Top modeling: studies and measurements

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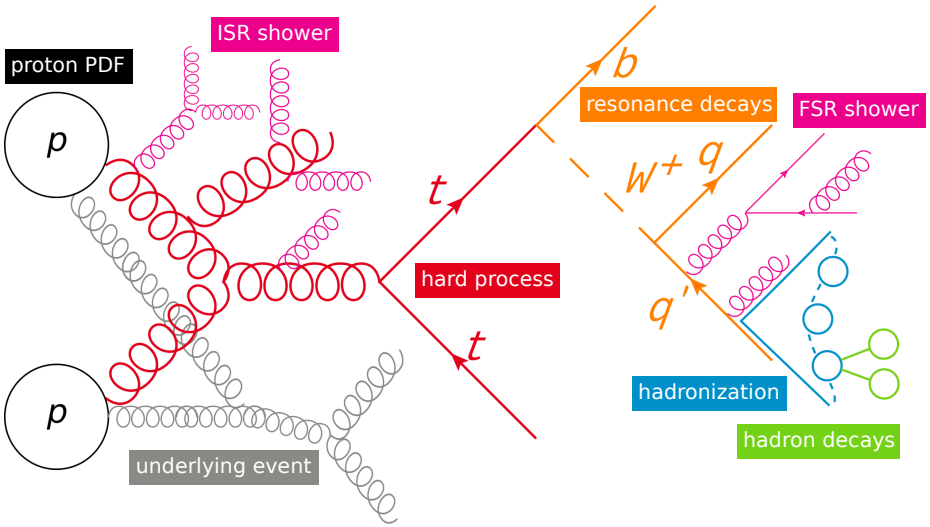
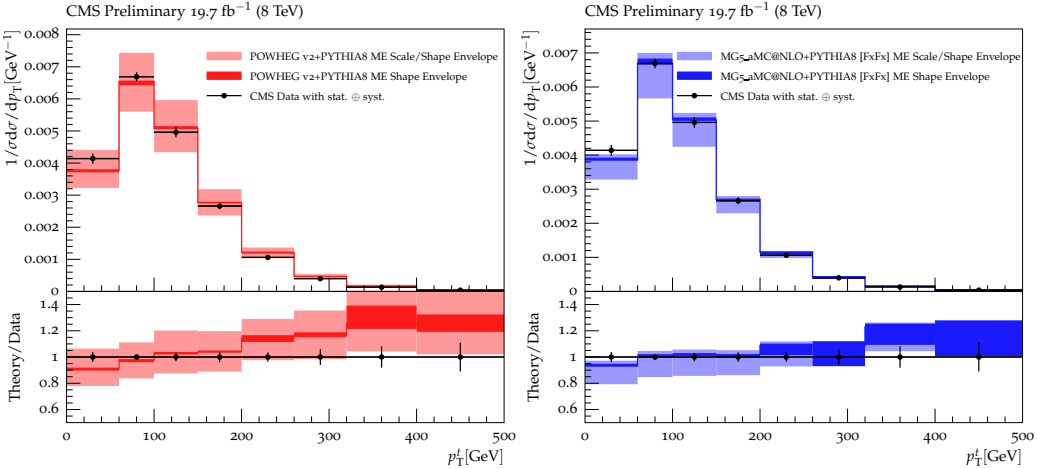
Overview of $t\bar{t}$ event generation



- Each stage contained in multi-purpose generators but there also specialized tools
- Relying on measurements to improve generators!

ME generators and scale uncertainties

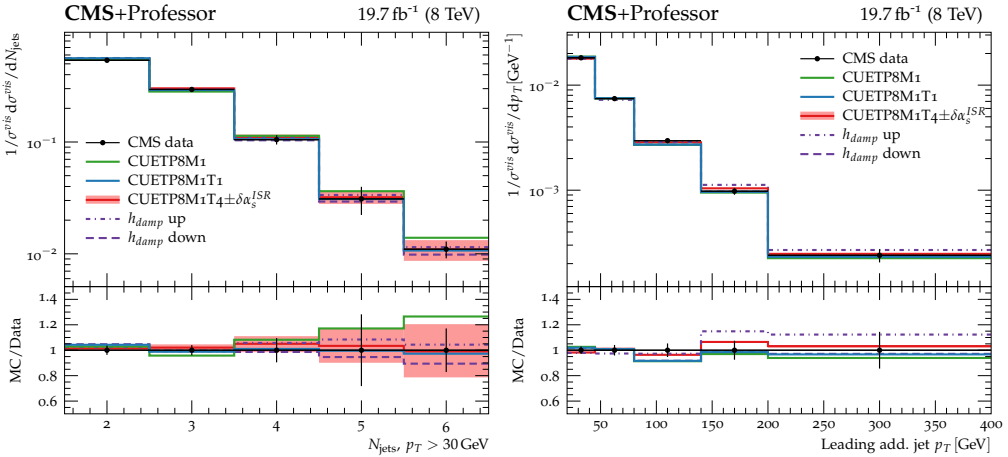
CMS PAS TOP-15-011



- Vary renormalization and factorization scales by factors $1/2$ and 2
- Powheg ($t\bar{t}$@NLO): data not covered by (small) shape scale uncertainties
  - can cover data when bins are assumed as uncorrelated
- MG5_aMCatNLO ($t\bar{t} + 2$ jets@NLO): larger shape variations, agreement with data

Tuning radiation using $t\bar{t}$ data

CMS PAS TOP-16-021

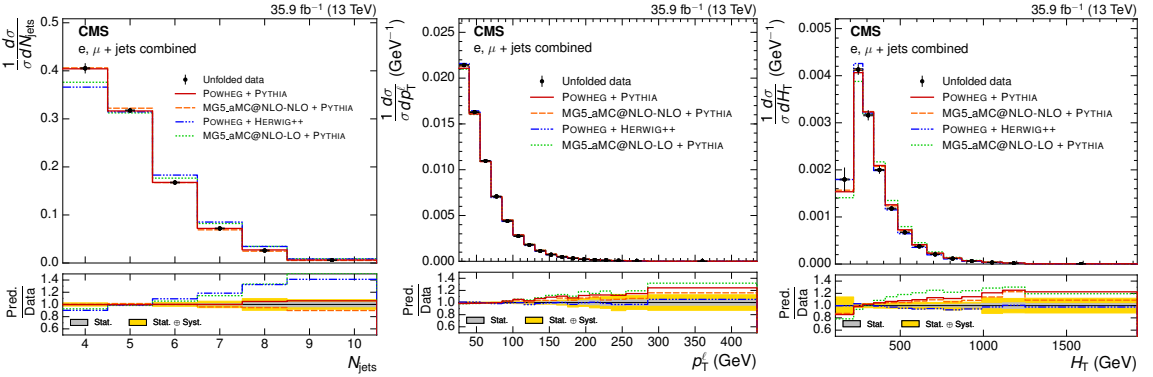


- Jet multiplicity predicted by Pythia8 default/Monash tune is too high
  $\rightarrow$ tune α_s^{ISR} to data, finding significantly lower values
- default/Monash: $\alpha_s^{\text{ISR}} = 0.1365$, CMS $\alpha_s^{\text{ISR}} = 0.1108$, ATLAS ATTBAR: $\alpha_s^{\text{ISR}} = 0.121$

Measurement of kinematic event variables

CMS TOP-16-014

- Measuring kinematic distributions in $t\bar{t}$ →lepton+jets, no top reconstruction: jet multiplicity, HT, ST, W p_T, lepton p_T, MET

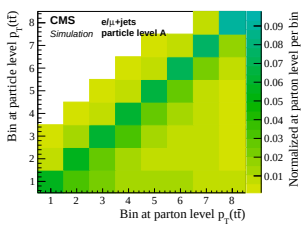


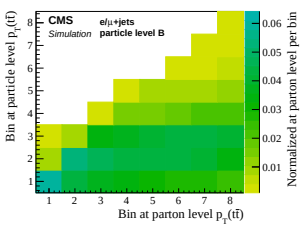
- Powheg+Pythia 8 agrees well for jet multiplicity – tuned to 8 TeV data
- Lepton p_T shows similar trend as top p_T. HT also driven by top decay products?

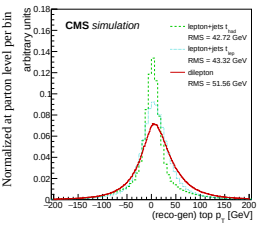
Object definitions for top analyses at the particle level

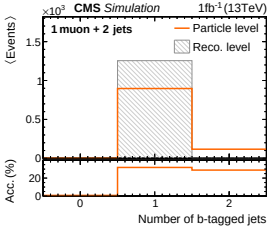
CMS CMS-NOTE-2017-004

- Presents objects that are safe to use for generator comparisons and compatible with Rivet
  - No access to quarks and gluons, only hadrons, leptons and photons
  - "Dressed" leptons: cluster lepton with surrounding FSR photons
  - "Ghost" tagging for bottom/charm jets (and taus)
- Discusses some physics cases
  1. Different approaches for top reconstruction in lepton+jets: mass-based vs. $p_T - \Delta R$ based
  2. Compared particle→reco level top/$t\bar{t}$ p_T resolution in lepton+jets and dilepton
  3. Presented implementation of single top at particle level





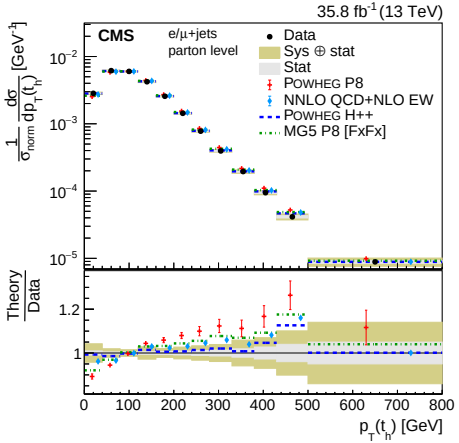


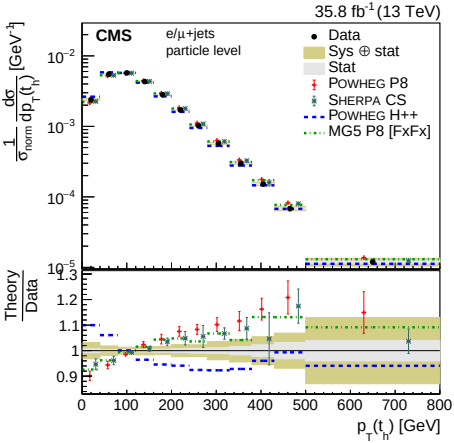


Measurement of differential cross sections

CMS TOP-17-002

- (Double!) differential cross section as function of **top** p_T, rapidity (had/lep, leading/trailing), $t\bar{t}$ p_T, mass, rapidity, jet p_T/η, ΔR_t; jet multiplicity, gap fractions



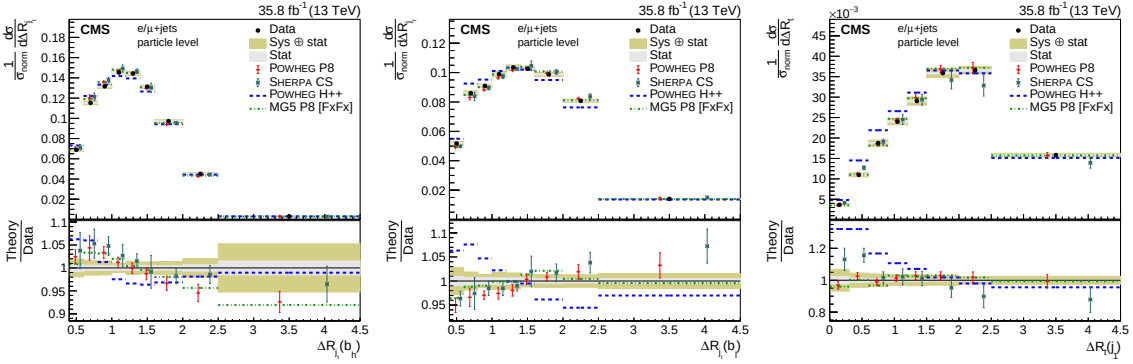


- Top p_T still not well described:
  - NNLO QCD + NLO EW agrees better with the data than Powheg+Pythia 8
  - Powheg+Herwig agrees at parton but not at particle level!

Measurement of differential cross sections

CMS TOP-17-002

- Interesting data on the ΔR between had/lep b jets and nearest jet from $t\bar{t}$ system, not well described by any MC generator



- Right plot: Herwig++ yields too much extra radiation in direction of the top quarks. Could explain the softer top p_T we see for Herwig!

Jet substructure in $t\bar{t}$ events

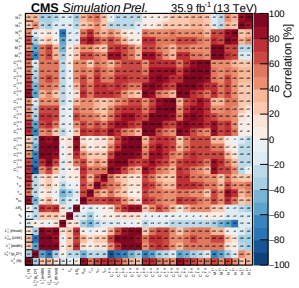
CMS PAS TOP-17-013

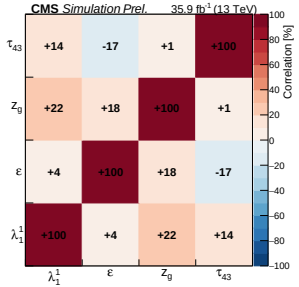
Motivation

- Fragmentation of quarks and gluons to jets described by parton shower + hadronization model
- Current models are tuned to LEP $Z \to q\bar{q}$ data
- Uncertainties relevant for many measurements, e.g. top mass

Measurement in $t\bar{t} \to$ lepton+jets

- "Standard candle" in pp collisions
- Jet substructure for each flavor: bottom, light-enriched, gluon-enriched
- Exhaustive analysis: more than 20 observables
  - Generalized angularities λ_β^κ (particle multiplicity, p_T dispersion, width, ...)
  - Eccentricity, soft drop observables, N-subjettiness, energy correlation function ratios

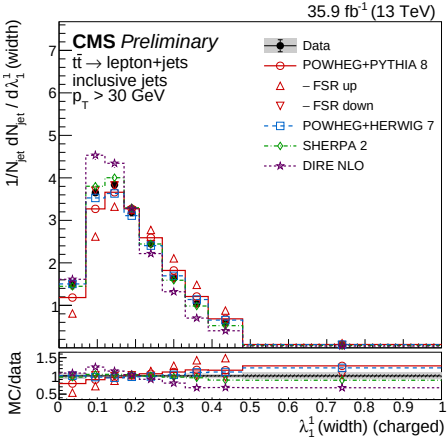


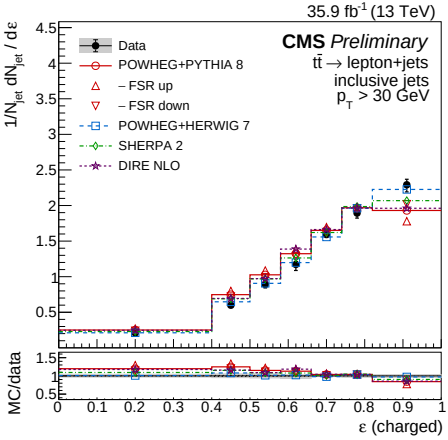


Jet substructure: jet width, eccentricity

CMS PAS TOP-17-013

- Jet width λ_1^1, $\lambda_\beta^\kappa = \sum_i z_i^\kappa \left(\frac{\Delta R(i,\hat{n}_r)}{R}\right)^\beta$ with $z_i = p_\mathrm{T}^i / \sum_i p_\mathrm{T}^i$ and recoil-free axis $\hat{n}_r$
- ⋆ Dire (NLO) 2.001: full $b \to bg$ structure not covered yet, ○ Pythia 8 requires FSR down





- $\varepsilon = 1 - \frac{v_\mathrm{min}}{v_\mathrm{max}}$ with the eigenvalues of $M = \sum_i E_i \times \begin{pmatrix} (\Delta\eta_{i,\hat{n}_r})^2 & \Delta\eta_{i,\hat{n}_r}\Delta\phi_{i,\hat{n}_r} \\ \Delta\phi_{i,\hat{n}_r}\Delta\eta_{i,\hat{n}_r} & (\Delta\phi_{i,\hat{n}_r})^2 \end{pmatrix}$
- Perfectly circular jet: $\varepsilon = 0$, elliptical jet: $\varepsilon \to 1$; best agreement with □ Herwig 7

Jet substructure: softdrop splitting function, N-subjettiness

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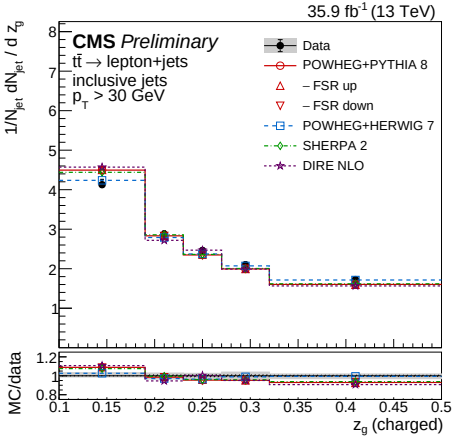
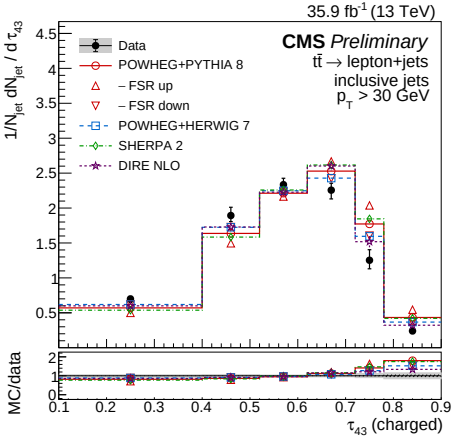
- Groomed momentum fraction z_g: related to QCD splitting function, independent of α_s
- Best agreement with ☐ Herwig 7 (angular-ordered)





- τ_{NM} used for distinguishing jets with N or M subjets, correlated with multiplicity

Underlying event in $t\bar{t}$ events

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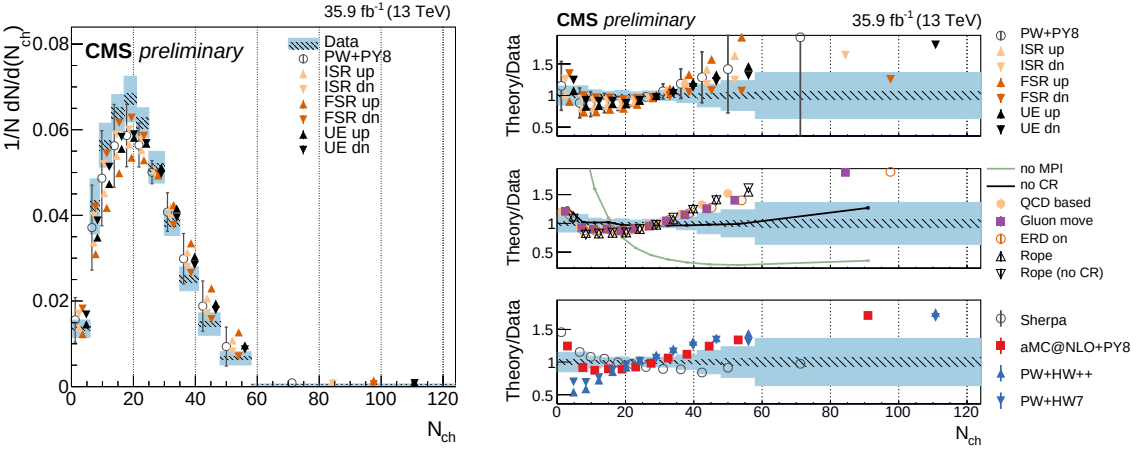
- Probe the underlying event in high-scale process → measured in $t\bar{t}$ dilepton events: charged multiplicity, summed/average momenta; event shapes: sphericity/aplanarity/C/D

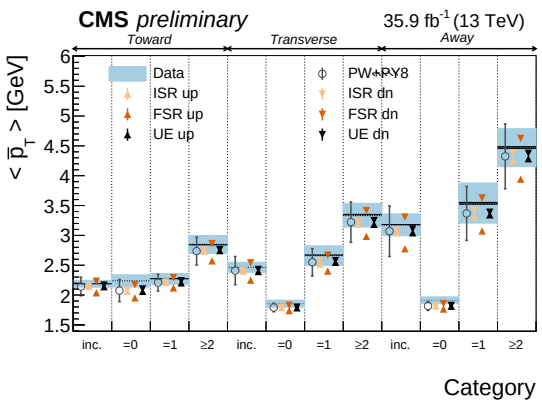


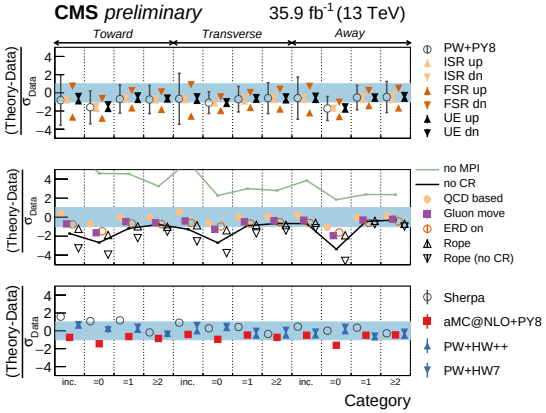
- Large sensitivity to ISR/FSR variations, prefer less radiation
- Data compared to large range of models: CR models, rope hadronization, Sherpa, Herwig

Underlying event: measurement in different categories

CMS PAS TOP-17-015

- Measured in categories of N_{jets},dilepton p_T, dilepton mass, and region wrt $p_T(\ell\ell)$
- Mean charged particle p_T in toward/transverse/away region for different N_{jet}:



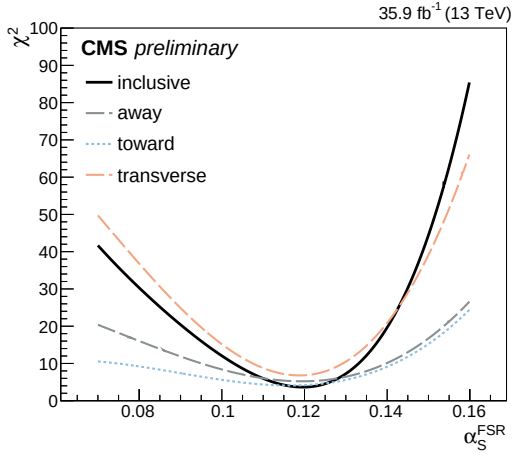


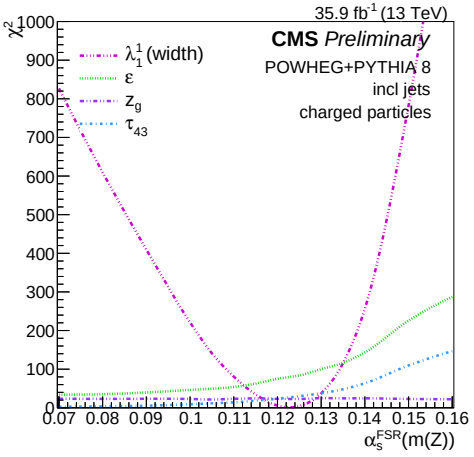
- Large dependence on N_{jet} for transverse/away regions
- Same mean p_T for transverse and away when $N_{jet} = 0$

Fits of Powheg+Pythia 8 $\alpha_s^{\mathrm{FSR}}(m_Z)$

CMS PAS TOP-17-013 CMS PAS TOP-17-015

- Scan of $\alpha_s^{\mathrm{FSR}}(m_Z)$ in underlying events and jet shape observables





- From $\overline{p_{\mathrm{T}}} \rightarrow \alpha_s^{\mathrm{FSR}}(m_Z) = 0.120 \pm 0.006$; from jet width $\rightarrow \alpha_s^{\mathrm{FSR}}(m_Z) = 0.1227 \pm 0.0013$
- Need more complete tuning to get agreement with all observables
- Comparison to world average needs CMW scheme and scale uncertainties ($\rightsquigarrow {}^{+0.014}_{-0.012}$)

Summary

- Gained first experience with tuning the MC generators to CMS $t\bar{t}$ data:
  jet p_T/multiplicity at 8 TeV to tune α_s^{ISR} and hdamp, used for 13 TeV samples
- Plethora of new particle-level measurements using 2016 data
  - kinematic event variables w/o top reconstruction
  - (double) differential $t\bar{t}$ cross sections with top reconstruction
  - jet substructure for different jet flavors
  - underlying event observables
- Probing different aspects of $t\bar{t}$ modeling, will allow for improving current MC generators
- All new analyses will be available in Rivet soon