June 21, 2023

The Higgs boson as a tool for discovery

Jim Brau
Oregon Quarknet

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The Higgs boson as a tool for discovery
or
Searching for dark matter & new physics

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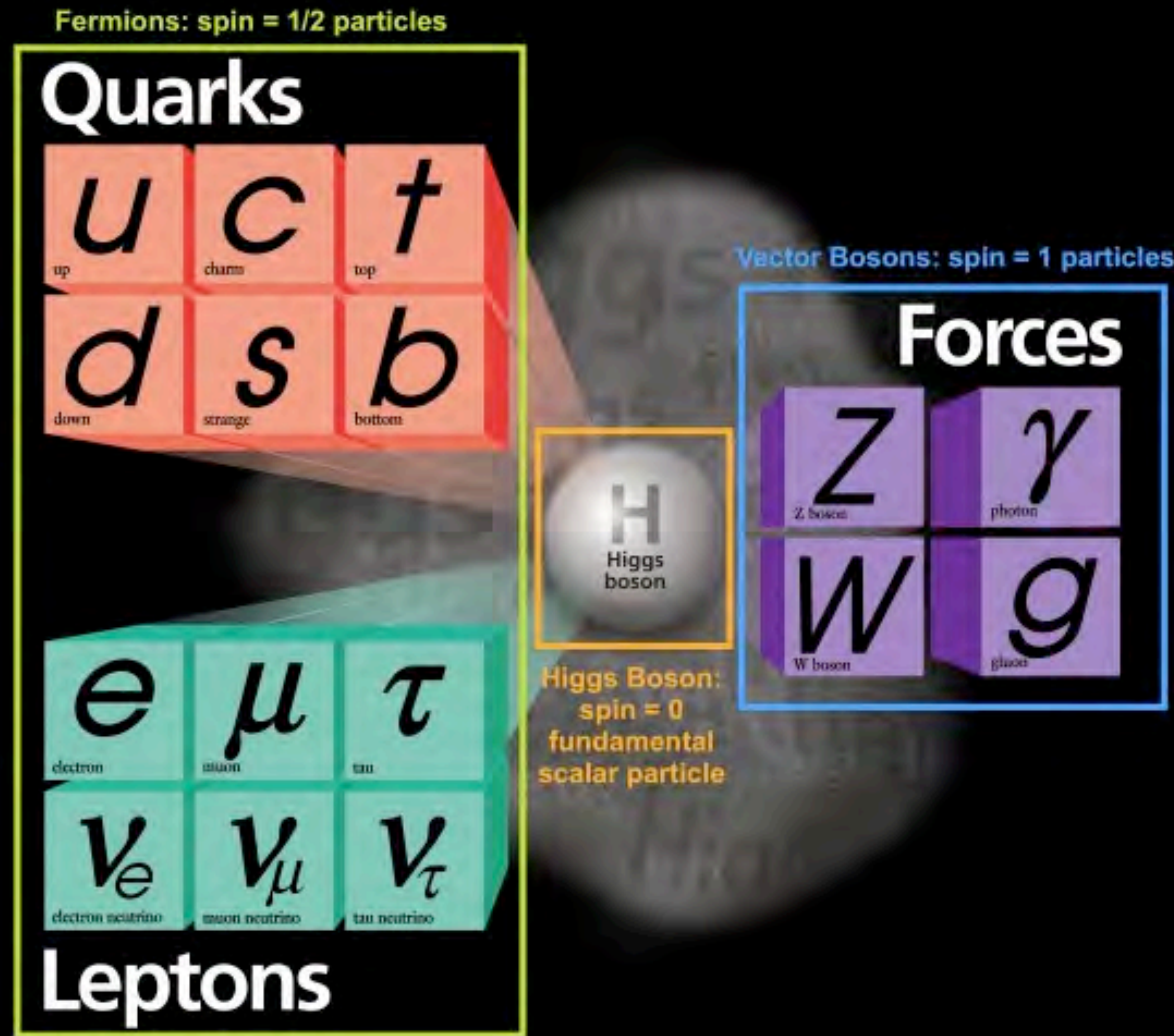
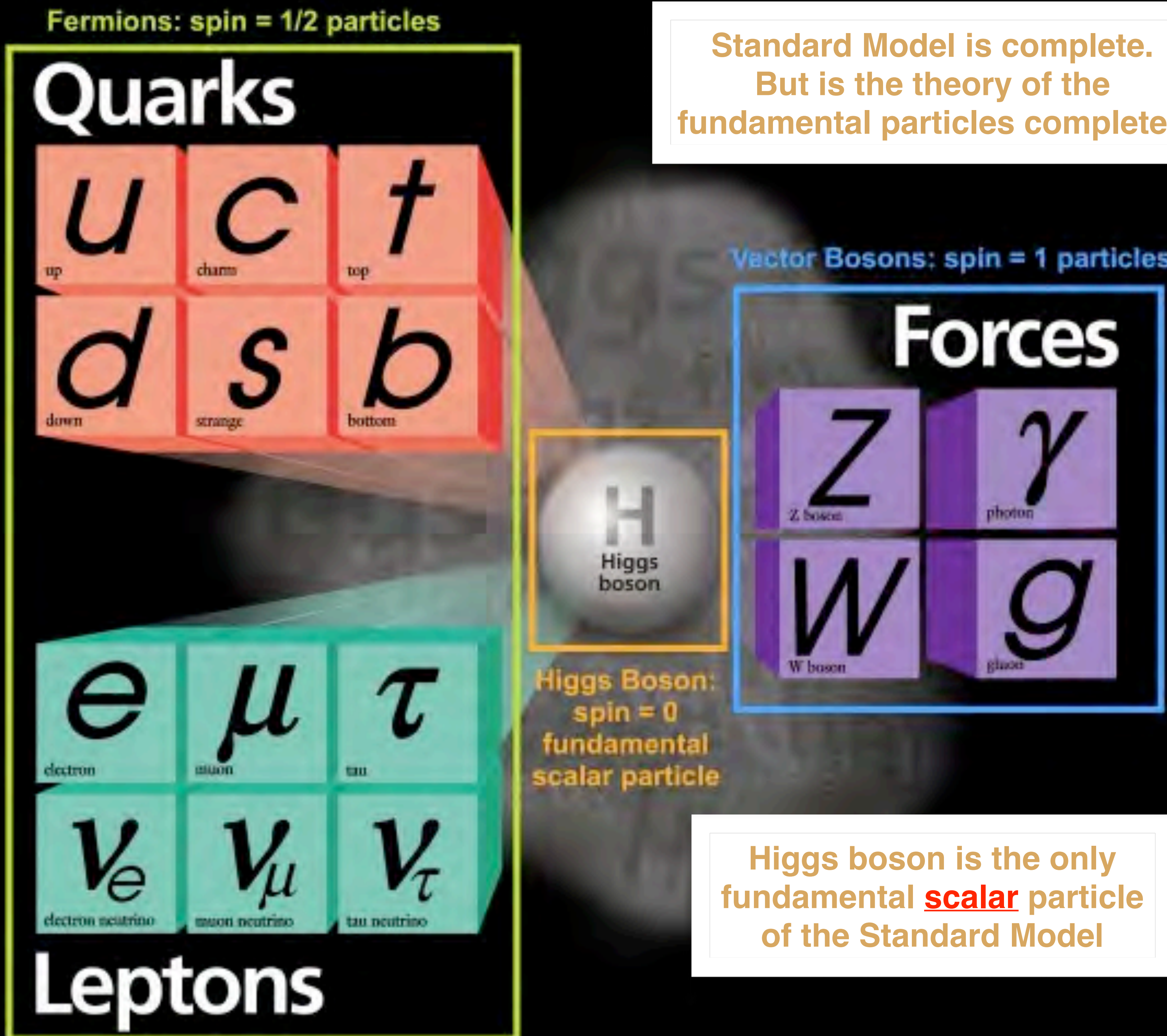

Fermions: spin = 1/2 particles
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons
H
Higgs boson
Higgs Boson: spin = 0 fundamental scalar particle
Vector Bosons: spin = 1 particles
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon

The Higgs boson

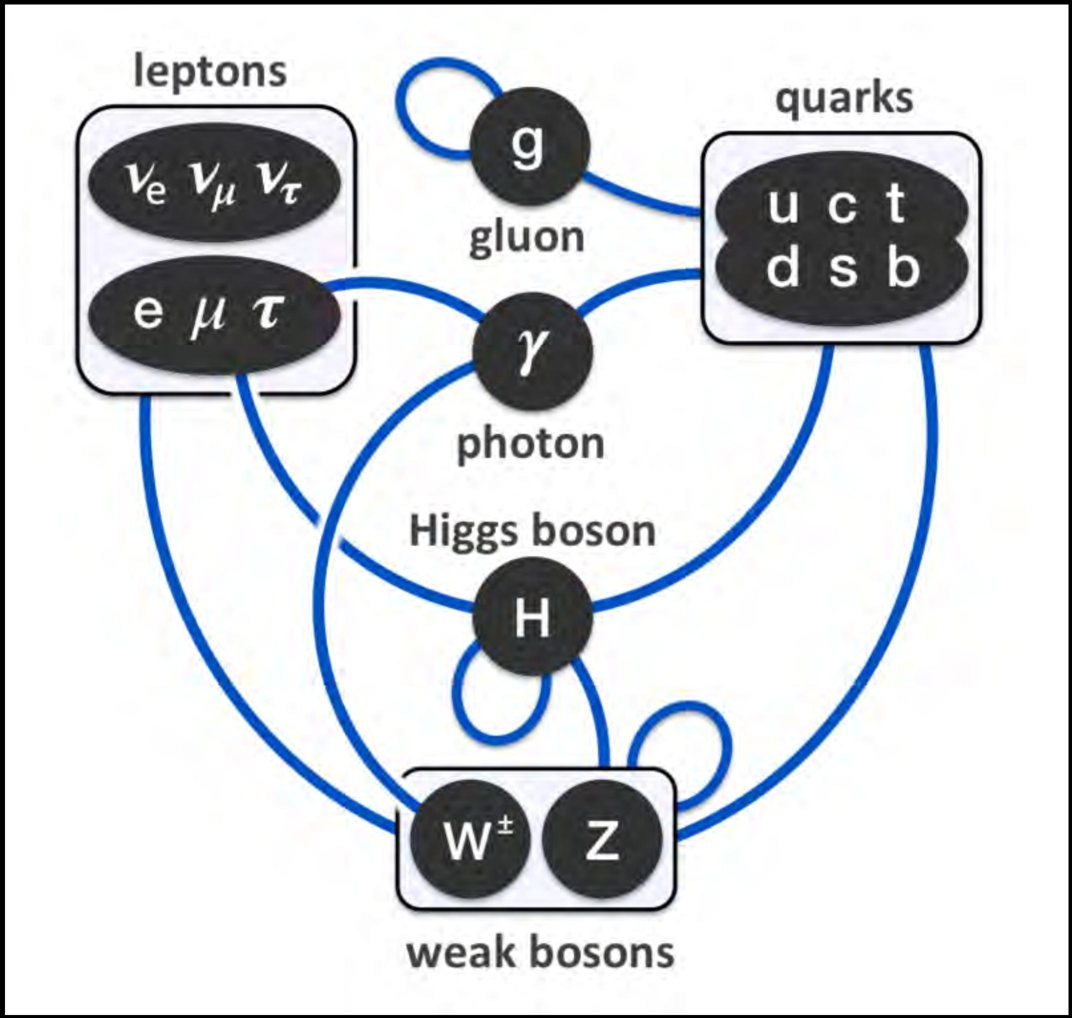
- The Higgs boson was "predicted" in 1964 to explain Electroweak Symmetry Breaking and origin of particle mass.
  - EWSB: $m(W), m(Z) >> m(\gamma)$ and $m(\gamma) = 0$
- It was discovered at the Large Hadron Collider (LHC) in 2012.
- Given the mass of the Higgs boson (125 GeV), its properties within the Standard Model are well defined.
  - Lifetime = 1.6×10^{-22} seconds, width = 4.2 MeV
  - $BR(h \rightarrow W^+W^-) = 21\%$ $BR(h \rightarrow bb) = 58\%$ $BR(h \rightarrow \gamma\gamma) = 0.2\%$
- The LHC continues improving Higgs boson measurements
  - deviations from SM could suggest answers to open questions.



Standard Model is complete.
But is the theory of the fundamental particles complete?

Higgs boson is the only fundamental <u>scalar</u> particle of the Standard Model

The Standard Model



Higgs boson is special

- Only known spinless (S=0) fundamental particle.
- Explains symmetry breaking in electroweak force.
- Gives mass to fundamental particles.
- First particle named "Particle of the Year".

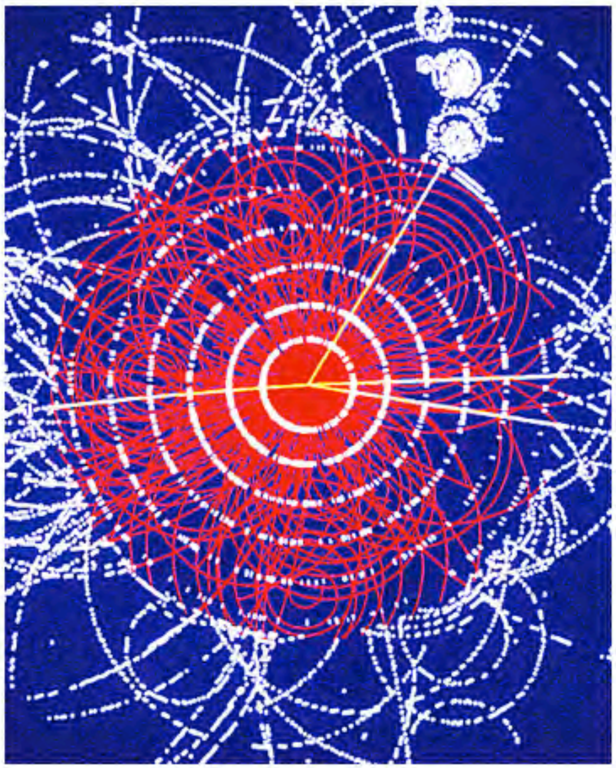
TIME's 2012 Person of the Year: *the Higgs Boson was among nominees!*

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012

18 *of* 40



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

19.74% **Definitely** 80.26% **No Way**

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Name	Definitely	No Way
Kim Jong Un	5,635,941	137,986
Jon Stewart	2,366,324	63,213
Undocumented Immigrants	1,554,085	328,710
Gabby Douglas	1,515,215	79,167
Aung San Suu Kyi and Thein Sein	1,487,945	56,021
Stephen Colbert	1,446,656	270,675
Chris Christie	1,368,767	401,011
Hillary Clinton	1,317,815	485,059
Ai Weiwei	1,151,120	456,897
Mohamed Morsi	874,486	2,032,540
Bashar Assad	857,339	353,982
E.L. James	782,583	245,593
Roger Goodell	691,870	99,026
Sheldon Adelson	618,678	427,300
Malala Yousafzai	340,205	48,453
The Mars Rover	102,477	294,597
Psy	100,722	100,308
Barack Obama	89,182	100,584
Felix Baumgartner	82,316	83,570
The Higgs Boson Particle	73,558	299,051

2012 Person of the Year

TIME's 2012 Person of the Year: *the Higgs Boson was among nominees!*

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The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012

18 of 40

SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

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The Higgs Boson: Particle of the Year

Forget Person of the Year – the discovery this summer by the Large Hadron Collider of the Higgs Boson particle was one of science's greatest achievements

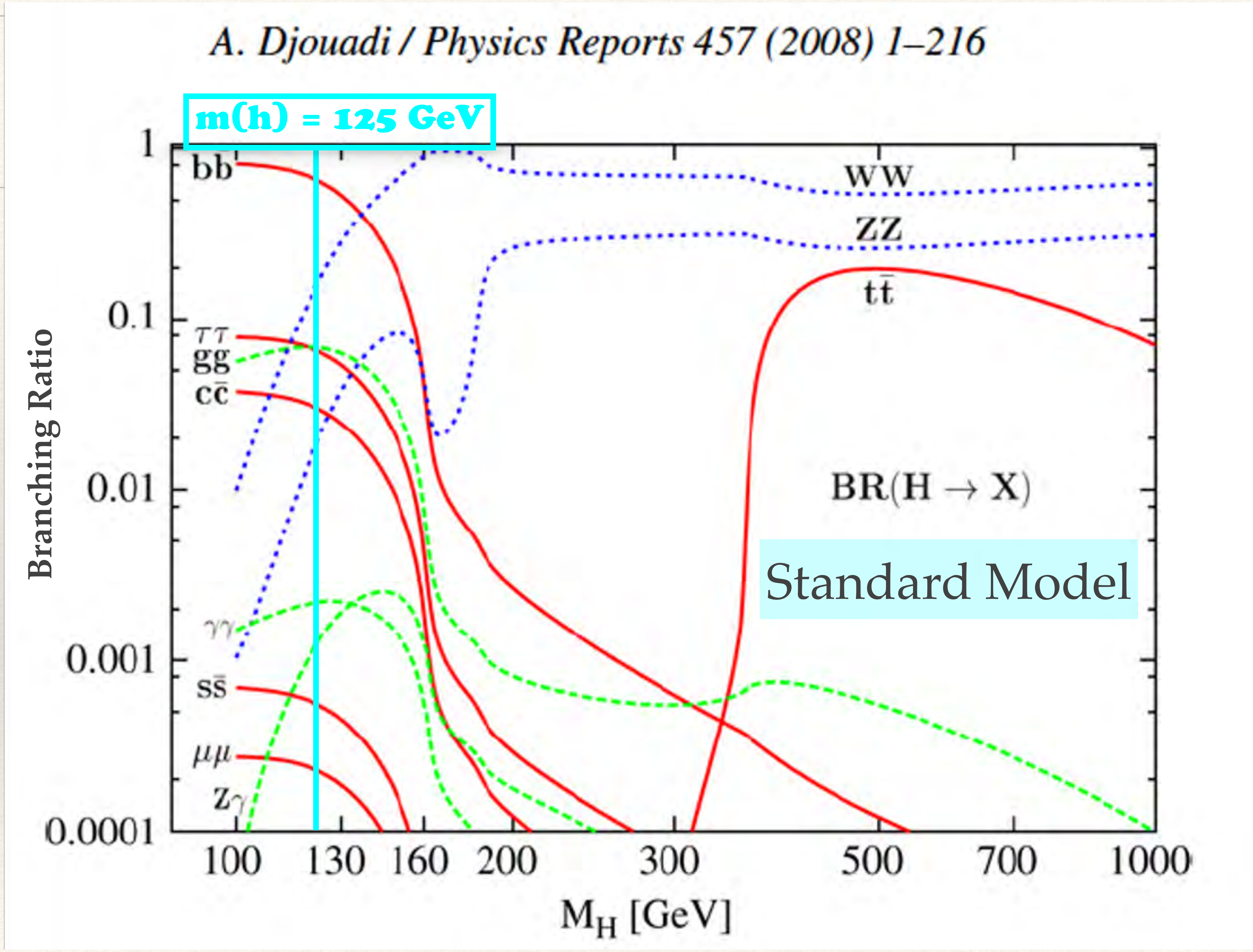
By TIME Staff @TIME | Dec. 19, 2012

physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

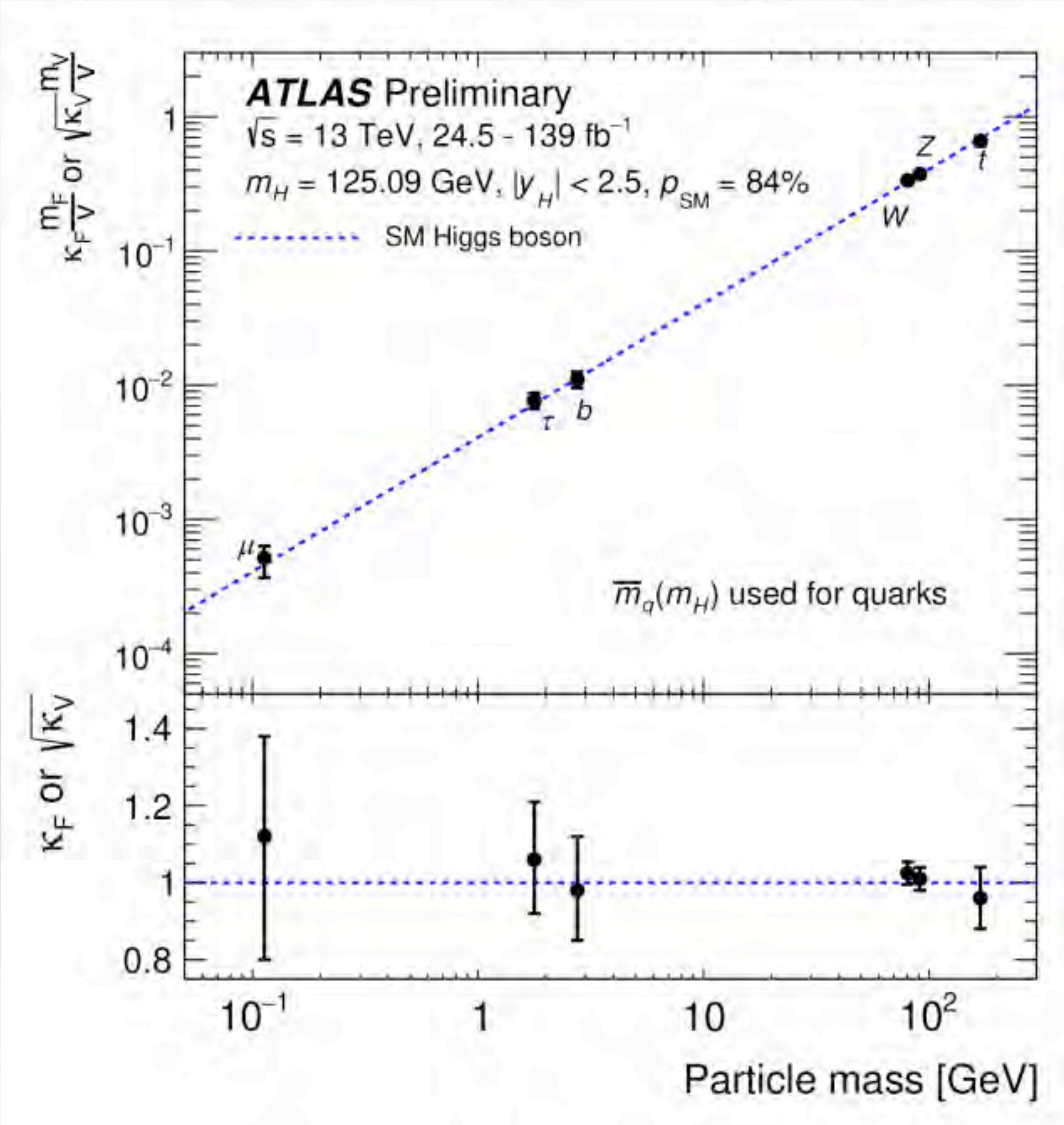
Higgs boson is special

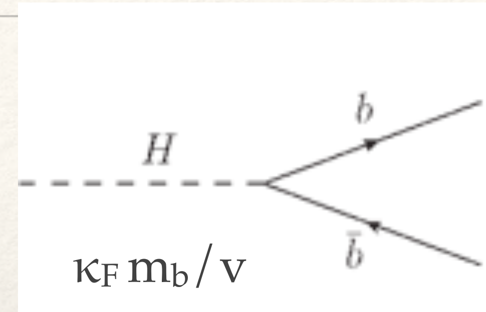
- Only known spinless (S=0) fundamental particle.
- Explains symmetry breaking in electroweak force.
- Gives mass to fundamental particles.
- First particle named "Particle of the Year".
- Potential "tool" for discovery of

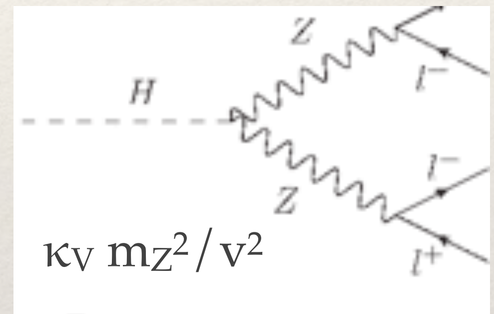
  Physics Beyond the Standard Model (BSM)


A. Djouadi / Physics Reports 457 (2008) 1–216
m(h) = 125 GeV
Branching Ratio
1
0.1
0.01
0.001
0.0001
bb
ττ
gg
cc̄
γγ
ss̄
μμ
Zγ
WW
ZZ
tt̄
BR(H → X)
Standard Model
100
130
160
200
300
500
700
1000
M_H [GeV]

Standard Model







v = 246 GeV

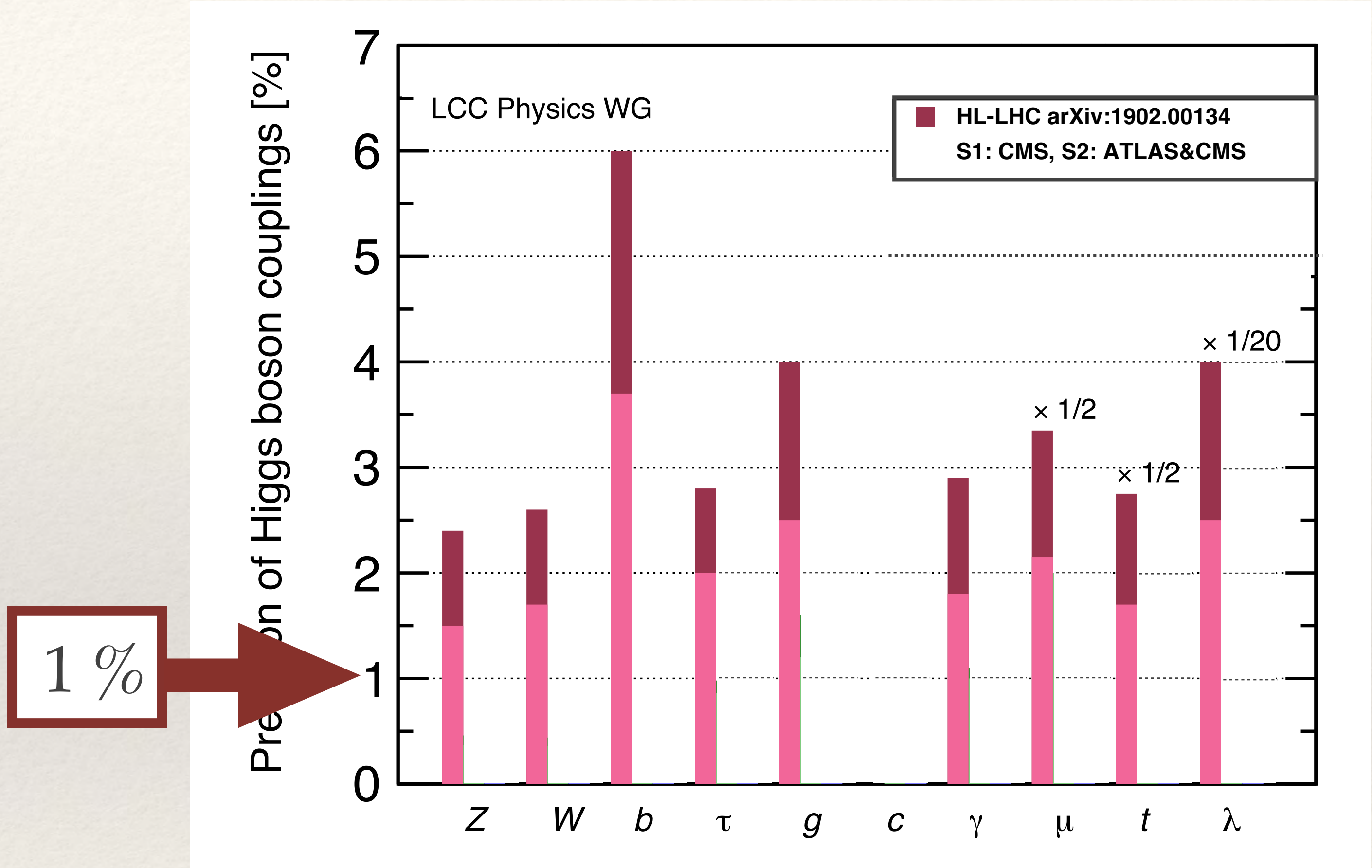
Higgs vacuum expectation value

LHC → High Luminosity LHC

- The High Luminosity LHC will stretch the Higgs physics reach:
  - ~2-5% precision for most Higgs couplings
  - Larger uncertainties on Zγ and charm
  - < 50% on the self-coupling
  - Higgs width 5%

Future Reach of HL-LHC

- S1, current projection
- **/model-dependent**
- S2, improved
- **/model-dependent**
  (HL-LHC adopted)



arXiv:1902:00134
arXiv:1903.01629

Projections Assume:

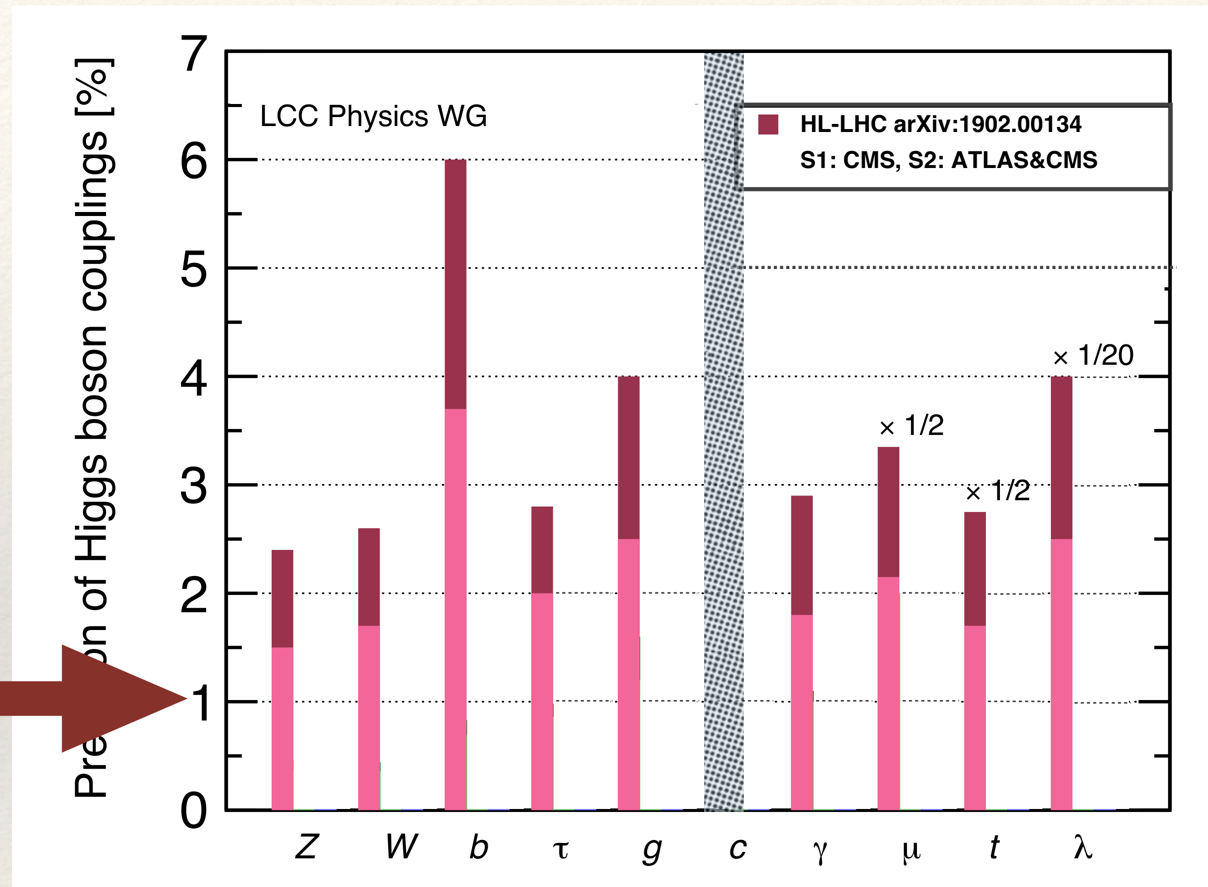
Higgs boson has no decay modes beyond those predicted in the SM.

Future Reach of HL-LHC

- S1, current projection
- **/model-dependent**
- S2, improved
- **/model-dependent**
  (HL-LHC adopted)

- Higgs boson production backgrounds at the LHC (strong interaction) limits the precision that can be achieved on these measurements:
  - ~2-6%
- **SPOILER ALERT**
  - The e+e- Higgs factory can greatly improve precision.

1 %

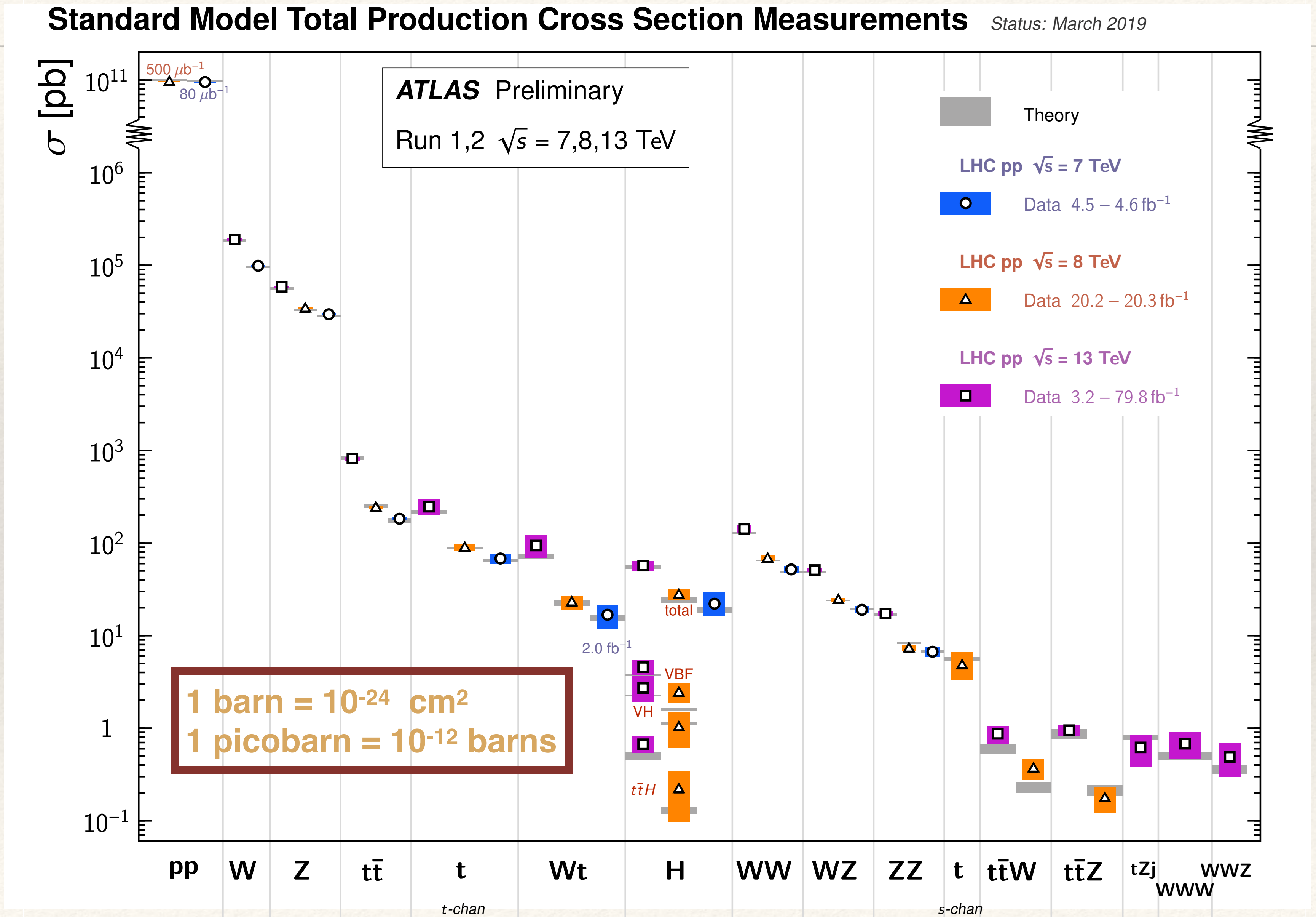


arXiv:1902:00134
arXiv:1903.01629

Projections Assume:

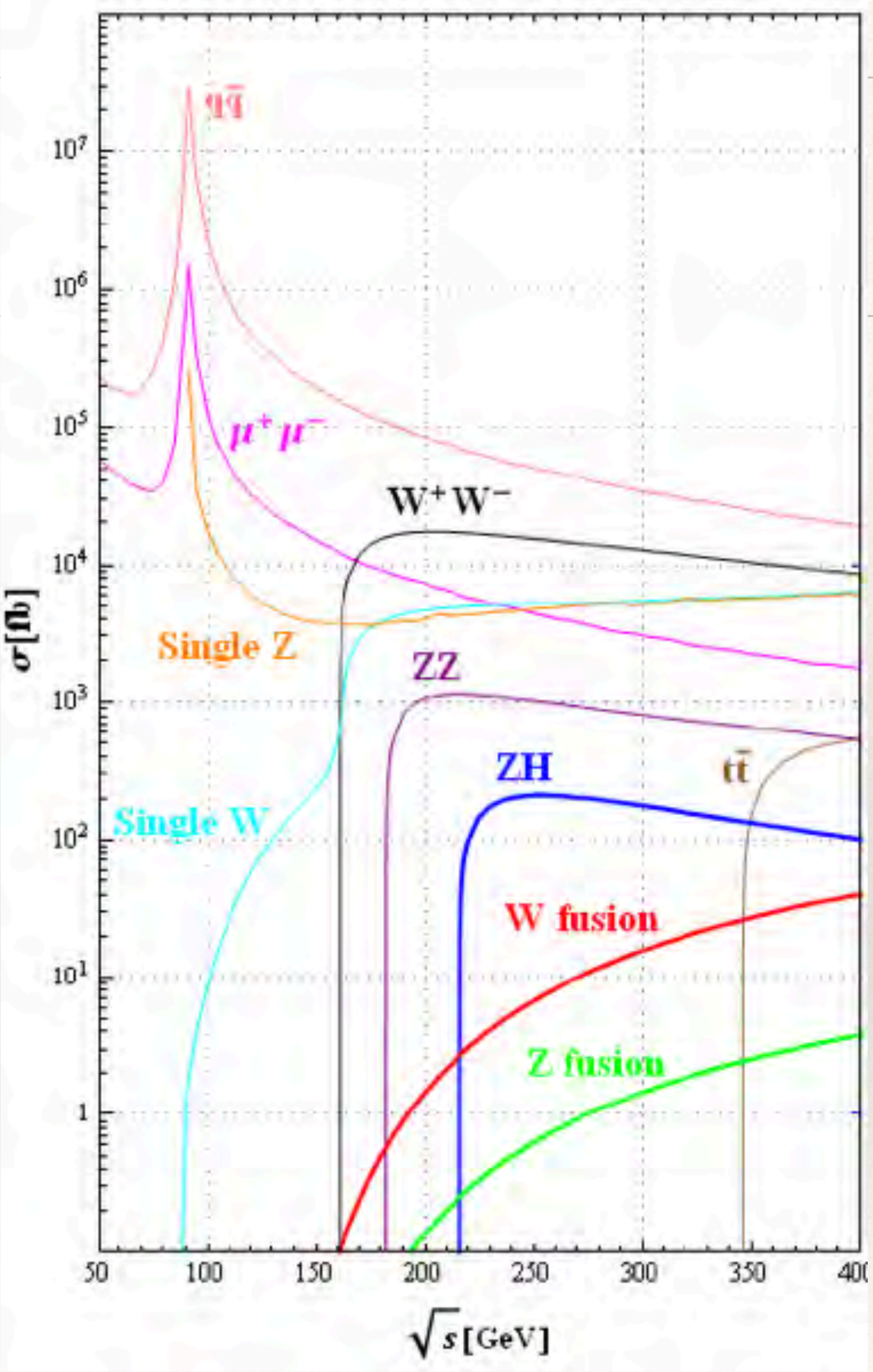
Higgs boson has no decay modes beyond those predicted in the SM.

Physics at the LHC



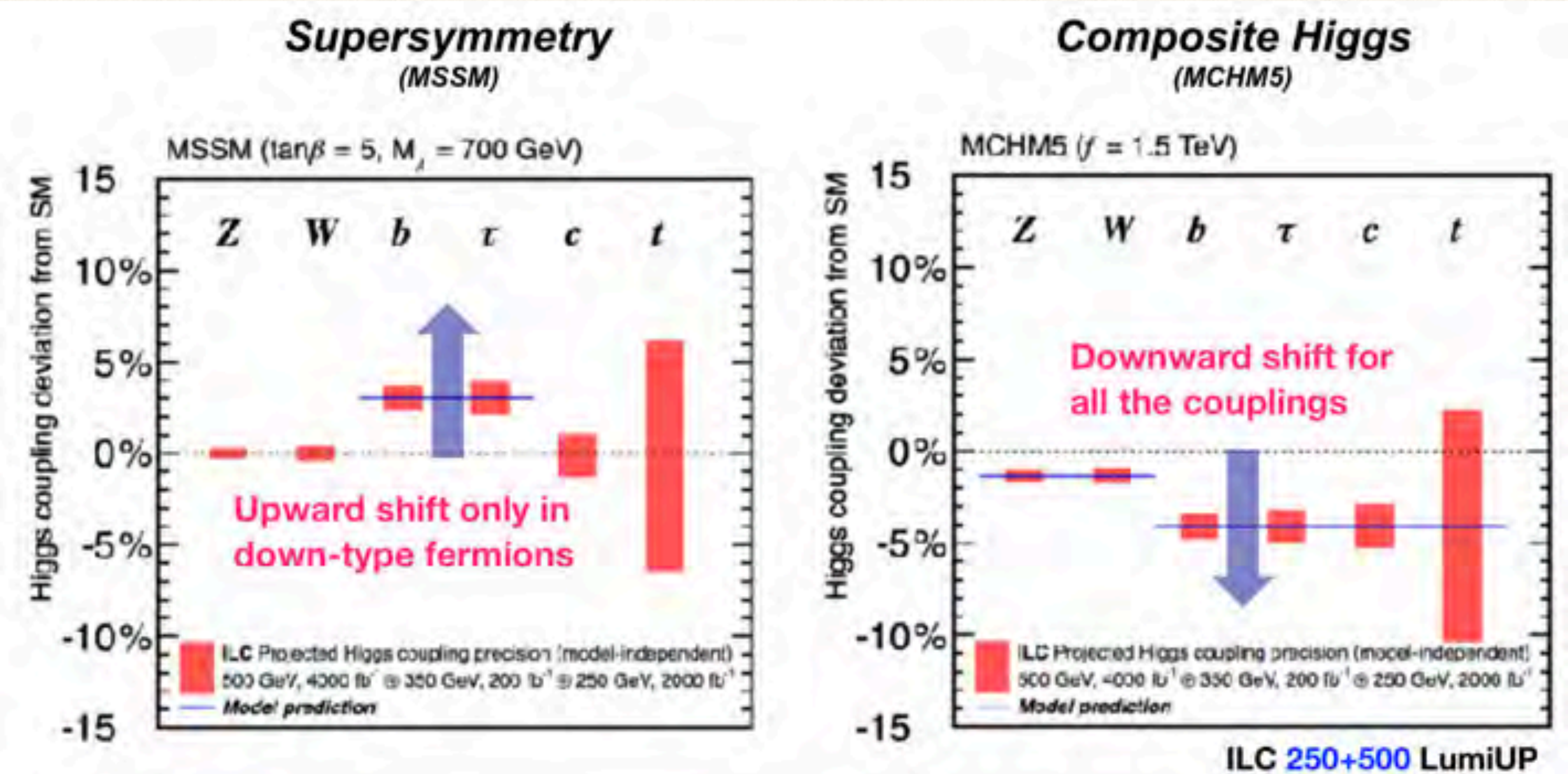
Physics at the Higgs factory

- Higgs boson production not nearly as rare as at the LHC
  - Backgrounds lower
  - Higher precision



Beyond the Standard Model

- Is the Standard Model complete?
  - Gives excellent description of most physics.
- But
  - No dark matter.
  - Higgs mass unnaturally small (Hierarchy Prob.) - compared to gravity.
  - Why matter dominates Universe (Baryon asym.)?
  - Why is electroweak symmetry broken?
  - or neutrino mass, dark energy, gravity …
- Properties of Higgs boson could point the way.
  - For example, is the Higgs boson elementary or a composite?


Supersymmetry
(MSSM)
MSSM (tanβ = 5, M_A = 700 GeV)
Higgs coupling deviation from SM
15
10%
5%
0%
-5%
-10%
-15
Z W b τ c t
Upward shift only in
down-type fermions
ILC Projected Higgs coupling precision (model-independent)
500 GeV, 4000 fb⁻¹ @ 350 GeV, 200 fb⁻¹ @ 250 GeV, 2000 fb⁻¹
Model prediction
Composite Higgs
(MCHM5)
MCHM5 (f = 1.5 TeV)
Higgs coupling deviation from SM
15
10%
5%
0%
-5%
-10%
-15
Z W b τ c t
Downward shift for
all the couplings
ILC Projected Higgs coupling precision (model-independent)
500 GeV, 4000 fb⁻¹ @ 350 GeV, 200 fb⁻¹ @ 250 GeV, 2000 fb⁻¹
Model prediction
ILC 250+500 LumiUP

Advantage of Higgs Studies at e^+e^-

Very low backgrounds and simple reactions in e^+e^-.

Environment allows for detectors of unprecedented accuracy.

Also, all decay modes are observed in e^+e^-,

with small, calculable backgrounds.

Polarization enhances sensitivity.

Higher precision, model-independent measurements feasible.

Sub-1% coupling measurements achievable.

Energy extendability (to 500-1000 GeV) accesses

top Yukawa and triple-Higgs couplings

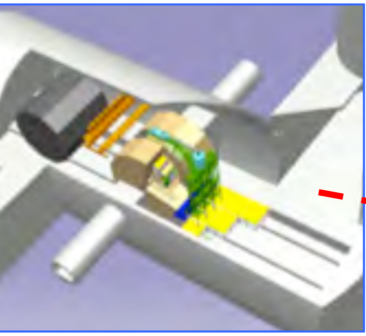
e^+e^- Higgs Factory proposals

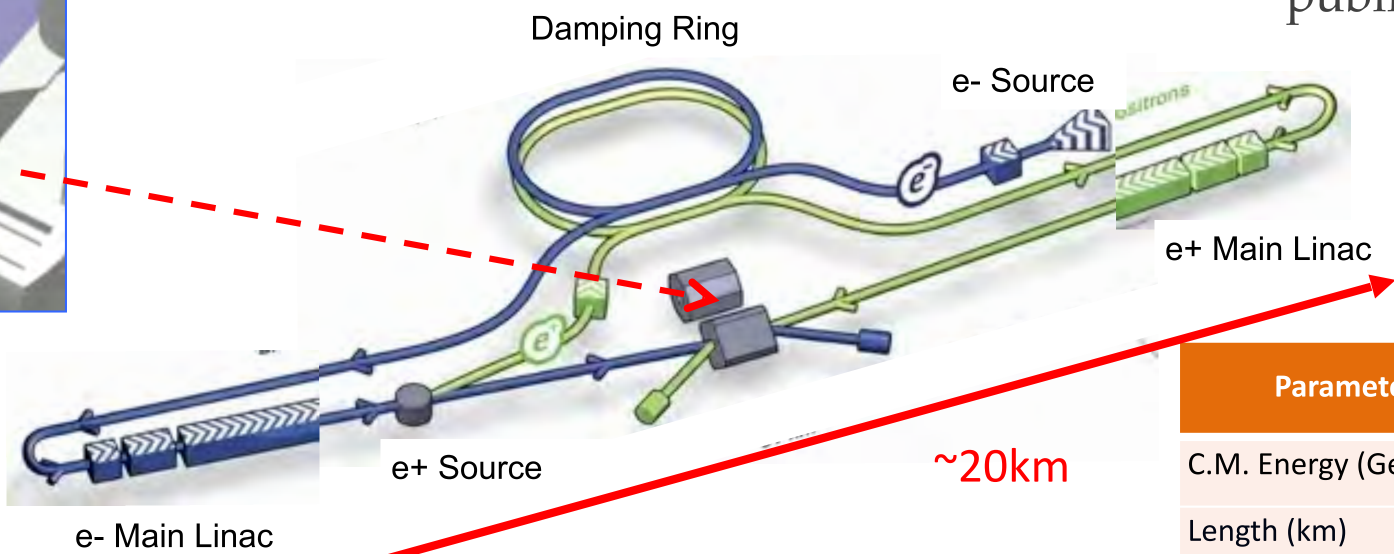
		√s	beam polarisation	∫Ldt for Higgs	R&D phase
LINEAR	ILC/C^3	0.1 - 1 TeV	e-: 80% e+: 30%	2000 fb^{-1} @ 250 GeV 200 fb^{-1} @ 350 GeV 4000 fb^{-1} @ 500 GeV	ILC TDR completed in 2013
LINEAR	CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1000 fb^{-1} @ 380 GeV 2500 fb^{-1} @ 1.5 TeV 5000 fb^{-1} @ 3 TeV	CDR completed in 2012
CIRCULAR	CEPC	90 - 240 GeV	e-: 0% e+: 0%	5600 fb^{-1} @ 240 GeV	CDR completed in 2018
CIRCULAR	FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	5000 fb^{-1} @ 250 GeV 1700 fb^{-1} @ 350 GeV	CDR completed in Jan 2019

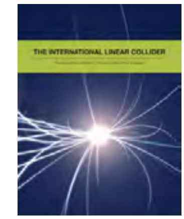
update based on J. Tian, LC School, DESY, 2018

International Linear Collider (ILC)

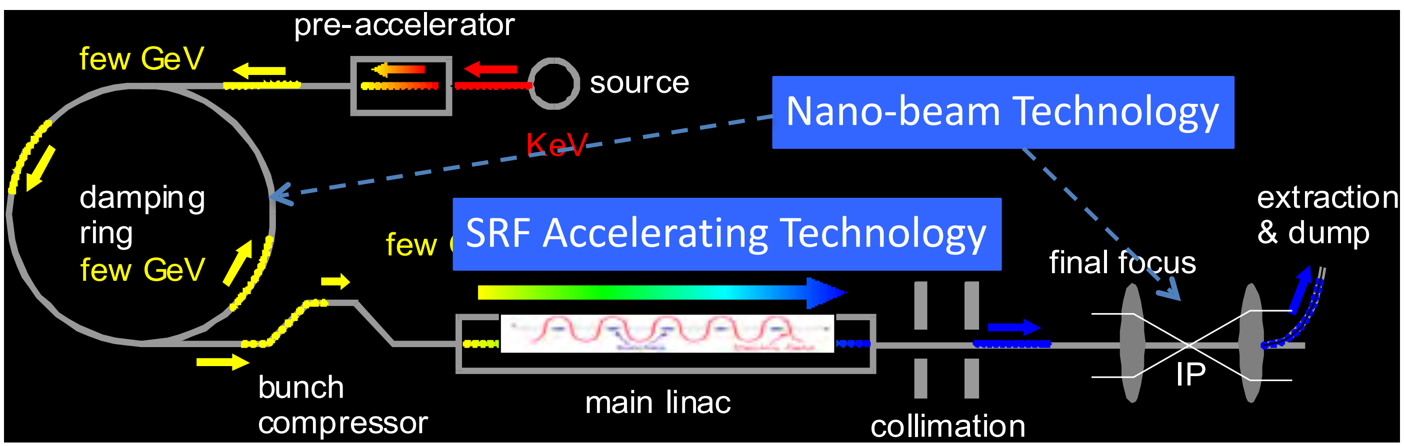
ILC TDR is 5-volumes, published 12 June 2013







Key Technologies



Parameter	Initial stage	TDR
C.M. Energy (GeV)	250	500
Length (km)	20	31
Luminosity (x10^{34})	1.35 (2.7, 5.4)	1.8
Repetition (Hz)	5 (10)	5
Beam Pulse Period (ms)	0.73	0.73
Beam Current (mA in pulse)	5.8	5.8
Beam size (y) at FF (nm)	**7.7**	**5.9**
SRF Cavity Gr (MV/m), Q_0	**31.5**, 1x10 ^{10}	**31.5**, 1x10 ^{10}

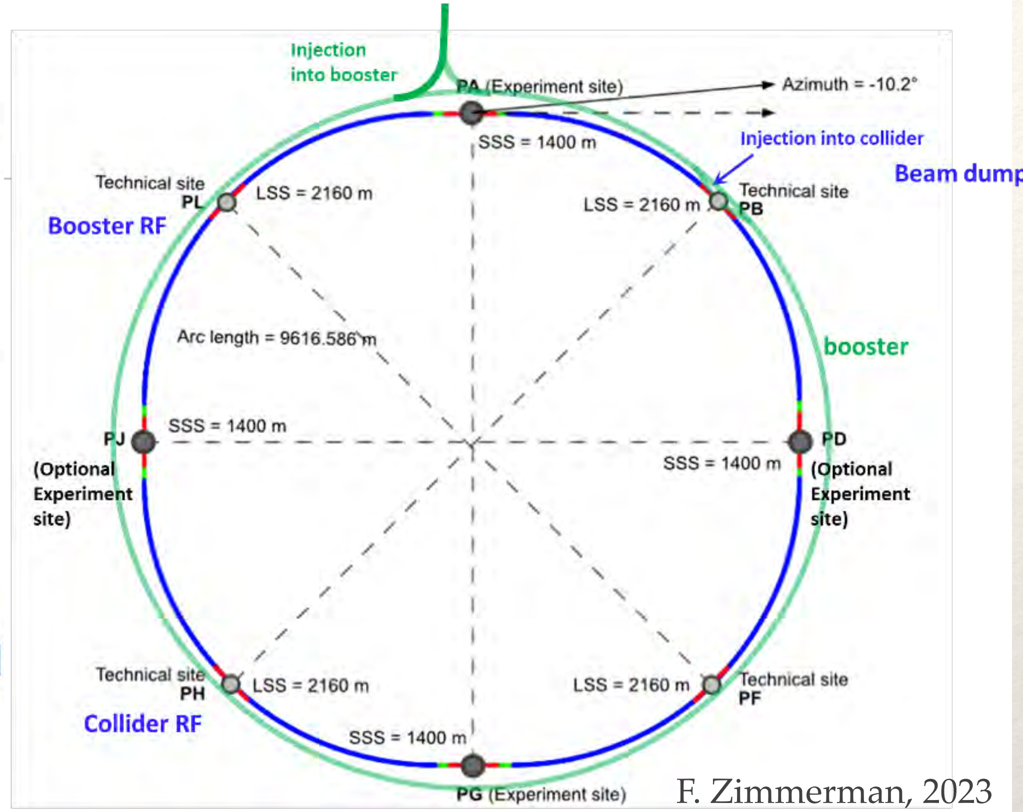
based on S. Michizono, 8 Nov 2017

Polarized electrons (± 80%) and positrons (± 30%)

arXiv:1711.00568 **arXiv:1903.01629**

Future Circular Collider (FCC-ee)

- **Double ring** e+ e- collider ~100 km → 91 km
- **Follows footprint of FCC-hh**, except around IPs
- **Asymmetric IR layout and optics** to limit synchrotron radiation towards the detector
- **2 IPs, large** horizontal crossing angle **30 mrad, crab-waist optics**
- **Synchrotron radiation power 50 MW/beam** at all beam energies
- **Top-up injection** scheme for high luminosity
- Requires **booster synchrotron in collider tunnel**



G. Taylor, Jan 2019

F. Zimmerman, 2023

Energy (GeV)	Design Luminosity (10^{34} cm^{-2} s^{-1}/IP)
90	182
160	19.4
240	7.3
375	1.33

SR/beam limited to ~50 MW

Unpolarized beams

CDR: CERN-ACC-2018-0057

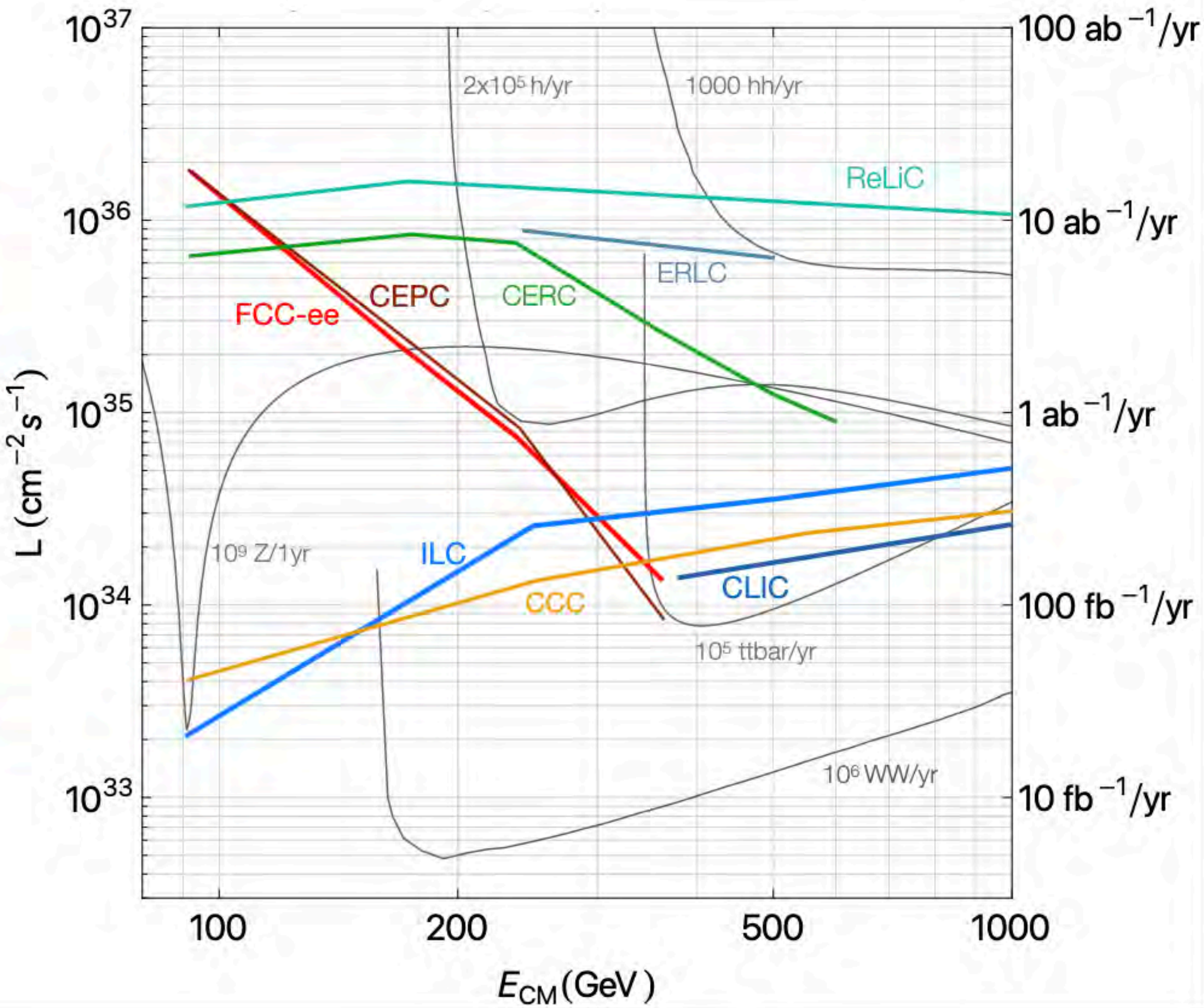
F. Zimmerman, SLAC P5, May 3, 2023

AF Collider Implementation Task

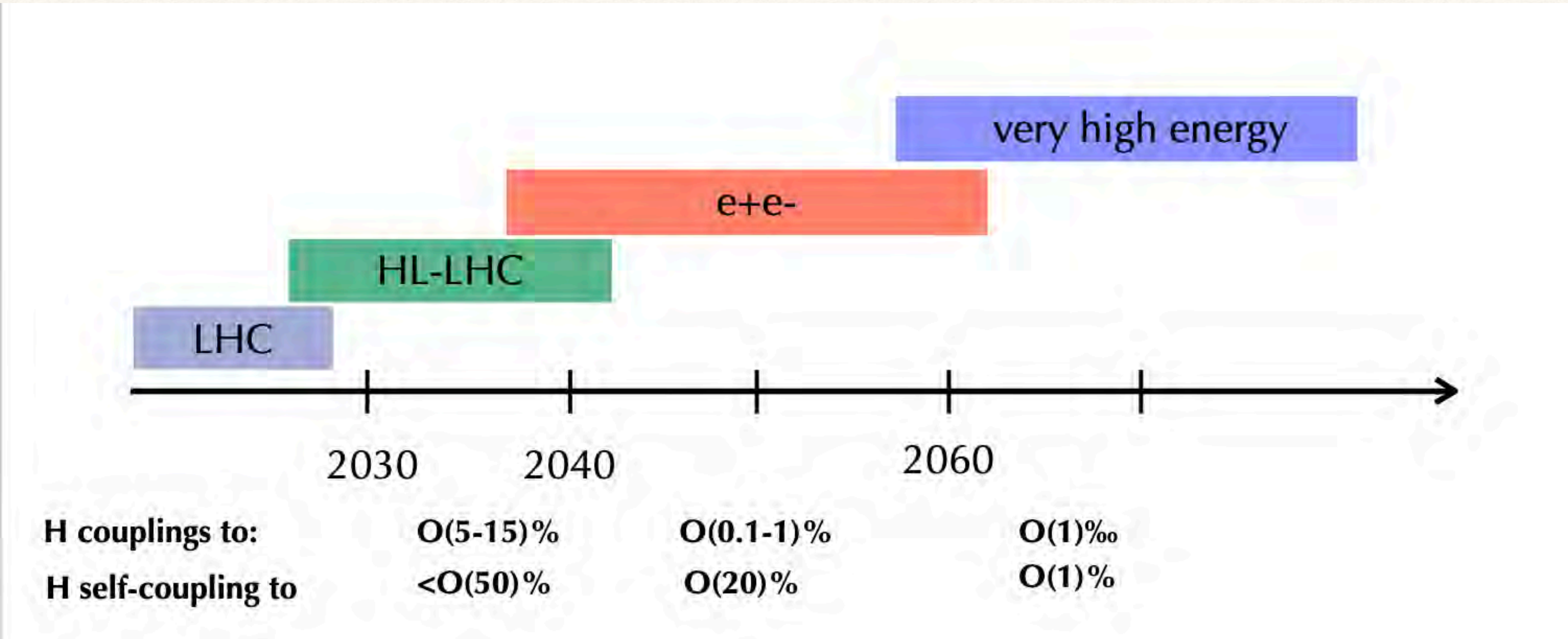
Higgs factory summary plot

- Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents.
- The right axis shows integrated luminosity for one Snowmass year (10^7 s).
- Also shown are lines corresponding to the required luminosity for yearly production rates of important processes.

Thomas Roser
P5 meeting
April 13, 2023



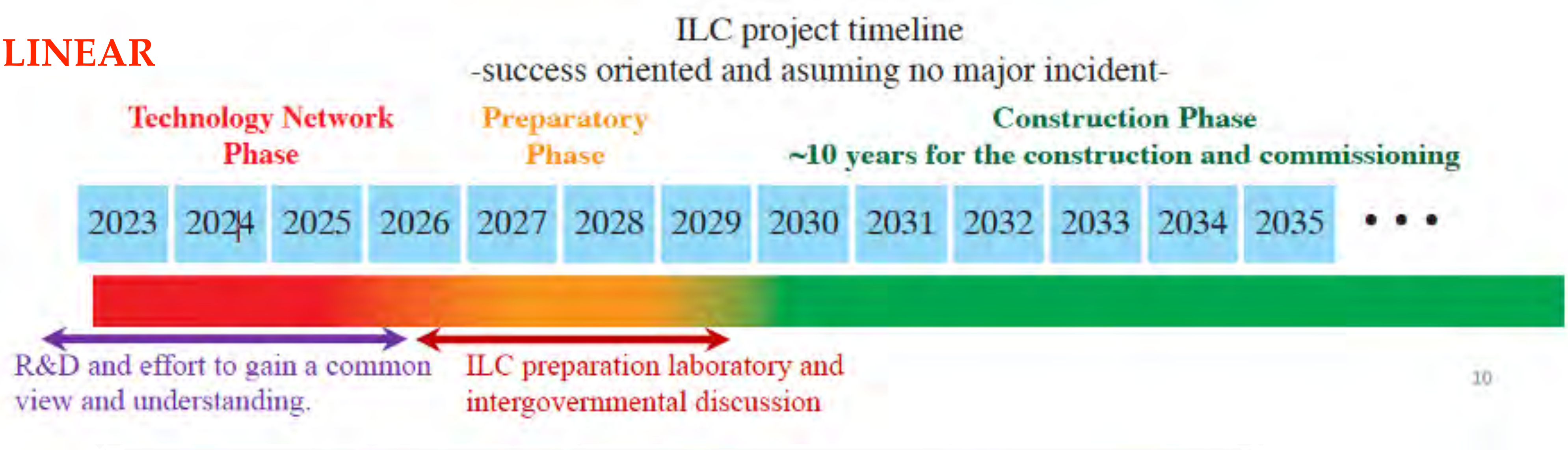
Future Collider Timeline

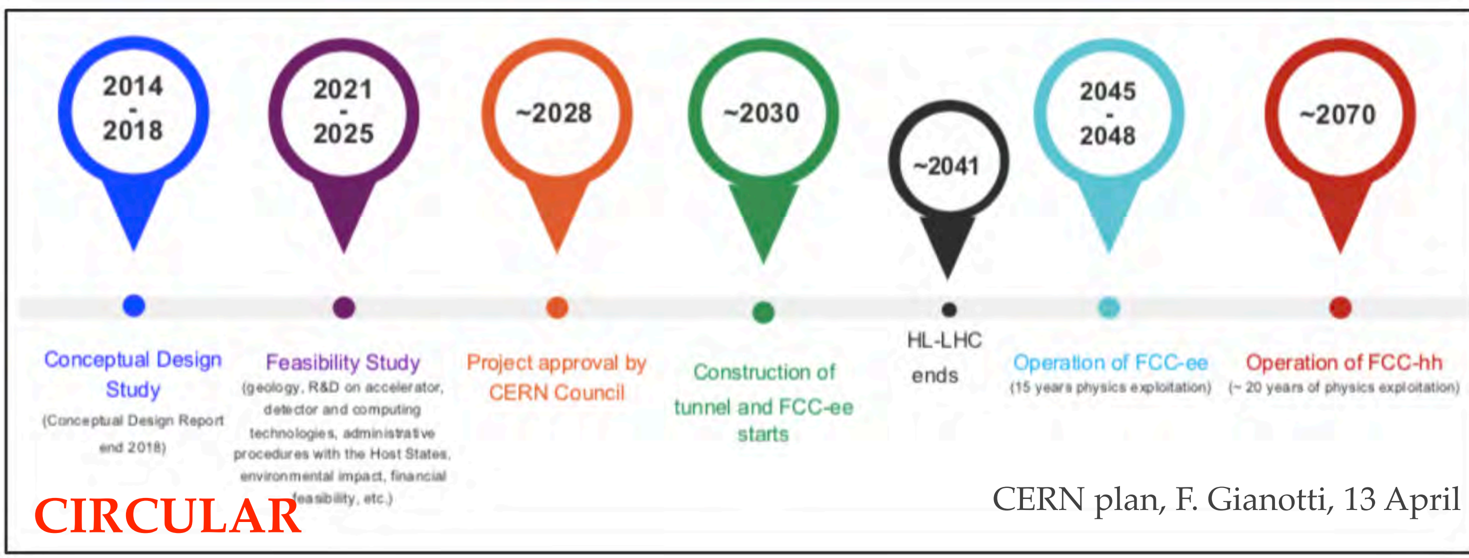


C. Vernieri – Snowmass 21 EF Workshop - Brown U. - March 2022

Process to achieve Higgs collisions by ~2040 (Linear) or ~2050 (Circular)

LINEAR





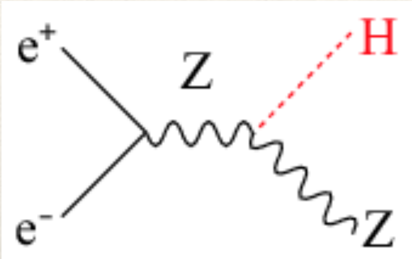
CIRCULAR

CERN plan, F. Gianotti, 13 April 2023

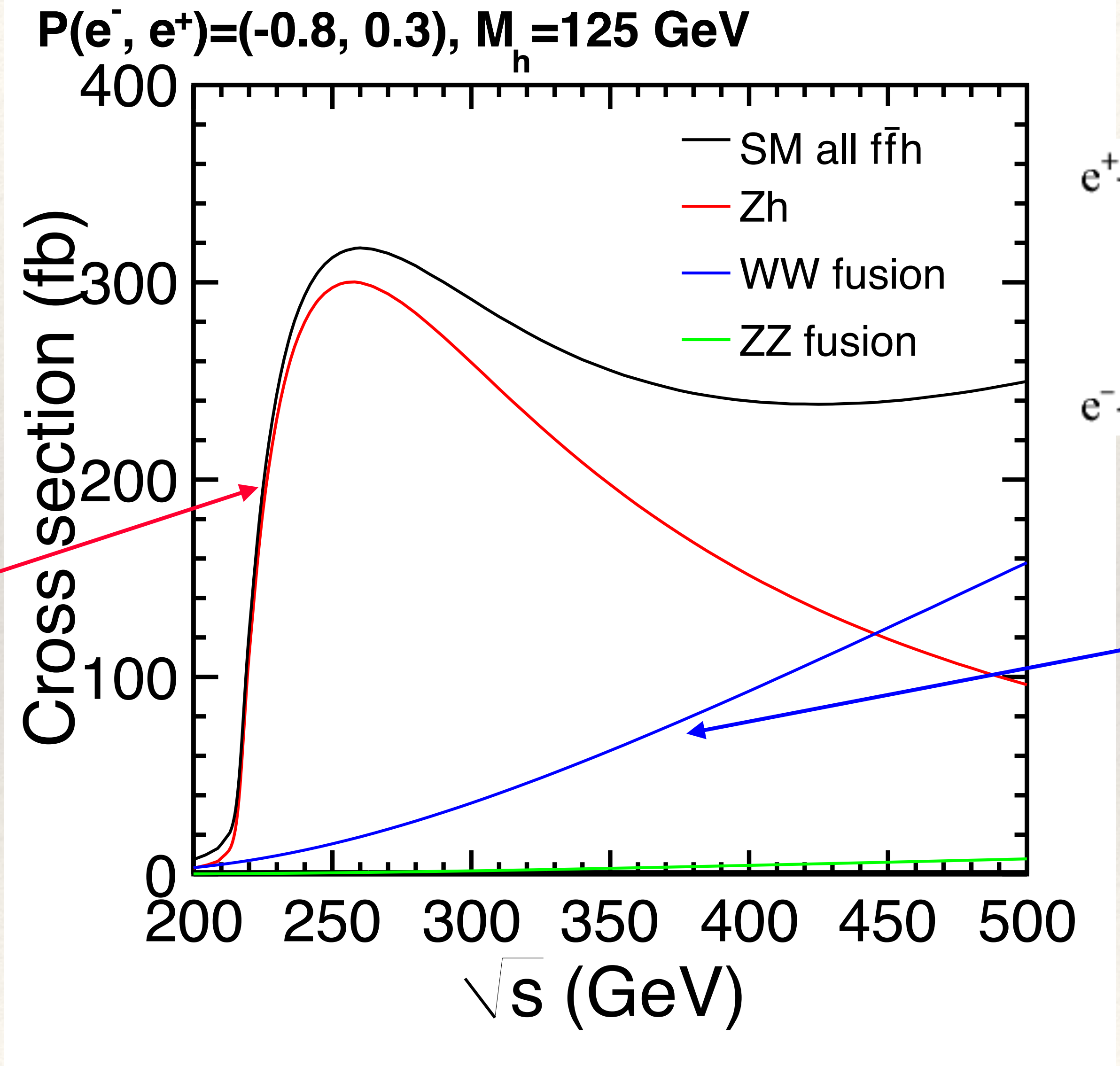
FCCee plan starts with Z, then WW, reaching Higgs ~2050

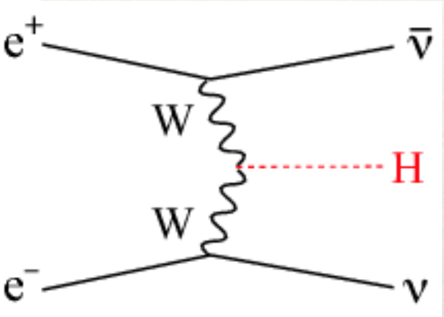
CEPC earlier?

Higgs Boson Cross Section



Higgs-strahlung peaks and falls with center-of-mass energy





WW fusion rising with center-of-mass energy

Higgstrahlung at 250 GeV

Higgs Factory observes Higgs recoiling from a Z, with known CM energy⇓

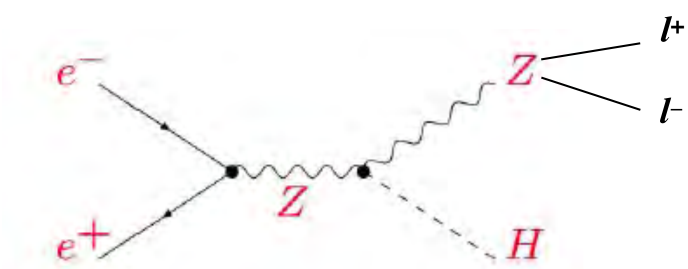
- powerful channel for unbiassed tagging of Higgs events
- measurement of even invisible decays

(⇓ - some beamstrahlung)

1. KNOWN INTIAL STATE

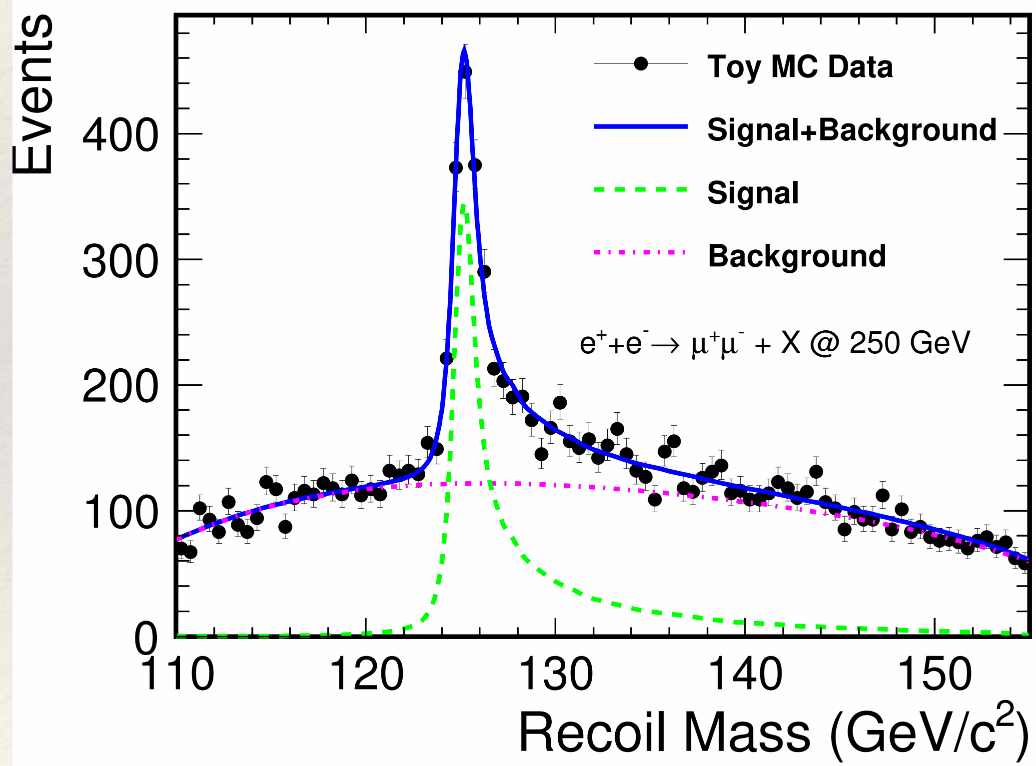
2. MEASURE Z→ *l*+*l*−

3. SELECT E(Z boson) = 110 GeV
M(recoil) = 125 GeV



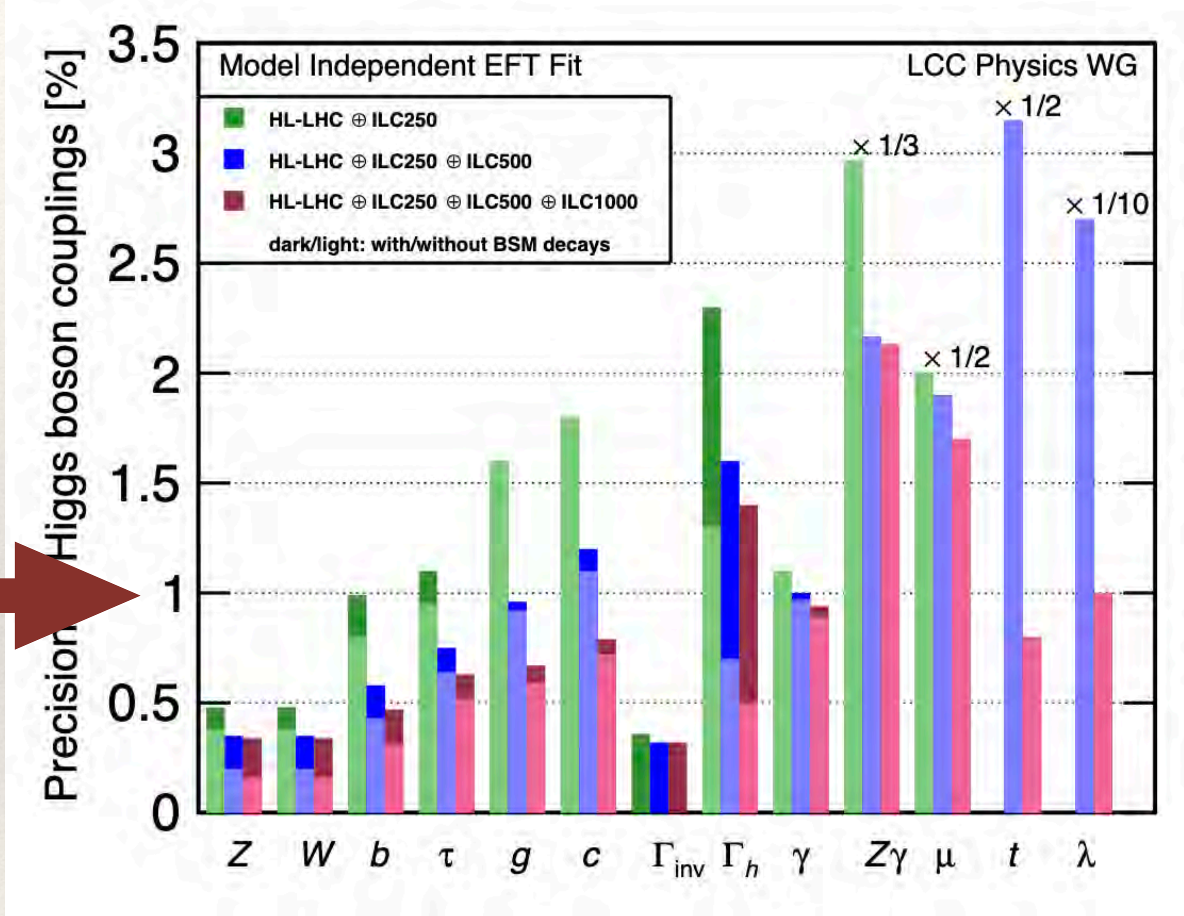
4. MEASURE RECOIL
AND OBSERVE DECAY

Invisible decays are included



arXiv:1604.07524, PRD94 (2016) 113002

HL-LHC Comparison (model-dependent)



1 %

arXiv:2203.07622

ALSO:

BR(invisible) < 0.16%

SM = 0.1%

arXiv:2203.08330

The darker bars show the results allowing invisible and exotic Higgs decay channels; the lighter bars assume that these BSM decays are not present.

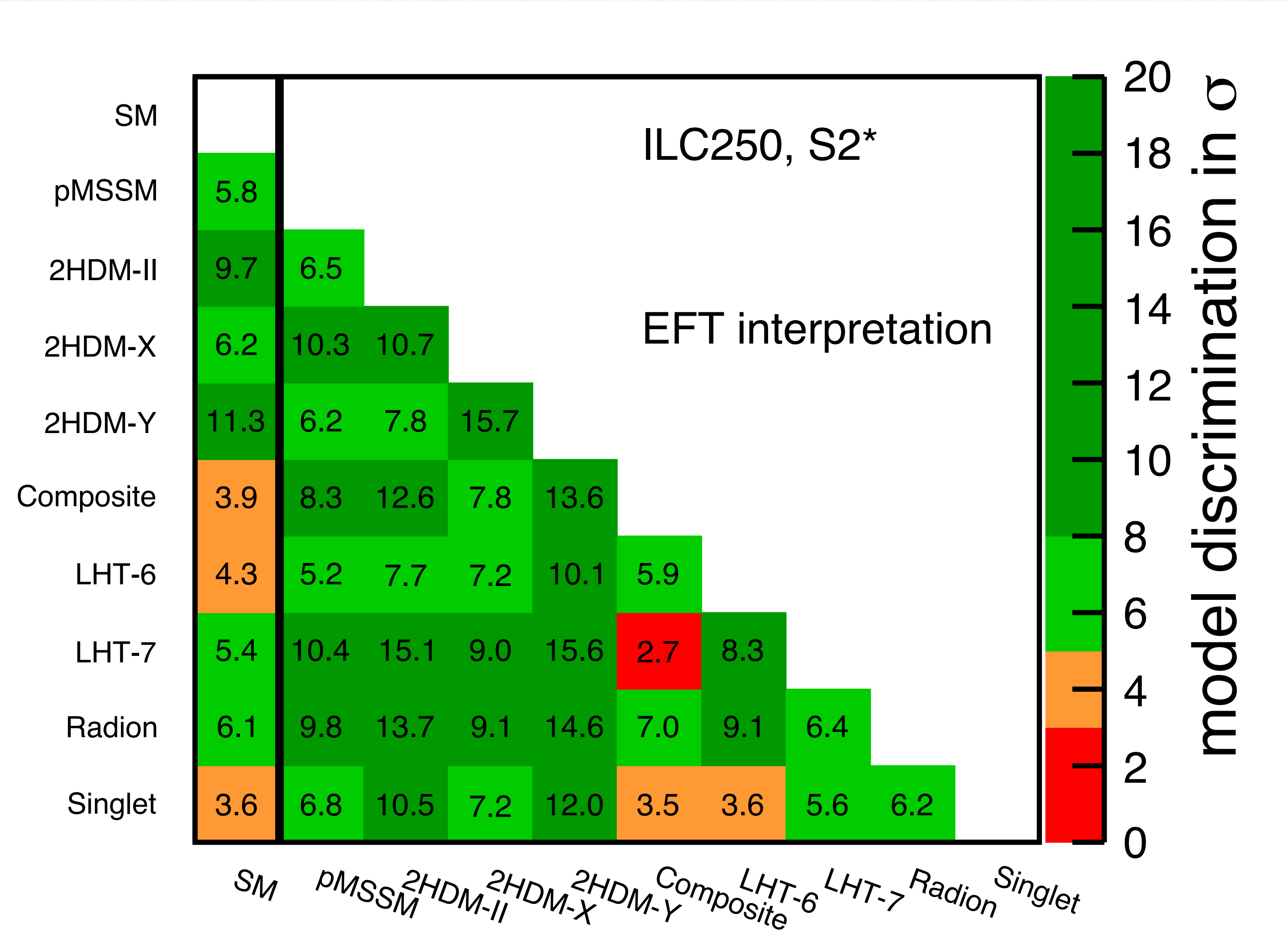
Testing New Physics Models

- Studied nine(9) models that are unlikely to be discovered by HL-LHC.
  - Masses beyond reach.

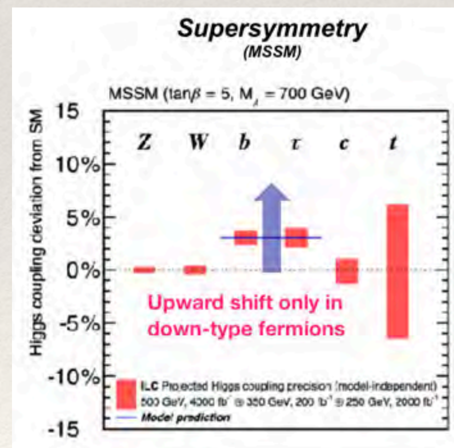
1. pMSSM SUSY [34]; high colored masses: m(bino) =3:4 TeV, m(gluino) = 4 TeV.
2. Type II 2-Higgs-doublet [36]; heavy Higgs bosons at 600 GeV and tan β = 7.
3. Type X 2-Higgs-doublet [36]; heavy Higgs bosons at 450 GeV and tan β = 6.
4. Type Y 2-Higgs-doublet [36]; heavy Higgs bosons at 600 GeV and tan β = 7.
5. Composite Higgs MCHM5, f = 1.2 TeV [38]; lightest new particle vectorlike top partner T at 1.7 TeV and very small single production.
6. Little Higgs with T-parity [39]; f = 785 GeV and top partner T at 2 TeV.
7. Little Higgs with T-parity [40]; f = 1 TeV and option B for light-quark Yukawa couplings; top partner T mass of 2.03 TeV.
8. Higgs-radion mixing [41]; radion mass is 500 GeV; other relevant extra-dimensional states can be at multi-TeV masses.
9. Model with Higgs singlet added to SM, motivated by EW baryogenesis with portal to dark matter sector [42]; singlet mass is 2.8 TeV, with mixing as permitted by decoupling.

arXiv:1710:07621

Model Discrimination - 250 GeV



- S1*, current projection **/model-independent**
- S2*, improved **/model-independent**



arXiv:1710.07621

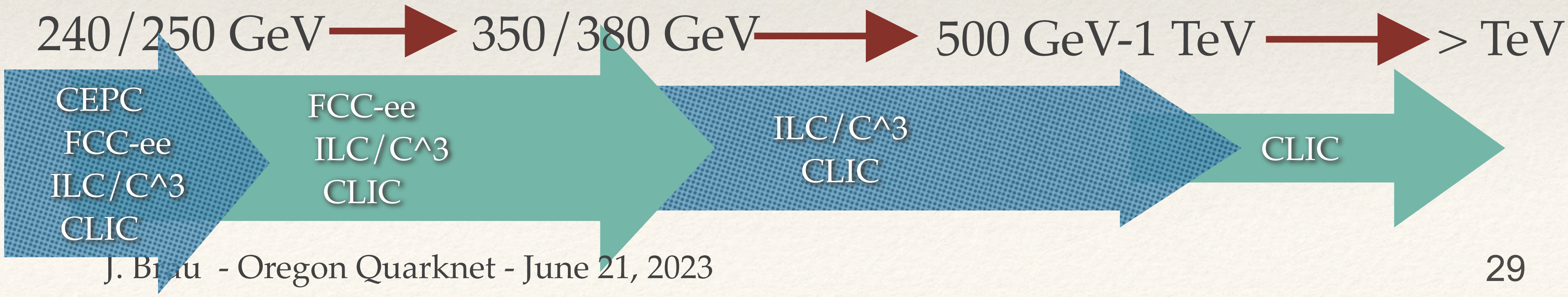
The Broader Physics Program

The physics opportunities of next-generation e^+e^- colliders emphasize precise measurement of **most** **Higgs boson couplings.**

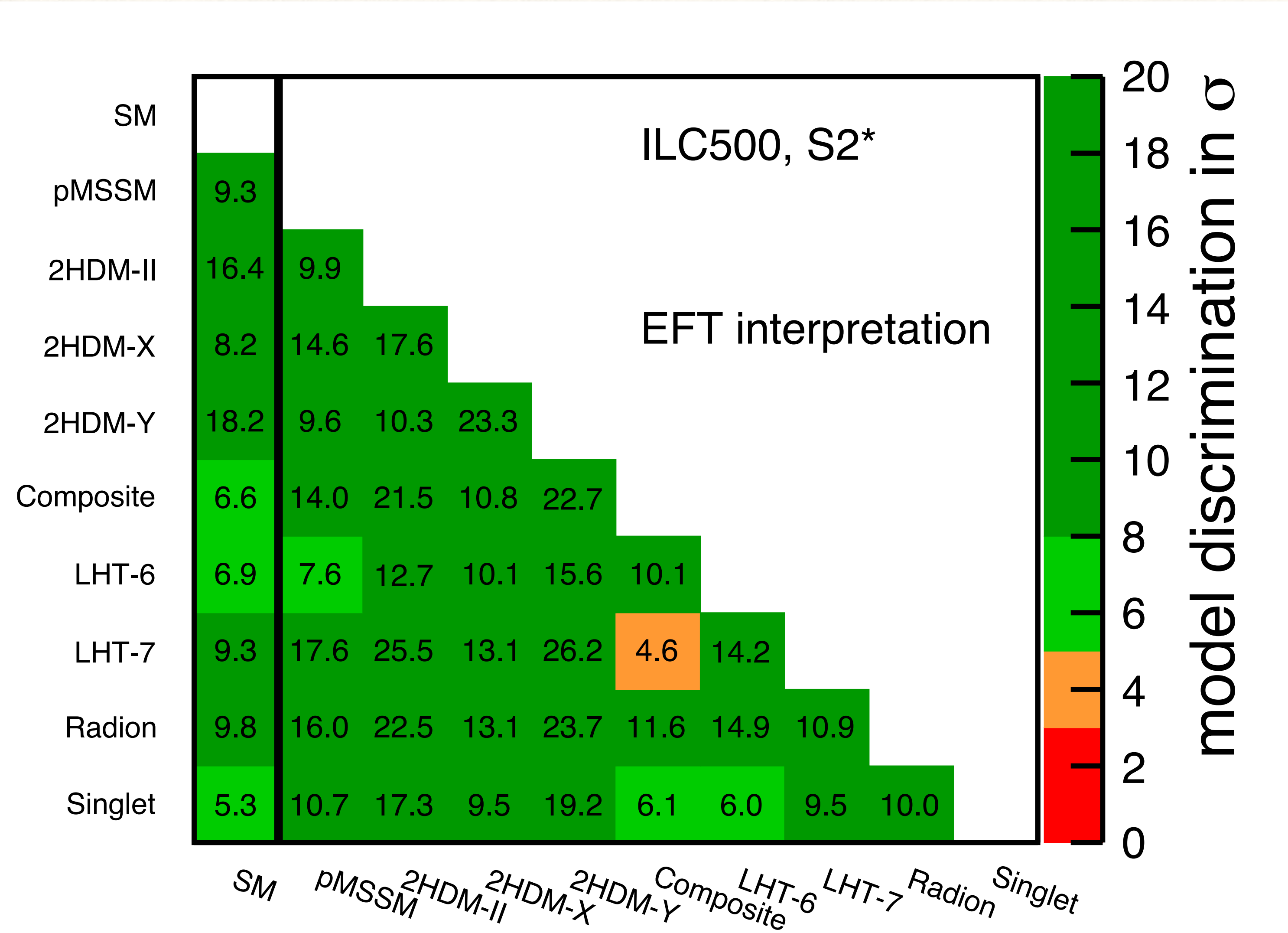
These are the centerpiece and FIRST PRIORITY.

But e^+e^- colliders also provide:

- search for **exotic modes of Higgs boson decay**
- search for **dark matter particles and other invisible states**
- search for **heavy resonances** through 2-fermion processes
- precise study of **W boson interactions** in $e^+e^- \rightarrow W^+W^-$
  - precise measurement of the **top quark mass**
  - precise measurement of **top quark electroweak couplings**
    - precise measurement of **top quark Yukawa coupling (tth)**
    - measurement of the **triple Higgs boson coupling**



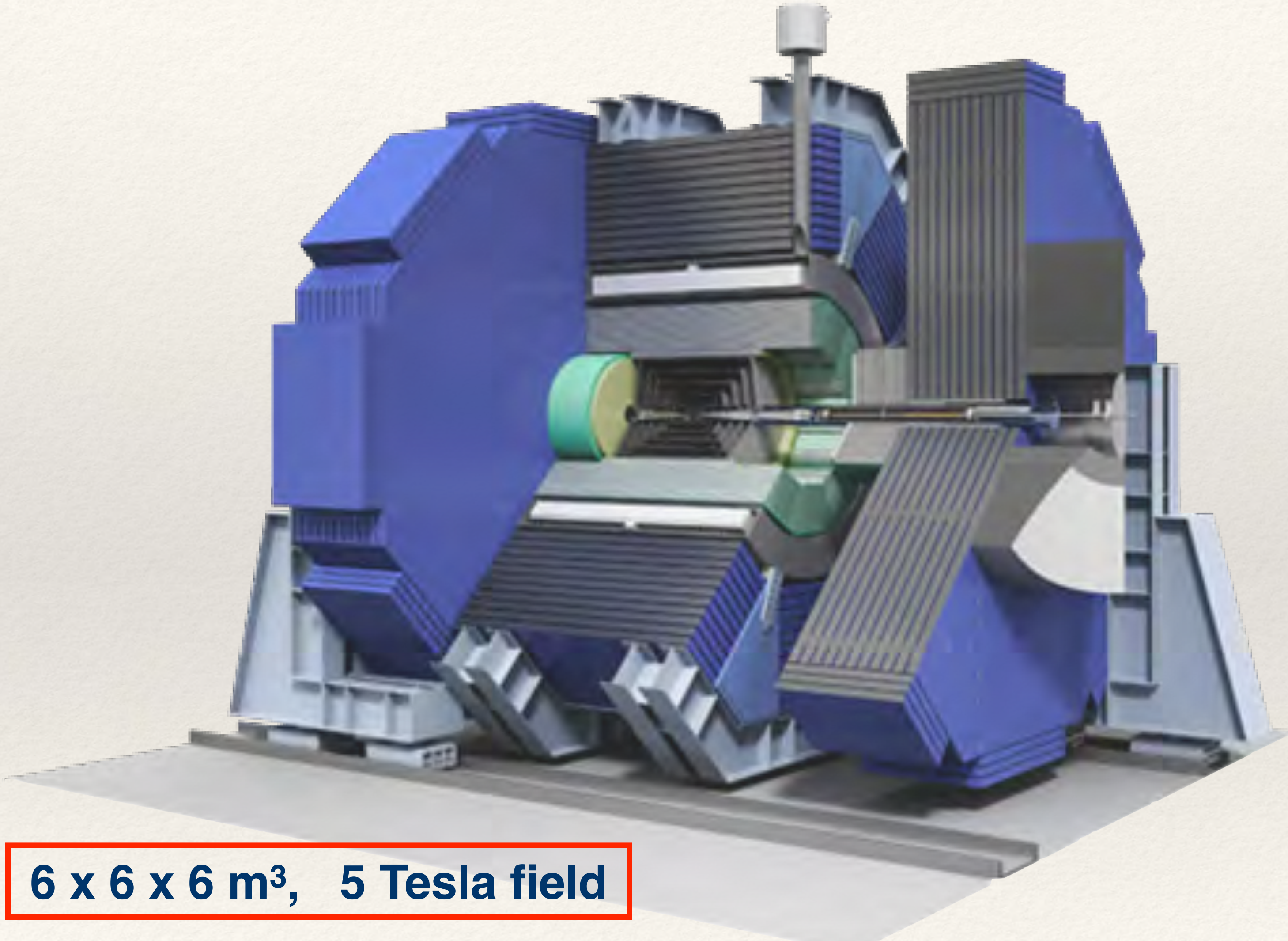
Model Discrimination (250+500)



- S1*, current projection **/model-independent**
- S2*, improved **/model-independent**

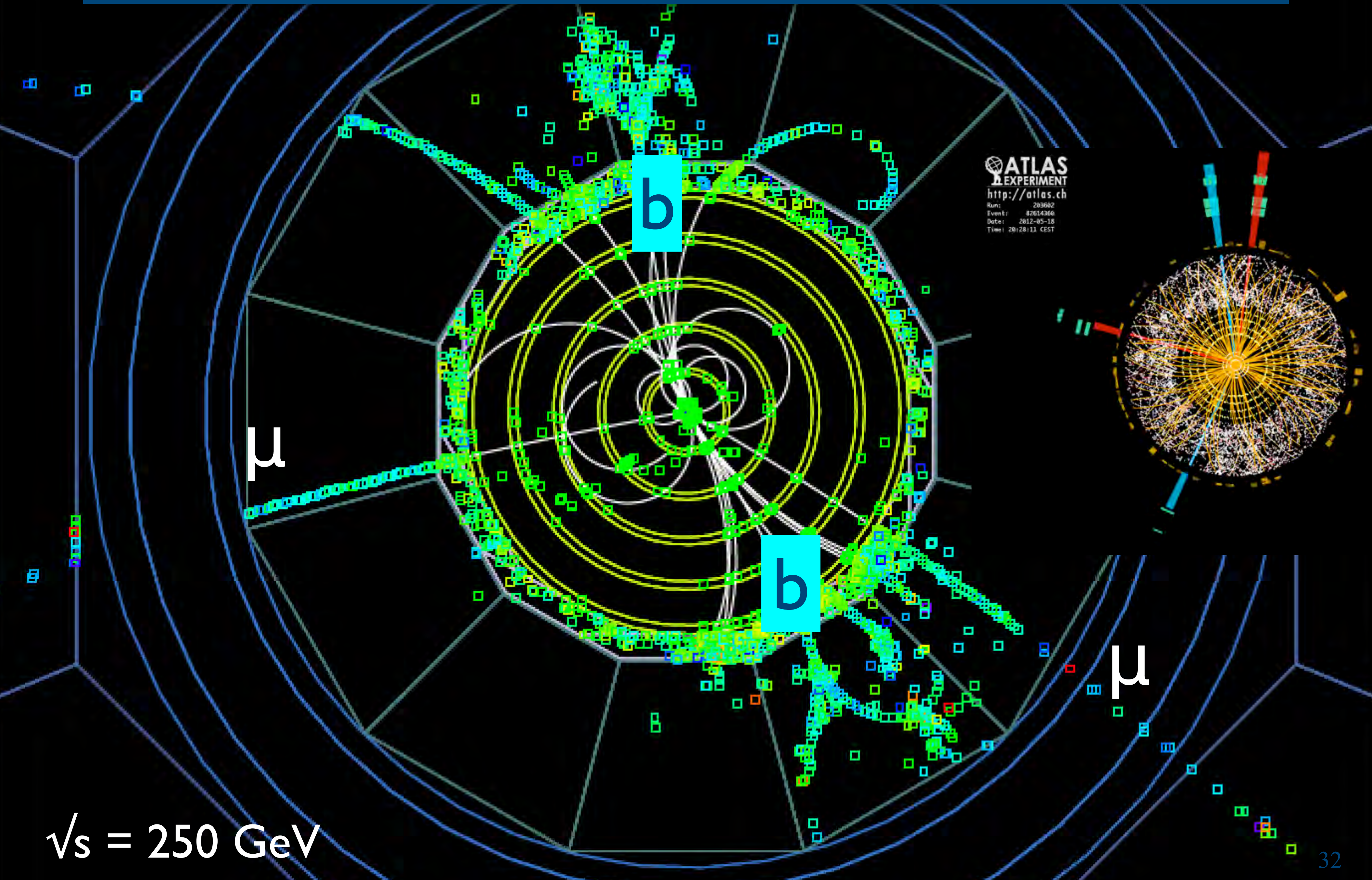
arXiv:1710.07621

SiD - a linear collider detector



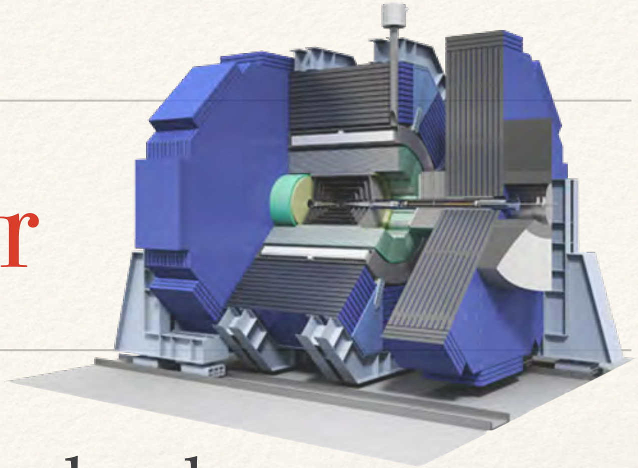
6 x 6 x 6 m^3, 5 Tesla field

$e^+e^- \to Zh; \quad Z \to \mu^+ \mu^-; \quad h \to b\bar{b}$



$\sqrt{s} = 250$ GeV

SiD - a linear collider detector



- Much detector development remains to be done.
- Oregon is particularly involved in developing a new calorimeter based on monolithic active pixels -
  - 25 um x 100 um.
  - Half a trillion pixels in final experiment.
- Small prototypes, larger modules, beam tests to verify design, and finally, construction. We need time to do all this work.

Summary

- BSM physics would impact Higgs boson couplings at the **percent level** for mass scales of TeV.
- Electron-positron colliders provide qualitatively improved, **percent level precision** on Higgs boson couplings, with **model-independent measurements**.
- Excellent science **already achievable at 250 GeV** from strength of Higgstrahlung reconstruction and EFT analysis.
  - **Higher energy** from upgrades extends physics program.
- In all scenarios for future LHC outcomes, there is a compelling **discovery potential**.
- Higgs factory collisions are possible by 2040.