The Higgs Boson & Beyond*

Tao Han
Univ. of Pittsburgh

June 27, 2018
CTEQ Summer School
Univ. of Puerto Rico - Mayaguez

* Beyond the SM & Beyond the LHC

What We Know Now?

What It Tells Us?

What Else We Would Like to Know?

How To Proceed From Here?

François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

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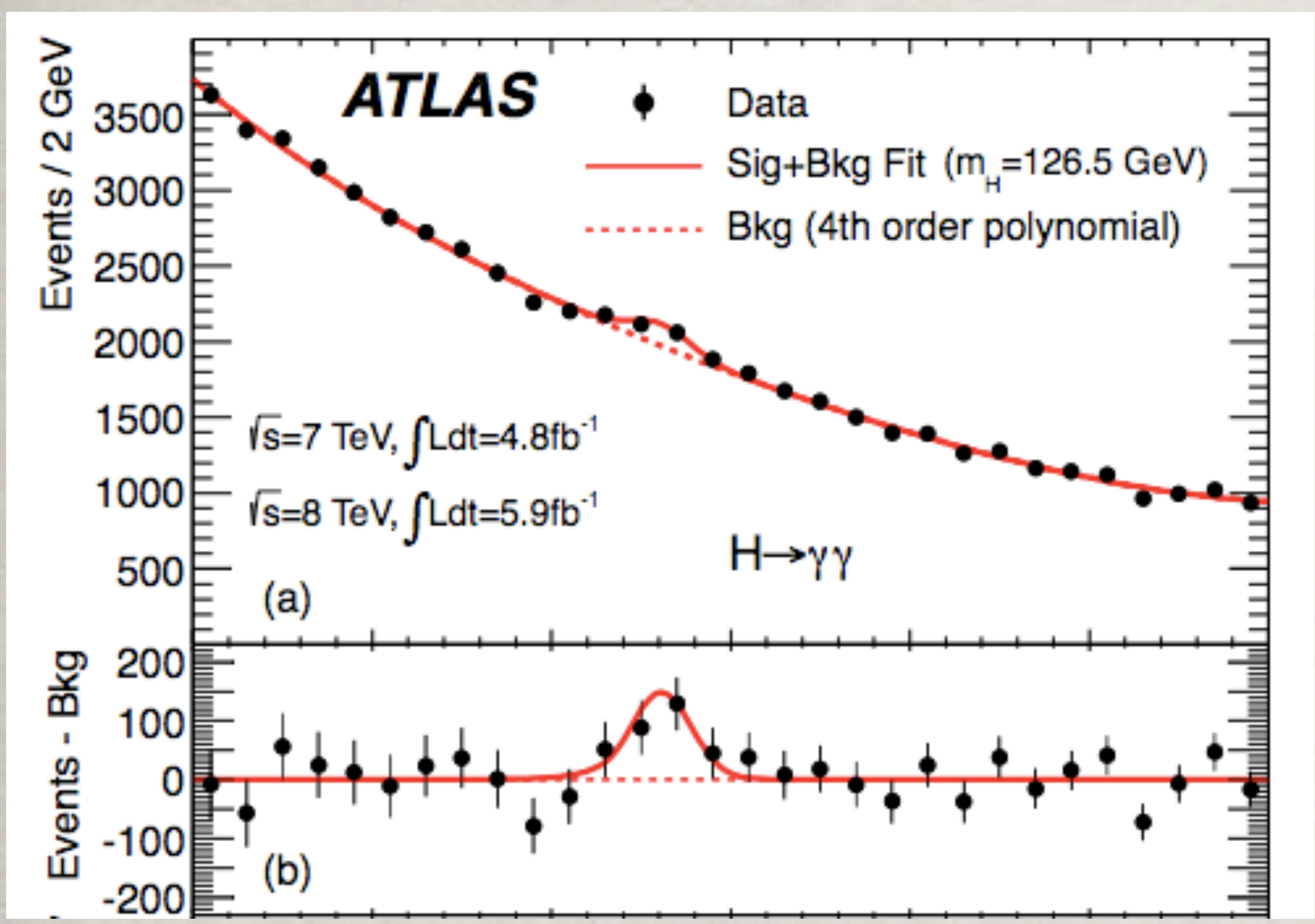
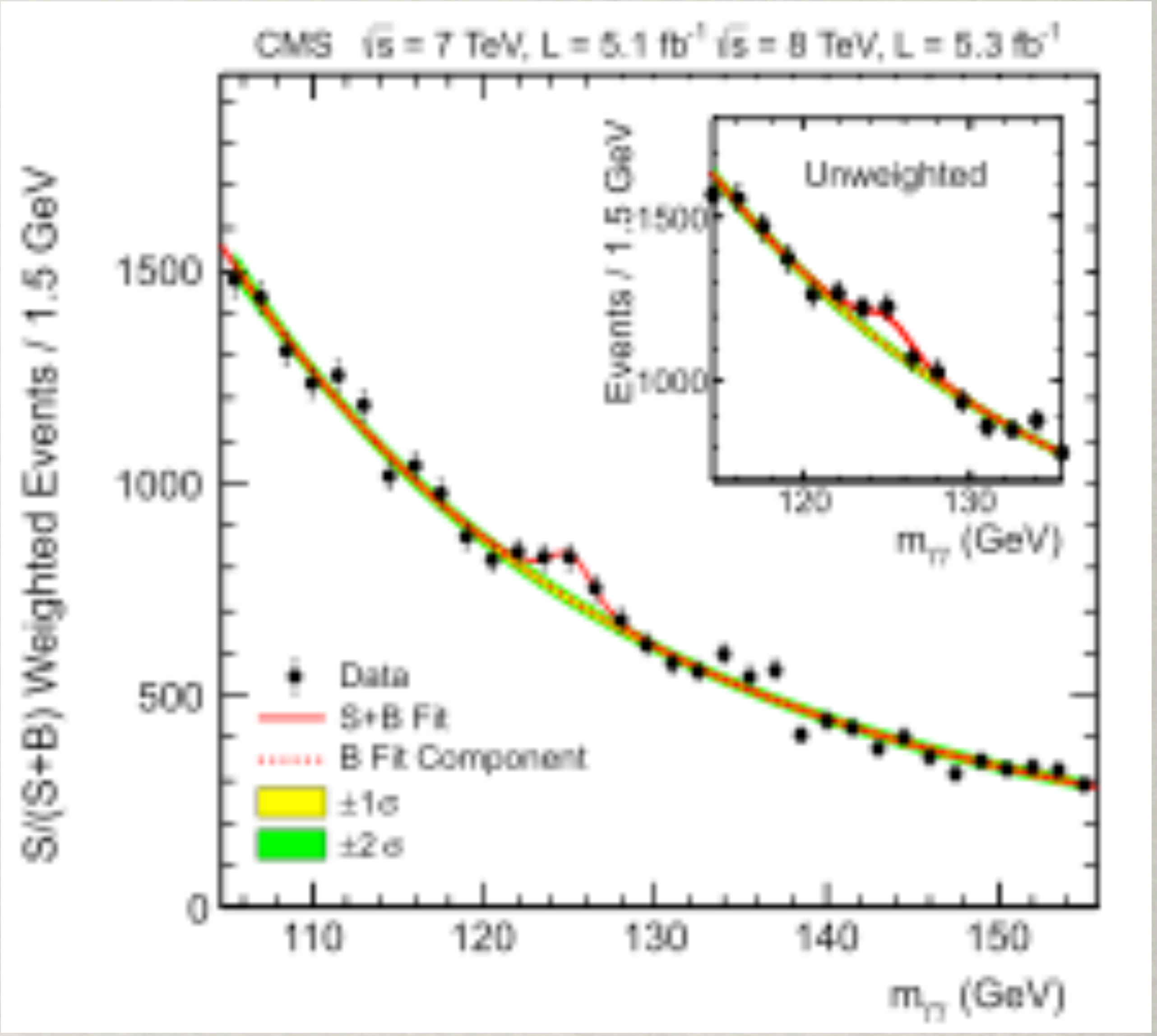
The discovery:
A neutral boson decay to two photons





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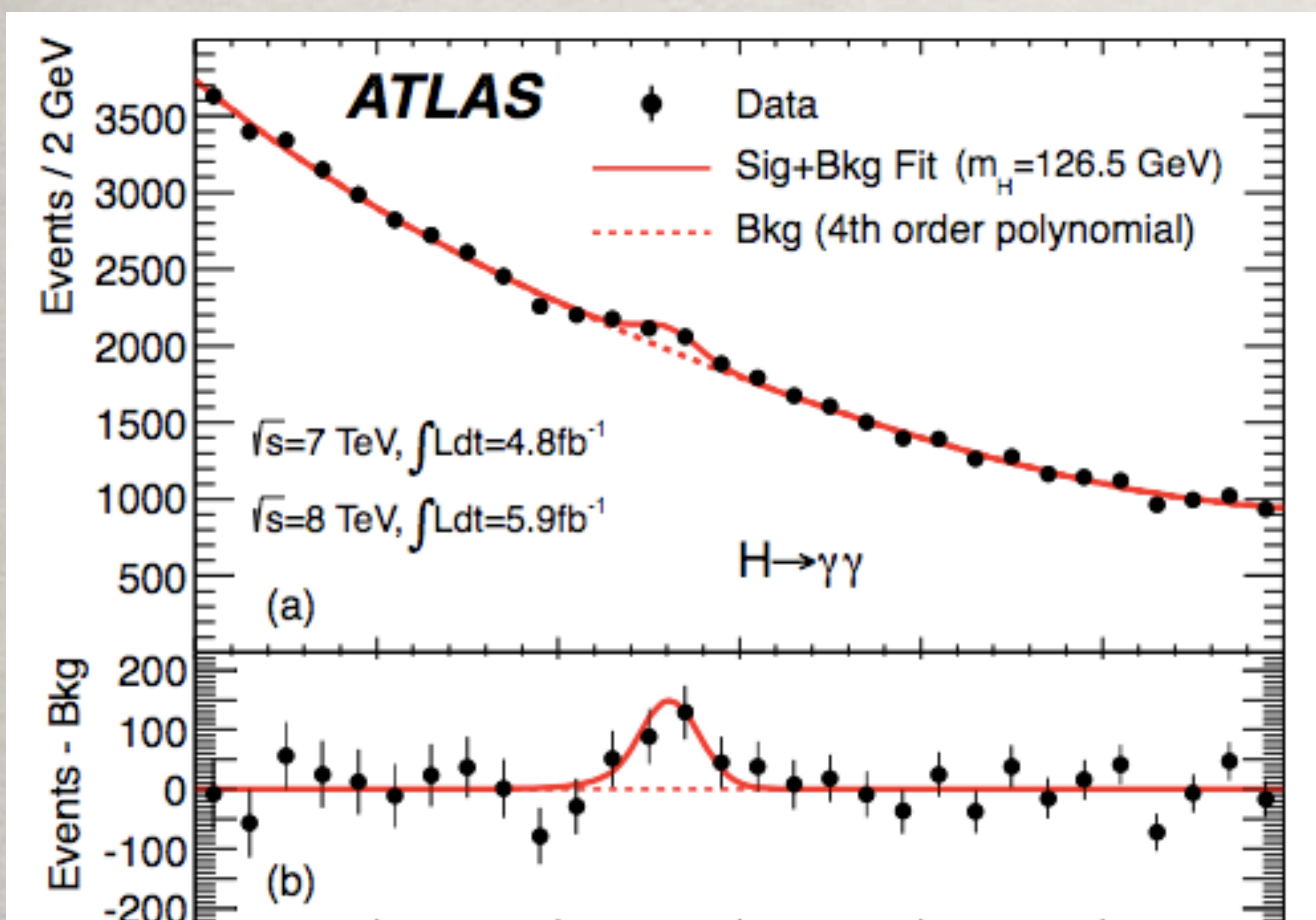
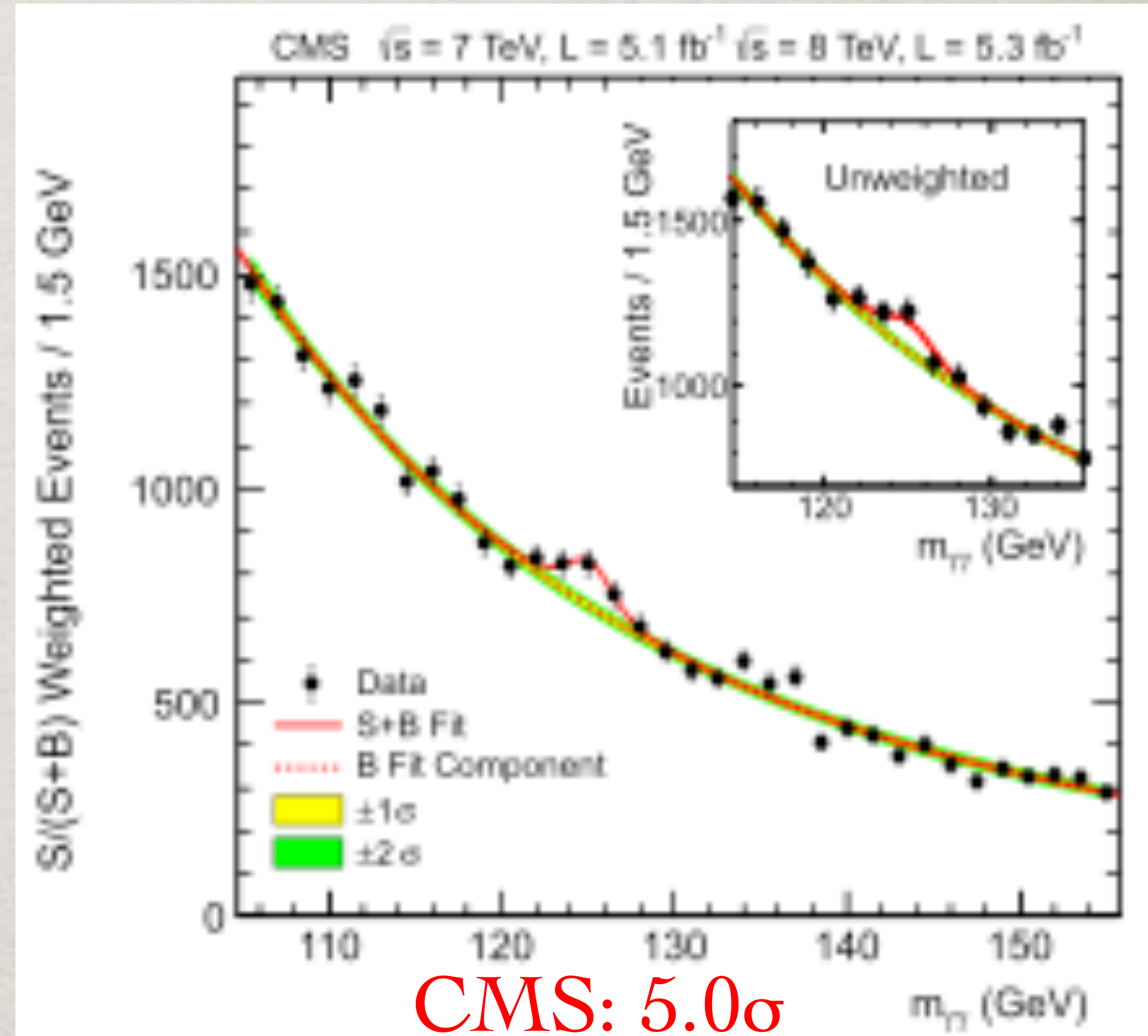


The combined signal significance:

ATLAS: 5.9σ



CMS: 5.0σ

Phys. Lett. B716, 1 (2012)

Phys. Lett. B716, 30 (2012)

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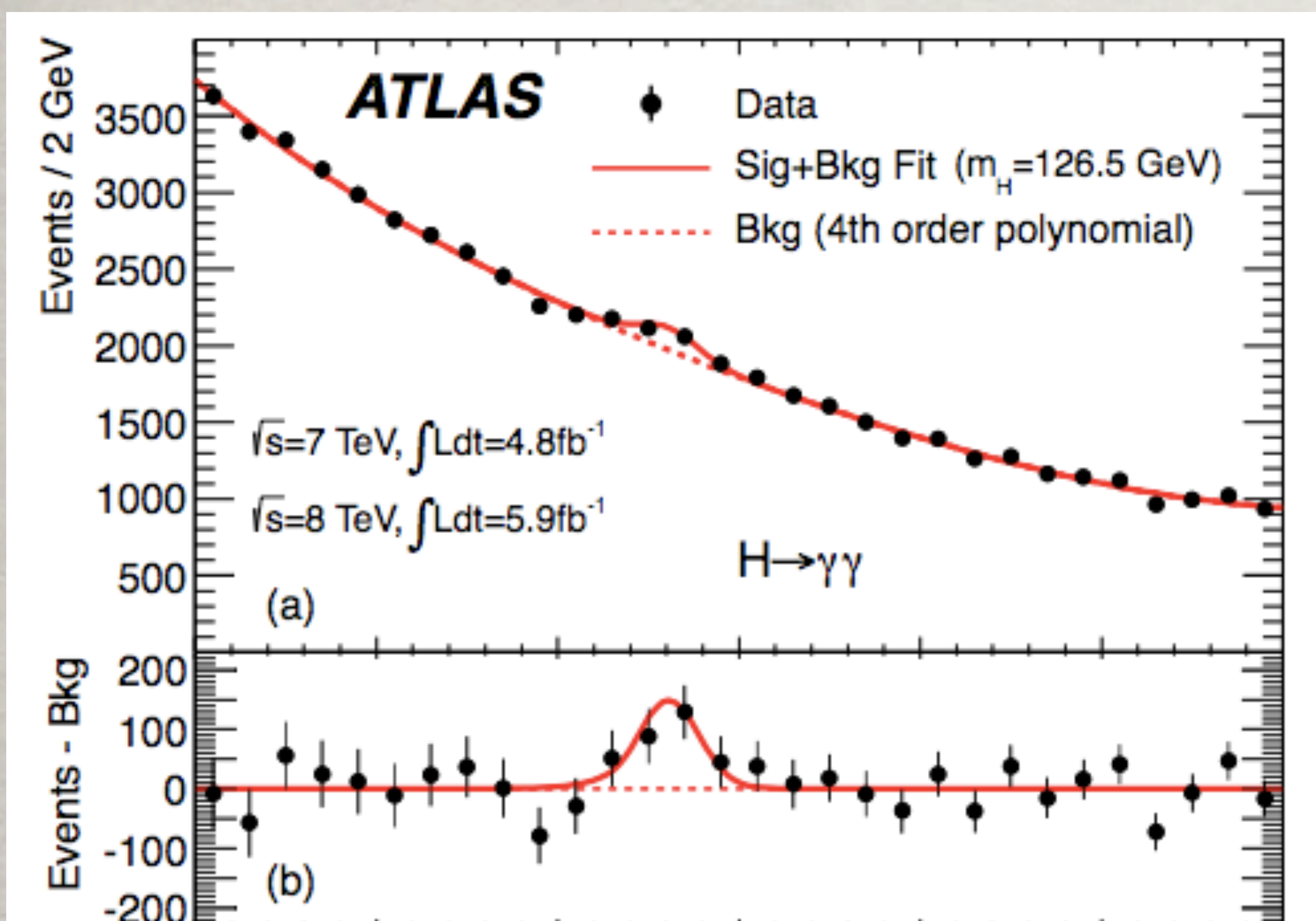

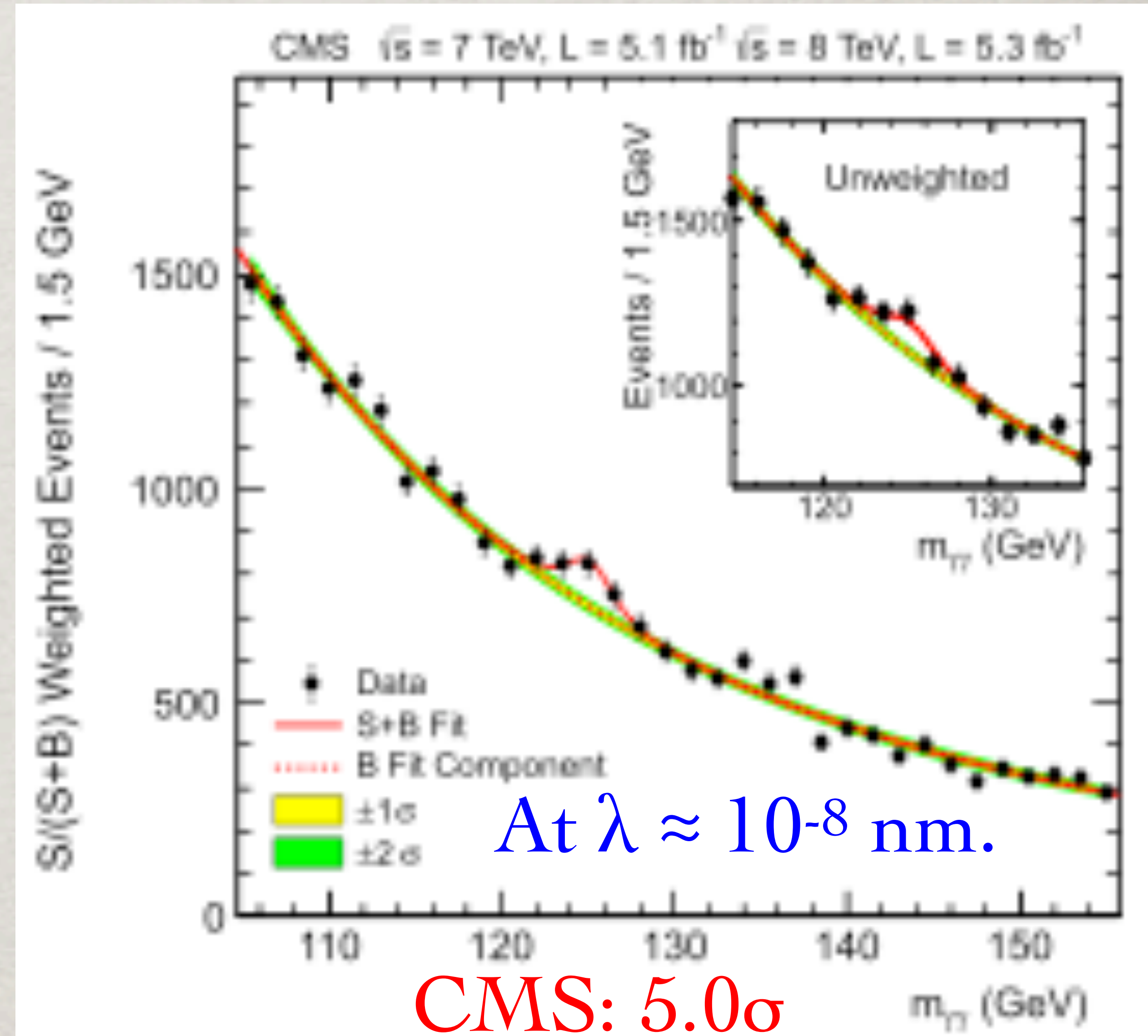

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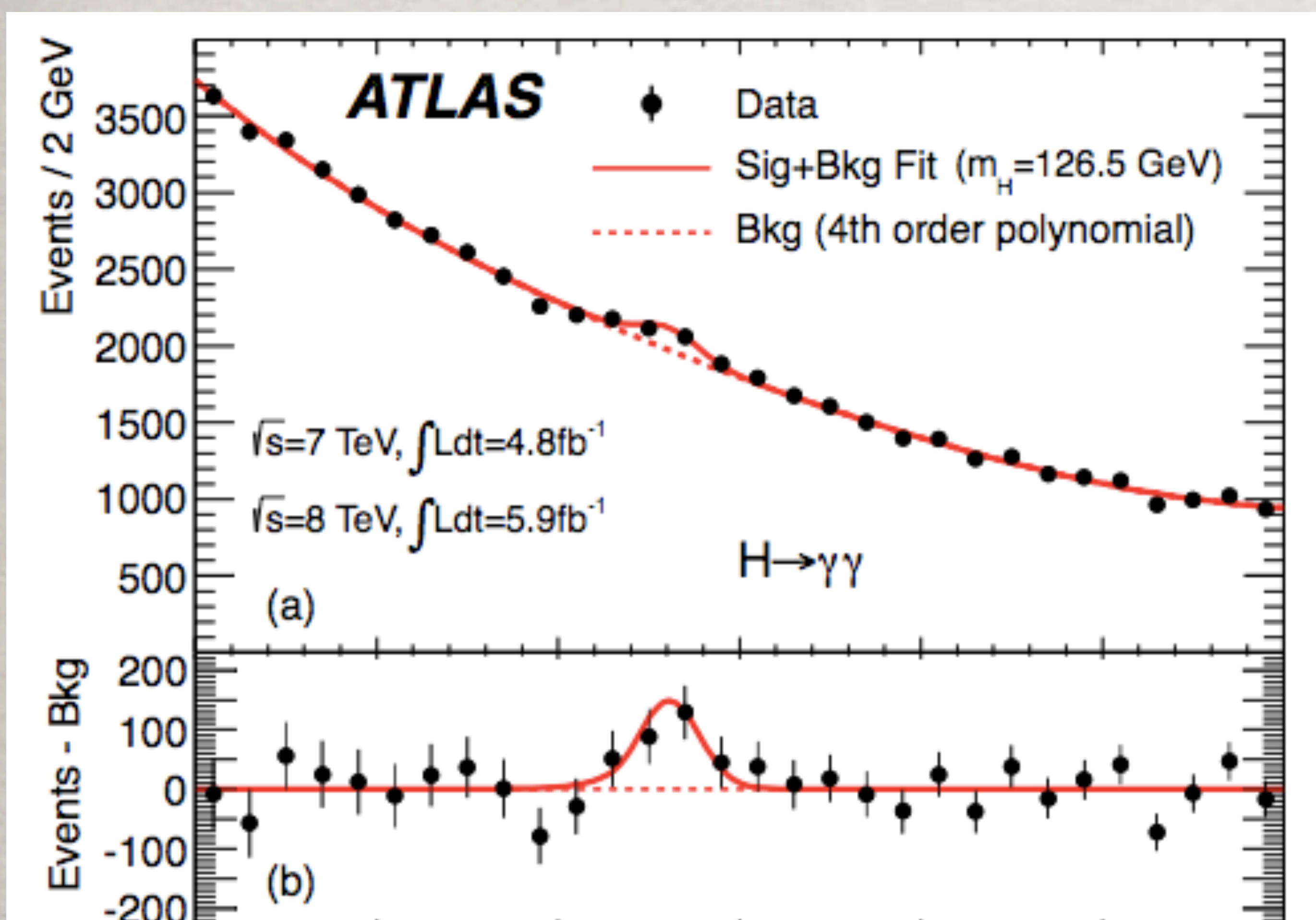

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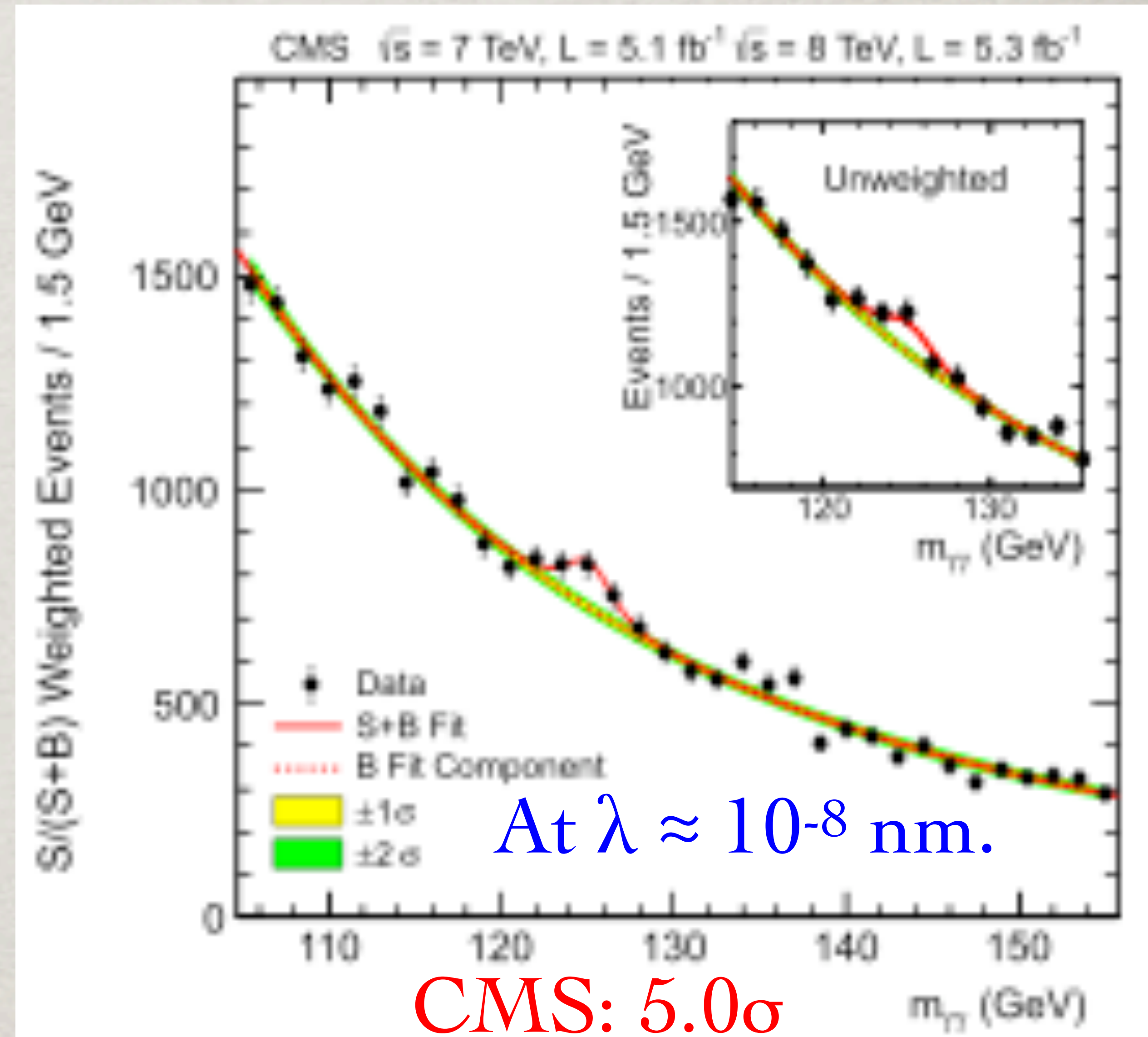

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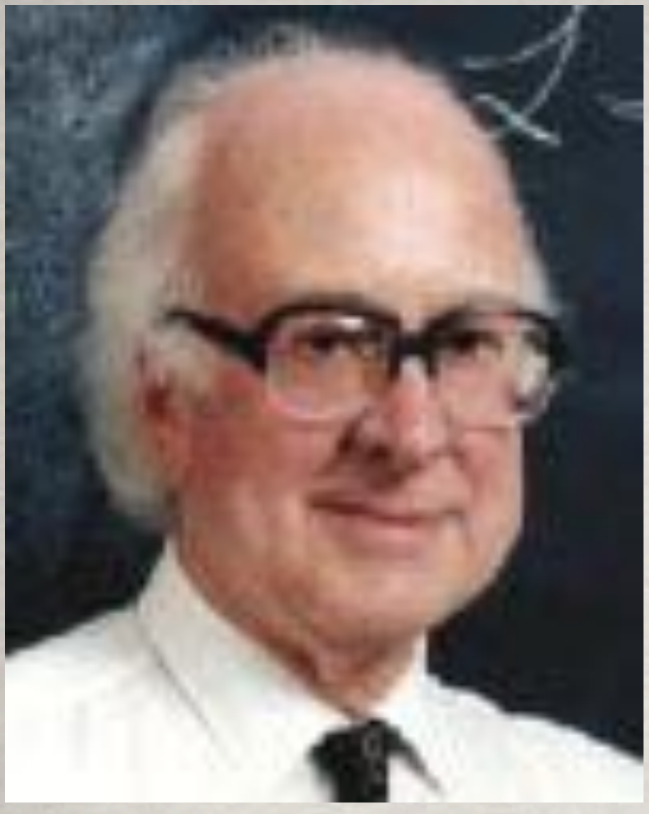
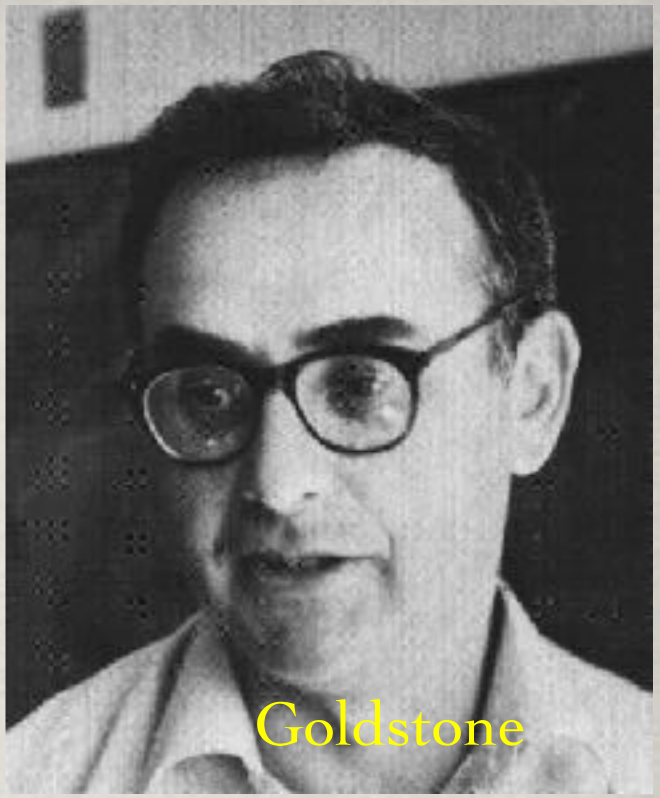
50 years theoretical work …

25 years experimental work …





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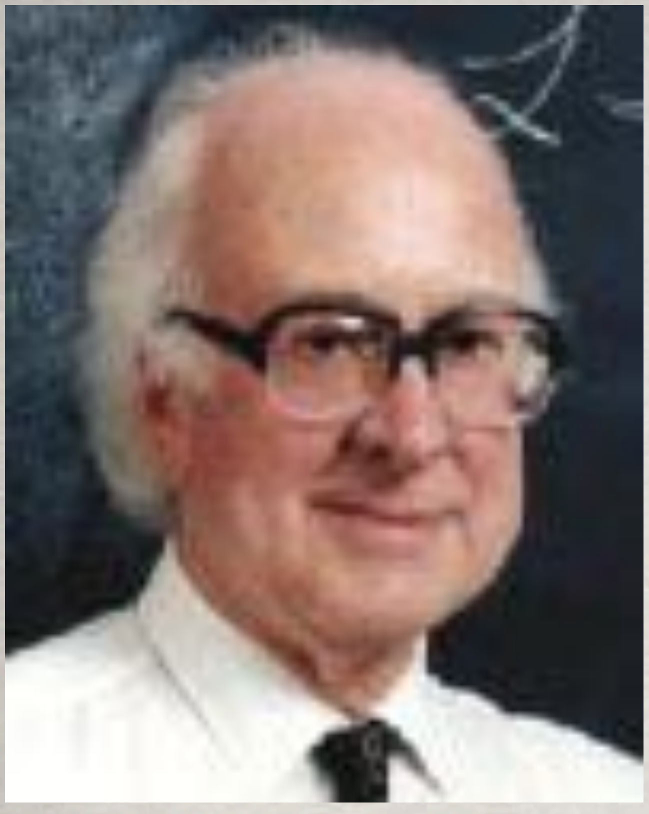

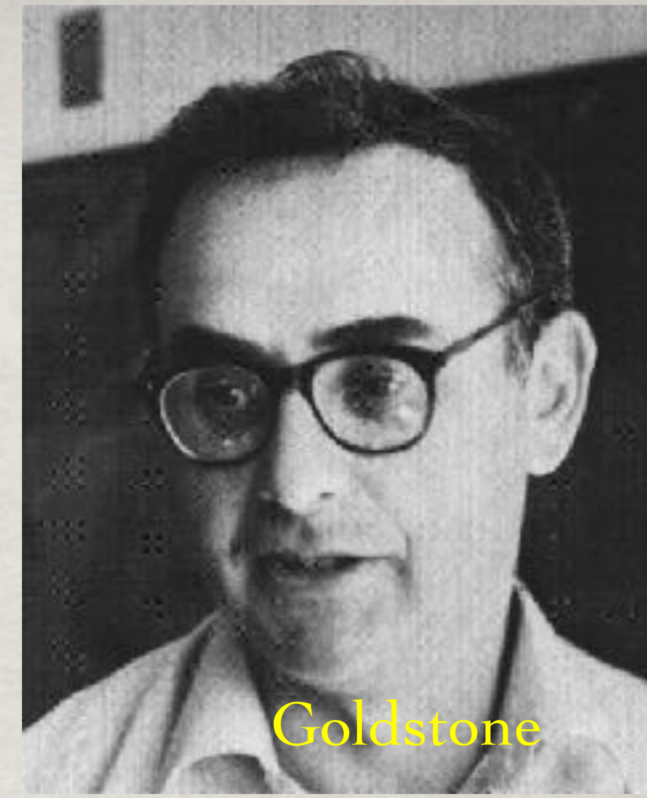

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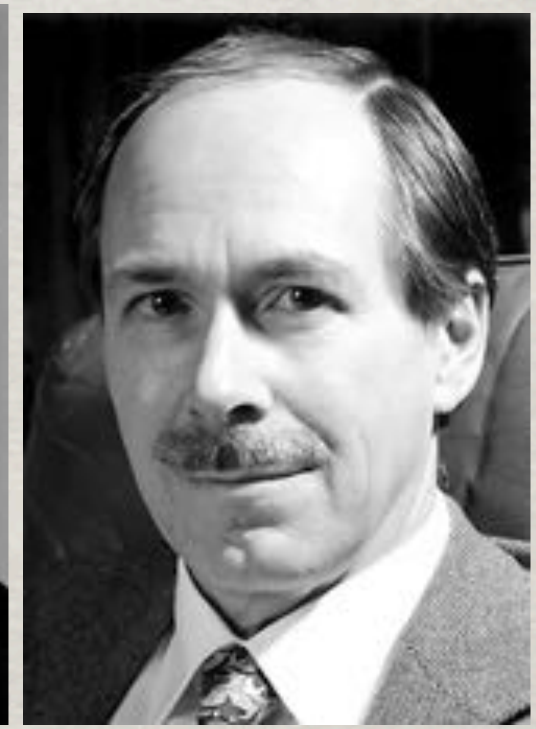
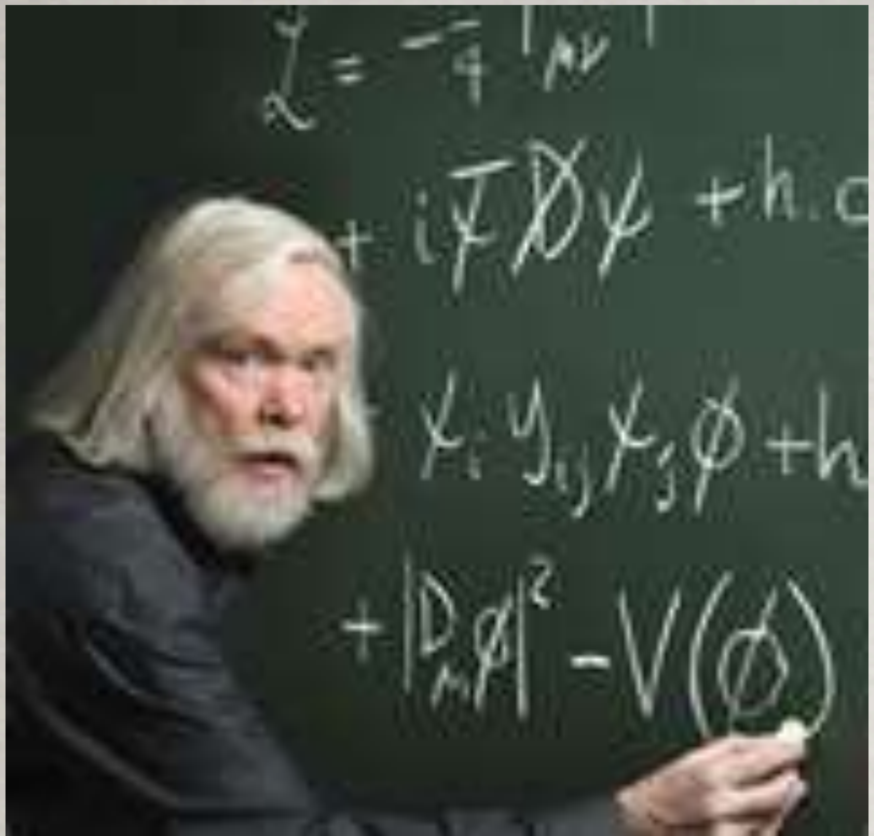
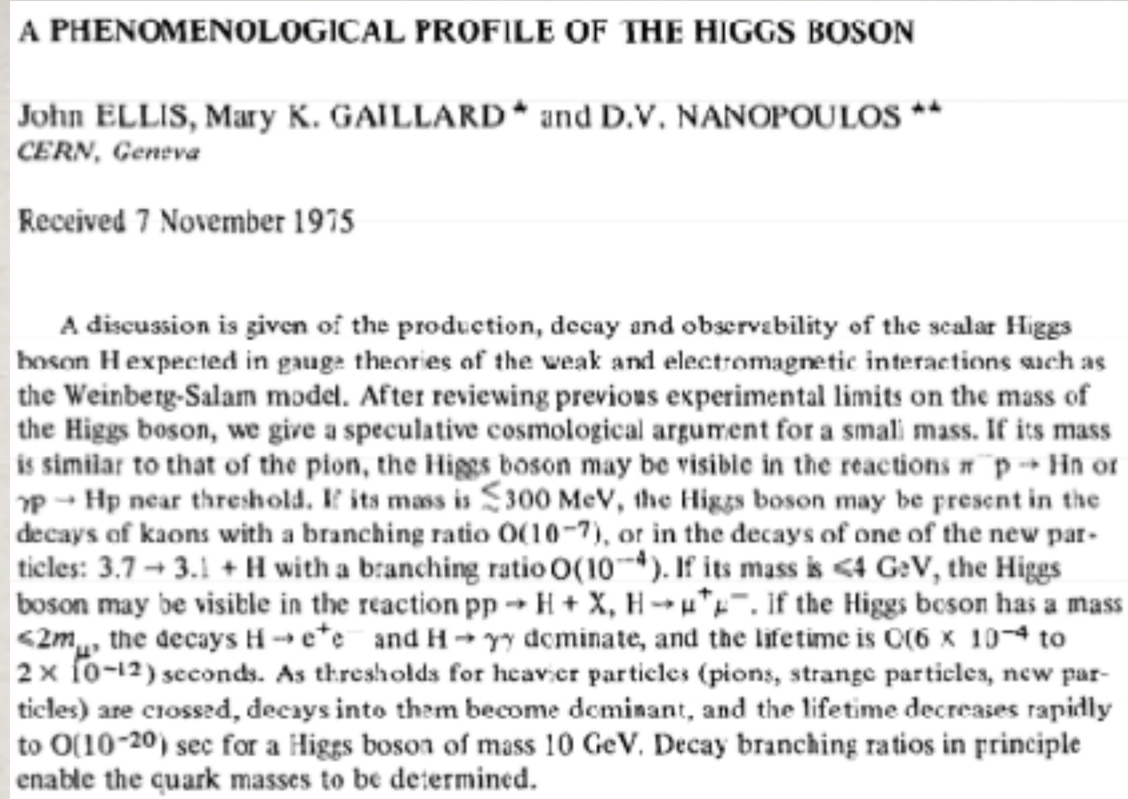


The Standard Model (1960-1967, 1972, 1973)





A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

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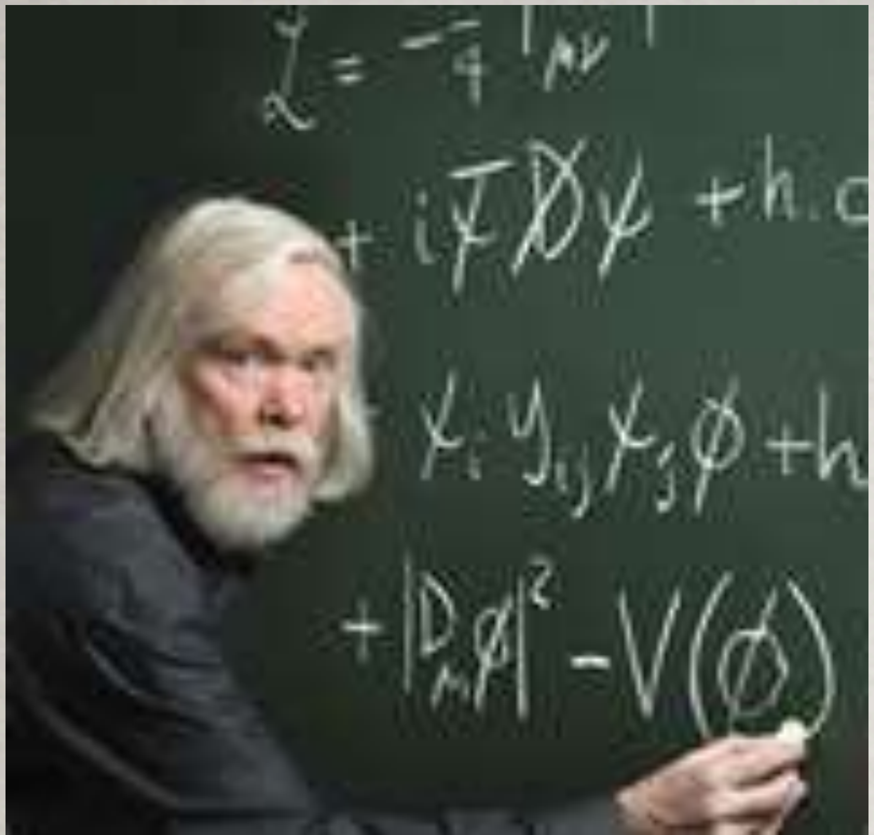

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The "EHLQ" (80's)

Supercollider Physics

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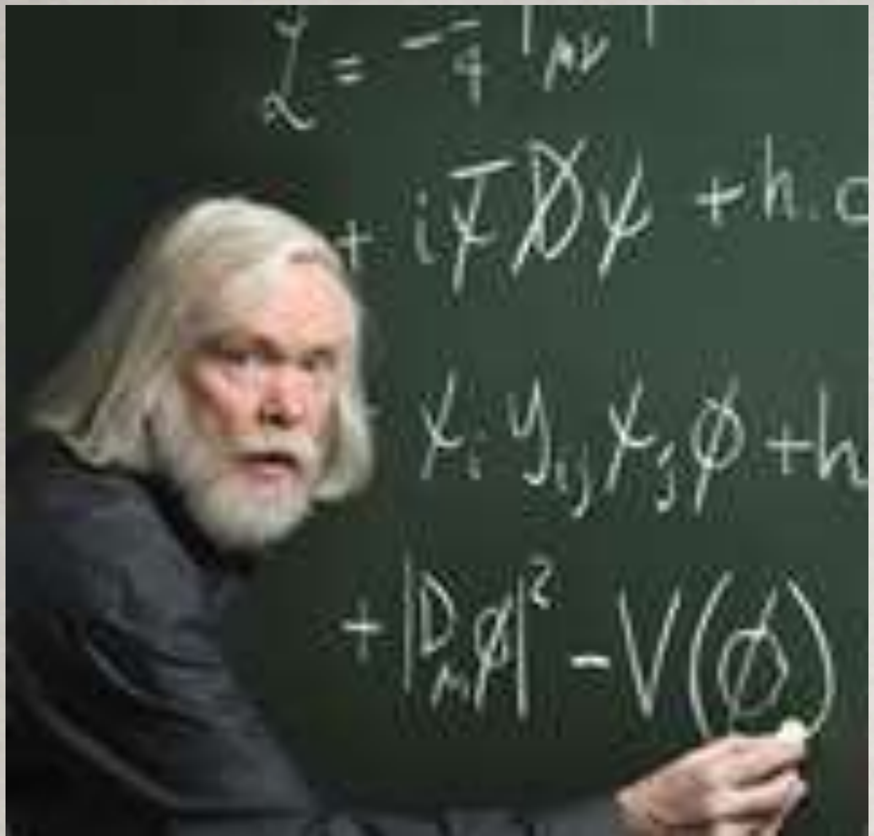

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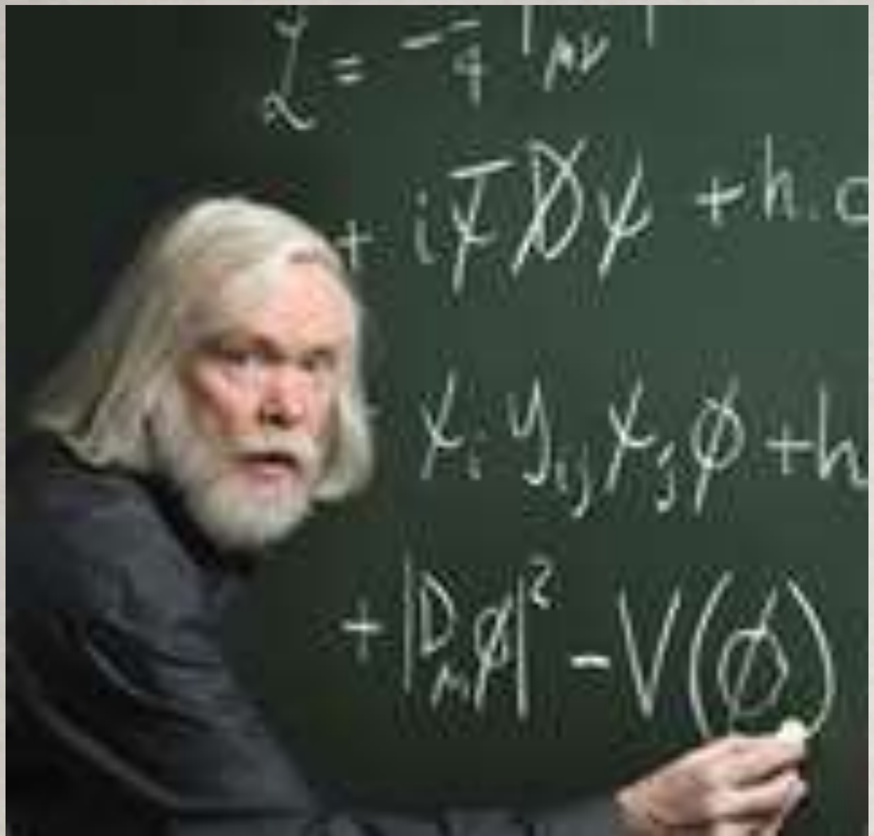

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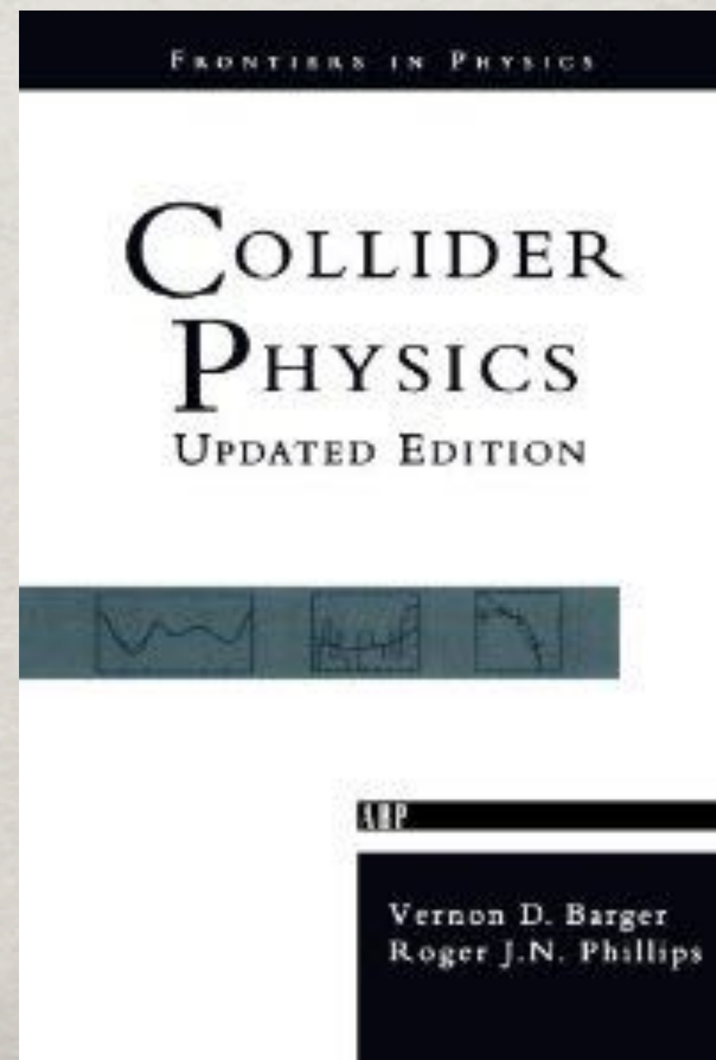

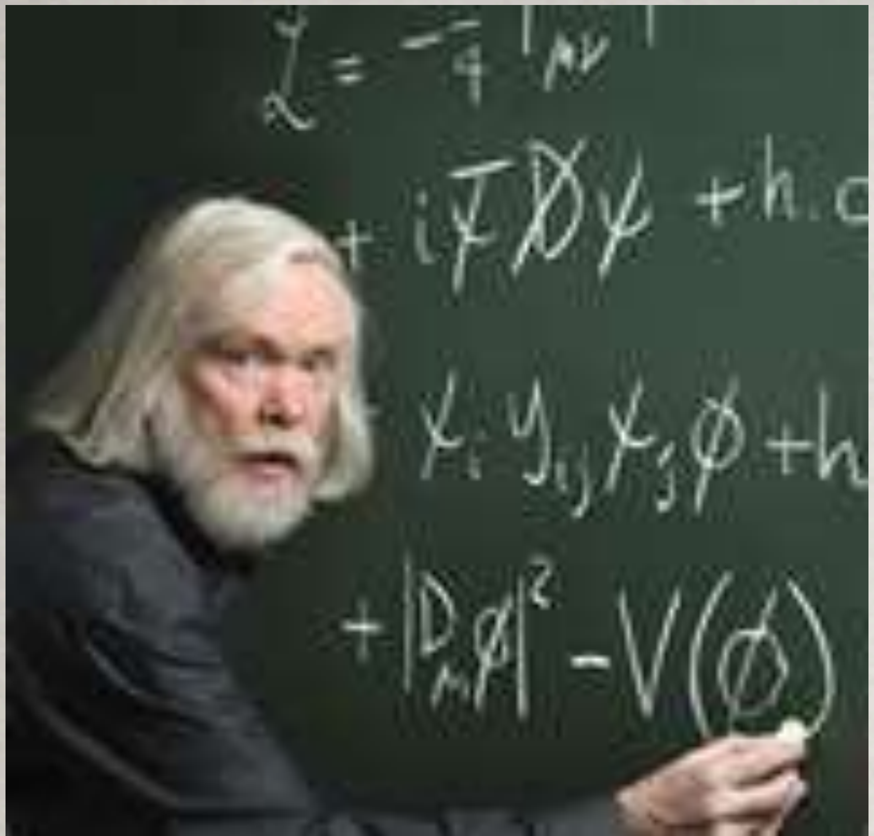

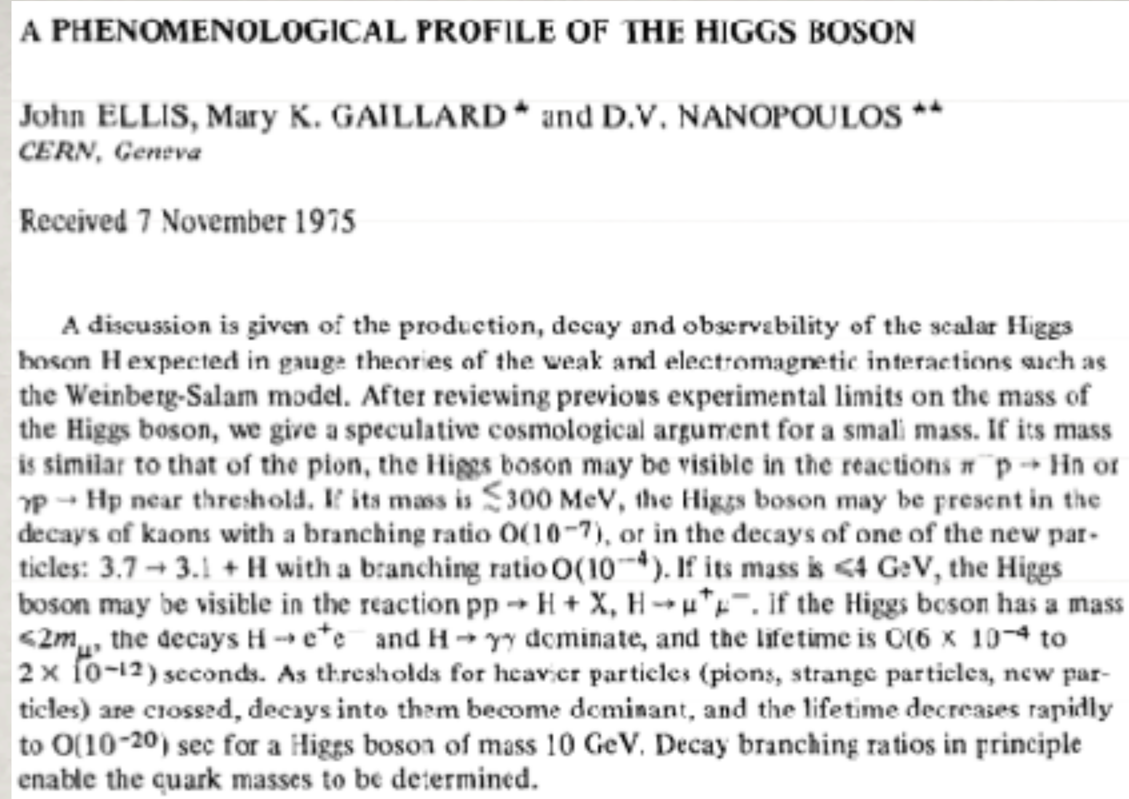

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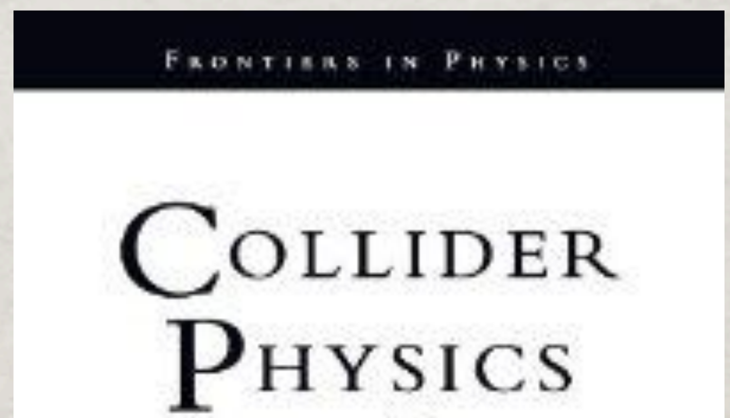

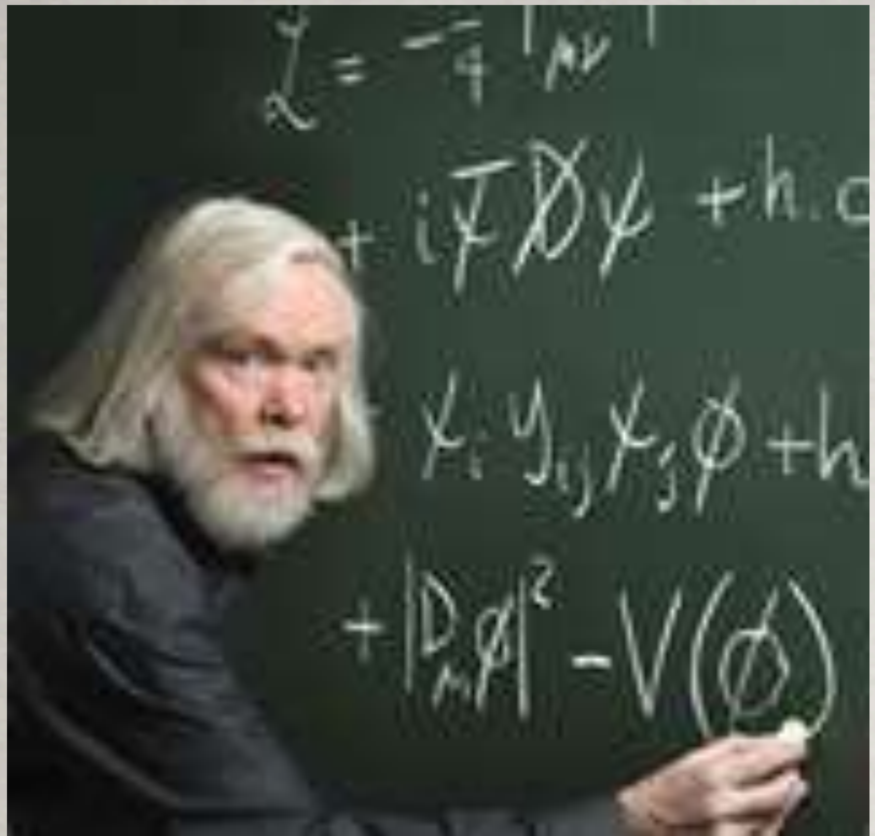

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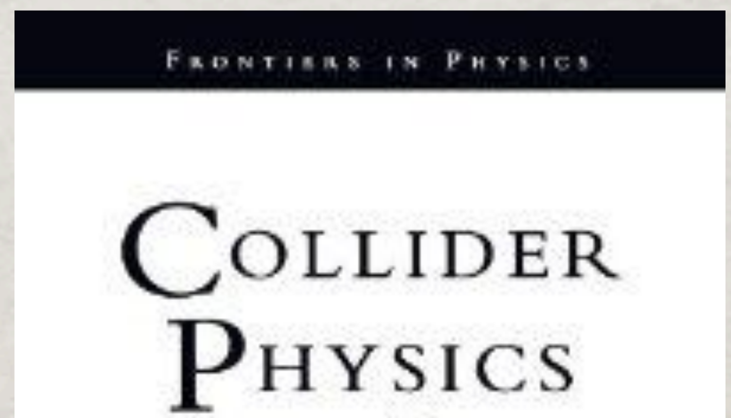

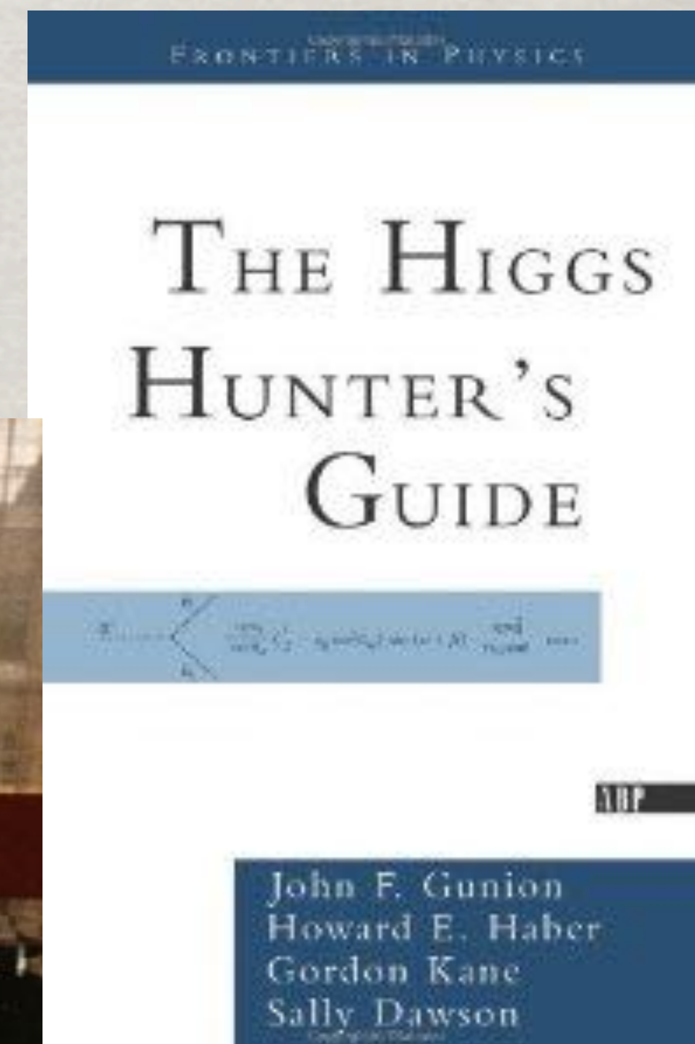

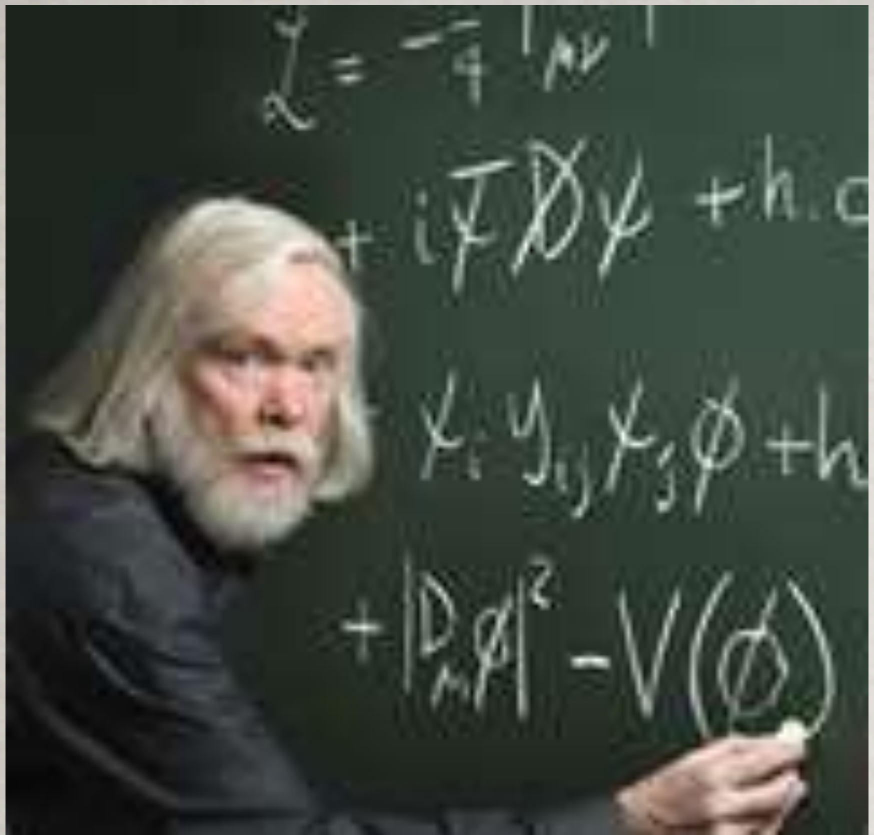

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Sakurai Prize 2017

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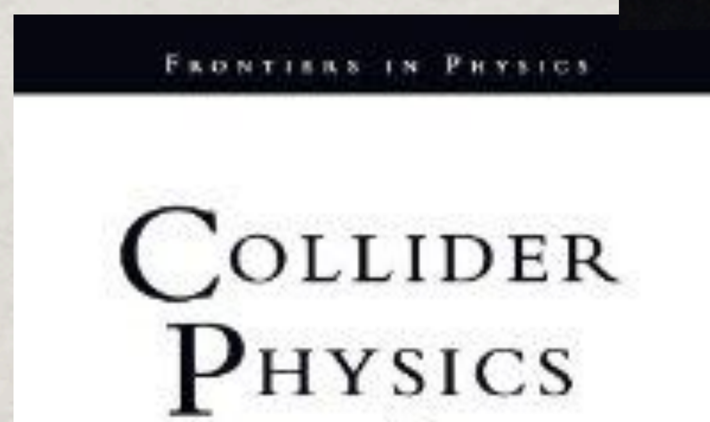

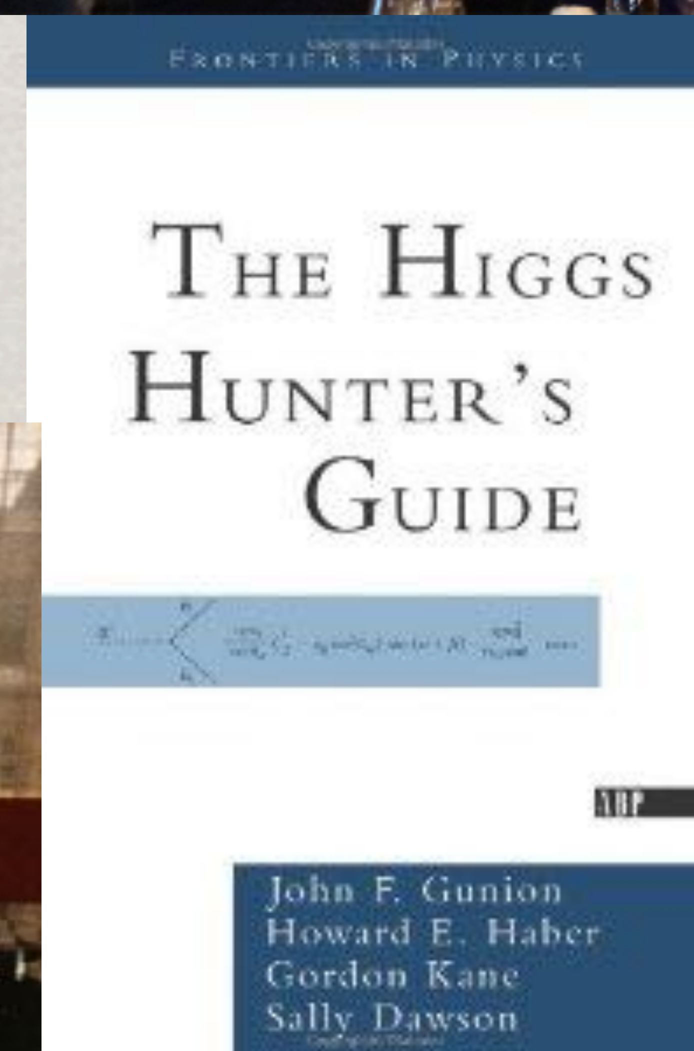

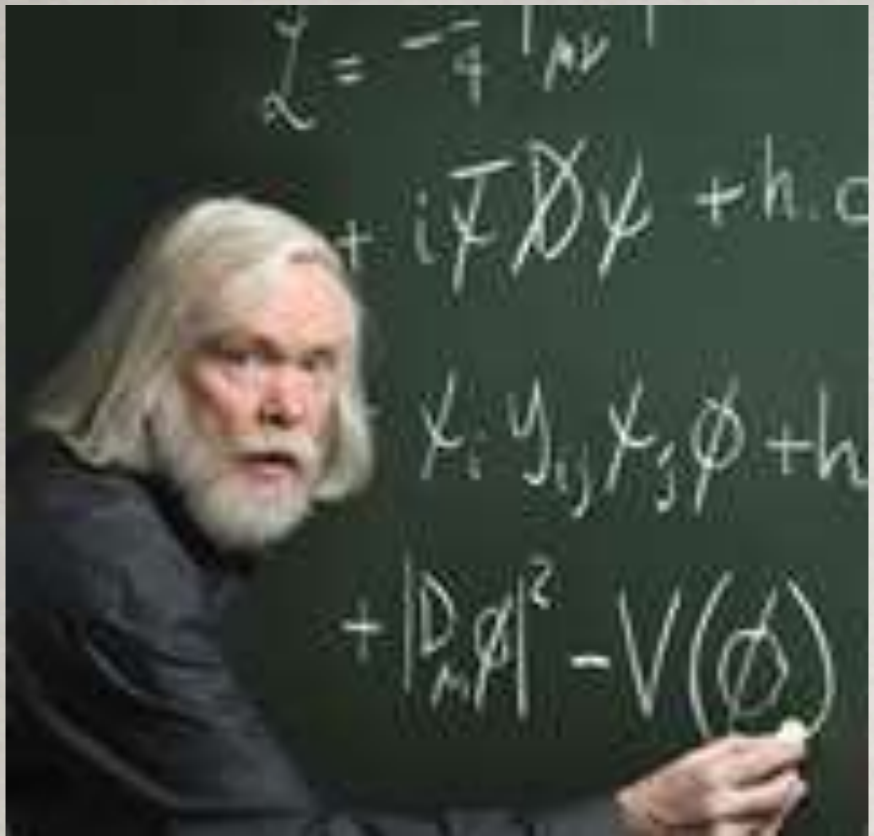

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We made it !

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Text

FRONTIERS IN PHYSICS

COLLIDER PHYSICS

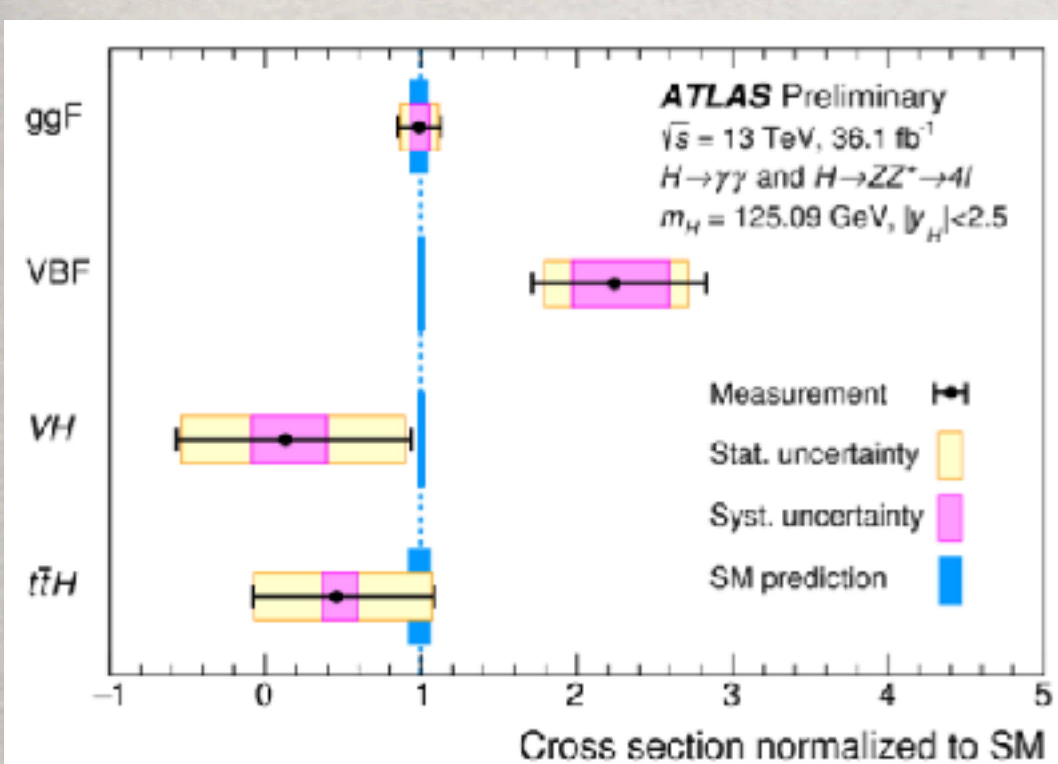
FRONTIERS IN PHYSICS

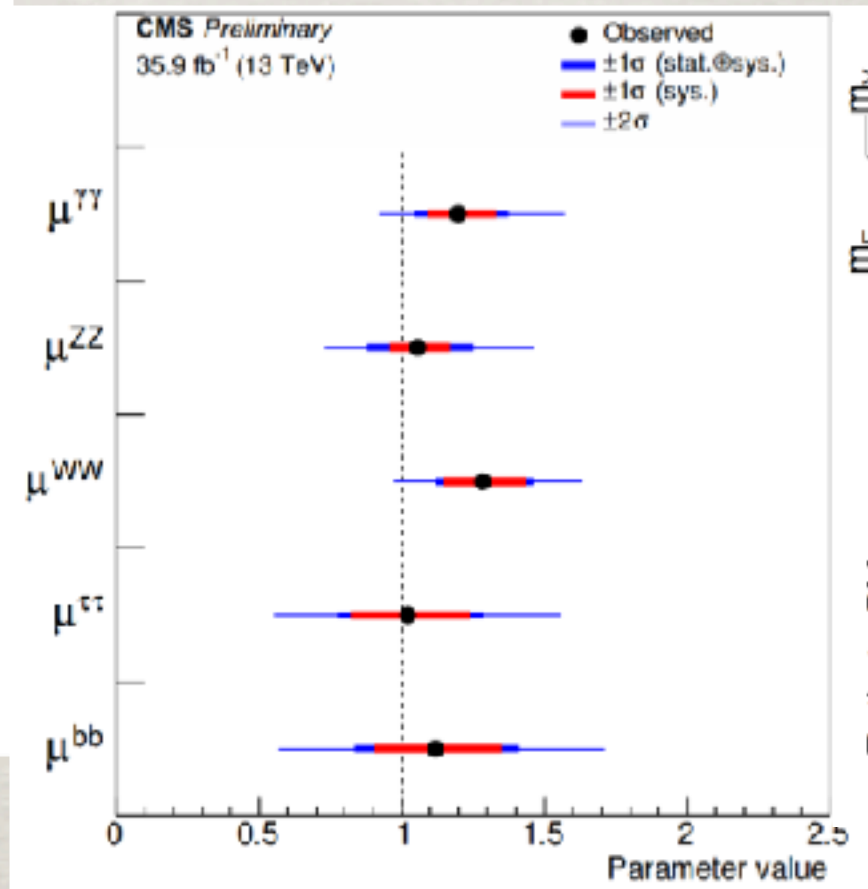
THE HIGGS HUNTER'S GUIDE

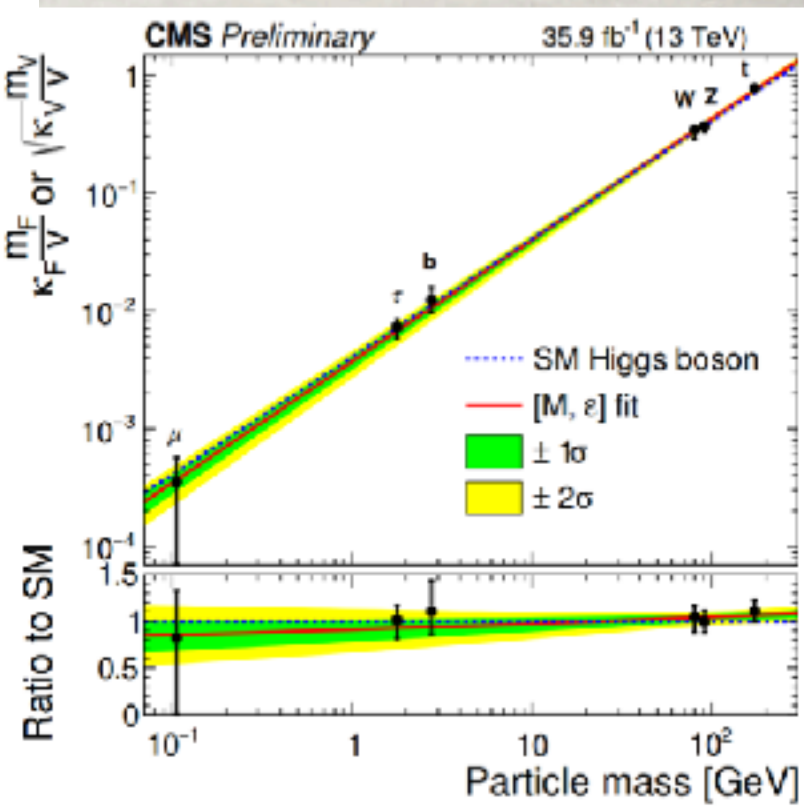
John F. Gunion
Howard E. Haber
Gordon Kane
Sally Dawson

Moriond 2018 on Higgs: (D. Sperka, ATLAS & CMS)

Four production channels with sensitivities;
Five decay channels observed;
Fermionic & bosonic couplings verified:



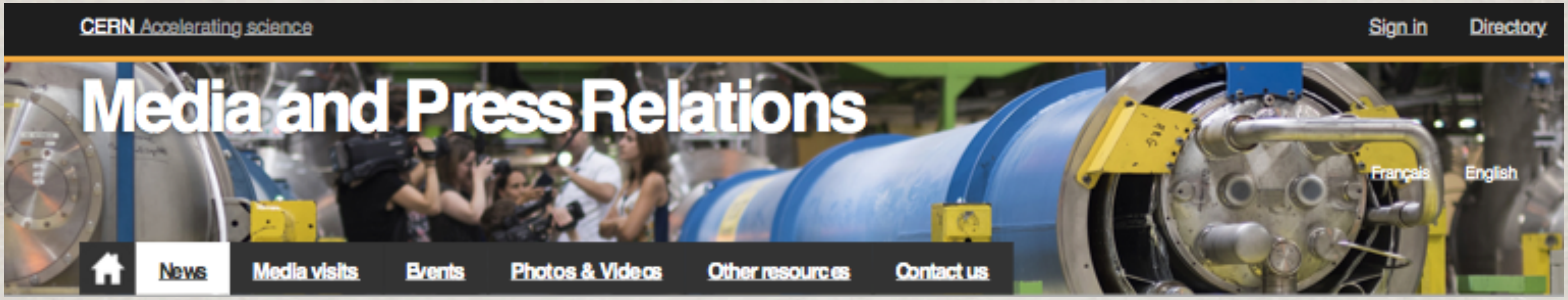


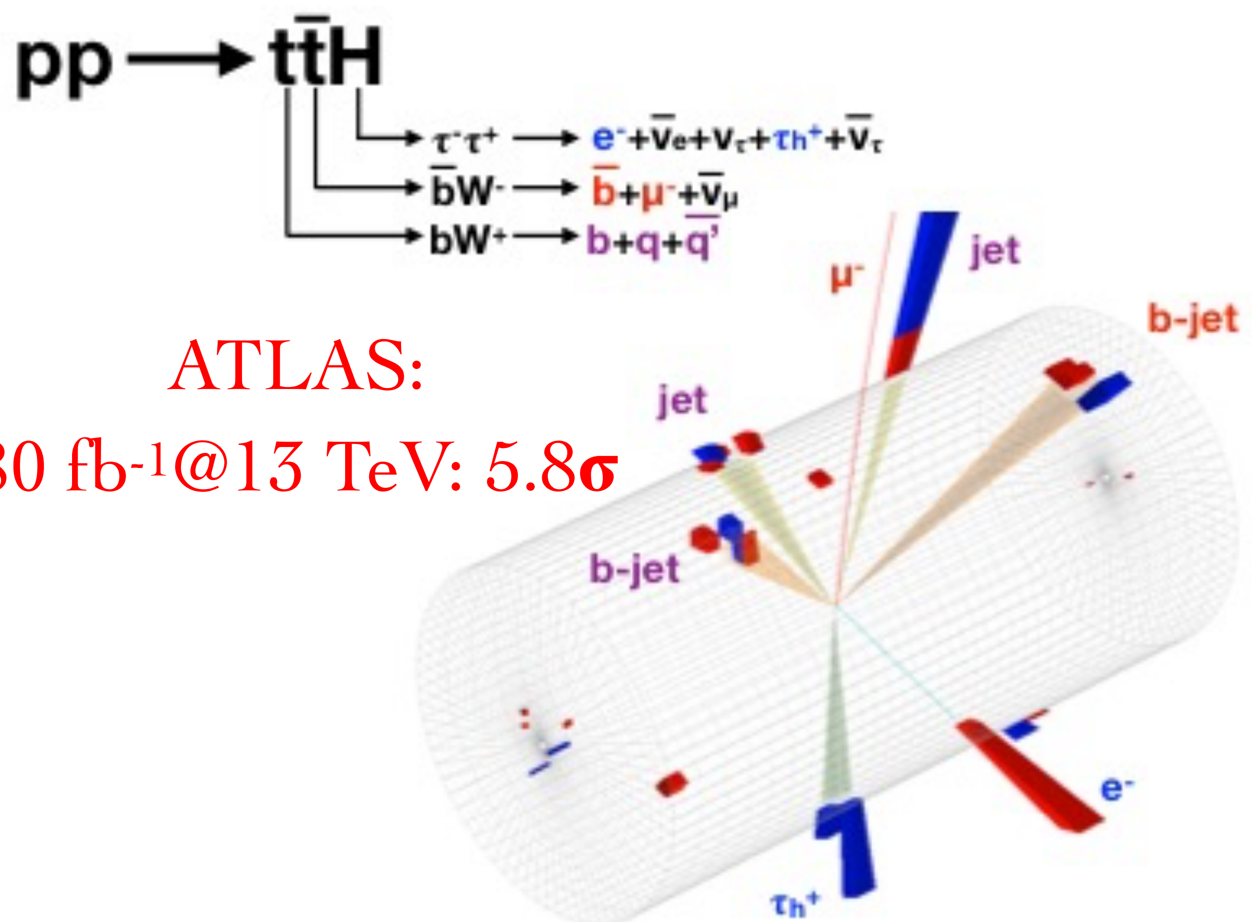


Measured mass accuracy < 0.2% :

$$m_H = 125.26 \pm 0.20(\text{stat}) \pm 0.08(\text{syst})\ \text{GeV}$$

June 4, 2018: CERN new release, ATLAS & CMS





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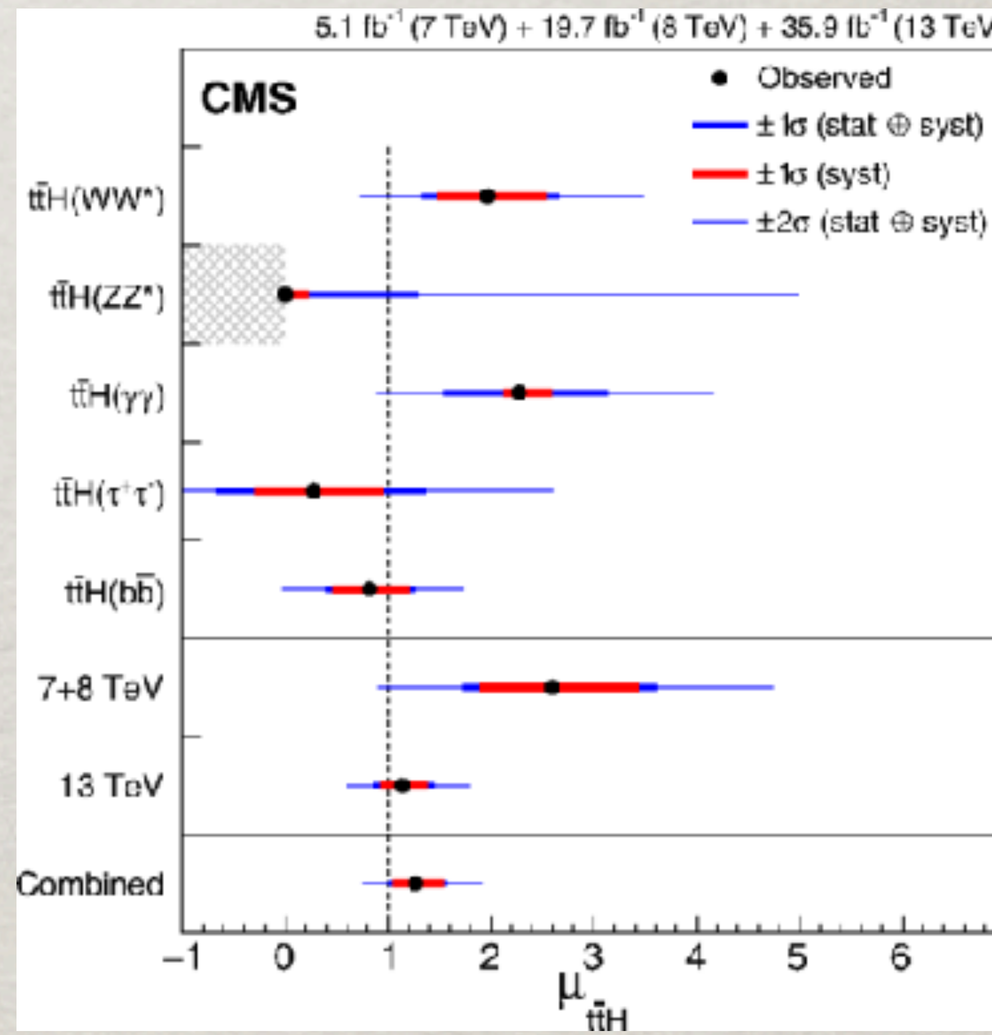

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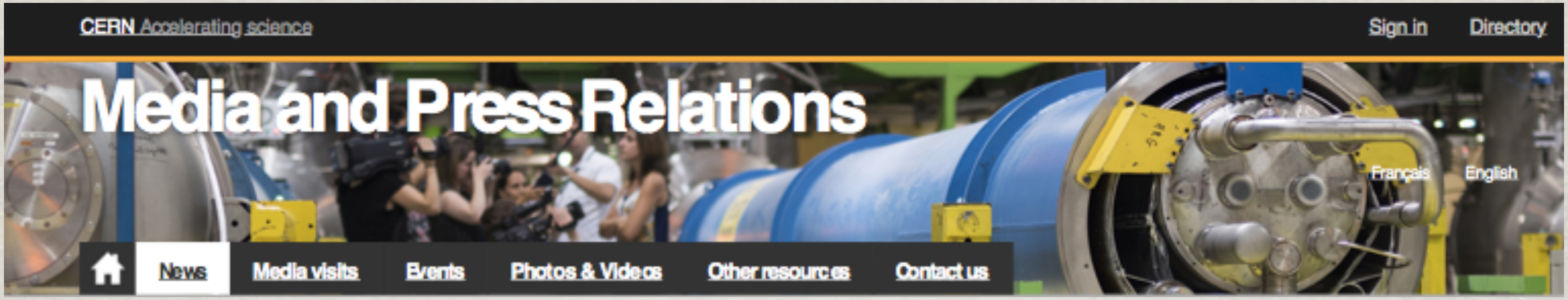

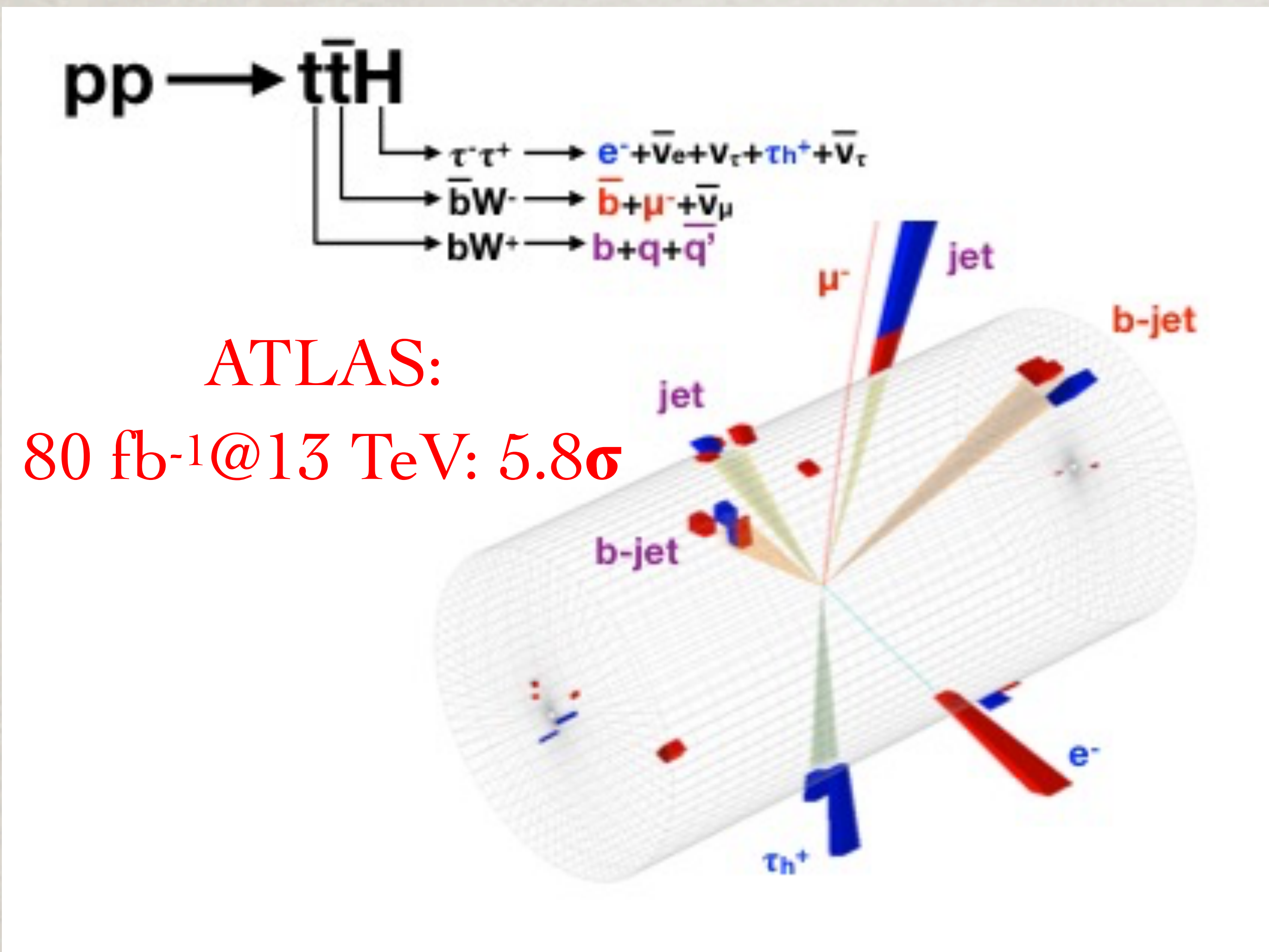

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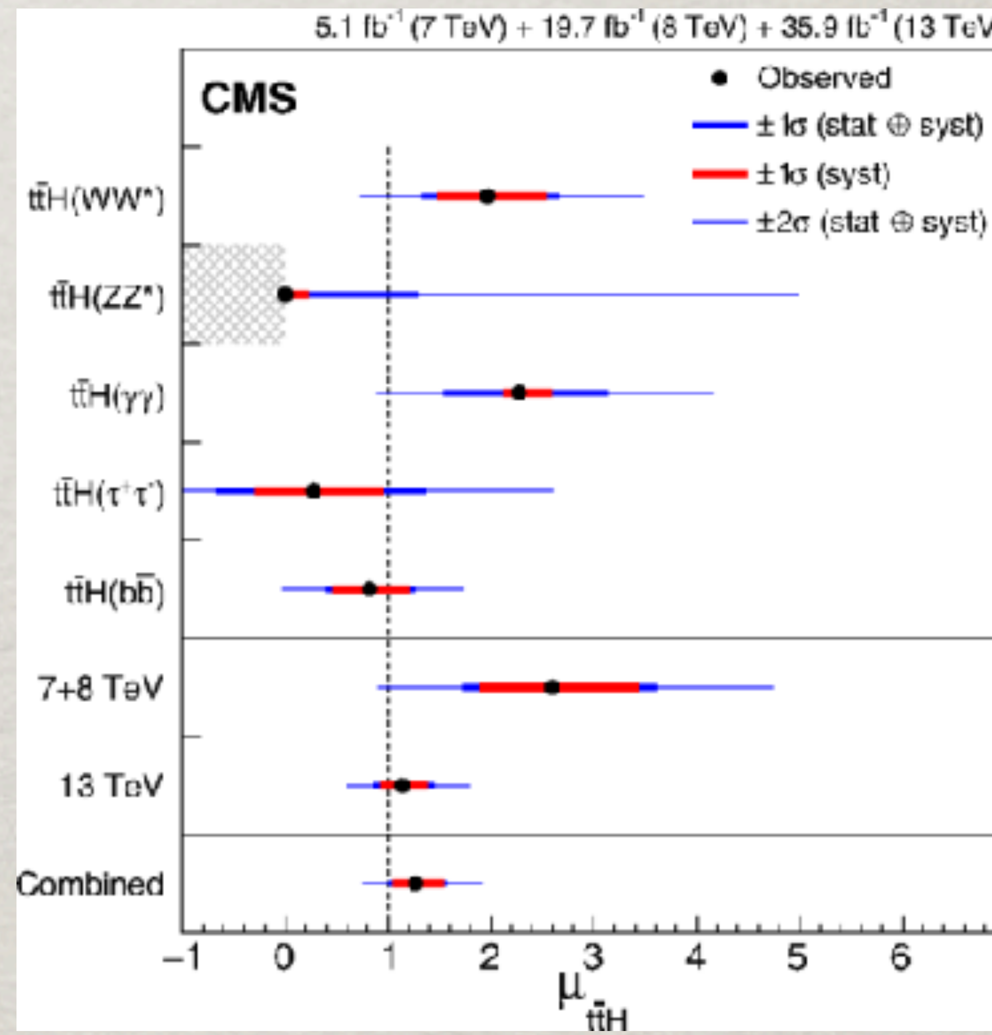

All indications: SM-like Higgs boson, "elementary" at a scale Λ < O(1 TeV)

What (else) We Know

m_H = 125 GeV

In the SM, the EWSB is parameterized as

$$\begin{aligned} V(|\Phi|) &= -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \\ &\Rightarrow \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 \end{aligned}$$

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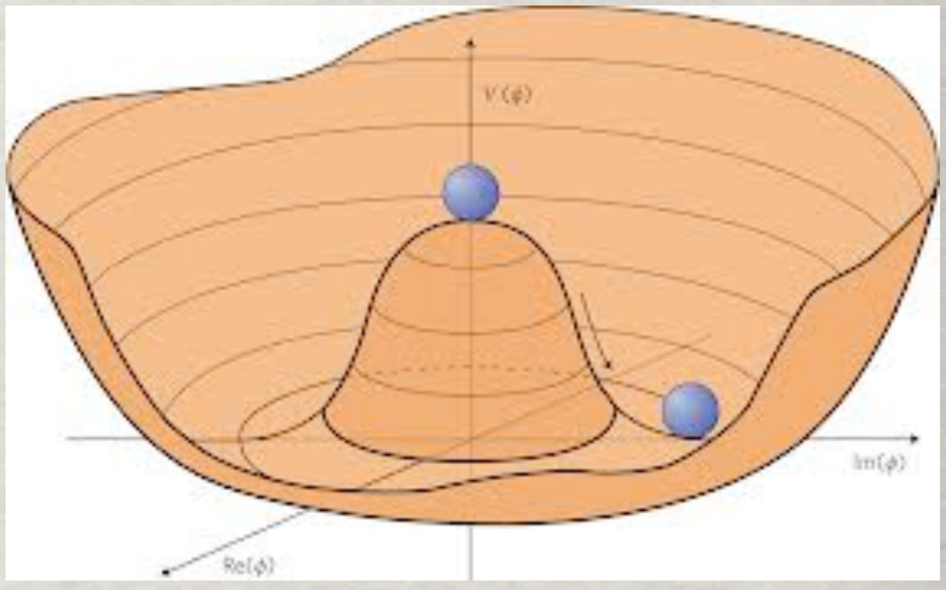

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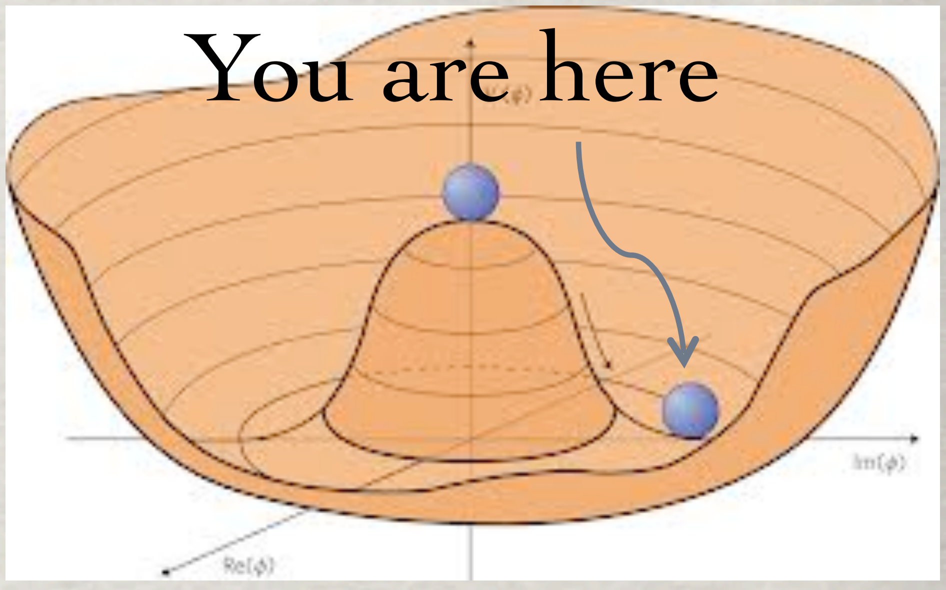

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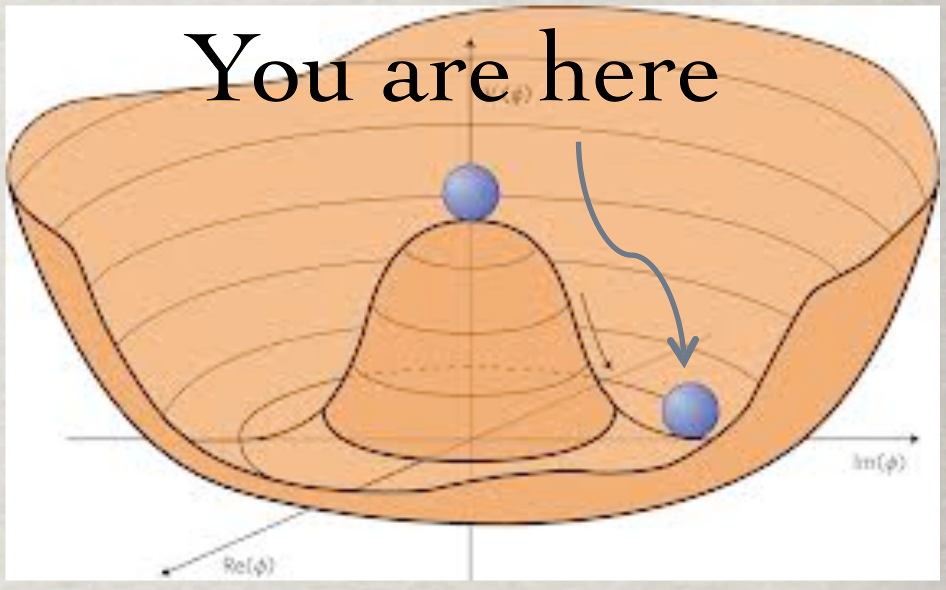

Consequently,

$$m_H^2 = 2\mu^2 = 2\lambda v^2 \quad \Rightarrow \quad \mu \approx 89 \text{ GeV}, \quad \lambda \approx \frac{1}{8}.$$

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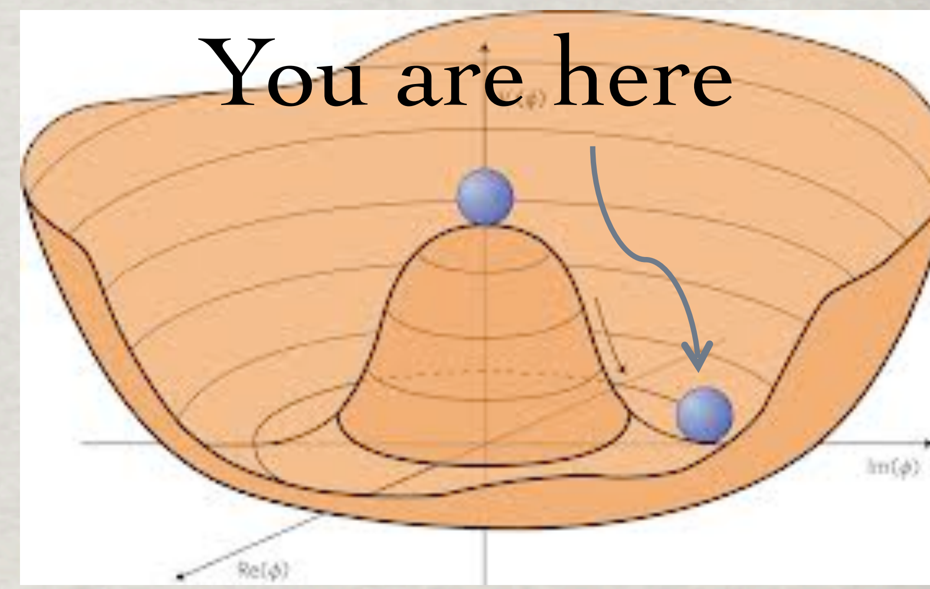

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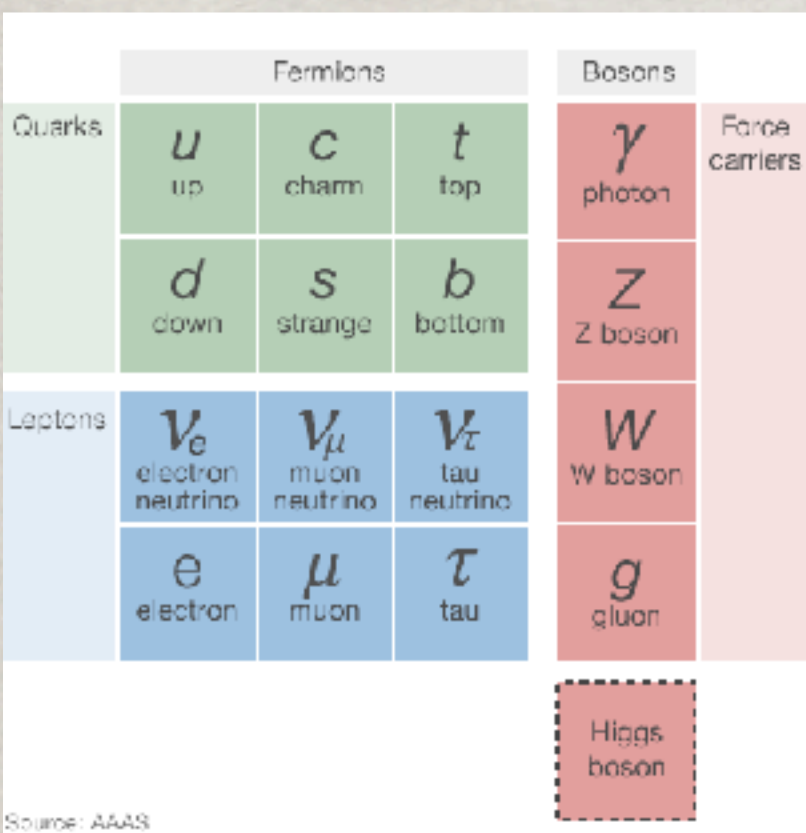

Completion of the SM: The 1st time!

A perturbative, renormalizable theory, valid up to a high scale of

TeV ? …, M_{Pl} ?

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Will History repeat itself (soon)?

New Era:
Under the Higgs lamp post

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The "Observation" papers:
Now ~~7,250~~ cites each!
8,350

Vast scope of topics, from
interpretations, explorations in & beyond the SM; applications in astronomy, cosmology, CC; strings/branes, to "Philosophical Perspectives …."

A Reminder:

A. The Higgs mechanism $\neq$ a Higgs boson !

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The theory is valid to a unitarity bound ~ 2 TeV

The existence of a light, weakly coupled Higgs boson carries important message for our understanding & theoretical formulation

in & beyond the SM –

Ultra-Violet completion / renormalizibility

What It tells us

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Already possess challenge to BSM theories.

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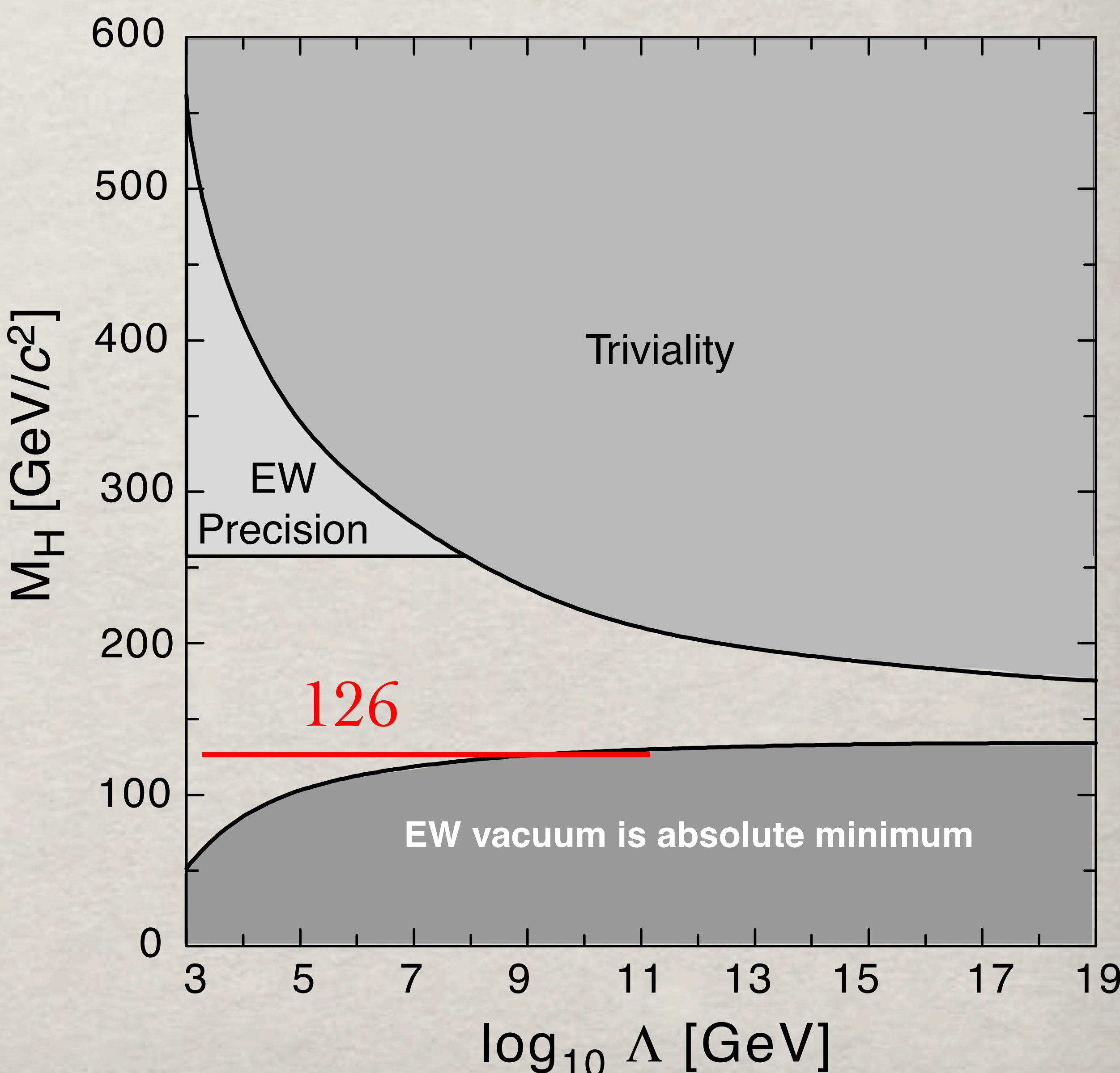

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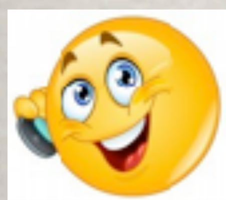

The SM can be a consistent perturbative theory up to M_{pl} ! allowing M_N, M_{GUT}, …

Bezrukov et al.,

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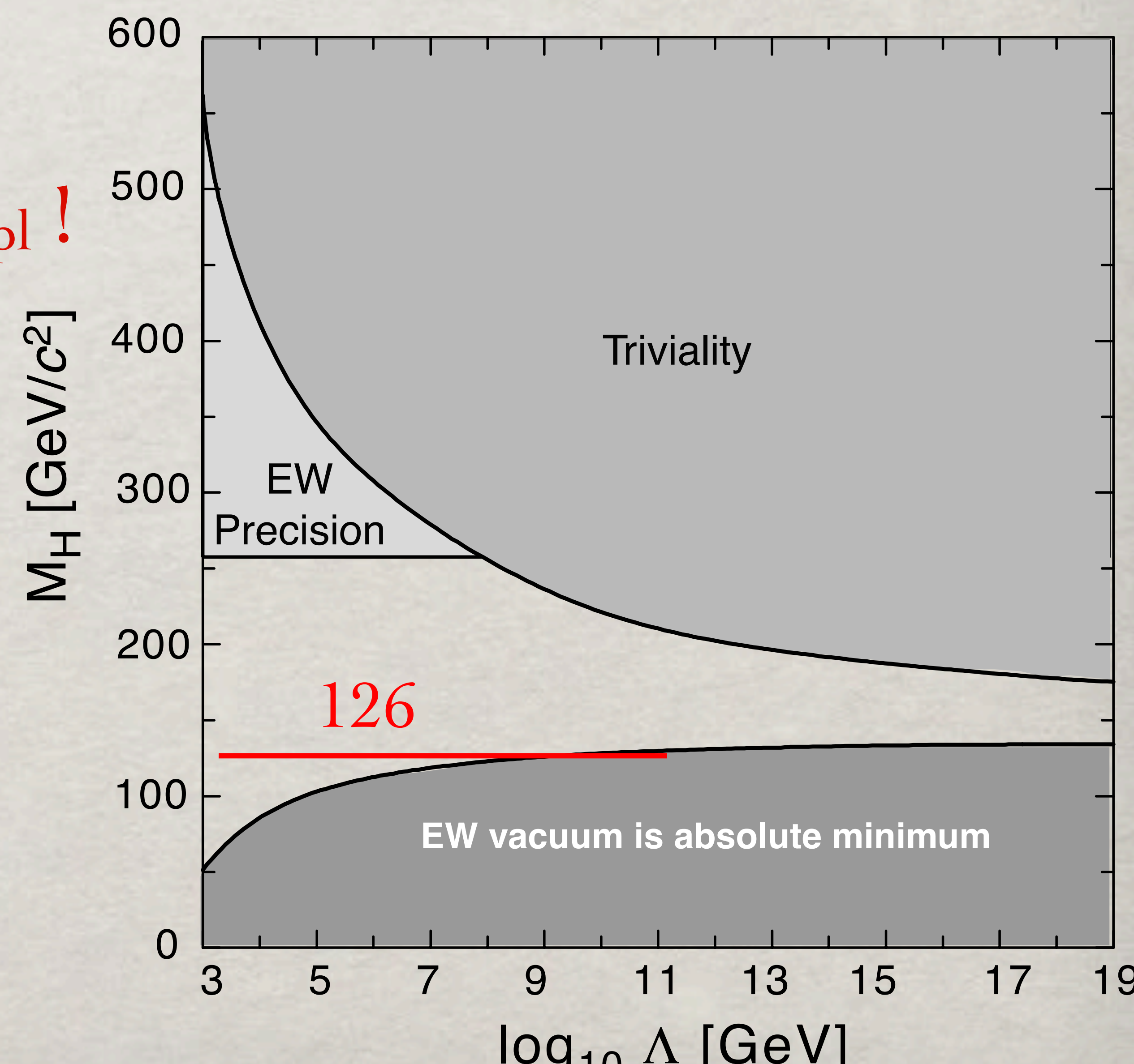

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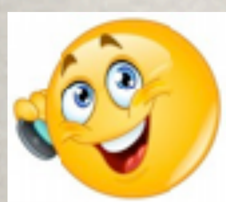

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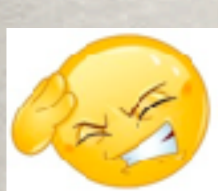
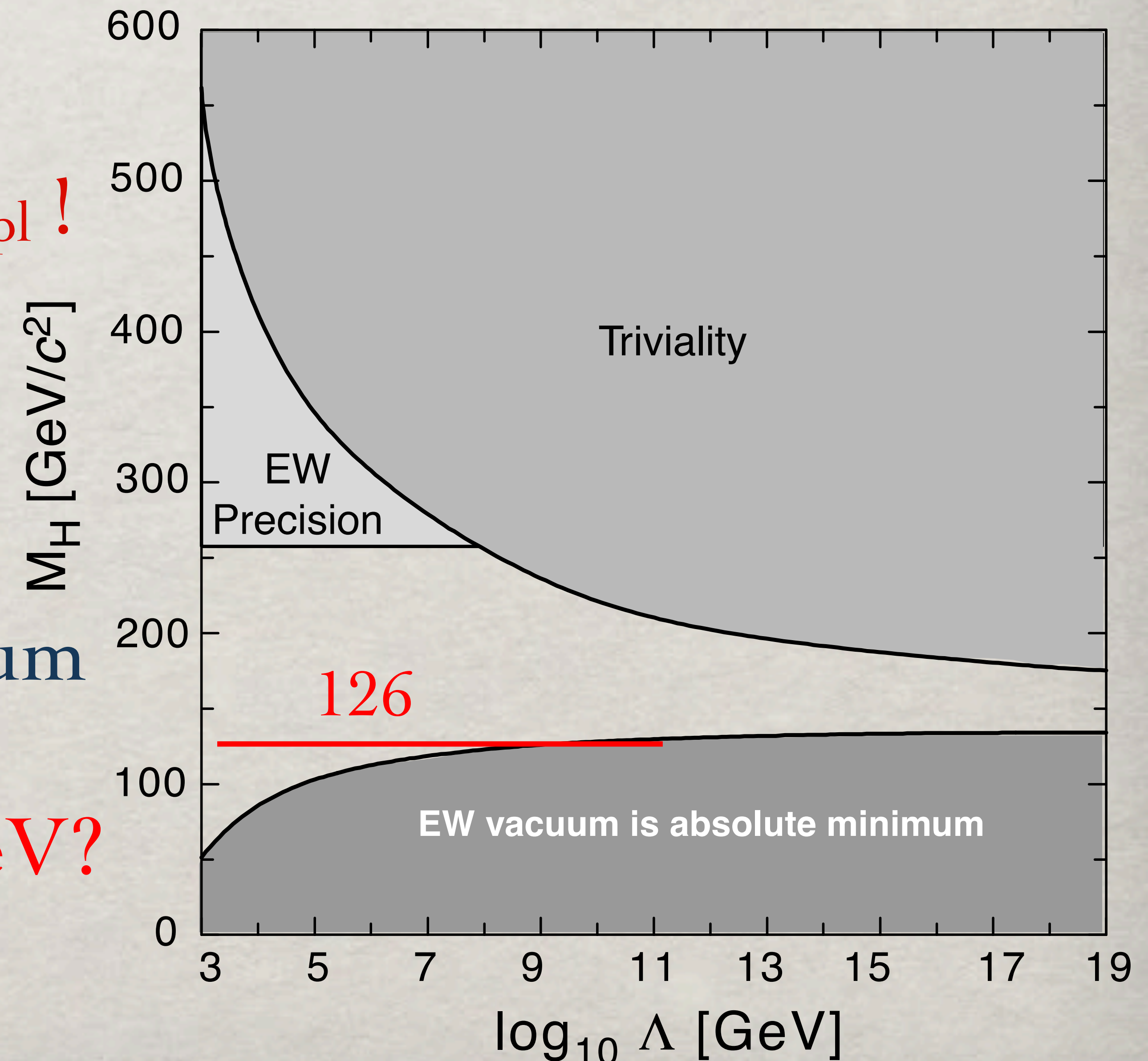


Top-Yukawa drags the vacuum meta-stable,

New physics below $10^{7\text{-}11}$ GeV?

Degrassi et al., arXiv:1205.6497;

Djouadi et al., arXiv:1207.0980



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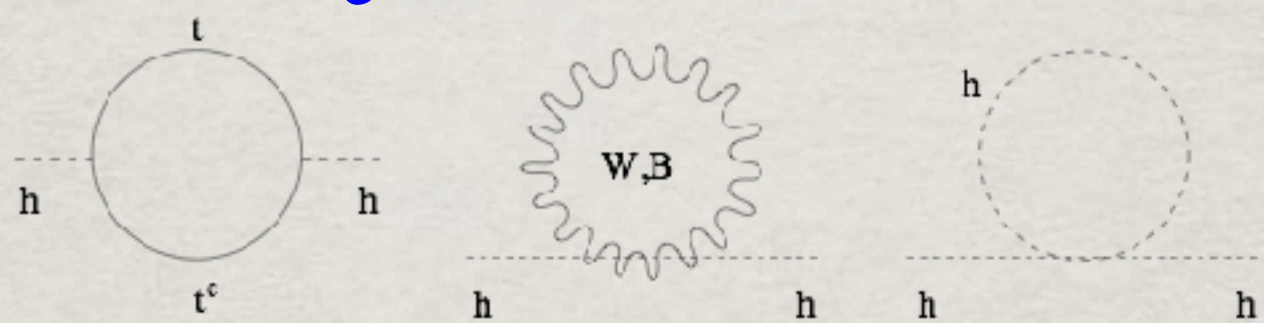

(a) (b) (c)

$$m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

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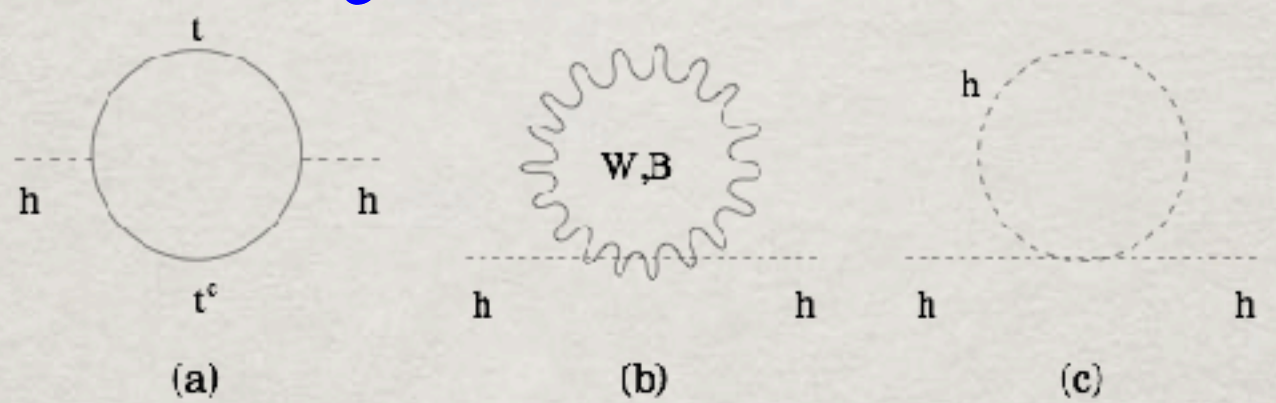

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Cancelation in perspective:

m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023

–36,127,890,984,789,307,394,520,932,878,928,917,398

= $(125\ \text{GeV})^2$! ?

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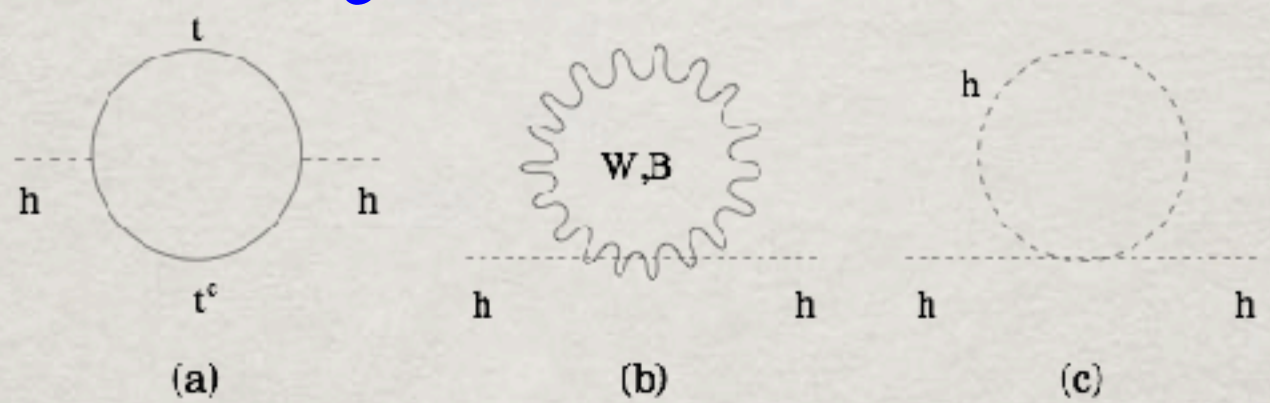

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Weak-scale Supersymmetry:

Extended symmetry between *opposite* spin & statistics

"s"-particles	symbol	spin	SUSY breaking mass param.
gluino charginos neutralinos	$\tilde{g}$ $\tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm}$ $\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$	1/2 1/2 1/2	M_3 M_2 $M_1,\ \mu,\ B$ $m_{H_u}^2,\ m_{H_d}^2$
sleptons	$\tilde{e}_L,\ \tilde{\nu}_{e_L},\ \tilde{e}_R$ $\tilde{\mu}_L,\ \tilde{\nu}_{\mu_L},\ \tilde{\mu}_R$ $\tilde{\tau}_1, \tilde{\tau}_2,\ \tilde{\nu}_{\tau_L}$	0 0 0	$m_{\ell L}^2$ $m_{\ell R}^2$
squarks	$\tilde{u}_L,\ \tilde{d}_L,\ \tilde{u}_R, \tilde{d}_R$ $\tilde{c}_L, \tilde{s}_L,\ \tilde{c}_R, \tilde{s}_R$ $\tilde{t}_1,\ \tilde{t}_2,\ \tilde{b}_1, \tilde{b}_2$	0 0 0	$m_{q_L}^2$ $m_{q_R}^2$
Higgs	$h^0,\ H^0,\ A^0,\ H^{\pm}$	0	$m_A^2,\ \tan\beta$

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Natural cancellations: $\tilde{t}$ versus t

$\tilde{W}$ versus W

$\tilde{H}$ versus H

H_d versus H_u,

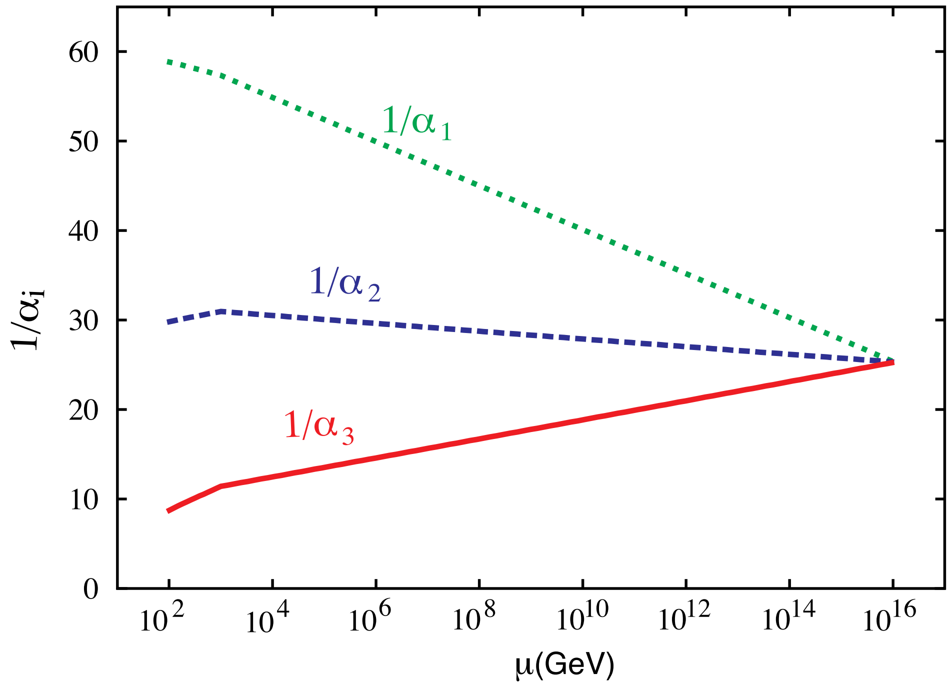
$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\, \frac{\lambda_f^2}{16\pi^2} \ln\left(\frac{\Lambda}{M_{SUSY}}\right).$$

Weak scale SUSY is natural if $M_{SUSY} \sim \mathcal{O}(1\ \text{TeV})$.

Additional Feature I :

- Unification of forces?

Do the forces E & M/Weak/Strong all unify into a single force ?



Possible if there is a TeV scale new physics threshold !

Additional Feature II :

Natural existence of a lightest, neutral fermion:
The “neutralino” as the WIMP
(weakly interacting massive particle)
cold dark matter candidate!

Additional Feature III :

Natural extension / maximal symmetry in quantum field theory;
Elegant mathematical structure;
Connection with quantum gravity/string theory.

Dynamical approach for mass generation:

- Technicolor: A lesson from QCD

  SU(N_{TC}) gauge theory, TC fermions $Q = U, D, ...$

  EWSB by TC-fermion condendation at Λ_{TC}:

$$v \sim \langle \overline{Q_L} Q_R \rangle^{1/3} \sim 246 \text{ GeV}.$$

√ no elementary scalar, like Higgs.

√ theory natural: Λ_{TC} dynamical.

√ predicts new strong dynamics at the TeV scale: π_T, η_T, ρ_T, ω_T...

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- Extended Technicolor:* Fermion mass generation

  G_{ETC} gauge theory, ETC fermions: $U, D, \ldots, \quad u, d\ldots$

  After intrgrating out ETC gauge bosons at the scale Λ_{ETC}, with TC-fermion condensate,SM fermion mass generated:

$$m_f \sim \langle \overline{Q_L} Q_R \rangle / \Lambda^2_{ETC} \sim \Lambda^3_{TC} / \Lambda^2_{ETC}.$$

Not supported by observation

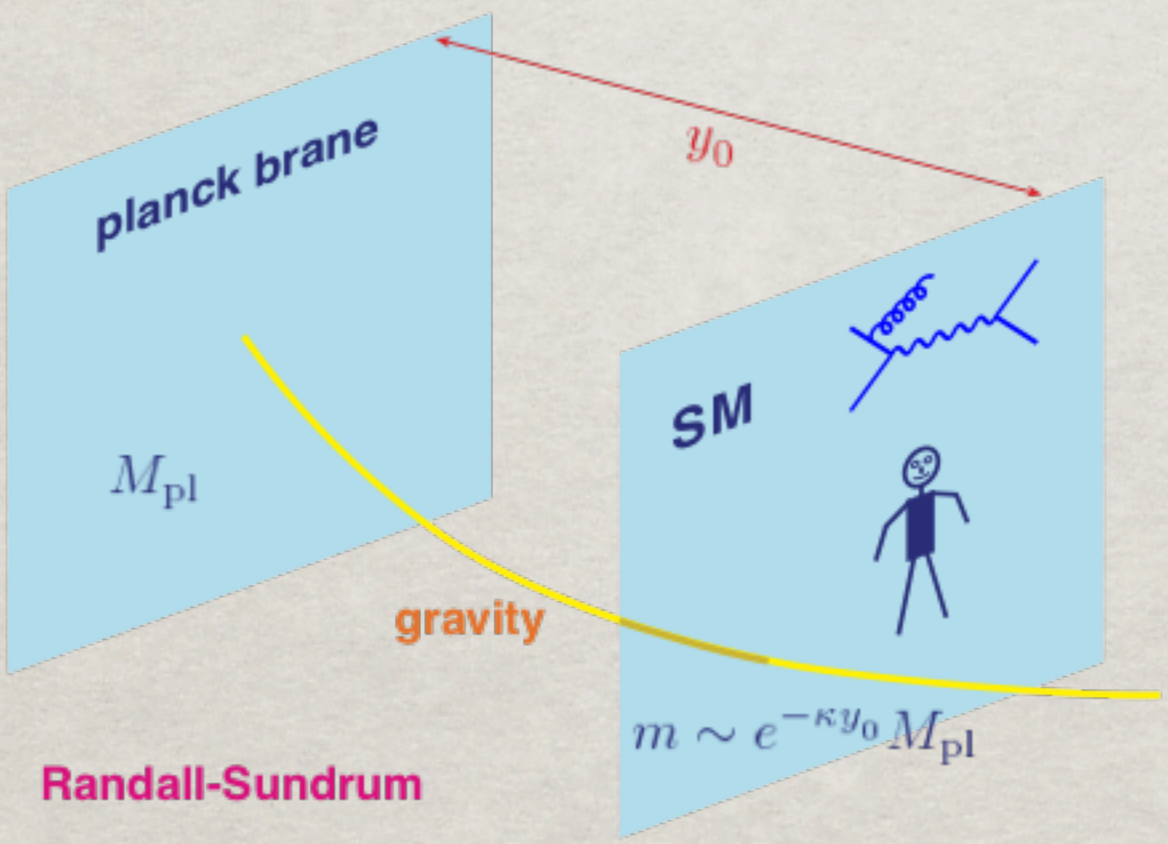
- "Warped" Extra-dimension Scenario: The Randall-Sundrum model

In a 5-dim space, Randall and Sundrum found a static solution of the form:*

$$ds^2 \sim e^{-2ky}\ \eta_{\mu\nu}\ dx^\mu dx^\nu - dy^2,$$

where k is the curvature scale in the 5^{th}-dim.

The extra dimension y is "warped".



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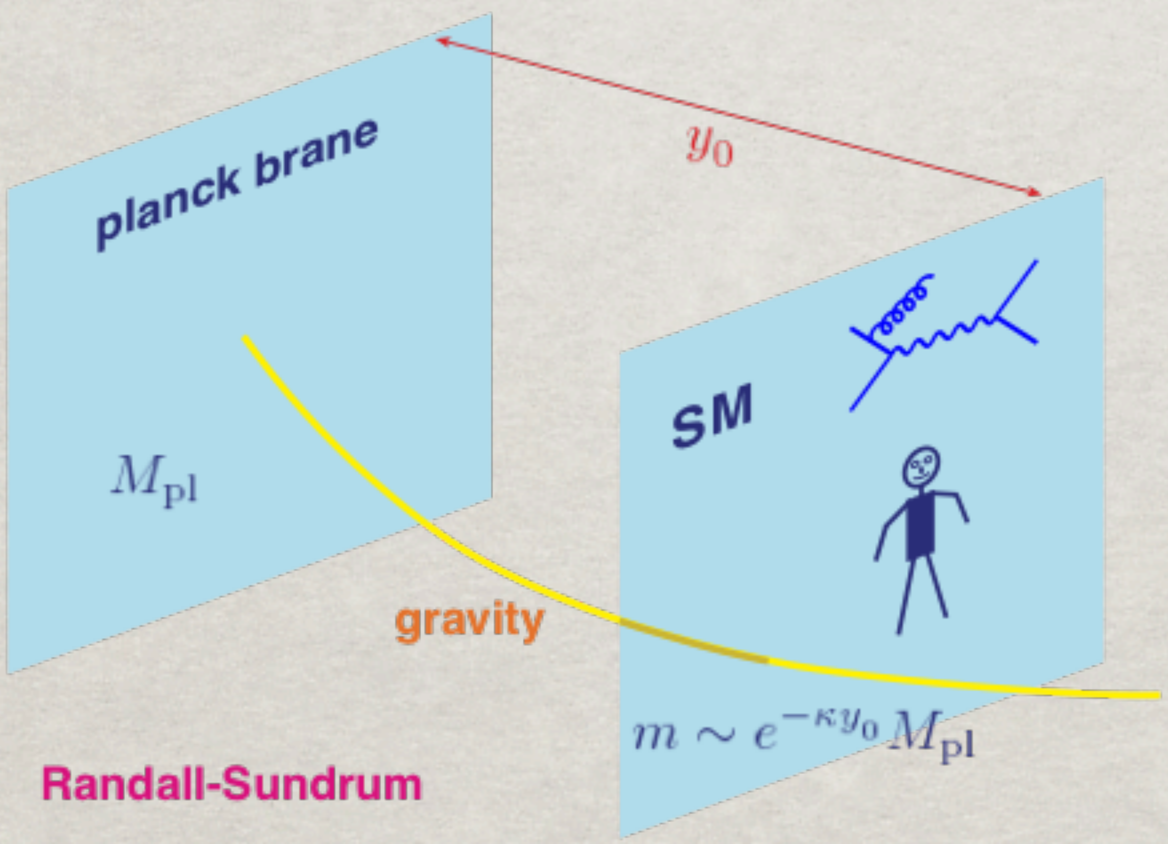

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Dual description to strong dynamics/composite theory!

Little Higgs Models: A less ambitious approach

keep the Higgs boson "naturally" light (at 1-loop level).

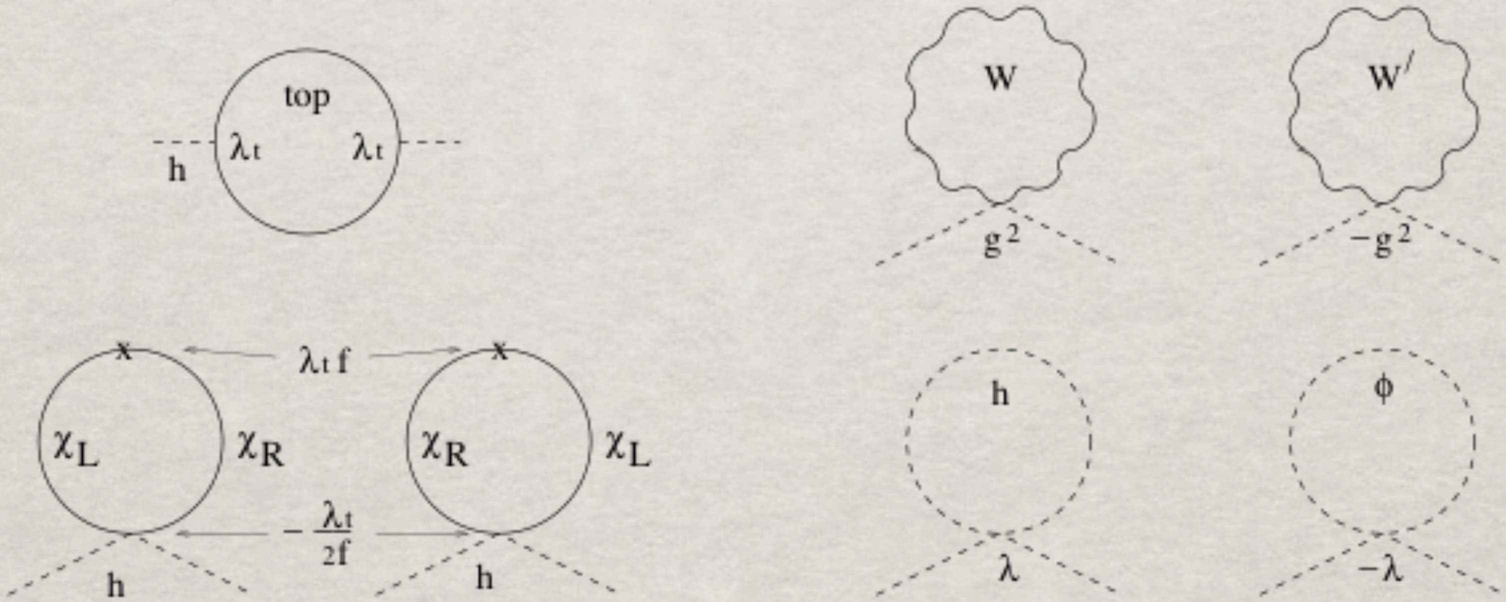
† Higgs is a pseudo-Goldstone boson from global symmetry breaking (at scale $4\pi f$)[‡]

† Higgs acquires a mass radiatively at the EW scale v, by collective explicit breaking

† Consequently, quadratic divergences absent at one-loop level[§]

$$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(cancellation among same spin states!)



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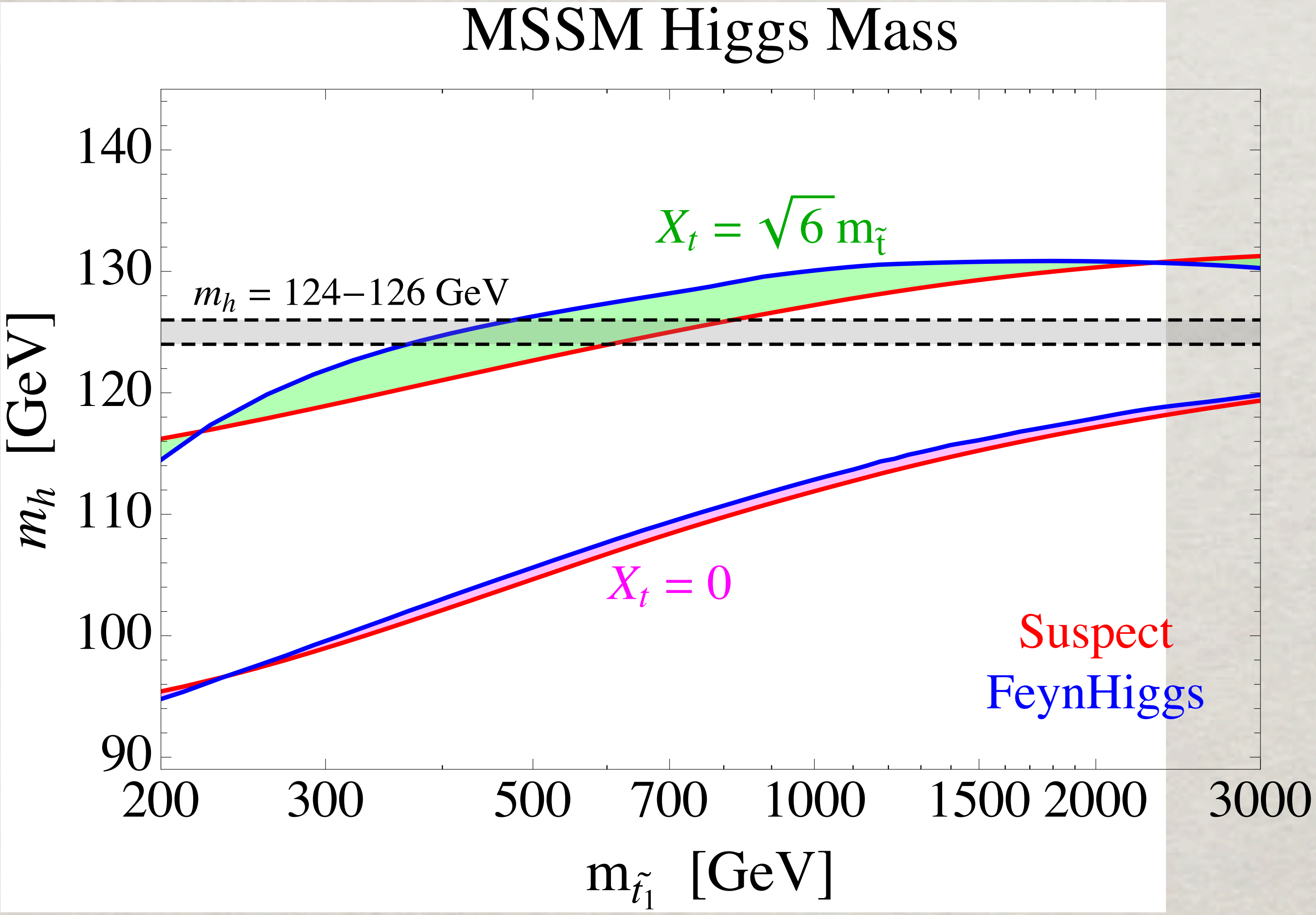

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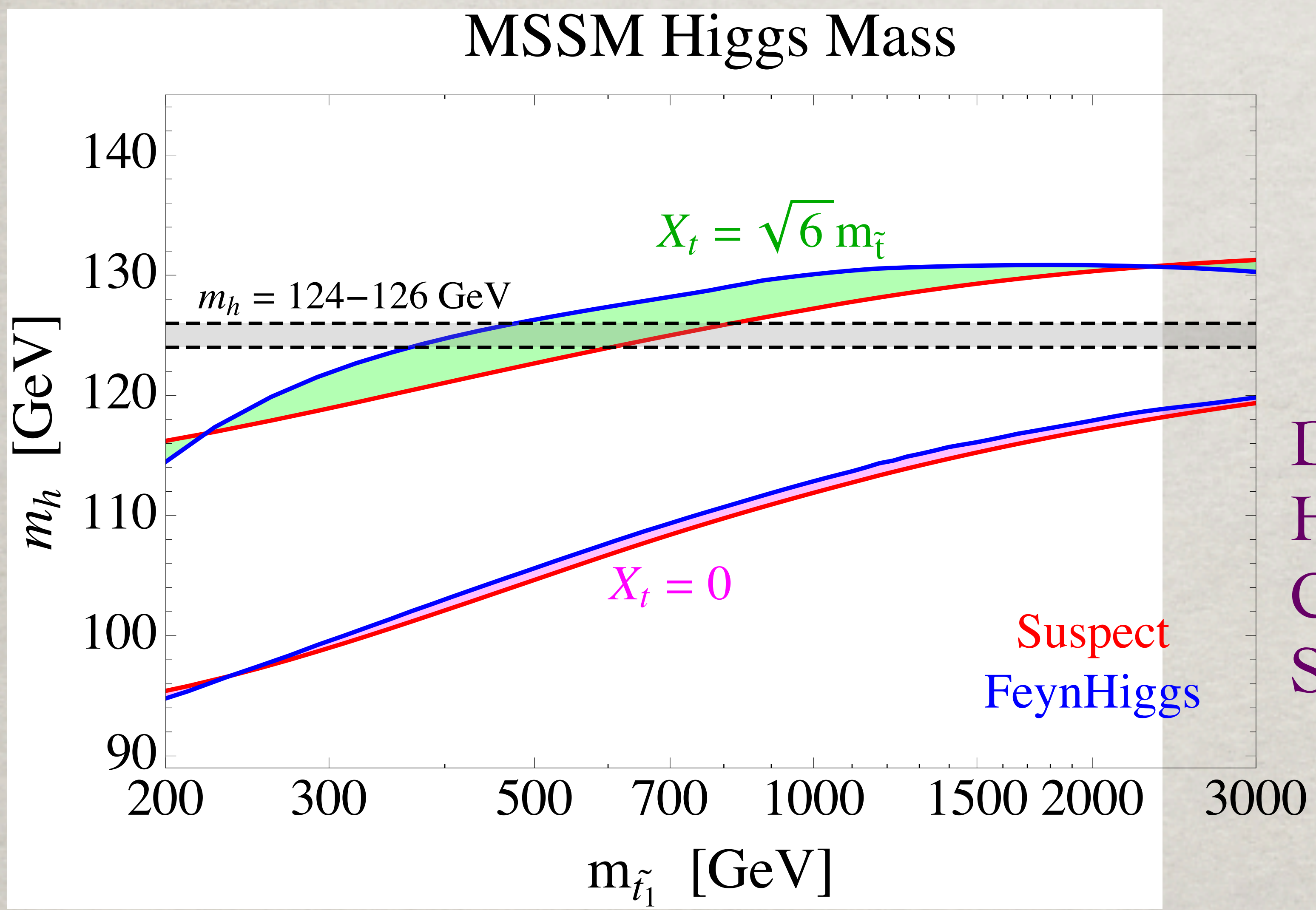
→ Need large $\tan\beta$; m_{stop} & mixing $X_t >> m_t$



Barbieri, Giudice, 1988
Kitano et al, 2005
Giudice, 2007
Feng, 2013

Draper, Shih, Meade, Reece, 2011
Hall, Pinner, Ruderman, 2012
Carena et al., 2012, 2013
S. Heinemeyer et al., 2012-2014

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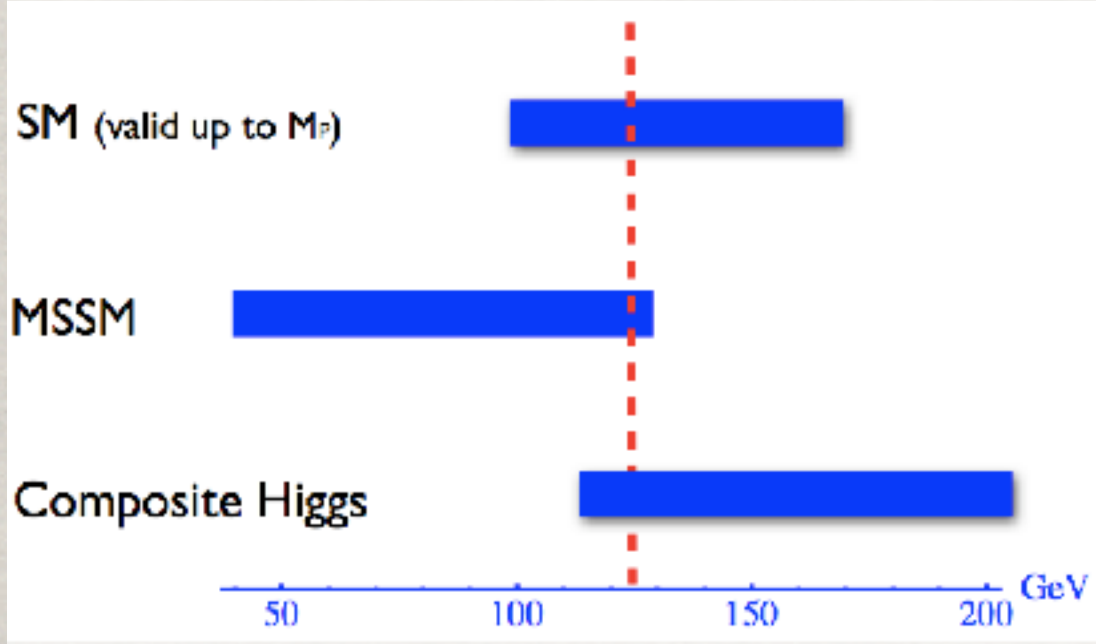

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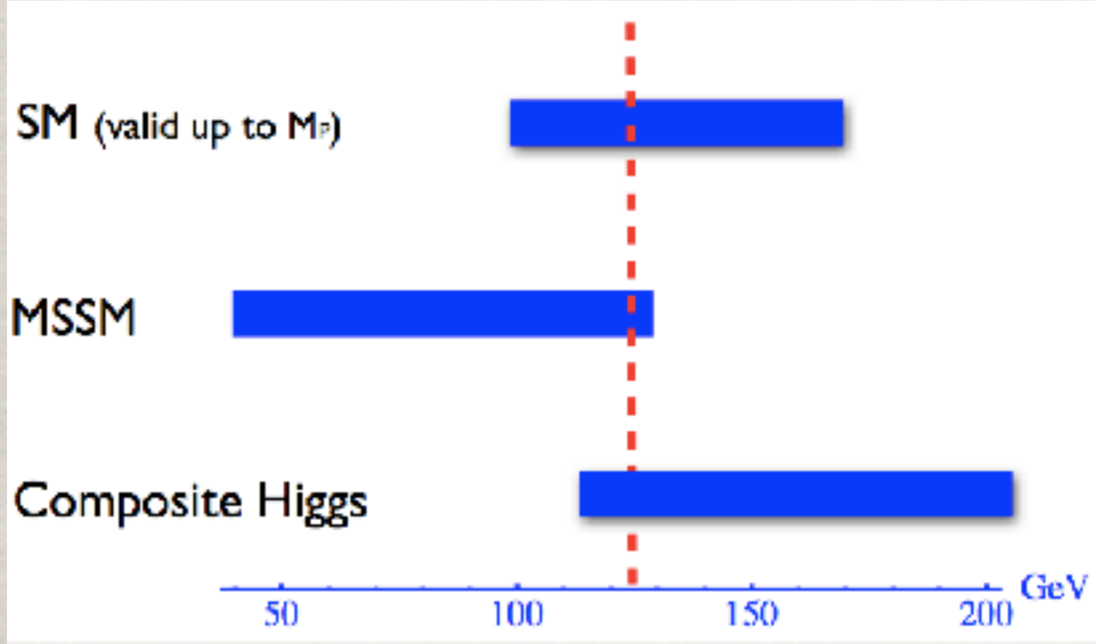

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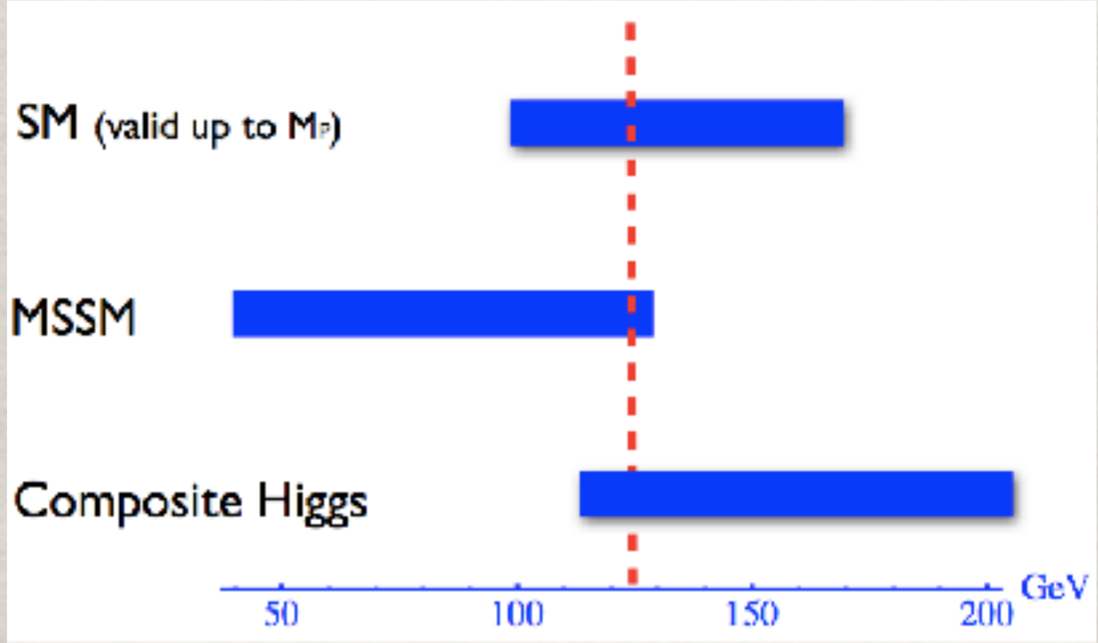

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Too heavy to be light; too light to be heavy!

What We Wish to Know
in the LHC Era

1. The Nature of EWSB

$$
\begin{aligned}
V(|\Phi|) &= -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \\
&\Rightarrow \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4
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$$v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV} \qquad m_H \approx 126 \text{ GeV}$$
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O(1) deviation on λ_{hhh} could make EW phase transition strong 1st order!

X.M.Zhang (1993); C. Grojean et al. (2005)

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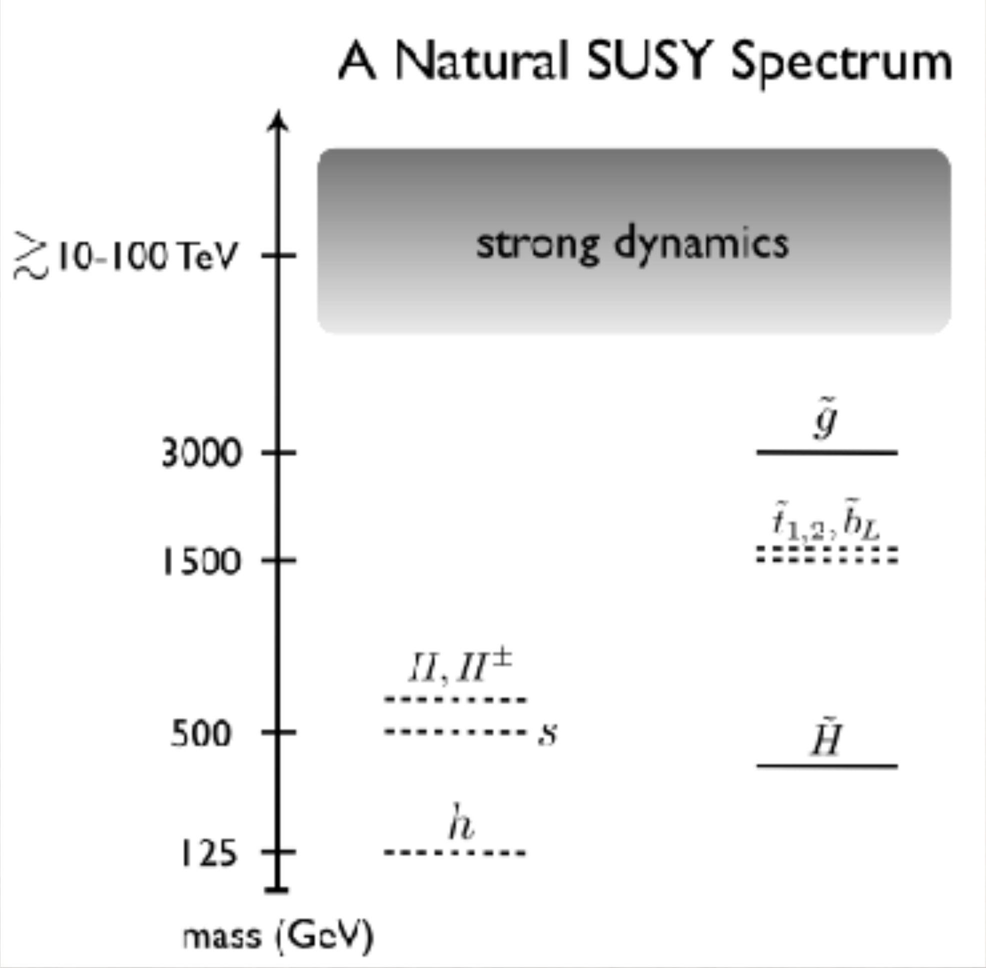
Cohen, Kaplan, Nelson, 1996
Hall, Pinner, Ruderman, 2012
Baer, Barger, Huang, Tata, 2012



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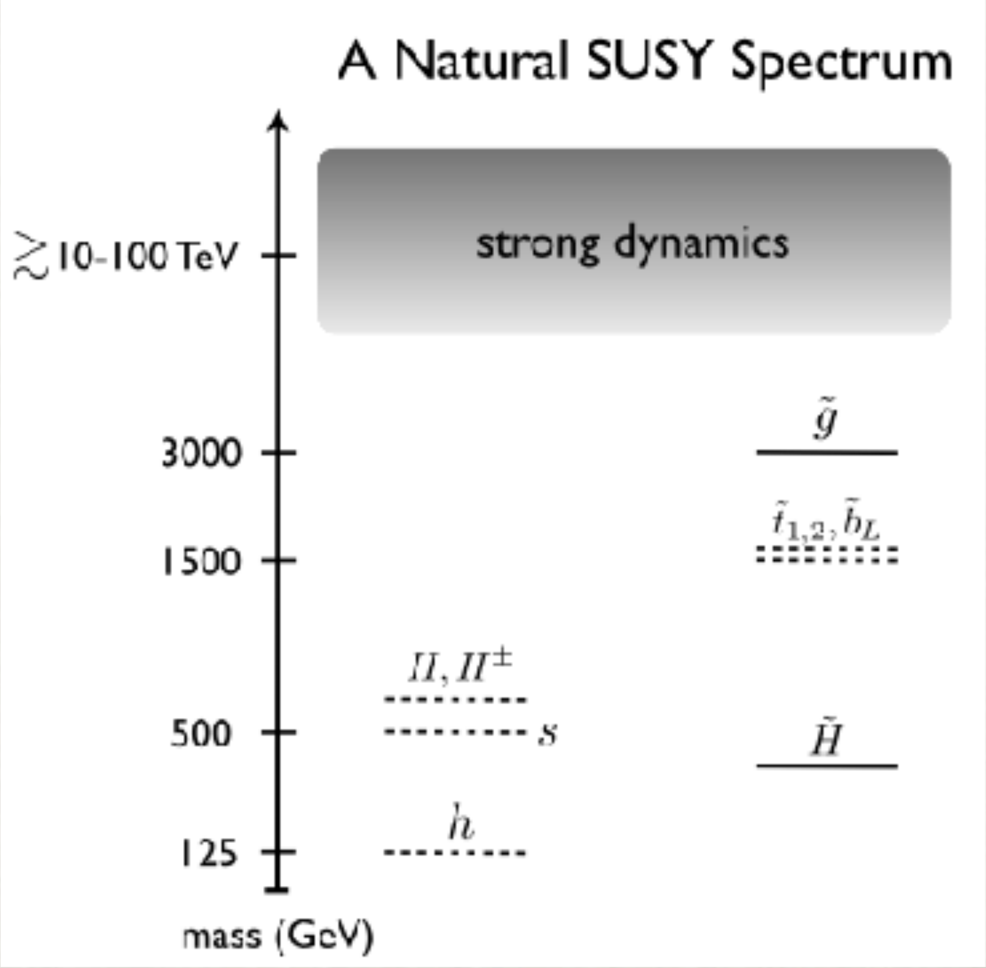

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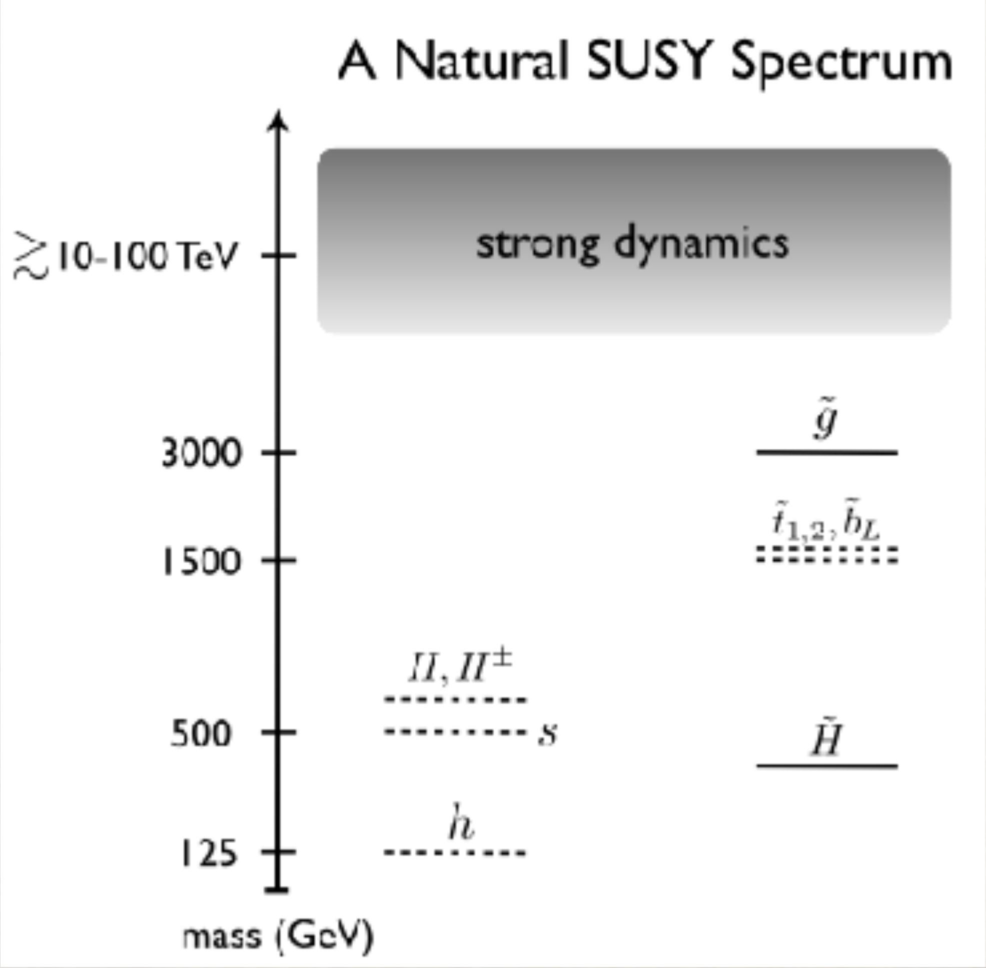

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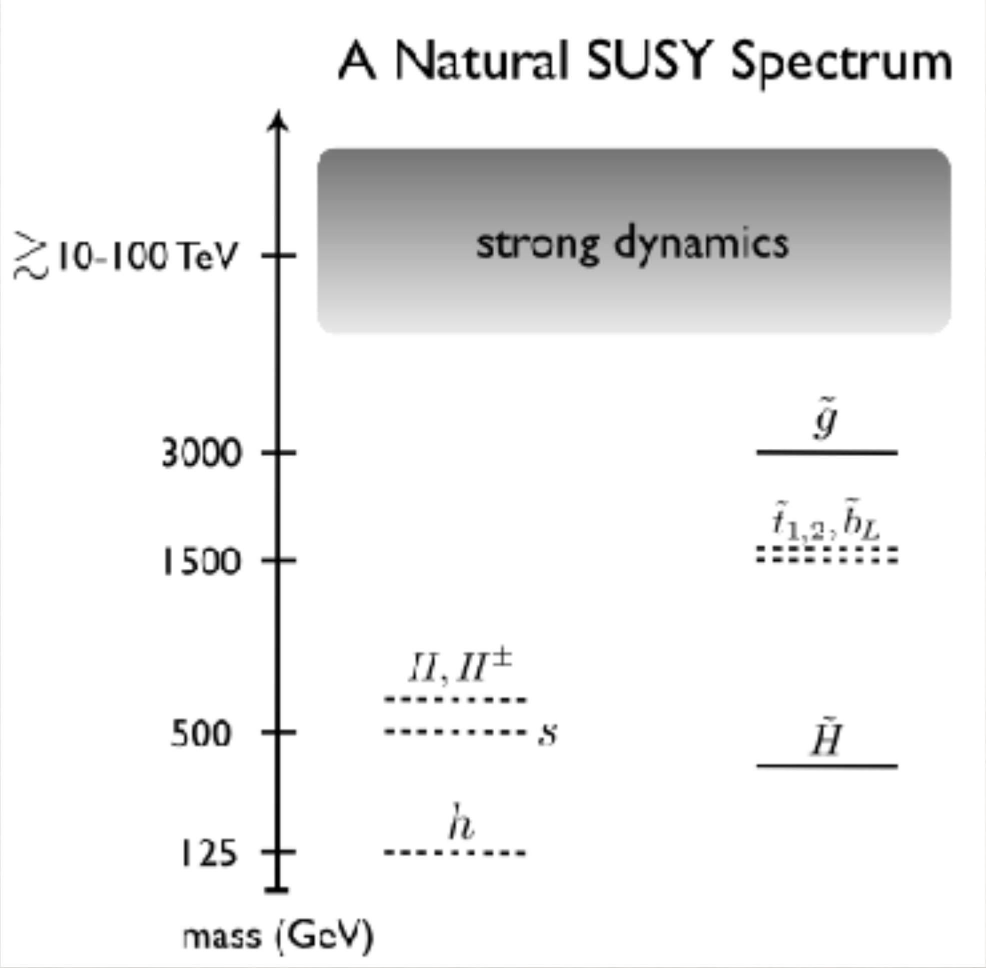

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- "Compositeness": the T', current ATLAS limit:

$M_T > 480$ GeV, for $M_A < 100$ GeV.

3. Extended Higgs sector?

The Higgs boson should have not only relatives: $\tilde{t},\ \tilde{b},\ \tilde{H}^{\pm,0};\ \ T',$

But also siblings: $H_i^0,\ A_j^0,\ H^{\pm},\ H^{\pm\pm}, \dots .$

Haber, 2012
Branco, Ferreira, Rebelo, Sher, Silva, arXiv:1106.0034;
Coleppa, Kling, Su, arXiv:1305.0002.

- Two Higgs Doublet Model (2HDM):
  rich phenomenology, Type II SUSY option …

Ellwanger, Gunion et al., 2012
S. King et al., 2012
R. Barbieri et al., 2013, ……

- Plus a singlet:
  NMSSM, solve the μ-problem, relax fine-tune, light DM...

- Triplet Model:
  m_ν , L-R symmetric theories, Little Higgs …
  neutrino mass connection via Type II seesaw.

MSSM Higgs Sector

- **Type II Two Higgs Doublet Model**

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_u^0 \to v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad H_d^0 \to v_d/\sqrt{2}$$

$$v_u^2 + v_d^2 = v^2 = (246\mathrm{GeV})^2 \qquad \tan\beta = v_u/v_d$$

after EWSB
5 physical Higgses
CP-even Higgses: h^0, H^0
CP-odd Higgs: A^0
Charged Higgses: $H^\pm$

- **tree level masses determined by mA, tanβ**

$$m^2_{h^0,H^0} = \frac{1}{2}\left((m_A^2 + m_Z^2) \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}\right)$$

$$m^2_{H^\pm} = m_A^2 + m_W^2, \quad \cos^2(\beta-\alpha) = \frac{m^2_{h^0}(m_Z^2 - m^2_{h^0})}{m_A^2(m^2_{H^0} - m^2_{h^0})}.$$

$$m_{h^0} \approx \min\{m_A, m_Z\}|\cos 2\beta|, \quad m_{H^0} \approx \max\{m_A, m_Z\}, \quad m_{H^\pm} \approx \max\{m_A, m_W\}.$$

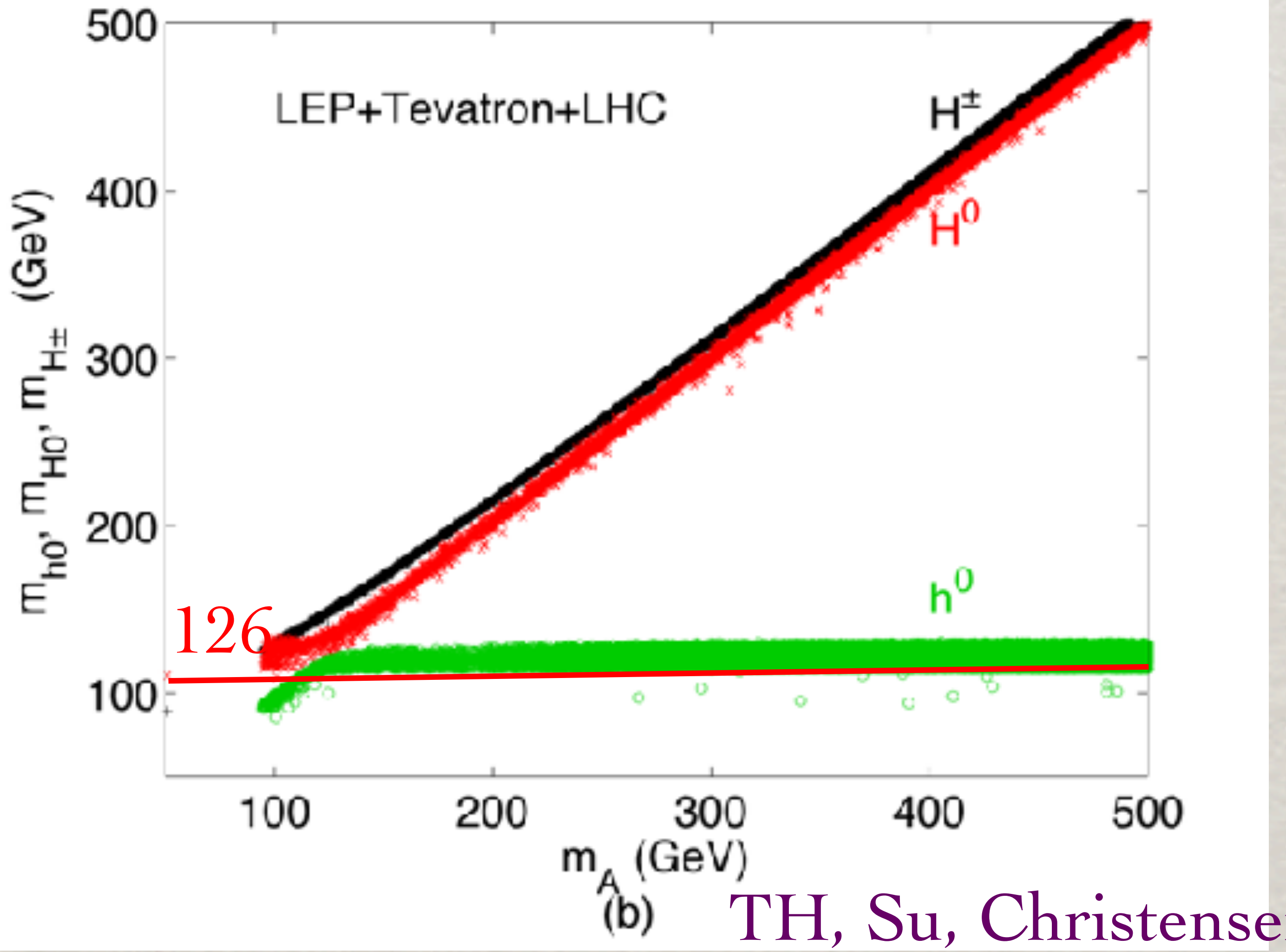
Example: MSSM Two Higgs-Doublet Model after the discovery:

Arbey et al., 2011, 2012
Baer et al., 2012
Heinemeyer et al., 2012
Carena 2012, 2013, … …

5 Higgs bosons: $h^0,\ H^0,\ A^0,\ H^\pm$

Tree-level masses given by $M_A,\ \tan\beta$

Collider bounds:



TH, Su, Christensen, arXiv:1203.3207

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(a). Dark Matter

$H^\dagger H$ is the only bi-linear SM gauge singlet.

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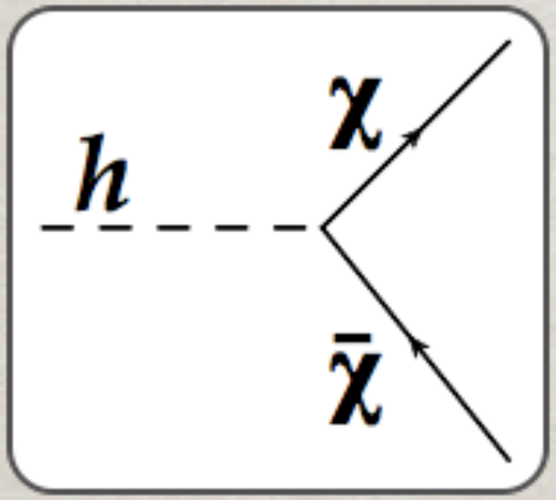

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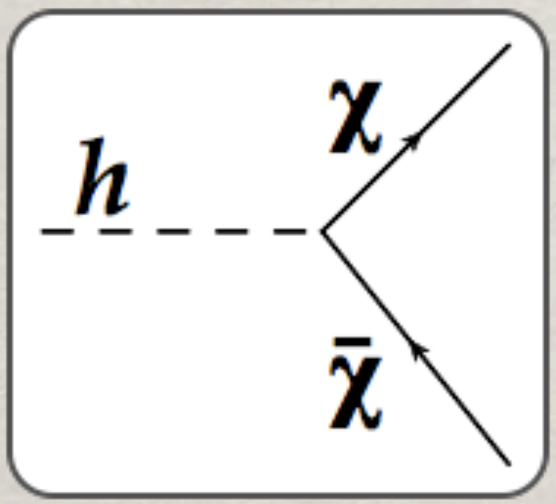
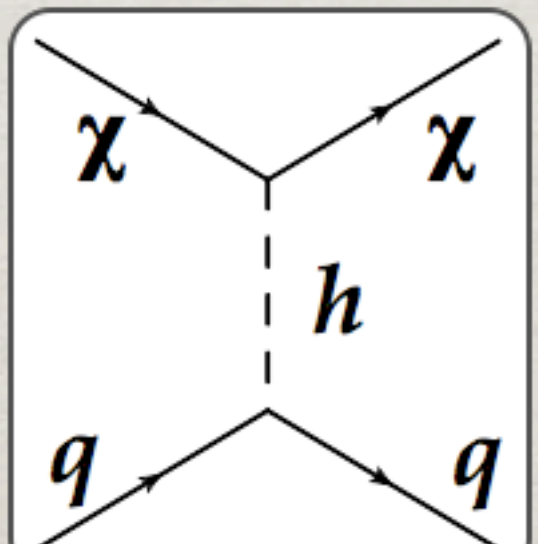
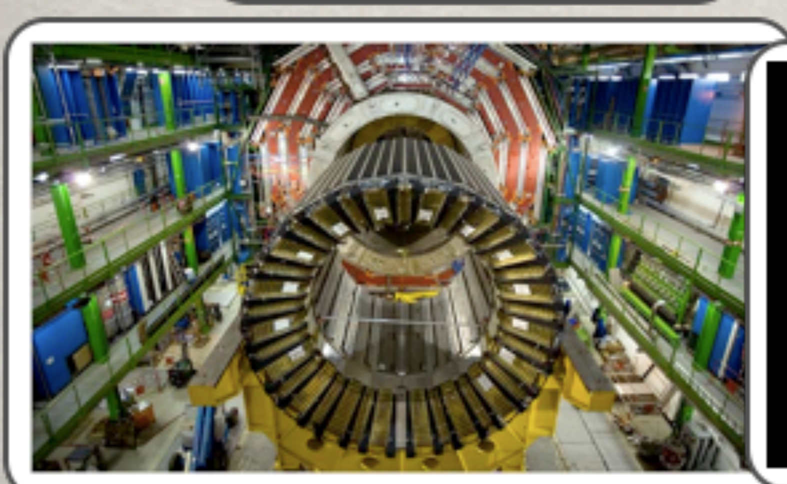
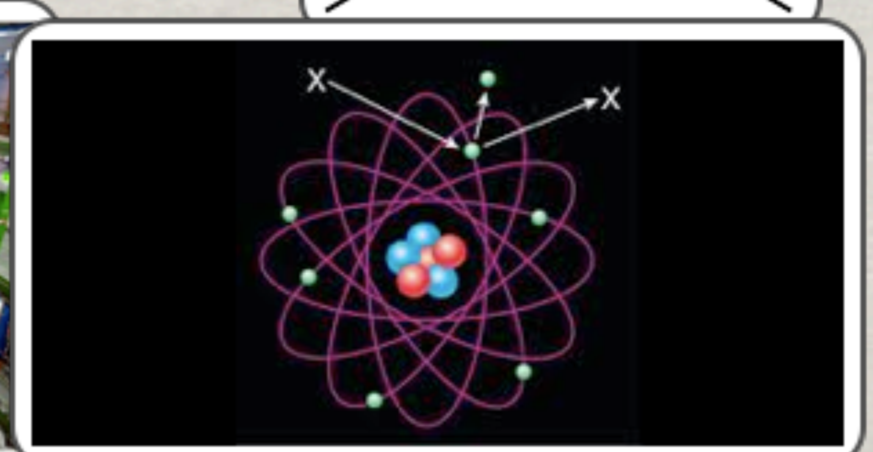


Direct detection







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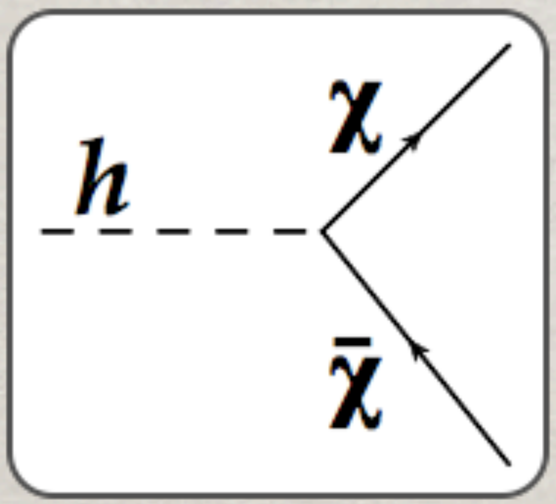
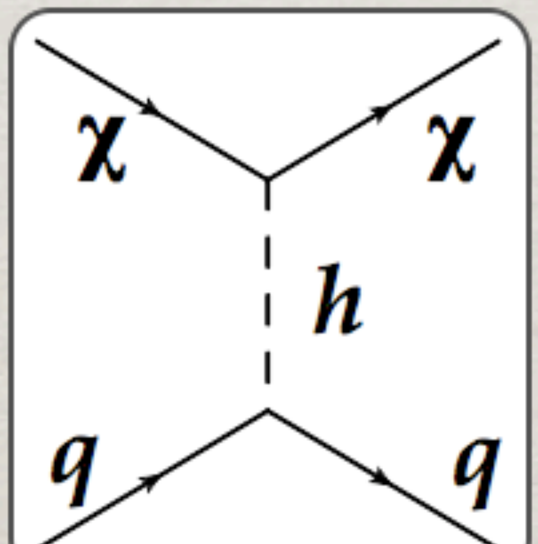
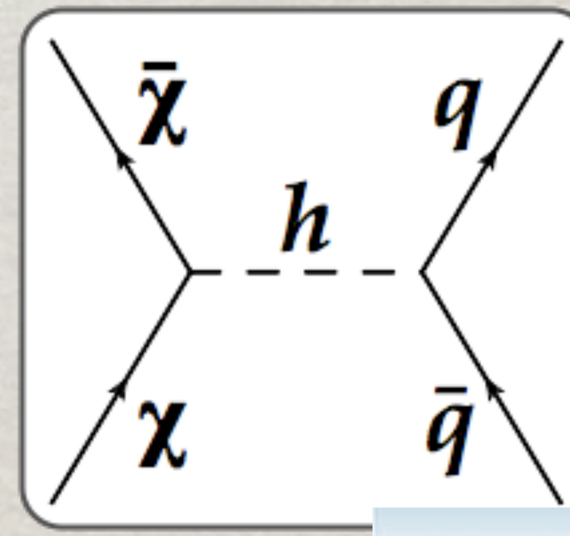
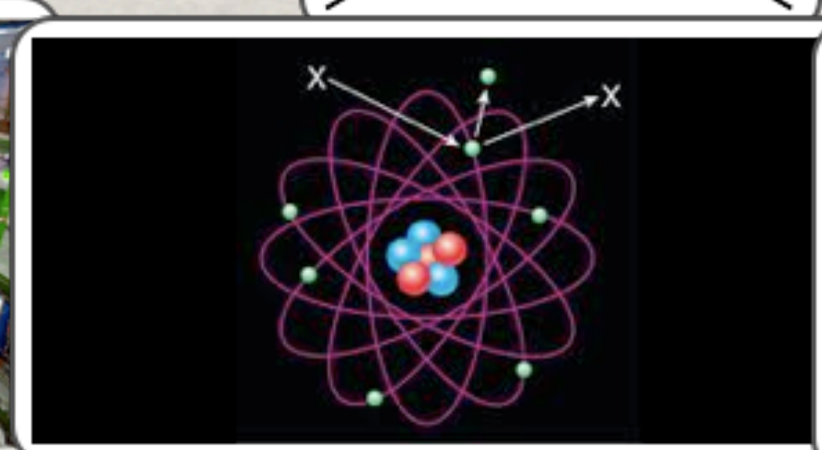
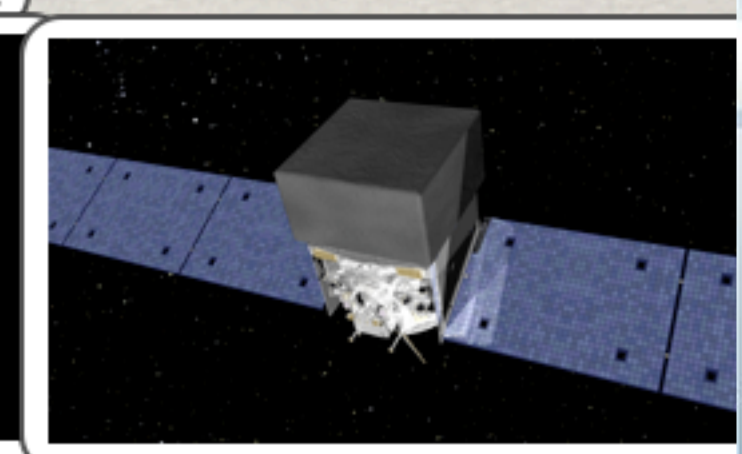
Missing energy at LHC Direct detection Indirect detection

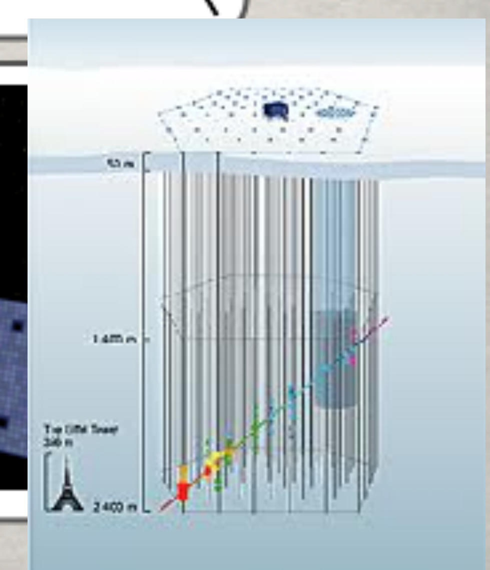






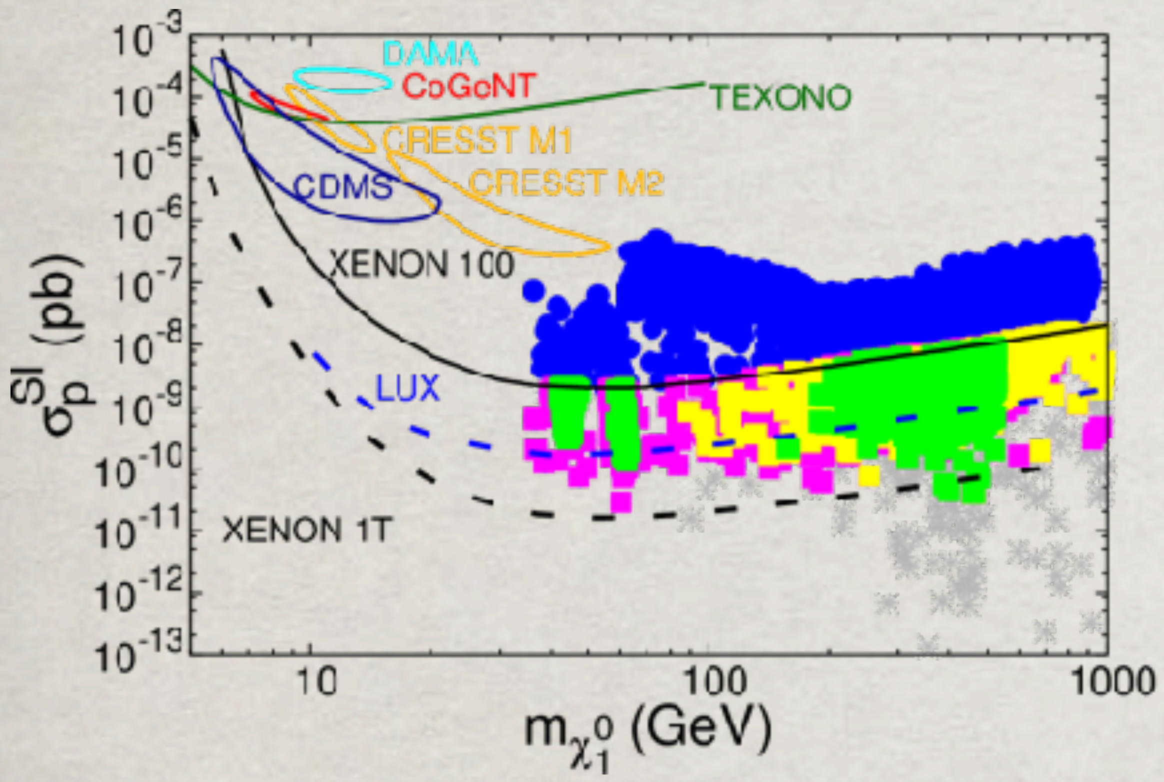






SUSY Higgs funnel soon covered by direct searches:

TH, Z.Liu, A.Natarajan, arXiv:1303.3040



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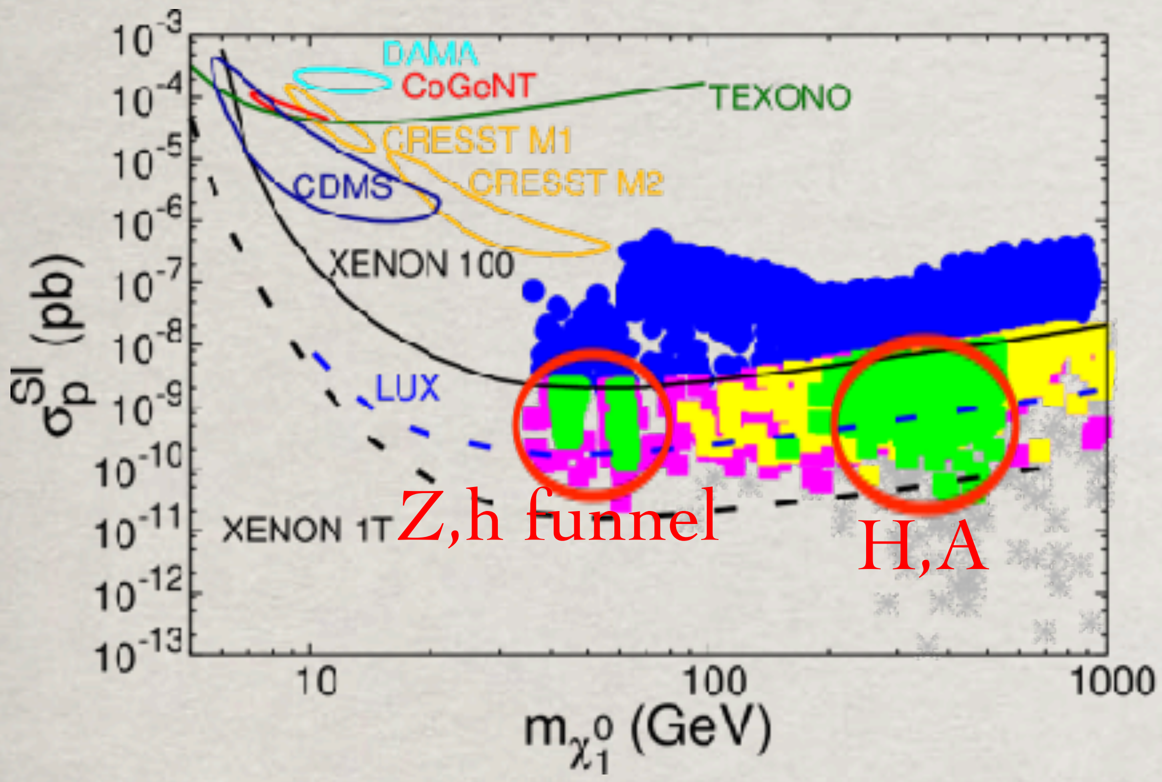

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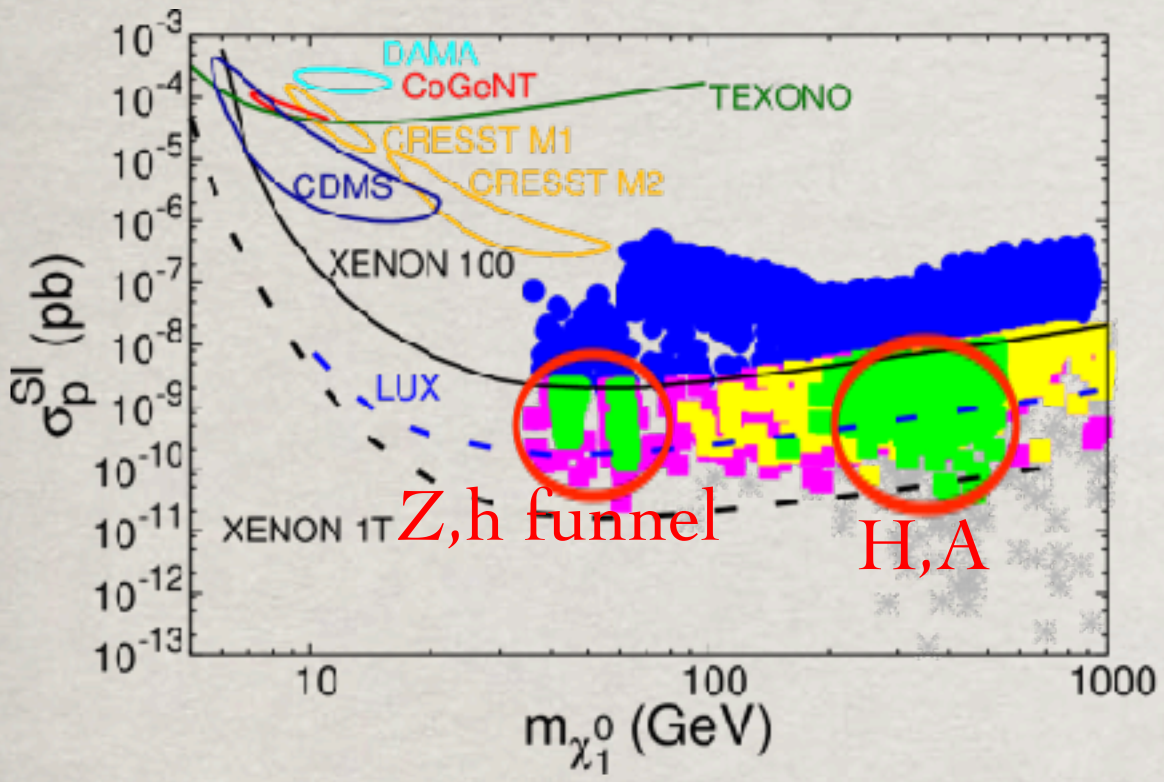

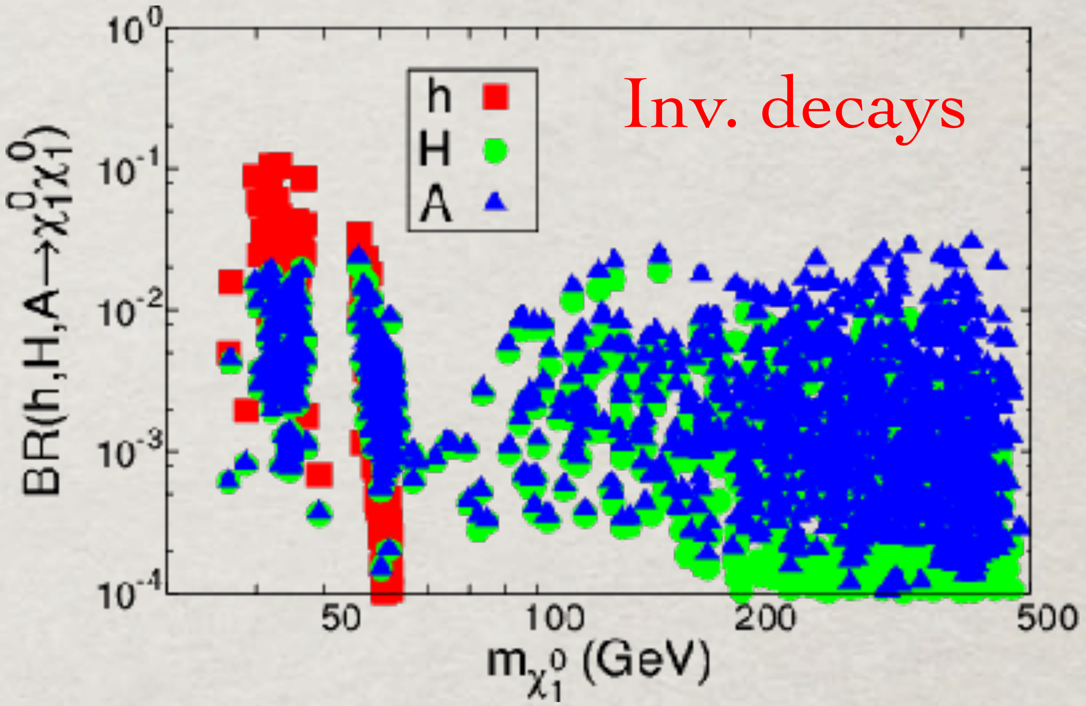

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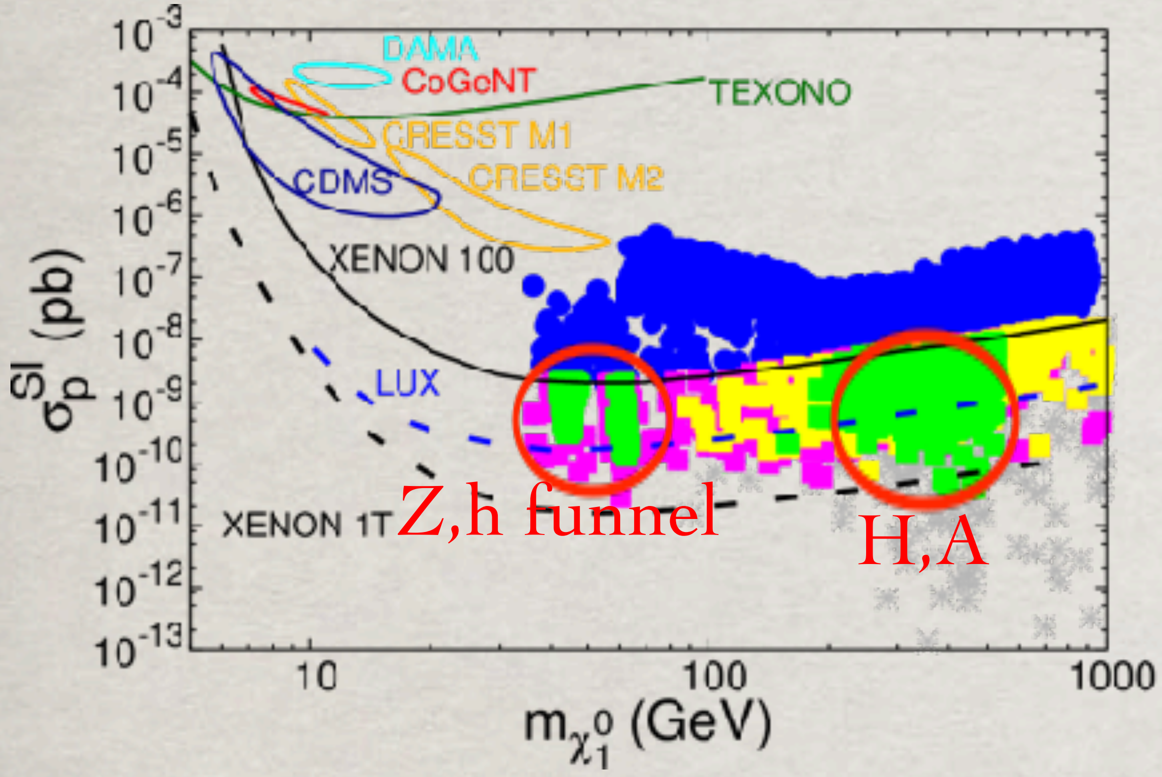

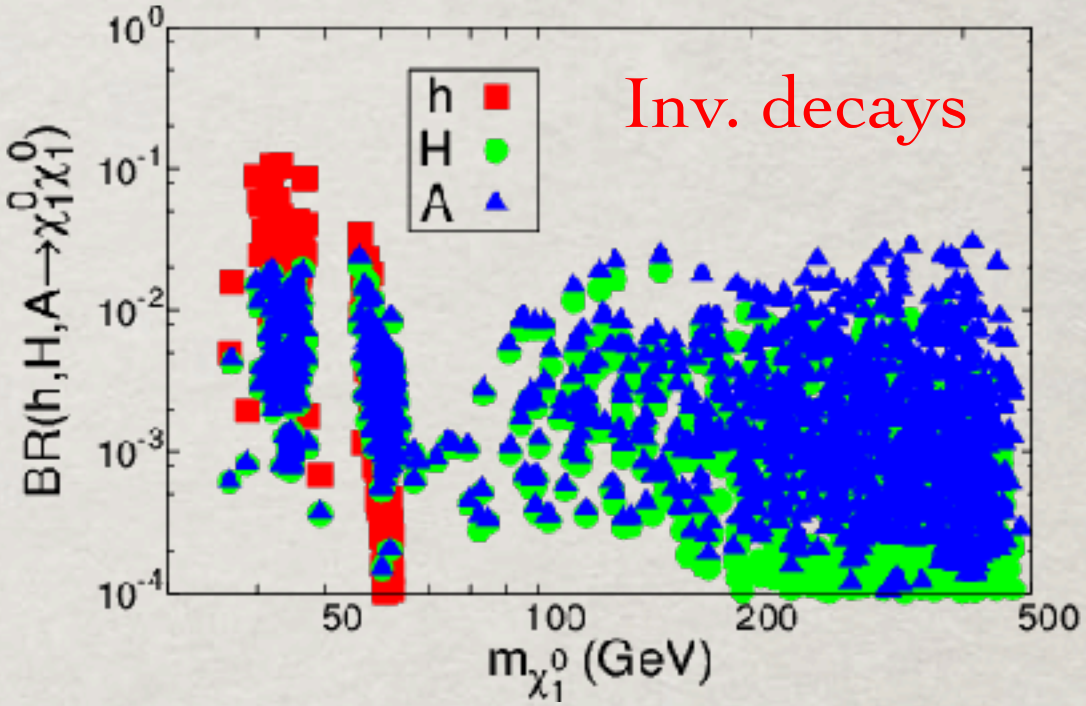

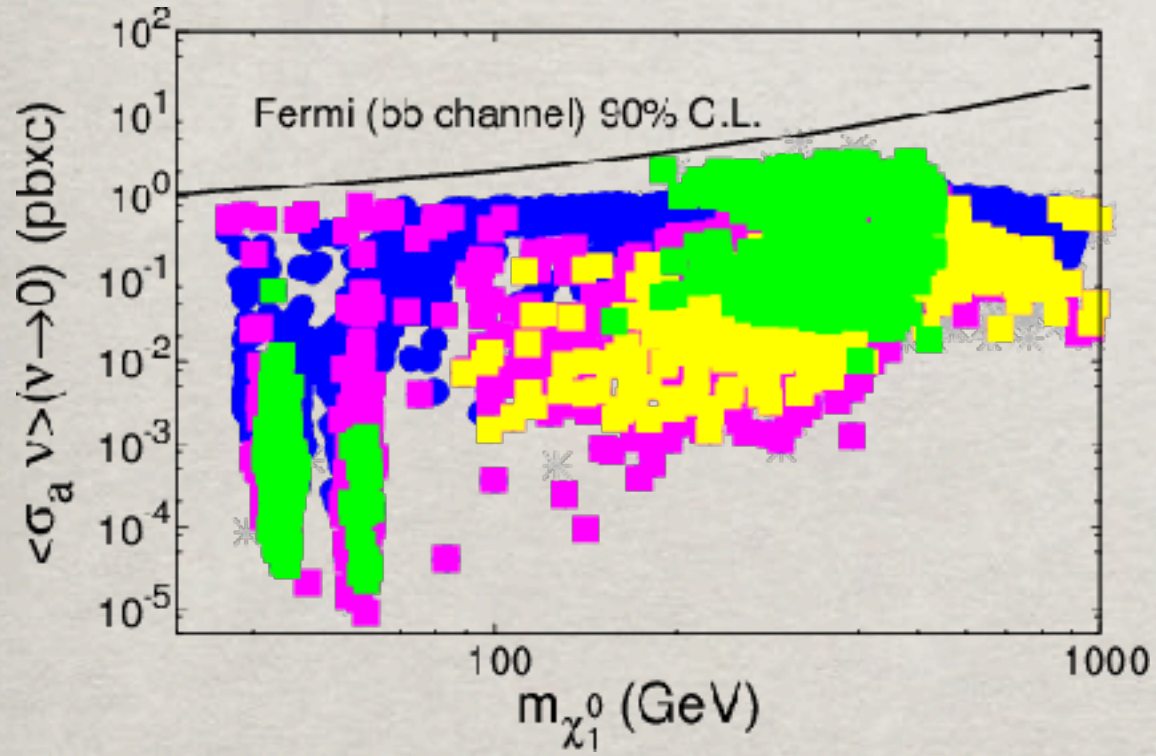

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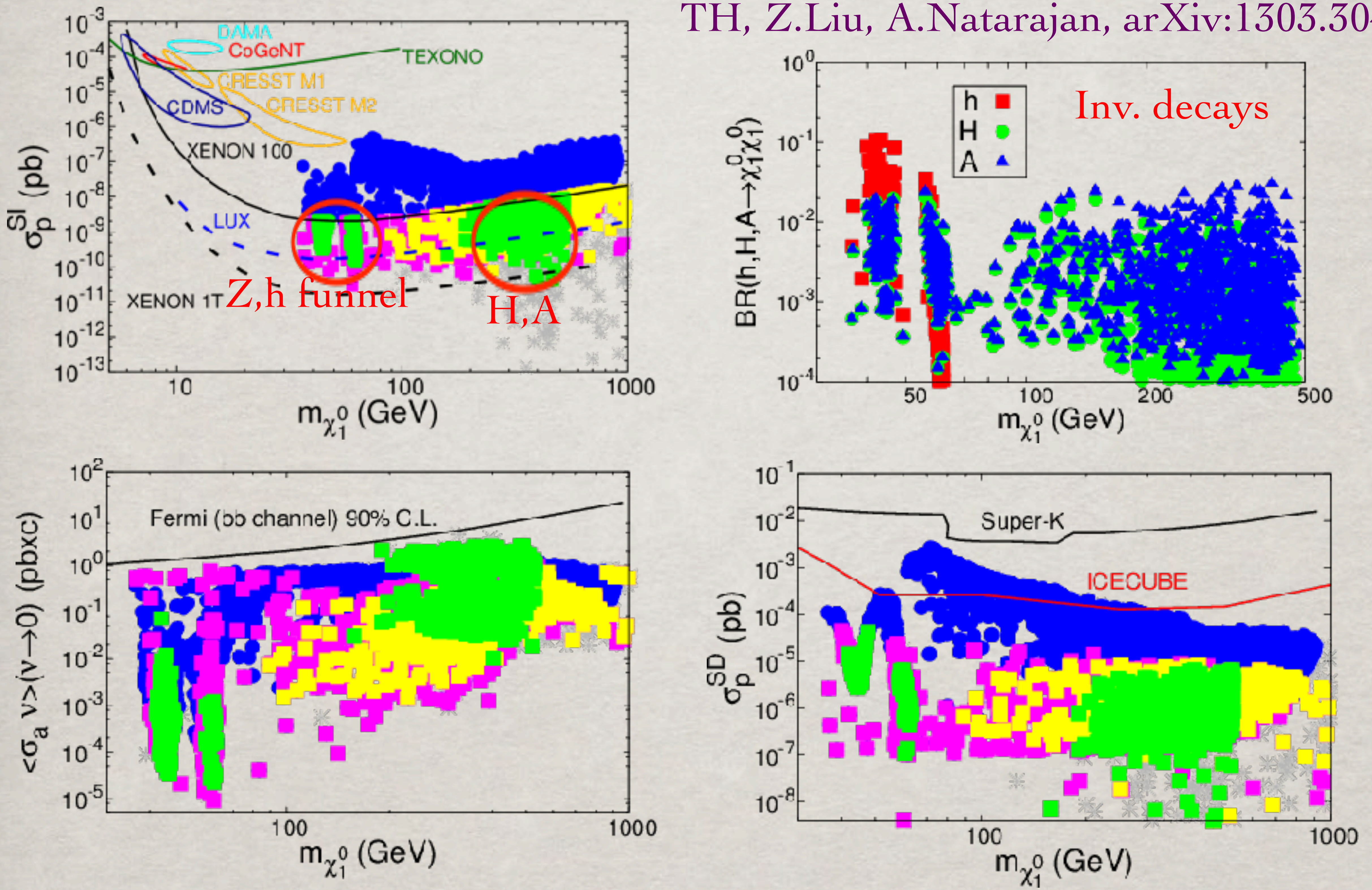

Cahill-Rowley, Rizzo, Hewett et al. arXiv:1305.6921
Fowlie, Roszkowsky et al., arXiv:1306.1567

Other potential consequences

(b). Baryon – anti-baryon Asymmetry

For M_H = 125 GeV,

EW baryogenesis needs light sparticles:

$m_{stop} \approx 150$ GeV

plus a light neutralino, singlets …

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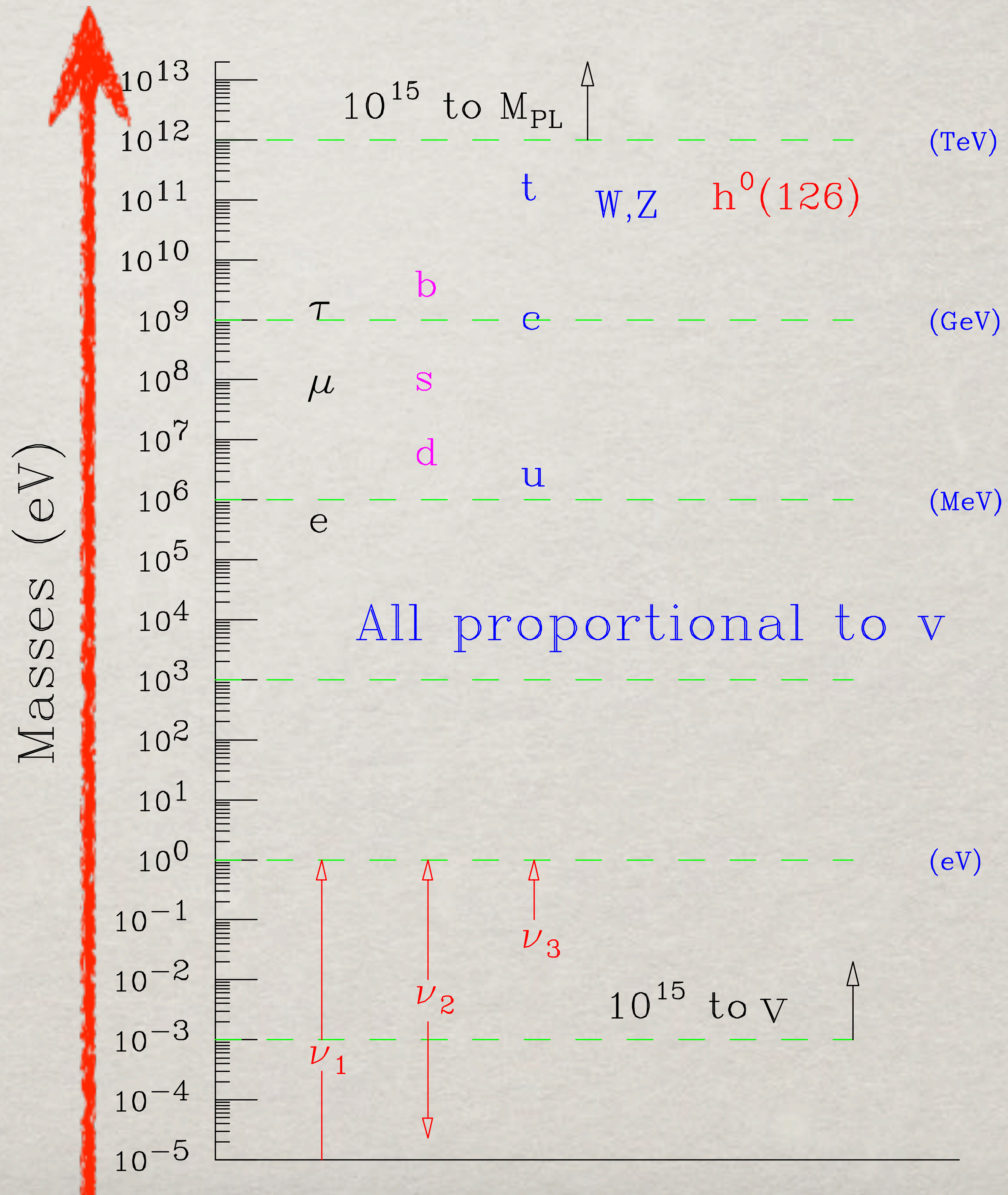
The existence of a fundamental scalar encourages the consideration of scalar fields in cosmological applications.

5. Flavor & Yukawa Couplings

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- New CP-violation sources?

Higgs Yukawa couplings as the pivot!



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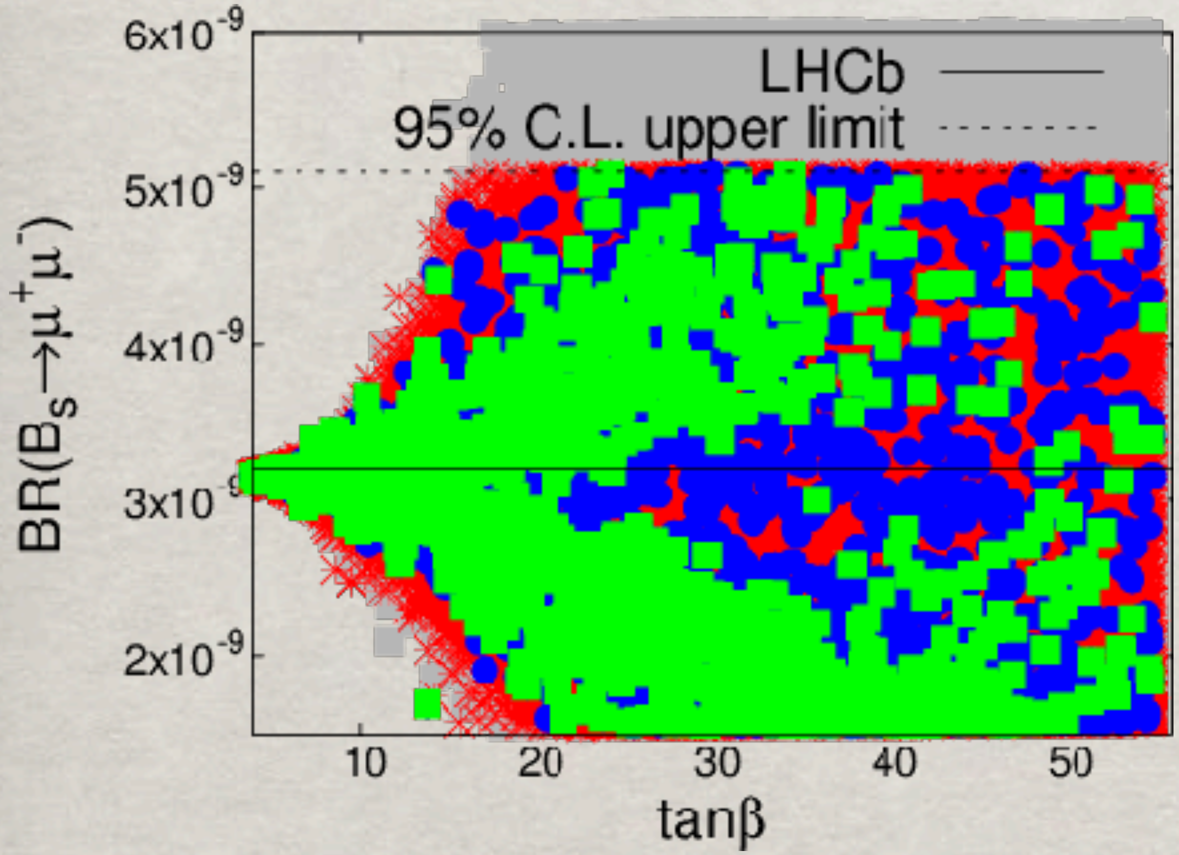
TH, Liu, arXiv:1303.3040
Carena et al., arXiv:1305.5761.



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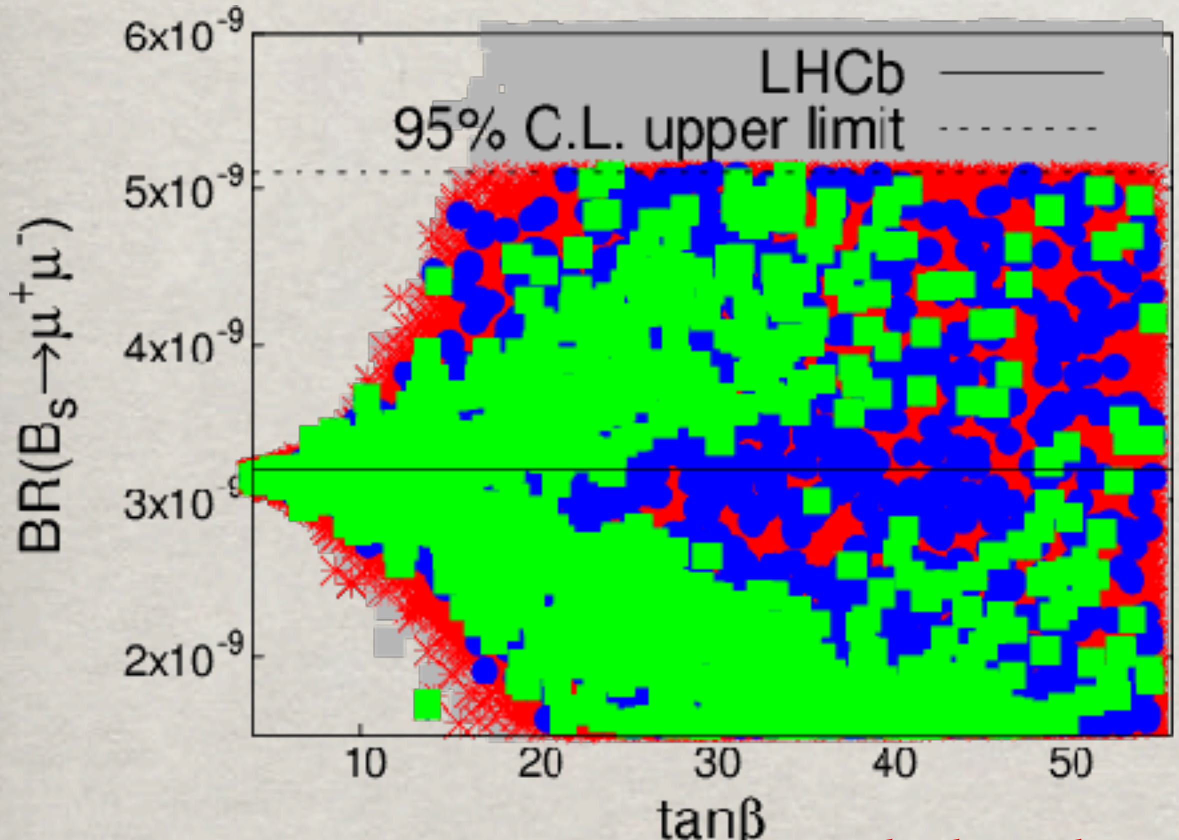

Most recent LHCb+CMS:
arXiv:1411.4413

$B(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$ and
$B(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$,

$\mathcal{S}_{SM}^{B_s^0} = 0.76^{+0.20}_{-0.18}$ and $\mathcal{S}_{SM}^{B^0} = 3.7^{+1.6}_{-1.4}$.

**With Belle 2 as well,
likely a surprise to breakthrough!**

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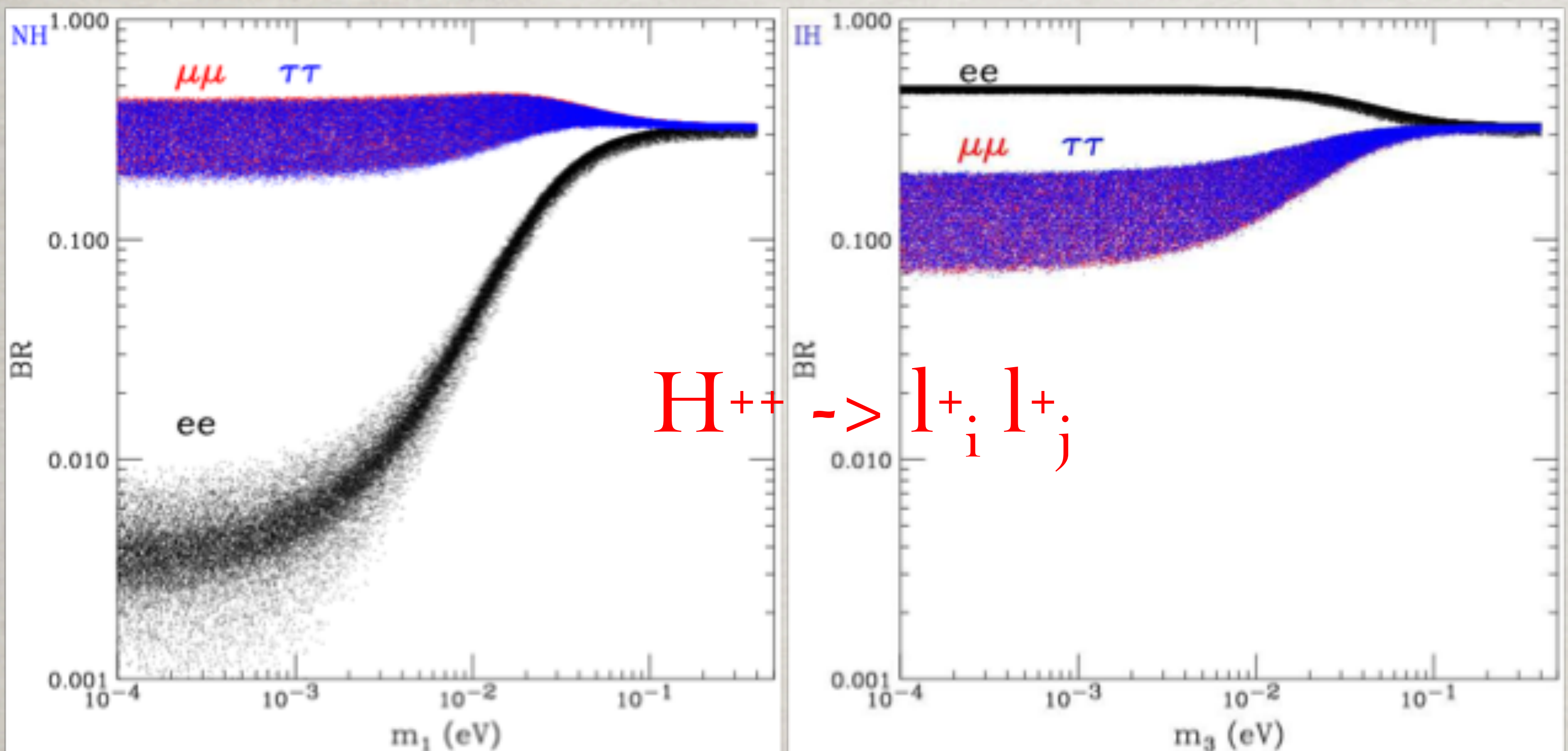

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Fileviez-Perez et al., 2008.
Chaudhuri, Grimus, Mukhopadyaya, arXiv:1305.5761
Chun et al., arXiv:1305.0329

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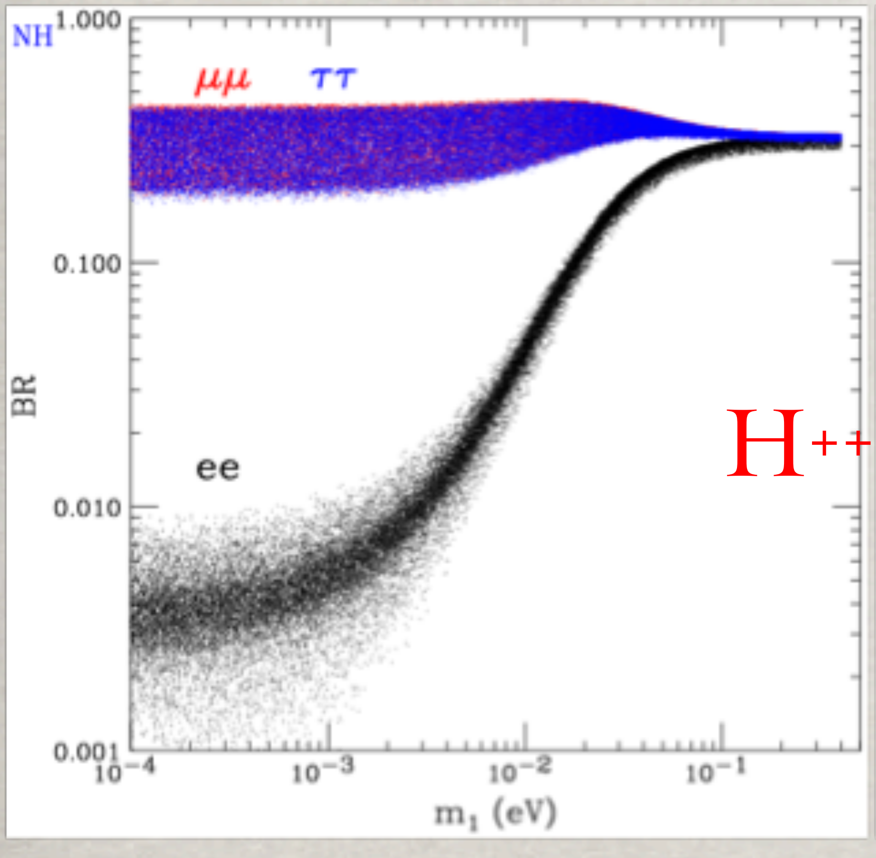

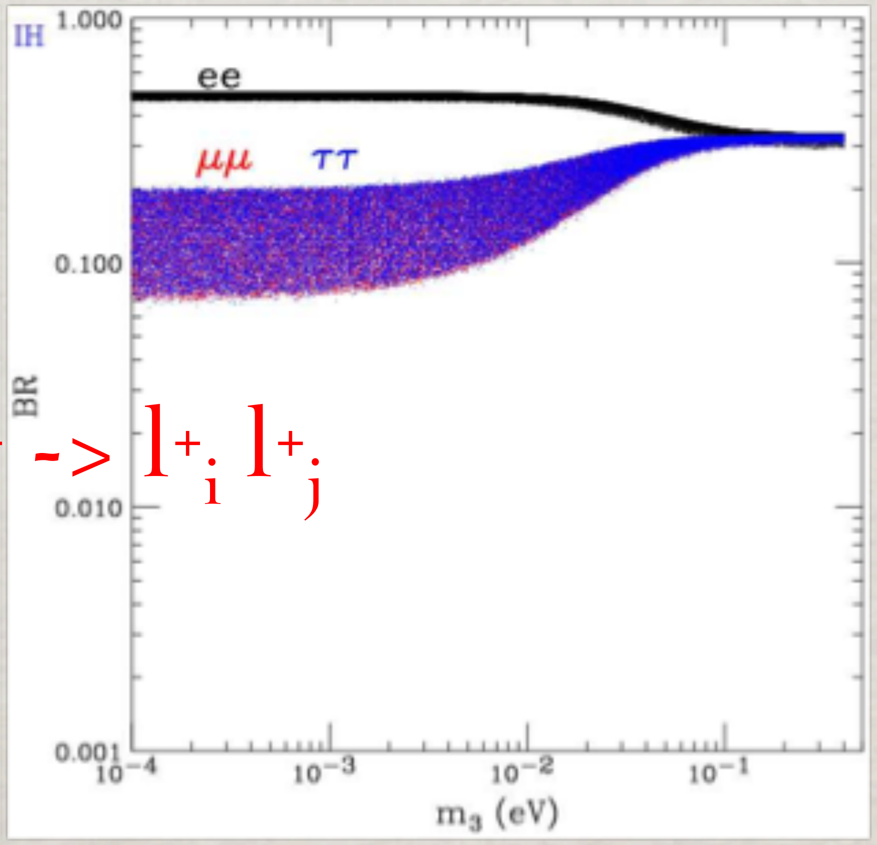

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$T^+ \to H\, l^+_i$, $T^0 \to W^\pm\, l$

Senjanovic et al., arXiv:0904.2309.

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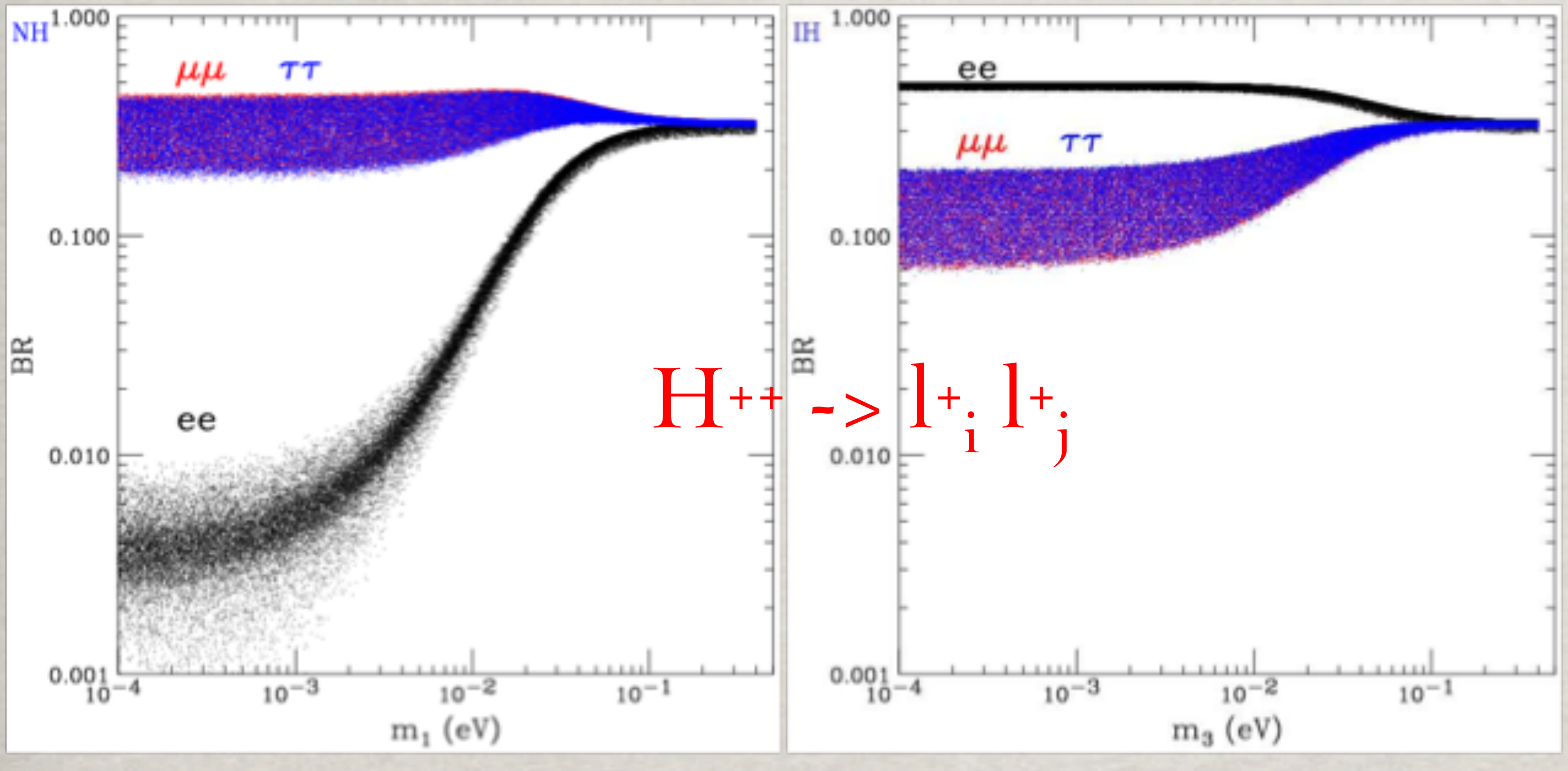

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Senjanovic et al., arXiv:0904.2309.

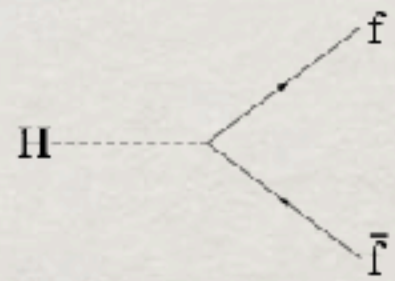
Watch out: $H^0 \to \mu\tau$ $(l^+_i\, l^-_j)$ for BSM flavor physics!

TH, Marfatia, PRL (2001)
Harnik, Kopp, Zupan, 2013

6. Couplings & Width

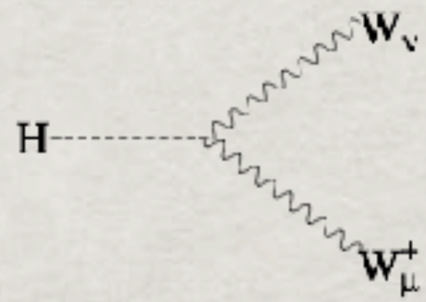
Higgs boson couplings encode its properties:

Yukawa coupling

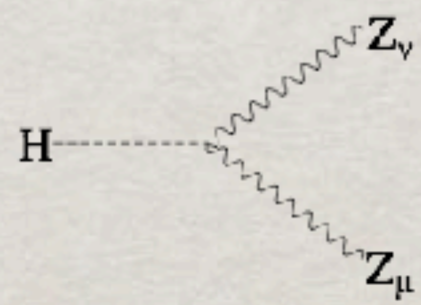


$$-i\frac{m_f}{v}\left(1+\Delta_f\right)$$

EWSB



$$ig\, m_W\,(1+\Delta_W)g_{\mu\nu}$$



$$ig\,\frac{1}{\cos\theta_W}\,m_Z\,(1+\Delta_Z)g_{\mu\nu}$$

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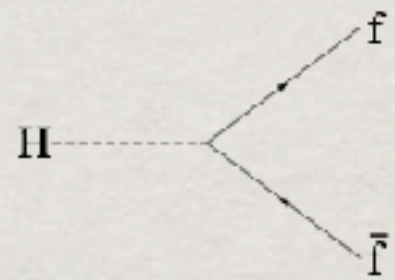

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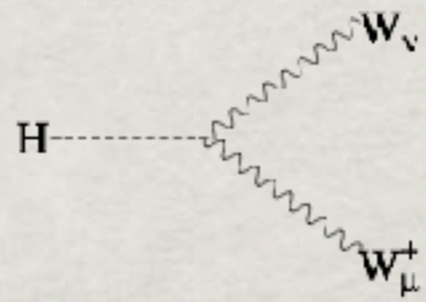

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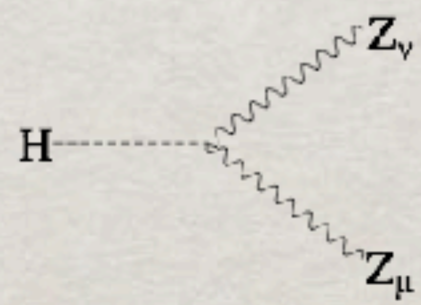

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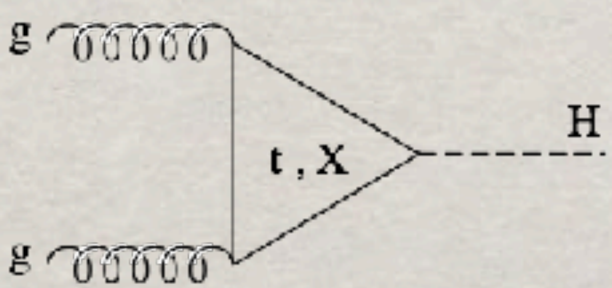
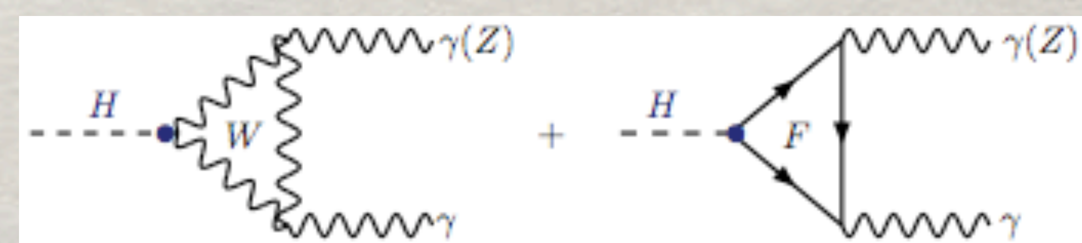
Color/charged particles in loops:





Precision Higgs Physics

In a pessimistic scenario, the LHC does not see a new particle associated with the Higgs sector, then the effects of a heavy state on Higgs coupling g_i at the scale M:

$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2) \approx \text{a few \% for } M \approx 1 \text{ TeV}$$

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LHC 14 TeV, $3ab^{-1}$:	8%	15%	few%	50%

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If no deviations, I'd DEFINE it THE SM Higgs!

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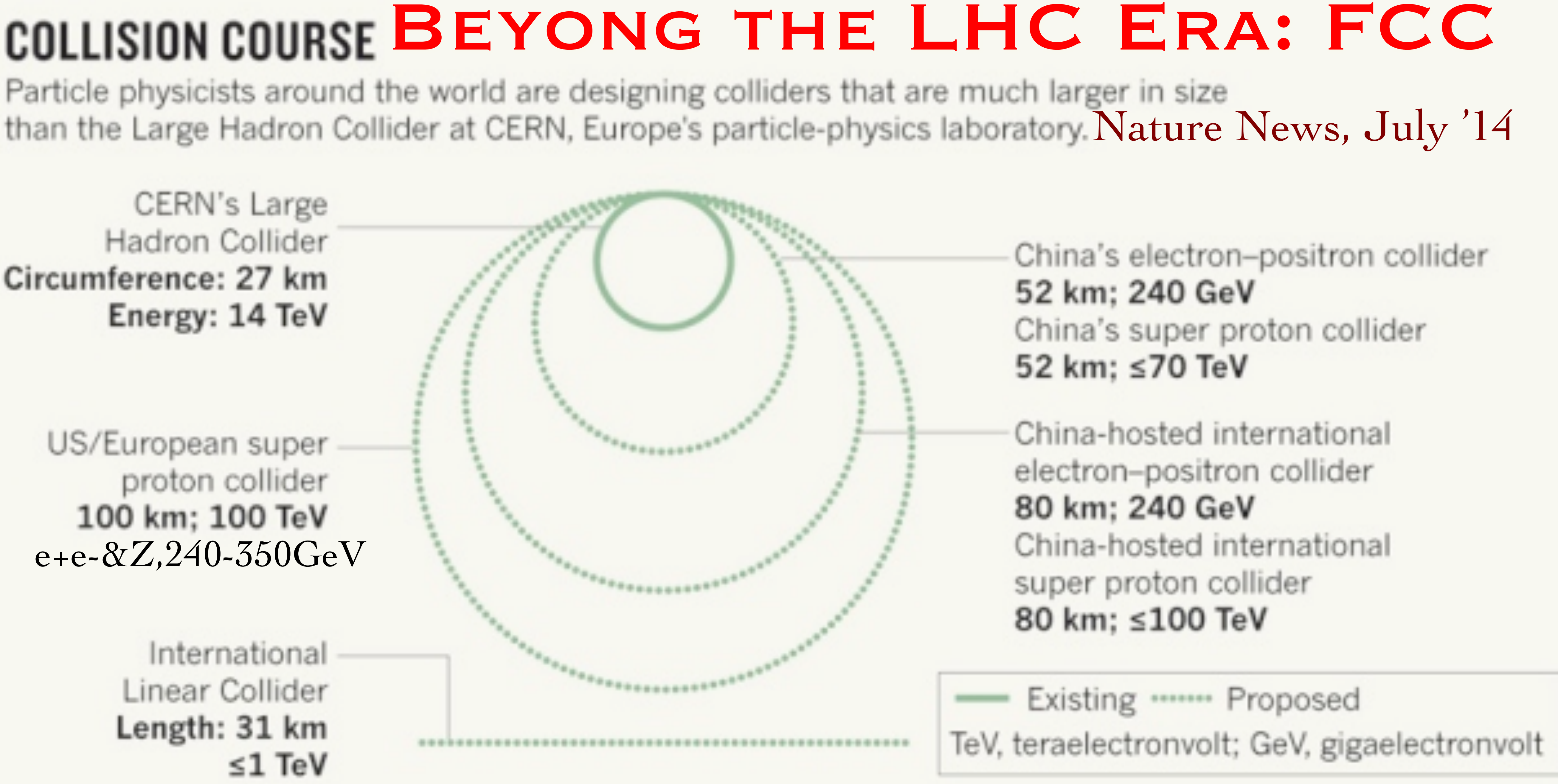
Beyong the LHC Era: FCC



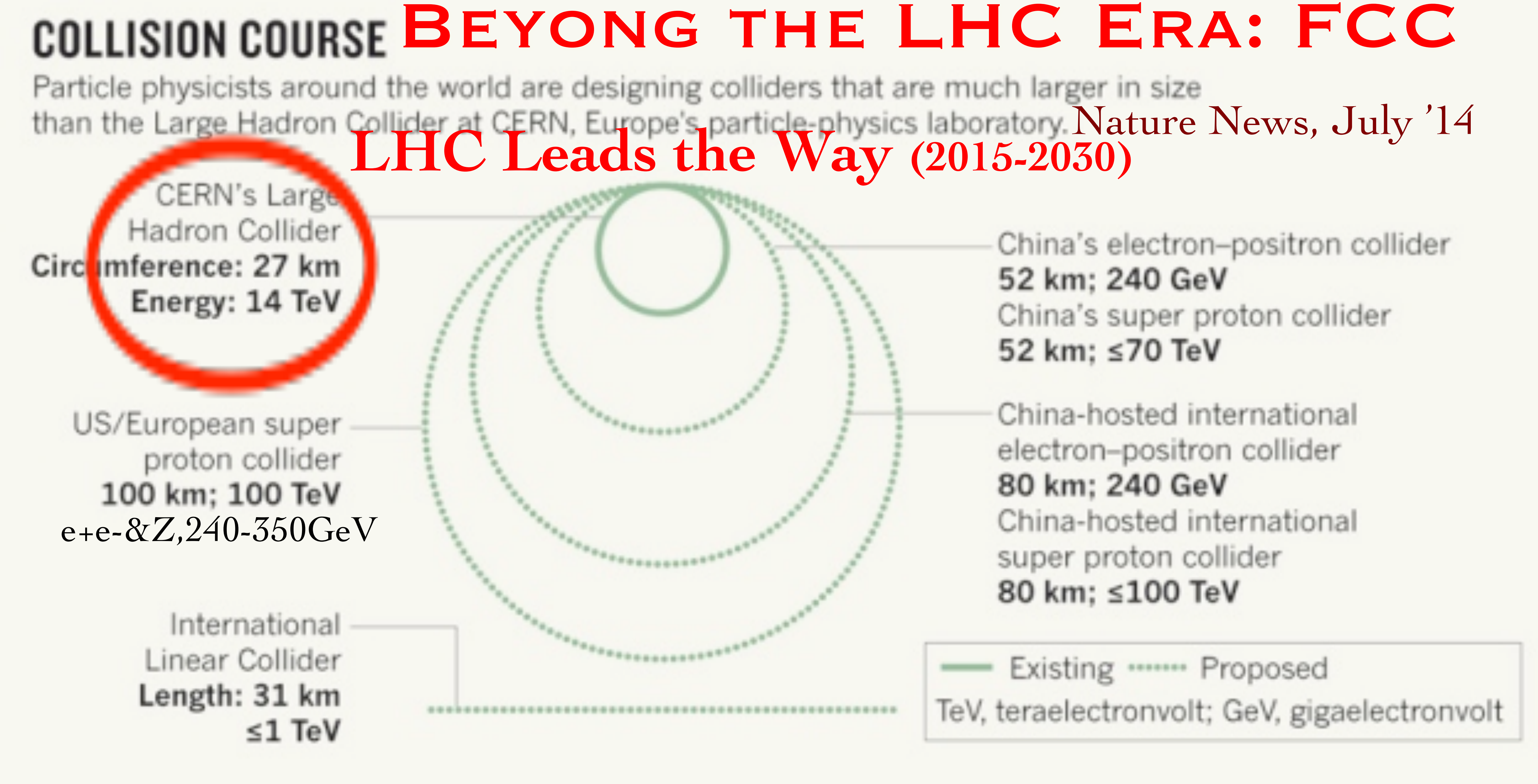
Nature News, July '14

e+e-&Z,240-350GeV

Beyond the LHC Era: FCC

LHC Leads the Way (2015-2030)

Nature News, July '14



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Nature News, July '14

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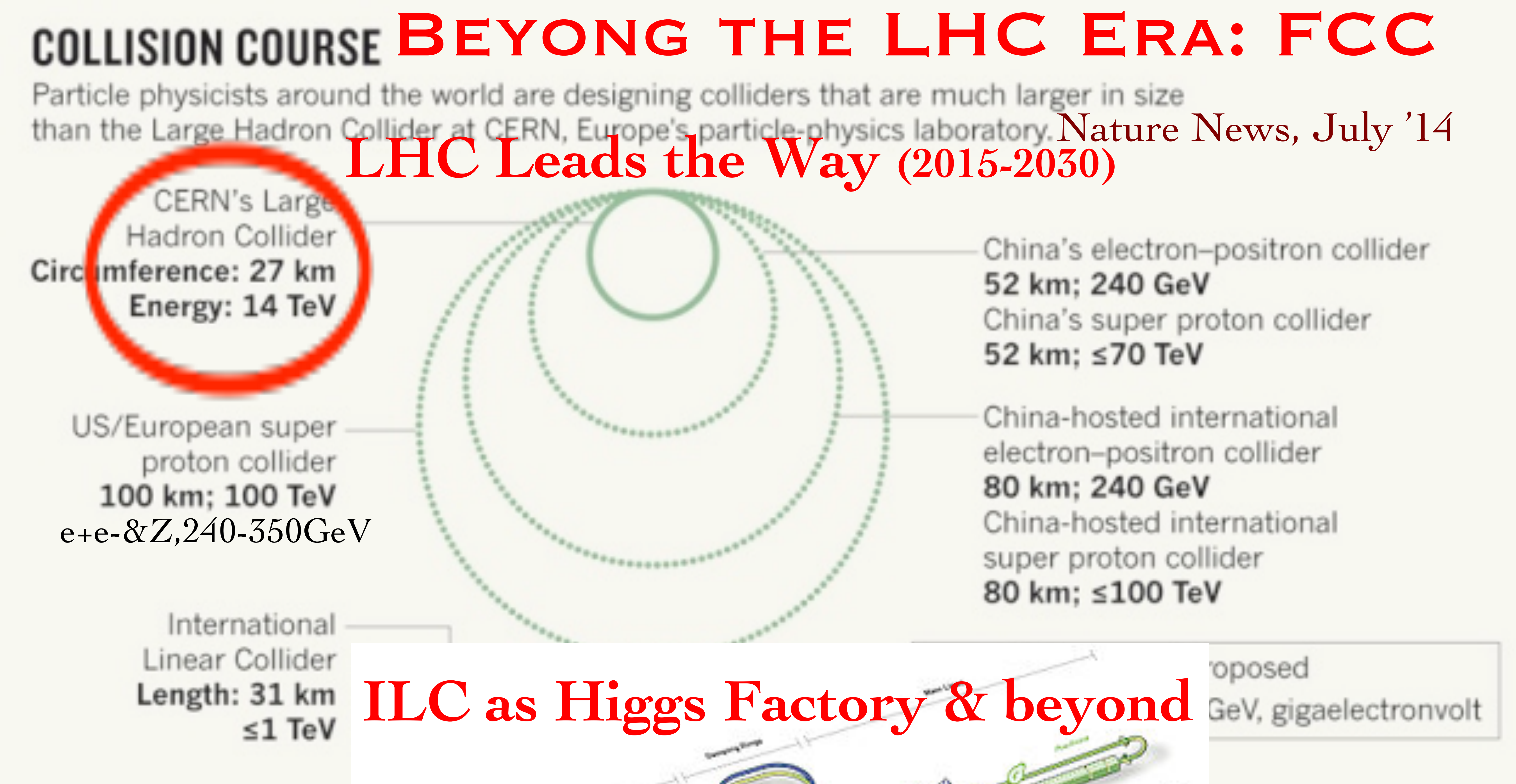
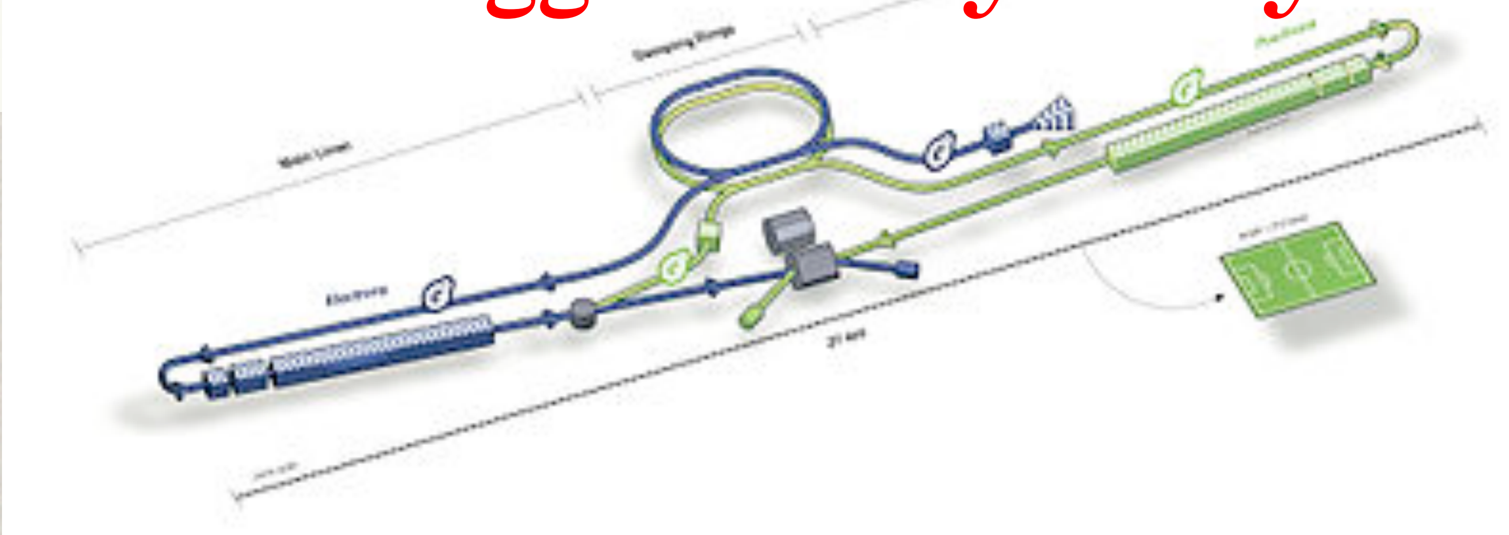


e+e-&Z,240-350GeV

ILC as Higgs Factory & beyond



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Nature News, July '14

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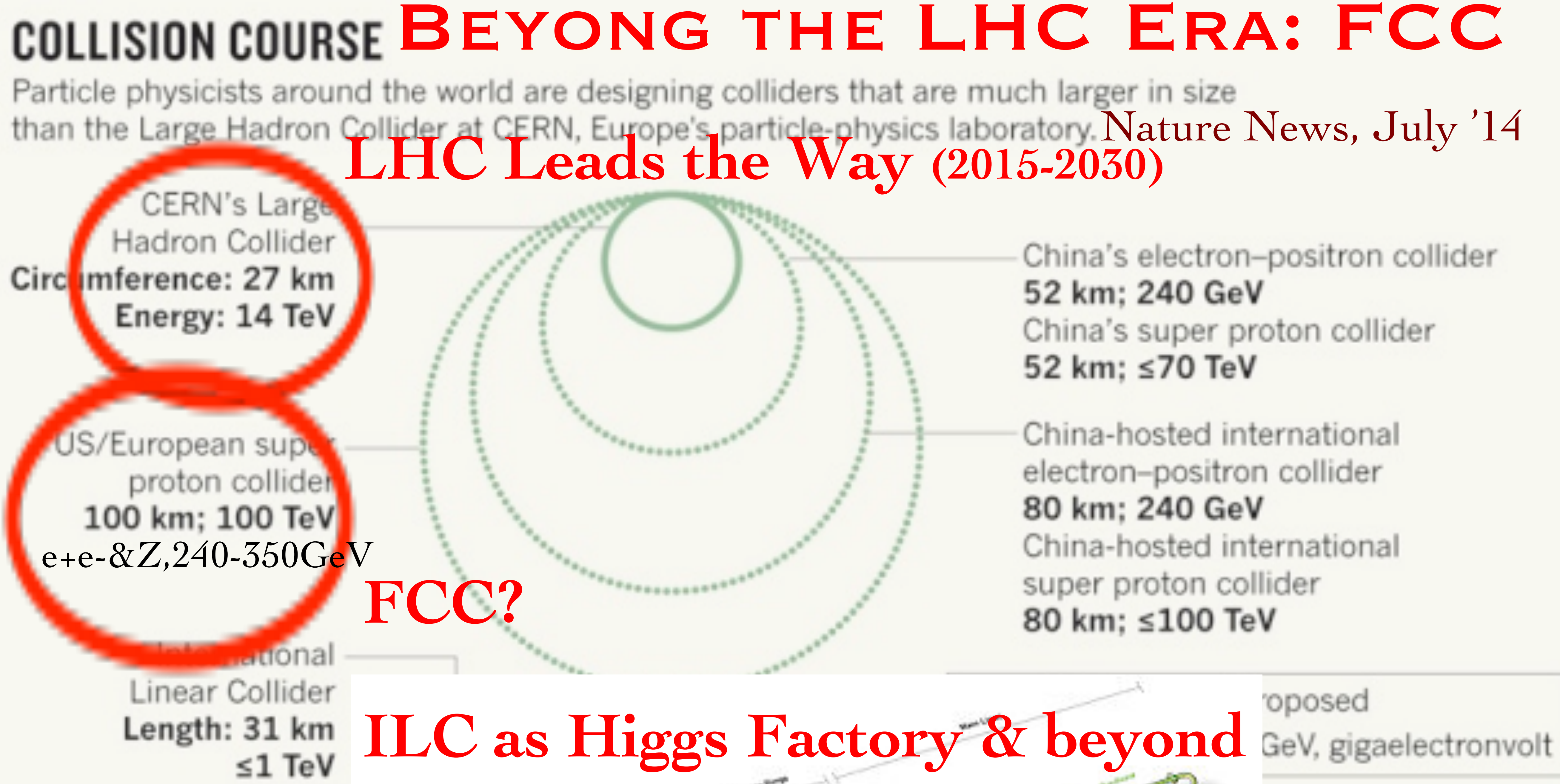

e+e-&Z,240-350GeV

FCC?

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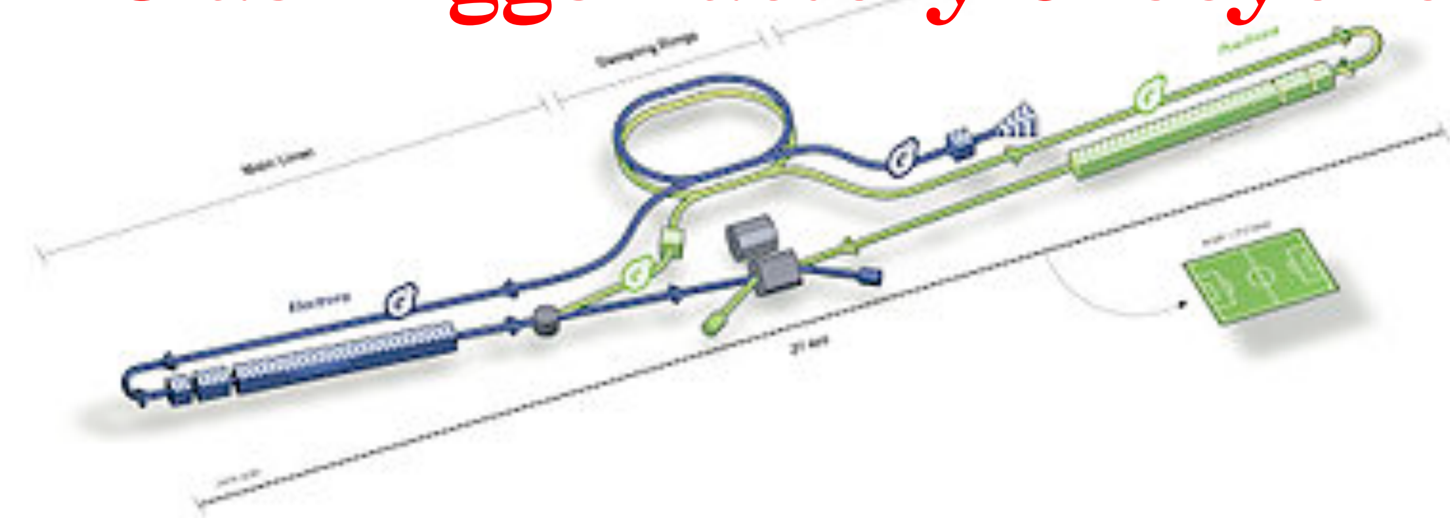
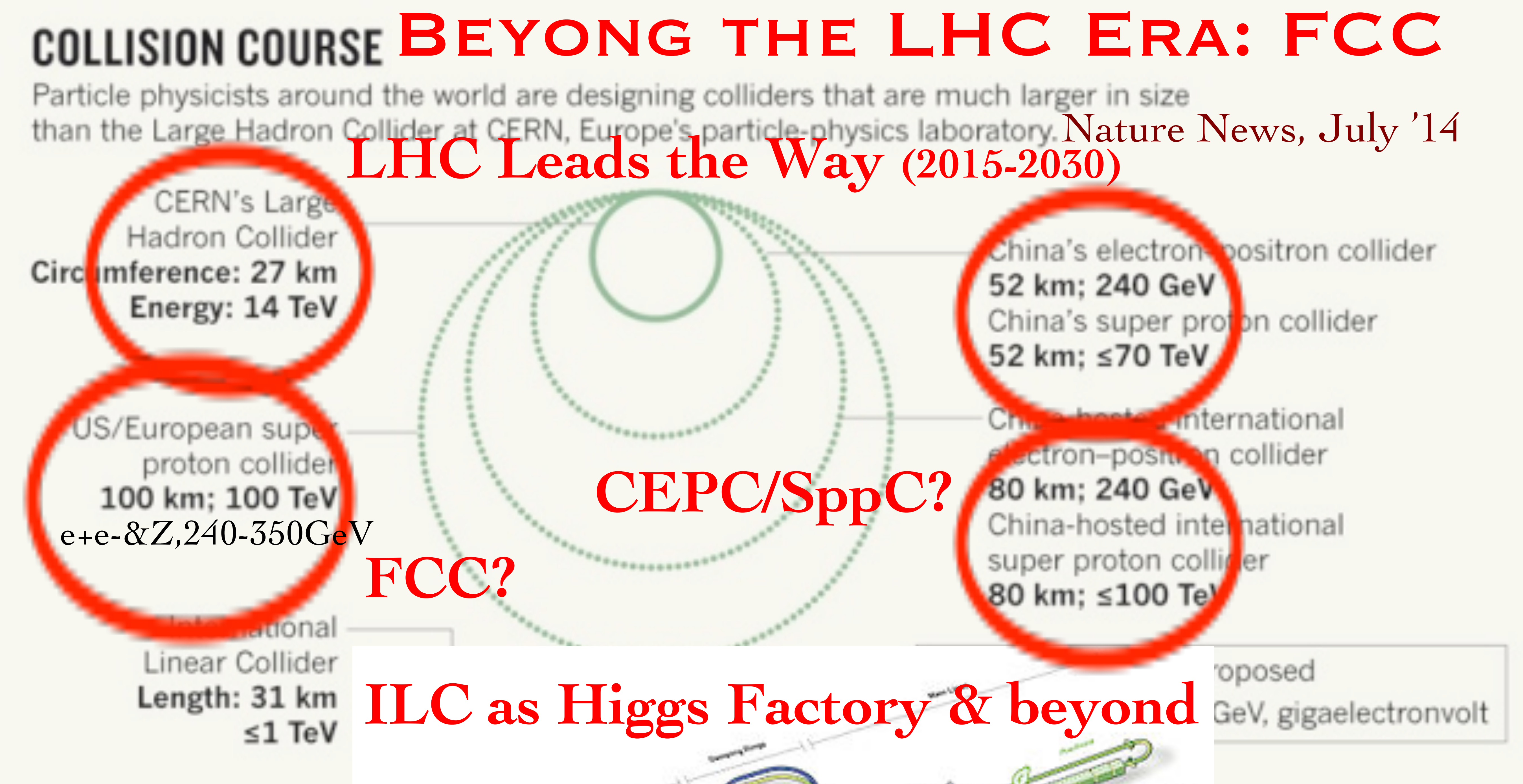


Beyond the LHC Era: FCC

Nature News, July '14



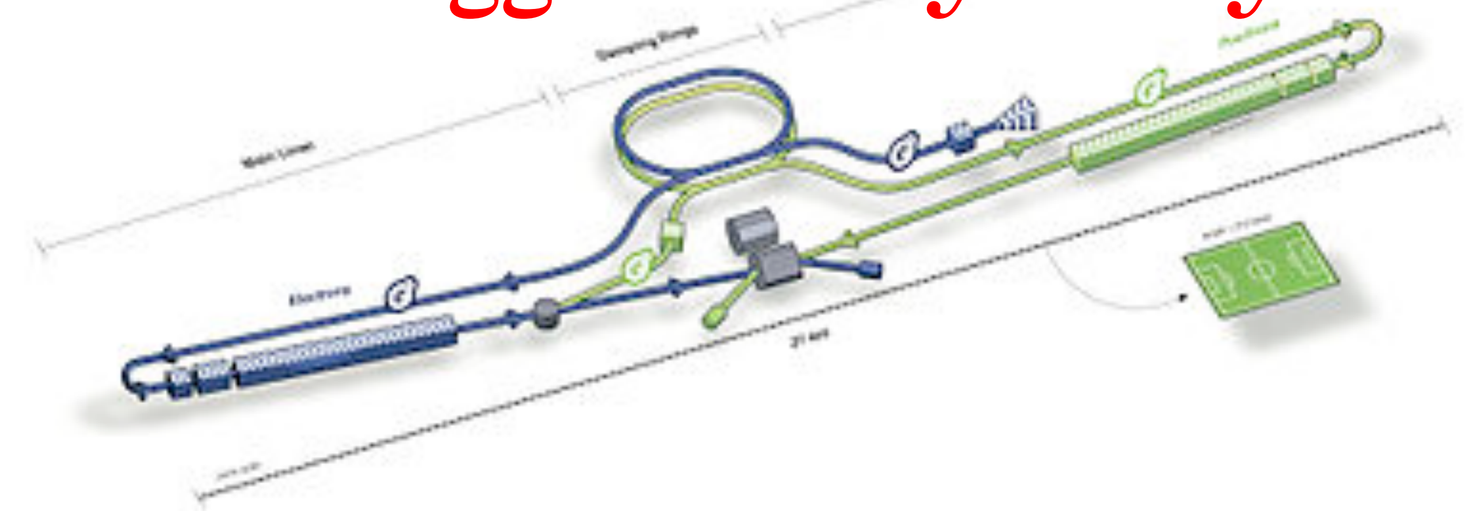
LHC Leads the Way (2015-2030)

e+e-&Z,240-350GeV

FCC?

CEPC/SppC?

ILC as Higgs Factory & beyond



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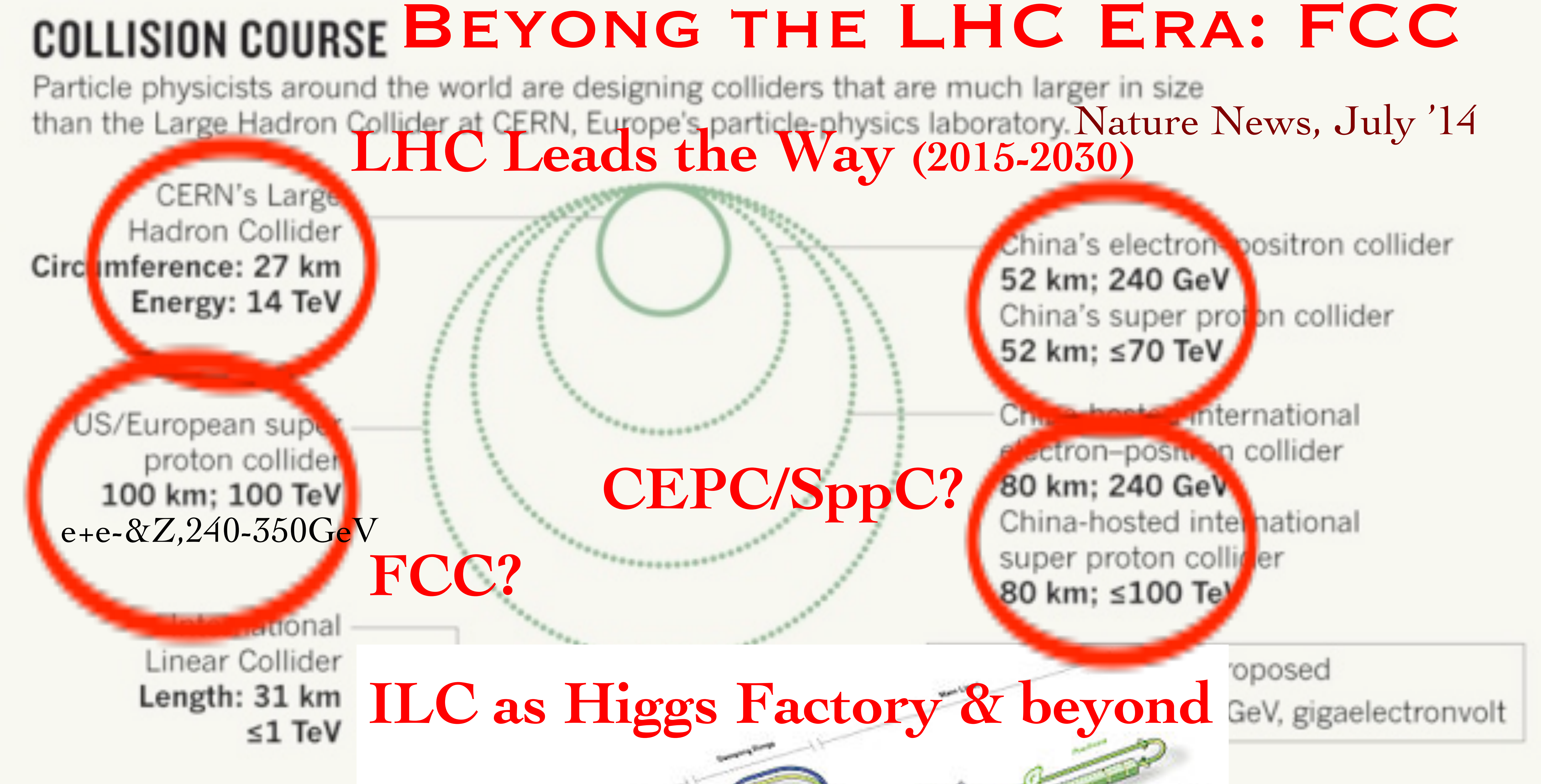


ILC as Higgs Factory & beyond

Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

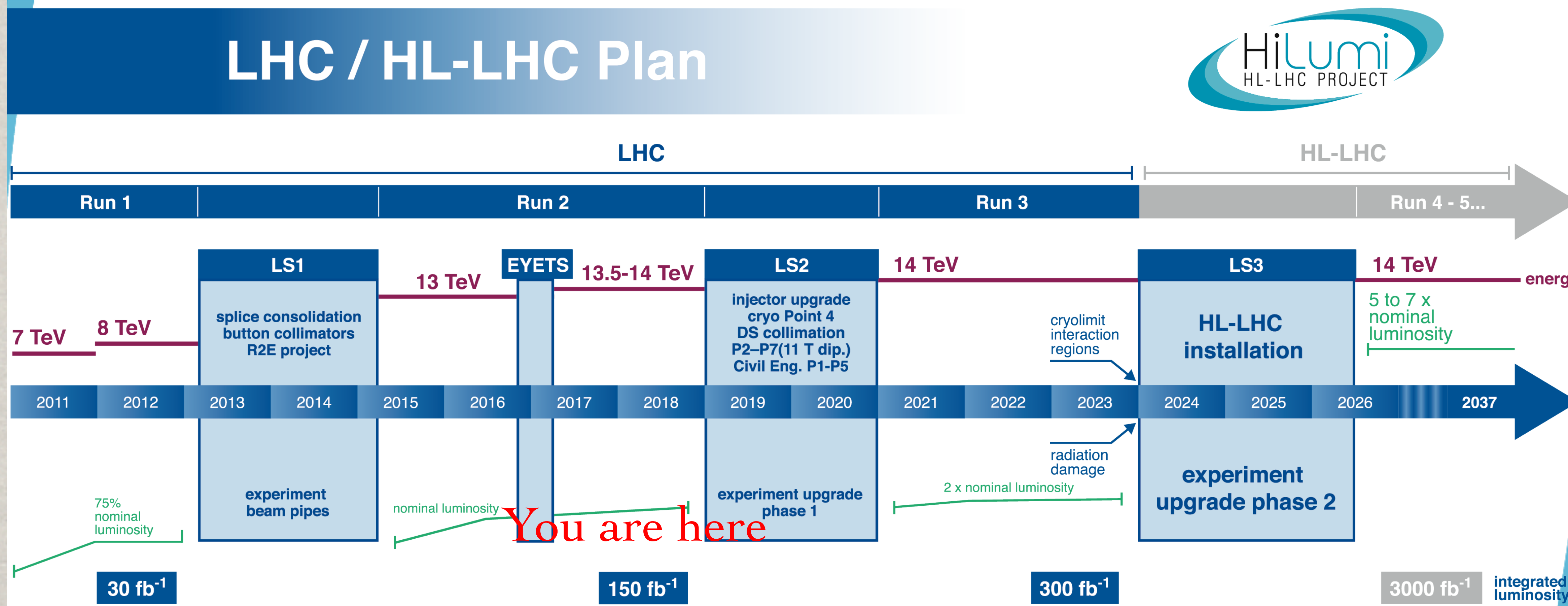
Snowmass 1310.8361

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
dt (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

HL-LHC:
The Energy & Precision Frontier

Sasha Valishev

Timeline & Goal:
Commissioning 2026; 3 ab^{-1} by 2037 (250 fb^{-1}/y)



Levelled Luminosity $L = 5\times10^{34} cm^{-2} s^{-1}$

HE-LHC: The New Energy Frontier

Vladimir Shiltsev, this workshop

HE-LHC design goals and basic choices

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$)

key technologies:

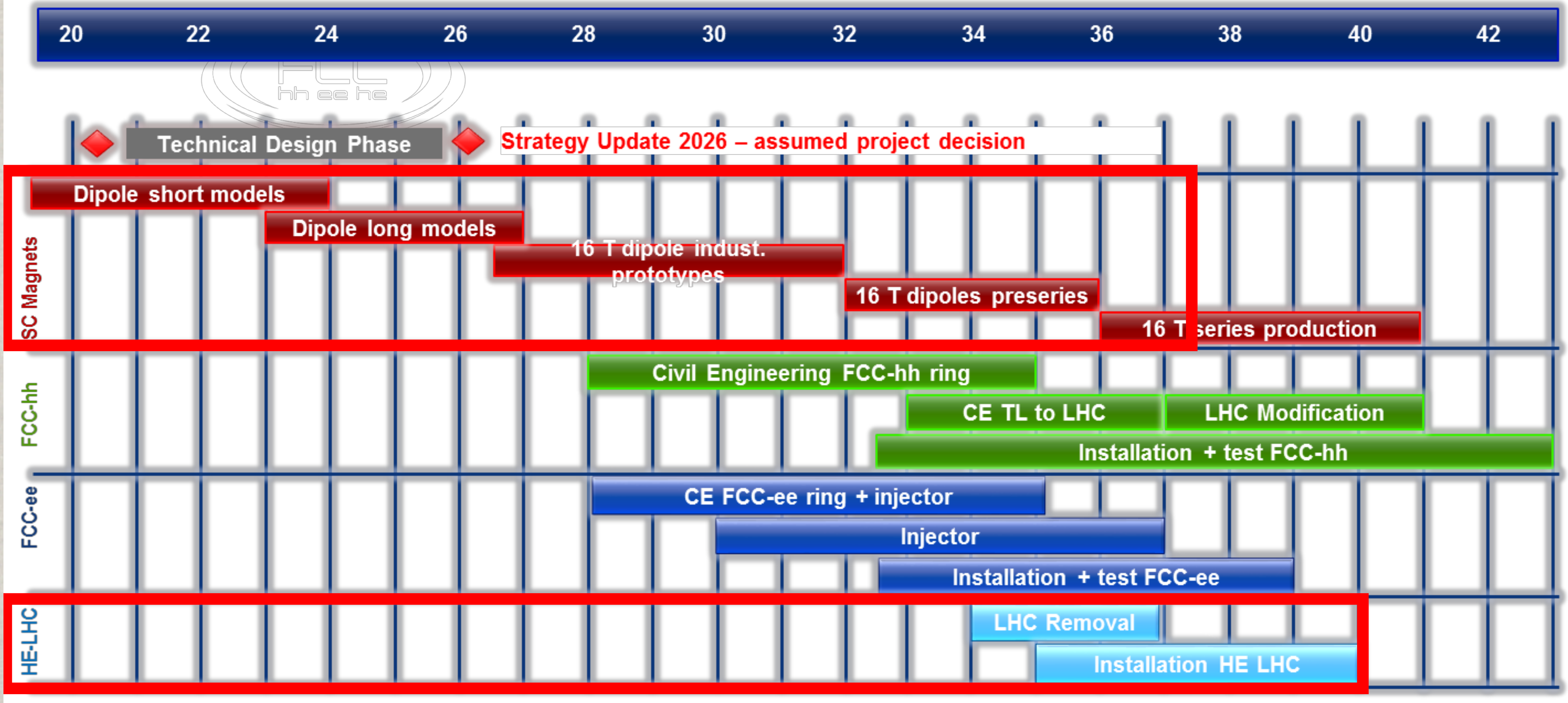
- FCC-hh magnets (curved!) & FCC-hh vacuum system
- HL-LHC crab cavities & electron lenses

beam:

- HL-LHC/LIU parameters (25 ns baseline, also 5 ns option)

Fastest Possible Technical Schedules

M. Benedikt, F. Zimmermann ‘17

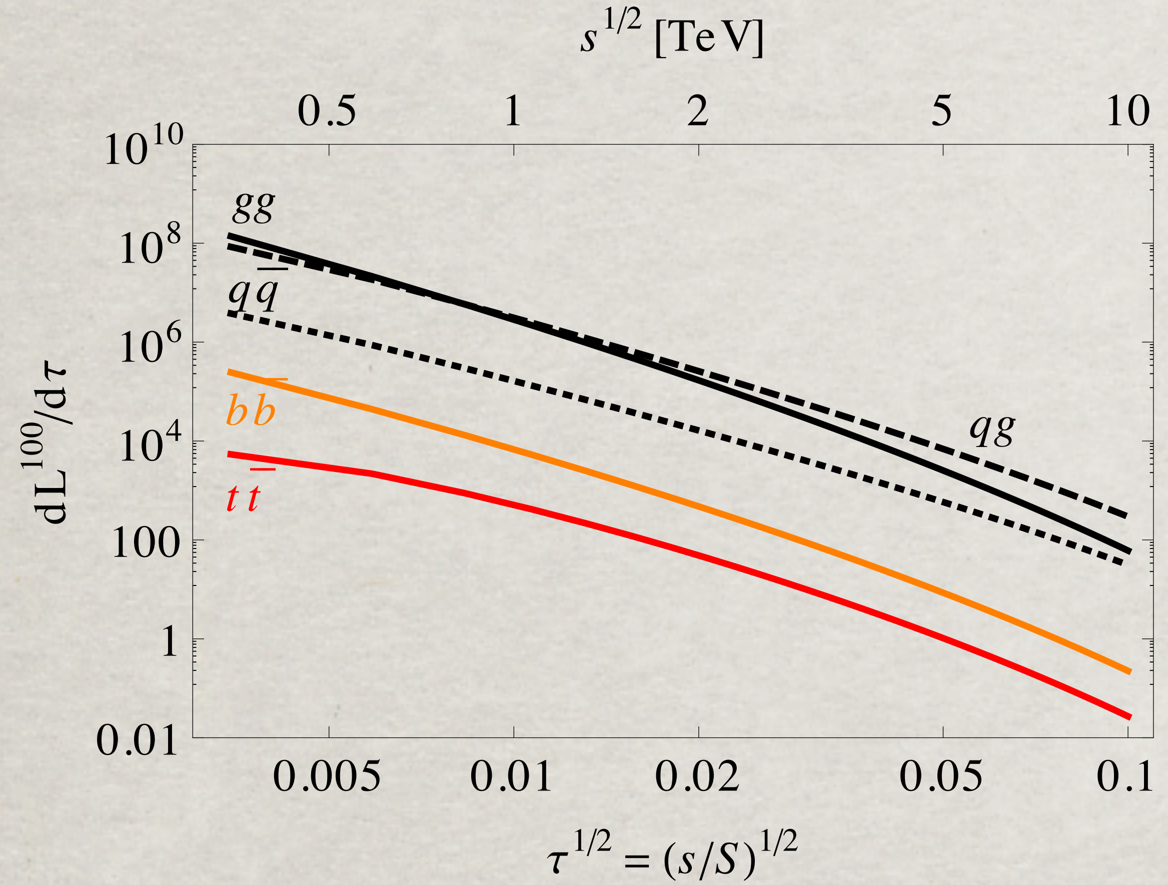


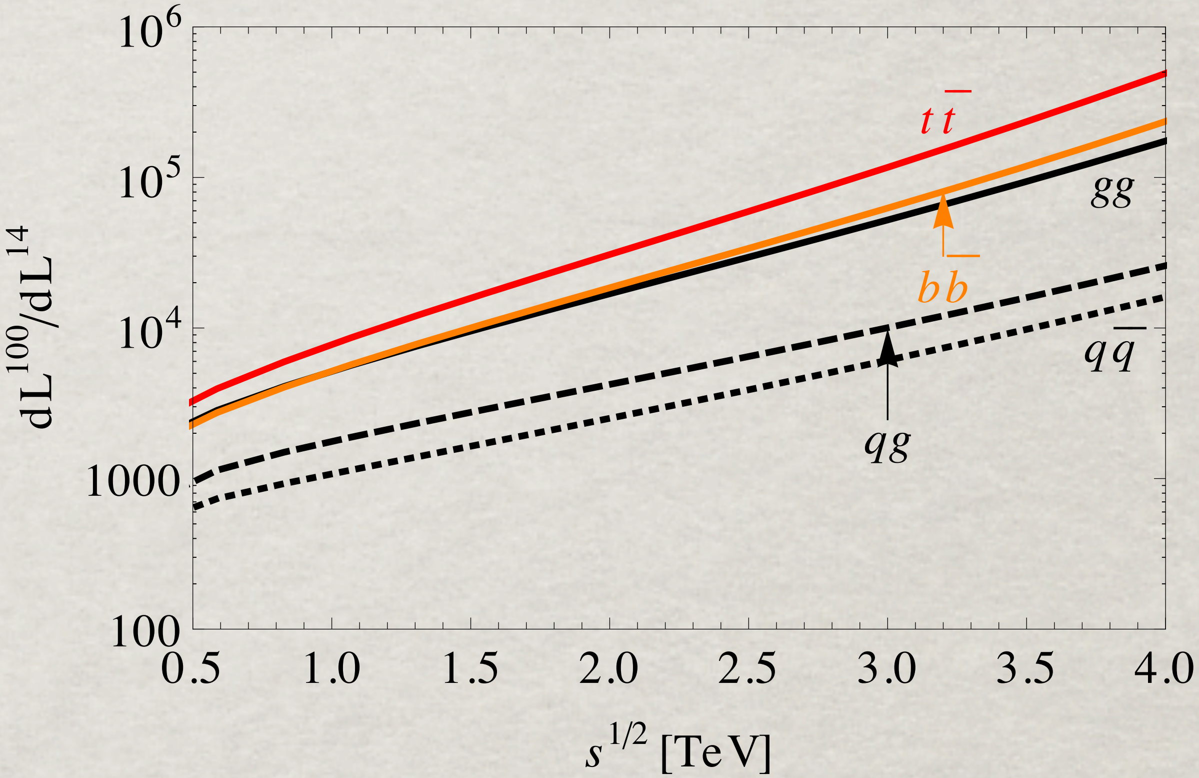
HE-LHC design & construction

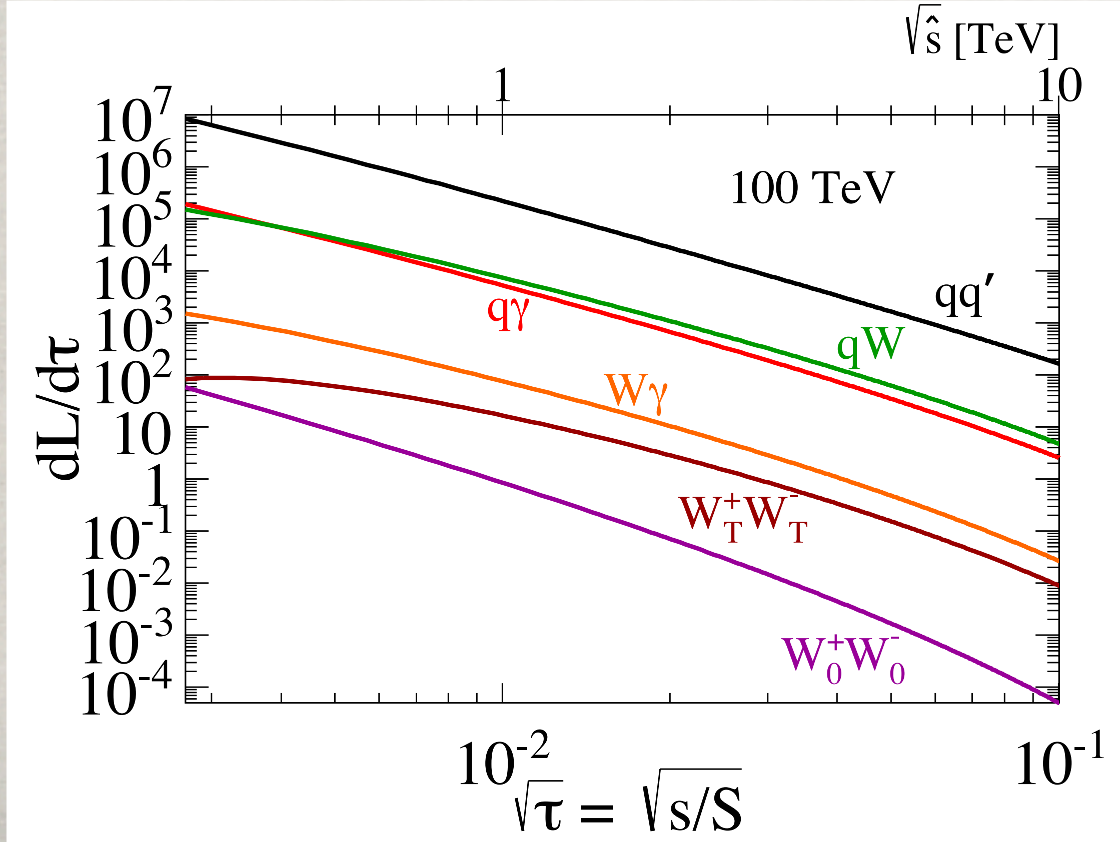
technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

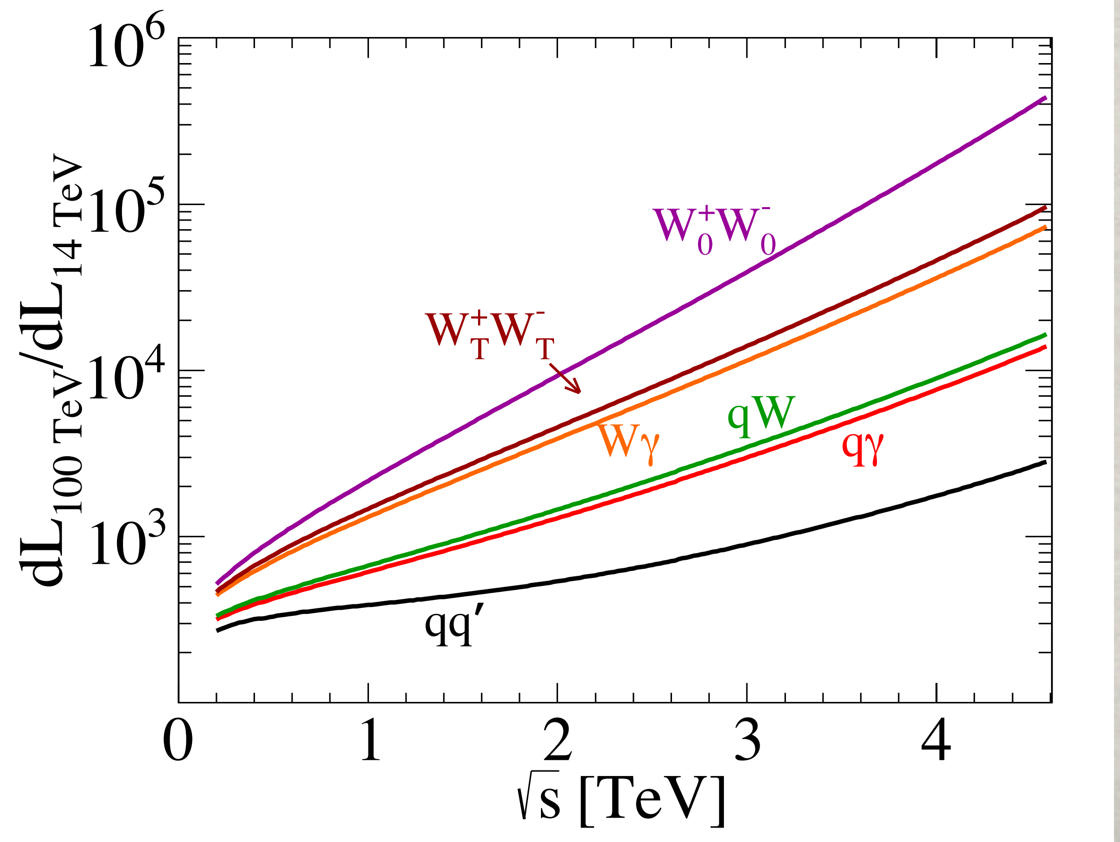
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)
- Options: FCC-ee @ 2039; FCC-hh @ 2043.

The Next Energy Frontier:
100 TeV Hadron Collider

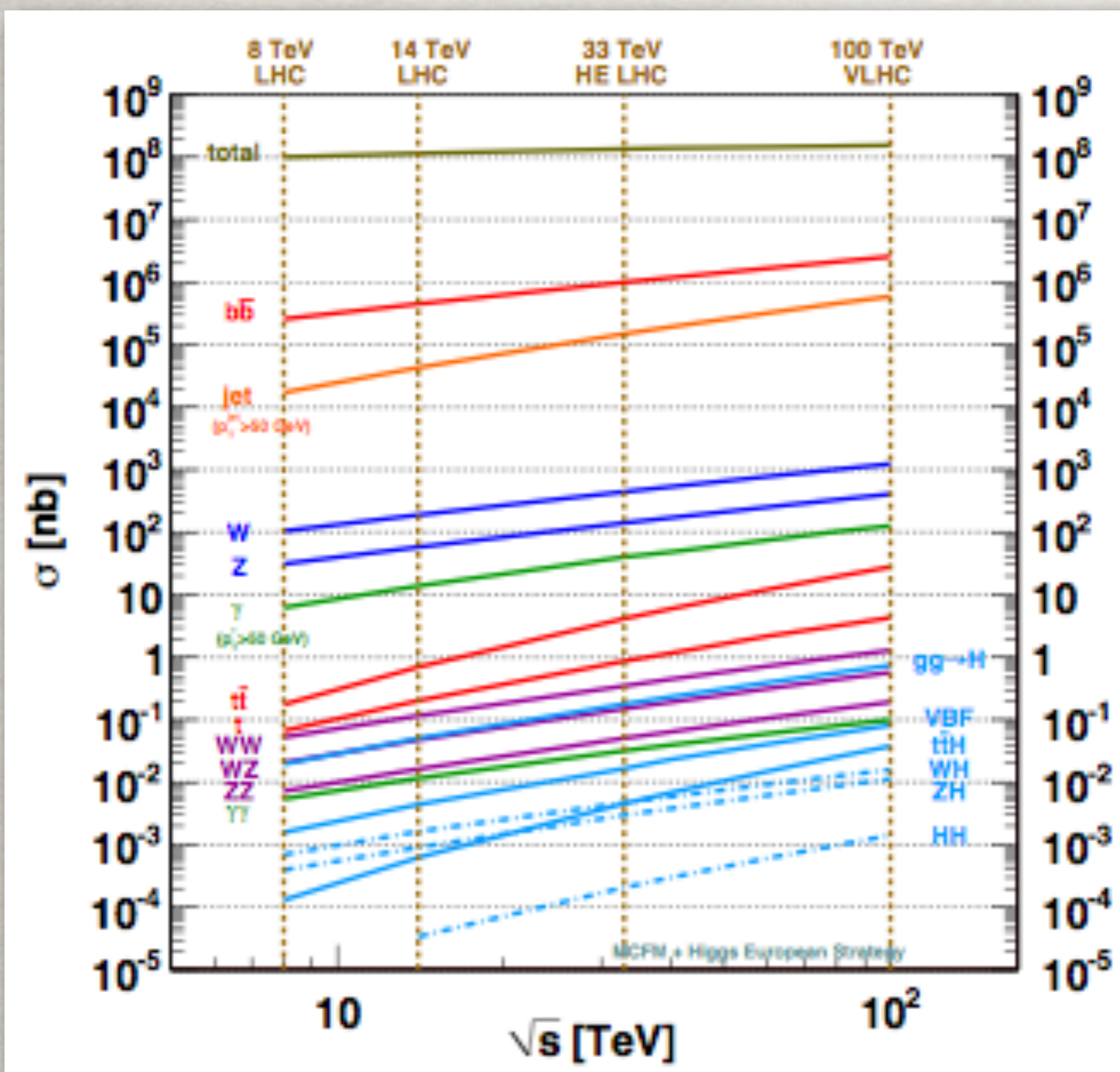




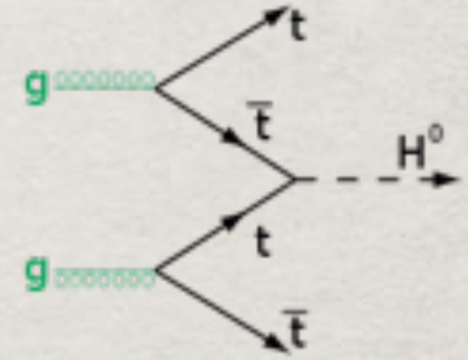


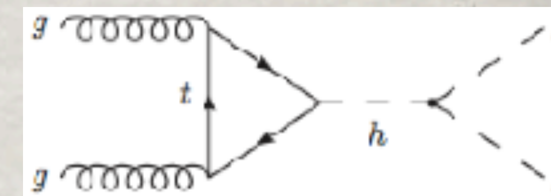


Higgs Production @ SPPC



Snowmass QCD Working Group: 1310.5189





Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10³

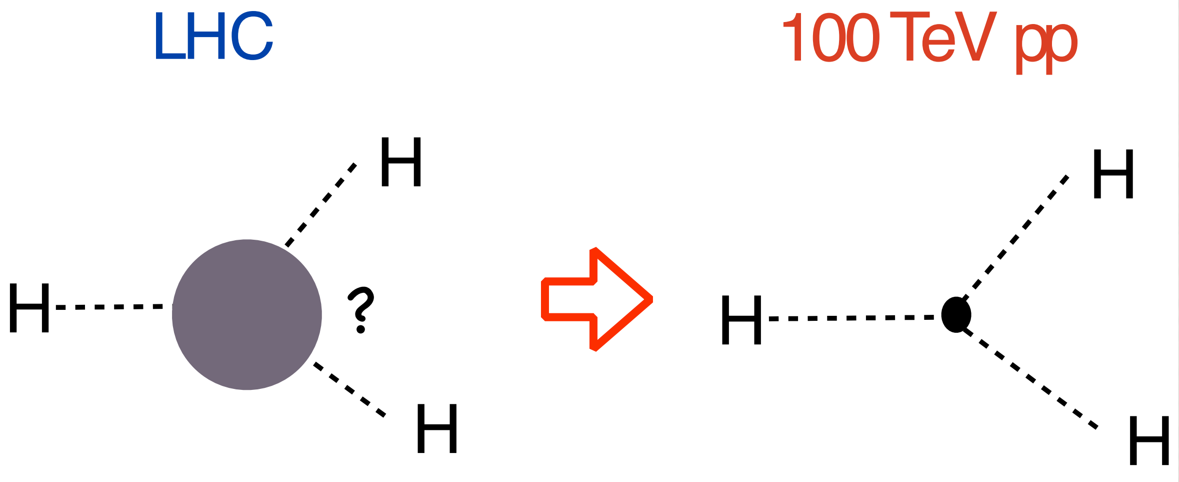
λ_t : 1%

λ : 8%

Higgs Self-couplings:

$$\mathcal{L} = -\frac{1}{2} m_H^2 H^2 - \frac{g_{HHH}}{3!} H^3 - \frac{g_{HHHH}}{4!} H^4$$

$$g_{HHH} = 6 \quad v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6 \quad = \frac{3m_H^2}{v^2}.$$



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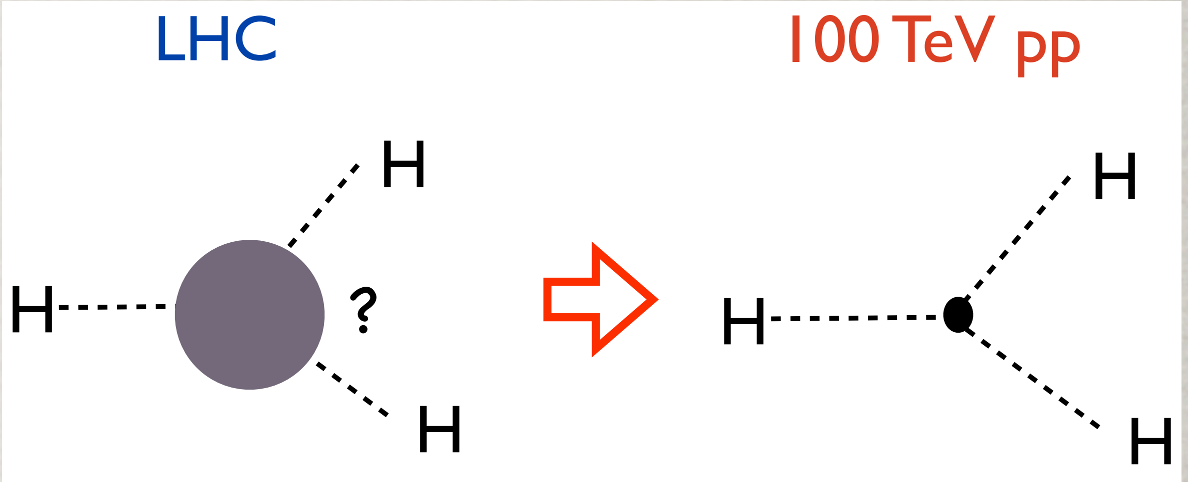


Triple coupling sensitivity:

Test the shape of the Higgs potential, and the fate of the EW-phase transition!

	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/expt	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

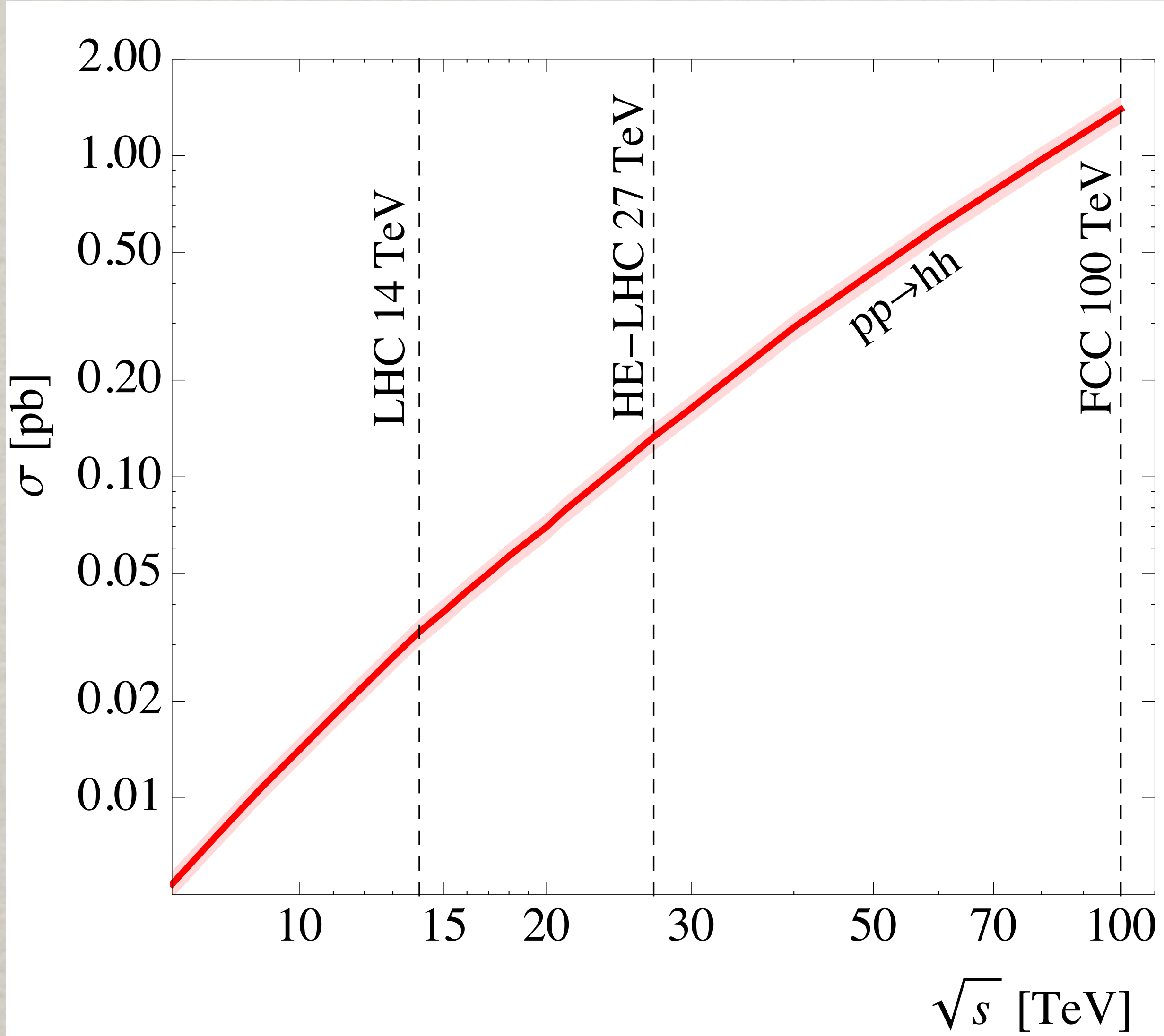
Snowmass 1310.8361

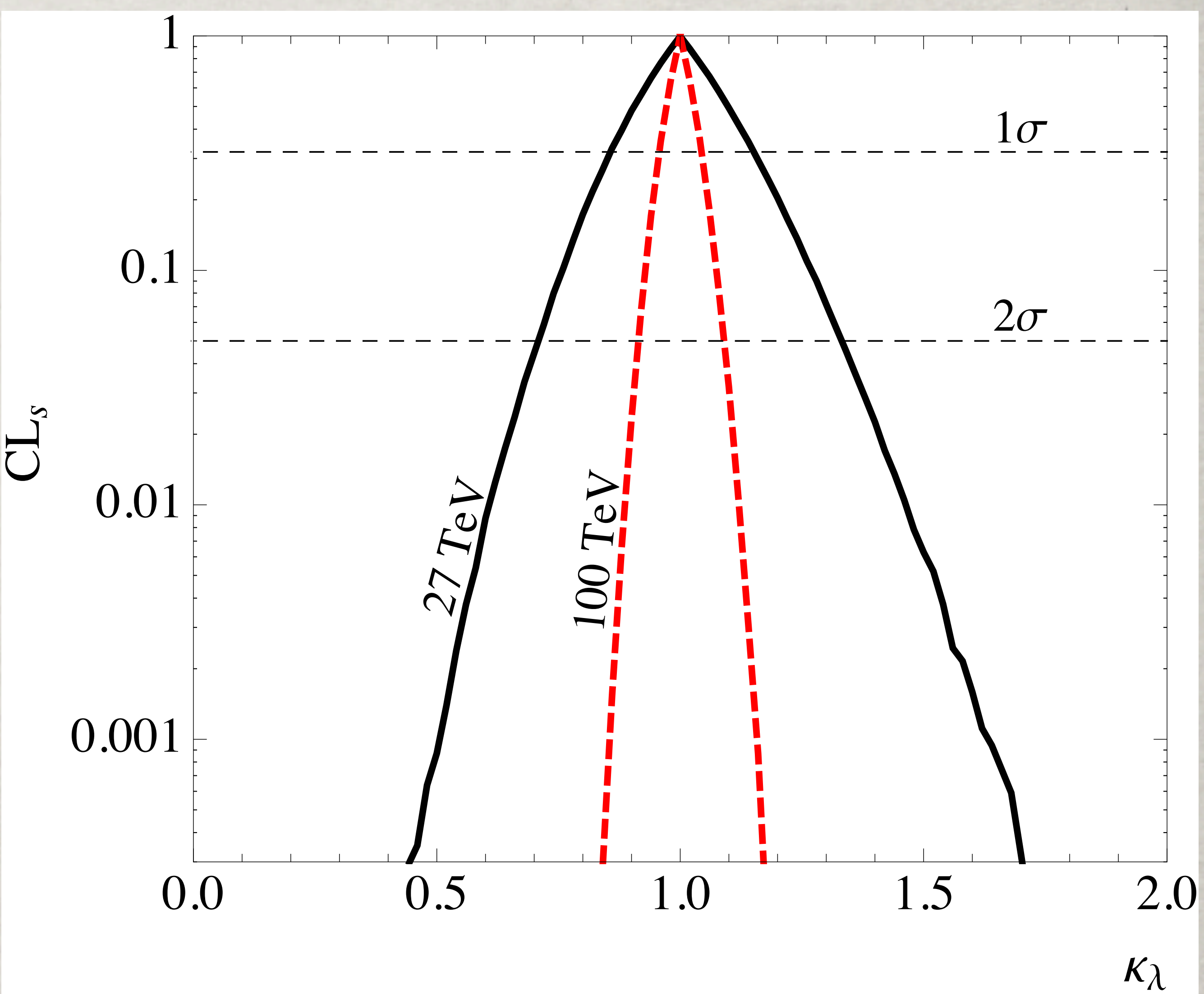
Adequate to test EW phase transition strong 1st order:

→ O(1) deviation on λ_{hhh}

HE-LHC: Higgs self-coupling

D. Goncalves, TH, F. Kling, T. Plehen, M. Takeuchi, arXiv:1802.04319.





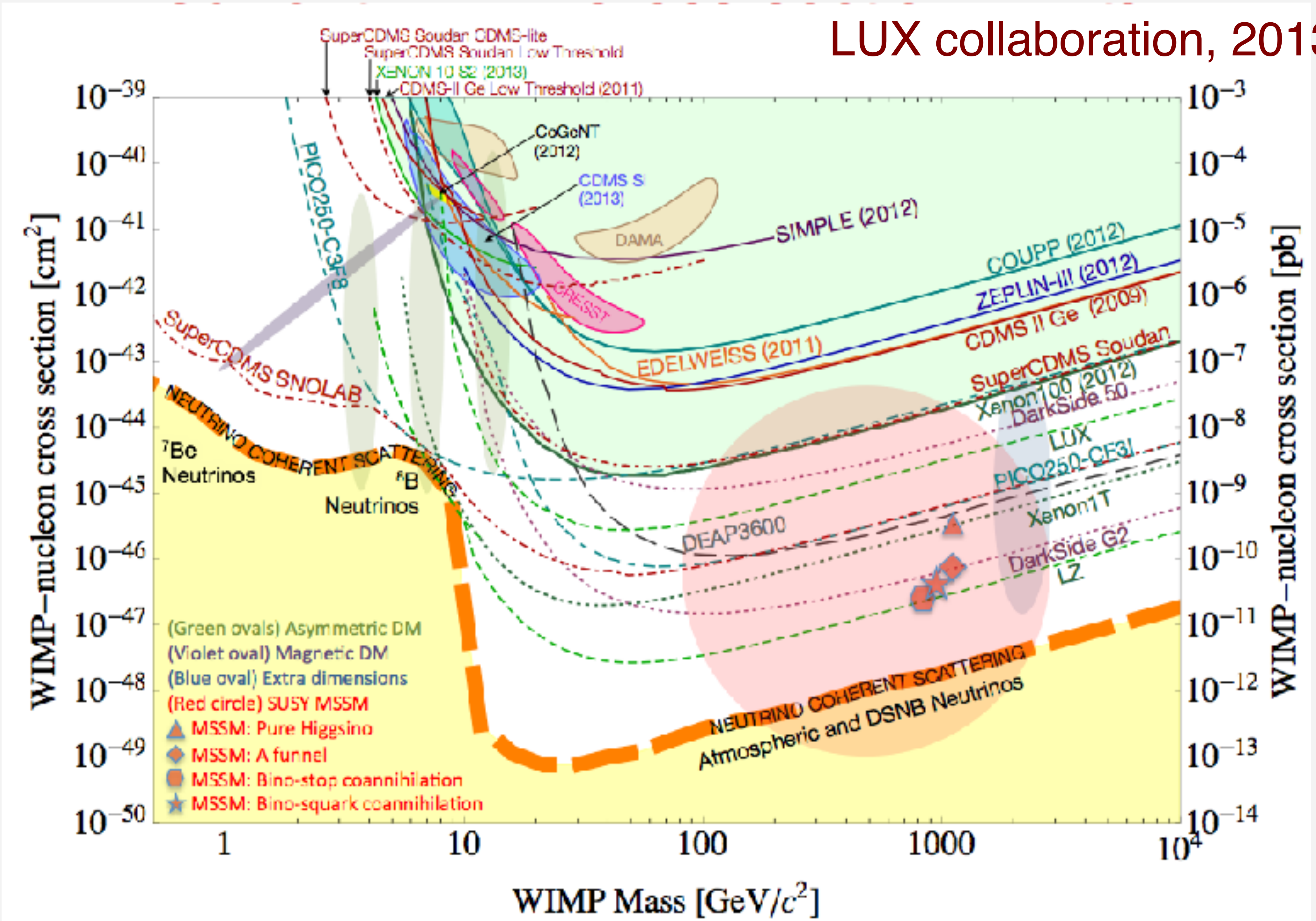
Cross section increases ~3x.

hh → bb ***γγ***: **δλ** ~ 30% @ 2**σ**

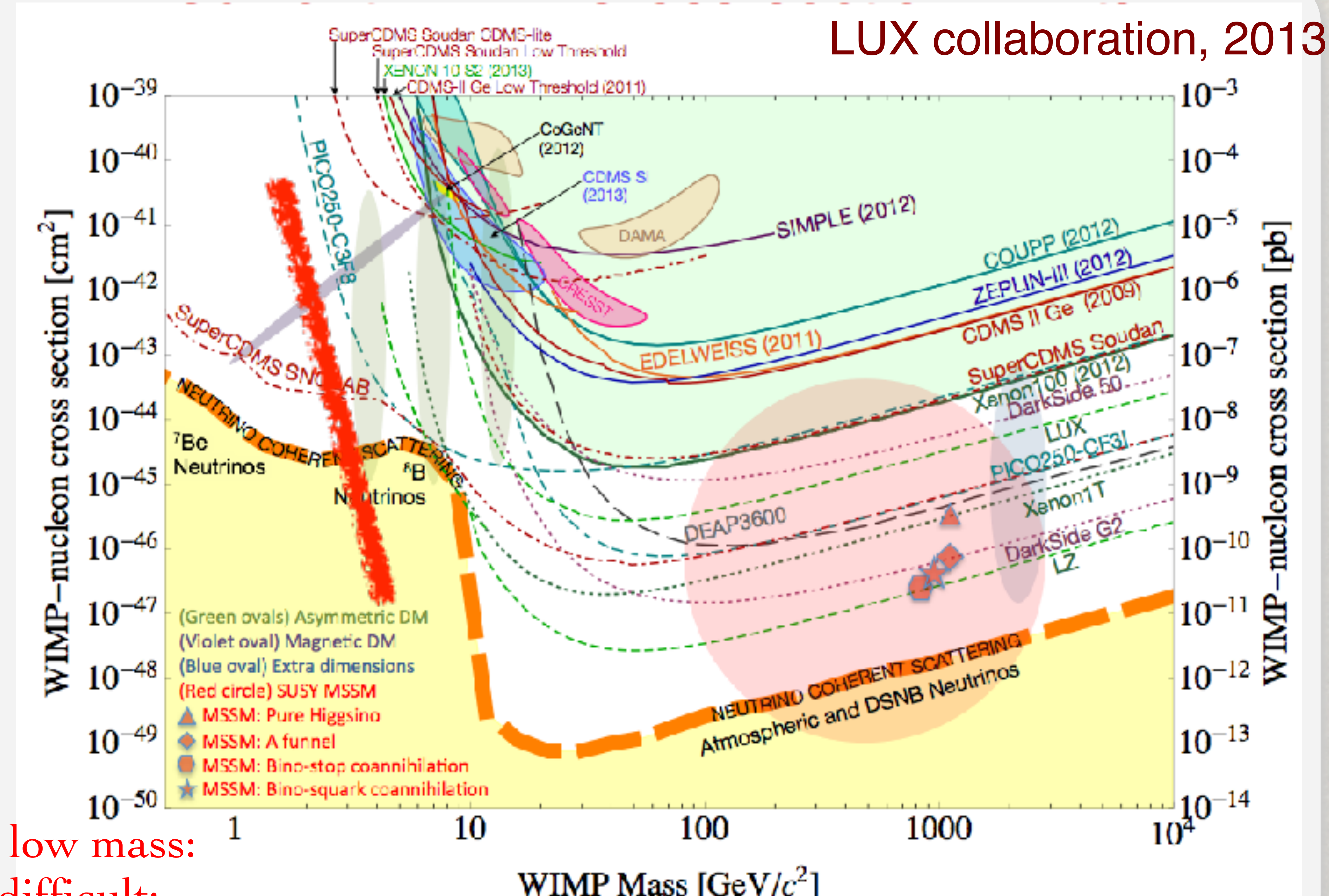
Also, S. Homiller, P. Meade, this workshop.

DM Searches

LUX collaboration, 2013

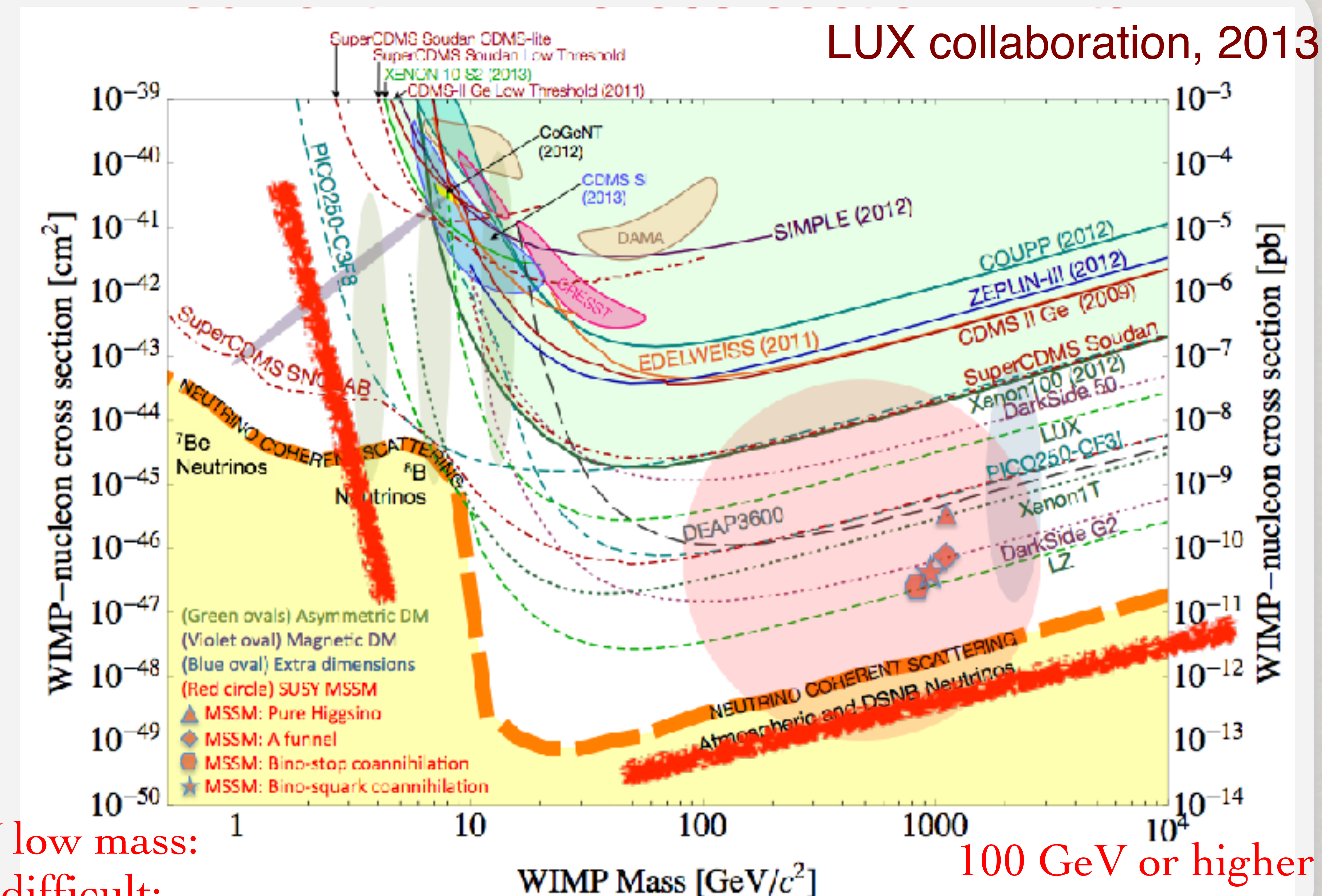


DM Searches



GeV low mass:
DD difficult;
Collider complementary

DM Searches

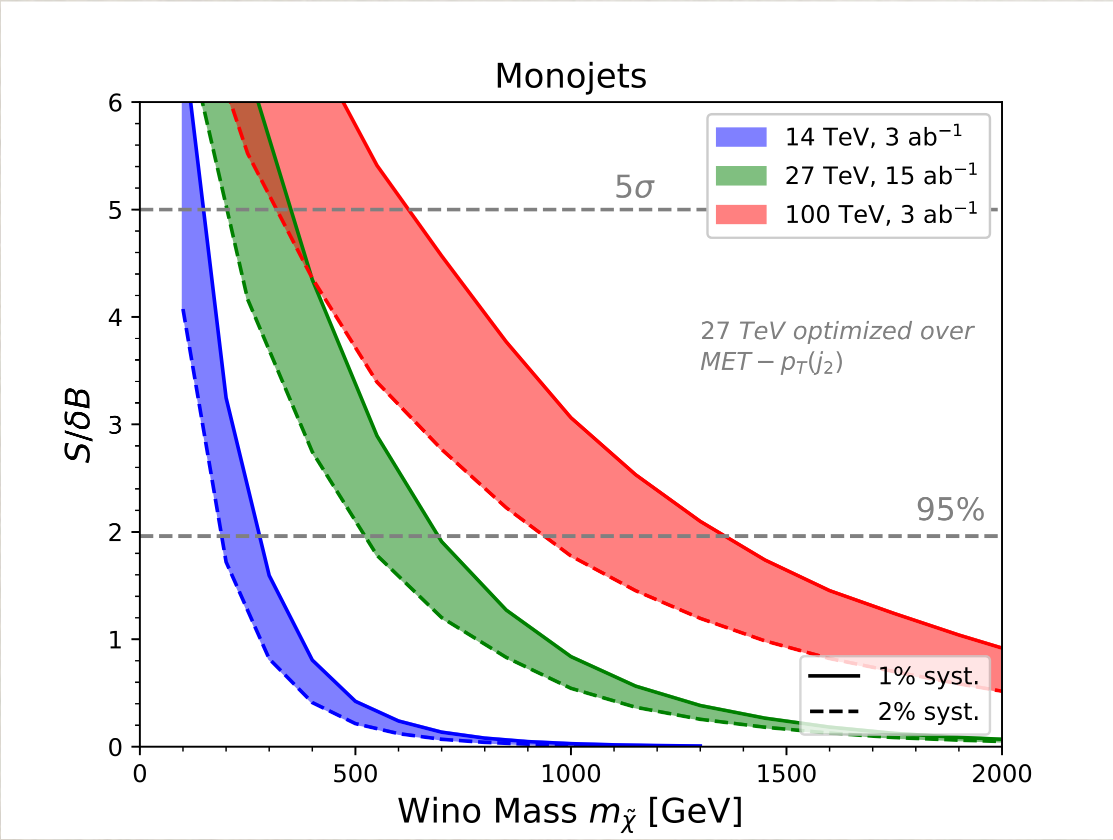


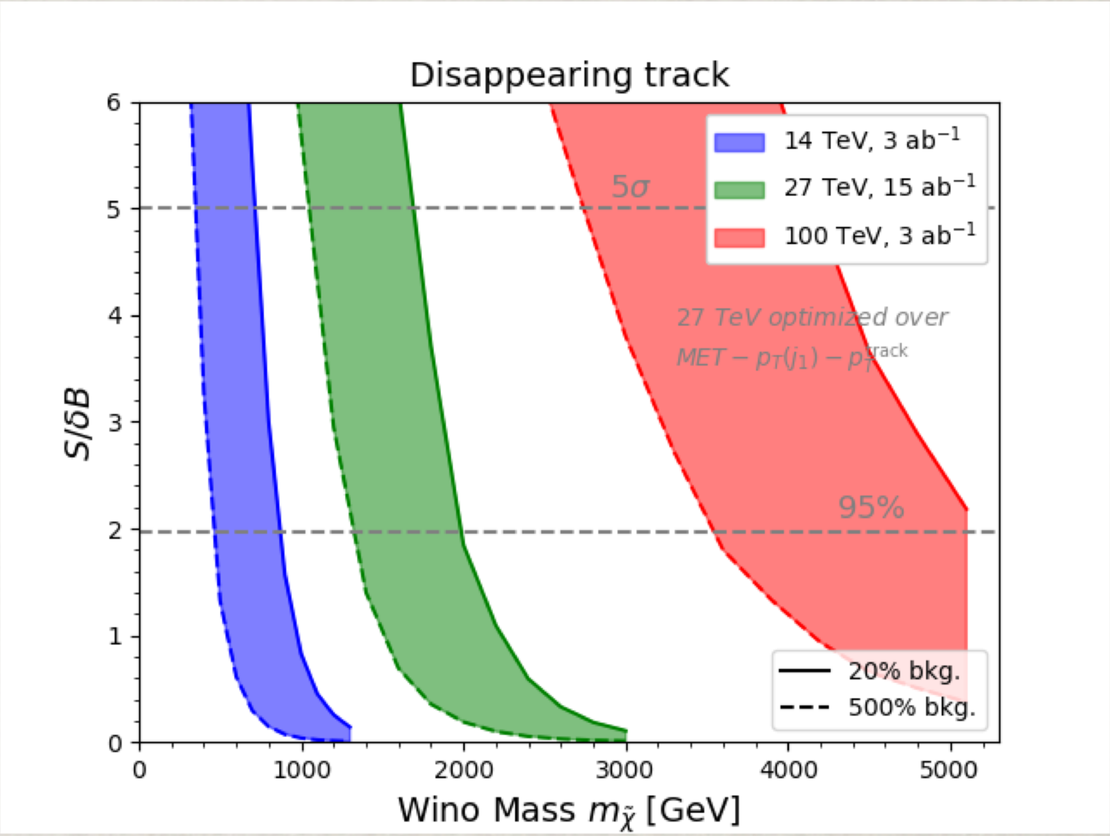
GeV low mass:
DD difficult;
Collider complementary

100 GeV or higher mass:
DD + ID + HE Collider

HE-LHC: WIMP Dark Matter

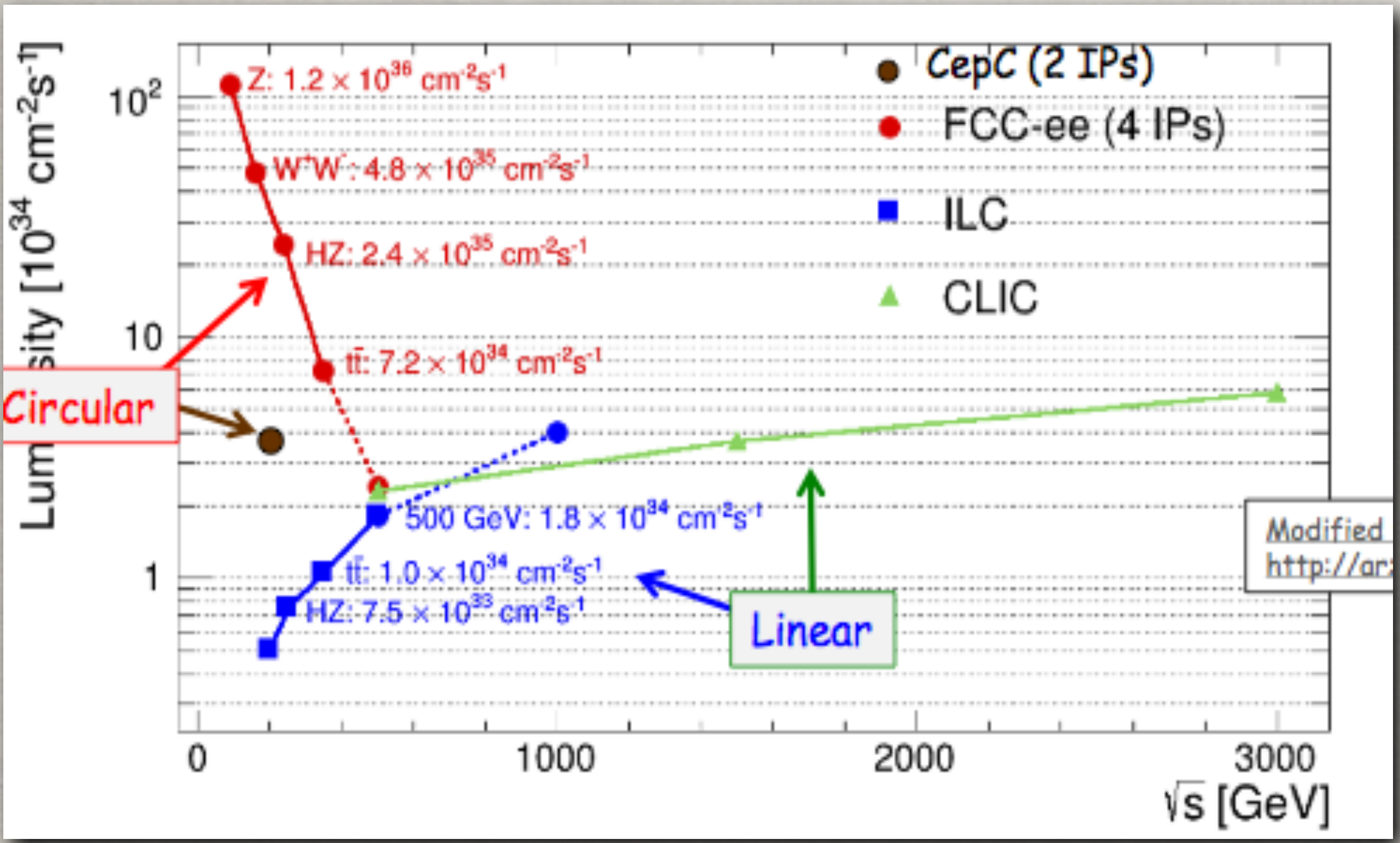
TH, S. Mukhopadhyay, X. Wang, this workshop;
M. Low, D. Egana-Ugrinovic, J. Ruderman, L.-T. Wang, to appear.





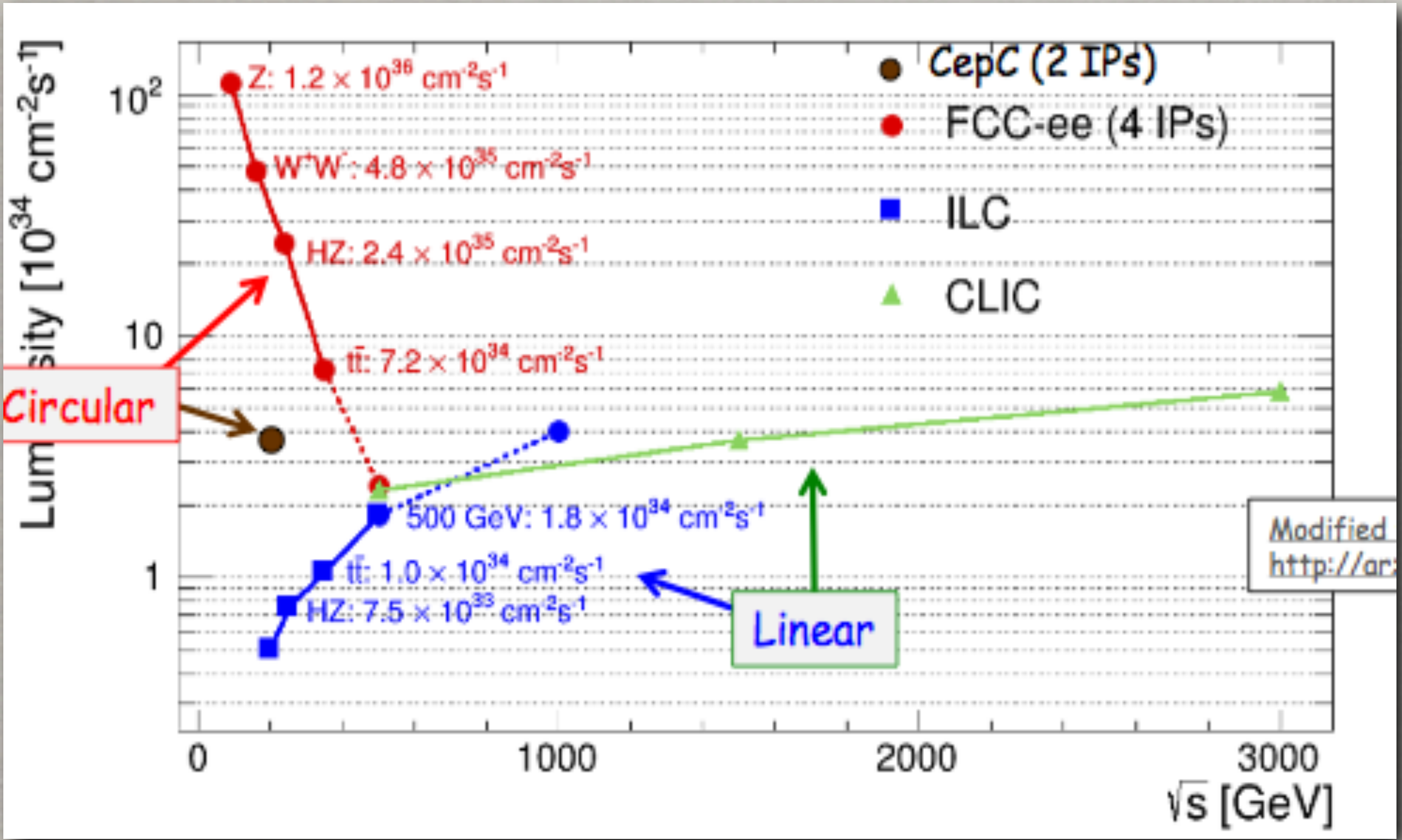
	2**σ**@HL-LHC →	HE-LHC →	FCC
Wino monojet:	300 GeV	700 GeV	1400 GeV
Wino disappearing track:	800 GeV	2000 GeV	5000 GeV
Higgsino monojet:	200 GeV	500 GeV	900 GeV
Higgsino disappearing track:	250 GeV	500 GeV	1100 GeV

e+e- colliders: Energy/Lumi projection



TLEP Report: 1308.6176

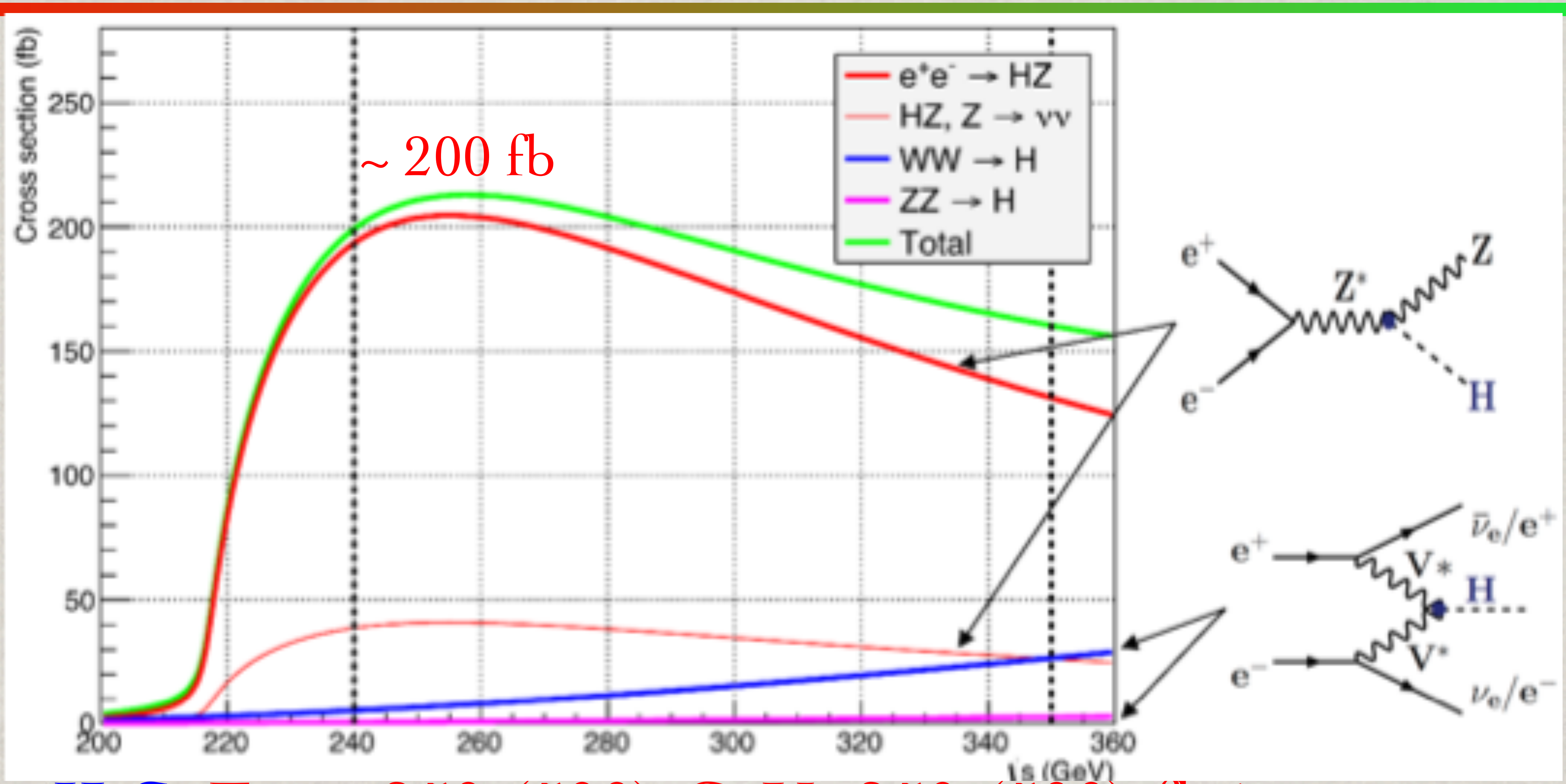
e^+e^- colliders: Energy/Lumi projection



TLEP Report: 1308.6176

E_{cm}	running time	statistics (FCC-ee)
	b,c,τ	10^{11} b,c,τ
90 GeV	1-2 yrs	10^{12} Z (Tera Z)
160 GeV	1-2 yrs	10^{8}- 10^{9} WW(Oku W)
240 GeV	4-5 yrs	$2x10^{6}$ ZH (Mega H)
350 GeV	4-5 yrs	10^{6} tt (Mega top)

Higgs-Factory: Mega (10^6) Higgs Physics



ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

- Model-independent measurement: ILC Report: 1308.6176

$\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV

(HL-LHC: assume SM, $\Gamma_H \sim 5\text{-}8\%$, $\Delta m_H \sim 50$ MeV)

- TLEP 10^6 Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

TLEP Report: 1308.6176

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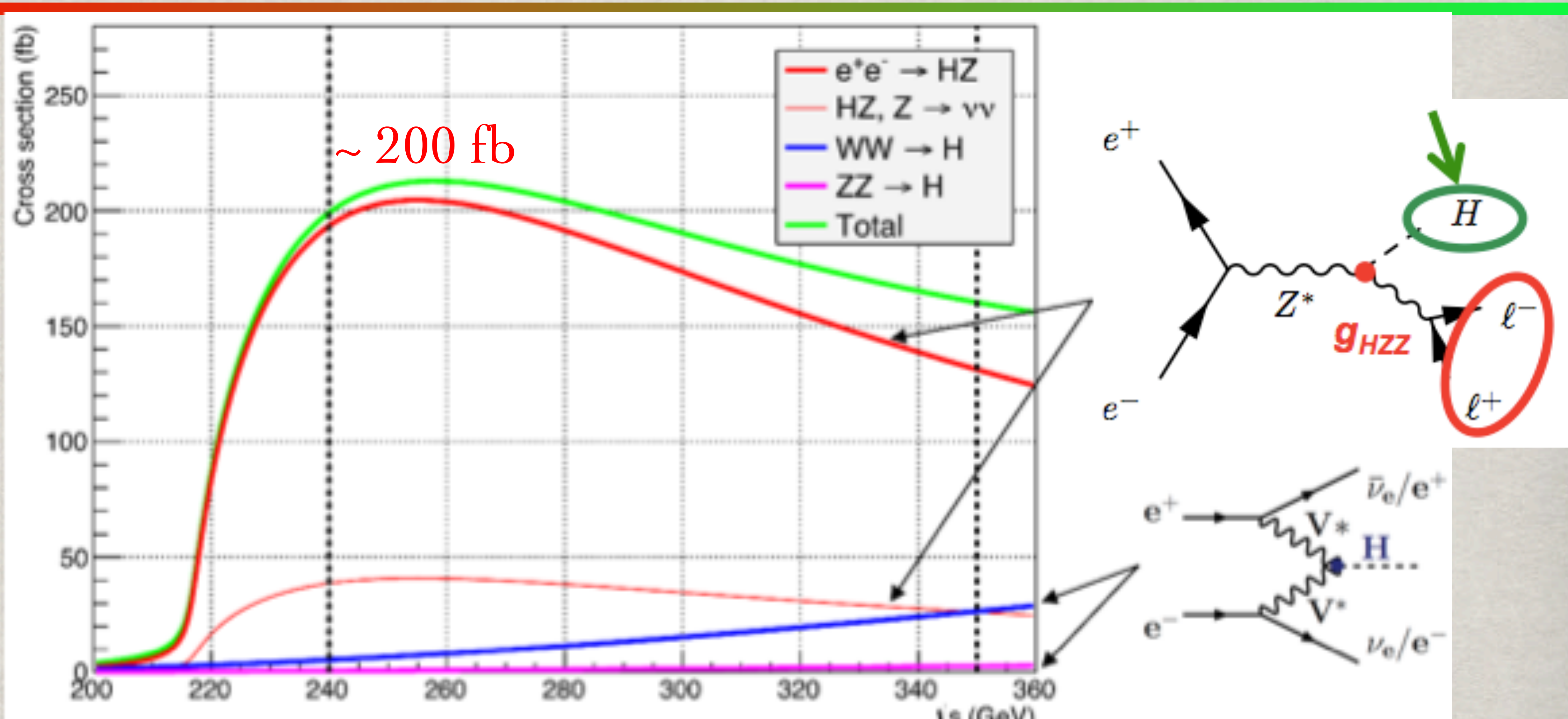

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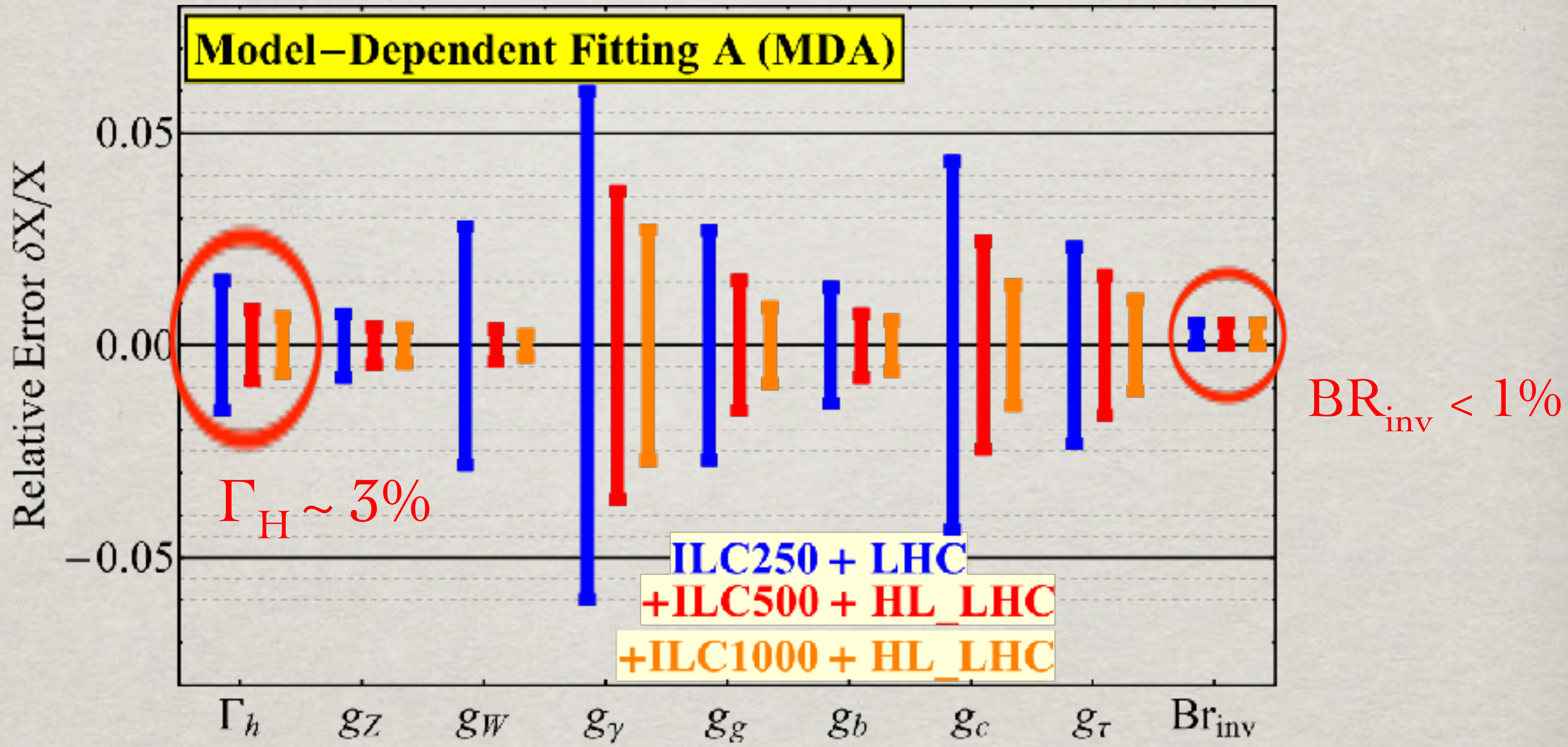
TLEP Report: 1308.6176

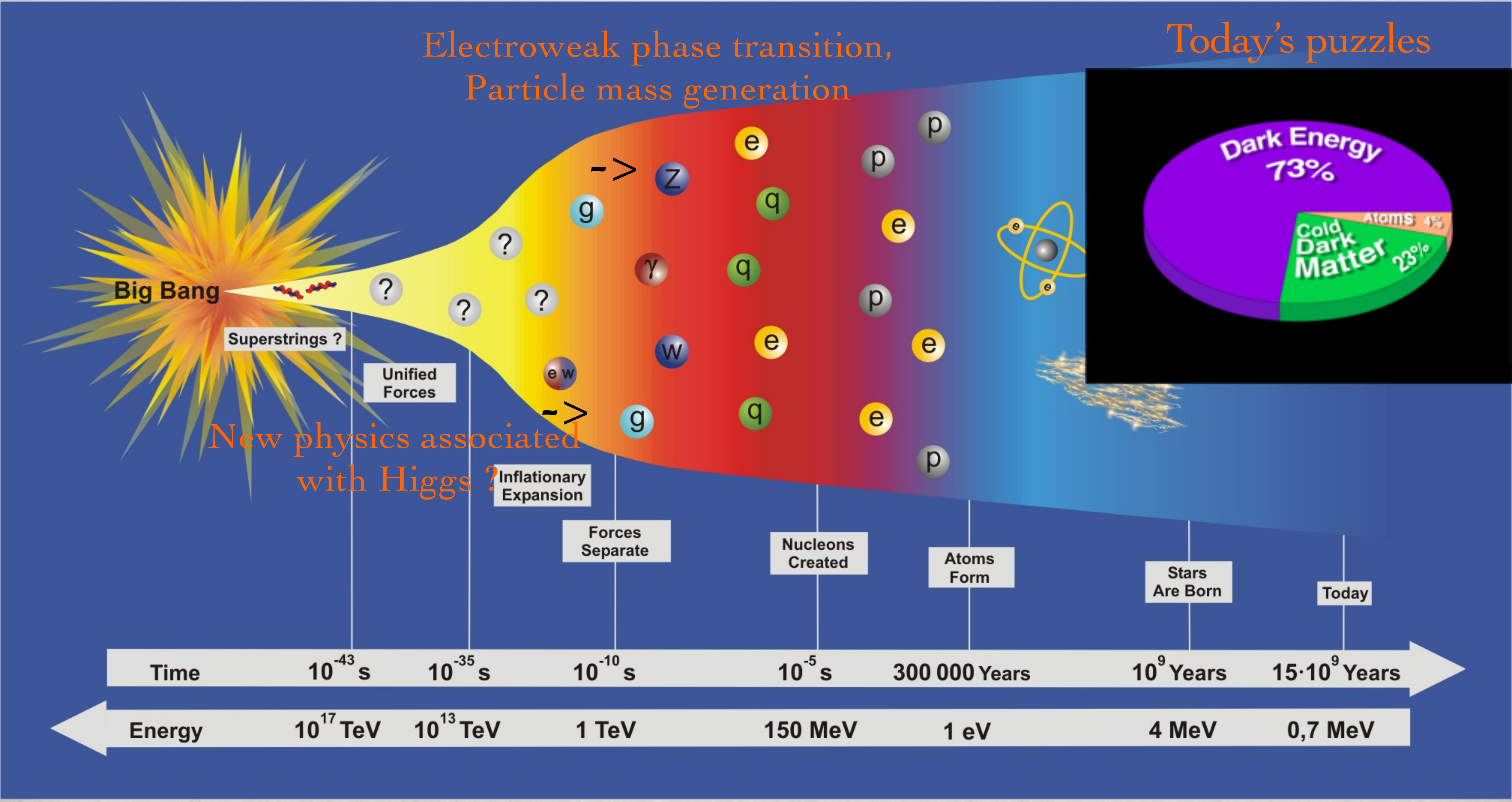
Higgs Total Width & Invisibale BR:

TH, Z.Liu, J.Sayre, arXiv:1311.7155



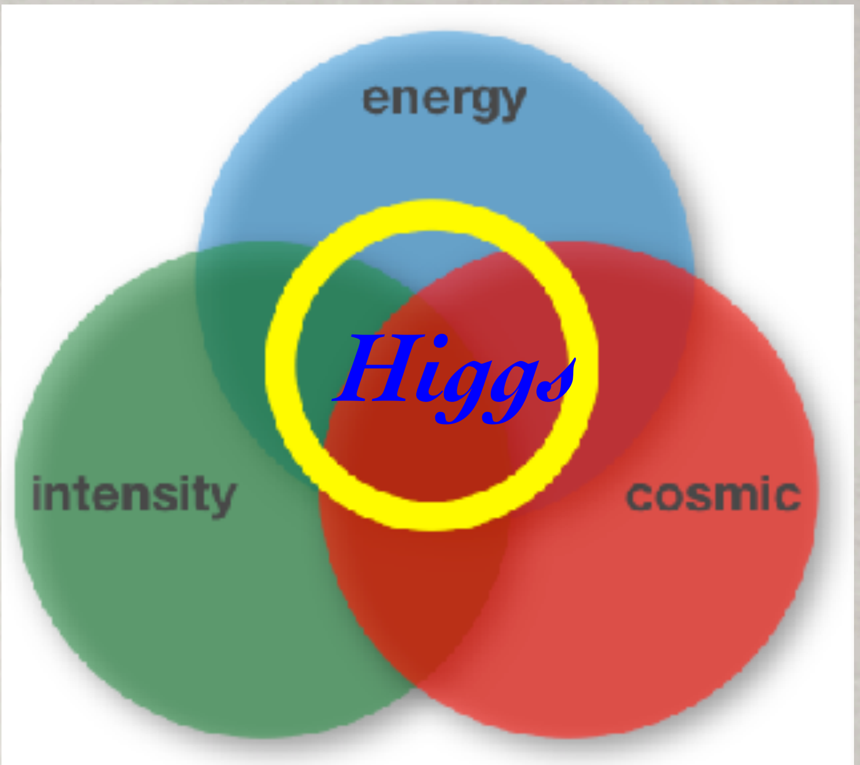
Also see, Peskin, arXiv:1312.4974
including ILC luminosity upgrade.

A Grand Picture:



Summary:

- The Higgs boson is a new class, at a pivotal point of energy, intensity, cosmic frontiers.



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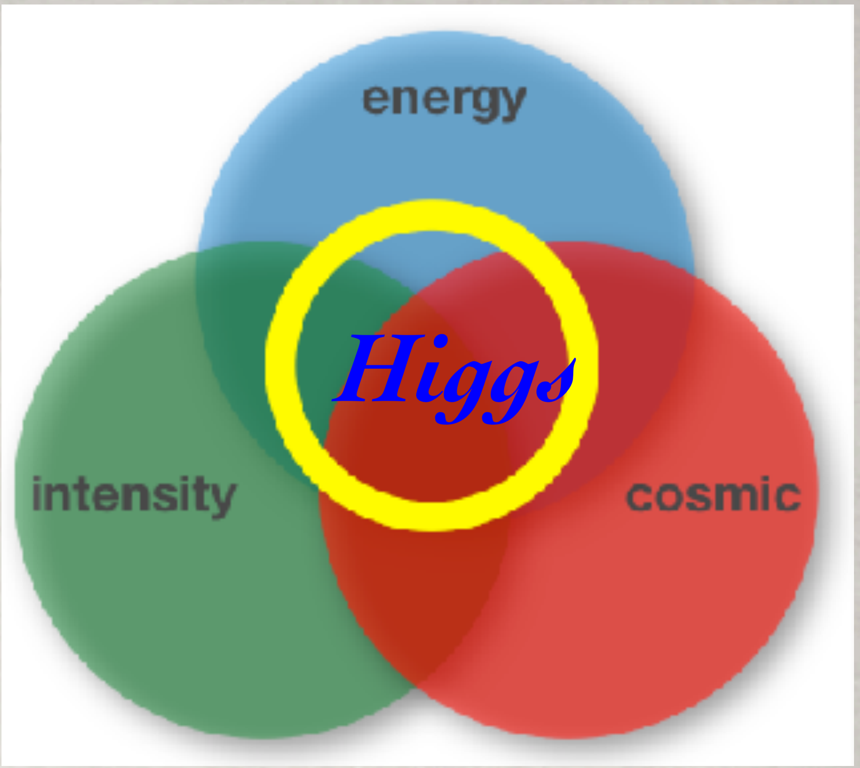

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"Naturally speaking":

- It should not be a lonely solitary particle; has an

"interactive friend circle": $t,\ W^{\pm},\ Z$

"relatives": $\tilde{H}^{0,\pm},\ \tilde{t},\ \tilde{b},\ (\tilde{g});\ S,\ \tilde{S}...$

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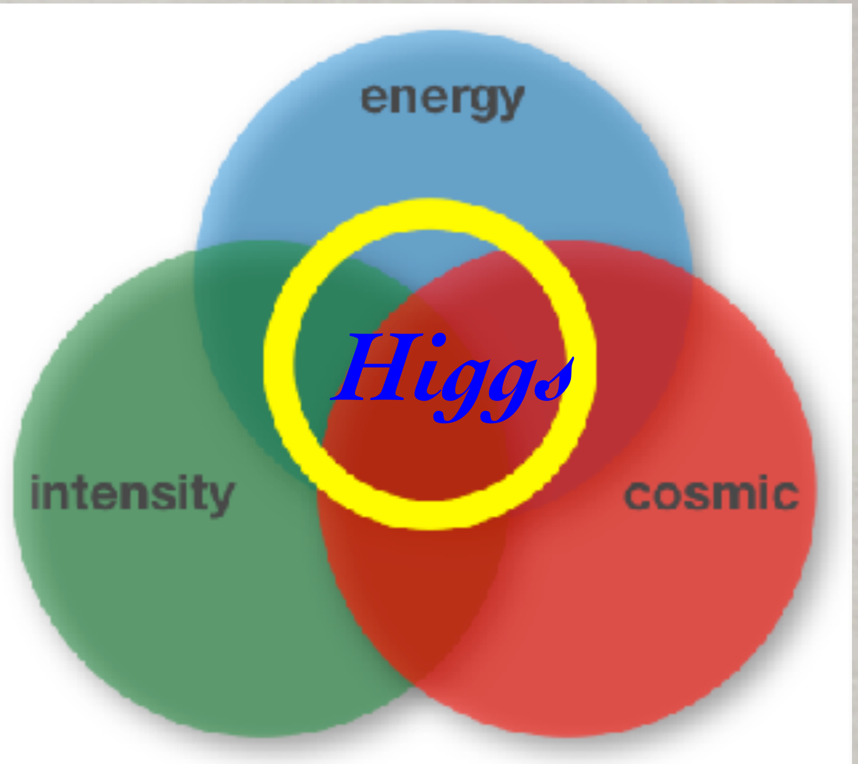

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  LHC lights the way: g~10%; λ_{HHH} ~ 50%; $Br_{inv.}$~ 20%

  CEPC/SppC: g~1%; λ_{HHH} < 10%; $Br_{inv.}$ ~ 2%; Γ_{tot} < 6%

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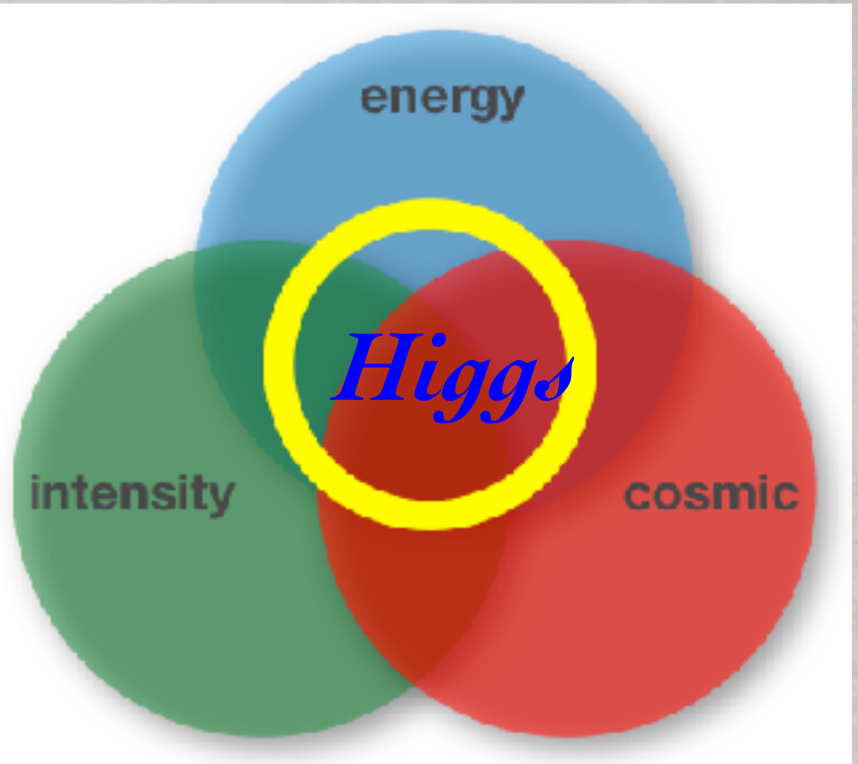

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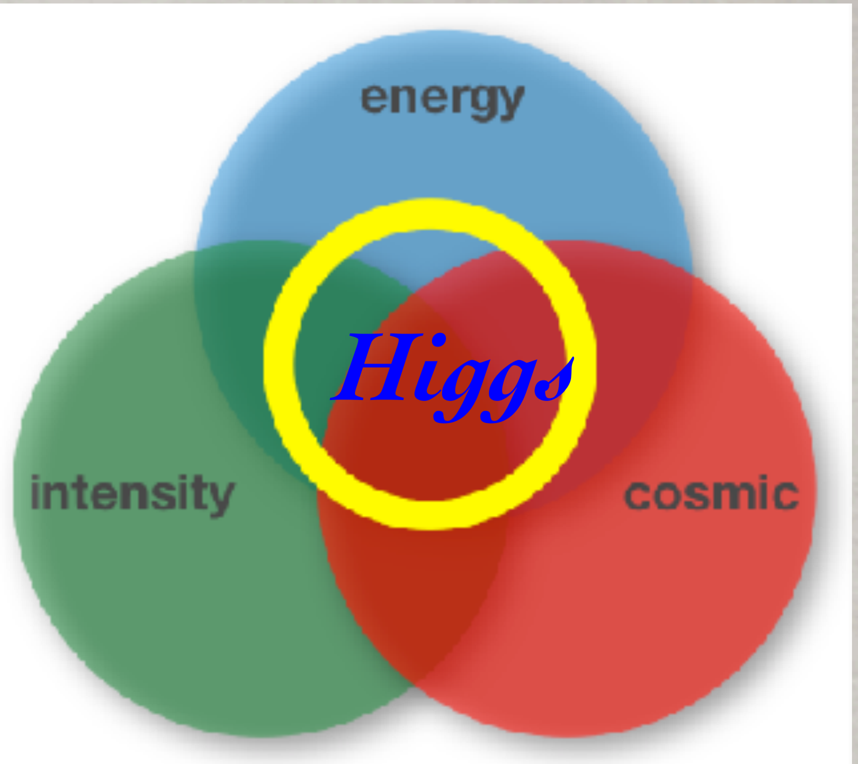

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An exciting journey ahead!

- Precision Higgs physics:
  LHC lights the way: g~10%; λ_{HHH} ~ 50%; $Br_{inv.}$ ~ 20%
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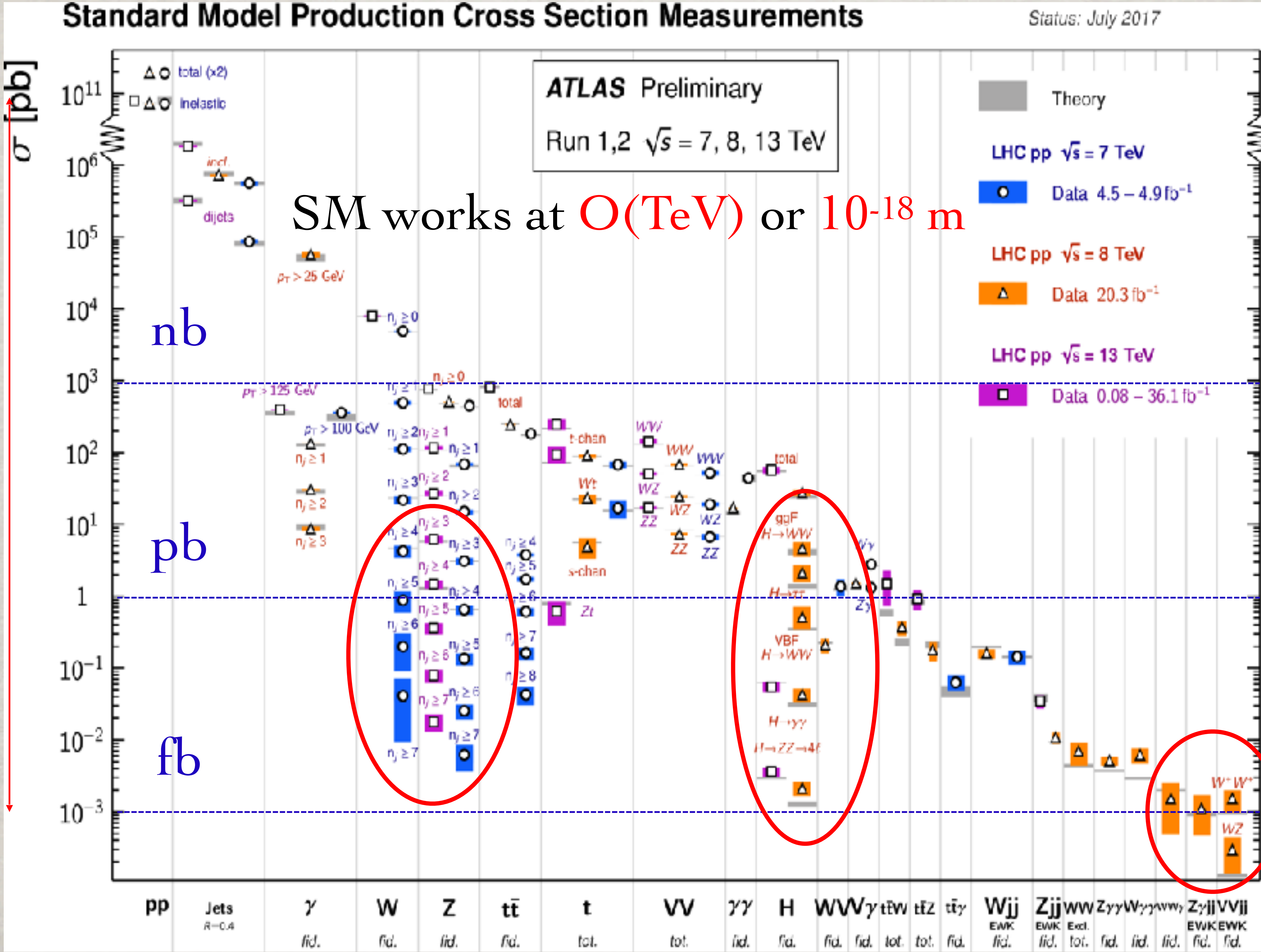
  WIPM DM mass ~ 1 – 5 TeV

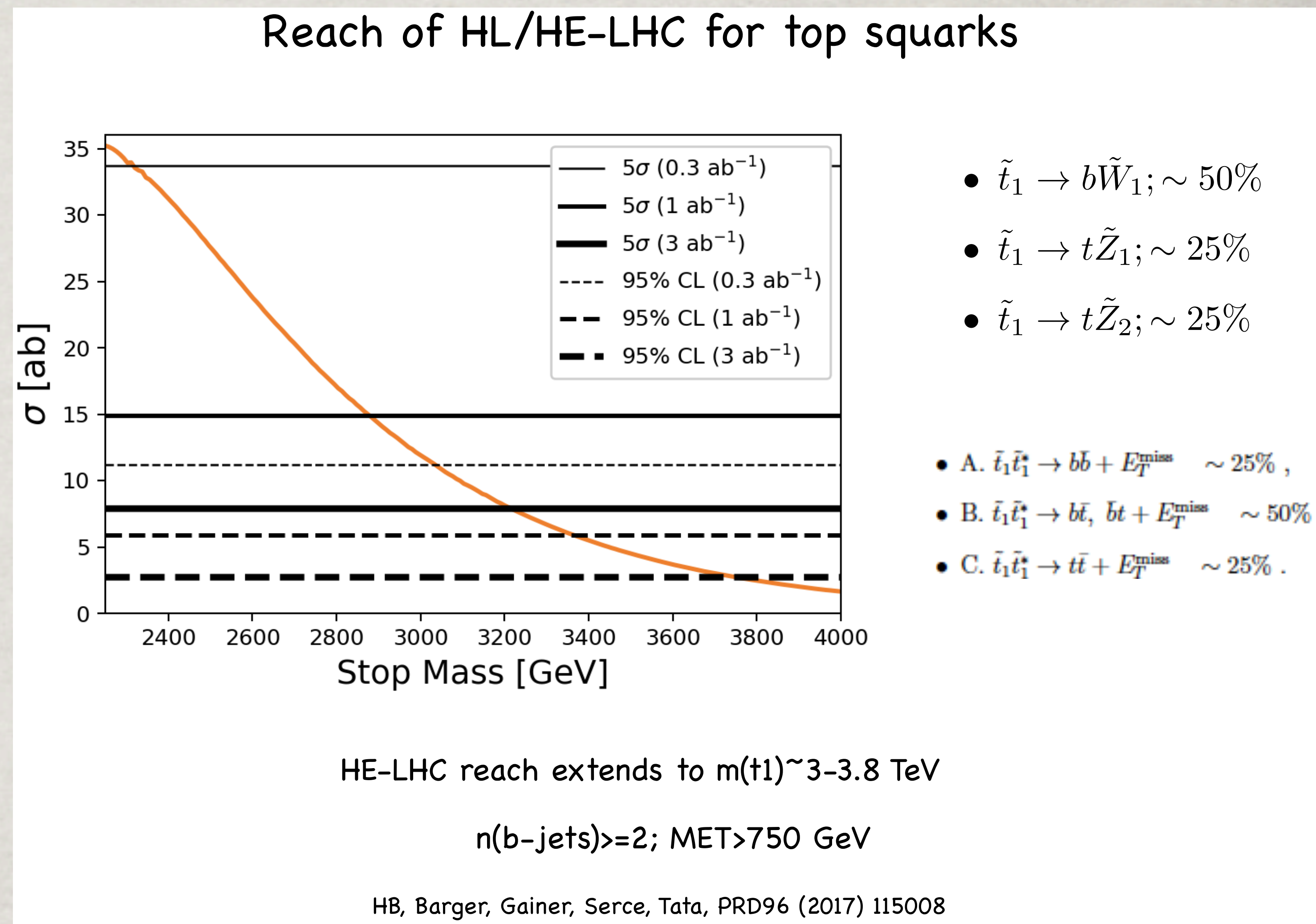
LHC Rocks!



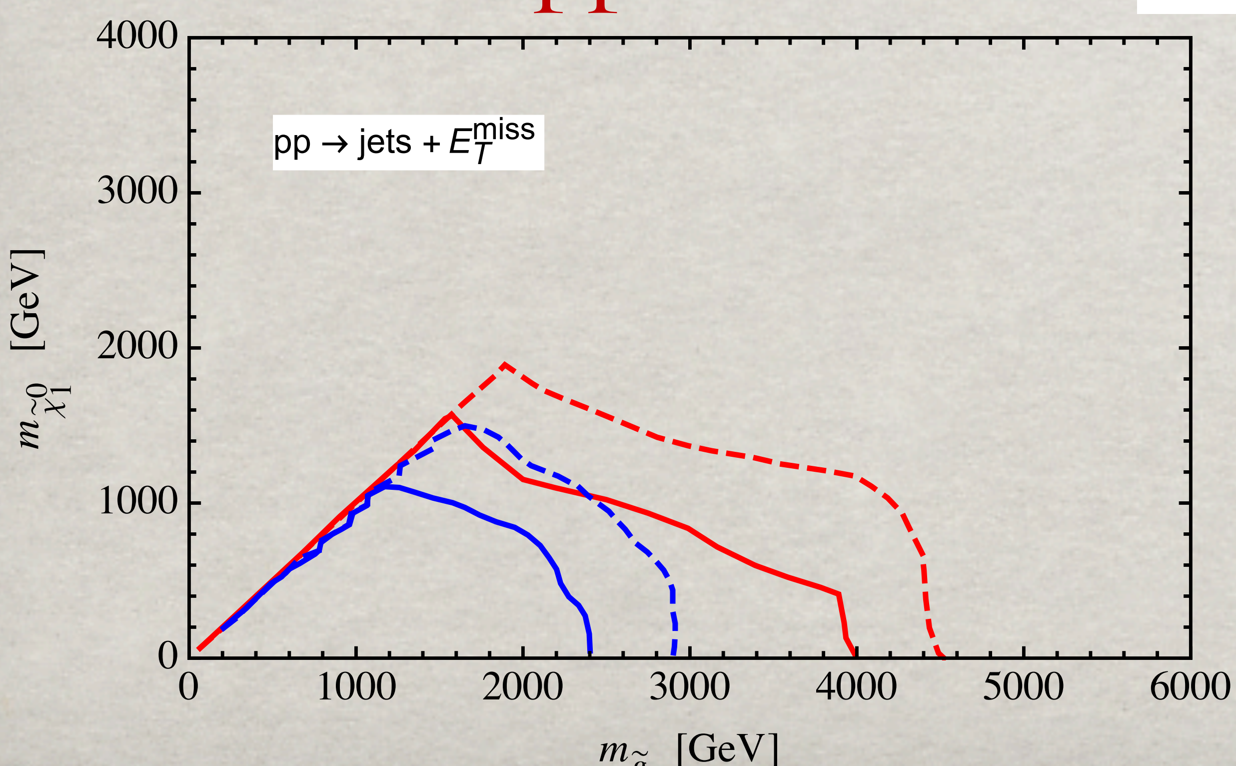
O(14)

HE-LHC: Extended SUSY Reach:

H. Baer, this workshop.



A recent update:
TH, A. Ismail, B. Haghi,
to appear.



27 TeV, 15000 fb^{-1}, exclusion %95 CL

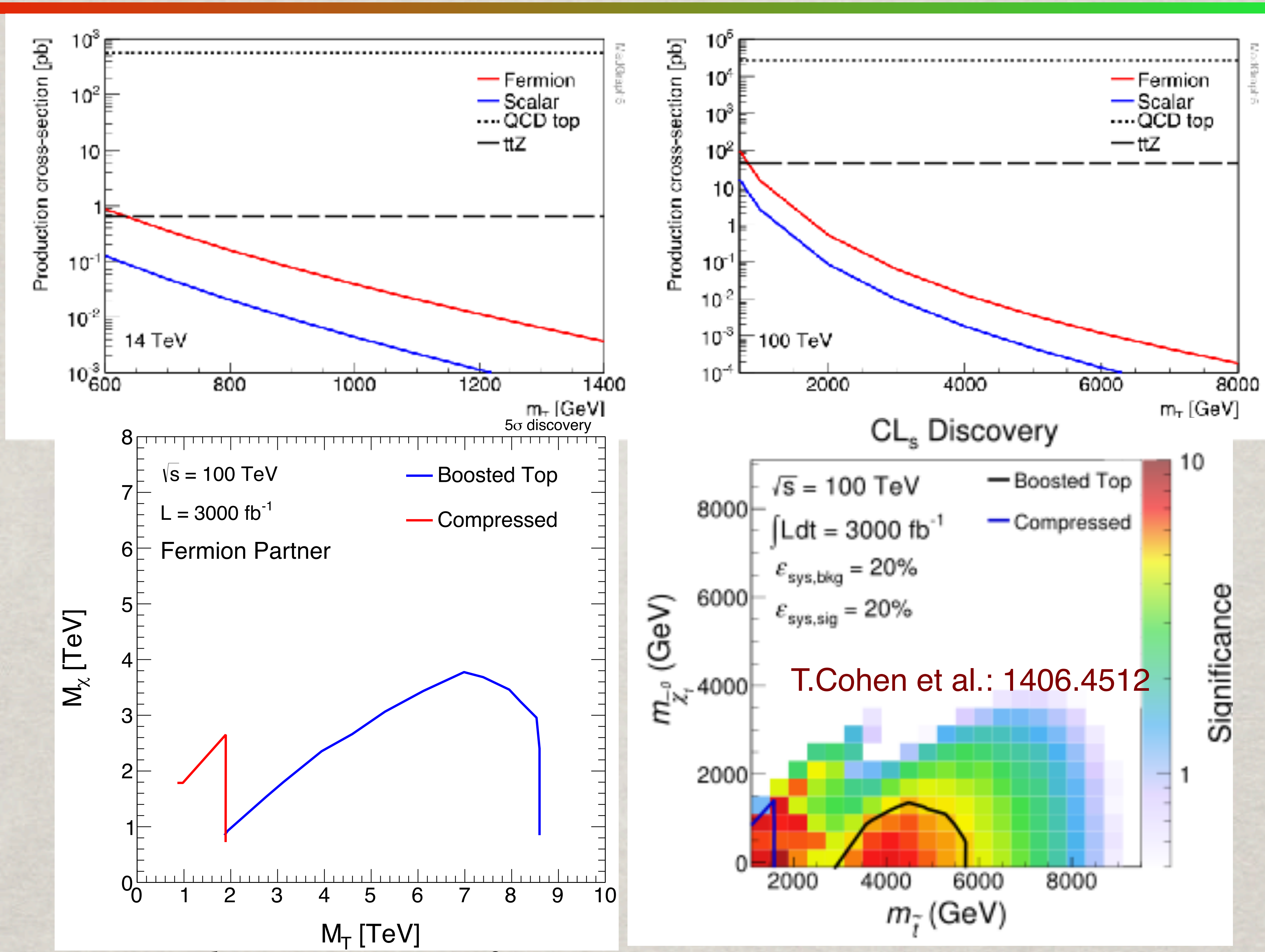
27 TeV,15000 fb^{-1}, 5σ discovery

14 TeV, 3000 fb^{-1}, exclusion %95 CL, ATLAS 2014

14 TeV,3000 fb^{-1}, 5σ discovery, ATLAS 2014

HE-LHC improves 50%-60%

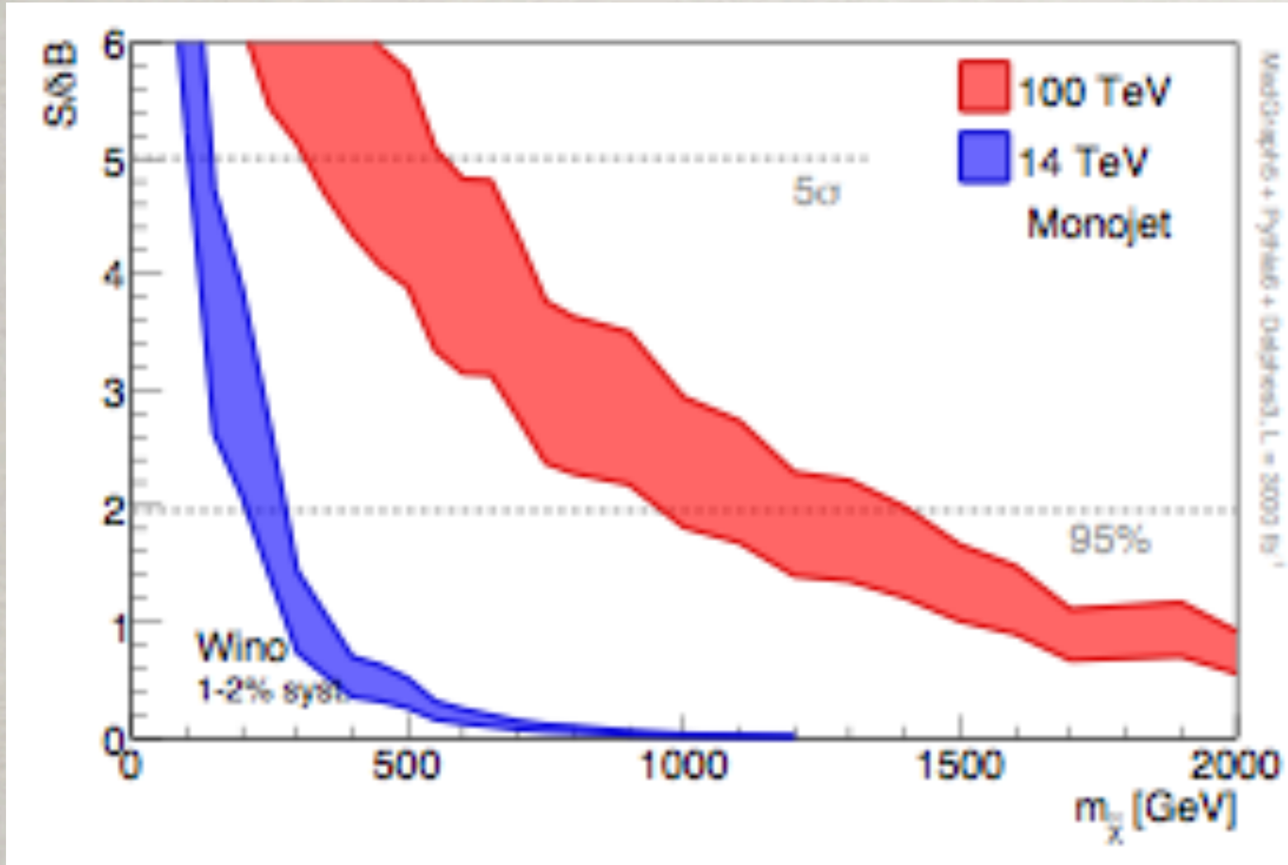
Pushing the "Naturalness" limit

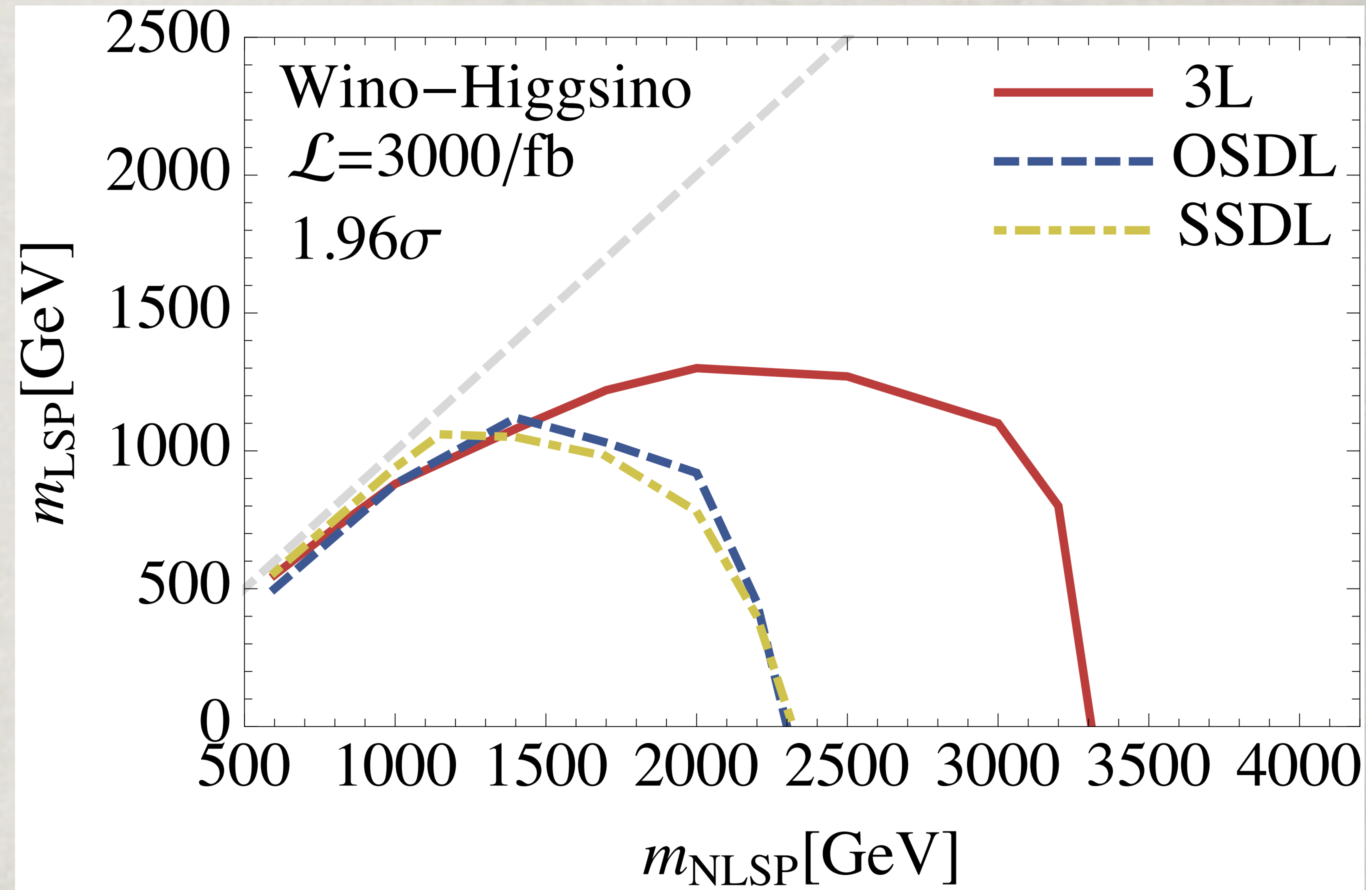


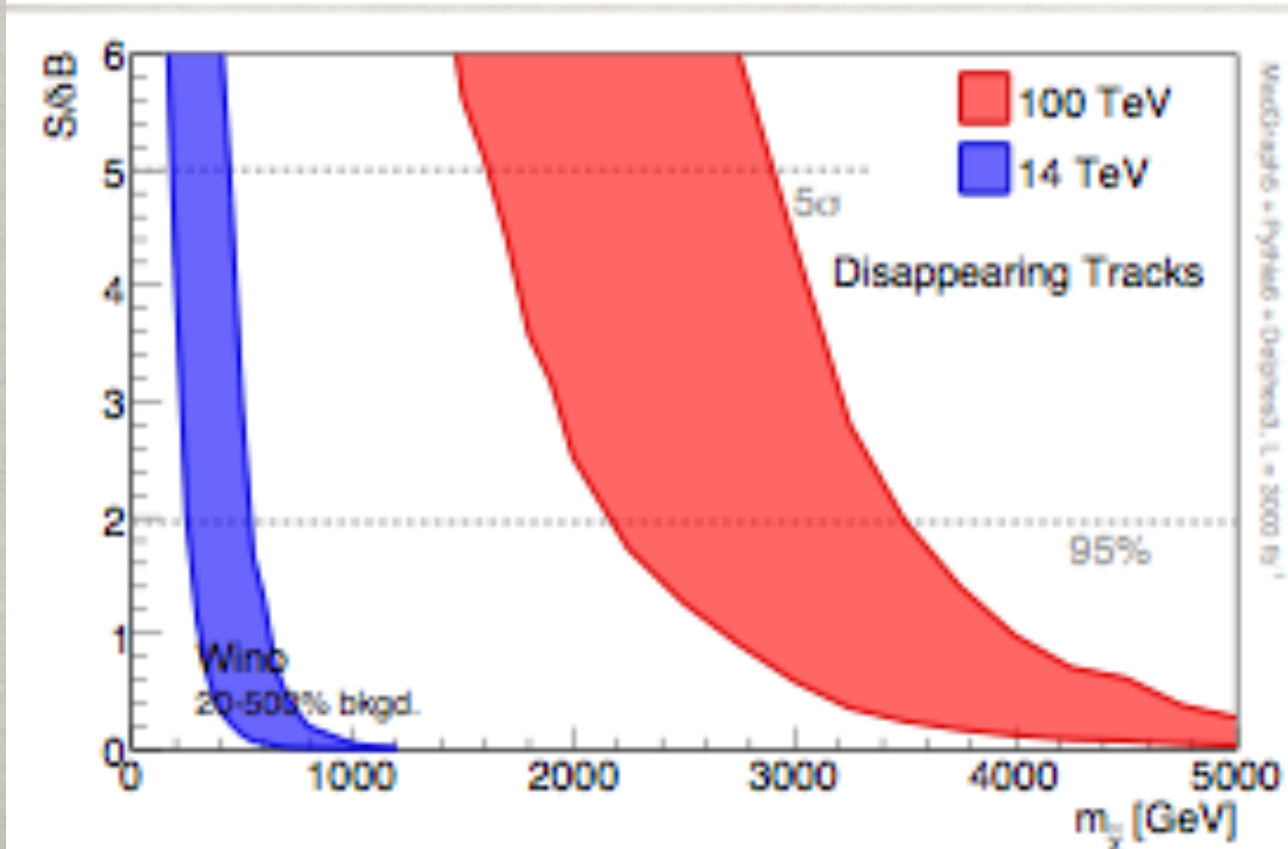
The Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

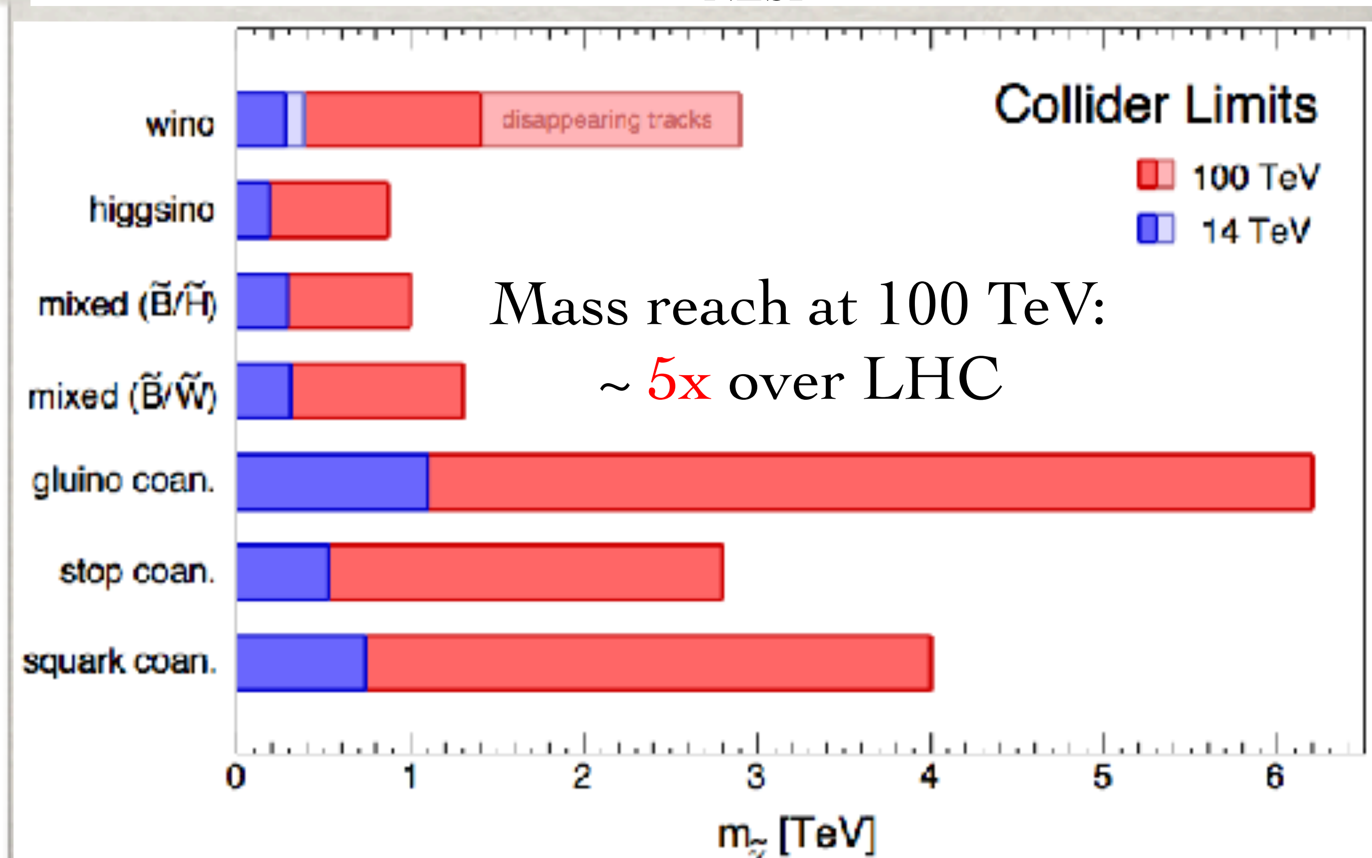
Thus, m_{stop} > 8 TeV -> 10^{-4} fine-tune!

WIMP DM: $M_{\rm DM} < 1.8\ \text{TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$



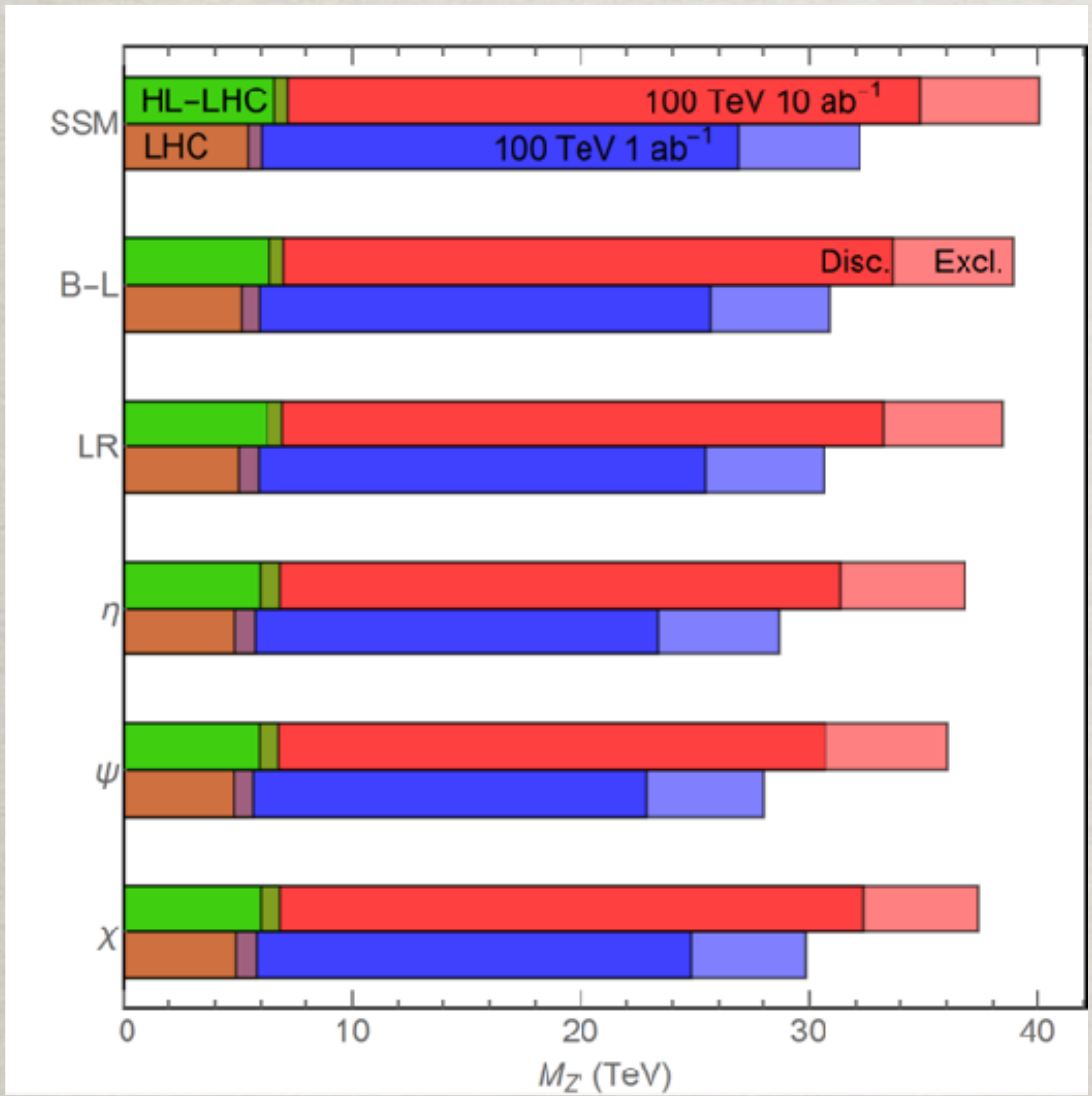






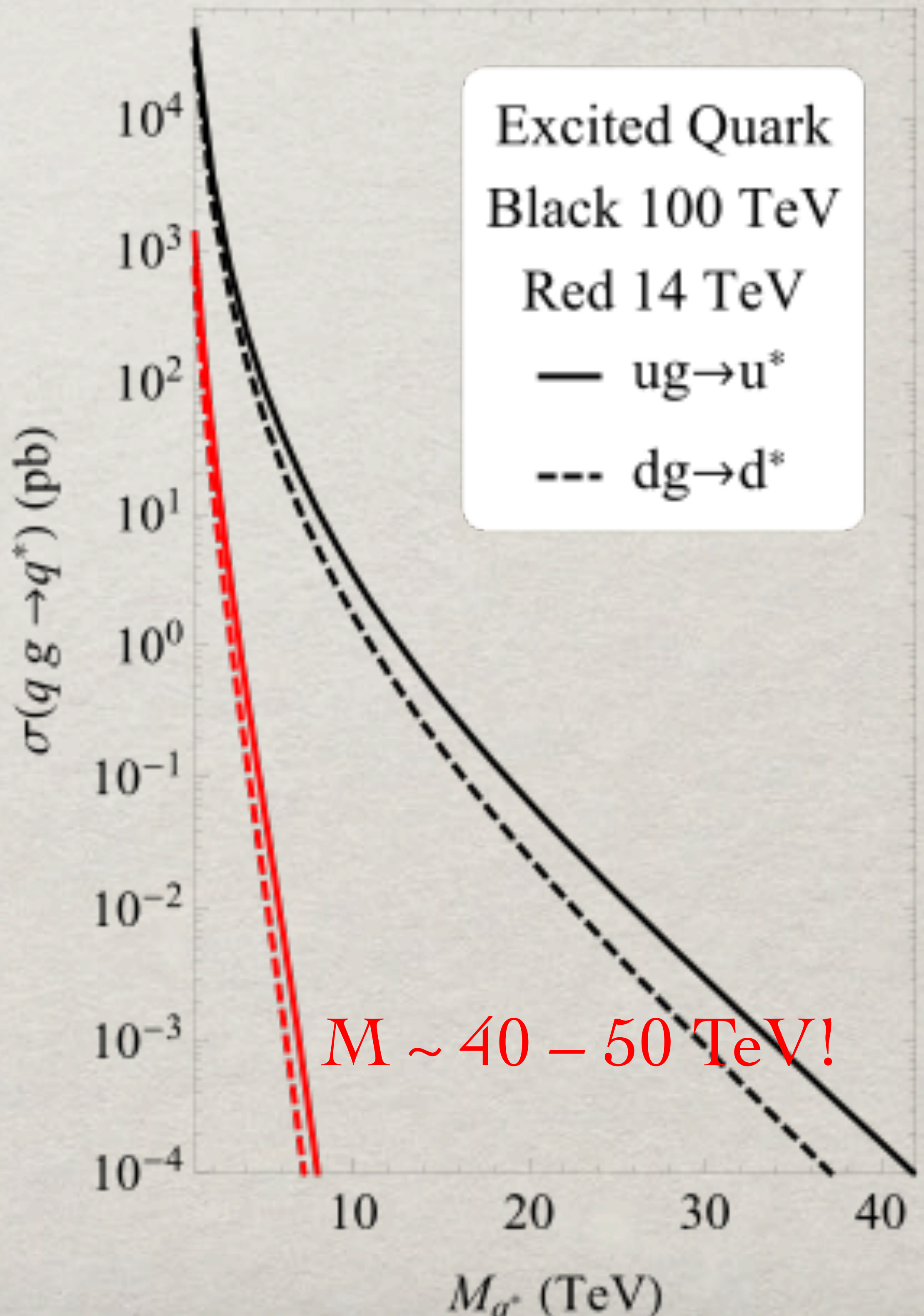
New Particle Searches

Electroweak Resonances: Z',W'



~ 6x over LHC

Colored Resonances:



Z-Factory: Tera (10^{12}) Z Physics

TLEP Report: 1308.6176

- Clean environment, ΔEcm < 1 MeV, 10^5 x LEP-I
- possible longitudinal polarization
- Precision measurements (statistical):

Z-ploe: ΔM_Z, $\Delta \Gamma_Z < 0.1$ MeV, $\Delta \sin^2\theta_w < 10^{-6}$;

$\Delta M_W \sim O(1 \text{ MeV})$, $\Delta m_t \sim O(10 \text{ MeV})$, $\Delta m_H \sim O(10 \text{ MeV})$.