"Closing Talk" On Open Issues

Tao Han
PITT PACC, Univ. of Pittsburgh
TsingHua Univ. / CFHEP, Beijing

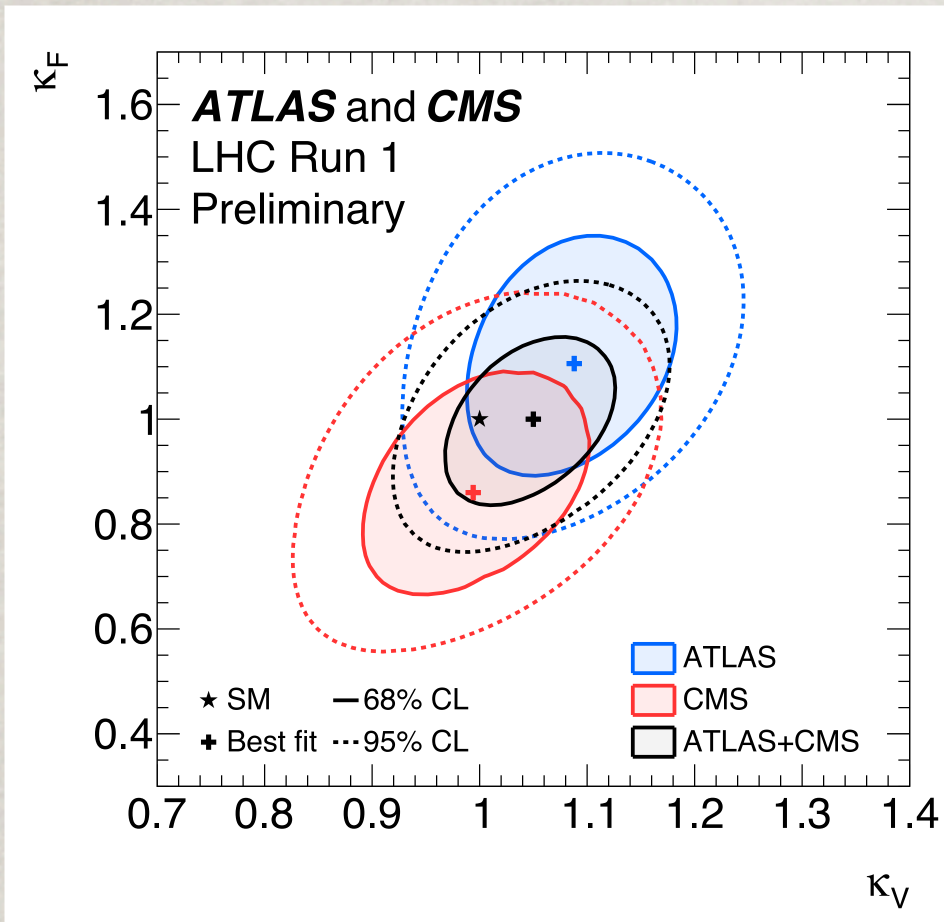
IAS Program on HEP, HKUST, Jan. 21, 2016

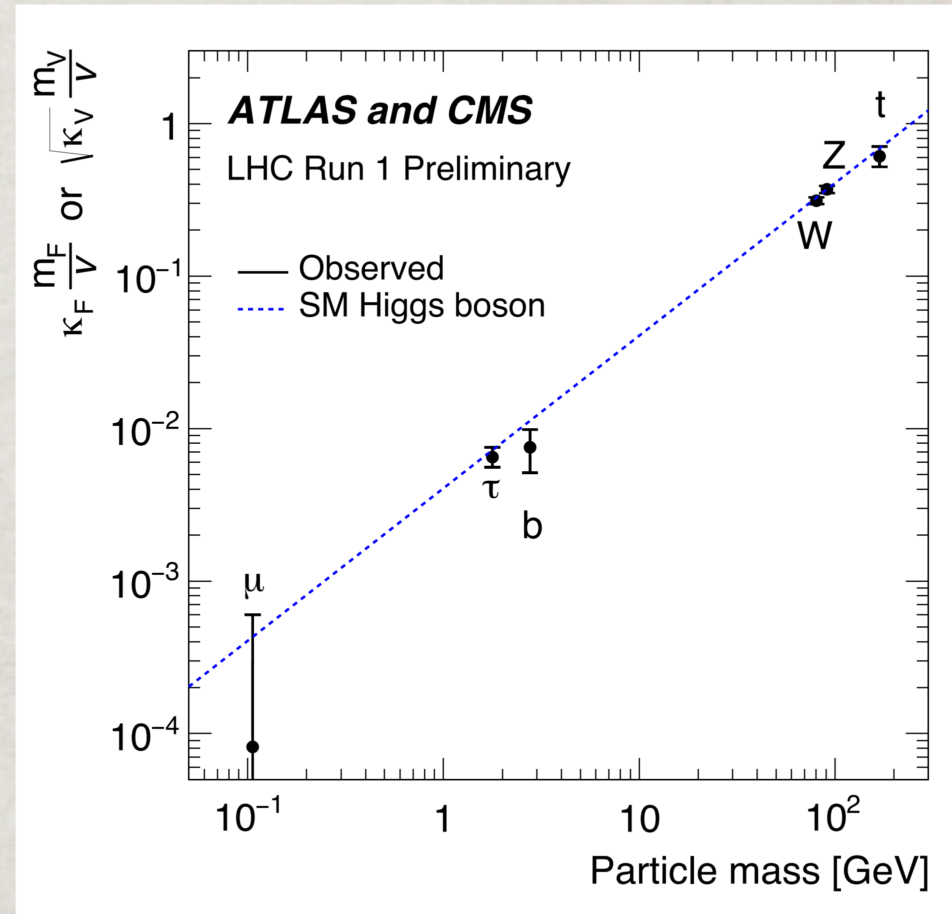
FHEP

Summer 2015 LHC Run 1 update:

5σ for both fermion coupling $h \rightarrow \tau\tau$
& bosonic coupling $WW \rightarrow h$

LHCP 2015, Sept
St. Petersburg





- it's neutral, spin-0, parity-even
- it couples to mass, non-universally

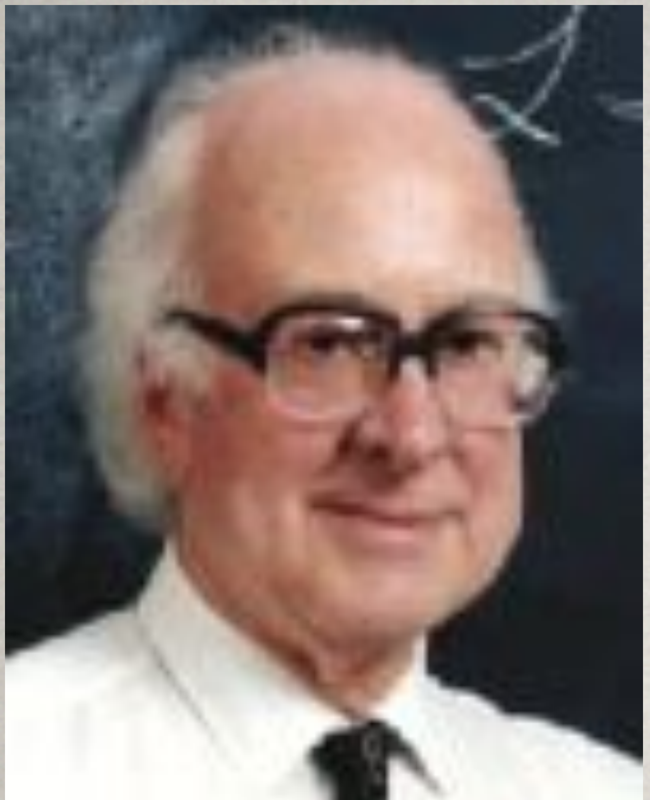
All indications point to a SM-like, Higgs boson "elementary" at a scale Λ < O(1 TeV)

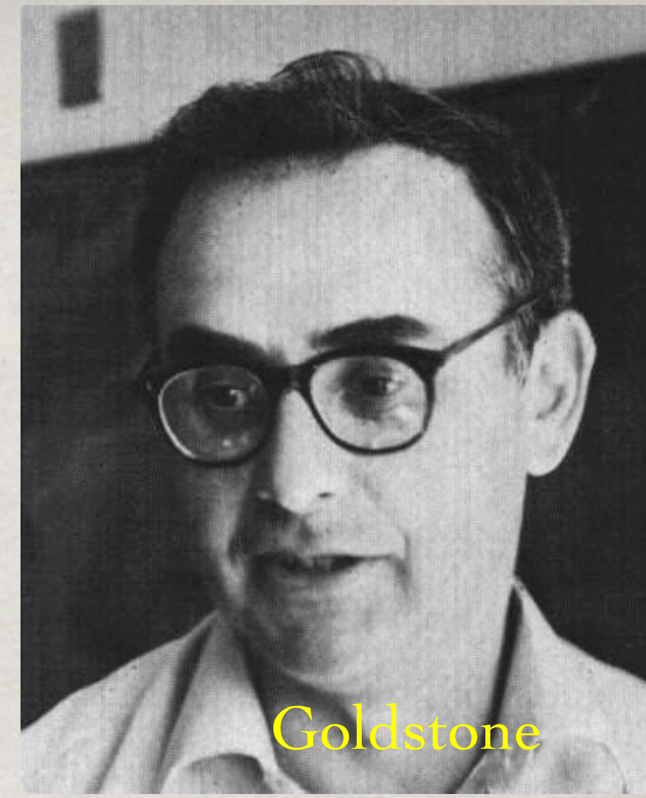
François Englert and Peter W. Higgs

"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"

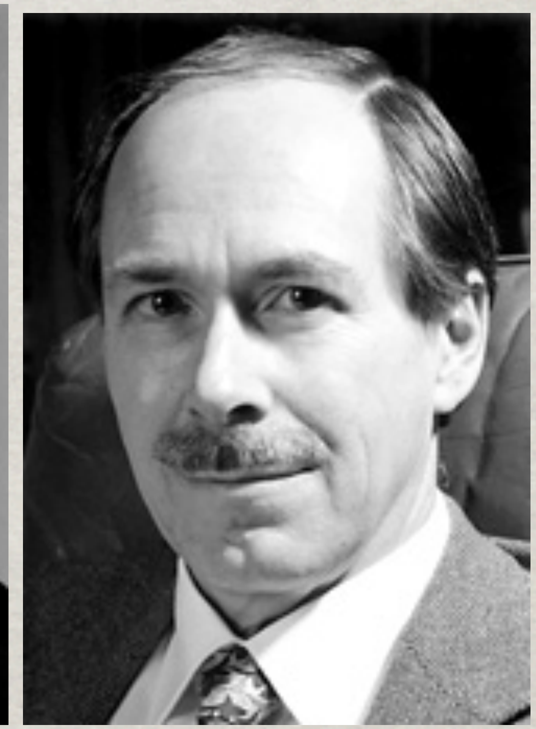
50 years theoretical work …

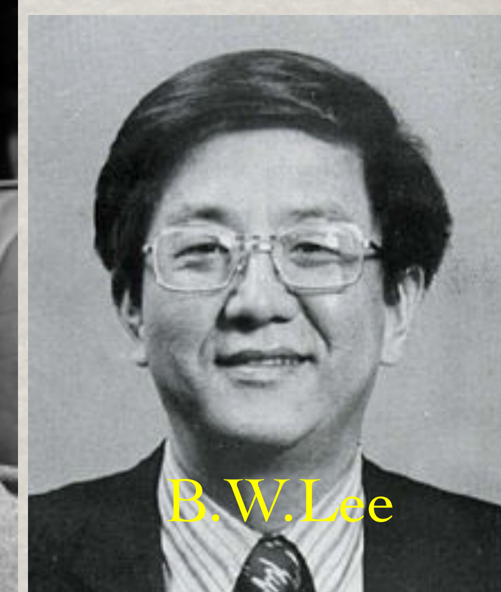
25 years experimental work …



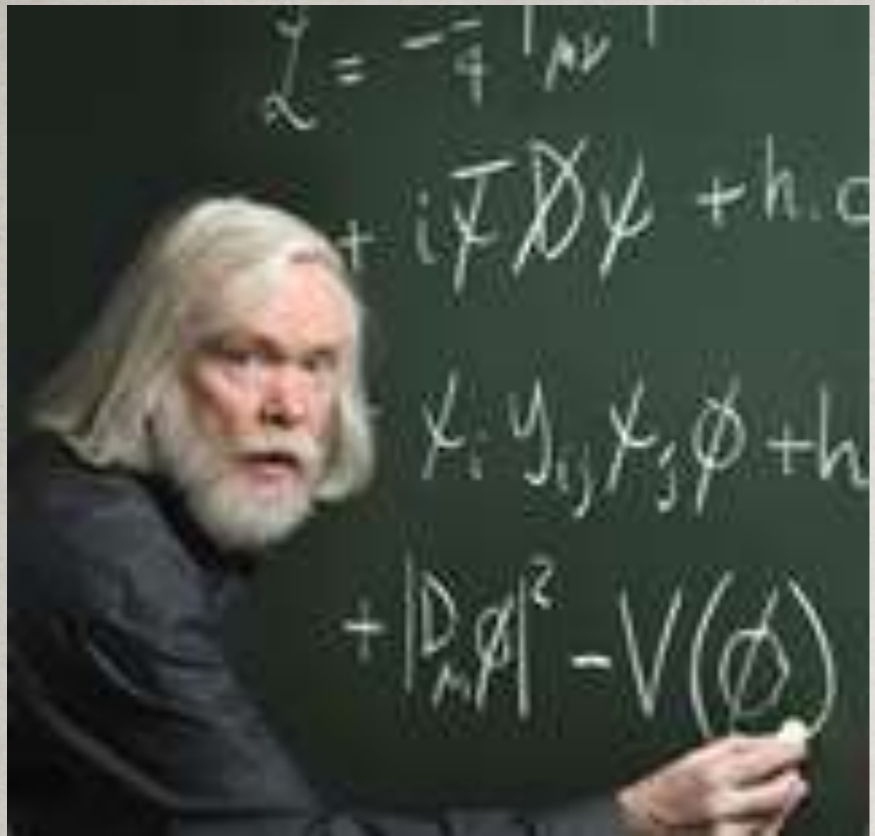


The Higgs mechanism (1964)





The Standard Model (1960-1967, 1972)



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits
the Higgs boson, we give a speculative cosmological argument for a small
is similar to that of the pion, the Higgs boson may be visible in the reacti
$\gamma p \to Hp$ near threshold. If its mass is $\lesssim 300$ MeV, the Higgs boson may b
decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one
ticles: $3.7 \to 3.1 + H$ with a branching ratio $O(10^{-4})$. If its mass is $\leqslant 4$ Ge
boson may be visible in the reaction $pp \to H + X$, $H \to \mu^+\mu^-$. If the Higgs
$\leqslant 2m_\mu$, the decays $H \to e^+e^-$ and $H \to \gamma\gamma$ dominate, and the lifetime is O(
2×10^{-12}) seconds. As thresholds for heavier particles (pions, strange pa
ticles) are crossed, decays into them become dominant, and the lifetime
to $O(10^{-20})$ sec for a Higgs boson of mass 10 GeV. Decay branching rati
enable the quark masses to be determined.

Higgs Phenomenology (70's)

Fermi National Accelerator Laboratory

We made it !

The "EHLQ" (80's)

FERMILAB-Pub-84/17-T
LBL-16875
DOE/ER/01545-345
February, 1984

Supercollider Physics

Berkeley, CA 94720

K. LANE
Ohio State University,† Columbus, OH 43210

C. QUIGG
Fermi National Accelerator Laboratory*
P.O. Box 500, Batavia, IL 60510

FRONTIERS IN PHYSICS

COLLIDER PHYSICS

FRONTIERS IN PHYSICS

THE HIGGS HUNTER'S GUIDE

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

2015: A Great Year for HEP!

T. Kajita & A. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Fundamental Physics Break Through Prize

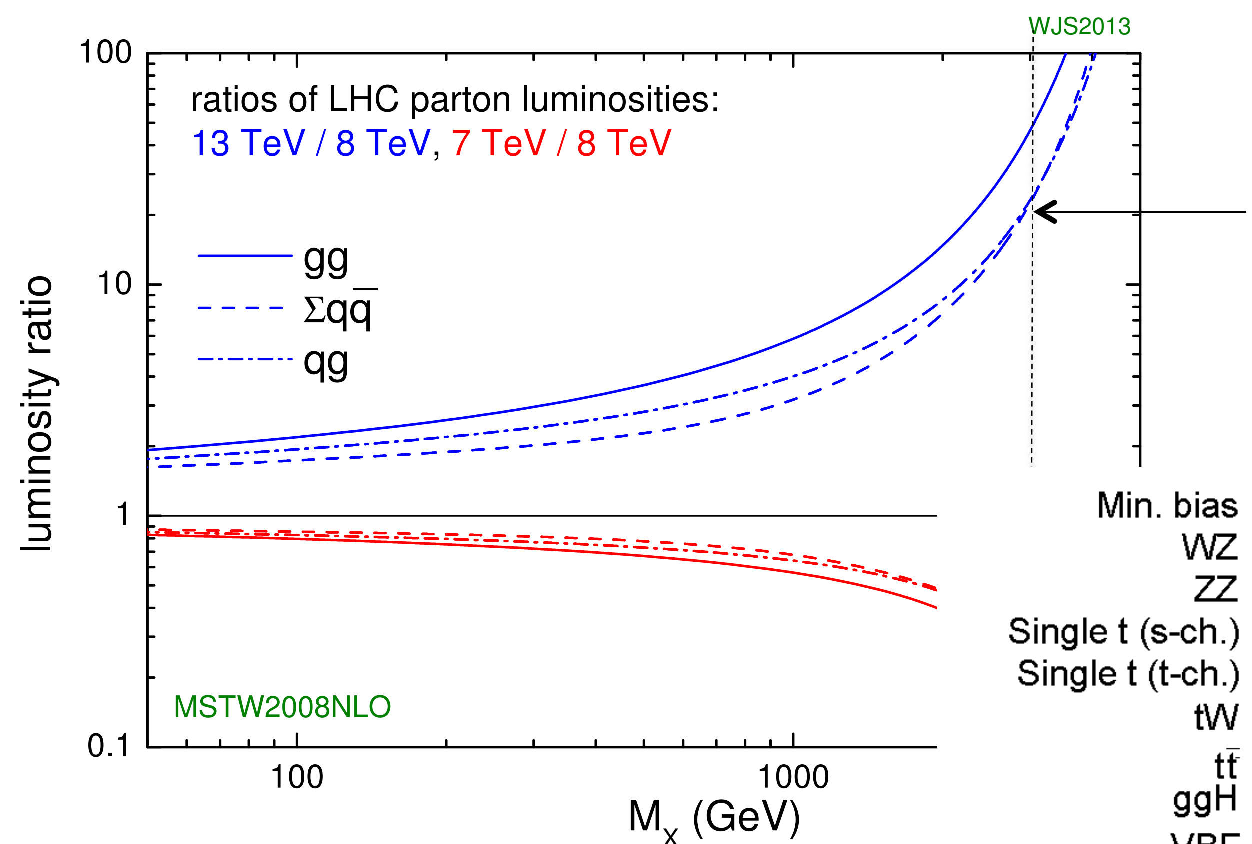
Daya Bay, K2K/T2K, KamLand, SNO, SuperK

"For the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics."

2015: A Great Year for HEP!

LHC completed the 1st-phase Run 2@13 TeV!

LHC Jamboree Dec. 2015: Marumi Kado: ATLAS; Jim Olson: CMS

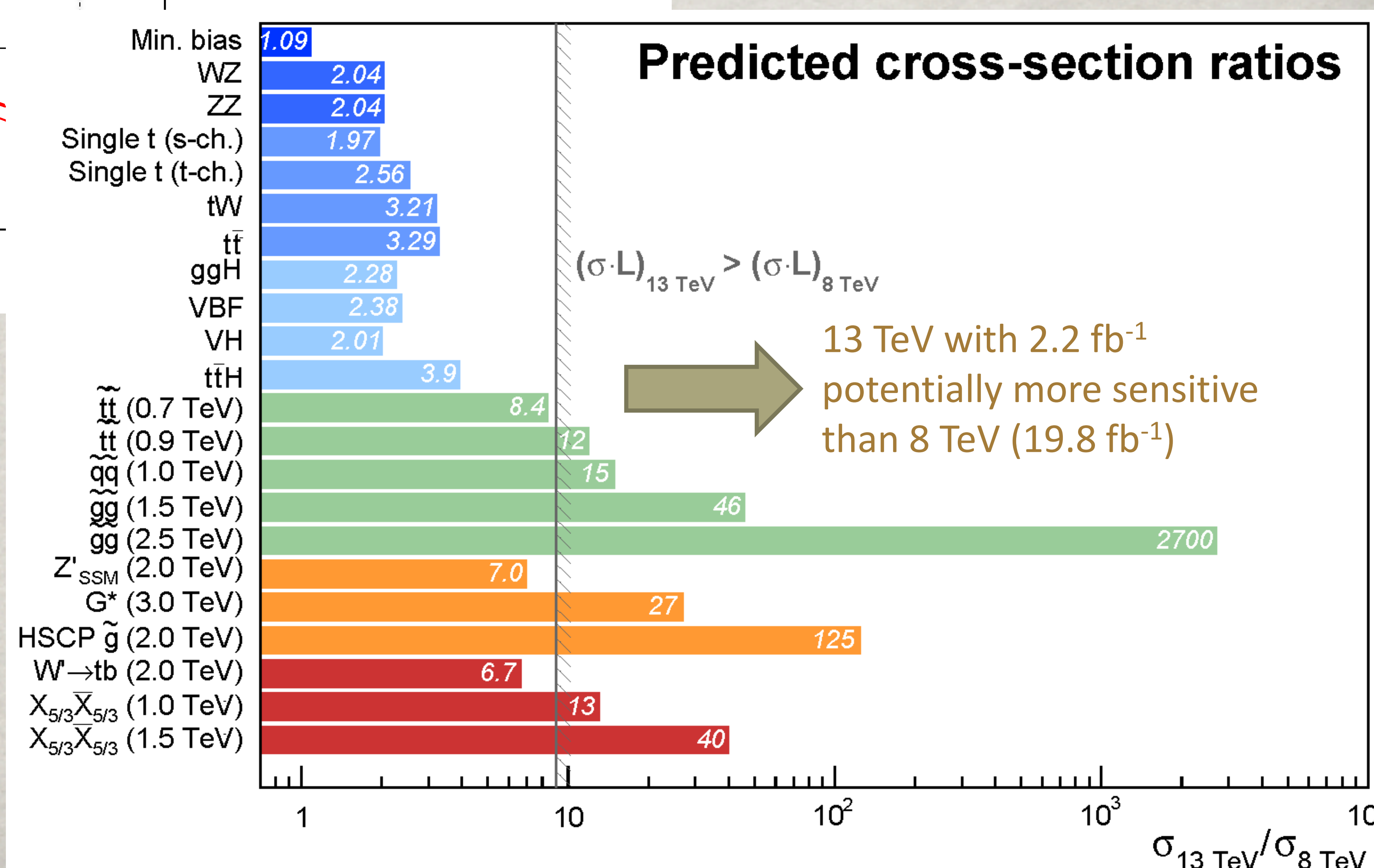


Ratio of 13 TeV / 8 TeV
Cross sections:

- Z' at 3 TeV: **20**
- q* at 4 TeV: **56**
- QBH at 5 TeV: **370**
- QBH at 6 TeV: **9000**

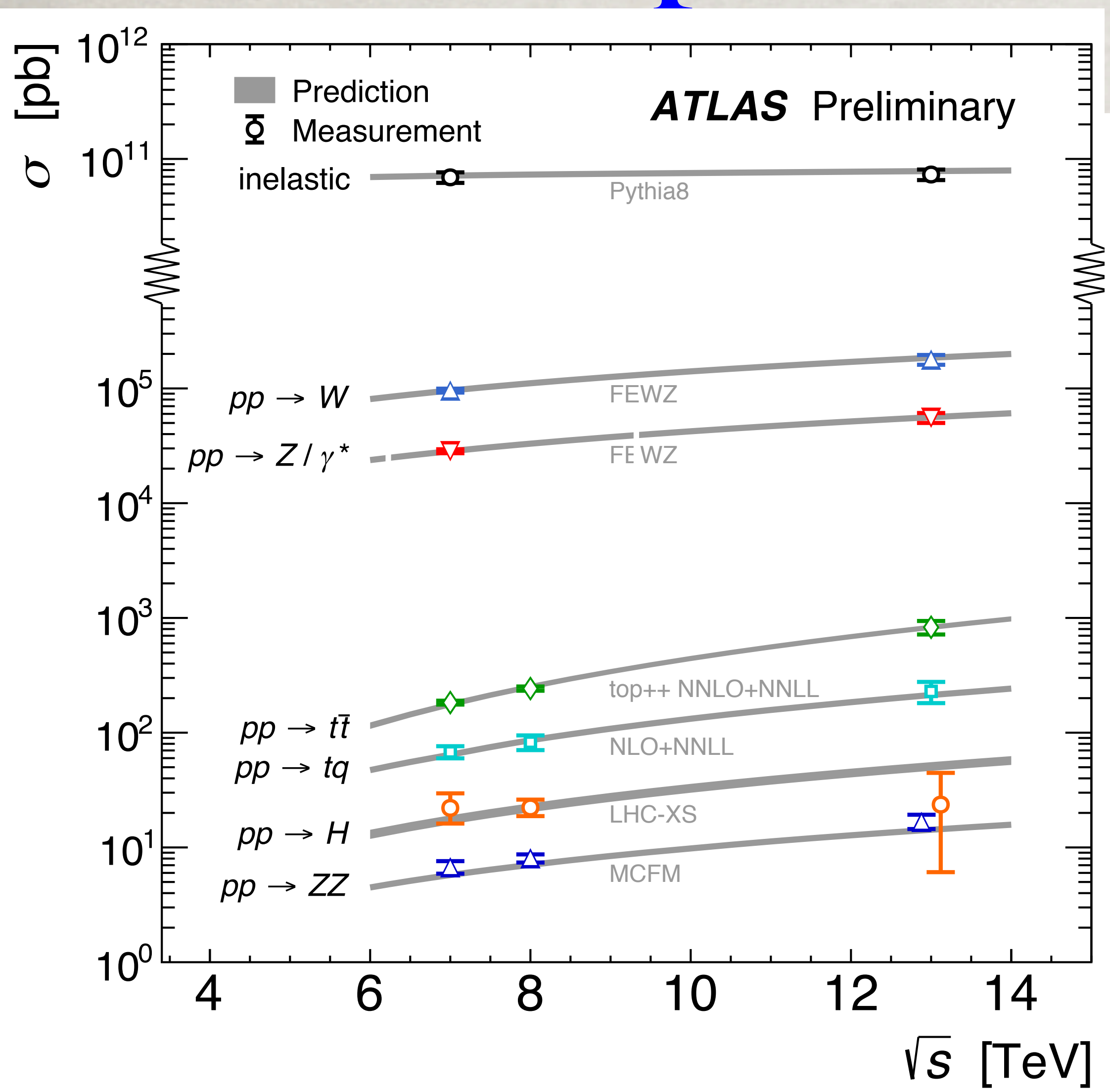
Serguei Ganjour,
this conference

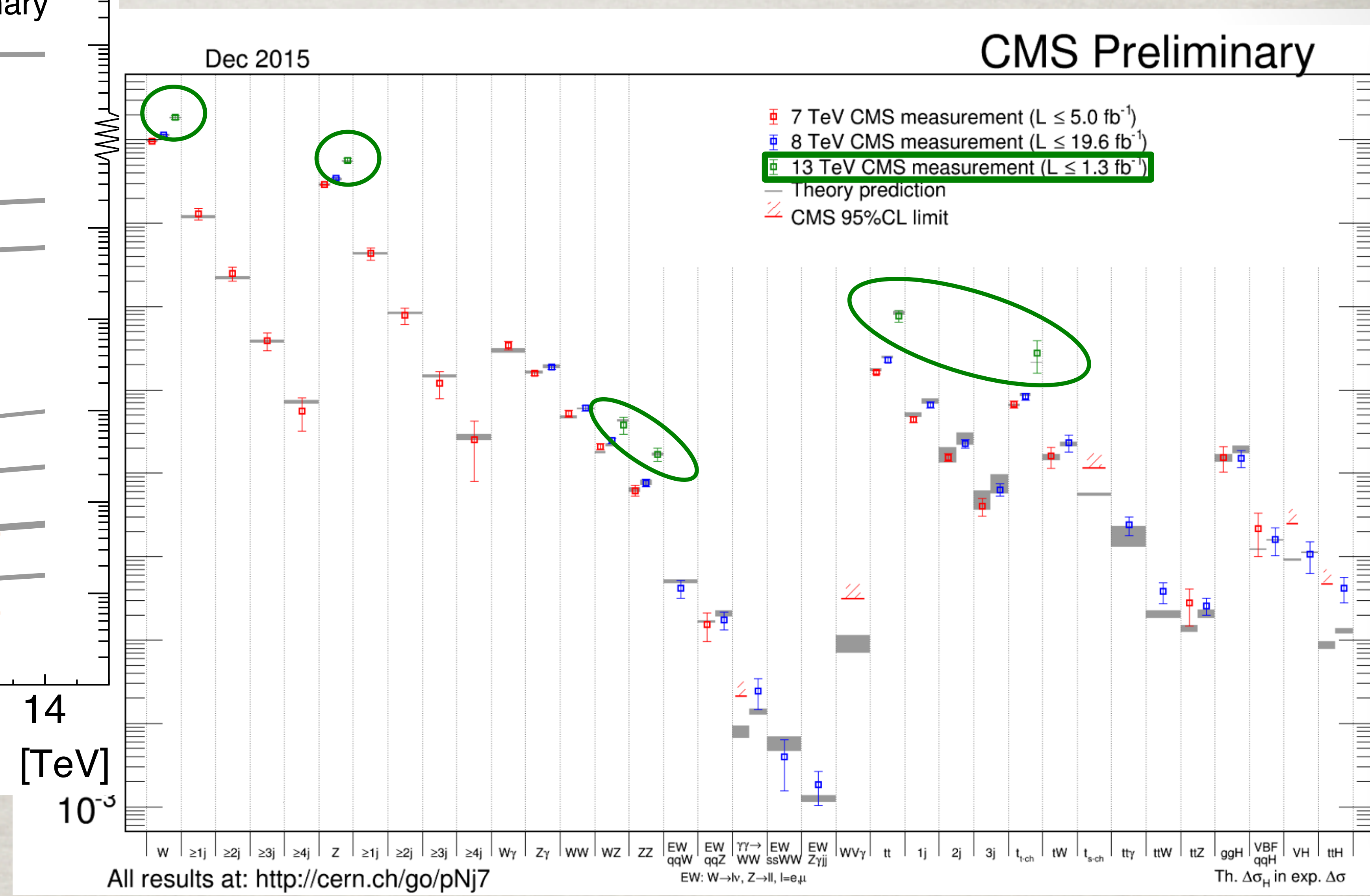
Marching into higher scales!



2015: A Great Year for HEP!

LHC completed the 1st-phase Run 2@13 TeV!





Consistent with SM at higher energies; no Higgs yet

New physics bounds beyond Run 1

Di-boson excess at 8 TeV un-confirmed

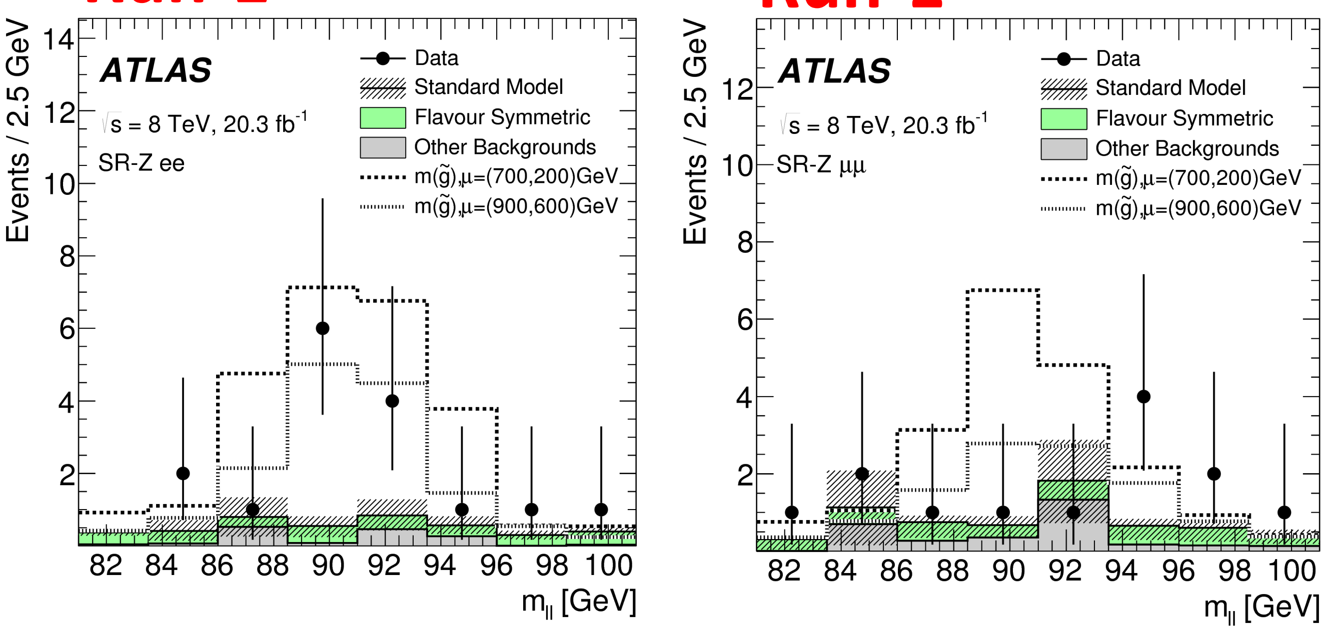
Prelude for discoveries? Z + MET signature (ATLAS only)

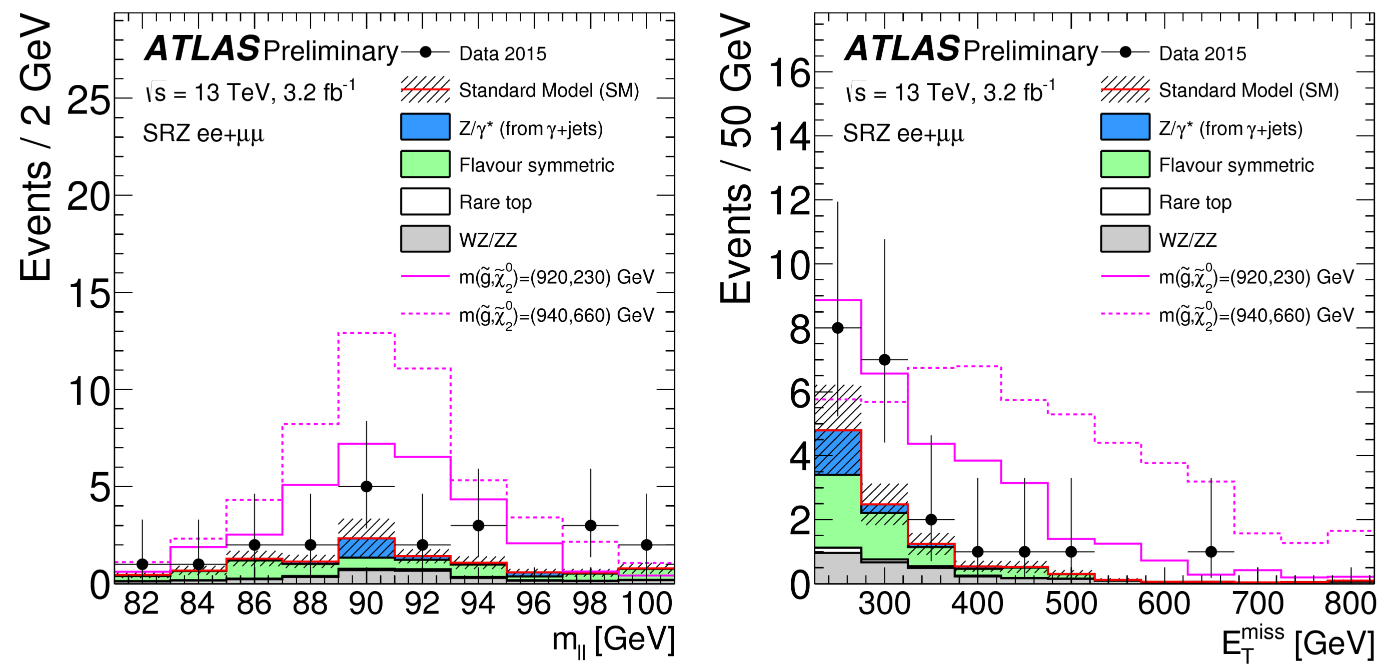
See Tom Rizzo's seminar

Check of an excess seen in ATLAS (not in CMS) at Run-1

29 events *obs* **10.8±2.2** *exp* (3σ excess)

Run-1 **Run-1**





21 events *obs* (e ~ μ) and **10.4±2.4** *exp* (**2.2σ excess** at intermediate MET)

Watch it out !

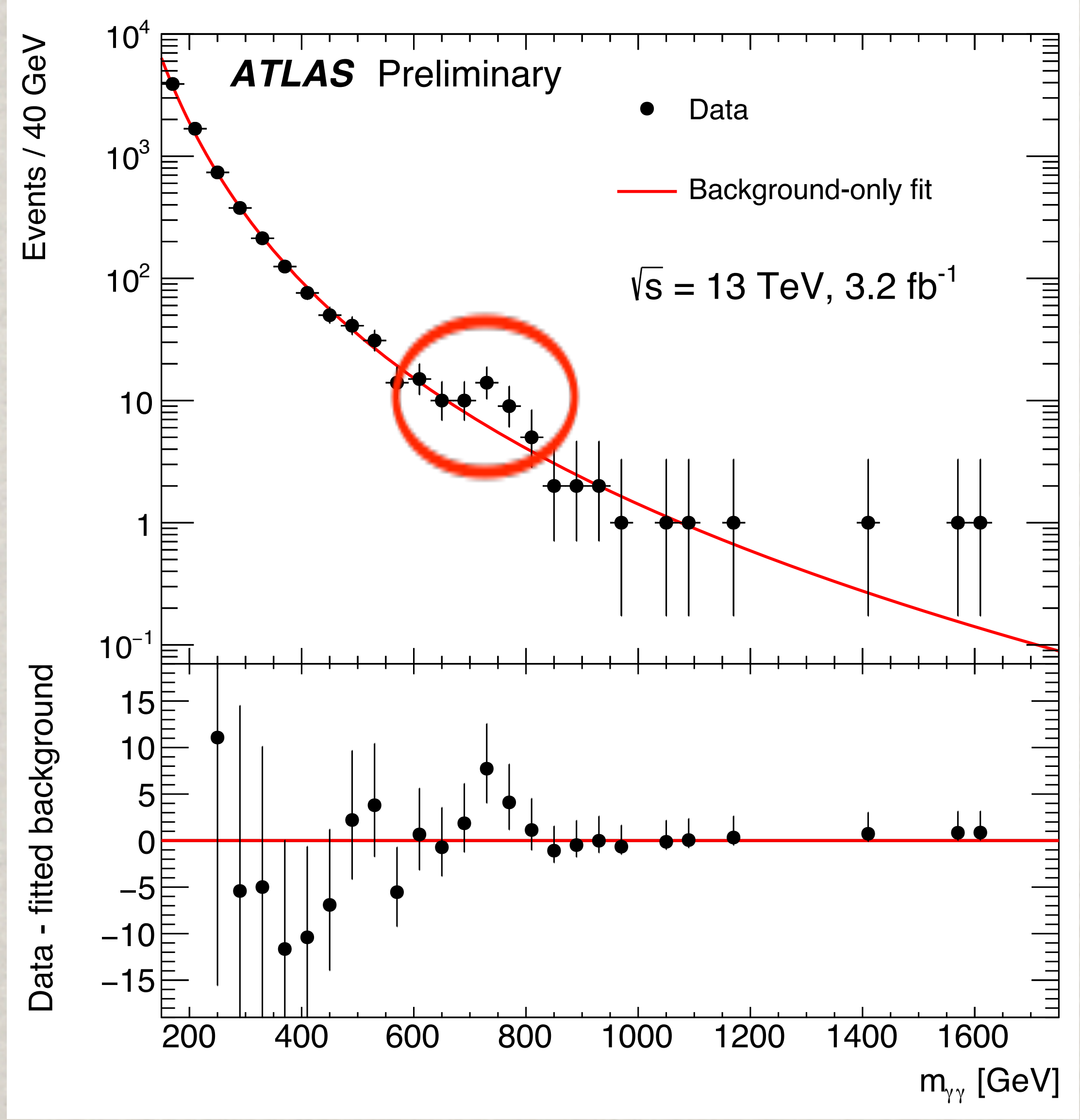
Same-sign di-lepton excess?

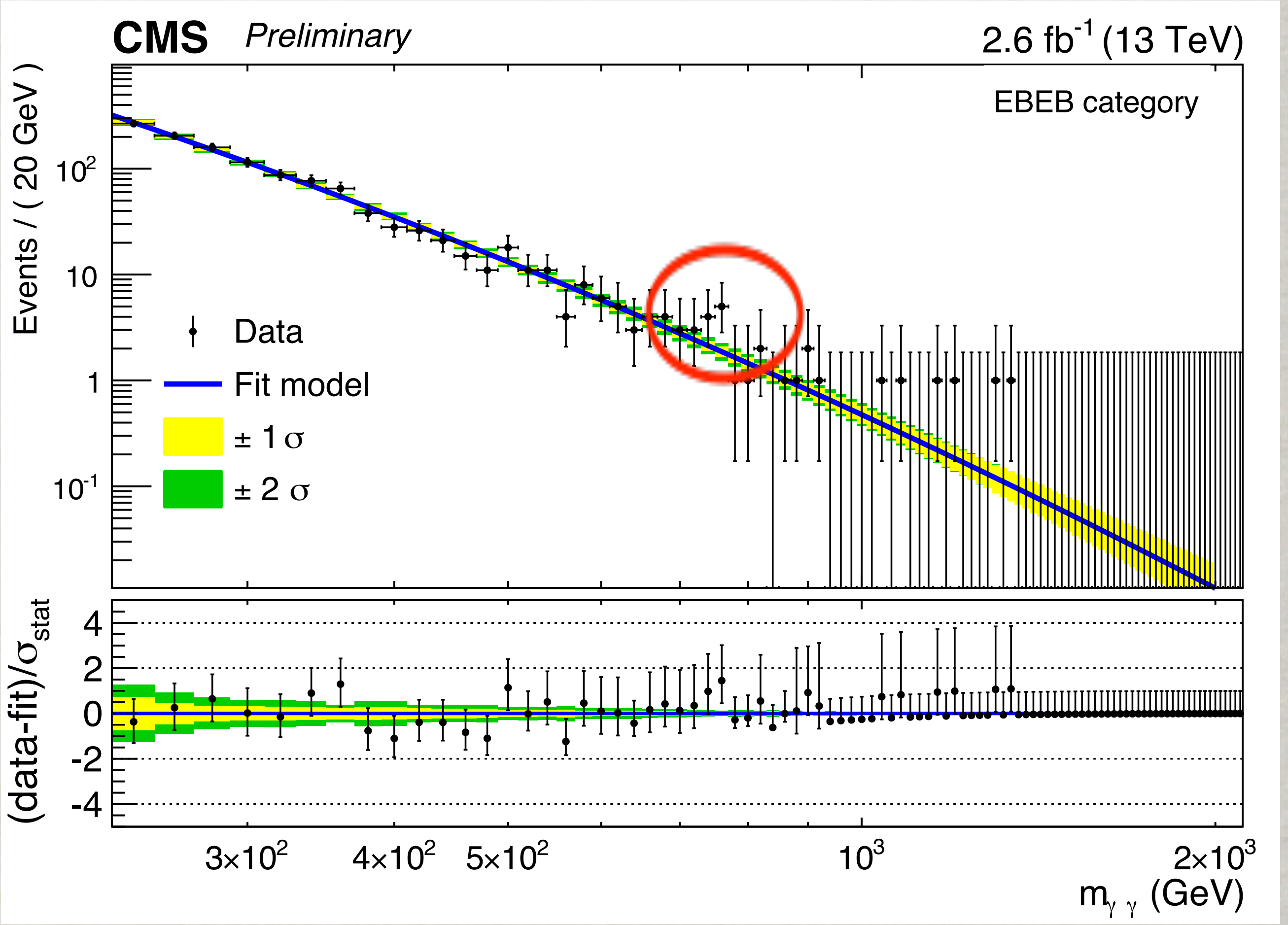
See Ian Low (a theorist) claim

Prelude for discoveries? 750 GeV Bump

Serguei Ganjour

The observation:





Significance @ CMS

Local: 2.6σ; Global: 1.2σ

- Statistics?
- Look-elsewhere?
- Fitting functions?
- Large width?

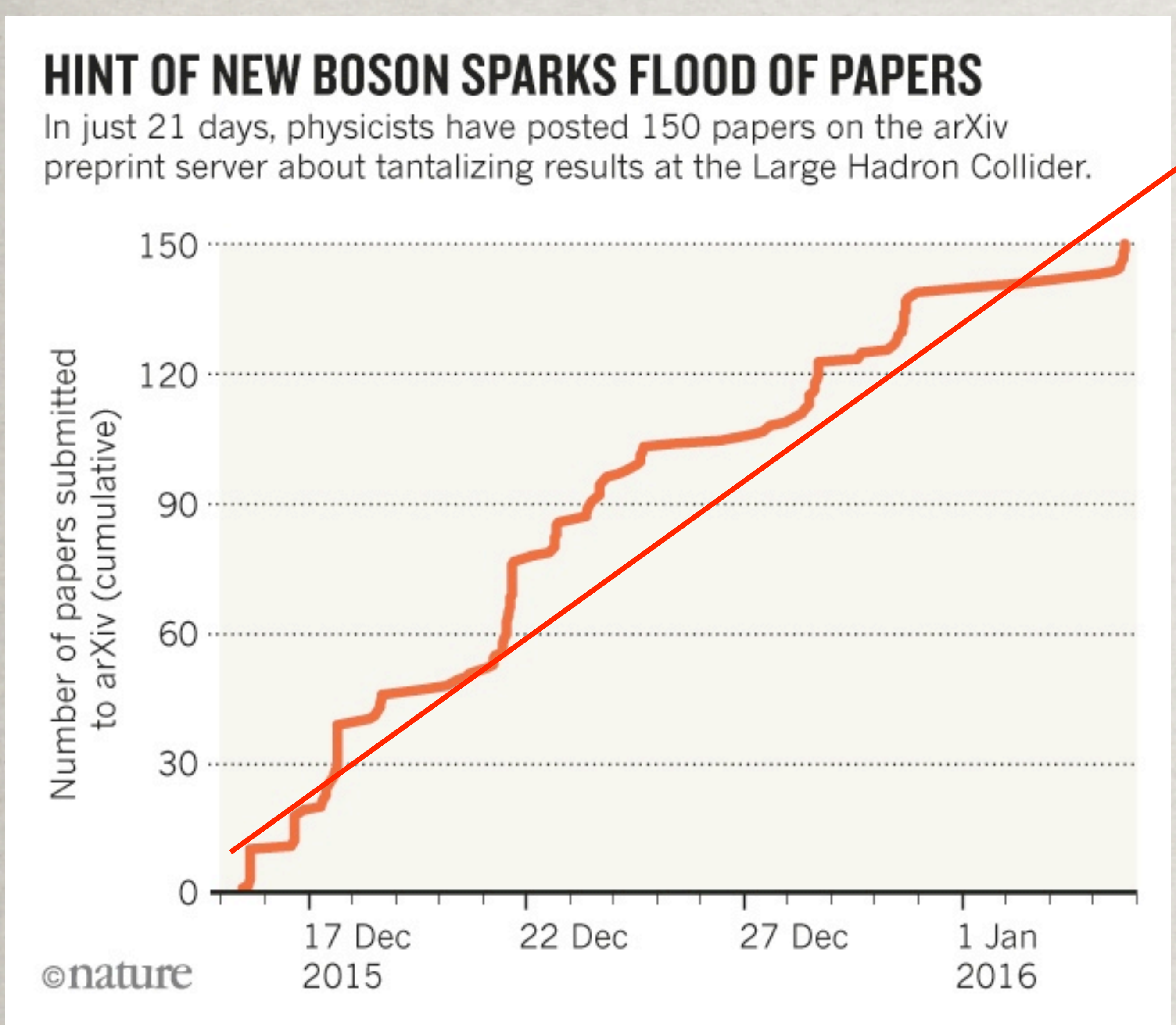
Significance @ ATLAS

Local: 3.6σ; Global: 2.0σ

$\sigma_{\gamma\gamma} \approx (7 - 10)$ fb $\quad (\approx \sigma_h(\gamma\gamma)/10)$

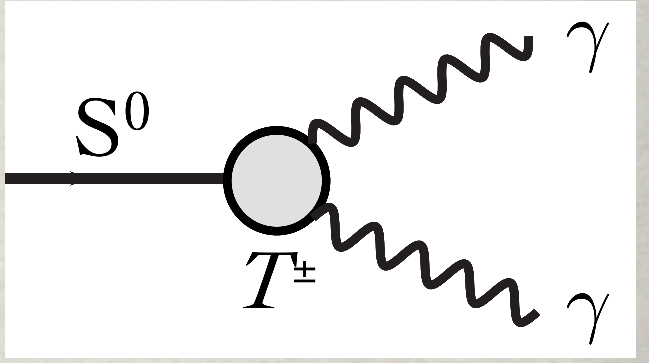
750 GeV Bump Fever!

Implications:



Nature, Paul Ginsparg

$pp \to S^0 \to \gamma\gamma$



Need :

1. (pseudo-)scalar singlet
2. (vector-like-)quarks
   + (all sort) variations
3. Sizeable $BR_{\gamma\gamma}$, large width?
4. Large Yukawa $y \sim 5$!

Come to the discussion session today.

A Reminder:

The Higgs mechanism ≠ a Higgs boson !

From theoretical point of view,
3 Nambu-Goldstone bosons were all we need!
A non-linear realization of the gauge symmetry:

$$U = \exp\{i\omega^i \tau^i / v\}, \quad D_\mu U = \partial_\mu U + igW_\mu^i \frac{\tau^i}{2} U - ig' U B_\mu \frac{\tau^3}{2}$$

$$\mathcal{L} = \frac{v^2}{2}[D^\mu U^\dagger D_\mu U] \to \frac{v^2}{4}(\sum_i g^2 W_i^2 + g'^2 B^2)$$

Lee, Quigg, Thacker (1977)

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 –
UV completion / renormalizibility .

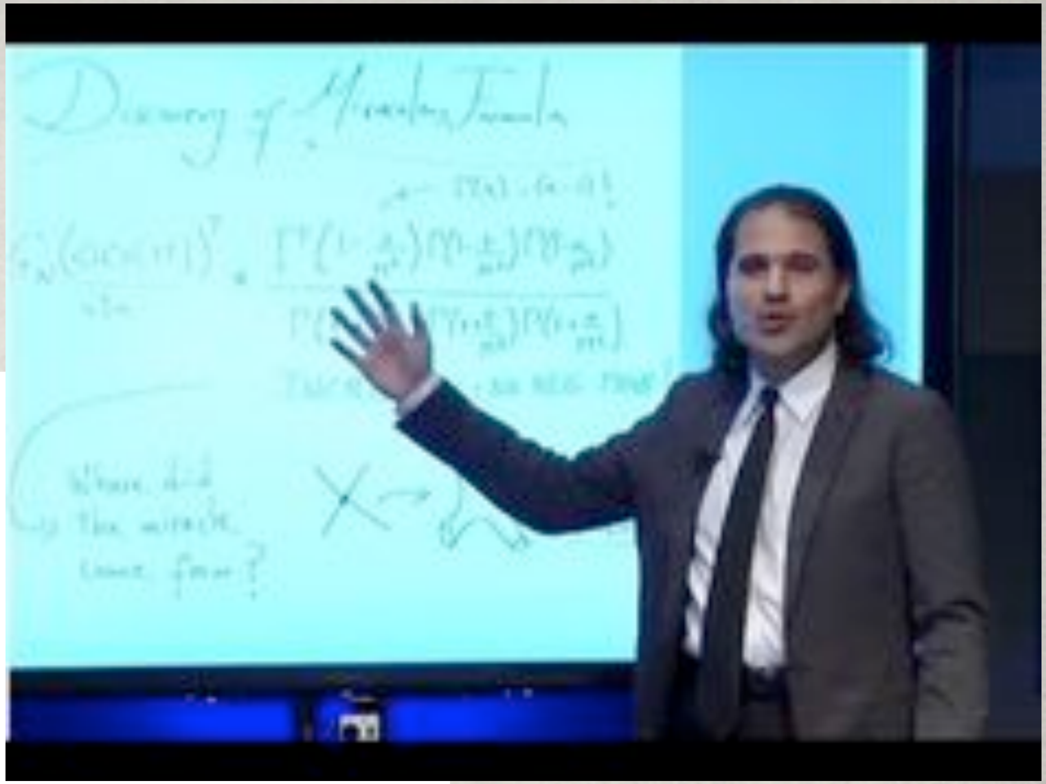
"... most of the grand underlying principles have been firmly established. (An eminent physicist remarked that) the future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiments (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

Will History repeat itself (soon)?

Nima Arkani-Hamed
(Director of CFHEP, Beijing)



The central questions today are not details — but structural: origin of spacetime, UV/IR connection, standard model → real theory

Under the Higgs lamp post

This conference: Chris Quigg; Mat Reece; Mathew McCulough; Christophe Grojean; Shufang Su

Questions:

- A "Natural" Higgs sector?
  (SUSY, Twin-Higgs, composite, relaxation…)
- The nature of the EW phase transition?
- Higgs portal to new physics?
- … …

A "natural" EW theory?
"Naturalness" → TeV scale new physics.

- SUSY:

Relevant to the Higgs
and the "Most Wanted":

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

Current LHC bounds:

$m_{\tilde{t}} > 200 - 680\ \mathrm{GeV},$

$m_{\tilde{\chi}^{\pm}} > 100 - 600\ \mathrm{GeV}\ \ (\mathrm{depending\ on}\ m_{\chi^0})$

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

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

- Alternatives: Twin Higgs; (color) neutral naturalness

Understand "the 5th force"

$$V = -\mu^2 |\phi|^2 + \lambda|\phi|^4$$

a new dimensionless (truly) self-coupling.

- **In the SM, λ is a free parameter,**
  now measured at collider energies $\lambda \approx 0.13$
- **In SUSY, it is related to the gauge couplings**

tree-level: $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4$ ← a bit too small

- **In composite/strong dynamics,**
  harder to make λ big enough.

(due to the loop suppression by design)

A "natural" EW theory should provide understanding of λ

→ already possess challenge to BSM theories.

The Nature of EWSB

$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

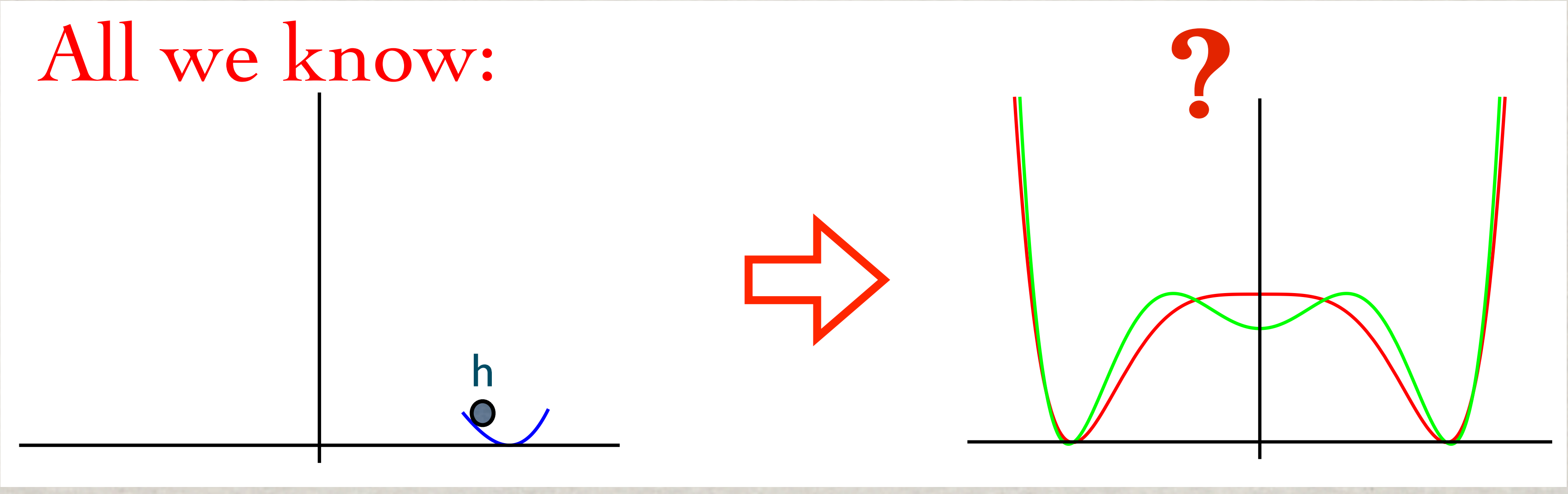
$$\Rightarrow \quad \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

Fully determined at the weak scale:

$v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV $\quad m_H \approx 126$ GeV

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

It cannot be a 1st order phase transition



O(1) deviation on λ_{hhh} could make EW phase transition strong 1st order!

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

The Higgs portals to Cosmos?

(a). Dark Matter

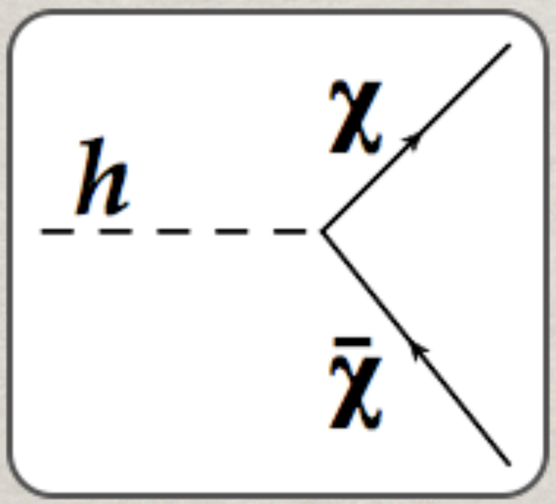
$H^\dagger H$ is the only bi-linear SM gauge singlet.

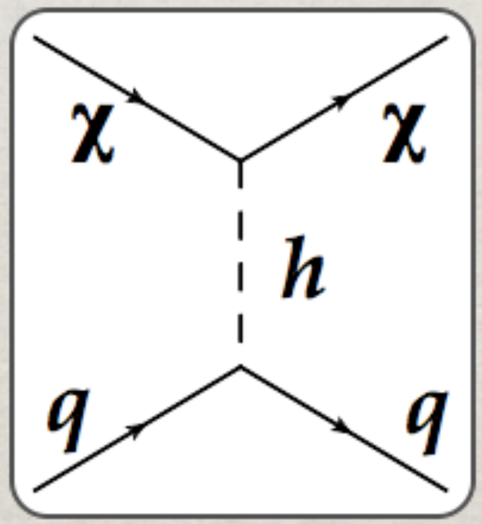
Bad: May lead to hierarchy problem with high-scale physics;

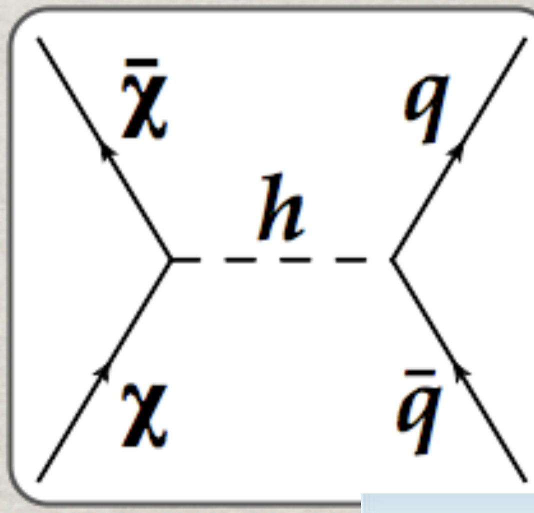
Good: May readily serve as a portal to the dark sector:

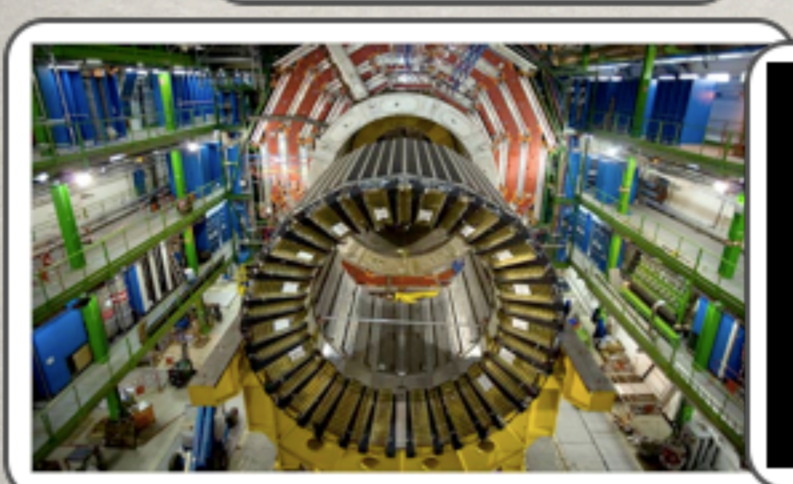
$$k_s H^\dagger H\ S^* S, \qquad \frac{k_\chi}{\Lambda} H^\dagger H\ \bar{\chi}\chi.$$

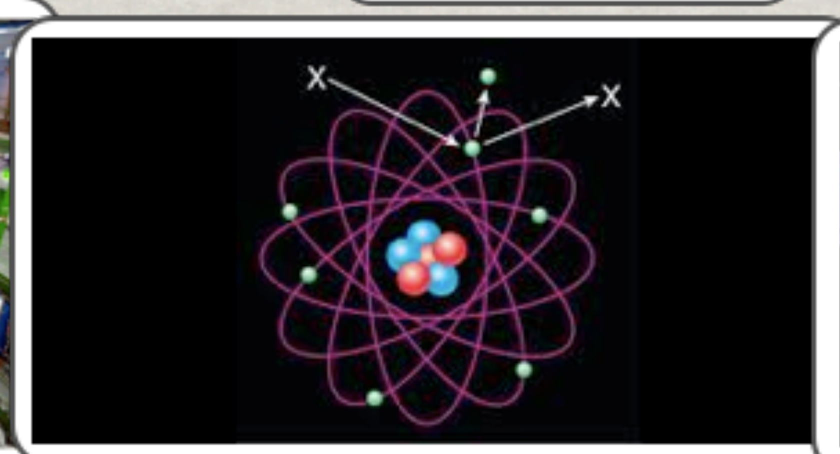
Missing energy at LHC — *Direct detection* — *Indirect detection*

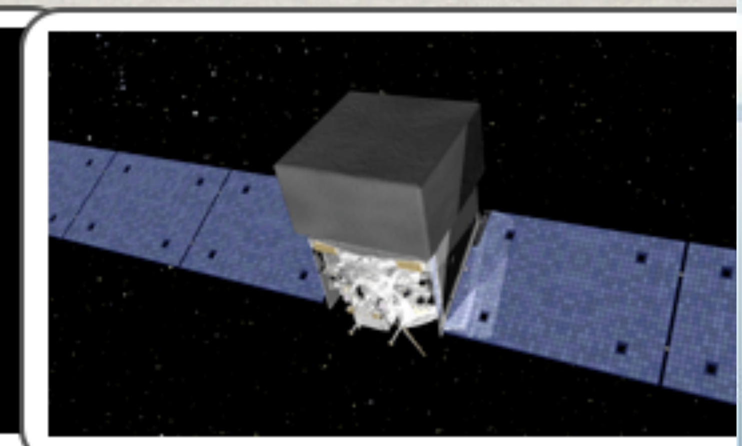


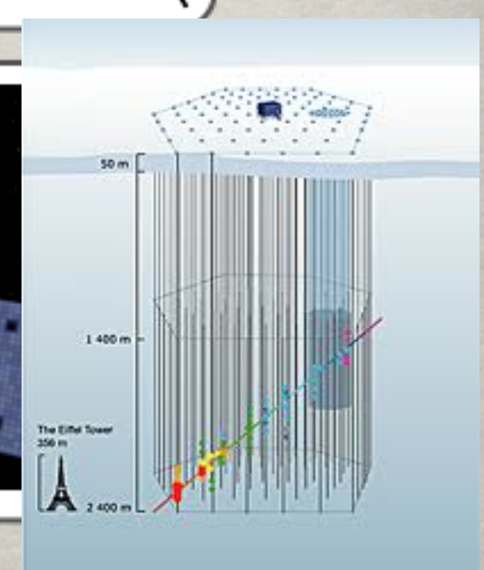












Other potential consequences

(b). Baryon – anti-baryon Asymmetry

For m_h = 125 GeV,
EW baryogenesis needs light sparticles:
m_{stop} ≈ 150 GeV
plus a light neutralino, singlets …

Carena et al., 2011;
Chung, LT Wang, 2011.

(c). Higgs as an inflaton?
(d). Higgs field & Dark Energy?
(e). "Relaxation" of week-scale?

Bezrukov, 2008;
Nakayama, 2011.

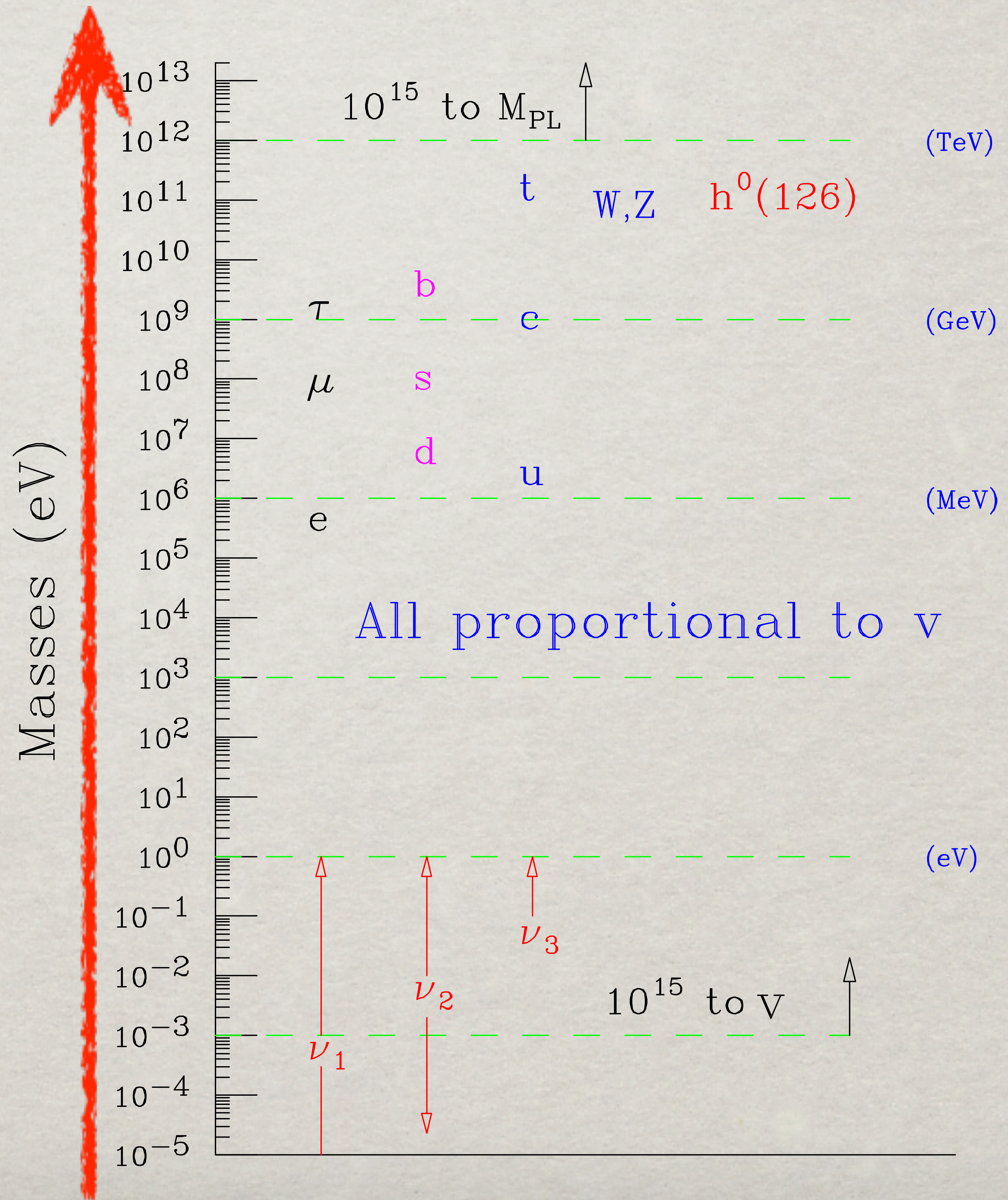
Graham, Kaplan, Rajendran; Christophe Grojean

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

Flavor & Yukawa Couplings

- Particle mass hierarchy
- Patterns of quark, neutrino mixings: Big^{n} puzzle!
- New CP-violation sources?

Higgs Yukawa couplings as the pivot!



Dim-5: Neutrino Masses

The leading SM gauge invariant operator is at dim-5:*

*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

$$\frac{1}{\Lambda}\,(y_\nu LH)(y_\nu LH) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\,\overline{\nu_L}\,v_R^c.$$

The See-saw spirit: †

If $m_\nu \sim 1$ eV, then $\Lambda \sim y_\nu^2$ (10^{14} GeV).

$$\Lambda \Rightarrow \begin{cases} 10^{14} \text{ GeV for } y_\nu \sim 1; \\ 100 \text{ GeV for } y_\nu \sim 10^{-6}. \end{cases}$$

- Type I: add N_R (Majorana?)
- Type II: add Y=1 scalar Φ-triplet ($\Phi^{++,+-,0}$)
- Type III: add Y=0 fermion T-triplet ($T^{+,0,-}$)

S. Antusch, O. Fischer, this conference

Cheng-Wei Chiang

Lead to rich phenomenology.
SM Higgs is always the pivot!

Dim-6: Rich Physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{g_i^2}{\Lambda_{\rm NP}^2}\mathcal{O}_i$$

O(2000) independent operators of all combinations,

Most of the 4-fermions operators bounded by FCNC:

$g_i/\Lambda < 1/(30 - 100)$ TeV

Michael Spannowsky,

High scale or flavor symmetry?

What controls the mixing structure:

"Minimal Flavor Violation" for BSM?

The b rare decays are pushing the limits:

e.g. LHCb+CMS: arXiv:1411.4413

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

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

Watch out the Higgs: t → hc, hu, τμ

George Hou;
Kai-Feng Chen
TH, Marfatia PRL, '01
R. Harnik et al., '13

Dim-6: Rich Physics

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{g_i^2}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$$

Genuine Higgs operators to parameterize new physics g_i/Λ

Operators involving bosons only

$$\mathcal{O}_H = 1/(2v^2)\left(\partial^\mu\left(\Phi^\dagger\Phi\right)\right)^2$$
$$\mathcal{O}_T = 1/(2v^2)\left(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right)^2$$
$$\mathcal{O}_6 = -\lambda/(v^2)\left(\Phi^\dagger\Phi\right)^3$$
$$\mathcal{O}_B = (ig')/(2m_W^2)\left(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right)(\partial^\nu B_{\mu\nu})$$
$$\mathcal{O}_W = (ig)/(2m_W^2)\left(\Phi^\dagger \sigma^i \overleftrightarrow{D}^\mu \Phi\right)(D^\nu W_{\mu\nu})^i$$
$$\mathcal{O}_{HB} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$$
$$\mathcal{O}_{HW} = (ig)/m_W^2\,(D^\mu\Phi)^\dagger\sigma^i(D^\nu\Phi)W^i_{\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2/m_W^2\,\Phi^\dagger\Phi\,B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_S^2/m_W^2\,\Phi^\dagger\Phi\,G^A_{\mu\nu}G^{A\mu\nu}$$
$$\mathcal{O}_{H\tilde{B}} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)\tilde{B}_{\mu\nu}$$
$$\mathcal{O}_{H\tilde{W}} = (ig)/m_W^2\,(D^\mu\Phi)^\dagger\sigma^i(D^\nu\Phi)\tilde{W}^i_{\mu\nu}$$
$$\mathcal{O}_{B\tilde{B}} = g'^2/m_W^2\,\Phi^\dagger\Phi\,B_{\mu\nu}\tilde{B}^{\mu\nu}$$
$$\mathcal{O}_{G\tilde{G}} = g_S^2/m_W^2\,\Phi^\dagger\Phi\,G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

Zhen Liu, this conference

V. Barger et al (2003);
G. Giudice et al. (2007)
Ian Low et al. (2008)

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:

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

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

Higgs coupling deviations:

Δ:	VVH	bbH,ττH	ggH,γγH	HHH
Composite	(3-9)%	$(1\ \text{TeV}/f)^2$	(tree-level)	100%
H^0, A^0		$6\%\ (500\ \text{GeV}/M_A)^2$		
T'			$-10\%\ (1\ \text{TeV}/M_T)^2$ (loop)	
LHC 14 TeV, $3ab^{-1}$:	8%	15%	few%	50%

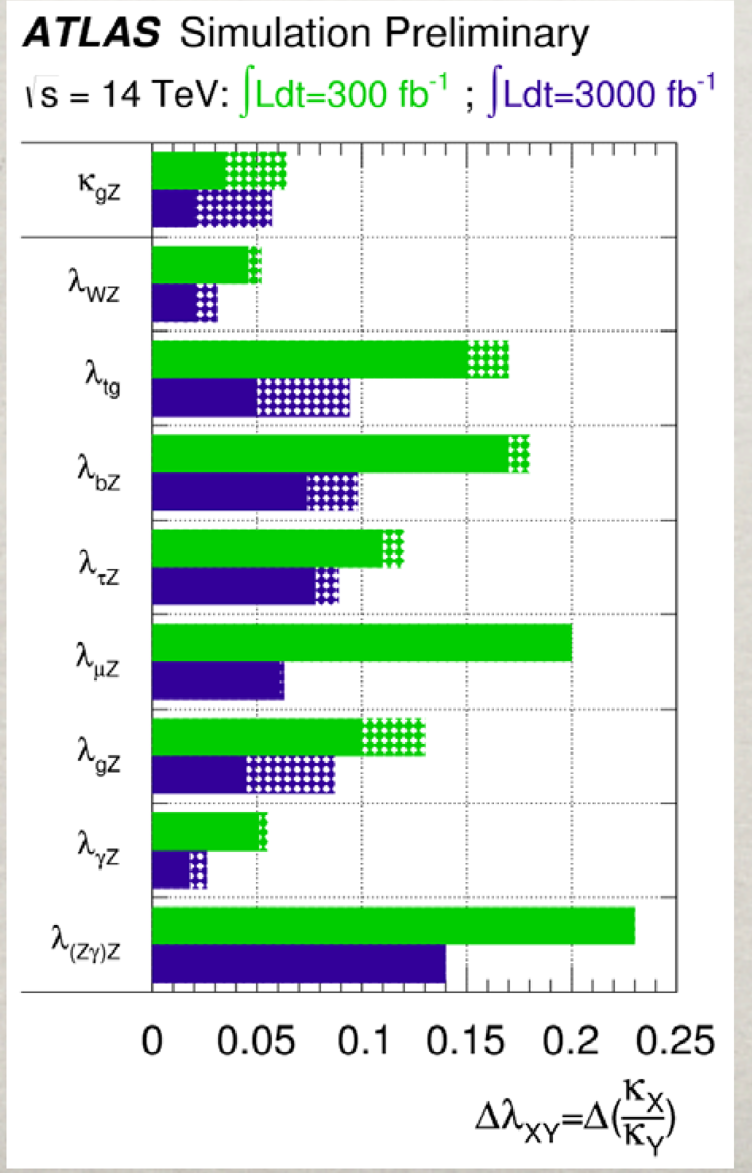
Future Is Bright!

LHC will be on the 2st phase Run 2@13 TeV, and on to HL-LHC:

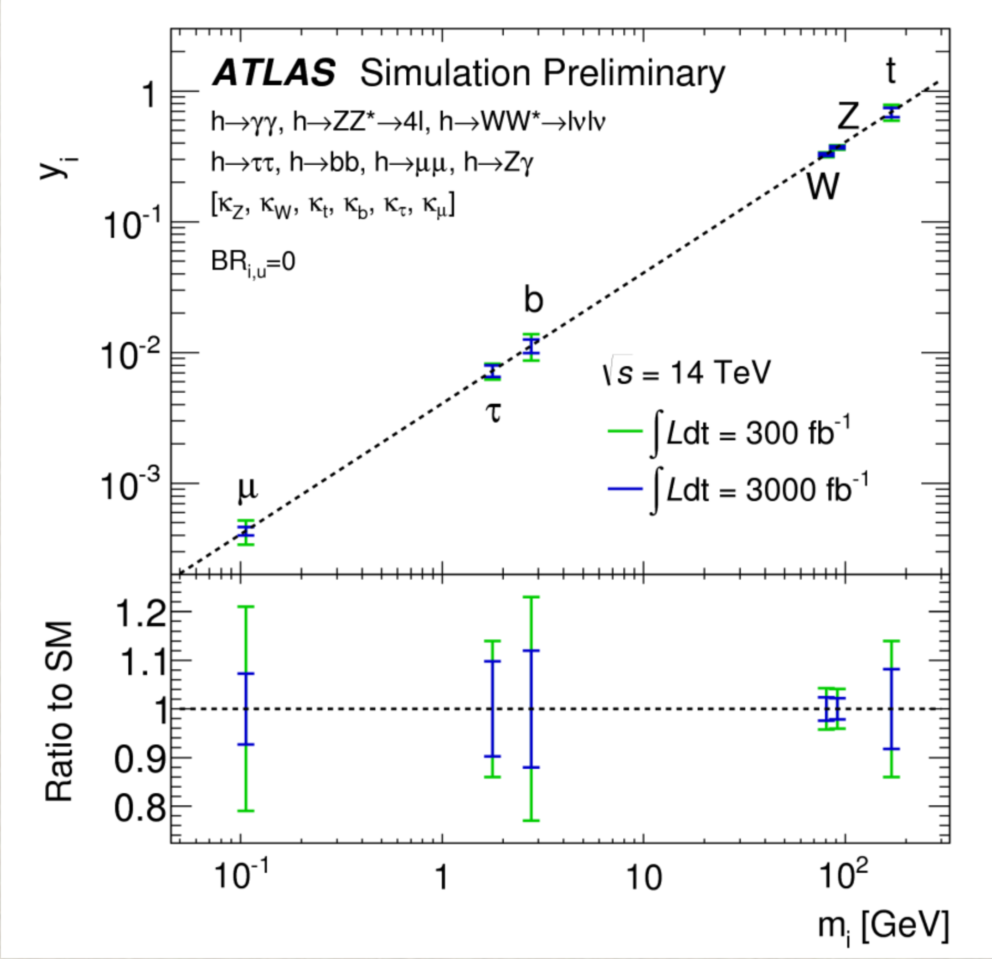
Prospects at HL-LHC

Jianming Qian, this conference

Significant improvements are expected from the ongoing and future LHC program



ATL-PHYS-PUB-2014-016



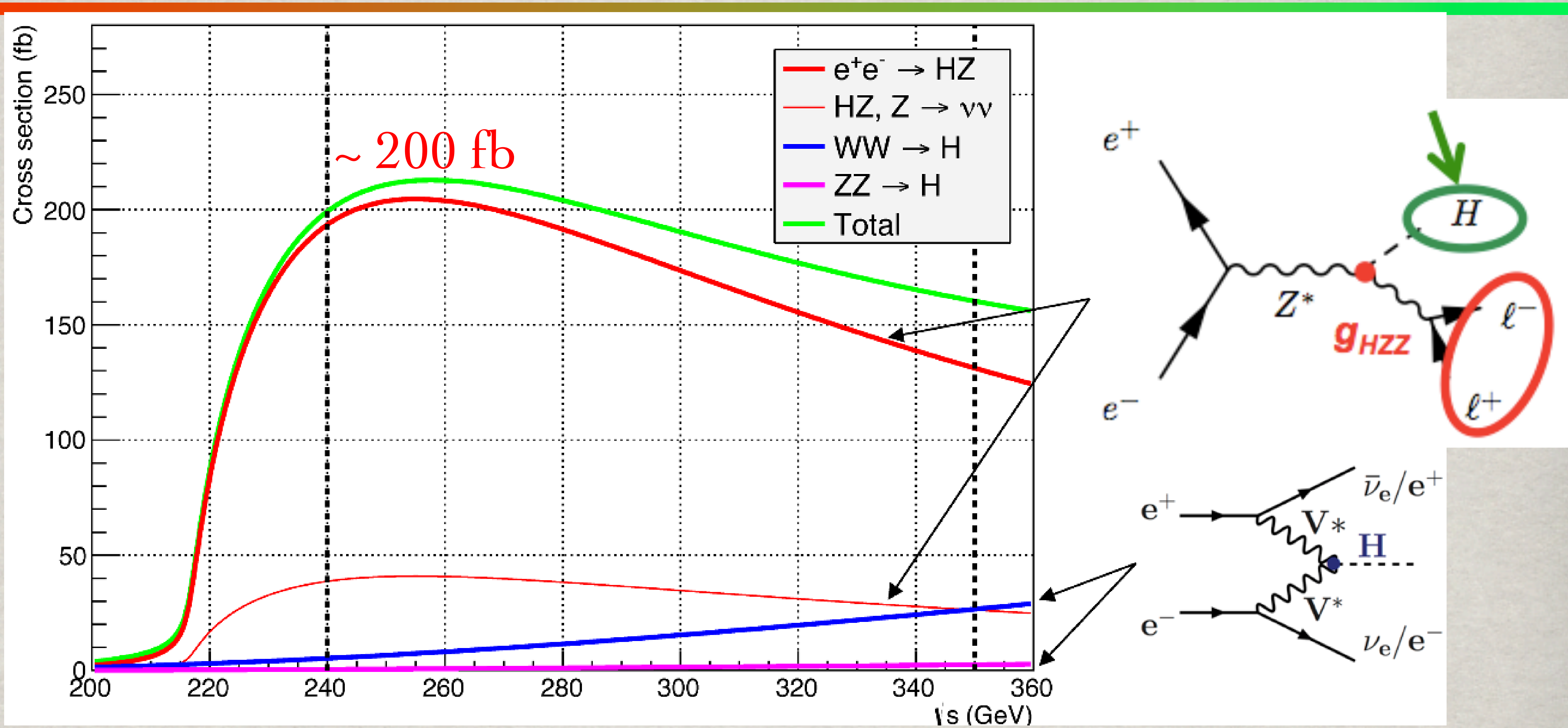
Higgs Factory

Any arrival of a new particle welcomed with a "factory"

- Kaon factory (TRIUMF, '81)
- Tau-charm factory (CLEO, BEPC, 90's and on)
- Z-factory (LEP-1, '89)
- W-factory (LEP-2, 2000; Tevatron, '83-2011)
- B-factory (BaBar,'08; Belle,'10; LHCb,'10; Belle-2)
- Top factory (Tevatron, LHC,'10 & on)
- Higgs factory: A must ! (ILC, CEPC/FCC-ee)

Manqi Ruan, Jinming Qian,
Akira Yamamoto, this conferene

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, $\Gamma_H \sim$ 5-8%, $\Delta m_H \sim 50$ MeV)

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

  TLEP Report: 1308.6176

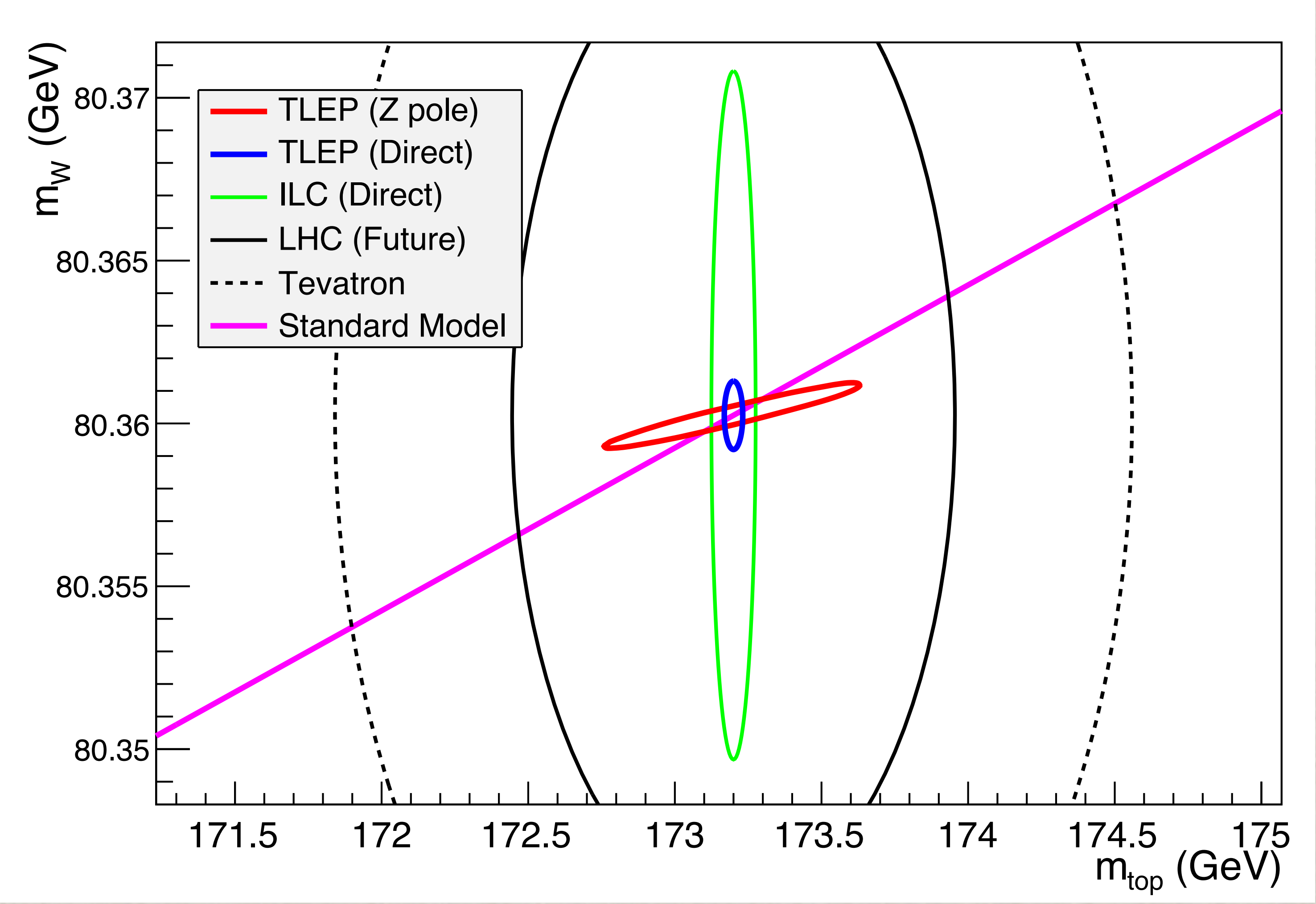
Z-Factory: Tera (10^{12}) Z Physics

TLEP Report: 1308.6176

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

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

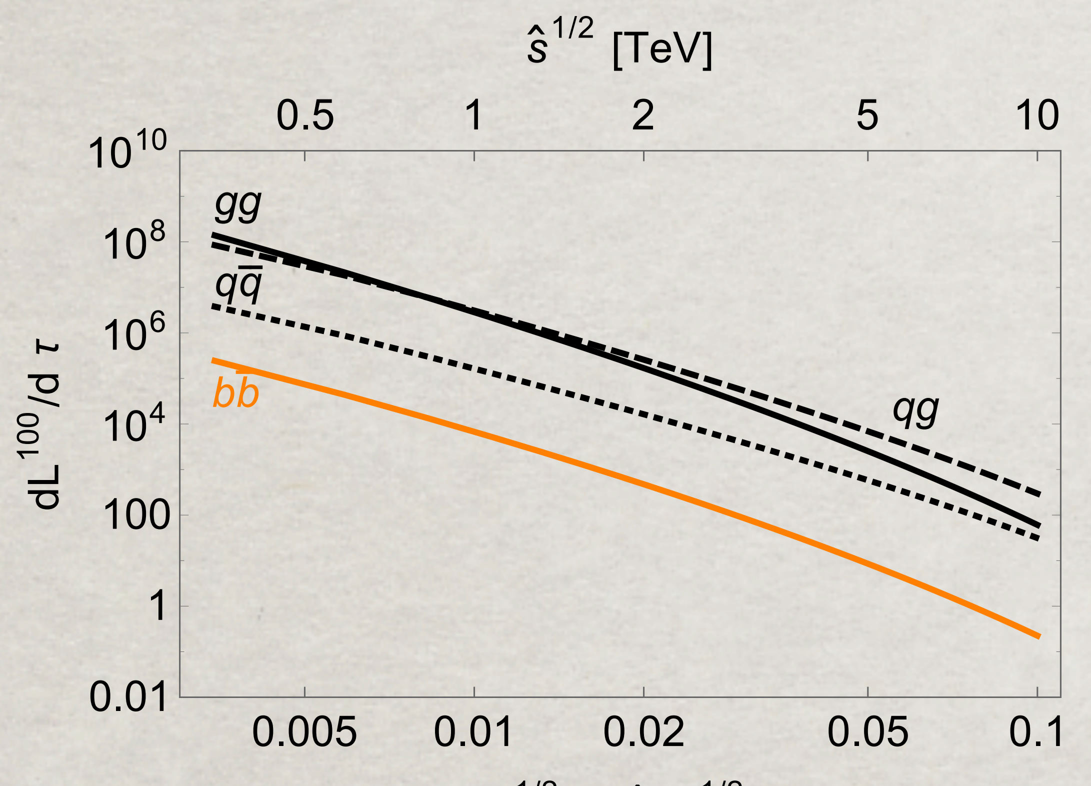
$\Delta M_W \sim O(1\ \text{MeV})$, $\Delta m_t \sim O(10\ \text{MeV})$, $\Delta m_H \sim O(10\ \text{MeV})$.

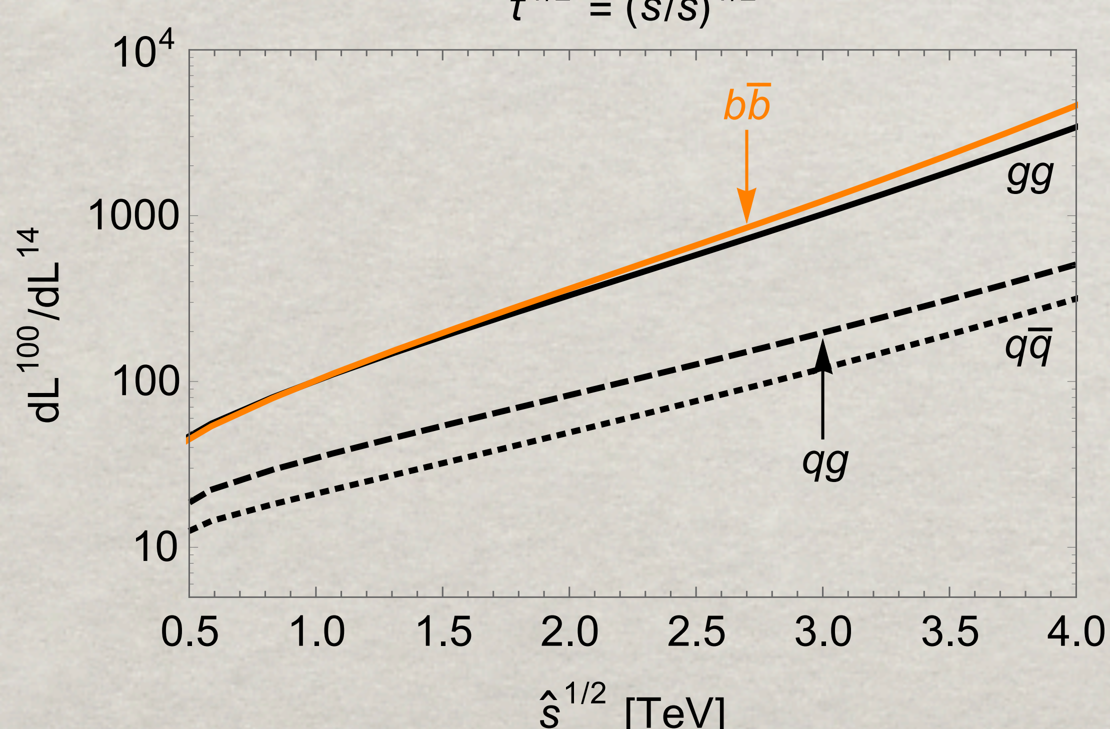


The Next Energy Frontier:
Tevatron → LHC → 100 TeV pp Collider

7x 7x

N. Arkani-Hamed, TH, M.Mangano, L.-T. Wang: arXiv:1511.06495



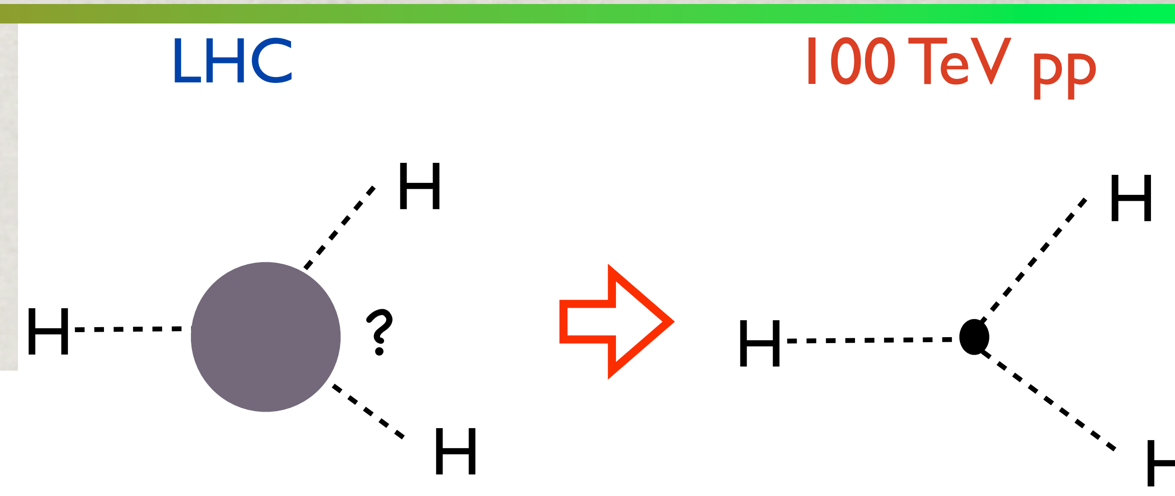


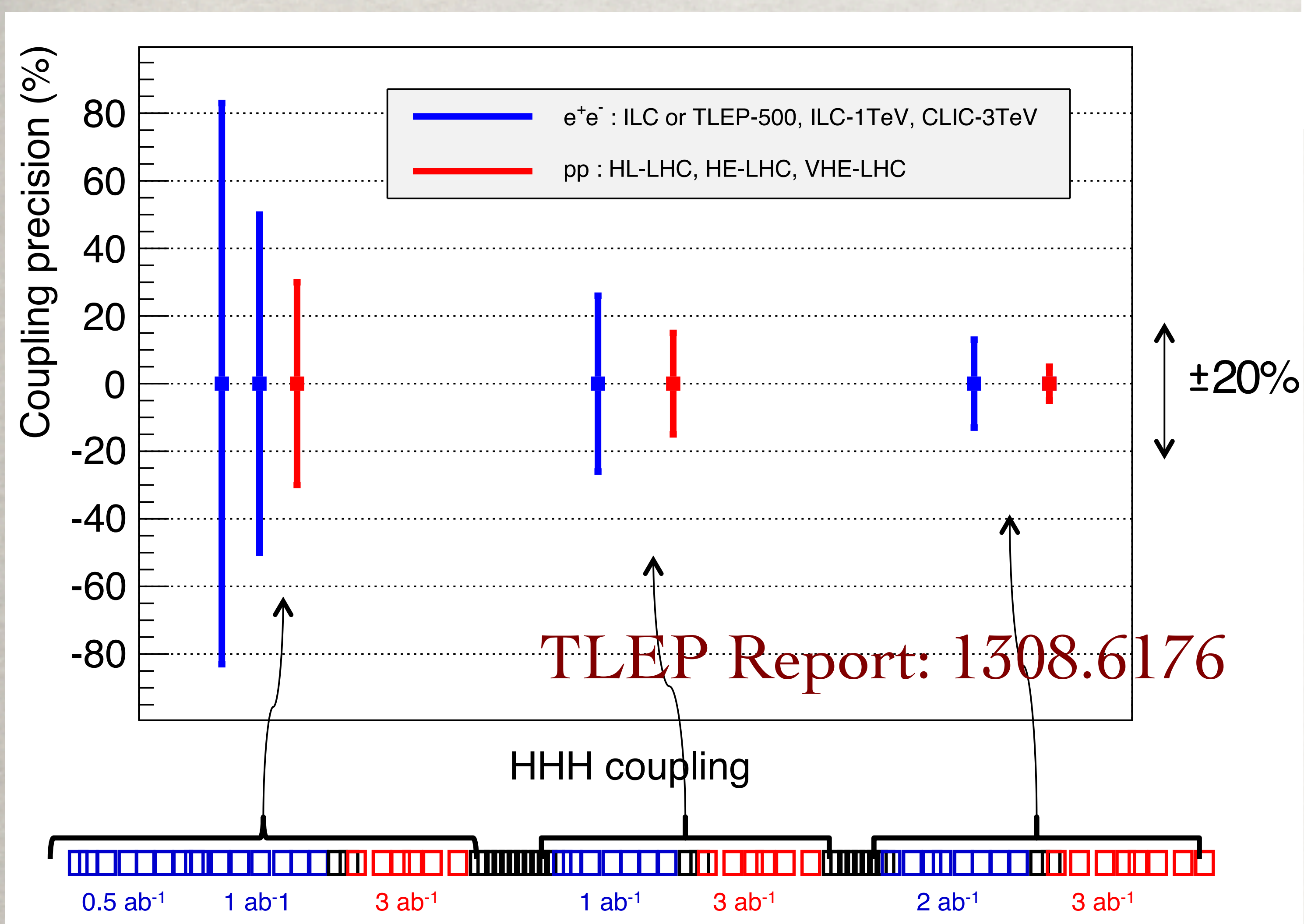
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

Higgs Self-couplings:

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

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





TLEP Report: 1308.6176

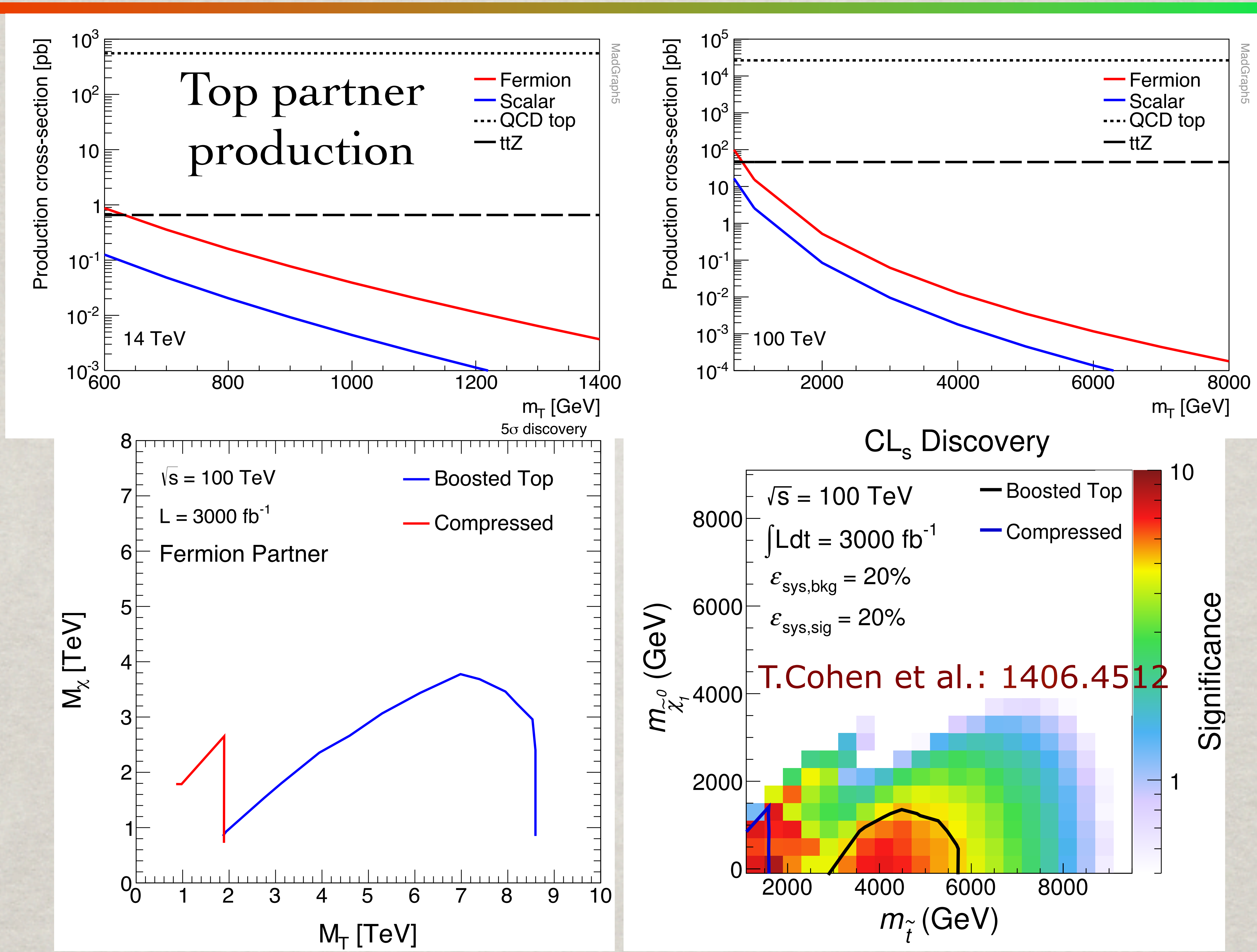
Triple coupling sensitivity:

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

Snowmass 1310.8361

	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‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

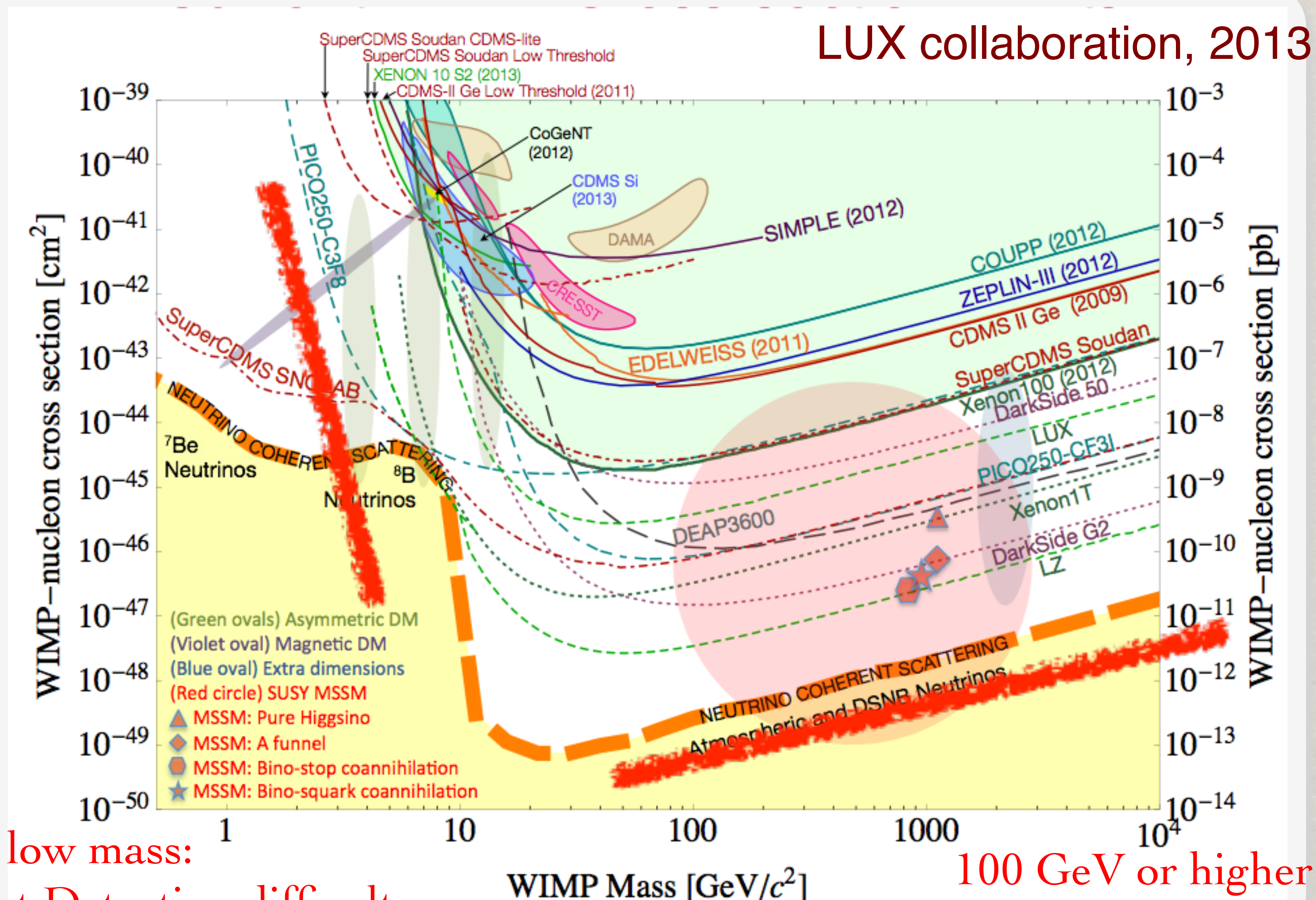
Pushing the “Naturalness” limit



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!

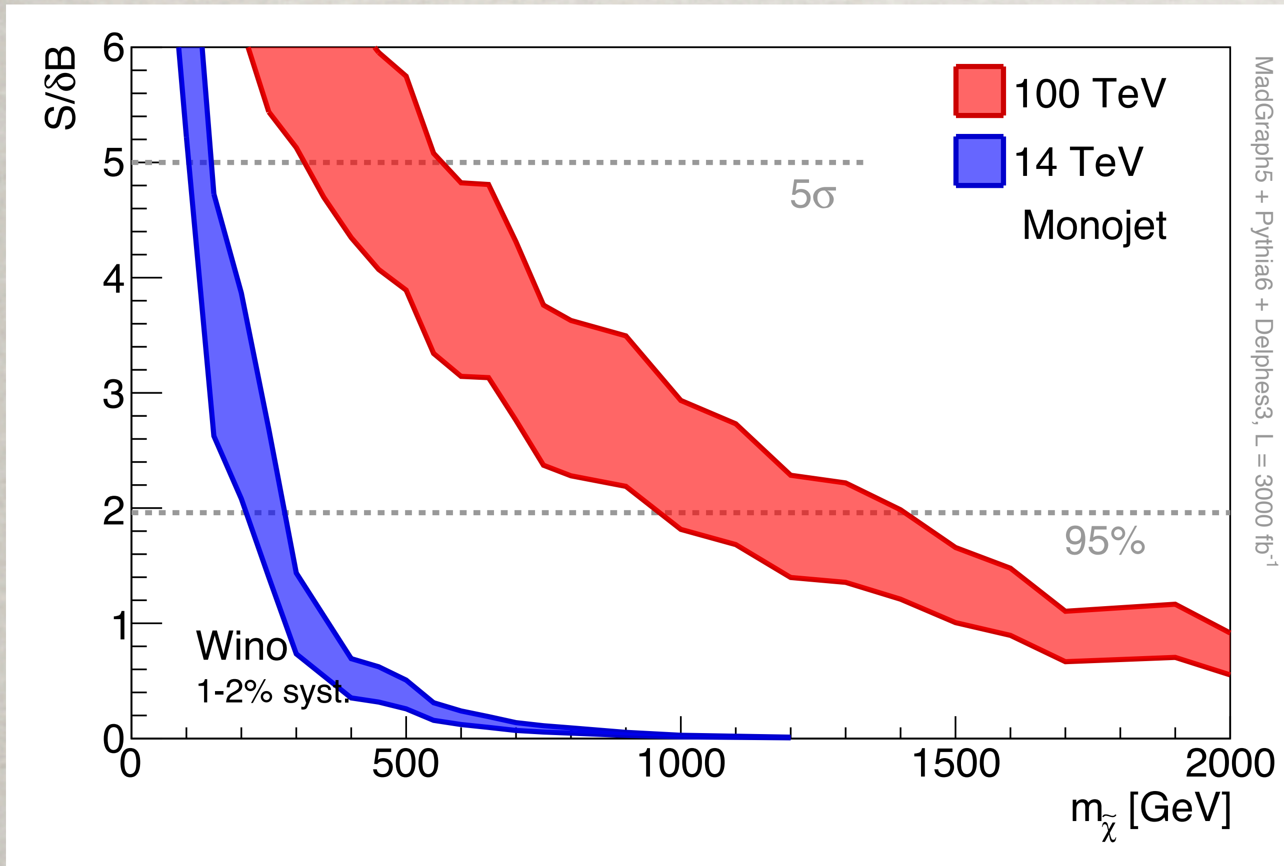
DM Searches

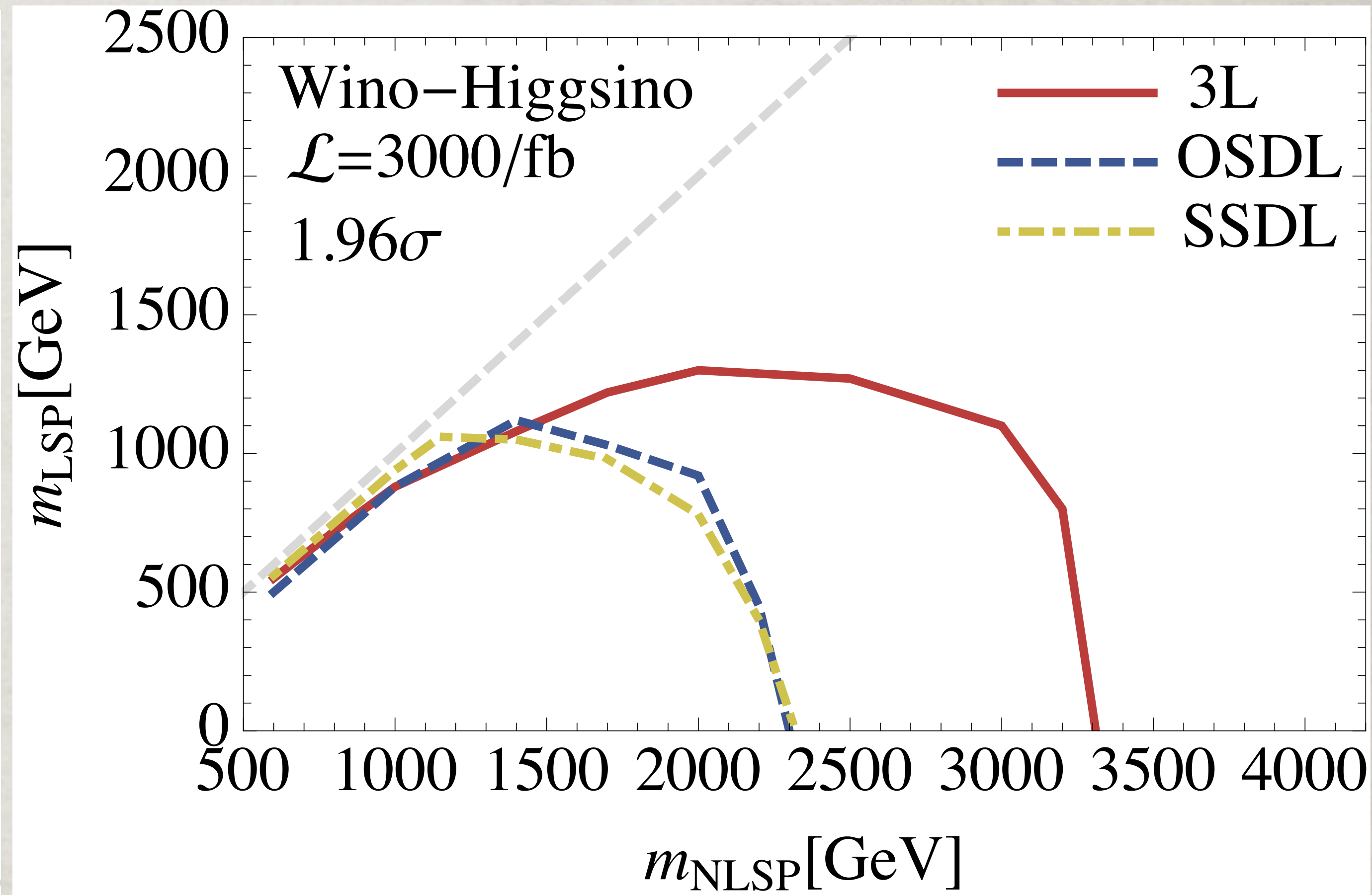


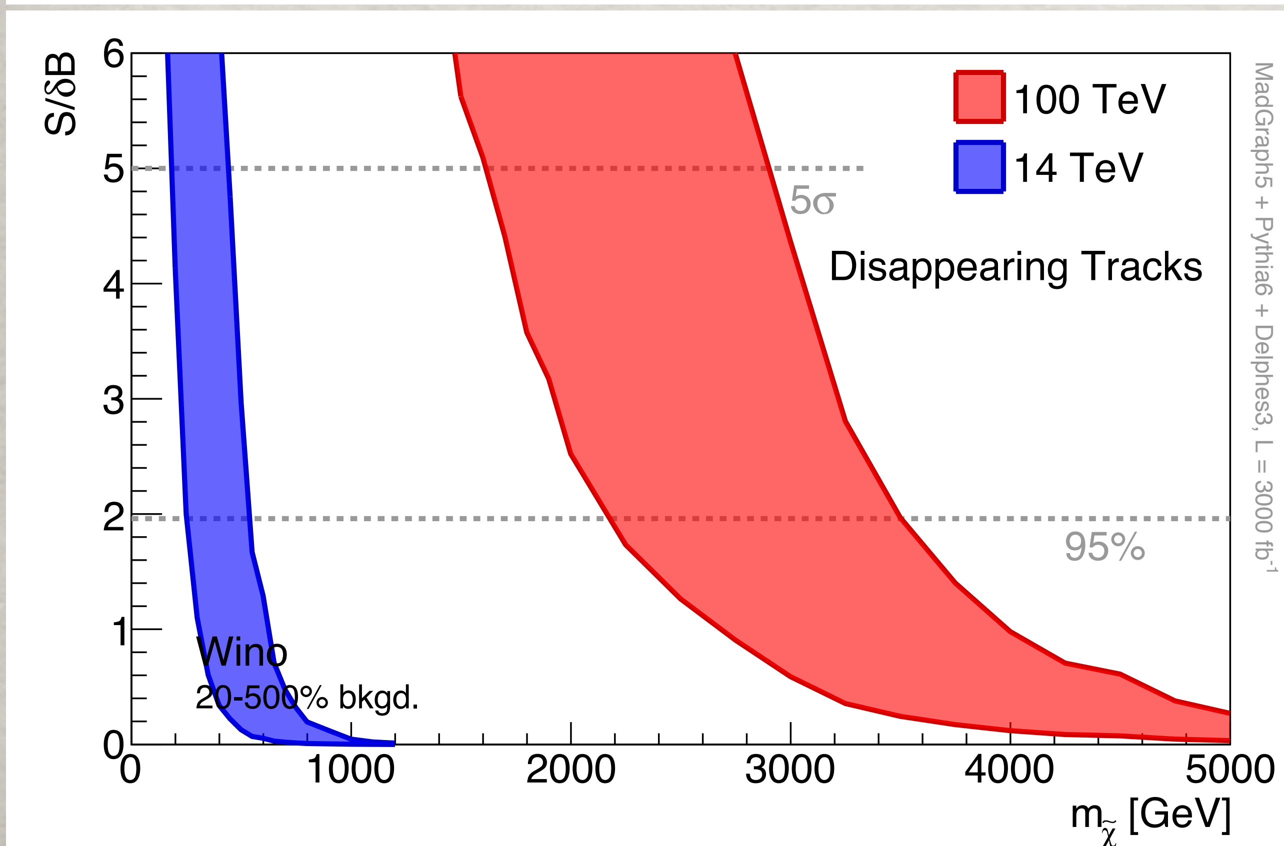
GeV low mass:
Direct Detection difficult;
Collider complementary

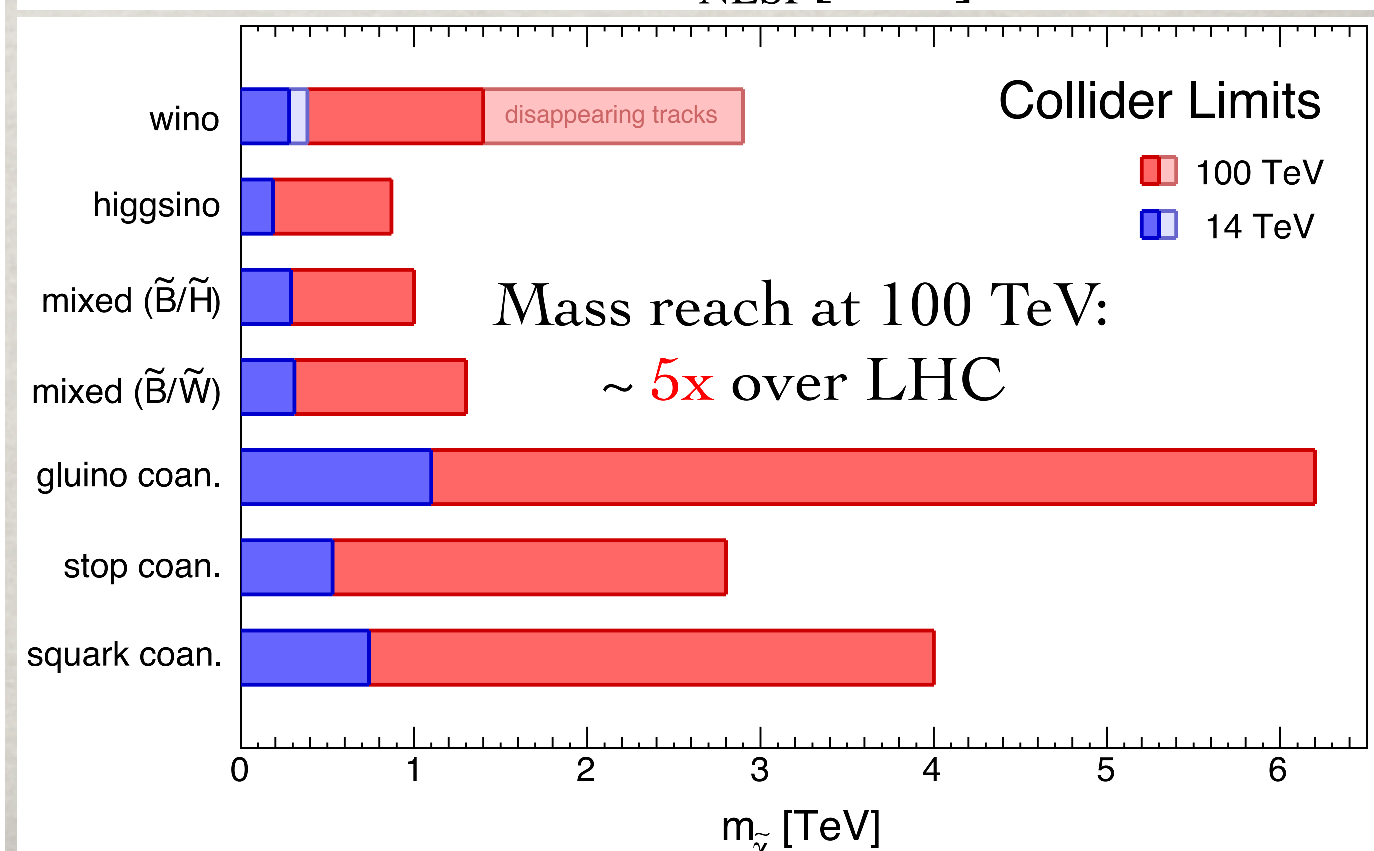
100 GeV or higher mass:
DD + ID + HE Collider

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









Summary

It is an exciting time in HEP!

- LHC leads the way: Run2, HL-LHC
- Flavor physics: LHCb, Belle2, neutrino expts
- Cosmo/astro observations

New discoveries will be from the frontiers!

It is exciting to think about the future

- Higgs factory (ILC/CEPC/FCC-ee)is a "must"!
- 100 TeV pp collider will take us a big leap:

Fine-tune $<10^{-4}$; $\lambda_{hhh} < 10\%$; WIMP DM ~ 5 TeV

In closing, it is an exciting conference!

Thank you, IAS - HKUST!
Especially,
Tao (Jr.), Henry, Prudence &
Charlie, Jie, Joao, Shan, Yanjun