東京大学 THE UNIVERSITY OF TOKYO

TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY

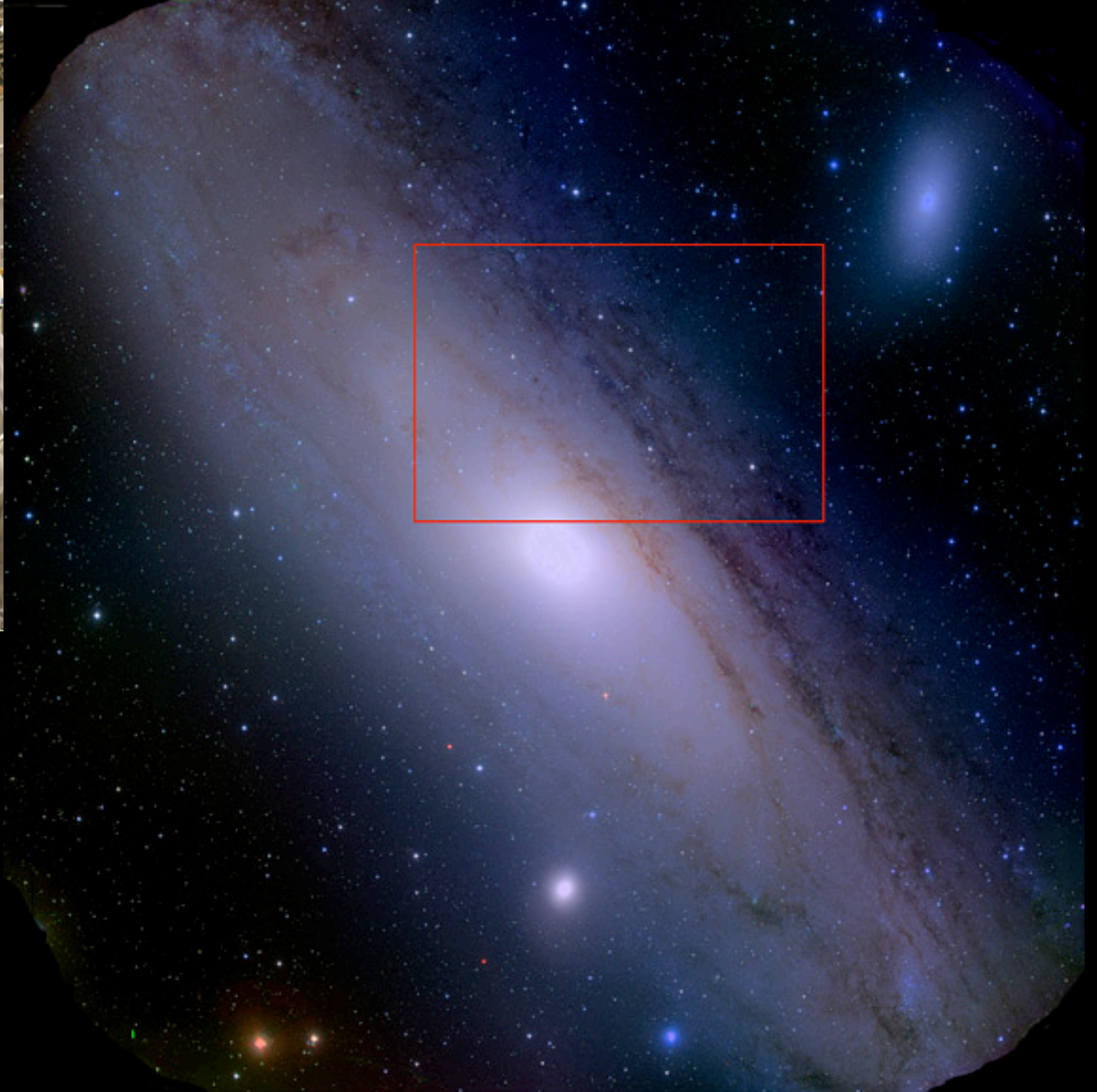
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

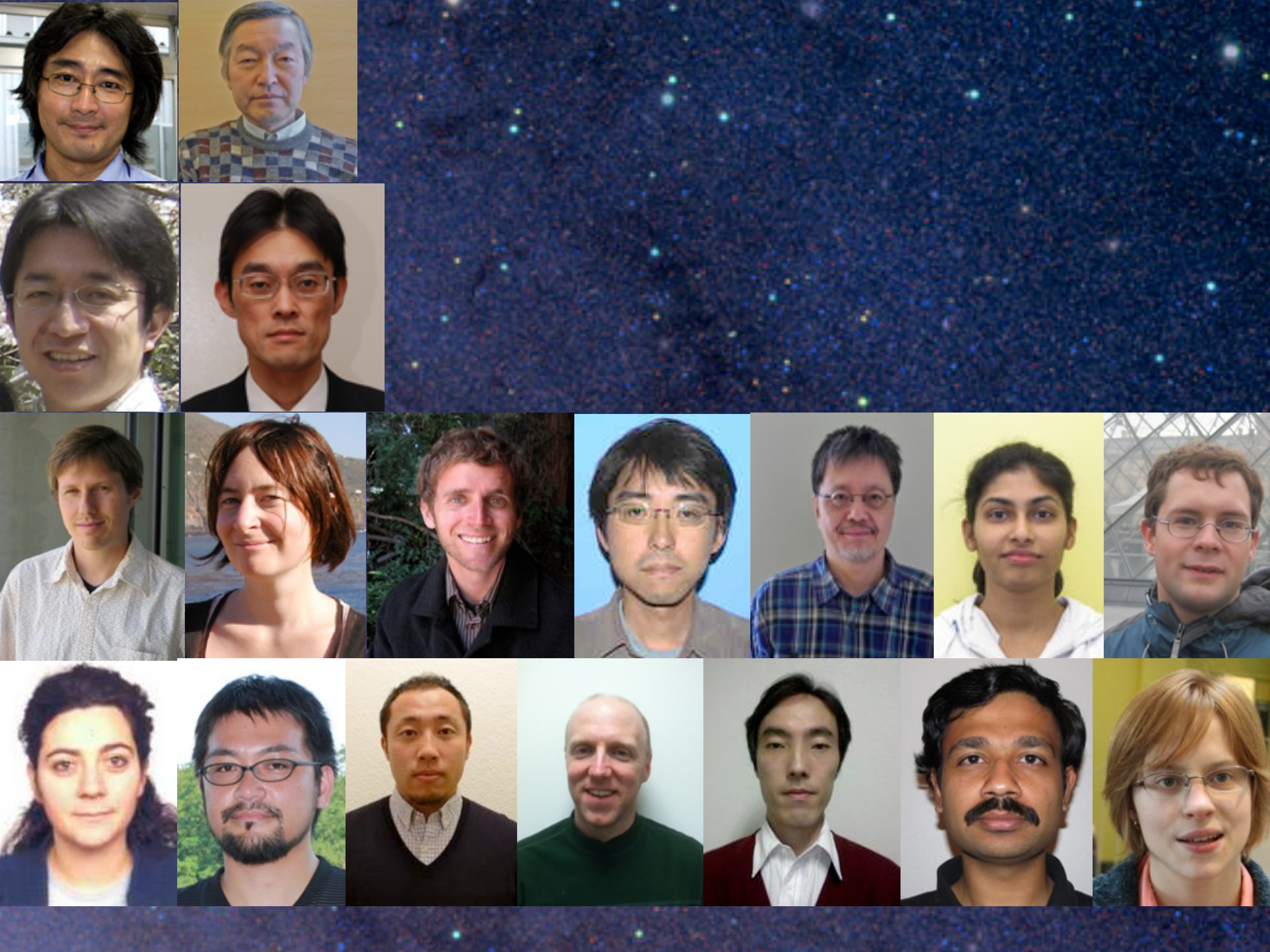
Welcome to Kavli IPMU!

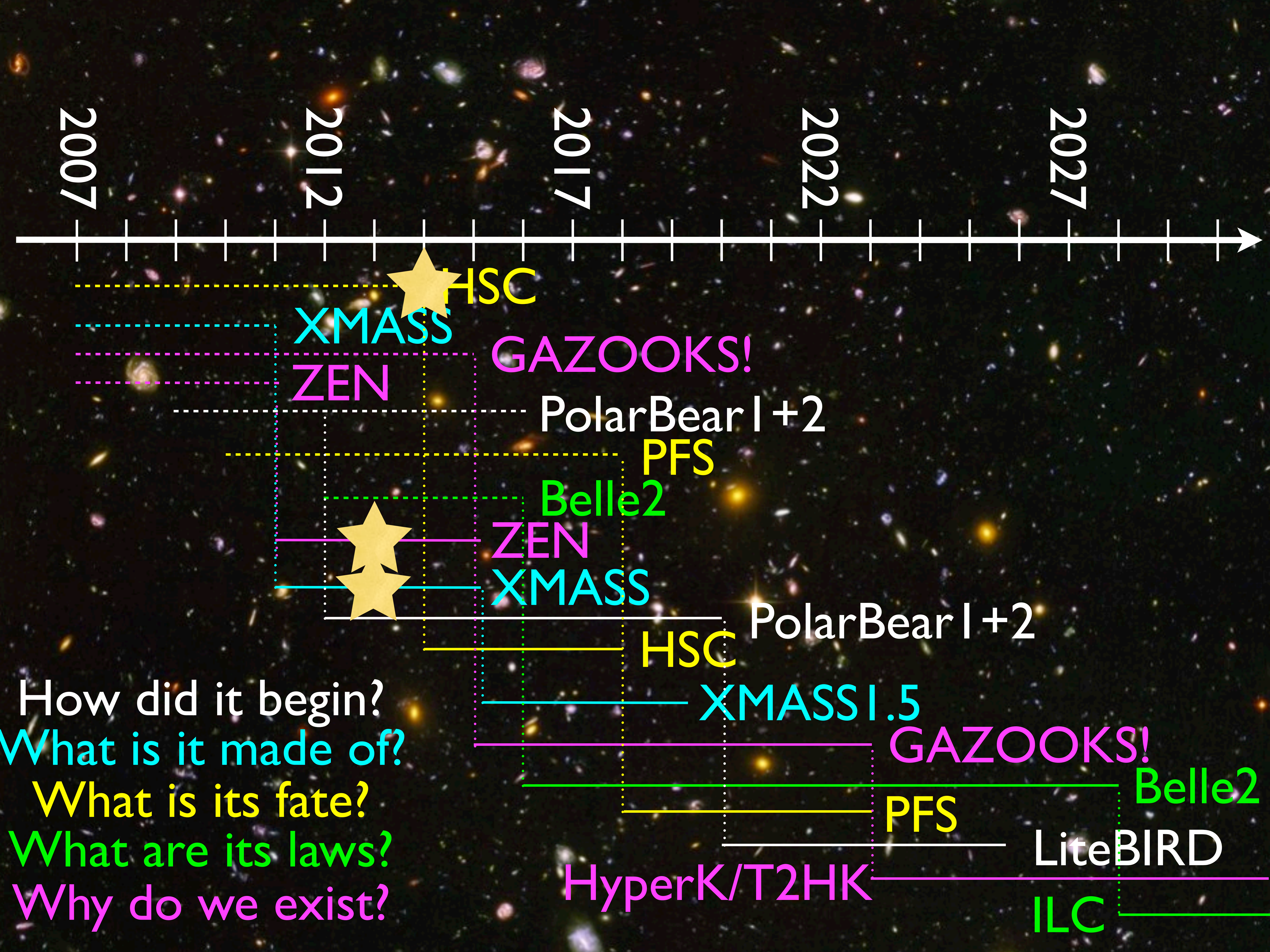
Oct 2007

Oct 2013

870M pixels,
3t, 1000xHST






2007
2012
2017
2022
2027
HSC
XMASS
GAZOOKS!
ZEN
PolarBear1+2
PFS
Belle2
ZEN
XMASS
PolarBear1+2
HSC
XMASS1.5
GAZOOKS!
Belle2
PFS
LiteBIRD
HyperK/T2HK
ILC
How did it begin?
What is it made of?
What is its fate?
What are its laws?
Why do we exist?

東京大学 THE UNIVERSITY OF TOKYO

TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

BERKELEY CENTER FOR THEORETICAL PHYSICS

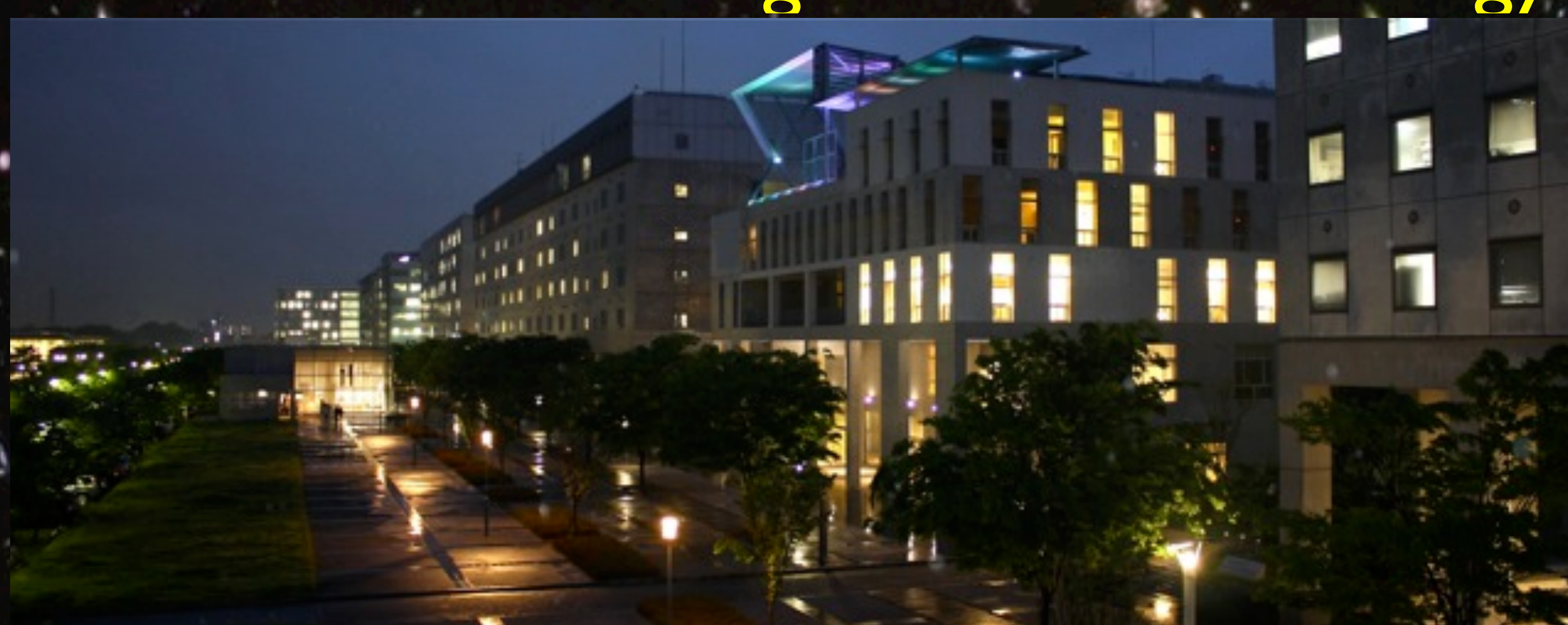
BERKELEY LAB

Is there Life after Higgs?

Hitoshi Murayama (Berkeley & Kavli IPMU)

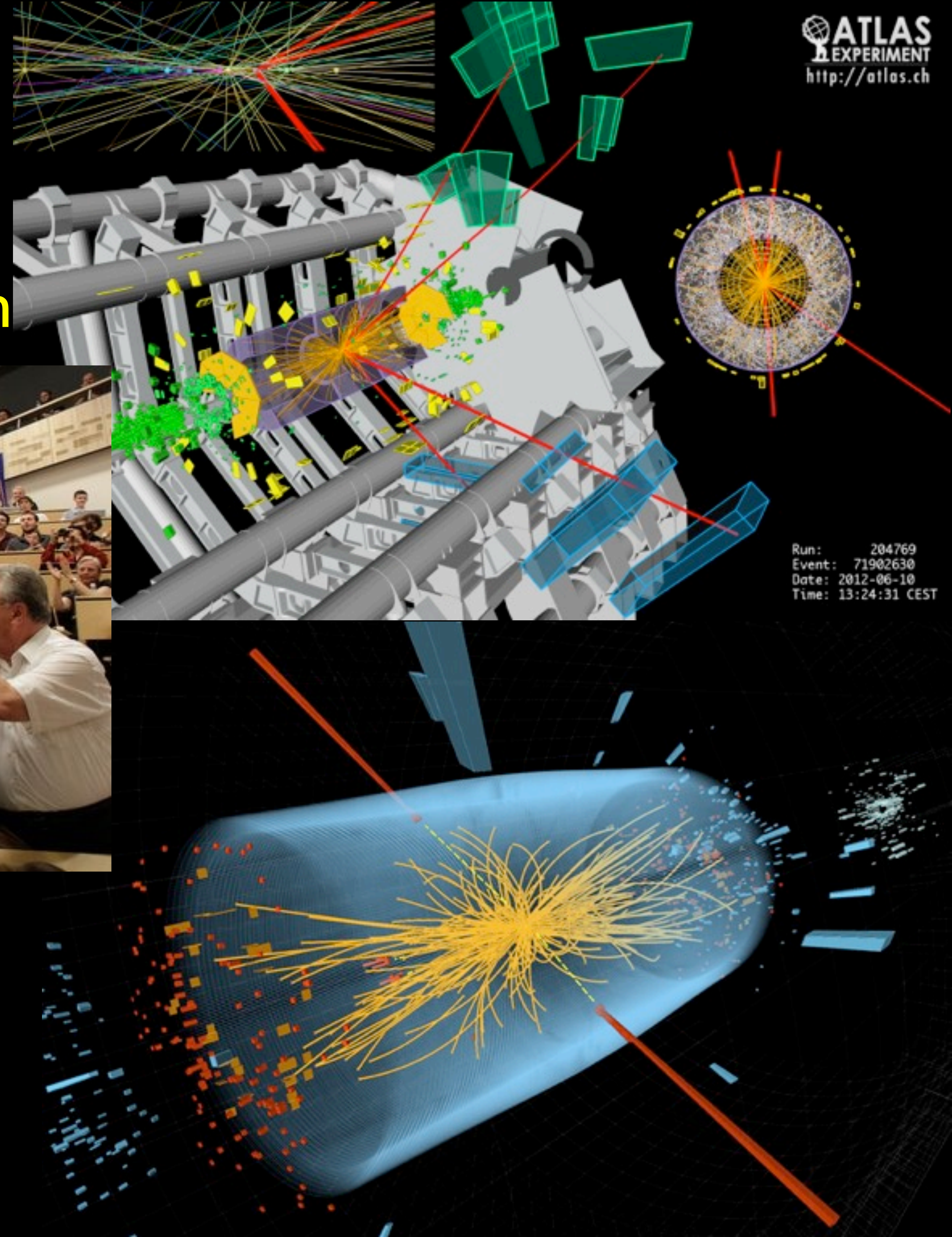
Dec 2, 2013

SUSY: Model Building and Phenomenology



2012.7.4

discovery of Higgs boson

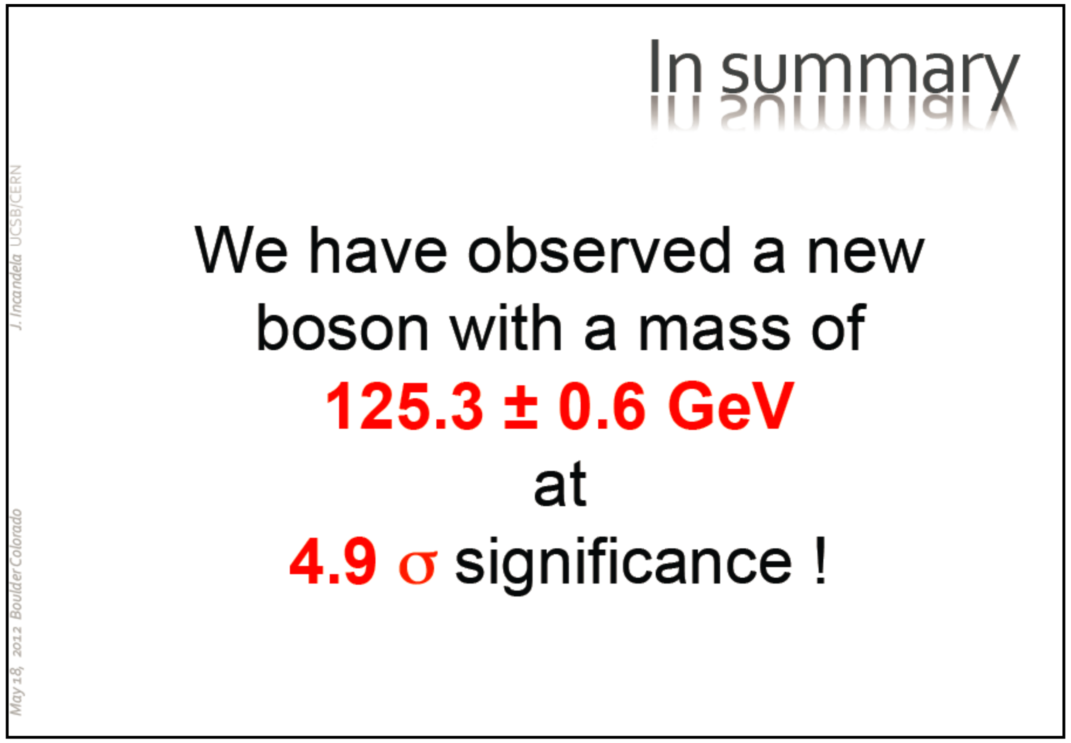


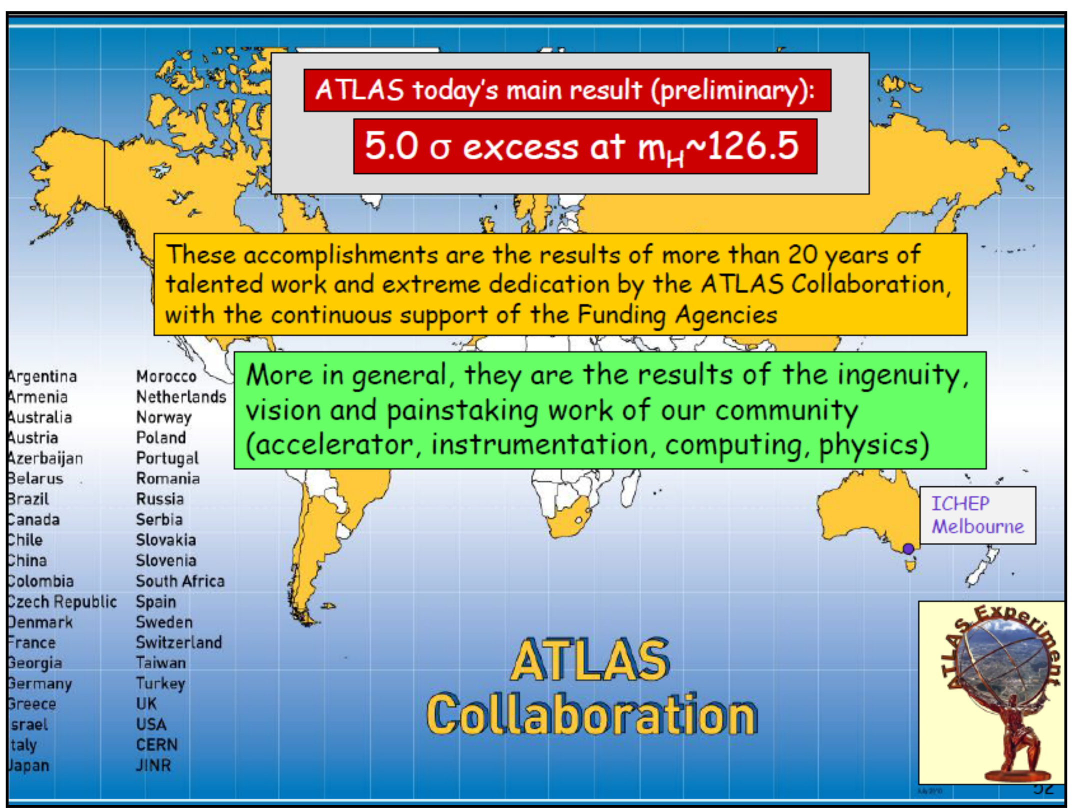
theory : 1964

design : 1984

construction : 1998

July 4, 2012


In summary
J. Incandela UCSB/CERN
May 18, 2012 Boulder Colorado
We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !


ATLAS today's main result (preliminary):
5.0 σ excess at m_H~126.5
These accomplishments are the results of more than 20 years of talented work and extreme dedication by the ATLAS Collaboration, with the continuous support of the Funding Agencies
More in general, they are the results of the ingenuity, vision and painstaking work of our community (accelerator, instrumentation, computing, physics)
Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ICHEP Melbourne
ATLAS Collaboration
ATLAS Experiment


CERN
Higgs search
update 04.07.2012


Higgsdependence Day
July 4, 2012

CERN official statements

Higgs-like boson

↓

a Higgs boson

have seen $hZ_\mu Z^\mu$ ~~$hZ_{\mu\nu}Z^{\mu\nu}$ $hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$ $h_{\mu\nu}Z^{\mu\rho}Z^{\nu}_{\rho}$~~

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

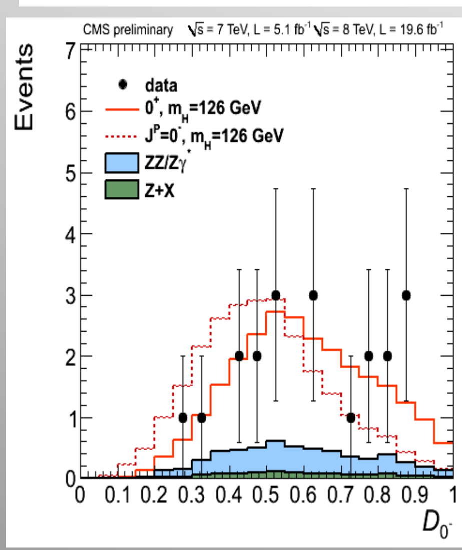
only way $h\langle h\rangle Z_\mu Z^\mu$

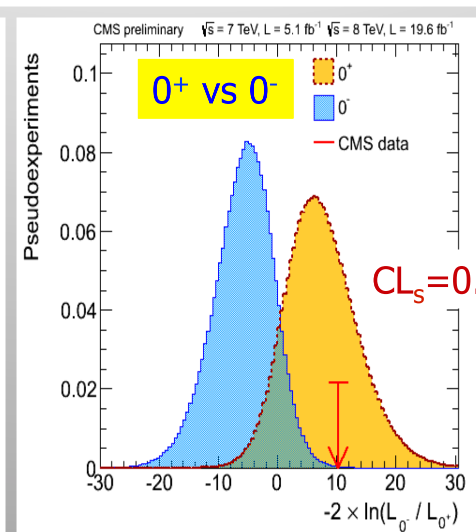
we have discovered a particle that **has a value in vacuum**

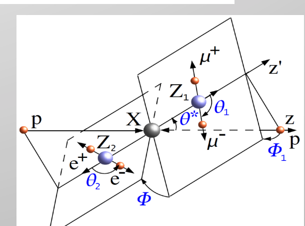
Spin/Parity Hypothesis Tests

Spin/parity hypothesis tests: $H \to ZZ \to 4l$ channel

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





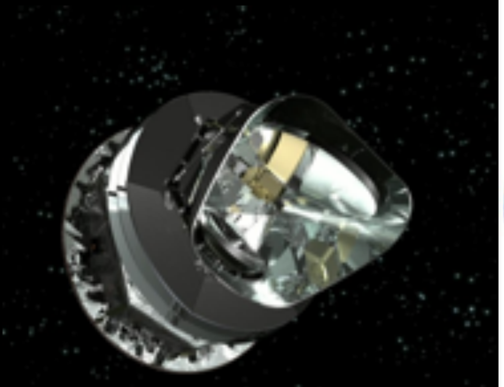


J^P	CL_s
0^-	0.16%
0^+_h	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

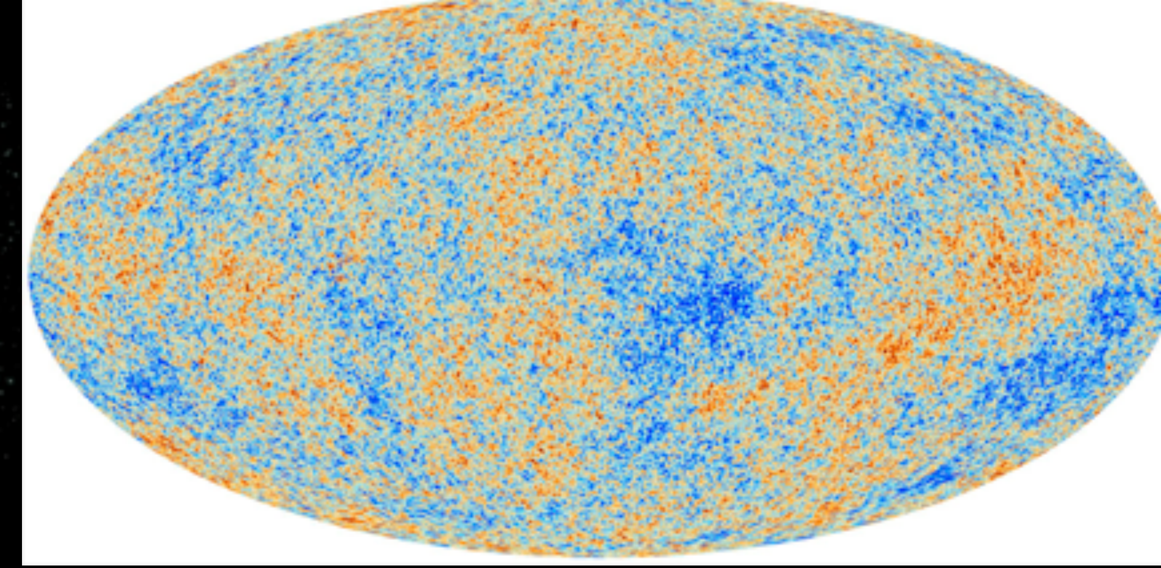
More J^P hypotheses have been tested in a similar way →

KAVLI IPMU

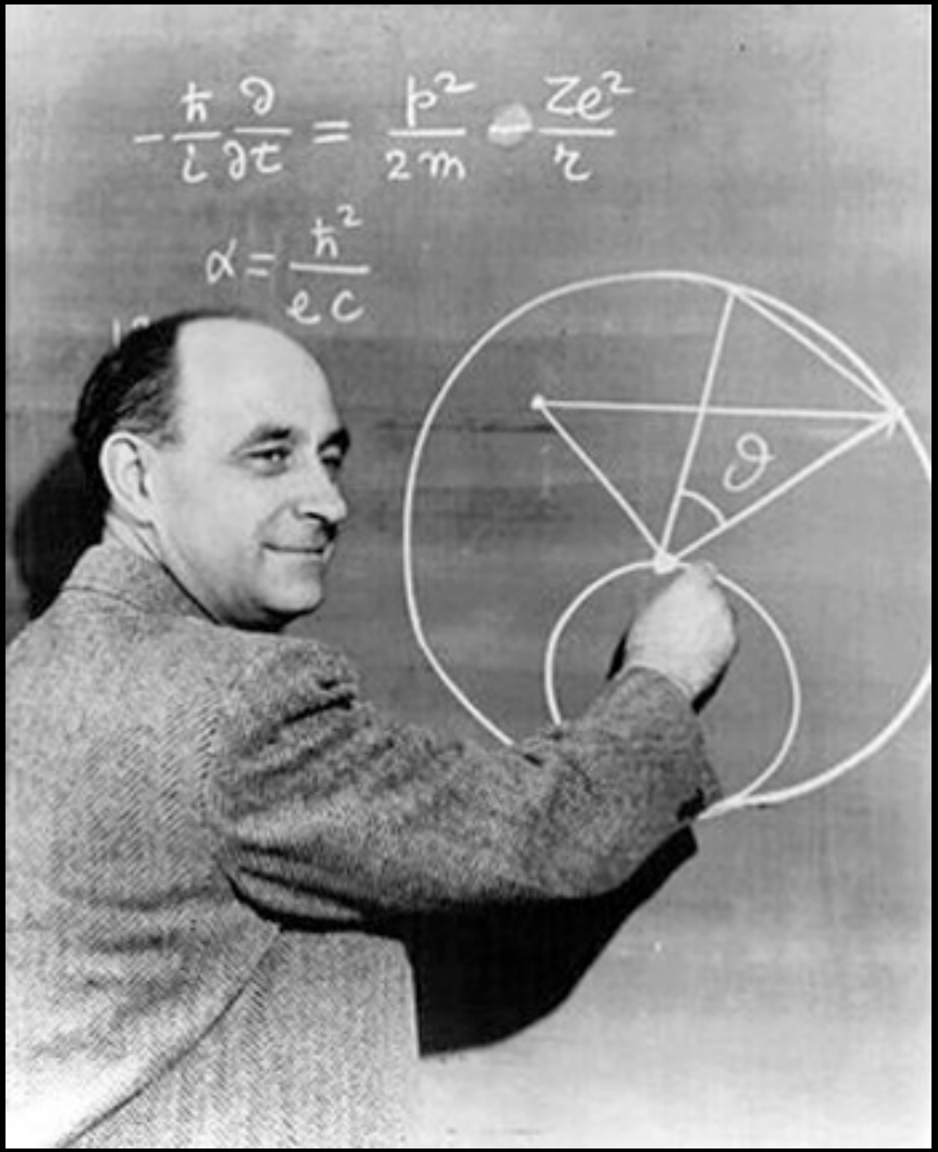
Minimal



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!!!*

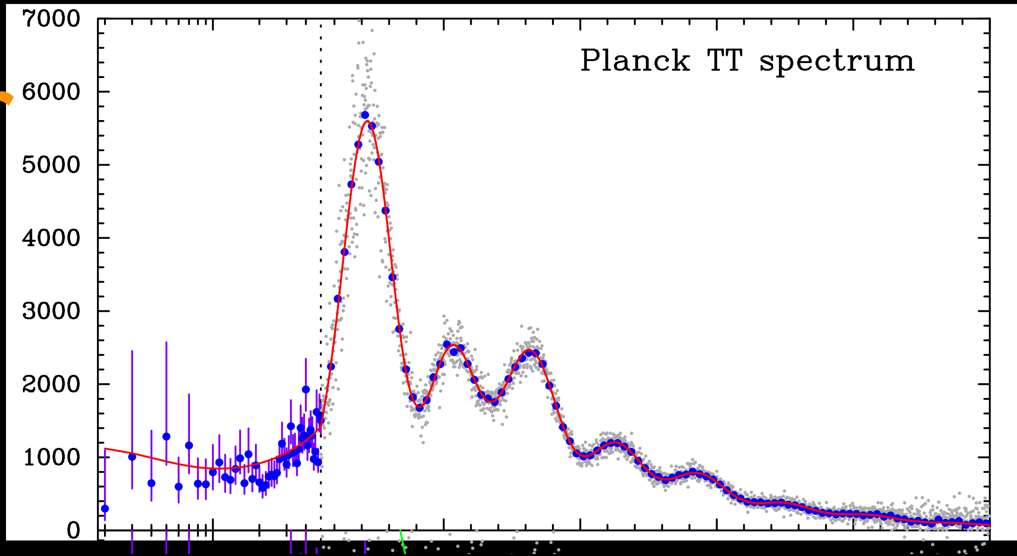


Where do we go next?

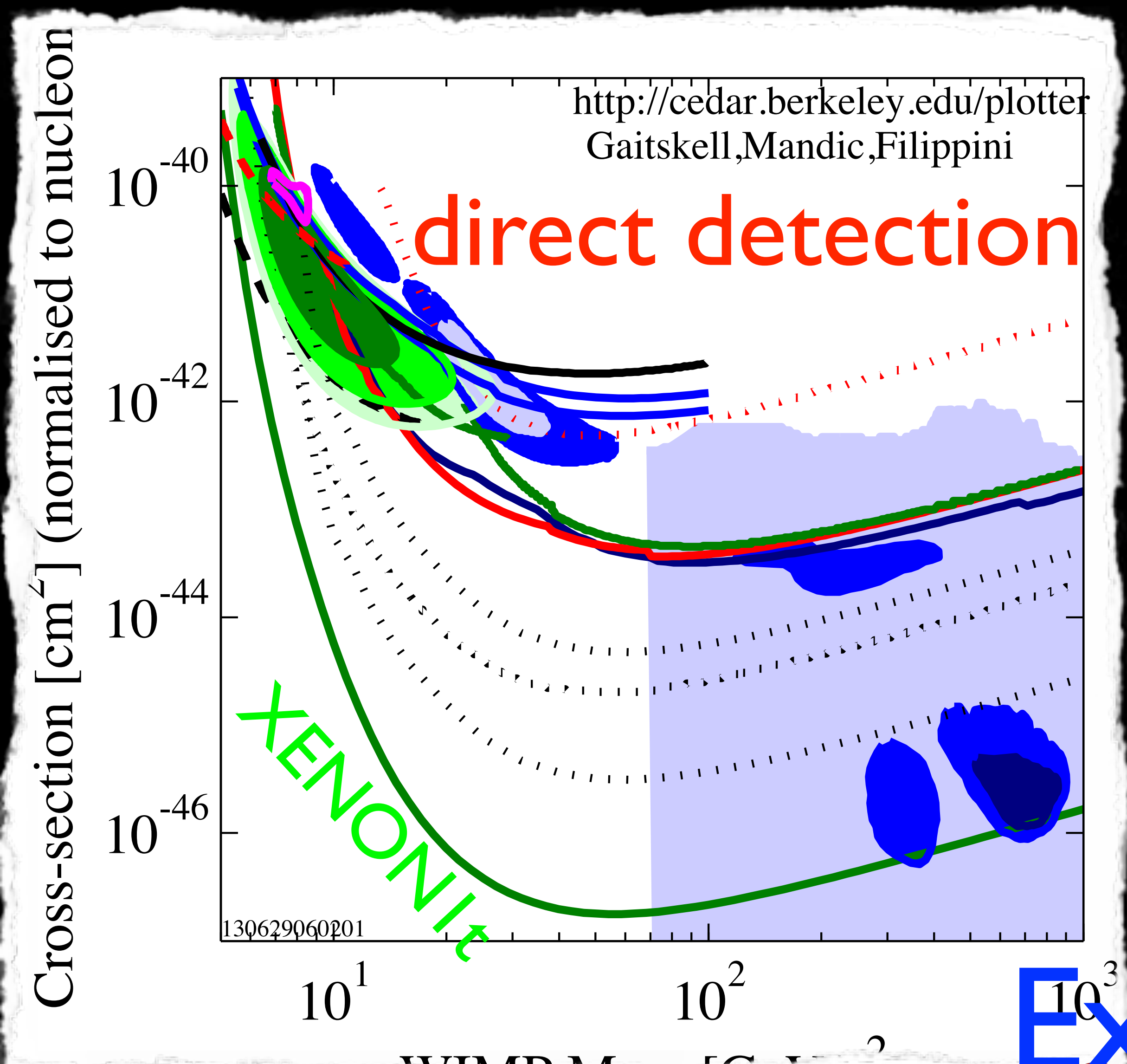
Is particle physics over?

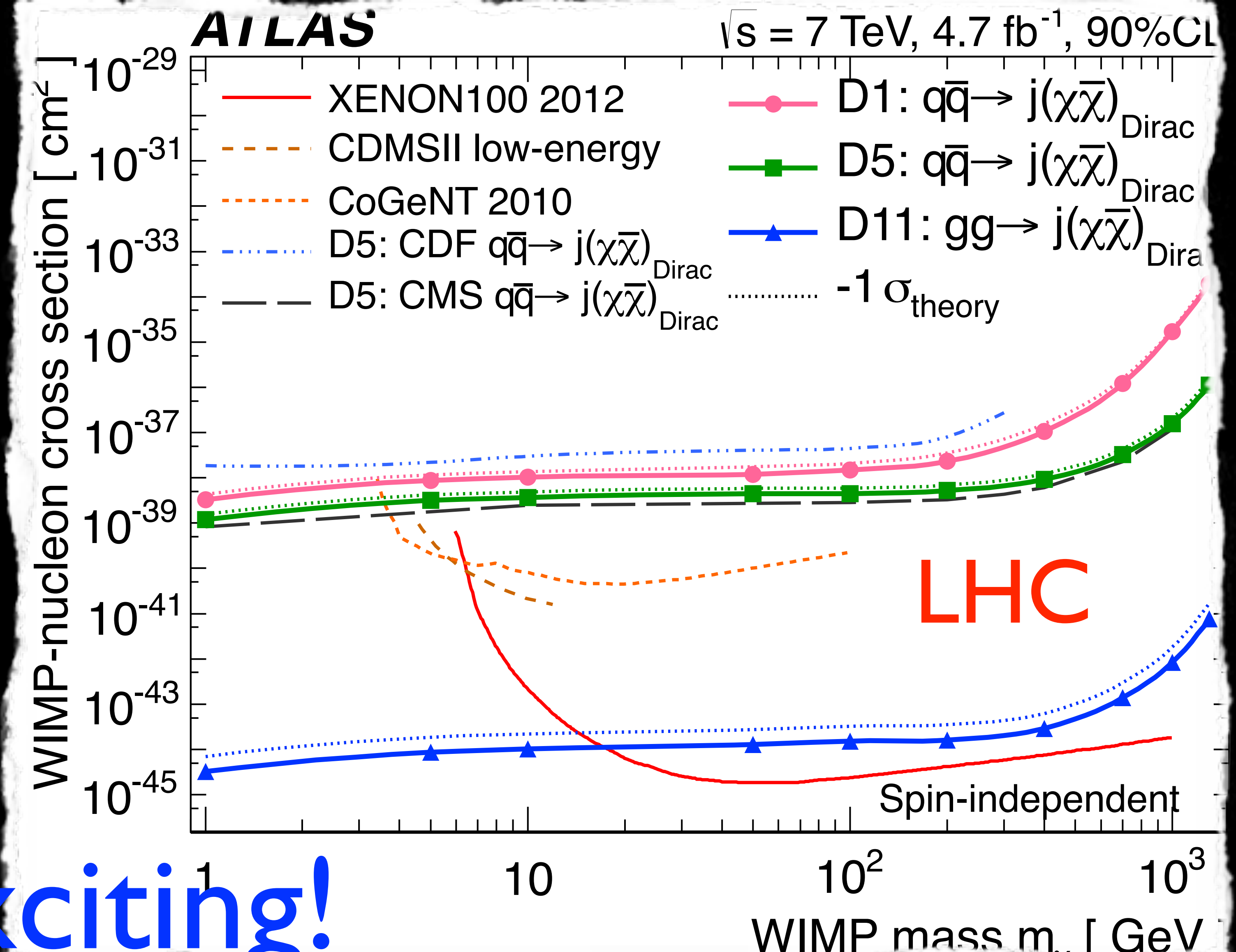
Five evidences for physics beyond SM

- 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

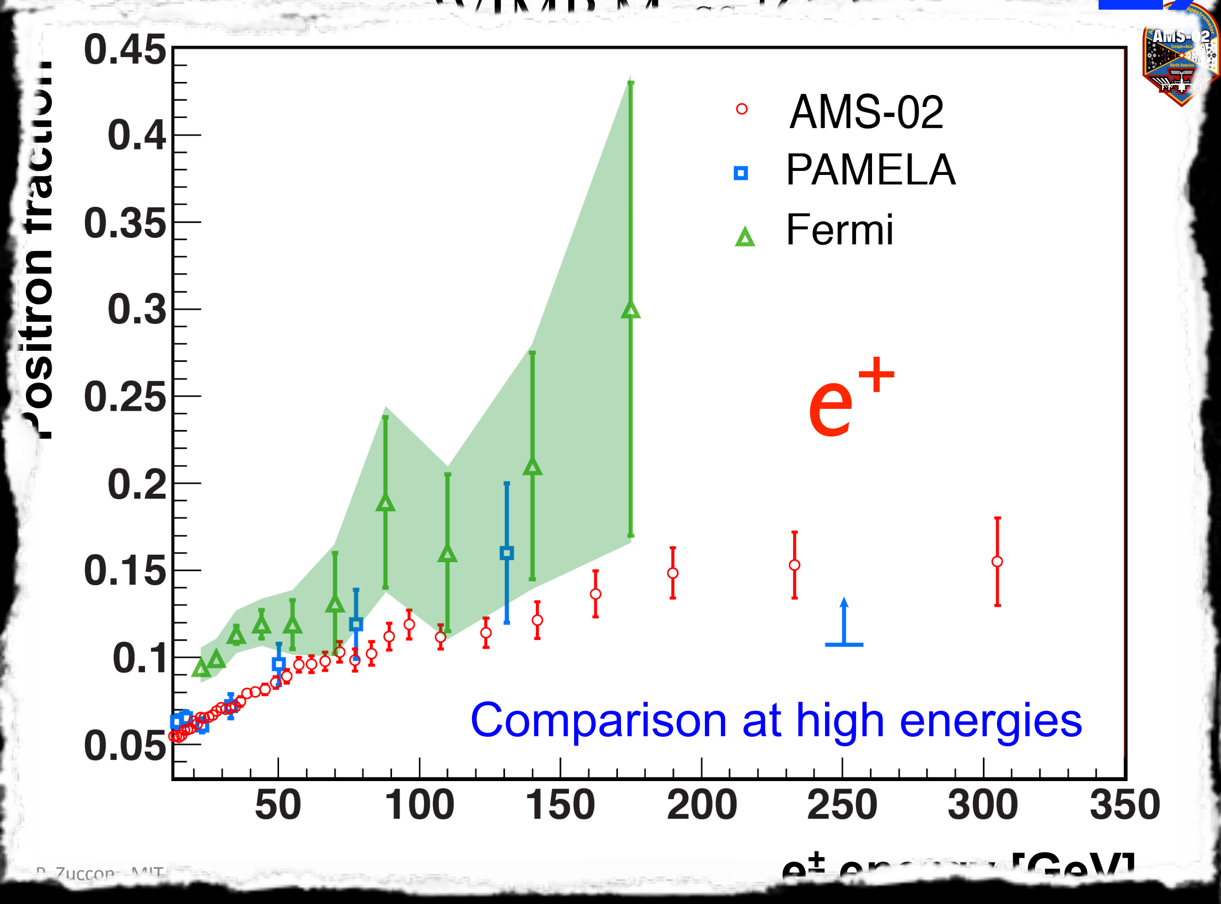


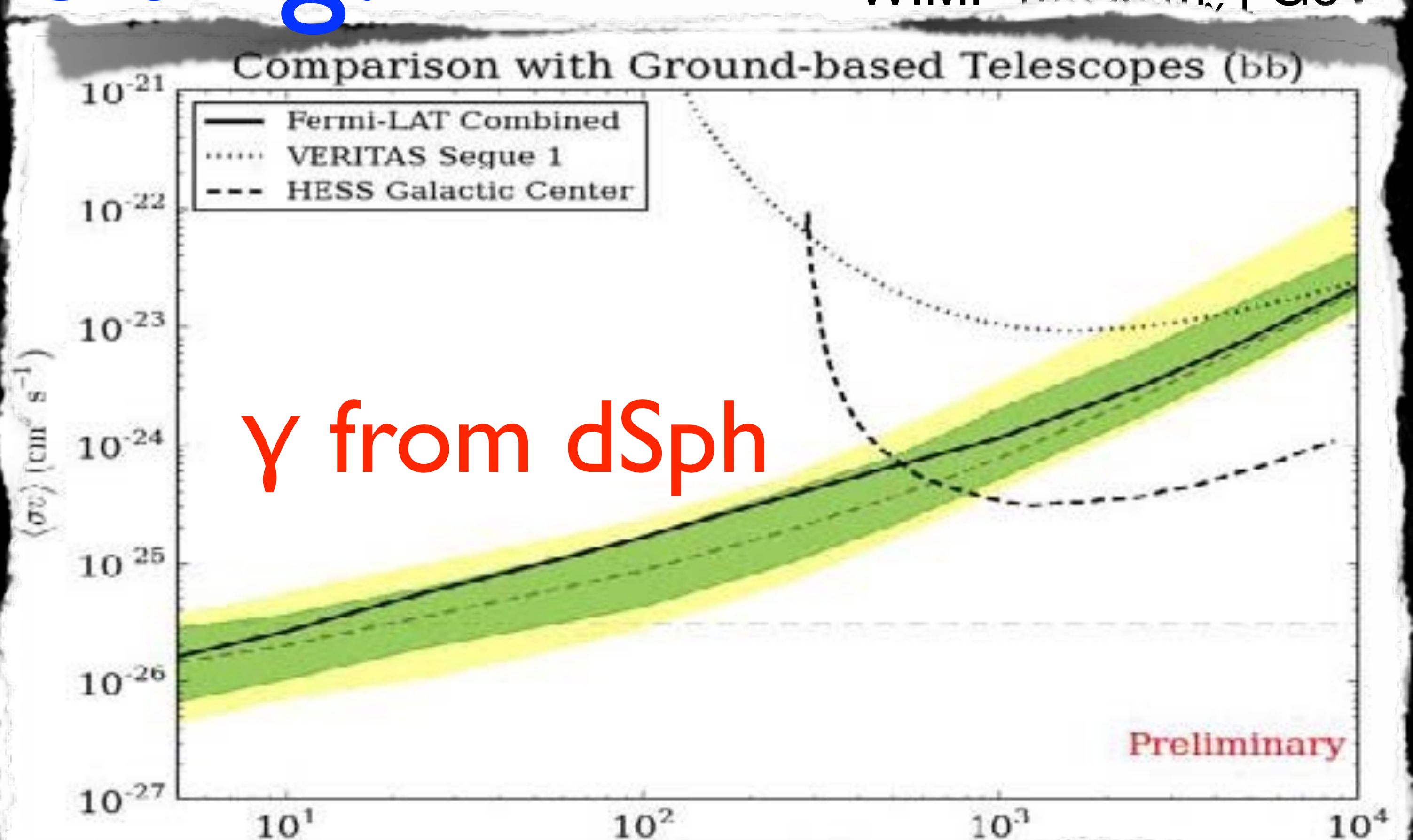
We don't really know their energy scales...


http://cedar.berkeley.edu/plotter
Gaitskell,Mandic,Filippini
direct detection
XENON1t
Cross-section [cm²] (normalised to nucleon)
10⁻⁴⁰
10⁻⁴²
10⁻⁴⁴
10⁻⁴⁶
10¹
10²
10³
130629060201


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)Dirac
-1 σtheory
LHC
Spin-independent
WIMP-nucleon cross section [cm²]
WIMP mass mχ [GeV]

Exciting!

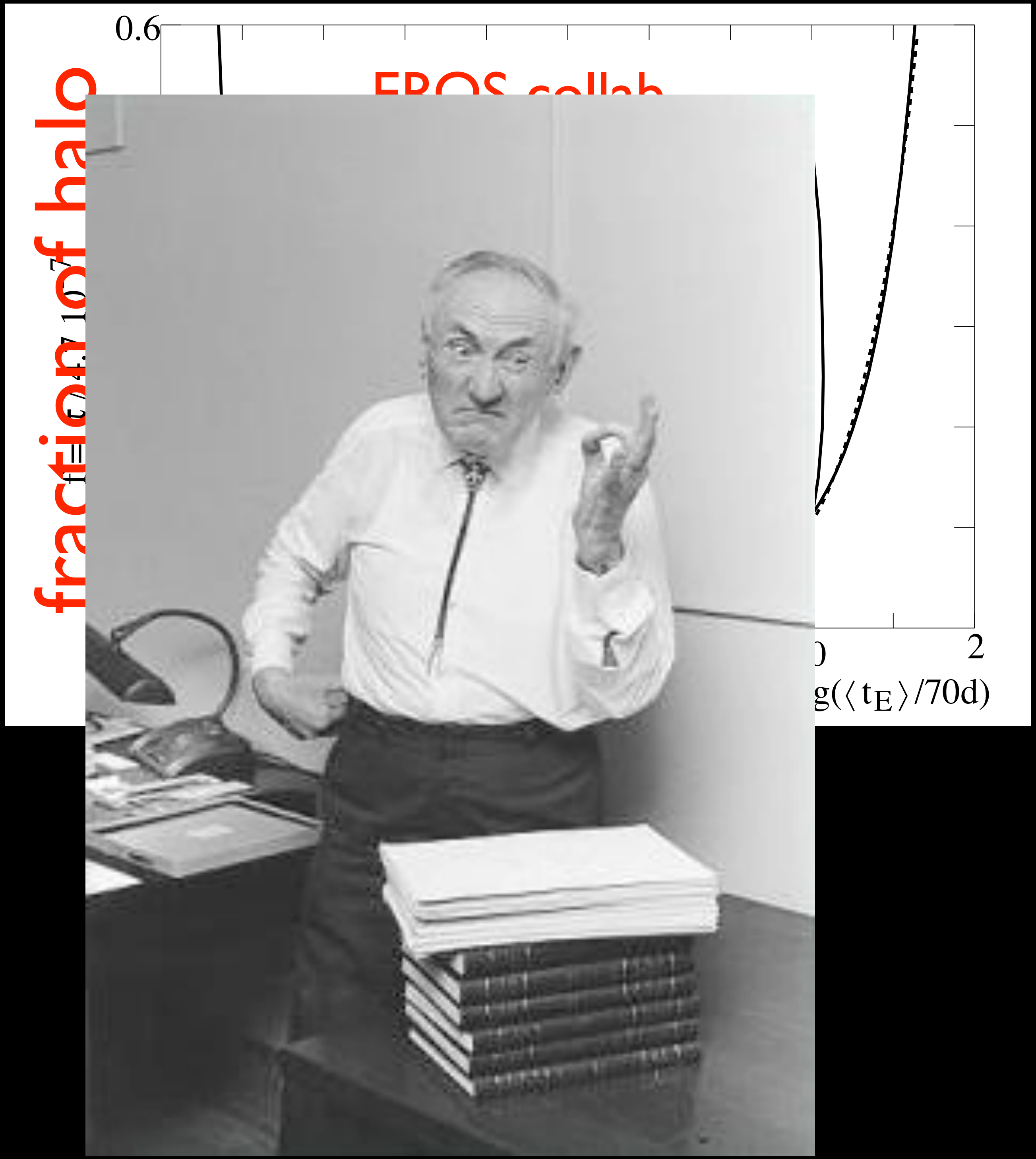

AMS-02
PAMELA
Fermi
e⁺
Comparison at high energies
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
50
100
150
200
250
300
350


Comparison with Ground-based Telescopes (bb)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
γ from dSph
Preliminary
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²⁷
10¹
10²
10³
10⁴

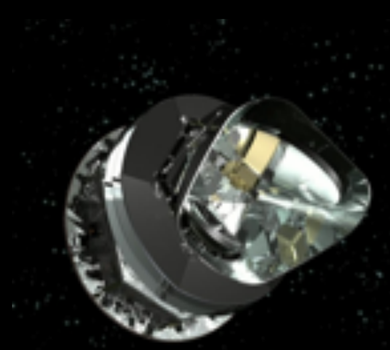
mass of dark matter

- 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

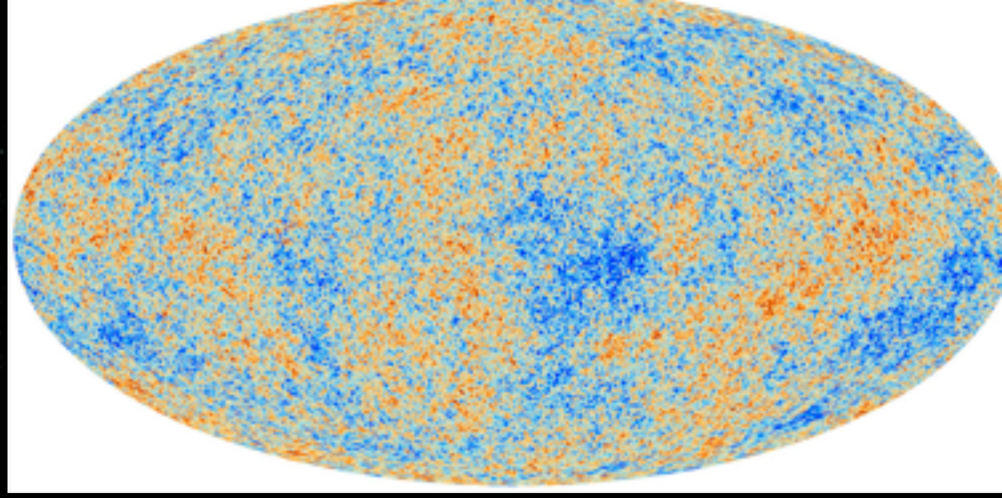
need to keep our mind open



Baryon Asymmetry



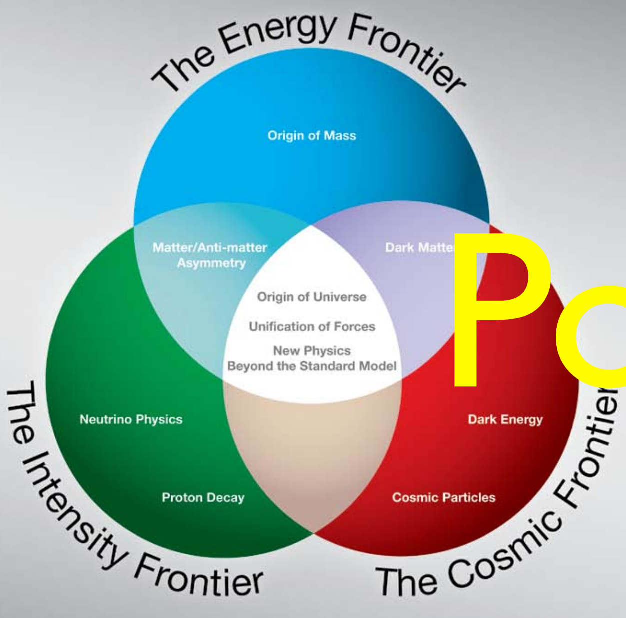
Planck

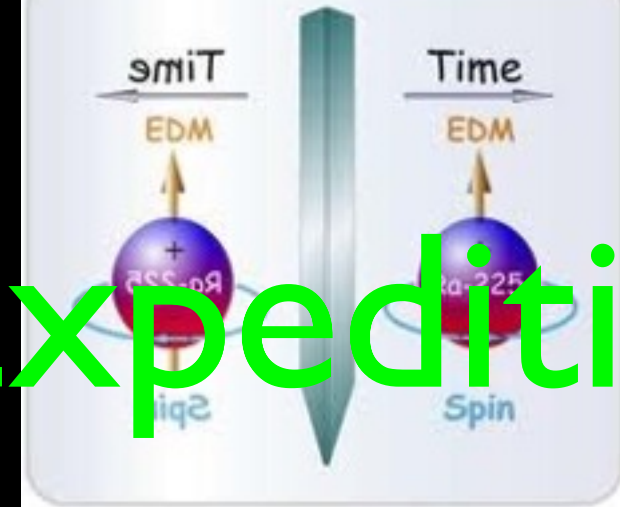


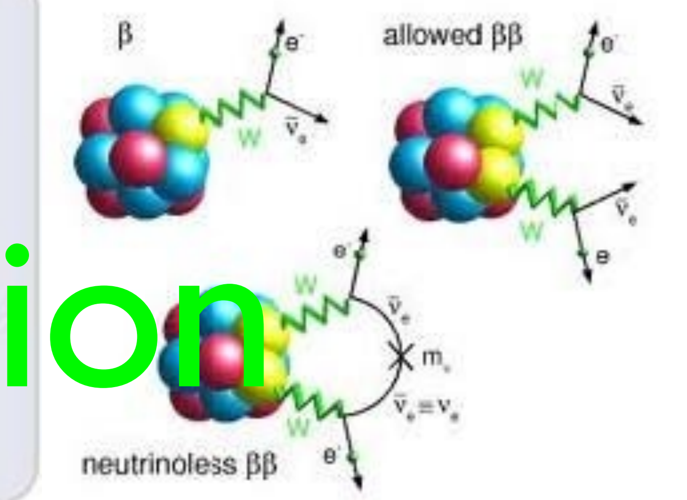
- with success of inflation, it can't be the initial condition of the Universe
- Kobayashi and Maskawa phase can only explain $\eta_b \approx \alpha_W^5 J \approx 10^{-27}$
- new sources of CPV are needed
- we also need to see how anti-matter can turn into matter

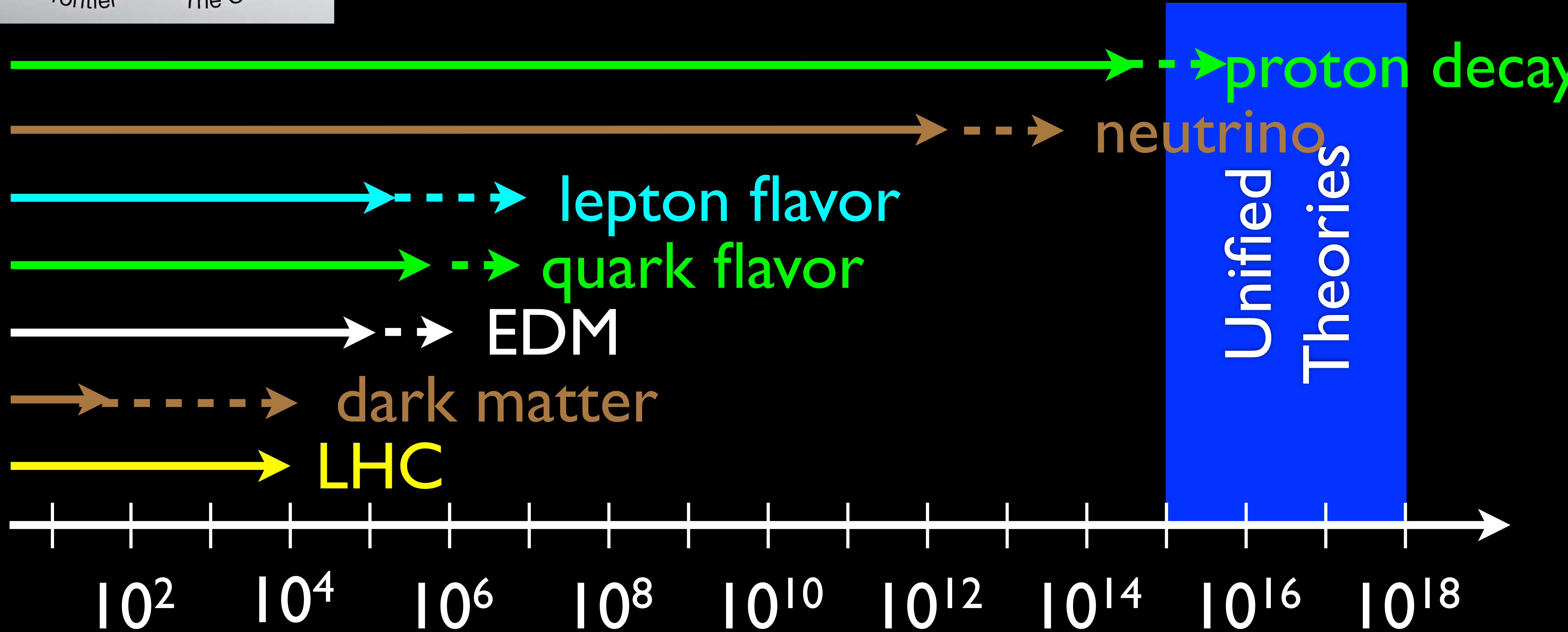
quark sector: LHCb, SuperKEKB, rare kaon decays
lepton sector: CPV in neutrinos, $0\nu\beta\beta$, LFV
both sectors: proton decay

Power of Expedition









experimental reach [GeV]

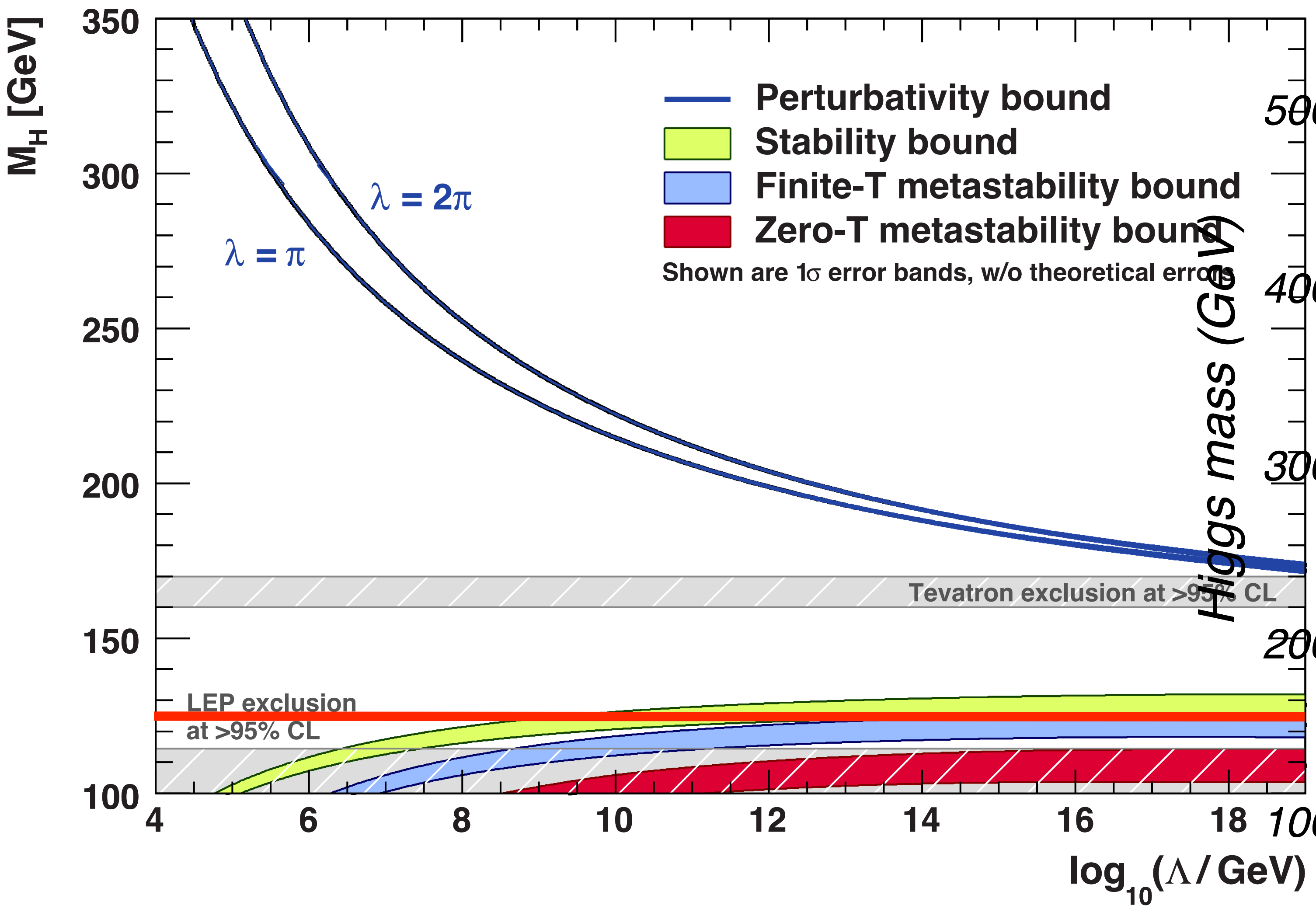
(with significant simplifying assumptions)

baryon asymmetry

Is energy frontier dead?

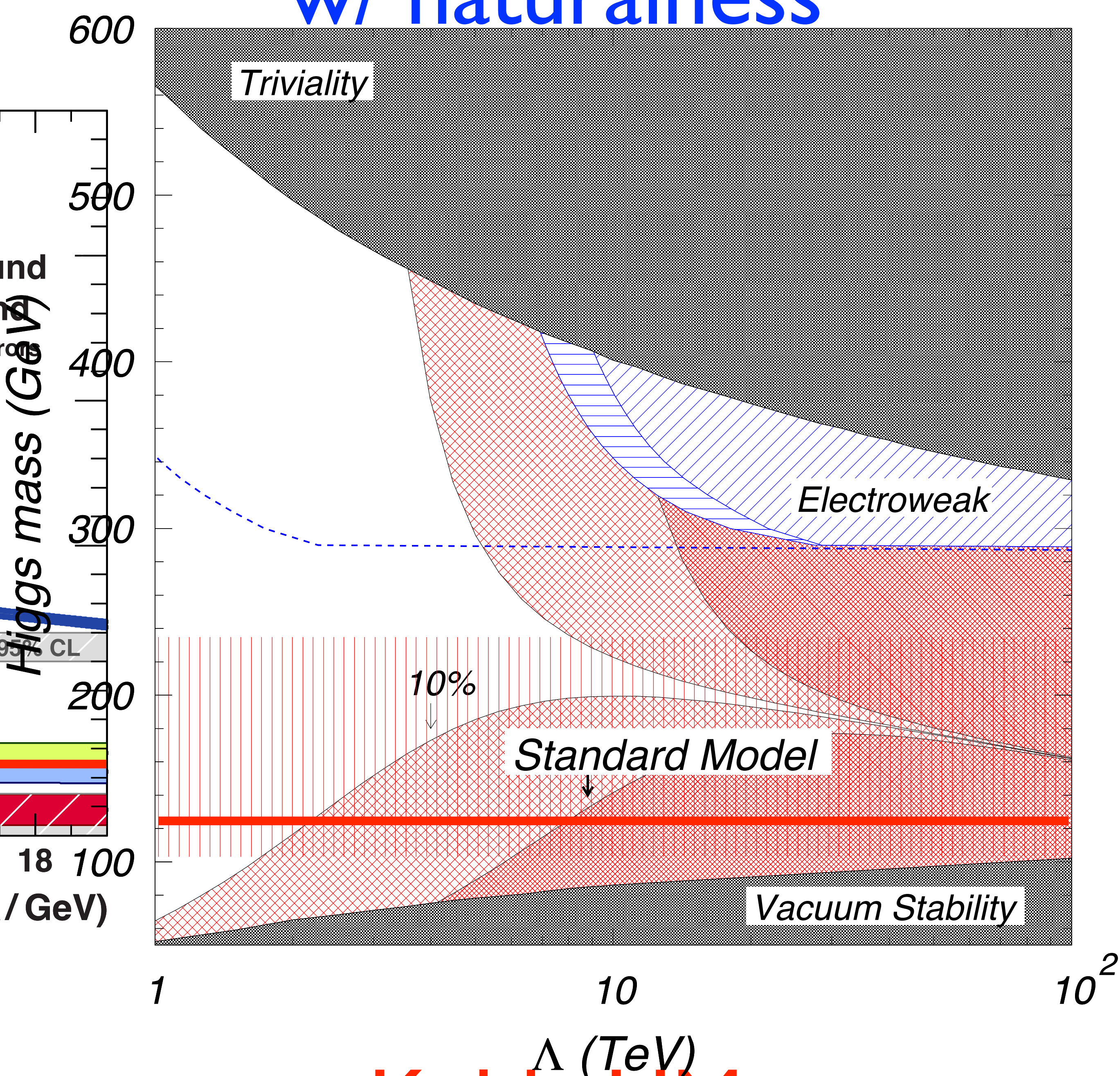
Next energy scale

w/o naturalness

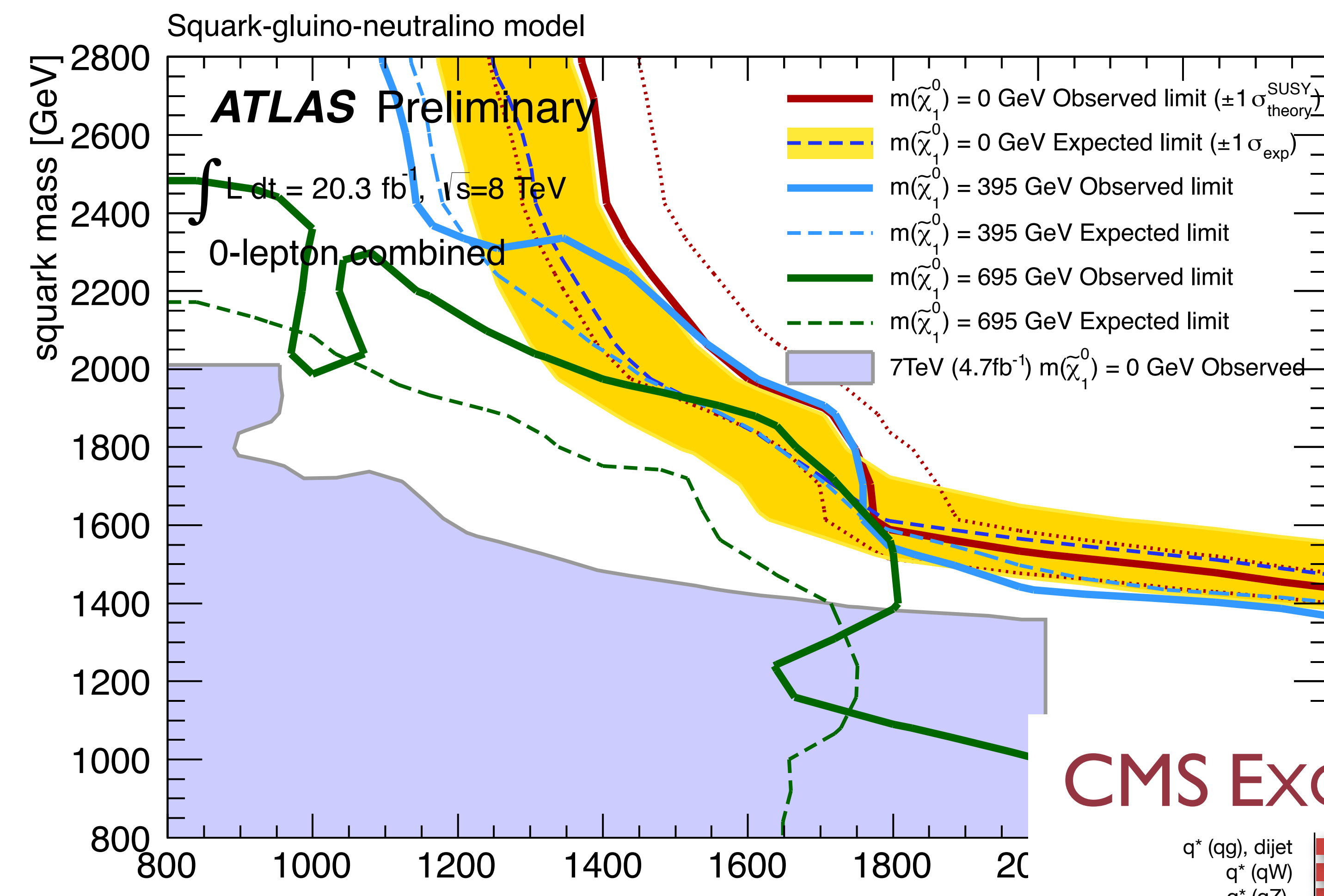


Harigaya, Matsumoto, HM

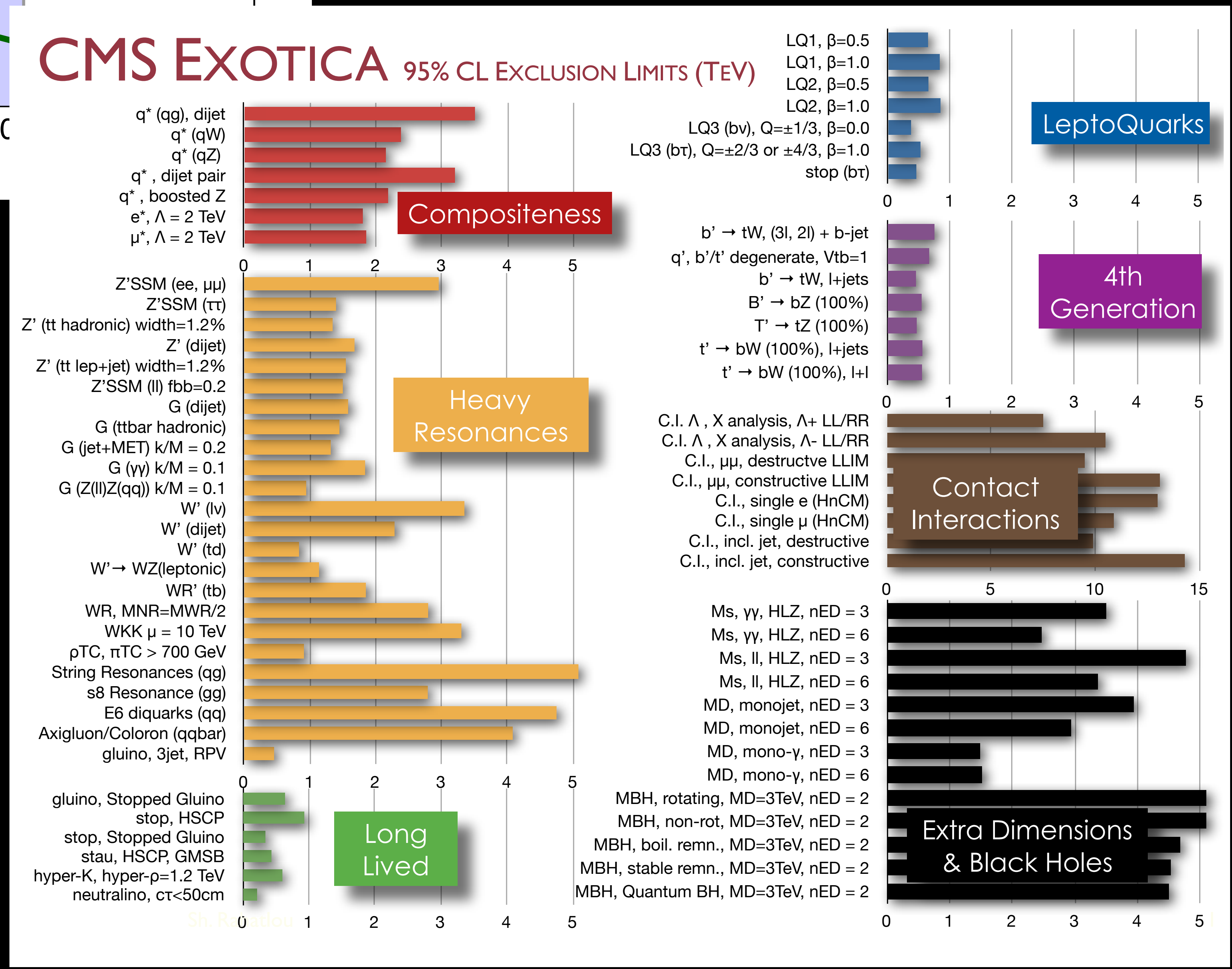
w/ naturalness



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

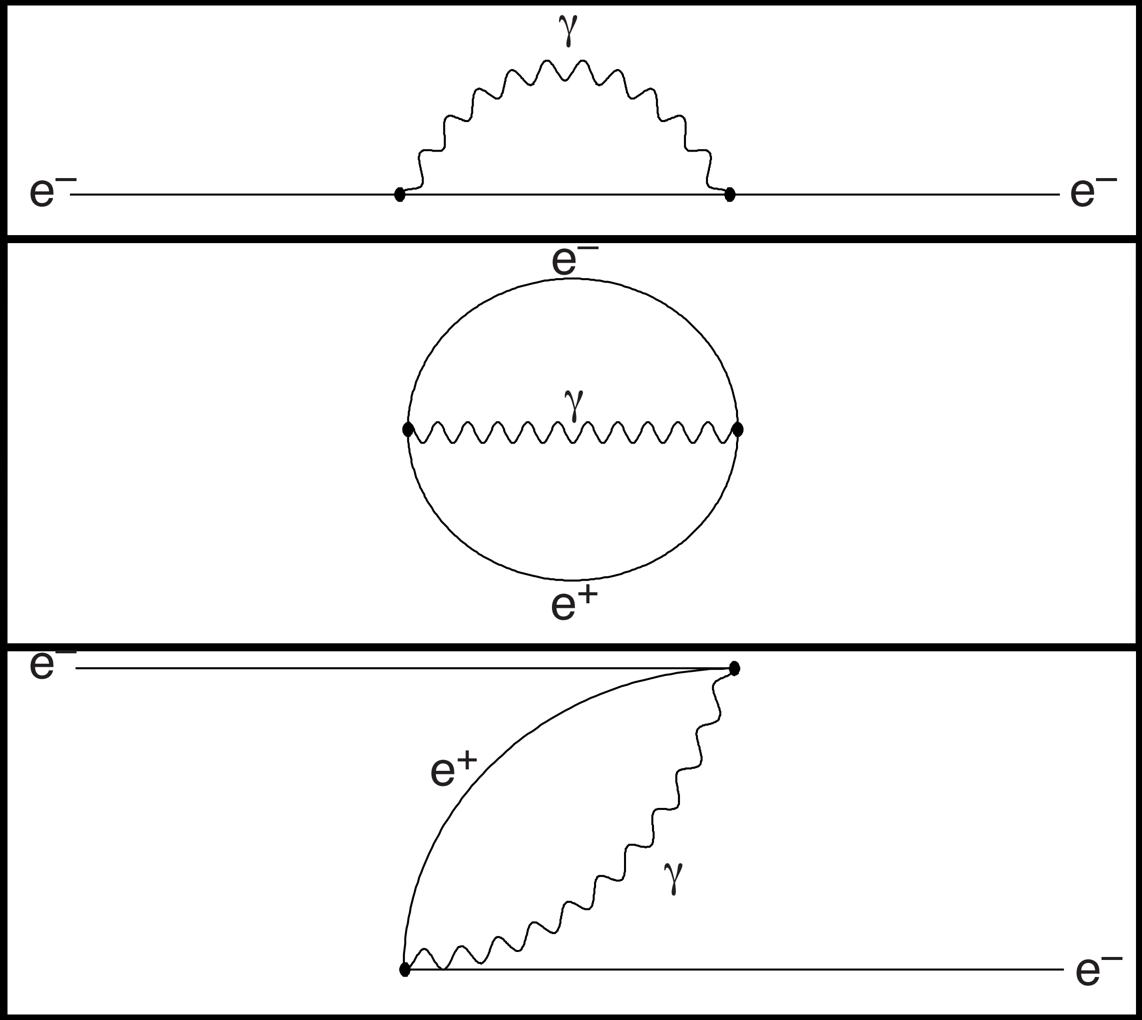
- Electron creates a force to repel itself

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

- quantum mechanics and anti-matter

$\Rightarrow$ only 10% of mass even

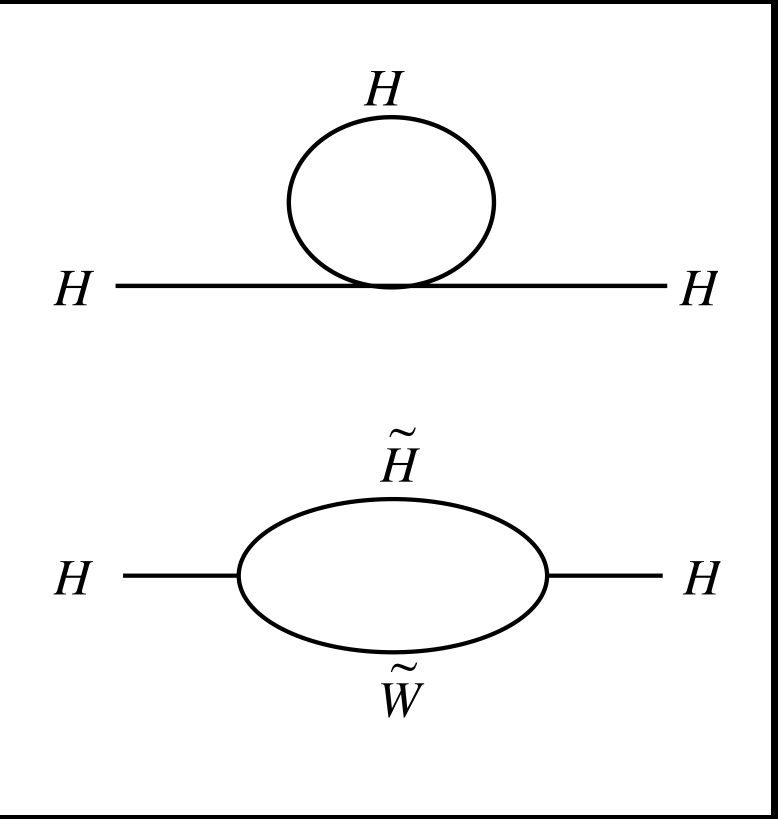
for Planck-size $r_e \sim 10^{-33}$cm



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

Higgs mass is natural by doubling #particles?

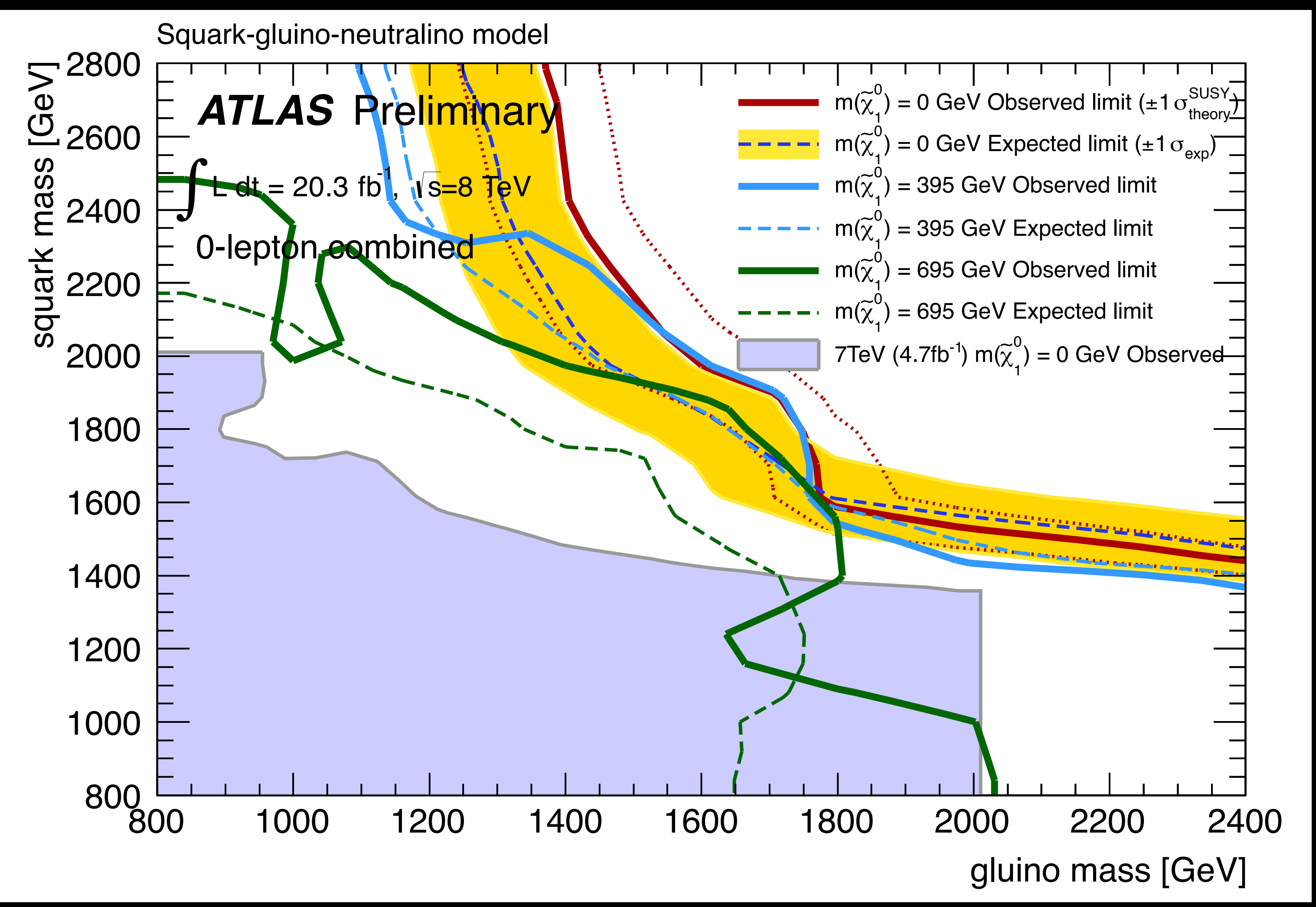
- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

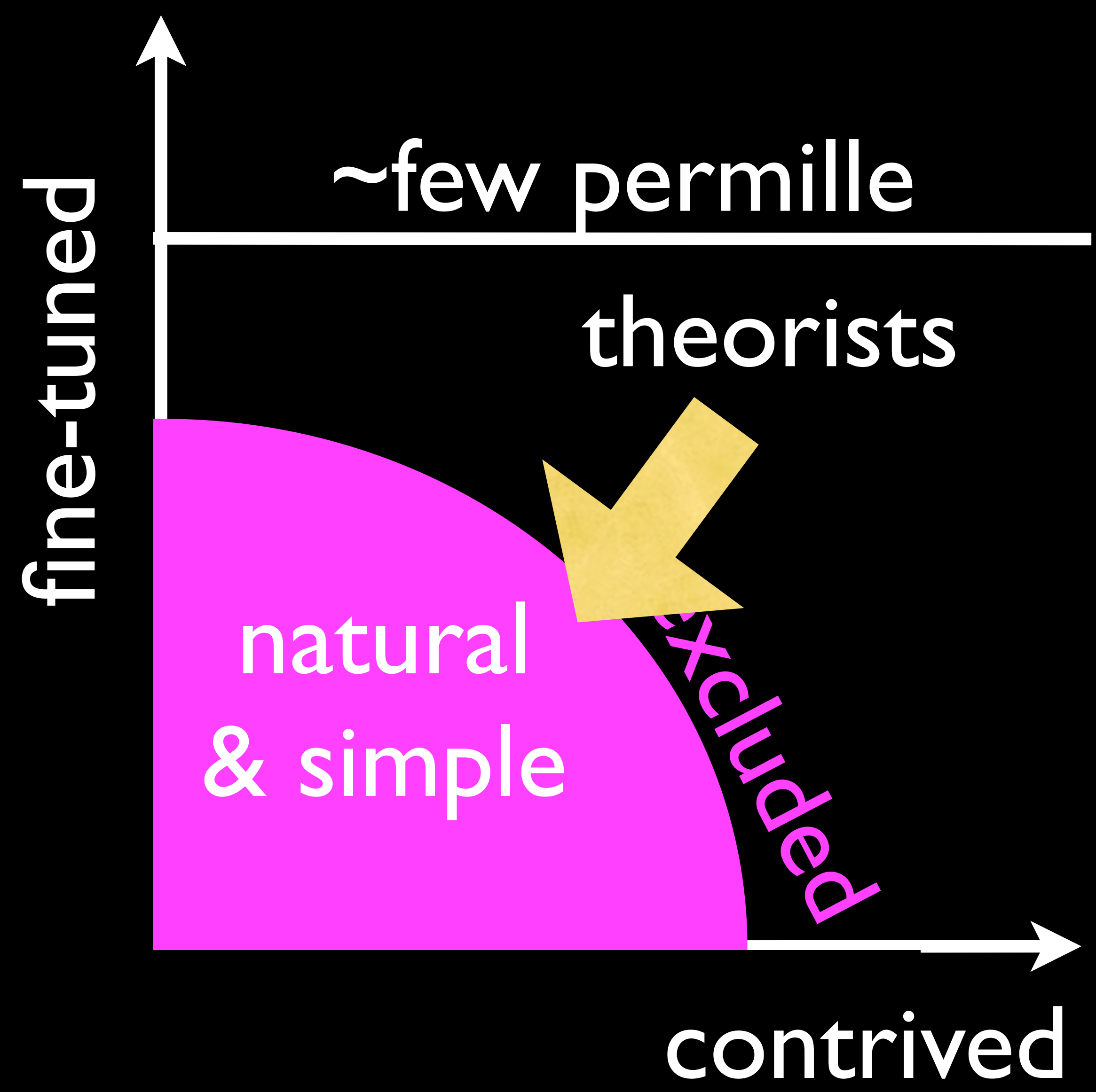


$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

⇒ I still take it seriously

no sign of new physics





Higgs mass vs SUSY

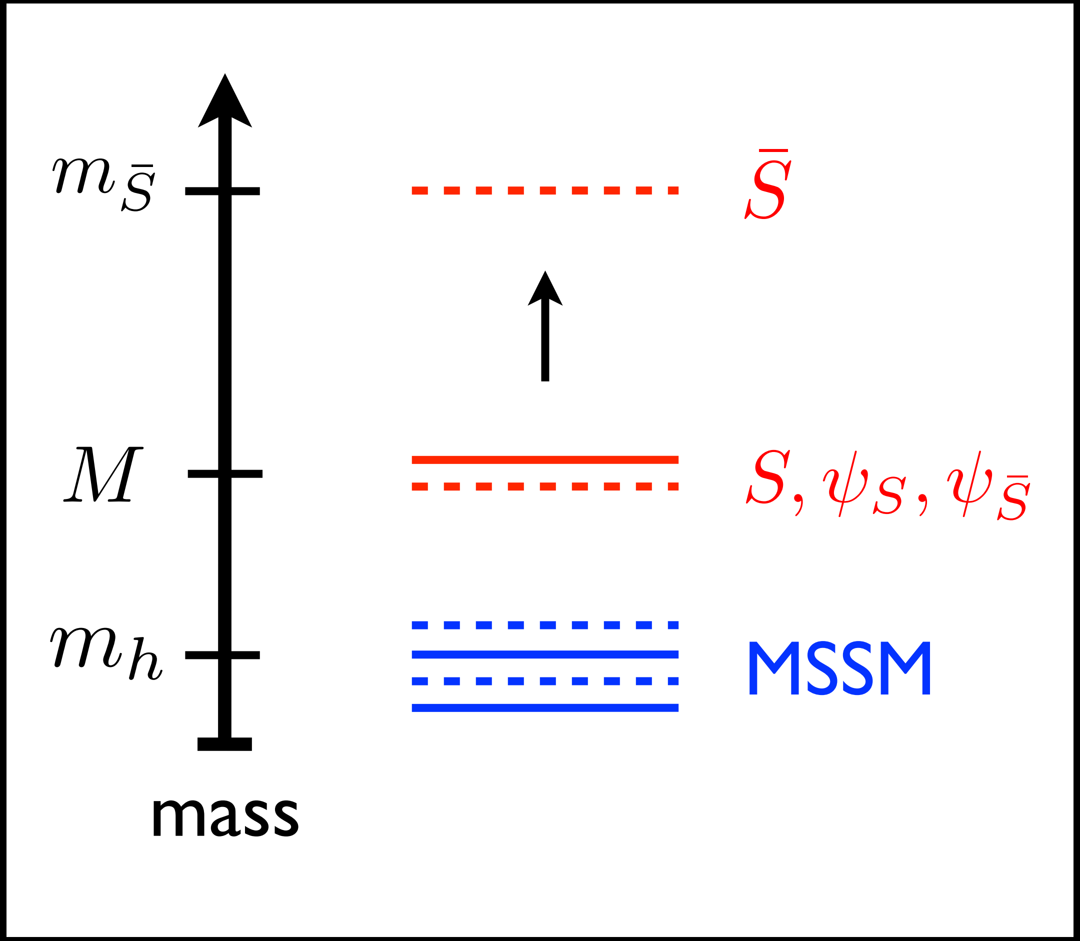
- Higgs is heavier than MSSM prediction
- need to make stop heavy?
- tension with naturalness

$\Rightarrow$Dirac NMSSM

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

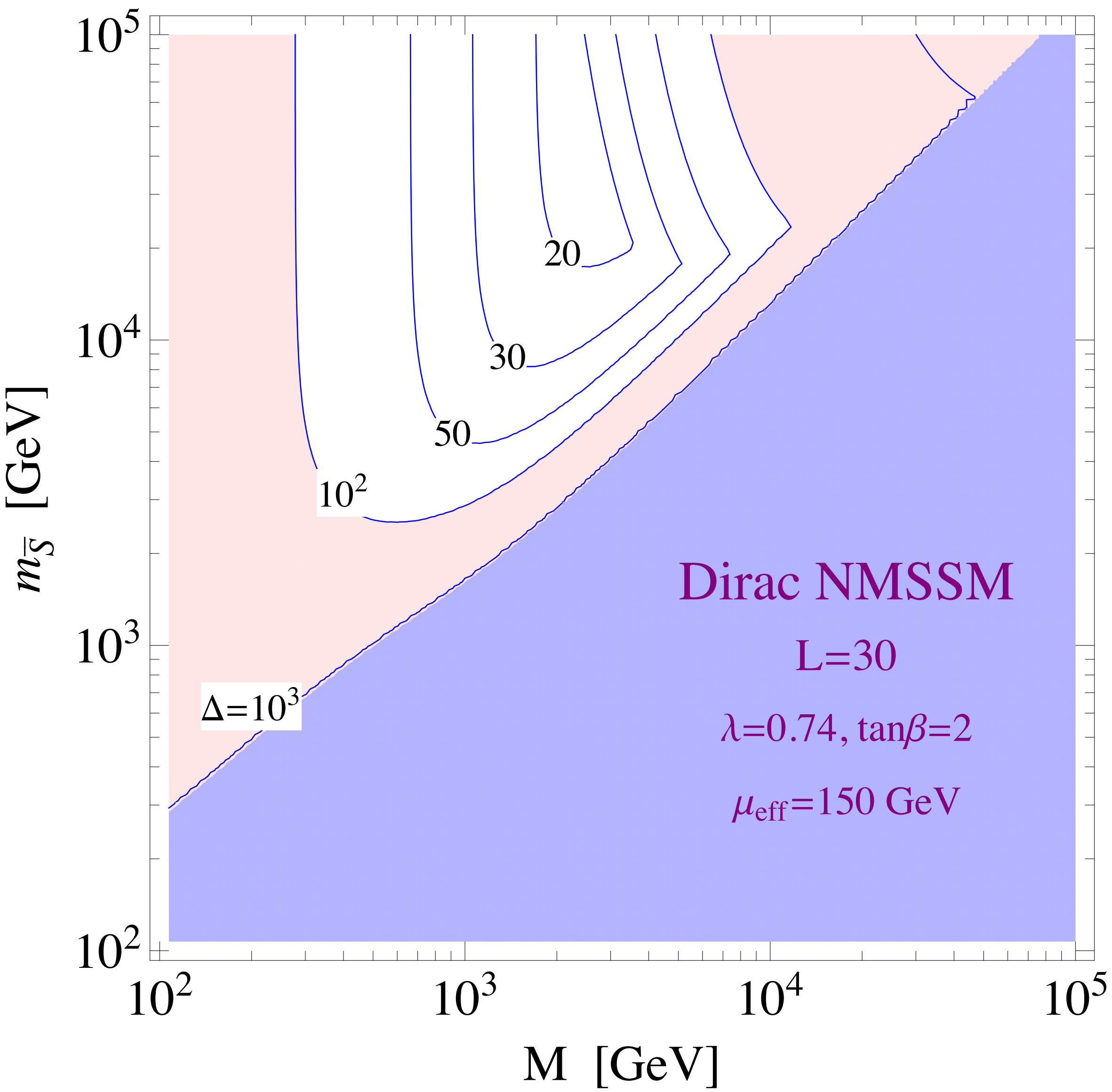
semi-soft SUSY breaking

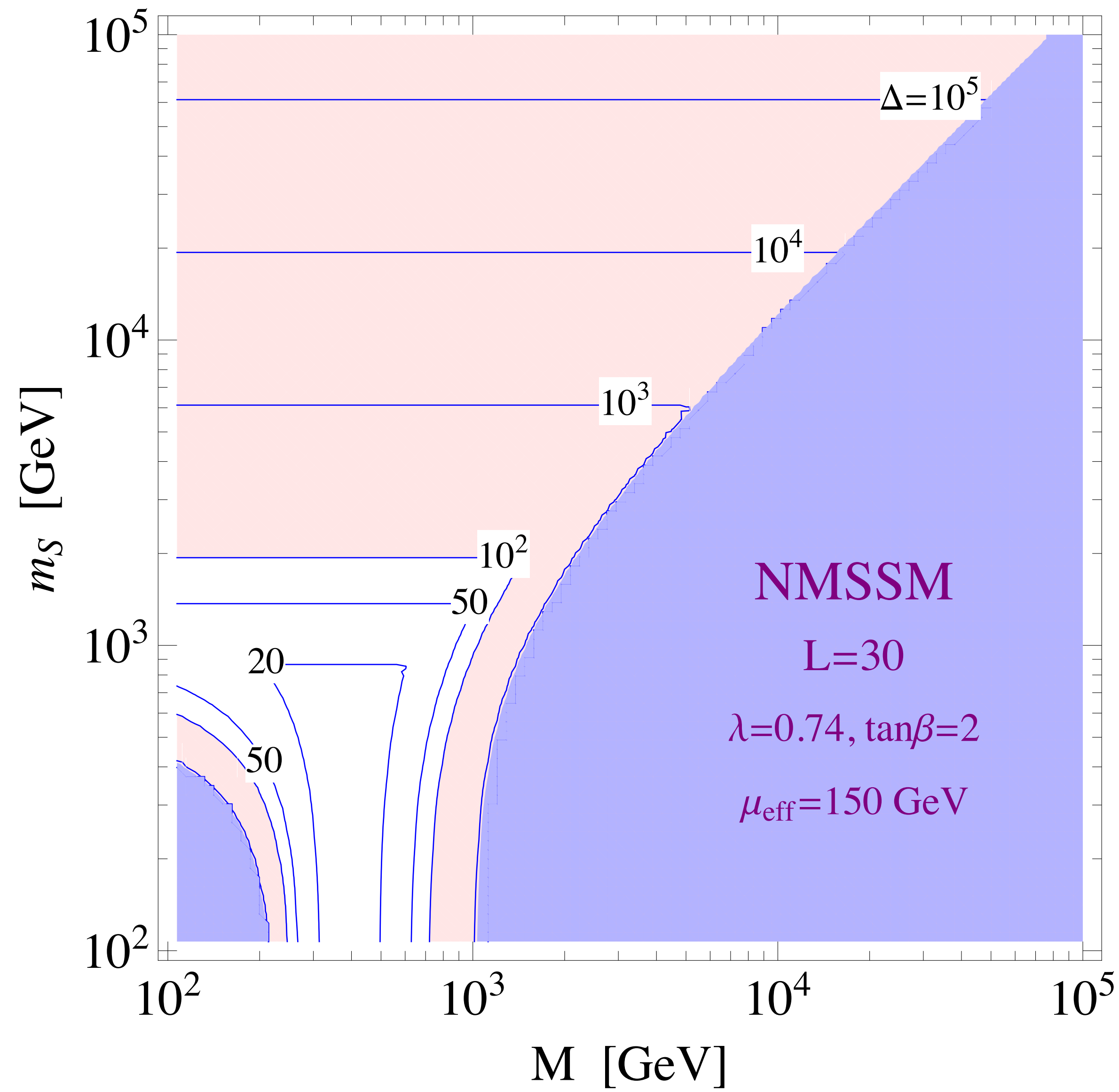
$$W = \lambda H_u H_d S + M S \bar{S}$$



Lu, HM, Ruderman, Tobioka

NMSSM vs NMSSM





semi-soft SUSY breaking

- "Dirac NMSSM"
- we introduce a singlet with a Dirac mass
- send SUSY breaking to infinity
- we retain *non-decoupling* *F*-term potential
- yet no naturalness issue

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

$$V = |\lambda S|^2 (|H_u|^2 + |H_d|^2) + |\lambda H_u H_d + M \bar{S}|^2 + m_S^2 |S|^2 + m_{\bar{S}} |\bar{S}|^2$$

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

$$V = |\lambda S|^2 (|H_u|^2 + |H_d|^2) + \lambda^2 \left(1 - \frac{M^2}{M^2 + m_{\bar{S}}^2}\right) |H_u H_d|^2 + m_S^2 |S|^2$$

$$\int d^4\theta \frac{m_{\bar{S}}^2 \theta^2 \bar{\theta}^2}{M^2 + m_{\bar{S}}^2} |H_u H_d|^2$$

semi-soft SUSY breaking

- decoupled limit has no Sbar scalar but only Sbar *fermion*
- it can be cast into a form of soft term

$$\int d^4 \left(\bar{S}^\dagger \bar{S} + \theta^2 \bar{\theta}^2 M D_\alpha S D^\alpha \bar{S} + c.c.\right)$$

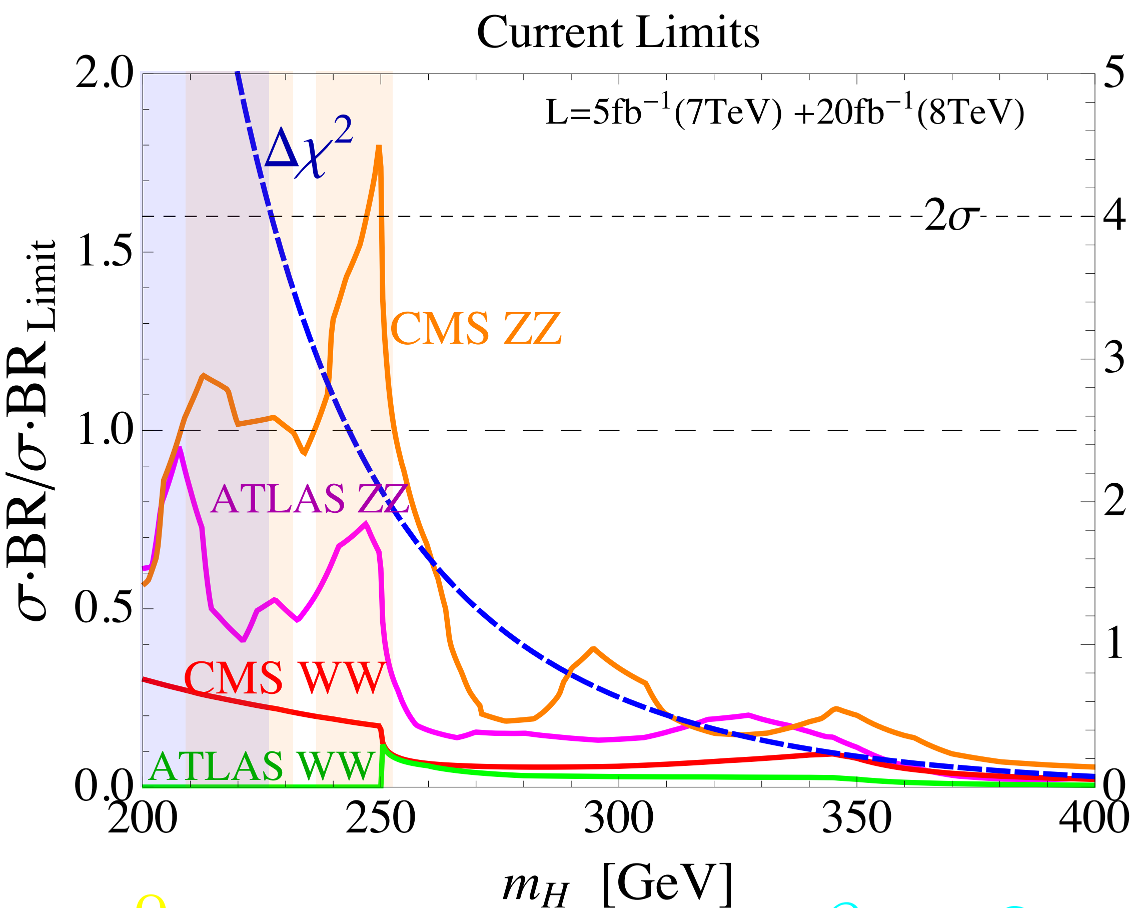
- this is why decoupled scalar does not upset hierarchy
- "semi-soft"

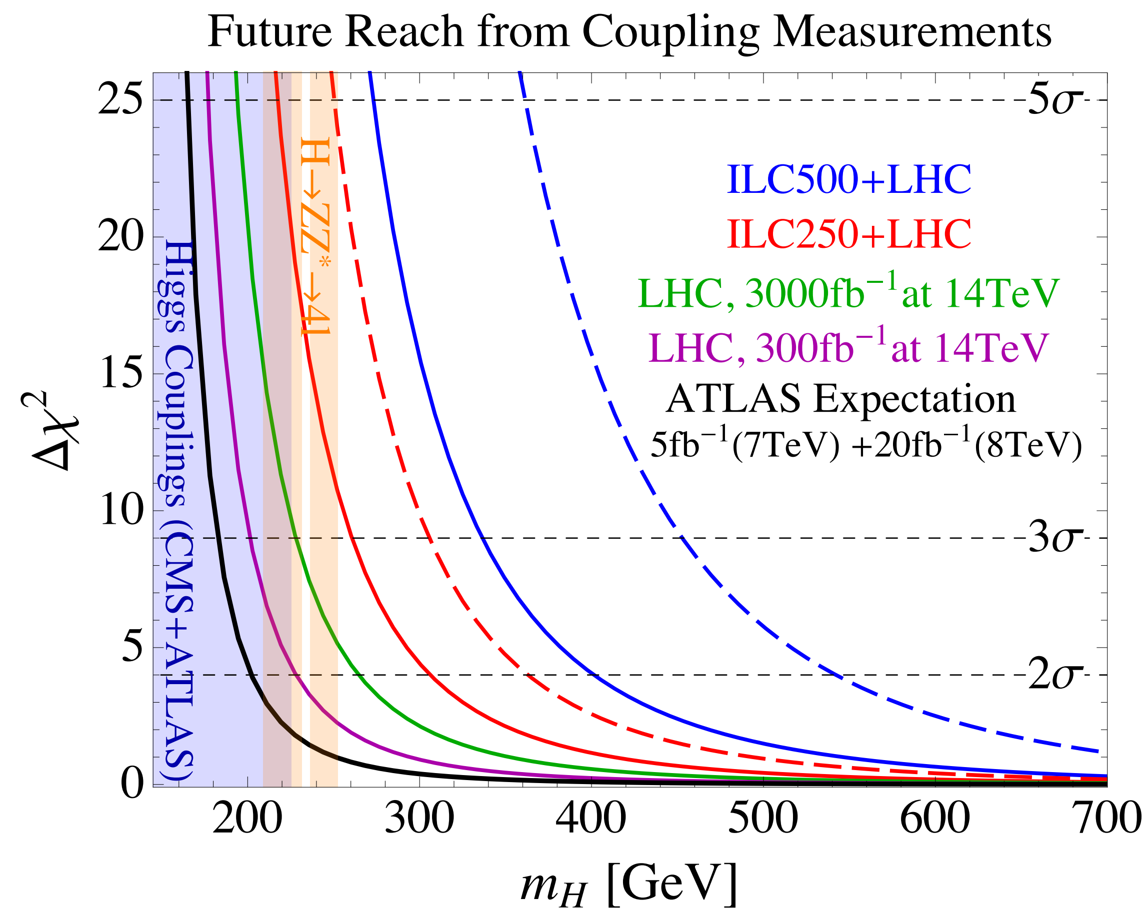
$$W = \lambda H_u H_d S + \cancel{M S \bar{S}}$$

$$\begin{aligned} V =& |\lambda S|^2 (|H_u|^2 + |H_d|^2) \\ &+ |\lambda H_u H_d \cancel{+ M \bar{S}}|^2 \\ &+ m_S^2 |S|^2 \cancel{+ m_{\bar{S}}^2 |\bar{S}|^2} \end{aligned}$$

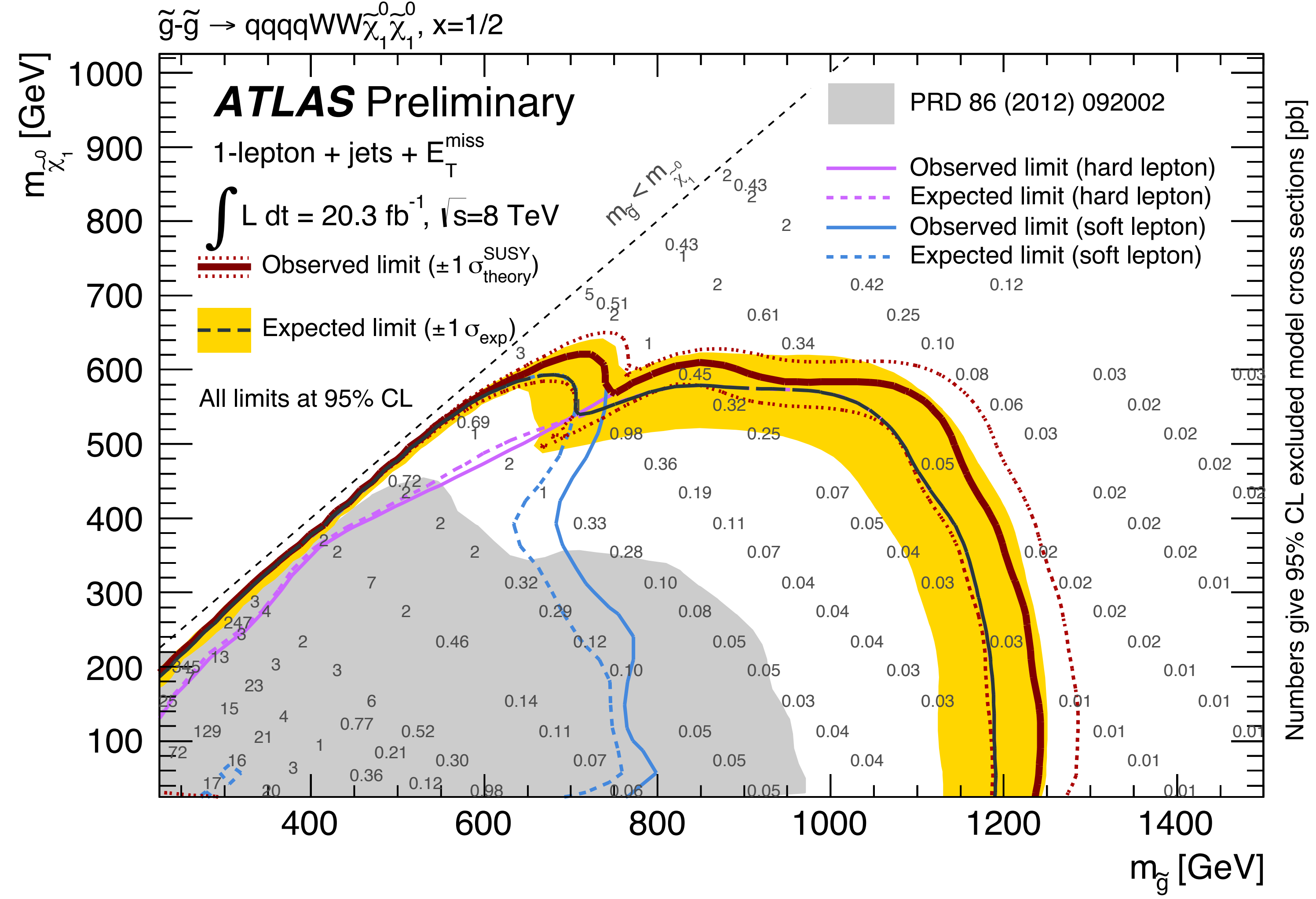
$$m_{\bar{S}}^2 \to \infty$$

future searches

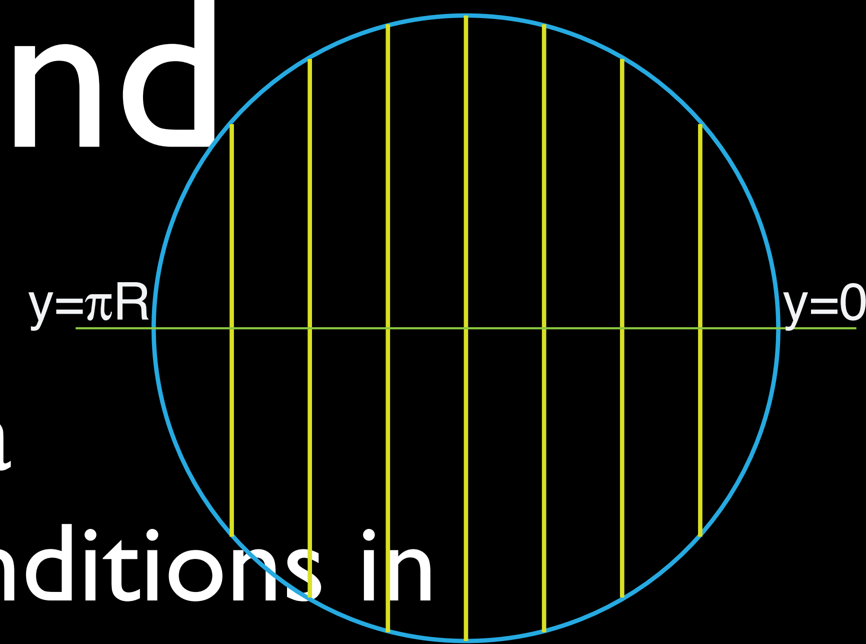




$H^0 \to 4l, hh$ $\tan\beta \approx 2$



found



the data

dary conditions in

$= T^{-1}, \quad P^2 = 1 \quad T = e^{i\alpha}$

- @tree level, all SUSY particles degenerate at α/*R* similar to UED
- even sfermions and gauginos degenerate
- only free parameter is μ
- SUSY as light as 1TeV 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

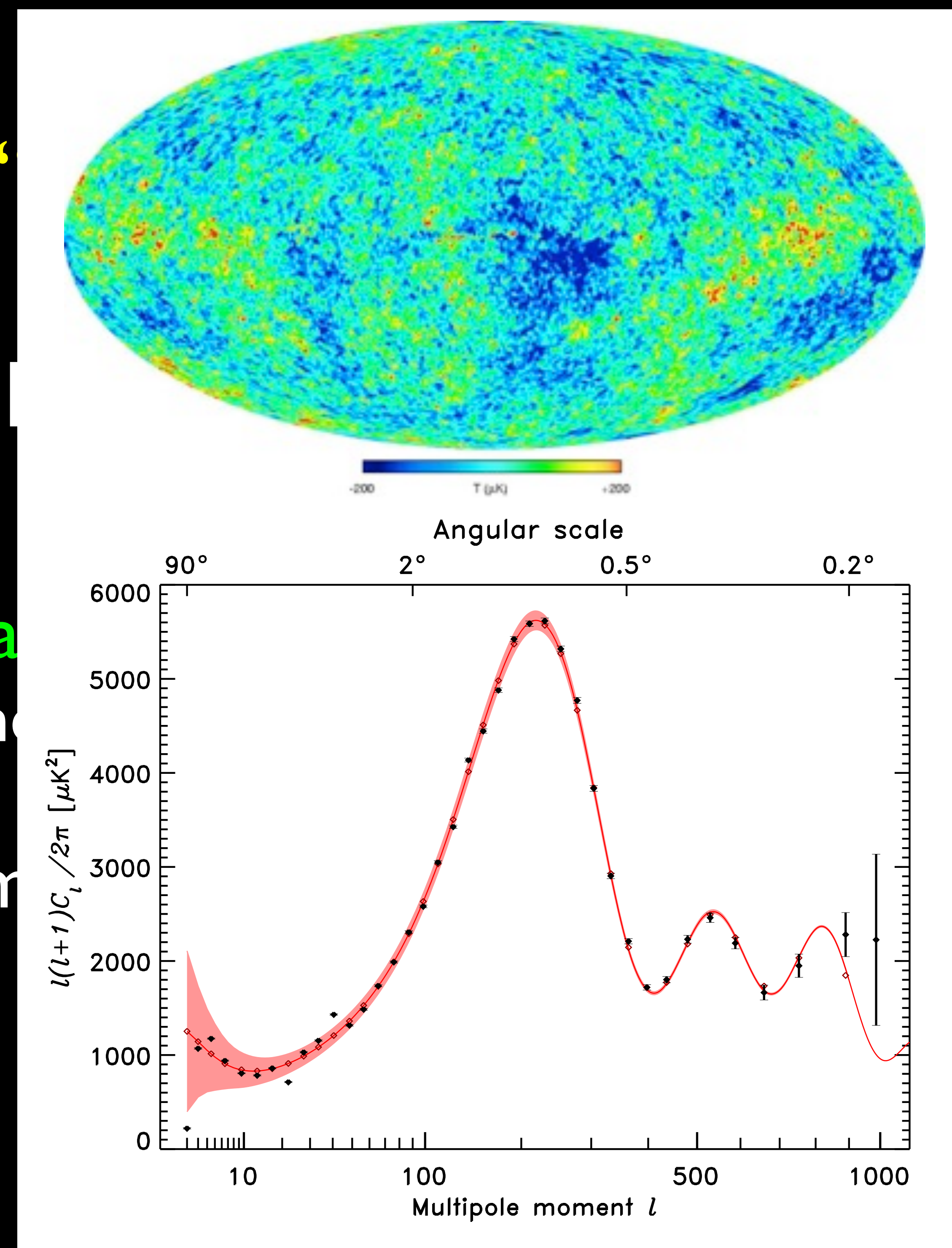
“

“Ba ”

A n e

the

Tim



patience

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

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

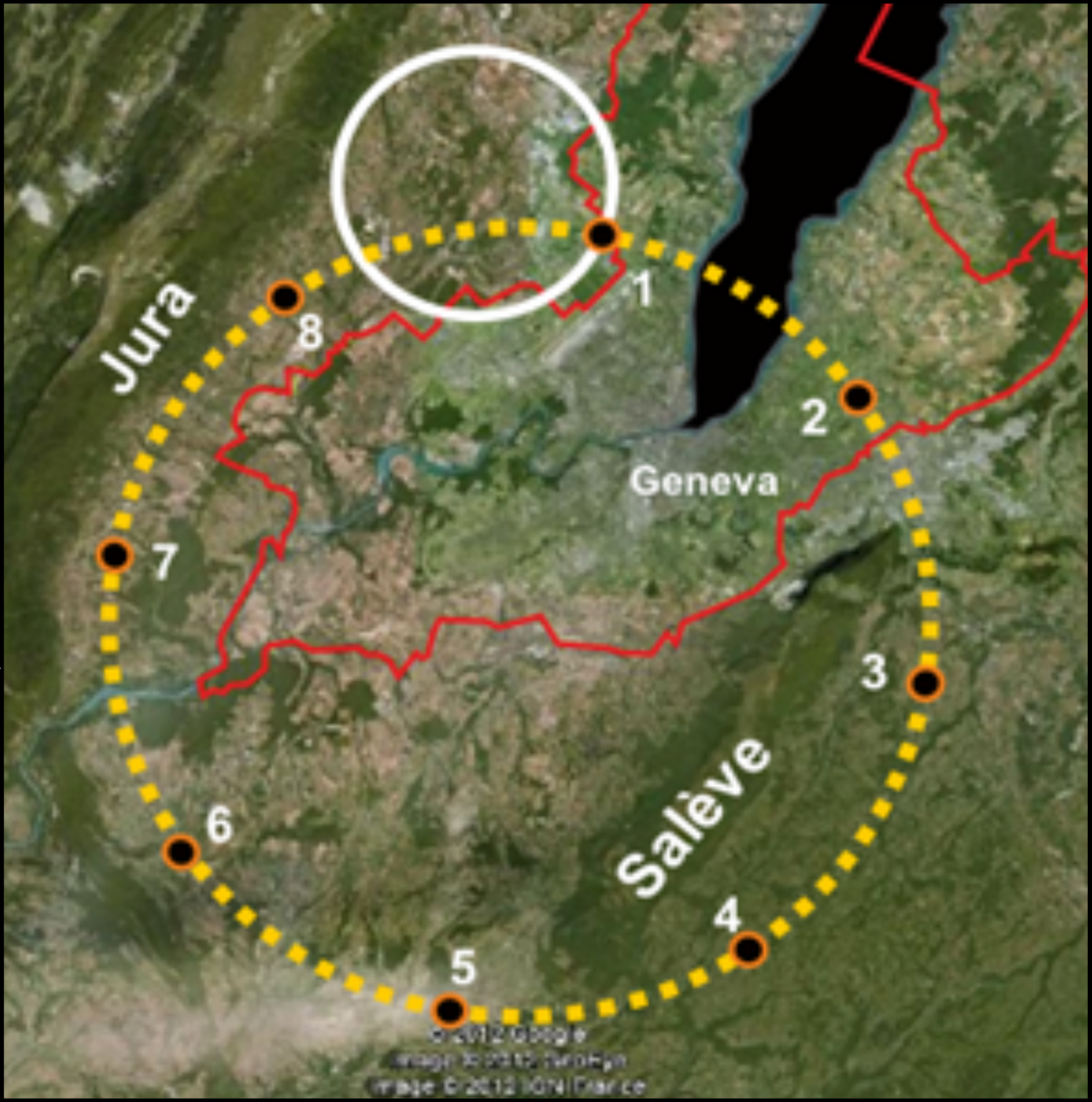
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

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 … T. A. Fuess,[1] Y. Fukui,[14]
S. Funaki,[32] G. Gagliardi,[23] S … arfinkel,[25] C. Gay,[9] S. Geer,[7]
D. W. Gerdes,[17] P. Giannetti, … i,[13] M. Gold,[19] J. Gonzalez,[22]
A. Gordon,[9] A. T. Goshaw,[6] K. G … H. Grassmann, … L. Groer, … 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

What will we learn from Higgs?


Higgs boson
need to find everything
under the lamp post
learn where
to go next

uncomfortable

- Higgs boson is the *only spin 0 particle* in the standard model
  - one of its kind, no context
  - but does the most important job
- looks rather artificial
- also superficial, doesn't explain dynamics behind the condensate
- *Higgsless theories*: now dead

Theory for Scalar Bosons?

Supersymmetry

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

composite

- spins cancelled among constituents of Higgs boson
- condensate by a strong attractive force, holography

Extra dimension

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

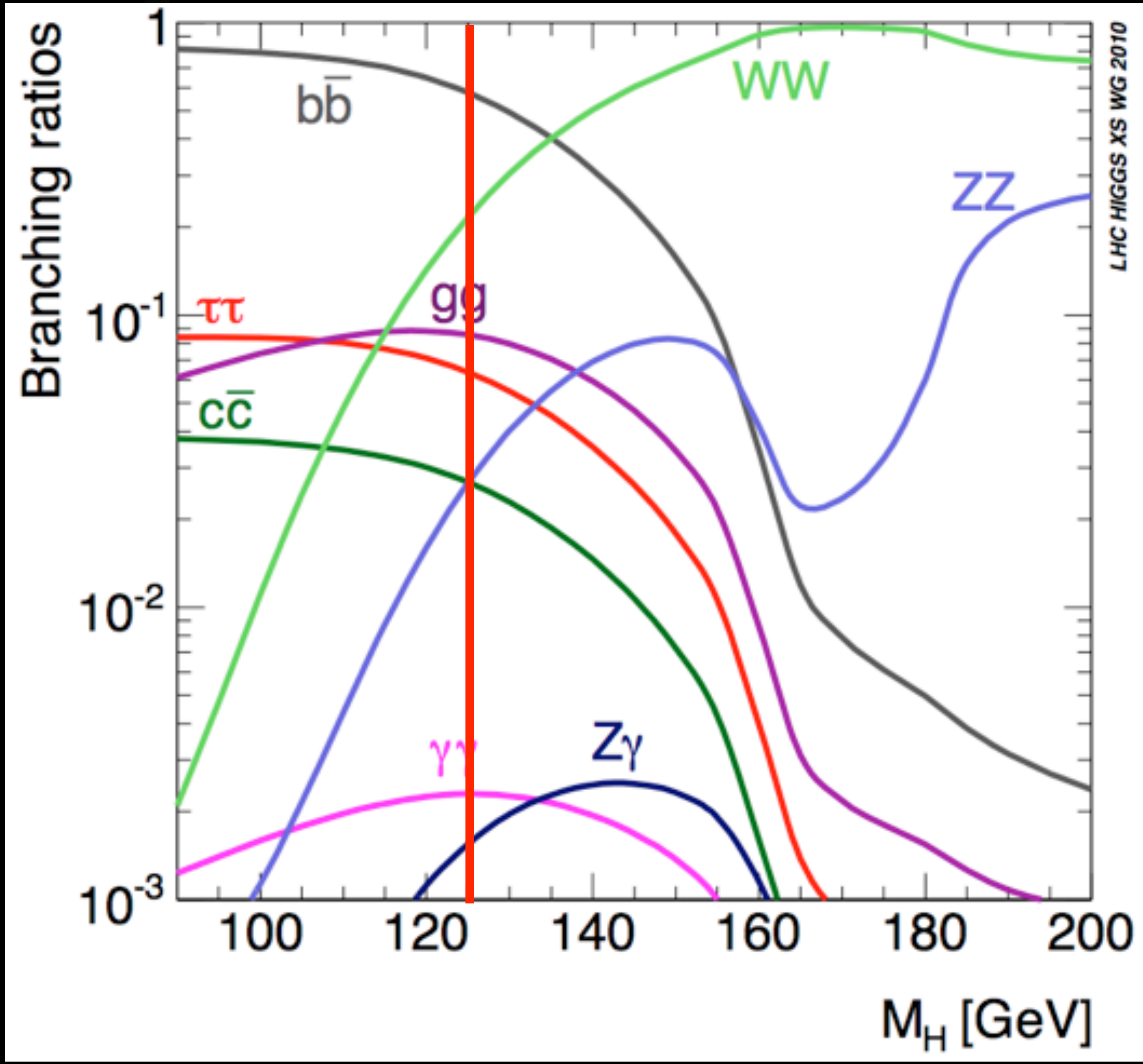
argument

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

History of Colliders

1. precision measurements of neutral current (*i.e.* polarized *e*+*d*) predicted m_W, m_Z
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 ???

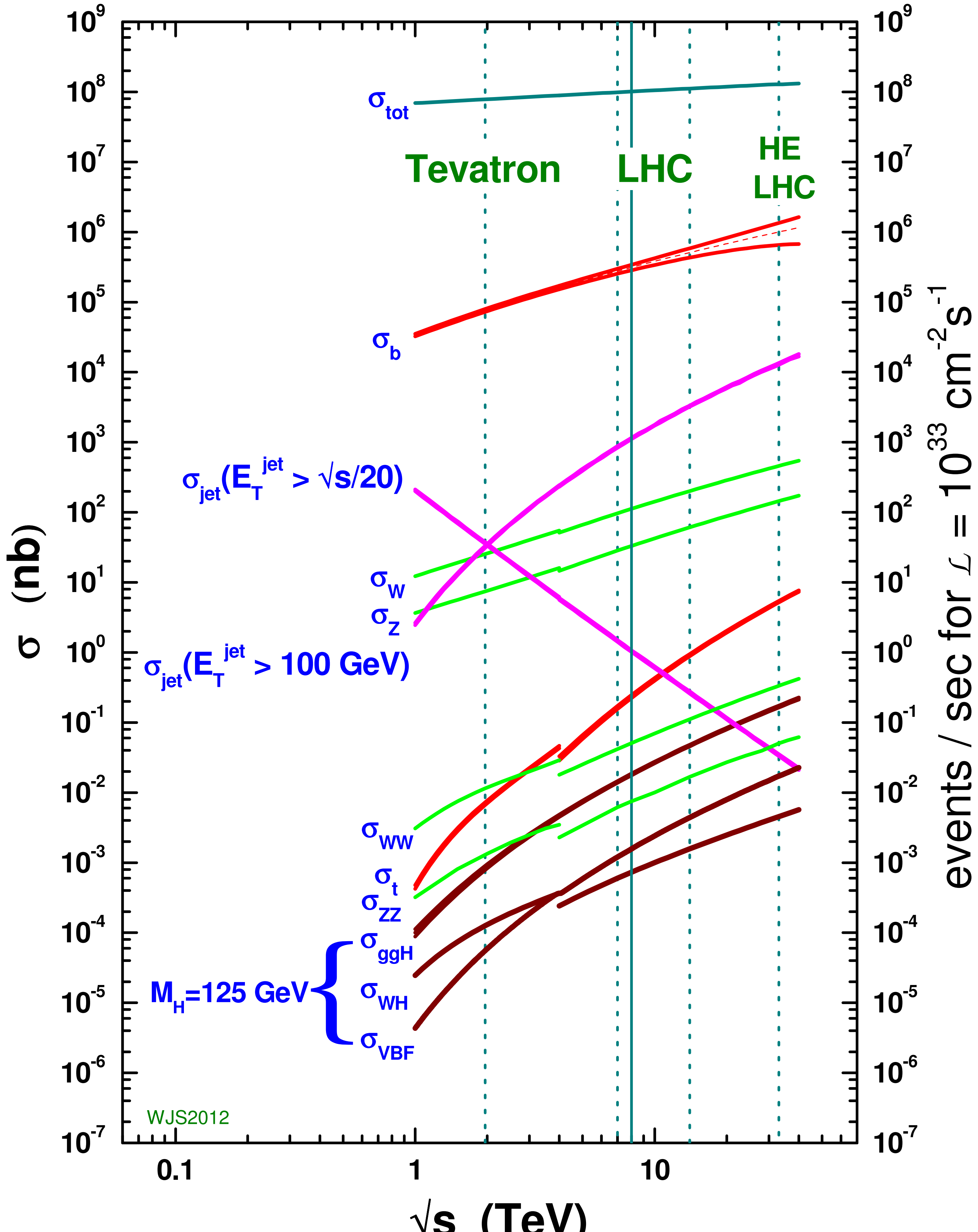
dream case for experiments



can measure them all!

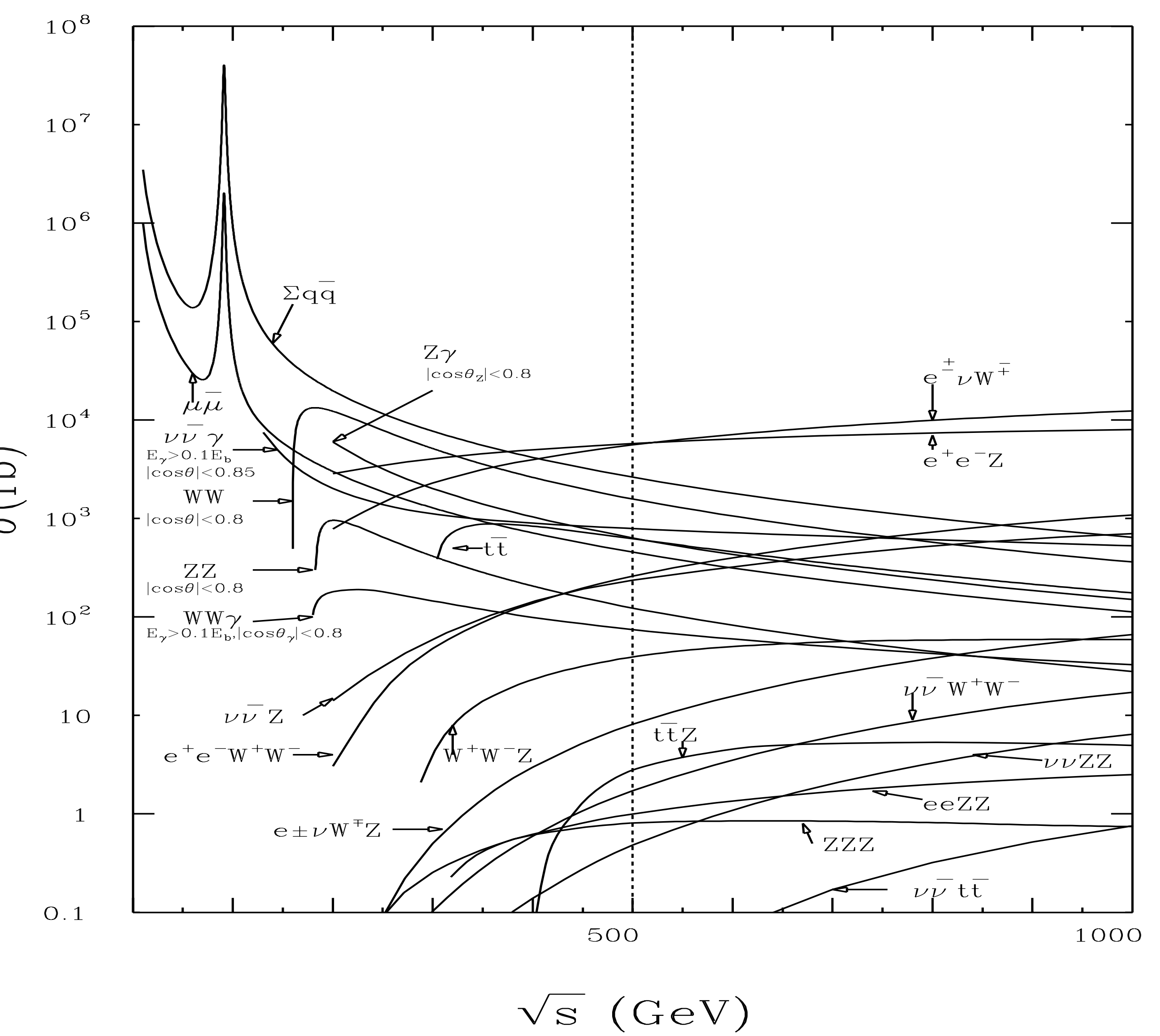
$p\,\bar{p}$

proton - (anti)proton cross sections

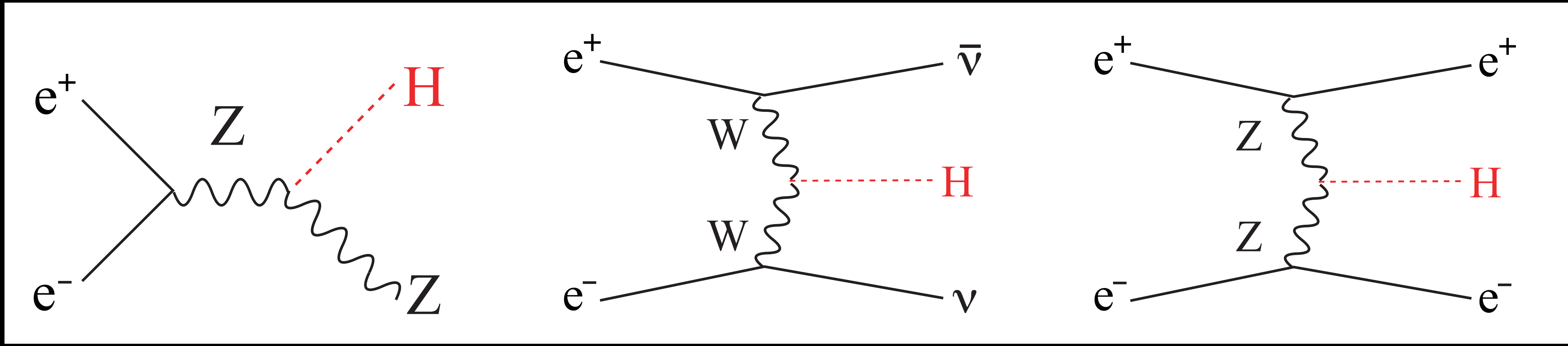


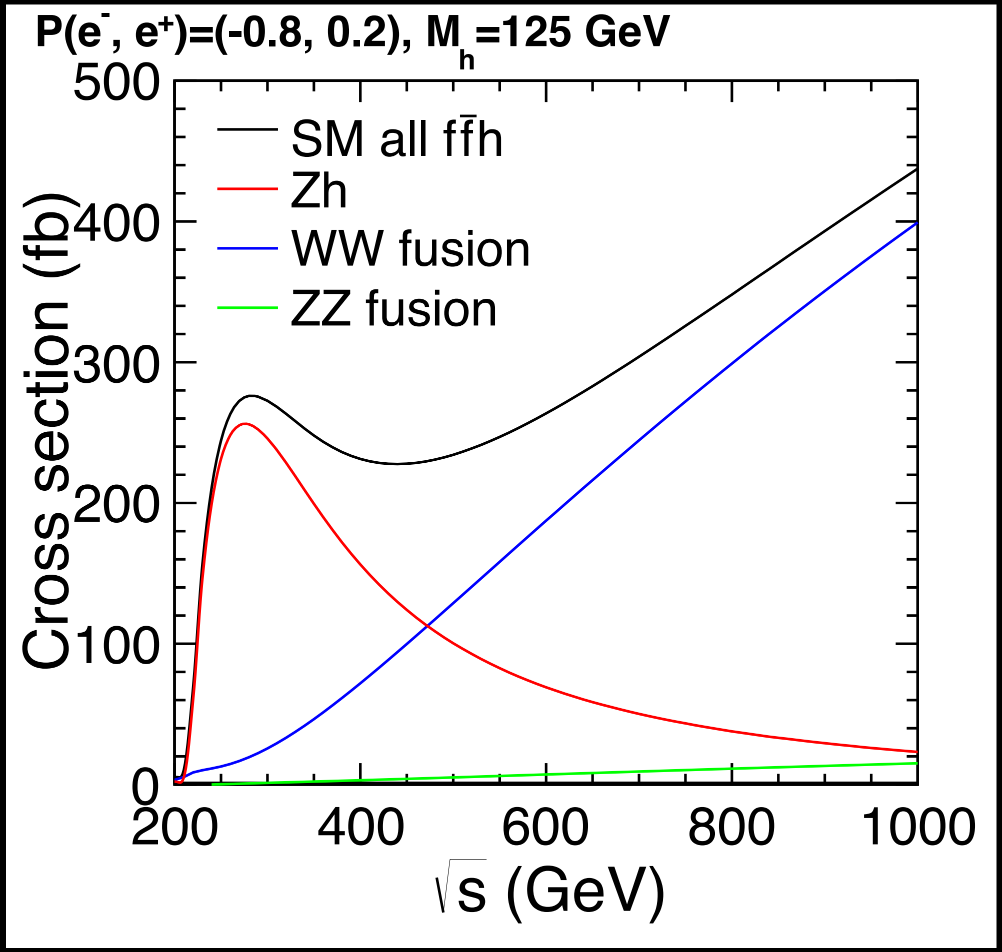
e^+e^-

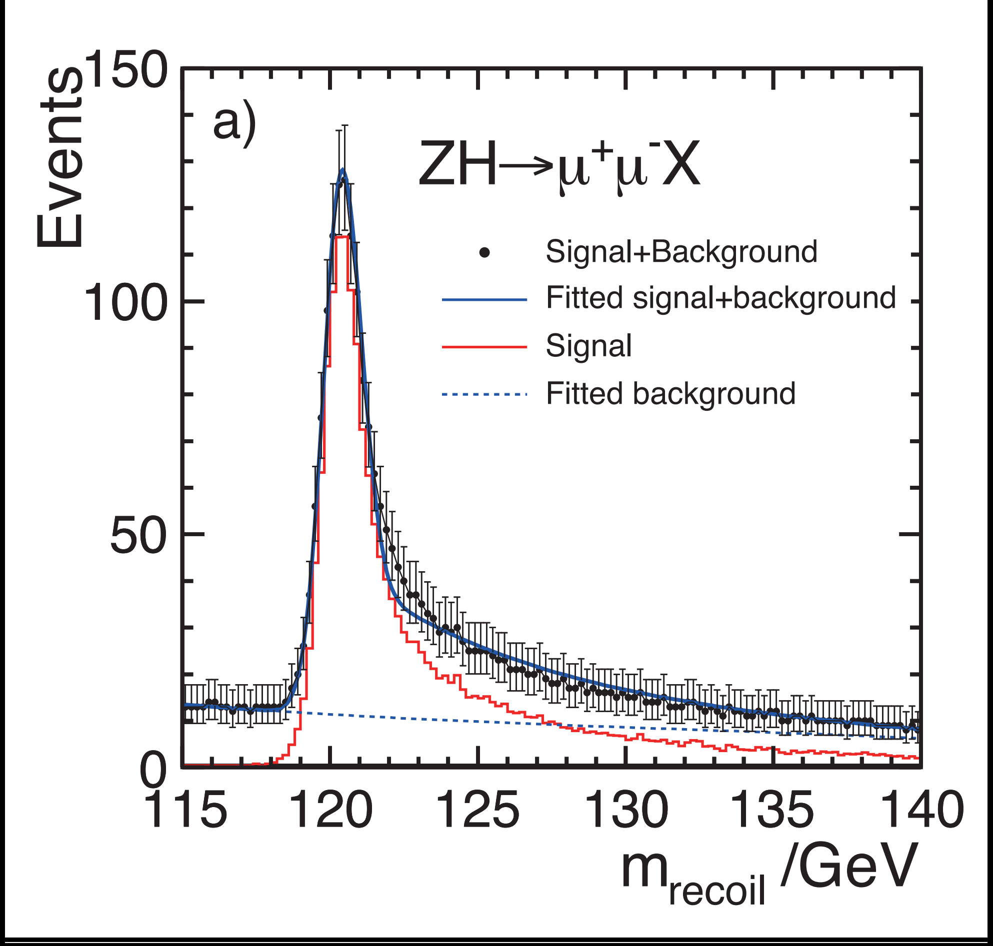
Cross sections

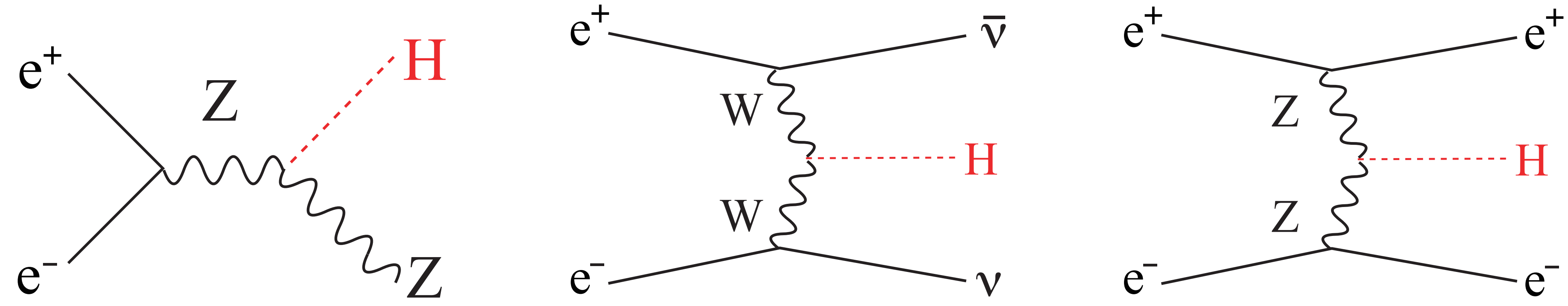


production mechanisms

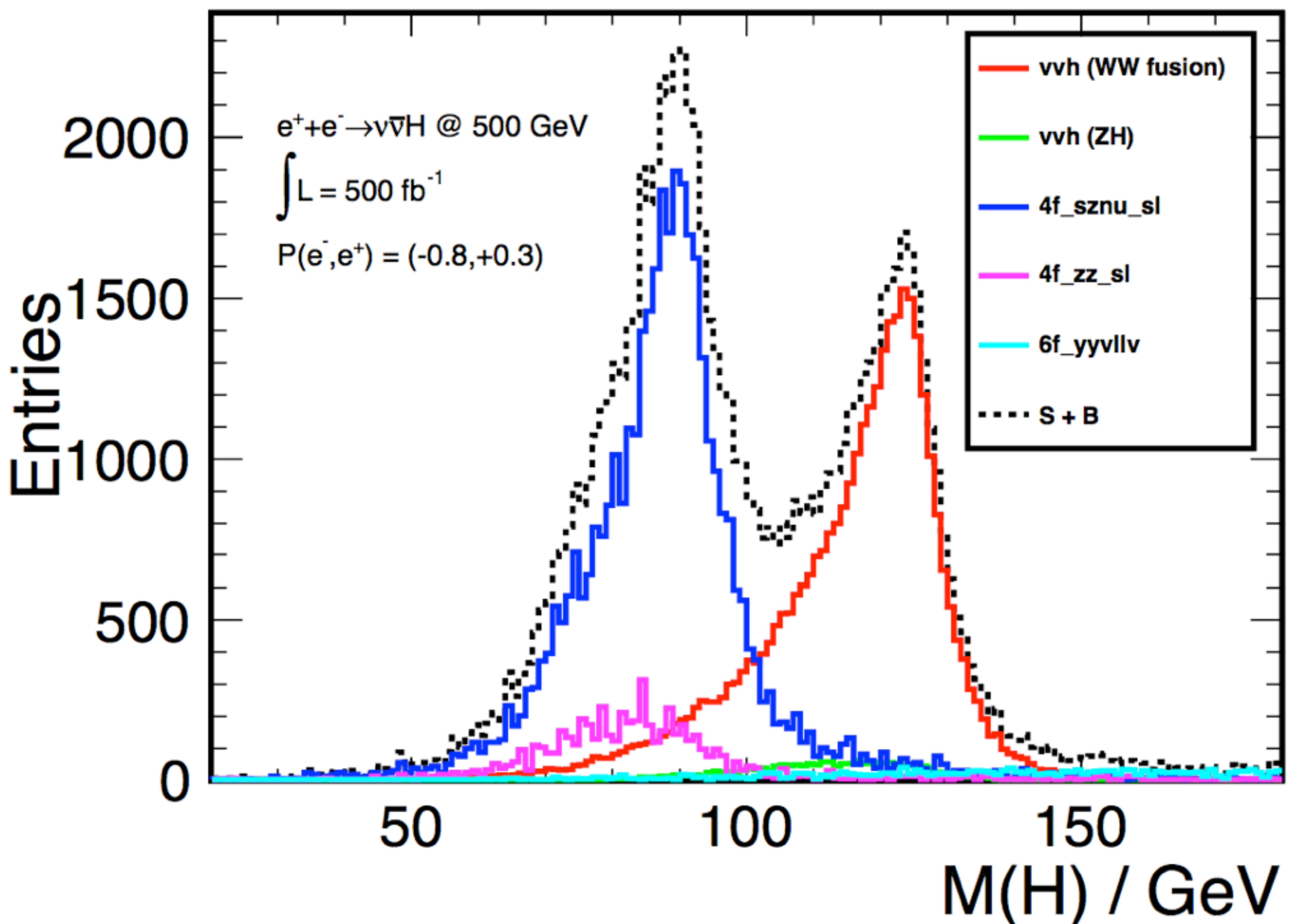




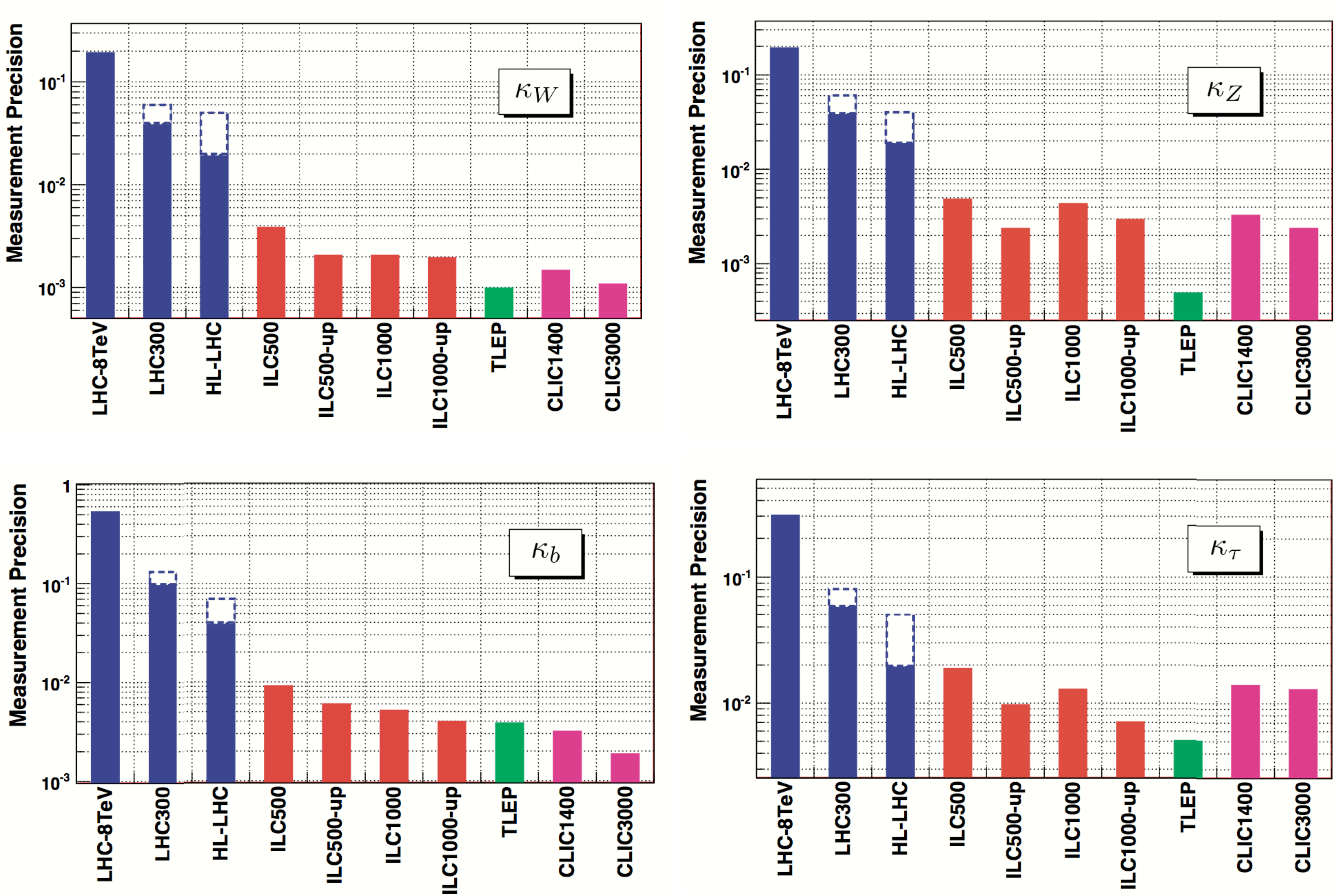




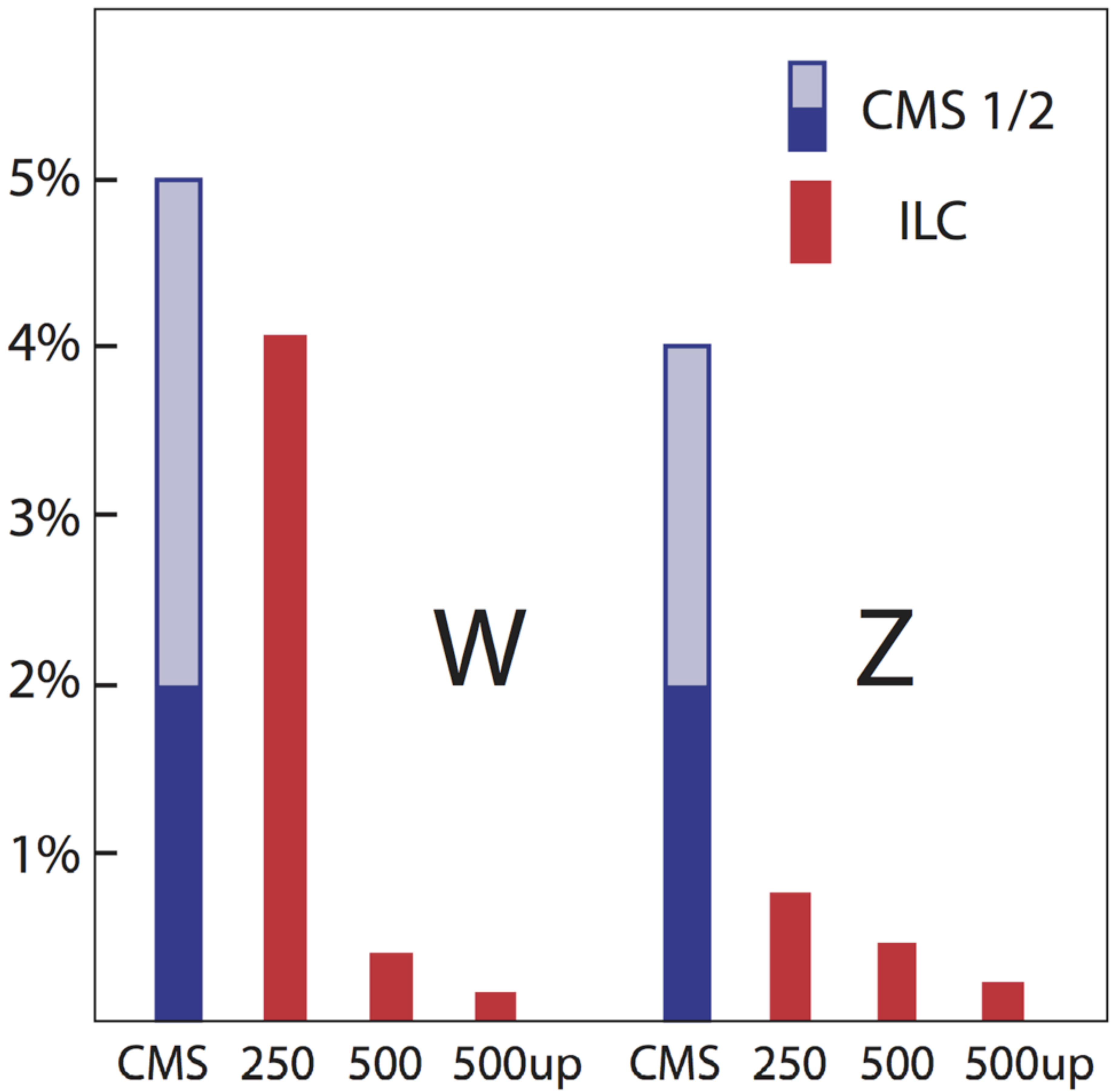
e+
e-
Z
H
Z
e+
e-
W
W
H
ν̄
ν
e+
e-
Z
Z
H
e+
e-



e+ + e- → νν̄H @ 500 GeV
∫L = 500 fb-1
P(e-,e+) = (-0.8,+0.3)
vvh (WW fusion)
vvh (ZH)
4f_sznu_sl
4f_zz_sl
6f_yyvllv
S + B
Entries
0
500
1000
1500
2000
50
100
150
M(H) / GeV

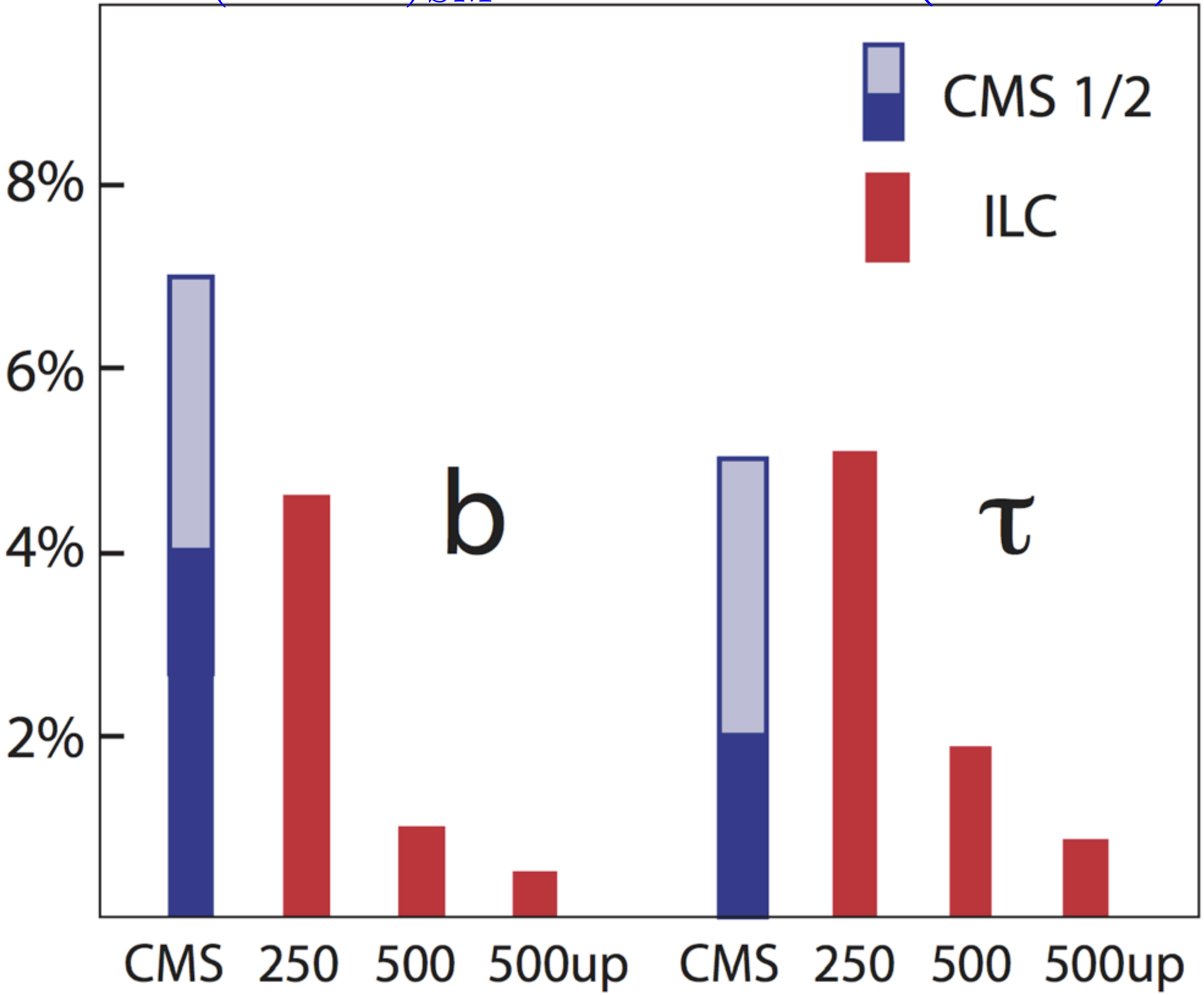


Snowmass Higgs report

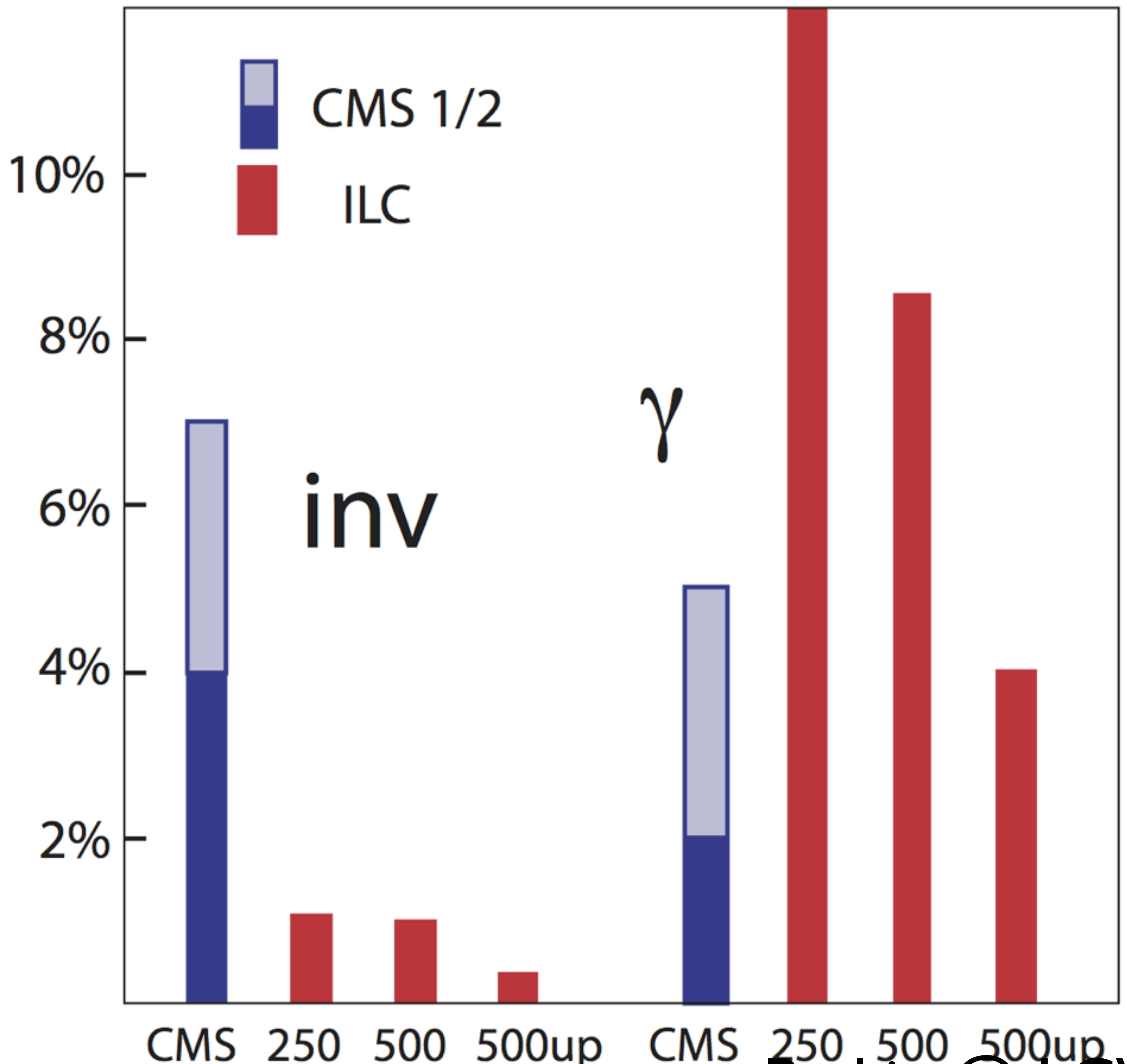


Peskin @ LCWS 2013

$$\frac{BR(h \to b\bar{b})}{BR(h \to b\bar{b})_{\rm SM}} \sim 1 + \mathcal{O}(10\%) \left(\frac{400\,\mathrm{GeV}}{m_A} \right)^2$$

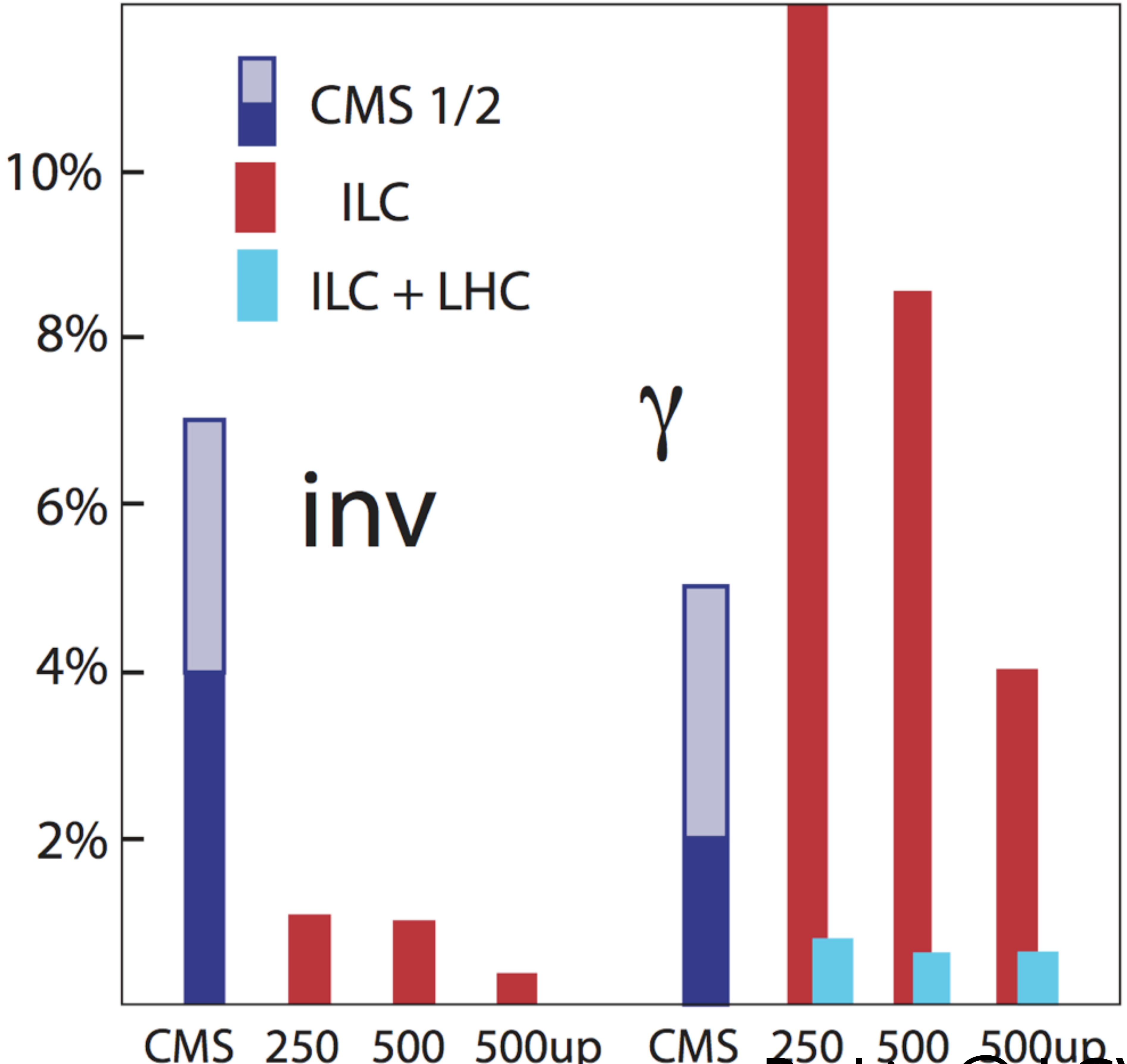


Peskin @ LCWS 2013



Peskin @ LCWS 2013

add LHC measurement h to ZZ/γγ



Peskin @ LCWS 2013

Composite Higgs

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

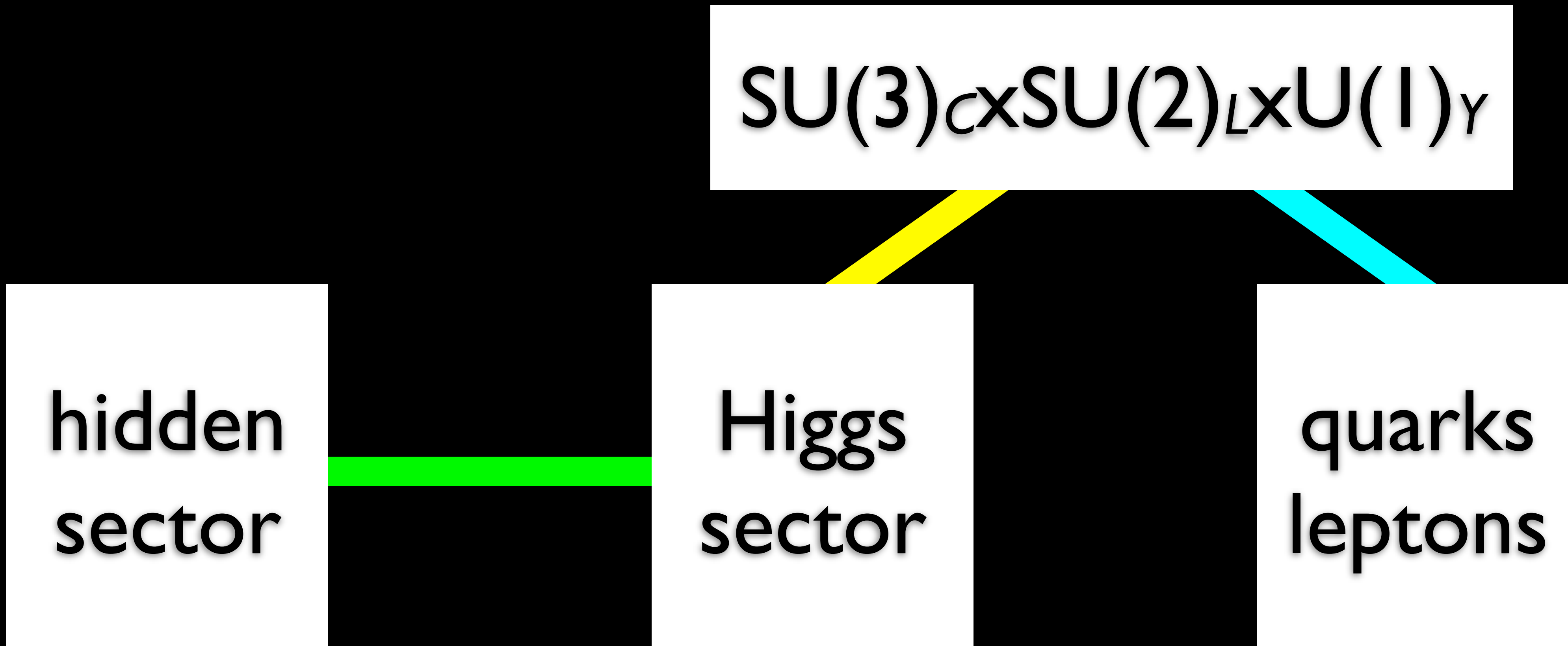
$$
\begin{aligned}
\mathcal{L}_{\rm SILH} =\ & \frac{c_H}{2f^2}\partial^\mu \left(H^\dagger H\right)\partial_\mu \left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& - \frac{c_6 \lambda}{f^2}\left(H^\dagger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

Giudice, Grojean, Pomarol, Rattazzi

0.1% ⇒ 4πf~70 TeV

Higgs as a portal

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



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

Higgs oblique correction

- new particles may appear only in the loops of Higgs propagator
- "oblique corrections"
- only three operators
- O_T already constrained by *T*-param, comparable precision
- O_H provides new window

$$\mathcal{O}_6 = -\frac{\lambda}{f^2}(H^\dagger H)^3$$

$$\mathcal{O}_T = \frac{1}{2f^2}(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H)$$

$$\mathcal{O}_H = \frac{1}{2f^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H)$$

Henning, Lu, HM

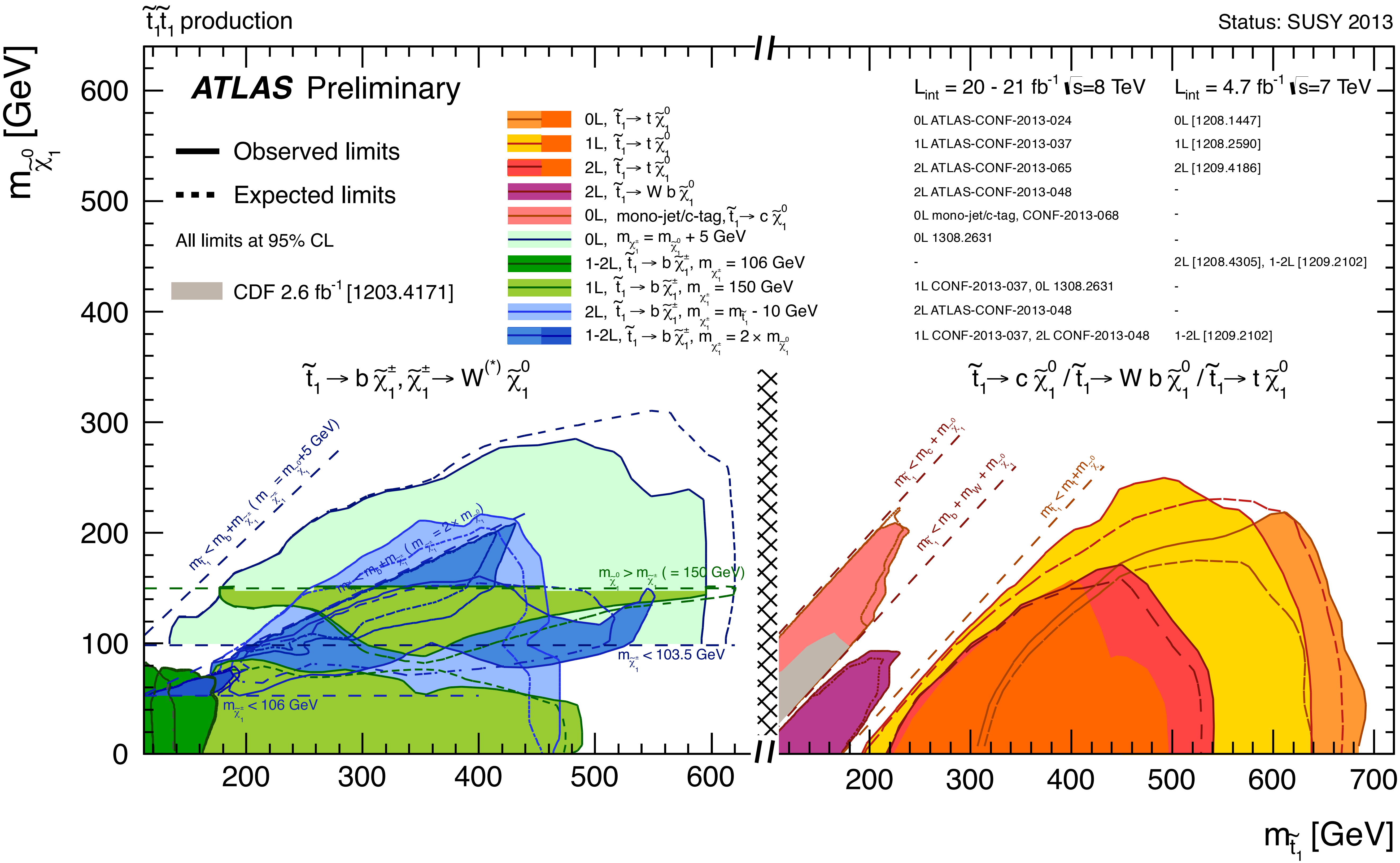
Higgs oblique correction

- Higgs wave function modified
- changes *all* couplings the same way
- suppose 0.1% measure
- tree-level: Higgs-radion mixing
- even sensitive to loops
- stops (Craig, Englert, McCullough) ~600 GeV
- other examples?

$$\mathcal{O}_H = \frac{1}{2f^2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H)$$
$$= \frac{v^2}{2f^2}(\partial h)^2 + O(h^3)$$

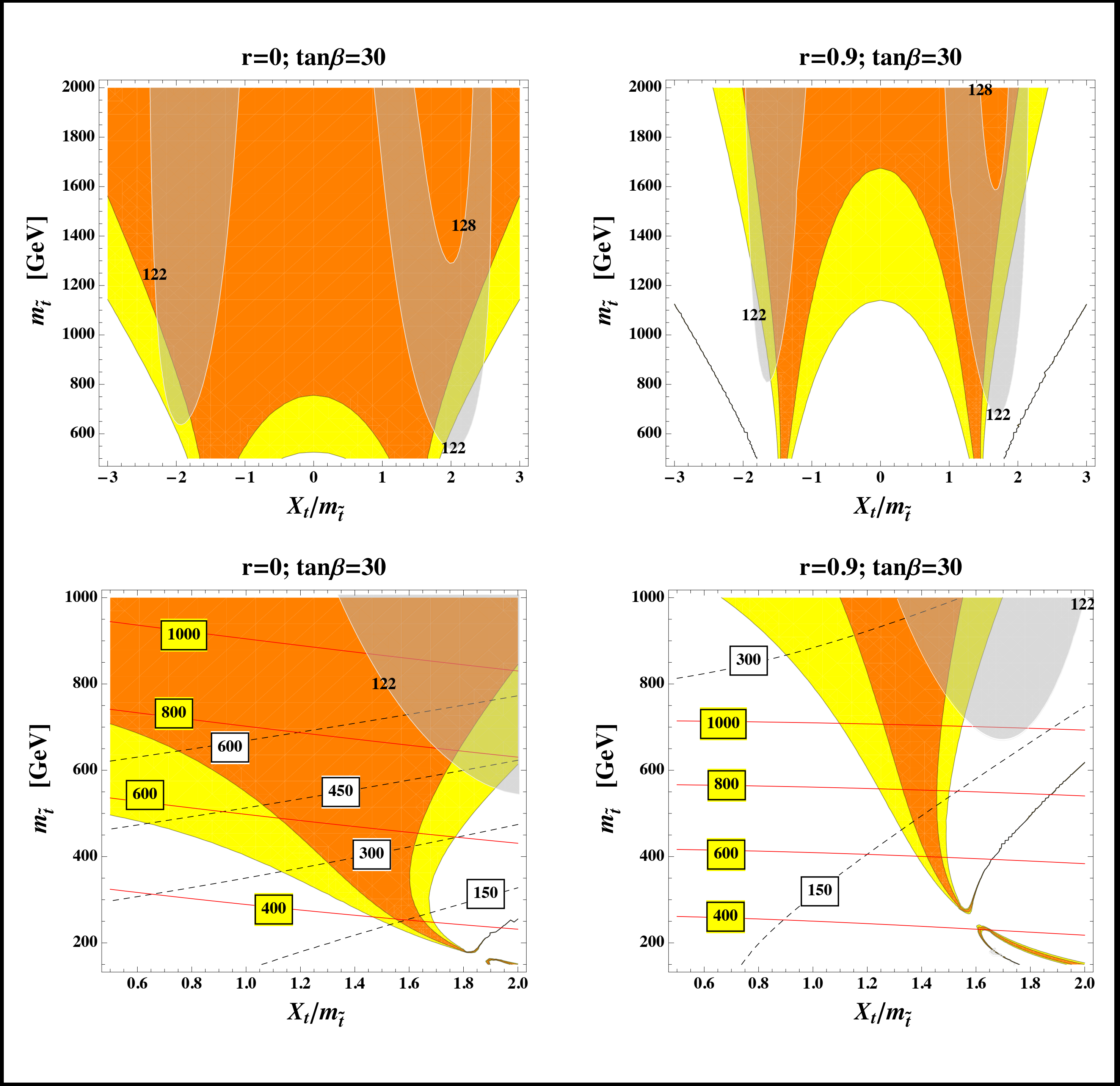
$$\frac{v^2}{8\pi^2 m_{\tilde{t}}^2}$$

stop search @ LHC



loop decays

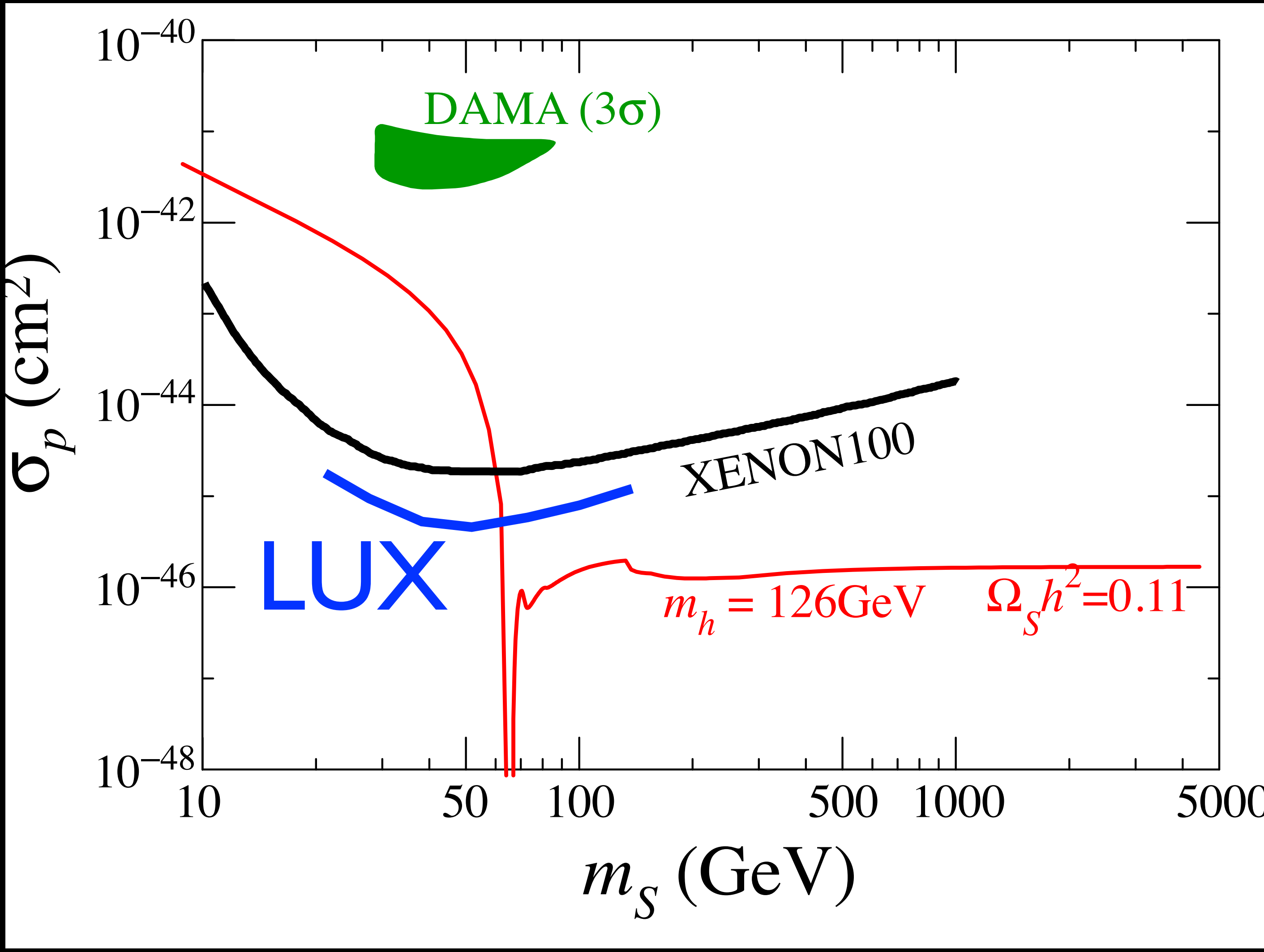
- h to γγ due to loops
- eventually better than 1% measurements
- stops (Gori, Low) even beyond 2 TeV



5%, 10% contours

invisible width unlikely?

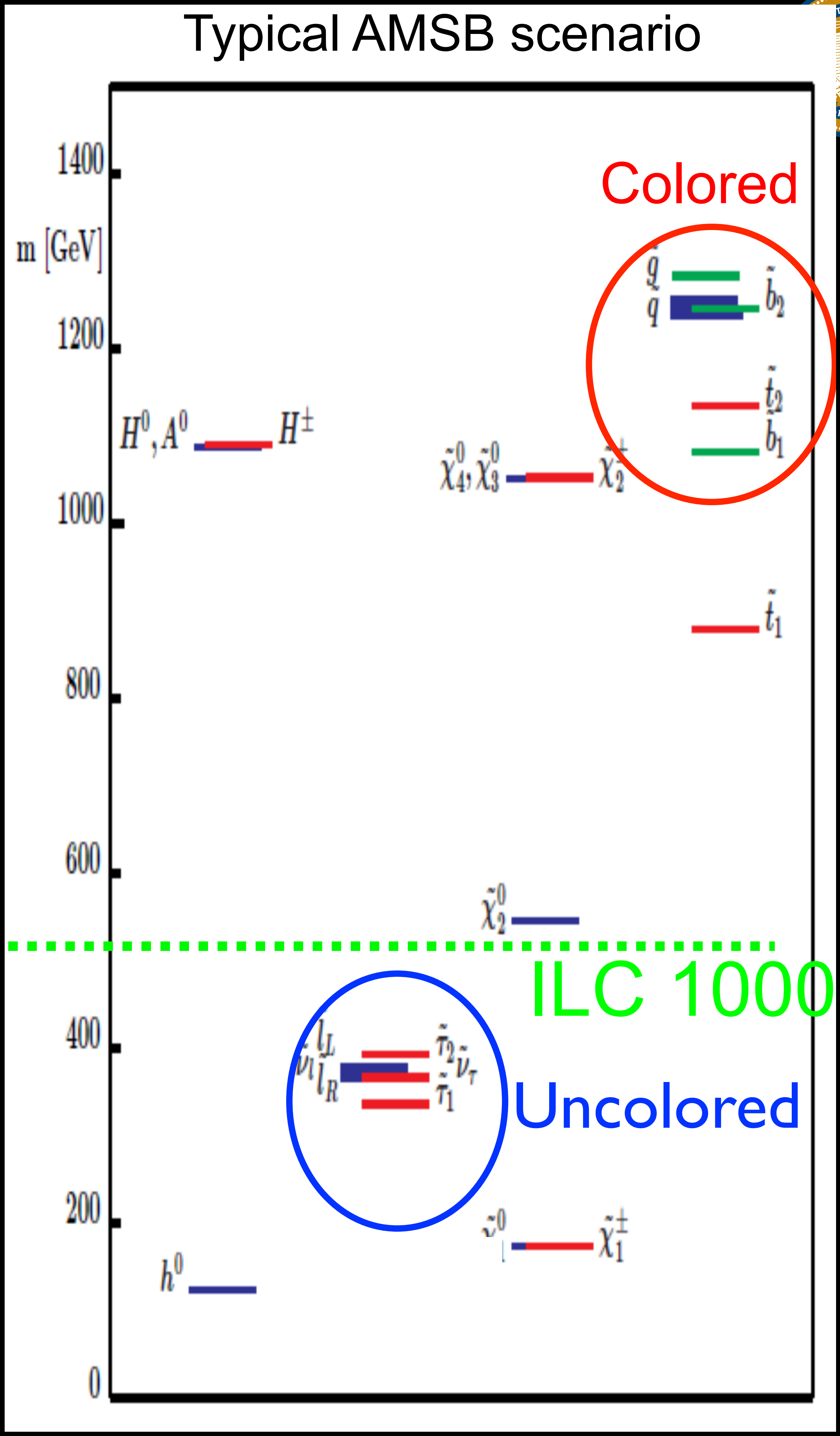
- dark matter clearly a new degree of freedom
- assign odd Z_2 parity to S, everything else even
- *t*-channel Higgs exchange for direct detection



$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4.$$

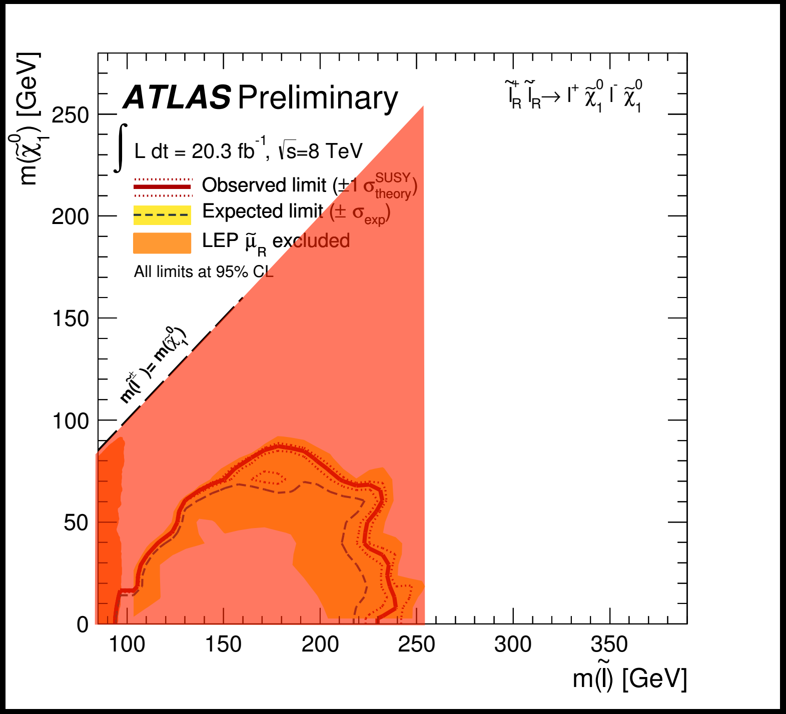
New physics

- *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

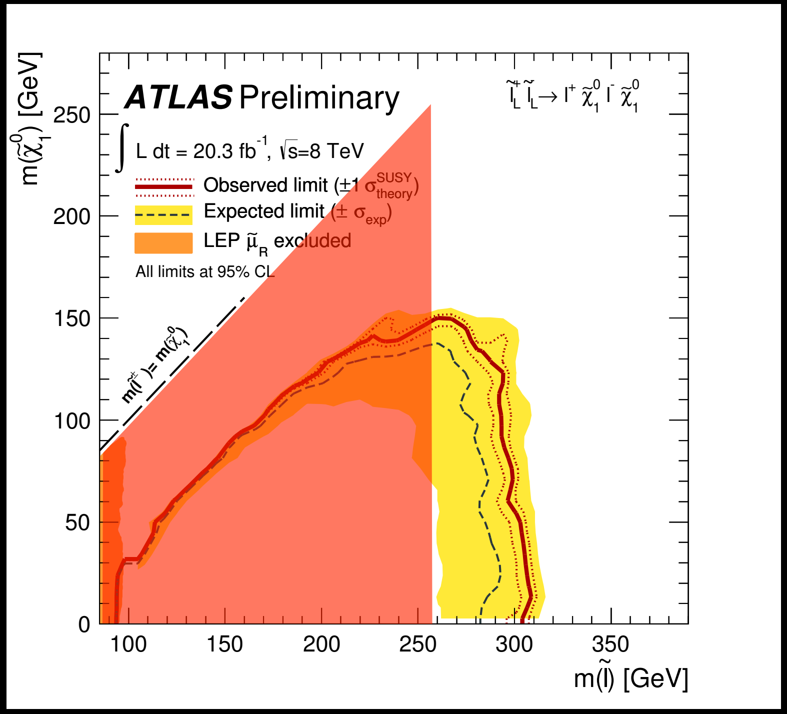


electroweak states

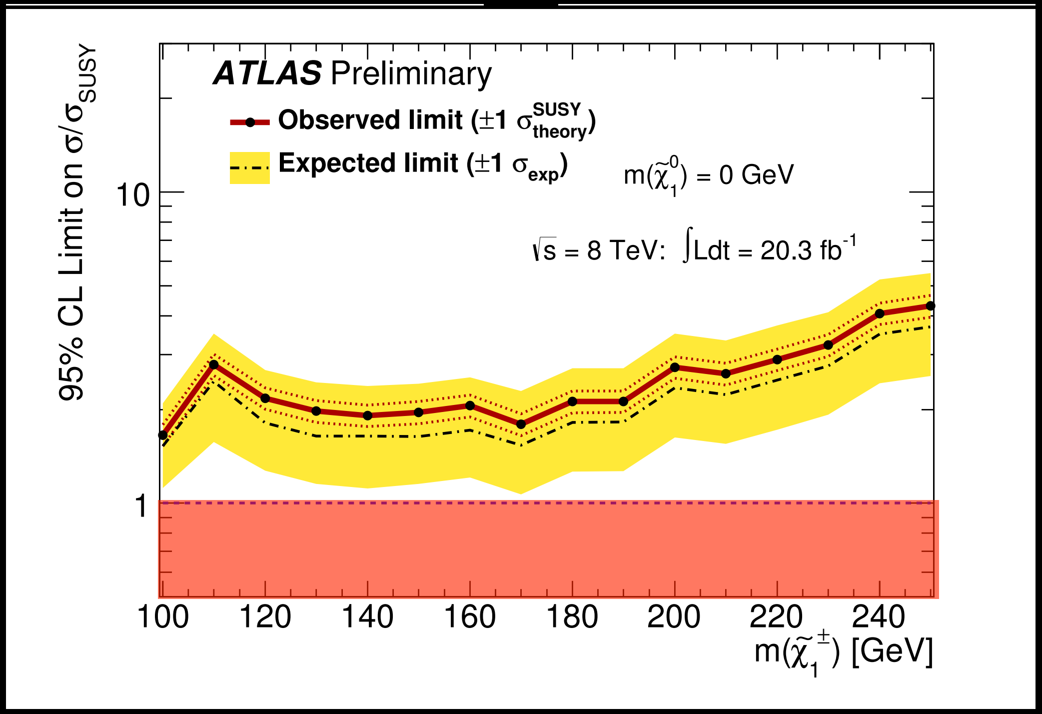
$\tilde{l}_R$



$\tilde{l}_L$

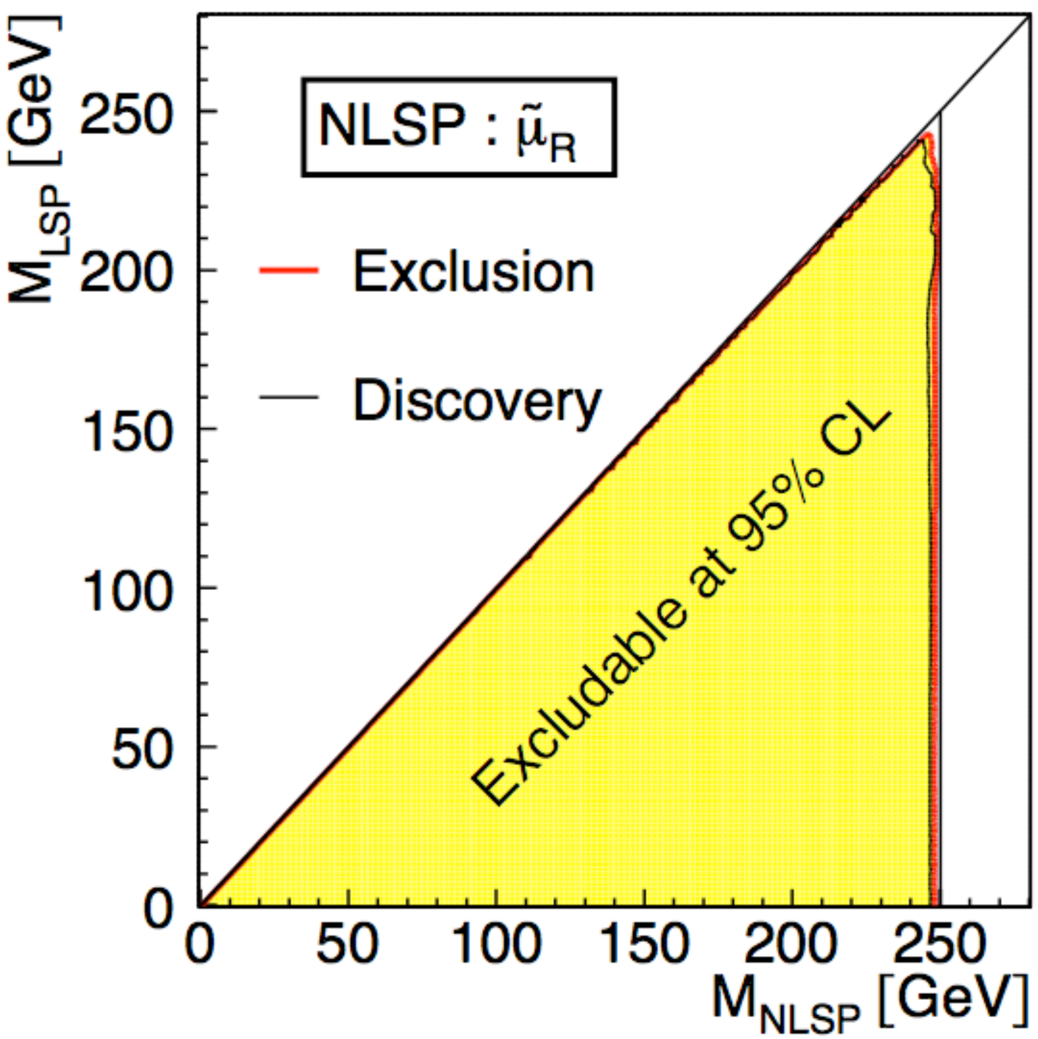


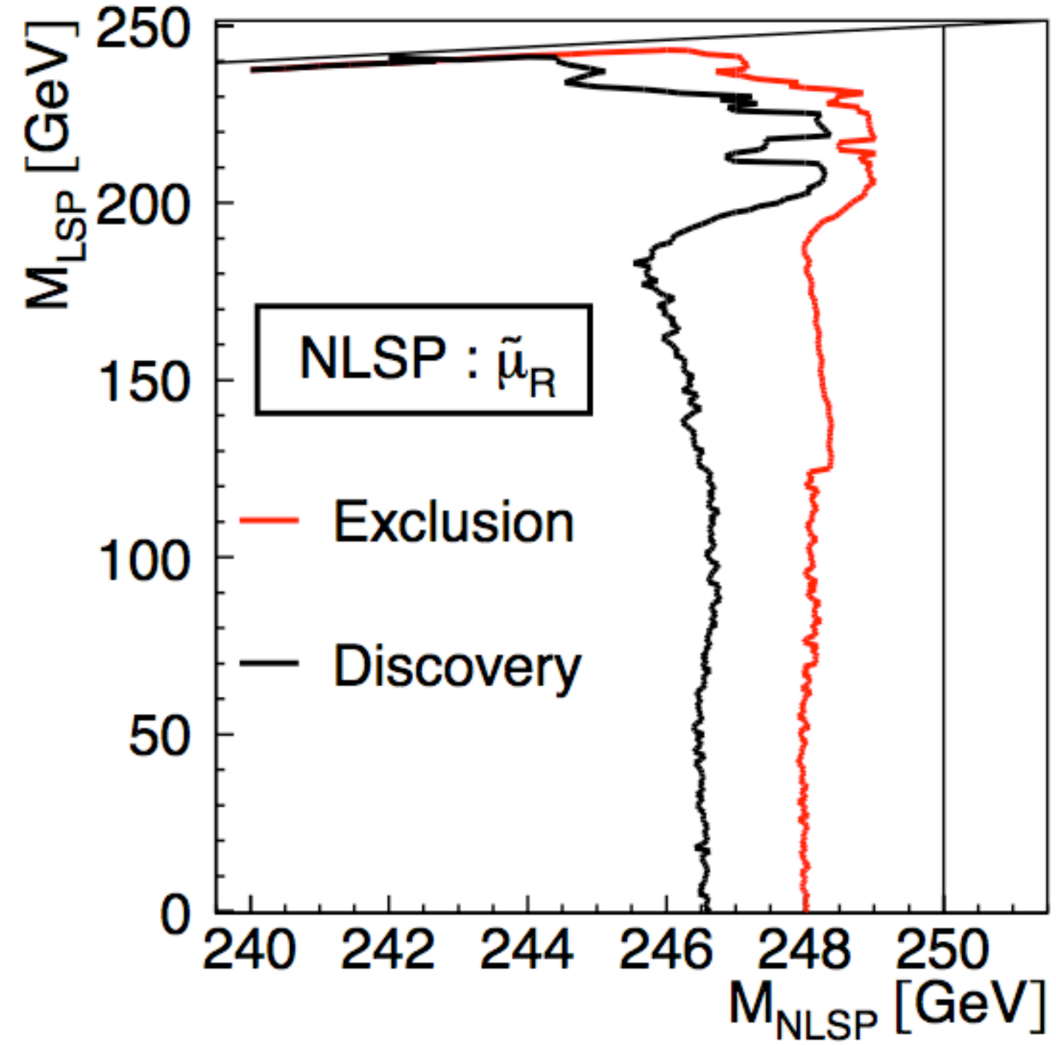
$\tilde{\chi}^{\pm}$



@ILC500

discovery up to $\sqrt{s}/2$ means ...

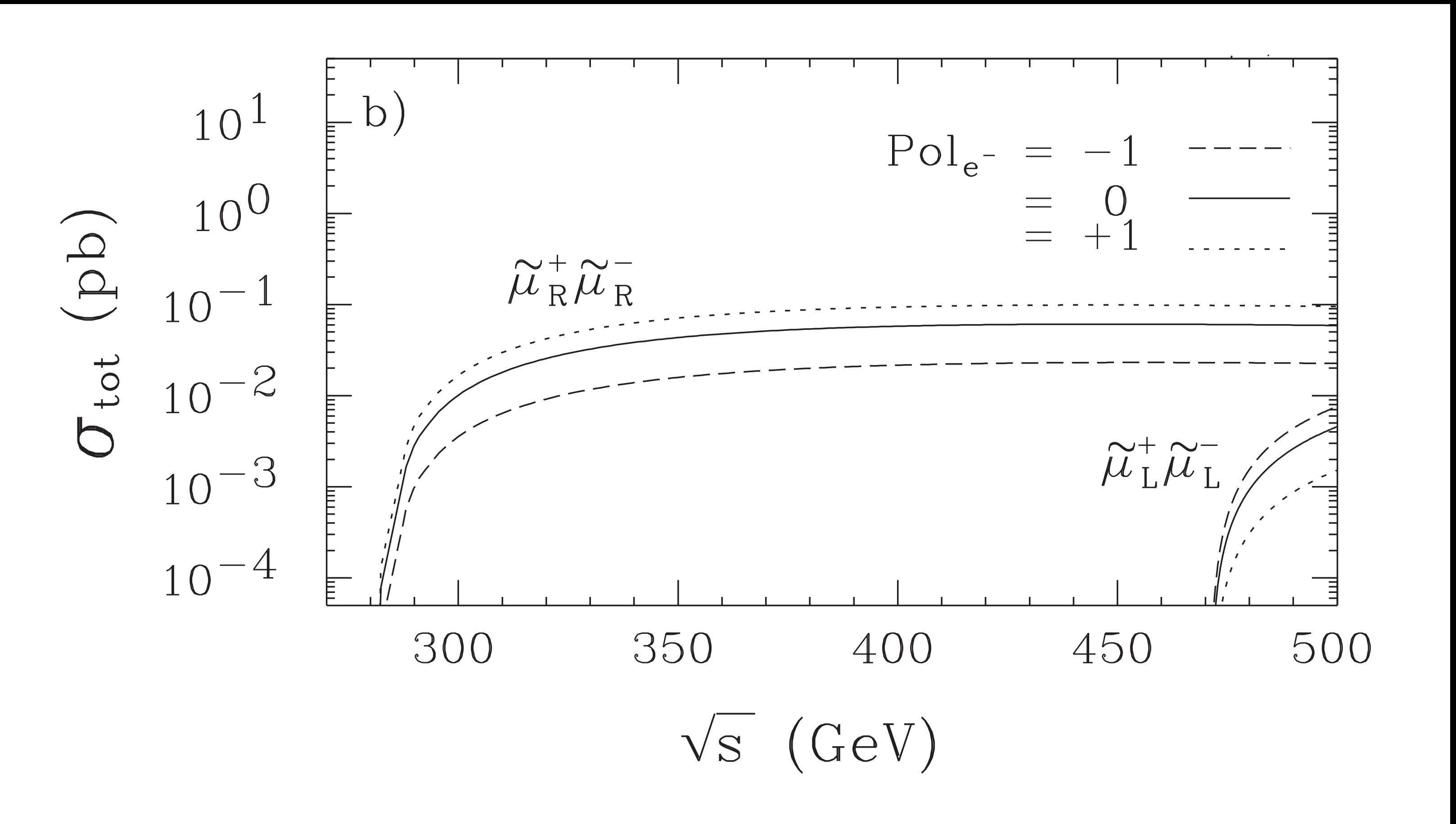


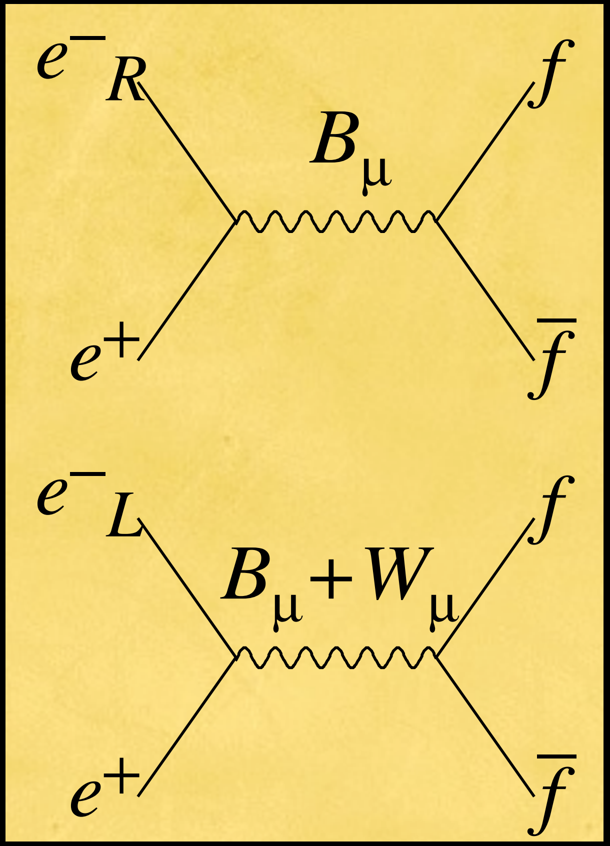


ILC BSM White Paper

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



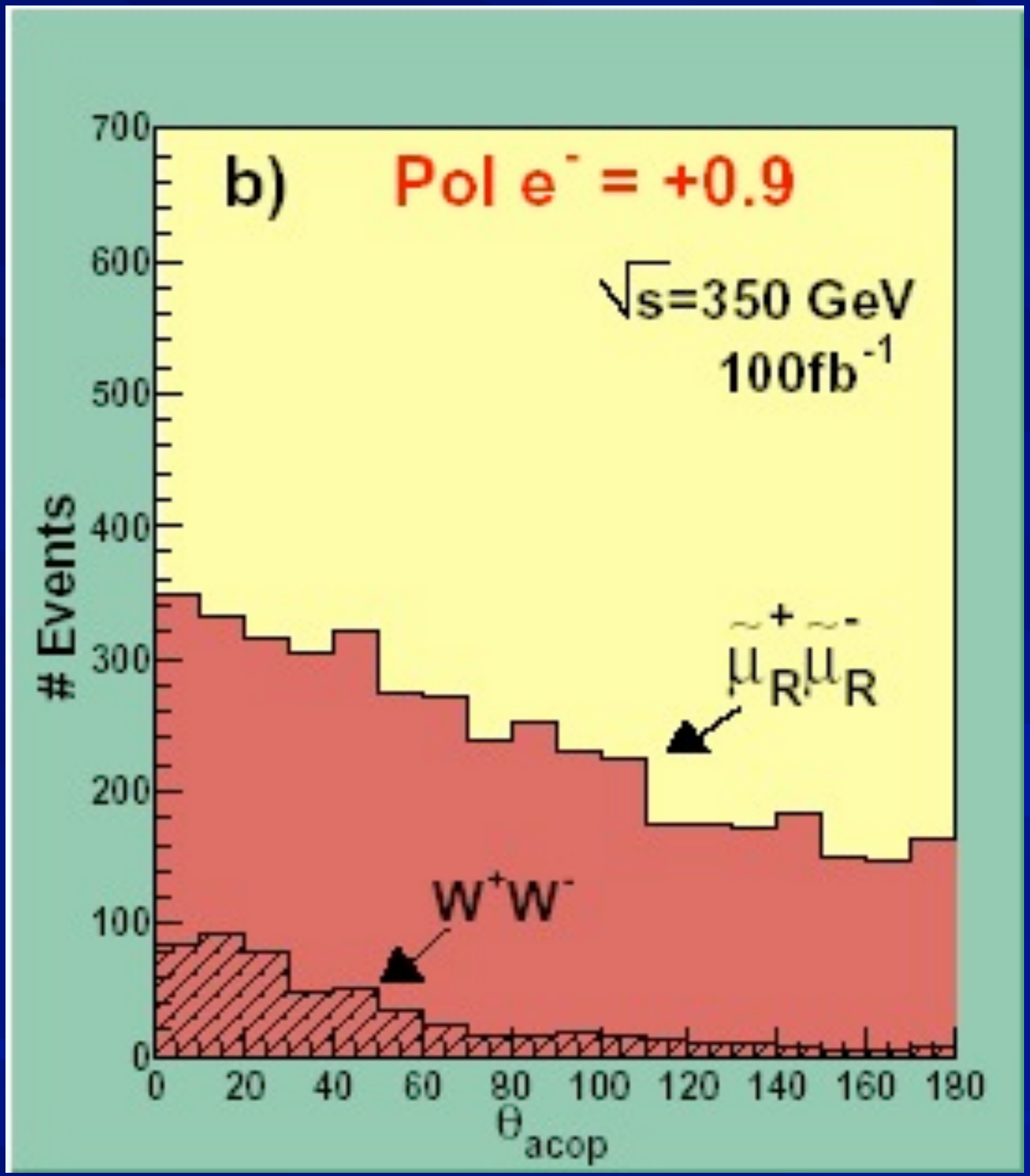


$\propto (g'^2 Y_f)^2$

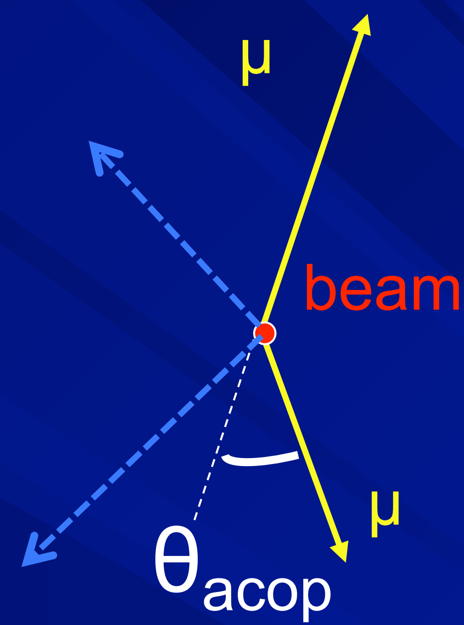
$\propto (g'^2 Y_f + g^2 I_{3f})^2$

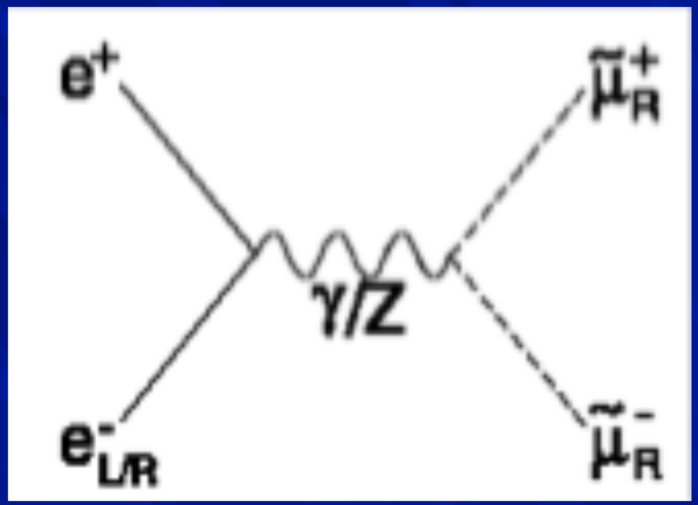
Power of electron polarization at ILC

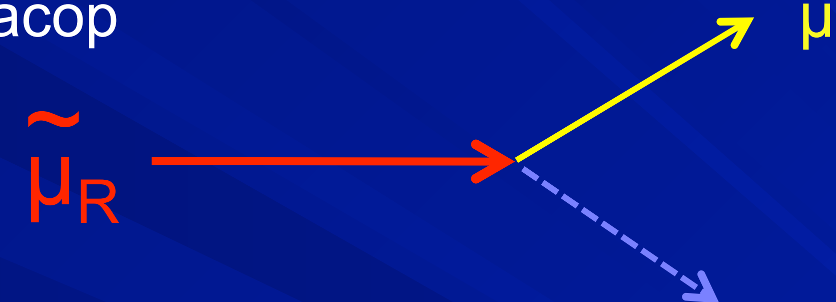
Scalar muon production



Polarized (90% e^-_R)

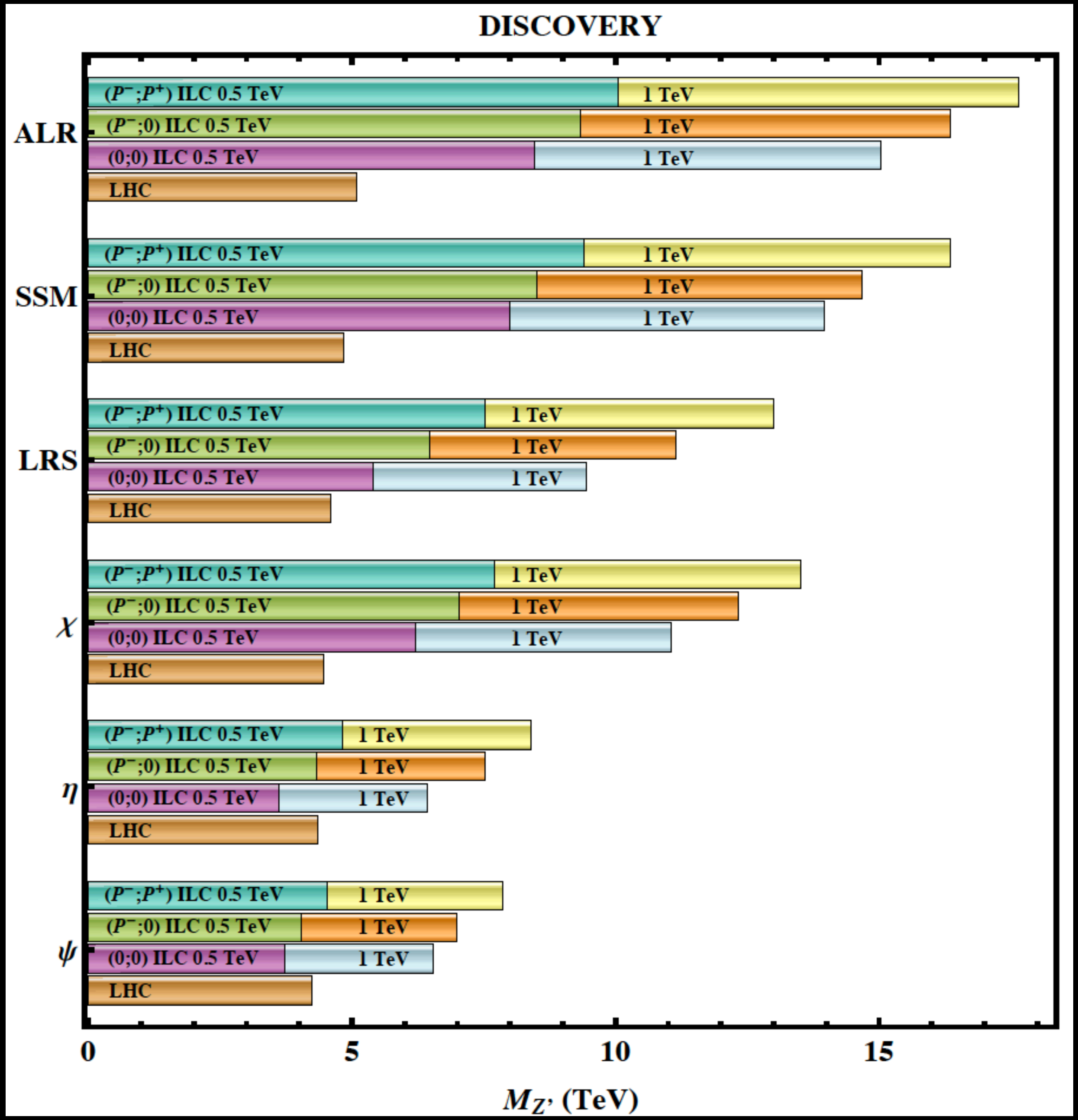


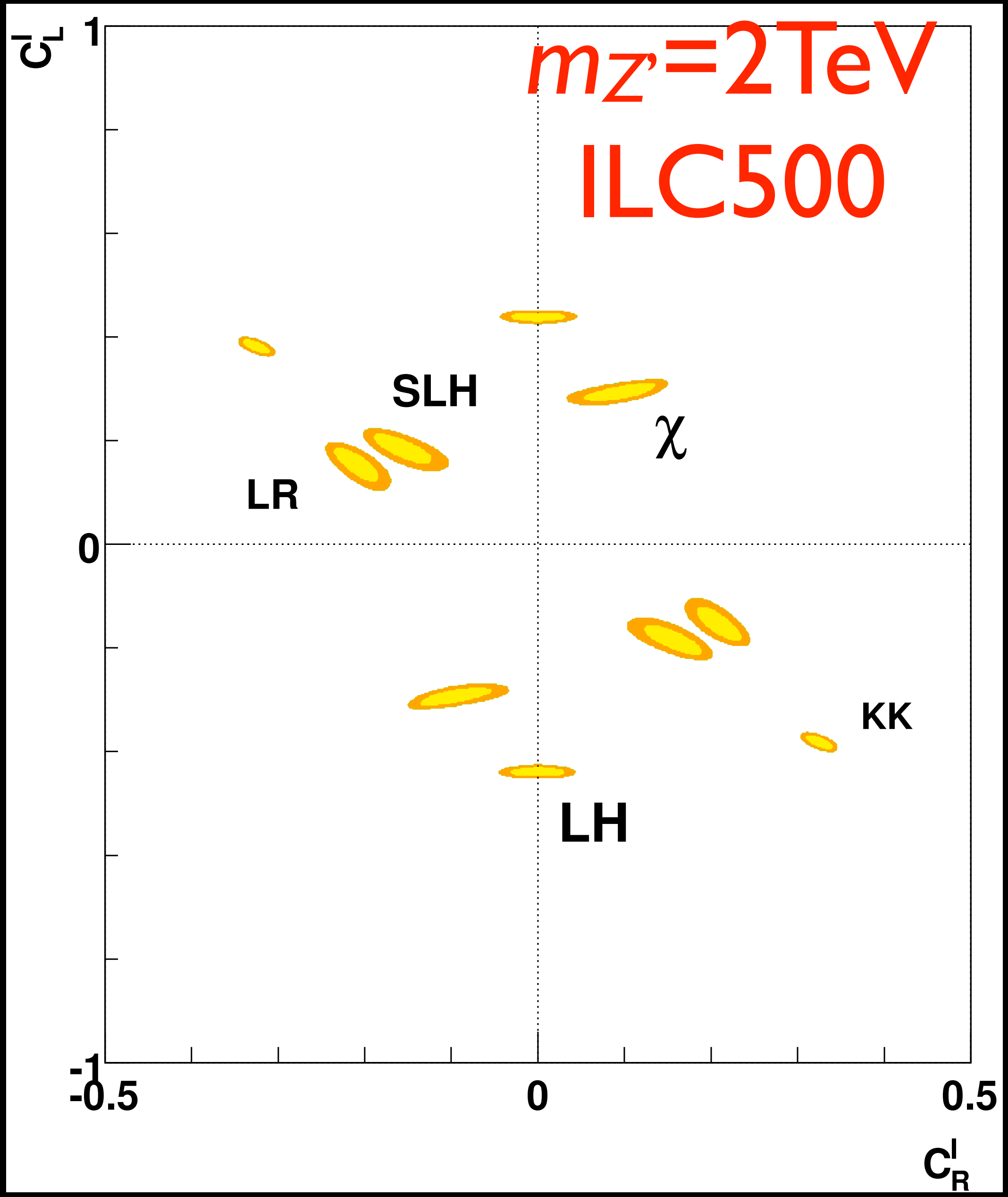




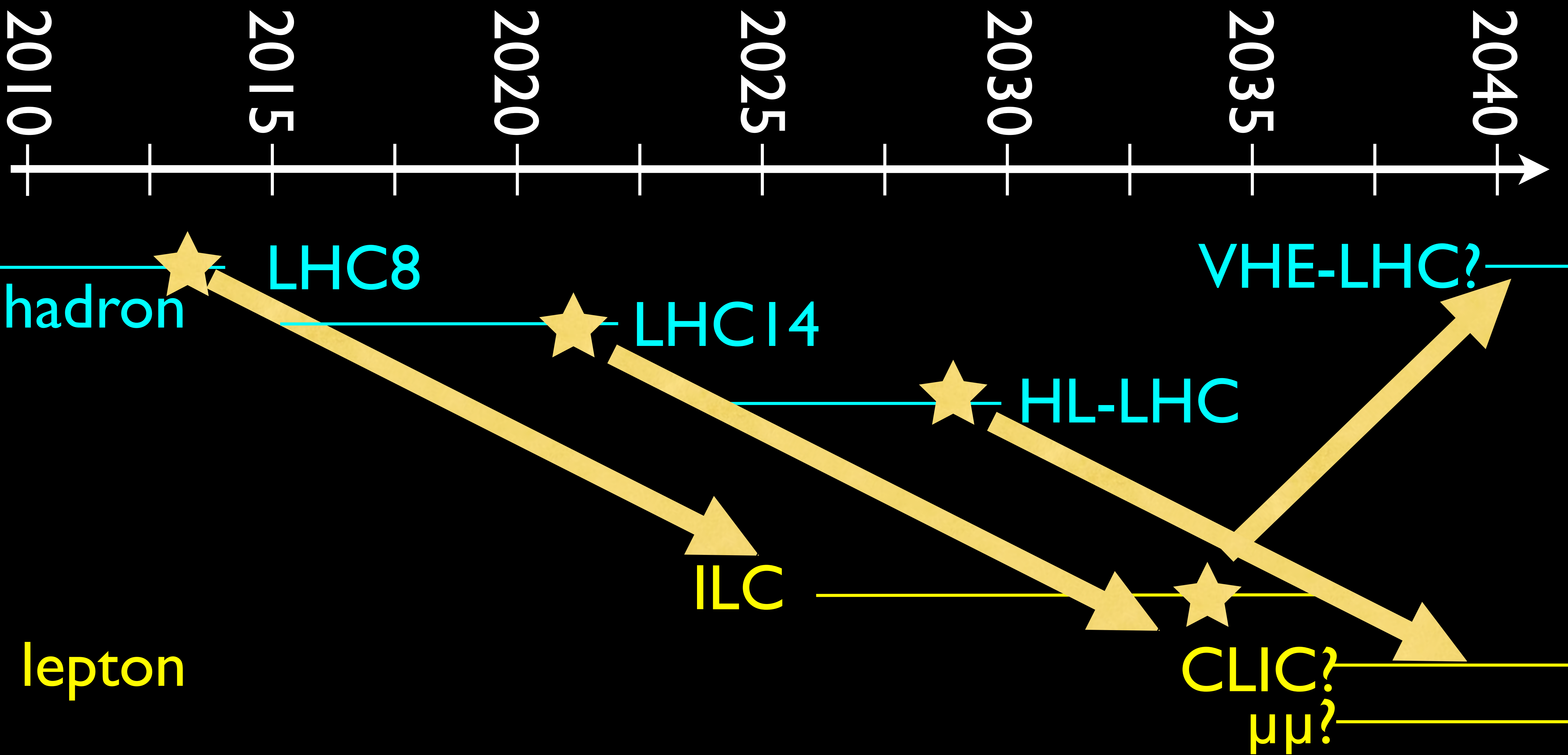
Background signal

a new gauge boson





timeline?


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