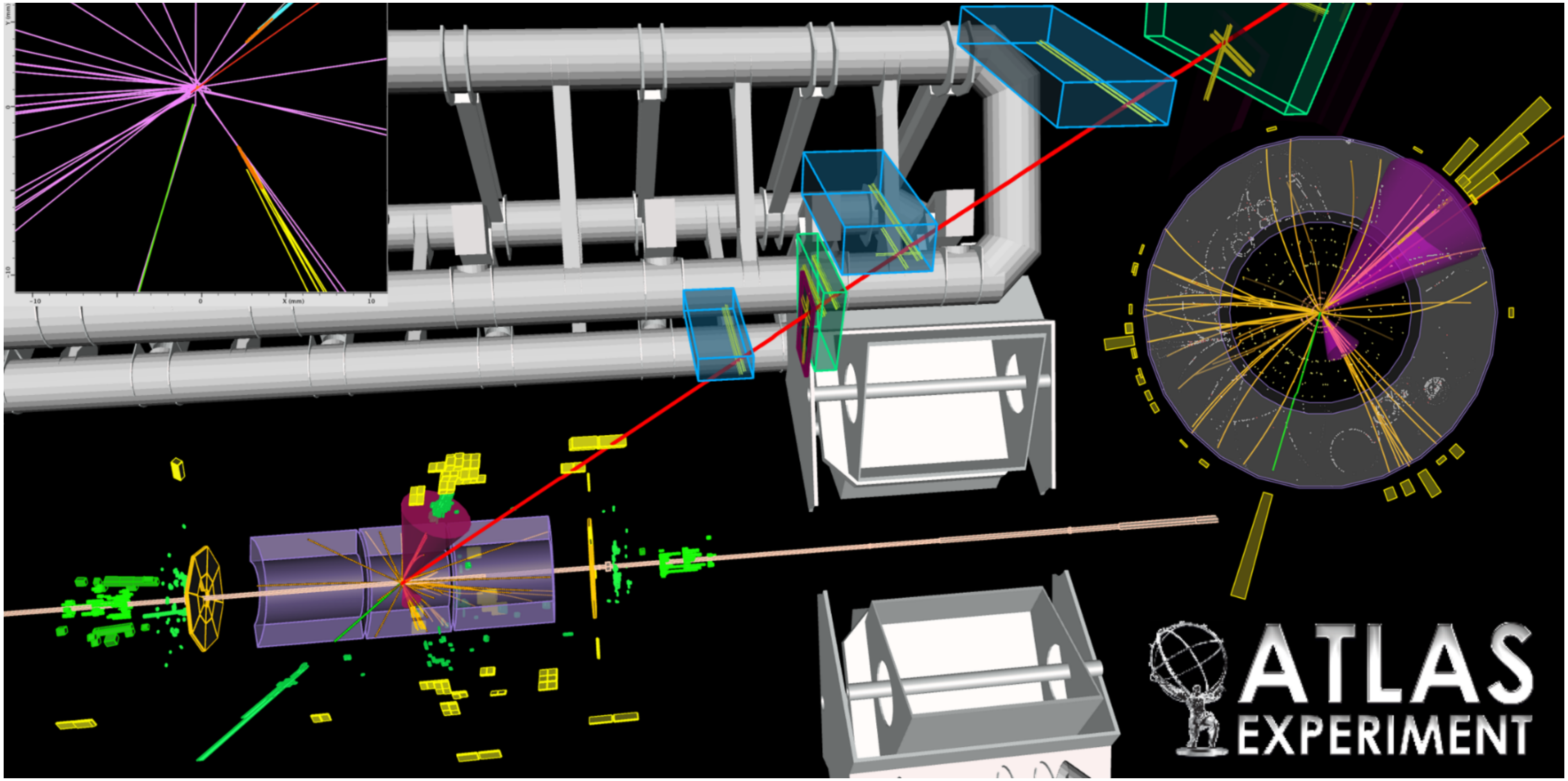
Top quark couplings



María Moreno Llácer
(maria.moreno.llacer@cern.ch)

6th ComHEP: Colombian Meeting on High Energy Physics

After the Higgs boson discovery, **Standard Model (SM) measurements** have two main goals:
- validate SM in new energy regime and **improve precision** of known SM parameters
- **test SM for new physics** (NP) contributions

Electro-weak, Higgs and top quark physics have a great potential in both of these goals:
- unique signatures
- several rare processes predicted by SM, where the loop contributions (e.g. from NP particles) can give sizable effects, become sensitive tools to probe the NP models
- enough data for precision measurements of rare processes!
- theoretical predictions for most of the processes can be calculated with high precision

Very rich programme → several physics results → global interpretations

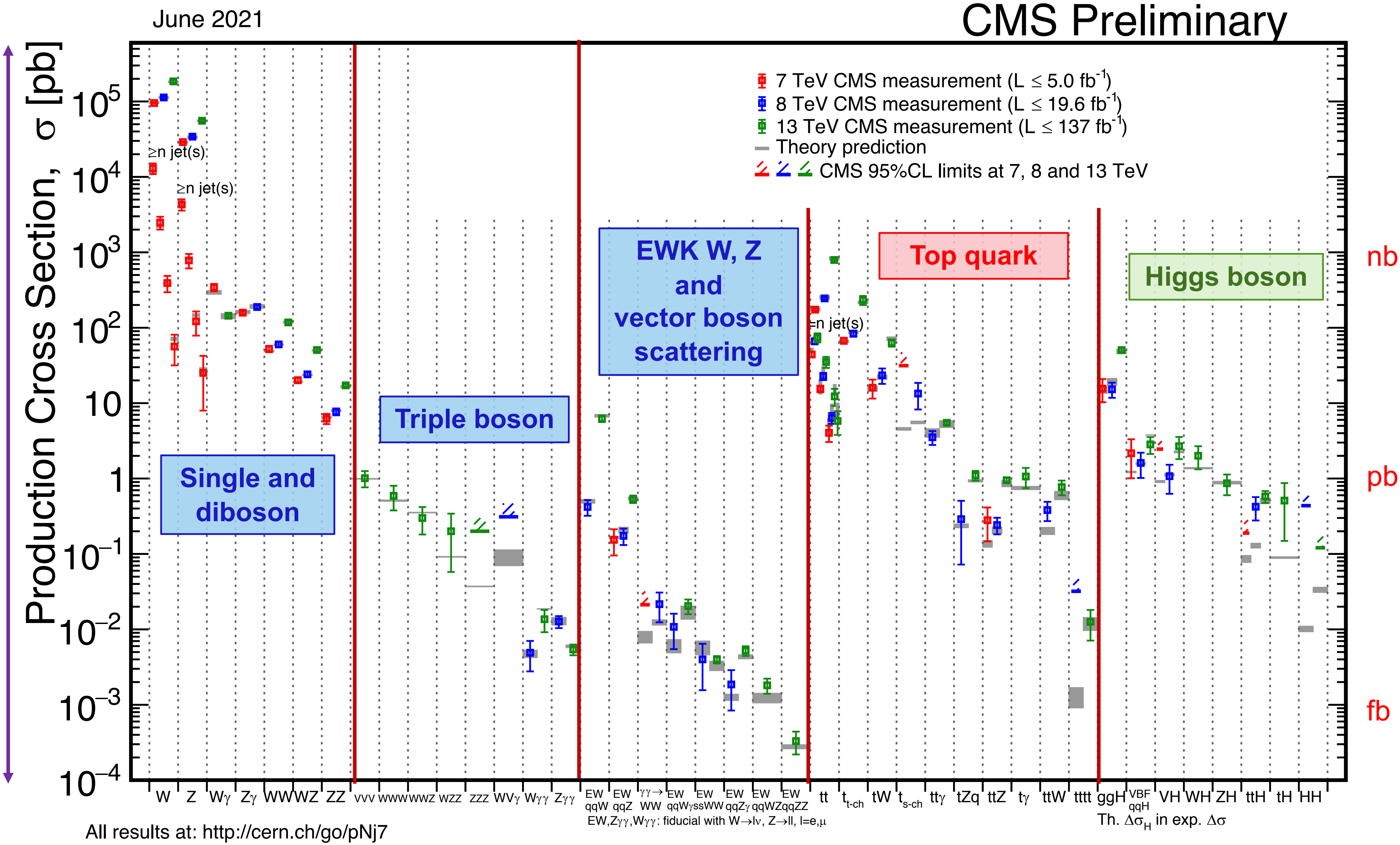
Here, focus on LHC measurements to study top quark couplings and present a recent global fit to top quark electro-weak couplings.

All results are available in:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

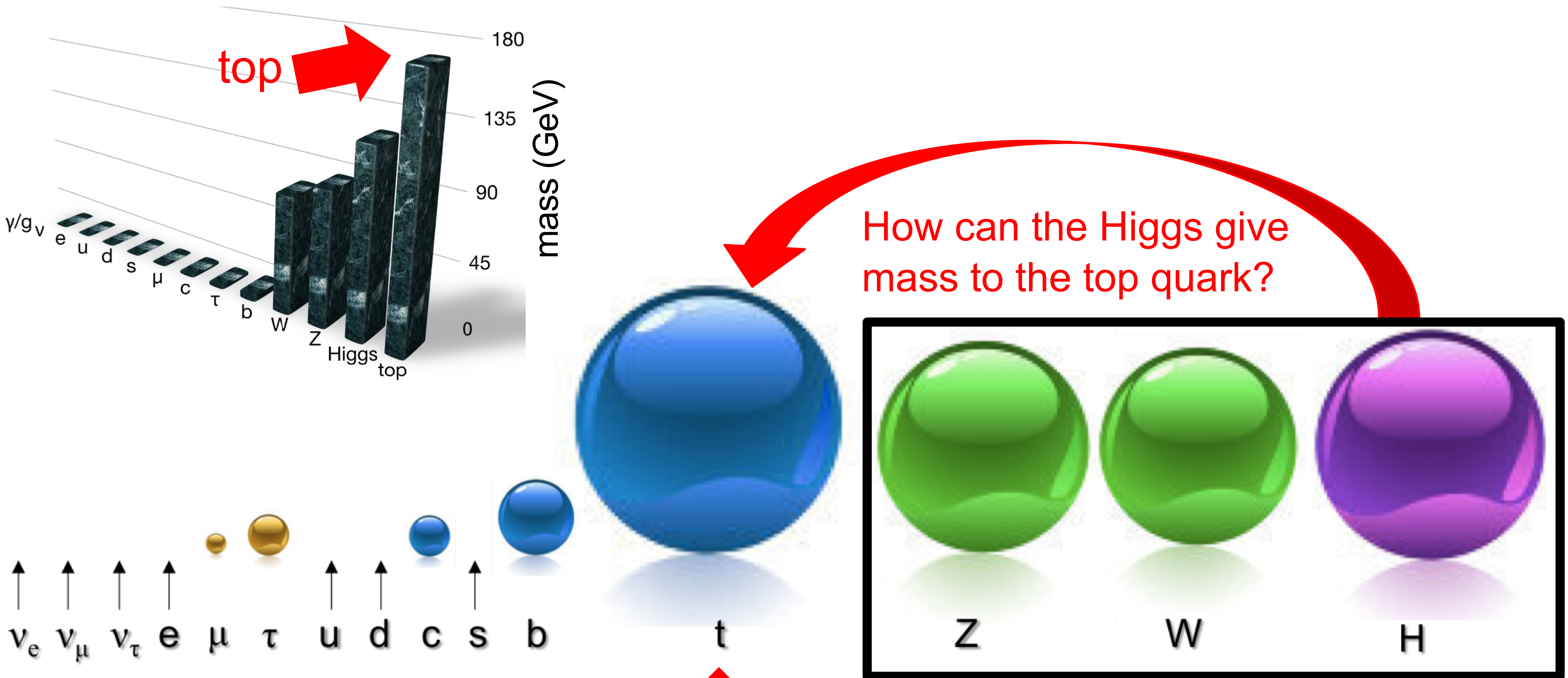
Thanks to LHC & the detectors!

Events @ LHC Run 2 (140 fb^{-1})	
W bosons	27000 10^6
Z bosons	8000 10^6
Top quarks	130 10^6
Higgs bosons	8 10^6

Cross sections measured for several SM processes



The special relevance of the top quark



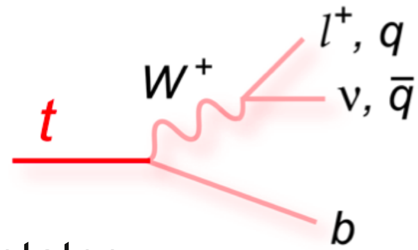
Volume of sphere proportional to particle mass

most massive of the elementary particles
even more than the Higgs boson

The top quark: a special case in the Standard Model

from both theoretical and experimental sides

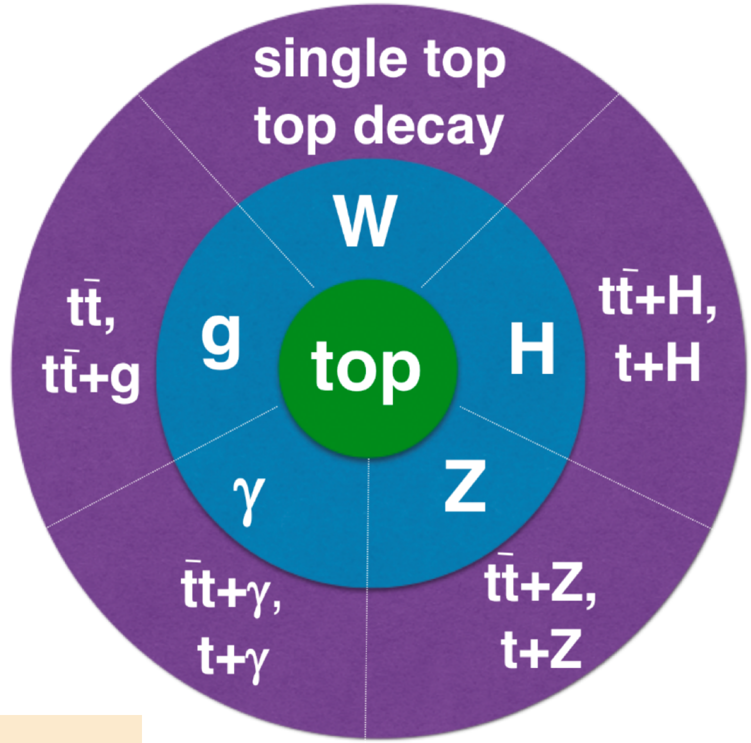
- **most massive** fundamental particle known to date
  m_{top} (~172 GeV) > m_{Higgs} (~125 GeV)



- **short lifetime** → unique properties
  - decays (into a $t \to W^+ b$) before forming bound states
  - **the only "bare" quark**
  - properties studied through its decay products

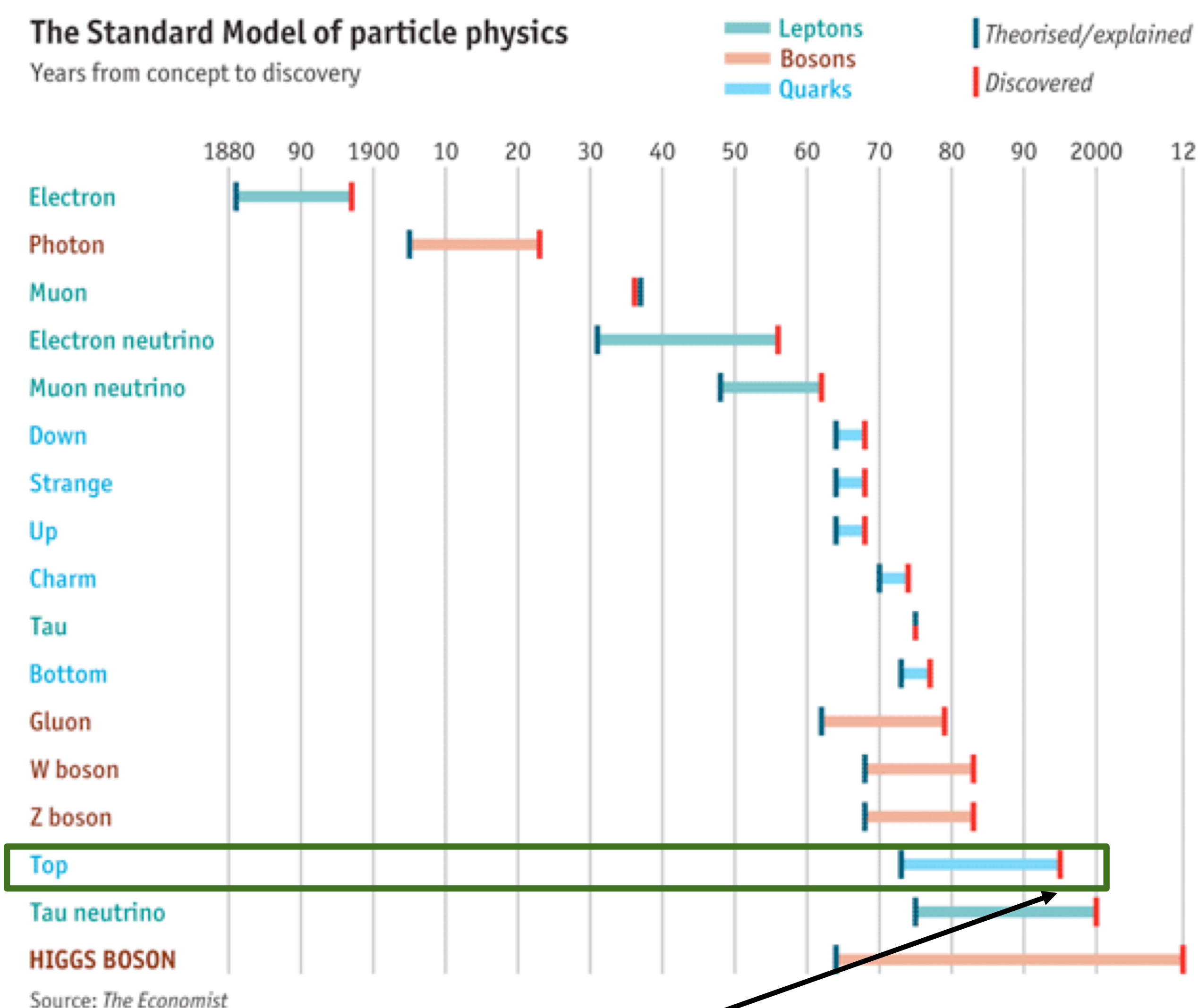
- **"feels" all forces** (couples to all bosons)

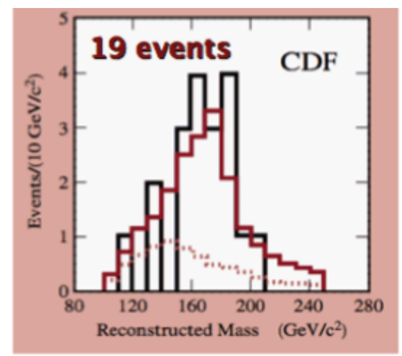
- **large coupling to Higgs boson**
  - strength (top Yukawa) ~1

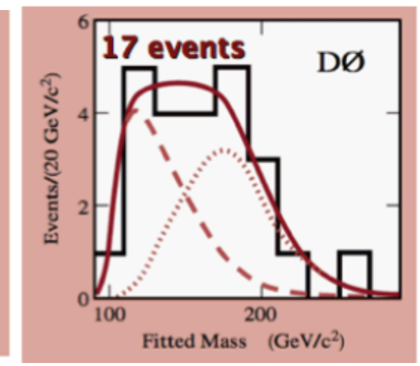


Crucial to measure its properties with high precision.
Inspiring us to look Beyond the Standard Model.

Top quark discovery in 1995



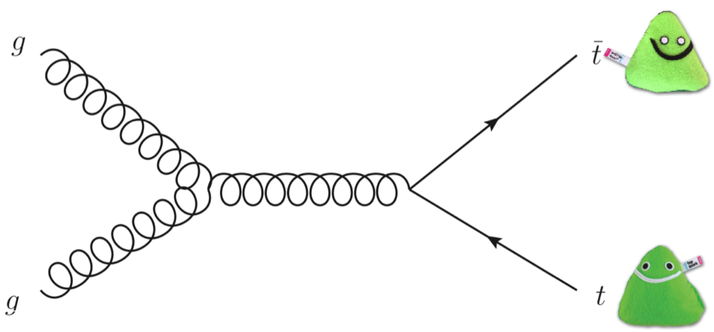




__1995:__ Top quark discovery at Tevatron (Fermilab)

Top quark production at the Large Hadron Collider

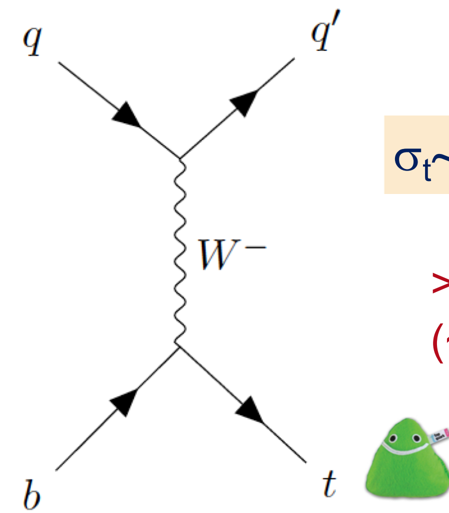
Pair production: top+antitop (via strong interaction)



σ_{tt}~830 pb

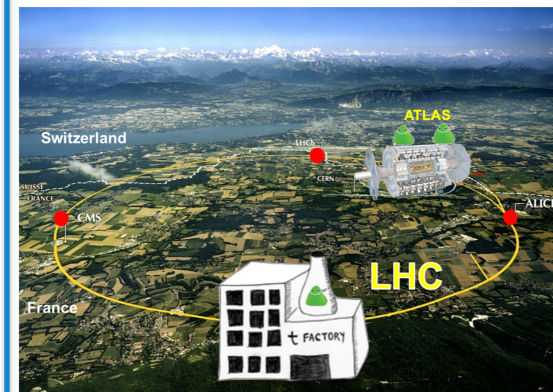
> 100 million pairs (~15 pairs/s)

Single production: top or antitop (via electro-weak interaction)



σ_t~10-200 pb

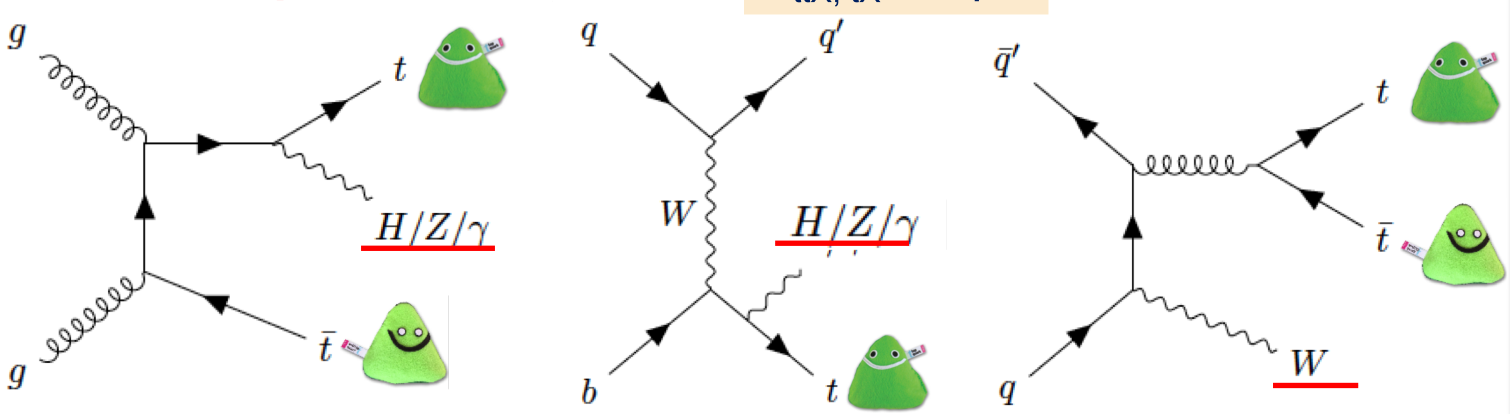
> 30 million (~ 5 events/s)



The LHC is a TOP quark factory

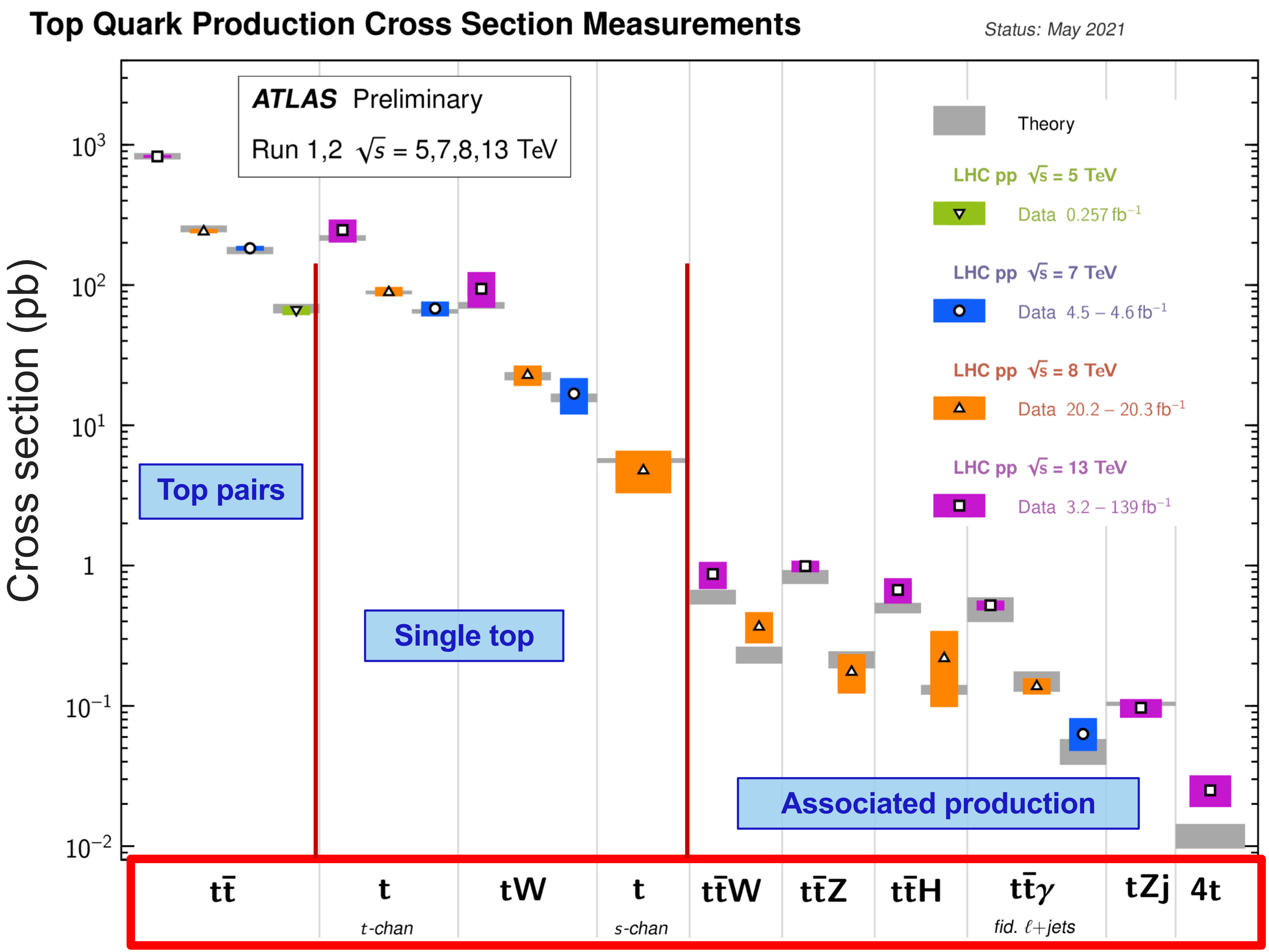
Associated production

$\sigma_{ttX,\ tX} < 1$ pb (< 5 events/ 200 s)



Cross sections given at 13 TeV

Reaching very rare processes as data increase



Cross sections increase with energy

1 event every second

1 event every 100 s

So far, experimental results confirm the Standard Model

Increasing number of differential measurements, reaching very high precision, also EFT interpretations

Top quark couplings

Top quark couples to other SM fields through its **gauge and Yukawa interactions**

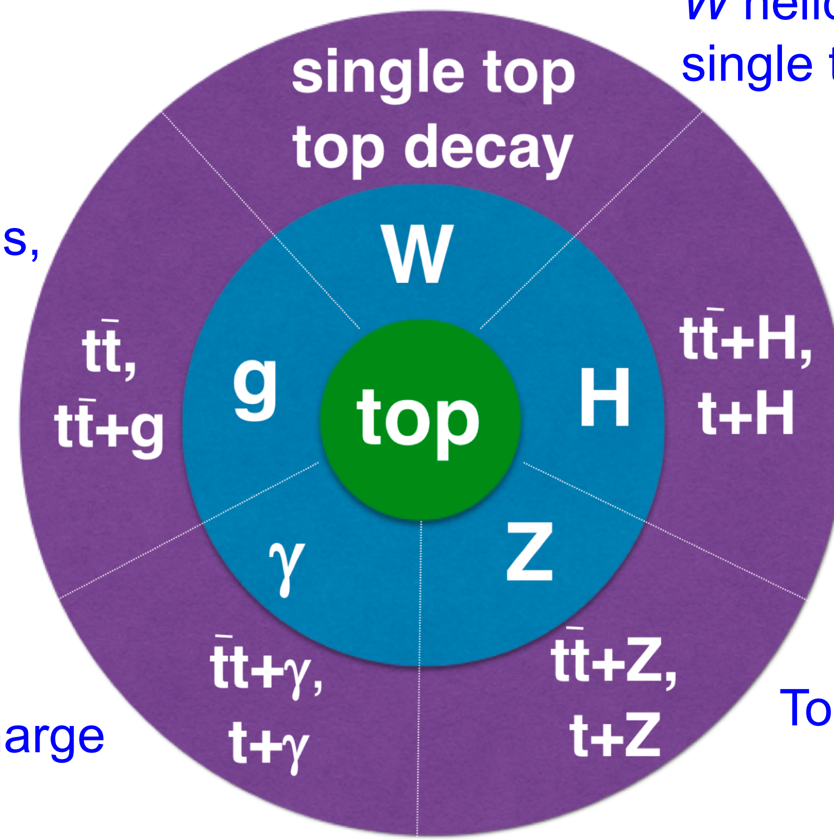
t→*Wb* coupling and *tt* strong production studied already at the Tevatron

High statistics at the LHC: *tt*+bosons (γ, *Z*, *W* and *H*) became available

- *tt*+γ/*Z*/*W* processes observed with Run1 data
- *tt*+*H* and *t*+*Z* processes observed with Run 2 data

W helicity and several single top quark measurements

Differential cross-sections, spin correlations, charge asymmetry, etc.



Top Yukawa coupling

Top electric charge

Top weak isospin

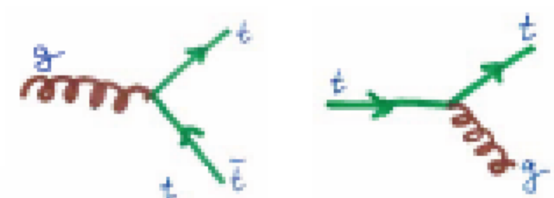
top + X coupling: how to measure it?

Flavour changing charged current

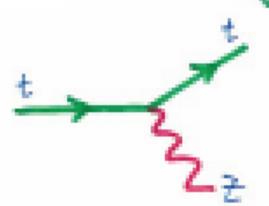
- **Wtb**

Flavour conserving neutral current

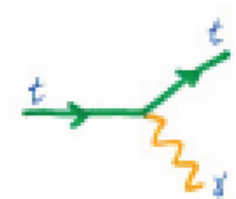
- **tgt**



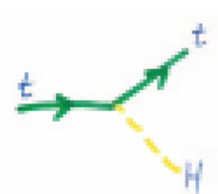
- **tZt**



- **tγt**

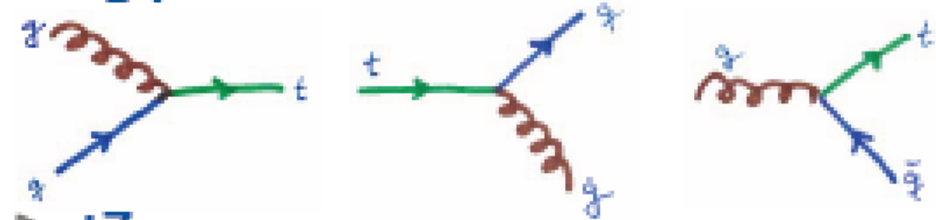


- **tHt**

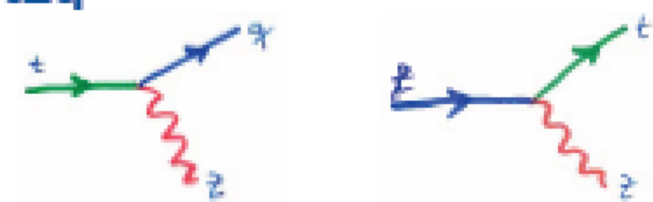


… and neutral current

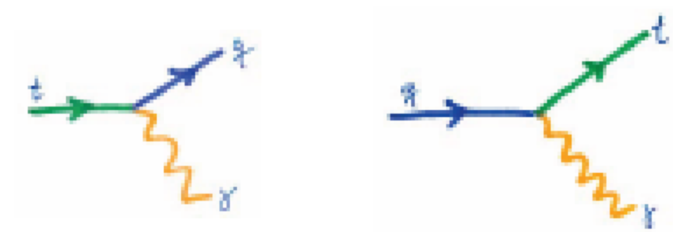
- **tgq**



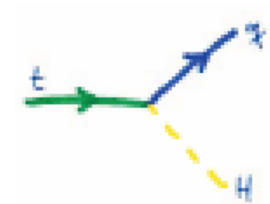
- **tZq**



- **tγq**



- **tHq**



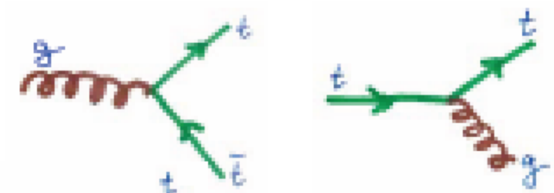
Top coupling to W bosons (*Wtb* vertex)

Flavour changing charged current

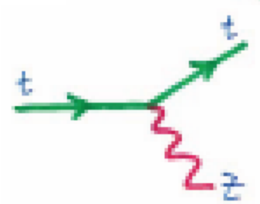
- **Wtb**

Flavour conserving neutral current

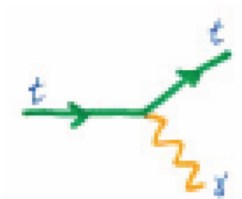
- **tgt**



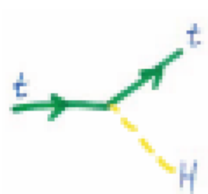
- **tZt**



- **tγt**

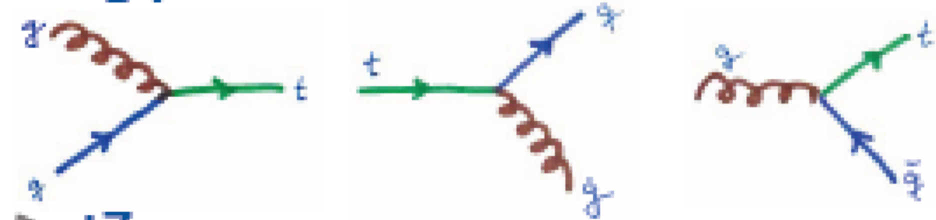


- **tHt**

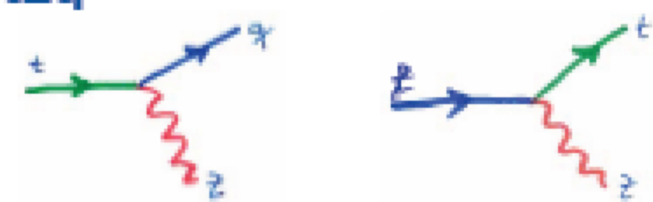


… and neutral current

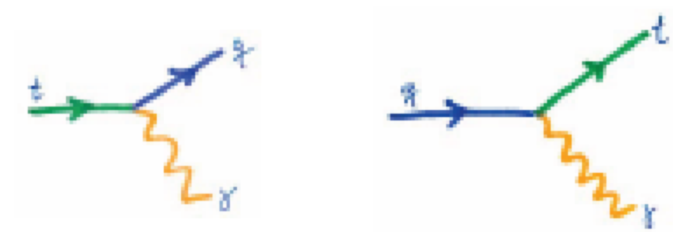
- **tgq**



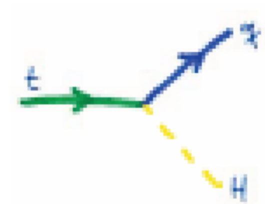
- **tZq**



- **tγq**



- **tHq**



Top quark production in electro-weak interactions

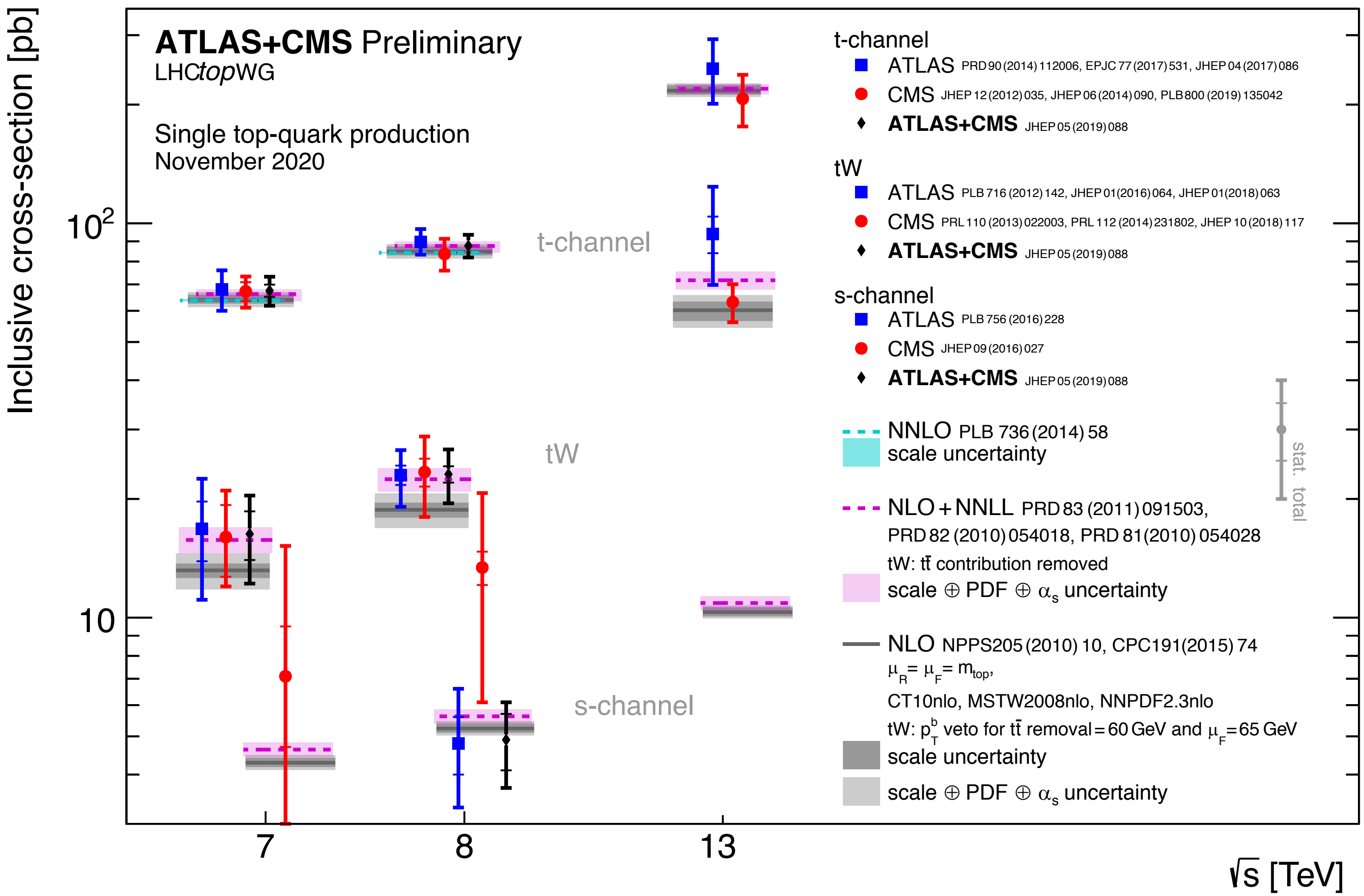
coupling to W bosons

The *Wtb* vertex has a V-A structure, described by $\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu} V_{L} P_{L} t W_{\mu}^{-} + \text{h.c.}$

From **single top quark production cross sections**, V_L can be extracted:

Combinations of ATLAS and CMS results using full Run 1 published

JHEP05(2019)088



→ **(7 TeV) 8.4%**
(8 TeV) 6.7%

→ **(7 TeV) 25%**
(8 TeV) 16%

→ **(8 TeV) 30%**

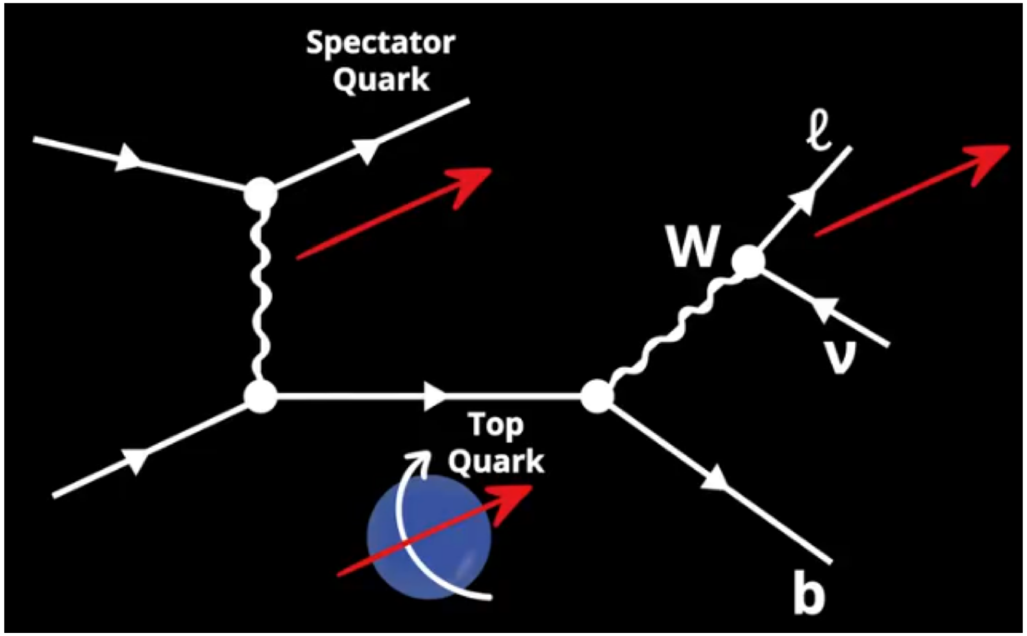
Exp. unc. larger than theory prediction unc. (4-8%)

s-ch. challenging, still not observed at LHC (only evidence)

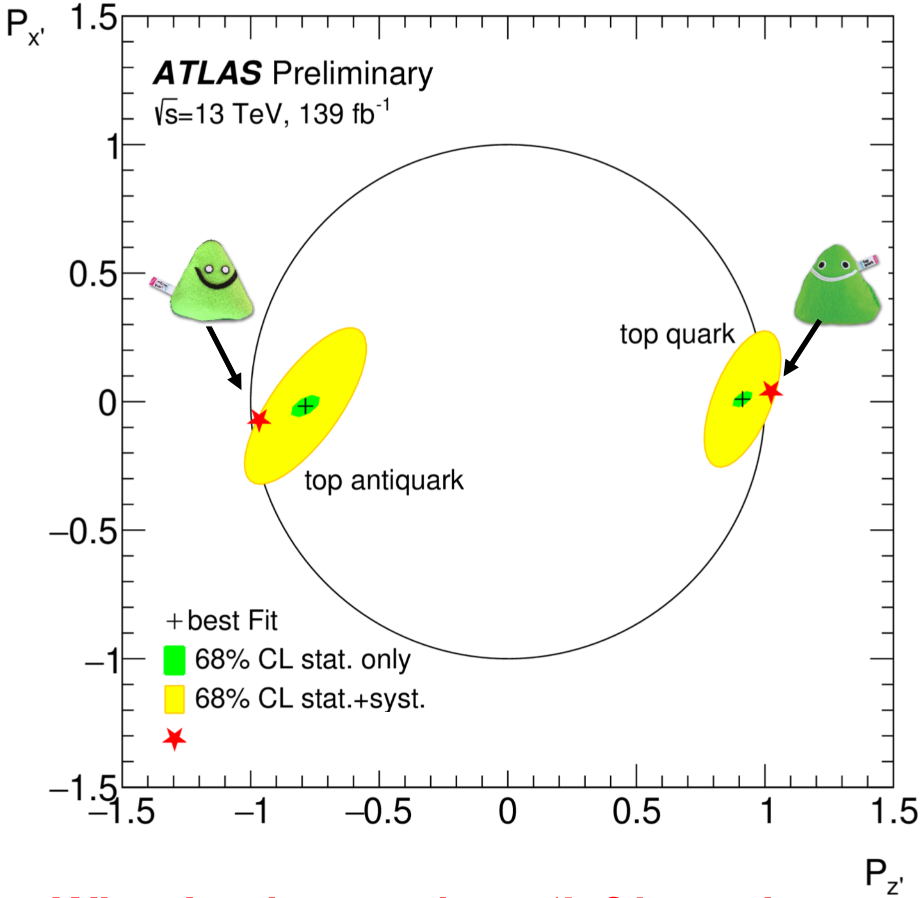
Polarised single top or antitop quarks

High polarisation ($|P_z|$~0.9) expected along one direction. Such is reflected in angular distributions of its decay products.

→ **Exactly what we measured!**



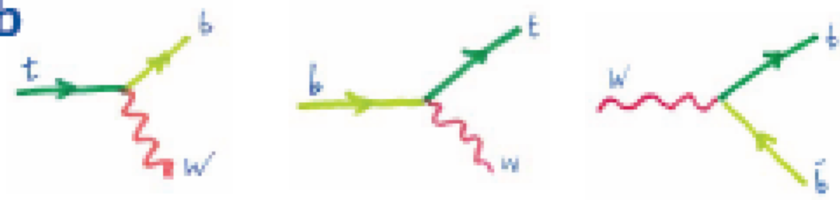
1st measurement of full polarization for both top and antitop quarks



What is observed are 'left' quarks and 'right' antiquarks

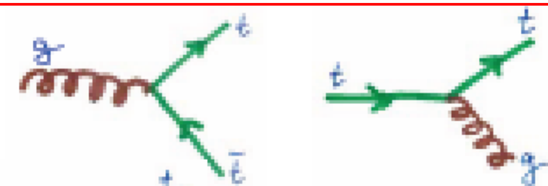
Flavour changing charged current

- Wtb

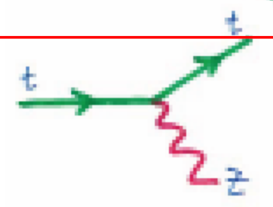


Flavour conserving neutral current

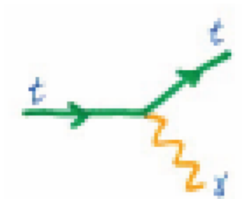
- tgt



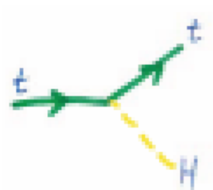
- tZt



- tγt

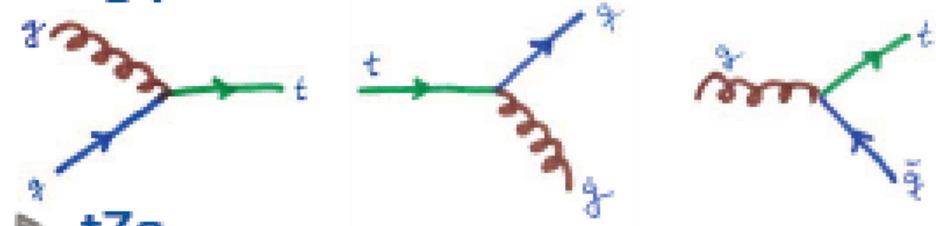


- tHt

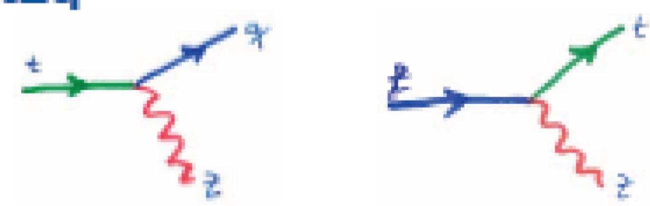


… and neutral current

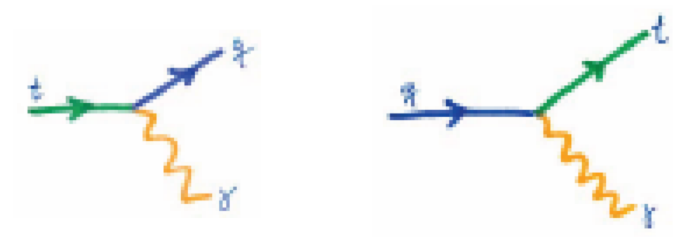
- tgq



- tZq



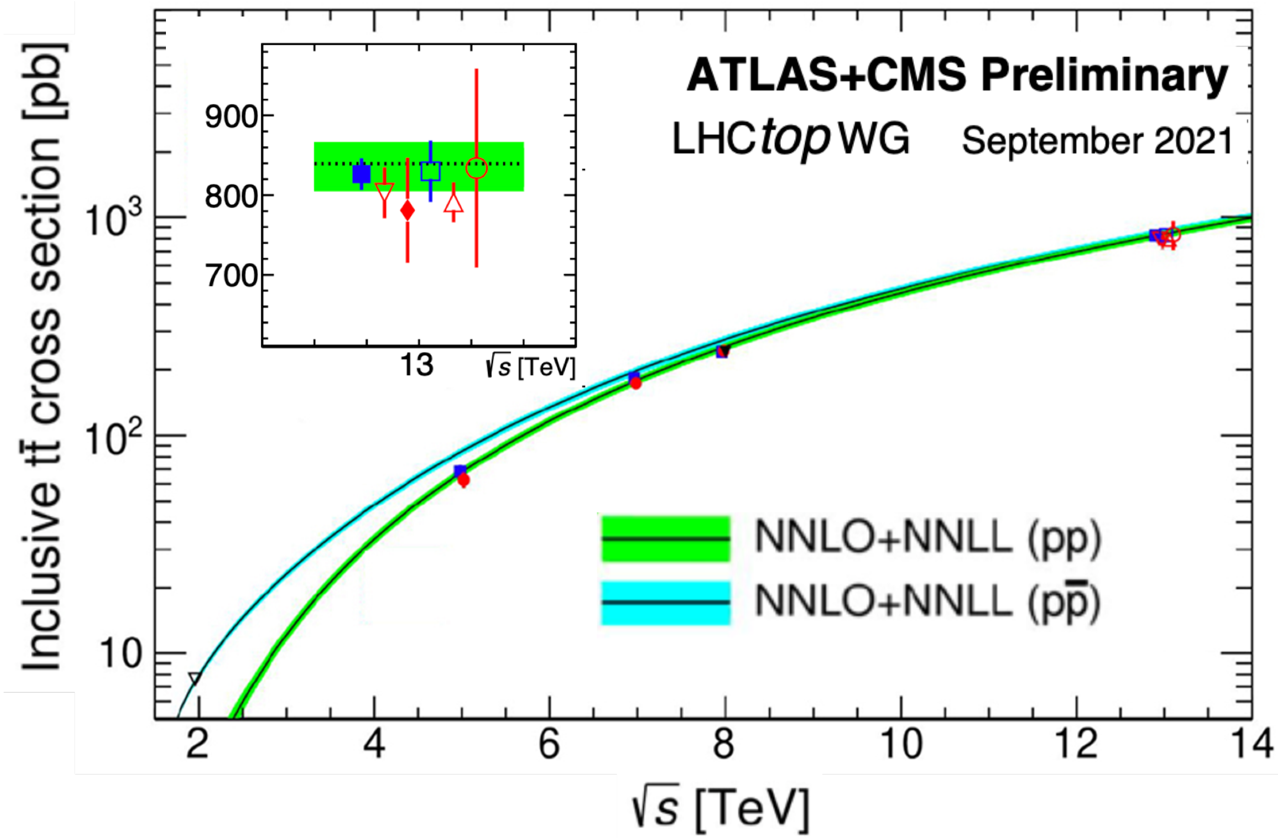
- tγq

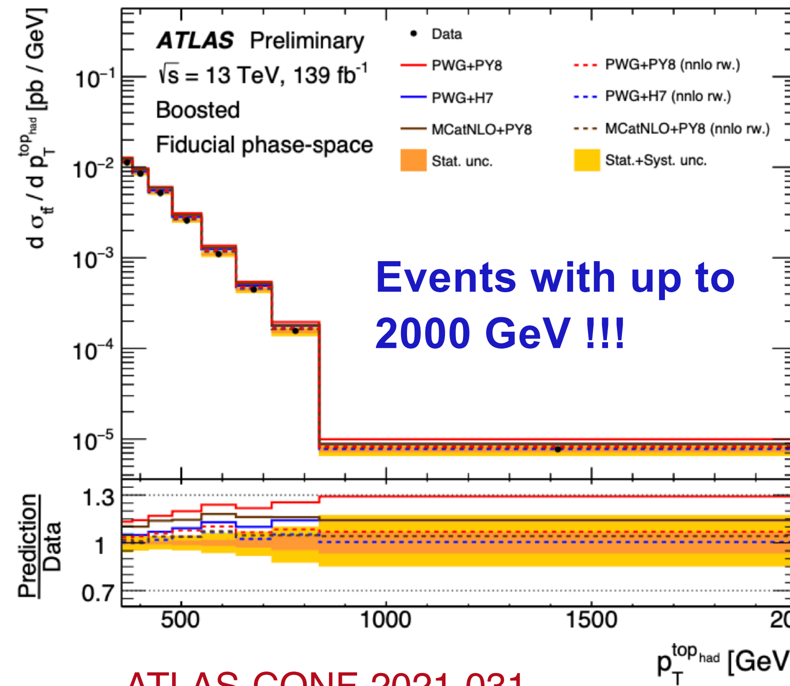


- tHq

Top quark production in strong interactions

coupling to gluons





ATLAS-CONF-2021-031

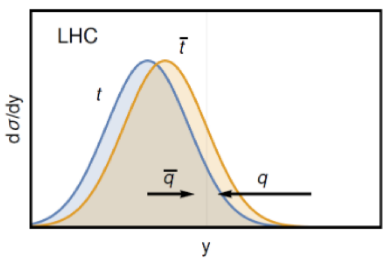
- Very precise *tt* cross sections measurements
  - 2.4% experimental unc.
  - boosted: XS overestimated by several predictions NLO+PS
- Differential measurements: increasing number of variables in all ch.; also 3D
- Results agree with theoretical calculations (NNLO precision)
- **The main limitation now is in theoretical modelling**

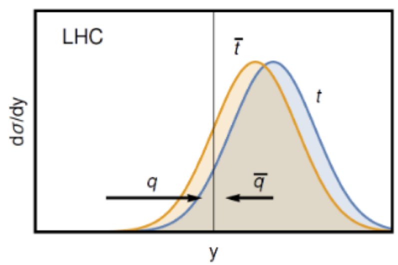
Charge asymmetry in top quark pair production

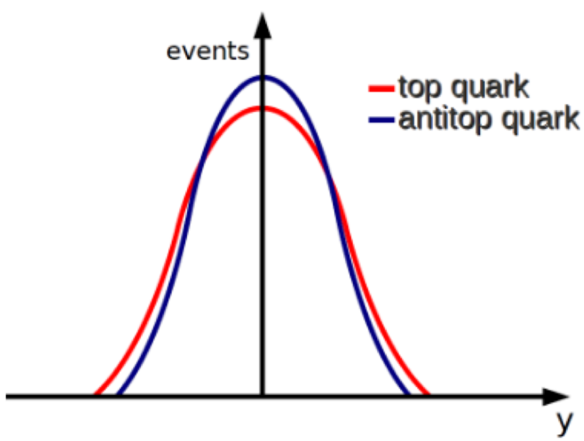
Sensitive to very small effects

ATLAS-CONF-2019-026

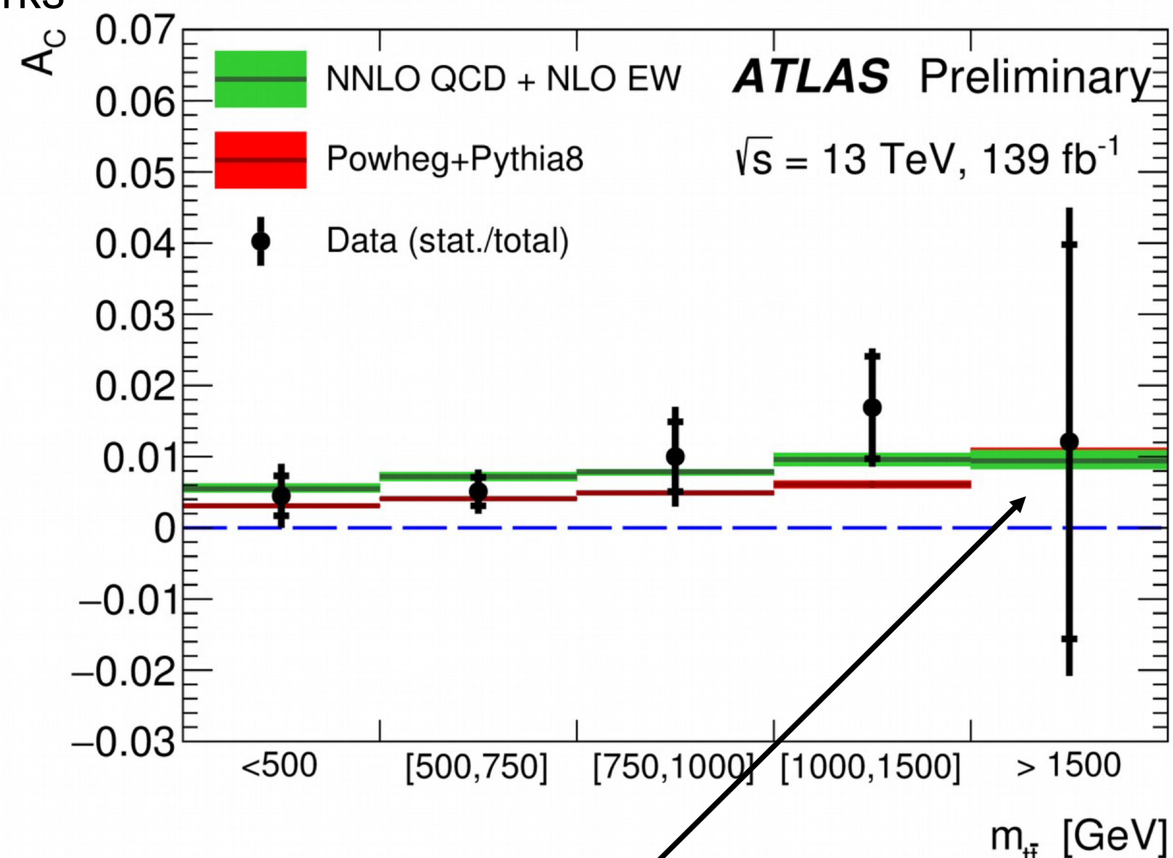
At the LHC, due to the proton structure, the top quarks are produced more energetic (less central) than antitop quarks
→ rapidity difference
→ asymmetry (~6 per mil effect)







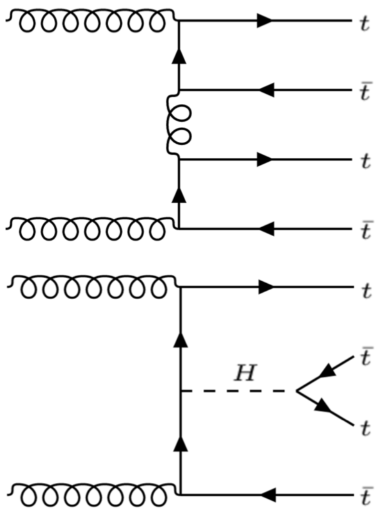
→ We measured: A_C=(0.0060±0.0015)
Evidence of such small effect!!

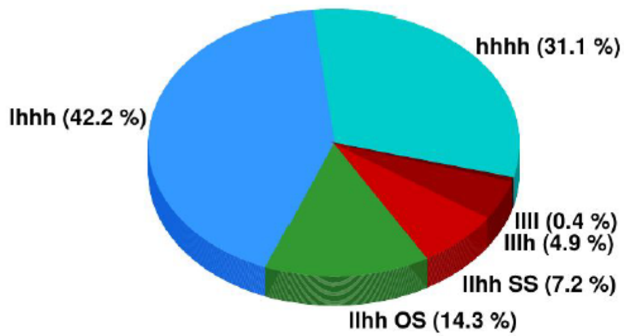


effect enhanced for energetic top quarks!

Limited by data statistics

Production of four top quarks at once

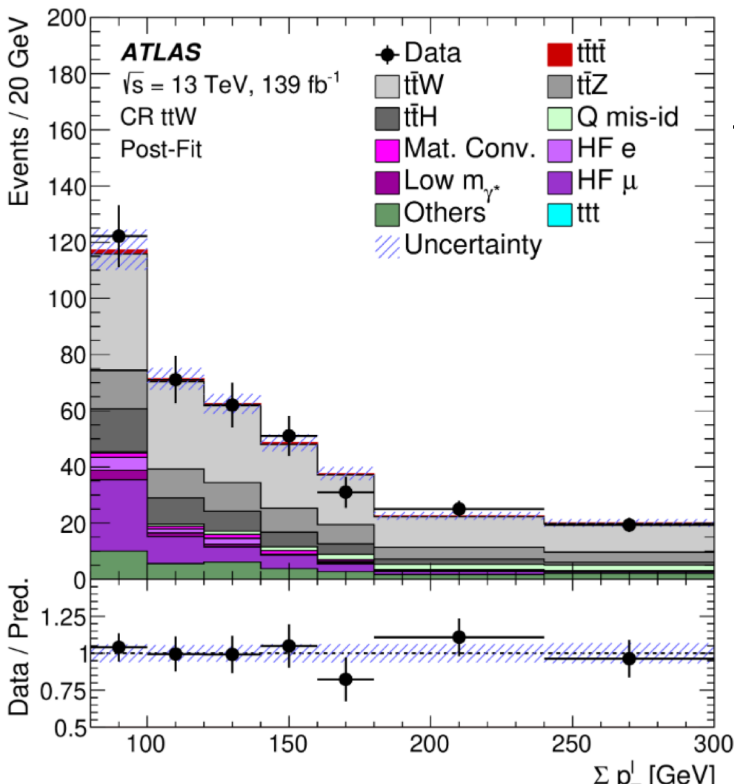




Exploit events with ≥1l.

One of the most spectacular mechanisms

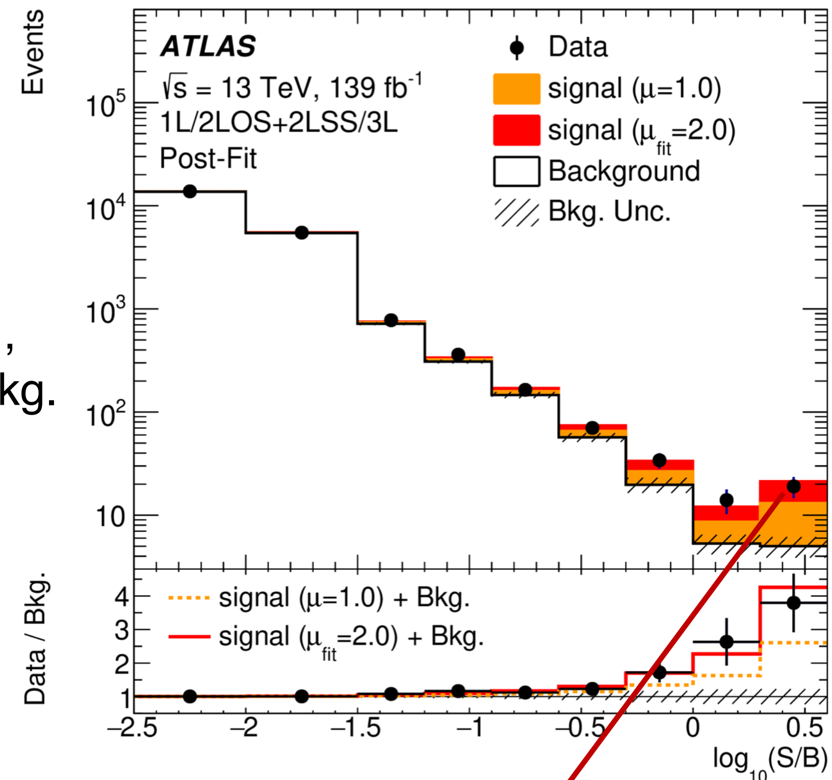
- quite energetic $\sqrt{s} \geq 4m_{top} \sim 700$ GeV
- very challenging: 12 final state objects
- sensitive to new physics



For most sensitive ch., ttW+jets is the main bkg.

NF=1.6 ± 0.3

Good post-fit modelling



arXiv: 2106.11683

$$\frac{\sigma_{tttt}}{\sigma^{SM}_{tttt}} \sim 2.0 \pm 0.8$$

Significance: 4.7σ (expected: 2.6σ)

→ Very close to observation of 4-tops production

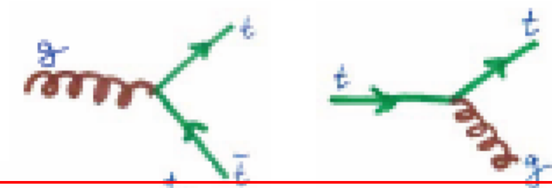
Top coupling to γ/Z/H bosons

Flavour changing charged current

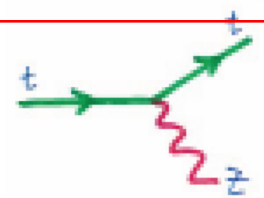
- Wtb

Flavour conserving neutral current

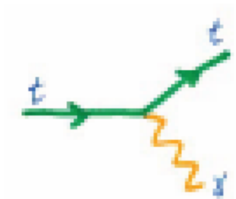
- tgt



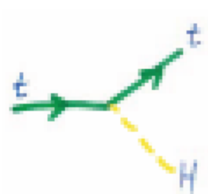
- tZt



- tγt

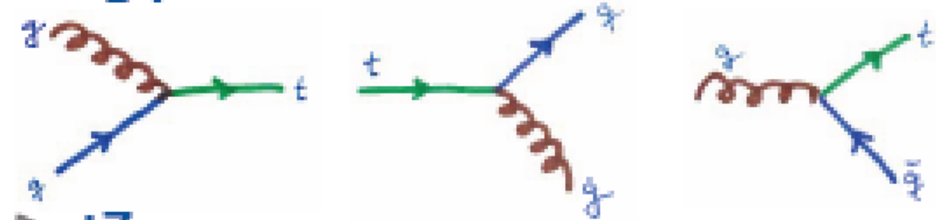


- tHt

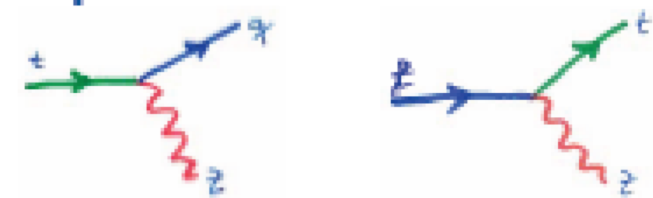


… and neutral current

- tgq



- tZq

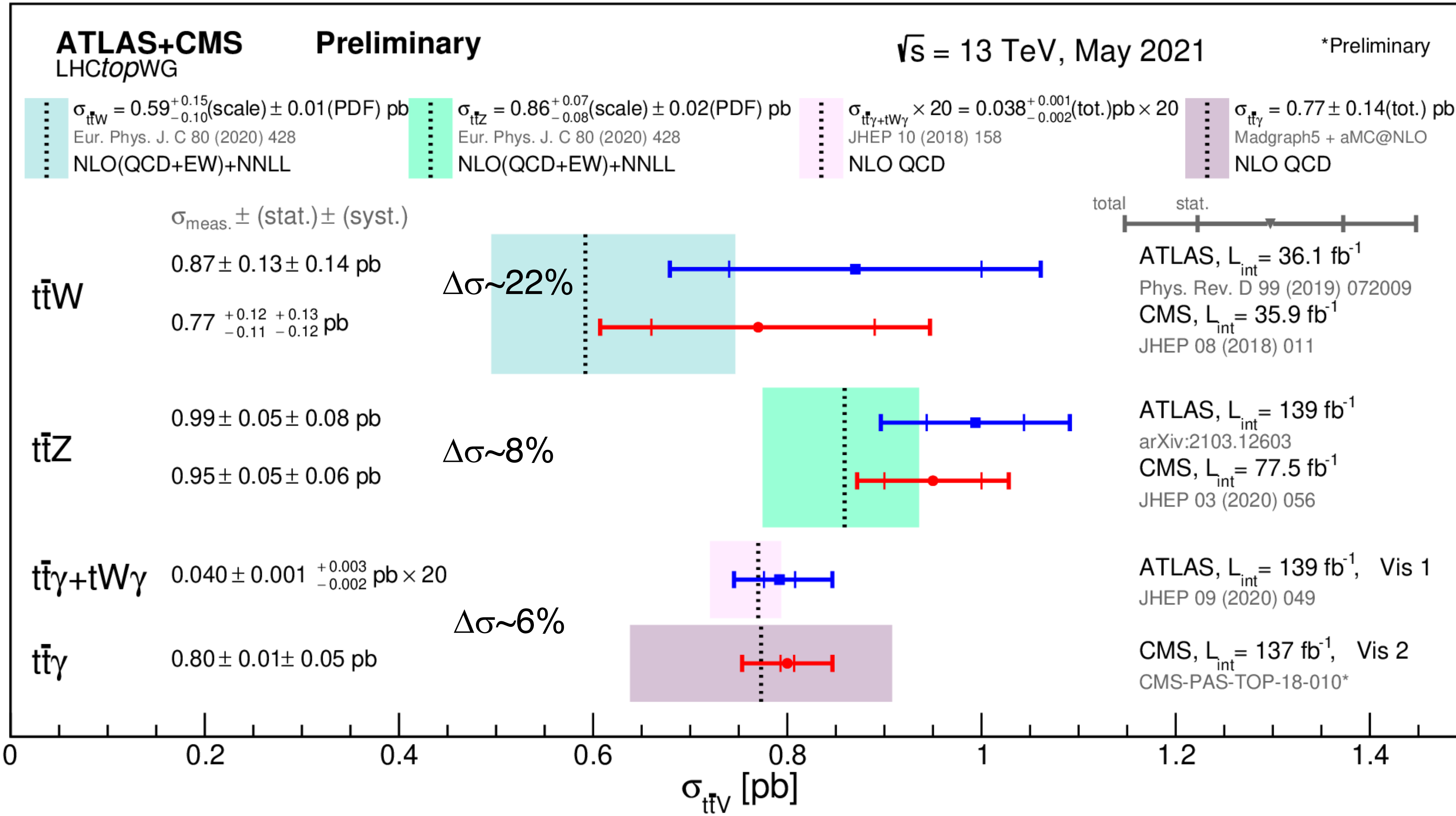


- tγq

- tHq

One of the highlights of LHC Run 2, but very challenging for both experimental and theoretical sides

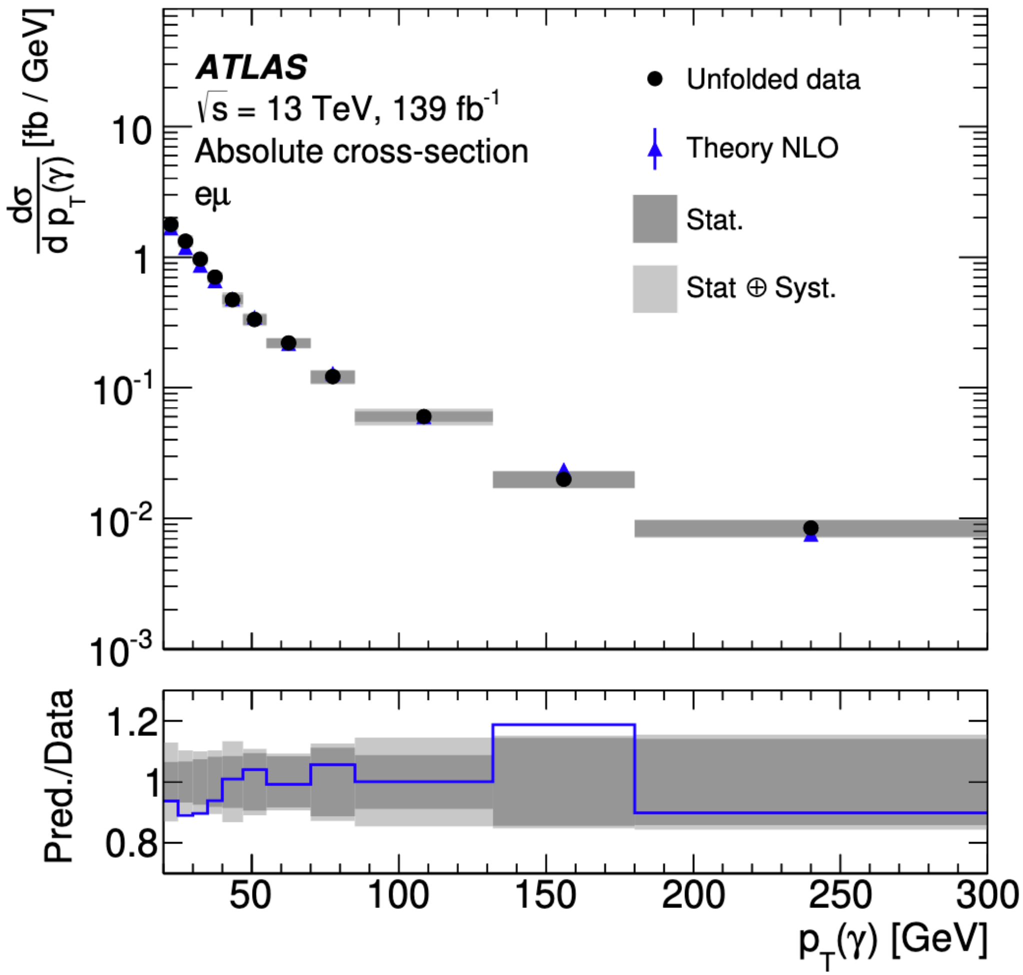
tt+X and t+X production cross sections



- *ttW* measured consistently higher than SM in both experiments
- *tZ* process also observed ($\Delta\sigma\sim15\%$) and evidence of $t\gamma$ ($\Delta\sigma\sim30\%$)
- *tH* (sensitive to sign of top Yukawa coupling): only upper limits ($\sigma<8*\sigma_{SM}$)

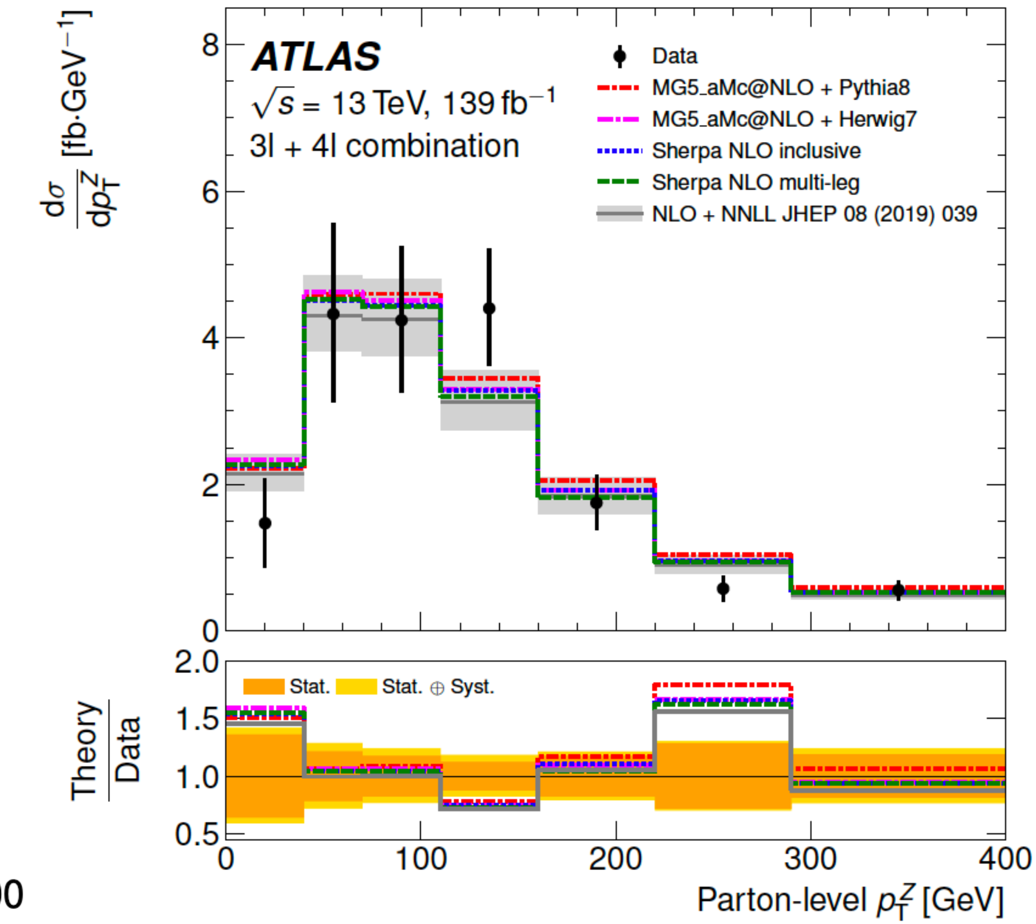
Even differential $tt\gamma$ and ttZ cross sections

Interaction with photon: $tt\gamma$ rates



Inclusive $tt\gamma$ and ttZ cross sections measured with 8% precision.

with Z boson: ttZ rates

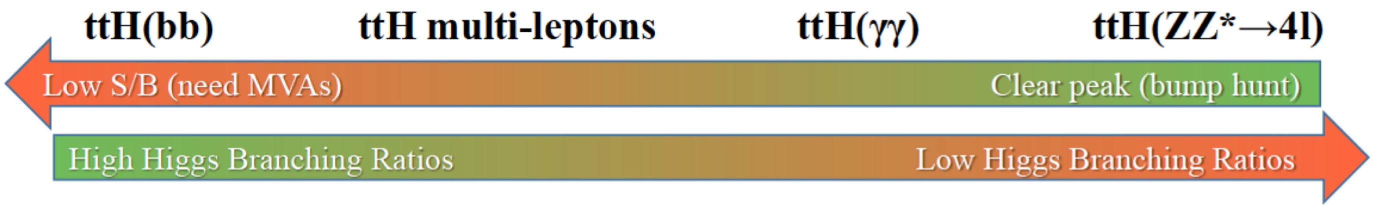


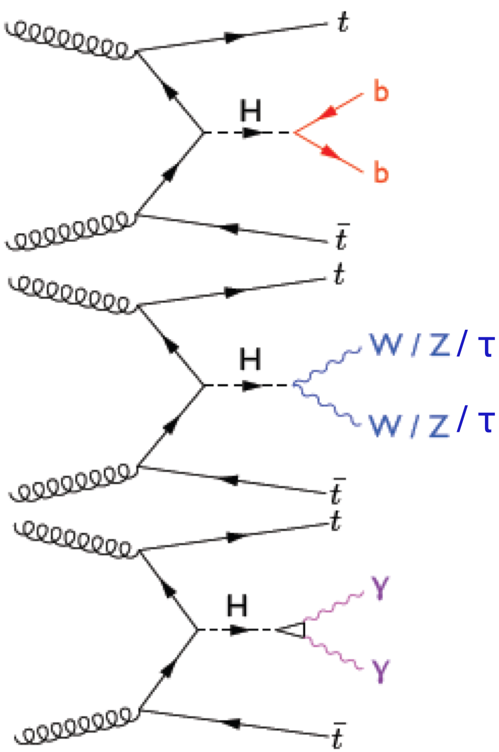
Note: tZ differential measurements became available this summer but not included in our fit.

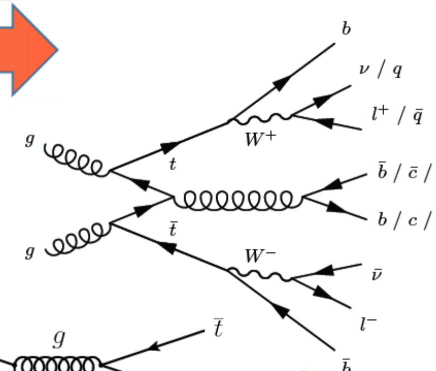
$t\,t\,H \rightarrow b\,W^+\,b\,W^-\;H \rightarrow bb$ + (jjjj/lνjj/lνlν) + (bb/WW*/ττ/ZZ*/γγ)

- Large number of final states which are typically very complex
- Different channels, different backgrounds and systematic uncertainties
- With the increased statistics, changes in leading channels

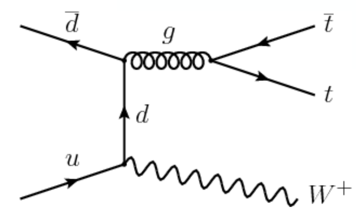
70k events in LHC Run 2



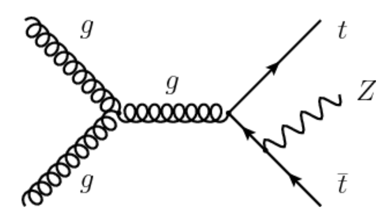


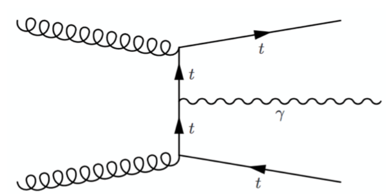


tt+H (H→bb) vs. tt+jets (g→bb)



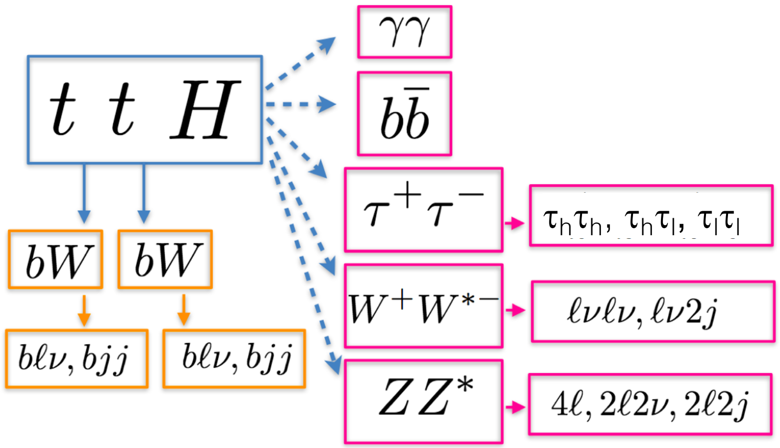
tt+H (H→WW,ττ, ZZ*) vs. tt+W/Z*

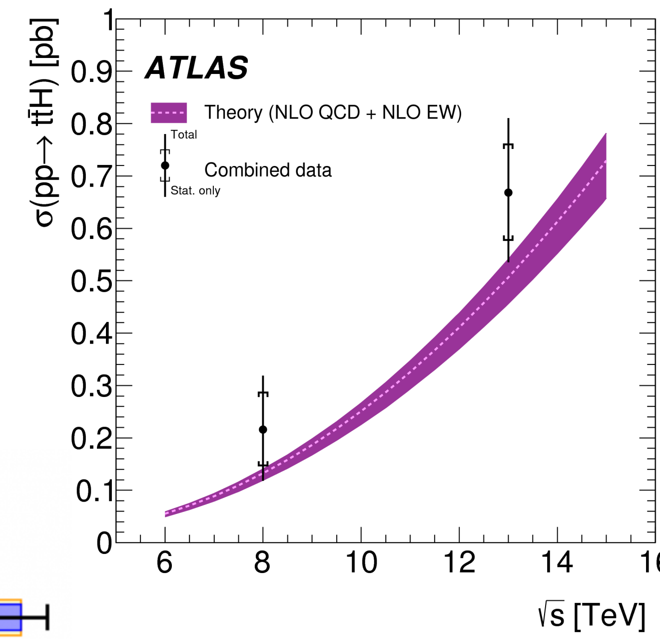


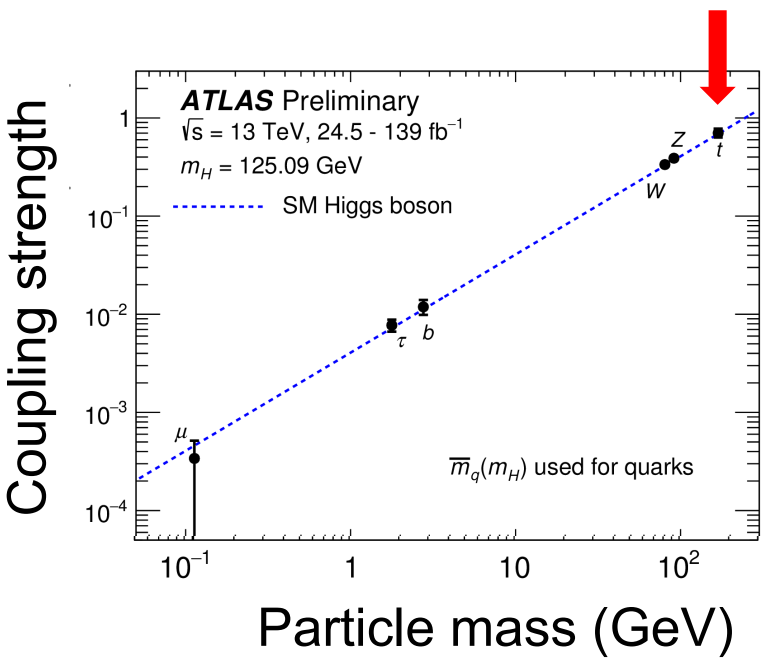


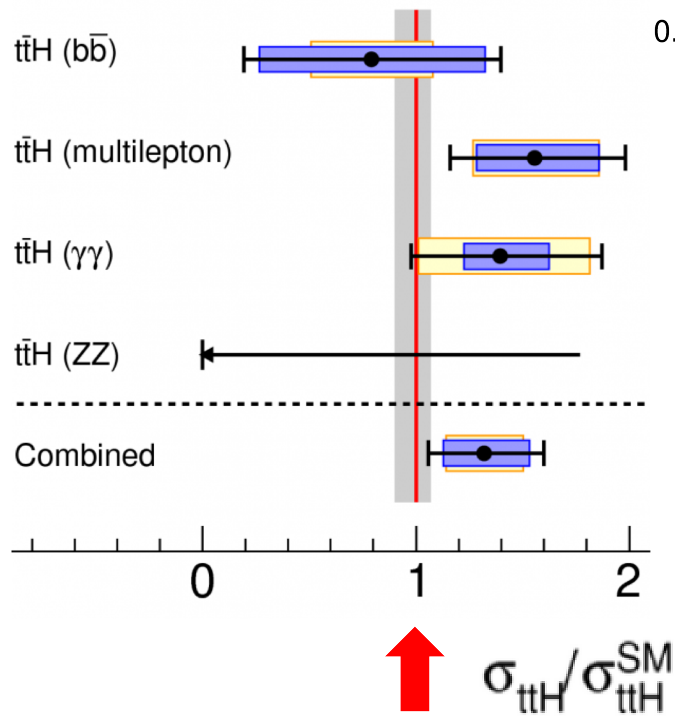
tt+H (H→γγ) vs. tt+γ(γ)

Direct probe of top-Higgs coupling: *ttH* production





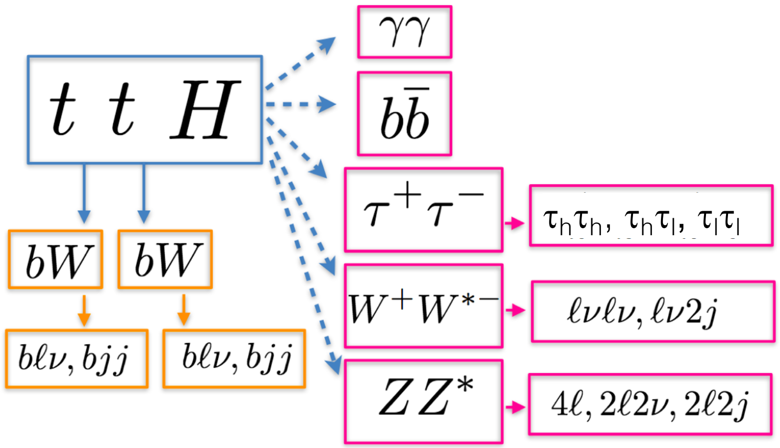




Standard Model:

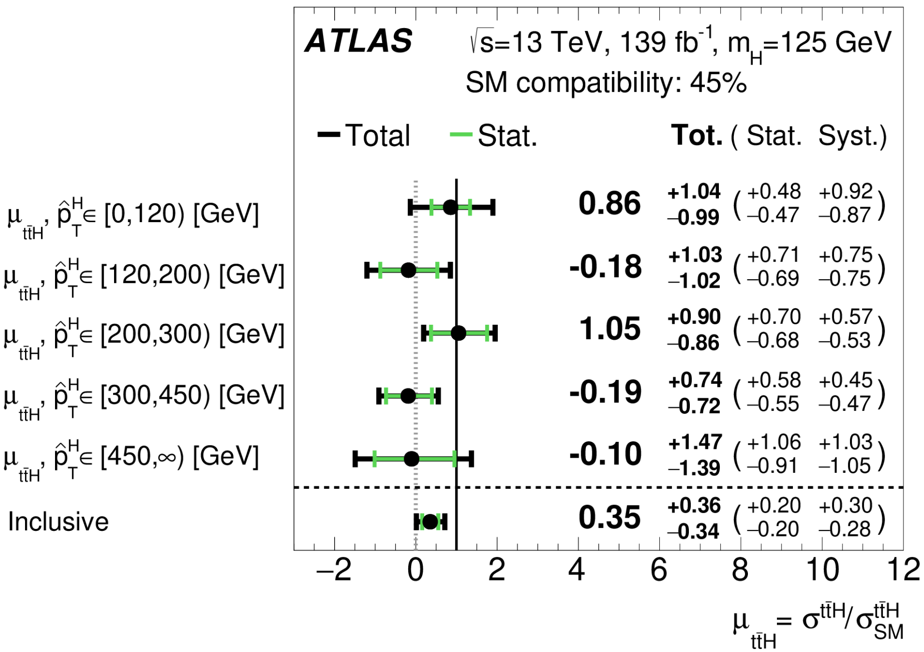
$$\frac{\sigma_{\rm ttH}}{\sigma_{\rm ttH}^{\rm SM}} = 1$$

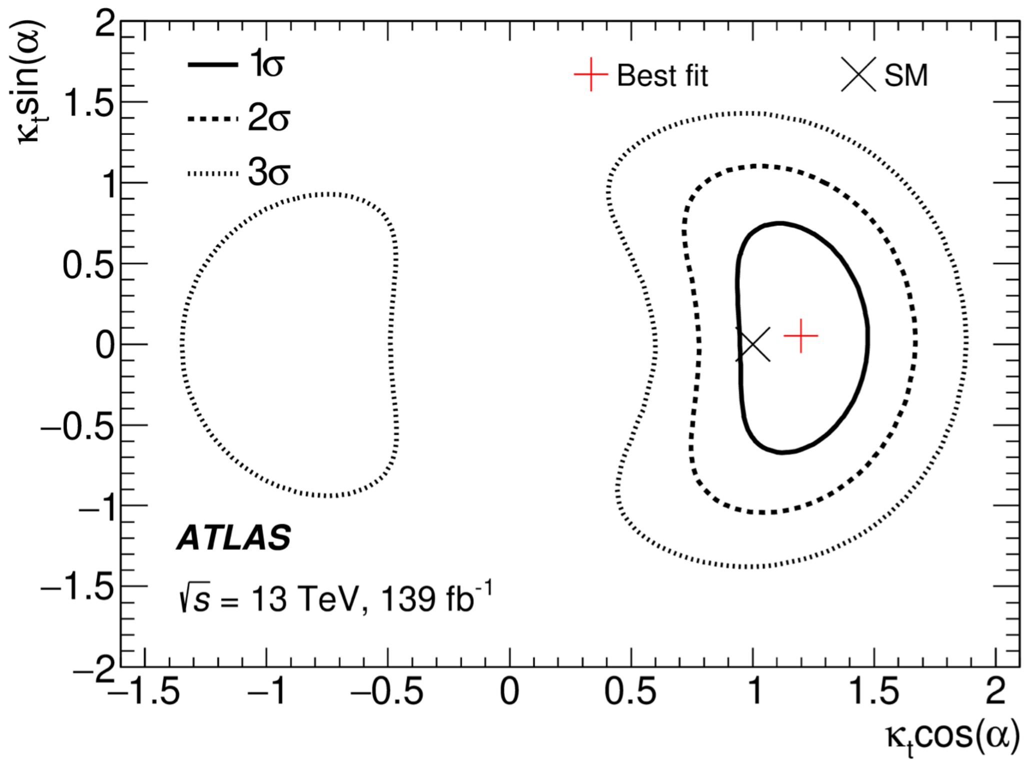
Direct probe of top-Higgs coupling: *ttH* production



For H→$\gamma\gamma$, $\delta\sigma_{ttH}$~25% and also:
- measurement of 5 STXS bins
- CP analysis: mixing angle |α|< 43º @ 95% CL
a pure CP-odd coupling excluded >3σ

For H→bb, also measurement of 5 STXS bins



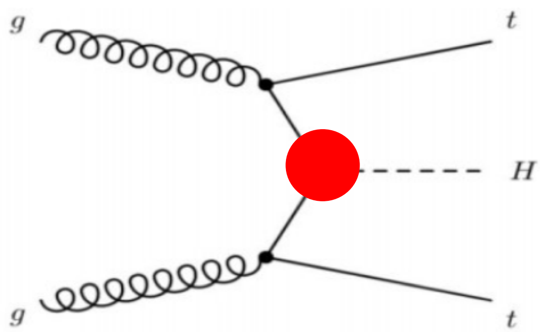


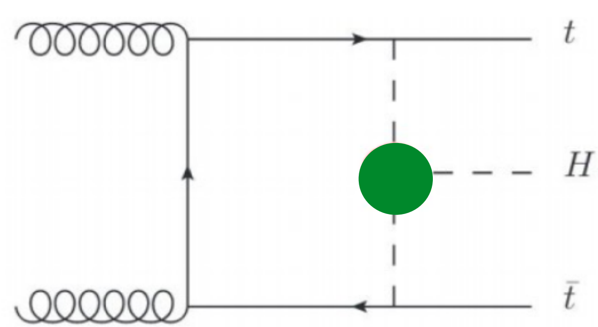
Also searches for tH, upper limits in XS: $\sigma_{tH} < 6\sigma_{SM}$

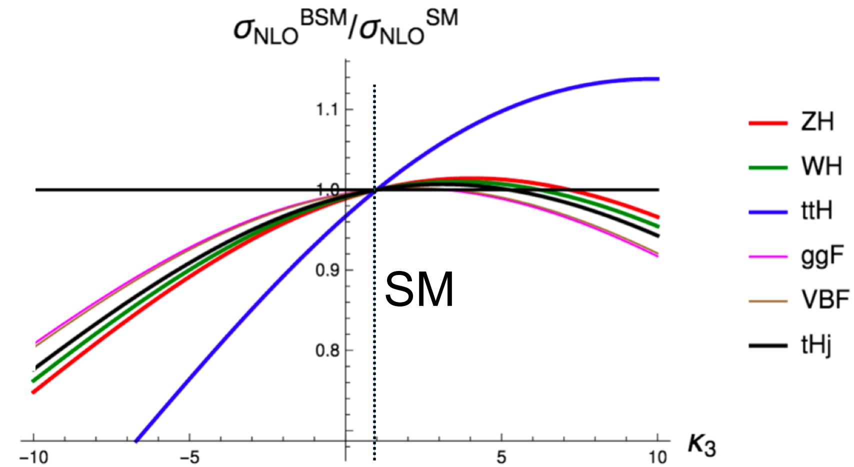
Imagine *ttH (or tH)* is measured to be different from SM…

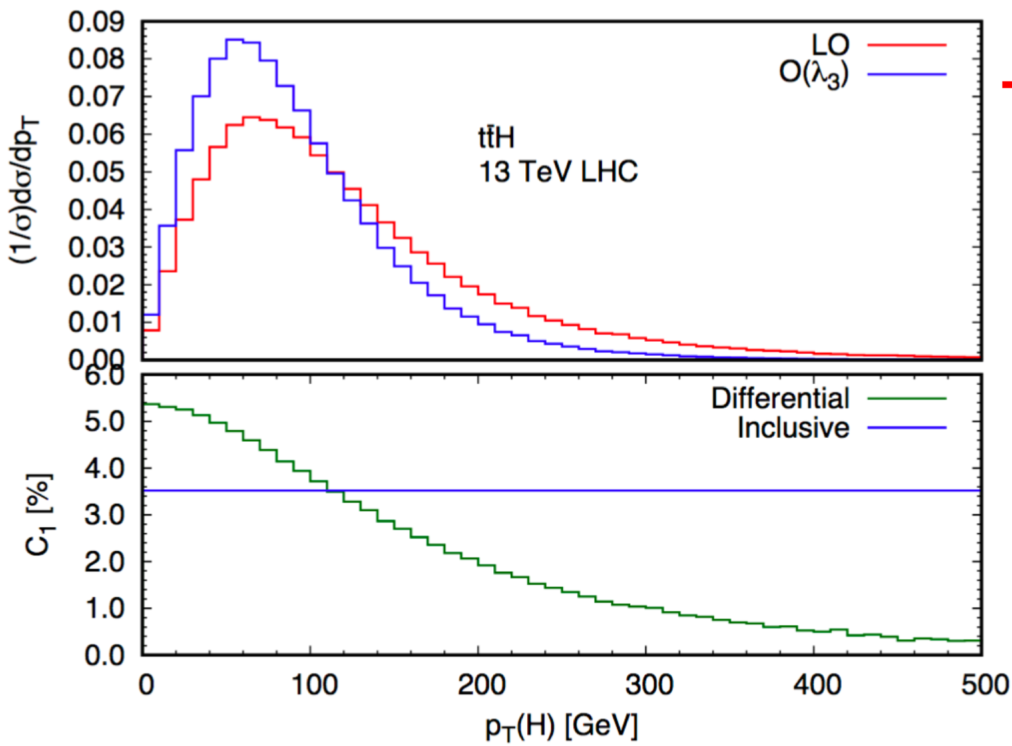
Who is the responsible ?

EPJC (2017) 77: 887









The power of differential measurements:

Variations in Higgs-self coupling (λ_3) will affect the shape of kinematic, e.g. low $p_T(H)$ region would be highly affected while it is not deformed in the tail…

New Physics effects?

: differential measurements

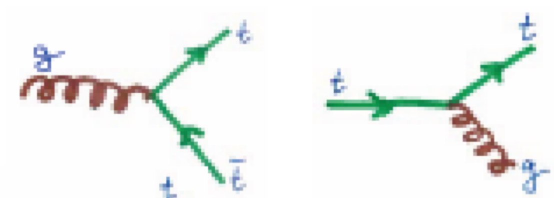
Flavour changing neutral currents

Flavour changing charged current

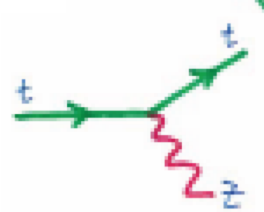
- Wtb

Flavour conserving neutral current

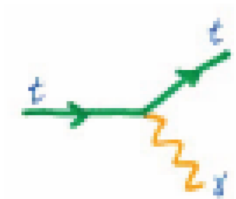
- tgt



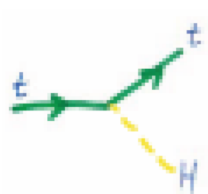
- tZt



- tγt

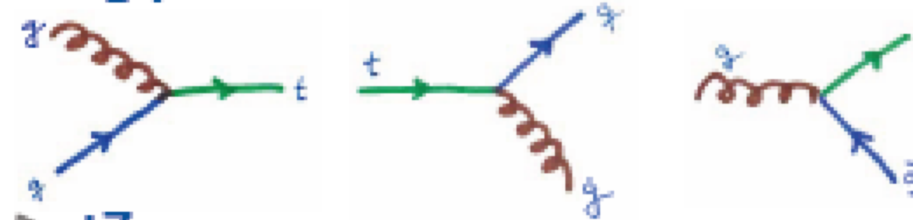


- tHt

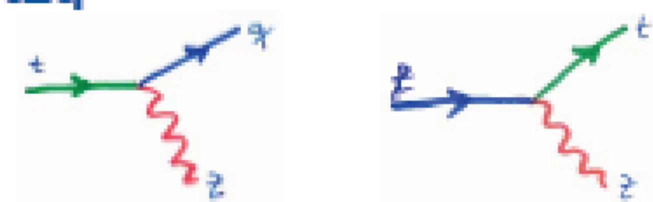


… and neutral current

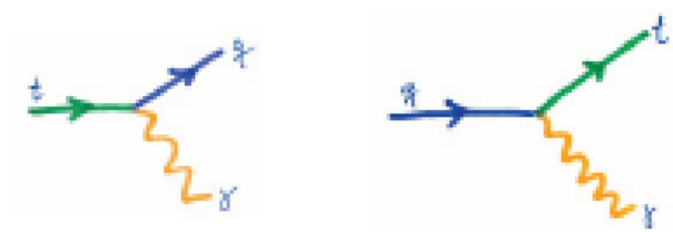
- tgq



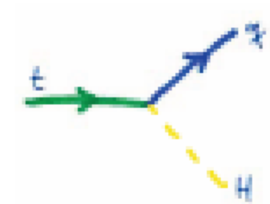
- tZq

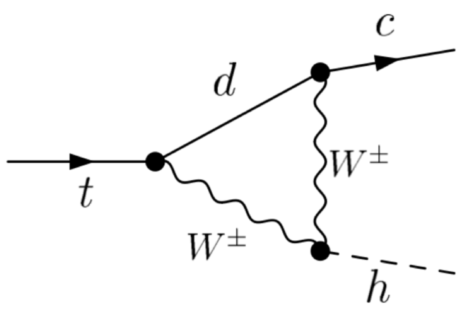


- tγq

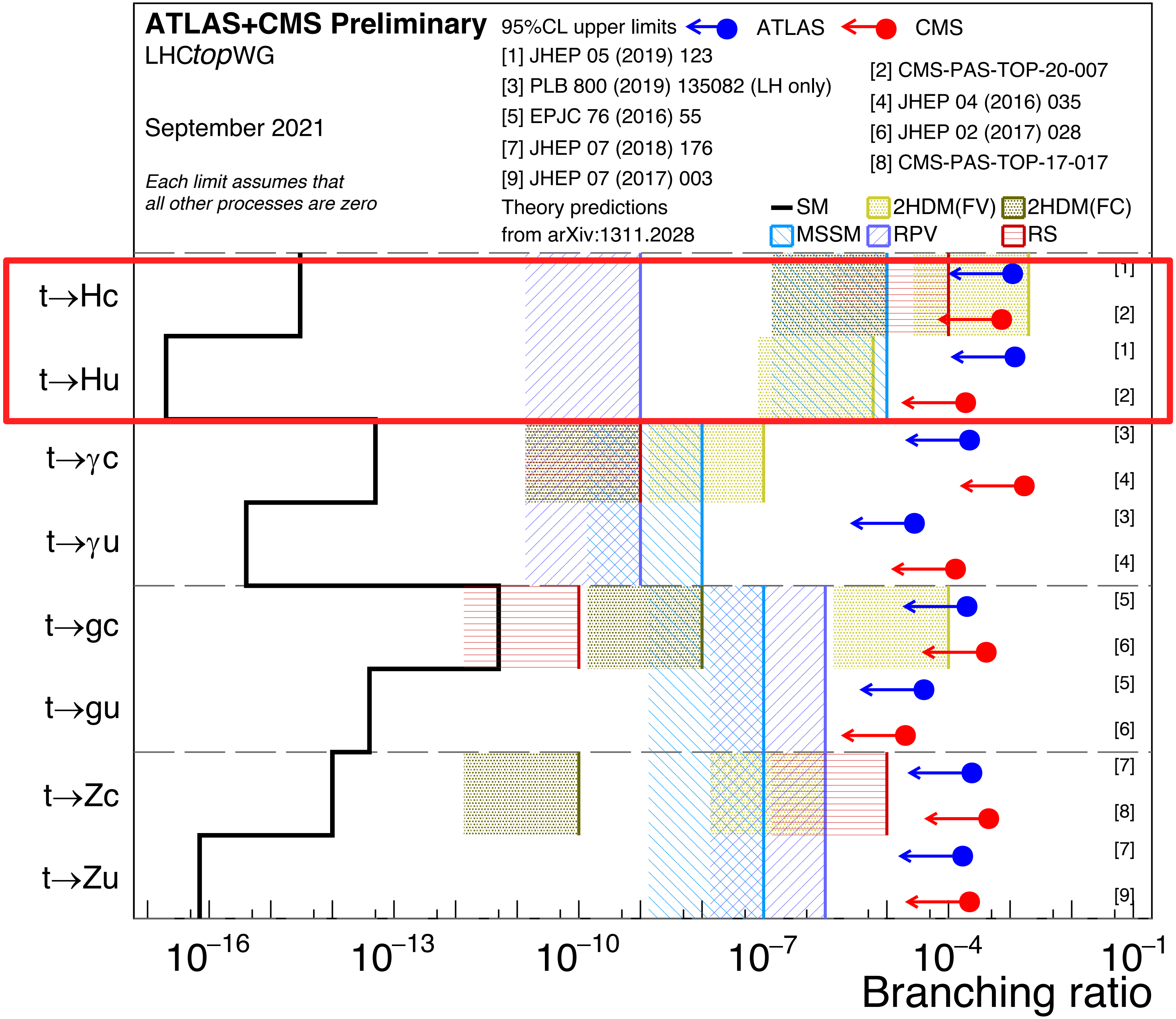


- tHq



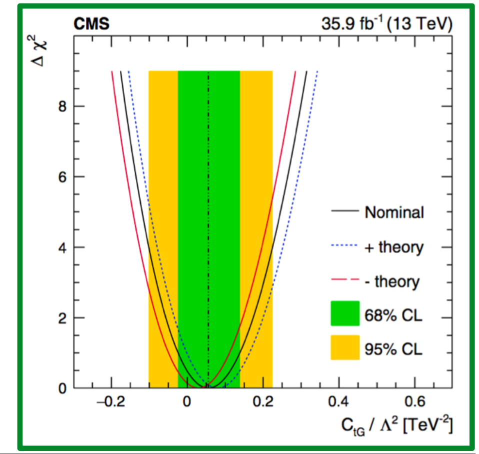

c
d
t
W±
W±
h

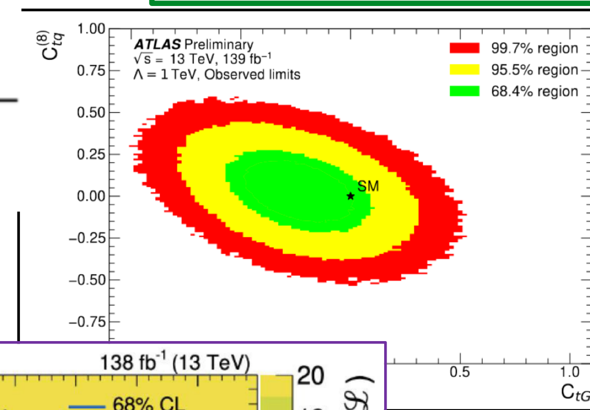
BR(t→qH)< 10^{-4}

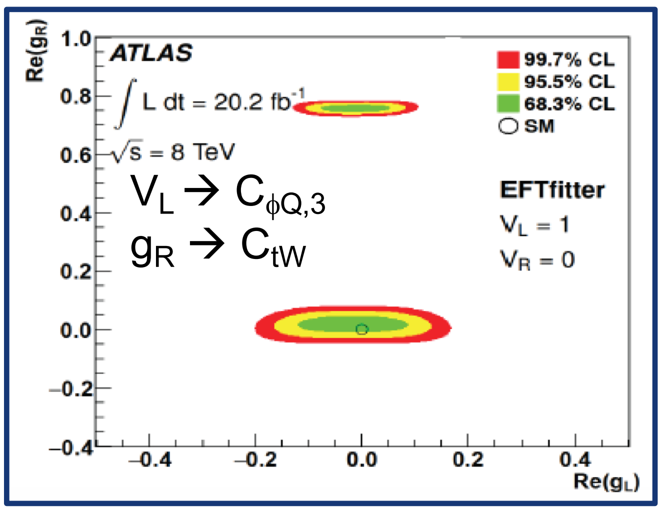

ATLAS+CMS Preliminary
LHCtopWG
September 2021
Each limit assumes that
all other processes are zero
95%CL upper limits
ATLAS
CMS
[1] JHEP 05 (2019) 123
[2] CMS-PAS-TOP-20-007
[3] PLB 800 (2019) 135082 (LH only)
[4] JHEP 04 (2016) 035
[5] EPJC 76 (2016) 55
[6] JHEP 02 (2017) 028
[7] JHEP 07 (2018) 176
[8] CMS-PAS-TOP-17-017
[9] JHEP 07 (2017) 003
Theory predictions
from arXiv:1311.2028
SM
2HDM(FV)
2HDM(FC)
MSSM
RPV
RS
t→Hc
t→Hu
t→γc
t→γu
t→gc
t→gu
t→Zc
t→Zu
10^−16
10^−13
10^−10
10^−7
10^−4
10^−1
Branching ratio

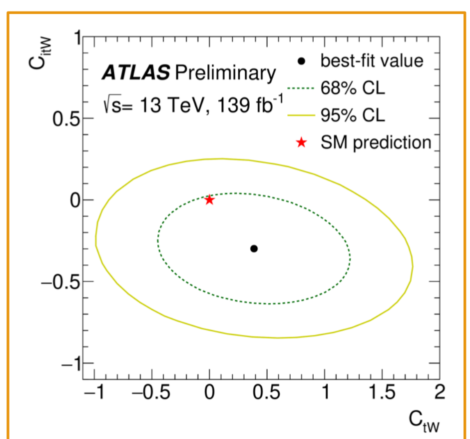
EFT constraints

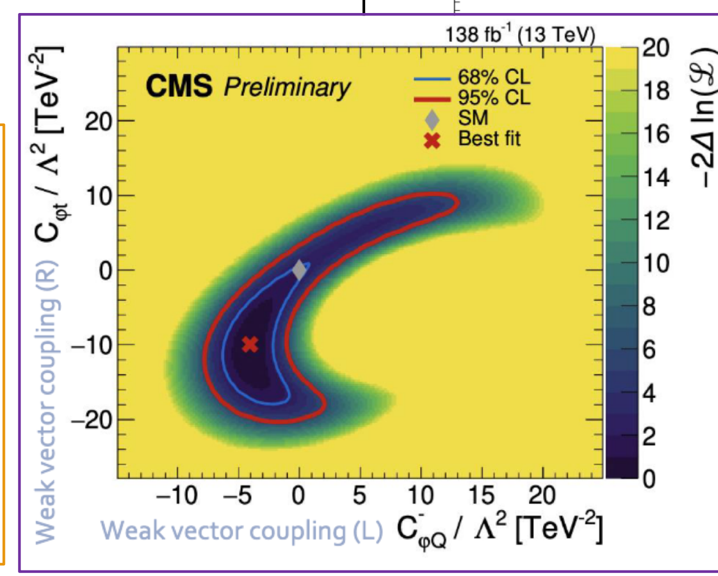
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	$1L^2$		
$pp \to tj$	N		L	L				L^2	L^2	1L		
$pp \to tW$	L		L	L				L^2	L^2	1N	N	
$pp \to t\bar{t}$	L									2L-4N	L	
$pp \to t\bar{t}j$	L									2L-4N	L	
$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
$pp \to t\bar{t}W$	L								L	1L-2L		
$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
$pp \to t\bar{t}H$	L						L			2L-4L	L	L
$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N











Measurements used in our fit to top quark EW couplings

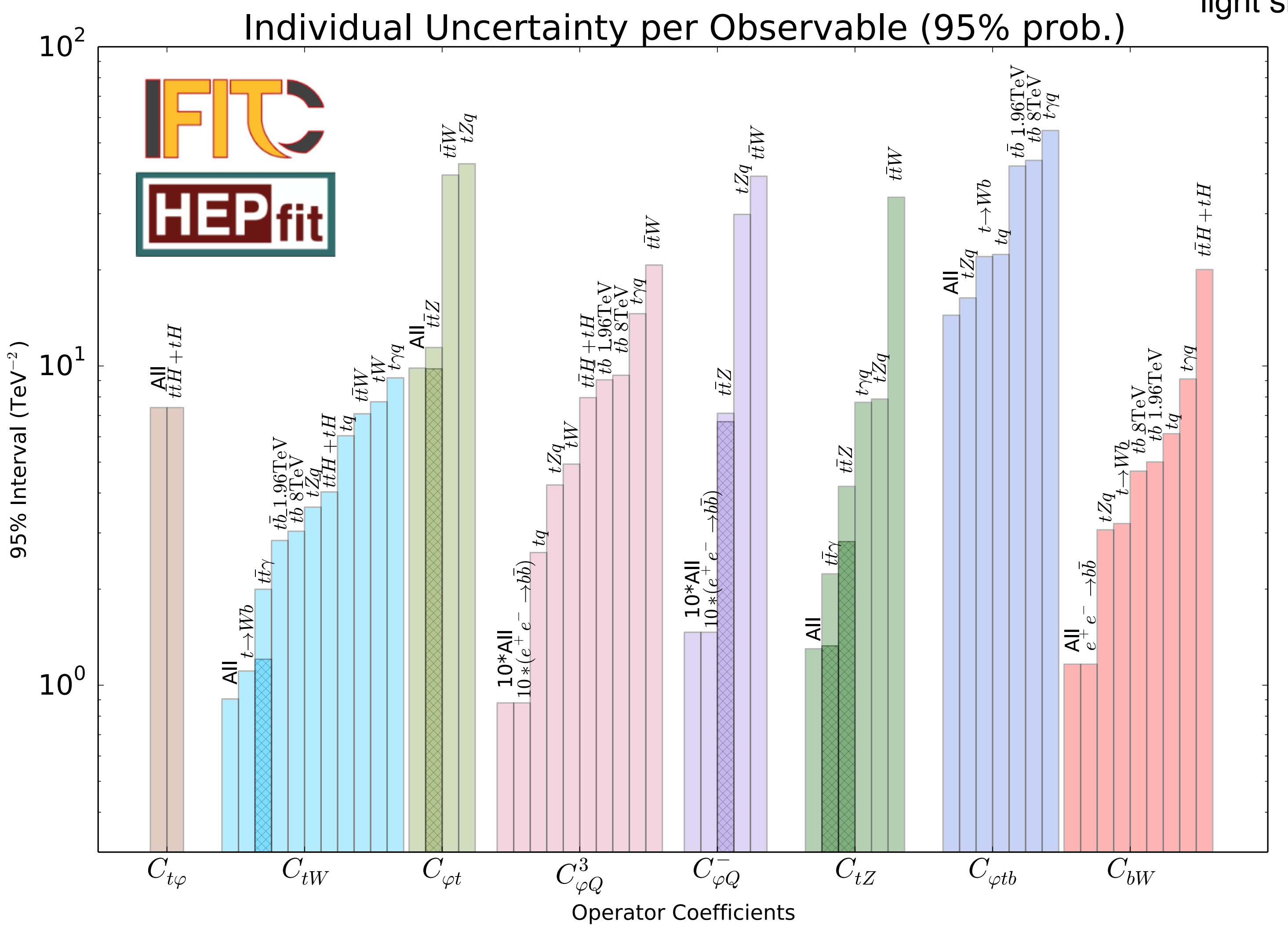
arXiv: 2107.13917

Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \to Wb$	$F_0,\ F_L$	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	$R_b\ ,\ A_{FBLR}^{bb}$	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD

* LH/RH couplings of t/b quarks to Z: $O_{\varphi t}, O^{-}_{\varphi Q}, O^{(3)}_{\varphi Q}$
* EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
* Top Yukawa: $O_{t\varphi}$
* Charged current interaction: $O_{\varphi tb}$

arXiv: 2107.13917

dark shades: differential $t\bar{t}Z$ and $t\bar{t}\gamma$ meas.
light shades (full length): inclusive ”



Sensitivity coming from:

C_{tW} → W helicity and $t\bar{t}\gamma$

$C_{\varphi t}$ → $t\bar{t}Z$

$C^{-}_{\varphi Q}$ & $C^{(3)}_{\varphi Q}$ → LEP/SLD

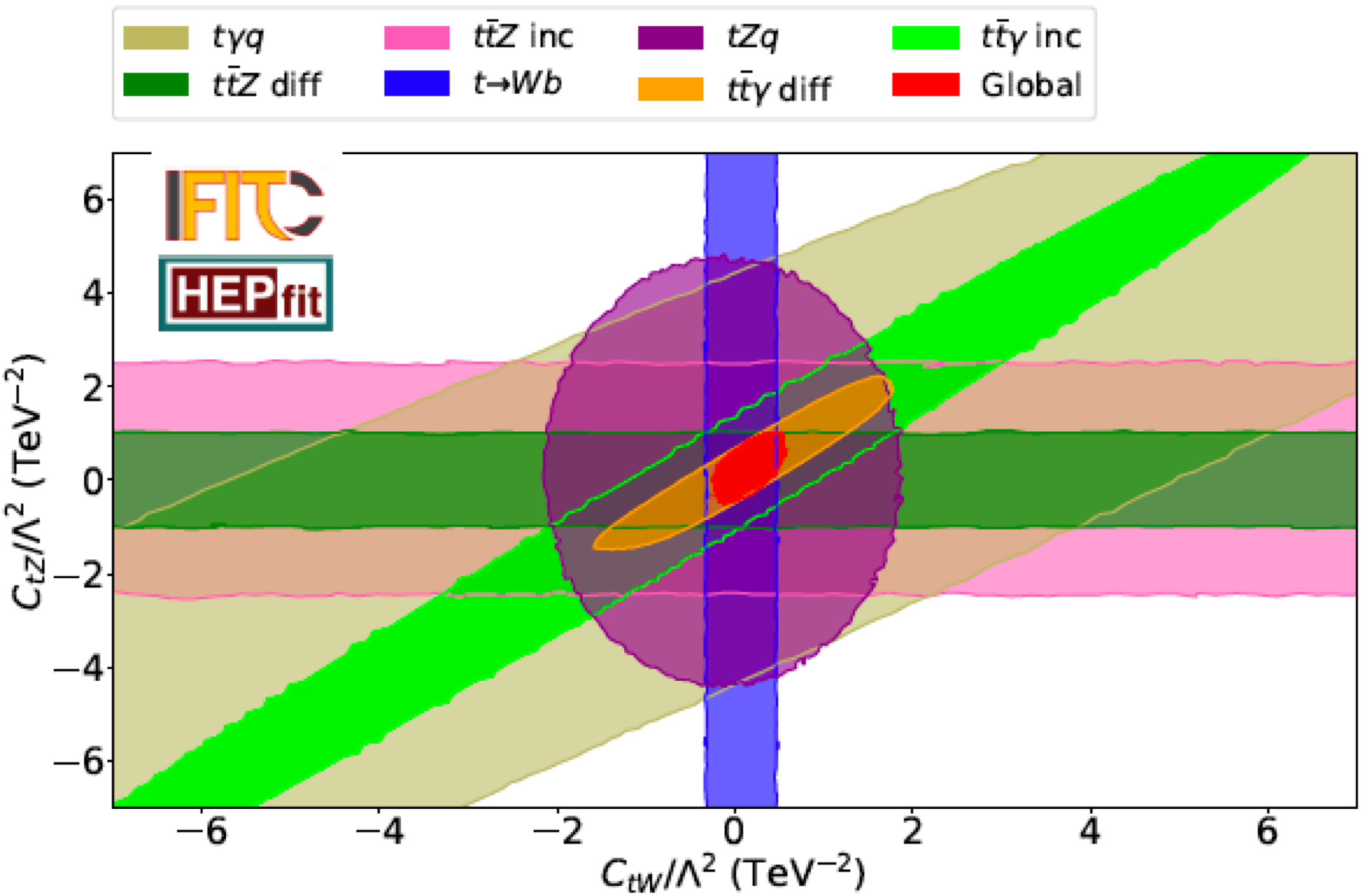
C_{tZ} → $t\bar{t}\gamma$ and $t\bar{t}Z$

$C_{\varphi tb}$ → tZ and W helicity

Significant improvement from $t\bar{t}Z$ and $t\bar{t}\gamma$ differential measurements ☺

arXiv: 2107.13917

* LH/RH couplings of t/b quarks to Z: $O_{\varphi t}, O^{-}_{\varphi Q}, O^{(3)}_{\varphi Q}$
* EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
* Top Yukawa: $O_{t\varphi}$
* Charged current interaction: $O_{\varphi tb}$



95% prob. bounds

Sensitivity coming from:
C_{tW} → W helicity and $t\bar{t}\gamma$
C_{tZ} → $t\bar{t}\gamma$ and $t\bar{t}Z$

Significant improvement from $t\bar{t}Z$ and $t\bar{t}\gamma$ differential measurements ☺

arXiv: 2107.13917

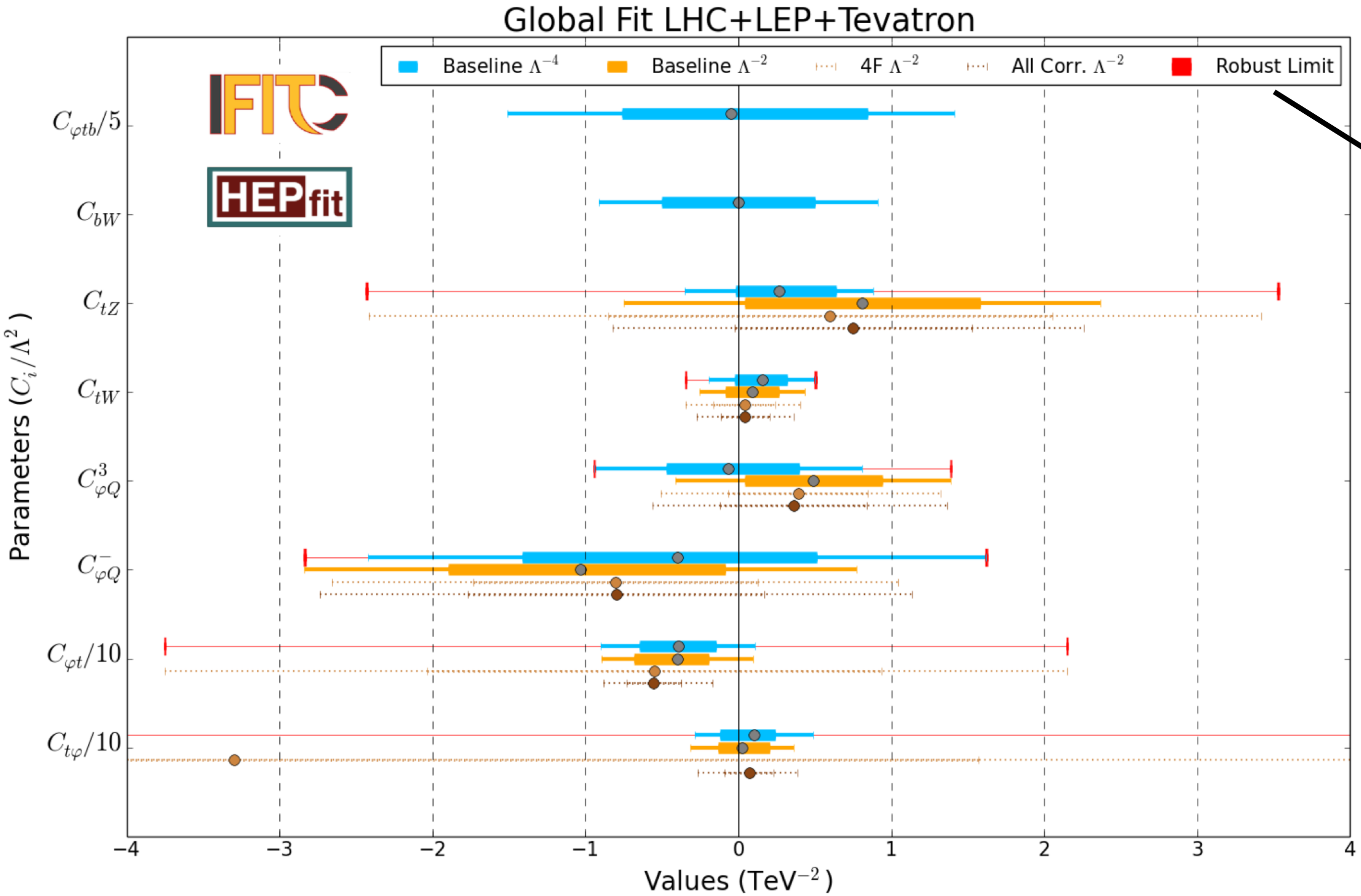
✓ A **significant improvement** compared to other previous fits

✓ Constraints of **linear** (only Λ^{-2} terms) global fit are similar to those of the **quadratic** (Λ^{-2}+Λ^{-4}) fit

- Overall comparable results
- Main difference between the two sets of results seen for C_{tZ}

✓ Bounds compatible with SM within 2σ

✓ 95% prob. bounds: ± 0.35 - 8 TeV^{-2}



Check the robustness of the fit:

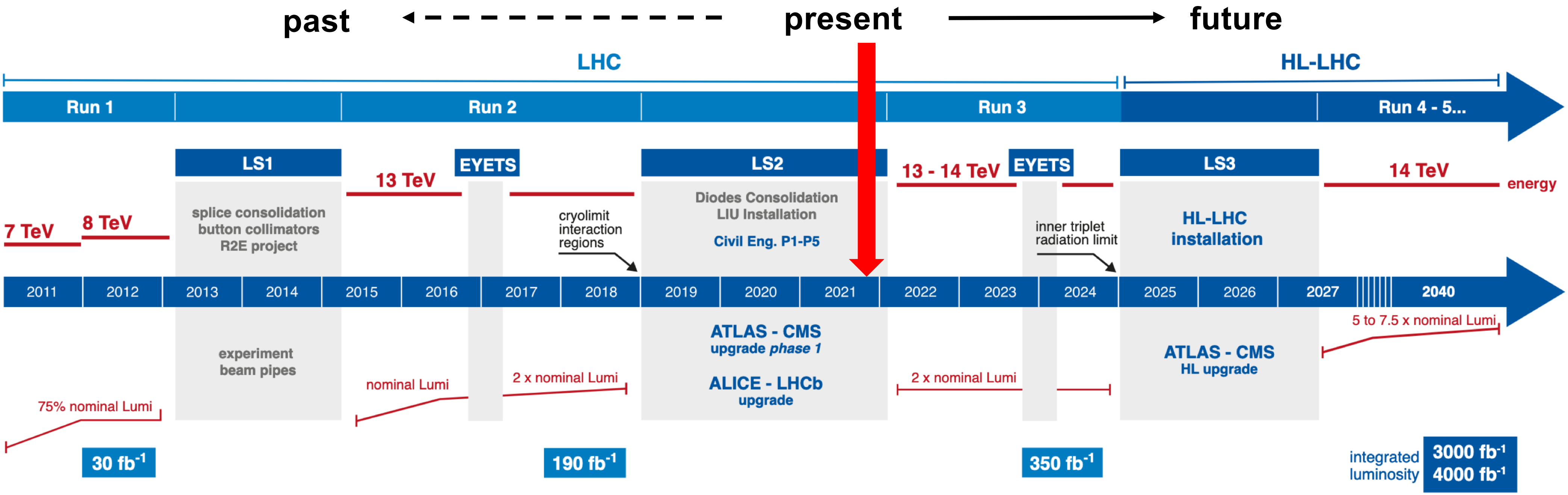
1) Extension of our basis: with 7 4-fermion qqQQ operators and C_{tG}

2) Correlations between different observables (ansatzs for non-published correlations have been estimated)

3) Missing higher-orders in α_S in EFT parametrisations

→ **Robust limits:** envelope obtained from results of new fits with these effects

Summary



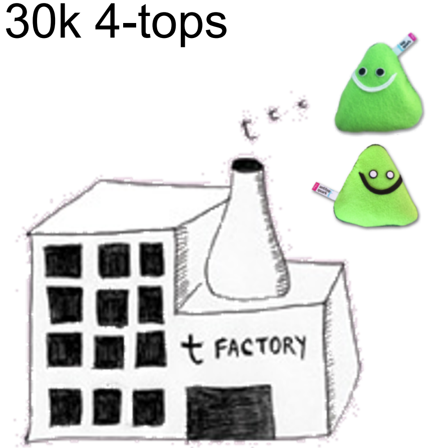
Challenges ahead:

- Experimental systematic uncertainties
- even more difficult in future runs
- More "global" approaches
- Theory uncertainties

Opportunities:

Vast top quark sample:
3B tt pairs, 1.5M ttH, 30k 4-tops

Join us !



THANKS FOR YOUR ATTENTION

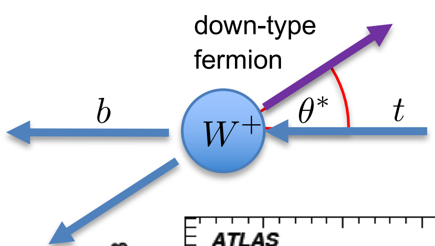
Top coupling to *W* bosons: *W* helicity fractions

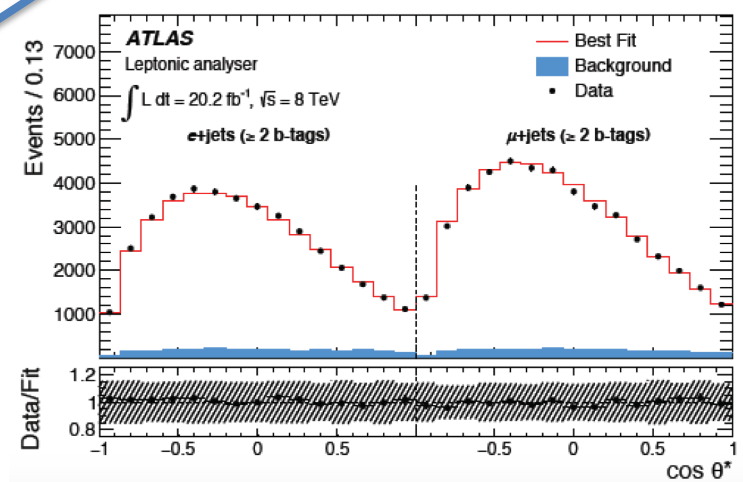
Test V-A structure via angular observables → *W* helicity fractions JHEP 08 (2020) 051

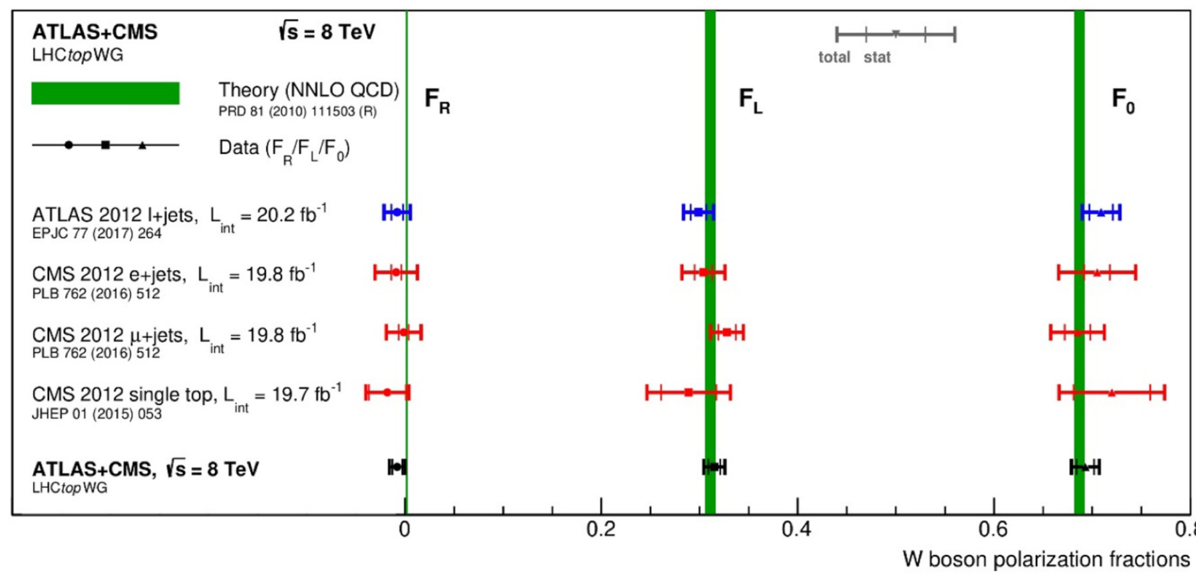
W bosons from top quark decays → 3 possible polarizations: longitudinal, left and right handed

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

F_0 ~0.7 F_L ~0.3 F_R ~0







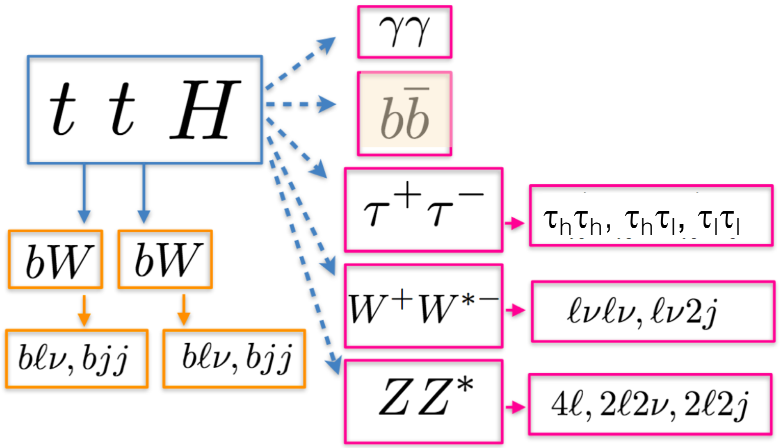
A more general extension of the SM Lagrangian for *tWb* vertex:

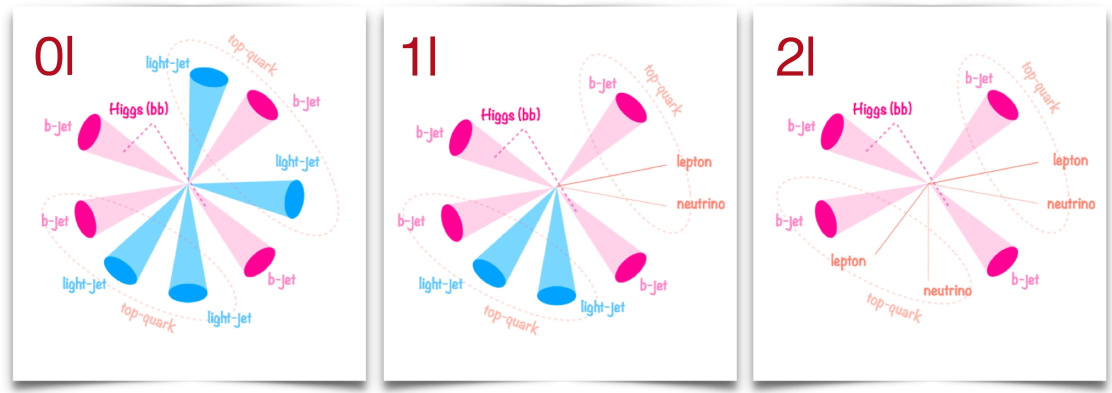
$$L_{Wtb} = -\frac{g}{\sqrt{2}}\bar{u}_b\gamma^\mu\left(V_L P_L + V_R P_R\right)u_t W^+_\mu - \frac{g}{\sqrt{2}}\bar{u}_b\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(g_L P_L + g_R P_R\right)u_t W^+_\mu + \text{h.c.}$$

$SM \Rightarrow V_L = V_{tb} \sim 1$ $V_R = g_L = g_R = 0$

$$V_L = V_{tb} + c^{(3)}_{\varphi q}\frac{v^2}{\Lambda^2} \simeq 1 + c^{(3)}_{\varphi q}\frac{v^2}{\Lambda^2}$$
$$V_R = \frac{1}{2}c_{\varphi tb}\frac{v^2}{\Lambda^2}$$
$$g_R = \sqrt{2}\,c_{tW}\frac{v^2}{\Lambda^2}$$
$$g_L = \sqrt{2}\,c_{bW}\frac{v^2}{\Lambda^2}.$$

ttH (H→bb): large branching fraction but huge background



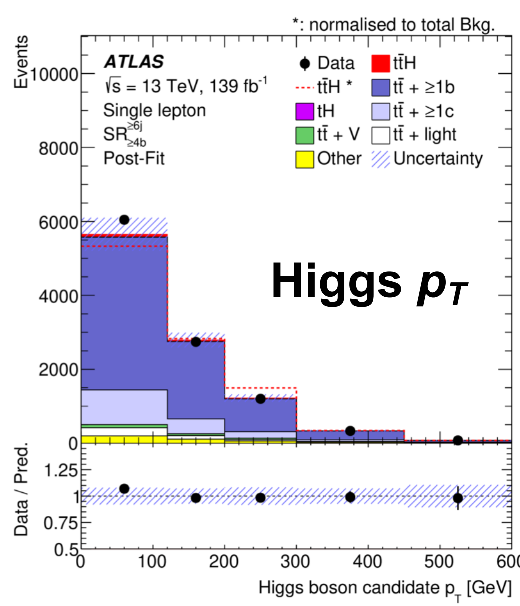


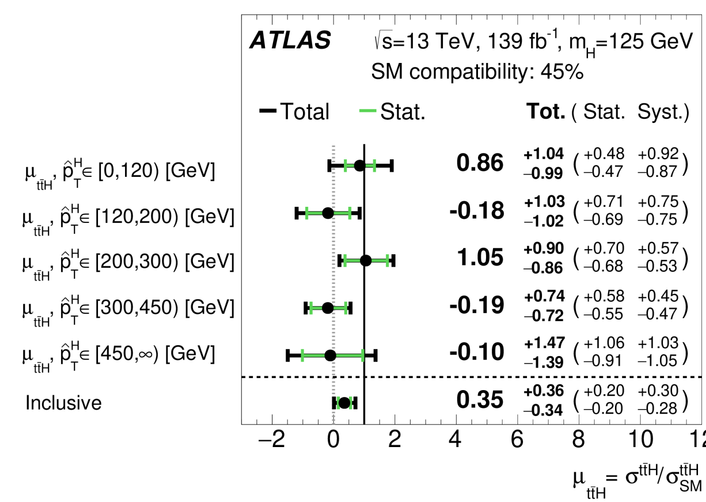
- Fermion-only production and decay
- Higgs boson reconstruction possible, but challenging due to large combinatorics
- **Biggest challenge**: tt+bb background with large theory uncertainty

Significance
ATLAS (139 fb^{-1}; ≥1l): 1.0σ (expected 2.7σ)
CMS (77.4 fb^{-1}): 3.9σ (expected 3.5σ)

- Event categorization based on # jets and b-tags
- Cascade of MVAs
- Systematically limited

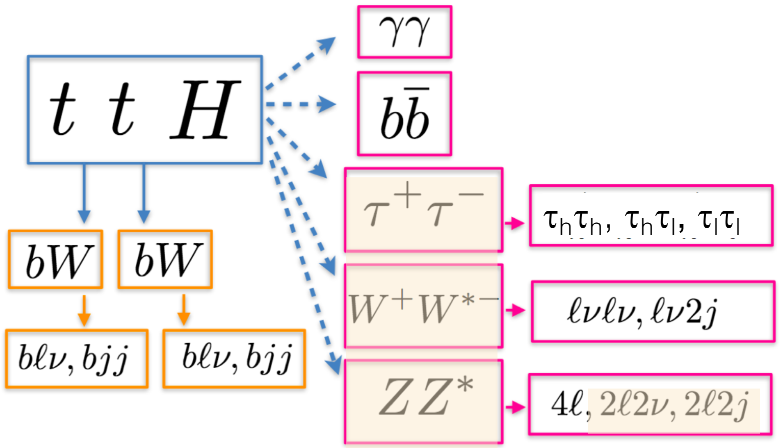
Also measurement of 5 STXS bins

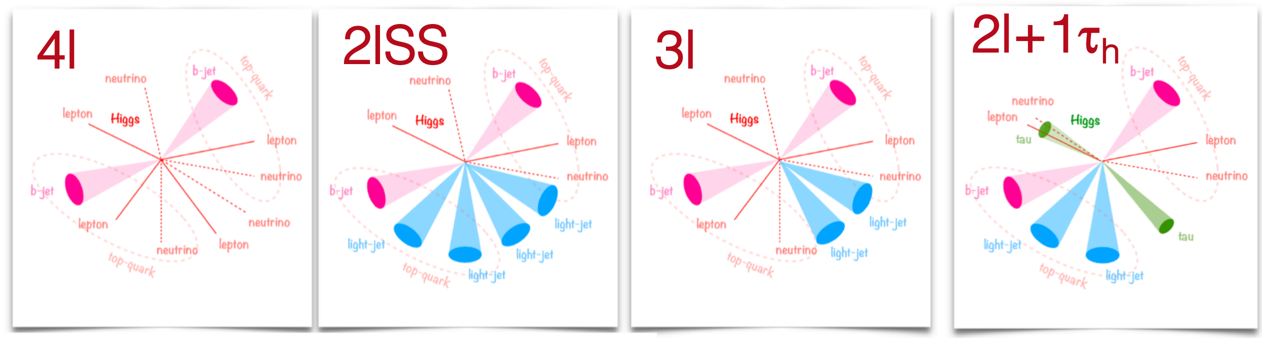




arXiv:2111.06712

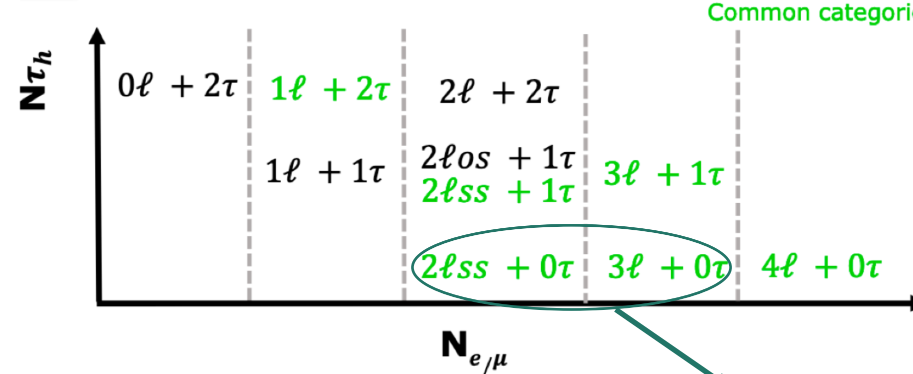
ttH ($H \to WW^*, \tau\tau, ZZ^*$): suppressing *ttW* and non-prompt





- Distinct multi-lepton signatures (up to 10 explored!)
- Higgs reconstruction is difficult

Common categories



most sensitive ch.

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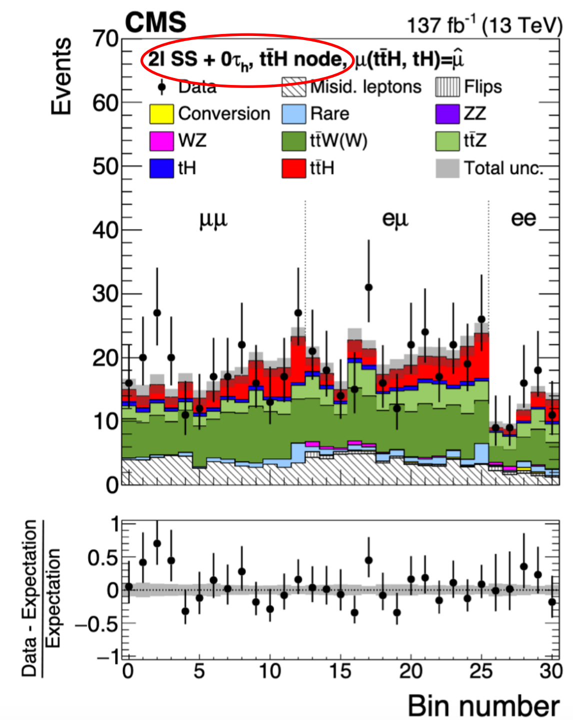


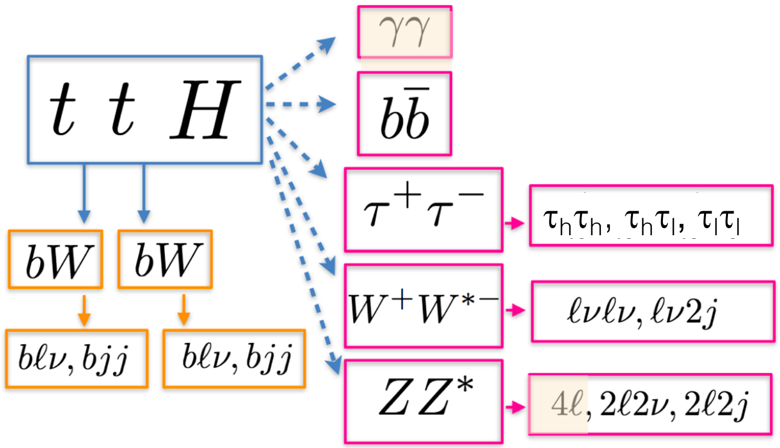
- Powerful multivariate discriminant:
  - object-level to reduce non-prompt leptons
  - event-level to discriminate ttH from main bkgs.
- Uncertainties: statistical ~ systematics

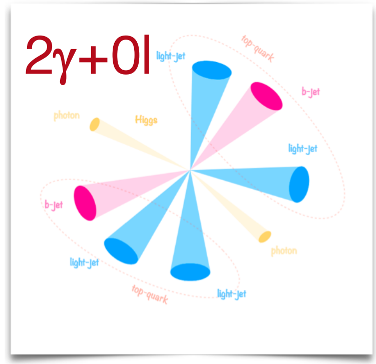
Significance
ATLAS (80 fb^{-1}; 6 ch): 1.8σ (expected 3.1σ)
CMS (137 fb^{-1}; 10 ch): 4.7σ (expected 5.2σ) → $\delta\sigma_{ttH}$~25%

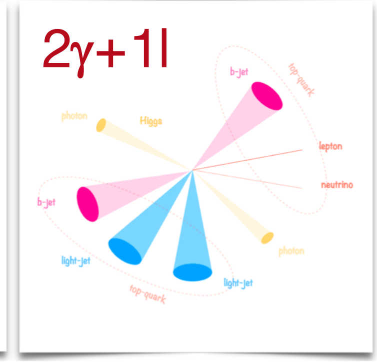
CMS also studied tH signal:
μ_{tH} = 5.7 ± 2.7(stat) ± 3.0(syst)
1.4σ significance (0.3σ expected)

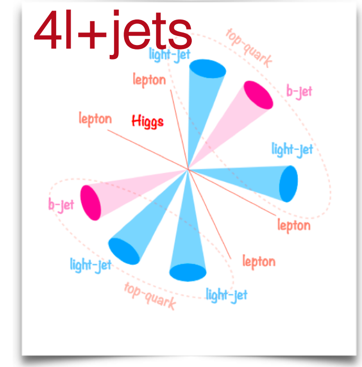
New ATLAS H→ττ analysis (137 fb^{-1}) includes 0l+2τ_h, obtaining 1σ significance

ttH (H→γγ, ZZ*→4l): very clean bumps





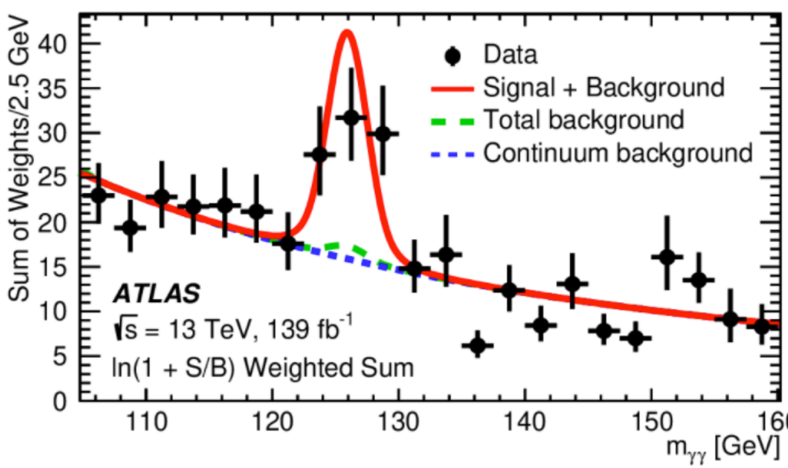




- Small rate
- Very clean final state with high S/B
- Clear Higgs peak

- Statistically limited

Significance (139 fb^{-1}):
γγ ➔ >5σ
ZZ*(4l) ➔ expected 1.2σ



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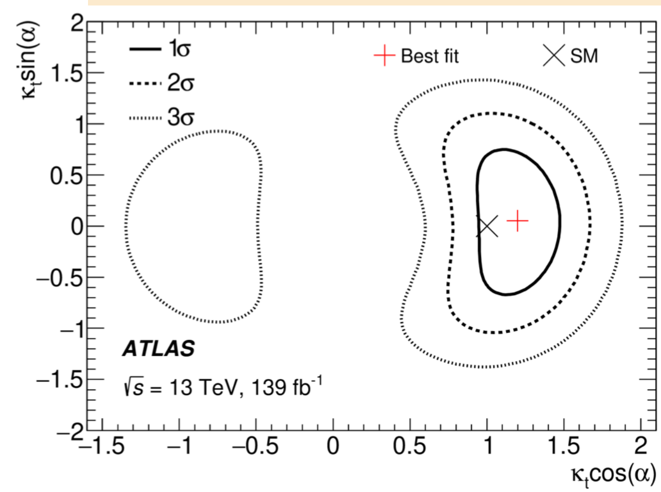
For H→γγ, $\delta\sigma_{ttH}$~25% and also:
- measurement of 5 STXS bins
- CP analysis: mixing angle |α|< 43º @ 95% CL
a pure CP-odd coupling excluded >3σ



Also searches for tH, upper limits in XS: $\sigma_{tH}<6\sigma_{SM}$

OPERATORS AND PHYSICS IMPLICATIONS

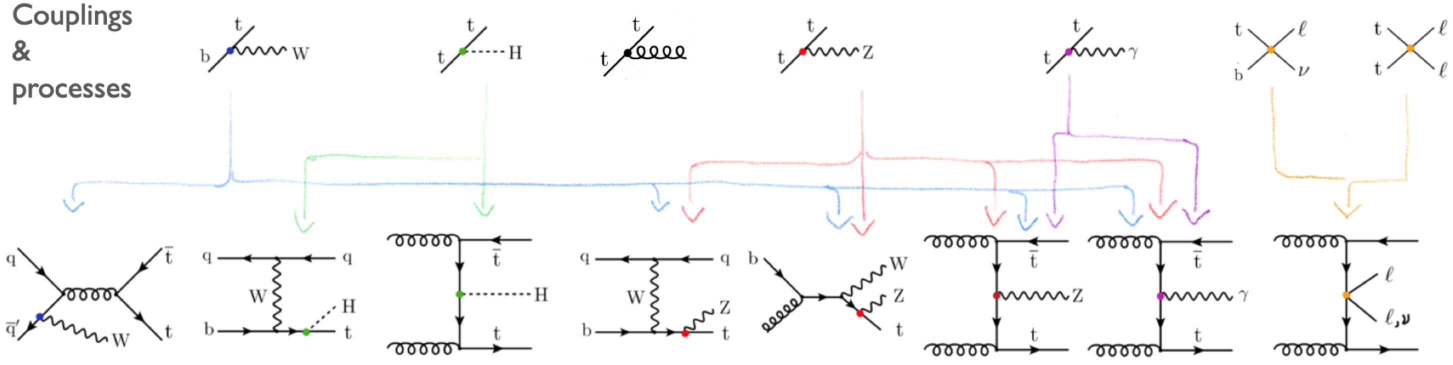
SMEFT Lagrangian

$$\mathcal{L} = \mathcal{L}_{4,\mathrm{SM}} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \boxed{\frac{1}{\Lambda^2}\mathcal{L}_6} + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}_6' + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Operators

$\mathcal{O}_{\phi\mathrm{tb}}$	$i(\tilde\phi D_\mu \phi)(\bar t_R \gamma^\mu b_R) + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tB}}$	$i(\bar q_L \sigma^{\mu\nu} t_R)\tilde\phi B_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(3)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar q_L \gamma^\mu \tau^I q_L)$	$\mathcal{O}^1_{qq}$	$(\bar q_L \gamma_\mu q_L)(\bar q_L \gamma^\mu q_L)$
$\mathcal{O}_{\mathrm{t}\phi}$	$(\phi^\dagger\phi)\,\bar q_L t_R \tilde\phi + \mathrm{h.c.}$	$\mathcal{O}_{\mathrm{tG}}$	$i(\bar q_L \sigma^{\mu\nu}\lambda^a t_R)\tilde\phi G^a_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(1)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar q_L \gamma^\mu q_L)$	$\mathcal{O}^8_{qq}$	$(\bar q_L \gamma_\mu T^A q_L)(\bar q_L \gamma^\mu T^A q_L)$

Couplings & processes



Parametrized predictions

$$N\left(\frac{\vec c}{\Lambda^2}\right) = S_0 + \sum_j S_{1j}\frac{c_j}{\Lambda^2} + \sum_j S_{2j}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} S_{3jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

2 quarks + bosons

Operator	Definition	Lead processes affected
$‡O^{(ij)}_{\mathrm{u}\varphi}$	$\bar q_i u_j \tilde\varphi\,(\varphi^\dagger\varphi)$	$t\bar tH$, tHq
$O^{1(ij)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_i\gamma^\mu q_j)$	$t\bar tH$, $t\bar tl\nu$, $t\bar tl\bar l$, tHq, $tl\bar lq$
$O^{3(ij)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_i\gamma^\mu\tau^I q_j)$	$t\bar tH$, $t\bar tl\nu$, $t\bar tl\bar l$, tHq, $tl\bar lq$
$O^{(ij)}_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_i\gamma^\mu u_j)$	$t\bar tH$, $t\bar tl\nu$, $t\bar tl\bar l$, $tl\bar lq$
$‡O^{(ij)}_{\varphi ud}$	$(\tilde\varphi^\dagger iD_\mu\varphi)(\bar u_i\gamma^\mu d_j)$	$t\bar tH$, $tl\bar lq$, tHq
$‡O^{(ij)}_{uW}$	$(\bar q_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde\varphi W^I_{\mu\nu}$	$t\bar tH$, $t\bar tl\nu$, $t\bar tl\bar l$, tHq, $tl\bar lq$
$‡O^{(ij)}_{dW}$	$(\bar q_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu}$	$t\bar tH$, $t\bar tl\bar l$, tHq, $tl\bar lq$
$‡O^{(ij)}_{uB}$	$(\bar q_i\sigma^{\mu\nu} u_j)\,\tilde\varphi B_{\mu\nu}$	$t\bar tH$, $t\bar tl\nu$, $t\bar tl\bar l$, tHq, $tl\bar lq$
$‡O^{(ij)}_{uG}$	$(\bar q_i\sigma^{\mu\nu}T^A u_j)\,\tilde\varphi G^A_{\mu\nu}$	$t\bar tH$, $t\bar tl\nu$, $t\bar tl\bar l$, tHq, $tl\bar lq$

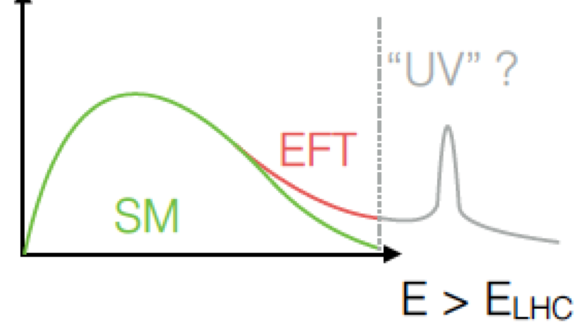
2 quarks + 2 leptons

Operator	Definition	Lead processes affected
$O^{1(ijkl)}_{\ell q}$	$(\bar\ell_i\gamma^\mu\ell_j)(\bar q_k\gamma^\mu q_\ell)$	$t\bar tl\nu$, $t\bar tl\bar l$, $tl\bar lq$
$O^{3(ijkl)}_{\ell q}$	$(\bar\ell_i\gamma^\mu\tau^I\ell_j)(\bar q_k\gamma^\mu\tau^I q_\ell)$	$t\bar tl\nu$, $t\bar tl\bar l$, $tl\bar lq$
$O^{(ijkl)}_{\ell u}$	$(\bar\ell_i\gamma^\mu\ell_j)(\bar u_k\gamma^\mu u_\ell)$	$t\bar tl\bar l$
$O^{(ijkl)}_{eq}$	$(\bar e_i\gamma^\mu e_j)(\bar q_k\gamma^\mu q_\ell)$	$t\bar tl\bar l$, $tl\bar lq$
$O^{(ijkl)}_{eu}$	$(\bar e_i\gamma^\mu e_j)(\bar u_k\gamma^\mu u_\ell)$	$t\bar tl\bar l$
$‡O^{1(ijkl)}_{\ell equ}$	$(\bar\ell_i e_j)\,\varepsilon\,(\bar q_k u_\ell)$	$t\bar tl\bar l$, $tl\bar lq$
$‡O^{3(ijkl)}_{\ell equ}$	$(\bar\ell_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\bar q_k\sigma_{\mu\nu}u_\ell)$	$t\bar tl\nu$, $t\bar tl\bar l$, $tl\bar lq$

Model-independent interpretations: effective field theories

- The LHC is entering a "precision era" and approaching the limits of the 'energy frontier'
- Most experimental results consistent with SM expectations
- No clear evidence for new physics from direct searches
- Complementary approach: **SMEFT**

Sketch from Ken Mimasu



The effects of new physics at a scale Λ can be described by an effective Lagrangian in which new physics effects are parametrised.

Operator expansion:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

These operators can induce corrections to SM couplings (e.g. anomalous couplings of the top quark to the gauge or Higgs bosons) → effective vertices: ttW, ttZ, ttH, ttγ, ttg ...

- → need to identify which operators contribute to each process
- → need to parametrized predictions for each observable in terms of those operators

$$\sigma = \sigma_{\text{SM}} + \underbrace{\frac{1}{\Lambda^2}\sum C_i O_i}_{\text{SM}\ \times \text{D6}} + \underbrace{\left(\frac{1}{\Lambda^2}\sum C_i O_i\right)\left(\frac{1}{\Lambda^2}\sum C_j O_j\right)}_{\text{D6}\times\text{D6}} + \underbrace{O(1/\Lambda^4)}_{\text{SM}\ \times\text{D8}}$$

Dependence derived with **MadGraph5_aMC@NLO,** plus **SMEFT@NLO** and **TEFT_EW**

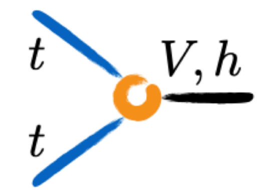
Basis: complete, non-redundant set of operators
Dimension 6: 59 (76 real) - 2499 operators → affecting top quark interactions:

- Depends on CP/flavour assumptions
- New parameters to be measured at the LHC & beyond

Two-fermion op.: QQ + V,G,φ

Four-fermion op: QQQQ
QQqq
QQll

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$
$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2
$pp \to tj$	N		L	L				L^2	L^2
$pp \to tW$	L		L	L				L^2	L^2
$pp \to t\bar{t}$	L								
$pp \to t\bar{t}j$	L								
$pp \to t\bar{t}\gamma$	L	L	L						
$pp \to t\bar{t}Z$	L	L	L	L	L	L			
$pp \to t\bar{t}W$	L								L
$pp \to t\gamma j$	N	L	L	L				L^2	L^2
$pp \to tZj$	N	L	L	L	L	L		L^2	L^2
$pp \to t\bar{t}t\bar{t}$	L								
$pp \to t\bar{t}H$	L						L		
$pp \to tHj$	N		L	L			L	L^2	L^2



$\mathcal{O}_{tG}$ - $t\bar{t}g$ vertex

$\mathcal{O}_{tW}, \mathcal{O}_{tB}$ - $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices

$\mathcal{O}_{\phi t}, \mathcal{O}_{\phi Q^3}, \mathcal{O}_{\phi Q^1}$ - $t\bar{t}Z$ vertex

Dim-6 two-fermion operators relevant for top quark physics

Sketch from Fabio Maltoni

Measurements used in our fit to top quark EW couplings

arXiv: 2107.13917

Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \to Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	~ 91 GeV	202.1 pb^{-1}	LEP/SLD

Legacy measurements from LEP/SLD and Tevatron

Measurements used in our fit to top quark EW couplings

arXiv: 2107.13917

Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \to Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD

Single top quark production cross sections and *W* boson helicity fractions (sensitive to *tWb* vertex) from LHC Run-1 combination (ATLAS+CMS)

Measurements used in our fit to top quark EW couplings

arXiv: 2107.13917

Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \to Wb$	$F_0,\ F_L$	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD

tt+X and t+X production cross sections measured by ATLAS or CMS at 13 TeV.
Since no combinations are currently available, one single measurement has been used.
Comprehensive combinations will be carried by LHC collaborations for Run-2 legacy measurements.

arXiv: 2107.13917

HL-LHC S2 (3000 fb^{-1})

- stat. & exp. syst. → $1/\sqrt{L}$
- theory normalization+ ~~modeling~~ → ½

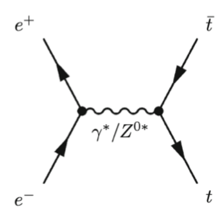
ILC 250 (2000 fb^{-1})

σ_{bb} & A^{FB}_{bb} at 2 pol. $\mathcal{P}_{e^-}, \mathcal{P}_{e^+} = \pm 0.8, \mp 0.3$

ILC 500 (4000 fb^{-1})

σ_{bb} & A^{FB}_{bb}

optimal observables for tt



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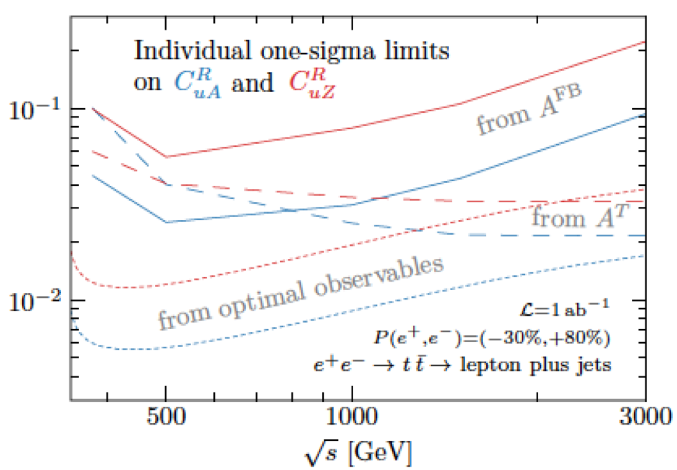
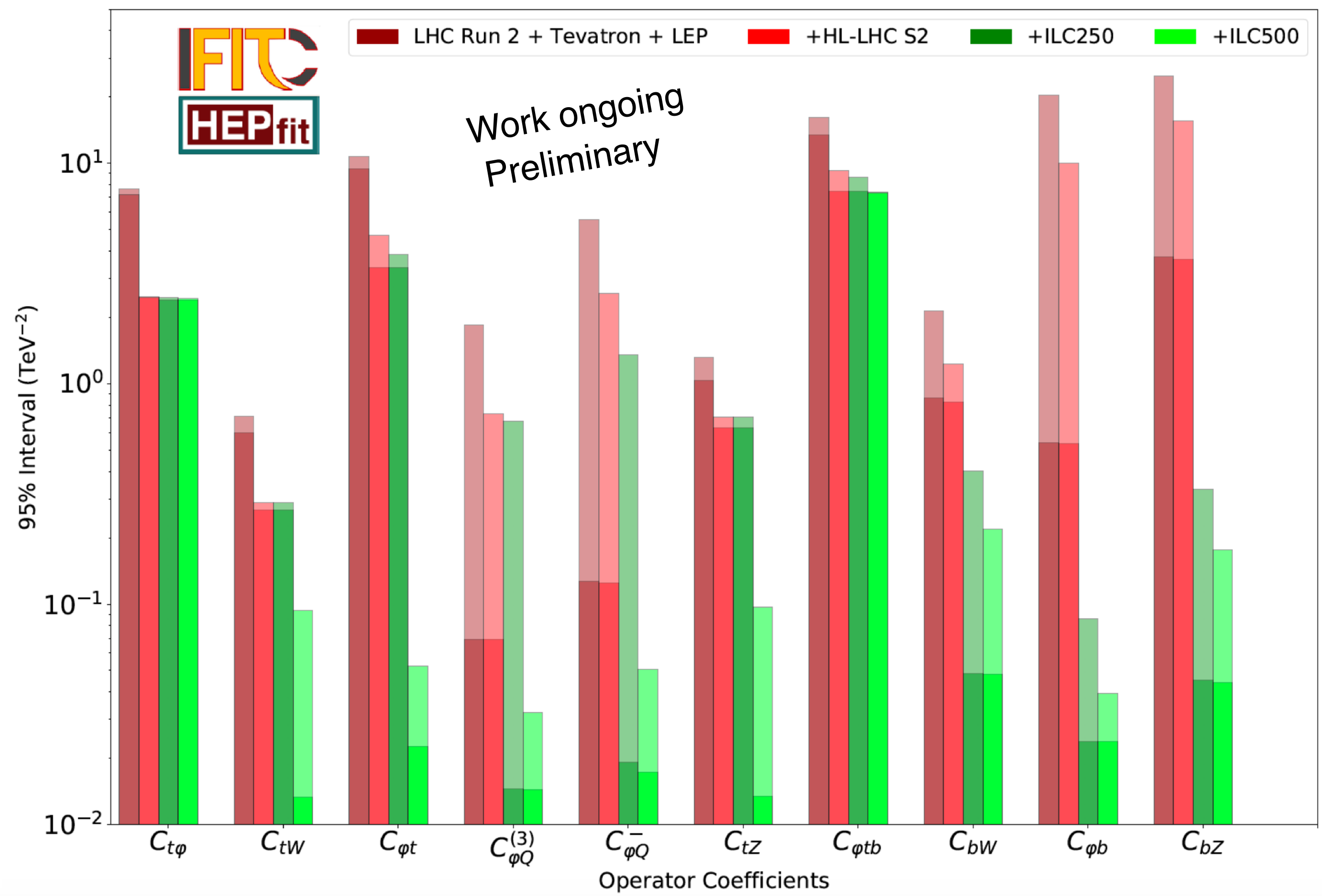
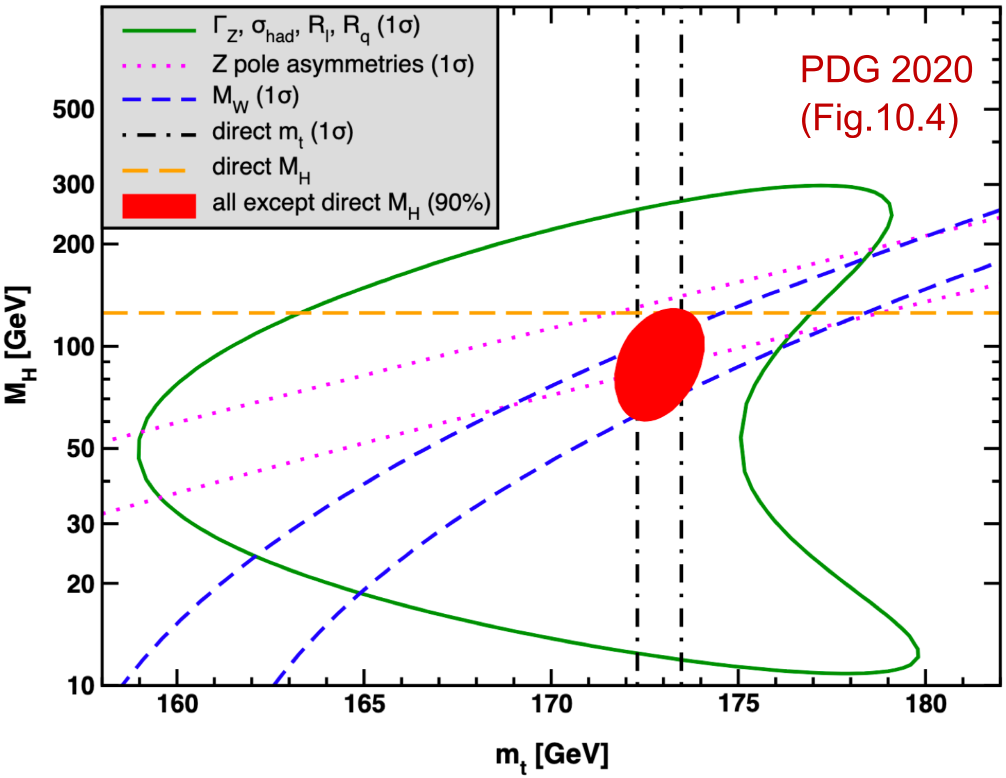


dark shades: individual constraints

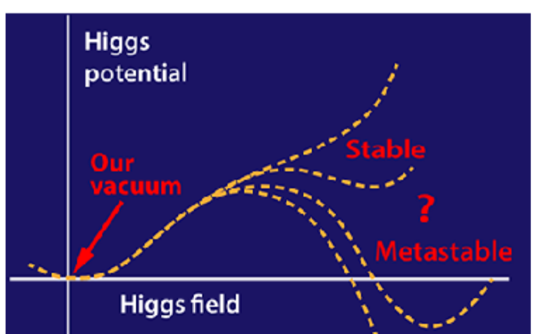
light shades (full bar): constraints from global fit



Top quark mass: a very important parameter of the SM

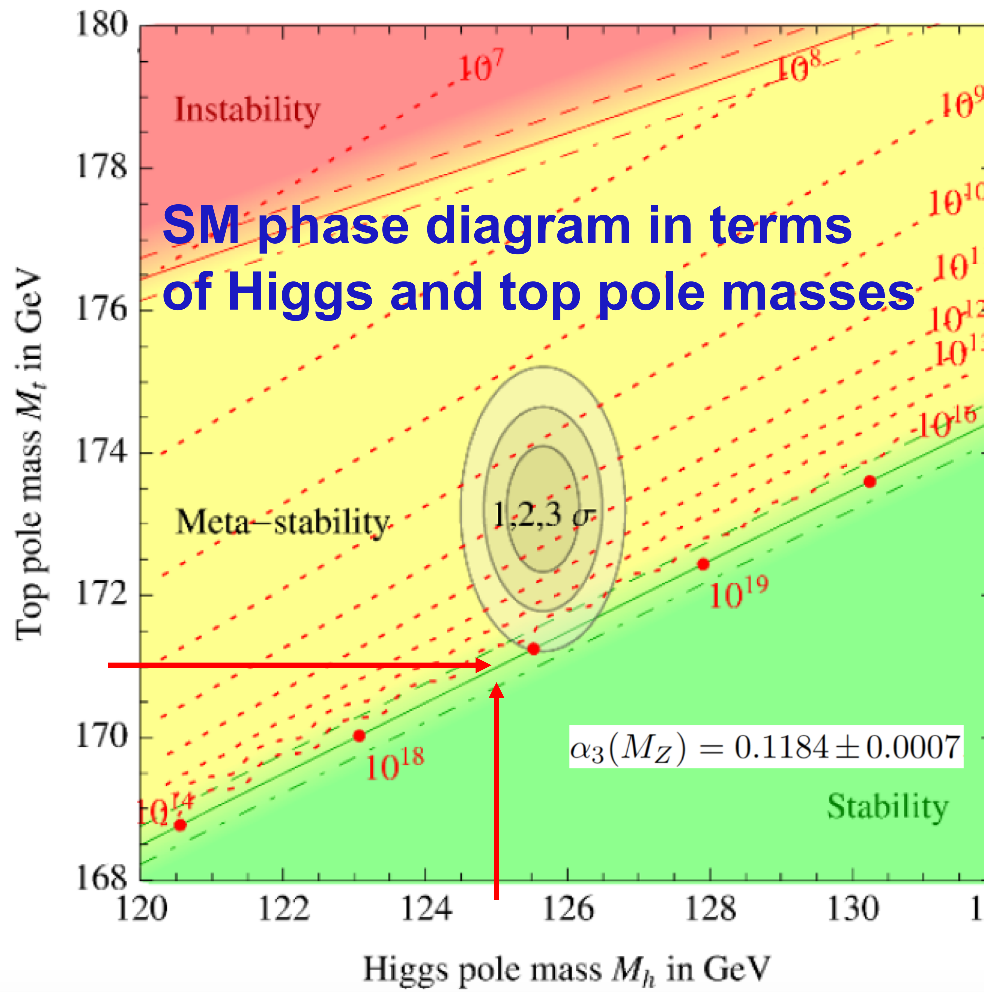


Recent measurements:
$\delta m_H \sim 0.11\%$, $\delta m_t \sim 0.3\%$



Global EW fits

- important consistency test of the SM
- good agreement between measured and indirect predictions (*p*-value: 0.48, before FNAL g-2)



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