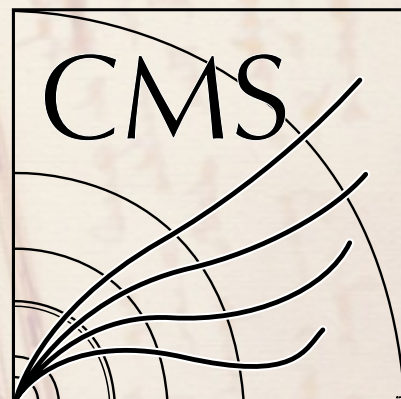


Top-Higgs coupling and how we measure it

Ted Kolberg (FSU)
QuarkNet, 23 July 2018



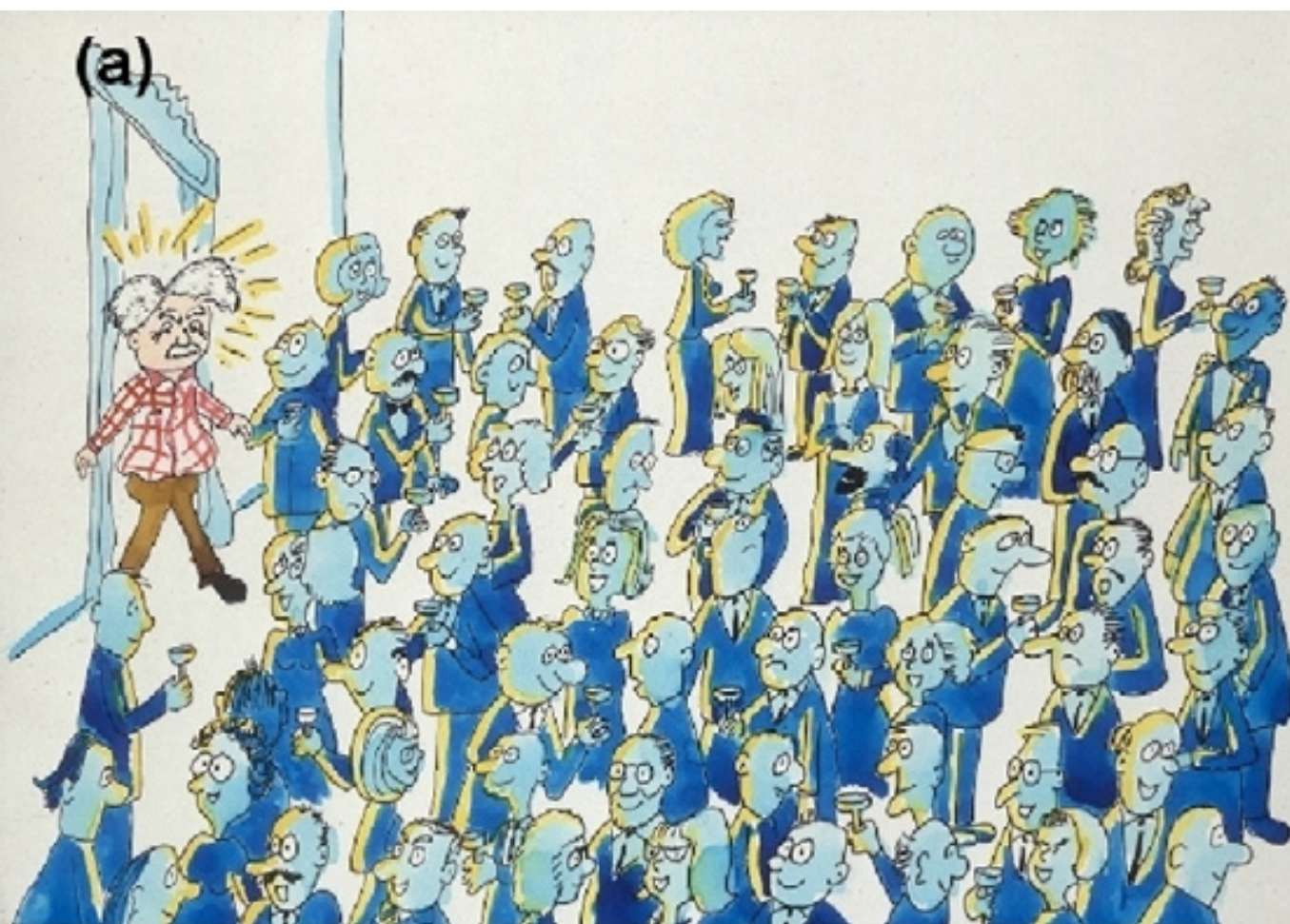
Overview

- 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.

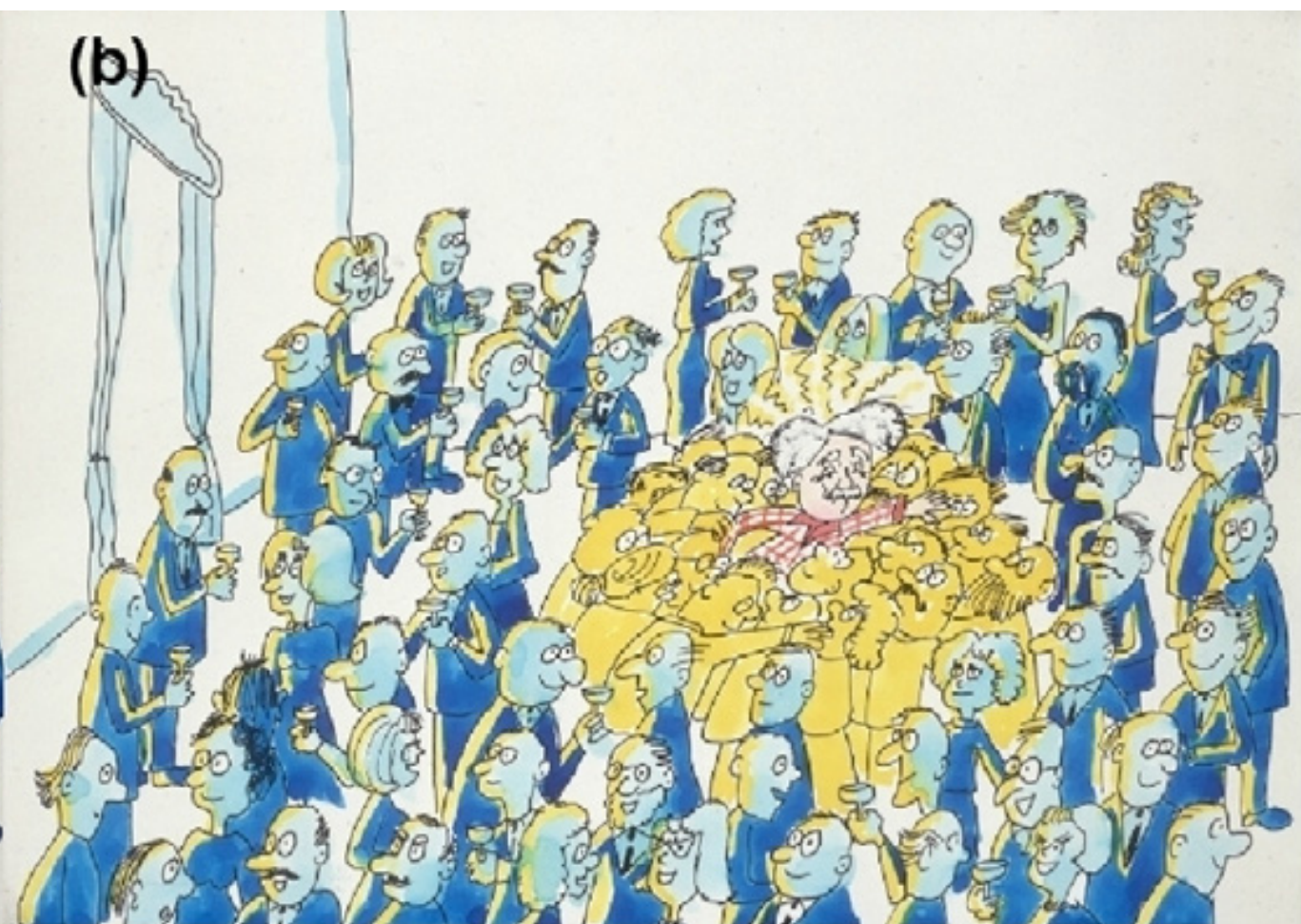
Standard Model of Elementary Particles

three generations of matter (fermions)						
	I	II	III			
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$	
charge	$2/3$	$2/3$	$2/3$	0	0	
spin	$1/2$	$1/2$	$1/2$	1	0	
QUARKS	u up	c charm	t top	g gluon	H Higgs	SCALAR BOSONS
	$\approx 4.7 \text{ MeV}/c^2$ $-1/3$ $1/2$ d down	$\approx 96 \text{ MeV}/c^2$ $-1/3$ $1/2$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$ b bottom	0 0 1 γ photon		
	$\approx 0.511 \text{ MeV}/c^2$ -1 $1/2$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $1/2$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $1/2$ τ tau	$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson		
LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 $1/2$ ν_e electron neutrino	$< 1.7 \text{ MeV}/c^2$ 0 $1/2$ ν_μ muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$ ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson		GAUGE BOSONS

(a)



(b)



(c)

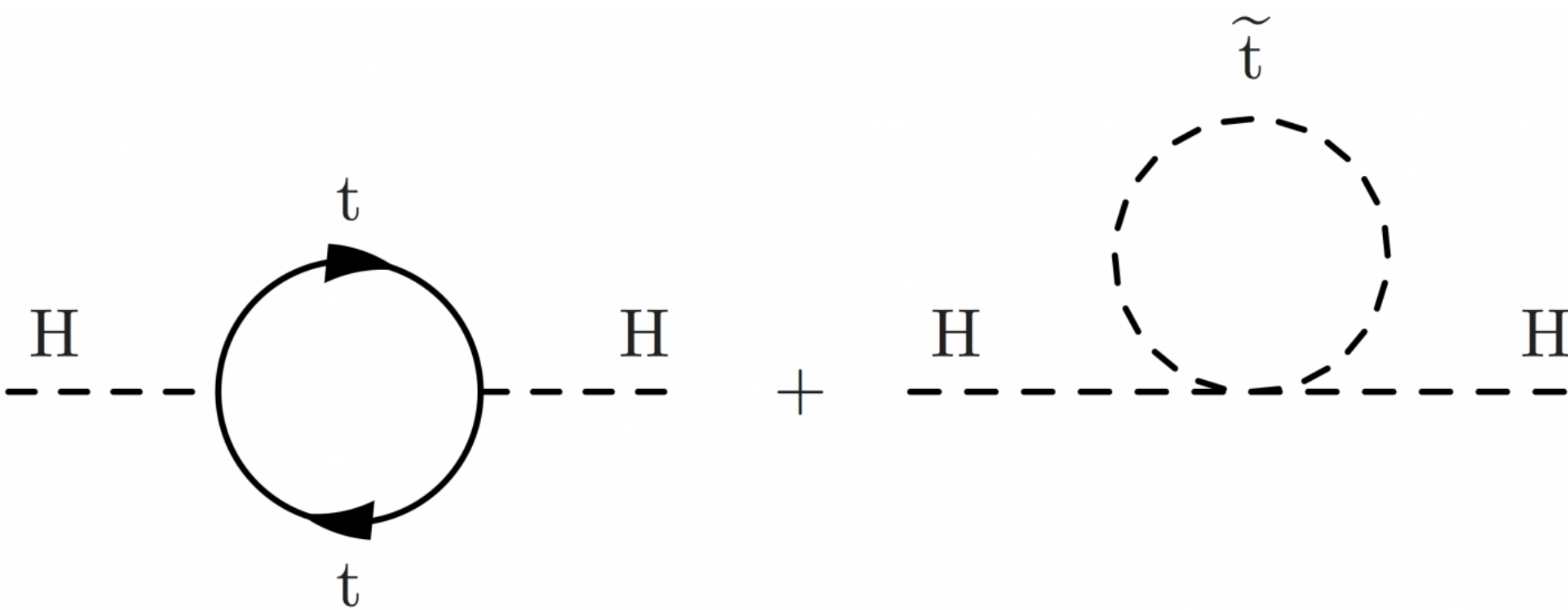


(d)



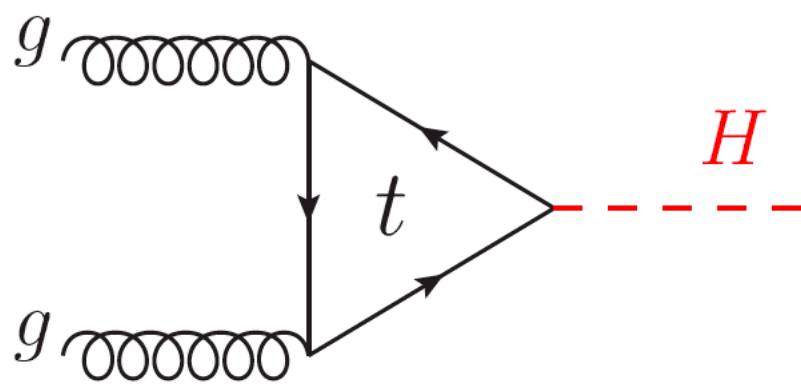
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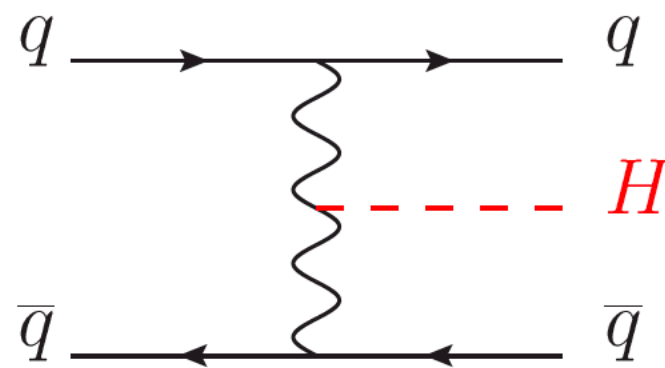
$$\Delta m_H^2 =$$


The diagram shows two Feynman diagrams representing corrections to the Higgs mass. The first diagram on the left consists of a central solid circle with two arrows indicating a clockwise loop of top quarks (t). This circle is connected to two horizontal dashed lines, each labeled with an 'H' for Higgs boson. The second diagram on the right is similar, but the central loop is represented by a dashed circle, indicating a loop of top squarks (\tilde{t}). It is also connected to two horizontal dashed lines labeled 'H'. The two diagrams are separated by a plus sign, and the entire expression is followed by another plus sign and an ellipsis (\dots), indicating a series of terms.

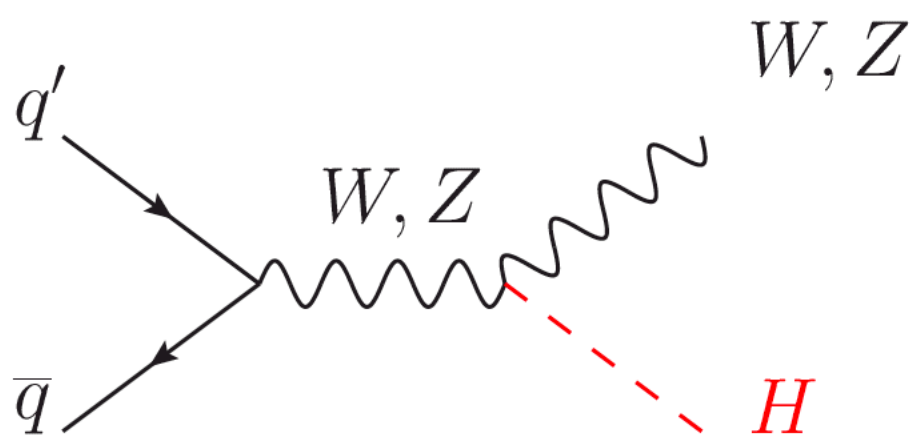
$$+ \dots$$



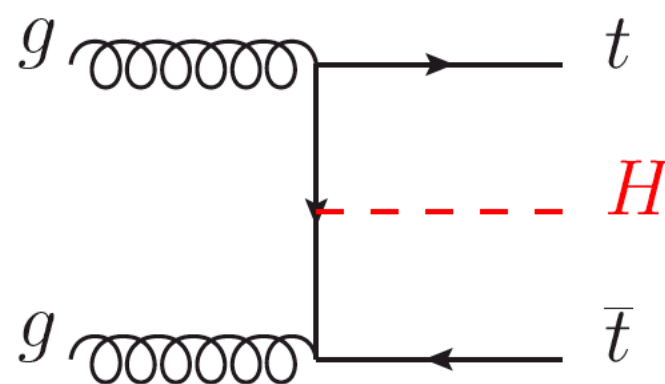
(a)



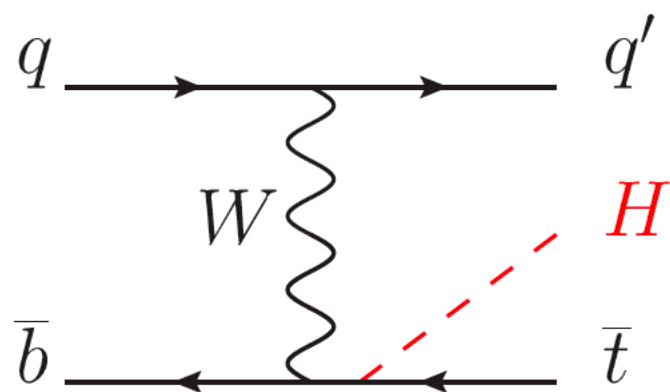
(b)



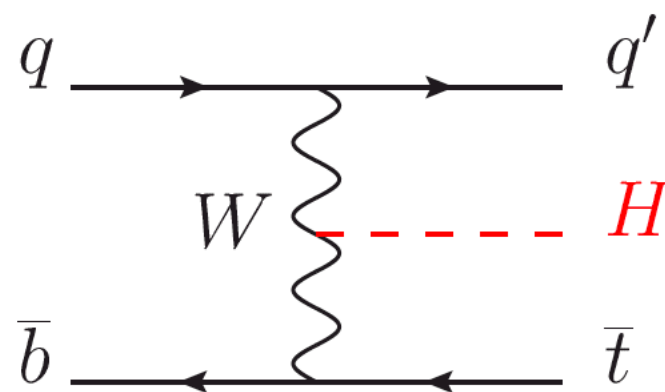
(c)



(d)



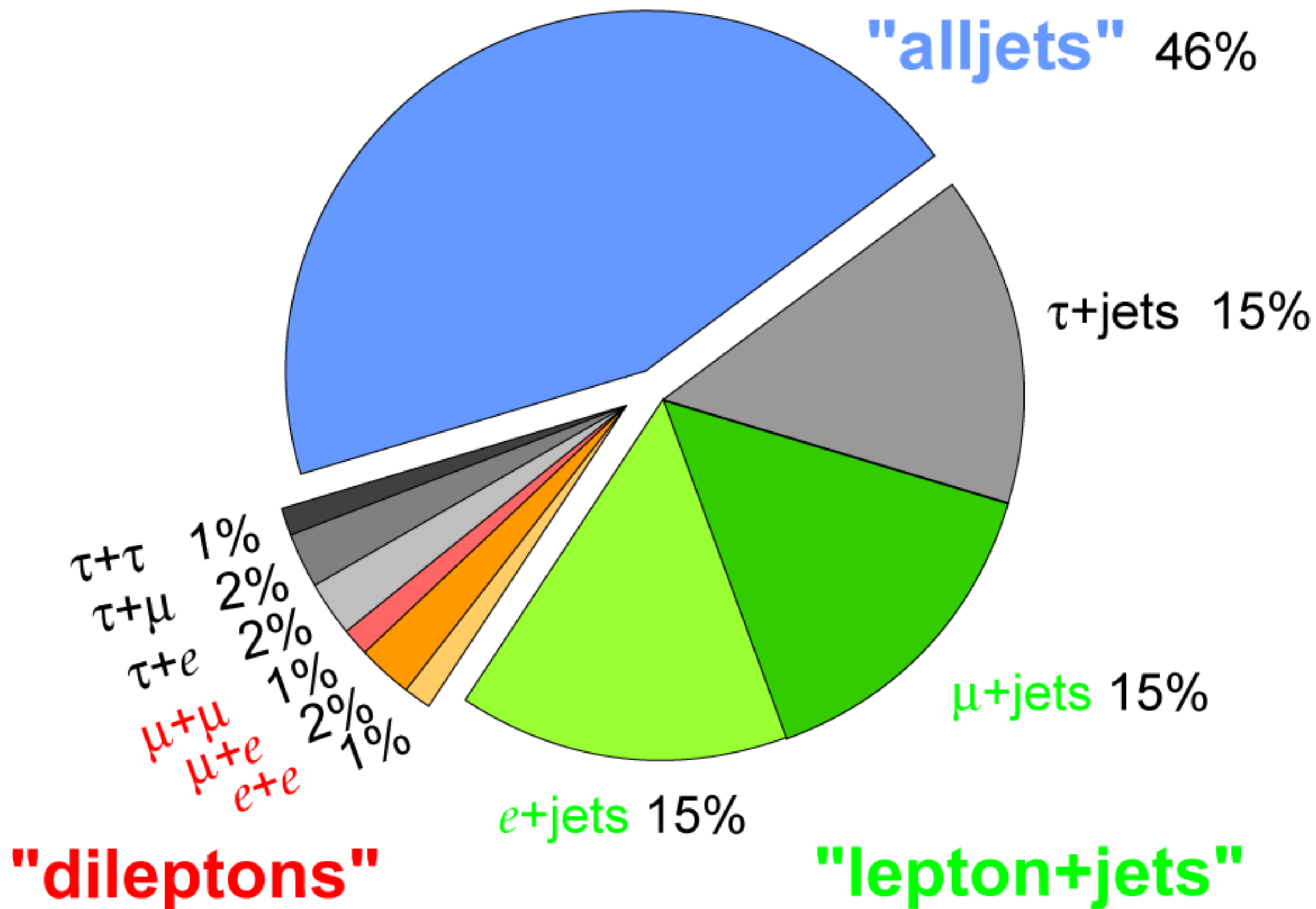
(e)



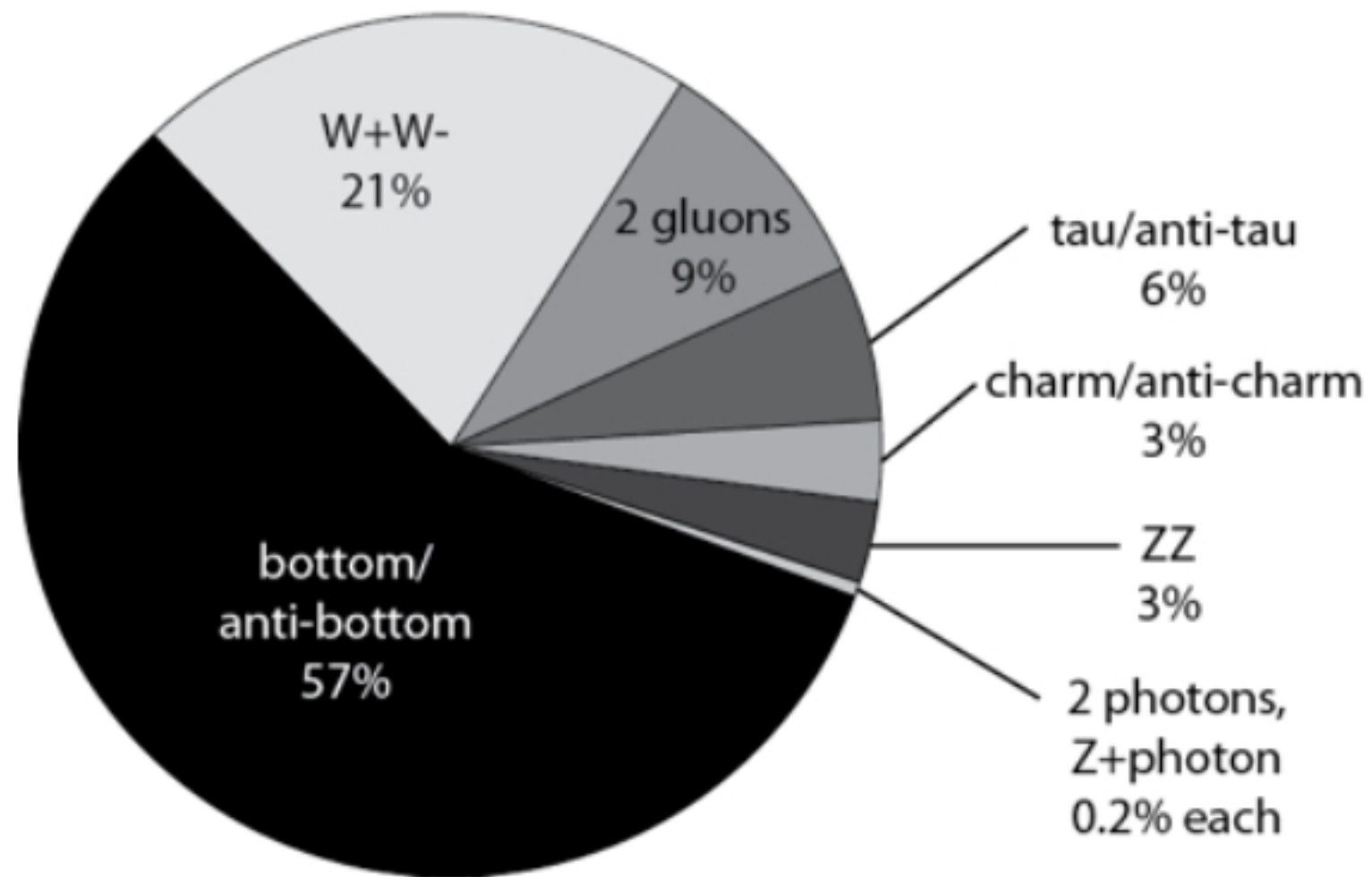
(f)

\sqrt{s} (TeV)	Production cross section (in pb) for $m_H = 125$ 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

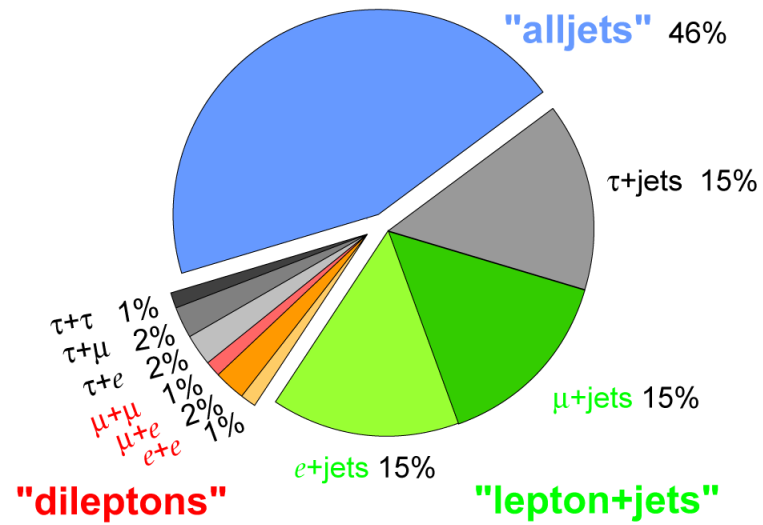
Top Pair Branching Fractions



Decays of a 125 GeV Standard-Model Higgs boson

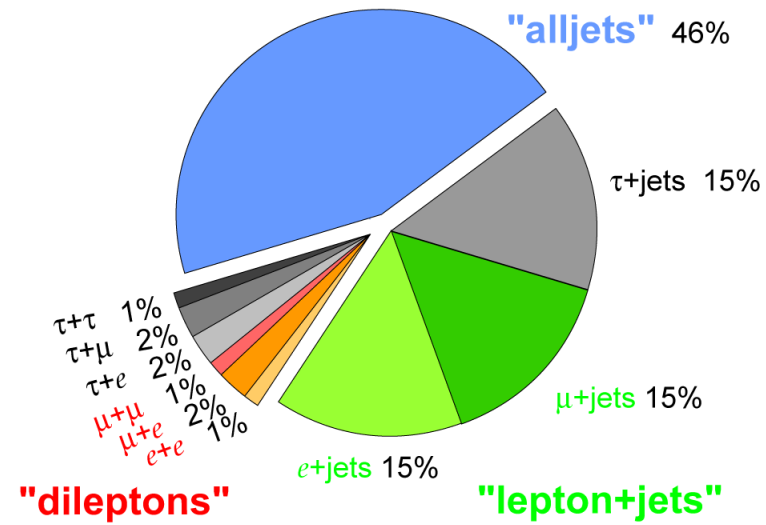


Top Pair Branching Fractions



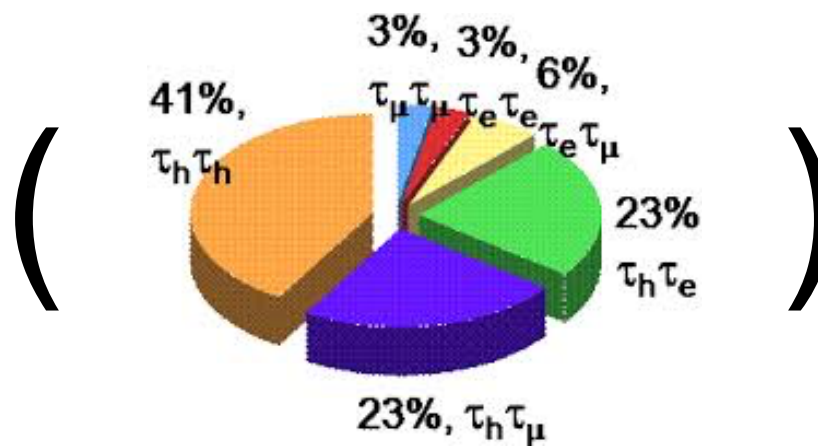
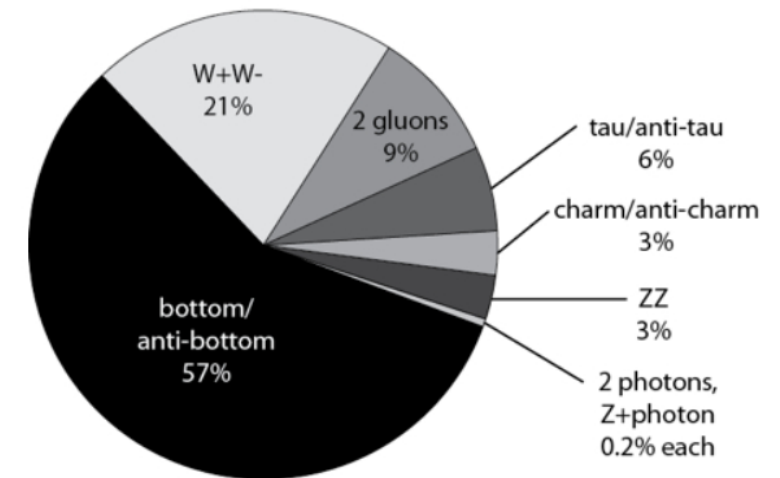
×

Top Pair Branching Fractions

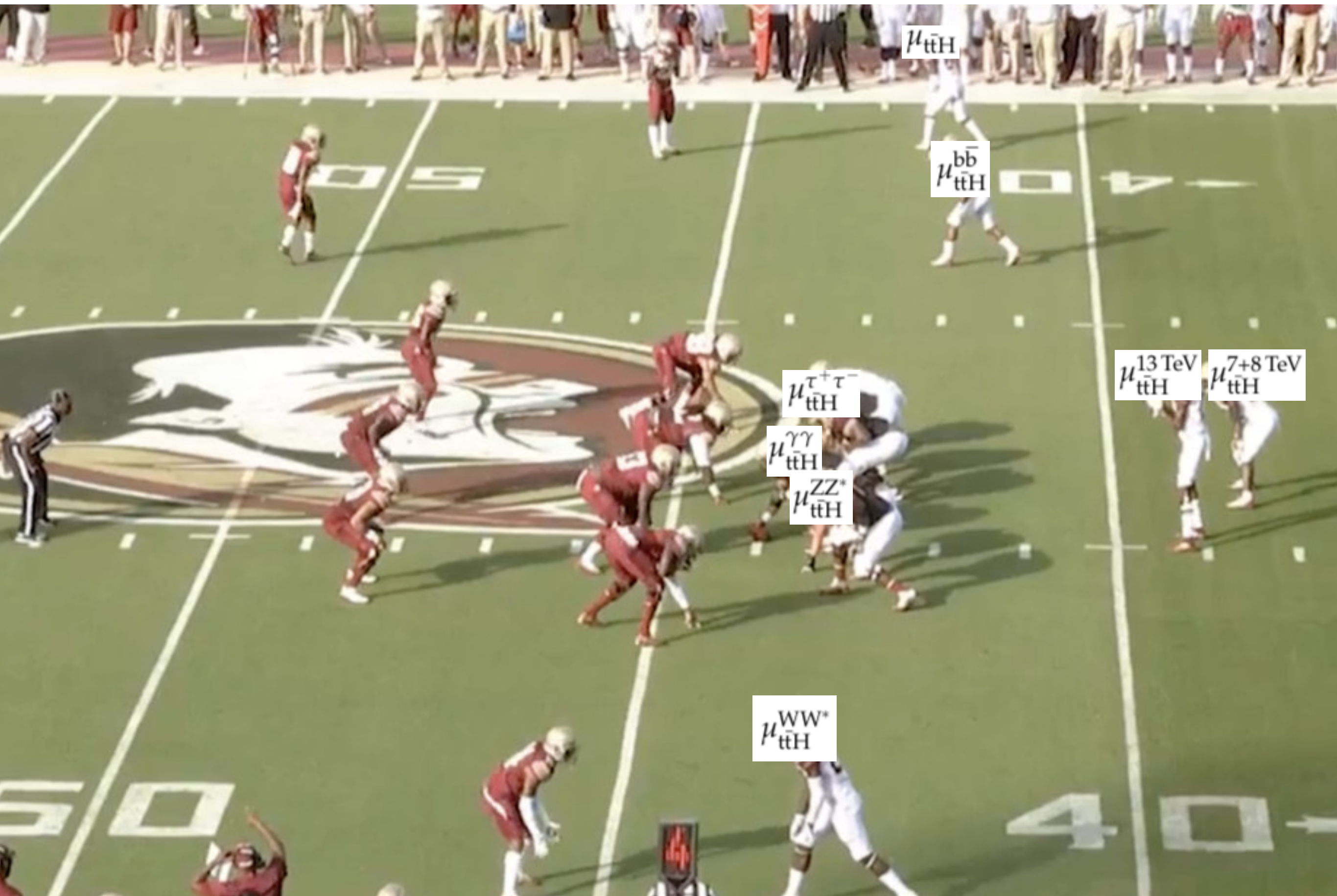


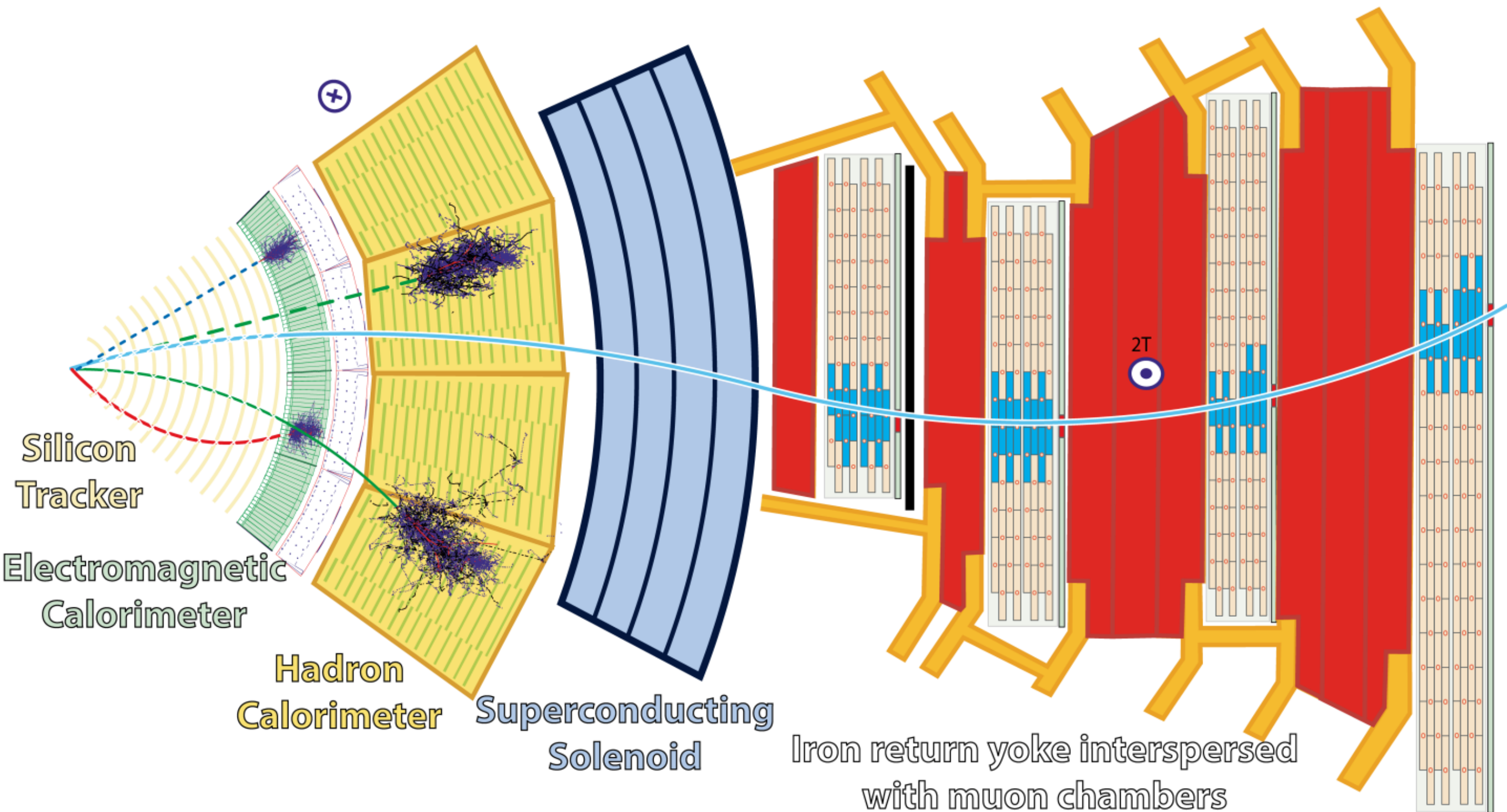
×

Decays of a 125 GeV Standard-Model Higgs boson





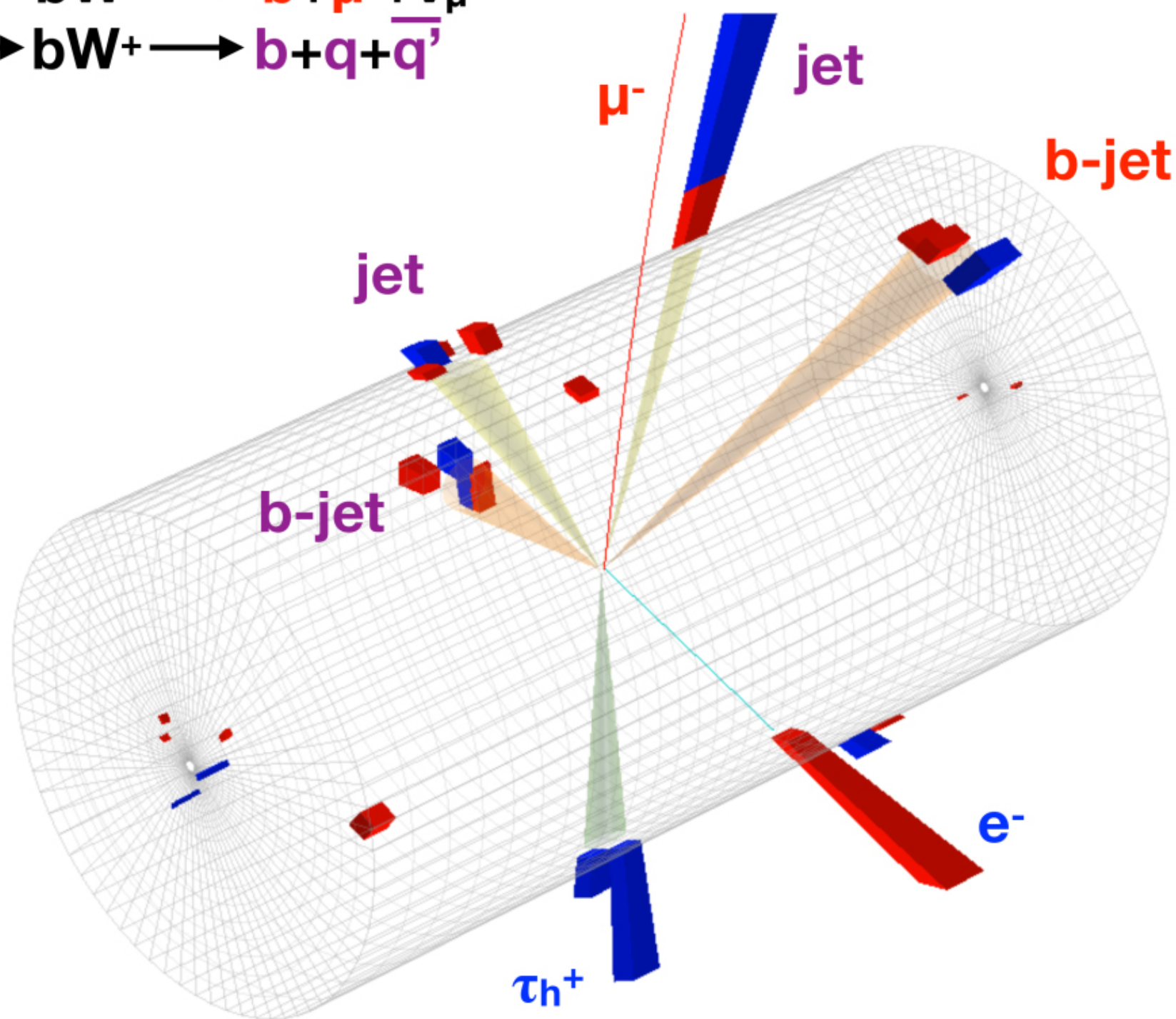




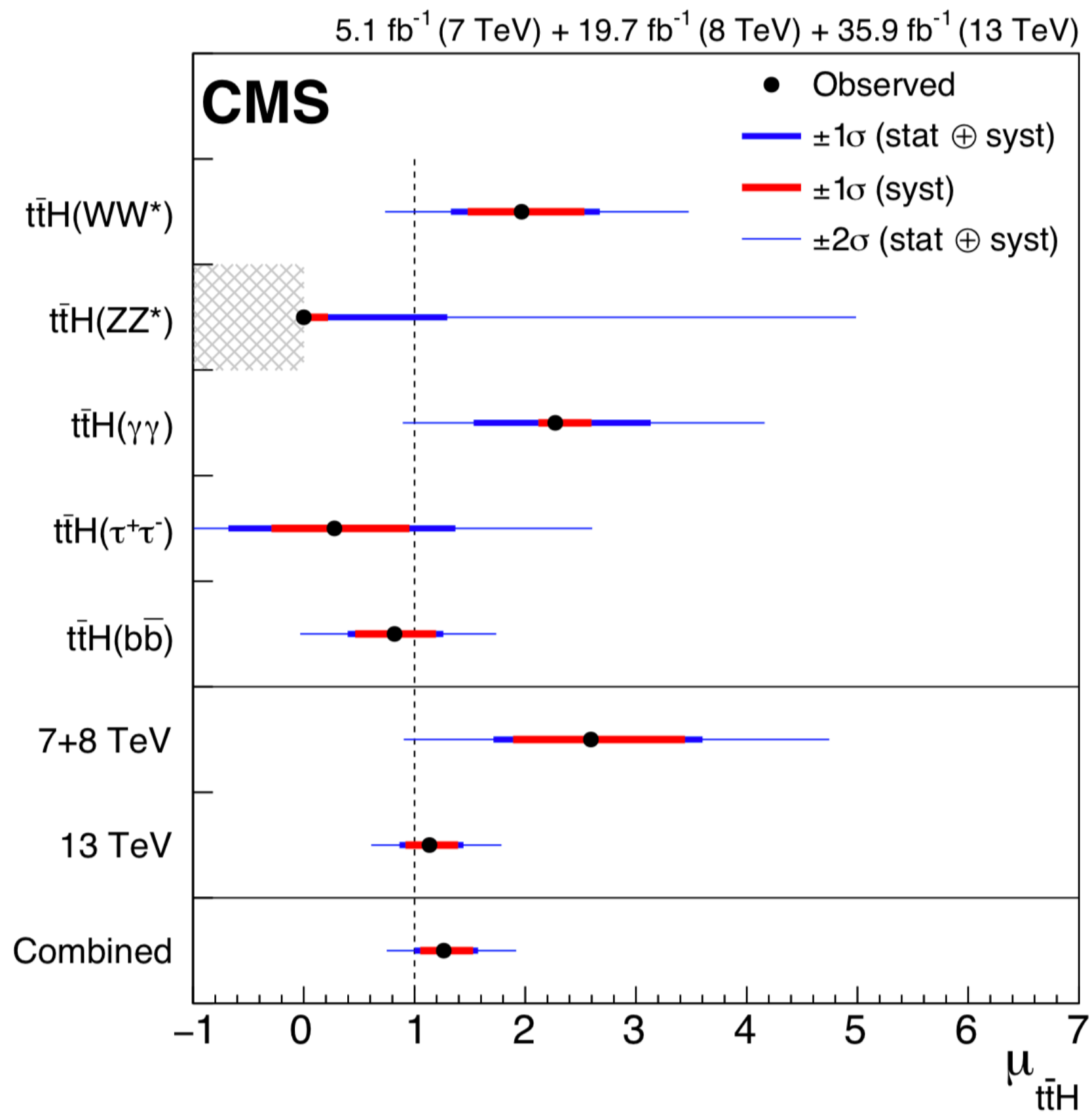
- Muon
- Electron
- Charged hadron (e.g. pion)
- - - Neutral hadron (e.g. neutron)
- - - Photon

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

$\tau^-\tau^+ \rightarrow e^- + \bar{\nu}_e + \nu_\tau + \tau_h^+ + \bar{\nu}_\tau$
 $\bar{b}W^- \rightarrow \bar{b} + \mu^- + \bar{\nu}_\mu$
 $bW^+ \rightarrow b + q + \bar{q}'$



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



‘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?