Measurement of colour flow in $t\bar{t}$ events with the ATLAS detector

ATLAS-CONF-2017-069

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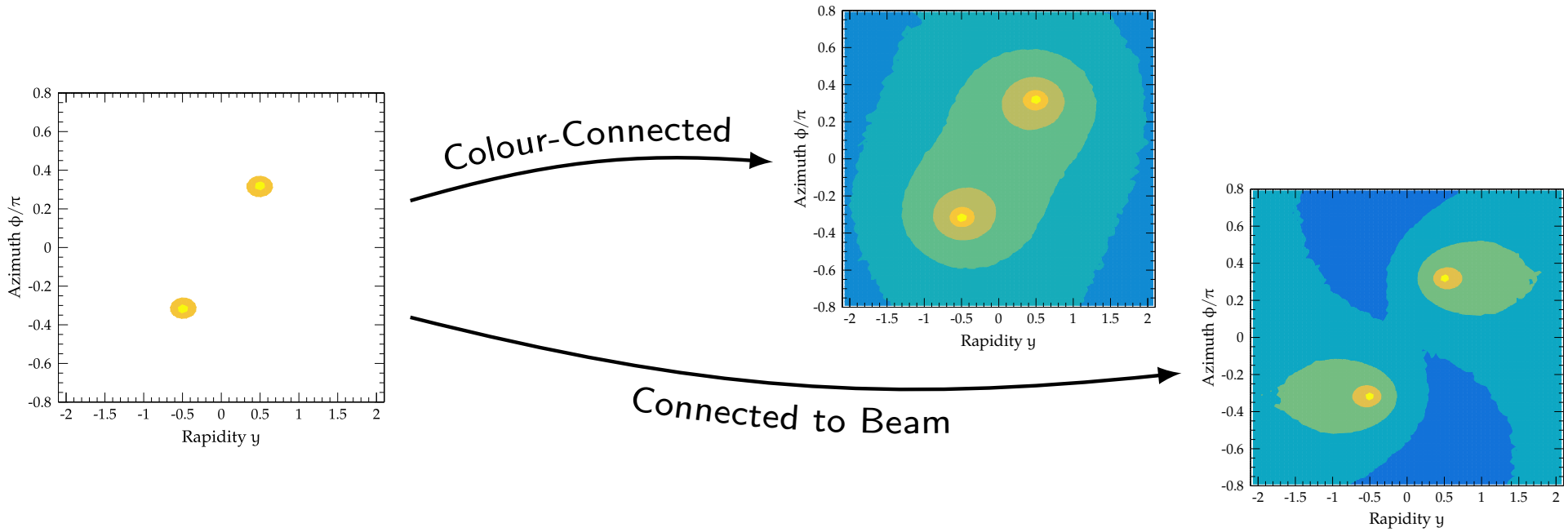
on behalf of the ATLAS collaboration

Introduction

- Colour connection of hard objects affects energy distribution $\underbrace{\textbf{within}}_{\text{jet substructure}}$ and $\overbrace{\textbf{between}}^{\text{jet superstructure}}$ jets



- Goal: Extract information about **connection type** and **properties**
- Can be used for MONTE-CARLO validation / tuning, ...
- Allow to construct truly orthogonal event selection observable
  e.g. for assigning b's in $t\bar{t}H(\rightarrow b\bar{b})$

New first measurement of this type at 13 TeV New

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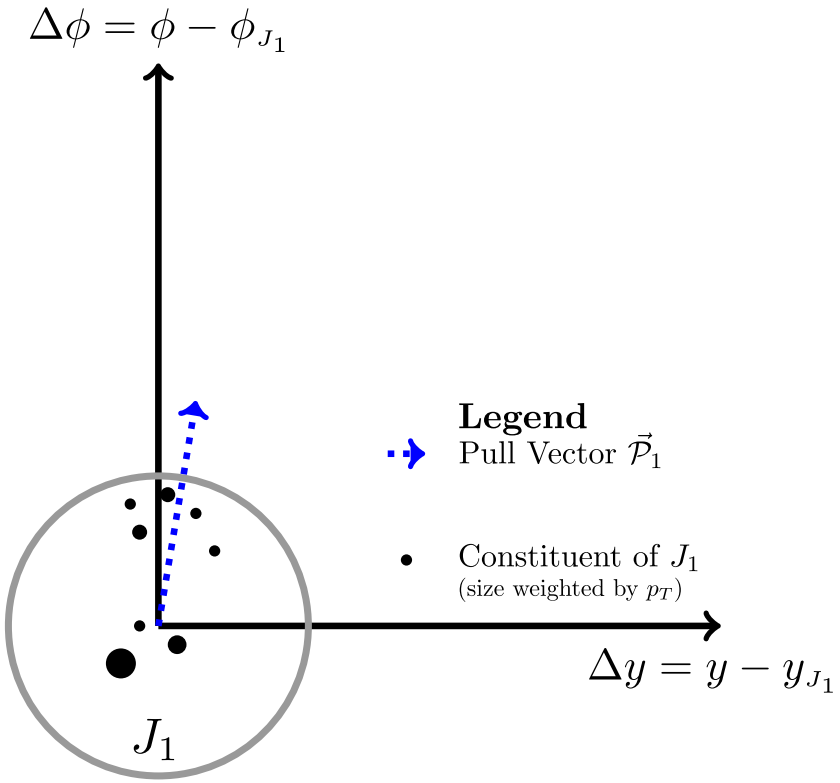
The Jet Pull

- Measure quantities derived from **jet pull vector**
  → p_T-weighted radial jet moment



$$\vec{\mathcal{P}}(J_1) = \sum_{i \in J_1} \frac{p_T^i \cdot |\vec{r}_i|}{p_T^J} \vec{r}_i$$

→ **jet pull vector magnitude** $|\vec{\mathcal{P}}|$

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The Jet Pull

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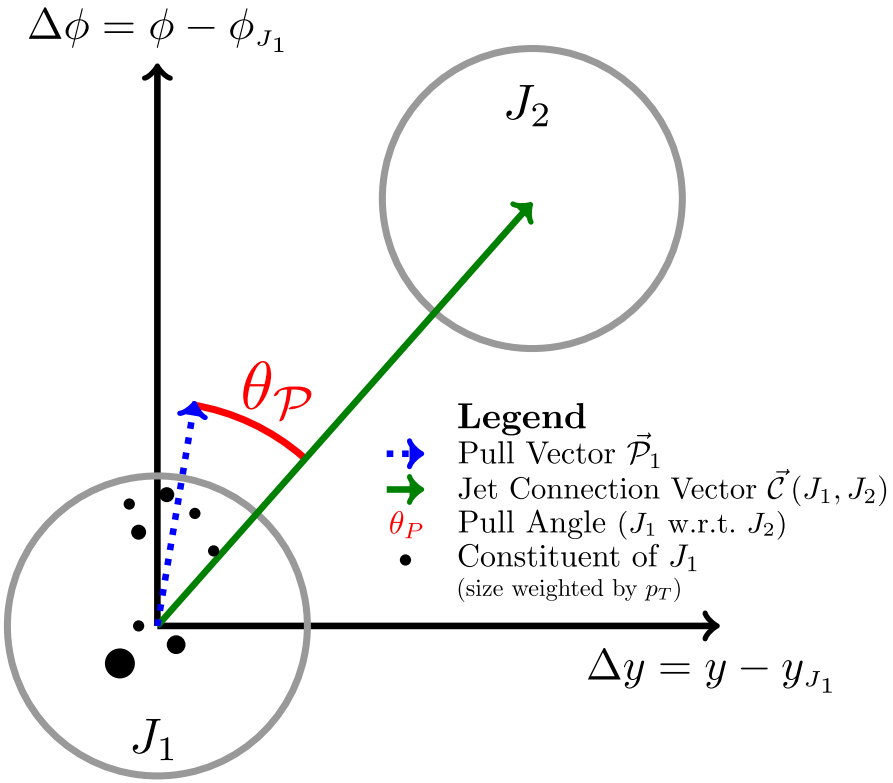

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→ **jet pull vector magnitude** $|\vec{\mathcal{P}}|$

$$\vec{\mathcal{C}}(J_1, J_2) = \vec{J}_2 - \vec{J}_1$$

$$\theta_{\mathcal{P}}(J_1, J_2) = \sphericalangle\left(\vec{\mathcal{P}}(J_1), \vec{\mathcal{C}}(J_1, J_2)\right)$$

→ **jet pull angle** $\theta_{\mathcal{P}}$

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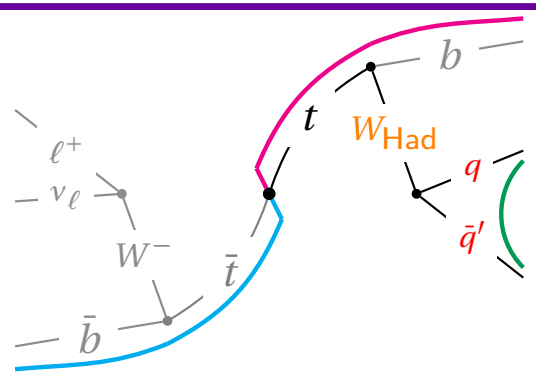
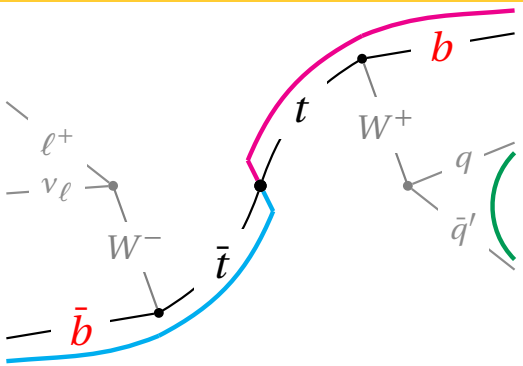
Analysis Strategy

1. Apply event selection for $t\bar{t} \to \ell + \text{jets}$ signal
2. Select target jets for calculation



- Probe true colour connection
- Select two leading non-b-tagged jets: j_1^W, j_2^W



- Probe remnant colour flow across event
- Select two leading b-tagged jets: j_1^b, j_2^b

3. Calculate observables for selected jets, measure detector-level spectra
   → Use jet-associated tracks, previous measurement w/ calo clusters ▷ Phys. Lett. B750 475

$\theta_{\mathcal{P}}\left(j_1^W, j_2^W\right)$ $\theta_{\mathcal{P}}\left(j_2^W, j_1^W\right)$ New $|\vec{\mathcal{P}}\left(j_1^W\right)|$ New

$\theta_{\mathcal{P}}\left(j_1^b, j_2^b\right)$ New

4. Remove detector effects from measurement by unfolding to particle-level
   → use D'Agostini iterative bayesian technique
5. Compare normalised particle-level spectra to simulation-based predictions

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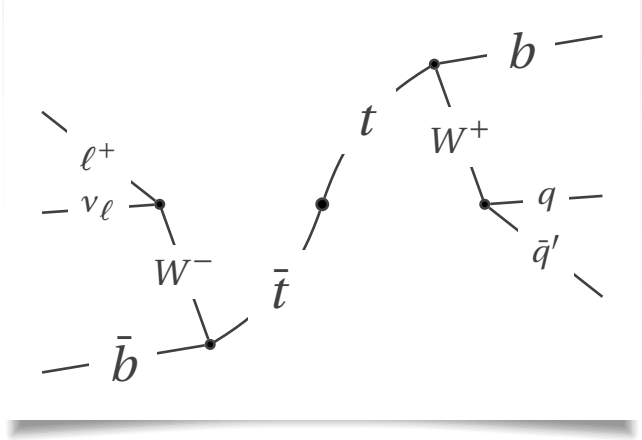
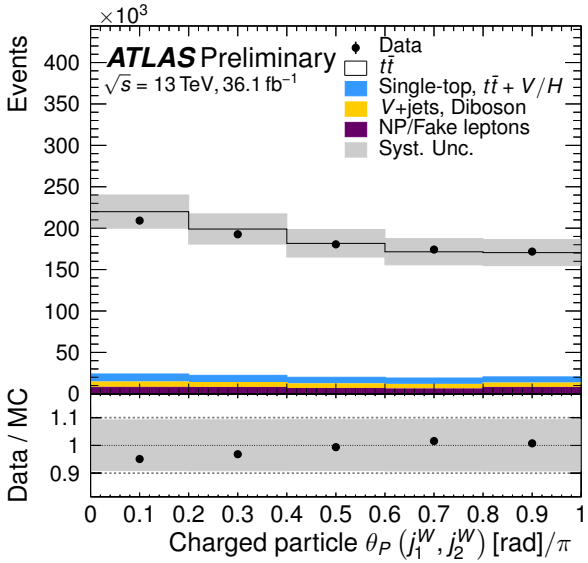
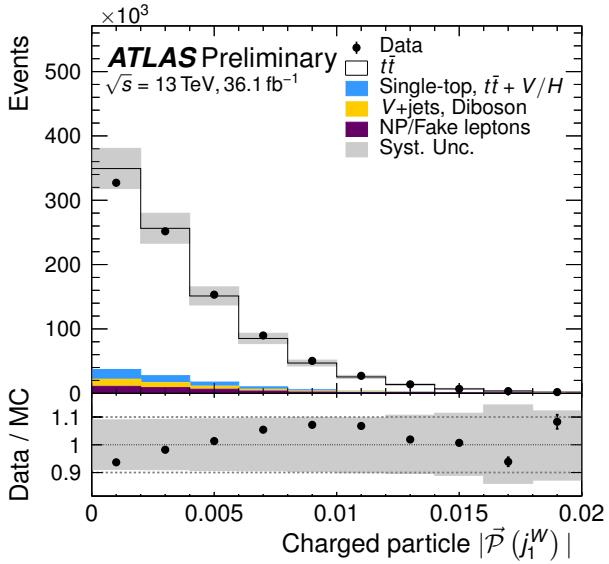
Selection

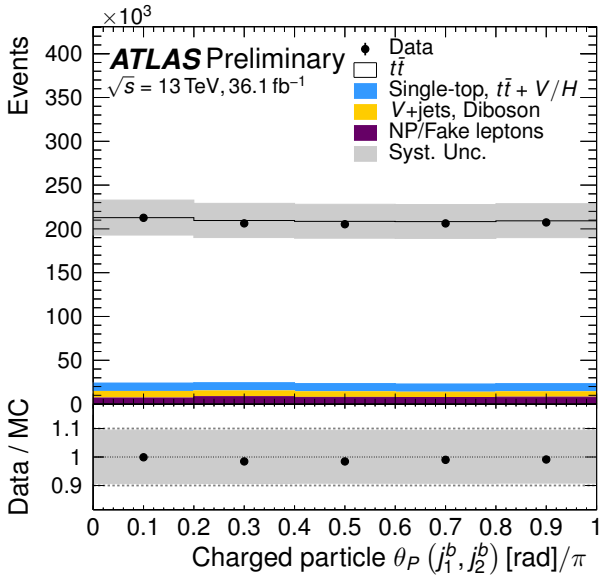


Event Selection

- ✂ $==1$ lepton ($p_T > 27\,\text{GeV}$, $|\eta| < 2.5$)
- ✂ $==0$ veto lepton ($p_T > 25\,\text{GeV}$, $|\eta| < 2.5$)
- ✂ ≥ 4 jets ($p_T > 25\,\text{GeV}$, $|\eta| < 2.5$)
- ✂ ≥ 2 b-tags (70 % eff. WP)
- ✂ $E_T^{\text{Miss}} > 20\,\text{GeV}$







→ estimated signal fraction ~ 89 %

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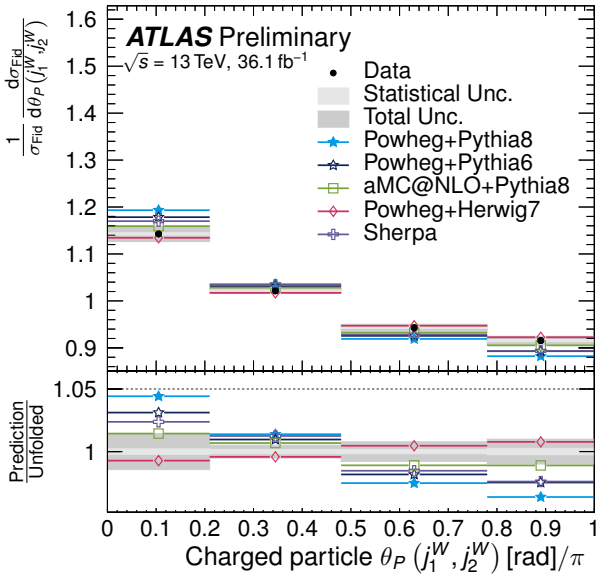
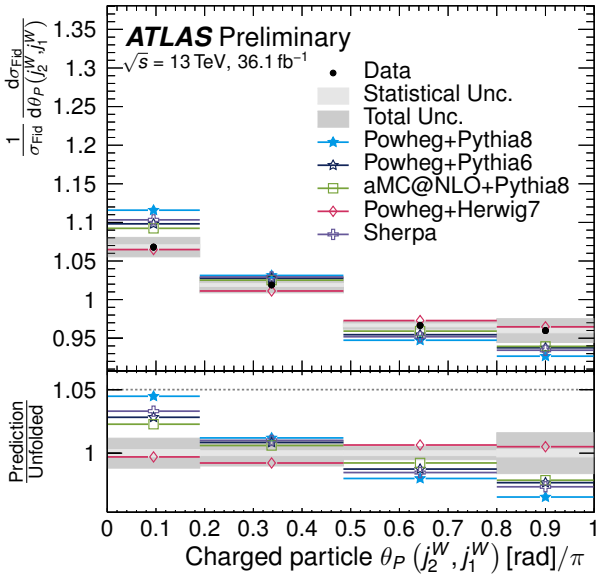
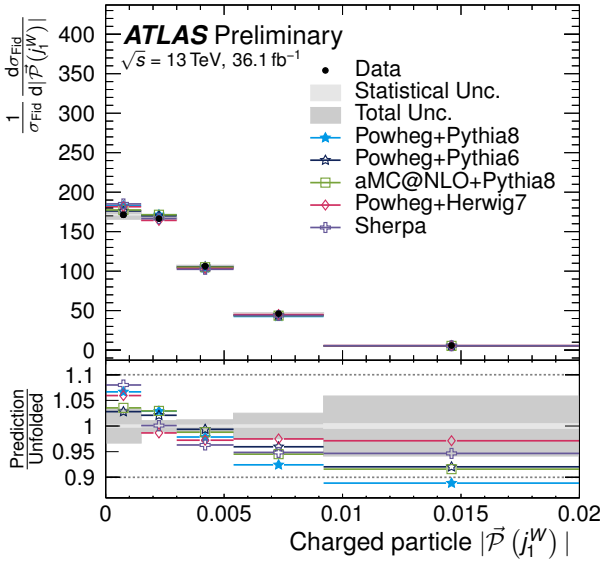
Results







- Uncertainties dominated by signal modelling
- Statistical uncertainty sub-dominant

Angle: Predictions suggest stronger effect than observation
→ more sloped pull angle

Magnitude: Data favours larger value
→ "wider" jets

- Mostly poor modelling from MCs
- Powheg+Herwig7 generally does a good job

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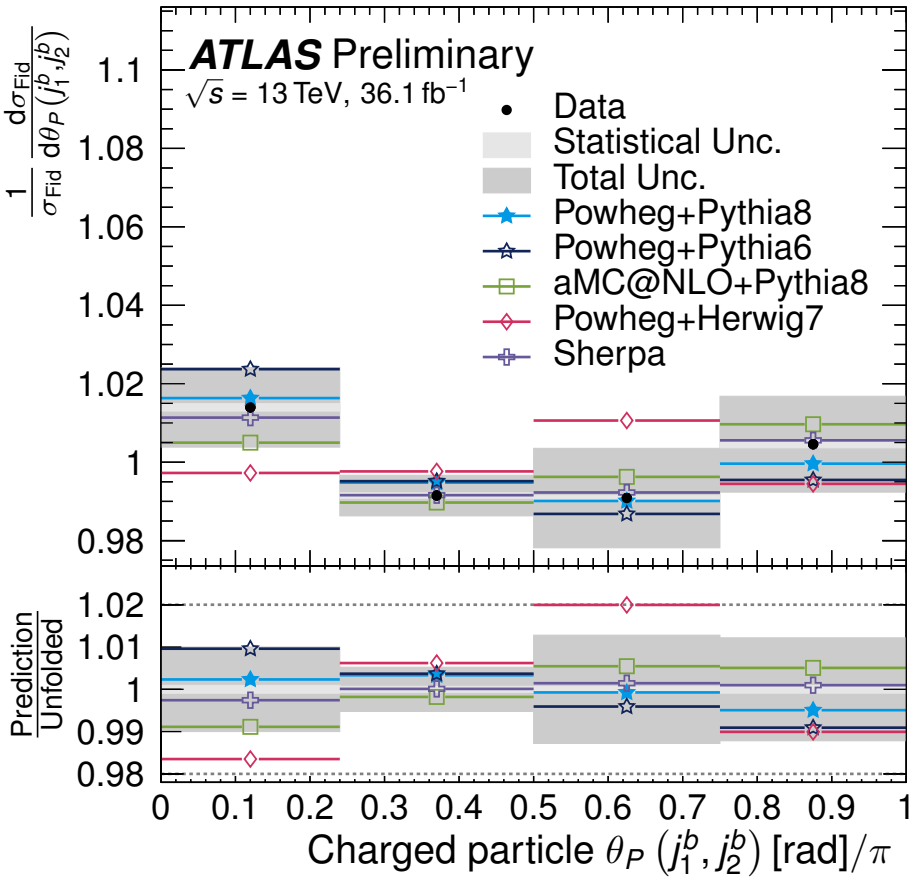
Results

- Uncertainties dominated by signal modelling
- Statistical uncertainty sub-dominant
- As expected, very flat distribution
- Agreement reversed:
  - Powheg+Herwig7 models observation poorly
  - Other predictions offer much better description



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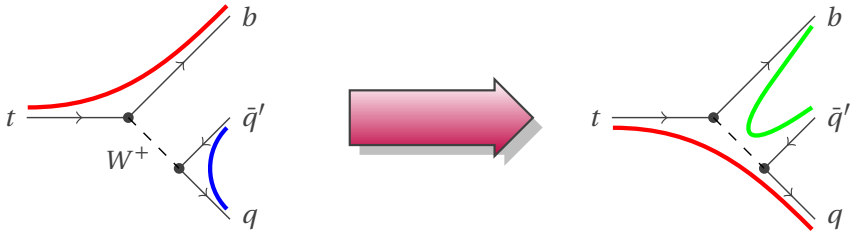
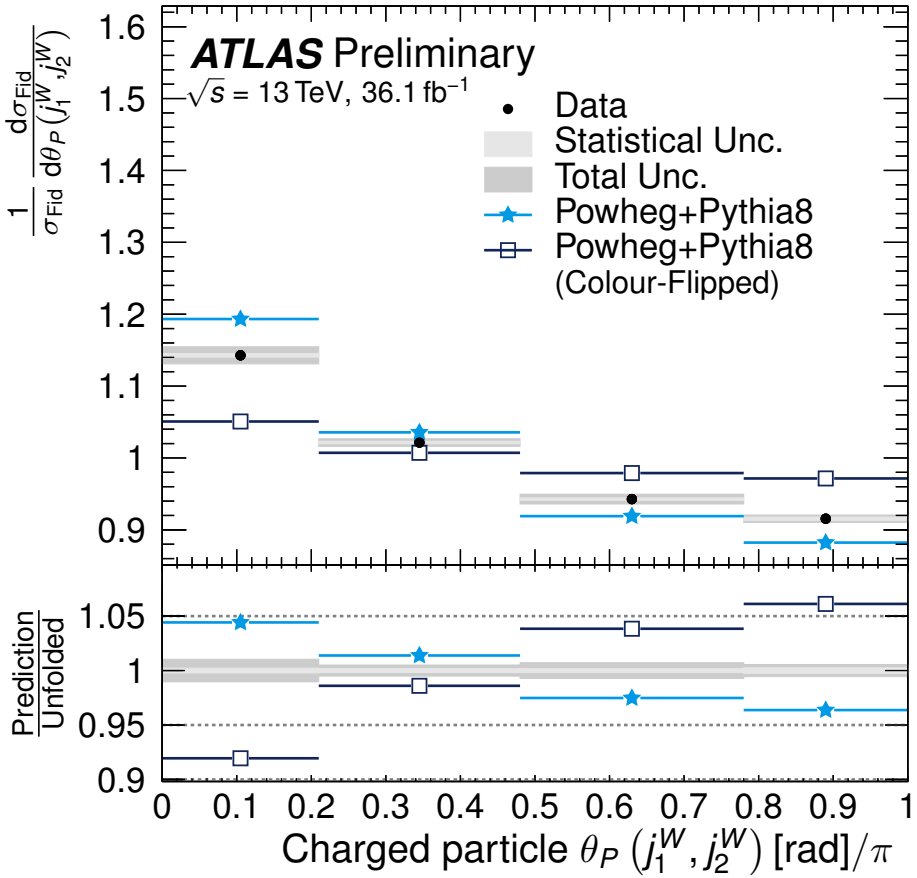
Results

- Comparison to maximally violating exotic ("colour-flipped") colour flow model:
  replace W_{Had} by ad-hoc colour-octet



- Predicted colour flow shows significantly less sloped pull angle



- Goodness-of-fit tests show data prefers SM-like distribution over exotic
  ... but Powheg+Pythia8 does not provide a good description either

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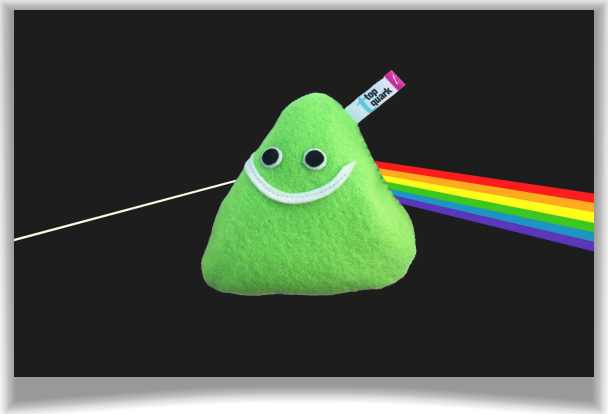
Conclusion



- A measurement of colour flow using jet pull properties with 36.1 fb^{-1} of 13 TeV pp data measured by the ATLAS experiment was presented
- Detector-level spectra are unfolded to particle-level using iterative bayesian technique
- Normalised fiducial spectra are compared to various predictions obtained from MC

- An **improved precision** respective to 8 TeV measurement is achieved
- Several Monte-Carlo predictions show poor modelling of jet pull vector properties
  → We can barely exclude the exotic colour model against our SM predictions
- **No one-fits-all prediction**:
  → Powheg+Herwig7 offers best description of pull angle from W-jets but worst for b-jets

- Measurement uncertainty dominated by signal modelling uncertainties
- Low statistical uncertainty suggests **future doubly-differential measurement**

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Backup

Event Selection Yields

Sample	Yield		
$t\bar{t}$	1 026 000	$\pm$	95 000
$t\bar{t}V$	3270	$\pm$	250
$t\bar{t}H$	1711	$\pm$	97
Single-top	48 400	$\pm$	5500
Diboson	1440	$\pm$	220
$W+$jets	27 700	$\pm$	4700
$Z+$jets	8300	$\pm$	1400
NP/Fake leptons	53 000	$\pm$	30 000
Total Expected	1 170 000	$\pm$	100 000
Observed	1 153 003		

$\rightarrow$ estimated signal fraction $\sim 89\,\%$

Systematic Uncertainty Breakdown

$\Delta\theta_P\left(j_1^W, j_2^W\right)$ [%]	$\theta_P\left(j_1^W, j_2^W\right)$			
	$0.0 - 0.21$	$0.21 - 0.48$	$0.48 - 0.78$	$0.78 - 1.0$
Hadronisation	0.63	0.22	0.27	0.09
Generator	0.37	0.24	0.50	0.06
Colour Reconnection	0.11	0.26	0.03	0.53
b-Tagging	0.35	0.12	0.20	0.31
Non-Closure	0.25	0.07	0.08	0.30
ISR / FSR	0.32	0.12	0.15	0.01
Other	0.25	0.20	0.11	0.18
JER	0.12	0.13	0.21	0.03
JES	0.13	0.06	0.13	0.07
Tracks	0.09	0.04	0.05	0.07
Syst.	0.97	0.52	0.68	0.72
Stat.	0.22	0.18	0.17	0.26
Total	0.99	0.55	0.71	0.76

- Signal modelling uncertainties (generator, hadronisation, . . .) evaluated using alternate MC

χ^2 Goodness-of-Fit Test Results

Sample	$\theta_{\mathcal{P}}(j_1^W, j_2^W)$		$\theta_{\mathcal{P}}(j_2^W, j_1^W)$		$\theta_{\mathcal{P}}(j_1^b, j_2^b)$		$\lvert\vec{\mathcal{P}}(j_1^W)\rvert$	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg+Pythia8	50.7 / 3	< 0.001	20.5 / 3	< 0.001	1.5 / 3	0.690	26.2 / 4	< 0.001
Powheg+Pythia6	24.0 / 3	< 0.001	8.2 / 3	0.041	3.0 / 3	0.385	9.7 / 4	0.045
aMC@NLO+Pythia8	6.2 / 3	0.104	4.6 / 3	0.200	1.9 / 3	0.597	18.4 / 4	0.001
Powheg+Herwig7	2.5 / 3	0.478	2.1 / 3	0.543	5.7 / 3	0.128	10.0 / 4	0.041
Sherpa	23.4 / 3	< 0.001	11.7 / 3	0.008	0.2 / 3	0.974	14.6 / 4	0.006
Powheg+Pythia8$\star$	21.0 / 3	< 0.001	20.5 / 3	< 0.001	0.9 / 3	0.821	13.0 / 4	0.011
Flipped Powheg+Pythia8$\star$	48.1 / 3	< 0.001	35.6 / 3	< 0.001	2.8 / 3	0.427	18.5 / 4	< 0.001

When comparing the data with the prediction for the exotic flipped colour flow model, the model itself is considered as an additional source of signal modelling uncertainty and thus added to the covariance matrix. Calculations which include this additional systematic are marked with $\star$.