Measurement of differential $\mathrm{t\bar{t}}$ production cross sections for high-p_T top quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV

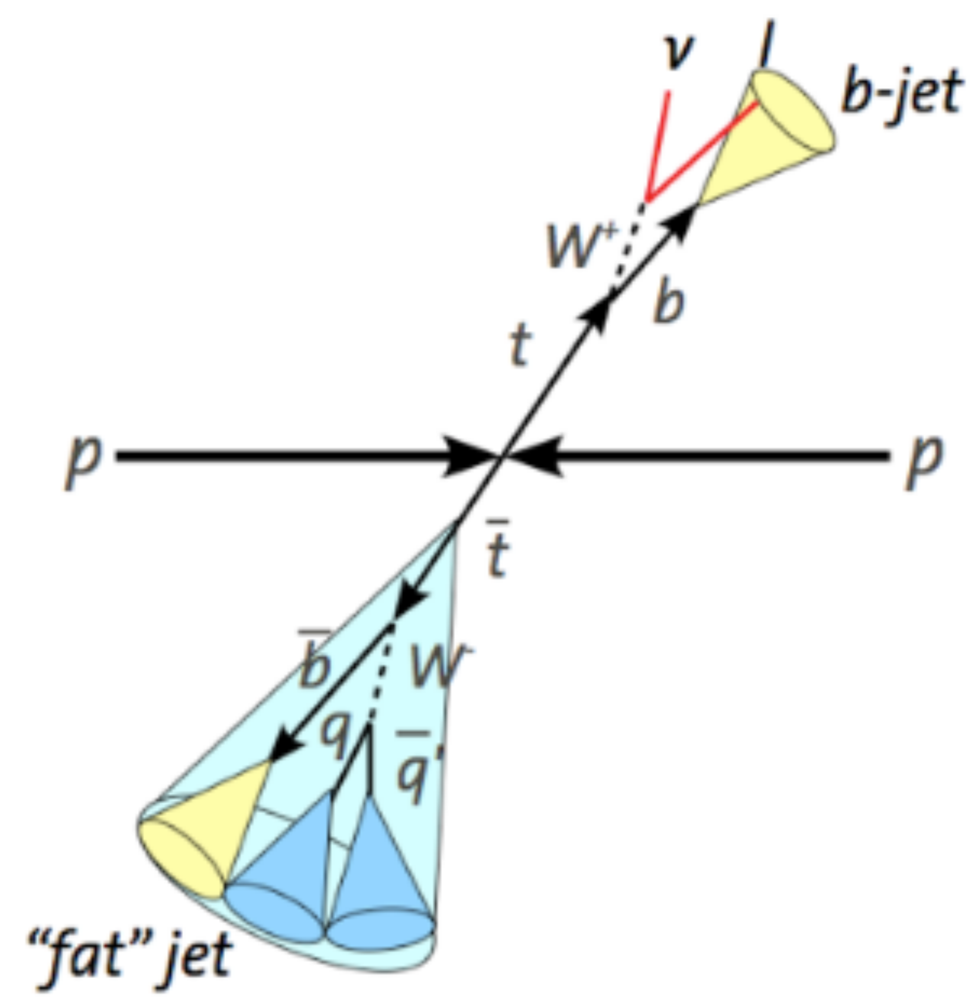
l+jets channel

Please see hadronic slides for analysis overview and documentation

TOP-18-013: l+jets Channel Overview

- Measurement of differential $t\bar{t}$ cross section in l+jets channel for p_T(top) > 400 GeV
  - p_T(top), |y|(top) distributions
  - Particle and parton level
  - Full 2016 dataset, 35.9 fb-1
- Final state: lepton + b jet + t jet + MET
- Characterize events by whether b and t jet candidates pass tagging requirements
- Perform simultaneous likelihood fit to extract background normalizations, t tagging SF
- Unfold background-subtracted data distribution to parton and particle levels

Note:
Plots / tables for paper
NEW since preapproval



Event Selection

- ==1 μ(e) passing Medium(Tight) ID
  - p_T > 50 GeV, |η| < 2.1, miniIso* < 0.1
  - Veto additional leptons (Medium ID, no miniIso requirement)
  - In e channel, require $|\Delta\phi(e/j, E_T^{miss}) - 1.5| < 1.5 * \frac{E_T^{miss}}{110\ \mathrm{GeV}}$ for e or leading jet
- ≥1 b jet candidate
  - AK4 (anti-kt, R=0.4) jet with p_T > 50 GeV, |η| < 2.4
  - 0.3 < ΔR(ℓ, jet) < π/2
- ≥1 t jet candidate
  - AK8 (anti-kt, R=0.8) jet with p_T > 400 GeV, |η| < 2.4
  - ΔR(ℓ, jet) > π/2
- $E_T^{miss} > 35(50)\ \mathrm{GeV}$ for μ(e) channel

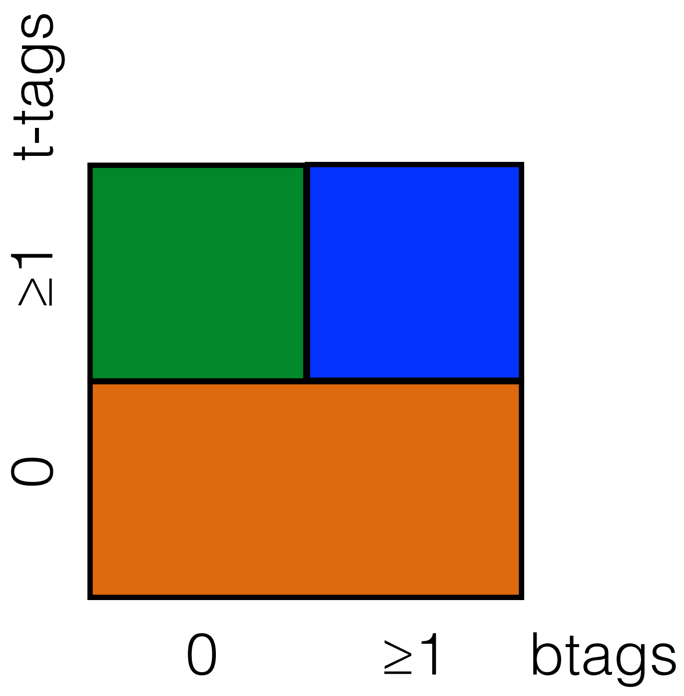
*Summed track p_T divided by lepton p_T, for tracks in a cone around the lepton whose radius scales inversely with lepton p_T

μ trigger:
HLT_Mu40_eta2p1_PFJet200_PFJet50

e trigger:
HLT_Ele45_CaloIdVT_GsfTrkIdT_PFJet200_PFJet50

Kinematic Regions

- Classify events based on whether b and t jet candidates pass tagging requirements
- b tag
  - CSVv2 < 0.8484 (Medium WP)
- t tag
  - 105 < SoftDrop jet mass < 220 GeV
  - N-subjettiness ratio τ_{32} < 0.81
- Categories
  - **0t**: t jet candidate fails t tag
  - **1t0b**: t jet candidate passes t tag, b jet candidate fails b tag
  - **1t1b**: t and b jet candidates both pass tag



Samples / Backgrounds

- TTbar
  - Powheg sample with tune CUETP8M2T4; used for semileptonic (signal) and non-semileptonic
- MC modeled backgrounds
  - Single top (Powheg for tW- and t-channel, aMC@NLO for s-channel)
  - W+Jets (MadGraph): binned in H_T to increase statistics; split into W+light and W+heavy flavor
  - Z+Jets (MadGraph)
  - Diboson (Powheg): WW, WZ, ZZ
  - QCD (MadGraph): used to cross-check data-driven estimate; binned in H_T to increase statistics
- Data-driven QCD
  - Shape from QCD-dominated data sideband

All MC samples interfaced with Pythia8

Final background normalizations extracted from kinematic fit

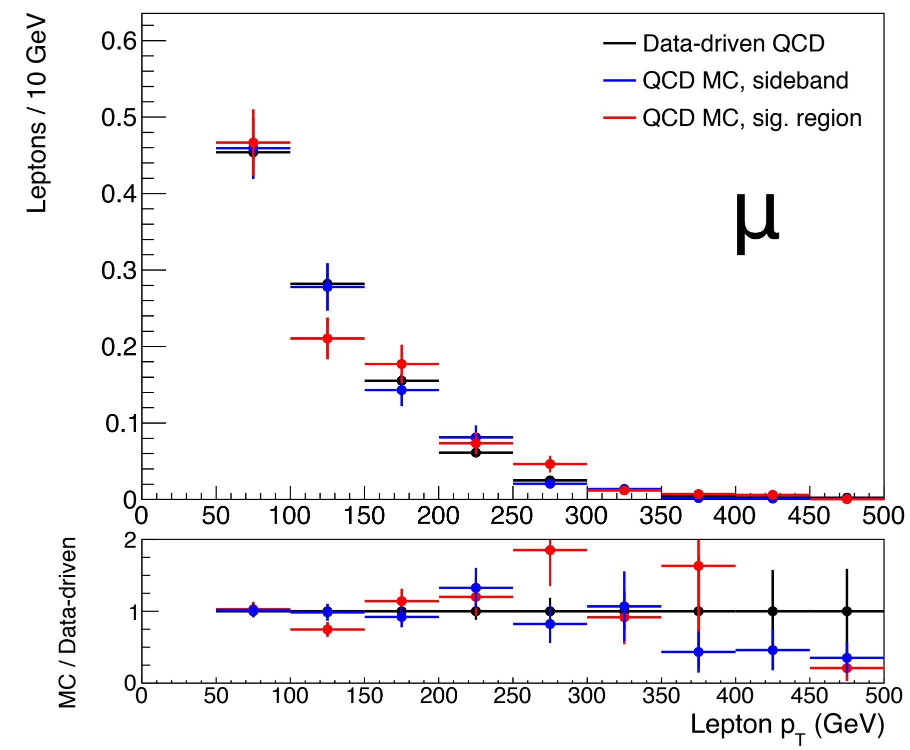
Correction Factors

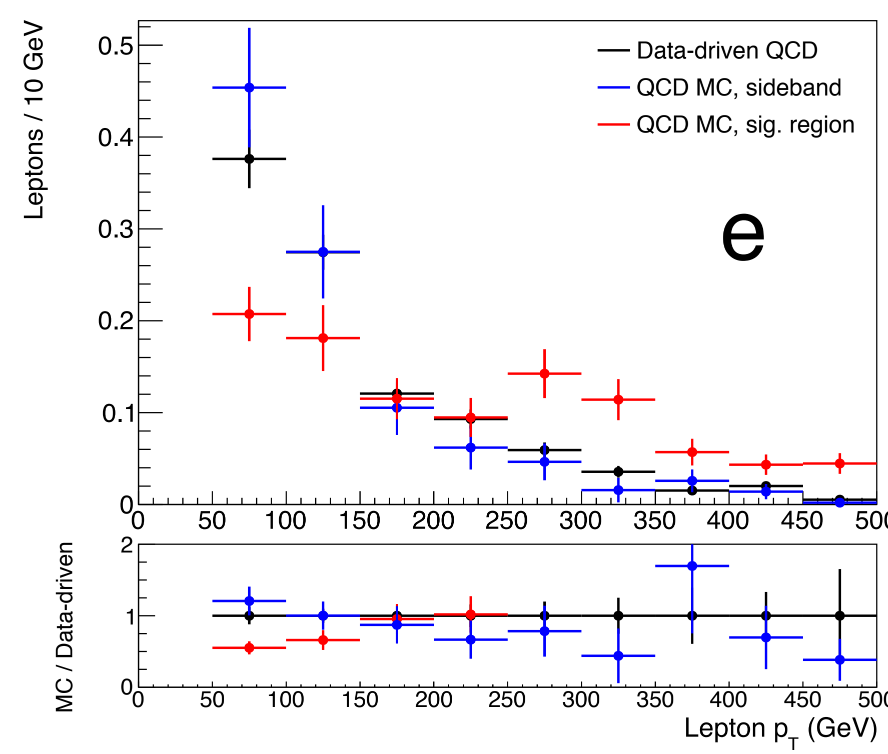
- PU reweighting
- Lepton efficiencies
  - Trigger — custom T&P in dileptonic boosted $t\bar{t}$ sample
  - ID — μ from POG; e from SUS PAG
  - Isolation — μ assessed to be ~1; e from SUS PAG
- Jet energy corrections
  - Summer16_23Sep2016V3
- Jet energy resolution
- b tagging SF
- t tagging SF
  - Correlated with cross section, extracted from simultaneous fit

Standard POG-approved values used

QCD Estimation

- Define QCD dominated data sideband
  - 0.1 < miniIso < 0.2; Medium electron ID
- Subtract expected non-QCD contributions
  - 28(33)% contamination in μ(e) channel
- Compare QCD shape in data sideband against QCD MC in data sideband and signal region
  - Generally good agreement
  - Largest deviations are in electron p_T and η



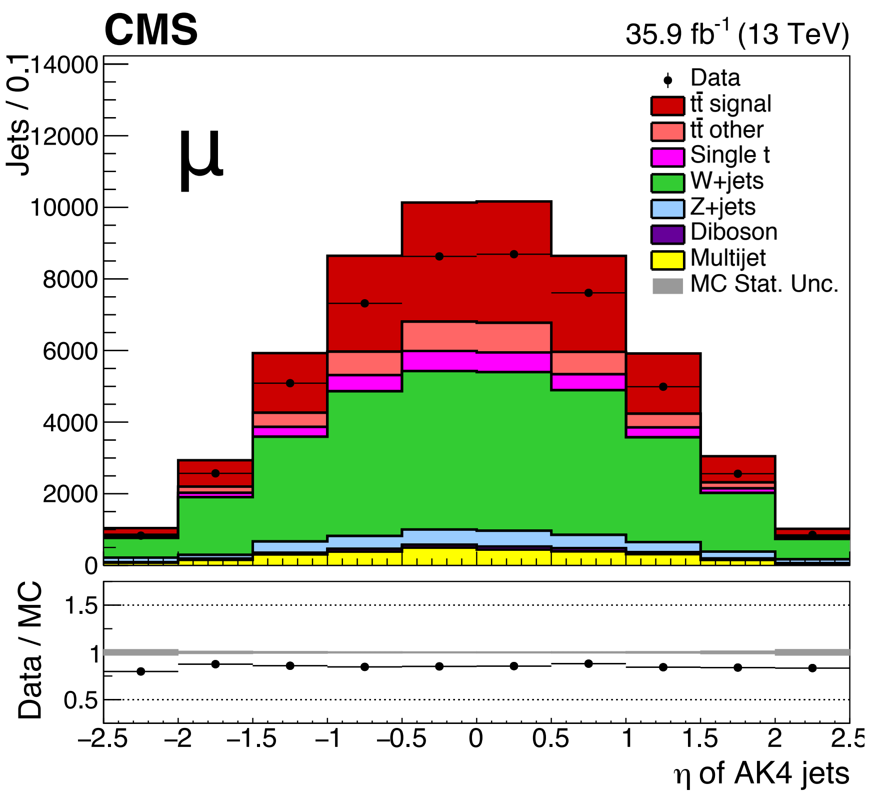


Expected and Observed Event Counts

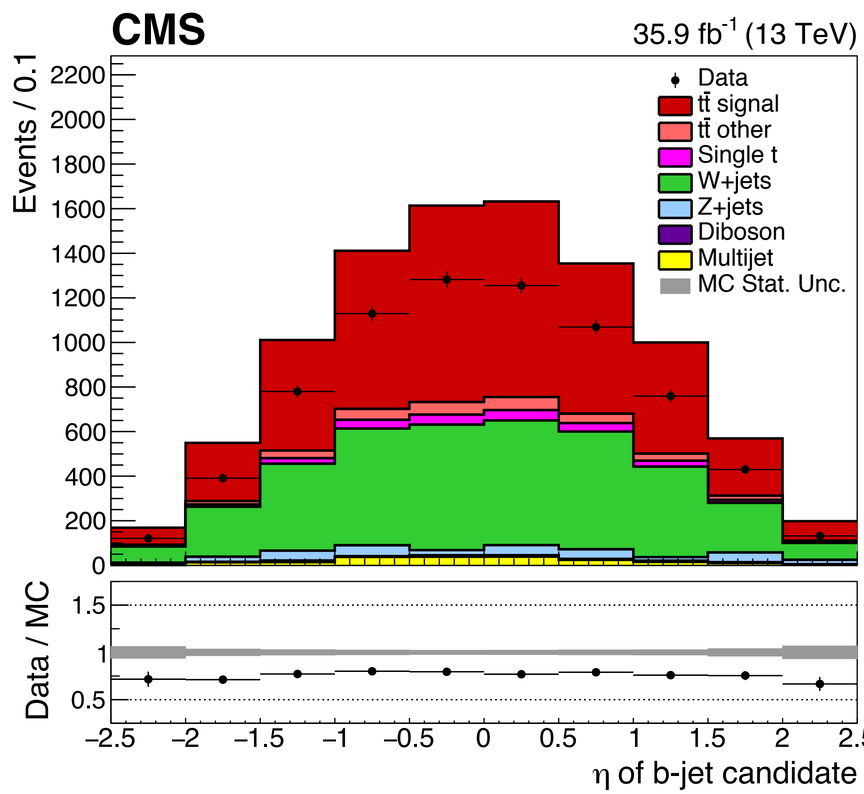
Sample	Number of events (μ+jets channel)			
	Preselection	0t	1t0b	1t1b
$t\bar{t}$ (signal)	26491 ± 102	17290 ± 118	4819 ± 72	4382 ± 41
$t\bar{t}$ (non-semilep)	4748 ± 43	4145 ± 46	318 ± 19	285 ± 10
Single top	3257 ± 16	2871 ± 17	249 ± 6	137 ± 3
W+jets	30861 ± 43	27155 ± 46	3566 ± 15	139 ± 3
Z+jets	3070 ± 122	2726 ± 128	318 ± 42	26 ± 11
Diboson	595 ± 19	552 ± 19	40 ± 5	3 ± 1
QCD	2992 ± 72	2741 ± 69	197 ± 20	53 ± 8
Total	72014 ± 186	57481 ± 200	9508 ± 90	5025 ± 45
Data	60672	49137	7348	4187
MC / Data excess	19%	17%	29%	20%

Sample	Number of events (e+jets channel)			
	Preselection	0t	1t0b	1t1b
$t\bar{t}$ (signal)	16492 ± 80	10417 ± 93	3168 ± 59	2907 ± 33
$t\bar{t}$ (non-semilep)	3475 ± 37	3036 ± 39	249 ± 16	190 ± 8
Single top	2203 ± 13	1944 ± 14	165 ± 5	93 ± 3
W+jets	18306 ± 36	16083 ± 37	2143 ± 12	80 ± 2
Z+jets	1259 ± 77	1075 ± 83	167 ± 31	16 ± 9
Diboson	391 ± 15	361 ± 16	27 ± 4	2 ± 1
QCD	2630 ± 112	2345 ± 103	263 ± 45	22 ± 7
Total	44755 ± 167	35261 ± 172	6183 ± 83	3312 ± 36
Data	39313	31559	4801	2953
MC / Data excess	14%	12%	29%	12%

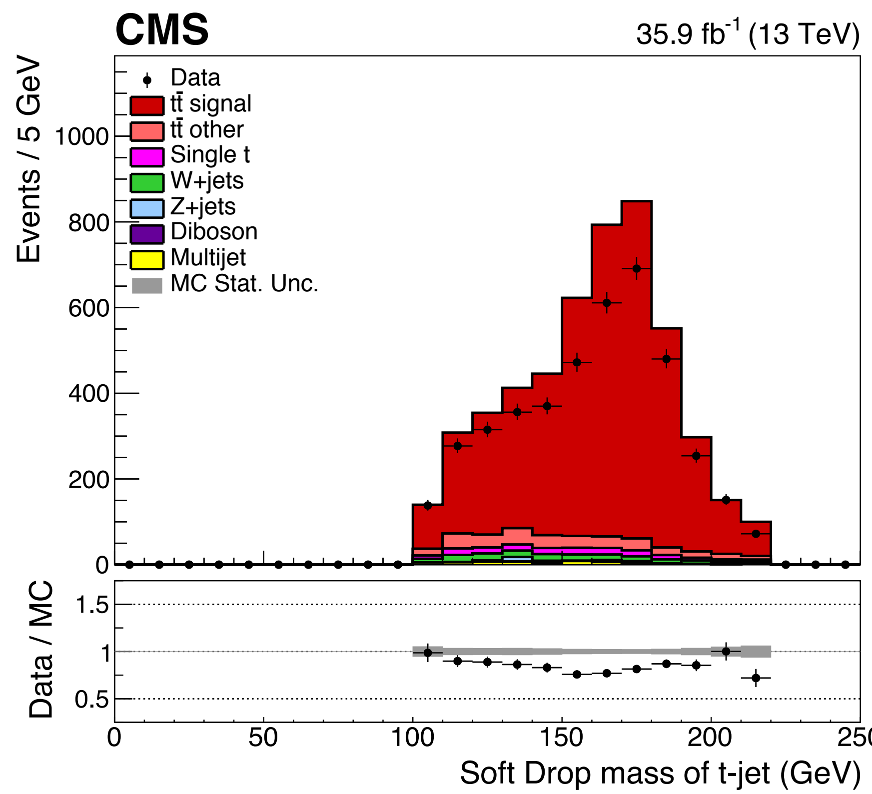
Prefit Kinematic Distributions



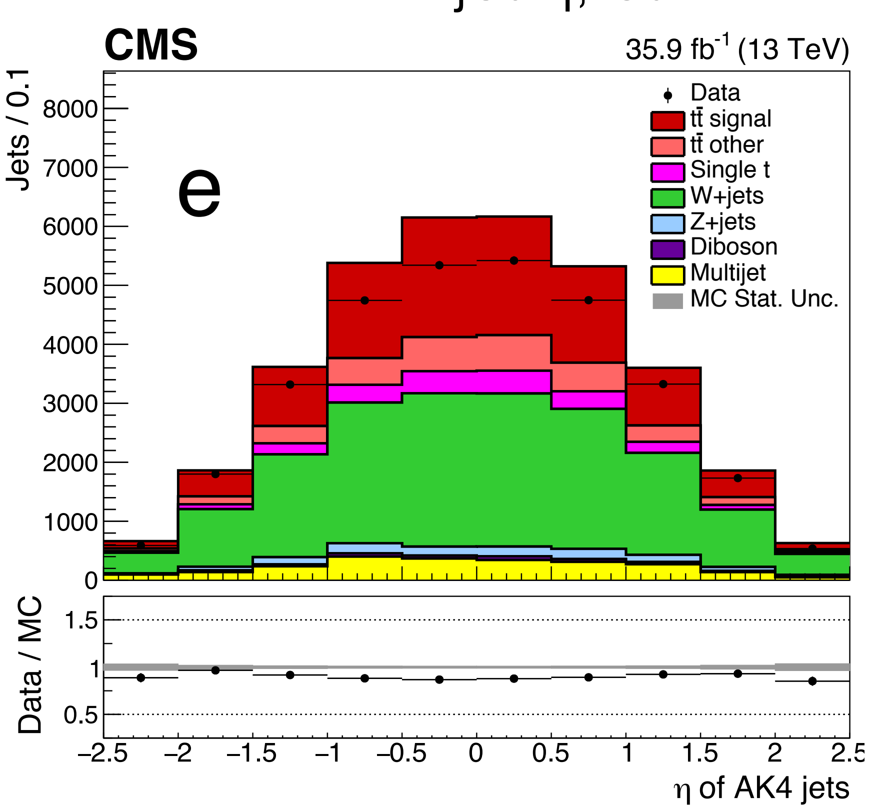
AK4 jet η, 0t

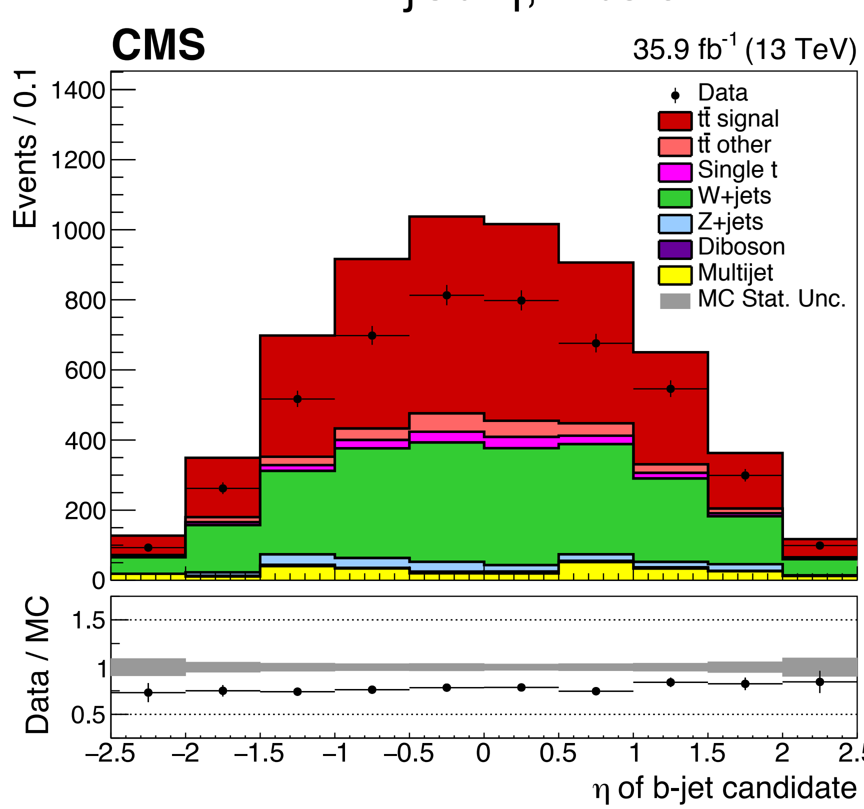


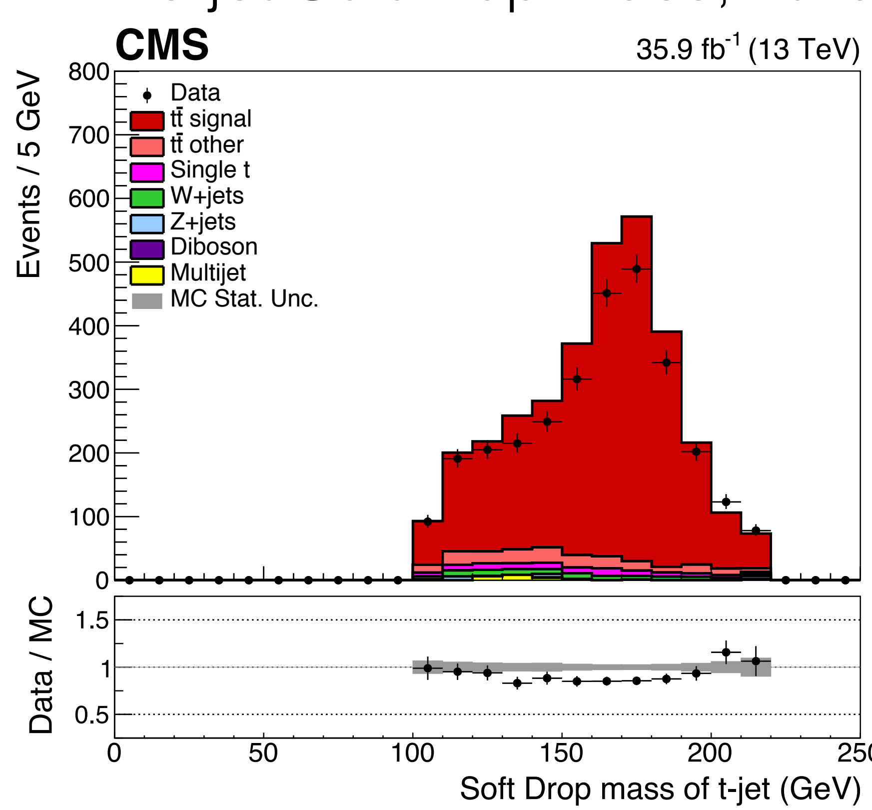
AK4 jet η, 1t0b



AK8 jet SoftDrop mass, 1t1b



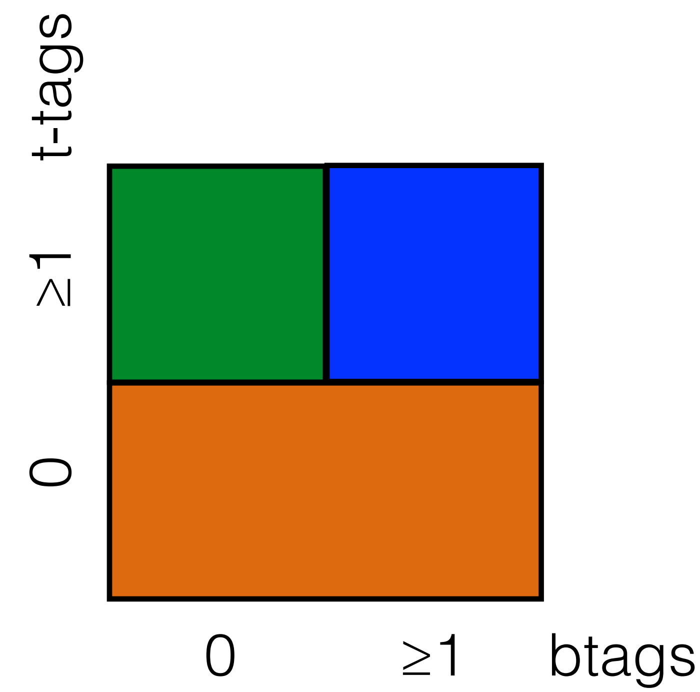




Simultaneous Likelihood Fit

- Use tagging status to define kinematic regions
  - 0t
  - 1t0b
  - 1t1b

Background dominated ↑↓ Signal dominated



- Perform simultaneous kinematic fit in 3 regions to simultaneously extract t tag SF, background normalizations
  - Systematic uncertainties enter as nuisance parameters
  - Using Higgs Combine package

Fit templates:
0t — AK4 jet η
1t0b — AK4 jet η
1t1b — AK8 jet SD mass

Best signal/background discrimination, QCD well-modeled, uncorrelated w/ AK8 jet p_T

Systematic Uncertainties — Experimental

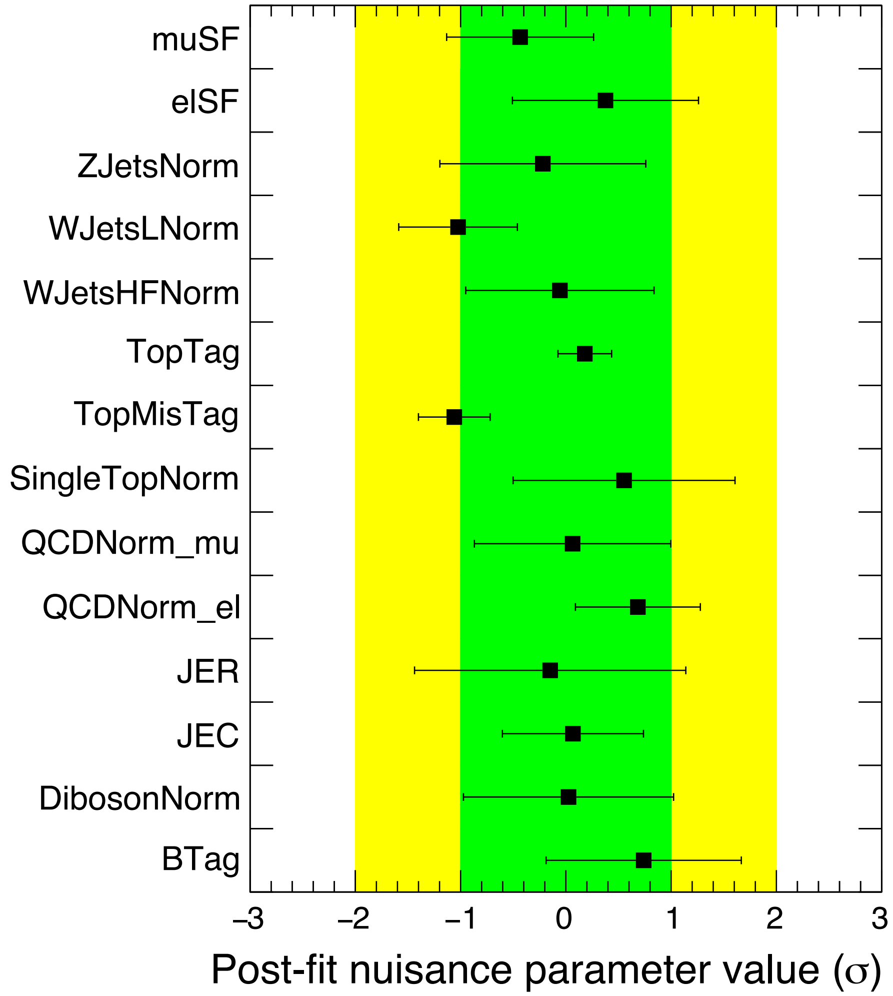
- Correction factor uncertainties provided by respective POGs
  - **Lepton ID / iso / trigger SFs, JEC, JER, b tag SF**
- Uncertainties to be constrained by fit given conservative a priori values
  - **t tag SF**: 25% uncertainty
    - Separate SFs for t tag ($\mathrm{t\bar{t}}$, single top) and t mistag
  - **Background normalizations**: 50(30)% for QCD(other backgrounds)
    - Separate normalizations for e and μ channel QCD
    - Separate normalizations for W+light and W+heavy flavor
- **Lumi, pileup** uncertainties not included in fit

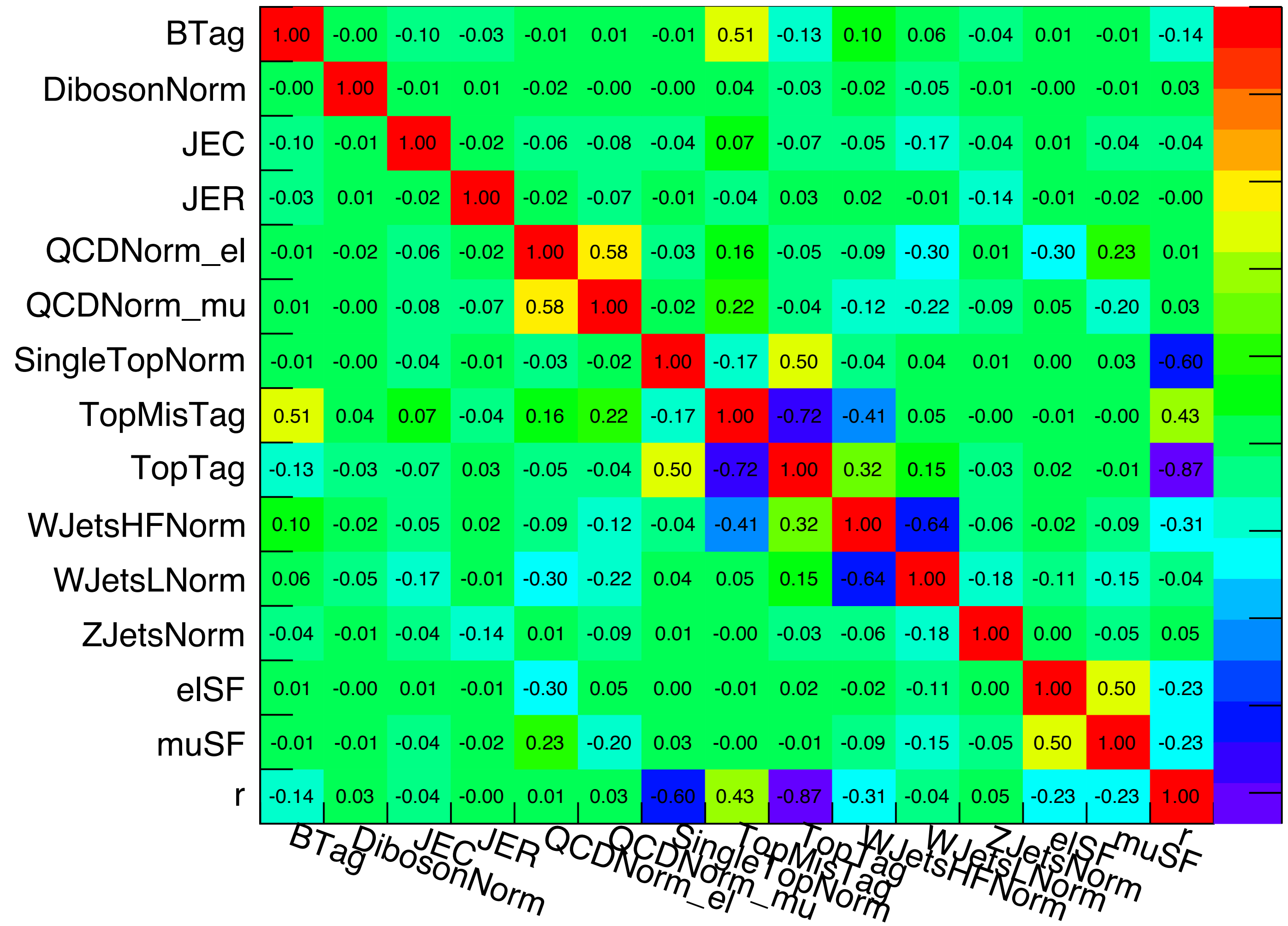
Systematic Uncertainties — Theoretical

- PDF: standard deviation of 100 NNPDF3.0 MC replicas
- Renormalization and factorization scales (μR/μF): envelope of separately scaling μR, μF by 0.5, 2.0 (excluding anticorrelated variations)
- Initial and final state radiation (ISR, FSR): α_S for ISR(FSR) varied by factor of 2($\sqrt{2}$)
- Matrix element to parton shower (ME-PS) matching: resummation damping factor h_{damp} varied by ±1σ
- Color reconnection: variant sample generated with color reconnection model (MPI-based + QCD-inspired + gluon move) applied
- Underlying event: tune CUETP8M2T4 parameters varied by ±1σ

Theoretical uncertainties not included in fit

Fit Results: Nuisances





$r = 0.81 \pm 0.05$

t (mis)tag uncertainties constrained from conservative a priori value
Posterior nuisances generally agree with a priori
Expected anticorrelation between t tag and t mistag, W+LF and W+HF

Fit Results: t tag SF

NEW since preapproval:
t tag SF shape uncertainty

- Nominal t tag SF extracted in fit is inclusive
- p_T and $|\eta|$ dependence of t tag SF assessed by fitting in two bins of t jet p_T or $|\eta|$
  - p_T <(>) 500 GeV; $|\eta|$ <(>) 1.0
  - Fit performed simultaneously in both bins, with all nuisances besides t tag SF fully correlated
- Difference between inclusive and binned t tag SF interpreted as shape uncertainty

Posterior nuisance parameters

	Top-tag SF	Top-mis-tag SF
Inclusive	0.18 ± 0.25	-1.06 ± 0.34
Top jet $p_T < 500$ GeV	0.09 ± 0.24	-1.00 ± 0.37
Top jet $p_T > 500$ GeV	-0.14 ± 0.26	-0.53 ± 0.39
Top jet $\|\eta\| < 1.0$	0.20 ± 0.26	-1.21 ± 0.35
Top jet $\|\eta\| > 1.0$	0.06 ± 0.27	-0.94 ± 0.39

Posterior SFs

t tag*: 1.04 ± 0.06 (fit)
± 0.01-0.08 (shape)

t mistag: 0.79 ± 0.06 (fit)
± 0.01-0.10 (shape)

*compare against 1.06 +0.09/-0.04 (JME POG)

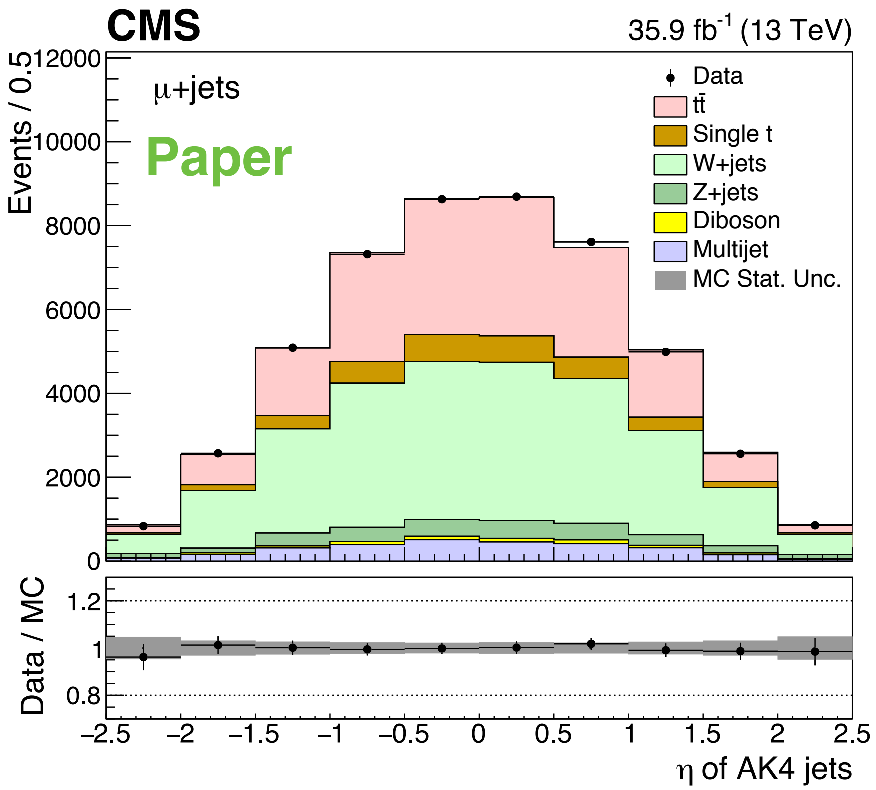
Postfit Event Counts

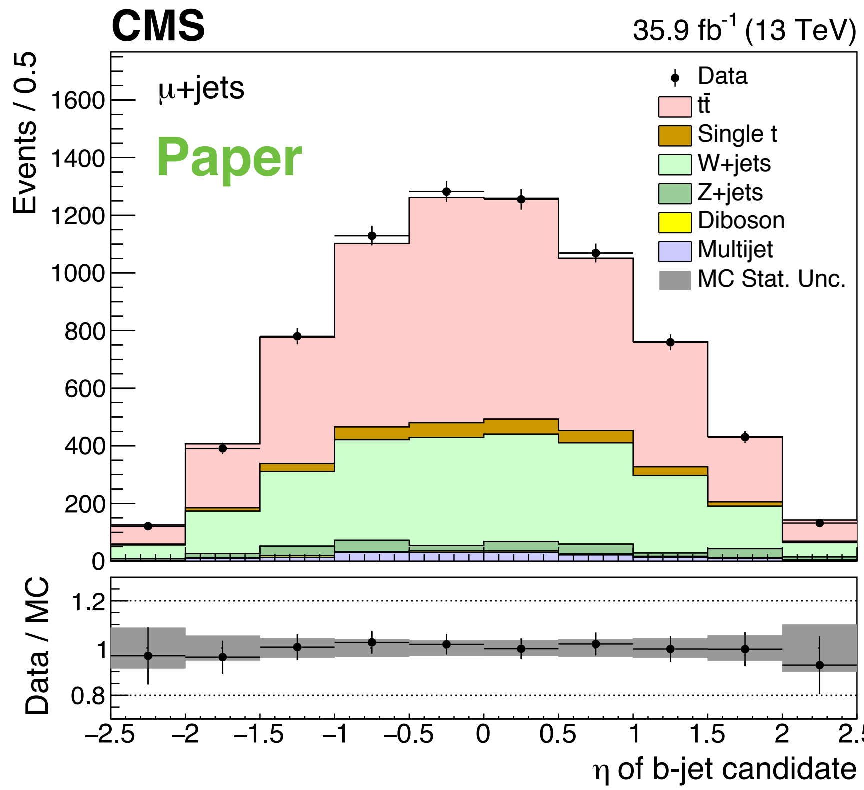
Paper

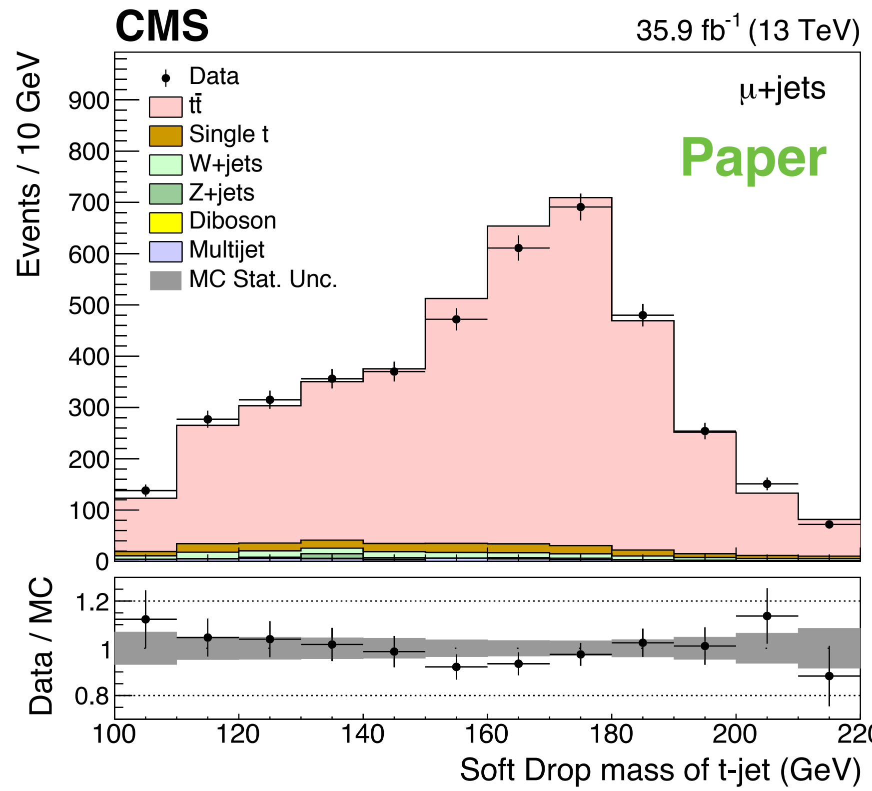
Process	Number of events (μ+jets channel) 0t	1t0b	1t1b
$t\bar{t}$	16772 ± 1438	4245 ± 174	3905 ± 80
Single t	3286 ± 587	282 ± 68	153 ± 34
W+jets	23104 ± 2871	2368 ± 318	105 ± 20
Z+jets	2582 ± 680	234 ± 69	19 ± 10
Diboson	557 ± 155	31 ± 10	2 ± 1
Multijet	2833 ± 1207	159 ± 76	43 ± 22
Total	49135 ± 3549	7320 ± 383	4228 ± 93
Data	49137	7348	4187

Process	Number of events (e+jets channel) 0t	1t0b	1t1b
$t\bar{t}$	10707 ± 938	2835 ± 116	2670 ± 66
Single t	2267 ± 403	191 ± 47	107 ± 24
W+jets	13945 ± 1742	1445 ± 194	62 ± 12
Z+jets	1068 ± 295	118 ± 37	17 ± 15
Diboson	373 ± 105	22 ± 7	2 ± 1
Multijet	3200 ± 735	242 ± 80	31 ± 30
Total	31560 ± 2171	4854 ± 247	2889 ± 79
Data	31559	4801	2953

Postfit Kinematic Distributions



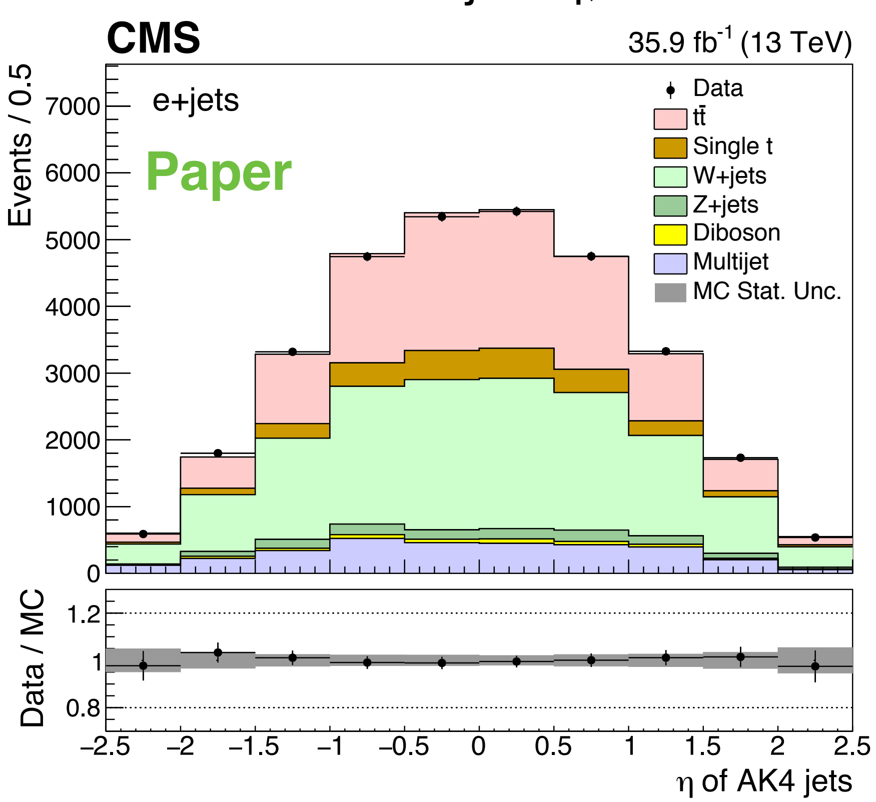


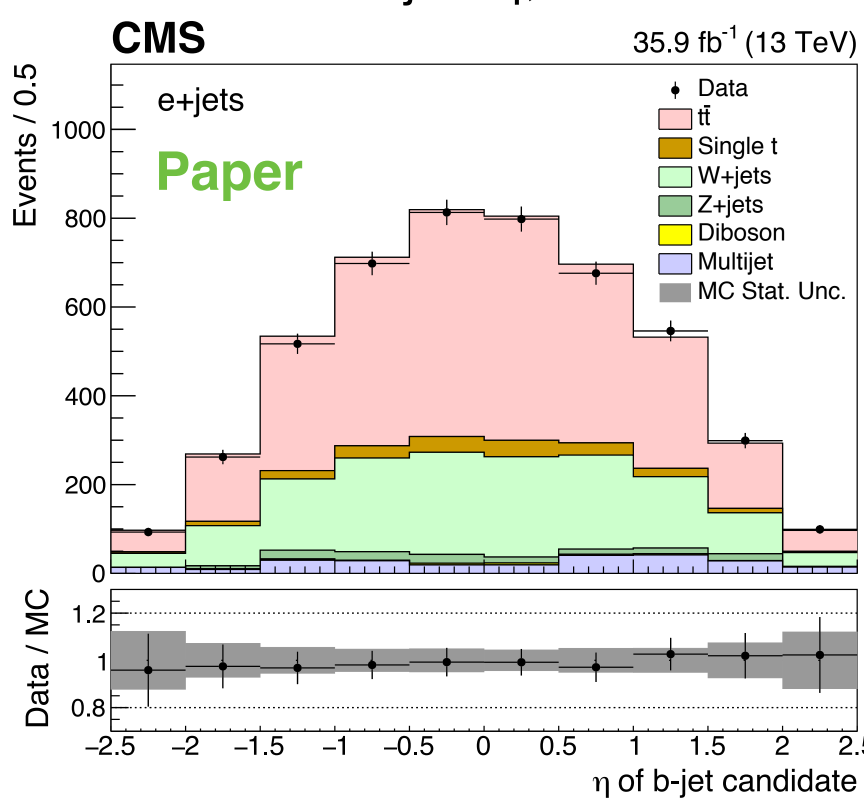


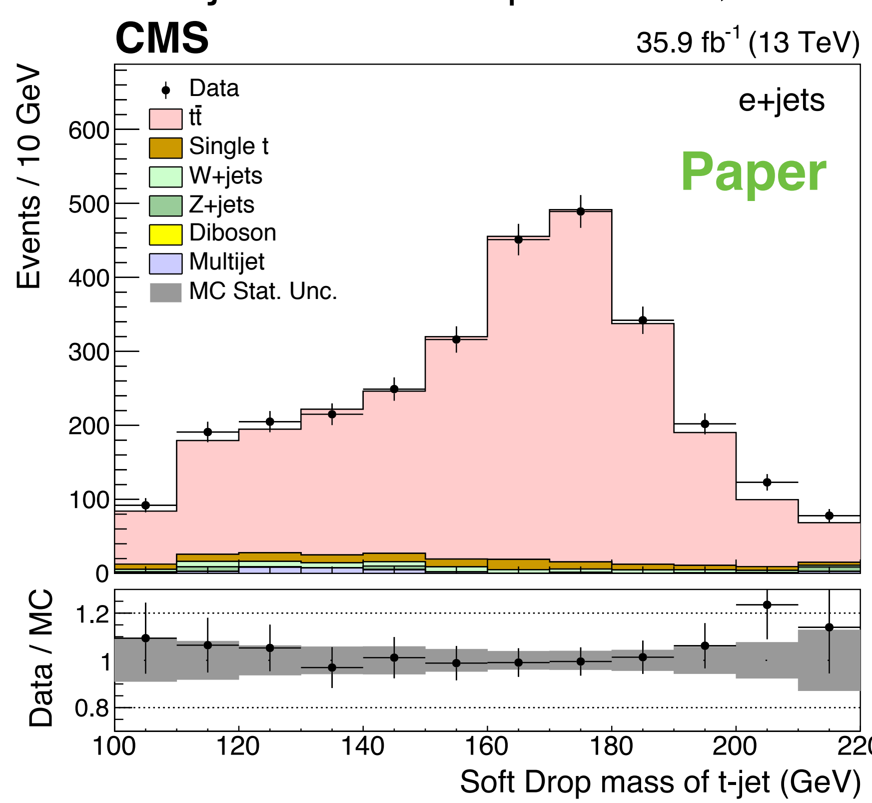
AK4 jet η, 0t

AK4 jet η, 1t0b

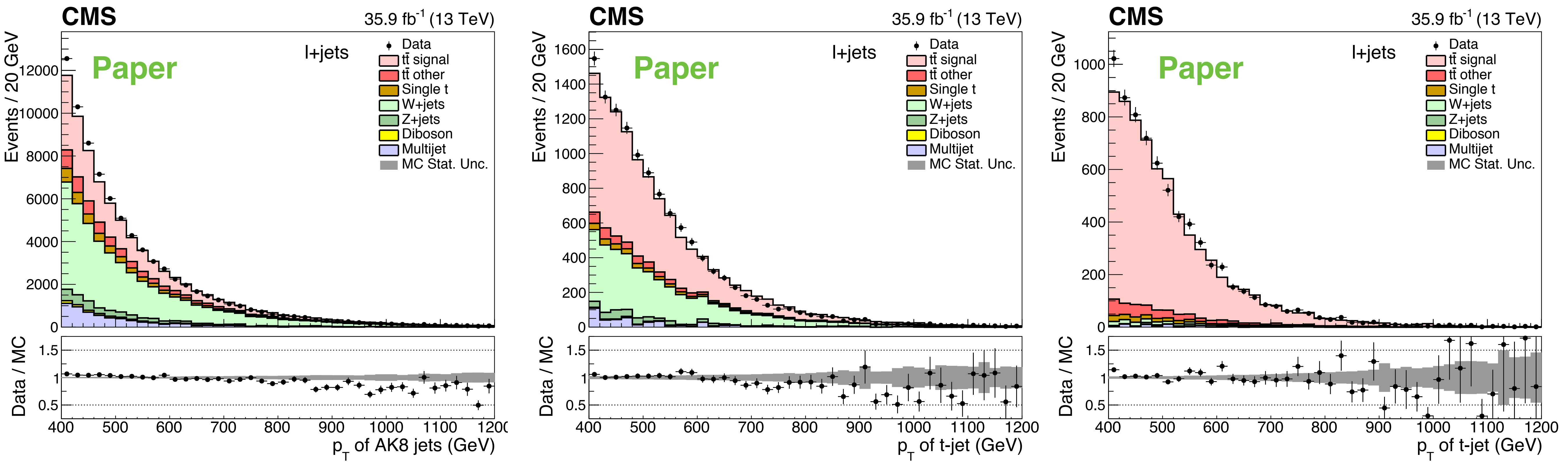
AK8 jet SoftDrop mass, 1t1b



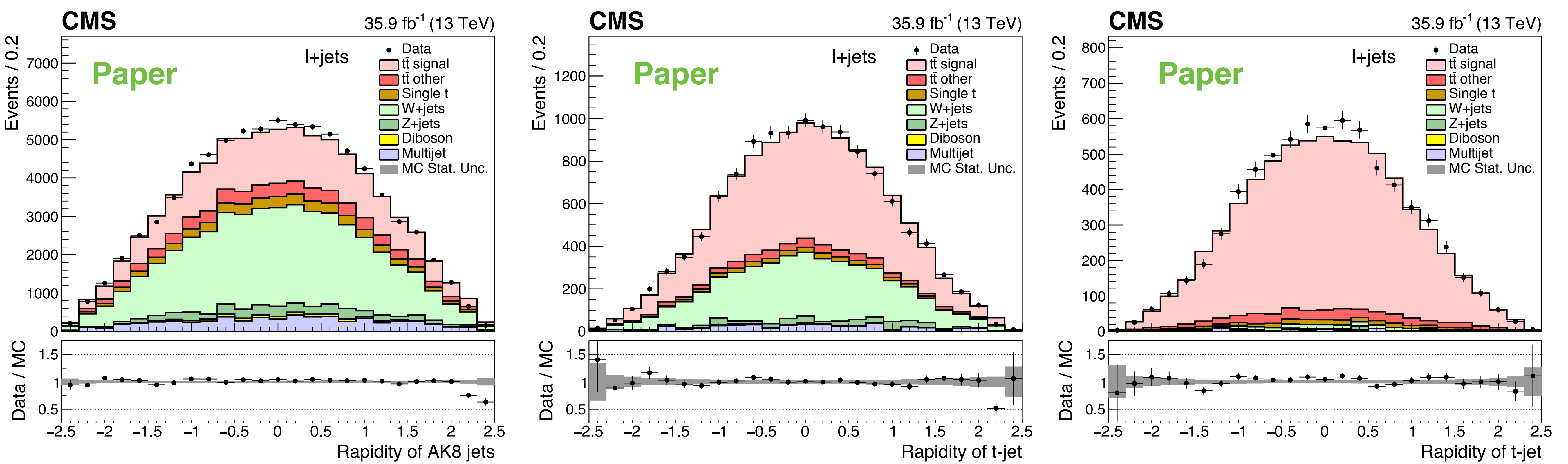




Postfit Kinematic Distributions (cont.)



0t 1t0b 1t1b



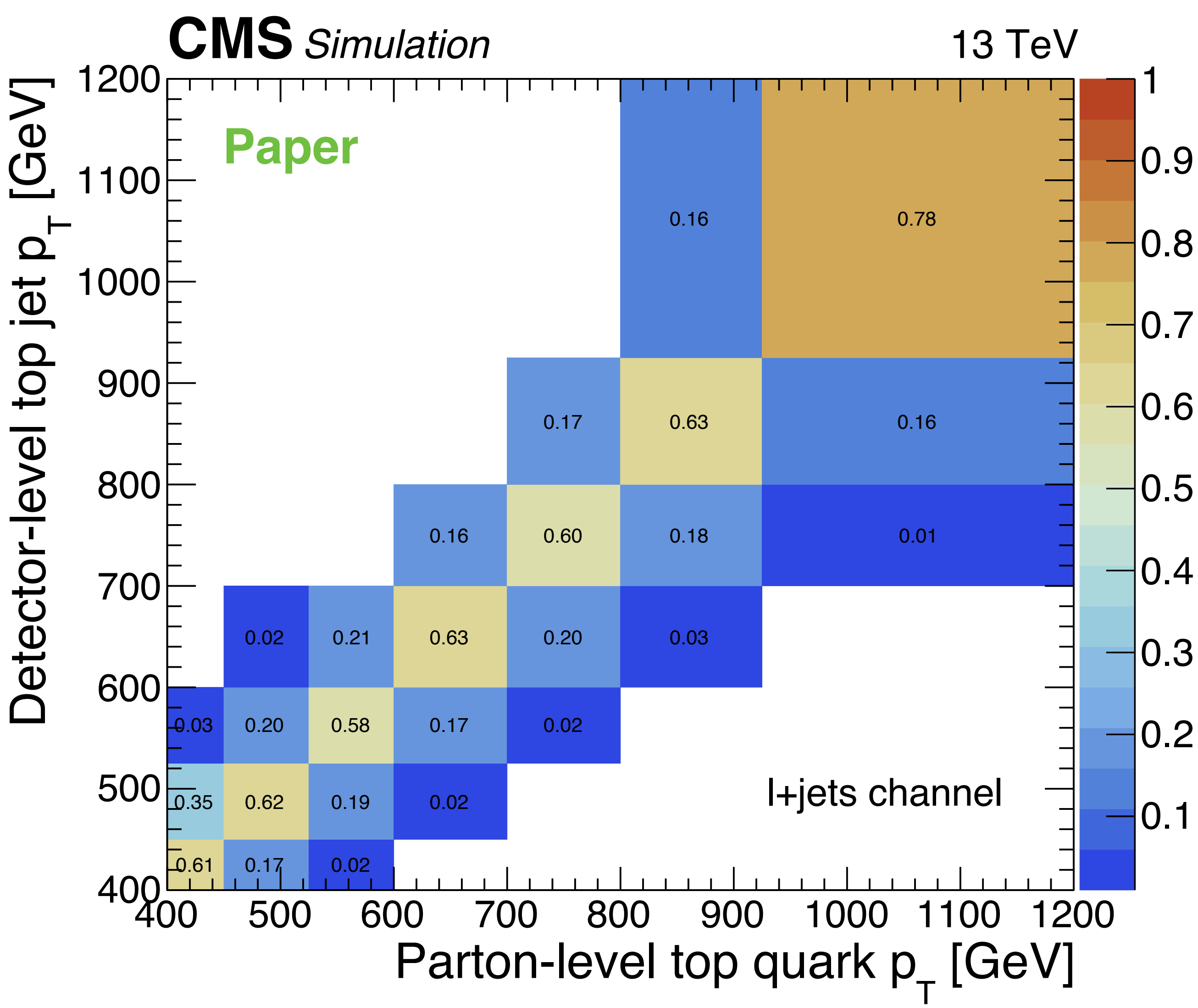
Unfolding

- Unfold measured p_T(top), |y|(top) distributions to give cross section at particle and parton level
  - Measured distribution: background-subtracted data in 1t1b signal region
- Unfolding method: TUnfold
  - Regularized matrix inversion
- Unfolding performed without regularization
  - Best performance, determined by measuring bias and uncertainty in MC closure tests
- Dedicated high-mass TTbar samples (700 < m($\mathrm{t\bar{t}}$) < 1000, m($\mathrm{t\bar{t}}$) > 1000 GeV) used to improve response matrix statistics

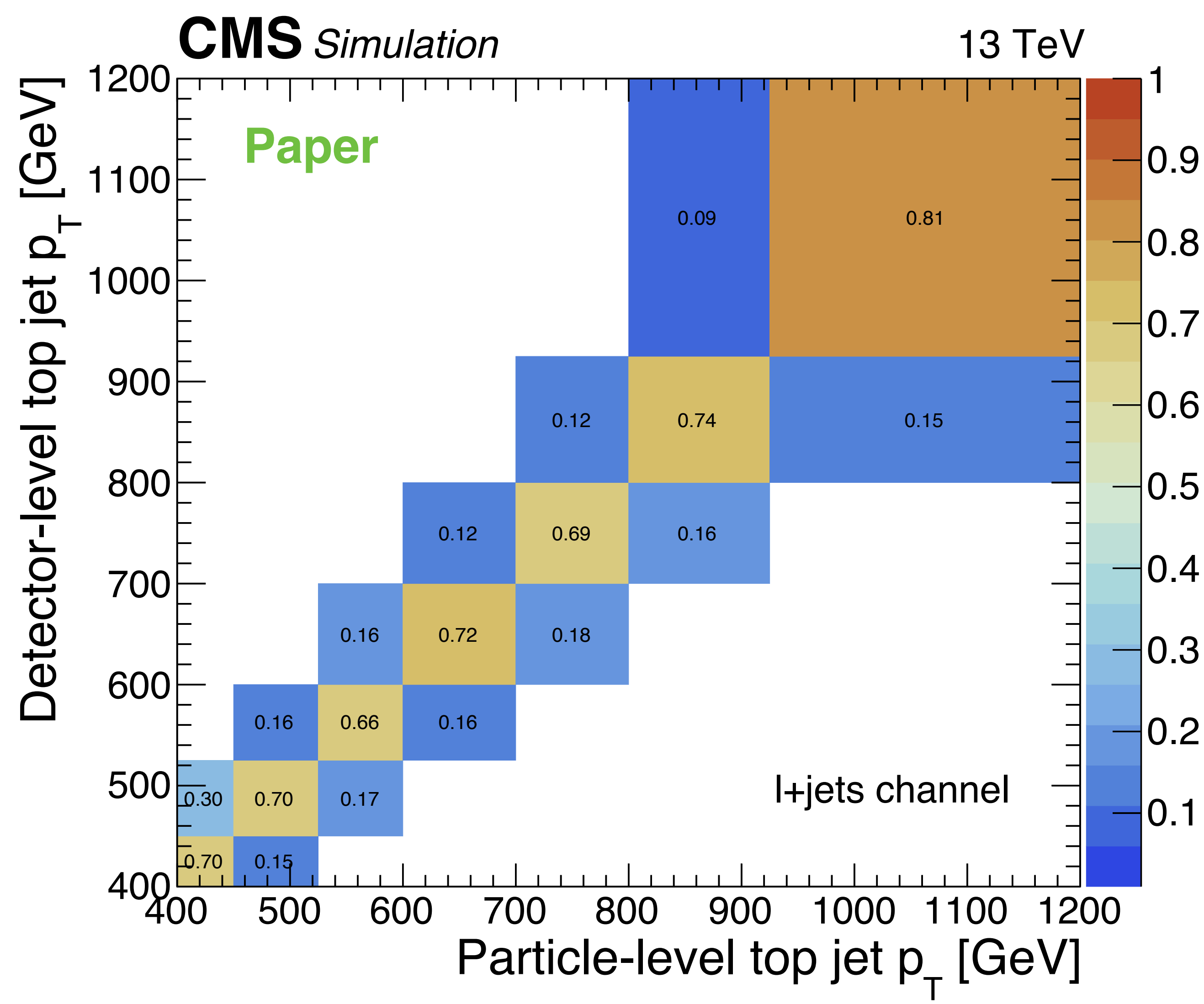
Parton and Particle Level Phase Spaces

- Parton level
  - Selection: semileptonic $t\bar{t}$, top quark p_T > 400 GeV
    - ==1 μ/e (isPromptFinalState, or isDirectPromptTauDecayProductFinalState from isPromptDecayed τ)
  - Top quark: isLastCopy top quark (after FSR) with sign opposite the lepton
- Particle level
  - Selection
    - ≥1 particle-level AK8 jet with p_T > 400 GeV, $|\eta| < 2.4$, and $105 < m_{jet} < 220$ GeV
    - ≥1 particle-level AK4 jet with p_T > 50 GeV, $|\eta| < 2.4$ originating from a b quark
    - ==1 μ/e with p_T > 50 GeV, $|\eta| < 2.1$
  - Top jet: leading particle-level AK8 jet

Response Matrices: p_T

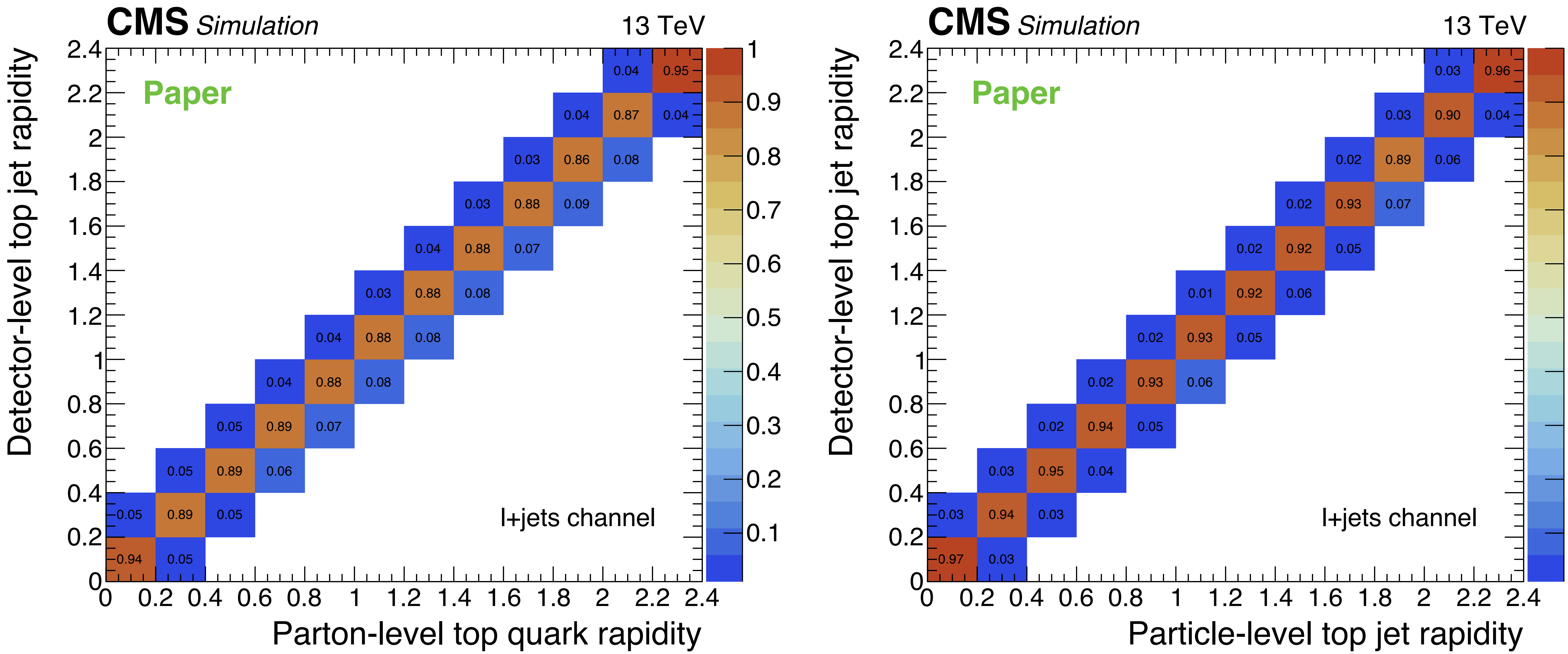


parton level



particle level

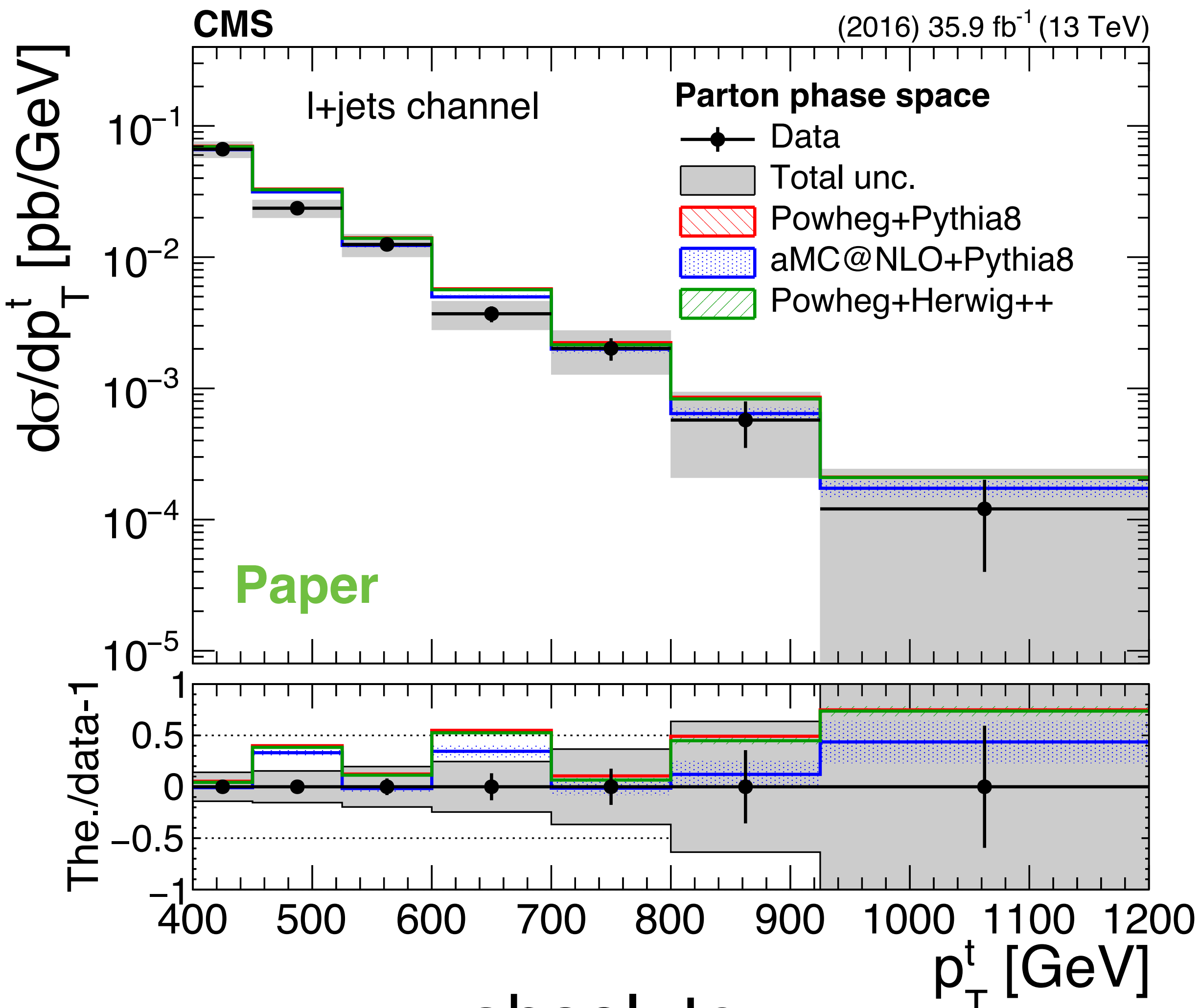
Response Matrices: |y|



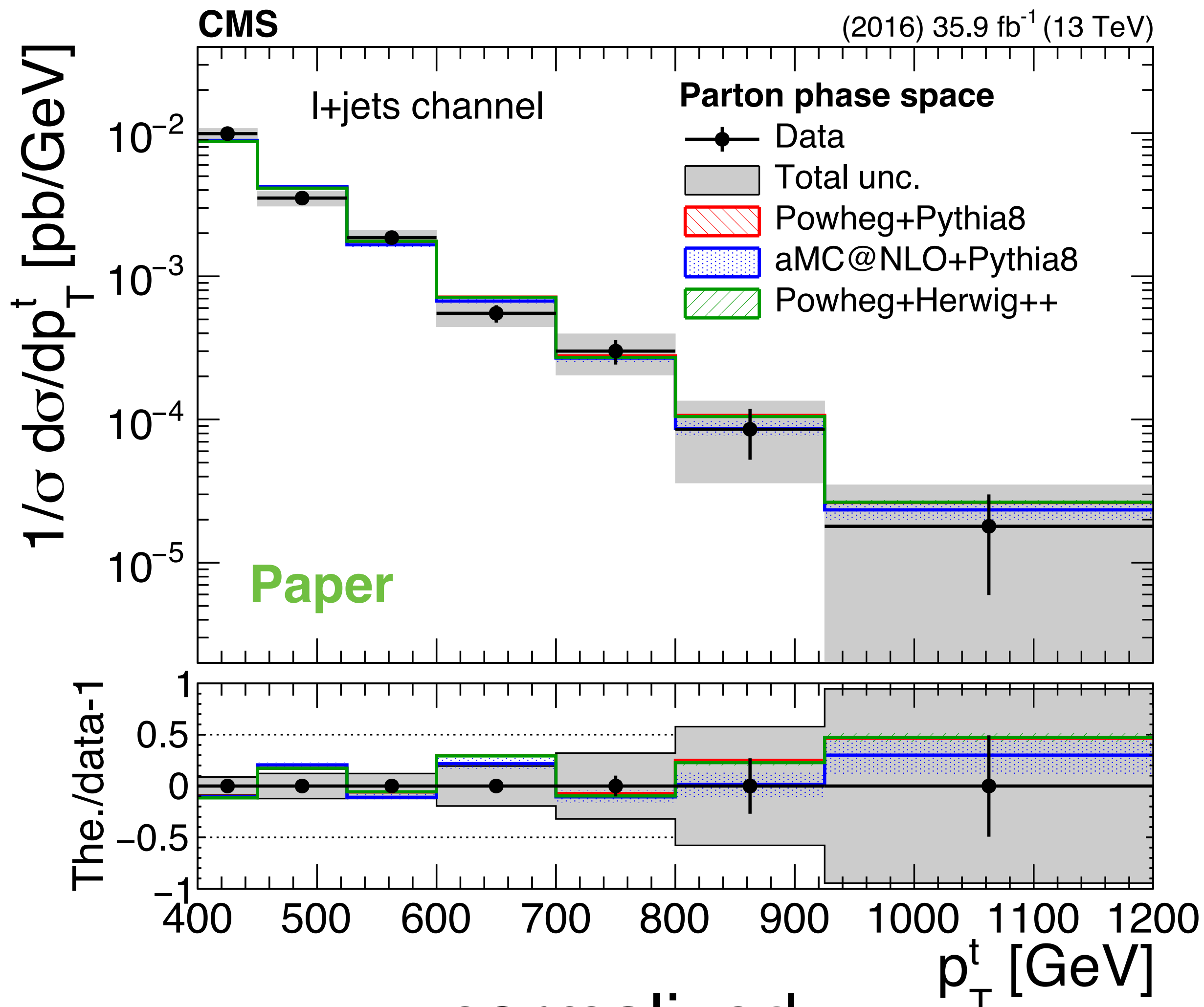
parton level particle level

NEW since preapproval

Unfolded data — parton level p_T



absolute



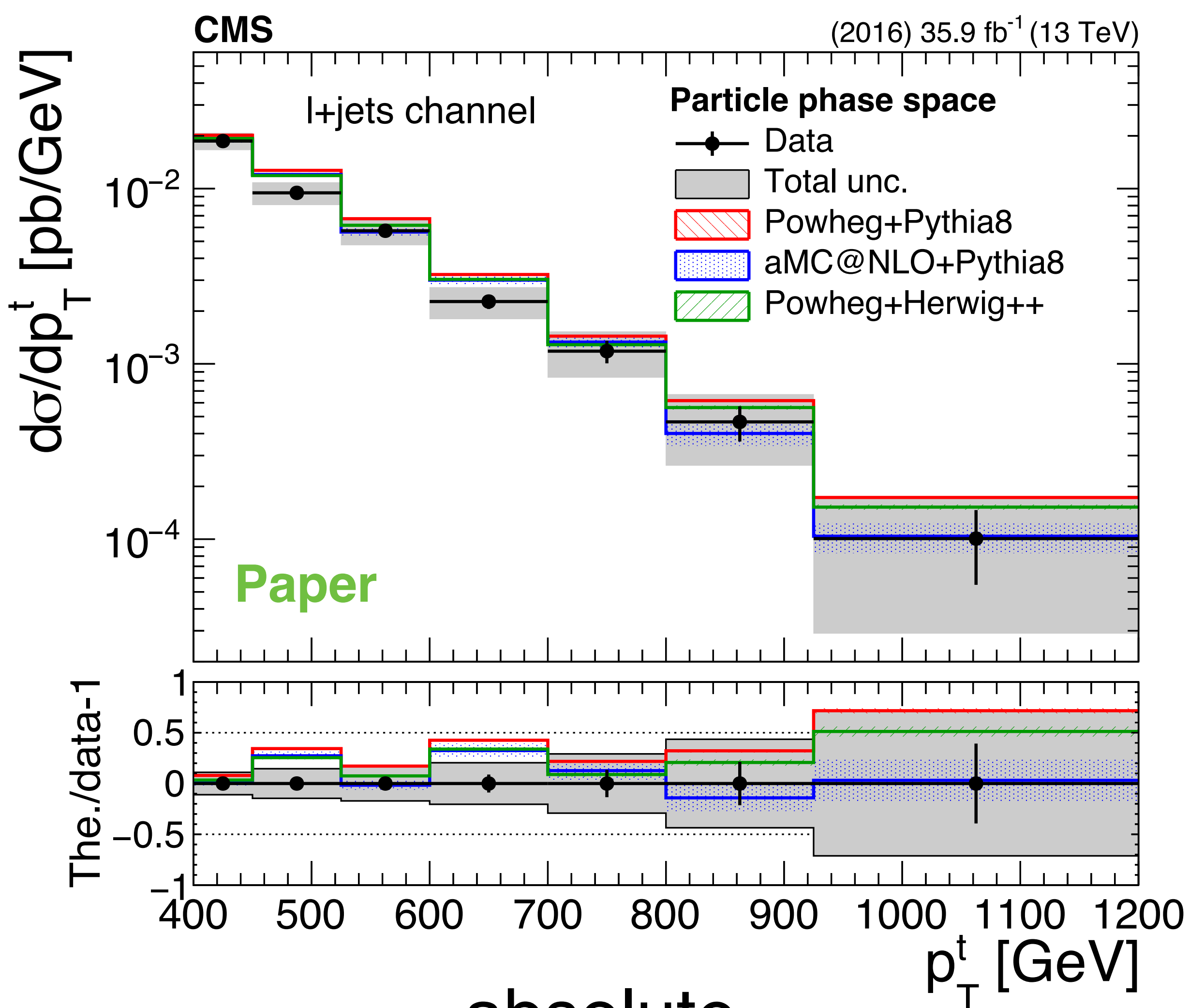
normalized

Theory somewhat overpredicts data for all models, but describes p_T shape well

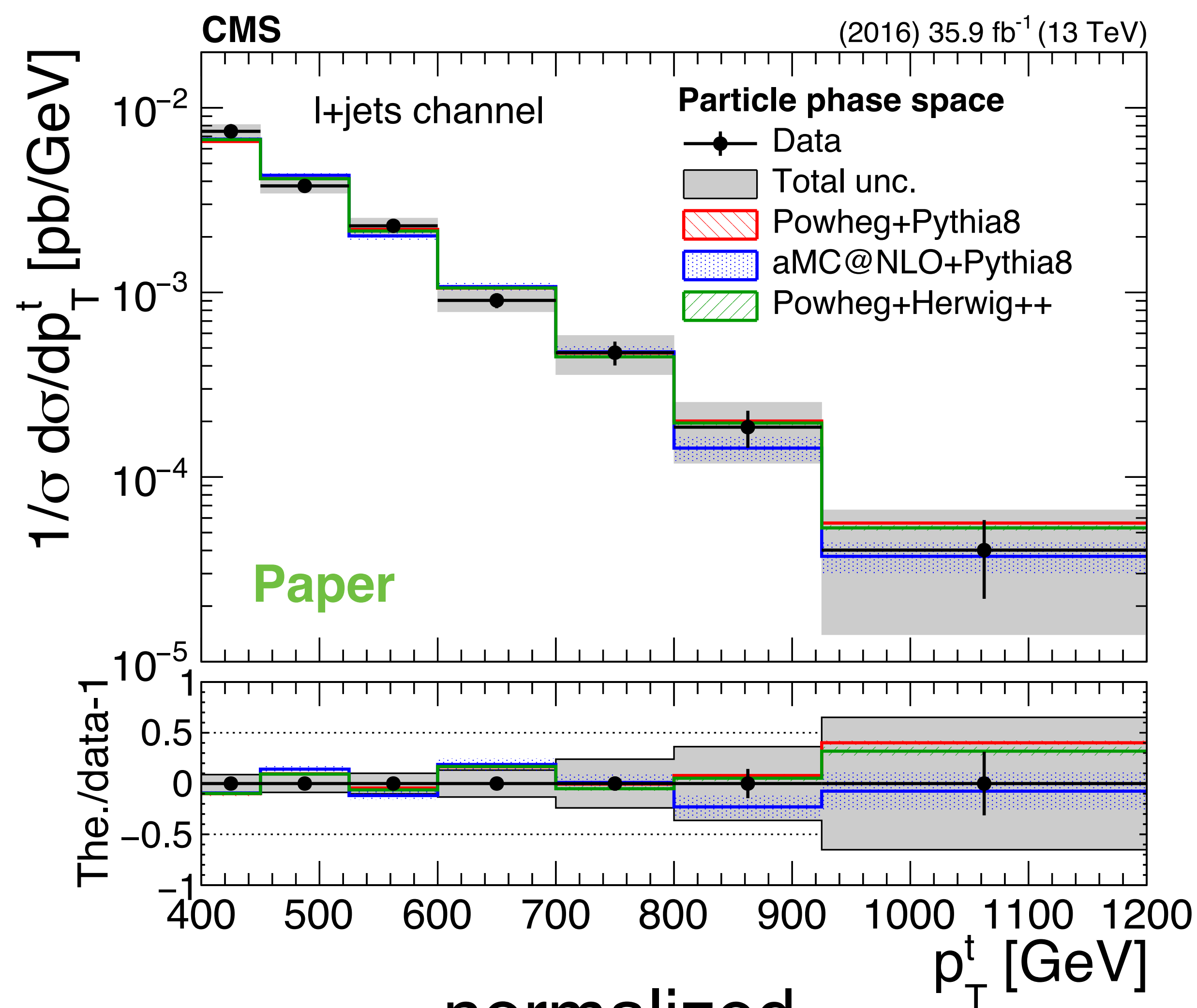
aMC@NLO has best agreement

NEW since preapproval

Unfolded data — particle level p_T



absolute



normalized

Smaller uncertainty on measurement than at parton level

Theory somewhat overpredicts data for all models, but describes p_T shape well

aMC@NLO has best agreement

NEW since preapproval

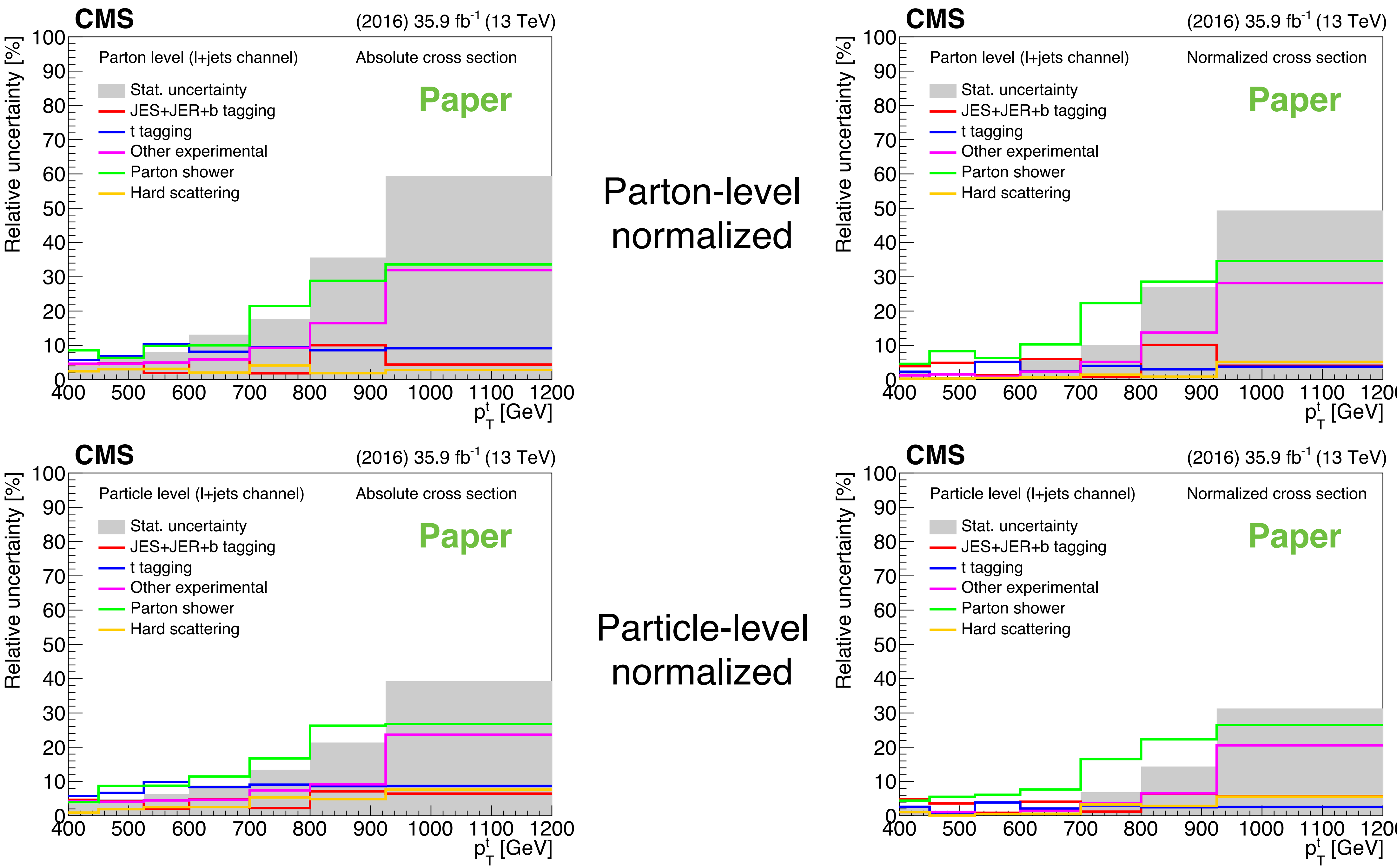
Unfolded Data — Uncertainties for p_T

Parton-level absolute

Parton-level normalized

Particle-level absolute

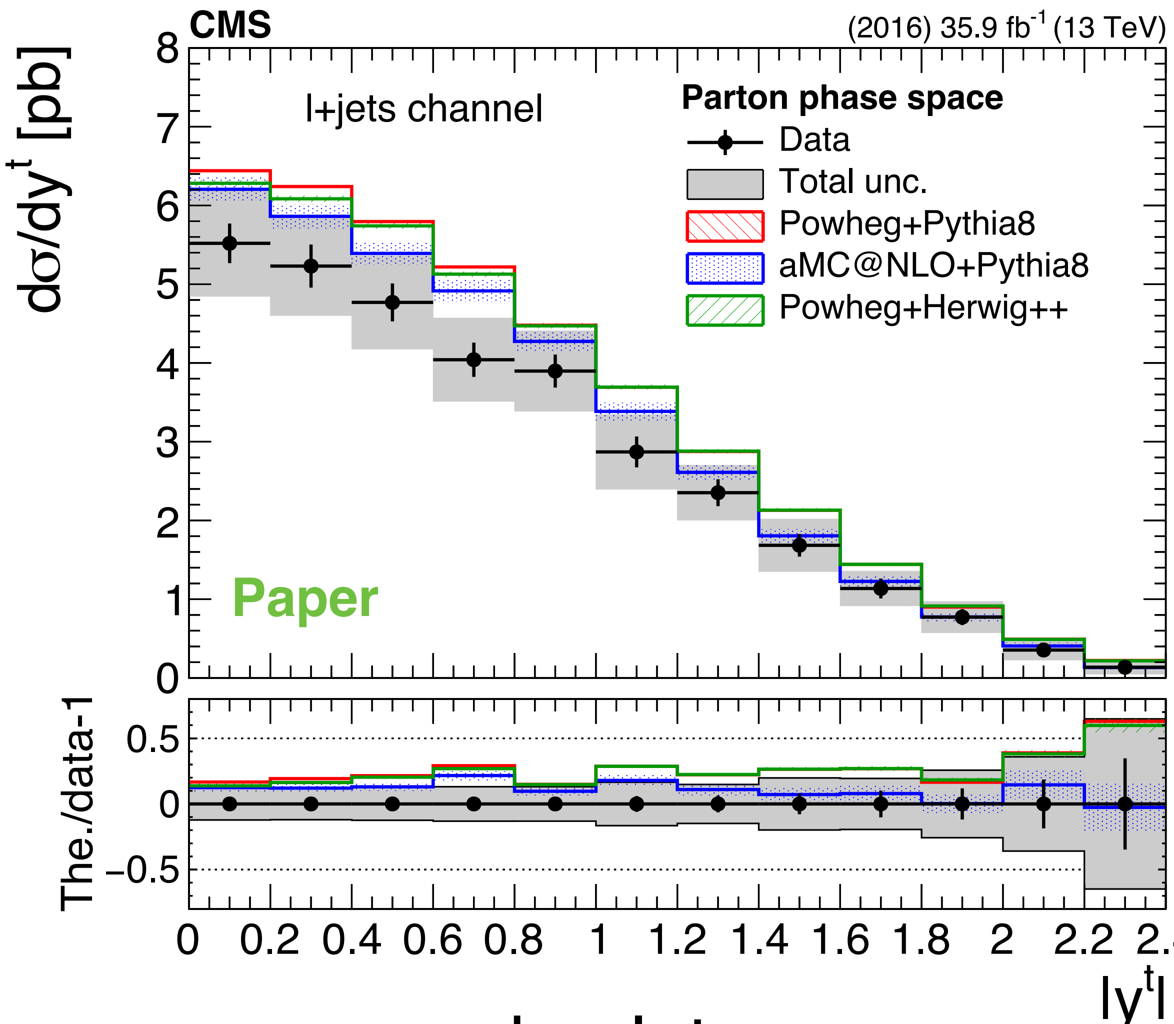
Particle-level normalized



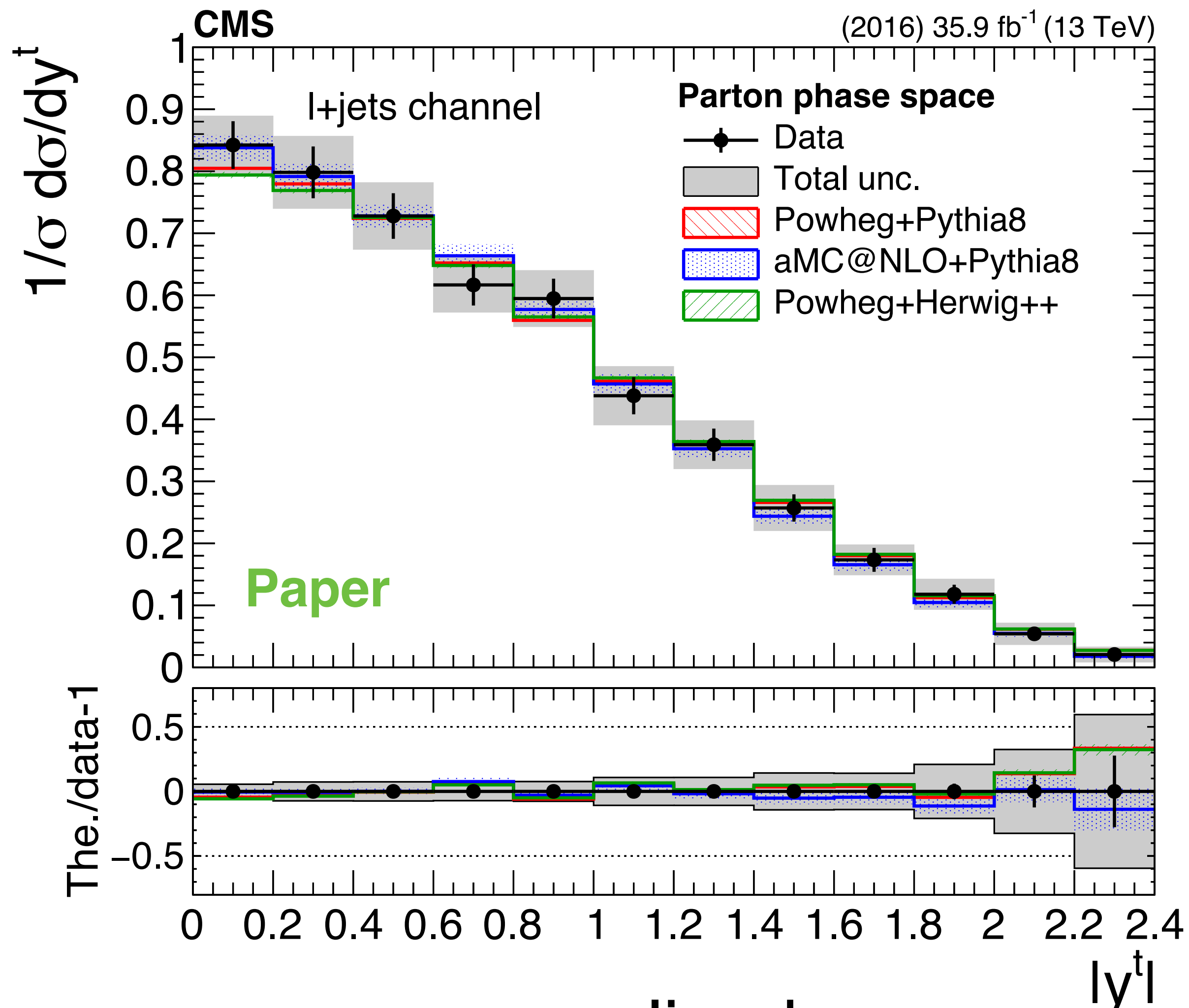
Parton shower dominant uncertainty at both parton and particle level
Stat uncertainty dominant at high p_T; systematics dominant at low p_T

NEW since preapproval

Unfolded data — parton level |y|



absolute



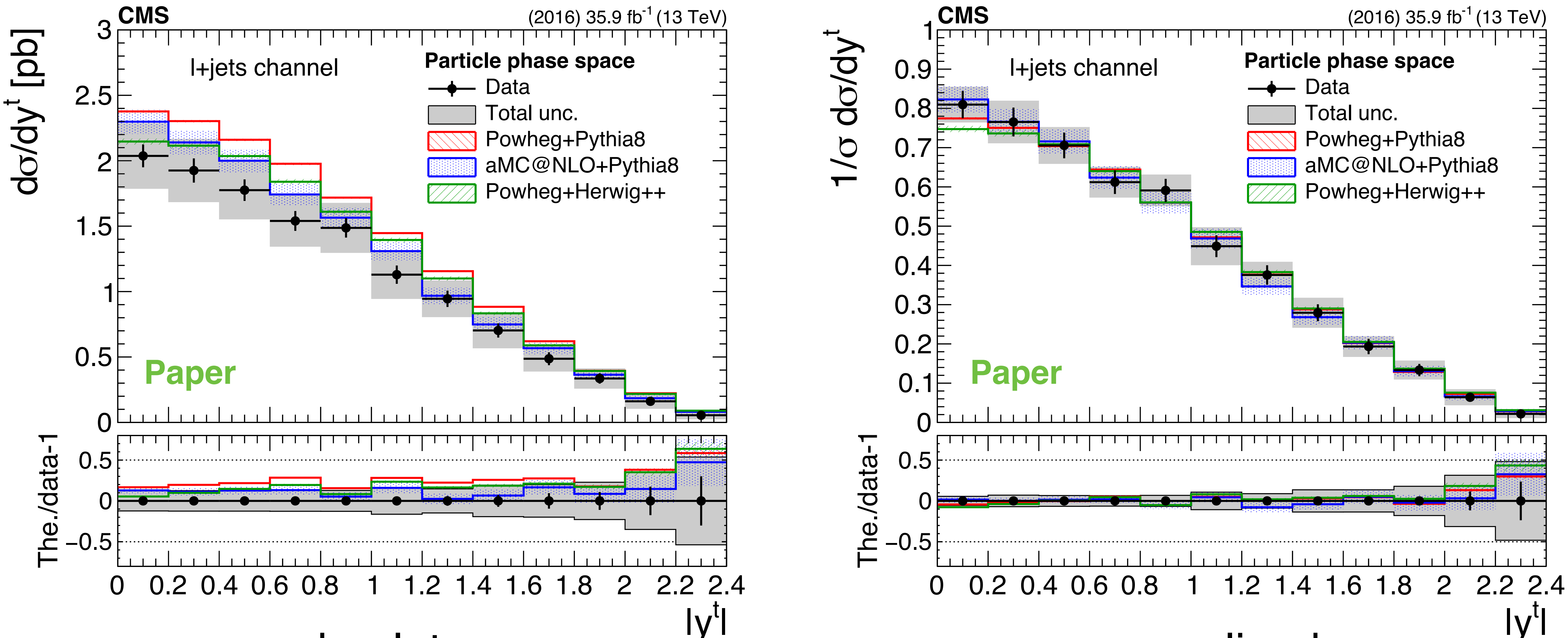
normalized

Theory somewhat overpredicts data for all models

aMC@NLO predicts slightly more central distribution than Powheg; data favors aMC@NLO

NEW since preapproval

Unfolded data — particle level |y|



absolute normalized

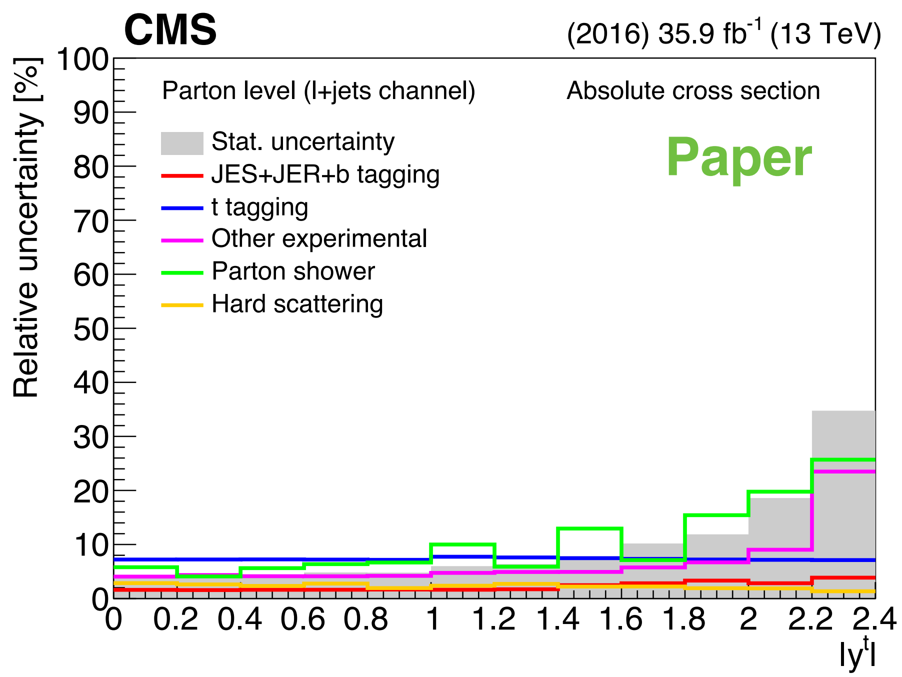
Theory somewhat overpredicts data for all models; less so for aMC@NLO than Powheg

All models predict slightly more forward distribution than data

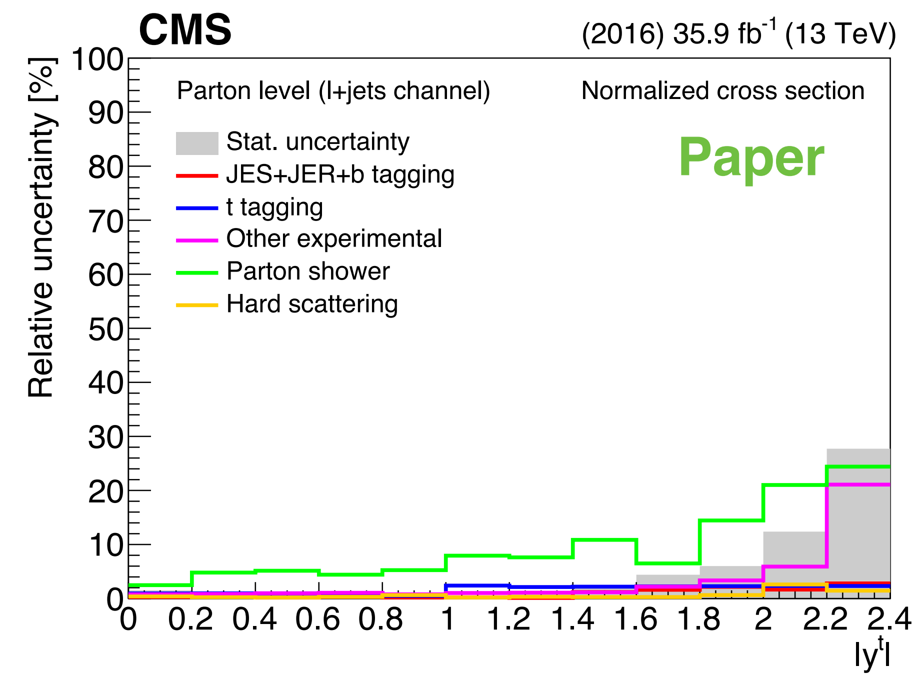
NEW since preapproval

Unfolded Data — Uncertainties for |y|

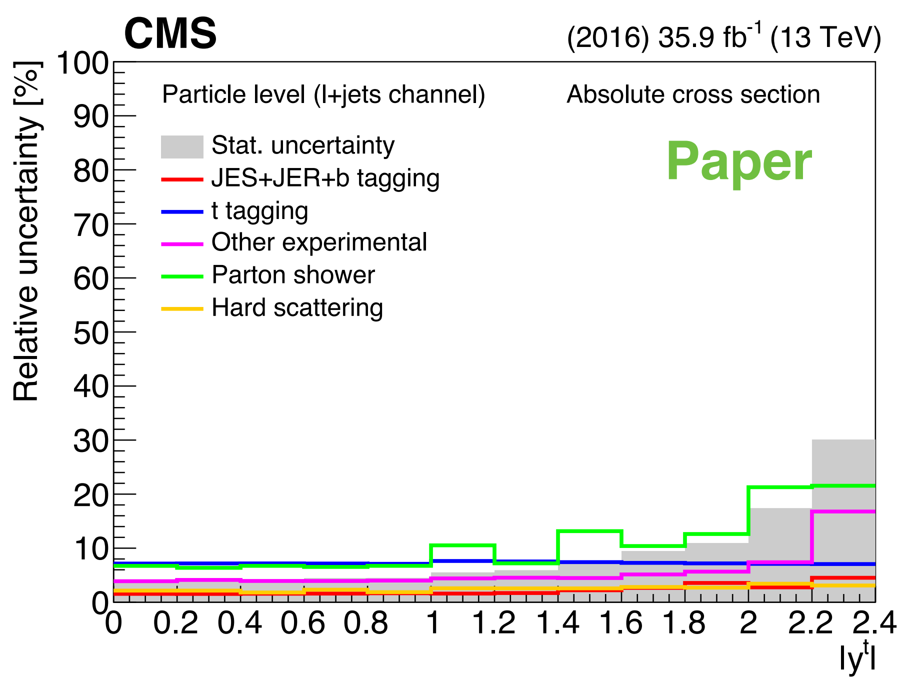
Parton-level absolute



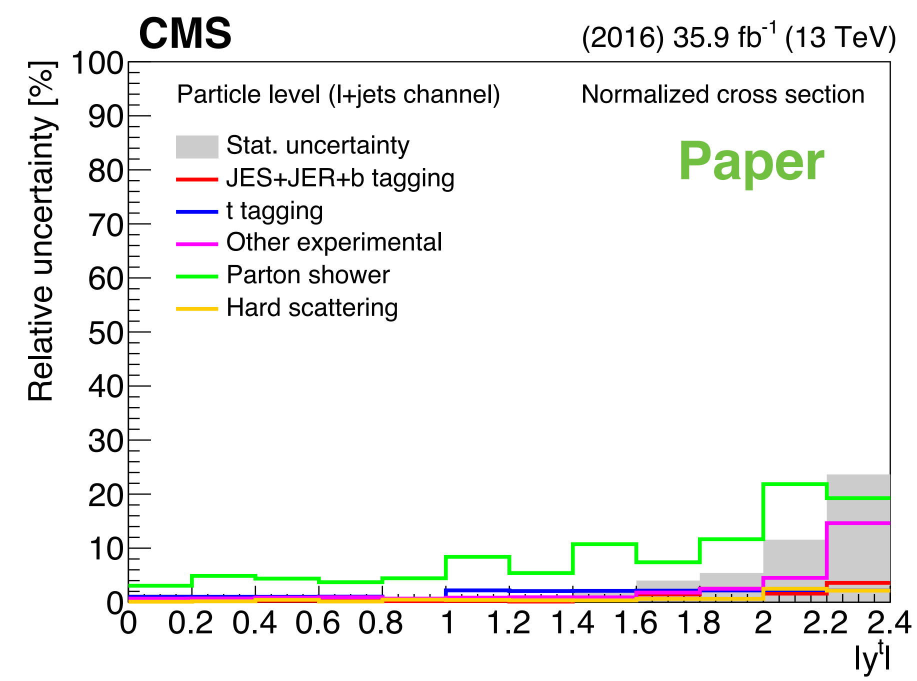
Parton-level normalized



Particle-level absolute



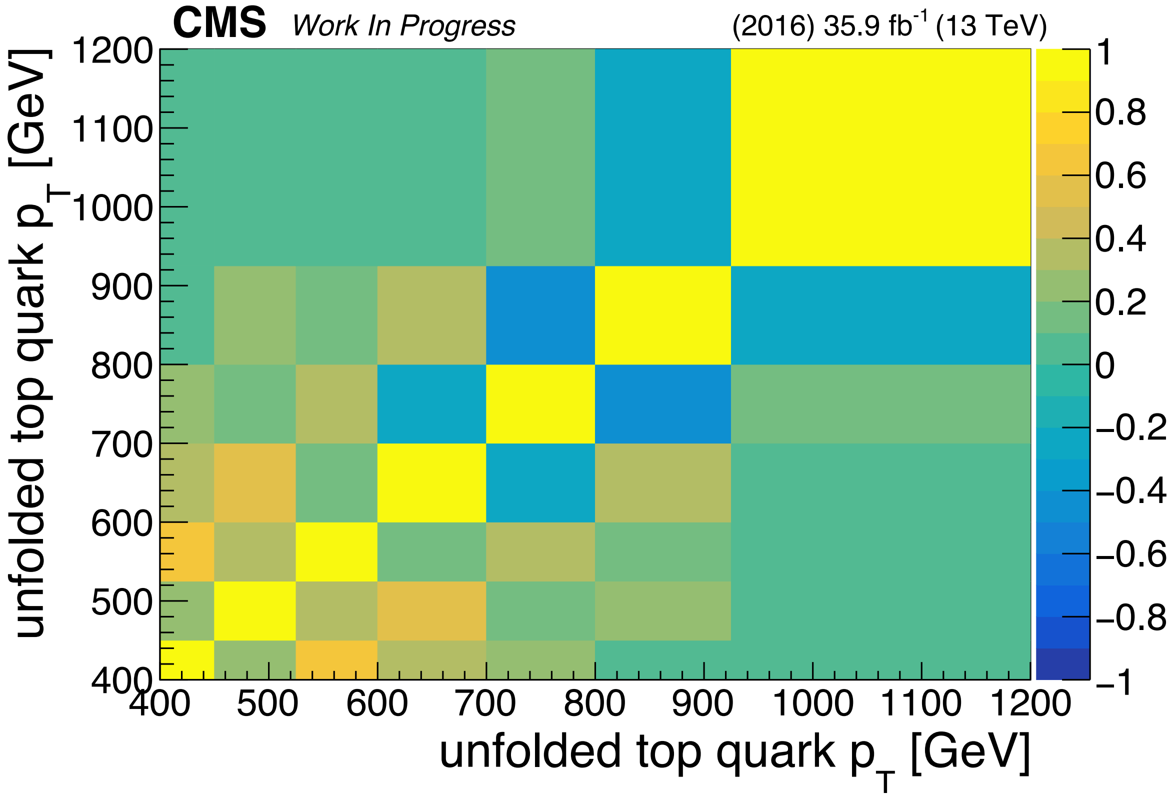
Particle-level normalized

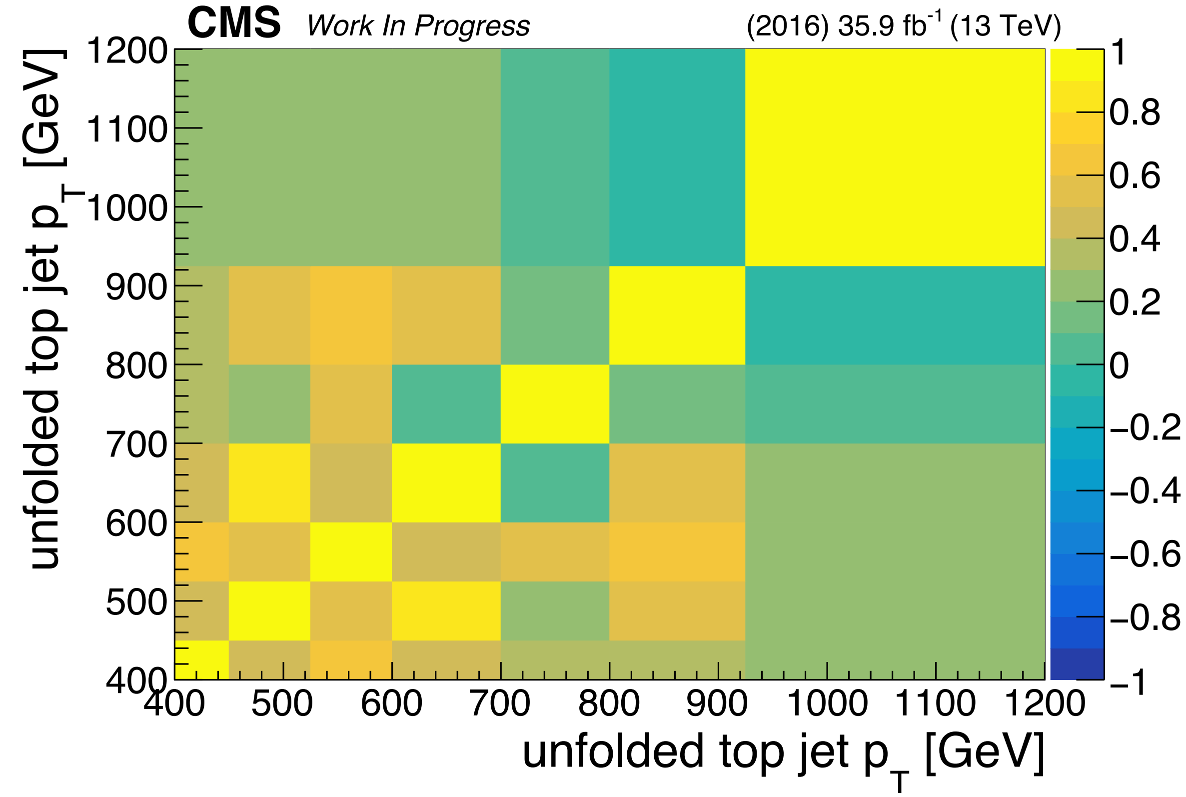


Parton shower dominant uncertainty at both parton and particle level
Stat uncertainty dominant only at very high |y|; systematics dominant at low |y|

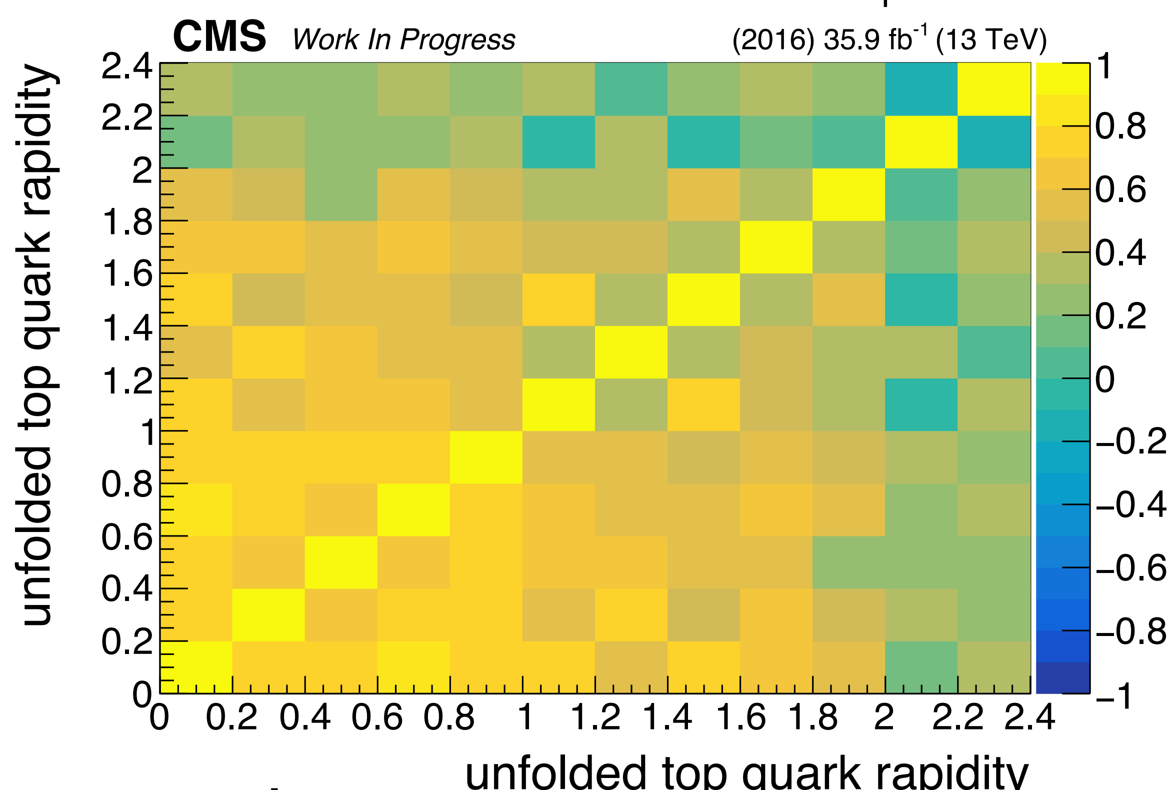
Correlation Matrices

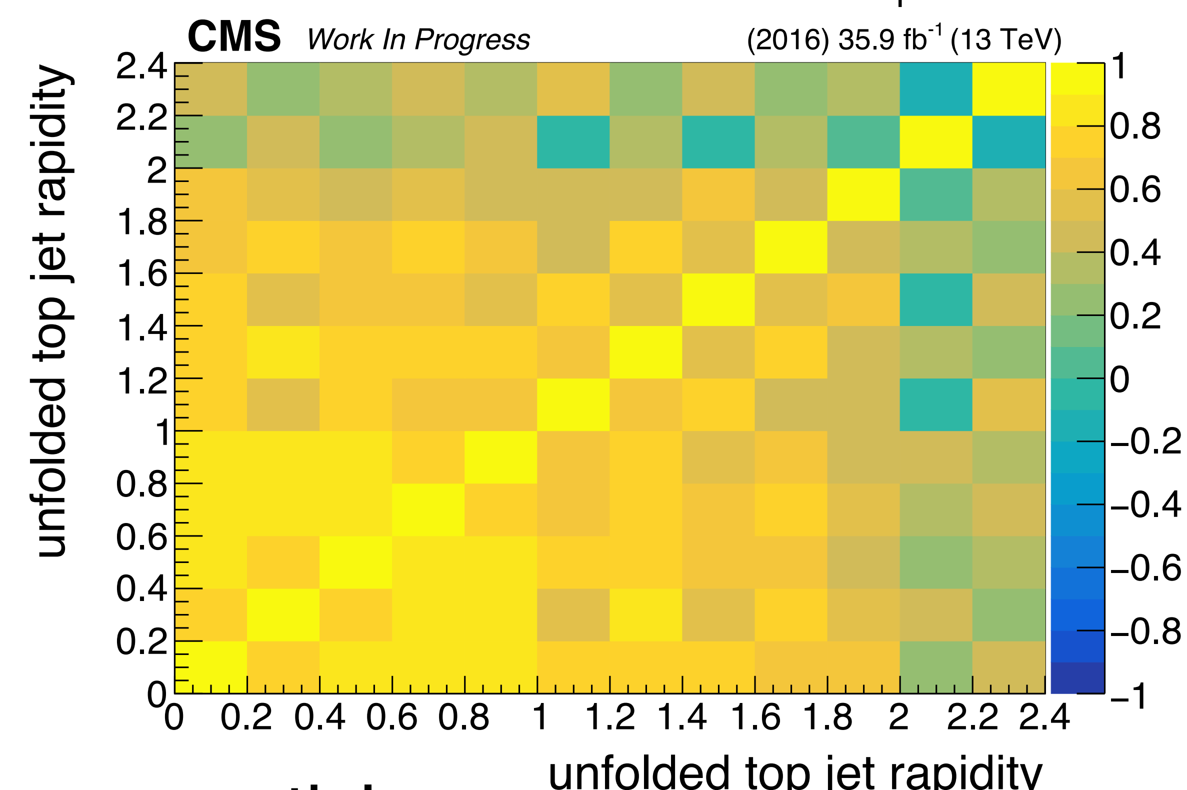
p_T





|y|





parton

particle

Summary

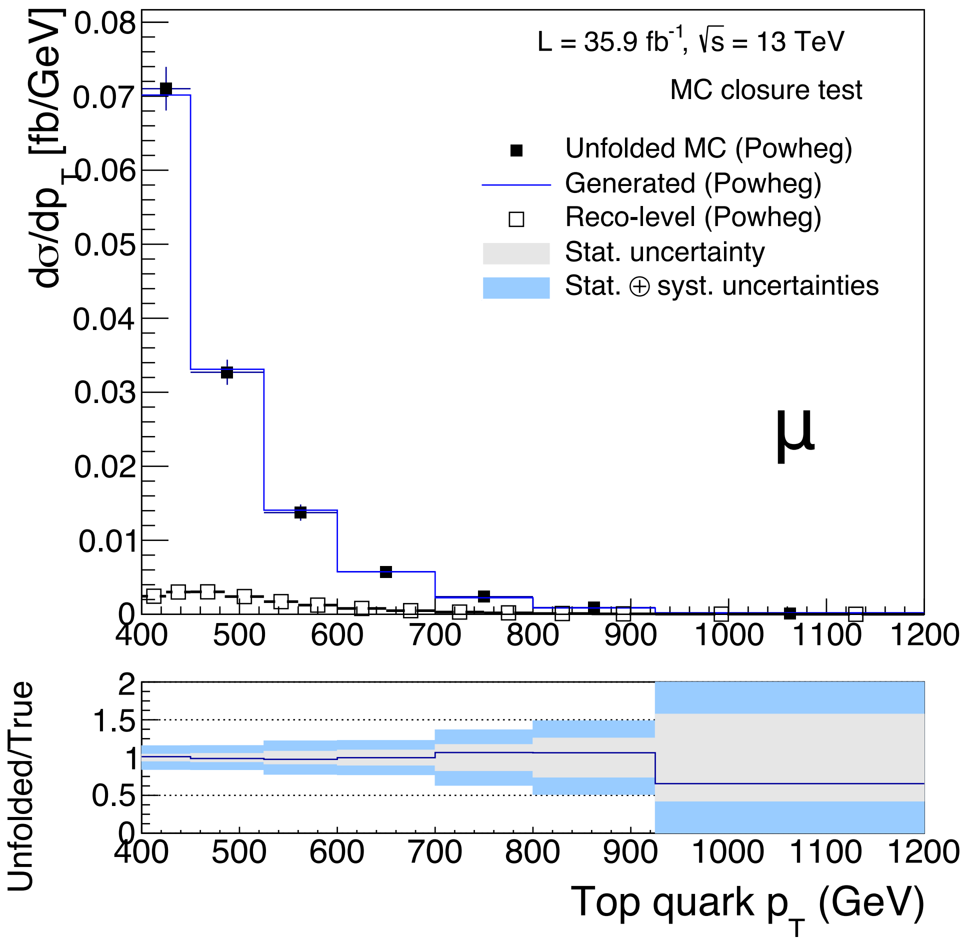
- Presented measurement of boosted differential $t\bar{t}$ cross section in l+jets channel
  - Particle and parton levels
  - p_T(top) and |y|(top), absolute and normalized
  - Compared to predictions from Powheg+Pythia8, Powheg+Herwig++, and aMC@NLO+Pythia8
- All models overpredict the absolute cross section (~20%)
- Differential distributions generally well described —> change from previous measurements
- We see the approval of TOP-18-013

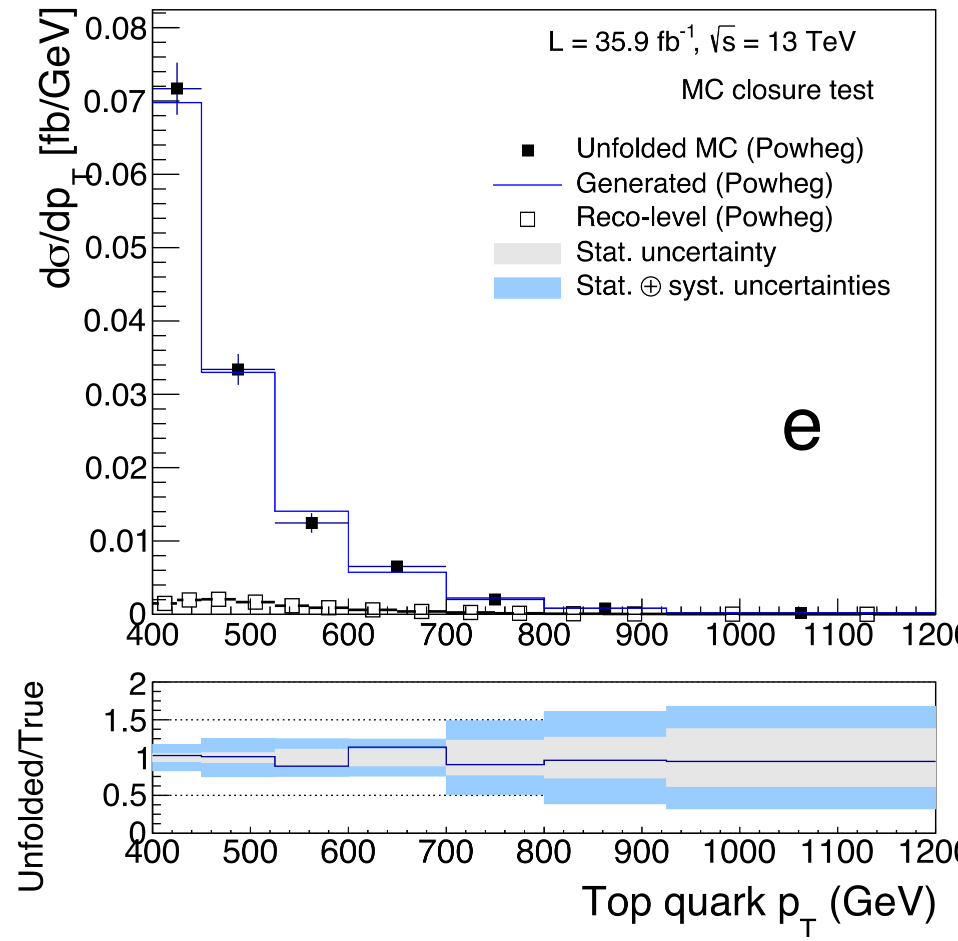
BACKUP

Closure Tests — Parton Level p_T

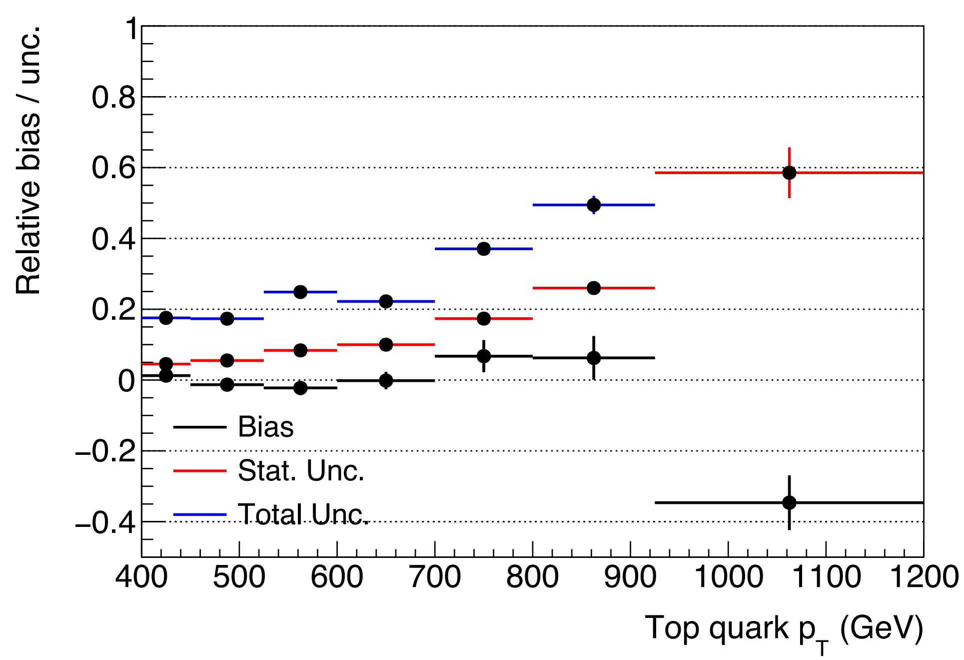
Unfold half sample with half sample

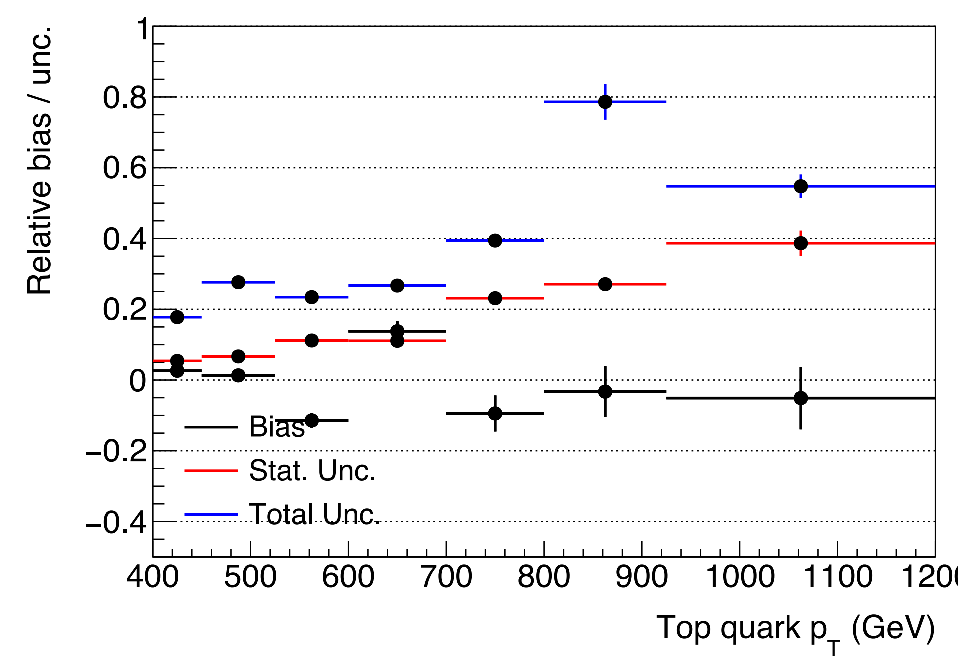
Include systematic uncertainties





Average bias, stat. unc., and total unc. for 1000 toys

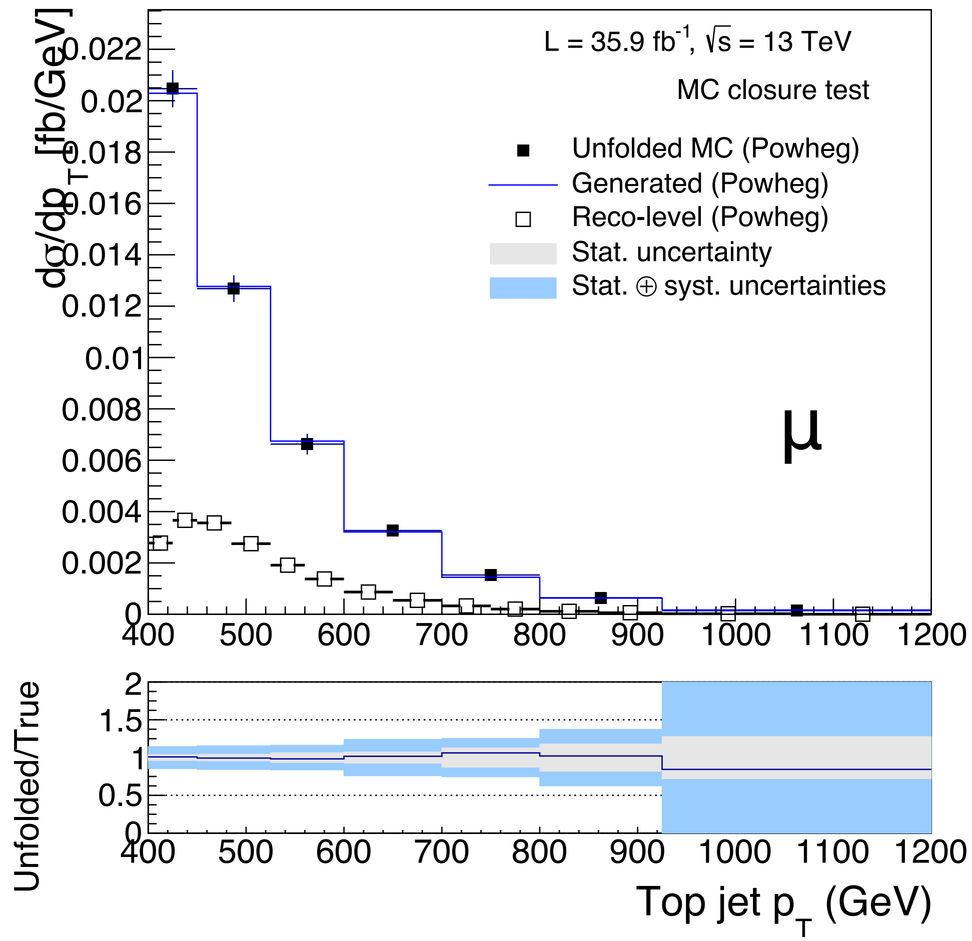


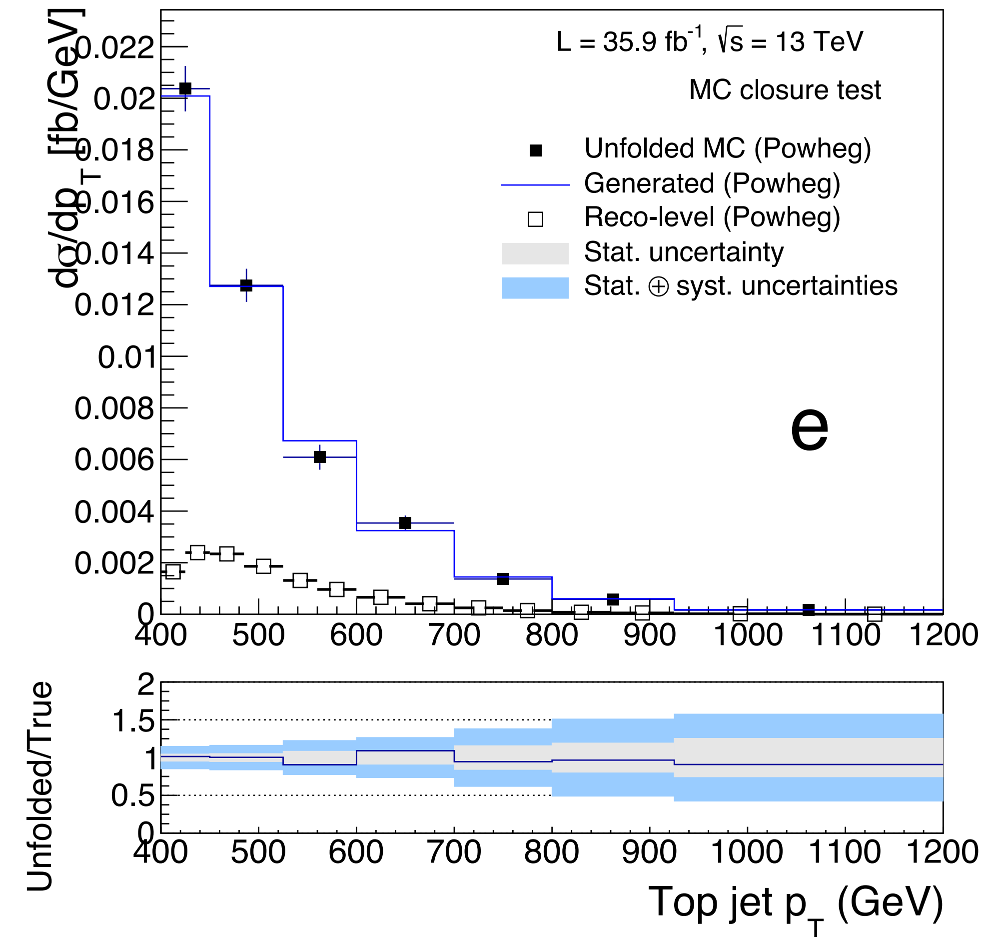


Closure Tests — Particle Level p_T

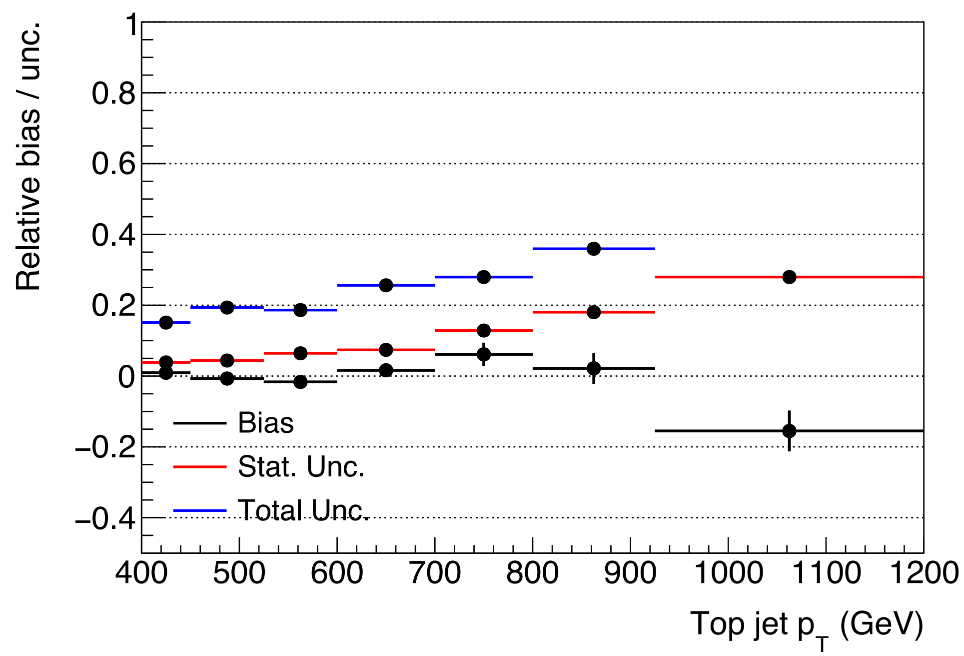
Unfold half sample with half sample

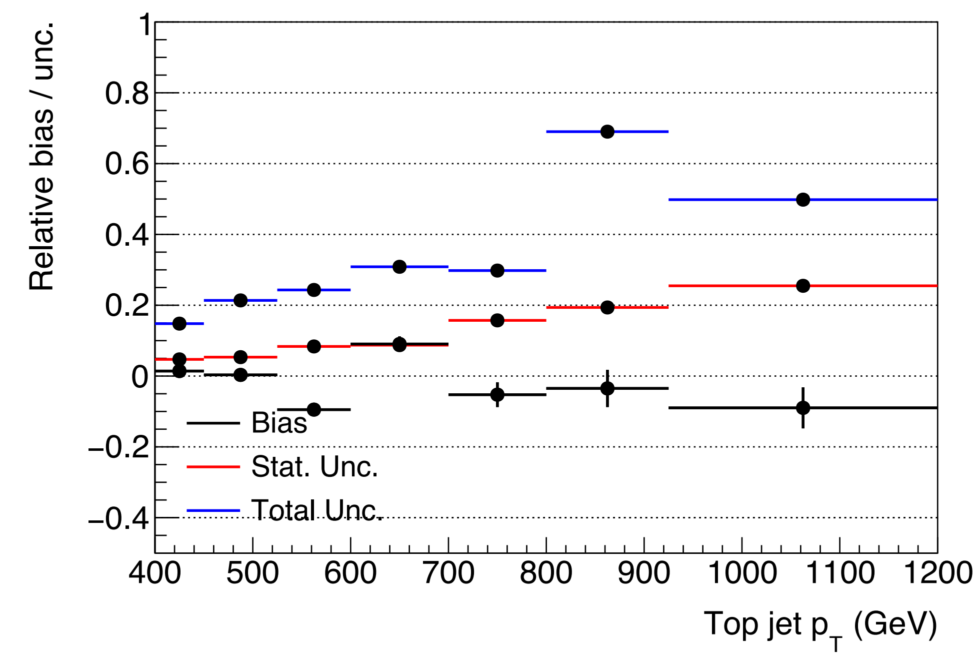
Include systematic uncertainties





Average bias, stat. unc., and total unc. for 1000 toys

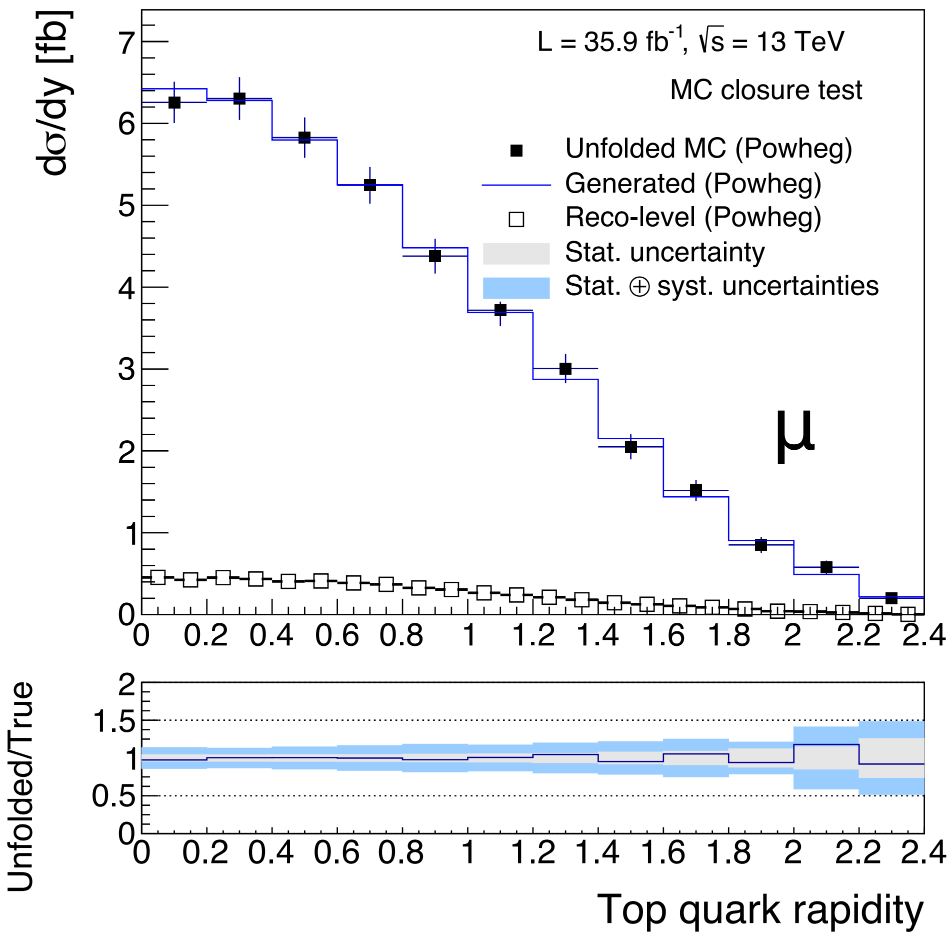


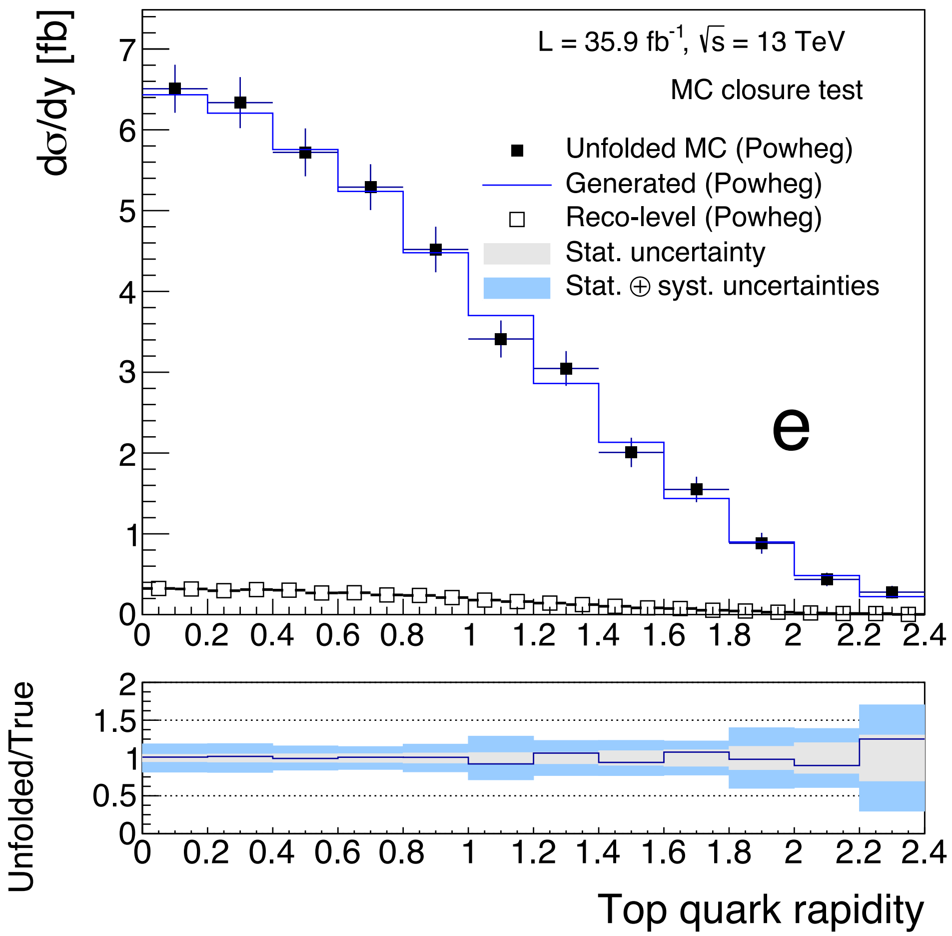


Closure Tests — Parton Level |y|

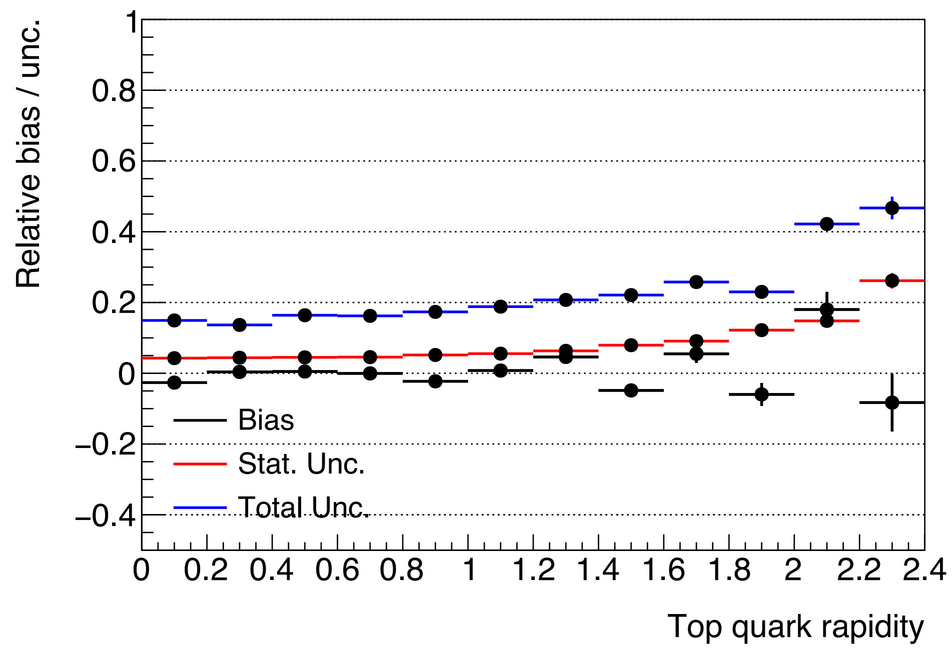
Unfold half sample with half sample

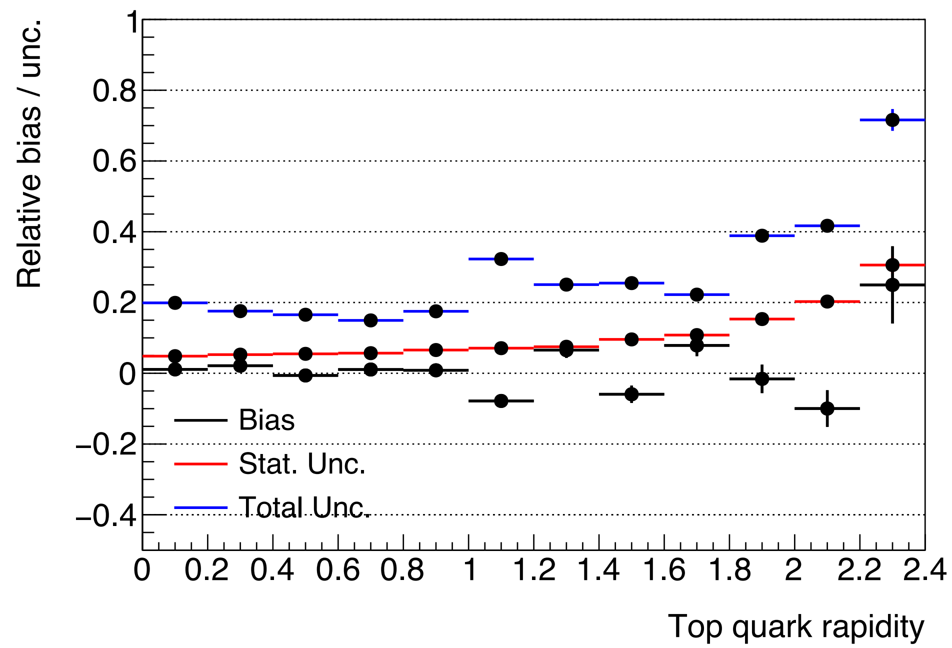
Include systematic uncertainties





Average bias, stat. unc., and total unc. for 1000 toys

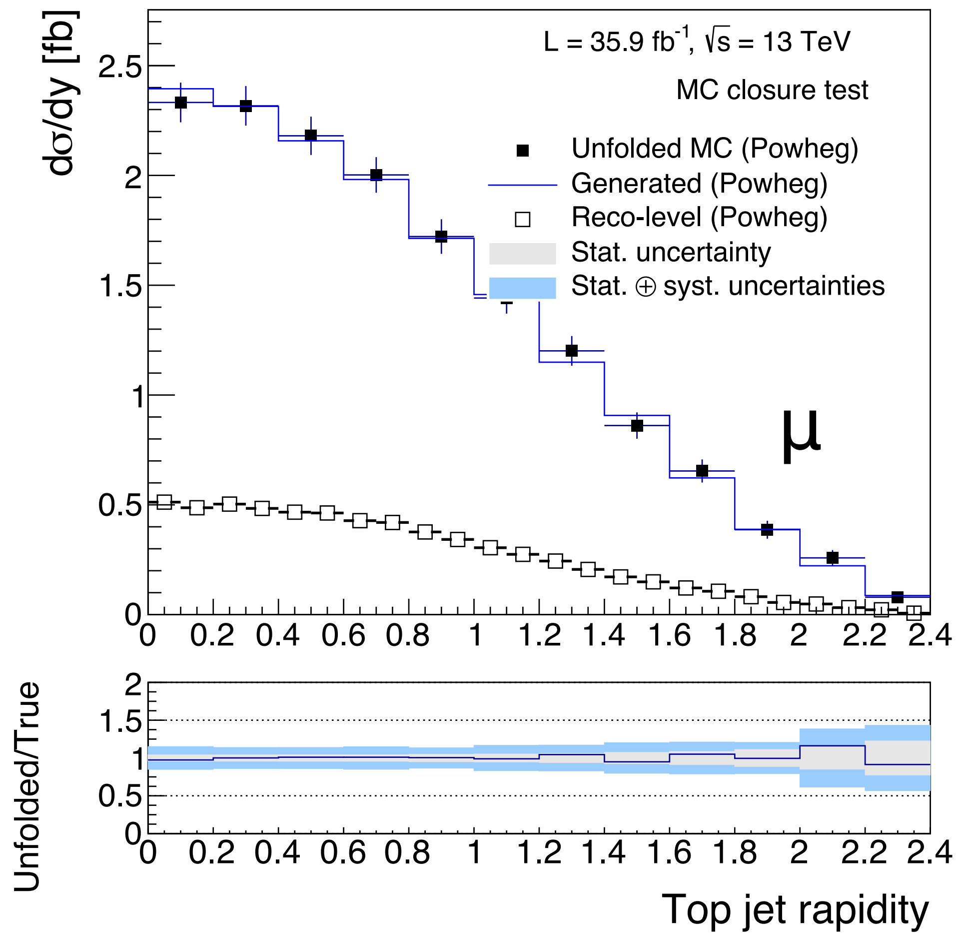


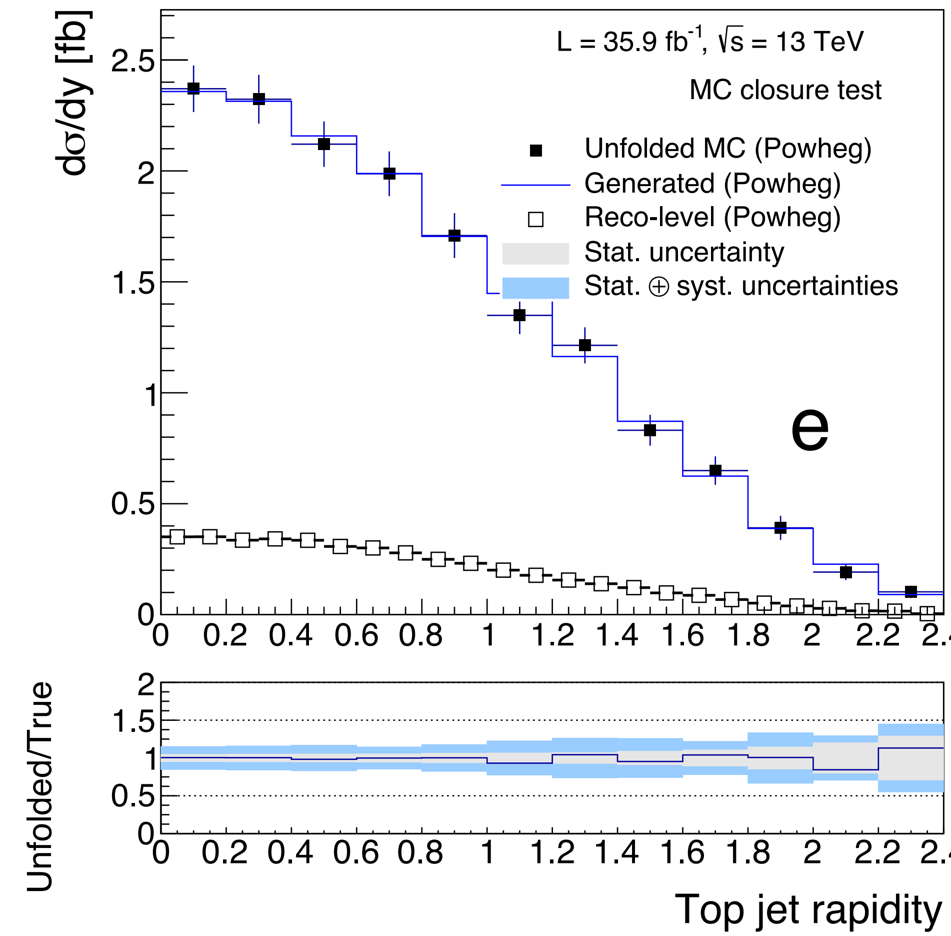


Closure Tests — Particle Level |y|

Unfold half sample with half sample

Include systematic uncertainties





Average bias, stat. unc., and total unc. for 1000 toys