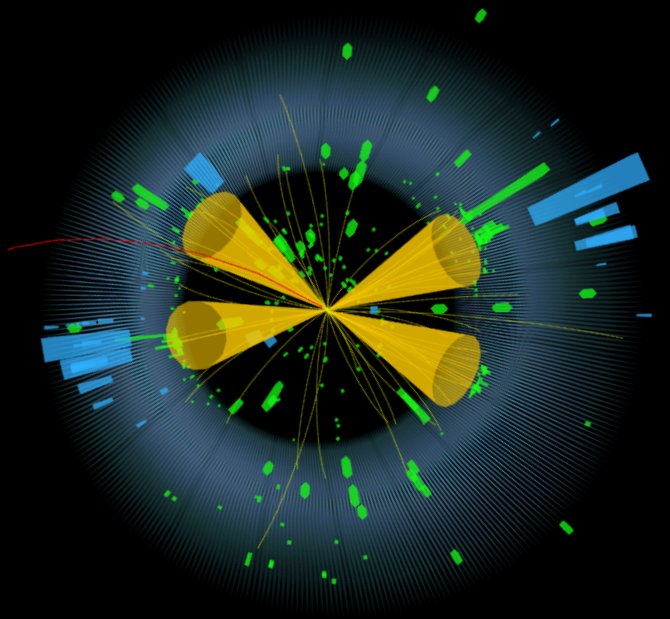
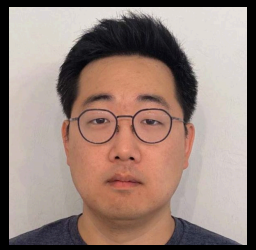
Recent CMS results on Higgs physics

CIPANP
August 30, 2022

LHC is “Staying on target”





Philip Chang
University of Florida

Higgs physics is broad and I cannot cover all!

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http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

169	HIG-19-016	Measurement of the Higgs boson inclusive and differential fiducial production cross sections in the diphoton decay channel with pp collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	25 August 2022
168	HIG-21-001	Searches for additional Higgs bosons and for vector leptoquarks in $\tau\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	4 August 2022
167	HIG-21-006	Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	4 August 2022
166	HIG-21-003	Search for the exotic decay of the Higgs boson into two light pseudoscalars with four photons in the final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	2 August 2022
165	HIG-21-015	Search for the Higgs boson decay to a pair of electrons in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	30 July 2022
164	HIG-21-010	Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	4 July 2022
163	HIG-22-001	A portrait of the Higgs boson by the CMS experiment ten years after the discovery	Nature 607 (2022) 60	4 July 2022
162	HIG-20-004	Search for nonresonant Higgs boson pair production in the four leptons plus two b jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	22 June 2022
161	HIG-21-002	Search for Higgs boson pairs decaying to WWWW, WW$\tau\tau$, and $\tau\tau\tau\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	21 June 2022
160	HIG-20-013	Measurements of the Higgs boson production cross section and couplings in the WW boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to EPJC	20 June 2022
159	HIG-20-010	Search for nonresonant Higgs boson pair production in final state with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	19 June 2022
158	HIG-20-008	Search for Higgs boson decays into Z and J/ψ and for Higgs and Z boson decays into J/ψ or Υ pairs in pp collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	7 June 2022
157	HIG-21-008	Search for Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV	Accepted by PRL	11 May 2022
156	HIG-20-007	Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\tau\tau$ final state	Accepted by PRD	10 May 2022
155	HIG-20-018	Search for light Higgs bosons from supersymmetric cascade decays in pp collisions at $\sqrt{s} = 13$ TeV	Accepted by EPJC	28 April 2022
154	HIG-19-014	Search for Higgs boson decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV	Accepted by JHEP	27 April 2022
153	HIG-19-010	Measurements of Higgs boson production in the decay channel with a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to EPJC	27 April 2022
152	HIG-20-005	Search for Higgs boson pair production in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	PRL 129 (2022) 081802	19 February 2022
151	HIG-21-013	First evidence for off-shell production of the Higgs boson and measurement of its width	Submitted to NP	14 February 2022
150	HIG-20-003	Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV	PRD 105 (2022) 092007	27 January 2022

Just this year alone starting January, CMS produced 20 papers!

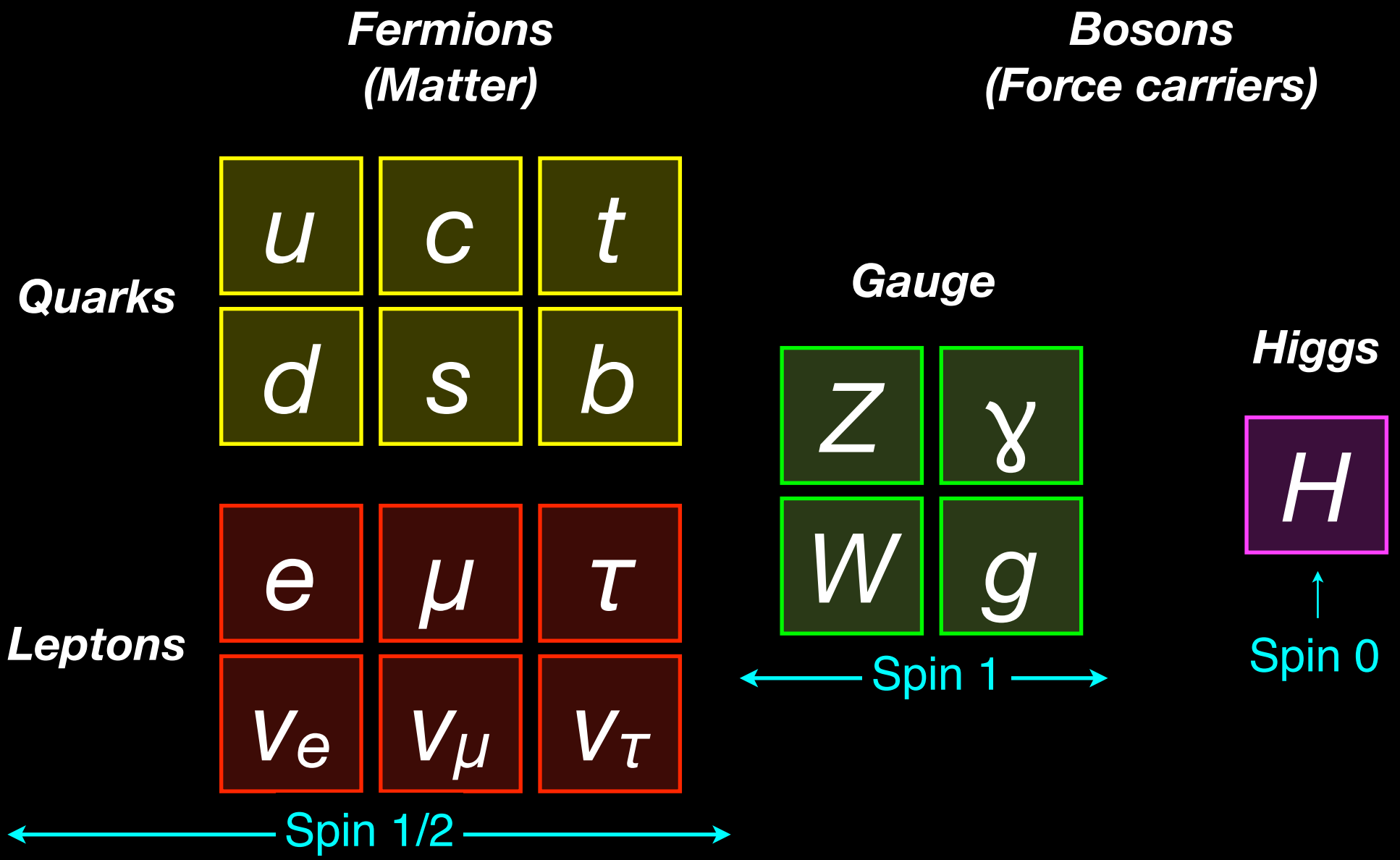
Higgs Physics

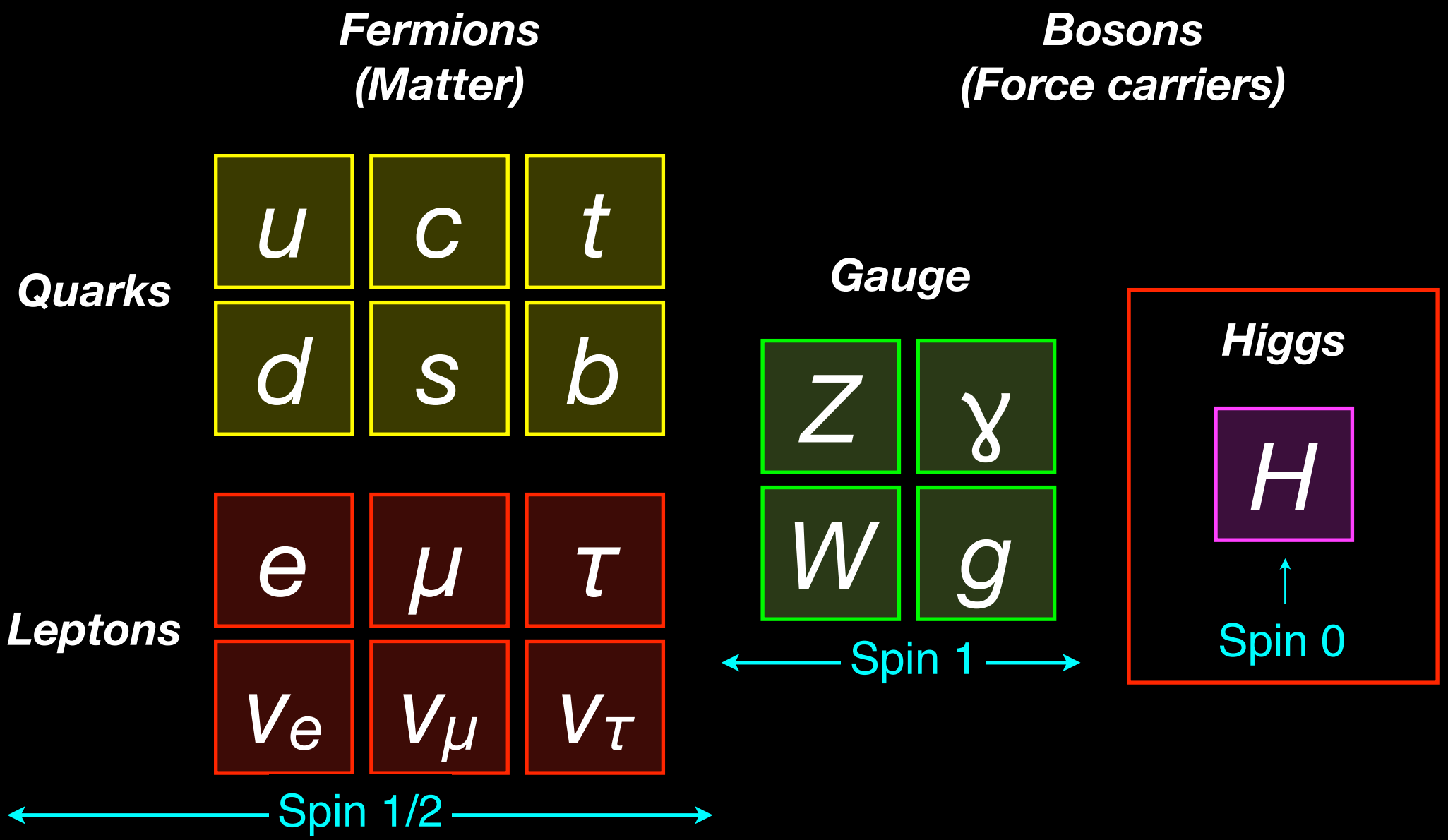
Higgs production / decay

Higgs properties

Looking for unexpected Higgs behaviors

Future


Fermions
(Matter)
Bosons
(Force carriers)
Quarks
u
c
t
d
s
b
Leptons
e
μ
τ
νe
νμ
ντ
Spin 1/2
Gauge
Z
γ
W
g
Spin 1
Higgs
H
Spin 0


Fermions
(Matter)
Bosons
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Leptons
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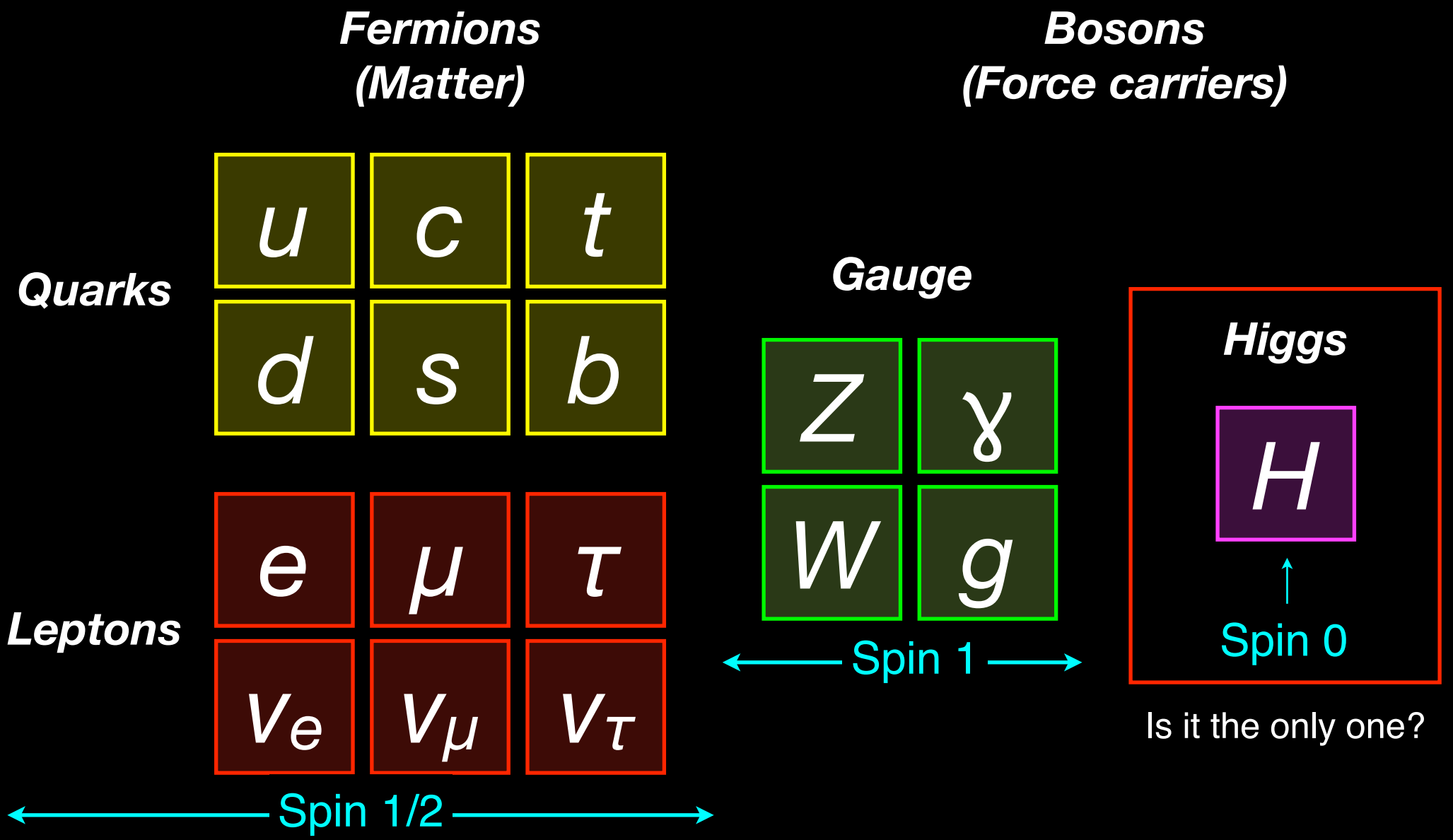
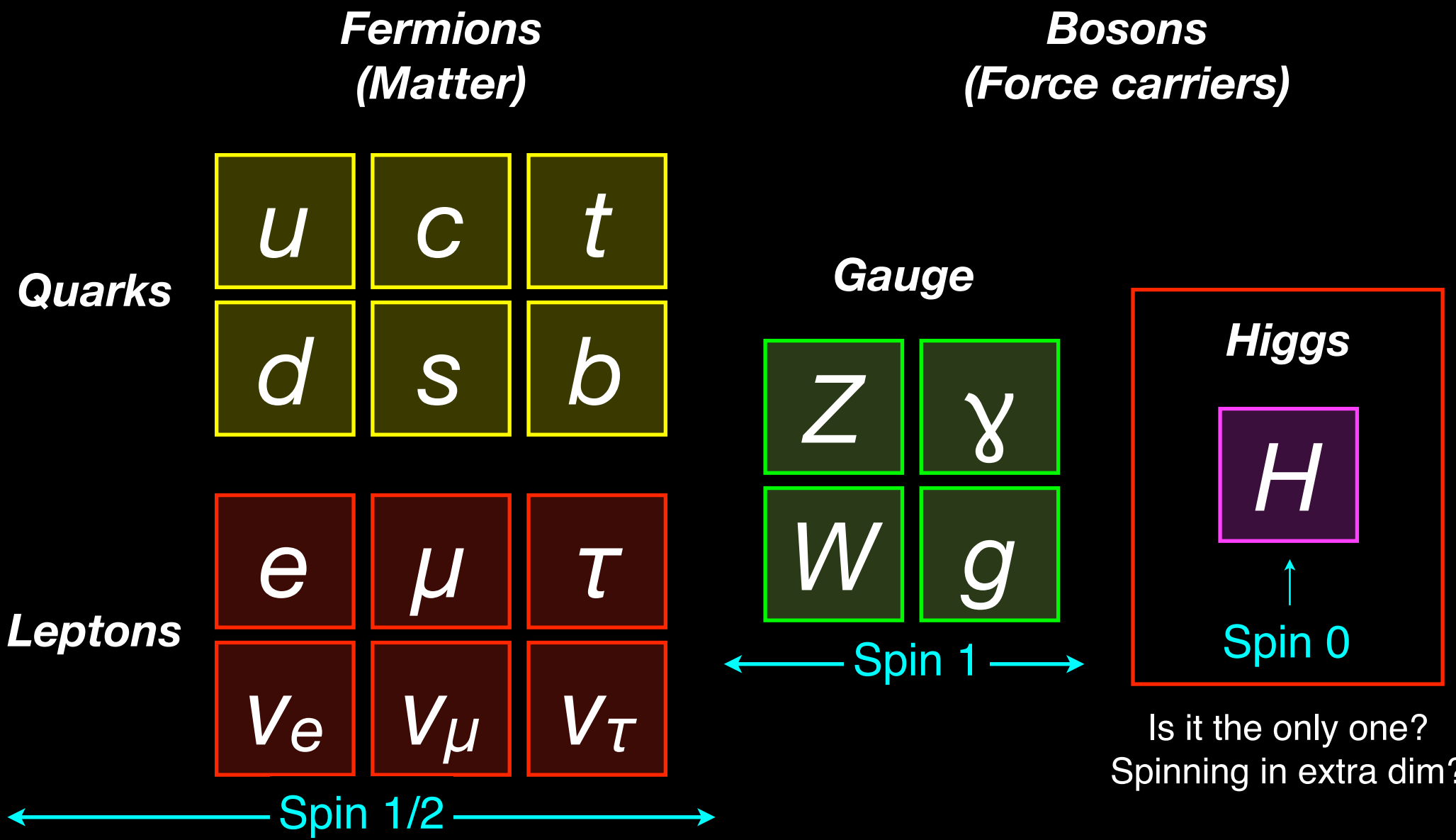
Spin 1/2
Gauge
Z
γ
W
g
Spin 1
Higgs
H
Spin 0



Is it the only one?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νμ
ντ
Spin 1/2
Gauge
Z
γ
W
g
Spin 1
Higgs
H
Spin 0
Is it the only one?
Spinning in extra dim?

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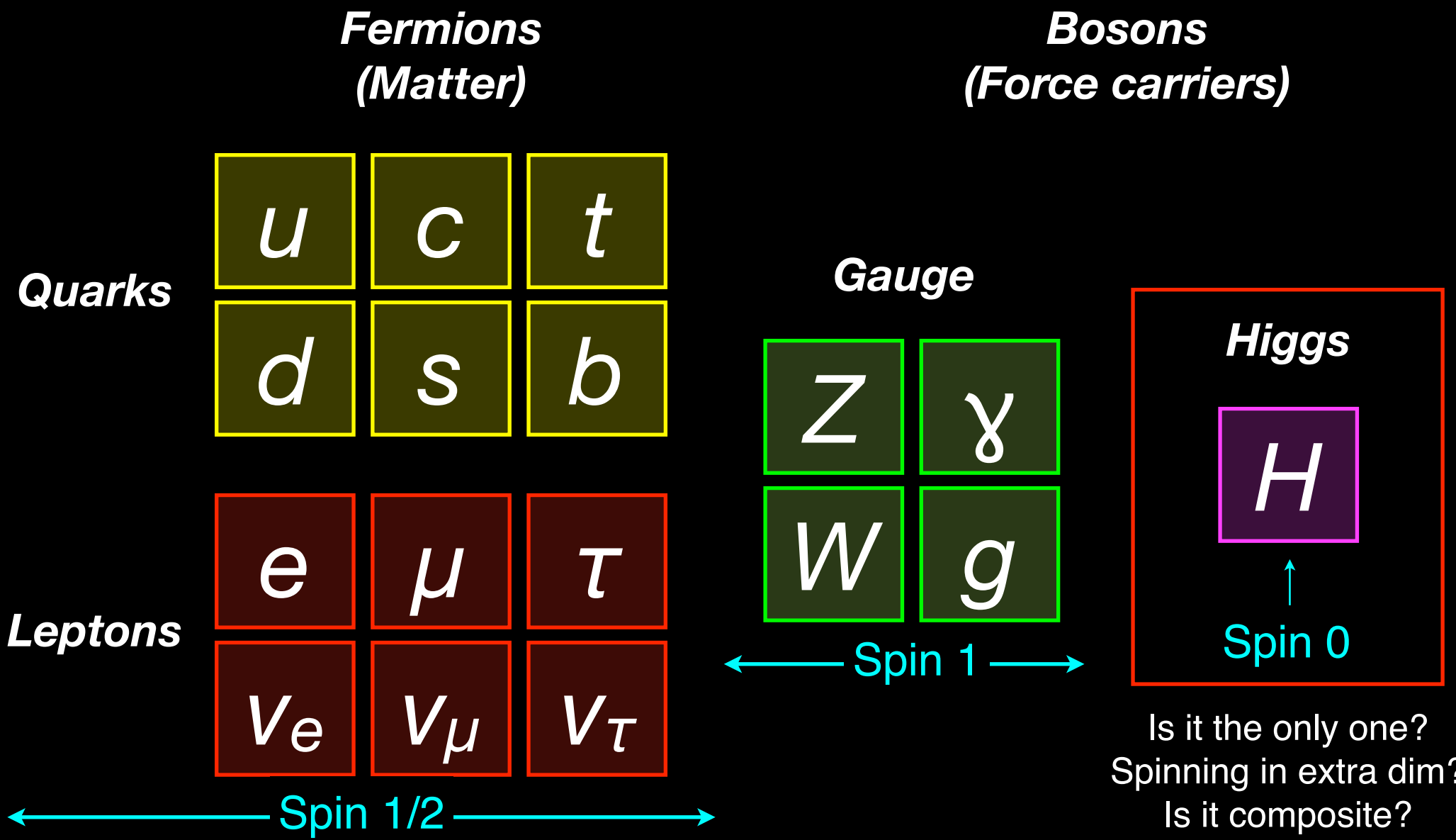
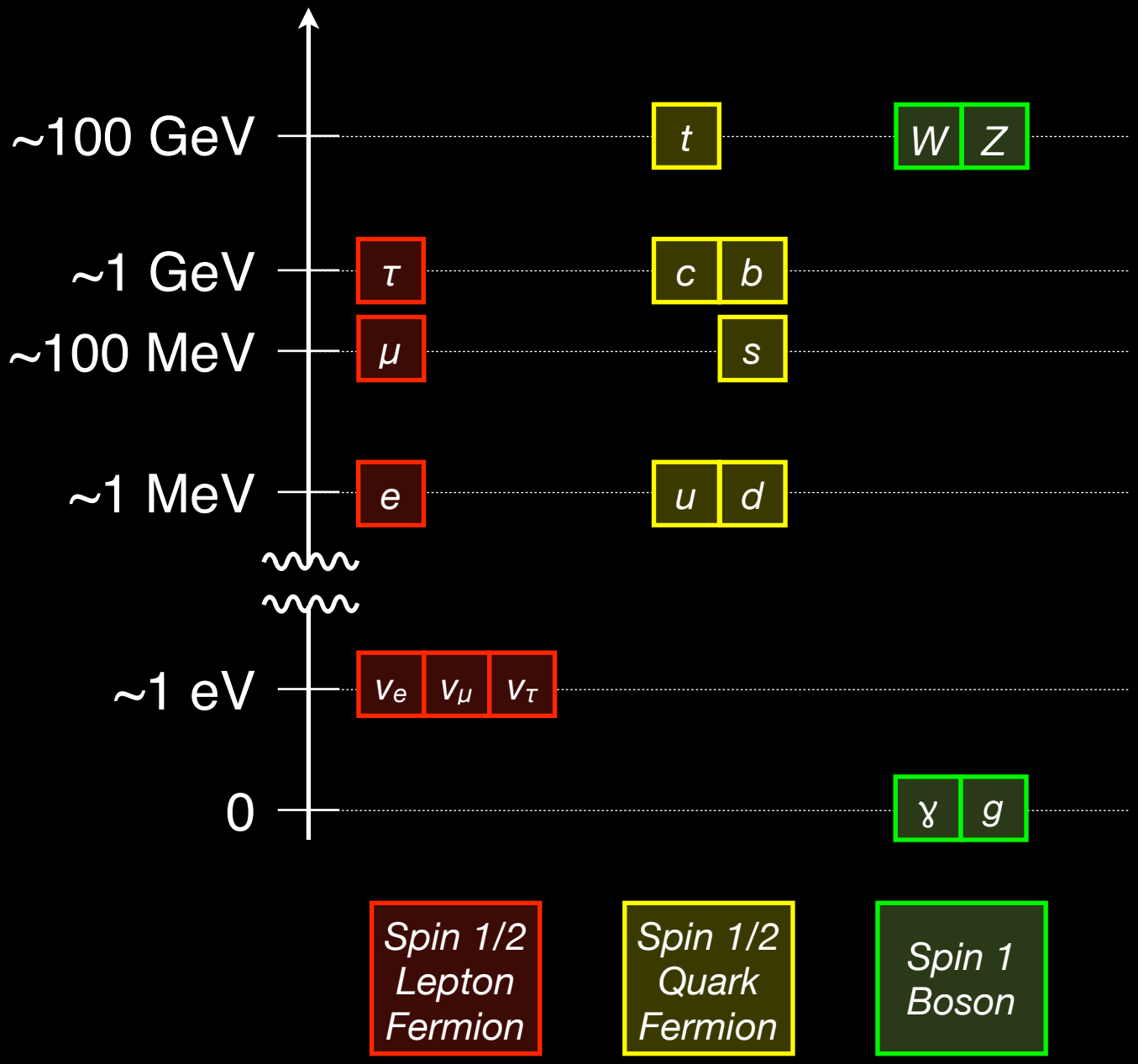
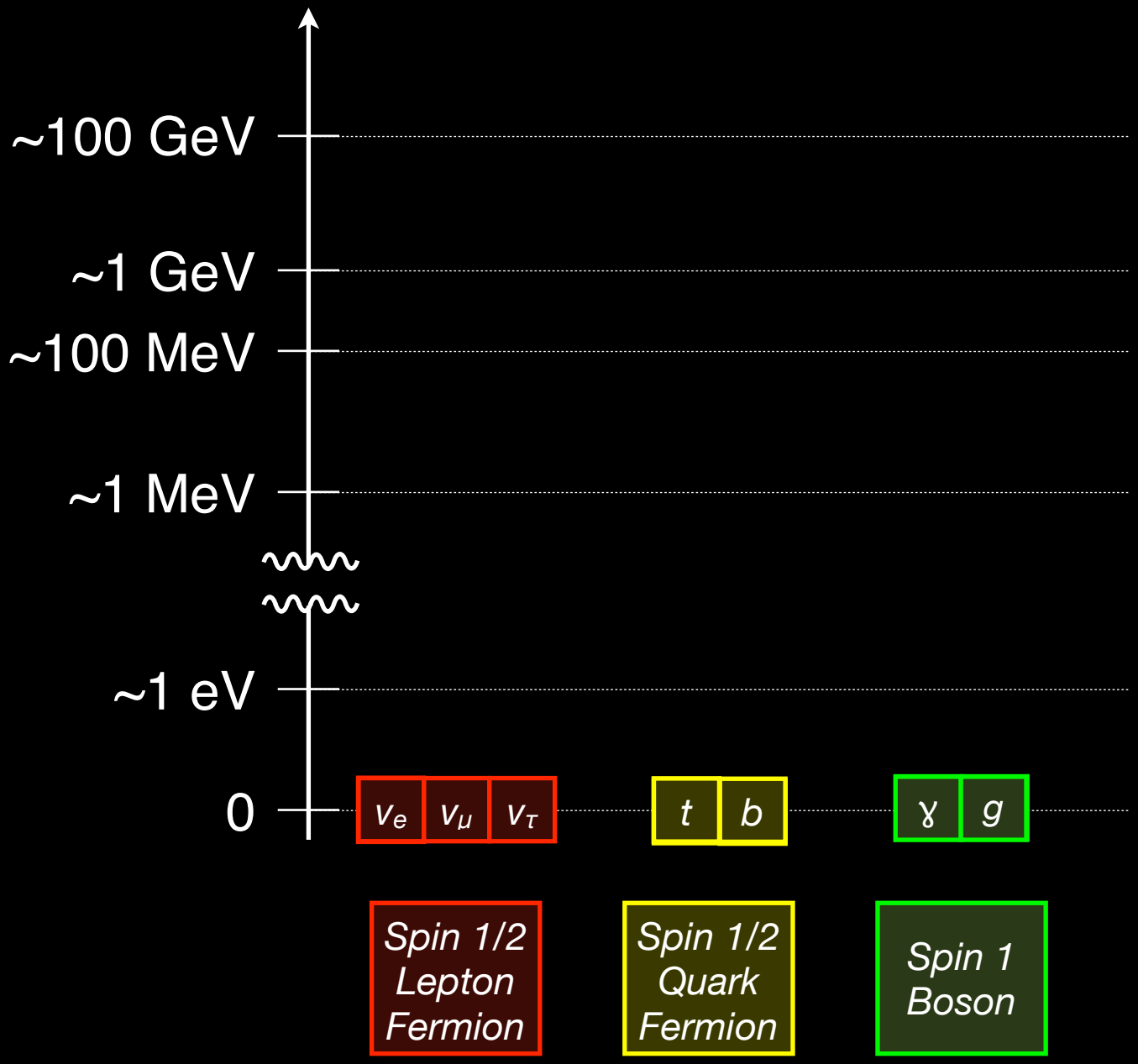
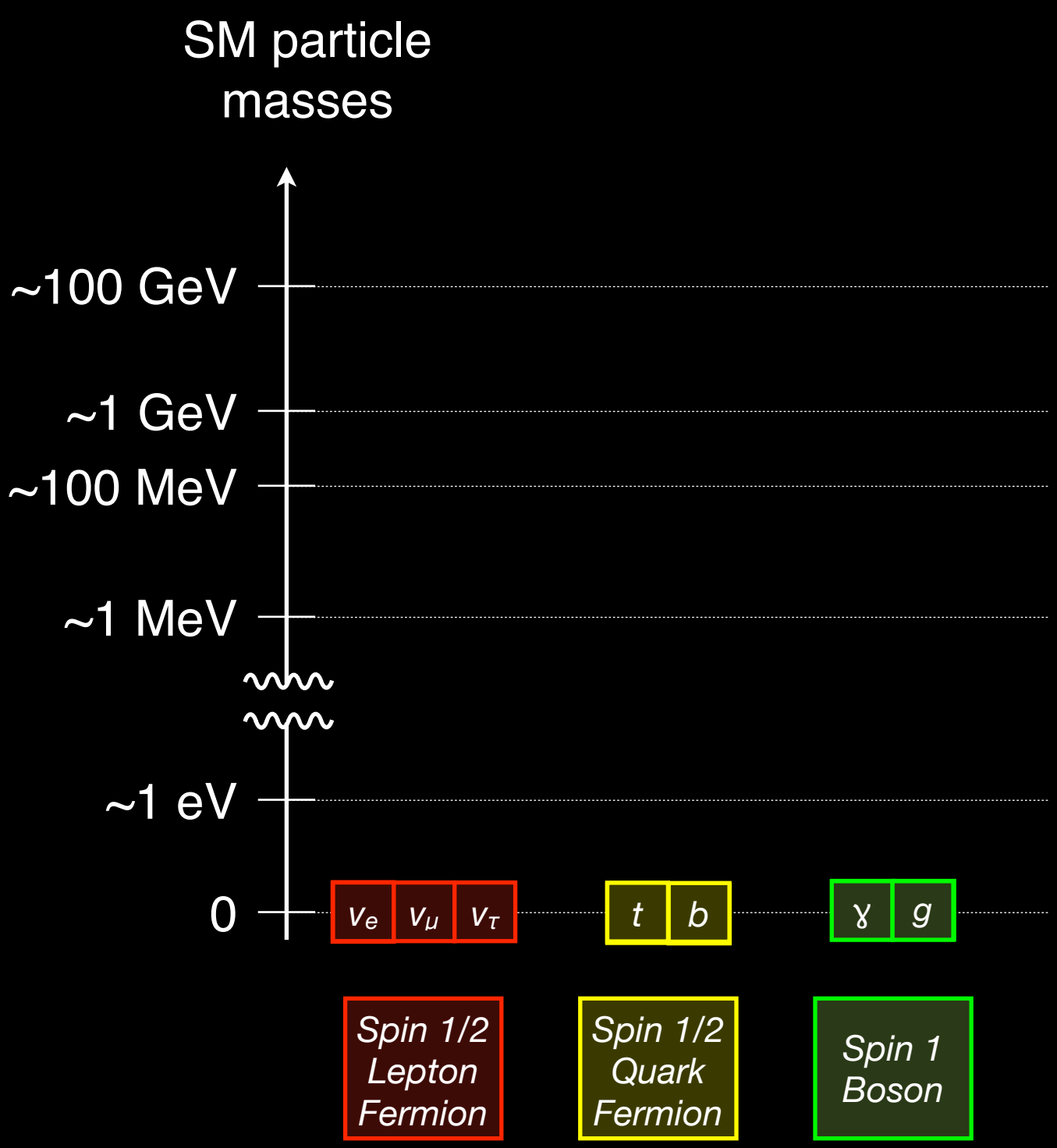


SM particle masses



SM particle masses

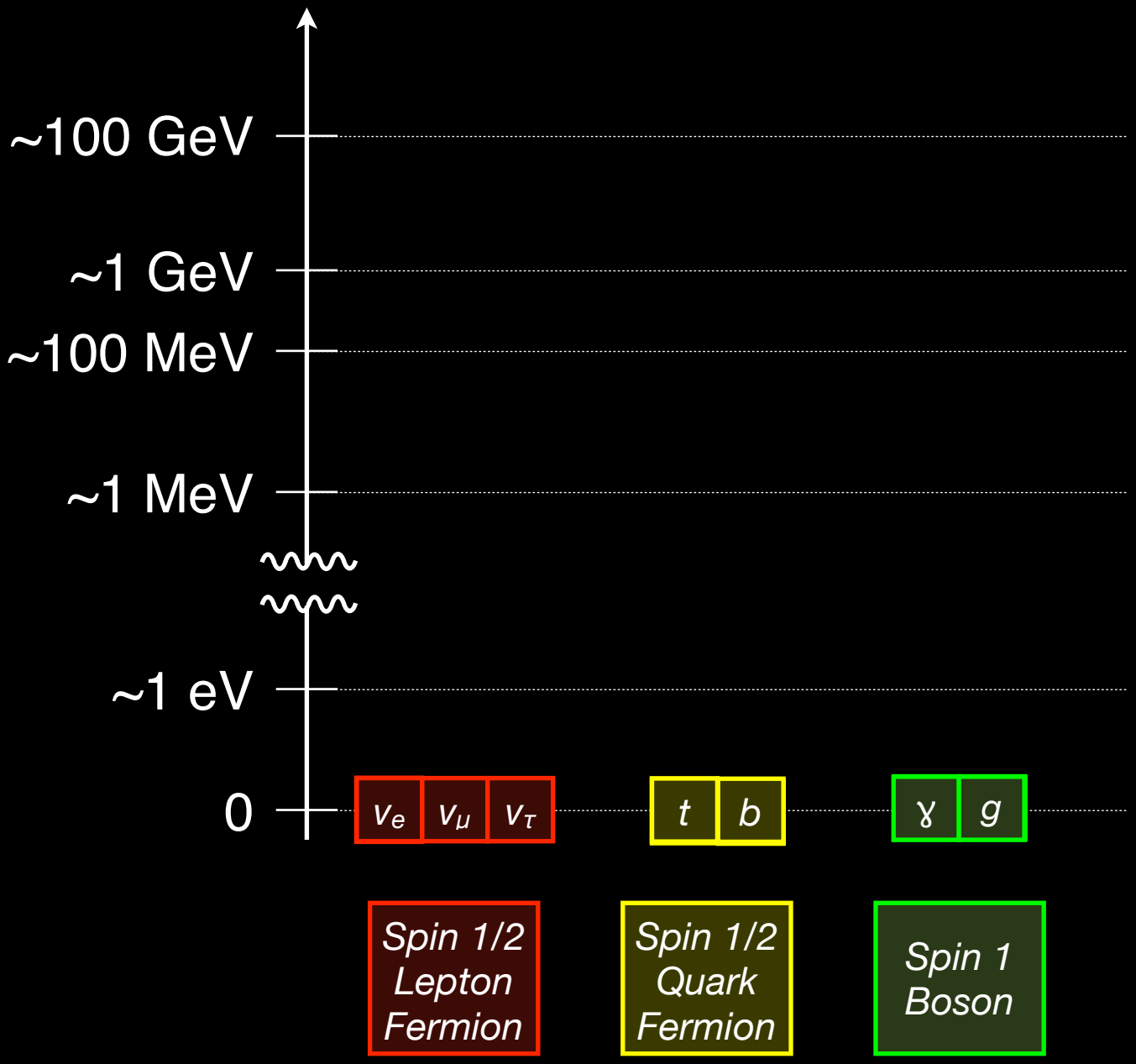


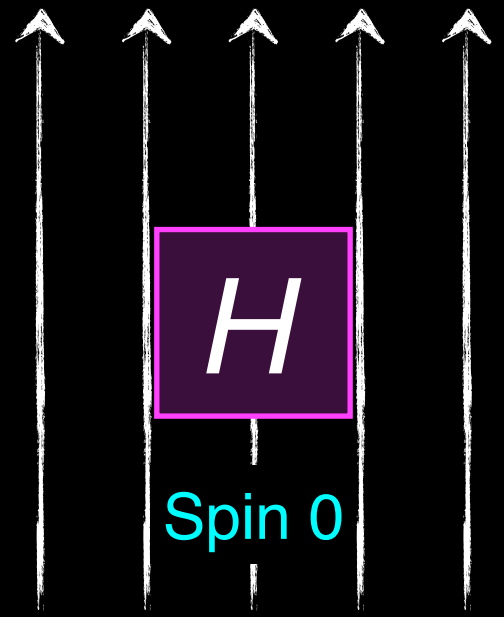

SM particle masses
~100 GeV
~1 GeV
~100 MeV
~1 MeV
~1 eV
0
ν_e ν_μ ν_τ
t b
γ g
Spin 1/2 Lepton Fermion
Spin 1/2 Quark Fermion
Spin 1 Boson

H

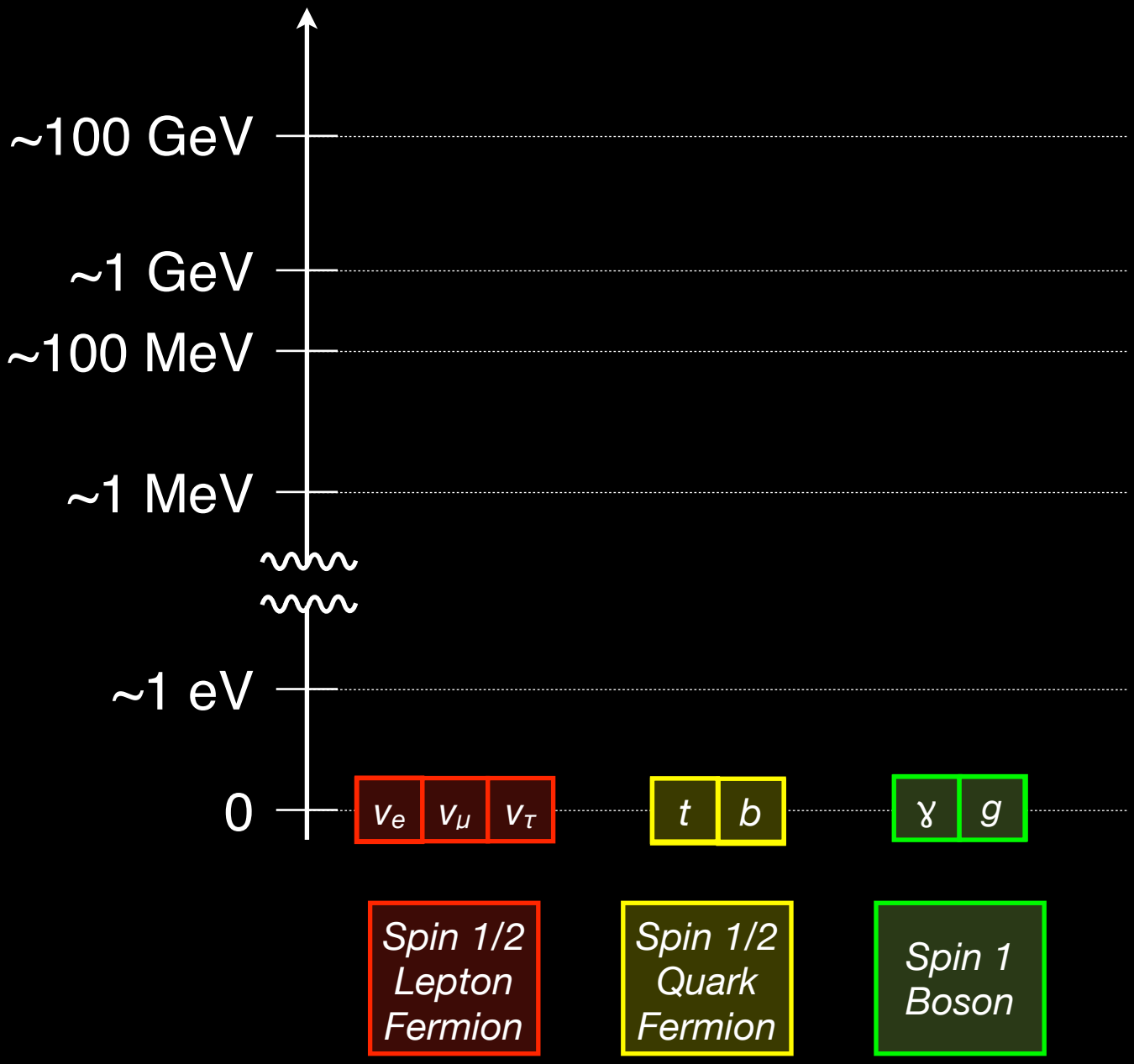
Spin 0

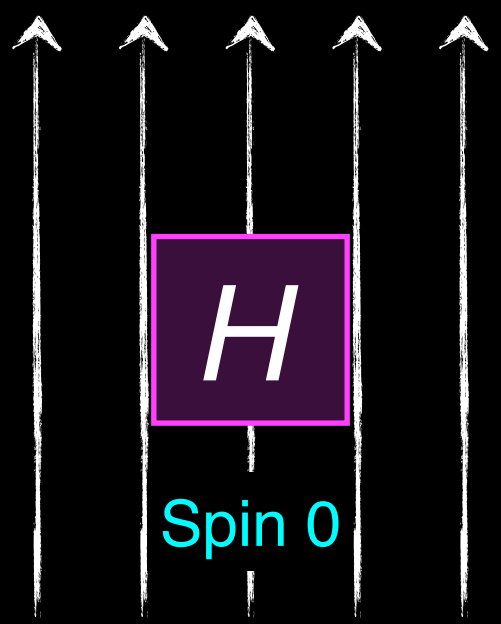
SM particle masses

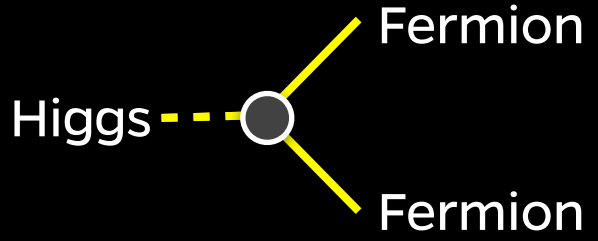


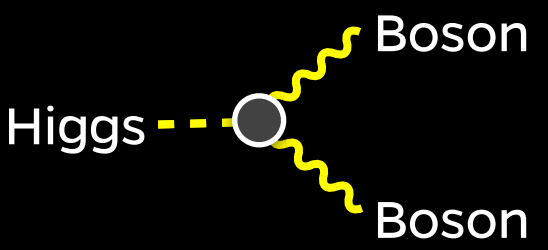


SM particle masses

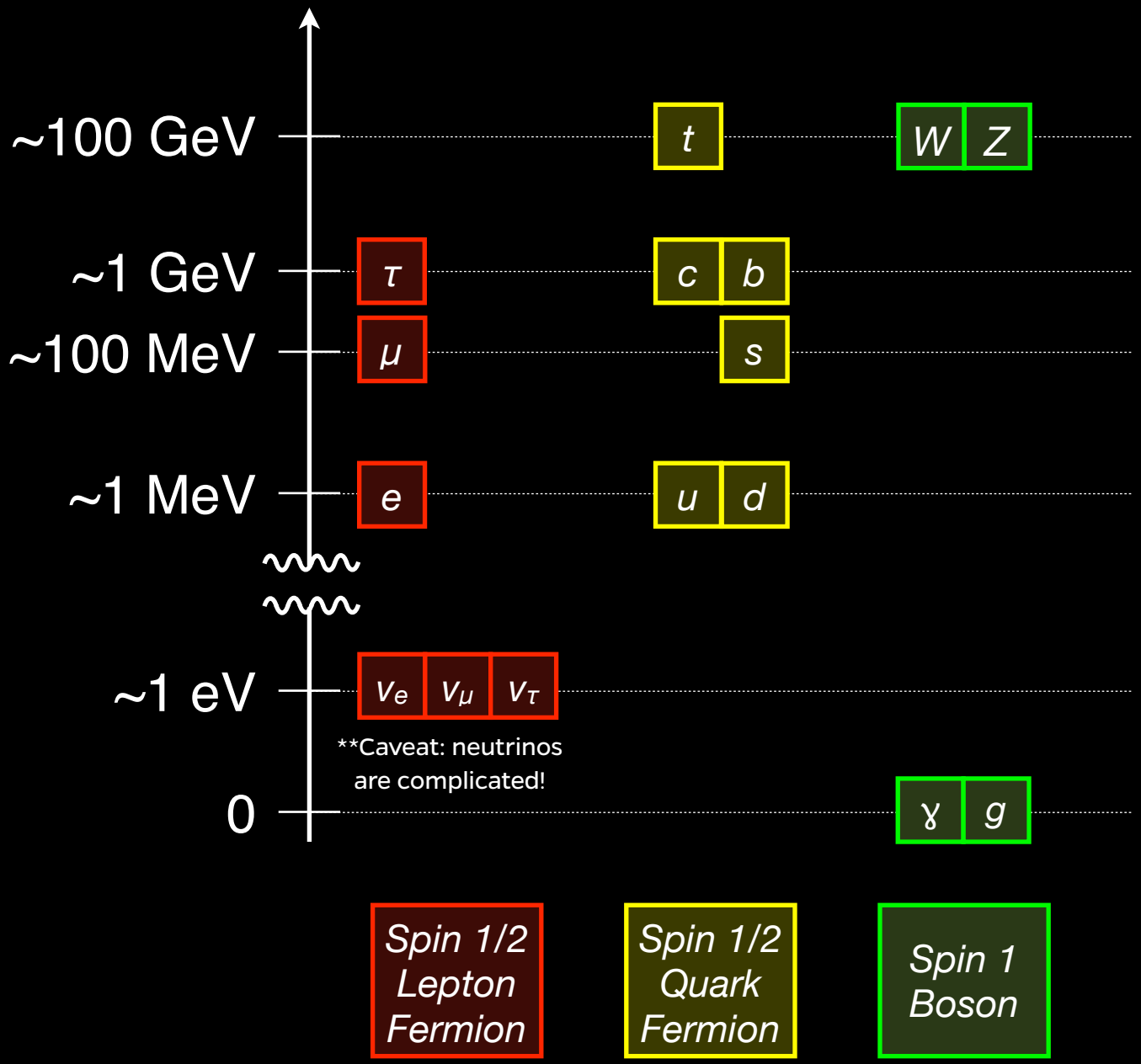


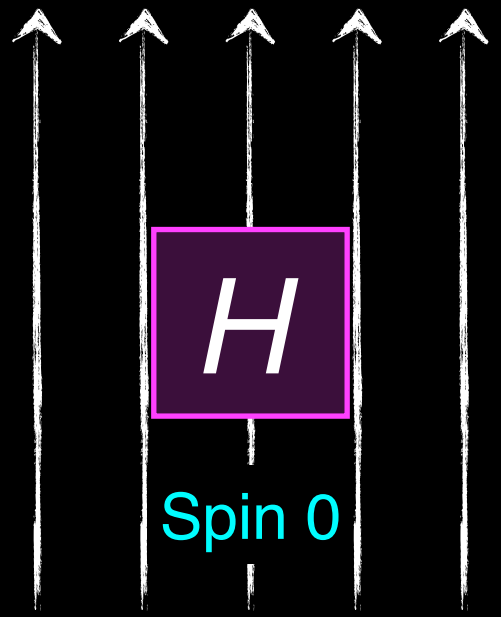


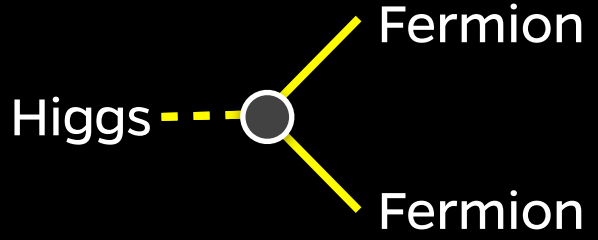


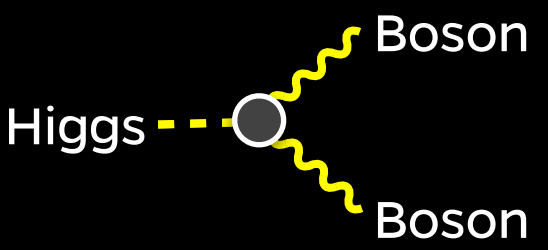


SM particle masses









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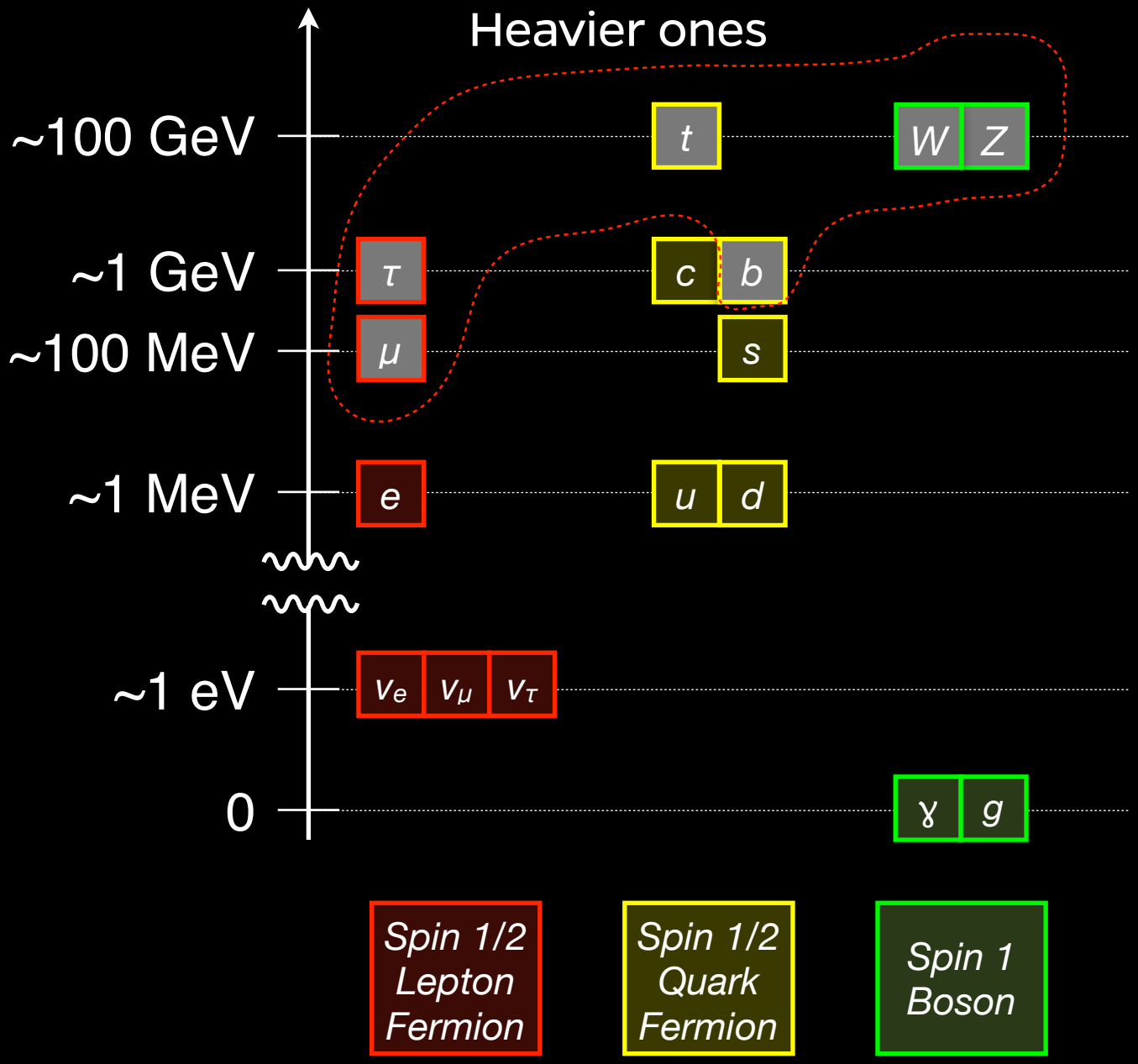

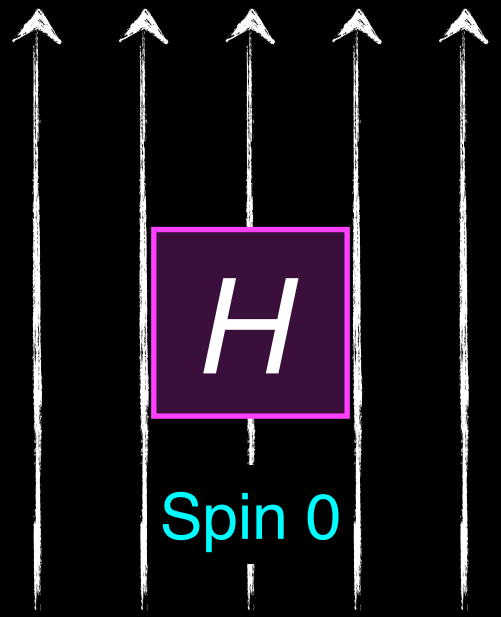

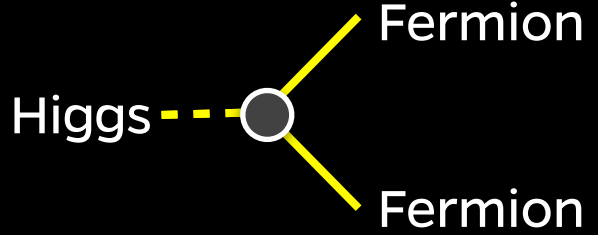

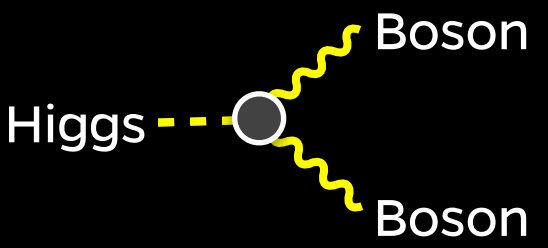

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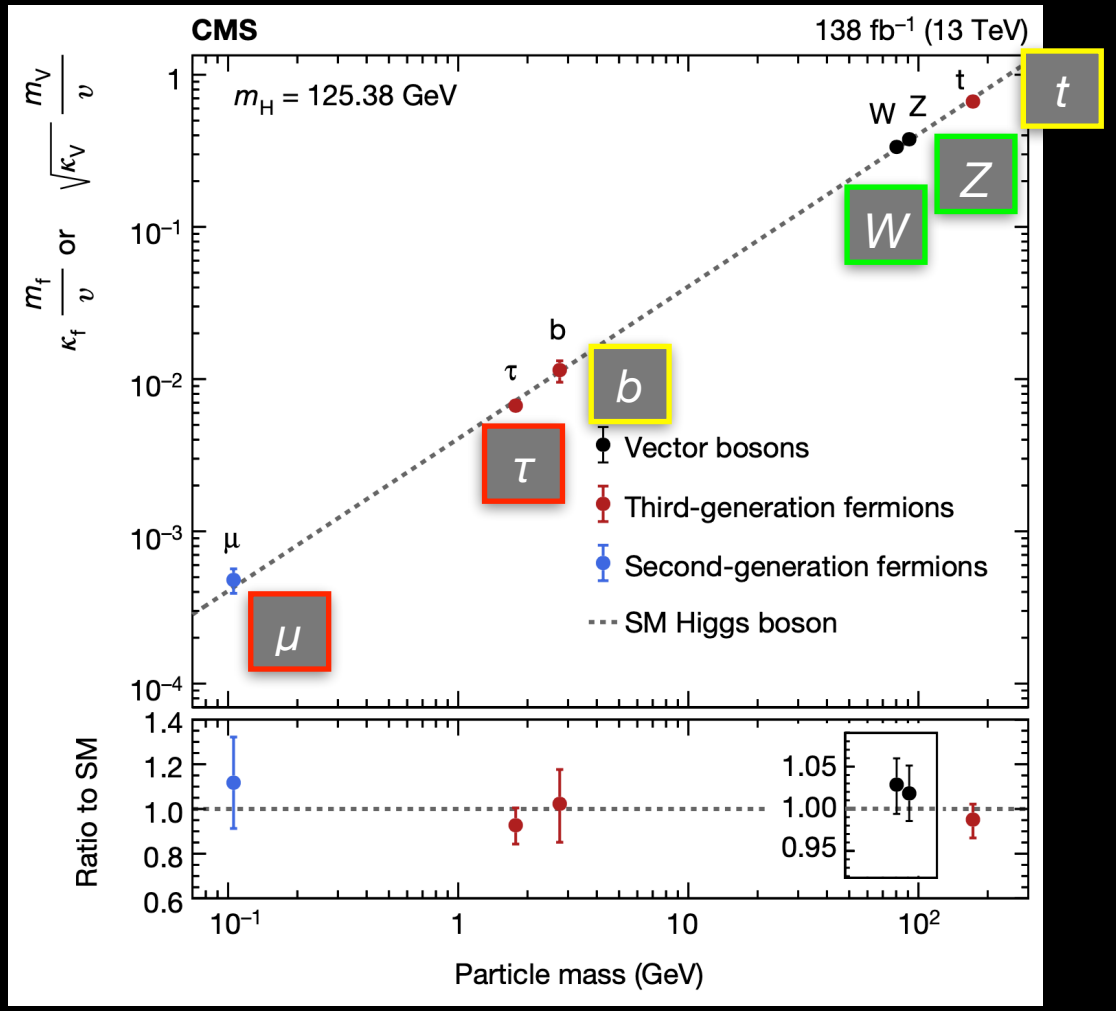
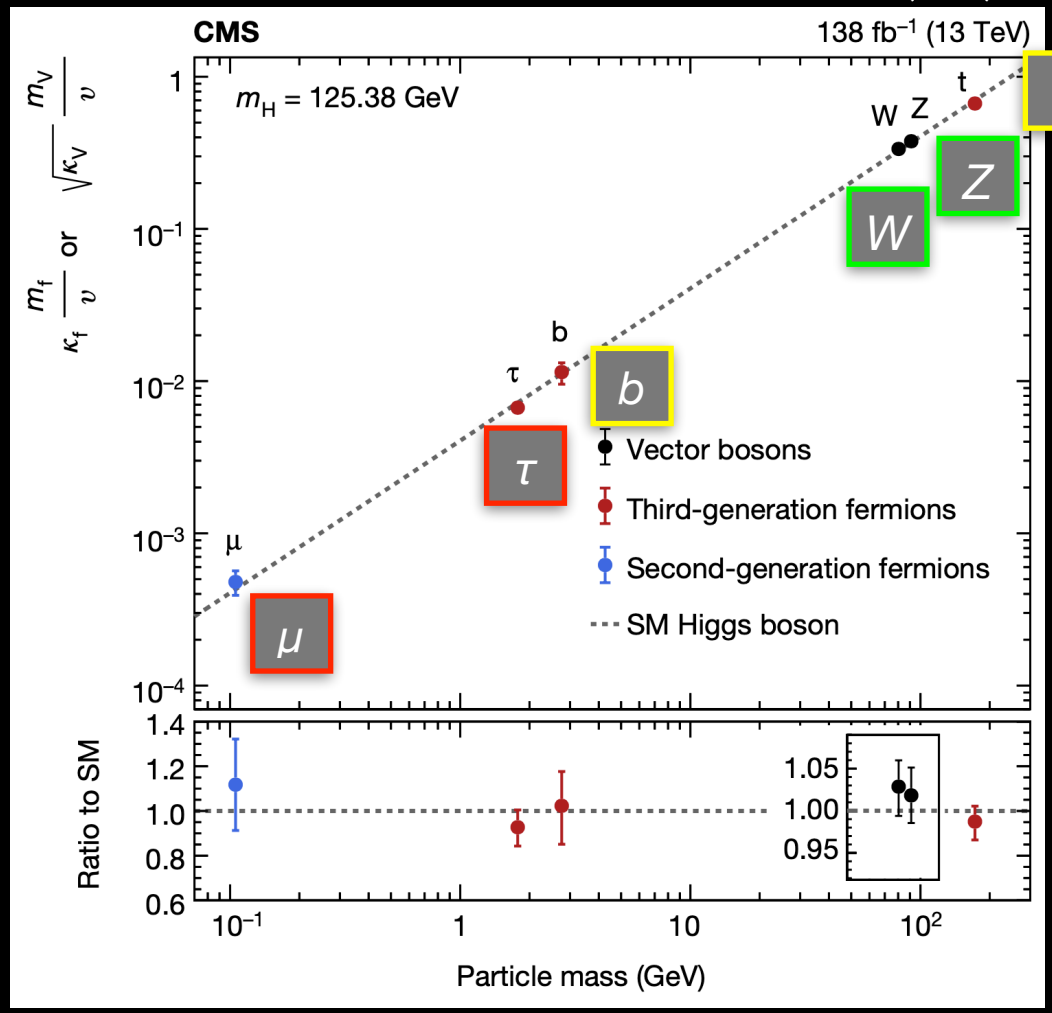
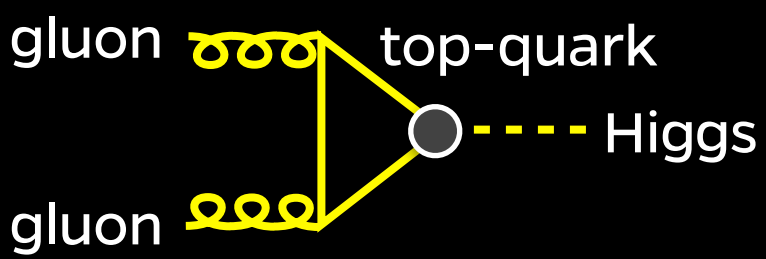


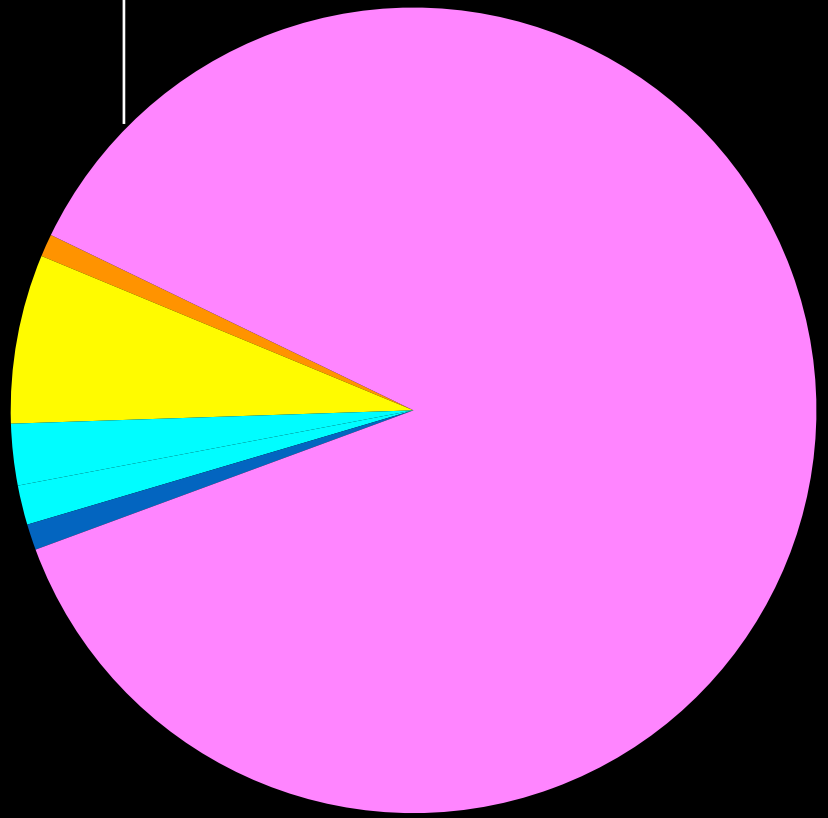
Coupling strength

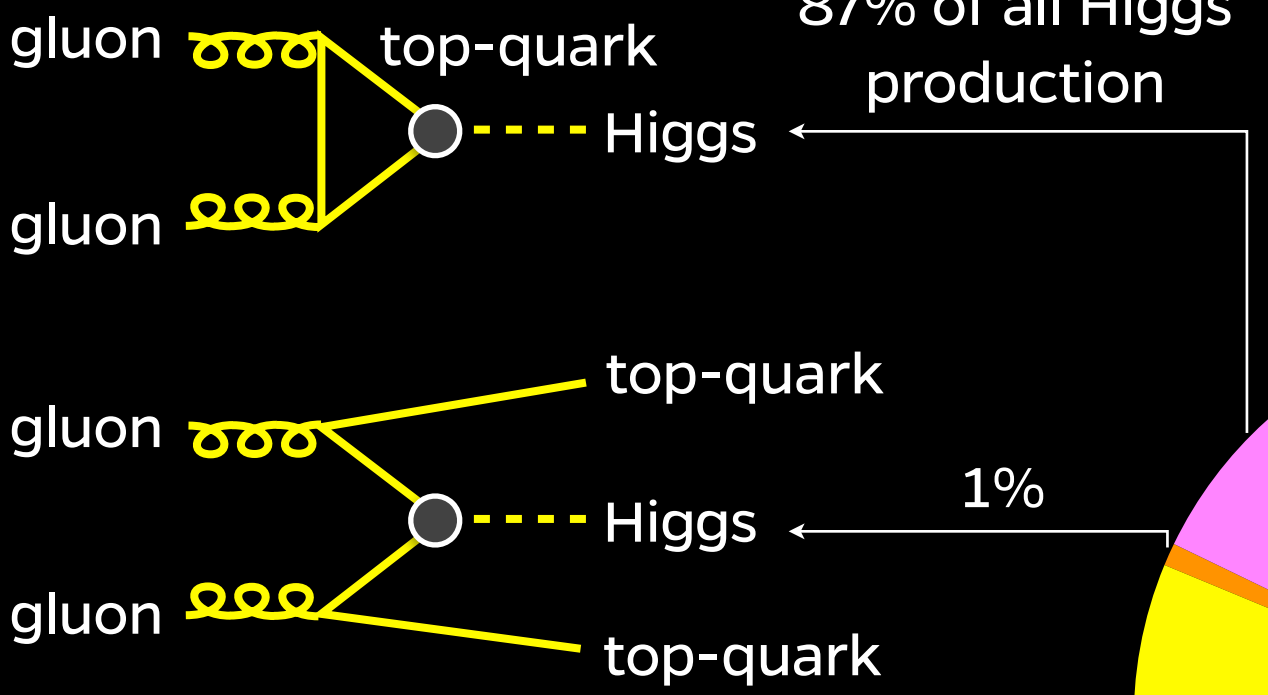


Particle mass



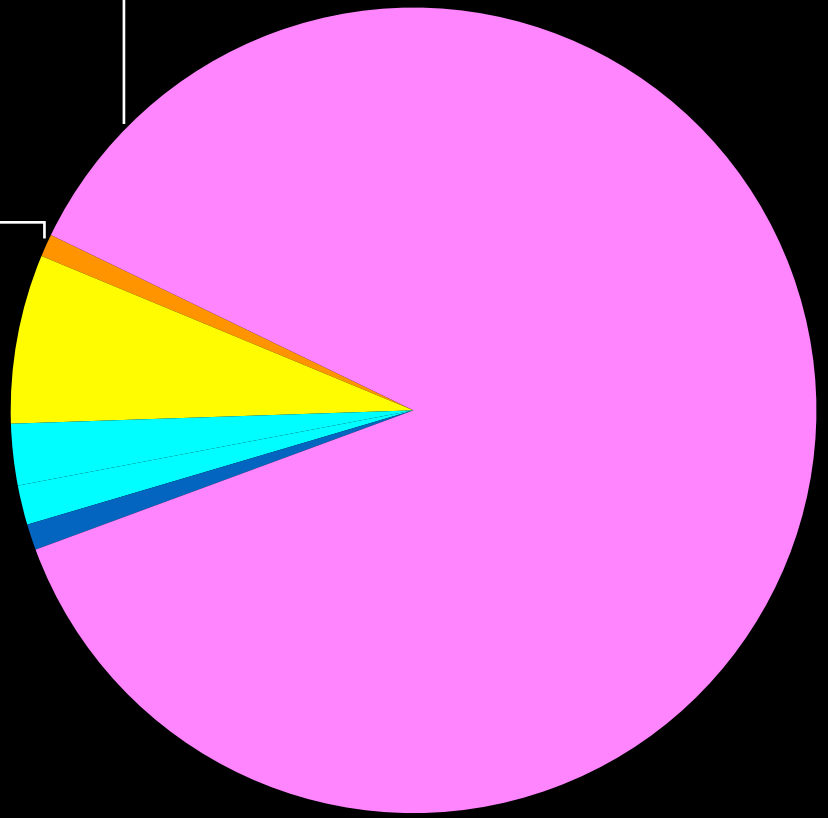
87% of all Higgs production

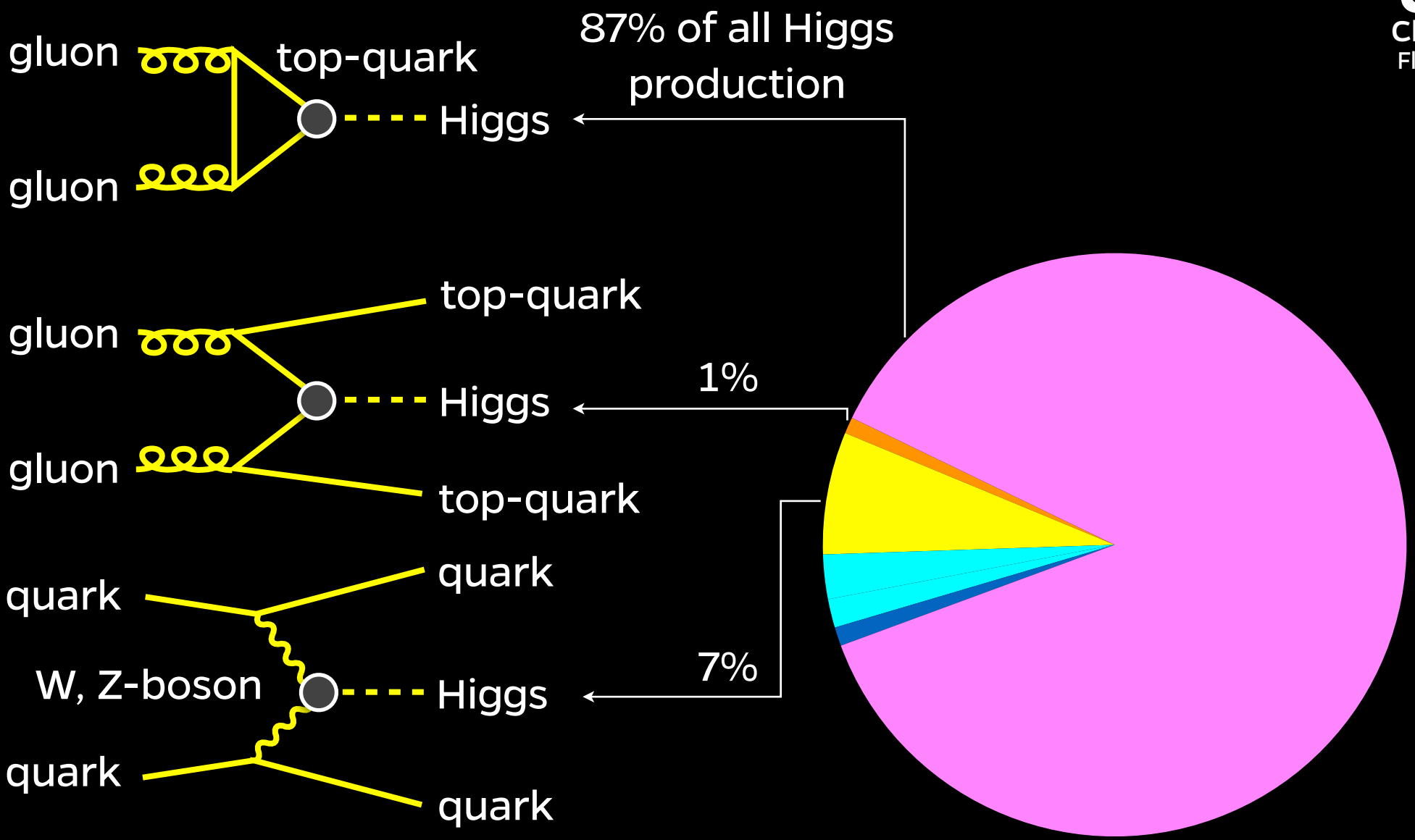


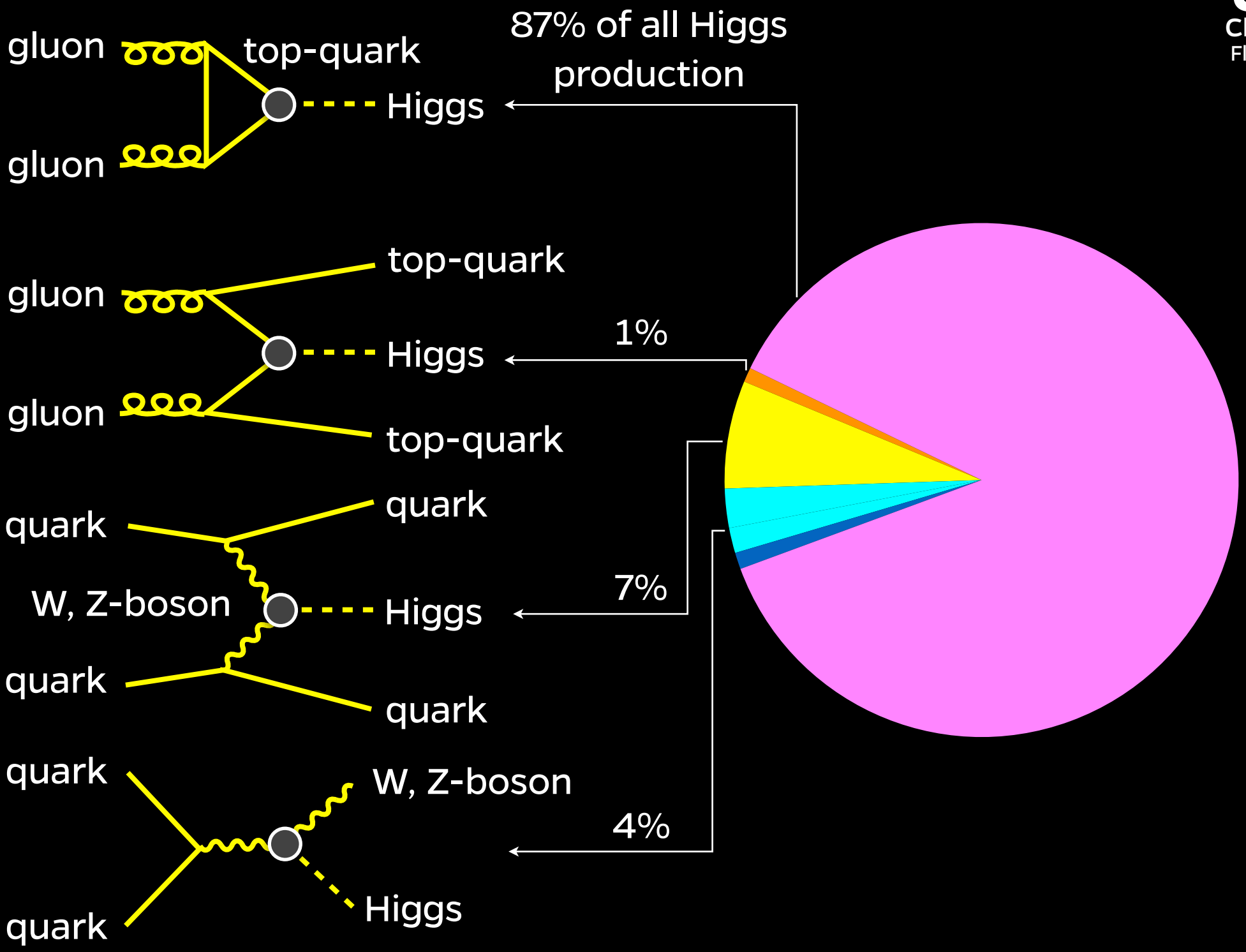


87% of all Higgs production

1%




gluon
top-quark
Higgs
gluon
87% of all Higgs production
top-quark
gluon
Higgs
1%
gluon
top-quark
quark
quark
W, Z-boson
Higgs
7%
quark
quark


gluon
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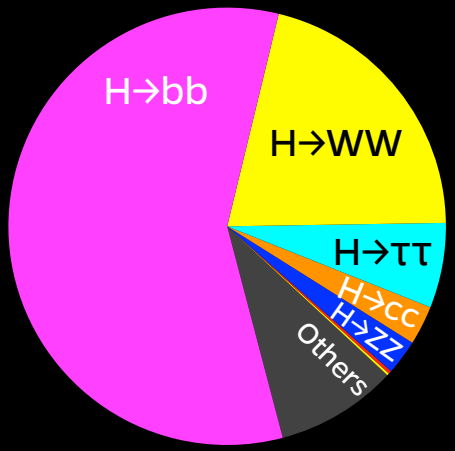
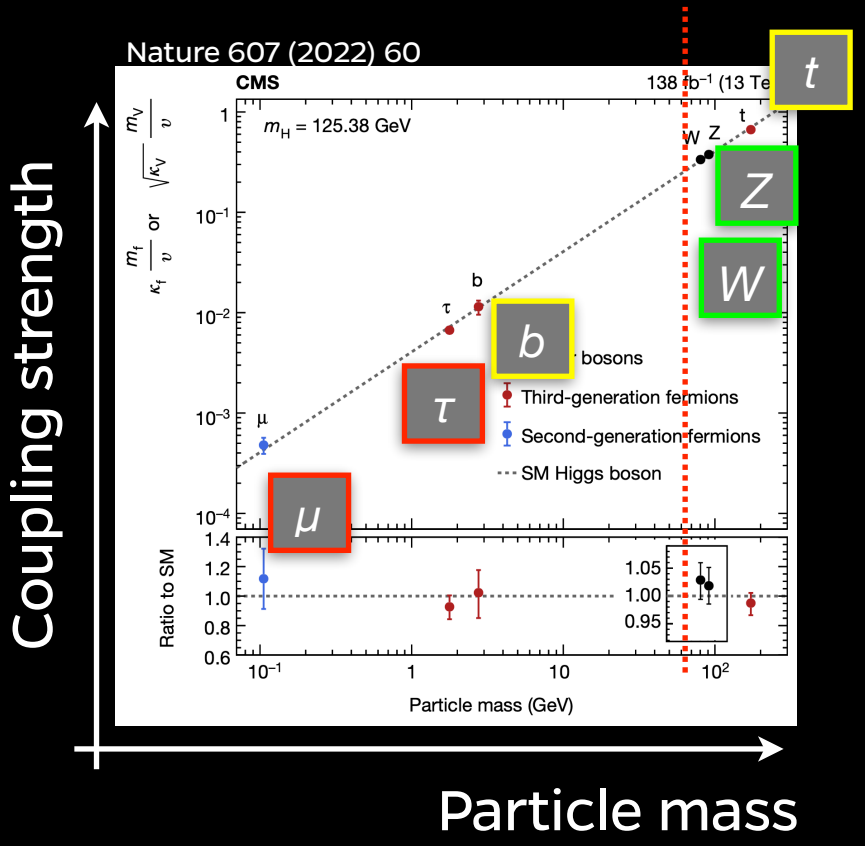
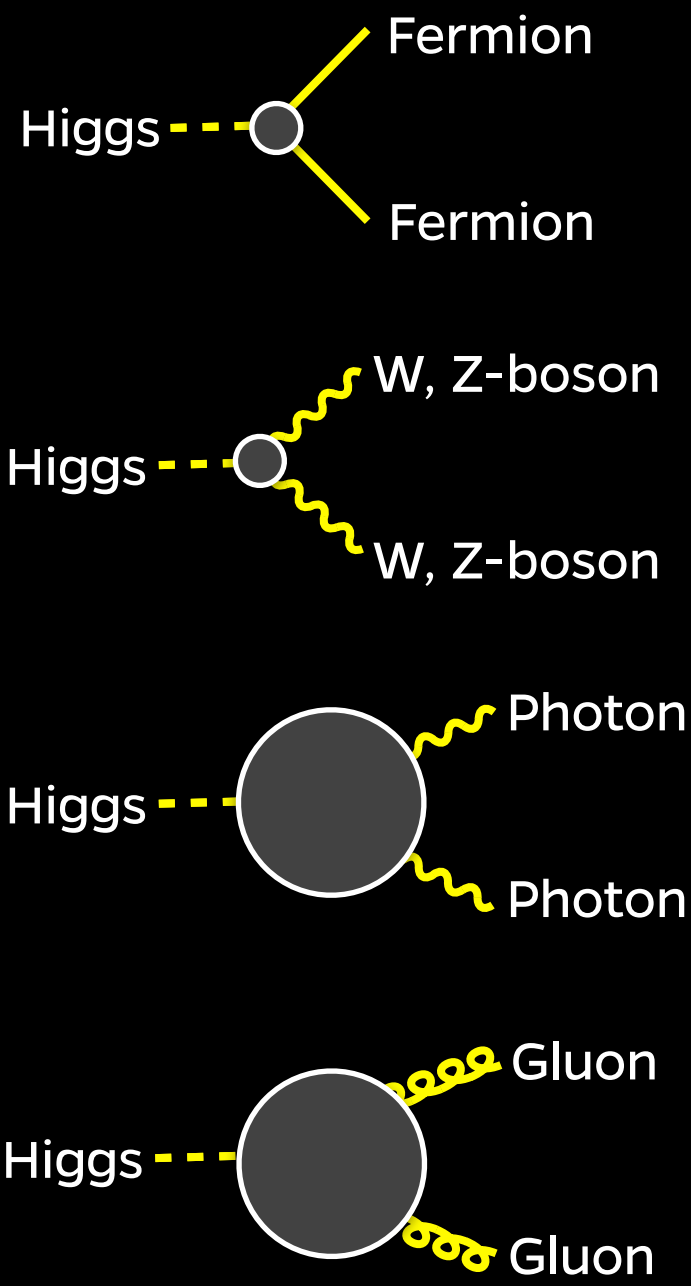
Higgs
gluon
87% of all Higgs production
top-quark
gluon
Higgs
1%
gluon
top-quark
quark
quark
W, Z-boson
Higgs
7%
quark
quark
quark
W, Z-boson
4%
quark
Higgs



Nature 607 (2022) 60



**makes the width very small



Number of Higgs boson produced

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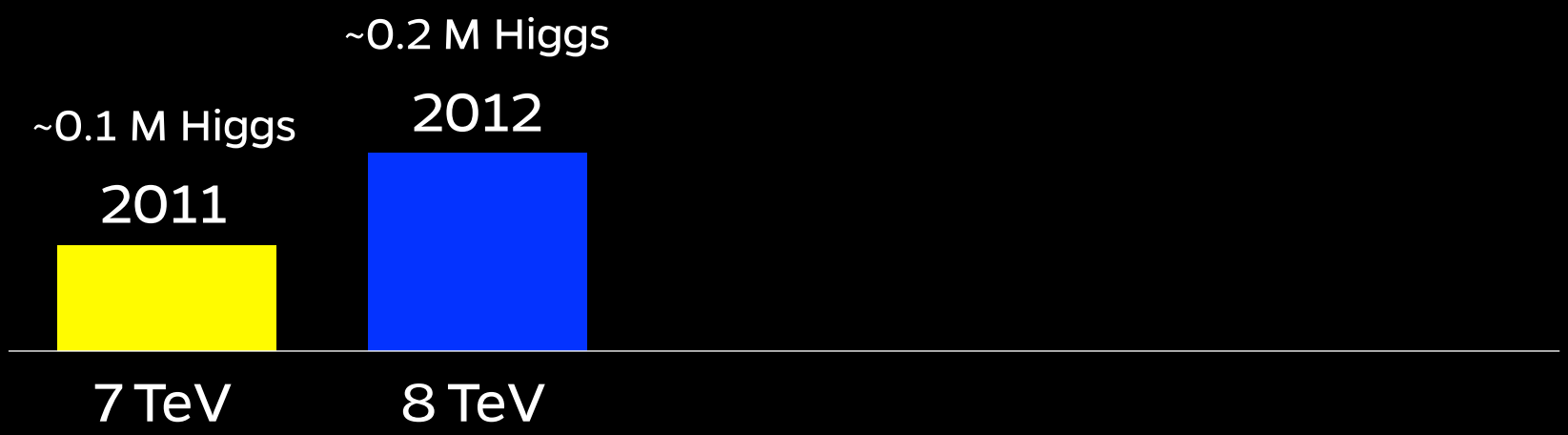
Years	Runs	Energy	Luminosity	# of Higgs
2011	Run 1	7 TeV	~5 fb^{-1}	~100 K
2012	Run 1	8 TeV	~6 fb^{-1}	~200 K



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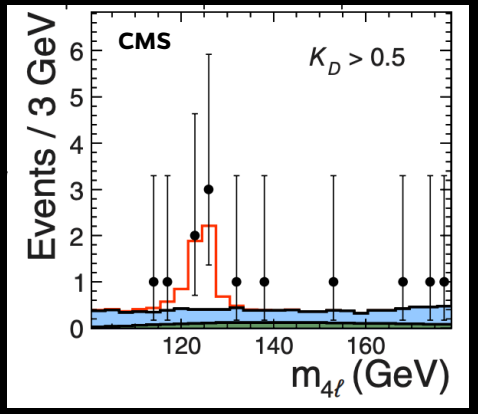

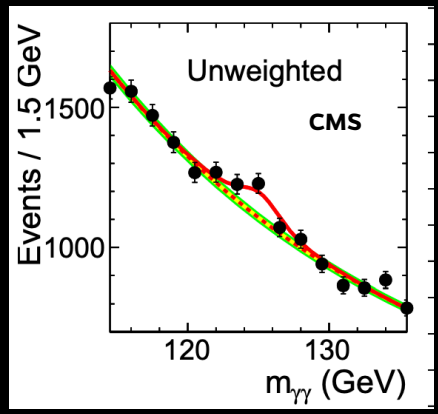

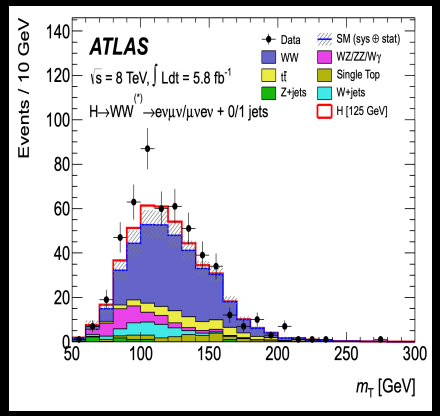

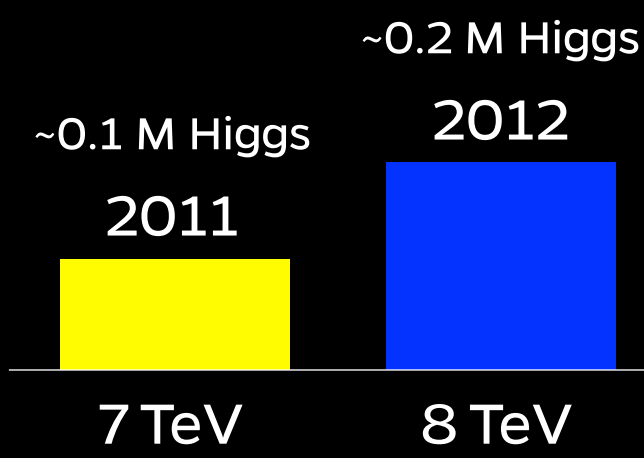

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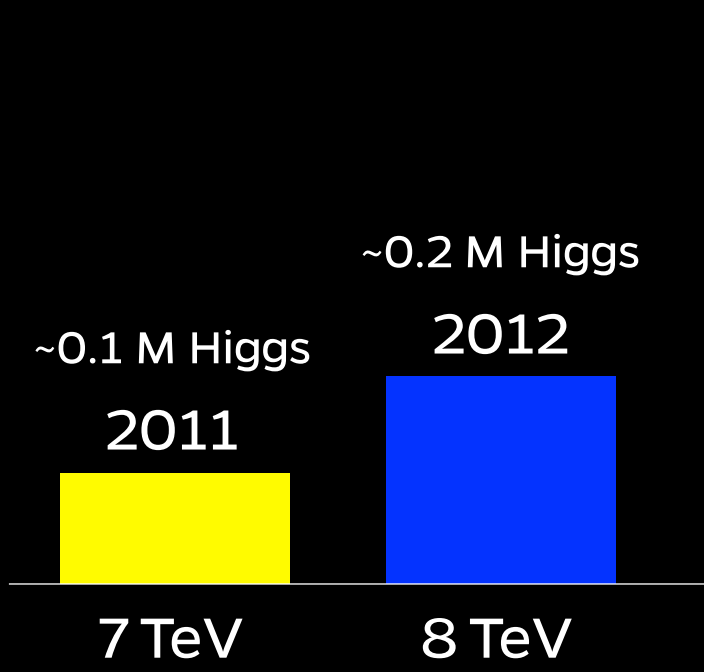
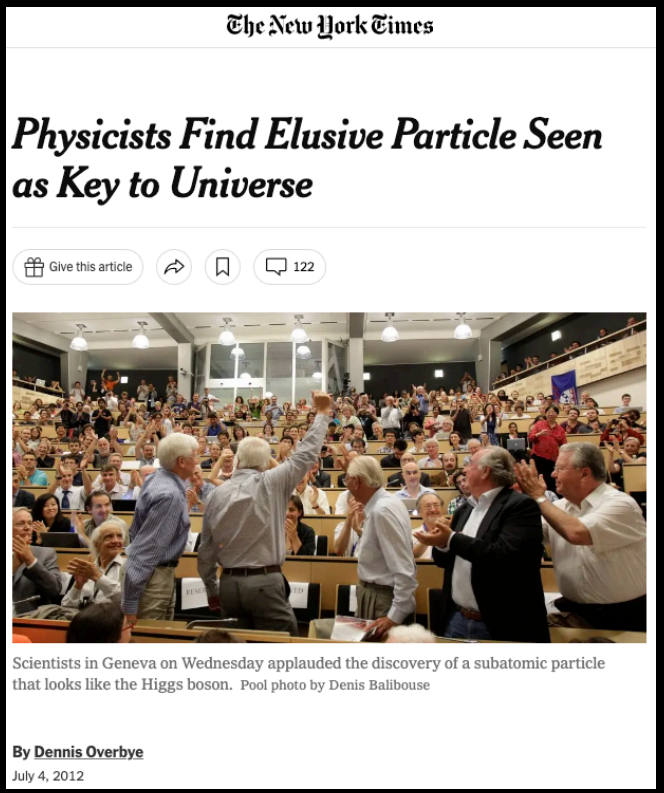


2012
Nobel Prize

Englert Higgs



The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Give this article 122

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

By Dennis Overbye
July 4, 2012

Number of Higgs boson produced

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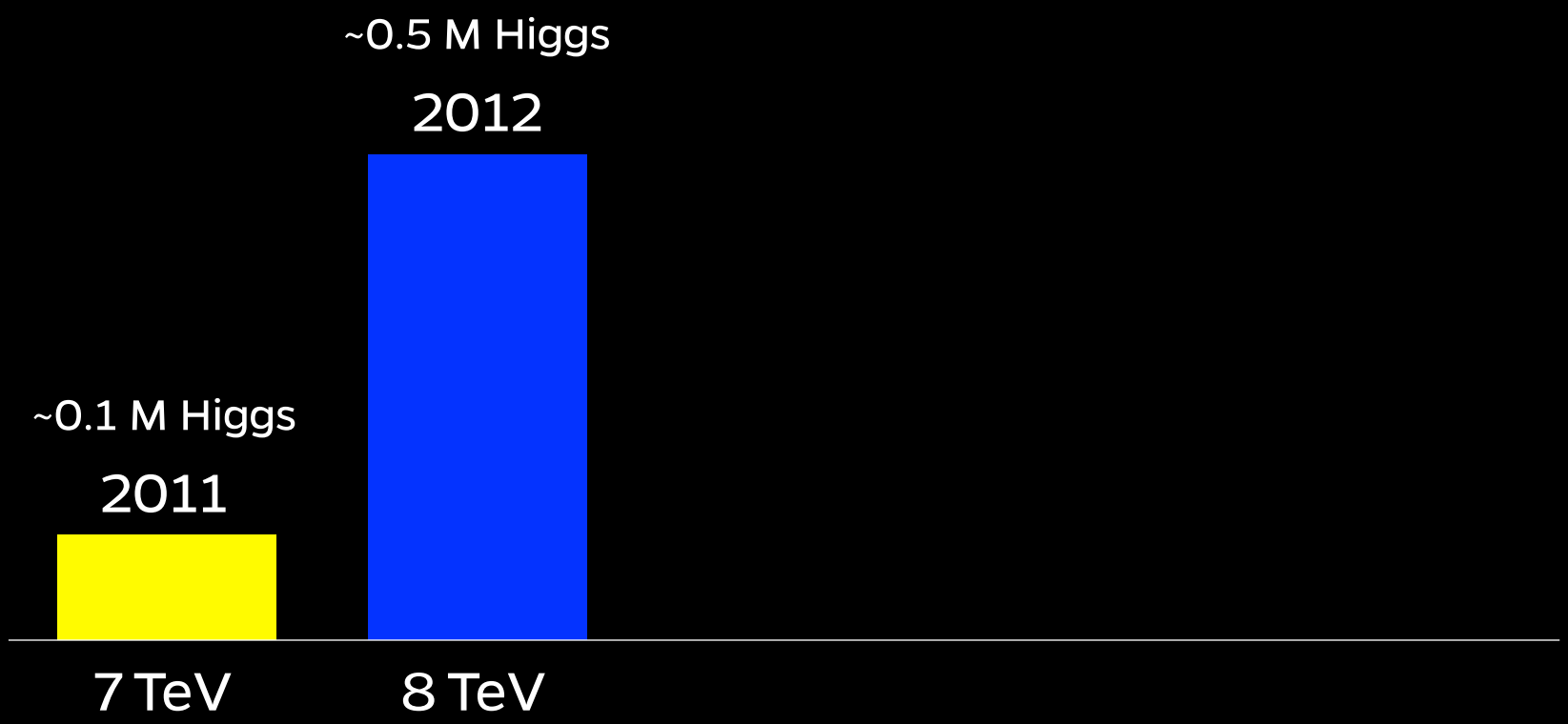
Years	Runs	Energy	Luminosity	# of Higgs
2011	Run 1	7 TeV	~5 fb^{-1}	~100 K
2012	Run 1	8 TeV	~20 fb^{-1}	~500 K



Number of Higgs boson produced

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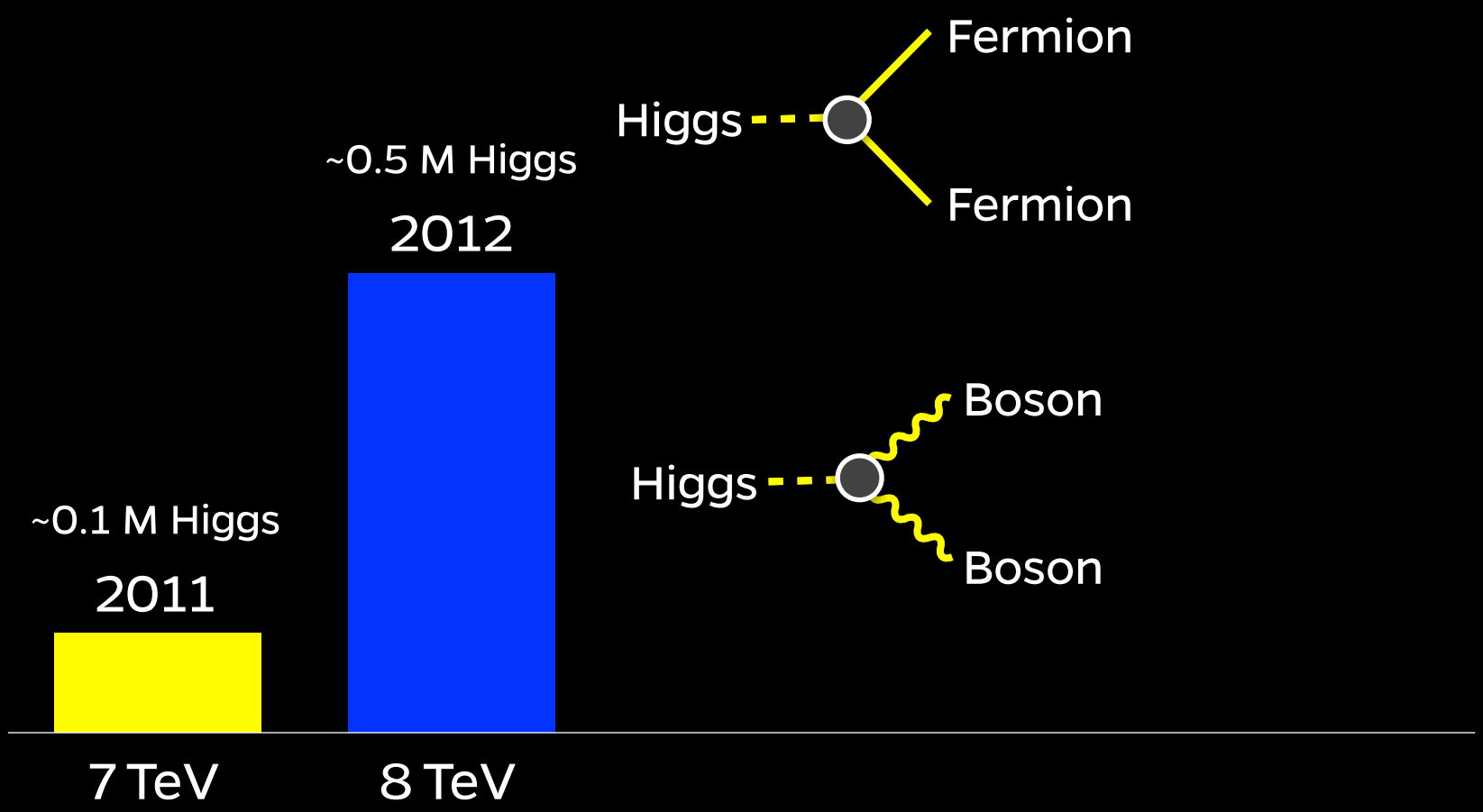

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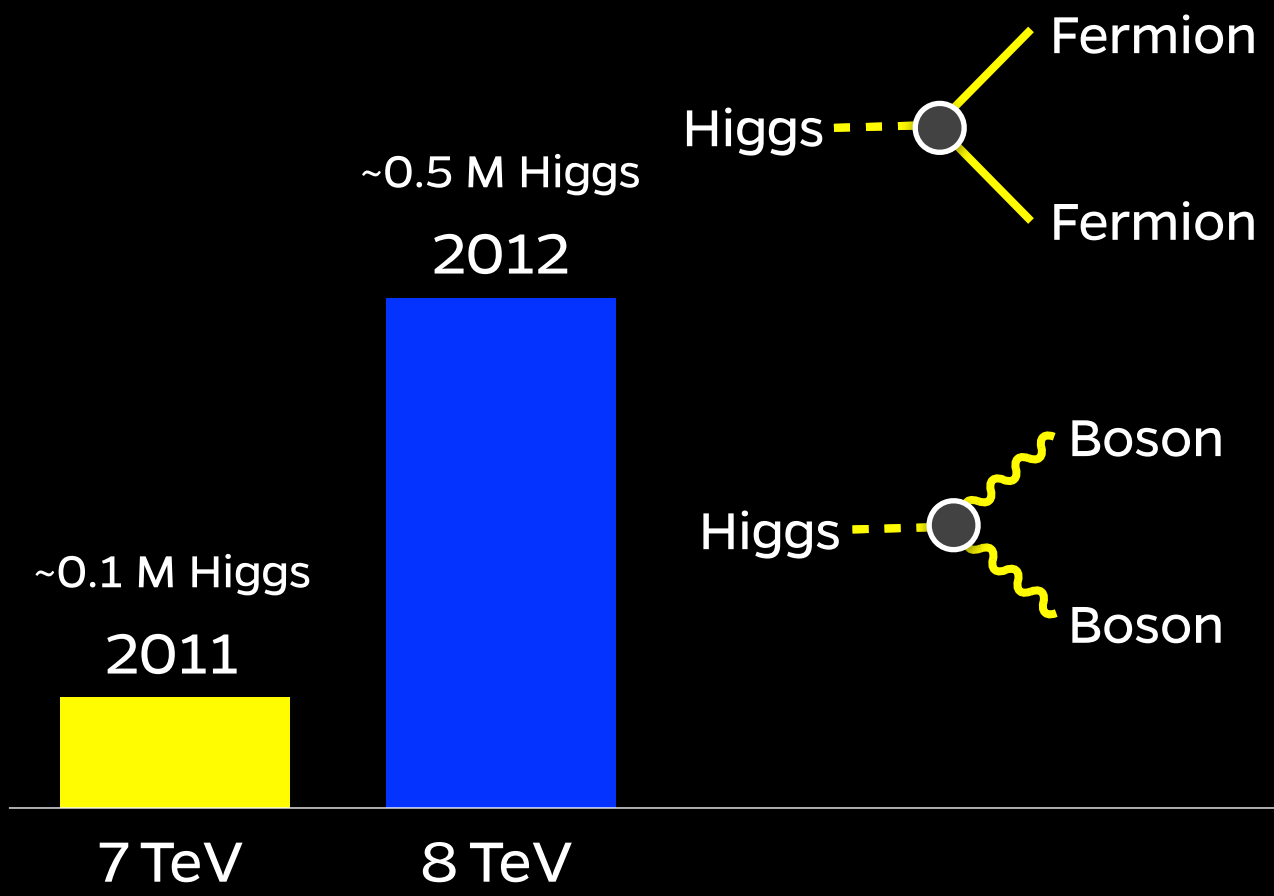

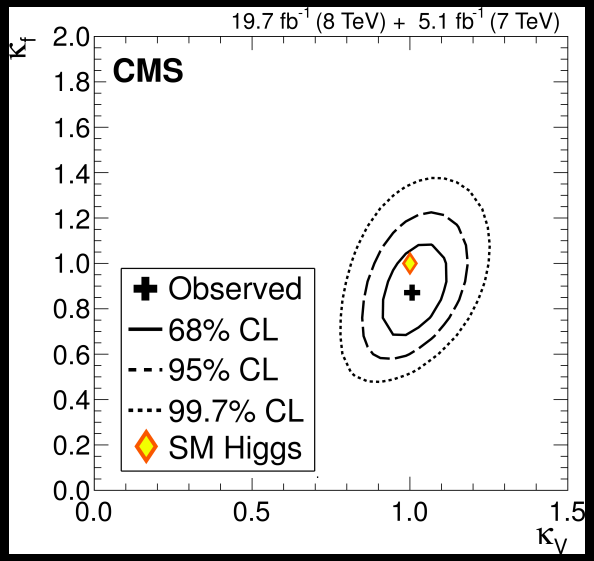

Number of Higgs boson produced

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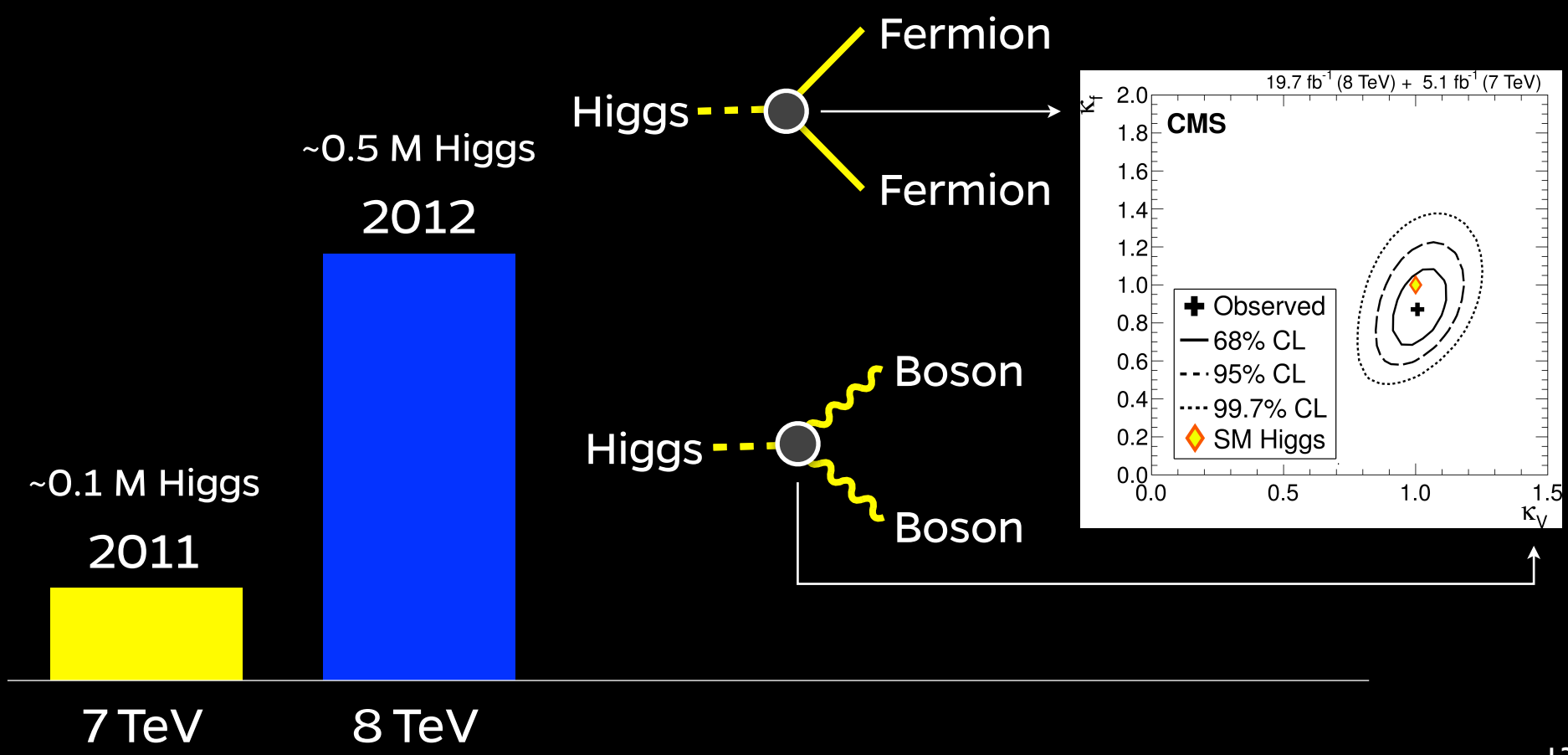

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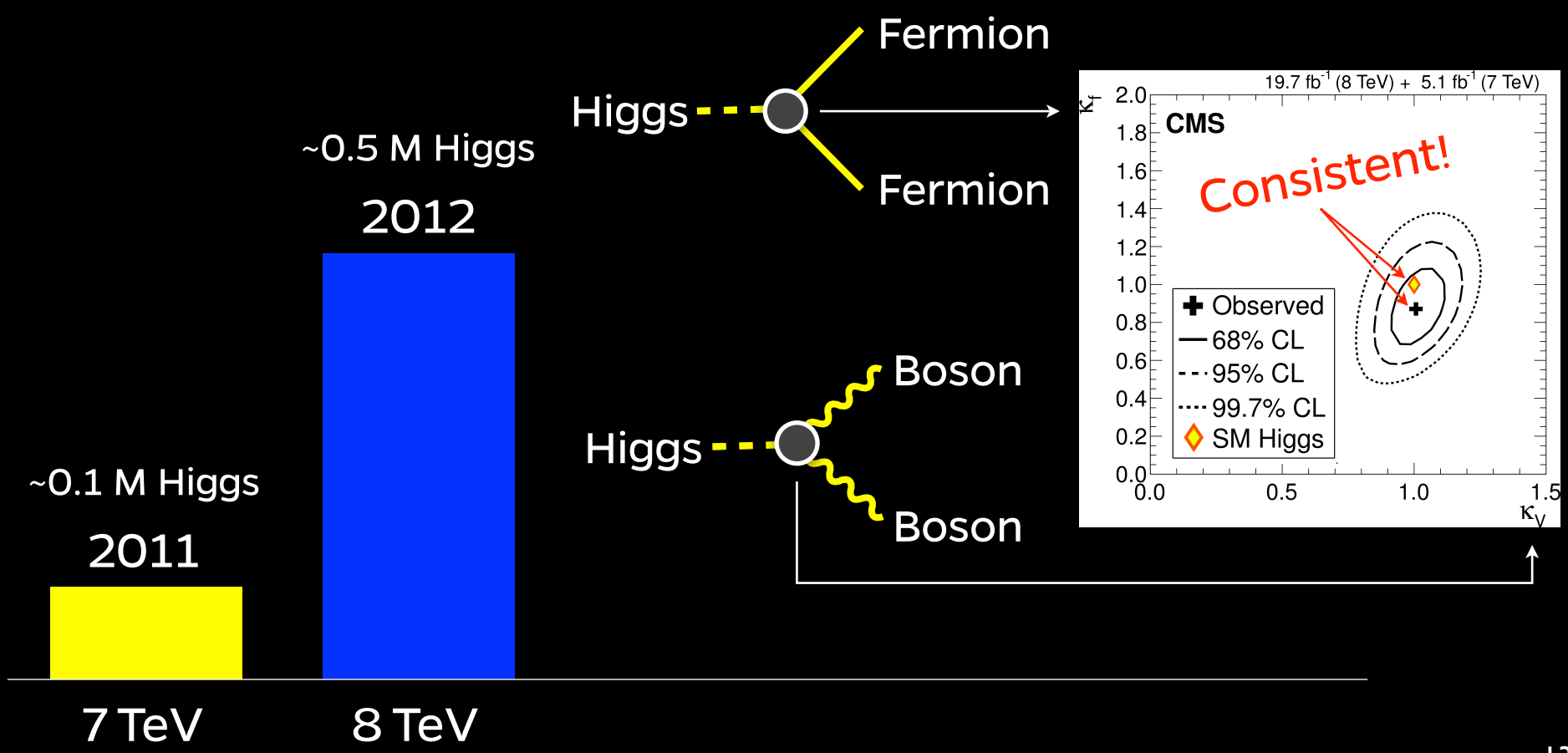

Number of Higgs boson produced

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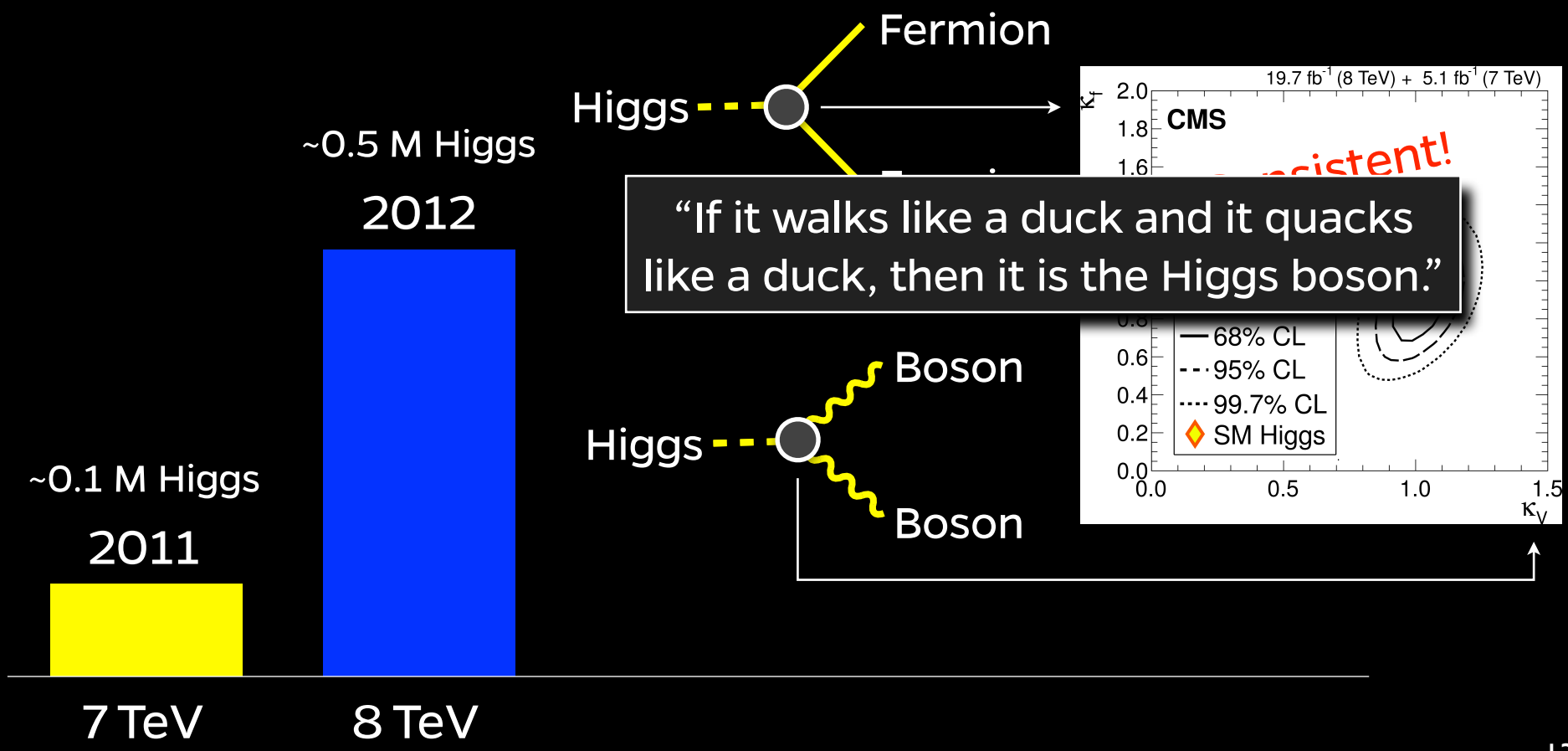

Number of Higgs boson produced

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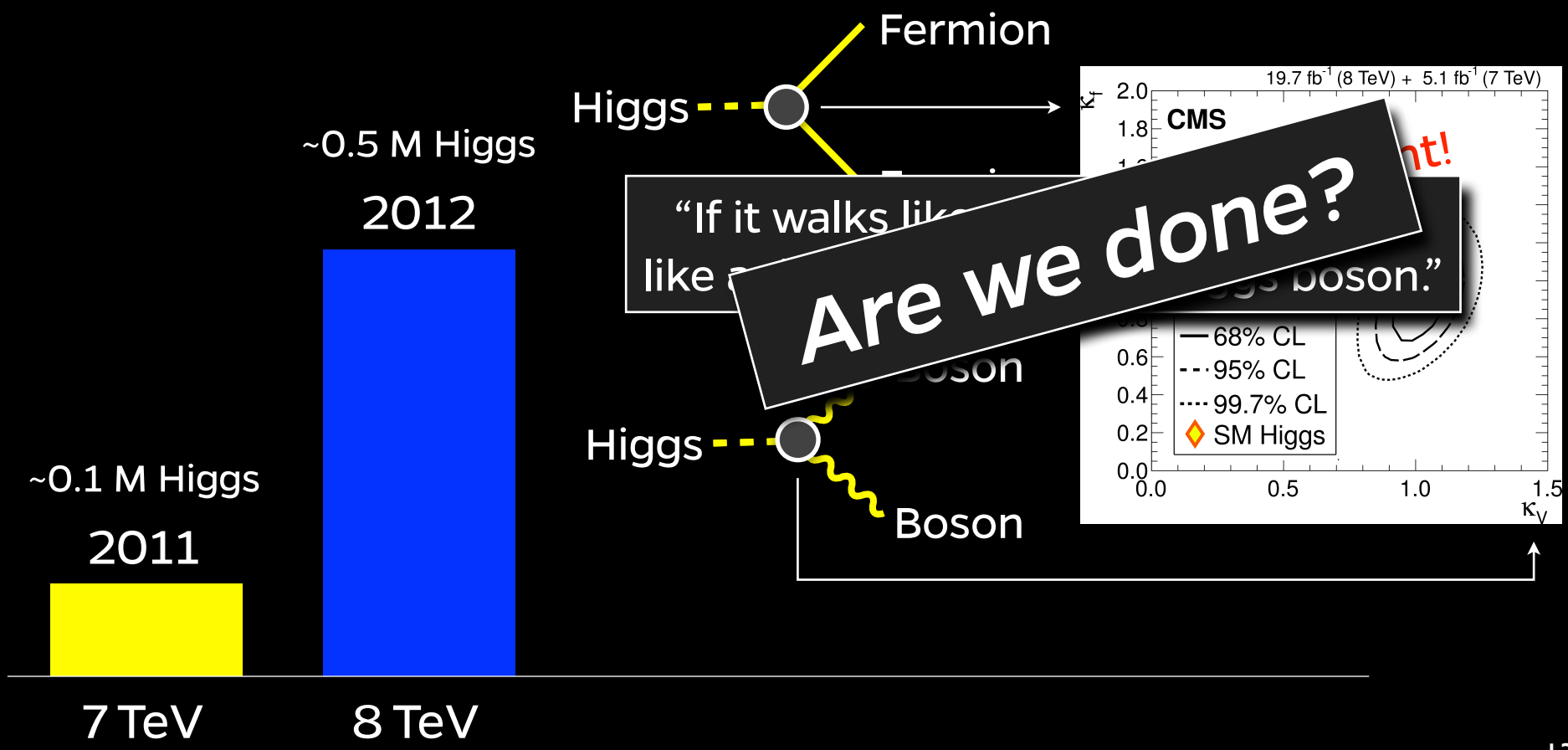

Number of Higgs boson produced

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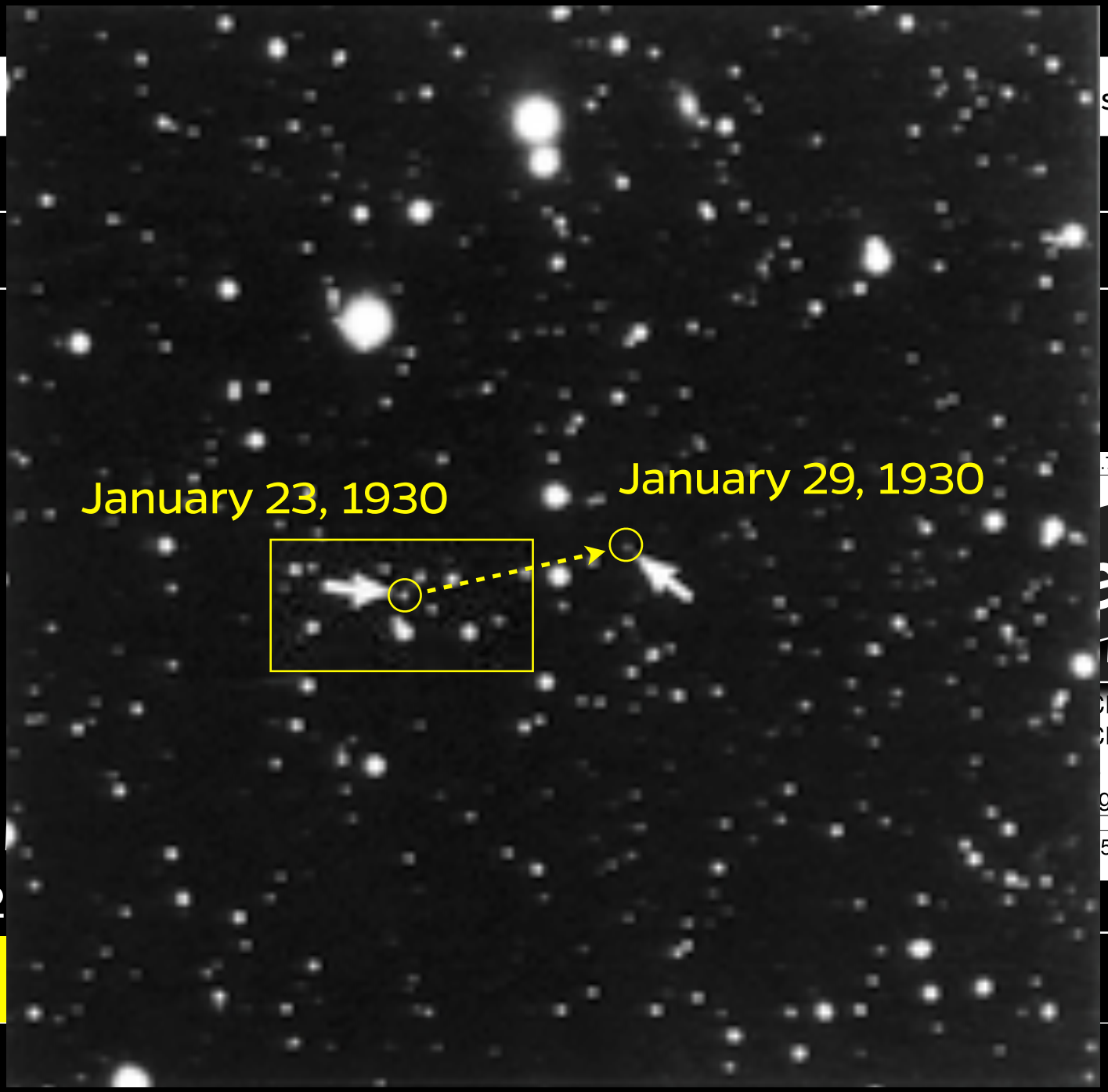

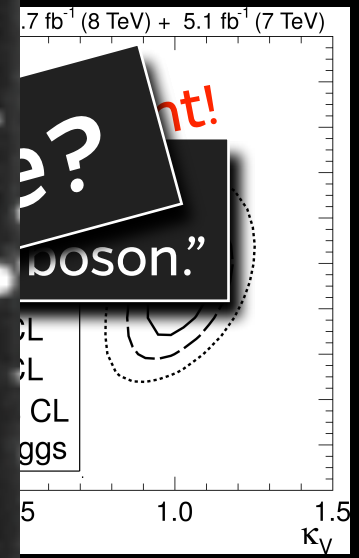

~0.1

2

7

Number of Higgs boson produced

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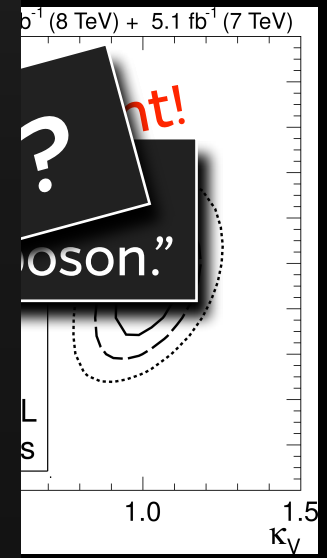
1930 Lowell Observatory



"If it walks like a duck and it quacks like a duck, then it is Pluto."

~0.1

2

7

“Portrait” of the Higgs boson

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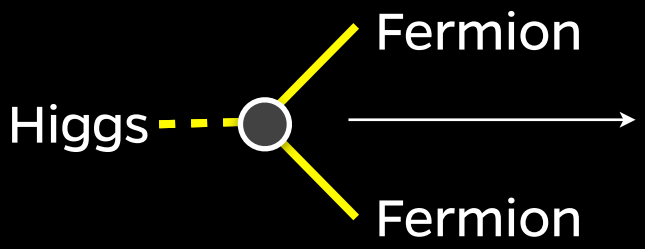

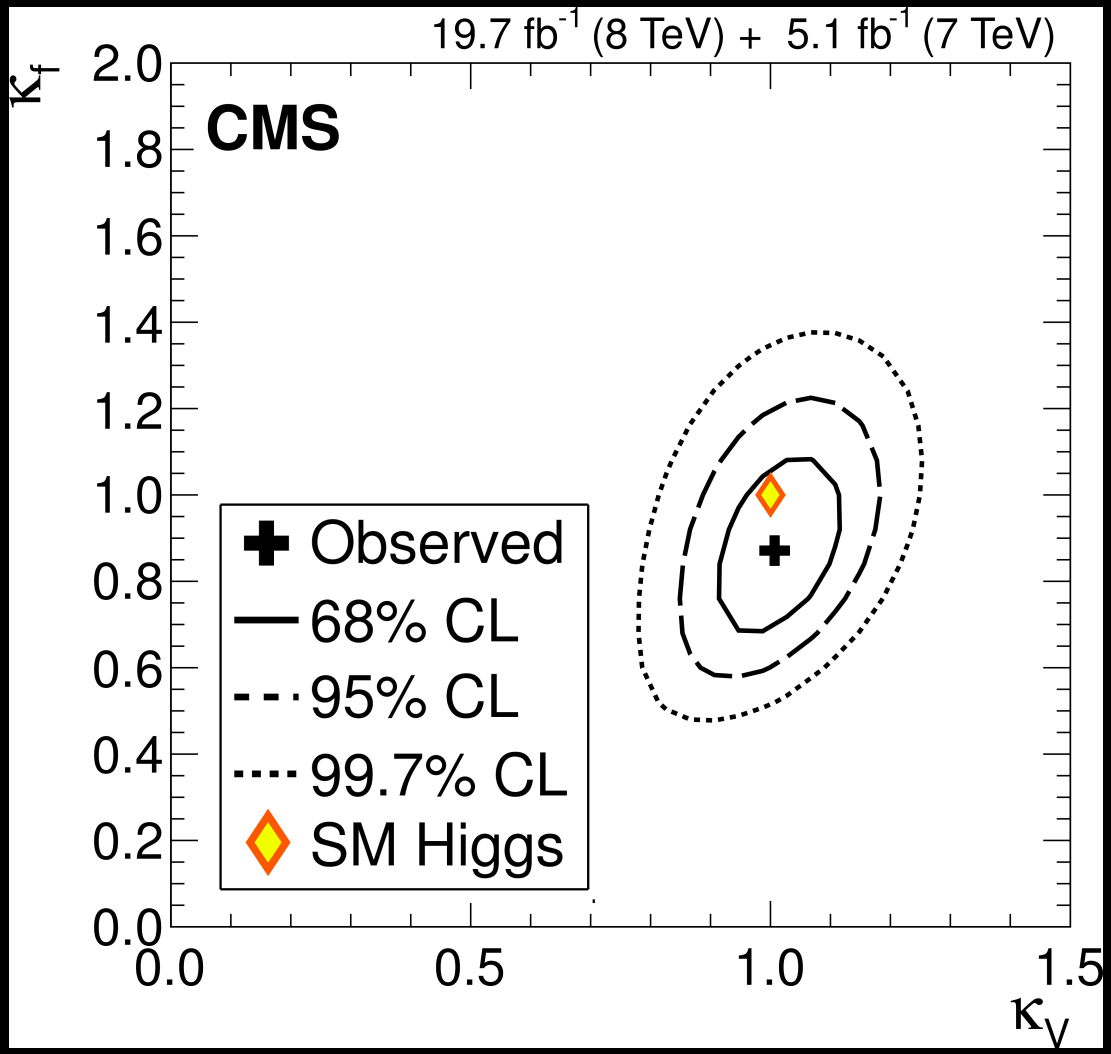

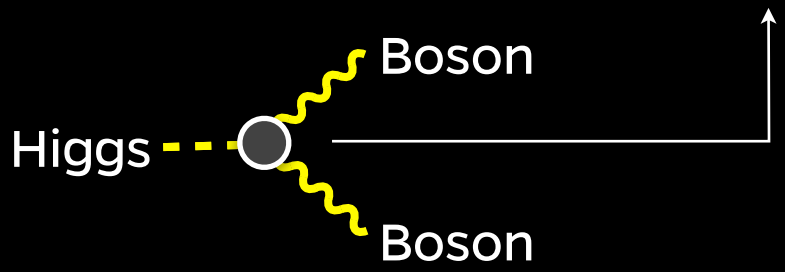

“Portrait” of the Higgs boson

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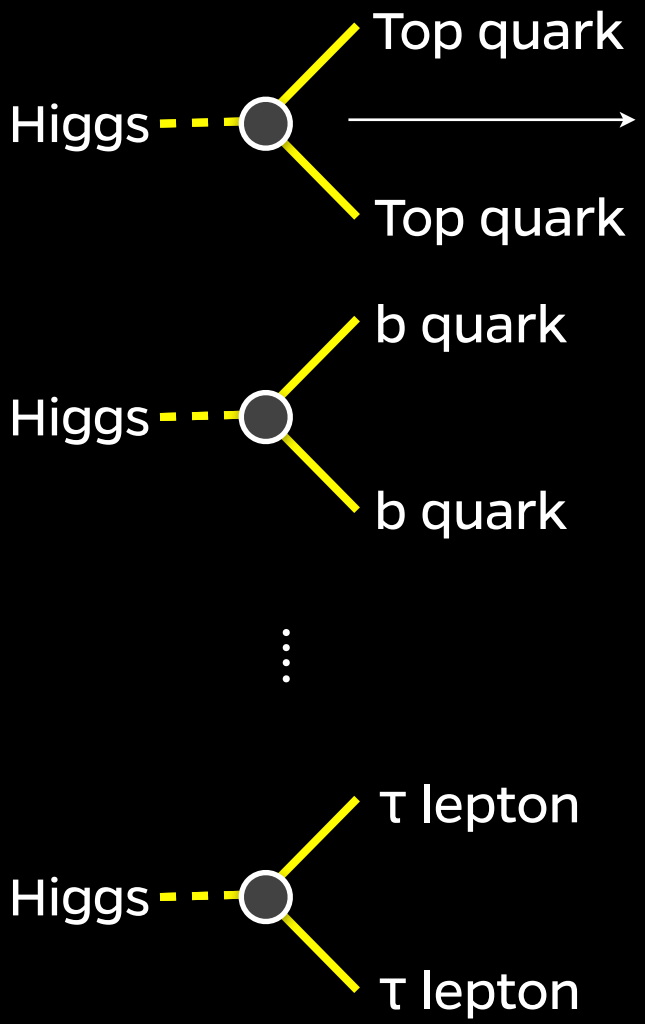

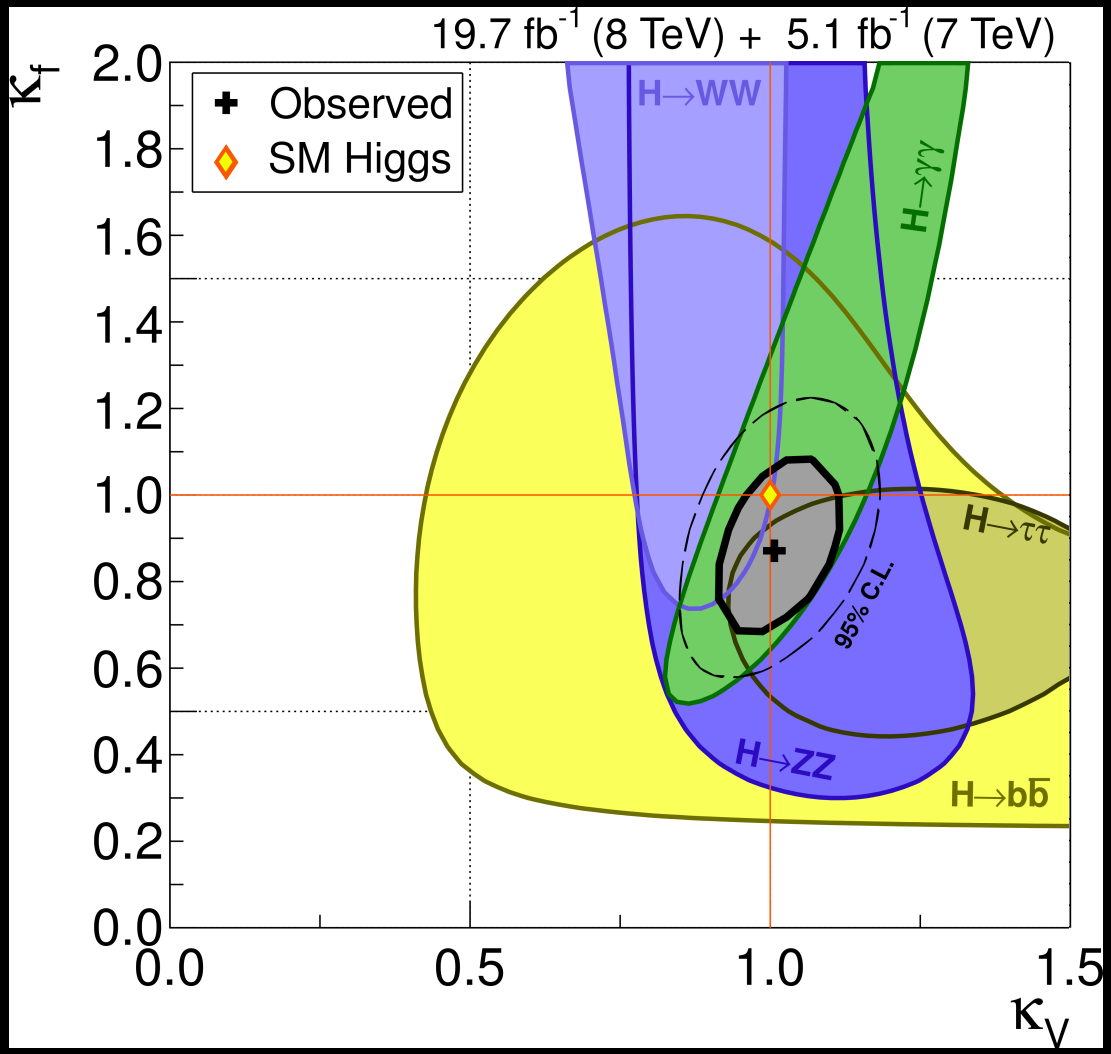

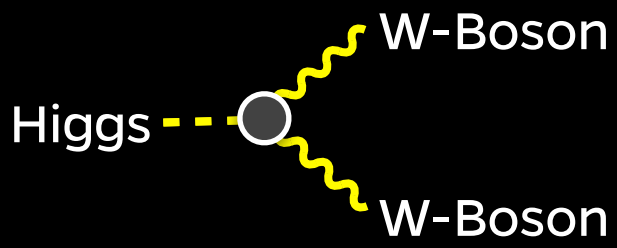

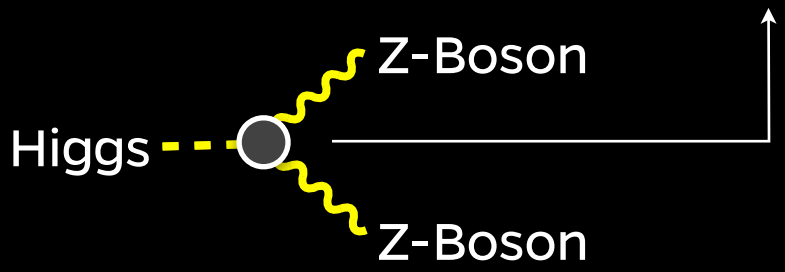

“Portrait” of the Higgs boson

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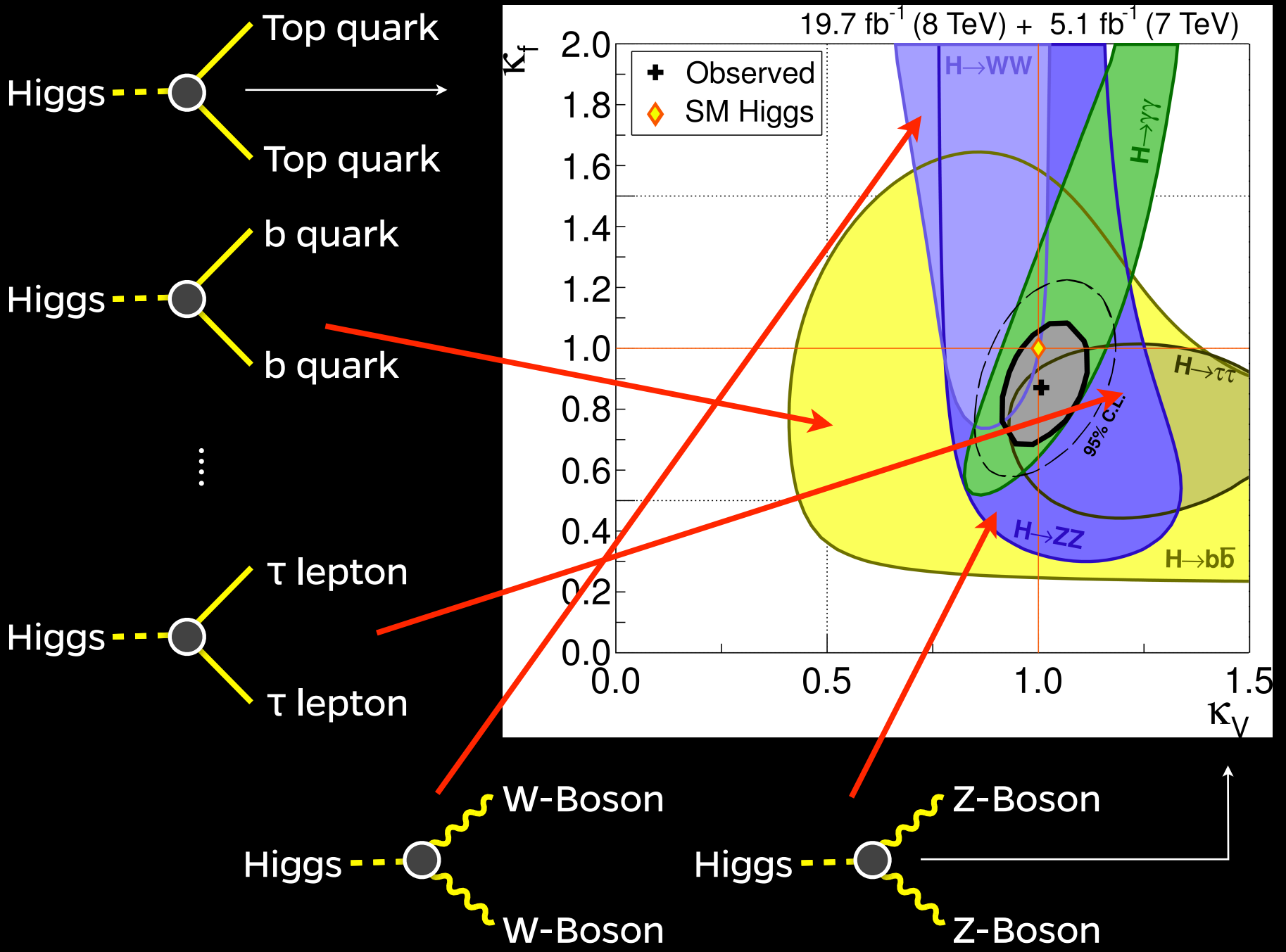

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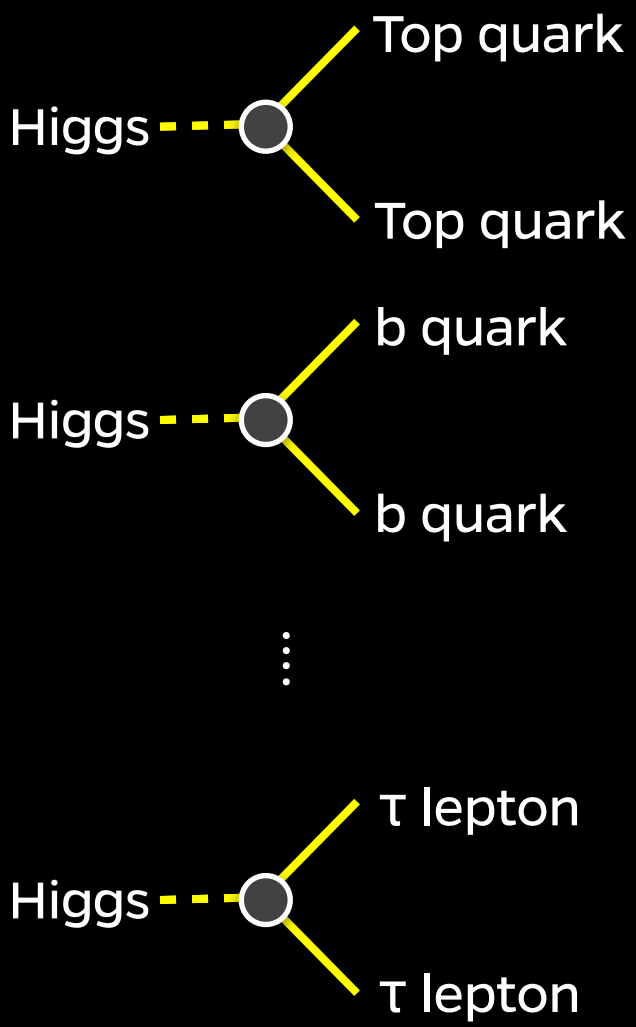

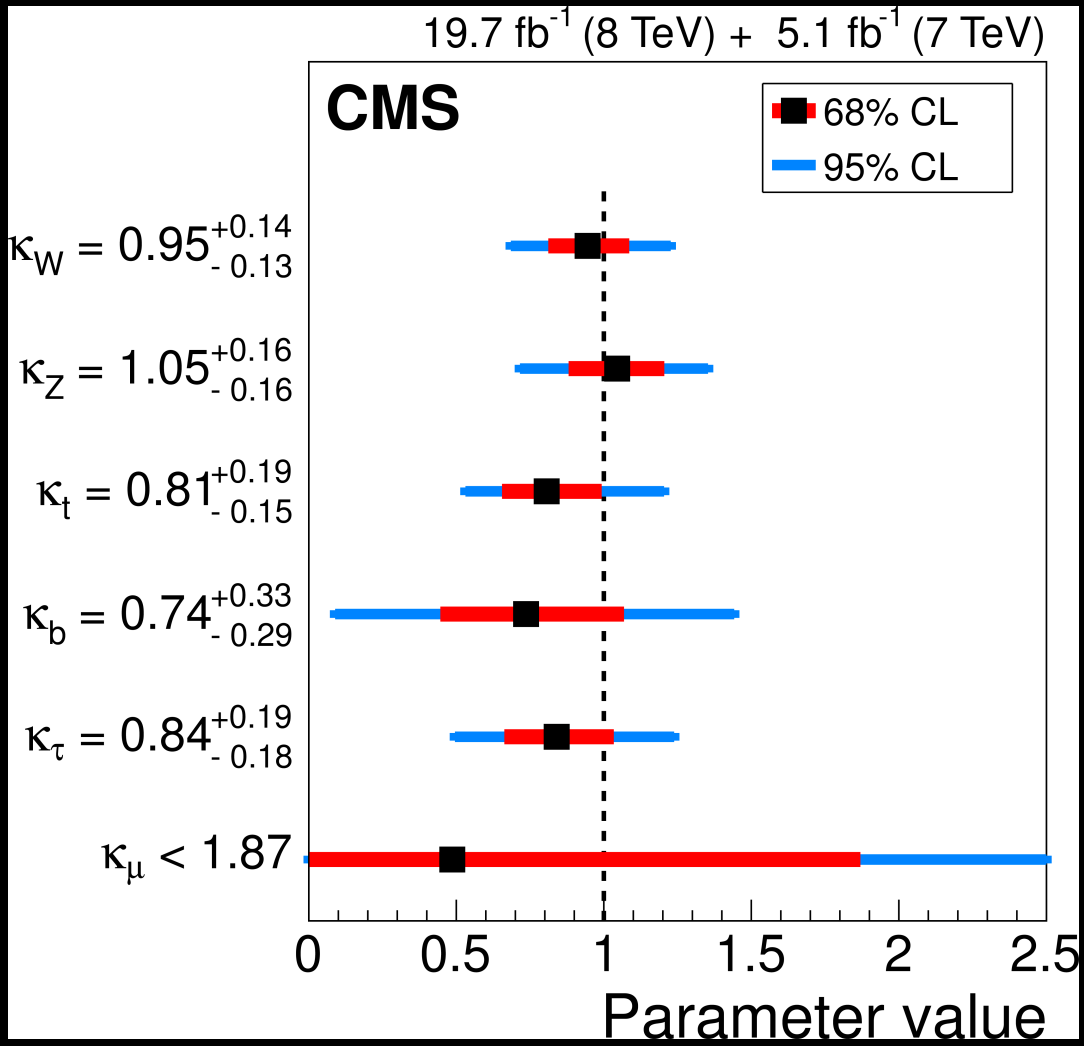

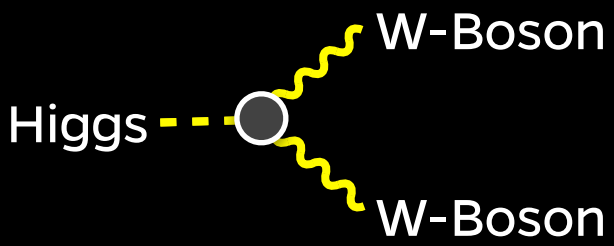

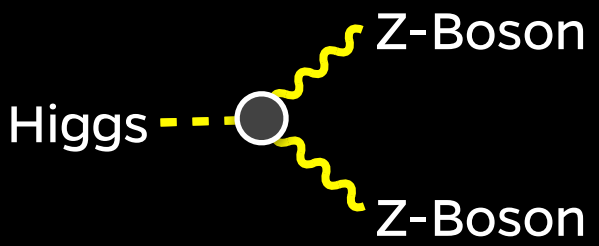

“Portrait” of the Higgs boson

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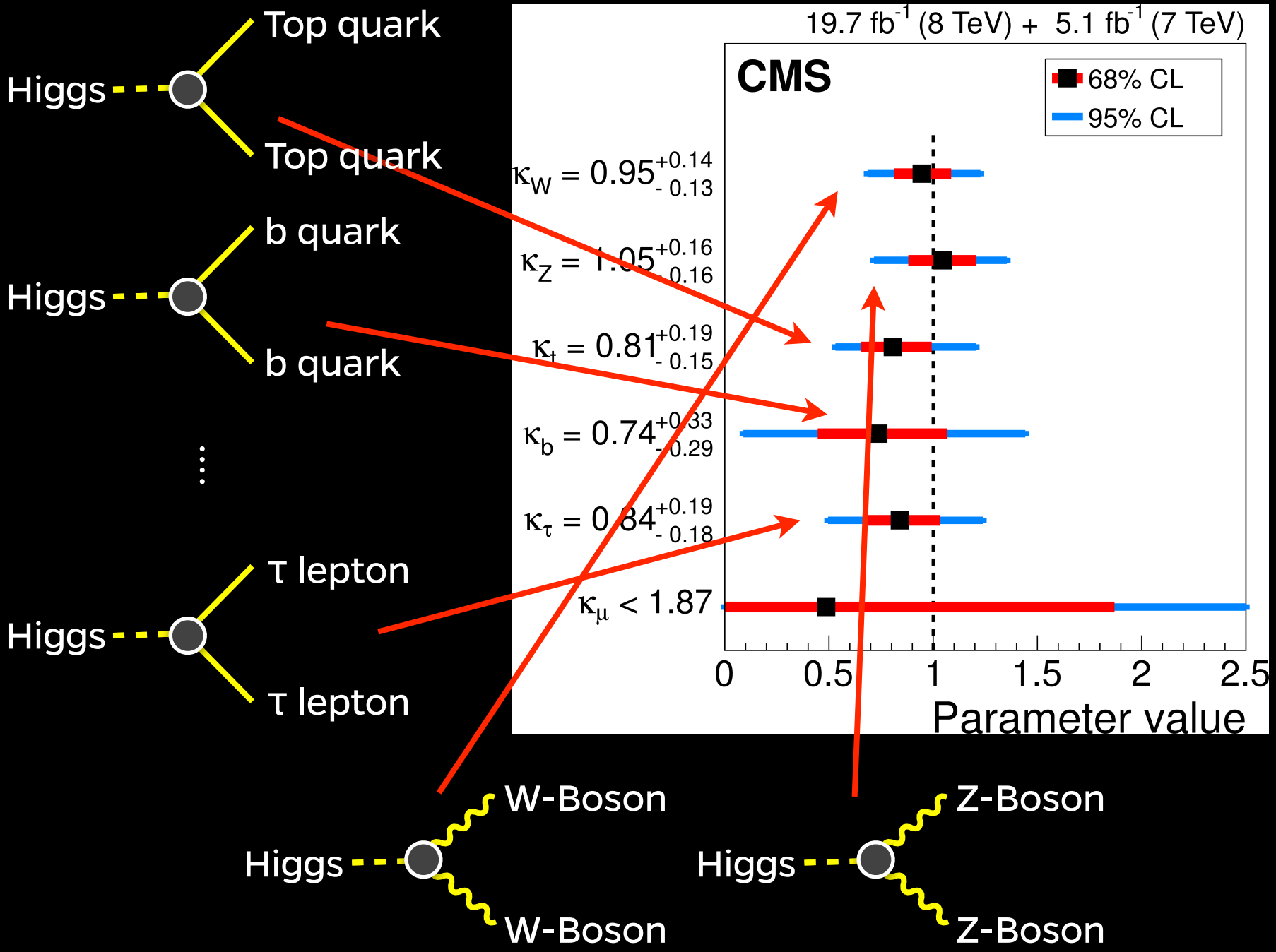

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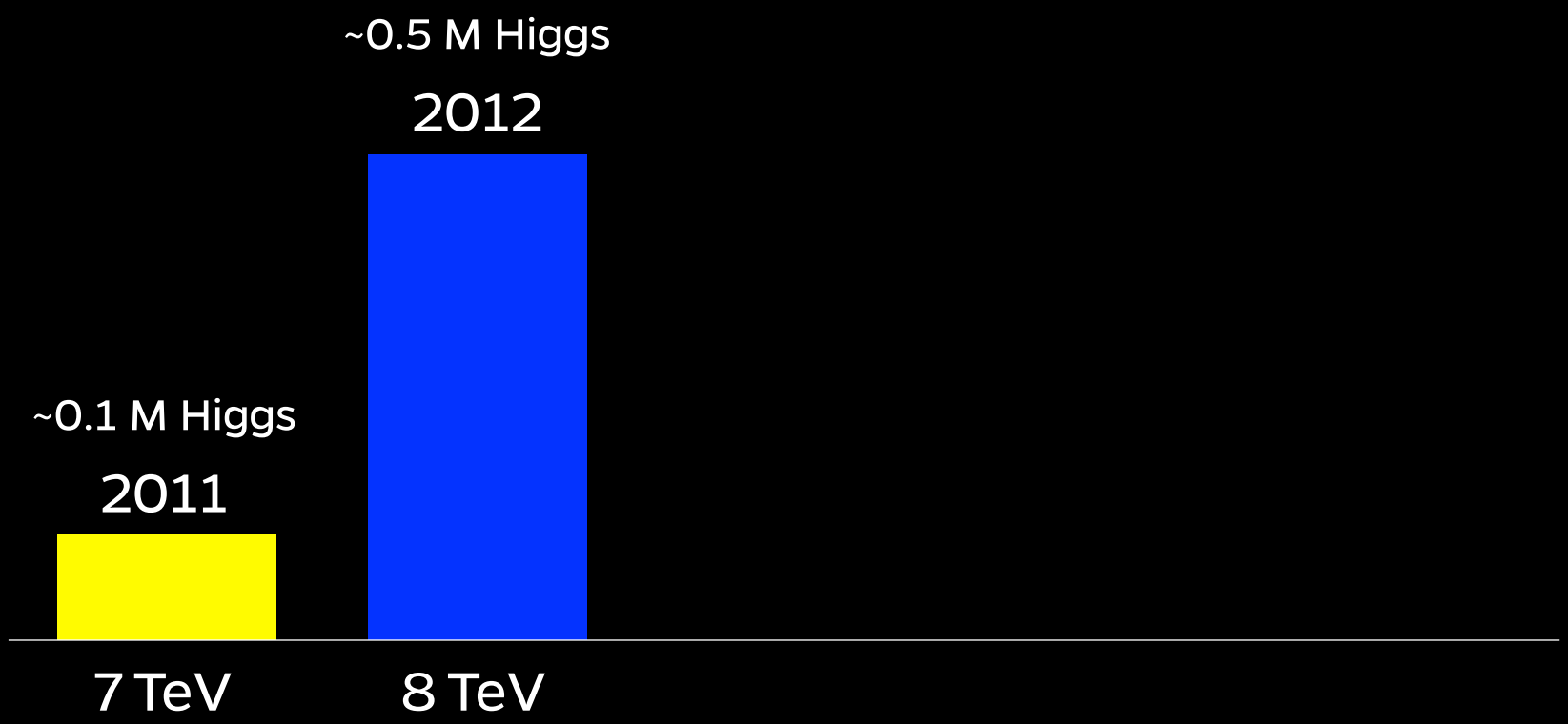

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An order of magnitude larger dataset is available!

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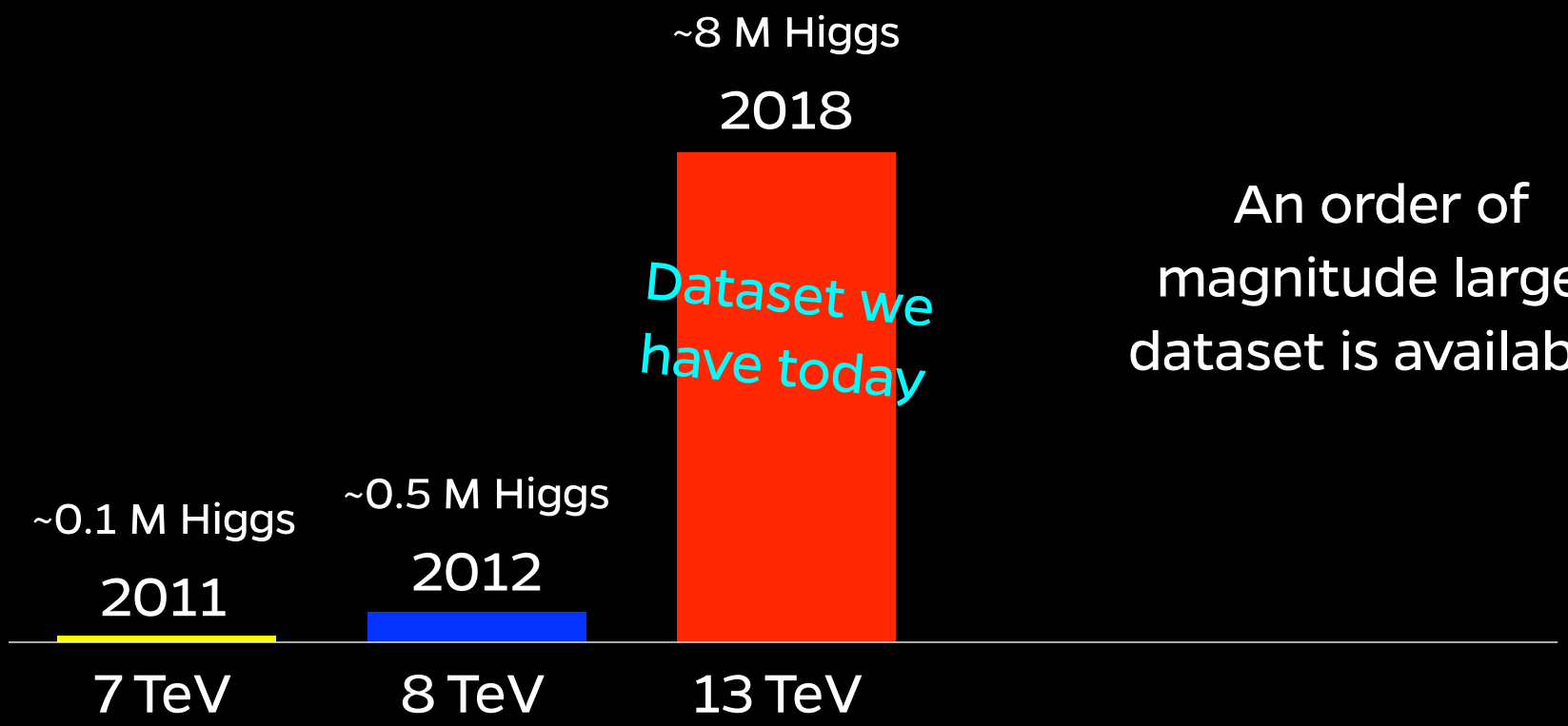

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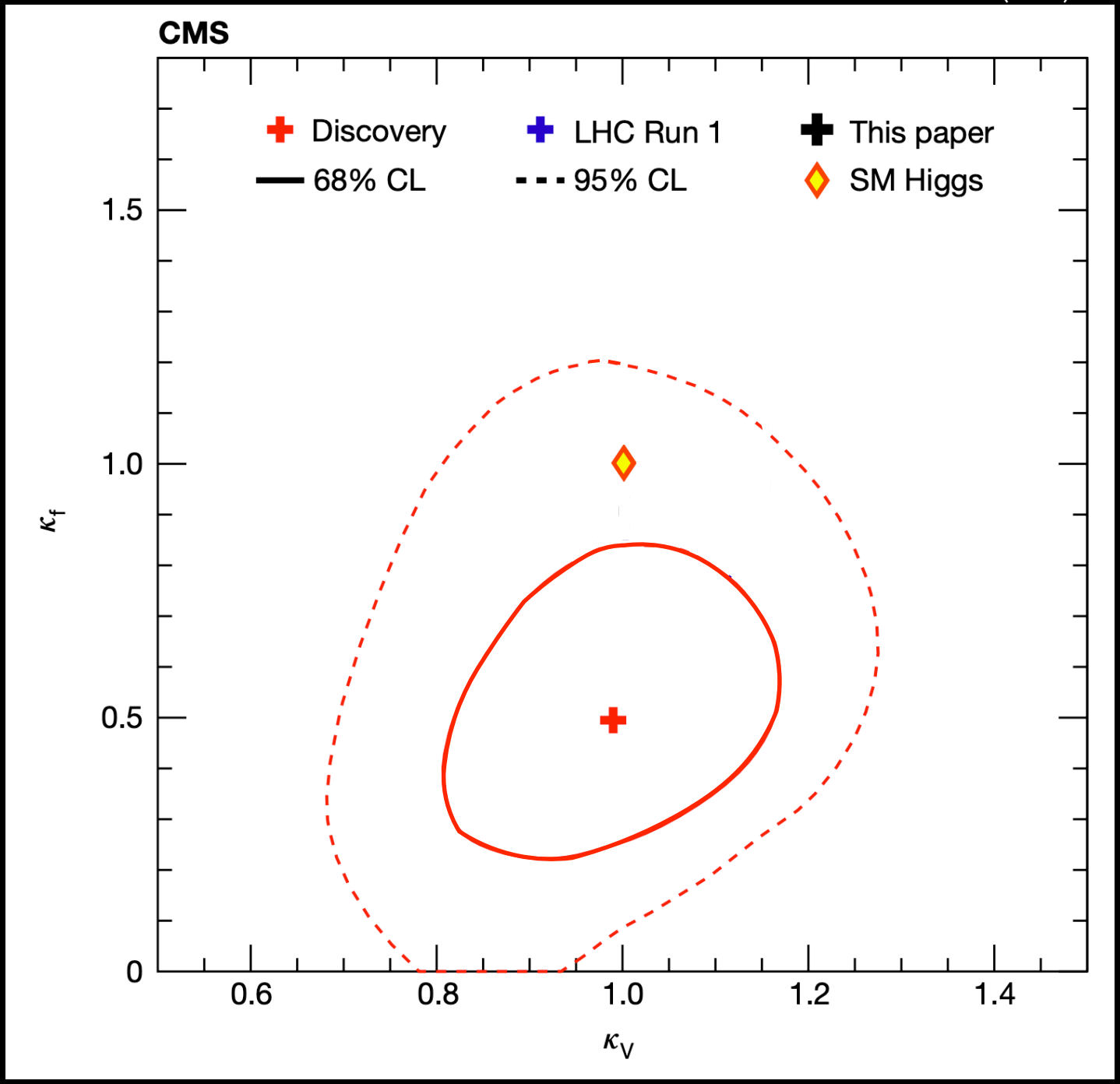
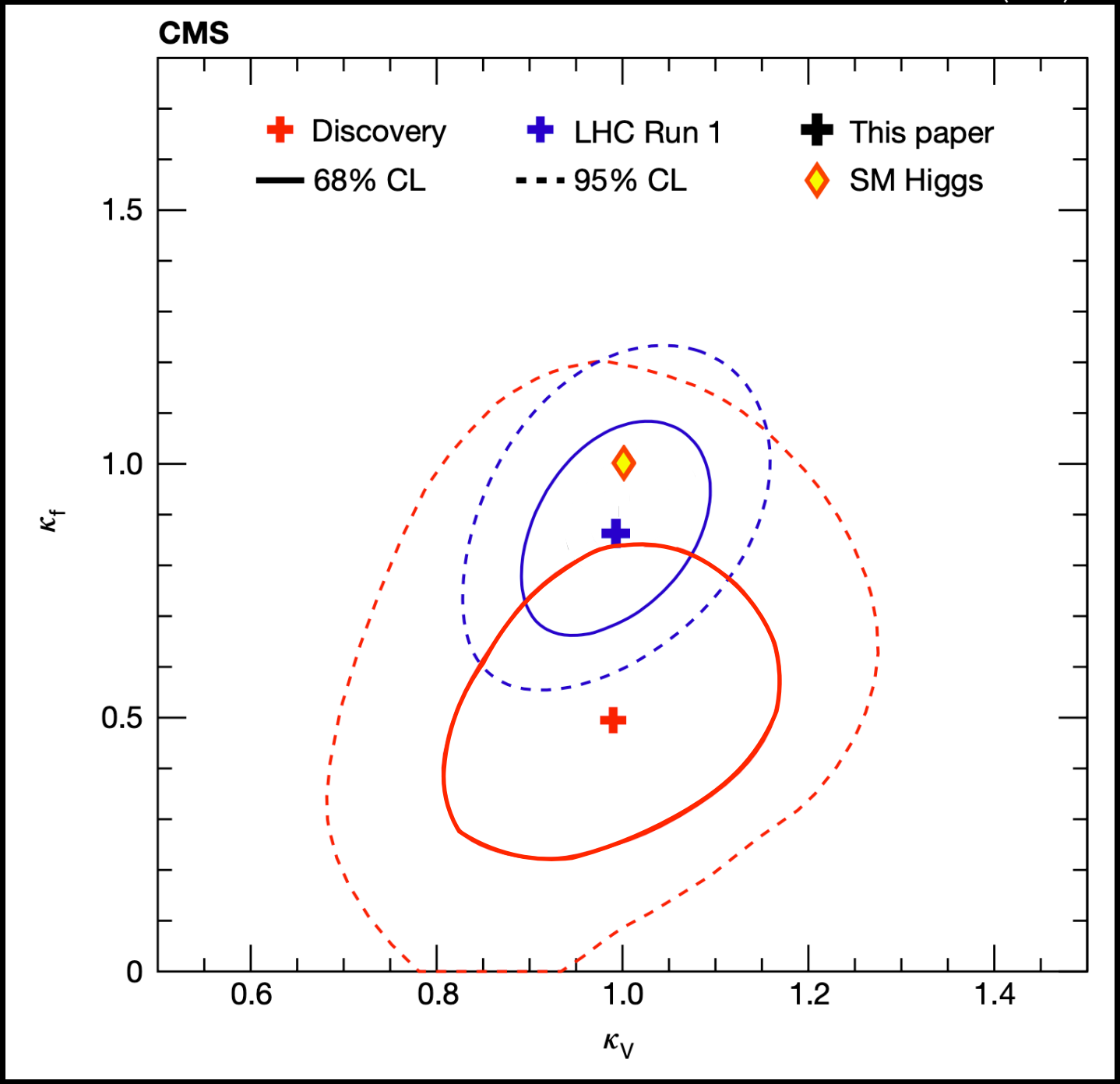
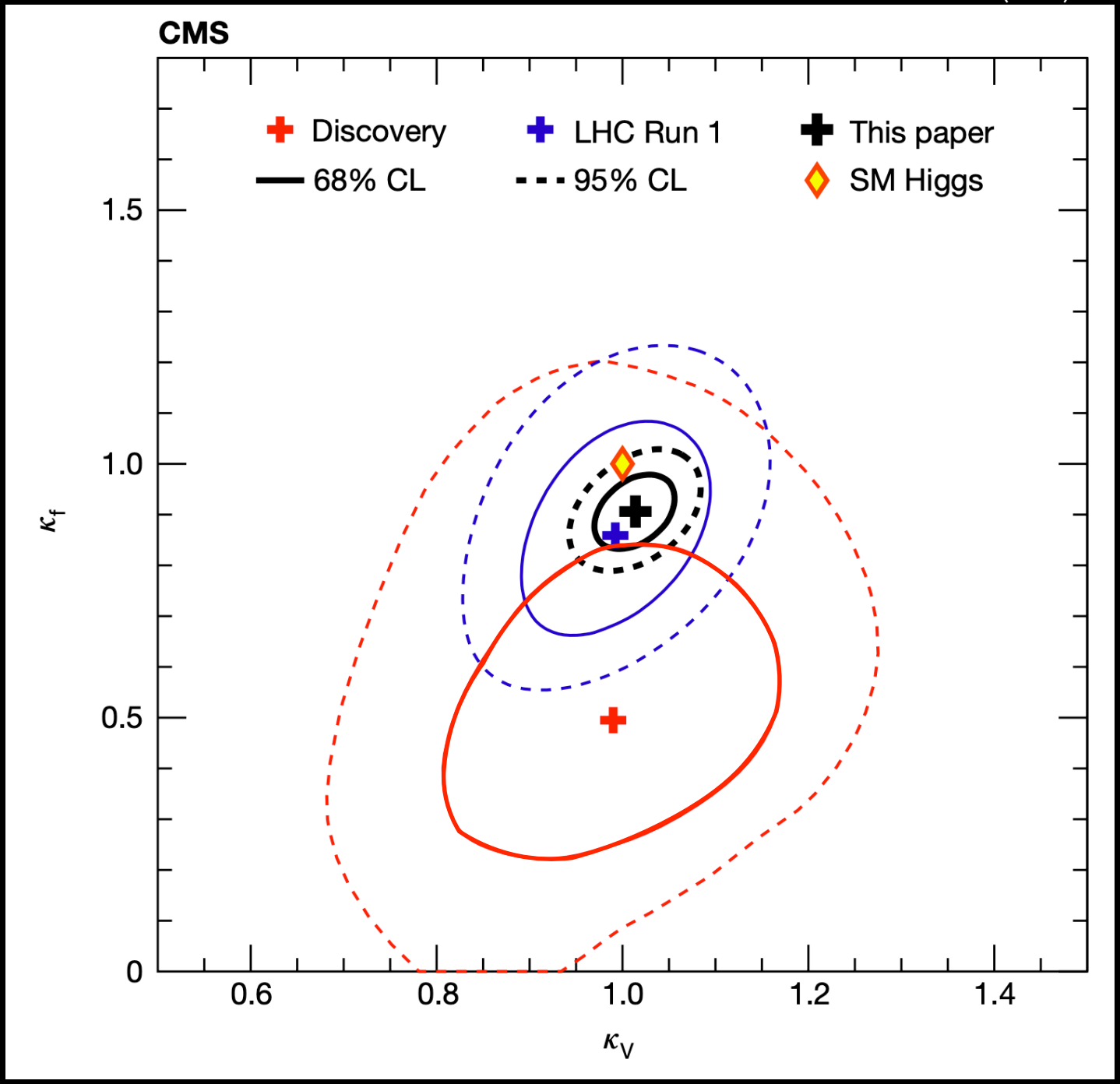
Nature 607 (2022) 60



Nature 607 (2022) 60



Nature 607 (2022) 60



10 year anniversary of discovery of Higgs boson

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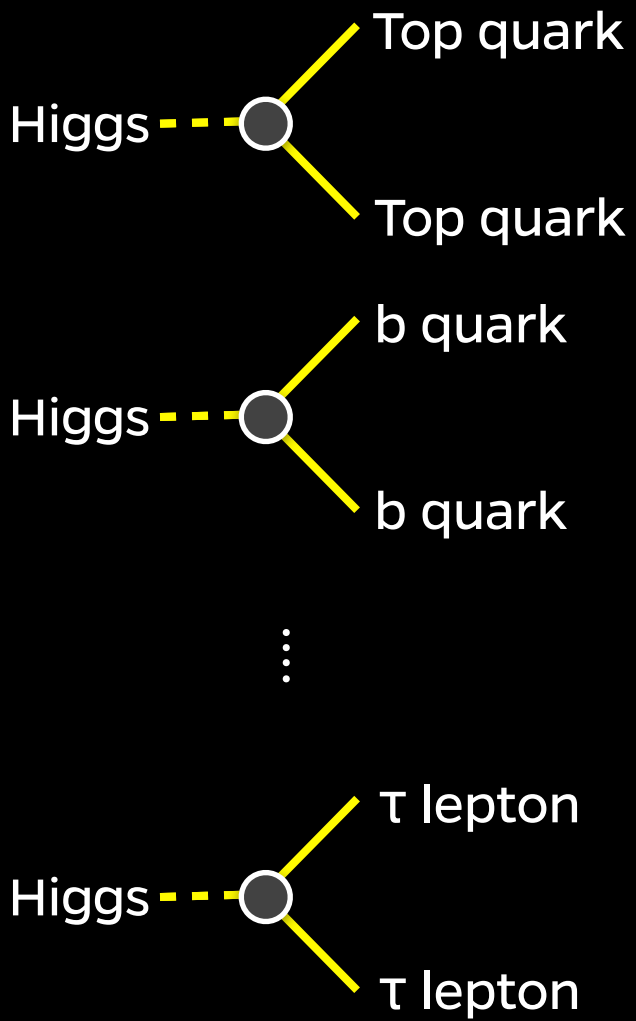

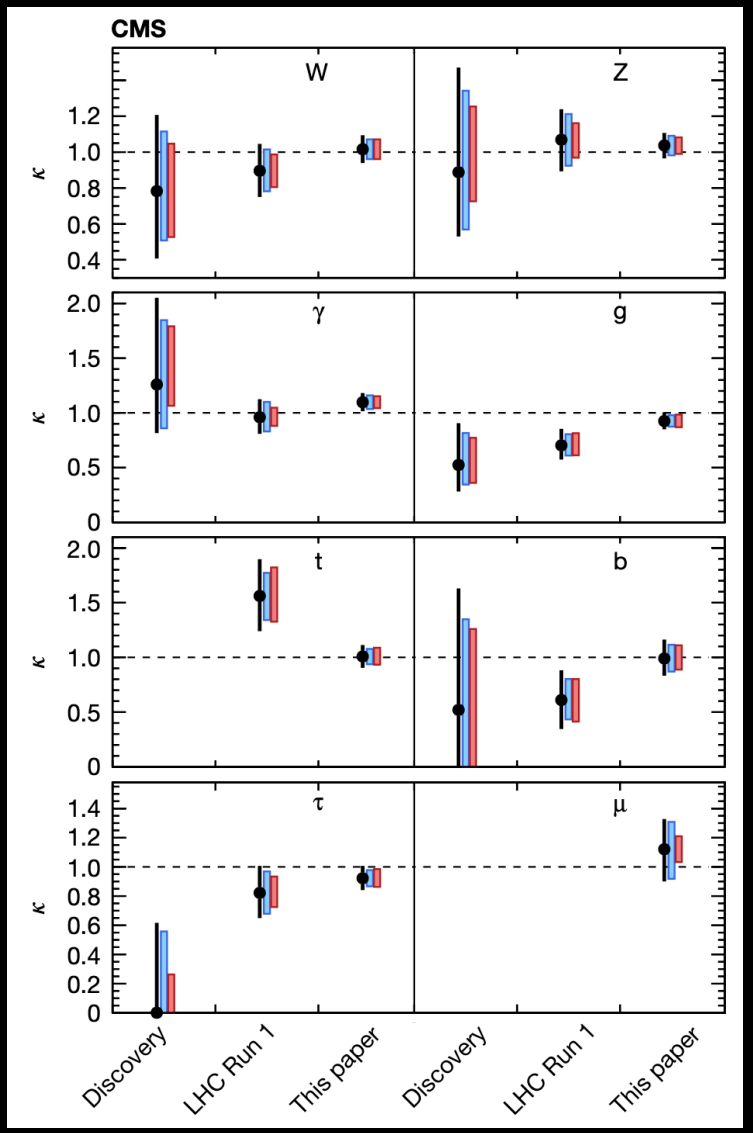

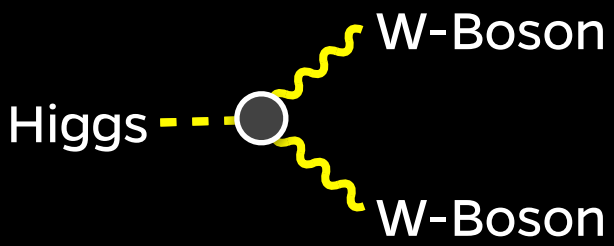

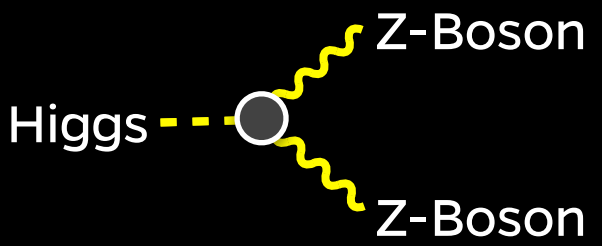

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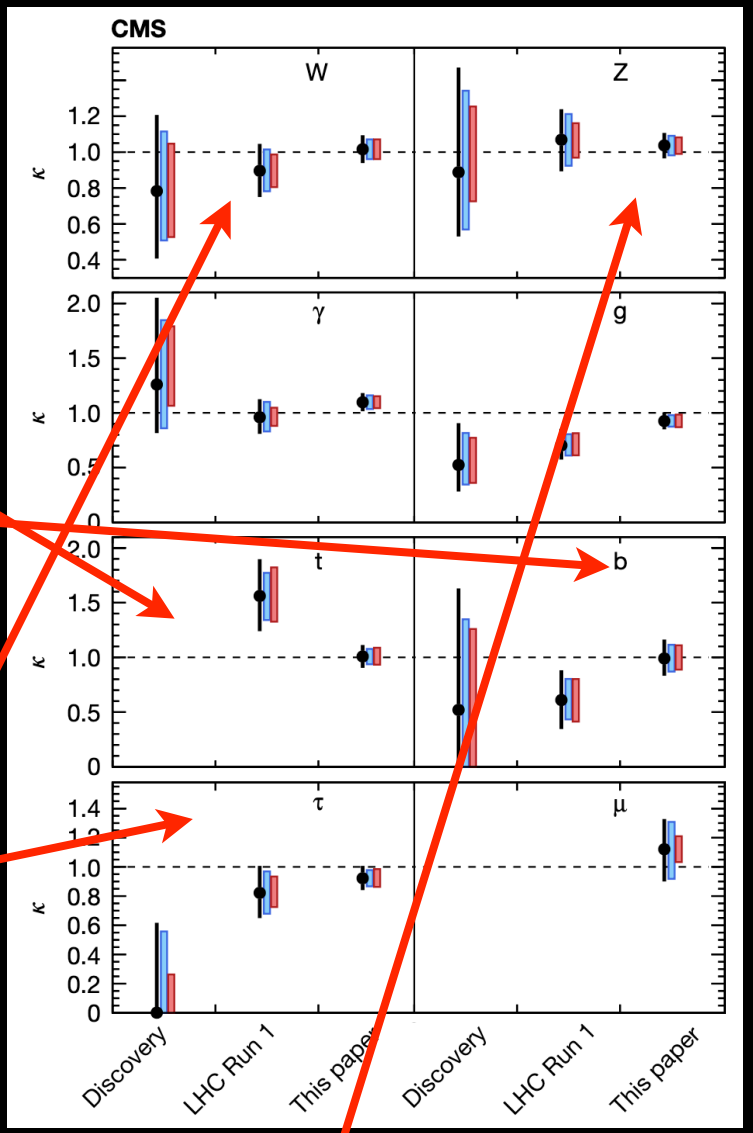
Higgs — Top quark
Higgs — Top quark
Higgs — b quark
Higgs — b quark
⋮
Higgs — τ lepton
Higgs — τ lepton



Higgs — W-Boson
Higgs — W-Boson
Higgs — Z-Boson
Higgs — Z-Boson

10 year anniversary of discovery of Higgs boson

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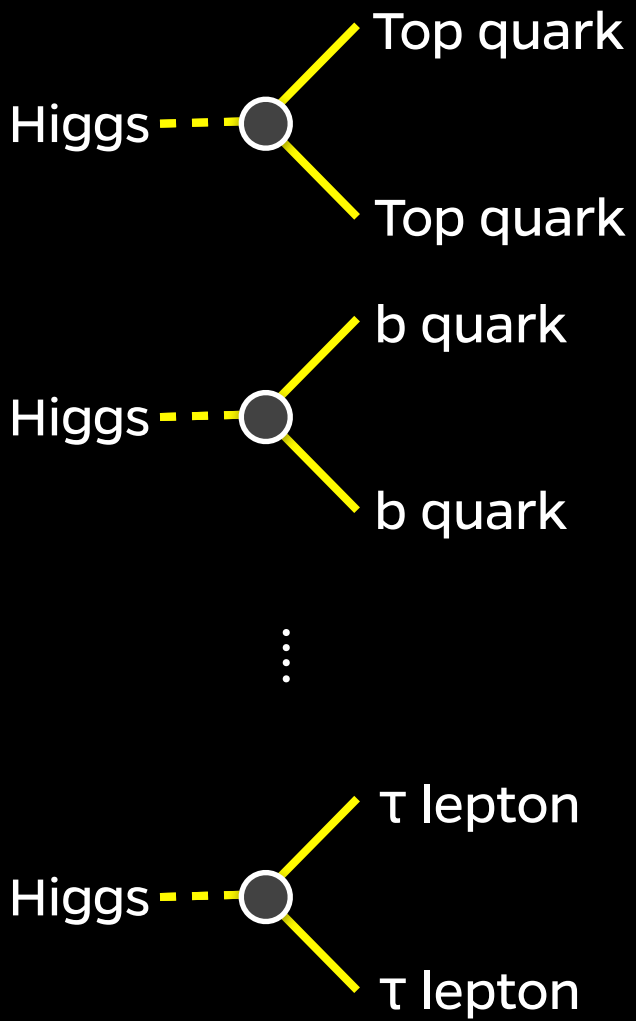

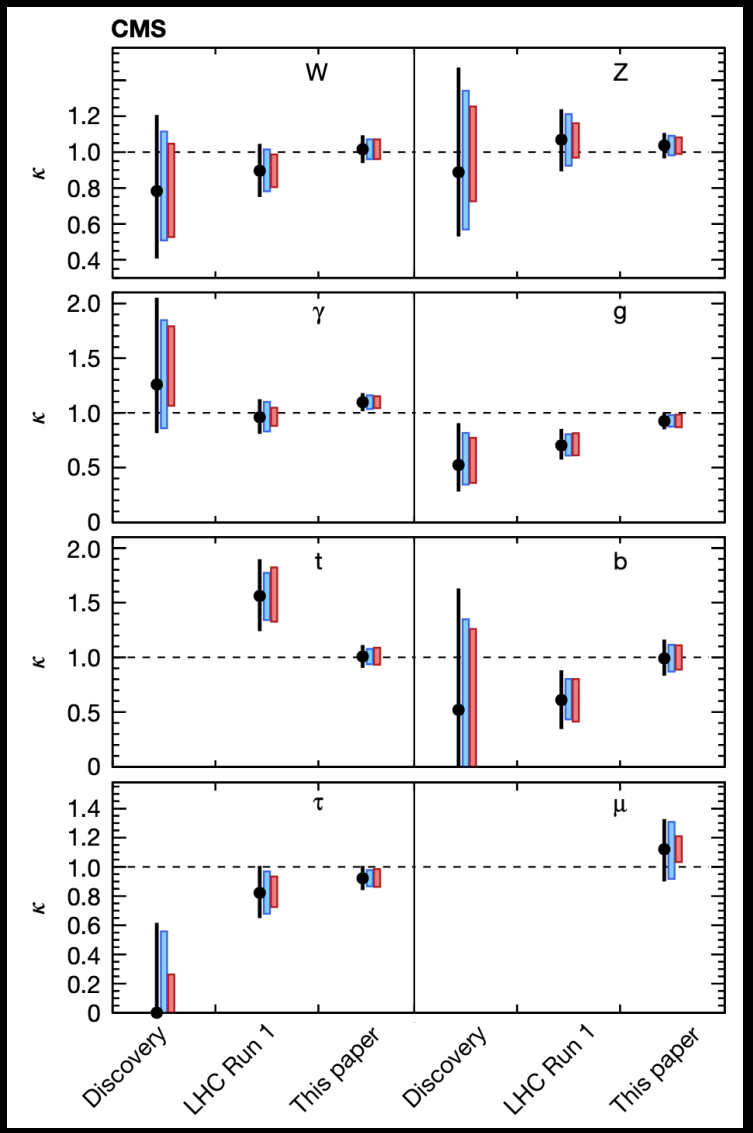

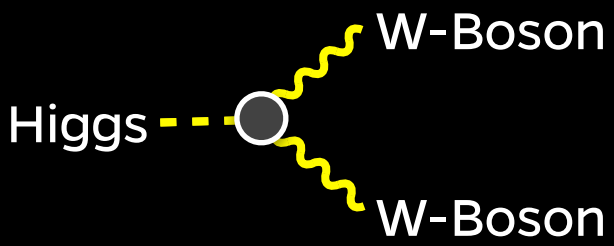

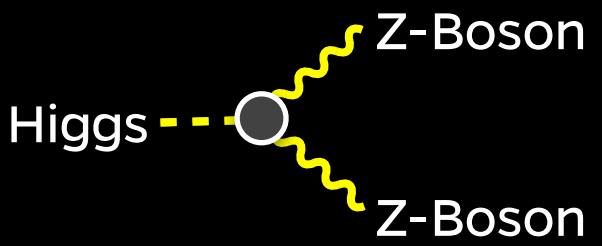

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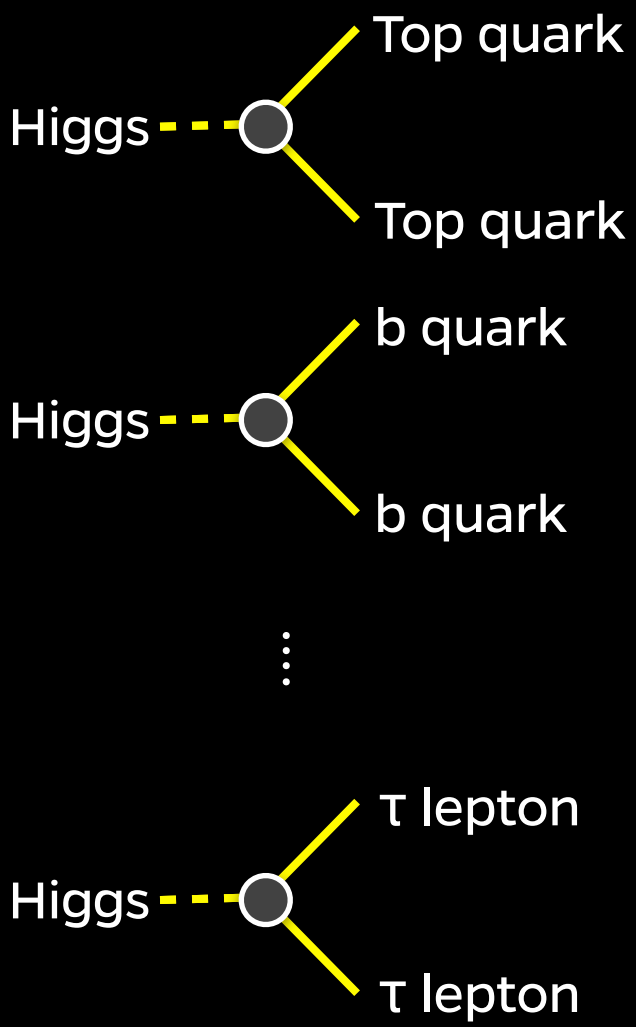

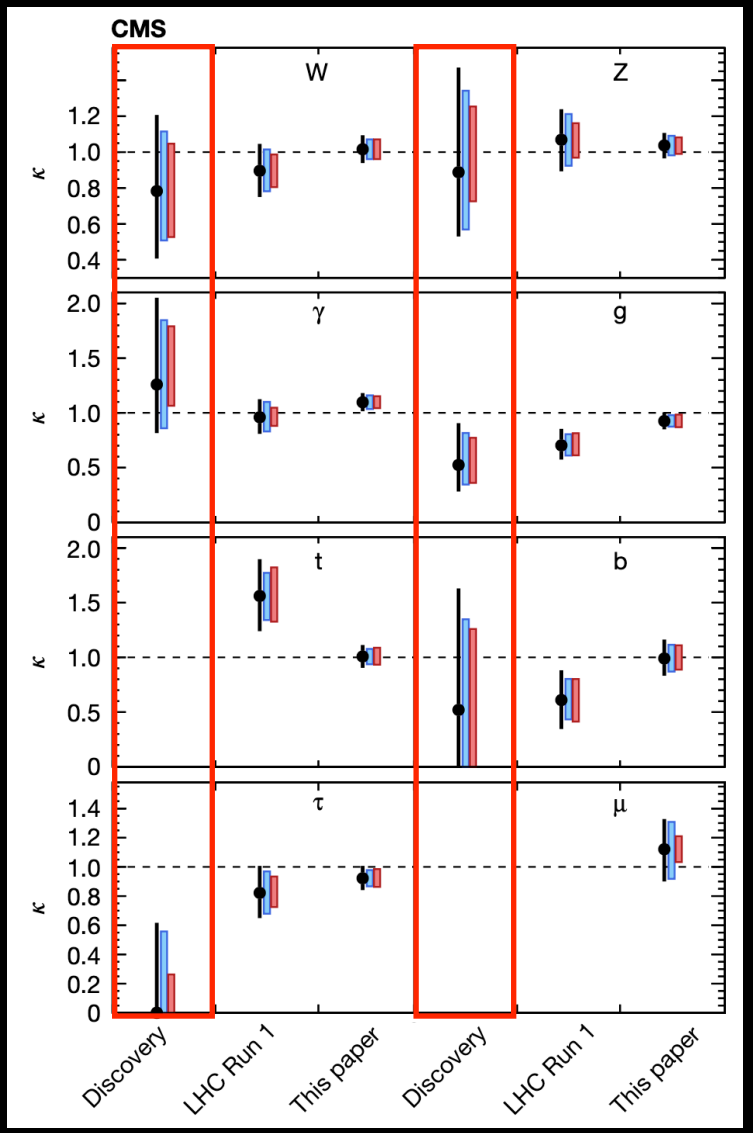

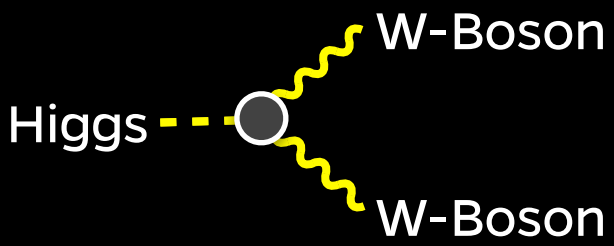

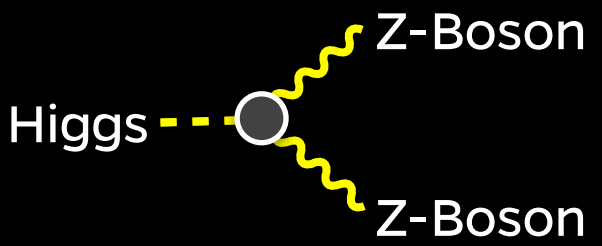

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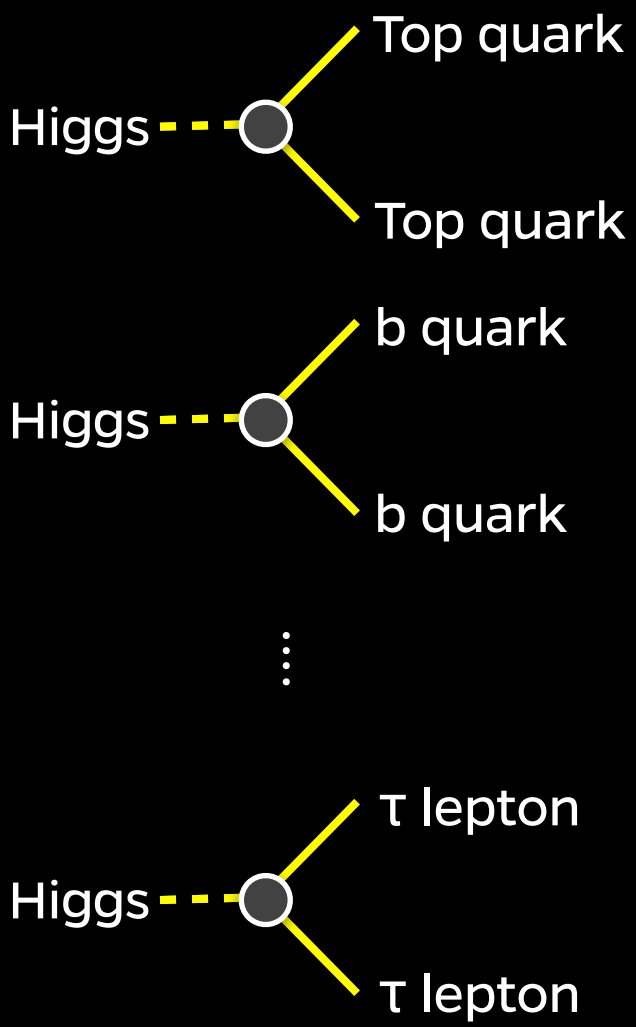

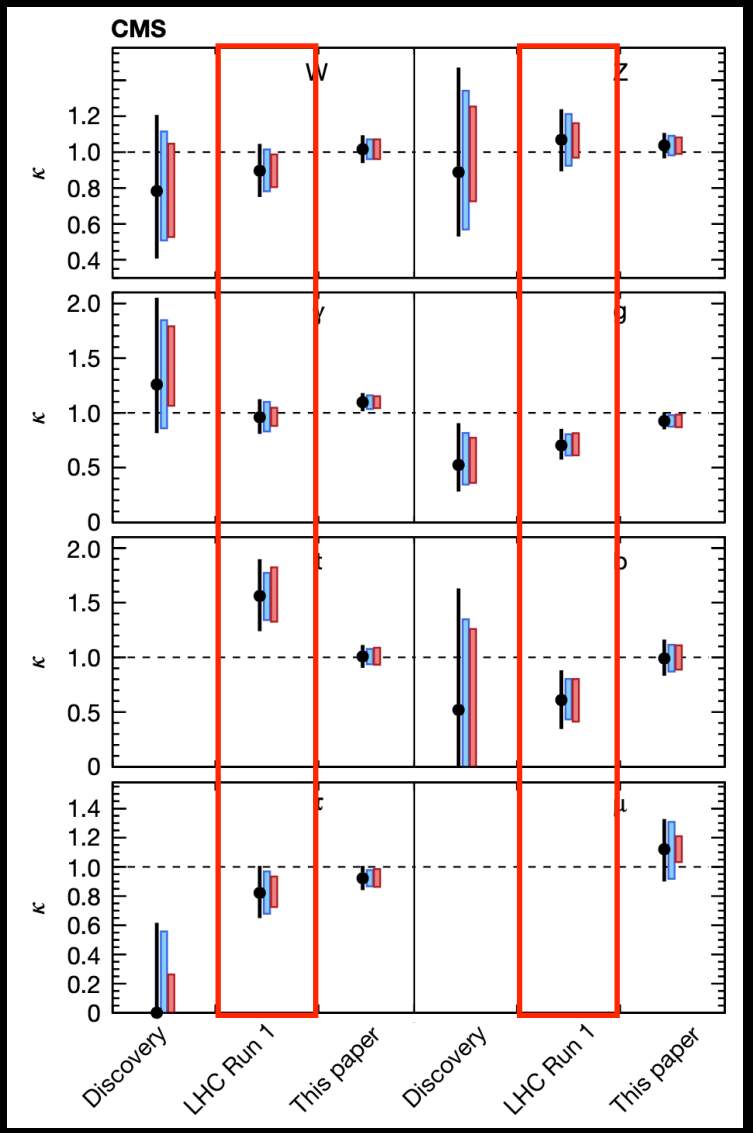

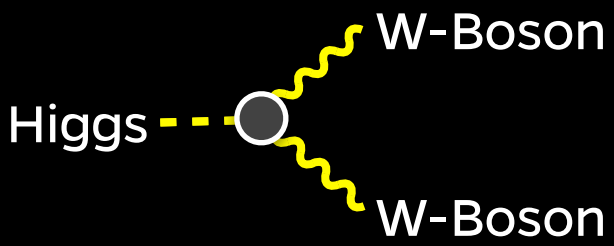

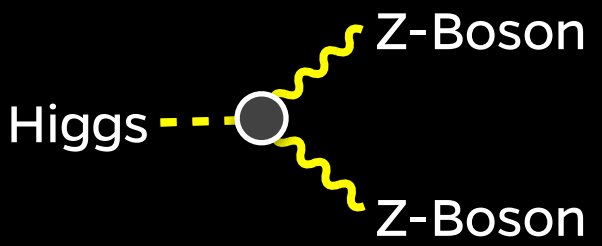

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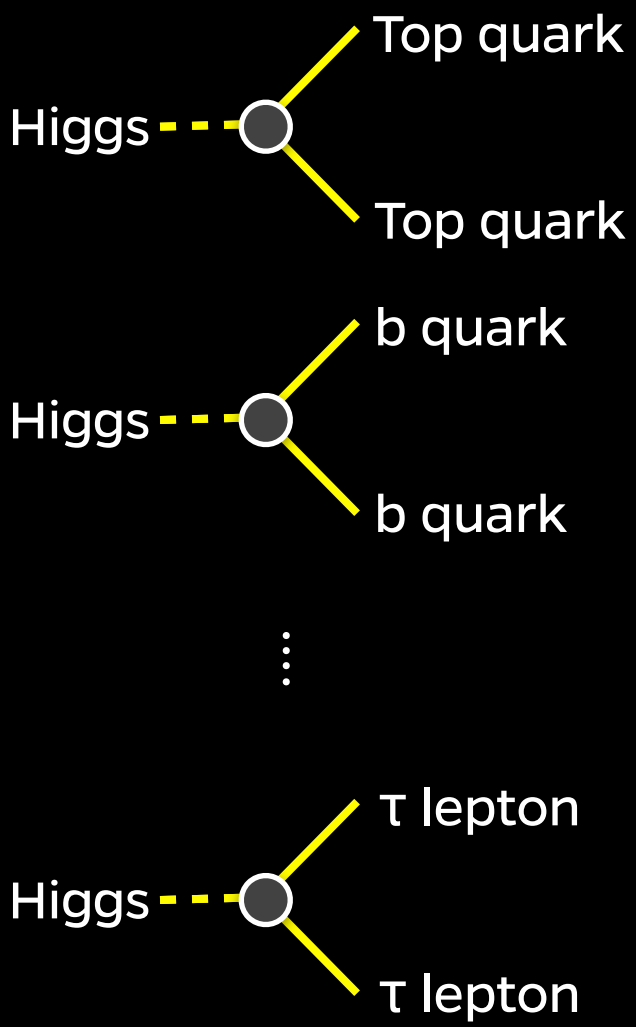

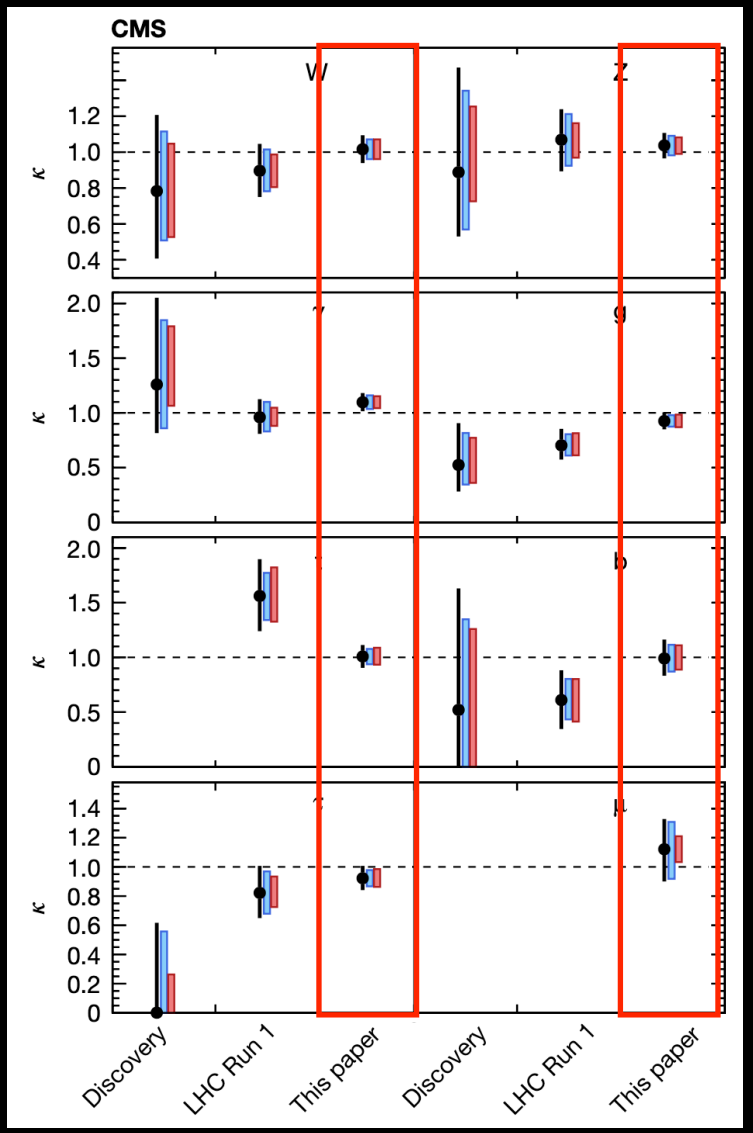

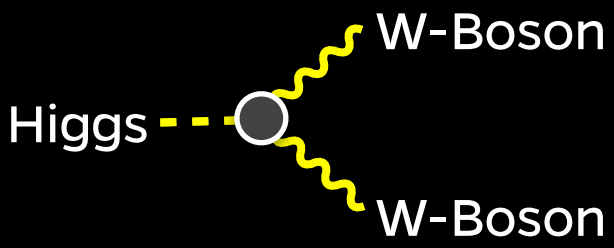

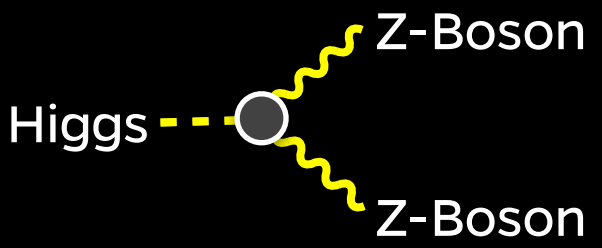

10 year anniversary of discovery of Higgs boson

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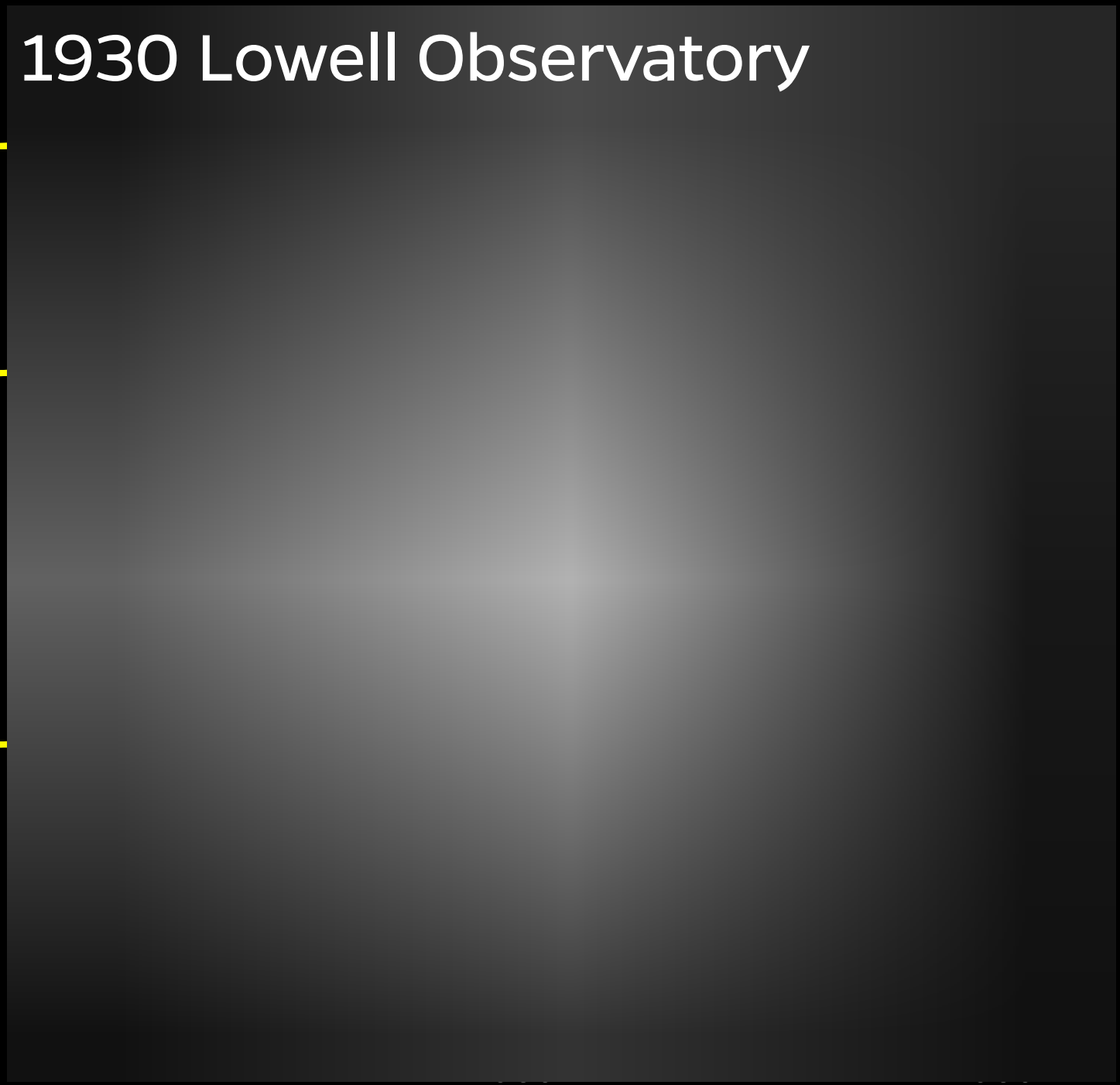

Higgs

Higgs

Higgs

10 year anniversary of discovery of Higgs boson

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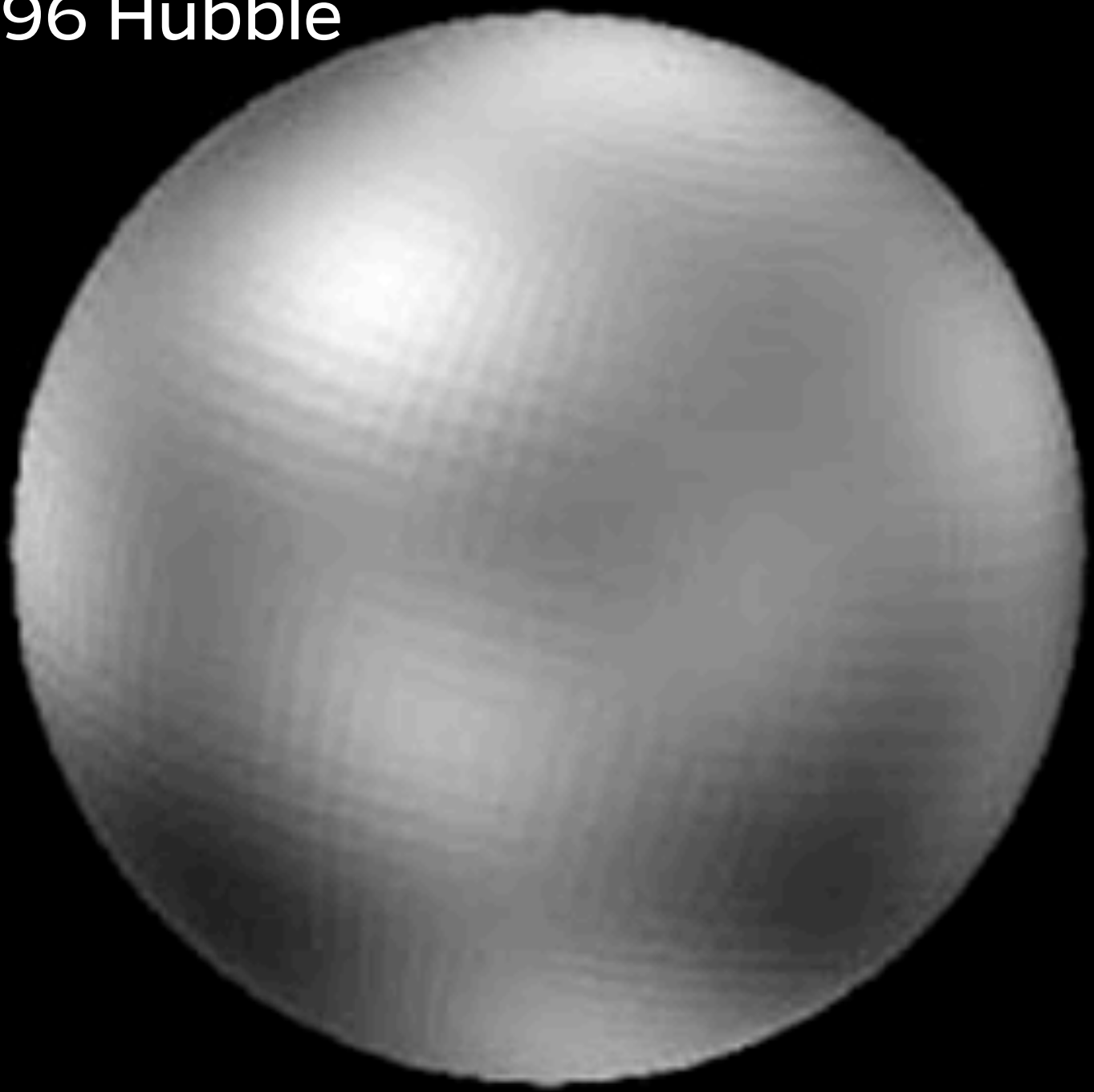
1996 Hubble

Higg

Higg

Higg



Mass of Higgs boson

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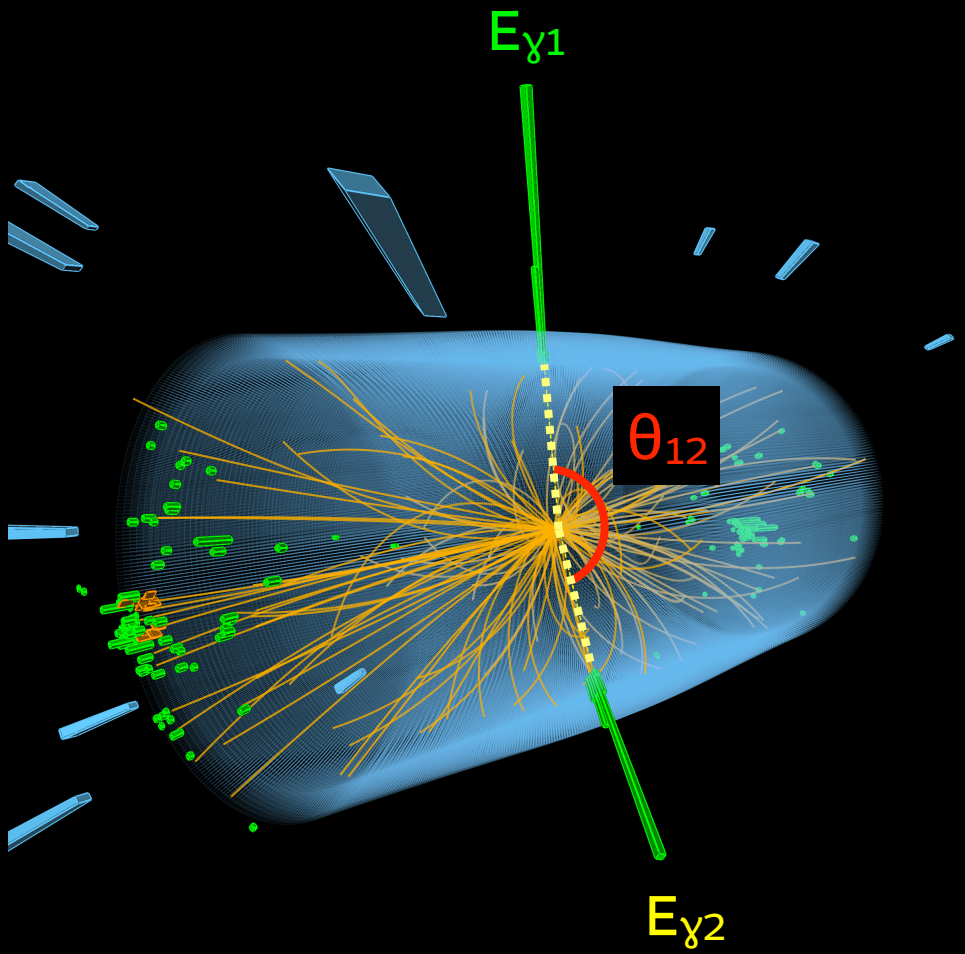

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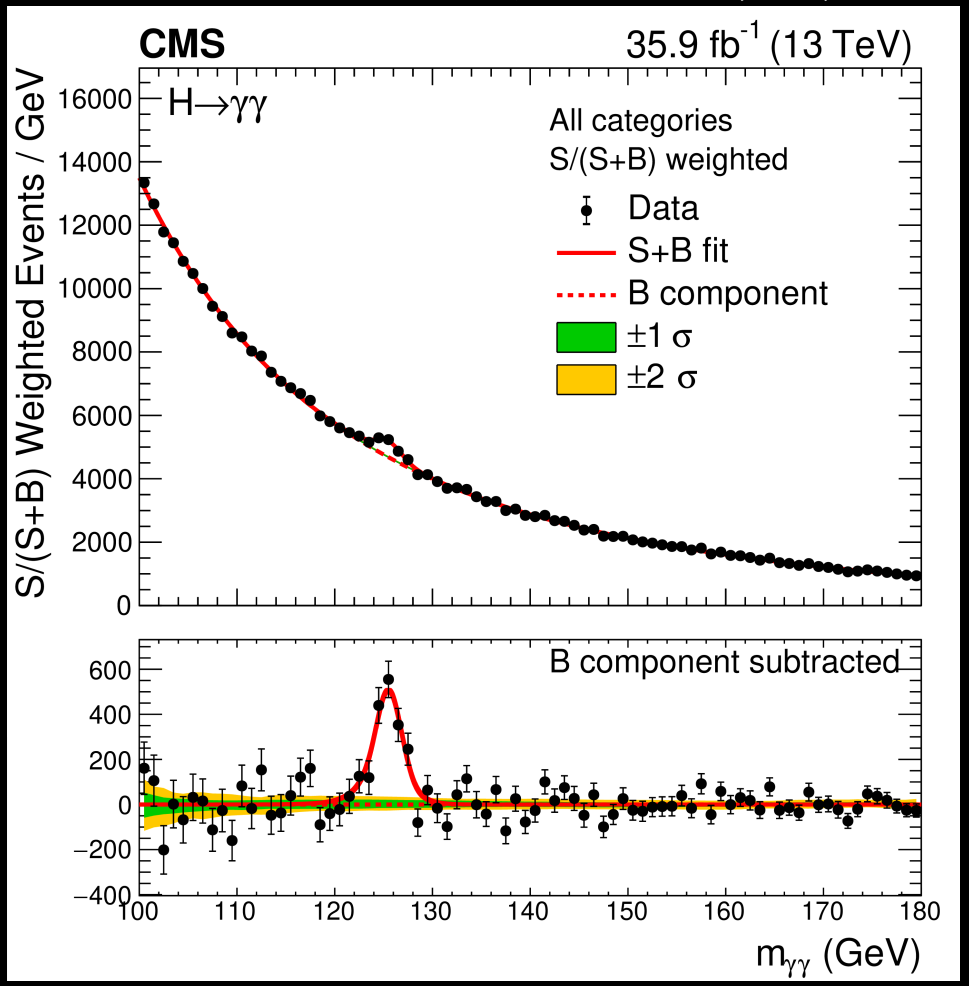

$m_{\gamma\gamma}^2 = 2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{12})$

Calibration Vertexing

M_H = 125.38 ± 0.14 (± 0.11 stat ± 0.08 syst) GeV

Per mille precision

Decay of Higgs boson

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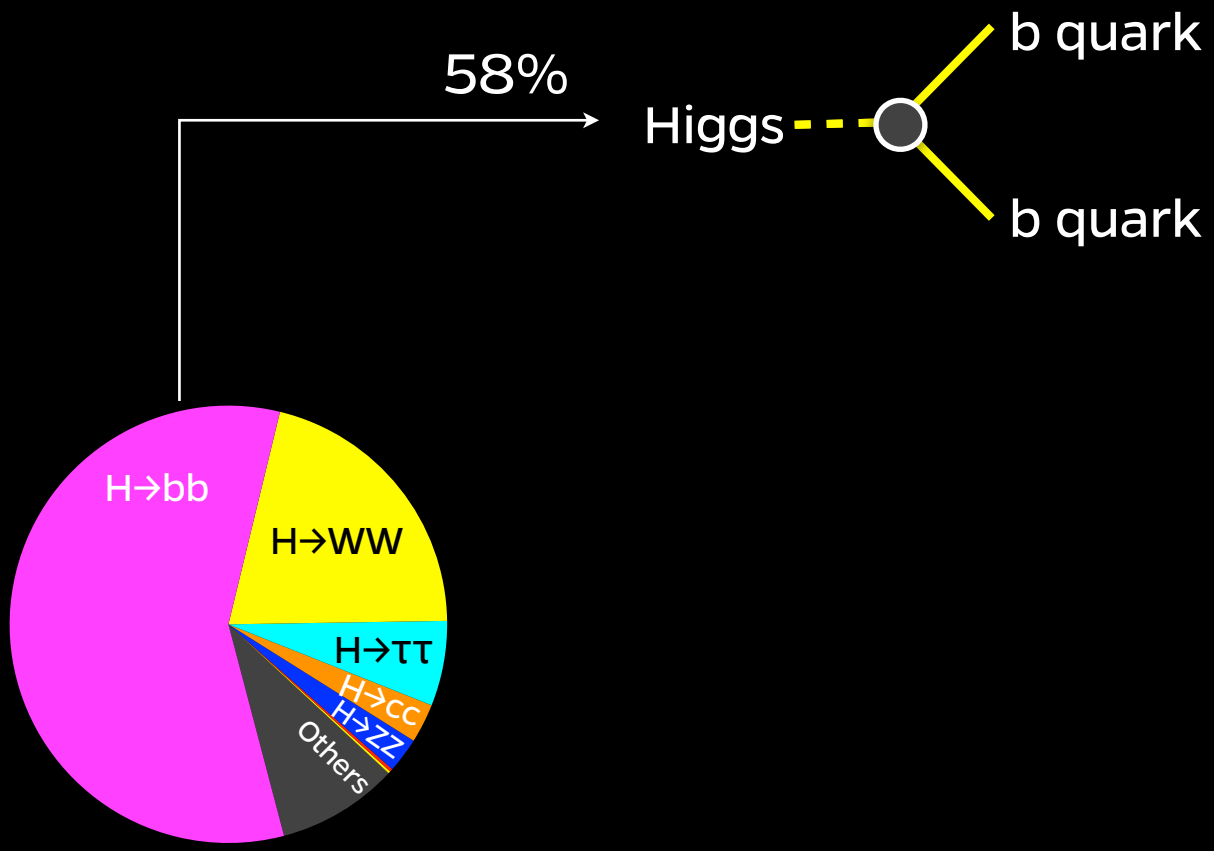

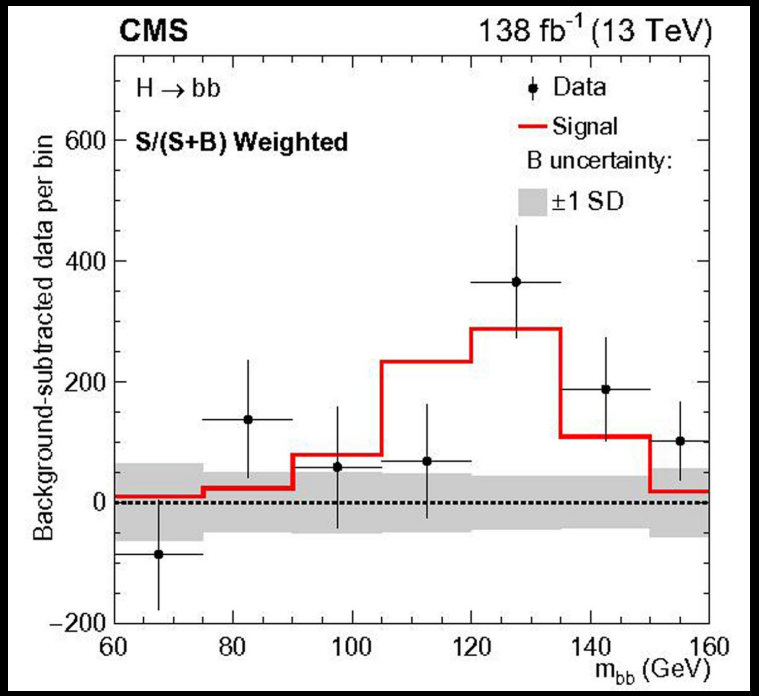

Decay of Higgs boson

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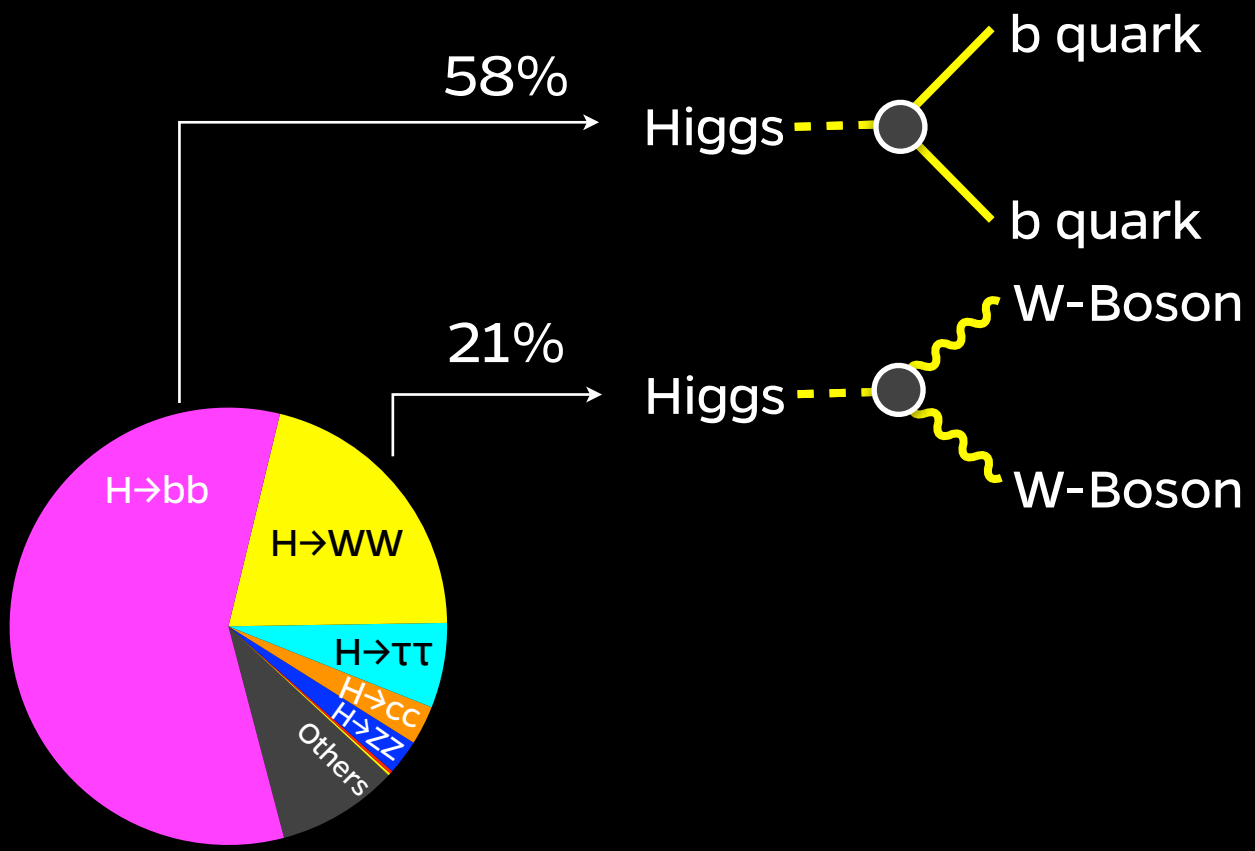
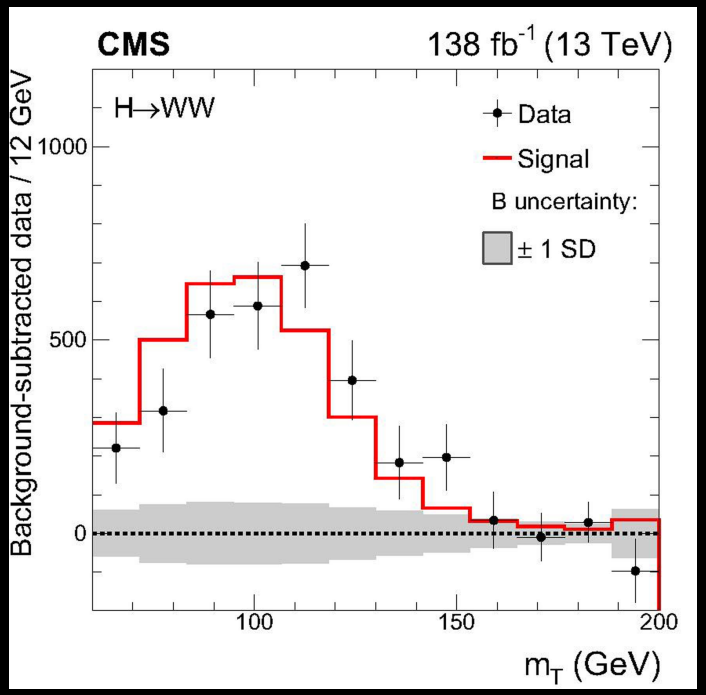
Nature 607 (2022) 60





Decay of Higgs boson

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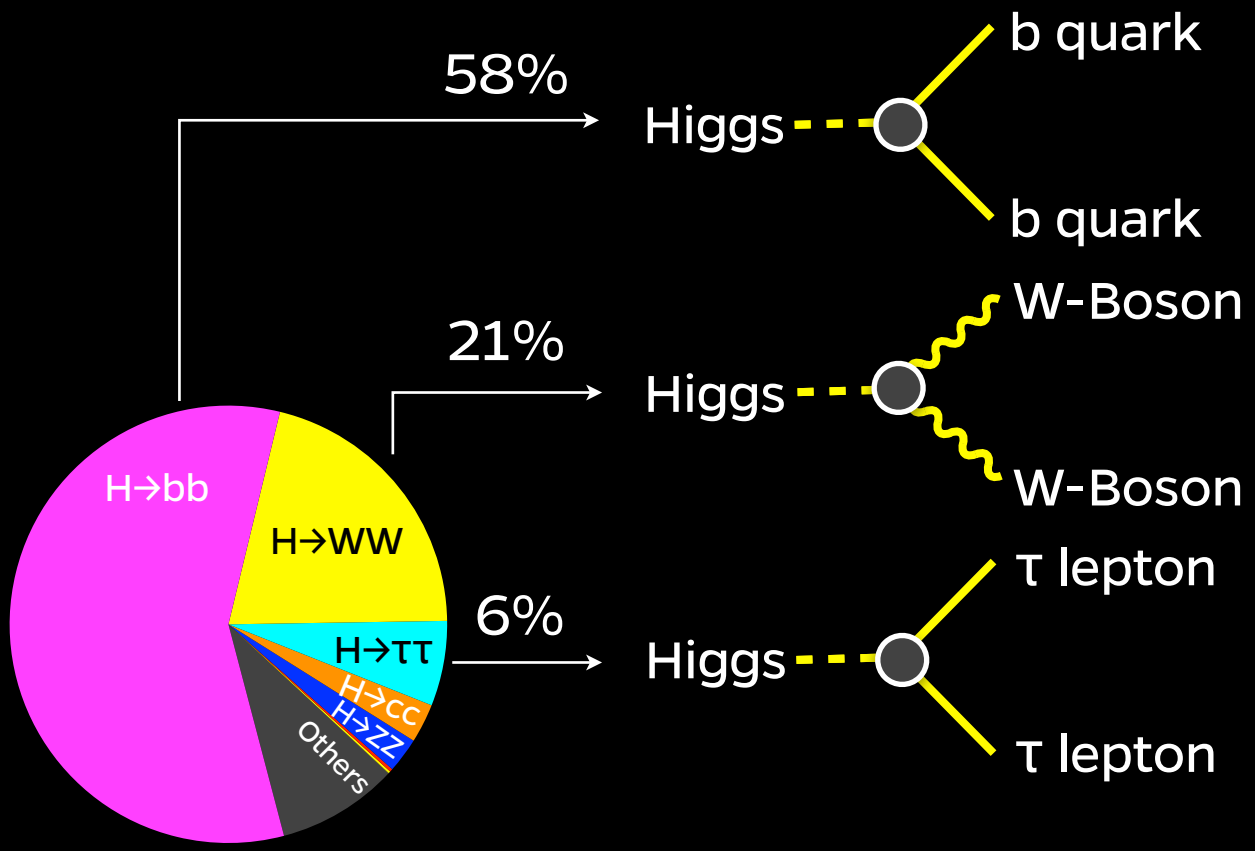
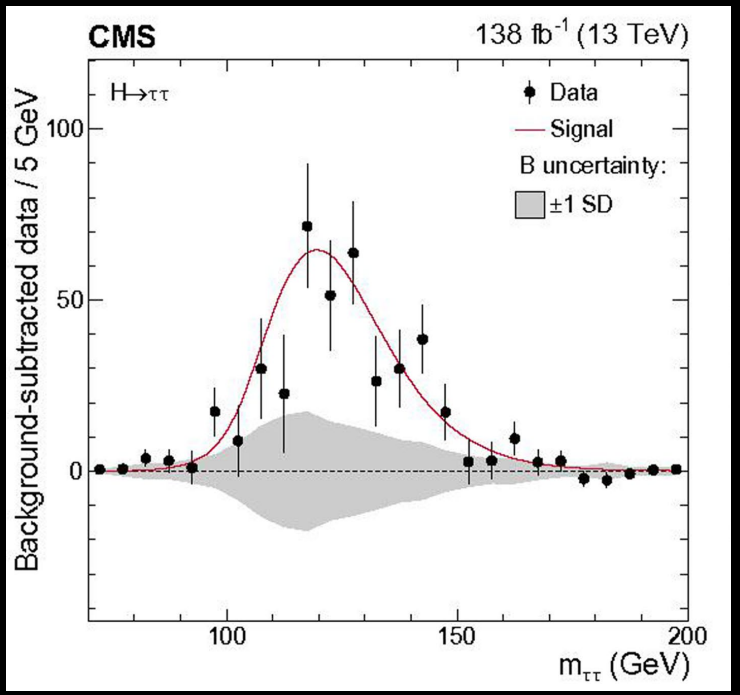
Nature 607 (2022) 60





Decay of Higgs boson

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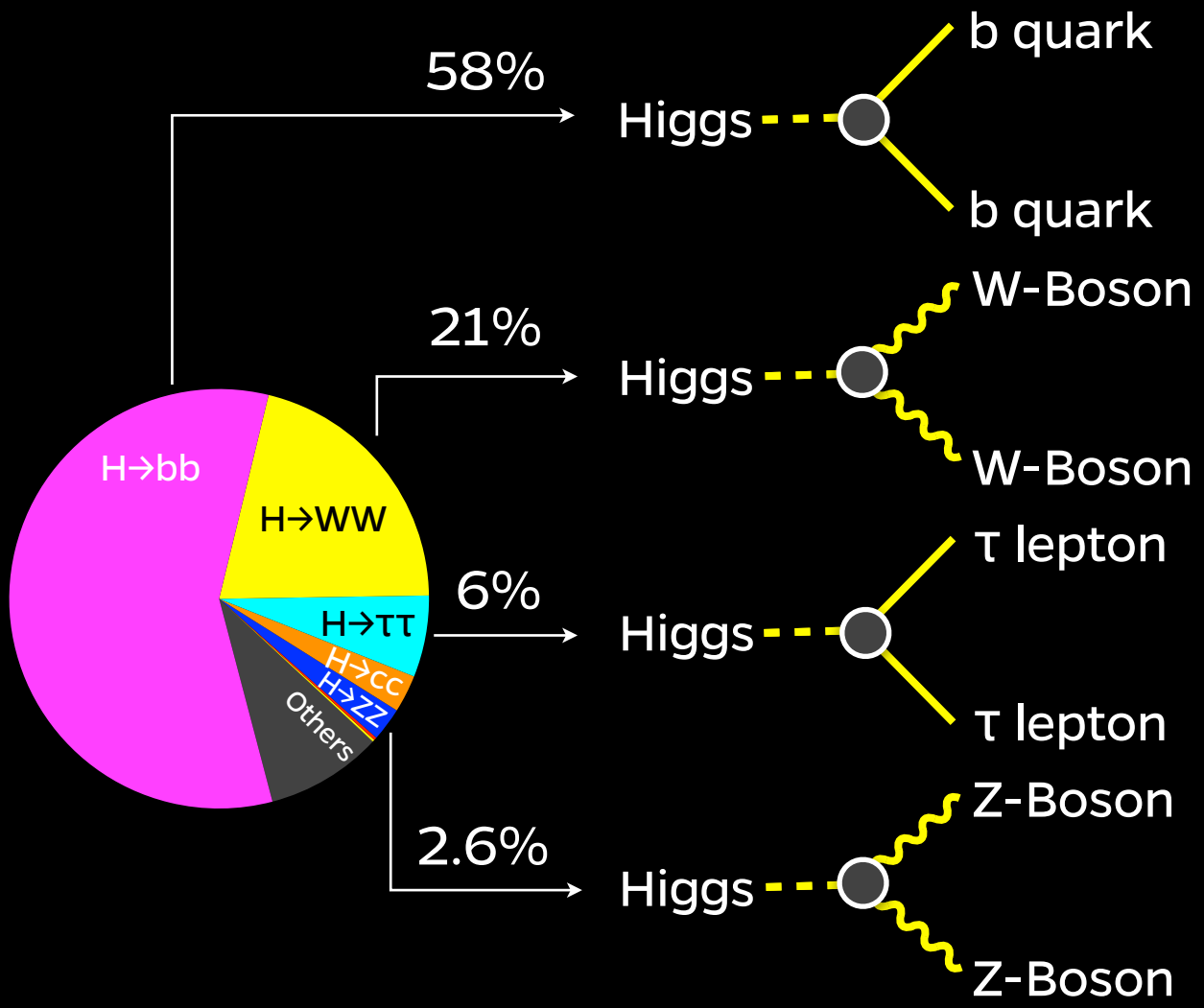

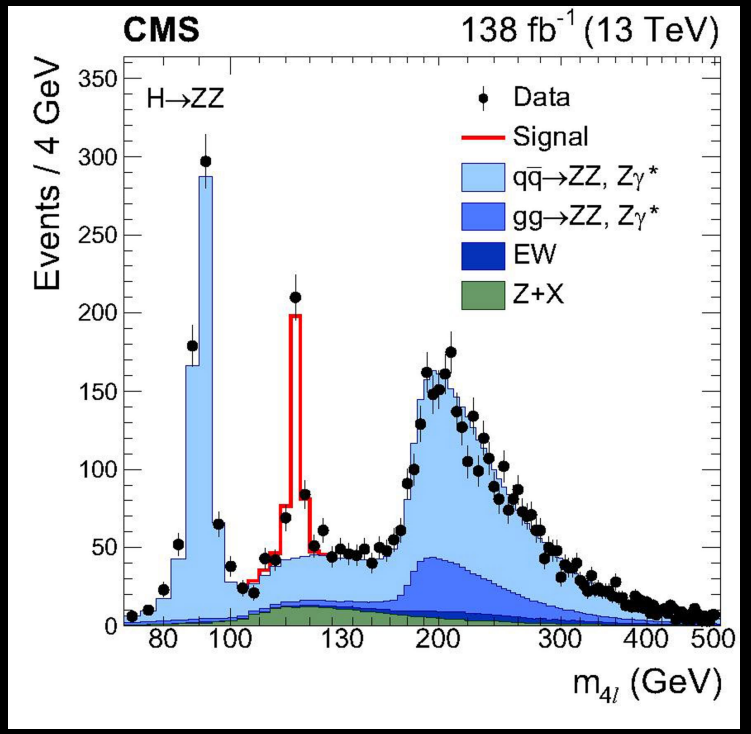

Decay of Higgs boson

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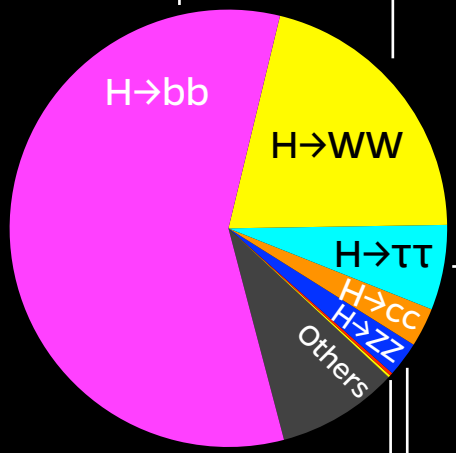


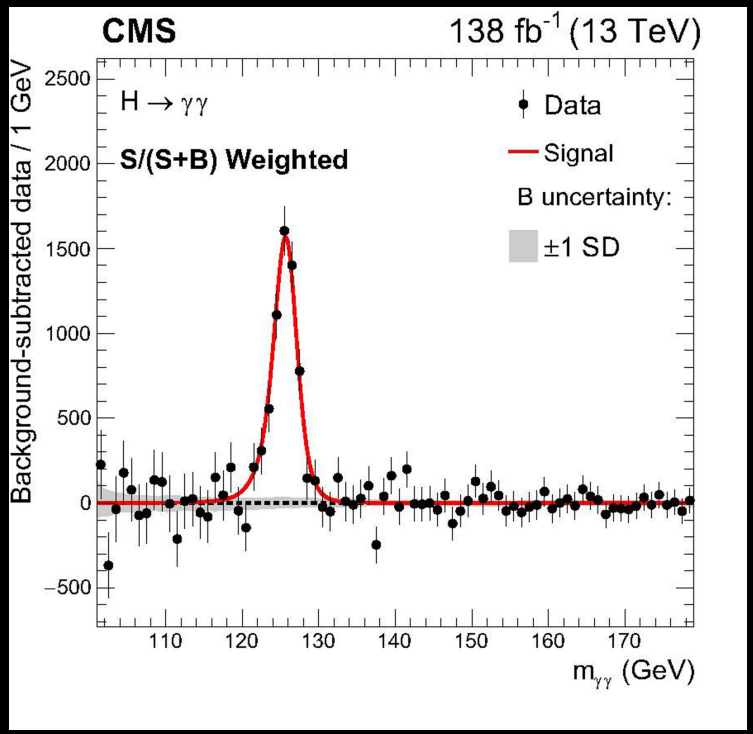
58% → Higgs → b quark, b quark

21% → Higgs → W-Boson, W-Boson

6% → Higgs → τ lepton, τ lepton

2.6% → Higgs → Z-Boson, Z-Boson

0.23% → Higgs → Photon, Photon



Decay of Higgs boson

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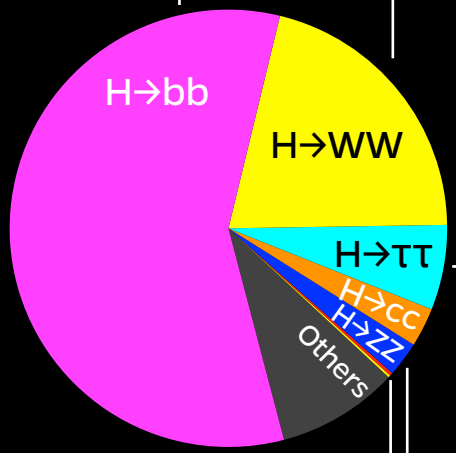

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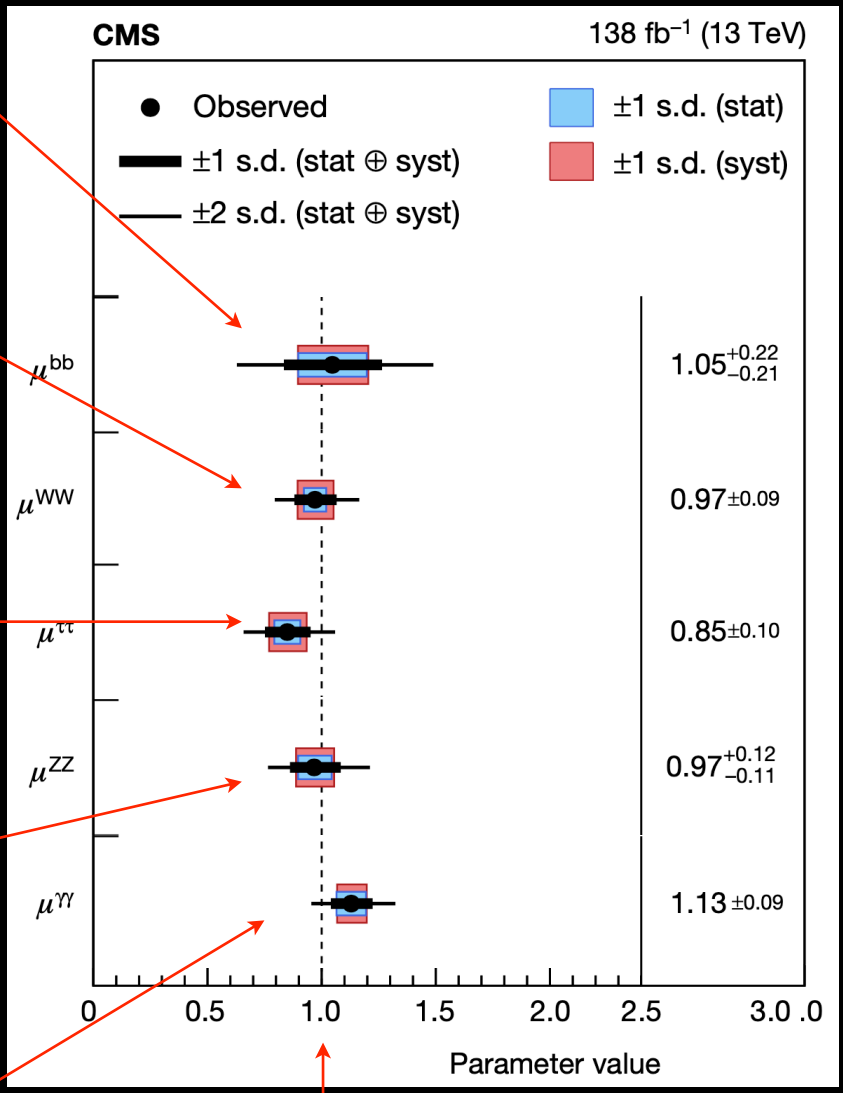

SM expectation

Decay of Higgs boson

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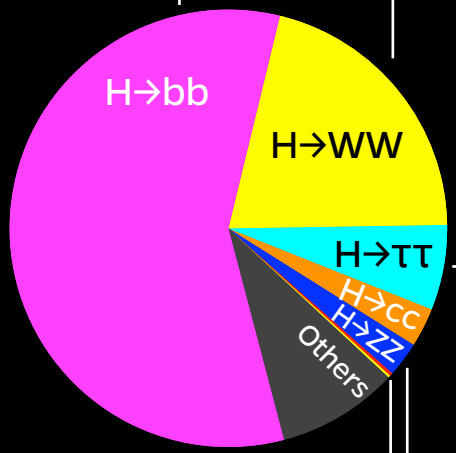

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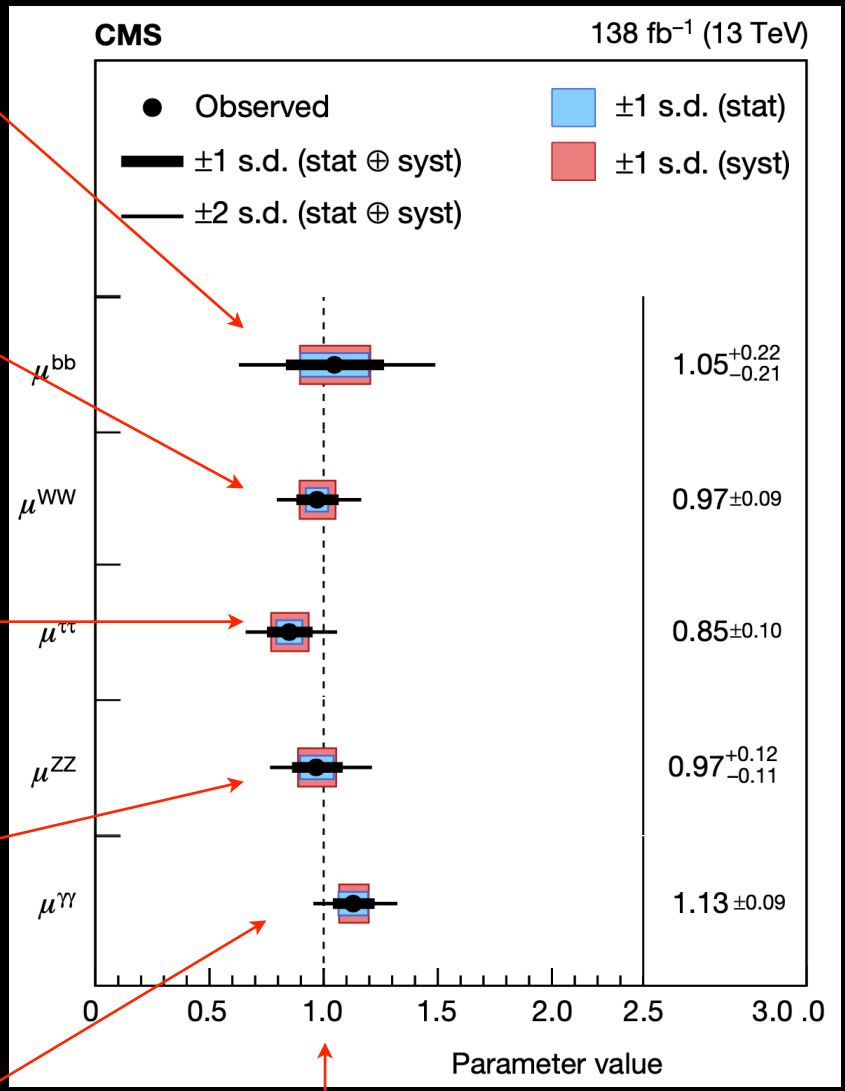

SM expectation

Decay of Higgs boson

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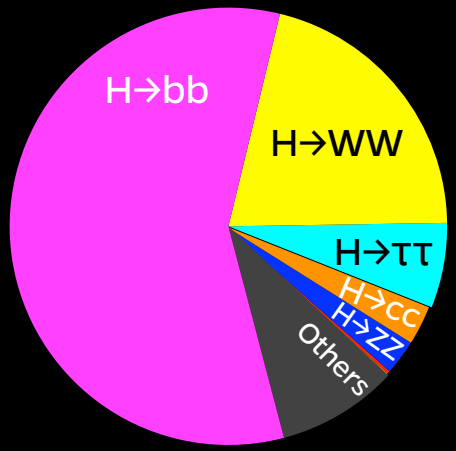

Decay of Higgs boson

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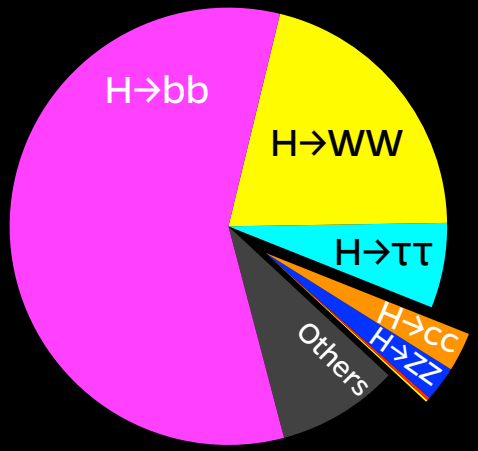

Decay of Higgs boson

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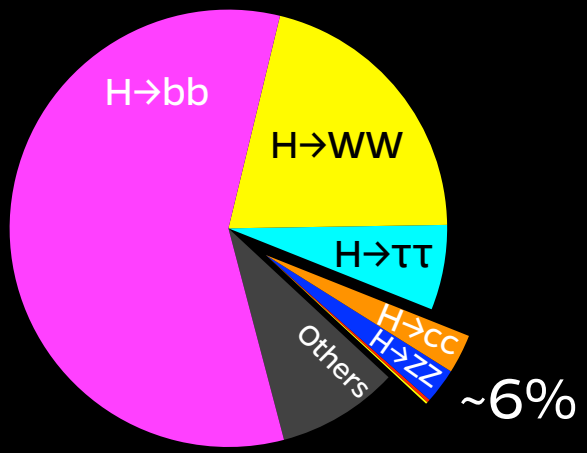

Pushing the frontier

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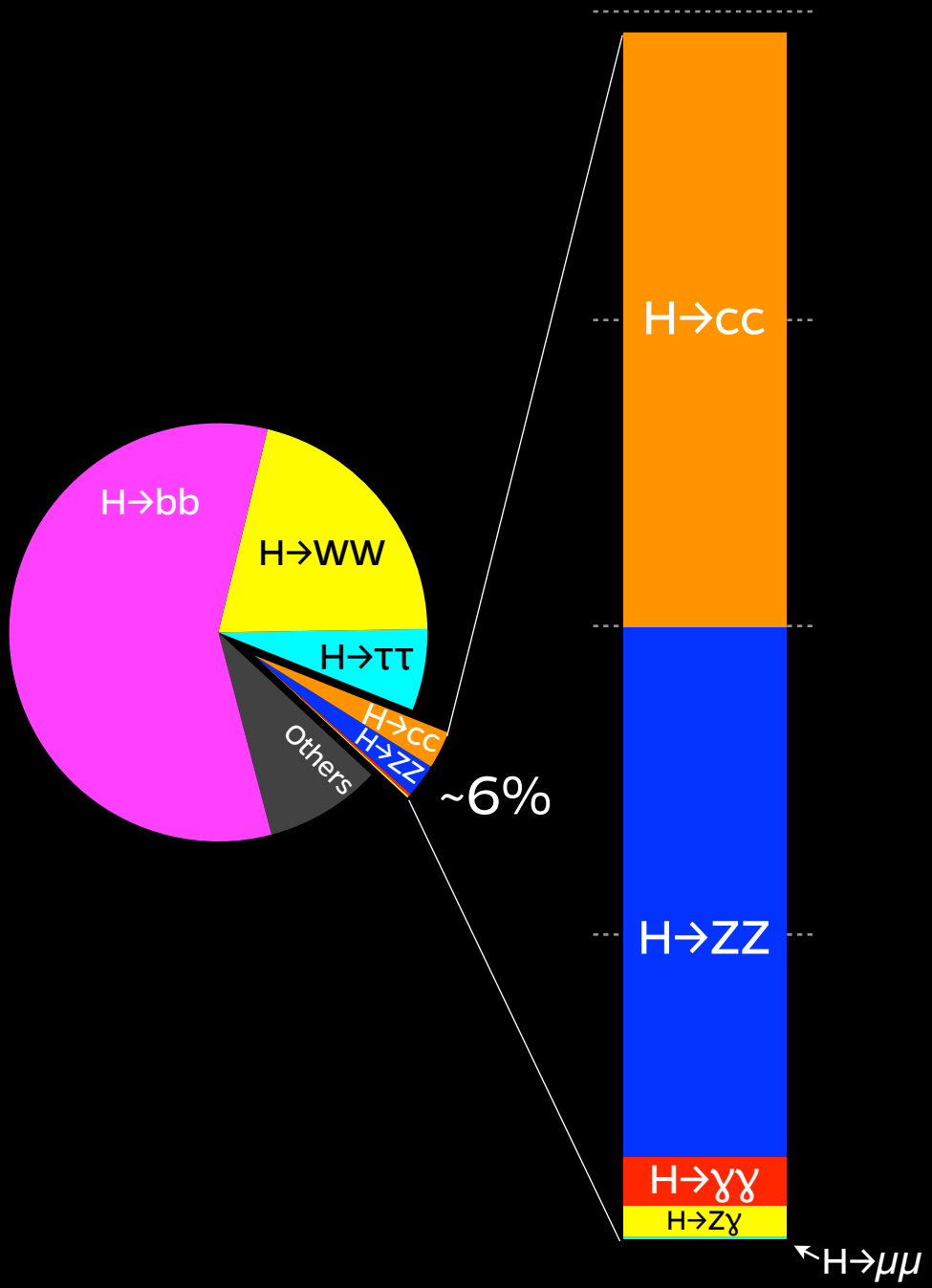

Pushing the frontier

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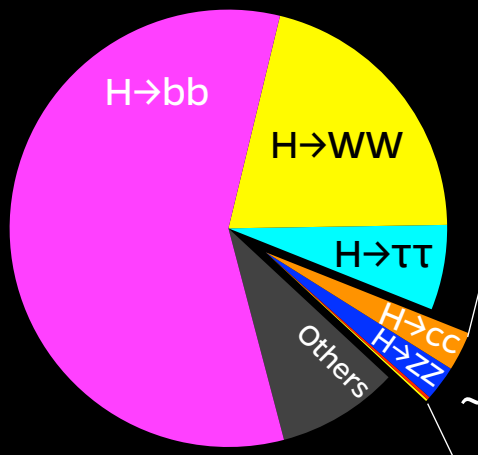
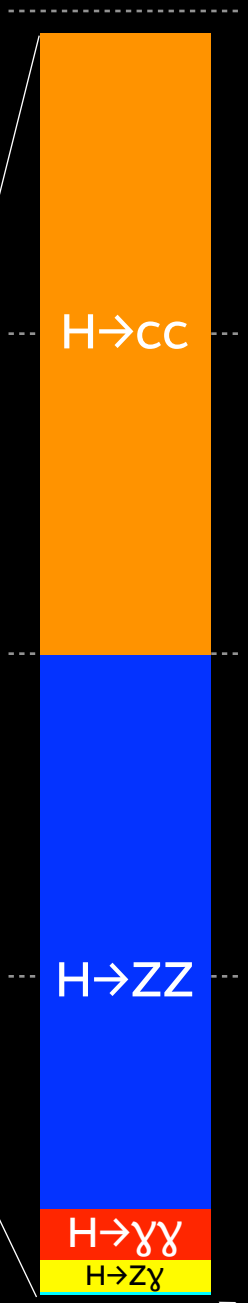
Chang
Florida

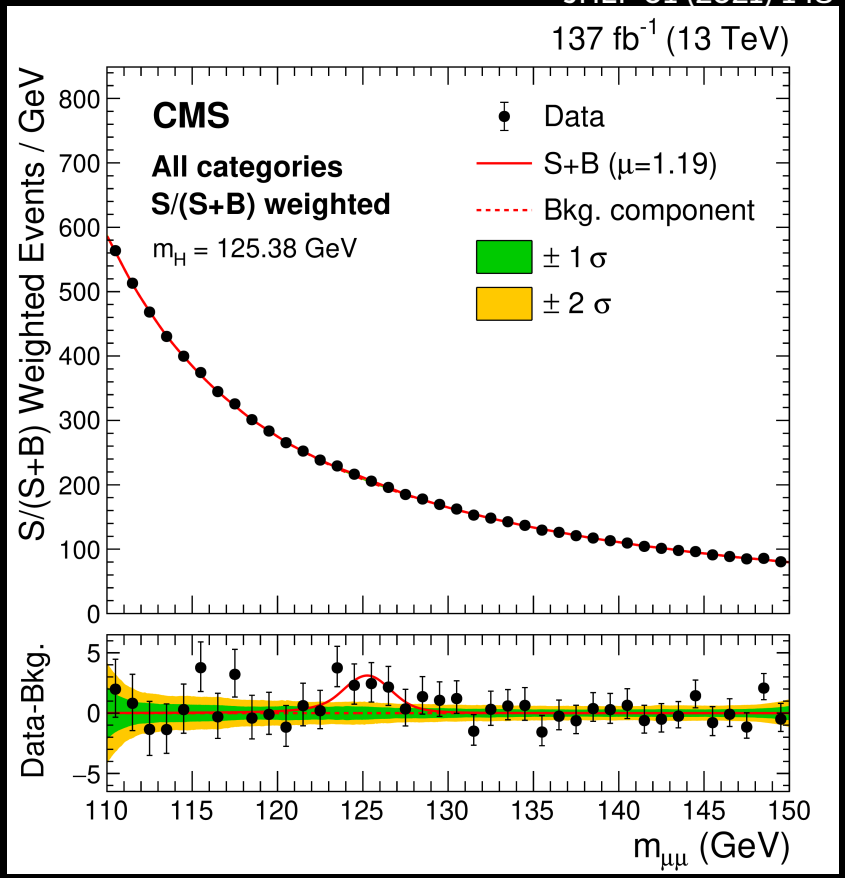


~6%

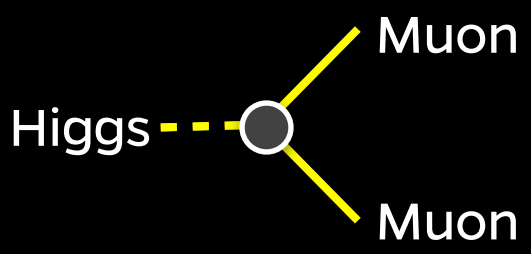


3 σ evidence

JHEP 01 (2021) 148



H→μμ 0.022%



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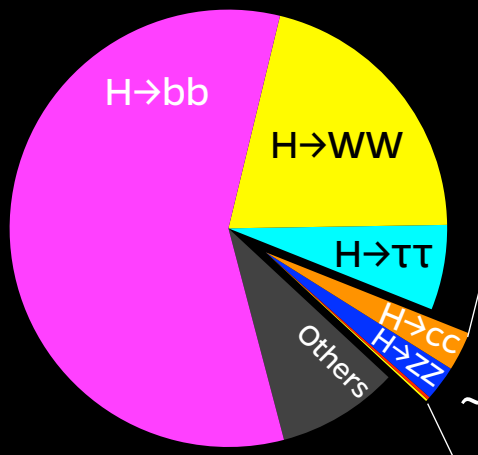
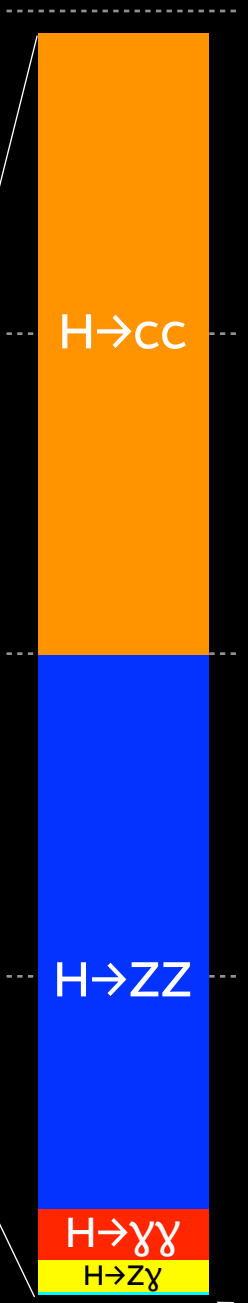


~6%



H→μμ

0.022%

3 σ evidence

With 4x data
⇒ 5σ

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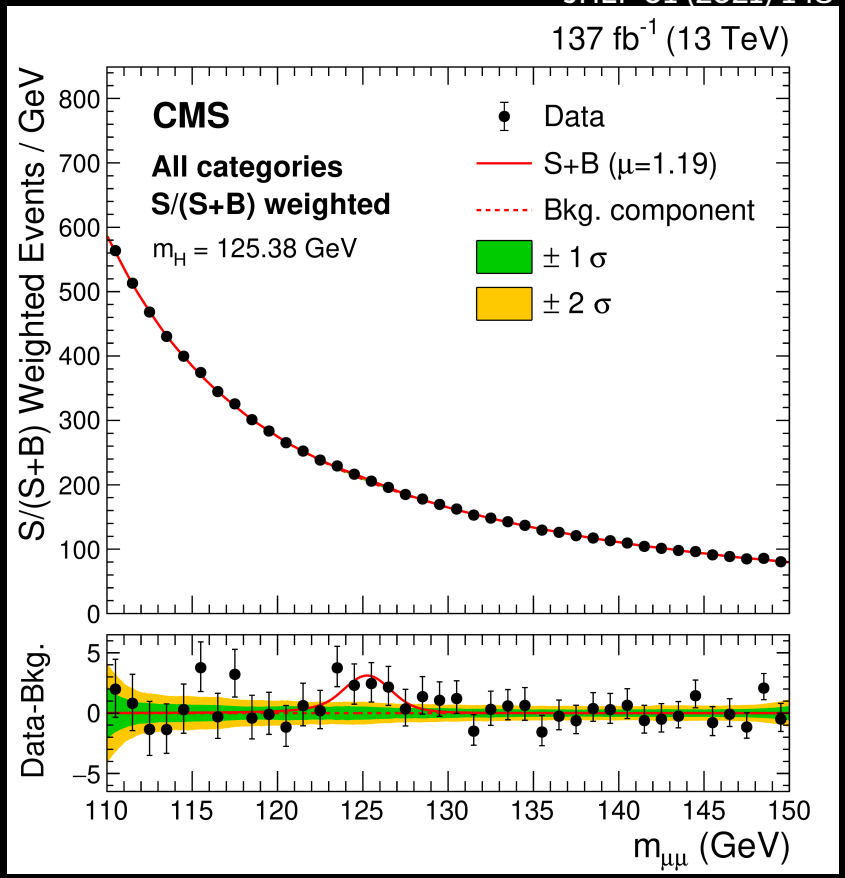

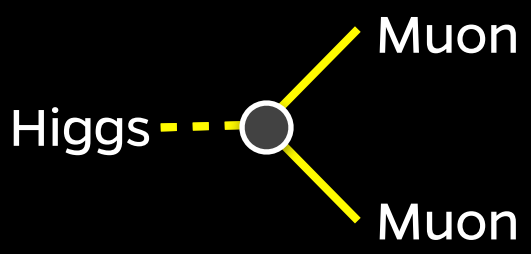

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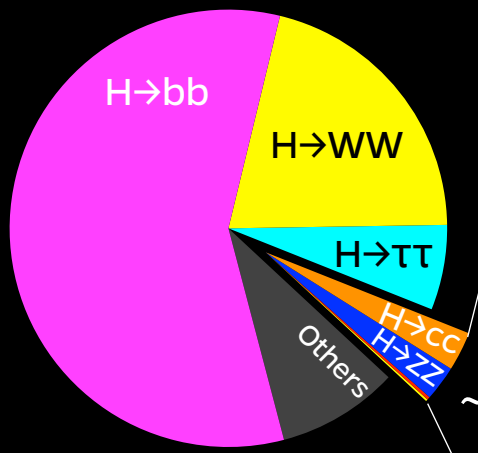
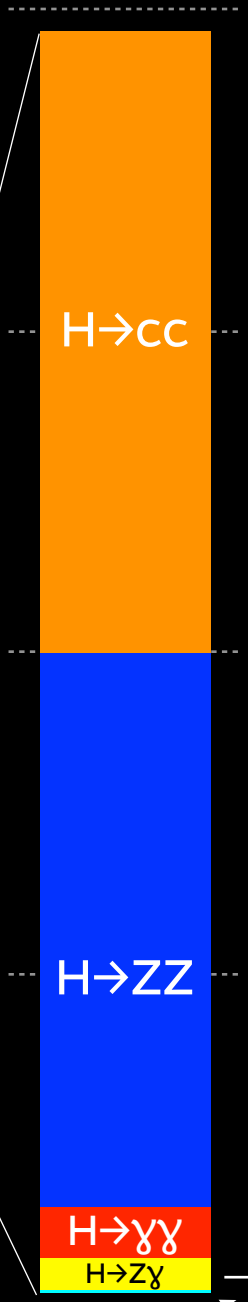
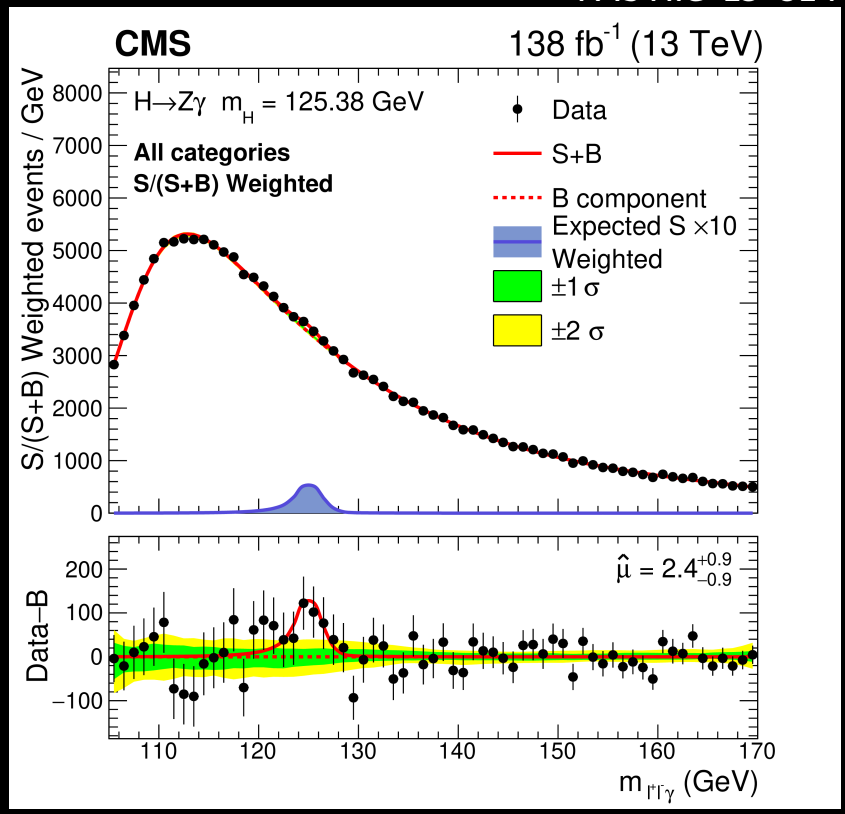


~6%



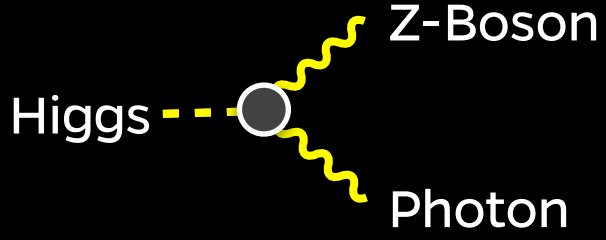
2.7 σ_{obs}
(1.2σ_{exp})

PAS HIG-19-014



0.15%

H→$\mu\mu$



Pushing the frontier

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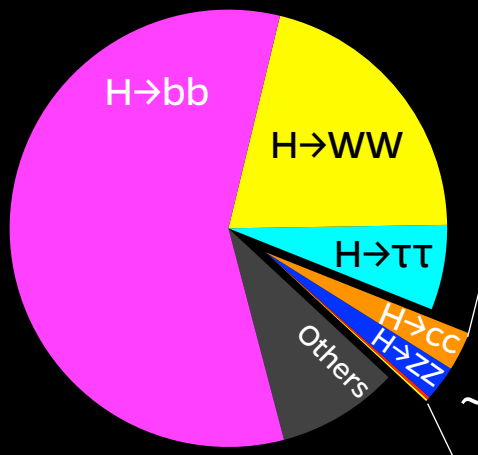


~6%

H→cc

H→ZZ

H→γγ

H→Zγ

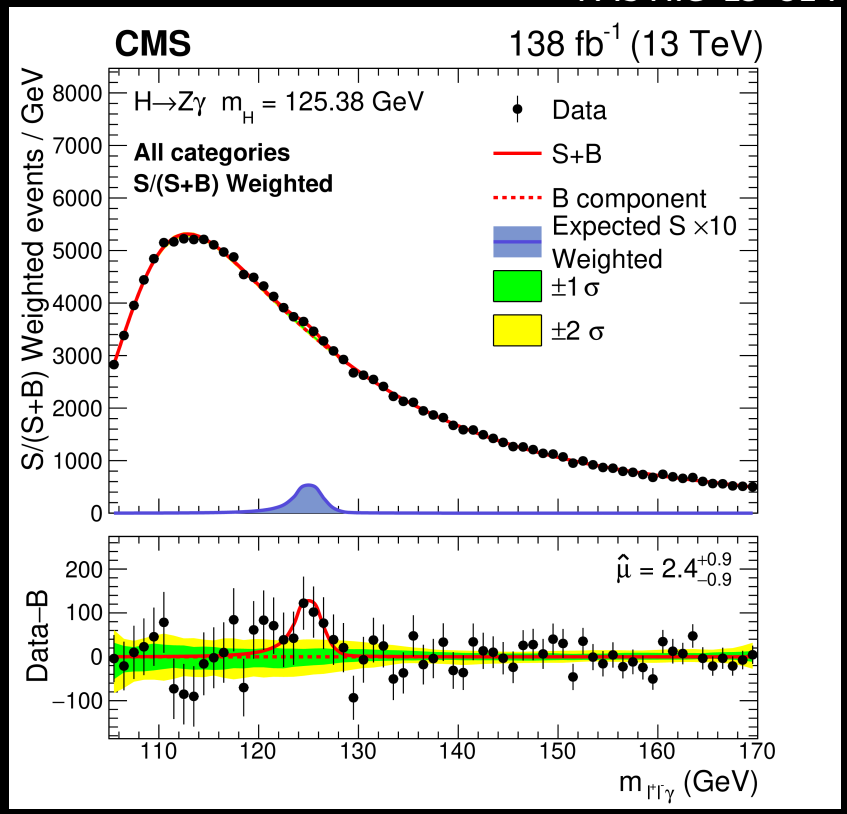
H→μμ

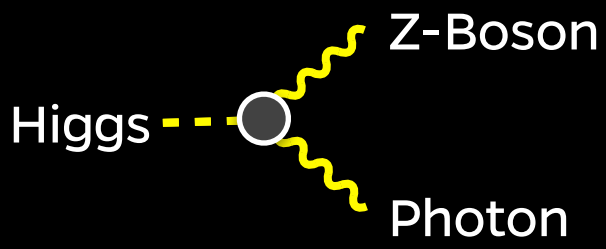
2.7 σ_{obs}
(1.2σ_{exp})

With 20x data
⇒ 5σ

0.15%

PAS HIG-19-014





Pushing the frontier

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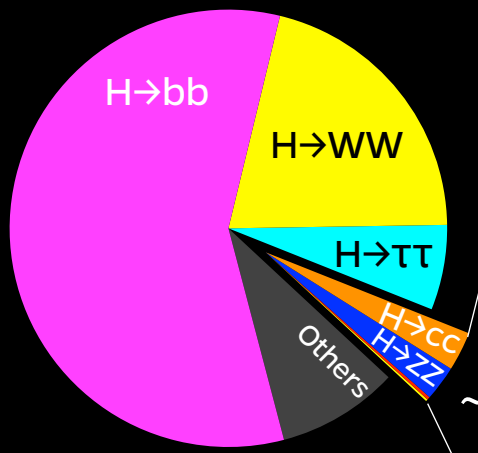
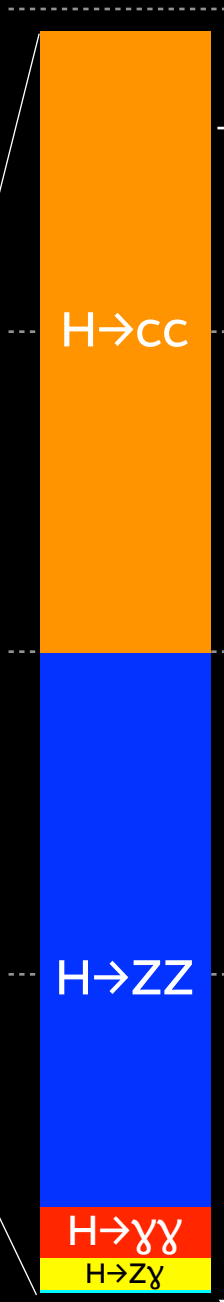


~6%

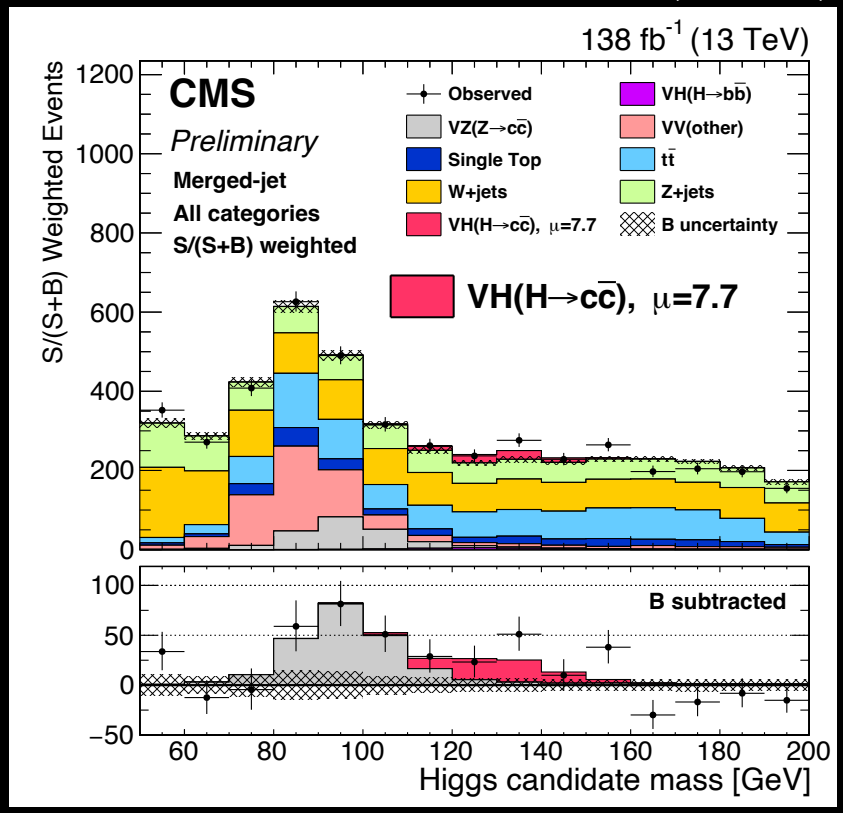


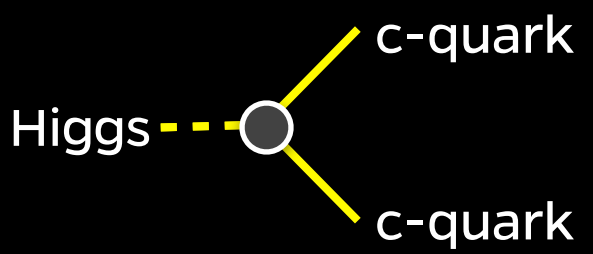
H→μμ

2.9%

Upper limit
14x SM
expectation

CMS: PAS HIG-21-008 (Feb 2022)





Width of Higgs boson

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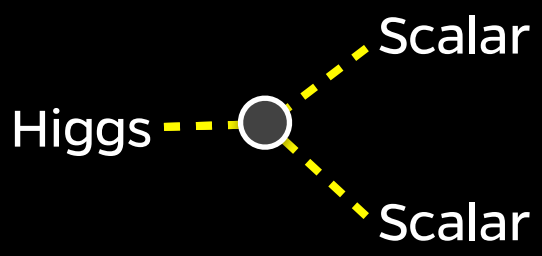
In SM, width of Higgs boson is small = 4.1 MeV



Even if a small coupling to the Higgs can change the width drastically

$\Rightarrow$ It is important to check the width and
possibility of any additional branching ratio

Width of Higgs boson

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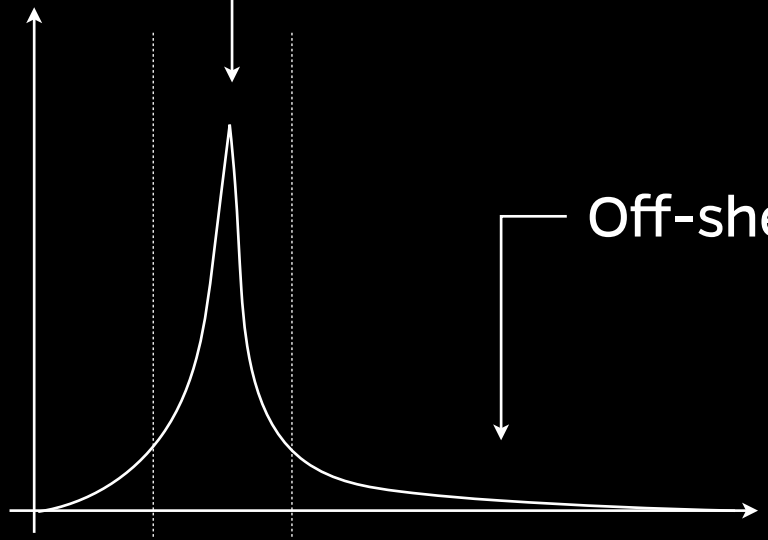
$$\text{Rate} \sim \frac{(\text{couplings})^2}{(p^2 - m_H^2) + m_H^2 \Gamma_H^2}$$

$$\text{On-shell Rate} \sim \frac{(\text{couplings})^2}{\cancel{(p^2 - m_H^2)} + m_H^2 \Gamma_H^2} \propto \frac{(\text{couplings})^2}{\Gamma_H^2}$$

$$\text{Off-shell Rate} \sim \frac{(\text{couplings})^2}{\cancel{(p^2 - m_H^2)} + \cancel{m_H^2 \Gamma_H^2}} \propto (\text{couplings})^2$$



$$\frac{\text{Off-shell rate}}{\text{On-shell rate}} \sim \Gamma_H^2$$

Width of Higgs boson

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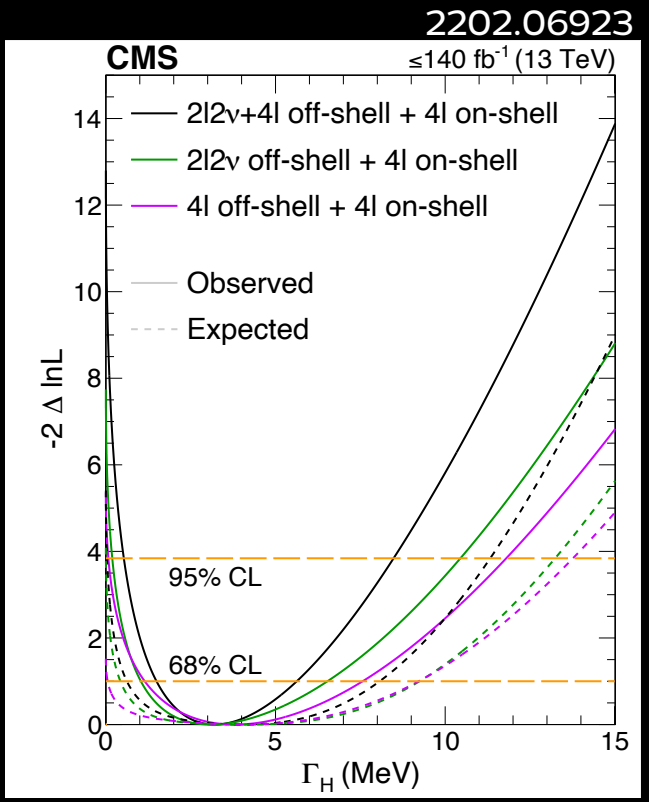

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

First evidence for Higgs off-shell production with 3.6σ significance and probed Higgs width

Additional Non-SM Branching Ratio (invisible)

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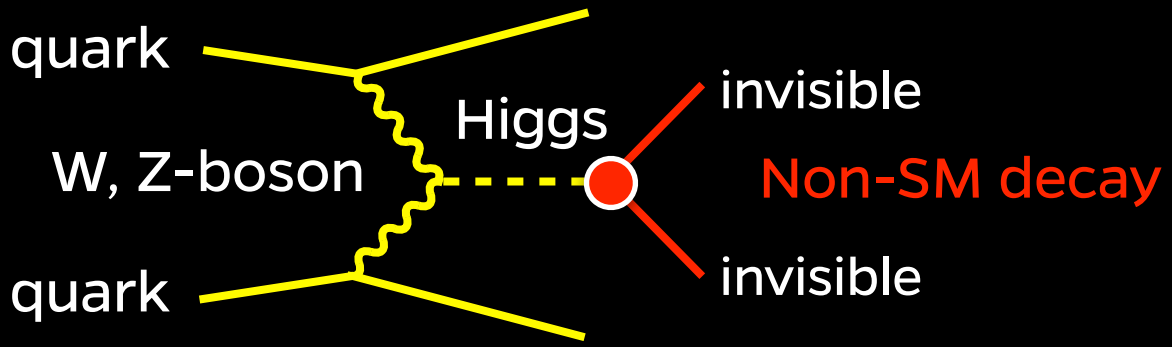
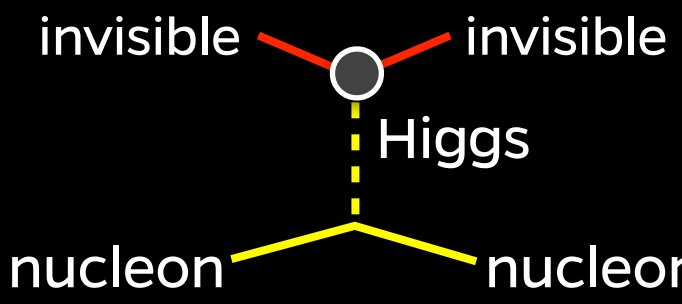
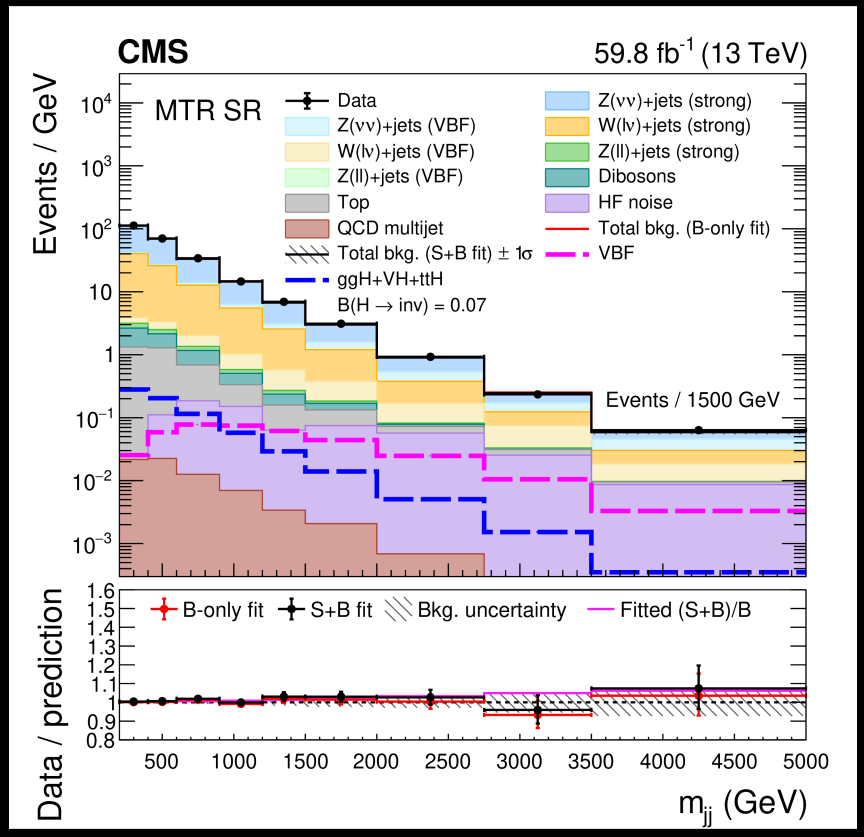
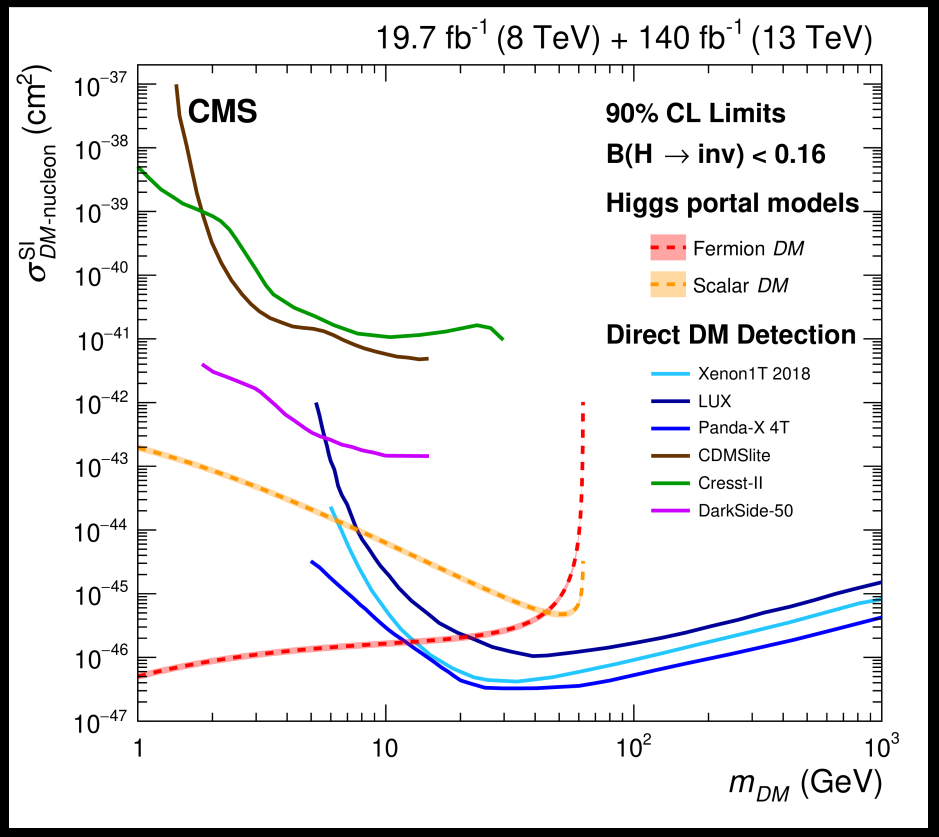


DM?







BR(H→invisible) ≤ 18%

Phys. Lett. B 793 (2019) 520

Additional Non-SM Branching Ratio (visible)

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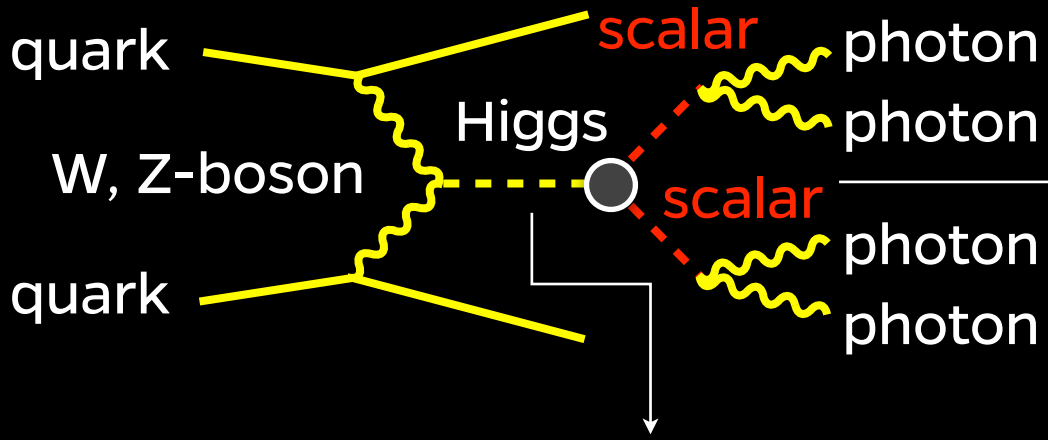
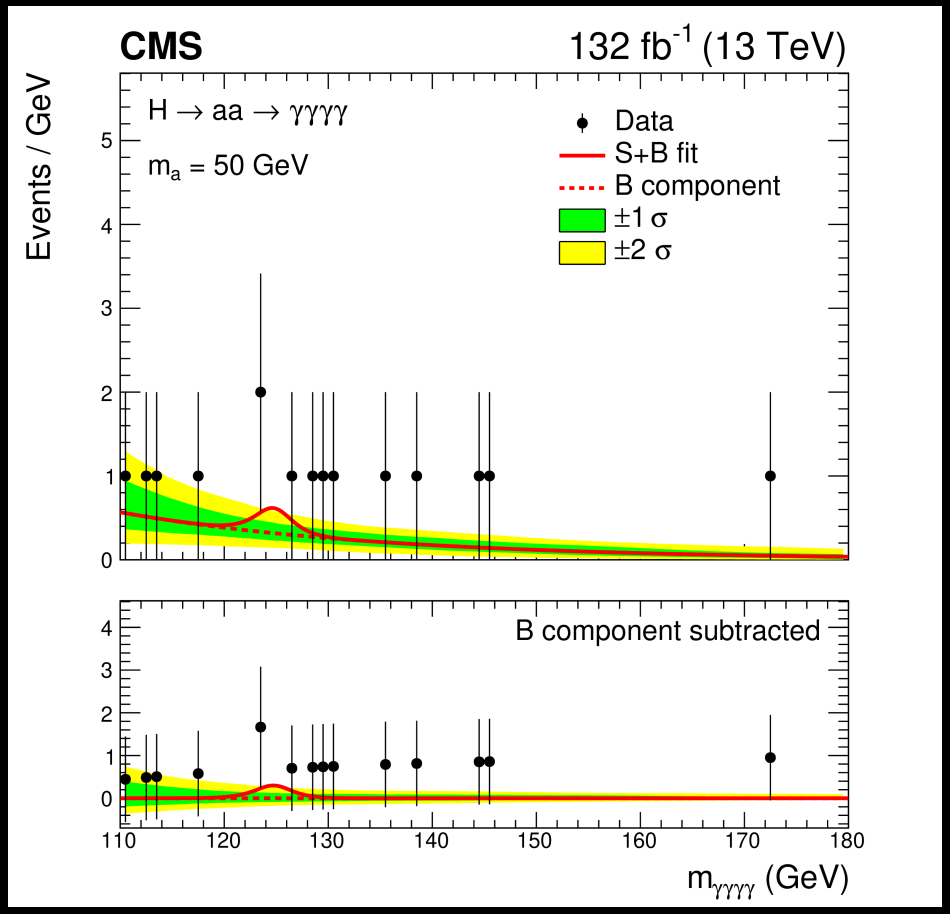
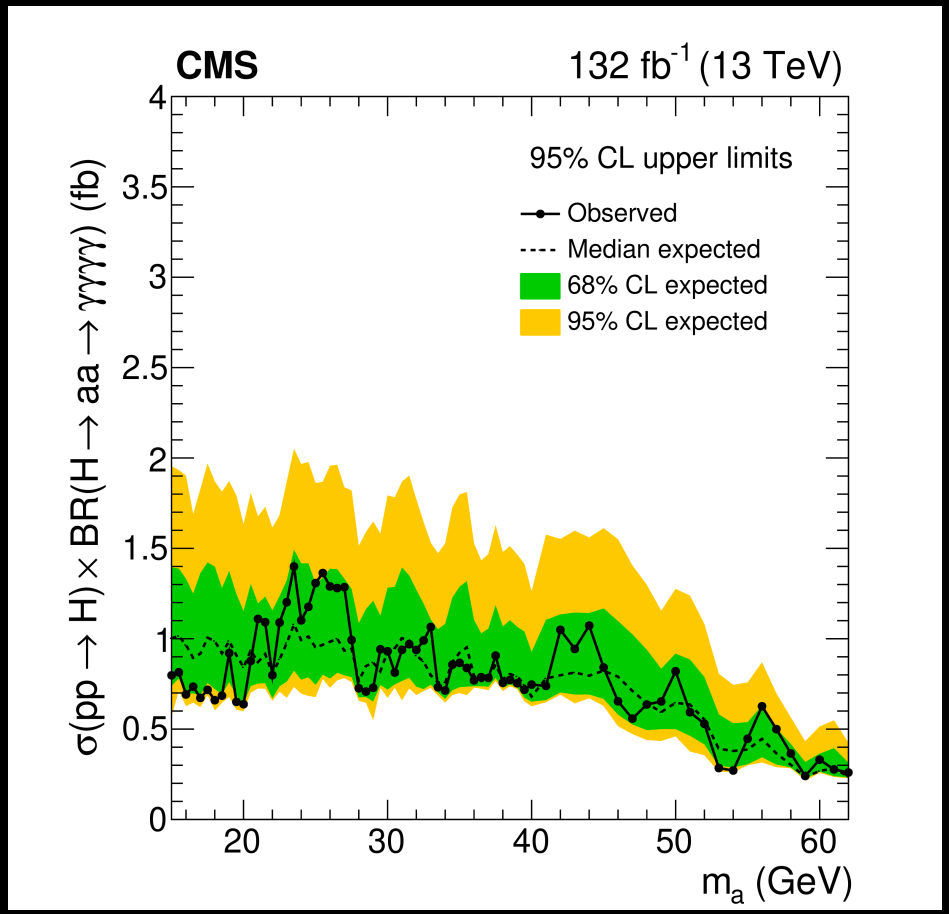
2208.01469







Going deeper into the big data of Higgs boson

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Spin 1 Boson

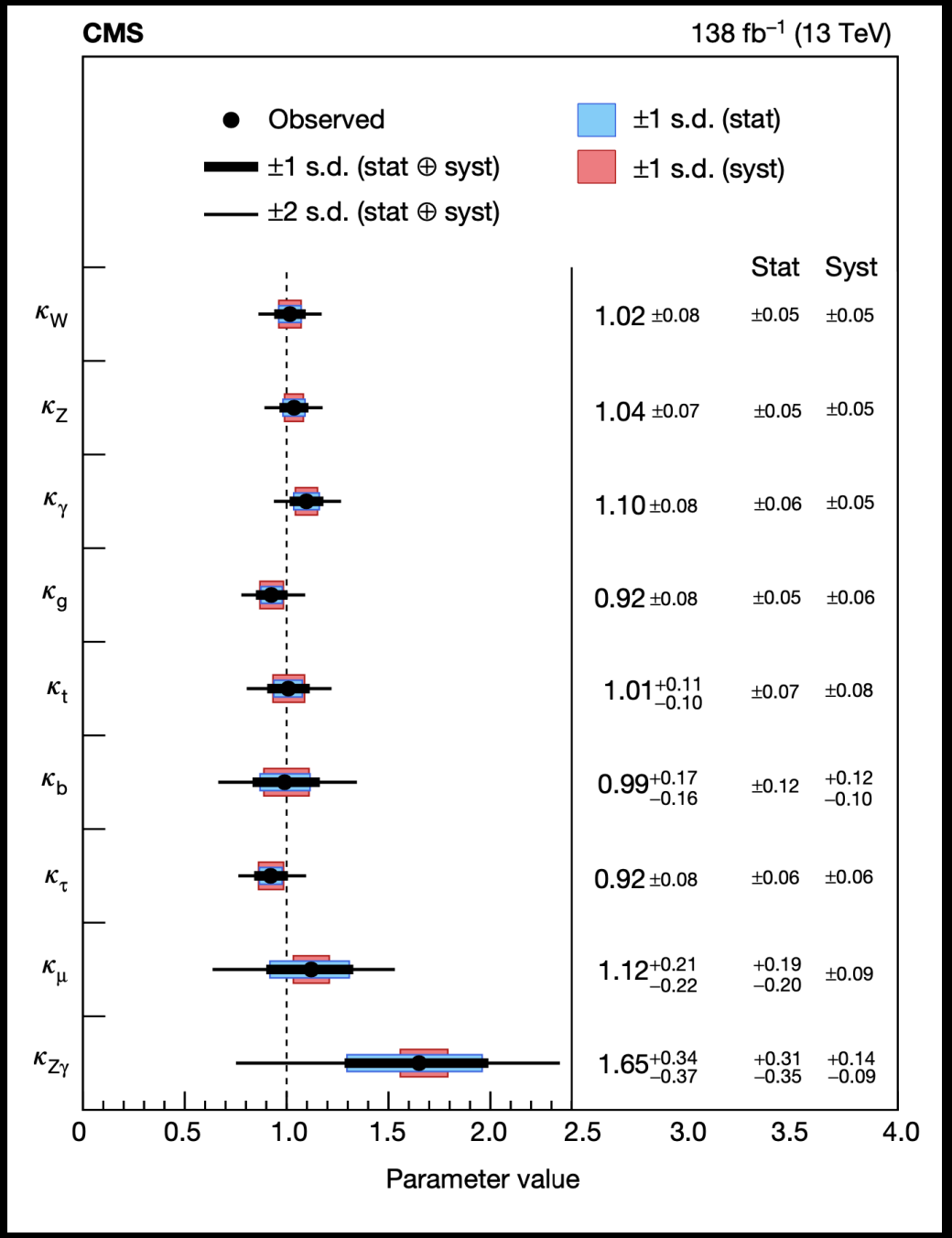
Spin 1/2 Quark Fermion

Spin 1/2 Lepton Fermion

Via loop

Via loop

Via loop



This is like asking whether the newly found planet is a circle

~10%

~15%

~20%

~40%

Going deeper into the big data of Higgs boson

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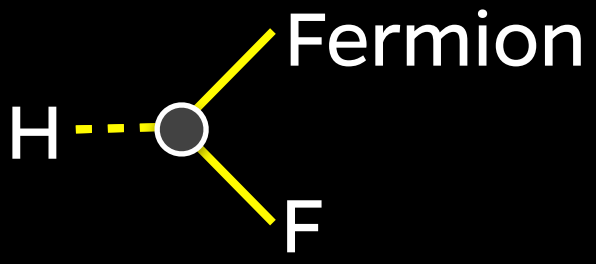
How do these couplings really look like?



Going deeper into the big data of Higgs boson

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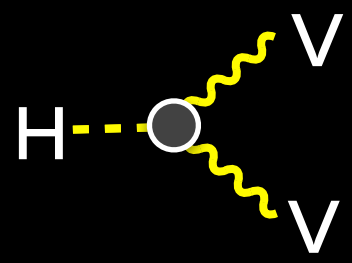
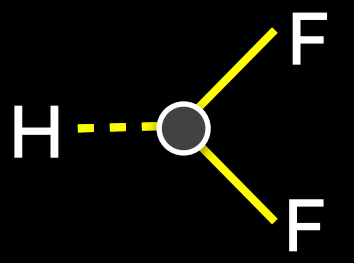
Overall ~agrees with SM between 10 - 40% (for the ones we probed)





Via loop W

Z

Via loop γ

Via loop g

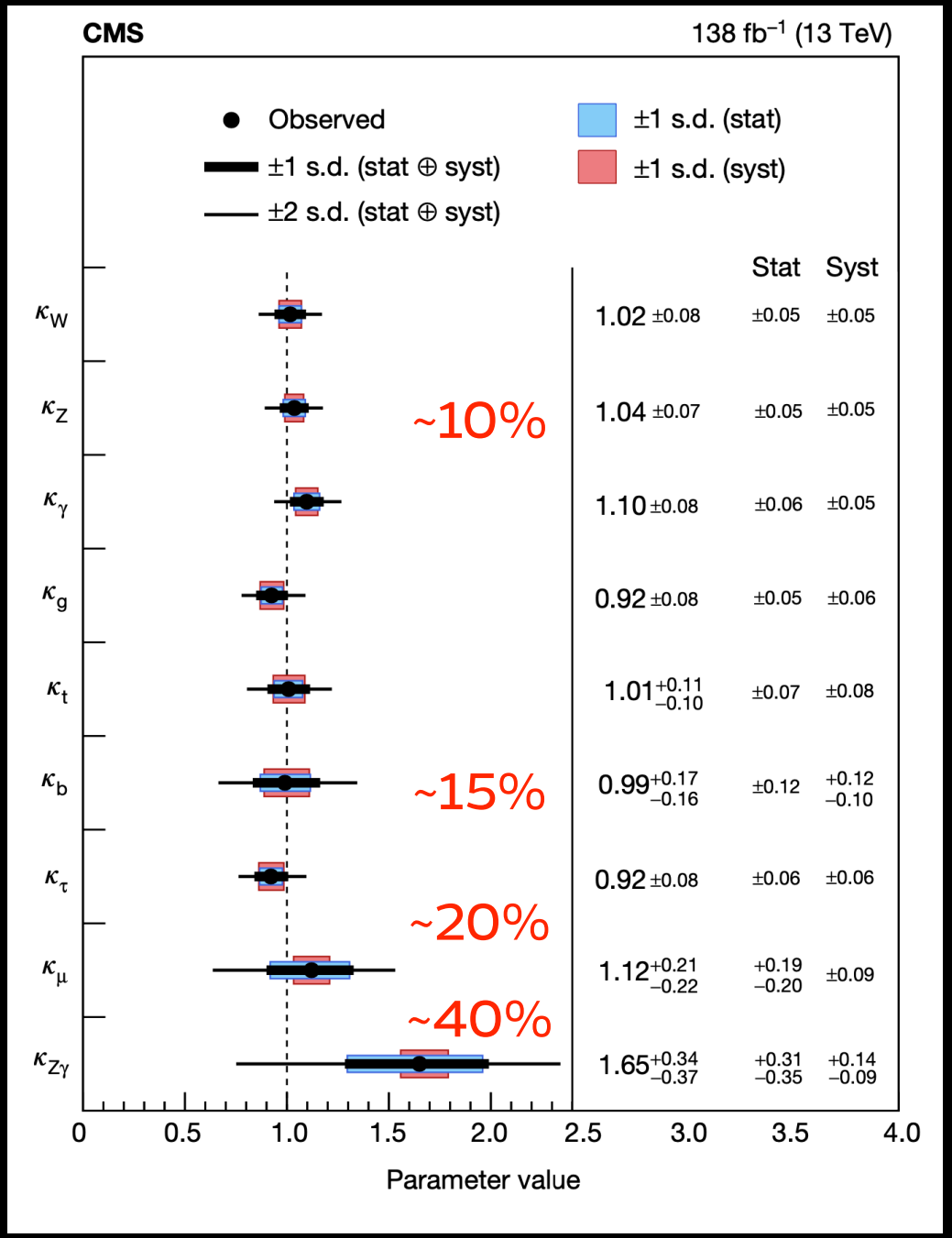
t

b

τ

μ

Via loop Z γ



Going deeper into the big data of Higgs boson

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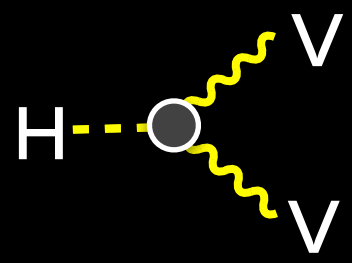
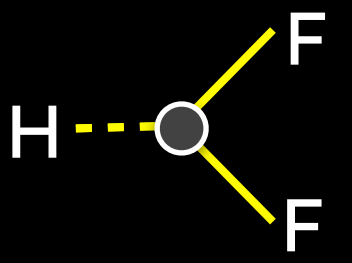
This is like asking whether the newly found planet is a circle





Via loop W

Via loop Z

Via loop γ

Via loop g

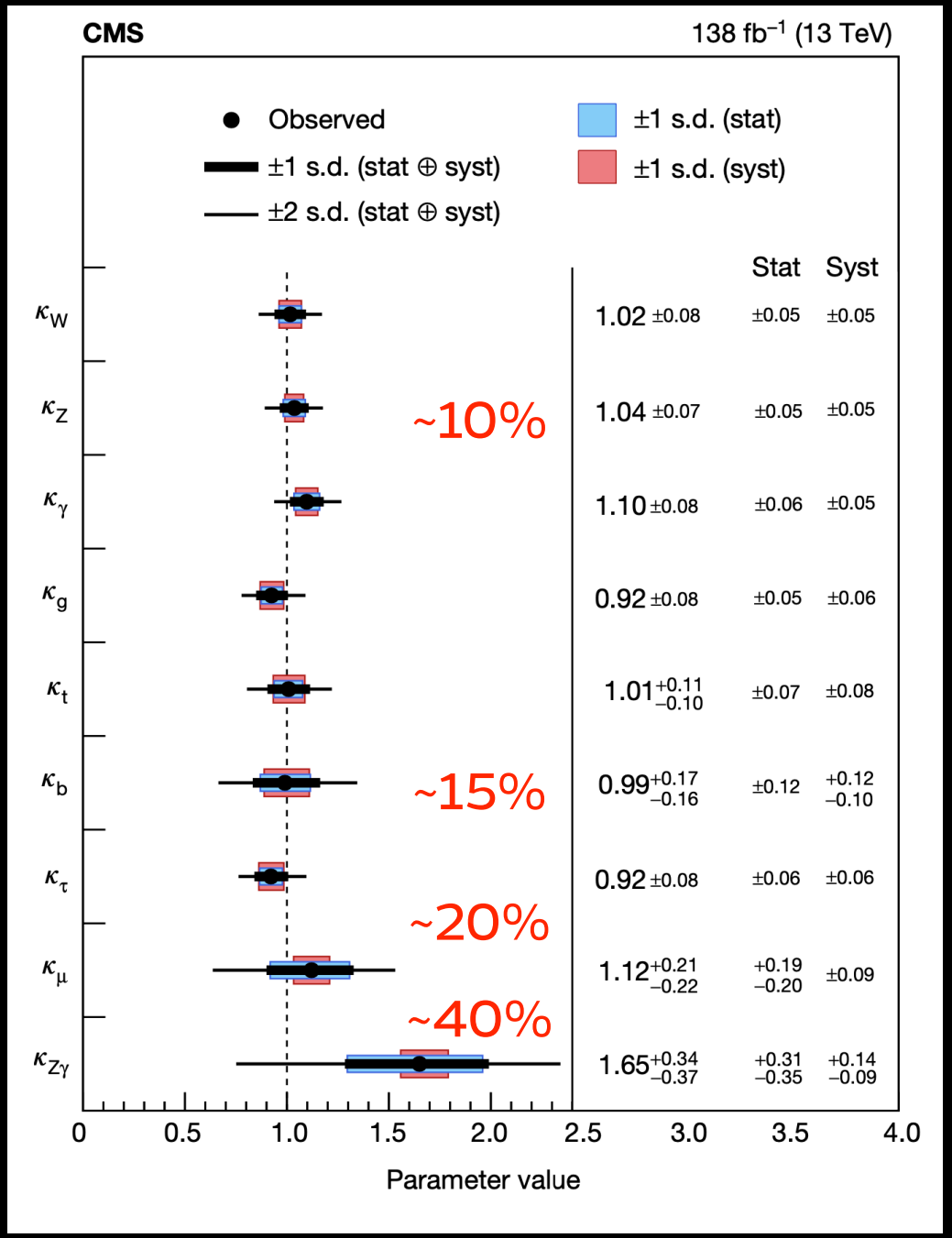
t

b

τ

μ

Via loop Z γ



Going deeper into the big data of Higgs boson

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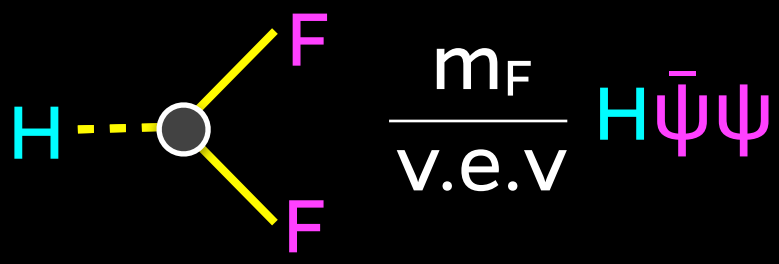
$$\frac{m_V^2}{v.e.v} H V_\mu V^\mu$$



$$\frac{m_F}{v.e.v} H \bar{\psi}\psi$$

Going deeper into the big data of Higgs boson

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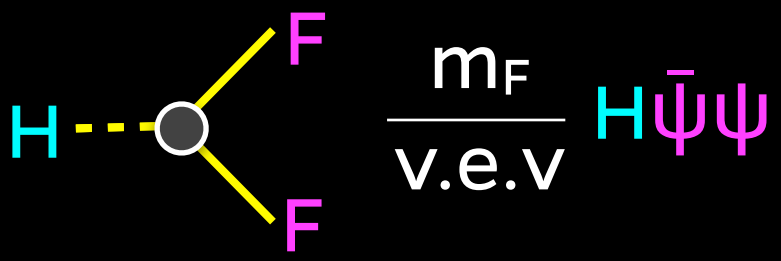
$$\frac{m_V^2}{v.e.v} H V_\mu V^\mu$$

In SM, following are ~zero

$$H F_{\mu\nu} F^{\mu\nu}$$
$$H F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$H V_\mu \Box V^\mu$$
$$\Box H V_\mu V^\mu$$



$$\frac{m_F}{v.e.v} H \bar{\psi}\psi$$

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$$i H \bar{\psi} \gamma_5 \psi$$

Going deeper into the big data of Higgs boson

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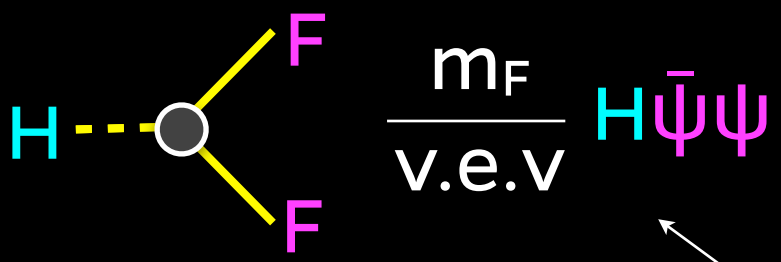


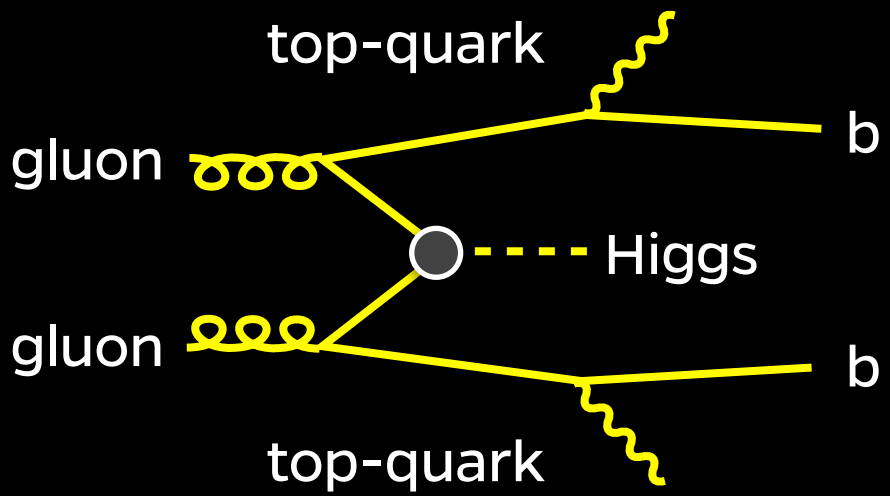
$$\frac{m_F}{v.e.v} H \bar{\psi}\psi$$

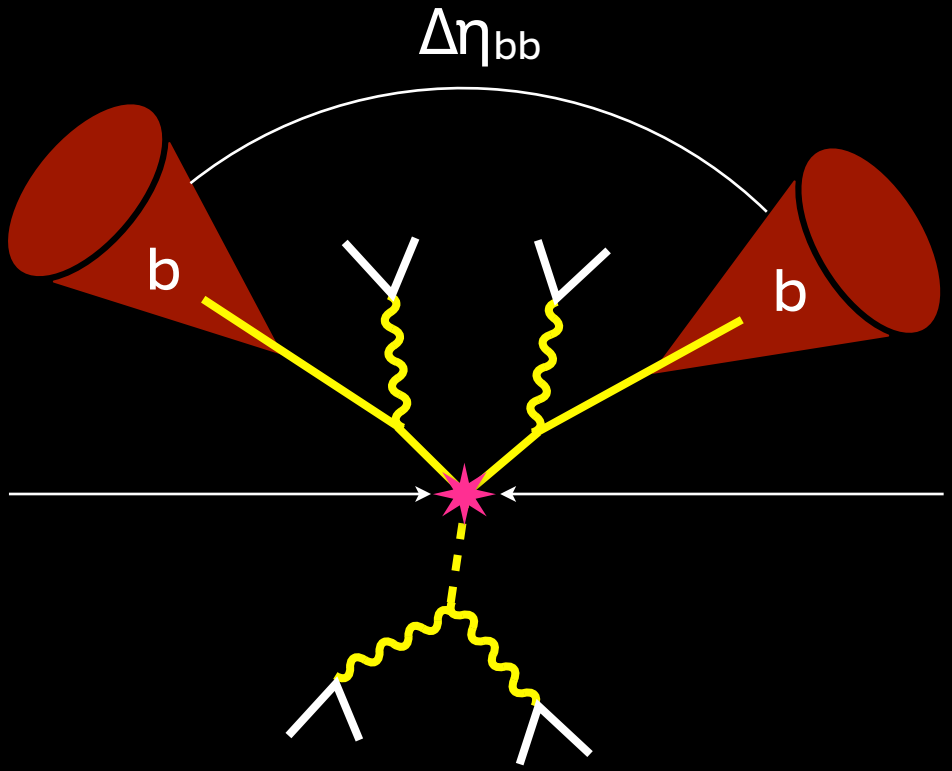
In SM, following is ~zero

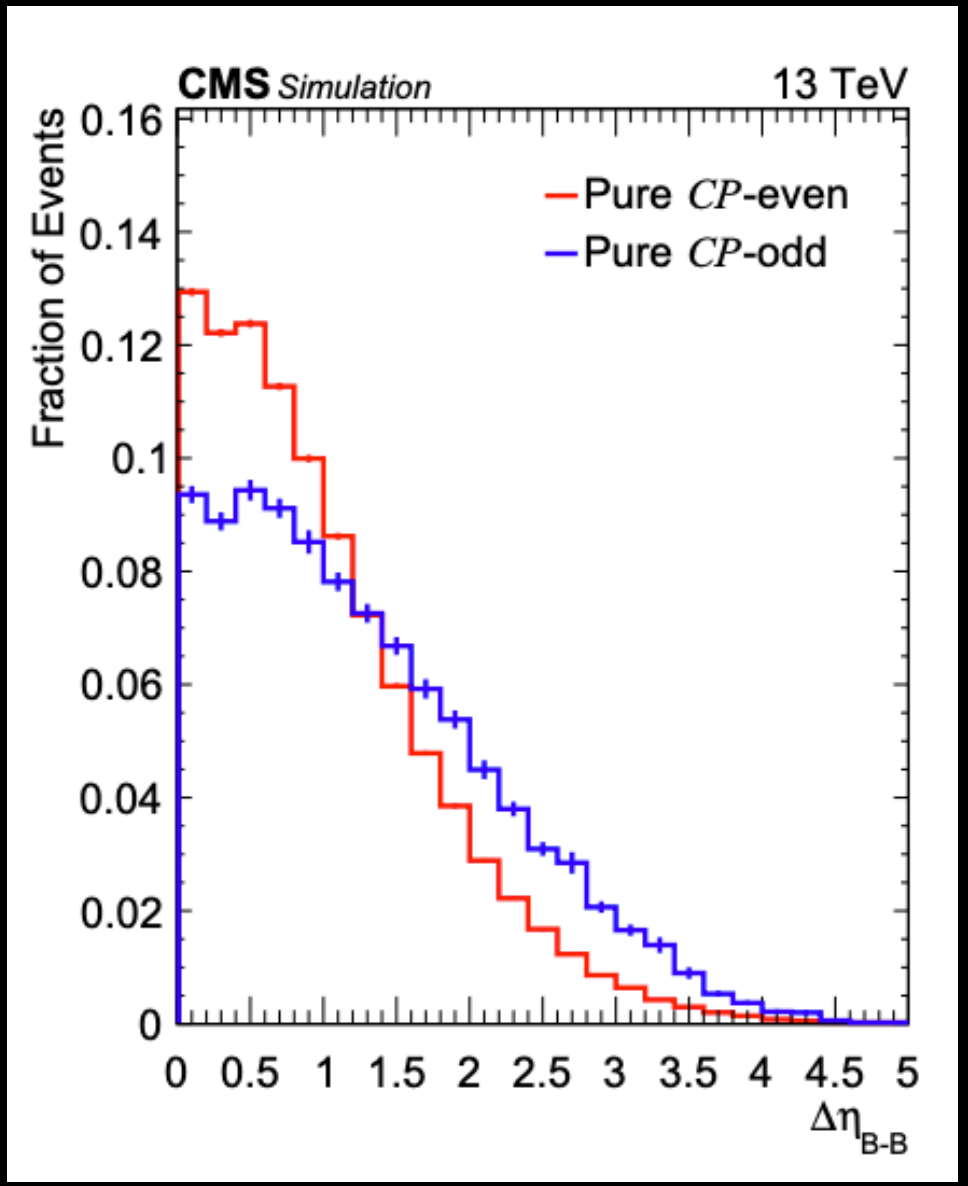
$$i H \bar{\psi} \gamma_5 \psi$$

k_F CP-even

$\tilde{k}_F$ CP-odd


top-quark
gluon
b
Higgs
gluon
b
top-quark


Δηbb
b
b


CMS Simulation
13 TeV
Pure CP-even
Pure CP-odd
Fraction of Events
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
ΔηB-B

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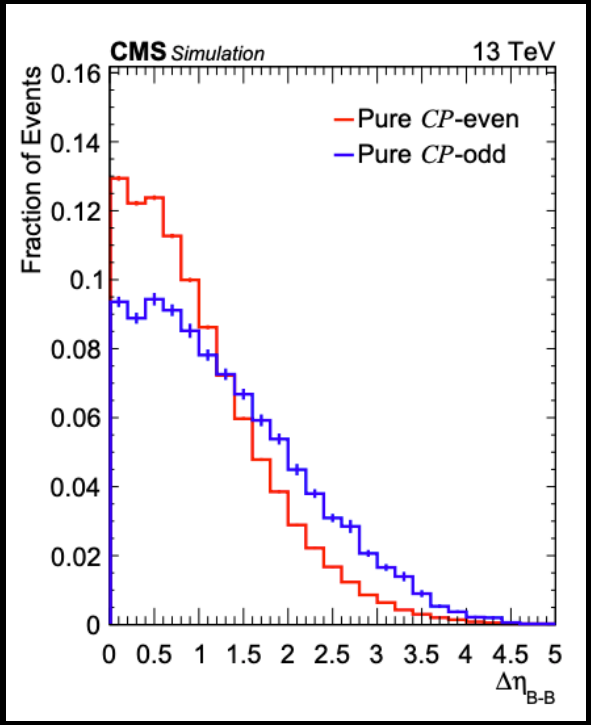
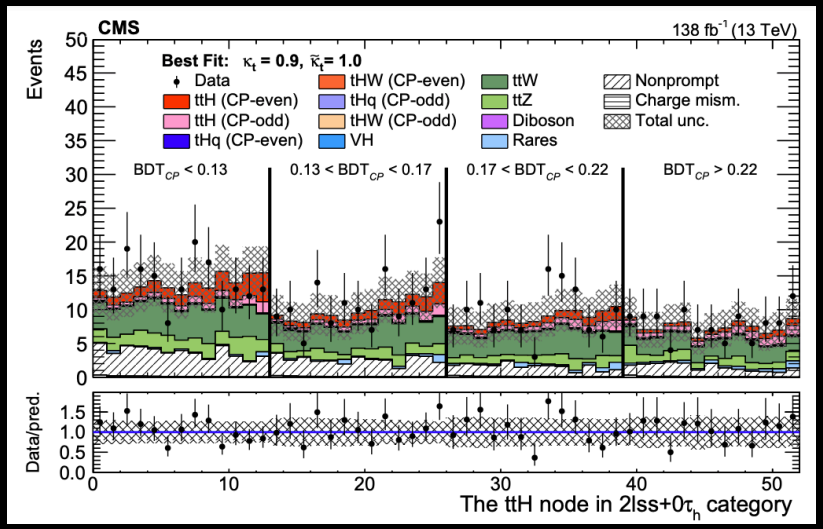


Table 4: Input features for the three BDTs. A check mark (✓) indicates the variable is used in a given final state, whereas a long dash (—) indicates the variable is not used in that final state.

Variable description	$2\ell SS + 0\tau_h$	$2\ell SS + 1\tau_h$	$3\ell + 0\tau_h$
p_T of jet 1	—	—	✓
p_T of jet 2	—	—	✓
p_T of lepton 1	✓	✓	✓
p_T of lepton 2	✓	✓	✓
p_T of lepton 3	—	—	✓
p_T of τ lepton	—	✓	—
η of lepton 1	✓	✓	—
η of lepton 2	✓	✓	—
η of τ lepton	—	✓	—
ϕ of lepton 1	✓	✓	—
ϕ of lepton 2	✓	✓	—
ϕ of τ lepton	—	✓	—
$m_T(l_1, p_T^{miss}) + p_T^{miss}$	✓	—	—
$m_T(l_2, p_T^{miss}) + p_T^{miss}$ system	✓	—	—
ΔR of lepton 1 to its closest jet	✓	✓	✓
ΔR of lepton 2 to its closest jet	✓	✓	✓
Invariant mass of the reconstructed $t\bar{t}H$ system ($M_{t\bar{t}H} = \sum_i p^{lep_i} + \vec{p}_T^{\,miss} + \sum_{i \le k} p^{jet_i *}$)	✓	✓	✓
$\Delta\eta$ of two jets with highest b score in the laboratory frame ($\Delta\eta_{BB}$)	✓	✓	✓
$\Delta\eta$ of the two leptons in frame of two most-likely b jets	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the dilepton system frame	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the ℓ_1-ℓ_2 system frame	—	—	✓
$\Delta\eta$ of two jets with highest b score in the ℓ_1-ℓ_3 system frame	—	—	✓
$\Delta\phi$ of the two leptons in frame of two most-likely b jets	—	✓	—
$\Delta\phi$ of two jets with highest b score in the dilepton system frame	—	✓	—
Average ΔR among all jets	✓	✓	—
Jet multiplicity	✓	✓	—
p_T^{miss}	✓	✓	—
Azimuthal angle of $\vec{p}_T^{\,miss}$	✓	✓	—
Highest BDT score of jet triplet from t	✓	✓	—
Higgs jet tagger	—	✓	—
Angle of $t\bar{t}$ and H boson in $t\bar{t}H$-system	—	✓	—
Angle between two t in $t\bar{t}$-frame	—	✓	—
$\Delta R_{l_3-l_1} = \sqrt{(\eta_{\ell_3} - \eta_{\ell_1})^2 + (\phi_{\ell_3} - \phi_{\ell_1})^2}$	—	—	✓
$\Delta R_{l_1-l_2} = \sqrt{(\eta_{\ell_1} - \eta_{\ell_2})^2 + (\phi_{\ell_1} - \phi_{\ell_2})^2}$	—	—	✓
$\Delta R_{l_2-l_3} = \sqrt{(\eta_{\ell_2} - \eta_{\ell_3})^2 + (\phi_{\ell_2} - \phi_{\ell_3})^2}$	—	—	✓
$\eta_{jet1} - \eta_{jet2}$	—	—	✓
$p_T^{jet1} + p_T^{jet2} + p_T^{jet3} + p_T^{miss}$	—	—	✓
Total number of variables	19	25	16

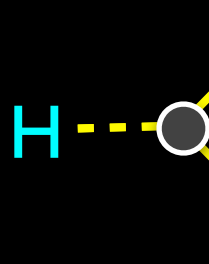
* k = 6 (4) in the $2\ell SS + 0\tau_h$ ($2\ell SS + 1\tau_h$ and $3\ell + 0\tau_h$) final state

Trained machine learning using multiple input variables to discriminate CP-odd vs. CP-even



CP-even like events

CP-odd like events



$$\frac{m_F}{v.e.v} H\bar{\psi}\psi$$

In SM, following is ~zero

$$i H\bar{\psi}\gamma_5\psi$$

k_F CP-even

$\tilde{k}_F$ CP-odd

Fit to extract fraction of CP-even vs. odd

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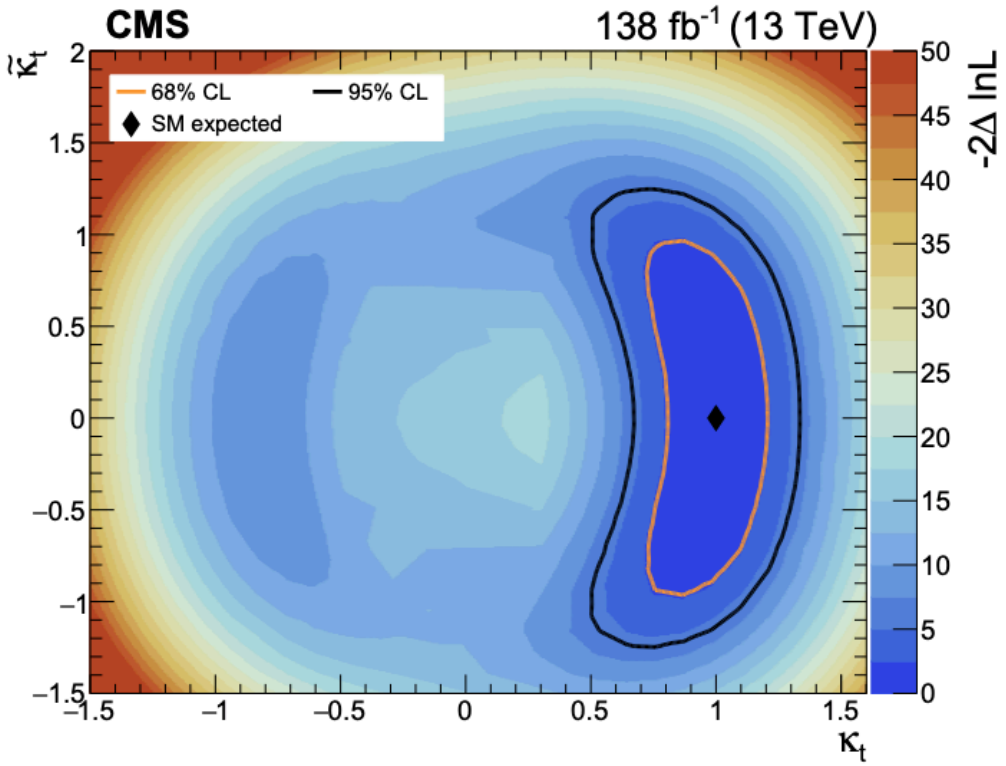

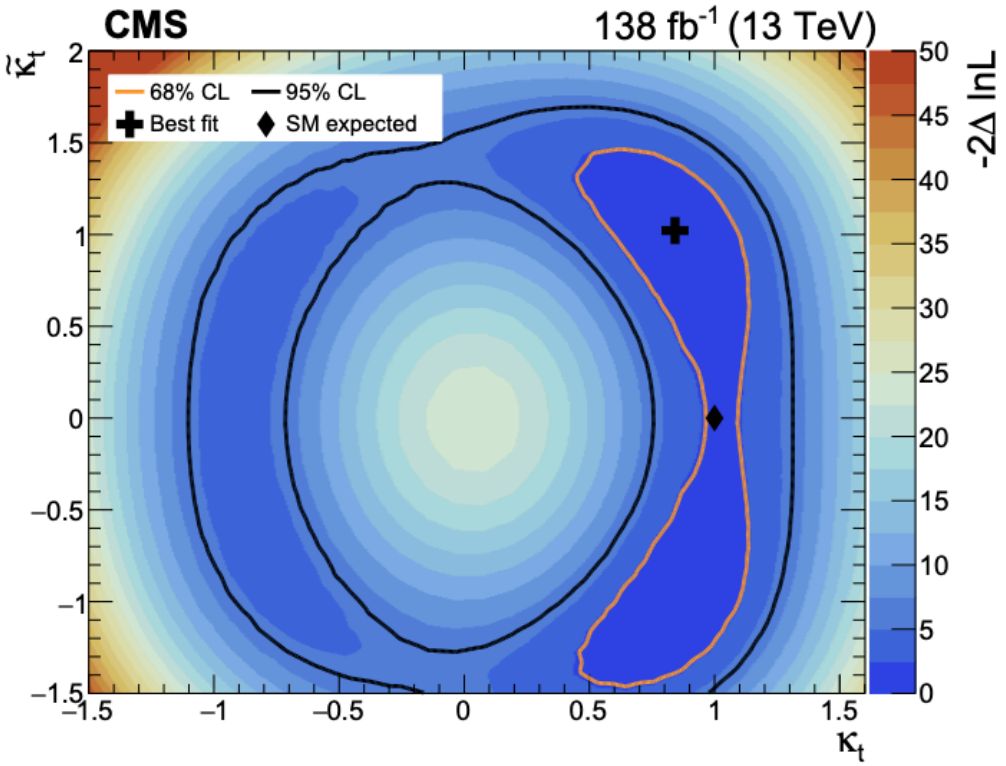

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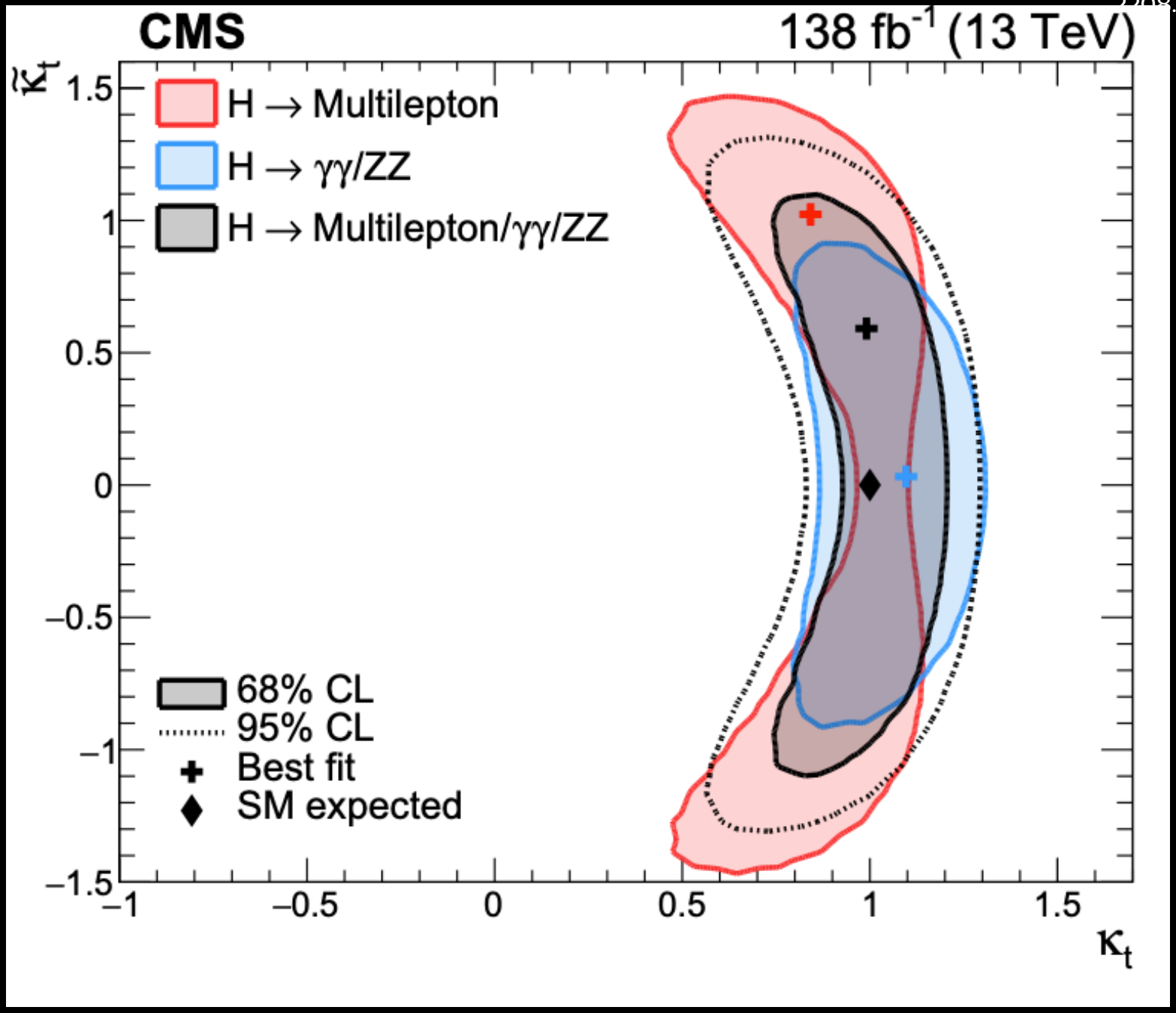

Taking a deep dive

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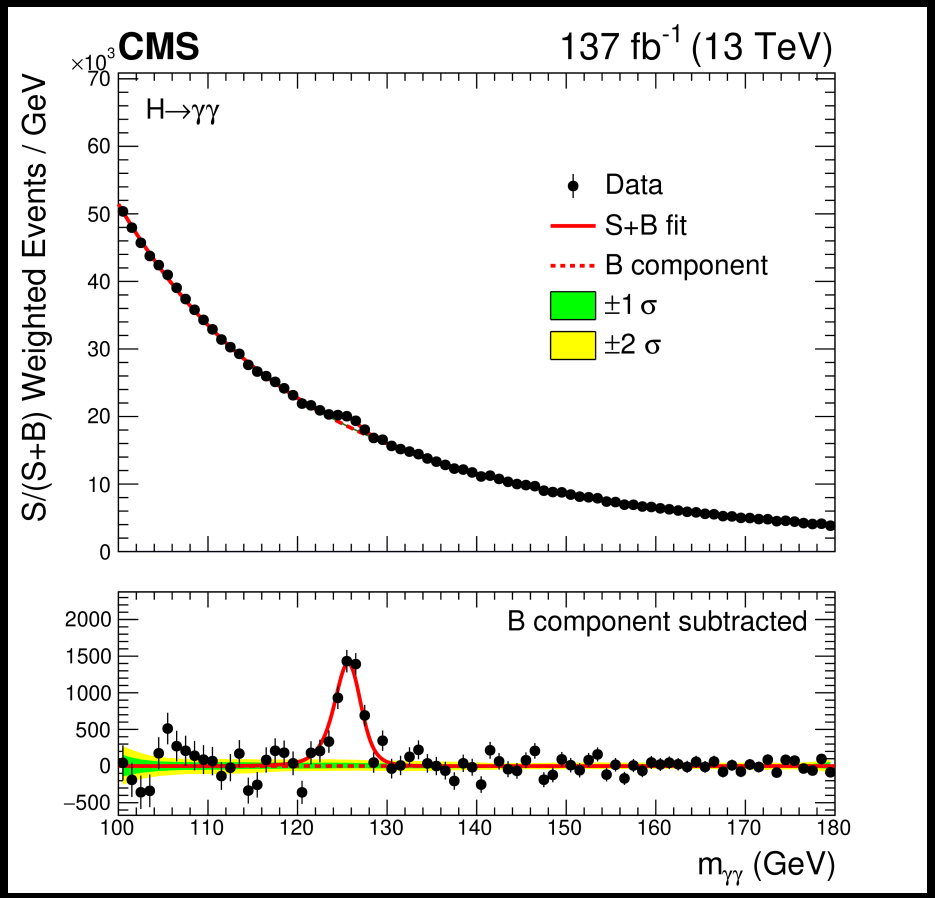
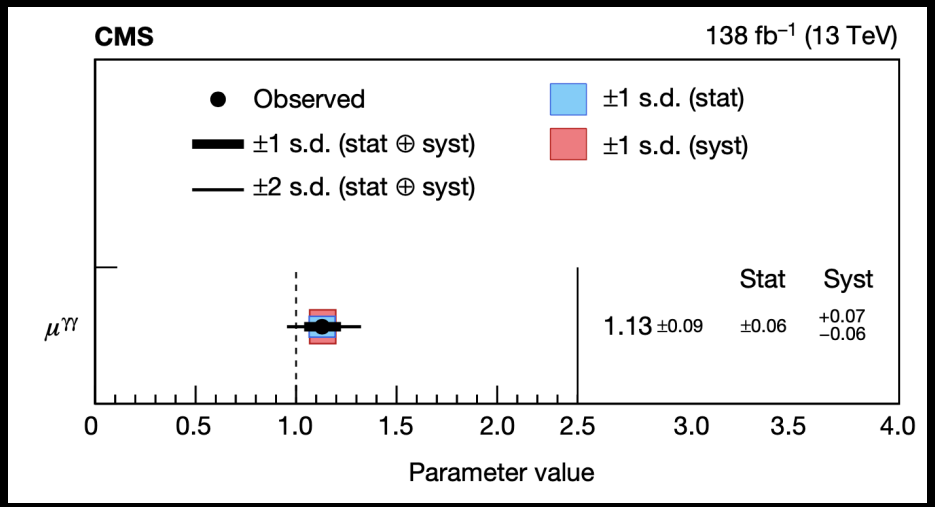
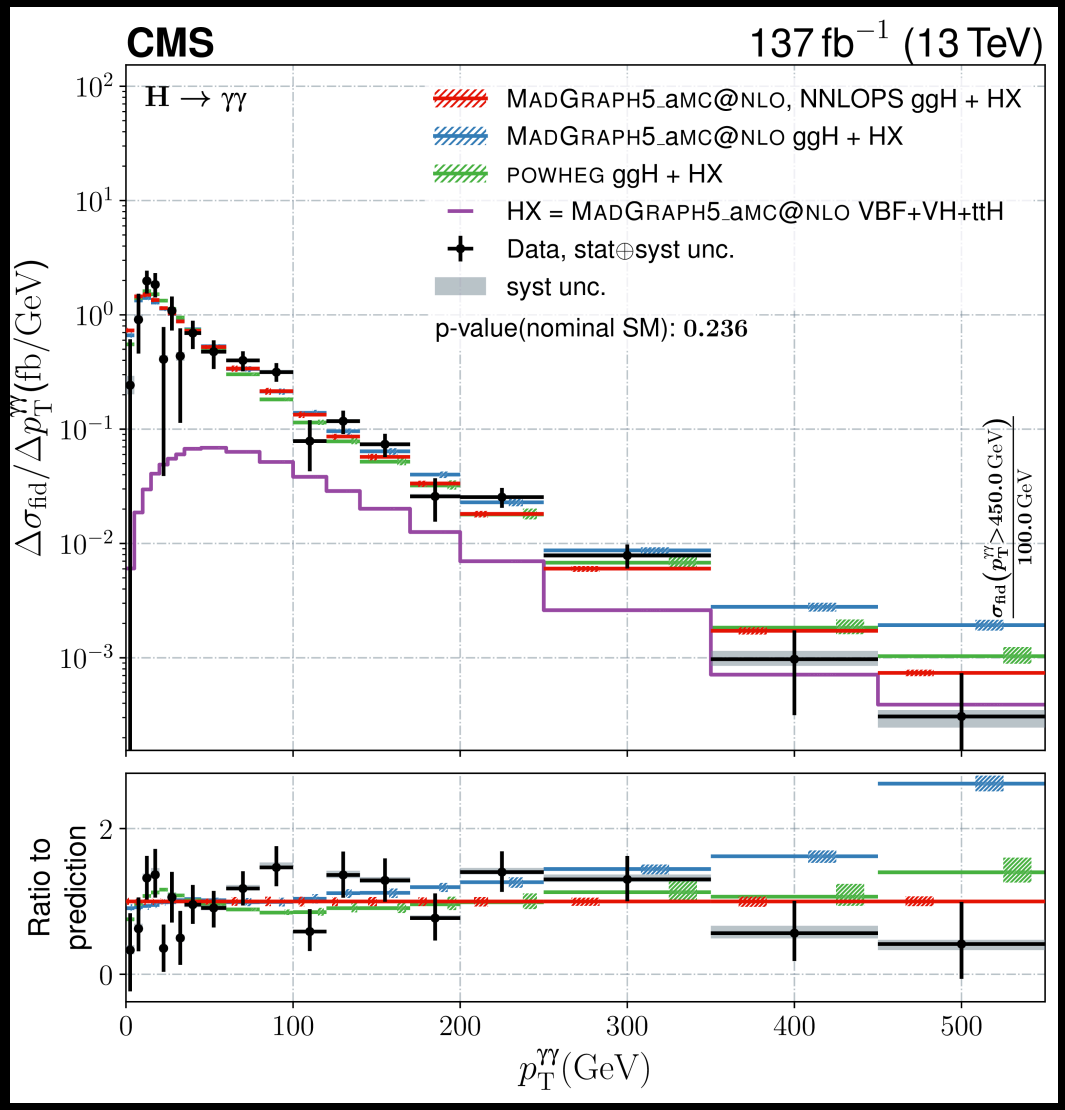
CMS-HIG-19-016







Taking a deep dive

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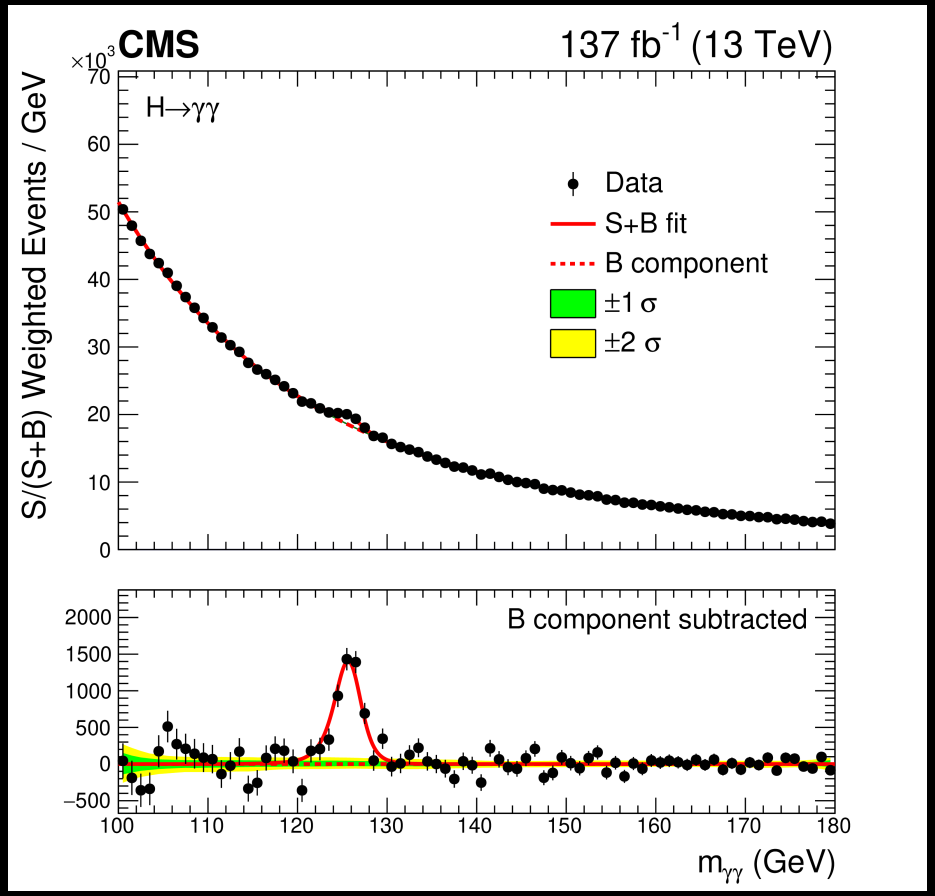
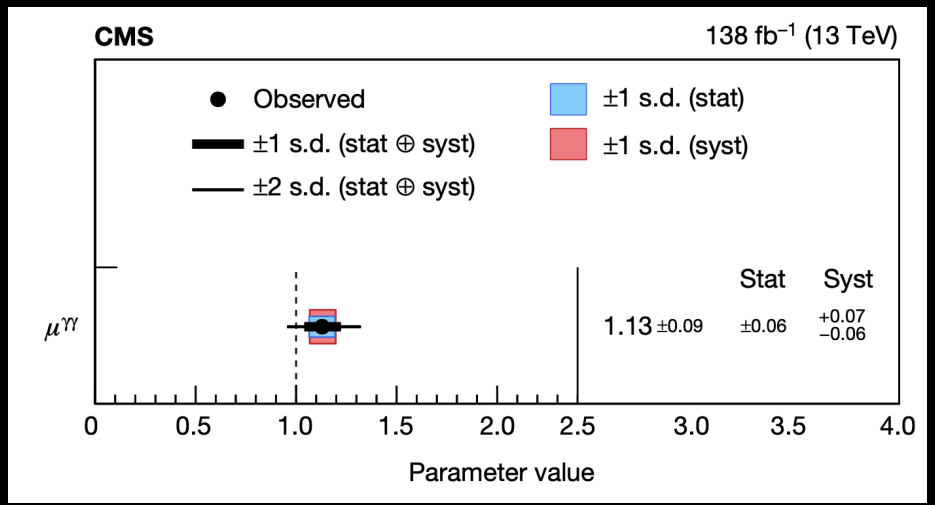
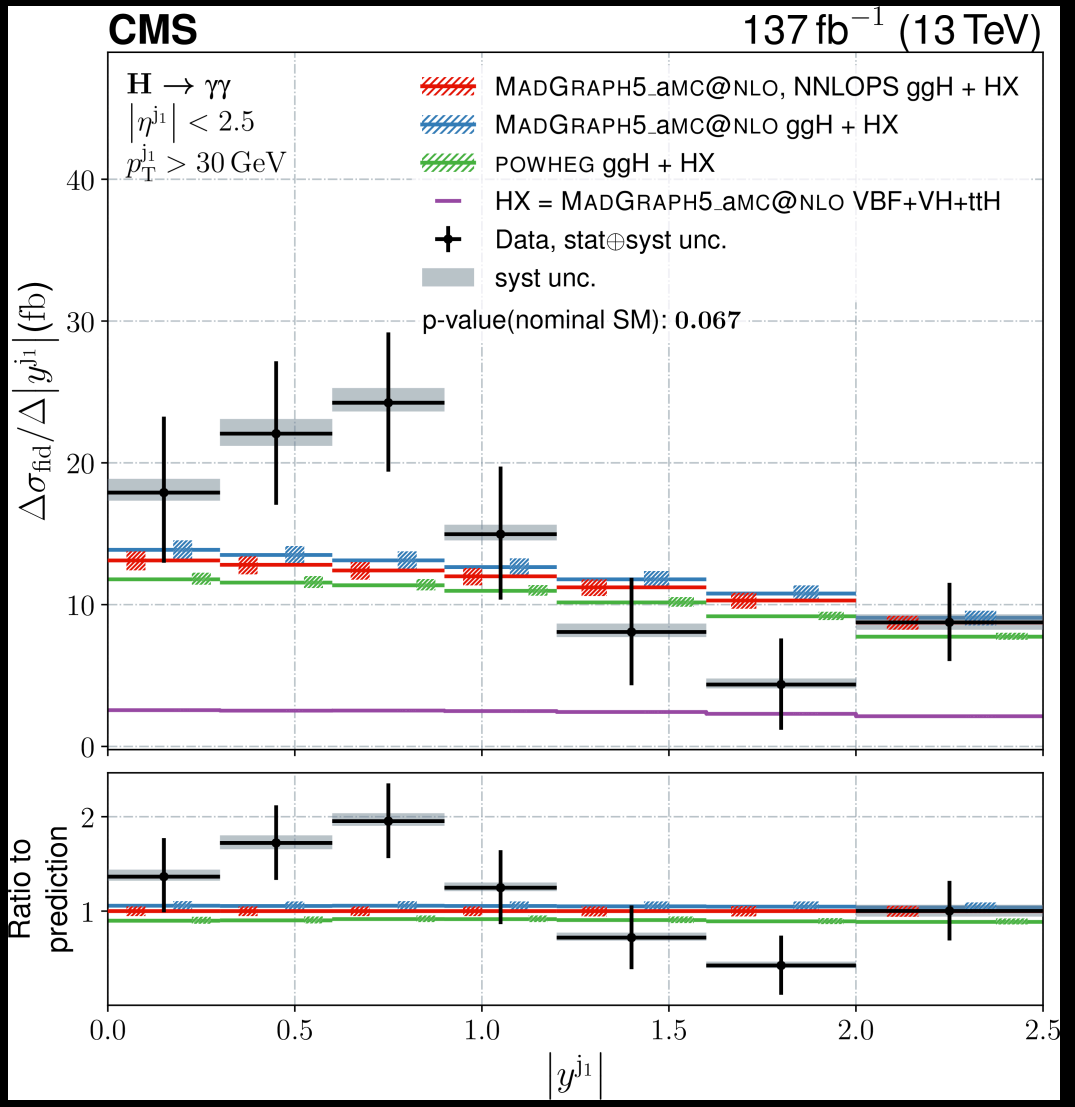
CMS-HIG-19-016







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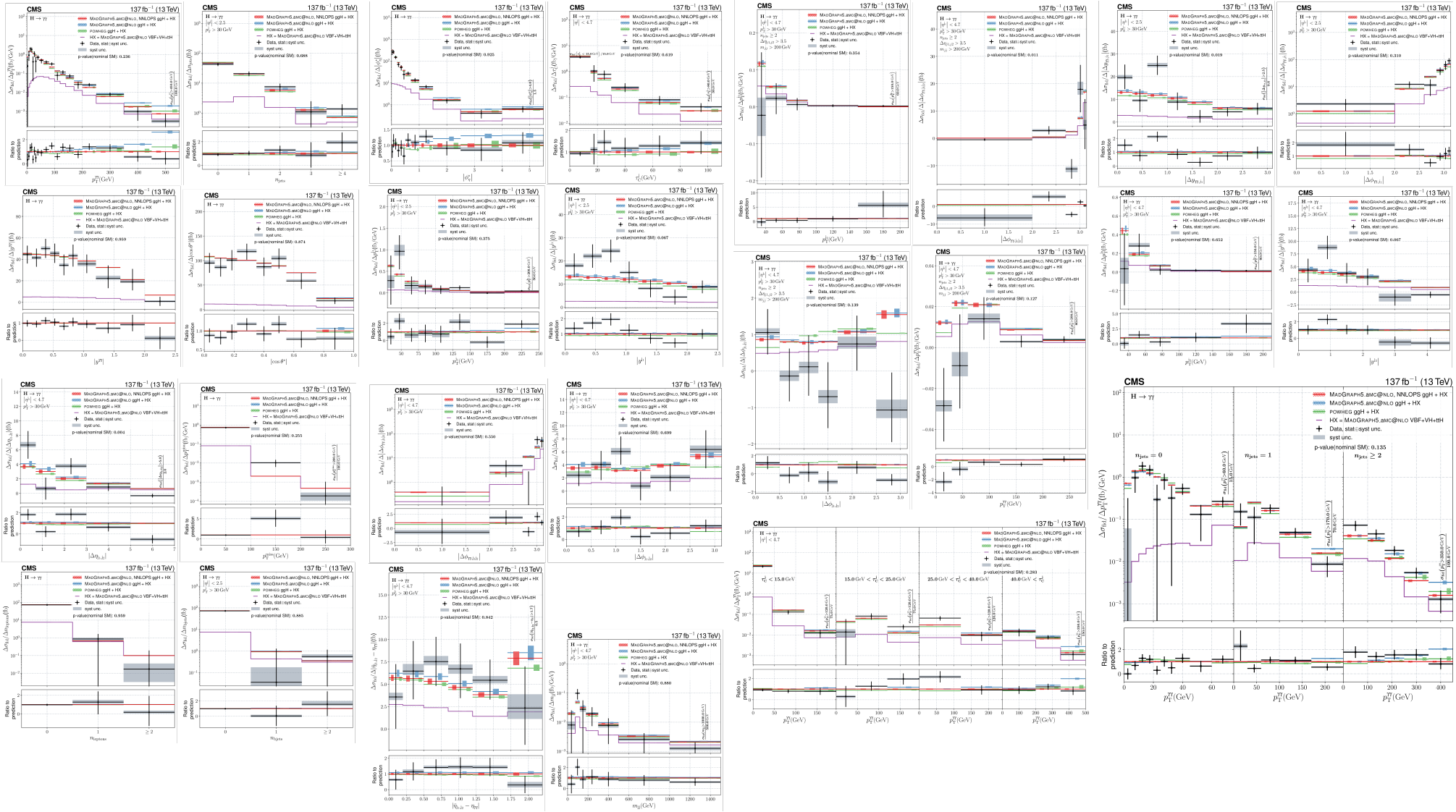
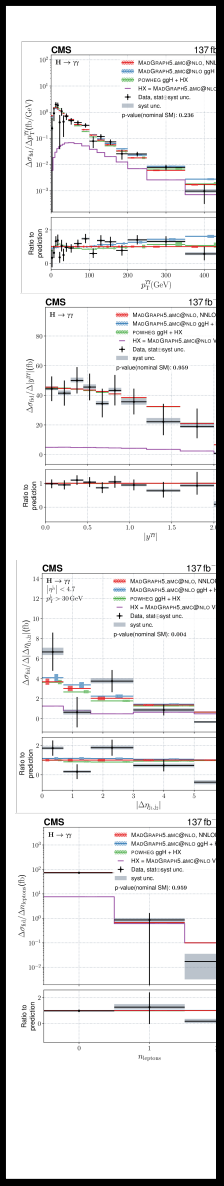
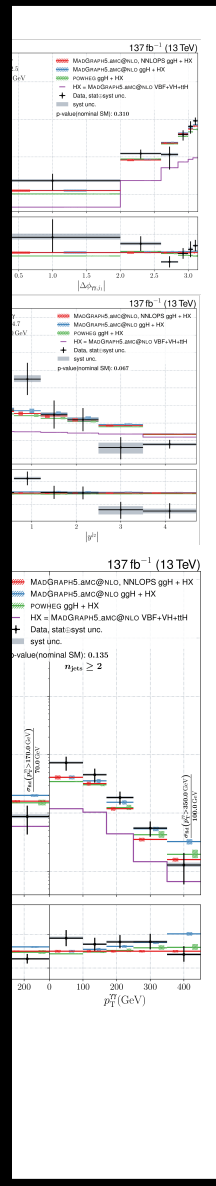


Further dissecting and comparing with expectations

1996 Hubble


CMS
137 fb
H → γγ
MadGraph5_amc@nlo, NNL
MadGraph5_amc@nlo ggH
powheg ggH + HX
HX = MadGraph5_amc@nlo
Data, stat⊕syst unc.
syst unc.
p-value(nominal SM): 0.236
Ratio to prediction
CMS
137 fb
H → γγ
MadGraph5_amc@nlo, NNLO
MadGraph5_amc@nlo ggH +
powheg ggH + HX
HX = MadGraph5_amc@nlo V
Data, stat⊕syst unc.
syst unc.
p-value(nominal SM): 0.959
Ratio to prediction
CMS
137 fb
H → γγ
|y^γγ| < 4.7
p_T^γγ > 30 GeV
MadGraph5_amc@nlo, NNLO
MadGraph5_amc@nlo ggH +
powheg ggH + HX
HX = MadGraph5_amc@nlo V
Data, stat⊕syst unc.
syst unc.
p-value(nominal SM): 0.004
Ratio to prediction
CMS
137 fb
H → γγ
MadGraph5_amc@nlo, NNLO
MadGraph5_amc@nlo ggH +
powheg ggH + HX
HX = MadGraph5_amc@nlo V
Data, stat⊕syst unc.
syst unc.
p-value(nominal SM): 0.959
Ratio to prediction


137 fb⁻¹ (13 TeV)
MadGraph5_amc@nlo, NNLOPS ggH + HX
MadGraph5_amc@nlo ggH + HX
powheg ggH + HX
HX = MadGraph5_amc@nlo VBF+VH+tH
Data, stat⊕syst unc.
syst unc.
p-value(nominal SM): 0.310
137 fb⁻¹ (13 TeV)
MadGraph5_amc@nlo, NNLOPS ggH + HX
MadGraph5_amc@nlo ggH + HX
powheg ggH + HX
HX = MadGraph5_amc@nlo VBF+VH+tH
Data, stat⊕syst unc.
syst unc.
p-value(nominal SM): 0.067
137 fb⁻¹ (13 TeV)
MadGraph5_amc@nlo, NNLOPS ggH + HX
MadGraph5_amc@nlo ggH + HX
powheg ggH + HX
HX = MadGraph5_amc@nlo VBF+VH+ttH
Data, stat⊕syst unc.
syst unc.
p-value(nominal SM): 0.135
n_jets ≥ 2

Number of Higgs boson produced

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Years	Runs	Energy	Luminosity	# of Higgs
2011	Run 1	7 TeV	~5 fb^{-1}	~100 K
2012	Run 1	8 TeV	~20 fb^{-1}	~500 K
2015 - 2018	Run 2	13 TeV	~140 fb^{-1}	~8 M

Number of Higgs boson produced

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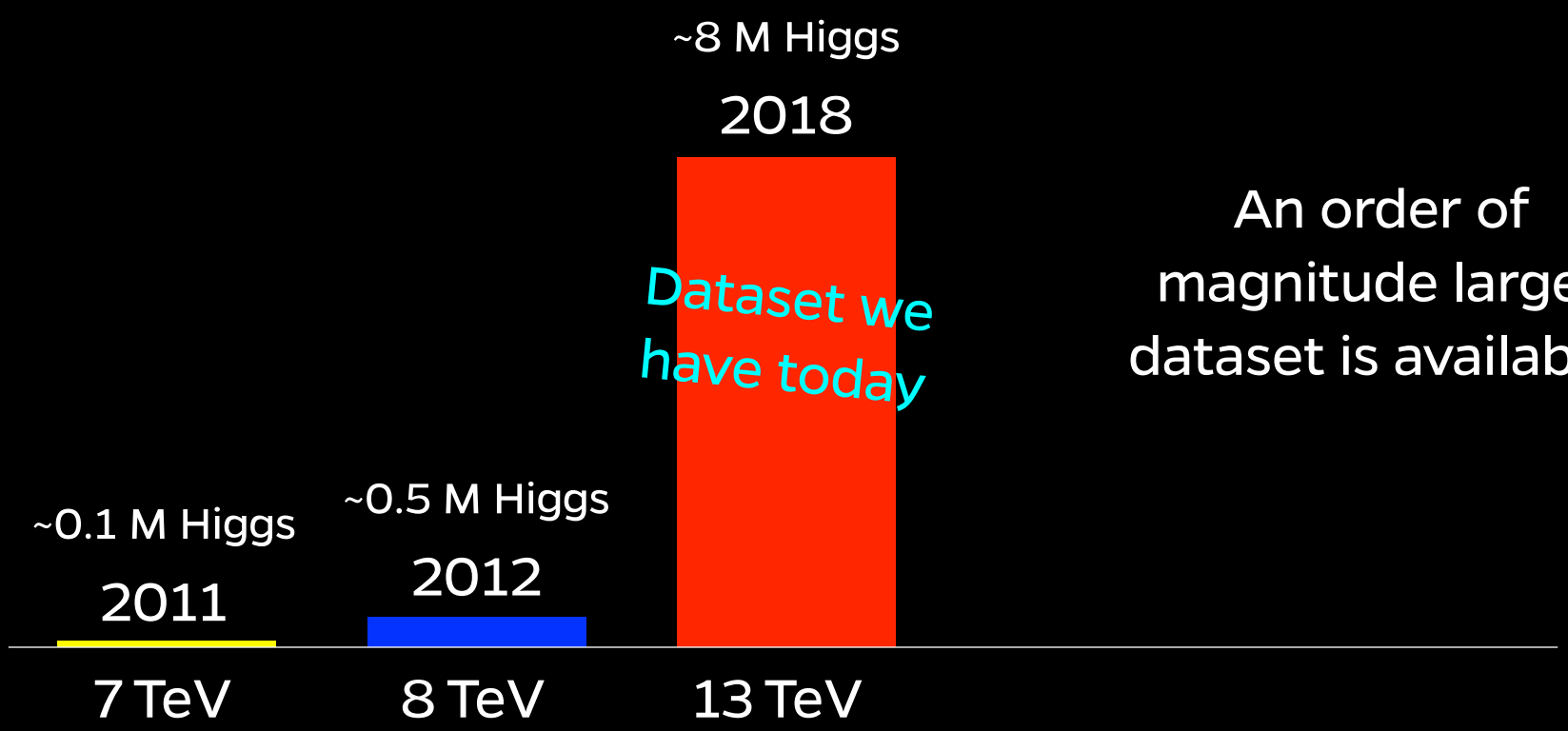

An order of magnitude larger dataset is available!

Number of Higgs boson produced

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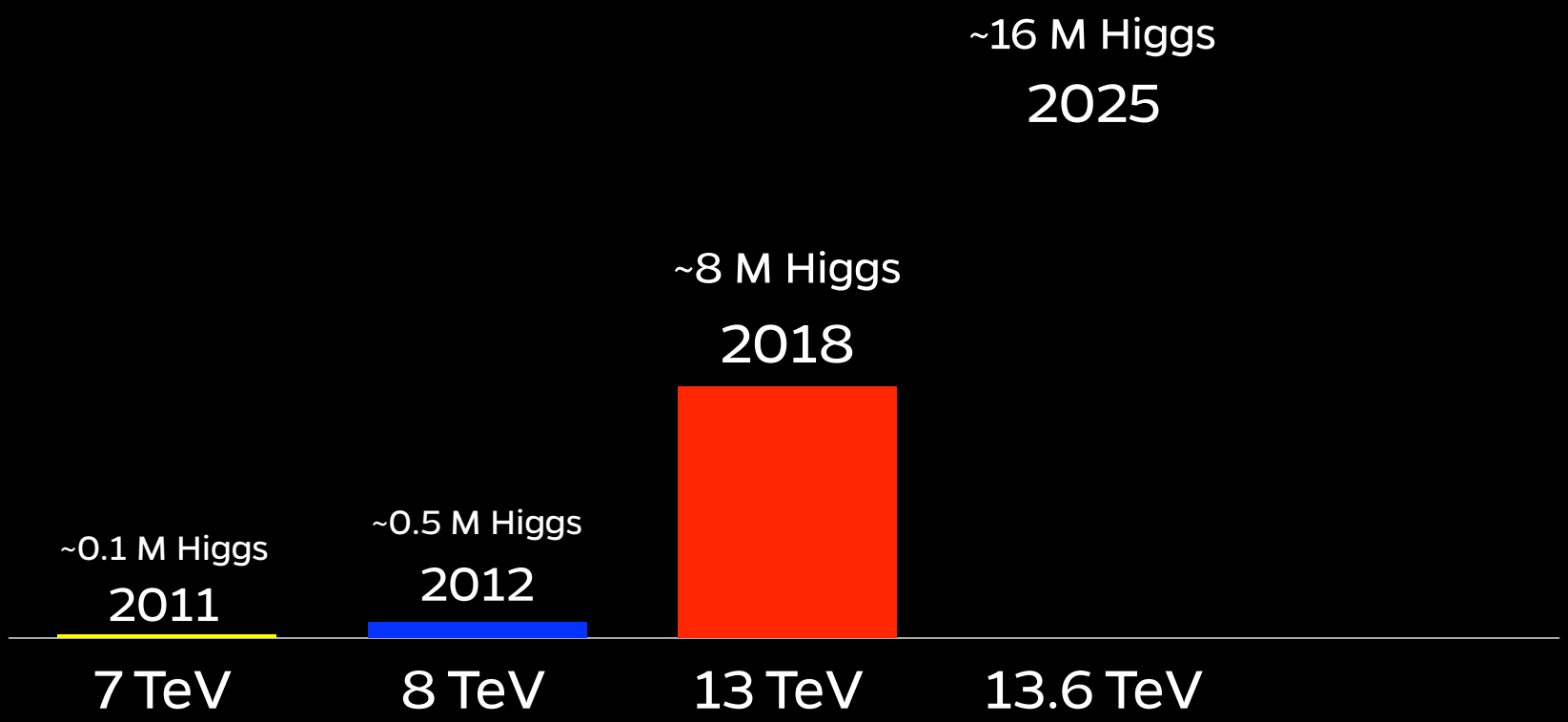
2015 - 2018	Run 2	13 TeV	~140 fb^{-1}	~8 M
2022 - 2025	Run 3	13.6 TeV	~300 fb^{-1}	~16 M



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2015 - 2018	Run 2	13 TeV	~140 fb^{-1}	~8 M
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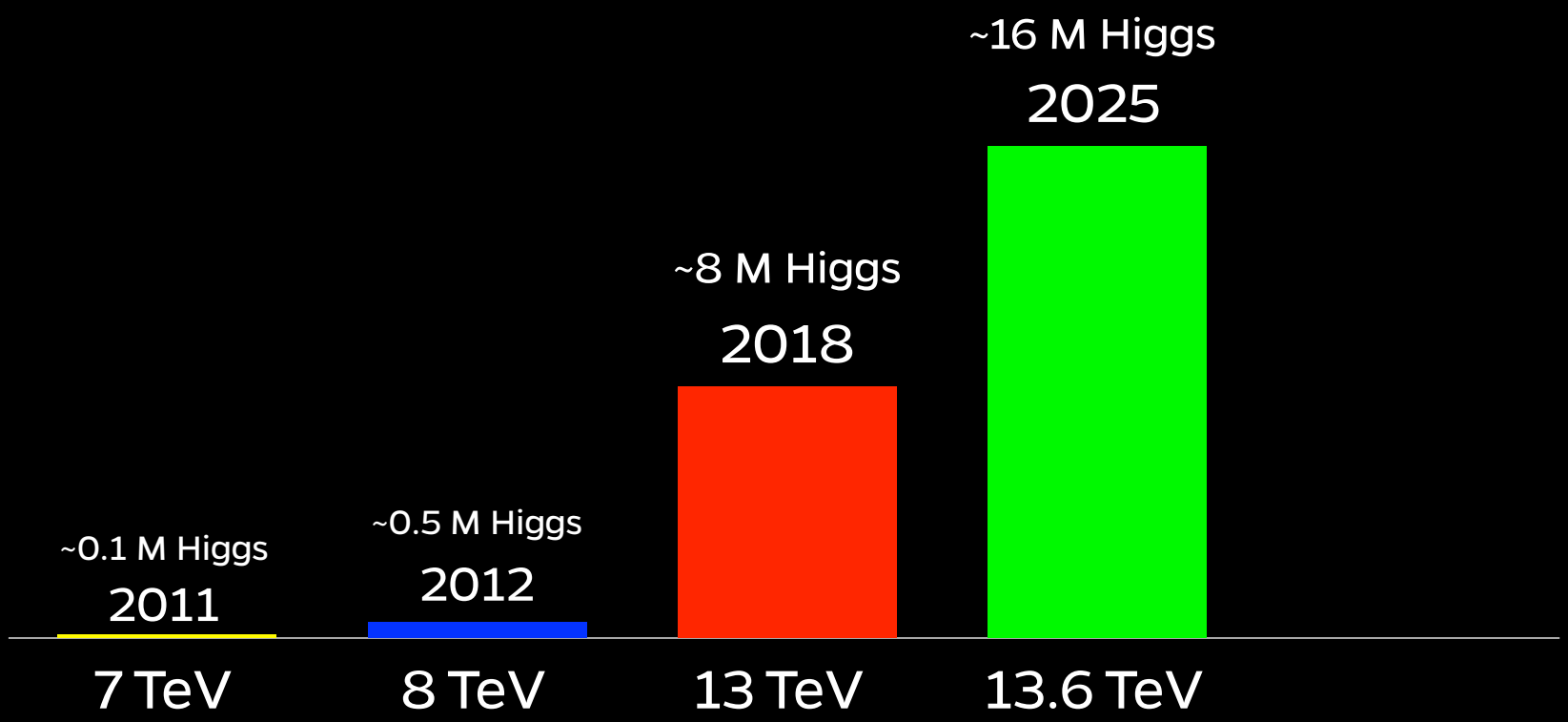

Number of Higgs boson produced

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2012	Run 1	8 TeV	~20 fb^{-1}	~500 K
2015 - 2018	Run 2	13 TeV	~140 fb^{-1}	~8 M
2022 - 2025	Run 3	13.6 TeV	~300 fb^{-1}	~16 M
2029 - 2042	HL-LHC	14 TeV	~3000 fb^{-1}	~200 M

2042

~200 M Higgs

Number of Higgs boson produced

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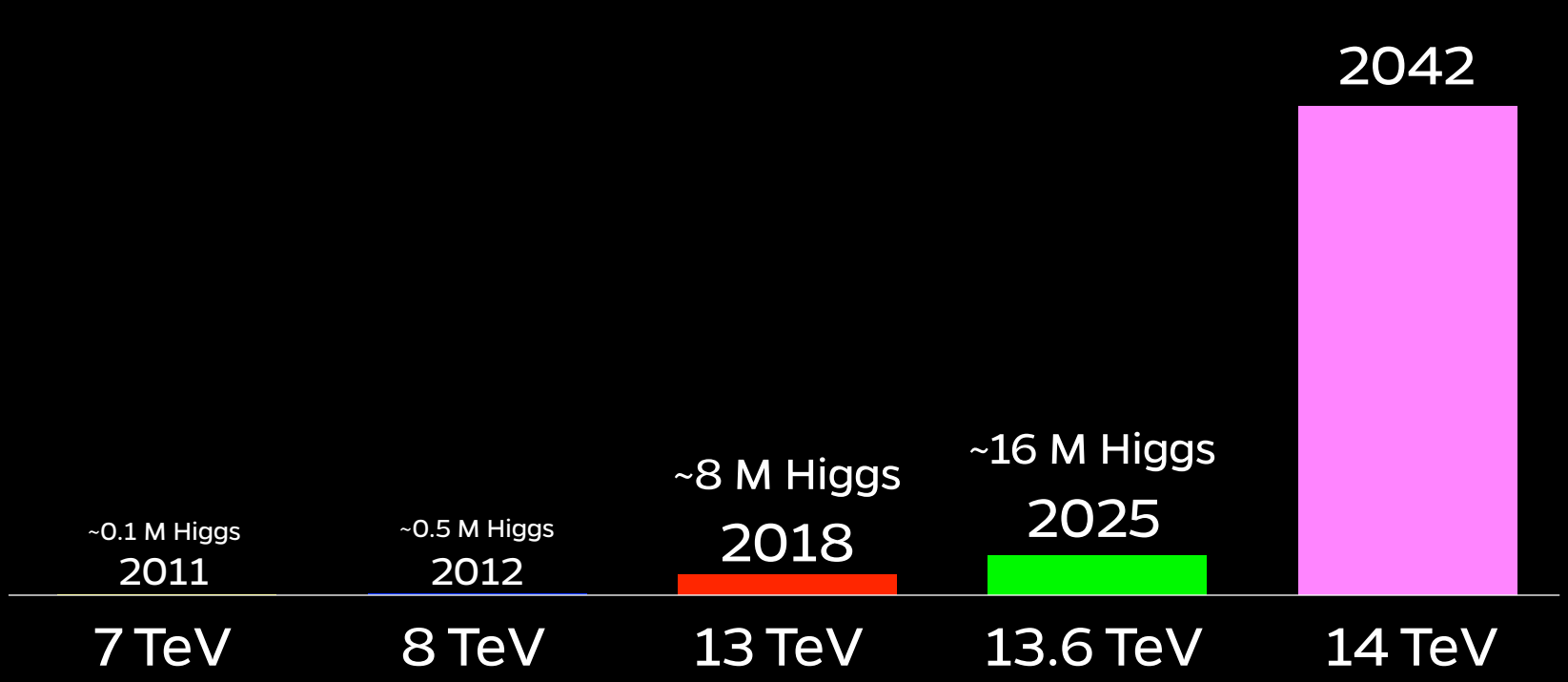
Years	Runs	Energy	Luminosity	# of Higgs
2011	Run 1	7 TeV	~5 fb^{-1}	~100 K
2012	Run 1	8 TeV	~20 fb^{-1}	~500 K
2015 - 2018	Run 2	13 TeV	~140 fb^{-1}	~8 M
2022 - 2025	Run 3	13.6 TeV	~300 fb^{-1}	~16 M
2029 - 2042	HL-LHC	14 TeV	~3000 fb^{-1}	~200 M



Number of Higgs boson produced

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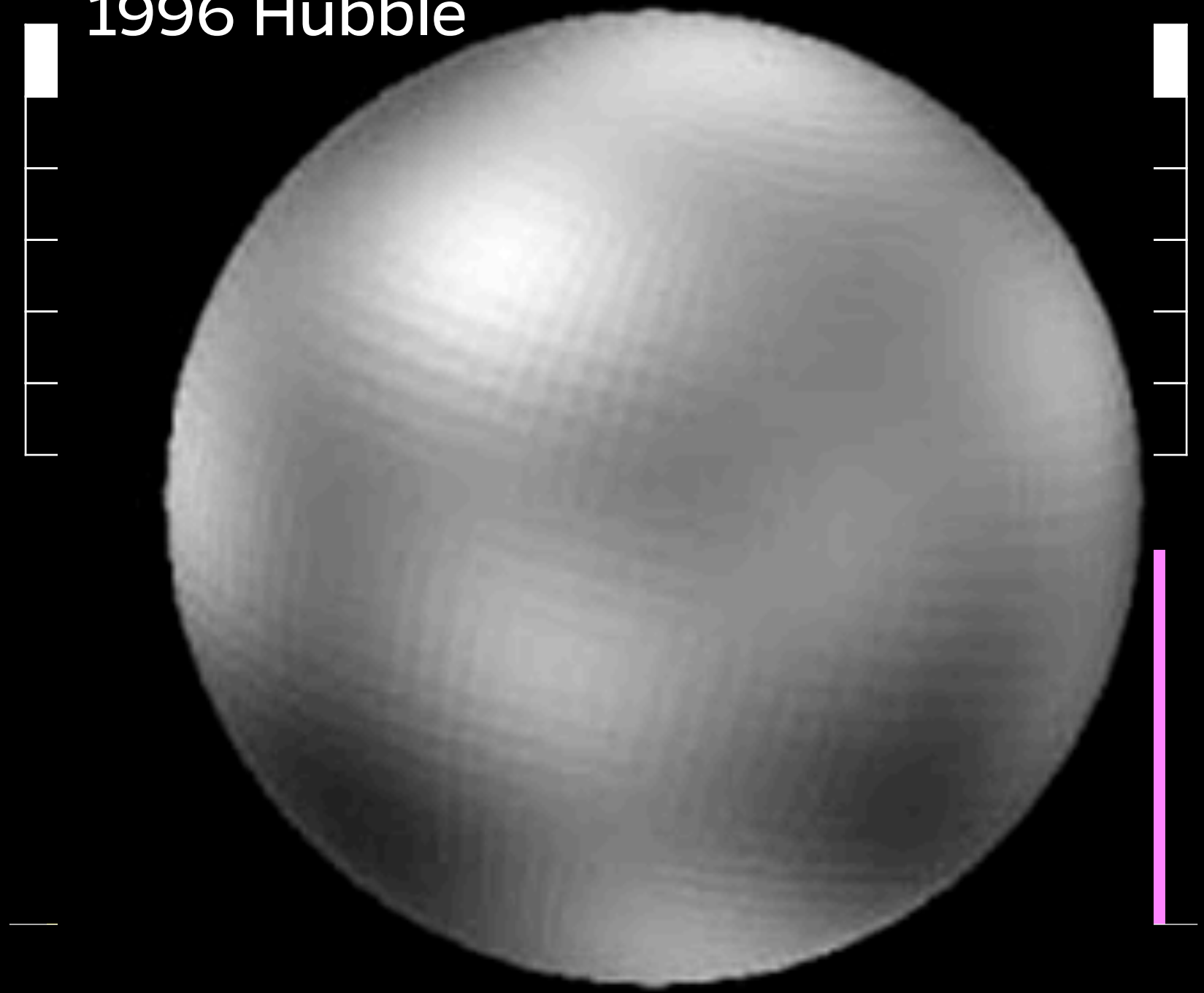
1996 Hubble



~200 M
Higgs

Number of Higgs boson produced

UF
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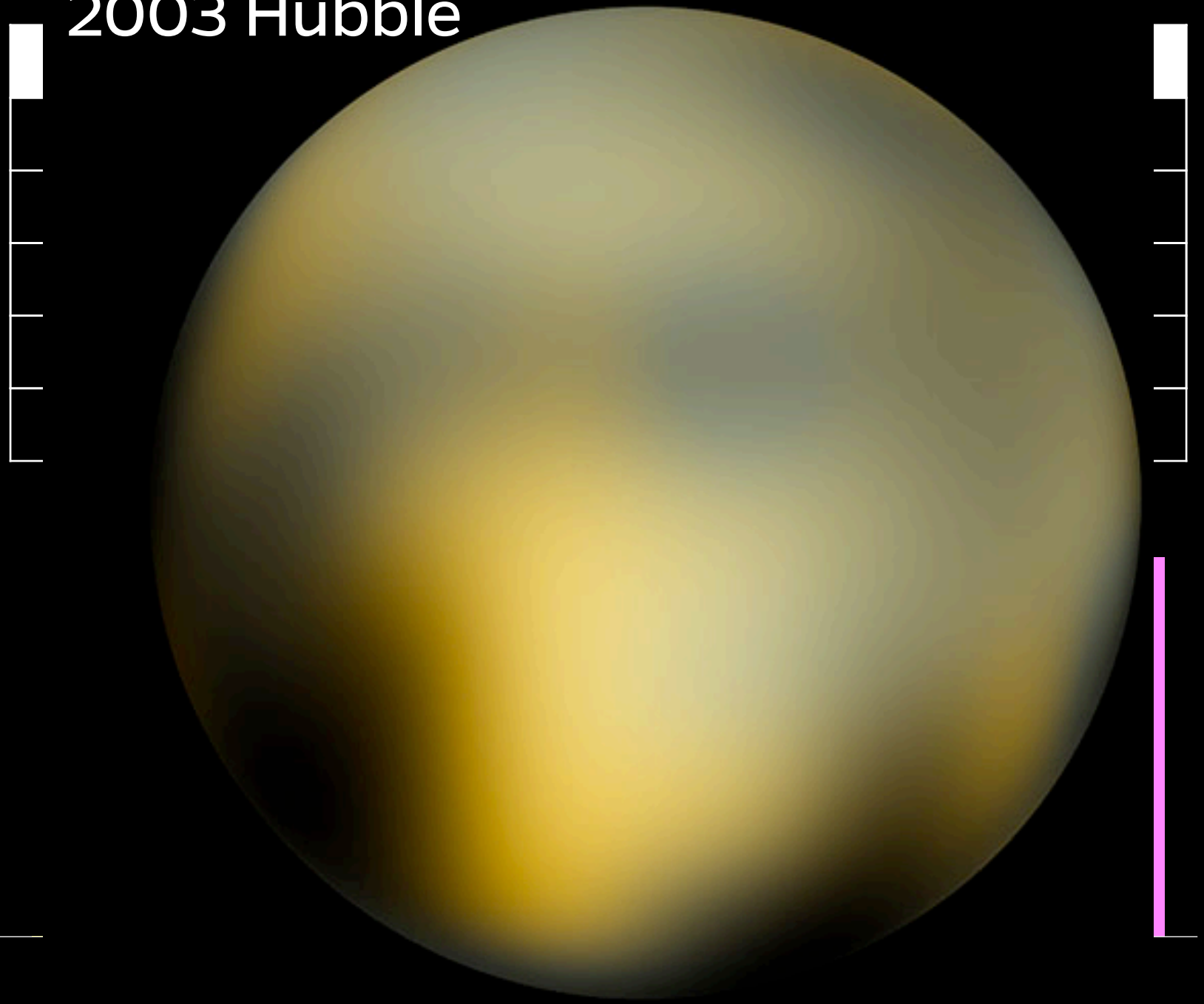
Florida

2003 Hubble



~200 M
Higgs

More Higgs couplings

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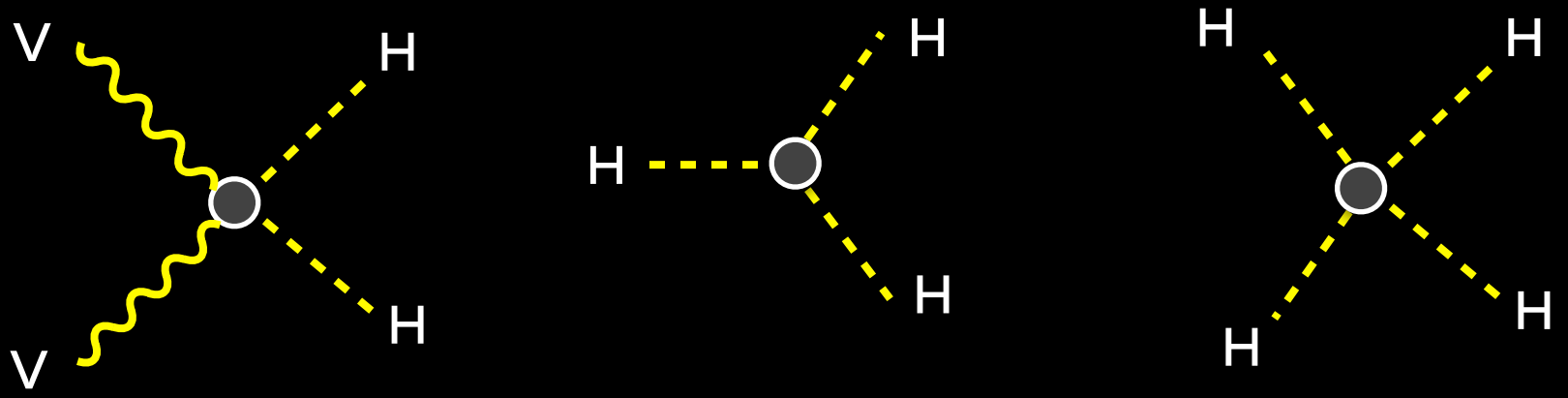
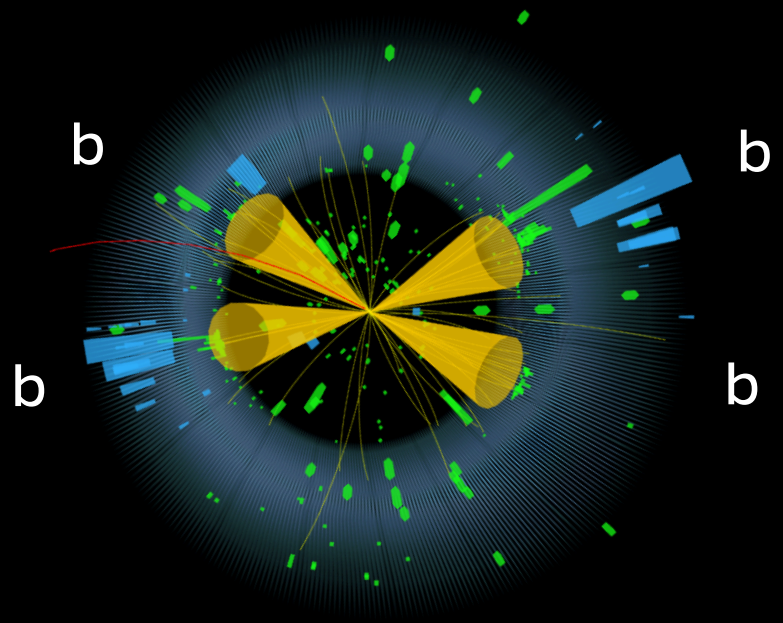


These couplings require at least two Higgs in the process to probe



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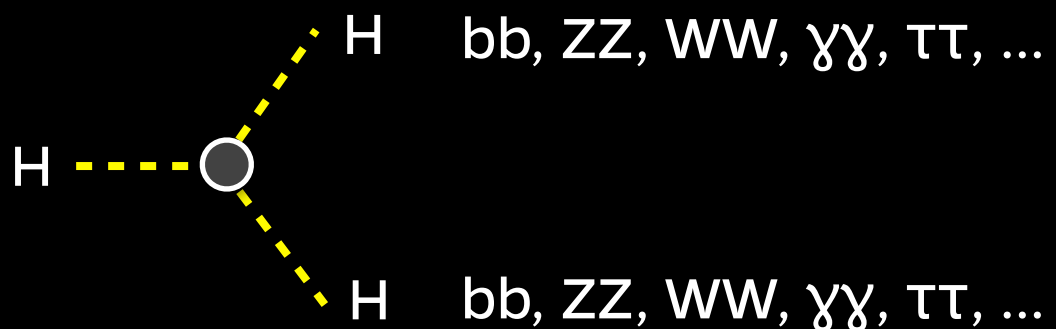
Nature 607 (2022) 60

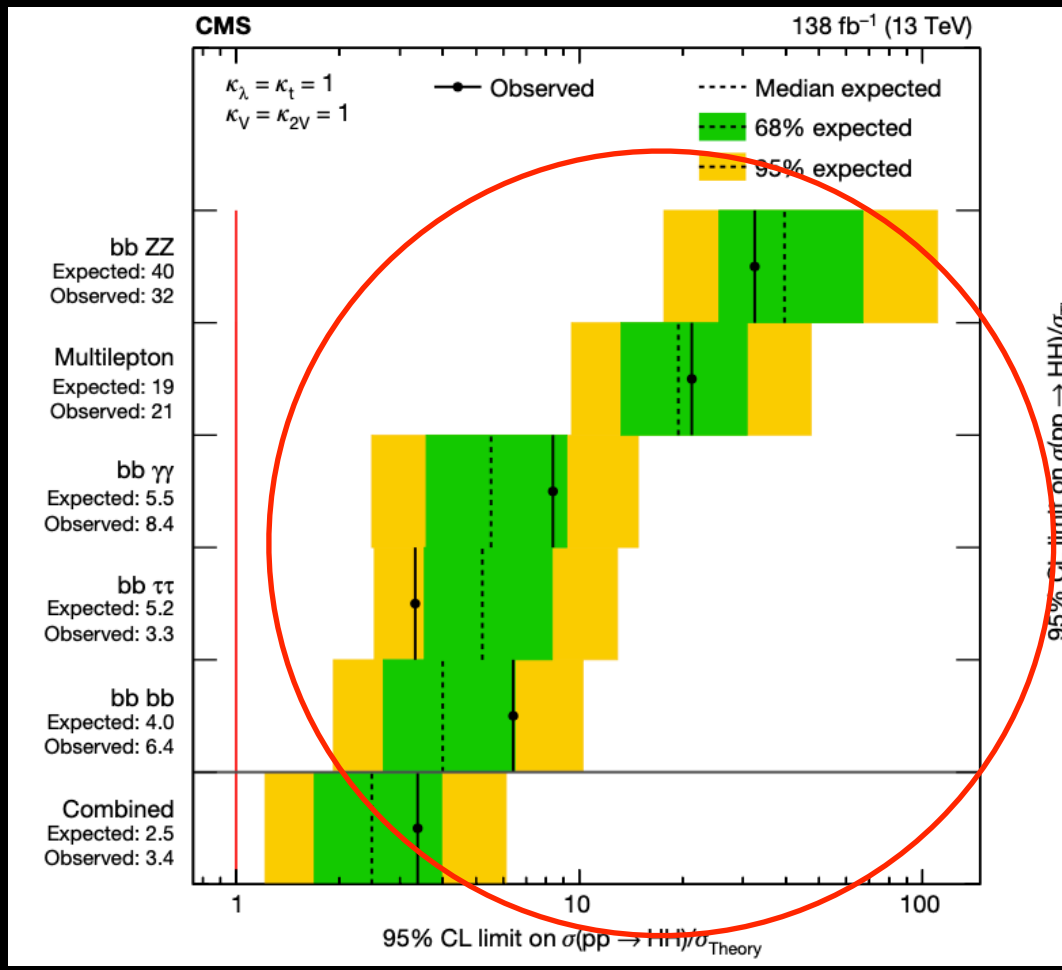


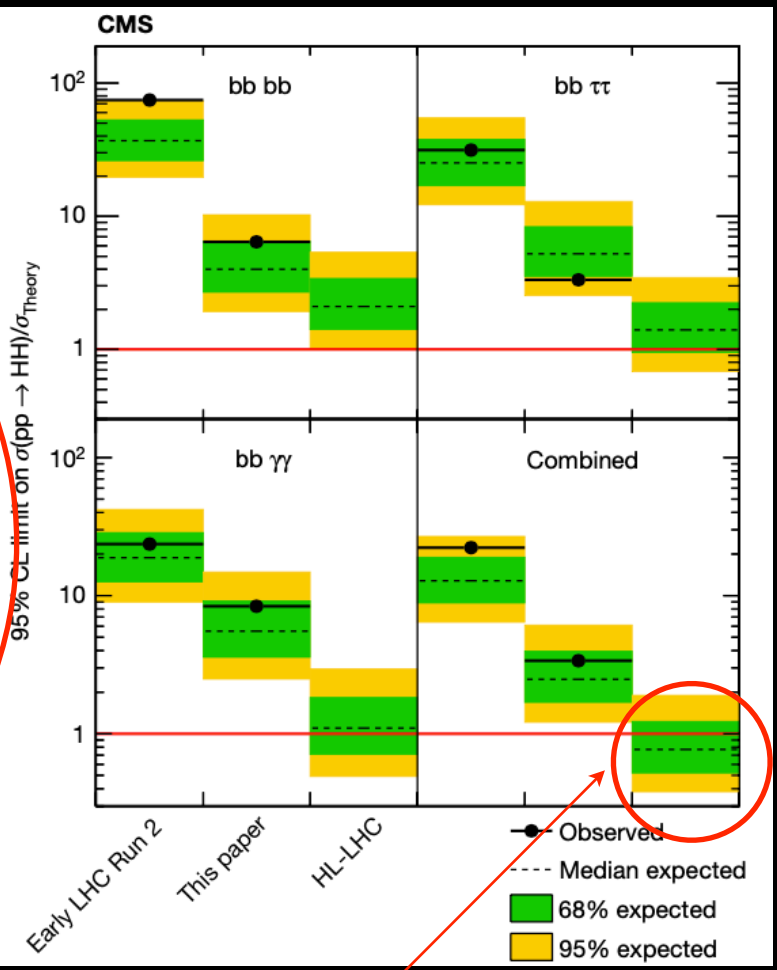
HH→bbZZ

HH→bbγγ

HH→bbττ

HH→bbbb





SM

Today
(~8M Higgs)

200M Higgs

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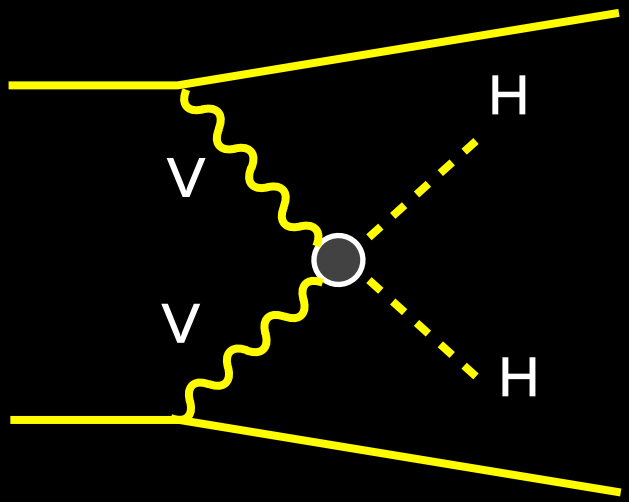
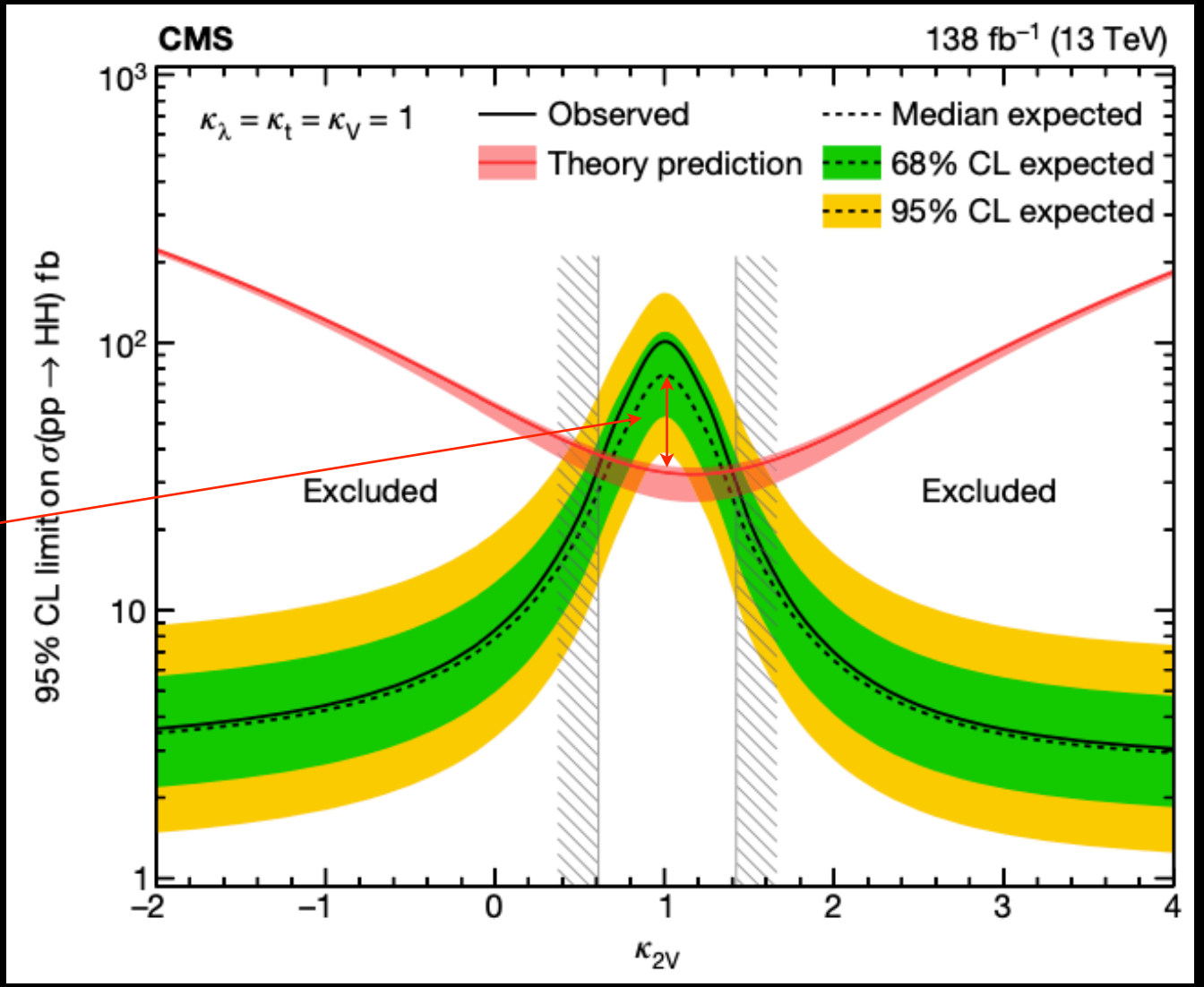
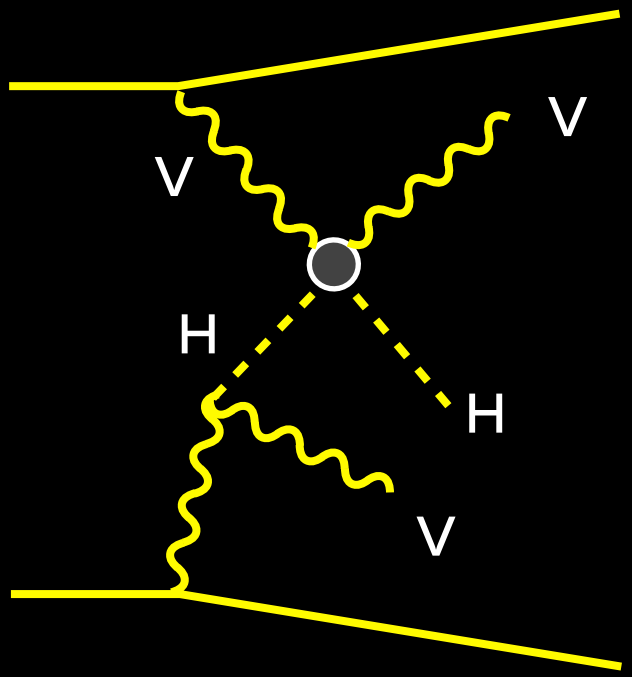
Nature 607 (2022) 60



Large gap to cover to observe SM



~40% constraint



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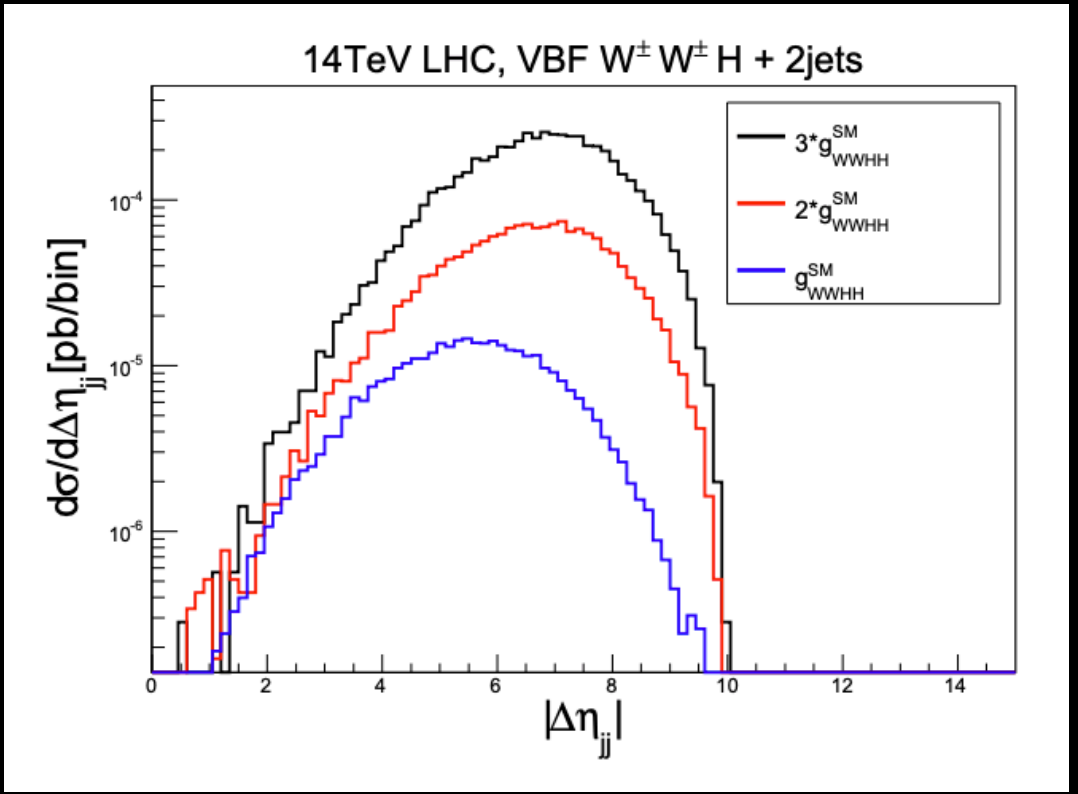

New ways are also being investigated

Summary

Since the discovery Higgs boson has been studied in detail

Mass, Width, Couplings, CP, and differential

Pushing new frontier via searching for new processes

involving the Higgs boson

In the future we will have a much more precise portrait of

the Higgs

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The Energy Frontier vision in a nutshell

Part of it is what we talked about today

It is essential to

- Complete the HL-LHC program,
- Start now a targeted program for detector R&D for Higgs Factories
- Support a fast start of the construction of a Higgs factory
- Ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a *muon collider* or a *hadron collider*.

Higgs factory allows much "sharper" portrait picture of Higgs

Support to AF, CEF, CompF, IF, and TF is crucial to the realization of the EF vision

Energy Frontier Highlight

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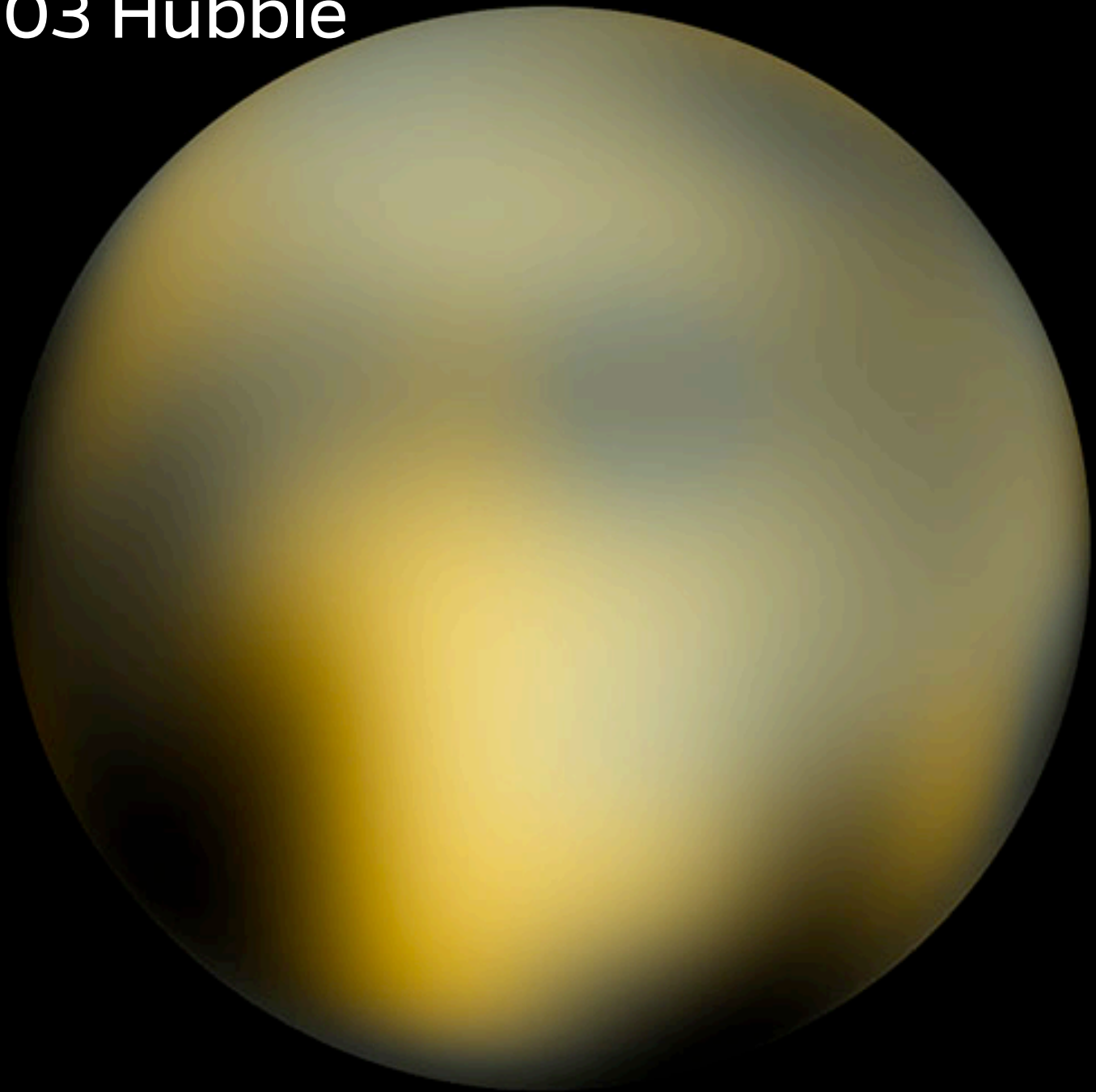
2003 Hubble



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It is essenti

- Complete
- Start now
- Support a
- Ensure the frontier fa

Support to AF

h
Higgs

energy

EF vision

Energy Frontier Highlight

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2015 New Horizon

The E

It is essenti

- Complete
- Start now
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- Ensure the frontier fa

Support to AF

h
Higgs

energy

EF vision