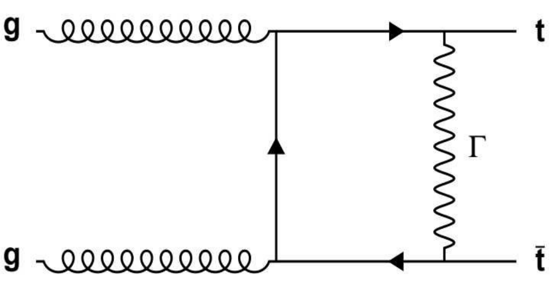
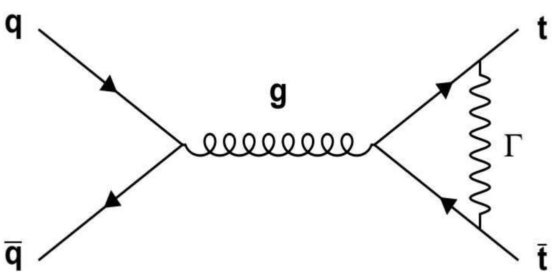
Top Quark Physics at the Precision Frontier

Fermilab LPC, May 16, 2019

Extracting the top Yukawa coupling from differential $\sigma_{t\bar{t}}$ in CMS

- Introduction and motivation
- Weak corrections
  - -2% effect on total cross section
  - Enhanced for large values of g_t
  - Sensitive variables: $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$
- ℓ+jets selection
- $t\bar{t}$ reconstruction
  - 3 jets: novel technique
  - 4 jets
- Extraction of strength of Yukawa coupling
- Conclusions





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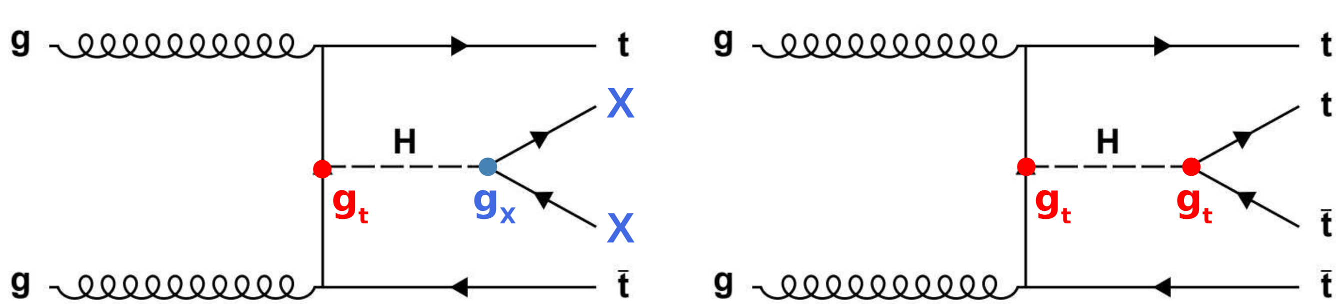
On behalf of the CMS Collaboration

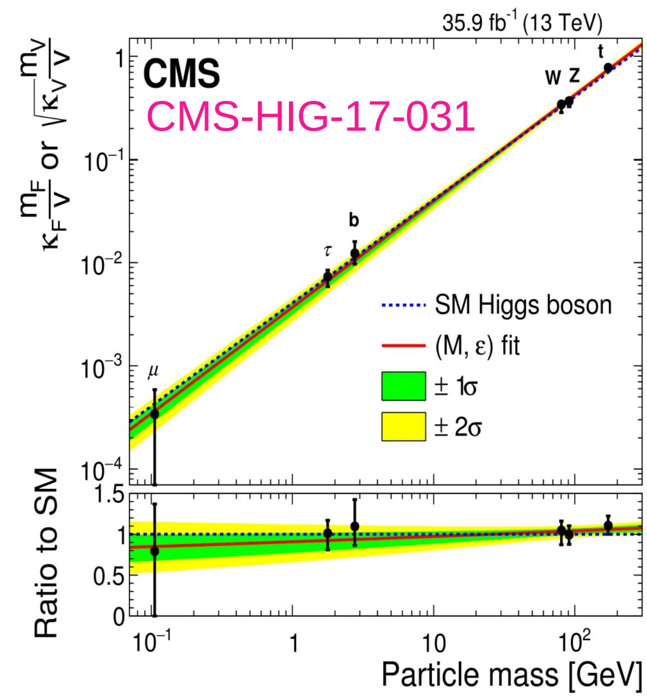
Top quark Yukawa coupling

- Fermion mass terms generated by Higgs mechanism
  - Yukawa coupling between Higgs field (ϕ) and left-handed fermion doublets (L) and right-handed fermion singlets (R)

$$\mathcal{L}_{\text{Yukawa}} = -\mathbf{g}\left[\bar{\mathbf{L}}\phi\mathbf{R} + \bar{\mathbf{R}}(\phi^{\mathbf{T}})^{*}\mathbf{L}\right] = -\mathbf{g}\frac{\mathbf{v}}{\sqrt{\mathbf{2}}}\mathbf{q}\bar{\mathbf{q}} = -\mathbf{m_q}\mathbf{q}\bar{\mathbf{q}}$$

- For top quark: $g_t = \sqrt{2}m_t/v \approx 1$
  - Any deviation could be a sign of new physics
- Can measure g_t directly in $t\bar{t}H$ production

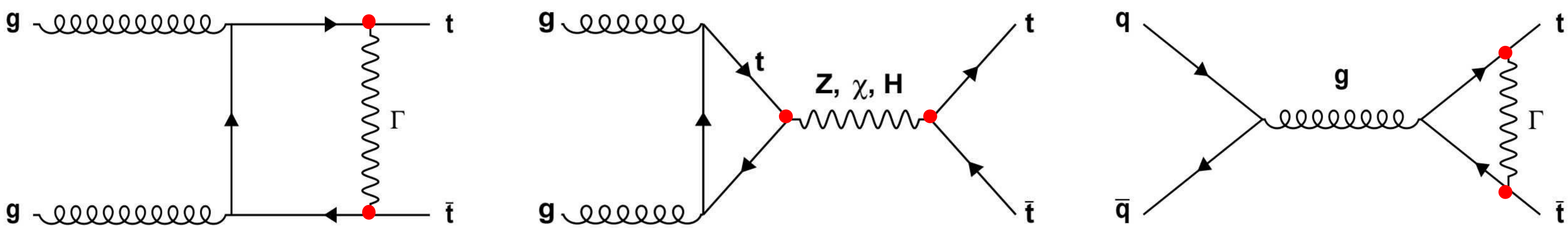




  - Depends on H coupling to other particles in decay
  - Except for 4-top final state

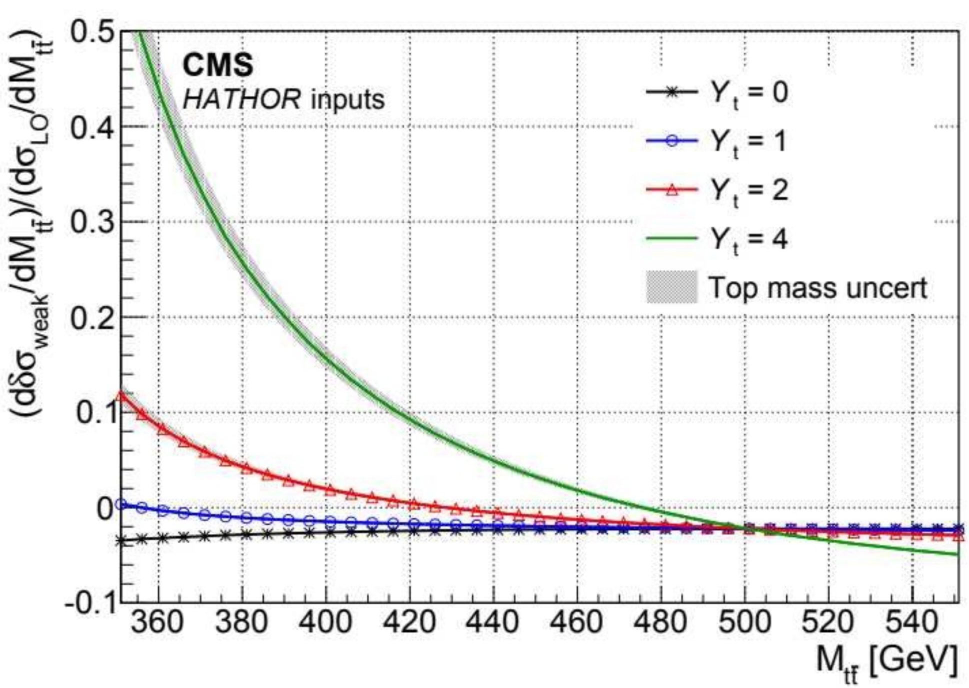
Weak corrections to $t\bar{t}$ production

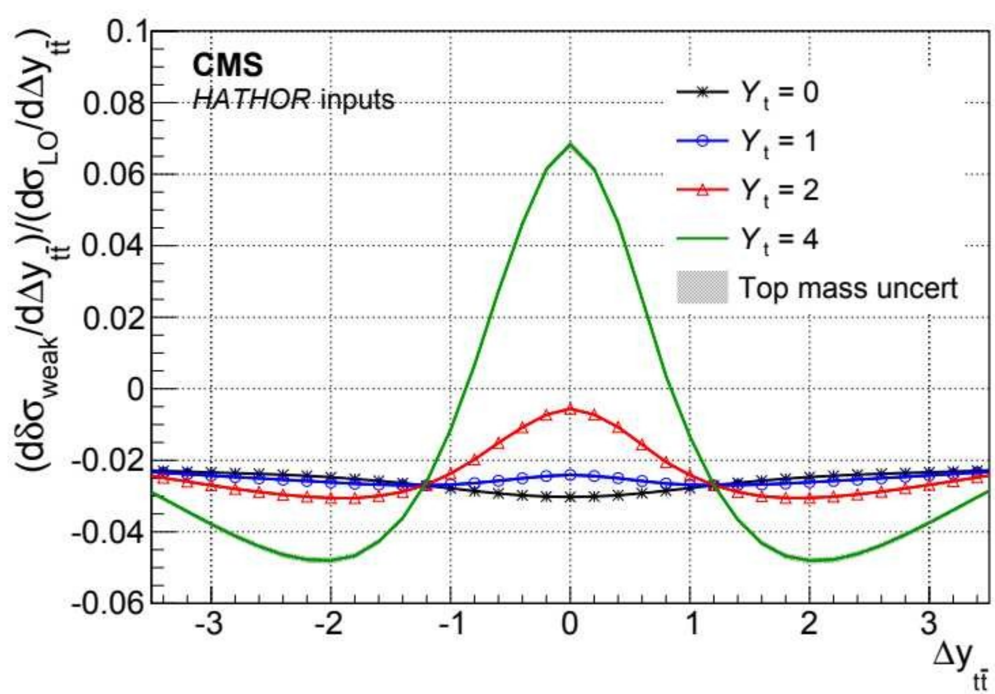
- Another way to measure g_t independently of other H couplings is through weak corrections in $t\bar{t}$ production



P. Uwer et al. [arXiv: 1305.5773, PRD 91, 014020 (Feb 2015)]

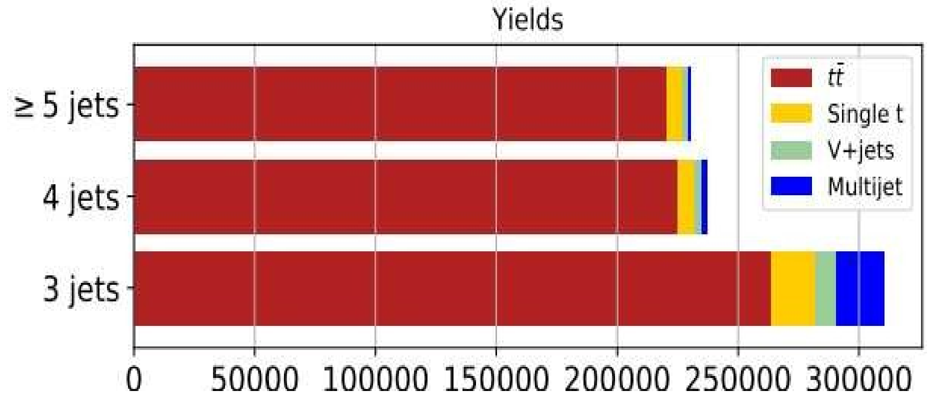
- Hathor 2.1 is used to calculate the contribution to the LO $\alpha_W\ \sigma_{tt}$
  - Apply as 2D scale factors to POWHEG → templates in $Y_t = g_t/g_t^{SM}$



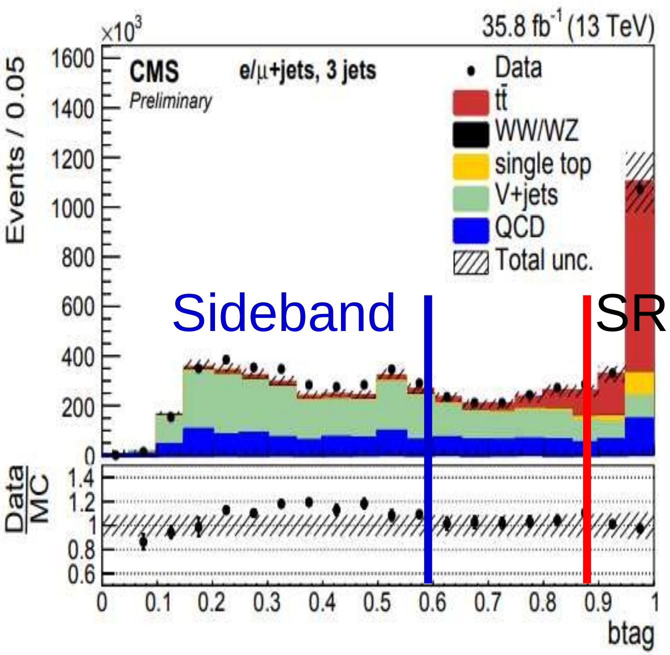


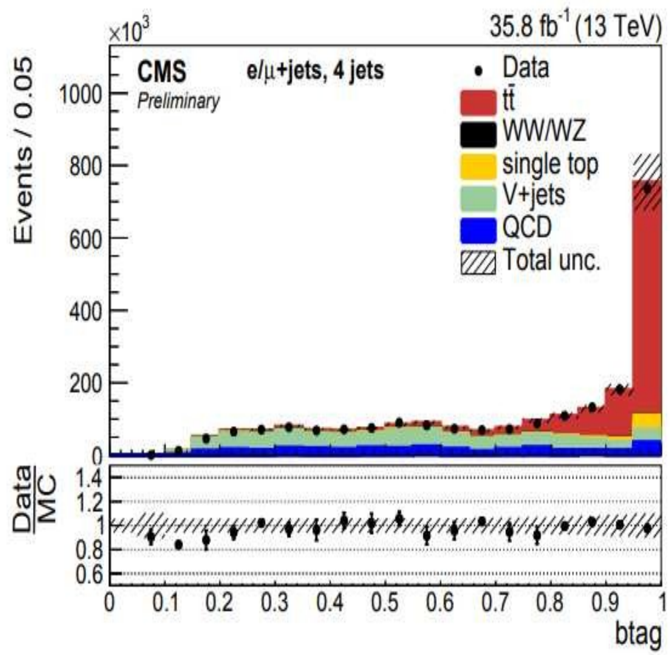
35.8 fb^{-1} ℓ+jets selection

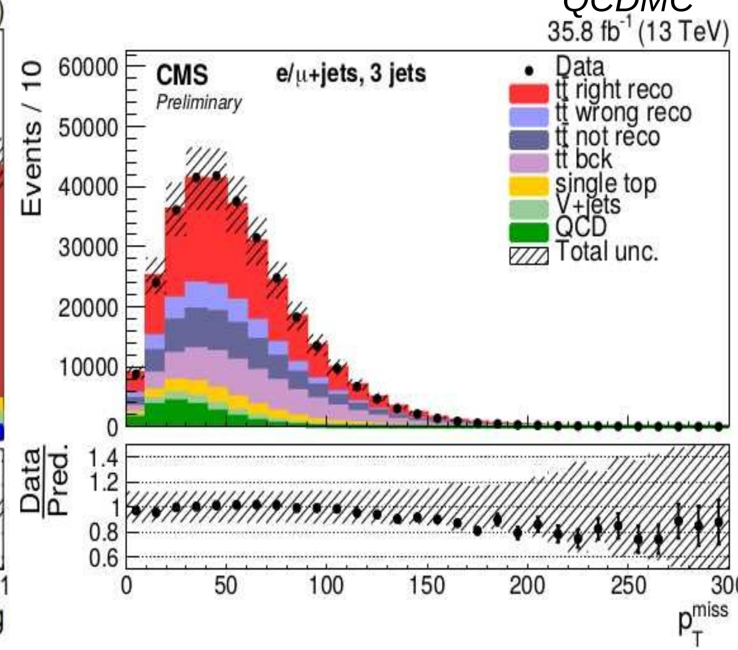
- Triggers based on isolated leptons
  - 1 isolated e or μ, p_T>30 GeV, |η|<2.4
  - ≥3 jets with p_T>30 GeV, |η|<2.4
  - ≥2 b-tagged (ε_b≈65% ; ε_{qg}≈3%)



- Background modeling:
  - Single top: POWHEG (t-ch), Madgraph5 (tW)
  - W+jets and Drell Yan+jets: POWHEG
  - QCD multijets: shape from data sideband defined by CSV<0.6
    - QCD normalization by transfer factor from data: $N_{QCD}^{SR} = N_{resDATA}^{CR} \frac{N_{QCDMC}^{SR}}{N_{QCDMC}^{CR}}$



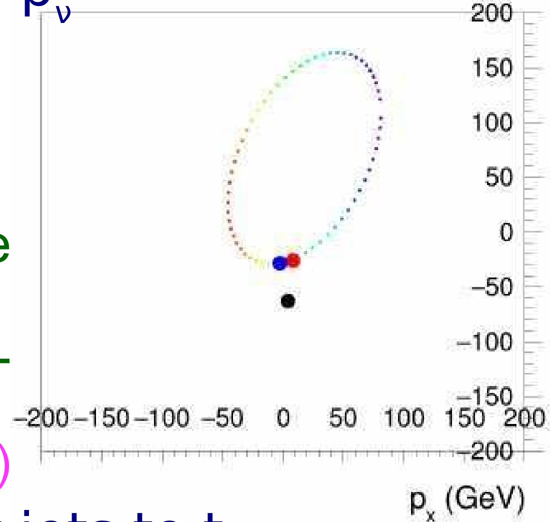


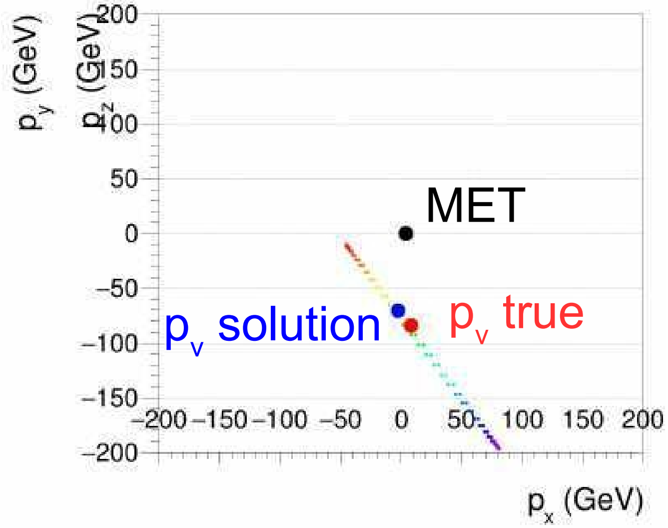


$t\bar{t}$ reconstruction in ≥4 jet events

- 2 b-tags: assume they are from top
- Need to find correct jet assignment to tops
- First, we need to determine p_ν
  - Use mass constraints on the leptonic side
  - Each equation describes an ellipsoid in momentum space
  - Choose p_ν as the point with minimum distance D_ν to MET

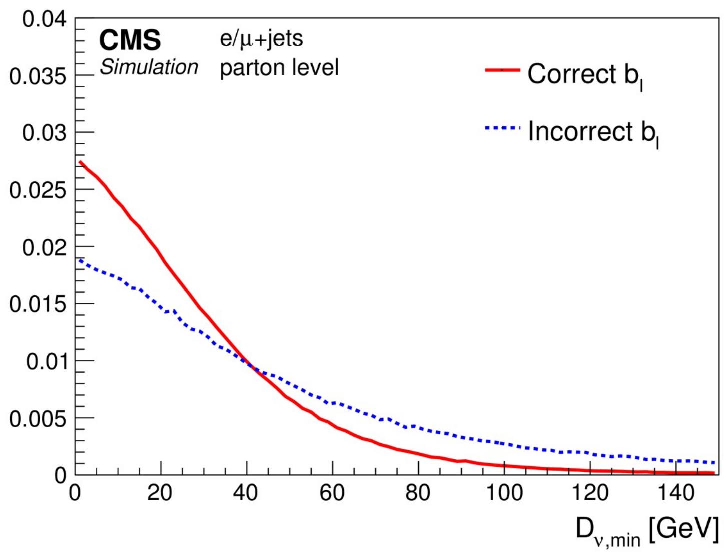
$$(p_\nu + p_\ell)^2 = m_W^2$$
$$(p_\nu + p_\ell + p_{b_\ell})^2 = m_t^2$$

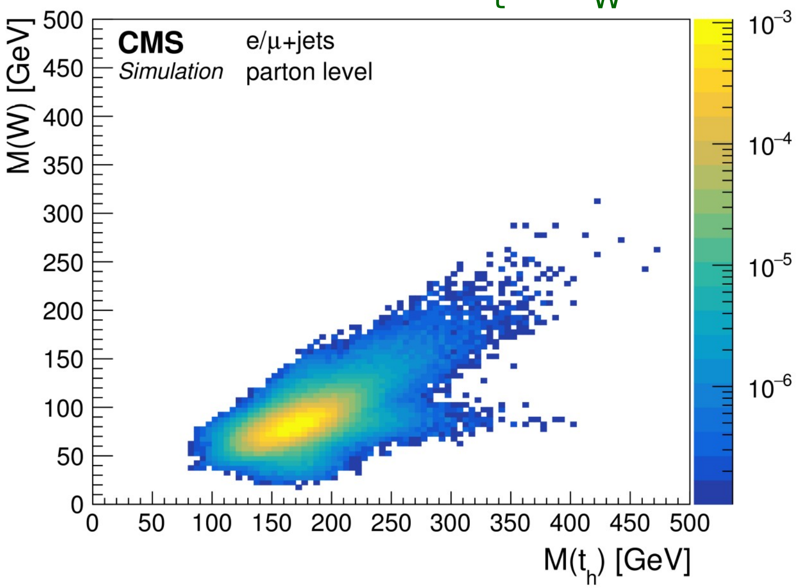




Nucl. Instrum. Meth. A 736, 169 (2014)

- Next need to assign correct jets to t_{had}
  - Calculate probability from 2D distributions of m_t, m_W on hadronic side





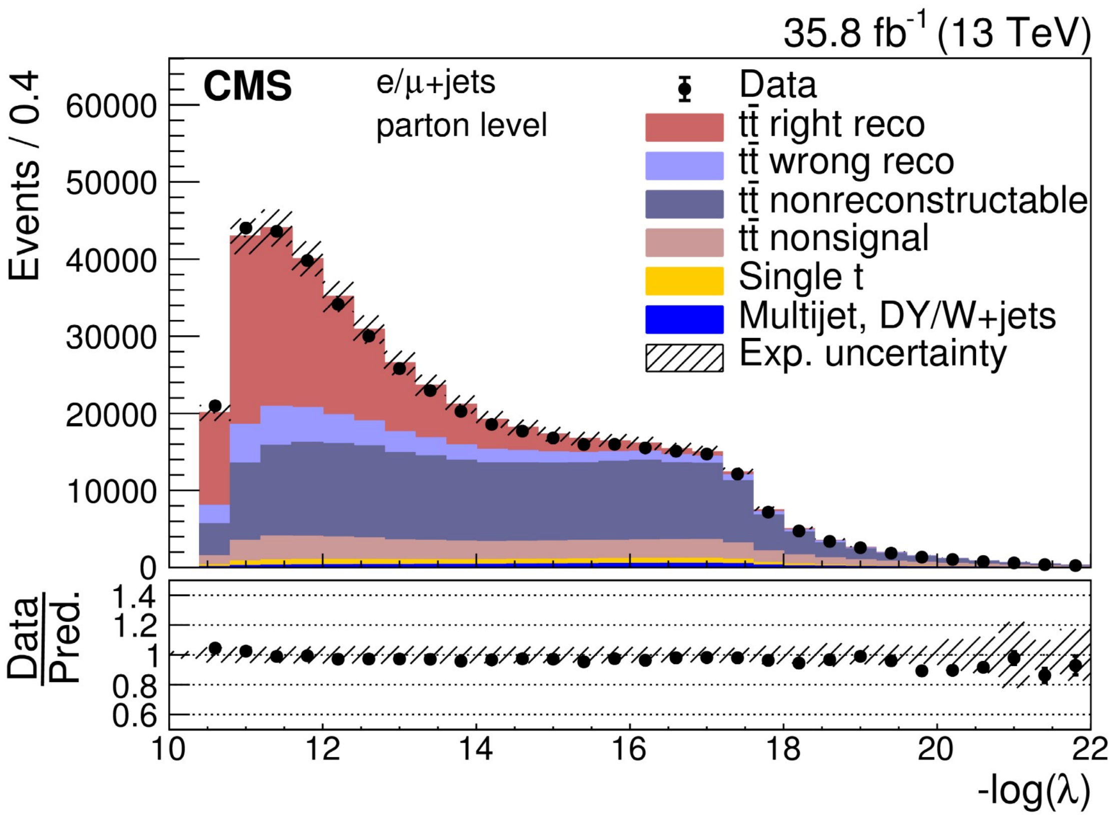
$t\bar{t}$ reconstruction in ≥4 jet events

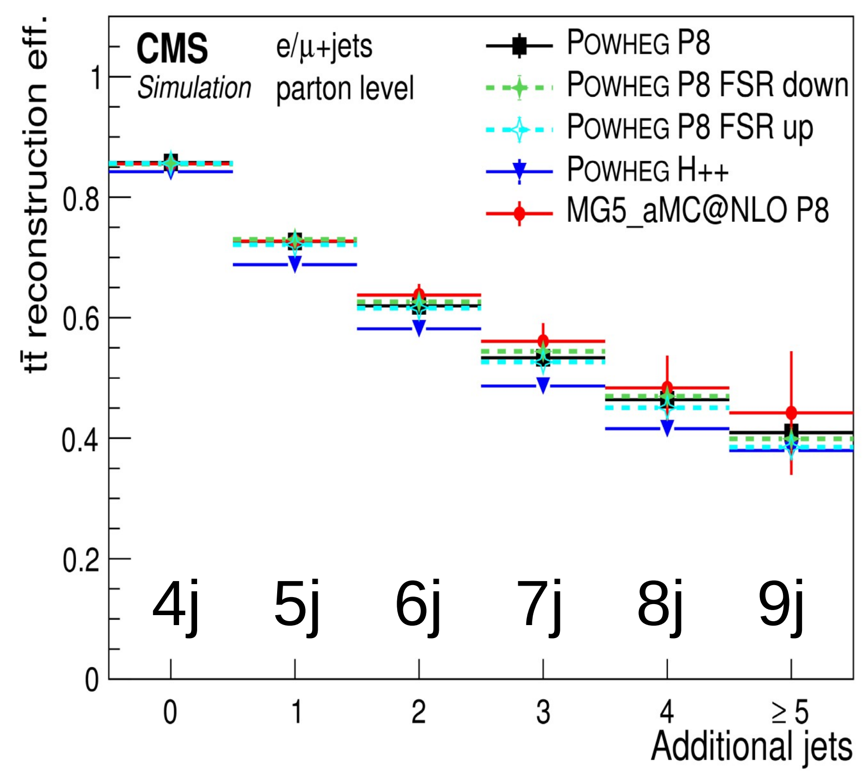
- Finally, build final discriminant combining the m_{Whad},m_{thad} probability and $D_{\nu\,min}$ probability

$$-\ln(\lambda_4) = -\ln\left(P_{\mathrm{m}}(m_{\mathrm{W_h}}, m_{\mathrm{t_h}})\right) - \ln\left(P_{\nu}(D_{\nu,\mathrm{min}})\right)$$

- Select permutation with lowest -ln(λ)

CMS-TOP-17-002: PRD 97 (2018) 112003



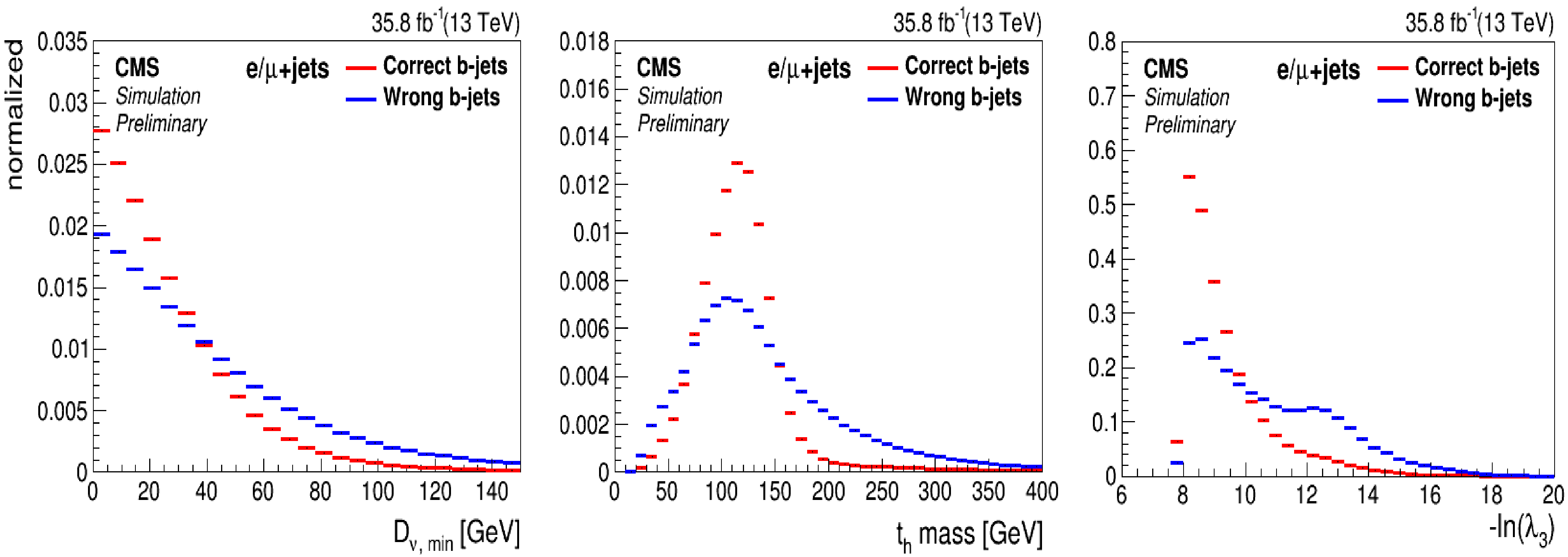


$t\bar{t}$ reconstruction in 3 jet events

- At the threshold of tt production, quarks from $t\bar{t}$ decay are likely to have p_T or η outside our acceptance
  - In 93% of 3 jet events one of the soft jets from W is lost
- Now use the hadronic top mass and the leptonic $D_{\nu,min}$

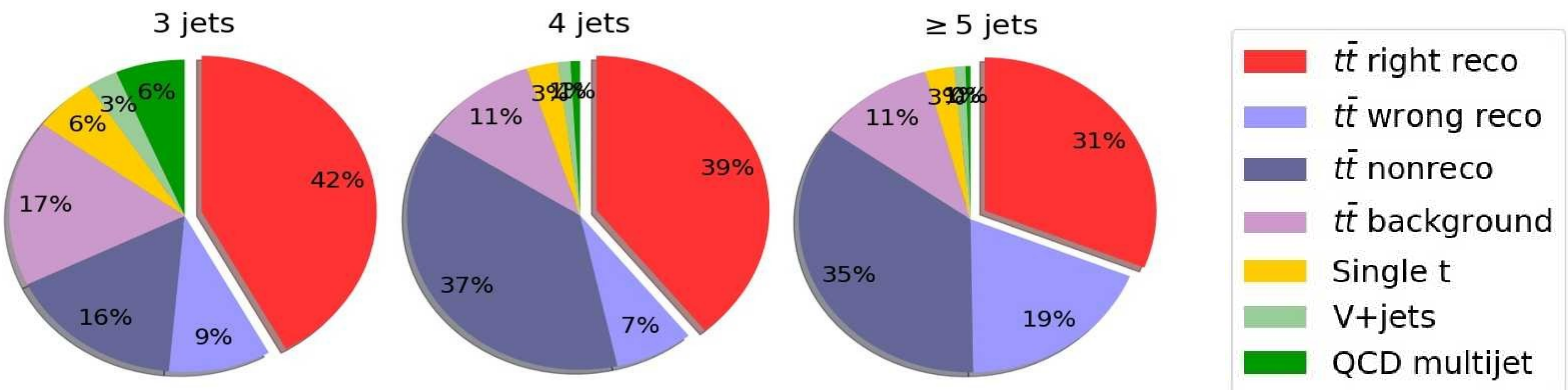
$$-\ln(\lambda_3) = -\ln(P_{m_{t_h}}) - \ln(P_\nu(D_{\nu,\min}))$$

- This method correctly identifies 80% of assignments

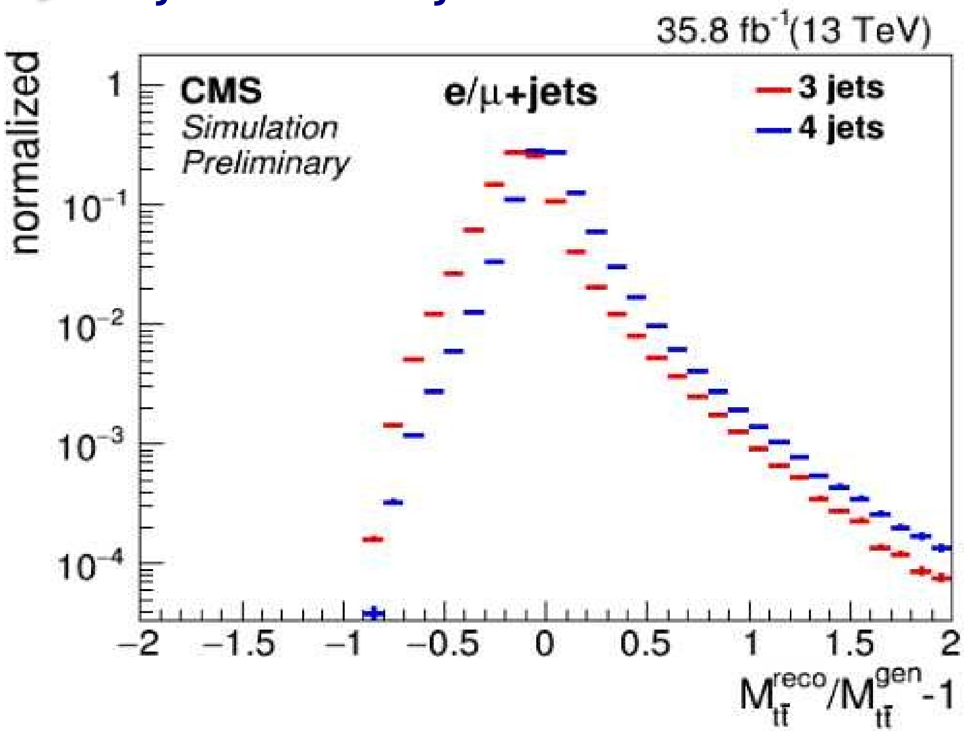


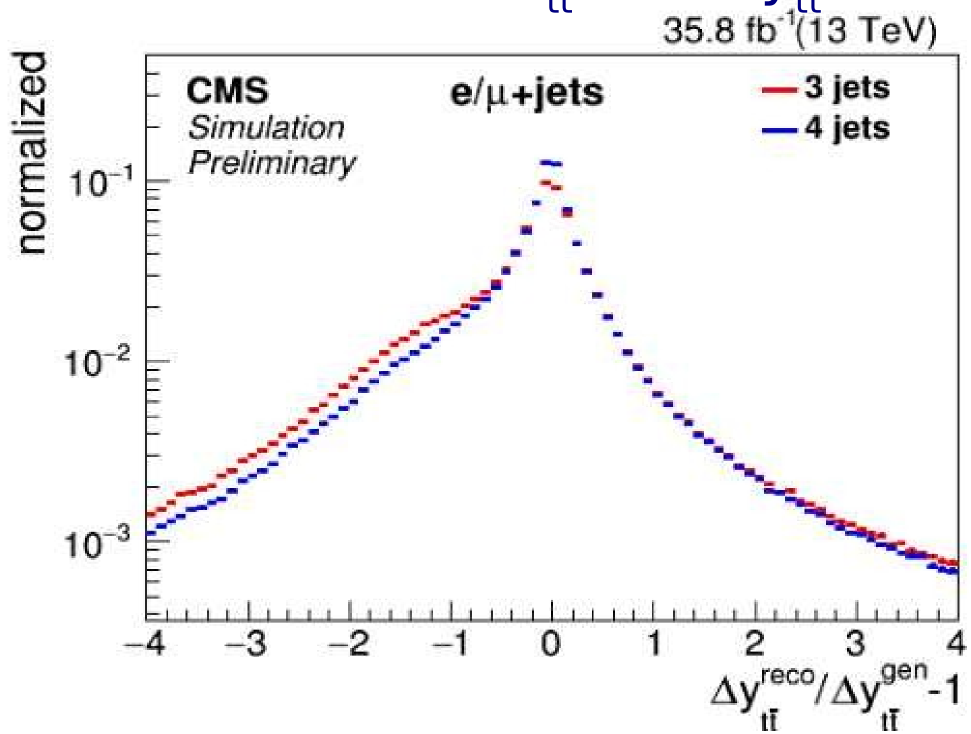
Impact of 3 jet events

- Purity of $t\bar{t}$: 85% in 3 jet, 95% in 4 jet category

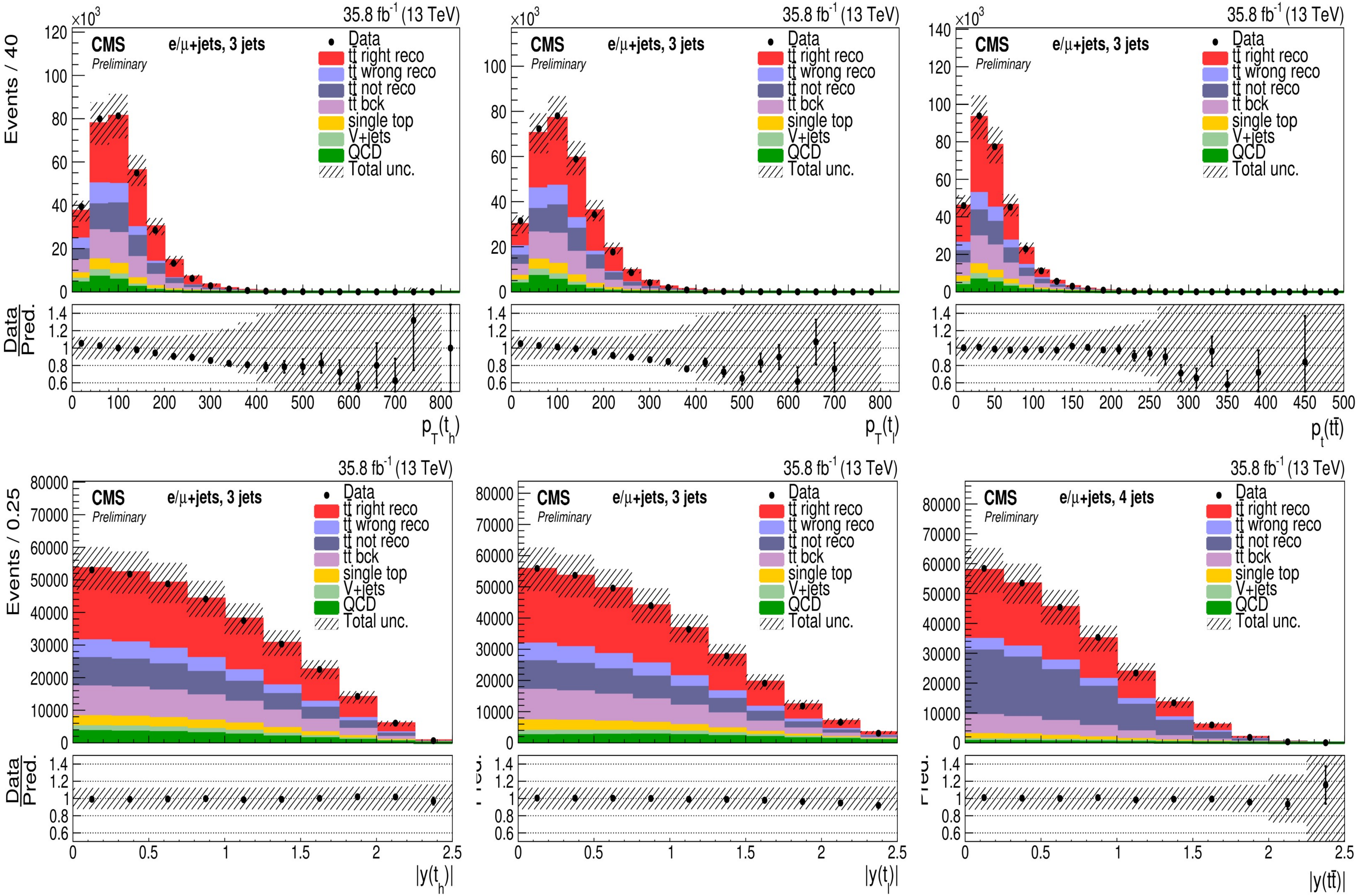


- 3 jet and 4 jet events have a similar resolution in $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$

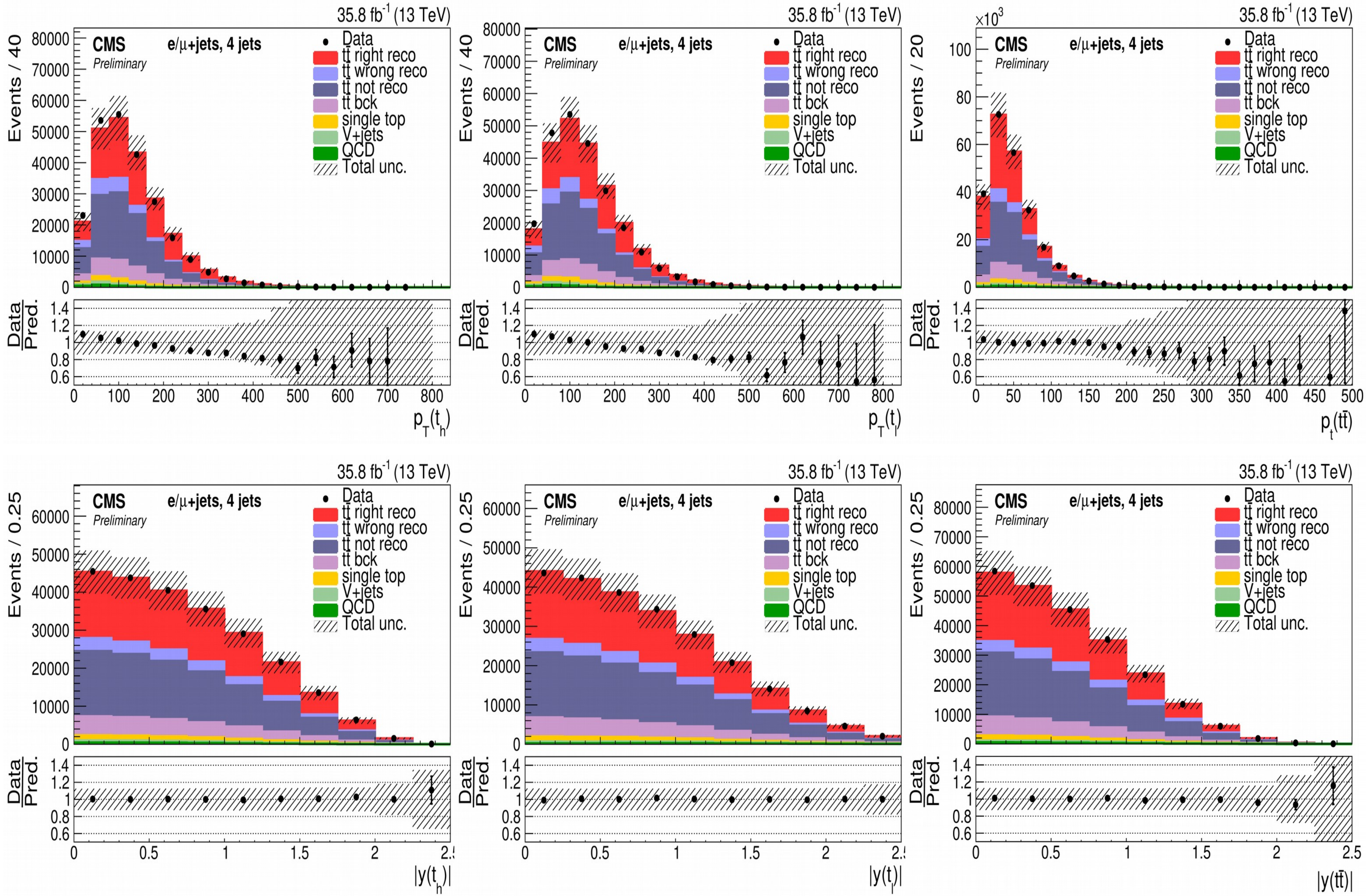




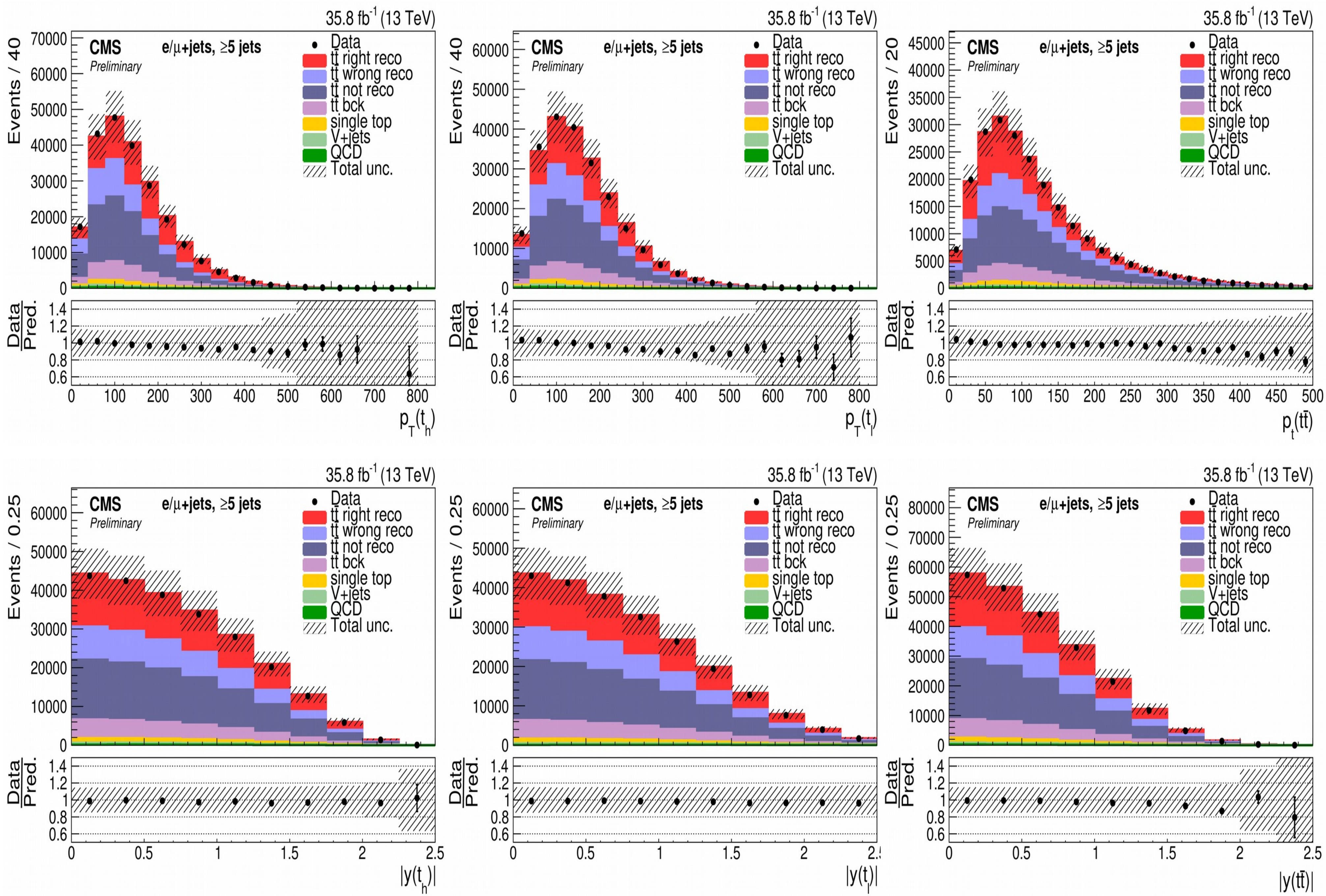
Control plots: 3 jets



Control plots: 4 jets

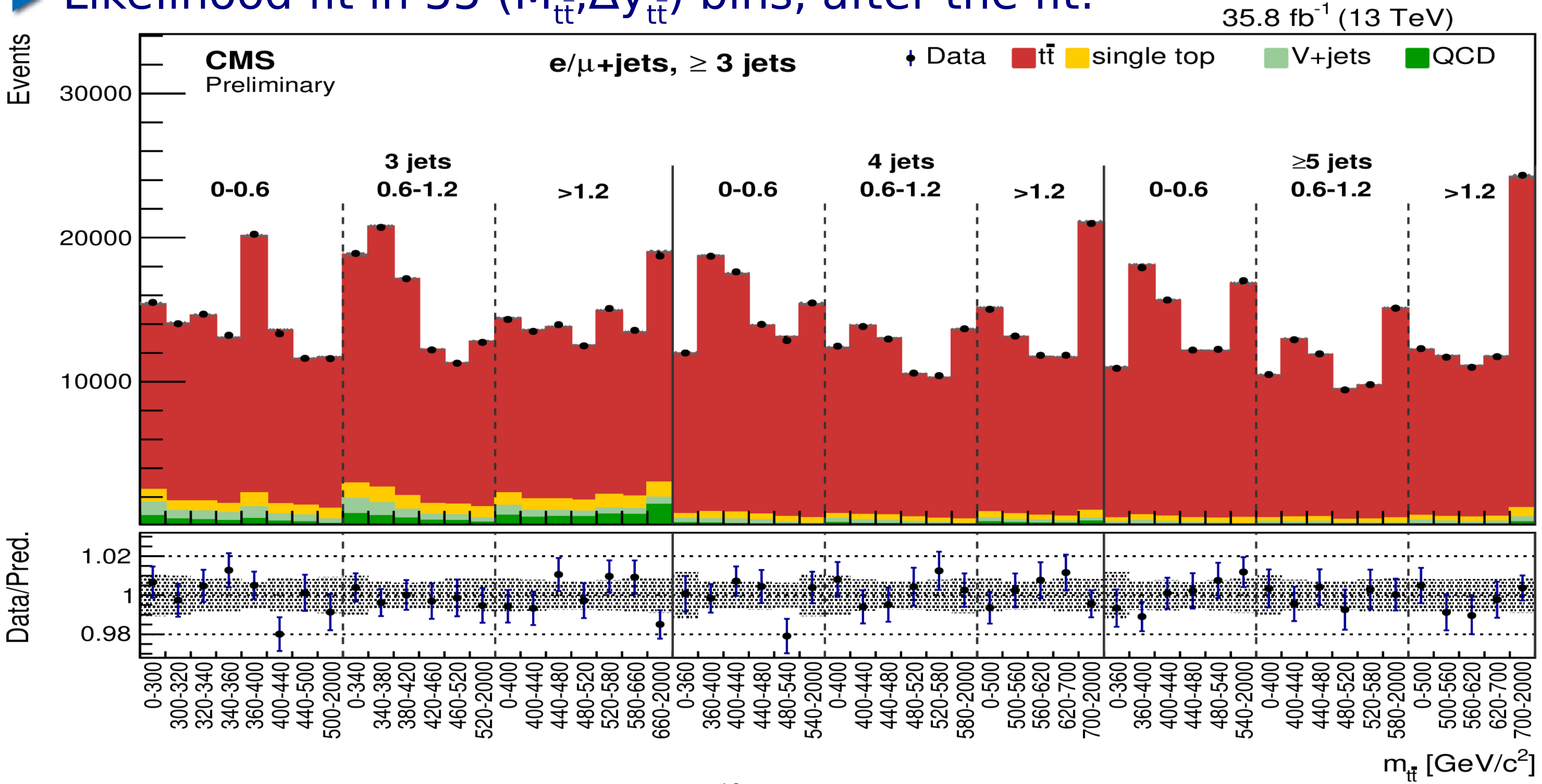


Control plots: ≥5 jets

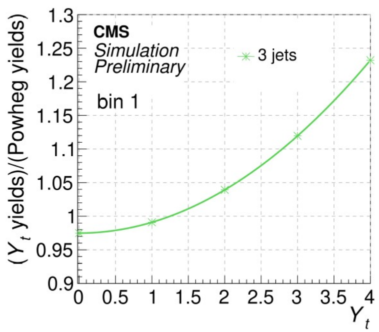


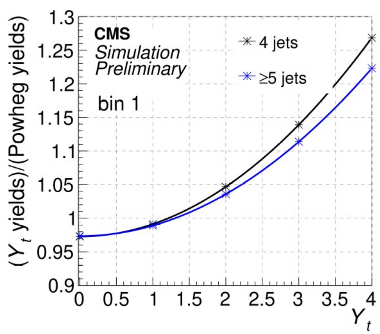
Extracting the Yukawa coupling

- Likelihood fit in 55 ($M_{t\bar{t}}$,$\Delta y_{t\bar{t}}$) bins, after the fit:



- Templates of strength of weak correction/uncorrected yields at detector level vs Y_t





Systematic uncertainties

- Jet energy corrections are the dominant source
- QCD shape uncertainty derived by b-tagging inversion → larger uncertainties for 3 jets channel
- Δm_t from ±1GeV MC samples
- Top p_T modeling: compare to NNLO distributions
- Uncertainty due to weak correction estimated by (scale variation)x(weak correction) → tiny systematic, low impact

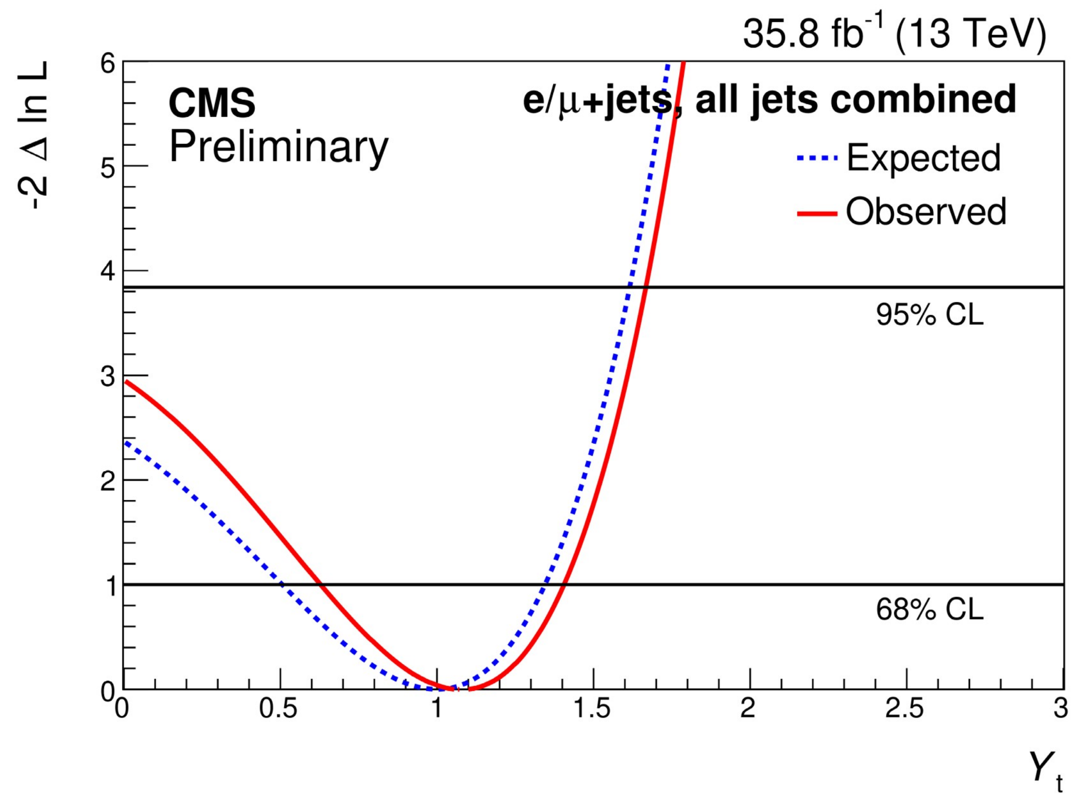
Uncertainty	$t\bar{t}$	single t	V+jets	QCD
Luminosity	2.5%	2.5%	2.5%	2.5%
Pileup	shape	shape	-	-
Lepton ID/trigger	shape	shape	shape	-
JEC (19 independent variations)	shape	shape	-	-
JER	shape	-	-	-
b tagging scale factor	shape	shape	shape	-
b-mistag scale factor	shape	shape	shape	-
Background normalization	-	15%	30%	30%
CSV inversion on QCD template	-	-	-	shape
Factorization & renormalization scale	shape	shape	shape	-
PDF	shape	shape	-	-
$\alpha_s(M_Z)$ in PDFs	shape	shape	-	-
Top quark mass	shape	-	-	-
Top quark p_T modeling	shape	-	-	-
Parton Shower				
-NLO shower matching	shape	-	-	-
-ISR	2%/2%/3%	-	-	-
-FSR	shape	shape	-	-
-Color reconnection	shape	-	-	-
-b-jet fragmentation	shape	shape	-	-
-B hadron branching fraction	shape	shape	-	-
Weak correction $\delta_{QCD}\delta_{EW}$	shape	-	-	-

Results

- Combined 95% CL limits:
  - Expected $Y_t < 1.62$
  - Observed $Y_t < 1.67$
- Our analysis is systematics limited

PAS TOP-17-004

Channel	Expected 95% CL	Observed 95% CL
3 jets	$Y_t < 2.17$	$Y_t < 2.59$
4 jets	$Y_t < 1.88$	$Y_t < 1.77$
5 jets	$Y_t < 2.03$	$Y_t < 2.23$
Combined	$Y_t < 1.62$	$Y_t < 1.67$



- Result from $t\bar{t}H \rightarrow t\bar{t}t\bar{t}$ with 35.8 fb^{-1}: $Y_t < 2.1$ @ 95%CL

CMS-TOP-17-009: EPJC 78 (2018) 140

- Result from $t\bar{t}H \rightarrow t\bar{t}t\bar{t}$ with 137 fb^{-1}: $Y_t < 1.7$ @ 95%CL

PAS TOP-18-003

Conclusions

- Use HATHOR 2.1 to derive weights $\delta\sigma_{weak}$/LO as a function of $M_{t\bar{t}}$, $\Delta y_{t\bar{t}}$, g_t

$$\frac{\delta\sigma_{\rm EW}^{\rm 13TeV}}{\sigma_{\rm LO}} = (-2.63 + 0.0029 g_Y + 0.63 g_Y^2)\%,$$

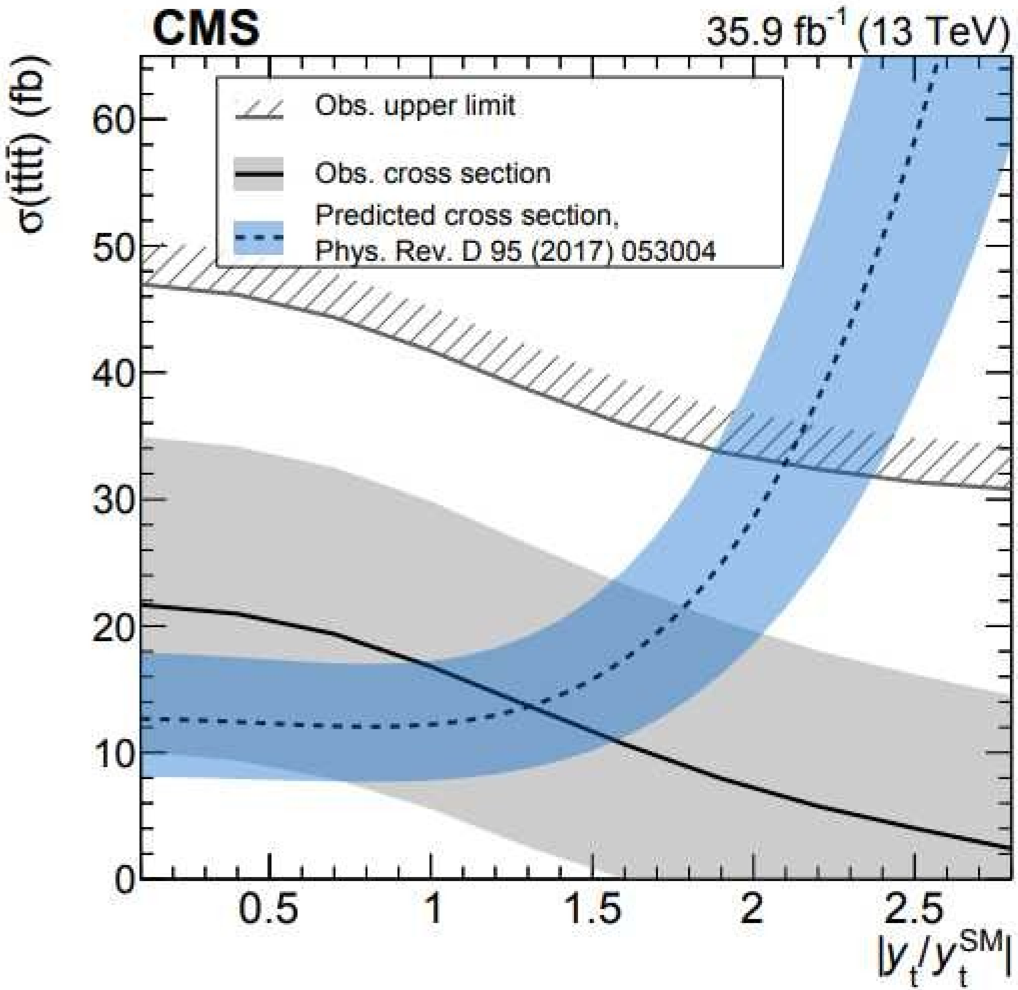
PRD 91 (2015) 014020

- Obtain modified $t\bar{t}$ POWHEG templates
- Follow reconstruction from ℓ+jets differential σ analysis TOP-17-002
- Introduced novel reconstruction technique for 3 jet events in $t\bar{t} \to \ell$+jets
  - 80% efficiency for correct parton/jet assignment in 2 b-tagged sample
  - Resolution in $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ similar to 4 jet category
- Define all $t\bar{t}$ combinations (correct, wrong, etc) as signal, non $t\bar{t}$ components as backgrounds
- Profile likelihood ratio in bins of $M_{t\bar{t}}$, $\Delta y_{t\bar{t}}$: derive strength of gt

95% CL limits Expected: $g_t < 1.62\ g_t^{SM}$; Observed: $g_t < 1.67\ g_t^{SM}$

- Comparable in sensitivity to ttH → 4t results
  - Complementary measurement
- Now working on dilepton final state and full Run II data

Extras


CMS
35.9 fb-1 (13 TeV)
σ(tt̄tt̄) (fb)
Obs. upper limit
Obs. cross section
Predicted cross section,
Phys. Rev. D 95 (2017) 053004
0
10
20
30
40
50
60
0.5
1
1.5
2
2.5
|y_t/y_t^SM|