Snowmass 2013 Energy Frontier

XLIII International Symposium on Multiparticle Dynamics
September 20, 2013

Chip Brock

Michigan State University

- 30,000 ft View

- the Snowmass Process

- The Energy Frontier process

- reports from the subgroups

themes

content

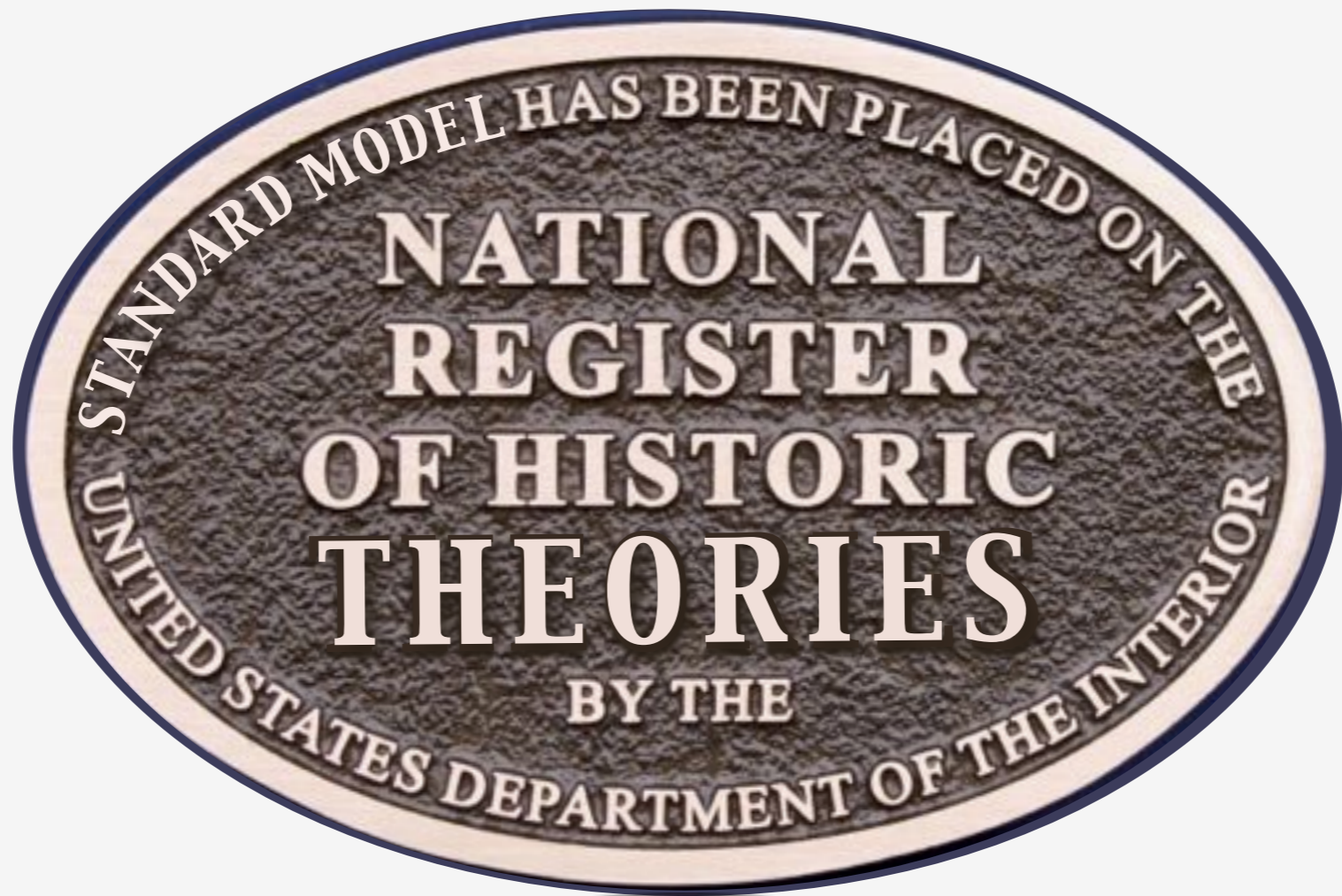message

- cases for future programs

seems like we oscillate:
Things are Great!
Things are Terrible!

ROUND.

BY CHARLES DICKENS.

BOOK THE FIRST. RECALLED TO LIFE.

PRICE 2d.

CHAPTER I. THE PERIOD.

It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to Heaven, we were all going direct the other way—in short, the period was so far like the present period, that some of its noisiest authorities insisted on its being received, for good or for evil, in the superlative degree of comparison only.

There were a king with a large jaw and a queen with a plain face, on the throne of England; there were a king with a large jaw and a queen with a fair face, on the throne of France. In both countries it was clearer than crystal to the lords of the State preserves of loaves and fishes, that things in general were settled for ever.

It was the year of Our Lord one thousand seven hundred and seventy-five. Spiritual revelations were conceded to England at that favoured period, as at this. Mrs. Southcott had recently attained her five-and-twentieth blessed birthday, of whom a prophetic private in the Life Guards had heralded the sublime appearance by announcing that arrangements were made for the swallowing up of London and Westminster. Even the Cock-lane ghost had been laid only a round dozen of years, after rapping out its messages, as the spirits of this very year last past (supernaturally deficient in originality) rapped out theirs. Mere messages in the earthly order of events had lately come to the English Crown and People, from a congress of British subjects in America: which, strange to relate, have proved more important to the human race than any communications yet received through any of the chickens of the Cock-lane brood.

France, less favoured on the whole as to matters spiritual than her sister of the shield and trident, rolled with exceeding smoothness down hill, making paper money and spending it. Under the guidance of her Christian pastors, she

humane were his ancestors, not dirty his deeds, and the that work went

entertained herself, besides, with such humane achievements as sentencing a youth to have his hands cut off, his tongue torn out with pincers, and his body burned alive, because he had not kneeled down in the rain to do honour to a dirty procession of monks which passed within his view, at a distance of some fifty or sixty yards. It is likely enough that, rooted in the woods of France and Norway, there were growing trees, when that sufferer was put to death, already marked by the Woodman, Fate, to come down and be sawn into boards, to make a certain movable framework with a sack and a knife in it, terrible in history. It is likely enough that in the rough outhouses of some tillers of the heavy lands adjacent to Paris, there were sheltered from the weather that very day, rude carts, bespattered with rustic mire, snuffed about by pigs, and roosted in by poultry, which the Farmer, Death, had already set apart to be his tumbrils of the Revolution. But that Woodman and that Farmer, though they work unceasingly, work silently, and no one heard them as they went about with muffled tread: the rather, forasmuch as to entertain any suspicion that they were awake, was to be atheistical and traitorous.

In England, there was scarcely an amount of order and protection to justify much national boasting. Daring burglaries by armed men, and highway robberies, took place in the capital itself every night; families were publicly cautioned not to go out of town without removing their furniture to upholsterers' warehouses for security; the highwayman in the dark was a City tradesman in the light, and, being recognised and challenged by his fellow-tradesman whom he stopped in his character of "the Captain," gallantly shot him through the head and rode away; the mail was waylaid by seven robbers, and the guard shot three dead, and then got shot dead himself by the other four, "in consequence of the failure of his ammunition:" after which the mail was robbed in peace; that magnificent potentate, the Lord Mayor of London, was made to stand and deliver on Turnham Green, by one highwayman, who despoiled the illustrious creature in sight of all his retinue; prisoners in London gaols fought battles with their turnkeys, and the majesty of the law fired blunderbusses in among them, loaded with rounds of shot and ball; thieves snipped off diamond crosses from the necks of noble lords at Court drawing-rooms; musketeers went into St. Giles's, to search for contraband goods, and the

Isn't this the best of times

and the best of times?

the 2012 discovery

- completed the historic Standard Model story:

  unrelenting 40 year effort.

  of remarkable accuracy & precision

STANDARD MODEL HAS BEEN PLACED ON THE

NATIONAL
REGISTER
OF HISTORIC
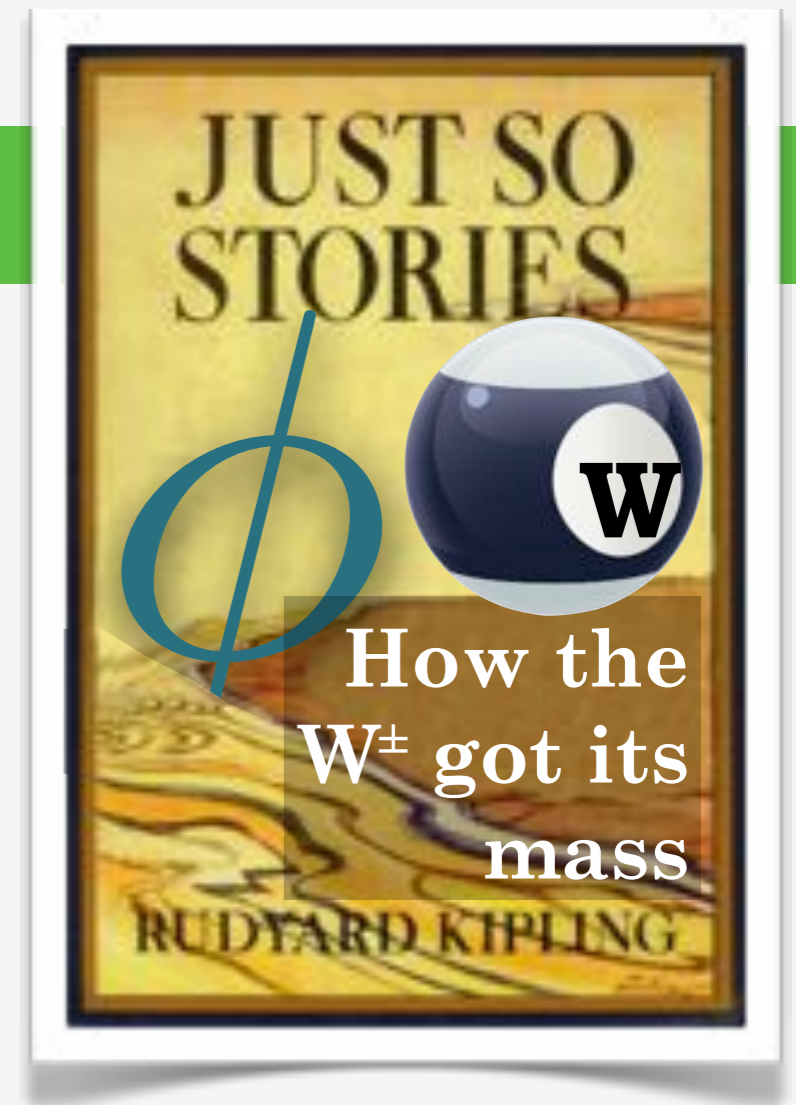THEORIES

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

Standard
Model

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 ± 0.001		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	0.1035 ± 0.0007	−0.5	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.2146 ± 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

the 0+ object is not your father's particle!
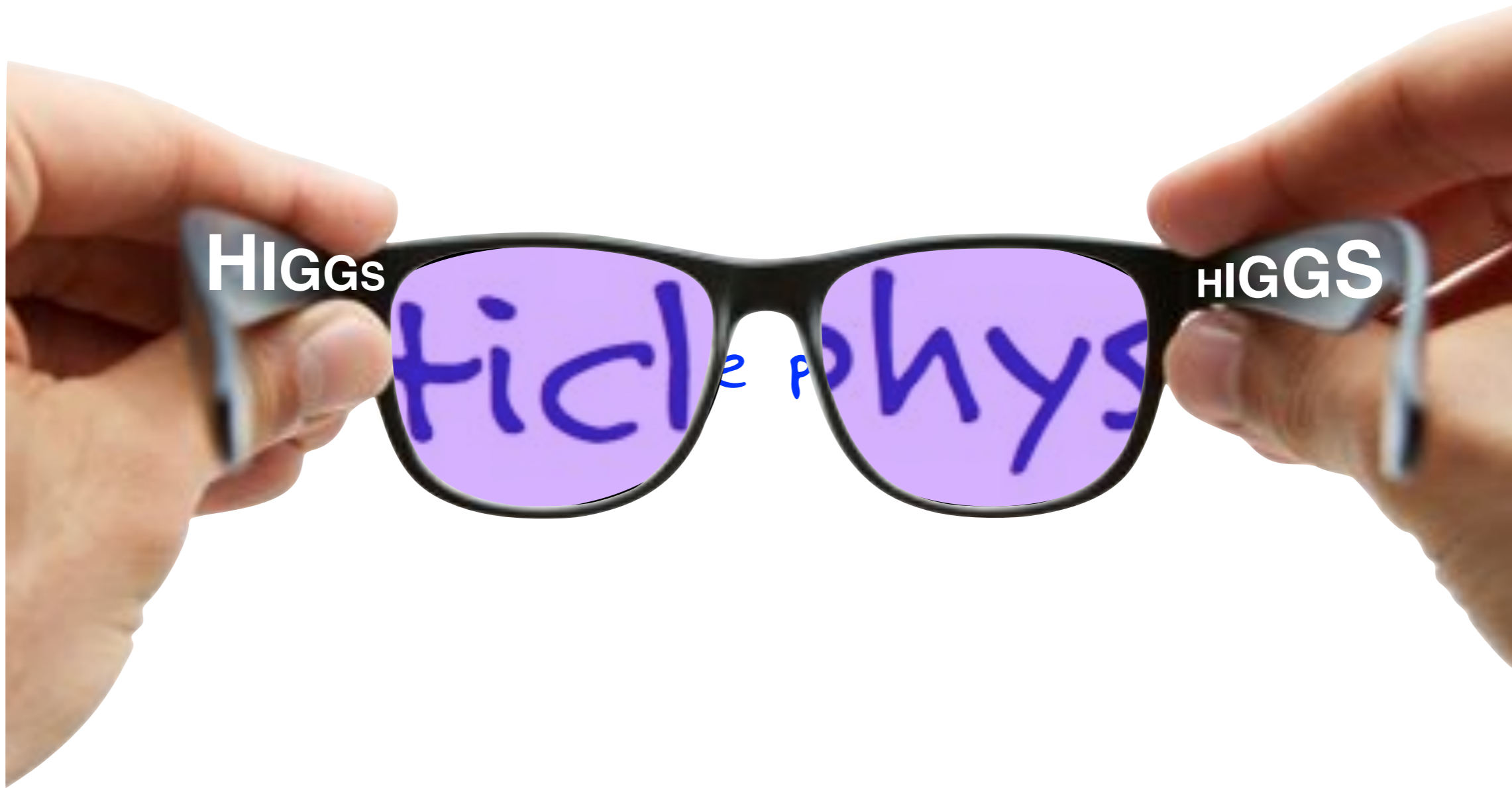
particle physics

what's embarrassing

about the Standard Model?

Standard Model

- the nature of the Higgs particle

- the Higgs Story

$$\phi \rightarrow v + h$$
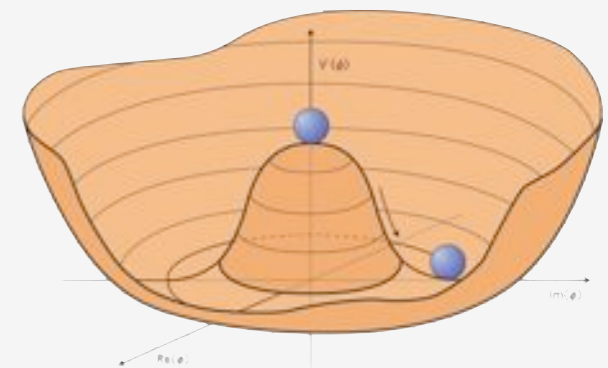
Deep Puzzles

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

$$\left(\begin{array}{c} u \\ d \end{array} \right) \left(\begin{array}{c} c \\ s \end{array} \right) \left(\begin{array}{c} t \\ b \end{array} \right)$$

$$\left(\begin{array}{c} \nu_e \\ e \end{array} \right) \left(\begin{array}{c} \nu_\mu \\ \mu \end{array} \right) \left(\begin{array}{c} \nu_\tau \\ \tau \end{array} \right)$$

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

■ an elementary singlet

■ **quantum numbers of vacuum**
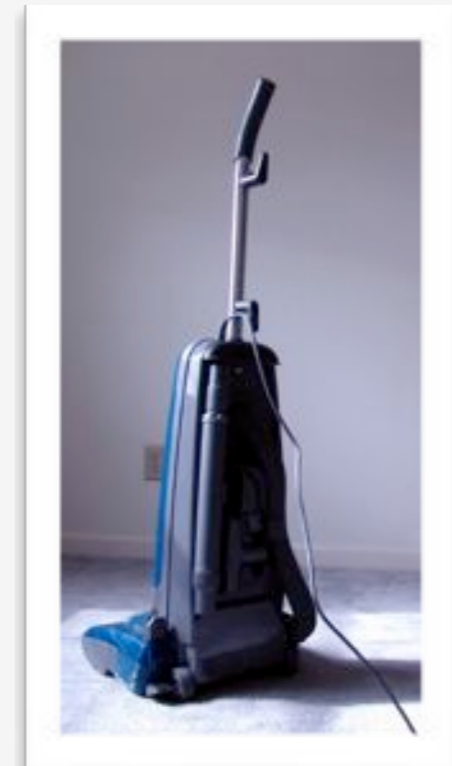
is it alone?

a part of a family?

different in tiny details?

Higgs story

■ stranger.
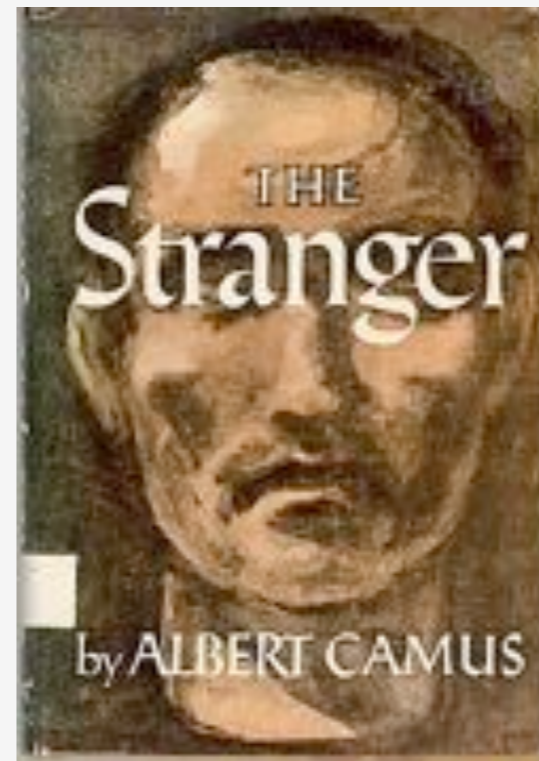
SM is not a dynamical explanation

I can draw free-body diagrams and make a SM of walking
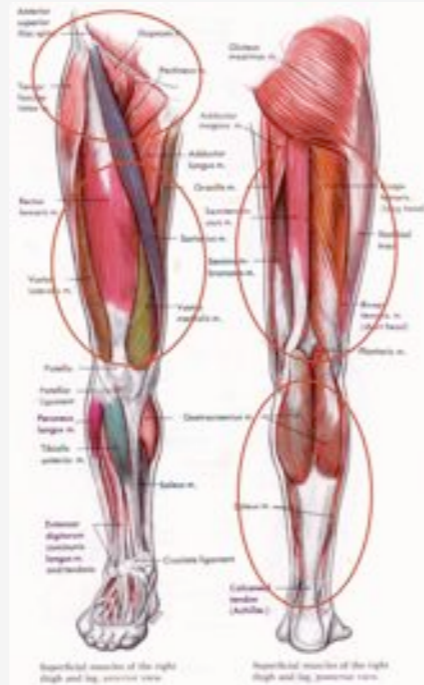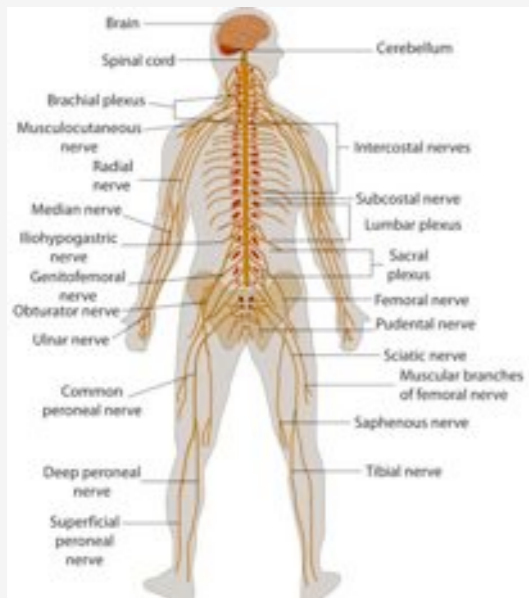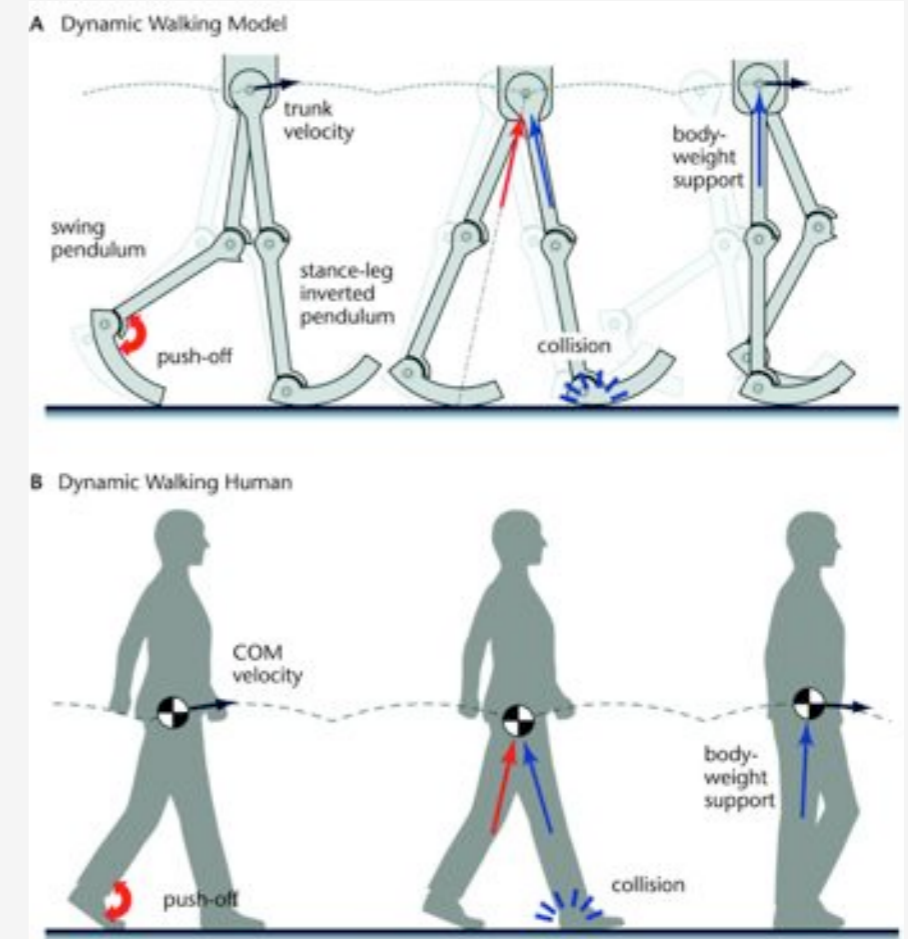
But it's not the actual physiology of walking!
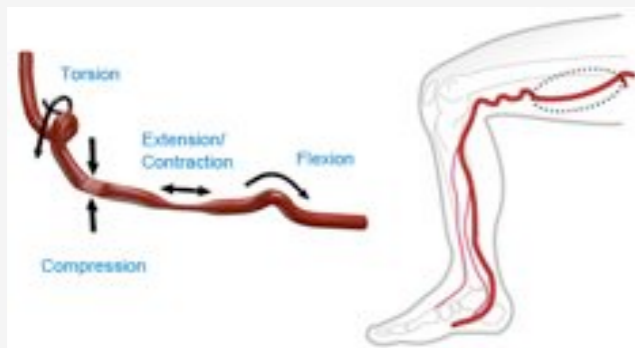
Much confusion centers on

- the "Higgs" Potential.

Much of our work is unpacking it:

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

vacuum energy

Higgs mass

instability?

Yukawa couplings

LOOPS

not mysticism

- **"Loops" are at the core of our language**

  traditionally highly predictive

  highly accurate
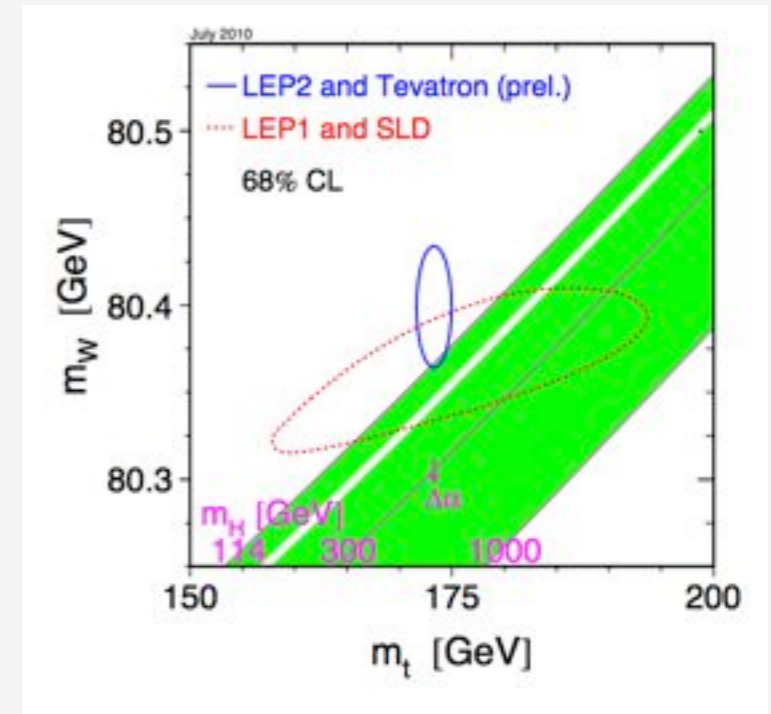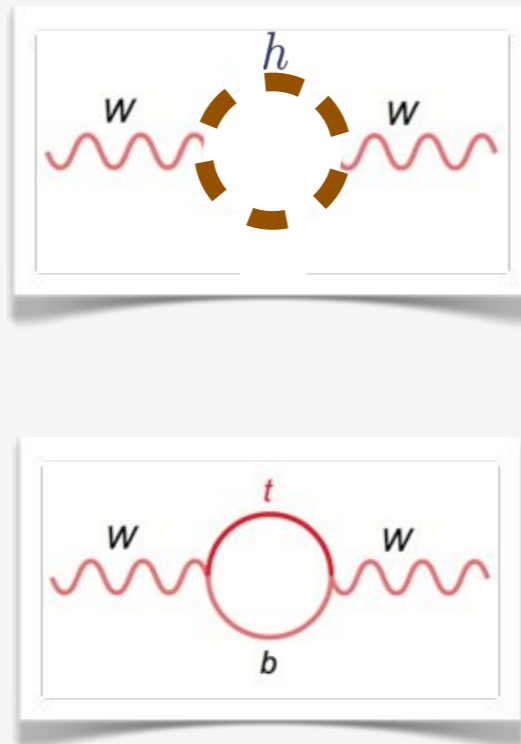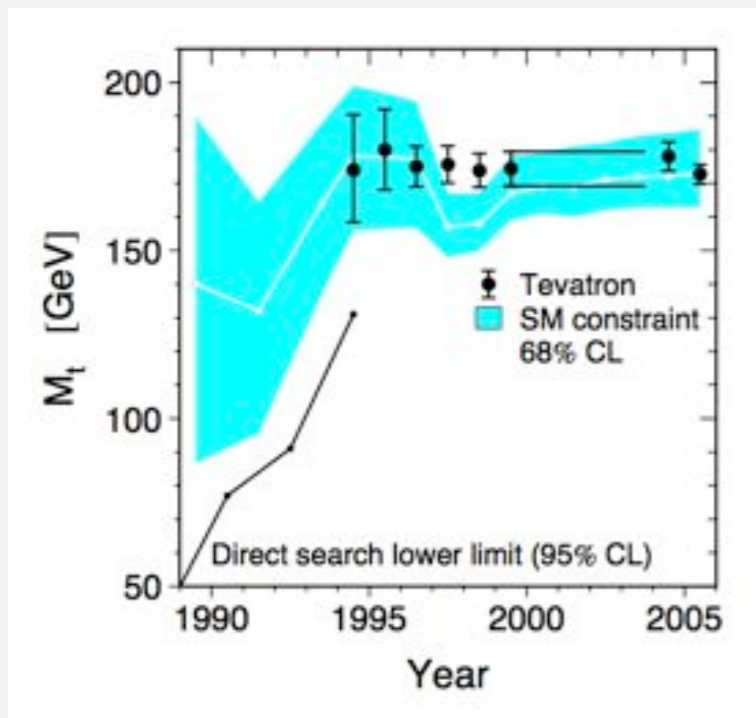
EW fits: top quark

EW fits: Higgs boson

James D. Bjorken   Sidney D. Drell
Associate Professor   *Professor*
Stanford Linear Accelerator Center
Stanford University

Relativistic Quantum Mechanics

McGraw-Hill Book Company
New York   St. Louis   San Francisco   Toronto   London   Sydney

symmetry   dimensionless

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

γ

e —————————— e

---

164   *Relativistic quantum mechanics*

logarithm in (8.40) is replaced by $\log(\lambda/m)$. This may be verified by a direct calculation of the integral in (8.38) in the limit $p^2 \to m^2$.

8.5 Renormalization of the Electron Propagator

The modification of the electron propagator thus far has been the replacement, according to (8.34),

$$\frac{i}{\not{p}-m} \to \frac{i}{\not{p}-m} + \frac{i}{\not{p}-m}(-i\Sigma(p))\frac{i}{\not{p}-m}$$

$$= \frac{i}{\not{p}-m-\Sigma(p)} + O(\alpha^2) \quad (8.41)$$

From (8.40), we write

$$\Sigma(p) = \delta m - [Z_2^{-1} - 1 + C(p)](\not{p}-m) \quad (8.42)$$

with

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

and

$$Z_2^{-1} - 1 + C(p) \cong \frac{\alpha}{4\pi}\left(\log\frac{\Lambda^2}{m^2} + 4\log\frac{m^2-p^2}{m^2}\right)$$

$$m\lambda \ll p^2 - m^2 \ll m^2$$

$C(p)$ is chosen such that at $\not{p} = m$, $C(p) = 0$; it thus contains no dependence upon the cutoff Λ. At $\not{p} = m$ this becomes

$$Z_2^{-1} - 1 = \frac{\alpha}{4\pi}\left(\log\frac{\Lambda^2}{m^2} - 2\log\frac{m^2}{\lambda^2}\right) \quad (8.43)$$

Using (8.42) we may now rewrite (8.41) as follows:

$$\frac{i}{\not{p}-m-\Sigma(p)} = \frac{iZ_2}{(\not{p}-m)[1+Z_2 C(p)]-Z_2\delta m}$$

$$= \frac{iZ_2}{(\not{p}-m-\delta m)[1+C(p)]} + O(\alpha^2) \quad (8.44)$$

We identify $m_{ph} = m + \delta m$ as the physical mass of the electron; the parameter m in the Dirac equation is, like the bare charge, another unmeasured number. The necessity of mass renormalization already occurs in classical electrodynamics; experiments on a free electron

[1] For the complete second-order contribution to the electron self-energy part see R. Karplus and N. M. Kroll, *Phys. Rev.*, **77**, 536 (1950). See also J. M. Jauch and F. Rohrlich "The Theory of Photons and Electrons," Addison-Wesley Publishing Company, Inc., Reading, Mass., 1955.
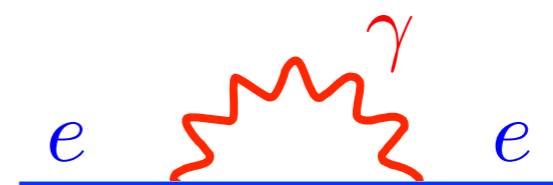
How about a spin 0, elementary particle?

■ ϕ with mass μ

$$\mu^2 = \mu_0^2 + \Big(\ \underset{\phi}{\text{——}}\ \overset{\psi}{\bigcirc}\ \underset{\phi}{\text{——}}\ \Big)$$

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

symmetry   dimensionless

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

elativistic
m
hanics
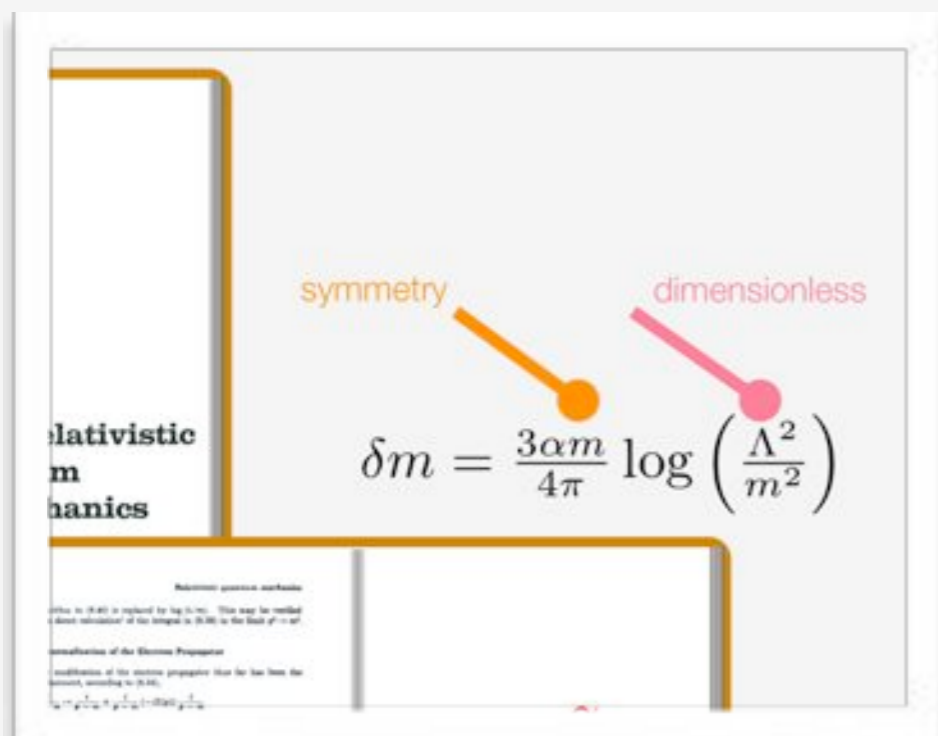
An enormous fine-tuning

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

$$M_H^2 = M_{\text{tree}}^2 + \left(\begin{array}{c} H \\ \underset{H \quad H}{\bigcirc} \end{array}\right) + \left(\begin{array}{c} t \\ H \underset{t}{\bigcirc} H \end{array}\right) + \left(\begin{array}{c} W,Z \\ H \quad H \end{array}\right)$$

m_t^2

$M_H \sim 125$ GeV/c^2

M_{physical}^2

M_{tree}^2

M_H^2

$M_{W,Z}^2$

un-fine tuning?

0
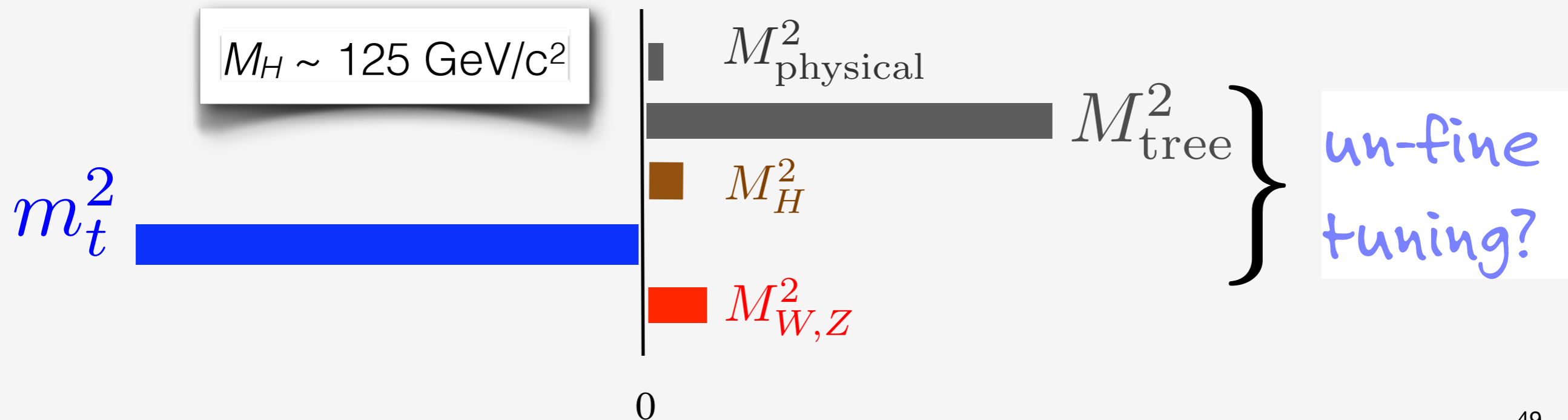
if next scale is ■ the Planck Scale?

$$M_H^2 = \text{nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n60,000}$$
$$- \text{nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n44,375}$$
$$M_H^2 = 125^2$$

"coincidence"?

not a scientific word!

Perhaps a huge hint?

of something "BSM"?

- no shortage of ideas

$$M_H^2 = M_{\text{tree}}^2 + \left(\overset{H}{\underset{H \quad H}{\bigcirc}} \right) + \left(\underset{H}{\overset{t}{\bigcirc}} \underset{\bar{t}}{H} \right) + \left(\overset{W,Z}{\underset{H \quad H}{\text{}}} \right) + \left(\text{---}\,\text{BSM}\,\text{---} \right)$$

$M_H \sim 125\ \text{GeV/c}^2$

M_{physical}^2

M_{tree}^2

m_t^2

M_H^2

new stuff

$M_{W,Z}^2$

0
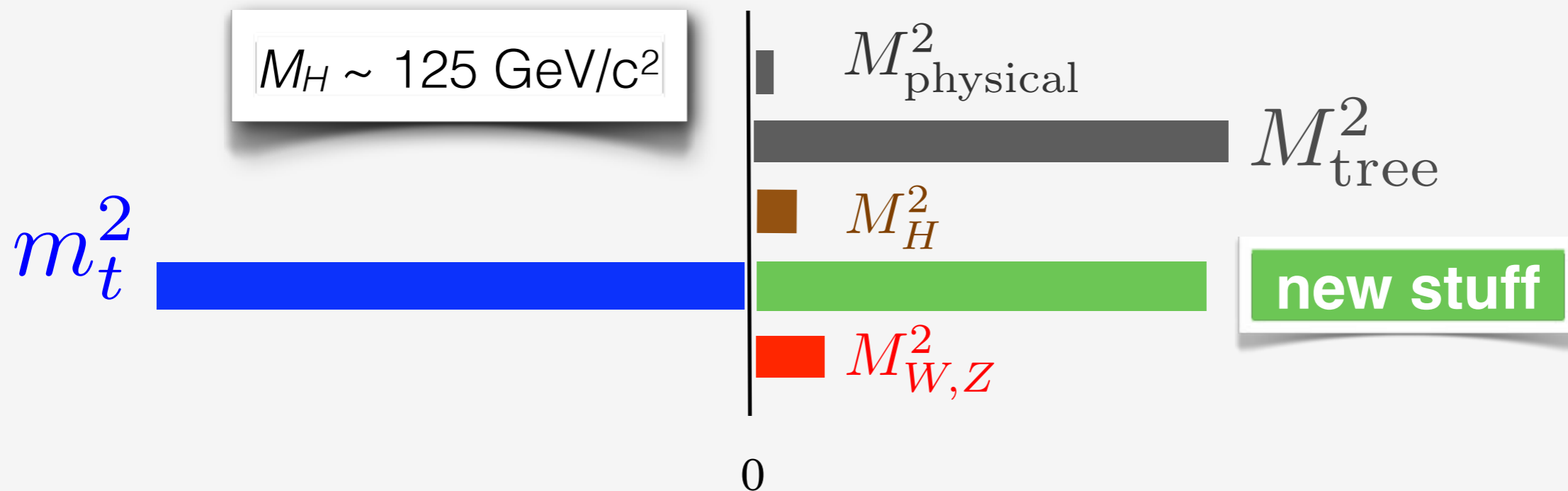
gotta find that new stuff

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?

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

■ the quartic coupling runs

mixing up M_H and m_t

M_H is itself odd!

Nima Arkani–Hamed, et al. arXiv:0801.2399
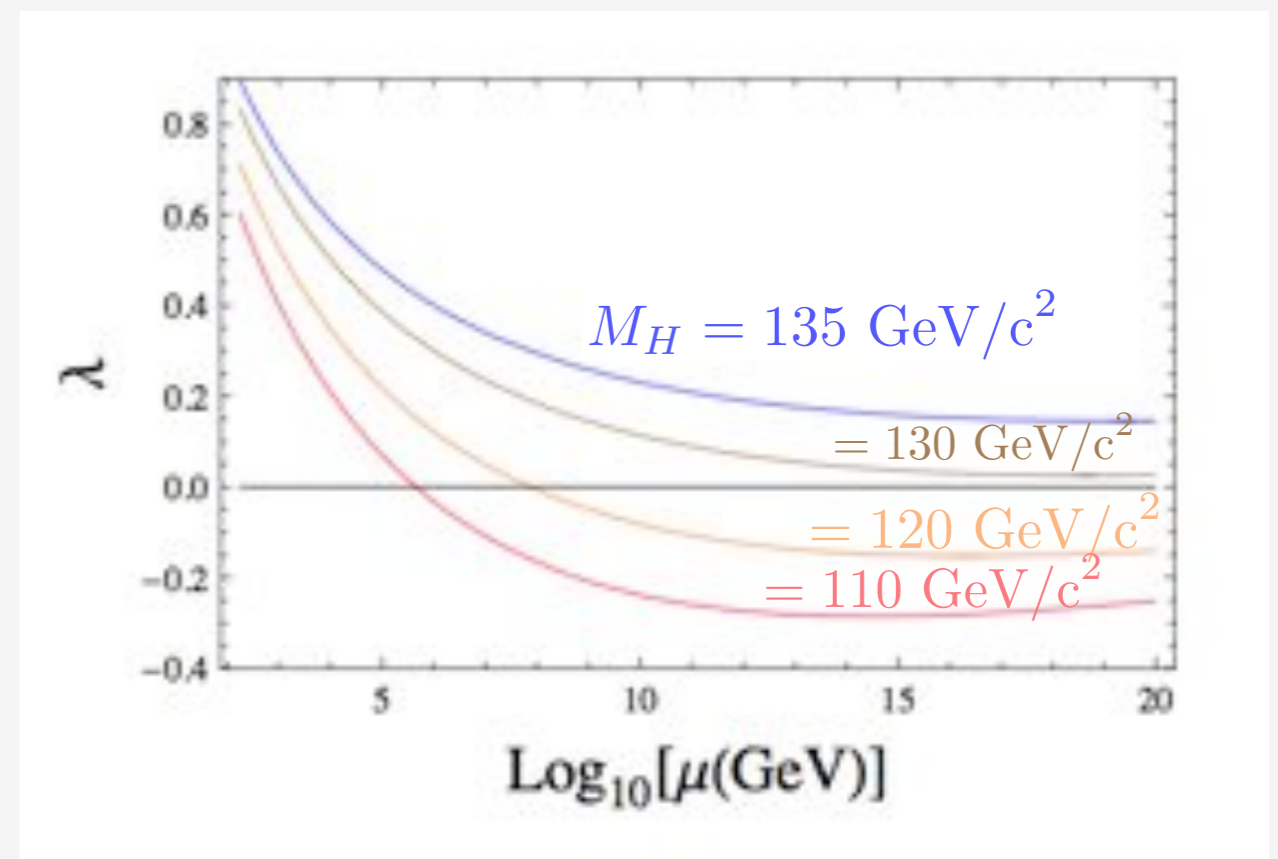
So, where do you stand? :)

- 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

never
theorize

hints
welcome

theory
guarantees
new physics

We know of *experimental* BSM physics.

Serious experimental anomalies

- The Higgs Boson mass is small.

- v'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

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:

energy
intensity
cosmic

This was our organizational reality:

energy
Frontier

cosmic
Frontier

intensity
Frontier

computing
Frontier

outreach
Frontier

"capabilities"

facilities
Frontier

instr.
Frontier

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

Particle Physics Project Prioritization Panel (P5)

Home   Charge   Membership   Meetings   Submissions   Useful Links   HEPAP

About The Particle Physics Project Prioritization Panel (P5)

The particle physics community is developing an updated strategic plan for the United States that can be executed over a ten-year timescale, in the context of a twenty-year global vision for the field. The Particle Physics Project Prioritization Panel (P5) is charged with developing this plan under various budget scenarios. P5 is a subpanel of the High Energy Physics Advisory Panel (HEPAP) that serves both the Department of Energy's Office of High Energy Physics and the National Science Foundation.

The chair of P5 is Professor Steven Ritz from the University of California, Santa Cruz.

The P5 process follows directly on the heels of the Snowmass process organized by the American Physical Society's Division of Particles and Fields. Through the Snowmass process the U.S. particle physics research community identified the most compelling scientific opportunities and the technologies required to seize those opportunities. The Snowmass process culminated in a nine-day-long meeting at the University of Minnesota in July and August of 2013. The final Snowmass reports, expected in November, will serve as input to P5.

Please check this page regularly for news and information about P5 activities. There will also be mechanisms for the particle physics community to provide input, documents, and feedback to P5.

Read the 2008 Particle Physics Project Prioritization Panel Report

paper trail

Report of
Snowmass
2013

Intensity
Frontier

Cosmic
Frontier

Energy
Frontier

Instrumentation
Frontier

Capabilities
Frontier

Computing
Frontier

Outreach,
Education
Frontier

paper,
30pp
ea.

Higgs

EW

Top

NP

QCD

Flavor

...

White
Paper

on-line,
30-80pp
ea.

paper trail

Jon Rosner @snowing

AFAIK OMG EF, IF, & CF 4 sure rule!!!! IMO <3 :)
#snowmass #higgs #theta13

executive tweet

Snowmass 2013

one-page "3 fold"

Report of the 2013 Community Summer Study
Executive Summary

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 allovertheplace 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
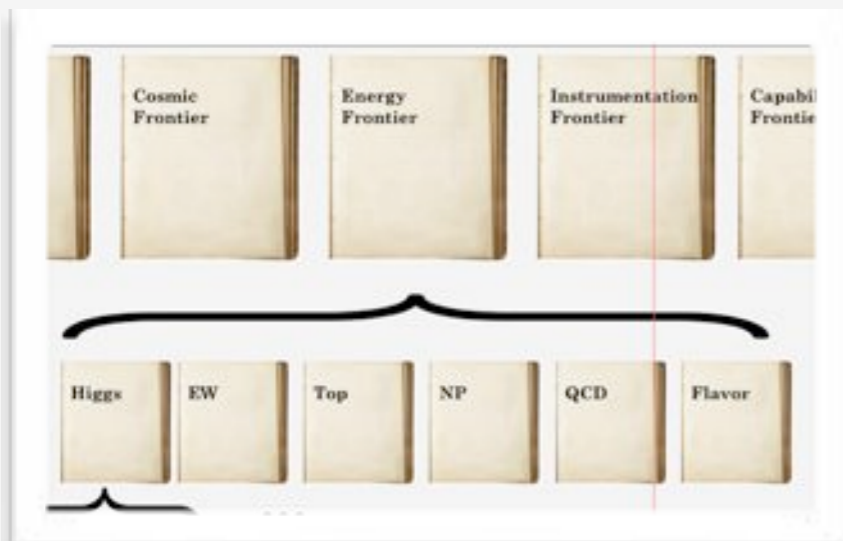
■ two points

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			
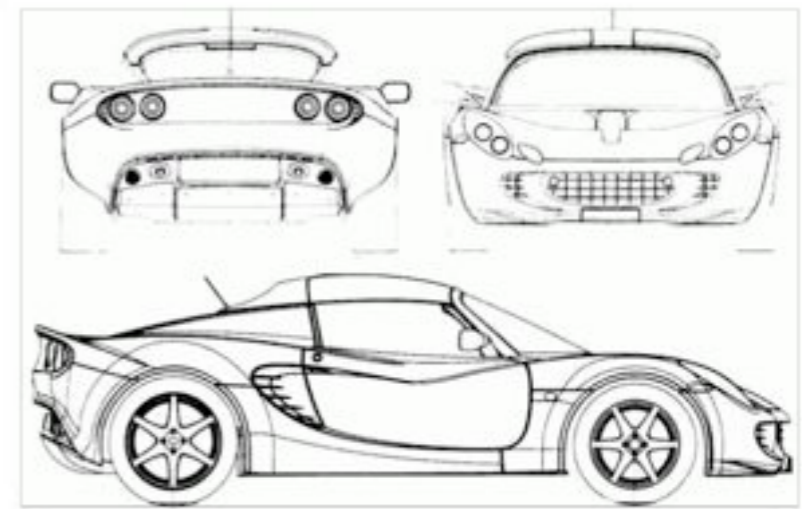
Exclusion

- we always speak of "exclusion plots"

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

No exclusion.

Discovery

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

300/fb
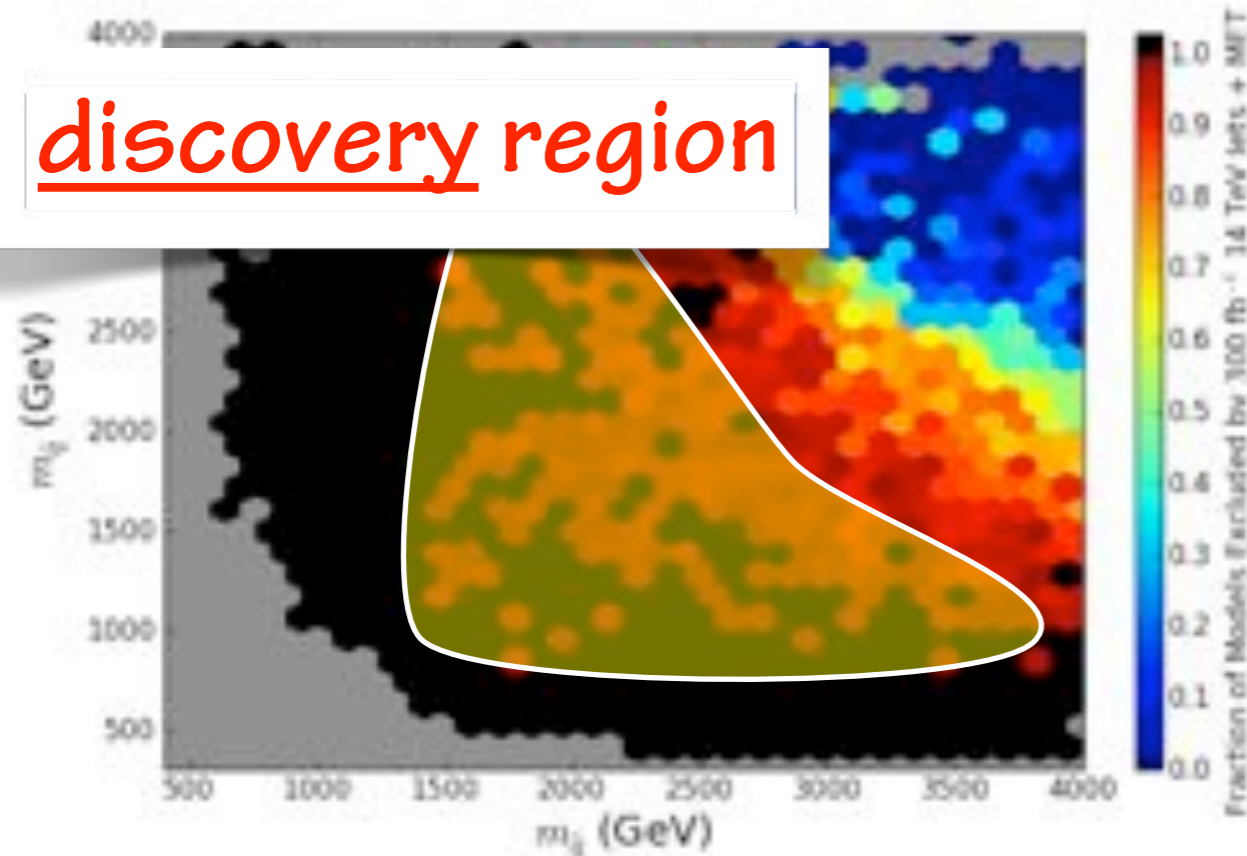
3000/fb
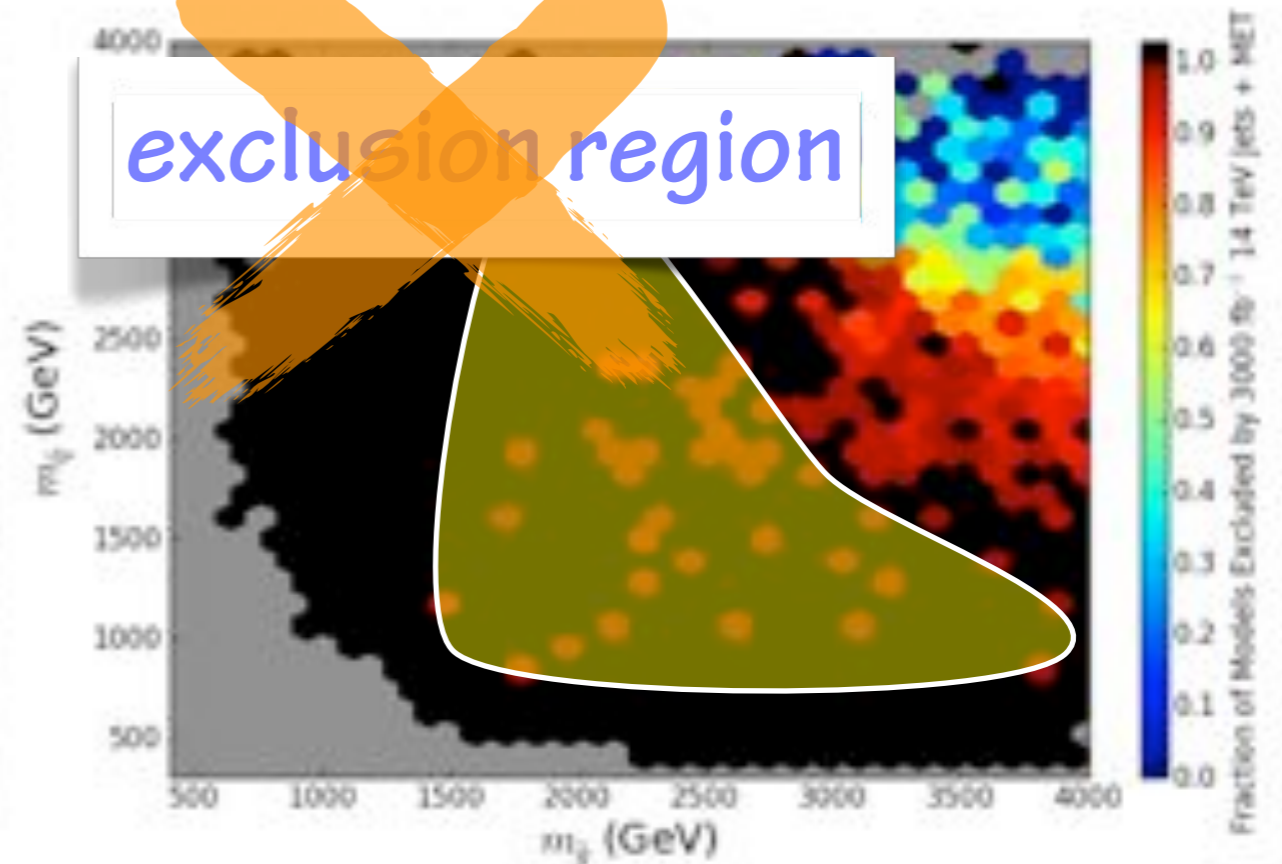
subgroup reports

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?
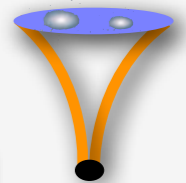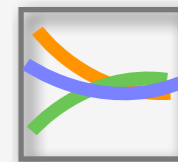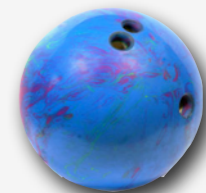
■ The Higgs Boson

Higgs Boson 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

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

$$\kappa_i \times y_{ij}^{SM}$$
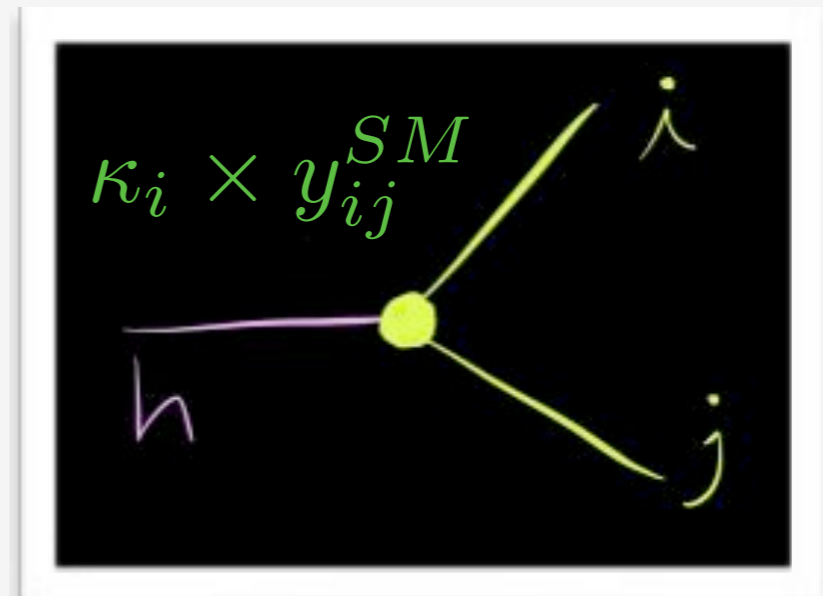
$$i, j = f, \ell, W, Z, ``V", ``g"$$

couplings

Early results are in line

- for fermions and VBs

The precision Higgs boson program has begun.
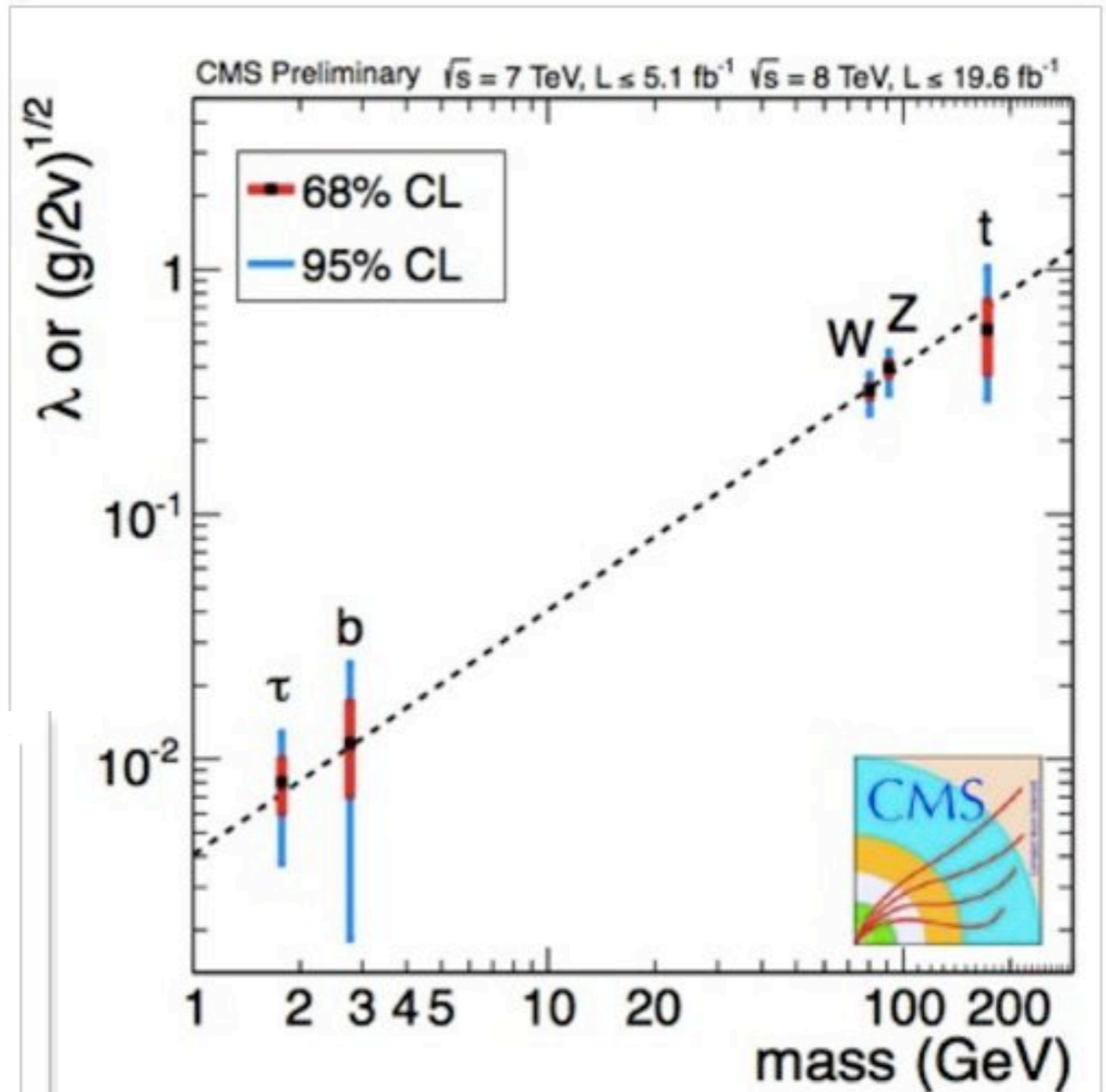
How well do we need to know couplings?

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

$\kappa_i \qquad \kappa_j \qquad \kappa_k \quad \ldots$

SM
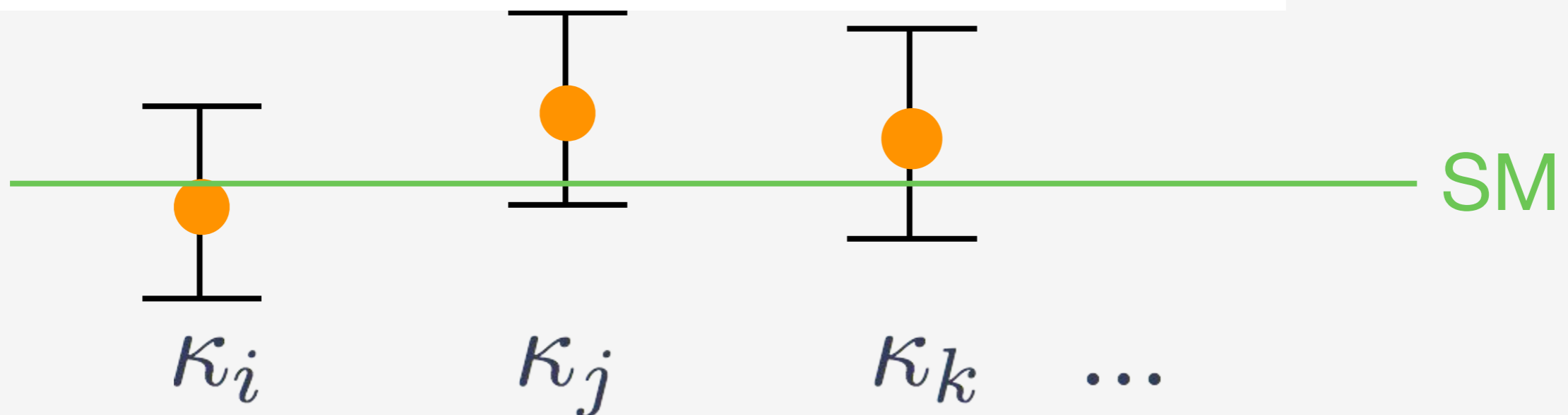
precision for precision's sake?

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-%

κ_i $\qquad$ κ_j $\qquad$ κ_k ...

SM
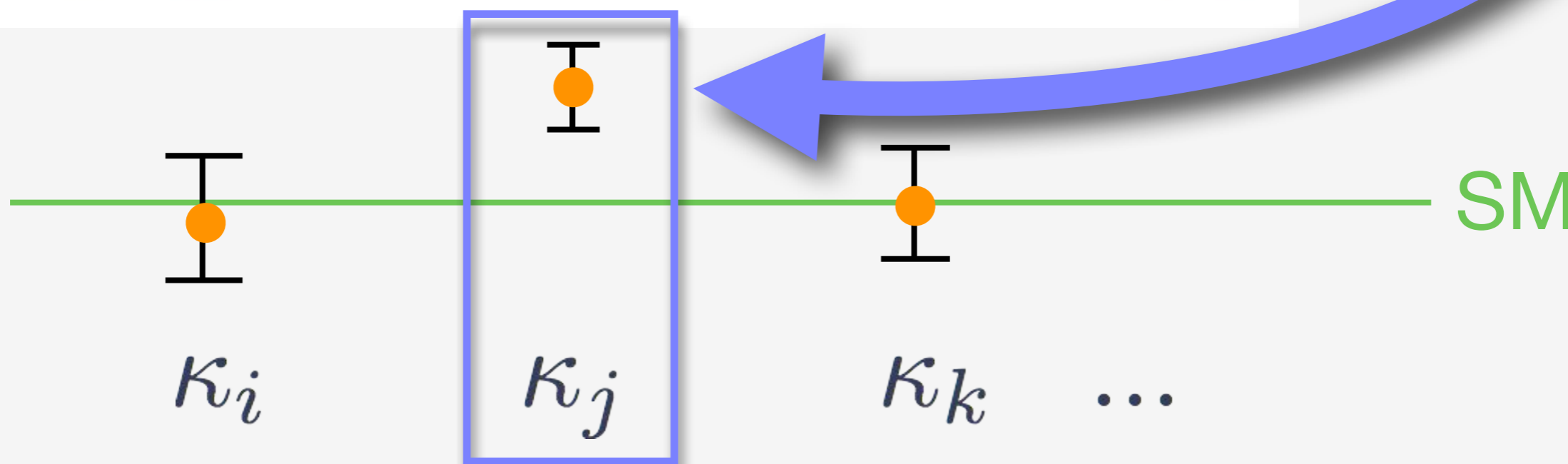
Current precision is multiple 10's%.
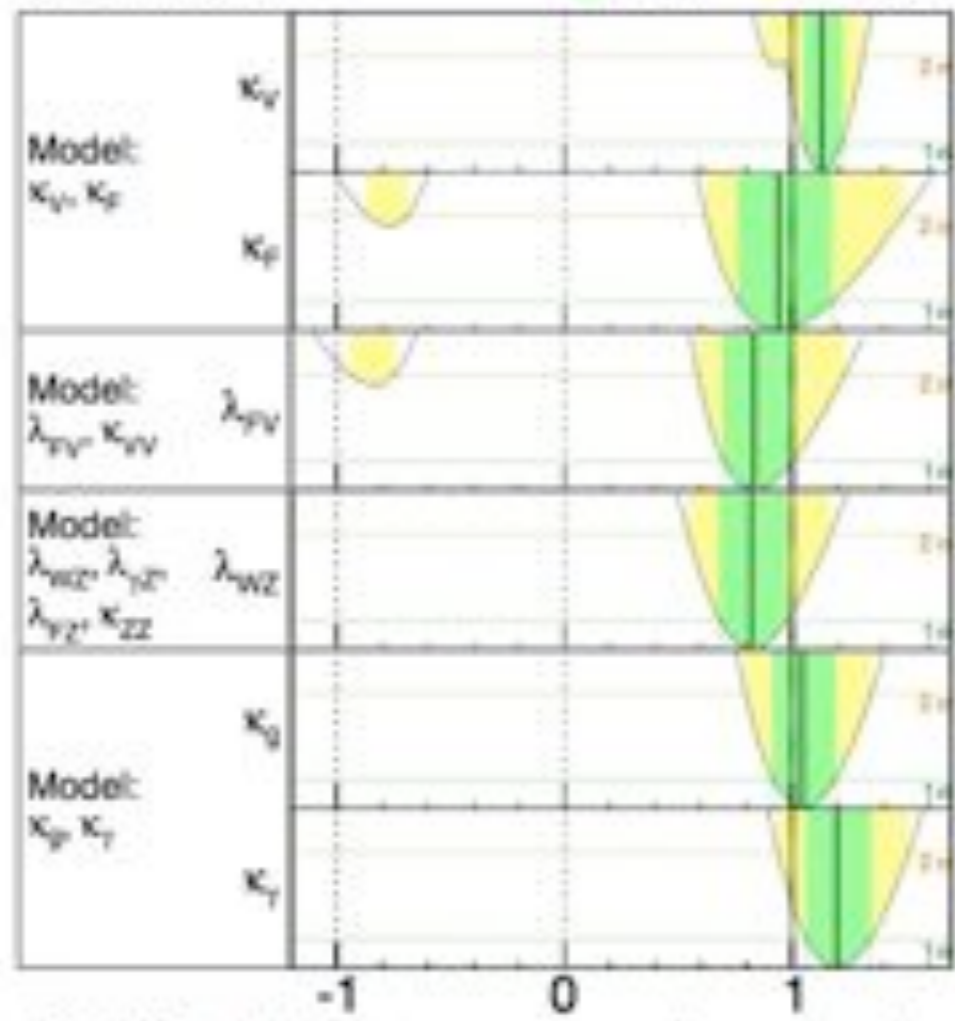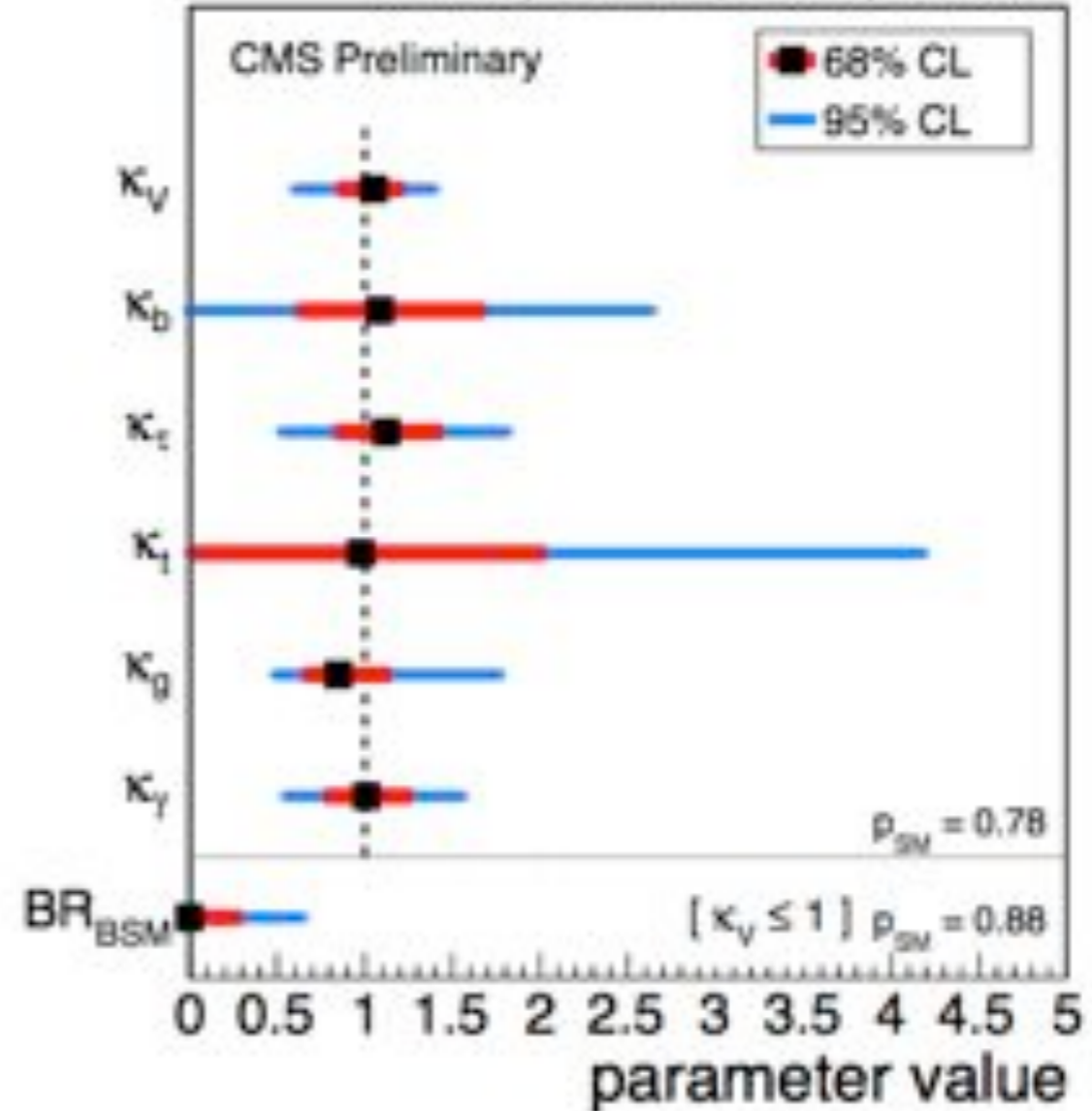
Evaluation of coupling extrapolations

Extrapolating LHC requires a strategy

- ■ 2 numbers shown:*

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

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

and

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

	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
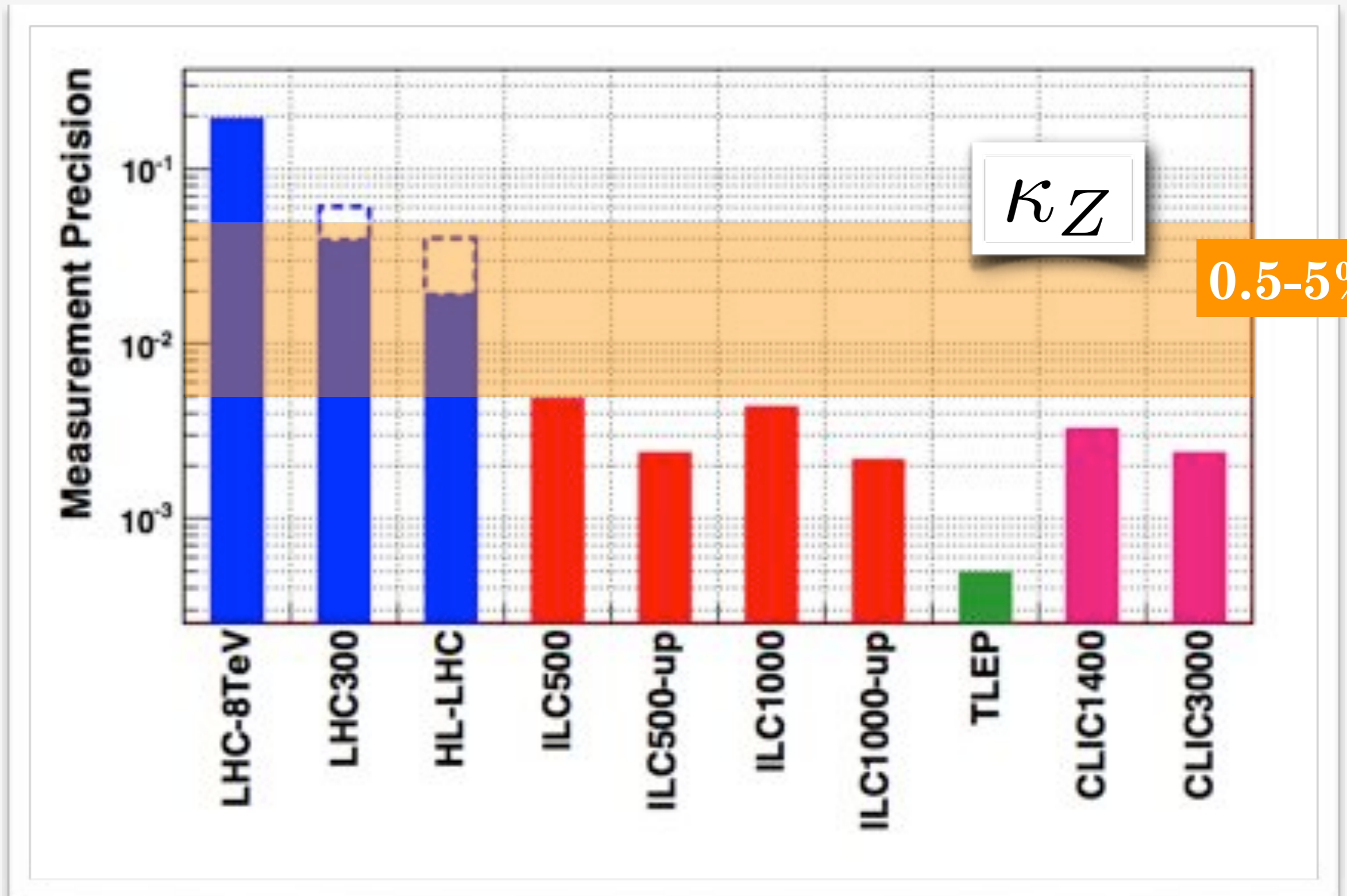
Precision in kappa by facility
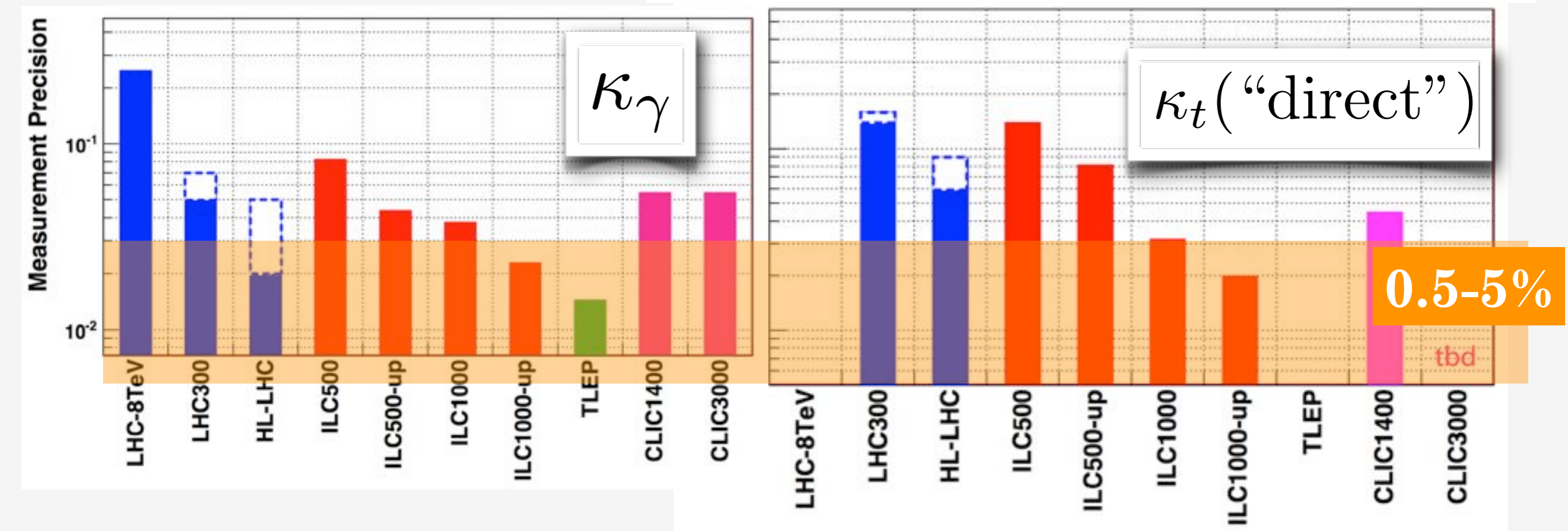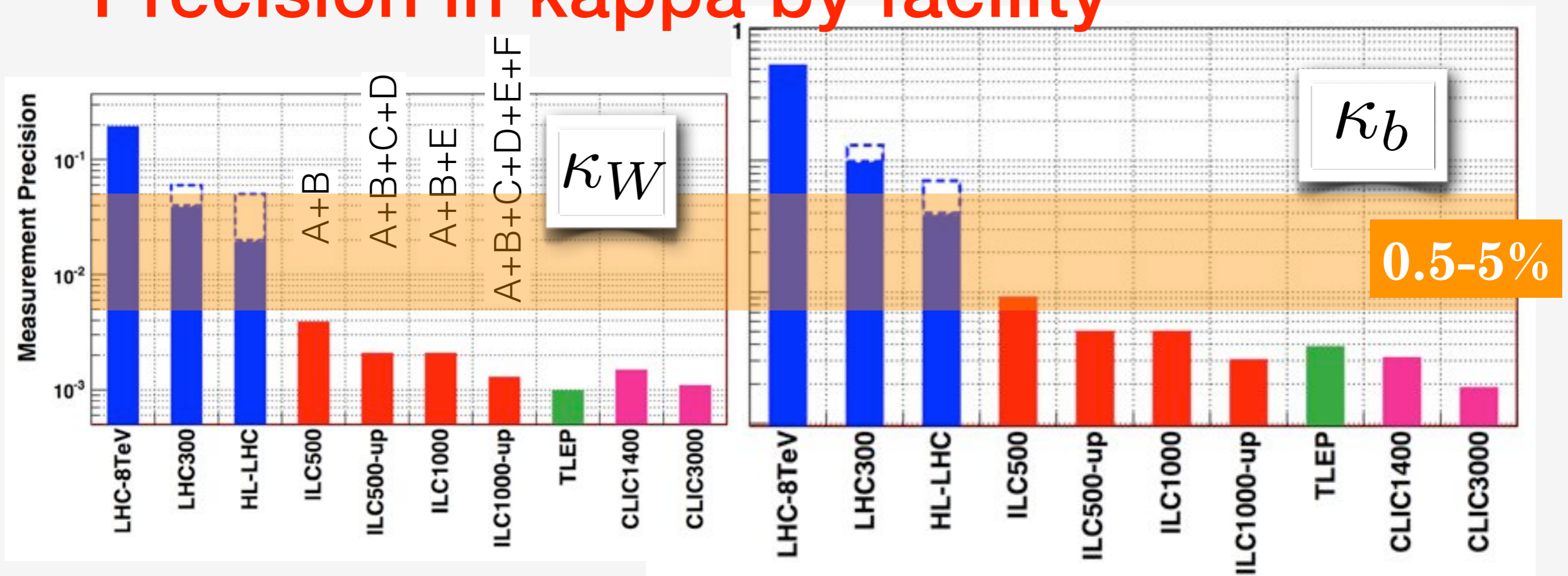
Higgs Self-Coupling

Critical feature of SM

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

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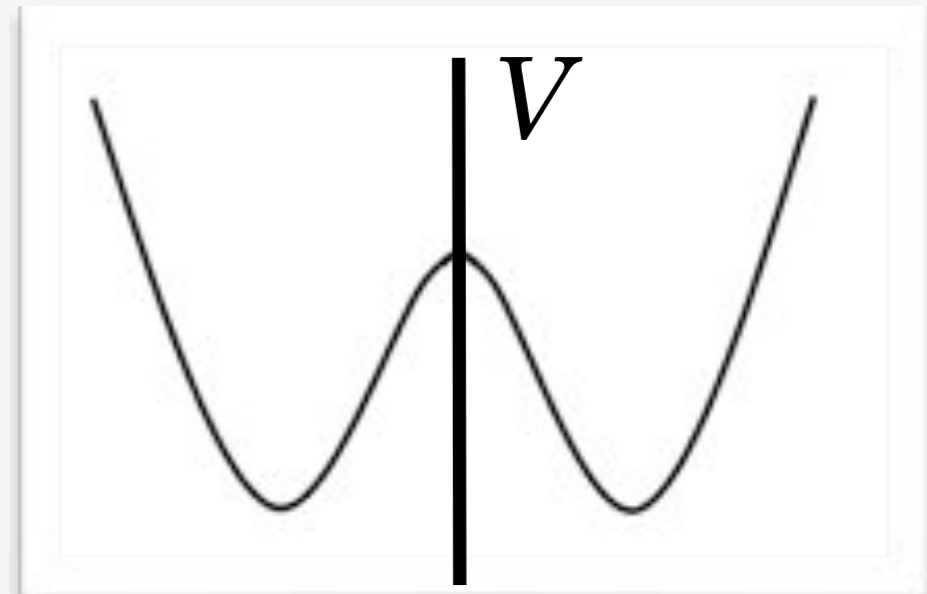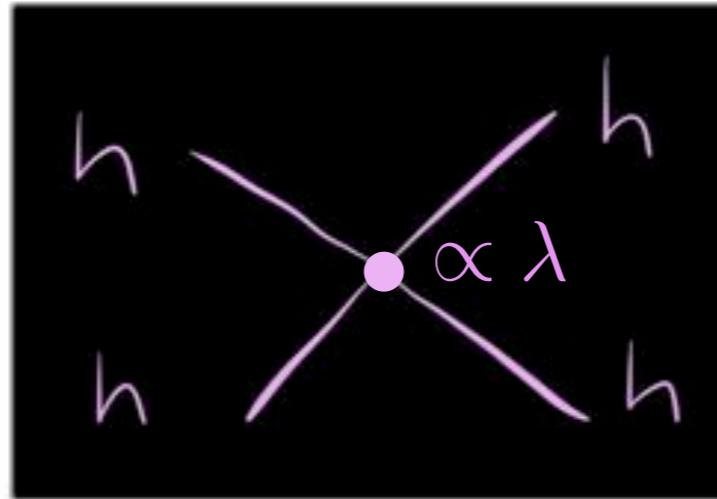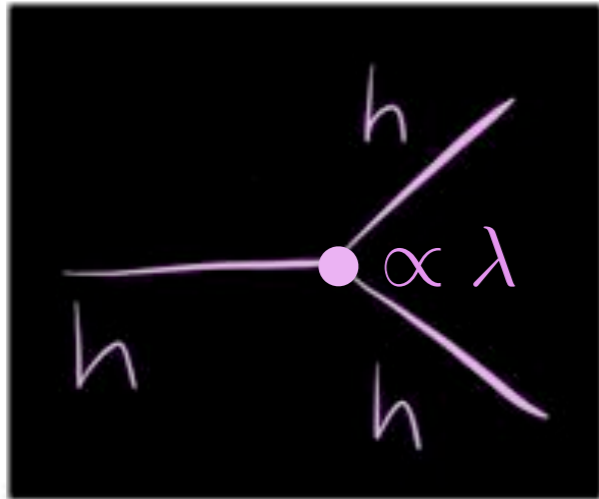
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L} dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

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.
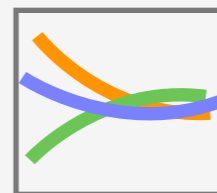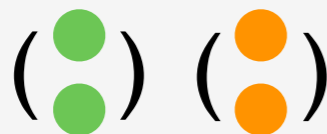
- **Precision Study of Electroweak Physics**

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
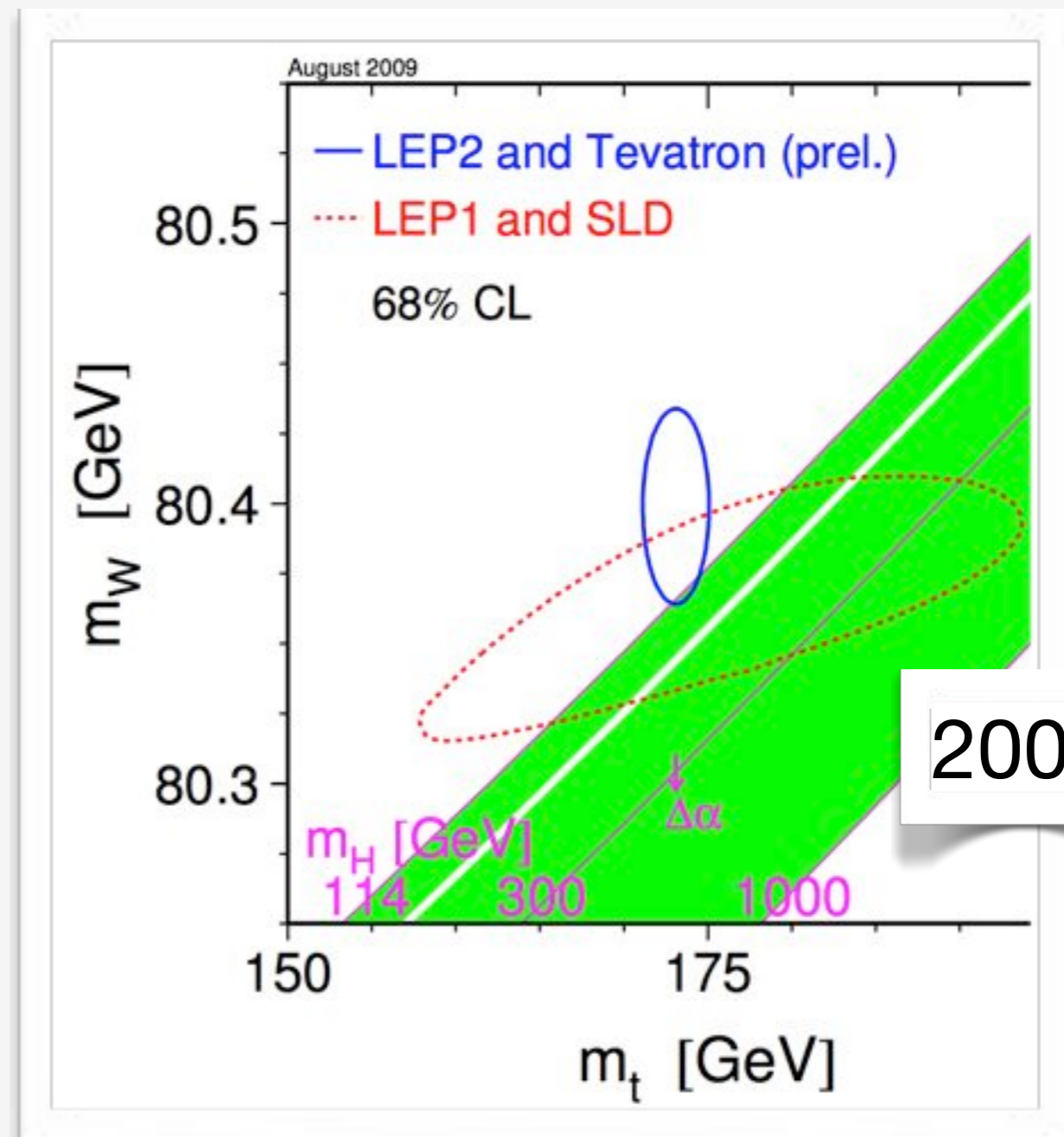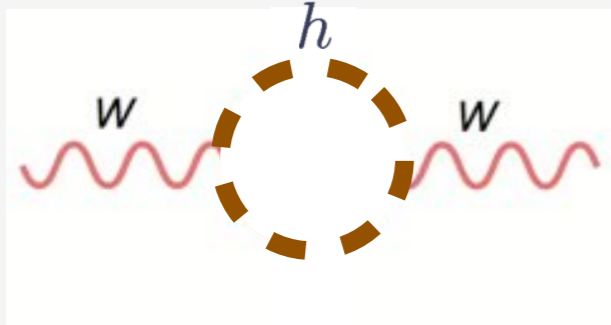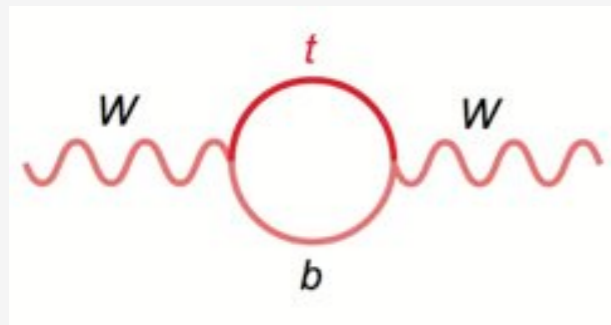
Now...a new target: BSM

Premium on M_W

■ Systematics goal of $M_W = \pm 5$ MeV/c^2

$\delta M_W \sim 5$ MeV/c^2

$\delta M_W \sim 500$ MeV/c^2
δm_t

$\delta M_W \sim 5$ MeV/c^2

This is now a BSM search

experimental errors 68% CL / collider experiment:

— LEP2/Tevatron: today
— LHC
— ILC/GigaZ

$M_h = 125.6 \pm 3.1$ GeV

MSSM

SM | $M_H = 125.6 \pm 0.7$ GeV

MSSM

SM, MSSM

Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '13

M_W [GeV]

80.60

80.50

80.40

80.30

168   170   172   174   176   178

m_t [GeV]
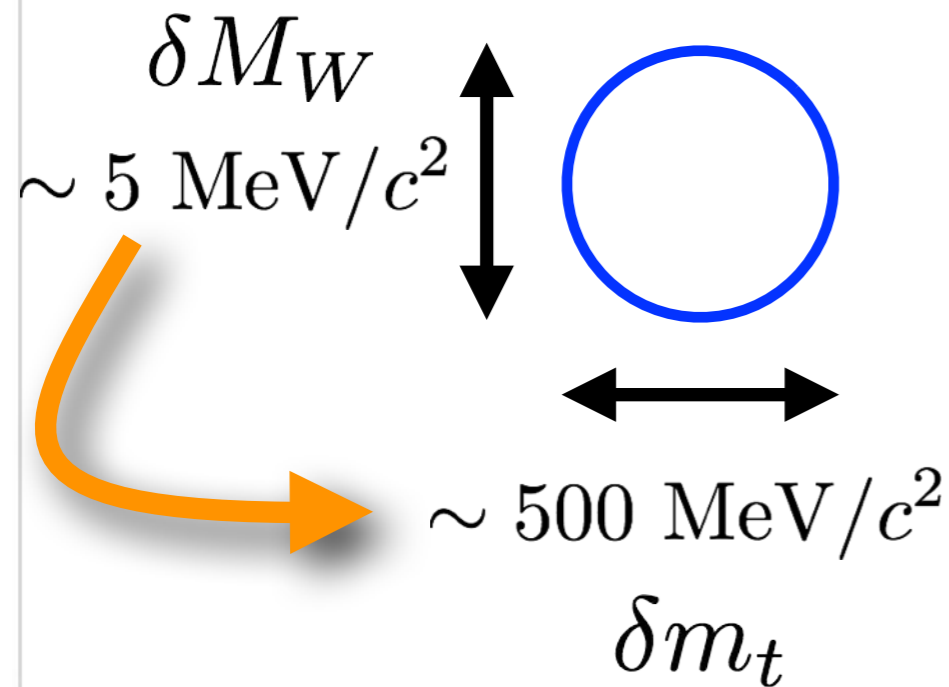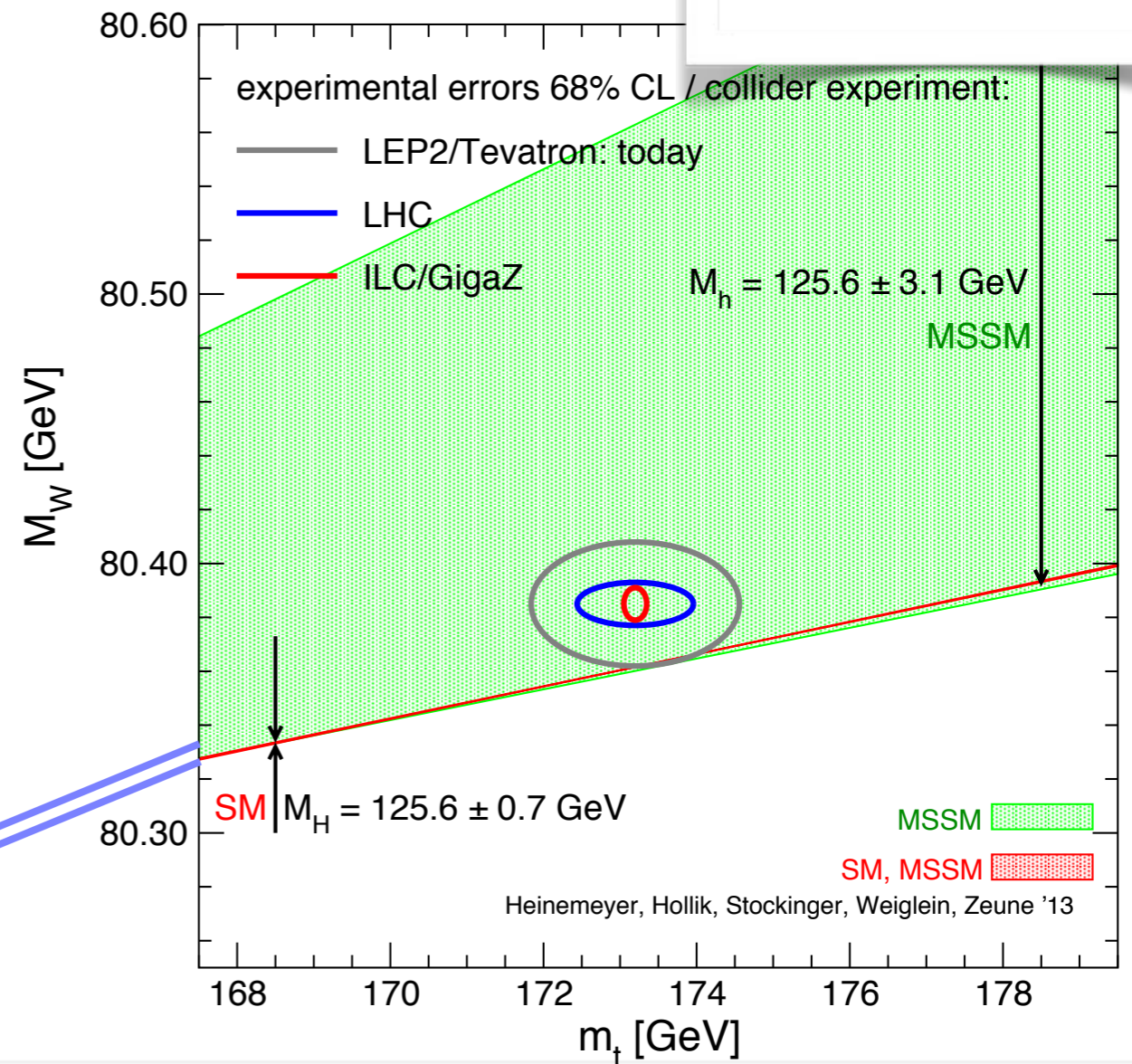
achievable M_W precision: few MeV/c^2

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
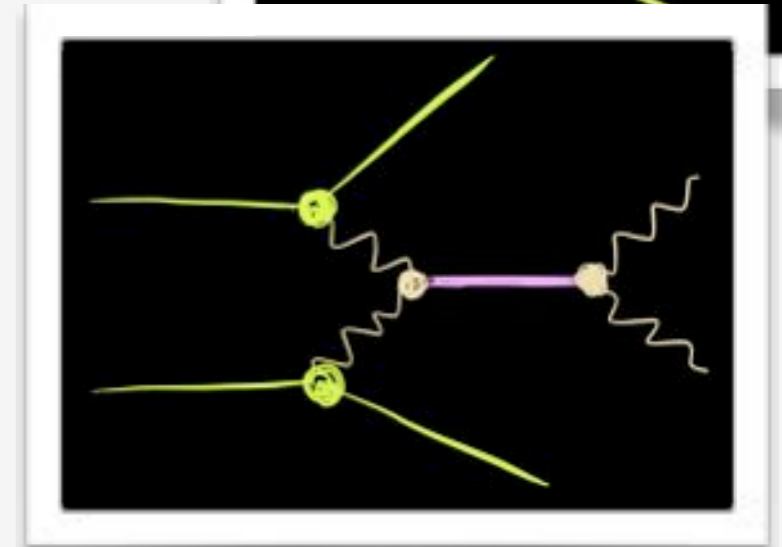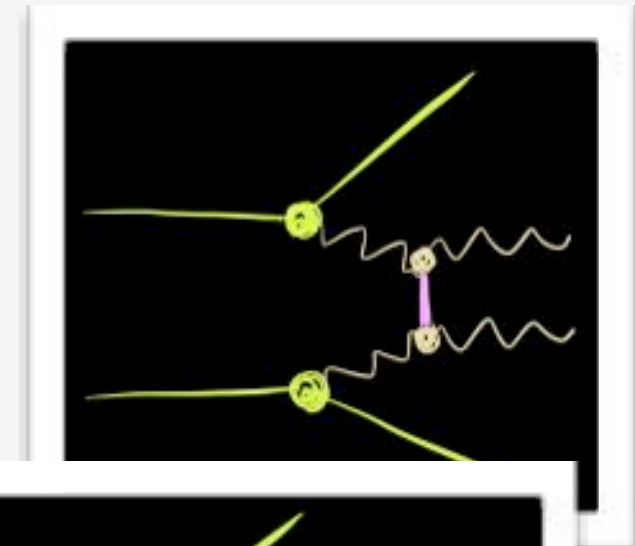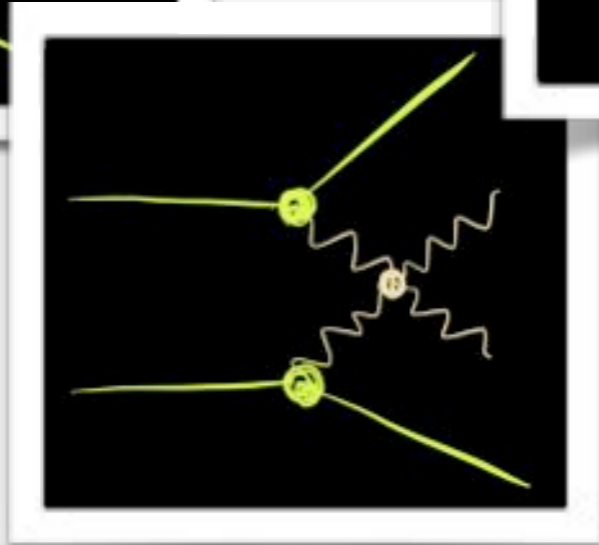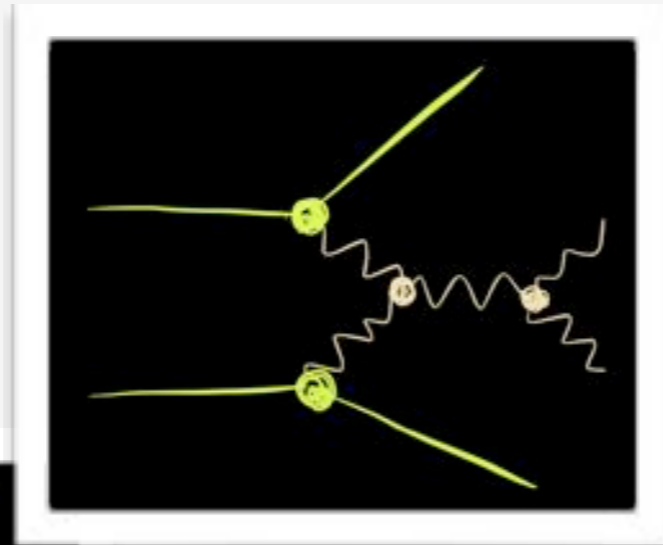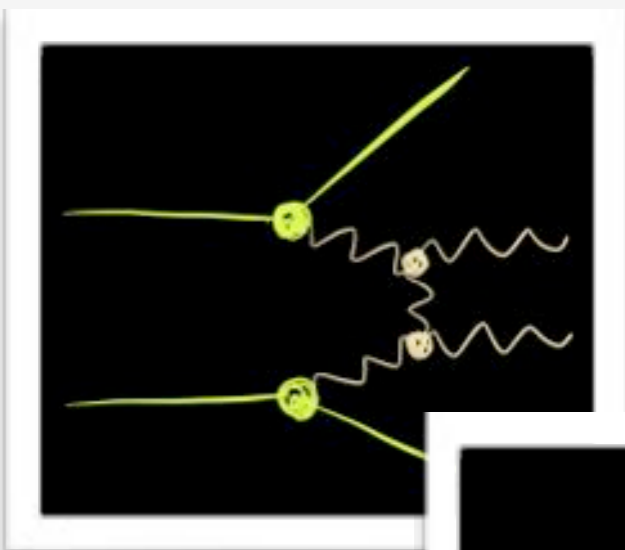
searching beyond: quartic VB scattering

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

some new physics?

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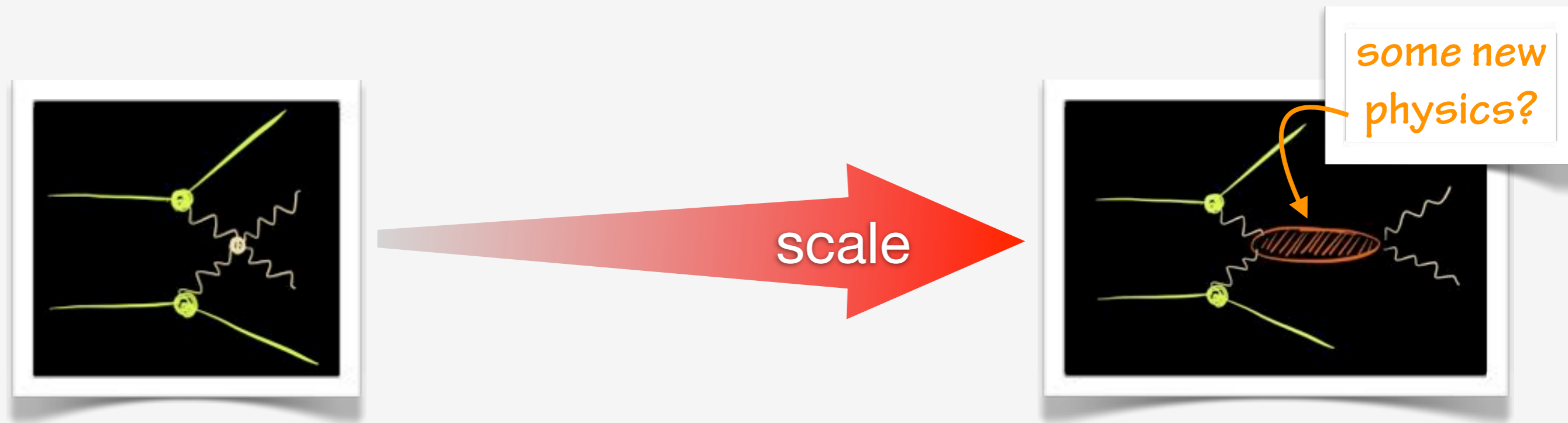
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_i \frac{f_j}{\Lambda^4} \mathcal{O}_j + \cdots$$

VB Scattering

Effective Operator Machinery built into Madgraph for Snowmass

Sensitivity to non-standard gauge interactions
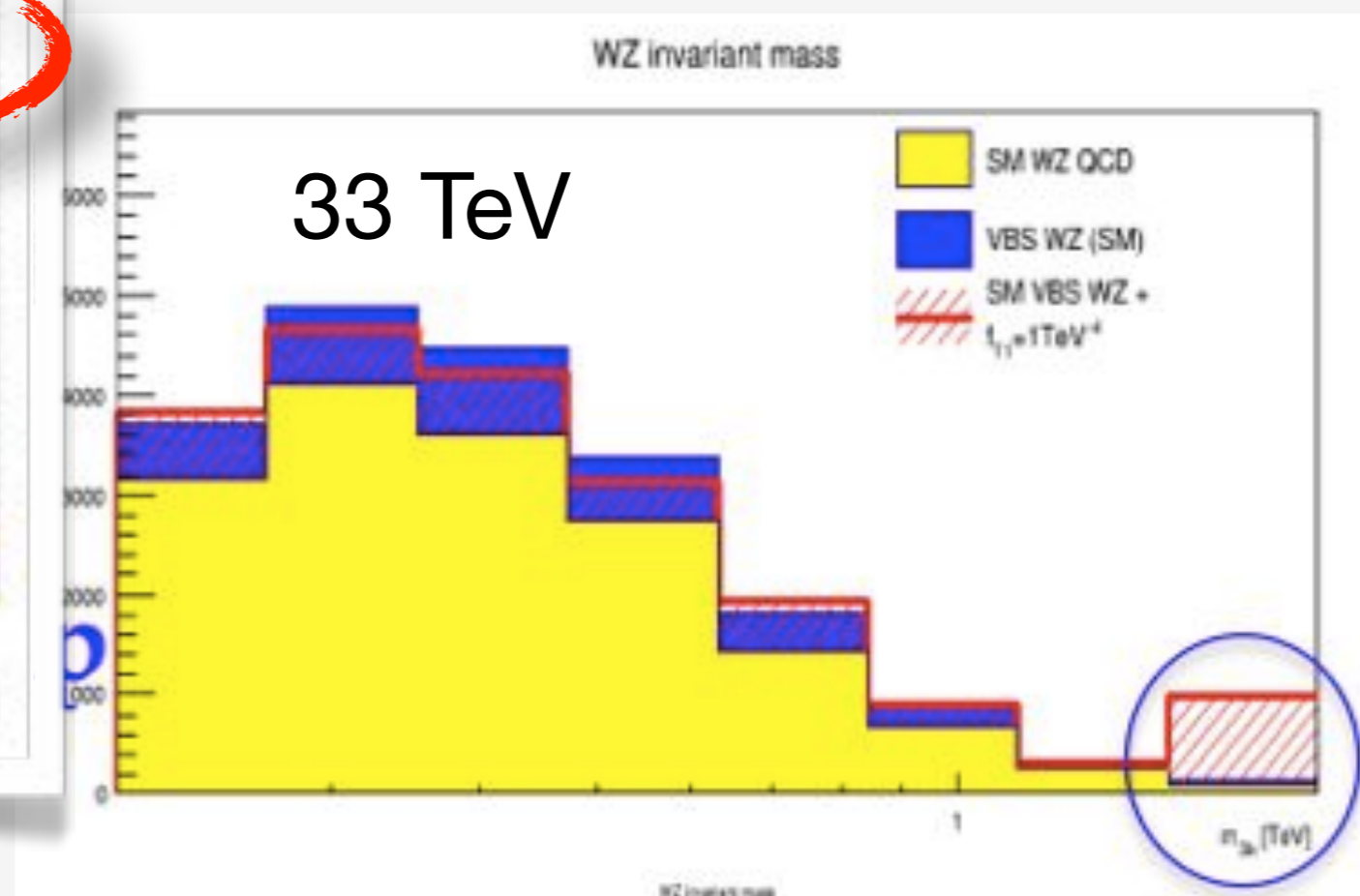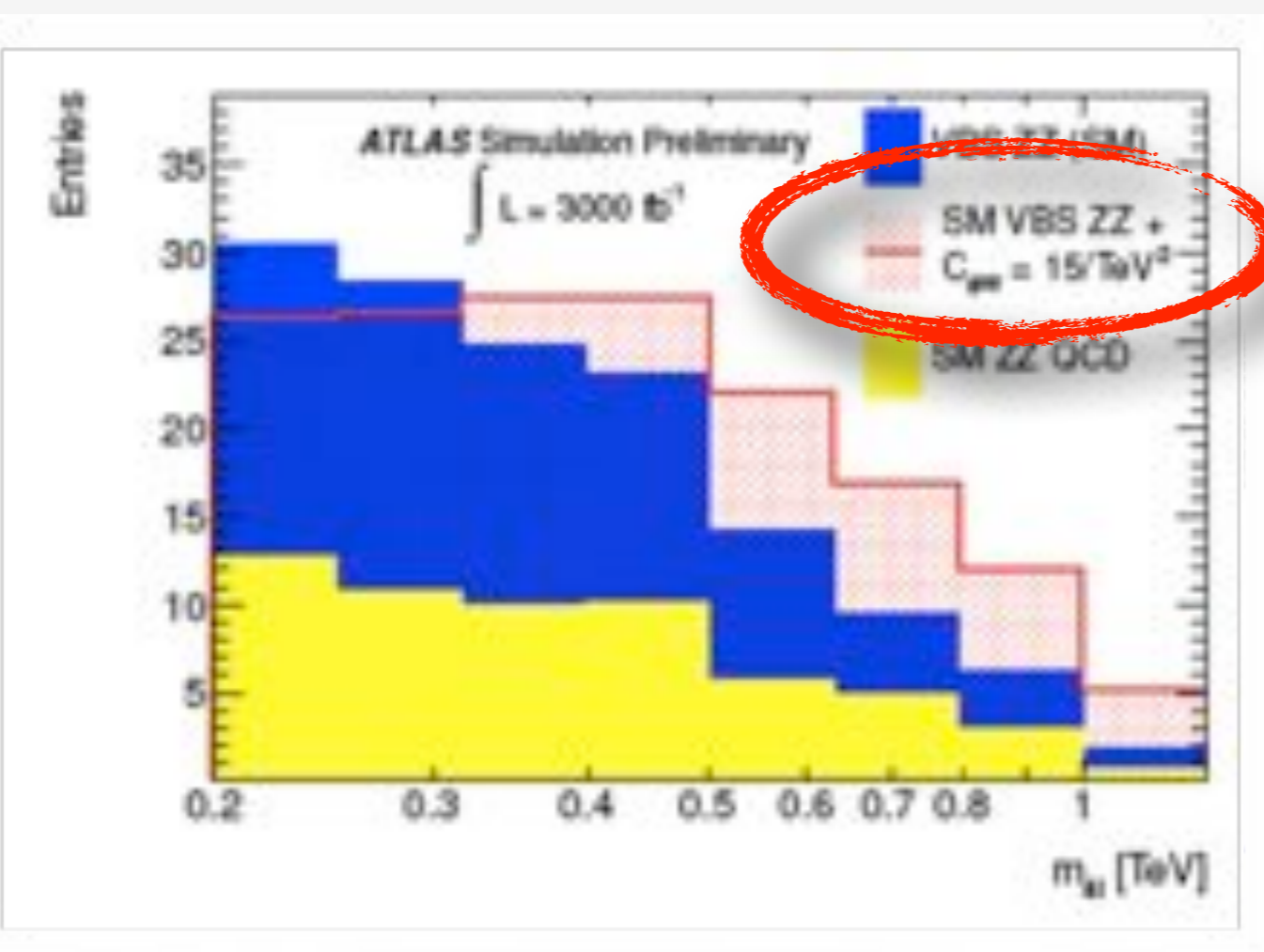
VB Scattering

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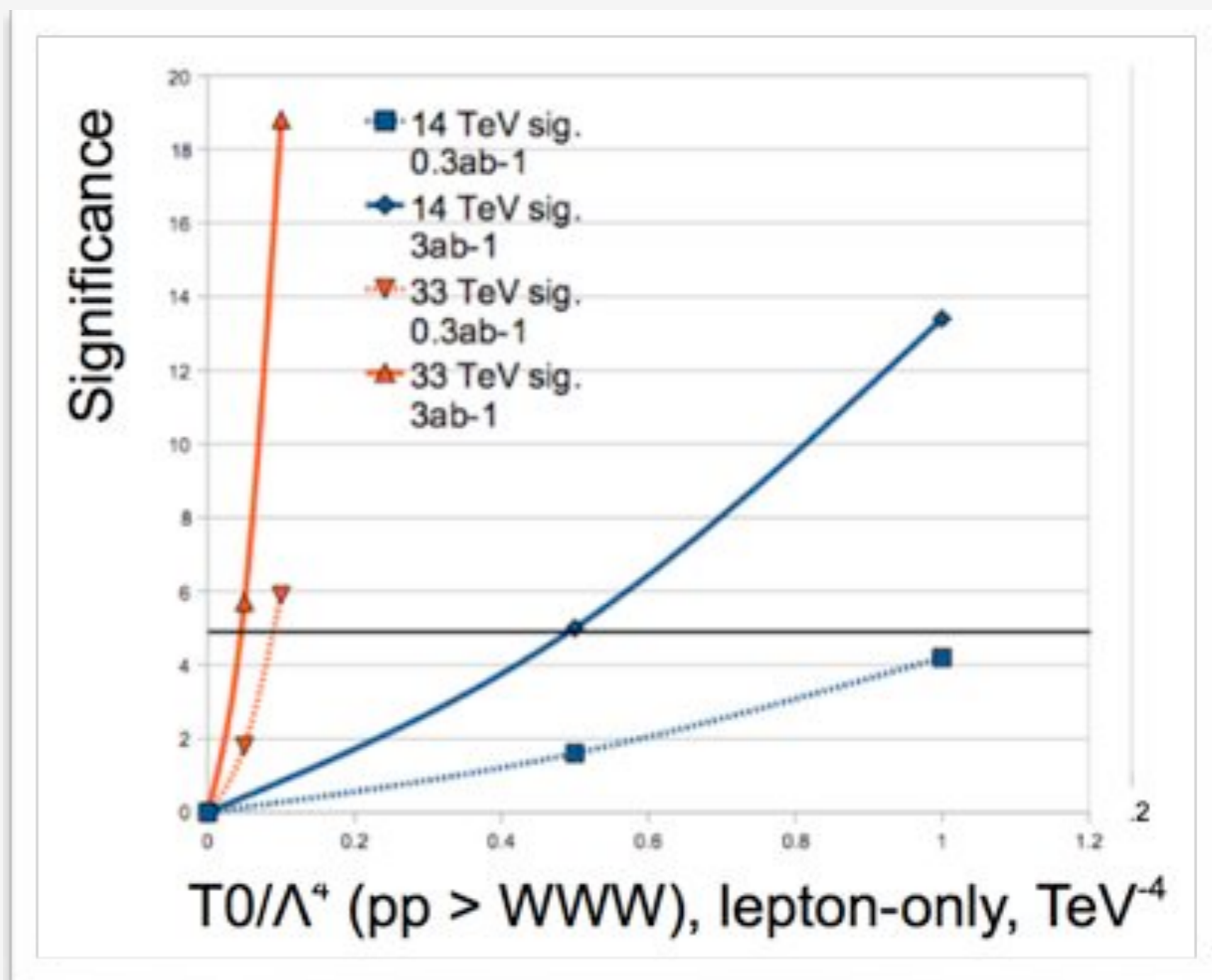
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_i \frac{f_j}{\Lambda^4}\mathcal{O}_j + \cdots$$

The EW physics message

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

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

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.
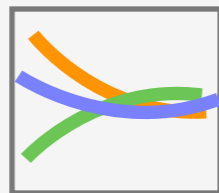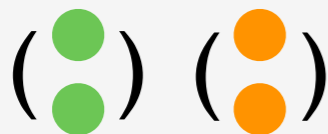
Fully Understanding the Top Quark

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?

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

■ **EWPOs**

keep up with M_W precision

■ **fundamental parameter**

Yukawa coupling to Higgs

close to weak scale

stability argument sensitivity

POST CARD

Correspondence   Address

A Hint?   To: 2013
From: Nature

#5064
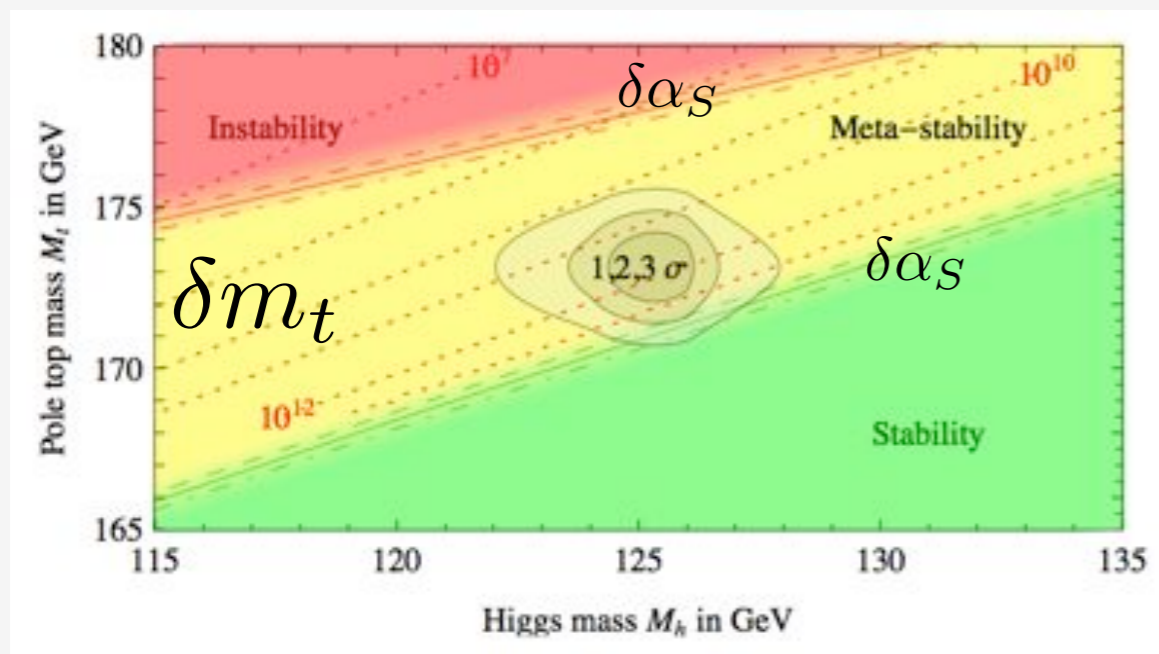
A precision, theoretically sound m_t is doable at LHC

$m(b\ell)$ endpoint method for m_t at LHC
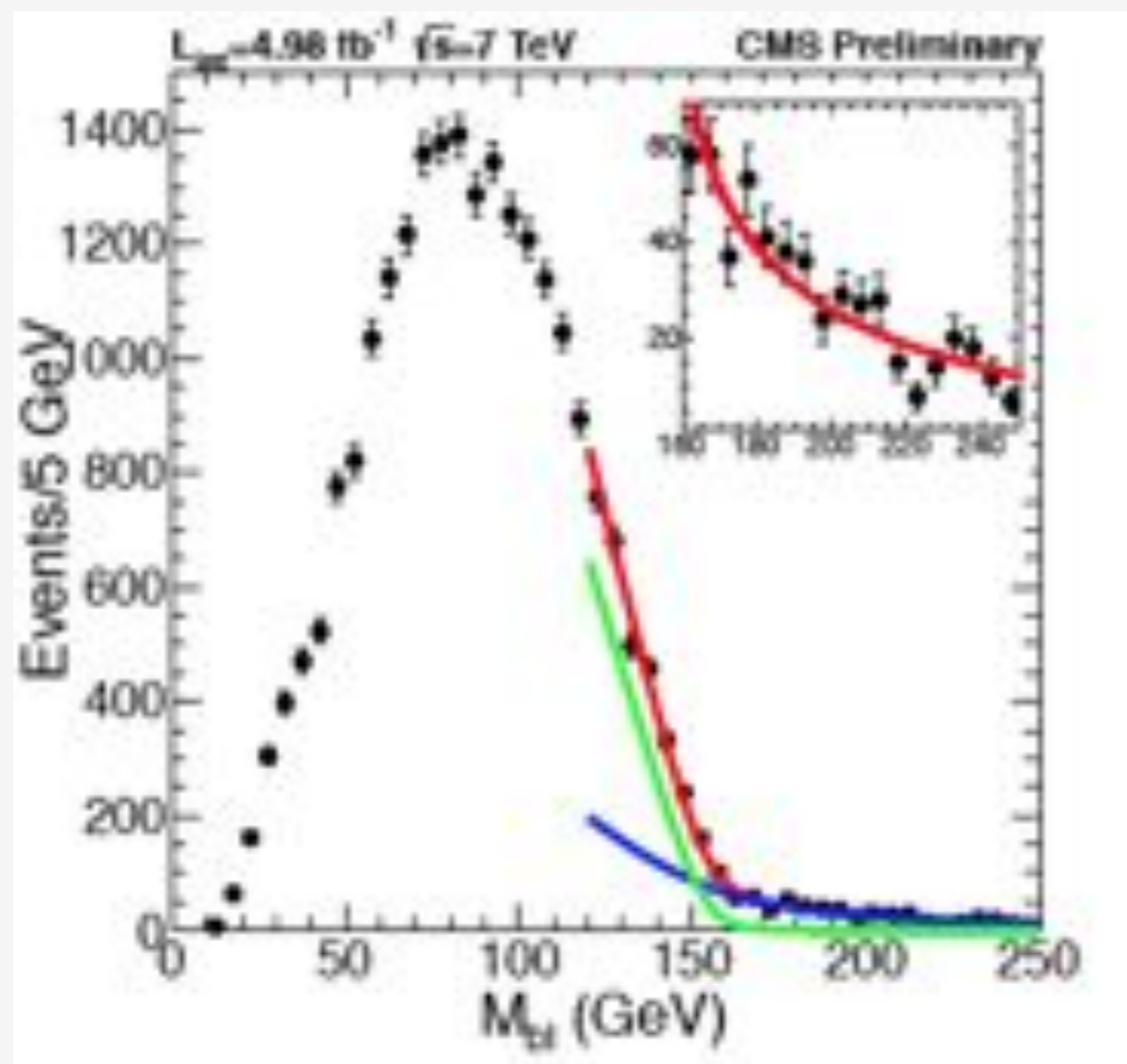
- $\delta m_t \sim 500$ MeV/c^2 ultimately

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
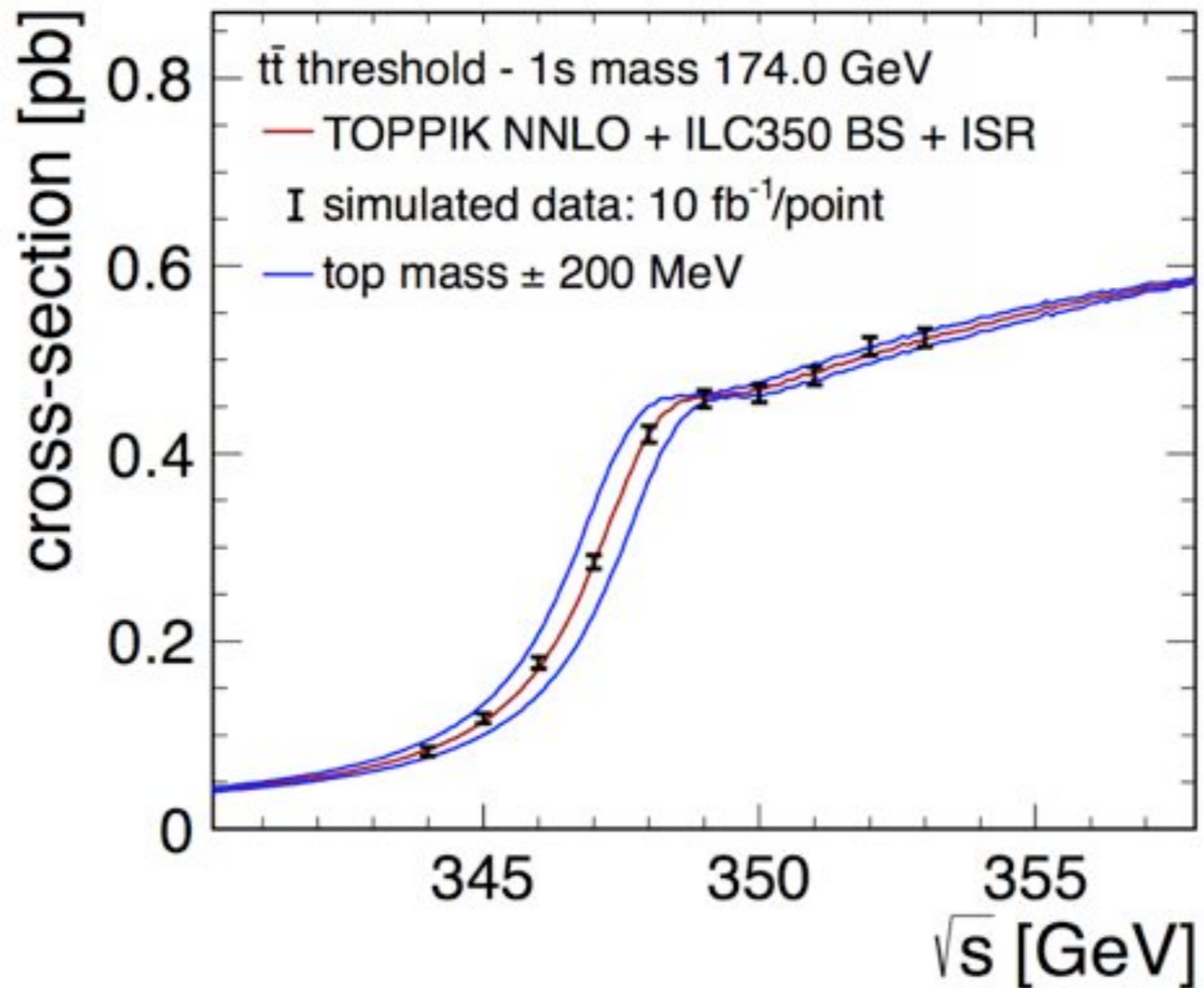
EW top-Neutral VB couplings

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
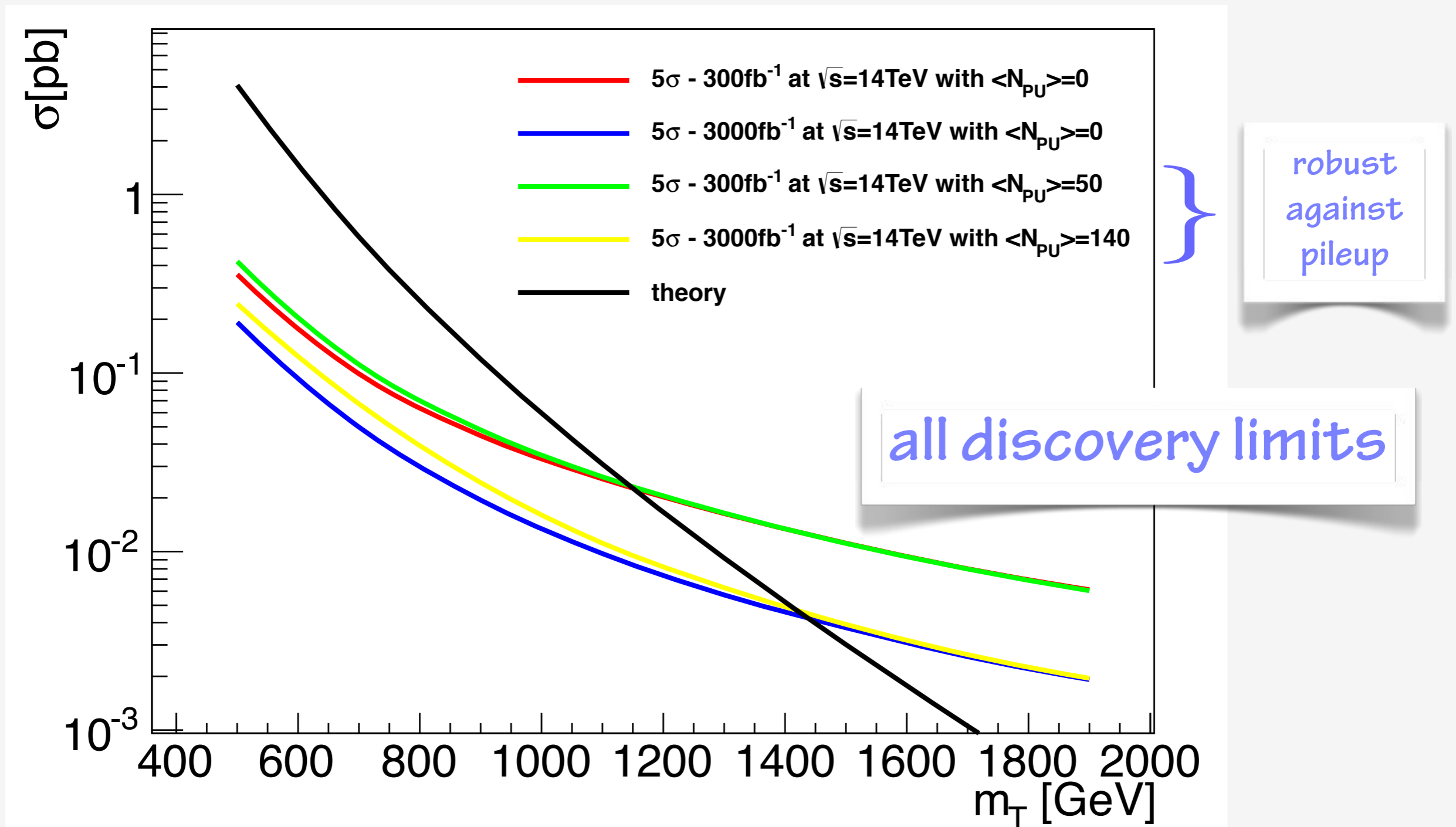
Analysis techniques inoculate against pileup

Restore the performance with boosted techniques of grooming and trimming.
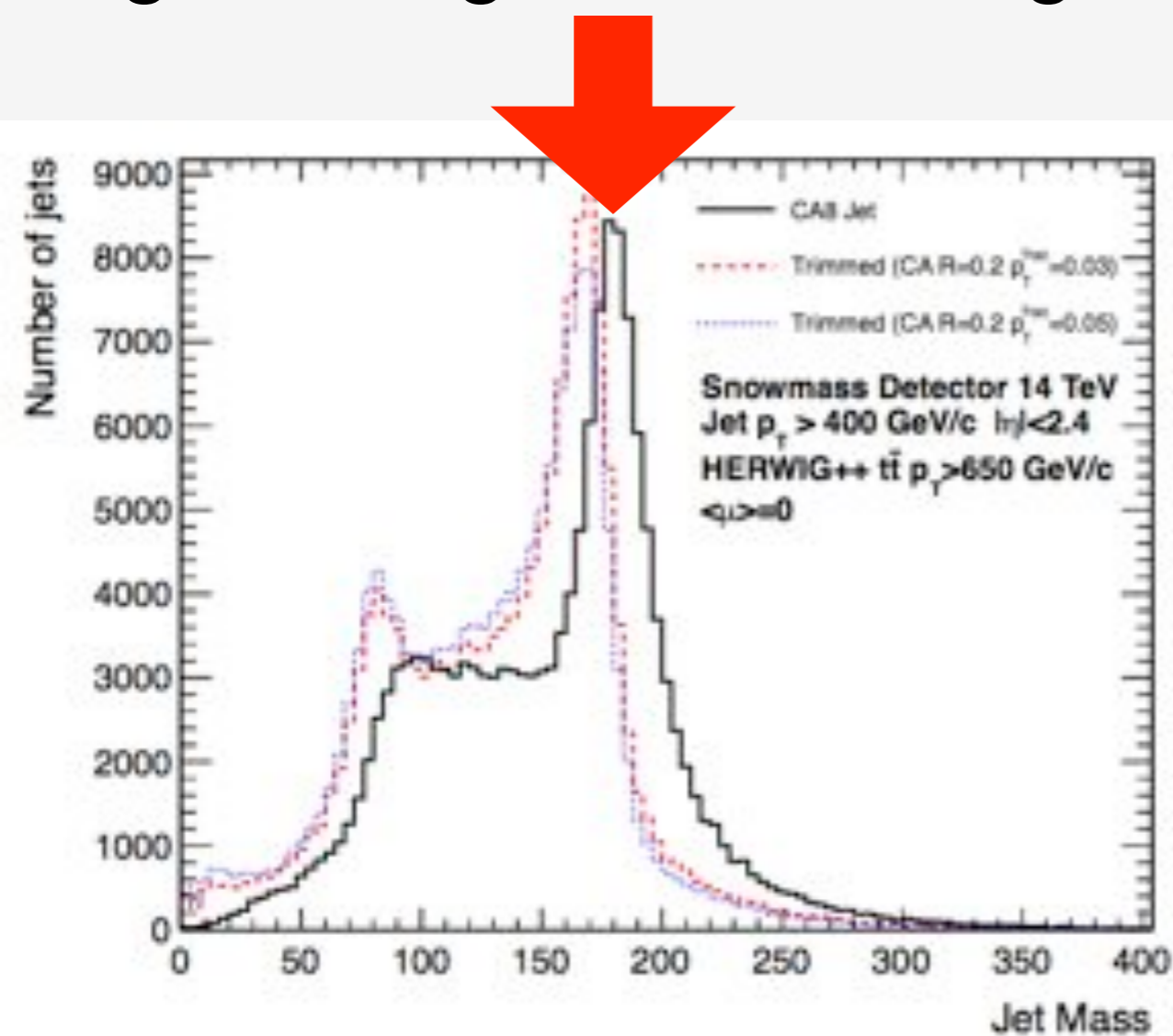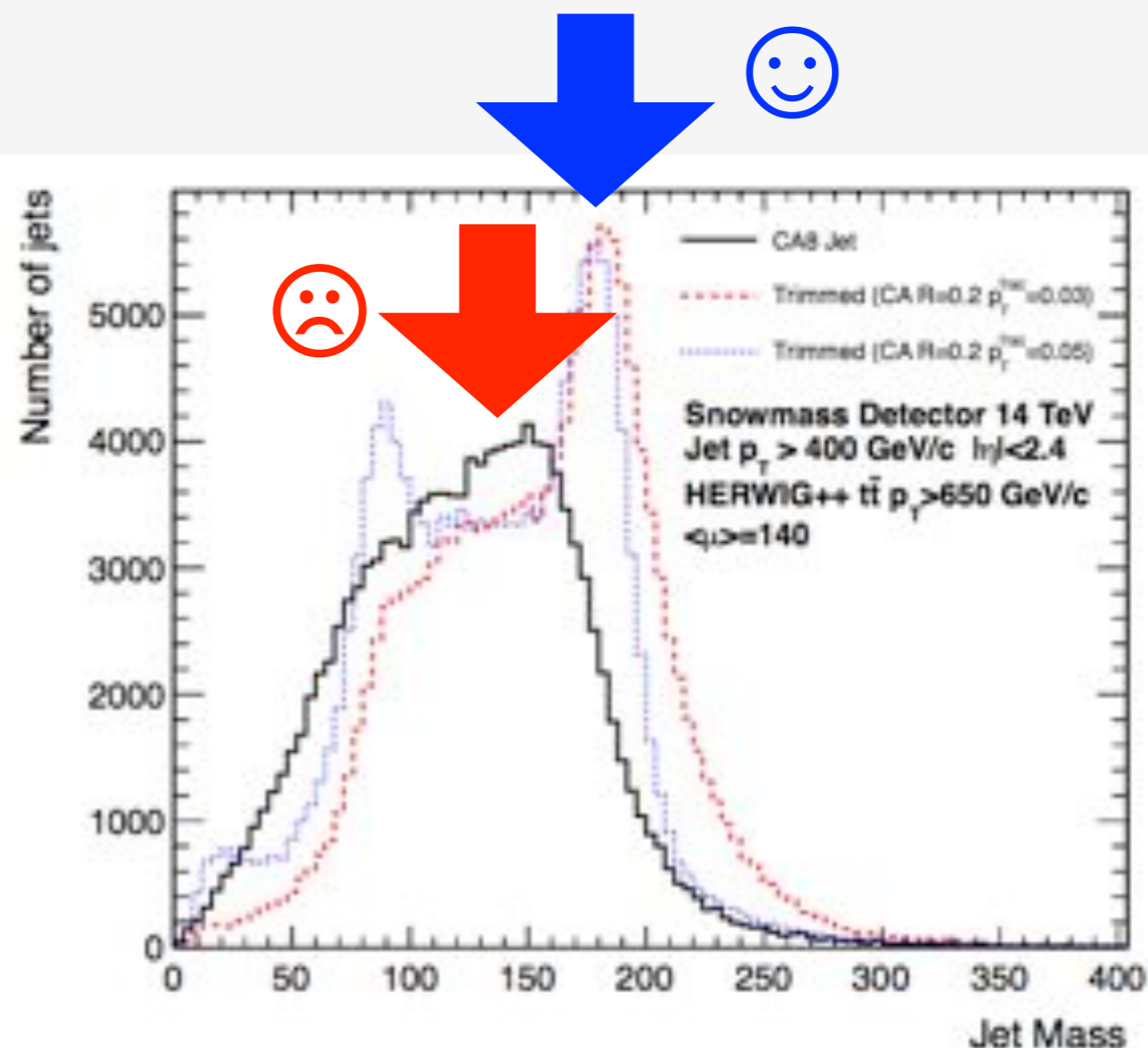
pileup = 0   = 140

The Top Quark physics message

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

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.
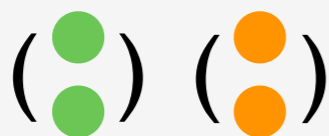
Quantum Chromodynamics and the Strong Force

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
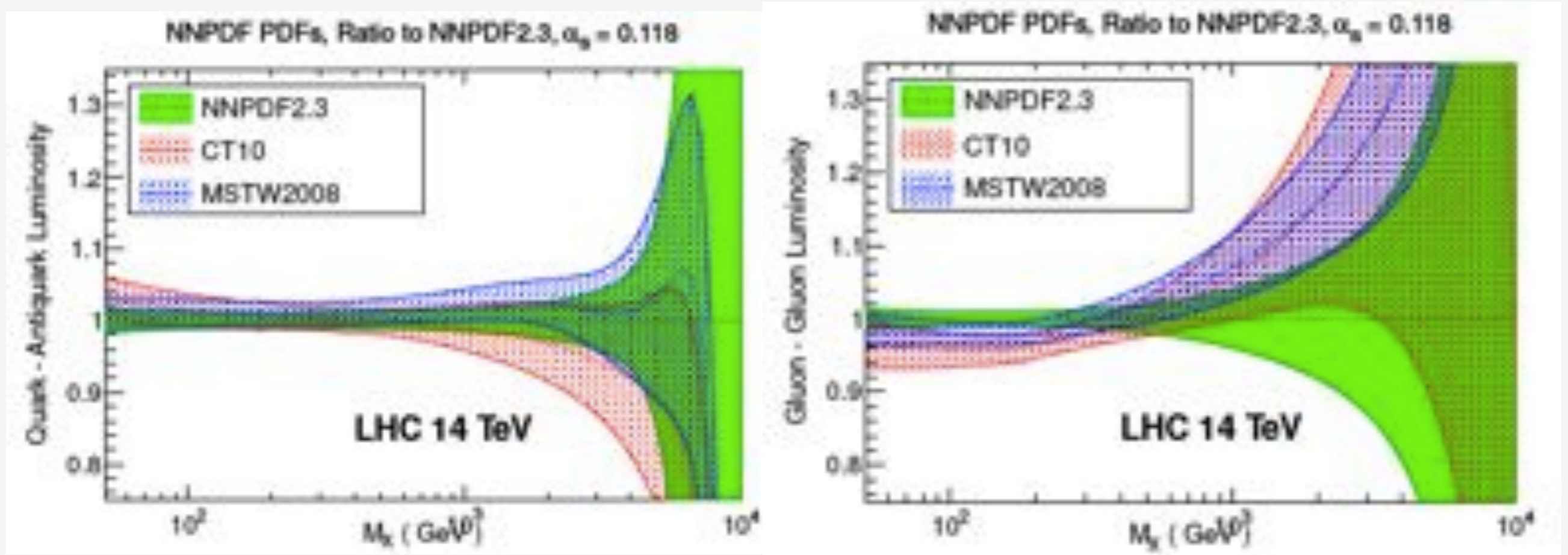
Juan Rojo

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

full rapidity coverage required

complementary role of ATLAS,CMS and LHCb
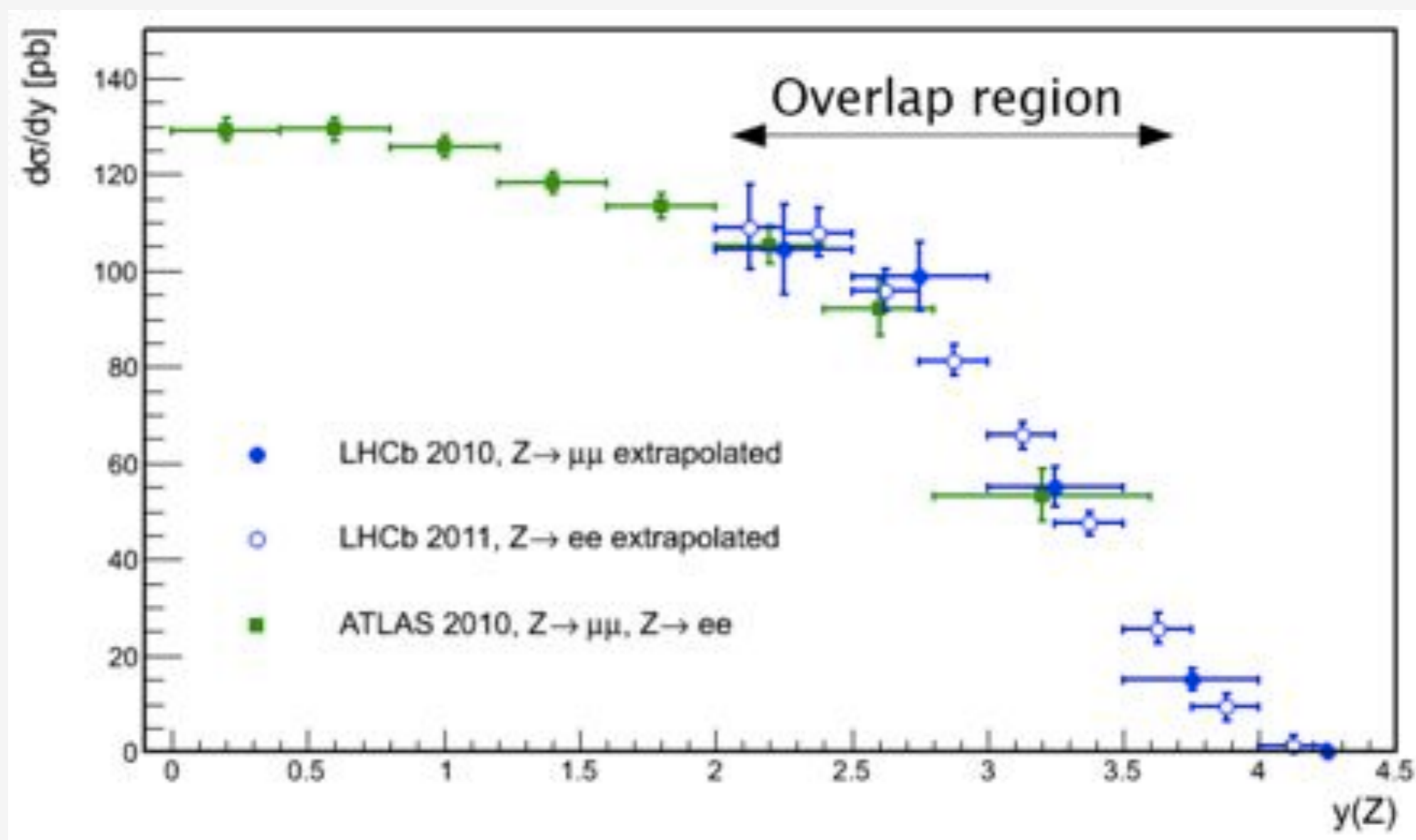
Photon PDF and QED

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

Juan Rojo
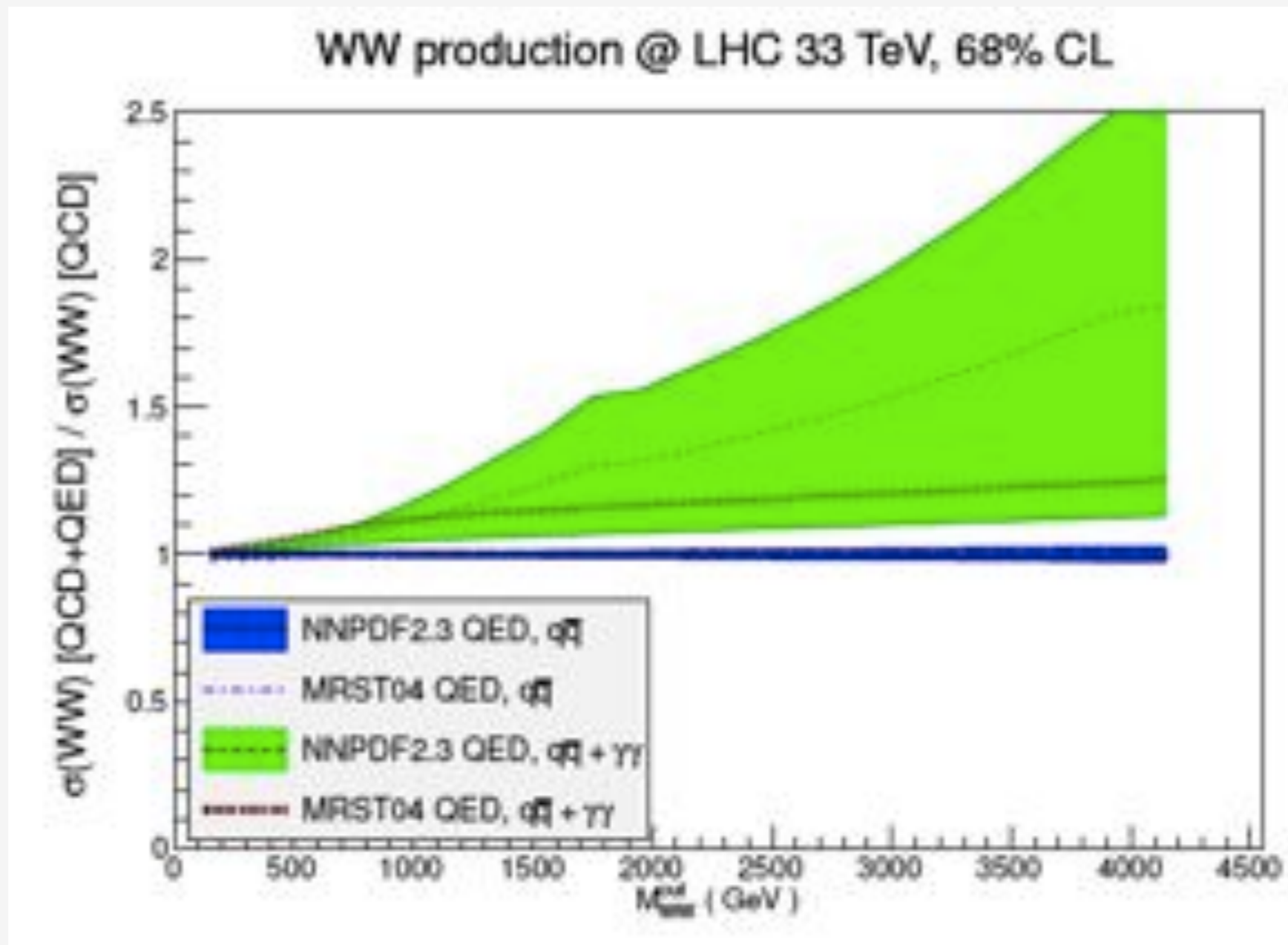
Electroweak Sudakov

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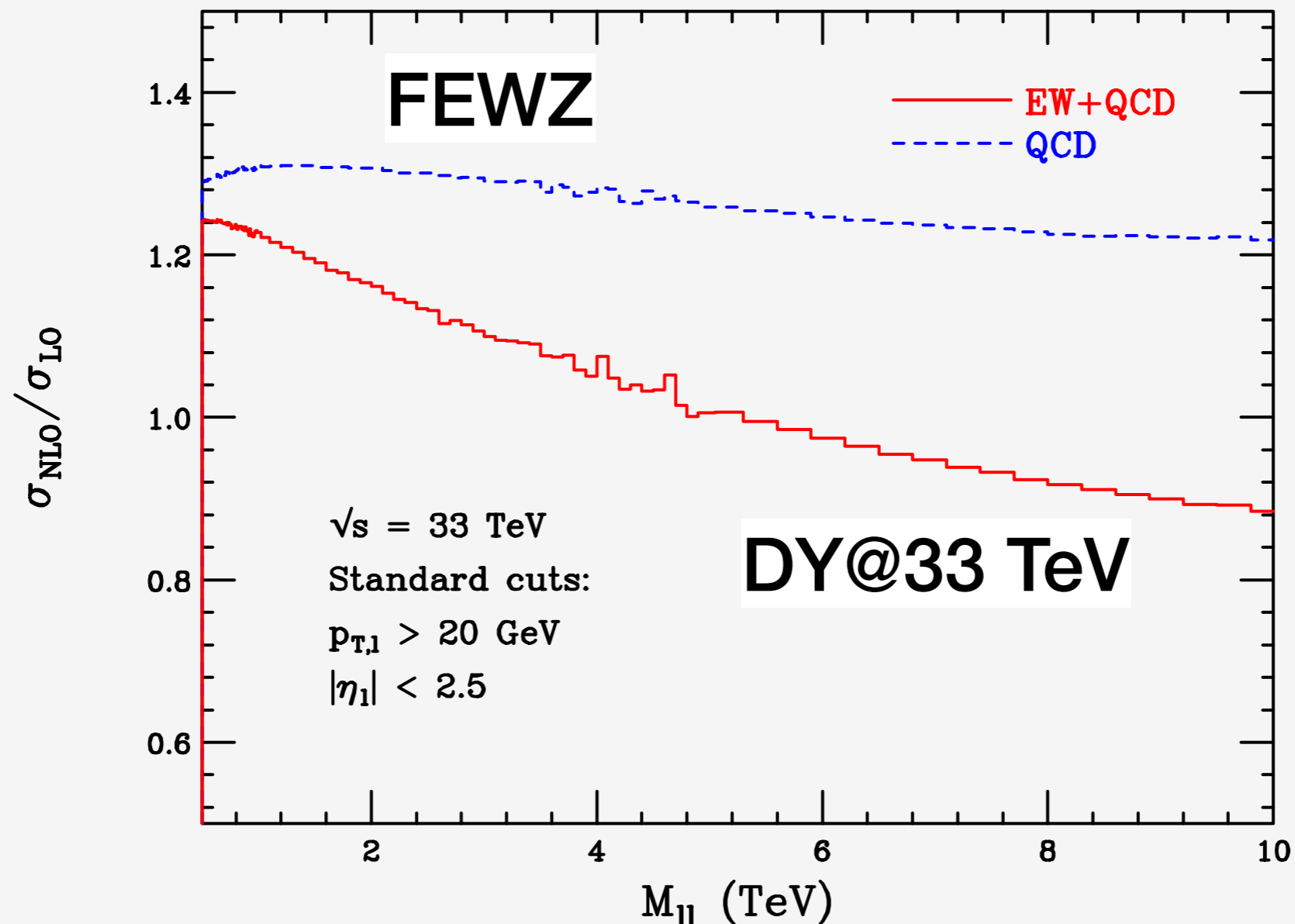
Kaland Mishra

NNLO

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

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

Higgs and many other LHC analyses.

Czakon-Mitov
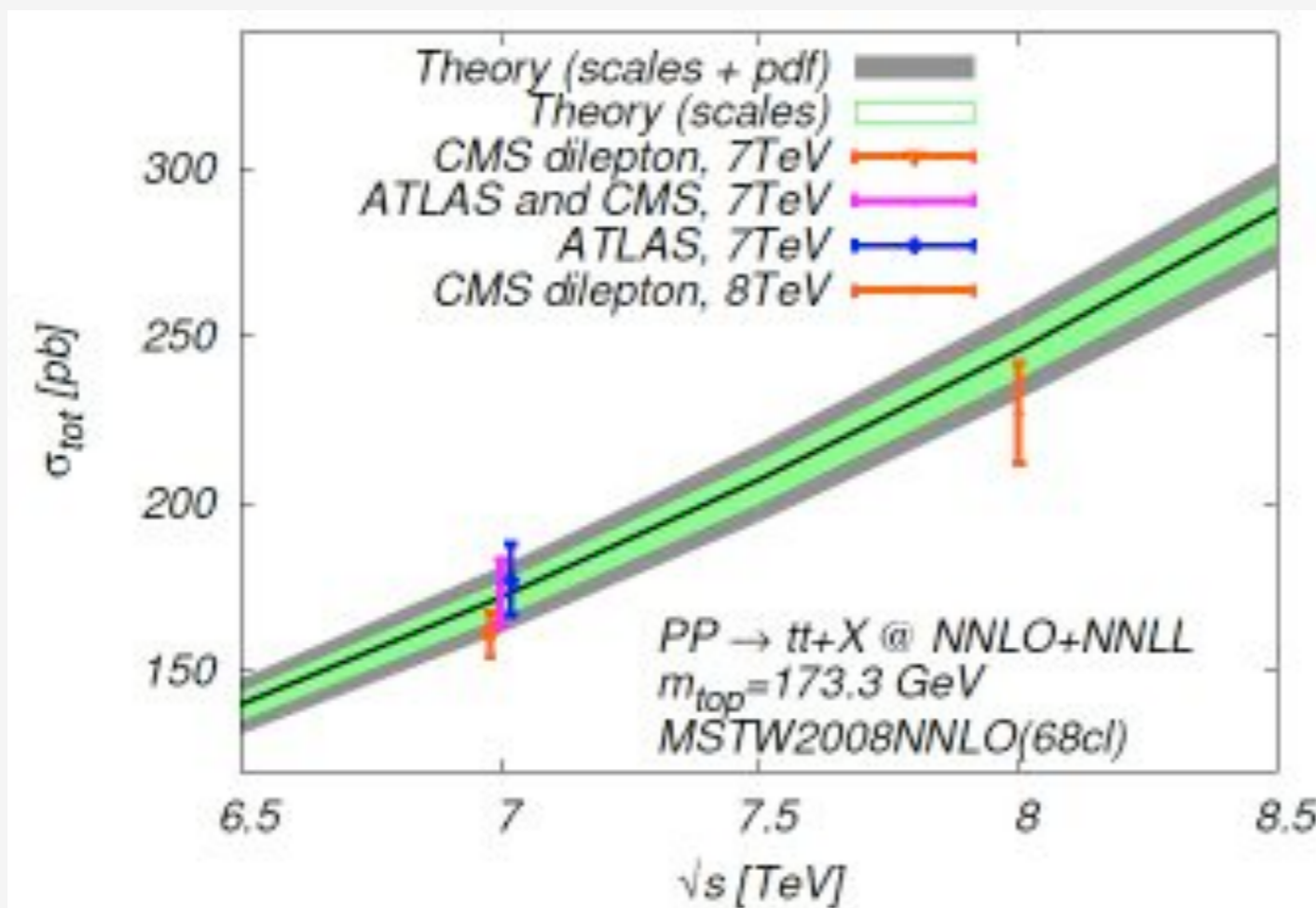
Precision inputs from Lattice

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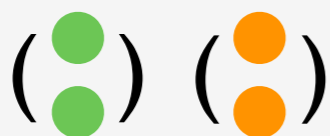
- **The Path Beyond the Standard Model – New Particles, Forces, and Dimensions**

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.
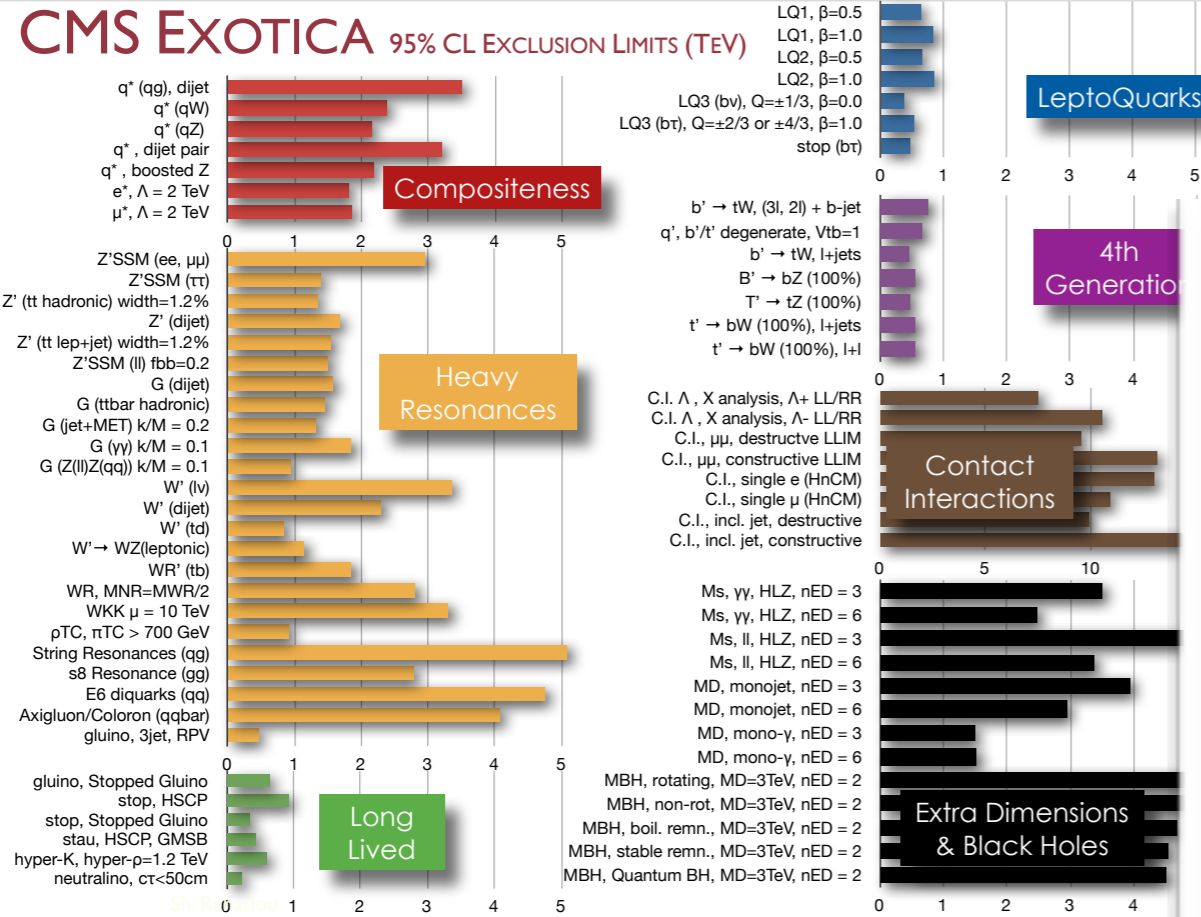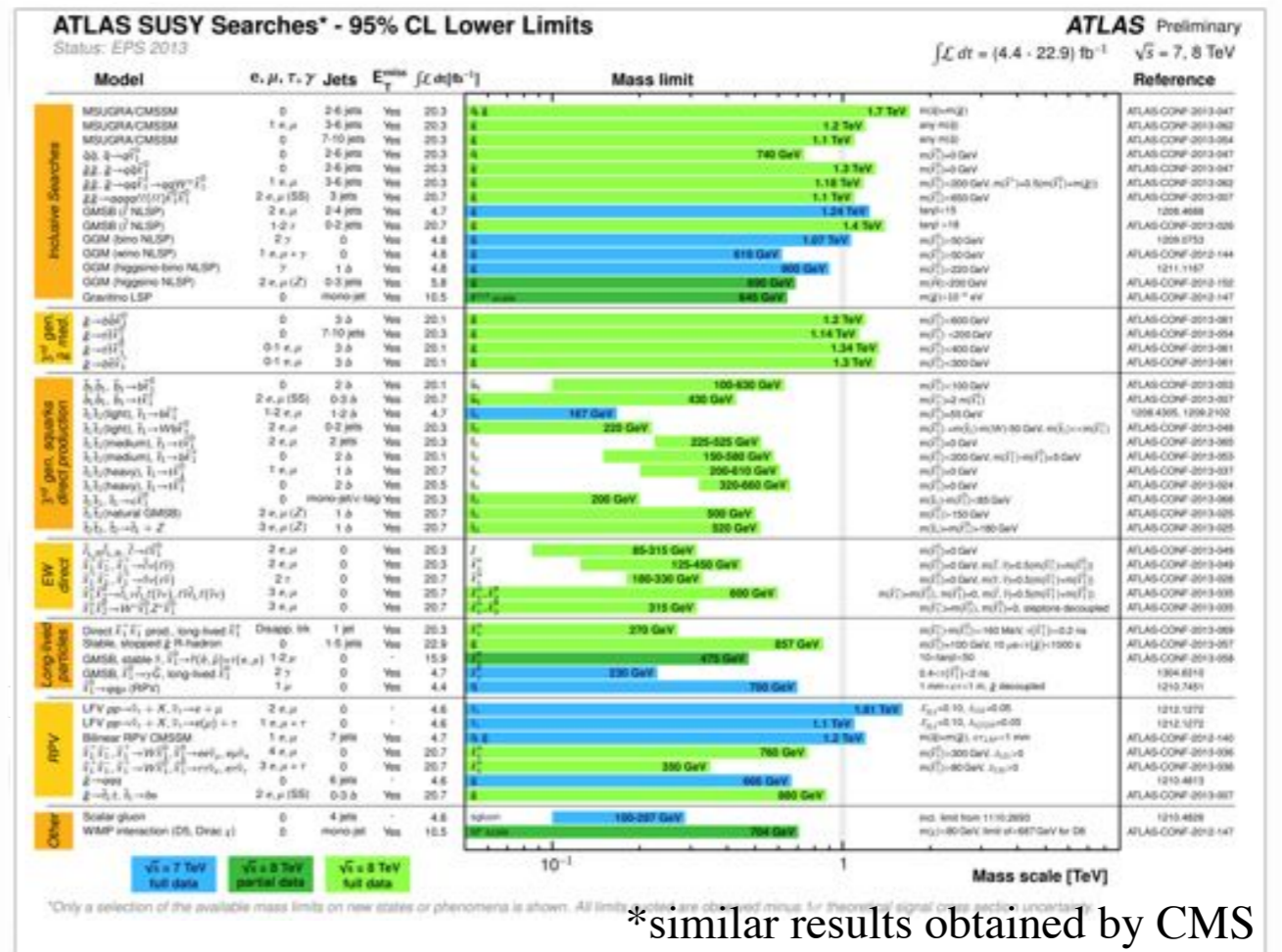
gain from now to 300/fb & beyond

x2 in gluino mass reach 8-14 TeV,

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

  factors of 2 for 33 TeV and 100 TeV
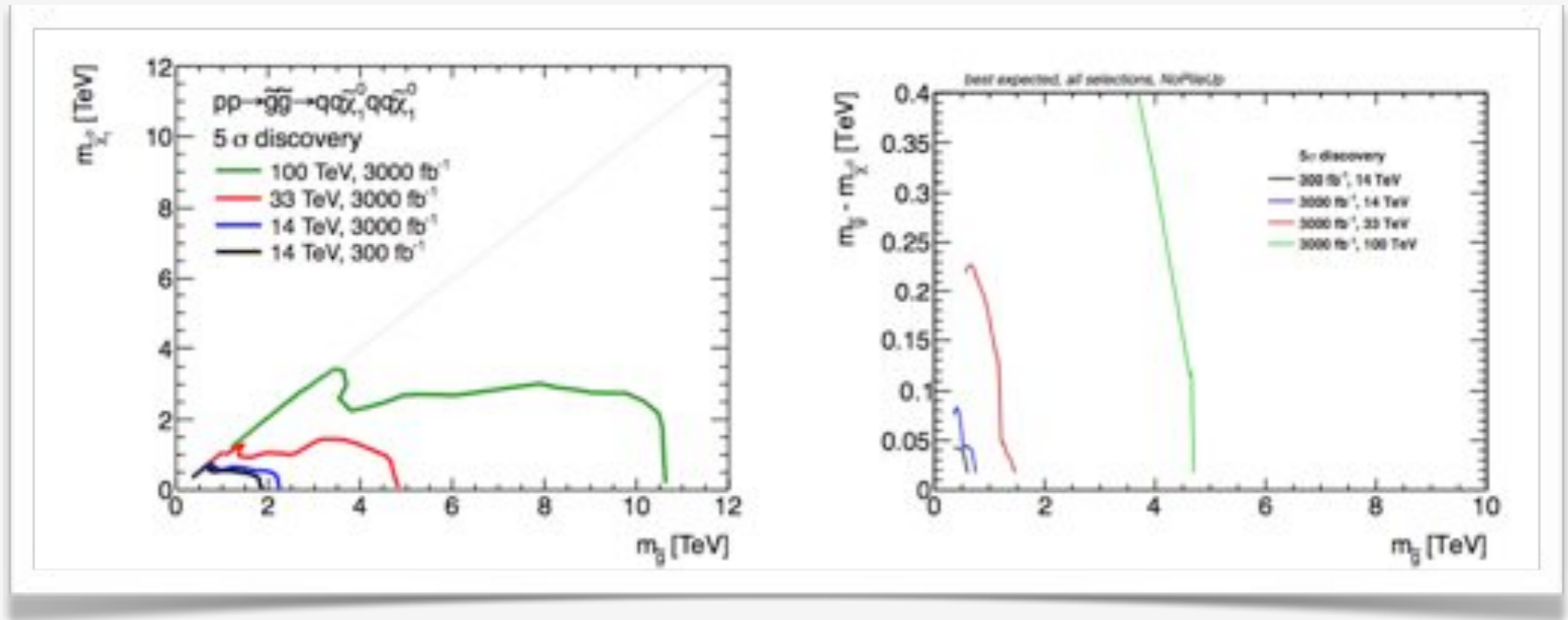
SUSY reach: x2 from E_cm, 1.3 in 𝓛
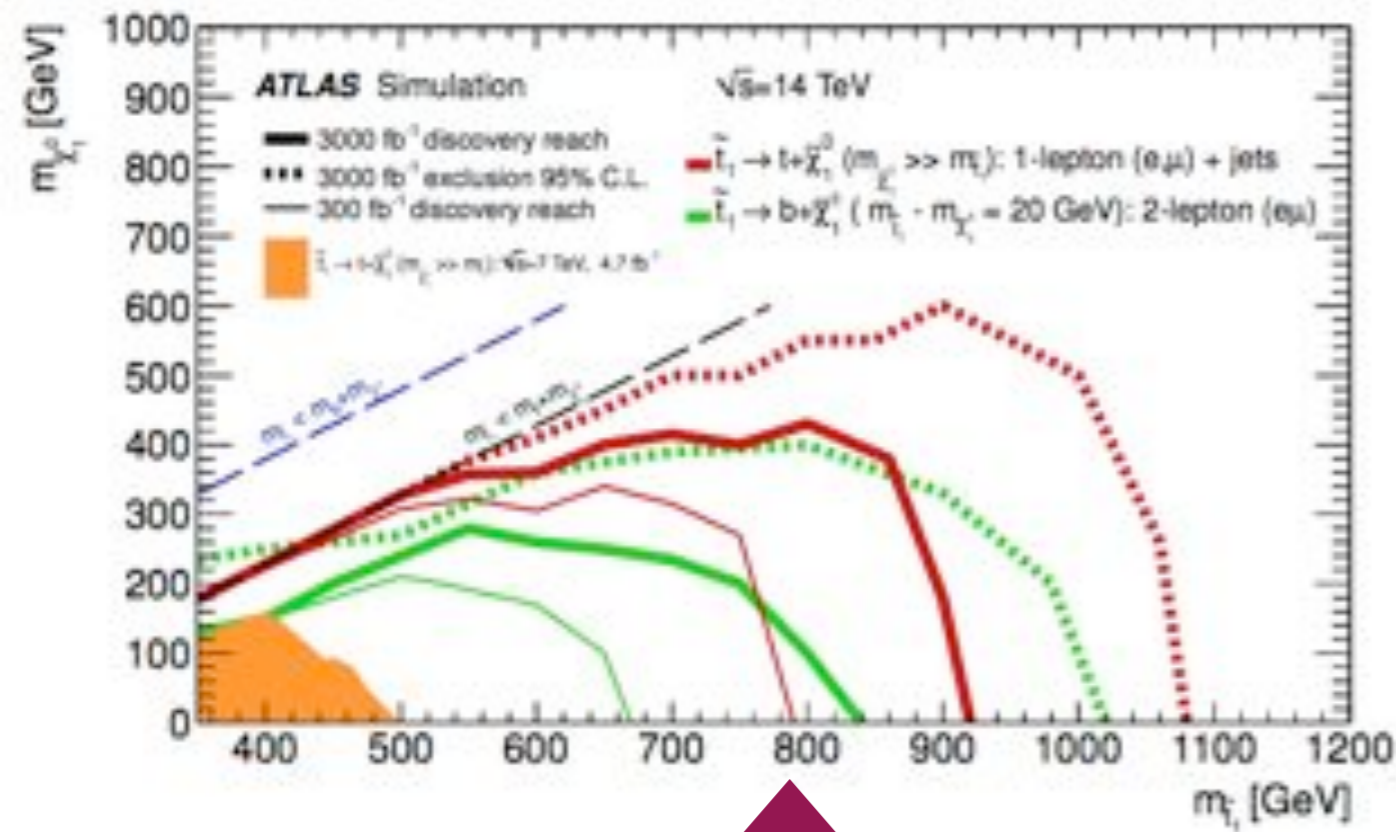
In the pMSSM survey of SUSY models

- squark/gluino mass plane

300/fb
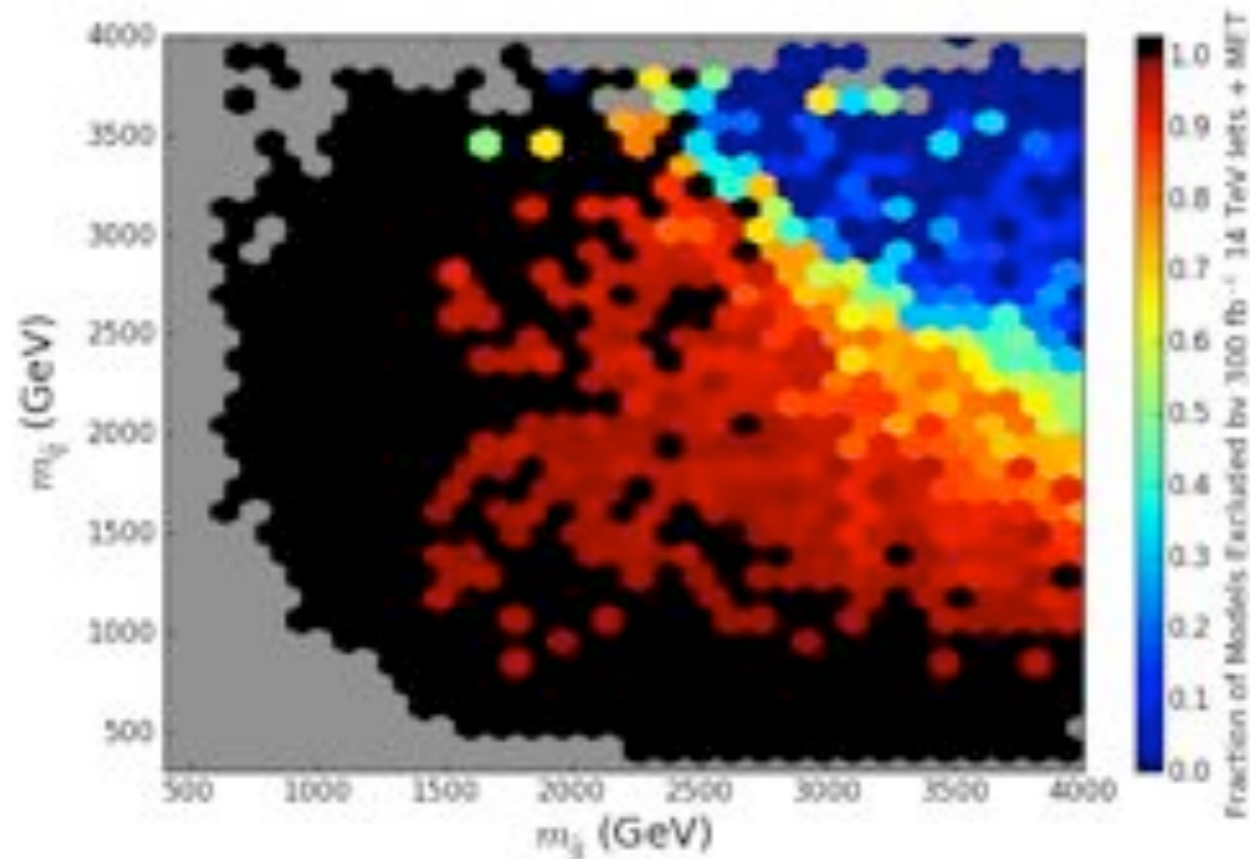
3000/fb
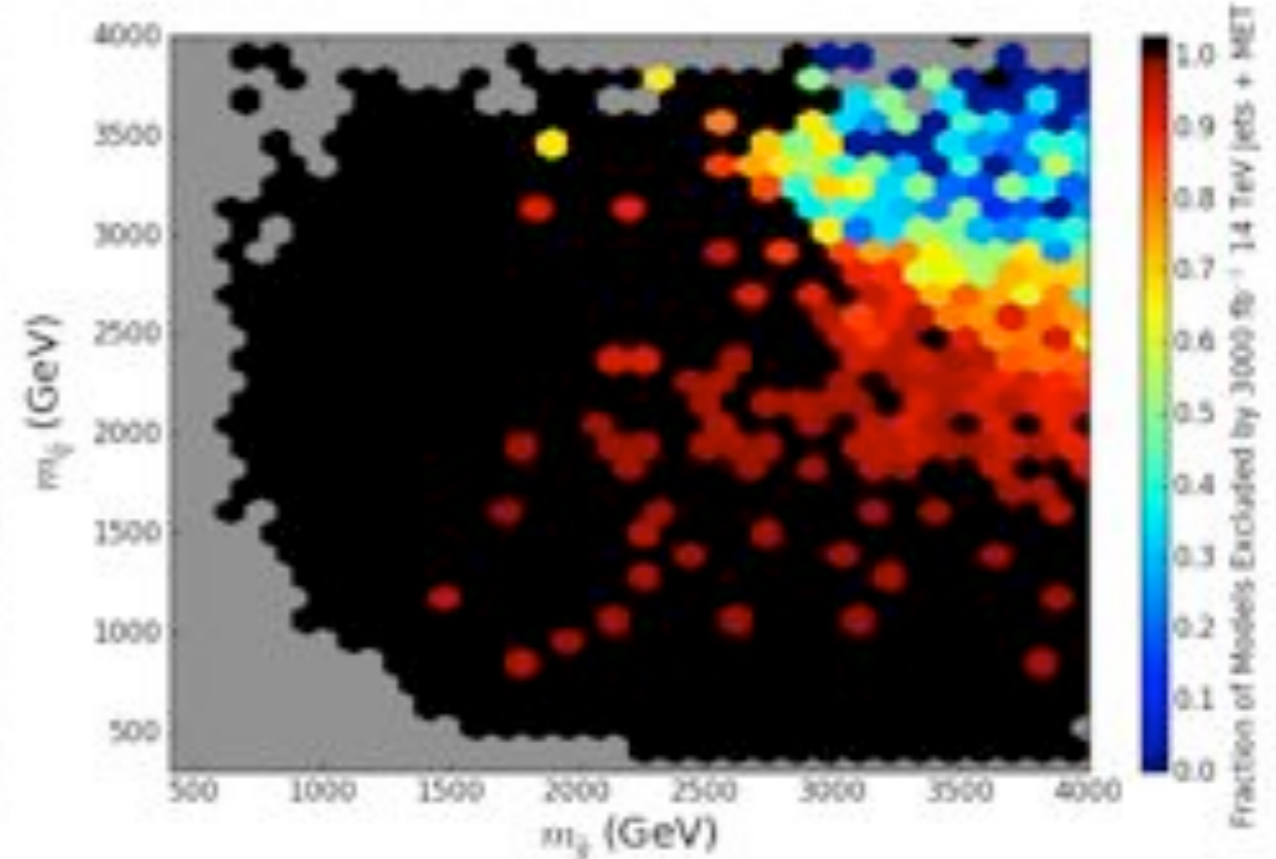
Note closing of loopholes in addition to increased energy reach.

Cahill-Rowley et al.
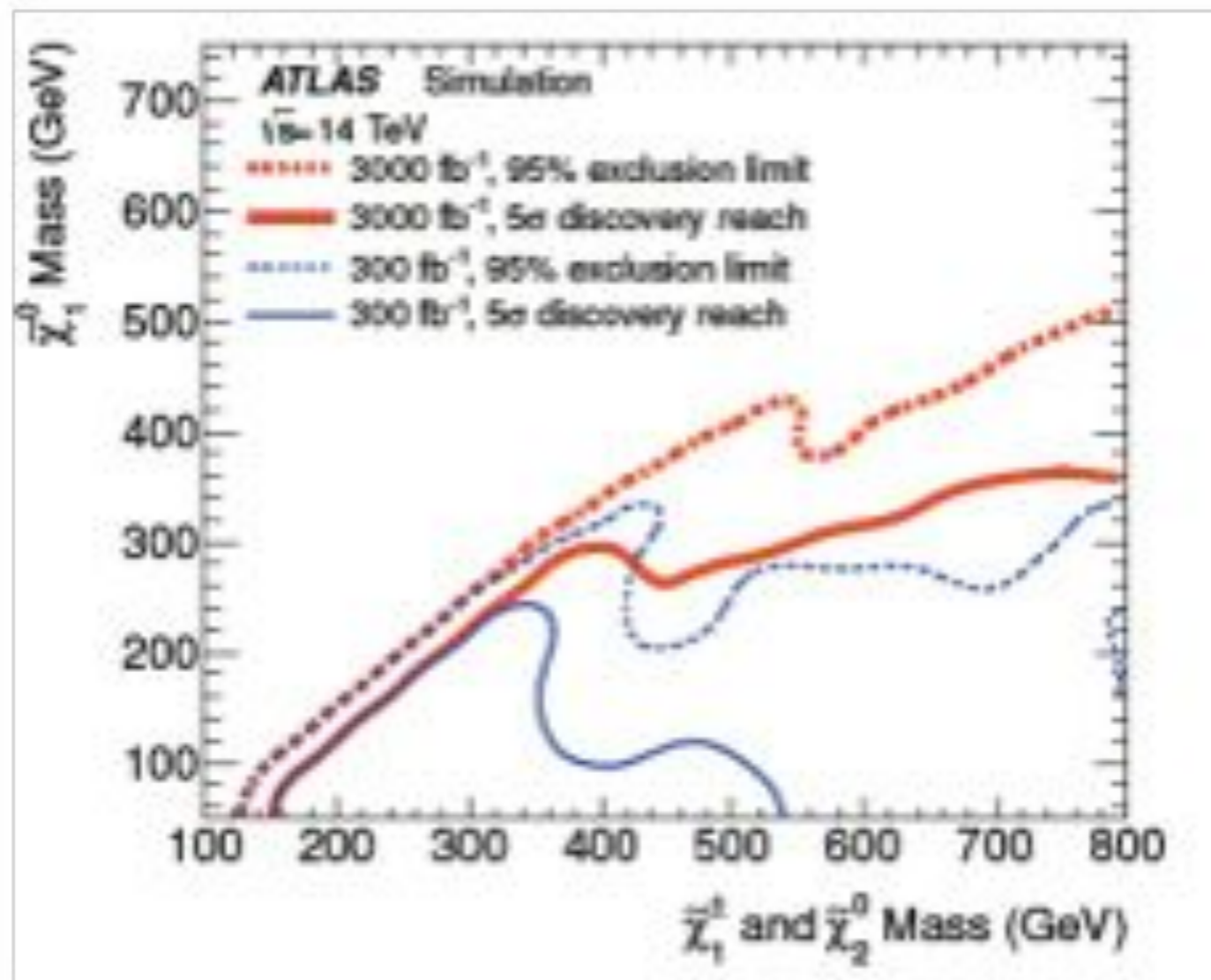
m_{stop} reach: ~50% from E_{cm}, 1.5 in $\mathcal{L}$
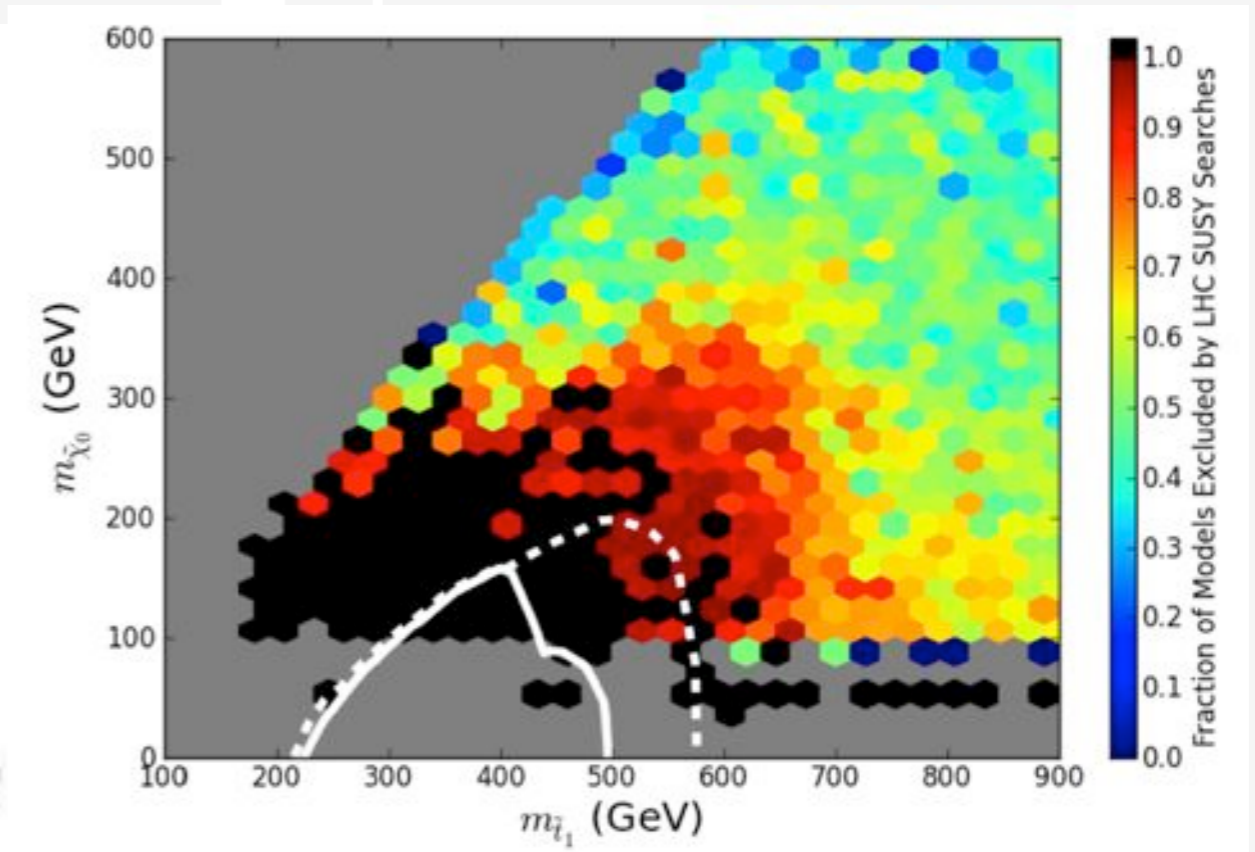
300/fb reach
stop-> t + neutralino

3000/fb reach
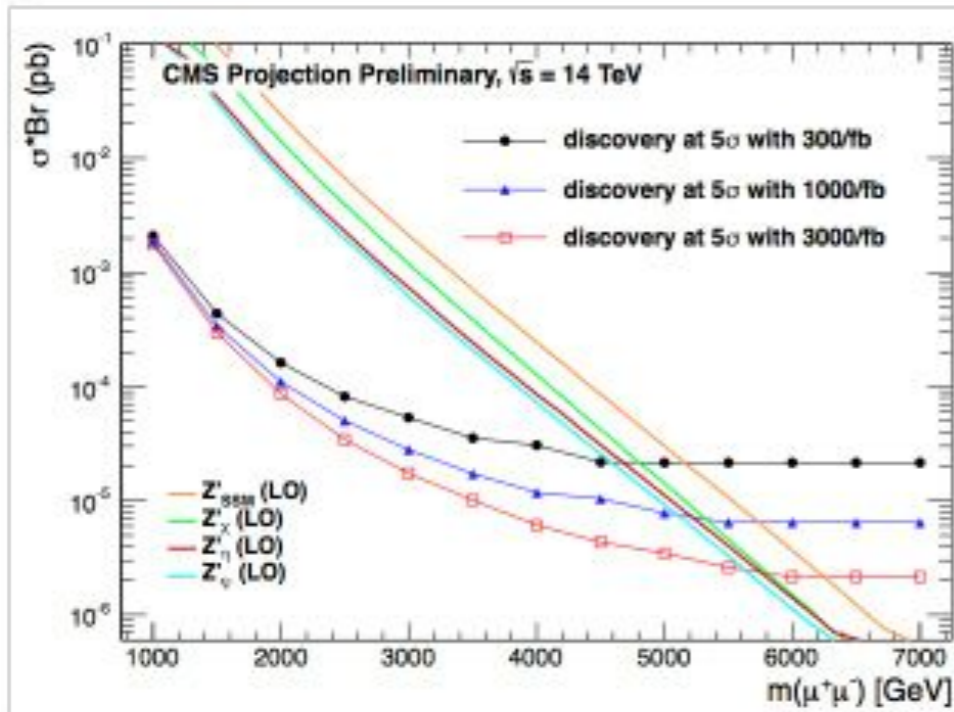stop-> t + neutralino

Cahill-Rowley et al.

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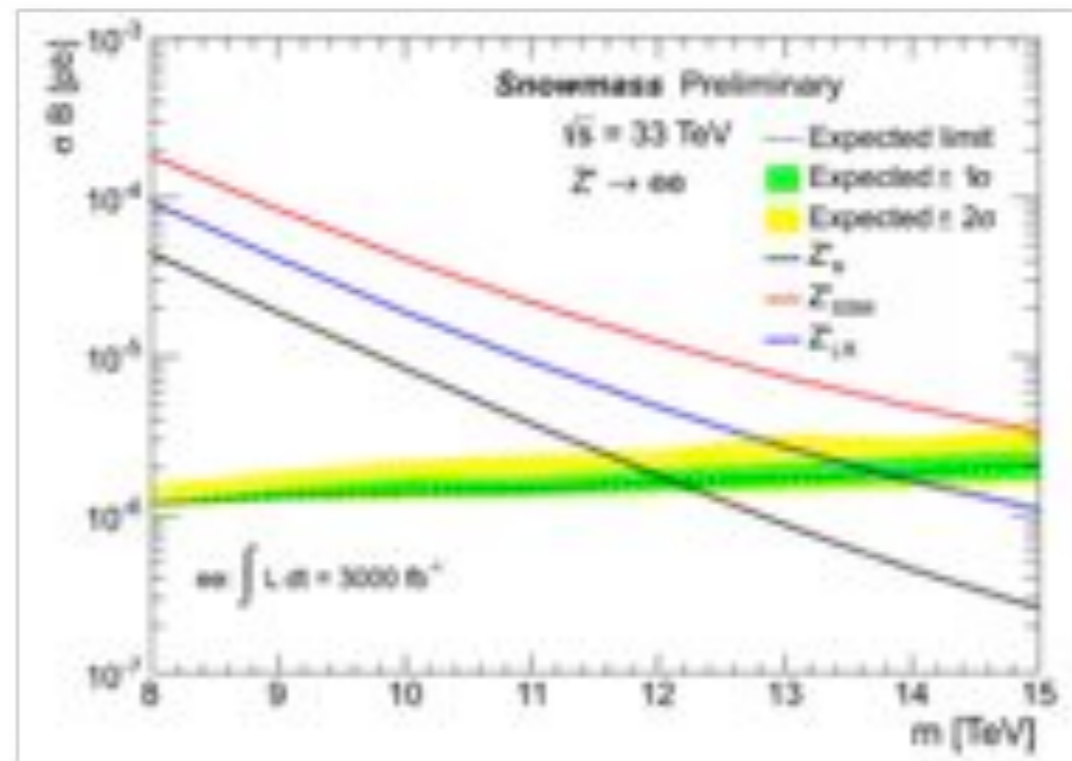
x 2 again...300/fb to 3000/fb

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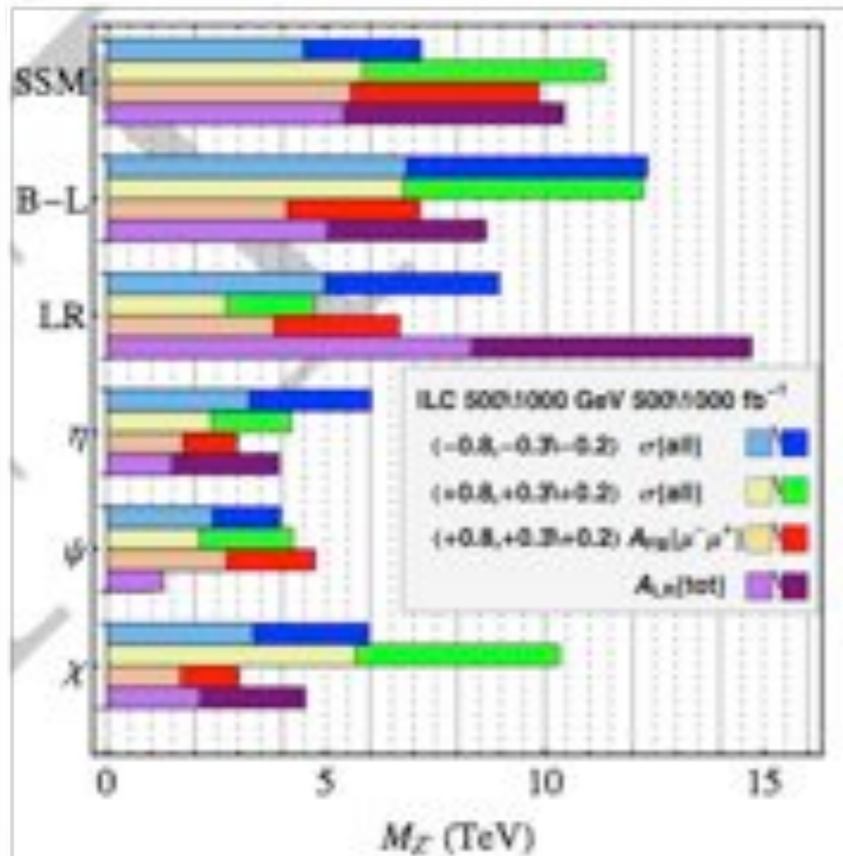
Z' sensitivity

5-6+ TeV Discovery range at 14 TeV LHC
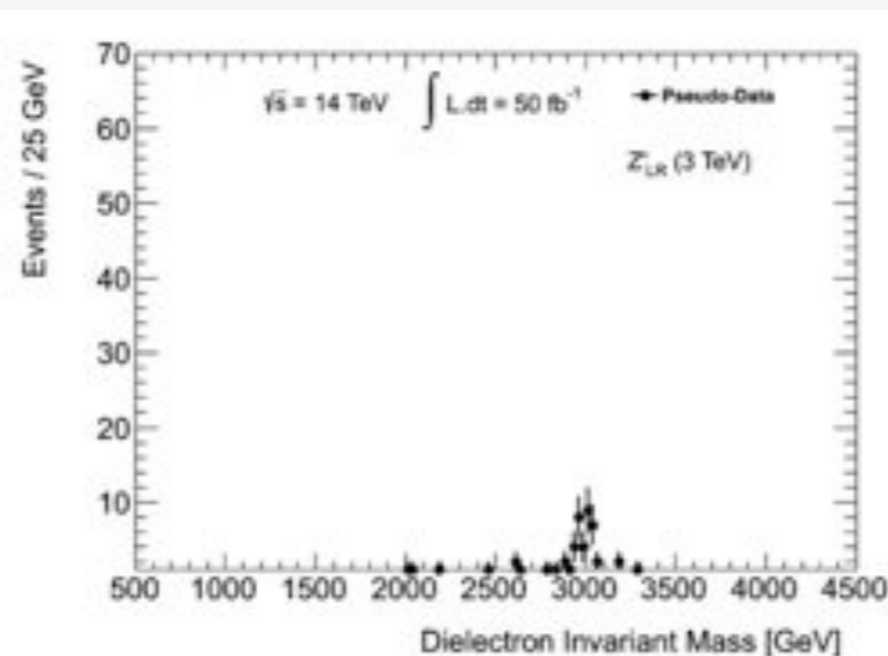

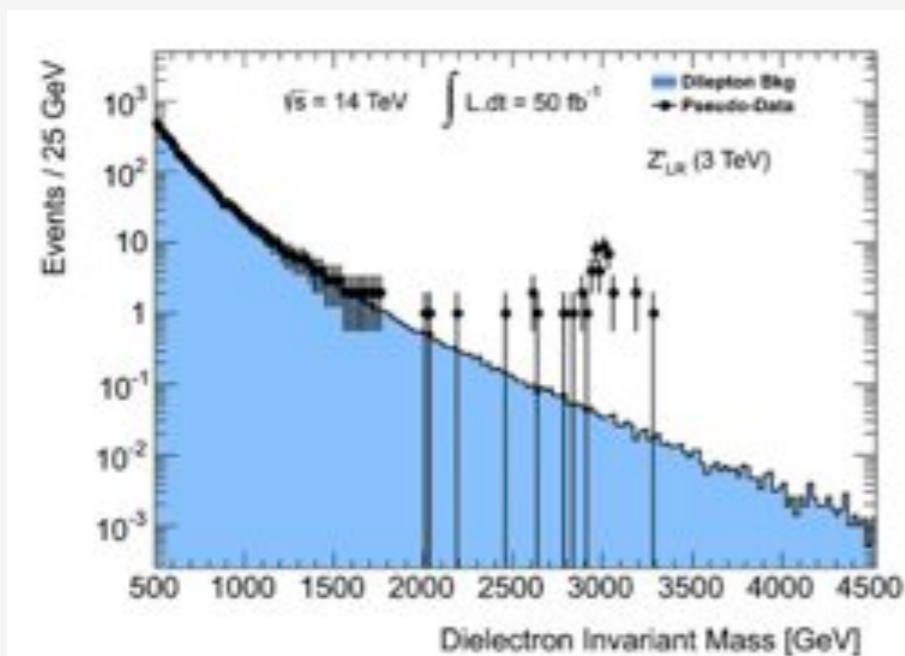12-15 TeV limit range at 33 TeV pp

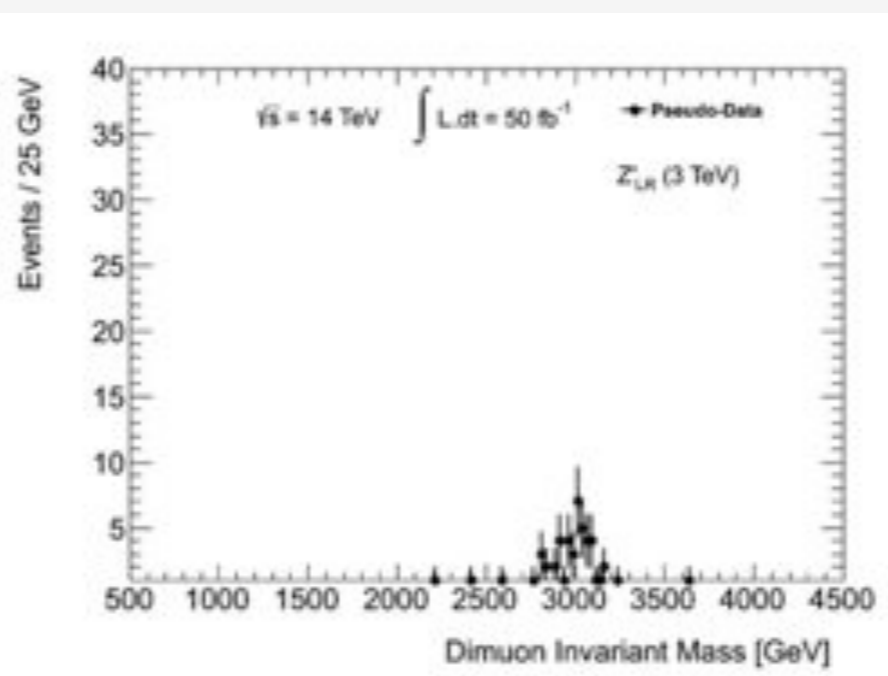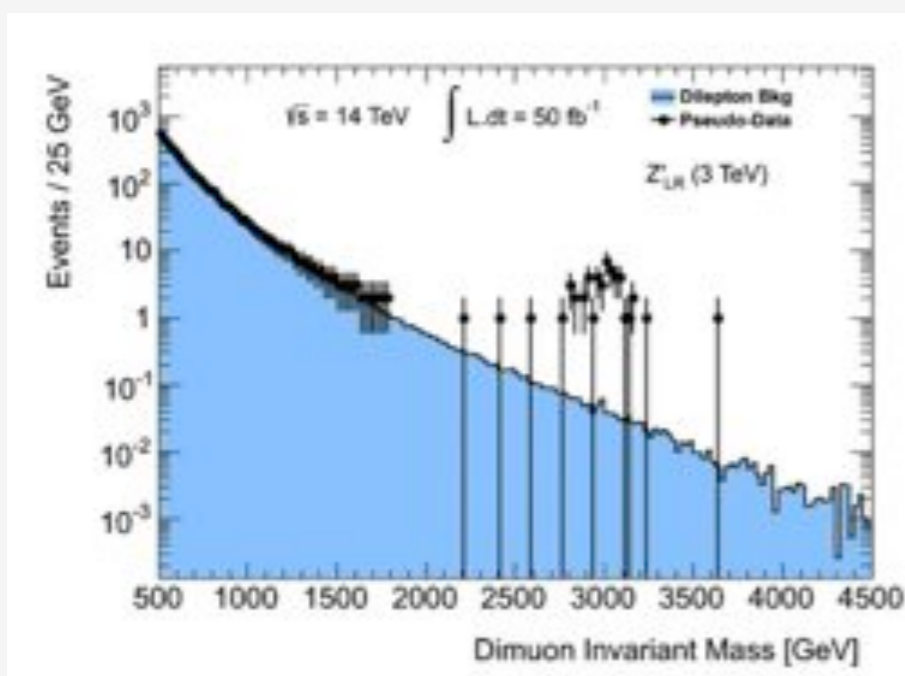ILC asymmetry interference, beyond LHC

Z', a Run 2 discovery target

Electrons and muons would nail it   100/fb

electrons

muons

Z', a Run 2 discovery target

Electrons and muons would nail it   100/fb
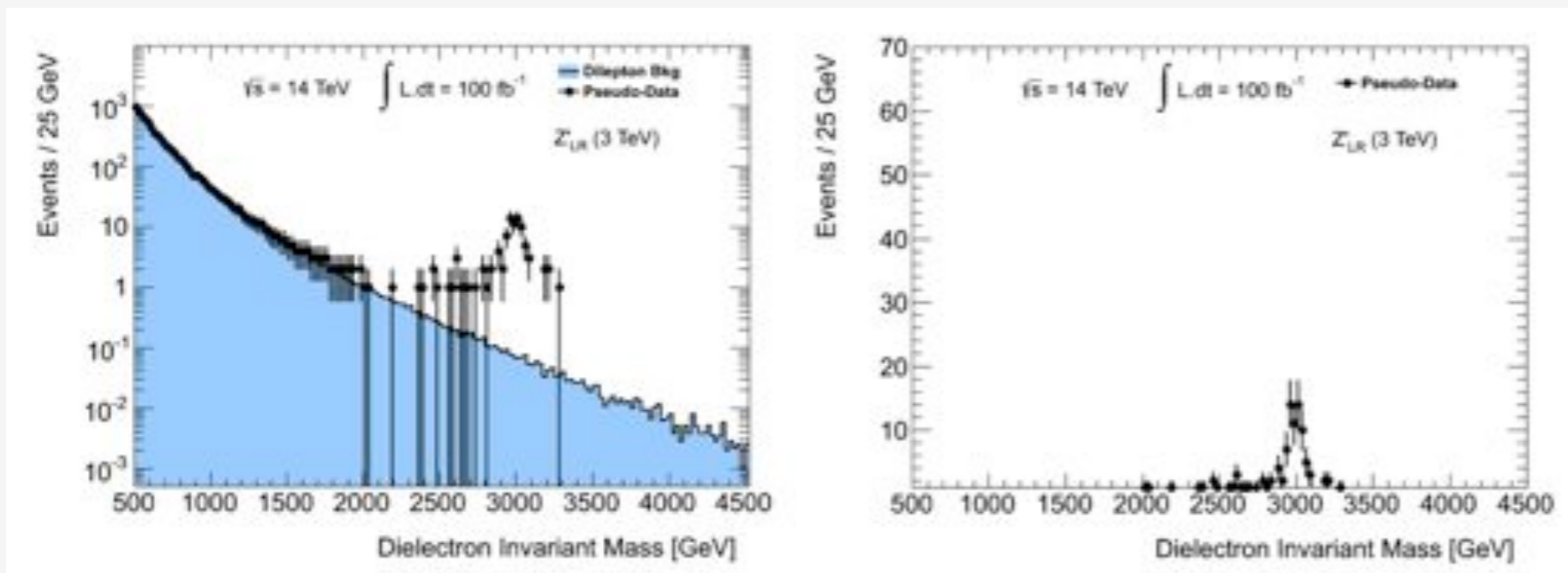
electrons
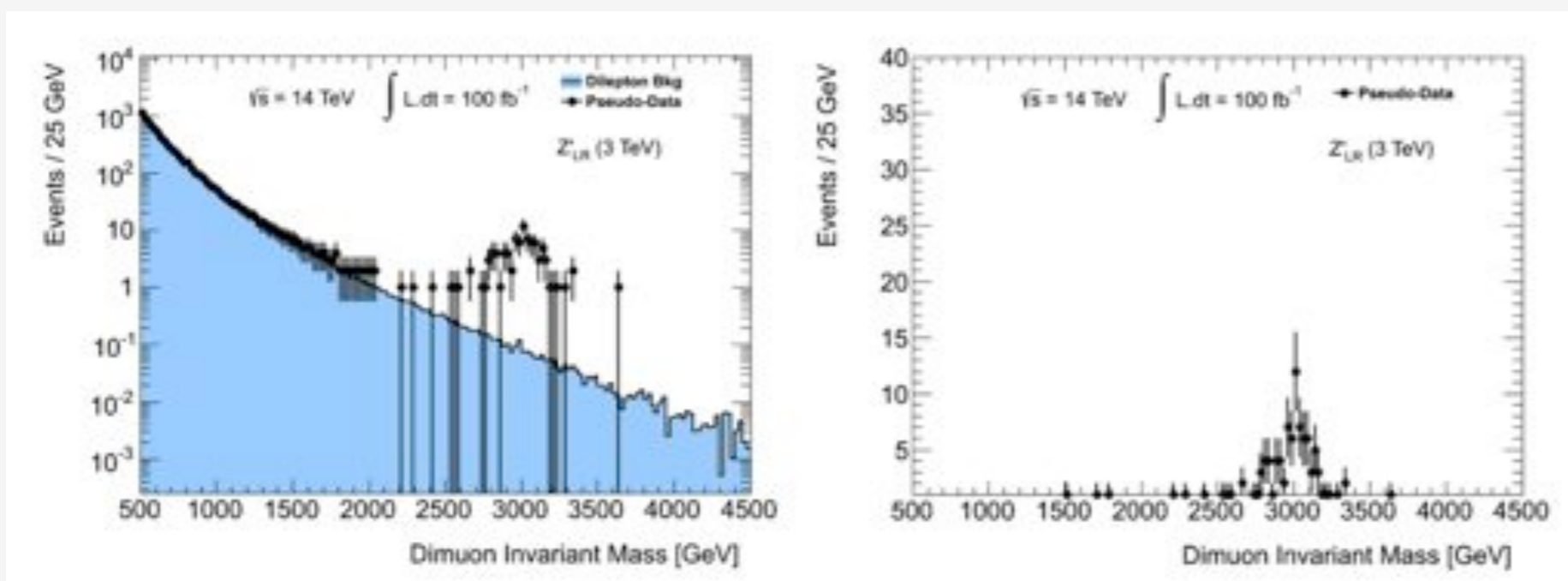
muons

Finding the identity of a Z'

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

LHC 14 TeV 300(3000) fb^{-1}, 3 TeV Z', $\Delta\chi^2 = 4$
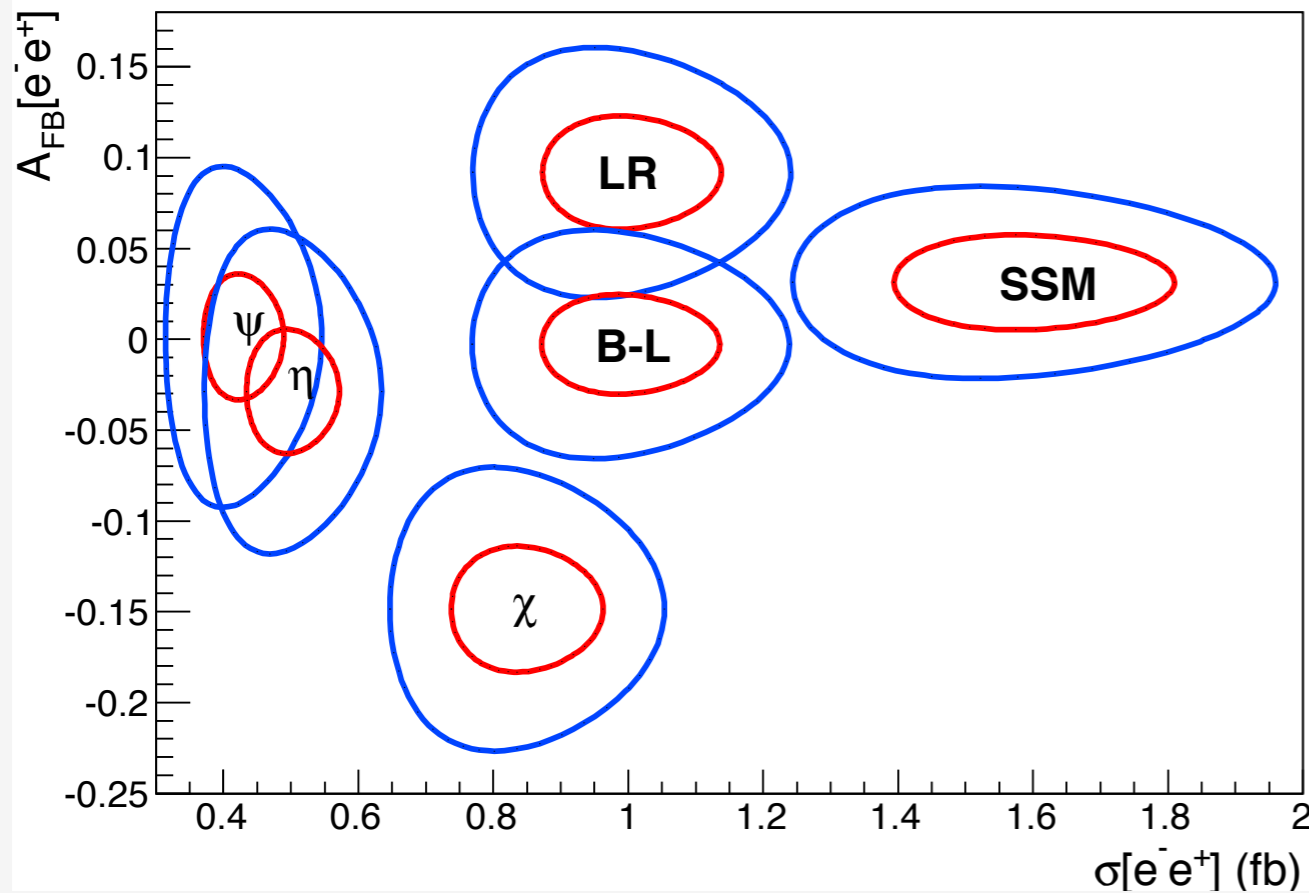
E6 from LR, etc LHC A$_{FB}$

ILC 500 GeV 500+500 fb^{-1} P(e$^-$,e$^+$)=(+.8,+.3)+(-.8,-.3), 3 TeV Z', $\Delta\chi^2$ = 1 (4
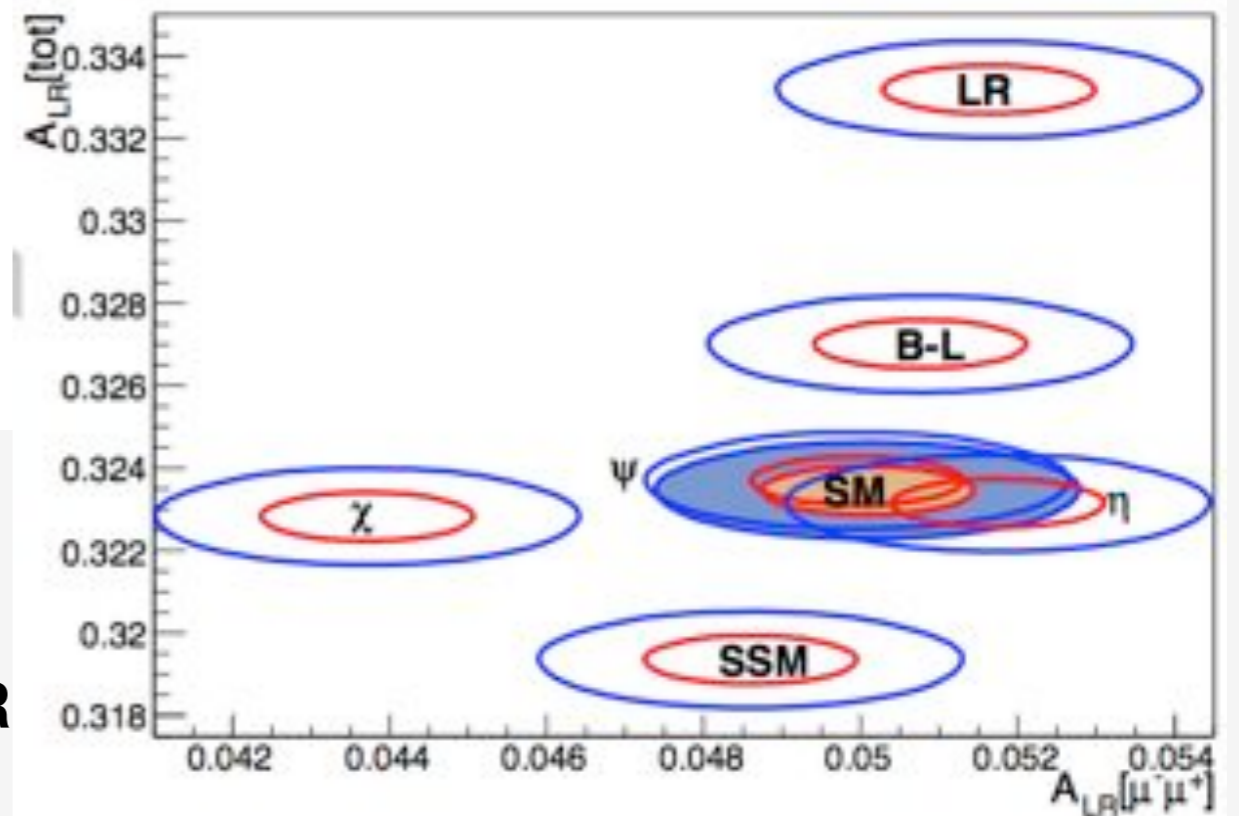
E6 from LR, etc ILC A$_{LR}$

Dark Matter Connection

nearly close the thermal relic range?
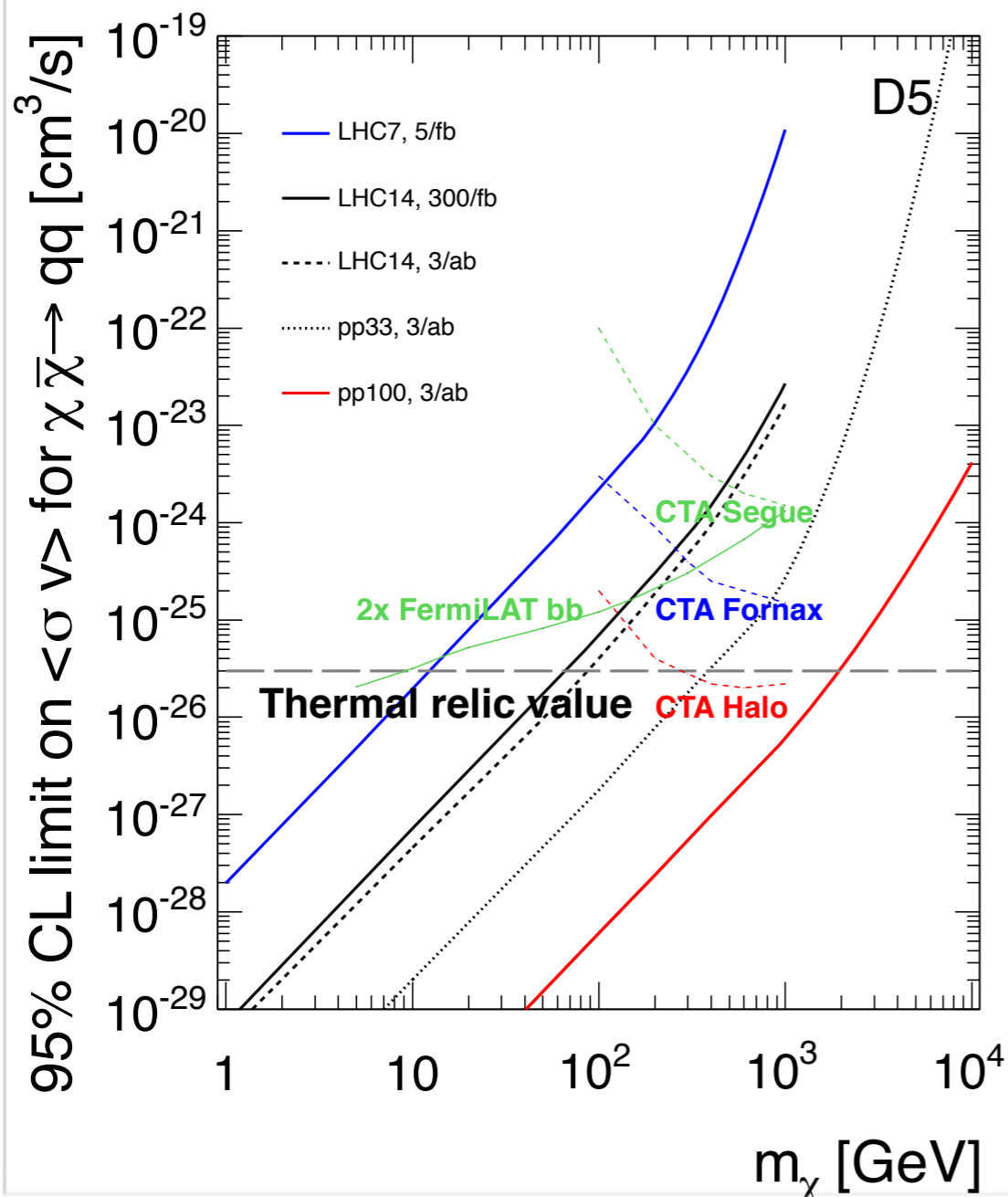
progressive increase in sensitivity

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

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

additionally

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

- SUSY neutralino
  decaying $\tilde{\chi}_1^0 \rightarrow W + \tau$

The TeV scale is in sight
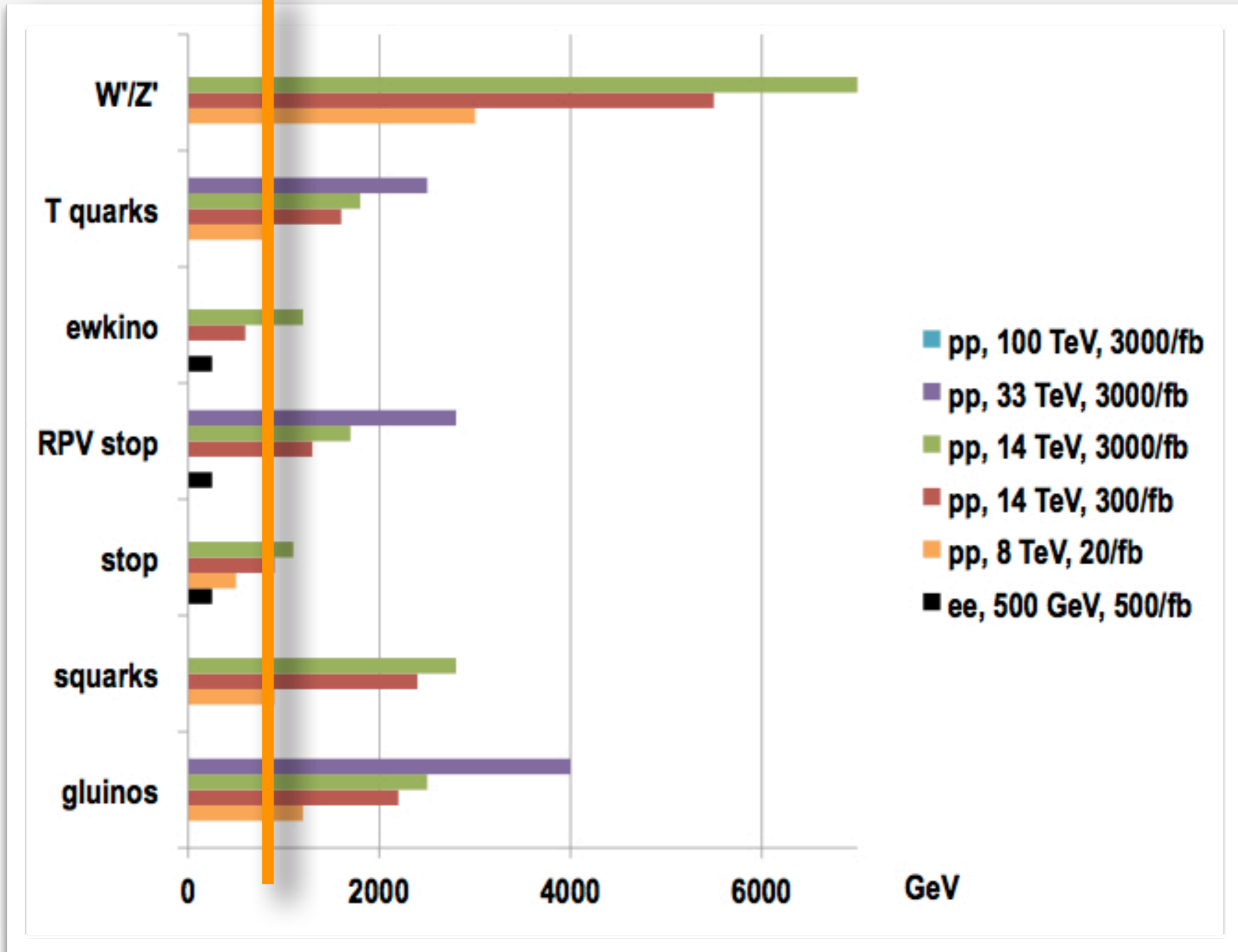
The NP Physics Message

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.
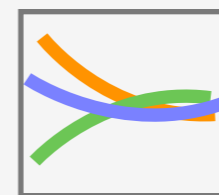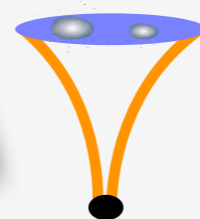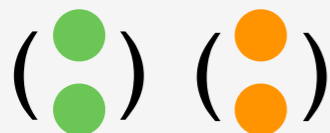
cases for future programs

■ the Snowmass lineup:

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

■ cases for machine B

are usually written as if machine A found nothing.

an obvious point

an obvious point

■ cases for machine B

are usually written as if machine A found nothing.

■ The most important cases for machine B?

to study the discoveries of machine A with more precision.

and to find additional particles or forces

LHC: 300 fb^{-1}

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.

the rest?

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

- are in the back of the slides

2 things and then conclusions

thing 1: the circles.
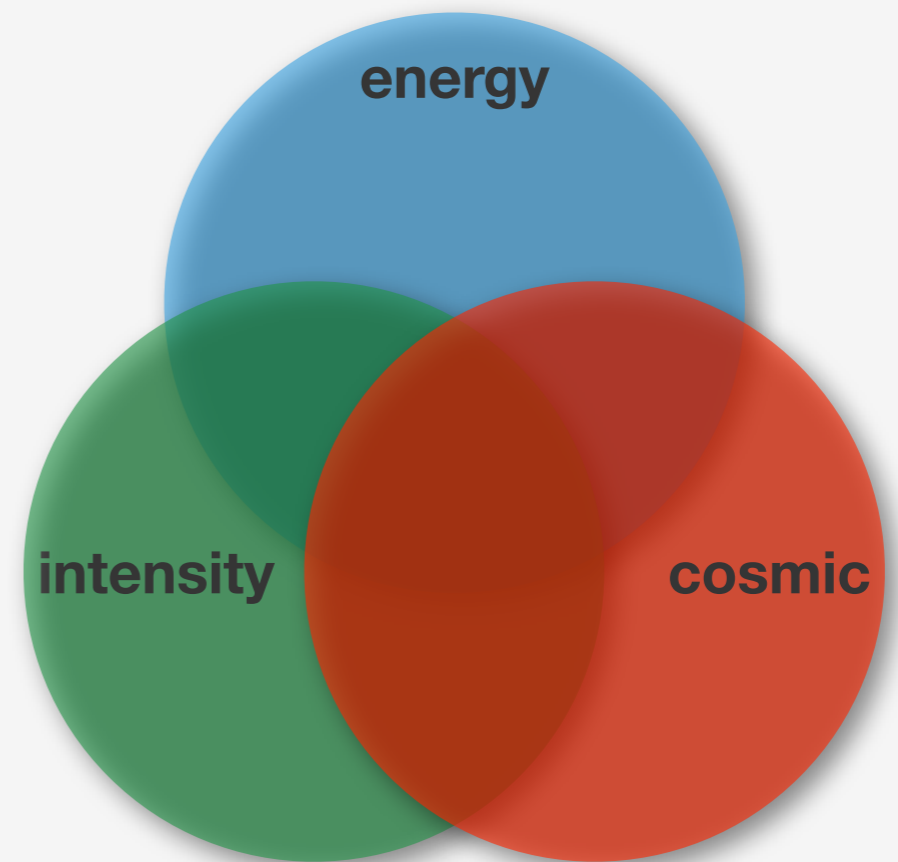
The new physics will bulge somewhere!
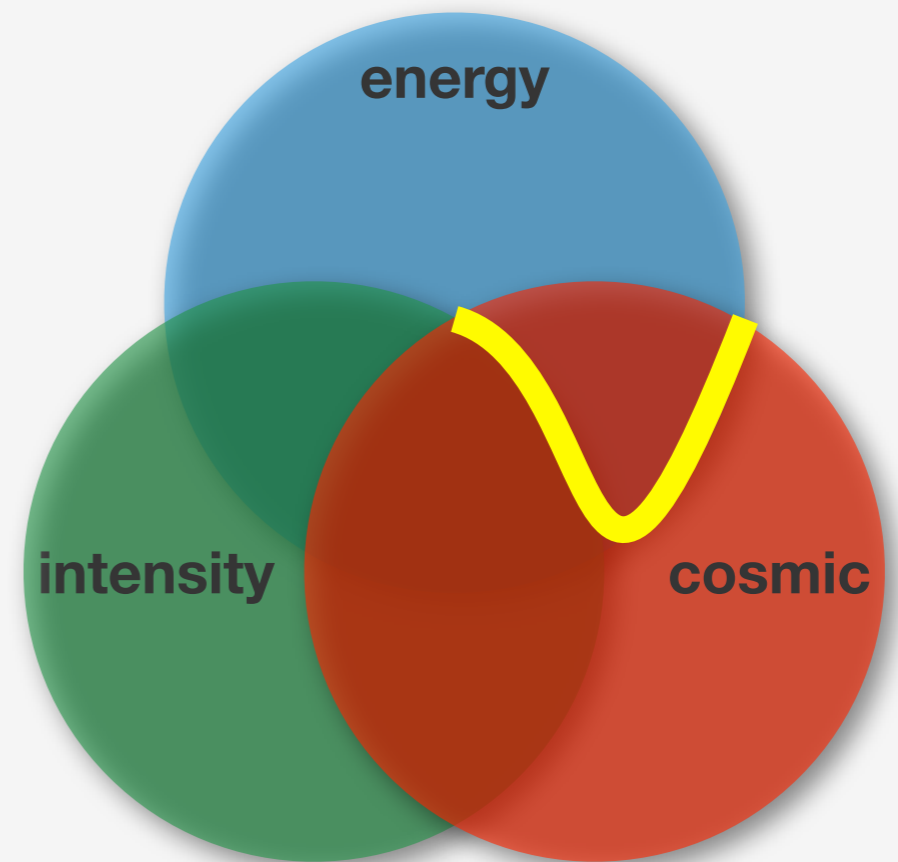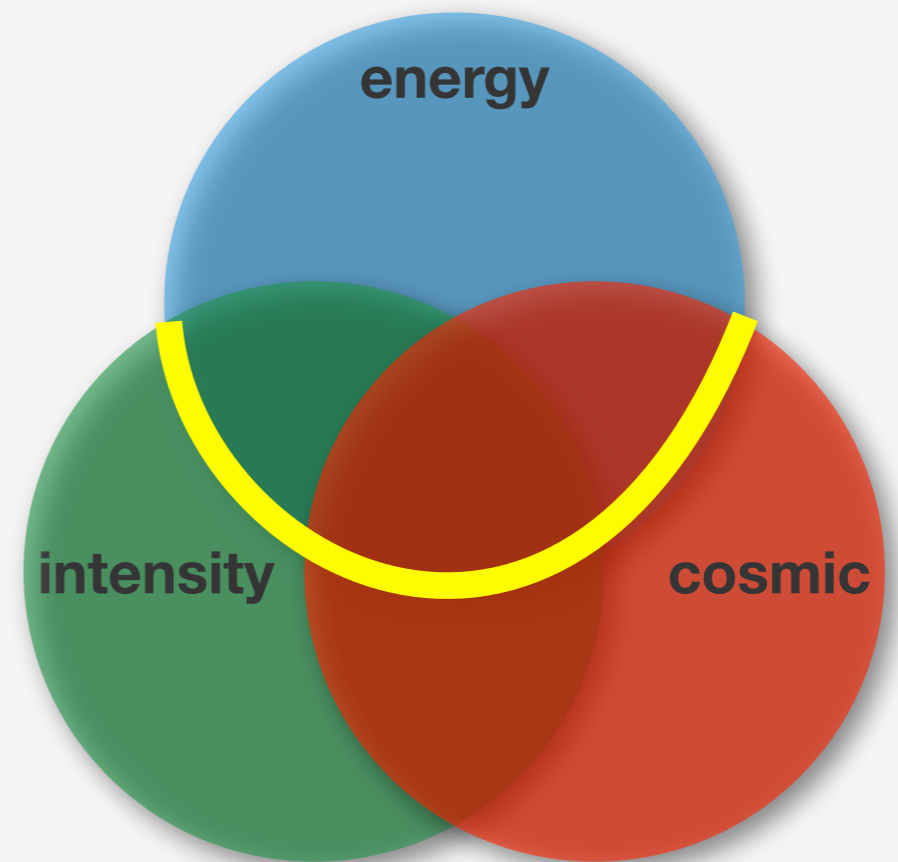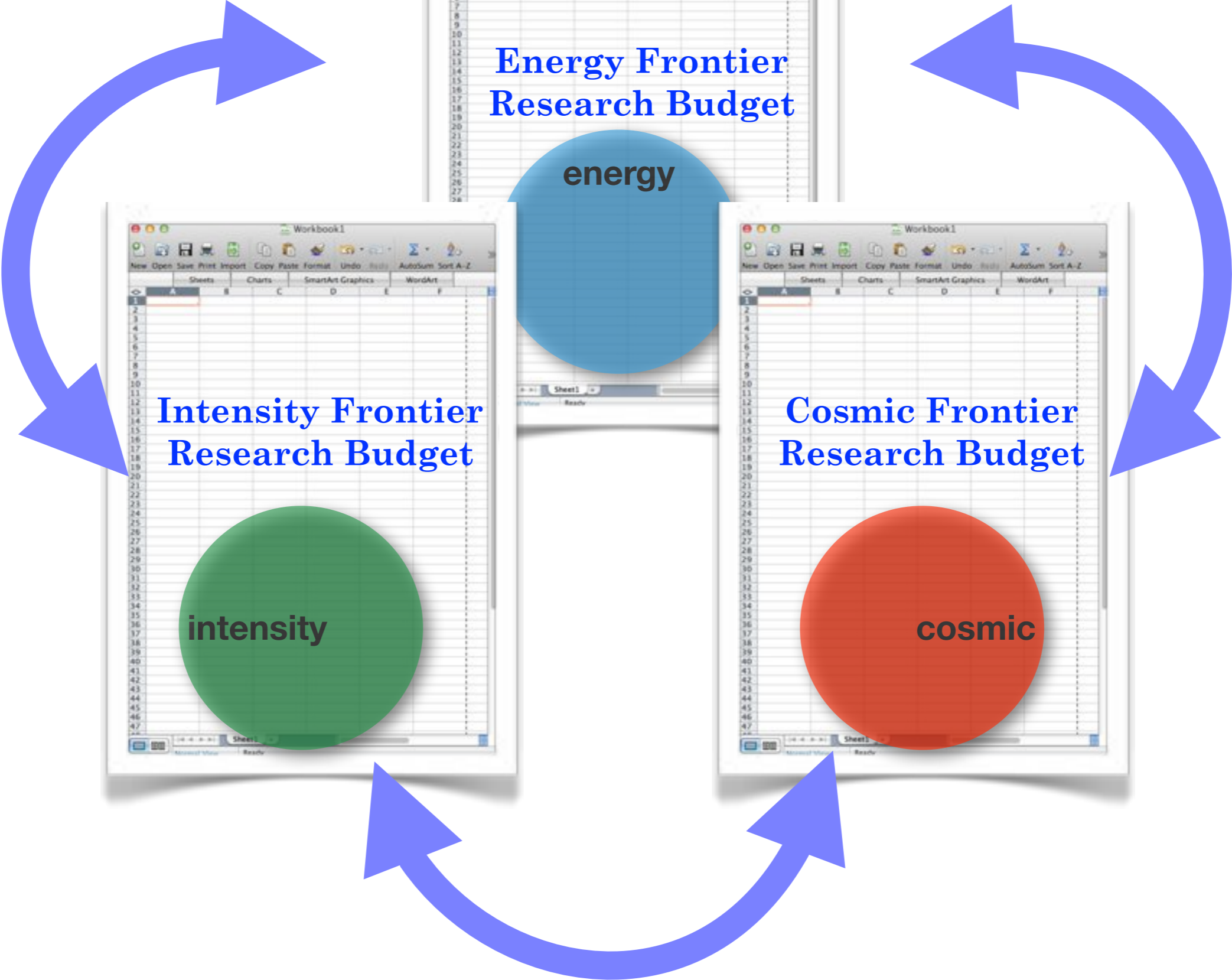
a unique "Frontier"

energy

intensity

cosmic

Energy Frontier Research Budget

energy

Intensity Frontier Research Budget

intensity

Cosmic Frontier Research Budget

cosmic

Energy Frontier
Research Budget

energy

Intensity Frontier
Research Budget

intensity

Cosmic Frontier
Research Budget

cosmic

Not good. Divisive
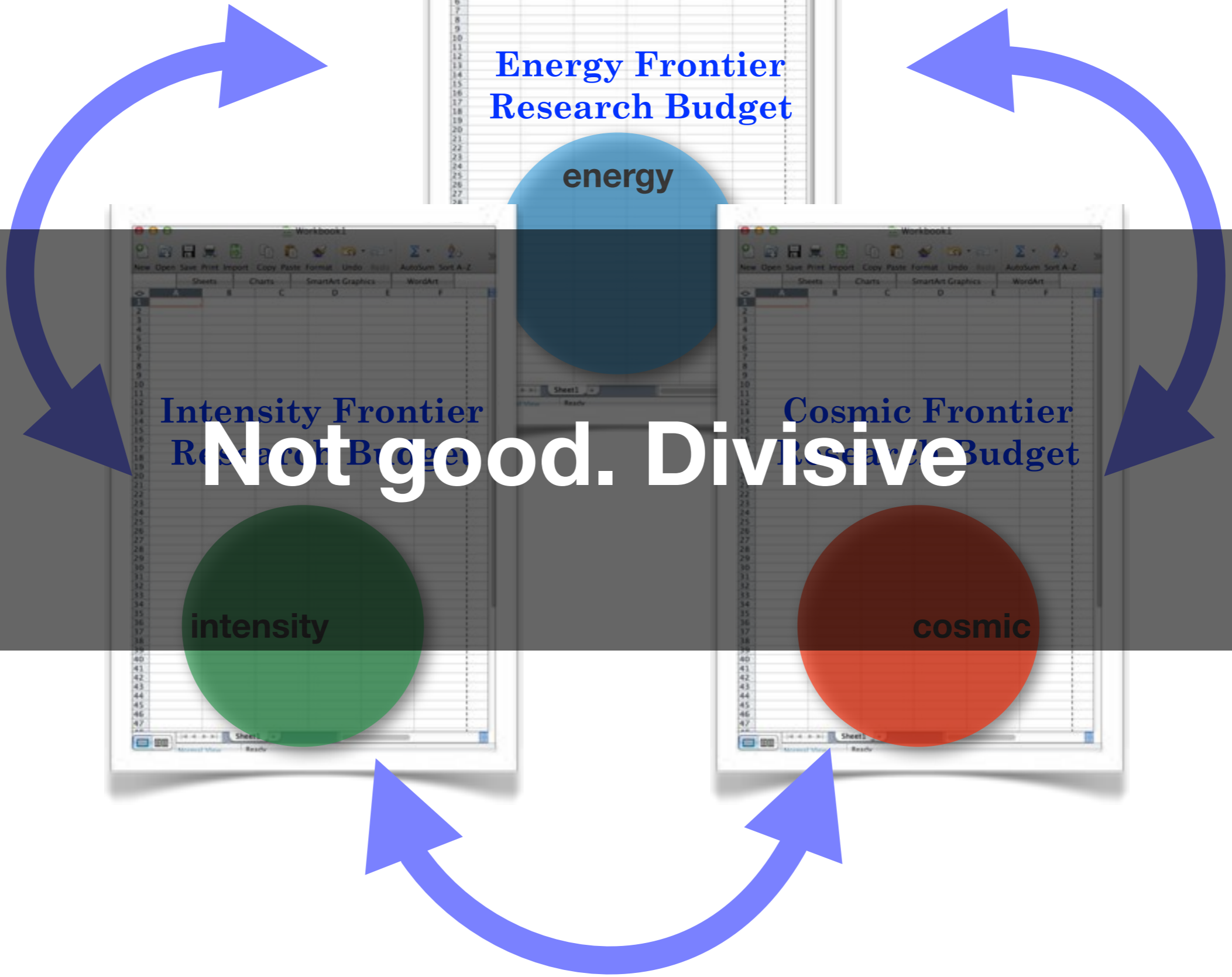
can we make ■ the "Frontier" metaphor work better for us?
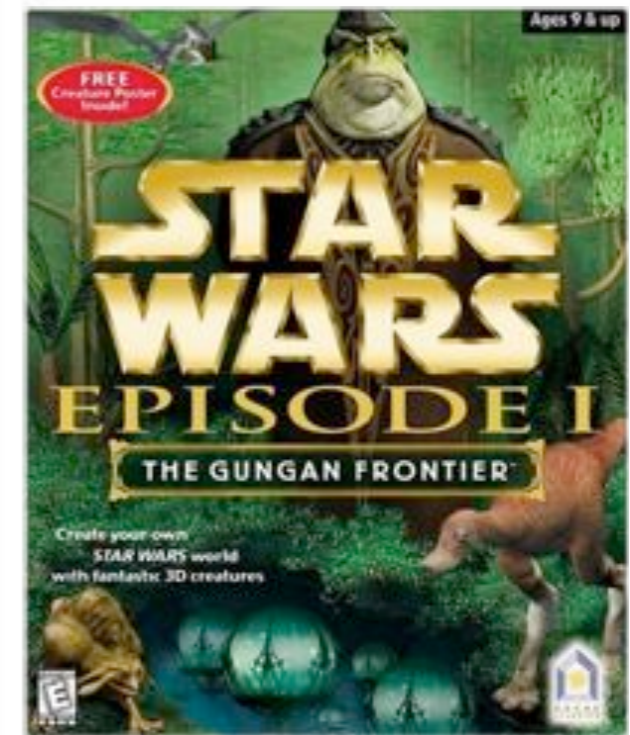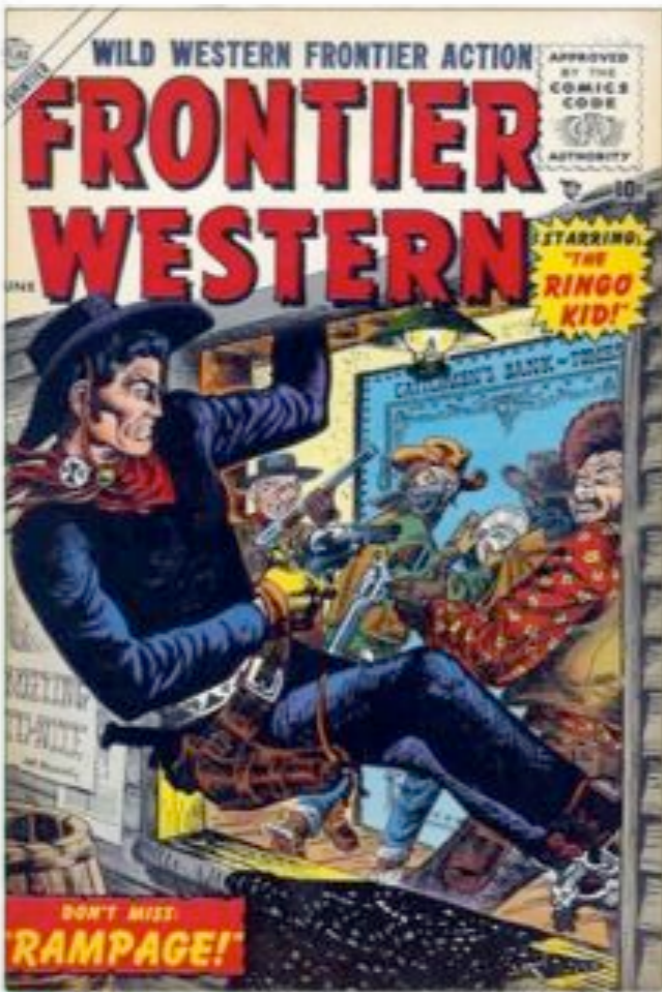
"Opening the Space Frontier, The Next Giant Step" by Robert McCall

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

thing 2: 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 N_R and expand the Higgs sector*

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

■ *then we have to find it*

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

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

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

Andre de Gouvea keeps making this point

Energy Frontier:
precision, mass reach, and surprise

- LHC: exquisite instruments

  proven capability

  precision and surprise

- Will point to the EF future at

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

Jack be nimble,
Jack be
quick,
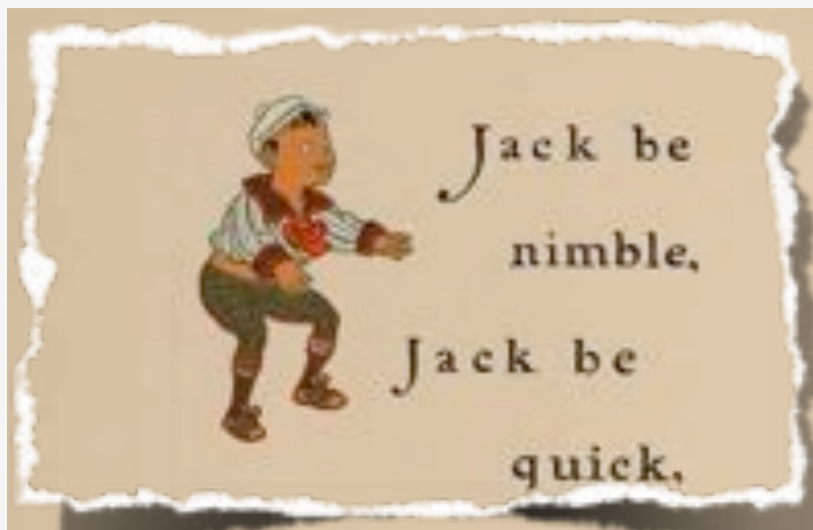
we'll do that by incrementally:

- 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"

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. [1]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%

LHC: 300 fb^{-1}

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.**

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4. First measurements of VV scattering.

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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}

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}

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

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

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,

2. **Higgs self-coupling, 10%**

or

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

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

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.**

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.)

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.

pp Collider: 33/100 TeV

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

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.