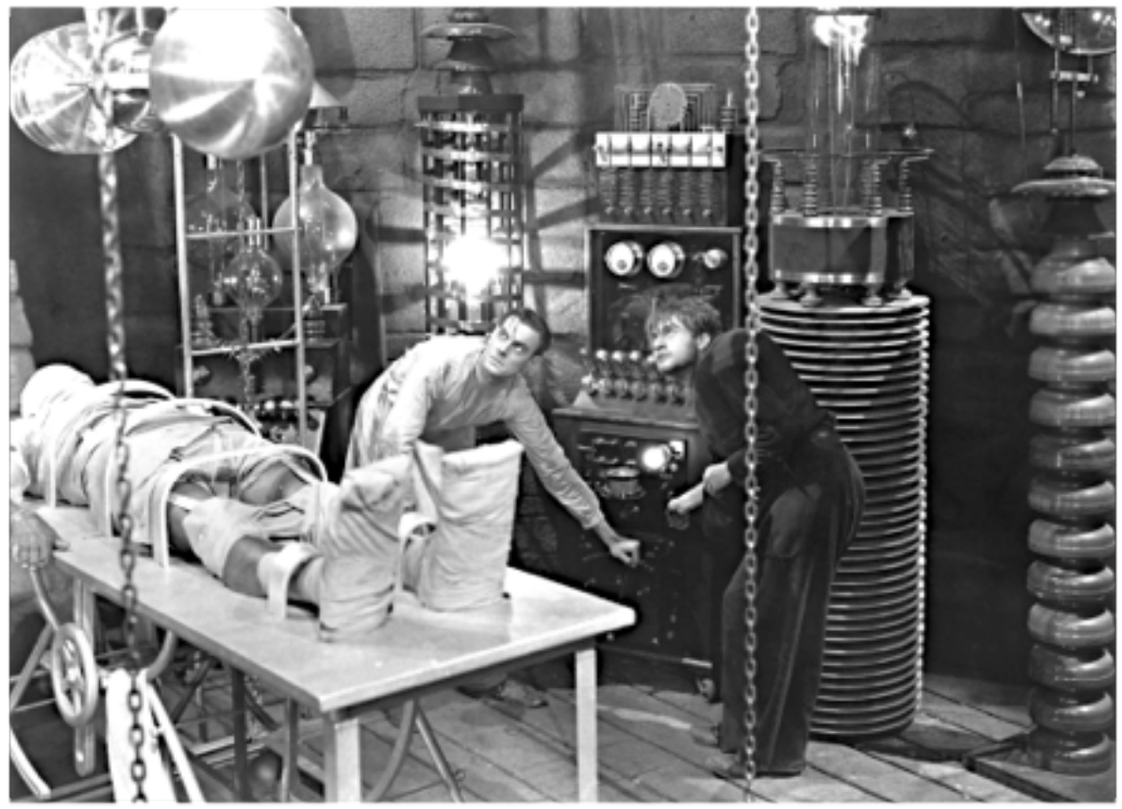
* incl polarization choices

Fast simulation tools

- LHC simulation strategies

  A Generic DELPHES 3 “Snowmass detector”

  Background simulations



- The LC community

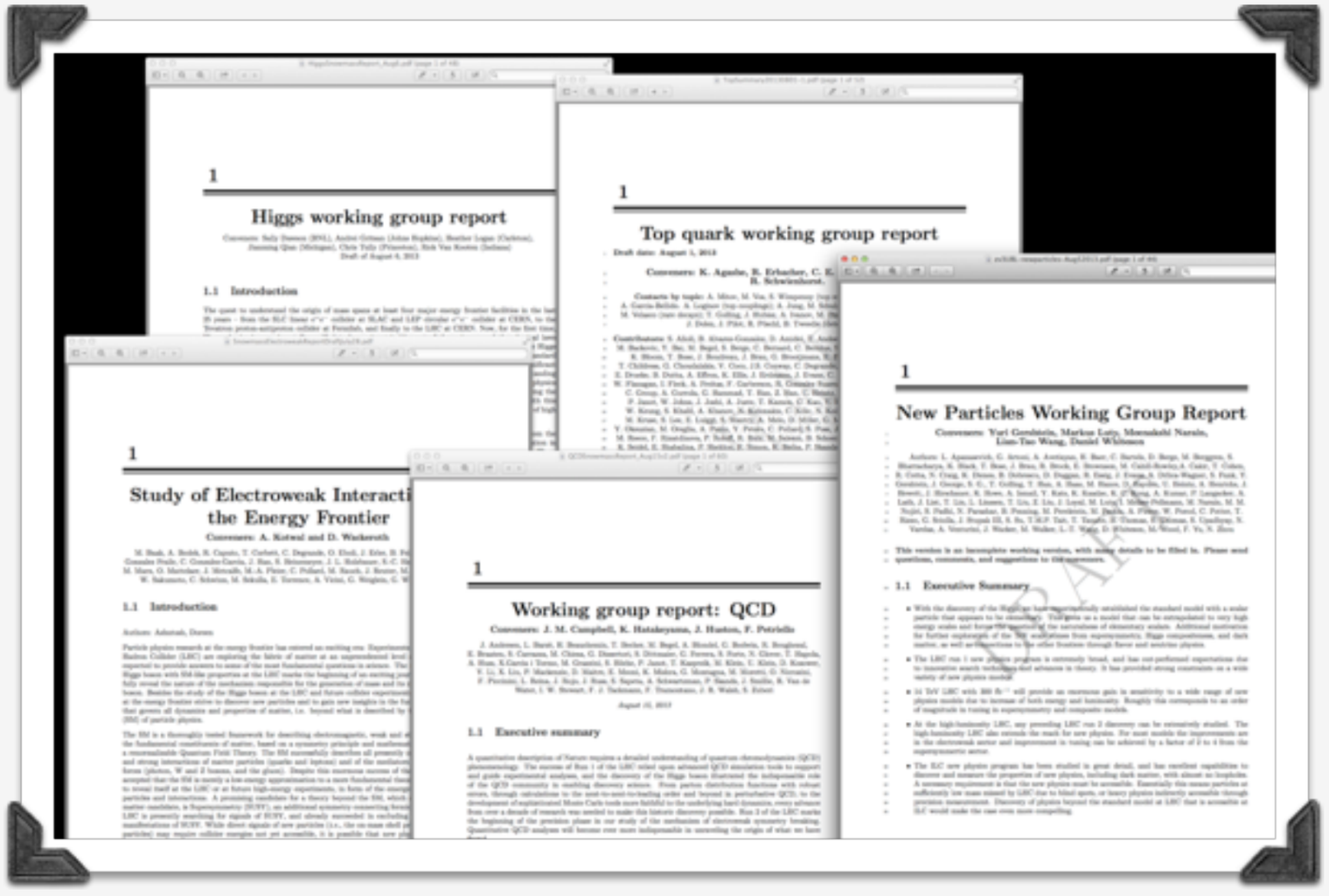
  Snowmass-specific analyses beyond the CLIC CDR & ILC TDR.

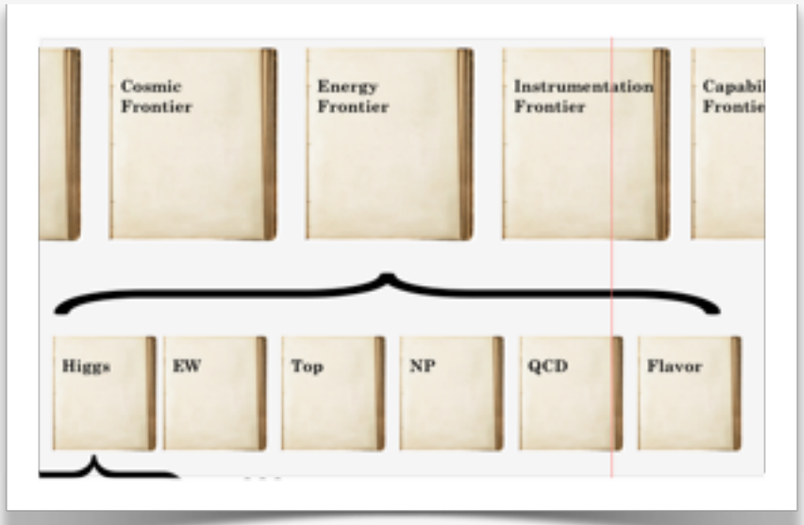
  Signal & complete SM background samples

Reports are being finished up

- 300 pages of technical detail

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

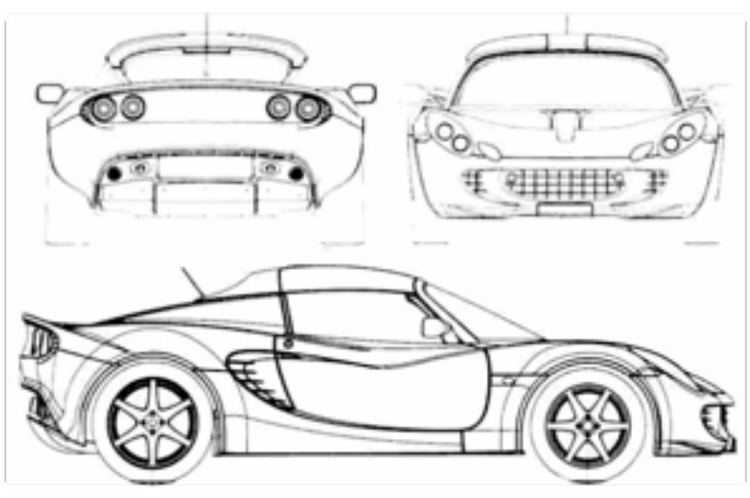




- an important point

Comments:

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



subgroup reports

Big Questions

1. How do we understand the Higgs boson?

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

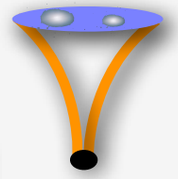
3. How do we understand the neutrinos?

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

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

6. How do we understand the dark energy?

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

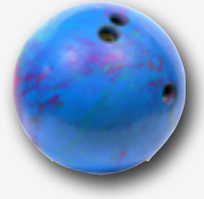


8. How do we understand the multiplicity of forces?

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

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

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



The Higgs Boson

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.

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

Higgs Boson Group Themes:

1. outline a precision Higgs program
   mystery of Higgs, theoretical requirements
2. projections of Higgs coupling accuracy
   measurement potential at future colliders
3. projections of Higgs property studies
   mass, spin-parity, CP mixture
4. extended Higgs boson sectors
   phenomenology and prospects for discovery

couplings

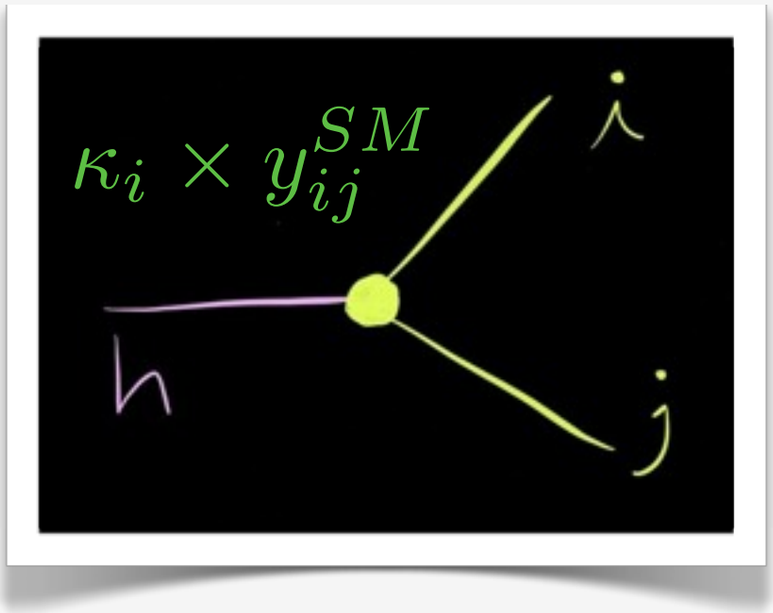
$$V(\text{Yukawa}) = \left[y_{ij} \bar{f}_{Li} f_{Rj} \phi + HC \right]$$

Higgs discovery spawned an industry

precision fitting of couplings,

- eg for fermions

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

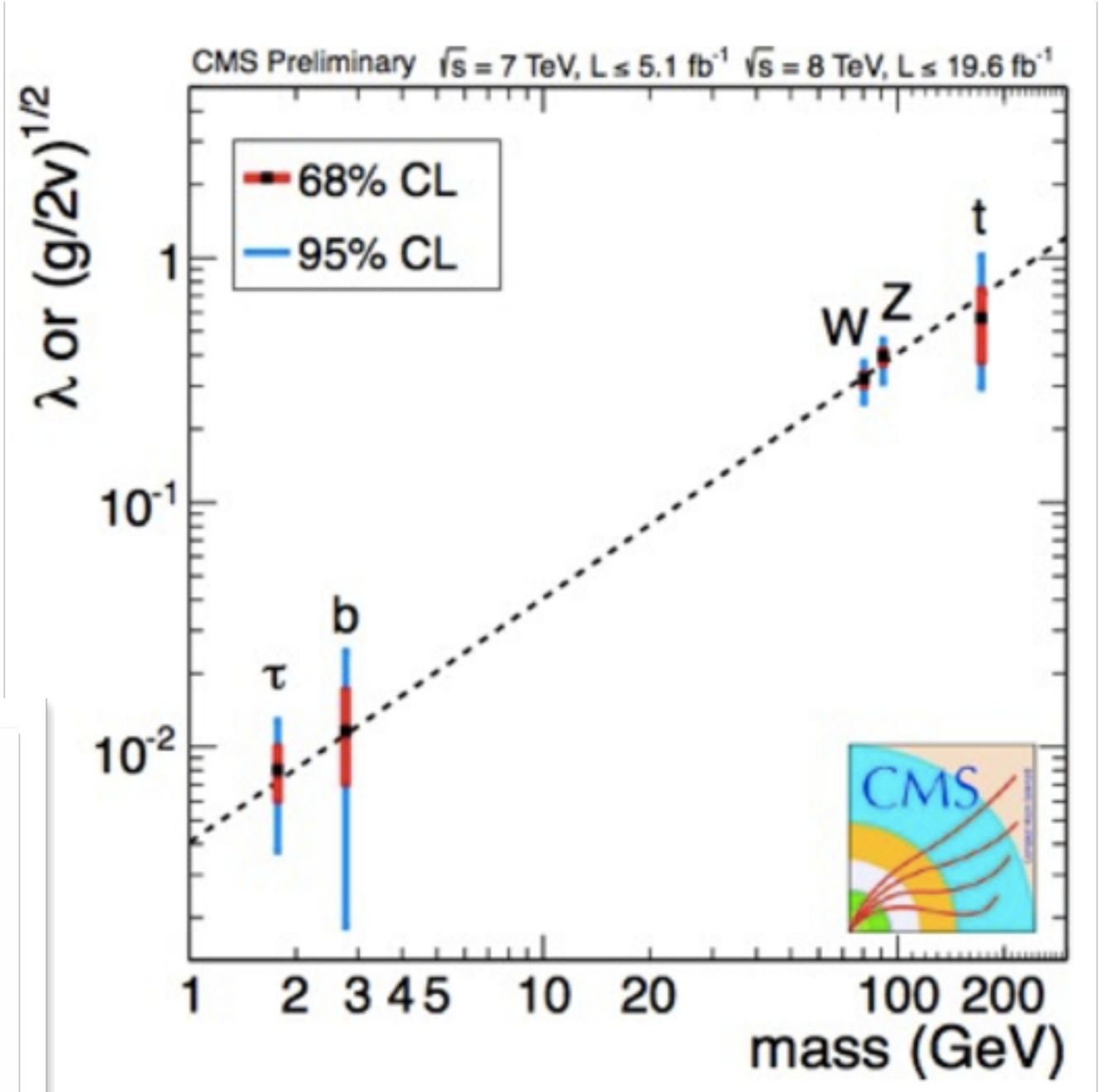


$$i, j = f, \ell, W, Z, \text{“}V\text{”}, \text{“}g\text{”}$$

couplings

Early results are in line

for fermions and VBs



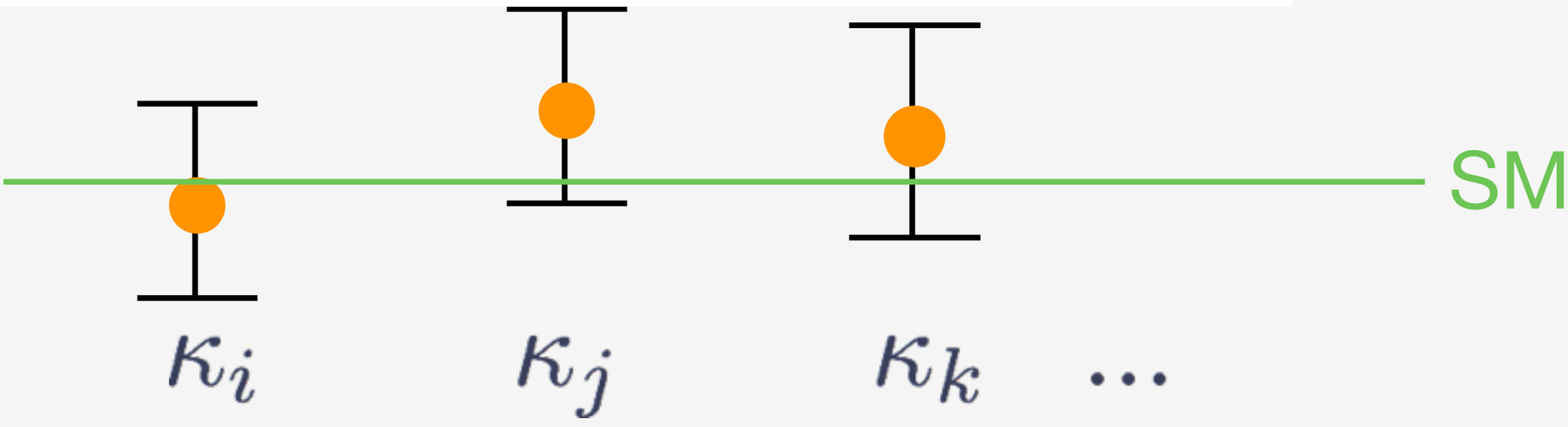
The precision Higgs boson program has begun.

How well do we need to know couplings?

Higgs group evaluated models

when new particles are ~1TeV:

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

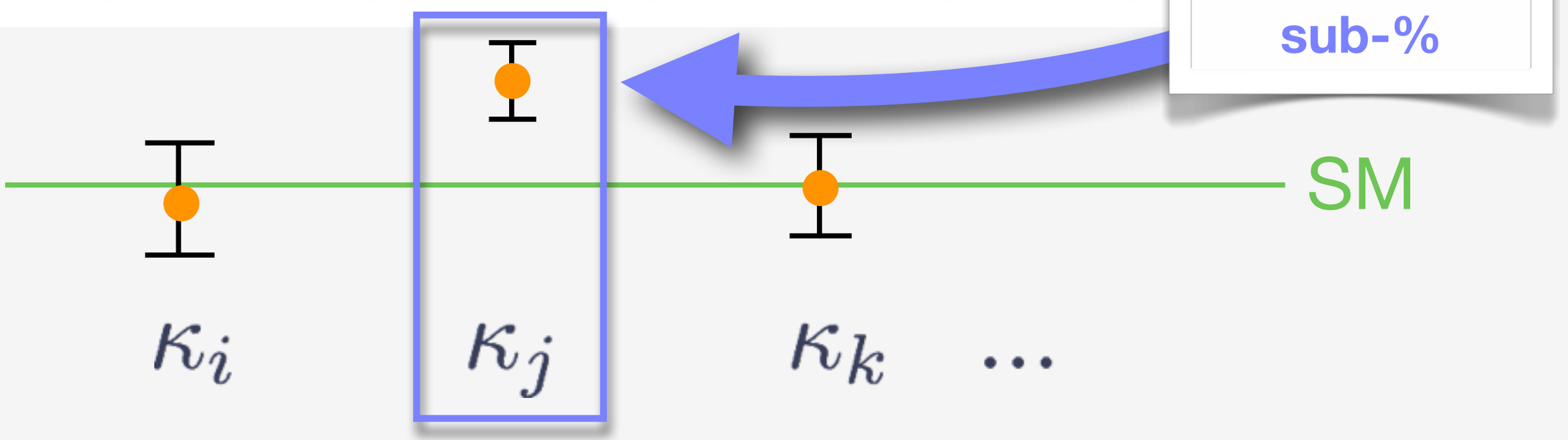


precision for precision's sake?

No - this is a discovery search

	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-%



precision for precision's sake?

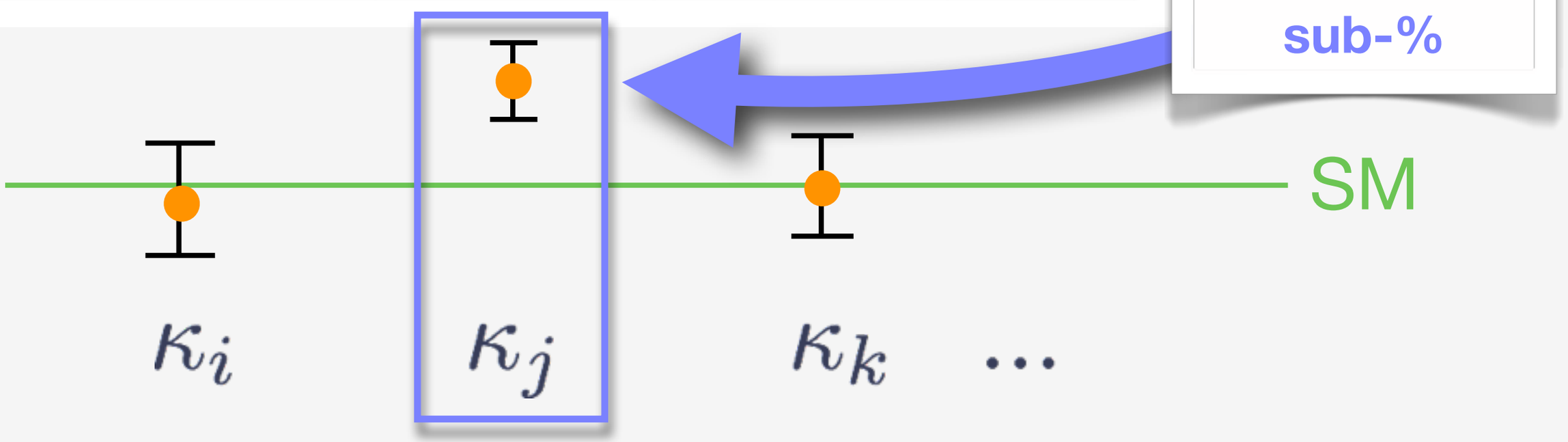
No - this is a discovery search

Current precision is multiple 10's%.

Yes...the precision Higgs boson program has indeed begun.

	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-%



Evaluation of coupling extrapolations

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%

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

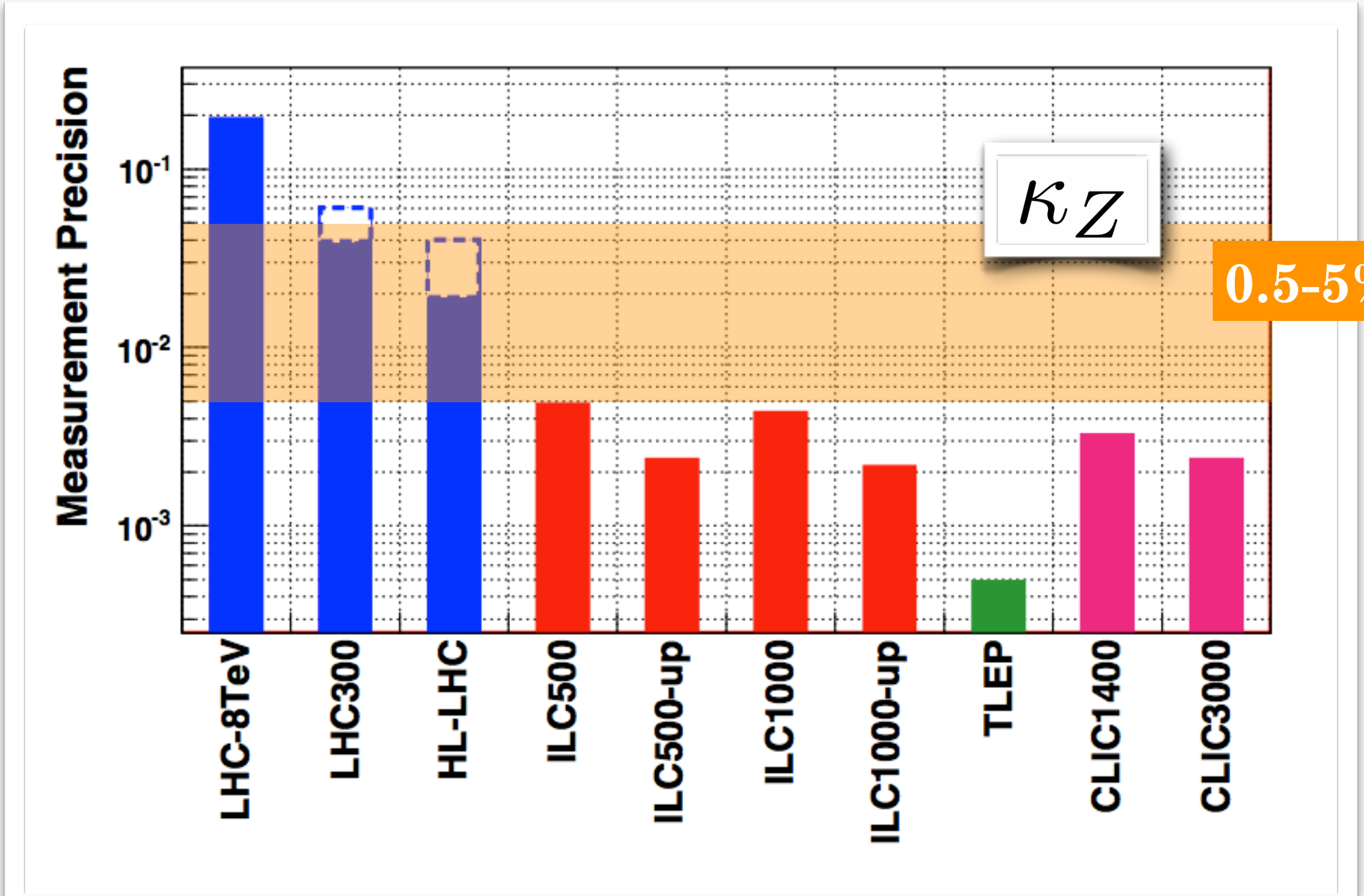
and

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

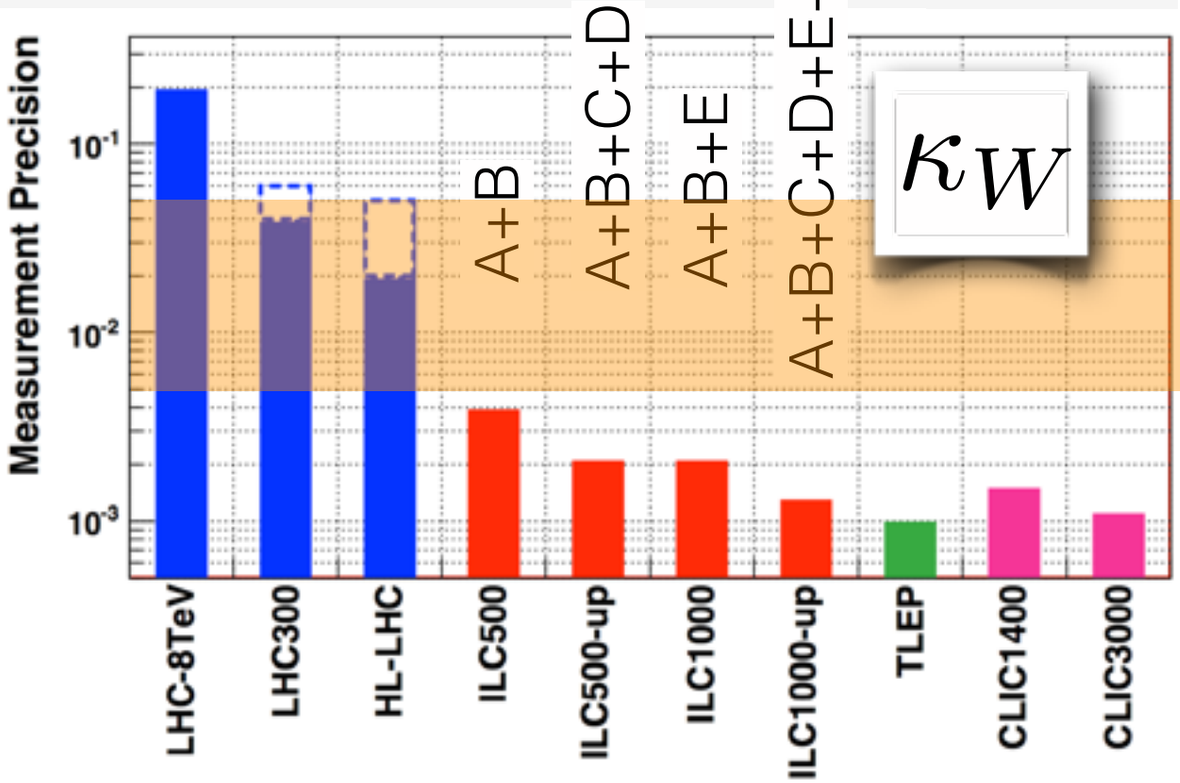
	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

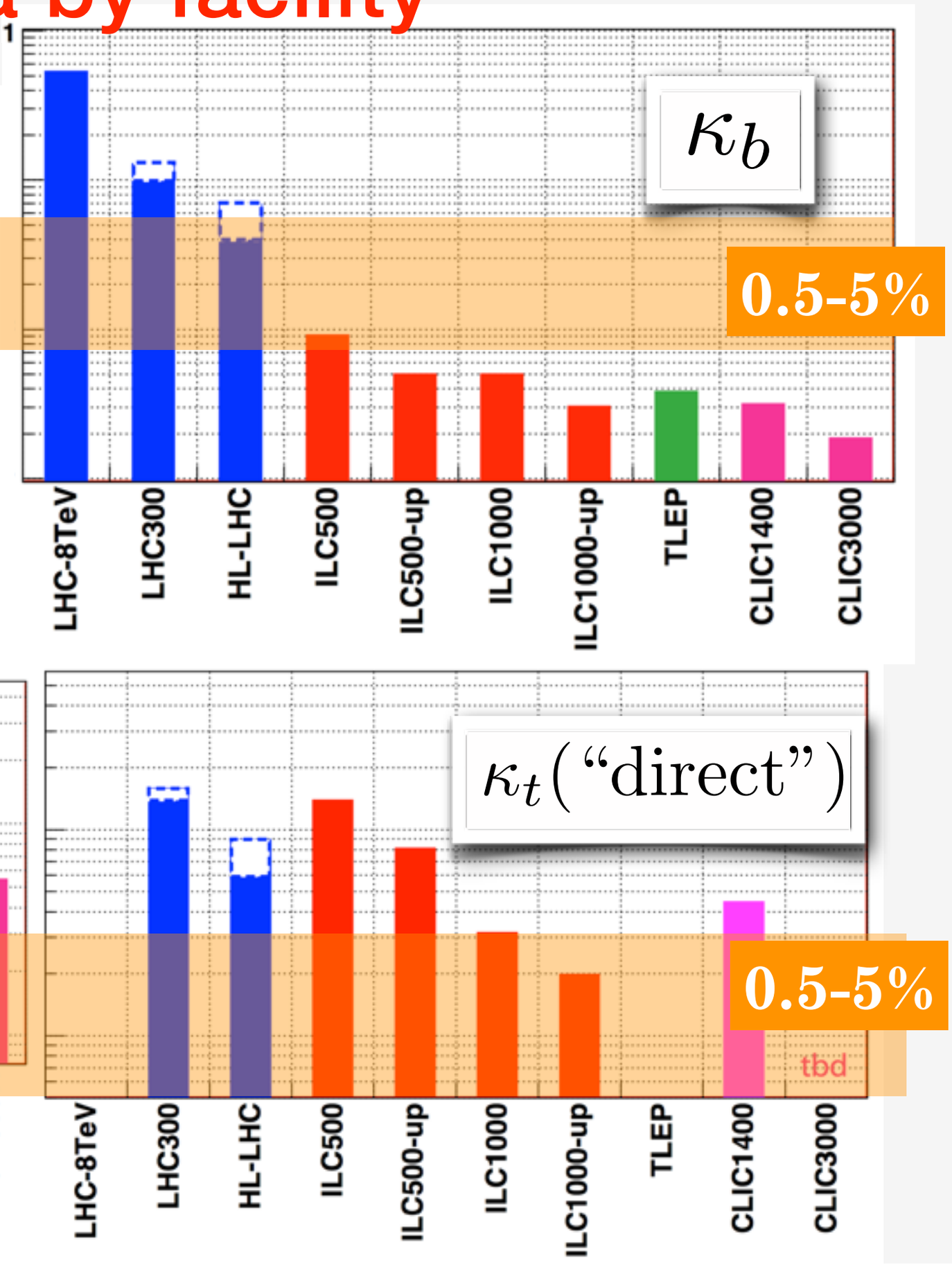
Benchmark for discovery is few % to sub-%

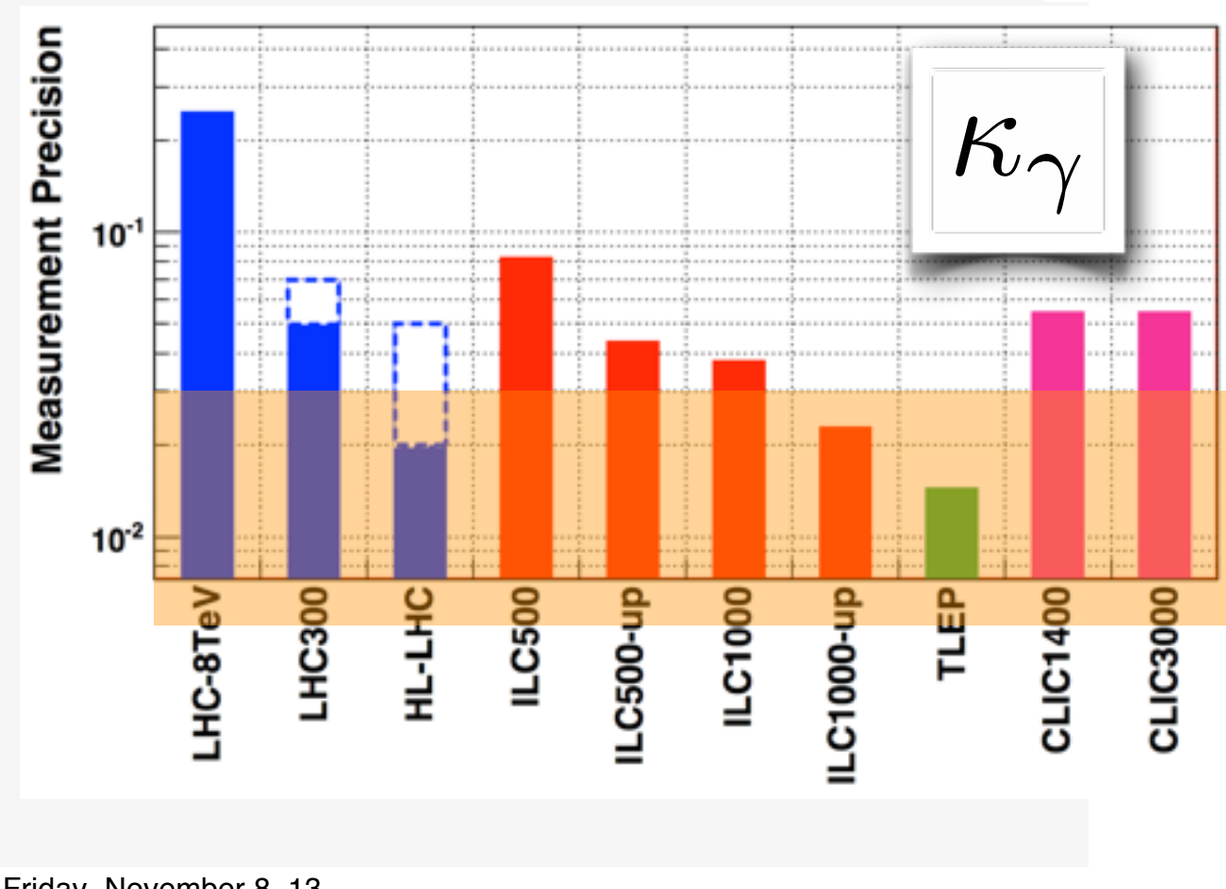
example precision by facility



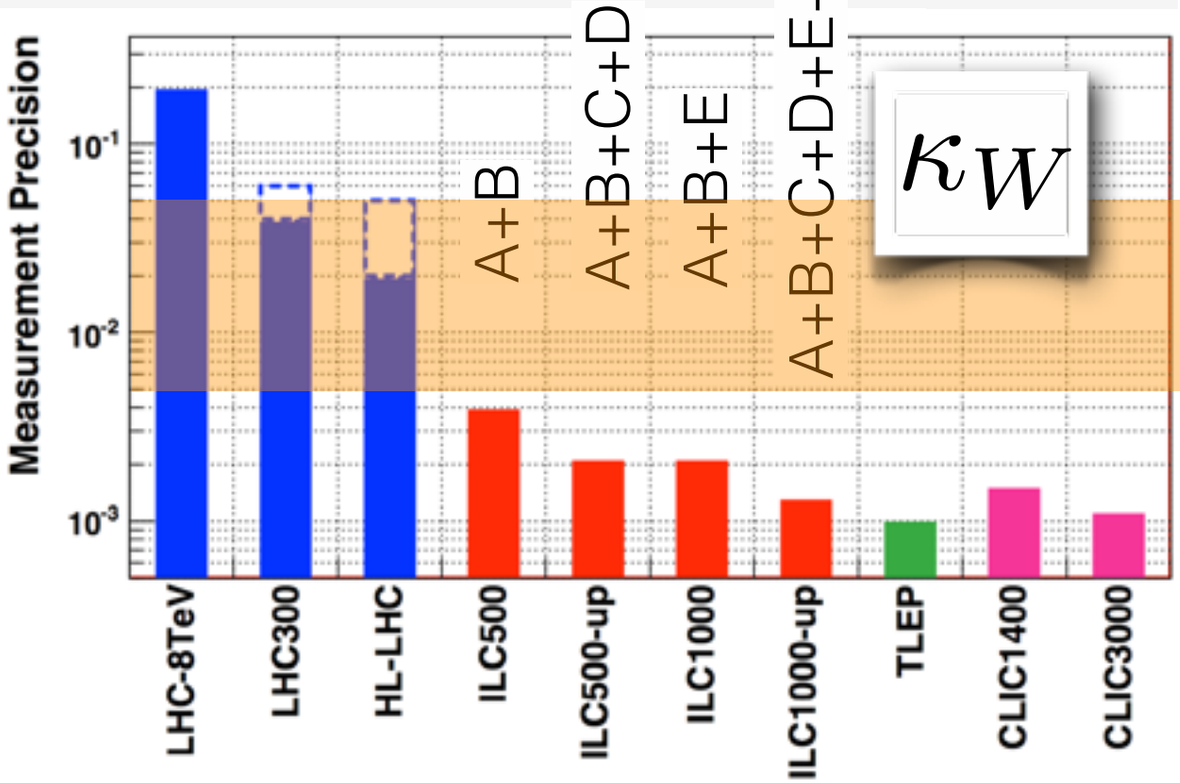
Precision in kappa by facility

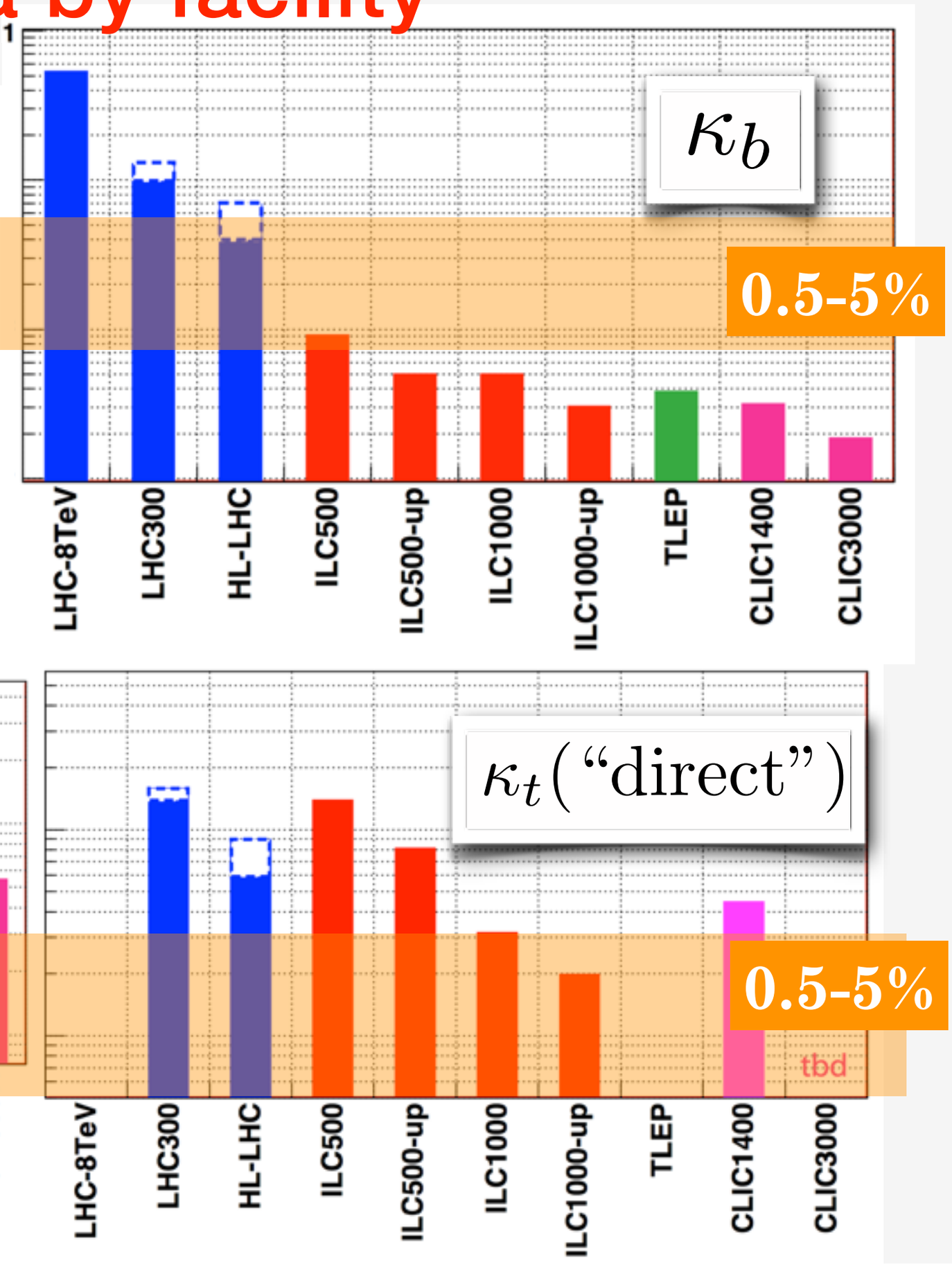


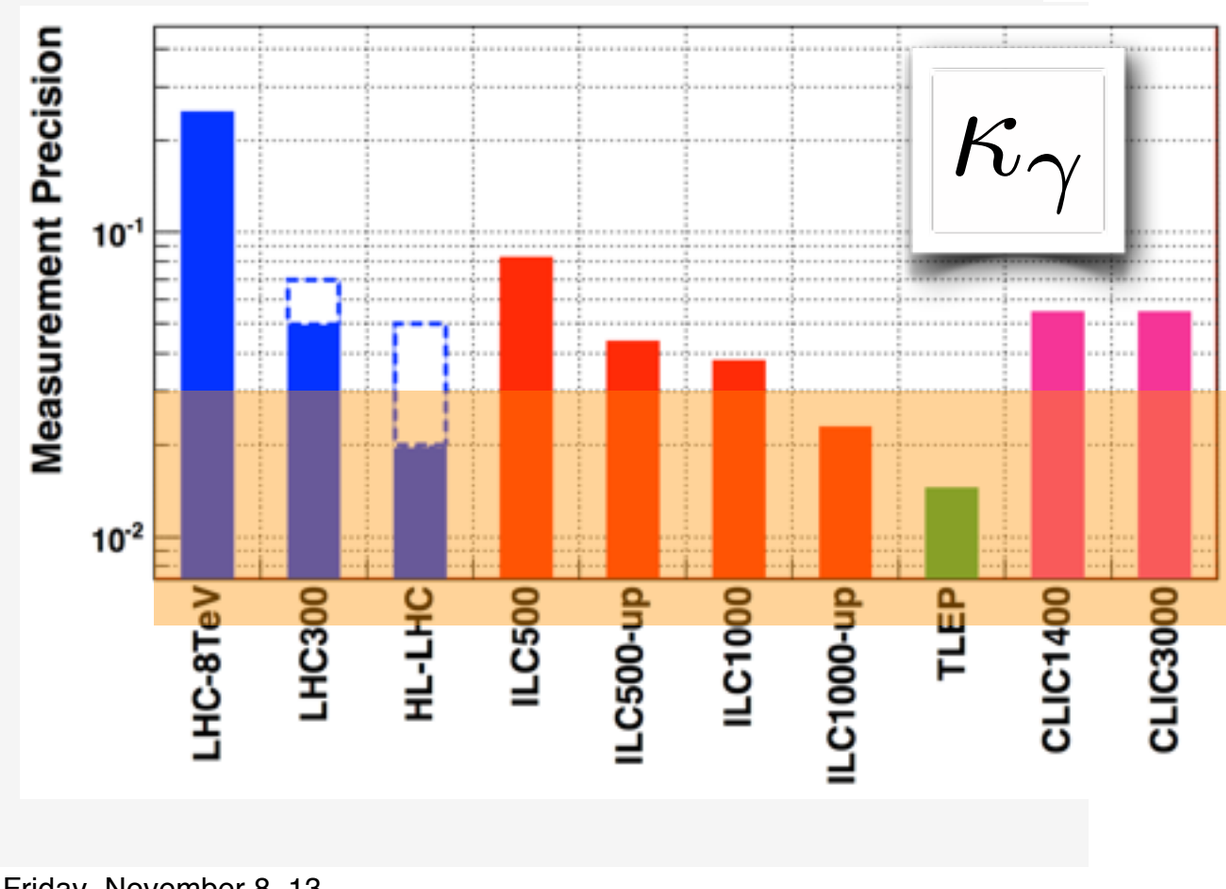




Precision in kappa by facility





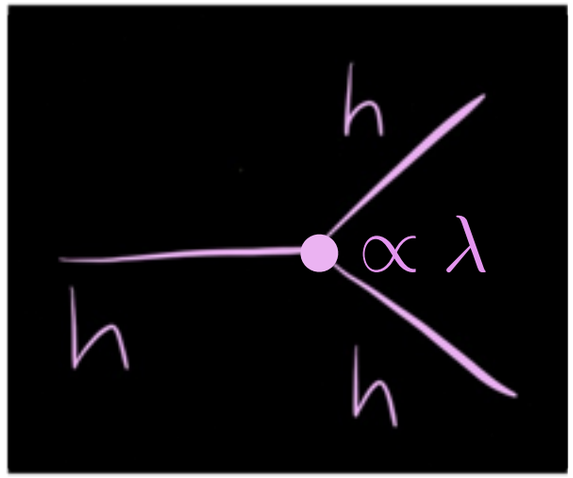


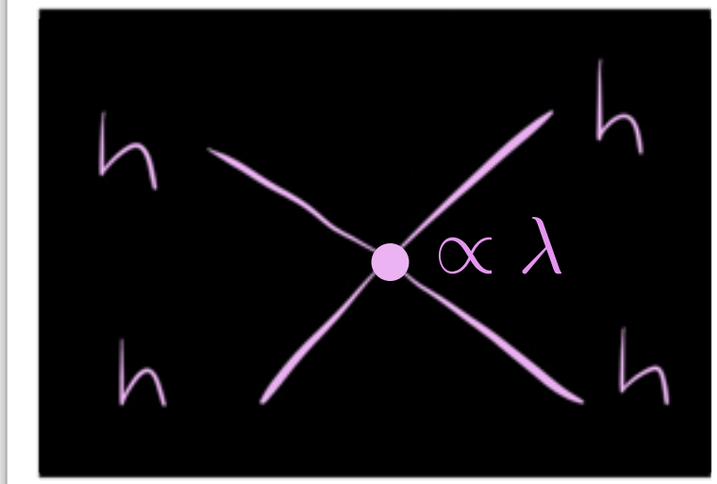
Higgs Self-Coupling

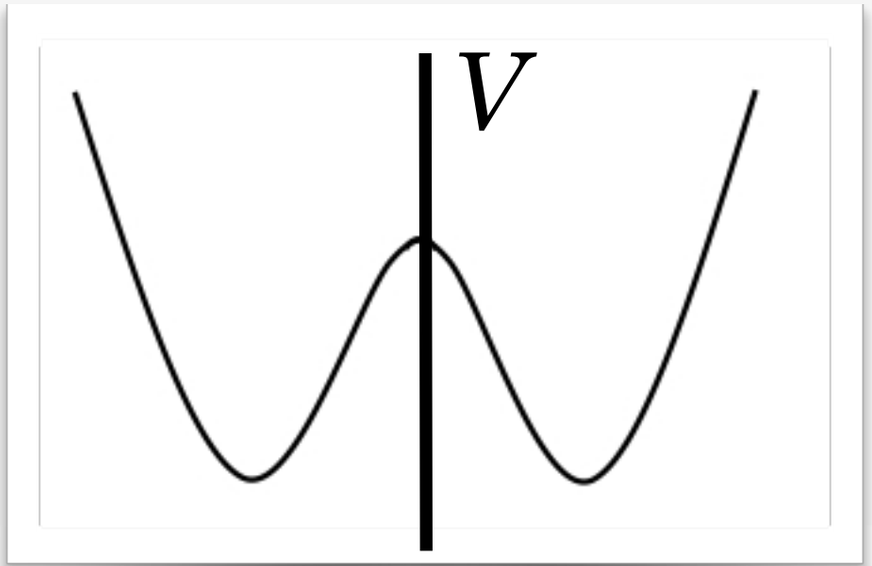
Critical feature of SM

extremely challenging

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





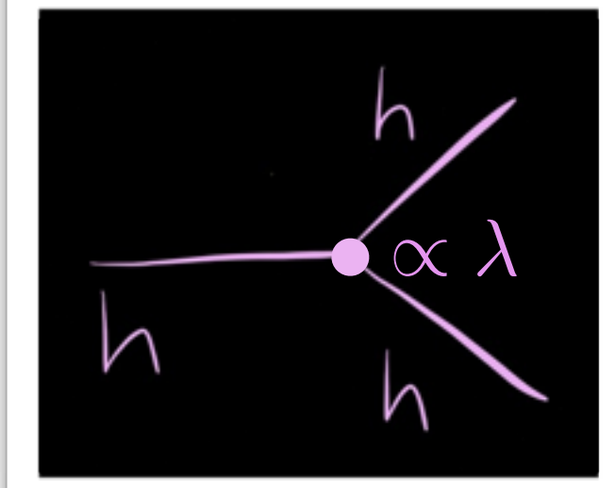


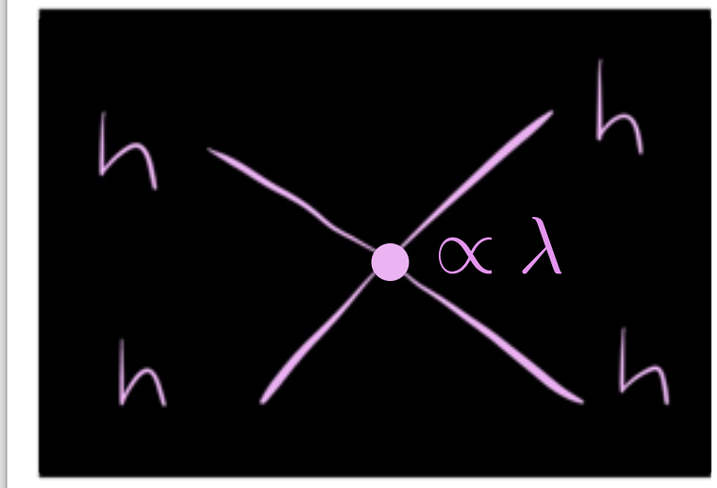
Higgs Self-Coupling

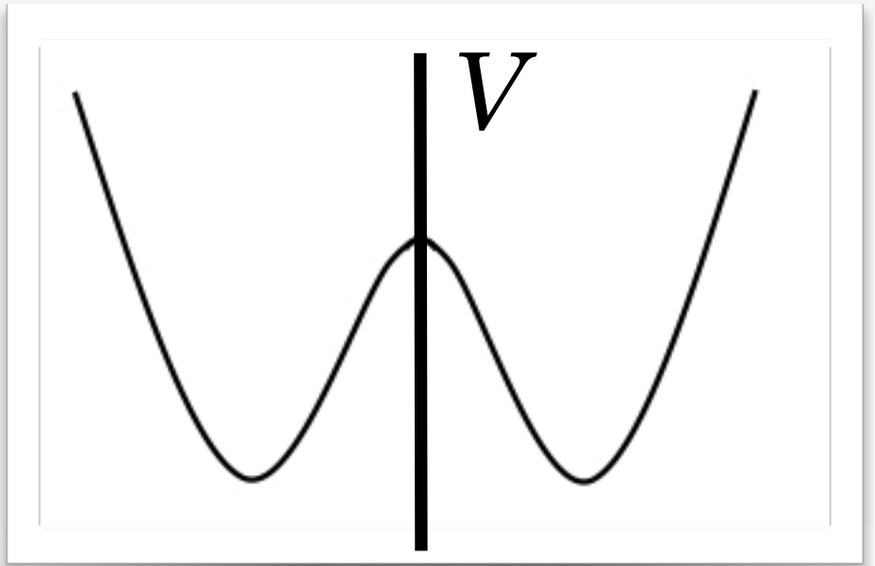
Critical feature of SM

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

extremely challenging







	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.

m_H & Γ_H can be determined to a few %

Mass

LHC: 50 MeV/c^2

ILC: 35 MeV/c^2

Total Width

LHC: limits on Γ

ILC: model-independent

MC: direct

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

Γ_W to few %

Higgs Properties & extensions

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

   LHC has begun the direct search

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

   Evidence for CP violation would signal and extended Higgs sector

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

The Higgs Boson message

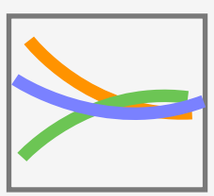
1. Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.

   The light Higgs boson must be explained.

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

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

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



Precision Study of Electroweak Physics

Electroweak: Themes

1. precision measurements:

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

   sensitive to new TeV particles in loops

2. studies of vector boson interactions

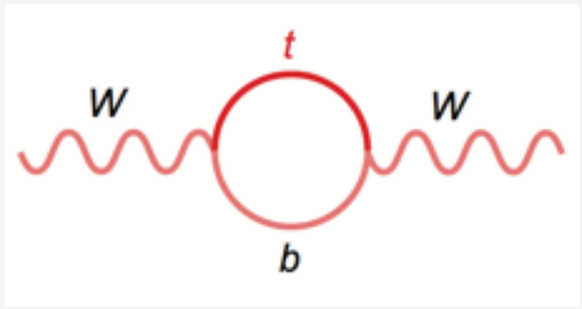
   triple VB couplings, VB scattering

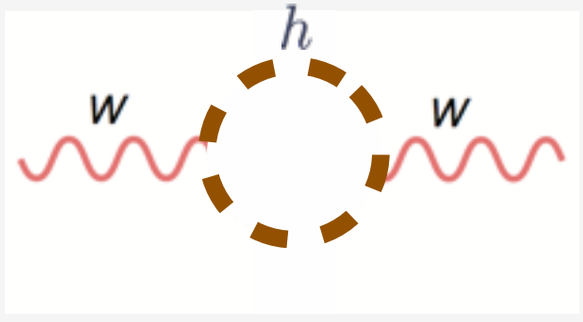
   - *Effective Field Theory approaches*
   - *sensitive to Higgs sector resonances*

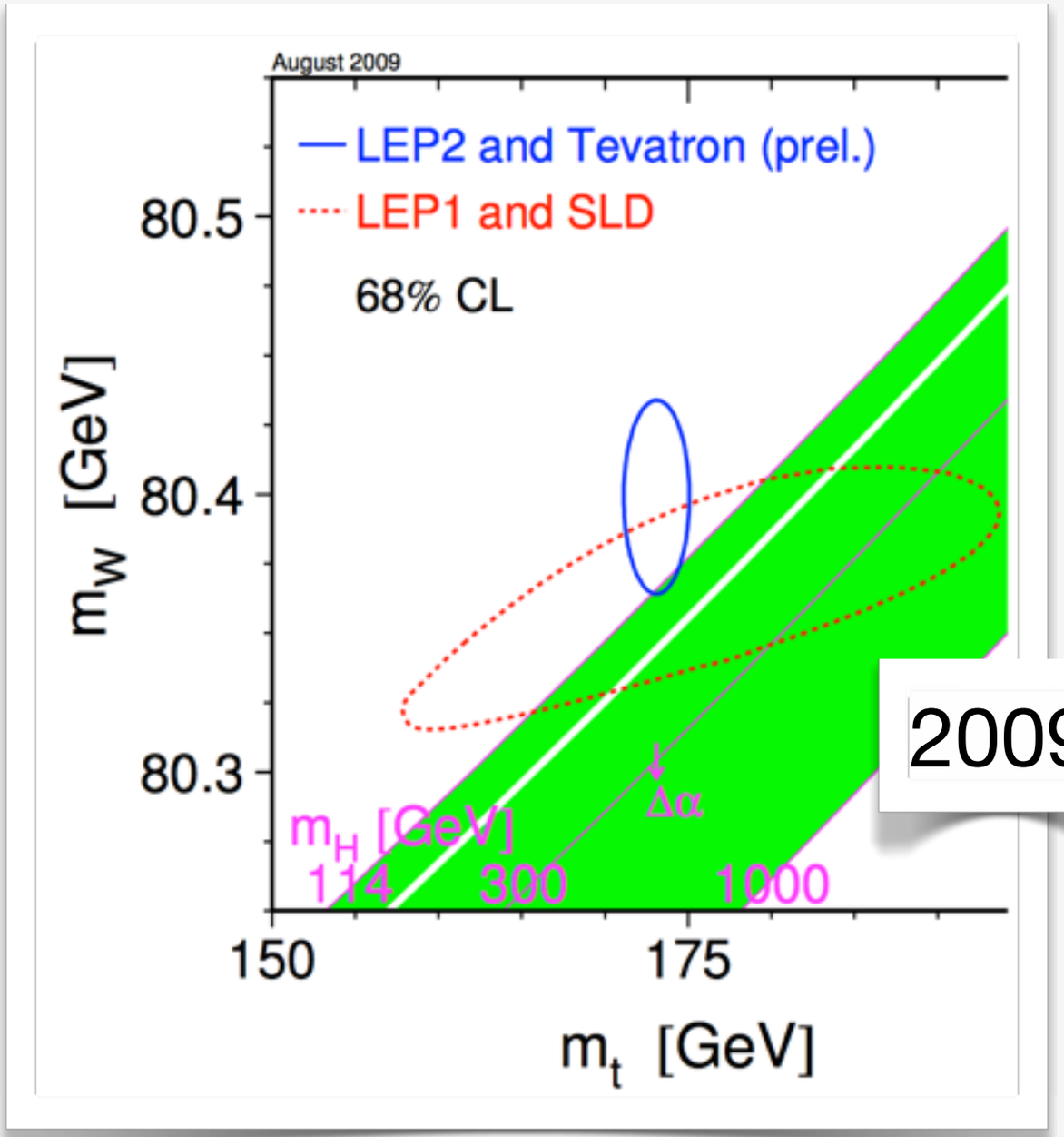
EWPOs

Electroweak Precision Observables

- Correlating the VBs, quarks, and Higgs boson



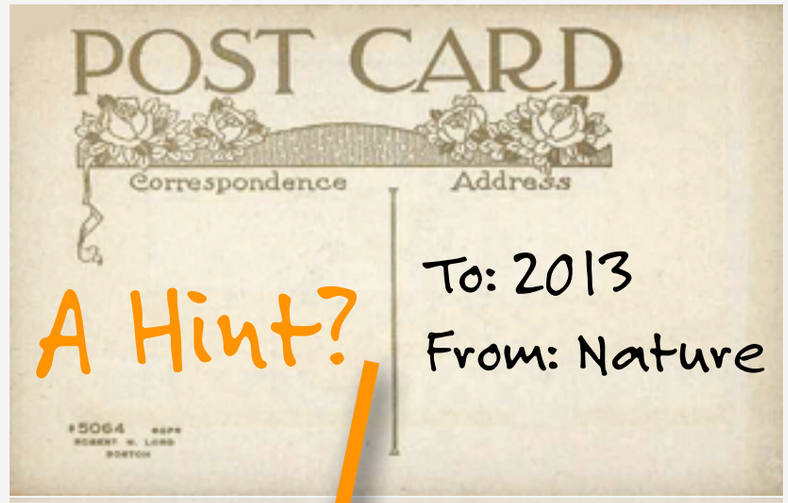


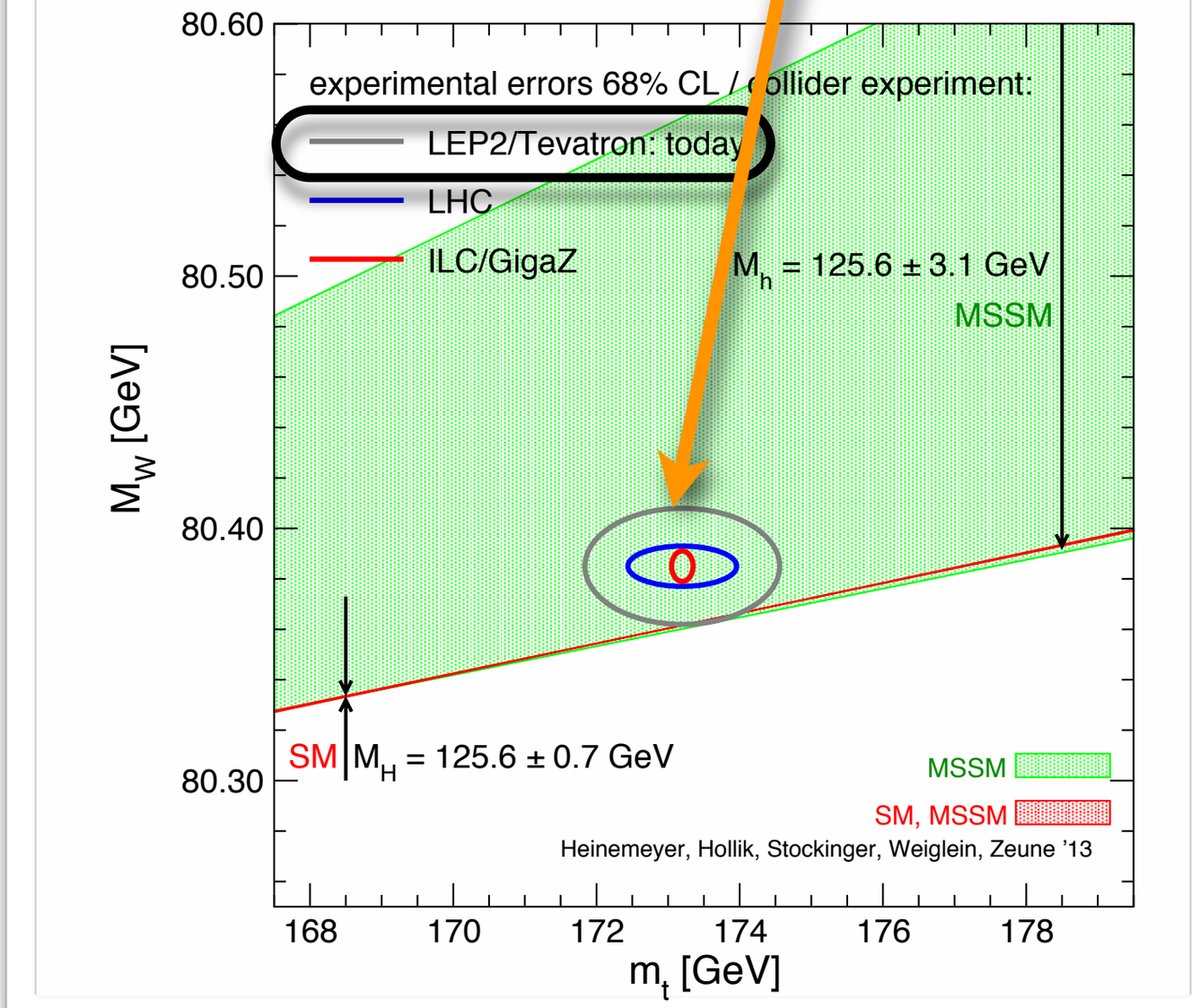


Now...a new target: BSM

Premium on M_W

Now fits include M_h

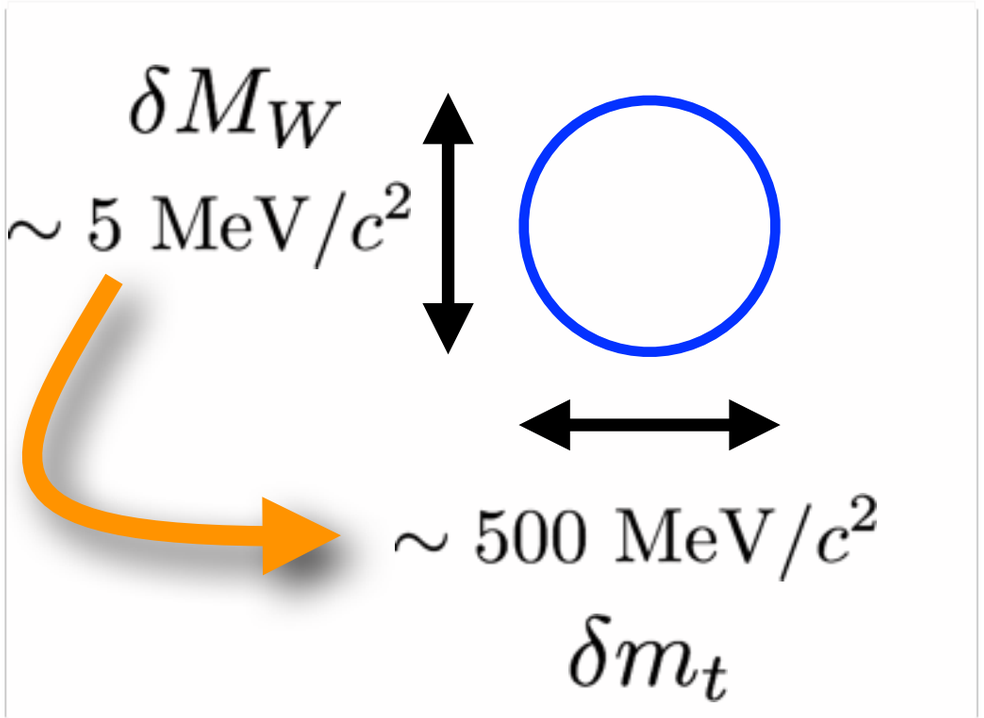




Now...a new target: BSM

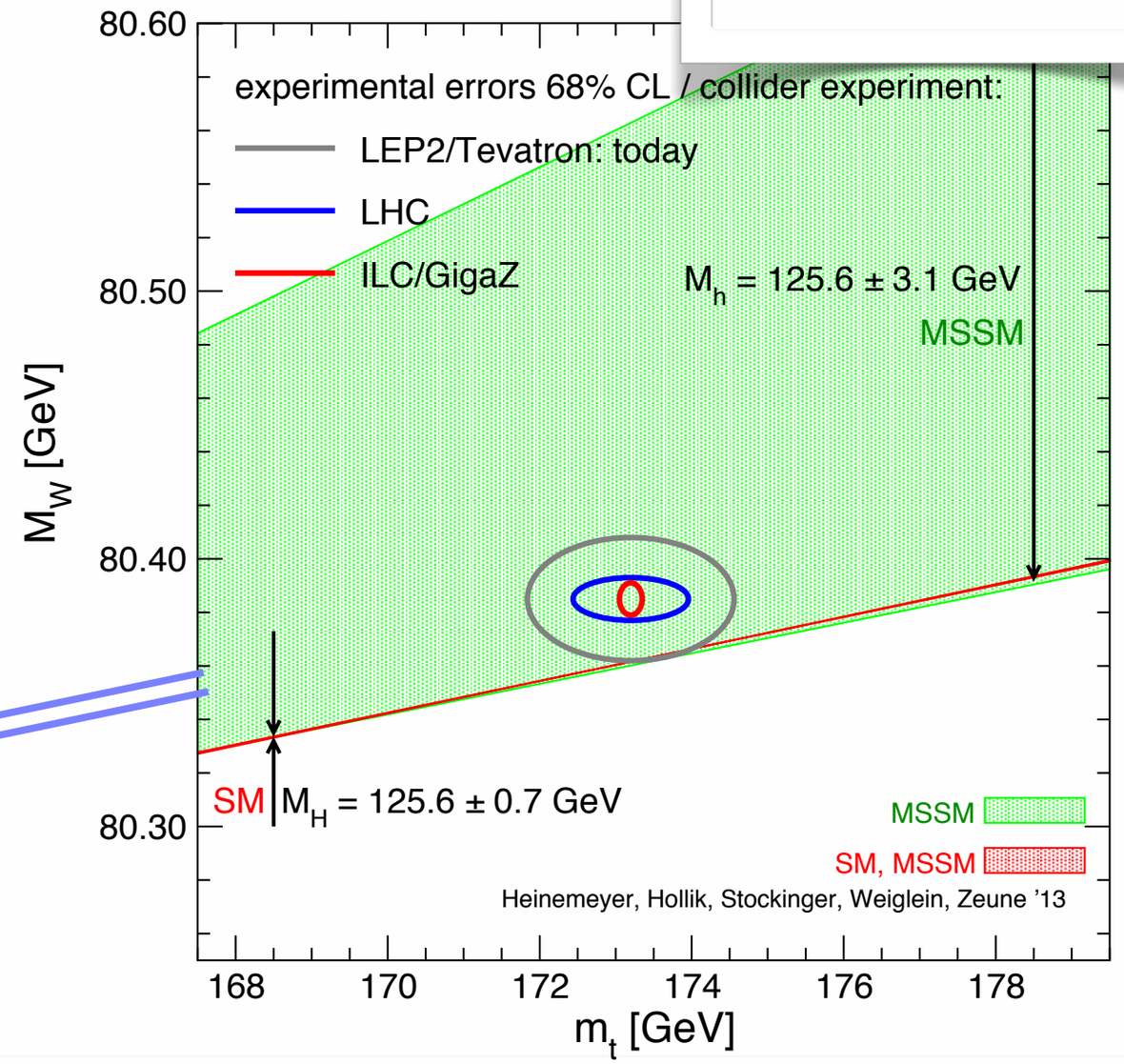
Premium on M_W

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



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

This is now a BSM search



Achievable M_W precision: few MeV/c^2

1. M_W at the LHC

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

   - *a critical need*

2. M_W at the lepton colliders

   A *WW* threshold program: $\delta M_W \sim 2.5 - 4$ MeV at ILC, sub-MeV at TLEP.

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

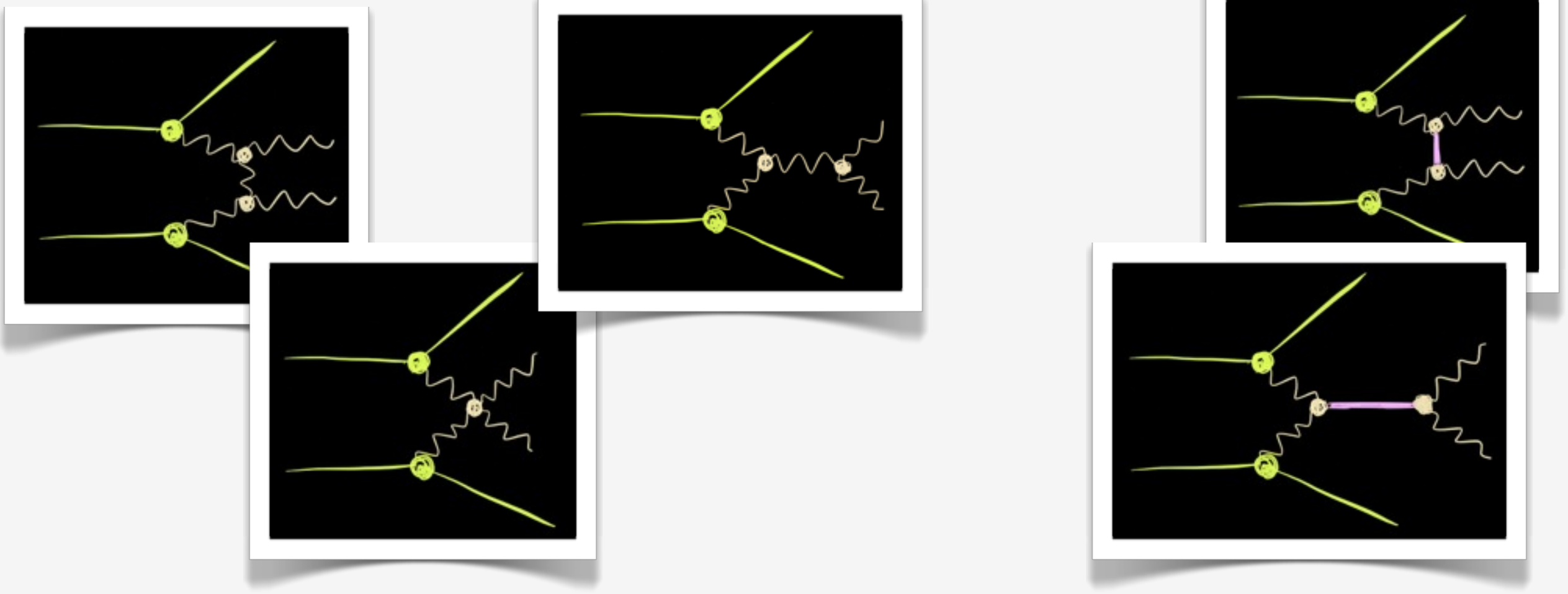
   Running at the *Z* at ILC (Giga-Z) can improve $\sin^2\theta_{\text{eff}}$ by a factor 10 over LEP/SLC;

   - *TLEP might provide another factor 4.*

EW scale - TeV?

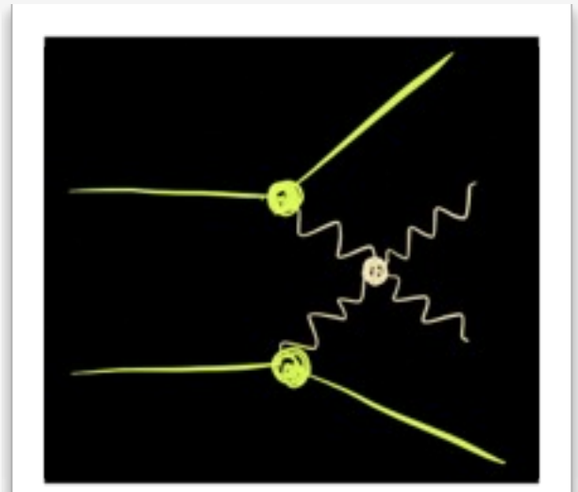
Weak Interaction theory broke down at TeV scale

Higgs tames this...one of its jobs

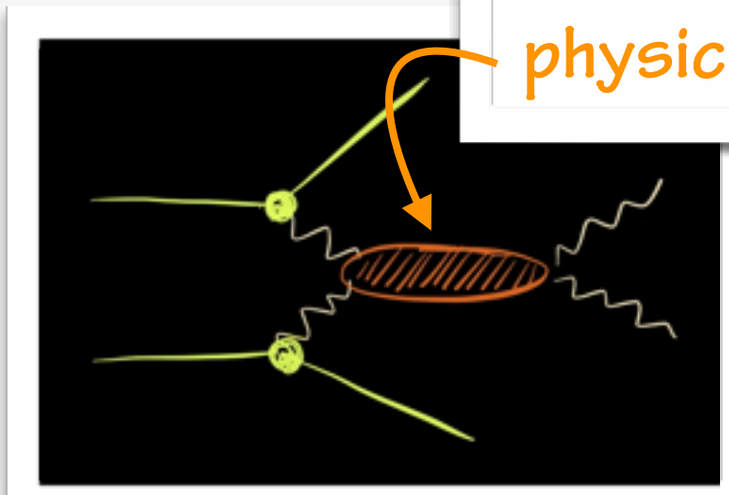


searching beyond: quartic VB scattering

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



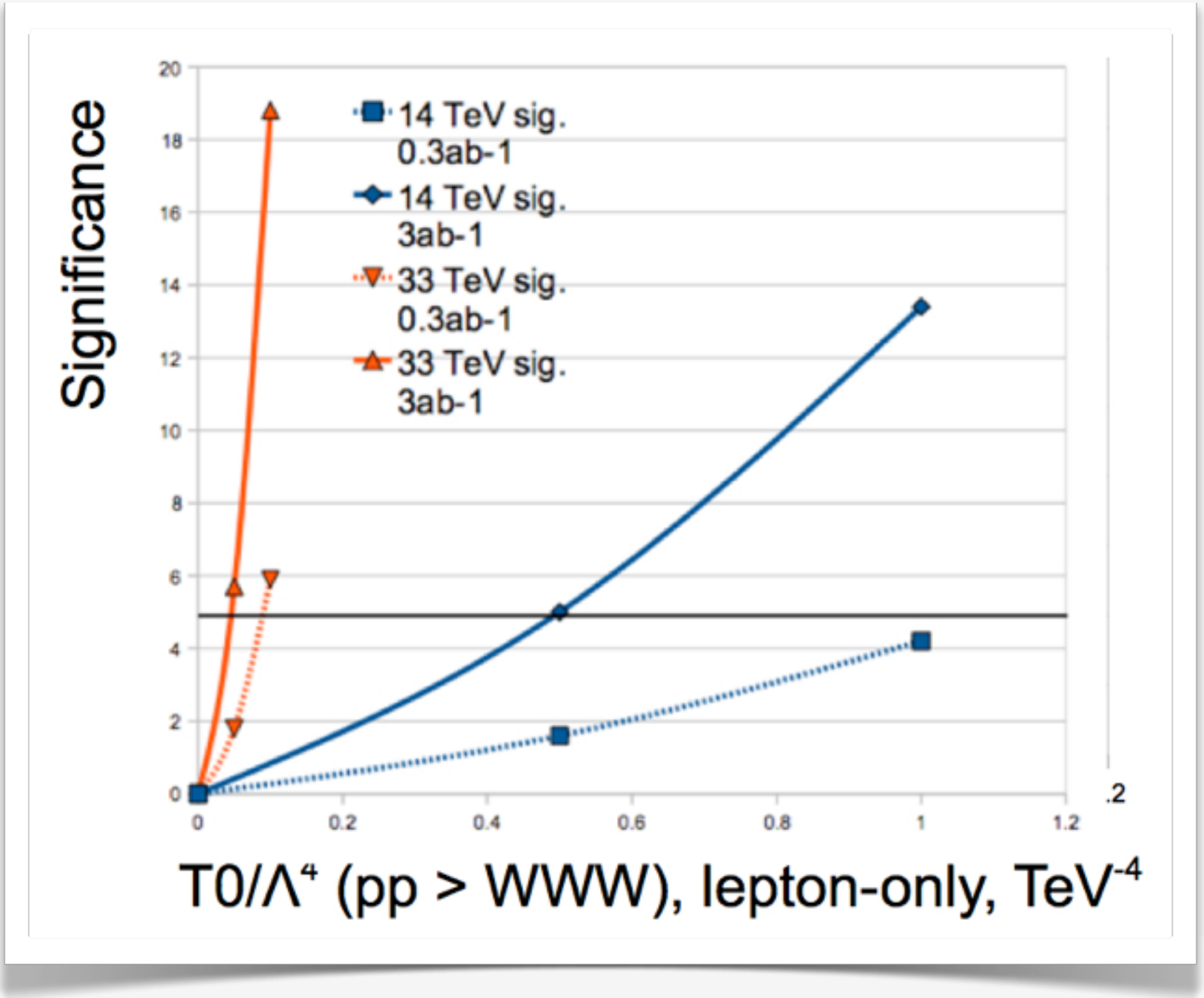
scale



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

VB Scattering

Luminosity and Energy win.



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

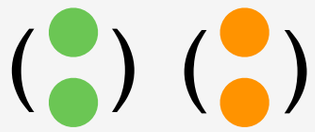
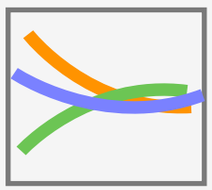
The EW physics message

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

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

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

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

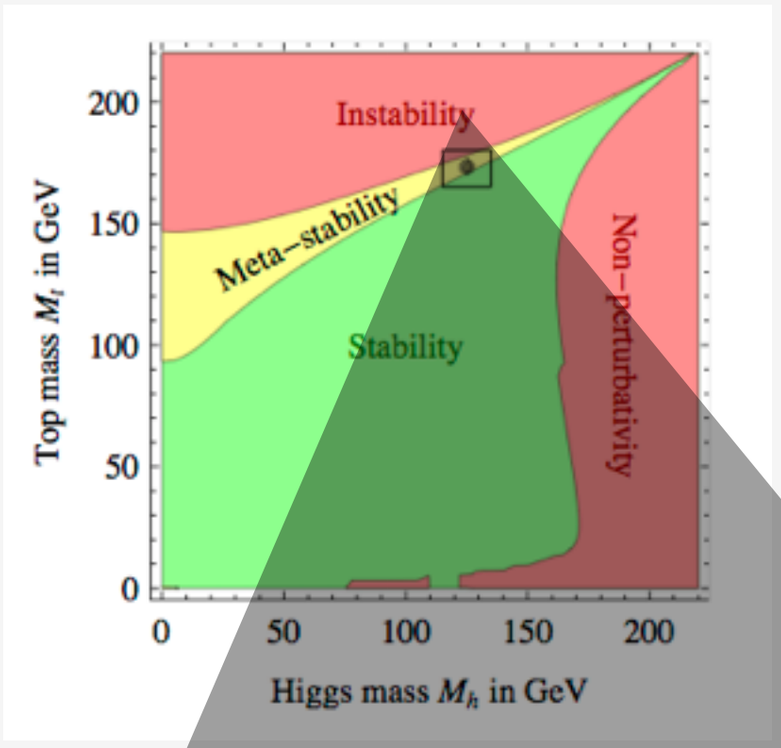
Fully Understanding the Top Quark

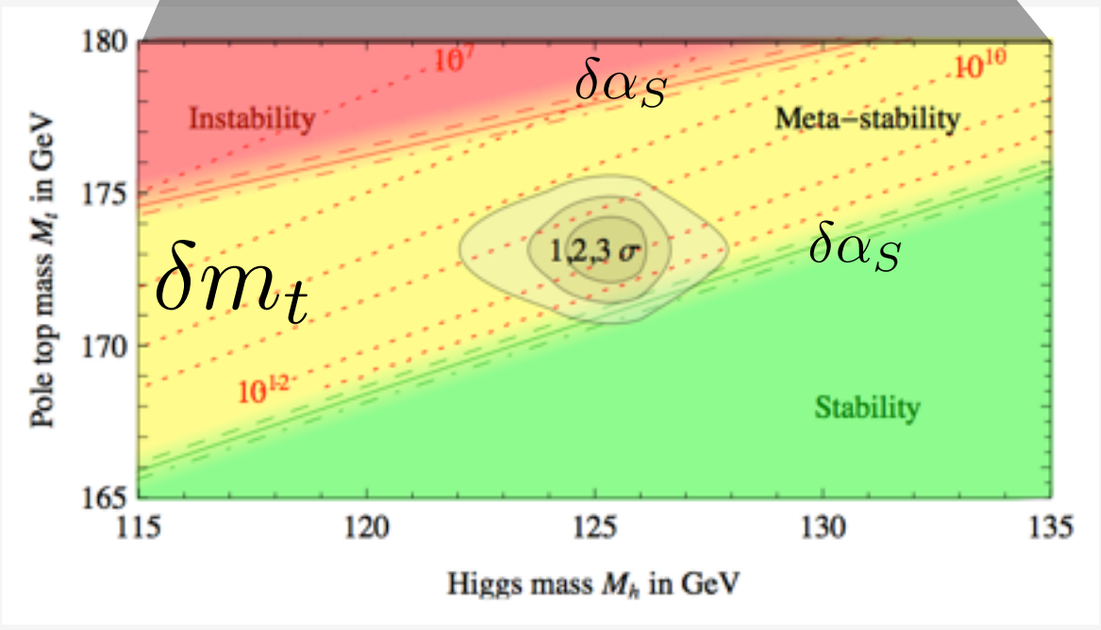
Top: Themes

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

why measure m_t precisely?

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





- EWPOs

  keep up with M_W precision

- fundamental parameter

  Yukawa coupling to Higgs

  close to weak scale

  stability argument sensitivity

why measure m_t precisely?

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

- EWPOs

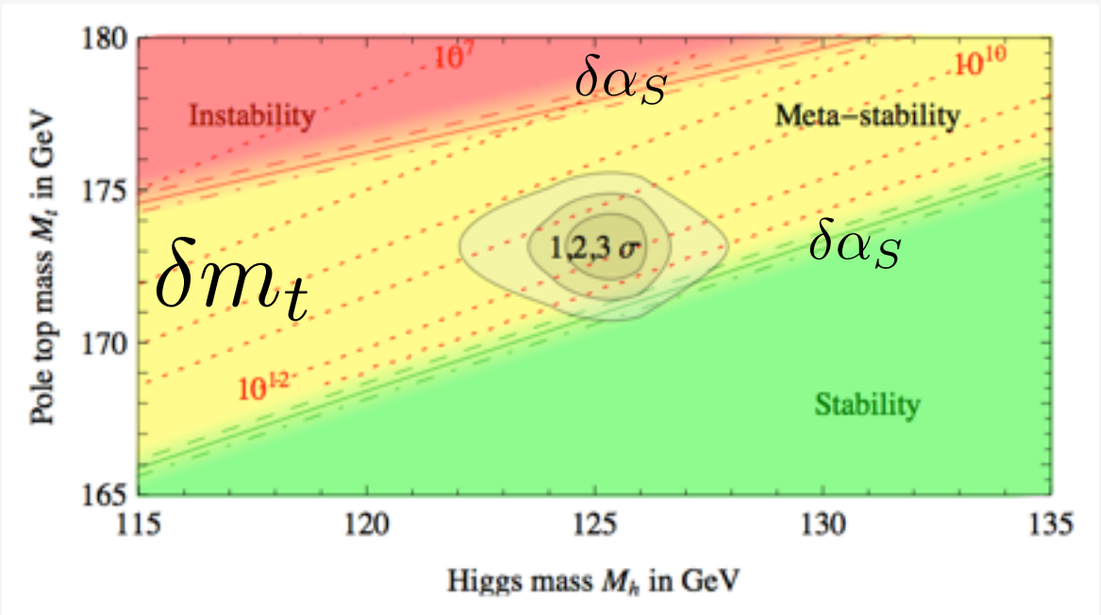
  keep up with M_W precision

- fundamental parameter

  Yukawa coupling to Higgs

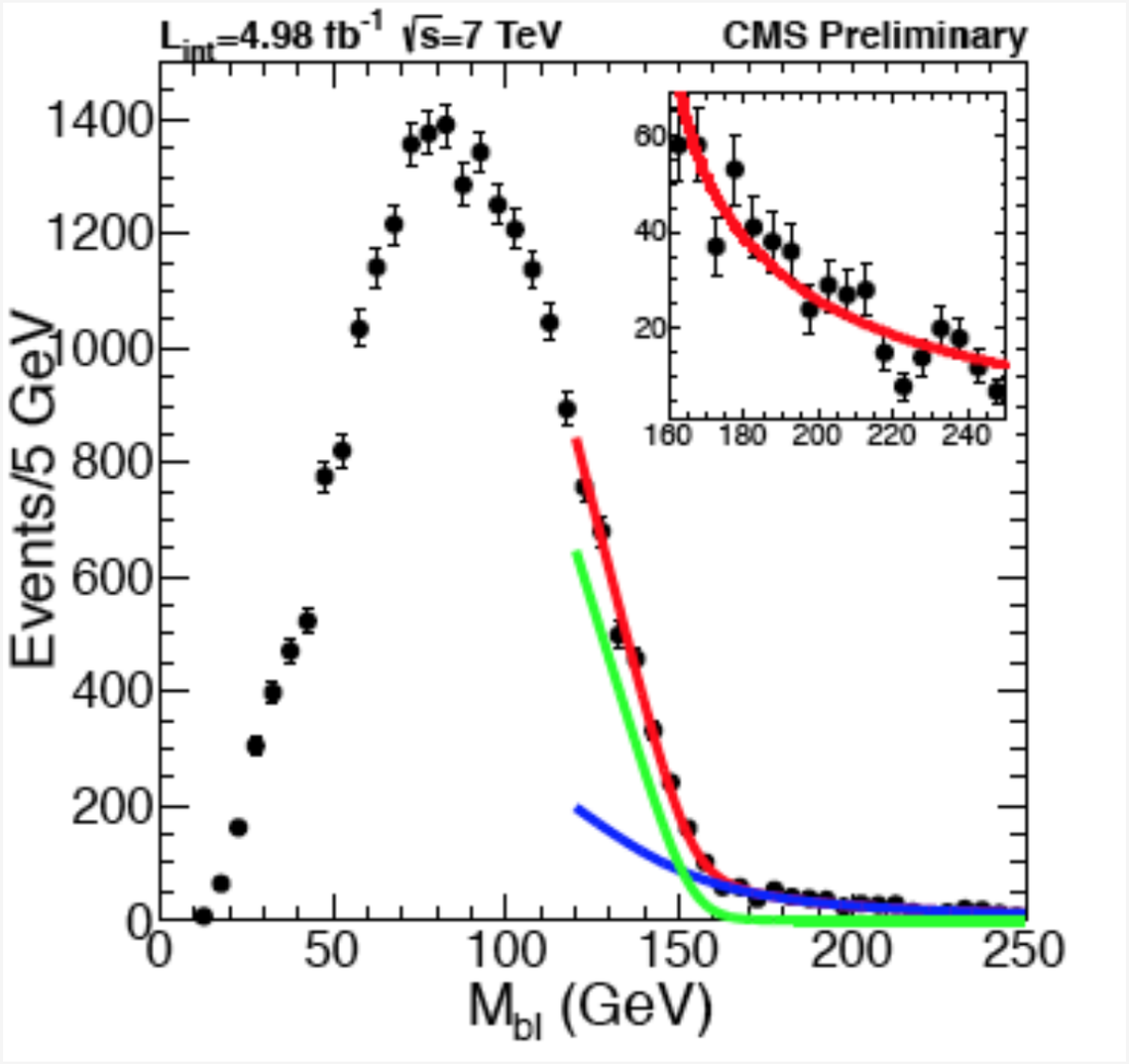
  close to weak scale

  stability argument sensitivity



A precision, theoretically sound m_t is doable at LHC

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

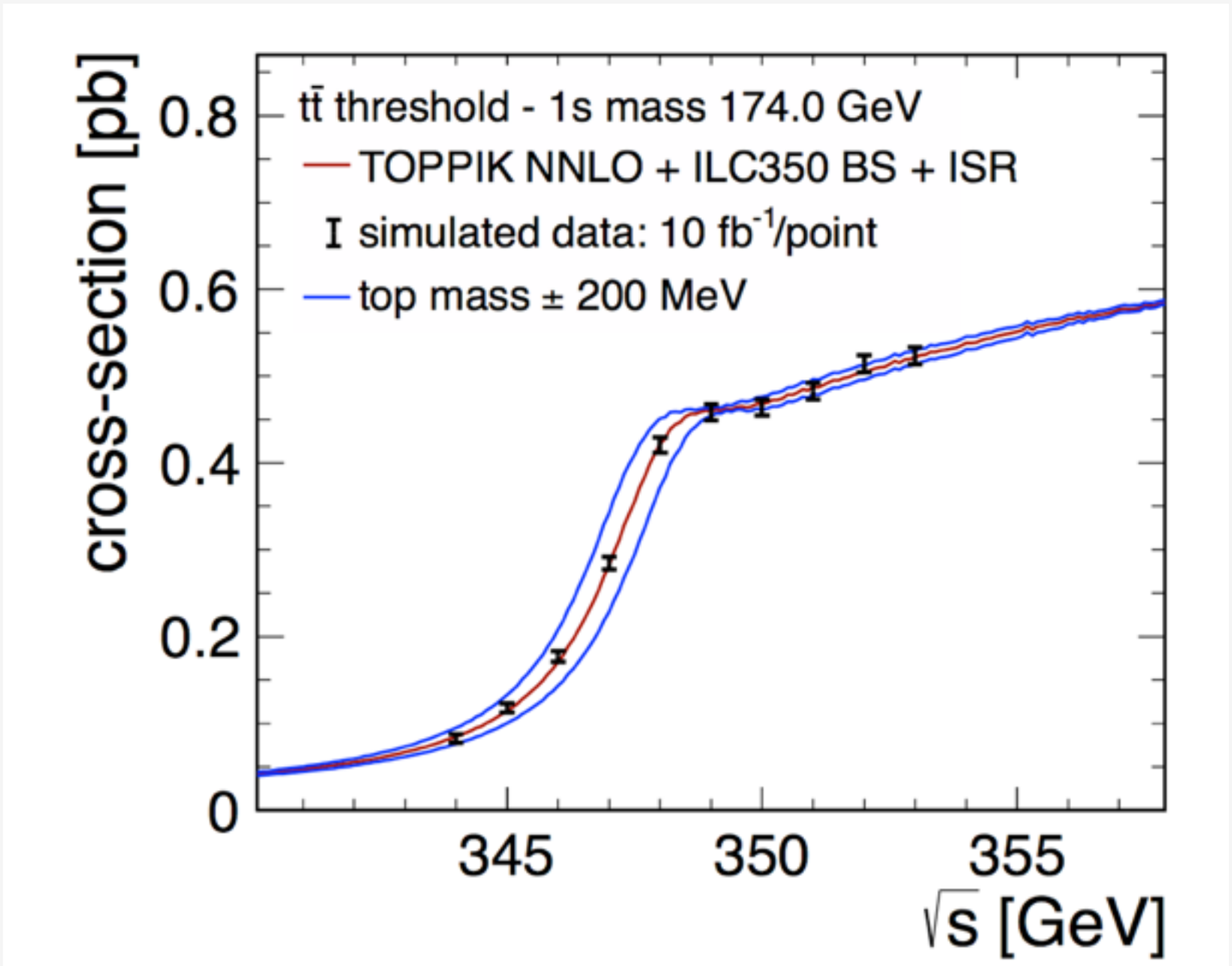


- $\delta m_t \sim 500$ MeV/c^2 ultimately

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

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-%

Flavor-changing top decay

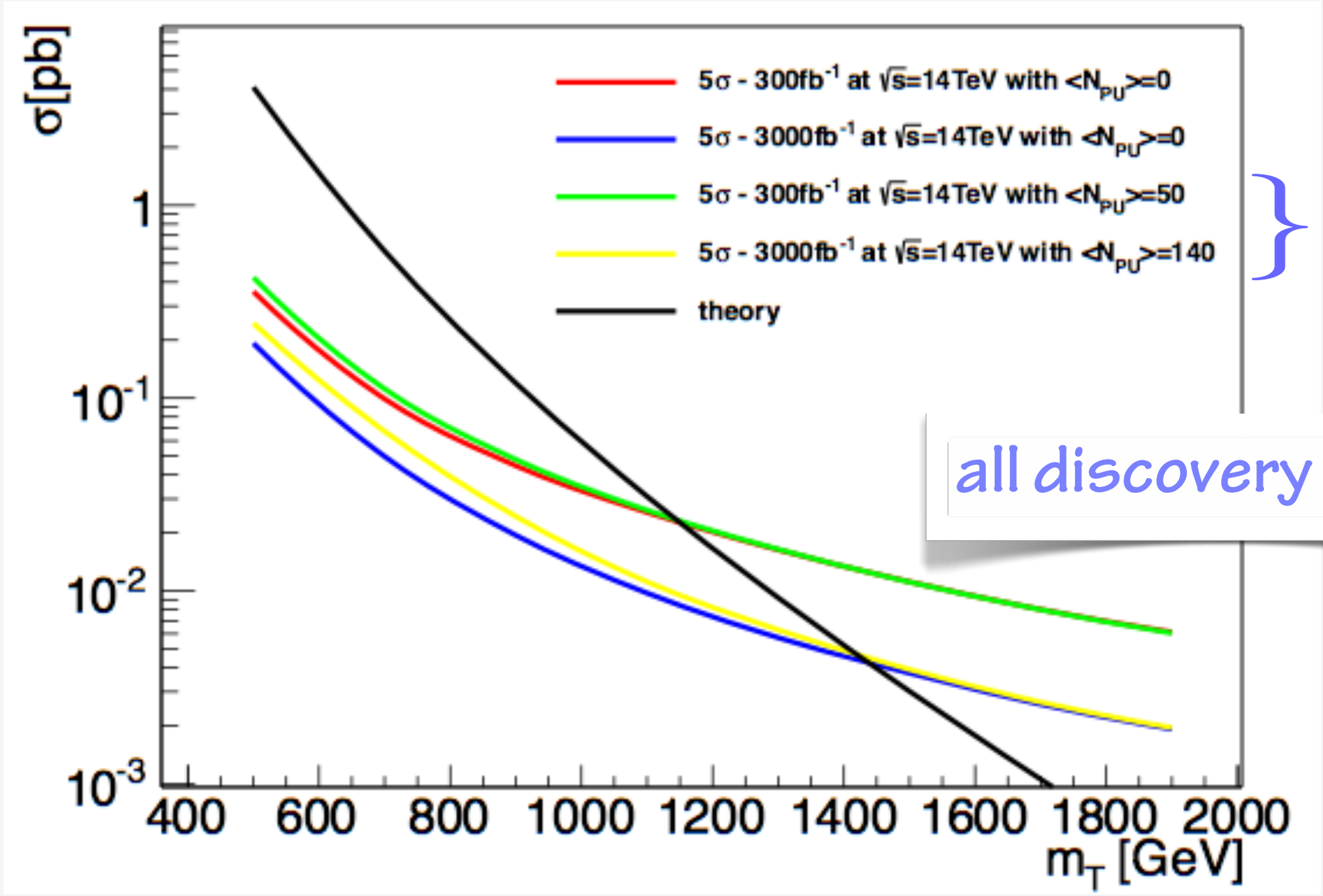
10^{-4} level probes BSM top decay models

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]

Top partner searches to 1.2-1.5 TeV

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



robust against pileup

all discovery limits

The Top Quark physics message

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

   LHC will search for the particles;

   Linear Colliders for coupling deviations.

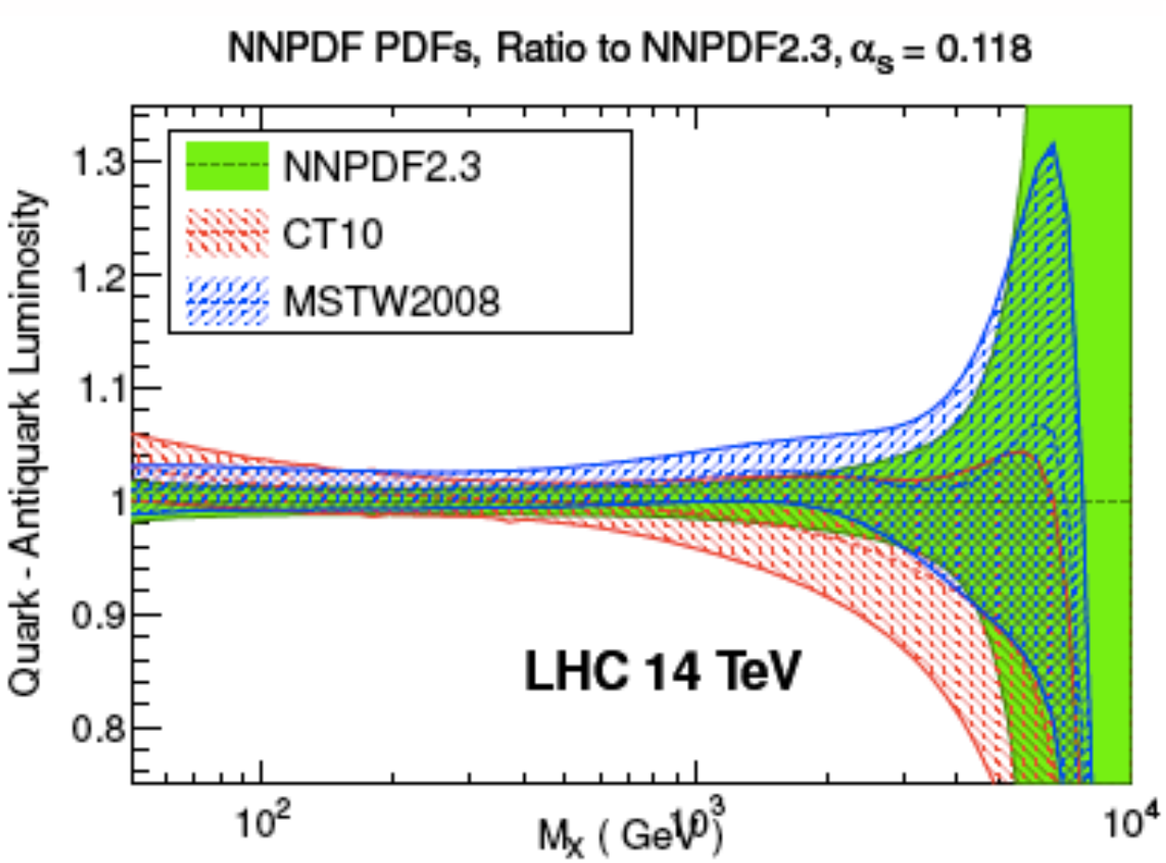
Quantum Chromodynamics and the Strong Force

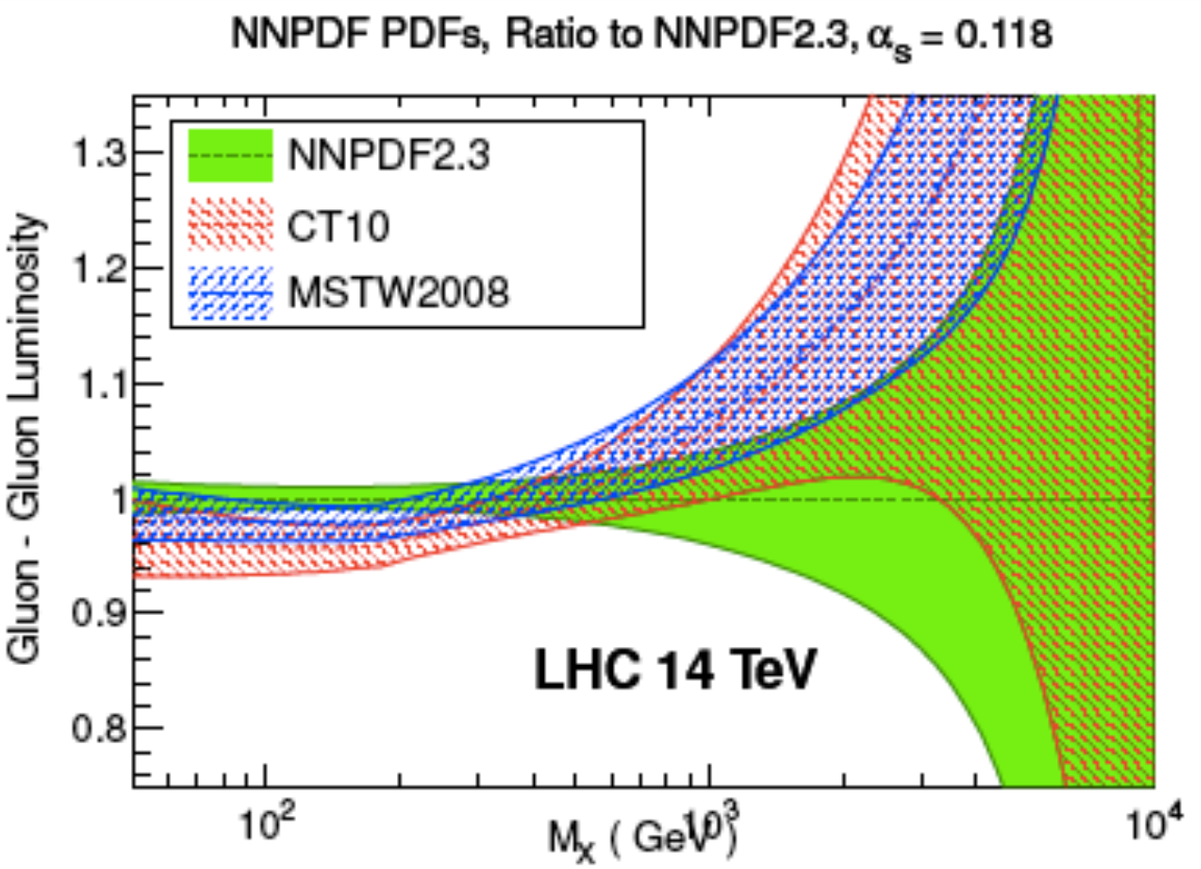
QCD: Themes

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

PDF uncertainties must improve

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



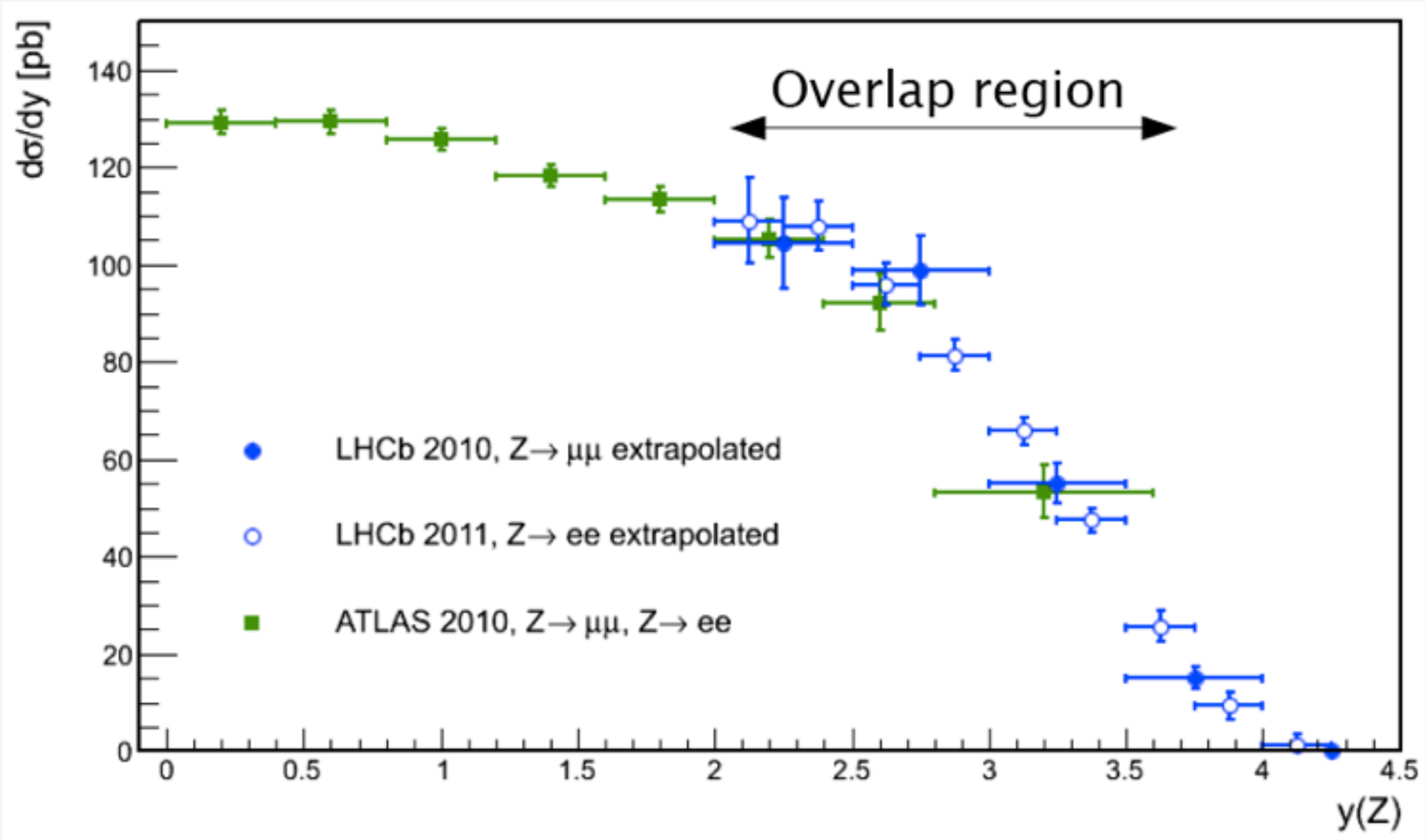


Juan Rojo

Improve at LHC with W, Z, top rapidity distributions

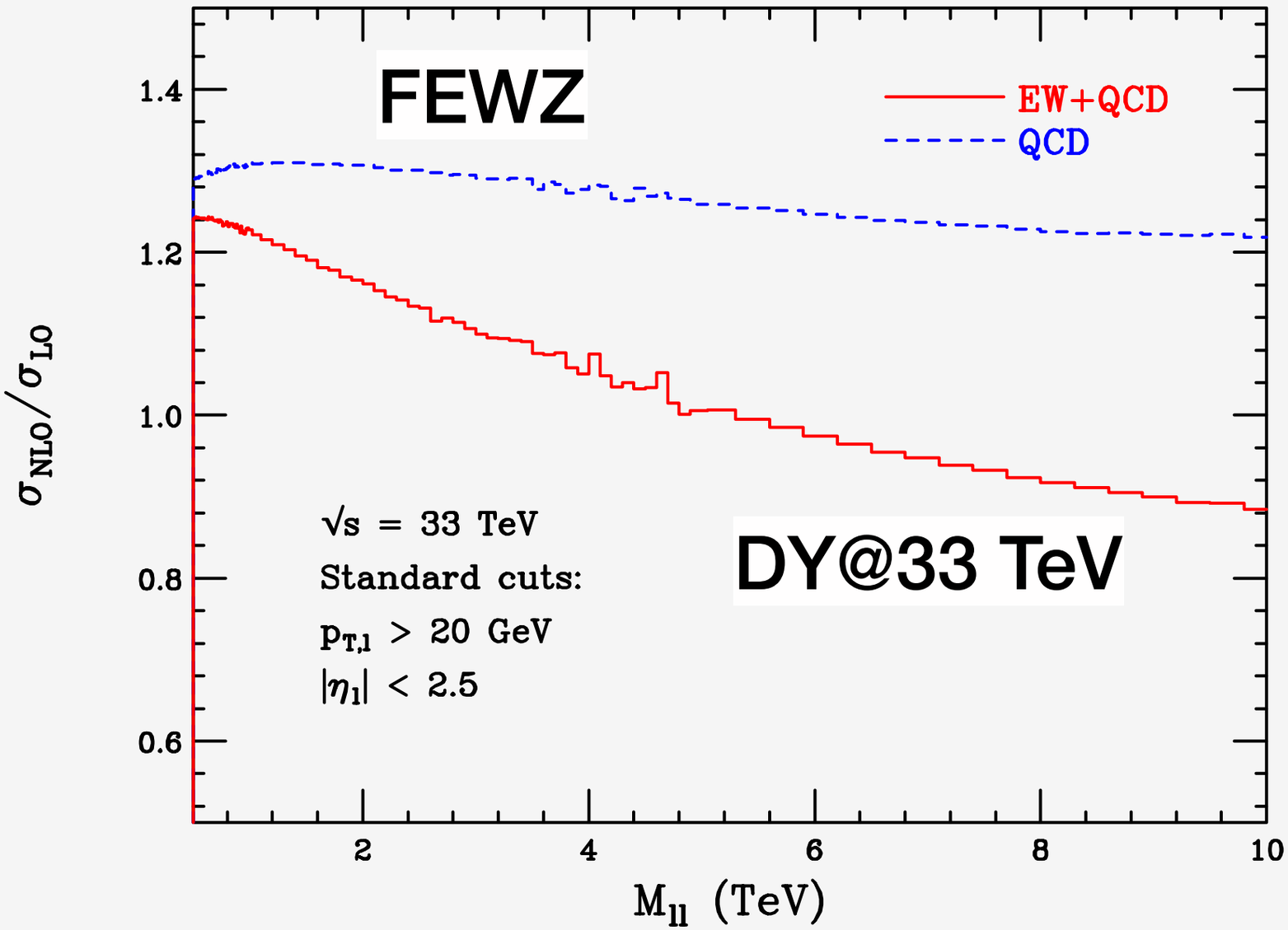
full rapidity coverage required

complementary role of ATLAS,CMS and LHCb



Electroweak Sudakov

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



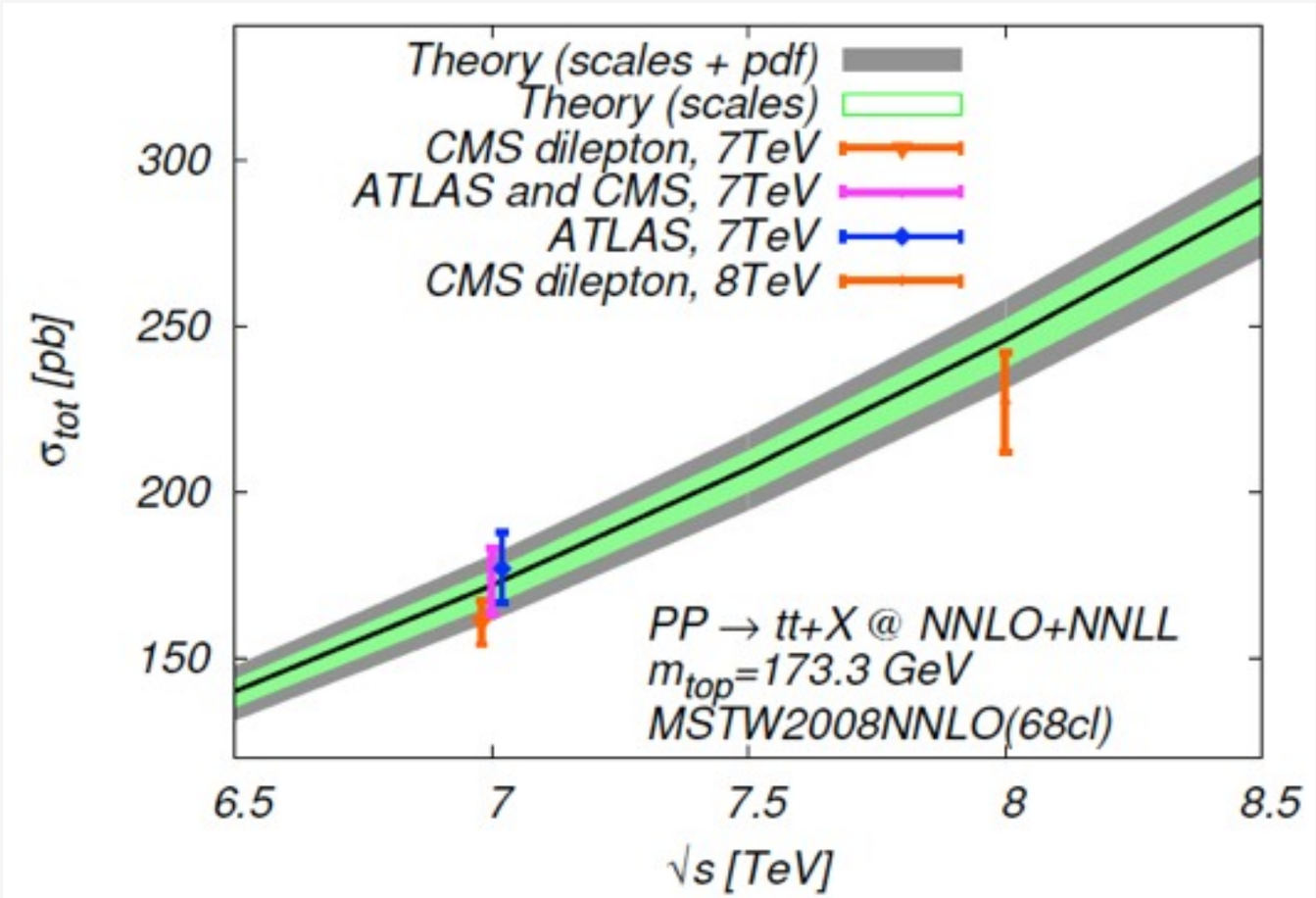
Kaland Mishra

NNLO

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

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

- Higgs 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.

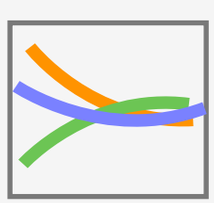
	Higgs X-section Working Group [34]	PDG[1]	Non-lattice	Lattice (2013)	Lattice (2018)	Prospects from ILC/TLEP/LHeC
$\delta\alpha_s$	0.002	0.0007	0.0012 [1]	0.0006 [24]	0.0004	0.0001–0.0006 [8, 27, 28]
δm_c (GeV)	0.03	0.025	0.013 [31]	0.006 [24]	0.004	-
δm_b (GeV)	0.06	0.03	0.016 [31]	0.023 [24]	0.011	-

Paul Mackenzie, Snowmass QCD report

The QCD Physics Message

1. Improvements in PDF uncertainties are achievable.
   - *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 for Higgs boson physics & M_W

   require continued advances in perturbative QCD.



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

NP: Themes

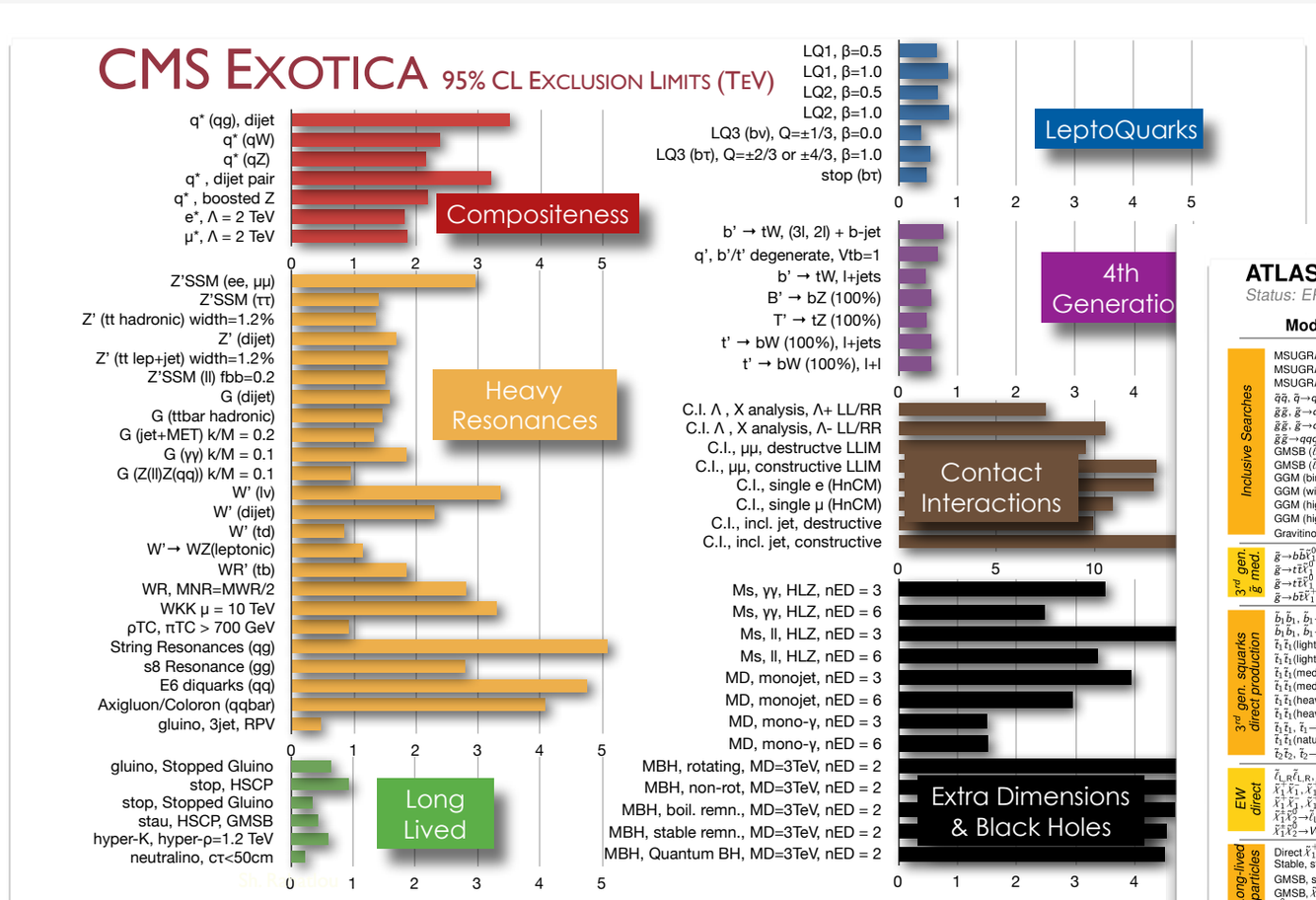
1. Necessity for new particles at TeV mass

the questions of fine tuning and dark matter are still open

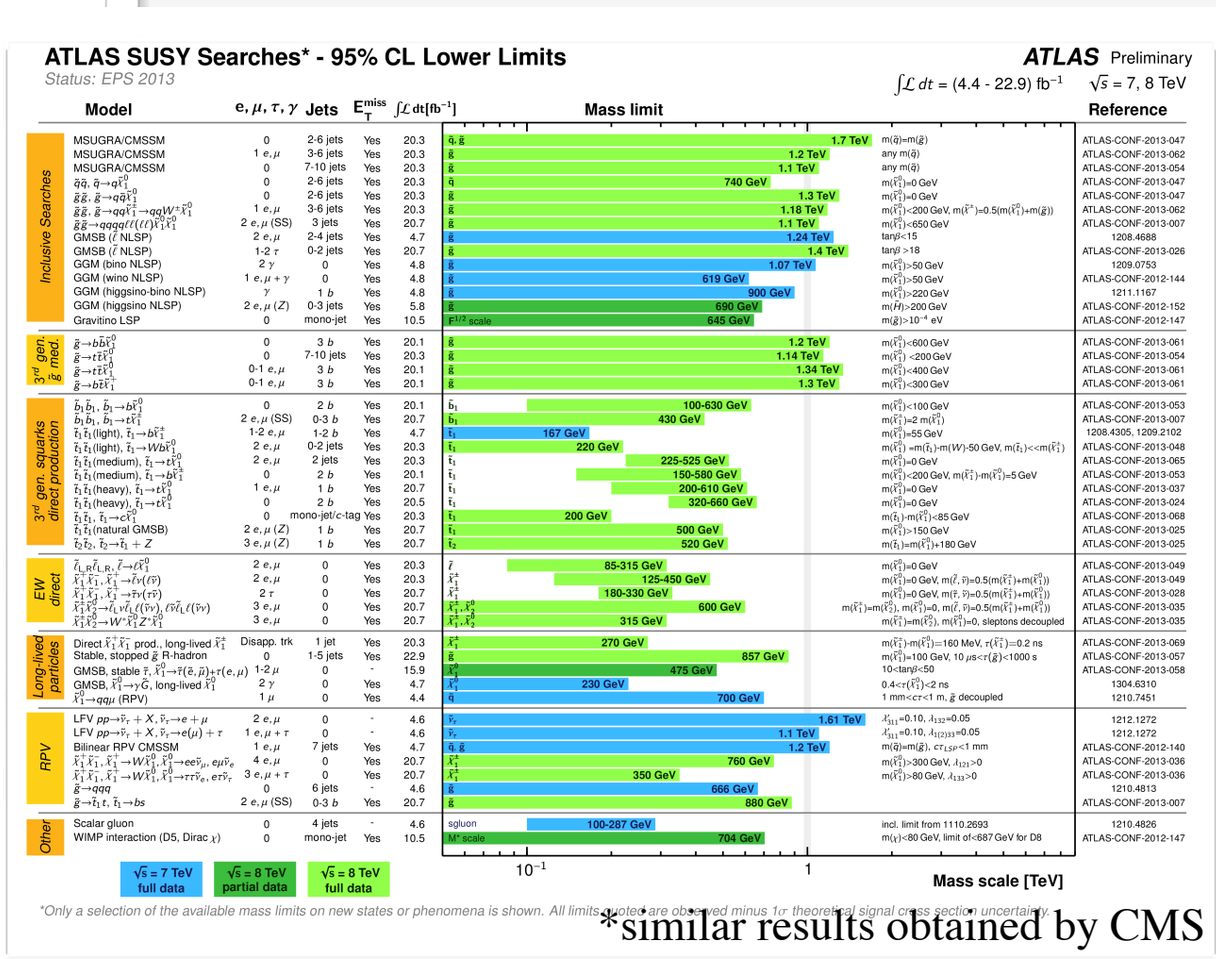
2. Candidate TeV particles
   - *weakly coupled: SUSY, Dark Matter, Long-lived*
   - *strongly coupled/composite: Randall-Sundrum, KK and Z' resonances, long-lived particles*
   - *evolution of robust search strategies*
3. Connection to dark matter problem
4. Connection to flavor issues

current LHC searches

New particle searches at the current LHC.



*similar results obtained by A

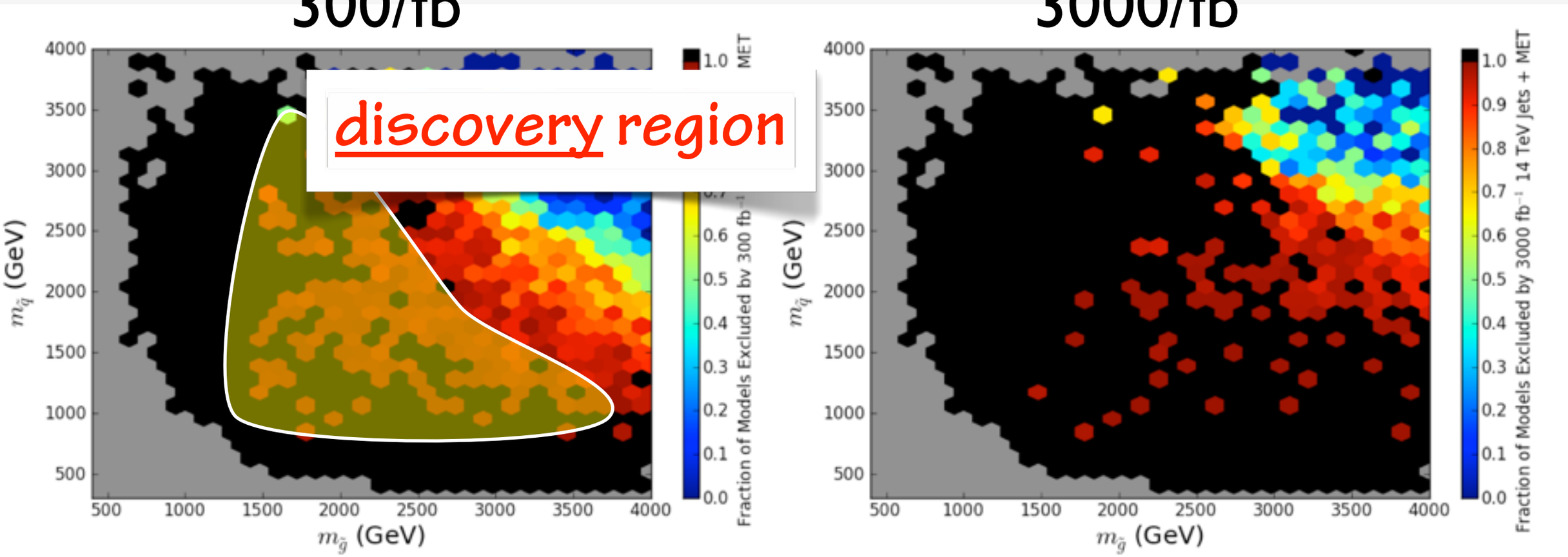


*similar results obtained by CMS

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

In the pMSSM survey of SUSY models

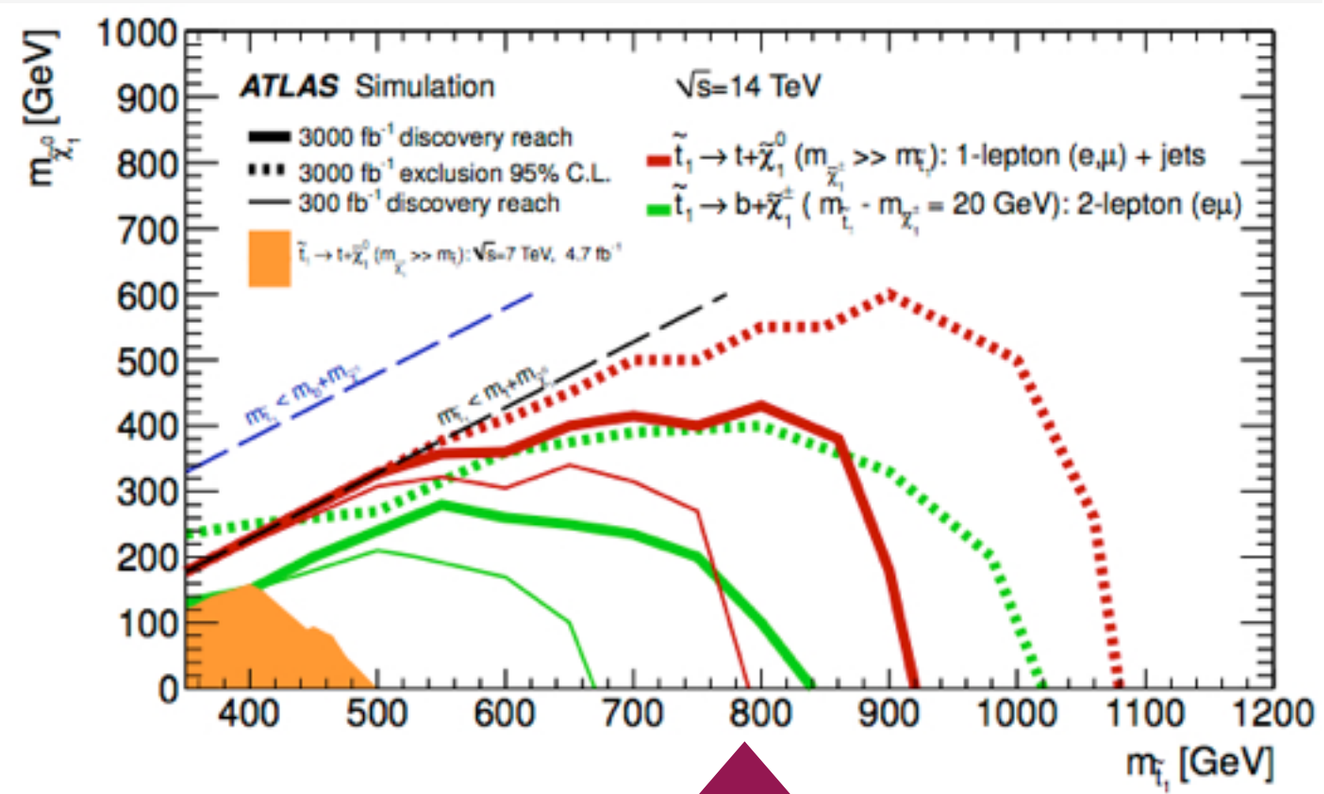
squark/gluino mass plane

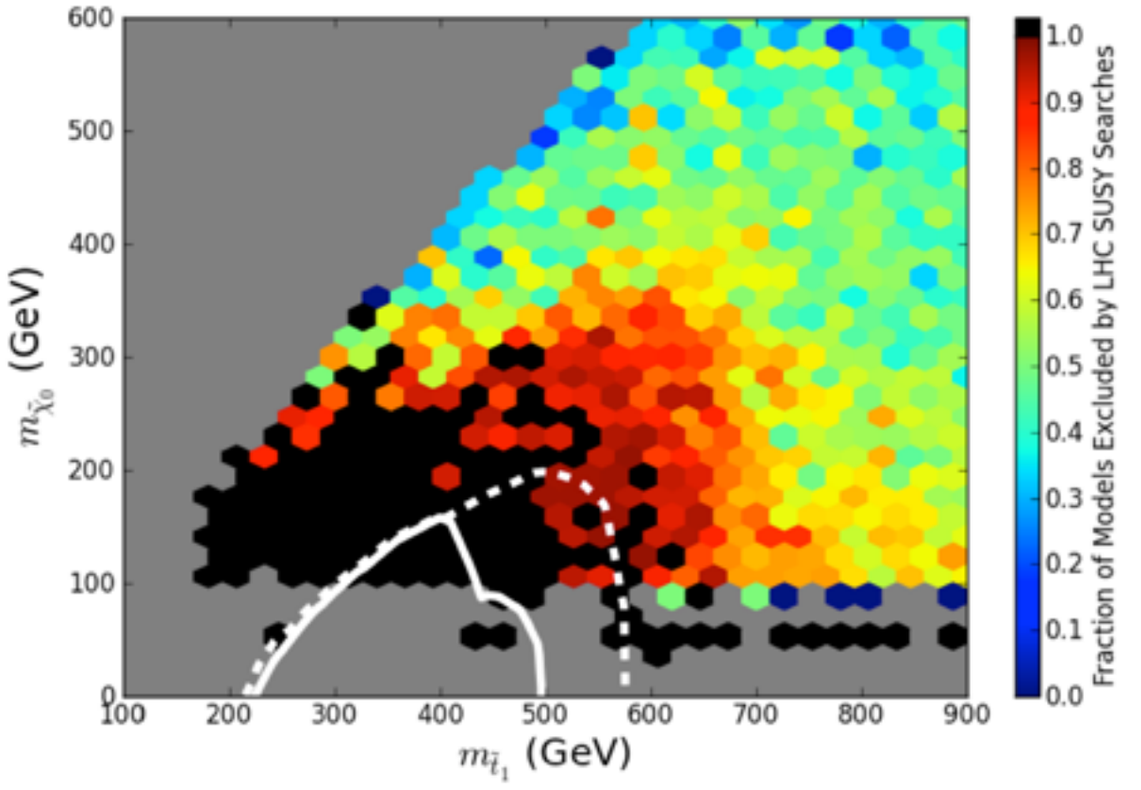


Note closing of loopholes in addition to increased energy reach.

Cahill-Rowley et al.

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



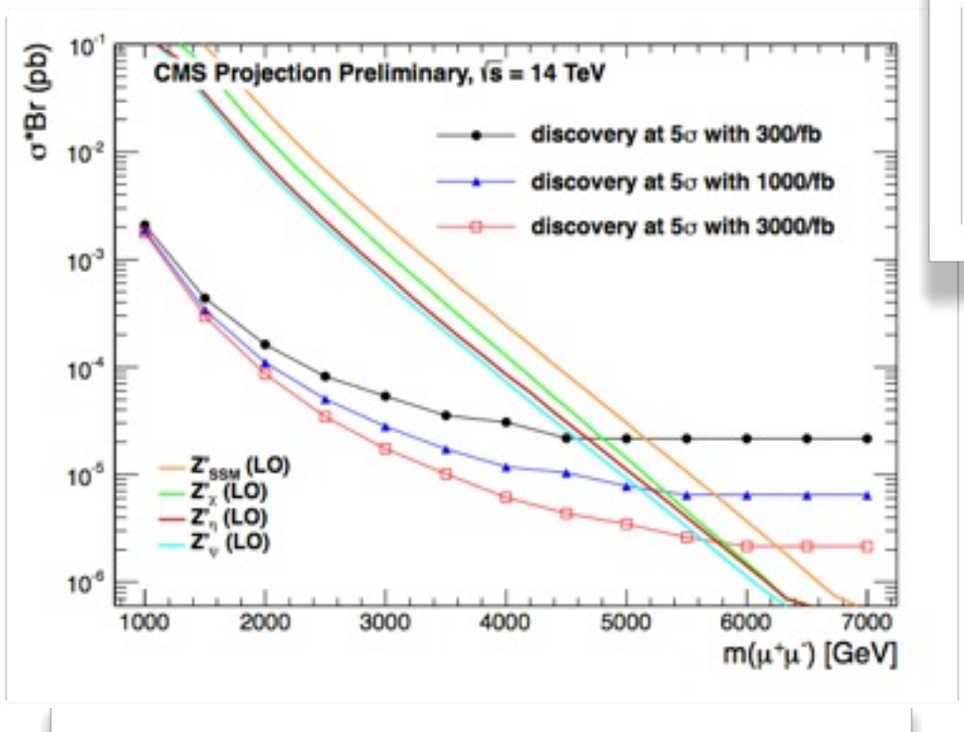


300/fb reach
stop-> t + neutralino

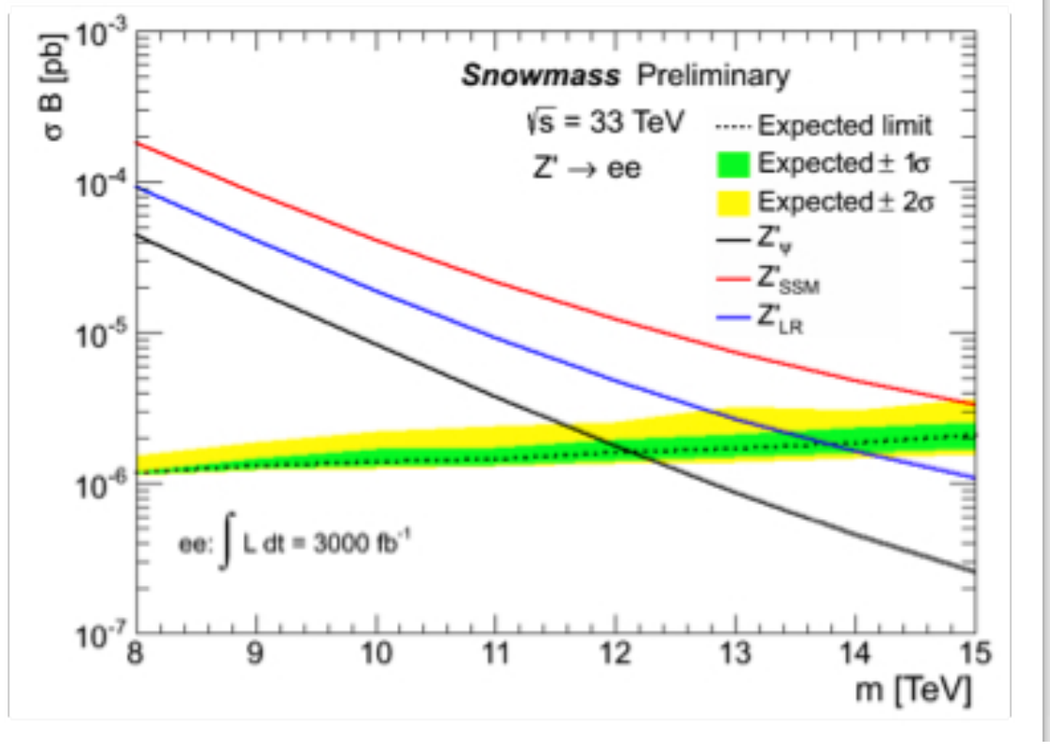
3000/fb reach
stop-> t + neutralino

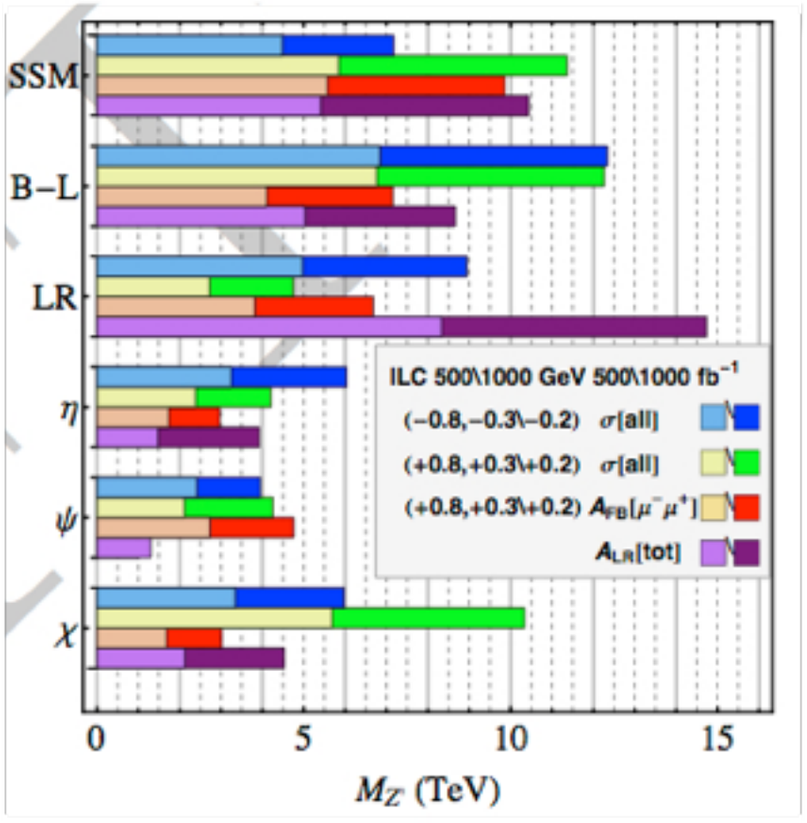
Cahill-Rowley et al.

Z’ sensitivity



5-6+ TeV Discovery range at 14 TeV LHC



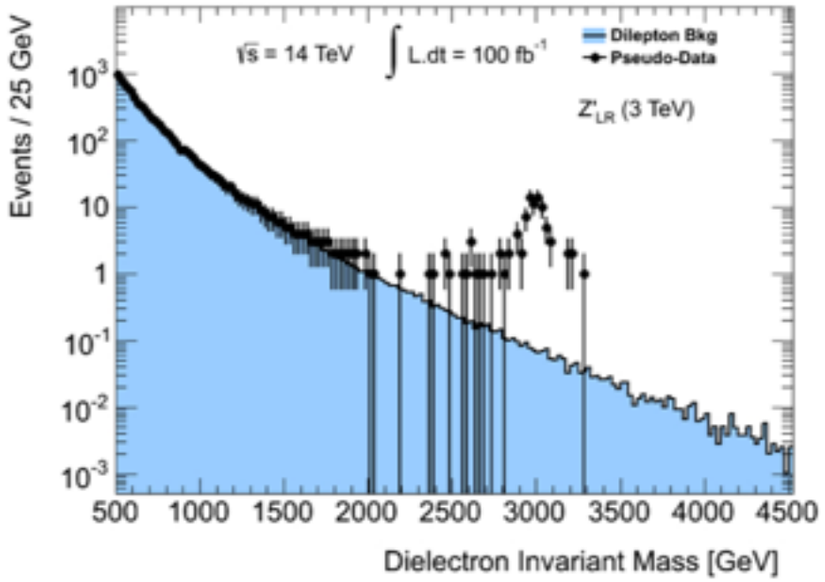


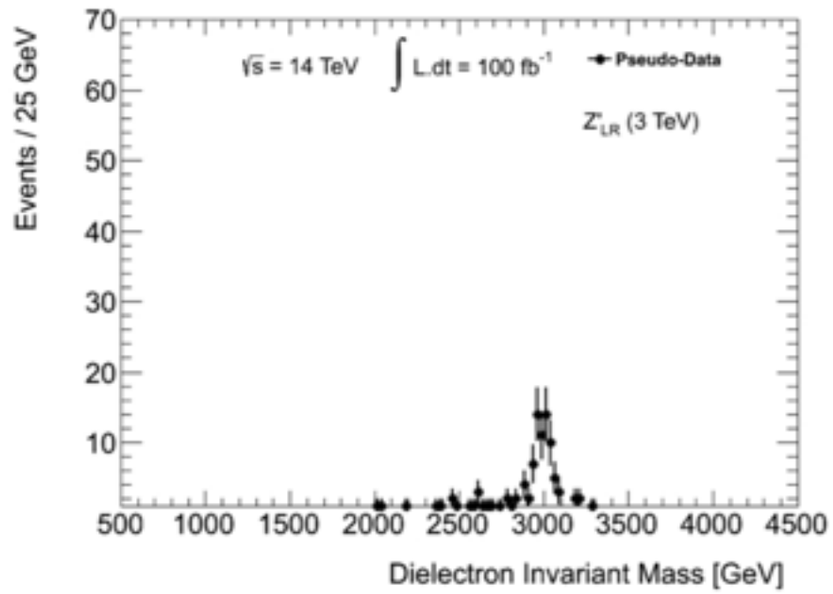
12-15 TeV limit range at 33 TeV pp

ILC asymmetry interference, beyond LHC

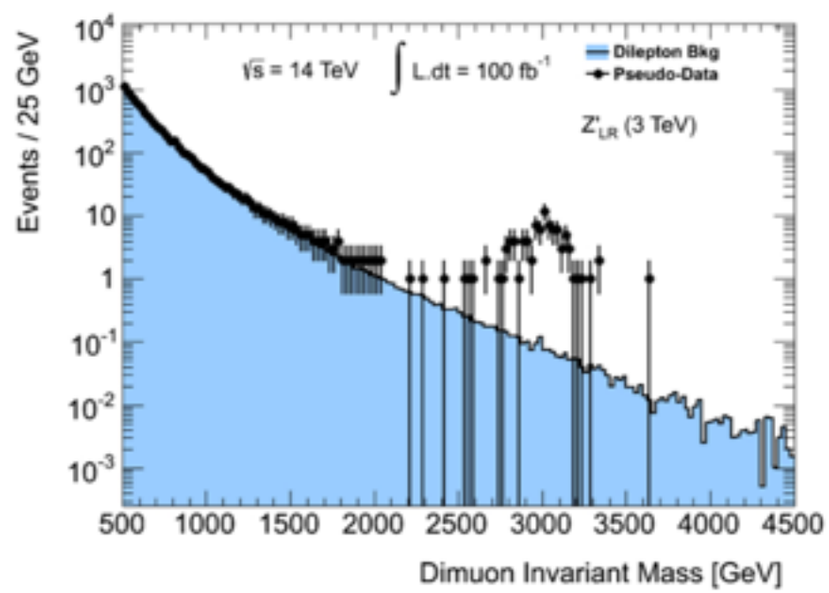
Z’, a Run 2 discovery target

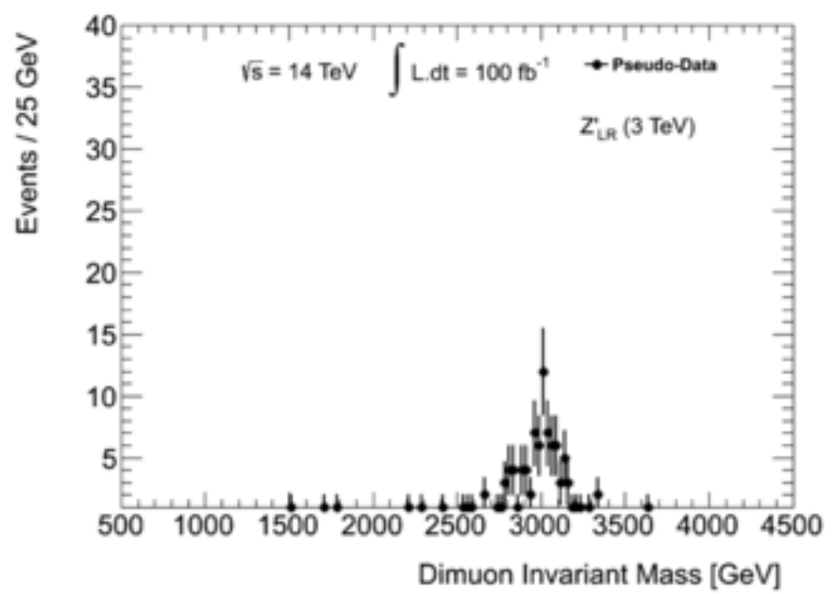
Electrons and muons would nail it **100/fb**





electrons

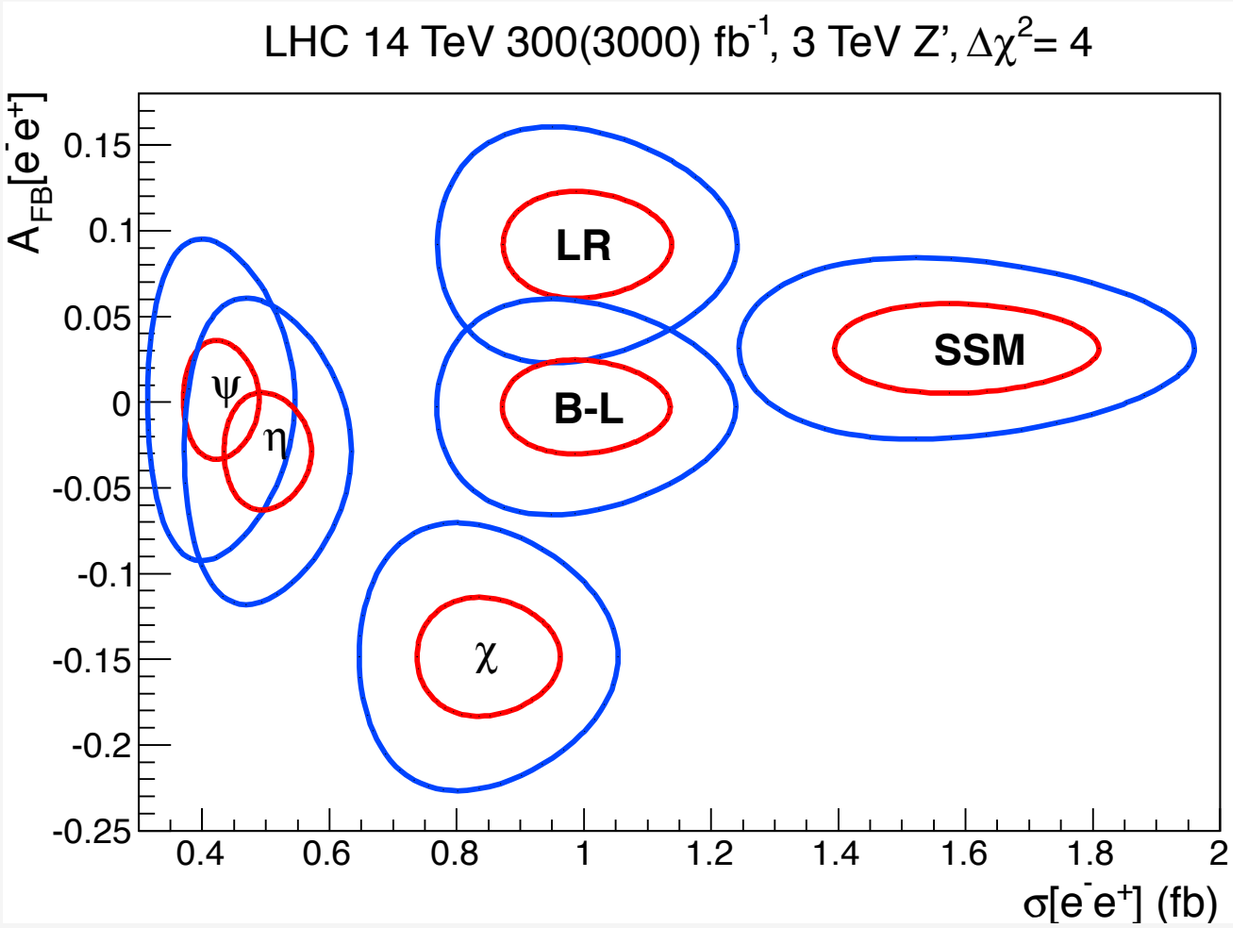




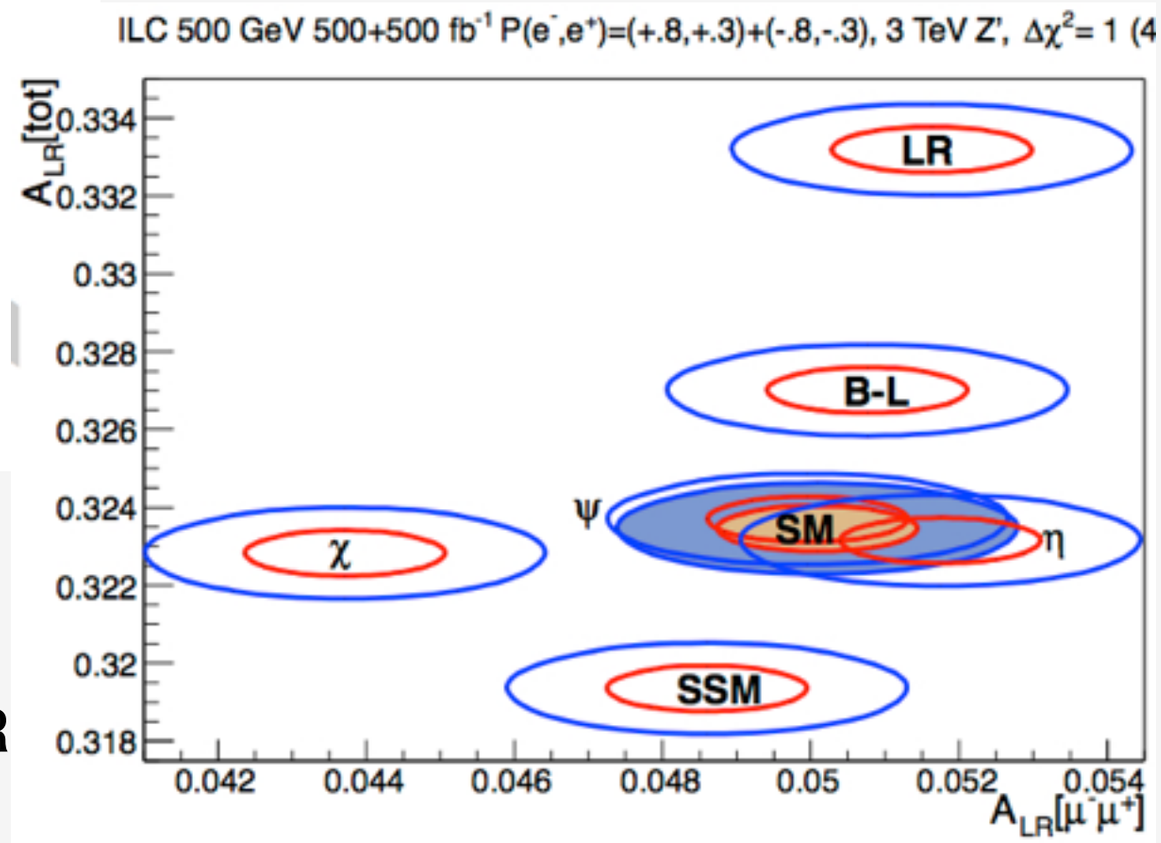
muons

Finding the identity of a Z'

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



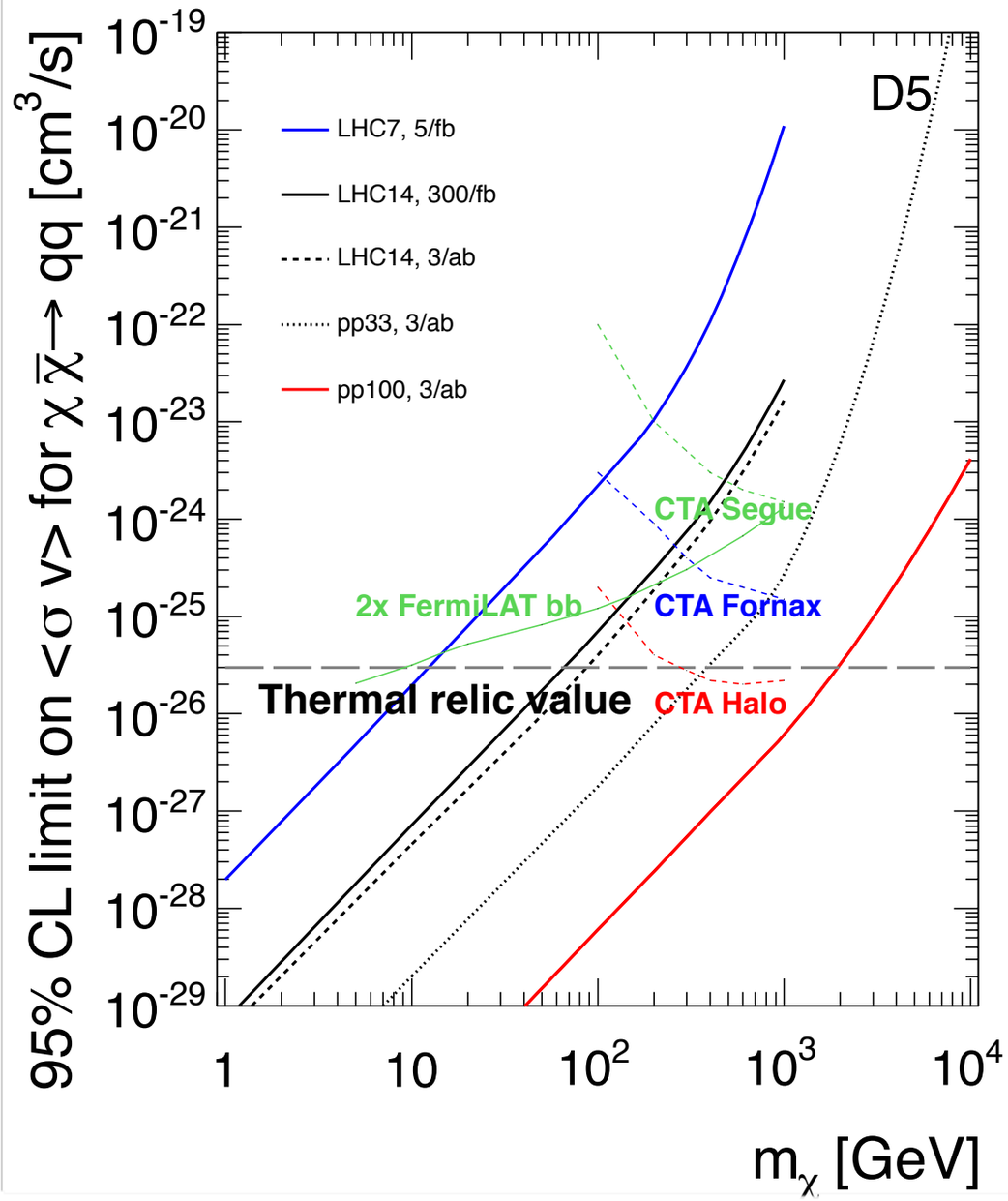
E6 from LR, etc LHC A_{FB}



E6 from LR, etc ILC A_{LR}

Dark Matter Connection

nearly close the thermal relic range?

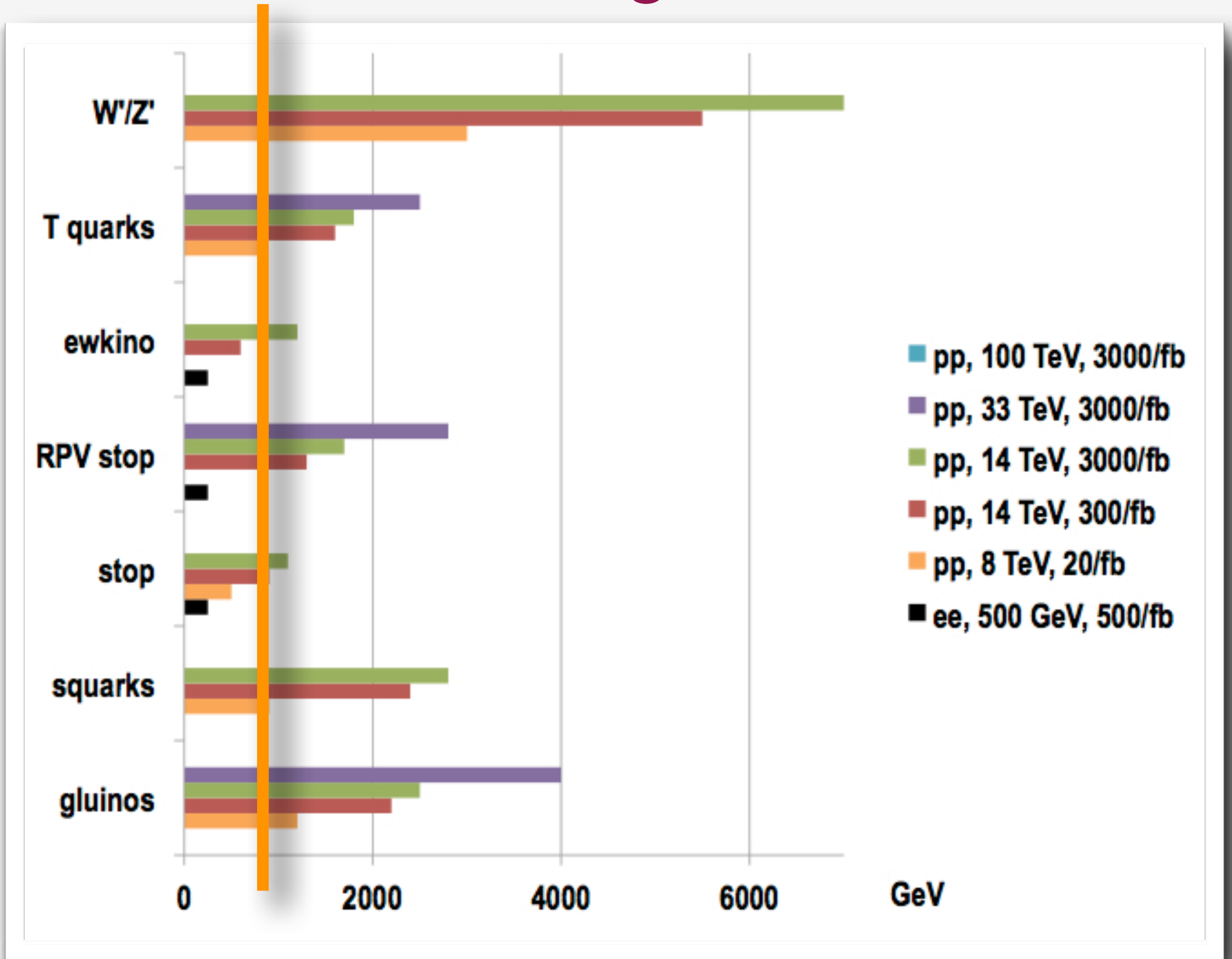


progressive increase in sensitivity

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

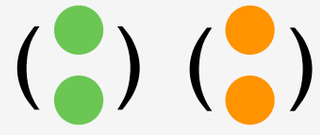
Likewise, VLHC closes the fine tuning requirement to 10^{-4}

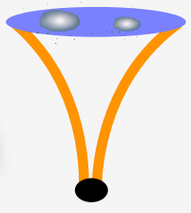
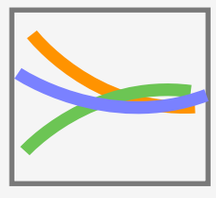
The TeV scale is in sight



The NP Physics Message

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



cases for future programs

- the Snowmass lineup:

LHC upgrades: 300, 3000/fb

Linear ee collider: 250/500, 1000 GeV

CLIC: 350 GeV, 1 TeV, 3 TeV

muon collider

photon collider

Circular ee collider: up to 350 GeV

pp Collider: 33/100 TeV

obvious point

- cases for machine B

  are usually written as if machine A found nothing.

- The most important cases for machine B?

  to study the discoveries of machine A with more precision.

  and to find additional particles or forces

LHC: 300 fb^{-1}

Higgs EW Top QCD NP/flavor

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

the rest?

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

- are in the back of the slides

2 things and then conclusions

thing 1: mass.

Let’s be clear.

We collider types say we know about Mass.

Really?

- As long as we know

  nothing about the neutral fermions

  &

  nothing about 85% of the gravitating universe

- We don’t know the Mass story.

This is serious.

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

- is it Dirac? – it's a tiny coupling to v
  - *then the Higgs sector could be expanded*
- is it Majorana? – it might talk to a different Higgs!
  - *then we have to find it*

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

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

Andre de Gouvea keeps making this point

This is serious.

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

- is it Dirac? – it's a tiny coupling to v
  - *then we need to find W' and expand the Higgs sector*
- is it Majorana? – it might talk to a different Higgs!
  - *then we have to find it*

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

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

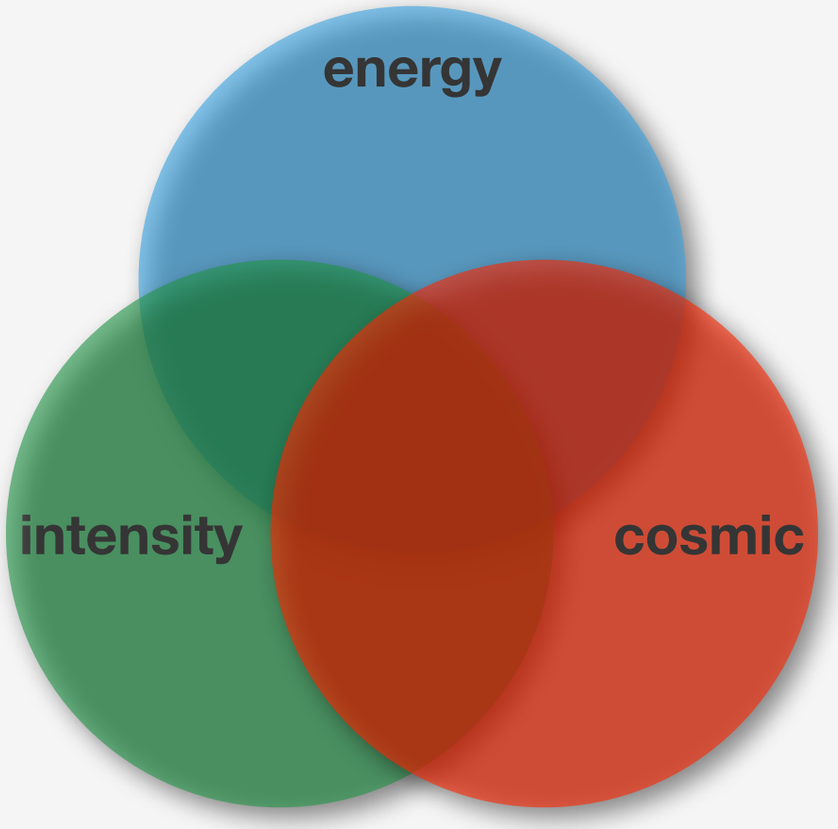
Understanding Mass is still "all hands on deck" physics – EF, IF, and CF!

Andre de Gouvea keeps making this point

thing 2: the circles.

The Bumper Sticker Frontier

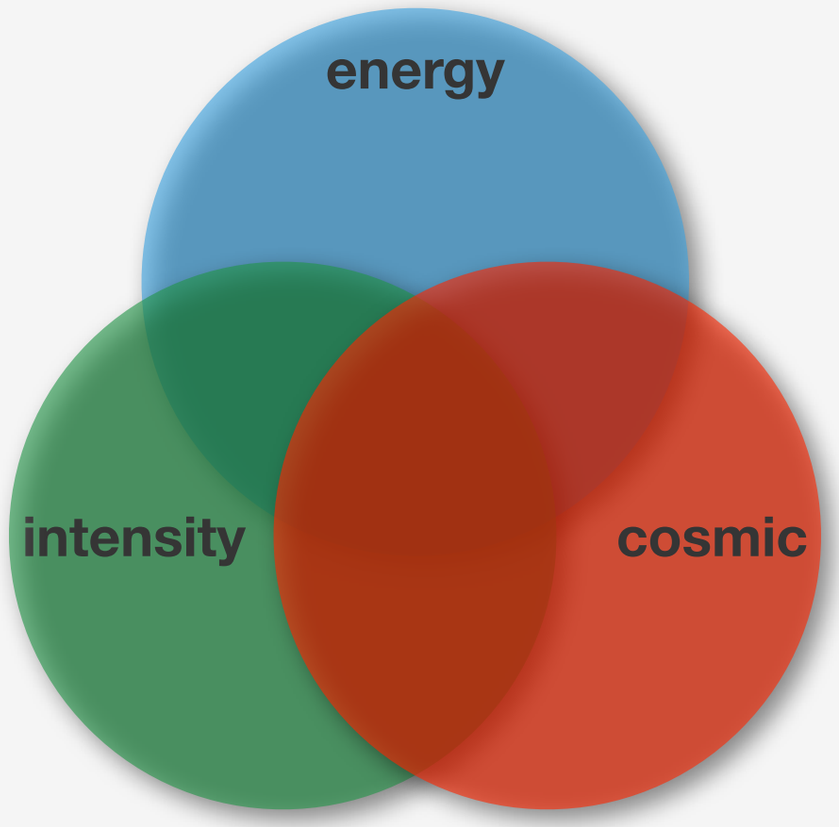
they’re pithy



- I’m rethinking...

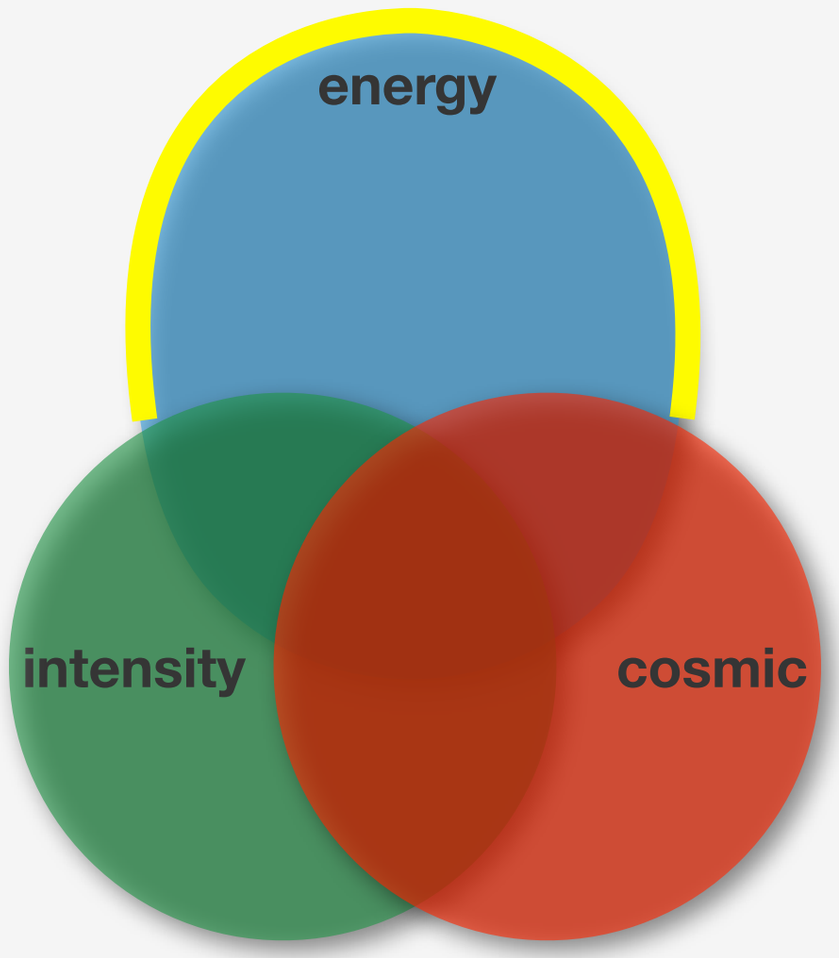
  maybe an apt metaphor

“Frontier”



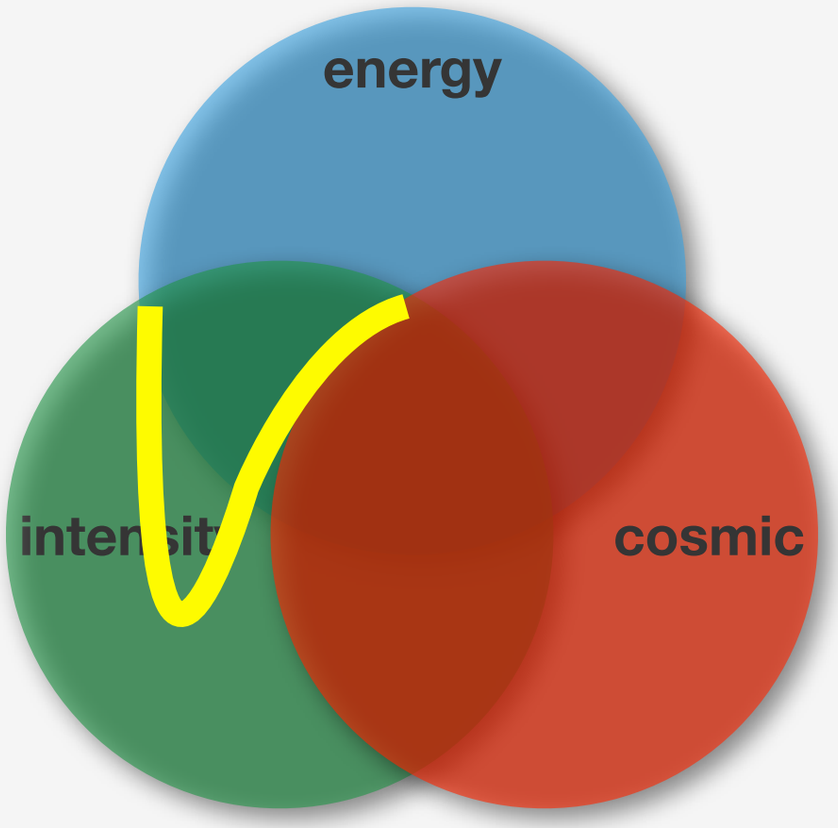
a unique
“Frontier”

- The new physics will bulge somewhere!



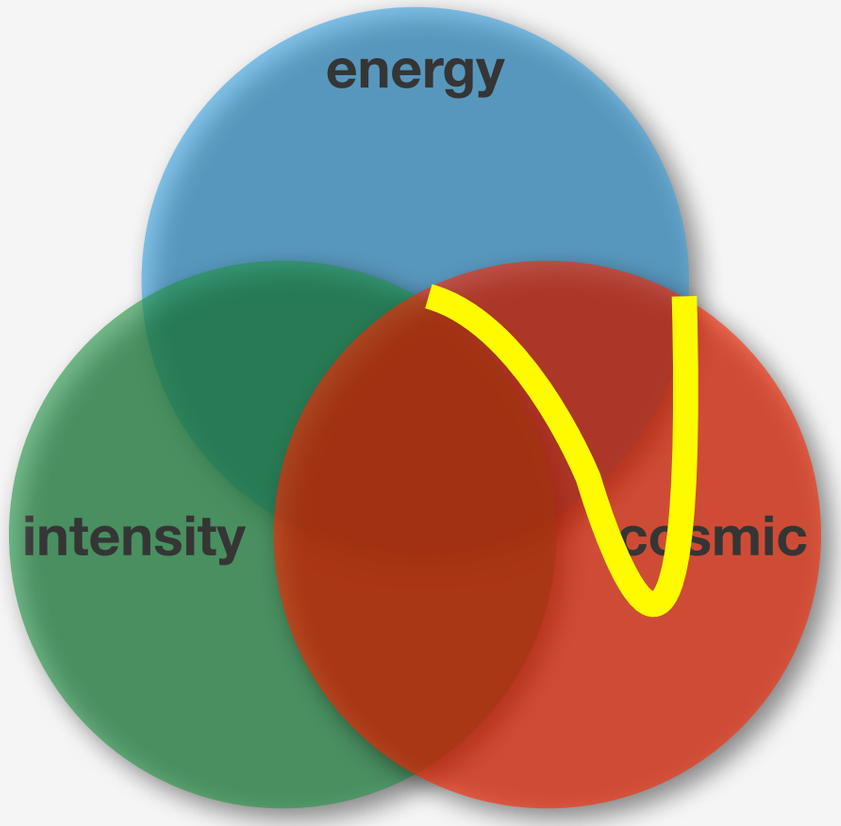
a shared
“Frontier”

- The new physics will bulge somewhere!



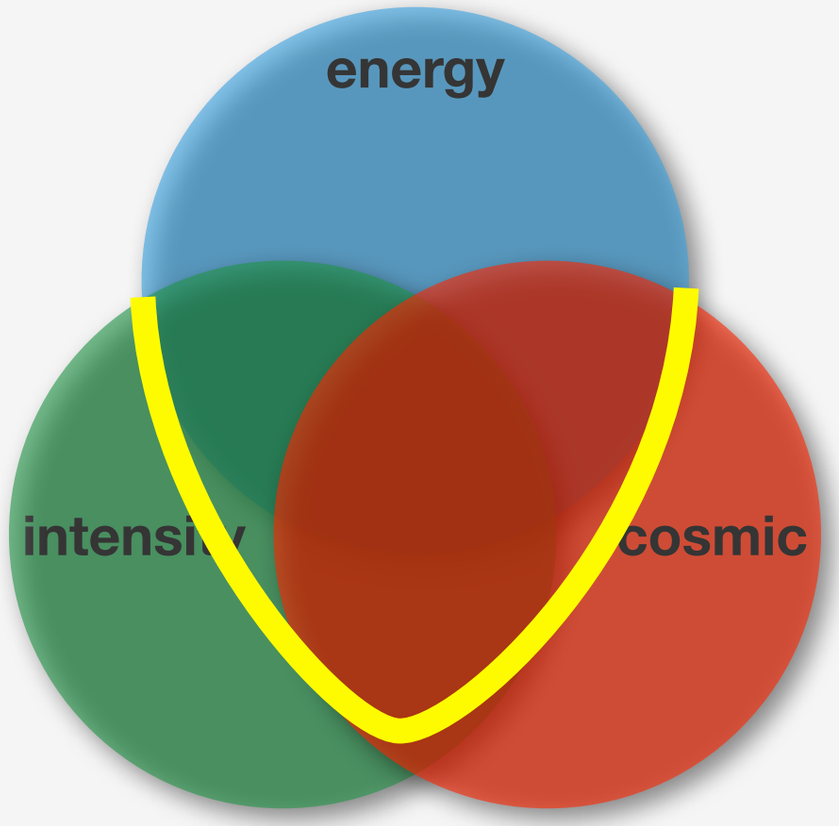
- The new physics will bulge somewhere!

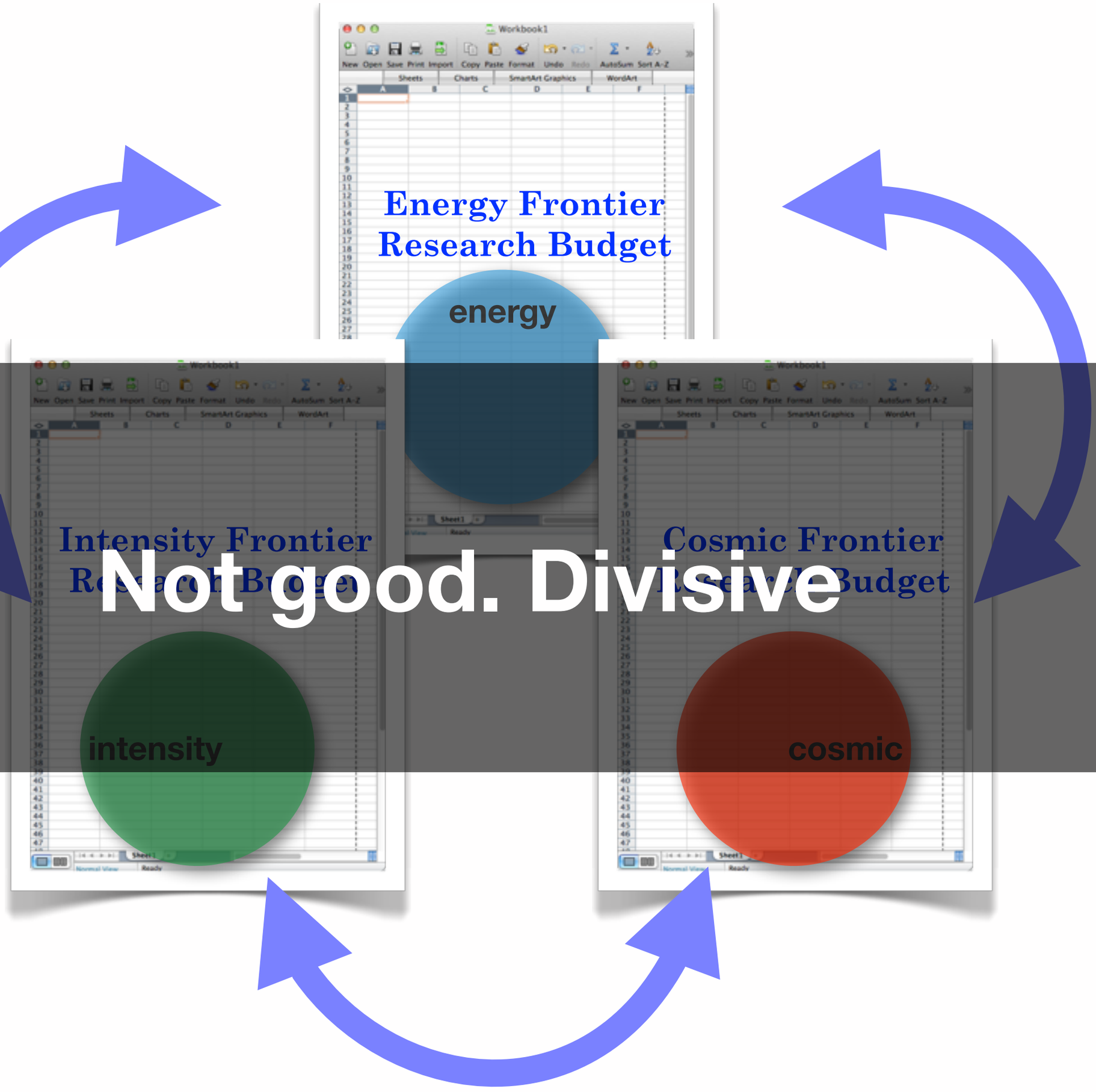
a shared “Frontier”



- but probably everywhere

a shared
“Frontier”

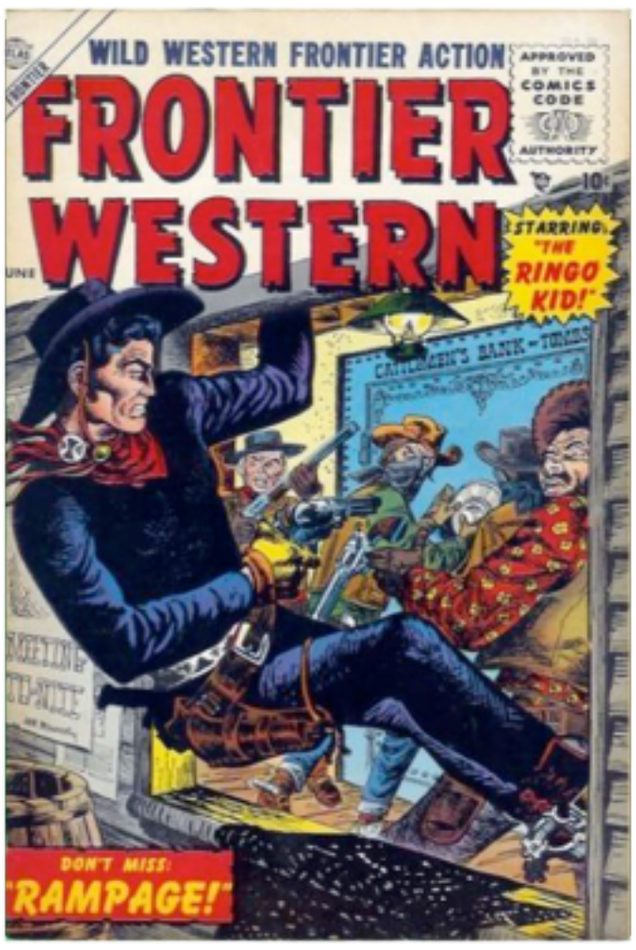


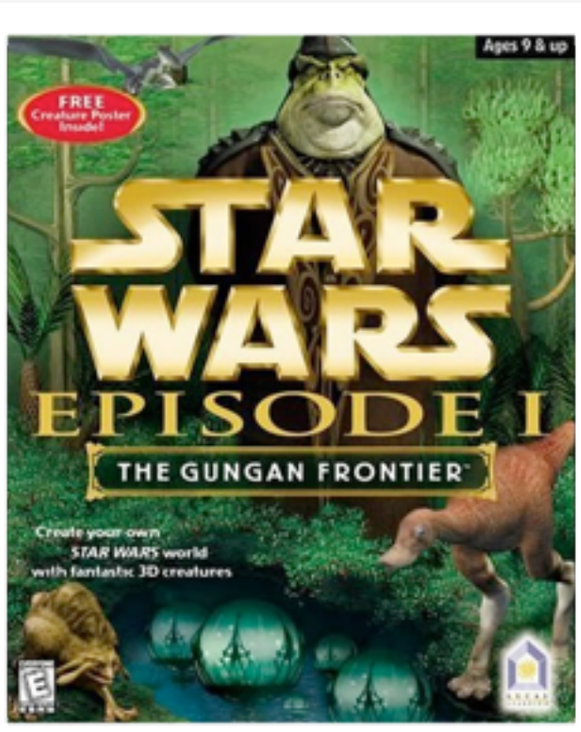


Not good. Divisive

can we make

- the “Frontier” metaphor work better for us?



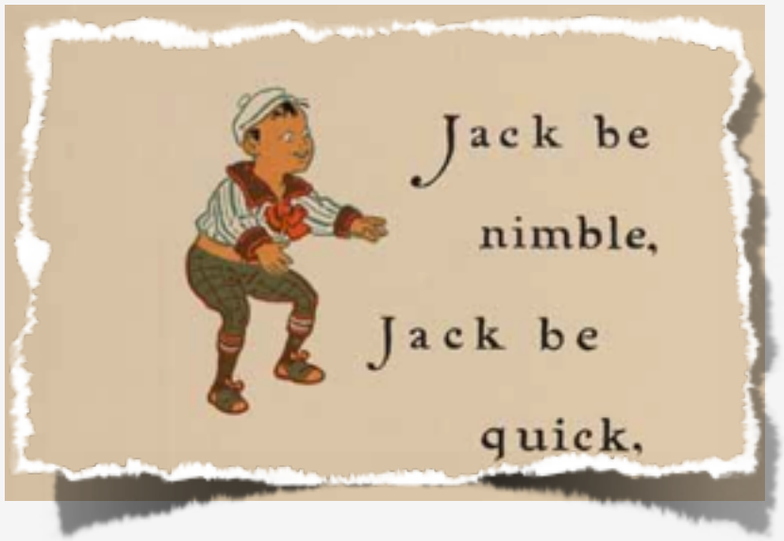


"Opening the Space Frontier, The Next Giant Step" by Robert McCall

http://www.allposters.com/-sp/Settlers-Building-Fences-around-a-Homestead-on-the-Frontier-1800s-Posters_i7780466_.htm

Friday, November 8, 13

Energy Frontier:
precision, mass reach, and surprise



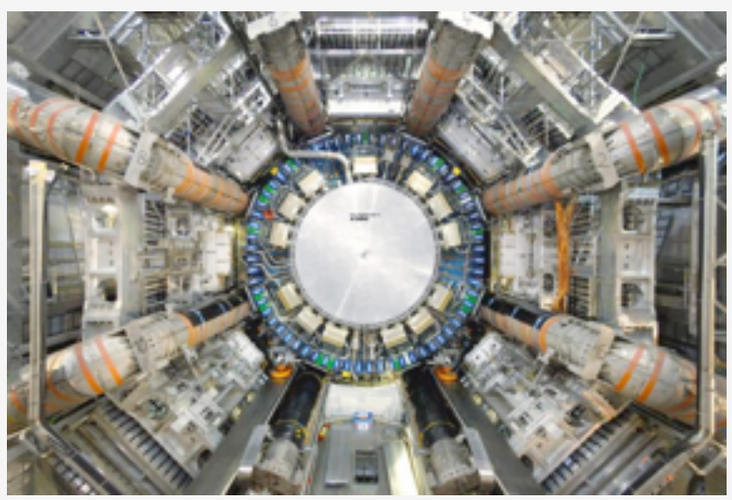
- LHC: exquisite instruments

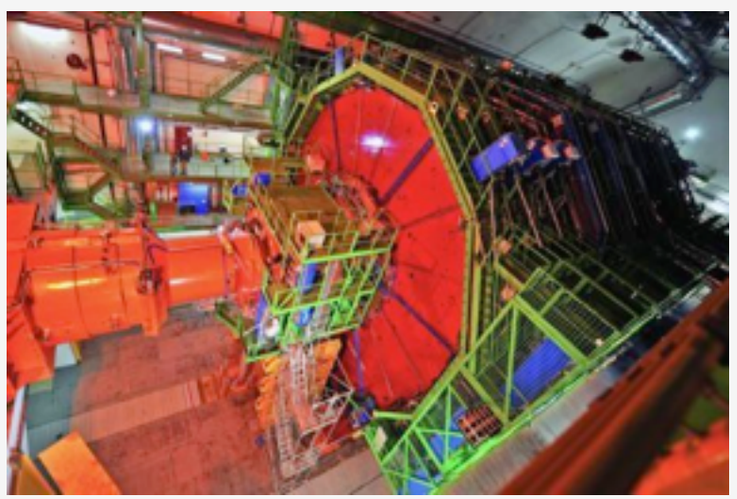
  proven capability for

  precision and **surprise**

- Will point to the EF future at

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





we'll do that by incrementally:

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

The Higgs particle changes everything.

why?

- Confirming the SM?

  No longer a goal

- Now we're exploring.

The real meaning of

“Frontier”

LHC: 300 fb^{-1}

Higgs EW Top QCD NP/flavor

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

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

10. **x2 sensitivity to new particles: supersymmetry, Z', top partners – key ingredients for models of the Higgs potential – and the widest range of possible TeV-mass particles.**

LHC: 300 fb^{-1}

Higgs EW Top QCD NP/flavor

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

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **The precision era in Higgs couplings: couplings to 2-10% accuracy, 1% for the ratio gamma gamma/ZZ.**

3. **First measurement of Higgs self-coupling.**

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

12. **EW particle reach increase by factor 2 for TeV masses.**

13. **Any discovery at LHC–or in dark matter or flavor searches–can be followed up**

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

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

ILC, up to 500 GeV

Higgs EW Top QCD NP/flavor

1. **Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs Γ, direct study of invisible & exotic Higgs decays**
2. **Model-independent Higgs couplings with % accuracy, great statistical & systematic sensitivity to theories.**

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

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

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

ILC, up to 500 GeV

Higgs EW Top QCD NP/flavor

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

ILC 1 TeV

Higgs EW Top QCD NP/flavor

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

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

7. **Any discovery of new particles dictates a lepton collider program:**

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

ILC 1 TeV

Higgs EW Top QCD NP/flavor

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

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

CLIC: 350 GeV, 1 TeV,

Higgs EW Top QCD NP/flavor

2. Higgs self-coupling, 10%

6. Model-independent search for new particles with coupling to gamma or Z to 1500 GeV: the expected range of masses for electroweakinos and WIMPs.

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

CLIC: 350 GeV, 1 TeV,

Higgs EW Top QCD NP/flavor

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

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

2. **Ability to produce the Higgs boson, and possible heavy Higgs bosons, as s-channel resonances.**

This allows sub-MeV Higgs mass measurement and direct Higgs width measurement.

Higgs EW Top QCD NP/flavor

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

1. Similar capabilities to e+e- colliders described above.

   (Still need to prove by physics simulation that this is robust against machine backgrounds.)

2. **Ability to produce the Higgs boson, and possible heavy Higgs bosons, as s-channel resonances.**

   This allows sub-MeV Higgs mass measurement and direct Higgs width measurement.

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

photon collider

Higgs EW Top QCD NP/flavor

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

photon collider

Higgs EW Top QCD NP/flavor

1. An ee collider can be converted to a photon-photon collider at ~ 80% of the CM energy.

   This allows production of Higgs or extended Higgs bosons as s-channel resonances, offering percent-level accuracy in gamma gamma coupling.

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

TLEP, circular e+e-

Higgs EW Top QCD NP/flavor

1. **Possibility of up to 10x higher luminosity than linear e+e- colliders at 250 GeV. Higgs couplings measurements might still be statistics-limited at this level.**

   (Note: luminosity is a steeply falling function of energy.)

TLEP, circular e+e-

Higgs EW Top QCD NP/flavor

1. **Possibility of up to 10x higher luminosity than linear e+e- colliders at 250 GeV. Higgs couplings measurements might still be statistics-limited at this level.**

   (Note: luminosity is a steeply falling function of energy.)

2. Precision electroweak programs that could improve on ILC by a factor 4 in sstw, factor 4 in mW, factor 10 in mZ.
3. Search for rare top couplings in e+e- -> t cbar, tubar at 250 GeV.
4. Possible improvement in alphas by a factor 5 over Giga-Z, to 0.1% precision.

pp Collider: 33/100 TeV

Higgs EW Top QCD NP/flavor

5. **Increased search reach over LHC, proportional to the energy increase, for all varieties of new particles (if increasingly high luminosity is available). Stringent constraints on “naturalness”.**
6. **Ability to search for electroweak WIMPs (e.g. Higgsino, wino) over the full allowed mass range.**

pp Collider: 33/100 TeV

Higgs EW Top QCD NP/flavor

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

Comments:

The Snowmass conveners have tried to come up with a set of Big Questions –

not necessarily *Quantum Universe*, but "professional" questions that motivate research.

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

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

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

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

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

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

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

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

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

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

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

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

Comments:

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

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

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

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