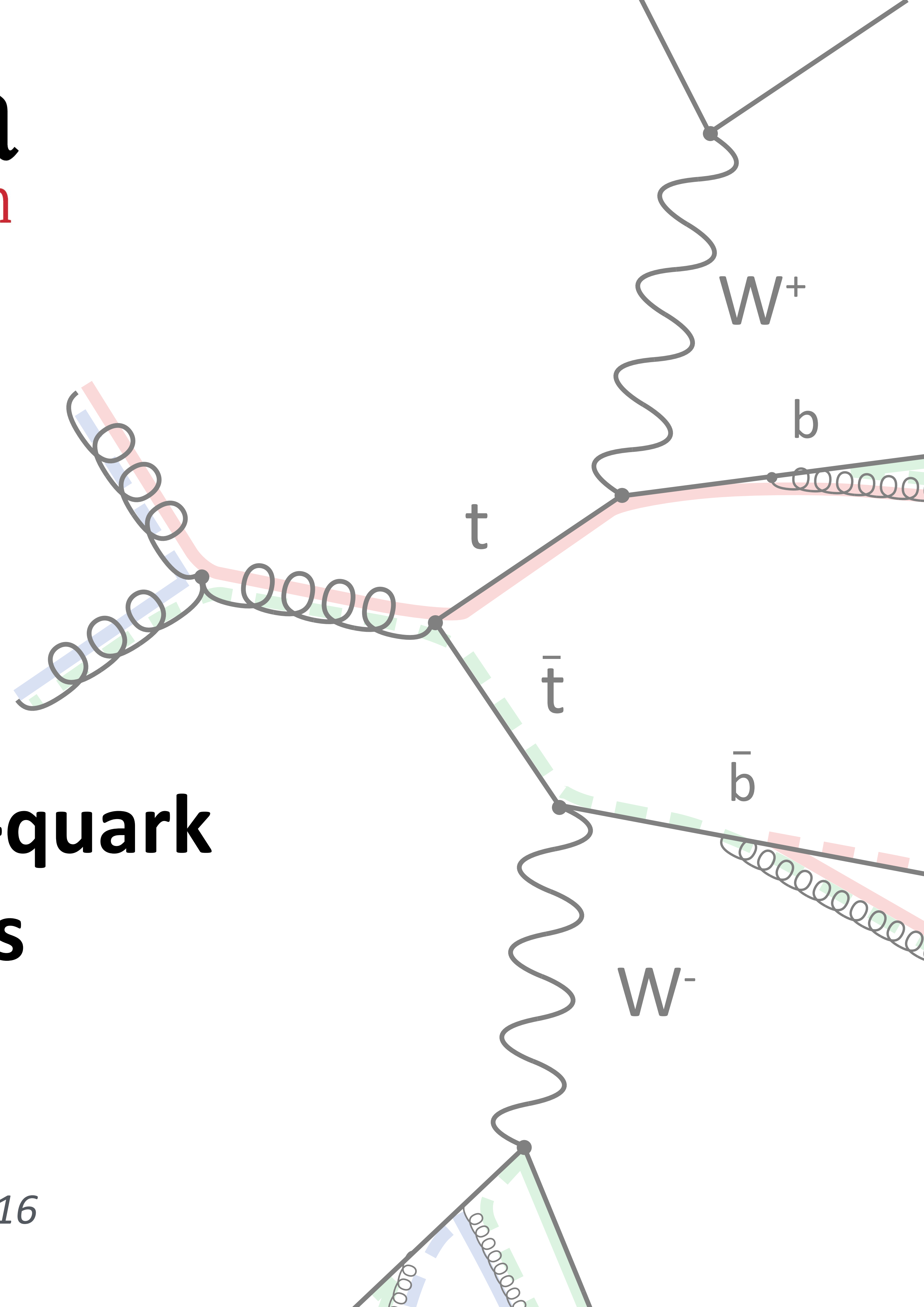
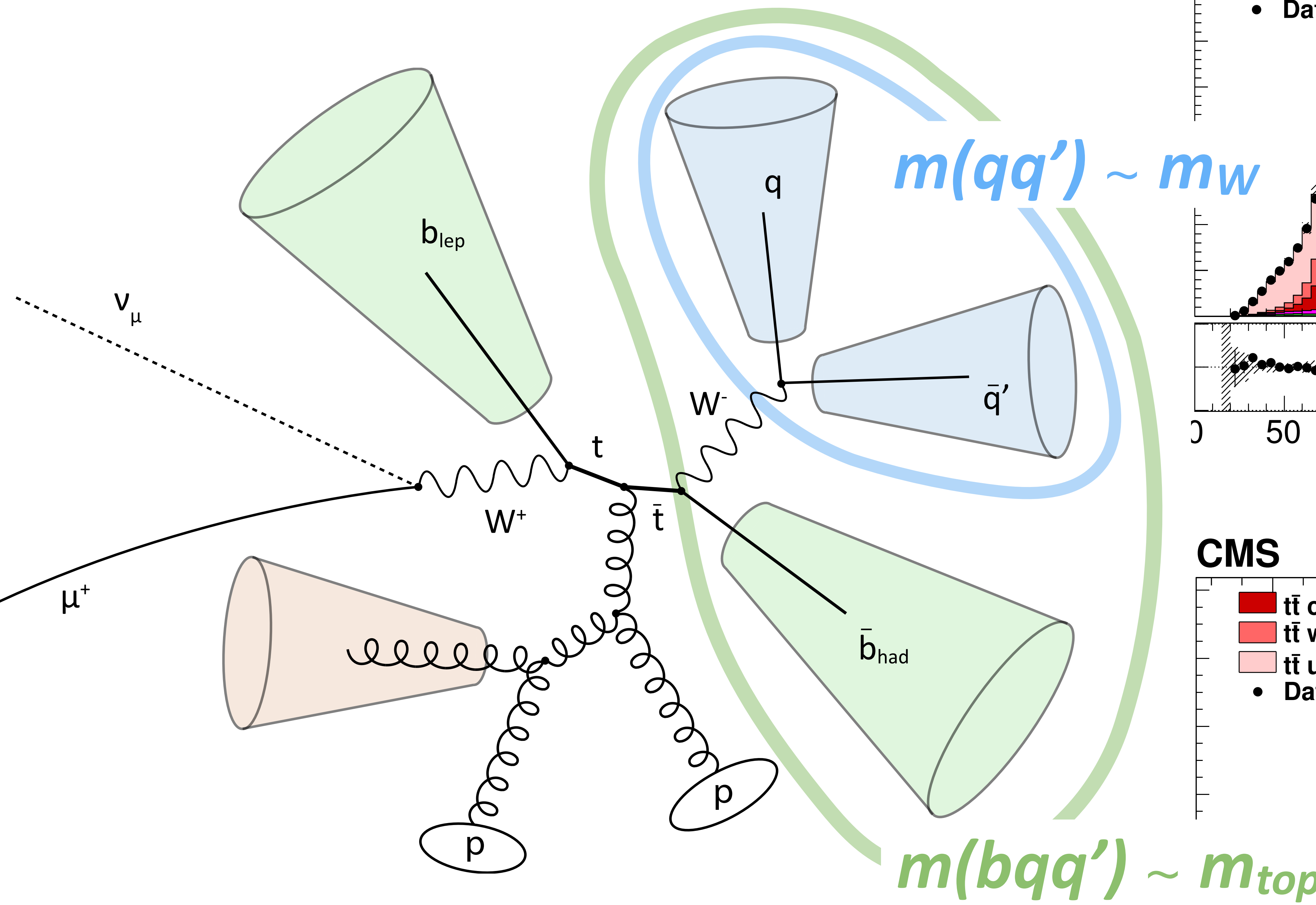
New results for top-quark mass measurements

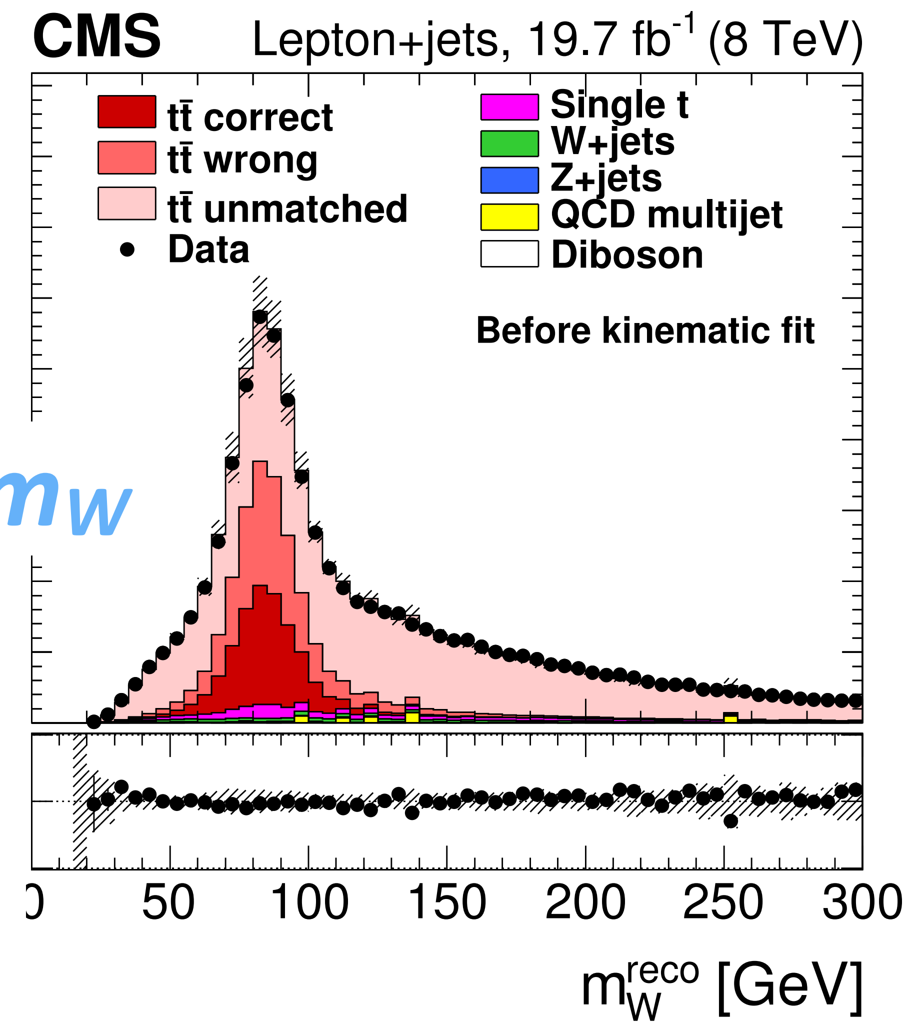


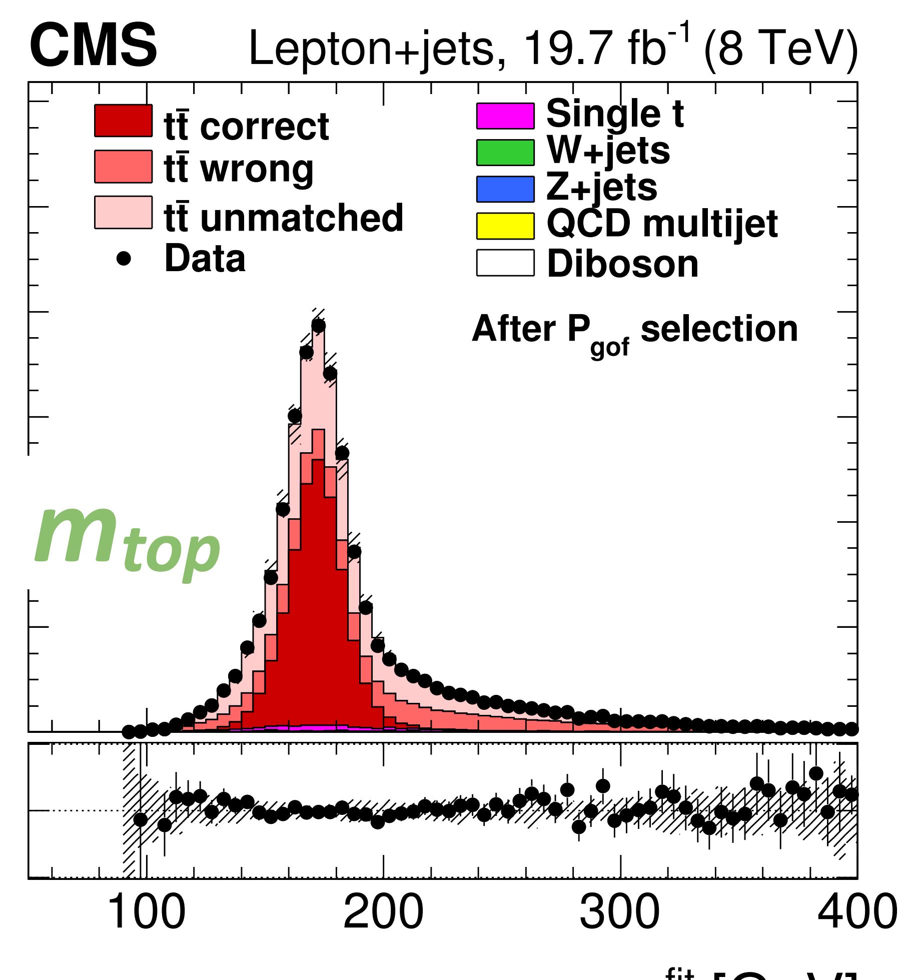
Benjamin Stieger (UNL)
on behalf of the CMS collaboration

LHCTopWG open meeting, May 18th 2016

Top mass in $t\bar{t}$ events







TOP-14-022 (2015) acc. by PRD

What are the dominant sources of systematics in standard methods?

- Experimental *Detector understanding*
  - Jet energy response calibration

~100–150 MeV

Signal modeling

- (b) hadronization modeling
  - Including effect on jet-energy scale

~350 MeV

- Hard-scattering process
  - ME generator comparisons
  - μ_R/μ_F scales, signal kinematics

~100–150 MeV

Lepton+jets channel	hybrid δm_t^{hyb} (GeV)
Experimental uncertainties	
Method calibration	0.04
Jet energy corrections	
– JEC: Intercalibration	+0.01
– JEC: In situ calibration	+0.12
– JEC: Uncorrelated non-pileup	−0.10
– JEC: Uncorrelated pileup	−0.04
Lepton energy scale	+0.01
E_T^{miss} scale	+0.04
Jet energy resolution	−0.03
b tagging	+0.06
Pileup	−0.04
Backgrounds	+0.03
Modeling of hadronization	
JEC: Flavor-dependent	
– light quarks (u d s)	+0.05
– charm	+0.01
– bottom	−0.32
– gluon	−0.08
b jet modeling	
– b fragmentation	<0.01
– Semileptonic b hadron decays	−0.16
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	-0.09 ± 0.07
ME-PS matching threshold	$+0.03 \pm 0.07$
ME generator	-0.12 ± 0.08
Top quark p_T	+0.02
Modeling of soft QCD	
Underlying event	$+0.08 \pm 0.11$
Color reconnection modeling	$+0.01 \pm 0.09$
Total systematic	0.48
Statistical	0.16
Total	0.51

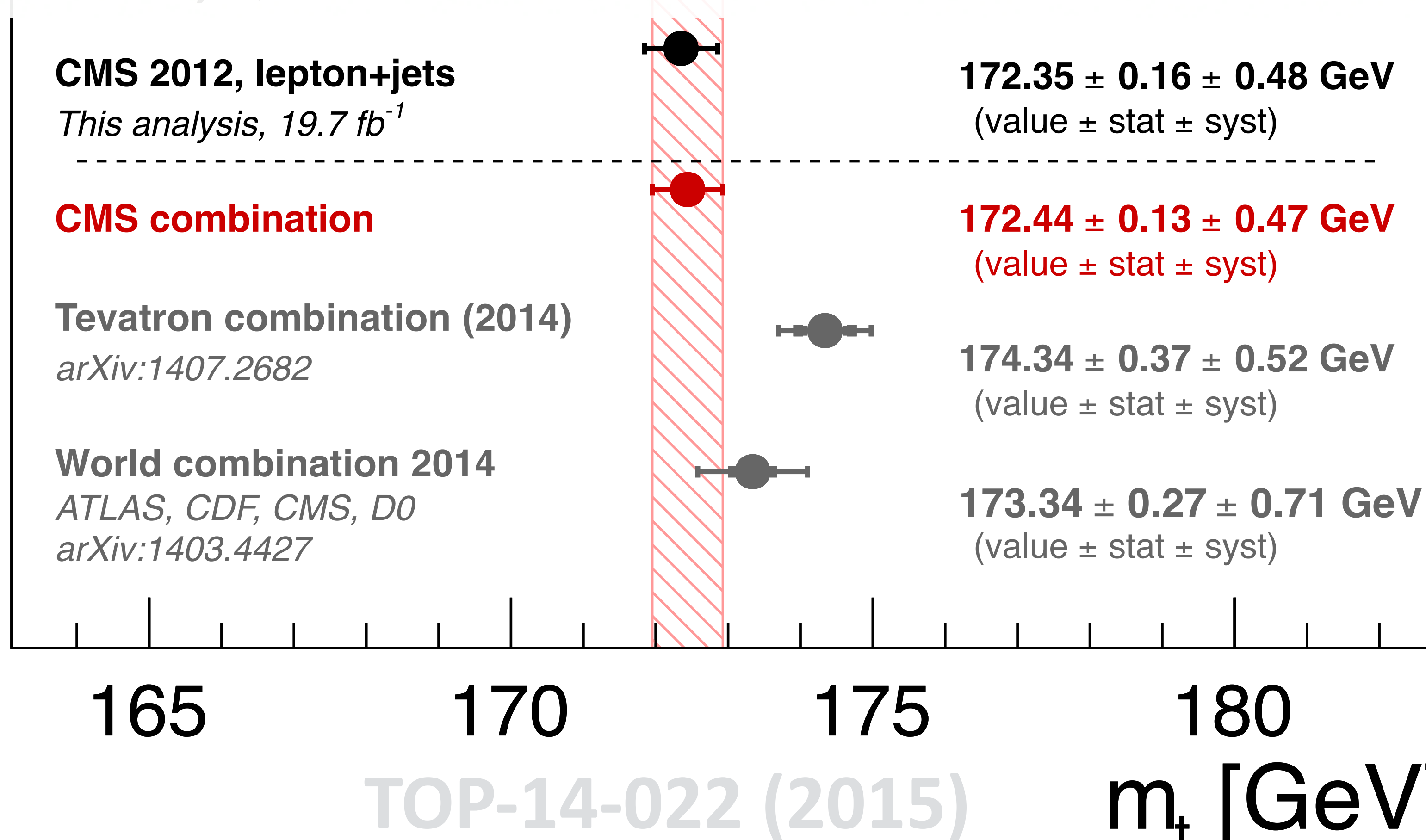
TOP-14-022 (2015) acc. by PRD

The most sensitive methods are limited by uncertainties from the modeling of (b) hadronization.

- Exploit full kinematic information of $t\bar{t}$ event
- Calibrated using Monte Carlo
- Reaching a precision of **order 500 MeV** (< 0.3%)

- Ultimately limited by understanding of hadronization modeling
  - Compare different hadronizers (Pythia vs. Herwig)
  - Dedicated studies

- How can we **improve**?
- What else can we **learn**?



TOP-14-022 (2015)

What can we gain from different approaches?

- Use experimentally clean(er) **observables**
  - Don't use jets, avoid hadronization issues
  - Alternative systematic sensitivities
  - Impact in combination with standard methods

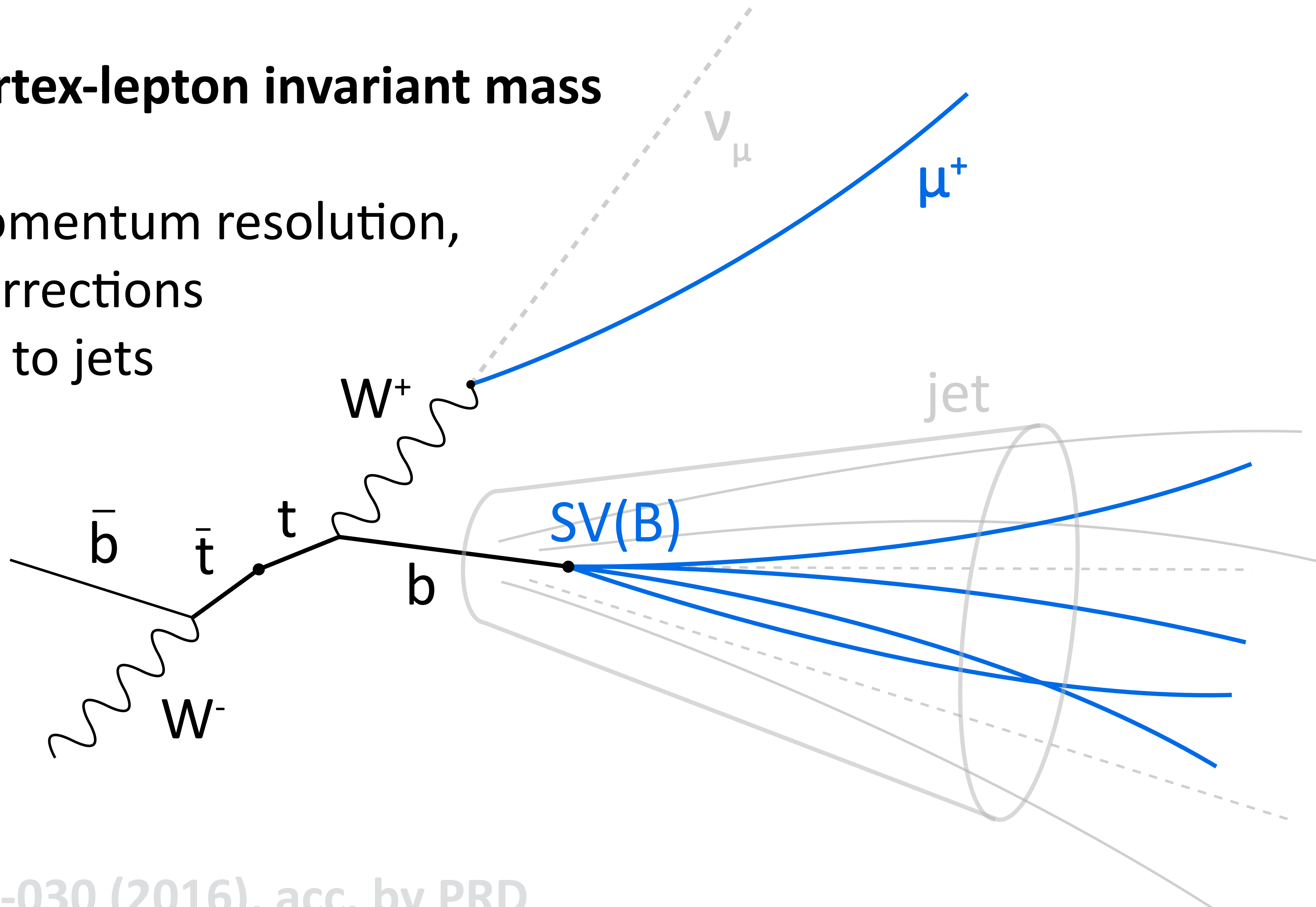
- **Theoretically-calculable** observables
  - Basic example: inclusive production cross-section
  - Shapes of lepton-b invariant mass (m_{lb}), $t\bar{t}$+jet invariant mass (ρ_S)

- Compare results from different **mass definitions**:
  - Kinematic "MC" mass, cross section, endpoints

- **Constrain modeling systematics** in the data—e.g.:
  - Hadronization: b fragmentation, semileptonic b hadron decays, …
  - Top quark p_T, scale uncertainties in differential cross sections
  - Underlying event

Reduce experimental uncertainties by using only charged tracks and leptons.

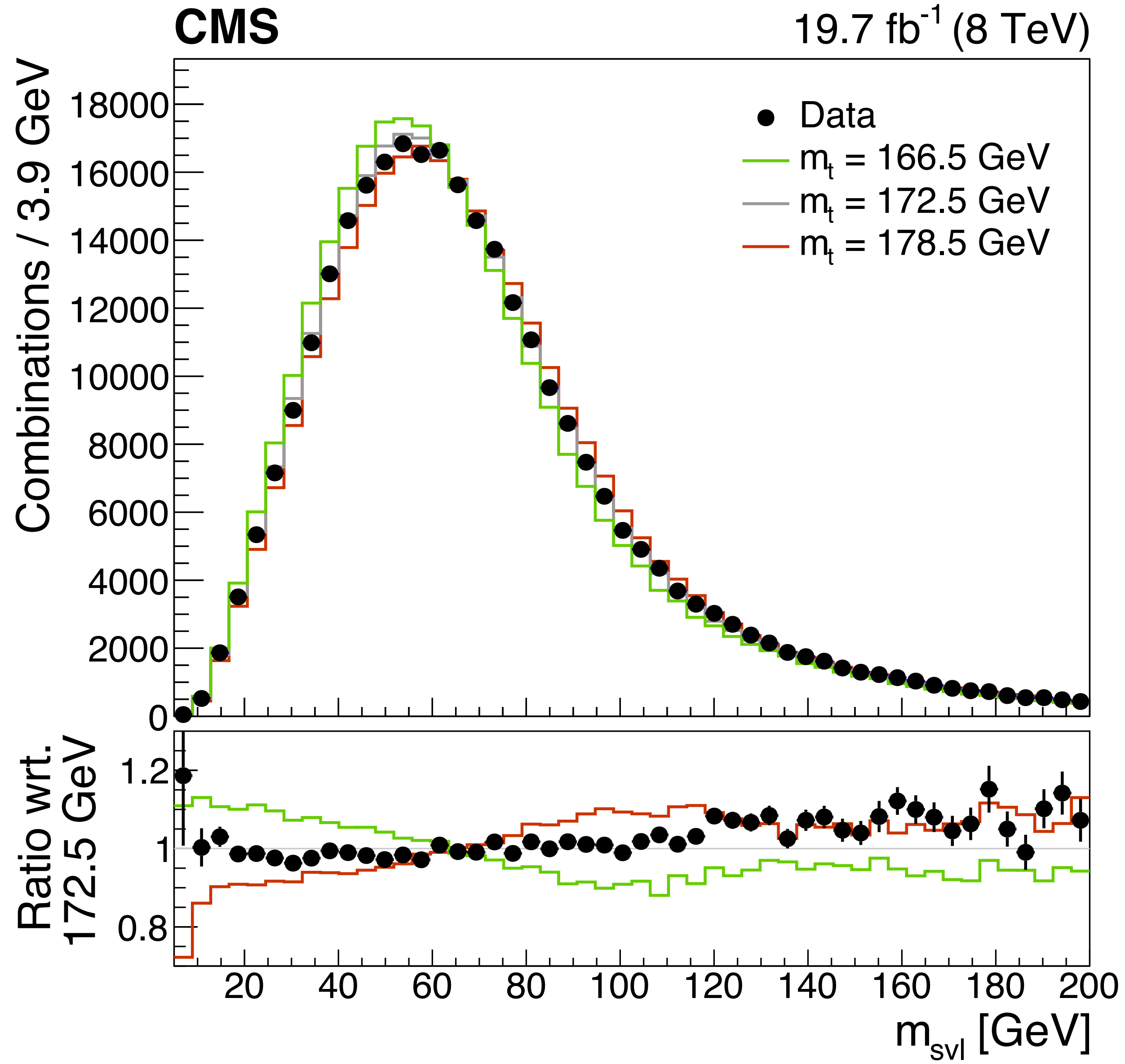
- Reconstruct **secondary vertex** from b-hadron decay
- Exploit **vertex-lepton invariant mass**
- Higher momentum resolution, smaller corrections compared to jets

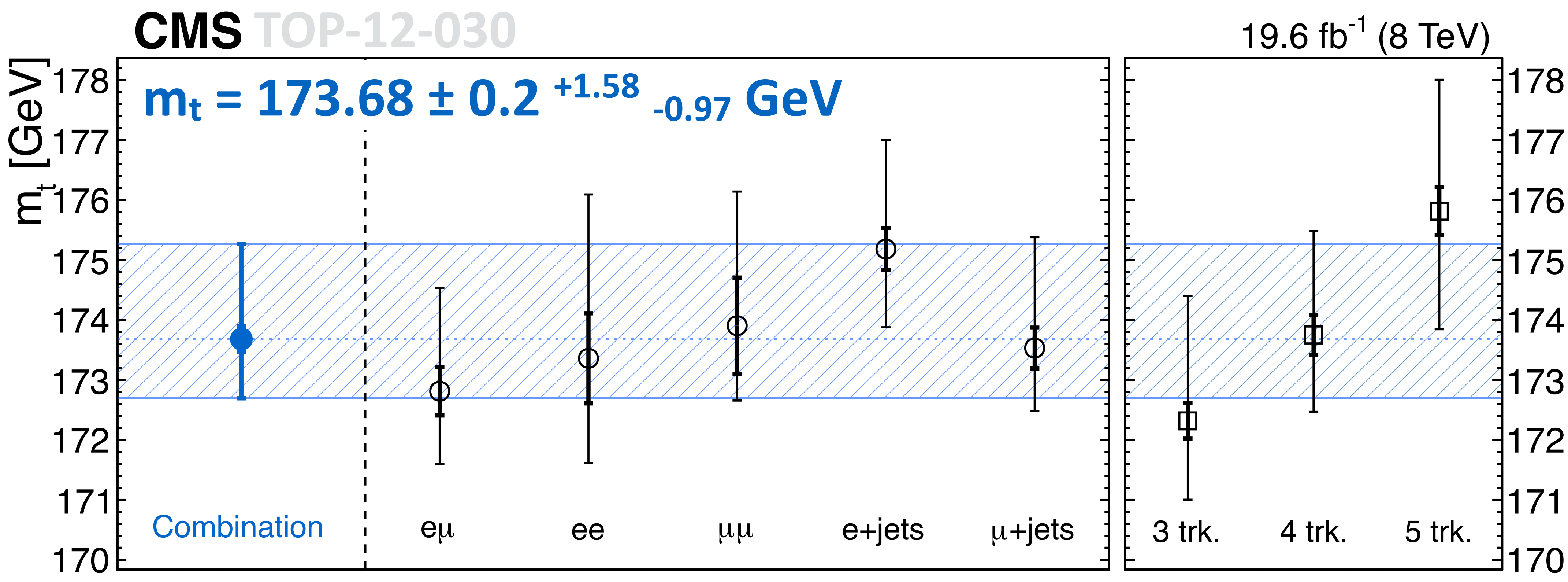


TOP-12-030 (2016), acc. by PRD

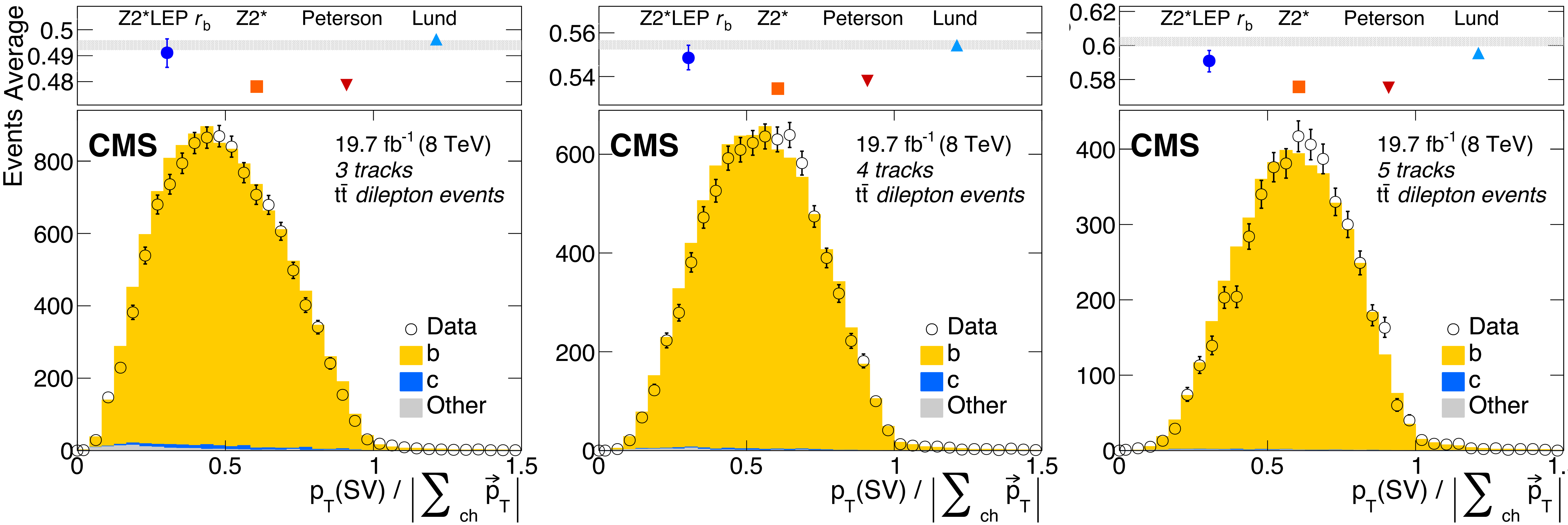
Lepton + Secondary Vertices

- Monte Carlo calibrated
- All lepton-vertex combinations in each event used
- Separate categories for:
  - SV-track multiplicity
  - l+jets and dilepton channels

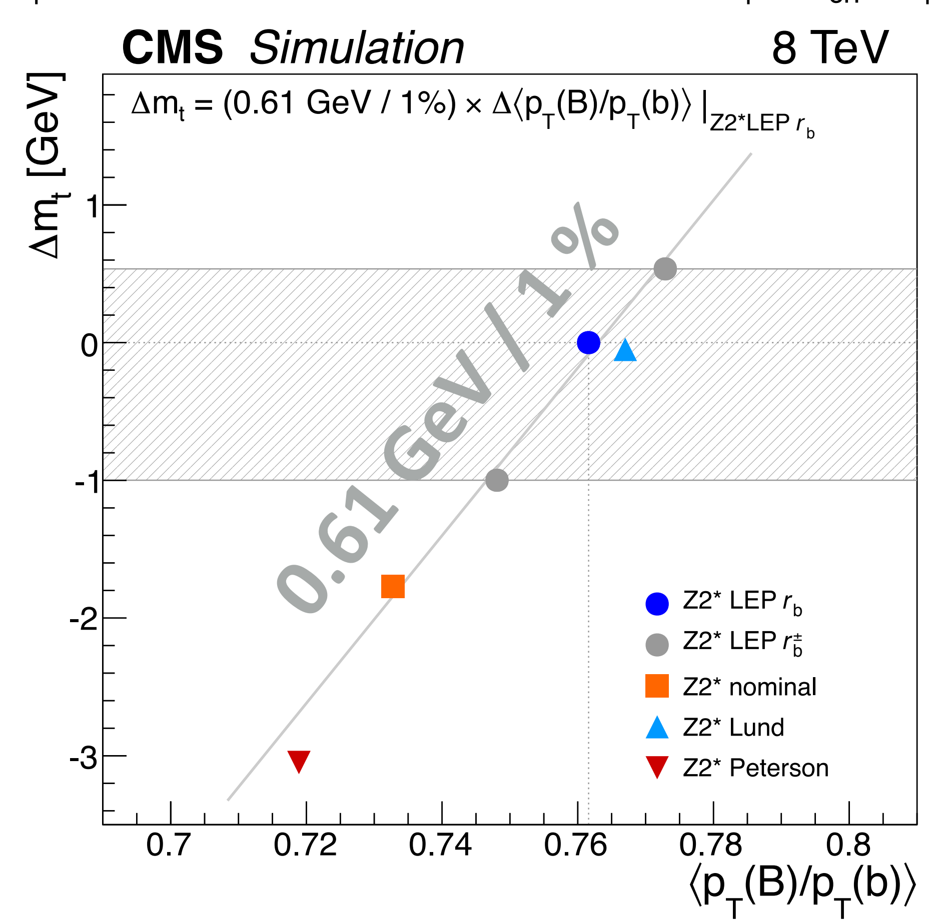




Studying b-quark fragmentation in the data



- Compare fraction of jet-momentum carried by secondary vertex for different fragmentation function shapes
  - Proxy for part.-to-hadr. momentum transfer
  - Tune with modified r_b (`PARJ47`) 1.0 → 0.59
- Dominant effect on measured top mass



TOP-12-030

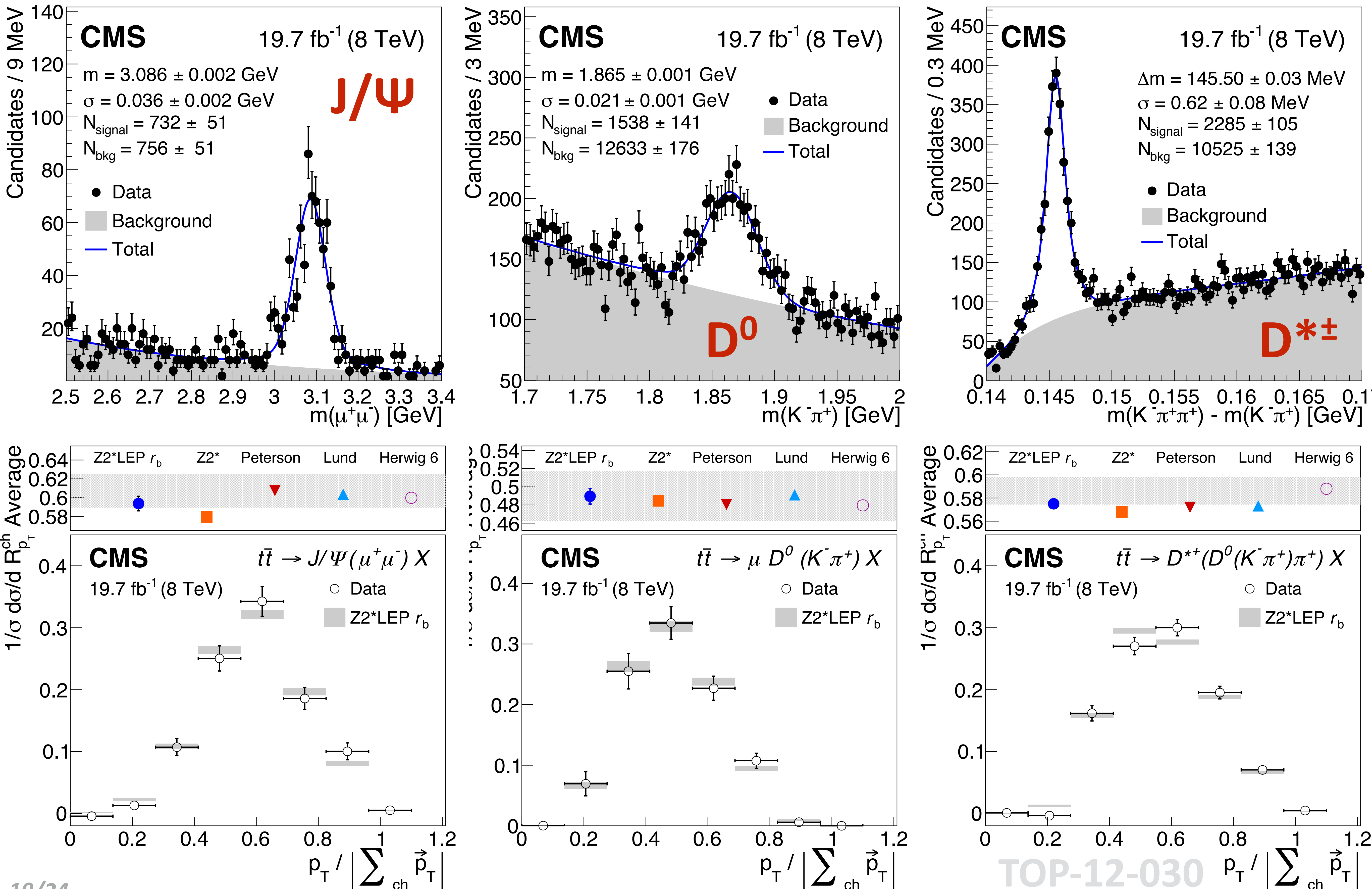
Dominant systematics

- b fragmentation modeling ~1 GeV
  - Possible to constrain from data?
- Top quark p_T ~800 MeV
- Experimental < 500 MeV
  - Lepton energy scales
  - Secondary vertex modeling
- Fully complementary to standard methods

Source	Δm_t [GeV]	
Theoretical uncertainties		
μ_R/μ_F scales $t\bar{t}$	$+0.22$	-0.20
μ_R/μ_F scales t (t-channel)	-0.04	-0.02
μ_R/μ_F scales tW	$+0.21$	$+0.17$
Parton shower matching scale	-0.04	$+0.06$
Single top quark fraction	-0.07	$+0.07$
Single top quark diagram interference (*)	$+0.24$	
Parton distribution functions	$+0.06$	-0.04
Top quark p_T	$+0.82$	
Top quark decay width (*)	-0.05	
b quark fragmentation	$+1.00$	-0.54
Semileptonic B decays	-0.16	$+0.06$
b hadron composition (*)	-0.09	
Underlying event	$+0.07$	$+0.19$
Color reconnection (*)	$+0.08$	
Matrix element generator (*)	-0.42	
$\sigma(t\bar{t}+\text{heavy flavor})$	$+0.46$	-0.36
Total theoretical uncertainty	$+1.52$	-0.86
Experimental uncertainties		
Jet energy scale	$+0.19$	-0.17
Jet energy resolution	-0.05	$+0.05$
Unclustered energy	$+0.07$	-0.00
Lepton energy scale	-0.26	$+0.22$
Lepton selection efficiency	$+0.01$	$+0.01$
b tagging	-0.02	-0.00
Pileup	-0.05	$+0.07$
Sec.-vertex track multiplicity (*)	-0.06	
Sec.-vertex mass modeling (*)	-0.29	
Background normalization	< 0.03	
Total experimental uncertainty	$+0.43$	-0.44
Total systematic uncertainty	$\mathbf{+1.58}$	$\mathbf{-0.97}$
Statistical uncertainty	$\mathbf{\pm 0.20}$	

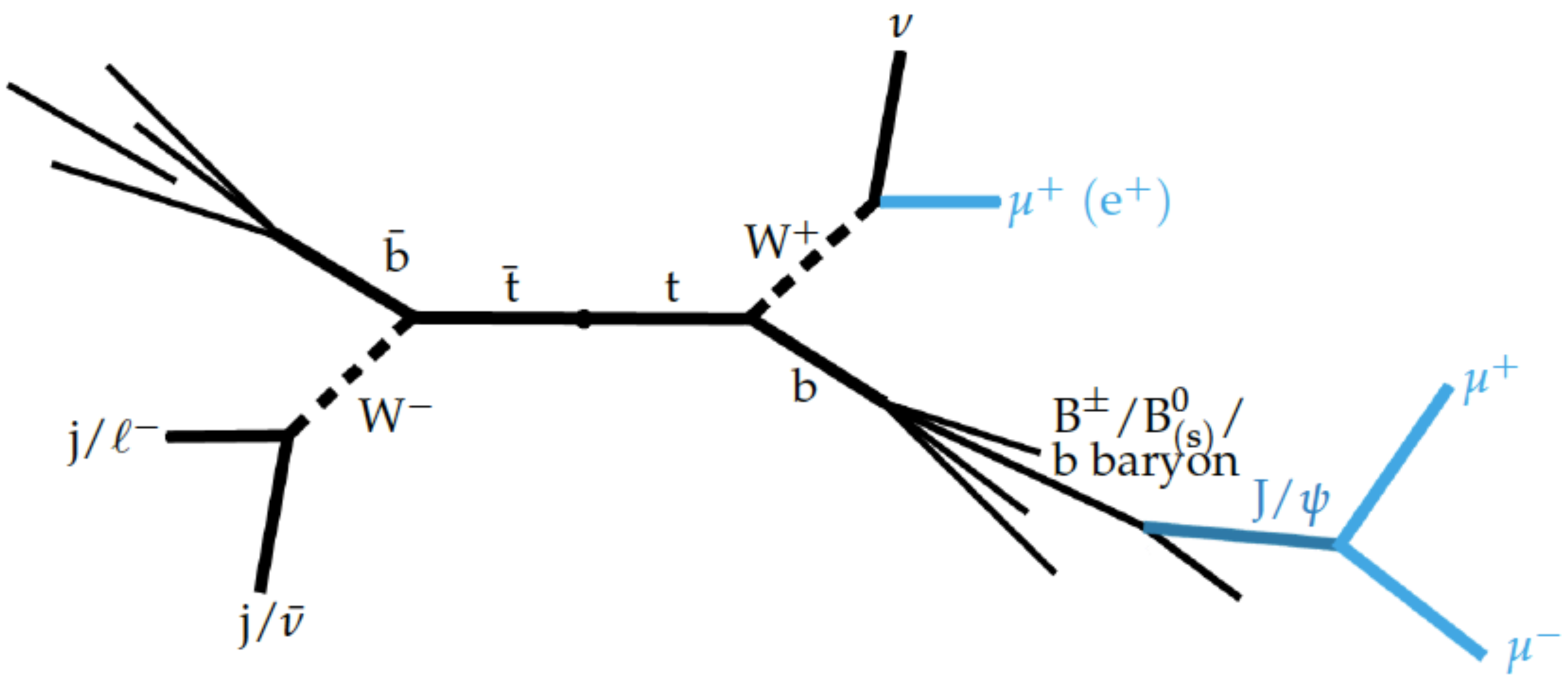
TOP-12-030

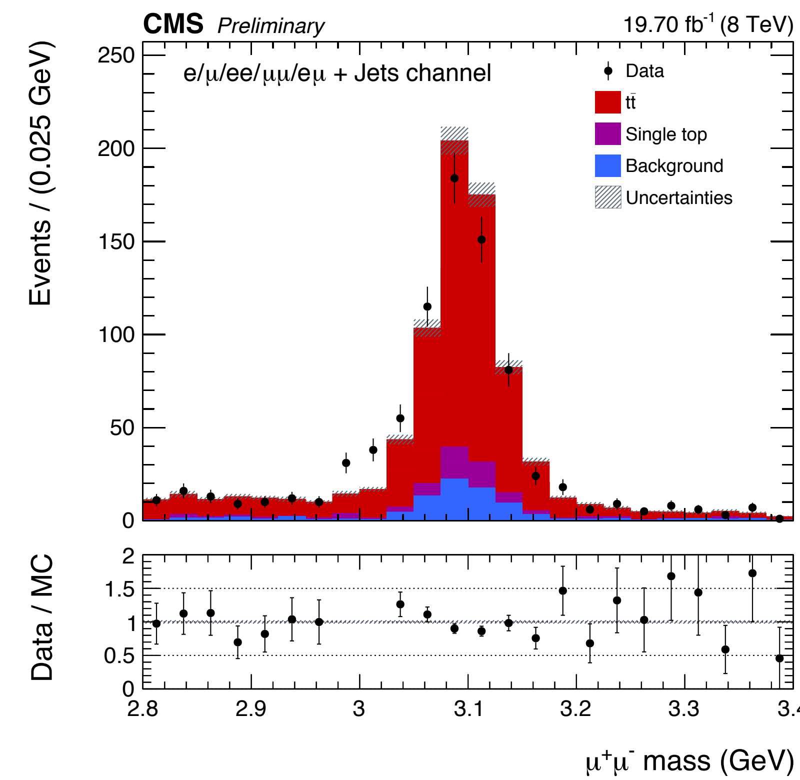
Charm mesons in b-hadronizations from top decays

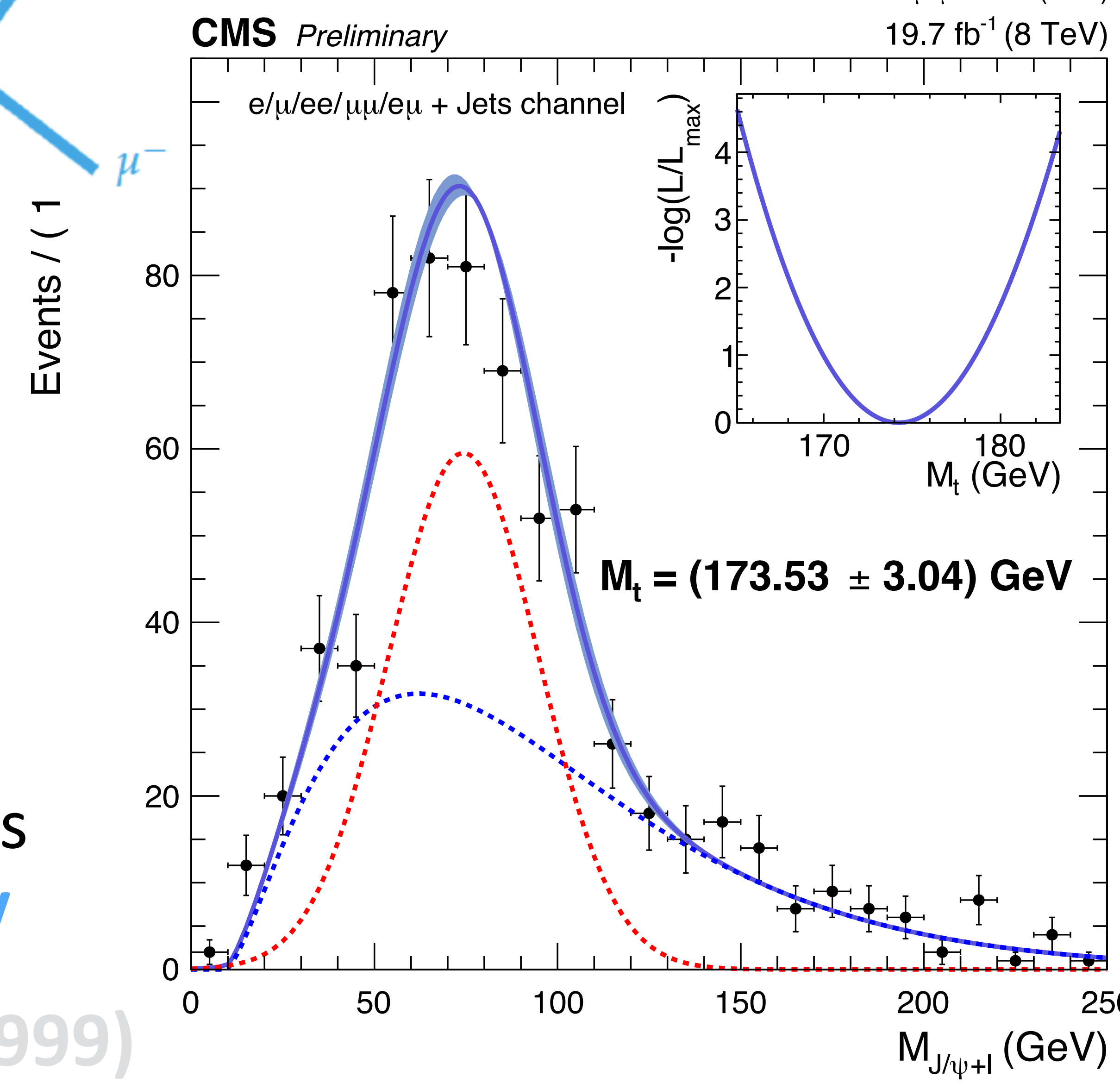


TOP-12-030

Using charmed mesons might provide an even cleaner observable.





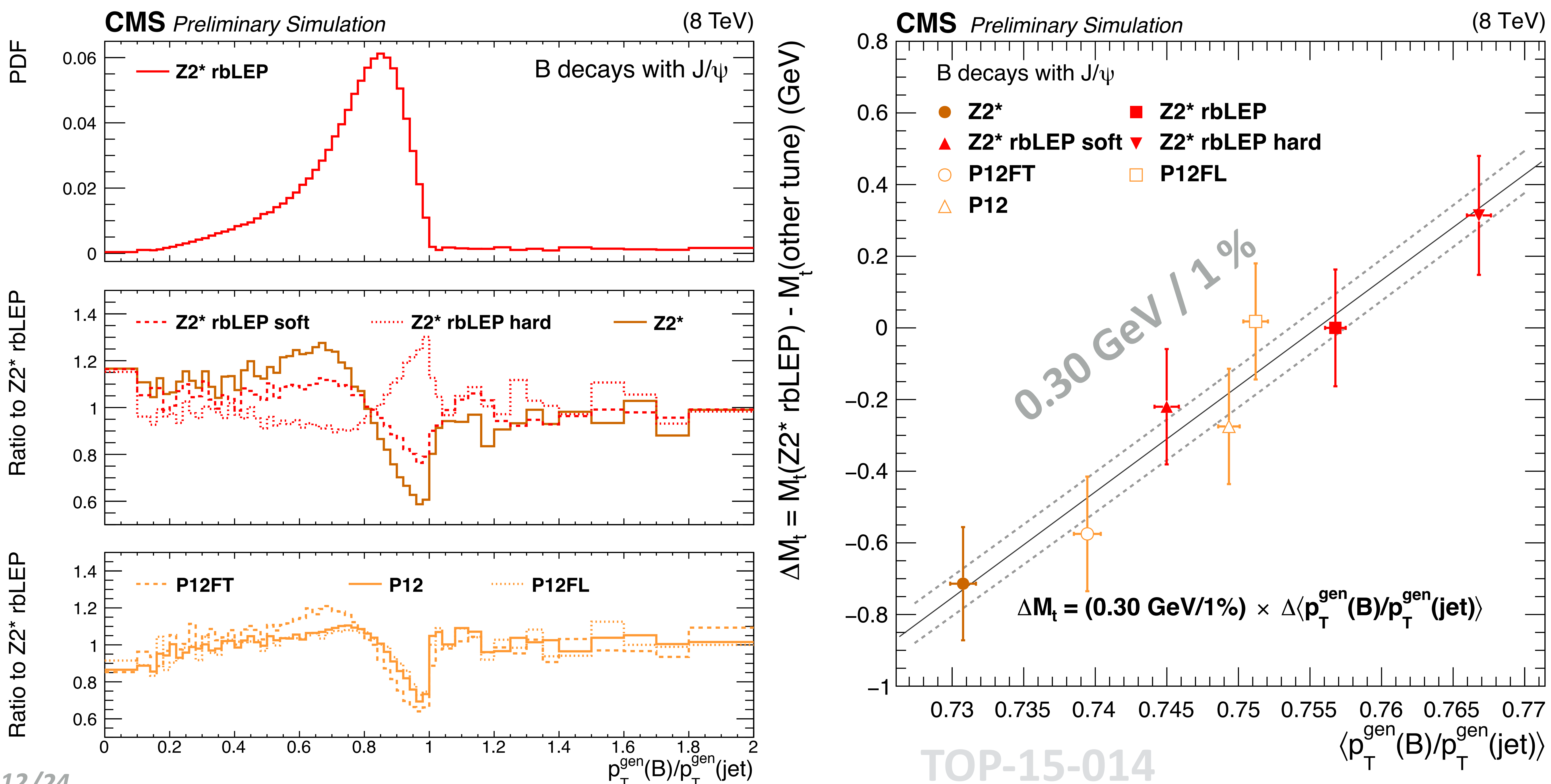


- **Lepton + J/Ψ** invariant mass
- Small branching fractions
  - 666 available events in 8 TeV dataset
  - Statistical uncertainty of **3.0 GeV**
- However < 1 GeV syst. uncertainty
  - b-fragmentation **~0.3 GeV**
  - Limited by top p_T modeling, QCD scales
  - Relevant exp. uncertainties **< 100 MeV**

TOP-15-014 (2016) Kharchilava (1999)

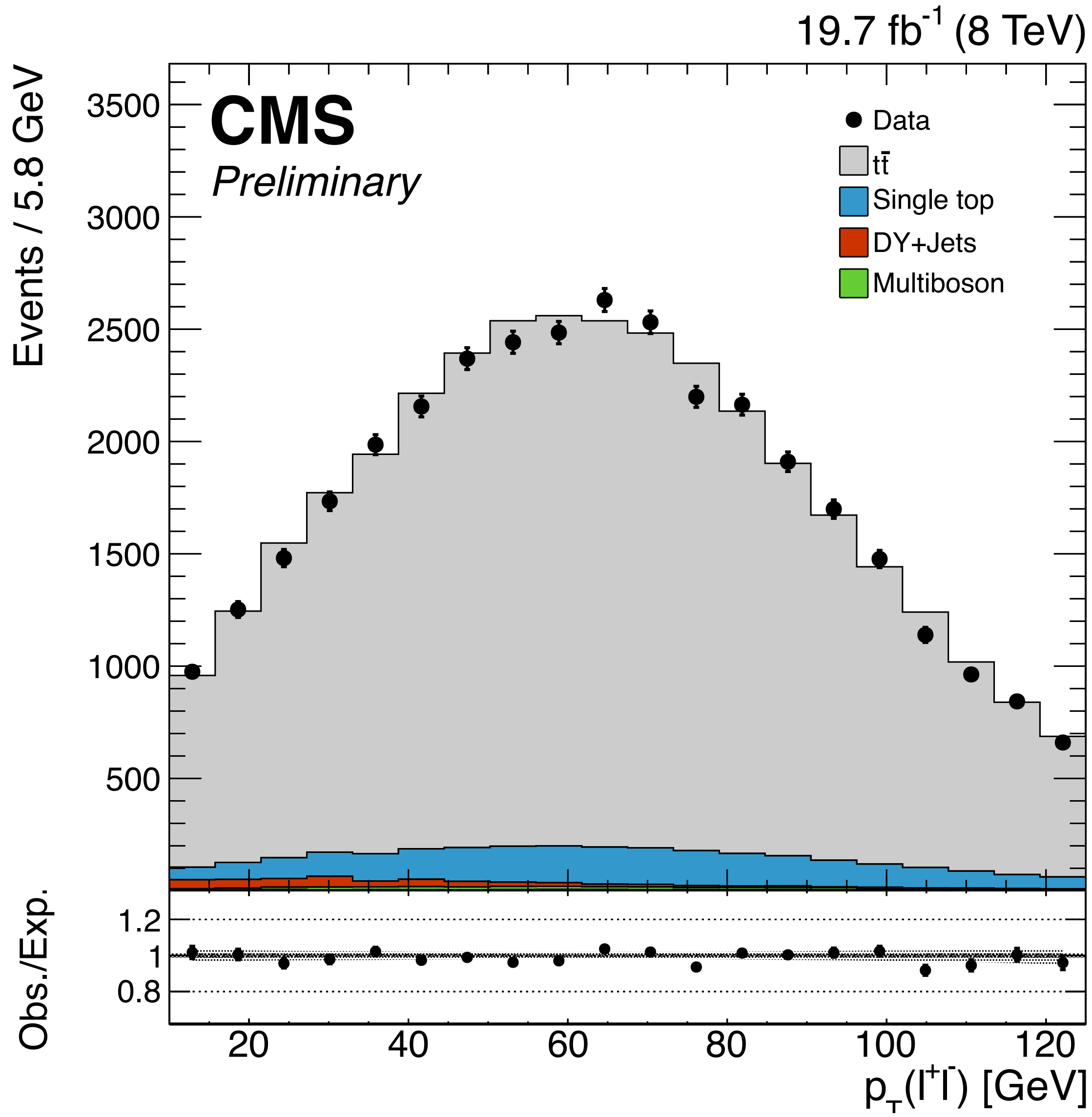
Exclusive reconstruction reduces sensitivity to variations in b-fragmentation

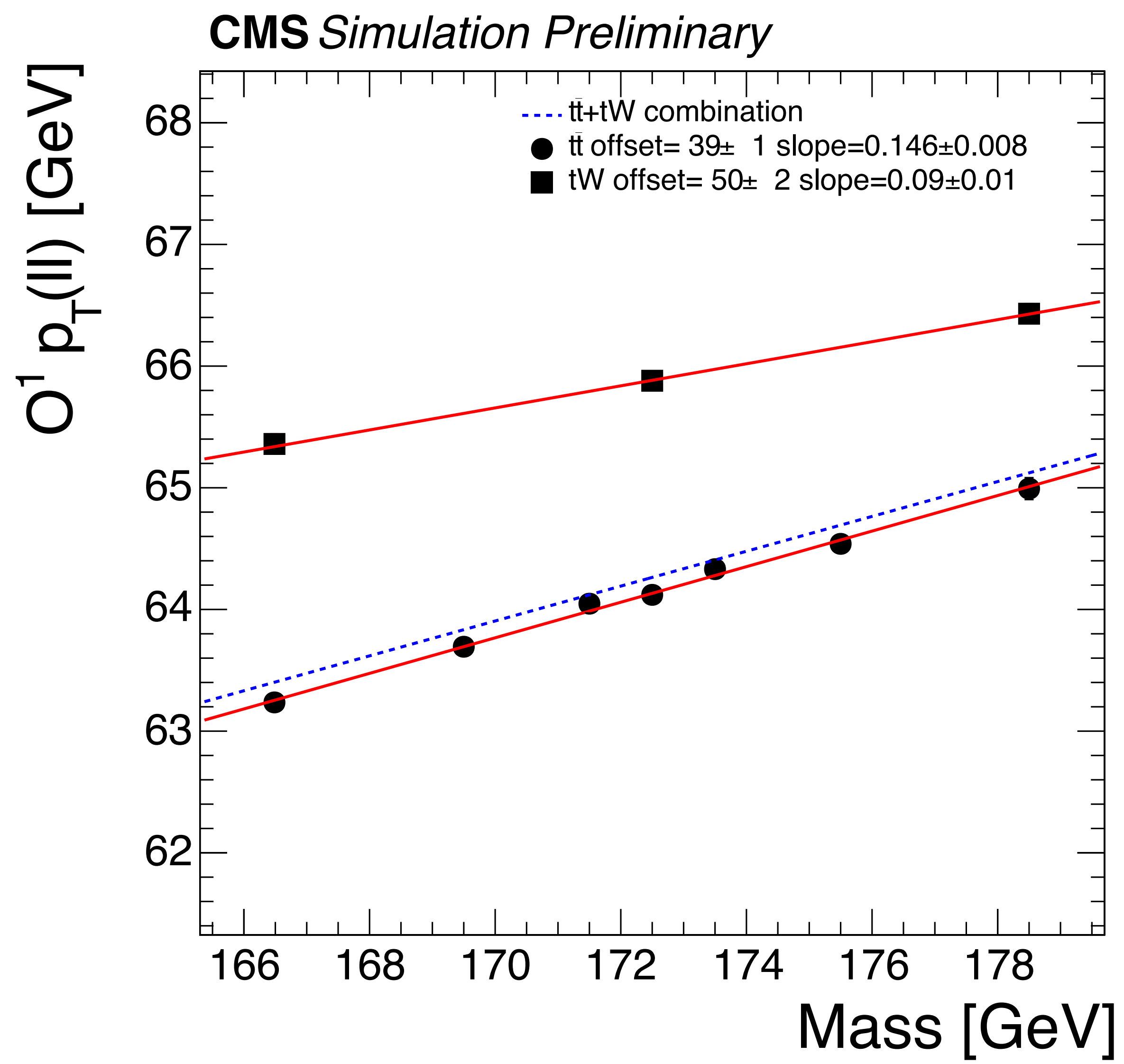
- Cost of reduced sensitivity (larger statistical uncertainty)



Ideal case would be an experimentally-clean, theoretically-calculable observable

- Dilepton kinematics proposed by ***Frixione and Mitov (2014)***
- $p_T(l^+l^-)$ found to show highest sensitivity to top mass
- Loss of sensitivity when unfolding



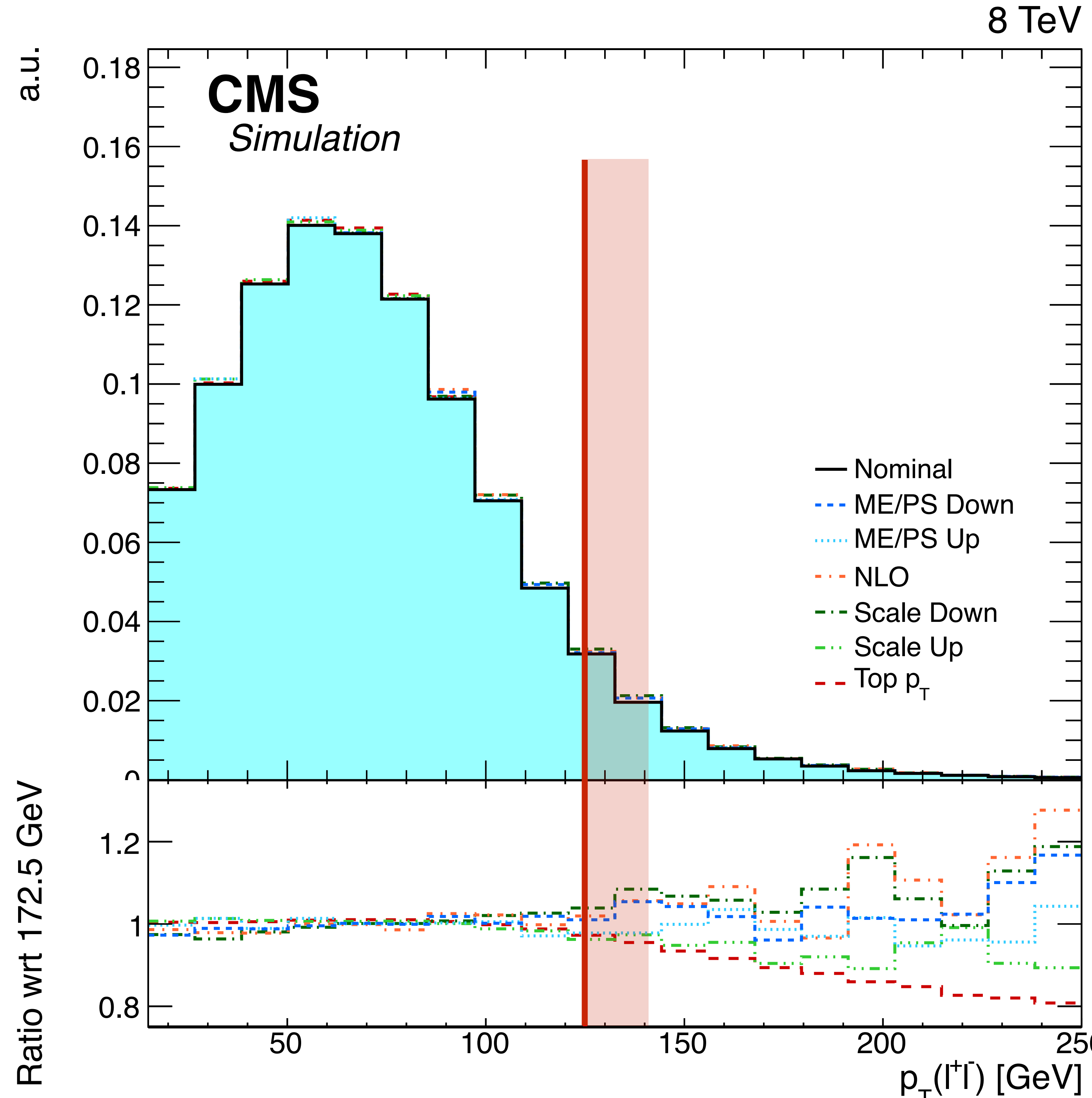


Note: direct use case for NNLO lepton kinematics in fiducial region (vs. m_{top})

TOP-16-002 (2016)

Promising experimental precision, but limited by QCD scale uncertainties and top p_T modeling.

- Caveat: using only **leading-order MC** in Run I (8 TeV)
- Furthermore, **top quark p_T mismodeling** has a large impact
- Experimentally limited only by lepton momentum scale



$$m_t = 171.7 \pm 1.1 \pm 0.5 \;^{+3.1}_{-2.5} \; +0.8 \text{ GeV}$$

(stat.) (exp.) (theo.) (top p_T)

TOP-16-002 (2016)

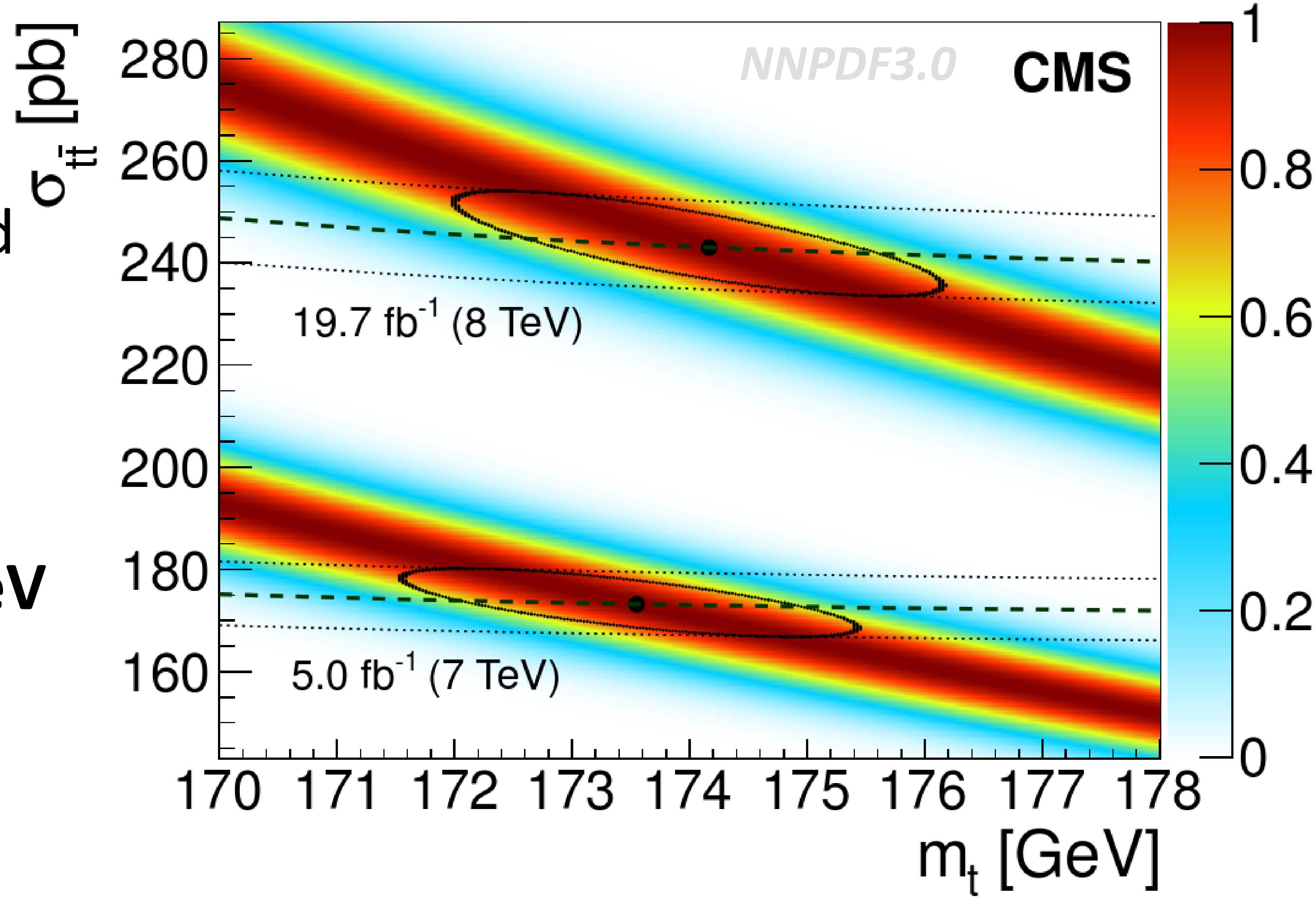
Pole mass extraction from the inclusive $t\bar{t}$ production cross-section reaching < 2 GeV precision

- Mass-dependence can be calculated at NNLO
  - Acceptance depends on m_t as well

- Fixed value of α_S

- Cross section limited by luminosity uncertainty

$m_t = 173.8^{+1.7}_{-1.8}$ GeV

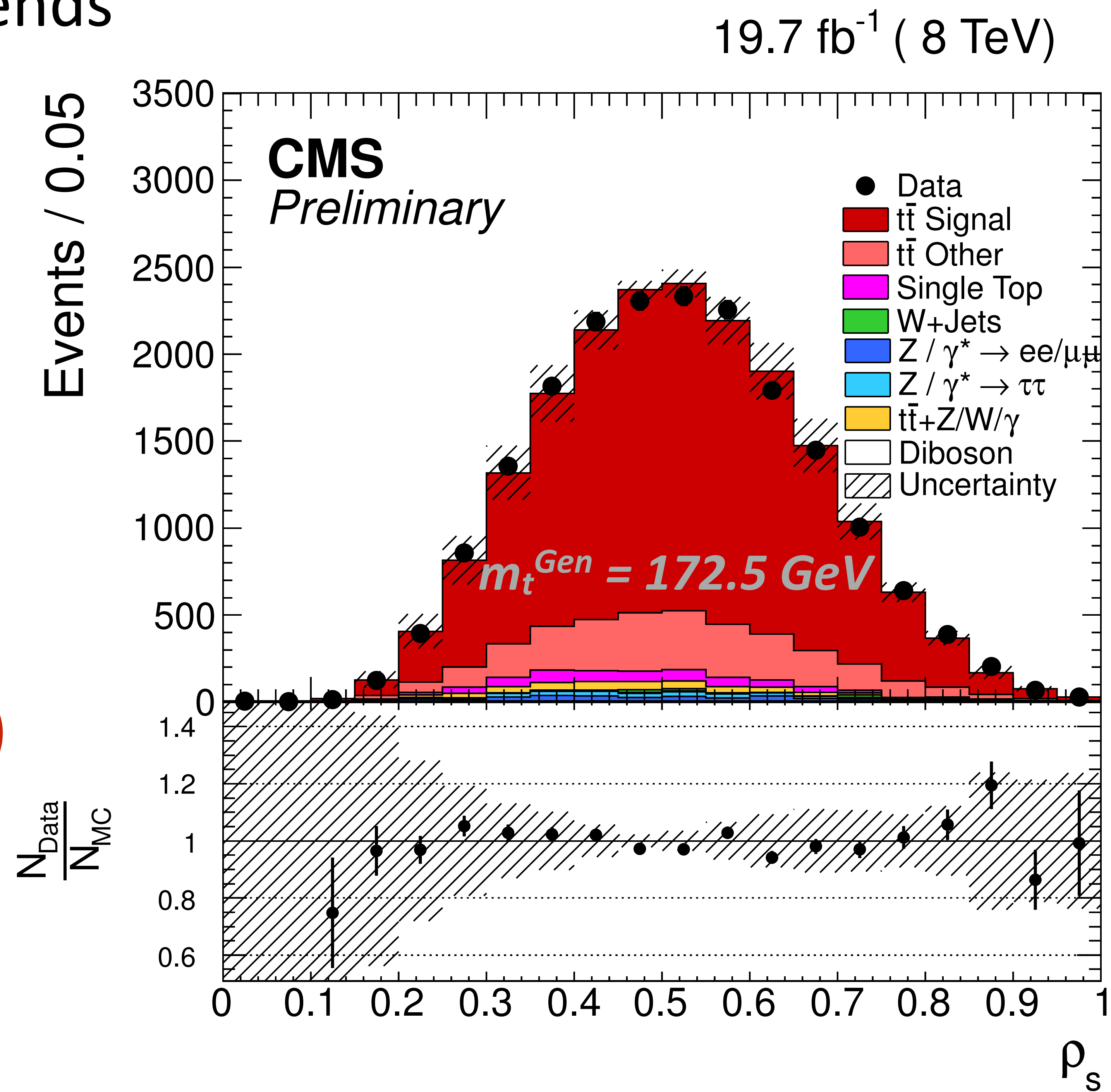


TOP-13-004 (2016) subm. to JHEP

Shapes are potentially more sensitive, and not limited by beam-related uncertainties.

NEW

- Primary QCD radiation depends on top quark mass
  - Calculable at NLO
- Study dileptonic $t\bar{t}$ events
  - At least one additional jet ($p_T > 50$ GeV)
- Measure diff. cross section versus $\rho_S = 2 \cdot m_0 / m(t\bar{t}, jet)$
- Unfold to particle level
  - Using MadGraph+PY6

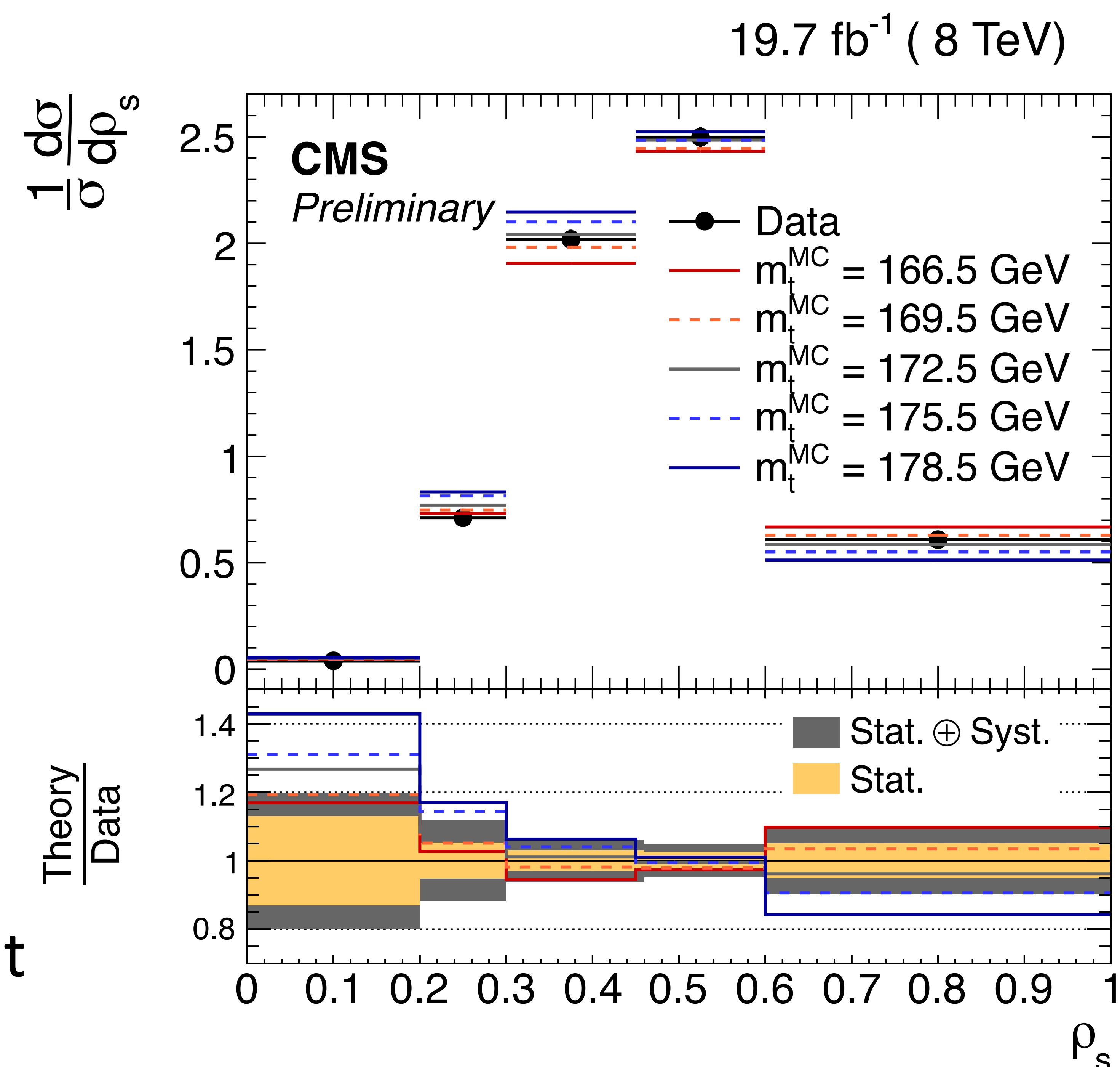


Alioli, Fuster, Moch, et al. (2013) TOP-13-006 (2016)

Compare particle-level measurement with POWHEG prediction at NLO

NEW

- POWHEGBOX ttJ setup
  - Interfaced to PYTHIA8
- Dominant systematics from μ_F/μ_R scale variations:
  - Effect on theo. prediction (POWHEG) $_{-1.6}^{+3.6}$ GeV
  - Effect on unfolding matrix (MadGraph) $^{+1.0}_{-2.8}$ GeV
- Fully independent of cross-section based measurement



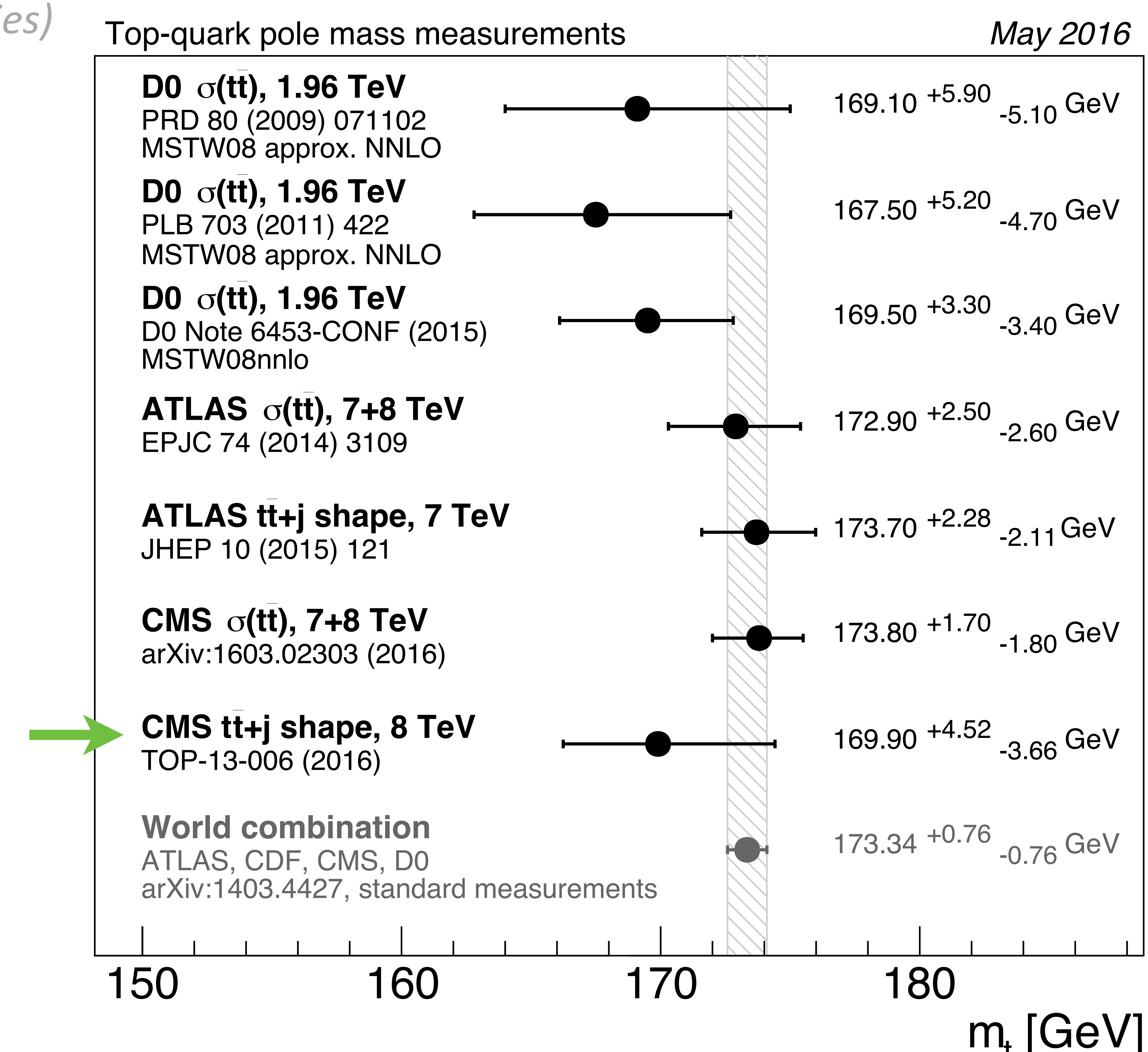
$$m_t = 169.9 \pm 1.1 \,^{+2.5}_{-3.1} \,^{+3.6}_{-1.6} \text{ GeV}$$

(stat.) (syst.) (theo.)

TOP-13-006 (2016)

Measurements based on comparing theory predictions agree well with MC-calibrated results

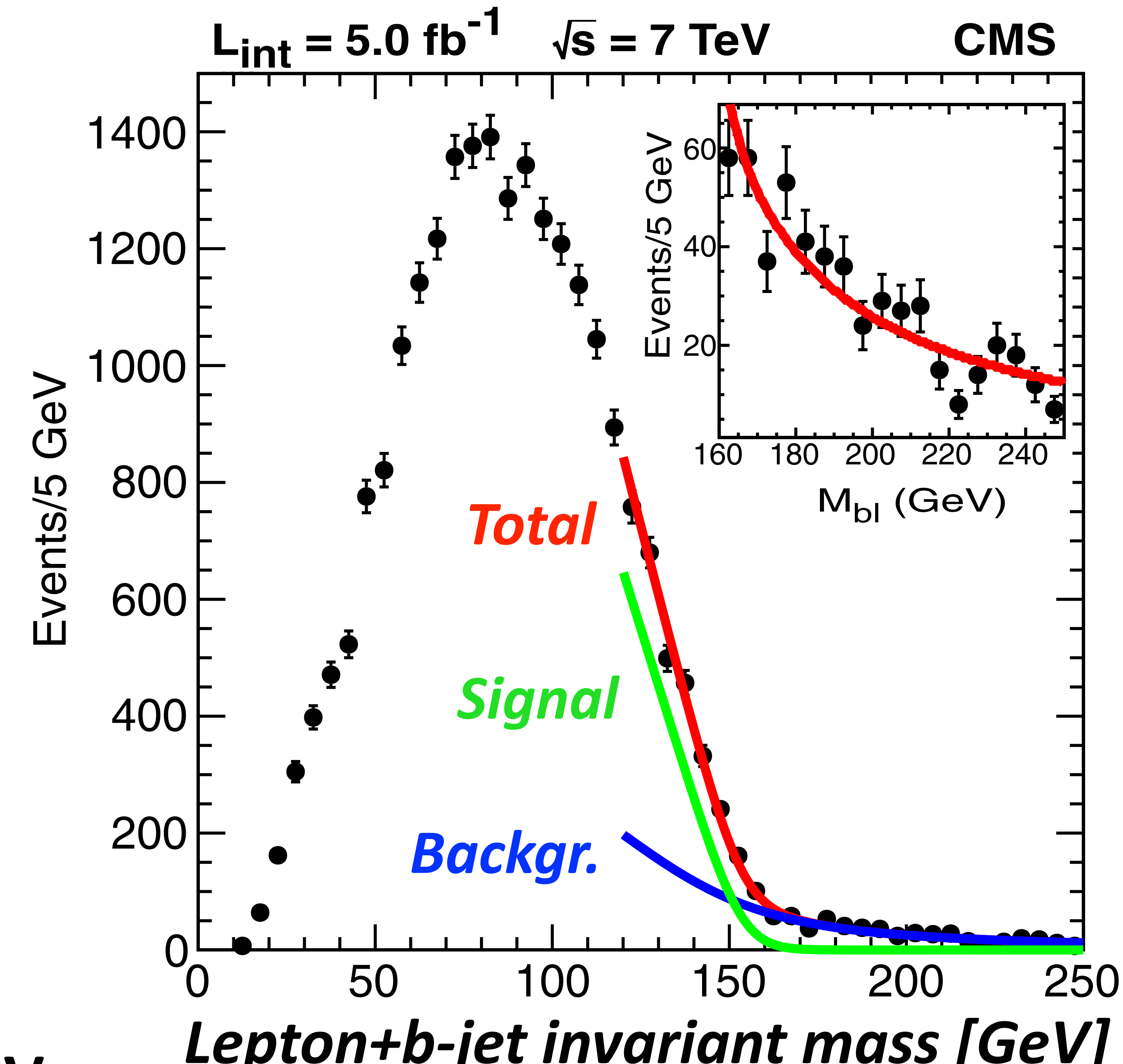
(within ~2 GeV uncertainties)



Next step: combination of these results!

Without relying on simulation, we can extract the top mass from the endpoints of kinematic distributions

- Endpoints depend on masses of particles involved in the decay
- Simultaneous fit of neutrino, W, and top masses
- Almost independent of simulation

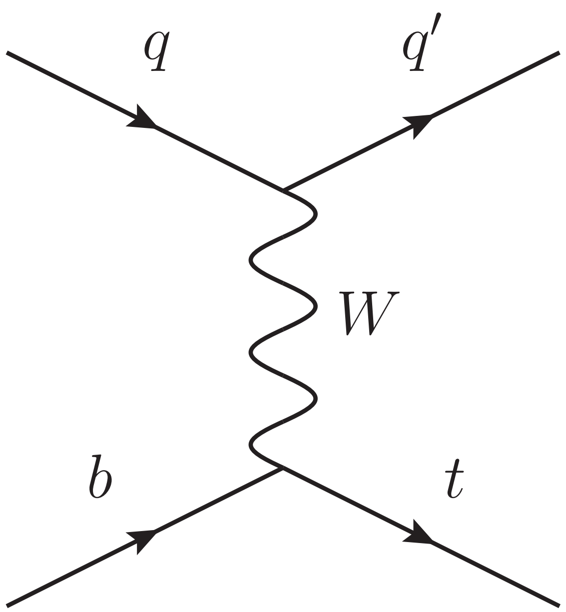


$m_t = 173.9 \pm 0.9\ ^{+1.7}_{-2.1}$ GeV

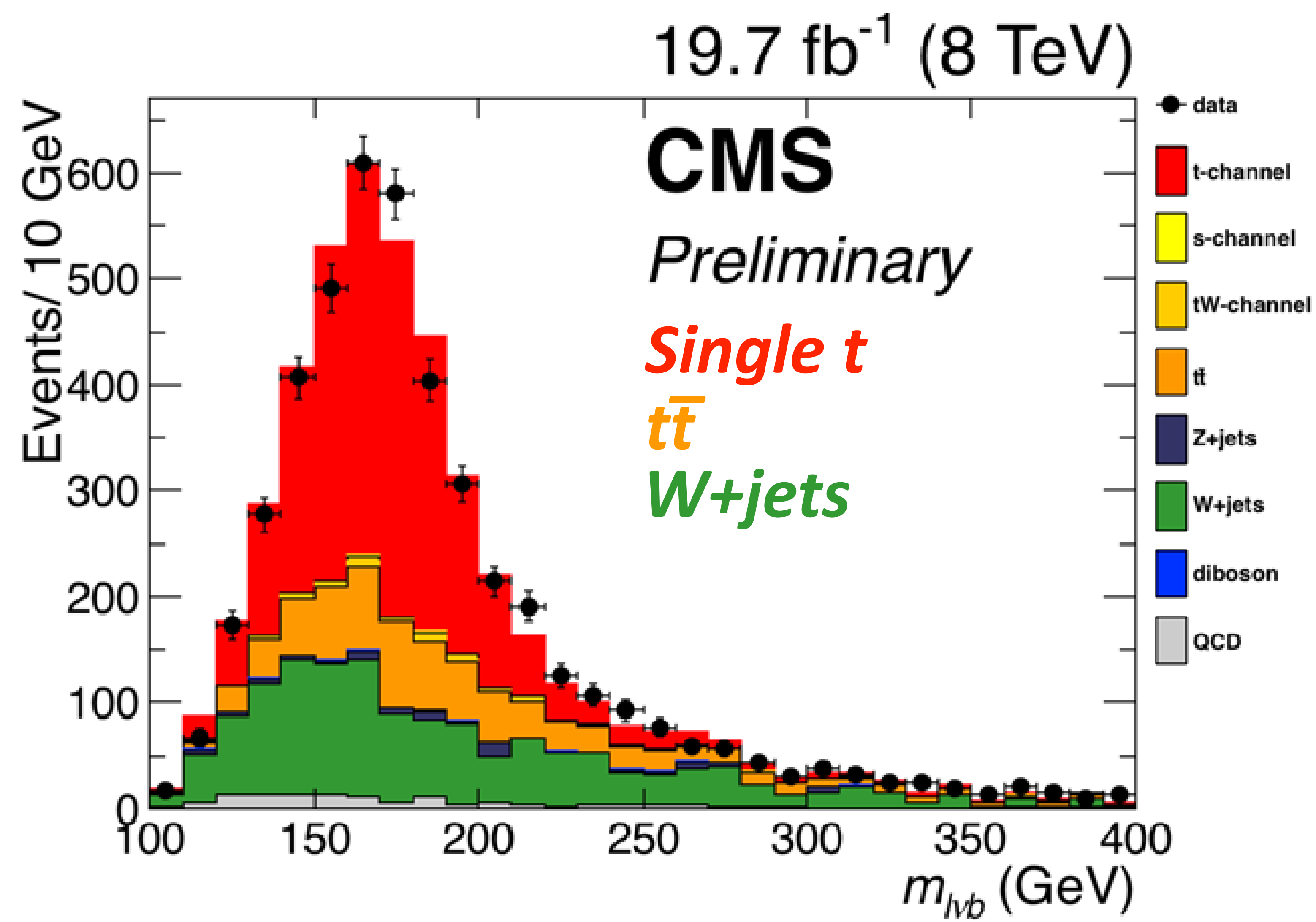
(stat.) *(syst.)*

TOP-11-027 EPJ C73 (2013) 2494

Single top production could potentially provide additional insights



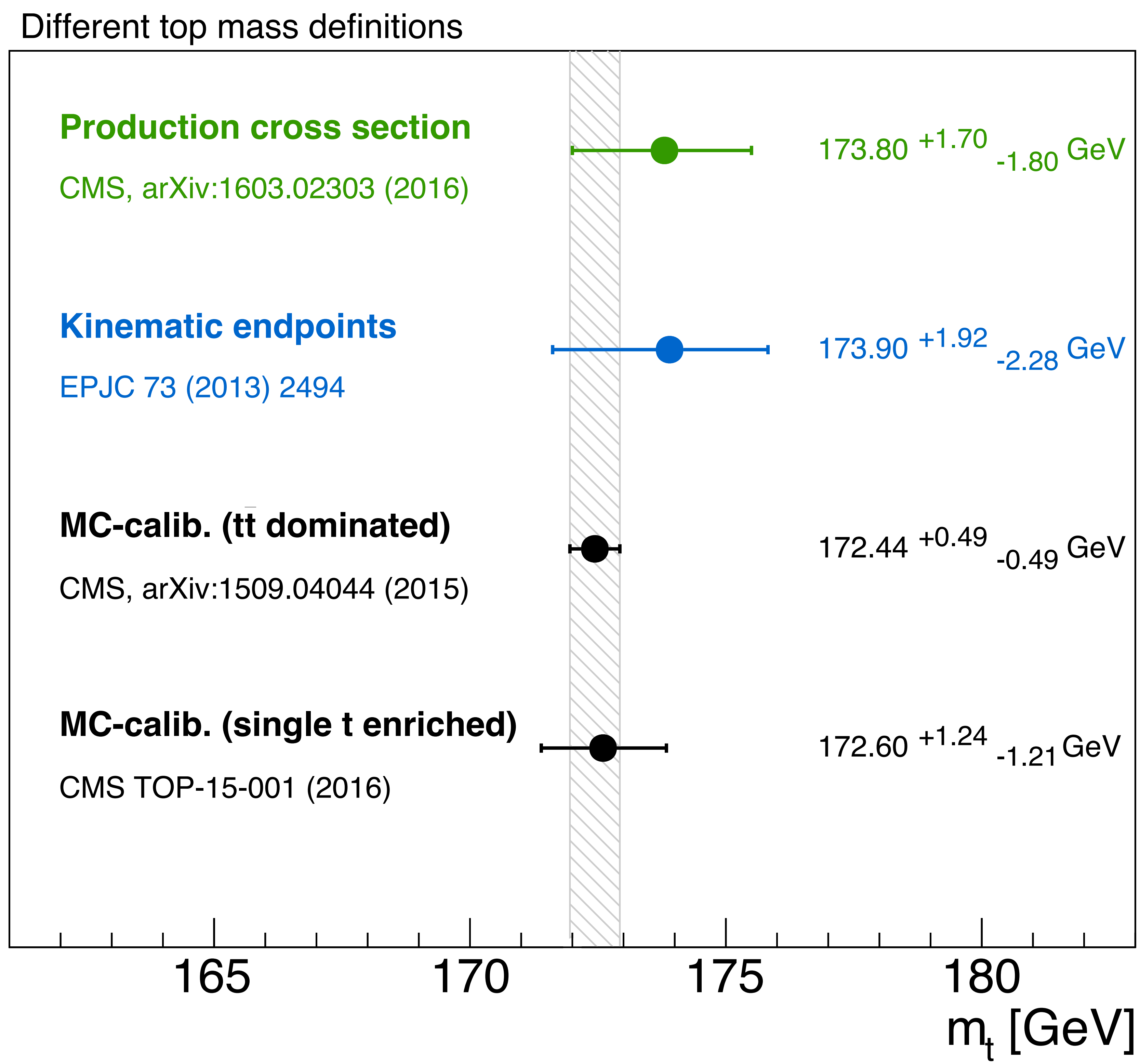
- Enrich selection in single top requiring a forward jet: $|\eta_j| > 2.5$
  - 71% t-channel single top, $t\bar{t} < 10\%$
- EWK mediated
  - Different color reconn.
  - Different hard scattering
  - Different pdfs
- Dominant systematics:
  - Jet energy scales
  - Background modeling
- Measure mass difference?



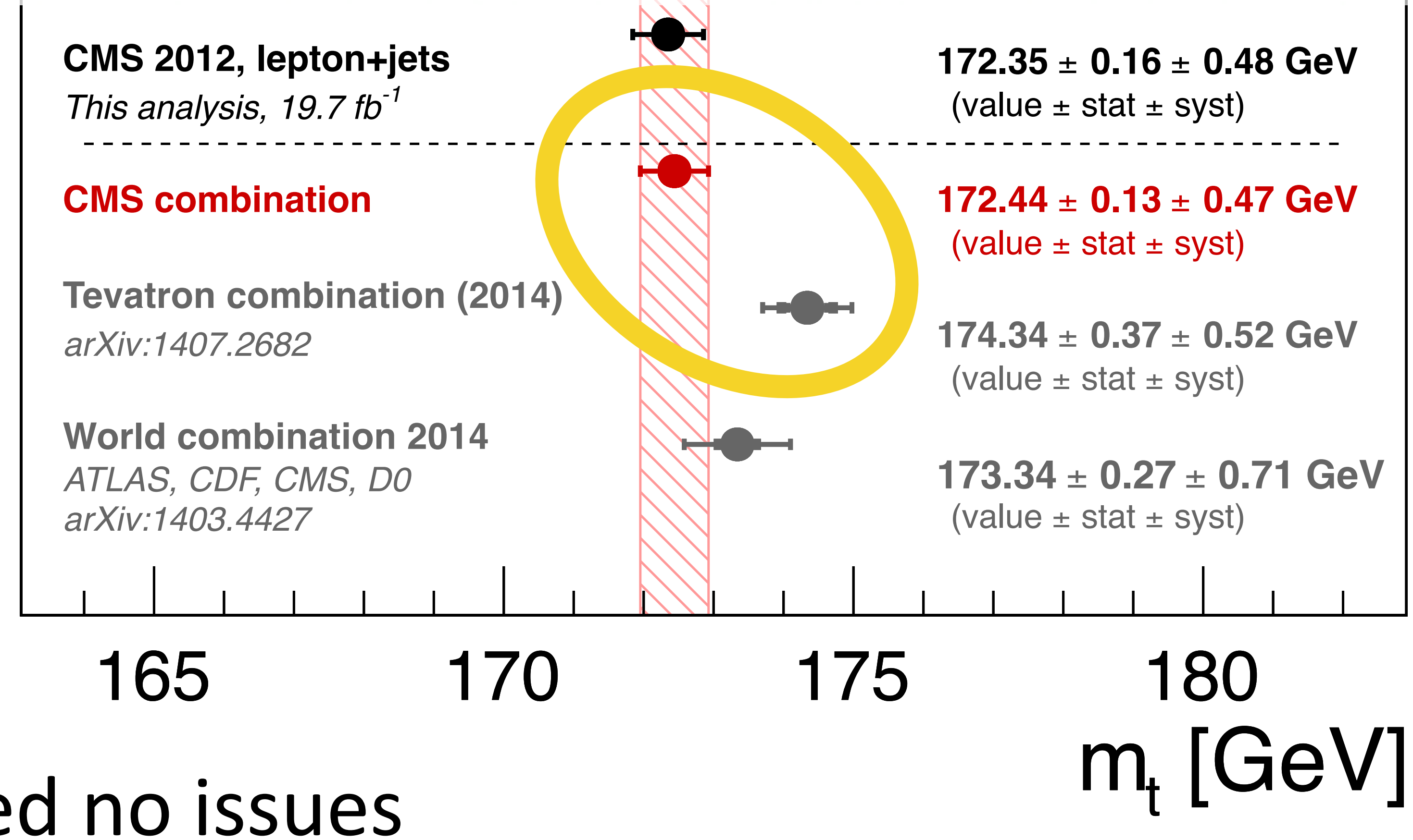
m_t = 172.6 ± 0.8 ± 1.0 GeV
(stat.) *(syst.)*

TOP-15-001 (2016)

As far as we can tell, different mass definitions yield consistent measurements.



CMS/D0 comparison



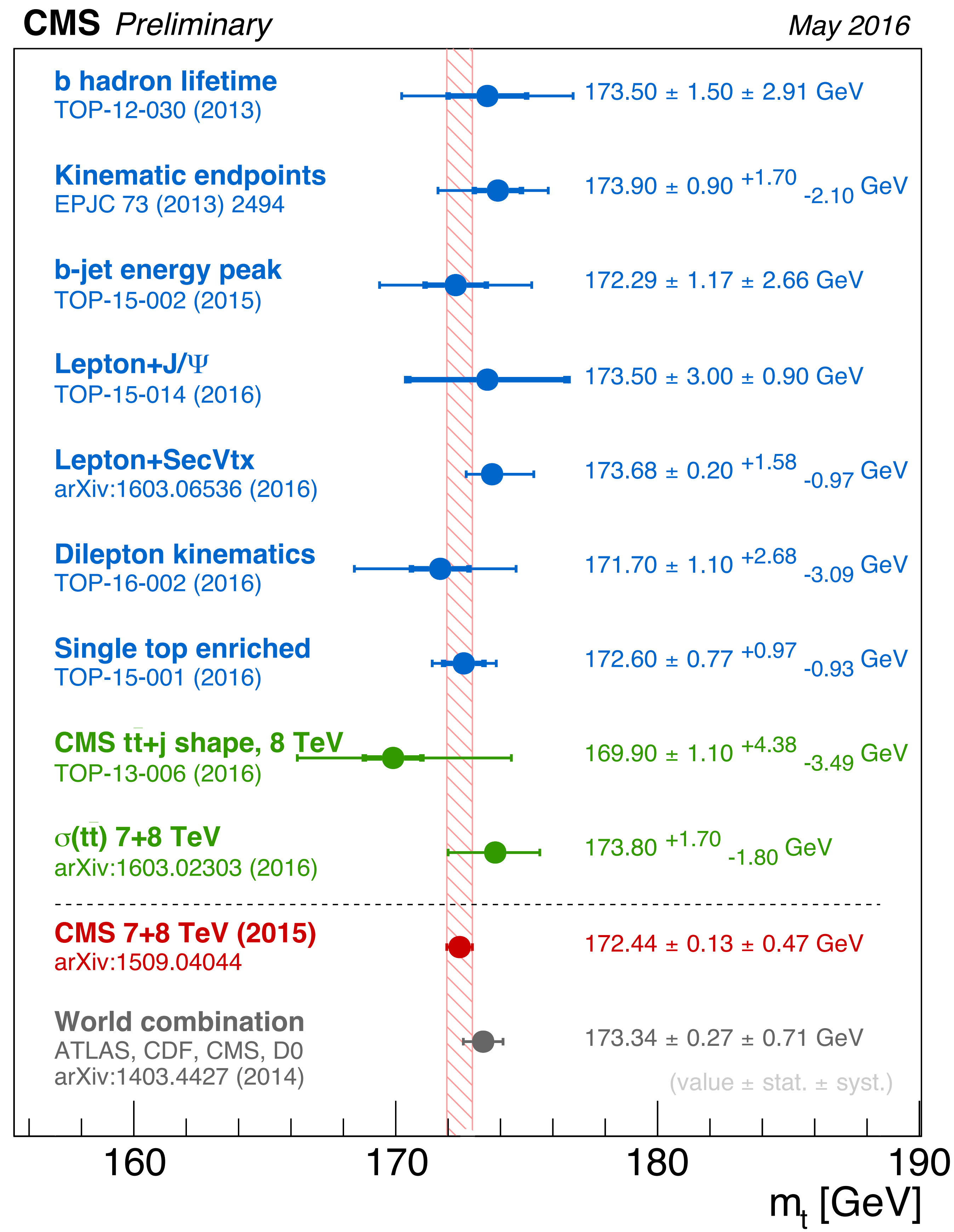
- 3 GeV discrepancy between the two most precise results (l+jets)

- Various cross checks revealed no issues
  - But sprouted fruitful discussions and collaboration

- Next step of common MC setup is well advanced
  - POWHEG + Pythia 6
  - CMS results consistent with published numbers
  - D0 results forthcoming

- More information on cross checks in *May 2015 open session*

- Sub 500 MeV precision from standard measurements
  - Challenging to advance further
  - Awaiting LHC Run I combination
- The precision is limited by our ability to model the signal
  - In particular related to the **b-quark hadronization**
  - On experimental side from influence in jet-energy scales
- Alternative methods can help tackle the issue from different sides and contribute to understanding of modeling
- Different techniques and employed mass definitions give consistent results (*so far*)



CMS public results: http://cms-results.web.cern.ch/cms-results/public-results/publications/

Additional material

lepton+SV

CMS TOP-12-030

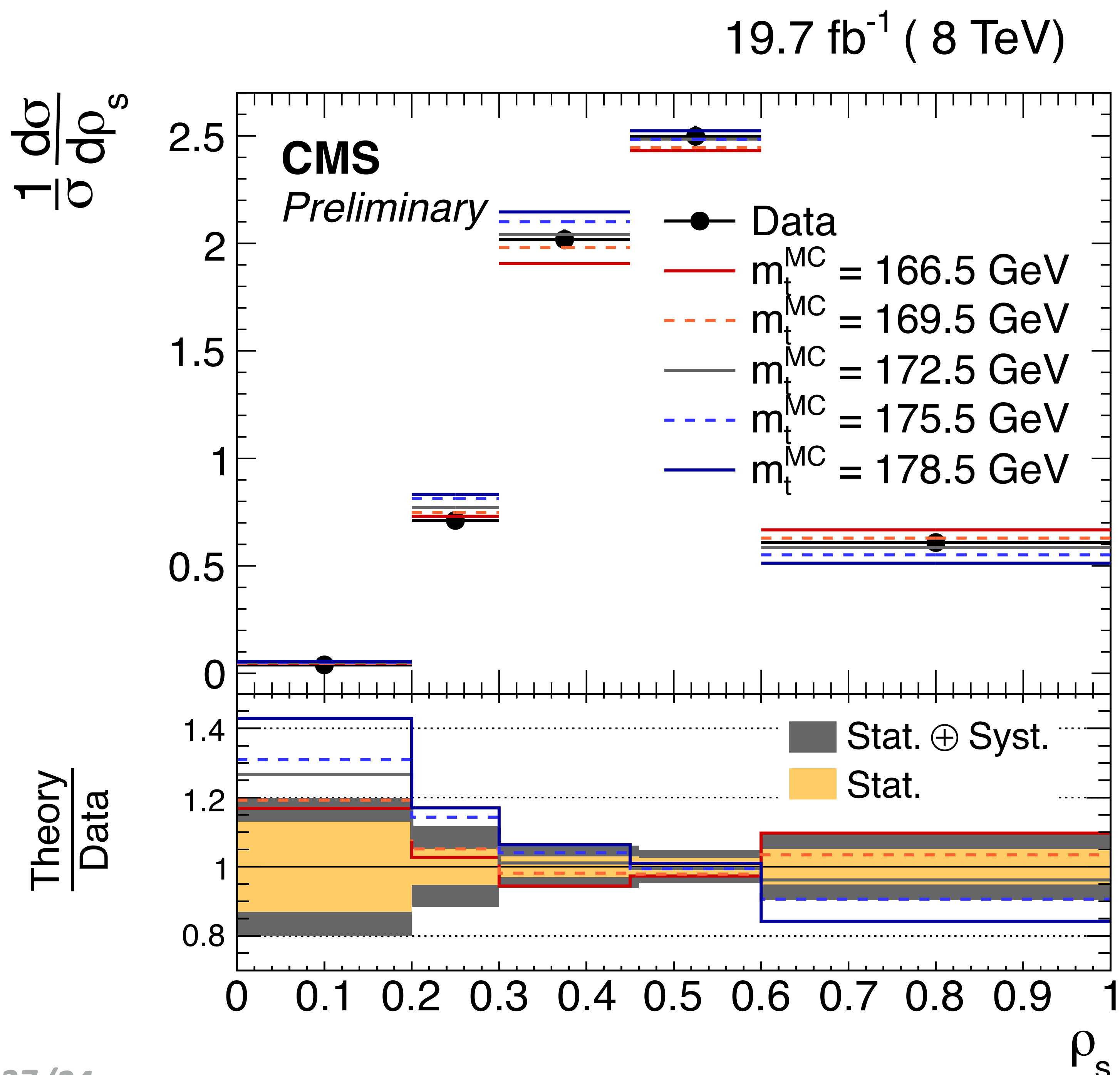
Source	Δm_t [GeV]	
Theoretical uncertainties		
μ_R/μ_F scales $t\bar{t}$	+0.22	−0.20
μ_R/μ_F scales t (*t*-channel)	−0.04	−0.02
μ_R/μ_F scales tW	+0.21	+0.17
Parton shower matching scale	−0.04	+0.06
Single top quark fraction	−0.07	+0.07
Single top quark diagram interference (*)	+0.24	
Parton distribution functions	+0.06	−0.04
Top quark p_T	+0.82	
Top quark decay width (*)	−0.05	
b quark fragmentation	+1.00	−0.54
Semileptonic B decays	−0.16	+0.06
b hadron composition (*)	−0.09	
Underlying event	+0.07	+0.19
Color reconnection (*)	+0.08	
Matrix element generator (*)	−0.42	
$\sigma(t\bar{t}$ + heavy flavor)	+0.46	−0.36
Total theoretical uncertainty	+1.52	−0.86
Experimental uncertainties		
Jet energy scale	+0.19	−0.17
Jet energy resolution	−0.05	+0.05
Unclustered energy	+0.07	−0.00
Lepton energy scale	−0.26	+0.22
Lepton selection efficiency	+0.01	+0.01
b tagging	−0.02	−0.00
Pileup	−0.05	+0.07
Sec.-vertex track multiplicity (*)	−0.06	
Sec.-vertex mass modeling (*)	−0.29	
Background normalization	< 0.03	
Total experimental uncertainty	+0.43	−0.44
Total systematic uncertainty	**+1.58**	**−0.97**
Statistical uncertainty	**±0.20**	

lepton+J/Ψ

CMS TOP-15-014

Source	Value (GeV)
Experimental uncertainties	
Monte Carlo statistics	±0.22
Muon momentum scale	±0.09
Electron momentum scale	±0.11
Modeling of the J/ψ candidate mass distribution	+0.09
Jet energy scale	< 0.01
Jet energy resolution	< 0.01
Trigger efficiencies	±0.02
Background normalization	±0.01
Pileup	±0.08
Theoretical uncertainties	
ME generator	−0.37
Renormalization scale	$\{^{+0.12}_{-0.46}$
ME-PS matching threshold	$\{^{+0.12}_{-0.58}$
top quark transverse momentum	+0.64
b fragmentation	±0.30
Underlying event	±0.13
Color reconnection modeling	+0.12
Parton density functions	$\{^{+0.39}_{-0.11}$
Total	$\{^{+0.89}_{-0.94}$

tt+1jet systematics



Source	Δm_t [GeV]
POWHEG $t\bar{t}$+jet modelling	$^{-1.6}_{+3.6}$
Jet-Parton Matching	$^{-0.1}_{+1.6}$
Q^2 Scale	$^{+1.0}_{-2.8}$
ME/Showering	± 0.4
Color Reconnection	± 0.7
Underlying Event	± 0.3
PDF	$^{+0.9}_{-0.1}$
Background	± 1.0
Jet Energy Scale	± 0.1
Jet Energy Resolution	± 0.1
Pile-Up	± 0.3
Trigger Eff.	< 0.1
Kinematic Reconstruction	< 0.1
Lepton Eff.	± 0.1
B-Tagging	± 0.3
Syst. uncertainty	$^{+2.5}_{-3.1}$
Stat. untertainty	± 1.1

TOP-13-006 (2016)