Higgs Physics

Open Questions and New Ideas

Hitoshi Murayama (Berkeley, Kavli IPMU Tokyo)

Snowmass Energy Frontier WS, July 21, 2020

LINEAR COLLIDER COLLABORATION

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

東京大学 THE UNIVERSITY OF TOKYO

UTIAS 東京大学国際高等研究所 THE UNIVERSITY OF TOKYO INSTITUTES FOR ADVANCED STUDY

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

2014 US P5 report:

"Use the Higgs boson as a new tool for discovery."

2017 JAHEP report:

"In light of the recent outcomes of the LHC Run 2, JAHEP proposes to promptly construct ILC as a Higgs factor with the center-of-mass energy of 250 GeV in Japan."

2020 European Strategy for Particle Physics:

"An electron-positron Higgs factory is the highest-priority next collider."

Michael Peskin yesterday

CHINA DAILY

Le Monde

LA DÉPÊCHE
La «particule de Dieu» existe

le dauphine
L'Univers livre enfin ses secrets

EL DIARIO

Libération
Physique des particules
La masse est dite

L'ECHO
Découverte du boson de Higgs
Particule élémentaire!

la Nouvelle République
La particule qui fait accélérer notre histoire

CORRIERE DELLA SERA

GULF NEWS

THE TIMES OF INDIA
Big bang moment: Scientists may have found 'God particle'

THE AUSTRALIAN
Carbon dealing not over for Labor

INDEPENDENT
EUREKA!

The New York Times

THE TIMES
Free inside
Diamond refuses to take blame for rate fix

Frankfurter Allgemeine

EL PAÍS
Levante

Milhares de moradores de bairros sociais em risco de perderem RSI

The Japan Times

Jornal Notícia

The Sydney

International Herald Tribune

LA RAZÓN

LA VANGUARDIA
El juez imputa a Rato y 32 consejeros de Bankia

Il Messaggero
Patto tra Monti e Merkel

Scientists prove existence of 'God particle'

DIE WELT

IL GAZZETTINO
Cancellata metà delle Province

LA STAMPA

la Repubblica

MK

מעריב

The Dallas Morning News

LA DÉPÊCHE
La «partic de Dieu» e

THE HINDU

The Telegraph
It walks, it quacks but best to...

l'Unità
Rai, colpo di mano di Schifani

The Gazette

THE JERUSALEM POST

LE BERRY RÉPUBLICAIN

L'EST RÉPUBLICAIN
Le secret du Big Bang percé

ALGEMEEN DAGBLAD
Ouderen mijden 'te dure' psychiater

আনন্দবাজার পত্রিকা
বিজ্ঞানের 'ঈশ্বর' দর্শন

la Croix
Le boson de Higgs enfin cerné

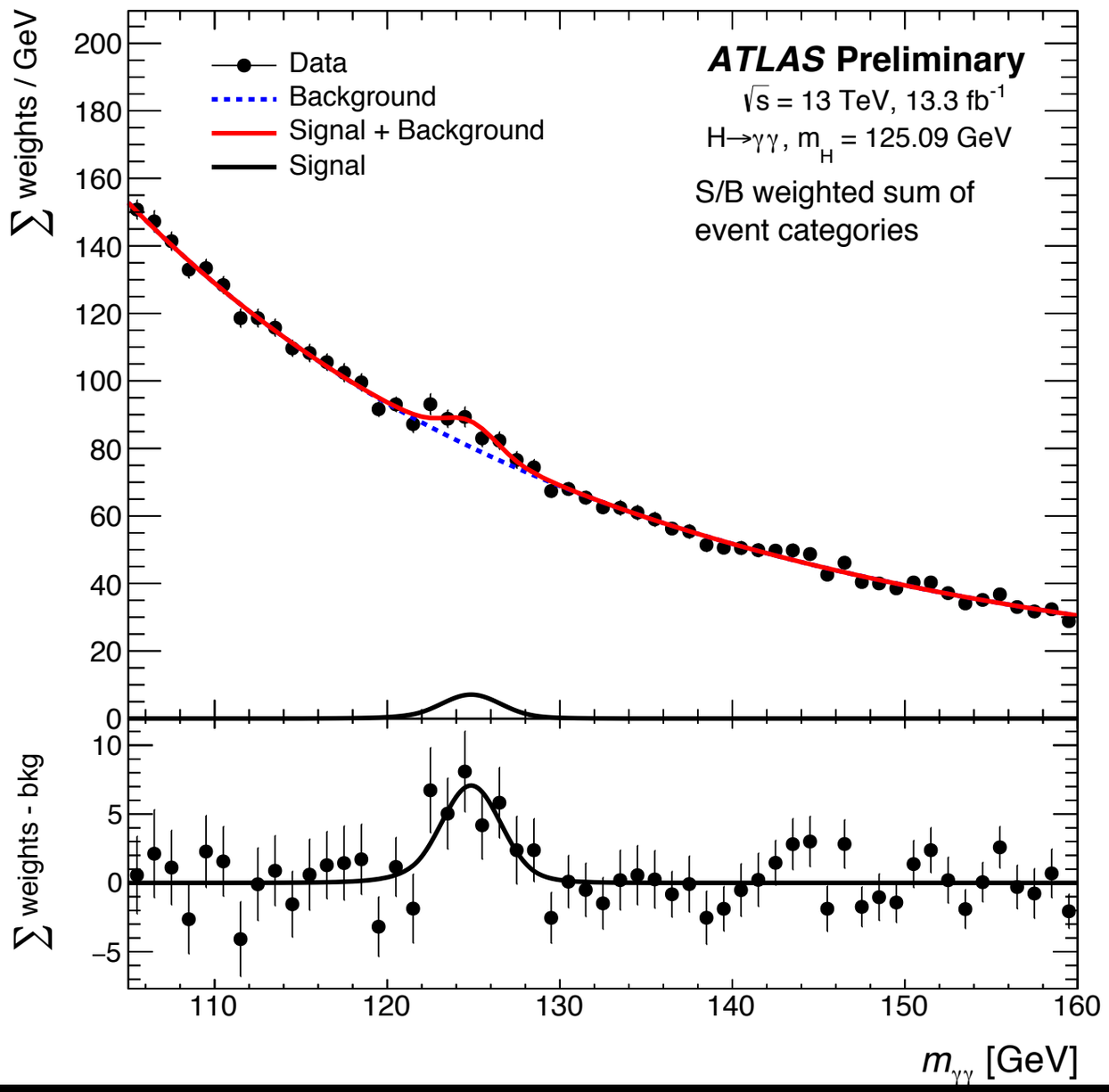
2012年(平成24)7月6日(木曜日)

宇宙探る基本理論完成へ

CERNでの実験概要(イメージ)

Higgs exists!

ATLAS-CONF-2016-067



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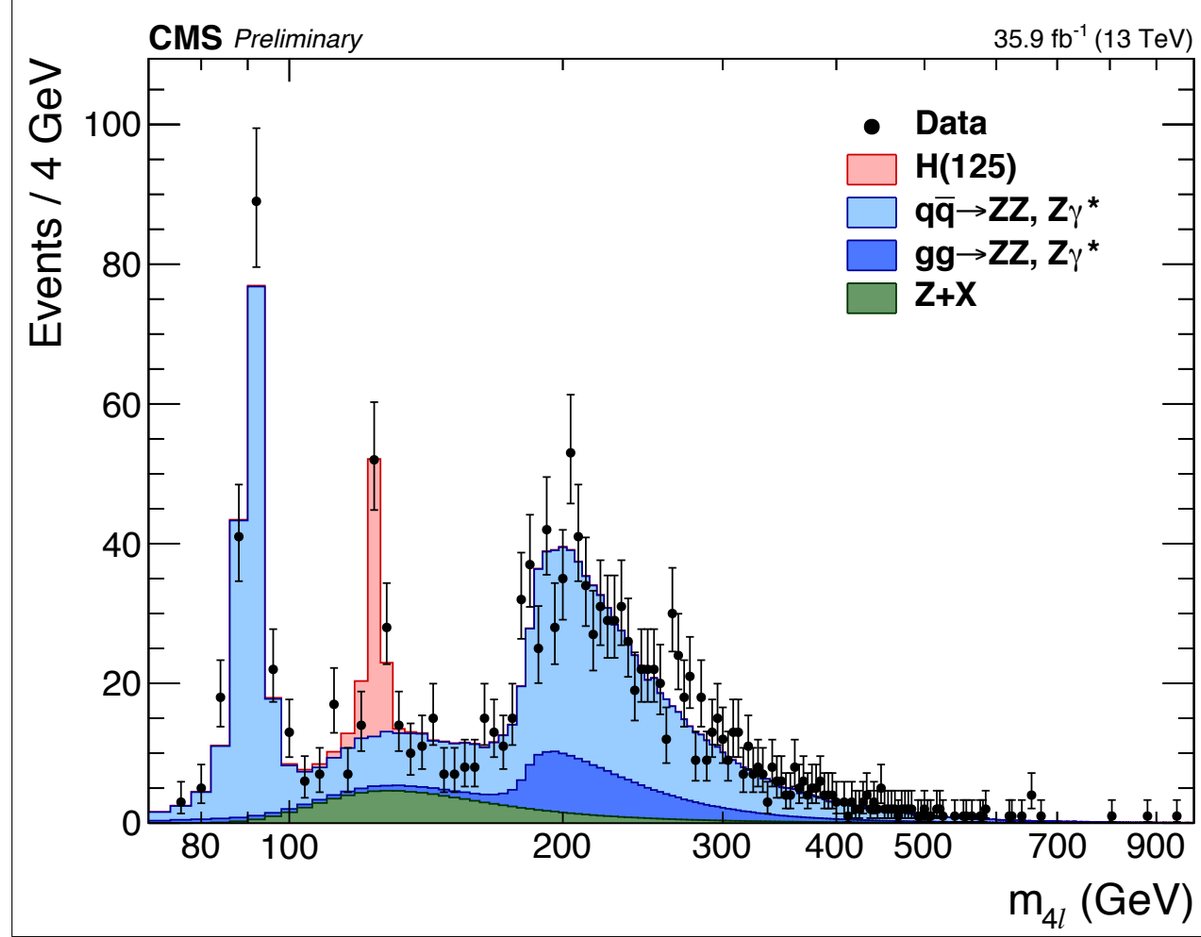
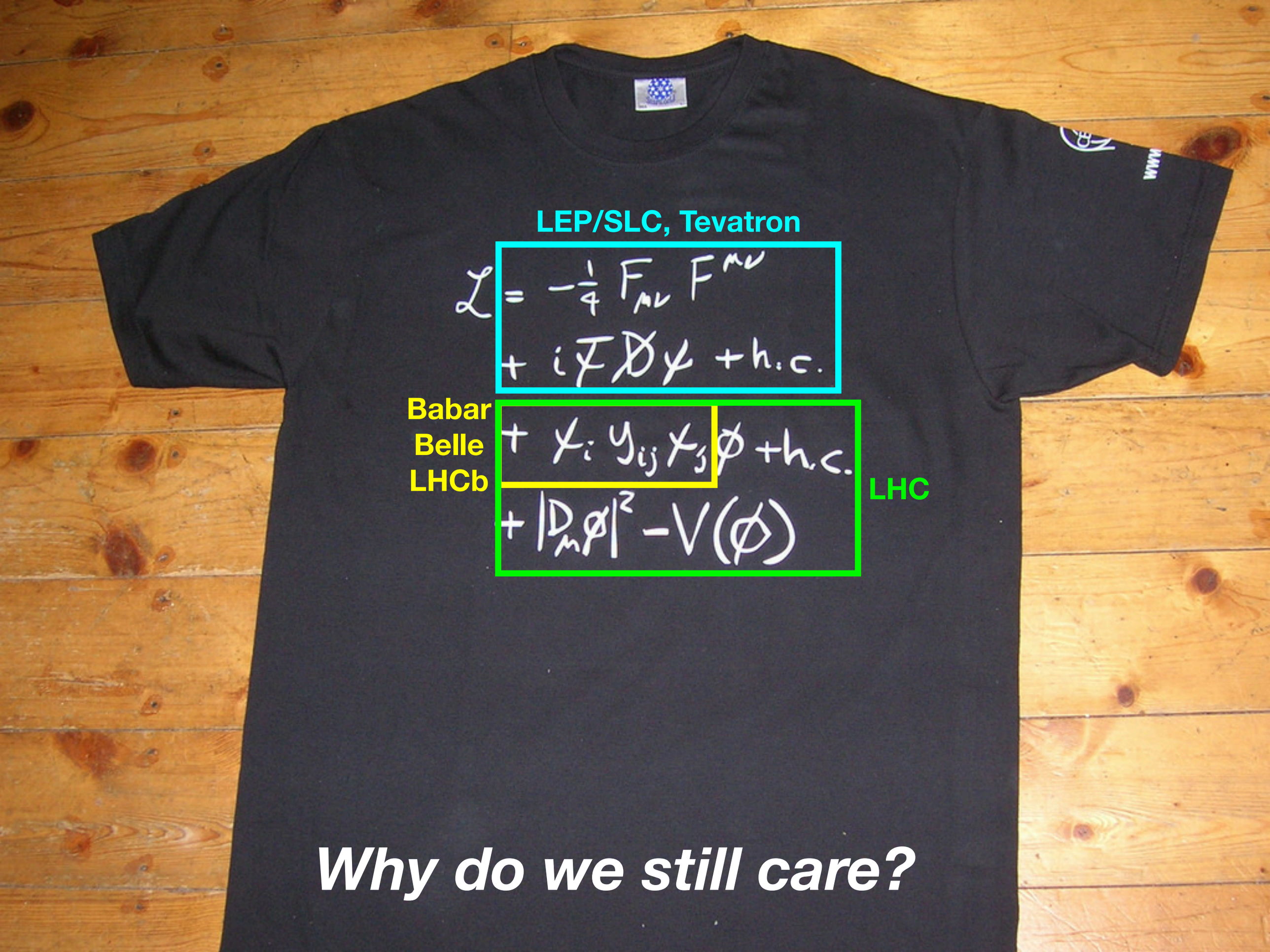
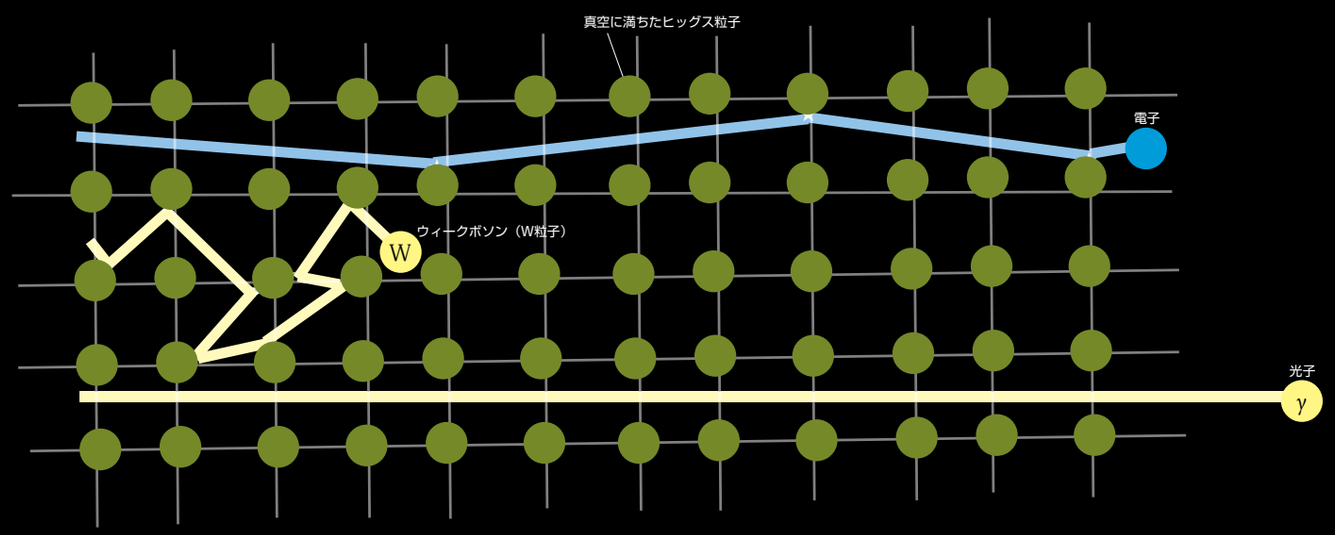


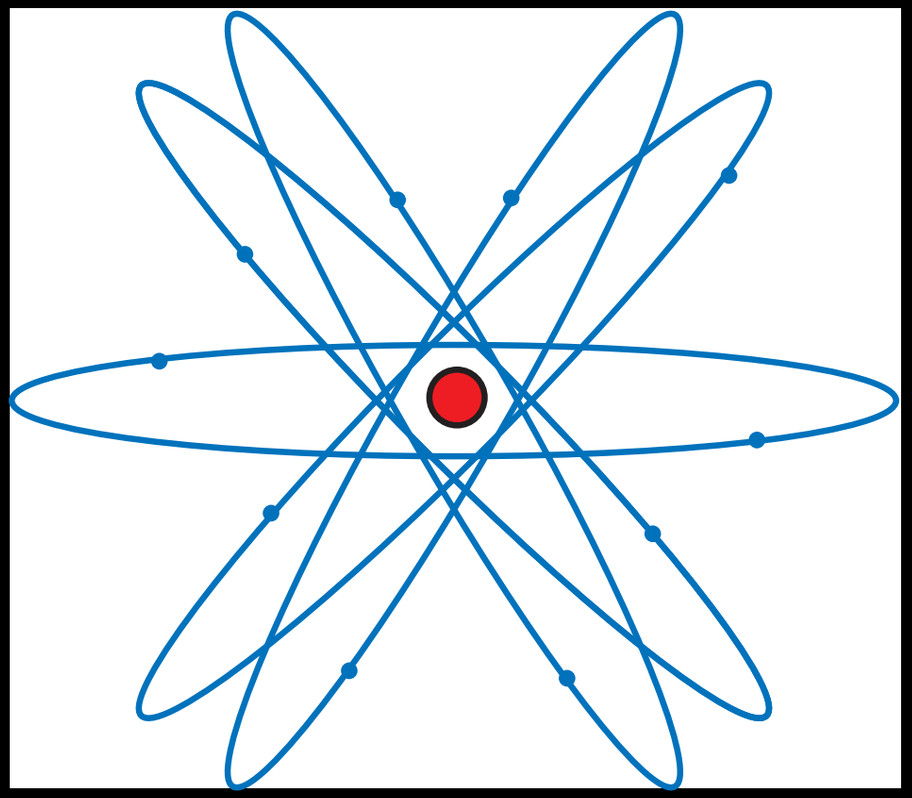
Jónatan Piedra


LEP/SLC, Tevatron
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
Babar
Belle
LHCb
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
LHC
Why do we still care?

Universe is filled with Higgs

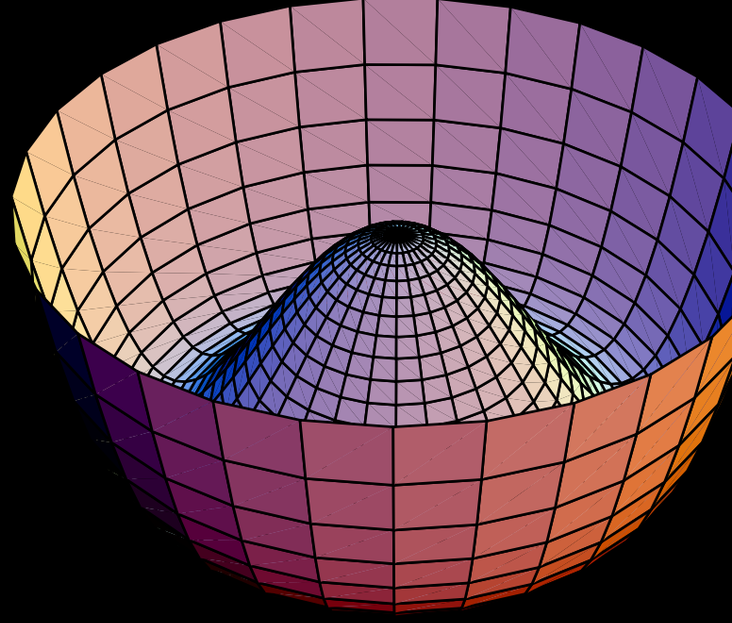


Particles slow down



Without Higgs,
we evaporate in
a billionth of a second

I hated it!



- Higgs boson is the *only spin 0 particle* in the standard model
  - we have never seen one before
  - one of its kind, no context
  - but does the most important job
- looks very artificial
- we still don't know *dynamics* behind the Higgs condensate
- *Higgsless theories*: now dead

Context for Scalar Bosons?

Supersymmetry

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

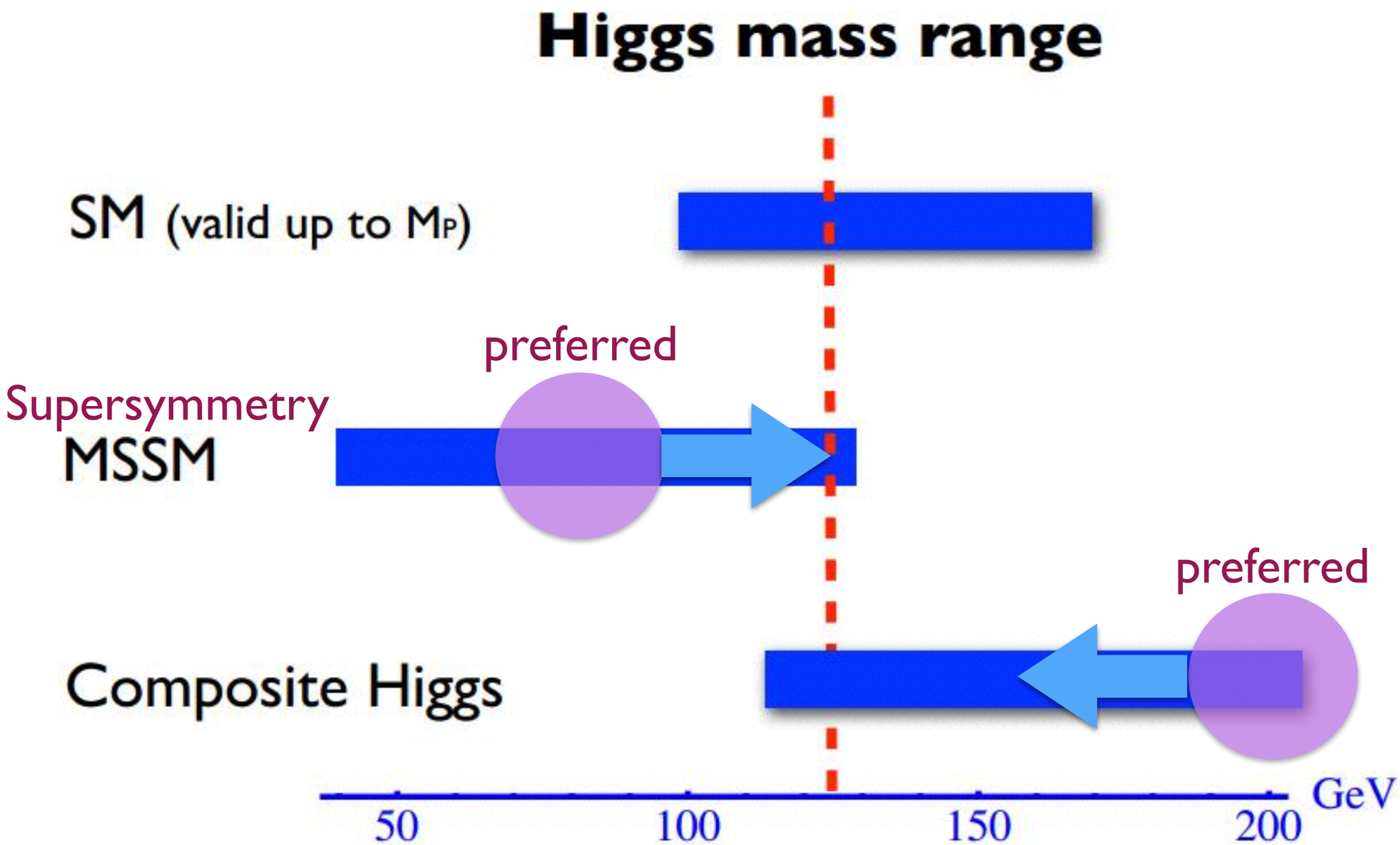
composite

- spins cancel among constituents
- condensate by a strong attractive force, holography
- top partner, pNGBs, vector-like quarks

Extra dimension

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

a different "naturalness" argument



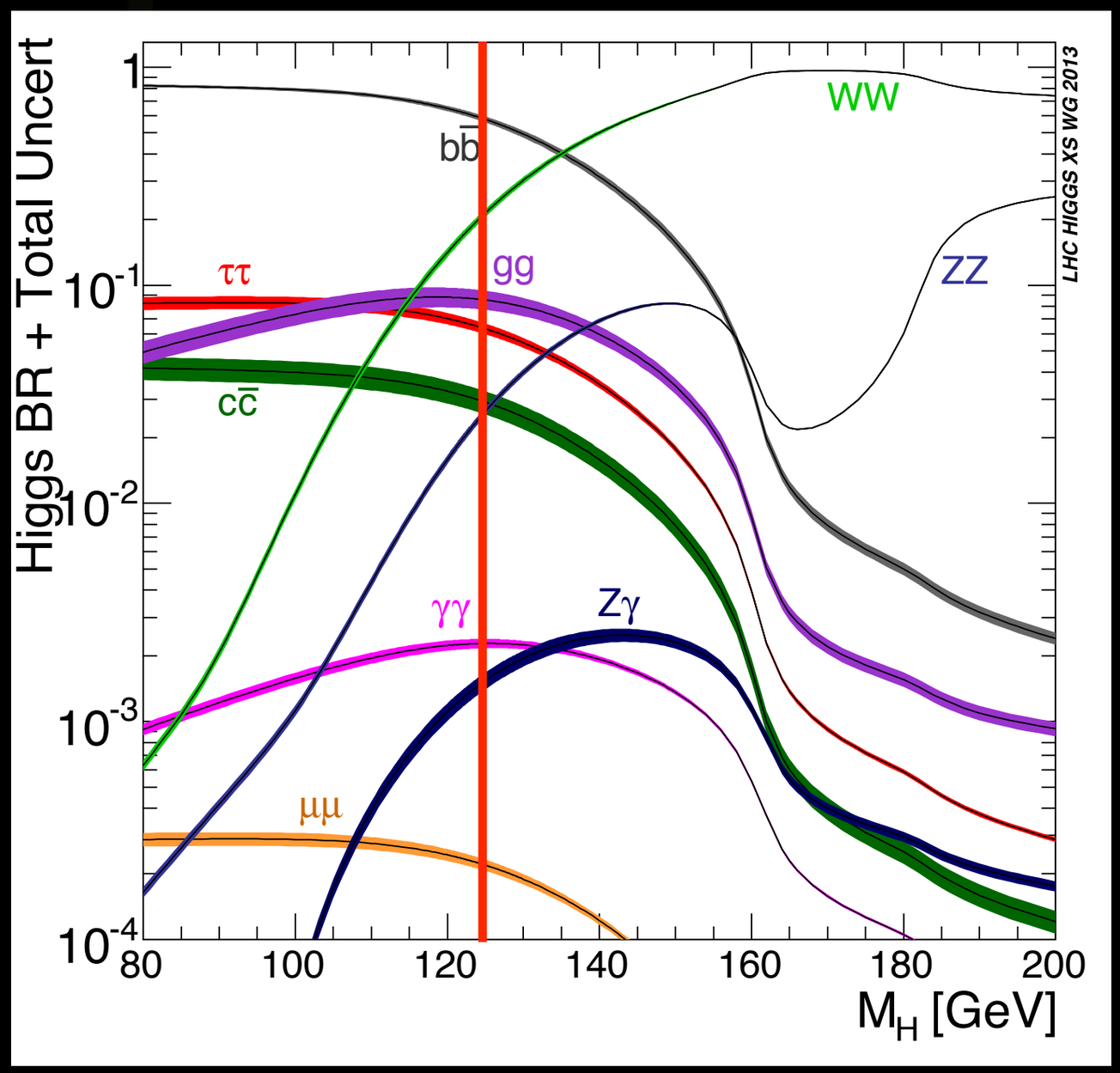
By A Pomarol

Hyung Do Kim

Nima’s anguish

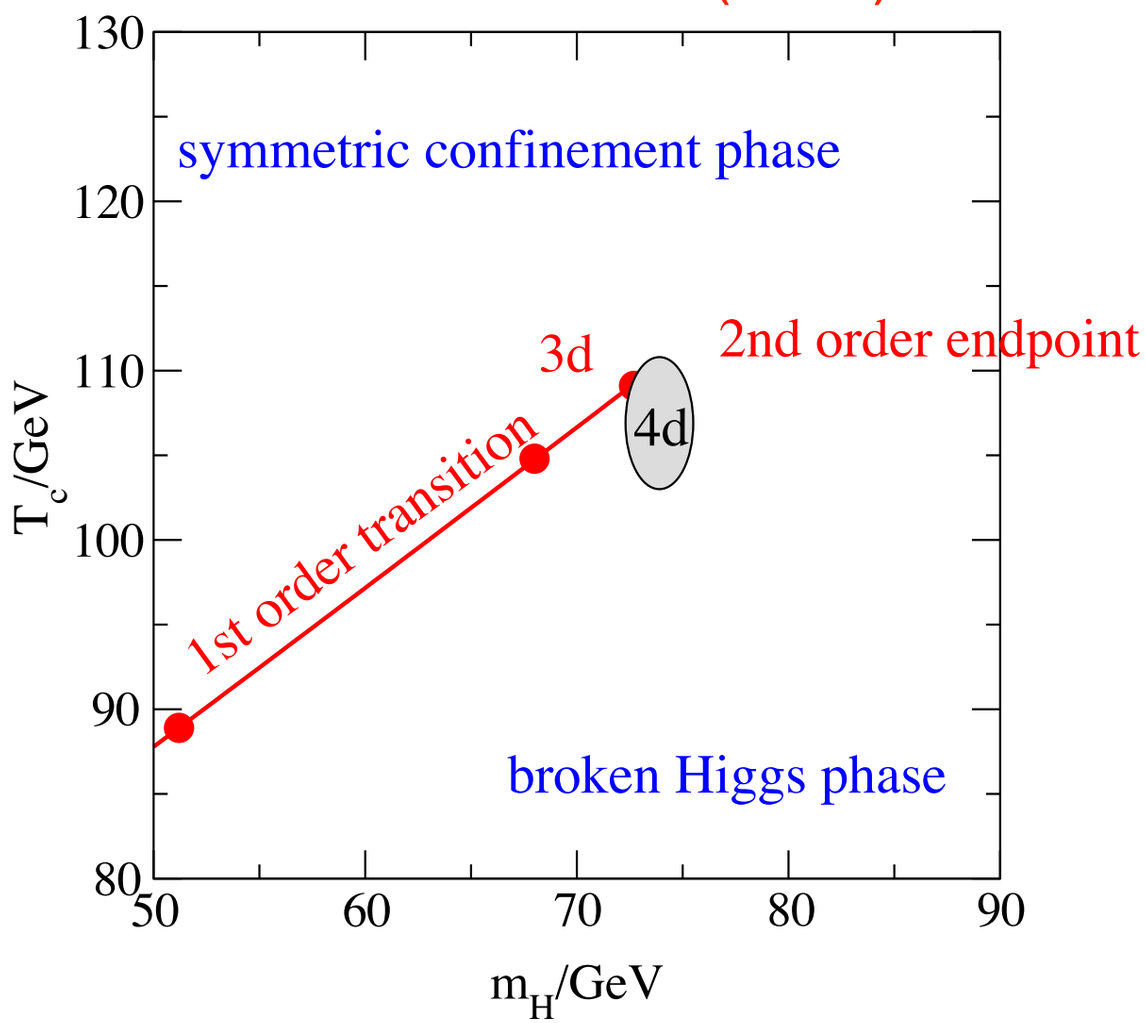
m_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

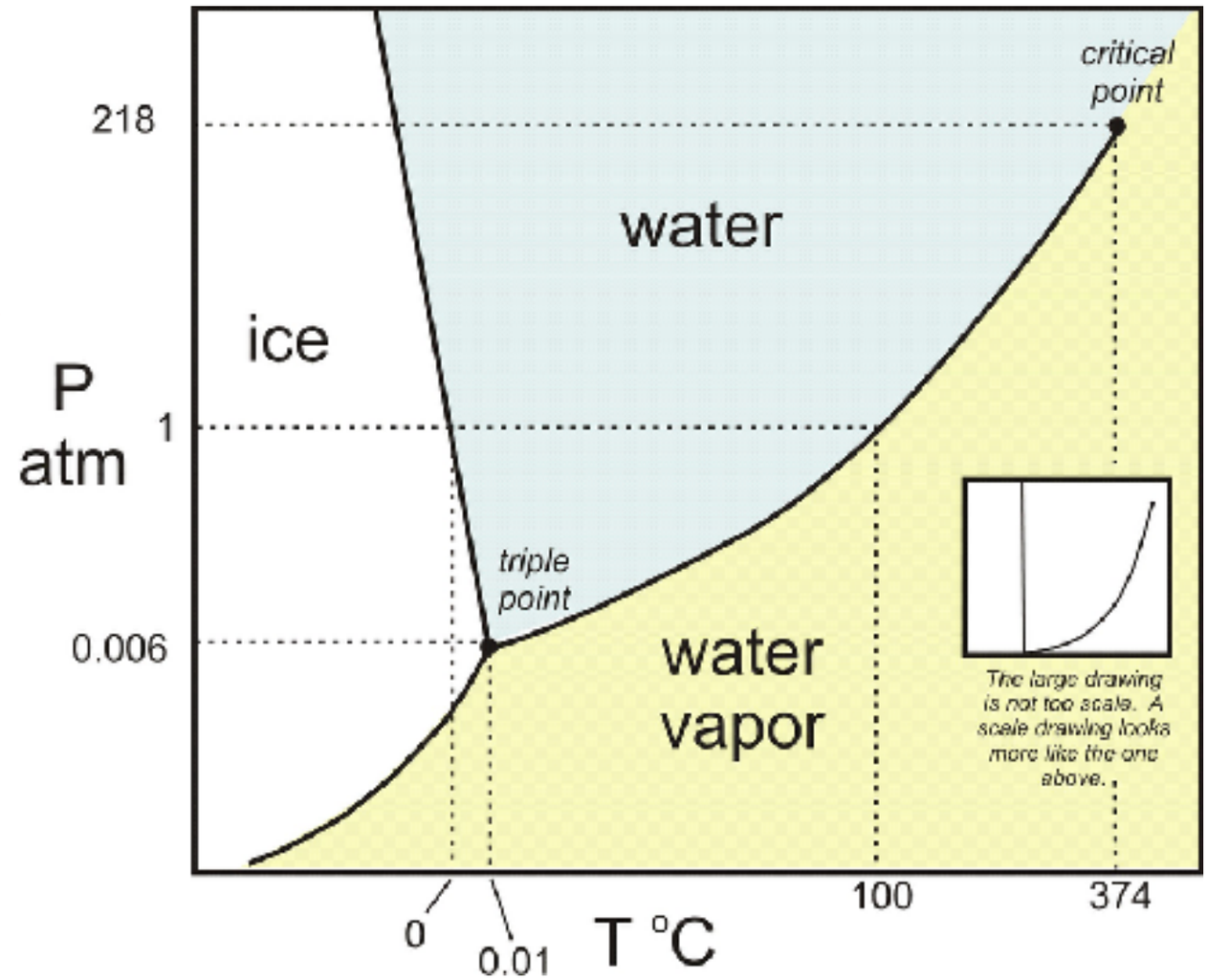
dream case for experiments



stupid not to do this!

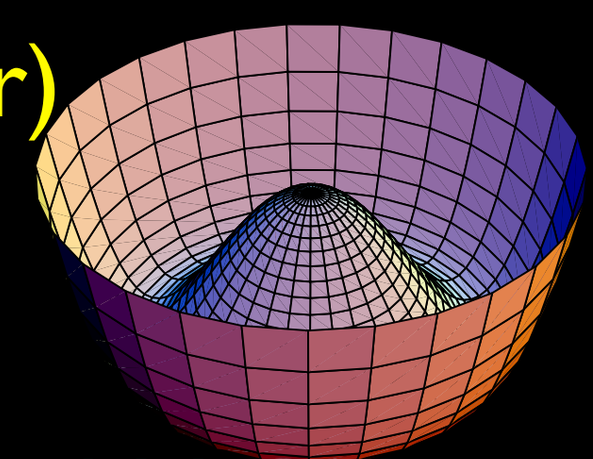
Mikko Laine (Bern)





$\langle H \rangle = 0$ from gauge invariance (Elitzur)

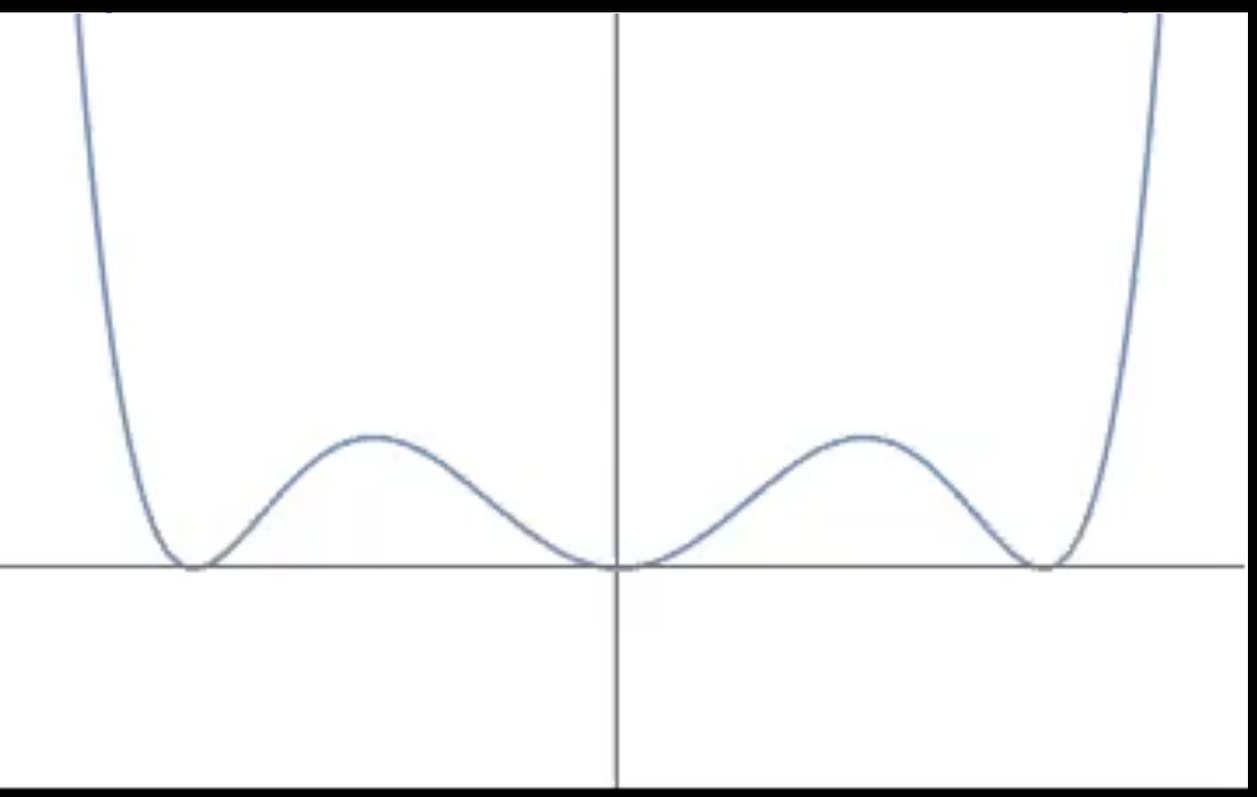
$\langle H^\dagger H \rangle$ is not an order parameter

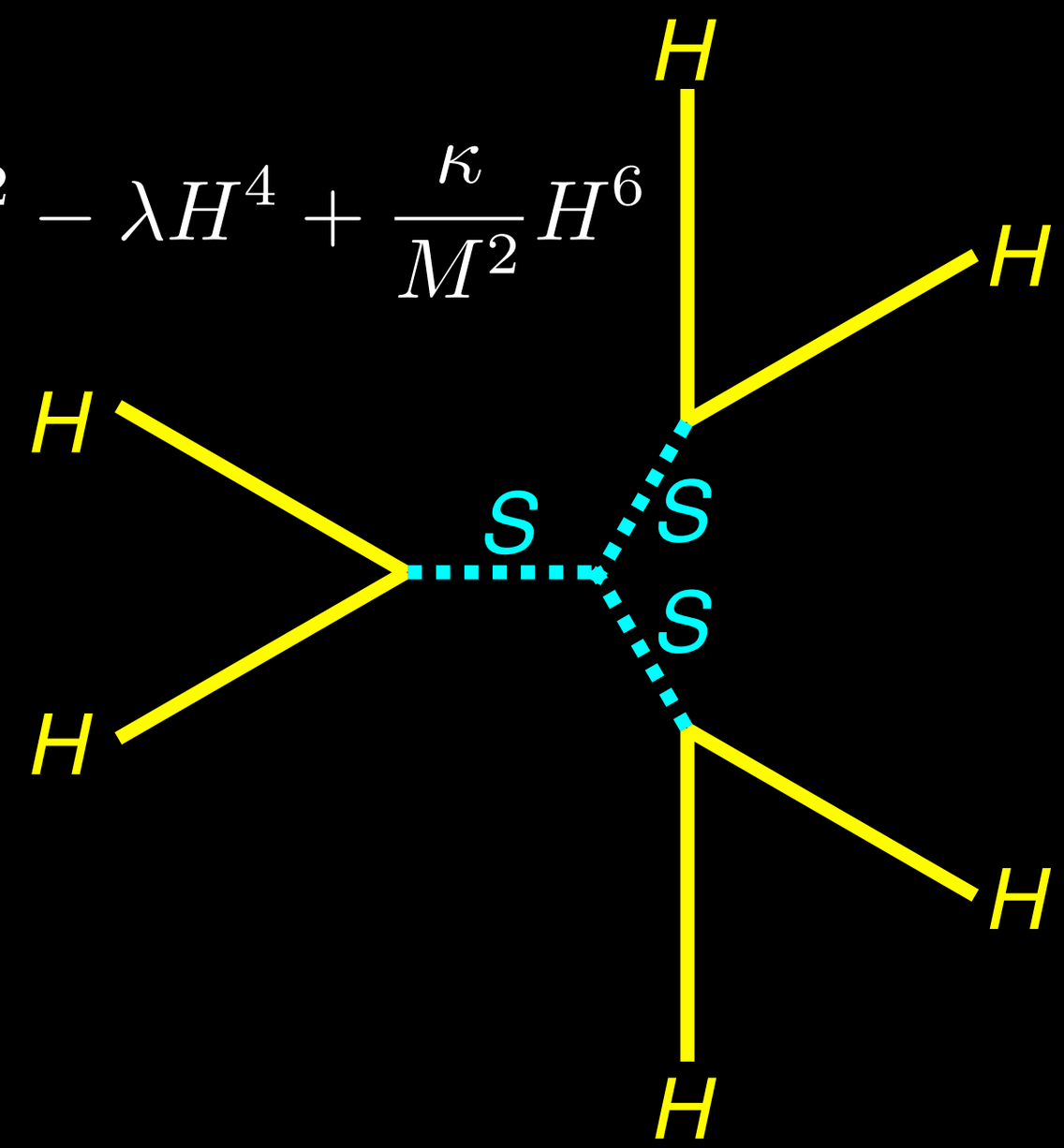


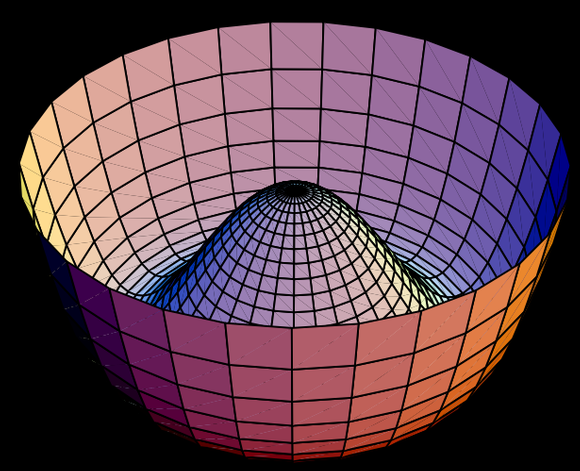
for m_h=125GeV, it is crossover

No phase transition in the Minimal Standard Model

$$V = \mu^2 H^2 - \lambda H^4 + \frac{\kappa}{M^2} H^6$$



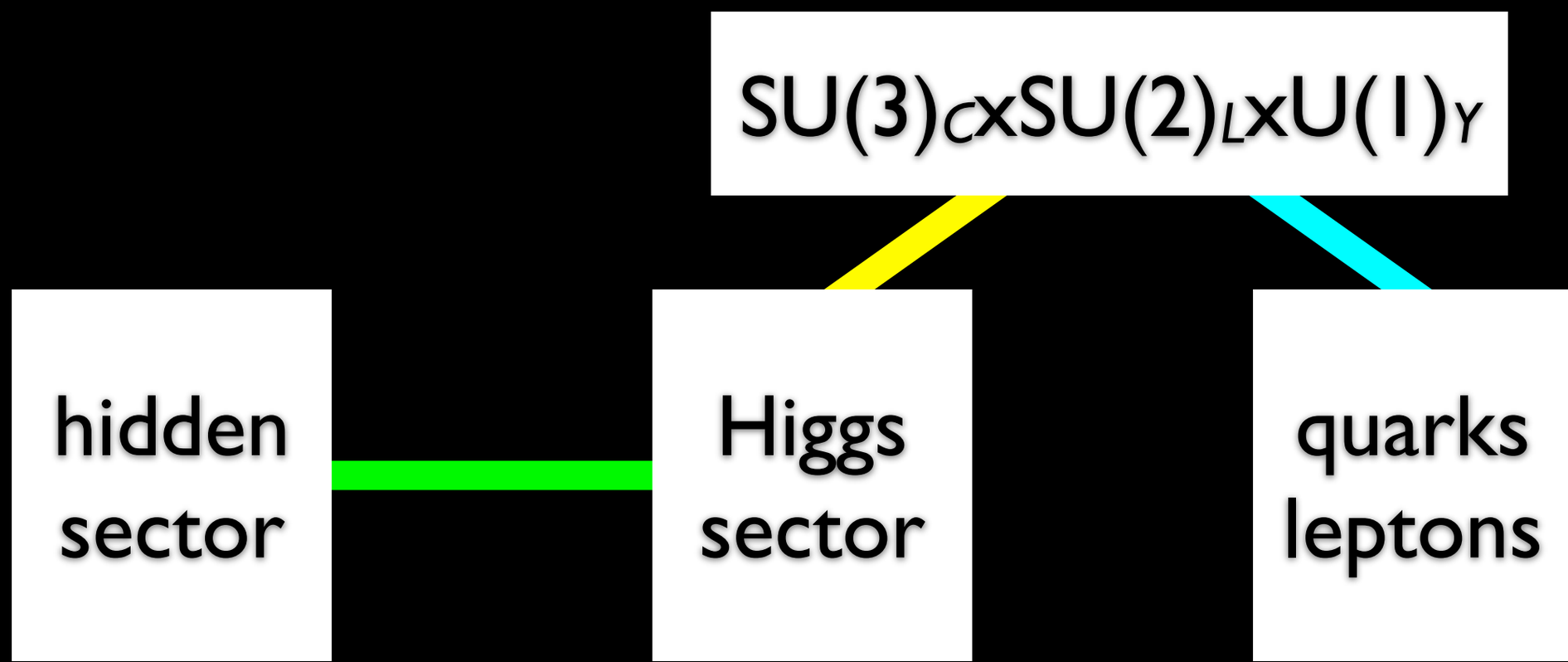




$$\lambda_{HHH} = 2.7\lambda_{HHH}^{SM}$$

Higgs as a portal

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

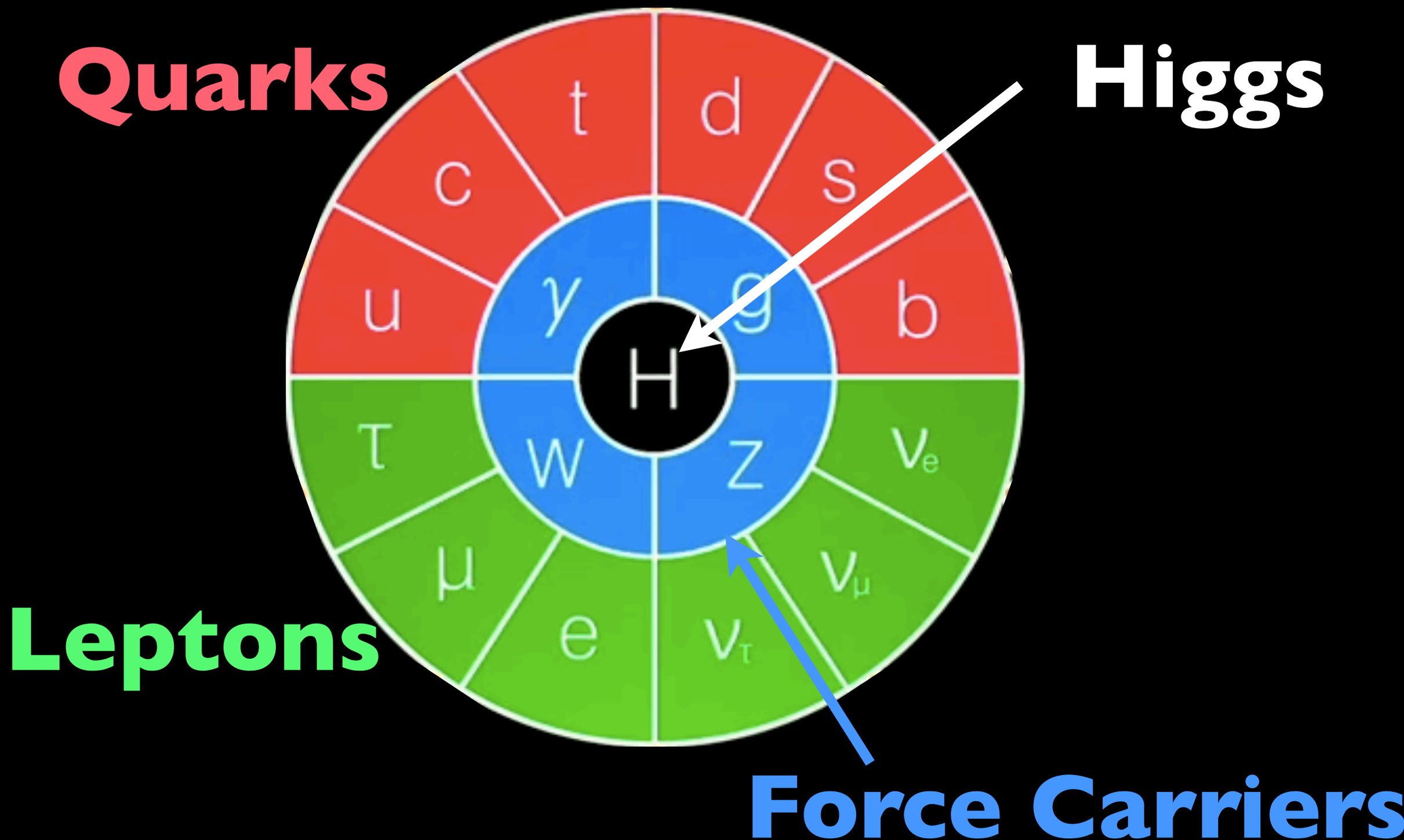


$$\mathcal{L} = \mathcal{O}_{hidden} H^\dagger H$$

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/SLC *nailed* the gauge sector
1. precision measurements of *W* and *Z* (*i.e.* LEP + Tevatron) predicted m_t and m_H
2. Tevatron discovered top, LHC discovered *a Higgs particle*
3. LC *nails* the top & Higgs sector?
1. precision measurements at LC predict ???

Standard Model



©Particle Fever

Higgs as central theme

- Higgs is at the center of the Standard Model
- the only particle that talks to everybody
- the only particle that doesn't spin
- the only particle that is condensed in the universe
- the lowest order coupling to new physics
- the source of all masses of elementary particles
- We don't know why it is the case for any of the points above

unbelievably important & special particle!

Effective Field Theory

- goal: establish deviation from the SM
- Effects of high-energy physics mostly disappear by power suppression

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- can be classified systematically

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda},$$
$$(H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

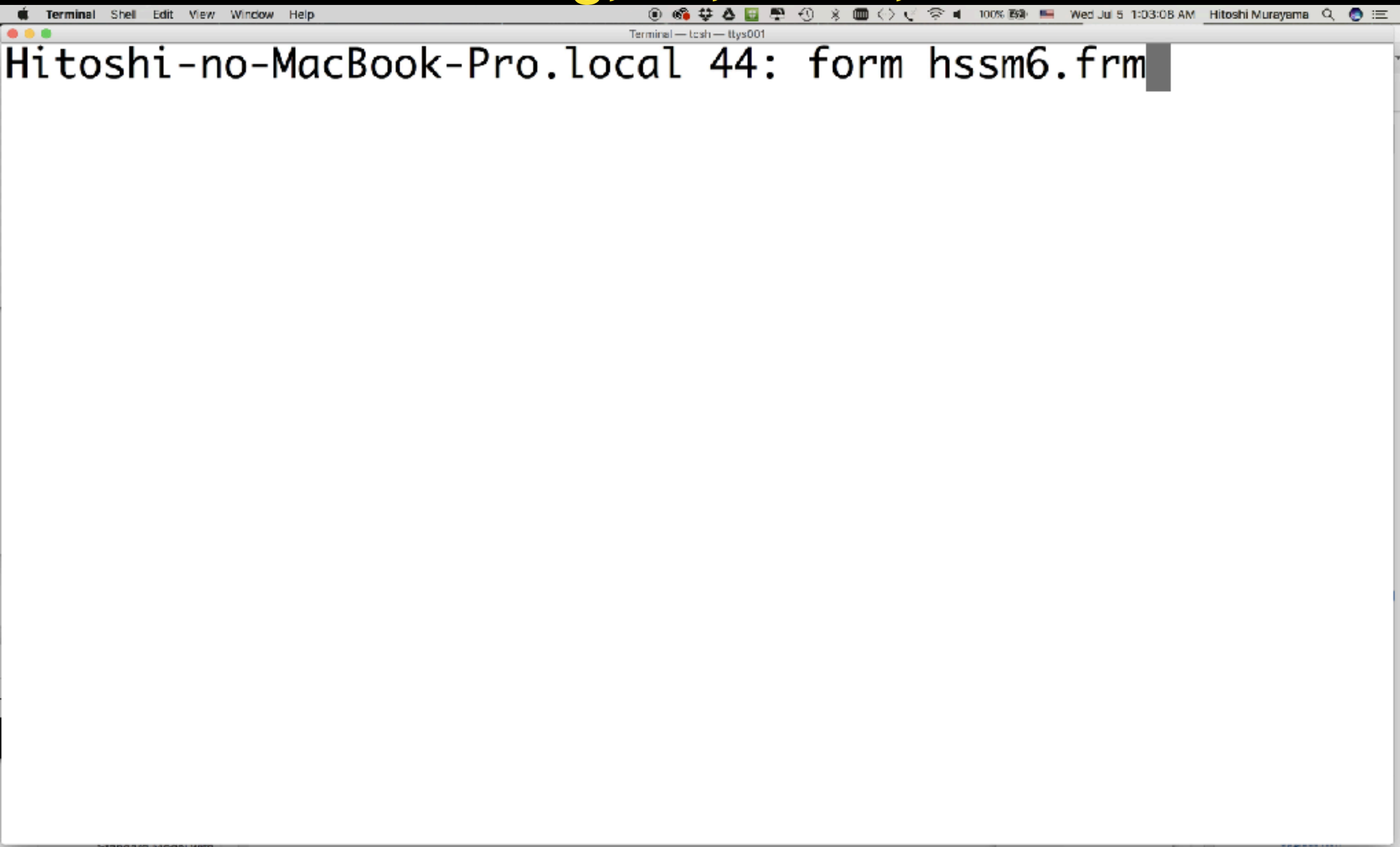
$$
\begin{aligned}
\widehat{H}_6 \;=\; & H^3 H^{\dagger\,3} + u^\dagger Q^\dagger H H^{\dagger\,2} + 2Q^2 Q^{\dagger\,2} + Q^{\dagger\,3} L^\dagger + Q^3 L + 2QQ^\dagger LL^\dagger + L^2 L^{\dagger\,2} + uQH^2 H^\dagger \\
& + 2uu^\dagger QQ^\dagger + uu^\dagger LL^\dagger + u^2 u^{\dagger\,2} + e^\dagger u^\dagger Q^2 + e^\dagger L^\dagger H^2 H^\dagger + 2e^\dagger u^\dagger Q^\dagger L^\dagger + eLHH^{\dagger\,2} + euQ^{\dagger\,2} \\
& + 2euQL + ee^\dagger QQ^\dagger + ee^\dagger LL^\dagger + ee^\dagger uu^\dagger + e^2 e^{\dagger\,2} + d^\dagger Q^\dagger H^2 H^\dagger + 2d^\dagger u^\dagger Q^{\dagger\,2} + d^\dagger u^\dagger QL \\
& + d^\dagger e^\dagger u^{\dagger\,2} + d^\dagger e Q^\dagger L + dQHH^{\dagger\,2} + 2duQ^2 + duQ^\dagger L^\dagger + de^\dagger QL^\dagger + deu^2 + 2dd^\dagger QQ^\dagger + dd^\dagger LL^\dagger \\
& + 2dd^\dagger uu^\dagger + dd^\dagger ee^\dagger + d^2 d^{\dagger\,2} + u^\dagger Q^\dagger H^\dagger G_R + d^\dagger Q^\dagger H G_R + HH^\dagger G_R^2 + G_R^3 + uQHG_L \\
& + dQH^\dagger G_L + HH^\dagger G_L^2 + G_L^3 + u^\dagger Q^\dagger H^\dagger W_R + e^\dagger L^\dagger H W_R + d^\dagger Q^\dagger H W_R + HH^\dagger W_R^2 + W_R^3 \\
& + uQHW_L + eLH^\dagger W_L + dQH^\dagger W_L + HH^\dagger W_L^2 + W_L^3 + u^\dagger Q^\dagger H^\dagger B_R + e^\dagger L^\dagger H B_R \\
& + d^\dagger Q^\dagger H B_R + HH^\dagger B_R W_R + HH^\dagger B_R^2 + uQHB_L + eLH^\dagger B_L + dQH^\dagger B_L + HH^\dagger B_L W_L \\
& + HH^\dagger B_L^2 + 2QQ^\dagger HH^\dagger \mathcal{D} + 2LL^\dagger HH^\dagger \mathcal{D} + uu^\dagger HH^\dagger \mathcal{D} + ee^\dagger HH^\dagger \mathcal{D} + d^\dagger u H^2 \mathcal{D} + du^\dagger H^{\dagger\,2} \mathcal{D} \\
& + dd^\dagger HH^\dagger \mathcal{D} + 2H^2 H^{\dagger\,2} \mathcal{D}^2 \,. \qquad (3.16)
\end{aligned}
$$

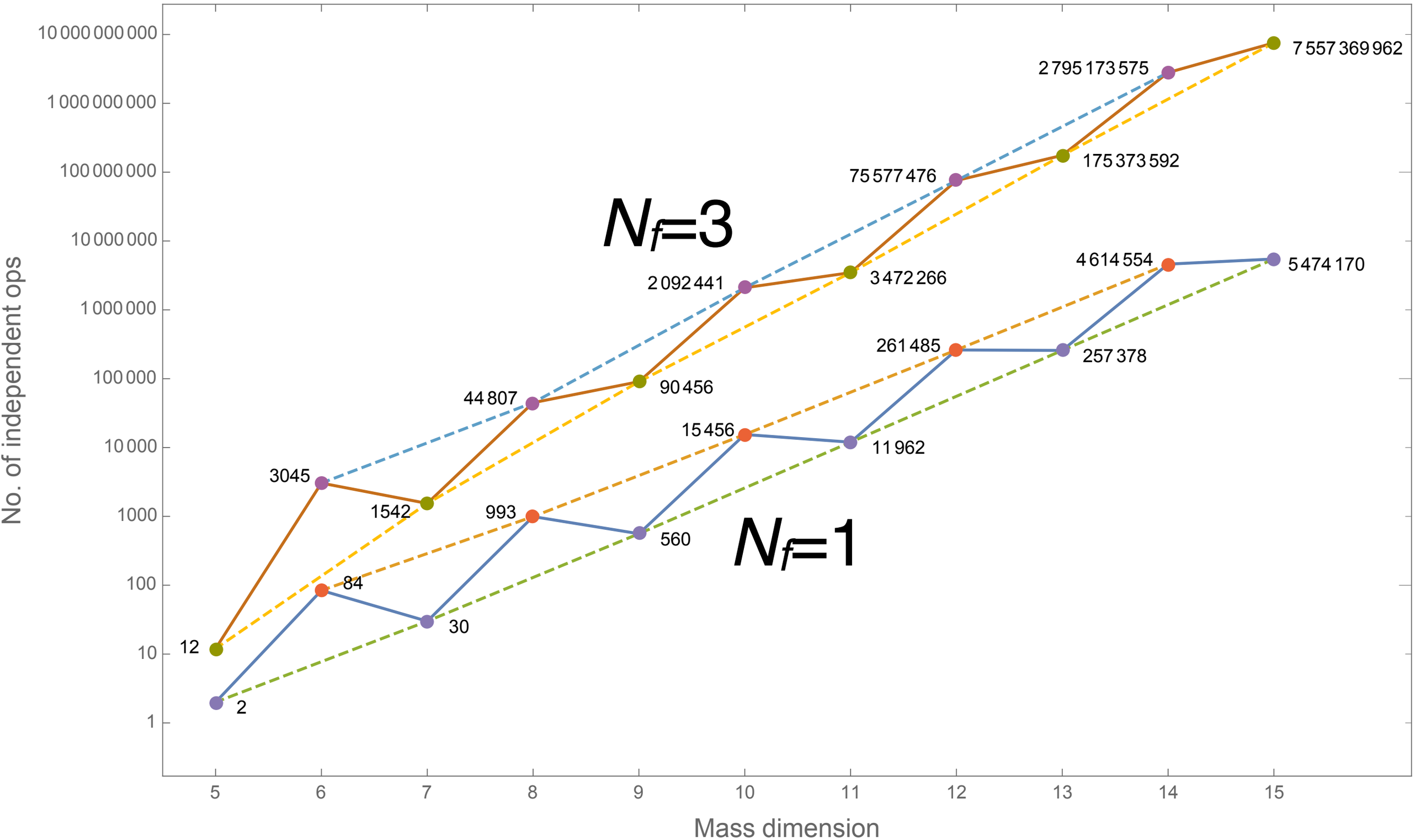
$\mathcal{D}$: space time derivative

it took community from 1980 to 2013

CFT to classify operators

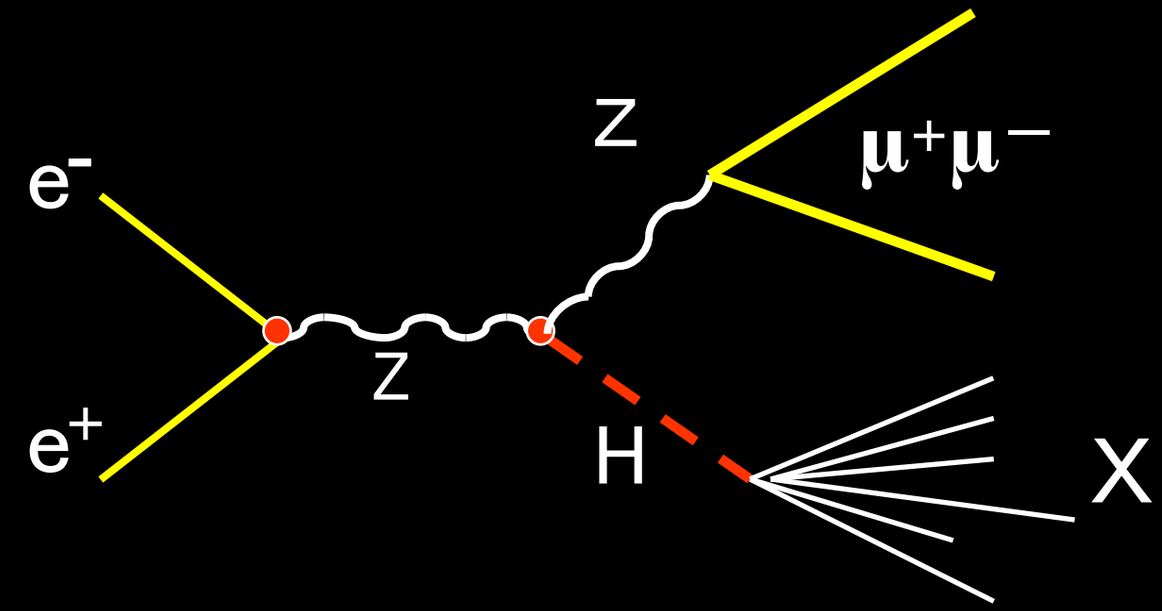
Henning, Lu, Melia, HM





algorithm for chiral Lagrangian, HEFT soon

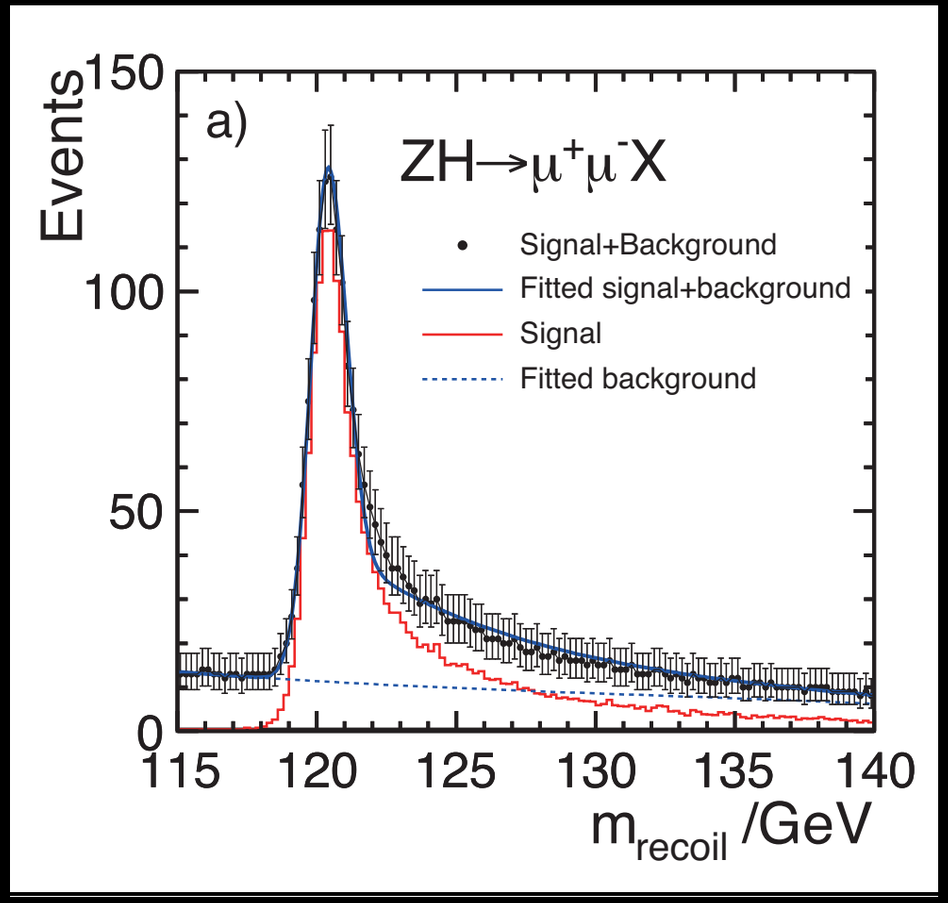
e^+e^-



$$M_X^2 = (E_{CM} - E_{\mu\mu})^2 - \mathbf{P}_{\mu\mu}^2$$

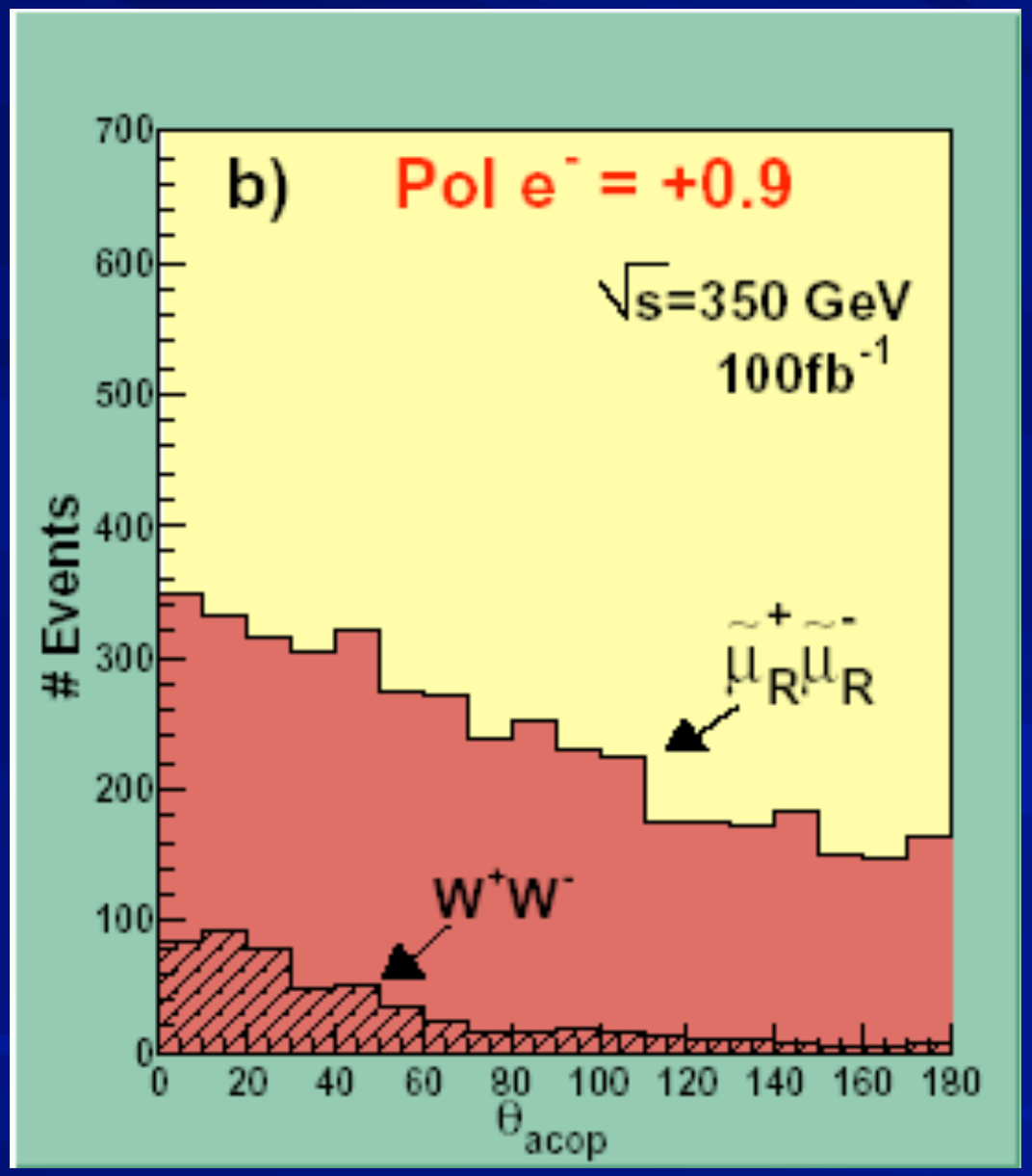
$$m_{\text{recoil}}^2 = m_Z^2 + s - 2\sqrt{s}E_Z$$

- simple kinematics
- no loss of the longitudinal momentum (modulo photon emission)
- can make use of all final states
  - not just easily identifiable particles (i.e. leptons@LHC)
- capture all information for a given event

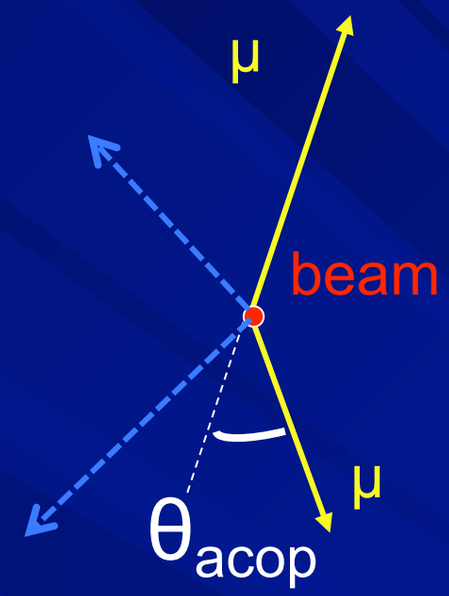


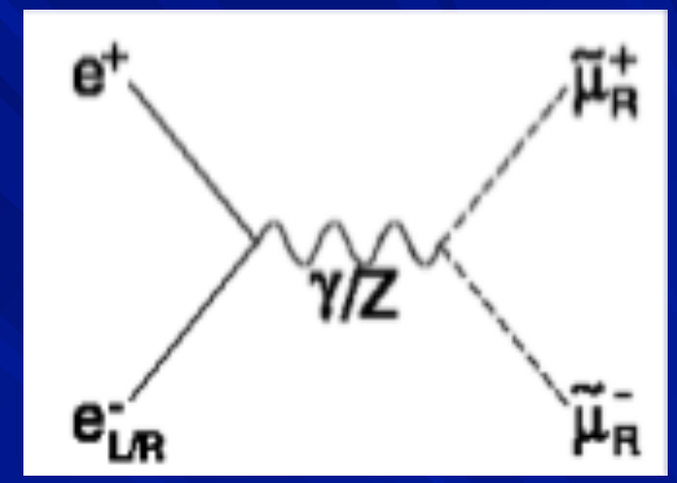
Power of electron polarization at ILC

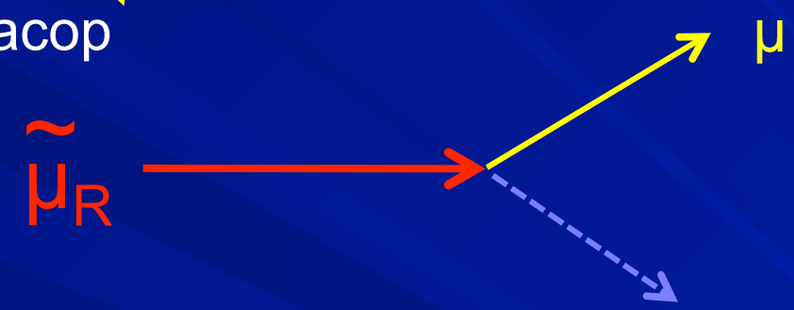
Scalar muon production

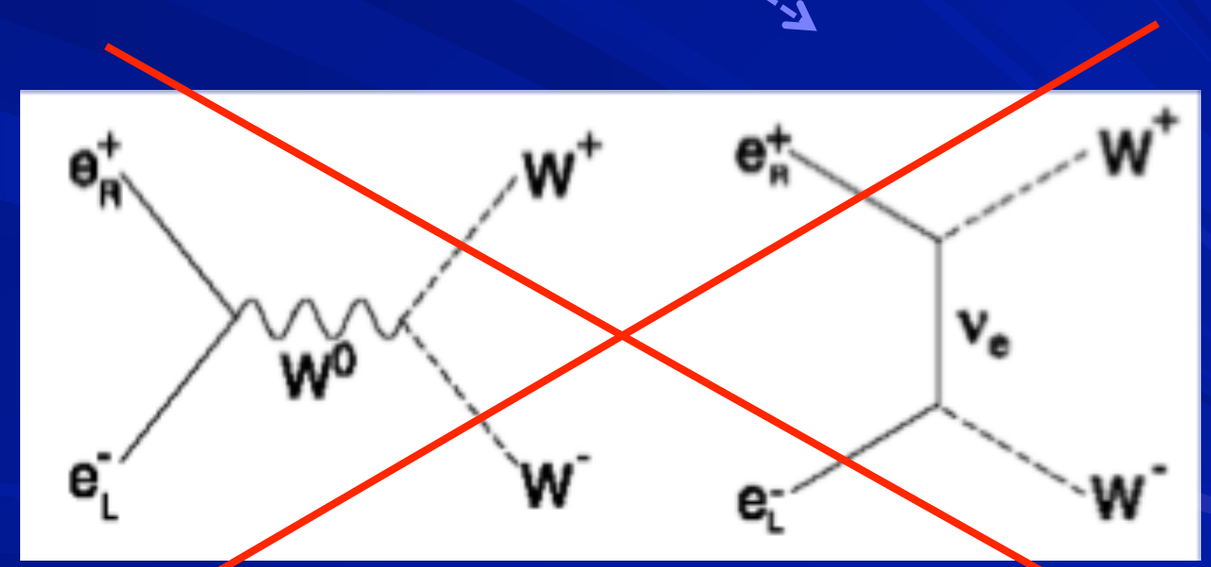


Polarized (90% e^-_R)









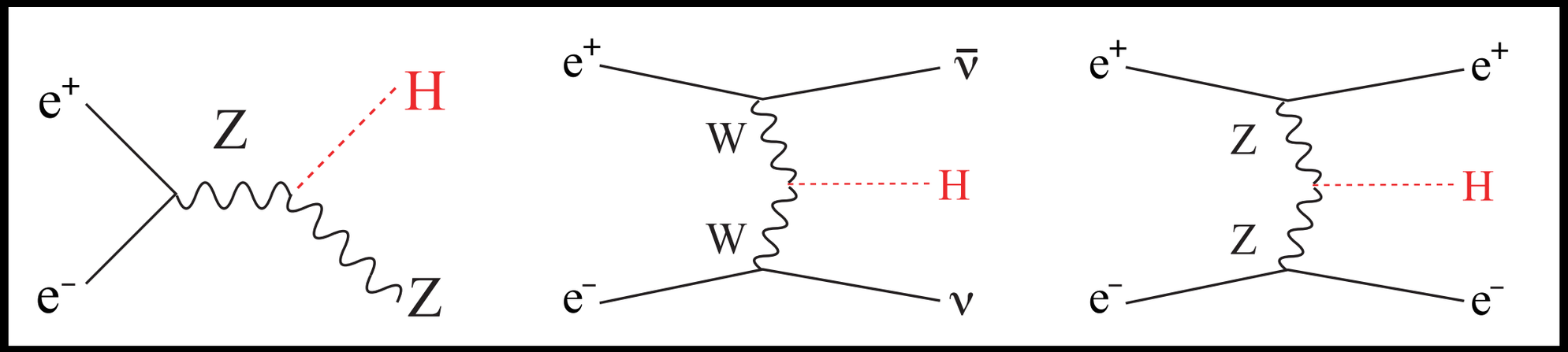
Background signal

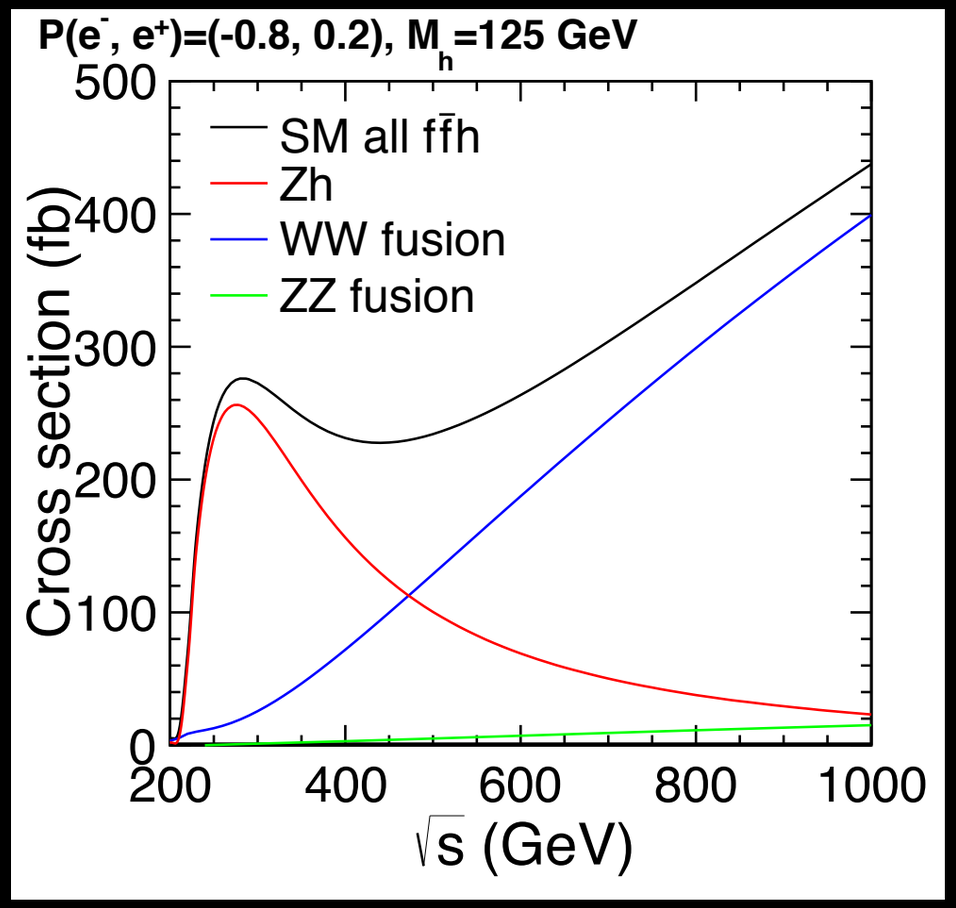
polarization important tool for separating different EFT operators

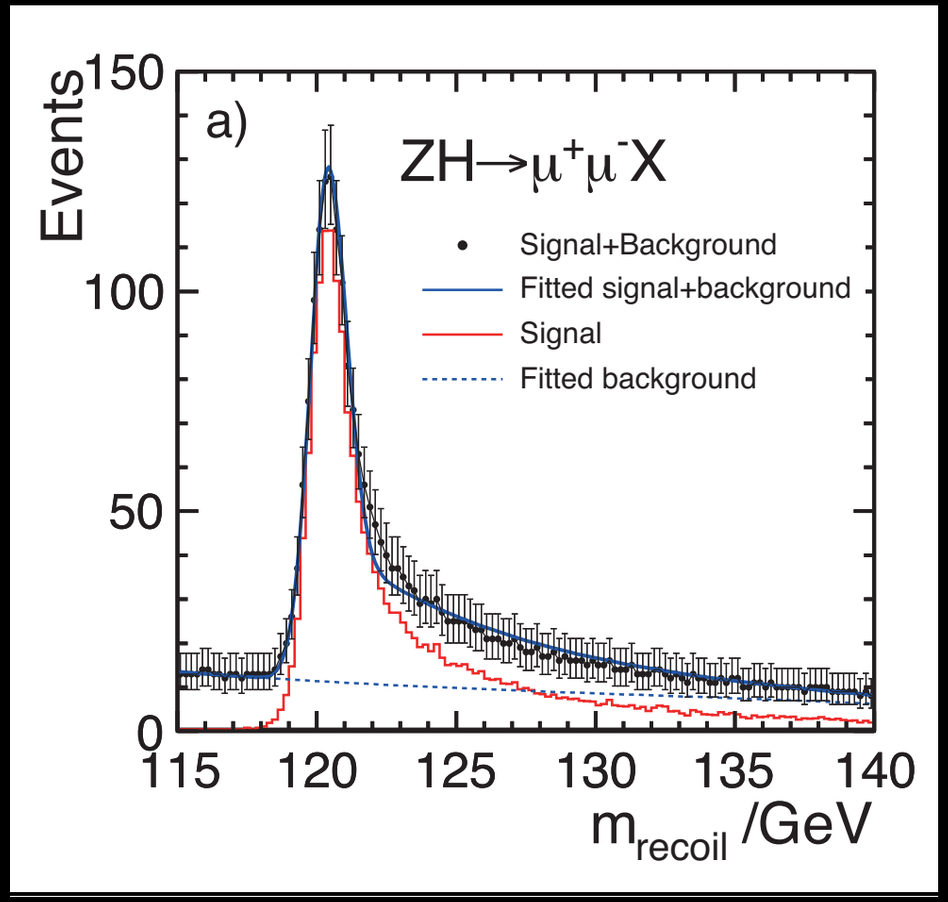
Sachio Komamiya @ Snowmass 2013

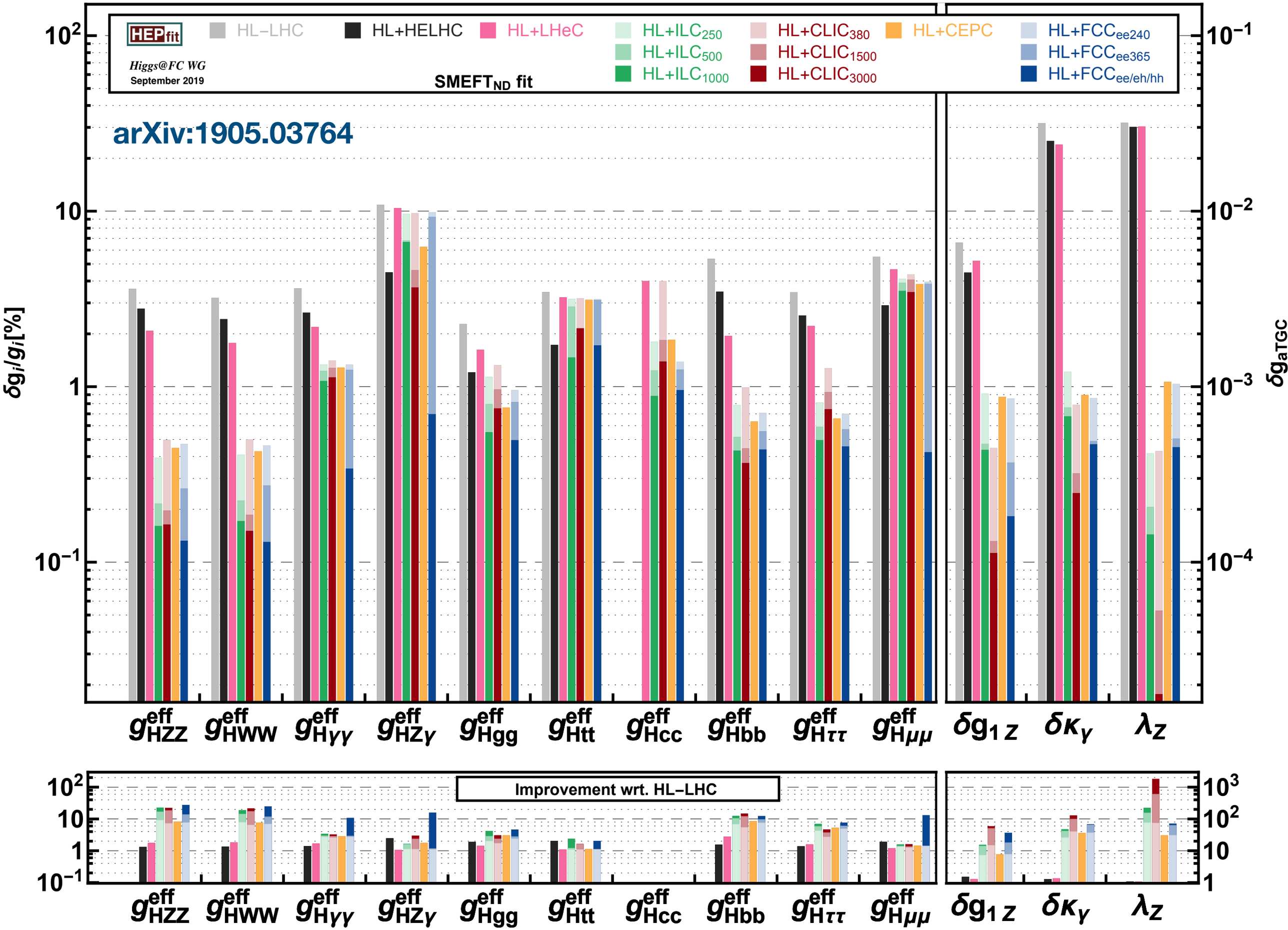
production mechanisms

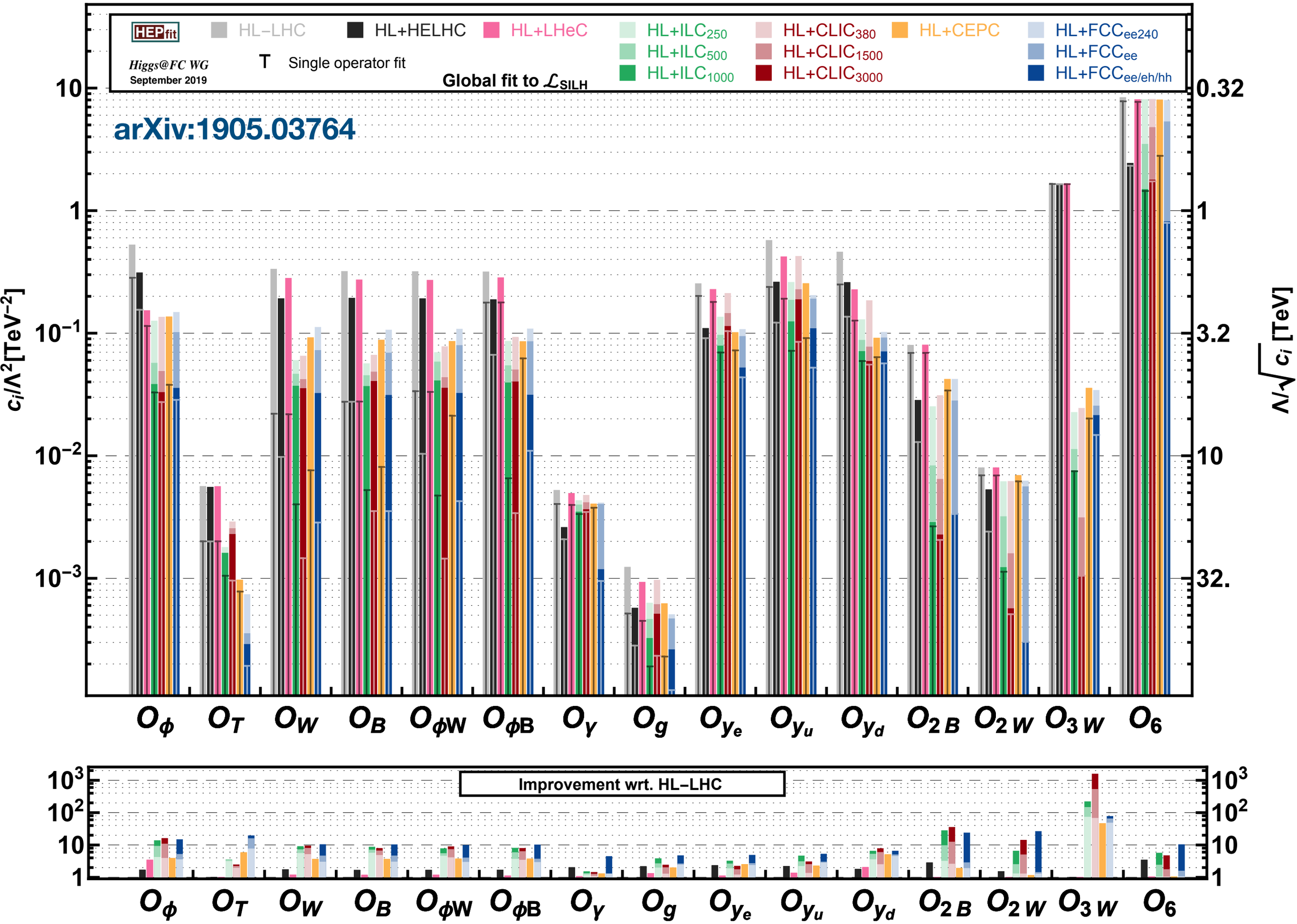
$$m^2_{\text{recoil}} = m_Z^2 + s - 2\sqrt{s}E_Z$$








HEPfit
Higgs@FC WG
September 2019
HL−LHC
HL+HELHC
HL+LHeC
HL+ILC250
HL+ILC500
HL+ILC1000
HL+CLIC380
HL+CLIC1500
HL+CLIC3000
HL+CEPC
HL+FCCee240
HL+FCCee365
HL+FCCee/eh/hh
SMEFTND fit
arXiv:1905.03764
δgi/gi[%]
δgaTGC
Improvement wrt. HL−LHC
g^eff_HZZ
g^eff_HWW
g^eff_Hγγ
g^eff_HZγ
g^eff_Hgg
g^eff_Htt
g^eff_Hcc
g^eff_Hbb
g^eff_Hττ
g^eff_Hμμ
δg1Z
δκγ
λZ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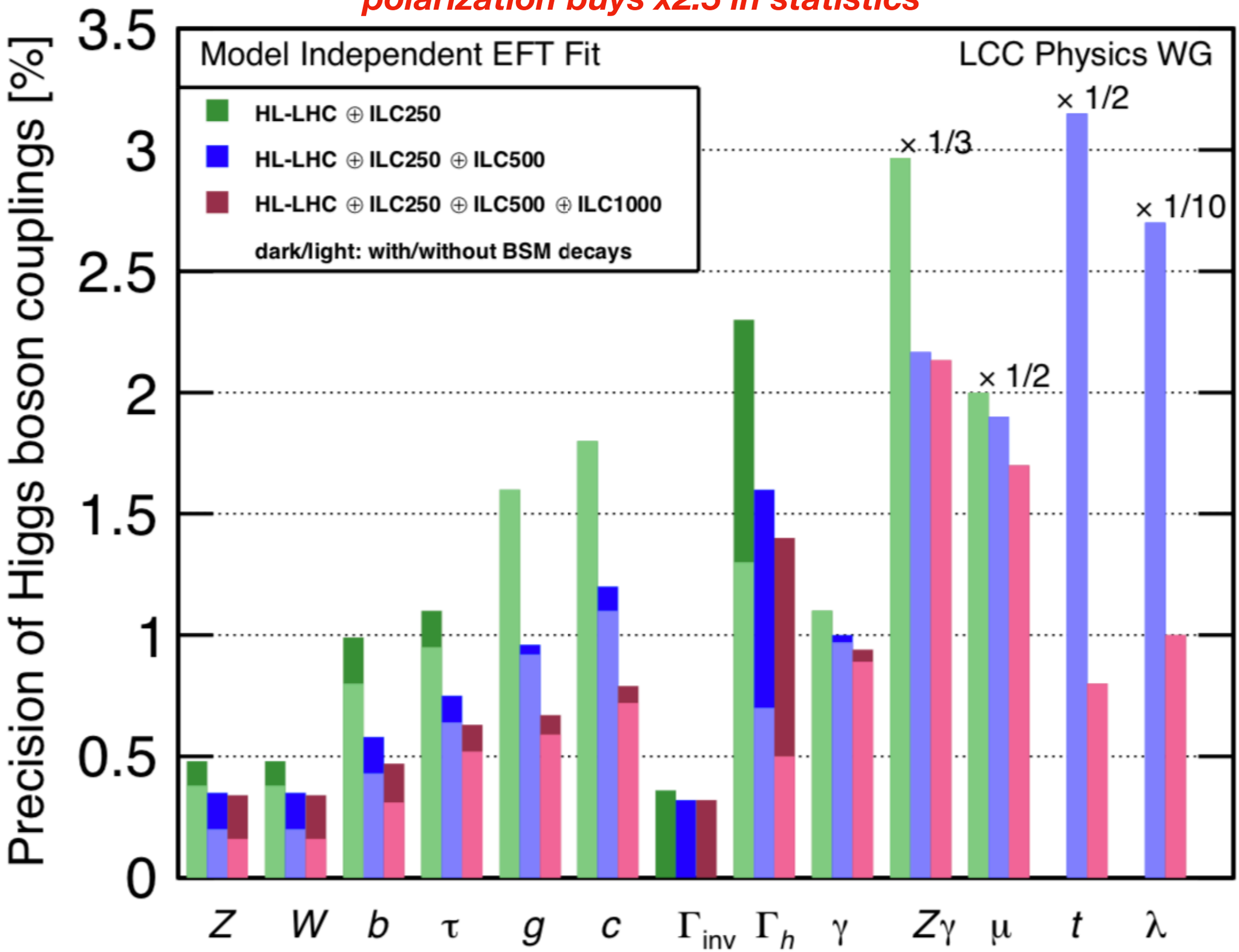
HL+CLIC380
HL+CLIC1500
HL+CLIC3000
HL+CEPC
HL+FCCee240
HL+FCCee
HL+FCCee/eh/hh
T Single operator fit
Global fit to $\mathcal{L}_{SILH}$
arXiv:1905.03764
c_i/Λ^2[TeV^{-2}]
$\Lambda/\sqrt{c_i}$ [TeV]
O_ϕ O_T O_W O_B $O_{\phi W}$ $O_{\phi B}$ O_γ O_g O_{y_e} O_{y_u} O_{y_d} O_{2B} O_{2W} O_{3W} O_6
Improvement wrt. HL−LHC

polarization buys x2.5 in statistics



arXiv:1908.11299

Michael Peskin yesterday

of “largely” improved H couplings (EFT)

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

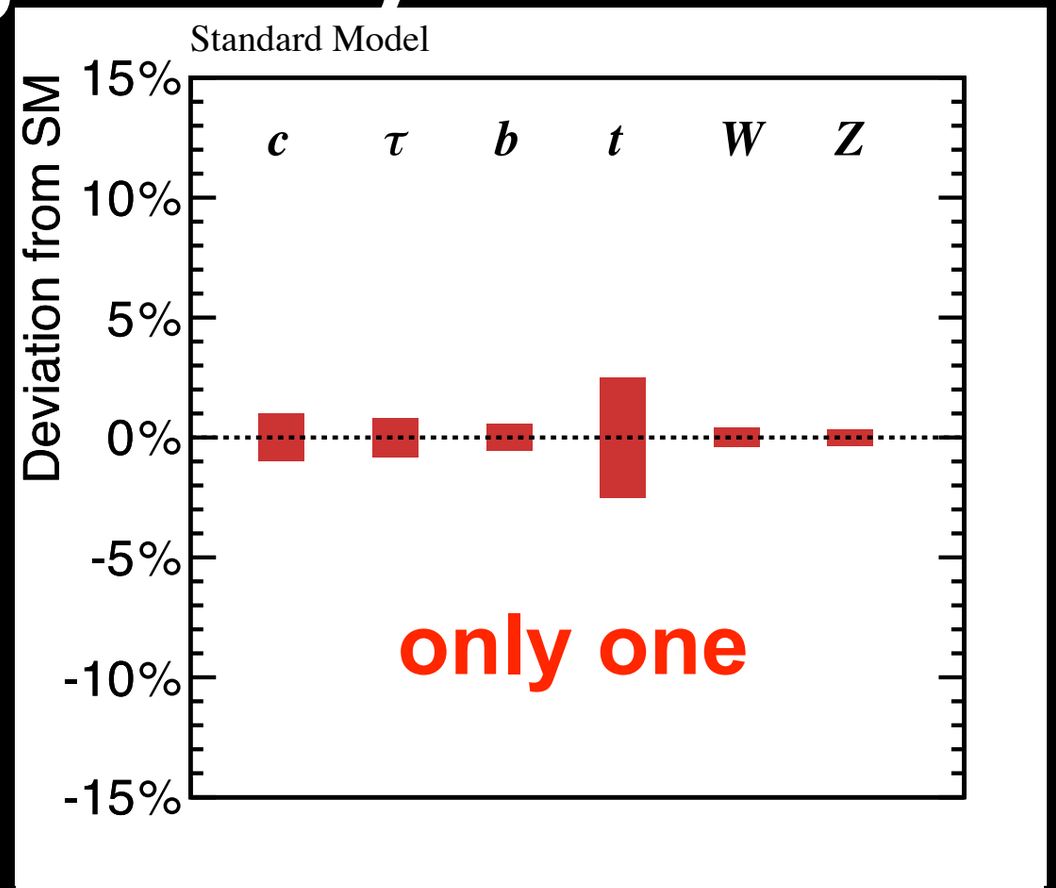
13 quantities in total

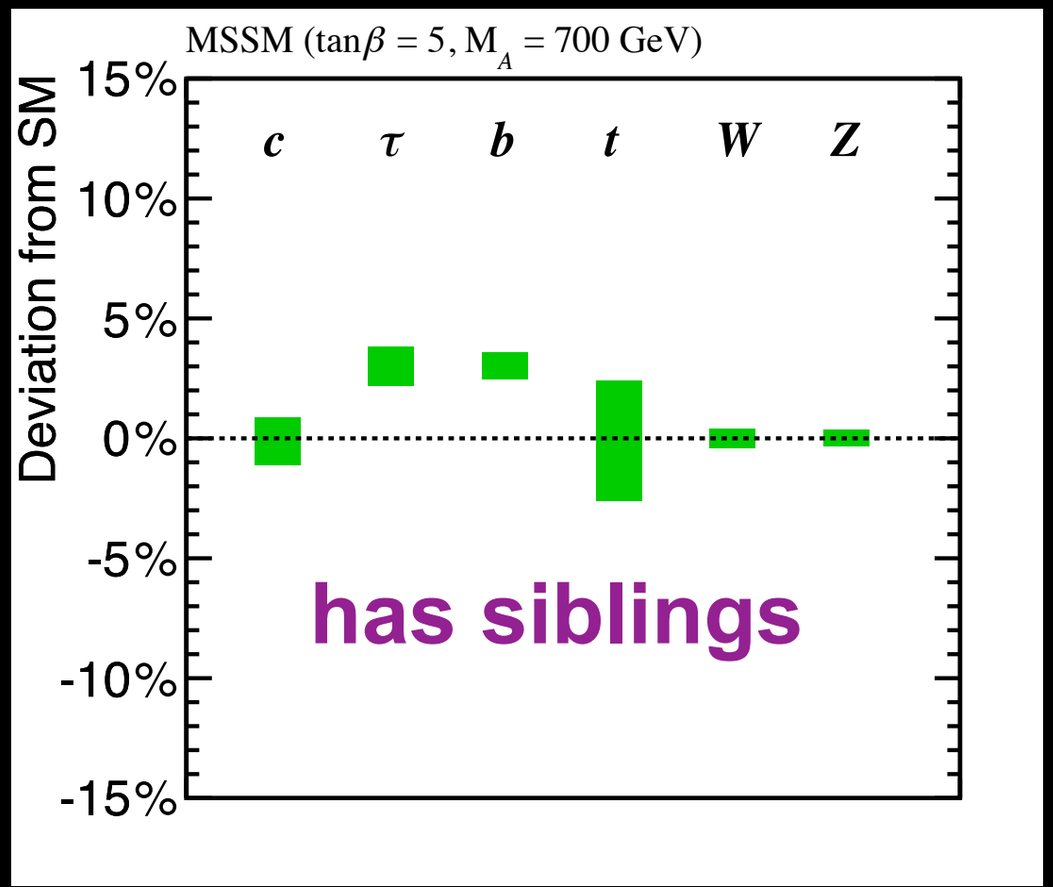
NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

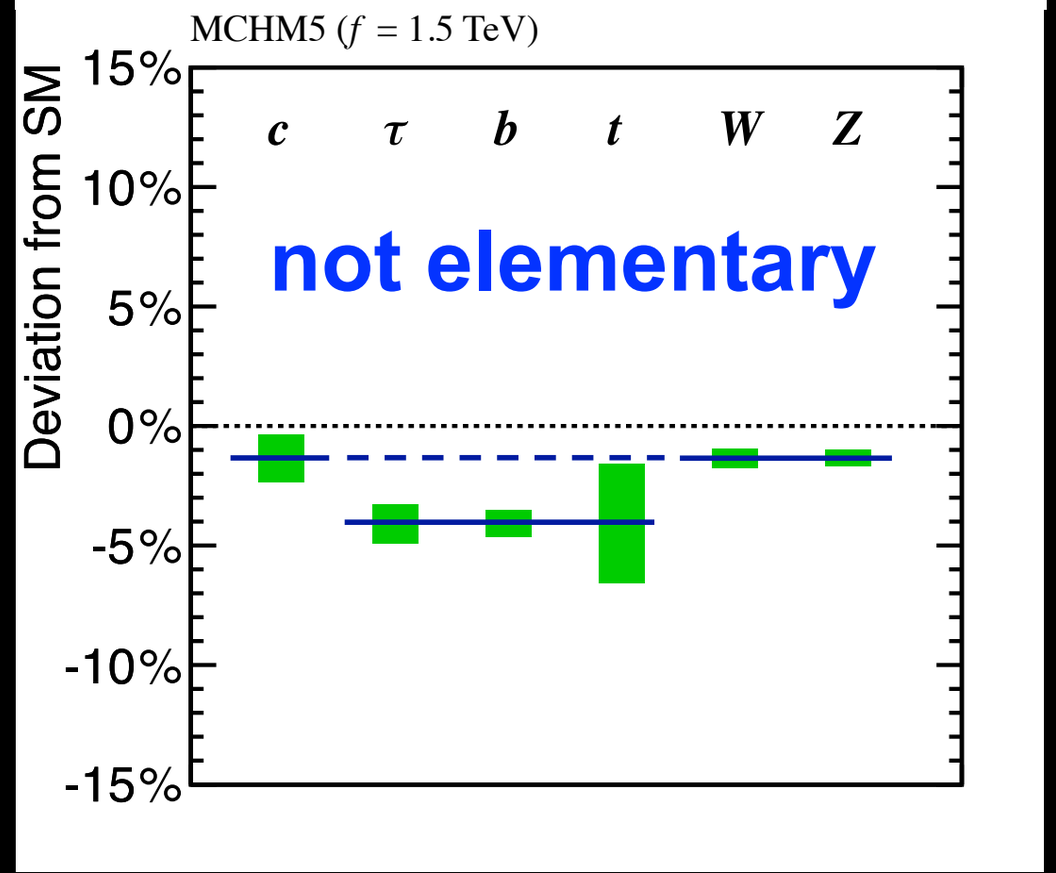
What is Higgs really?

Only one? (SM)
has siblings? (2DHM)
not elementary?

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

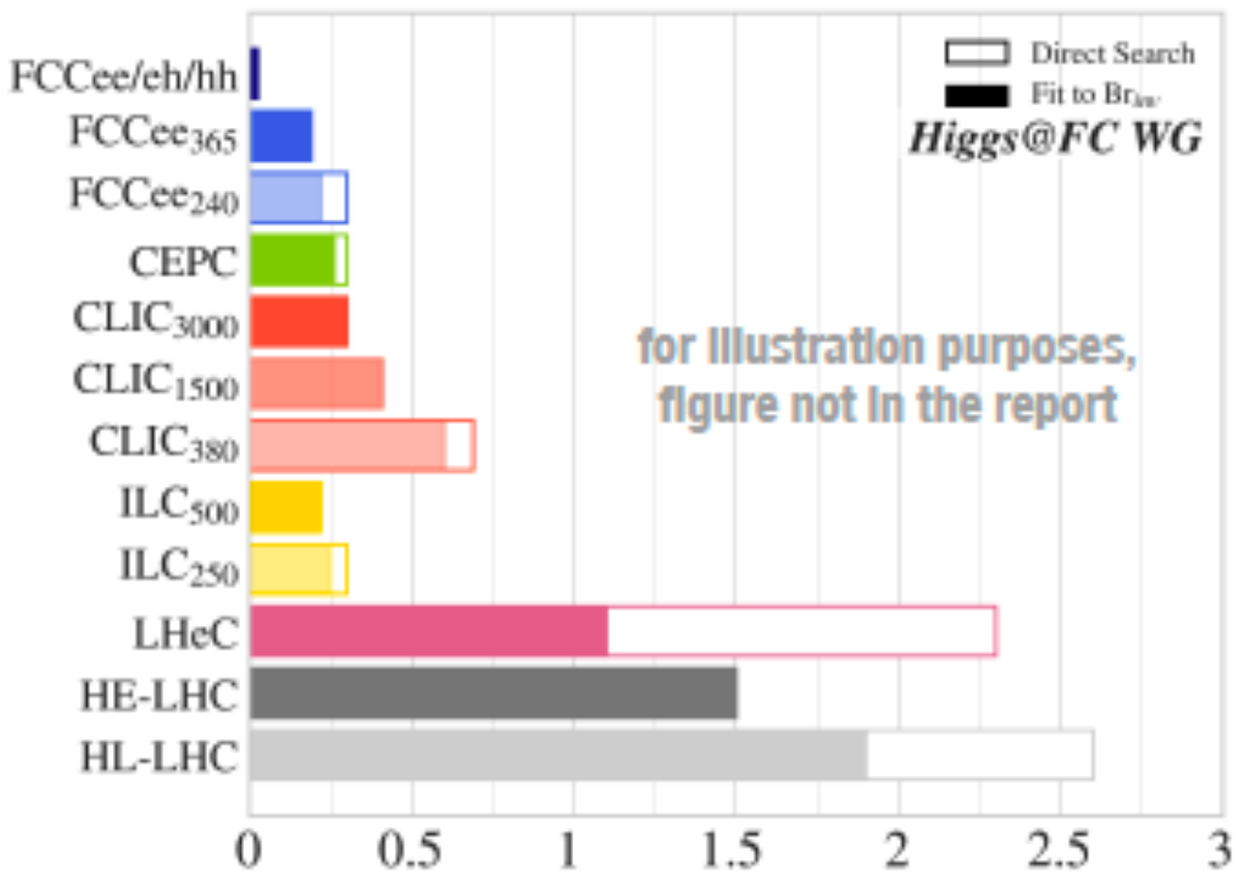


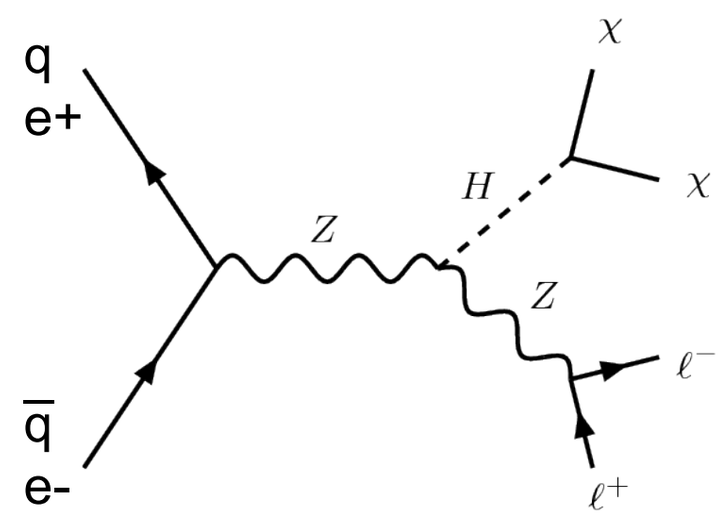




twin Higgs, dark sector

Invisible H decays: $H \rightarrow E_T^{miss}$





Direct searches dominate sensitivity

- **HL-LHC will have sensitivity to ~2.6%**
- **e+e- colliders improve to ~0.3%**
- **FCC-hh probes below SM value: ~0.025%**

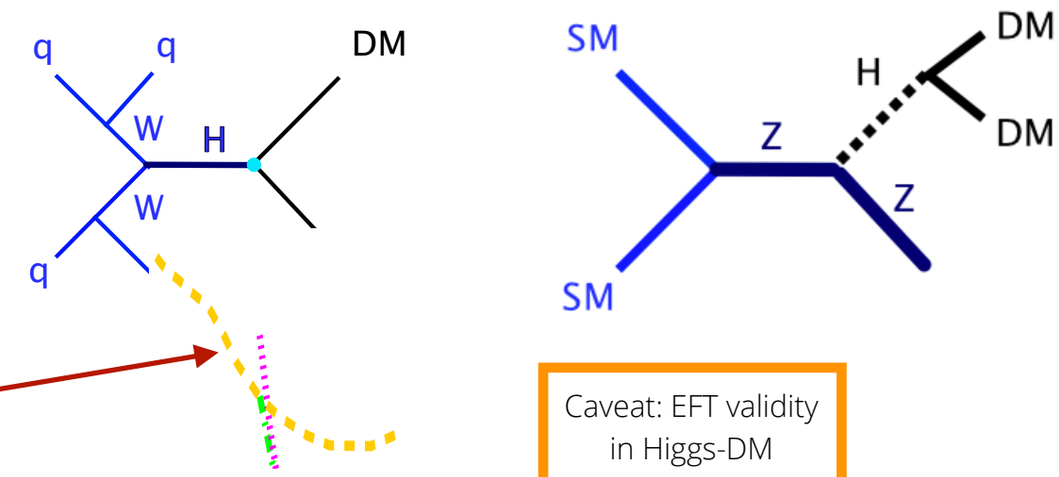
Higgs portal, plot for direct searches

- Limits on BR can be translated to limits in the DM-nucleon plane

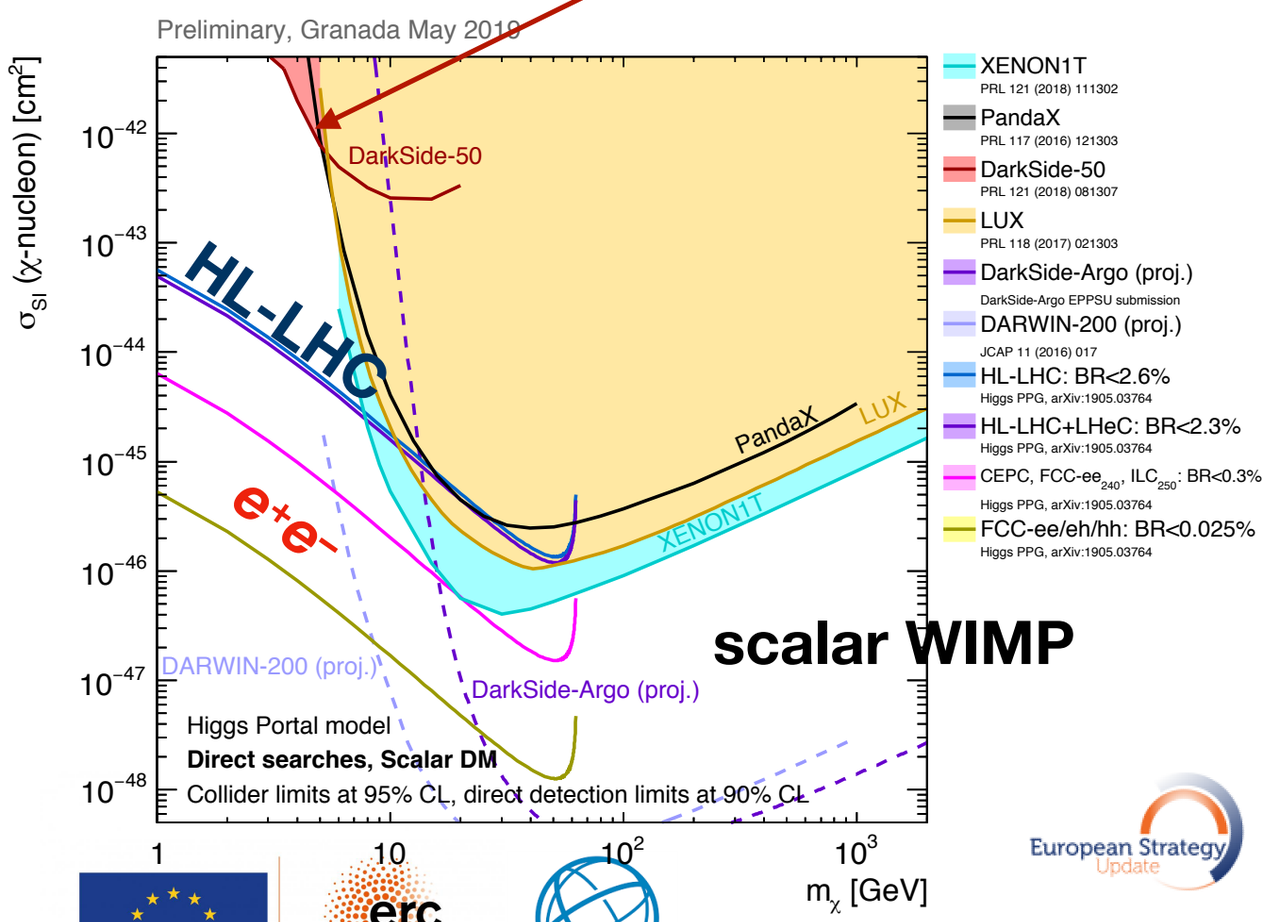
$$\sigma_{\chi N} = \Gamma_{\rm inv} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi\left(\frac{m_h}{m_\chi}\right), \qquad (15)$$

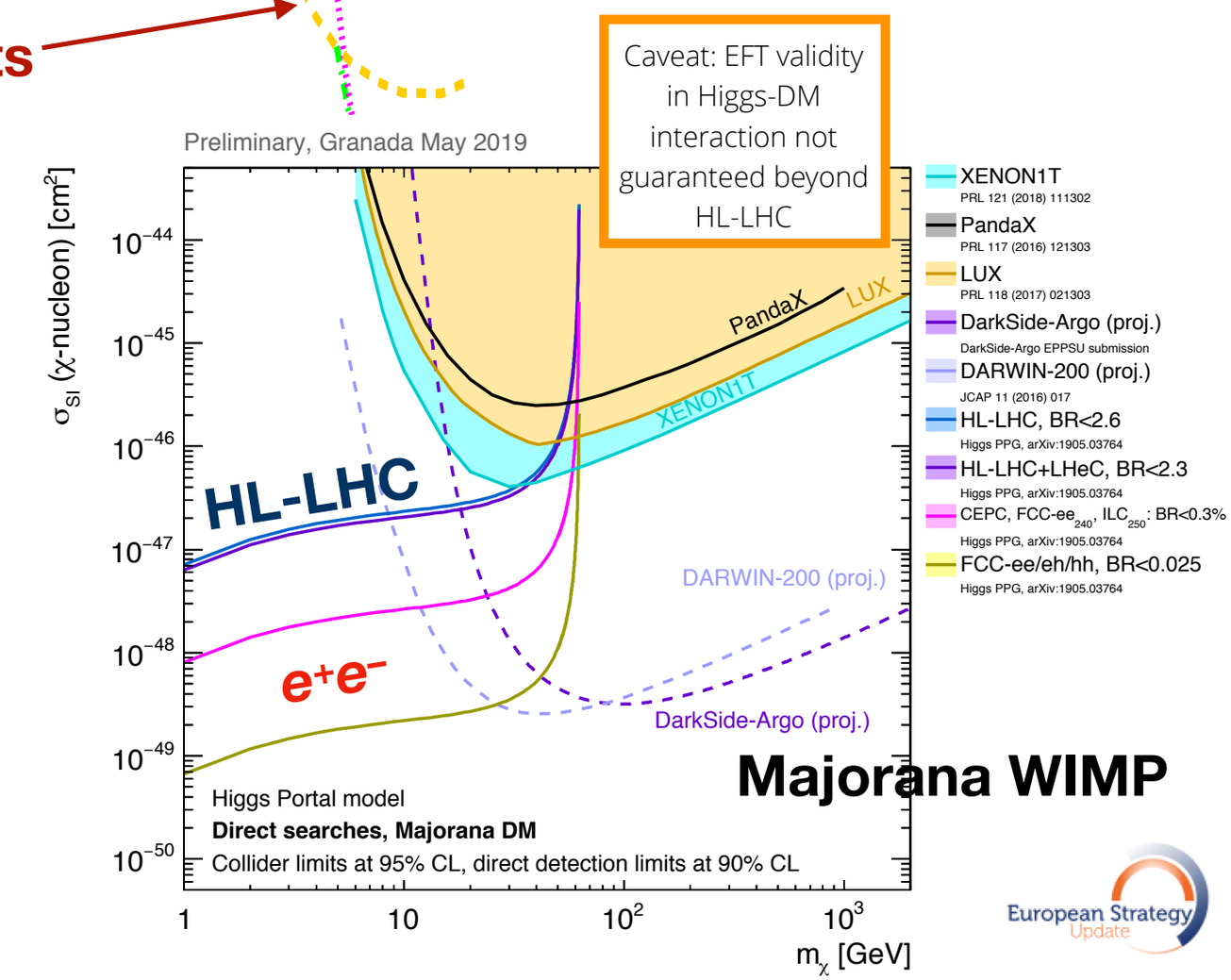
arXiv:1708.02245

where $g_S(x) = 1$,
$g_f(x) = 2/(x^2-4)$, $\beta = \sqrt{1-4m_\chi^2/m_h^2}$, $v = 246\,\mathrm{GeV}$



direct detection limits





European Strategy Update

European Research Council
Established by the European Commission

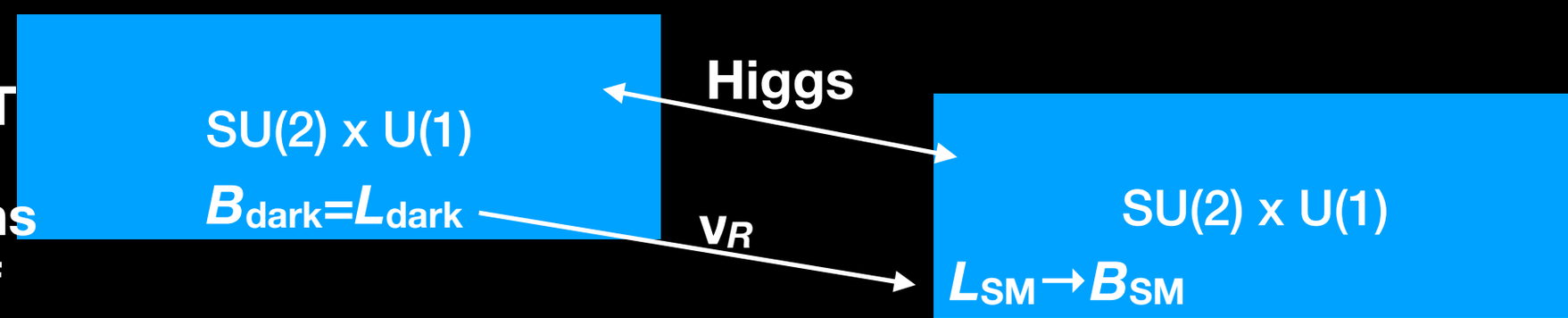
ATLAS EXPERIMENT

baryogengesis + DM

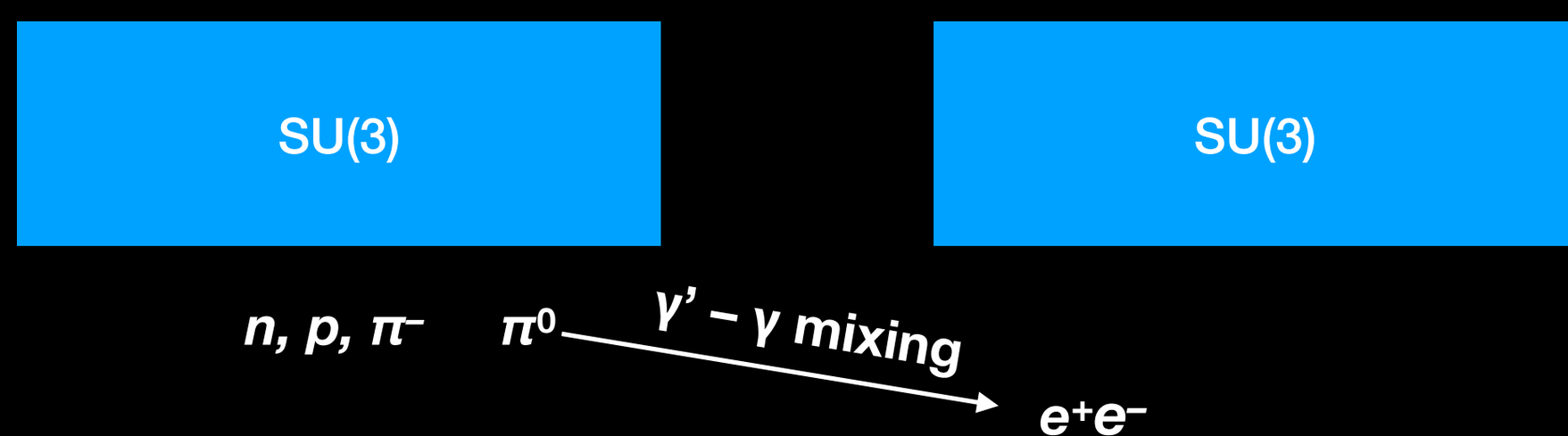
dark sector | **SM**

2 Higgs doublets with CPV 1st order PT

heavy leptons play role of top quark

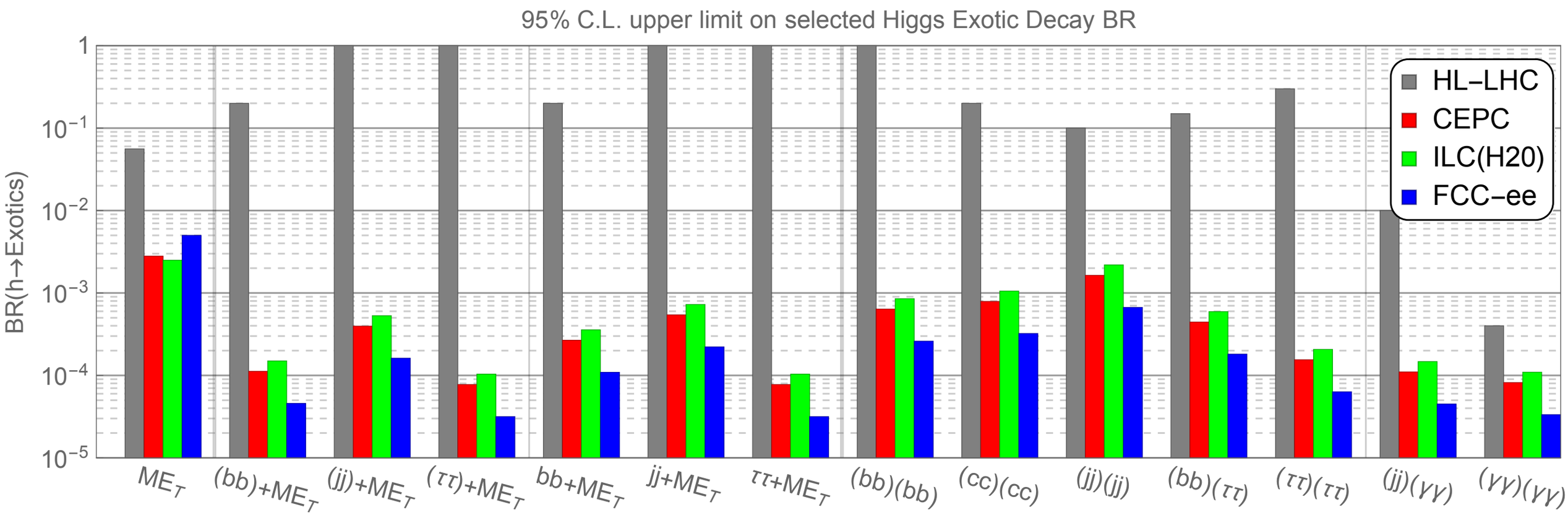


light *u, d*



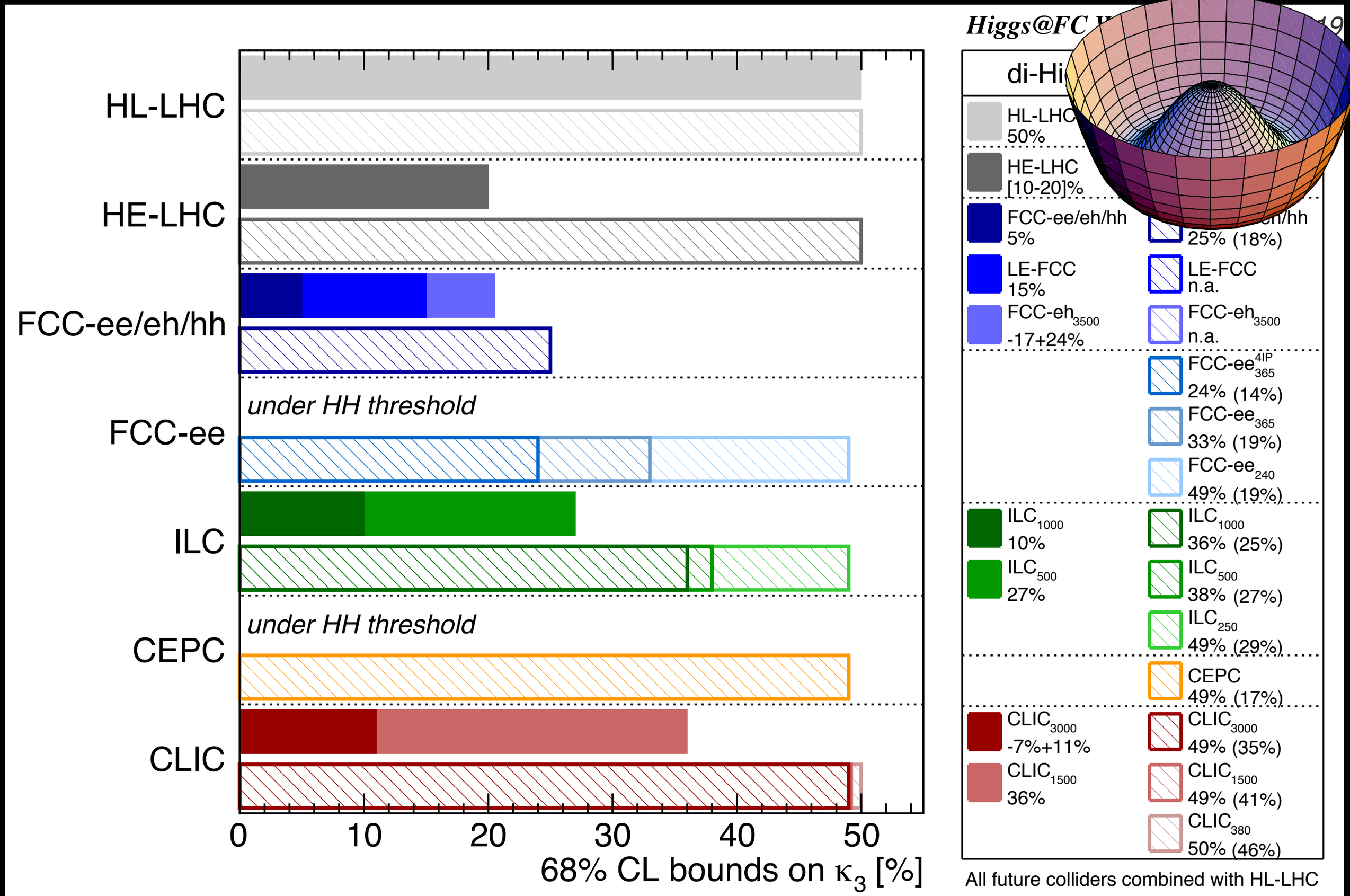
Eleanor Hall, Thomas Konstandin, Robert McGehee, HM + Géraldine Servant
arXiv:1911.12342

Higgs →dark sector →SM

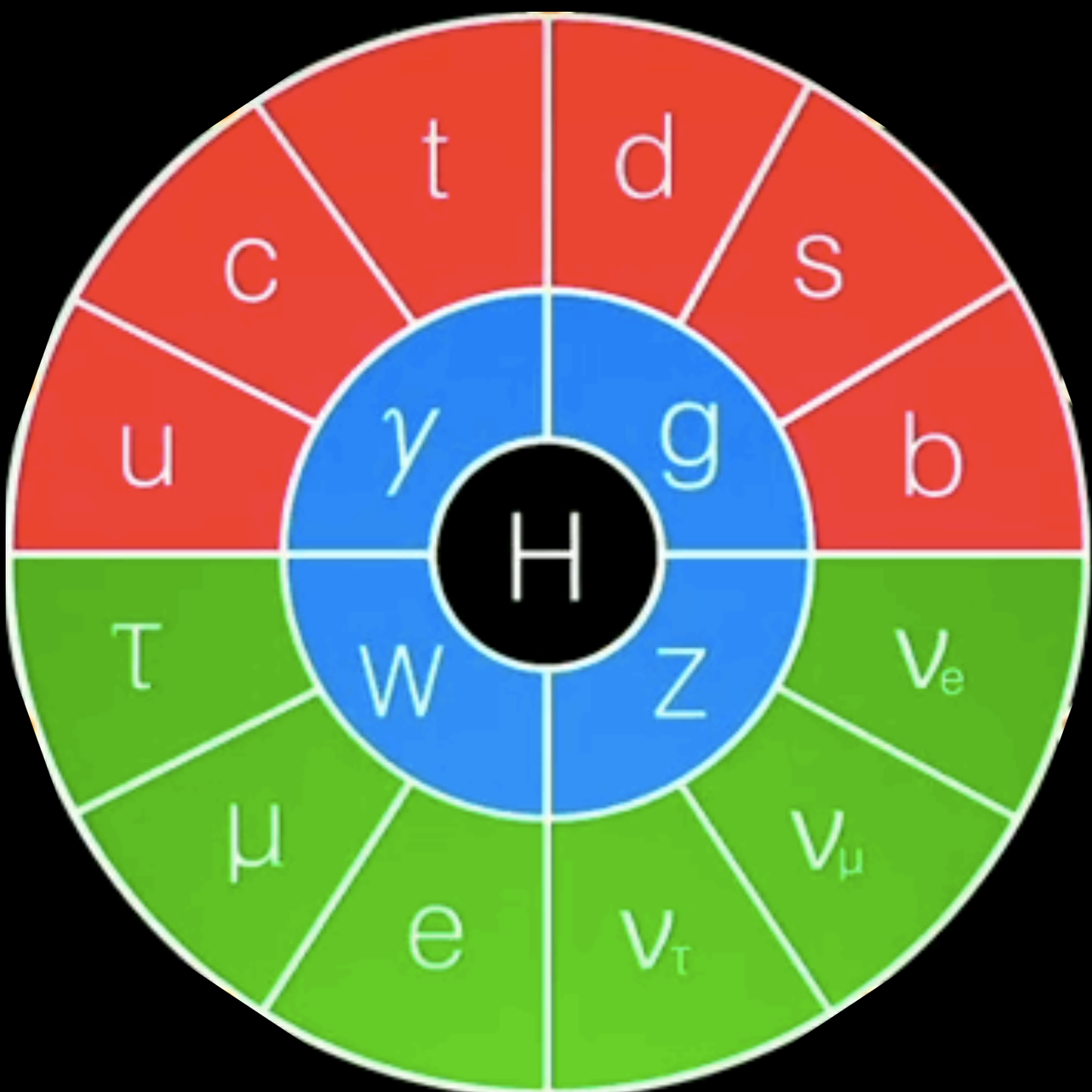


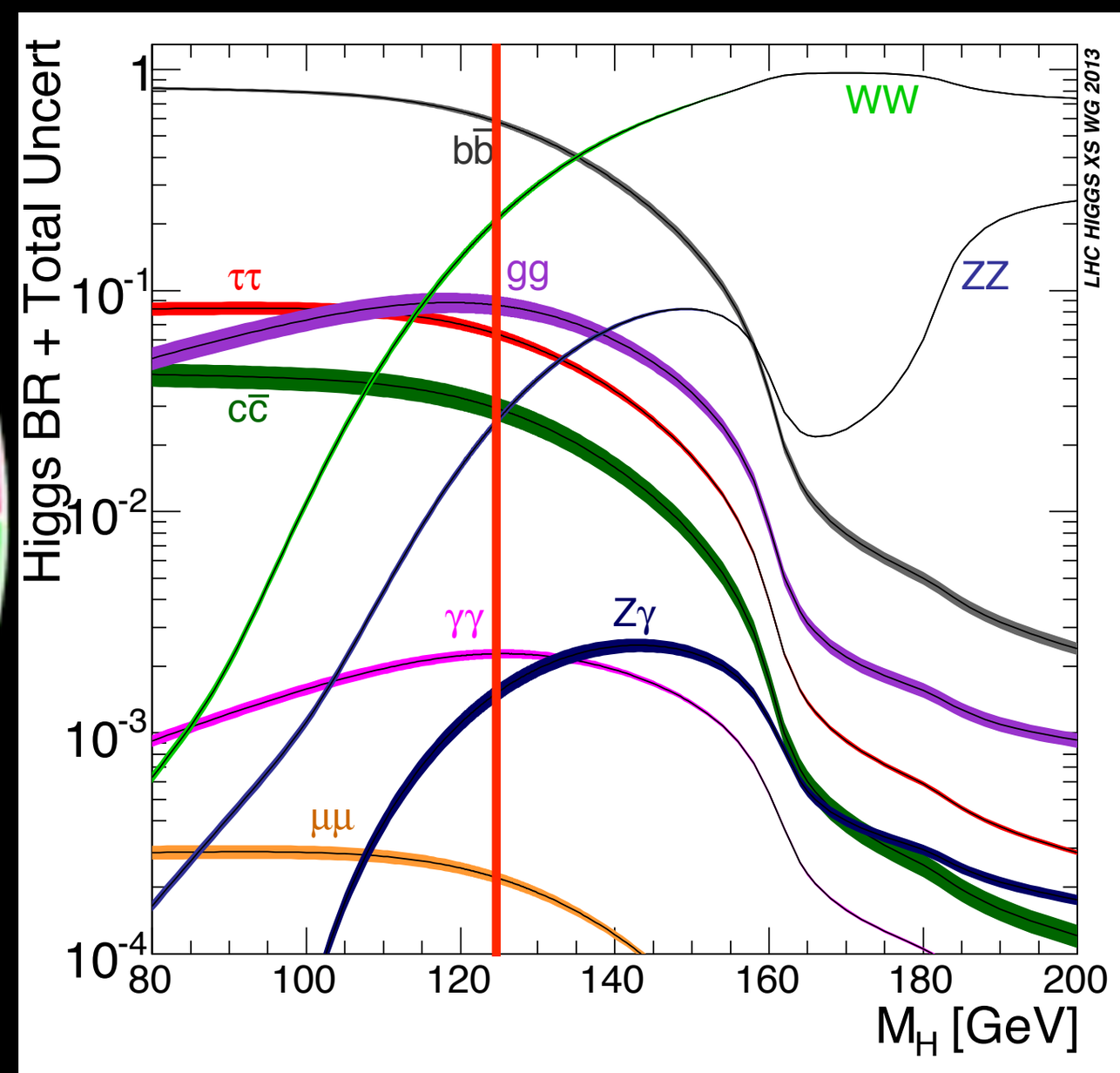
Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284

Why is Higgs condensed?



case for Higgs at LC





stupid not to do this!