

Top: Past, Present, and Future

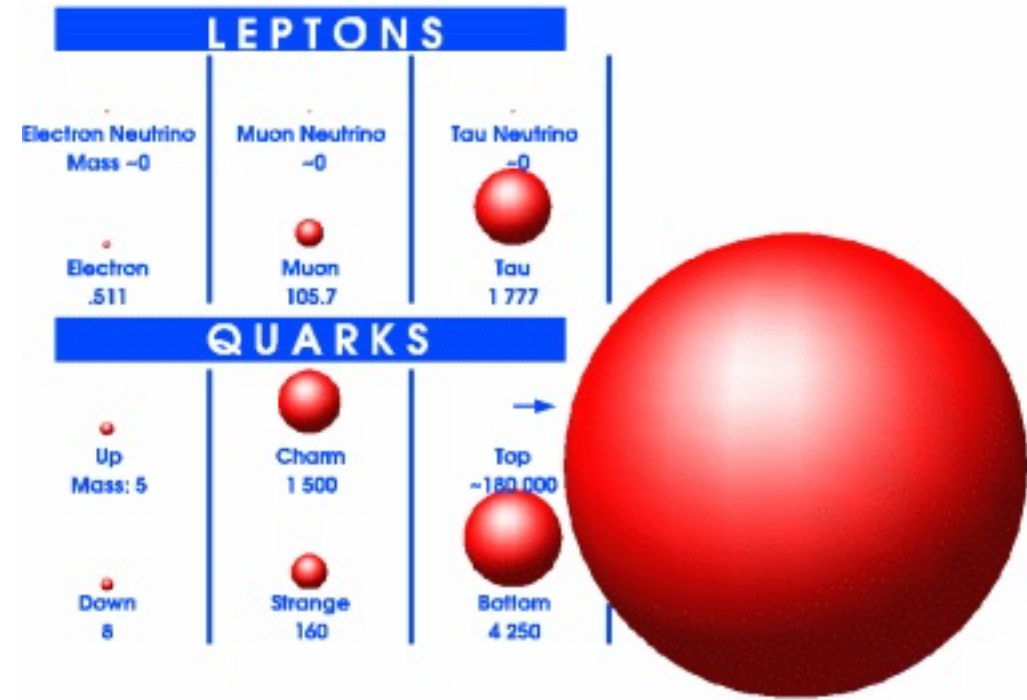
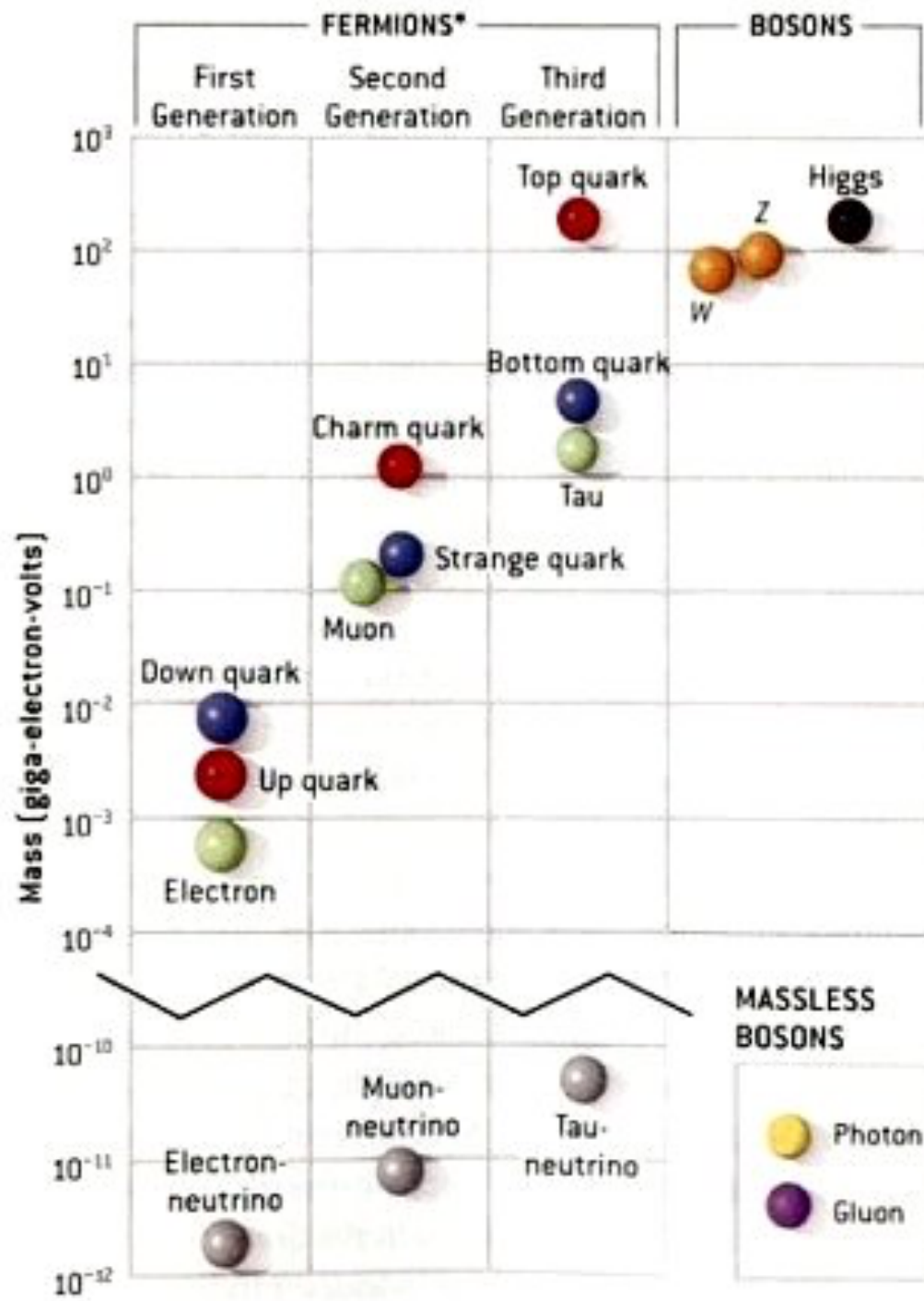
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Michigan State University
Lepton-Photon 2017
August 8, 2017

Top: Past, Present, and Future

- Top Matters - the effect of virtual top loops
- Top Couplings - theory and measurement
- Naturalness and the Hierarchy Problem
- Top as a Signal - new states coupling to top

Top Matters:
Large Mass -
Enhanced Coupling to EWSB Sector

Top Matters: Mass



$$m_t \approx 173 \text{ GeV}/c^2$$

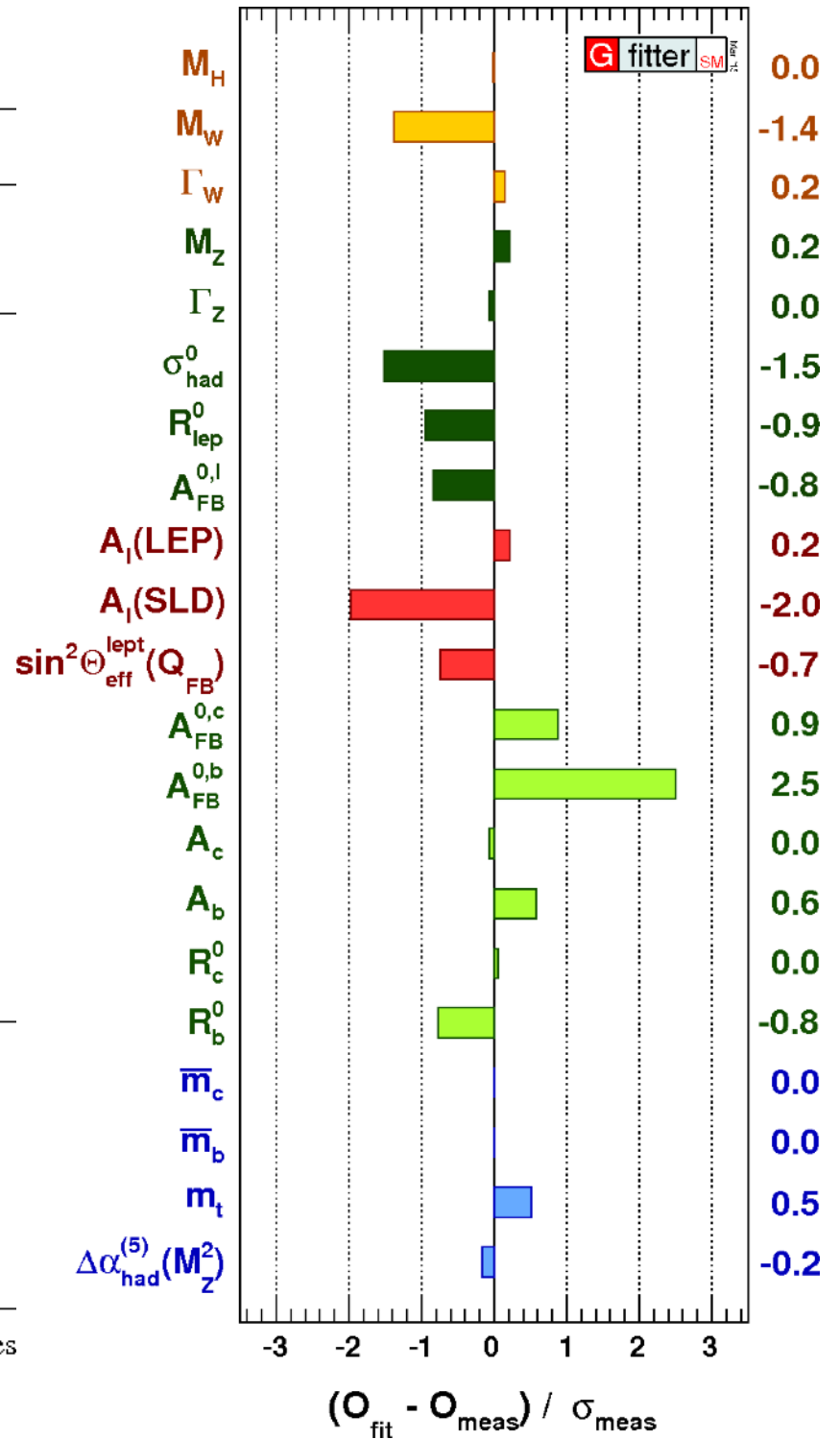
$$m_W \approx 80 \text{ GeV}/c^2$$

$$m_Z \approx 91 \text{ GeV}/c^2$$

$$m_H \approx 125 \text{ GeV}/c^2$$

Top Matters: Electroweak Corrections

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line
M_H [GeV] ^(o)	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}
M_W [GeV]	80.385 ± 0.015	-	80.364 ± 0.007	80.358 ± 0.008
Γ_W [GeV]	2.085 ± 0.042	-	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011
Γ_Z [GeV]	2.4952 ± 0.0023	-	2.4950 ± 0.0014	2.4946 ± 0.0016
σ_{had}^0 [nb]	41.540 ± 0.037	-	41.484 ± 0.015	41.475 ± 0.016
R_ℓ^0	20.767 ± 0.025	-	20.743 ± 0.017	20.722 ± 0.026
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	-	0.01626 ± 0.0001	0.01625 ± 0.0001
A_ℓ (*)	0.1499 ± 0.0018	-	0.1472 ± 0.0005	0.1472 ± 0.0005
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012	-	0.23150 ± 0.00006	0.23149 ± 0.00007
A_c	0.670 ± 0.027	-	0.6680 ± 0.00022	0.6680 ± 0.00022
A_b	0.923 ± 0.020	-	0.93463 ± 0.00004	0.93463 ± 0.00004
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	-	0.0738 ± 0.0003	0.0738 ± 0.0003
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	-	0.1032 ± 0.0004	0.1034 ± 0.0004
R_c^0	0.1721 ± 0.0030	-	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008
R_b^0	0.21629 ± 0.00066	-	0.21578 ± 0.00011	0.21577 ± 0.00011
\bar{m}_c [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	-
\bar{m}_b [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	-
m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\nabla)}$	$177.0^{+2.3(\nabla)}_{-2.4}$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	$2757 \pm 10^{(\dagger)}$	yes	2756 ± 10	2723 ± 44
$\alpha_s(M_Z^2)$	-	yes	0.1196 ± 0.0030	0.1196 ± 0.0030



^(o) Average of the ATLAS and CMS measurements assuming no correlation of the systematic uncertainties

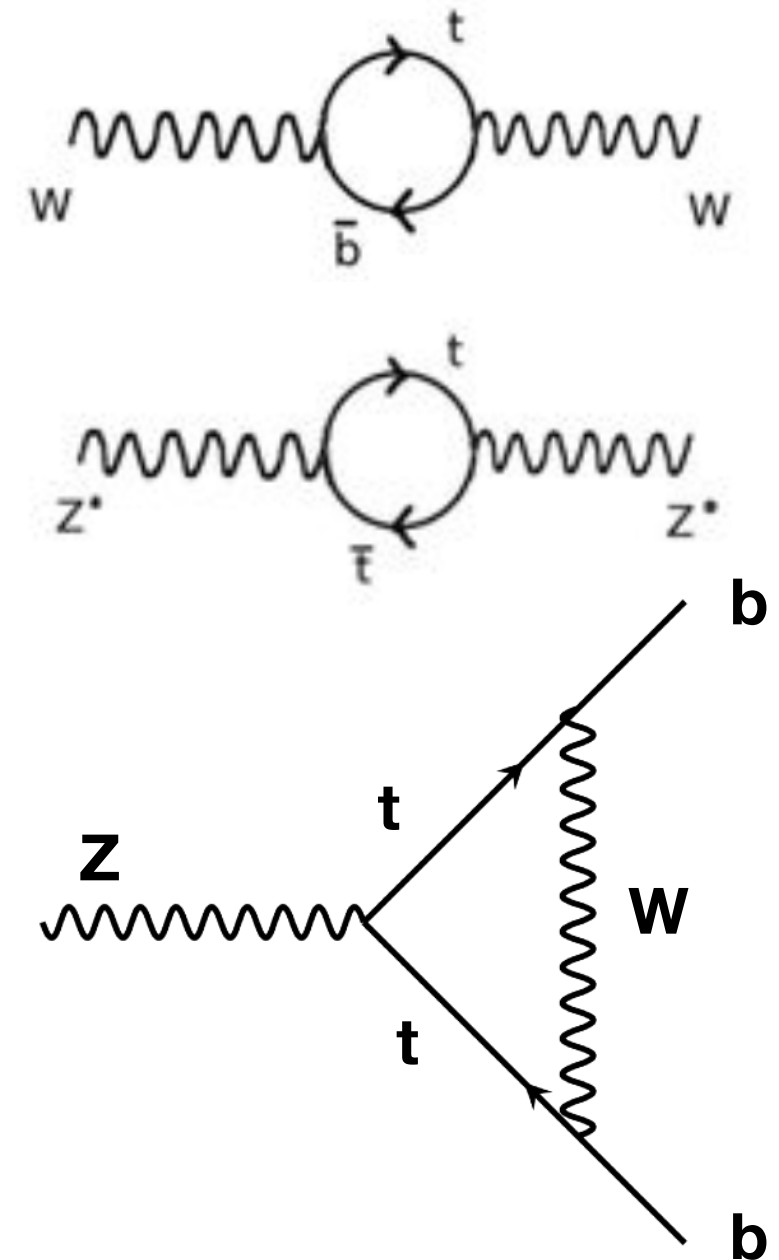
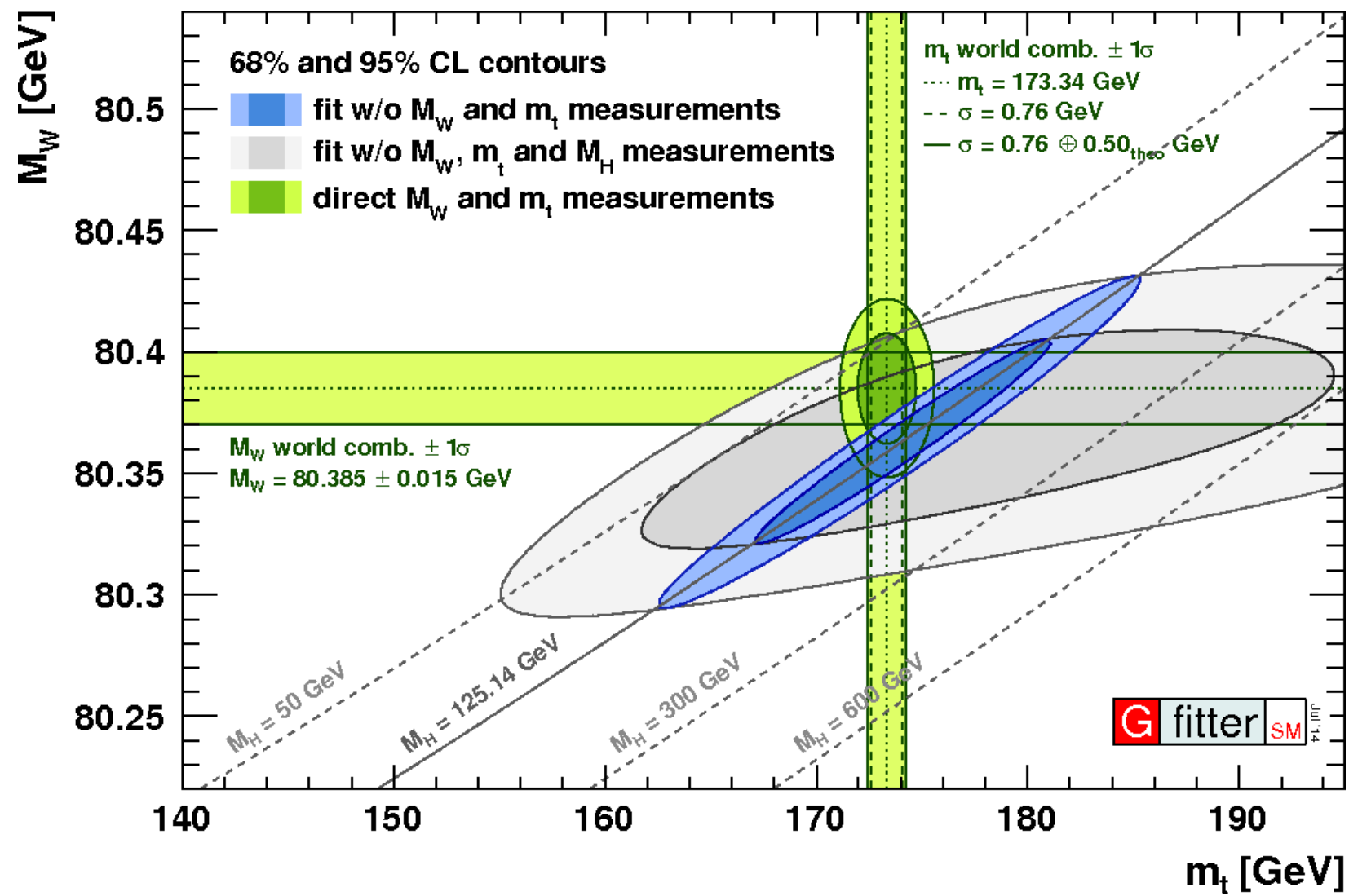
^(*) Average of the LEP and SLD A_ℓ measurements, used as two measurements in the fit.

^(\nabla) The theoretical top mass uncertainty of 0.5 GeV is excluded.

^(\dagger) In units of 10^{-5} .

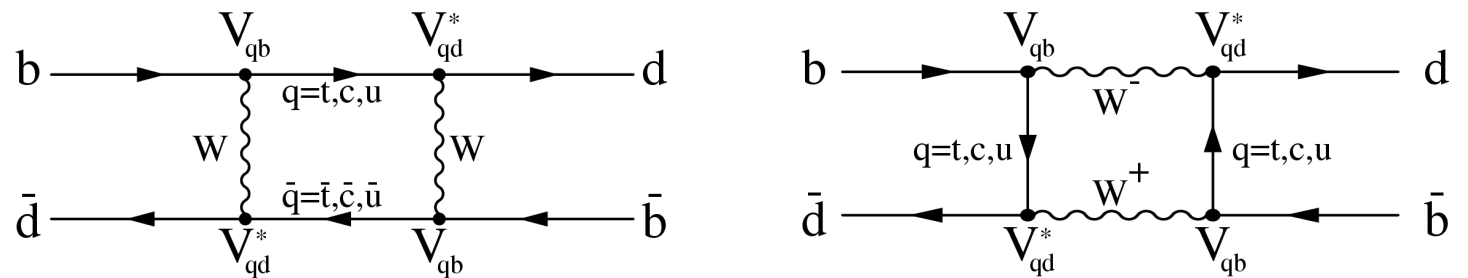
^(\Delta) Rescaled due to α_s dependence.

Top Matters: Electroweak Corrections

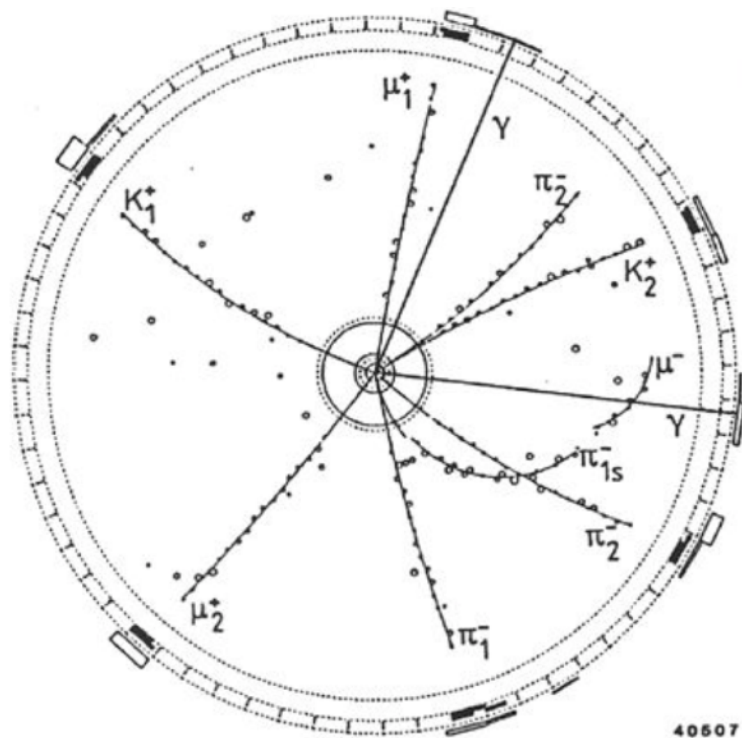


Top Matters: Flavor-Changing Neutral Currents

Example: $B_d - \bar{B}_d$



$$\Delta m_B \propto m_t^2 |V_{tb} V_{td}^*|^2 \approx 0.00002 \left(\frac{m_t}{\text{GeV}/c^2} \right)^2 \text{ps}^{-1}$$



ARGUS (1987):

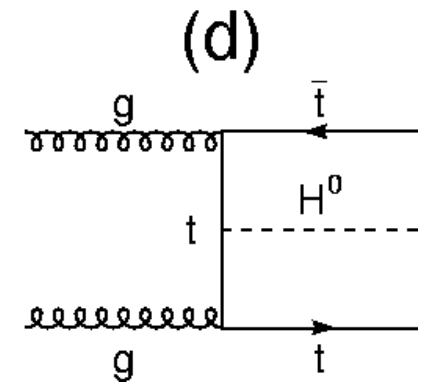
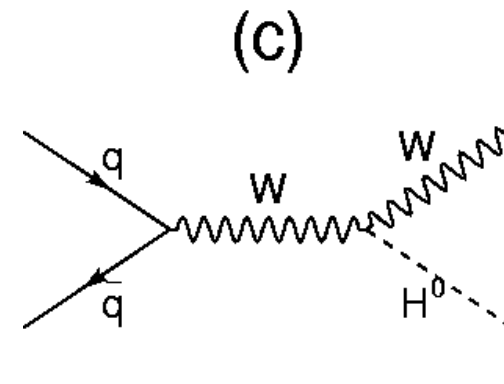
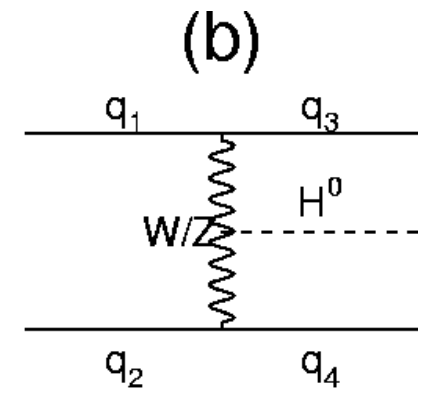
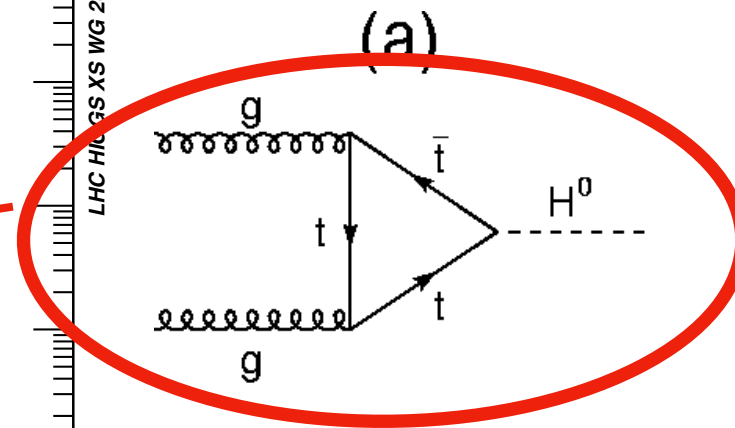
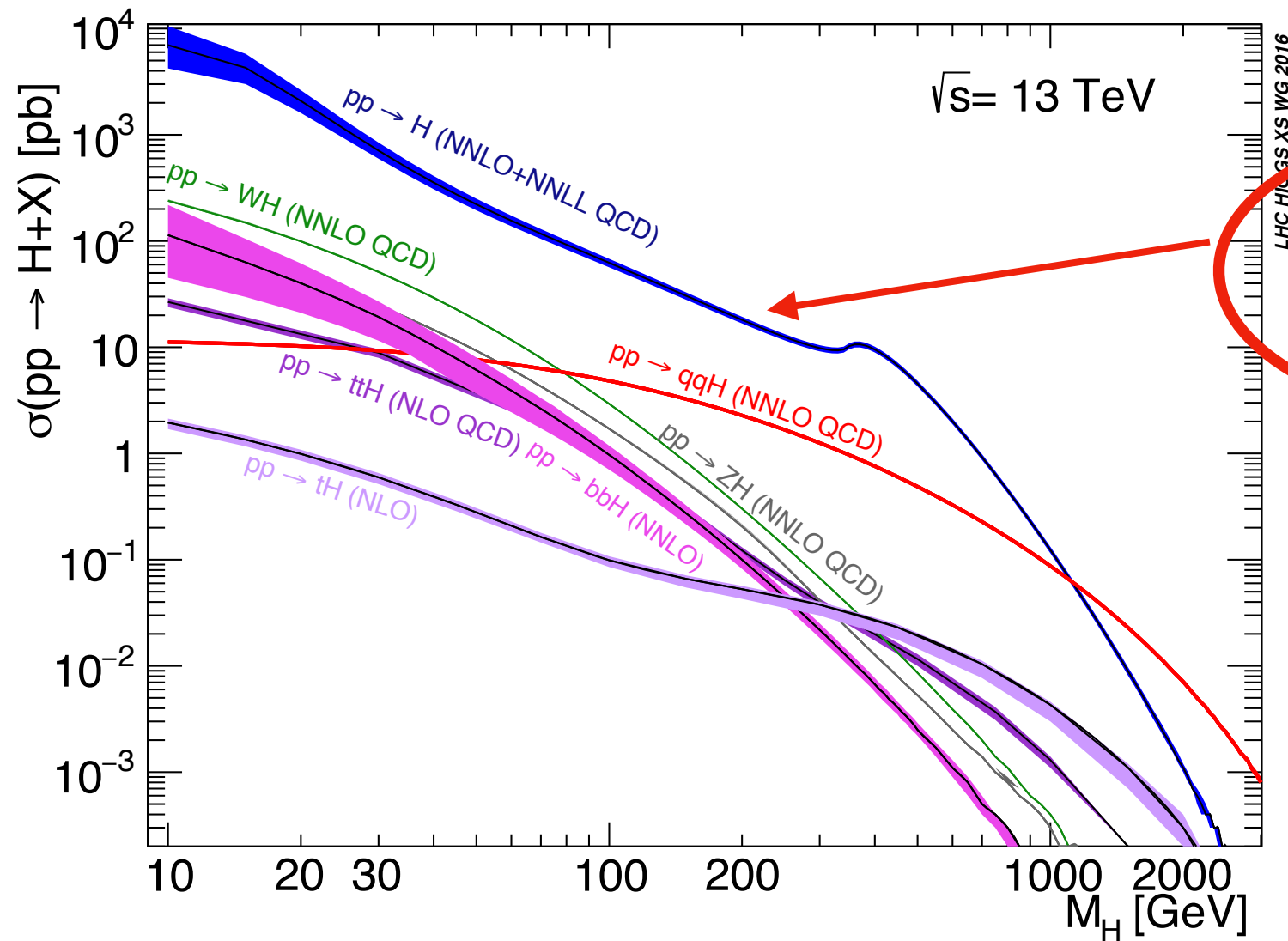
~17% of B_d mix before decaying

$\Delta m \sim 0.5 \text{ps}^{-1}$

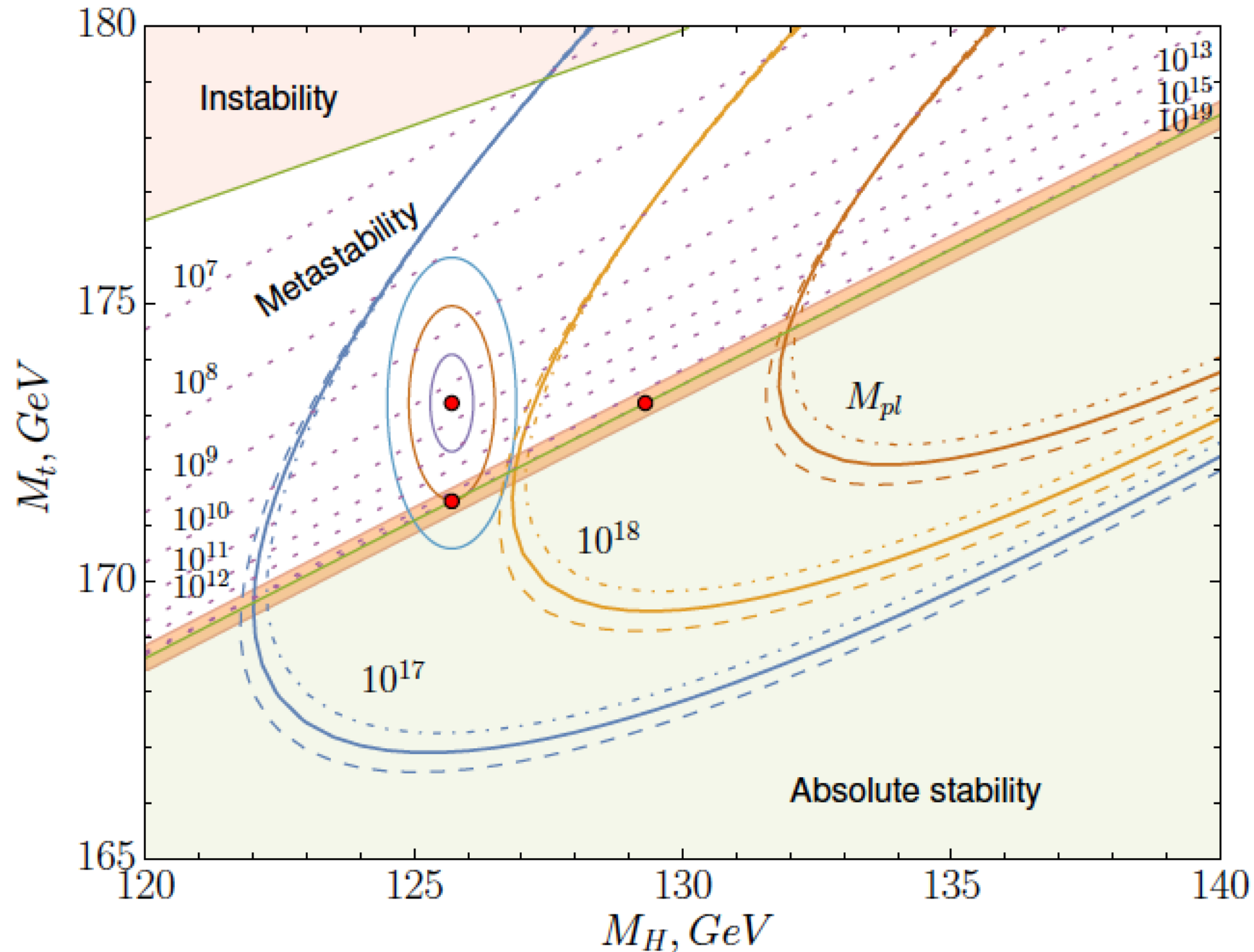
First indication of a heavy top!

$$m_t > 50 \text{GeV}/c^2$$

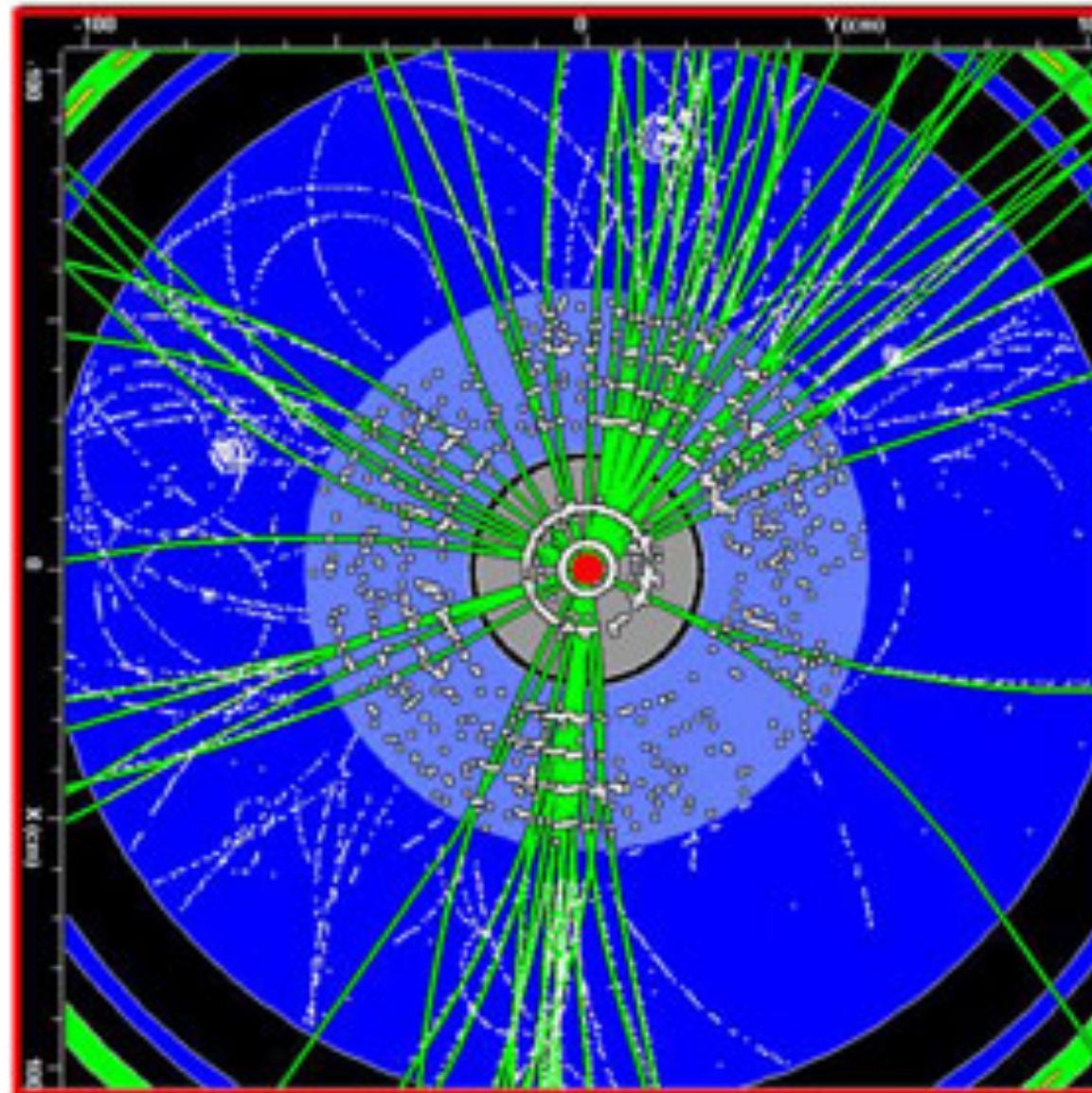
Top Matters: Higgs Production



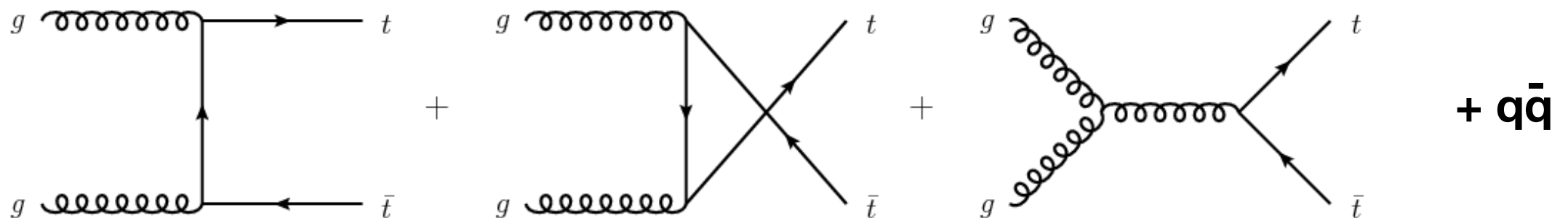
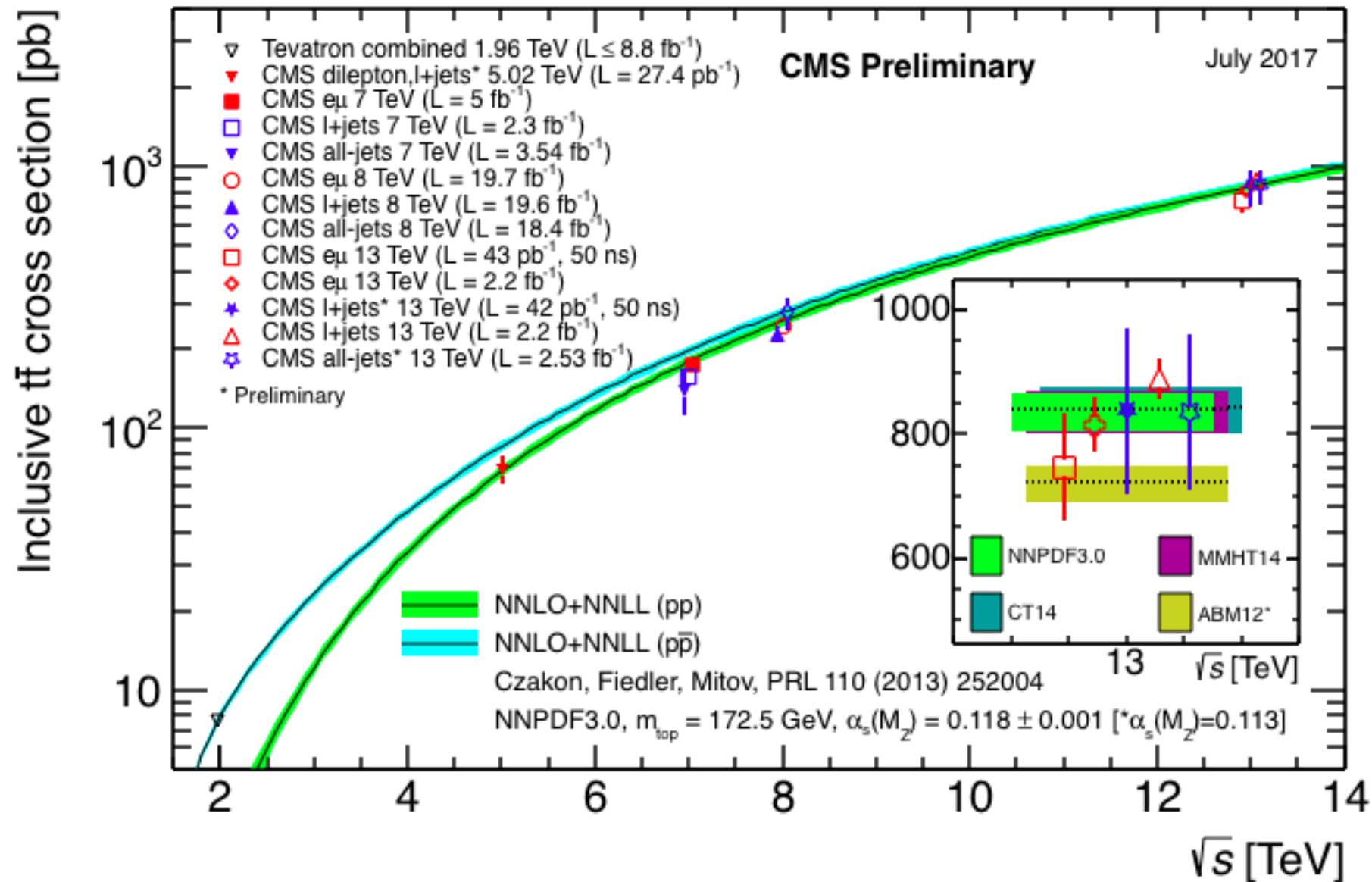
Top Matters: Higgs Potential (Meta-)Stability



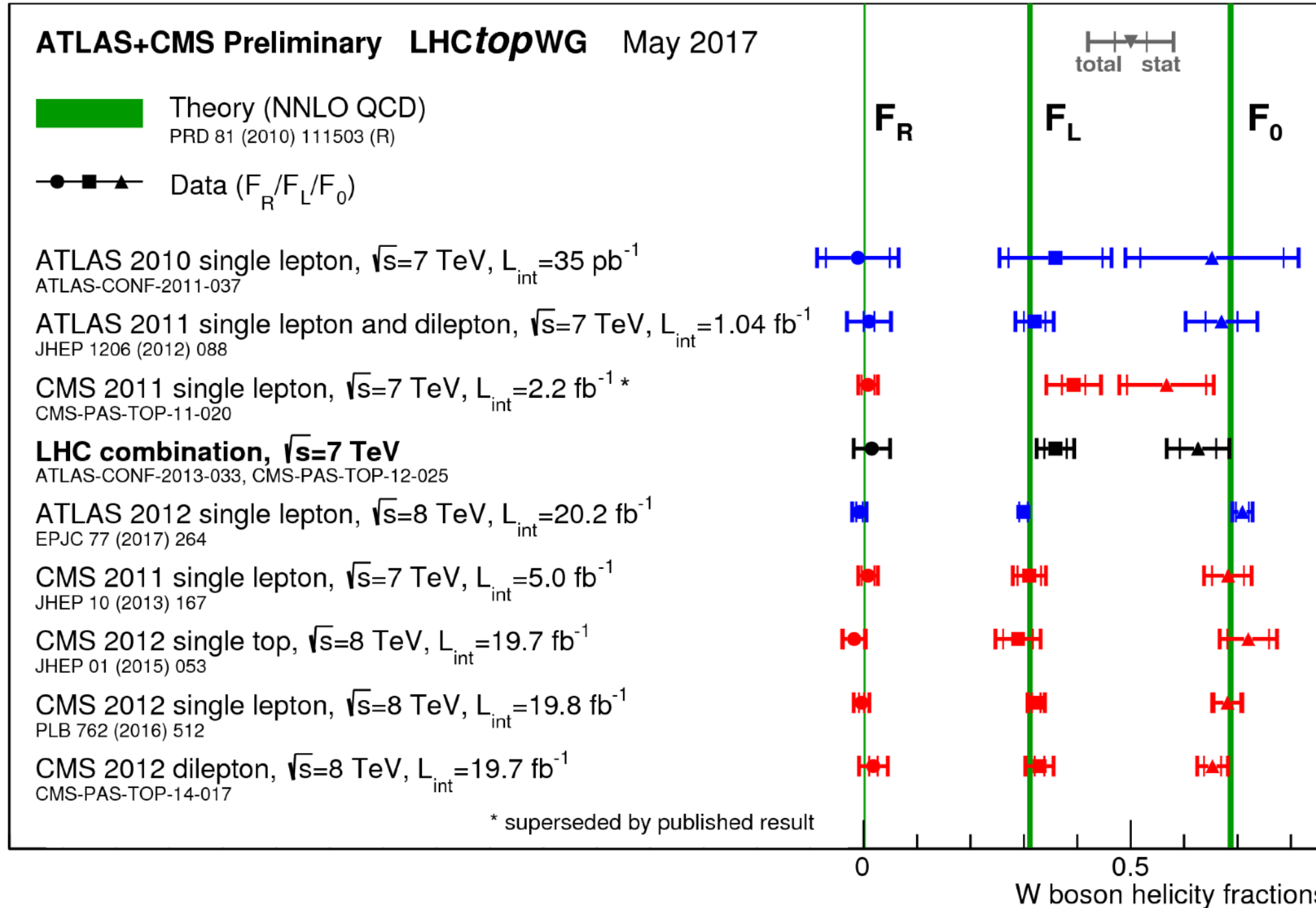
Top Couplings



Top Couplings - Color

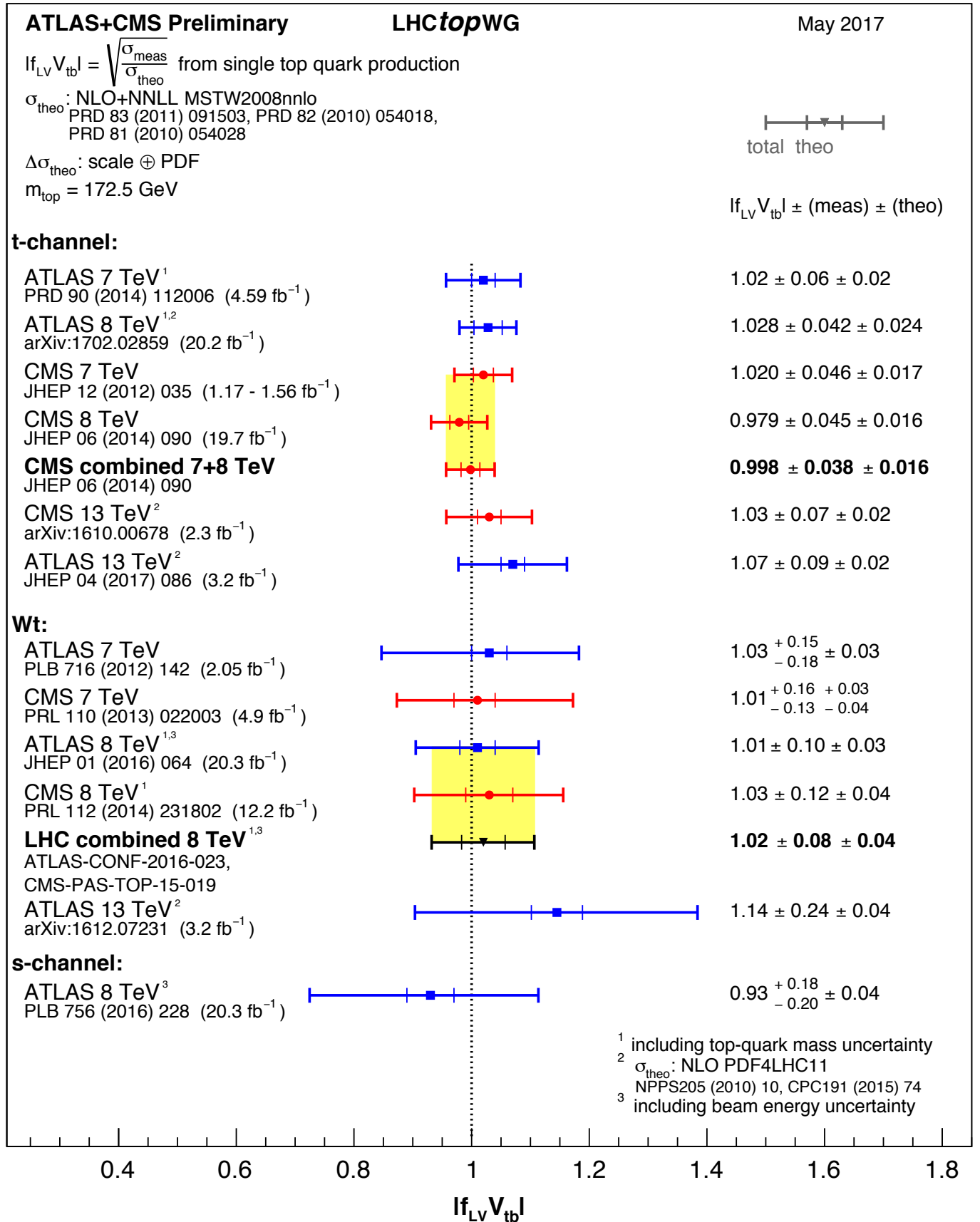
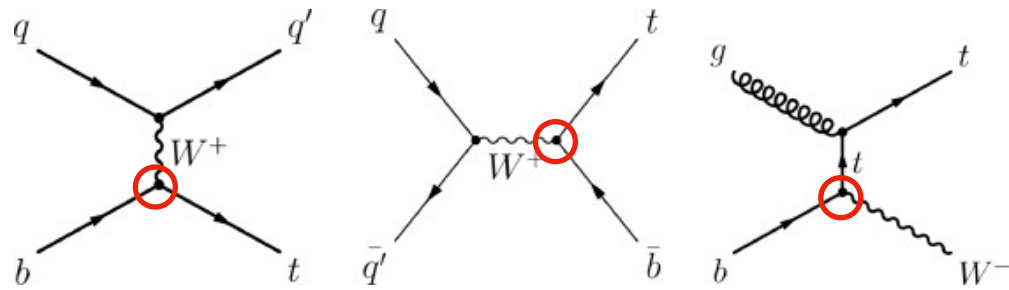


Top Electroweak Couplings: Top Decay



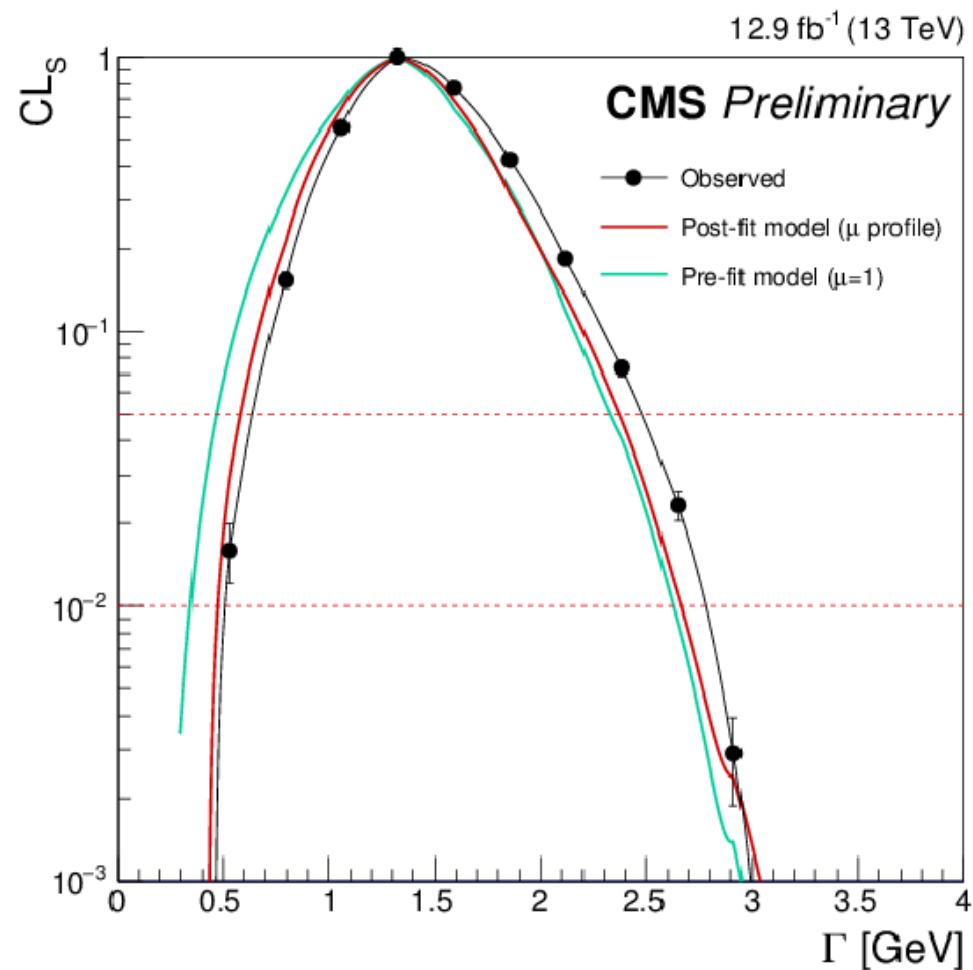
**W-boson
couplings
consistent
with
“V-A”**

Top Electroweak Couplings: Single Top



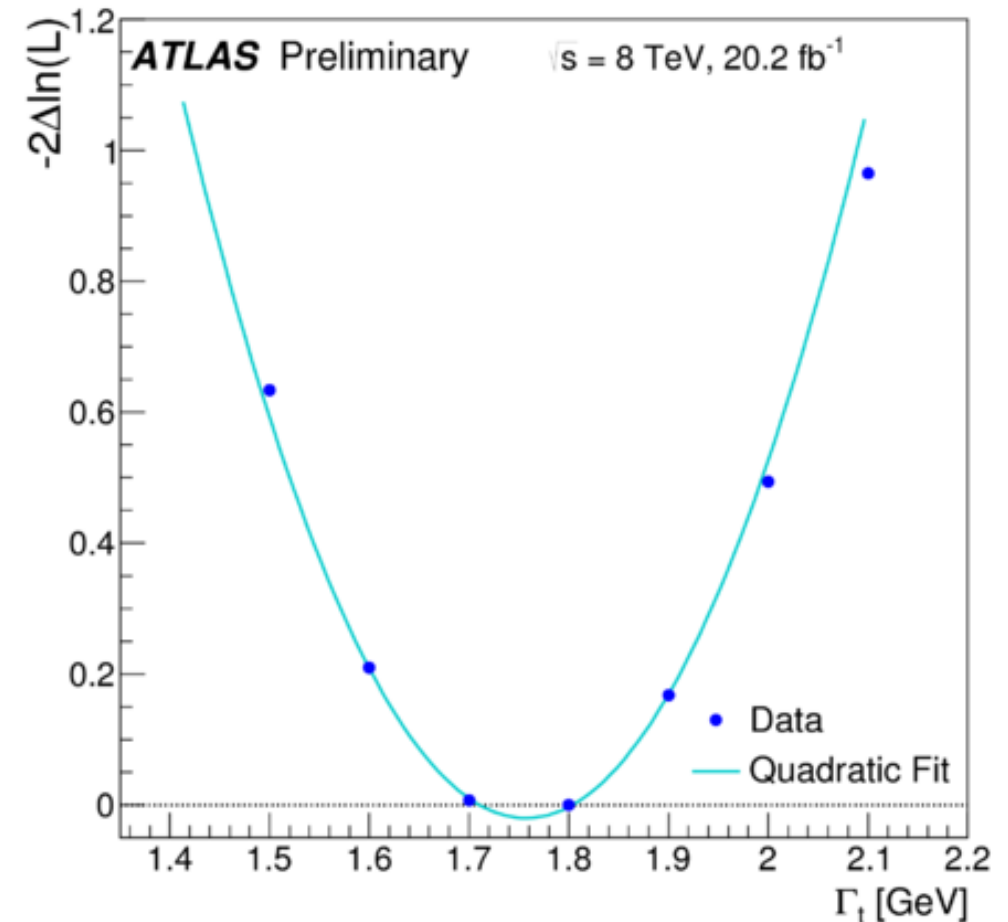
Top Width

$$\Gamma_t^{SM} = 1.322 \text{ GeV}$$



$$0.6 \leq \Gamma_t \leq 2.5 \text{ GeV, } 95\% \text{ CL}$$

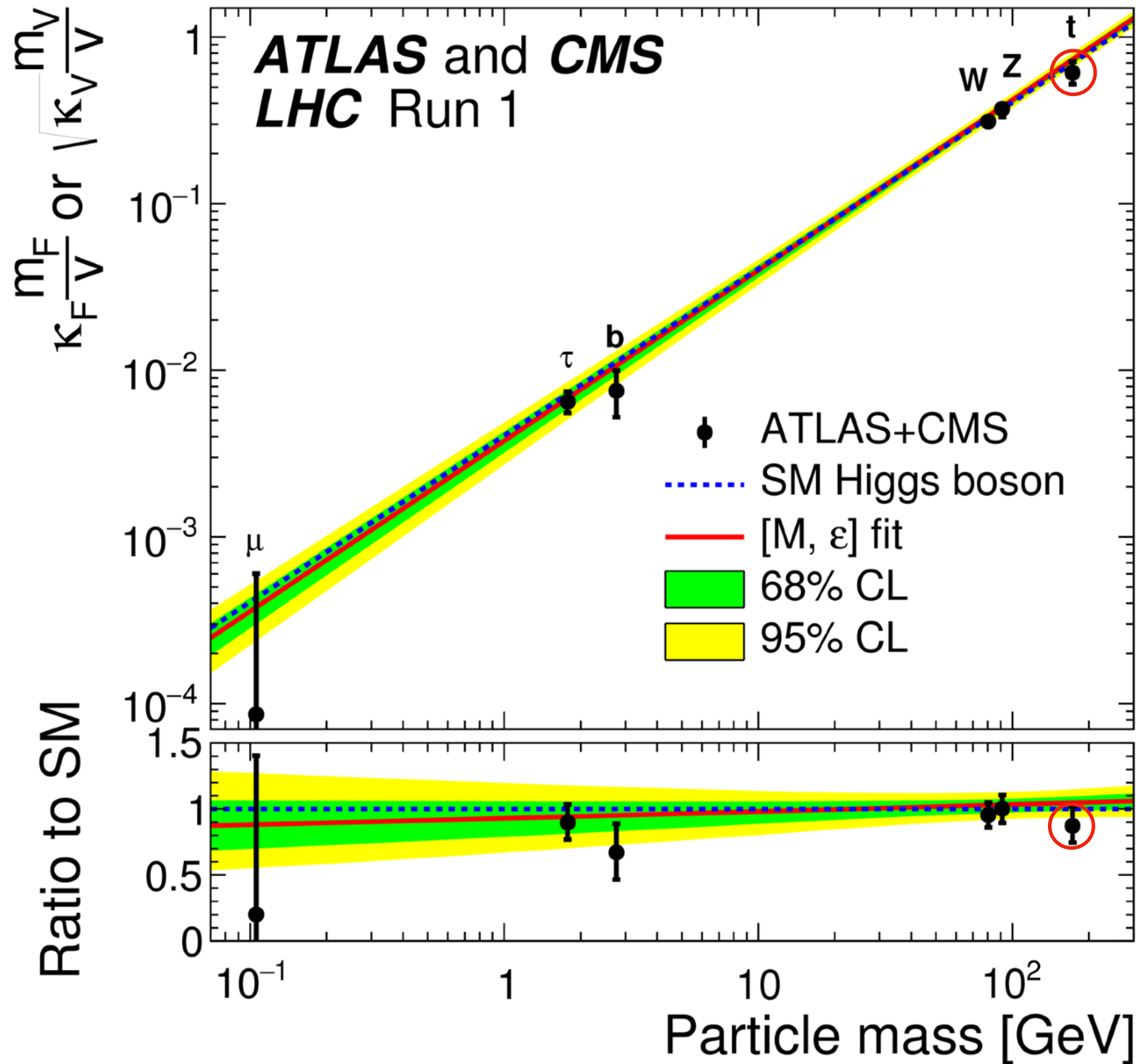
CMS-PAS-TOP-16-019



$$\Gamma_t = 1.76_{-0.76}^{+0.86} \text{ GeV}$$

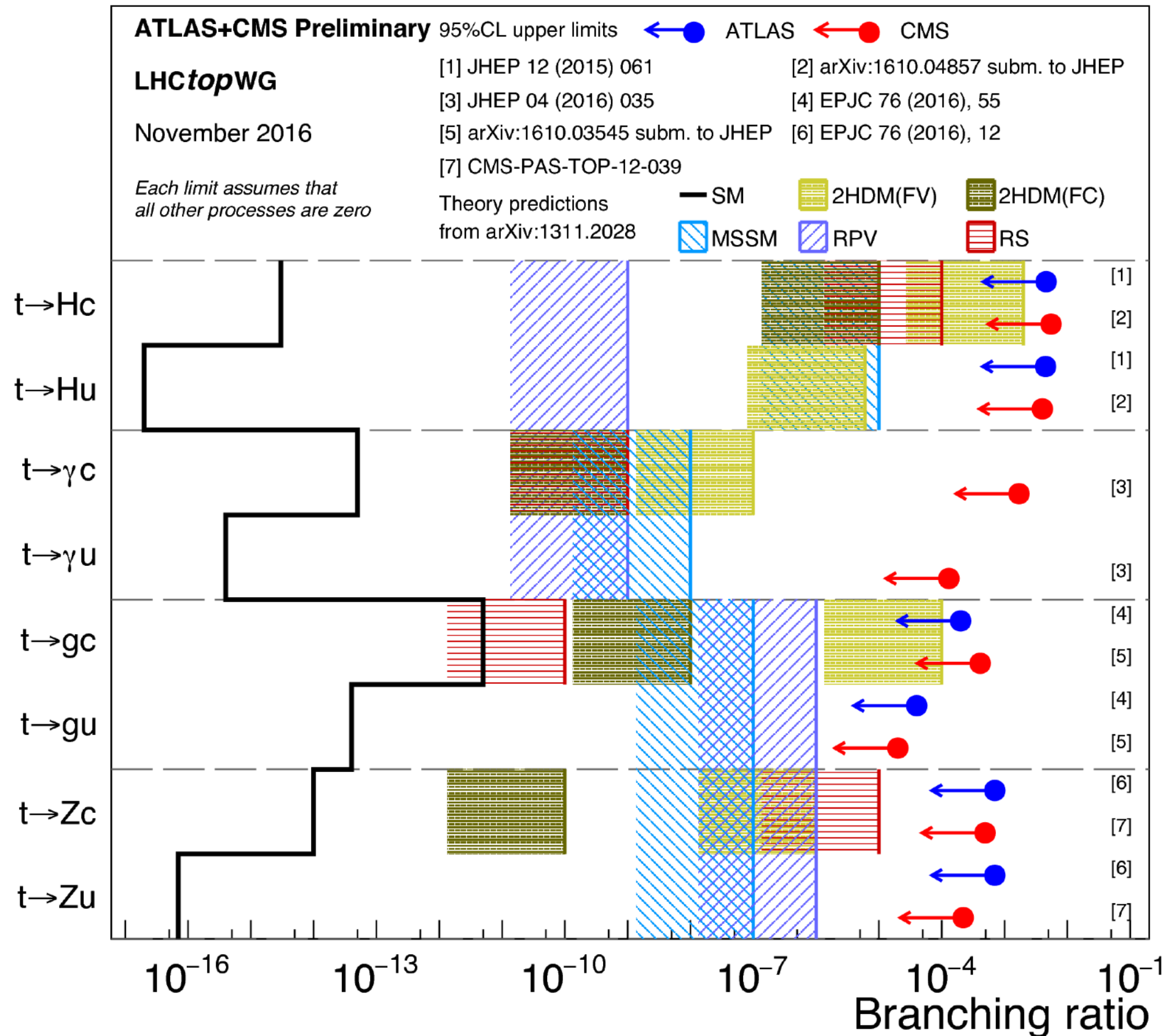
ATLAS-CONF-2017-056

Top Quark Higgs Coupling



Top: Flavor-Changing Decays

**No signs of
flavor physics
associated
with top!**

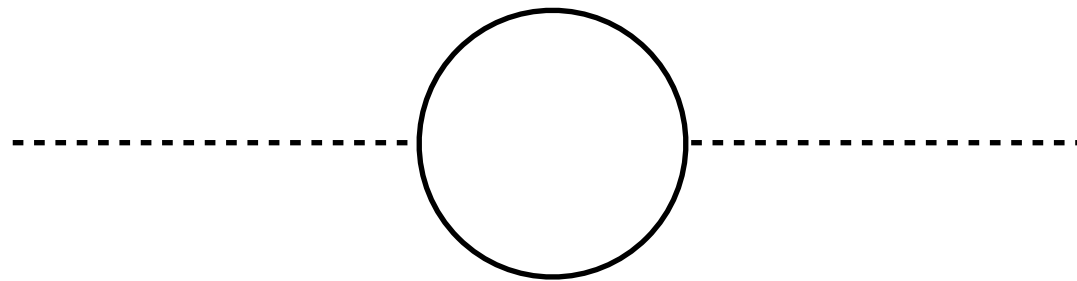


Naturalness and the Hierarchy Problem



The “Little” Hierarchy Problem

The top-quark is not a small perturbation to the EWSB sector!



$$\delta m_H^2 \propto \frac{2\lambda_t^2 \Lambda^2}{16\pi^2}$$

$$\delta m_H^2 < m_H^2 \Rightarrow \Lambda \leq 1 - 2 \text{ TeV}$$

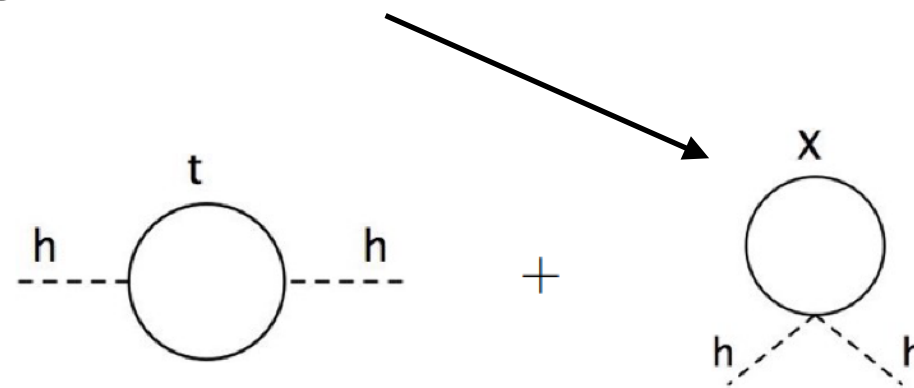
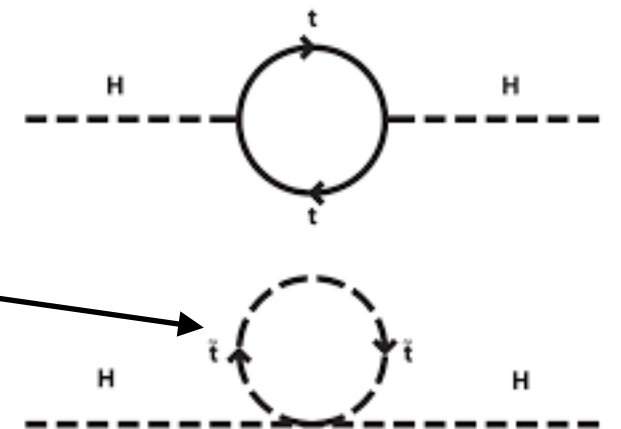
Where is the new physics?
(Is there something wrong with this argument?)

Traditional Approach: New Colored States

- Introduce a symmetry which ensures cancellation of offending divergences: if $[G_{\text{sym}}, G_{\text{SM}}]=0$, need colored states corresponding to the top.

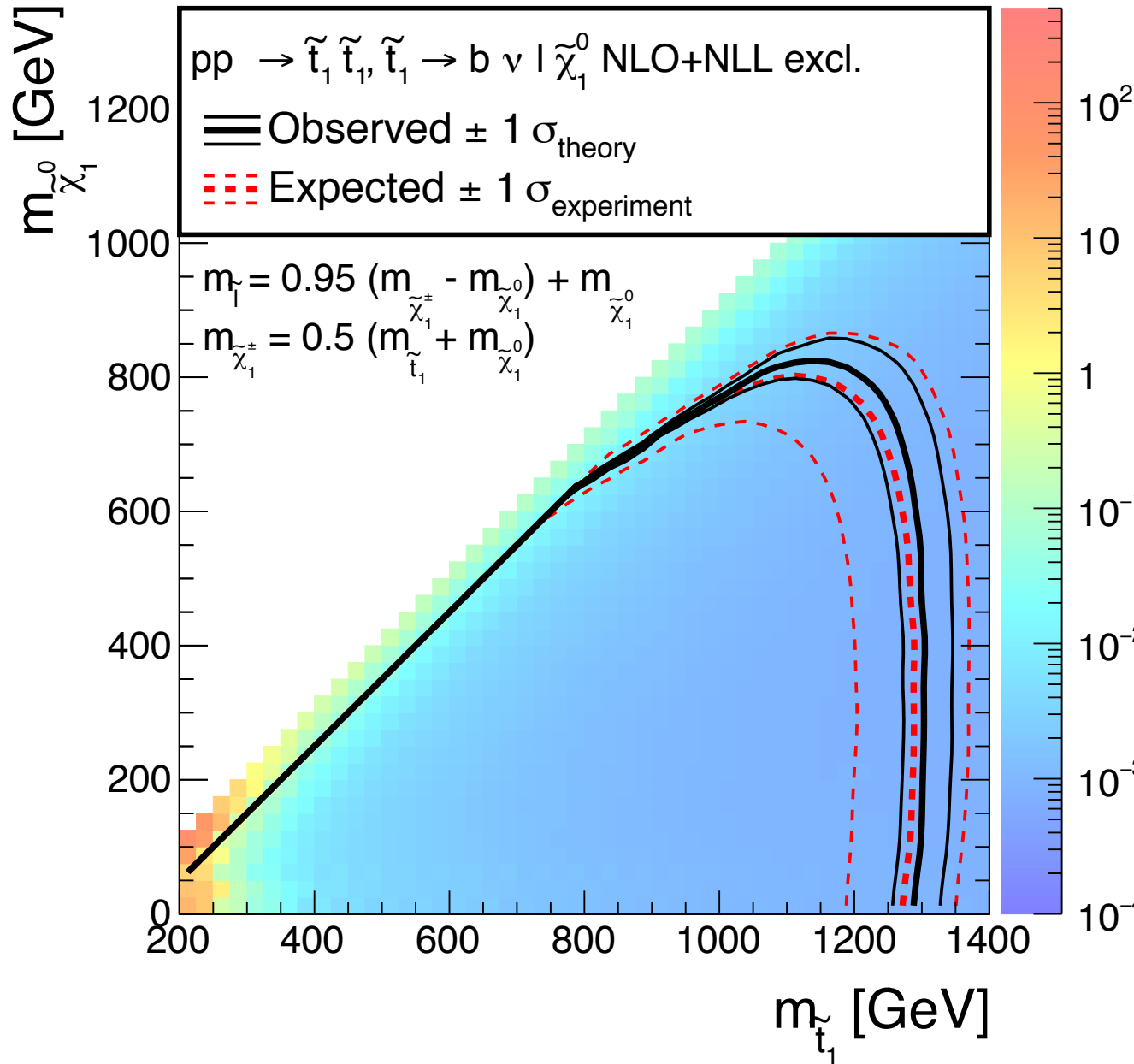
- SUSY: Top squarks, scalar partners

- Composite Higgs: fermionic top partners

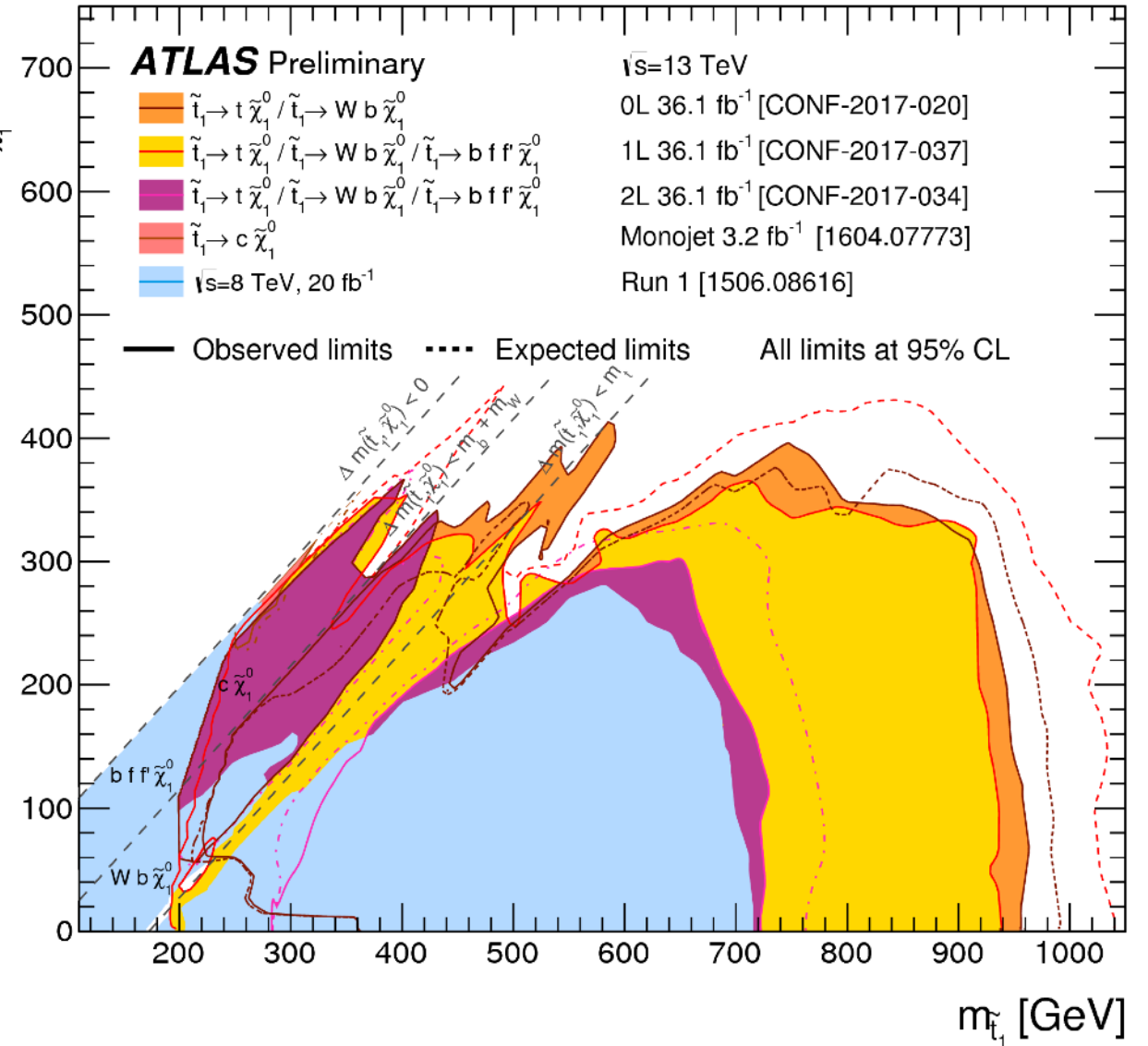


\tilde{t} searches ...

CMS Preliminary 35.9 fb⁻¹ (13 TeV)



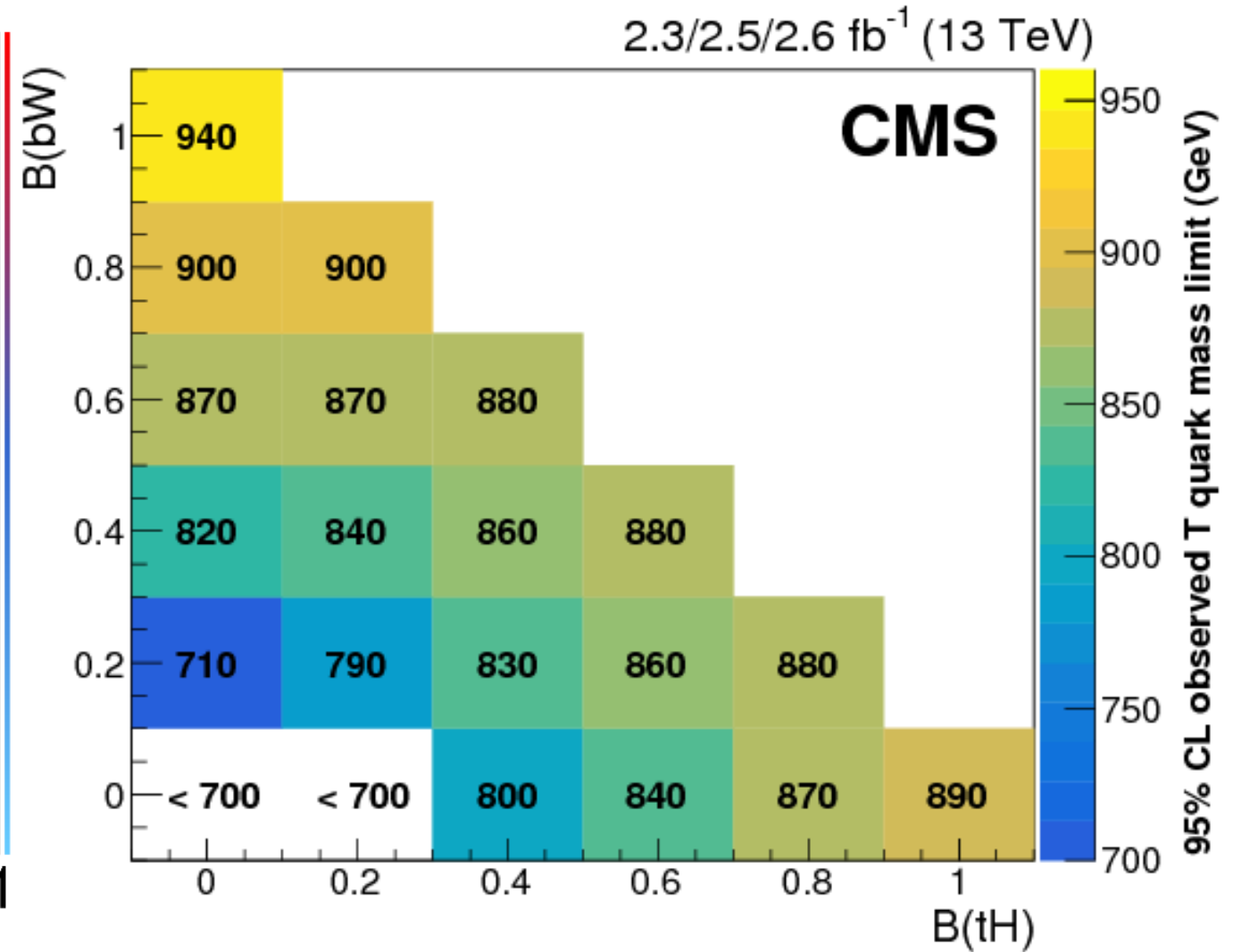
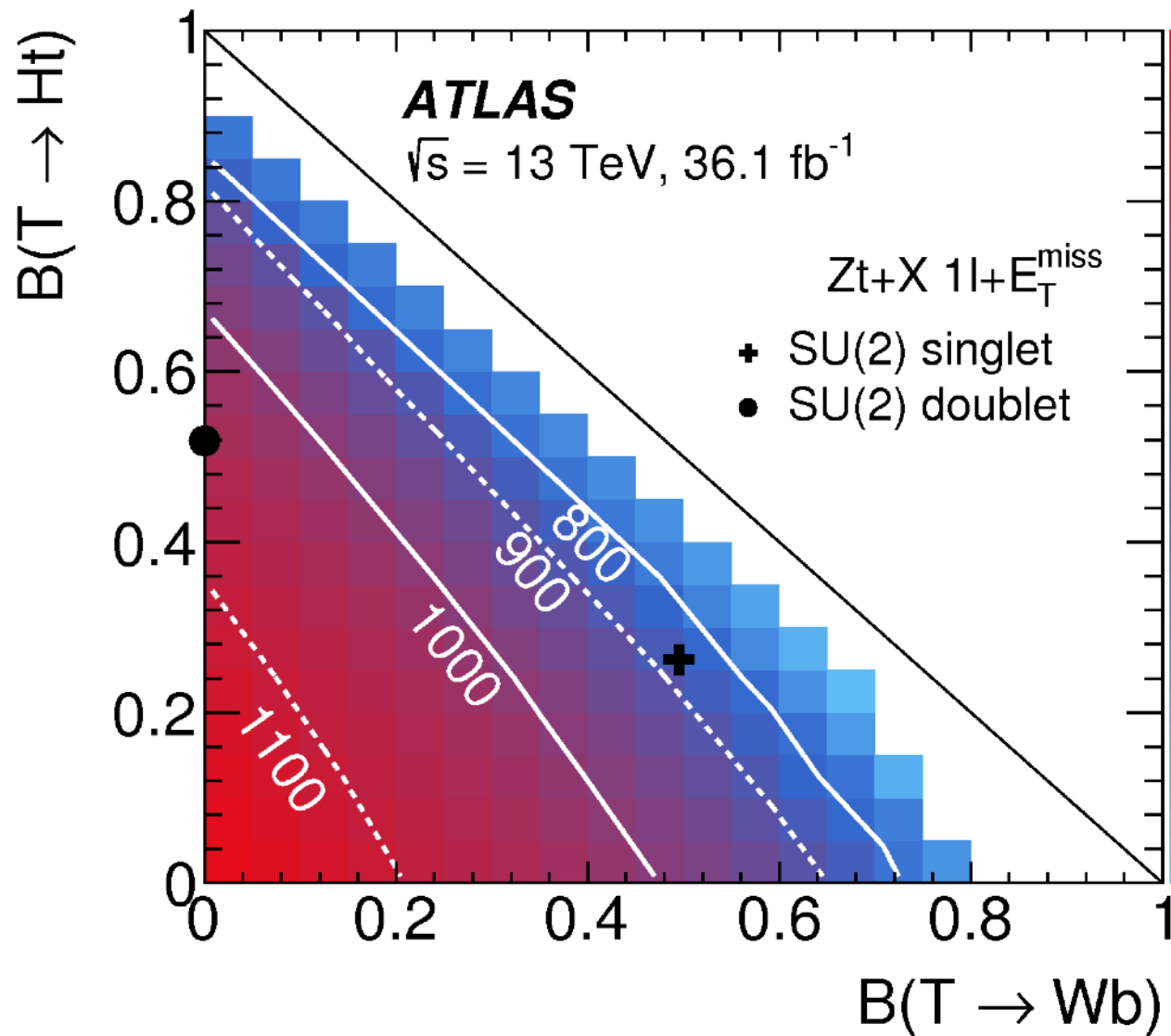
\tilde{t}_1, \tilde{t}_1 production, $\tilde{t}_1 \rightarrow b f \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ Status: May 2017



<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY>

<https://cms.cern/news/cms-new-results-Moriond-2017>

and vector T searches reaching the TeV scale!

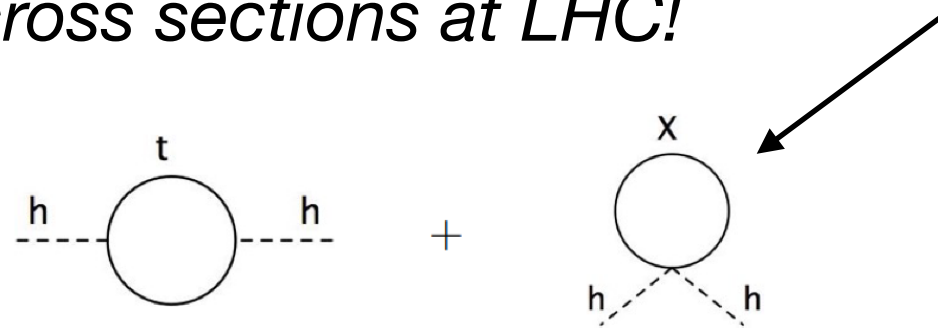


CMS arXiv:1706.03408

ATLAS arXiv:1705.10751

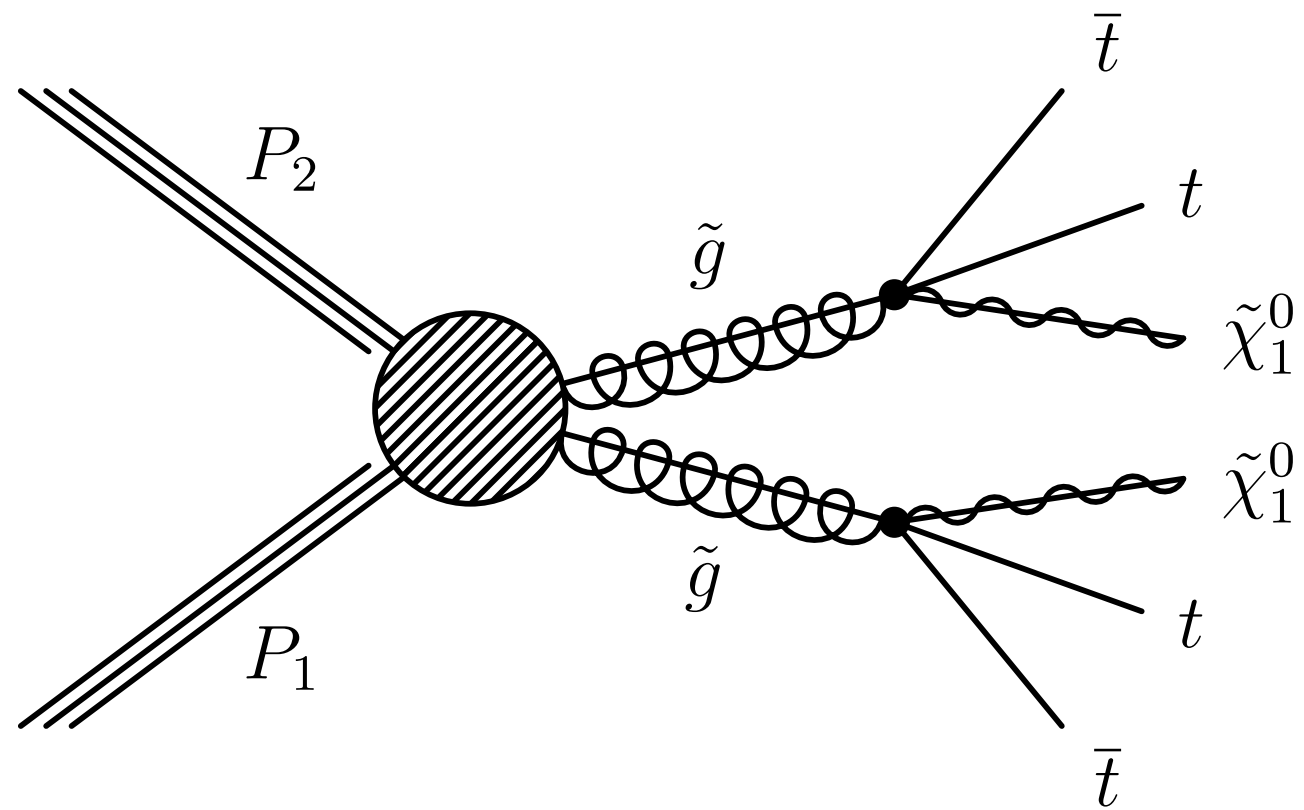
Neutral Naturalness: Colorless Top Partners?

- Introduce a symmetry which ensures cancellation of offending divergences: if $[G_{\text{sym}}, G_{\text{SM}}] \neq 0$, with *colorless states* corresponding to the top. *No large cross sections at LHC!*

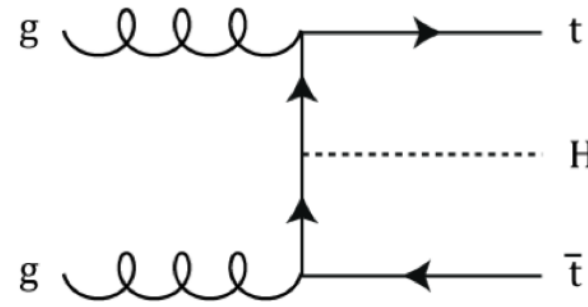


- Models (Twin Higgs, Folded SUSY, etc.) have partners charged under a new $SU(3)'$, instead, which get mass proportional to a new composite Higgs scale f .
- New sector may, or may not, have electroweak couplings - may only have couplings via Higgs! (Higgs portal...)
- Could give rise to long-lived particles, exotic signals. May require post-LHC colliders (lepton and hadron) for discovery...

Top as a Signal

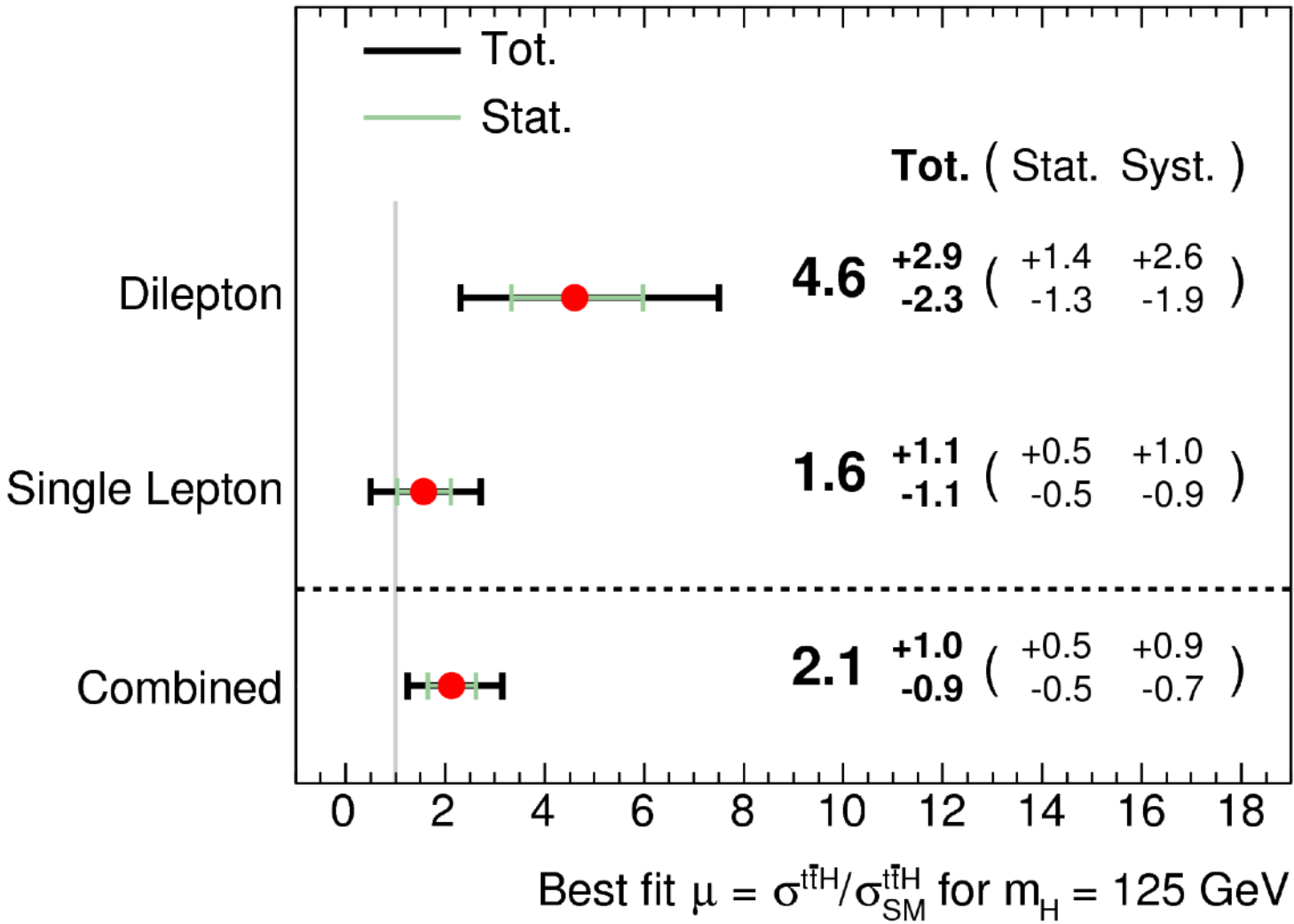


ttH

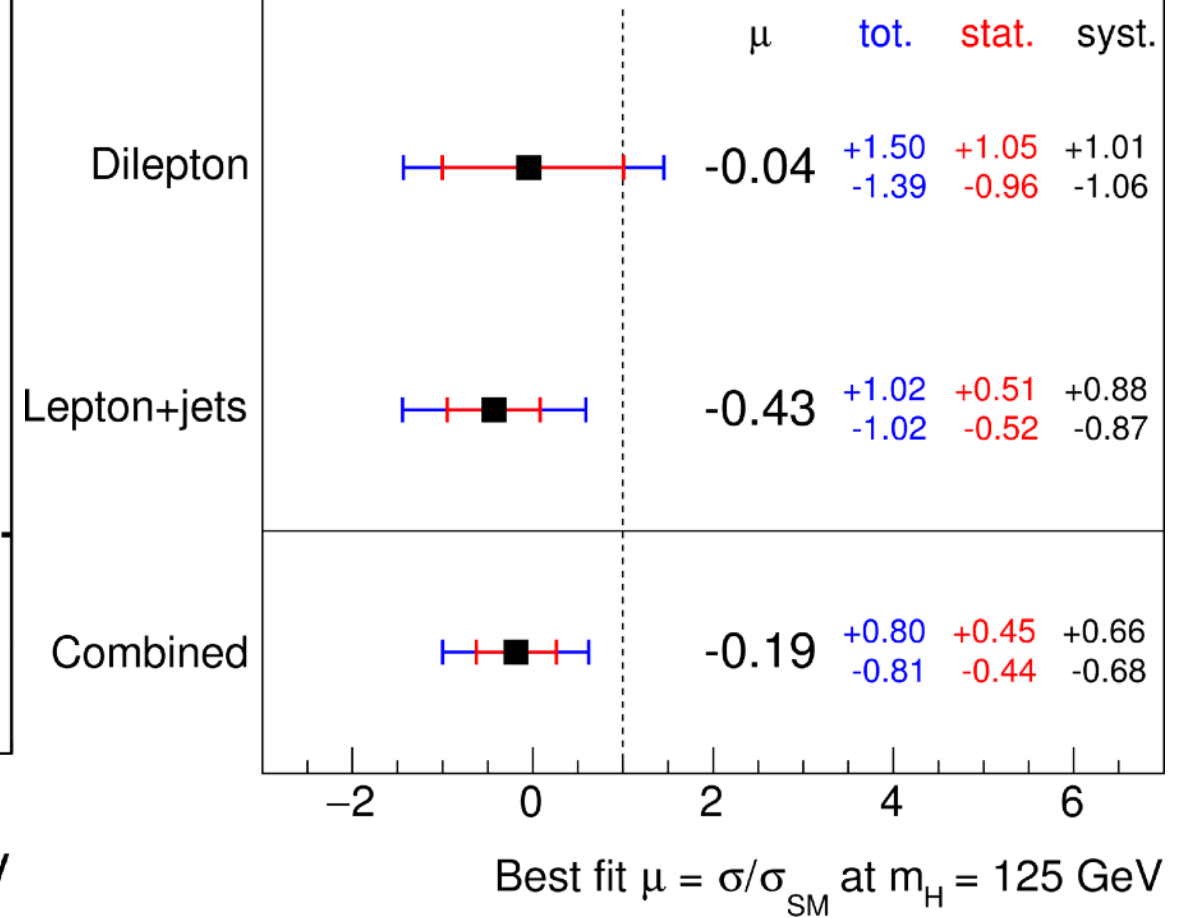


ATLAS Preliminary $t\bar{t}H$ ($b\bar{b}$), $\sqrt{s} = 13$ TeV, 13.2 fb^{-1}

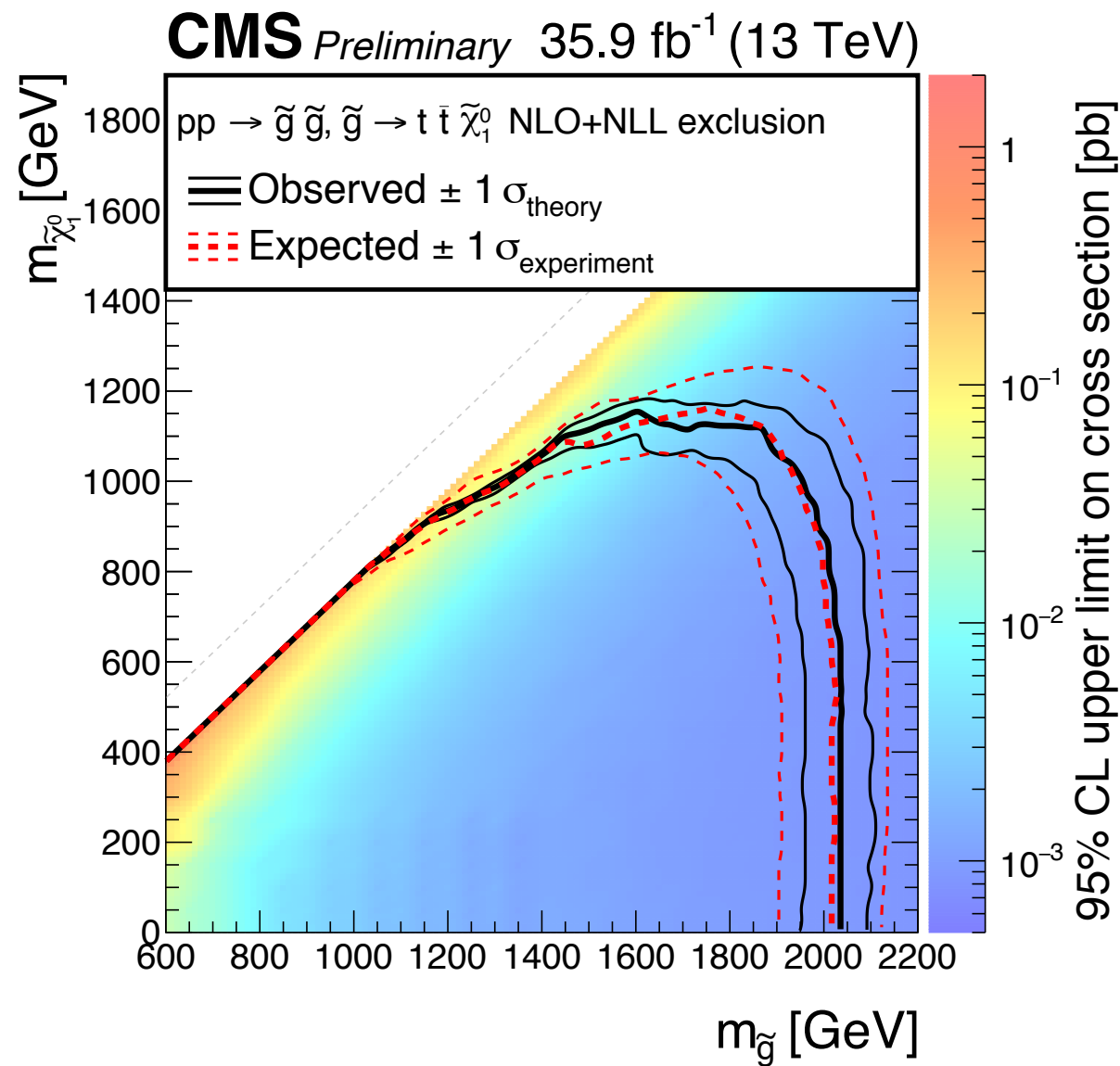
11.4 - 12.9 fb^{-1} (13 TeV)



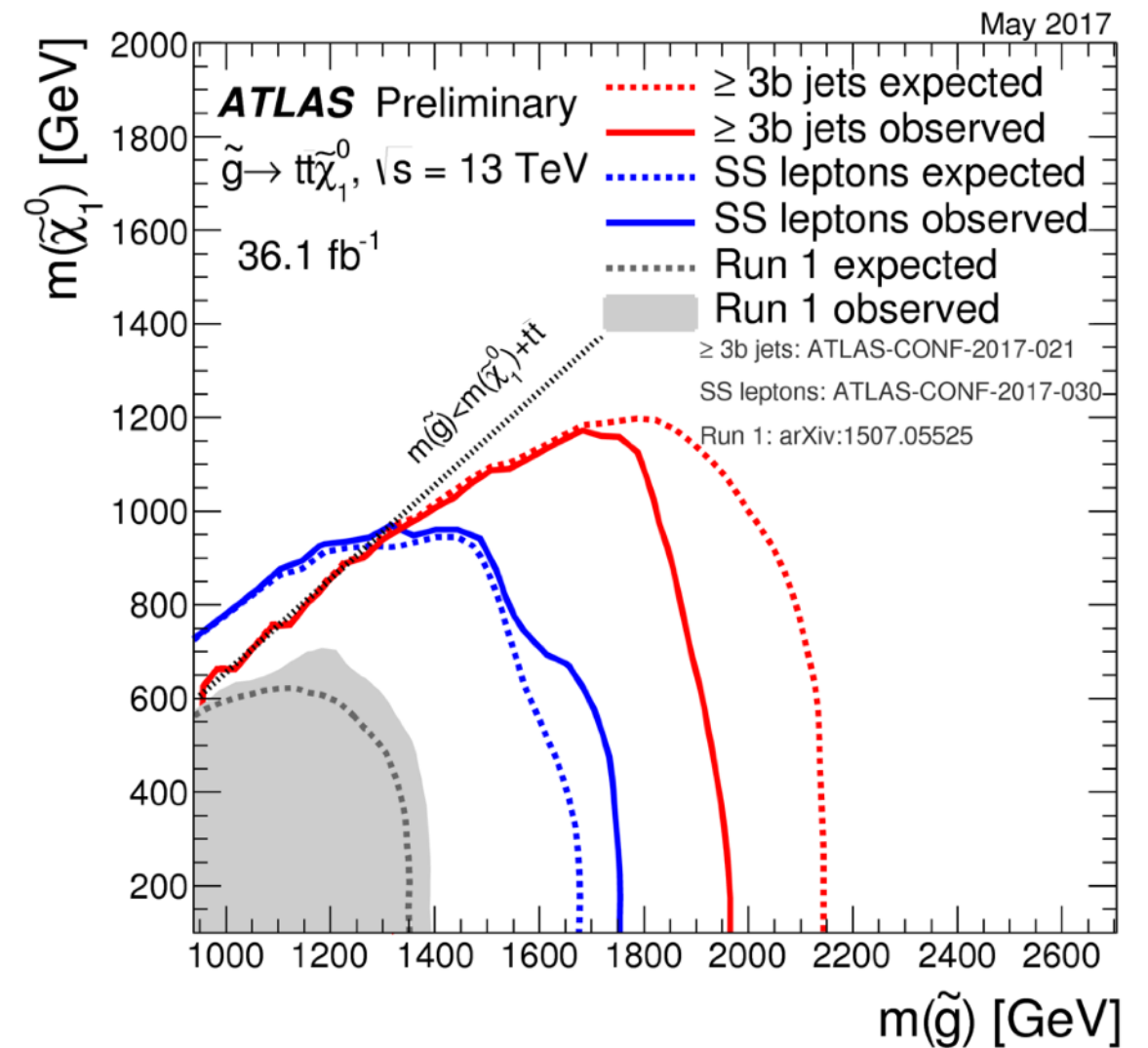
CMS Preliminary



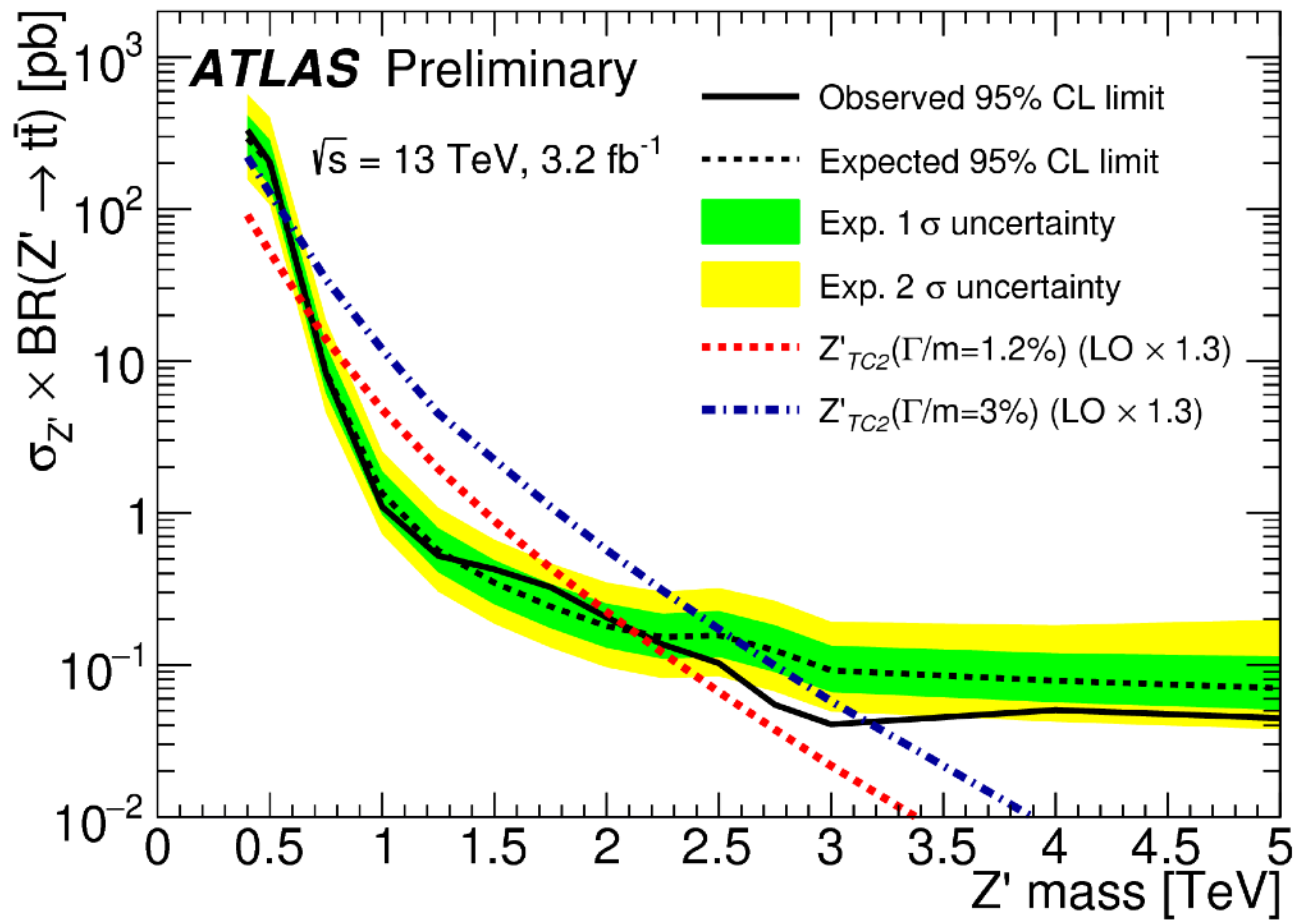
SUSY Decays to top



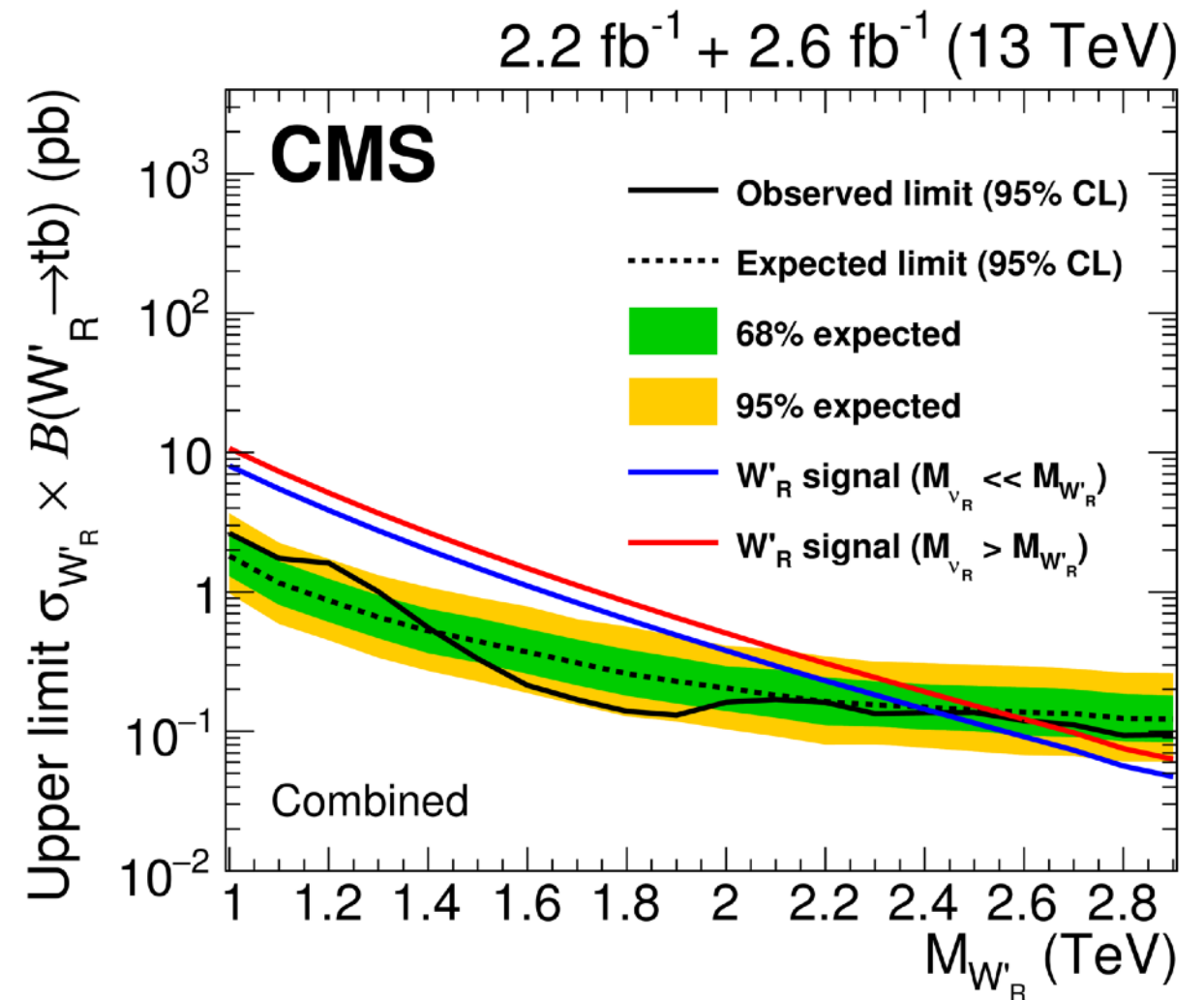
CMS-PAS-SUS-16-050



tt/tb Resonance Searches



ATLAS-CONF-2016-014

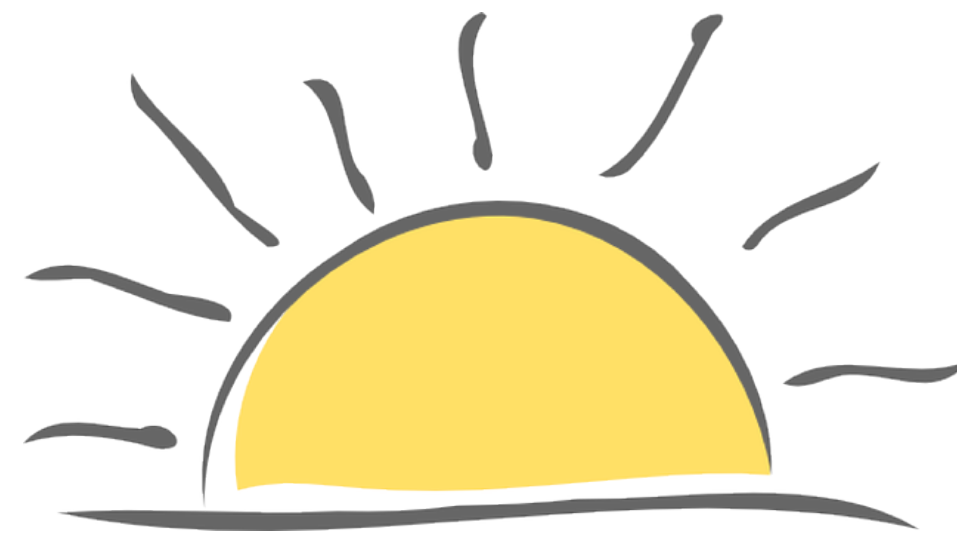
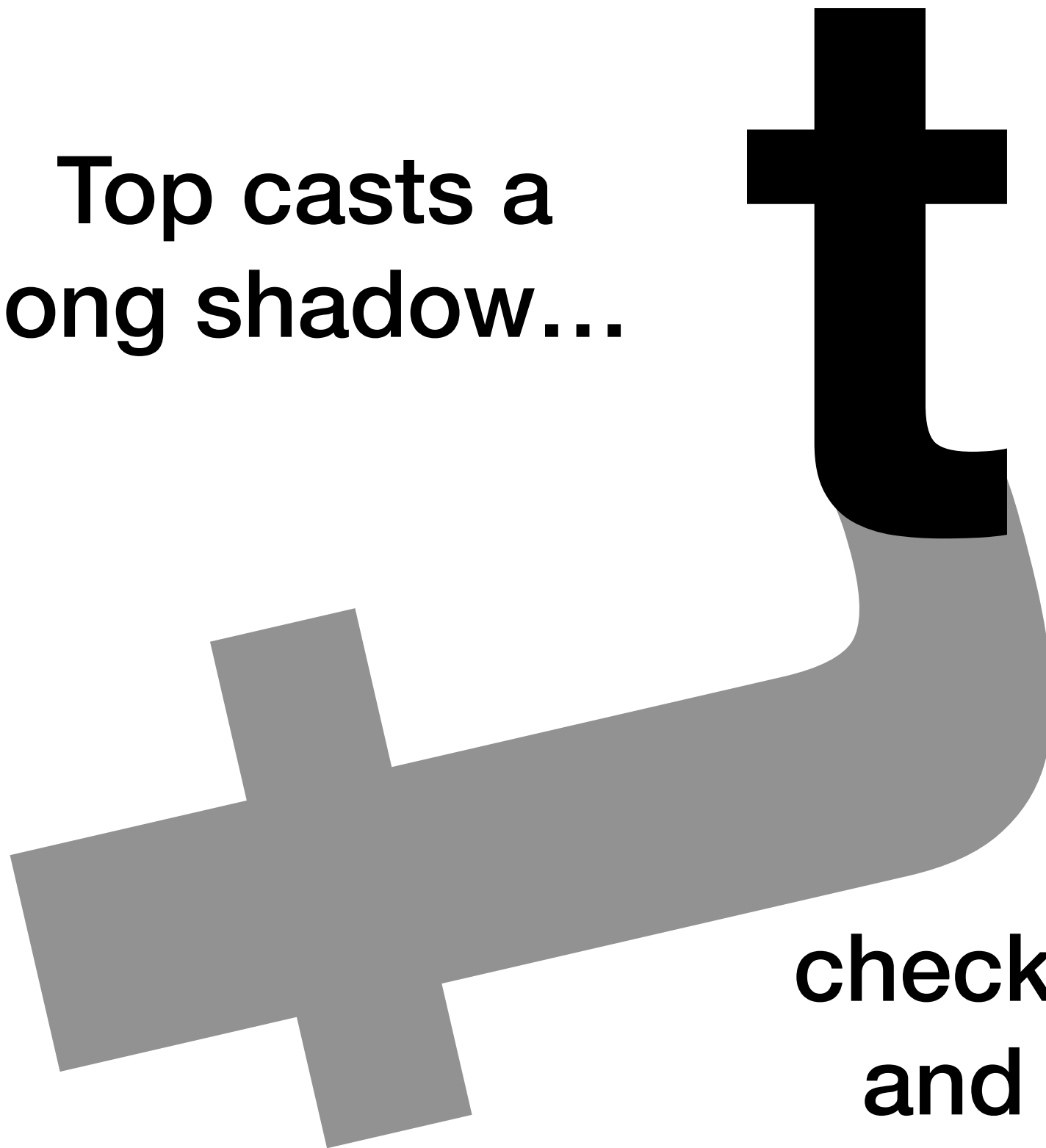


CMS-B2G-16-016

Top: What do we know?

- To a very good approximation, top:
 - is a $(3,2)_{+1/6}$ (left) and $(3,1)_{+2/3}$ (right) under $SU(3)_C \times SU(2)_W \times U(1)_Y$ under the electroweak gauge interactions,
 - has $V_{tb} \approx 1$, $|V_{ts}| \approx 0.04$, and $|V_{td}| \approx 0.009$,
 - and Yukawa coupling $y_t \approx \sqrt{2} m_t/v \approx 1$.
- *Top couples strongly to the EWSB sector, and many BSM theories imply*
 - *additional particles coupling to top - e.g. vector or fermionic partners, new gauge bosons or scalars,*
 - *Deviations in top couplings - $\frac{v^2}{\Lambda^2} = \mathcal{O}(10\%) \Rightarrow \Lambda \geq 1 \text{ TeV}$*
 - *Hierarchy & Naturalness: We are probing interesting energy scales!*

**Top casts a
long shadow...**



**... studies
check standard model
and constrain BSM**