

Top quark pair property measurements using the ATLAS detector at the LHC

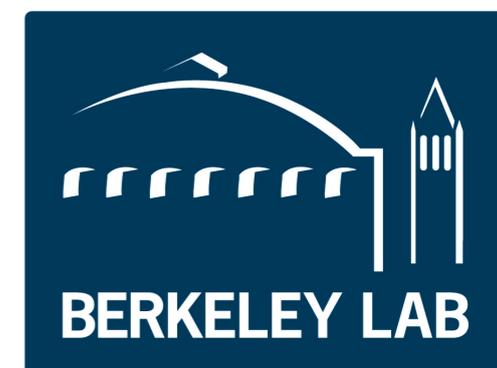


On behalf of
the ATLAS collaboration

Boyang Li
Tsinghua University, China

6-8 May 2019

Phenomenology 2019
Symposium



Outline

- Top quark Flavour Changing Neutral Current (FCNC) interactions:

- tqH interaction searches using top-quark pair events :

$$H \rightarrow \tau^+ \tau^- \quad H \rightarrow VV$$

$$H \rightarrow \bar{b}b \quad H \rightarrow \gamma\gamma$$

- tqZ interaction search:

$$t \rightarrow qZ \rightarrow ql^+l^-$$

- Top quark spin correlation measurements
- Measurement of colour flow using jet-pull observables in $\bar{t}t$ events
- Summary

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All based on 36fb-1 data

Top quark FCNC interactions

- FCNC process is highly suppressed in the Standard Model (SM) due to CKM unitarity:

[Phys. Rev. D 2 \(1970\) 1285](#) (GIM mechanism)

- SM top FCNC branching ratios [arXiv:hep-ph/0409342](#):

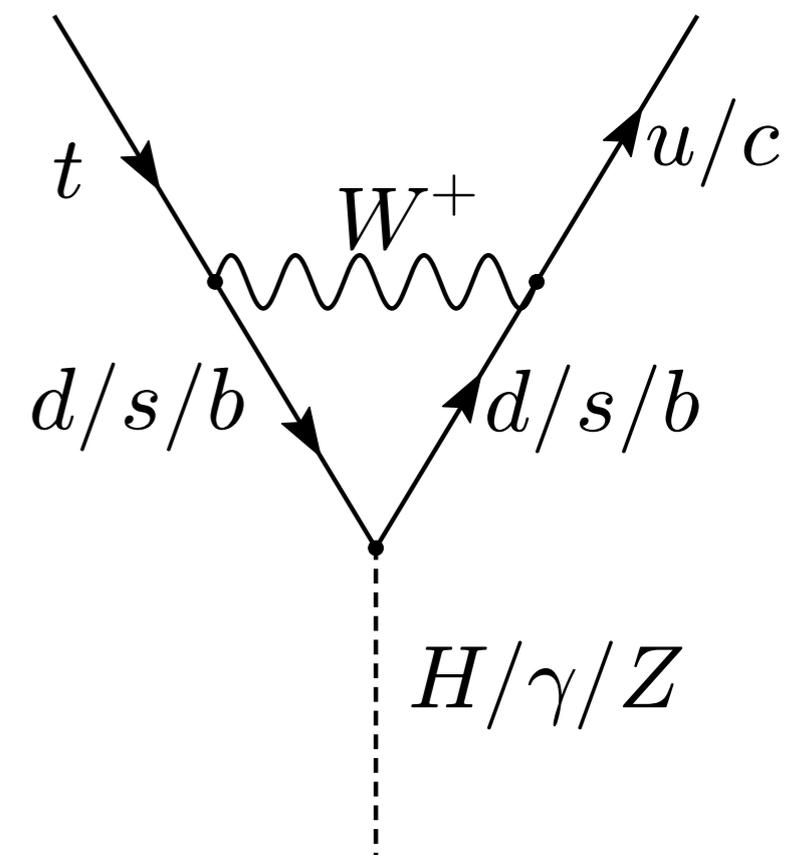
$$\text{Br}(t \rightarrow cH) \simeq 3 \times 10^{-15}$$

$$\text{Br}(t \rightarrow cZ) \simeq 1 \times 10^{-14}$$

$$\text{Br}(t \rightarrow cg) = (4.6^{+1.1}_{-0.9} \pm 0.2 \pm 0.4^{+2.1}_{-0.7}) \times 10^{-12}$$

$$\text{Br}(t \rightarrow c\gamma) = (4.6^{+1.2}_{-1.0} \pm 0.2 \pm 0.4^{+1.6}_{-0.5}) \times 10^{-14}$$

SM 1 loop FCNC

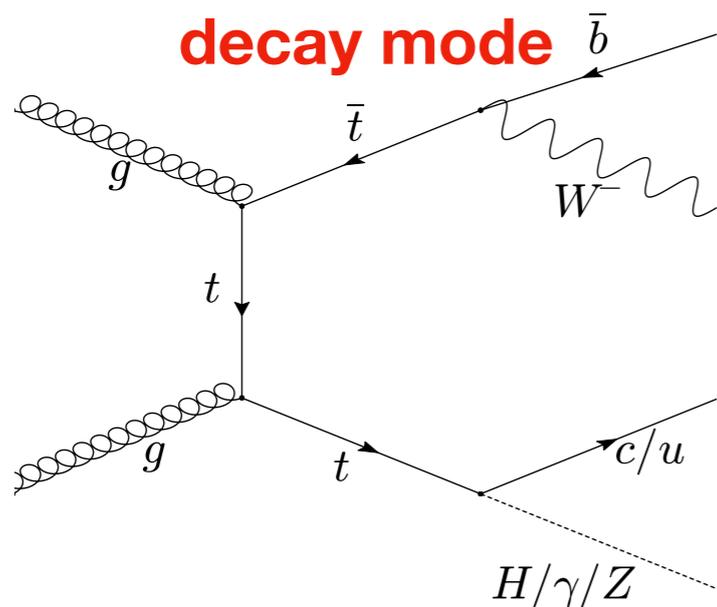


Top quark FCNC interactions

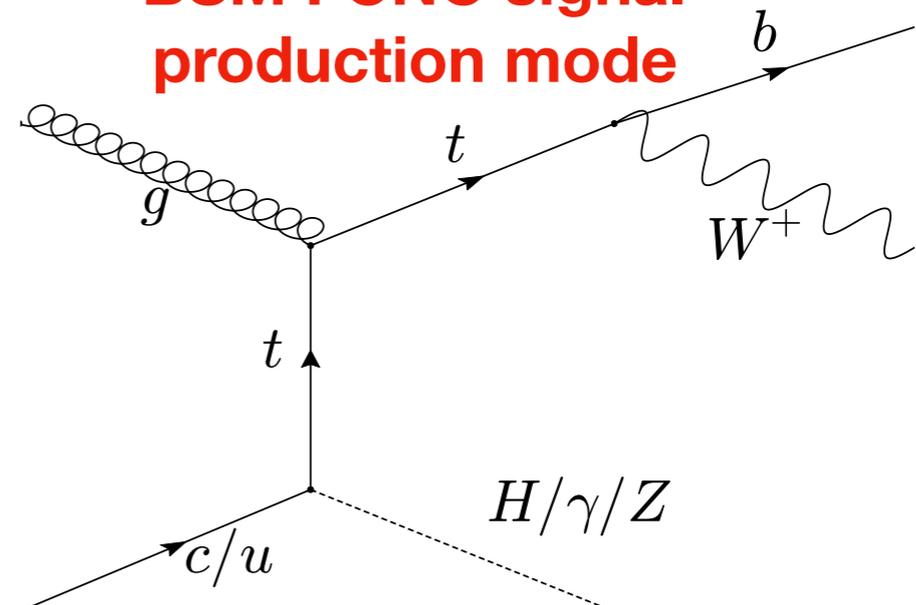
- In contrast, large enhancements in these branching ratios are possible in some beyond-SM scenarios: [arXiv:hep-ph/0409342](https://arxiv.org/abs/hep-ph/0409342)

	SM	QS	2HDM	FC 2HDM	MSSM	\mathcal{R} SUSY
$t \rightarrow uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}
$t \rightarrow u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}
$t \rightarrow ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}
$t \rightarrow uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$
$t \rightarrow cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \rightarrow c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \rightarrow cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \rightarrow cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

BSM FCNC signal decay mode



BSM FCNC signal production mode

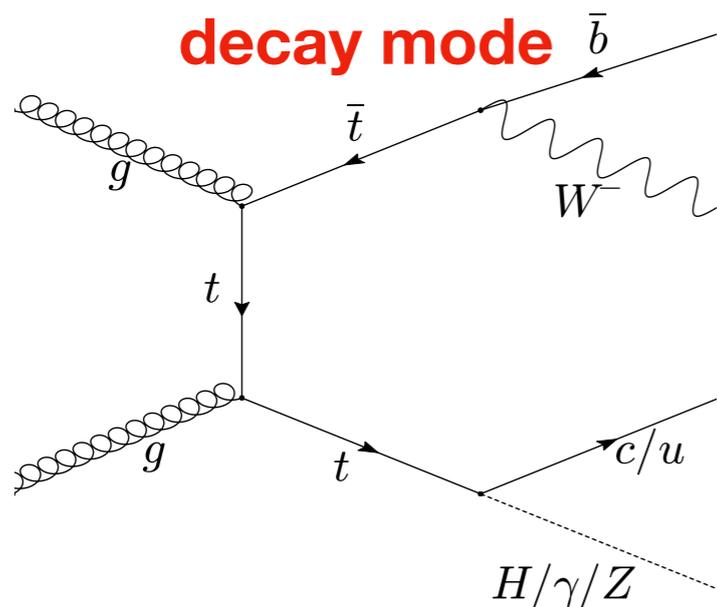


Top quark FCNC interactions

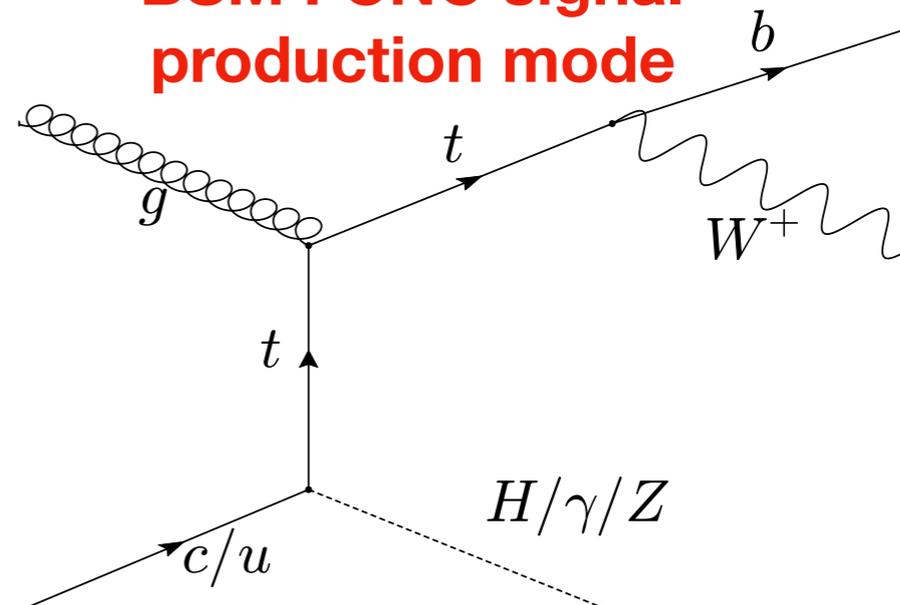
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BSM FCNC signal decay mode



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Overview of $\bar{t}t$ FCNC analyses

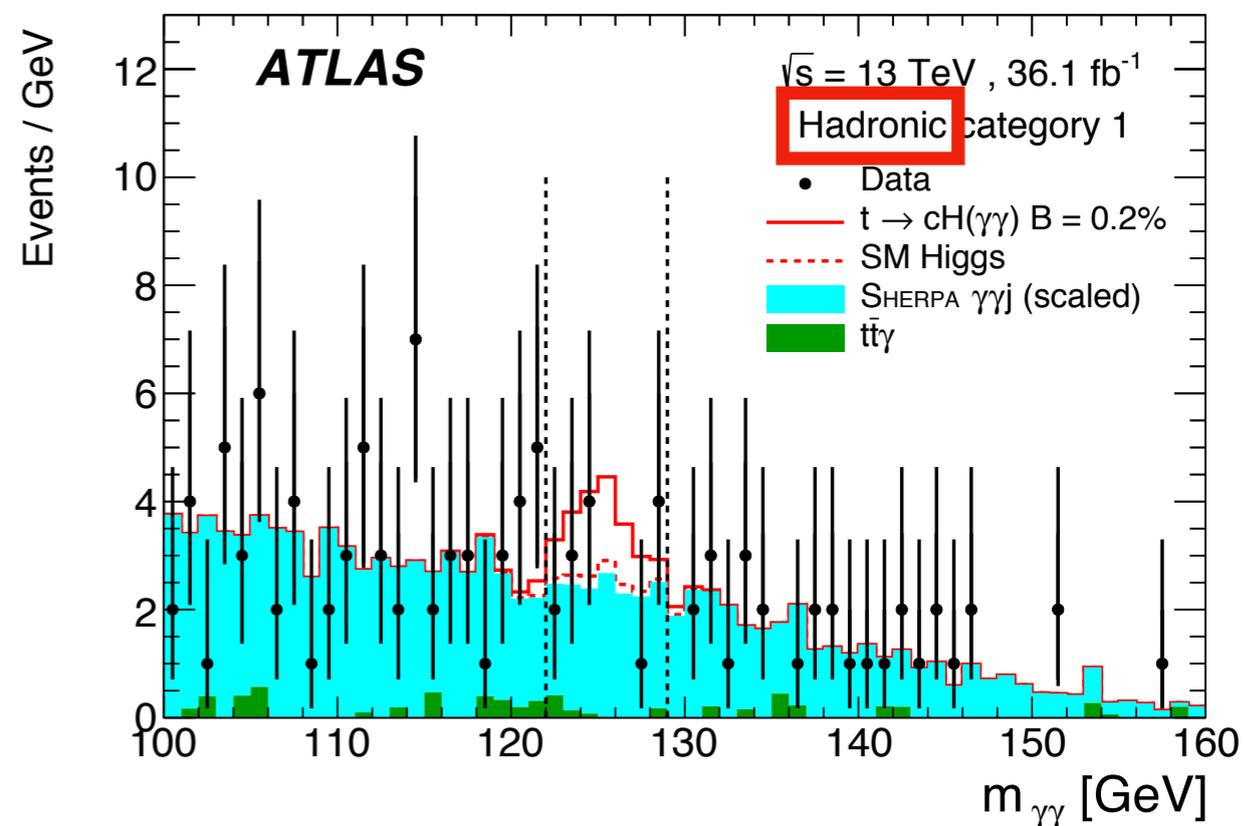
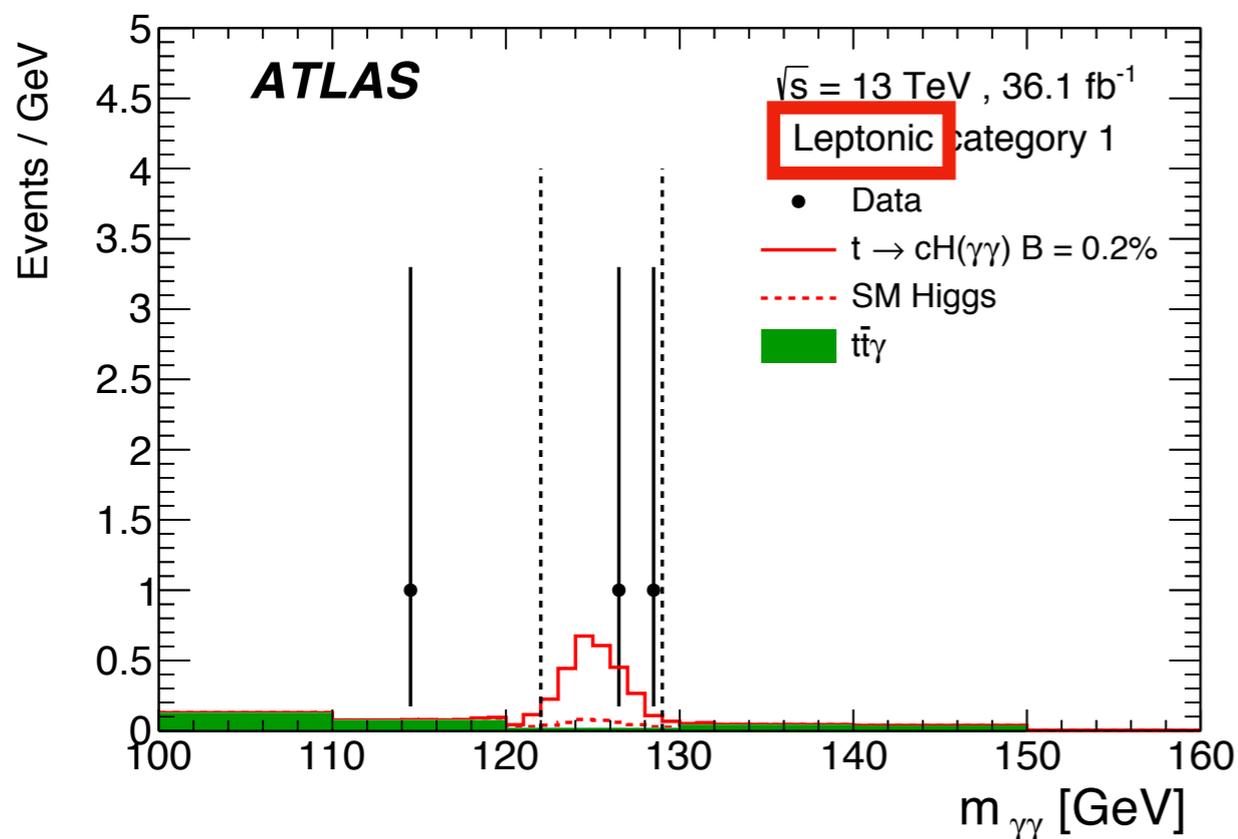
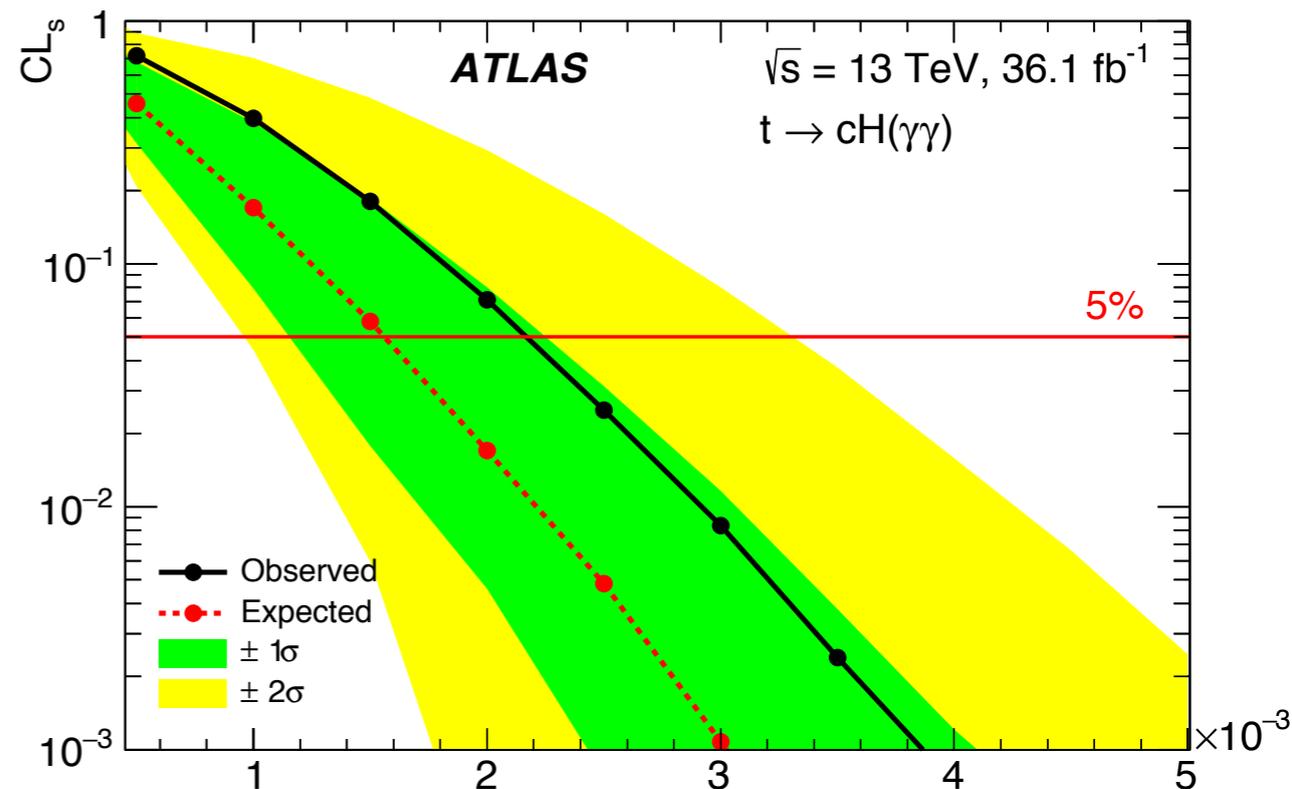
Channels	b-jet	jet	photon	lepton	tau	Major background	stat. method	limitation
$H \rightarrow \gamma\gamma$ hadronic	1	≥ 4	2	0	/	$\bar{t}t\gamma, \gamma\gamma+\text{jet}$	fit to $m_{\gamma\gamma}$ spectrum	stat.
$H \rightarrow \gamma\gamma$ leptonic	1	≥ 2	2	1	/	$\bar{t}t\gamma, W\gamma\gamma, Z\gamma\gamma$	event counting	stat.
$H \rightarrow VV$ 2ISS	1,2	≥ 4	/	2	0	Non-prompt $\bar{t}tV, \bar{t}tH$	fit to BDT	stat.
$H \rightarrow VV$ 3I	≥ 1	≥ 2	/	3	0		fit to BDT	stat.
$H \rightarrow \tau\tau$ lephad	1	≥ 3	/	1	≥ 1	$\bar{t}t$	fit to BDT	stat.
$H \rightarrow \tau\tau$ hadhad	1	≥ 3	/	0	≥ 2	Multi-jet, $\bar{t}t$	fit to BDT	stat.
$H \rightarrow bb$	3	4/5	/	1	/	$\bar{t}t$ +jets	fit to Likelihood	syst.
$Z \rightarrow ll$	1	≥ 2	/	3	/	Non-prompt $\bar{t}tZ, WZ$	fit to top-reconstruction χ^2	stat.

$t \rightarrow qH \rightarrow q\gamma\gamma$

Published on JHEP [October 2017]

[10.1007/JHEP10(2017)129]

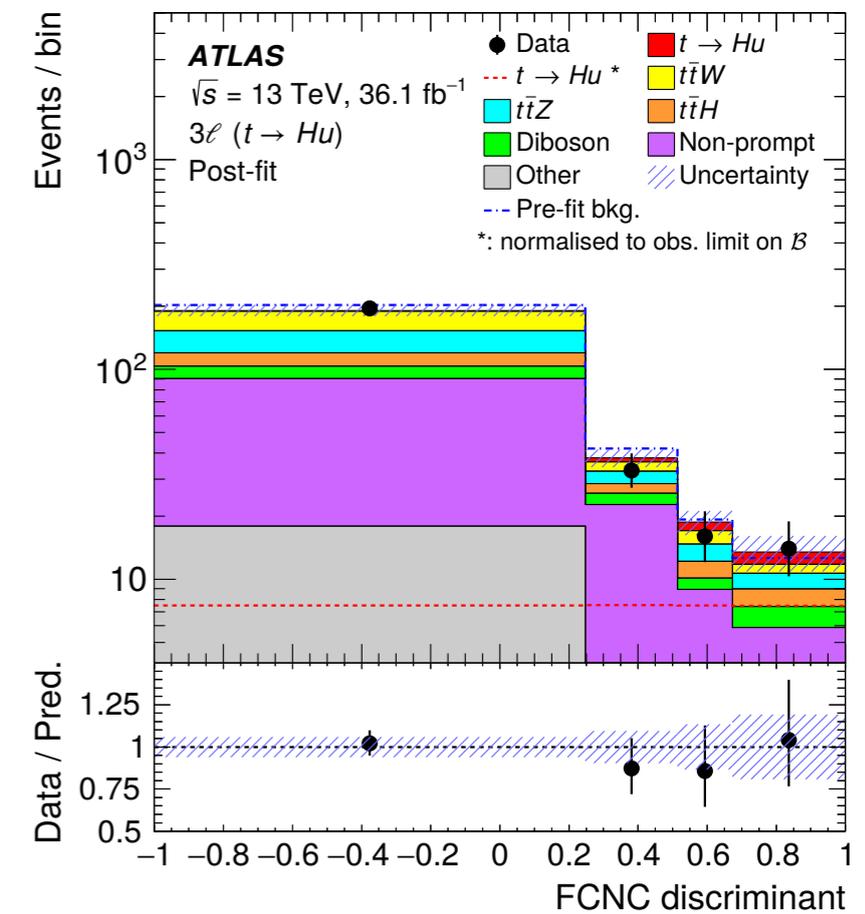
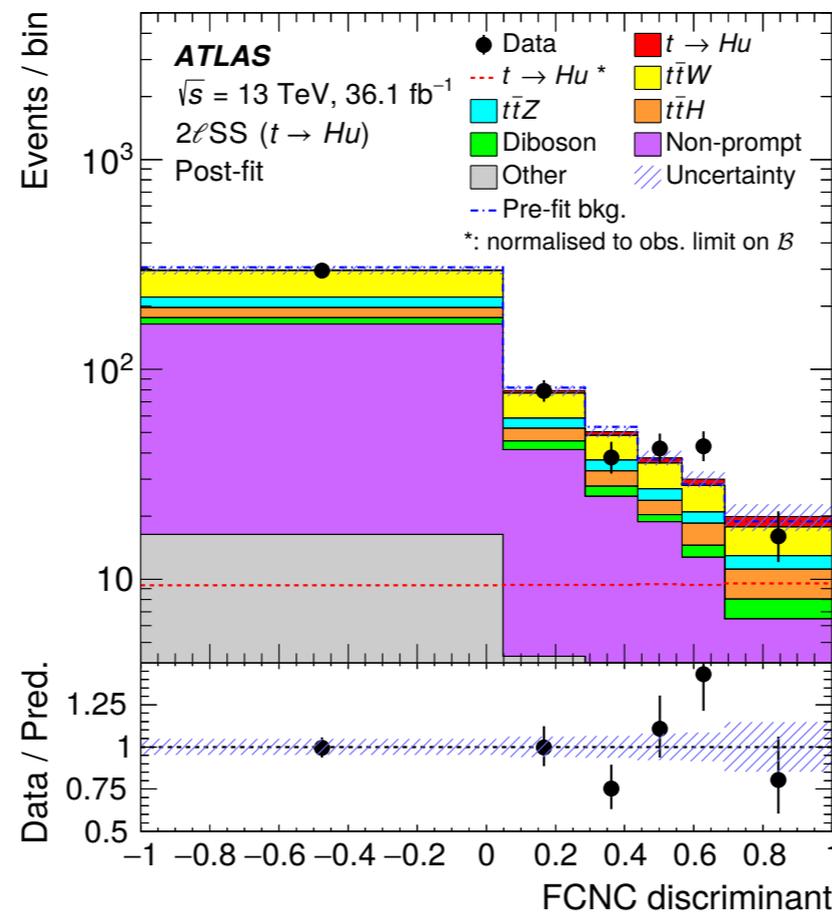
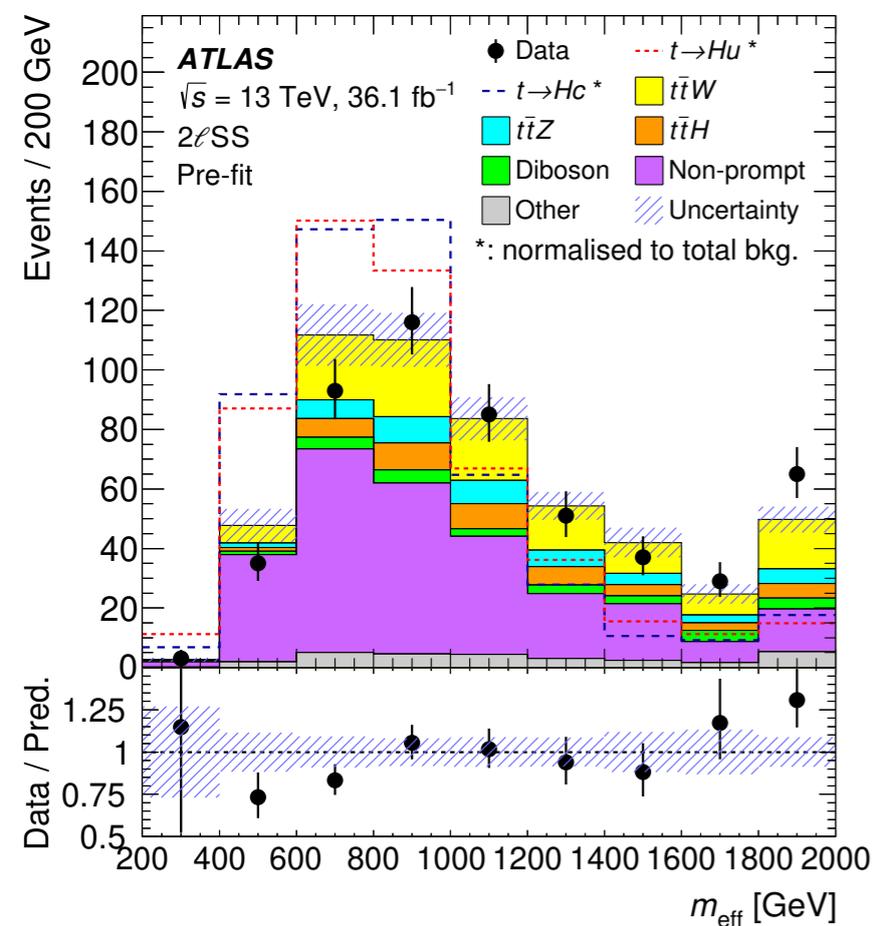
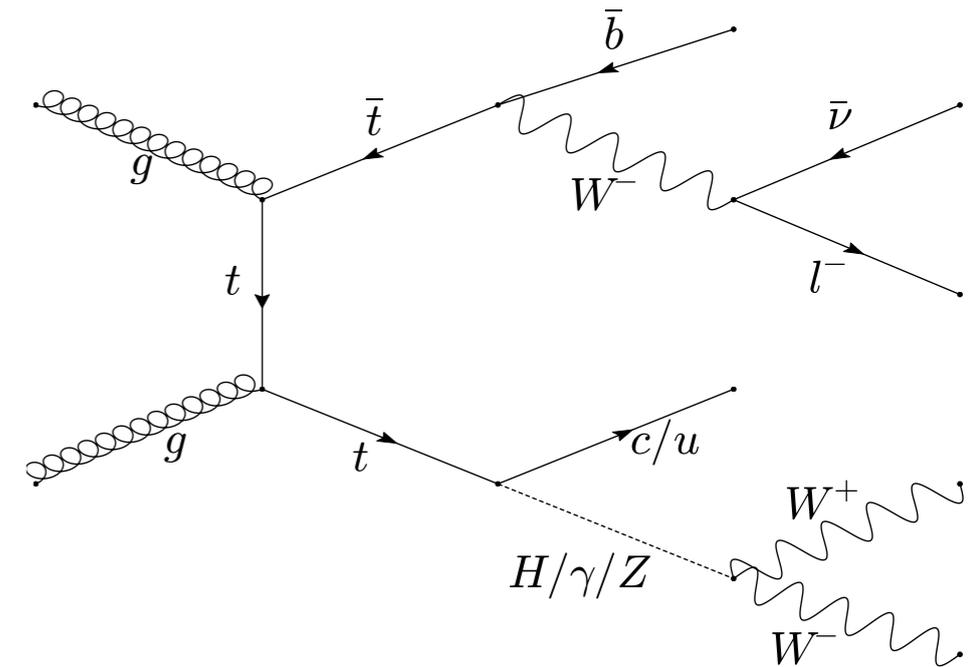
- Search both in hadronic and leptonic channel
- Signal regions:
 - Hadronic: 2γ , ≥ 4 jets with 1 b-tagged
 - leptonic: 2γ , ≥ 2 jets with 1 b-tagged, 1 lepton
- Strategy:
 - Hadronic: Fit $m_{\gamma\gamma}$ spectrum
 - Leptonic: Event counting



$t \rightarrow qH \rightarrow qVV$

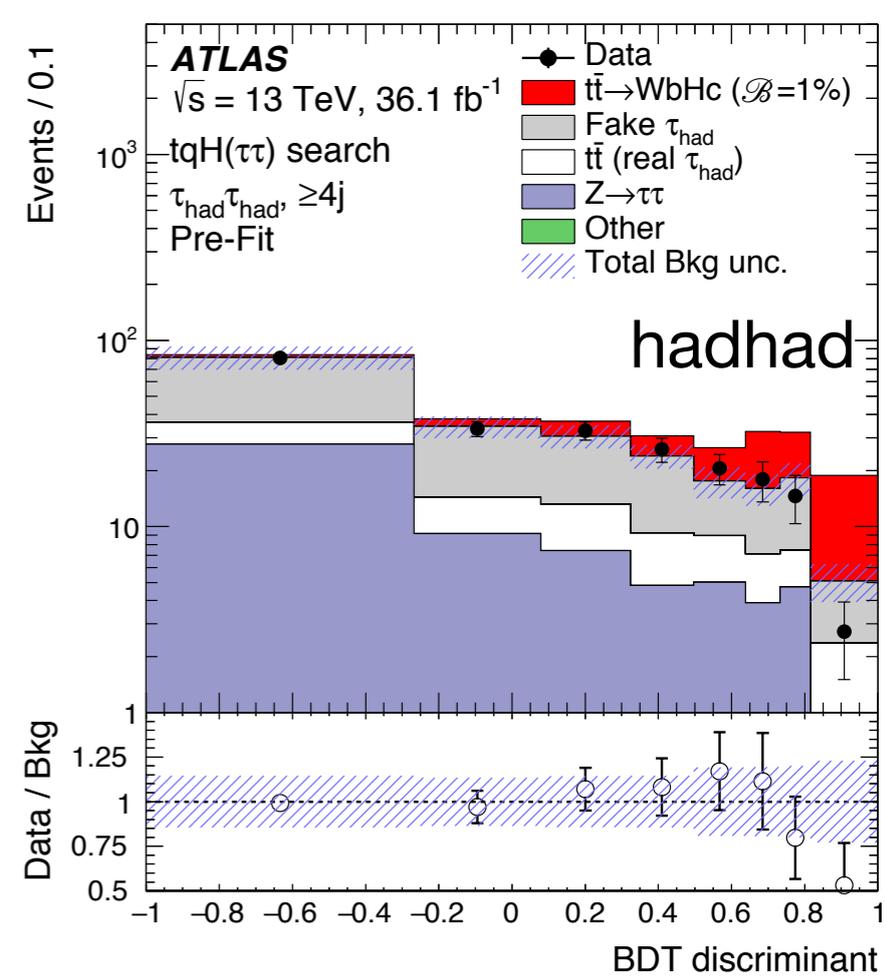
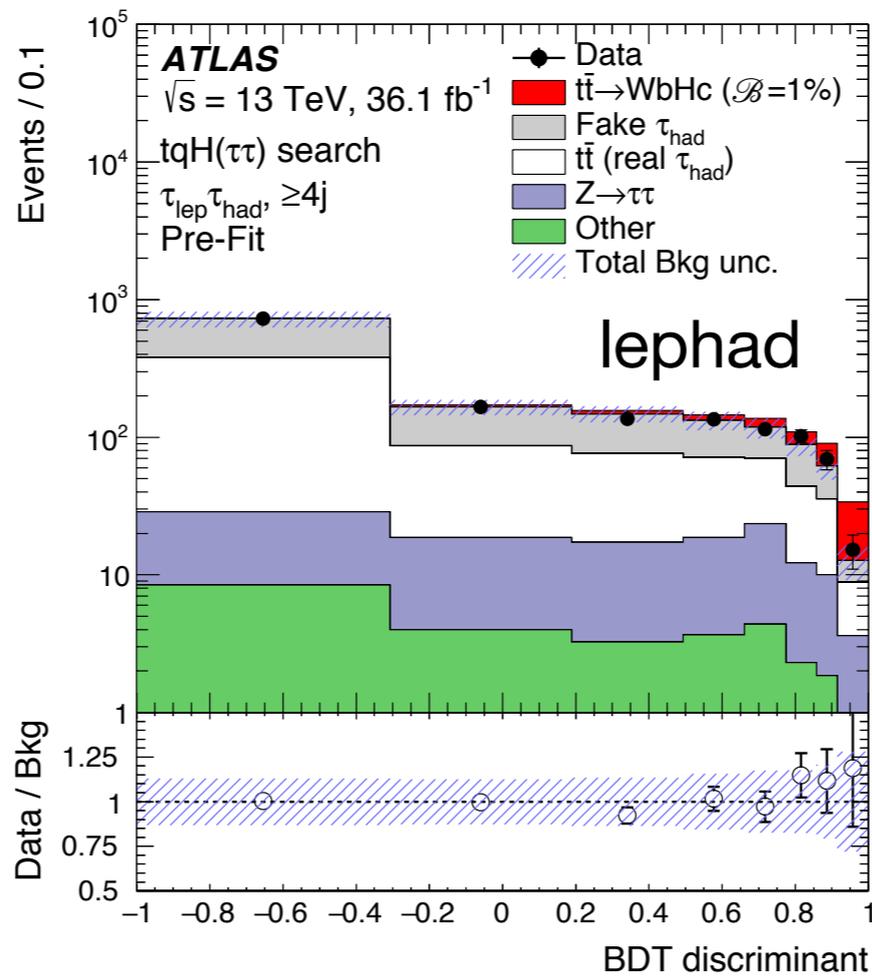
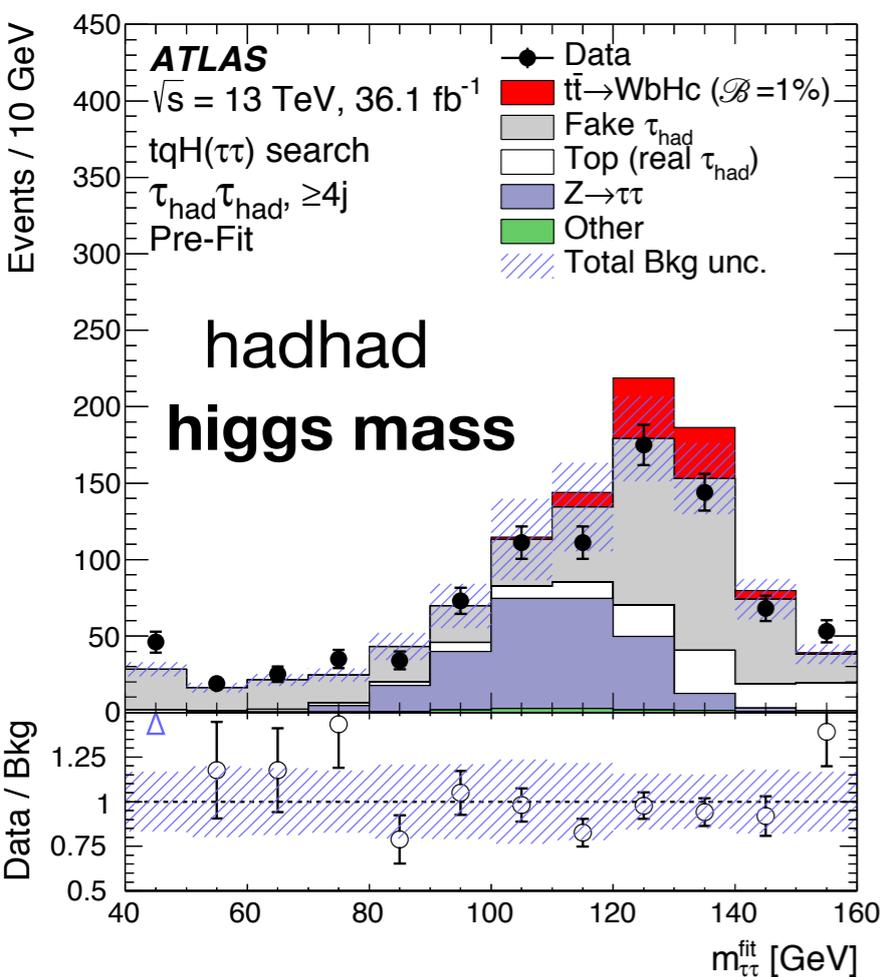
Published on PRD [Aug. 2018]
[Phys. Rev. D 98, 032002]

- Signal regions:
 - 2ISS: 2 same charged lepton, ≥ 4 jets with 1 or 2 b-tagged
 - 3l: 3 leptons, $\text{abs}(\Sigma\text{charge}) = 1$, ≥ 2 jets with ≥ 1 b-tagged
- Searches only in leptonic channel
- Strategy:
 - Estimate non-prompt leptons using matrix method
 - BDT discriminant fitting



$$t \rightarrow qH \rightarrow q\tau^+\tau^-$$

- combined paper with $H \rightarrow \bar{b}b$
- Signal regions:
 - lephad: ≥ 3 jets with 1 b-tagged
1 lepton, ≥ 1 tau
 - hadhad: ≥ 3 jets with 1 b-tagged,
2 taus
- Searches only in hadronic channel
- Strategy:
 - Data driven fake tau estimation using control regions
 - Kinematic fitting for neutrinos
 - BDT discriminant fitting

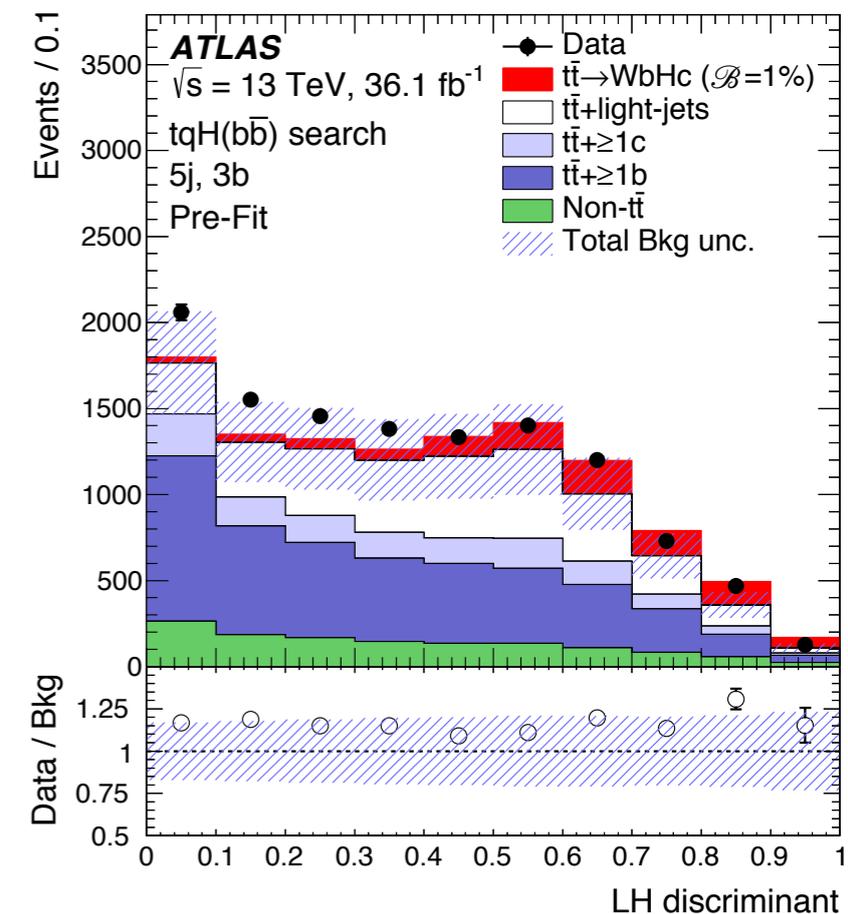
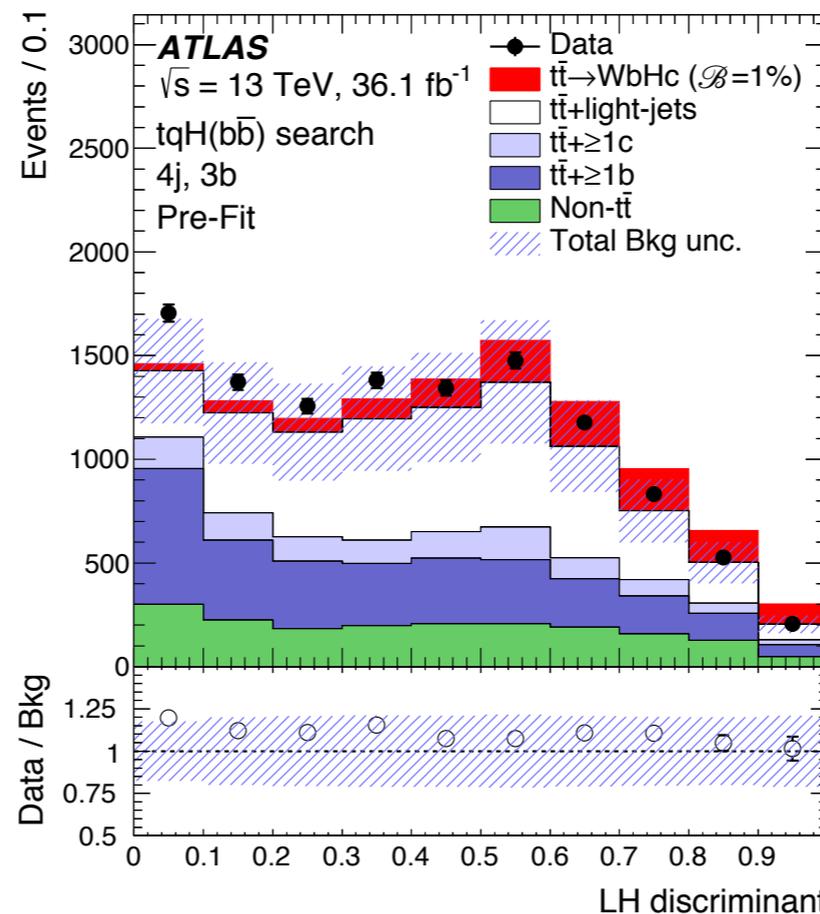
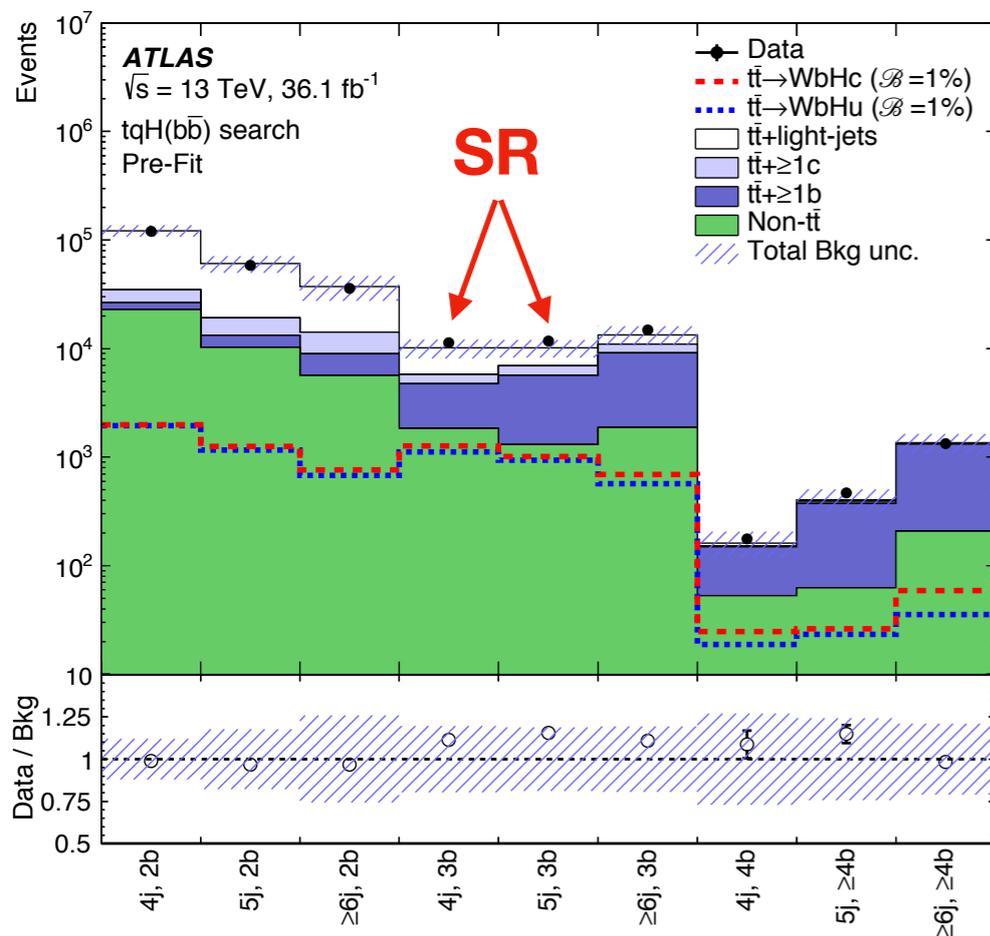


$t \rightarrow qH \rightarrow q\bar{b}b$

- combined paper with $H \rightarrow \tau^+\tau^-$
- Searches only in leptonic channel
- Signal region:
1 lepton, 4/5 jets, 3 b-jets

- Strategy:
 - MC based, constraining systematics using control region
 - Likelihood discriminant fitting

$$LH(\mathbf{x}) = \frac{P^{\text{sig}}(\mathbf{x})}{P^{\text{sig}}(\mathbf{x}) + P^{\text{bkg}}(\mathbf{x})}$$

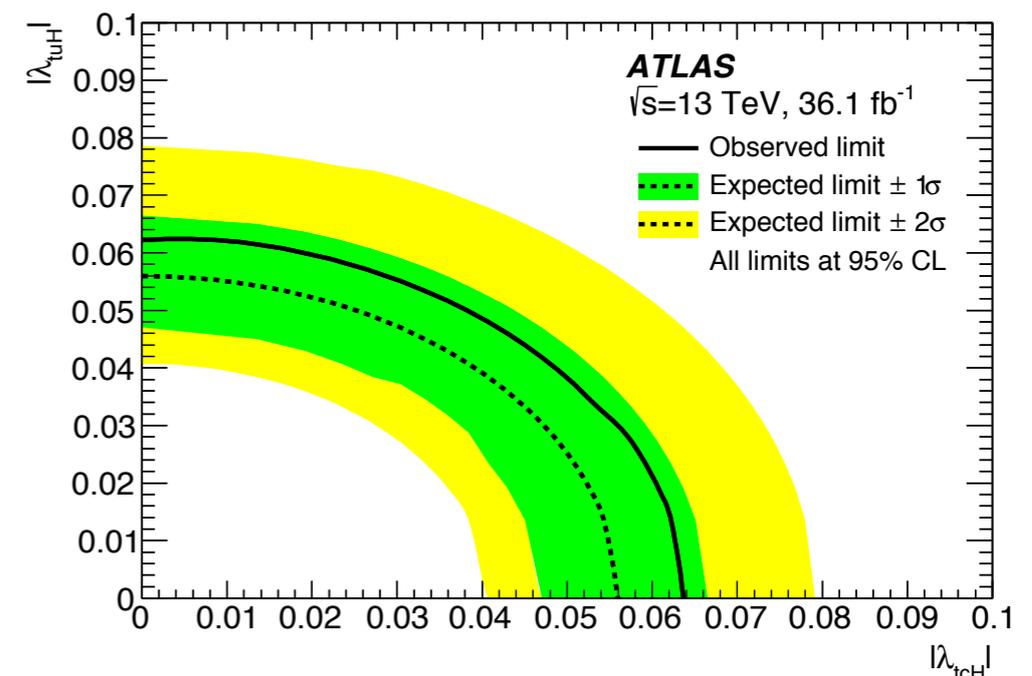
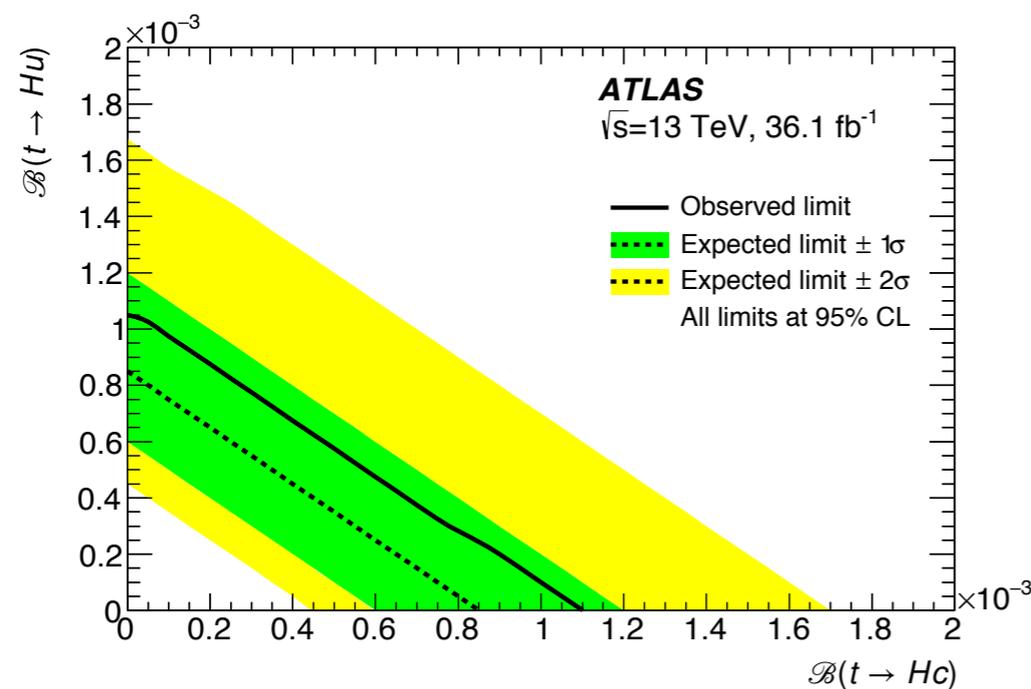
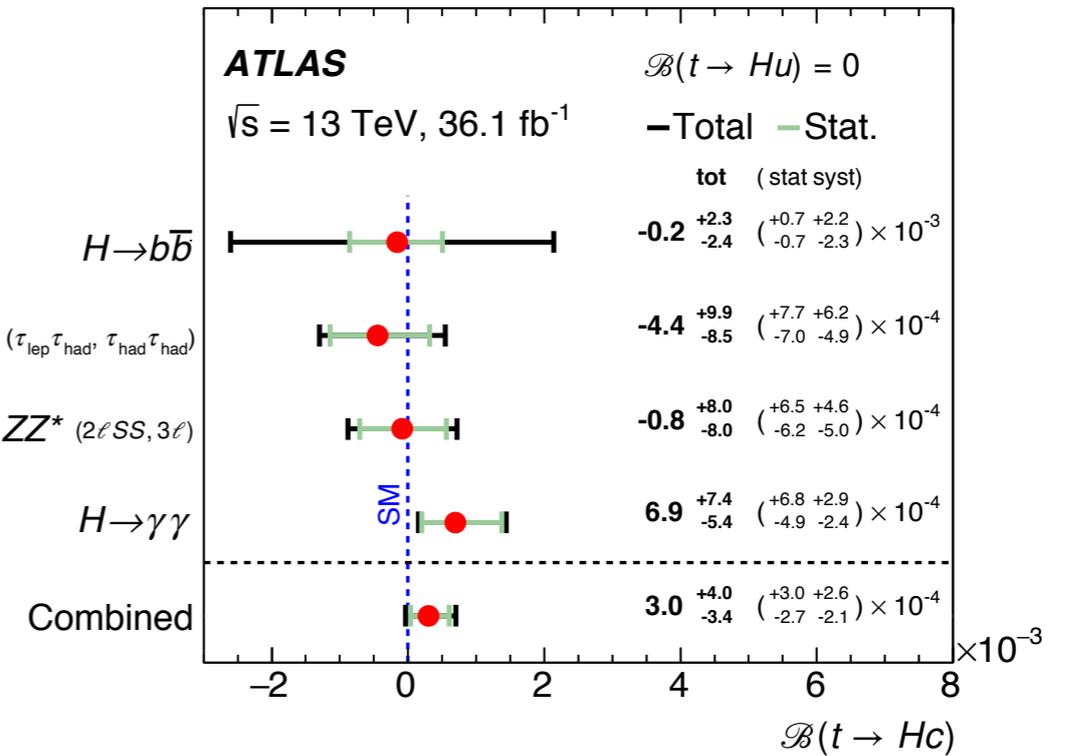
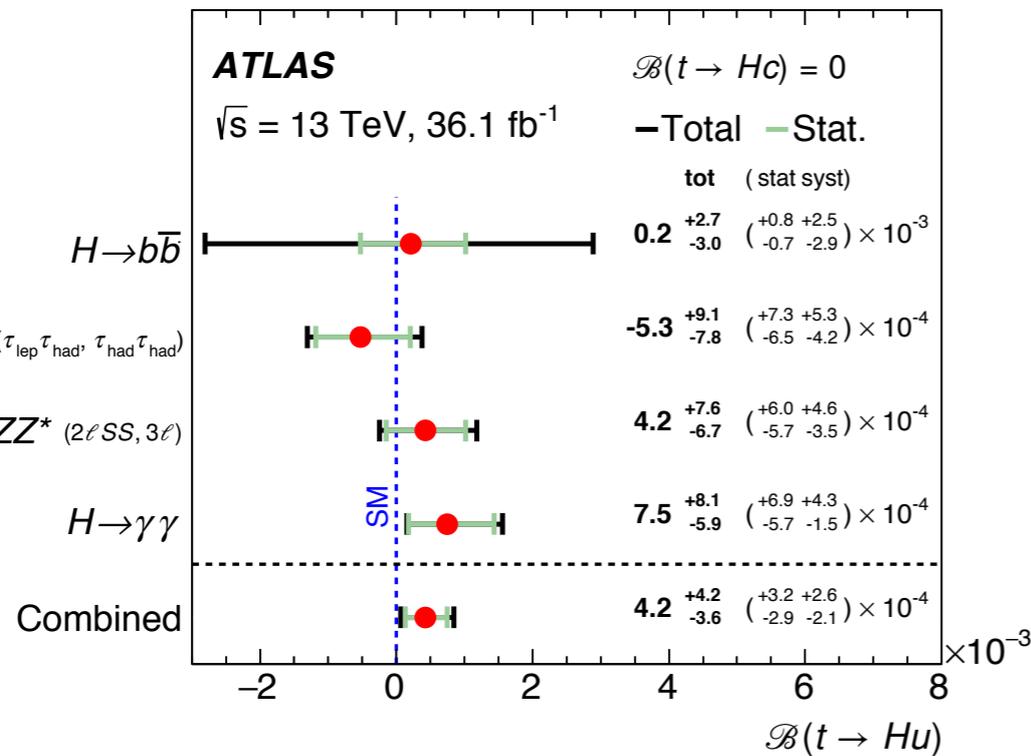


$t \rightarrow qH$ combination

Submitted to JHEP [Dec. 2018]

[arXiv:1812.11568]

- In $H \rightarrow \bar{b}b$, $H \rightarrow \tau^+\tau^-$ paper

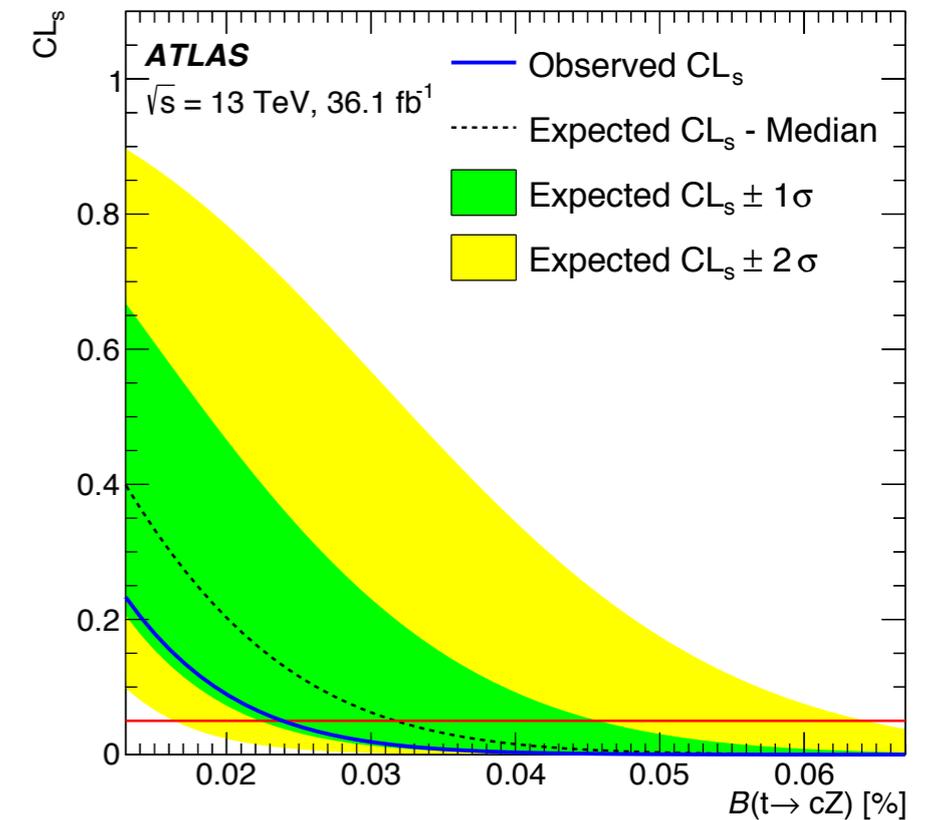
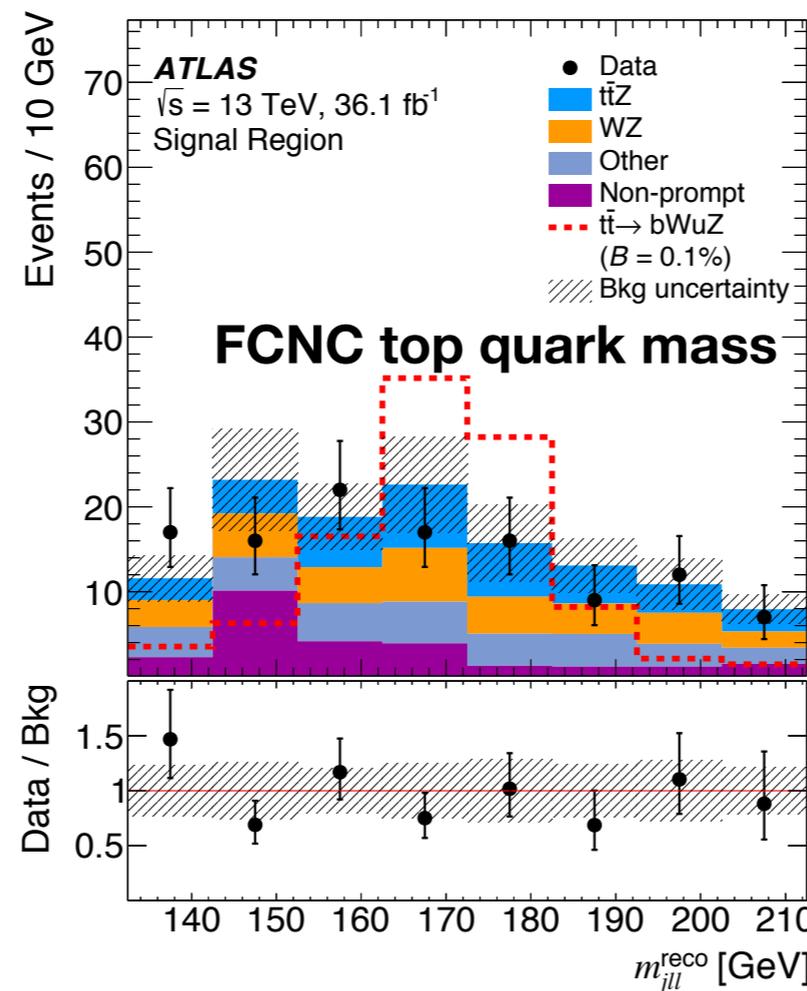
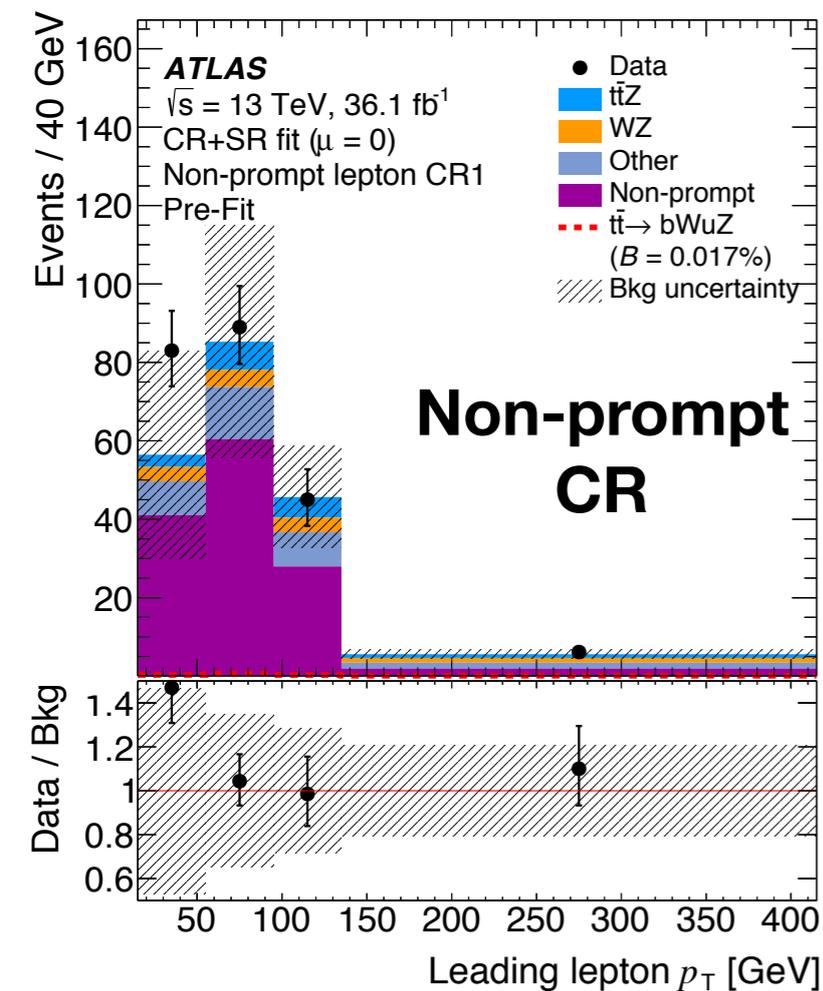


$$t \rightarrow qZ \rightarrow ql^+l^-$$

- Search only in leptonic channel
- Signal region:
 - 3 lepton, ≥ 2 jets, 1 b-jet

• Strategy:

- semi-data-driven non-prompt lepton estimation using control regions
- Kinematic fitting for neutrinos
- Simultaneous fit to the kinematic distributions in SR and CRs



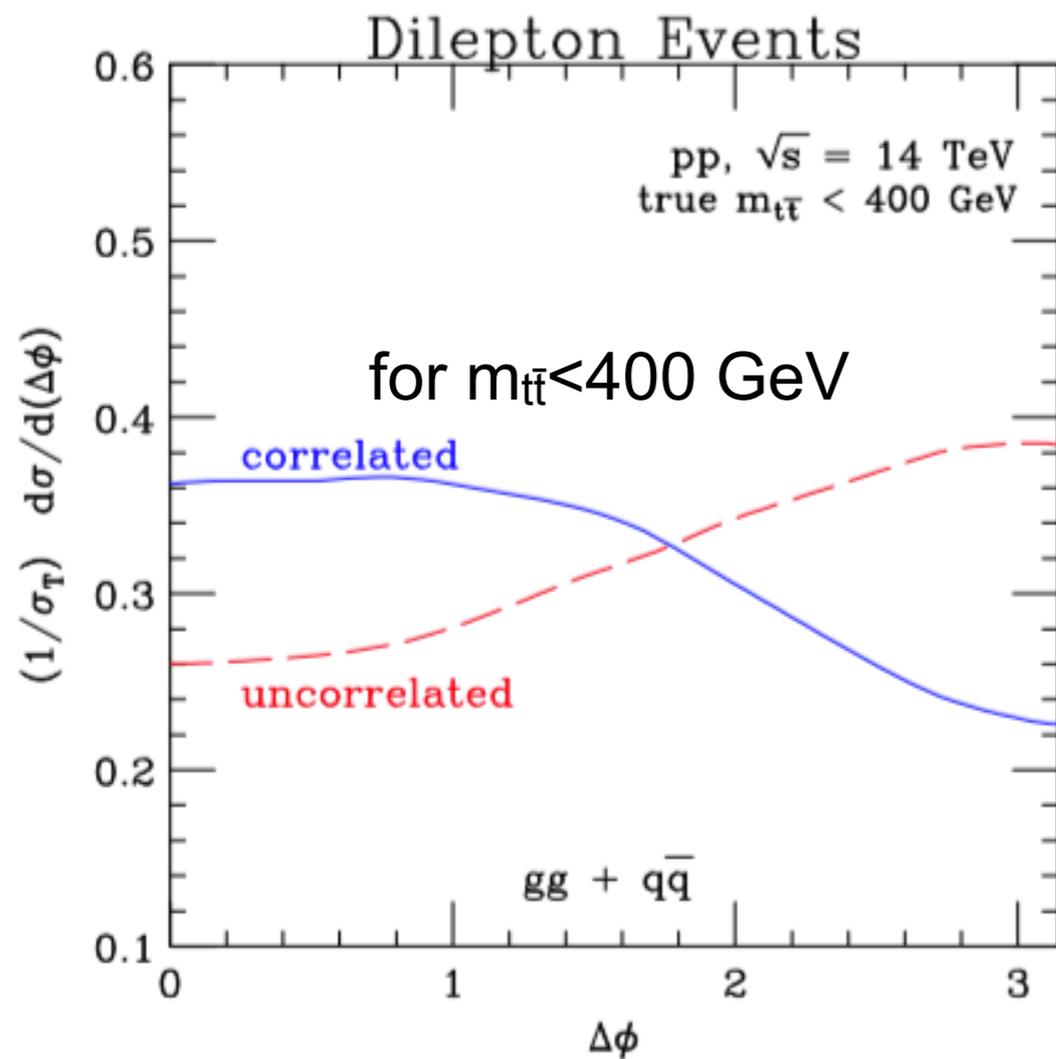
Observed(expected) 95% CL upper limit

BR in %	$t \rightarrow uH$		$t \rightarrow cH$		$t \rightarrow uZ$	$t \rightarrow cZ$
	leptonic	hadronic	leptonic	hadronic	leptonic, $Z \rightarrow l^+l^-$	
$H \rightarrow \gamma\gamma$	Combined result: 2.4 (1.7)		Combined result: 2.2 (1.6)			
$H \rightarrow VV(\text{ML})$	2ISS: 2.8 (2.1) 3l: 2.2 (2.1)	/	2ISS: 2.5 (2.0) 3l: 2.0 (2.5)	/		
$H \rightarrow \tau\tau$	/	1.7 (2.0)	/	1.9 (2.1)	0.17 (0.24)	0.24 (0.32)
$H \rightarrow bb$	5.2 (4.9)	/	4.2 (4.0)	/		
combined	1.2 (0.83)		1.1 (0.83)			

$\bar{t}t$ spin correlation

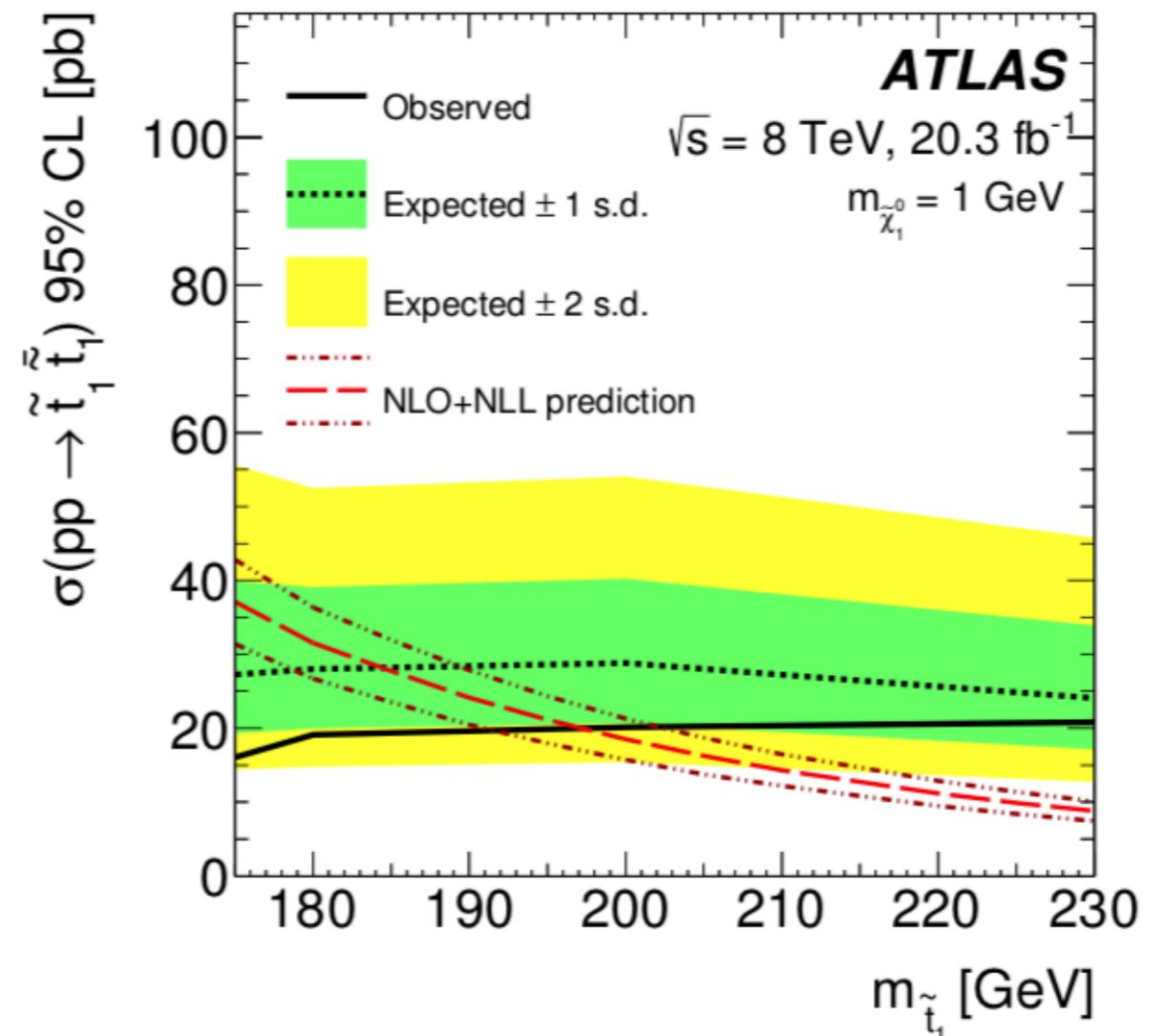
- $\bar{t}t$ spin correlation measurement can **only** be achieved in the **full leptonic channel** by observable $\Delta\phi$: absolute azimuthal opening angle between the two charged leptons

[arXiv:1202.2345]



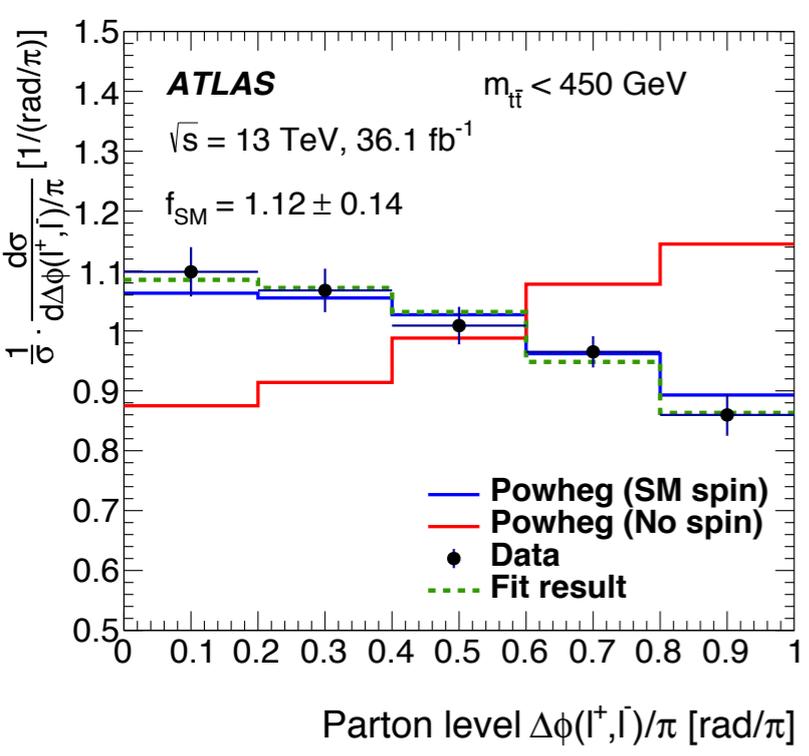
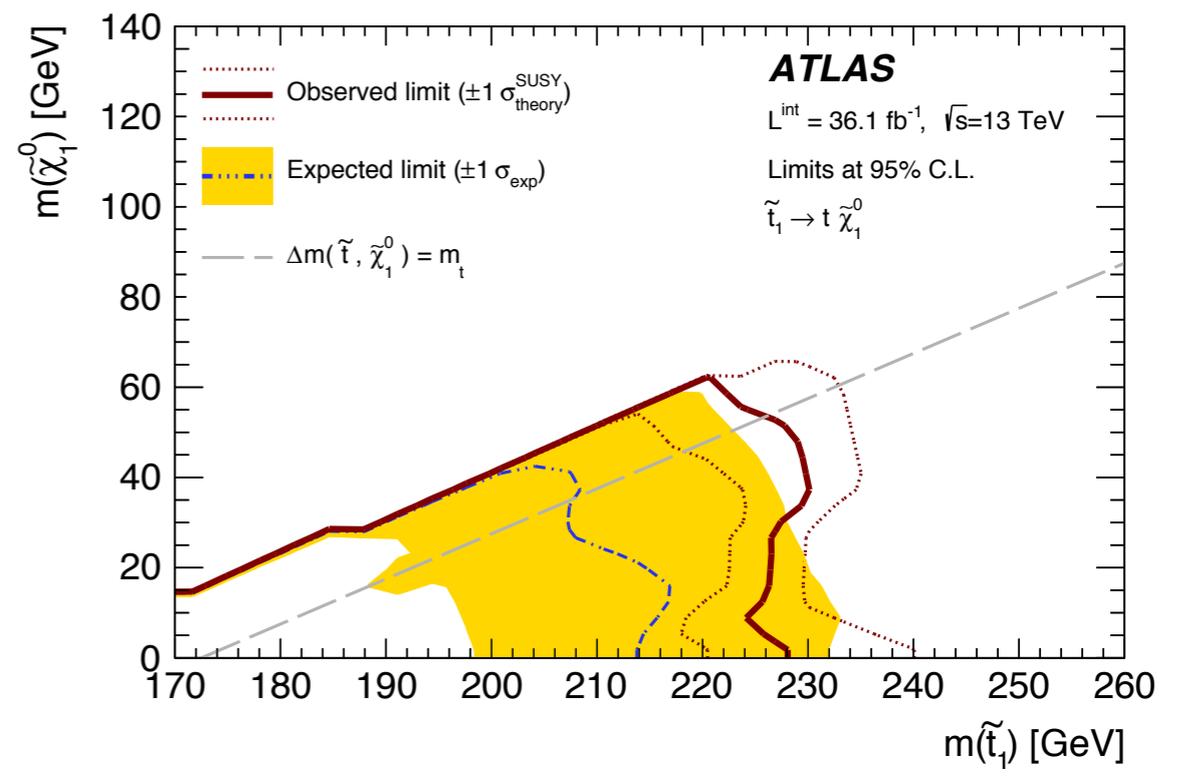
- Spin correlation measurements have also been used to search for BSM by searching for decreases in the expected SM spin correlation induced by $\bar{t}t$ decayed from SUSY particle stop

[Phys. Rev. Lett. 114 (2015) 142001]

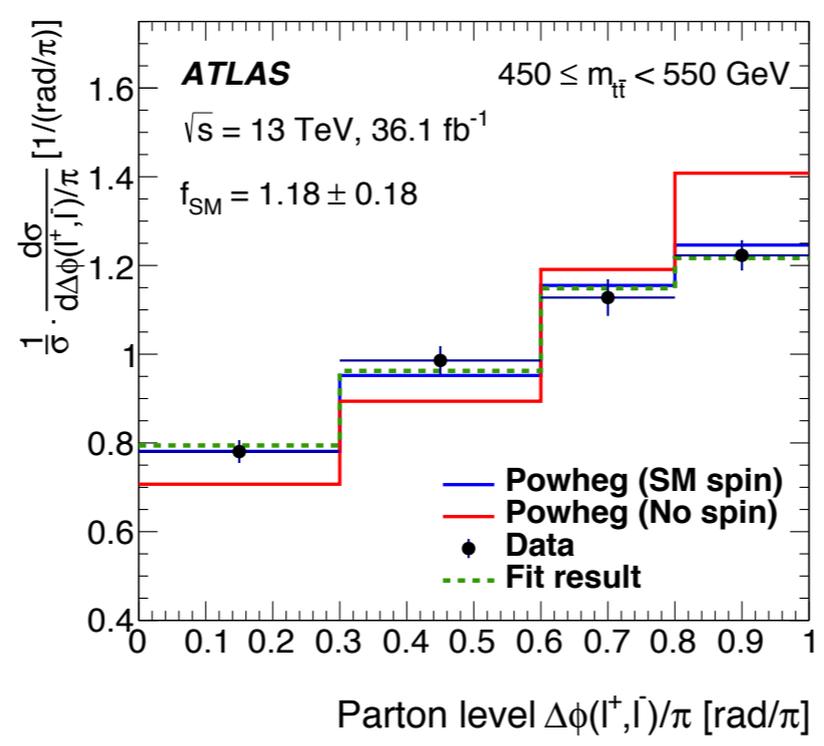


$\bar{t}t$ spin correlation

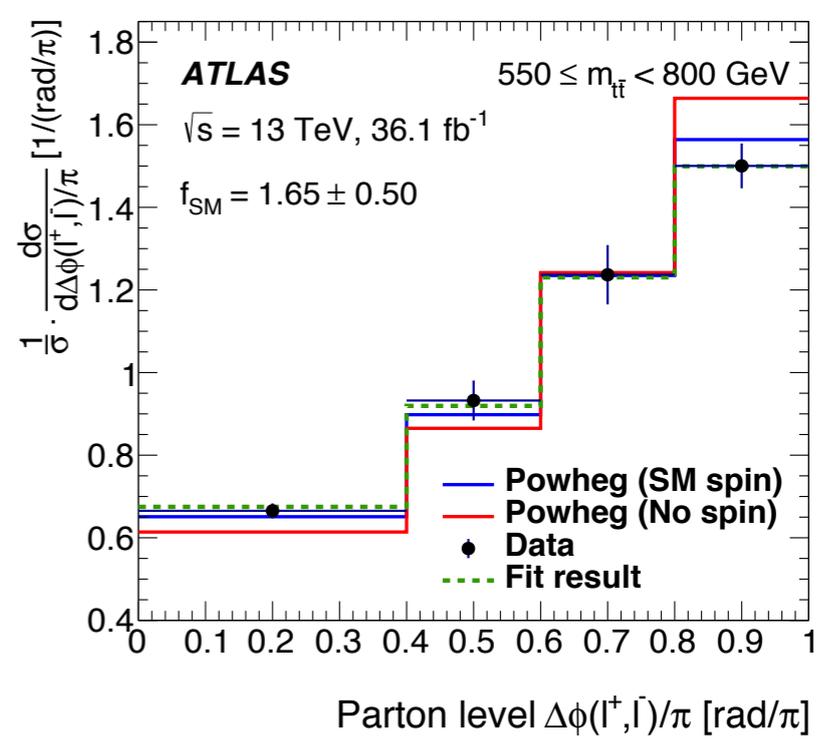
- Submitted to: EPJC [Mar. 2019]:
[\[arxiv:1903.07570\]](https://arxiv.org/abs/1903.07570)
- Signal region:
 ≥ 2 b-jet, 1 muon, 1 electron
- Strategy:
 - use neutrino weight method to reconstruct $\bar{t}t$ system
 - Unfolding data



$m_{\bar{t}t} < 450$ GeV



$450 \leq m_{\bar{t}t} < 550$ GeV

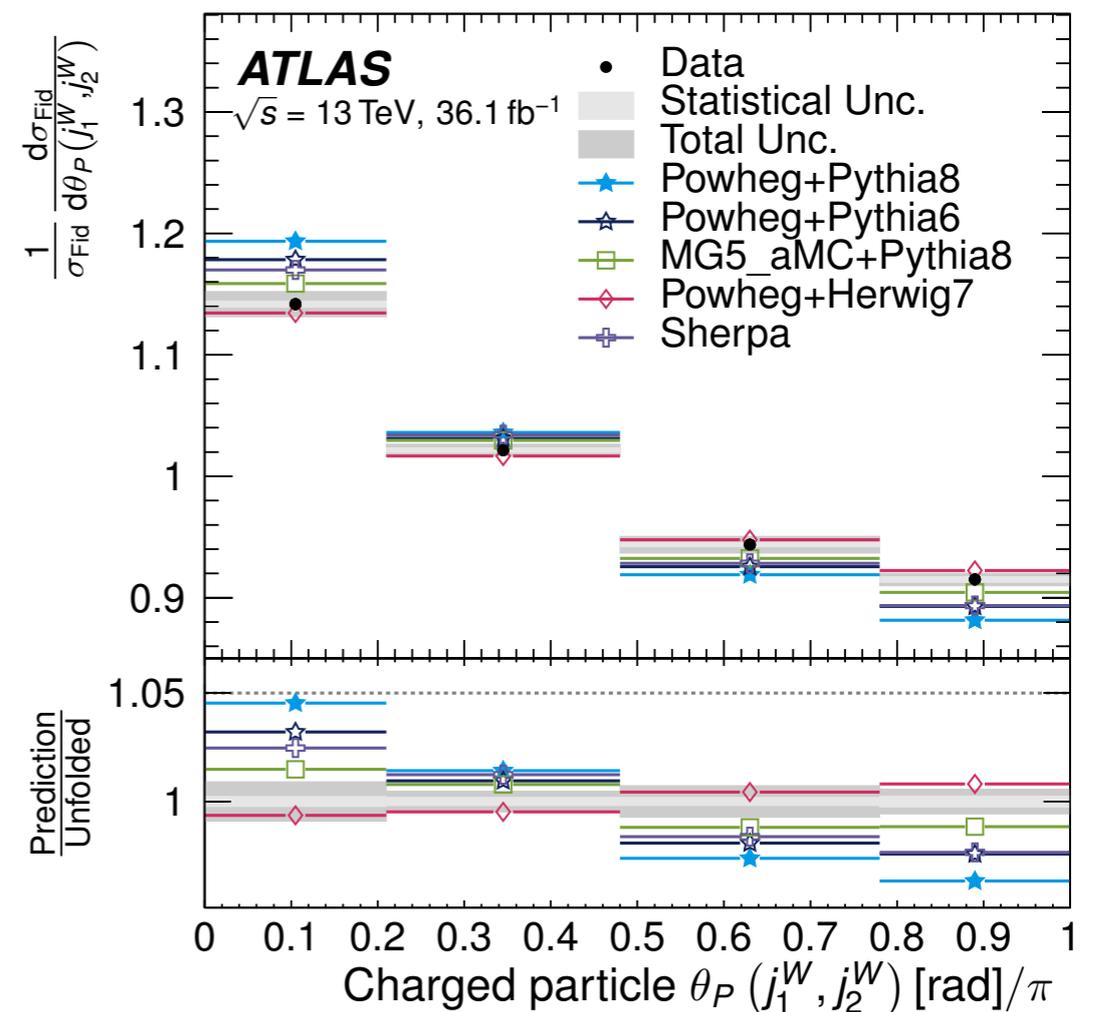
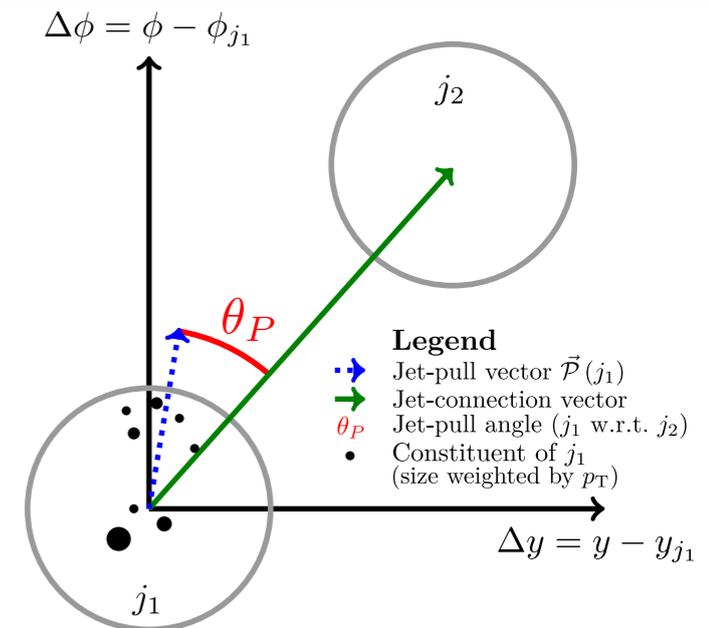
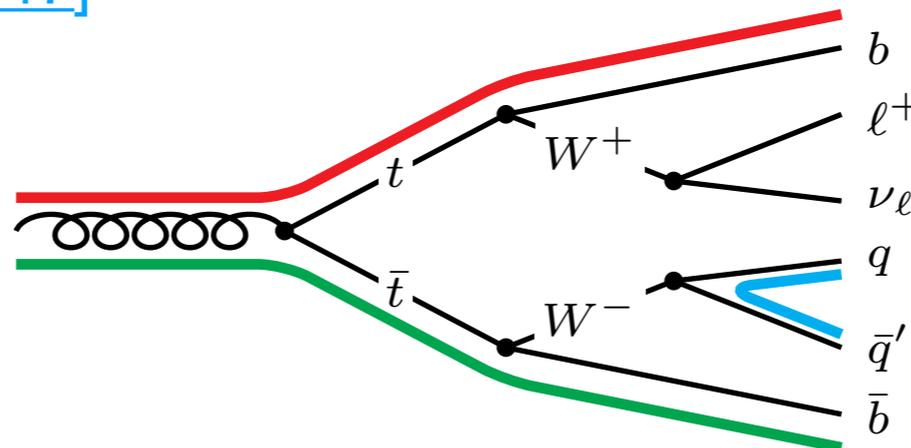


$550 \leq m_{\bar{t}t} < 800$ GeV

Measurement of colour flow

[[Eur. Phys. J. C \(2018\) 78: 847](#)]

- Signal region:
 - 1 lepton
 - 4 jets with 2 b-tagged
 - $E_T^{miss} > 20$ GeV
- Strategy:
 - Particle-level unfolding
 - matrix method for non-prompt/fake leptons
- Conclusion:
 - Powheg + Pythia 8 agrees poorly with the data.
 - Powheg+Herwig7 predictions exhibit much better agreement.

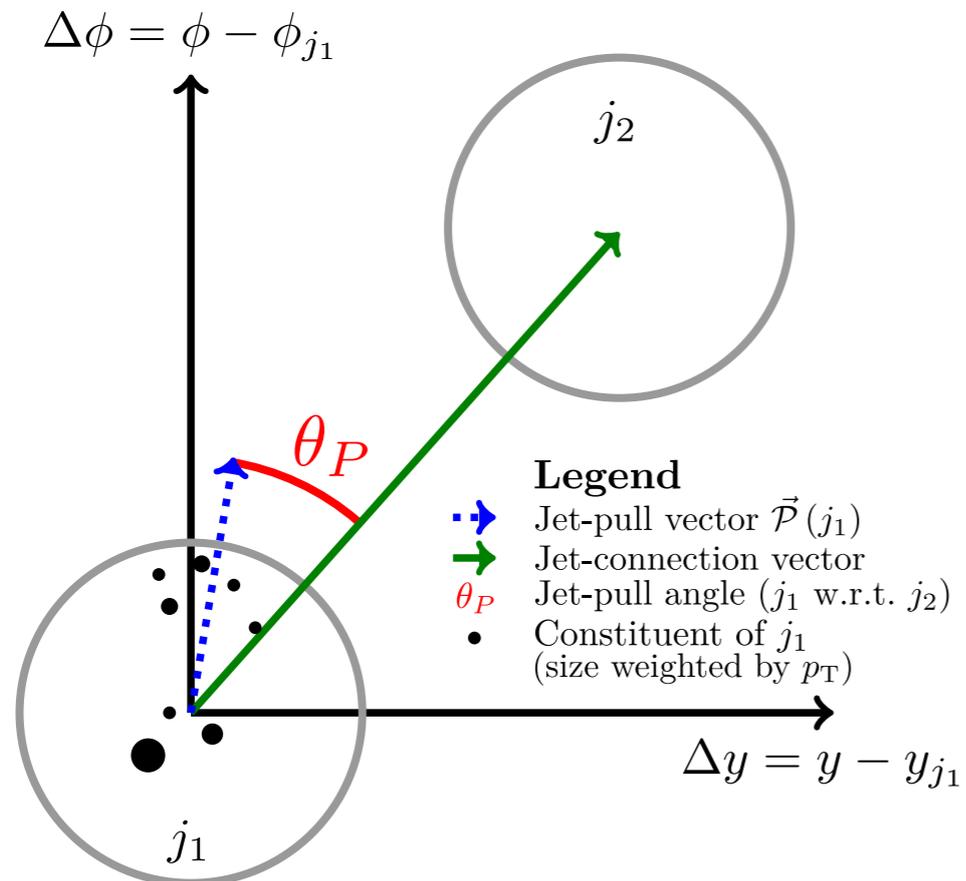
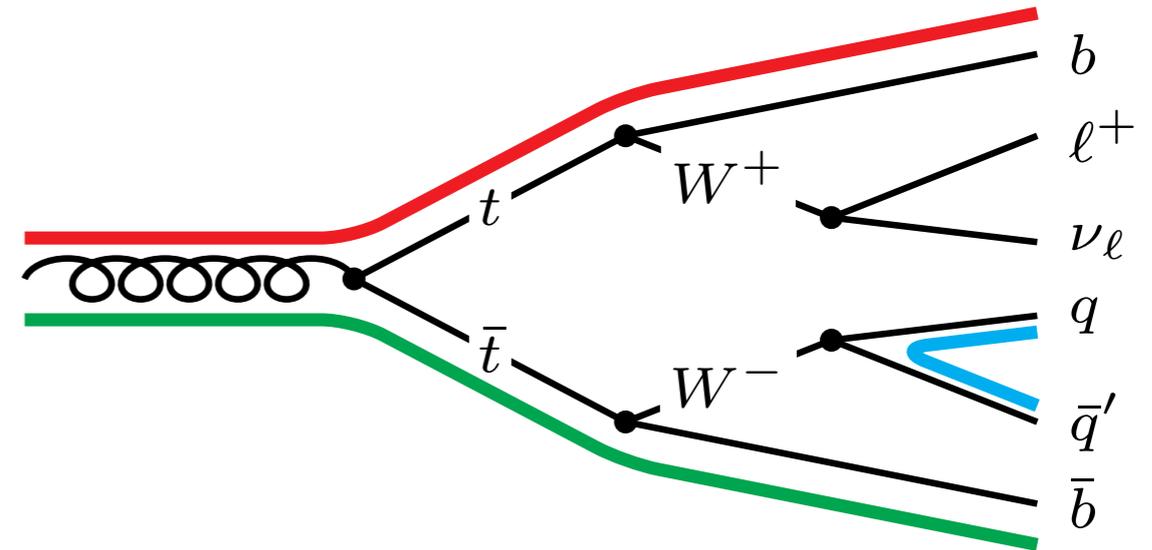


Summary

- Top quark FCNC decay:
 - No observation for top quark FCNC decays through H or Z. The most stringent upper limit up to date was set for t to qH decay branching ratio after combining all the channels in ATLAS.
 - The full run-2 analyses are coming and a much tighter limit is expected.
- The $\bar{t}t$ spin correlation was measured using the data up to 36fb⁻¹. The spin of the top quark pairs are correlated according to the measurement. No deviation from standard model was found. The upper limit for SUSY stop was set.
- The colour flow in the $\bar{t}t$ system was remeasured using 36fb⁻¹ data. The different theory predictions were compared to the unfolded data. The current default generator models the data badly however alternative one performs much better.

Backup

- Two quarks from W decay are colour connected because W boson is colour singlet.
- Two b-jets are not colour connected because gluon carries 2 colours.



- Jet Pull observable:

[Phys. Rev. Lett. 105 \(2010\) 022001](https://arxiv.org/abs/1001.1803)

$$\vec{P}(j) = \sum_{i \in j} \frac{|\vec{\Delta r}_i| \cdot p_T^i}{p_T^j} \vec{\Delta r}_i$$

- θ_p is expected to be small if j_1 and j_2 are colour connected

Backup

tqH bb systematics

Pre-fit impact on μ :

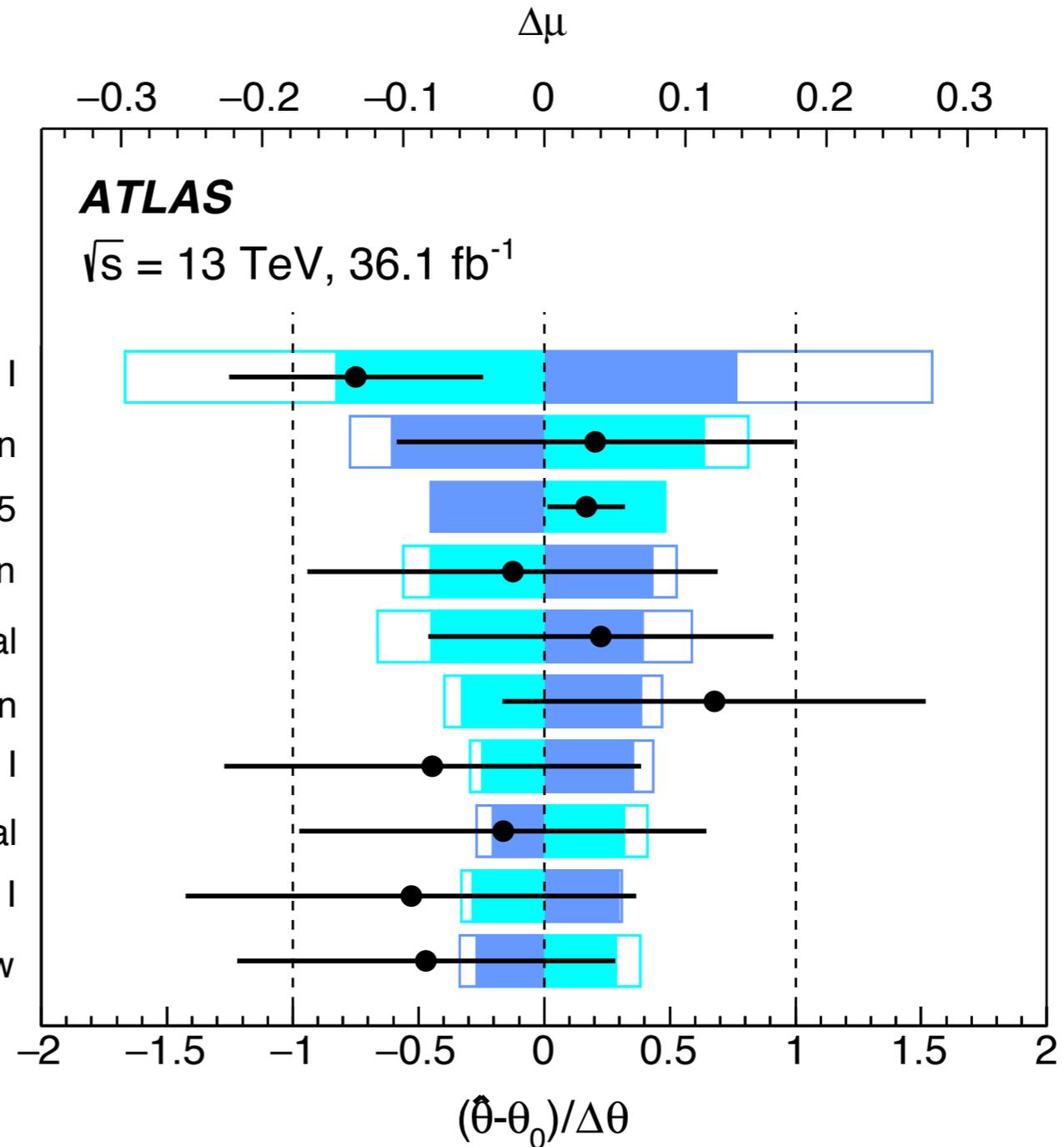
\square $\theta = \hat{\theta} + \Delta\theta$ \square $\theta = \hat{\theta} - \Delta\theta$

Post-fit impact on μ :

\blacksquare $\theta = \hat{\theta} + \Delta\hat{\theta}$ \blacksquare $\theta = \hat{\theta} - \Delta\hat{\theta}$

—●— Nuis. Param. Pull

- b-tagging: mis-tag (c) NP I
- $t\bar{t}$ +light-jets: PS & hadronisation
- $k(t\bar{t} \geq 1b) = 1.17 \pm 0.15$
- Jet energy scale: flavour composition
- $t\bar{t} \geq 1b$: SHERPA4F vs. nominal
- $t\bar{t} \geq 1c$: normalisation
- b-tagging: mis-tag (light) NP I
- $t\bar{t}$ +light-jets: SHERPA5F vs. nominal
- Jet energy scale: pileup NP I
- $t\bar{t} \geq 1b$: radHi / radLow



Backup

- neutrino weight method

The other weighting scheme, called **neutrino weighting** (ν WT) [6], steps the assumed η for each neutrino through a range of values at each m_t . Each step spans an equal fraction of the neutrino η distribution expected in $t\bar{t}$ production. At each step a weight is assigned based on the extent to which the \vec{E}_T measured in the event agrees with the sum of the neutrino \vec{p}_T 's in the solution. The Gaussian resolution of each component of the \vec{E}_T is 4 GeV. The weights at all η values are summed to give $W_o(m_t)$ in this method.

Backup

- Kinematic fitting for tautau

$$\chi^2 = -2 \ln \mathcal{P}_1 - 2 \ln \mathcal{P}_2 + \left(\frac{m_{\tau_1}^{\text{fit}} - 1.78}{\sigma_\tau} \right)^2 + \left(\frac{m_{\tau_2}^{\text{fit}} - 1.78}{\sigma_\tau} \right)^2 + \left(\frac{m_H^{\text{fit}} - 125}{\sigma_{\text{Higgs}}} \right)^2 + \left(\frac{E_{x,\text{miss}}^{\text{fit}} - E_{x,\text{miss}}}{\sigma_{\text{miss}}} \right)^2 + \left(\frac{E_{y,\text{miss}}^{\text{fit}} - E_{y,\text{miss}}}{\sigma_{\text{miss}}} \right)^2,$$

where $\mathcal{P}_i(\Delta R)$ are the probability distributions of the angular distance of the visible and invisible decay products in the tau decay, parametrized as a function of the momentum of the tau lepton. In the τ_{lep} mode where two neutrinos are present, it is extended to be the joint probability distribution of ΔR and m_{mis} with m_{mis} being the invariant mass of the neutrinos, denoted by $\mathcal{P}(\Delta R, m_{\text{mis}})$. These probability density functions are obtained from the MC simulation. Figure 3 illustrates the distributions of $\mathcal{P}(\Delta R, m_{\text{mis}})$ for τ_{lep} , and $\mathcal{P}(\Delta R)$ for τ_{had} , with the original tau's momentum in the range $60 \text{ GeV} < p < 80 \text{ GeV}$. Figures