Differential top pair production cross-sections

Dr Veronique Boisvert

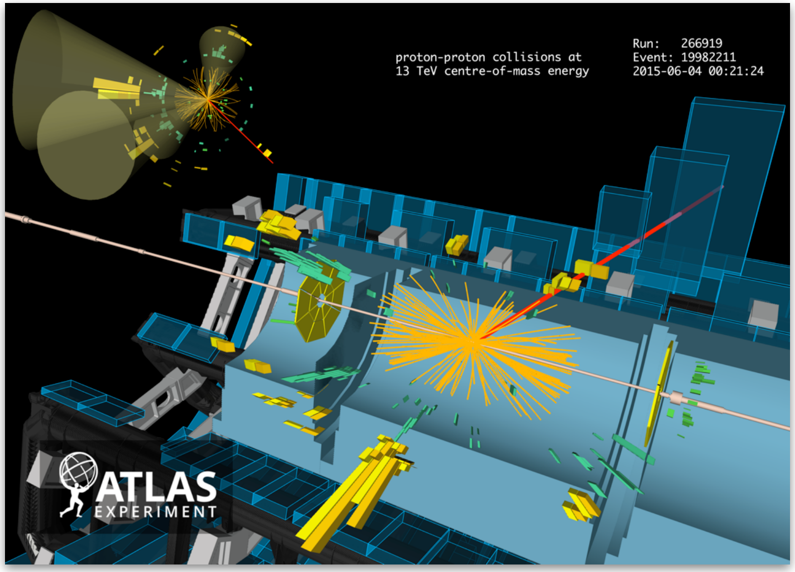
ROYAL HOLLOWAY UNIVERSITY OF LONDON

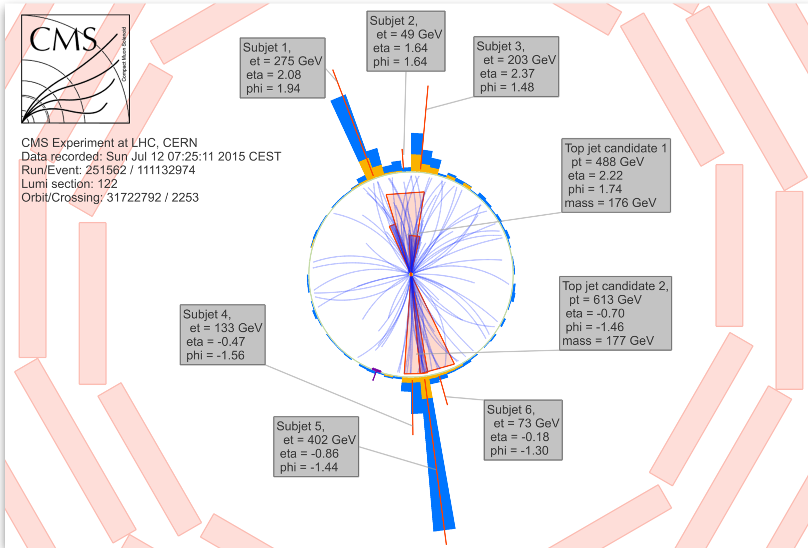
LHCTopWG at CERN November 21st 2016

Why measure the tt cross-section differentially?

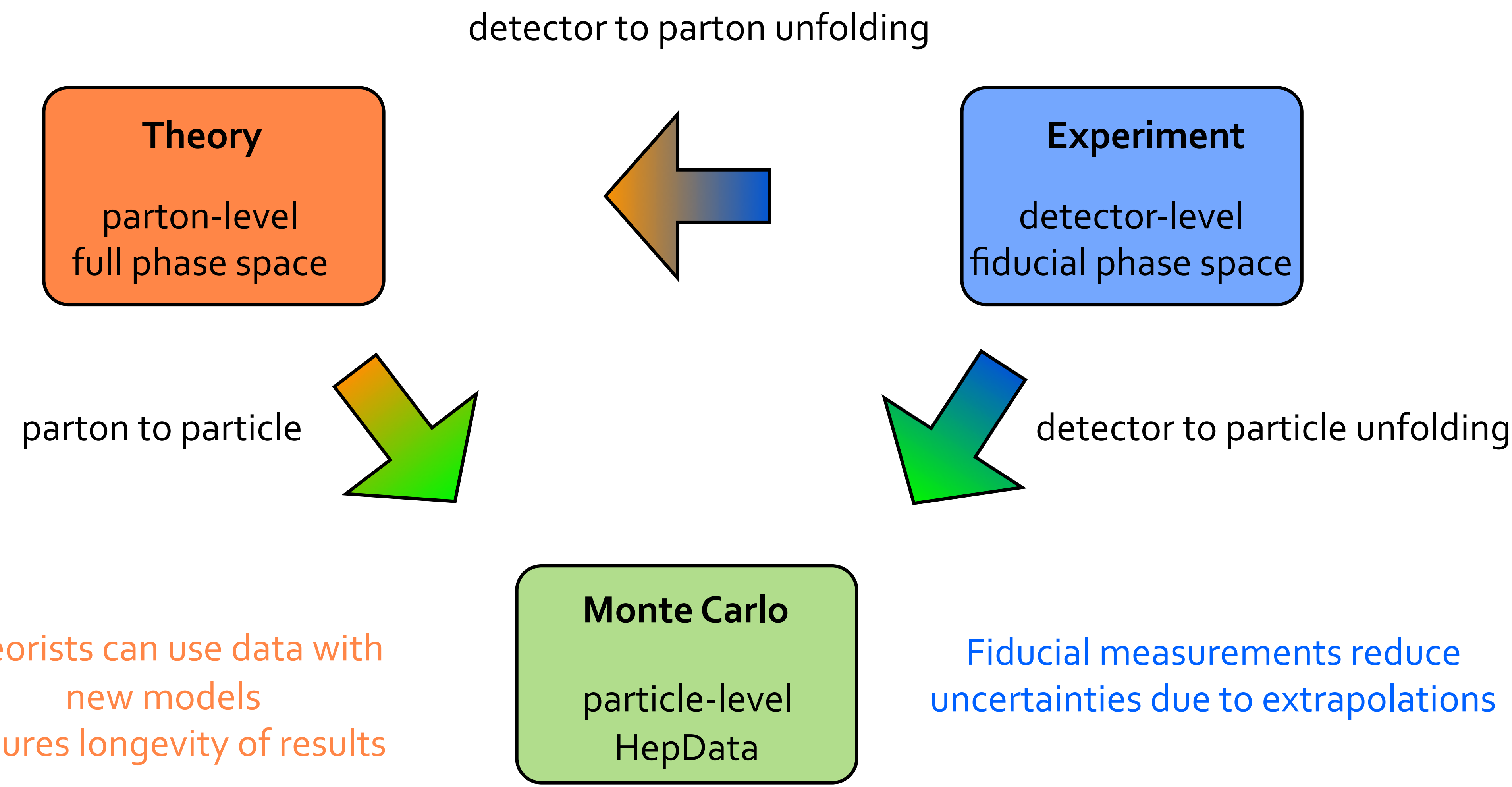
- Look for New Physics in ways that may elude direct searches
  - eg non-resonant production in m_{tt}
- Cross-check detailed QCD calculations
  - eg top quark p_T and its effect in Higgs physics and New Physics searches
- Help tune MC production
  - eg Powheg h_{damp} parameter from tt p_T
- Help constrain PDF
  - eg y(t) and y(tt)
- Good environment to develop new tools or study interesting corners of phase-space
  - Boosted algorithms

    A boosted top quark has high p_T (~>400 GeV) and its decay products are collimated into a large R~0.8-1.0 jet





Connecting experiments and theory



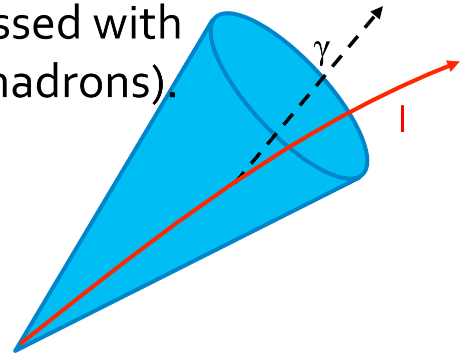
Theorists can use data with new models
Ensures longevity of results

Fiducial measurements reduce uncertainties due to extrapolations

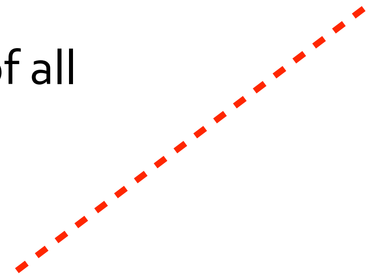
Rivet implementation:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopRivetAnalyses
CMS: TOP-16-021 (in preparation)

Particle-level objects

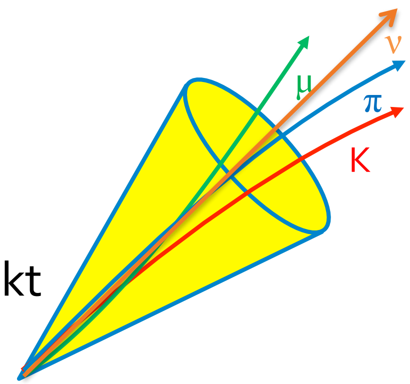
Charged leptons (not from hadrons) are dressed with the energy from nearby photons (not from hadrons). No isolation

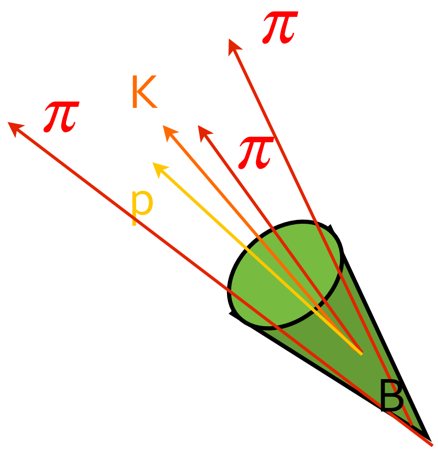


ETMiss calculated from the sum of all neutrinos not from hadrons



Jets are clustered from stable MC particle (excl. dressed leptons and neutrinos defined above) using anti-kt algorithm





b-jets defined by a jet containing a b-quark hadron

LHCTopWG recommendations:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions

Outline

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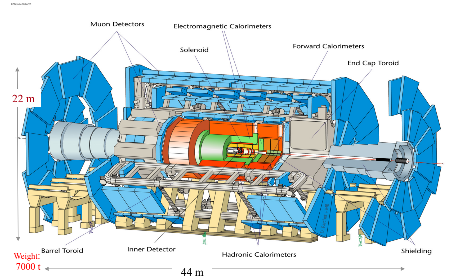
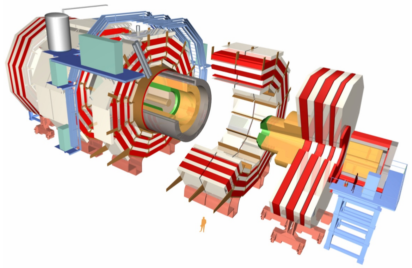
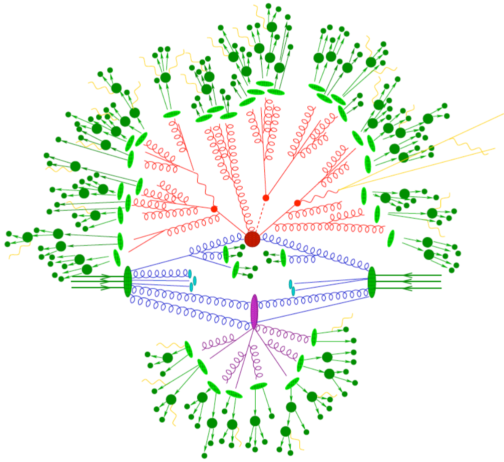
Physics

- Focus on recent measurements (mainly 13 TeV)
- Compare between ATLAS and CMS for:
    - Selection & Reconstruction algorithms
    - Unfolding techniques
    - Systematic uncertainties
    - Results
- Next talk (Efe) will cover:
    - MC samples and their tuning
    - Status of LHCTopWG plots







Recent measurements: 7/8 TeV

Physics

	ATLAS	CMS
dilepton	PRD 94(2016) 092003 7 & 8 TeV, resolved, parton JHEP 09 (2016) 074 8 TeV, resolved, particle, jet pT vs Njets (2D)	EPJ C75(2015) 542 8 TeV, resolved, parton, + lep+jets PAS-TOP-14-013 8 TeV, resolved, parton, 2D
l+jets	JHEP 06 (2015) 100 7 TeV, resolved, particle EPJ C76(2016) 538 8 TeV, resolved, parton/particle PRD 93(2016) 032009 8 TeV, boosted, parton/particle	EPJ C73(2013) 2339 7 TeV, resolved, parton/particle, + dil PRD 94(2016) 052006 7 & 8 TeV, resolved, particle TOP-14-012 (arXiv:1605.00116) 8 TeV, boosted, parton/particle
all-had		TOP-14-018 (arXiv:1509.06076) 8 TeV, resolved, parton/particle

Recent measurements: 13 TeV

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Physics

	ATLAS	CMS
dilepton	TOPQ-2016-04 resolved, particle TOPQ-2015-017 (arXiv:1610.09978) resolved, particle, Njets, gaps	PAS-TOP-16-007 resolved, particle PAS-TOP-16-011 resolved, parton
l+jets	CONF-2016-040 resolved/boosted,particle	PAS-TOP-16-008 (arXiv:1610.04191) resolved, parton/particle, 2D
all-had	CONF-2016-100 ~15 fb^{-1}, boosted,particle	PAS-TOP-16-013 resolved/boosted, parton

Selection & Reconstruction: dilepton

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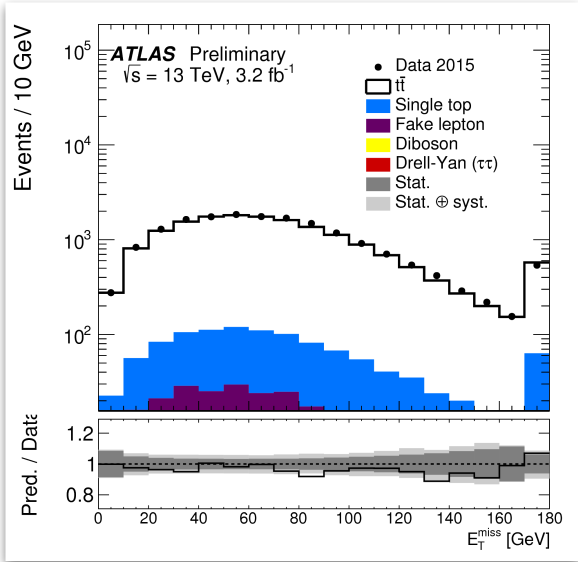
ATLAS

TOPQ-2016-04 TOPQ-2015-017

eμ p_T > 25 GeV
≥ 2 jets (anti-kt 0.4) p_T > 25 GeV
≥ 1 b-jets (76%)

Neutrino Weighting technique
m_t, m_W, scan over η(1), η(2)
20% inefficiency from not finding a solution
also suppresses background

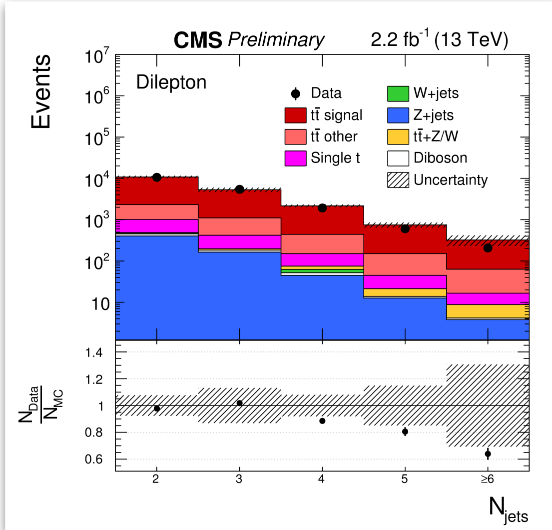


CMS

PAS-TOP-14-013 PAS-TOP-16-007 PAS-TOP-16-011

ee, μμ, eμ p_T > 20 GeV
m(ll)> 20 GeV
ee, μμ: MET> 40 GeV & |m(ll)-mZ| > 15 GeV
≥ 2 jets (anti-kt 0.5) p_T > 30 GeV
≥ 1 b-jets (80-85%)

Neutrino Weighting technique
m_t, m_W, 100 times
(smearing leptons and jets momenta)
5-10% inefficiency from not finding a solution



Selection & Reconstruction: lepton+jets

Physics

ATLAS

CONF-2016-040 (resolved)

e or μ p_T > 25 GeV
≥ 4 jets (anti-kt 0.4) p_T > 25 GeV
≥ 2 b-jets (77%)

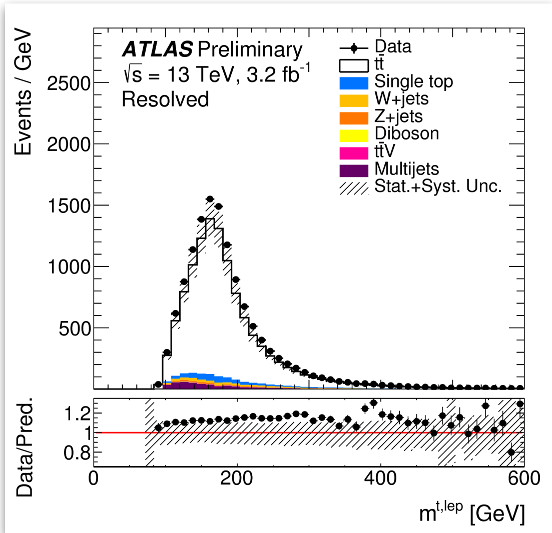
Pseudo-Top reco:
neutrino from mW
b-jet closest to lepton: leptonic top
light-jets closest to W: hadronic W
hadronic W+ other b-jet: hadronic top

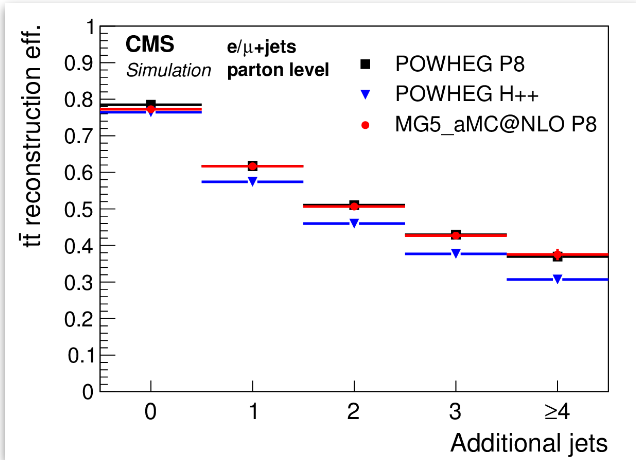
CMS

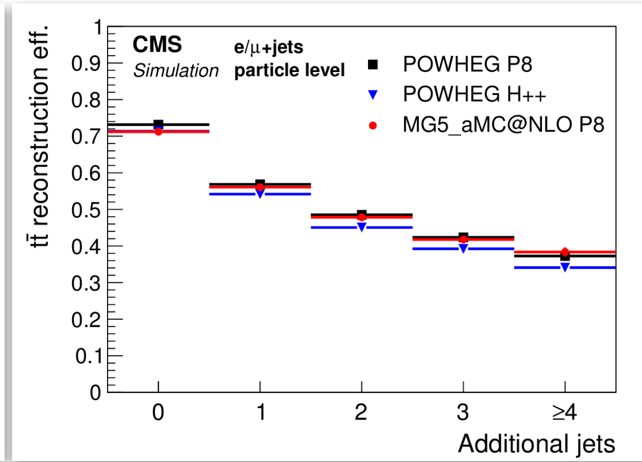
PAS-TOP-16-008 (resolved)

e or μ p_T > 30 GeV
≥ 4 jets (anti-kt 0.4) p_T > 30 GeV
≥ 2 b-jets (70% & 80%)

Likelihood kinematic fitting
Likelihood contains mass constraints
different evaluation for parton and particle
neutrino from m_t, m_W







Selection & Reconstruction: lepton+jets

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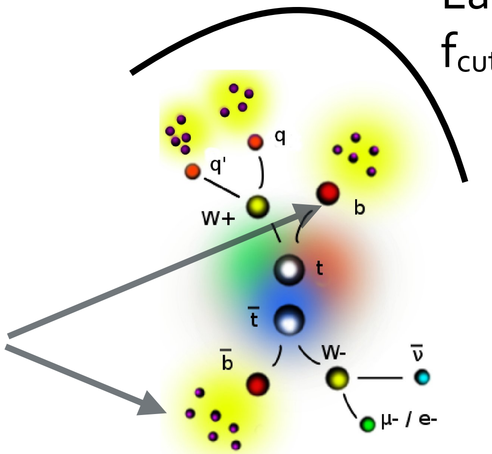
Physics

ATLAS

CONF-2016-040 (boosted)

e or μ p_T > 25 GeV
≥ 1 jets (anti-kt 0.4) p_T > 25 GeV
MET > 20 GeV, MET+m_{TW} > 60 GeV
≥ 1 trimmed large jets (anti-kt 1.0) with
300 GeV < p_T < 1500 GeV
TopTagging (80%):
calibrated jet mass and N-subjettiness τ_{32}

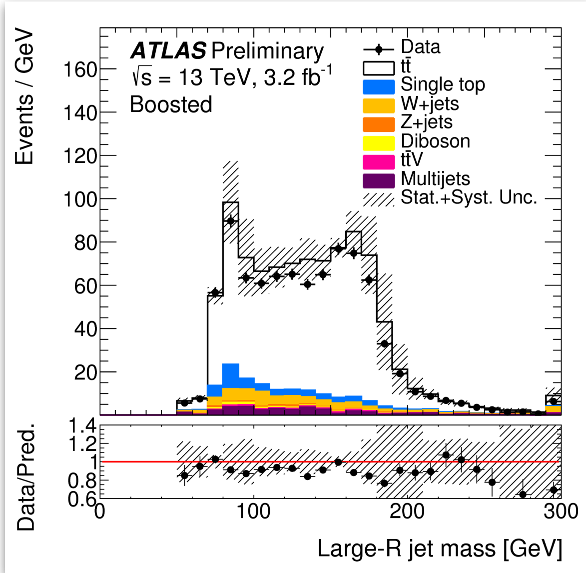
Large-jet (R_{sub}=0.2, f_{cut} =0.05)

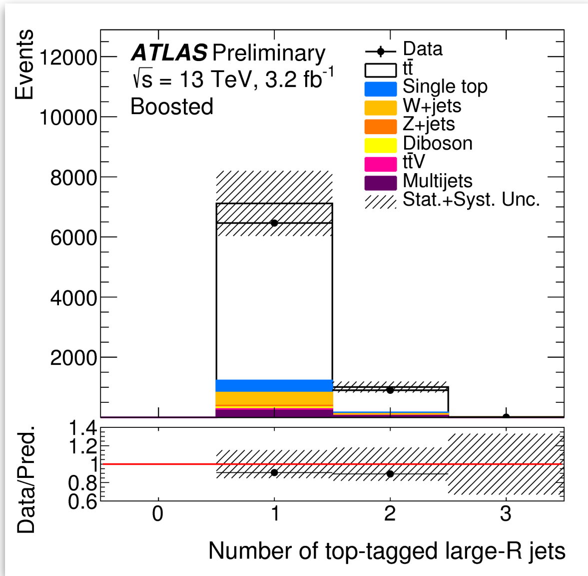


Either small-jet is b-tag

ΔR(Large-jet, small jet) > 1.5

ΔR(lepton, small jet) < 2.0





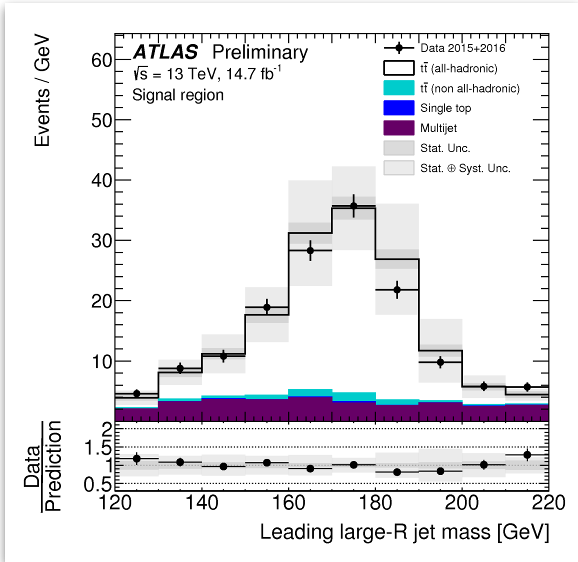
Selection & Reconstruction: all-hadronic

Physics

ATLAS

CONF-2016-100 (boosted)

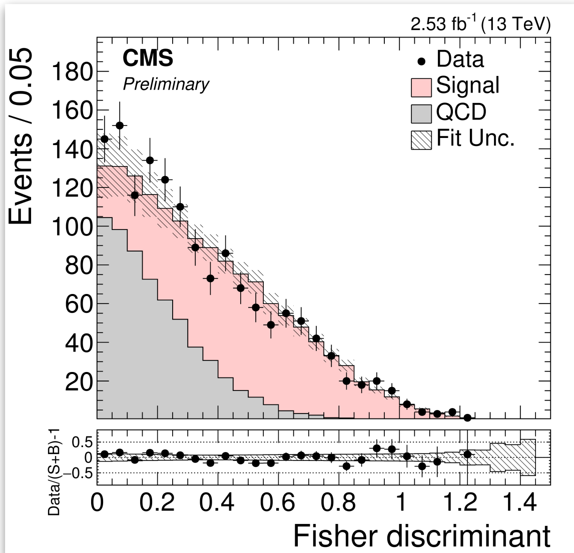
NO e or μ $p_T > 25$ GeV
≥ 2 jets (anti-kt 0.4) $p_T > 25$ GeV
≥ 2 trimmed large jets (anti-kt 1.0) with
350 GeV < p_T < 1500 GeV (leading p_T >500 GeV)
TopTagging (50%):
calibrated jet mass and N-subjettiness τ_{32}
≥ 2 b-jets $p_T > 25$ GeV (70%)
ΔR(b-jet, Large jet) < 1.0



CMS

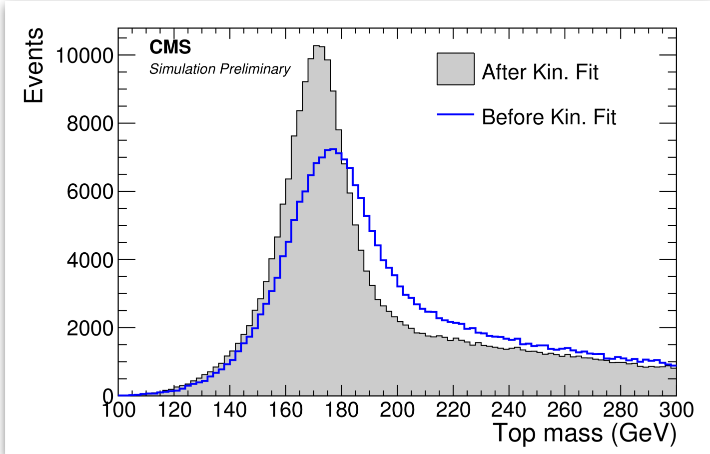
PAS-TOP-16-013 (boosted)

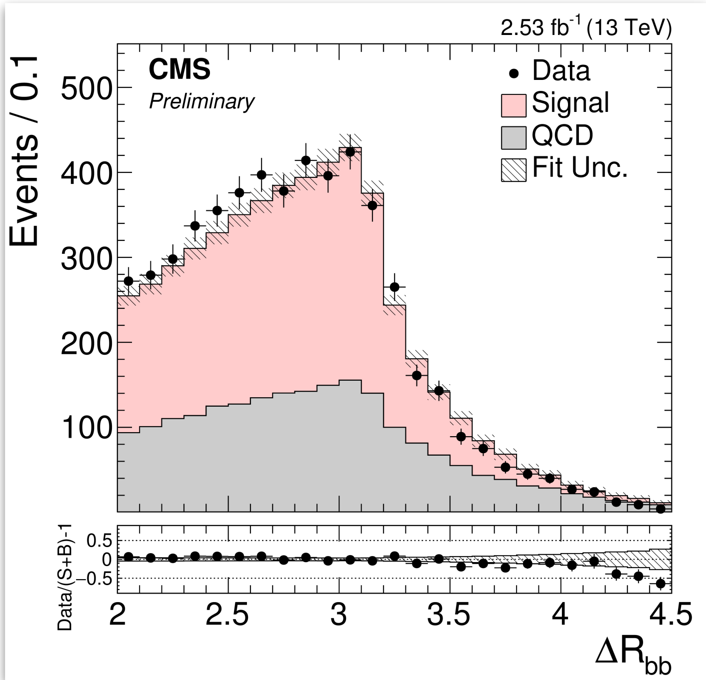
NO e or μ $p_T > 10$ GeV
≥ 2 jets (anti-kt 0.4) $p_T > 30$ GeV
≥ 2 Soft Drop large jets (anti-kt 0.8) with
$p_T > 200$ GeV (leading p_T >450 GeV)
≥ 2 b-jets (69%)
Event Fisher discriminant (τ_{32}, τ_{31}) > 0
150 < m_{SD} (leading large jet) < 200 GeV
Each large jet contains a b-jet

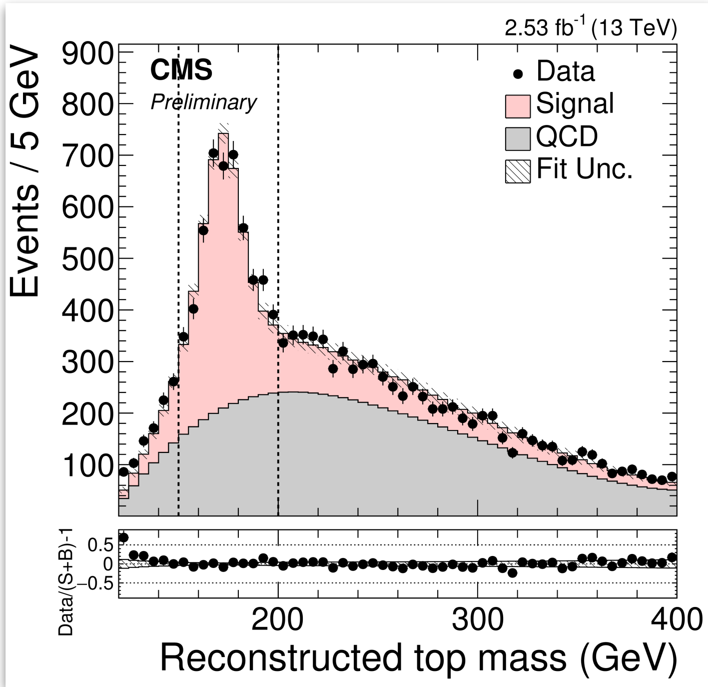


Selection & Reconstruction: all-hadronic

Physics







CMS

PAS-TOP-16-013 (resolved)

NO e or μ $p_T > 10$ GeV
≥ 6 jets (anti-kt 0.4) $p_T > 30$ GeV
$H_T > 500$ GeV, $p_T(6) > 45$ GeV
≥ 2 b-jets (69%)
ΔR(b,b) > 2.0
kin. fit prob. > 0.02
$150 < m_t < 200$ GeV

Unfolding techniques: ATLAS vs CMS

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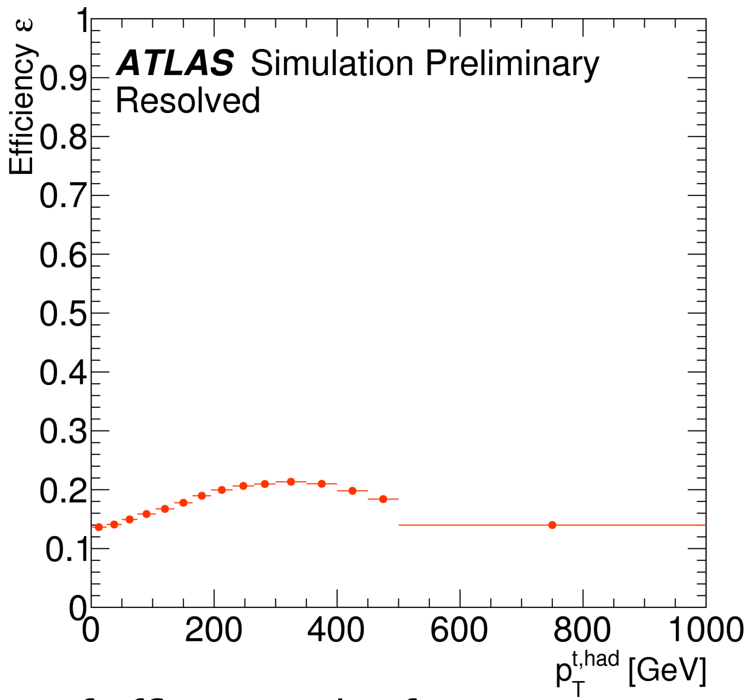
Physics

- Most analyses use Iterative Bayes-inspired regularized unfolding (d'Agostini) (IB)
- Some use Tikhonov regularisation within Single Value Decomposition (SVD)
- Both experiments check the unfolding by performing "closure" tests and "stress" tests
  - exact implementation differs
  - stress tests include injecting pseudo-data similar to New Physics signatures
- Both experiments do similar procedures for bin optimisation (check resolution and ensure migration is > 50% on diagonal)
- Both experiments do similar procedures for Bayesian N iterations optimisation
  - trade-off between unfolding bias (unfolding systematic) vs larger statistical uncertainties

$$\frac{d\sigma^{\text{fid}}}{dX^i} \equiv \frac{1}{\mathcal{L}\cdot\Delta X^i}\cdot\frac{1}{\epsilon^i}\cdot\sum_j \mathcal{M}_{ij}^{-1}\cdot f_{\text{match}}^j\cdot f_{\text{acc}}^j\cdot\left(N_{\text{reco}}^j - N_{\text{bg}}^j\right)$$



ex of efficiency plot from CONF-2016-040

Unfolding Techniques

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Physics

ATLAS

dilepton TOPQ-2016-04 TOPQ-2015-017

IB, N_{iter} = 6/4, no unf. systematic

lep+jets CONF-2016-040

IB, N_{iter} = 4, no unf. systematic

all-had CONF-2016-100

IB, no unf. systematic

CMS

dilepton TOP-16-011

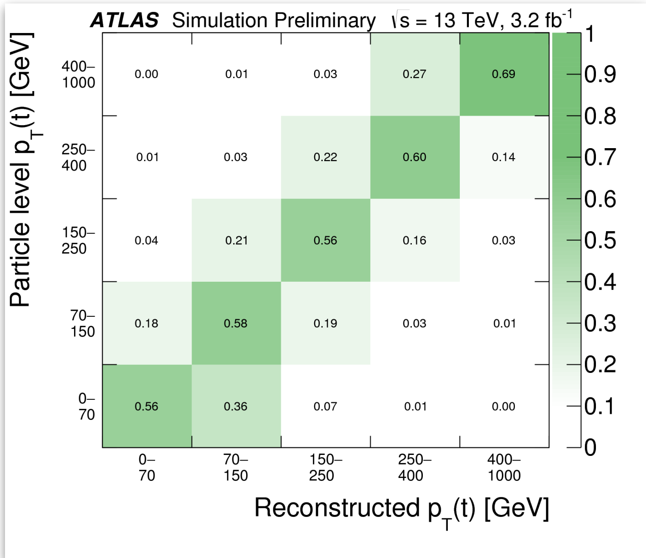
SVD, no unf. systematic

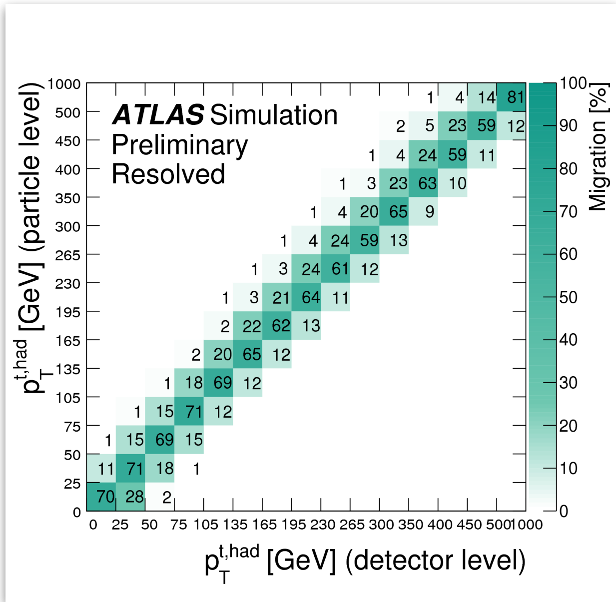
dilepton TOP-16-007

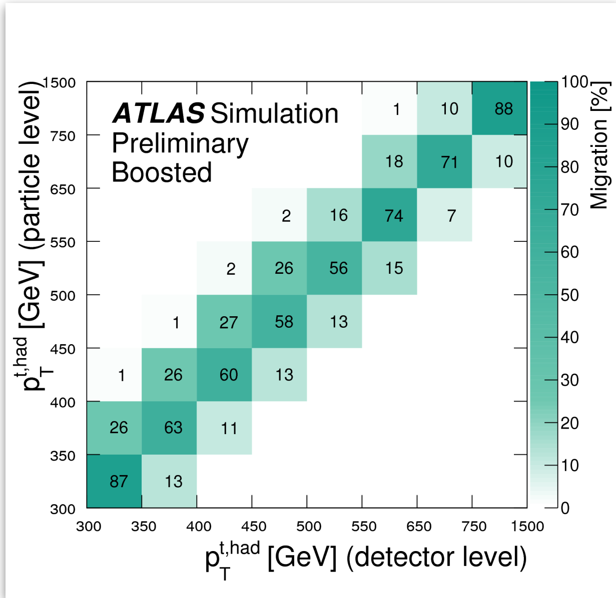
IB, N_{iter} opt. per observables, no unf. syst.

all-had TOP-16-013

IB, unfolding systematic (small)

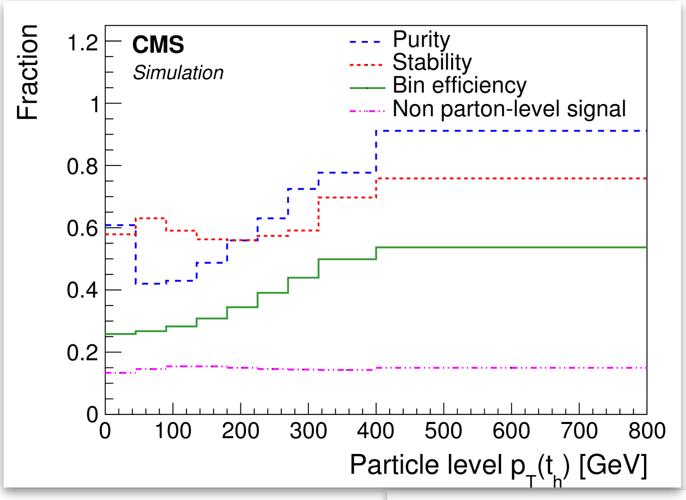


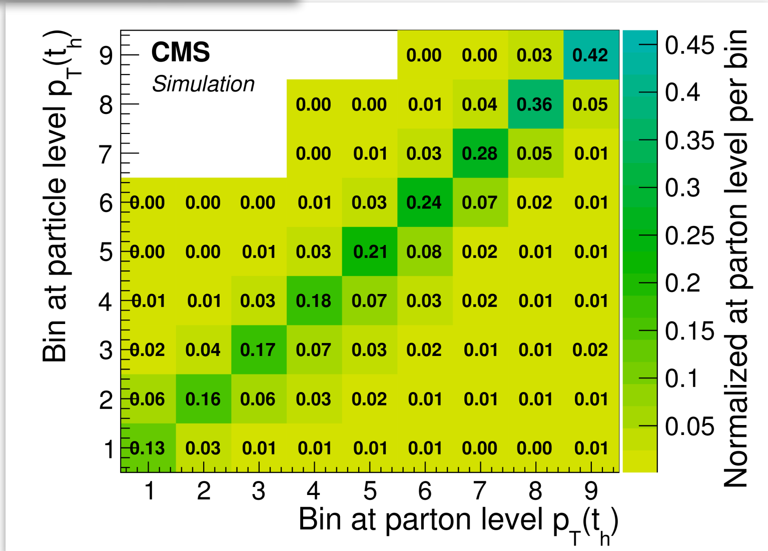




Unfolding Techniques

$$\left(\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y}\right)_{ij} = \frac{1}{\sigma}\cdot\frac{1}{\Delta x_i}\cdot\frac{1}{\Delta y_j}\cdot\frac{N_{ij}^{\text{signal unfolded}}}{\mathcal{B}\cdot\mathcal{L}}$$





CMS

dilepton TOP-14-013

TUnfold algorithm used. Unfolding done using χ^2 minimisation including term for the Tikhonov regularisation

2D mapped to many 1D.

lep+jets TOP-16-008

IB, N_{iter} optimized such that the χ^2 between a model and unfolded data at particle (parton) level same as χ^2 between folded model and data at detector level

2D: n x m: IB can be extended to a n . m vector with a n . m x n . m migration matrix

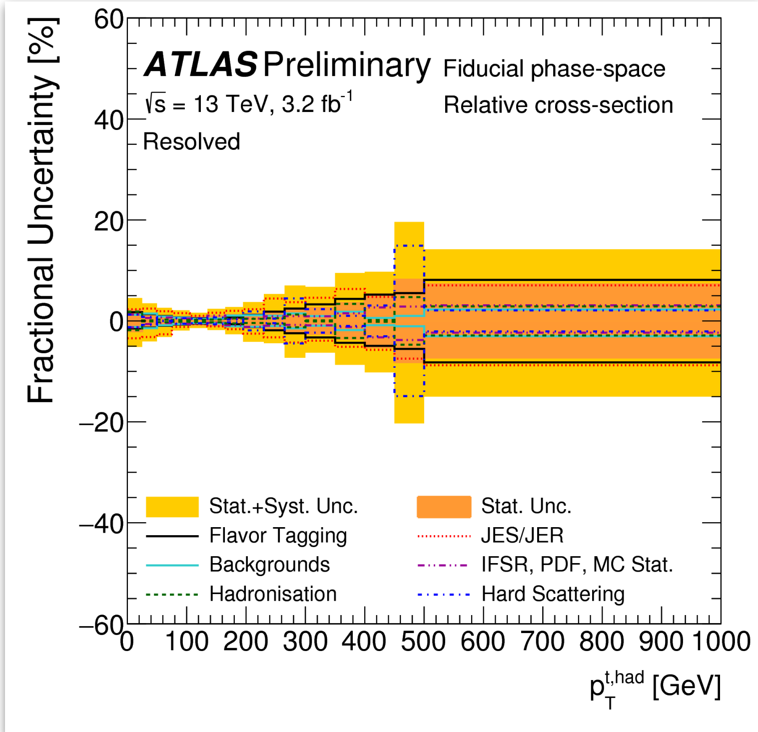
Systematic Uncertainties: lepton+jets

Physics

ATLAS

CONF-2016-040 (resolved)

Dominant: JES & signal modelling:
mostly NLO generator (MC@NLO vs Powheg)
and Parton Shower
(Powheg+Herwig++ vs Powheg+Pythia6)



CMS

TOP-16-008 (resolved)

Dominant: JES & signal modelling:
mostly NLO generator (MC@NLO vs Powheg)
and Parton Shower
(Powheg+Herwig++ vs Powheg+Pythia8 and scale)
2D: JES: 15% in bins with large Njets
and hadronisation + NLO generator reach up to 30%
for parton level

Source	Particle level [%]	Parton level [%]
Statistical uncertainty	1–5	1–5
Jet energy scale	5–8	6–8
Jet energy resolution	<1	<1
$\vec{p}_T^{miss}$ (non jet)	<1	<1
b tagging	2–3	2–3
Pileup	<1	<1
Lepton selection	3	3
Luminosity	2.7	2.7
Background	1–3	1–3
PDF	<1	<1
Fact./ren. scale	<1	<1
Parton shower scale	2–5	2–9
POWHEG+PYTHIA8 vs. HERWIG++	1–5	1–12
NLO event generation	1–5	1–10
m_t	1–2	1–3

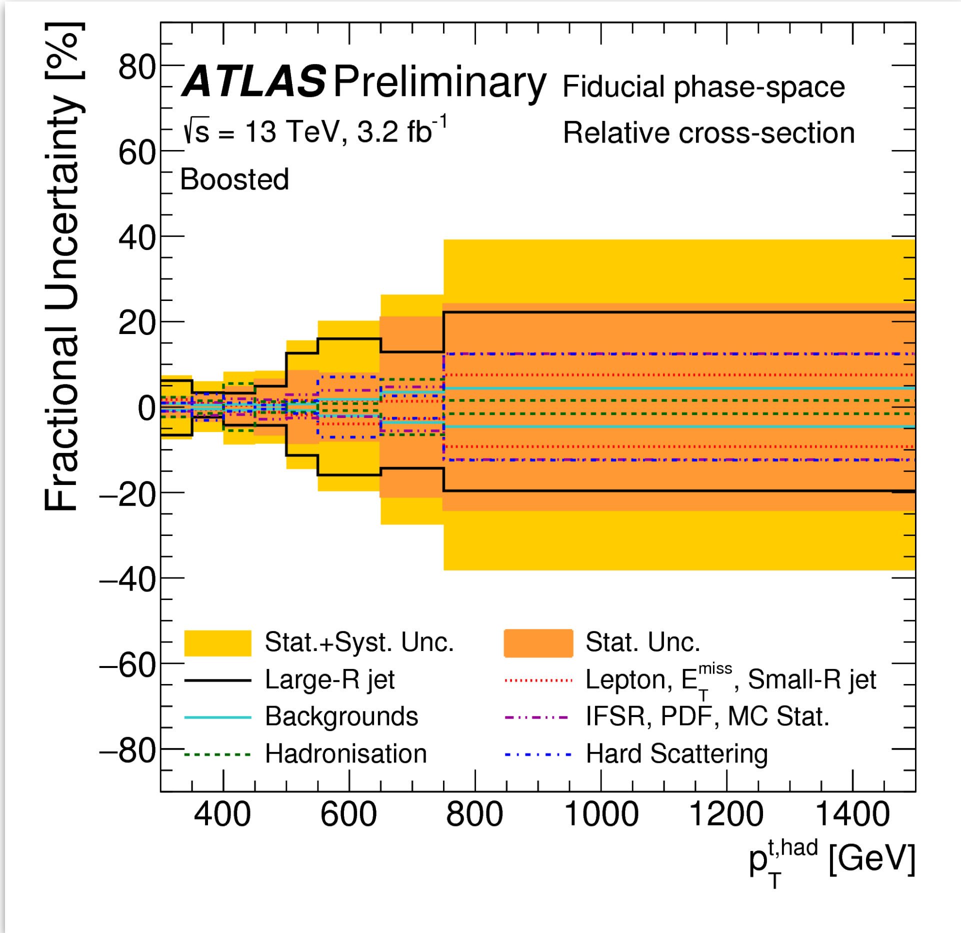
Systematic Uncertainties: lepton+jets

Physics

ATLAS

CONF-2016-040 (boosted)

Dominant: Large R-jet & signal modelling: mostly NLO generator (MC@NLO vs Powheg) and Parton Shower (Powheg+Herwig++ vs Powheg+Pythia6) and also Initial/Final State Radiation



Large R-jet uncertainties include:

- JES, Jet Mass Scale
- JER and Jet Mass Resolution (impact from degrading resolution by 20%)

Results! 142 unfolded plots!

Many useful observables!

- The 5 canonical ones: top: p_T, y; ttbar system: p_T, y, m
  - Extremely useful to theorists and for learning lessons
- Detector level ones: Njets, Nbjets, jet p_T, lepton ones, jets ones, H_T, Etmiss, etc.
  - Potential for precision
- Radiation ones
  - Sensitive to emission of radiation with the ttbar system

Results: dilepton top p_T: 1D

Physics

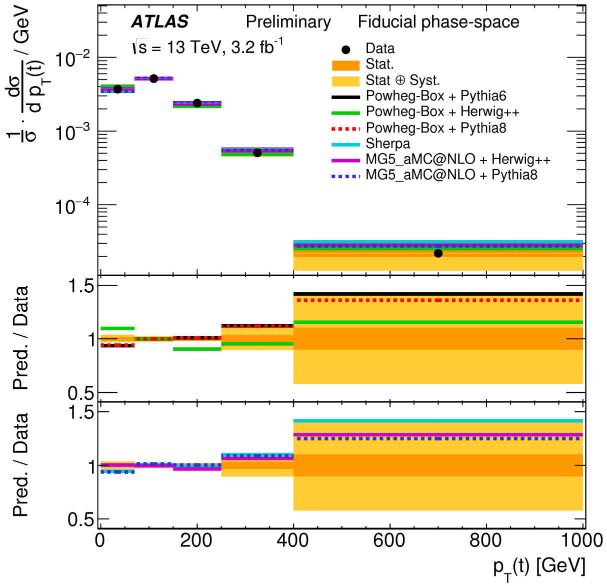
ATLAS

TOPQ-2016-04

CMS

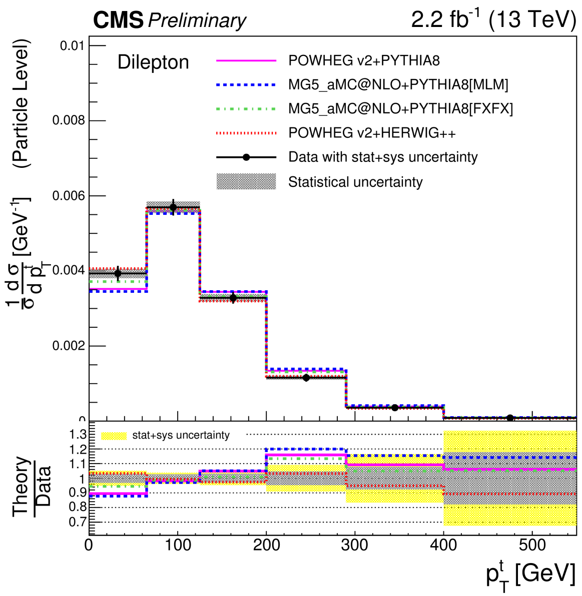
TOP-16-007 TOP-16-011

particle



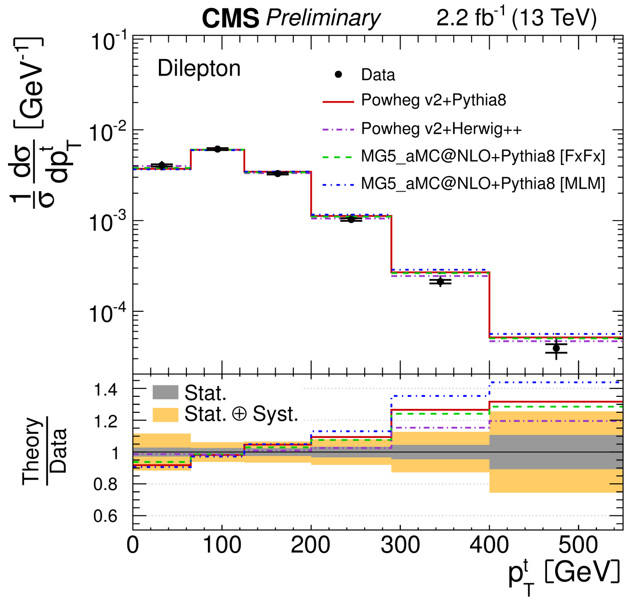
- Pow+Py: ok
- Pow+H: tension (p-value = 0.01)
- MC@NLO+H: good

particle



- Pow+Py: ~tension
- Pow+H: good
- MC@NLO+Py MLM: ~tension

parton



- Pow+H: best

Results: dilepton top p_T: 2D

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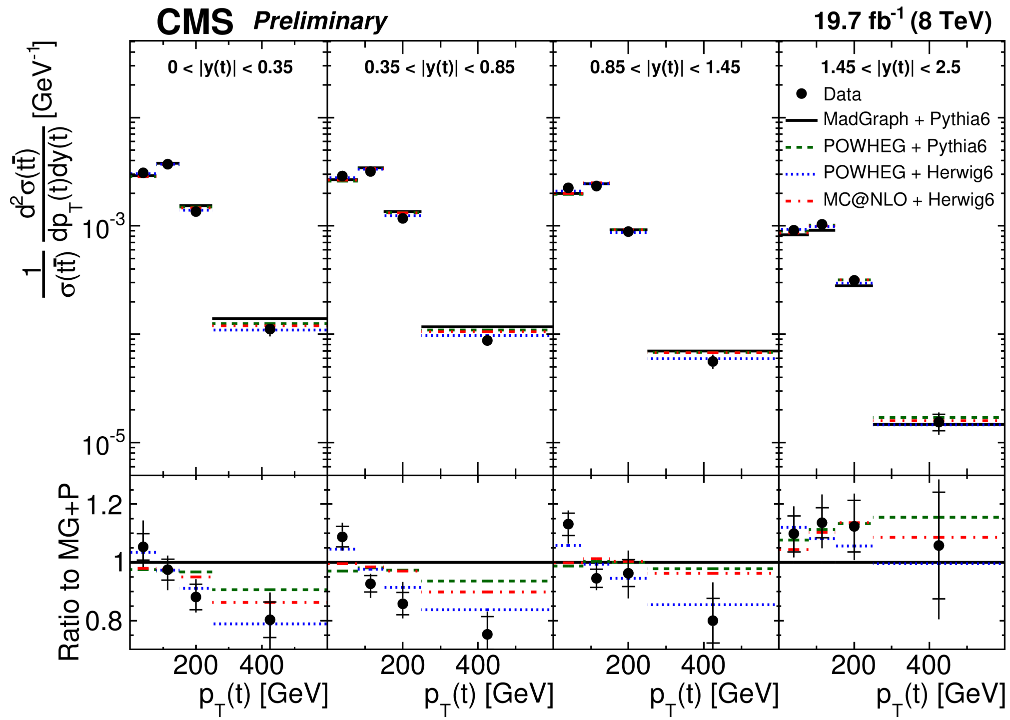
Physics

pT (t) vs y (t)

CMS TOP-14-013

parton



Also see back-up/ paper for constraints on PDF!

- Pow+H6: best

Distribution	dof	MadGraph+Pythia6	Powheg+Pythia6	Powheg+Herwig6	MC@NLO +Herwig6
$y(t)\ p_T(t)$	15	96	58	14	46
$M(t\bar{t})\ y(t)$	15	53	20	13	21
$M(t\bar{t})\ y(t\bar{t})$	15	19	21	15	22
$M(t\bar{t})\ \Delta\eta(t,\bar{t})$	11	163	33	20	39
$M(t\bar{t})\ p_T(t\bar{t})$	15	31	83	30	33
$M(t\bar{t})\ \Delta\phi(t,\bar{t})$	11	21	21	10	17

Results: lepton+jets top p_T: 1D

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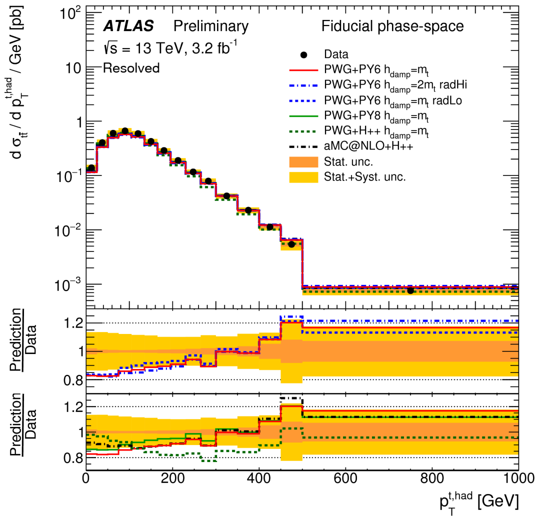
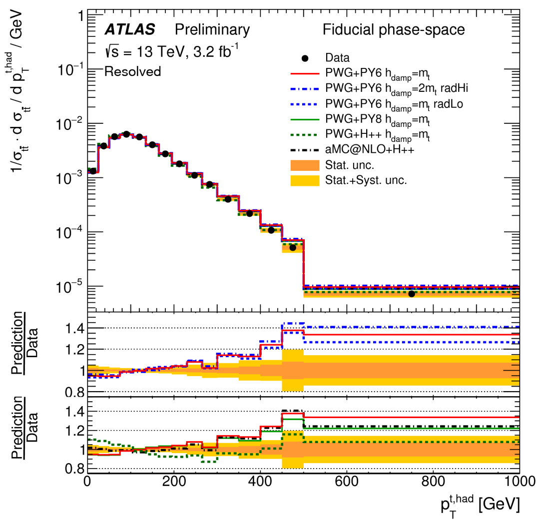
Physics

ATLAS

CONF-2016-040 (resolved)



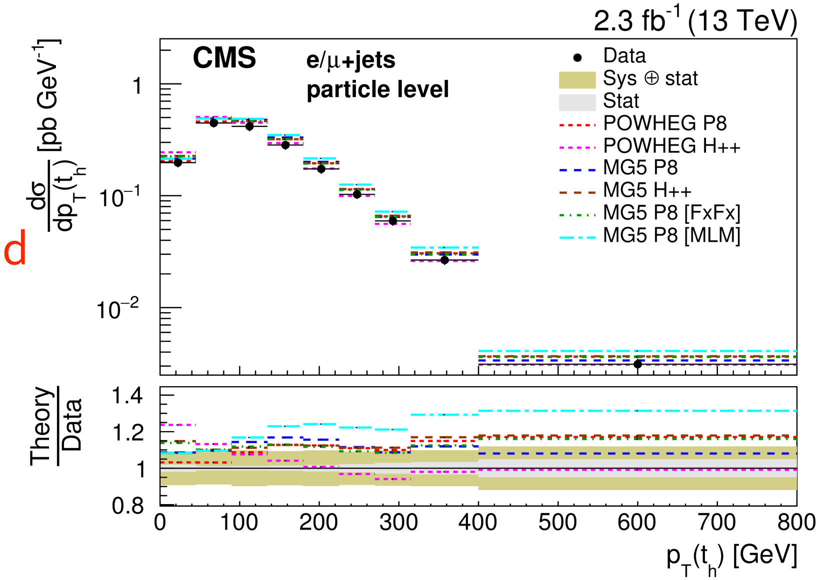
- Pow+Py: ok
- Pow+H: tension
- MC@NLO+H: good



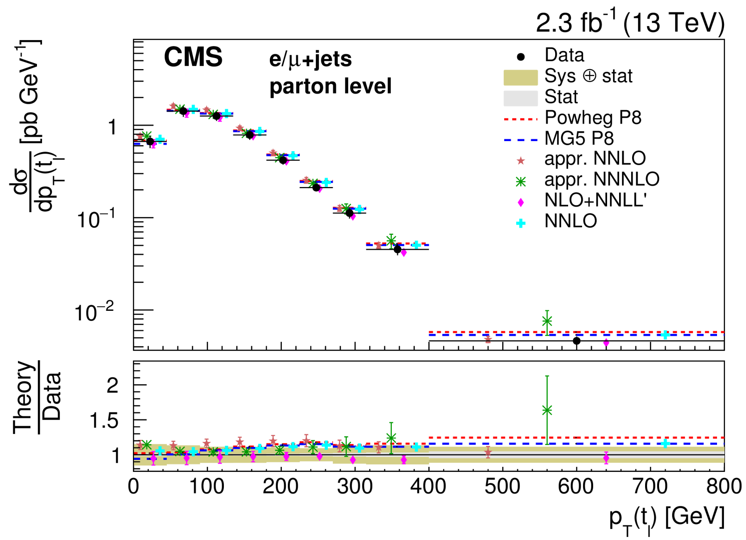
- all: ~tension
- espec. Pow+H

CMS

TOP-16-008 (resolved)



- Pow+Py: ok
- Pow+H: ok
- MC@NLO: depends on PS and matching
- NNLO: good

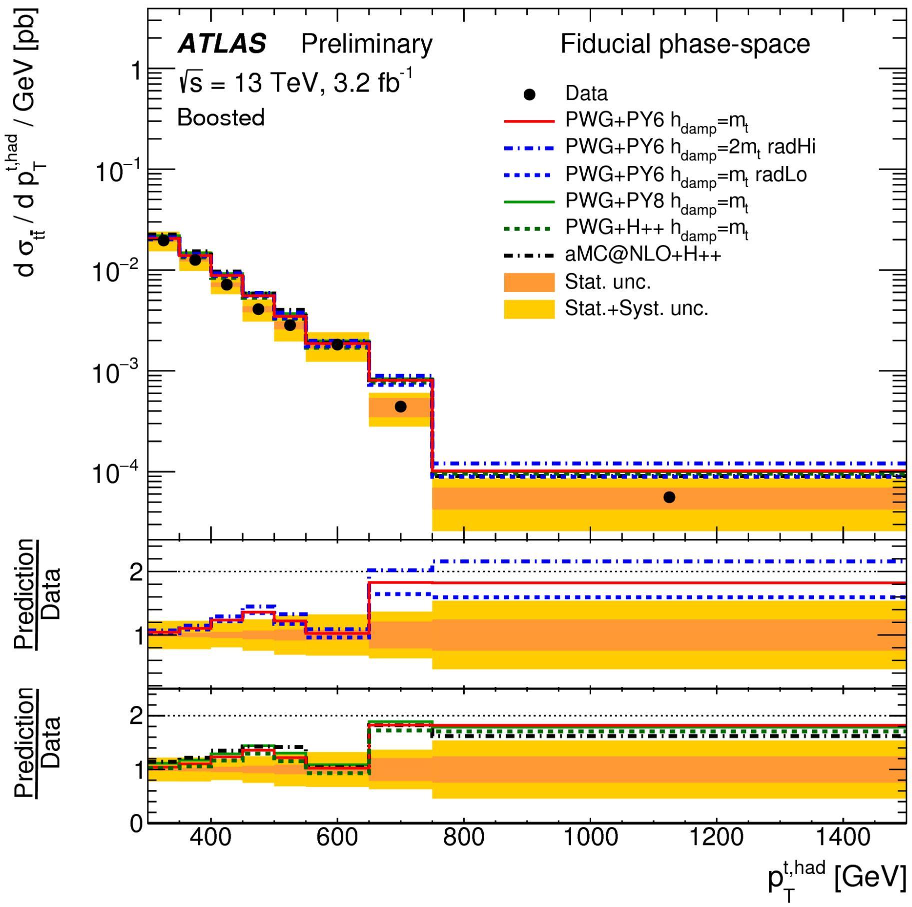


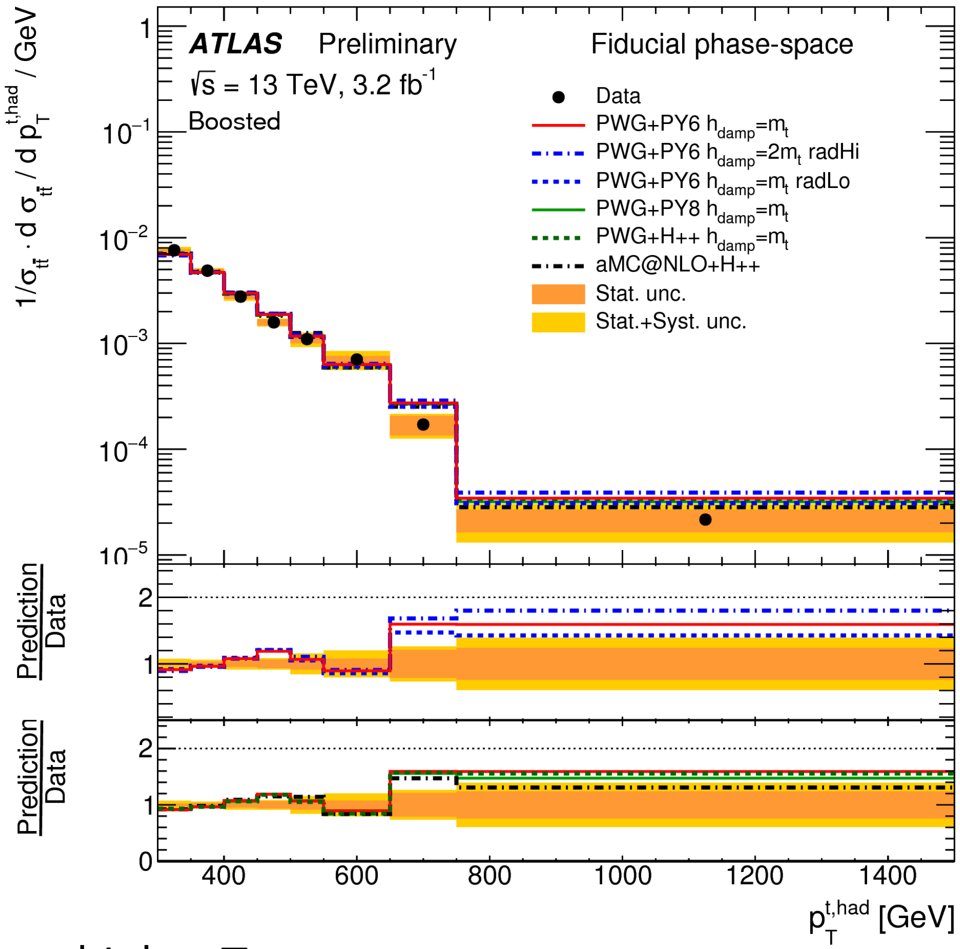
Results: lepton+jets top p_T: 1D boosted

Physics

ATLAS

CONF-2016-040 (boosted)





- all: ~tension at hight pT

Results: lepton+jets top p_T: 2D

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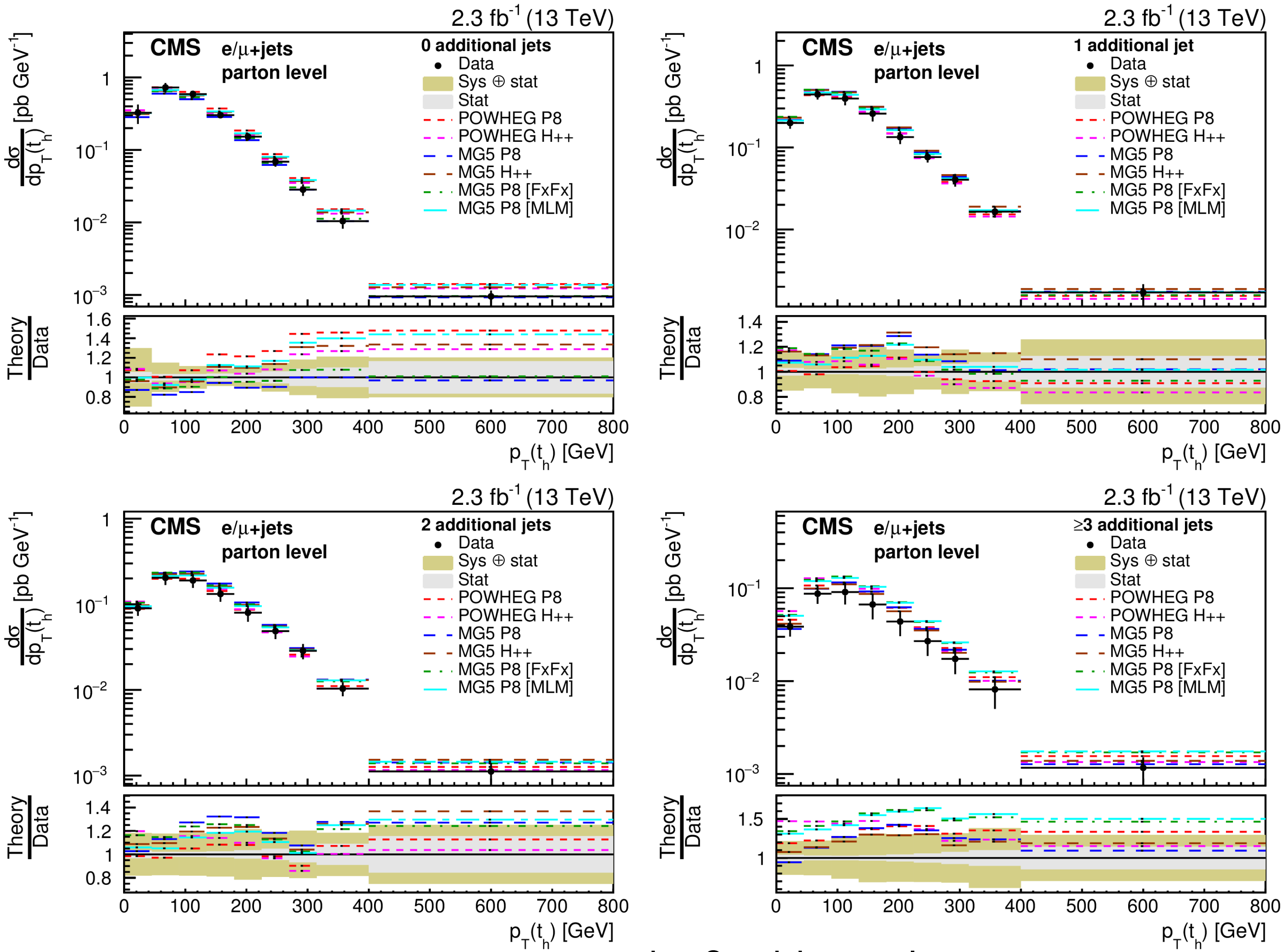
Physics

CMS TOP-16-008 (resolved)



- Most tension in the 0 additional jet region

Results: lepton+jets: 2D

Physics

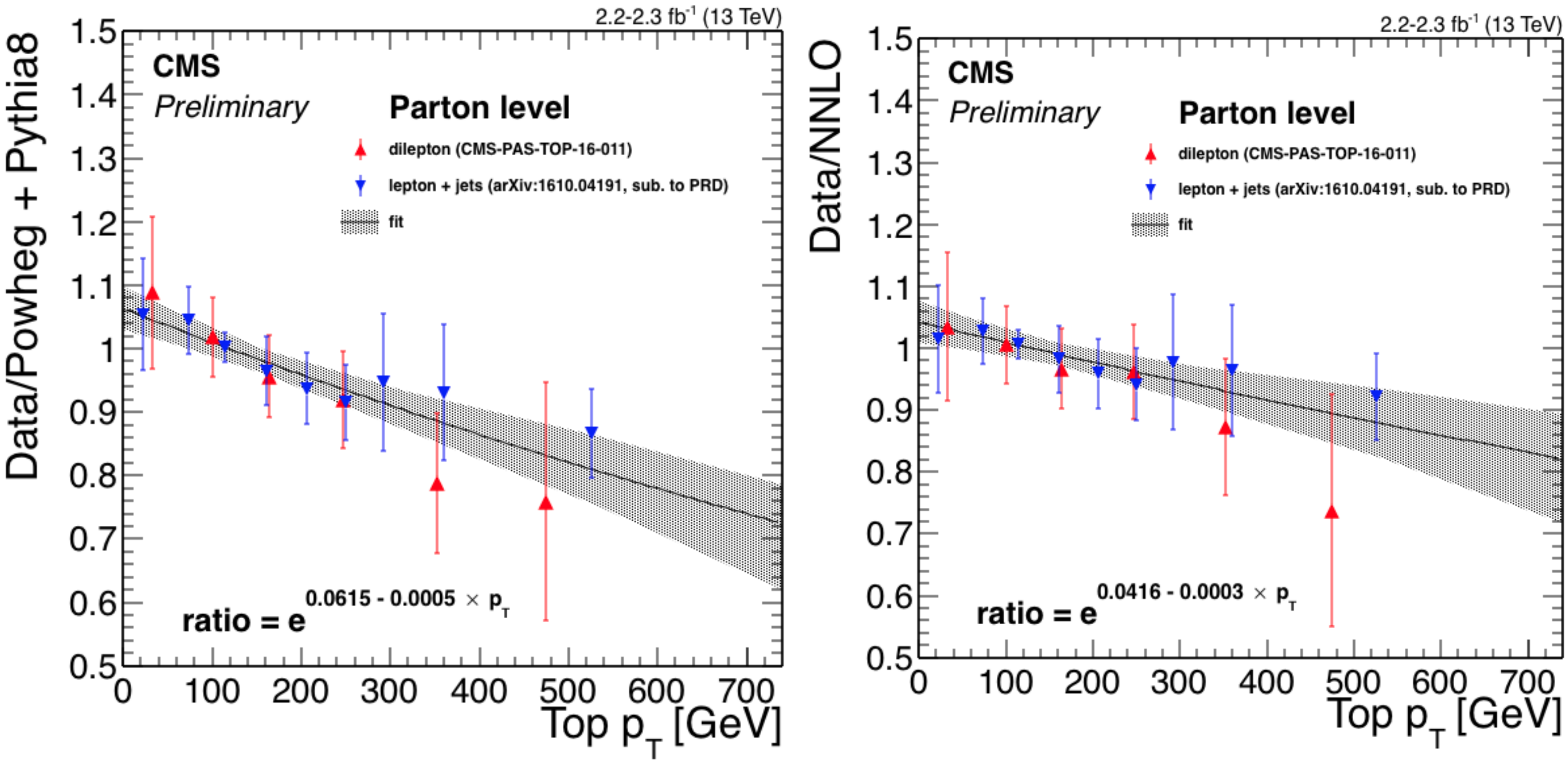
parton

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8		POWHEG+H++		MG5_aMC@NLO+P8 MLM	
	Order: NLO		Order: NLO		Order: LO, up to 3 add. partons	
$p_T(t_h)$	12.0/9	0.216	9.43/9	0.398	20.5/9	0.015
$\|y(t_h)\|$	5.02/7	0.657	5.59/7	0.589	5.81/7	0.562
$p_T(t_\ell)$	18.1/9	0.034	10.9/9	0.285	48.5/9	<0.01
$\|y(t_\ell)\|$	13.2/7	0.067	15.2/7	0.034	14.0/7	0.051
$M(t\bar{t})$	6.08/8	0.639	11.6/8	0.172	48.1/8	<0.01
$p_T(t\bar{t})$	1.35/5	0.930	5.53/5	0.354	18.3/5	<0.01
$\|y(t\bar{t})\|$	2.35/6	0.885	2.43/6	0.876	5.85/6	0.440
Additional jets	9.55/5	0.089	6.47/5	0.263	5.71/5	0.335
Additional jets *vs.* $p_T(t\bar{t})$	90.6/20	<0.01	144/20	<0.01	145/20	<0.01
Additional jets *vs.* $p_T(t_h)$	108/36	<0.01	49.5/36	0.067	84.2/36	<0.01
$\|y(t_h)\|$ *vs.* $p_T(t_h)$	59.4/36	<0.01	57.3/36	0.014	67.2/36	<0.01
$M(t\bar{t})$ *vs.* $\|y(t\bar{t})\|$	20.4/24	0.674	19.6/24	0.719	51.5/24	<0.01
$p_T(t\bar{t})$ *vs.* $M(t\bar{t})$	15.8/32	0.993	27.8/32	0.679	109/32	<0.01
	MG5_aMC@NLO+P8		MG5_aMC@NLO+H++		MG5_aMC@NLO+P8 FxFx	
	Order: NLO		Order: NLO		Order: NLO, up to 2 add. partons	
$p_T(t_h)$	11.6/9	0.240	16.8/9	0.052	10.6/9	0.301
$\|y(t_h)\|$	6.91/7	0.438	6.85/7	0.444	5.23/7	0.632
$p_T(t_\ell)$	18.7/9	0.028	32.4/9	<0.01	14.6/9	0.102
$\|y(t_\ell)\|$	19.1/7	<0.01	12.7/7	0.079	18.7/7	<0.01
$M(t\bar{t})$	11.3/8	0.186	6.59/8	0.582	29.8/8	<0.01
$p_T(t\bar{t})$	40.0/5	<0.01	25.8/5	<0.01	19.7/5	<0.01
$\|y(t\bar{t})\|$	3.01/6	0.808	2.52/6	0.866	2.86/6	0.826
Additional jets	19.9/5	<0.01	4.37/5	0.497	6.78/5	0.237
Additional jets *vs.* $p_T(t\bar{t})$	390/20	<0.01	294/20	<0.01	127/20	<0.01
Additional jets *vs.* $p_T(t_h)$	112/36	<0.01	49.0/36	0.072	56.5/36	0.016
$\|y(t_h)\|$ *vs.* $p_T(t_h)$	91.8/36	<0.01	123/36	<0.01	53.1/36	0.033
$M(t\bar{t})$ *vs.* $\|y(t\bar{t})\|$	29.8/24	0.192	19.2/24	0.741	38.7/24	0.030
$p_T(t\bar{t})$ *vs.* $M(t\bar{t})$	275/32	<0.01	78.2/32	<0.01	104/32	<0.01
	appr. NNLO		appr. NNNLO		NLO+NNLL′	
$p_T(t_h)$	25.3/9	<0.01	69.1/9	<0.01	9.68/9	0.377
$\|y(t_h)\|$	8.90/7	0.260	4.78/7	0.686	—	—
$p_T(t_\ell)$	23.1/9	<0.01	189/9	<0.01	4.41/9	0.882
$\|y(t_\ell)\|$	6.40/7	0.494	7.28/7	0.400	—	—
$M(t\bar{t})$	—	—	—	—	12.2/8	0.143
	NNLO					
$p_T(t_h)$	9.40/9	0.402				
$\|y(t_h)\|$	4.08/7	0.770				
$p_T(t_\ell)$	10.8/9	0.291				
$\|y(t_\ell)\|$	10.4/7	0.168				
$M(t\bar{t})$	11.2/8	0.190				
$p_T(t\bar{t})$	4.61/5	0.466				
$\|y(t\bar{t})\|$	2.26/6	0.894				

CMS

TOP-16-008 (resolved)

Results: dilepton + lepton+jets



Results: all-hadronic

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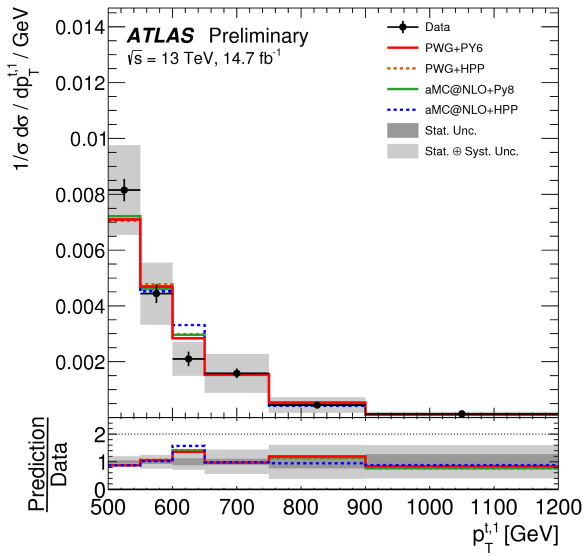
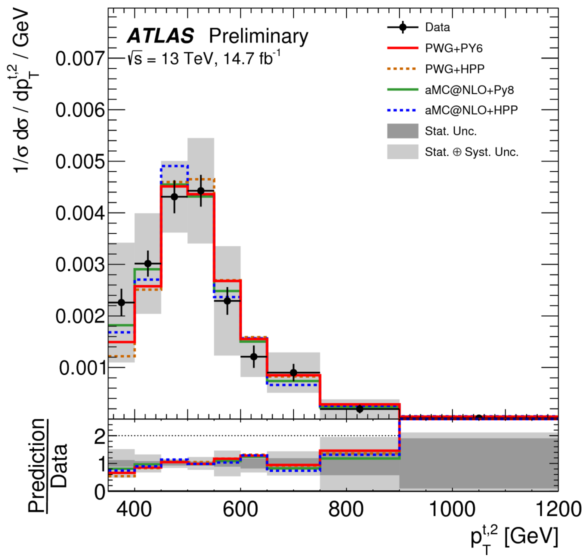
Physics

ATLAS

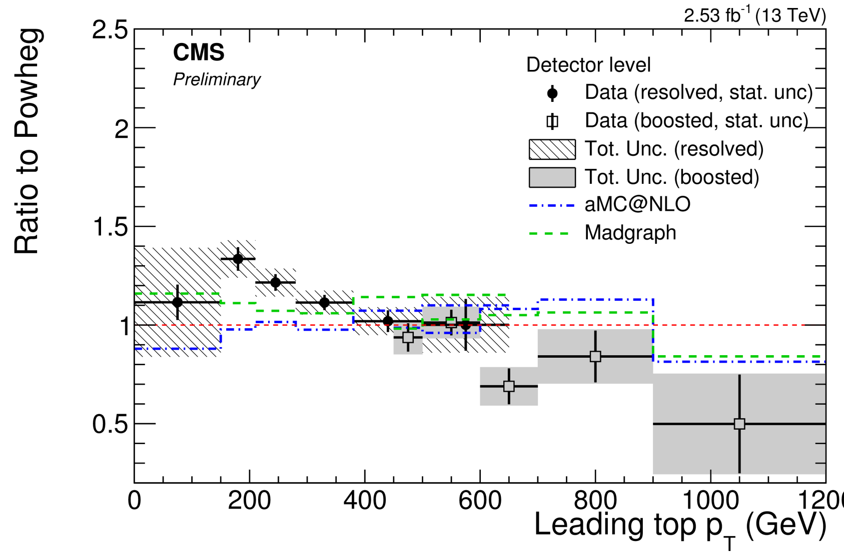
particle CONF-2016-100 (boosted)

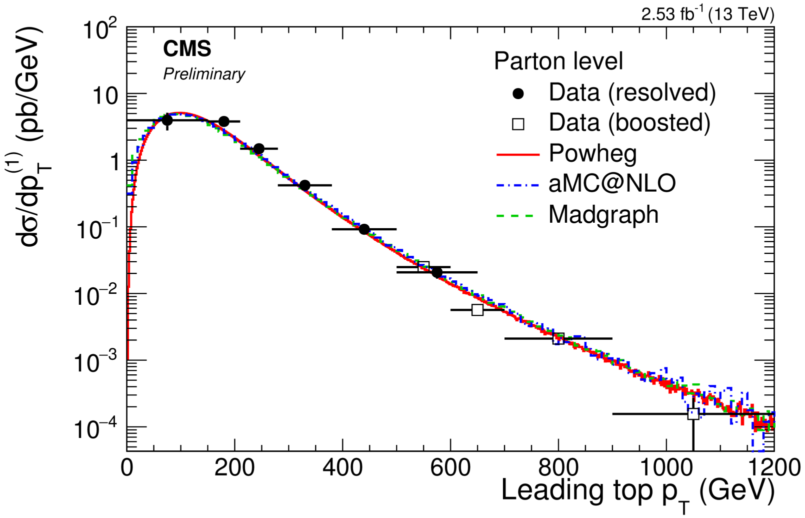




CMS

TOP-16-013 (resolved & boosted)



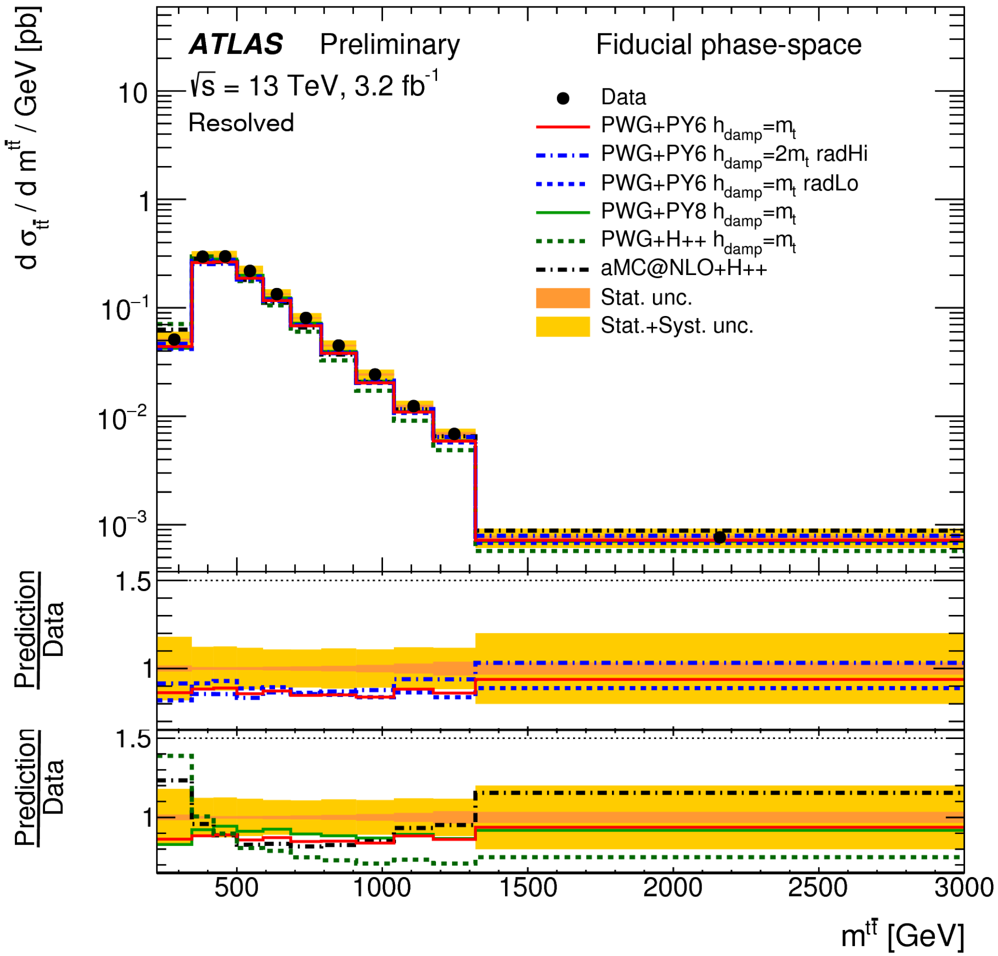


Invariant mass of tt system: lepton+jets

Physics

ATLAS

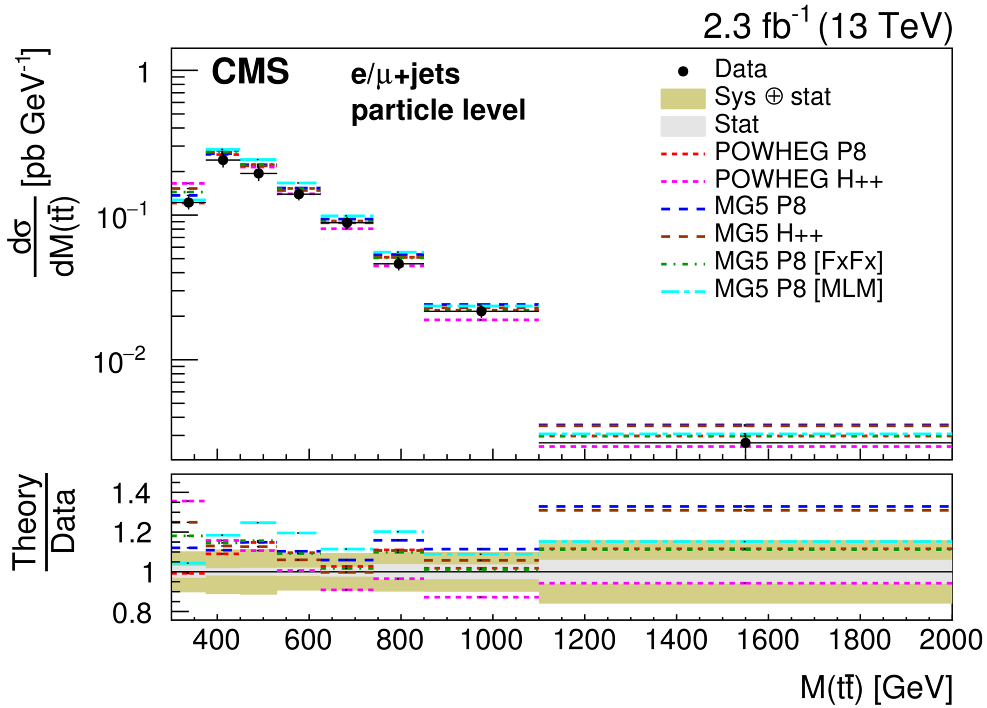
CONF-2016-040 (resolved)



- Pow+H: tension

CMS

TOP-16-008 (resolved)



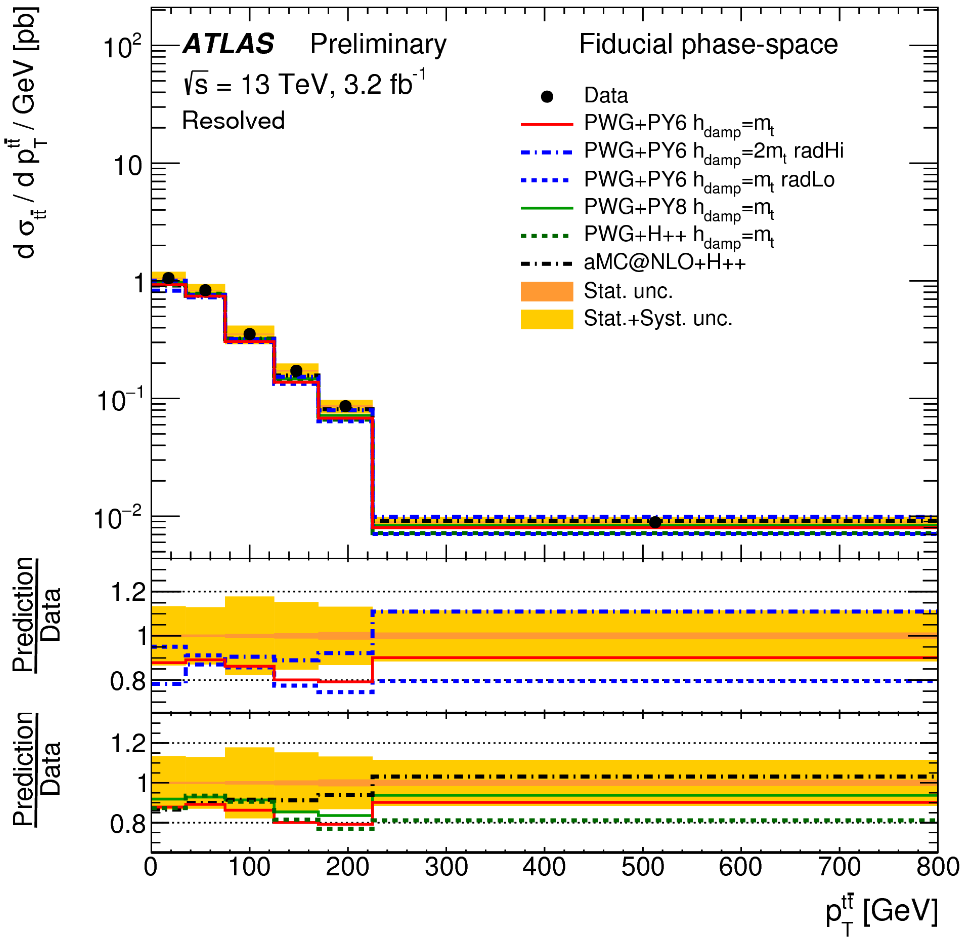
- Pow+Py: good
- Pow+H: tension
- MC@NLO: tension

P_T of tt system: lepton+jets

Physics

ATLAS

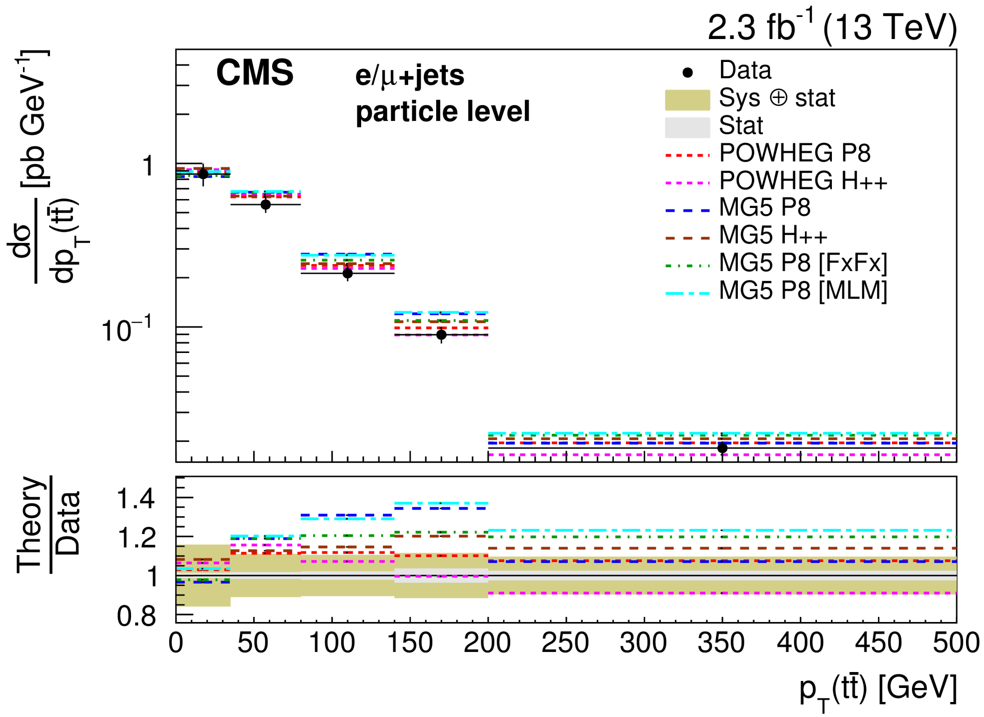
CONF-2016-040 (resolved)



- Pow+Py radHi: better than nom or radLo

CMS

TOP-16-008 (resolved)

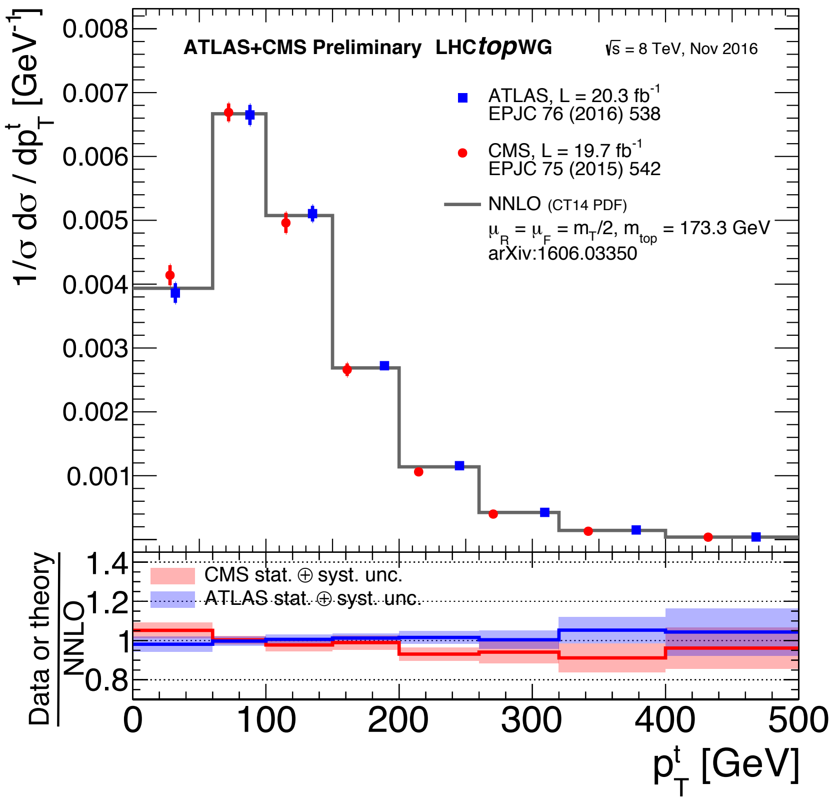


- tension for all except Pow+Py8

Conclusions

Royal Holloway University of London — Physics

- Huge amount of detailed results from ATLAS and CMS already at 13 TeV
- Should help constrain PDF, tune MC, input into EFT, etc.
- In general, although ATLAS and CMS take different approaches in terms of selection/ reconstruction, the uncertainties are similar
  - as expected the particle uncertainties are smaller than the parton ones
- CMS has started producing results unfolded over two variables (2D) among the top and ttbar observables
- Top quark p_T:
  - MC simulations still have slope at particle level/parton level
  - Parton level results seem to indicate that NNLO fixes this like at 8 TeV



backups

Systematic Uncertainties: dilepton

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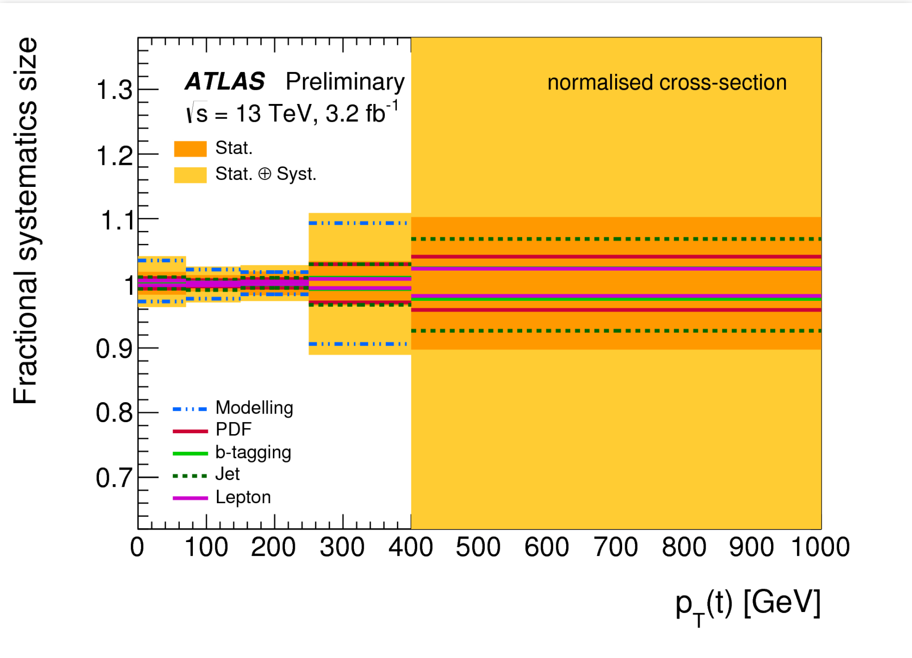
Physics

ATLAS

TOPQ-2016-04 TOPQ-2015-017

Dominant: signal modelling:
mostly Parton Shower & Hadronisation
(Powheg+Herwig++ vs Powheg+Pythia6)
also NLO generator (MC@NLO vs Powheg)
and PDF



CMS

TOP-14-013 TOP-16-007 TOP-16-011

Dominant: signal modelling:
NLO generator (MC@NLO vs Powheg)
and Hadronisation
(Powheg+Herwig++ vs Powheg+Pythia8)

μ_F, μ_R: factorization and renomarlization scale in Powheg and PS scale in Pythia8 changed by 2 and 1/2

Systematic uncertainty	Median of p_T^t [%]	Median of $p_T^{t\bar{t}}$ [%]	Median of $\Delta\phi^{t\bar{t}}$ [%]	Maximum of median [%]
Trigger	1	1	1	1
Pileup	1	1	1	1
Lepton SF	1	1	1	1
JES	1	1	1	2
JER	2	1	1	2
b jet SF	1	2	1	2
Background	3	3	4	6
μ_F and μ_R	1	4	5	5
MC modelling	3	7	12	12
Top quark mass	1	4	5	5
Hadronisation	6	4	2	6
PDF	1	1	1	2

Last bin in top pT: 400-550GeV: total uncertainty: 30%

TOP-16-007

Systematic Uncertainties: all-hadronic

Physics

ATLAS

CONF-2016-100 (boosted)

signal modelling:
mostly NLO generator (MC@NLO vs Powheg)
5-10% up to 20-30% at large values of observables
and Initial/Final State Radiation (IFSR)
10-20%
and Parton Shower
(Powheg+Herwig++ vs Powheg+Pythia6)
5-10%

IFSR uncertainty:
radHi: fact. & had. scales down by 0.5, h_{damp} up to 2mt, radHi tune of P2012
radLo: fact. & had. scales up by 2.0, h_{damp} unchanged, radLo tune of P2012

Large-R jets	+18 / -15
Monte Carlo signal modelling	±17
b-tagging	+13 / -12
Pileup	±2.9
Luminosity	±2.9
Small-R jets	±1.0
Total Systematic Uncertainty	+29 / -24

CMS

TOP-16-013 (resolved & boosted)

Parton Shower:
part not included in JES/b-tagging:
resolved: effect of fit prob. and DRbb in different models of PS
boosted: efficiency of Fisher cut using those models

inclusive

Analysis	Resolved	Boosted
Source	(%)	(%)
QCD background modeling	−1.0, +6.6	−2.7, +2.4
Subdominant backgrounds	±4.0	±4.0
Jet energy scale	−8.2, +9.0	−1.8, +1.6
Jet energy resolution	−0.7, +0.8	$\pm < 1$
b tagging	−5.5, +6.2	−10.5, +12.9
Trigger efficiency	−2.9, +3.2	−1.1, +0.9
Scale (μ_F and μ_R)	−1.5, +0.0	−1.5, +0.0
PDF	±1.0	±1.0
Parton shower	−5.0, +2.5	−7.0, +3.0
NLO generator	±2.0	±7.0
Total systematic	−12.4, +14.1	−15.4, +15.8
Statistical	±3.0	±6.3
Integrated luminosity	±2.7	±2.7

Radiation Observables

- The absolute value of the azimuthal angle between the two top quarks ($\Delta\phi^{t\bar{t}}$);
- the absolute value of the out-of-plane momentum ($\left|p_{\mathrm{out}}^{t\bar{t}}\right|$), *i.e.* the projection of top-quark three-momentum onto the direction perpendicular to a plane defined by the other top quark and the beam axis (z) in the laboratory frame [8]:

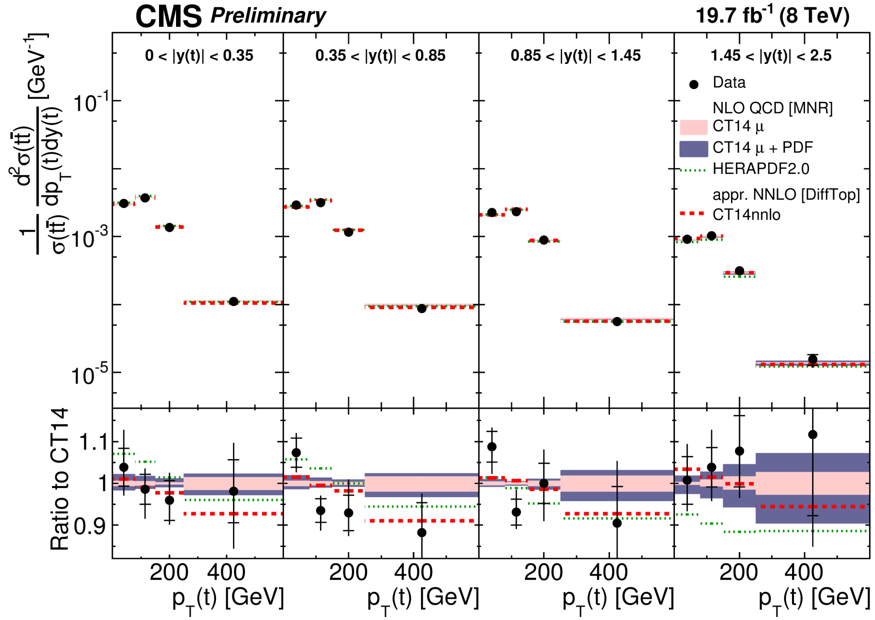
$$\left|p_{\mathrm{out}}^{t\bar{t}}\right| = \left|\vec{p}^{\;t,\mathrm{had}} \cdot \frac{\vec{p}^{\;t,\mathrm{lep}} \times \hat{z}}{|\vec{p}^{\;t,\mathrm{lep}} \times \hat{z}|}\right| ; \quad (2)$$

- the longitudinal boost of the $t\bar{t}$ system in the laboratory frame ($y_{\mathrm{boost}}^{t\bar{t}}$) [7];
- the production angle between the two top quarks ($\chi^{t\bar{t}}$) [7];
- the scalar sum of the transverse momenta of the two top quarks ($H_{\mathrm{T}}^{t\bar{t}}$) [10, 11]
- and the ratio of the transverse momenta of the hadronic W boson and the top quark from which it originates (R_{Wt}) [10, 11]

$$R_{Wt} = p_{\mathrm{T}}^{W,\mathrm{had}} / p_{\mathrm{T}}^{t,\mathrm{had}} . \quad (3)$$

Physics

CMS TOP-14-013



parton

Distribution	dof	χ^2 NLO $O(\alpha_s^3)$ nominal (including PDF uncertainties)						
		HERAPDF2.0	MMHT2014	CT14	NNPDF3.0	ABM11	JR14	CJ15
$y(\mathrm{t})\ p_\mathrm{T}(\mathrm{t})$	15	46 (40)	26 (24)	24 (21)	28 (25)	62 (51)	47 (47)	27 (24)
$M(\mathrm{t\bar{t}})\ y(\mathrm{t})$	15	52 (44)	22 (20)	19 (18)	14 (14)	71 (55)	44 (44)	26 (24)
$M(\mathrm{t\bar{t}})\ y(\mathrm{t\bar{t}})$	15	29 (25)	15 (15)	16 (15)	10 (10)	42 (31)	25 (25)	16 (16)
$M(\mathrm{t\bar{t}})\ \Delta\eta(t,\bar{t})$	11	46 (43)	31 (31)	32 (31)	45 (42)	48 (44)	39 (39)	33 (33)
$M(\mathrm{t\bar{t}})\ p_\mathrm{T}(\mathrm{t\bar{t}})$	15	485 (429)	377 (310)	379 (264)	251 (212)	553 (426)	428 (415)	413 (398)
$M(\mathrm{t\bar{t}})\ \Delta\phi(t,\bar{t})$	11	354 (336)	293 (272)	296 (259)	148 (143)	386 (335)	329 (324)	312 (308)

tt invariance mass at parton level

Physics

CMS
TOP-16-008 (resolved)