Top Quark Properties Measurements with ATLAS

Reinhild Yvonne Peters

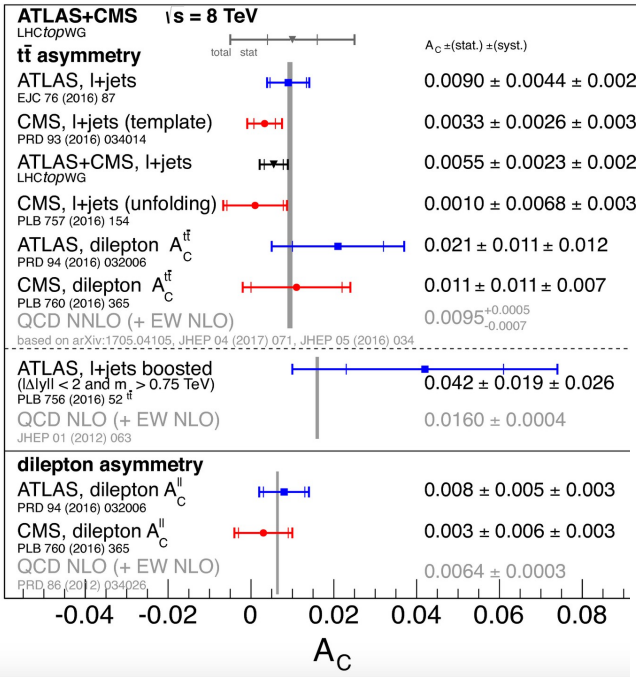
The University of Manchester

on behalf of the ATLAS Collaboration

Top Properties

- Charge
- Mass
- Spin correlation
- W helicity
- Colour Flow
- Asymmetry
- ....

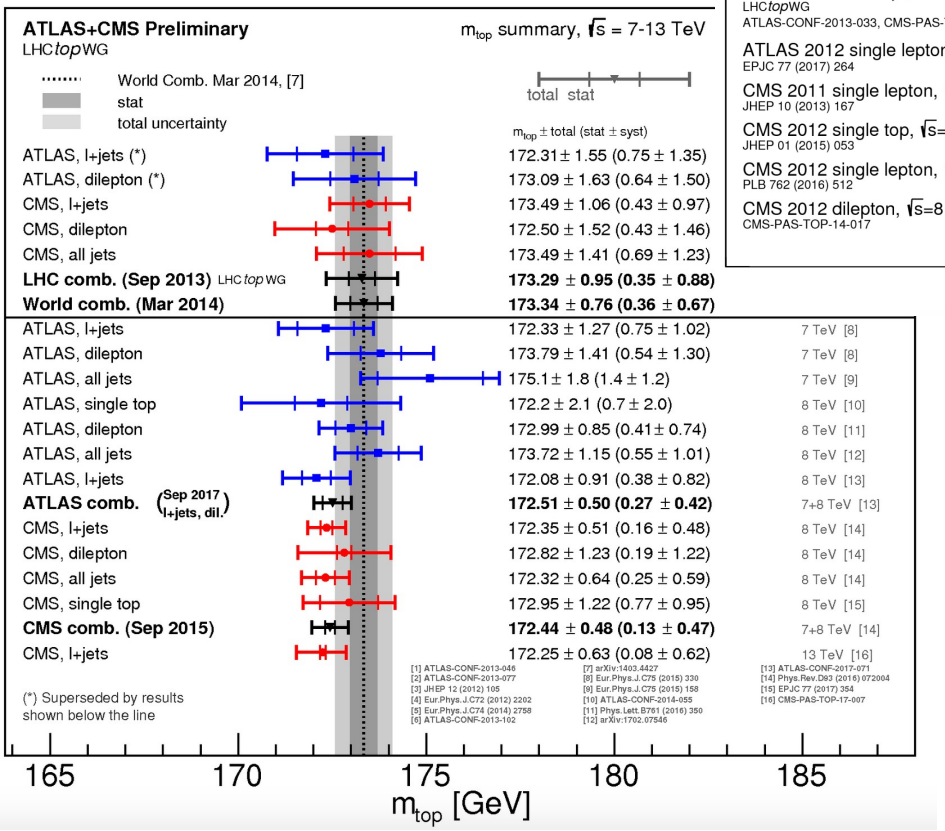
Top Properties: A Plethora of Precision Results

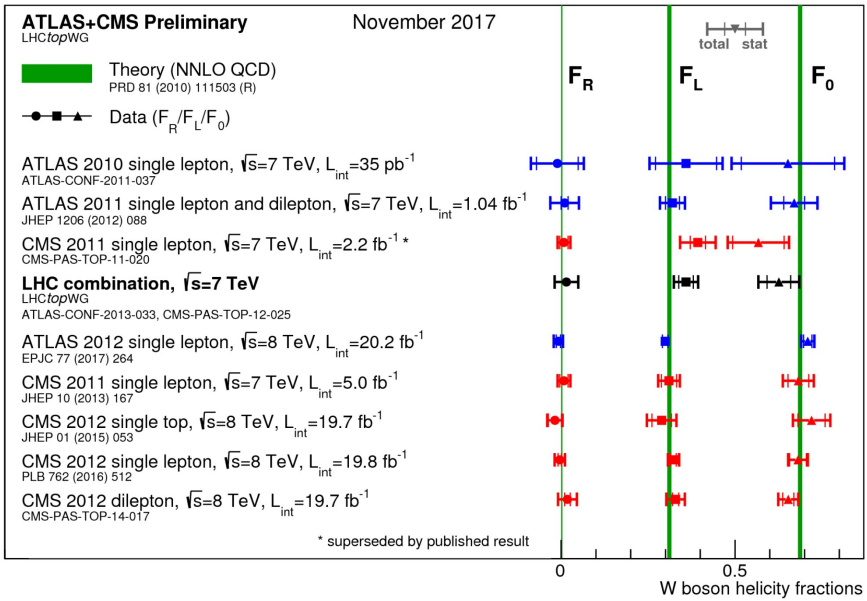


Asymmetries

Top Mass

(see Teresa's talk tomorrow)





W Helicity

Good agreement with SM...so far

and many many more...

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Top Properties 4 You

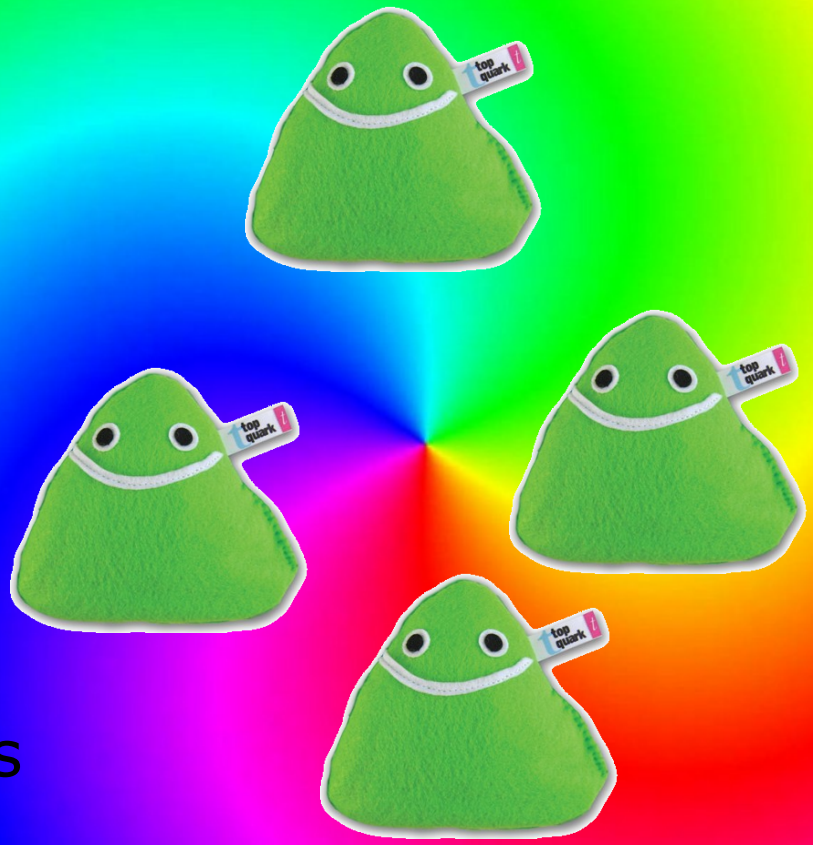
- Charge
- Mass
- **Spin correlation**
- W helicity
- **Colour Flow**
- Asymmetry
- ….

- **Bonus: 4top results**

Top Properties 4 You

- Charge
- Mass
- Spin correlation
- W helicity
- **Colour Flow**
- Asymmetry
- ....

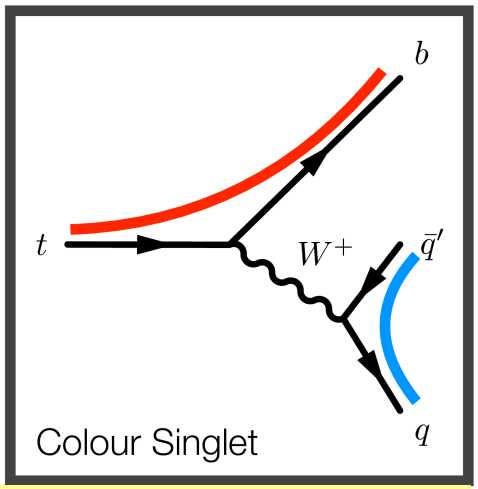
- Bonus: 4top results

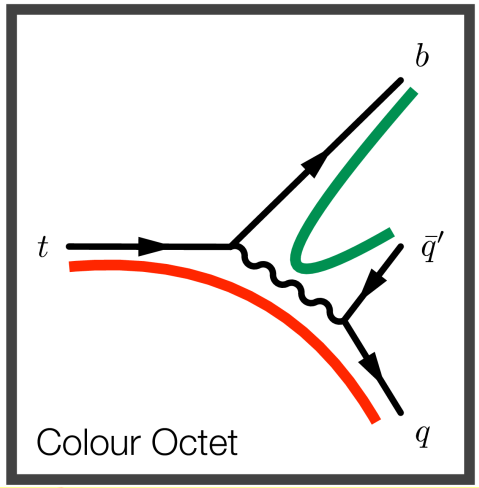


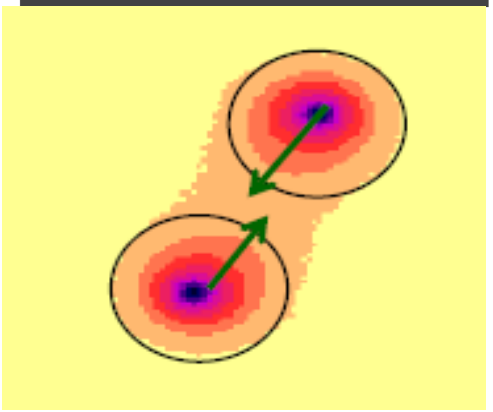
Colour Flow in Top

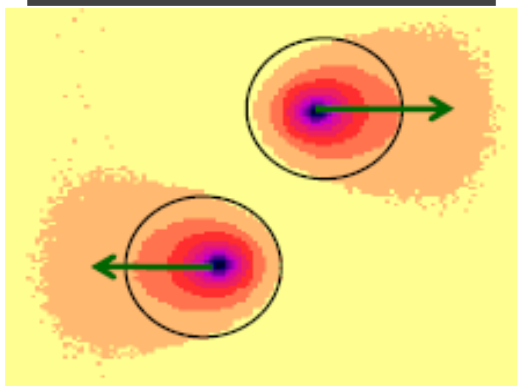
- Top events as laboratory to test colour-flow tool
- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles

Gallichio, Schwartz,
PRL 105, 022001 (2010)









Jet pull: vectorial sum of components within each jet → jet pull angle: angle wrt. connection line of pair of jets

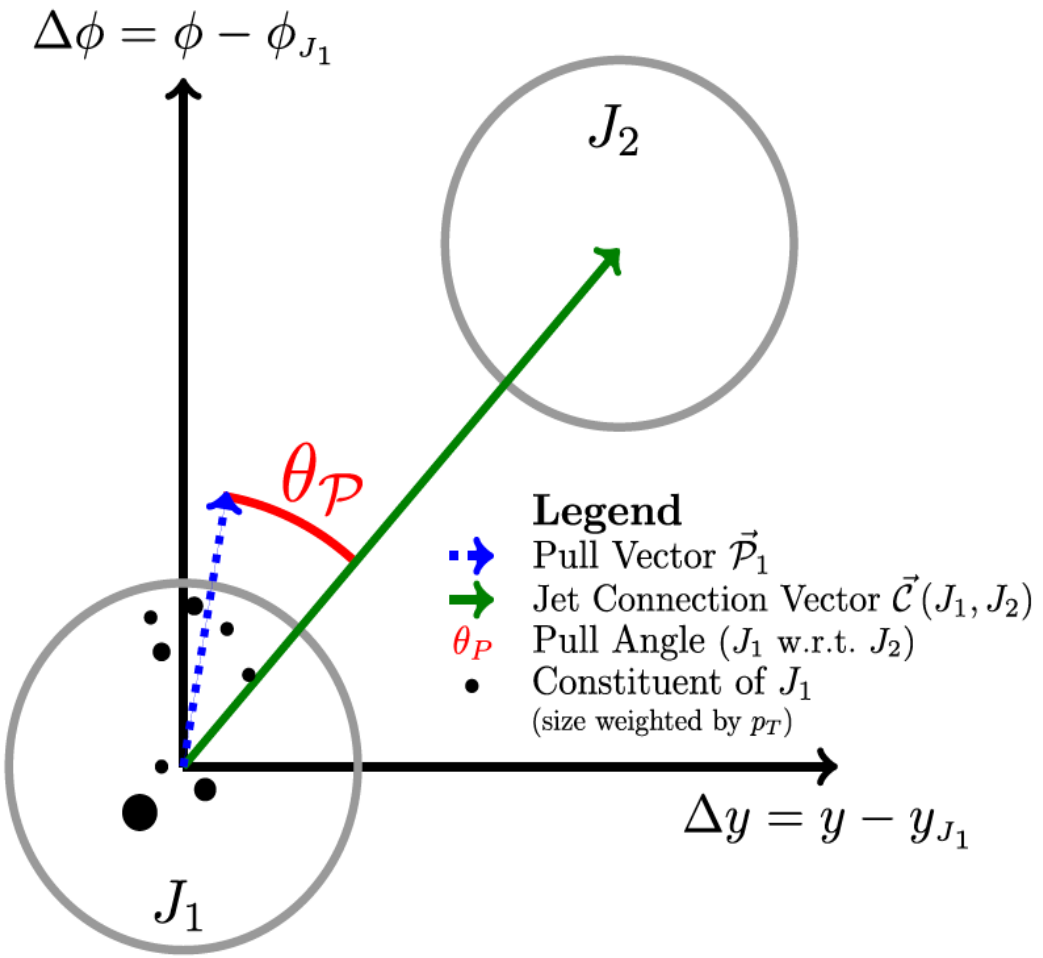
Color Flow Observable

Construct a local observable, constructed from particles within a chosen jet cone: Jet pull

- Pick a pair of jets in the event
- Build vectorial sum of jet components:

$$\vec{p} = \sum_i \frac{p_T^i |r_i|}{p_T^{jet}} \vec{r}_i$$

  - $\vec{r}_i$: position of jet component i relative to center of jet
  - p_T^i: transverse momentum of component i
  - p_T^{Jet}: transverse momentum of jet

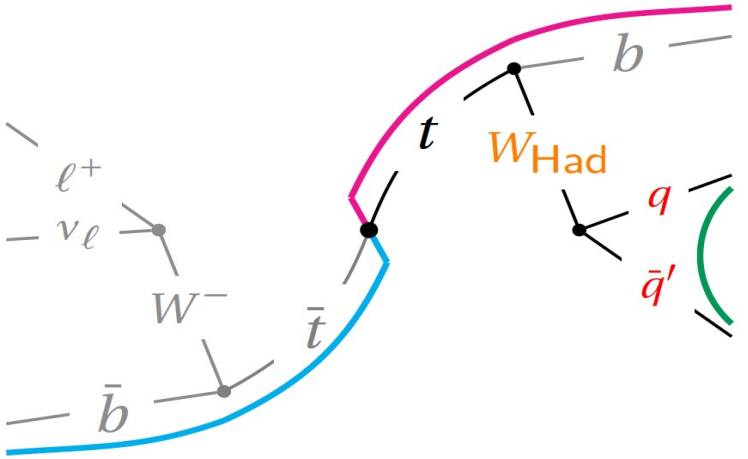


Gallicchio, Schwartz, PRL 105, 022001 (2010)

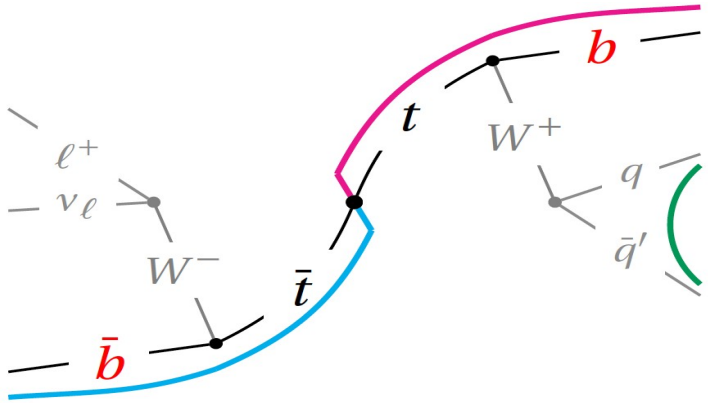
Colour Flow in Top

- Latest ATLAS analysis:
  Consider 4 variables in semileptonic $t\bar{t}$ events (>1 b-tagged jet)

- Two non-b-tagged jets:
  - Relative jet pull angles
  - Jet pull magnitude



- Two b-tagged jets
  - Relative jet pull angle

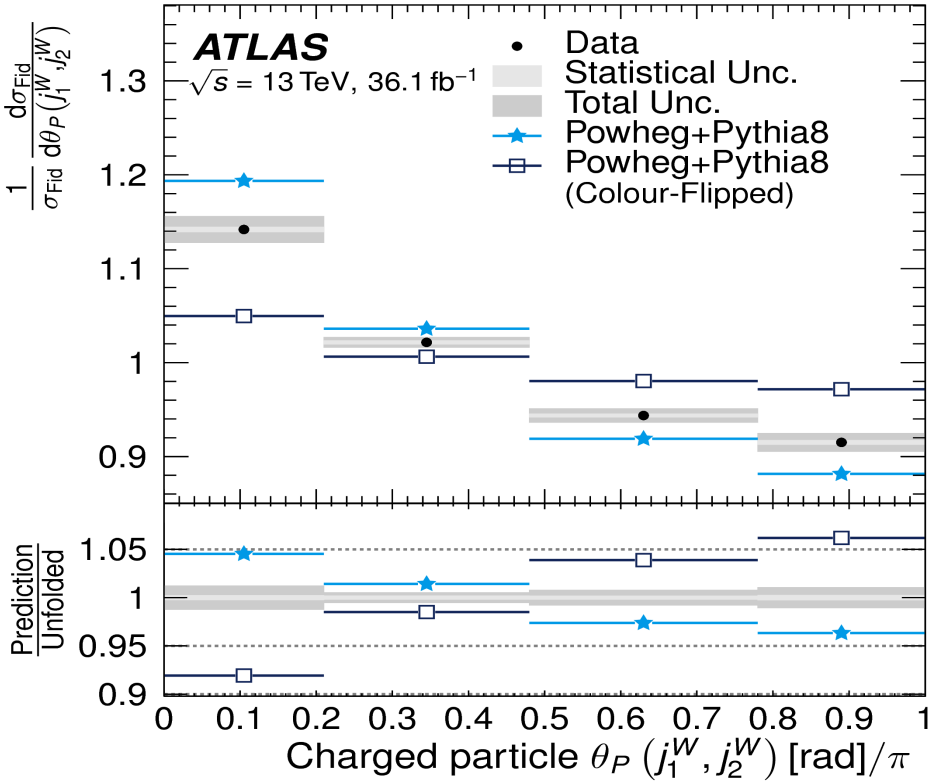


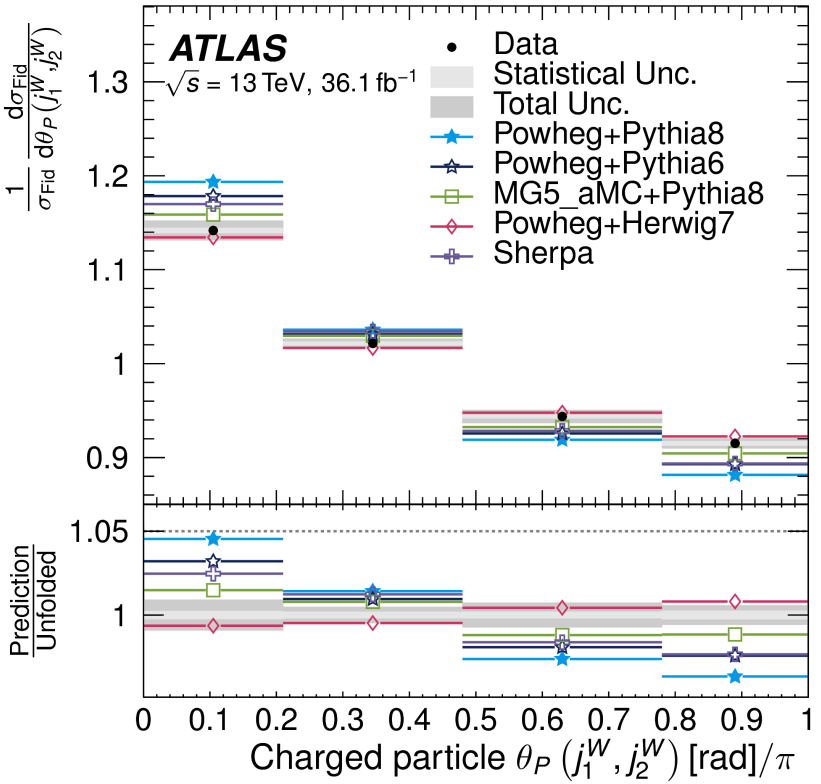
- Results corrected back to particle level

arXiv:1805.02935

Results for W daughters

- Correction to stable particle-level (iterative Bayesian unfolding)





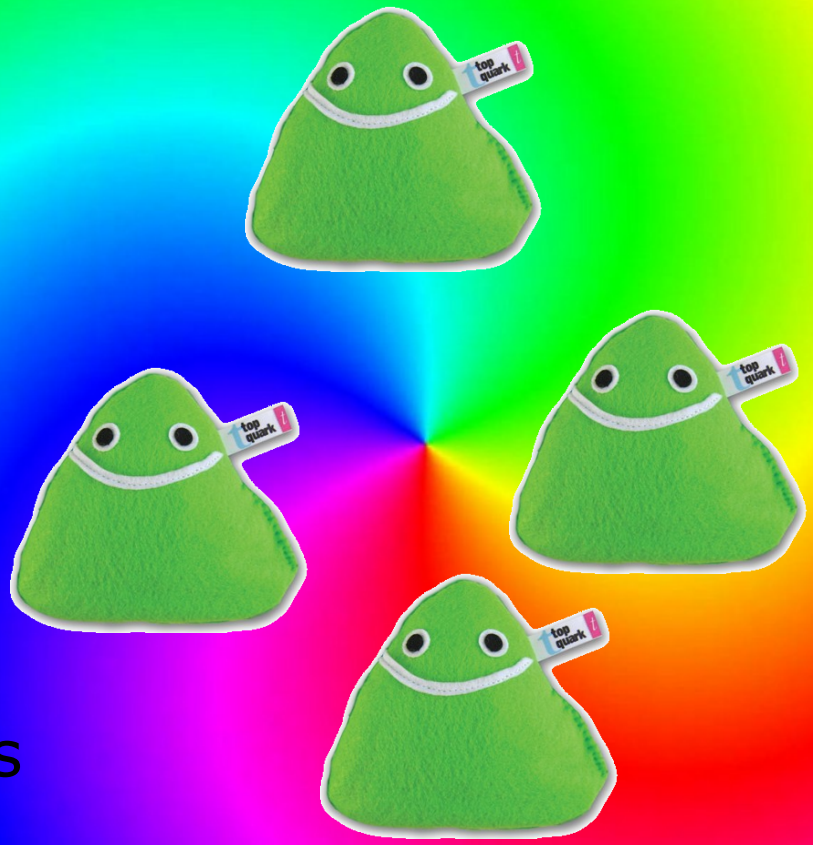
- Colour-flipped model disfavoured by the data
  (for this distribution χ^2/NDF: 45.3/3; SM Powheg+Pythia8: 17.1/3)
- MC modeling has room for improvement

arXiv:1805.02935

Top Properties 4 You

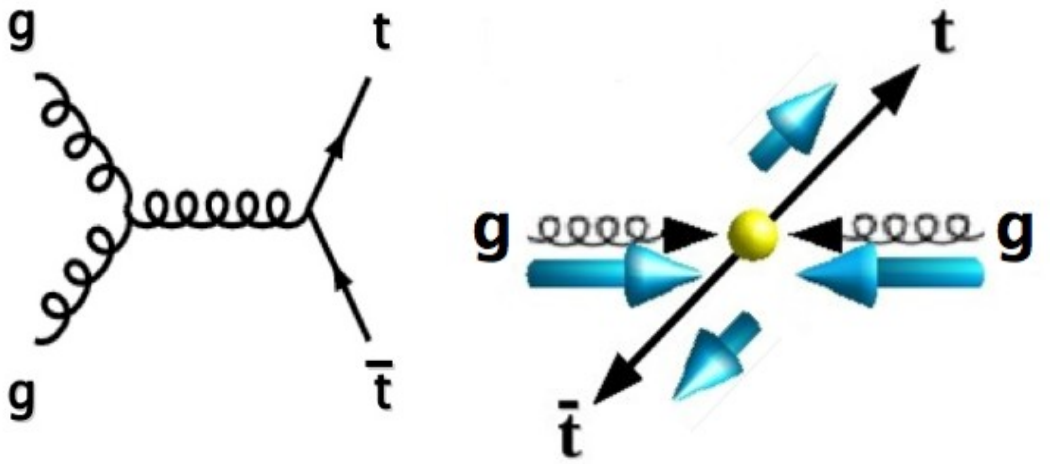
- Charge
- Mass
- **Spin correlation**
- W helicity
- Colour Flow
- Asymmetry
- ....

- Bonus: 4top results



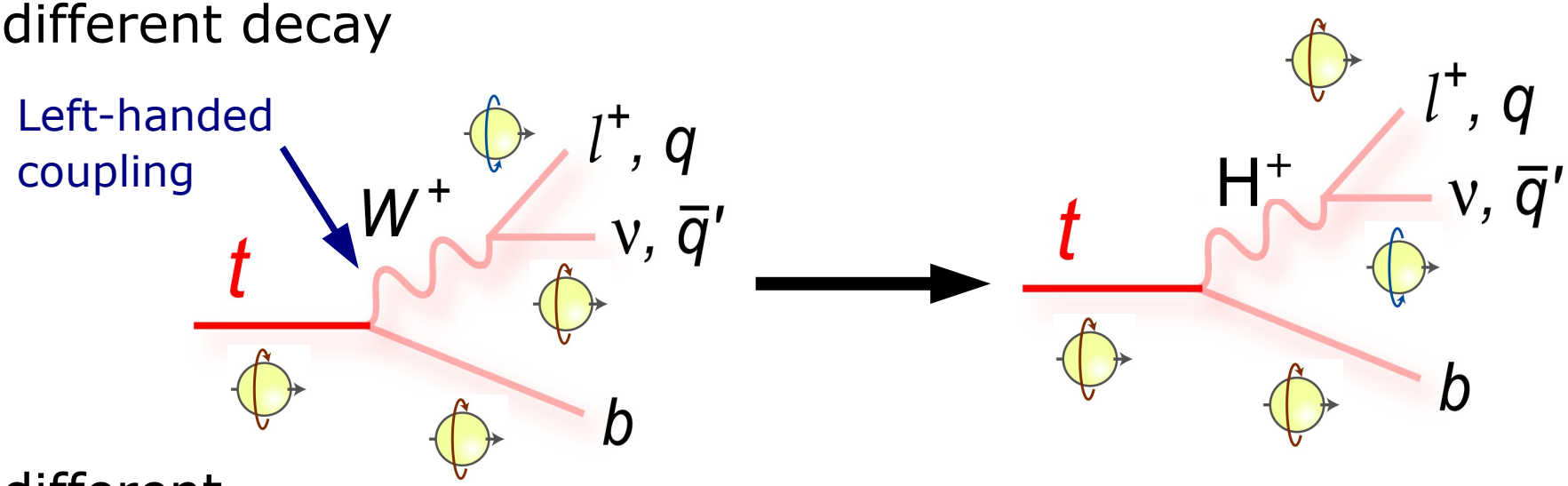
Spin Correlations

- Top quarks decay before fragmentation
  - Spin information is preserved
- Hadron colliders: top quarks produced un-polarized, but
  - New physics (NP) could induce polarization
    - e. g. NP causing forward-backward $t\bar{t}$ asymmetry → more left-handed tops
  - Correlation between top and antitop spin can be extracted

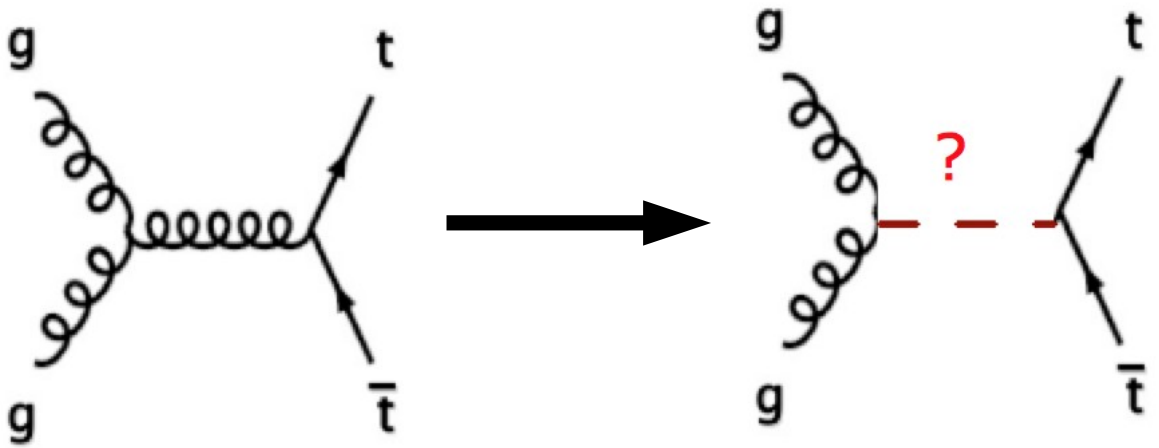


Spin Correlations

- Measured spin correlation can change
  - Due to different decay



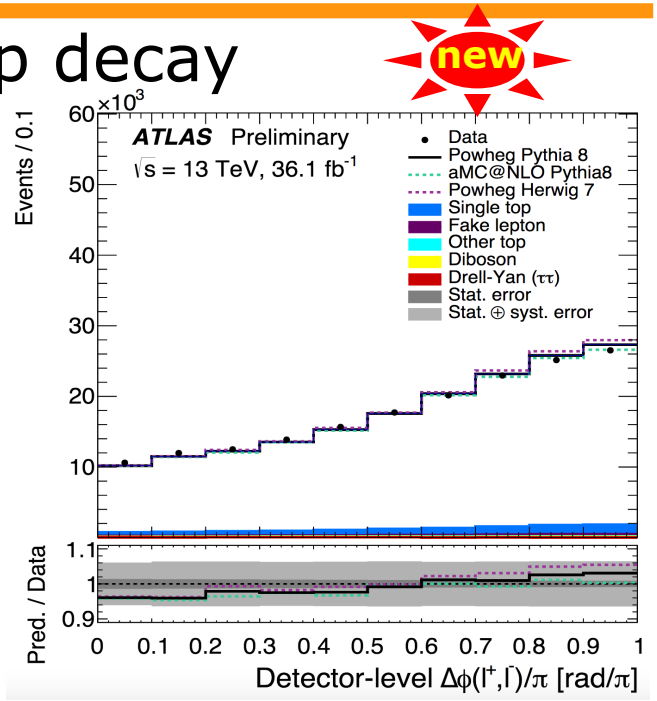
  - Due to different production

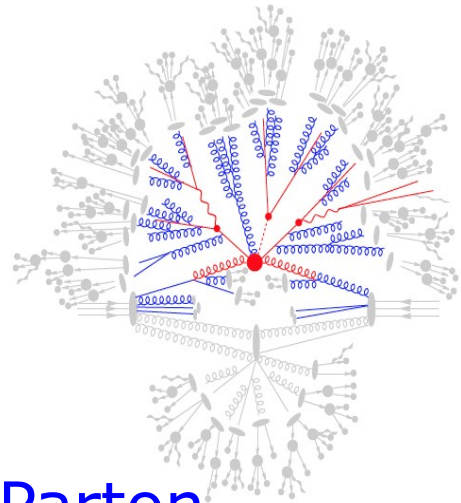


- Spin correlation: test the full chain form production to decay!

Analysis Strategy

- Highest spin analysing power: leptons from top decay
  → use dileptonic $t\bar{t}$ events ($e\mu$)
  - Very clean samples
- Use $\Delta\phi$ between both leptons
  → no kinematic event reconstruction required
- Unfolded differential measurements:
  - Parton-level
    - Inclusive and in bins of $m_{t\bar{t}}$
  - Particle level
    - Inclusive and in bins of $m_{t\bar{t}}$
- Full $t\bar{t}$ event reconstruction for $m_{t\bar{t}}$





Parton

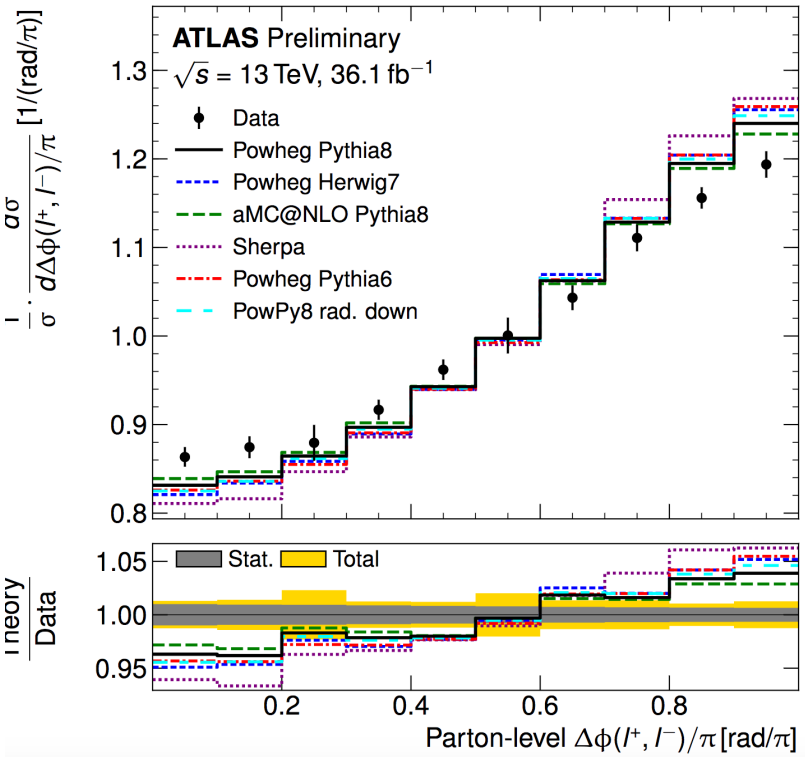
Particle

ATLAS-CONF-2018-027

Unfolded distributions

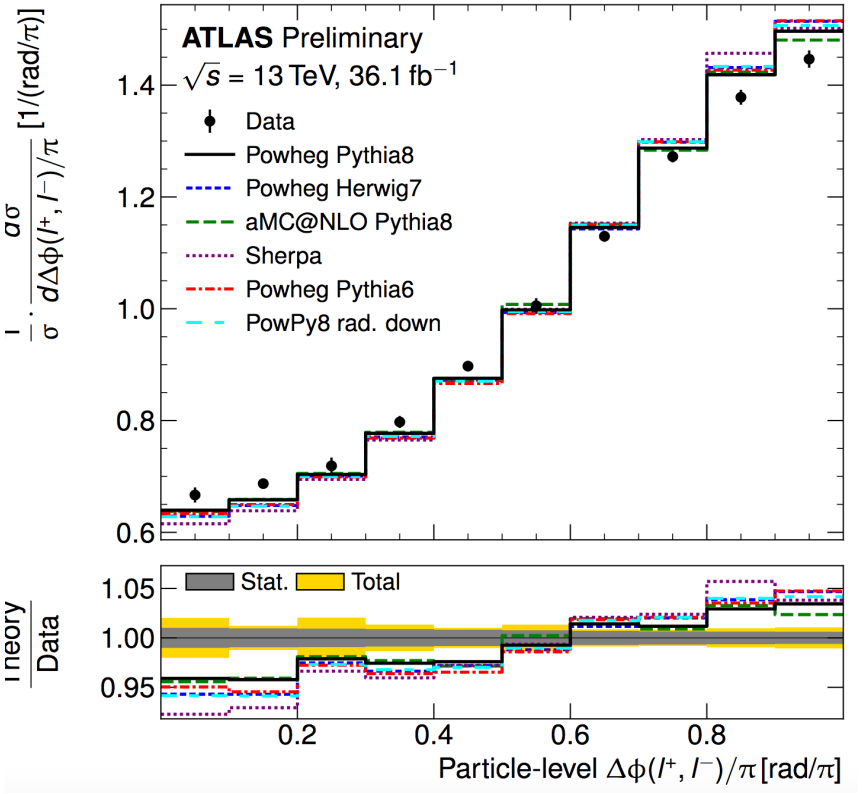
- Unfolded distributions compared to different MC predictions

Parton



new

Particle



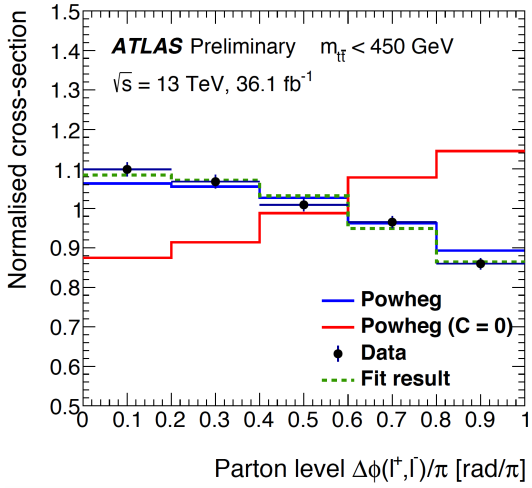
new

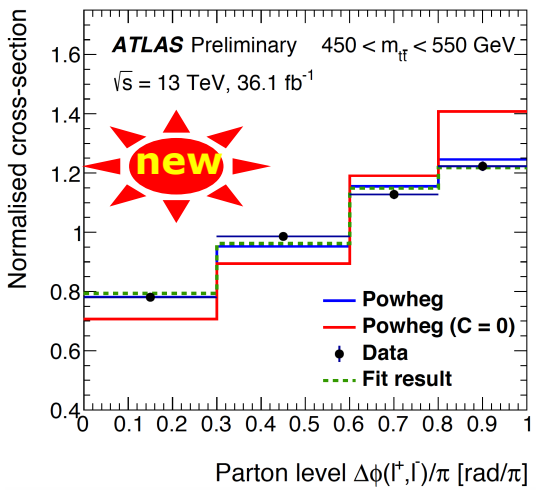
- Data shows shallower slope than prediction

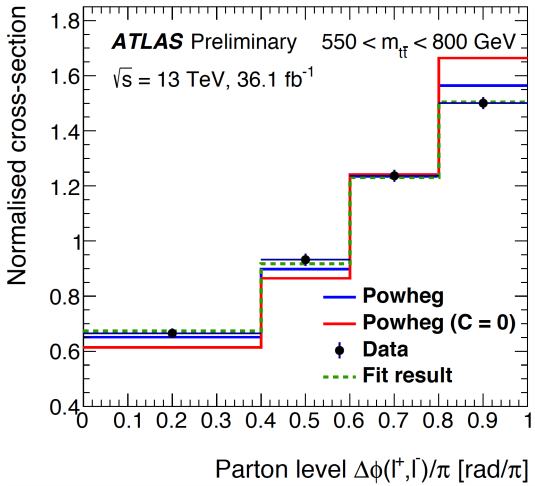
ATLAS-CONF-2018-027

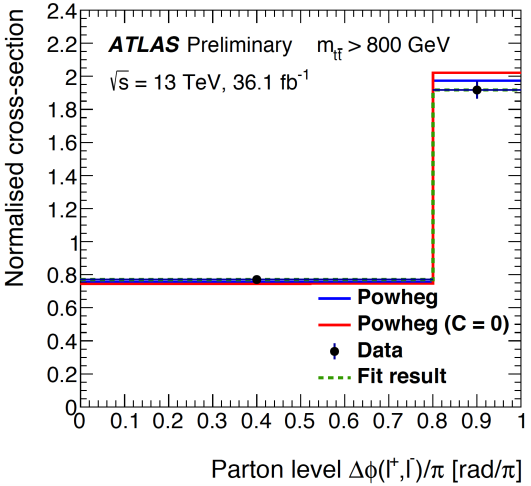
Template fit

- Fitting spin and no-spin hypotheses to parton-level distributions





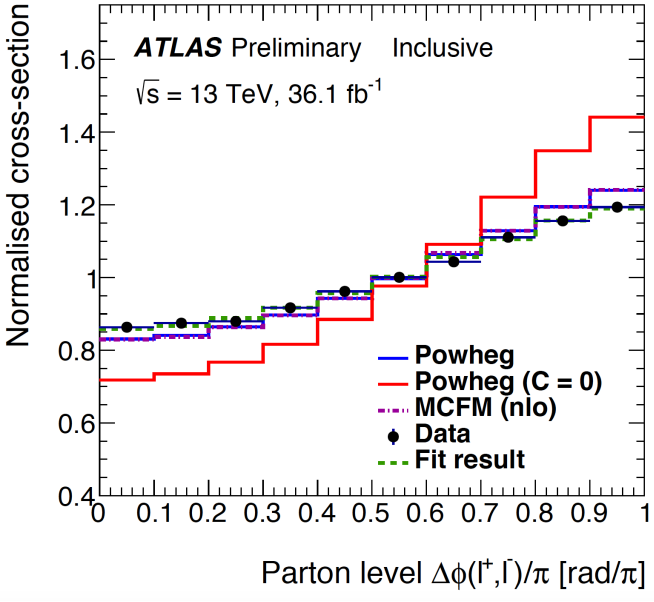




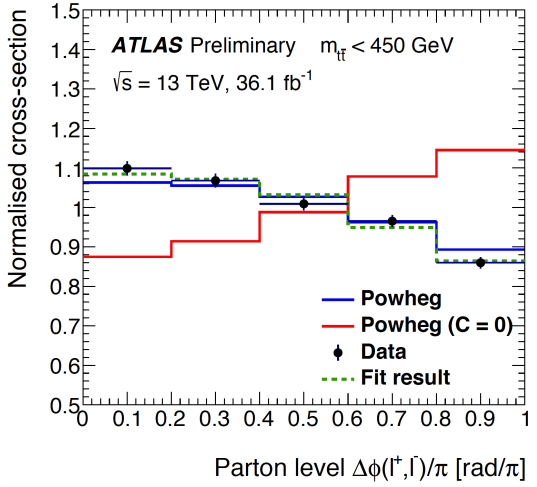
ATLAS-CONF-2018-027

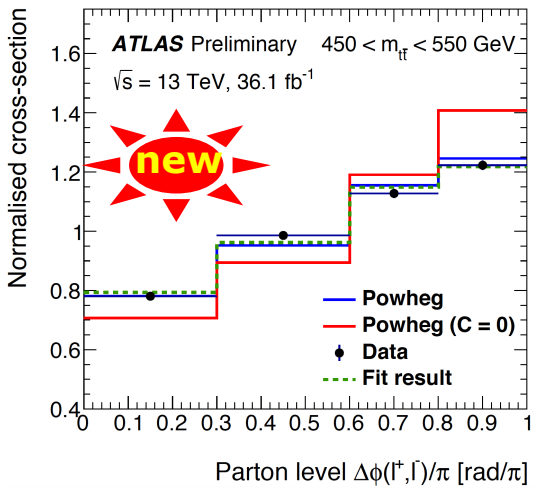
Template fit

- Fitting spin and no-spin hypotheses to parton-level distributions

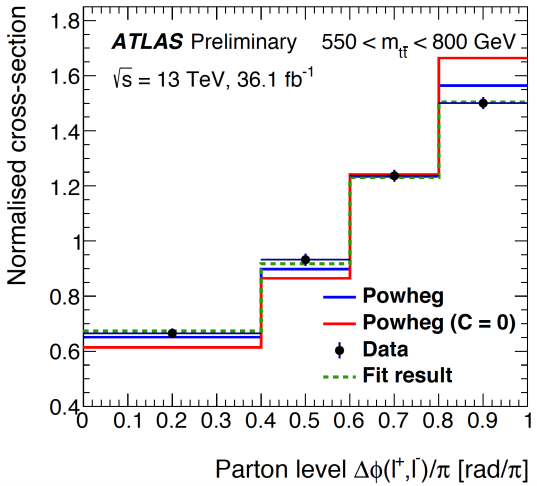


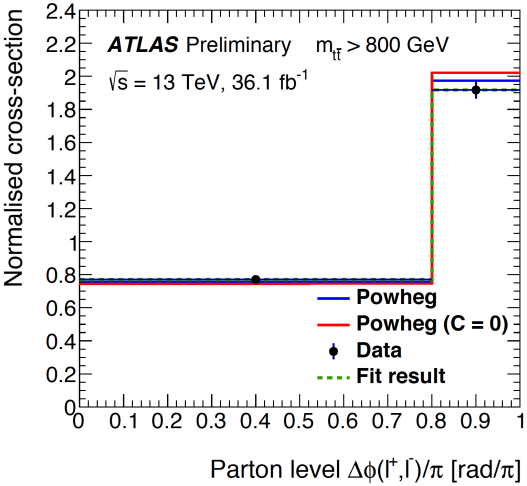
new





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)





- Spin correlations higher than SM prediction by 3.7σ
  (3.2σ including theory uncertainty)

ATLAS-CONF-2018-027

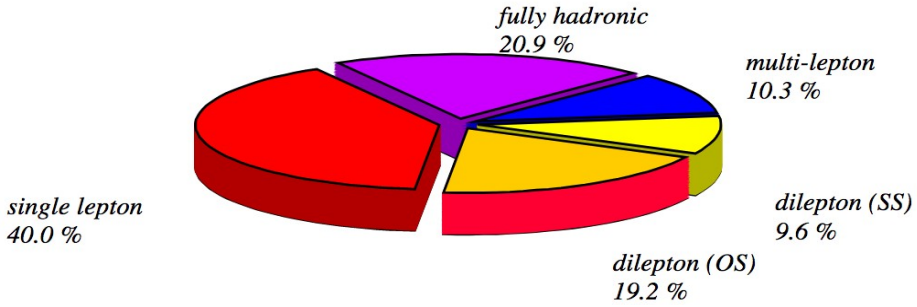
Top Properties 4 You

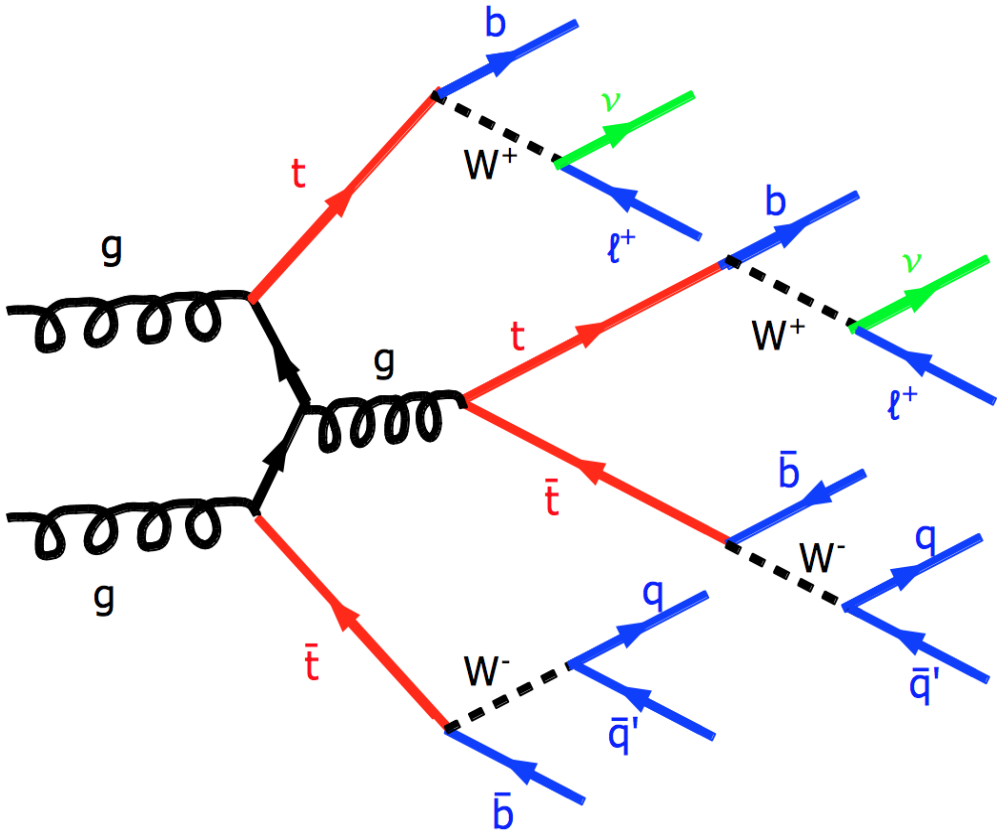
- Charge
- Mass
- Spin correlation
- W helicity
- Colour Flow
- Asymmetry
- ....

- **Bonus: 4top results**

Searches for 4top

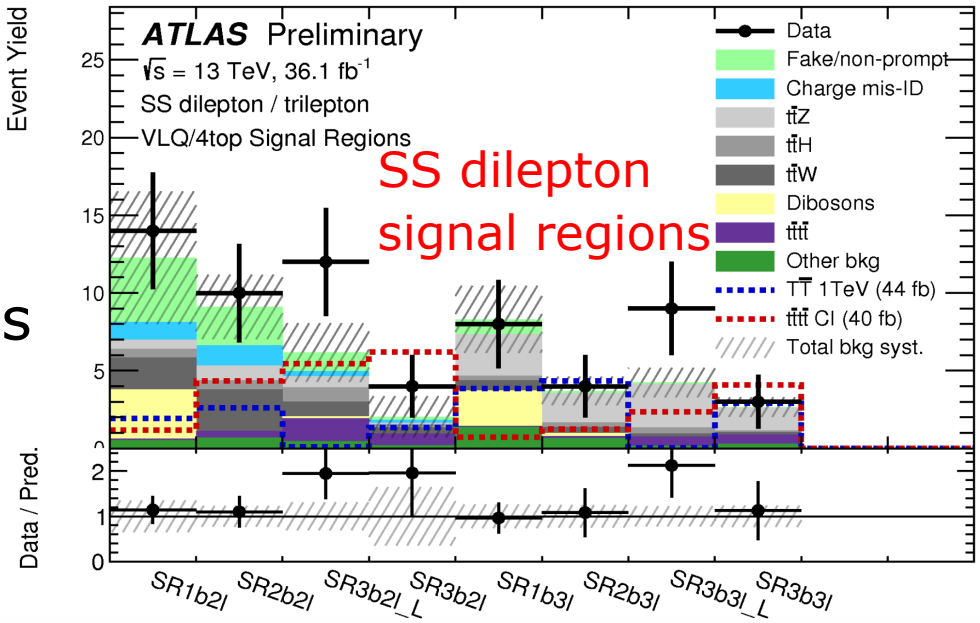
- $t\bar{t}t\bar{t}$ SM cross section 9.2fb
  - Can be enhanced by several new physics contributions
- New results in following final states:
  - Same-sign (SS) dilepton
  - Opposite sign (OS) dilepton
  - l+jets
- Interpretations in various NP models
  - tt (same sign top pair)
  - Vector-like quarks
  - 2HDM models (Heavy Higgs)
  - Extra dimensions
  - EFT

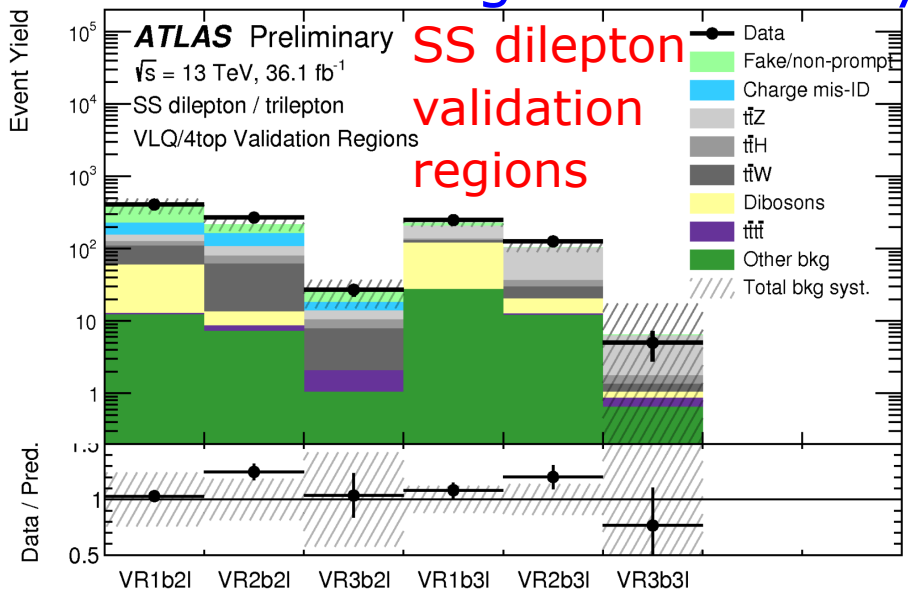




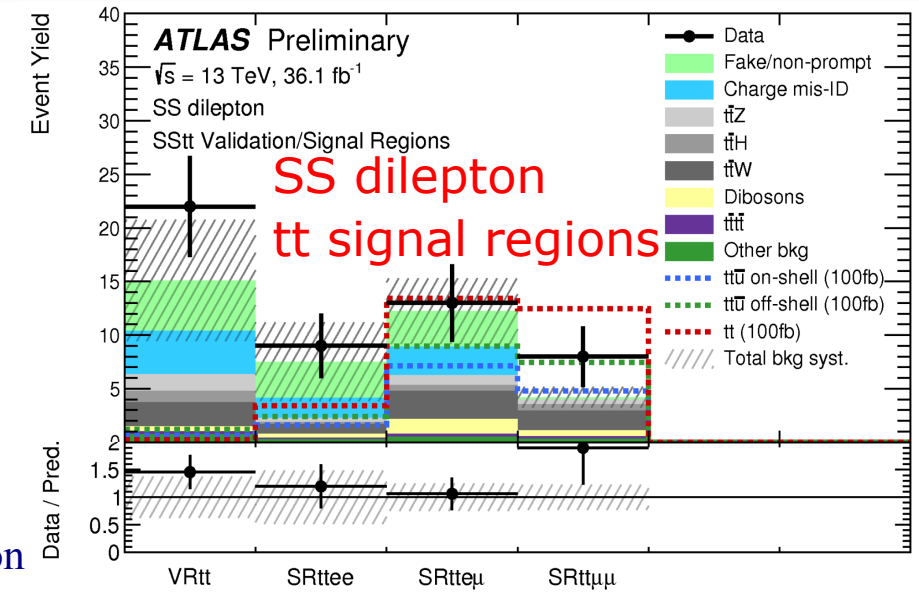
Analysis strategies & SS dilepton event categories

- Selection of events with high-p_T objects (leptons, b-jets, jets, MET)
  - For l+jets & OS dilepton: include mass-tagged reclustered large-R jets
- Divide into various categories
  - Validate background modeling and enhance signal-sensitivity

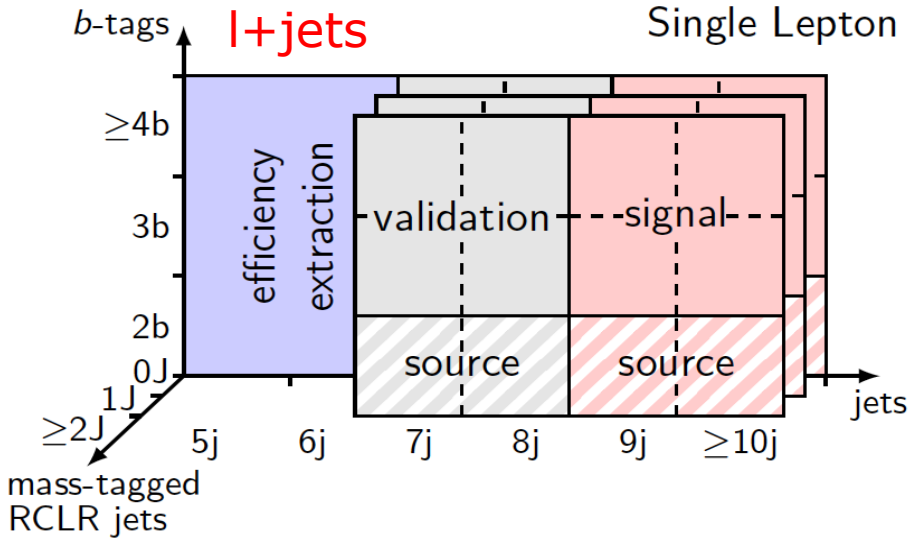


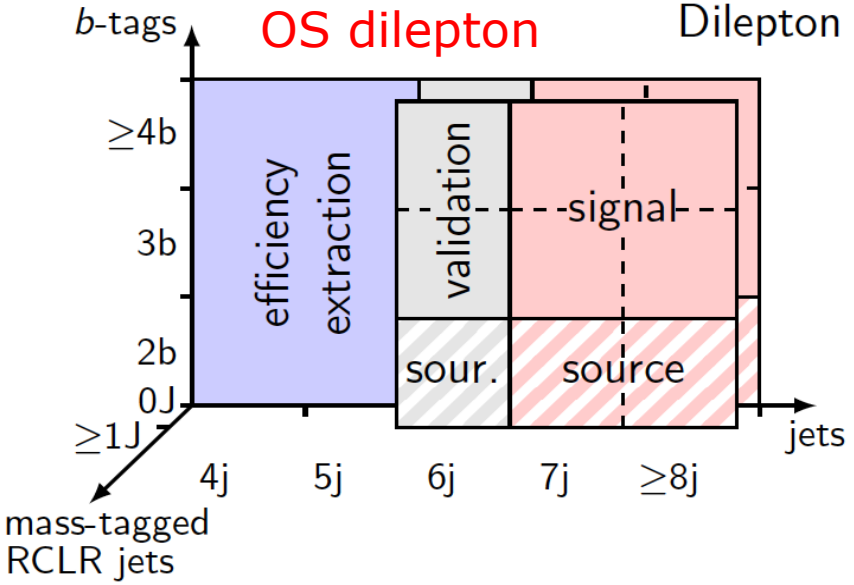


Paper in preparation

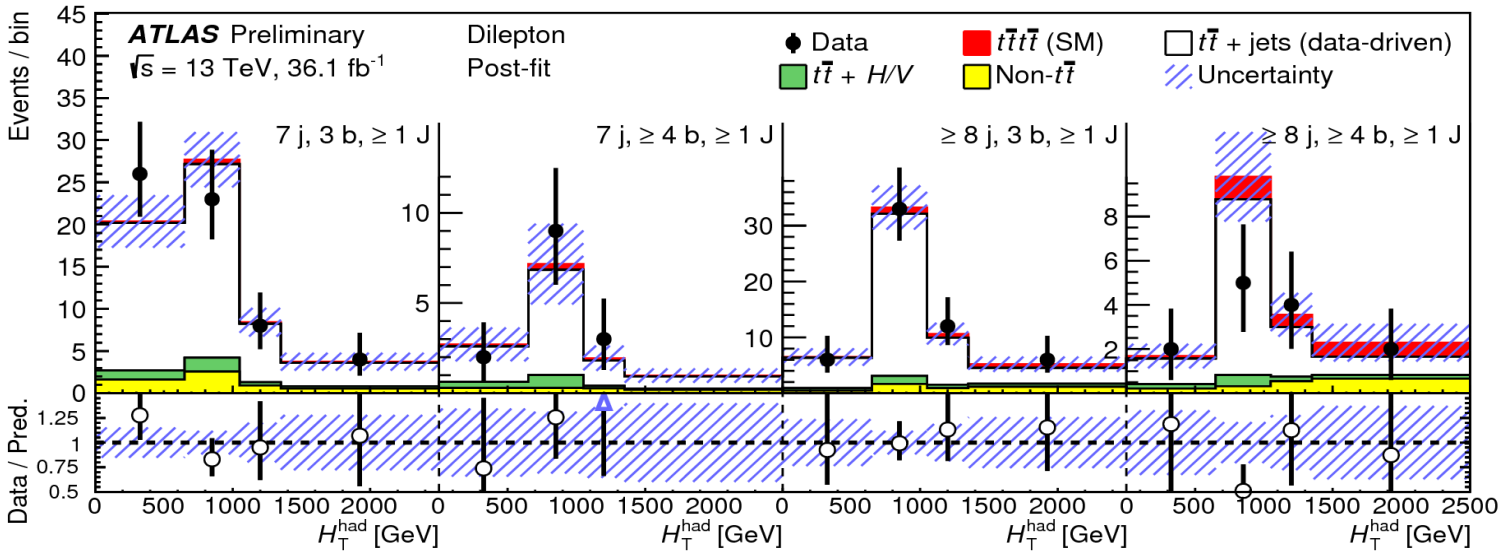


Event Categories OS dilepton & l+jets





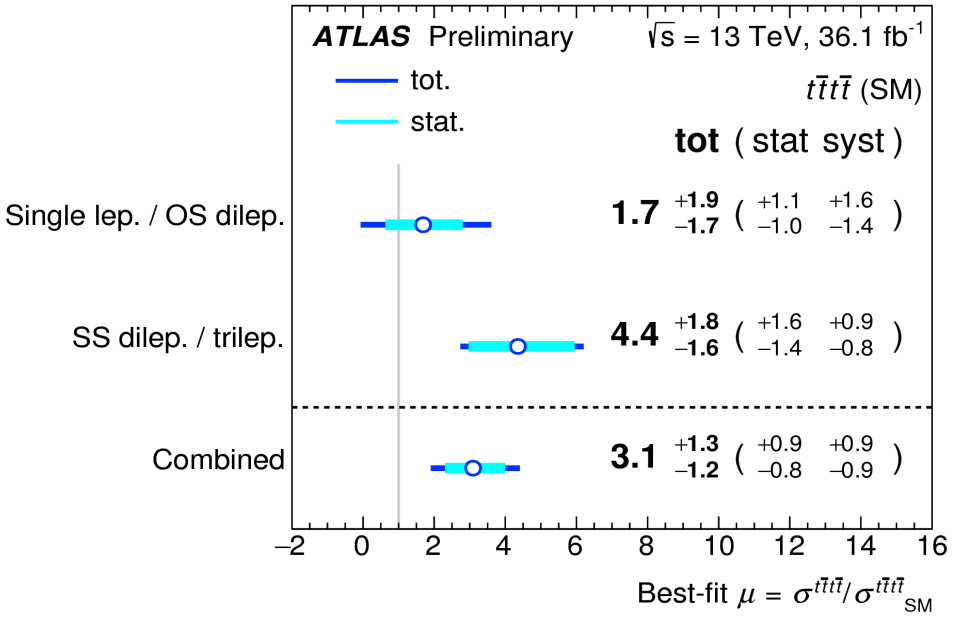
OS dilepton: example event-categories (post-fit)



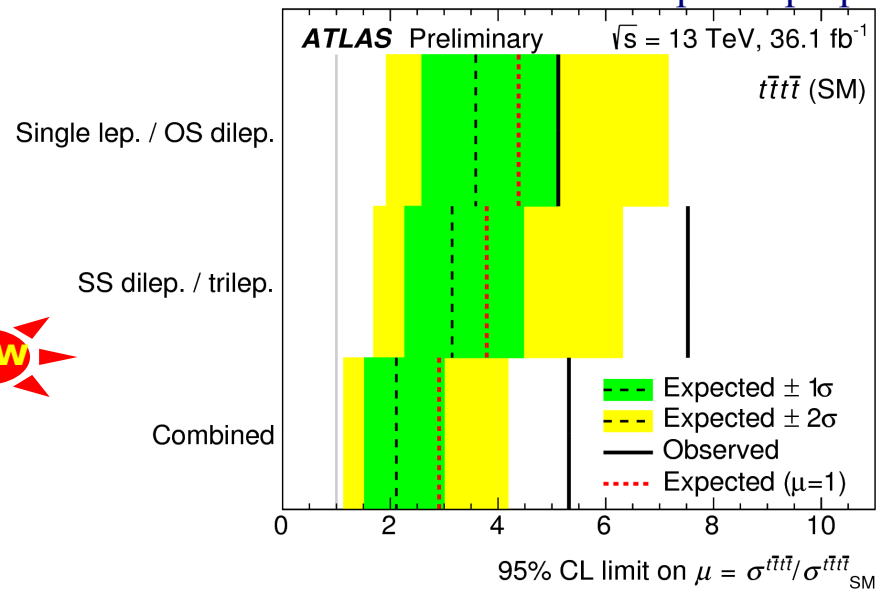
Paper in preparation

Fit: 4top

- L+jets & OS dilepton: profile likelihood fit to H_T^{had} (scalar sum of jet transverse momenta) in all 12 l+jets and 8 OS dilepton signal regions
- SS dilepton: Poisson likelihood ratio test (event counting)
- Combination: full fit to all regions; fully-correlated systematic uncertainties (background-modeling: uncorrelated)



Paper in preparation

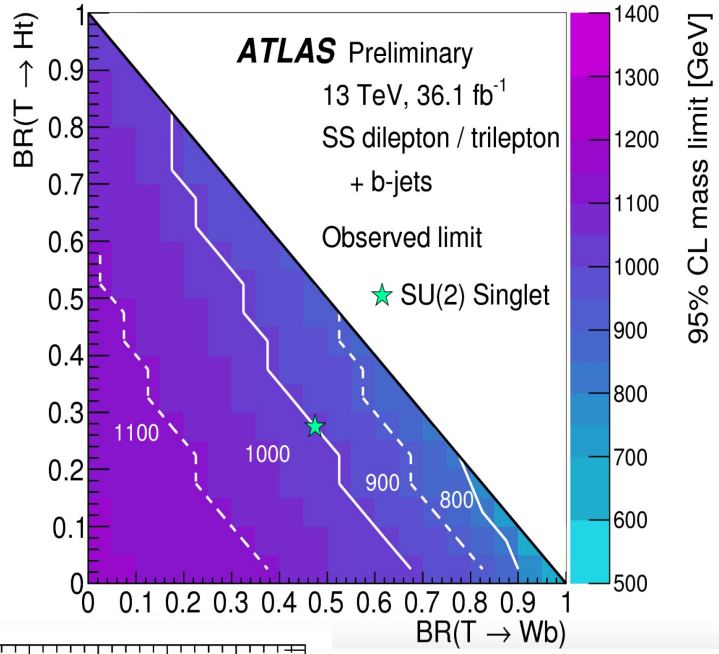


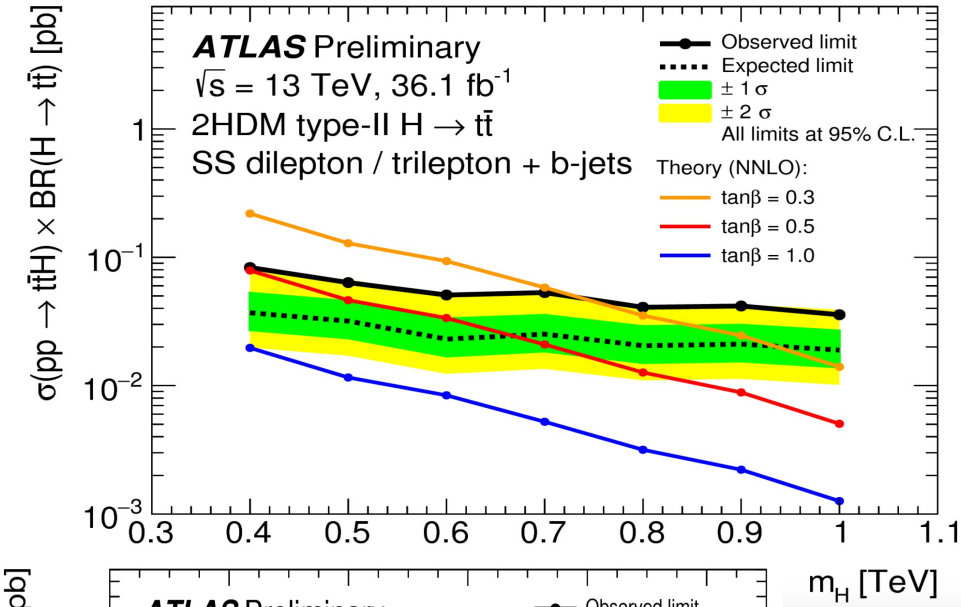
new

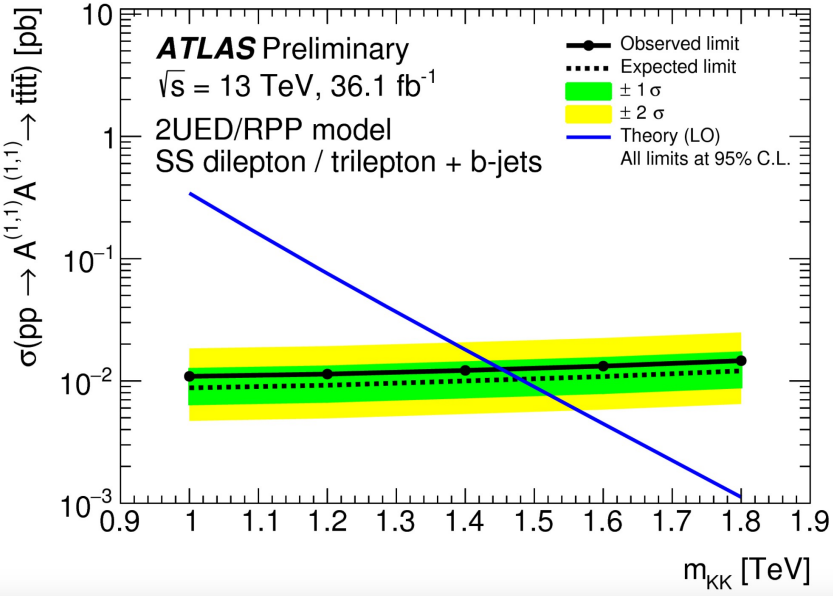
- Combined significance: 2.8σ ("can't help myself" SS dilepton: 3σ)

New Physics interpretations (SS dilepton only)

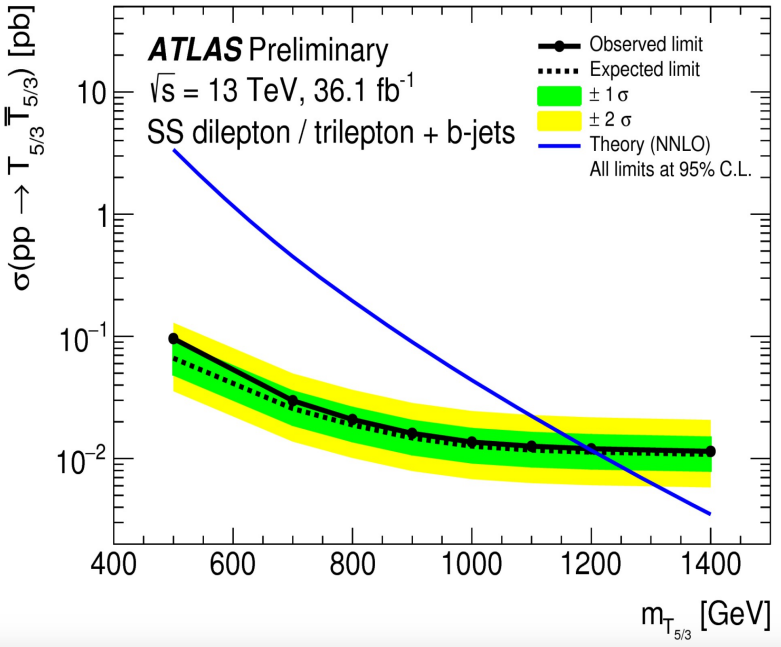
- Plethora of sensitive limits!







Paper in preparation



Summary

- Three recent top results shown → not just "the same old song"
  - Jet pull to explore QCD colour flow information
  - Spin correlations to test full chain from production to decay
  - 4Top searches, sensitive to plethora of new physics
- Colour flow: jet pull a sensitive observable for QCD colour → MC tuning?!
- Spin correlations: 3.7σ (3.2σ) deviation from SM shape for $\Delta\phi$
- 4top: observed value 2.8σ above background-only hypothesis

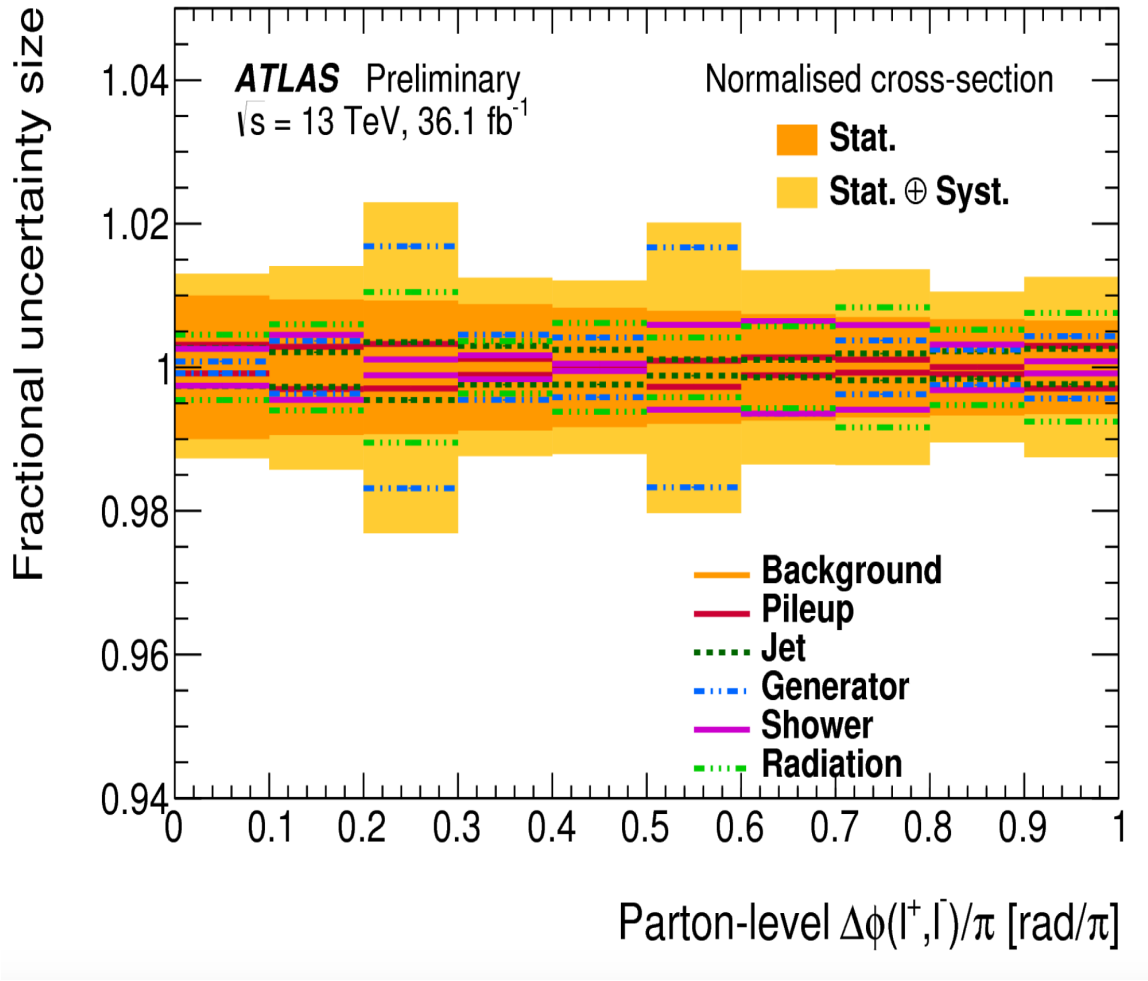
BACKUP

Colour Flow: Systematics

$\Delta\theta_P\left(j_1^W, j_2^W\right)$ [%]	$\theta_P\left(j_1^W, j_2^W\right)$			
	0.0 – 0.21	0.21 – 0.48	0.48 – 0.78	0.78 – 1.0
Hadronisation	0.55	0.13	0.24	0.14
Generator	0.32	0.25	0.50	0.01
b-tagging	0.35	0.13	0.20	0.31
Background model	0.30	0.16	0.16	0.27
Colour reconnection	0.22	0.16	0.16	0.18
JER	0.11	0.12	0.23	0.02
Pile-up	0.19	0.16	0.00	0.01
Non-closure	0.14	0.07	0.07	0.18
JES	0.12	0.06	0.14	0.06
ISR / FSR	0.15	0.02	0.12	0.02
Tracks	0.05	0.04	0.03	0.06
Other	0.02	0.01	0.01	0.02
Syst.	0.88	0.44	0.71	0.51
Stat.	0.23	0.19	0.19	0.25
Total	0.91	0.48	0.73	0.57

Spin correlations: systematics

- Parton level



4top: Systematics breakdown

- For l+jets and OS dilepton

Uncertainty source	$\pm\Delta\mu$	
$t\bar{t}$+jets modeling	+1.2	-0.96
Background-model statistical uncertainty	+0.91	-0.85
Jet energy scale and resolution, jet mass	+0.38	-0.16
Other background modeling	+0.26	-0.20
b-tagging efficiency and mis-tag rates	+0.33	-0.10
JVT, pileup modeling	+0.18	-0.073
$t\bar{t} + H/V$ modeling	+0.053	-0.055
Luminosity	+0.050	-0.026
Total systematic uncertainty	+1.6	-1.4
Total statistical uncertainty	+1.1	-1.0
Total uncertainty	+1.9	-1.7