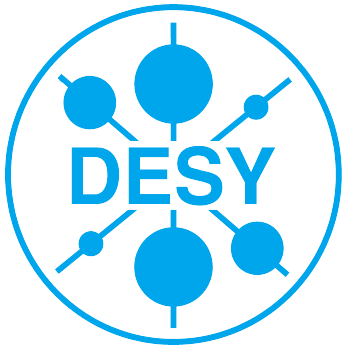
$t\bar{t}$ MC Modeling in ATLAS

John Keller (DESY)
on behalf of the ATLAS Top Group



Outline

- $t\bar{t}$ modelling and systematics — ATL-PHYS-PUB-2016-004
  - Overview of samples
  - Radiation systematics
  - Generator comparisons
  - Pythia8 studies
- NEW: $t\bar{t}$+cc production at NLO — To appear soon...

Summary of samples

Sample Name	ME Gen.	PS/UE Gen.	ME & PS/UE PDF	PS Tune	Matching
Powheg+Pythia6	Powheg-Box r2330.3	Pythia 6.427	CT10 & CTEQ6L1	P2012	Powheg Matching
Powheg+Pythia8	Powheg-Box r2330.3	Pythia 8.183	CT10 & CTEQ6L1	A14	Main31 (pThard=0 nFinal=2)
Powheg+Herwig++	Powheg-Box r2330.3	Herwig++ 2.7.1	CT10 & CTEQ6L1	UE-EE-5	Powheg Matching
aMC@NLO+Herwig++	aMC@NLO 2.2.1	Herwig++ 2.7.1	CT10 CTEQ6L1	UE-EE-5	MC@NLO
aMC@NLO+Pythia8	aMC@NLO 2.2.1	Pythia 8.183	NNPDF3.0 NNPDF2.3LO	A14	MC@NLO
Sherpa	Sherpa 2.1.1	Sherpa	CT10	Default	MEPS@NLO (Q=30 GeV)

Default & radiation syst

Comparison

Shower / hadronization syst

Generator syst

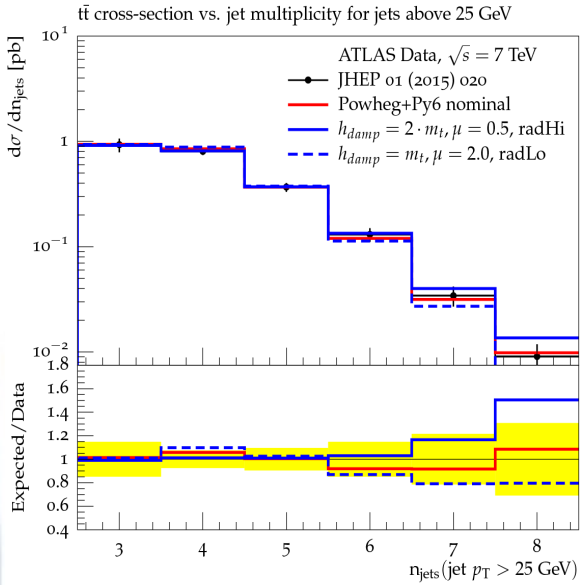
Comparison

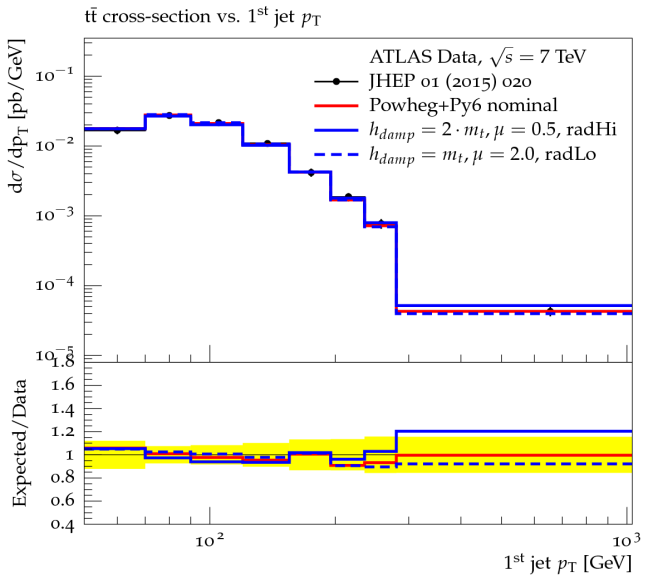
Comparison

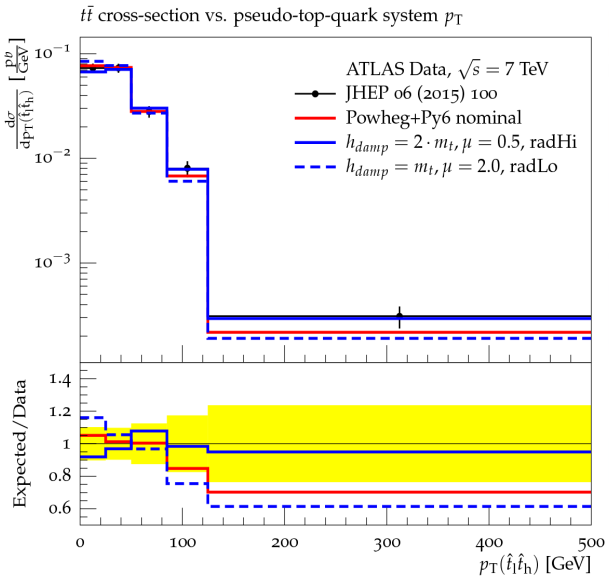
Radiation variations

- Default Powheg+Pythia6 sample uses $h_{damp}=m_{top}$, Perugia 2012 Tune, and renormalization and factorization scales defined as $\mu = \sqrt{m_{top}^2 + p_T^2}$
- Two samples produced to study effect of more or less radiation
  - Radiation Up: μ_R and μ_F scaled by 0.5, $h_{damp}=2*m_{top}$, Perugia 2012 radHi tune variation.
  - Radiation Down: μ_R and μ_F scaled by 2, $h_{damp}=m_{top}$, Perugia 2012 radLo tune variation.

Radiation variations: 7 TeV

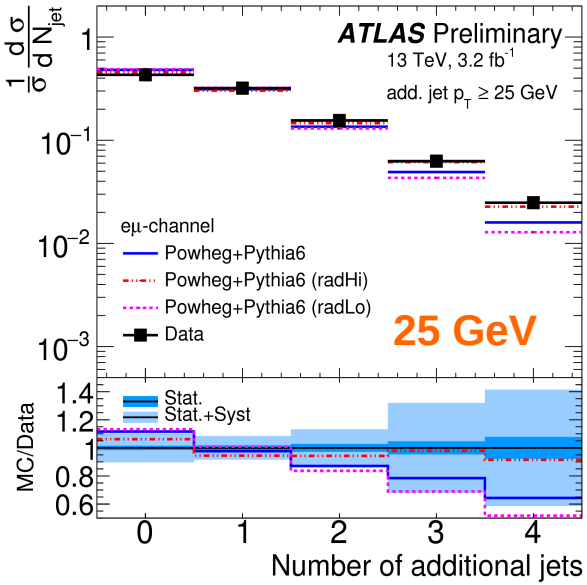




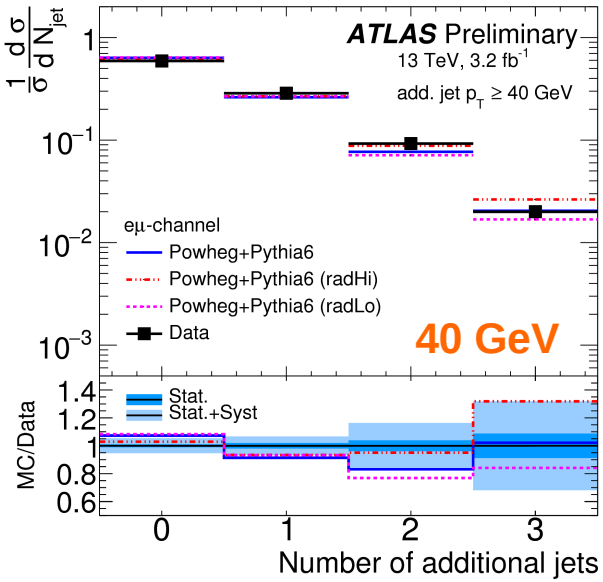


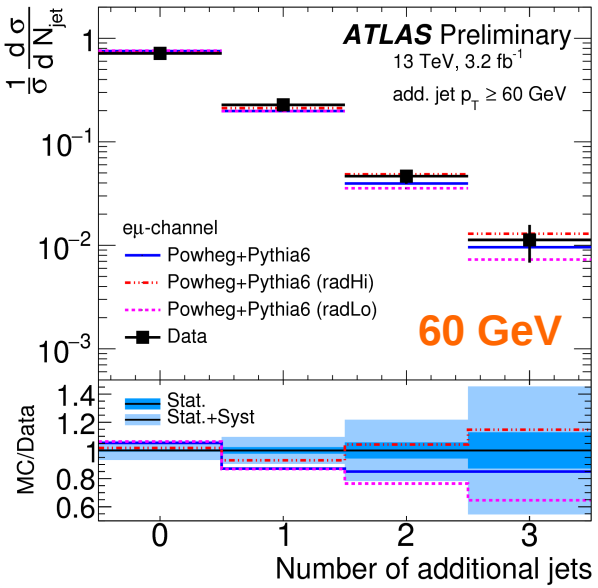
- Largest impact observed for jet multiplicity and p_T spectrum of $t\bar{t}$ system.
- Variations mostly bracket experimental uncertainties.

Radiation variations: 13 TeV

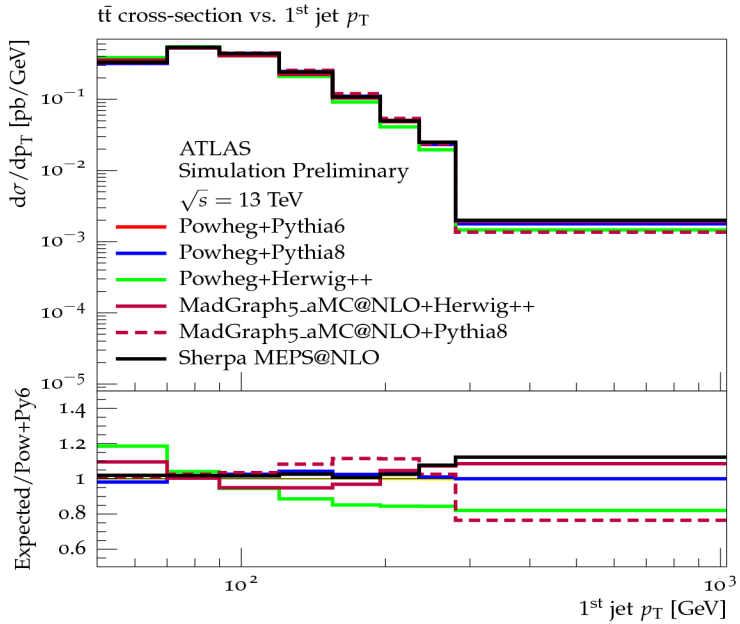


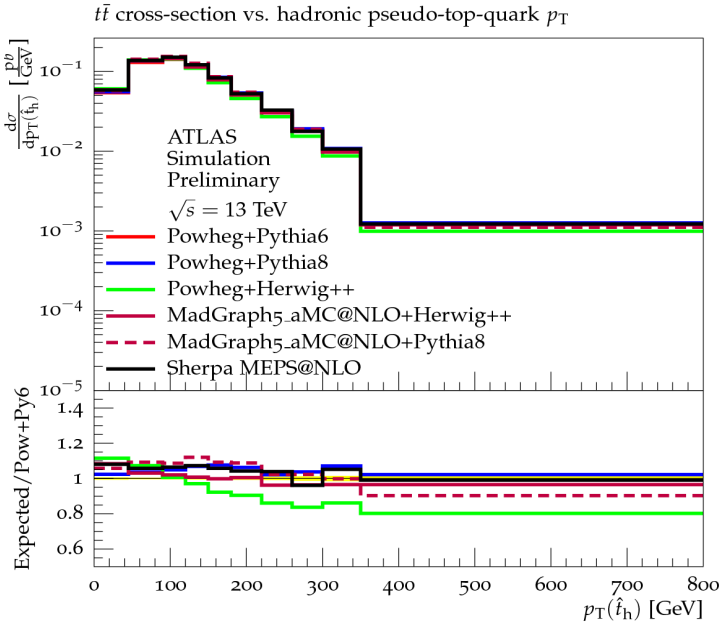
- High radiation variation shows best agreement with 13 TeV #jet spectra.
- Nominal Pow+Py6 still in good agreement within experimental uncertainties.
- Current precision not enough to further constrain radiation uncertainty.





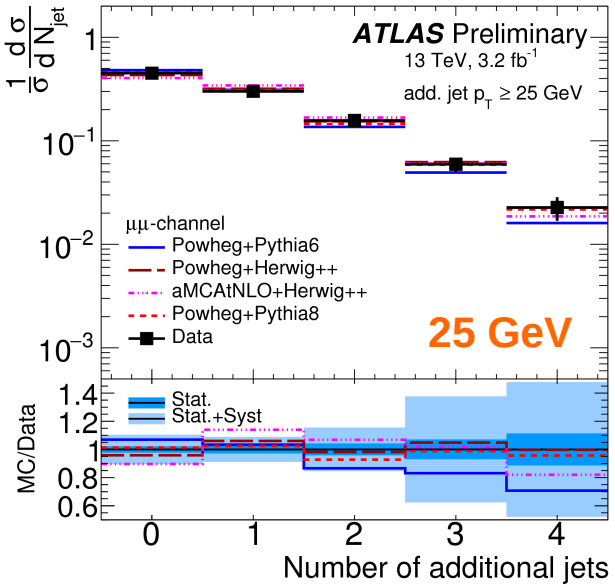
Generator comparisons



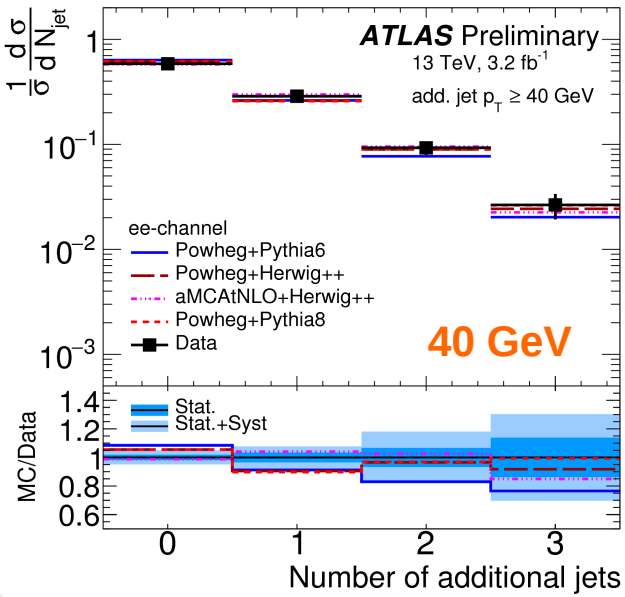


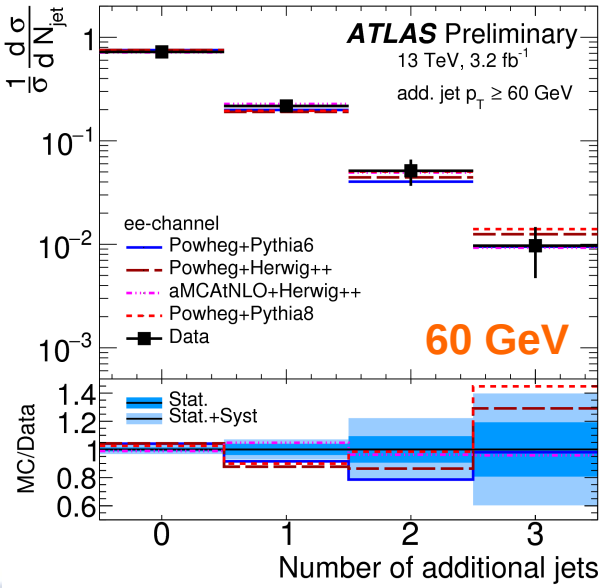
- Generator uncertainty taken from Powheg+Herwig++ vs. MG5_aMC@NLO+Herwig++.
- Pow/H++ a bit of an outlier, generator comparison with Pythia8 shower may be smaller.
- Prediction from Sherpa similar to others in many distributions.

Generator comparisons

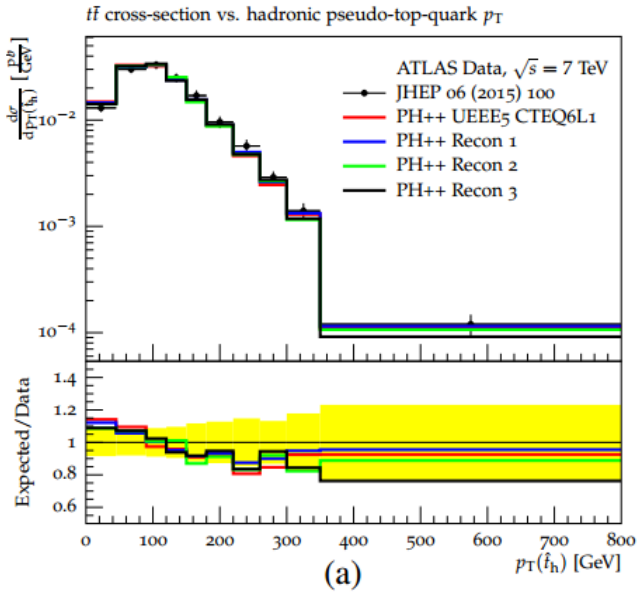


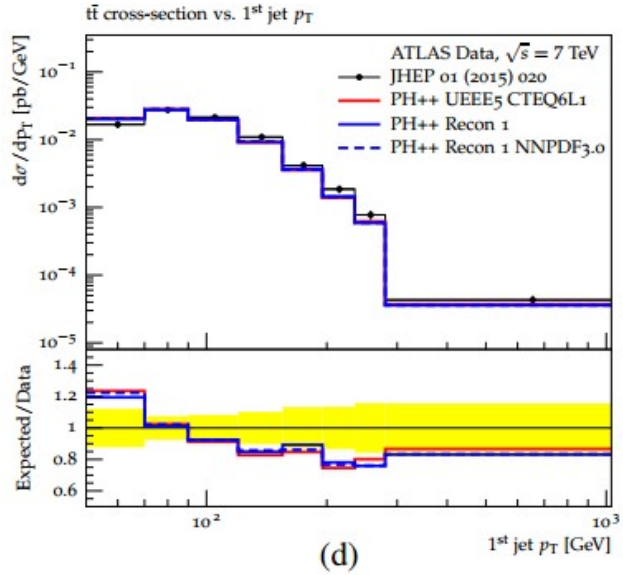
- 13 TeV jet multiplicity spectrum compared to Powheg with three shower models and to aMC@NLO.
- Good agreement among the predictions for low p_T jets.
- Powheg+Pythia6 is systematically low (but within uncertainties); hard to reach a conclusion on other options.





Herwig++ comparison



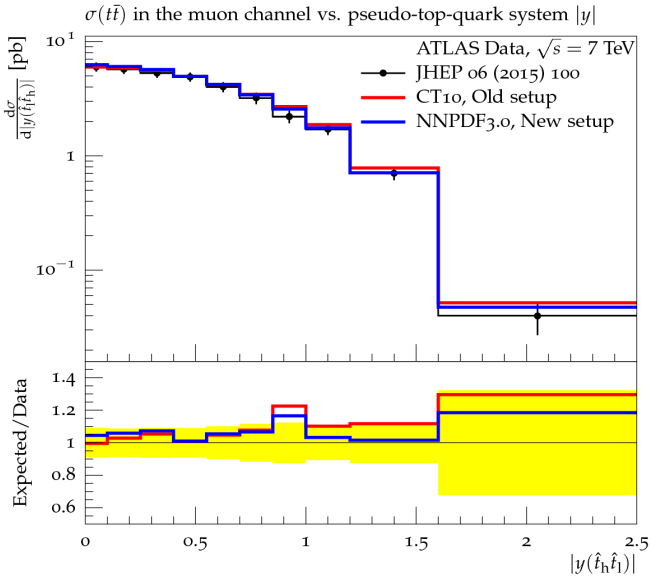


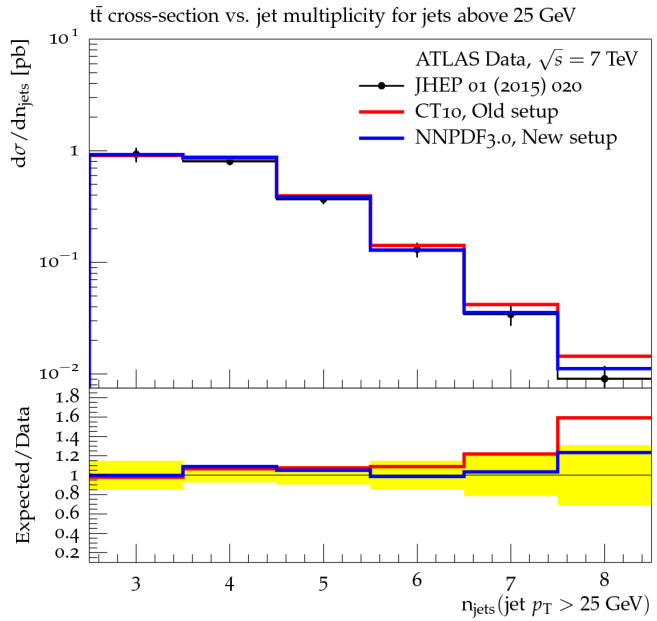
- Comparison to 7 TeV data shows significant disagreement for Powheg+Herwig++.
- Possible to improve a number of distributions:
  - FinalStateReconOption 1 improves top p_T spectrum.
  - NNPDF3.0 improves rapidity.
- Jet p_T spectrum continues to show disagreements.
- Implementation of Herwig7 is ongoing.

Powheg+Pythia8

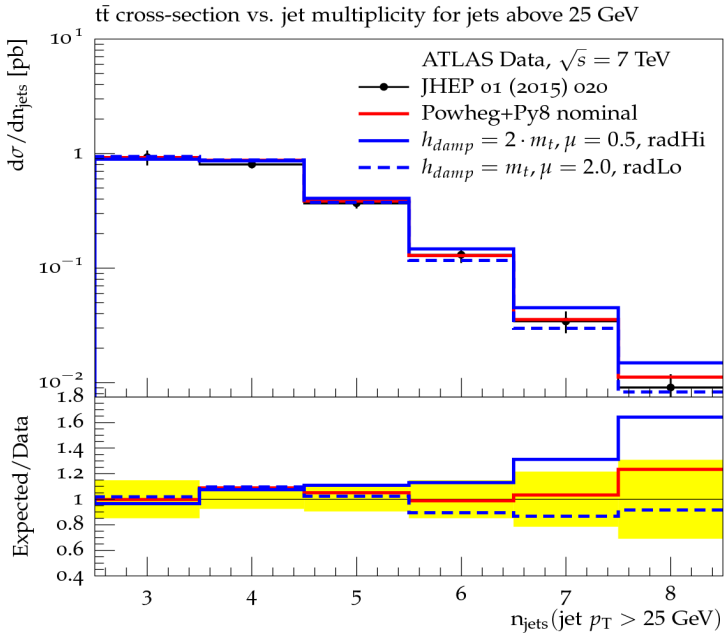
- Default settings above show poorer agreement for Powheg+ Pythia8 compared to Pythia6.
- Switch from CT10 to NNPDF improves top rapidity spectrum.
- Together with changes to Main31 settings, able to achieve good agreement in most distributions.

Parameter	Old Setup	New Setup
pTdef	1	2
pTemt	1	0
PDF	CT10	NNPDF3.0





Systematics with Pythia8



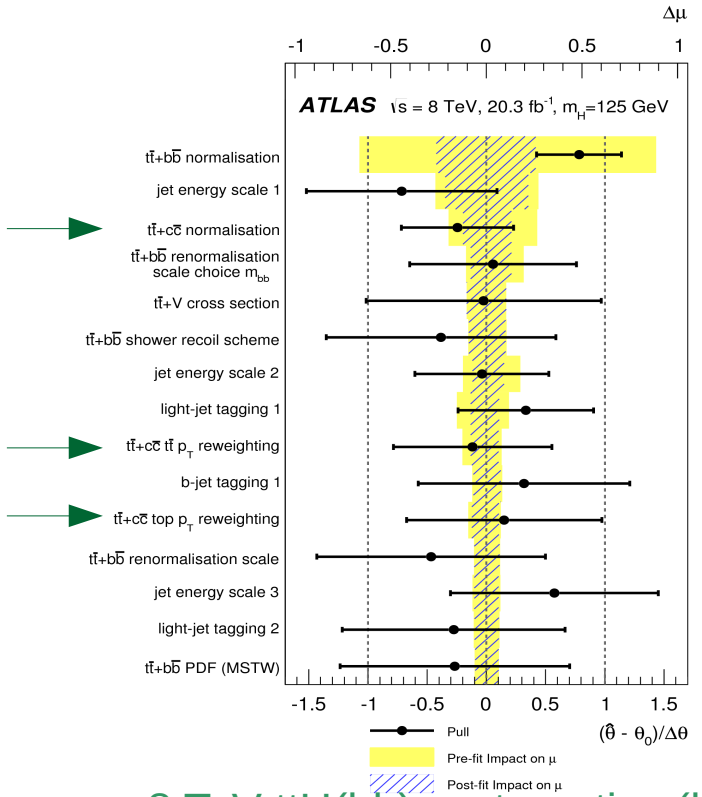
- MPI variation tested and seen to be negligible.
- Largest ISR/FSR tune variation chosen, combined with ME scale variations.
- Full systematic model therefore defined for Powheg+Pythia8 as default.

Source of Uncertainty	Samples	Procedure
Nominal	Powheg+Pythia8	N/A
Hard Scatter Generation	Powheg+Pythia8 vs. aMC@NLO+Pythia8	$\pm\|\Delta\|$
Parton Shower and Hadronization Model	Powheg+Pythia8 vs. Powheg+Herwig++	$\pm\|\Delta\|$
Scales and Additional Radiation	Powheg+Pythia8 Variations	Δ
Interference (Wt and $t\bar{t}$)	Powheg+Pythia8 DR vs. DS Schemes	$\pm\|\Delta\|$

Studies of $t\bar{t}+c\bar{c}$ at NLO

$t\bar{t}+c\bar{c}$: Motivation

- Theoretically challenging: multiple scales involved make perturbative convergence difficult.
- Experimentally challenging: hard to isolate charm jets from b or light.
- But a significant, unavoidable background for many LHC searches and measurements.



8 TeV ttH(bb) systematics (link)

8 TeV tt+bb measurement: simultaneous fit of b-tagging discriminants. (link)

Process	Observed cross-section [fb]	Statistical uncertainty (%)	Systematic uncertainty (%)	Total uncertainty (%)	Predicted cross-section [fb]
$ttbb$	13.5	±25	±27	±36	12.3
$ttbX$	61	±38	±69	±79	63
$ttcX$	270	±25	±81	±85	180
$ttlX$	5870	±4	±14	±15	5800
R_{ttbb}	1.30%	±25	±22	±33	1.27%

$t\bar{t}+c\bar{c}$: Production

- First attempt at NLO $t\bar{t}$+cc simulation with c's in ME, using:
  - MadGraph5_aMC@NLO 5.2.3.2
  - Herwig++ 2.7.1
  - CT10f3: 3-flavor scheme PDF
  - m_c=1.55 GeV, m_b = 4.95 GeV, m_t = 172.5 GeV
- Two choices for renormalization/factorization scale:

$H_T/4$ $\quad \mu = \frac{1}{4}\sum_{i \in FS} E_{T,i}$

CMMPS $\quad \mu = \prod_{i=t,\bar{t},c,\bar{c}} E_{T,i}^{1/4}$

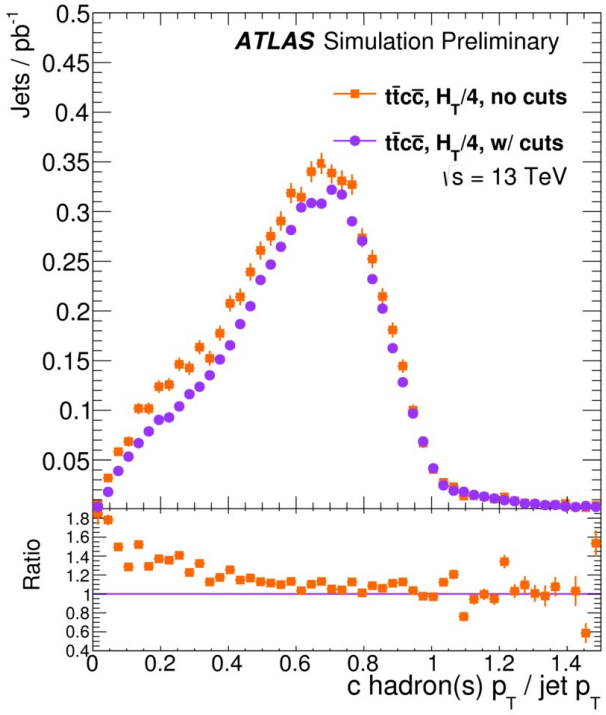
- CMMPS takes on low values as the p_T's go to 0. To avoid generator instabilities, introduced lower cutoff at 50 or 150 GeV.
- Compared to aMC@NLO/Herwig++ $t\bar{t}$ inclusive sample generated with same settings, and to Sherpa sample introduced before (0,1 jet @NLO, 2-5@LO).

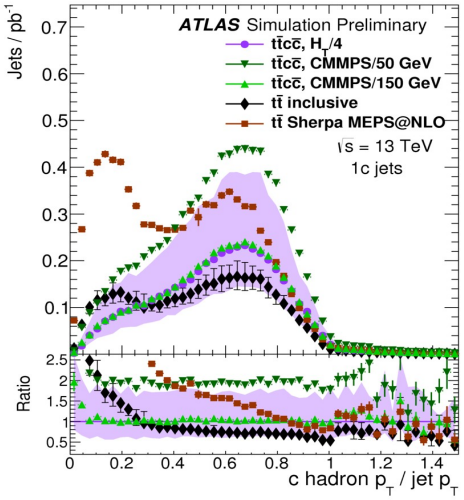
Definitions

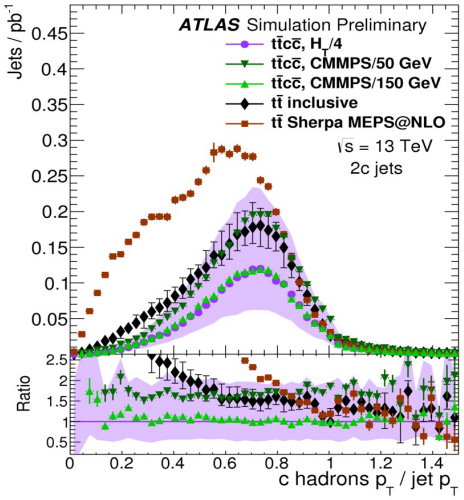
- Jets: particle level, anti-k_t 0.4, $p_T > 25$ GeV, $|\eta| < 2.5$.
- Jets labeled as b or c if they are matched to a 5 GeV b or c hadron, within $\Delta R < 0.4$. Hadrons from W, and hadrons from decays of other b or c hadrons, are excluded.
  - 1c jet: only one c hadron.
  - 2c jet: two or more c hadrons.
- Events must have exactly two b-jets, and either one lepton above 25 GeV, or two leptons above 20 GeV.
- Events with charm jets are then classified:
  - tt1c: One 1c jet and no other charm jet.
  - tt2c: One 2c jet and no other charm jet.
  - ttcc: Two or more charm jets (of either kind).

Effect of jet cuts

- aMC@NLO applies p_T cut of 5 GeV to light-flavor parton jets.
- Event generation unstable if cut not applied to c quarks → implies limiting the c quark phase space.
- Particle level jets have 25 GeV cut: can mitigate effect by removing jets where charm hadrons are small part of the momentum.

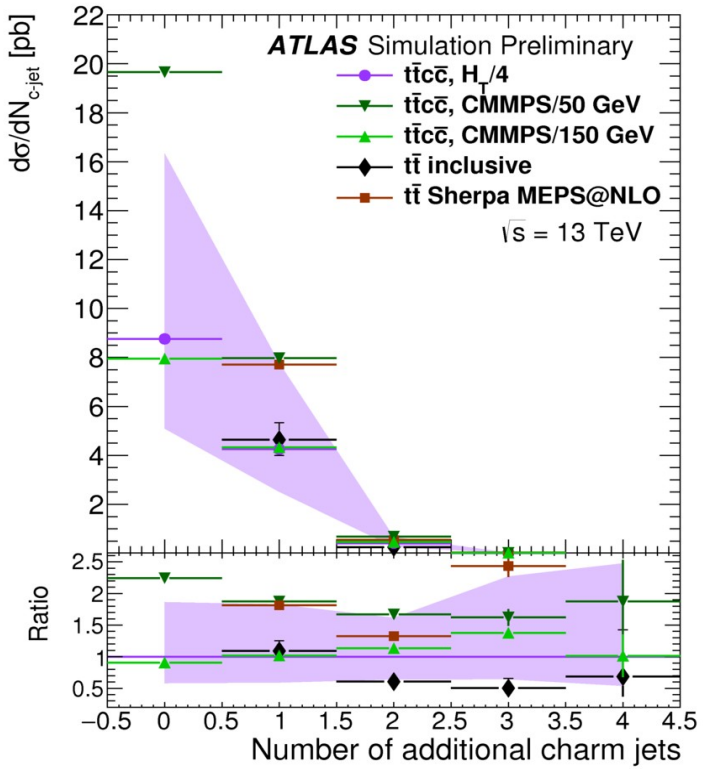






- Cut on "charm p_T fraction" at 0.4 applied for subsequent plots.
- Variable shows interesting variation among the samples considered.

Cross-section predictions

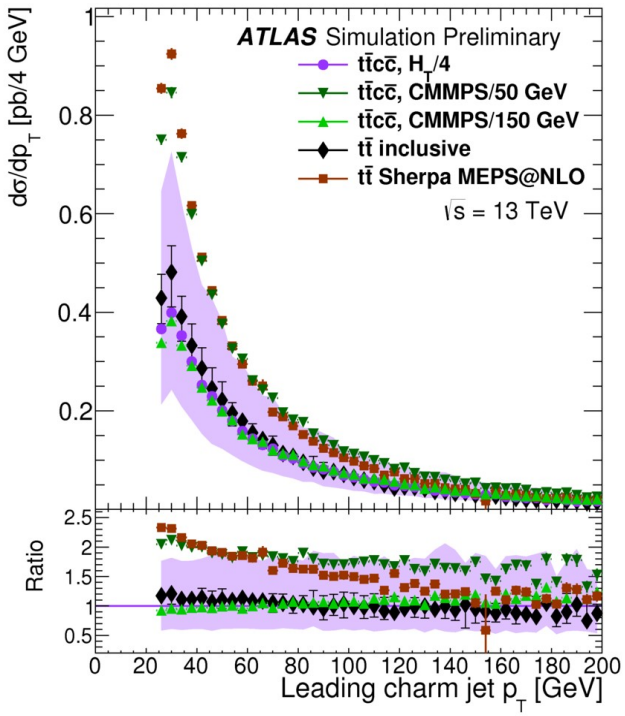


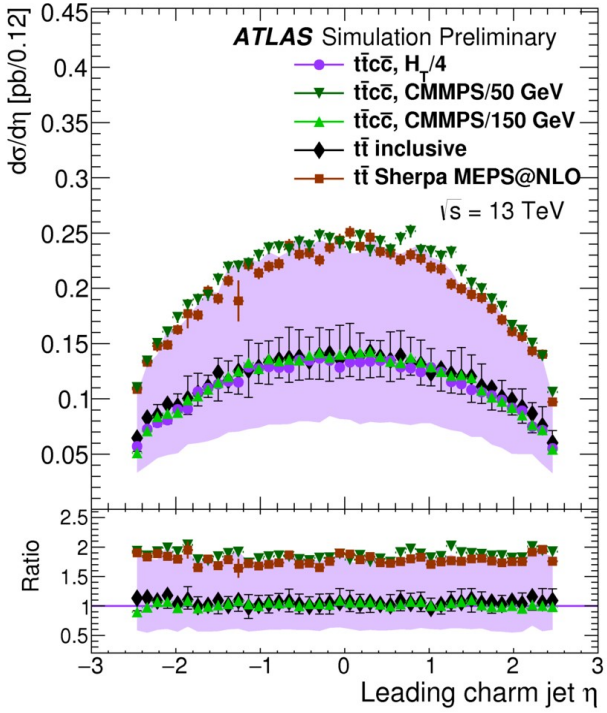
Purple band on $H_T/4$ and error bars on inclusive: variation of renorm/factorization scales 0.5, 2.

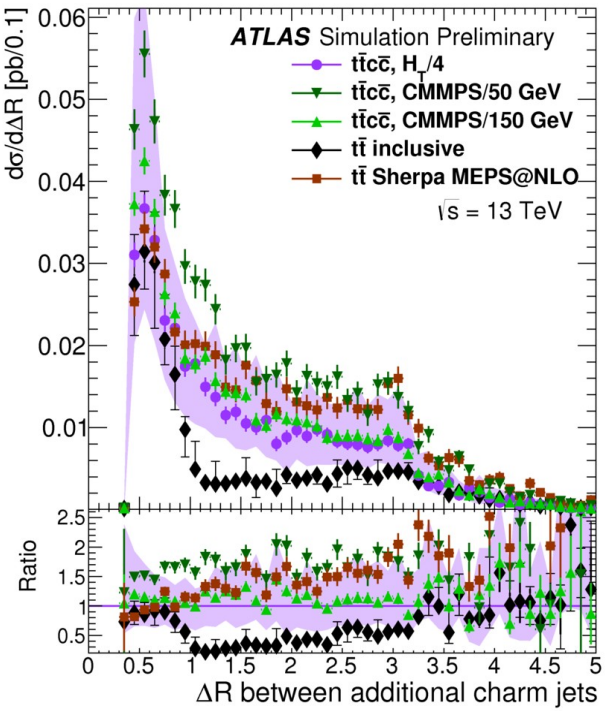
- Choice of scales has large effect on overall cross-section.
- Large uncertainty on NLO ME predictions when varying scales (up or down by factor of two).
- Inclusive prediction relatively high for merged c quarks, but low for well-separated c jets.

Sample	$tt1c$	$tt2c$	$ttcc$
$H_T/4$	$2.6^{+1.9}_{-1.0}$ pb	$1.6^{+1.5}_{-0.7}$ pb	$0.42^{+0.26}_{-0.15}$ pb
CMMPS, 50 GeV cutoff	$5.3^{+5.3}_{-2.4}$ pb	$2.6^{+2.9}_{-1.3}$ pb	$0.69^{+0.62}_{-0.29}$ pb
CMMPS, 150 GeV cutoff	$2.6^{+2.0}_{-1.0}$ pb	$1.6^{+1.6}_{-0.7}$ pb	$0.47^{+0.33}_{-0.19}$ pb
$t\bar{t}$ inclusive	$2.0^{+0.3}_{-0.3}$ pb	$2.5^{+0.4}_{-0.4}$ pb	$0.25^{+0.04}_{-0.04}$ pb
Sherpa MEPS	3.7 pb	3.6 pb	0.54 pb

Kinematic comparisons

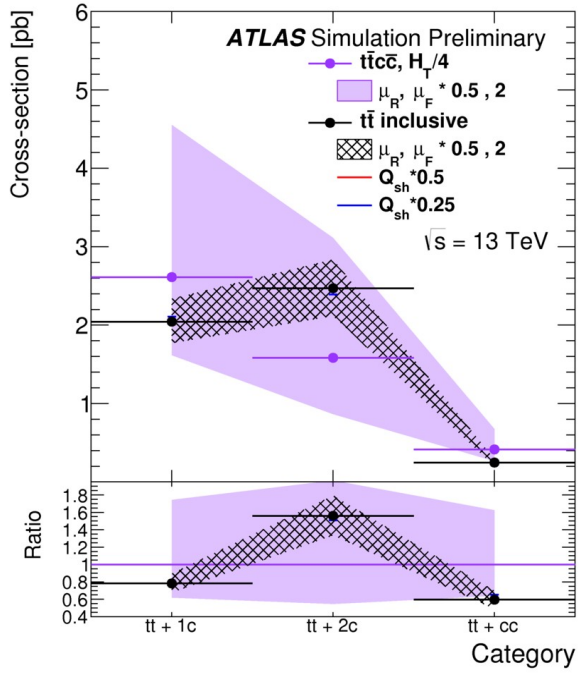






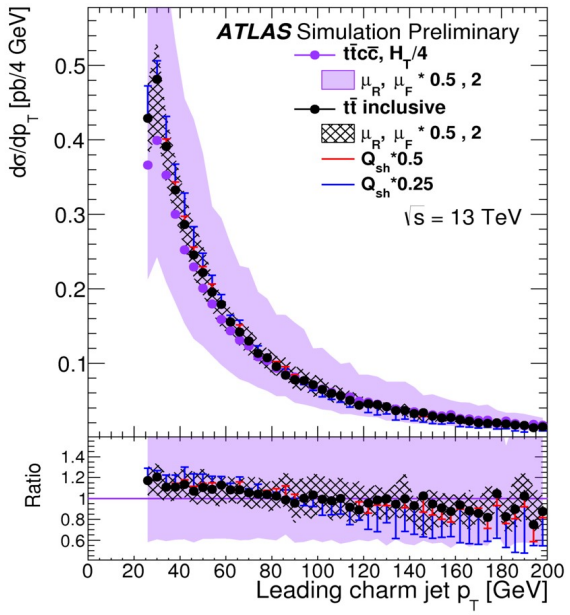
- Fairly good agreement in kinematics among NLO samples.
- Sherpa predicts much softer charm jet spectrum.
- Inclusive prediction very low for well-separated c-jets; opposite pattern observed for Sherpa.

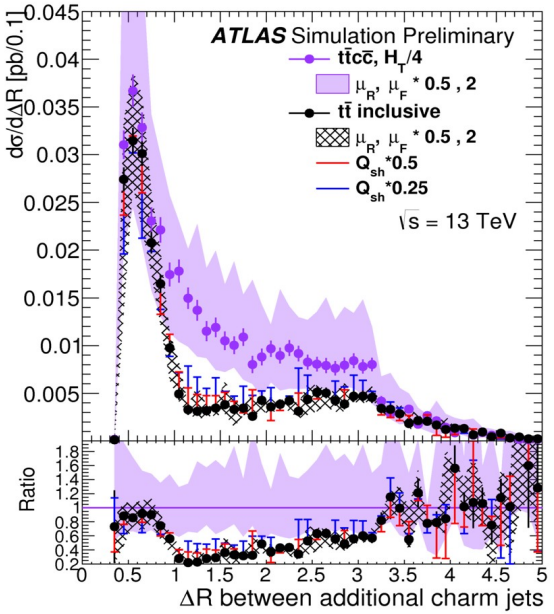
Shower scale variations



- Shower hard veto scale Q_{sh}: allows a variation of the matching systematics associated to MC@NLO method.
- Varied down by 0.5, 0.25 for inclusive sample: almost no variation in predicted cross-section or # of jets.

- Larger effect on kinematics: push toward softer and well-separated c jets, larger than hard-process scale variations.



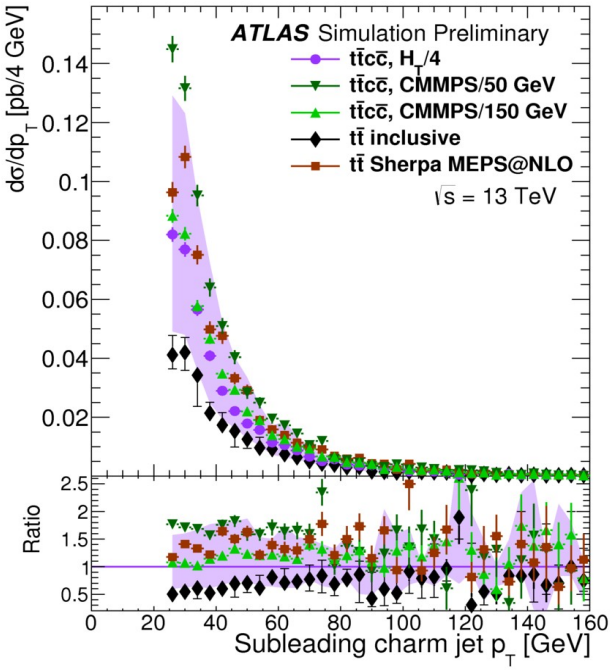


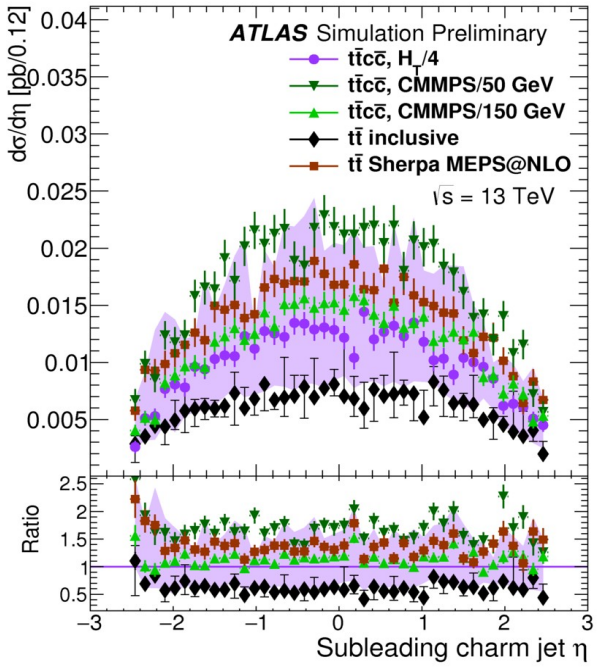
Summary

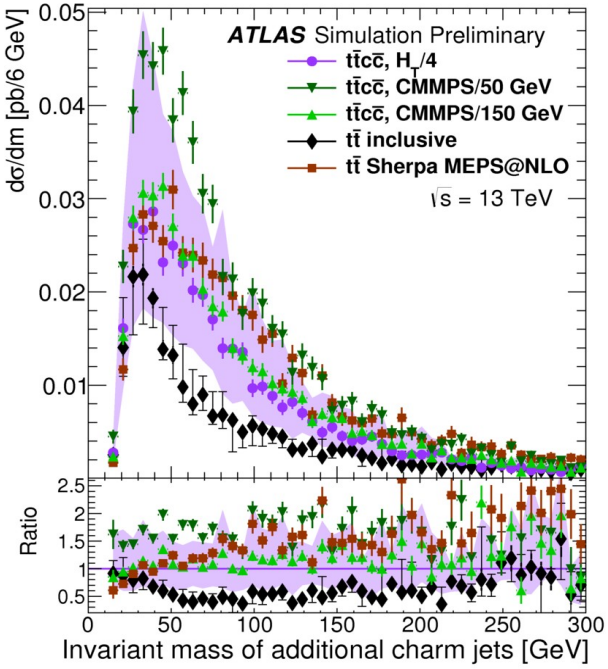
- Default Powheg+Pythia6 sample shows good agreement with many measurements. Slightly low for 13 TeV jet multiplicity, but easily covered by systematics.
- Modeling with Powheg+Pythia8 significantly improved with NNPDF3.0 and new settings. Moving towards this as default.
- Studies of Herwig++ and validation of Herwig7 ongoing.
- First predictions for $t\bar{t}$+cc with aMC@NLO+Herwig++ shown:
  - Large cross-section dependence on scale choice, but less dependence for kinematics.
  - Significant differences with respect to sample with charm quarks from parton shower: potentially not covered by default systematics of inclusive sample.

Backup slides

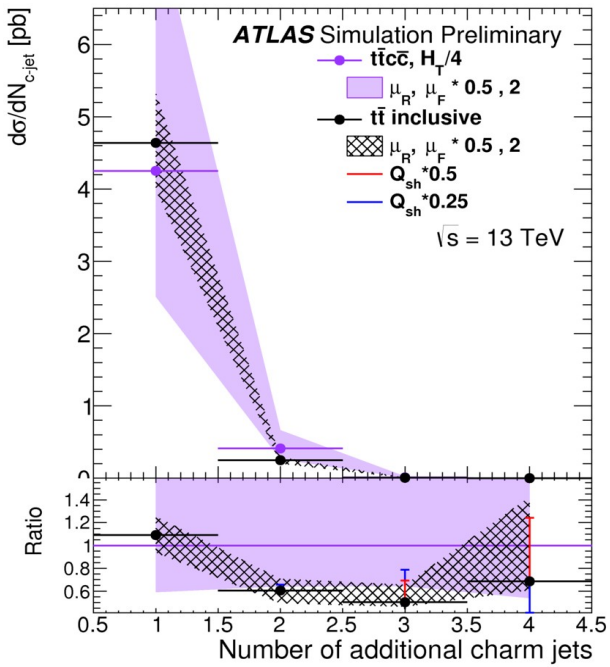
More kinematic comparisons

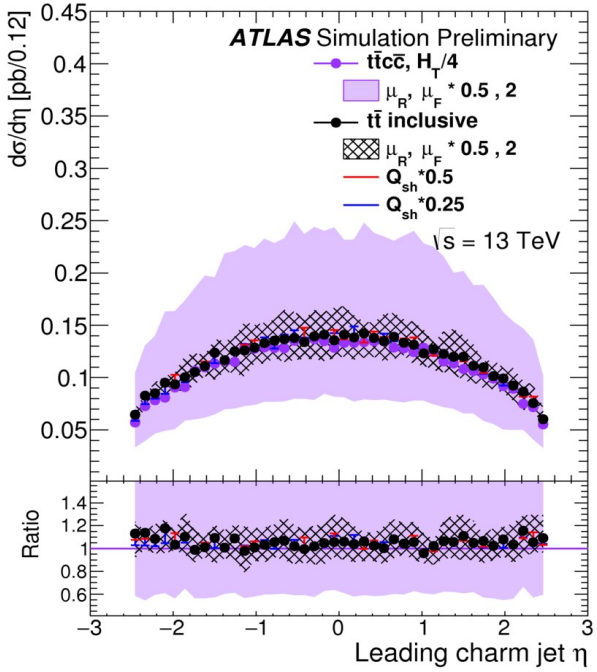


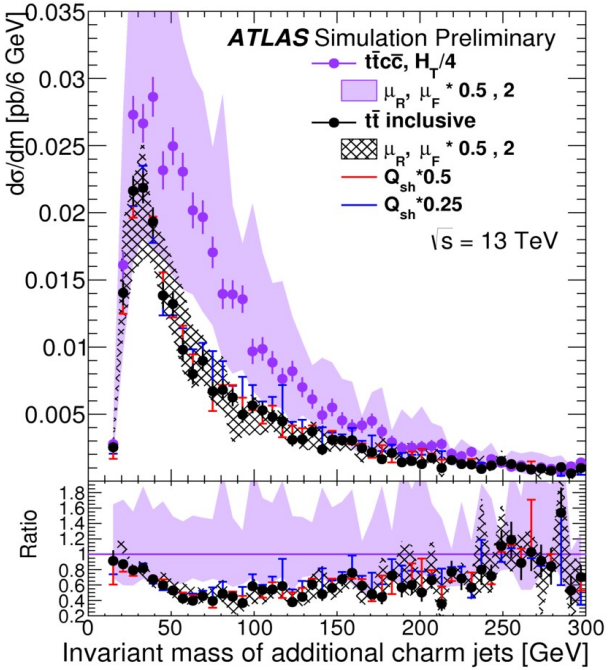




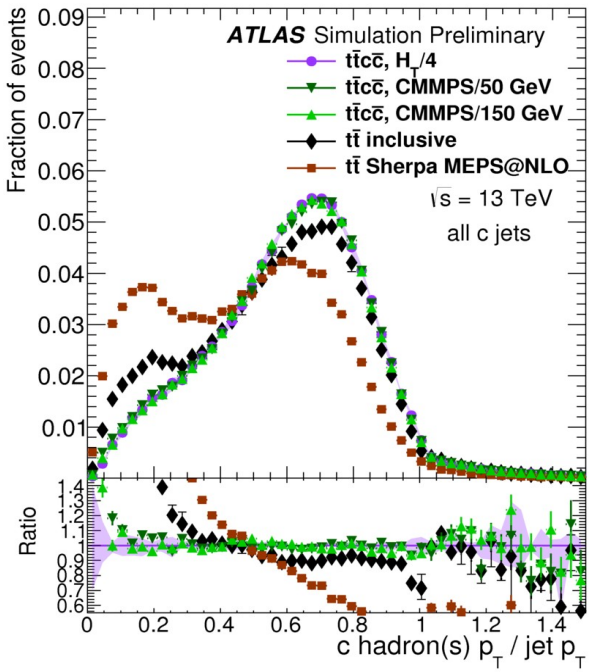
More Q_{sh} comparisons

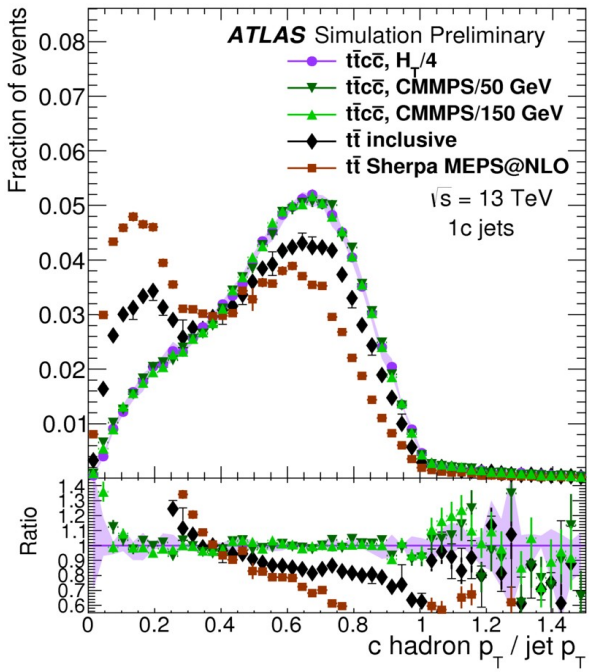


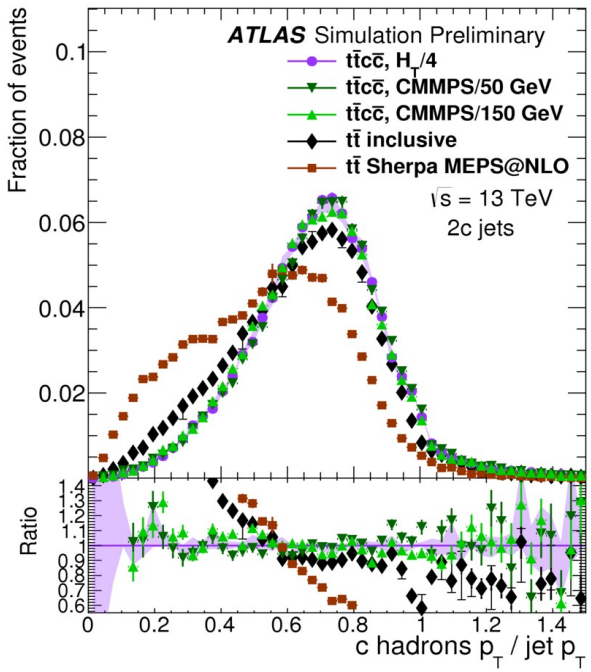




Shape comparisons

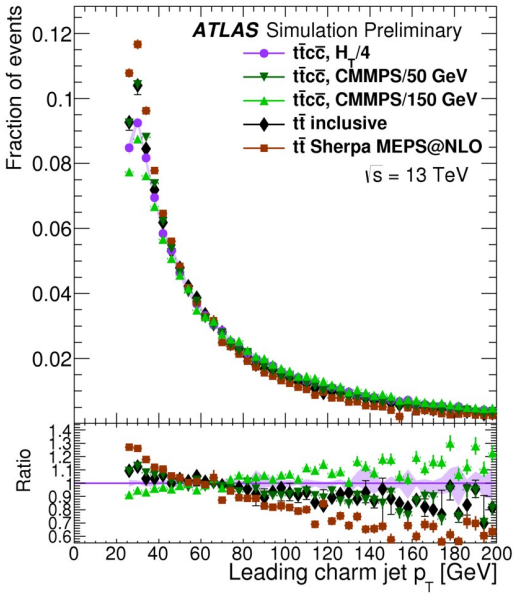


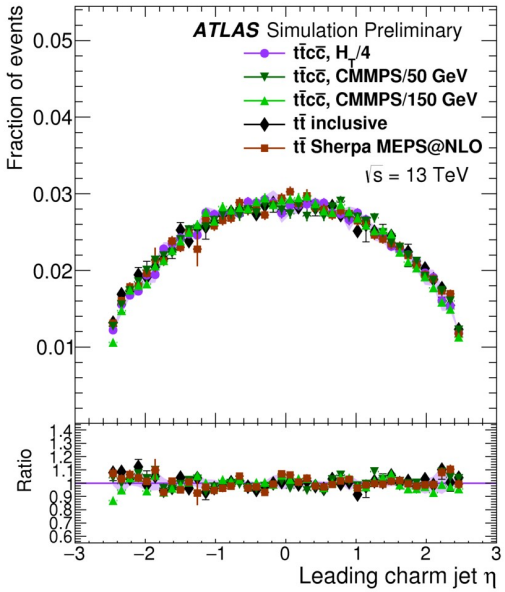


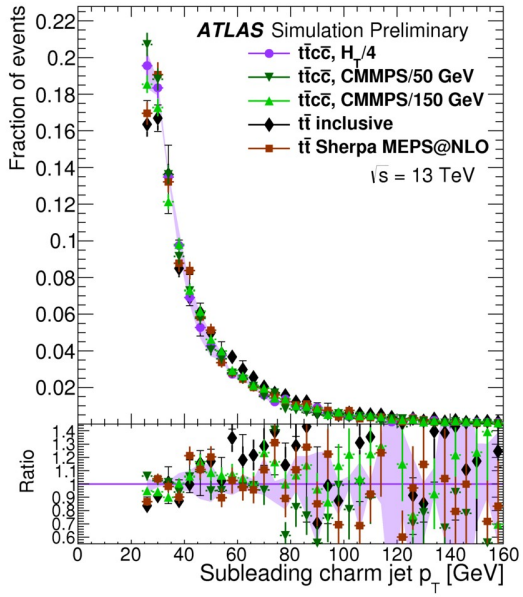


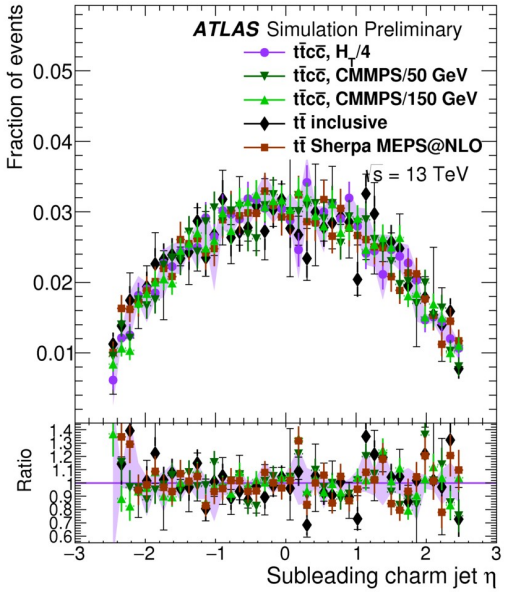
- Scale variations have similar shape to default sample → tiny scale uncertainty in shape comparison plots.

Shape comparisons

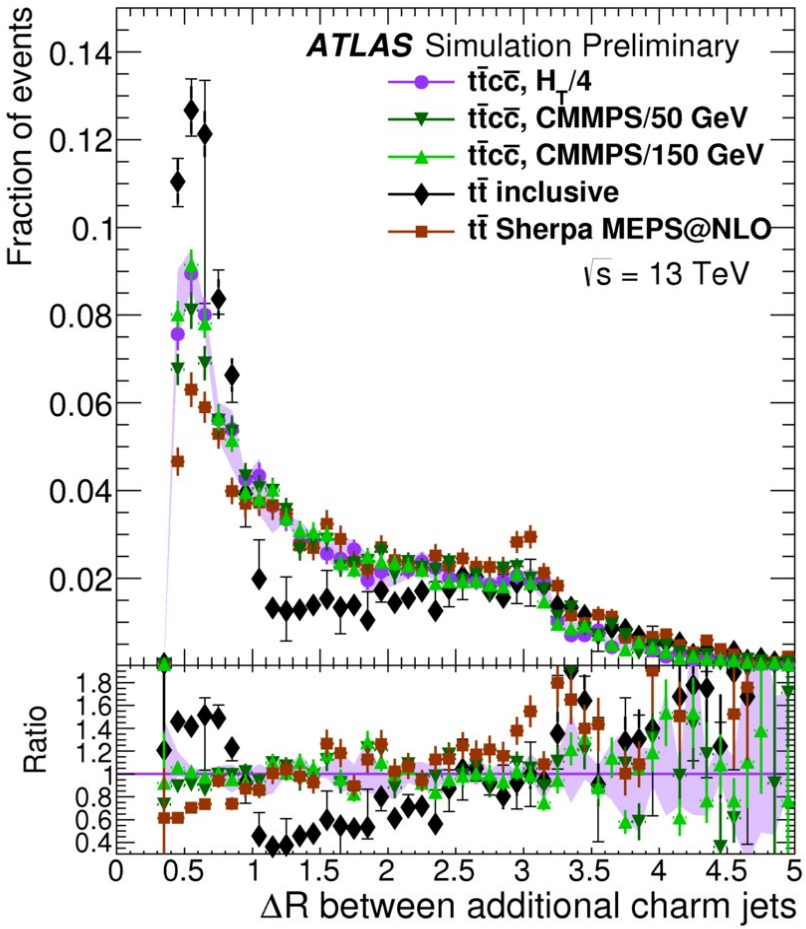


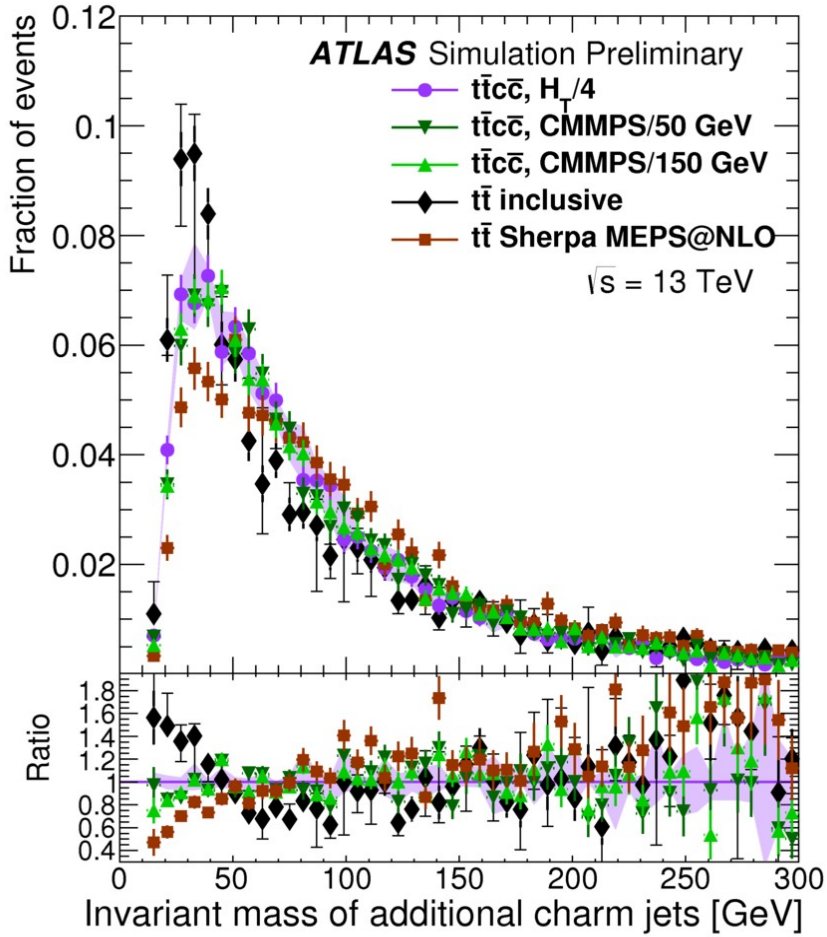






Shape comparisons





Pythia8 variations