Measurement of Differential $t\bar{t}$ Cross Section with Boosted Tops in e/μ+Jets Final State at 8 TeV Using CMS Data

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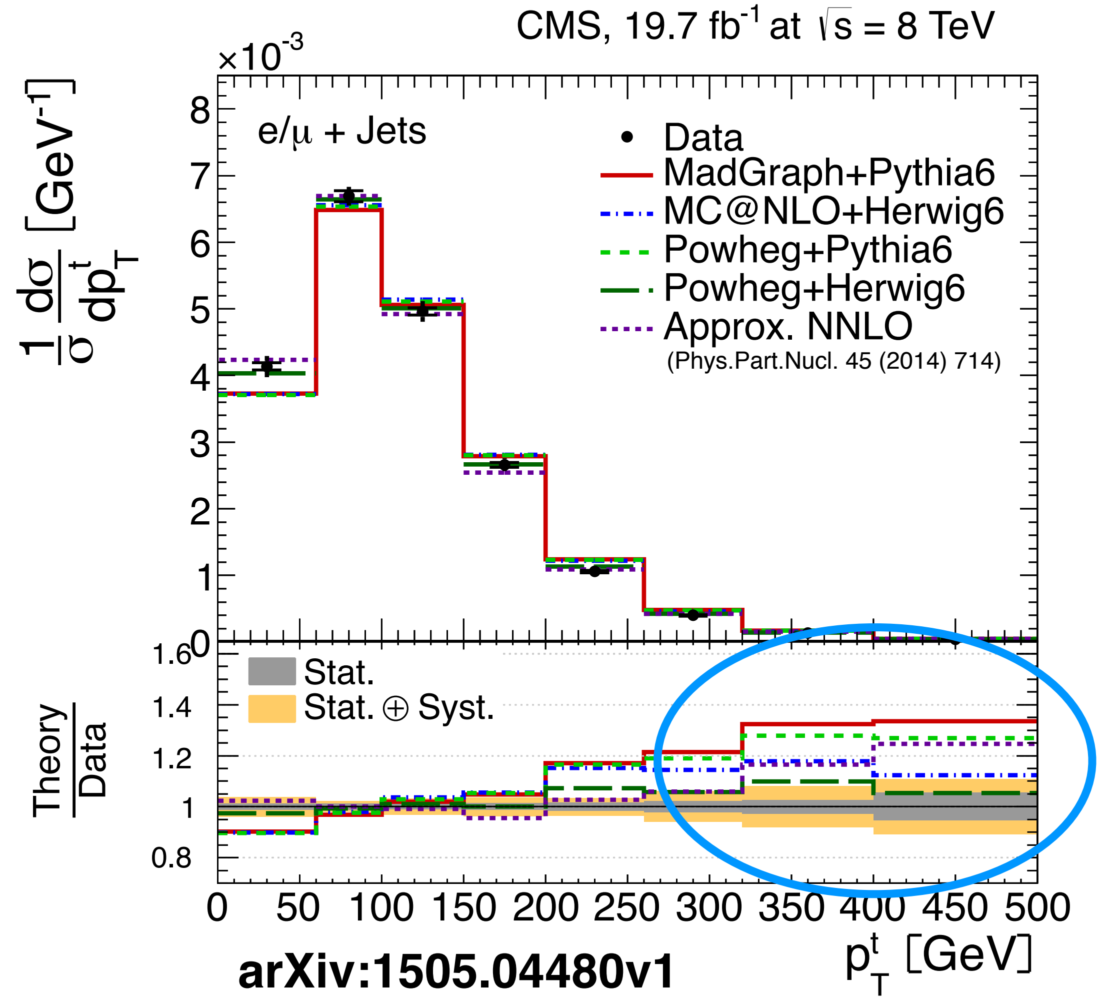
Introduction

- Goal: measure $t\bar{t}$ cross section at parton and particle level for p_T(top) > 400 GeV
  - Inclusive
  - Normalized differential
- Motivation
  - Extend measurement to higher energies
  - Important background for new physics searches
- First measurement at CMS

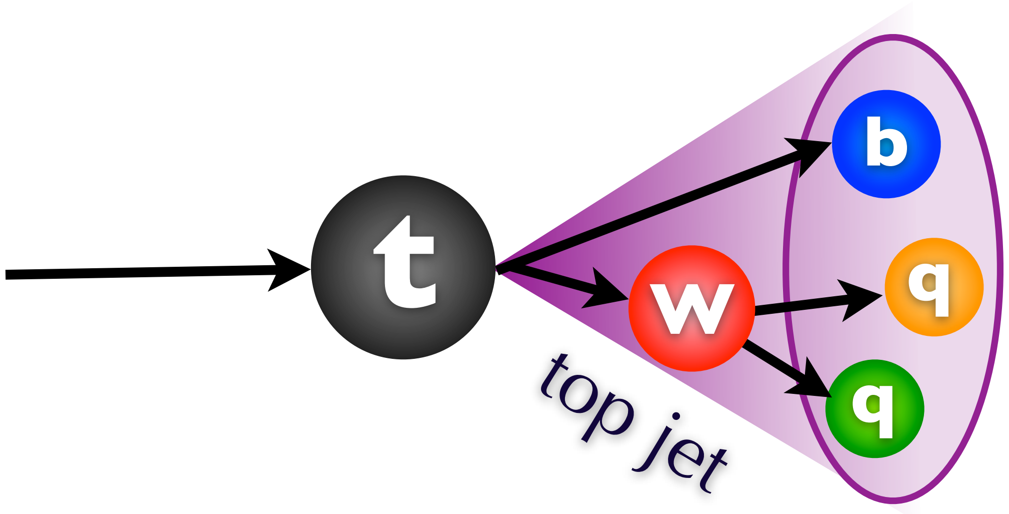


p_T(top) spectrum: MC tends to be harder than data

Documentation: CMS PAS TOP-14-012

Analysis Overview

- Measure $t\bar{t}$ cross section as a function of top p_T for p_T(top) > 400 GeV
  - Full 2012 8 TeV dataset (19.7 fb^{-1})
- e/μ+jets final state
  - Single electron or muon trigger
  - Hadronic top decay —> merged jet



Note: leptonic top decay products not merged

- Perform fit in several kinematic regions to determine top tagging efficiency, background rates, integrated cross section
- Correct background-subtracted data distribution to normalized differential cross section at particle and parton levels

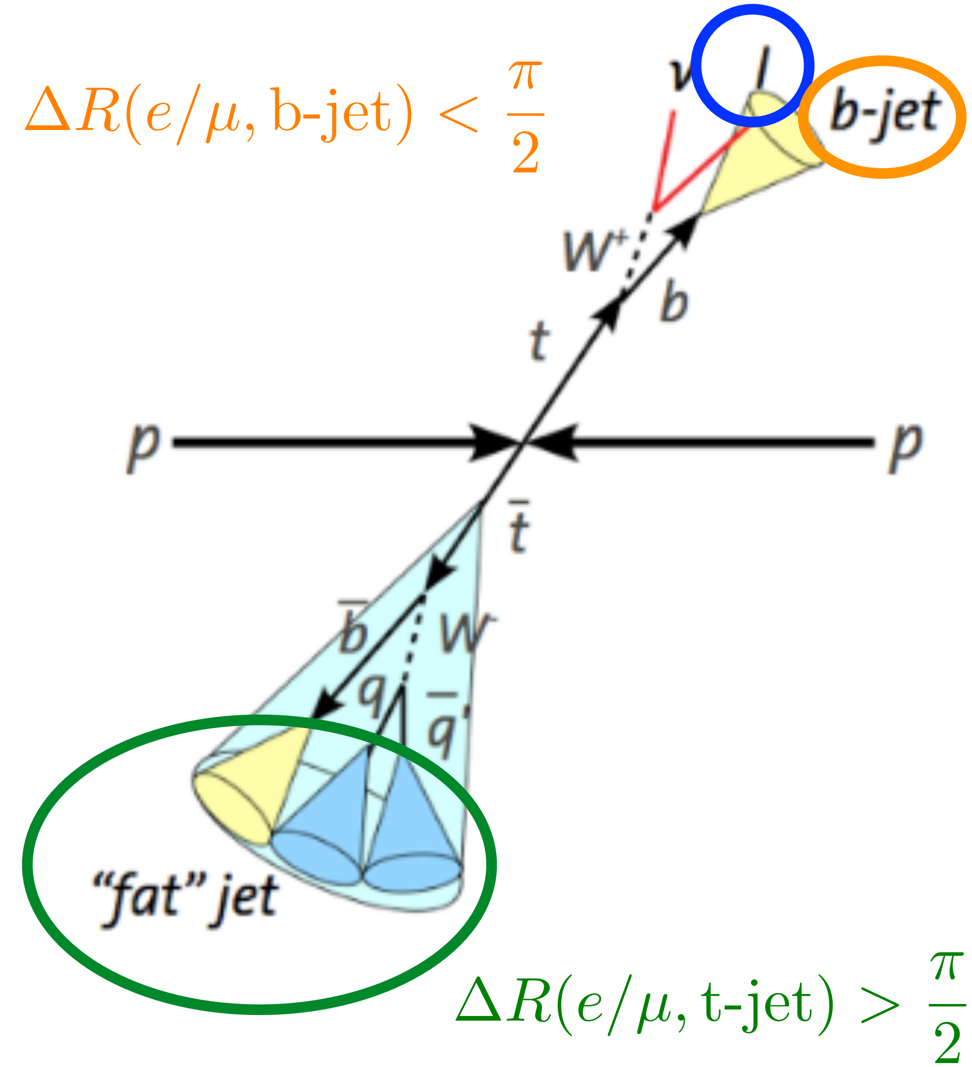
Selection

Muon (electron)

- p_T > 45 (35) GeV
- passes 2D cut
  - $\Delta R(e/\mu,\ \mathrm{j}) > 0.5$ OR $p_T^{\mathrm{rel}}(e/\mu,\ \mathrm{j}) > 25$ GeV
- electron passes triangular cut

$$|\Delta\phi(e \text{ or leading j}, E_T^{\mathrm{miss}}) - 1.5| < 1.5 * \frac{E_T^{\mathrm{miss}}}{75\ \mathrm{GeV}}$$

Reduce QCD



b-jet

- Anti-k_T jet, $\Delta R = 0.5$
- p_T > 30 GeV
- b-tagged*
  - secondary vertex mass > 0

t-jet

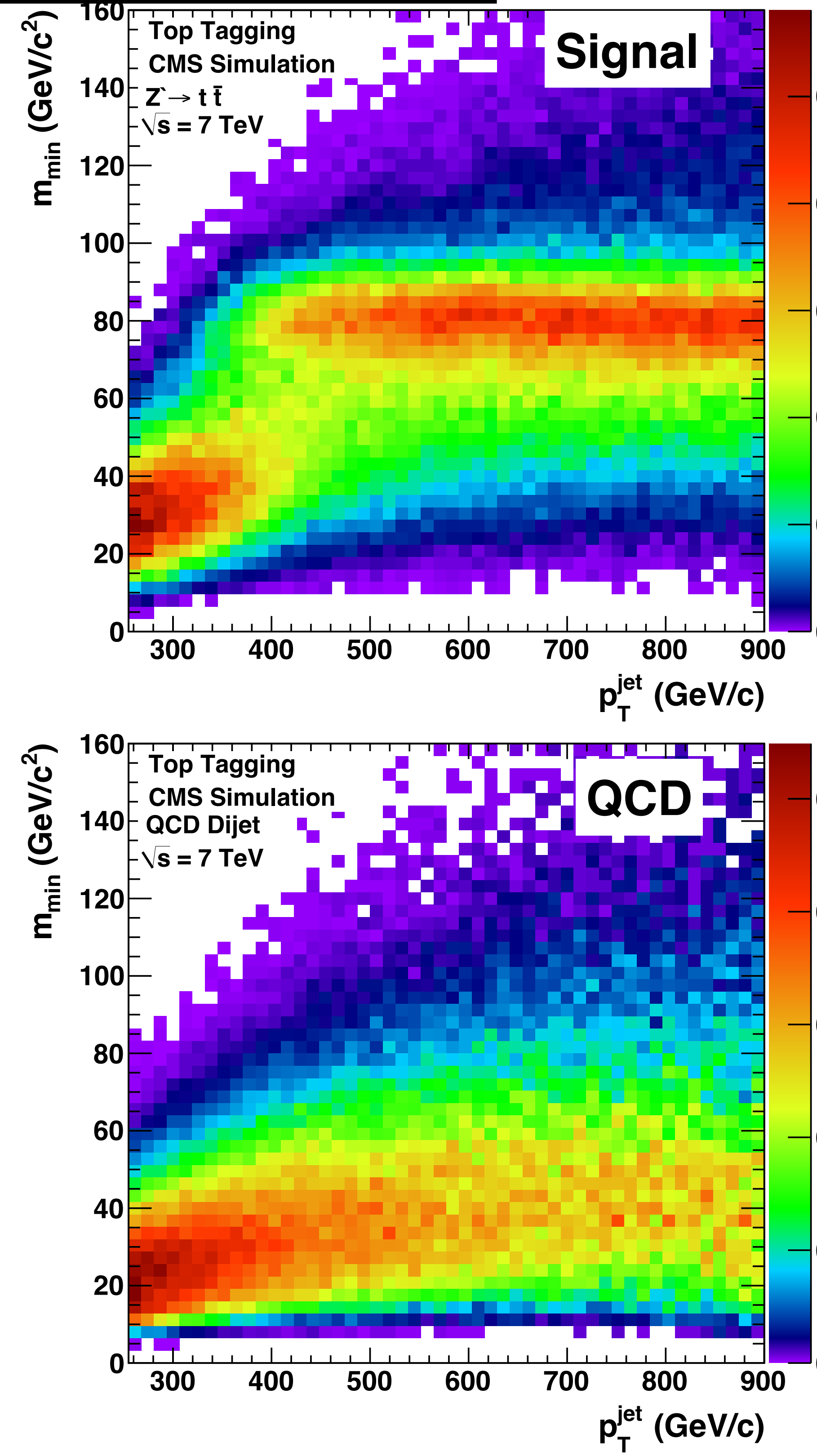
- Cambridge-Aachen jet, $\Delta R = 0.8$
- p_T > 400 GeV
- t-tagged* with CMS top tagger

*b(t)-jets without tagging requirement are 'b(t)-jet candidates'

CMS Top Tagger

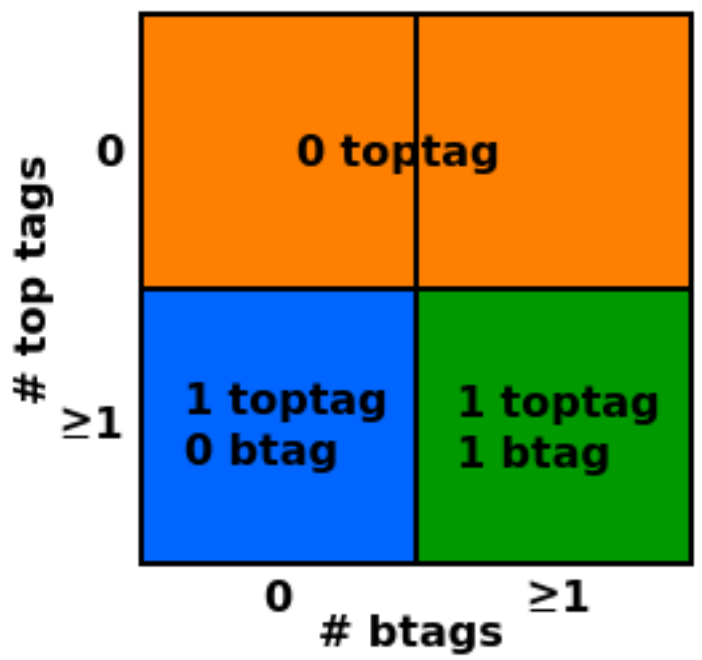
- Decay products of boosted top merge into single large-radius jet
  - Identify via jet substructure
- Need reasonable efficiency as low as p_T(top) = 400 GeV
- Use ‘CMS’ top tagger → 13-25% efficient, dependent on η
  - ref. CMS-PAS-JME-13-007
- Recluster jet to identify subjets
- Require
  - ≥ 3 subjets
  - Subjet pairwise minimum mass > 50 GeV
  - 140 GeV < jet mass < 250 GeV

CMS PAS JME-10-013



Kinematic Regions

- All events pass preselection:
  - Exactly one muon or electron
  - ≥ 1 b-jet candidate
  - ≥ 1 t-jet candidate → Reminder: $p_T > 400$ GeV

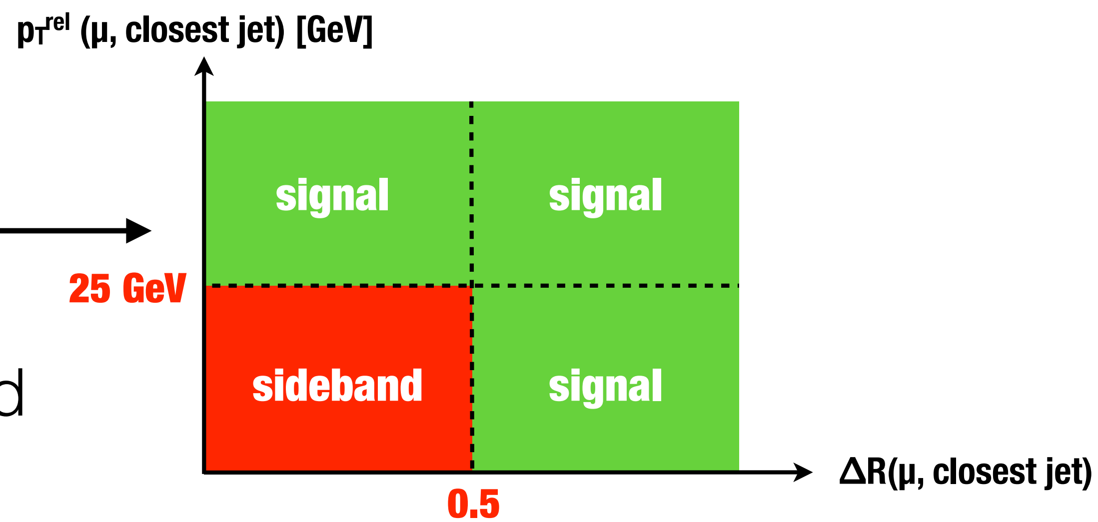


- Events divided into three exclusive kinematic regions:
  - 0 t-tag, ≥0 b-tag
  - 1 t-tag 0 b-tag
  - 1 t-tag 1 b-tag

↕ Background dominated (top) → Signal dominated (bottom)

Modeling

- Backgrounds: non-signal $t\bar{t}$, single top, W+Jets, QCD
- Determine rates using simultaneous fit in three kinematic regions → Fit simultaneously in μ/e channels; cross-check with separate fits
  - 0 t-tag, 1 t-tag 0 b-tag: fit lepton |η|
  - 1 t-tag 1 b-tag: fit secondary vertex mass of b-tagged jet
  - $t\bar{t}$, single top, W+Jets templates from MC → $t\bar{t}$ MC generated with POWHEG using CT10 PDF
  - QCD template from QCD-dominated data sideband (invert 2D cut on lepton) →
  - Also extract top tagging efficiency, integrated cross section

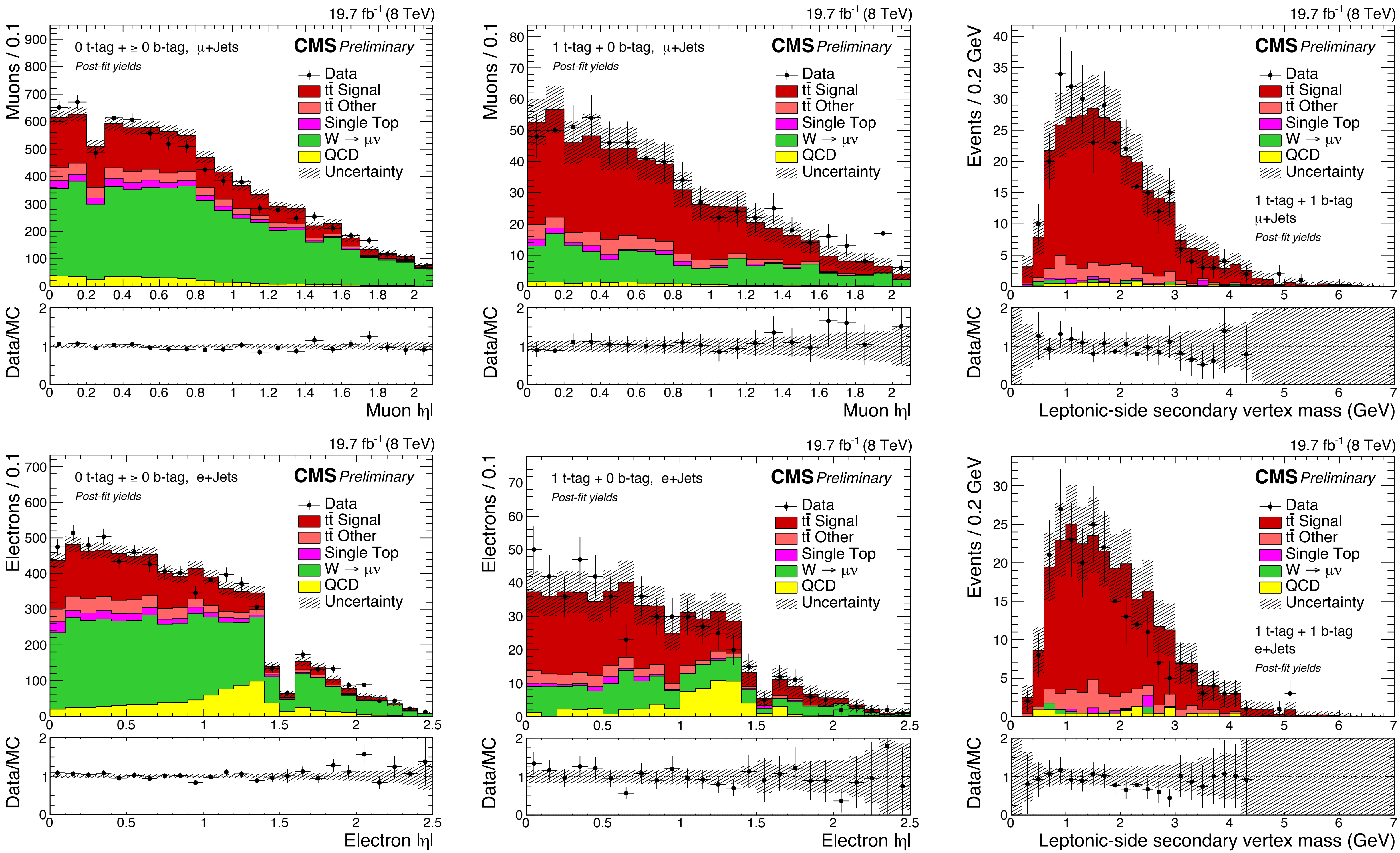


Fit Distributions

Reminder: these are kinematic distributions used in simultaneous fit

μ+jets

e+jets



0 t-tag | 1 t-tag 0 b-tag | 1 t-tag 1 b-tag

Systematic Uncertainties

Experimental uncertainties: nuisance parameters in fit

• Top tagging efficiency ✻	5%
• Background rates	
• Single top	45%
• W+Jets	7%
• QCD	15%(45%) ✻
• Jet Energy Scale ✻	1-2%
• Jet Energy Resolution ✻	4-7%
	Posterior fit uncertainties

Constrained values from fit used in normalized differential cross section

Theoretical uncertainties

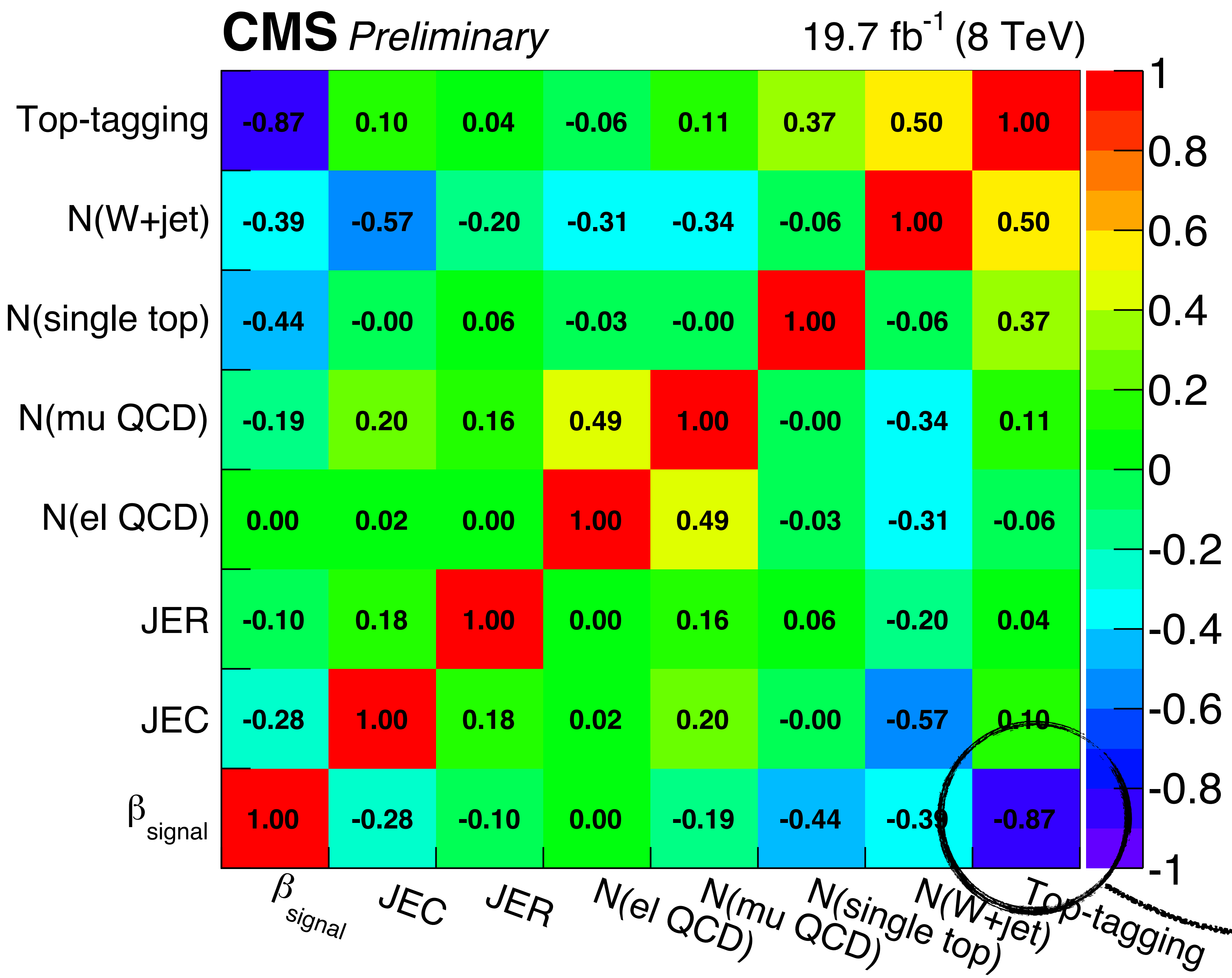
- PDF, Q^2
- Calculate separate cross sections, then compose envelope

✻ e(μ)

✻ shape uncertainty

✻ 17% additional uncertainty on efficiency for events with p_T(top) > 600 GeV

Nuisance Parameter Correlations



Cross section directly depends on top-tagging efficiency

Event Counts

CMS Preliminary

Sample	Number of events (μ+jets channel)		
	0 t tag	1 t tag, 0 b tag	1 t tag, 1 b tag
$t\bar{t}$(signal)	1923 ± 144	359 ± 27	271 ± 20
$t\bar{t}$(non-semilep)	478 ± 36	44.7 ± 3.4	29.7 ± 2.2
Single top	294 ± 135	14.4 ± 6.6	4.1 ± 1.9
W+jets	4786 ± 327	154 ± 11	3.9 ± 0.3
QCD	358 ± 169	13.4 ± 6.3	7.6 ± 3.6
Total	7838	586	317
Data	7712	622	306

CMS Preliminary

Sample	Number of events (e+jets channel)		
	0 t tag	1 t tag, 0 b tag	1 t tag, 1 b tag
$t\bar{t}$(signal)	1562 ± 117	289 ± 22	226 ± 17
$t\bar{t}$(non-semilep)	458 ± 34	40.0 ± 3.0	30.1 ± 2.3
Single top	261 ± 120	11.6 ± 5.3	3.2 ± 1.5
W+jets	3667 ± 250	130 ± 8.9	2.7 ± 0.2
QCD	757 ± 128	68 ± 11	10.5 ± 1.8
Total	6704	537	273
Data	6833	538	242

~25% signal   55-60% signal   ~85% signal

Signal normalization: gives inclusive cross section

Subtract normalized backgrounds from data to get measured

Uncertainties from fit: include all experimental uncertainties, no theoretical

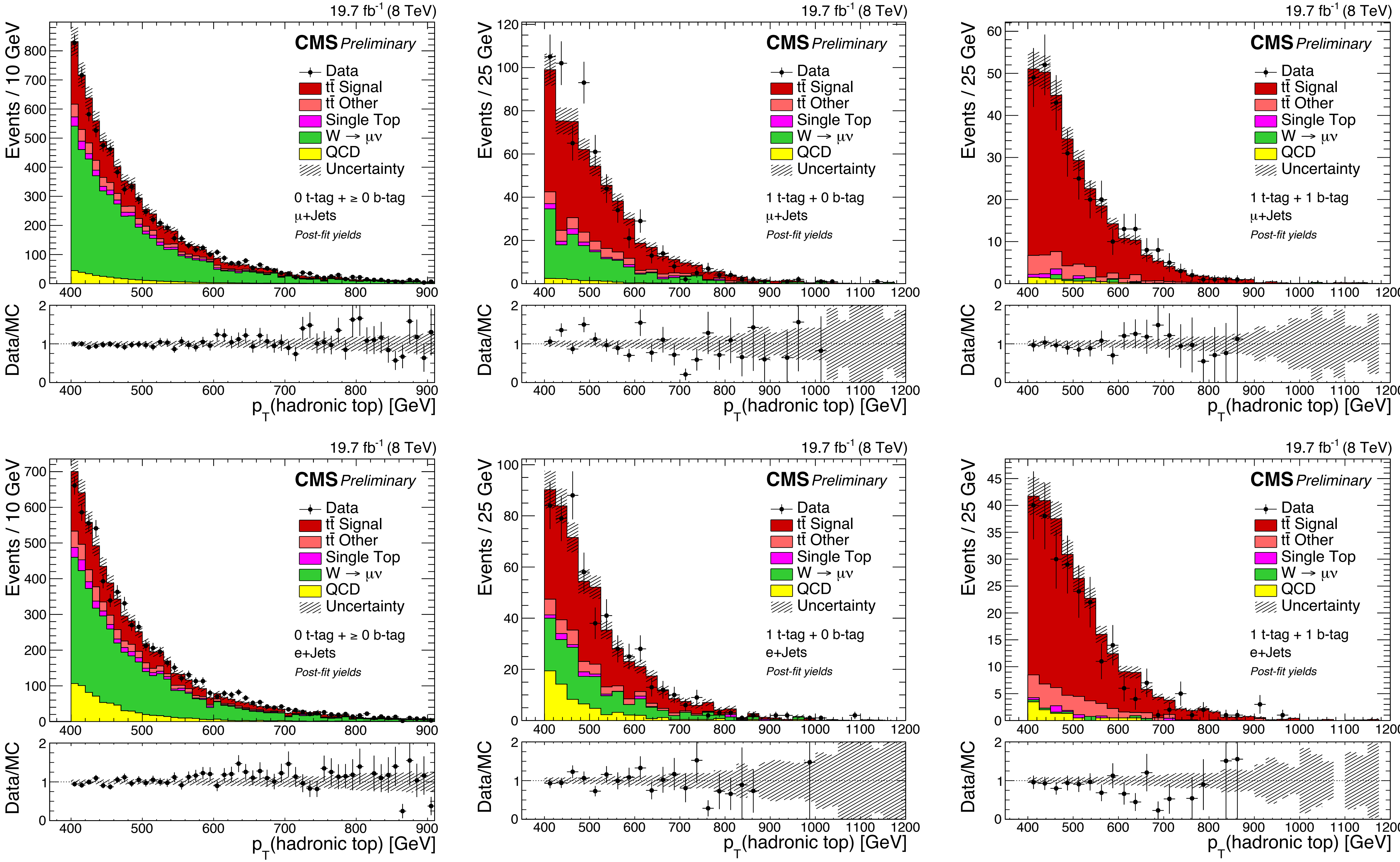
Use 1 t-tag 0 b-tag and 1 t-tag 1 b-tag regions in unfolding — signal dominated

p_T(top) Distributions

Note: $t\bar{t}$ (in red) from MC; **not** distribution used for differential cross section

μ+jets

e+jets



0 t-tag | 1 t-tag 0 b-tag | 1 t-tag 1 b-tag

Particle and Parton Level

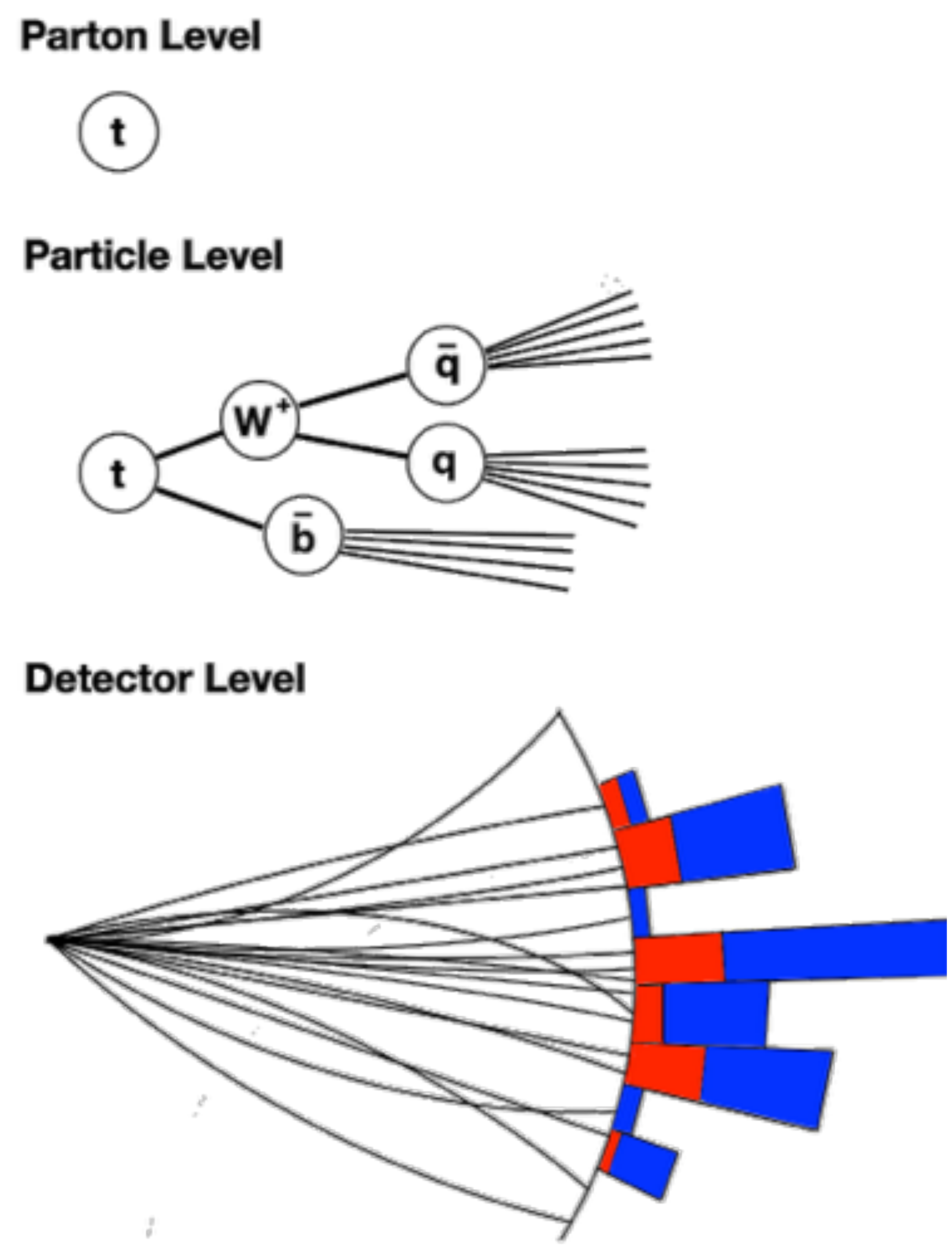
Measure cross sections at particle and parton level

- Particle level

Selection:
- Matches detector-level selection
- Reduces reliance on generator

  - ==1 gen-level e or μ, p_T > 45 GeV
  - ≥1 gen-level b-jet
    - anti-k_T R=0.5 jet, p_T > 30 GeV, $0.1 < \Delta\mathrm{R}(e/\mu, j) < \frac{\pi}{2}$
  - ≥1 gen-level t-jet
    - C/A R=0.8 jet, p_T > 400 GeV, $\Delta\mathrm{R}(e/\mu, j) > \frac{\pi}{2}$

- Parton level
  - Underlying event, prior to hadronization



Inclusive Cross Section

CMS Preliminary

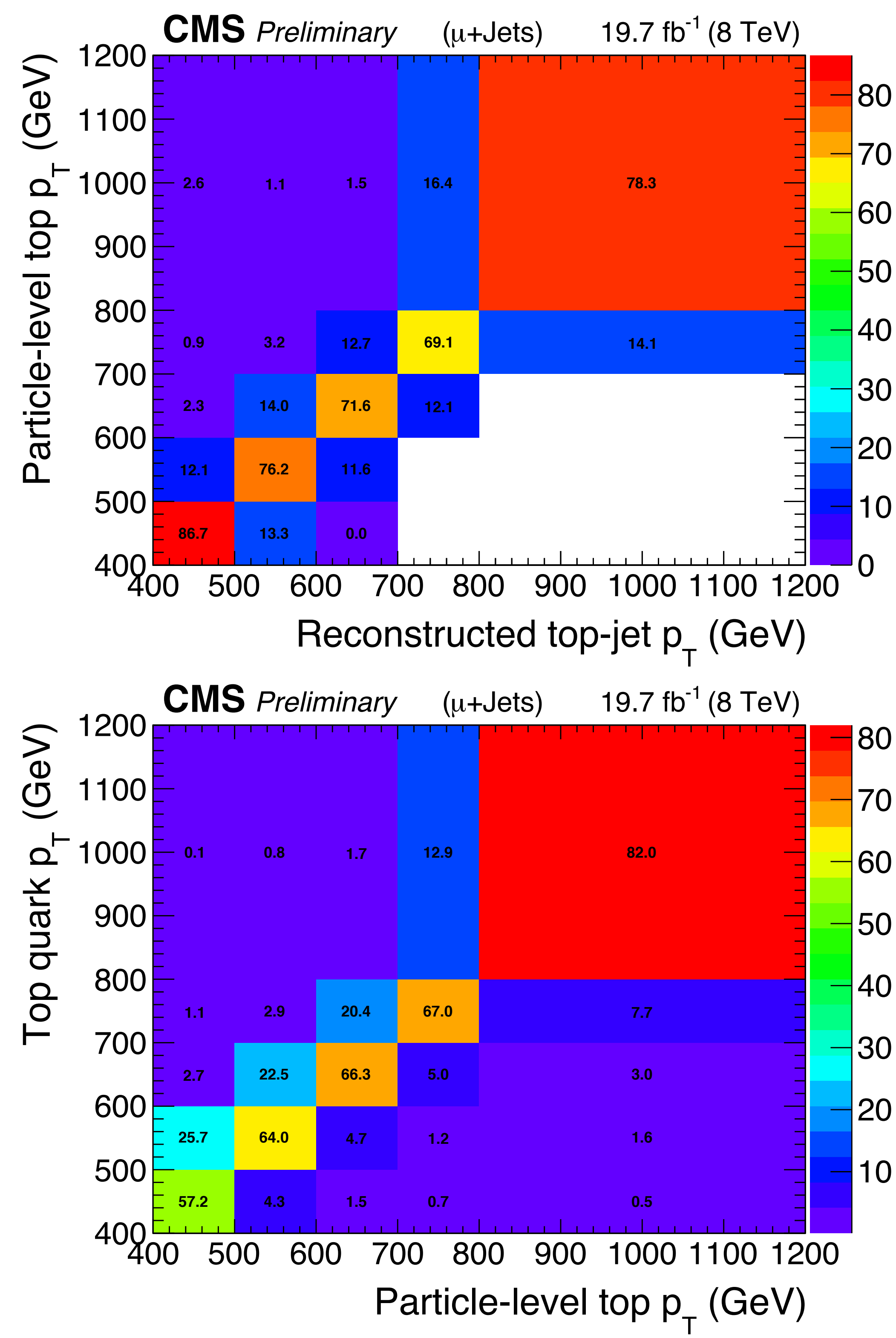
$$\text{particle-level}: \sigma_{t\bar{t}} = 1.28 \pm 0.09\ (\text{stat}+\text{syst}) \pm 0.10\ (\text{PDF}) \pm 0.09\ (\text{Q}^2) \pm 0.03\ (\text{lumi})\ \text{pb}$$
$$\text{parton-level}: \sigma_{t\bar{t}} = 1.44 \pm 0.10\ (\text{stat}+\text{syst}) \pm 0.13\ (\text{PDF}) \pm 0.15\ (\text{Q}^2) \pm 0.04\ (\text{lumi})\ \text{pb}$$

Powheg MC predicts σ = 1.49 pb at particle level,1.67 pb at parton level

- Uncertainties:
  - Stat + sys: uncertainty from fit, includes experimental uncertainties
  - PDF / Q^2: measure integrated cross section when varying CT10 PDF / POWHEG Q^2 within uncertainties; take envelope as uncertainty
  - Luminosity: 2.6% uncertainty

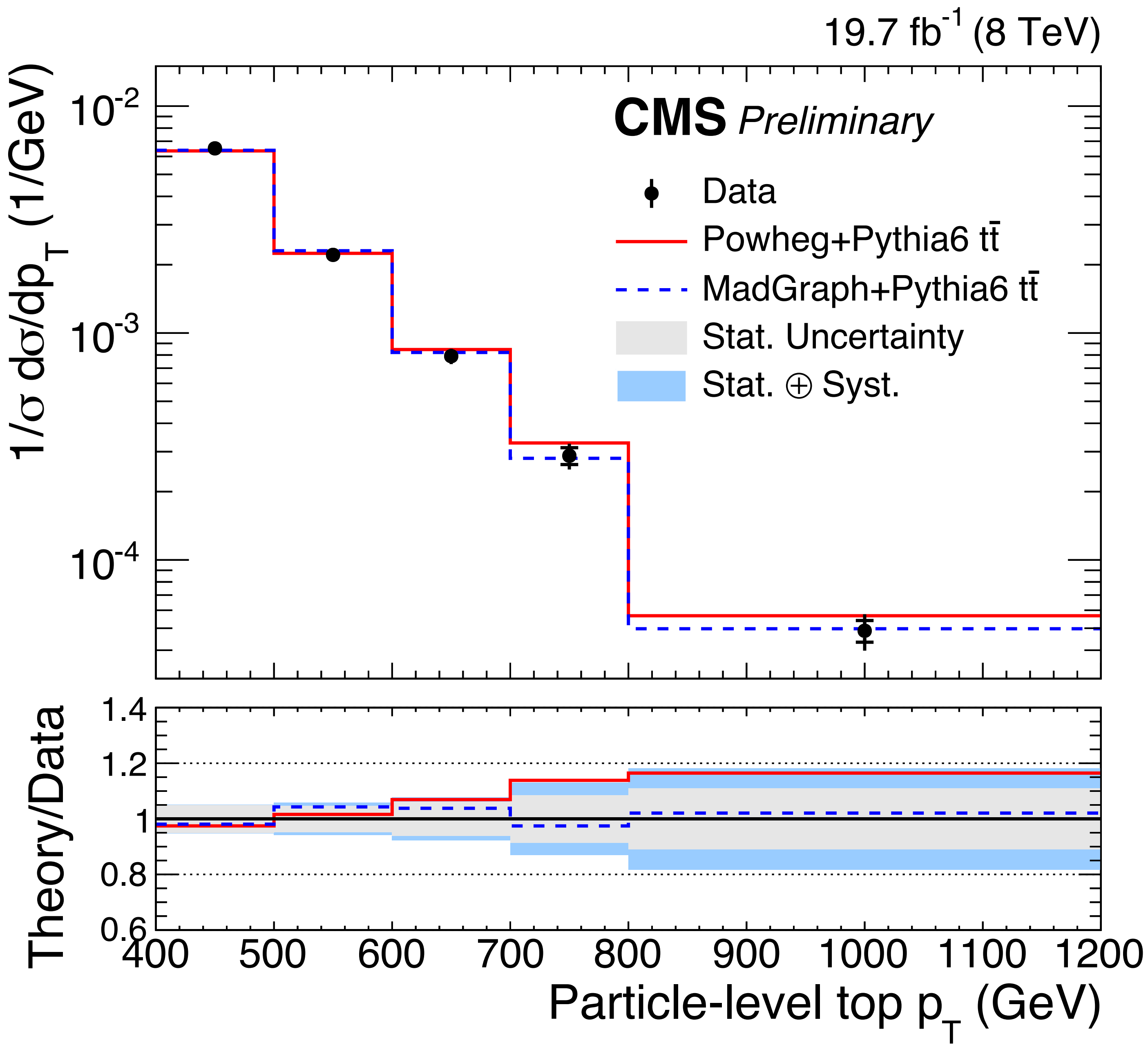
Differential Cross Section

- Measure normalized differential cross section
- Start with measured $t\bar{t}$ p_T(top) distribution
  - Background-subtracted data, using background normalizations from fit
- Unfold to correct for detector resolution, acceptance, selection efficiency
  - 2 steps: detector-level to particle-level, particle-level to parton-level
  - Singular Value Decomposition method
  - Use both 1 t-tag 0 b-tag and 1 t-tag 1 b-tag regions
- Unfold e/μ channels separately, then combine



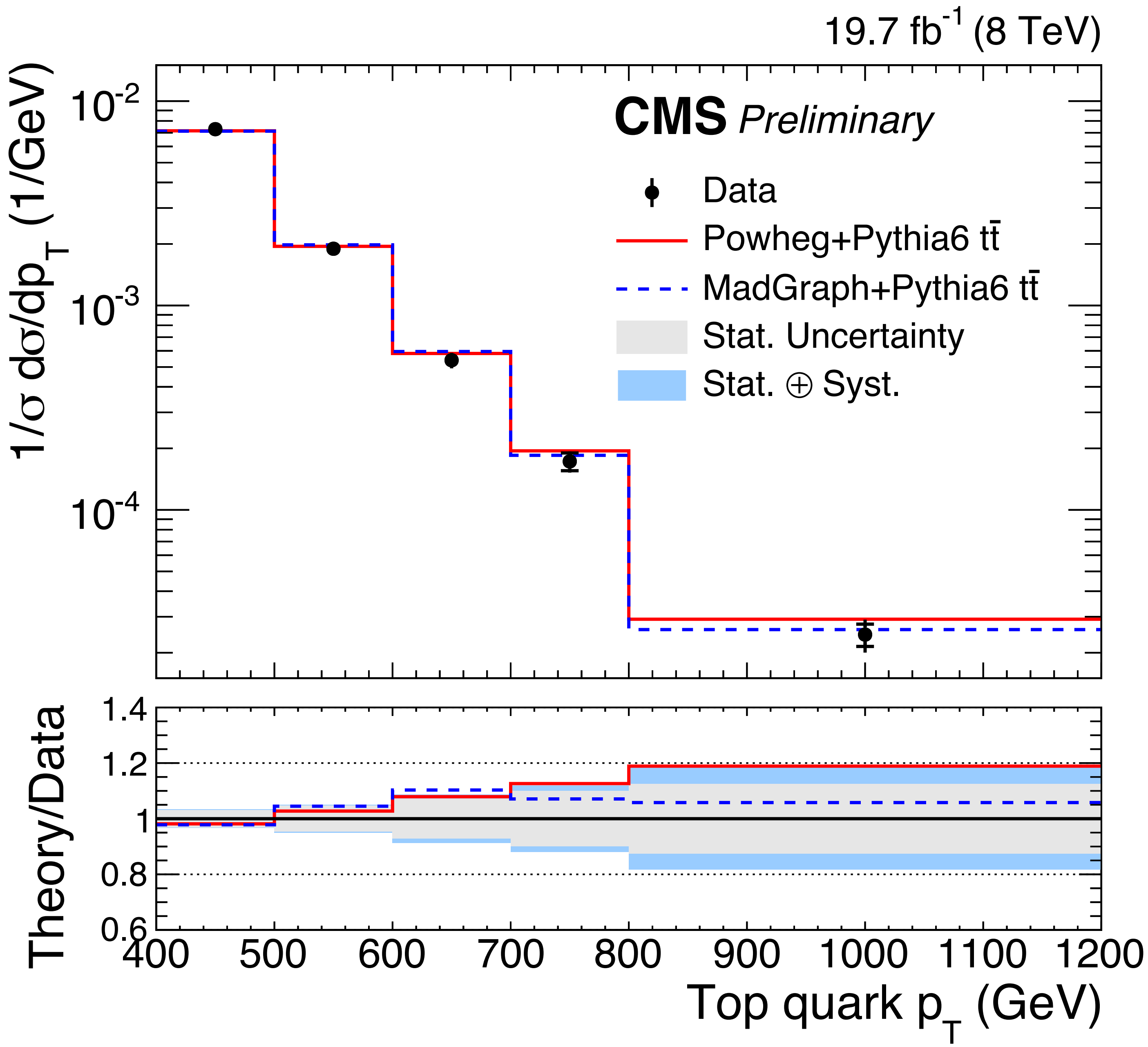
Response matrices for μ channel, normalized

Differential Cross Section at Particle Level



- POWHEG predicts harder distribution than measured
  - Consistent with trend at lower p_T
- 1-15% systematic uncertainty
  - Dominant contribution: Q^2
- 5-12% statistical uncertainty

Differential Cross Section at Parton Level



- POWHEG, MadGraph predict harder distribution than measured
    - Consistent with trend at lower p_T
- 1-13% systematic uncertainty
    - Dominant contributions: Q^2, top-tagging efficiency
- 5-12% statistical uncertainty

Conclusions

- Measured boosted $t\bar{t}$ cross section with respect to p_T(top)
  - First measurement at CMS
- POWHEG and MadGraph predict slightly harder p_T(top) distribution than data
  - Confirms trend from previous analyses
- Future plans: repeat analysis at 13 TeV
  - Greater statistics
  - Extend p_T reach of measurement

Backup

Trigger + MC Samples

- Trigger: non-isolated lepton
  - Single muon: $p_T^{\mu} > 40$ GeV
  - Electron+jets: $p_T^{e} > 30$ GeV + two jets with $p_T > 100, 25$ GeV
- MC samples

Sample	MC generator	PDF	Showering
$t\bar{t}$	POWHEG	CT10	PYTHIA6 tune Z2*
	MadGraph	CT10	PYTHIA6 tune Z2*
Single Top	POWHEG	CT10	PYTHIA6 tune Z2*
W+Jets	MadGraph	CTEQ6L1	PYTHIA6 tune Z2*

Used for cross-check

Jet Definitions

- Two standard clustering techniques used at CMS
- Regular jets: anti-kT
  - http://arxiv.org/abs/0802.1189
- Large-radius jets: Cambridge - Aachen
  - http://arxiv.org/abs/hep-ph/9907280 , http://arxiv.org/abs/hep-ph/9707323

Nuisance Parameter Uncertainties

Uncertainties on nuisance parameters prior to performing fit

Parameter	Constraint	Type
Top-tagging efficiency	$\pm 25\%$	Rate and shape
Jet energy scale	$\pm 1\sigma_{\text{jec}}$ ($\sim 1-4\%$)	Rate and shape
Jet energy resolution	$\pm 1\sigma_{\text{jer}}$ ($\sim 5-10\%$)	Rate and shape
QCD normalization	$\pm 100\%$	Rate only
W+jets normalization	$\pm 50\%$	Rate only
Single top normalization	$\pm 50\%$	Rate only
Non-semileptonic $t\bar{t}$ normalization	$\pm 50\%$	Rate only

JER/JEC: a priori uncertainties from CMS JME group (arXiv:1107.4277)