Colour Flow with Jet Pull

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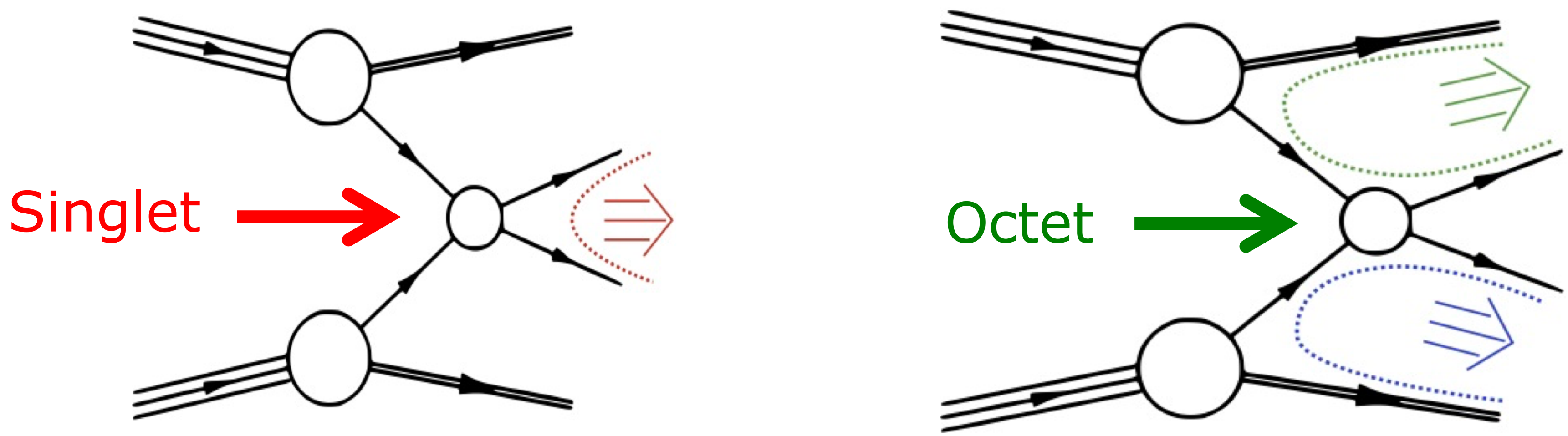
The University of Manchester

Colour Flow between Jets

- Jets carry colour, and are thus colour connected to other colour-charged objects
  - Pairing of connection depends on nature of decaying particles



- Particles created during hadronization should be concentrated along angular region spanned by the colour connected partons
  - Transverse jet profiles should not be round
  - Shape influenced by direction of colour flow!

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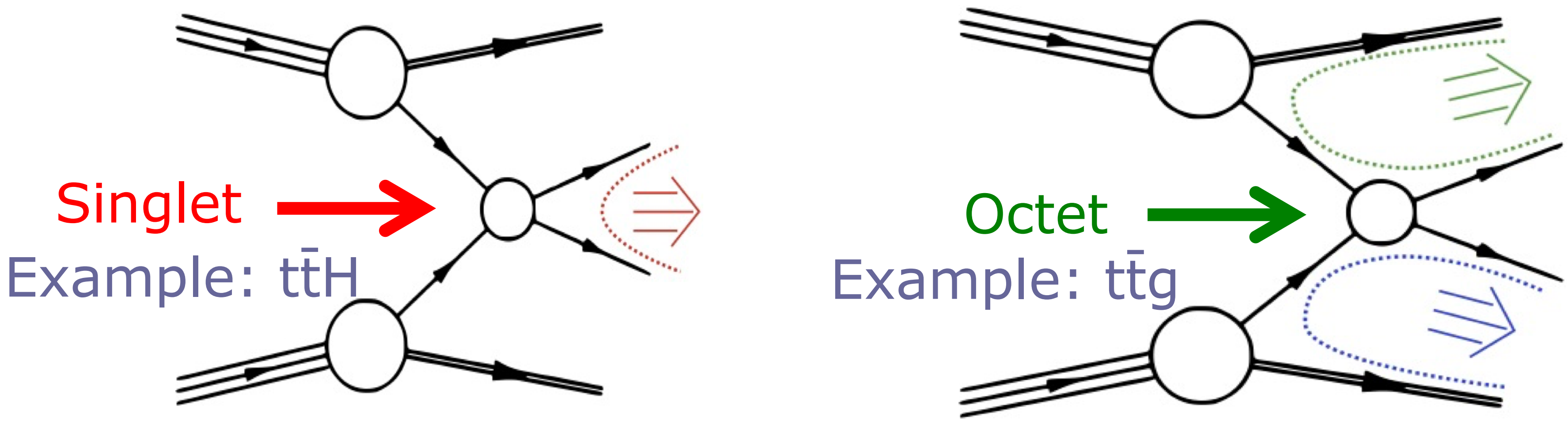

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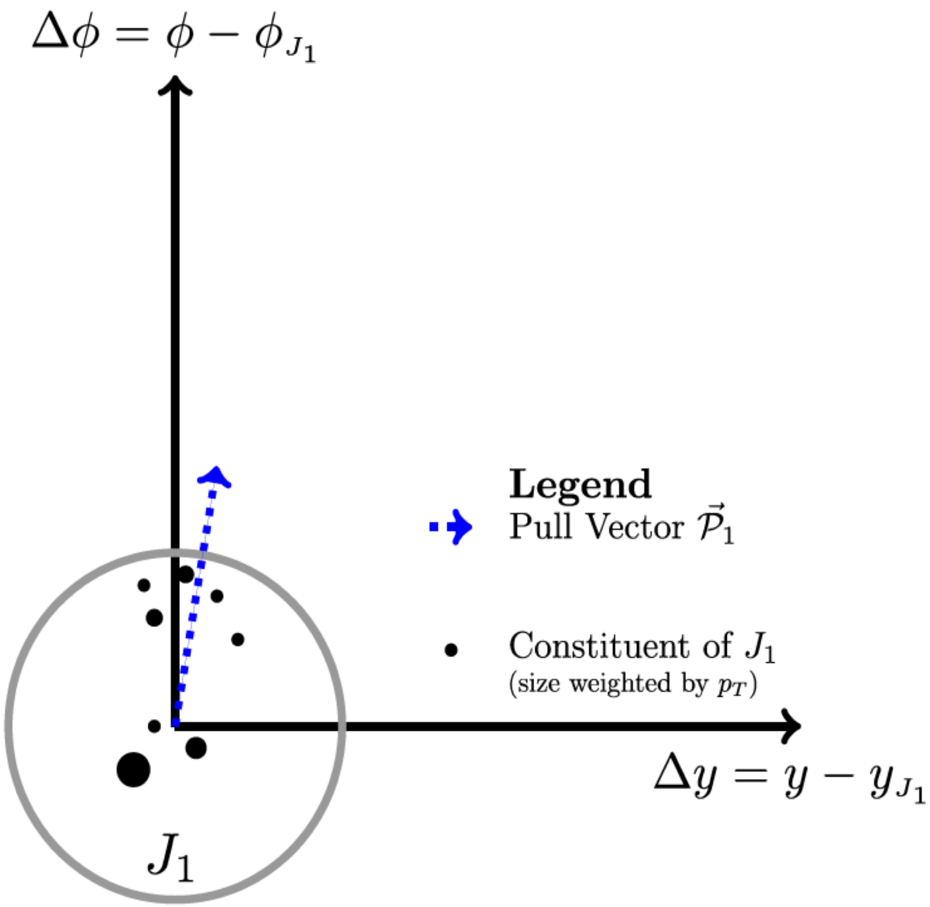
Colour Flow Observable

- Construct a local observable, constructed from particles within a chosen jet: Jet pull
- Pick a pair of jets in the event
- Build vectorial sum of jet components:

$$\vec{p} = \sum_i \frac{E_T^i \mid r_i \mid}{E_T^{jet}} \vec{r_i}$$

  - $\vec{r_i}$: position of jet component i relative to center of jet
  - E_T^i: transverse energy of component i
  - E_T^{Jet}: transverse energy of jet



Gallicchio, Schwartz, PRL 105, 022001 (2010)

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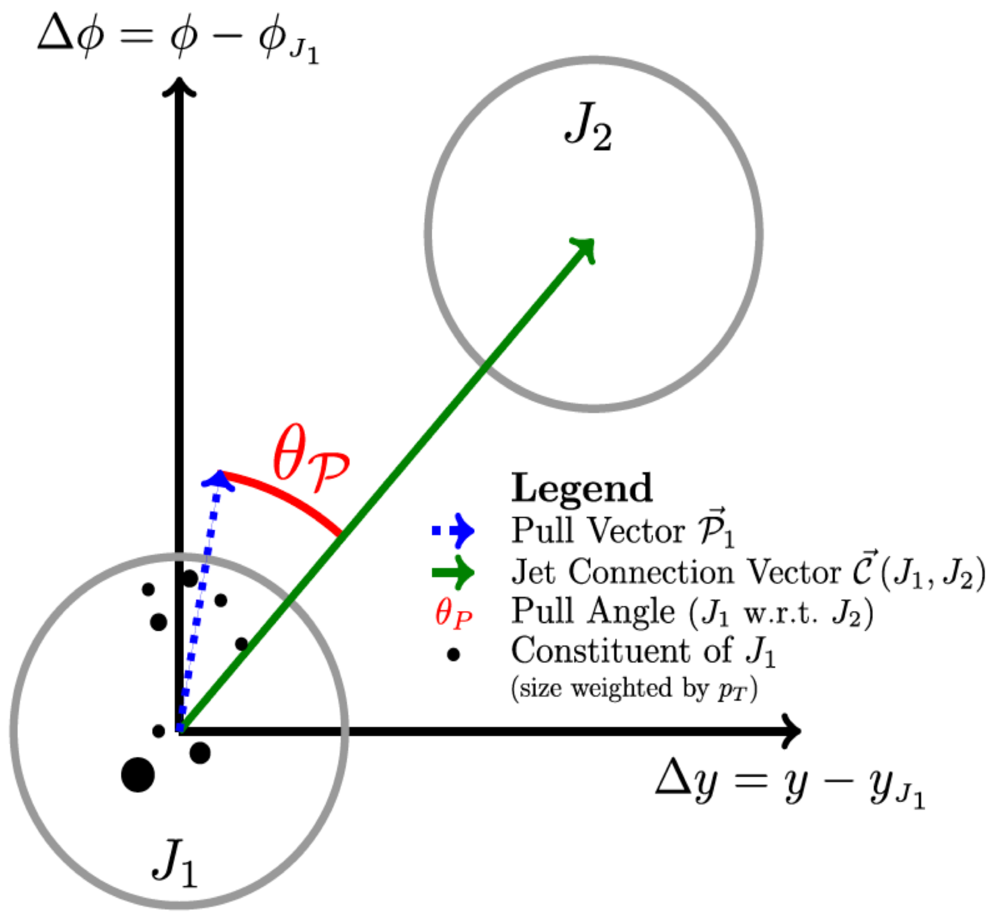
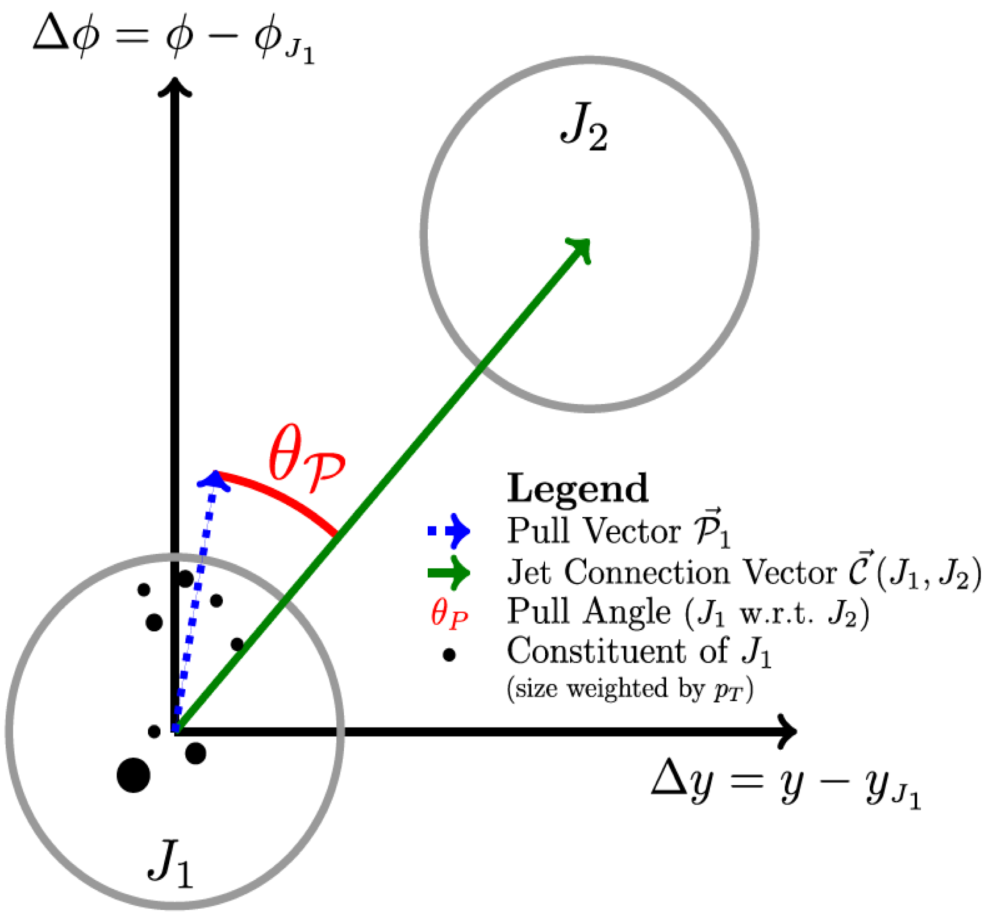


Gallicchio, Schwartz, PRL 105, 022001 (2010)

Colour Flow Observable

- Chosen particles can be constructed from:
  - Clusters of calorimeter cells
    - Gives energy components
  - Or tracks ("charged-particles pull")
    - Momentum instead of energy sum

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



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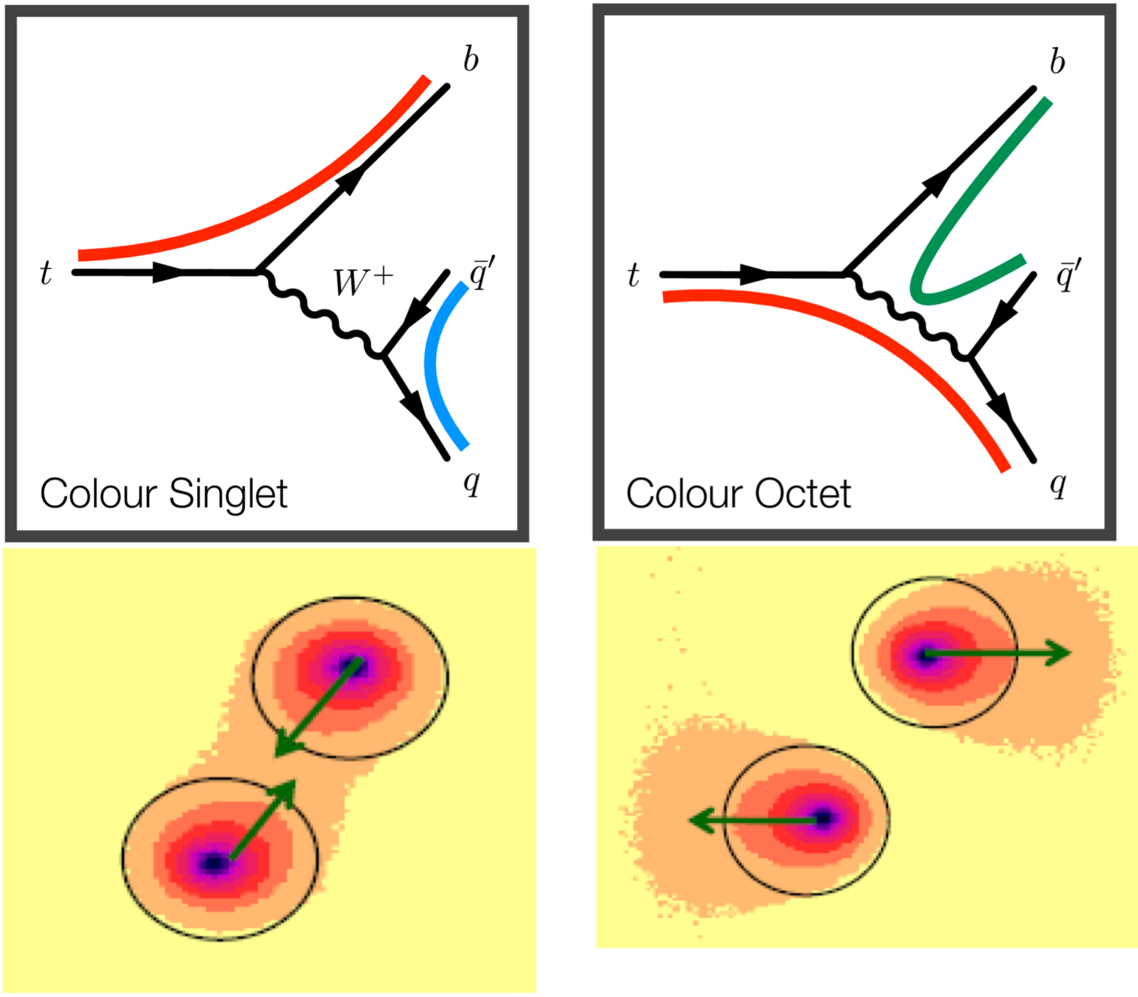
  - $\vec{r_i}$: position of jet component i relative to center of jet
  - p_T^i: transverse momentum of component i
  - p_T^{Jet}: transverse momentum of jet
- Earlier ATLAS analysis showed: charged-particle pull has better sensitivity due to better track resolution

PLB 750, 475-493 (2015)

Colour Flow in Top

- Use top events as laboratory to test new tools

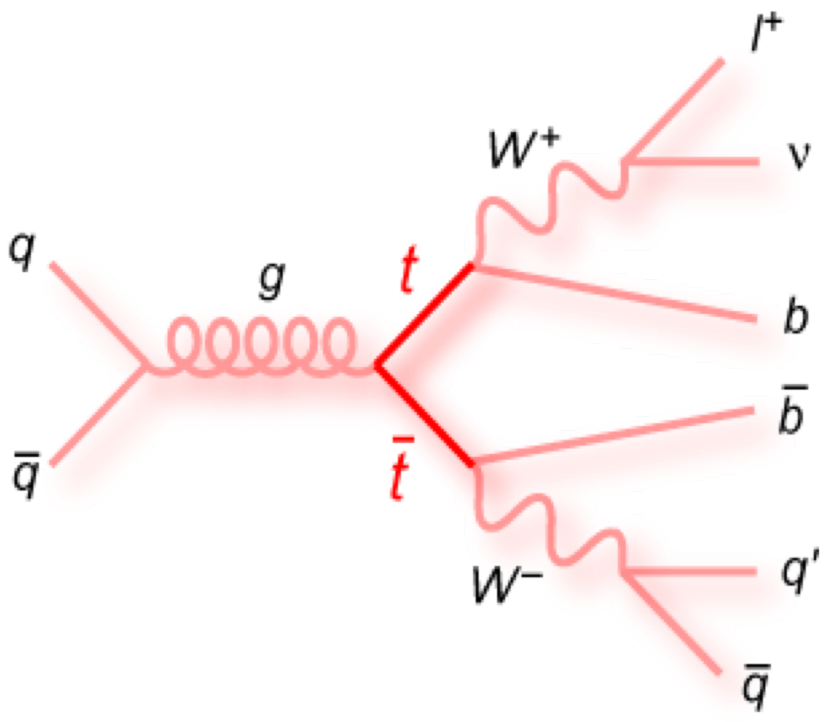
Gallichio, Schwartz,
PRL 105, 022001 (2010)



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

Event Selection

- Select semileptonic $t\bar{t}$ events
  - Clean sample for colour flow studies
  - 2 jets from W boson: jets from colour singlet



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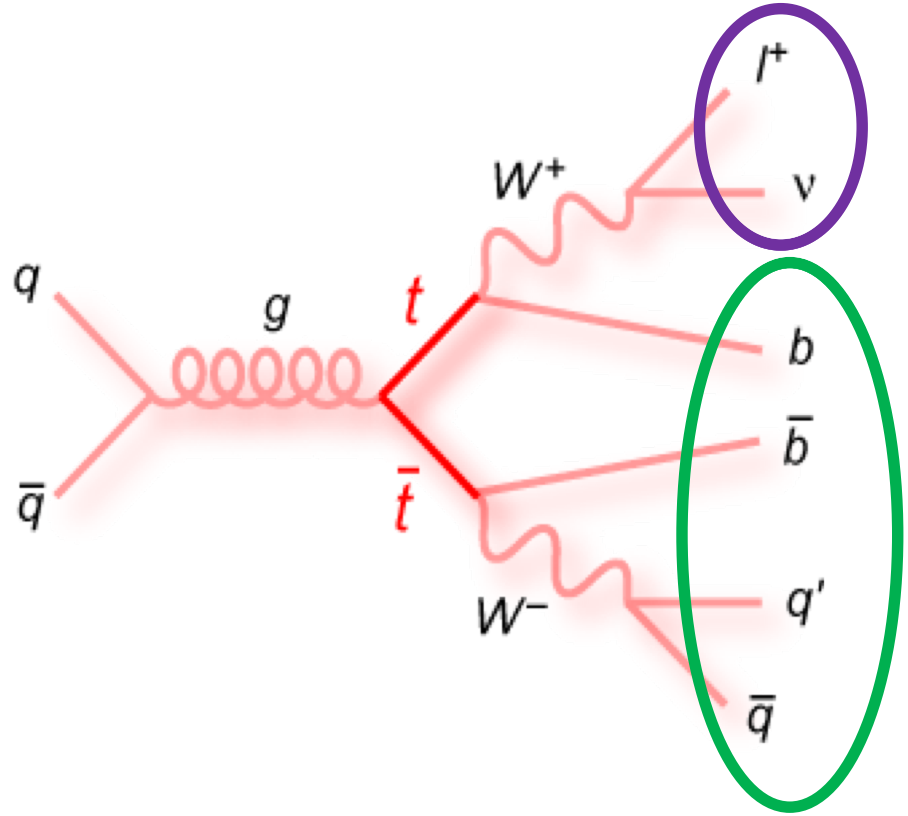

Exact 1 charged electron or muon

Missing transverse energy from neutrino

At least 4 jets

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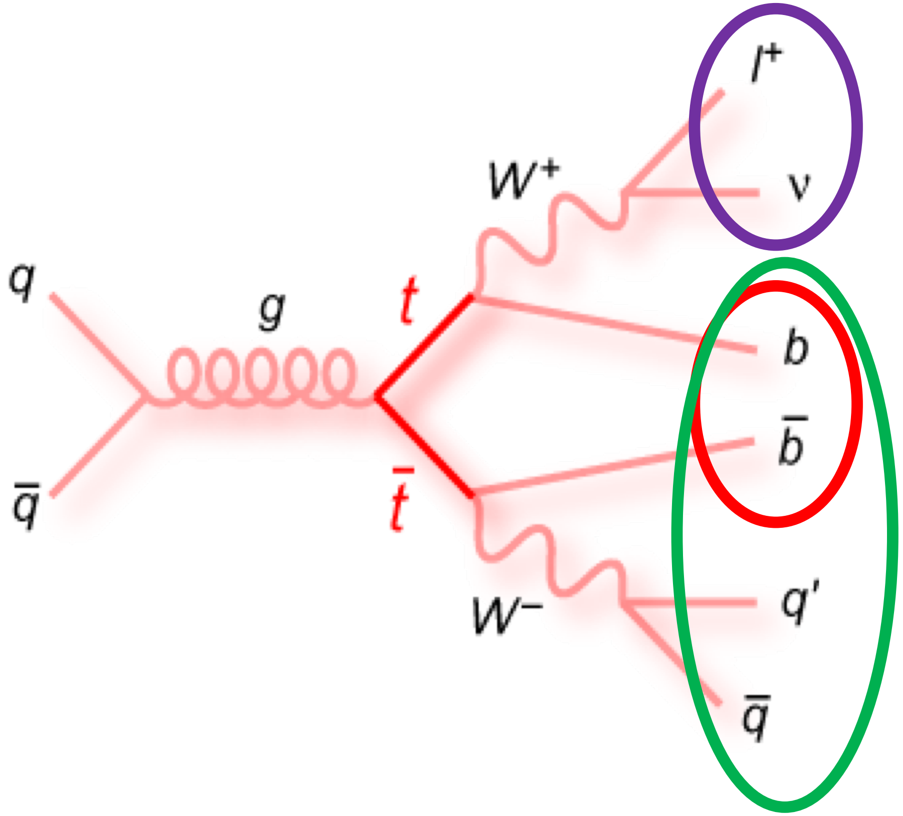

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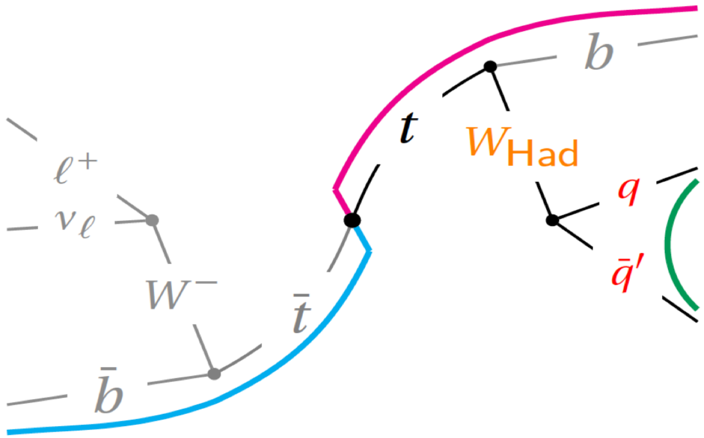
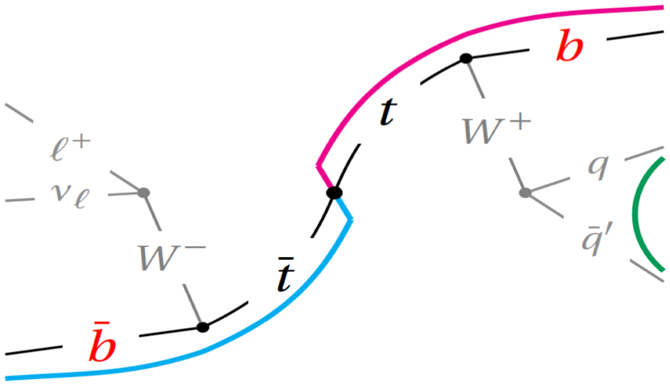
At least 2 of the jets b-tagged (jets identified as coming from hadonisation of b quark)

Colour Flow in Top

- Consider 4 observables in latest ATLAS 13 TeV analysis



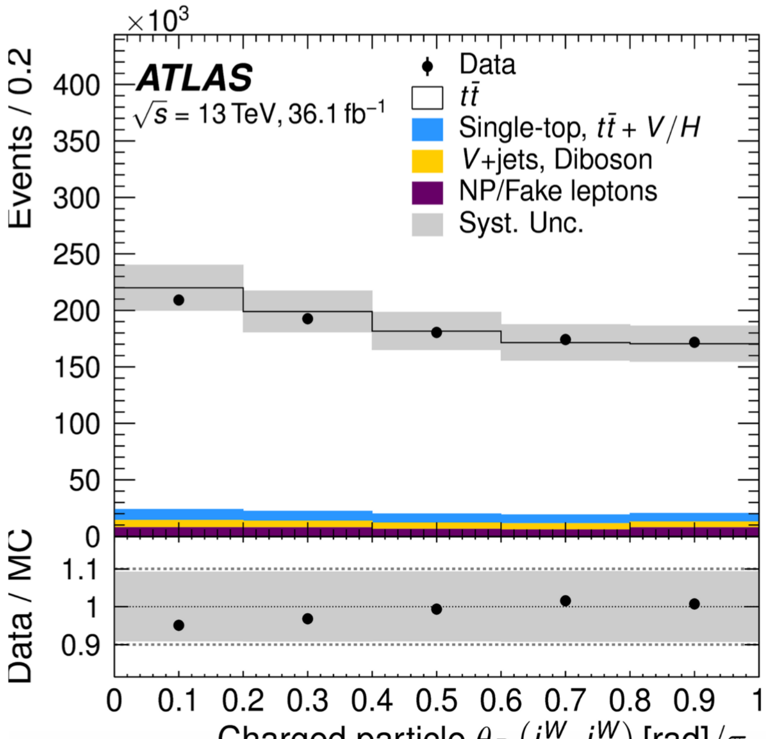
- Two non-b-tagged jets:
  - Relative jet pull angles
    - From highest-p_T jet to 2^{nd} highest and vice versa
  - Jet pull magnitude

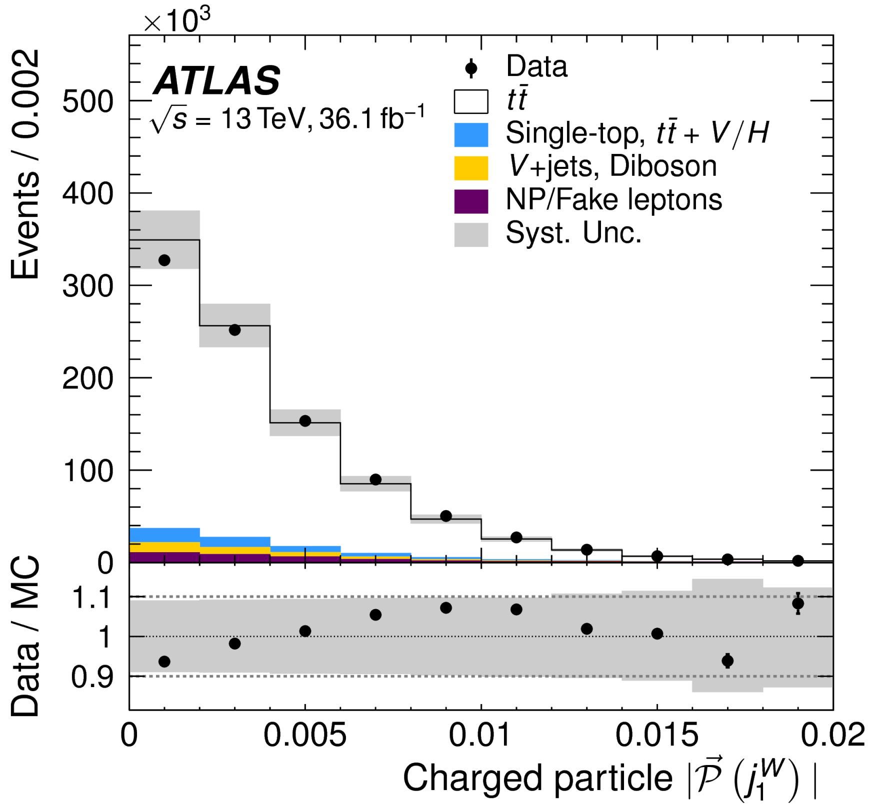


- Two b-tagged jets
  - Relative jet pull angle

Signal and Background

- Event selection results in sample rich in $t\bar{t}$ events
- Background-modeling:
  - Most backgrounds modeled with MC and theory prediction
  - Fake leptons modeled with data-driven method





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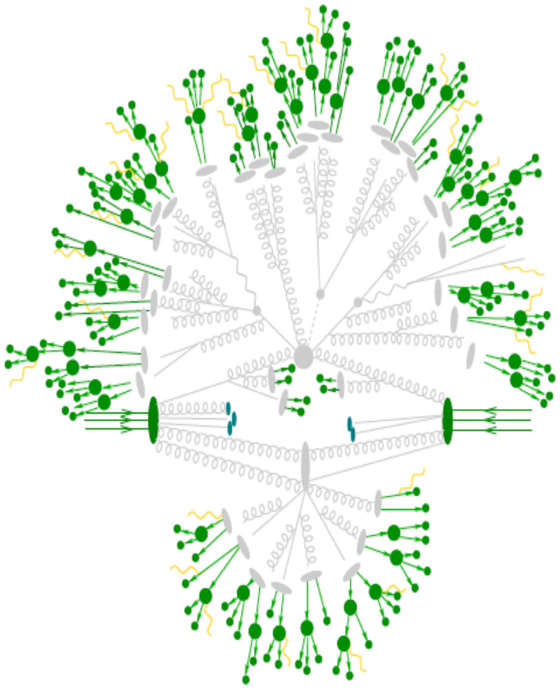
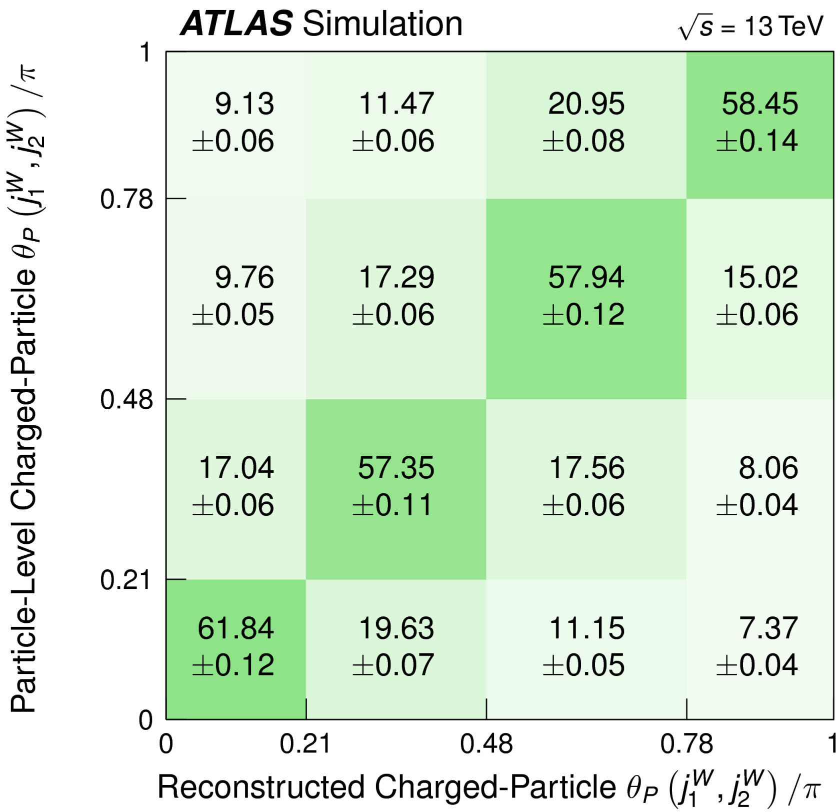
Particle-level and Corrections

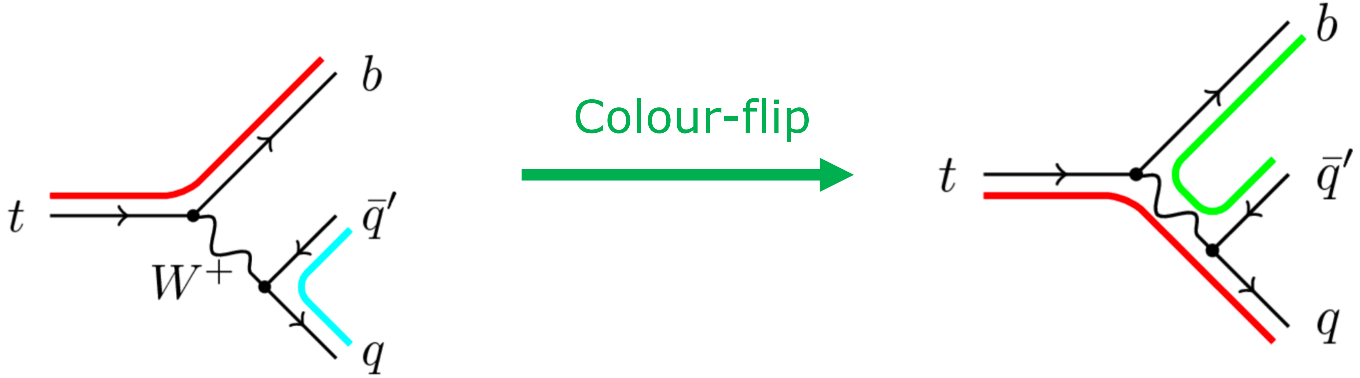
- Correcting observables to particle-level
  - Using stable particles with lifetimes >30 ps
- Background subtracted from data
- Iterative Bayesian unfolding
  - Migration matrix derived from $t\bar{t}$ MC





Analysis Strategy

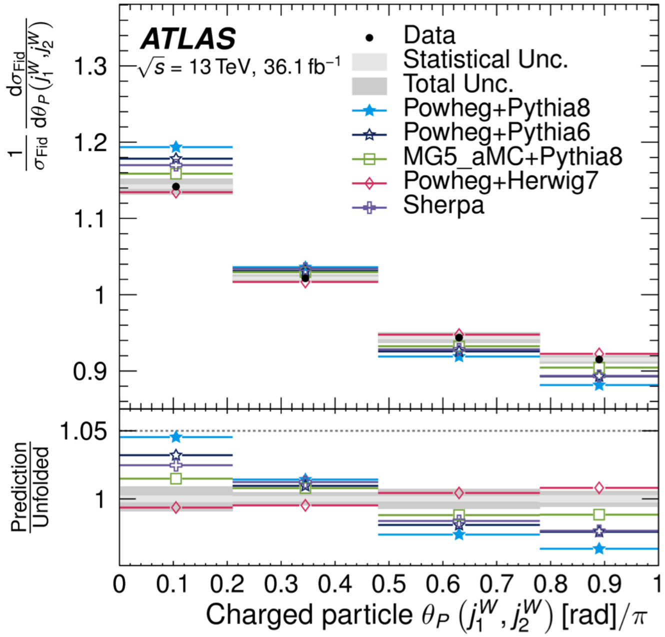
- Experimental systematic uncertainties, signal modeling uncertainties, background modeling uncertainties and unfolding procedure uncertainties are taken into account
- Normalised distributions extracted
  - Reduced uncertainty from normalization
- Comparison of unfolded distributions for two scenarios:
  - 1. Various different MC generators
  - 2. SM $t\bar{t}$ with a colour-flipped MC
    - Colour-flipped: replace colour-singlet W boson with ad-hoc colour-octet “W” by flipping colour-string

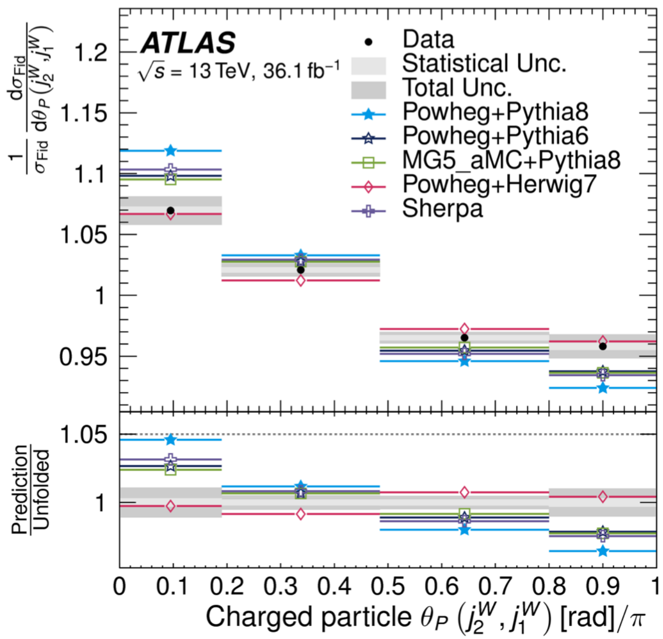


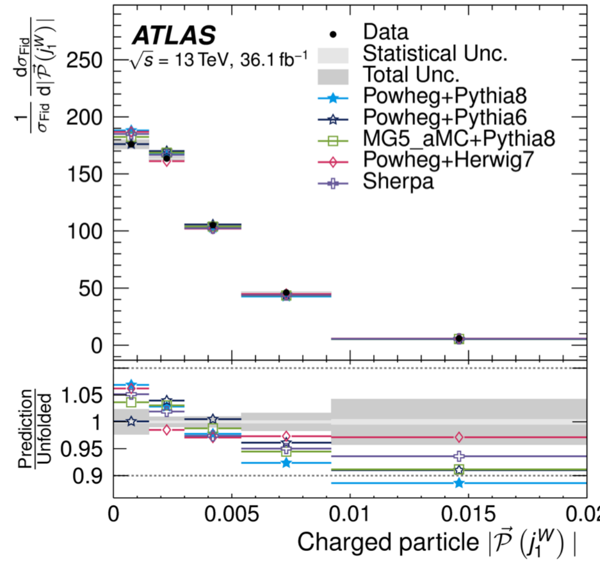
Systematics: Example

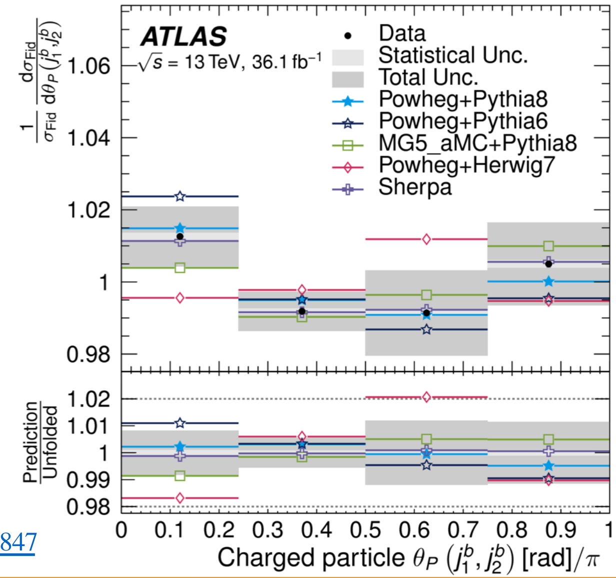
$\Delta\theta_P\left(j_1^W, j_2^W\right)$ [%]	$\theta_P\left(j_1^W, j_2^W\right)$			
	0.0 – 0.21	0.21 – 0.48	0.48 – 0.78	0.78 – 1.0
Hadronisation	0.55	0.13	0.24	0.14
Generator	0.32	0.25	0.50	0.01
b-tagging	0.35	0.13	0.20	0.31
Background model	0.30	0.16	0.16	0.27
Colour reconnection	0.22	0.16	0.16	0.18
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

Results: Comparison to MCs









- MC modeling has room for improvement
- Different MC model different distributions more or less well
- Within uncertainties, a single generator can not describe all observables

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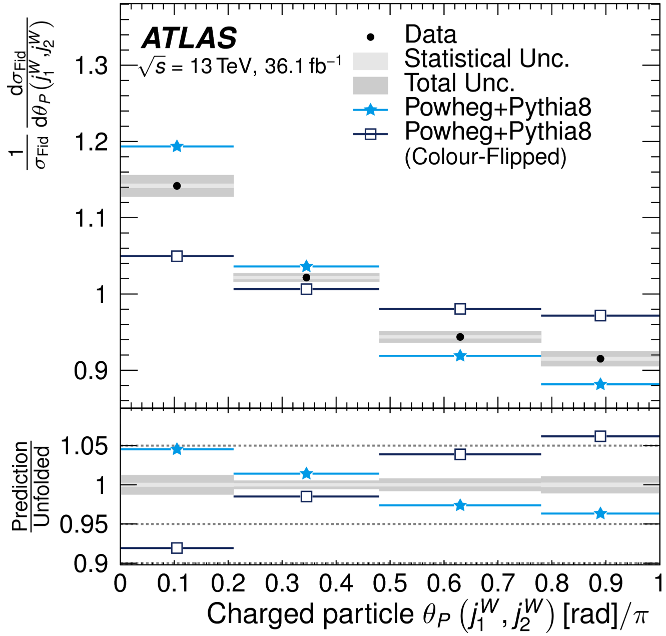
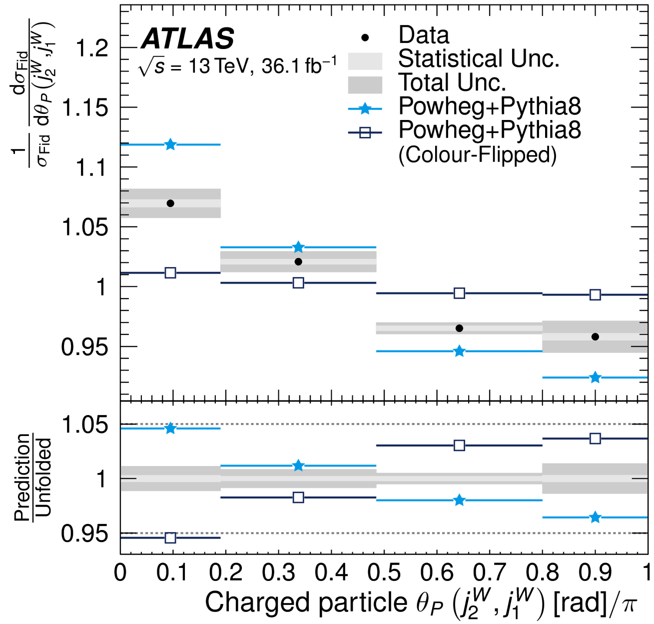
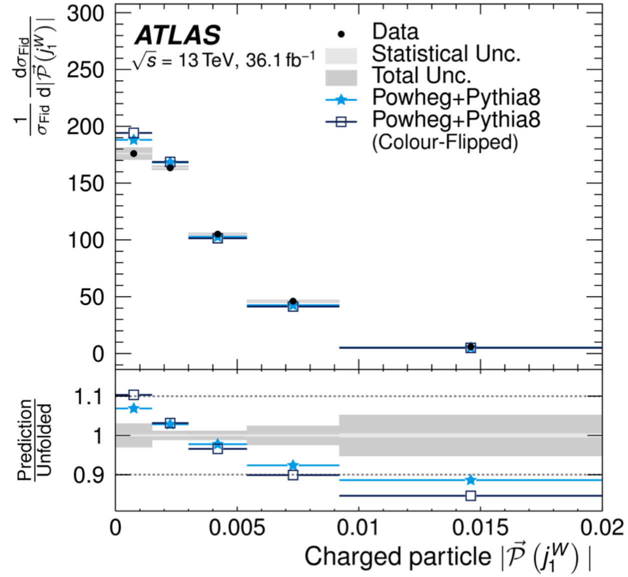
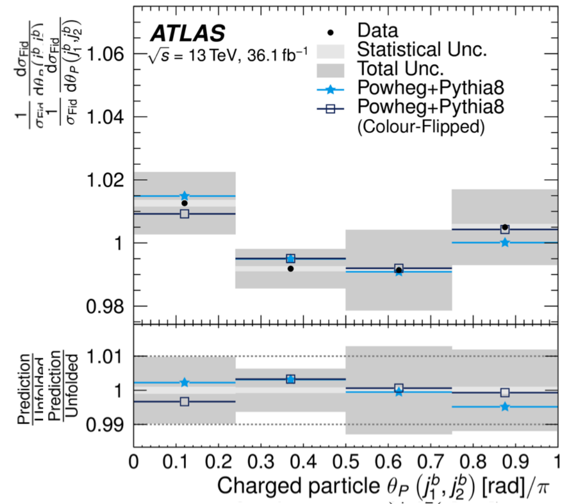
Results: Comparison to Colour-Flip Model









- Colour-flipped model disfavoured more by the data than SM
(for this distribution χ^2/NDF: 45.3/3; SM Powheg+Pythia8: 17.1/3)

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Summary

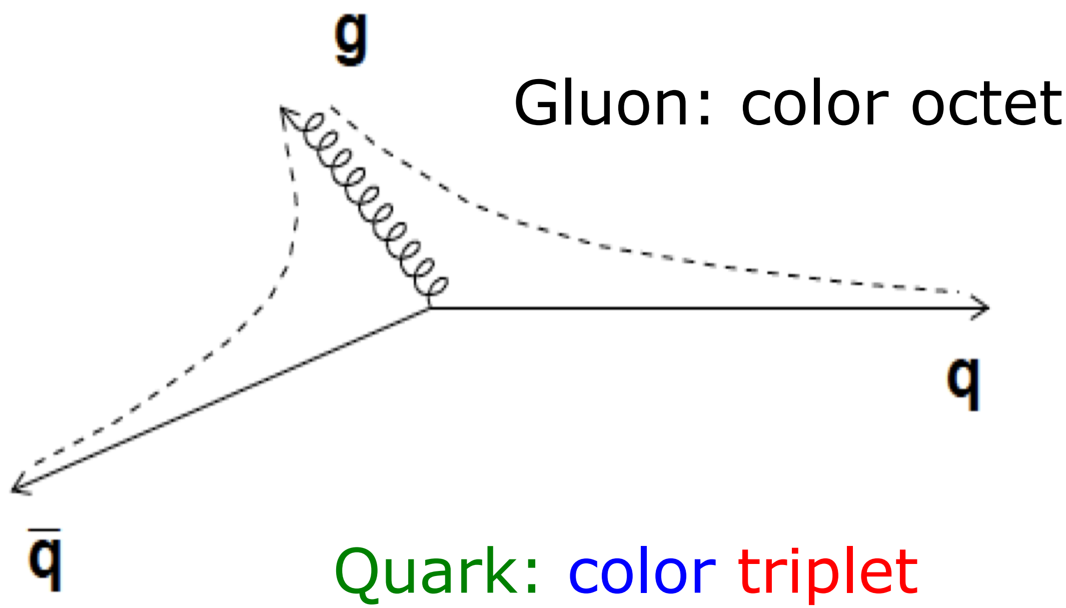
- Two measurements performed in ATLAS
  - 8 TeV: using calorimeter jets and charged particles from track-info
  - 13 TeV: only charged objects with track only
- Using $t\bar{t}$ events as laboratory to test QCD colour connections
- Comprehensive analysis performed on 13 TeV ATLAS data
  - Considering 4 different observables related to jet pull
- Could do measurement with more data
  - Or other observables?
  - Using particle flow?
  - Jet pull in boosted objects?!

Backup

Colour Flow: Intro

Colour coherence: QCD predicts increase of radiation where colour connection exists

Hadronization: Particles building up between colour-connected partons



Chi2

Sample	W_{Had} Pull		All Pull Angles		W_{Had} Pull Angles		Global	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg+Pythia8	92.4/ 10	< 0.001	78.6 / 9	< 0.001	64.0 / 6	< 0.001	119.4/ 13	< 0.001
Powheg+Pythia6	51.2/ 10	< 0.001	42.3 / 9	< 0.001	28.6 / 6	< 0.001	54.6/ 13	< 0.001
MG5_aMC+Pythia8	34.1/ 10	< 0.001	14.5 / 9	0.104	12.0 / 6	0.062	54.7/ 13	< 0.001
Powheg+Herwig7	36.8/ 10	< 0.001	40.9 / 9	< 0.001	6.3 / 6	0.396	95.2/ 13	< 0.001
Sherpa	60.0/ 10	< 0.001	27.5 / 9	0.001	26.6 / 6	< 0.001	62.8/ 13	< 0.001
Powheg+Pythia8*	90.5/ 10	< 0.001	77.9 / 9	< 0.001	62.3 / 6	< 0.001	119.4/ 13	< 0.001
Flipped Powheg+Pythia8*	660.1/ 10	< 0.001	171.6 / 9	< 0.001	164.3 / 6	< 0.001	714.7/ 13	< 0.001

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