

Future Machines

Hitoshi Murayama (Berkeley & Kavli IPMU)

July 27, 2013

Stephane Lavignac

More precisely, we would appreciate very much if you could give the talk on the physics potential of future machines from a theorist's perspective (including but not necessarily restricted to their potential in sheding light on the Higgs sector: a broader perspective would be interesting). There will also be an experimental talk on ILC and other machine prospects just before this theoretical talk.

July 4, 2012

In summary

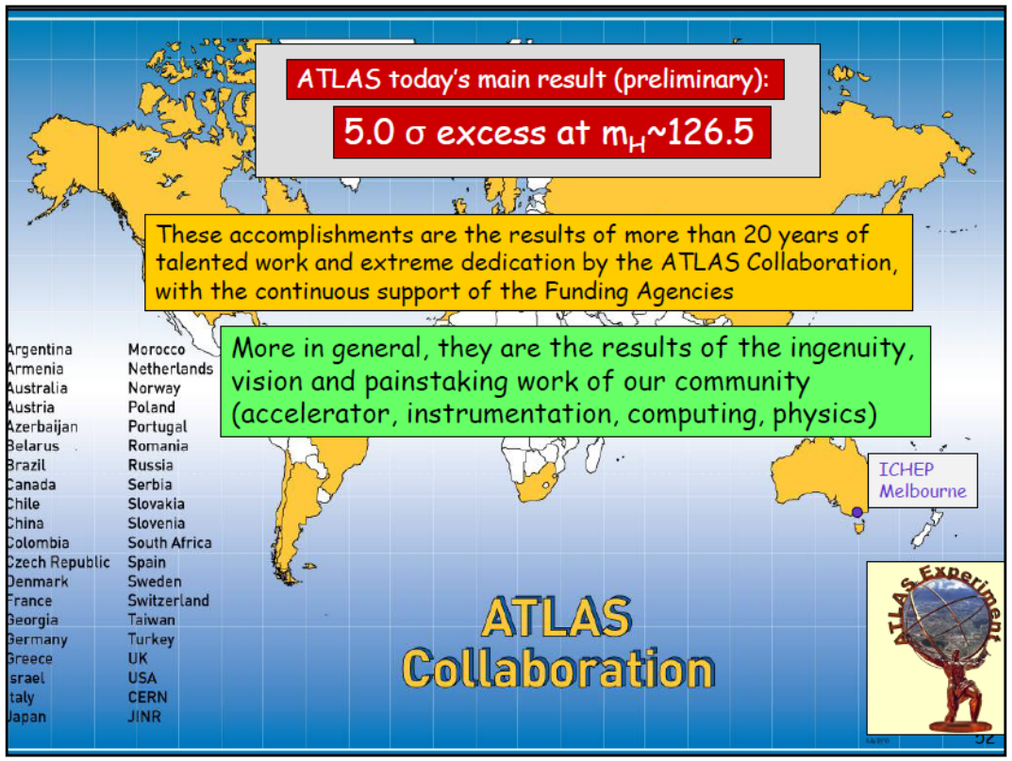
We have observed a new boson with a mass of

125.3 ± 0.6 GeV

at

4.9 σ significance !

J. Incandela UCSB/CERN
May 18, 2012 Boulder Colorado





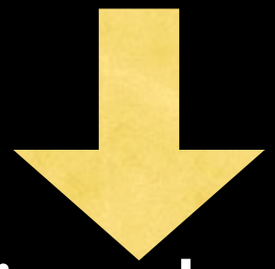


Higgsdependence Day
July 4, 2012



CERN official statements

Higgs-like boson

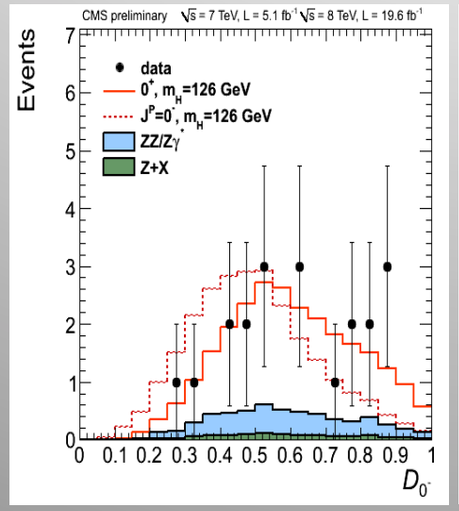


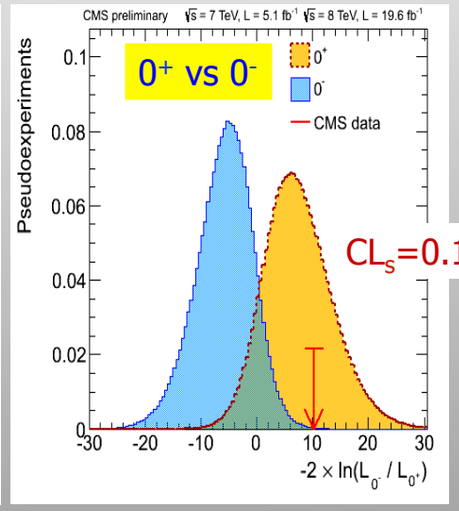
a Higgs boson

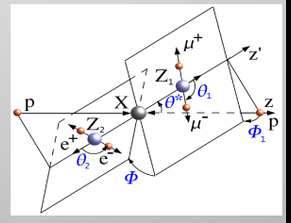
Spin/Parity Hypothesis Tests

Spin/parity hypothesis tests: H → ZZ → 4l channel

Kinematic discriminant built to describe the kinematics of production and decay of different J^P state of a "Higgs"

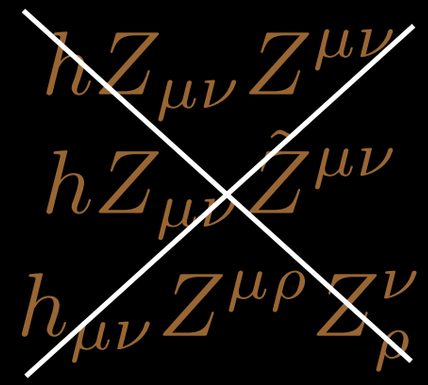






J^P	CL_s
0^-	0.16%
0^+_h	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

More J^P hypotheses have been tested in a similar way →



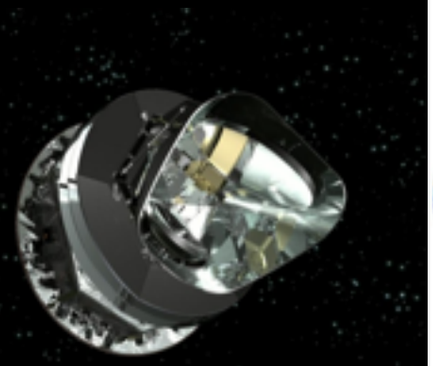
have seen $hZ_\mu Z^\mu$

but a gauge boson $\phi^\dagger\phi Z_\mu Z^\mu$

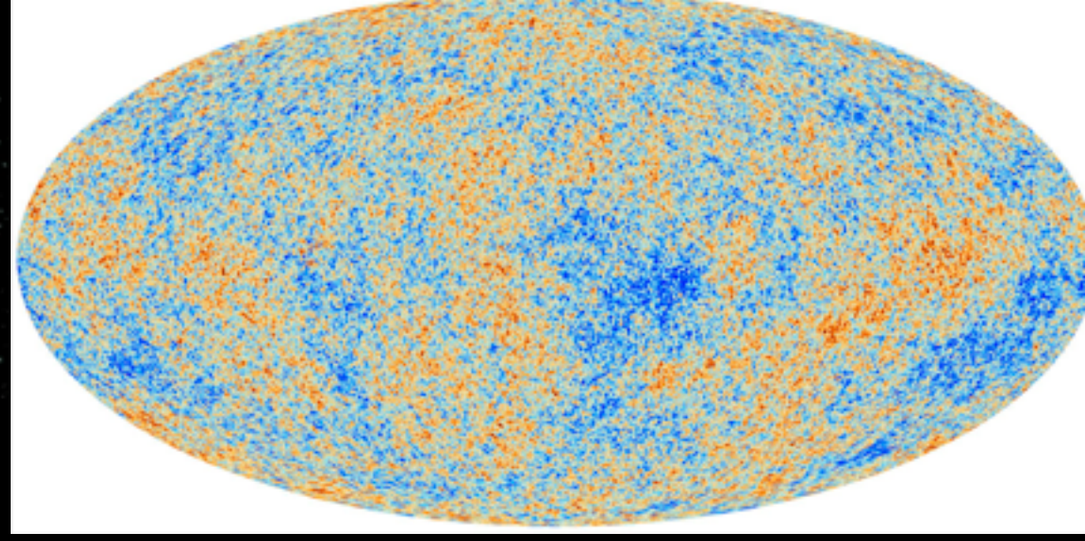
only way $h\langle h\rangle Z_\mu Z^\mu$

we have discovered a particle that has a value in vacuum

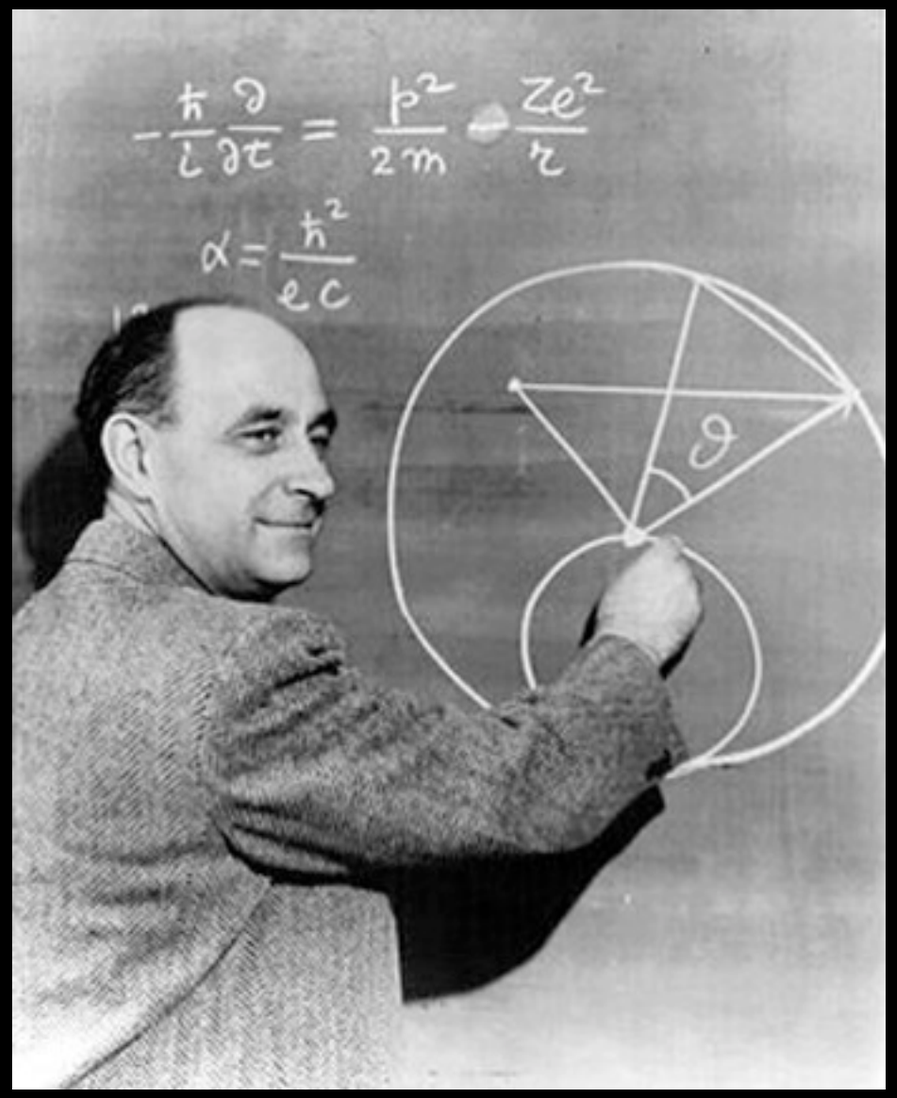
Minimal



Planck



- It looks very much like *the* Standard Model Higgs boson
- We've known the energy scale to probe since 1933
- now a UV complete theory of strong, weak, EM forces possibly valid up to even M_{Pl}
- cosmology also looks minimal single-field inflation (Planck)
- *the year of elementary scalars!!!*

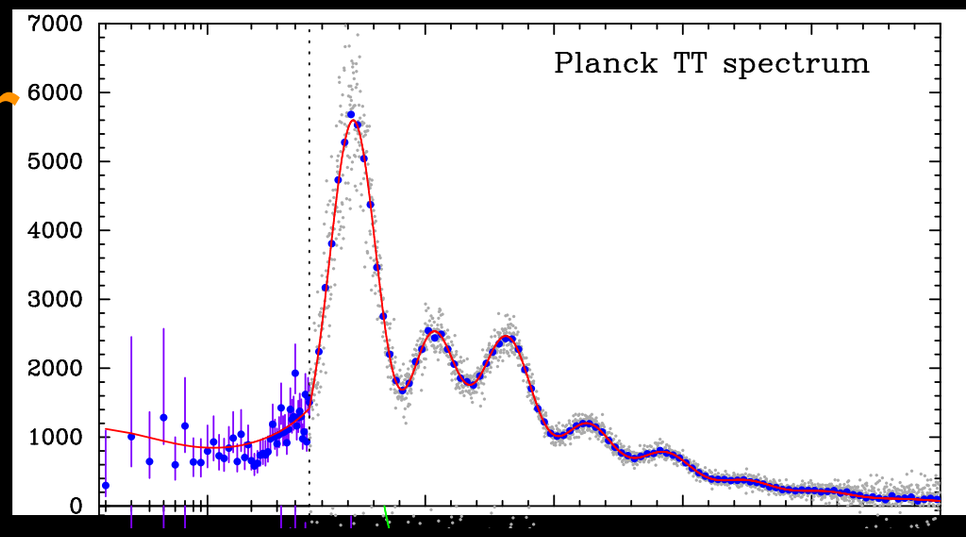


Where do we go next?

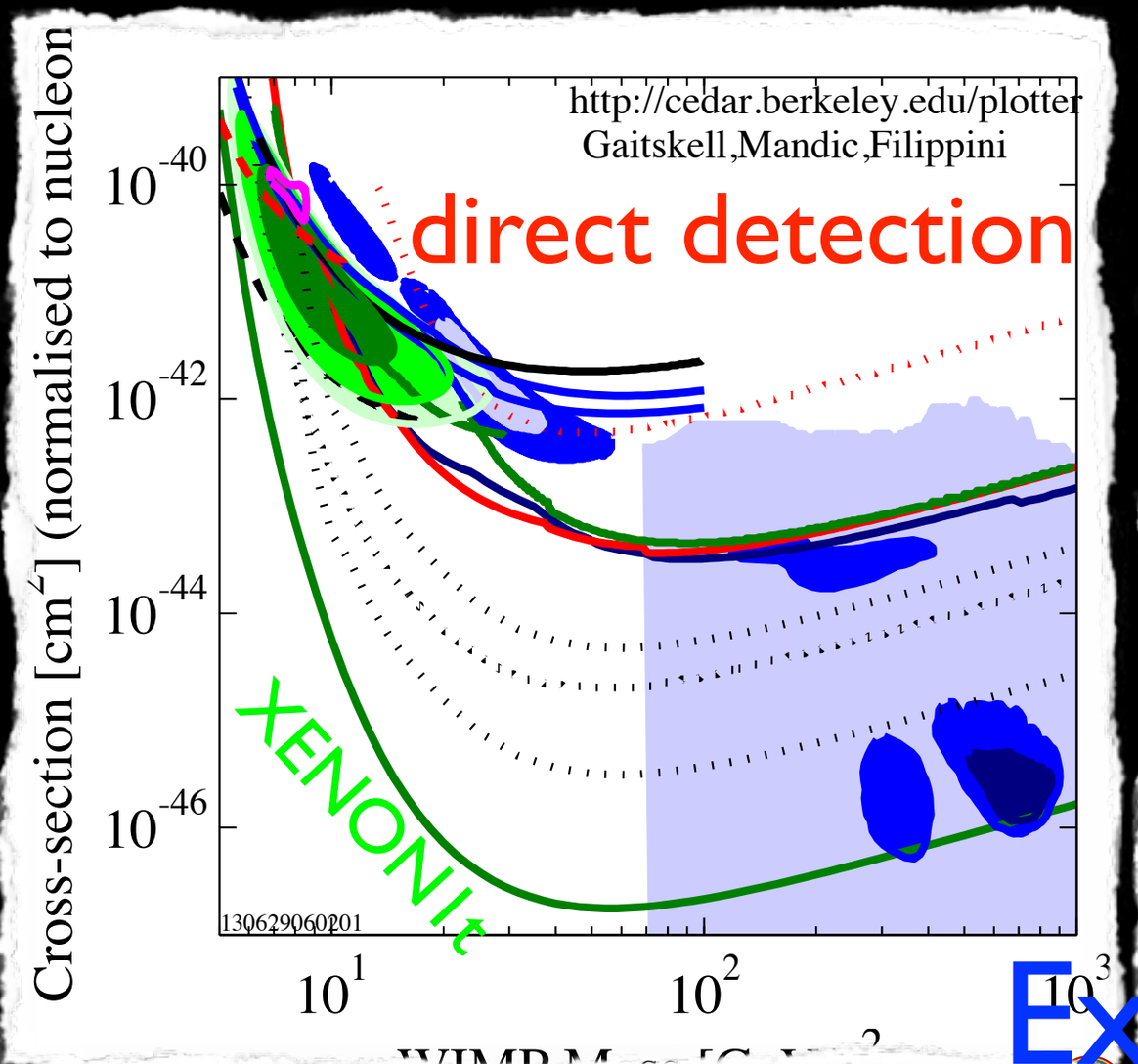
Is particle physics over?

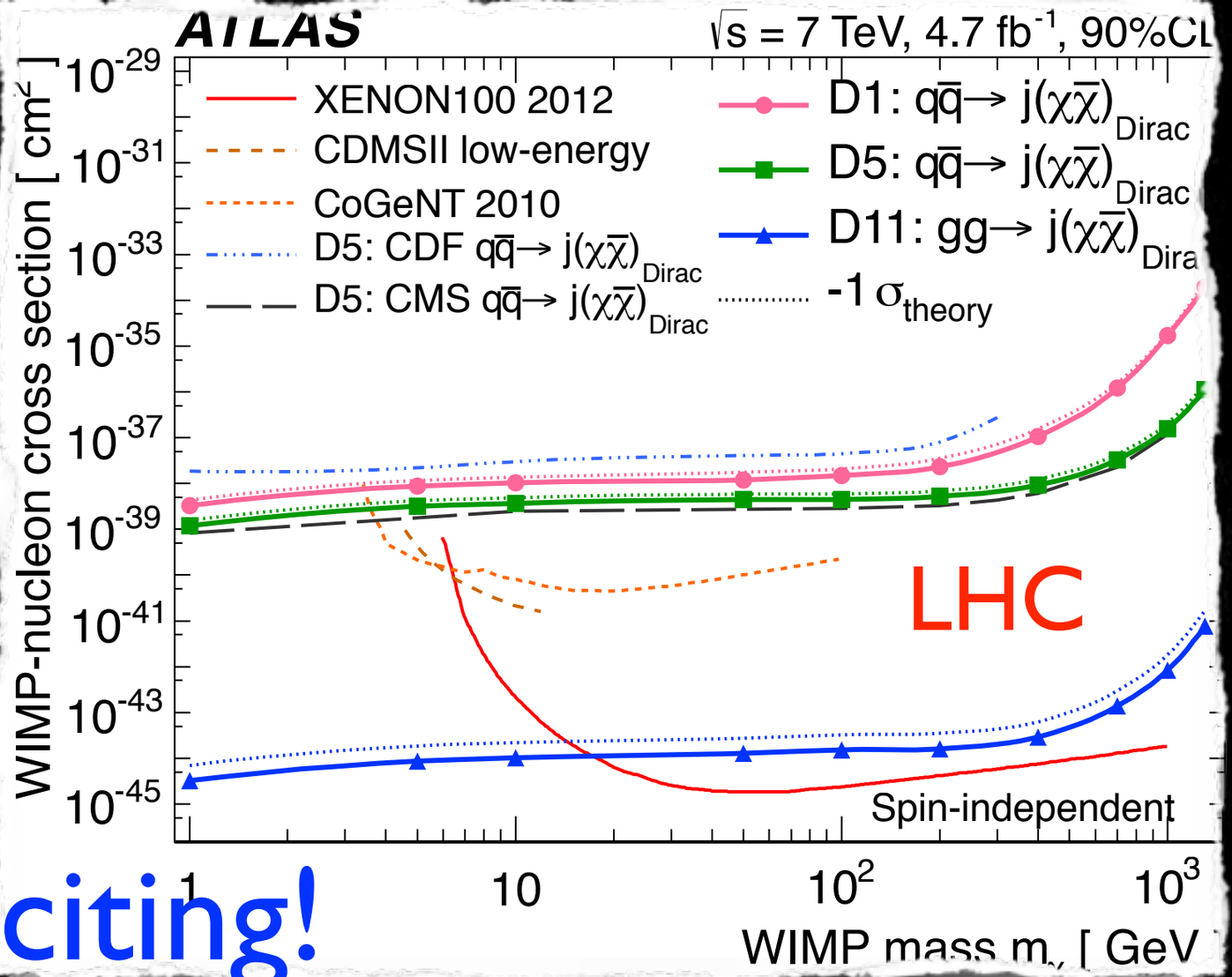
Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

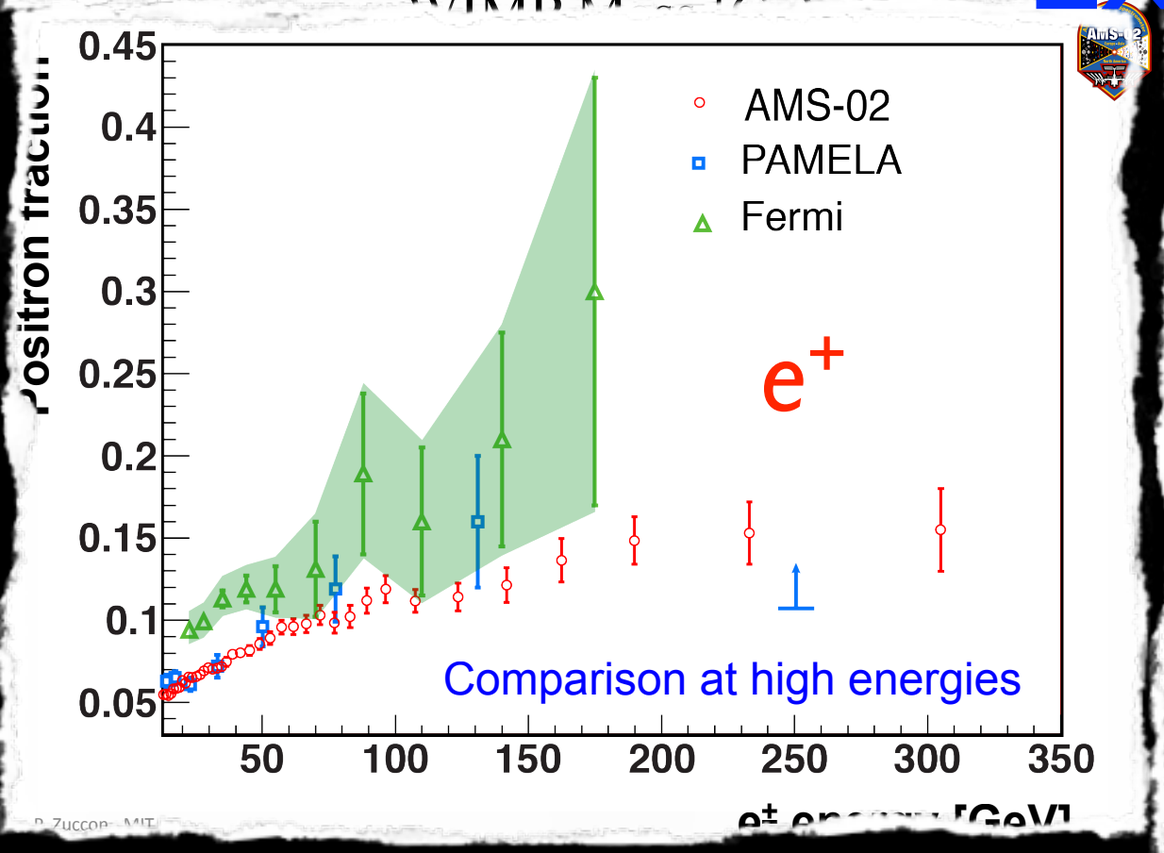


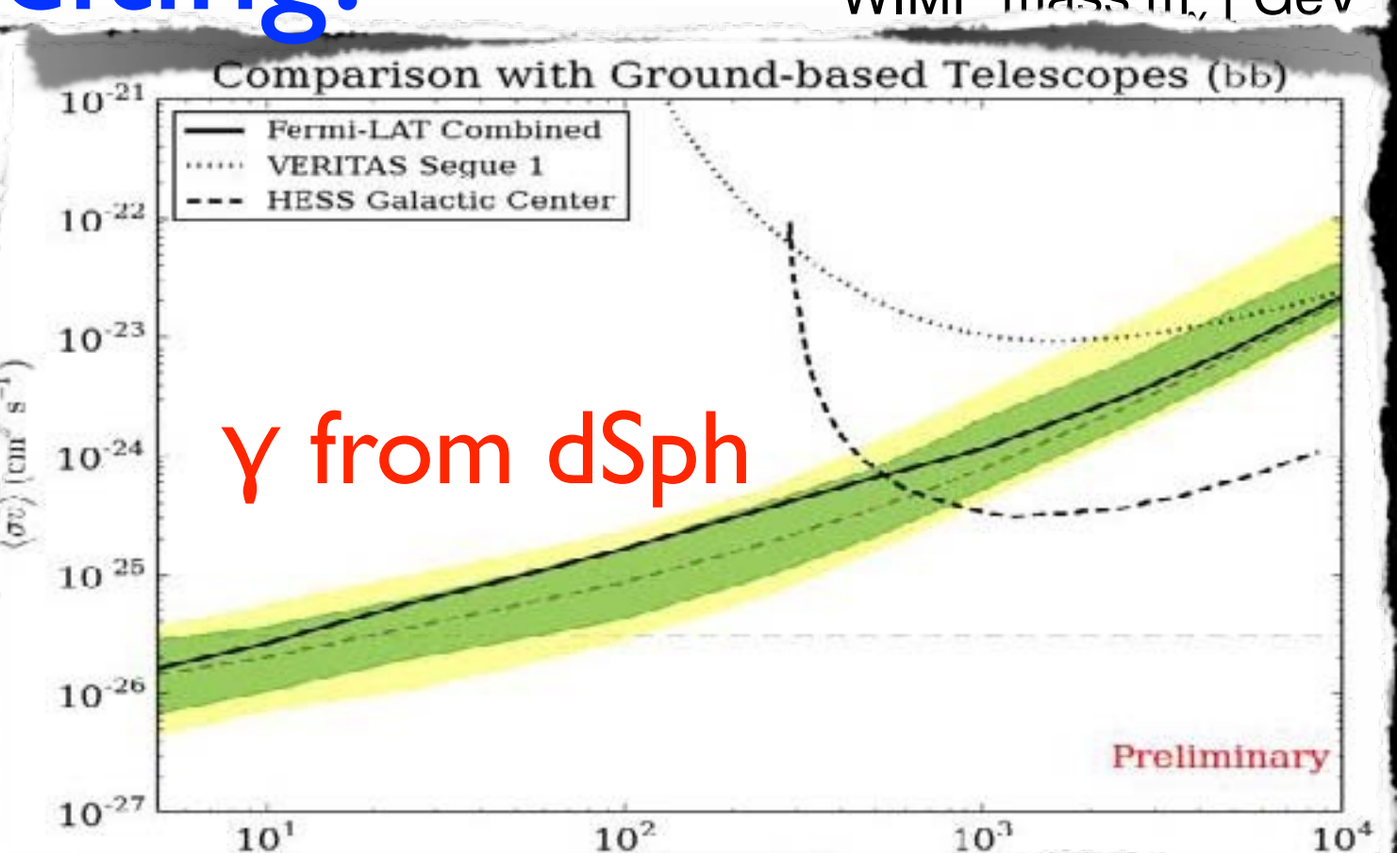
We don't really know their energy scales...


http://cedar.berkeley.edu/plotter
Gaitskell,Mandic,Filippini
direct detection
XENON1t
130629060201
Cross-section [cm²] (normalised to nucleon
10^-40
10^-42
10^-44
10^-46
10^1
10^2
10^3


ATLAS
√s = 7 TeV, 4.7 fb⁻¹, 90%CL
XENON100 2012
CDMSII low-energy
CoGeNT 2010
D5: CDF qq̄→ j(χχ̄)Dirac
D5: CMS qq̄→ j(χχ̄)Dirac
D1: qq̄→ j(χχ̄)Dirac
D5: qq̄→ j(χχ̄)Dirac
D11: gg→ j(χχ̄)Dira
-1 σtheory
WIMP-nucleon cross section [cm²]
10^-29
10^-31
10^-33
10^-35
10^-37
10^-39
10^-41
10^-43
10^-45
LHC
Spin-independent
1
10
10^2
10^3
WIMP mass m_χ [GeV

Exciting!

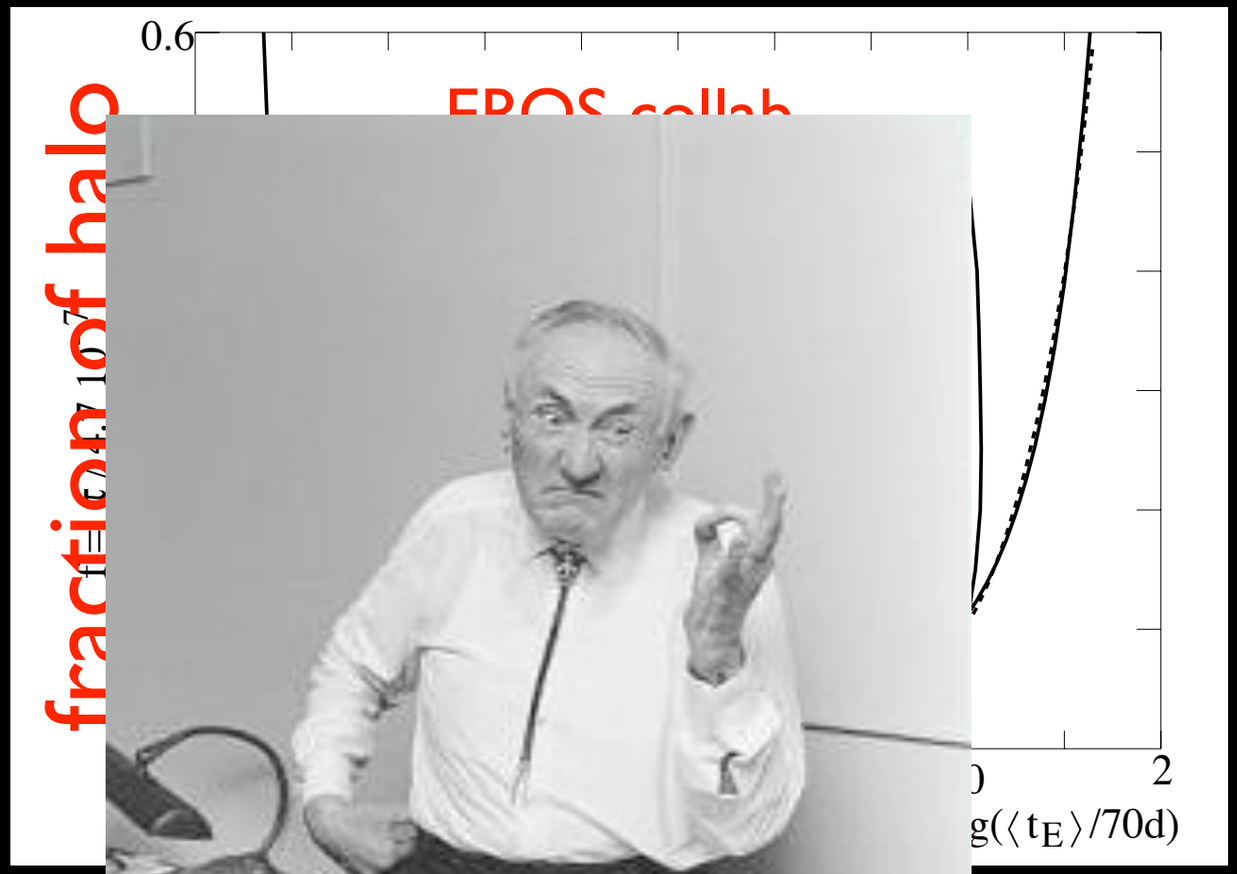

AMS-02
PAMELA
Fermi
e+
Comparison at high energies
Positron fraction
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
50
100
150
200
250
300
350
e± energy [GeV]


Comparison with Ground-based Telescopes (bb)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
γ from dSph
Preliminary
⟨σv⟩ [cm³ s⁻¹]
10^-21
10^-22
10^-23
10^-24
10^-25
10^-26
10^-27
10^1
10^2
10^3
10^4

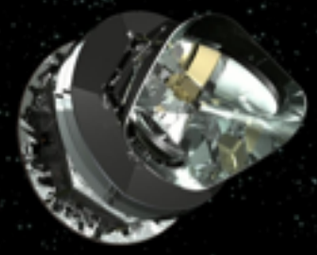
mass of dark matter

- upper limit comes from search for using gravitational microlensing
- lower limit comes from *uncertainty principle*
- 10^{-31} GeV to 10^{50} GeV
- we narrowed it down to within 81 orders of magnitude
- a big progress in 80 years since Zwicky

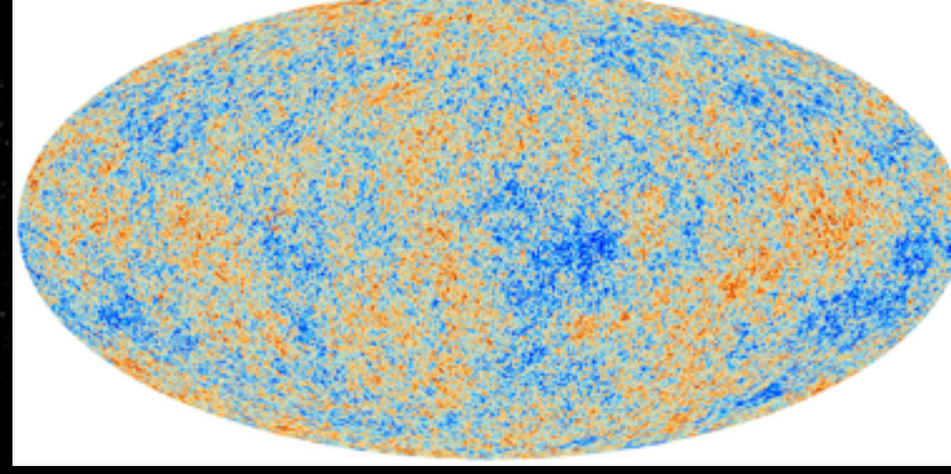
need to keep our mind open



Baryon Asymmetry



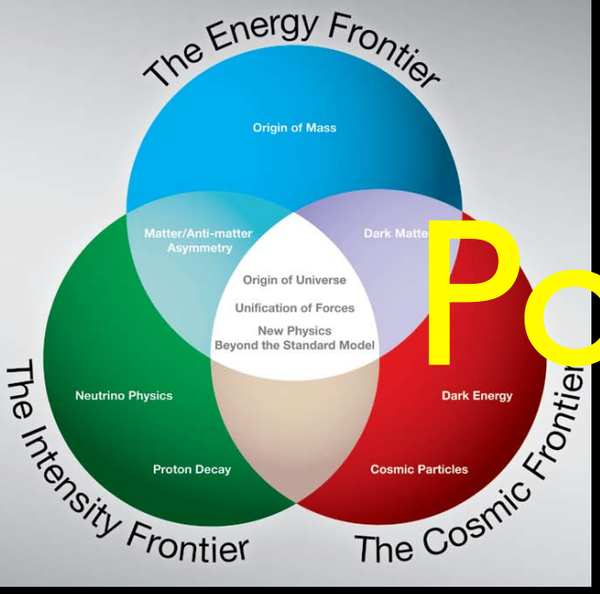
Planck



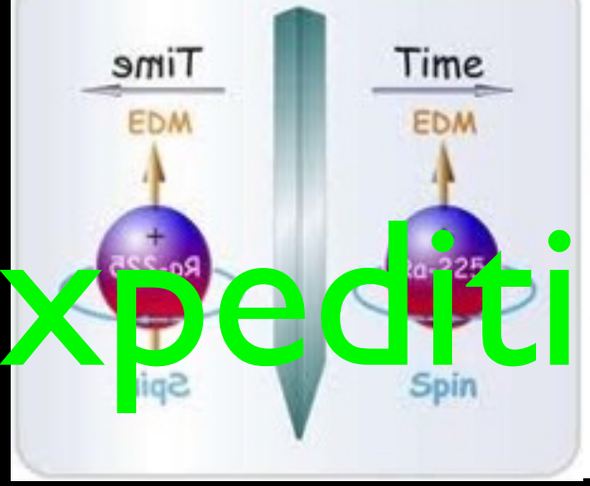
- with success of inflation, it can't be the initial condition of the Universe
- Kobayashi and Maskawa phase can only explain $\eta_b \approx \alpha_W^5 J \approx 10^{-27}$
- new sources of CPV are needed
- we also need to see how anti-matter can turn into matter

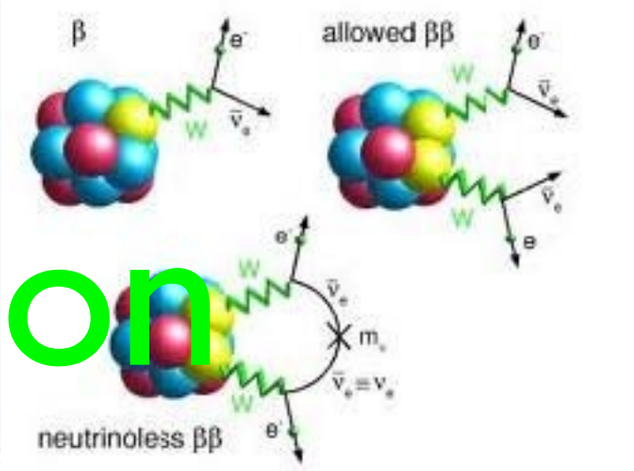


quark sector: LHCb, SuperKEKB, rare kaon decays
lepton sector: CPV in neutrinos, 0νββ, LFV
both sectors: proton decay



Power of Expedition





proton deay

neutrino

lepton flavor

quark flavor

EDM

dark matter

LHC

Unified Theories

10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18}

experimental reach [GeV]

(with significant simplifying assumptions)

baryon asymmetry

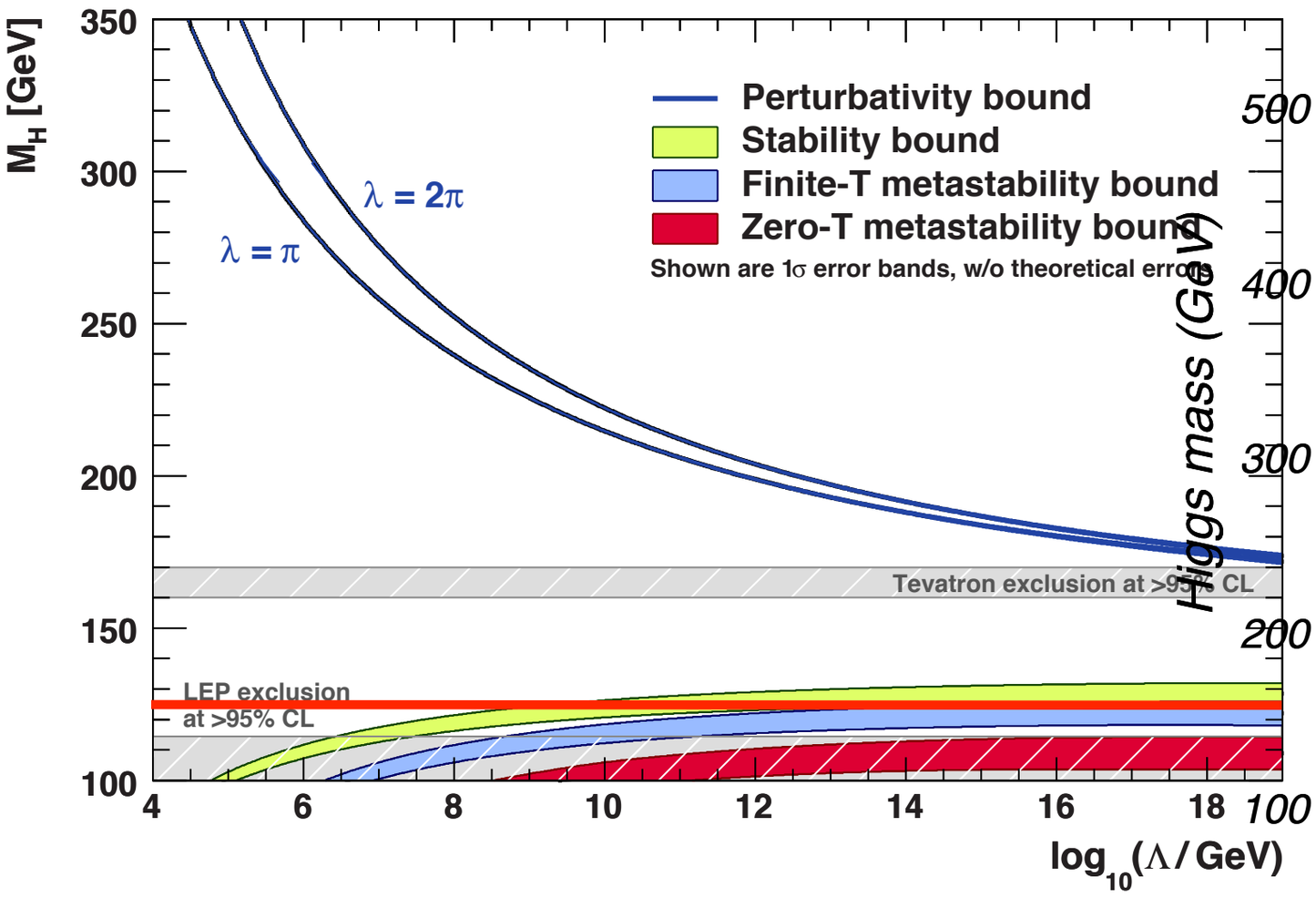
devil's advocate

- All evidences for physics BSM have come from non-accelerator experiments
- we don't know the next important energy scale in nature
- colliders probe only a very limited range of energy scale
- they are very expensive, too!

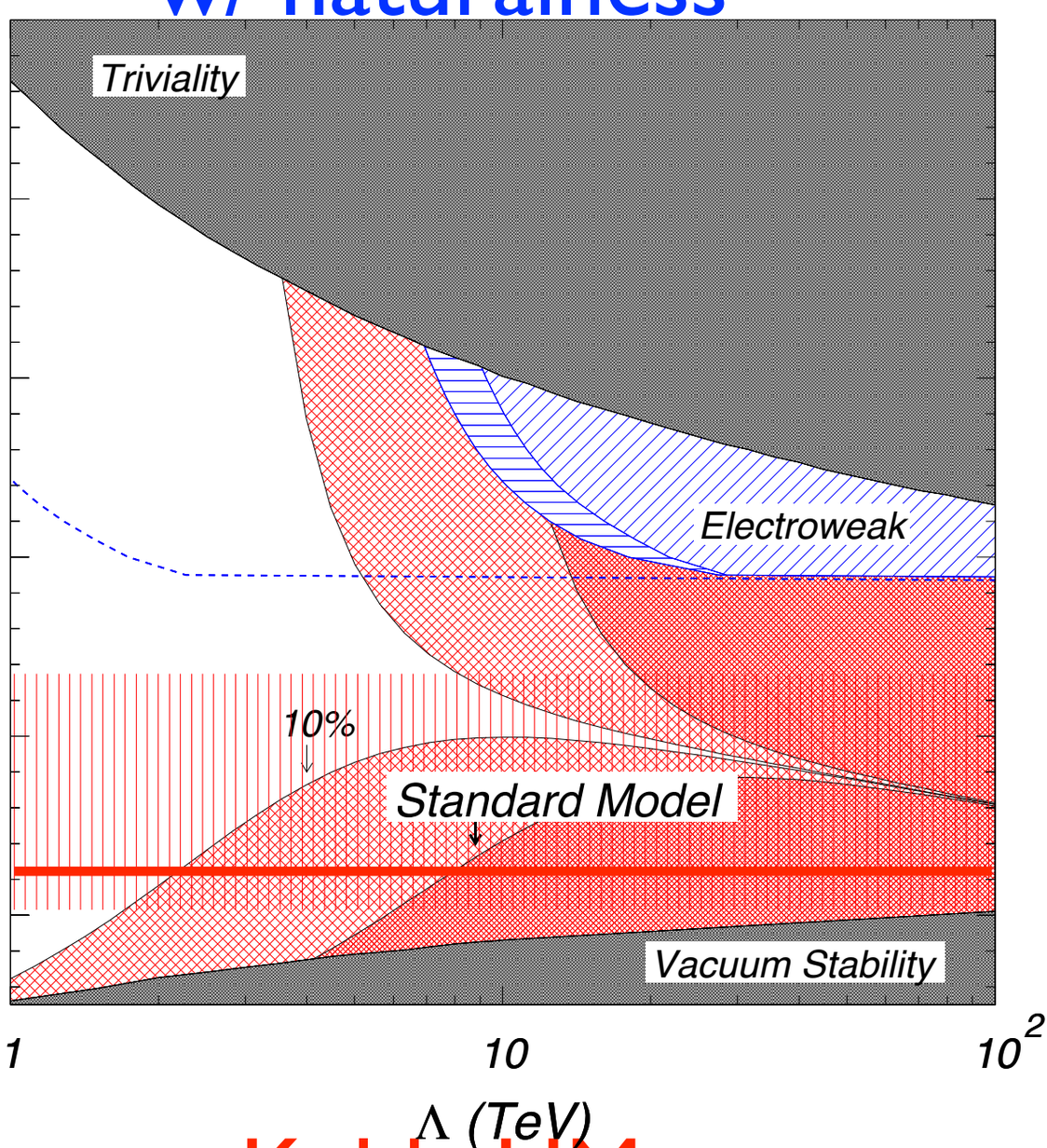
Is energy frontier dead?

Next energy scale

w/o naturalness

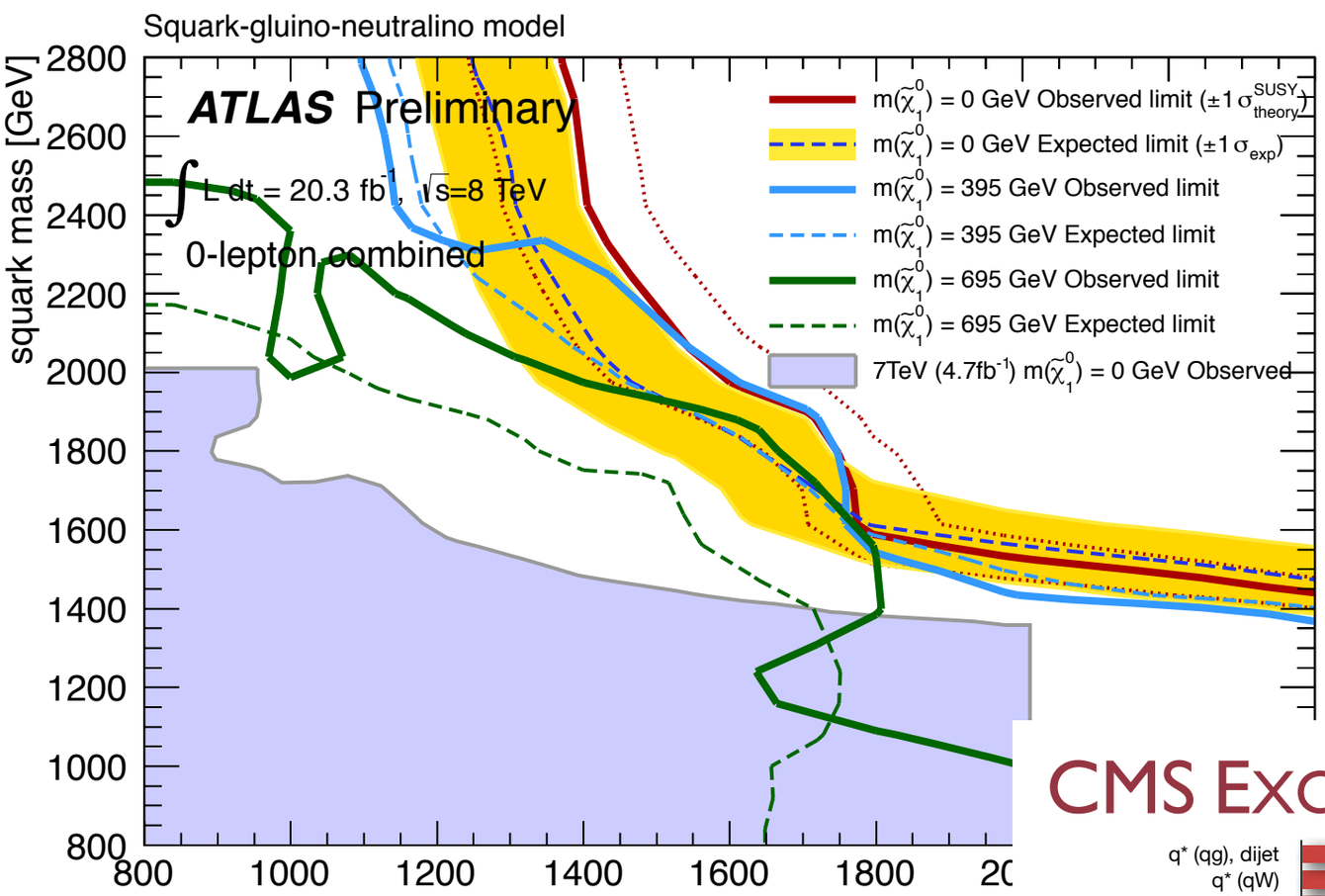


w/ naturalness

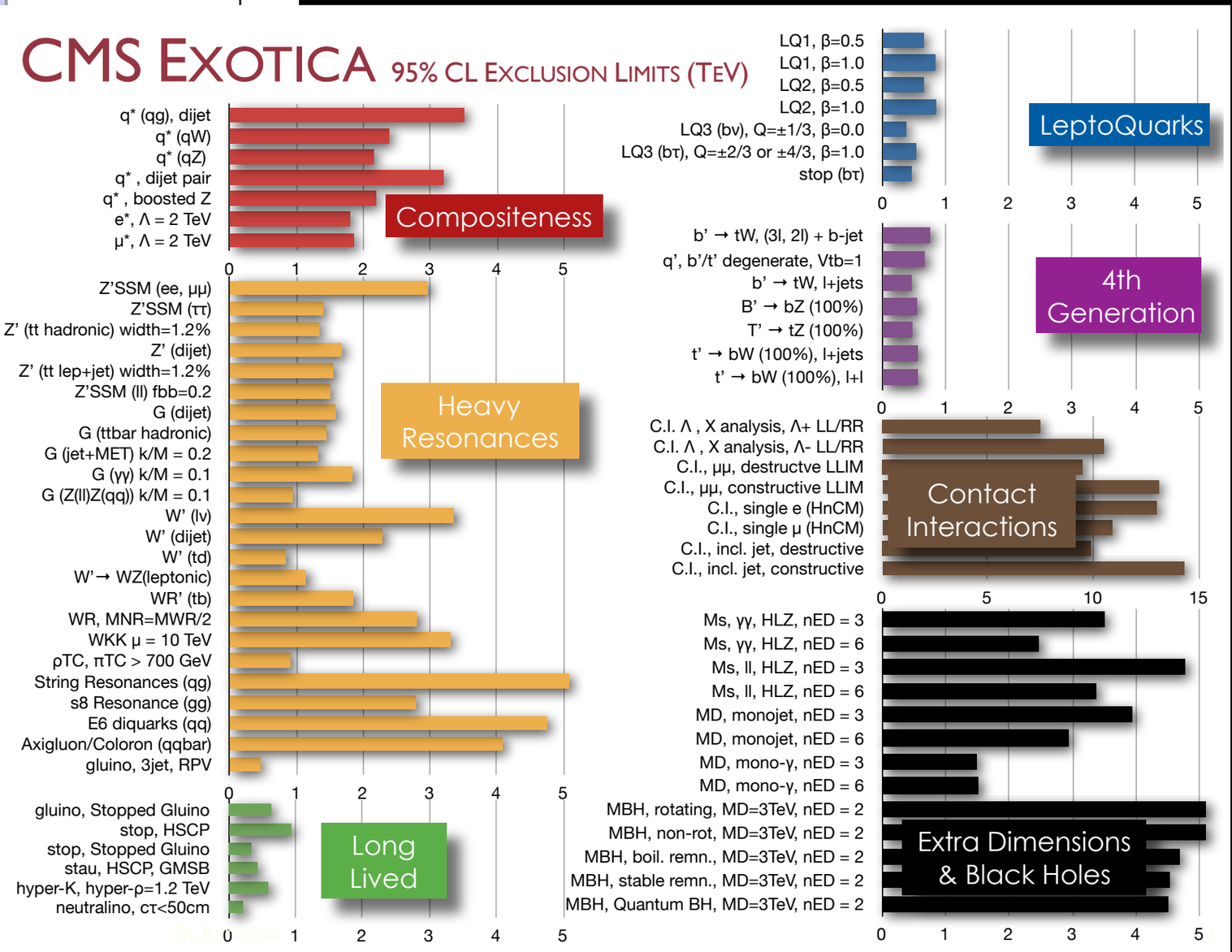


Harigayama, Matsumoto, HM

Kolda HM



no sign of
new physics
that explains Higgs!



Nima's anguish



m_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

Is naturalness dead?

Electron mass is natural by doubling #particles

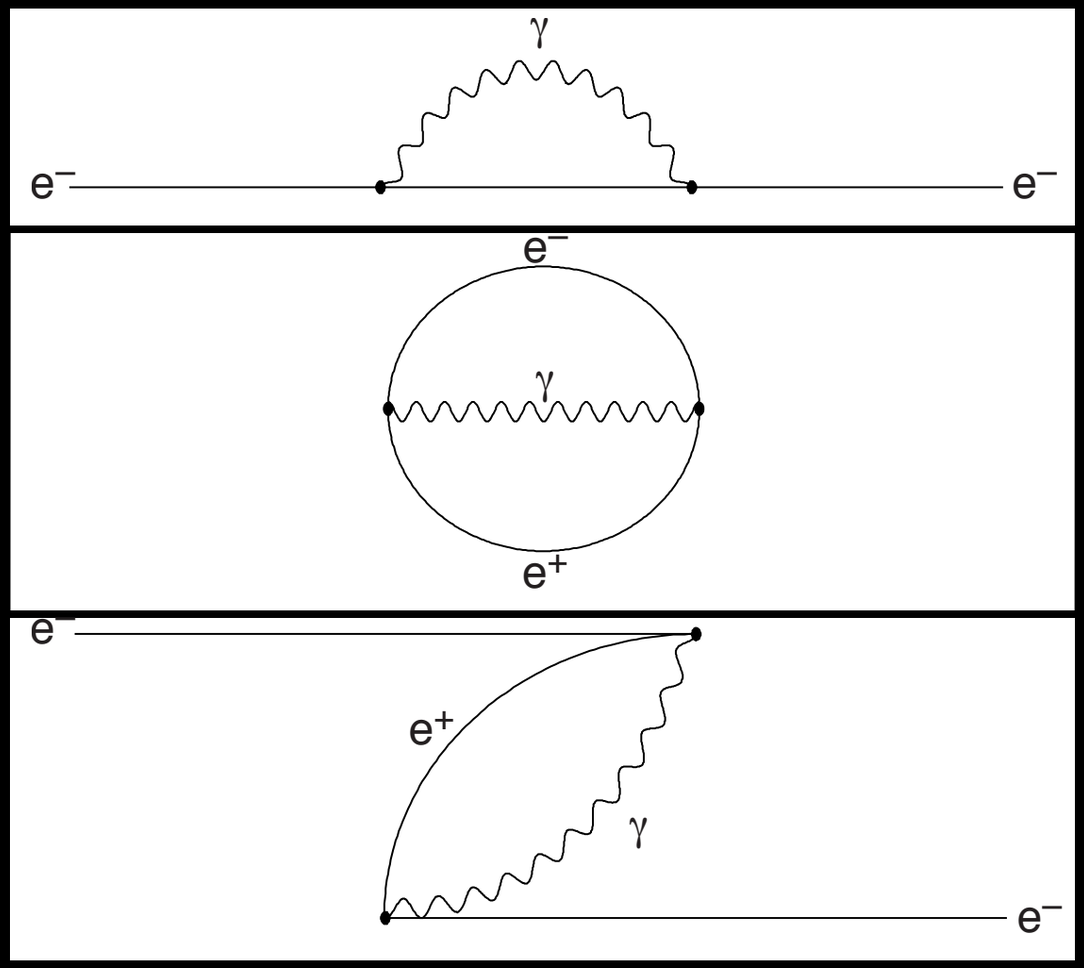
- Electron creates a force to repel itself

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

- quantum mechanics and anti-matter

⇒ only 10% of mass even

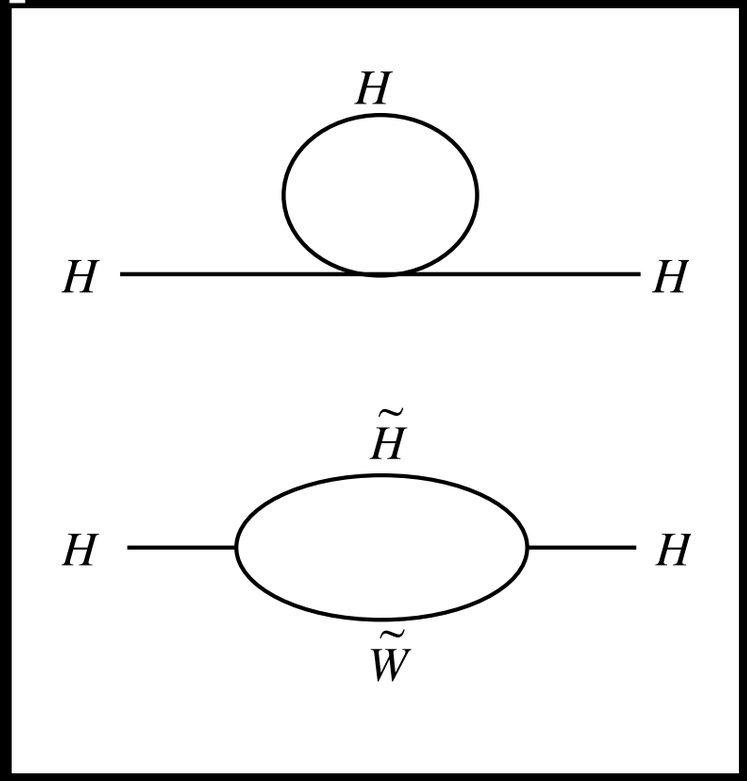
for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs mass is natural by doubling #particles?

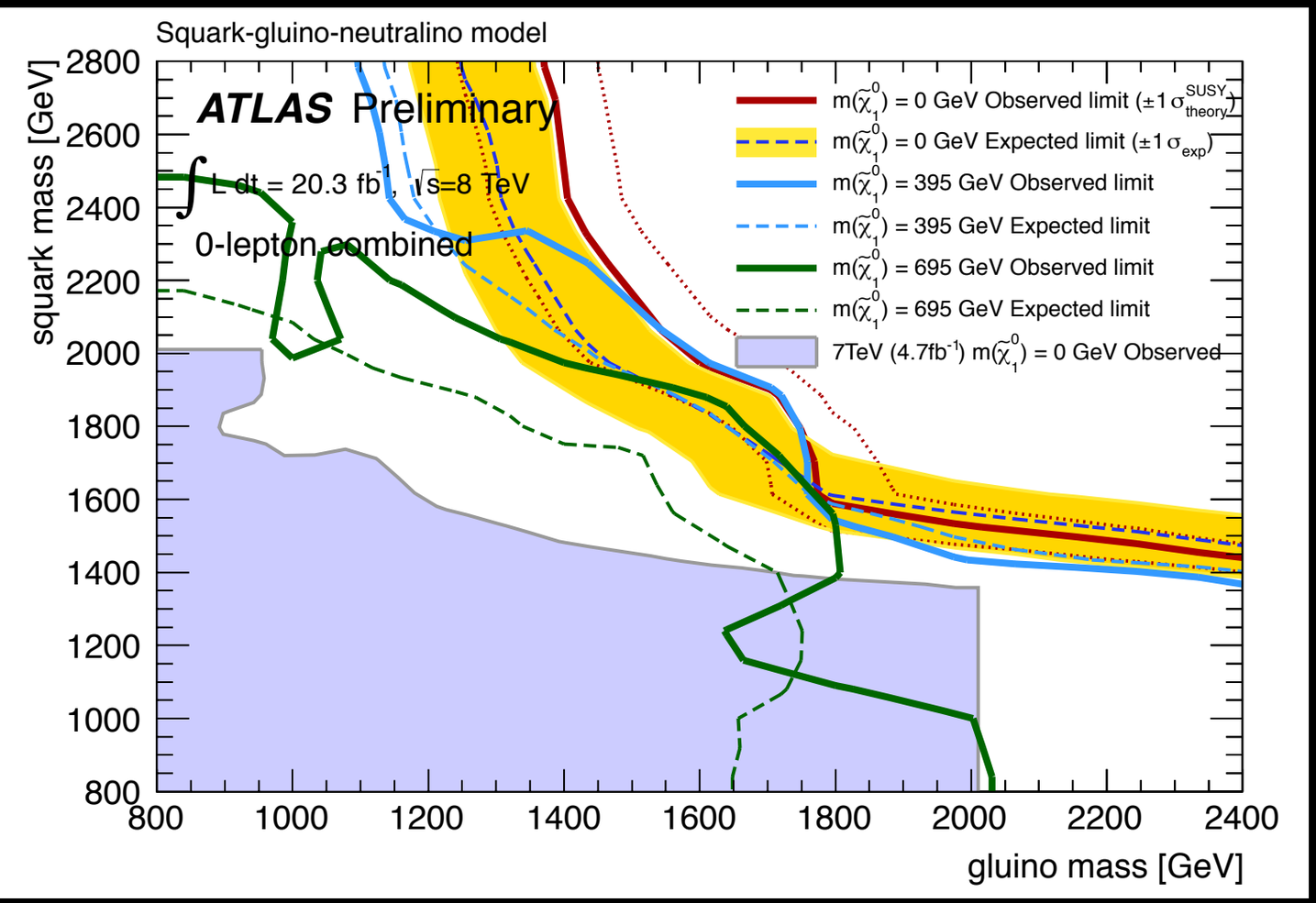
- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

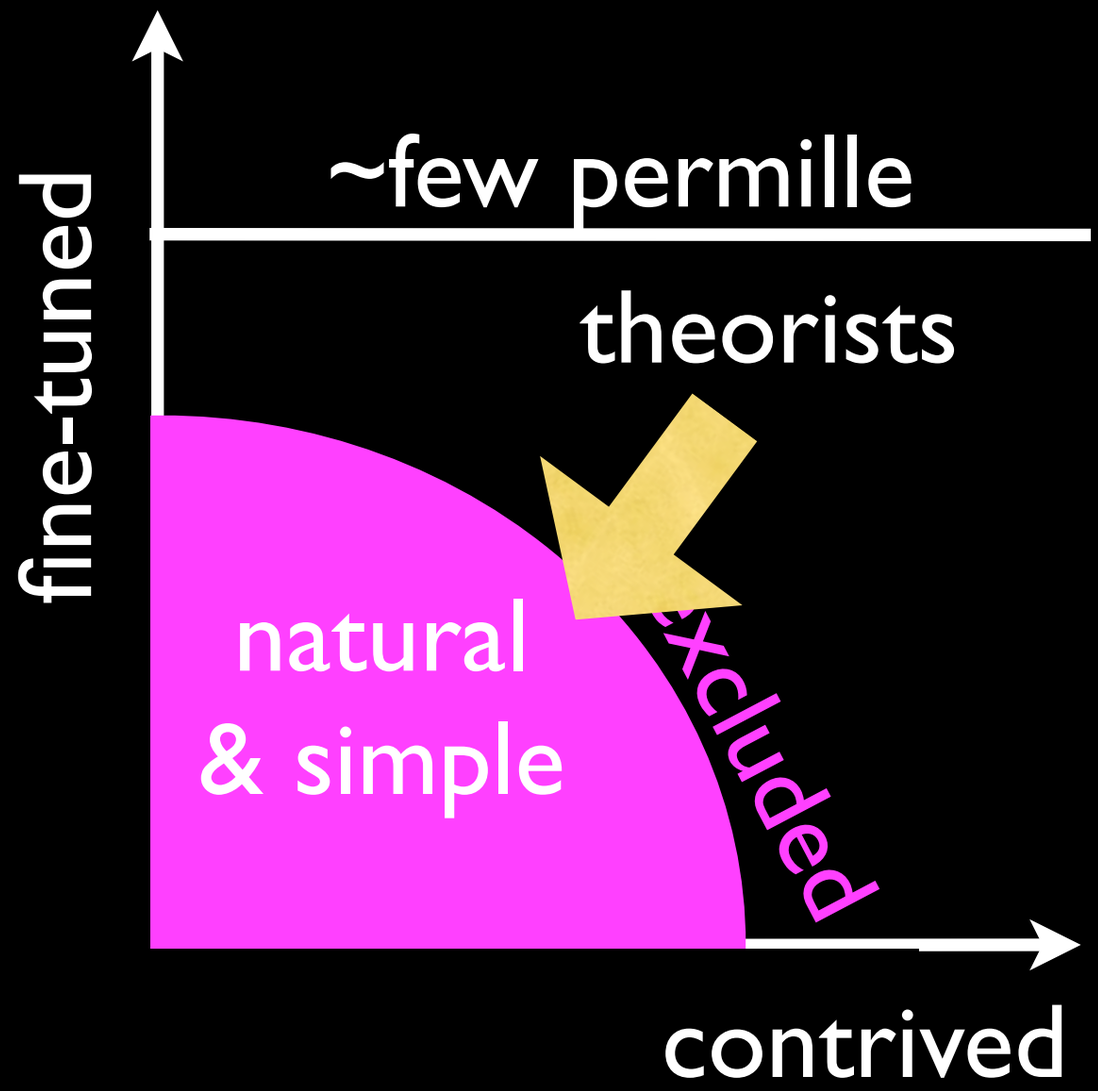


$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

⇒ I still take it seriously

no sign of new physics





Higgs mass vs SUSY

- Higgs is heavier than MSSM prediction

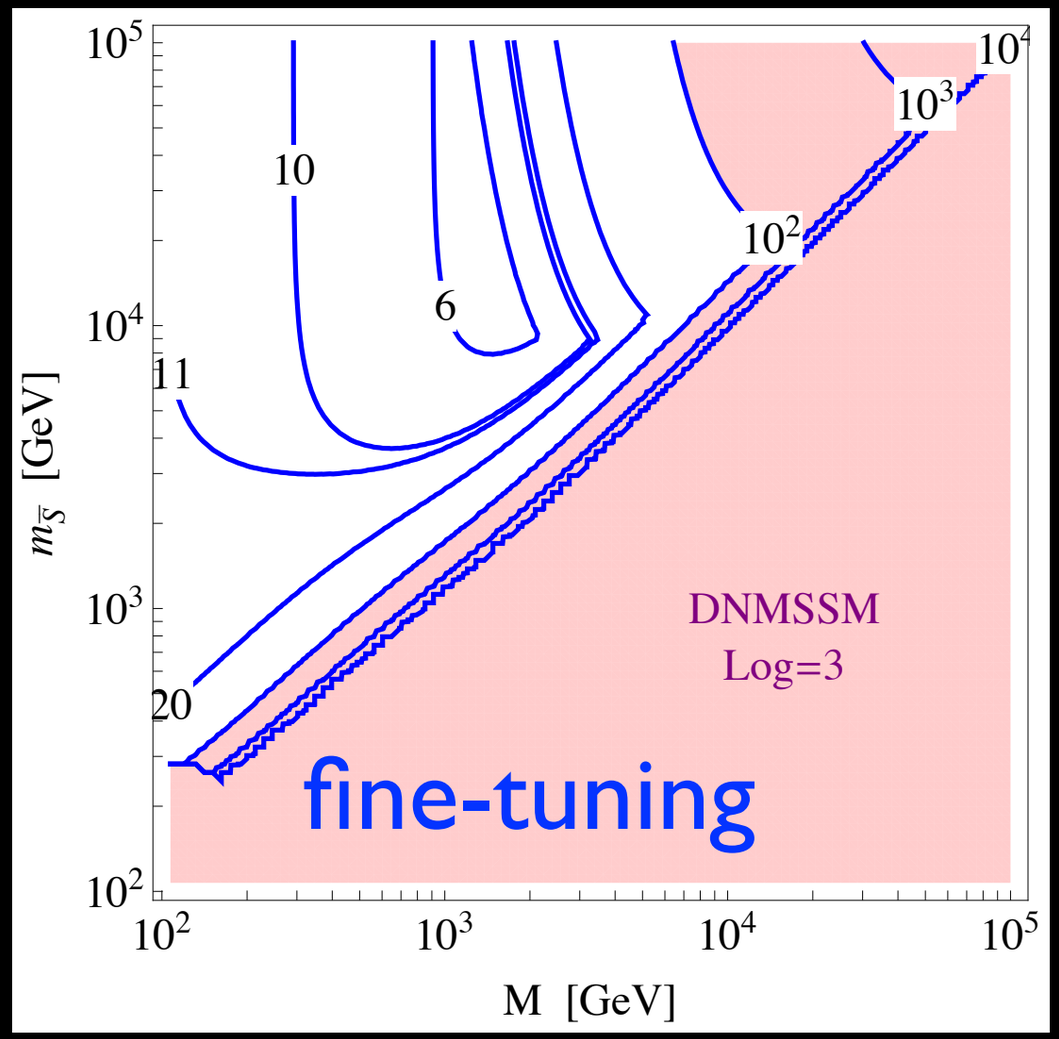
⇒Dirac NMSSM?

$$m_{\bar{S}}^2 \to \infty$$

semi-soft SUSY breaking

$$H^0 \to 4l, hh \quad \tan\beta \approx 2$$

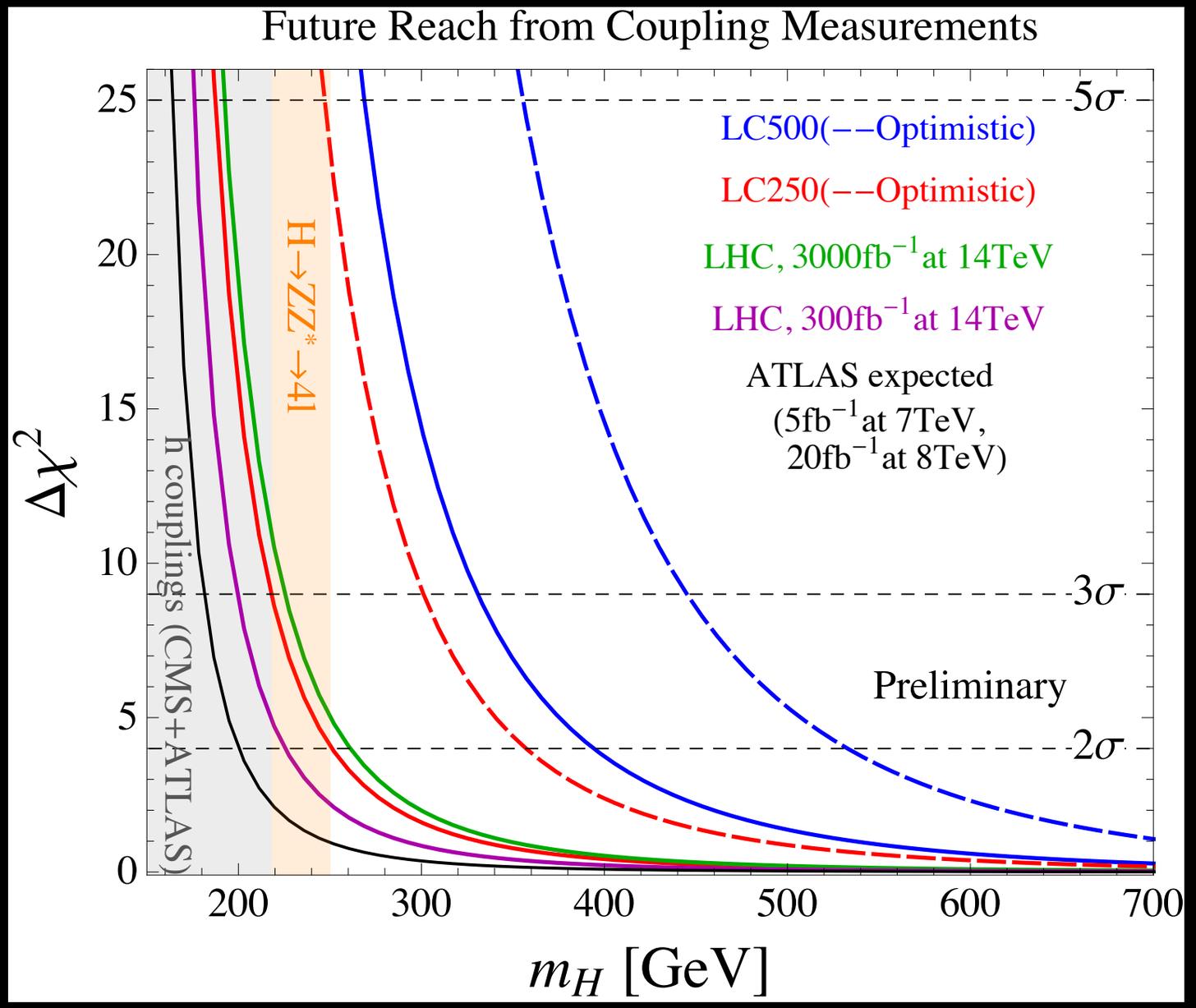
$$W = \lambda H_u H_d S + M S \bar{S}$$



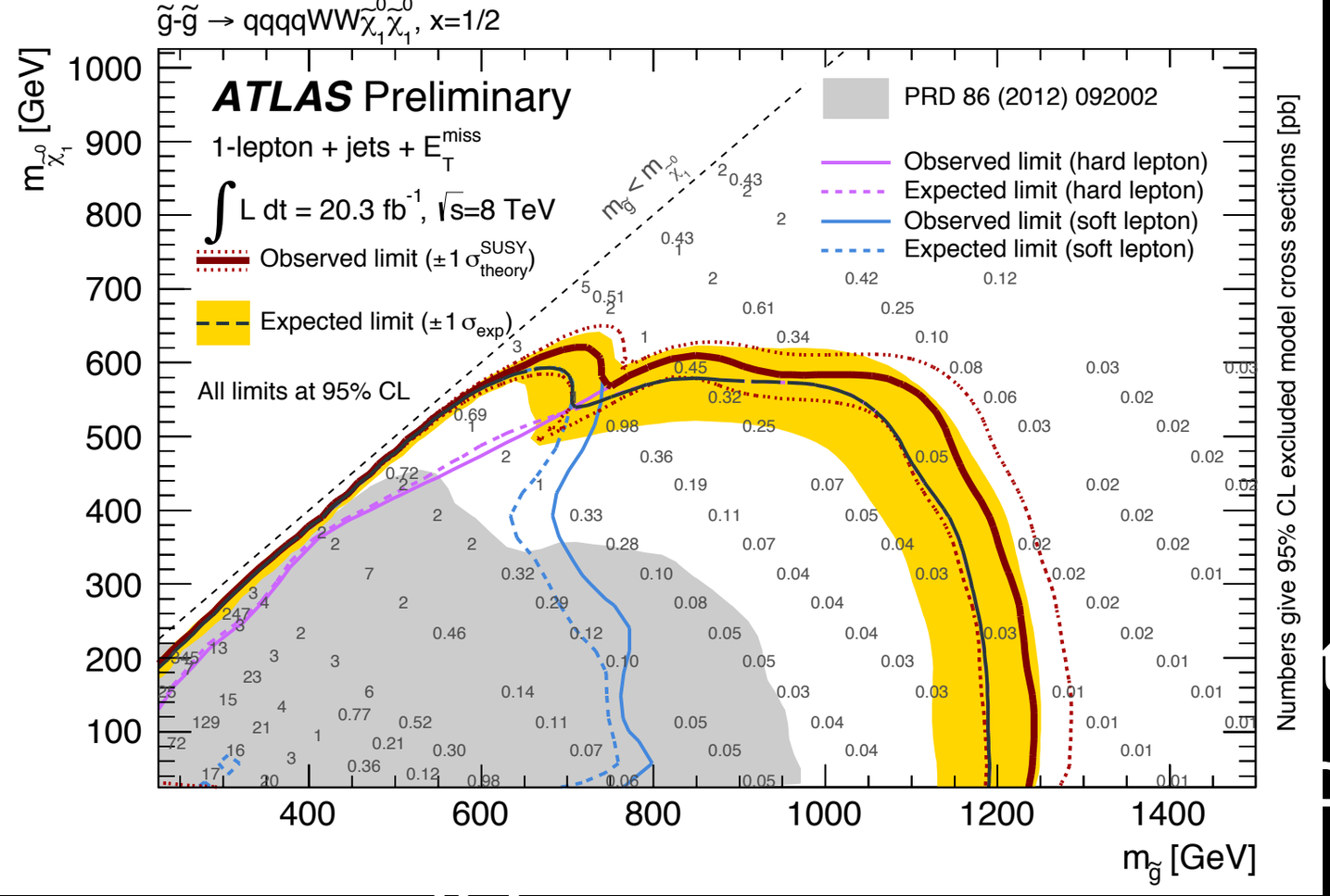
Lu, HM, Ruderman, Tobioka

Is Higgs alone?

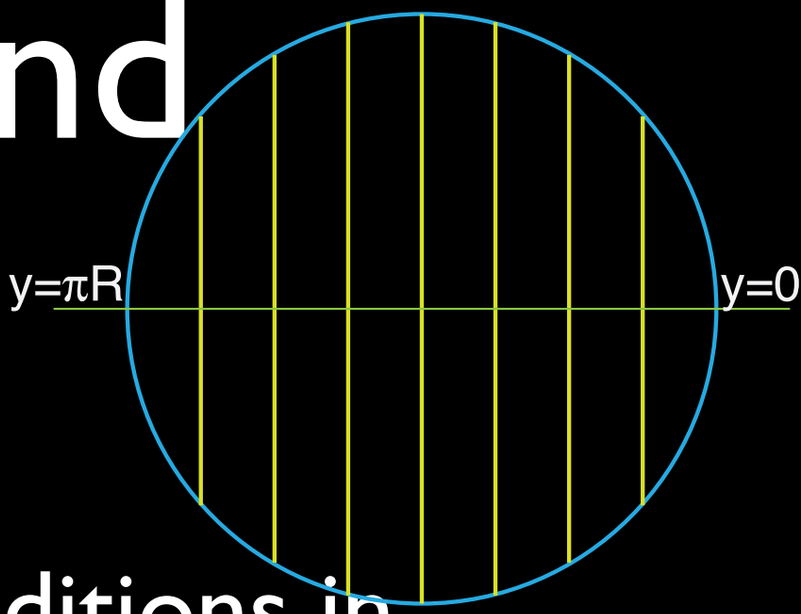
- Many models that try to explain m_h=125GeV require additional Higgs bosons
- precision measurements reveal their existence
- e.g. "Dirac NMSSM"



Lu, HM, Ruderman, Tobioka



found



the data

dary conditions in

5D

- @tree level, all SUSY particles degenerate at α/R similar to UED
- even sfermions and gauginos degenerate
- SUSY as light as 1 TeV still OK

HM, Nomura, Shirai, Tobioka

tag ISR
HM, Nojiri, Tobioka

uneasiness in cosmology

- Before COBE, upper limit on CMB anisotropy kept getting better and better
- Before 1998, the universe appeared younger than oldest stars
- cosmologists got antsy
- "crisis in standard cosmology"
- it turned out a little "fine-tuned"
  - low quadrupole
  - dark energy

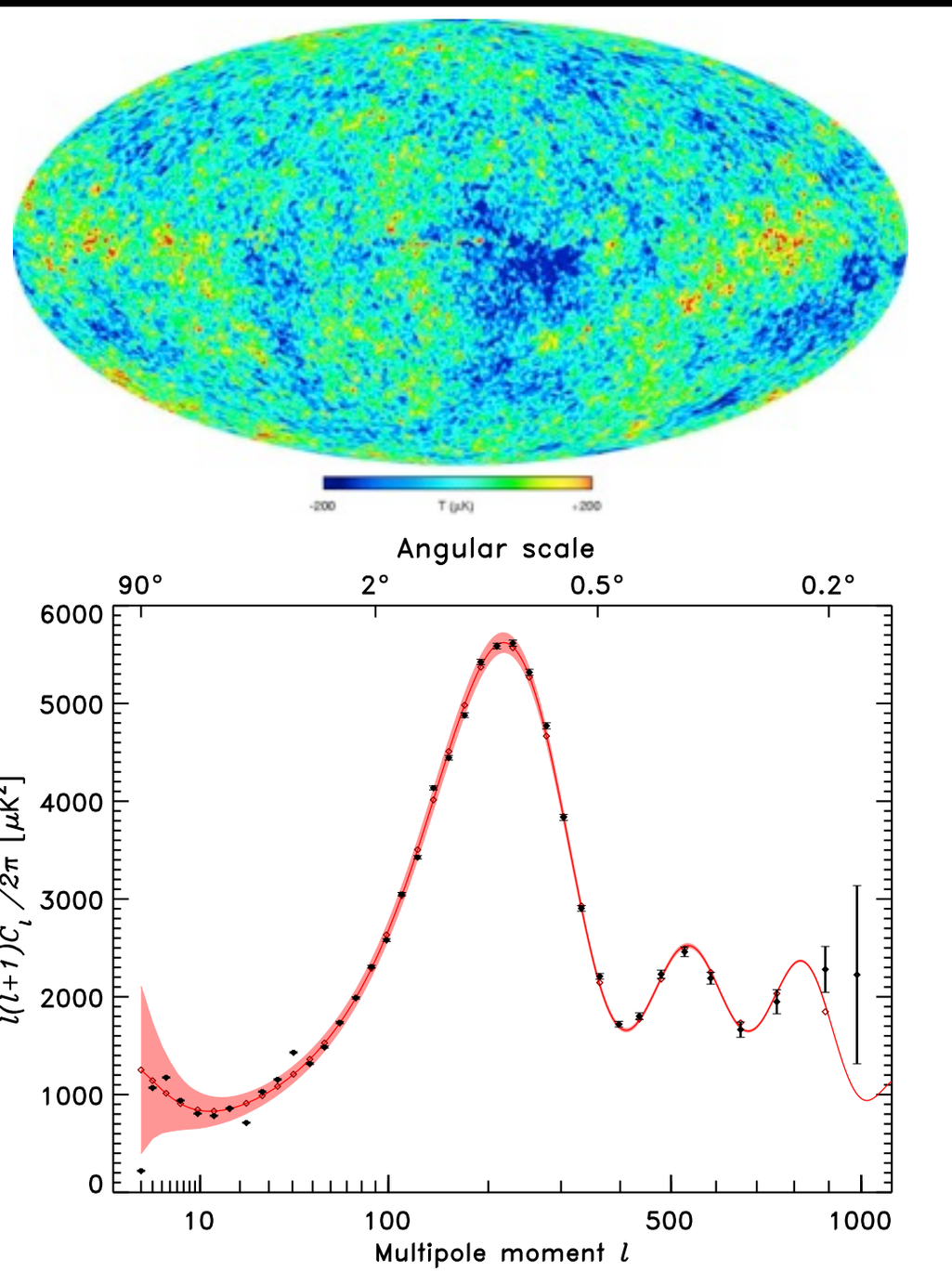
1% tuning

"Ba

A n

the

Tim



patience

It took 10 years for CDF to discover the top quark.

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

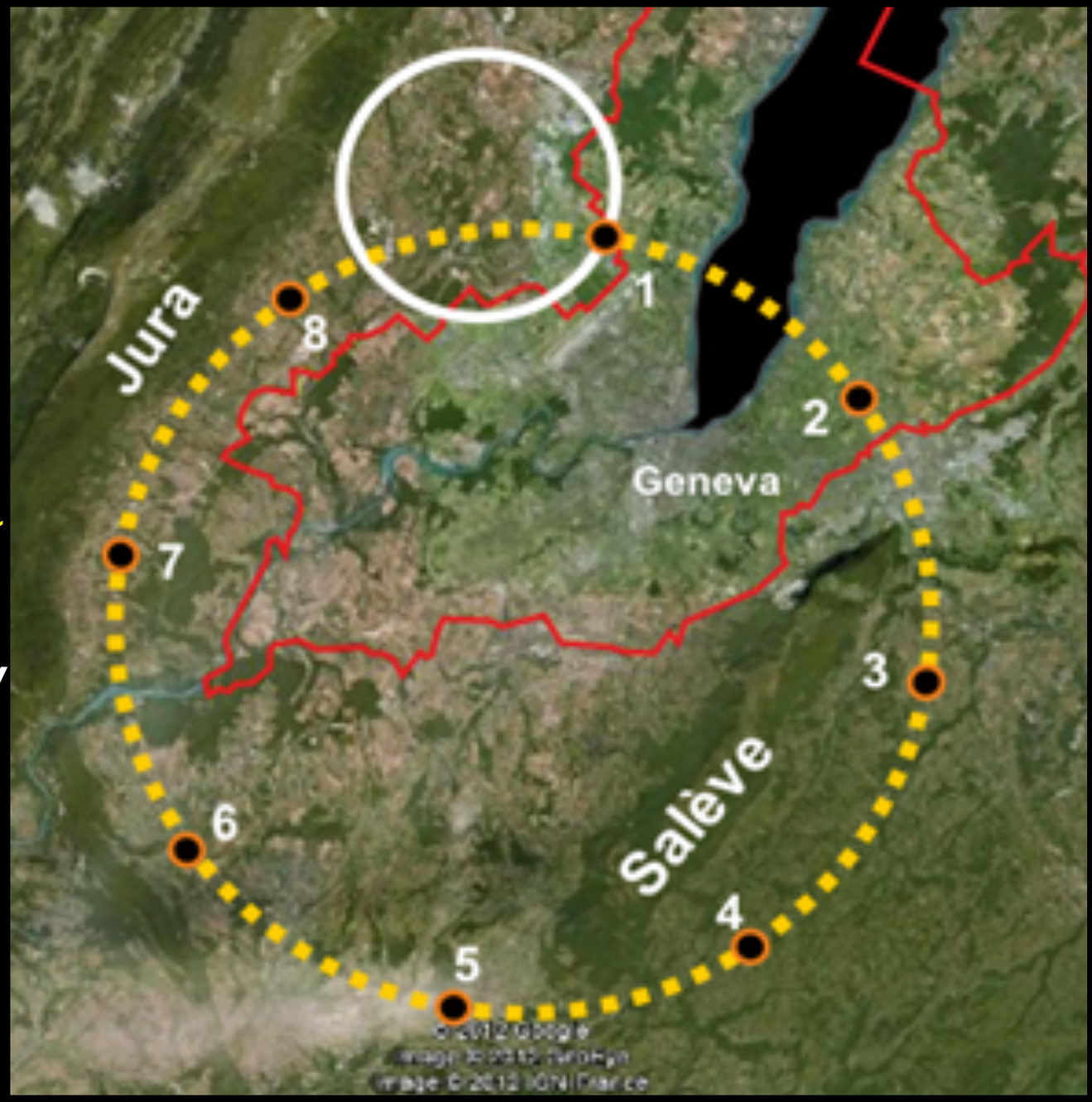
Observation of Top Quark Production in $\overline{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4] S. Aota,[32] G. Apollinari,[27] T. Asakawa,[32] W. Ashmanskas,[15] M. Atac,[7] P. Auchincloss,[26] F. Azfar,[22] P. Azzi-Bacchetta,[21] N. Bacchetta,[21] W. Badgett,[17] S. Bagdasarov,[27] M. W. Bailey,[19] J. Bao,[35] P. de Barbaro,[26] A. Barbaro-Galtieri,[15] V. E. Barnes,[25] B. A. Barnett,[13] P. Bartalini,[24] G. Bauer,[16] T. Baumann,[9] F. Bedeschi,[24] S. Behrends,[3] S. Belforte,[24] G. Bellettini,[24] J. Bellinger,[34] D. Benjamin,[31] J. Benlloch,[16] J. Bensinger,[3] D. Benton,[22] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[27] K. Biery,[12] M. Binkley,[7] D. Bisello,[21] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[26] W. Bokhari,[16] V. Bolognesi,[24] D. Bortoletto,[25] J. Boudreau,[23] G. Brandenburg,[9] L. Breccia,[2] C. Bromberg,[18] E. Buckley-Geer,[7] H. S. Budd,[26] K. Burkett,[17] G. Busetto,[21] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[13] C. Campagnari,[7] M. Campbell,[17] A. Caner,[7] W. Carithers,[15] D. Carlsmith,[34] A. Castro,[21] G. Cauz,[24] Y. Cen,[26] F. Cervelli,[24] H. Y. Chao,[29] J. Chapman,[17] M.-T. Cheng,[29] G. Chiarelli,[24] T. Chikamatsu,[32] C. N. Chiou,[29] L. Christofek,[11] S. Cihangir,[7] A. G. Clark,[24] M. Cobal,[24] M. Contreras,[5] J. Conway,[28] J. Cooper,[7] M. Cordelli,[8] C. Couyoumtzelis,[24] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] J. D. Cunningham,[3] T. Daniels,[16] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[24] M. Dell'Orso,[24] L. Demortier,[27] B. Denby,[24] M. Deninno,[2] P. F. Derwent,[17] T. Devlin,[28] M. Dickson,[26] J. R. Dittmann,[6] S. Donati,[24] R. B. Drucker,[15] A. Dunn,[17] N. Eddy,[17] K. Einsweiler,[15] J. E. Elias,[7] R. Ely,[15] E. Engels, Jr.,[23] D. Errede,[11] S. Errede,[11] Q. Fan,[26] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. F[illegible]tsch[illegible] T. A. Fuess,[1] Y. Fukui,[14] S. Funaki,[32] G. Gagliardi,[23] S[illegible] M.[illegible]arfinkel,[25] C. Gay,[9] S. Geer,[7] D. W. Gerdes,[17] P. Giannetti,[2] N. Gi[illegible]s,[27][illegible]i,[13] M. Gold,[19] J. Gonzalez,[22] A. Gordon,[9] A. T. Goshaw,[6] K. G[illegible]ulianos,[27] H. Grassmann,[7,*] L. Groer,[28] C. Grosso-Pilcher,[5] G. Guillian,[17] R. S. Guo,[29] C. Haber,[15] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[34] R. M. Hans,[35] K. Hara,[32] B. Harral,[22] R. M. Harris,[7]

LHC14, HL-LHC

higher energies?

- HL-LHC boosts reach
- We believe we should keep aiming at higher energies
- *100 TeV pp would be great!*
- problem: no argument for a particular energy scale yet
- we always had idea recently
  - SppS, LEP: *W* & *Z*
  - Tevatron: top
  - LHC: Higgs



we should start with the energy scale we know: Higgs

Is precision Higgs study worthwhile?

Higgs boson

need to find everything
under the lamp post

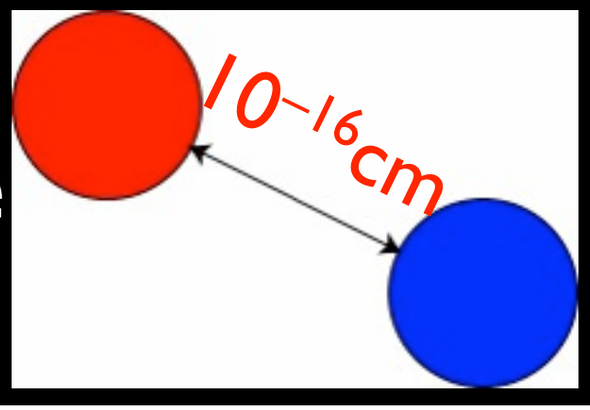
learn where
to go next

argument

- Higgs is absolutely important
- HL-LHC the highest priority
- ILC has evolutionary program on Higgs
  - 250GeV: *ZH*, branching fractions
  - 500GeV: *W*-fusion, *ttH*, self-coupling
  - 1 TeV: better *ttH*, self-coupling
- at the same time, hope for new physics
  - the same approach as LEP with *Z* & *W*

Cosmic Superconductor

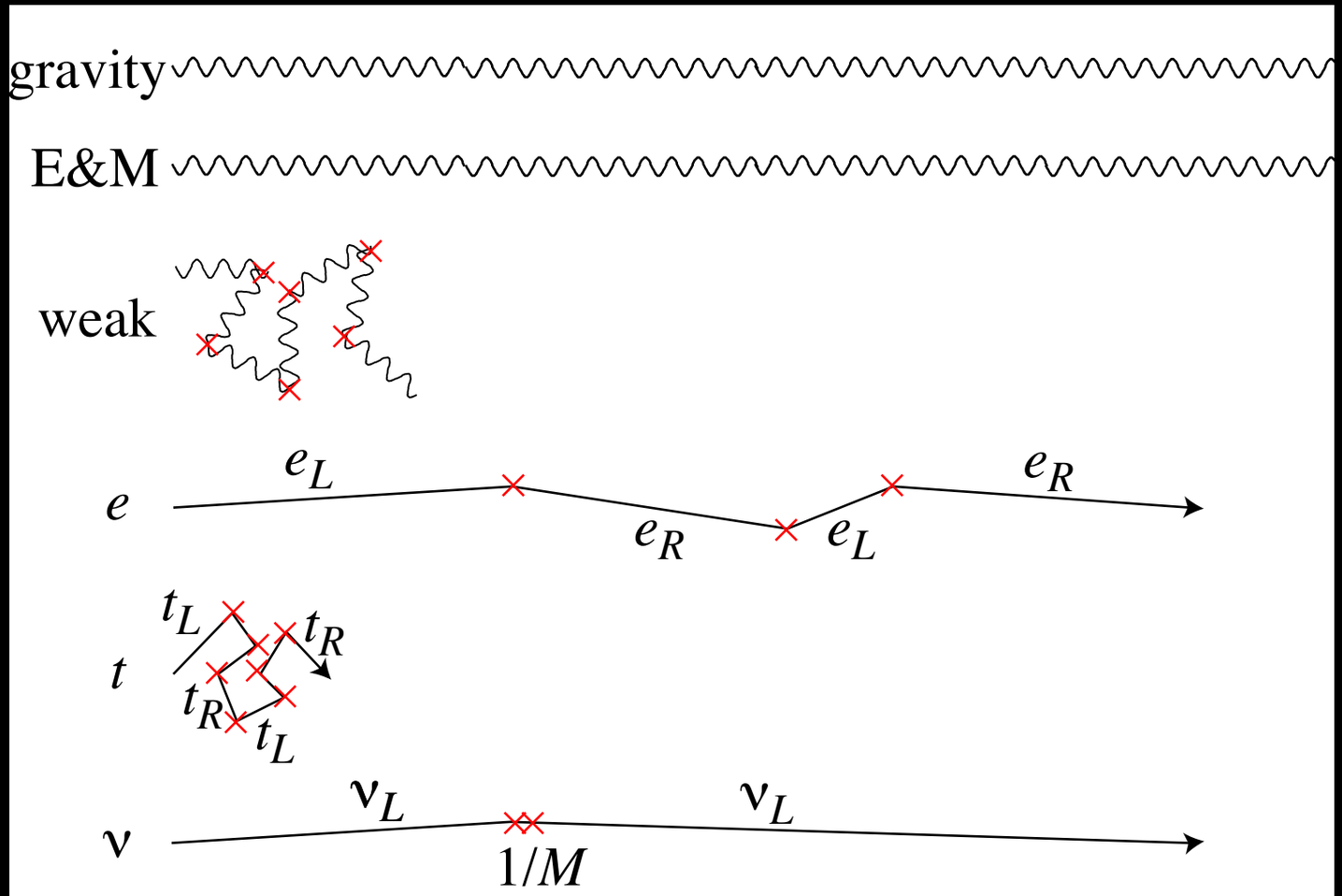
weak force

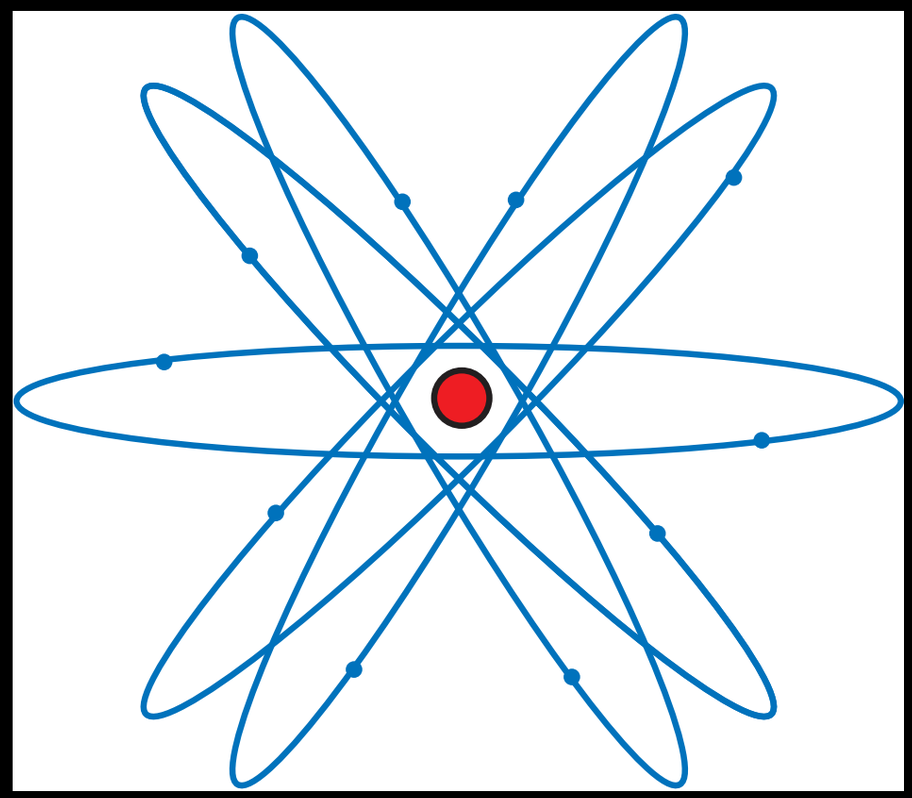


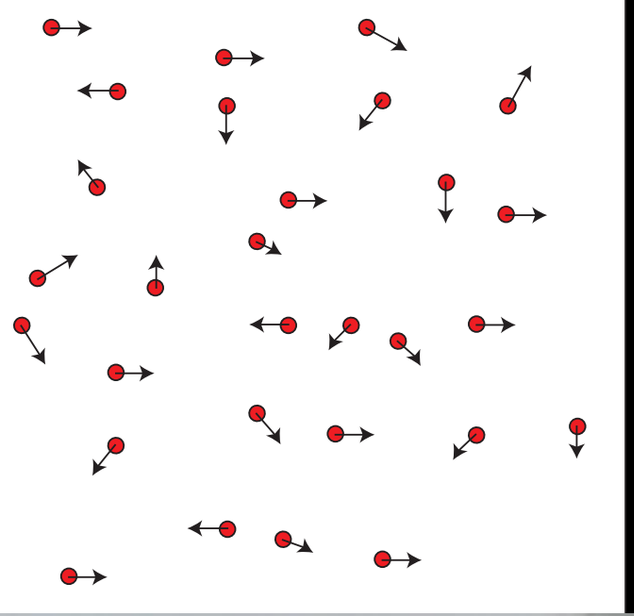


gravity

E&M

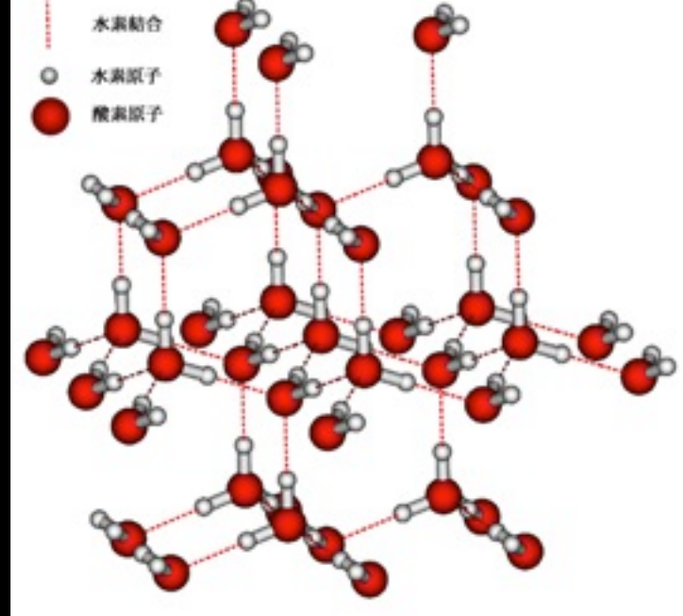






Higgs particle

4 quadrillion degrees







disorder ⇒ order



Who is Higgs?
Is it alone?
Any siblings?
Why frozen?





atoms

electrons

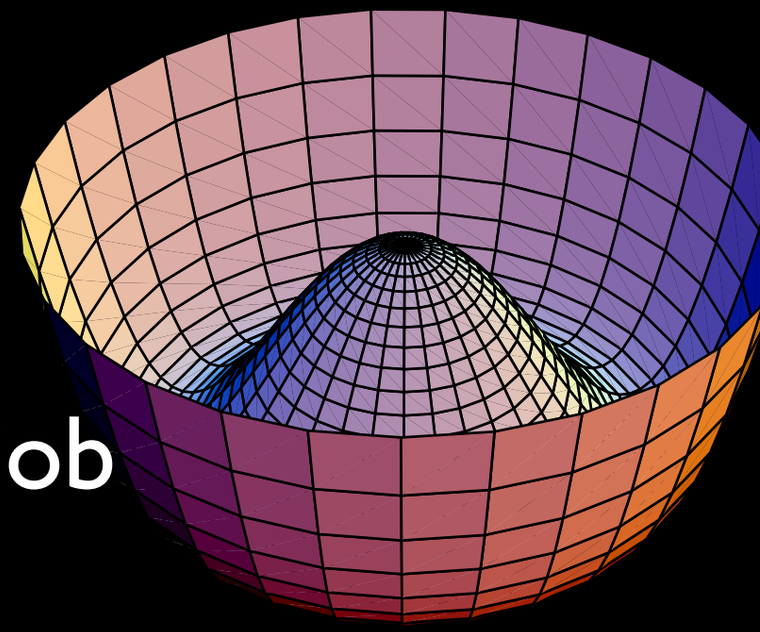
nuclei





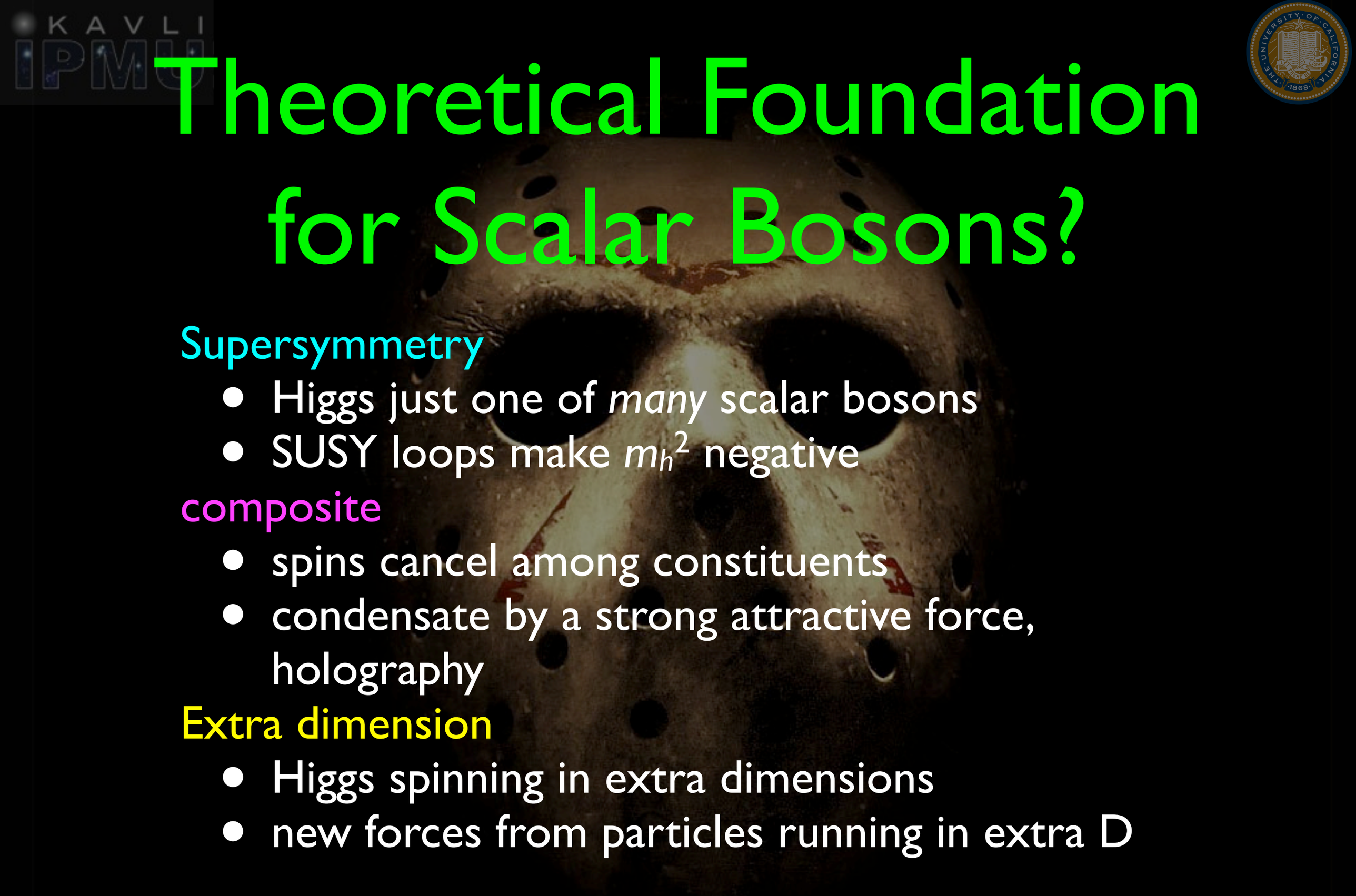
Spin

- Higgs boson is the *only spin 0 particle* in the standard model
  - it is *faceless*
  - one of its kind, no context
  - but does the most important job
- looks very artificial
- we still don't know *dynamics* behind the Higgs condensate
- *Higgsless theories*: now dead





Theoretical Foundation for Scalar Bosons?



Supersymmetry

- Higgs just one of *many* scalar bosons
- SUSY loops make m_h^2 negative

composite

- spins cancel among constituents
- condensate by a strong attractive force, holography

Extra dimension

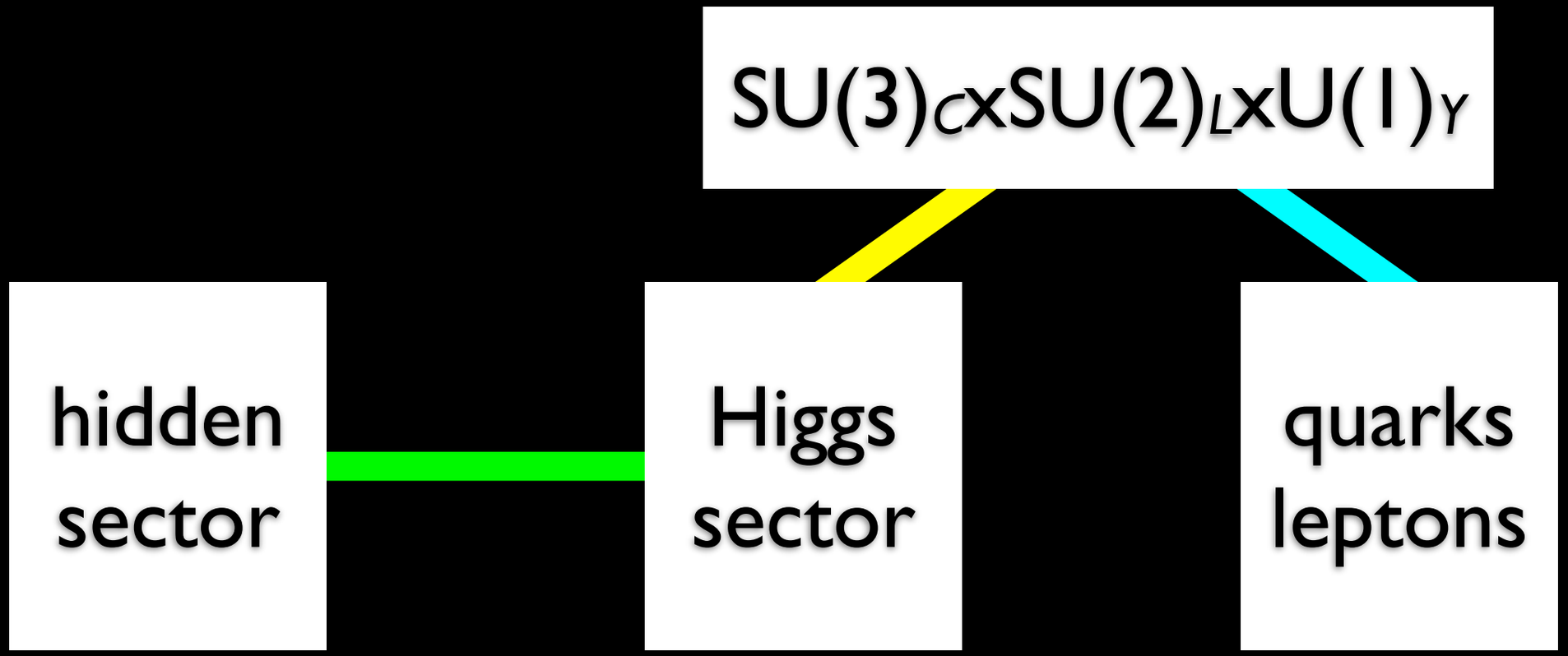
- Higgs spinning in extra dimensions
- new forces from particles running in extra D

not "naturalness" arguments



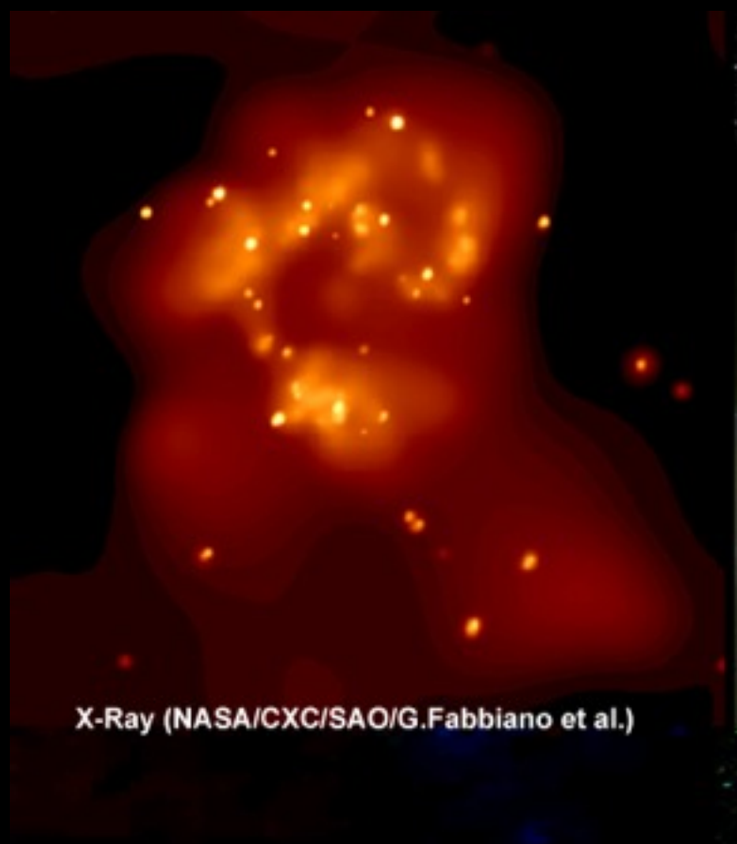
Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"

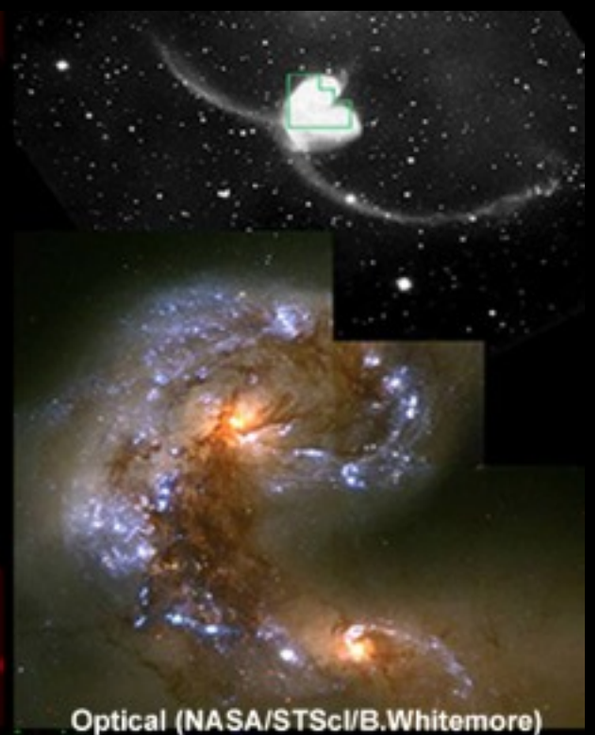


$$\mathcal{L} = \mathcal{O}_{hidden} H^\dagger H$$

Need many probes for full understanding



X-Ray (NASA/CXC/SAO/G.Fabbiano et al.)



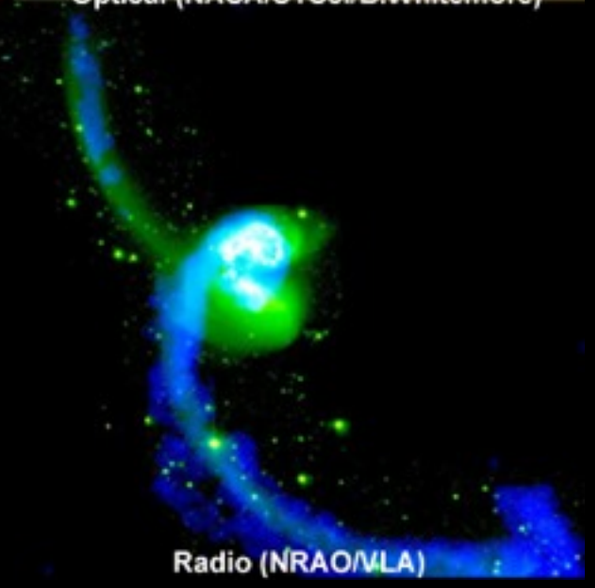
Optical (NASA/STScI/B.Whitemore)



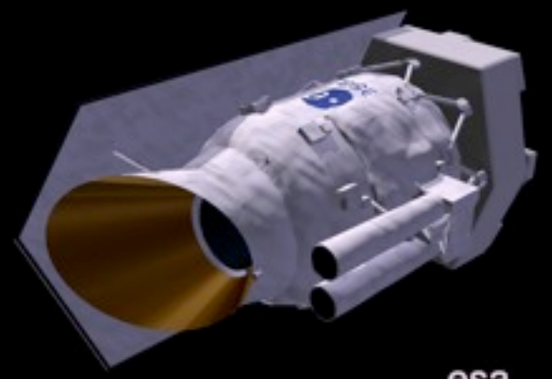




Infrared (ESA/ISO/L.Vigroux et al.)



Radio (NRAO/VLA)



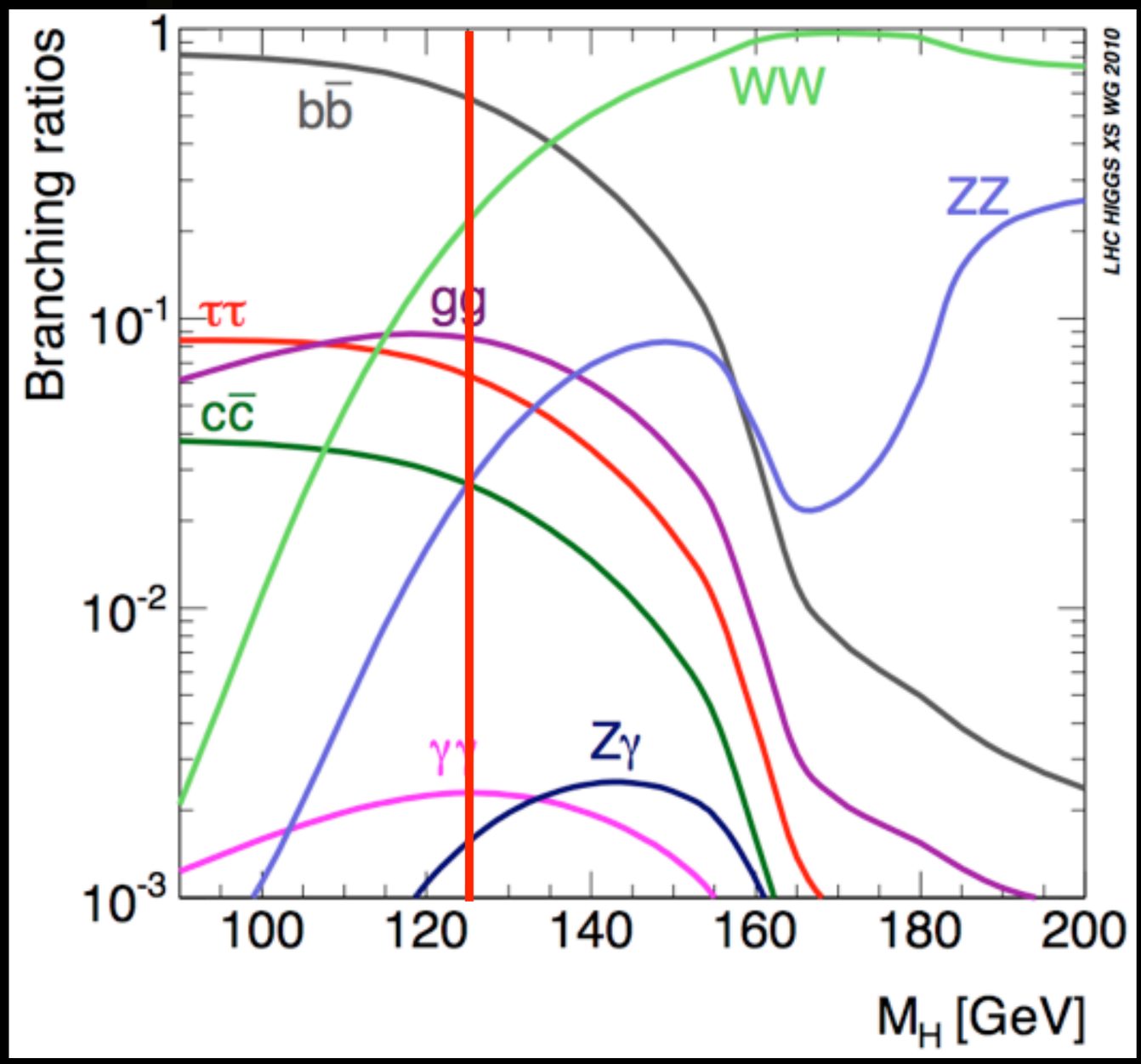


History of Colliders

1. precision measurements of neutral current (*i.e.* polarized *e*+*d*) predicted *mw*, *mz*
2. UA1/UA2 discovered W/Z particles
3. LEP *nailed* the gauge sector
1. precision measurements of W and Z (*i.e.* LEP + Tevatron) predicted m_H
2. LHC discovered *a Higgs particle*
3. LC *nails* the Higgs sector?
1. precision measurements at LC predict ???

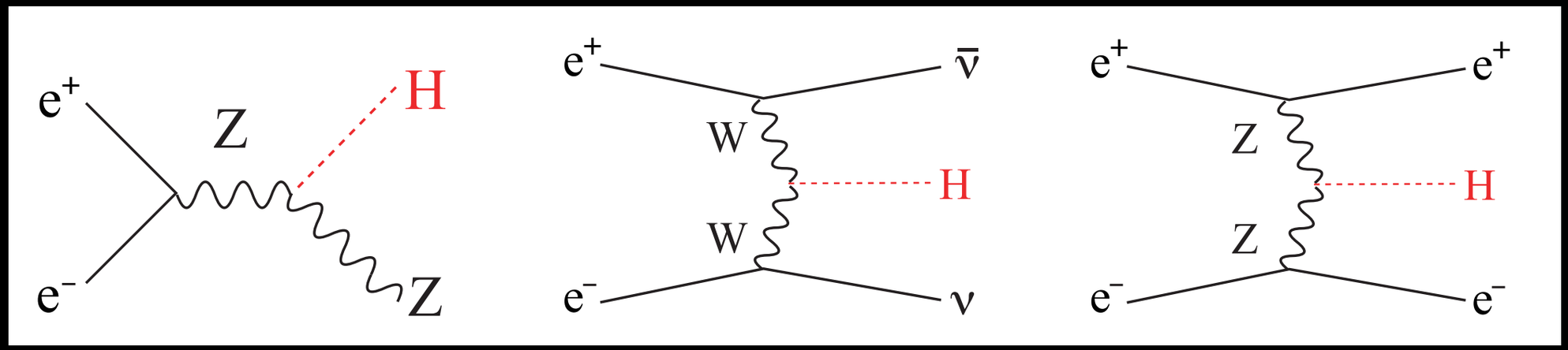


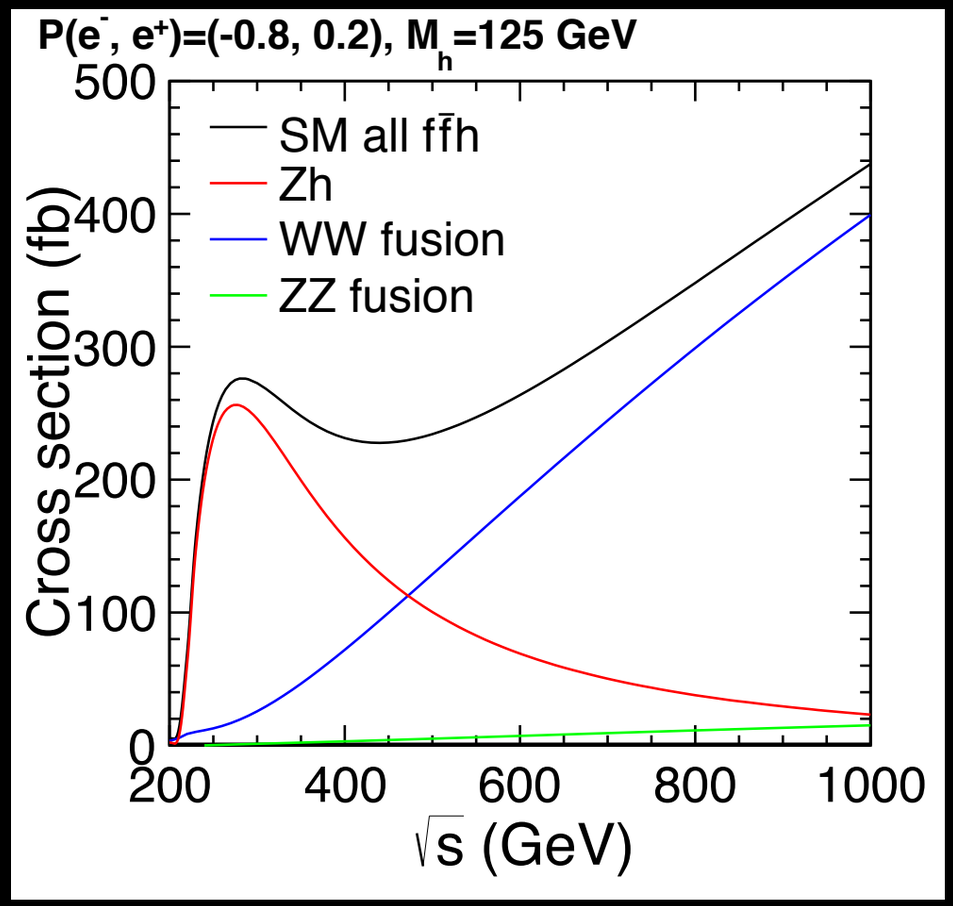
dream case for experiments

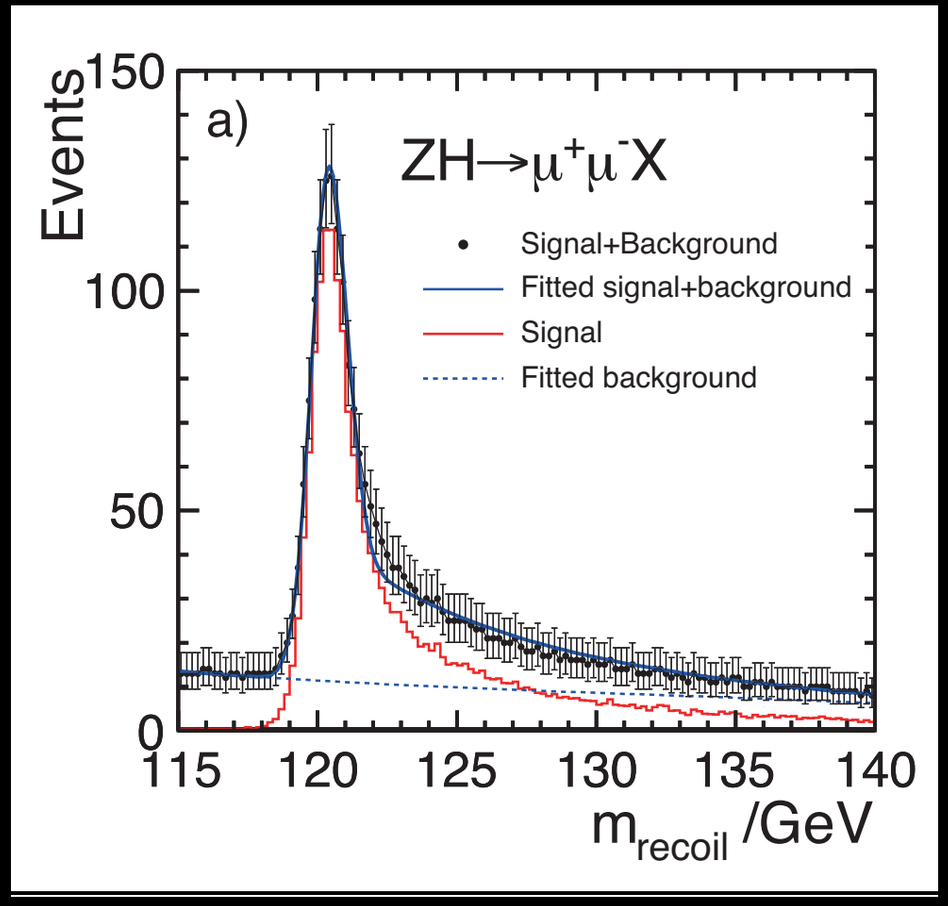


can measure them all!

production mechanisms

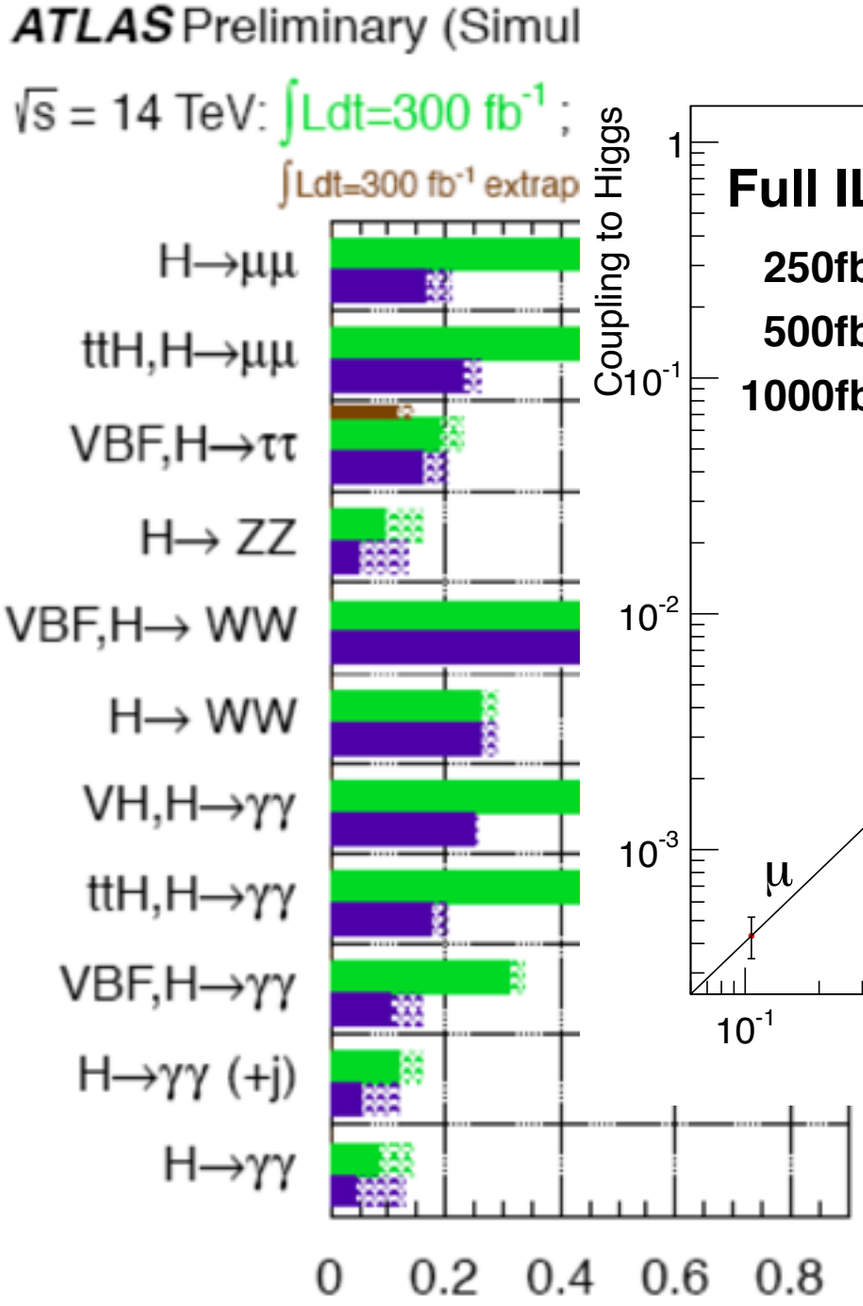


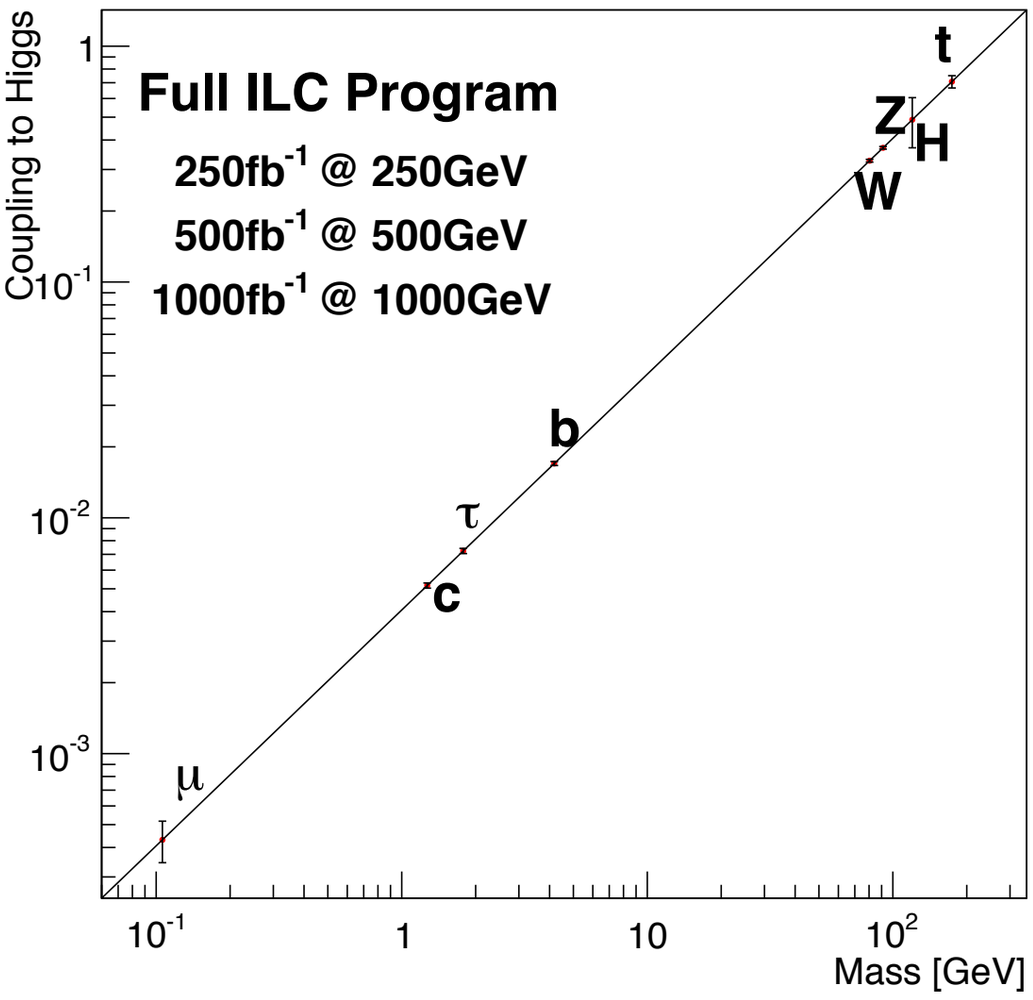


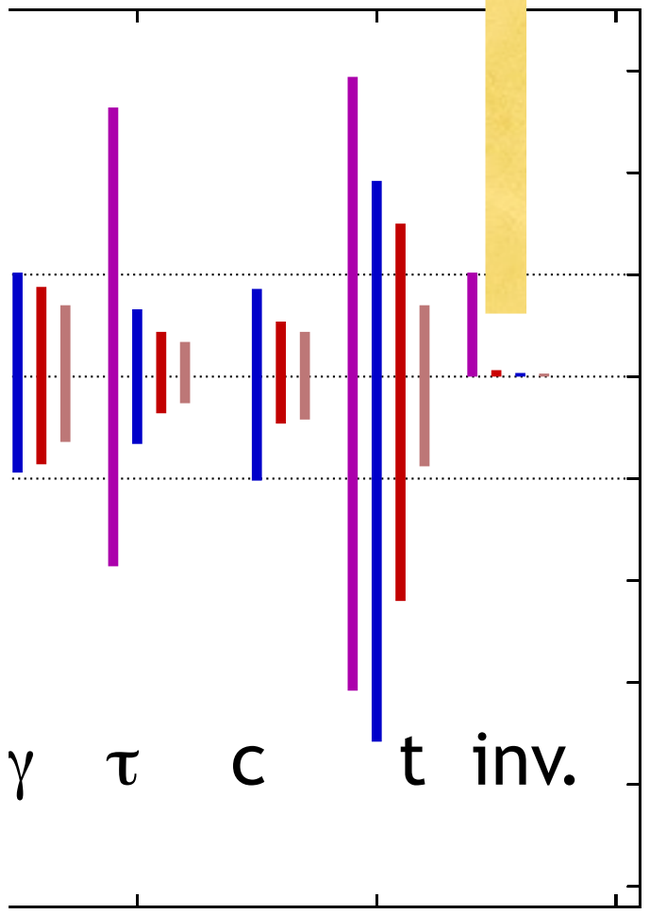


Milk every drop out of *h*(125)

dark matter?







energy reach ∝ (precision)$^{-1/2}$

Composite Higgs

- effect of compositeness appears as higher dimension operators
- precision Higgs measurements
- window to high-energy physics beyond TeV

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(H^\dagger\overleftrightarrow{D}_\mu H\right)$$
$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R + \text{h.c.}\right)$$
$$+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+\frac{ic_{HW}g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{ic_{HB}g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.$$

Giudice, Grojean, Pomarol, Rattazzi

ILC500 ⇒ 4πf~40 TeV

Couplings now and in the future

Now [Aspen/Moriond 2013]

- focus SM-like [secondary solutions possible]
- six couplings and ratios from data

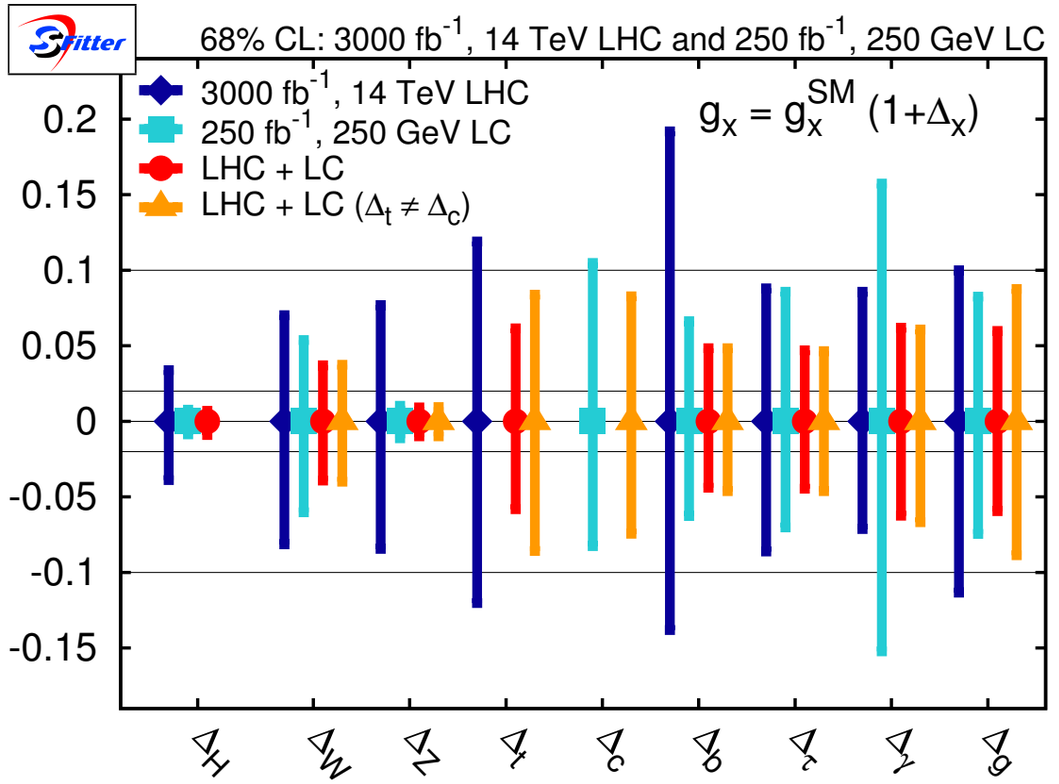
  g_b from width
  g_g vs g_t not yet possible

  [similar: Ellis etal, Djouadi etal, Strumia etal, Grojean etal]
- poor man's analyses: $\Delta_H, \Delta_V, \Delta_f$
- Tevatron $H \to b\bar{b}$ with little impact

Tilman Plehn
LC250

Future

- LHC extrapolations unclear
- theory extrapolations tricky
- ILC case obvious [500 GeV for now]
- interplay in loop-induced couplings



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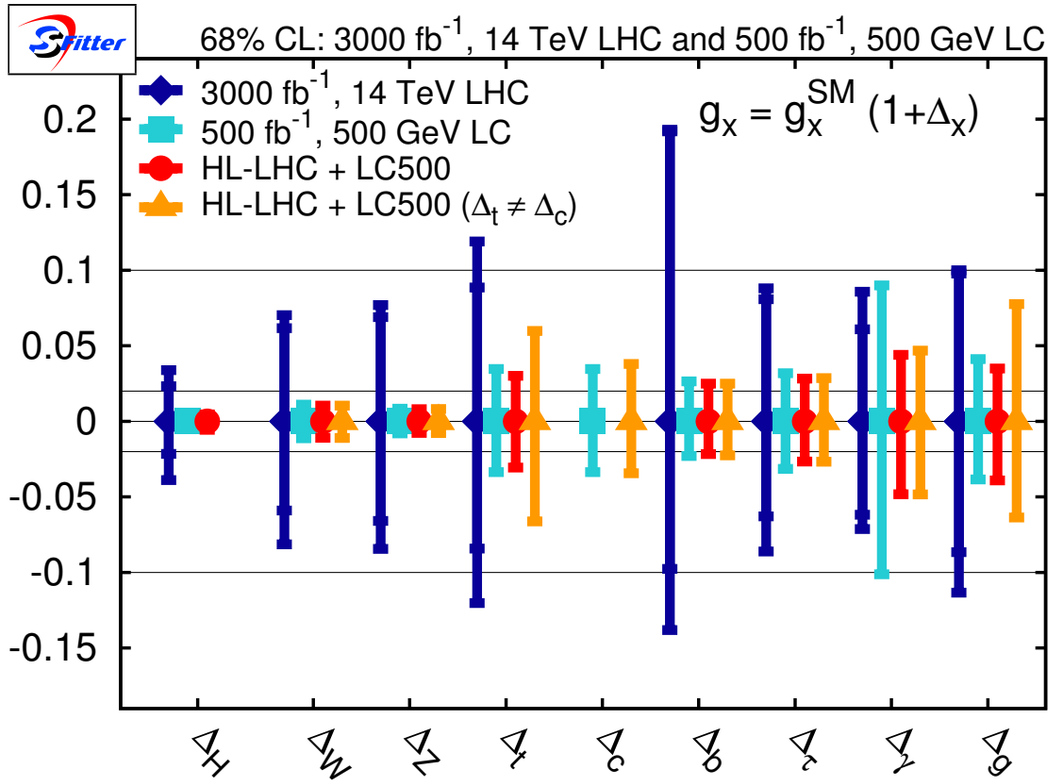
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Tilman Plehn
LC500

x3 better than LC250

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circular vs linear?

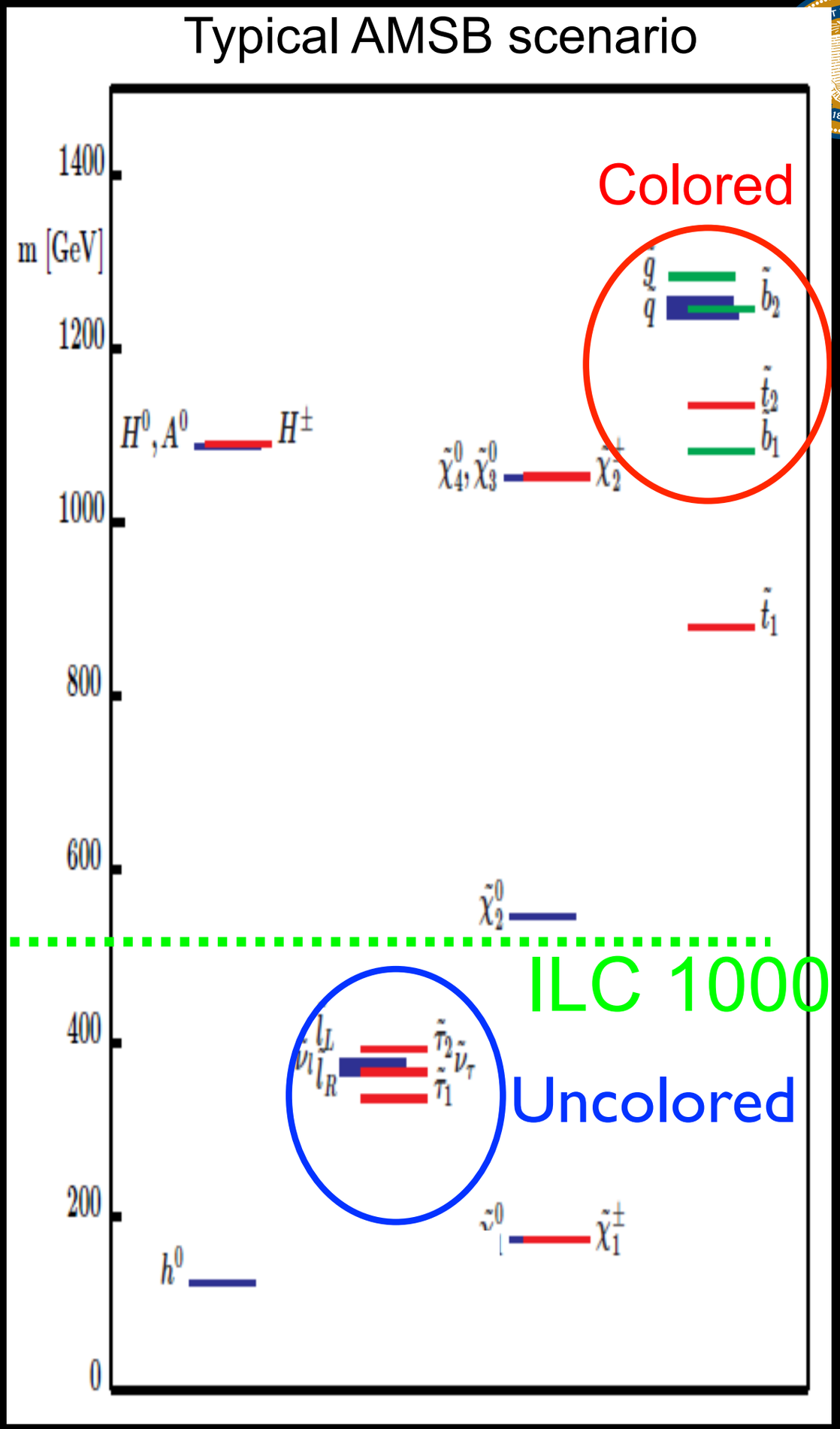
	power	lumi
ILC250	122MW	7.5E+33
TLEP	280MW	5.0E+34
ILC500	163MW	1.8E+34

TLEP x 2 detectors
ILC x 1.3 (polarization)

My prejudice:
circular no big advantage
no path beyond 350 GeV
no beam polarization at high E

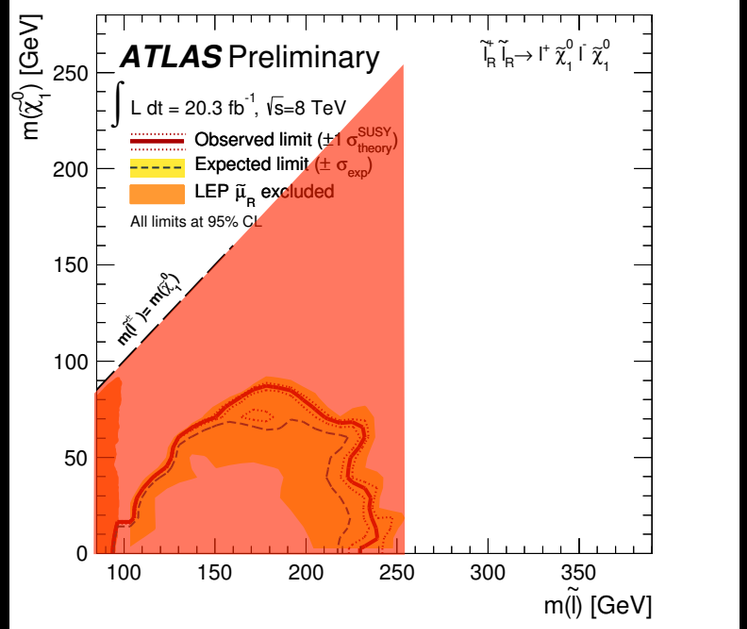
New physics

- *precision* Higgs measurements may reveal multi-Higgs nature
- deviation will give us upper limit on new physics scale
- access to color-neutral new particles?
- once any hint of new physics, upgradability is the key

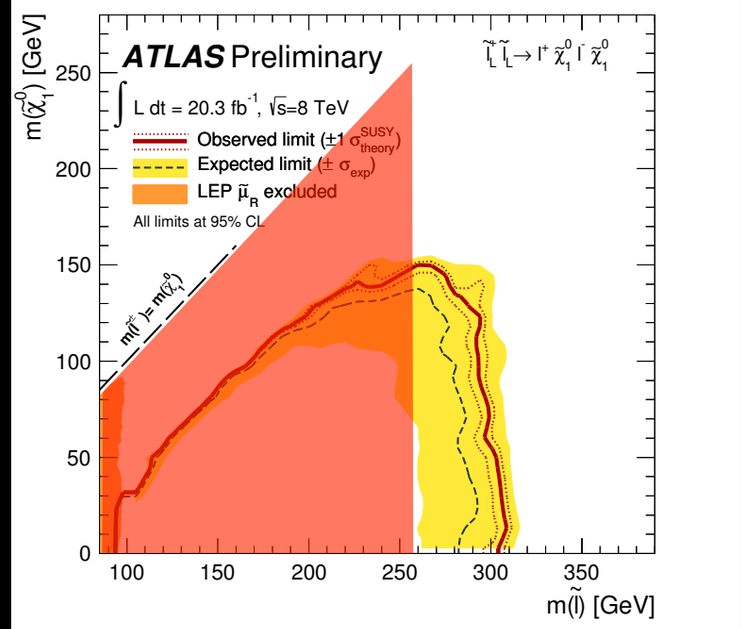


electroweak states

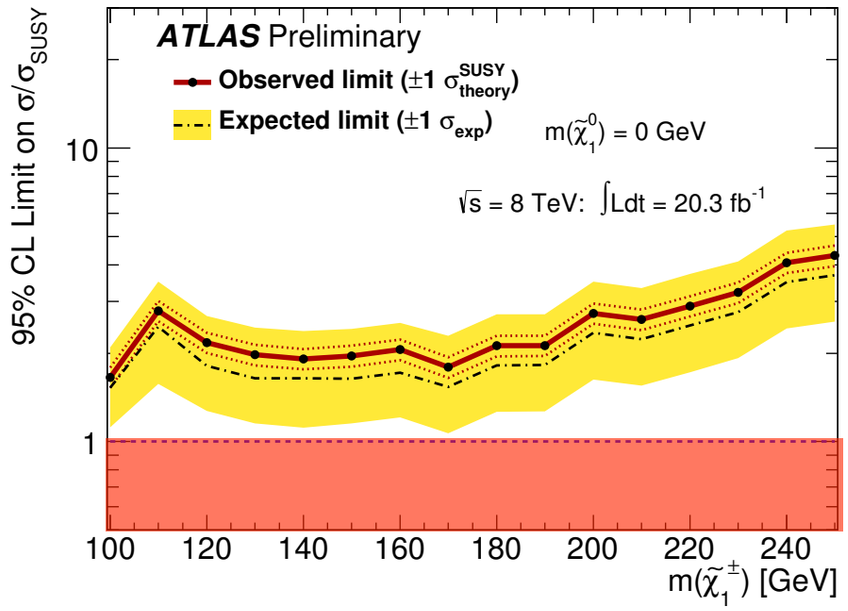
$\tilde{l}_R$



$\tilde{l}_L$



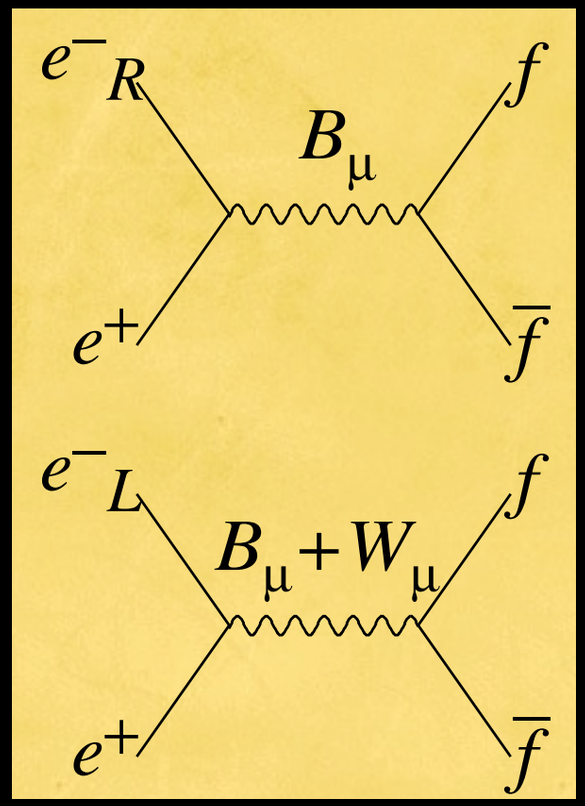
$\tilde{\chi}^{\pm}$



@ILC500

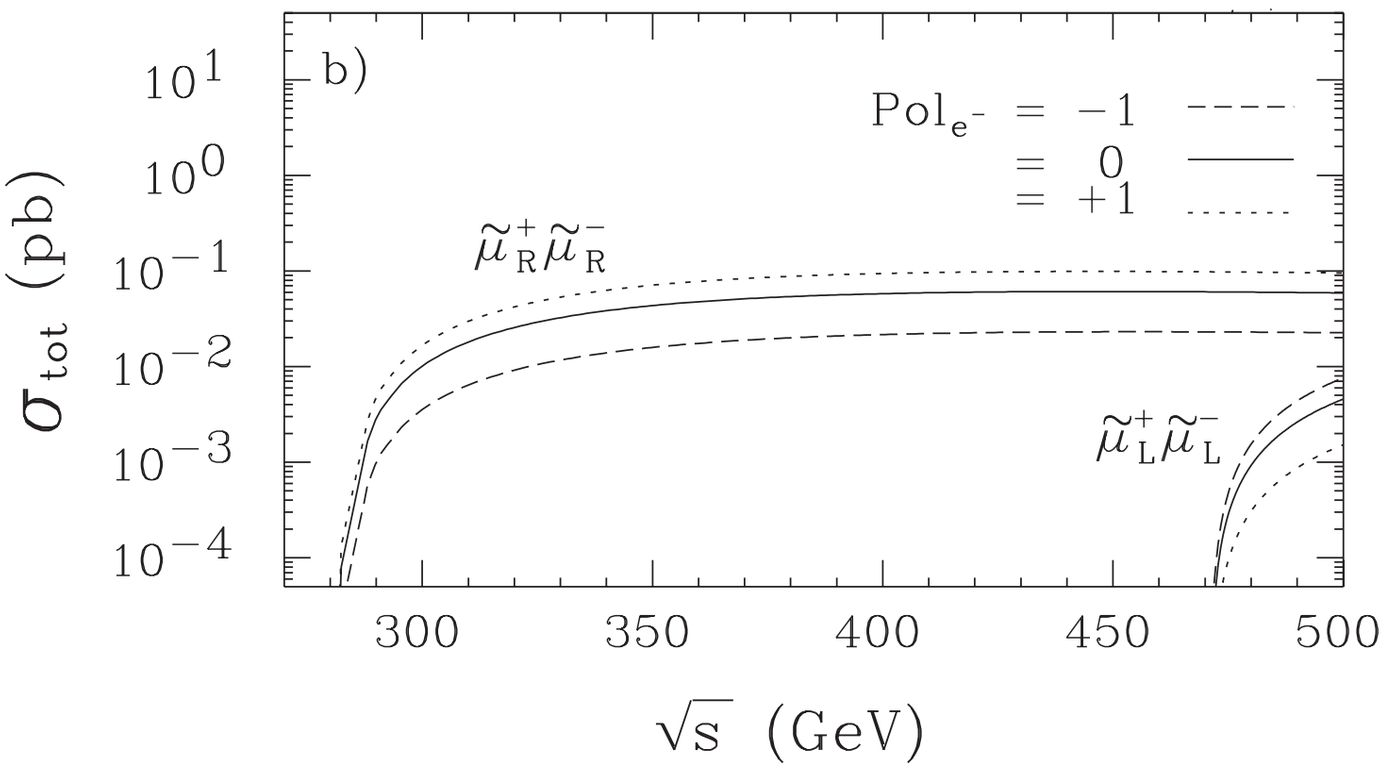
once new particle found

- Use polarized electron beam
- can ignore $m_Z^2 \ll s$
- e_R couples only to B_μ
- e_L couples to $B_\mu + W_\mu^0$
- can determine quantum #s

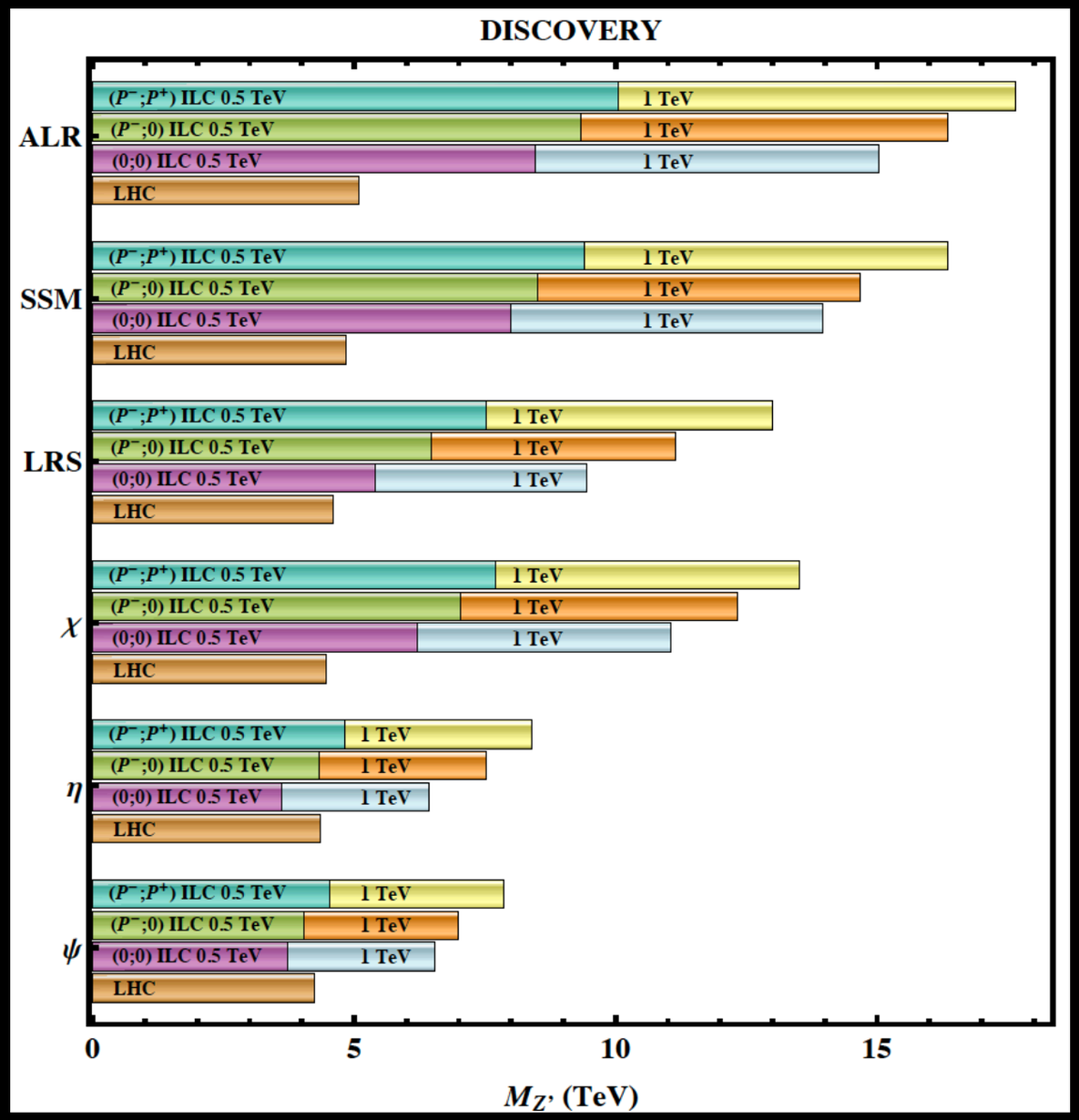


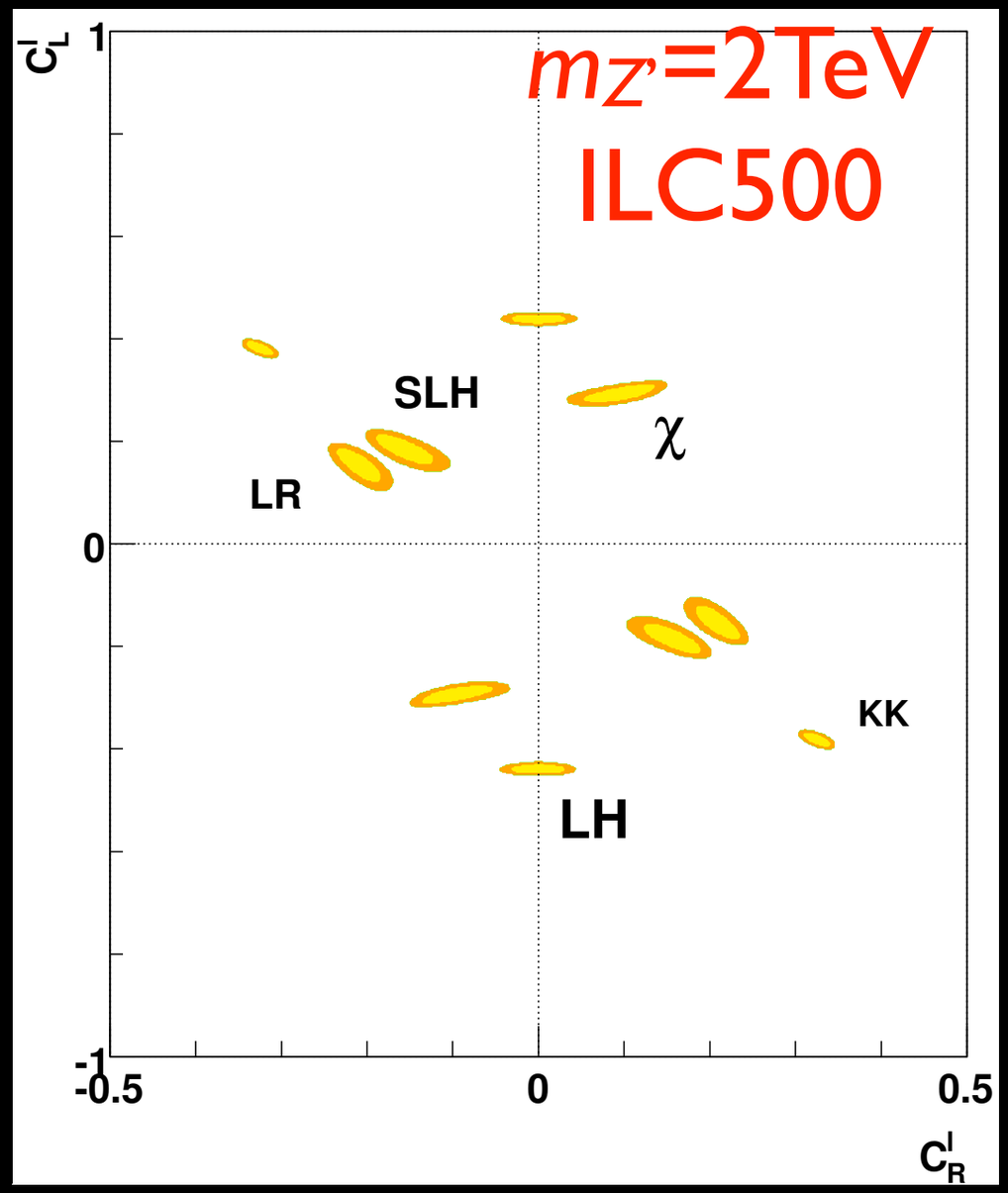
$\propto (g'^2 Y_f)^2$

$\propto (g'^2 Y_f + g^2 I_{3f})^2$



a new gauge boson





HL-LHC

- *h*(125) precision study
  - look for deviation from SM
  - test of unitarity cancellation in *WW*
  - 20–30% boost in discovery reach
  - of course hope for new physics!
  - we should definitely exploit LHC!

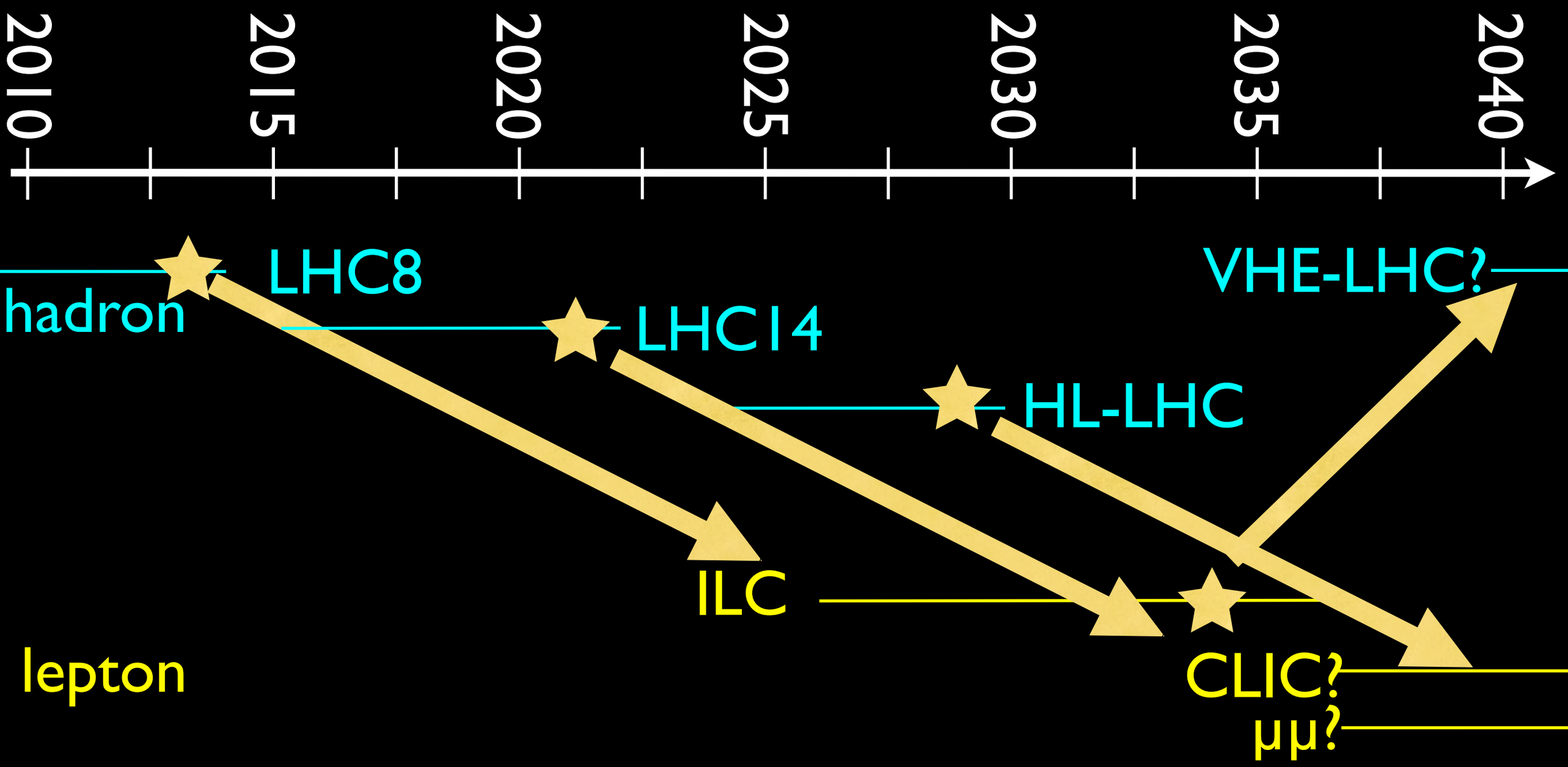
ILC

- *h*(125) higher precision study
  - look for deviation from SM
    - evolutionary program 250–1000 GeV
- search for new electroweak particles
- if nothing, we may want GigaZ, MegaW
- we need this, too!

further beyond

- VHE-LHC: best hope to go to higher energies
- CLIC: once new particle at LHC beyond Higgs, excellent case with definite energy
- μμ: *s*-channel Higgs production, possibly higher energy
- how do we justify the energy?
- meanwhile we develop technology

timeline?


2010
2015
2020
2025
2030
2035
2040
hadron
LHC8
LHC14
HL-LHC
VHE-LHC?
ILC
CLIC?
lepton
μμ?


私たちは
国際リニアコライダー
計画を応援しています。
We support the International
Linear Collider Project.
一関商工会議所／岩手県ILC推進協議会

theorist



experiments



healthy field!