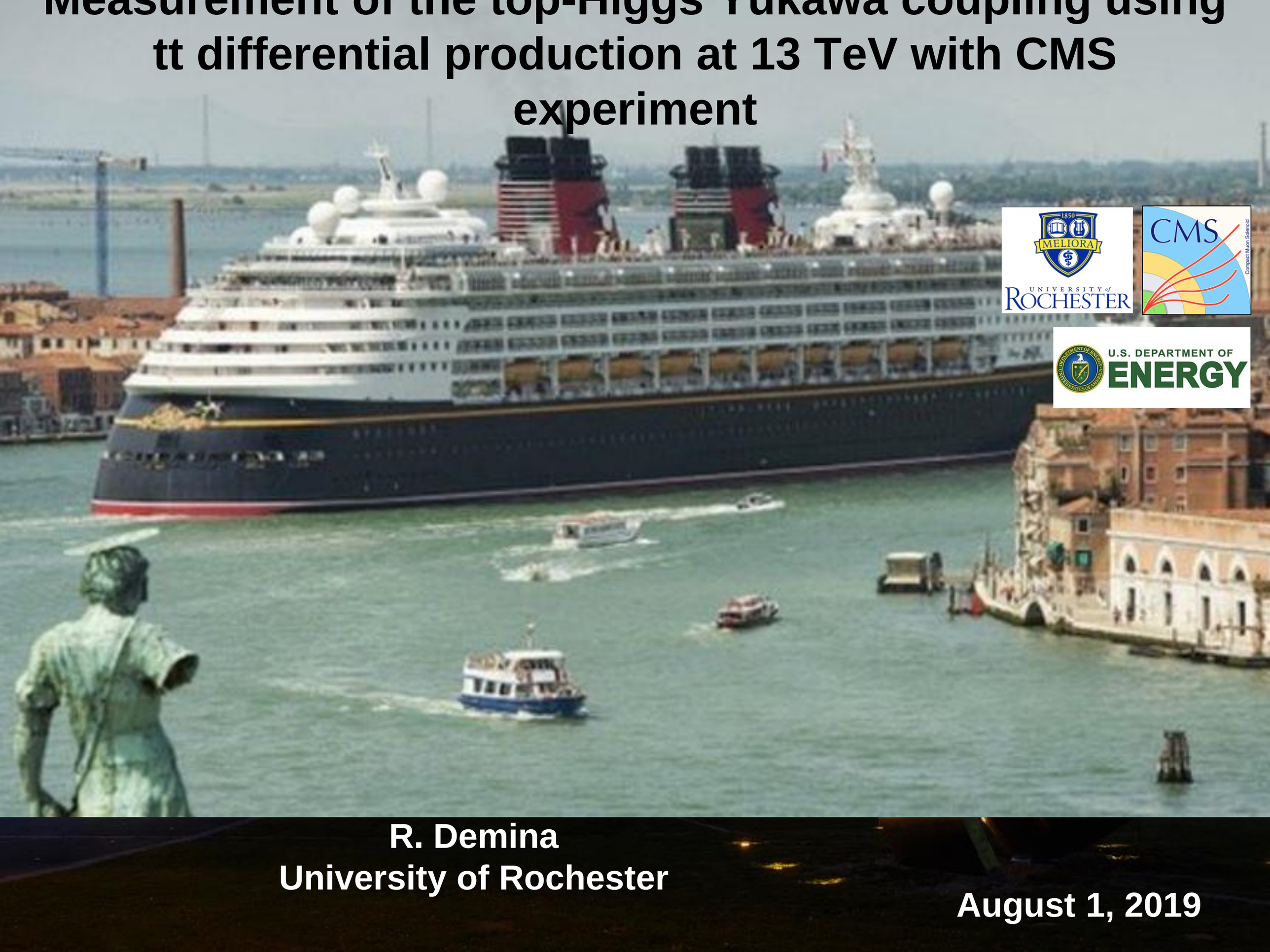
Measurement of the top-Higgs Yukawa coupling using tt differential production at 13 TeV with CMS experiment



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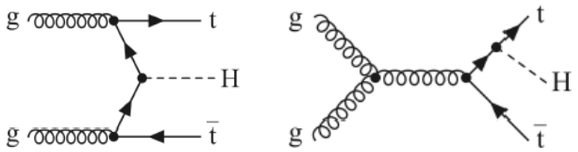
Motivation of this analysis

- **The top quark, as the heaviest known elementary particle, interacts with the Higgs boson with the largest Yukawa coupling, which can be probed**
  - **in ttH production**

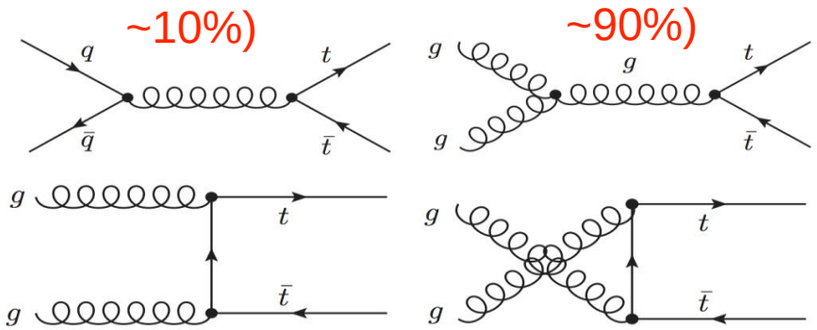


  - **in Higgs production via gluon fusion Higgs since virtual top is the main contributor to the loop**
  - **in search of four top production**
  - **using virtual Higgs exchange in top pair productions**
- **The first two cases depend on the Higgs coupling to its decay products, the second two are sensitive only to top Yukawa coupling**

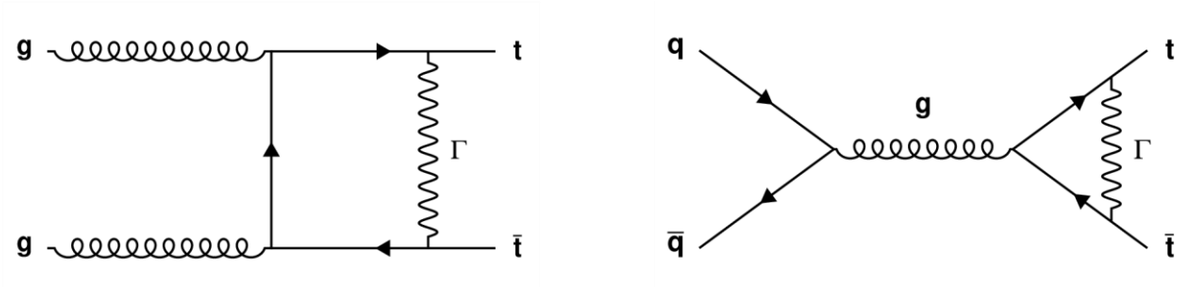
Born-level diagrams for tt production at LHC

qq annihilation (LHC 13 TeV ~10%)

gg fusion (LHC 13 TeV ~90%)



Examples of weak corrections to tt production, which include virtual Higgs exchange



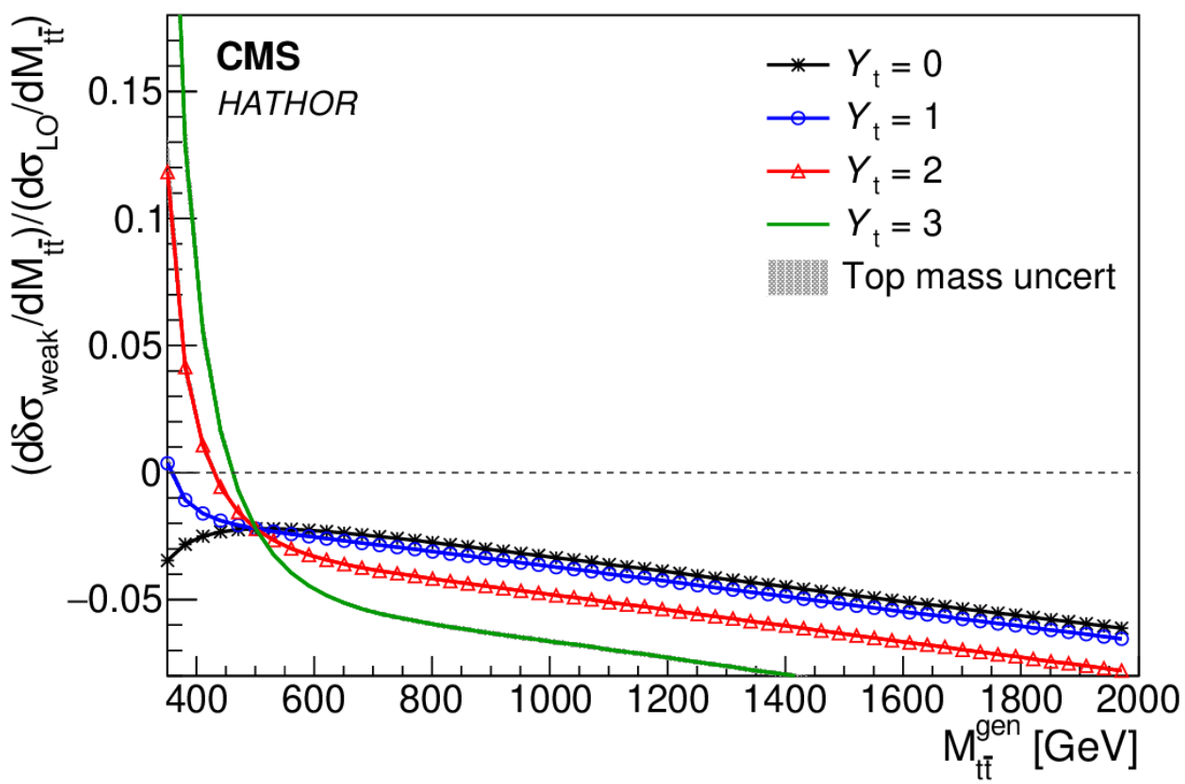
These diagrams interfere with Born-level diagrams resulting in quadratic dependence on Yt

(P. Uwer et al.) Phys. Rev. D 91, 014020 (Feb 2015)

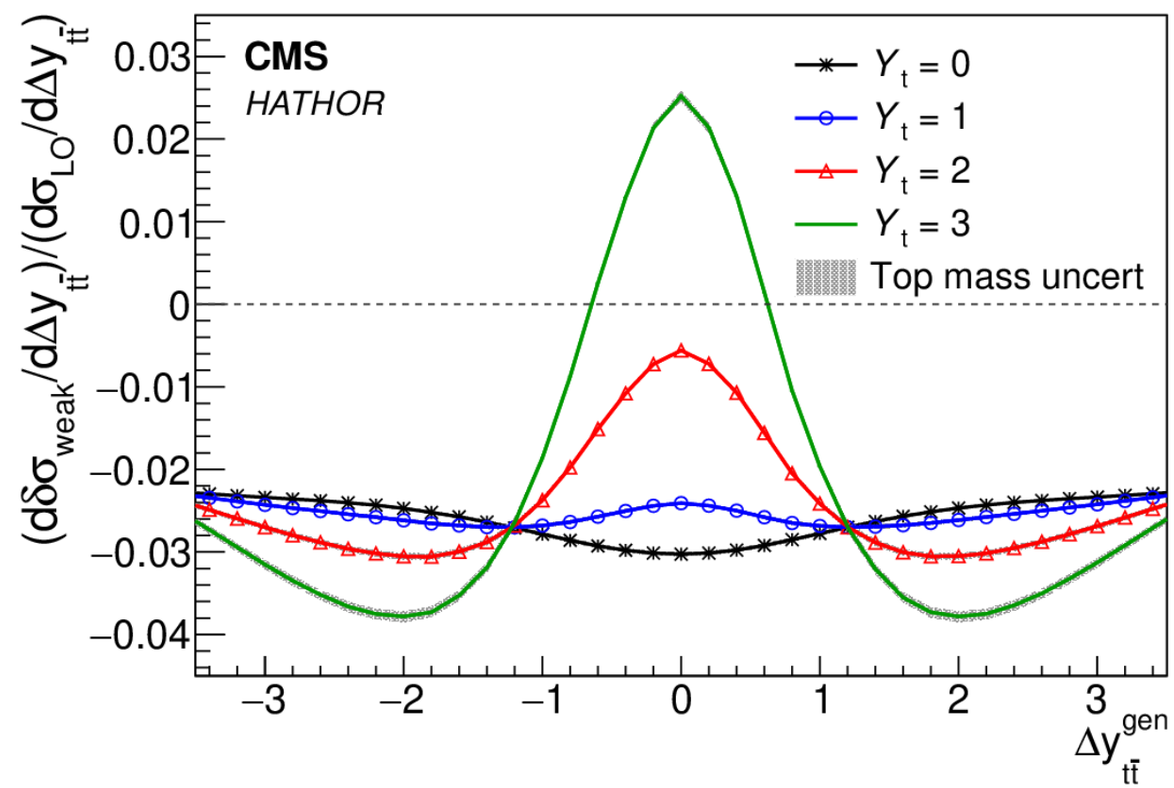
Effect of weak corrections on observables

- **Weak correction due to Higgs boson exchange lead to strong distortions of tt differential cross section near threshold region, which thus is sensitive to the top-Higgs coupling (Y_t)**

➔These features are exploited to measure Y_t based on top pair distributions in the invariant mass of ttbar pair(M_{tt}) the difference in rapidity of top and anti top quarks(ΔY)



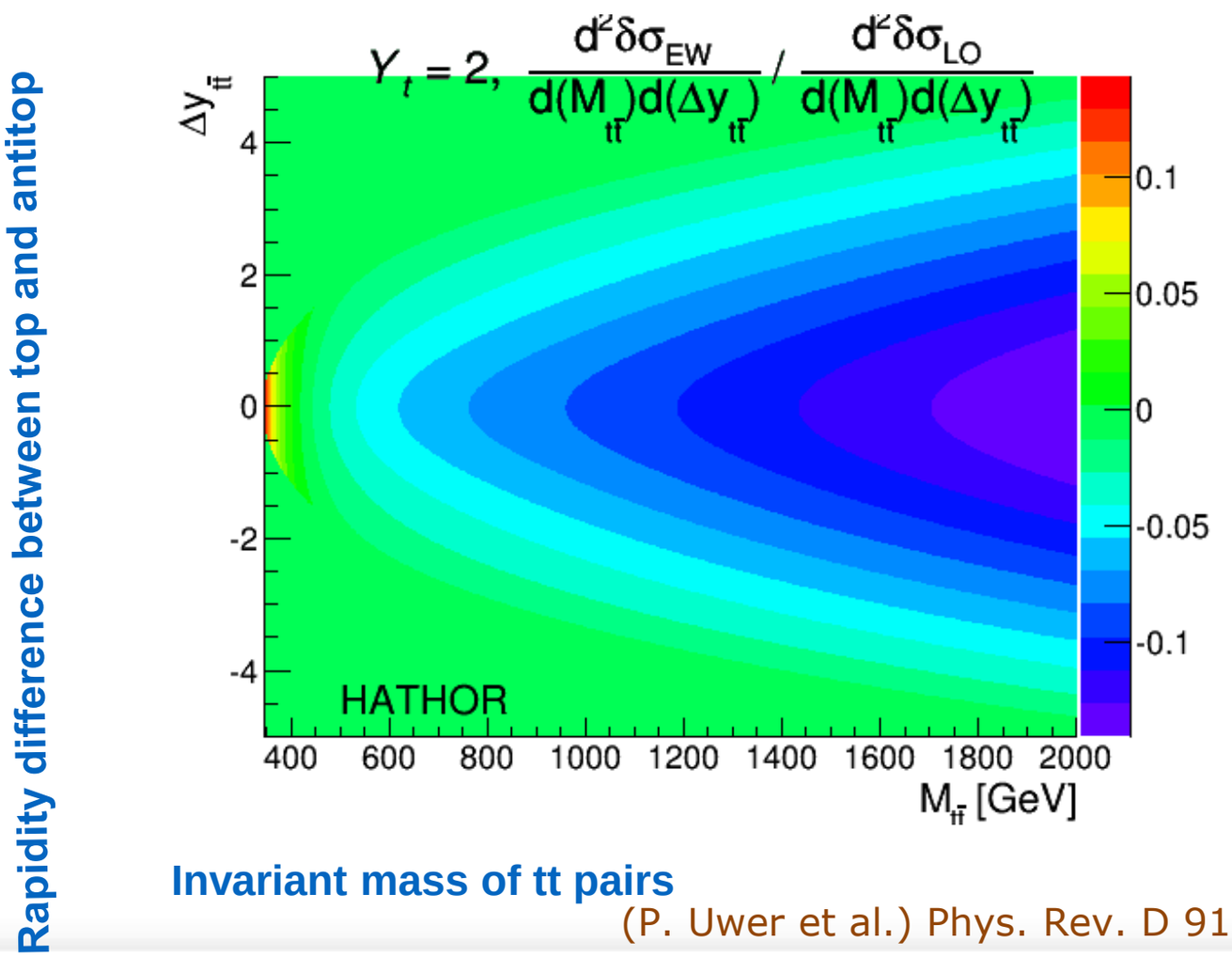
Invariant mass of tt pairs



Rapidity difference between top and antitop

Weak corrections

- Weak corrections to the leading order QCD cross section on ttbar production are derived using HATHOR for different values of Yt
- These corrections are applied as M_{tt} and ΔY dependent weights to POWHEG generated events at parton level
- Main effect is near the production threshold



(P. Uwer et al.) Phys. Rev. D 91, 014020 (Feb 2015)

Event selection and ttbar reconstruction

- Event selection

  ✓ Select events with one leptonically and one hadronically decaying W-bosons

  ✓ electron or muon and at least 3 jet with Pt>30 GeV, |η|<2.4 each

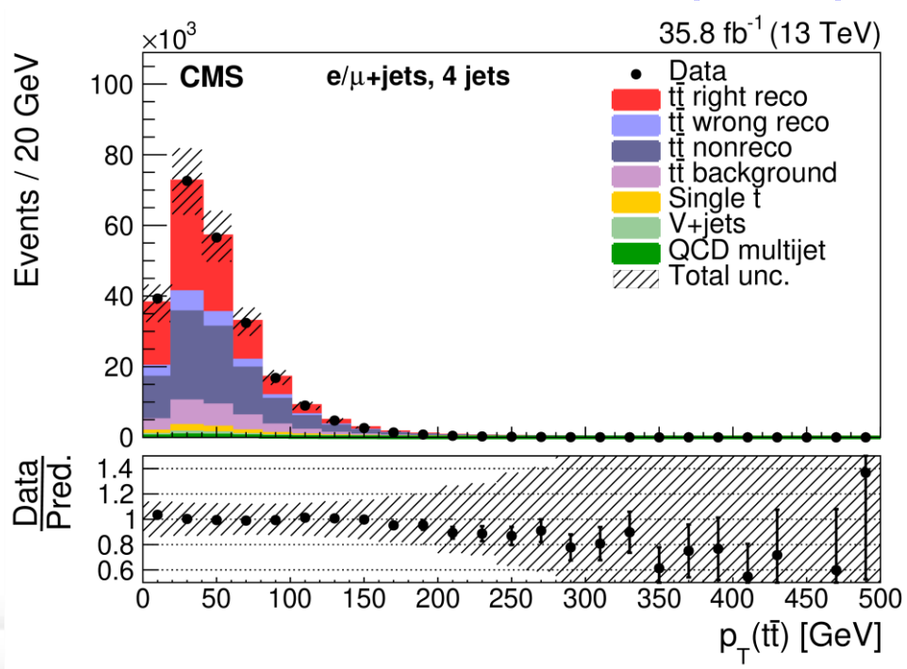
  ✓ two of the jets b-tagged

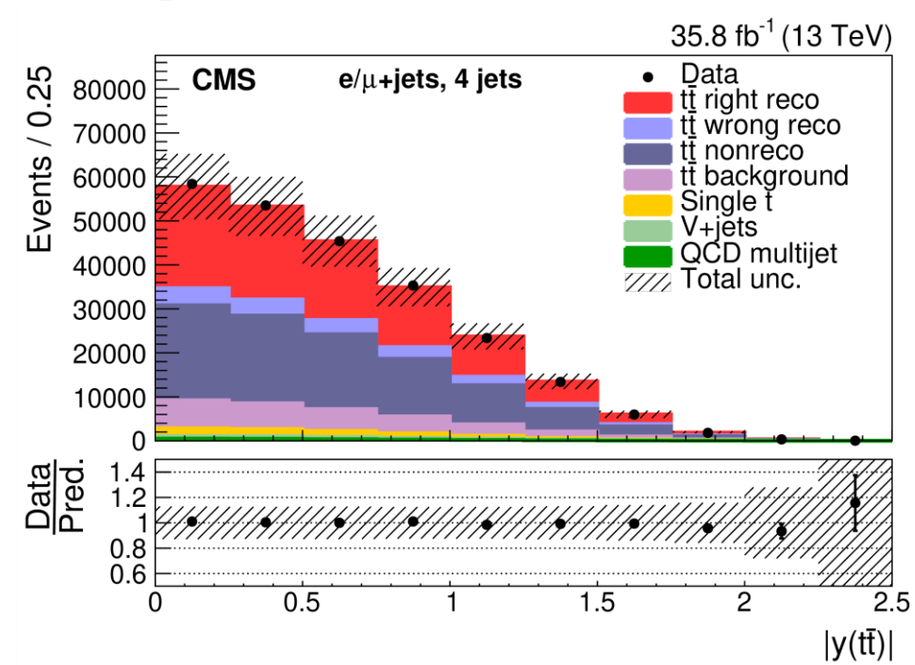
- tt reconstruction = assignment of jets to top decay products

  ✓ Newly developed reconstruction for the 3 jets category (one of the jets is lost)

Source	3 jets	4 jets	≥5 jets
$t\bar{t}$ right reco	130 520±150	92 900±130	71 640±110
$t\bar{t}$ wrong reco	29 298±73	17 356±57	43 073±89
$t\bar{t}$ nonreco	50 695±96	88 760±130	80 960±120
$t\bar{t}$ background	53 465±99	26 085±69	25 047±68
Single t	17 849±40	6922±27	6294±26
V+jets	8990±100	2824±52	2478±49
QCD multijet	19 840±69	2100±25	1080±30
Expected sum	310 650±250	236 950±210	230 570±210
Data	308 932	237 491	226 788

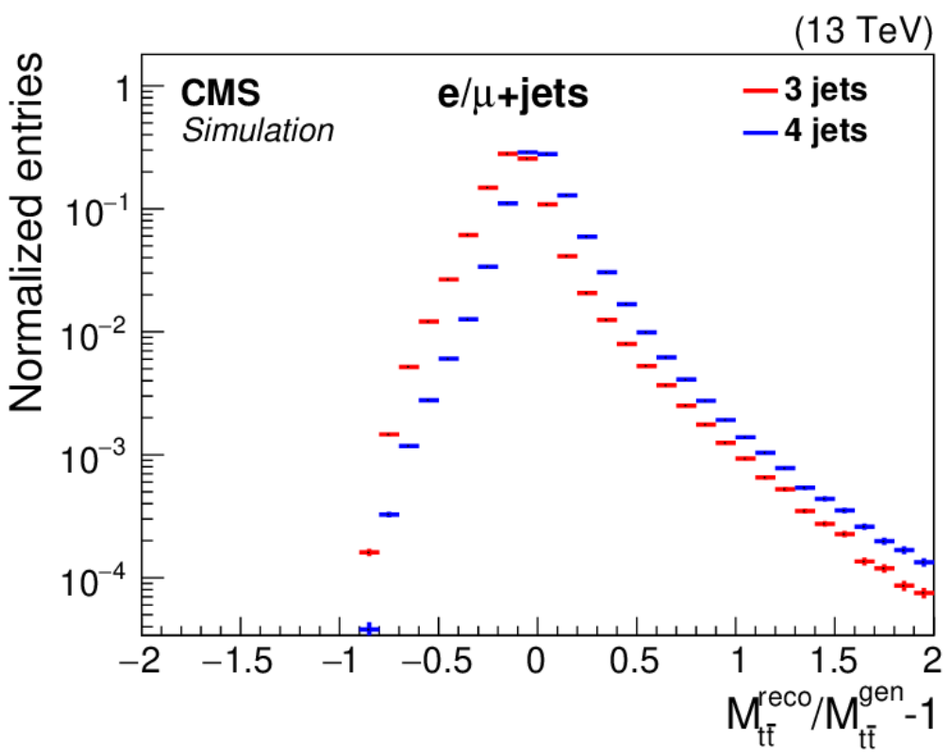
✓ For the 4/5 jets category employ the same algorithm as for the different cross section measurement [PRD 97 (2018) 112003, PRD 95 (2017) 092001]

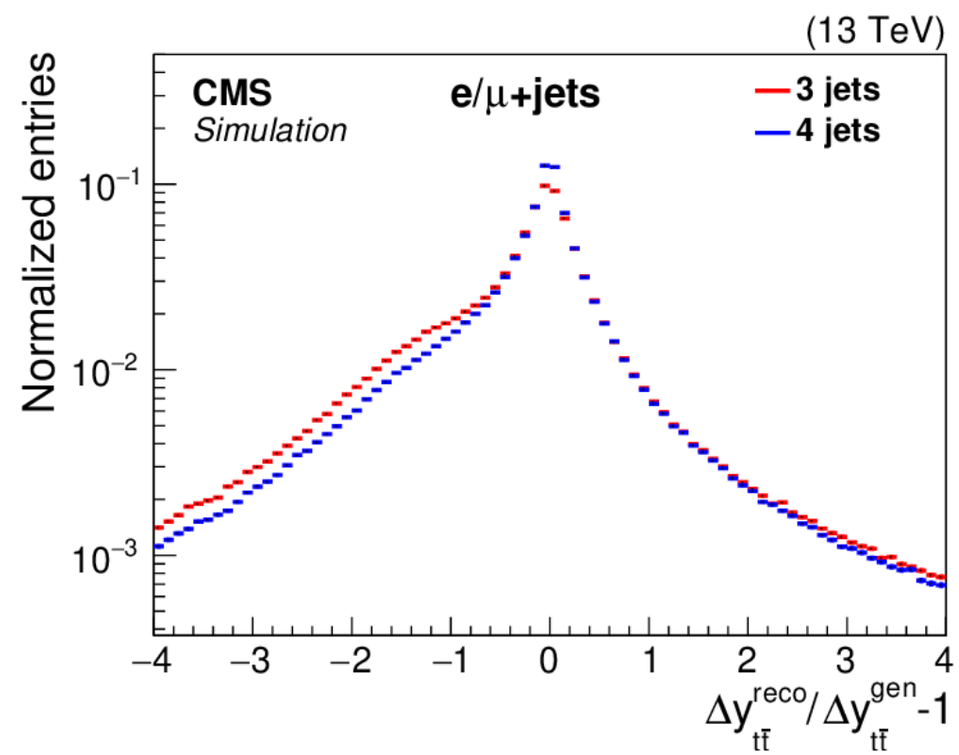




ttbar reconstruction in events with a lost jet

- **The most sensitive region to virtual Higgs exchange is near the threshold of the ttbar production**
- **In this kinematic region it is likely that one of the jets is out the acceptance or below the selection threshold in Pt**
- **We developed an algorithm to reconstruct events with one lost jet.**
- **Most likely it is one of the jets from hadronic W-boson decay.**
- **The assignment of b-jets to top decay quarks is done using the information from the neutrino solver and the kinematics of the remaining jets**
- **A combination of the b-jet on hadronic side and a light-quark jet forms a "proxy" for hadronically decaying top**
- **The performance is then similar to that of the events with all four jets from ttbar decay**

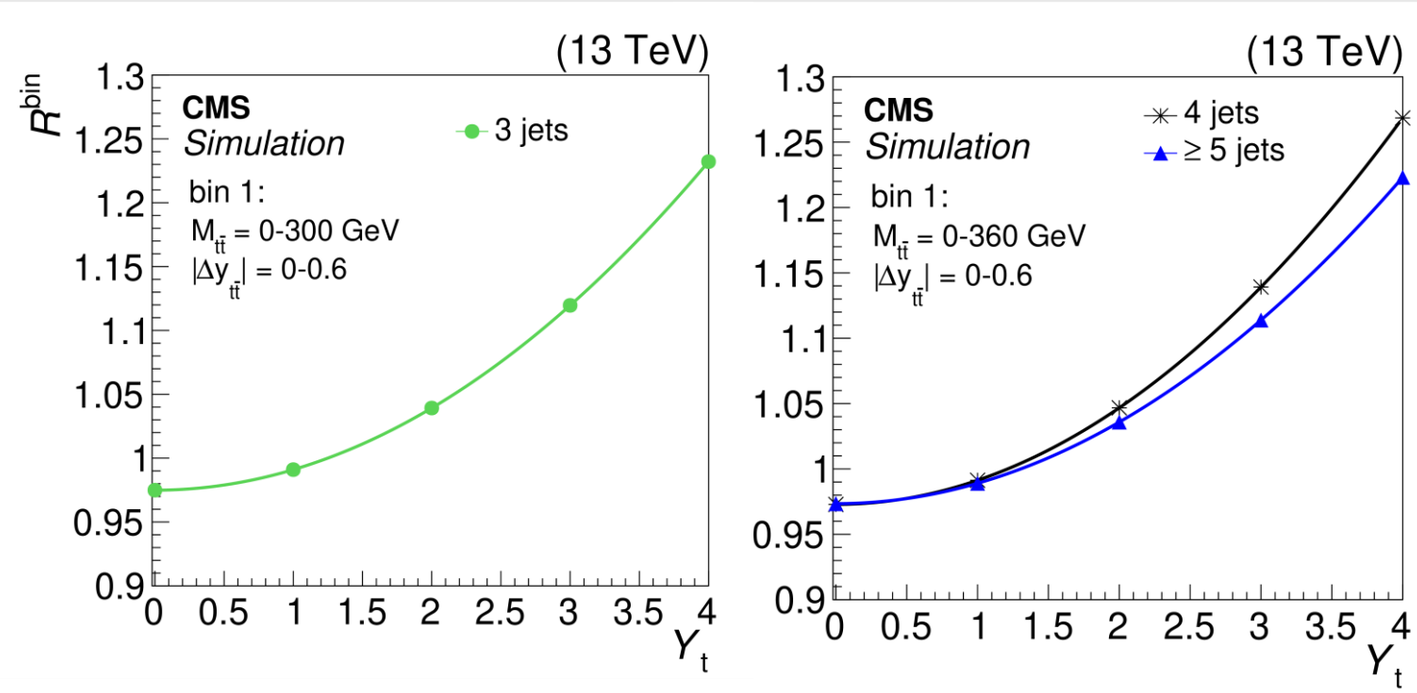




Statistical model

Data are binned over M_{tt} and Δy

- $R^{bin}(Y_t)=s(Yt)/s(POWHEG)$, where s(Yt) is expected yields for a given value of Yukawa coupling and s(POWHEG) is the SM prediction without EW corrections, is approximated by a quadratic equation in each bin



(and more bins…)

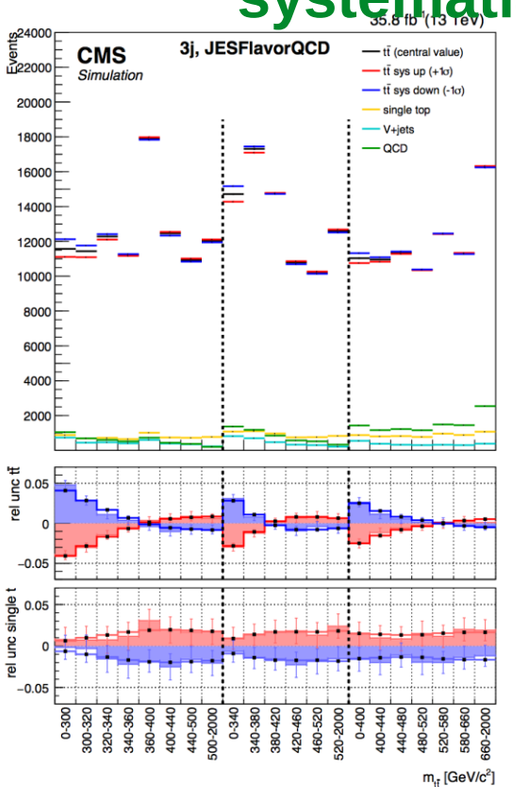
- A likelihood function is constructed and maximized

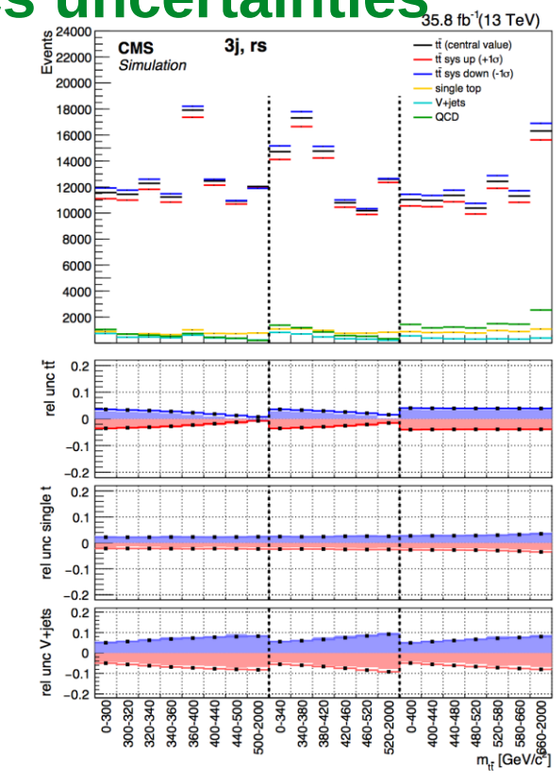
$$\mathcal{L} = \prod_{\text{bin} \in (M_{tt}, |\Delta y_t|)} \mathcal{L}_{\text{bin}} = \prod_{\text{bin}} \text{Pois}(n_{\text{obs}}^{\text{bin}} | s^{\text{bin}}(\theta) \times R^{\text{bin}}(Y_t) + b^{\text{bin}}(\theta)) \times \rho(\theta|\tilde{\theta})$$

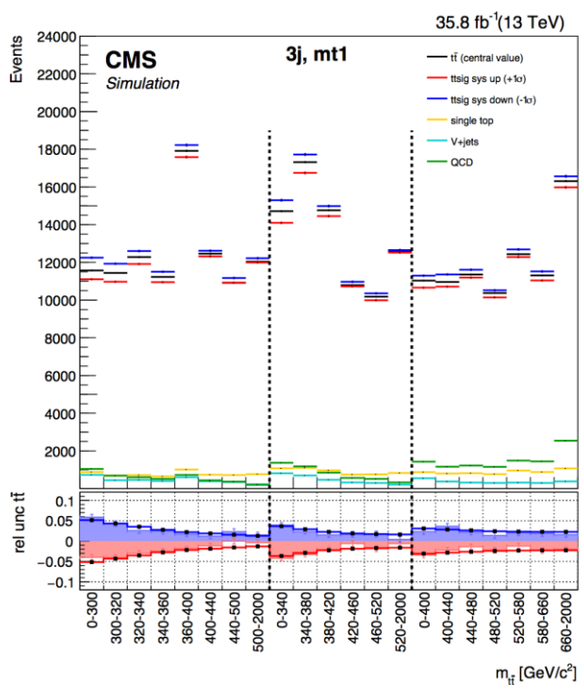
- where n^{bin}_{obs} is the number of observed events, b^{bin} is the expected background yield and
- $\boldsymbol{\rho(\theta)}$ are the pdfs for a suit of systematic <u>uncertainties</u> $\boldsymbol{\theta}$

Systematic Uncertainties

Examples of M_{tt} and Δy templates for systematics uncertainties







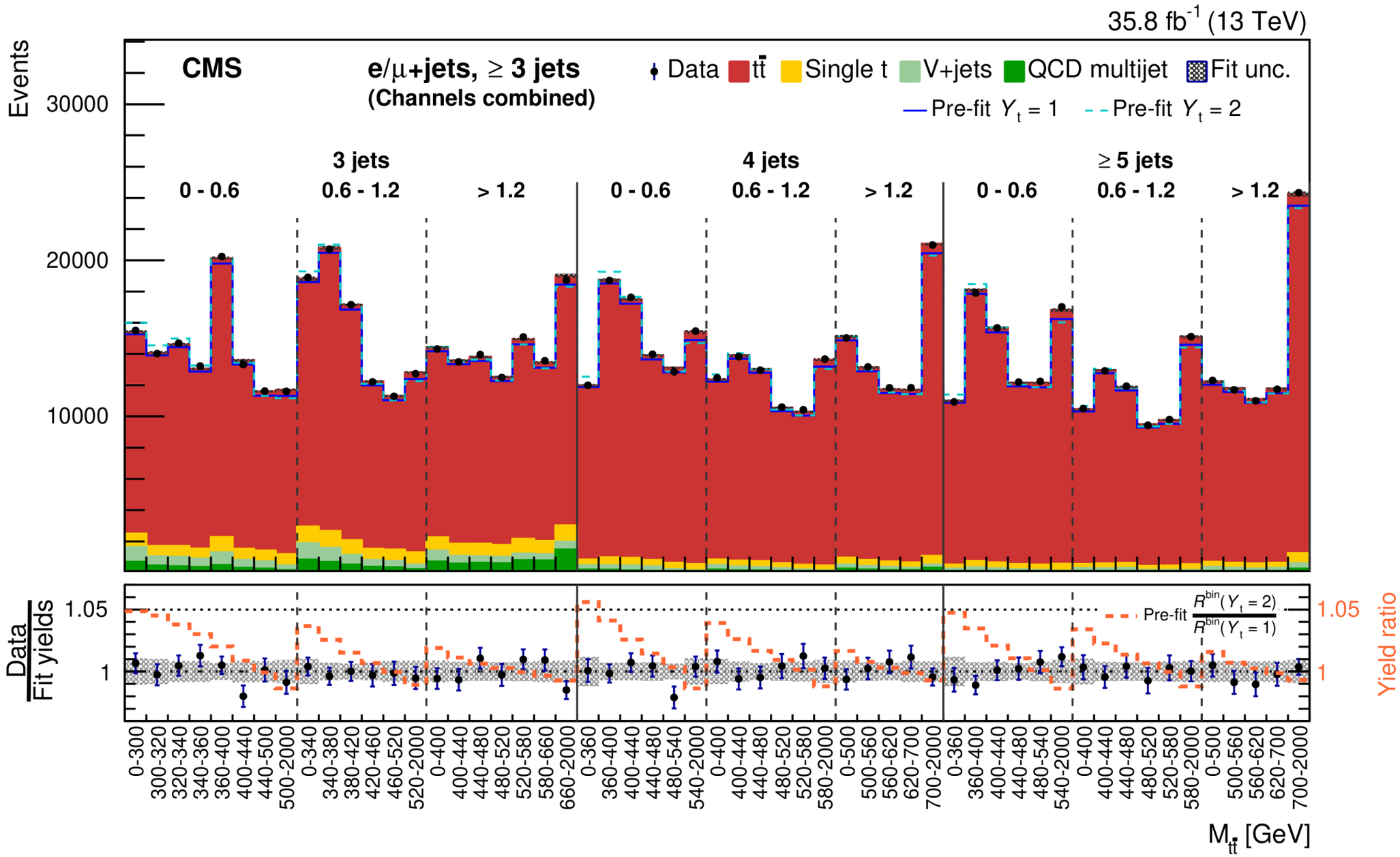
List of all uncertainties

Uncertainty	$t\bar{t}$	Single t	V+jets	QCD multijet
Integrated luminosity	2.5%	2.5%	2.5%	2.5%
Pileup	0–1%	0–1%	—	—
Lepton identification/trigger	1.9%	1.9%	1.9%	—
JEC	0–5%	0–5%	—	—
JER	0–0.6%	—	—	—
b tag scale factor	3%	3%	2–3%	—
b mistag scale factor	0.5%	1%	3–6%	—
Background normalization	—	15%	30%	30%
QCD multijet CR definition	—	—	—	0–60%
Factorization and renormalization scales	0–6%	2–5%	0–15%	—
PDF	0.5–1.5%	0.5–1.5%	—	—
$\alpha_S(m_Z)$ in PDFs	1%	1.5%	—	—
Top quark mass	1–5%	—	—	—
Top quark p_T modeling	0–0.5%	—	—	—
Parton shower				
-NLO shower matching	1.5–5%	—	—	—
-ISR	2–3%	—	—	—
-FSR	0–9%	0–12%	—	—
-Color reconnection	0–3%	—	—	—
-b jet fragmentation	0–3%	0–5%	—	—
-b hadron branching fraction	3%	2.5–3%	—	—
Weak correction $\delta_{QCD}\delta_W$	0–0.2% (Y_t =2)	—	—	—

Experiential

Theoretical

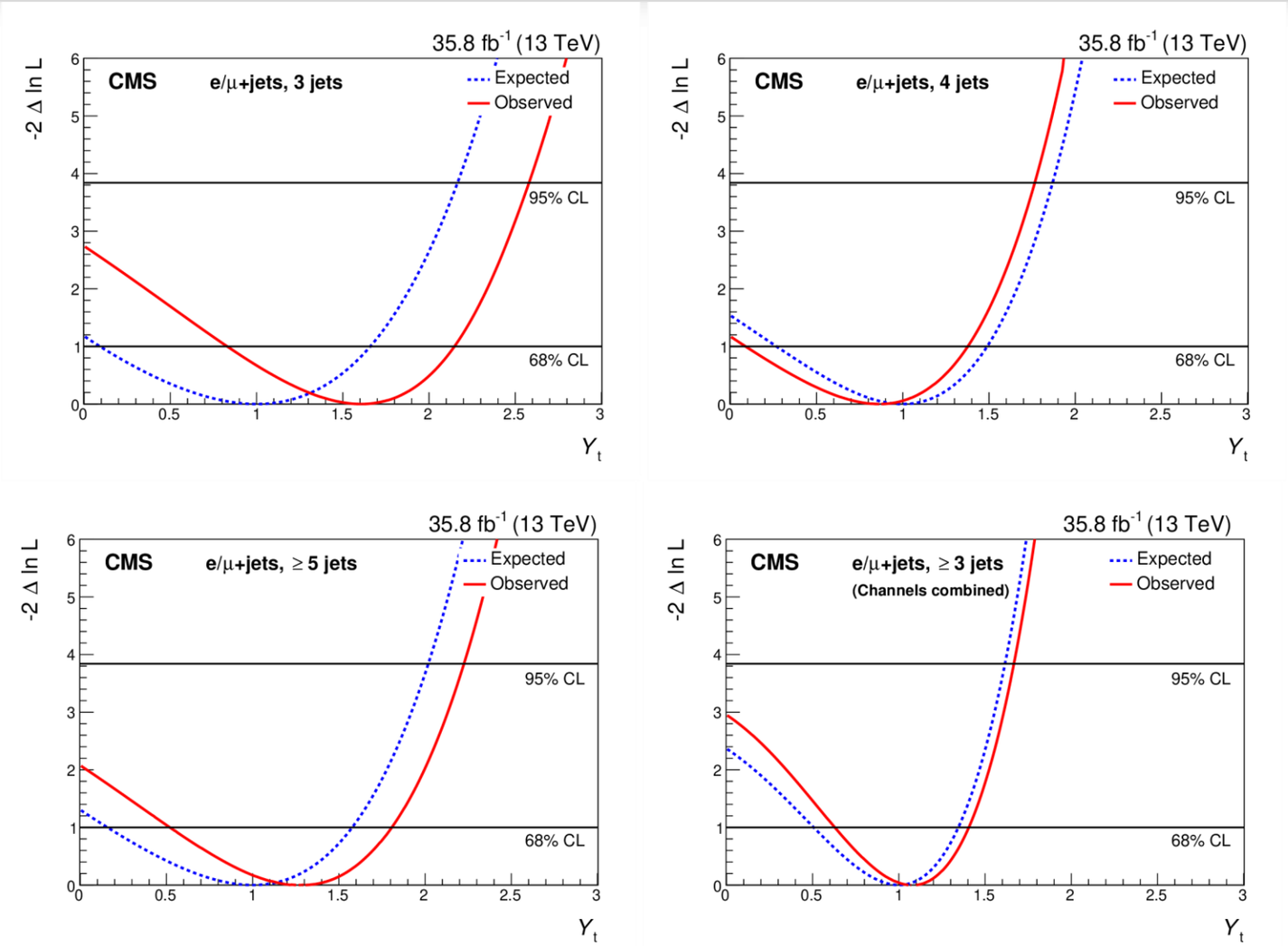
Fit to data yields



Data/MC ratio with data statistics uncertainty;
grey band refers to the post-fit uncertainty

Pre-fit expectations for Yt=1 and 2 are also shown

Likelihood scan vs Yukawa coupling

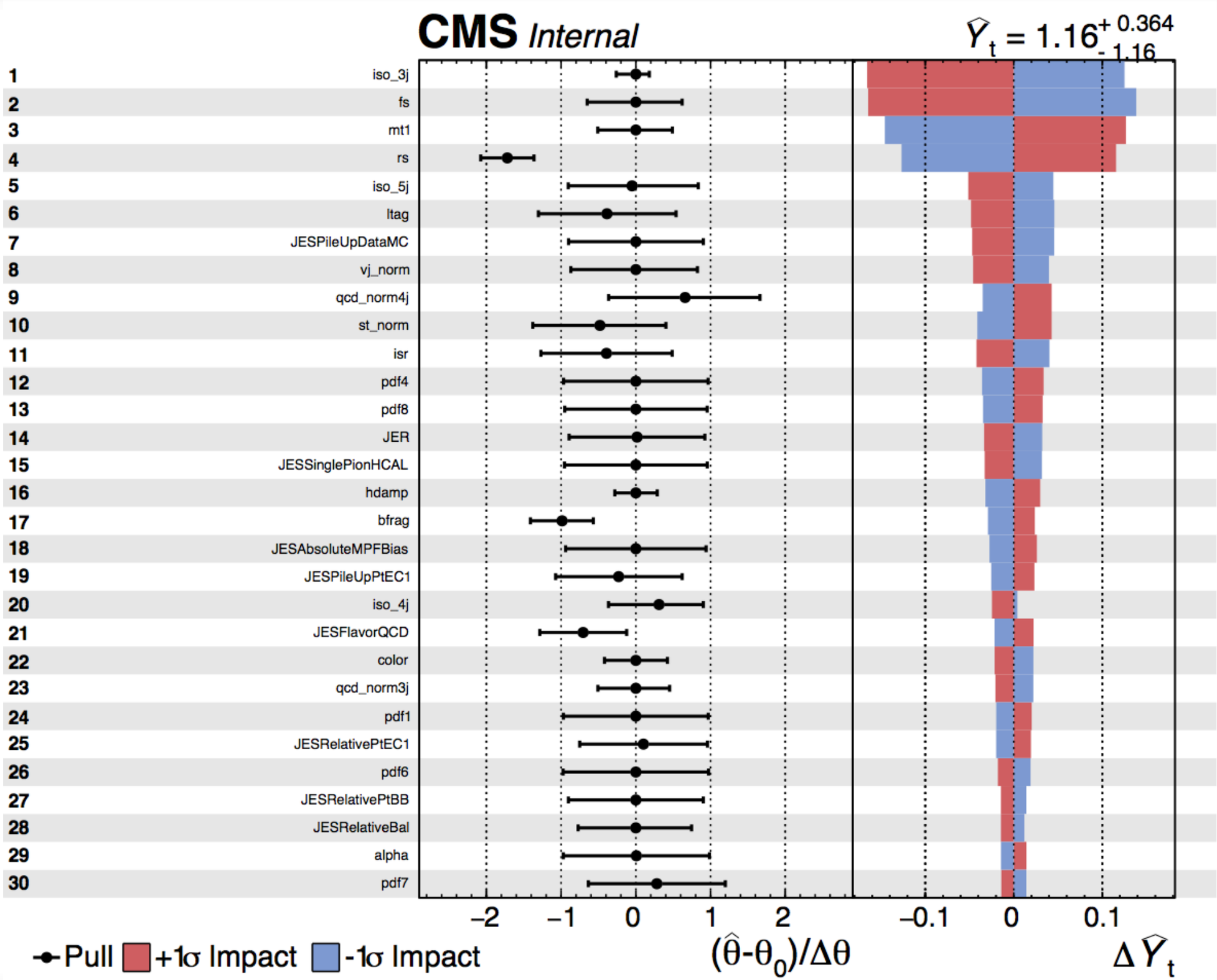


Channel	Best fit Y_t		95% CL upper limit	
	Expected	Observed	Expected	Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	<2.17	<2.59
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	<1.88	<1.77
≥5 jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	<2.03	<2.23
Combined	$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67

Summary

- We exploit kinematic distribution of the top pair production to measure top Higgs Yukawa coupling
- The sensitive variable are the invariant mass of the ttbar system and the rapidity difference between top and and antitop quarks
- The most sensitive region to the Yukawa coupling is near the threshold of ttbar production
- To maximize the statistics in the threshold region we developed an algorithm to reconstruct the ttbar system with one lost jet
- Using 35.8 fb^{-1} of lepton+jets data we were able to measure the value of the Yukawa coupling of $1.07^{+0.34}_{-0.43}$
- We set 95%C.L. observed/expected limit at 1.67/1.62.

Post fit nuisance parameters



Thoughts about combination

- Based on discussions with D. Sperka, A. Korytov, A. Gritsan
- Top Higgs Yukawa coupling is defined as a ratio to SM value, thus is the same as kappa_t in Higgs coupling measurement
- The analysis is not sensitive to other Higgs couplings (it is a good thing)
- Statistics method - use COMBINE
- Things to worry about:
  - systematic uncertainties, definition (e.g. # of JEC components, pdfs) the level of correlation
  - sensitivity to other Higgs coupling measurements (e.g. ttH) to ttbar as background, which in turn sensitive to Yt
    - probably a negligible effect since our sensitivity is coming predominantly from the threshold region (Mtt<500GeV), while all other processes require high momentum transfer
- Combination with other measurements of top Higgs Yukawa coupling is possible