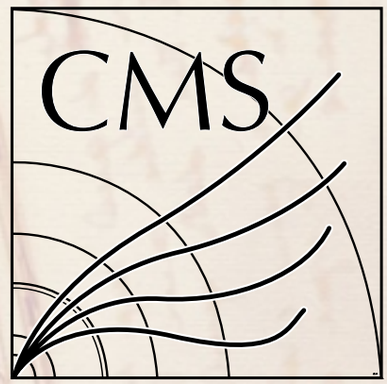
# Top-Higgs coupling and how we measure it

Ted Kolberg (FSU)

QuarkNet, 23 July 2018



# Overview

- Role of Higgs in the Standard Model of particle physics.
- Why top-Higgs coupling is important.
- Higgs production and decay modes.
- How to measure the top-Higgs coupling.
- What we learned and what will happen next.

# Standard Model of Elementary Particles

three generations of matter
(fermions)

| | I | II | III | | |
|---|---|---|---|---|---|
| mass | ≃2.2 MeV/c² | ≃1.28 GeV/c² | ≃173.1 GeV/c² | 0 | ≈125.09 GeV/c² |
| charge | 2/3 | 2/3 | 2/3 | 0 | 0 |
| spin | 1/2 | 1/2 | 1/2 | 1 | 0 |
| | u up | c charm | t top | g gluon | H Higgs |
| | ≃4.7 MeV/c² | ≃96 MeV/c² | ≈4.18 GeV/c² | 0 | |
| | -1/3 | -1/3 | -1/3 | 0 | |
| | 1/2 | 1/2 | 1/2 | 1 | |
| | d down | s strange | b bottom | γ photon | |
| | ≈0.511 MeV/c² | ≃105.66 MeV/c² | ≈1.7768 GeV/c² | ≈91.19 GeV/c² | |
| | -1 | -1 | -1 | 0 | |
| | 1/2 | 1/2 | 1/2 | 1 | |
| | e electron | μ muon | τ tau | Z Z boson | |
| | <2.2 eV/c² | <1.7 MeV/c² | <15.5 MeV/c² | ≈80.39 GeV/c² | |
| | 0 | 0 | 0 | ±1 | |
| | 1/2 | 1/2 | 1/2 | 1 | |
| | $\nu_e$ electron neutrino | $\nu_\mu$ muon neutrino | $\nu_\tau$ tau neutrino | W W boson | |

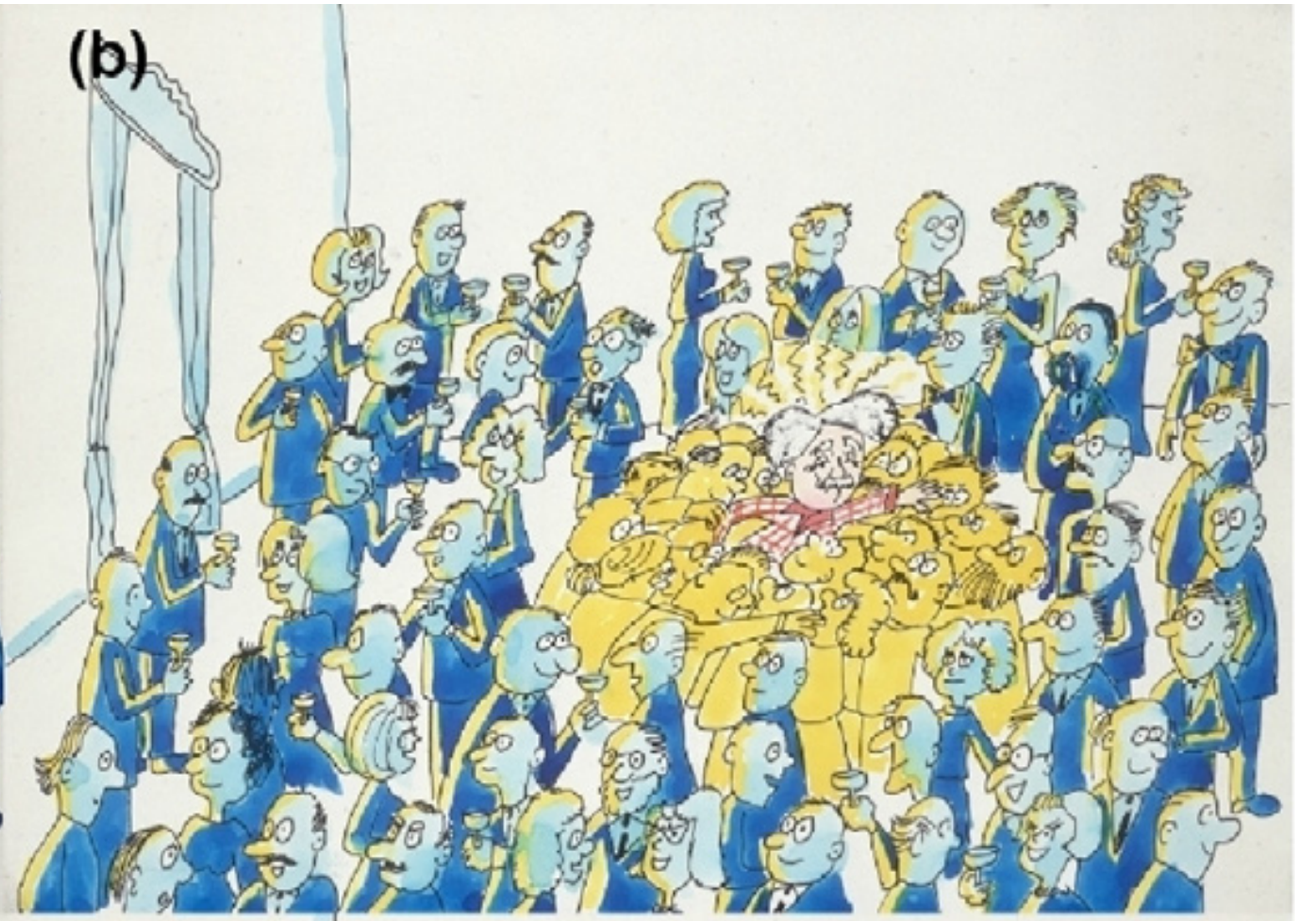
QUARKS

LEPTONS

GAUGE BOSONS

SCALAR BOSONS

(a)


(b)

(c)

(d)

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QUARKS

LEPTONS

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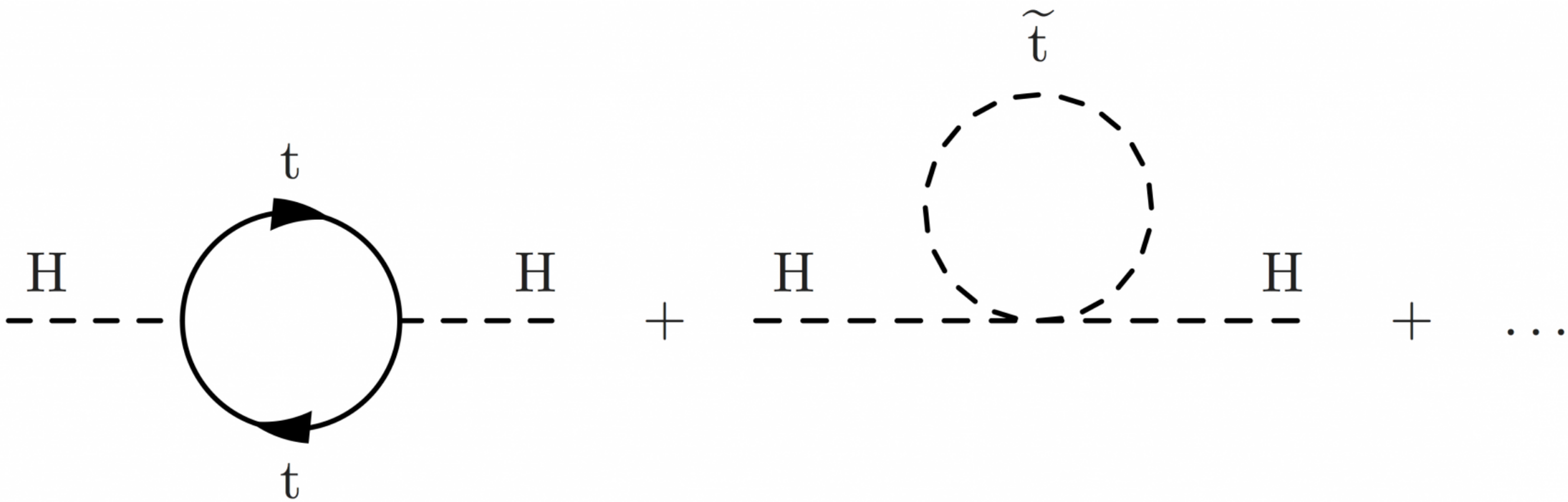
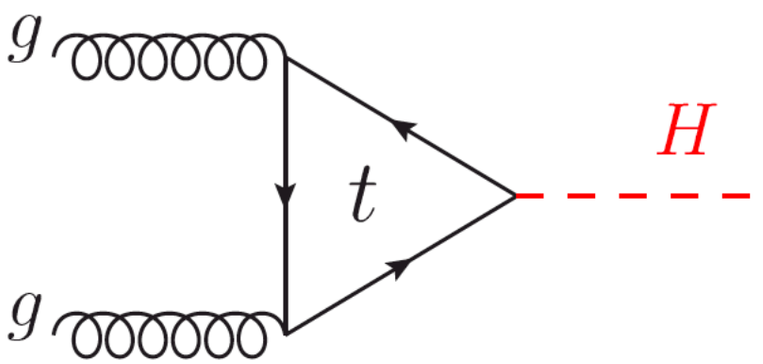
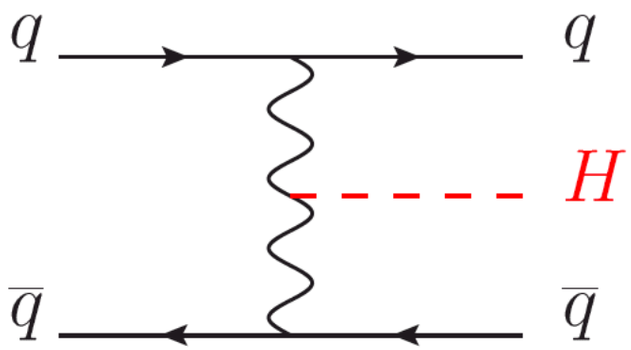
$$\Delta m_H^2 =$$

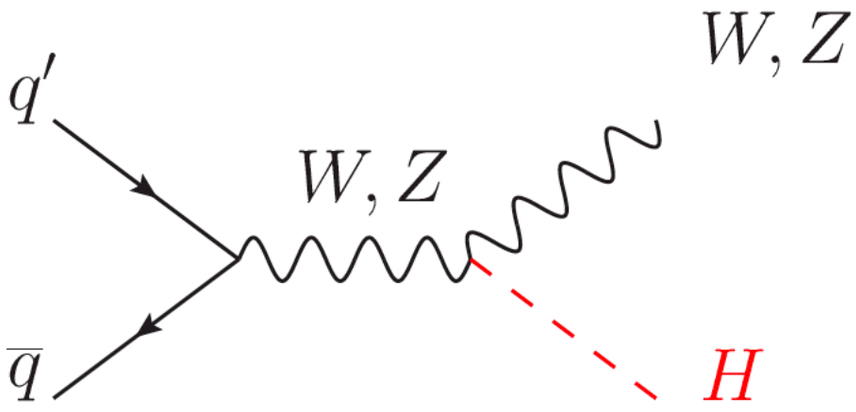



g
g
t
H

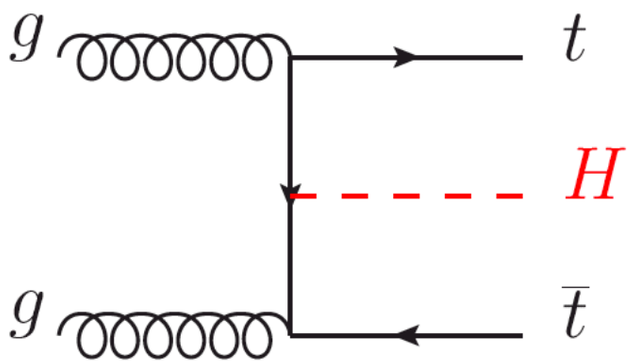
(a)


q
q
H
$\overline{q}$
$\overline{q}$

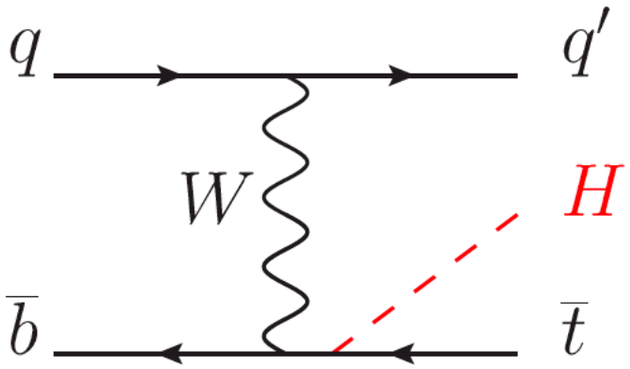
(b)


W, Z
q′
W, Z
$\overline{q}$
H

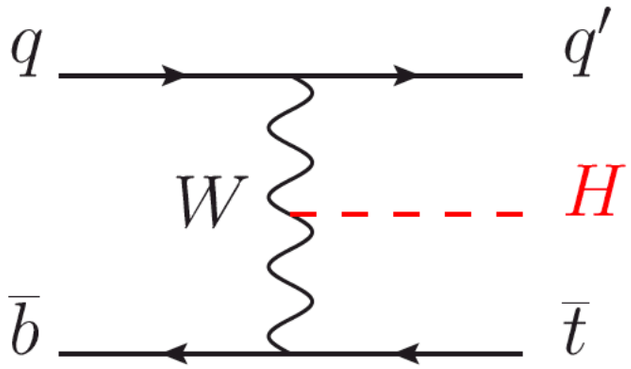
(c)


g
t
H
g
$\overline{t}$

(d)


q
q′
W
H
$\overline{b}$
$\overline{t}$

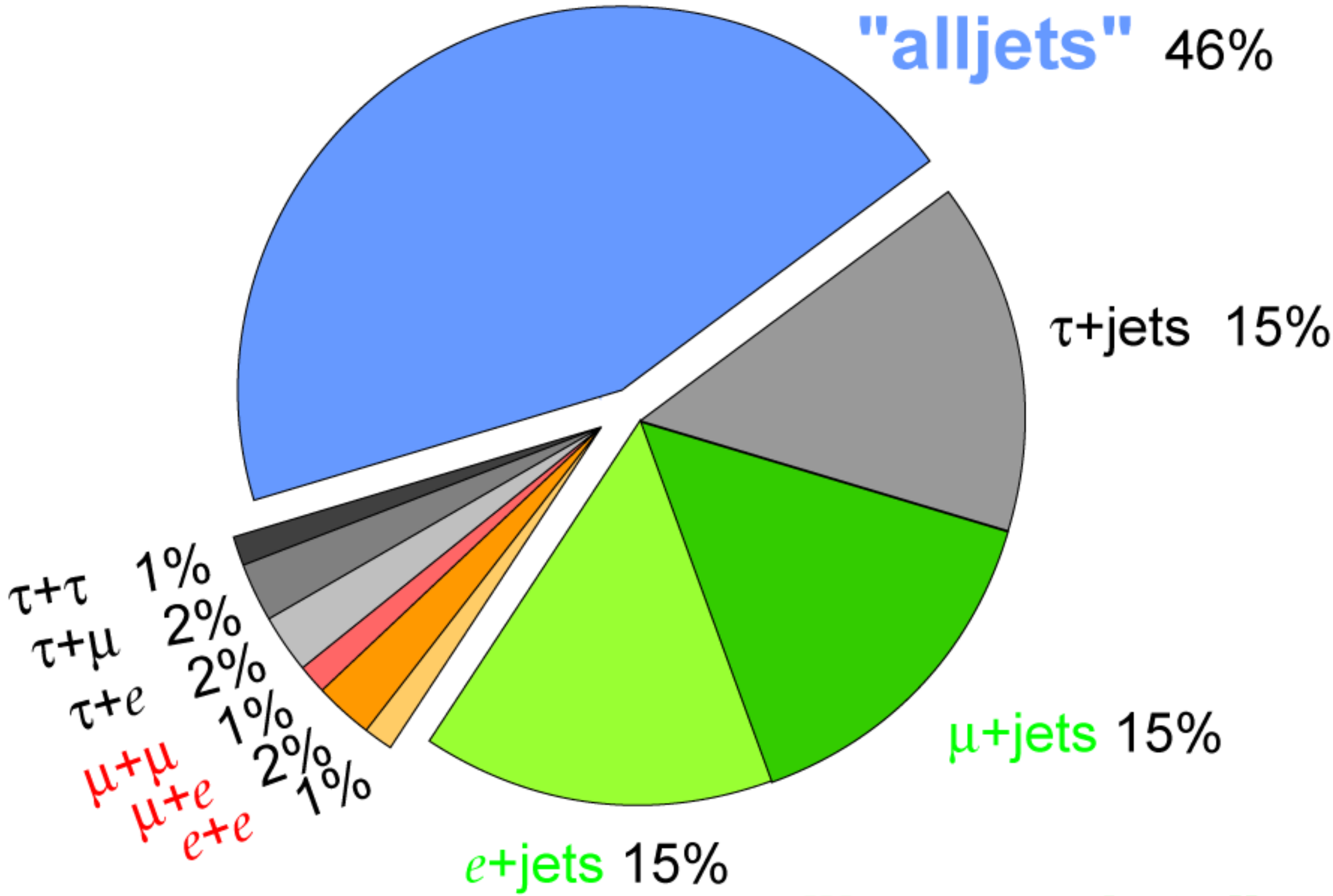
(e)

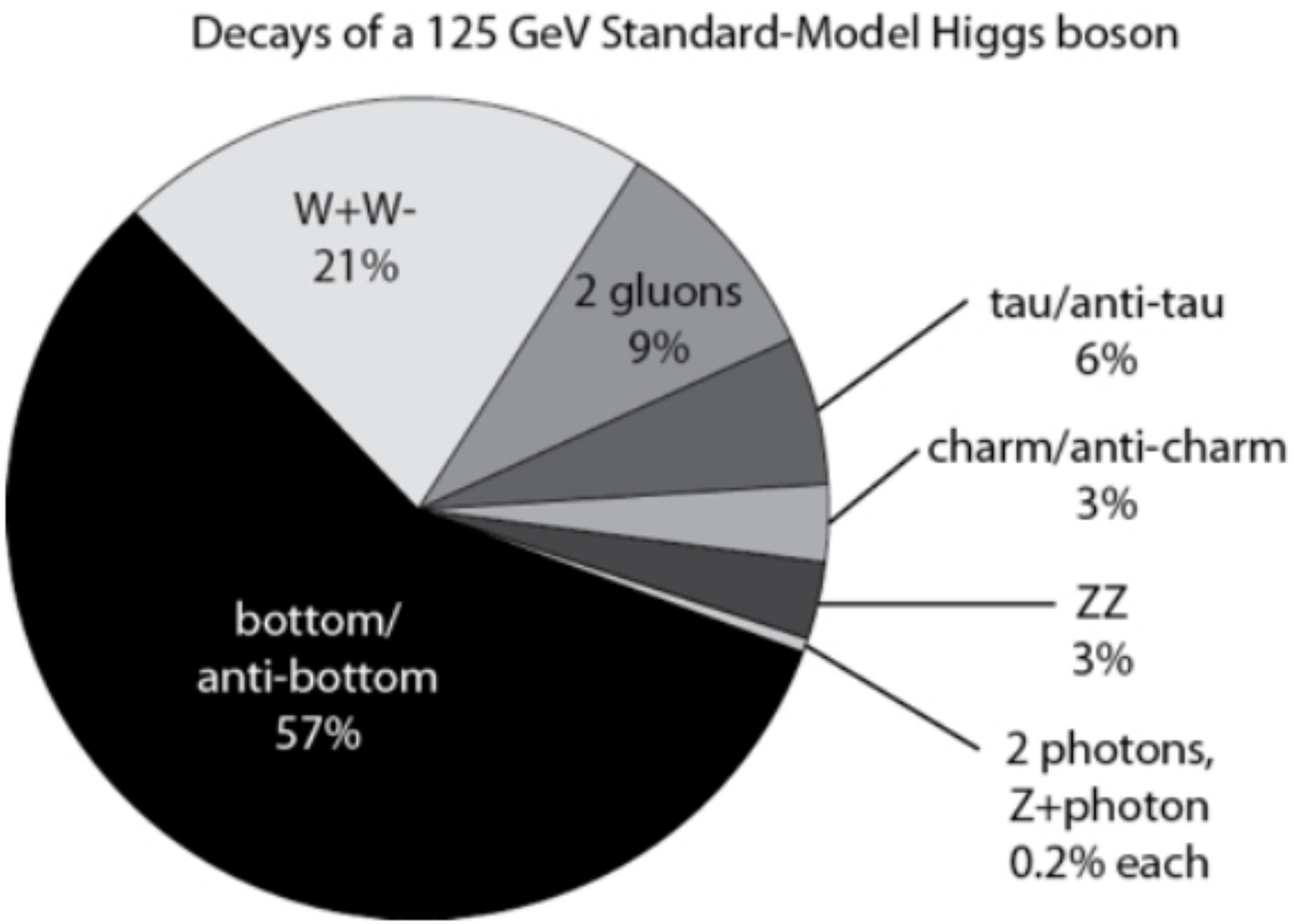

q
q′
W
H
$\overline{b}$
$\overline{t}$

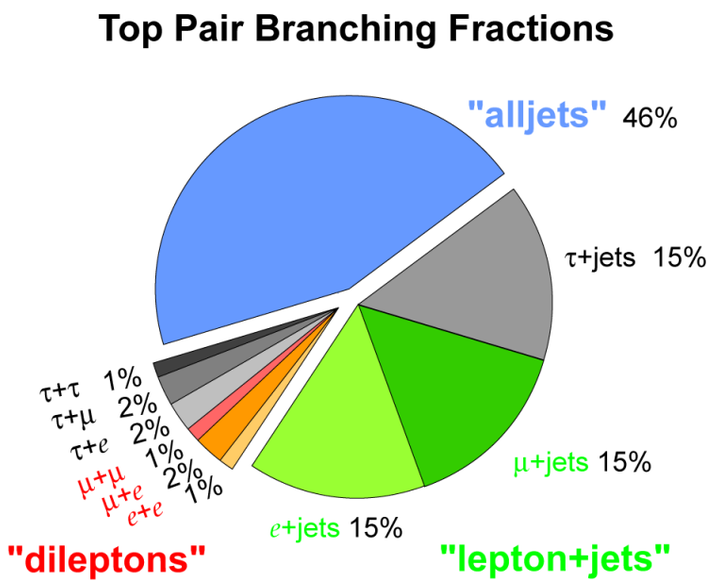
(f)

| $\sqrt{s}$ (TeV) | Production cross section (in pb) for $m_H = 125\,\text{GeV}$ | | | | | |
|---|---|---|---|---|---|---|
| | ggF | VBF | $WH$ | $ZH$ | $t\bar{t}H$ | total |
| 1.96 | $0.95^{+17\%}_{-17\%}$ | $0.065^{+8\%}_{-7\%}$ | $0.13^{+8\%}_{-8\%}$ | $0.079^{+8\%}_{-8\%}$ | $0.004^{+10\%}_{-10\%}$ | 1.23 |
| 7 | $16.9^{+5\%}_{-5\%}$ | $1.24^{+2\%}_{-2\%}$ | $0.58^{+3\%}_{-3\%}$ | $0.34^{+4\%}_{-4\%}$ | $0.09^{+8\%}_{-14\%}$ | 19.1 |
| 8 | $21.4^{+5\%}_{-5\%}$ | $1.60^{+2\%}_{-2\%}$ | $0.70^{+3\%}_{-3\%}$ | $0.42^{+5\%}_{-5\%}$ | $0.13^{+8\%}_{-13\%}$ | 24.2 |
| 13 | $48.6^{+5\%}_{-5\%}$ | $3.78^{+2\%}_{-2\%}$ | $1.37^{+2\%}_{-2\%}$ | $0.88^{+5\%}_{-5\%}$ | $0.50^{+9\%}_{-13\%}$ | 55.1 |
| 14 | $54.7^{+5\%}_{-5\%}$ | $4.28^{+2\%}_{-2\%}$ | $1.51^{+2\%}_{-2\%}$ | $0.99^{+5\%}_{-5\%}$ | $0.60^{+9\%}_{-13\%}$ | 62.1 |

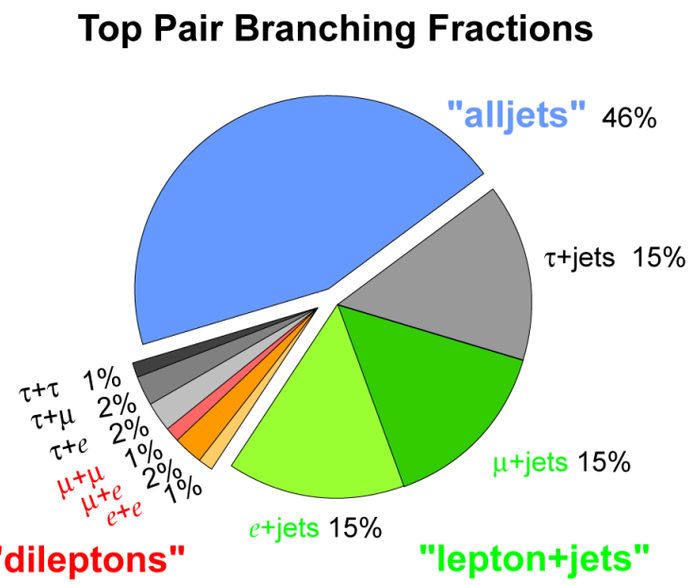
# Top Pair Branching Fractions




Decays of a 125 GeV Standard-Model Higgs boson
W+W-
21%
2 gluons
9%
tau/anti-tau
6%
charm/anti-charm
3%
ZZ
3%
2 photons,
Z+photon
0.2% each
bottom/
anti-bottom
57%


Top Pair Branching Fractions
"alljets" 46%
τ+jets 15%
μ+jets 15%
e+jets 15%
τ+τ 1%
τ+μ 2%
τ+e 2%
μ+μ 1%
μ+e 2%
e+e 1%
"dileptons"
"lepton+jets"

×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τ+jets 15%
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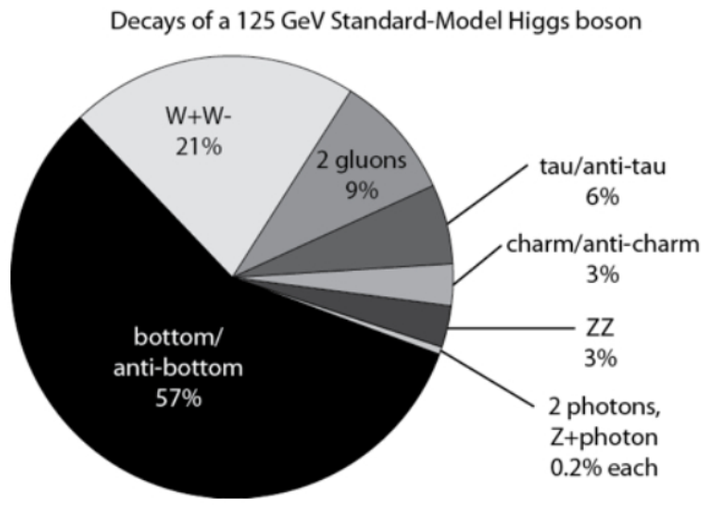
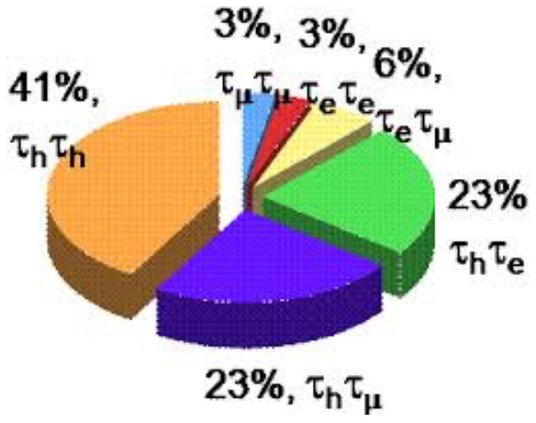
e+jets 15%
τ+τ 1%
τ+μ 2%
τ+e 2%
μ+μ 1%
μ+e 2%
e+e 1%
"dileptons"
"lepton+jets"

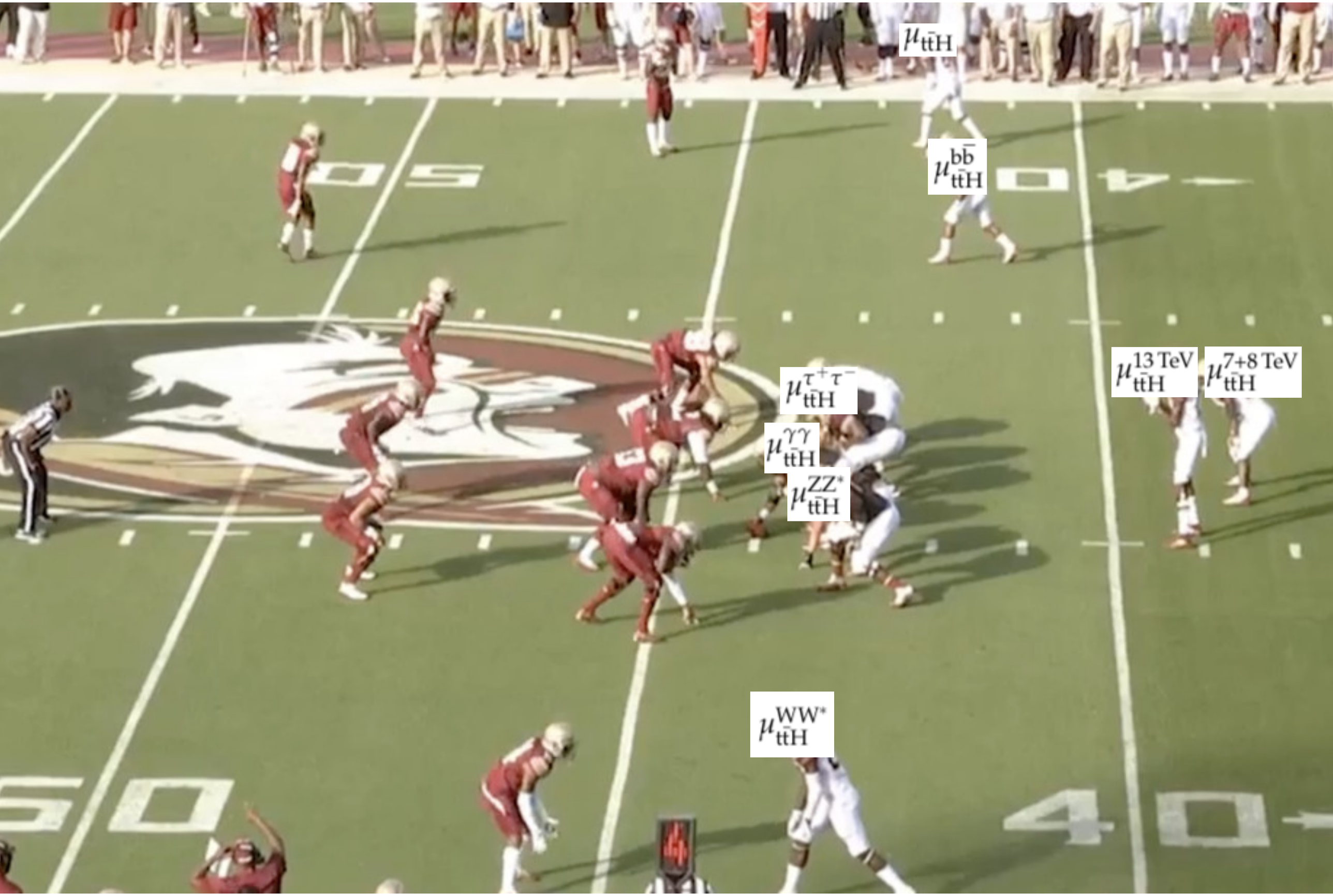
×

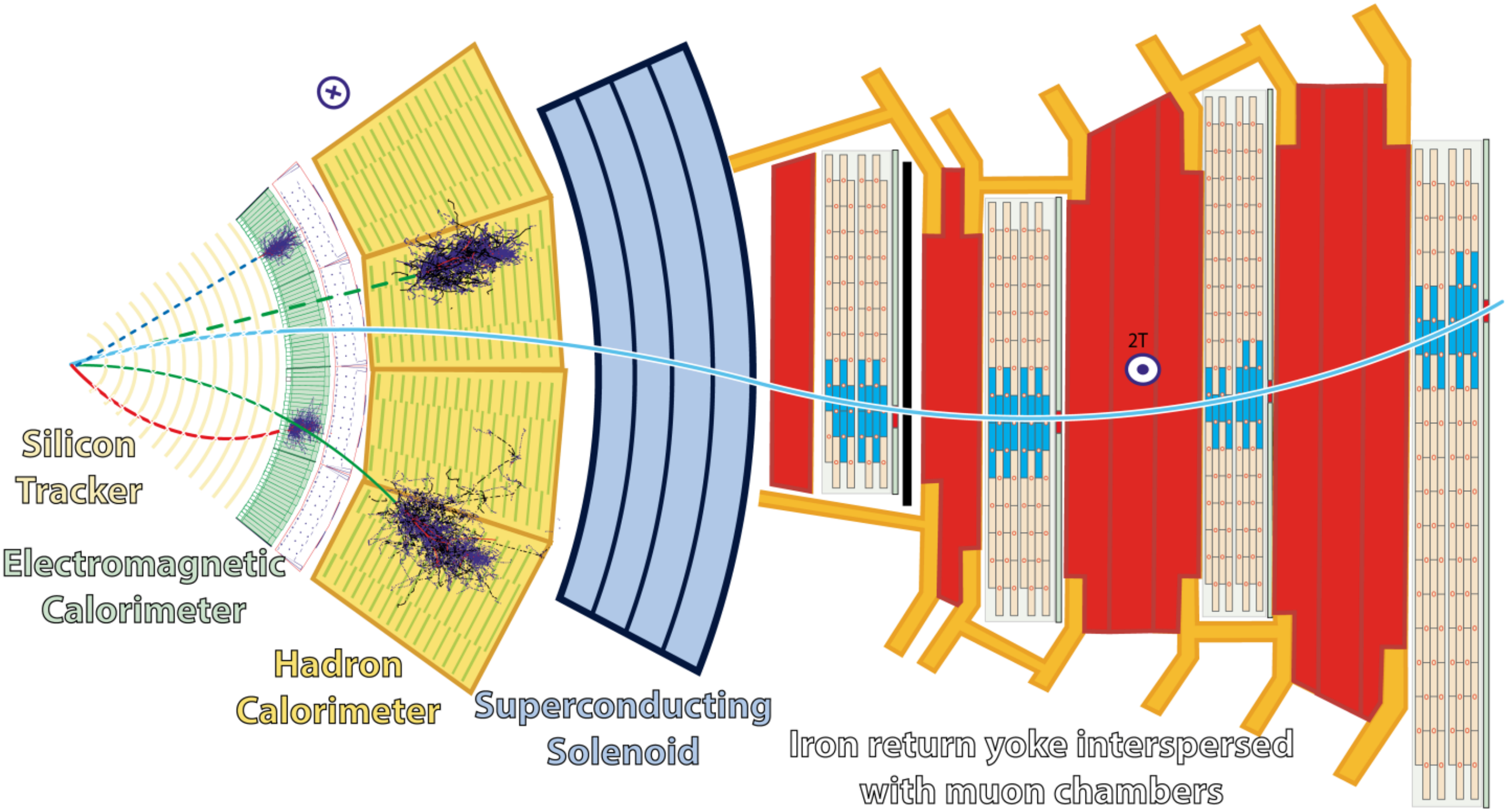

Decays of a 125 GeV Standard-Model Higgs boson
W+W- 21%
2 gluons 9%
tau/anti-tau 6%
charm/anti-charm 3%
ZZ 3%
2 photons, Z+photon 0.2% each
bottom/ anti-bottom 57%

(


41%, τhτh
3%, 3%, 6%, τμτμ τeτe τeτμ
23% τhτe
23%, τhτμ

)


$\mu_{t\bar{t}H}$
$\mu^{b\bar{b}}_{t\bar{t}H}$
$\mu^{\tau^+\tau^-}_{t\bar{t}H}$
$\mu^{\gamma\gamma}_{t\bar{t}H}$
$\mu^{ZZ^*}_{t\bar{t}H}$
$\mu^{WW^*}_{t\bar{t}H}$
$\mu^{13\,TeV}_{t\bar{t}H}$
$\mu^{7+8\,TeV}_{t\bar{t}H}$

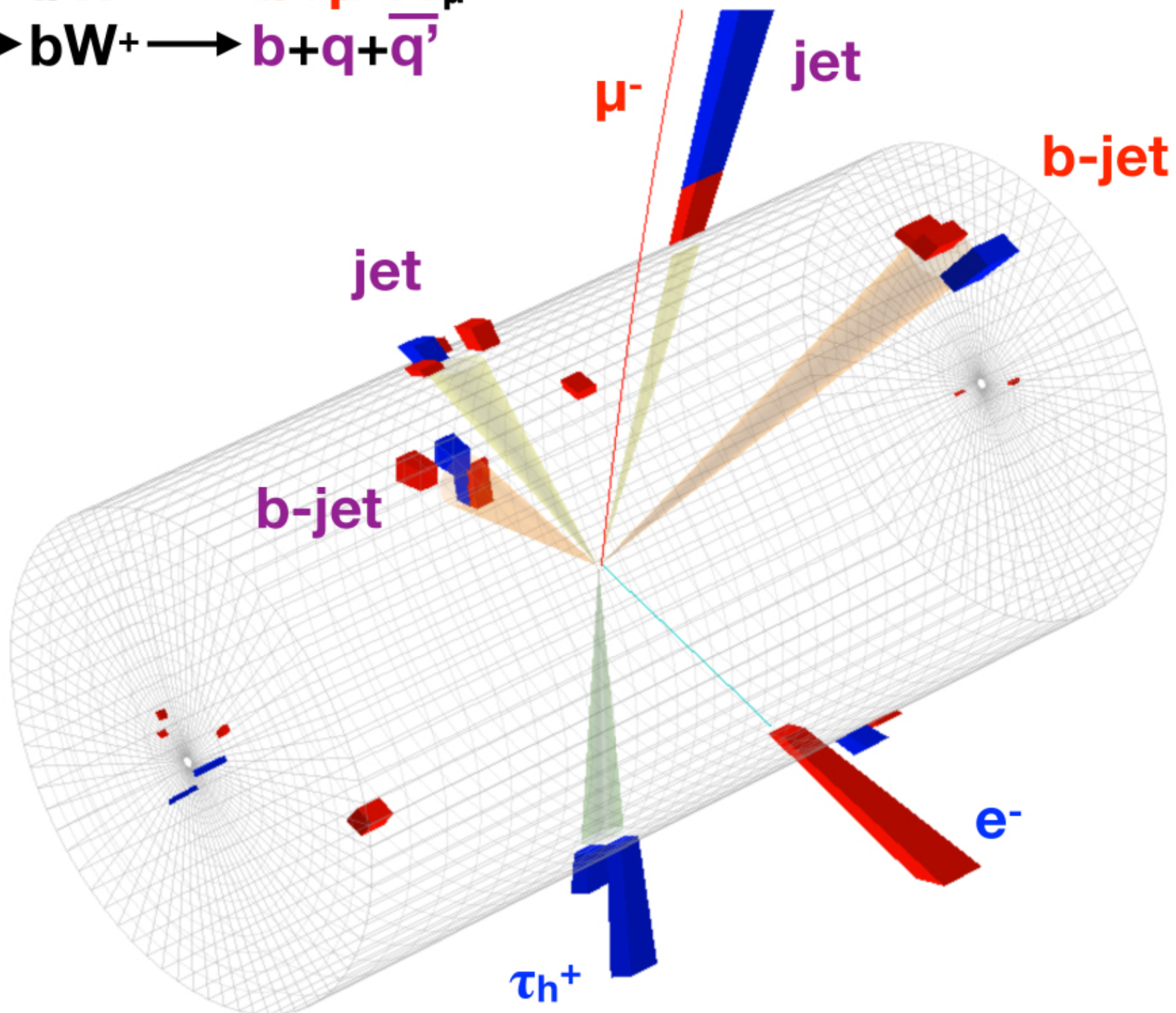

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with muon chambers
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

$pp \rightarrow t\bar{t}H$

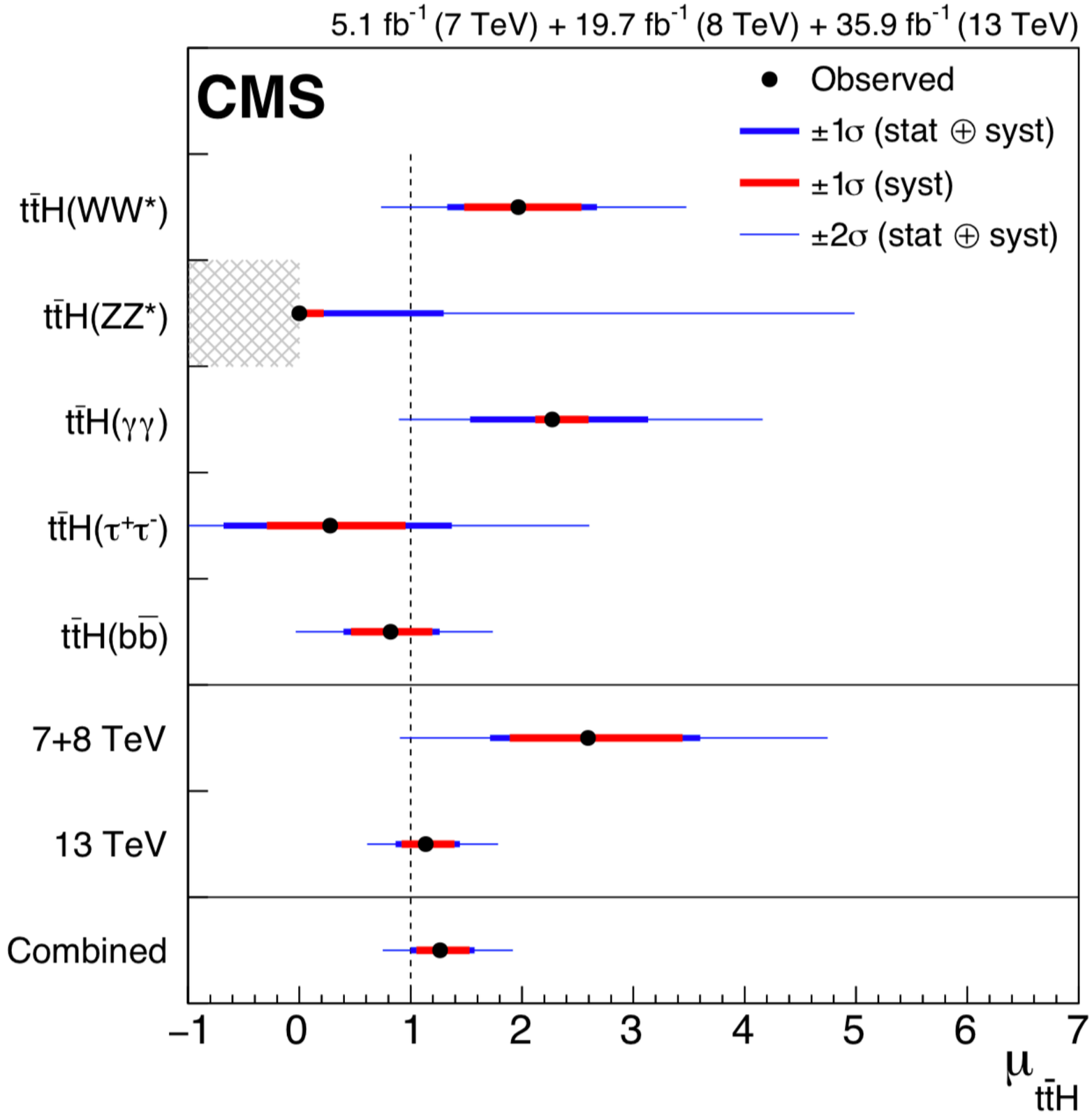
$\tau^-\tau^+ \rightarrow e^- + \bar{\nu}_e + \nu_\tau + \tau_h^+ + \bar{\nu}_\tau$

$\bar{b}W^- \rightarrow \bar{b} + \mu^- + \bar{\nu}_\mu$

$bW^+ \rightarrow b + q + \bar{q}'$



| Parameter | Best fit | Uncertainty: Stat | Expt | Thbgd | Thsig |
|---|---|---|---|---|---|
| $\mu_{t\bar{t}H}^{WW^*}$ | $1.97^{+0.71}_{-0.64}$ | $^{+0.42}_{-0.41}$ | $^{+0.46}_{-0.42}$ | $^{+0.21}_{-0.21}$ | $^{+0.25}_{-0.12}$ |
| | $\left(^{+0.57}_{-0.54}\right)$ | $\left(^{+0.39}_{-0.38}\right)$ | $\left(^{+0.36}_{-0.34}\right)$ | $\left(^{+0.17}_{-0.17}\right)$ | $\left(^{+0.12}_{-0.03}\right)$ |
| $\mu_{t\bar{t}H}^{ZZ^*}$ | $0.00^{+1.30}_{-0.00}$ | $^{+1.28}_{-0.00}$ | $^{+0.20}_{-0.00}$ | $^{+0.04}_{-0.00}$ | $^{+0.09}_{-0.00}$ |
| | $\left(^{+2.89}_{-0.99}\right)$ | $\left(^{+2.82}_{-0.99}\right)$ | $\left(^{+0.51}_{-0.00}\right)$ | $\left(^{+0.15}_{-0.00}\right)$ | $\left(^{+0.27}_{-0.00}\right)$ |
| $\mu_{t\bar{t}H}^{\gamma\gamma}$ | $2.27^{+0.86}_{-0.74}$ | $^{+0.80}_{-0.72}$ | $^{+0.15}_{-0.09}$ | $^{+0.02}_{-0.01}$ | $^{+0.29}_{-0.13}$ |
| | $\left(^{+0.73}_{-0.64}\right)$ | $\left(^{+0.71}_{-0.64}\right)$ | $\left(^{+0.09}_{-0.04}\right)$ | $\left(^{+0.01}_{-0.00}\right)$ | $\left(^{+0.13}_{-0.05}\right)$ |
| $\mu_{t\bar{t}H}^{\tau^+\tau^-}$ | $0.28^{+1.09}_{-0.96}$ | $^{+0.86}_{-0.77}$ | $^{+0.64}_{-0.53}$ | $^{+0.10}_{-0.09}$ | $^{+0.20}_{-0.19}$ |
| | $\left(^{+1.00}_{-0.89}\right)$ | $\left(^{+0.83}_{-0.76}\right)$ | $\left(^{+0.54}_{-0.47}\right)$ | $\left(^{+0.09}_{-0.08}\right)$ | $\left(^{+0.14}_{-0.01}\right)$ |
| $\mu_{t\bar{t}H}^{b\bar{b}}$ | $0.82^{+0.44}_{-0.42}$ | $^{+0.23}_{-0.23}$ | $^{+0.24}_{-0.23}$ | $^{+0.27}_{-0.27}$ | $^{+0.11}_{-0.03}$ |
| | $\left(^{+0.44}_{-0.42}\right)$ | $\left(^{+0.23}_{-0.22}\right)$ | $\left(^{+0.24}_{-0.23}\right)$ | $\left(^{+0.26}_{-0.27}\right)$ | $\left(^{+0.11}_{-0.04}\right)$ |
| $\mu_{t\bar{t}H}^{7+8\,TeV}$ | $2.59^{+1.01}_{-0.88}$ | $^{+0.54}_{-0.53}$ | $^{+0.53}_{-0.49}$ | $^{+0.55}_{-0.49}$ | $^{+0.37}_{-0.13}$ |
| | $\left(^{+0.87}_{-0.79}\right)$ | $\left(^{+0.51}_{-0.49}\right)$ | $\left(^{+0.48}_{-0.44}\right)$ | $\left(^{+0.50}_{-0.44}\right)$ | $\left(^{+0.14}_{-0.02}\right)$ |
| $\mu_{t\bar{t}H}^{13\,TeV}$ | $1.14^{+0.31}_{-0.27}$ | $^{+0.17}_{-0.16}$ | $^{+0.17}_{-0.17}$ | $^{+0.13}_{-0.12}$ | $^{+0.14}_{-0.06}$ |
| | $\left(^{+0.29}_{-0.26}\right)$ | $\left(^{+0.16}_{-0.16}\right)$ | $\left(^{+0.17}_{-0.16}\right)$ | $\left(^{+0.13}_{-0.12}\right)$ | $\left(^{+0.11}_{-0.05}\right)$ |
| $\mu_{t\bar{t}H}$ | $1.26^{+0.31}_{-0.26}$ | $^{+0.16}_{-0.16}$ | $^{+0.17}_{-0.15}$ | $^{+0.14}_{-0.13}$ | $^{+0.15}_{-0.07}$ |
| | $\left(^{+0.28}_{-0.25}\right)$ | $\left(^{+0.15}_{-0.15}\right)$ | $\left(^{+0.16}_{-0.15}\right)$ | $\left(^{+0.13}_{-0.12}\right)$ | $\left(^{+0.11}_{-0.05}\right)$ |




‘Observation’

# The future

# The future

- Now (through 2017, 50 $fb^{-1}$):  30k ttH events
- LHC run 3 (by 2023, 300 $fb^{-1}$):  200k ttH events
- HL-LHC (by 2038, 3000 $fb^{-1}$):  2M ttH events
- Future linear collider?