Top modelling and tuning in CMS

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on behalf of CMS collaboration

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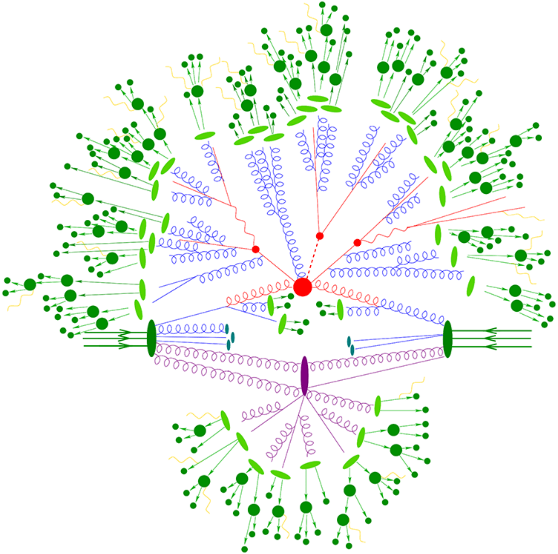
Event modelling

Ingredients:

- Hard scattering
- Initial and final state radiation (parton shower)
- Hadronisation
- Multiple parton interaction

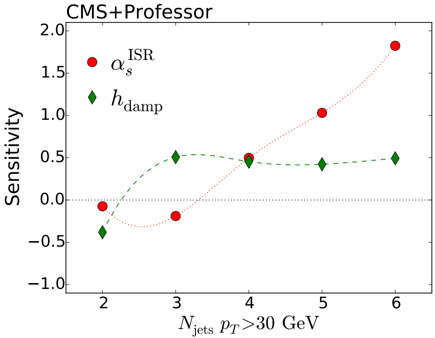


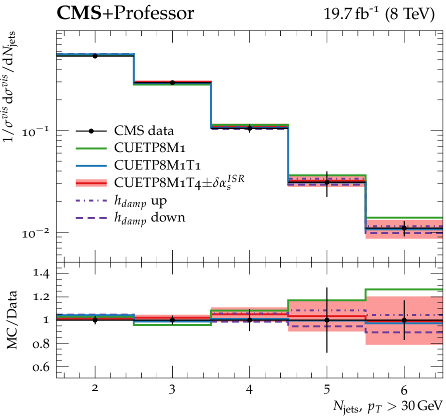
Not all ingredients are perturbatively computable:

- need phenomenological input
- tunable parameters are present also in perturbative ingredients

→ **use experimental data to constrain models**

Jet multiplicity in $t\bar{t}$ events [CMS-PAS-TOP-16-021]



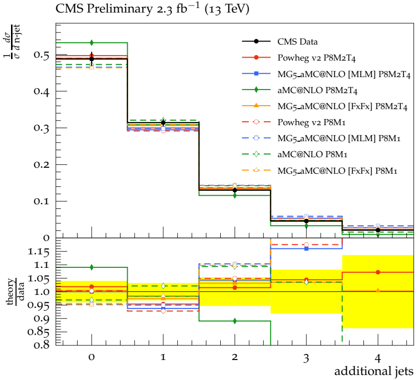


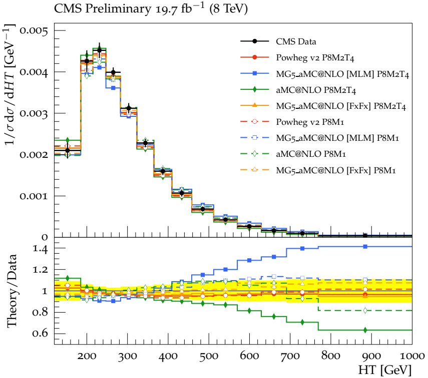
Jet multiplicity N_{jets} depends on α_s^{ISR} (high N_{jets}) and ME/PS matching h_{damp} (ratio 3/2):

- $h_{\mathrm{damp}} = 1.581^{+0.658}_{-0.585} m_t$
- $\alpha_s^{\mathrm{ISR}} = 0.1108^{+0.0145}_{-0.0142}$ (c.f. in Monash-based tune $\alpha_s^{\mathrm{ISR}} = 0.1365$)

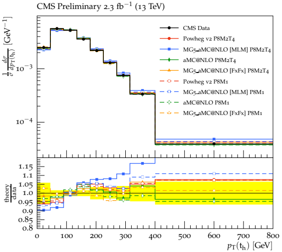
  $\rightarrow$ using this tuned α_s^{ISR}, underlying event and minimum bias data, new tune **CUETP8M2T4** is derived and used in top quark measurements with 2016 data

Performance of new tune [CMS-PAS-TOP-16-021]





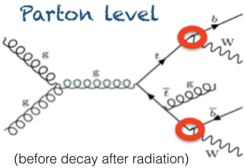
- Powheg(v2) + Pythia8 with new tune describes well N_{jets} and most of $t\bar{t}$ kinematic distributions
- similar for MG5_aMC@NLO [FxFx] with Pythia8
- ... except $p_T(t)$ (seen also with Run-I data)
- worse description by MG5_aMC@NLO [MLM]



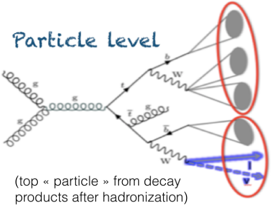
Top quark definition at particle level [CMS-NOTE-2017-004]

Parton-level top quark measurements are more prone to theoretical uncertainties:

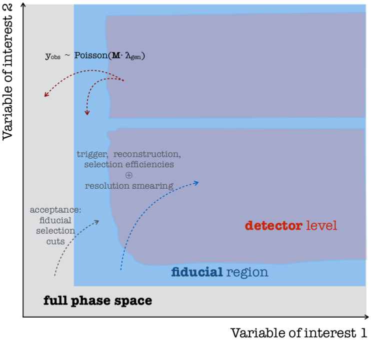
- due to large corrections applied to objects measured at detector level
- or just ill defined in some aspects (e.g. off-shell production and interference with background)



(before decay after radiation)



(top « particle » from decay products after hadronization)



Alternatively, top "particle" is constructed from measured decay products:

- using only observable particles
- closer relation to measured objects

→ of fundamental importance for differential top measurements

Measurements of $p_T(t)$ differential cross sections [PRD 97 (2018) 112003, CMS-PAS-TOP-17-014]

- Powheg+Herwig describes $p_T(t)$ better than Powheg+Pythia8

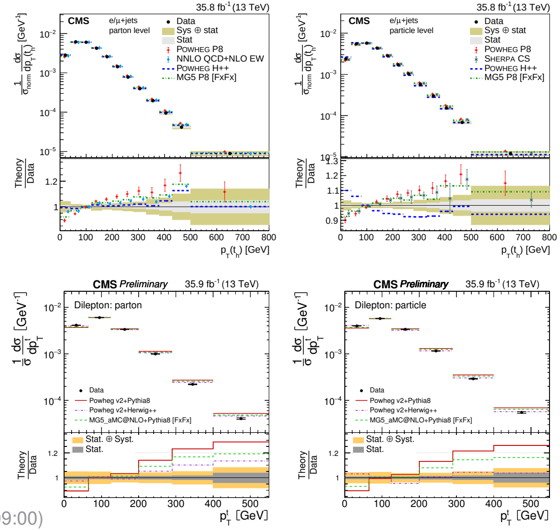
  ... but Powheg+Herwig describes other distributions worse

- at parton level, NNLO describes $p_T(t)$ better than NLO

  ... NNLO is not yet available for particle level predictions

- different level of agreement with theoretical predictions when looking at parton or particle level

  ... smaller data uncertainties at particle level



(see Douglas John Paul Burns' talk 5 July 09:00)

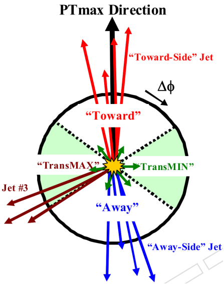
→ **stringent tests of theoretical predictions can be done at particle level**

Tuning of colour reconnection models using underlying event [CMS-PAS-TOP-17-007]

- Measurements of underlying event are used to constrain colour reconnection (CR) and multiple parton interaction models
- Introduces two new CR tunes based on models:
  - **(1)** "QCD-inspired": string formation beyond leading color
  - **(2)** "gluon-move": allows gluons to be moved to another string

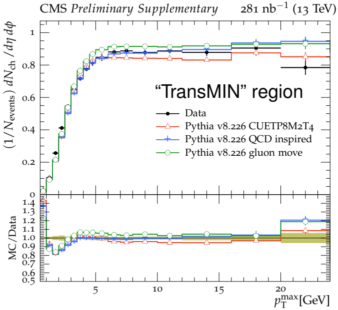
→ Important for evaluating systematic uncertainties in top quark measurements relative to CR, e.g. for top quark mass

(see Nataliia Kovalchuk's talk 7 July 17:30)

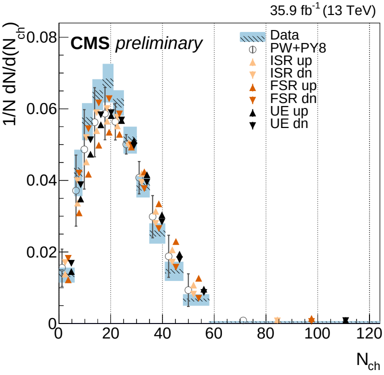


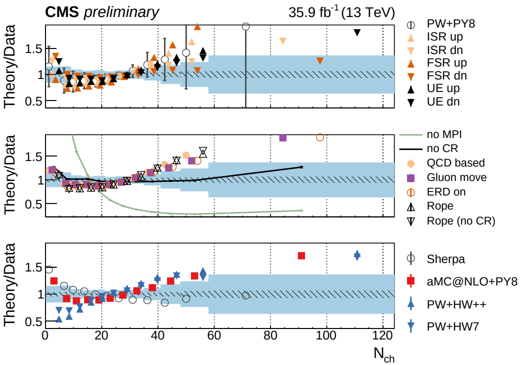
Parameters	CUETP8M2T4	QCD inspired	gluon move
MultipartonInteractions:**pT0Ref**	2.20	2.17	2.30
MultipartonInteractions:**expPow**	1.60	1.31	1.35
MultipartonInteractions:**ecmRef**	7000	7000*	7000*
MultipartonInteractions:**ecmPow**	0.25	0.25*	0.25*
ColourReconnection:**range**	6.59	-	-
ColourReconnection:**junctionCorrection**	-	0.12 (1.20)	-
ColourReconnection:**timeDilationPar**	-	15.9 (0.18)	-
ColourReconnection:**m0**	-	1.2 (0.3)	-
ColourReconnection:**m2lambda**	-	-	1.9 (1.0)
ColourReconnection:**fracGluon**	-	-	1.0* (1.0)
ColourReconnection:**dLambdaCut**	-	-	0.0* (0.0)
PDF set	NNPDF30_LO [JHEP 04 (2015)]	NNPDF30_LO	NNPDF30_LO
SpaceShower:alphaSvalue	0.1108*	0.1108*	0.1108*
Goodness of fit/dof	1.89 [CMS-PAS-TOP-16-021]	1.06	1.69

* = value kept fixed in the fit



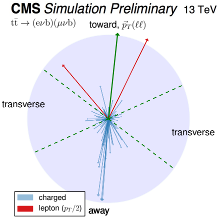
- Underlying event (UE) is studied in $t\bar{t}$ production using dilepton events:
  - at energy scale $\sim 2m_t \gg$ in previous studies of UE
  - test universality of UE hypothesis at different energy scales
- Various kinematic distributions of UE are sensitive to MC parameters:
  - e.g. charged particle multiplicity N_{ch} is sensitive to FSR

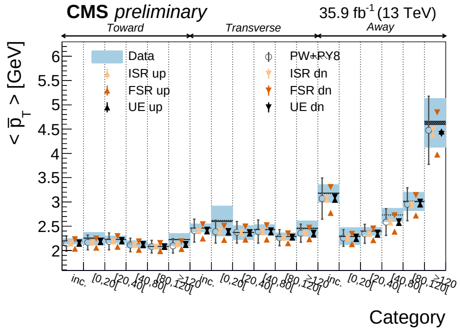




Underlying event in $t\bar{t}$ production [CMS-PAS-TOP-17-015]

- $|\vec{p}_T(ll)|$ provides further sensitivity:
  - correlated with $t\bar{t}$ and recoil (== UE)
  - allows further categorisation based on direction w.r.t ll
- Distributions of $|\vec{p}_T| = |\sum_{i=1}^{N_{ch}} \vec{p}_{T,i}|$ in different directions w.r.t leptons and in different $|\vec{p}_T(ll)|$ regions constrain α_s^{FSR}





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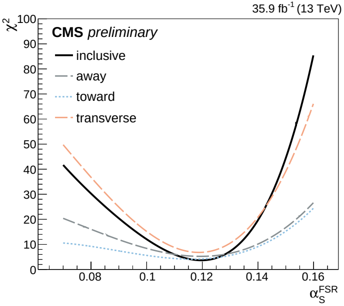


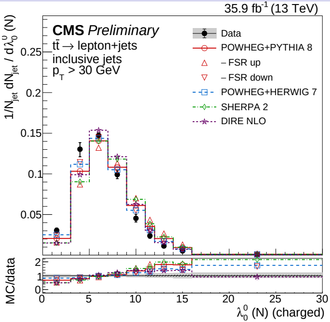
- Most distributions are in fair agreement with Pythia8 using CUETP8M2T4
  - for both Powheg or MG5_aMC@NLO
  - $\alpha_s^{FSR} = 0.120 \pm 0.006$: lower than in default Monash-based tune
- Default settings in Herwig++, Herwig7 and Sherpa are disfavored

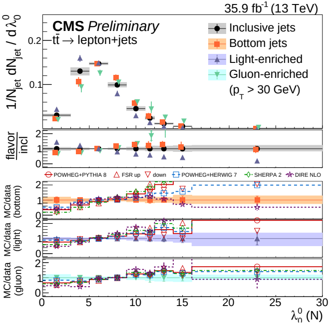
Jet substructure in $t\bar{t}$ events [CMS-PAS-TOP-17-013]

- Multiple jet substructure observables are measured in $t\bar{t}$ events
  - Generalized angularities
    $$\lambda_\beta^\kappa = \sum_i z_i^\kappa \left(\frac{\Delta R(i,\hat{n}_r)}{R}\right)^\beta$$
    - ★ λ_0^0: charged particle multiplicity
    - ★ λ_1^1: jet width
  - …(more than 20 observables are studied)
- Measured for inclusive and bottom, light-quark, and gluon jets from $t\bar{t}$
- Provided χ^2 for data-to-theory comparison:

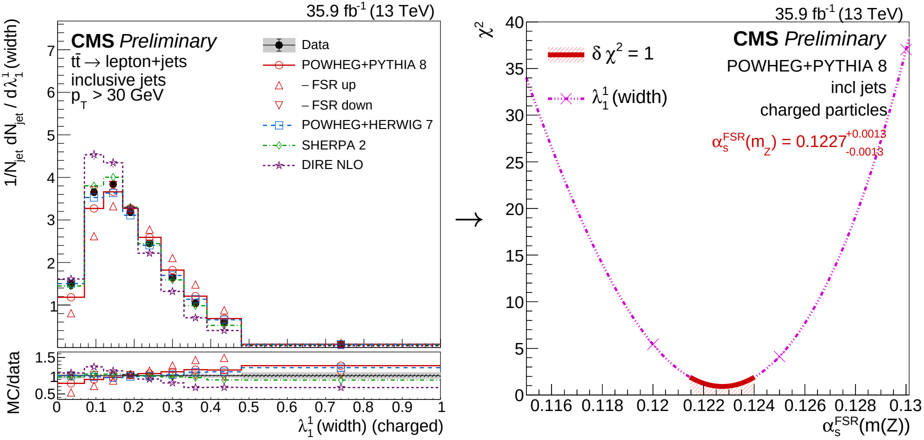
Observable	flavor	POWHEG +PYTHIA 8 FSR-down	POWHEG +PYTHIA 8 nominal	POWHEG +PYTHIA 8 FSR-up	POWHEG + HERWIG 7	SHERPA 2	DIRE NLO
$\alpha_s^{\mathrm{FSR}}(m_Z)$		0.1224	0.1365	0.1543	0.1262	0.118	0.1201
λ_1^1 (width)	incl	2.2	148.6	1153.9	62.5	48.1	673.3
ndf = 8	bottom	2.9	225.6	1754.6	18.8	92.1	2841.6
	light	7.0	59.2	518.5	44.2	20.4	46.8
	gluon	2.9	17.6	95.7	15.4	8.1	175.3

→ data on λ_1^1 prefer less FSR in Pythia8





Jet substructure in $t\bar{t}$ events [CMS-PAS-TOP-17-013]



- Used data on λ_1^1 to constrain α_s^{FSR}
  $\rightarrow$ compatible with other CMS extractions using $t\bar{t}$ data [CMS-PAS-TOP-17-015]
- Not all observables are well described
  $\rightarrow$ more complete tuning is needed to achieve better overall agreement
- Data can be compared to QCD calculations with higher-order corrections

Summary

- Using data to constrain theoretical models provides improved precision for new measurements:
  - e.g. $t\bar{t}$ Run-I data used to tune α_s^{ISR} [CMS-PAS-TOP-16-021] $\rightarrow$ further used in Run-II MC simulations
  - theoretical uncertainties are important in precision top measurements, e.g. measurement of top quark mass [arXiv:1805.01428]
- New analyses using Run-II top quark data:
  - Measurements of $t\bar{t}$ kinematics [JHEP04 (2018) 060, JHEP06 (2018) 002, PRD 97 (2018) 112003, CMS-PAS-TOP-17-014]:
    - ⋆ generally well describe by MC, except $p_T(t)$: higher-order corrections needed
    - ⋆ particle-level top quark definition is crucial for stringent tests of predictions [CMS-NOTE-2017-004]
  - Underlying event in $t\bar{t}$ [CMS-PAS-TOP-17-015]:
    - ⋆ tests universality of UE hypothesis at different energy scales
  - Jet substructure in $t\bar{t}$ [CMS-PAS-TOP-17-013]:
    - ⋆ exhaustive data for testing parton shower and hadronization models
- *All analyses will be available in RIVET for their future re-interpretation*

BACKUP

Underlying event in $t\bar{t}$ production [CMS-PAS-TOP-17-015]

Event generator	POWHEG (v2)	MG5_aMC@NLO	SHERPA 2.2.4
Matrix element characteristics			
Mode	hvq	FxFx Merging	OpenLoops
QCD scales (μ_R,μ_F)	m_T^t	$\sum_{t,\bar{t}} m_T/2$	
α_S	0.118	0.118	0.118
PDF	NNPDF3.0 NLO	NNPDF3.0 NLO	NNPDF3.0 NNLO
pQCD accuracy	$t\bar{t}$ [NLO]	$t\bar{t}$ +0,1,2 jets [NLO]	$t\bar{t}$ [NLO]
	1 jet [LO]	3 jets [LO]	
Parton shower			
Setup designation	Pw+Py8	aMC@NLO+Py8	SHERPA
PS	PYTHIA 8.219	PYTHIA 8.219	CS
Tune(s)	CUETP8M2T4	CUETP8M2T4	default
PDF	NNPDF2.3 LO	NNPDF2.3 LO	NNPDF3.0 NNLO
(α_S^{ISR}, α_S^{FSR})	(0.1108,0.1365)	(0.1108,0.1365)	(0.118,0.118)
ME Corrections	on	on	n/a
Setup designation	Pw+Hw++	Pw+Hw7	
PS	HERWIG++	HERWIG 7	
Tune(s)	EE5C	Default	
PDF	CTEQ6L1	MMHT2014lo68cl	
(α_S^{ISR}, α_S^{FSR})	(0.1262,0.1262)	(0.1262,0.1262)	
ME Corrections	off	on	