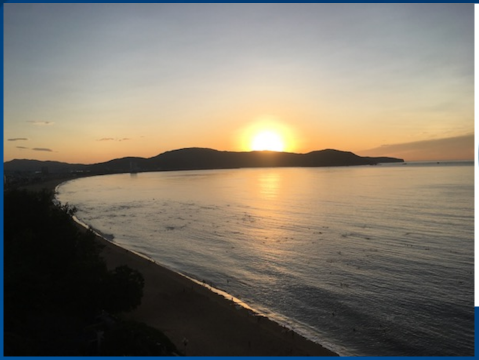


Top quark properties and rare processes from ATLAS, CMS, LHCb

Tae Jeong Kim (Hanyang University)
on behalf of the ATLAS, CMS, LHCb collaborations

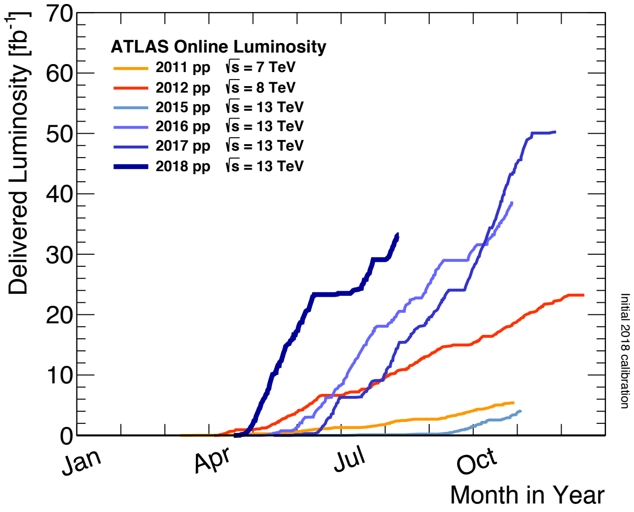
For ICISE2018: 25th Recontres du Vietnam
Windows on the Universe
10 Aug 2018 at Quy Nhon, Vietnam

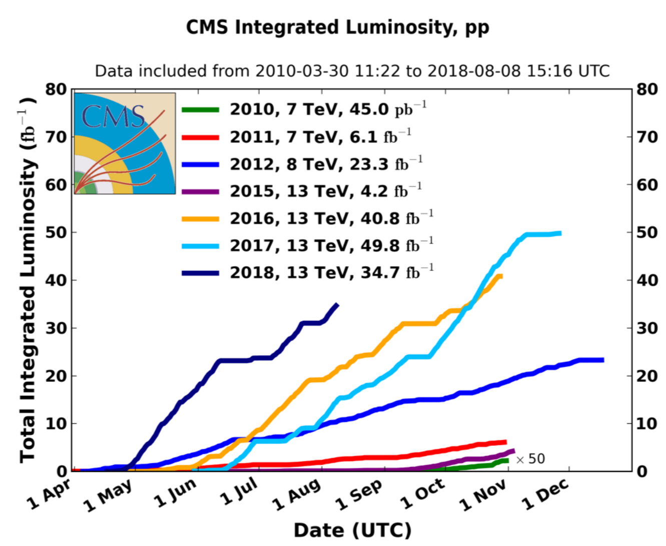
Outline

- Introduction
- Top quarks everywhere
  - Top quark cross section and mass
- Spin correlation
- FCNC
  - tu(c)H
  - tu(c)Z
- Conclusion

Introduction

- Top quark is the heaviest particle in the SM with $y_t \sim 1$
- It is believed to be the window on new physics
- We are collecting more data than ever
  - More than 100 fb^{-1} in total at 13 TeV since 2015
- No hints from bump hunting or other model dependent new physics searches
- To find hints of new physics, precision measurements and rare processes becomes more and more important
  - Reduce theoretical uncertainties for experimentally non-accessible area



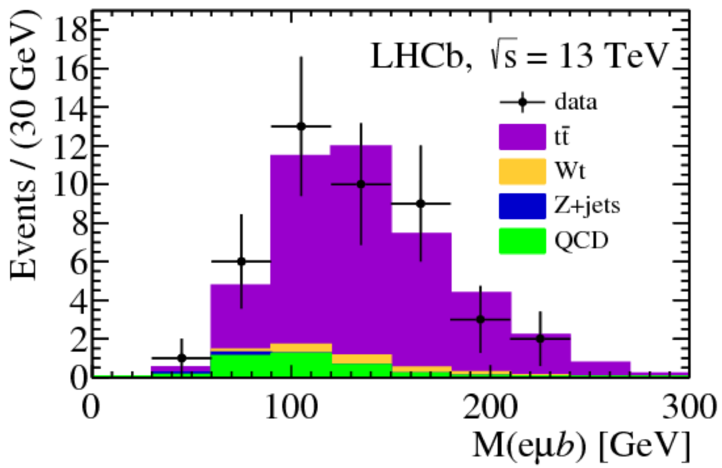


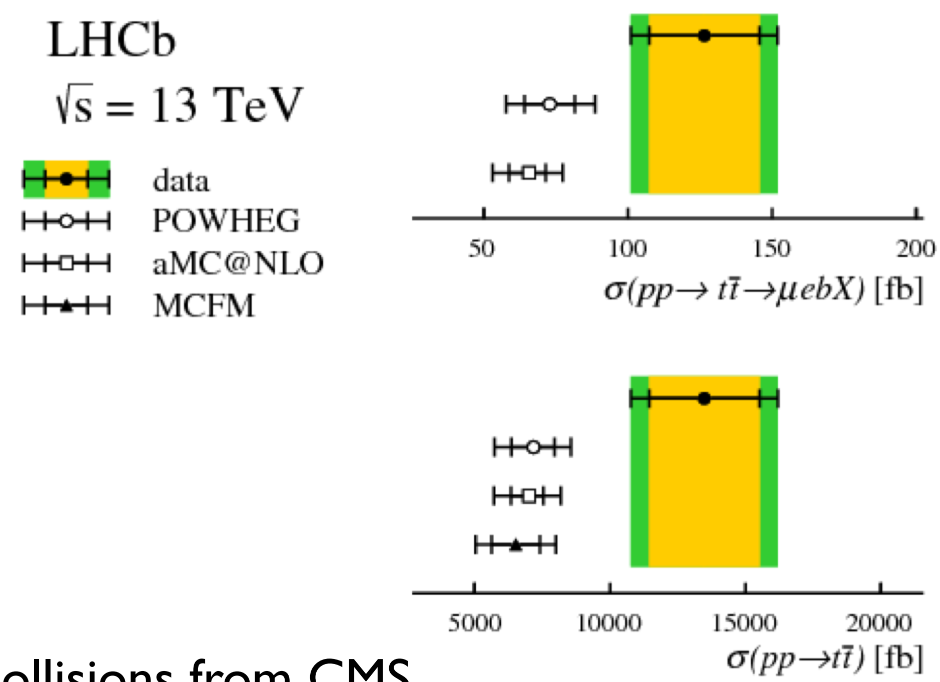
arXiv:1803.05188

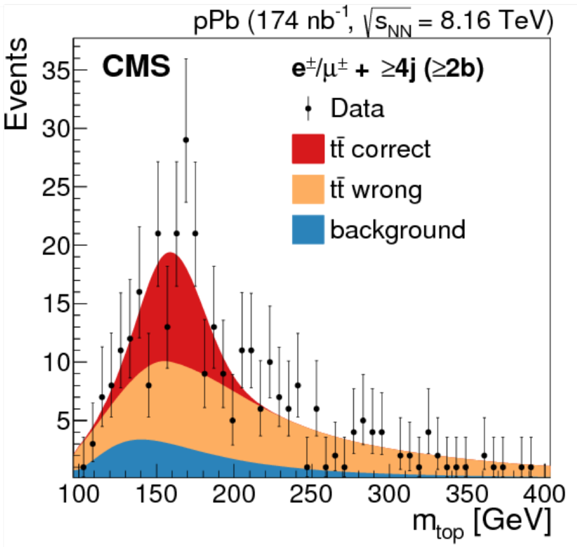
Top quarks everywhere

- Forward regions from pp collisions from LHCb
- 2 < |η| < 4.5

σ_{tt} = 126 ±19(stat) ±16(sys)± 5(lumi) fb





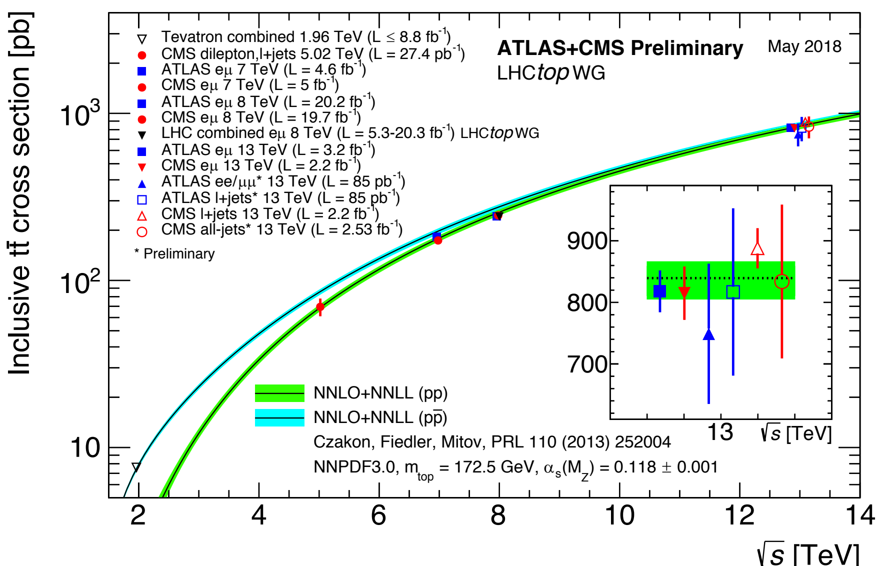


- pPb collisions from CMS
- σ_{tt} = 45±8 nb consistent with predictions
- Precise probe of the nuclear gluon density

PRL 119 (2017) 242001

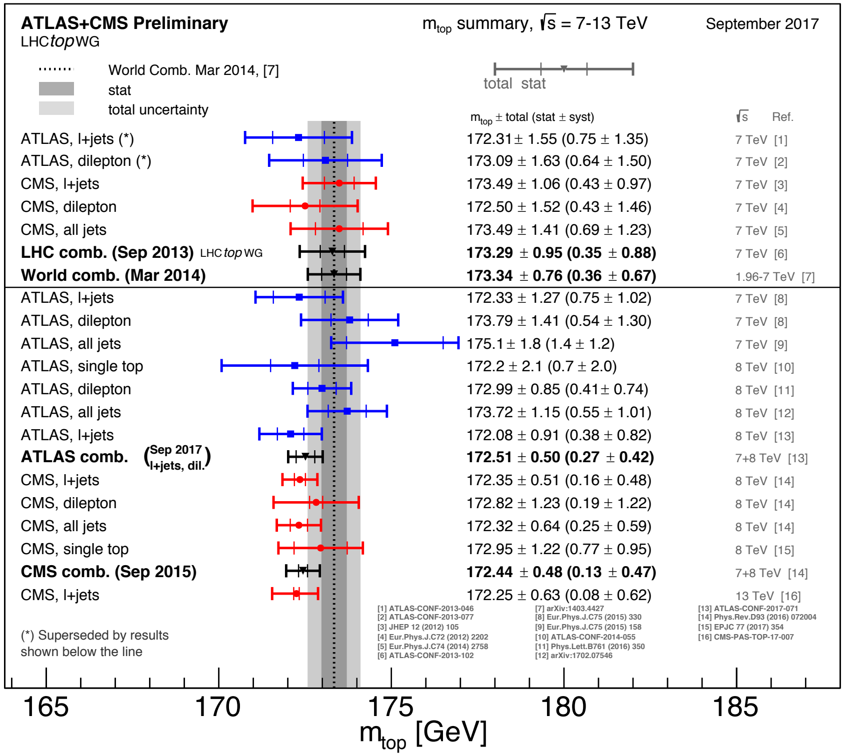
Top quark cross section and mass

- Top quark cross section not only for constraining theoretical uncertainty but also for extracting SM parameters



- 4% uncertainty from modeling and luminosity
- See the talk from Aran Garcia-Bellido on Tuesday

- Top quark mass is a key parameter in SM



- 0.3% mainly from JEC (flavor)
- 13 TeV results in all jet channel (CMS-PAS-TOP-17-008) : 172.34 ± 0.20 (stat+JSF) ± 0.76 (syst) GeV

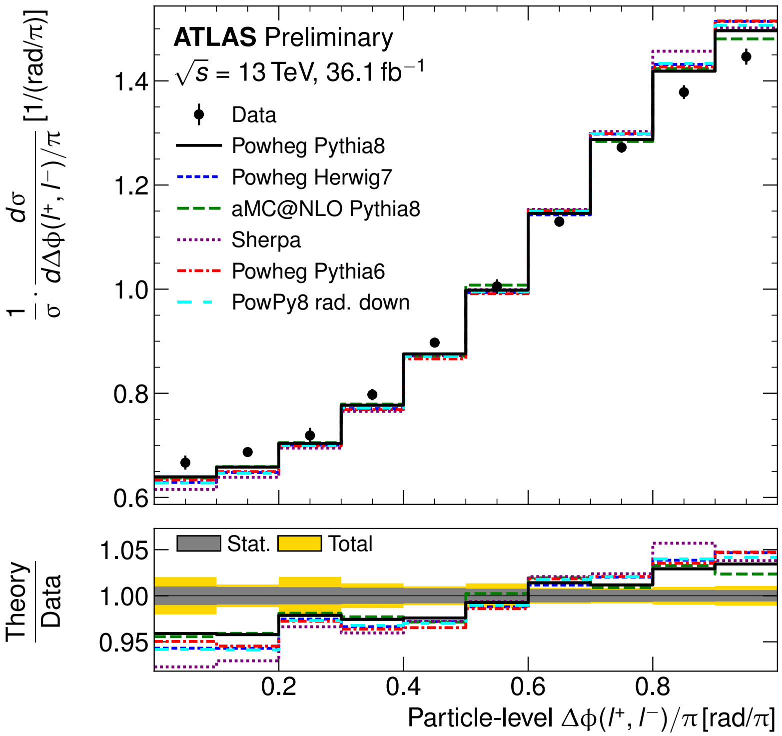
Spin correlations

- Top quark decays before hadronization
  - Preserve the spin information
- Top quarks are produced un-polarized at the LHC
- However, new physics (NP) can introduce polarization
  - NP causing forward-backward asymmetry
- Correlation between top and anti-top spin can be extracted
- Leptons from W in top decay carries almost the full spin information
- The simplest variable is $\Delta\phi$ between two leptons in dilepton ($e\mu$)

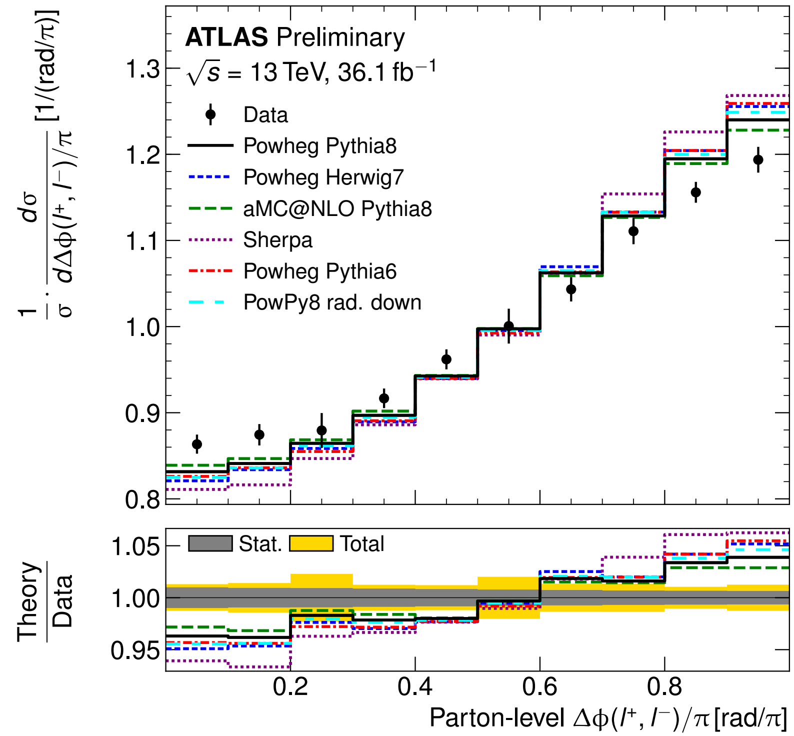
ATLAS-CONF-2018-027

Spin correlations (ATLAS)

Particle level
(all stable particles)



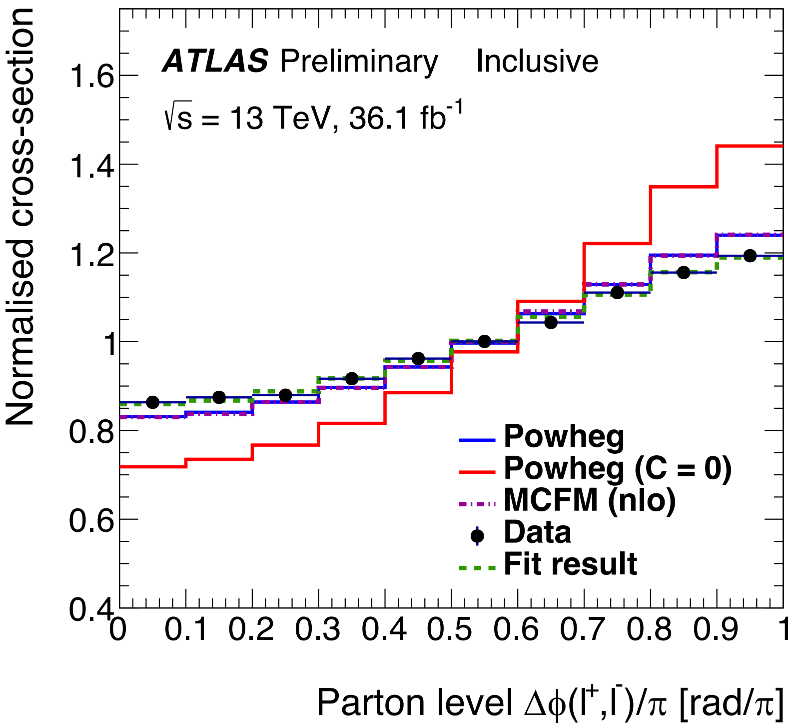
Parton level
(after radiation but before decay)



- Signal modeling is dominant uncertainty
- Jet energy and pileup uncertainties are also significant

Spin correlations (ATLAS)

ATLAS-CONF-2018-027



$$n_i = f_{\mathrm{SM}} \cdot n_{\mathrm{spin}} + (1 - f_{\mathrm{SM}}) \cdot n_{\mathrm{nospin}}$$

- f_{SM} as a function of m_{ttbar} is found to increases
- Uncertainty becomes larger than inclusive one
- Spin correlation (f_{SM} value) is larger than the SM prediction by 3.7 σ
  - Including theoretical uncertainty - by 3.2 σ
- The largest systematic uncertainty is from ttbar modeling

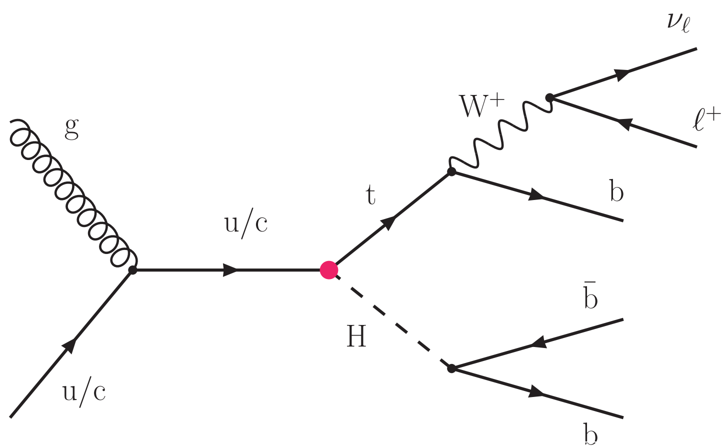
Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

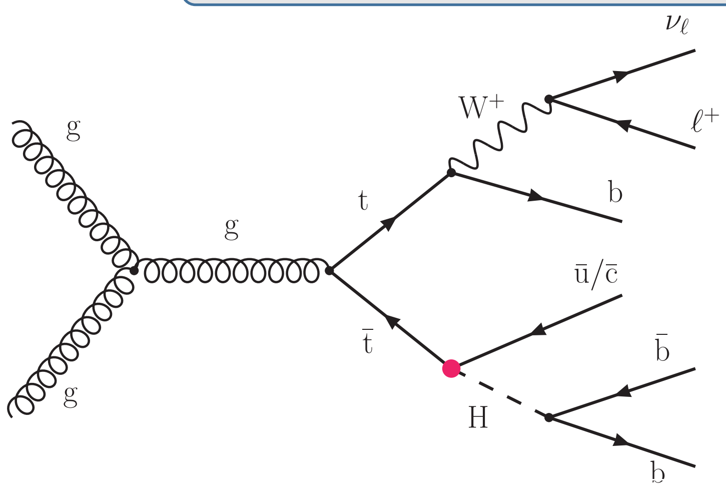
FCNC

- Top quark decays before hadronization.
  - almost 100% decays to b-quark and W boson in the SM.
- Decay to lighter down-type quarks (d or s) are allowed but suppressed due to CKM matrix.
- Flavor changing neutral currents (FCNC)
  - Transitions that change the flavor of a fermion without changing its charge.
  - FCNC is suppressed by GIM mechanism (can occur only at quantum loop corrections) → In the SM, the Br is $< 10^{-12}$
- FCNCs are enhanced in many beyond the SM.
- Any small deviation would indicate new physics.
- Top rare decay should be sensitive to new physics already.
- Model independent searches using effective Lagrangian were pursued.

$t \to qH$, $H \to b\bar{b}$ at 13 TeV (CMS)

JHEP 06(2018) 102 (arxiv: 1712.02399)

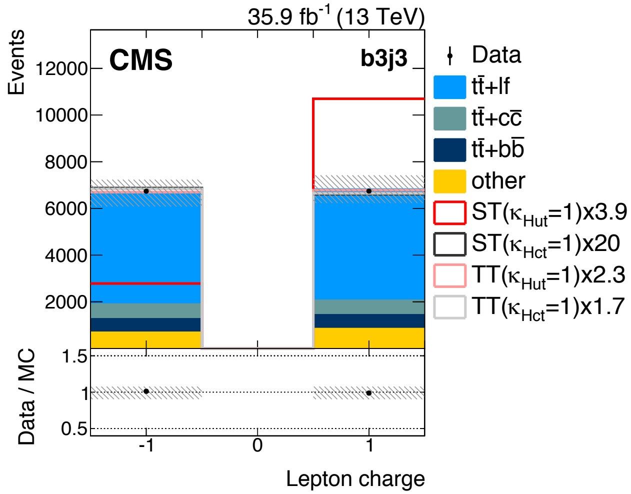


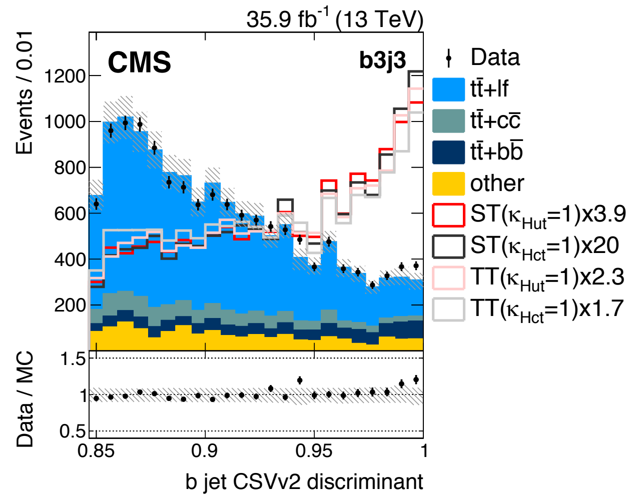


- First time to present the result of the analysis of the single top mode
- Two steps of BDT (Boosted Decision Tree) approaches
  - Assigning b jets to either top or Higgs: 75% correct assignment
  - Then, classification between signal and background
- Single lepton events + requiring 2/3/(4) b jets for Hut(Hct) coupling
- Categorize the events based on number of jets and b jets

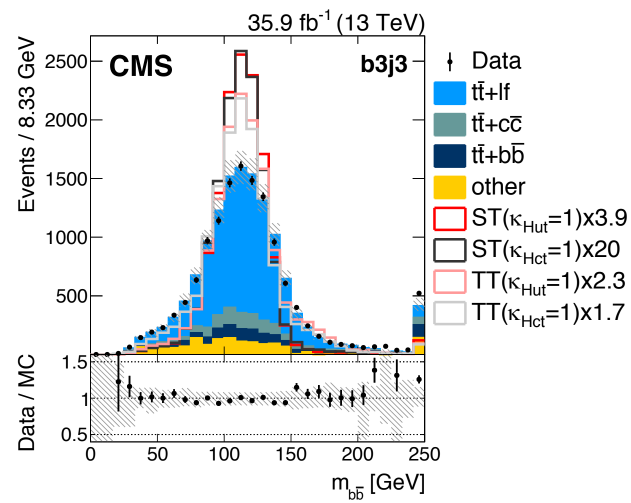
$t \to qH, H \to b\bar{b}$ at 13 TeV (CMS)

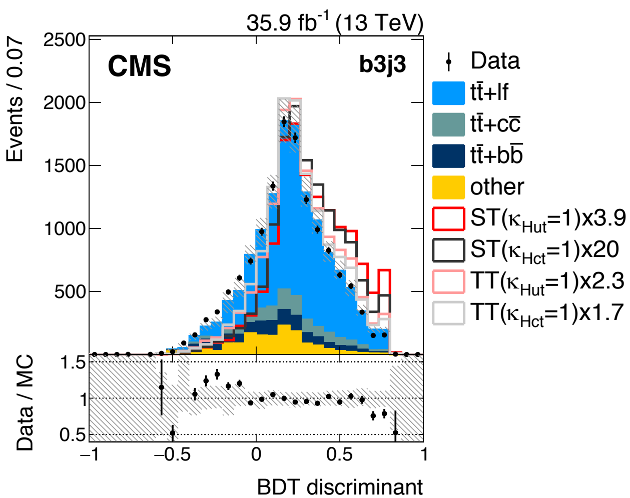
- Input variables for classification (3 jets and 3 b jets case)





The lowest p_T b jet from Higgs

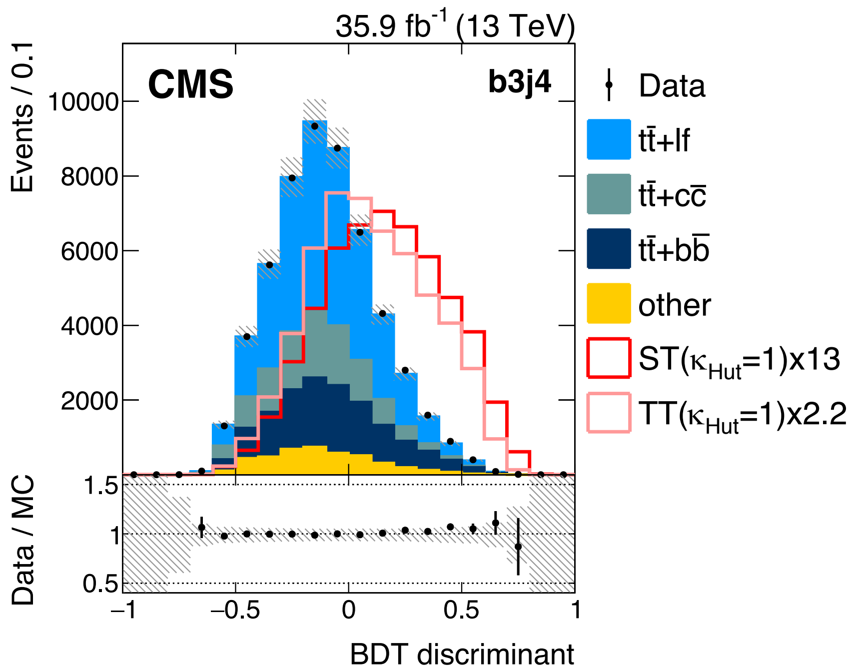




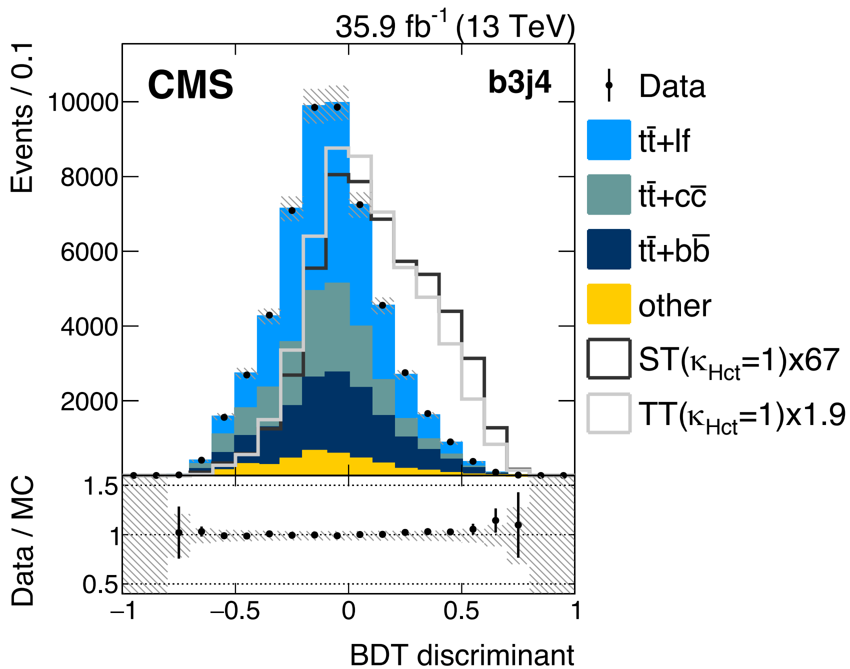
From the b jet assignment

$t \to qH, H \to b\bar{b}$ at 13 TeV (CMS)

- BDT output (3 b jets and 4 jets case)



Hut

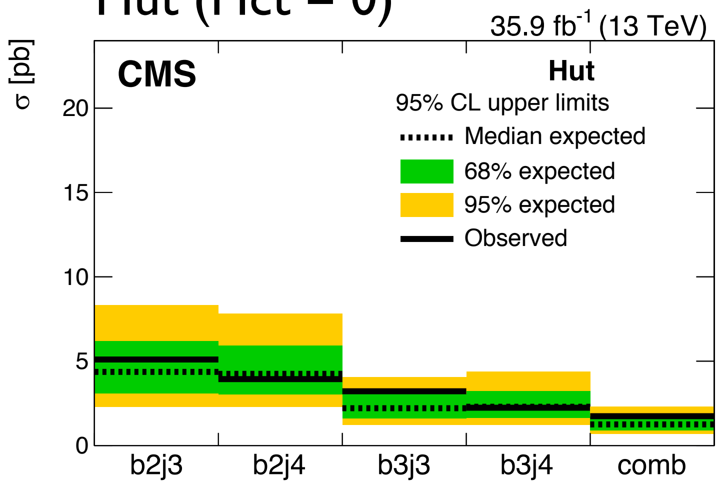


Hct

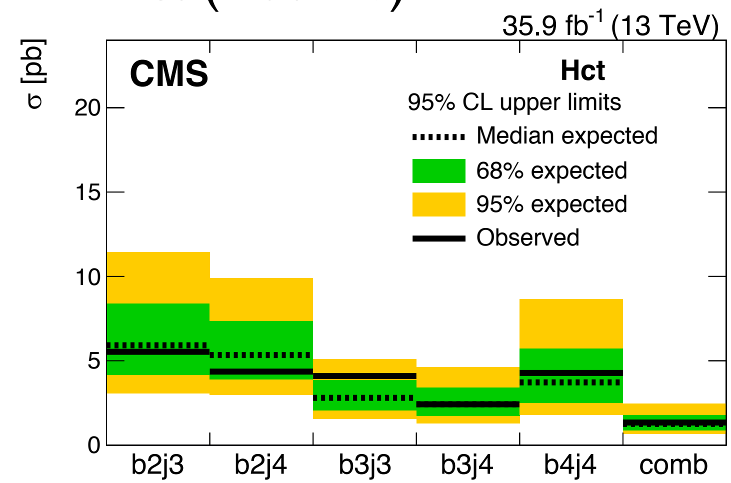
t→qH, H→b$\bar{b}$ at 13 TeV (CMS)

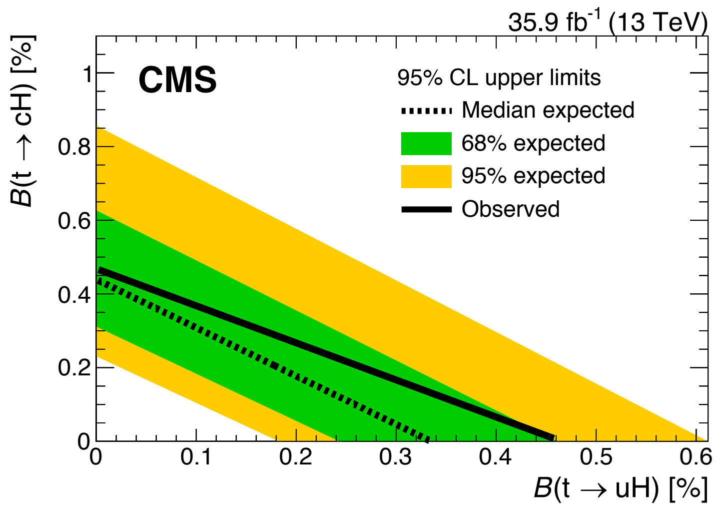
JHEP 06(2018) 102 ([arxiv: 1712.02399](https://arxiv.org/abs/1712.02399))

Hut (Hct = 0)



Hct (Hut = 0)



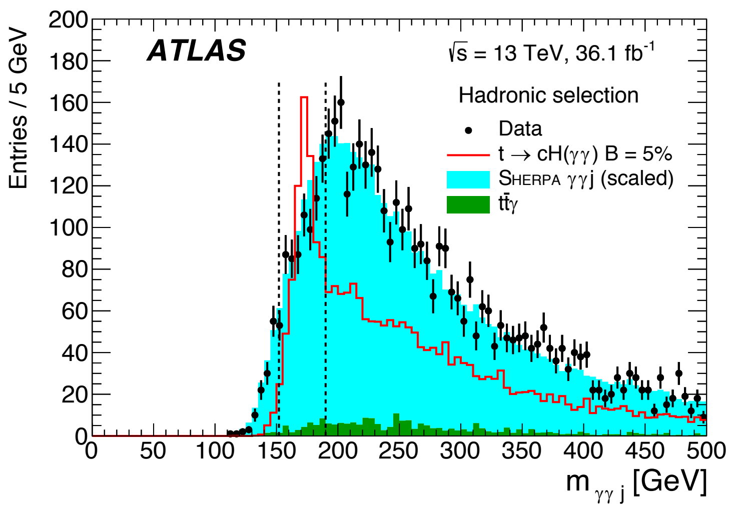


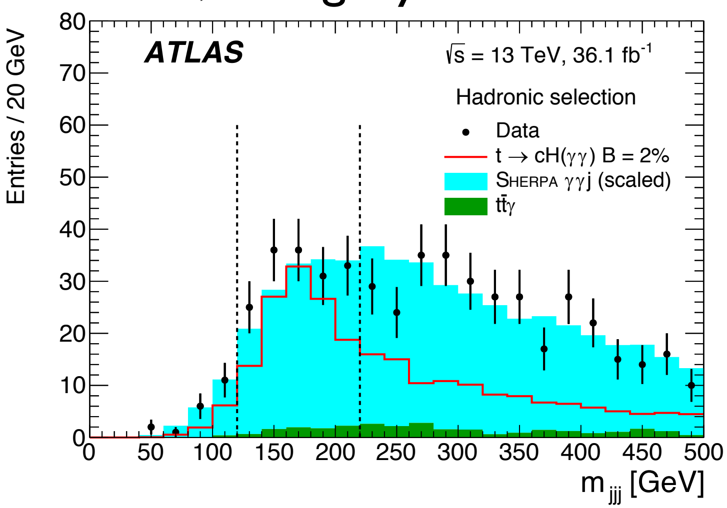
- Upper limit : observed (expected)
  - Br(t→Hu) < 0.47 (0.34)%
  - Br(t→Hc) < 0.47 (0.44)%

t→qH, H→$\gamma\gamma$ at 13 TeV (ATLAS)

JHEP 10(2017) 129 (arxiv: 1707.01404)

- At least two isolated photon
  - $p_T^{1st} > 40$ GeV and $p_T^{2nd} > 30$ GeV
- At least 4 jets ($p_T > 30$ GeV) and select 4 leading ones
- At least one b-tagged jet
- Hadronic channel
  - Top1 (FCNC) : $152 < M_1(\gamma\gamma j) < 190$ GeV
  - Top2 (Wb) : $120 < M_2(jjj) < 220$ GeV
  - Category 1 : Pass M1 and M2 requirements, Category 2 : Pass M1 but M2

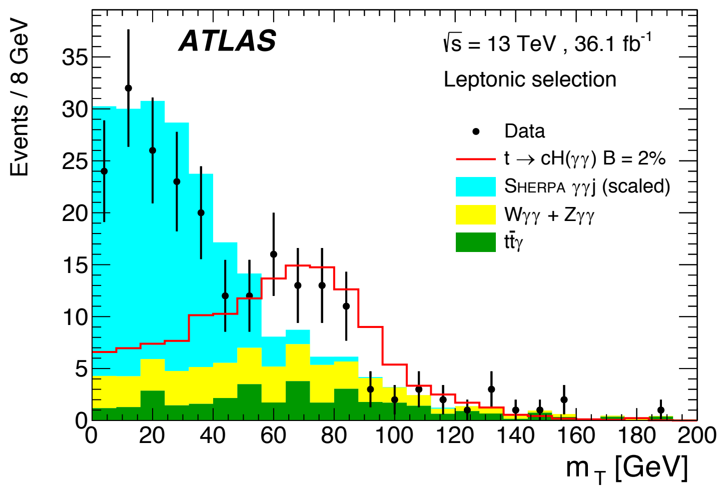


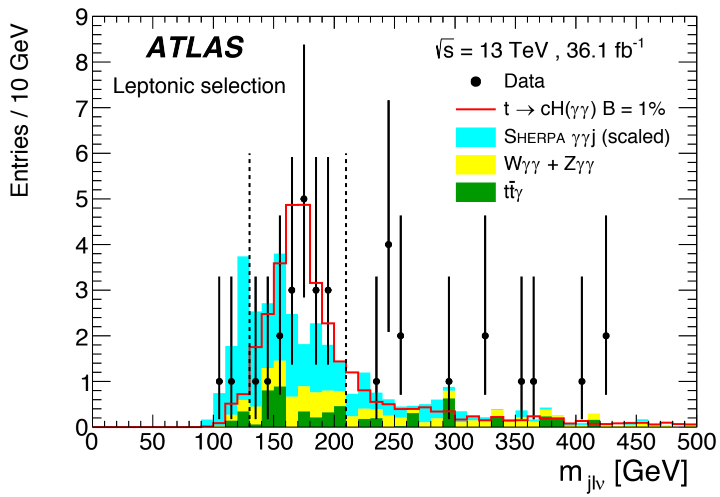


t→qH, H→$\gamma\gamma$ at 13 TeV (ATLAS)

Leptonic channel

- Exclusively one lepton required (p_T > 15 GeV/10 GeV for e/μ)
- At least 2 jets (p_T > 30 GeV) and select 2 leading jets
- m_T^W> 30 GeV to reject background mainly from $\gamma\gamma j$ events
- Top mass window
  - Top1 (FCNC) : 152 < $M_1(\gamma\gamma j)$ < 190 GeV,
  - Top2 (Wb) : 130 < $M_2(ljv)$ < 210 GeV



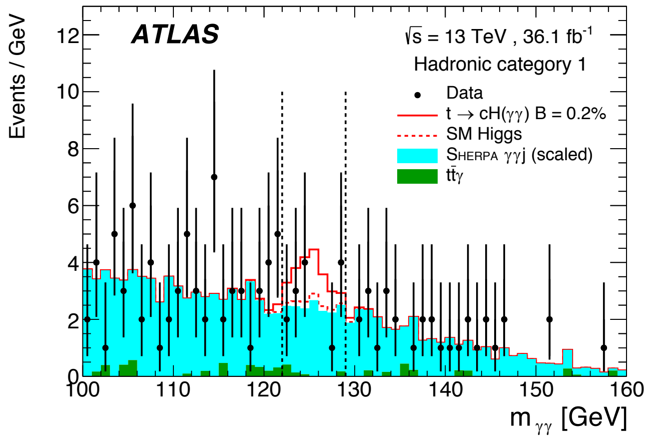


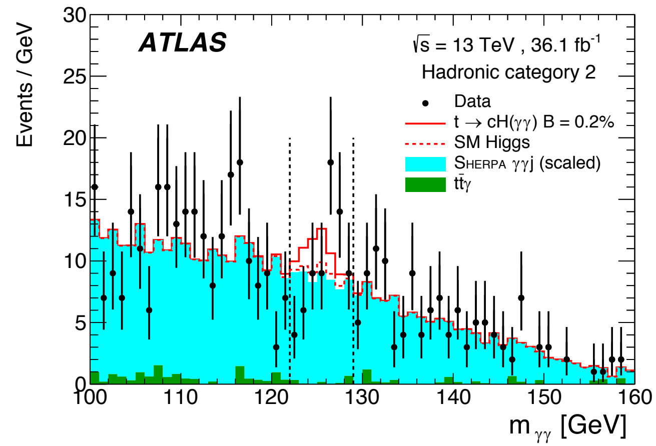
t→qH, H→$\gamma\gamma$ at 13 TeV (ATLAS)

M($\gamma\gamma$) for Category 1

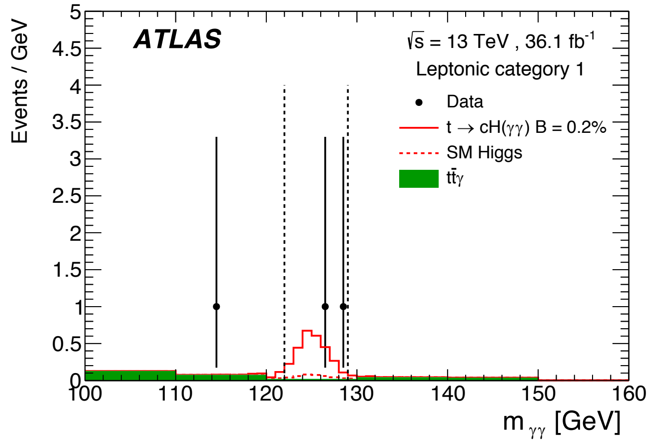
M($\gamma\gamma$) for Category 2

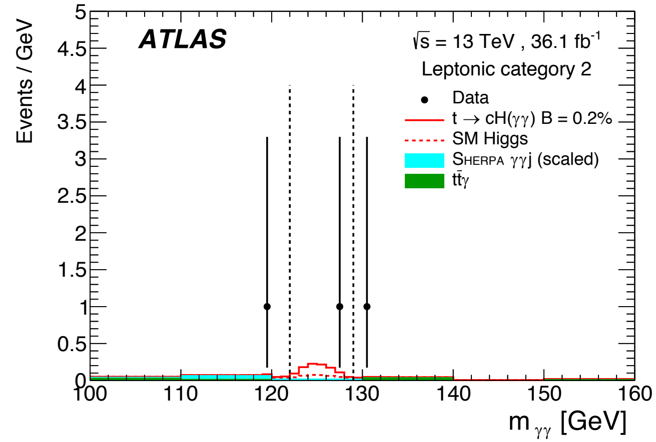
Hadronic (unbinned likelihood fitting)





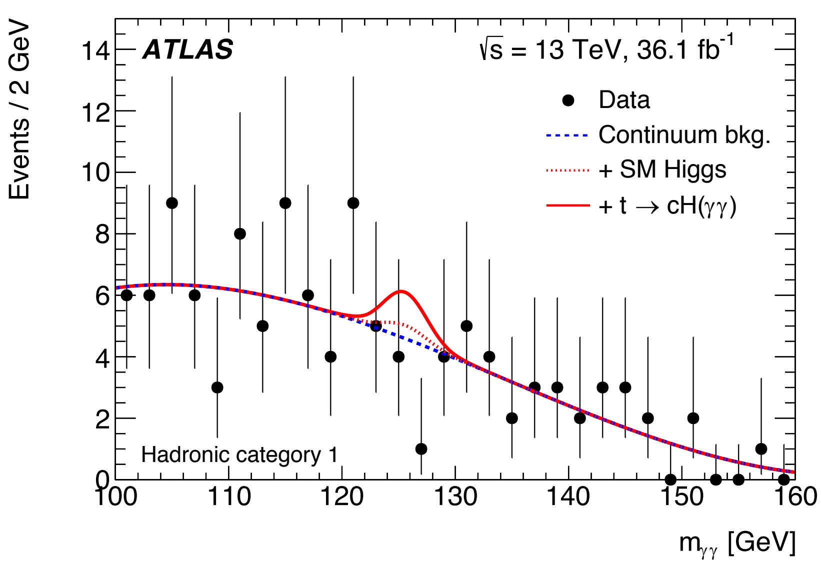
Leptonic (binned likelihood fitting)

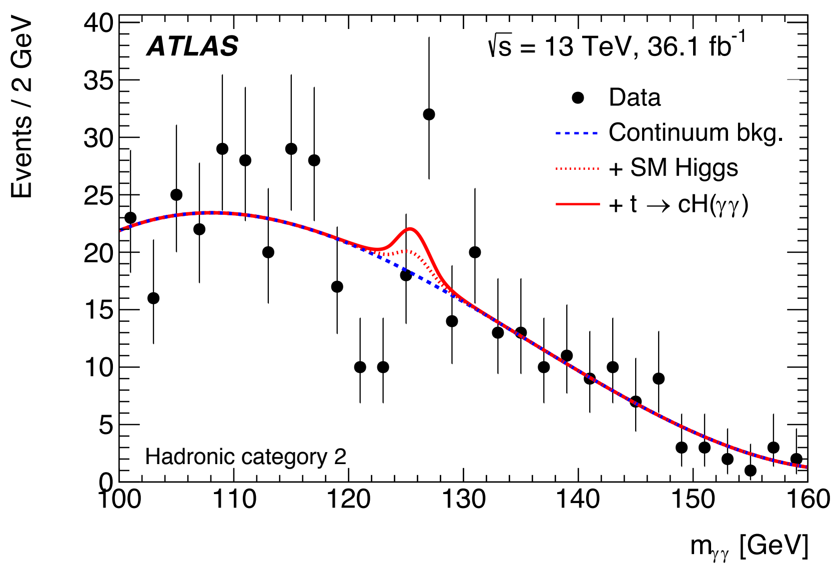




t→qH, H→$\gamma\gamma$ at 13 TeV (ATLAS)

- Signal distribution is described by a double-sided Crystal Ball function from the simulated FCNC signal and background by non-resonant diphoton mass distribution from $\gamma\gamma j$ sample (hadronic)
- Likelihood as a Poisson term for two bins (SR and CR) (leptonic)
- Systematic uncertainties : Signal MC generators, ISR/FSR/Hadronization, theory
- Upper limit : Br(t→ cH) < 0.22 (0.16)%, Br(t→ uH) < 0.24 (0.17)%

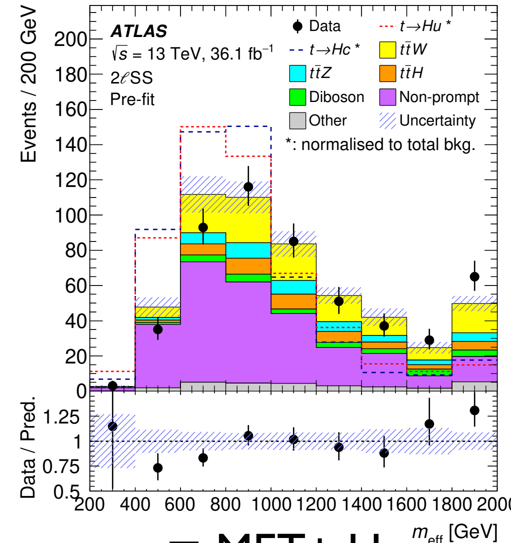




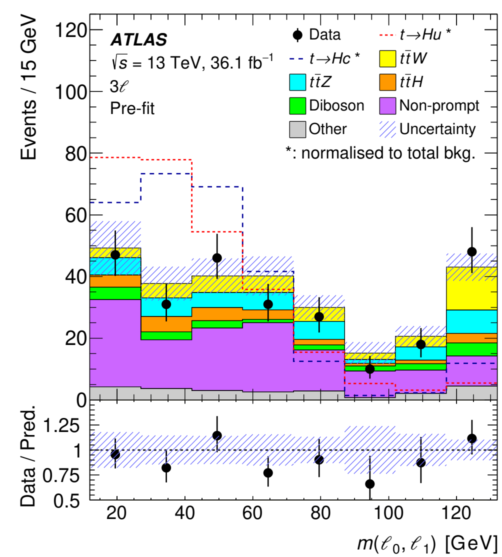
t→qH → q+multi-lepton + X (ATLAS)

arxiv: 1805.03483

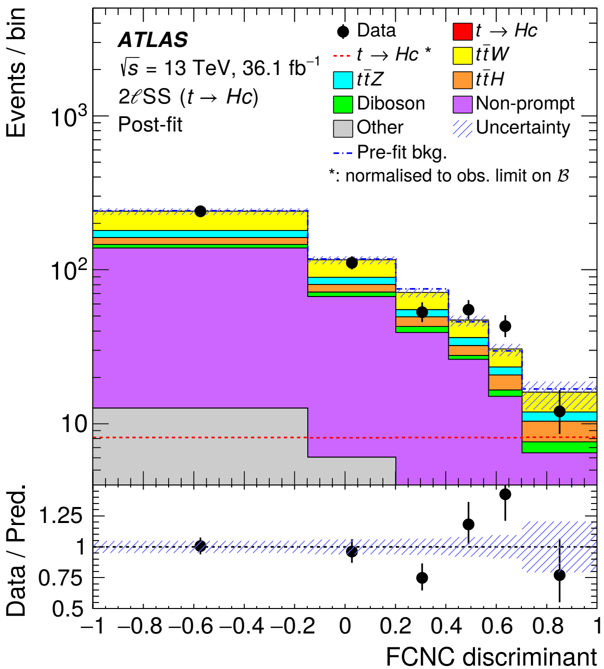
- Signal signature : t→ qH → q(WW^* / $\tau\tau$ / ZZ^*)
  - no hadronic tau decay
- Backgrounds : QCD and ttW
- Two same-sign leptons
  - Leptons with p_T > 20 GeV
  - At least 4 jets with p_T > 30 GeV, at least one b-tagged jet
- 3 leptons
  - $|M(l^+l^-$ or $3l) - 91.2|$ > 10 GeV
  - At least 4 jets, one of them is b-tagged
- BDT is used for signal and background separation

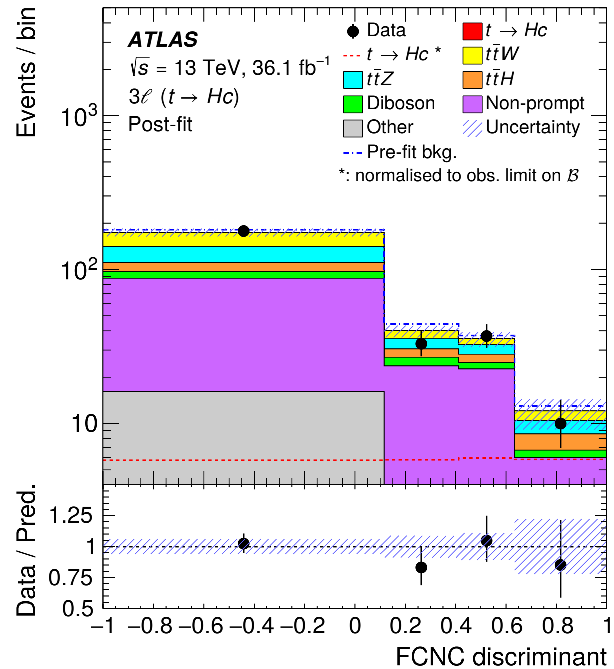


$m_{eff} \equiv$ MET+ H_T



t→qH → q+multi-lepton + X (ATLAS)





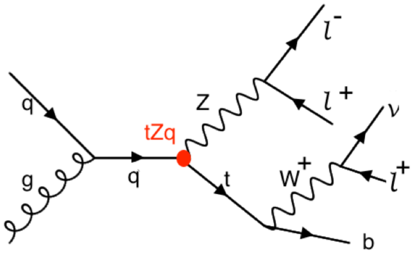
[arxiv: 1805.03483]

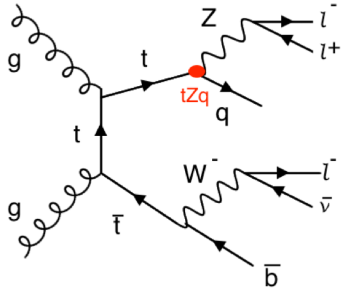
- Observed (expected) upper limit of t→cH is 0.16 (0.15)%
- Observed (expected) upper limit of t→uH is 0.19 (0.15)%
- The most stringent channel in ATLAS
- Dominant systematic uncertainties
  - signal MC generation, non-prompt background estimation

CMS-PAS-TOP-17-017

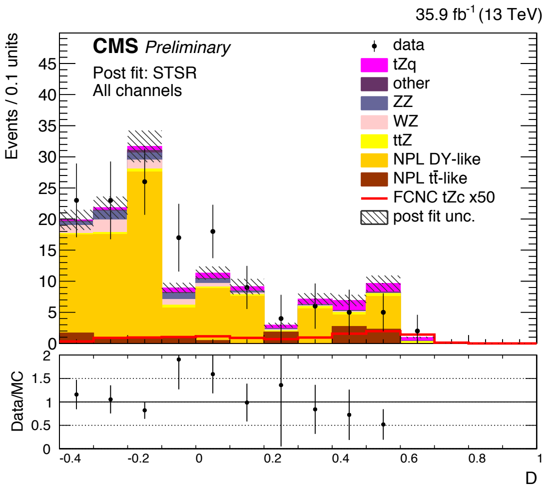
t → qZ → qll(CMS)

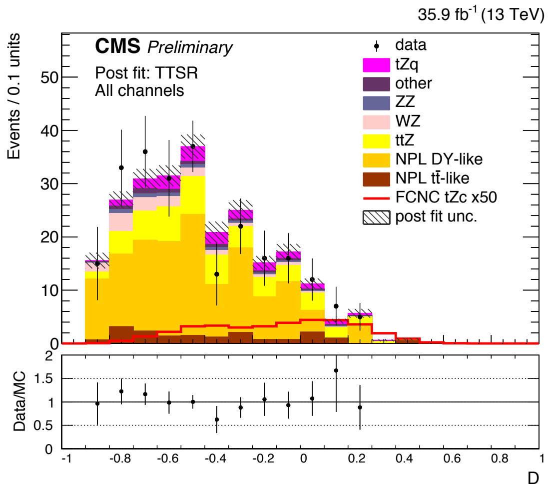
- Two event signal regions
- Single top production with 1 jet requirement
- Top quark decay in a top quark pair production with 2-3 jets requirement

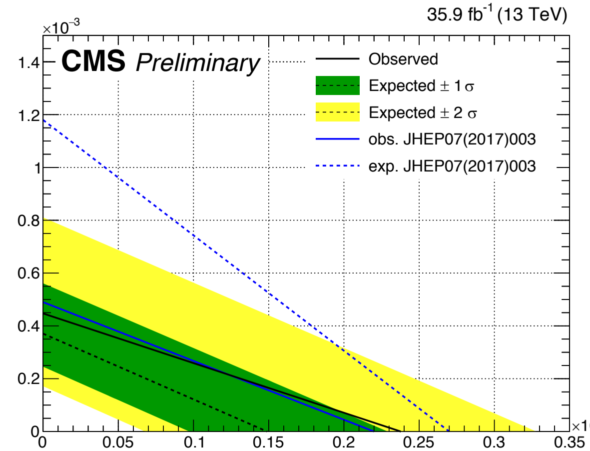




- Use BDT to separate FCNC signal from the backgrounds







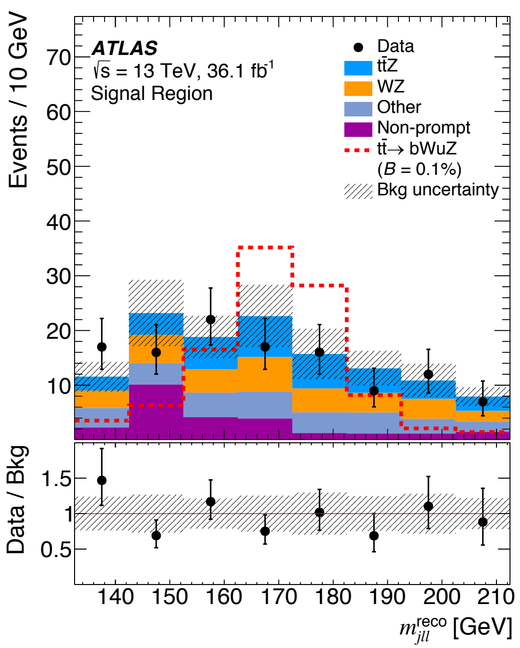
- Observed (expected) limits on branching ratios
  - Br(t→Zu) < 0.024 (0.015)%
  - Br(t→Zc) < 0.045 (0.037)%

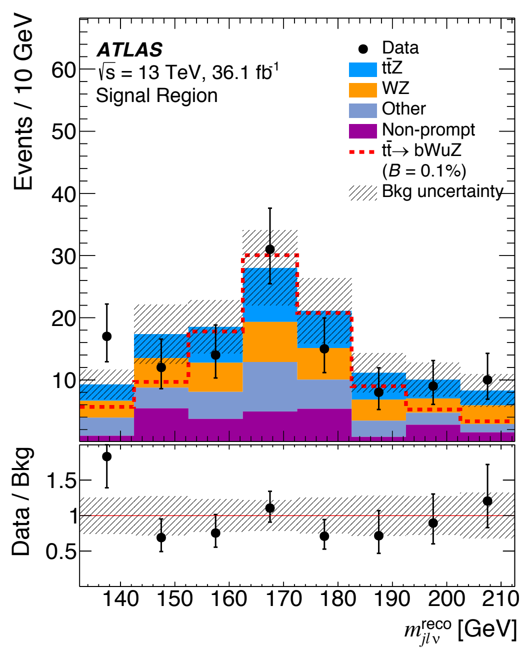
$t \rightarrow qZ \rightarrow qll$ (ATLAS)

arxiv: 1803.09923

- Event selection to remove backgrounds from ttZ, WZ, ZZ and QCD
  - Three isolated charged leptons
  - At least two jets with p_T > 25 GeV, at least one b-tagged jet
  - MET > 20 GeV
- Kinematic reconstruction

$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a \ell_a \ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b \ell_c \nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c \nu} - m_W\right)^2}{\sigma^2_W}$$

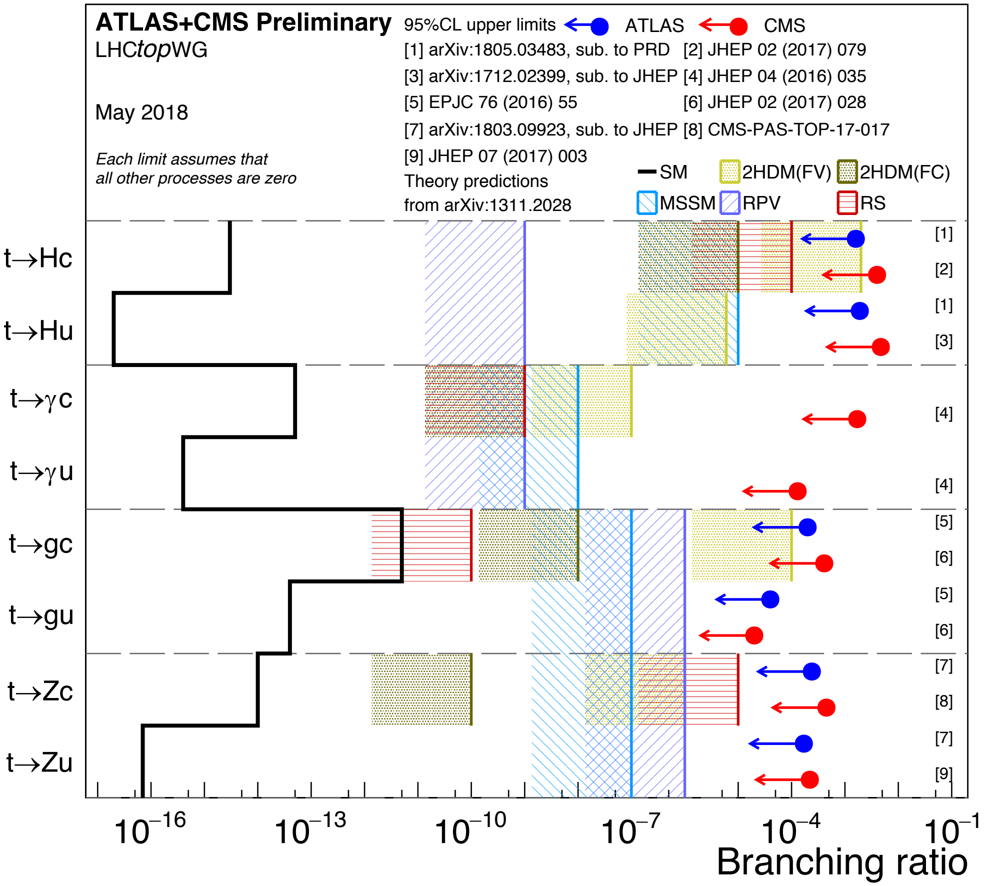




- Systematic uncertainties : theory normalization, background modeling
- To constrain uncertainties, five control regions are defined
- Observed (expected) upper limit
  - Br($t \rightarrow Zc$) < 0.024 (0.032)%
  - Br($t \rightarrow Zu$) < 0.017 (0.024)%

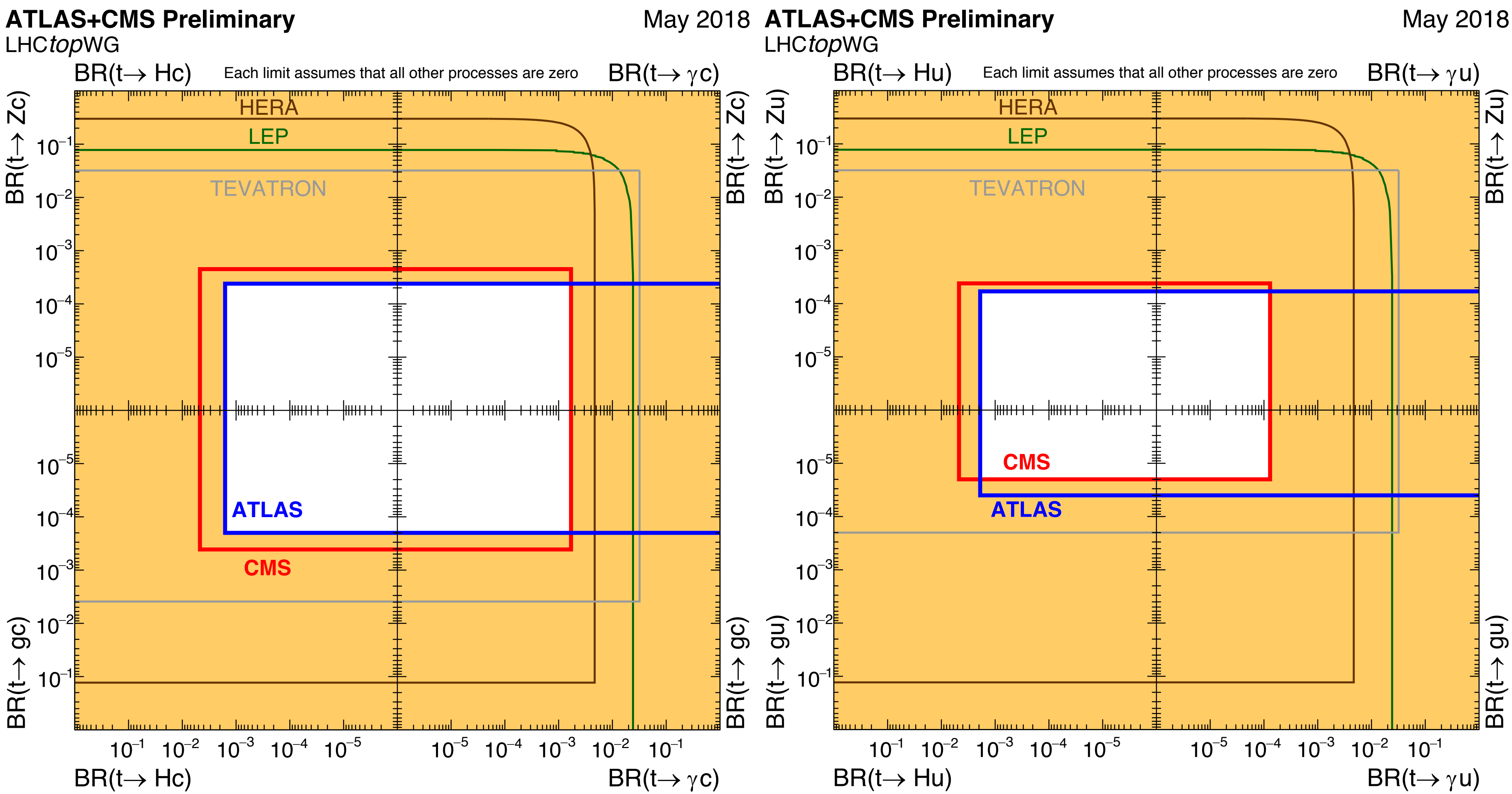
Summary of the current limits

- Start to touch the BSM predictions with the highest branching ratio



Summary of the current limits

- Survival region (white box) is getting narrower

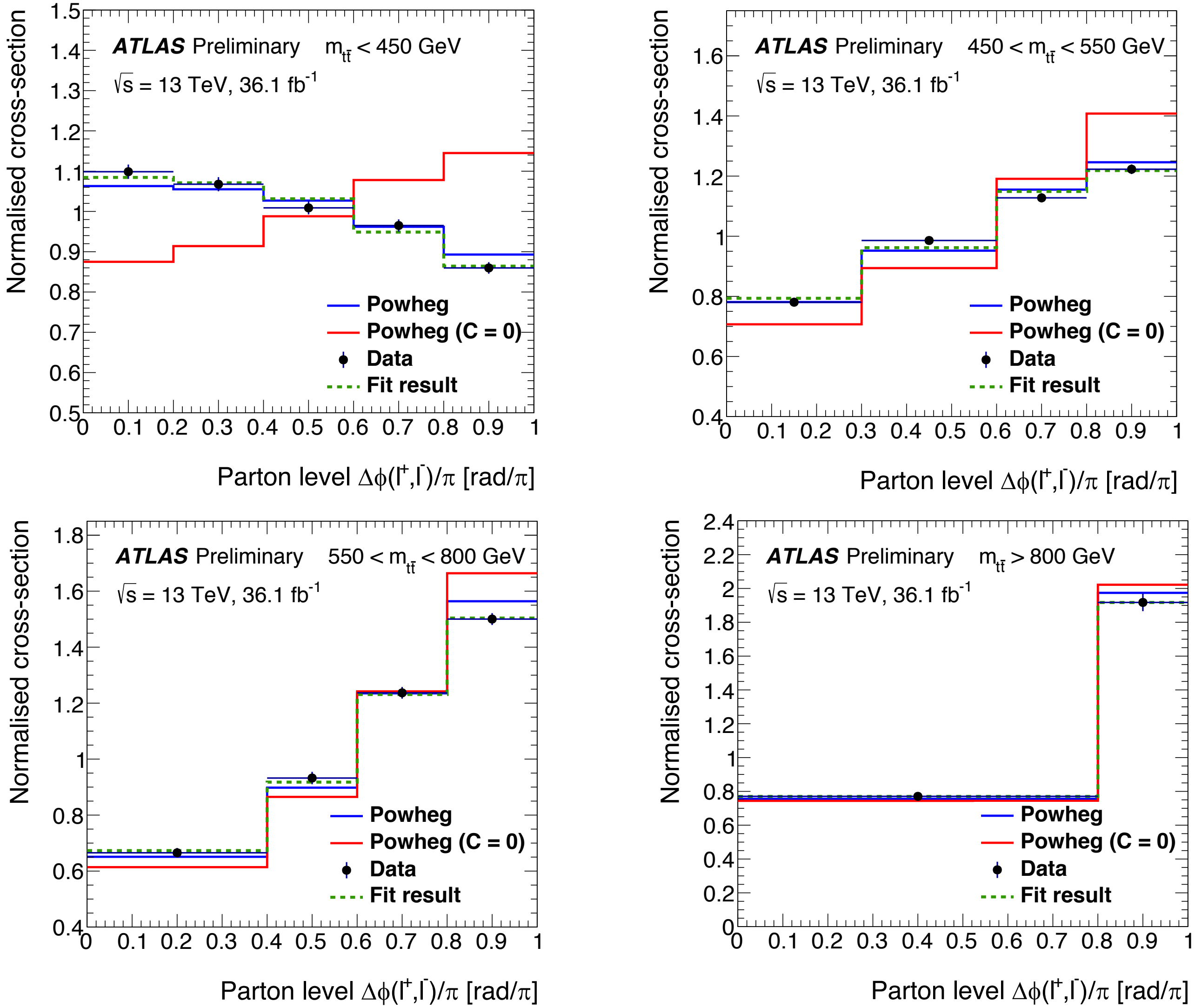


Conclusions

- LHC was indeed a top quark factory.
  - Top quarks are observed even from LHCb and pPb collisions at CMS and studied extensively
- Top quark properties are measured with high precision
- ATLAS and CMS have performed the rare top decay searches
- Rare processes in top quark sector beyond SM are now within reach
- Exciting time is ahead of us with more data in 2018.
- More results will be coming soon

Spin correlations (ATLAS)

ATLAS-CONF-2018-027

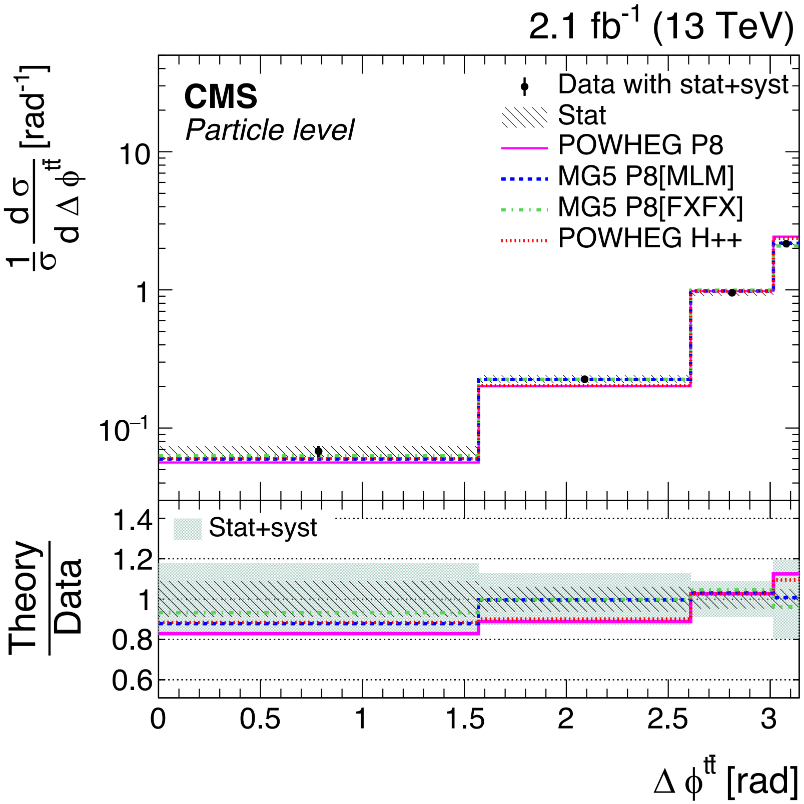


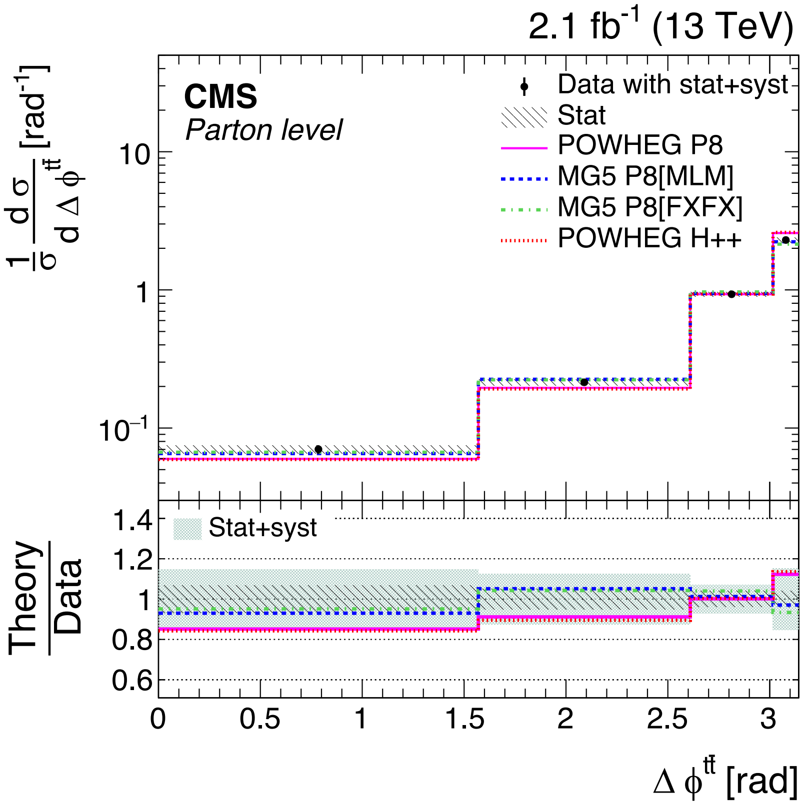
- f_{SM} as a function of m_{ttbar} is found to increases
- Uncertainty becomes larger than inclusive one

$\Delta\phi(t,\bar{t})$ (CMS)

JHEP 04 (2018) 060

- Differential cross section as a function of $\Delta\phi(t,\bar{t})$

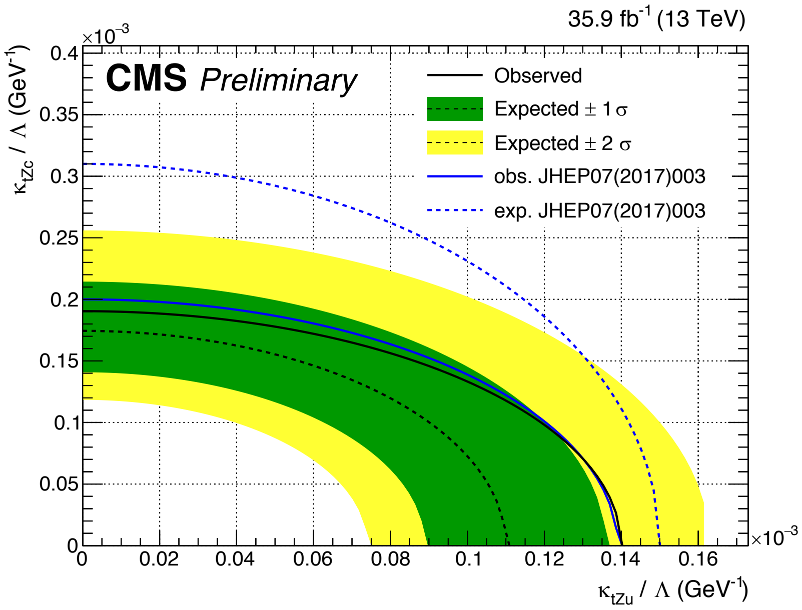




t → qZ → qll (CMS)

- Set limits on trilinear top-quark-boson couplings

$$\mathcal{L}_{\mathrm{FCNC}}^{tZq} = \sum_{\mathrm{q=u,c}} \left[\frac{\sqrt{2}}{4} \frac{g}{\cos\theta_{\mathrm{W}}} \frac{\kappa_{\mathrm{tZq}}}{\Lambda} \bar{t}\sigma^{\mu\nu} \left(f_{\mathrm{Zq}}^{\mathrm{L}} P_{\mathrm{L}} + f_{\mathrm{Zq}}^{\mathrm{R}} P_{\mathrm{R}} \right) \mathrm{q} Z_{\mu\nu} \right] + h.c.$$



T → qZ → qll (ATLAS)

Selection	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0 (CR1)	SR
No. leptons	3	3	4	3	3
OSSF	Yes	Yes	Yes	Yes	Yes
$\|m_{\ell\ell}^{\mathrm{reco}} - 91.2$ GeV$\|$	< 15 GeV	< 15 GeV	< 15 GeV	> 15 GeV	< 15 GeV
No. jets	≥ 4	≥ 2	≥ 1	≥ 2	≥ 2
No. b-tagged jets	2	0	0	0 (1)	1
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 20 GeV	> 40 GeV	> 20 GeV	> 20 GeV	> 20 GeV
$m_{\mathrm{T}}^{\ell\nu}$	-	> 50 GeV	-	-	-
$\|m_{\ell\nu}^{\mathrm{reco}} - 80.4$ GeV$\|$	-	-	-	-	< 30 GeV
$\|m_{j\ell\nu}^{\mathrm{reco}} - 172.5$ GeV$\|$	-	-	-	-	< 40 GeV
$\|m_{j\ell\ell}^{\mathrm{reco}} - 172.5$ GeV$\|$	-	-	-	-	< 40 GeV

Sample	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1
$t\bar{t}Z$	61 ± 6	16.5 ± 3.1	0 ± 0	6.1 ± 1.2	21.9 ± 2.9
WZ	6 ± 4	610 ± 40	0 ± 0	166 ± 13	20 ± 5
ZZ	0.07 ± 0.02	49 ± 9	89 ± 12	59 ± 10	9.0 ± 2.2
Non-prompt leptons	2.0 ± 2.3	41 ± 15	0 ± 0	177 ± 32	174 ± 21
Other backgrounds	13.4 ± 2.6	23 ± 5	1.1 ± 0.6	19 ± 6	33 ± 7
Total background	82 ± 7	737 ± 35	90 ± 12	426 ± 30	258 ± 20
Data	81	734	87	433	260
Data / Bkg	0.99 ± 0.14	1.00 ± 0.06	0.97 ± 0.16	1.02 ± 0.09	1.01 ± 0.10