Measurement of the $t\bar{t}$ charge asymmetry in highly boosted events in the single-lepton channel at 13TeV

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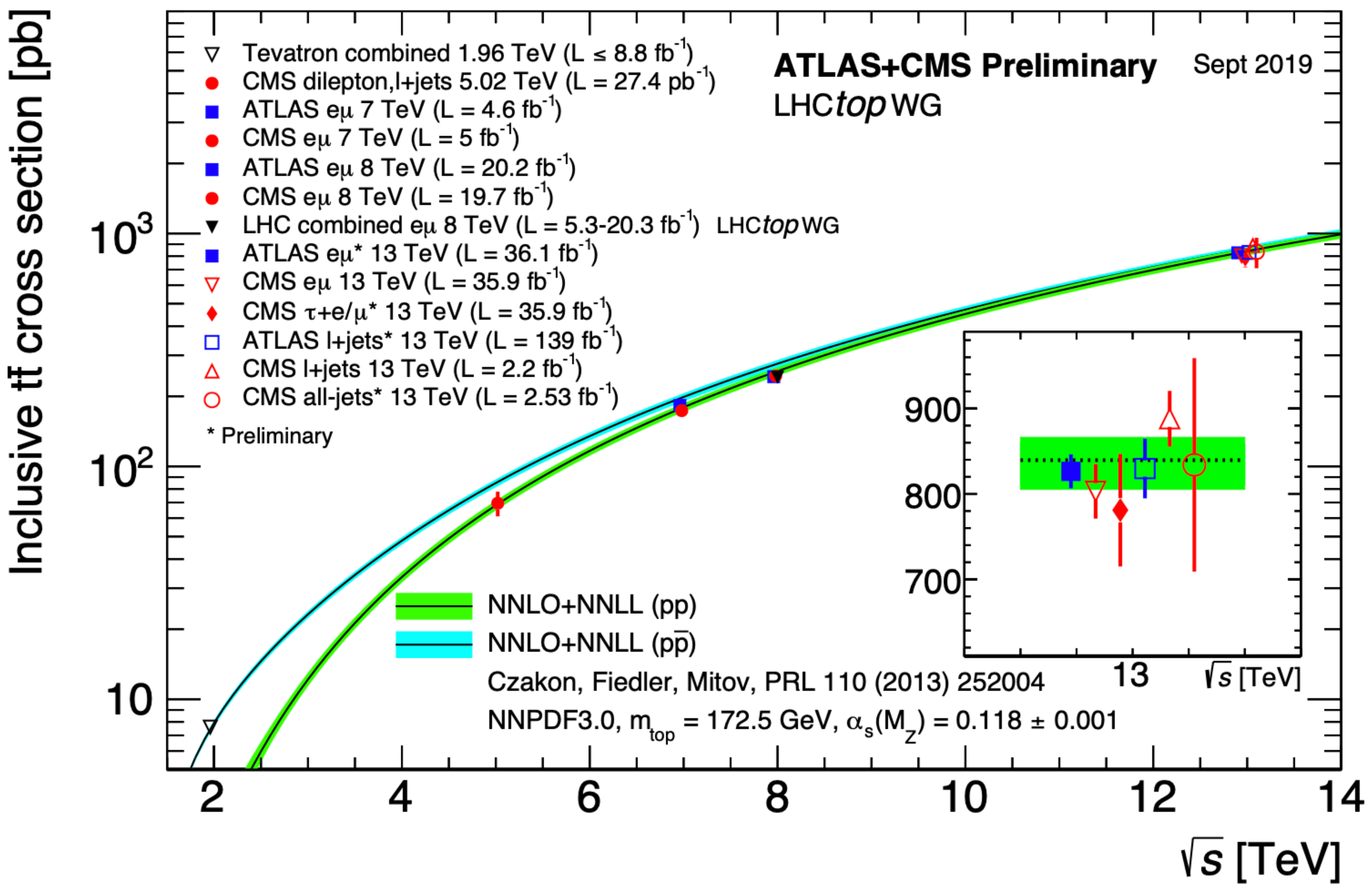
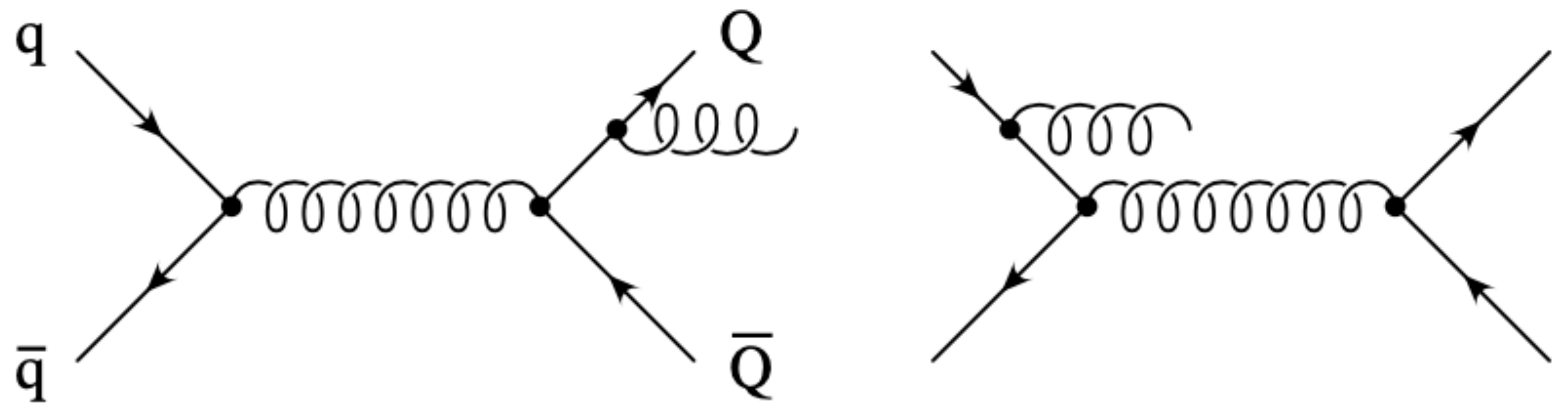
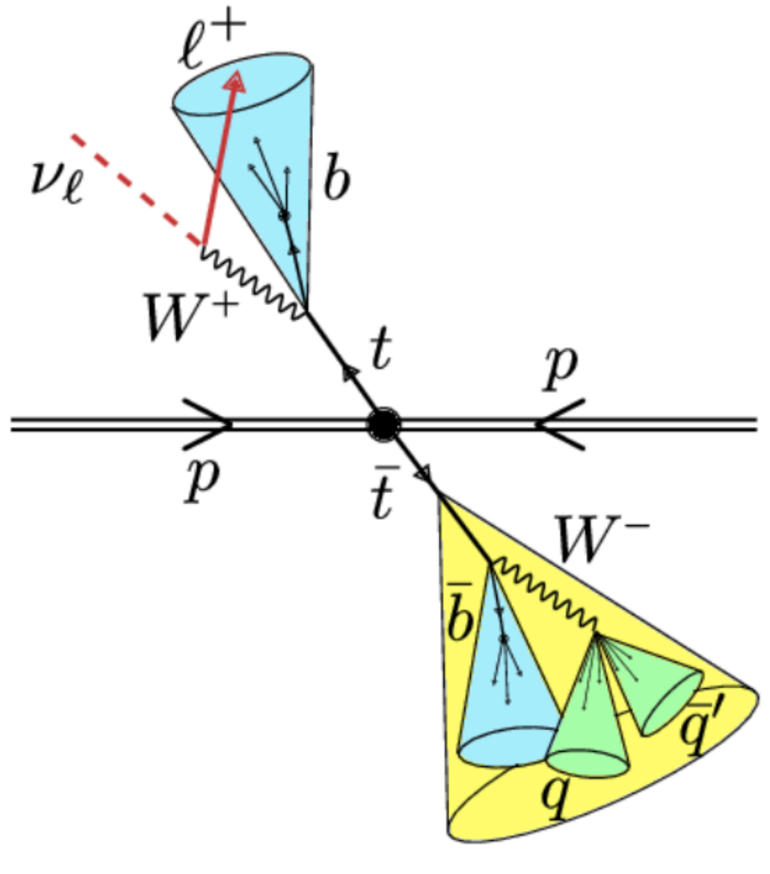
Introduction

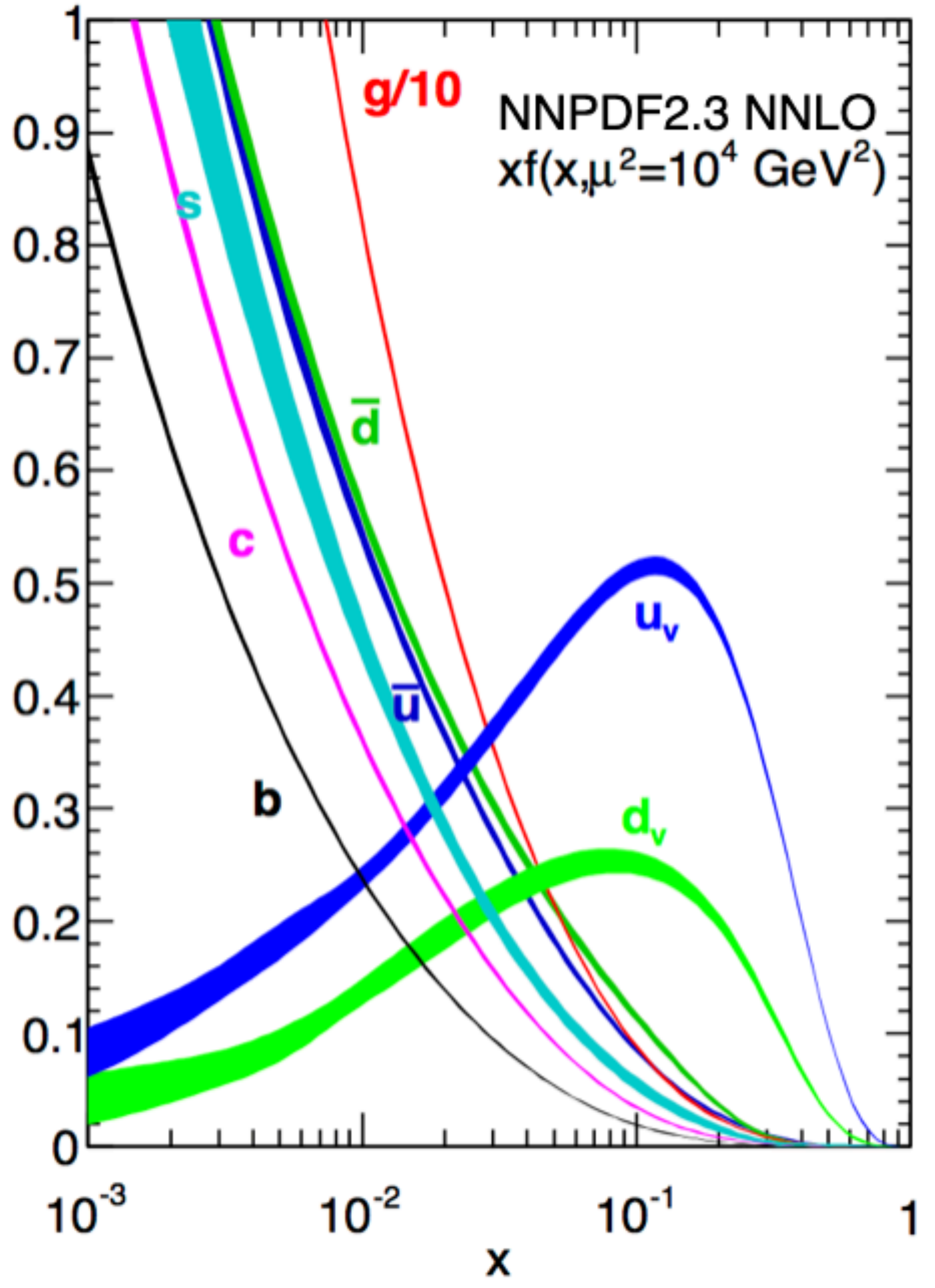
- The *heaviest elementary particle* top quark (m_{top} ~175 GeV) - plays a special role in SM and BSM processes
  - close to the **EWK breaking scale** and **high Yukawa coupling**
  - **decays before hadronizing** ->we can study the decay products
- At LO, $t\bar{t}$ symmetric under charge conjugation. At higher orders asymmetries from q$\bar{q}$ and qg initial states
- As a consequence of these asymmetries, the top quark is preferentially produced in the direction of the incoming quark.







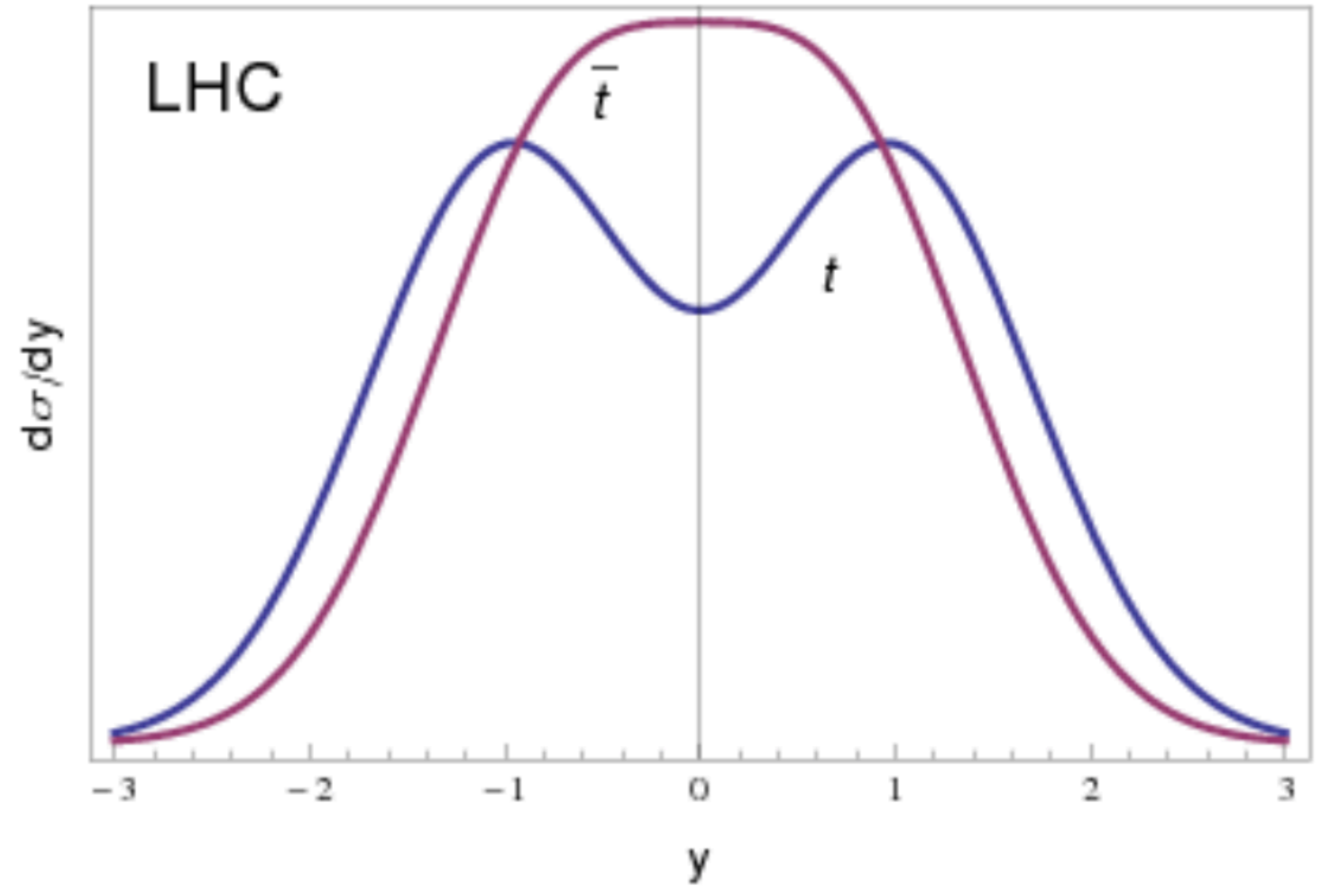
Charge Asymmetry in boosted topologies



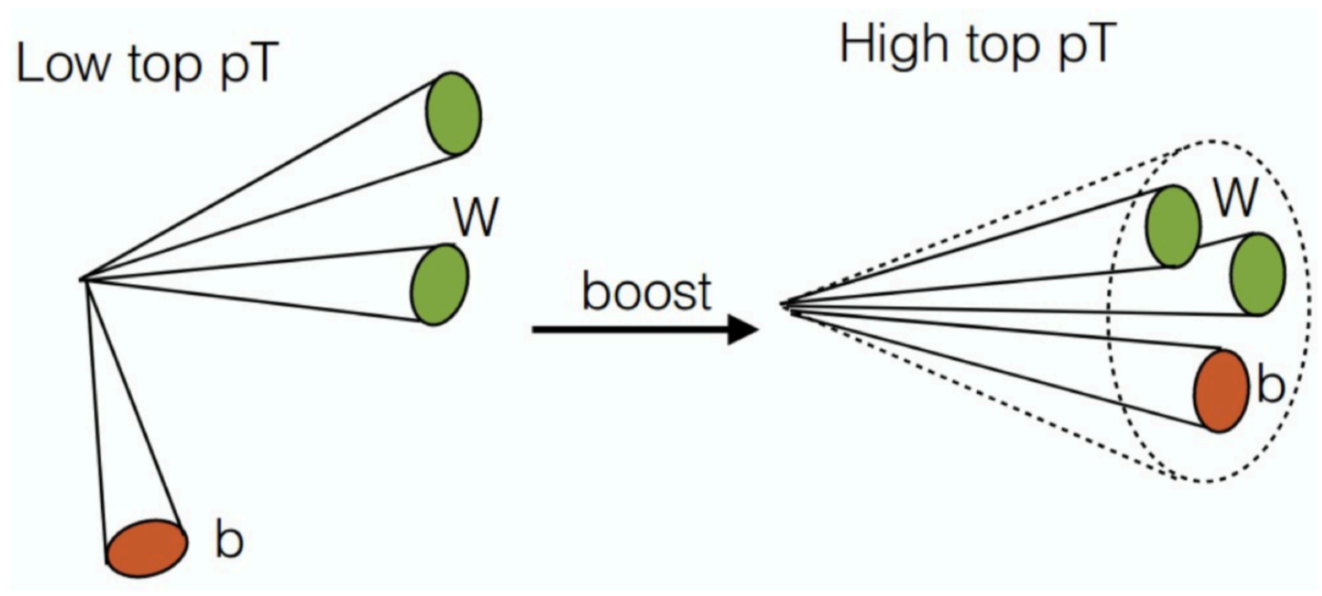
- At high momemtum transfer the contribution of valence quarks is higher
  - hence measuring A_C in boosted $t\bar{t}$ is more sensitive to any BSM process that might alter A_C
- Our measurement is the **first one to use CMS data at √s=13 TeV, optimizing the reconstruction of highly Lorentz boosted top quarks from $t\bar{t}$ events with an invariant mass above 750 GeV.**
- This measurement uses dedicated techiniques for:
  - Hadronically decaying top quark (top-tag and W-tag) using substructure variables.
  - leptonically decaying top quark - no isolation cuts are applied, lepton-jet cleaning applied, kinematic cuts for the boosted topology

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

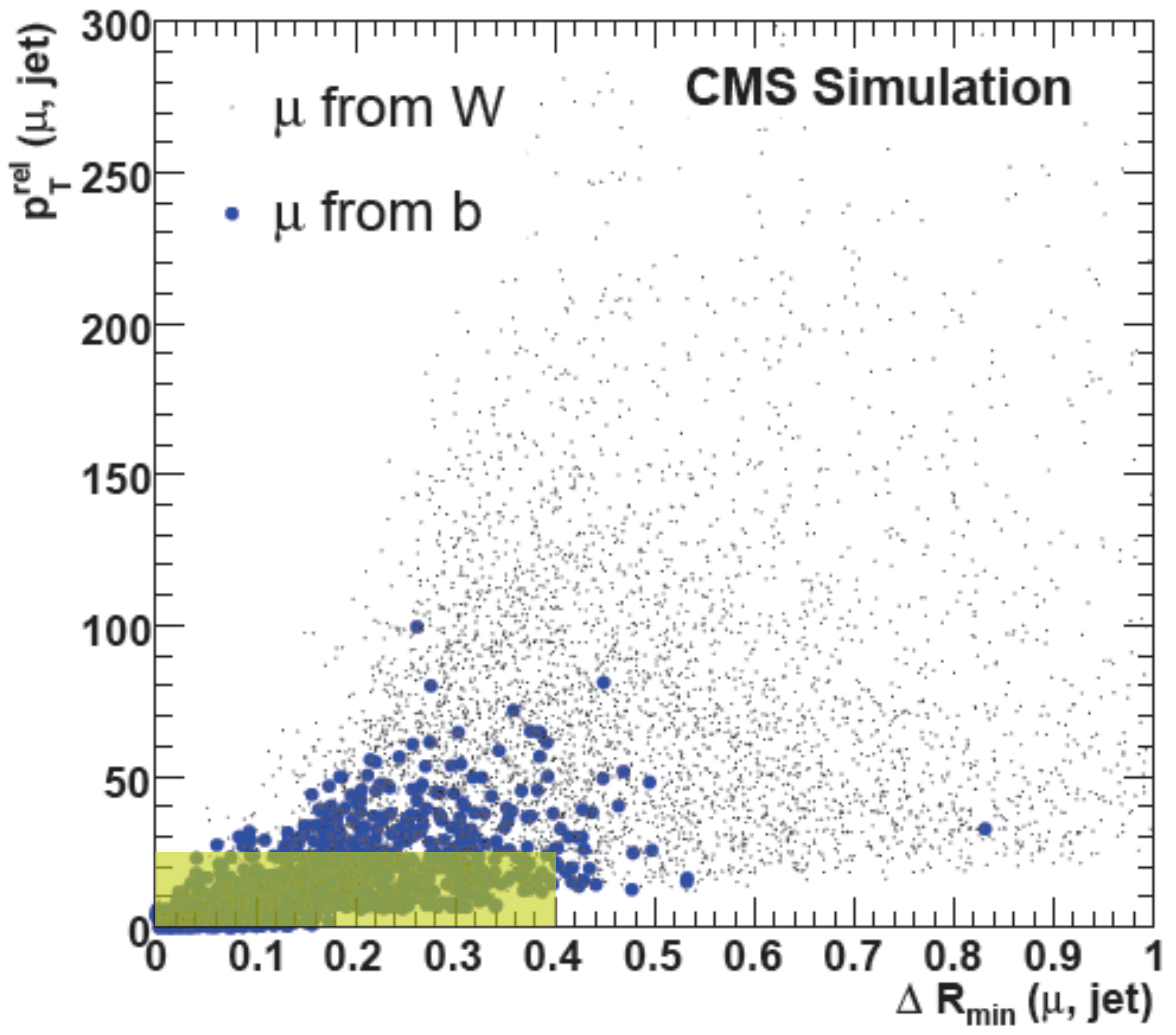
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

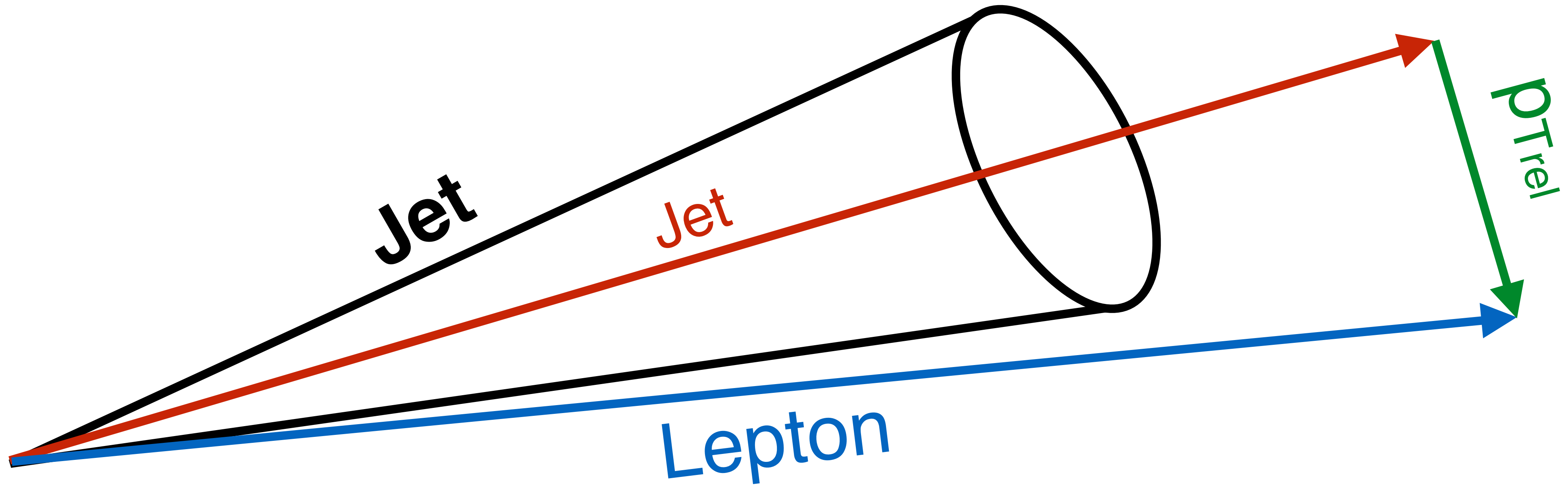


Event selection



- Exactly one lepton, with no isolation requirement
  - p_T > 55 (85) GeV for muon (electron)
- >=2 AK4 jets, leading jet with p_T >150 GeV, at least one of AK4 jets is b-tagged
- AK8 PUPPI jets with p_T >400 GeV
- Kinematic cuts to control QCD multijet background:
  - ΔR(lepton,jet) > 0.4 OR $p_{T(rel)}$(lepton,jet) > 25 GeV
- MET > 50 (120) GeV in muon (electron) channel
- MET+ p_T (μ) > 150 GeV in the muon channel



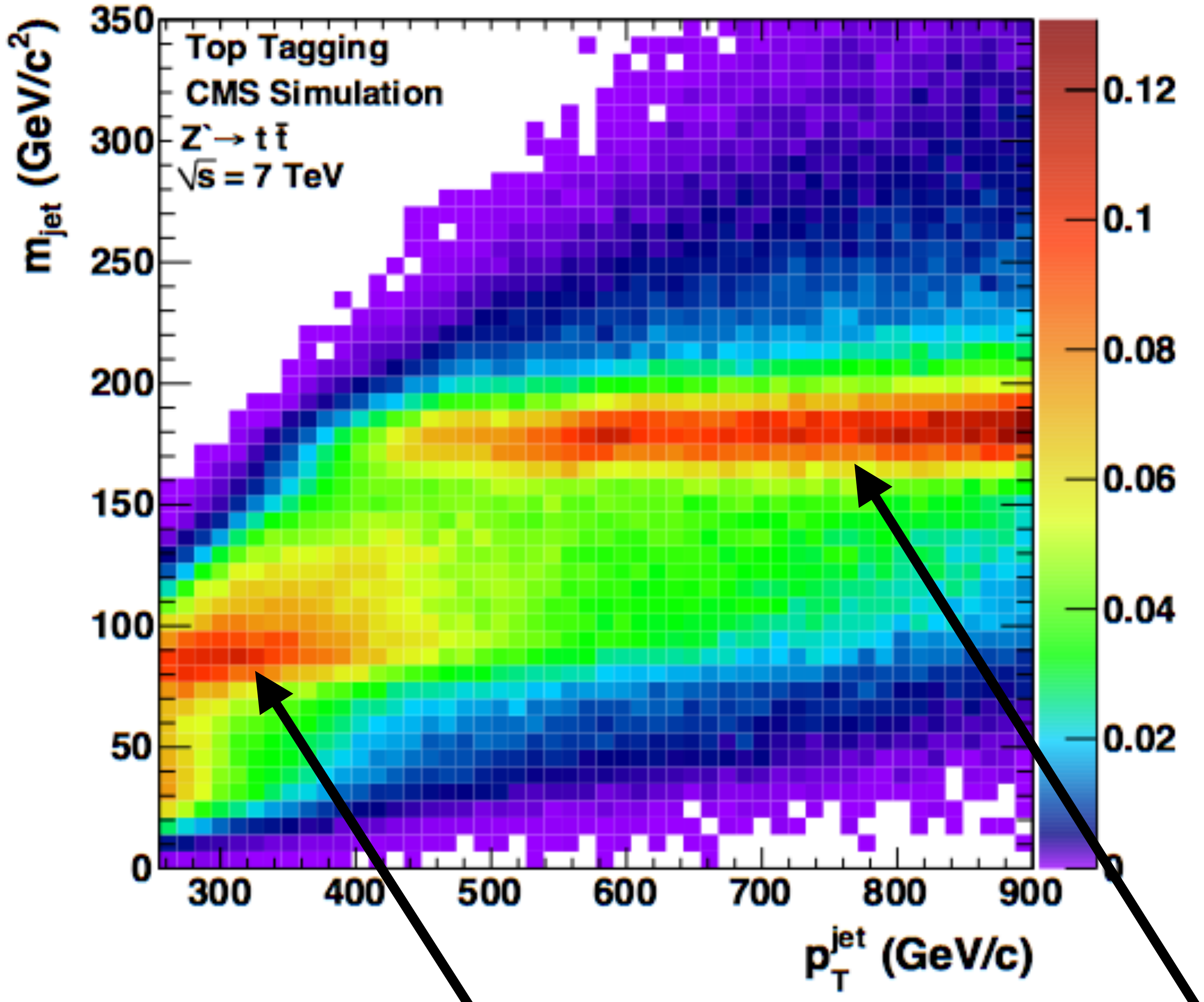


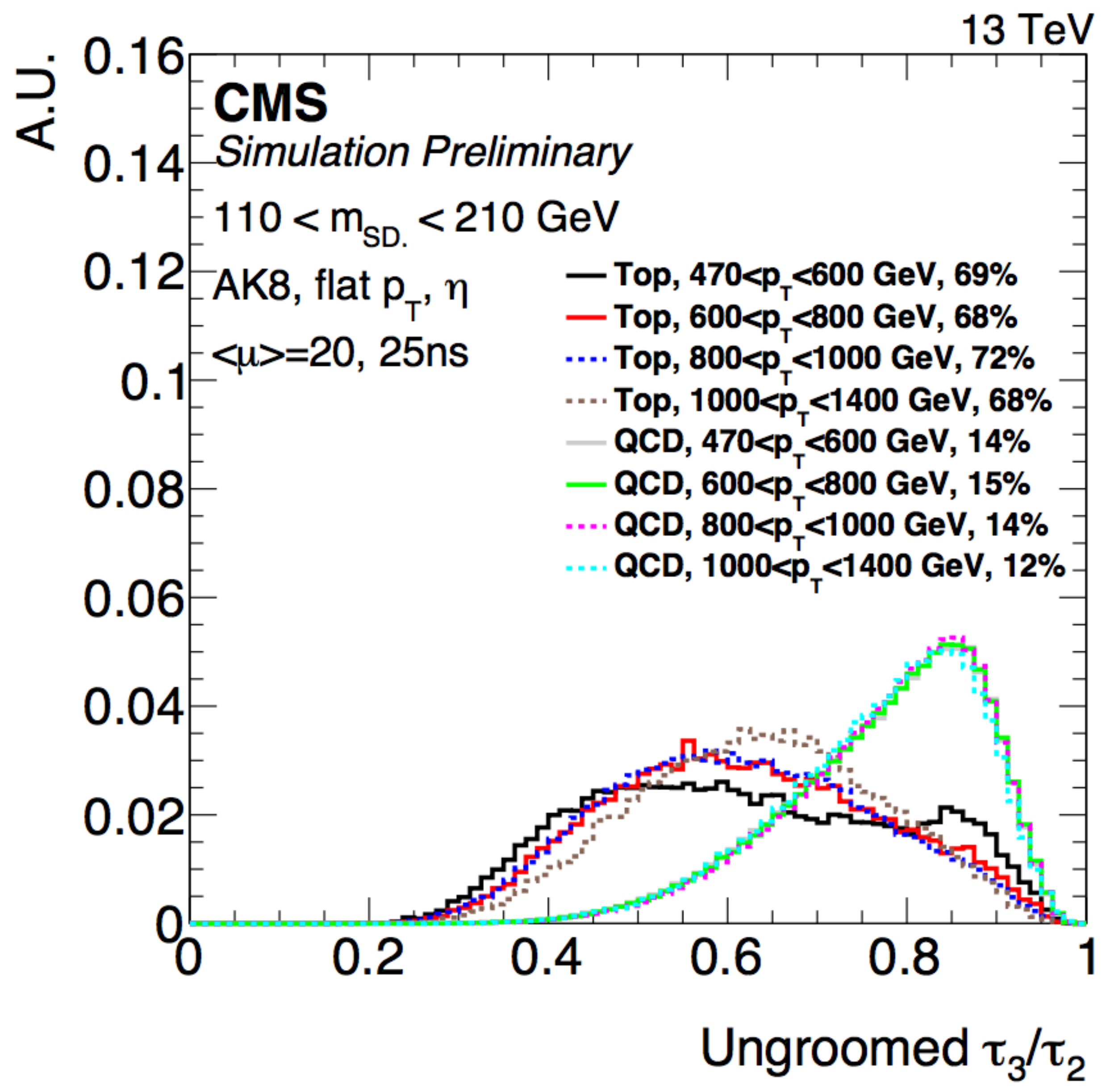
Top and W tagging

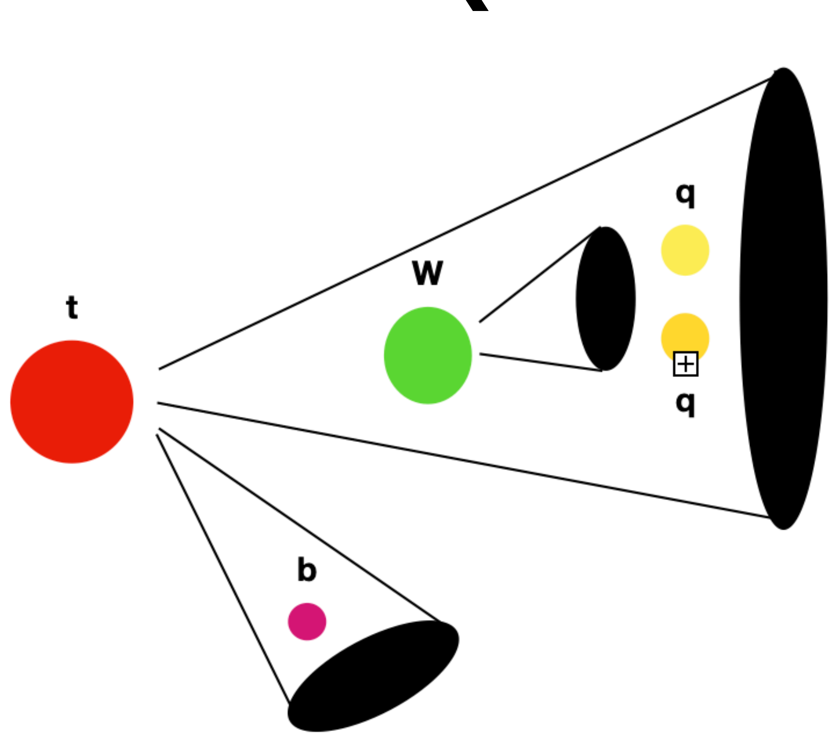
- Jets from a hadronic boosted top quark (W boson), will have three (two) groups of clusters where the jet energy is concentrated. These structures correspond to the quarks from the decay.

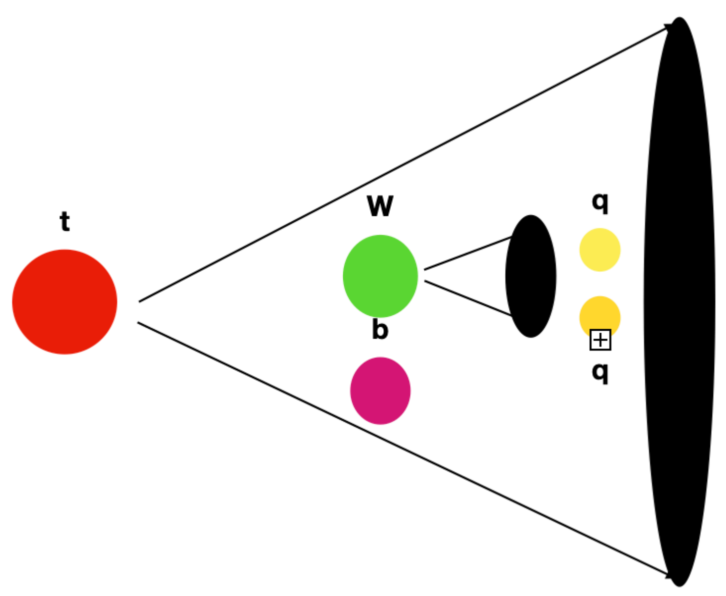
- Sub-structure techniques are applied to large footprint jets to identify top quarks:
  - Jet mass near to the top (W) mass (Soft drop mass: is a jet grooming algorithm to remove the soft and wide angle radiation from a jet) JHEP03(2011)015
  - Compatibility of a large radius jet having 3 (2 or 1 subjets) N-subjetiness: JHEP05(2014)146

	mSD	$\tau_{32} = \tau_3/\tau_2$
T-tagging	$105 < m_{SD} < 220$	< 0.65
W-tagging	$65 < m_{SD} < 105$	< 0.45



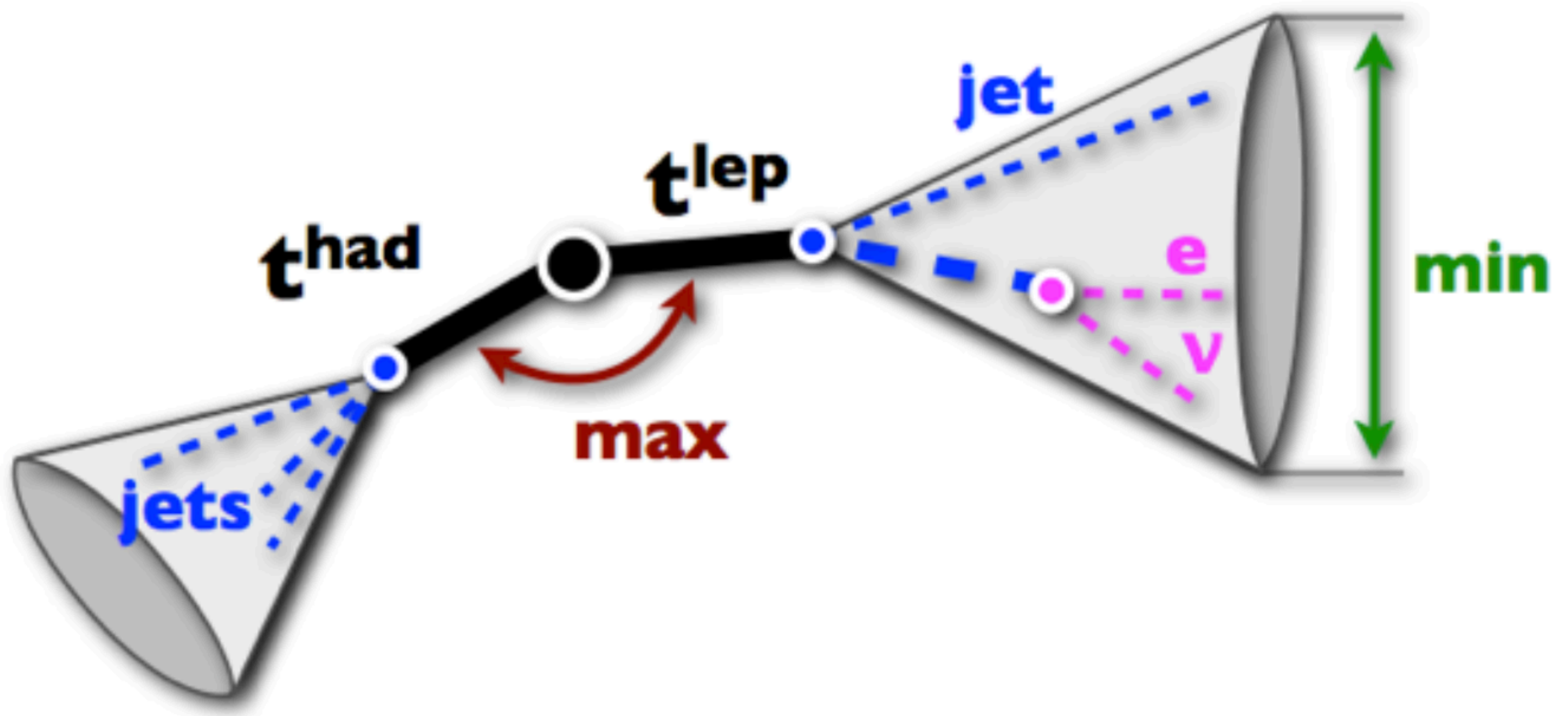






Event Reconstruction

$$\chi^2 = \chi^2_{lep} + \chi^2_{had} = [\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}}]^2 + [\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}}]^2$$



- Top quark pair events reconstructed by assigning the four vectors of the final decay products to either the *leptonic* (t_{lep}) or *hadronic* (t_{had}) top leg

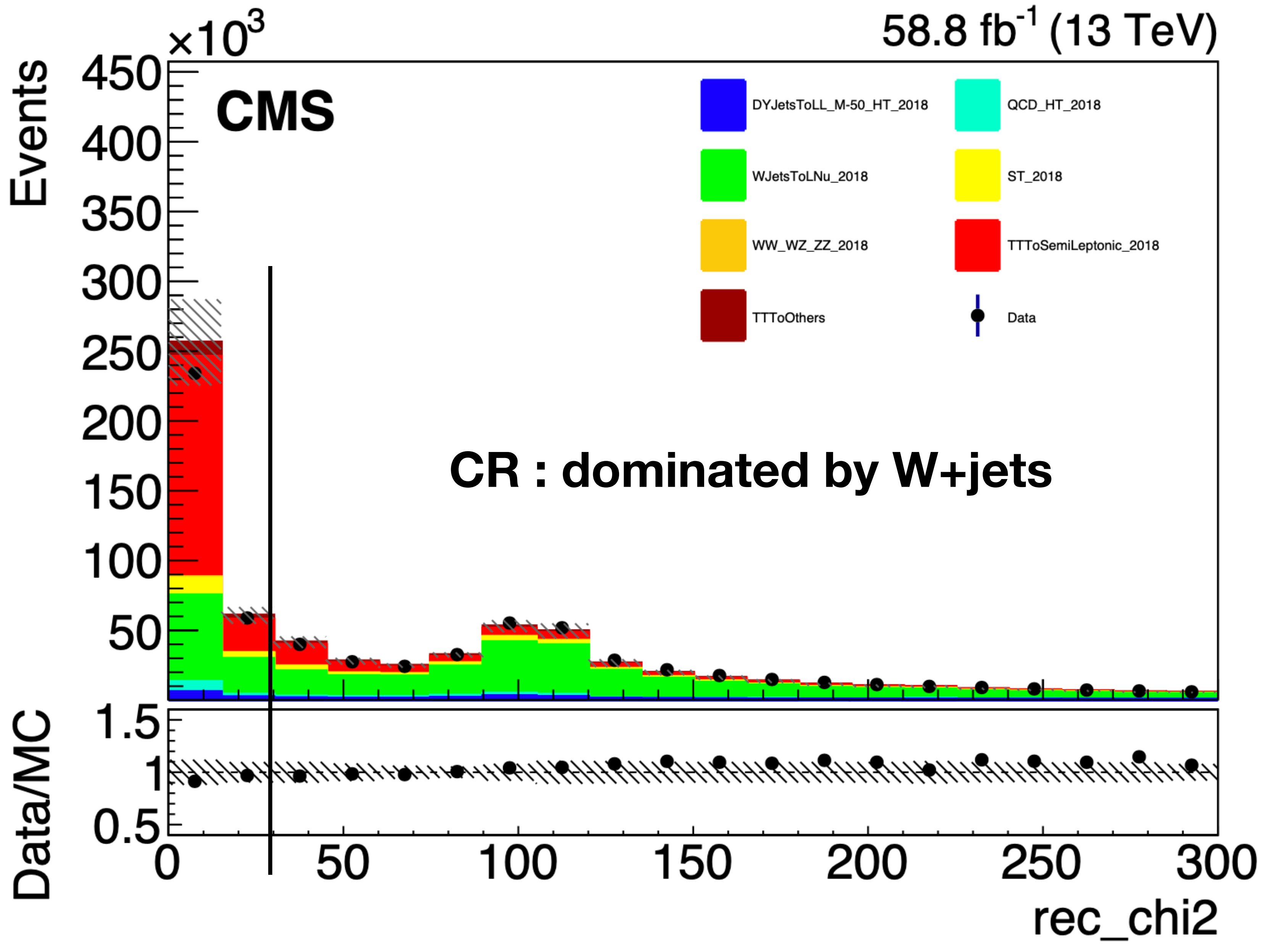
- For assigning the jets:

    - **boosted**:Top-tagged jets assigned to t_{had}, *AK4 jets with ΔR>0.8 from* t_{had} *are assigned to* t_{lep}

    - ***semi-resolved**:* W-tagged jet assigned to t_{had}; all possible assignments of *AK4* jets with ΔR>0.8 from W-tag are assigned to t_{lep} or t_{had} or neither.

    - **Resolved:** all possible assignments of AK4 jets constructed and assigned to t_{lep} or t_{had} or neither.

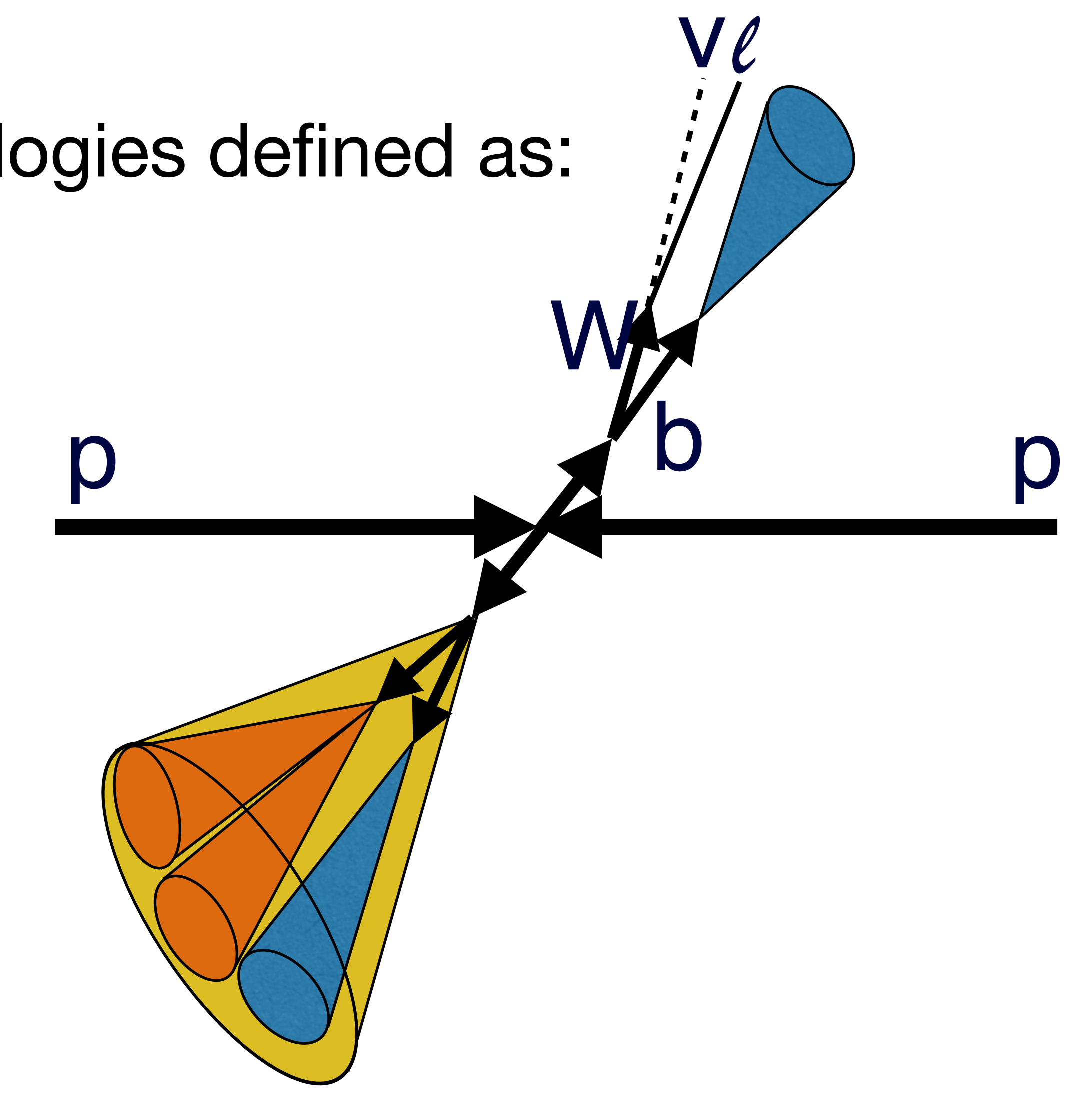
- All combinations are tested, but only the one satisfying minimum χ2 is kept-as reconstructed top masses are expected to be close to the top quark mass from simulation.



$\chi^2 < 30$

Final event categorization

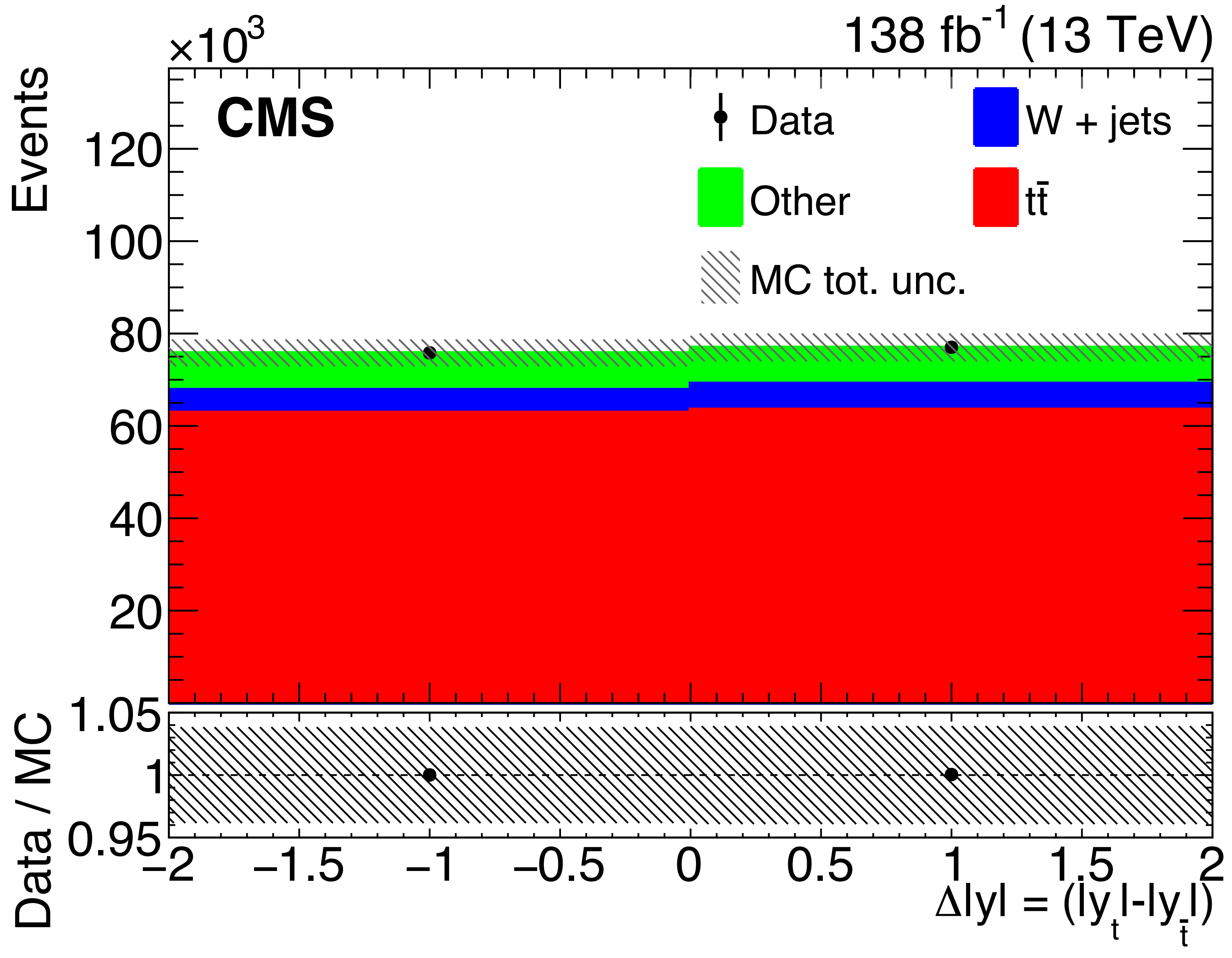
The measurements is performed in different channels corresponding to boosted, semi-resolved and resolved topologies defined as:

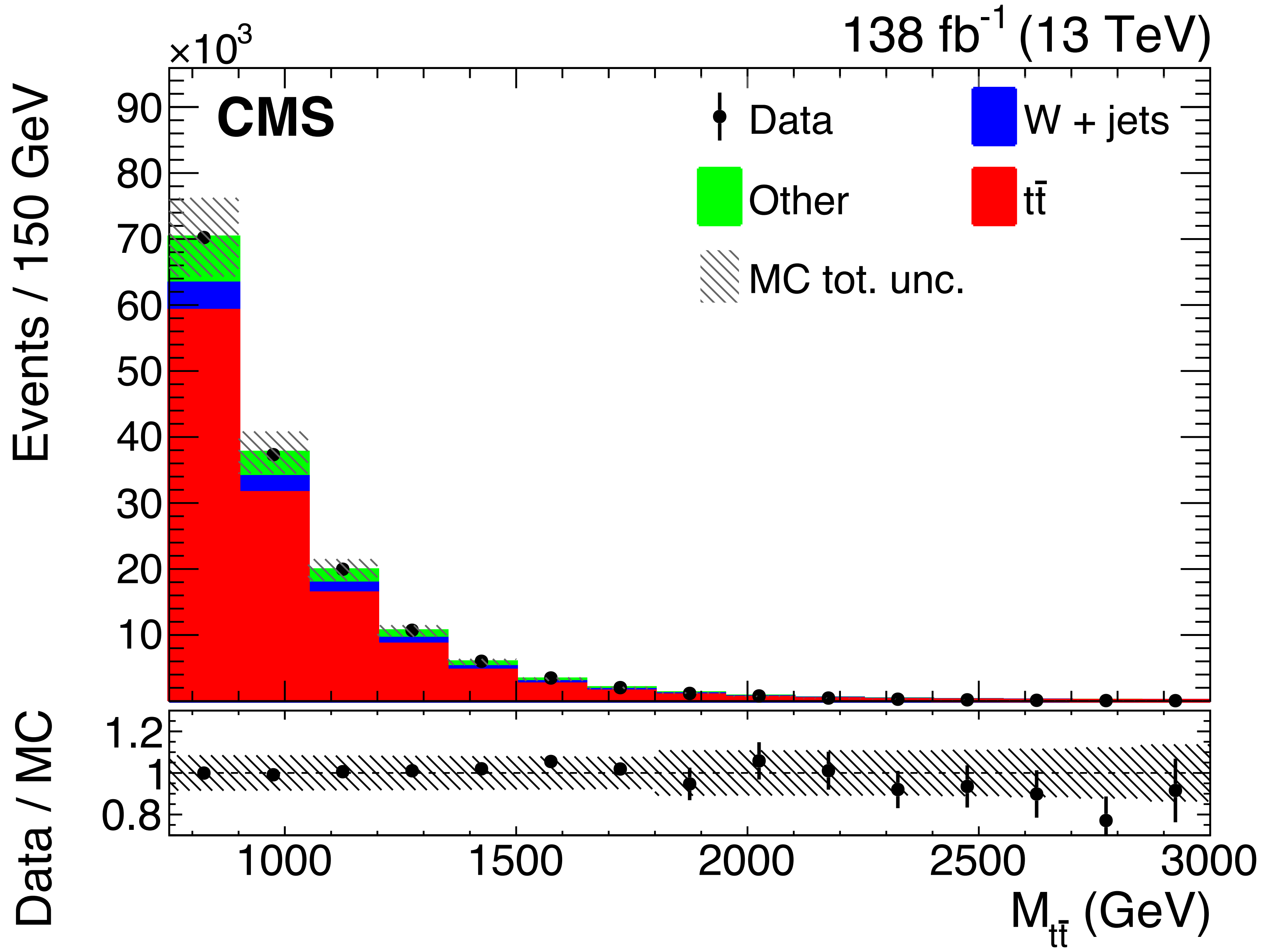


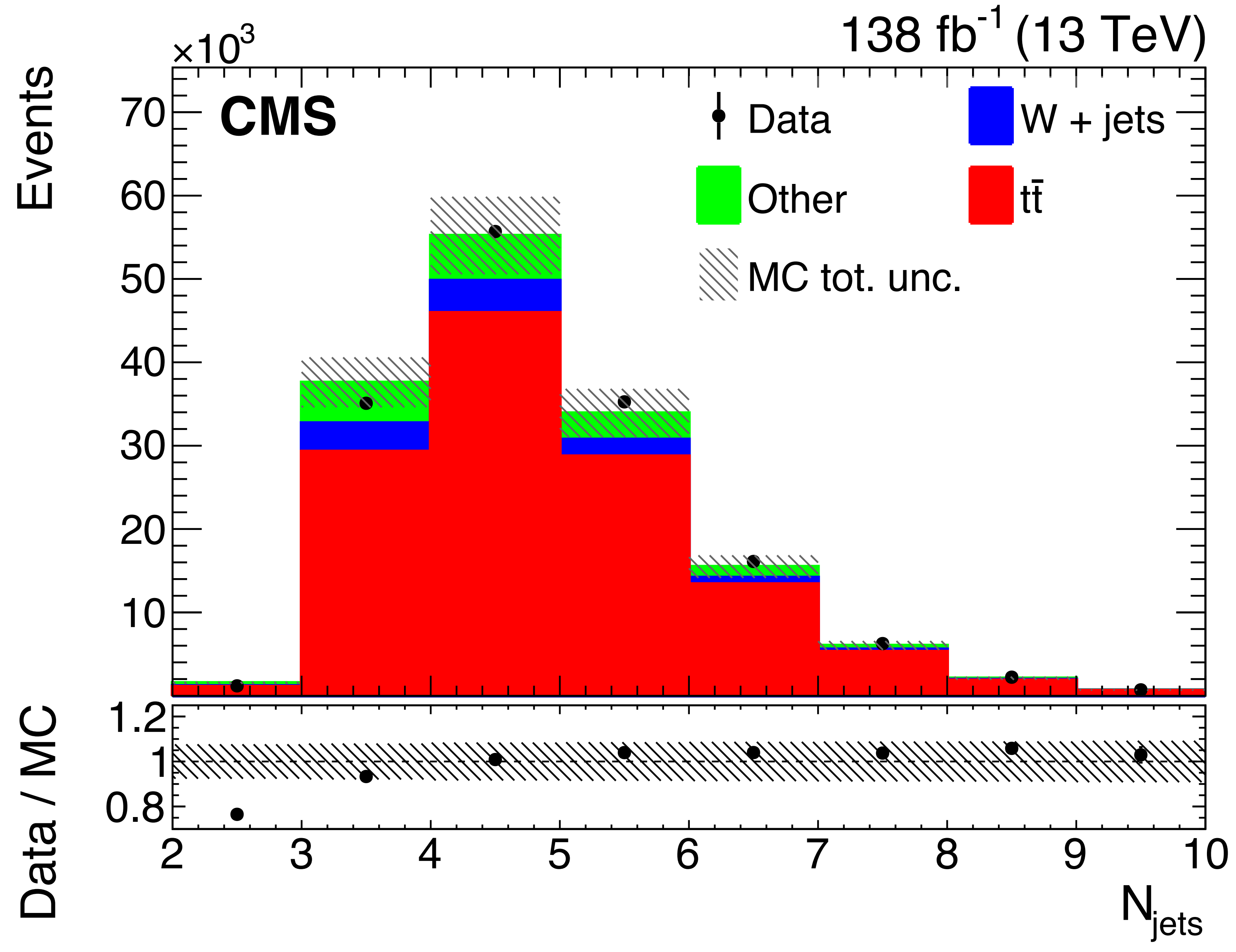
- Boosted: 1 Top tagged jets =1 **AND** 0 W tagged jets
- SemiResolved: 0 Top tagged jets = 0 **AND** 1 W tagged jets
- Resolved: 0 Top tagged jets = 0 **AND** 0 W tagged jets

- W and Top tags are exclusive, all events have >=1 b-tag

- We use events in the highly boosted region i.e. $M_{t\bar{t}} > 750$ GeV.







Unfolding

The goal of unfolding is to **correct the reconstructed data by removing the smearing** which is a result of poor detector resolution and acceptance

We are using a likelihood-based unfolding, using the **Higgs Combine tool**

$$\mathscr{L}_k = \prod_{j=1}^{N_{reco}} P(n_j; \sum_{i=1}^{N_{gen}} A_{ij}(\overrightarrow{\delta_u})\mu_i + b_j)N(\overrightarrow{\delta_u})$$

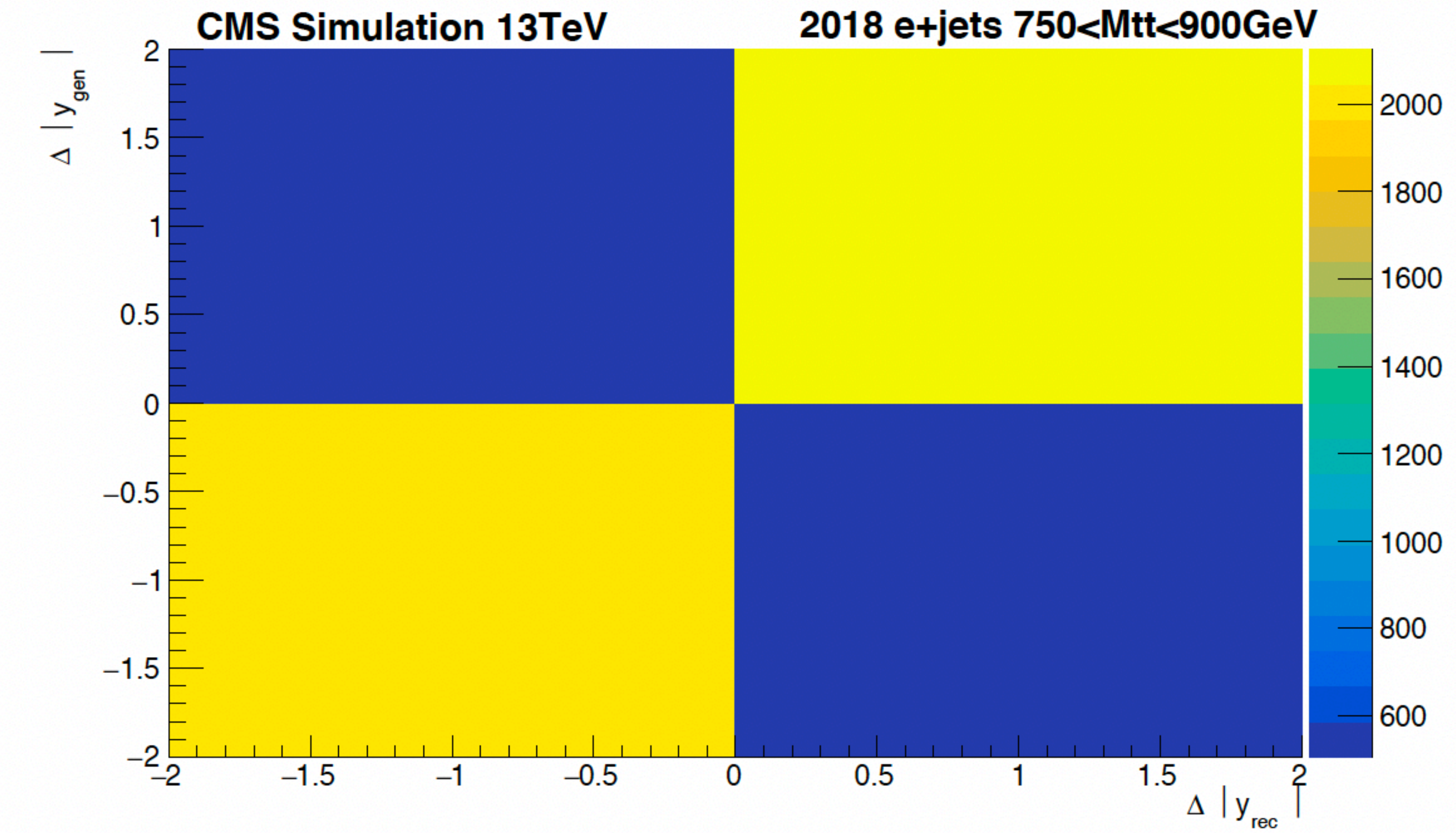
The way we construct the likelihood is via the datacard

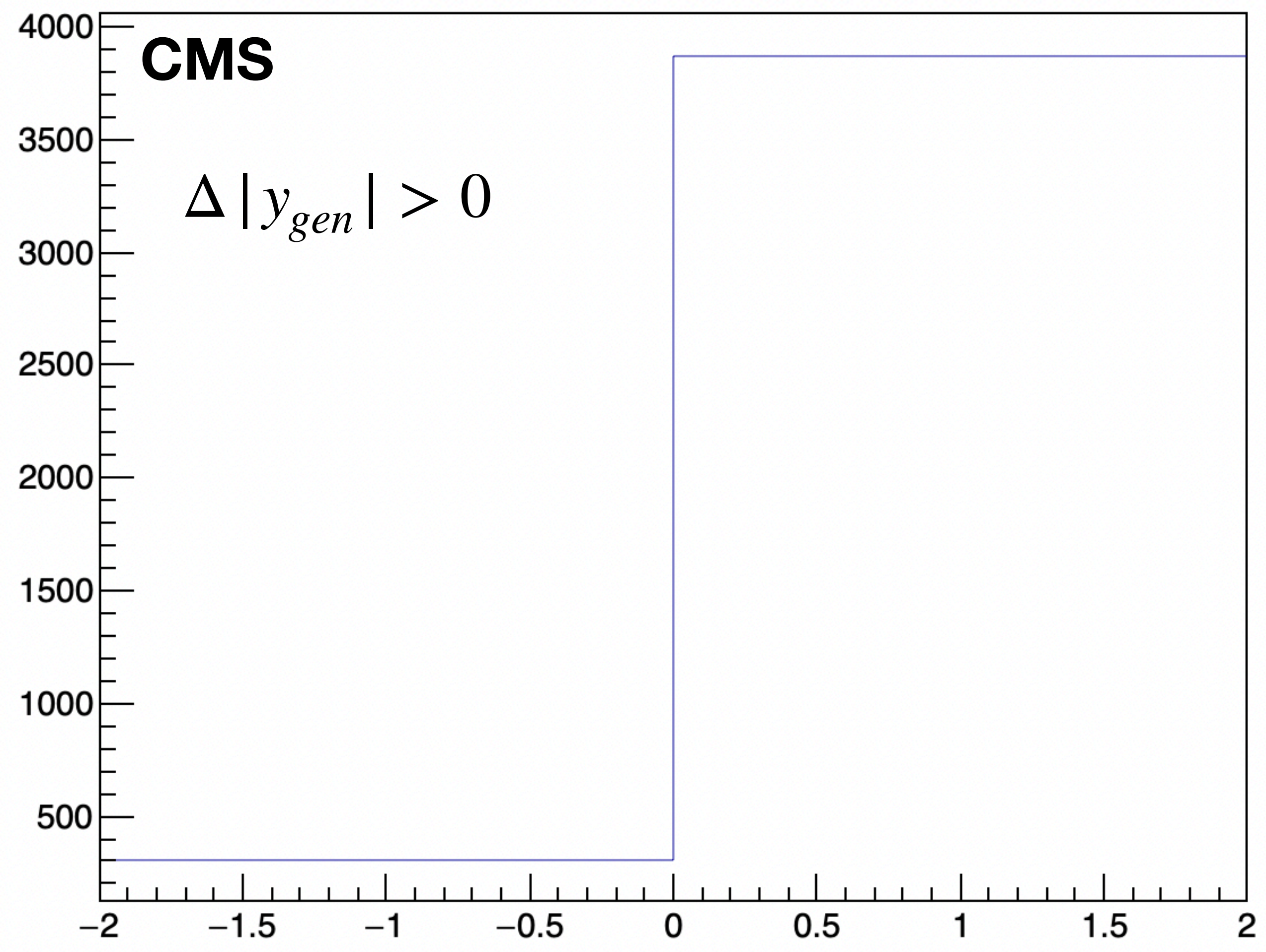
- Each datacard represents a reconstructed bin
- Each datacard describes the contribution from each of the common truth bins $\Delta|y_{gen}| > 0, \Delta|y_{gen}| < 0.$

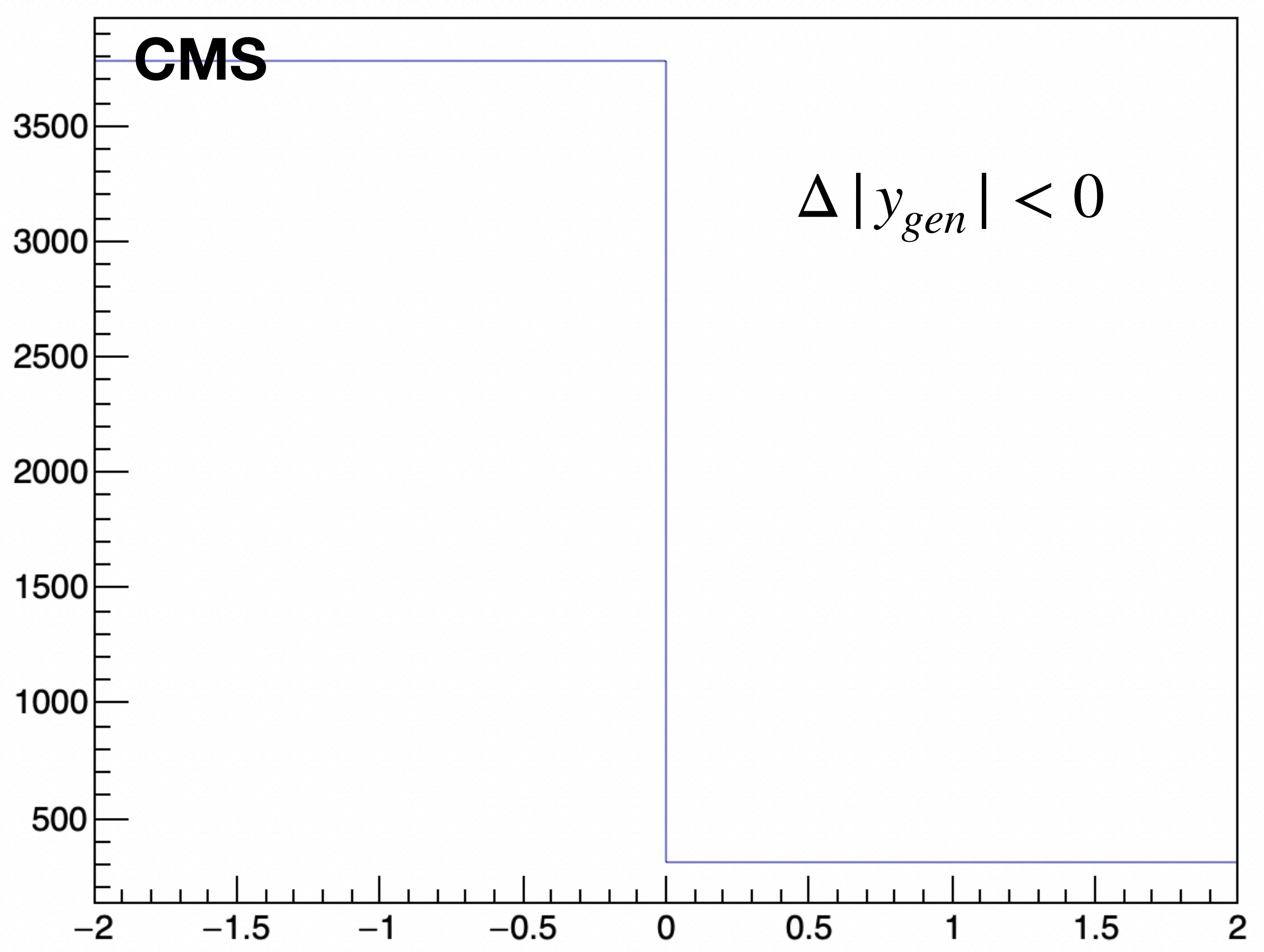
We have 12 datacards:

- **2 lepton flavors** (electrons and muons)
- **2 mass bins**
  - 750 Gev < Mttbar < 900 GeV
  - Mttbar > 900 GeV
- **3 years** (2016,2017,2018)

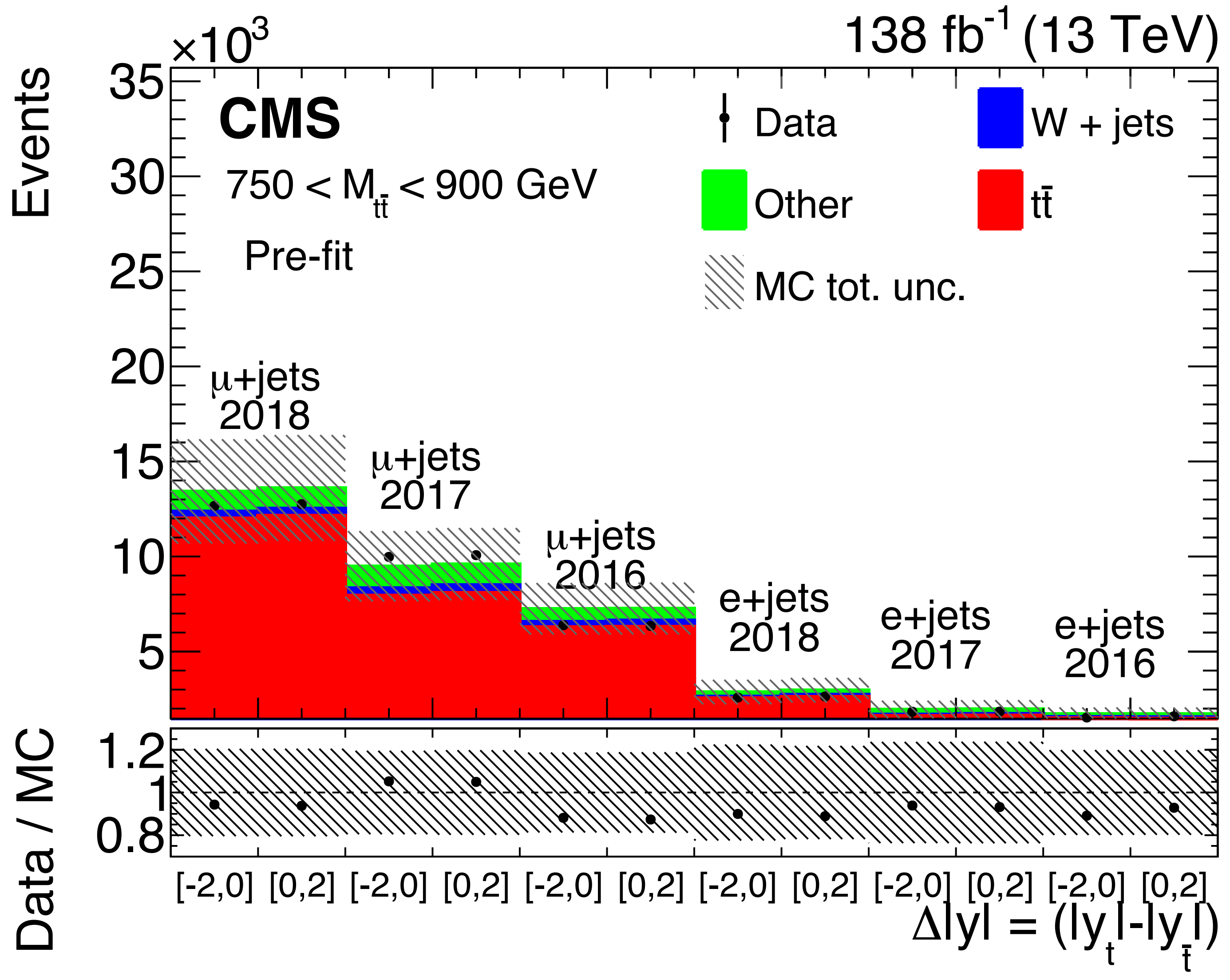
$\Delta|y|$ migrations are taken into account with the datacard.

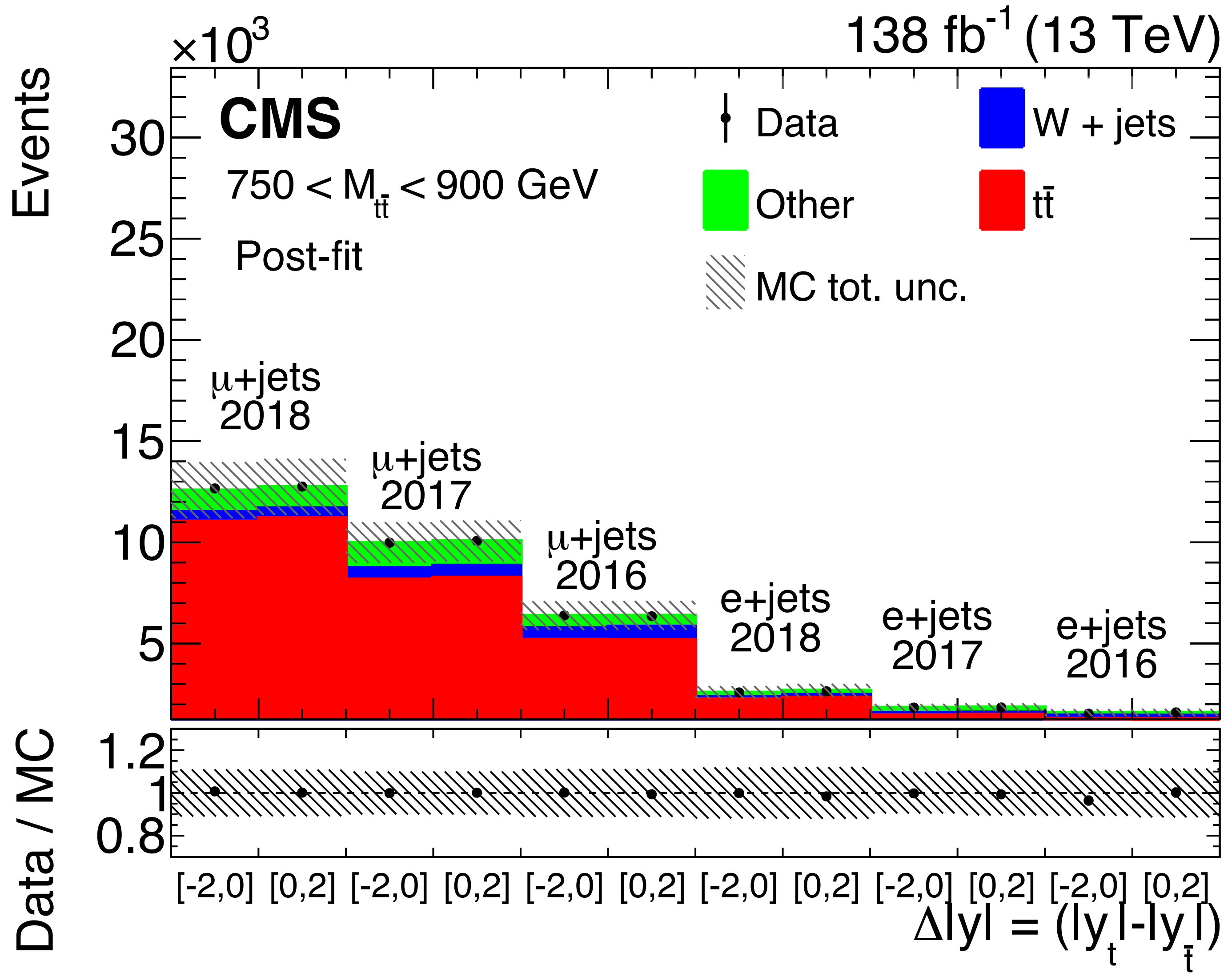


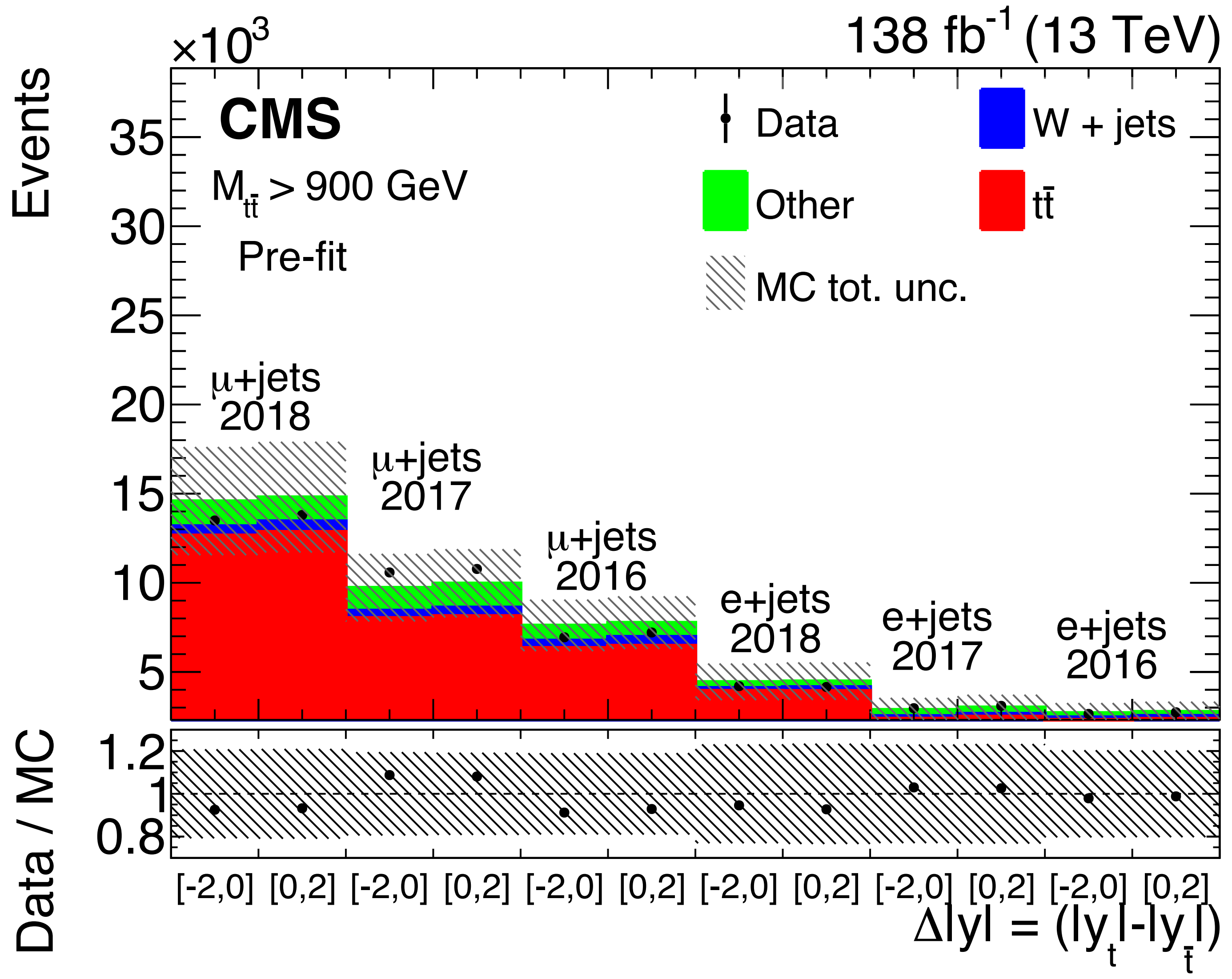


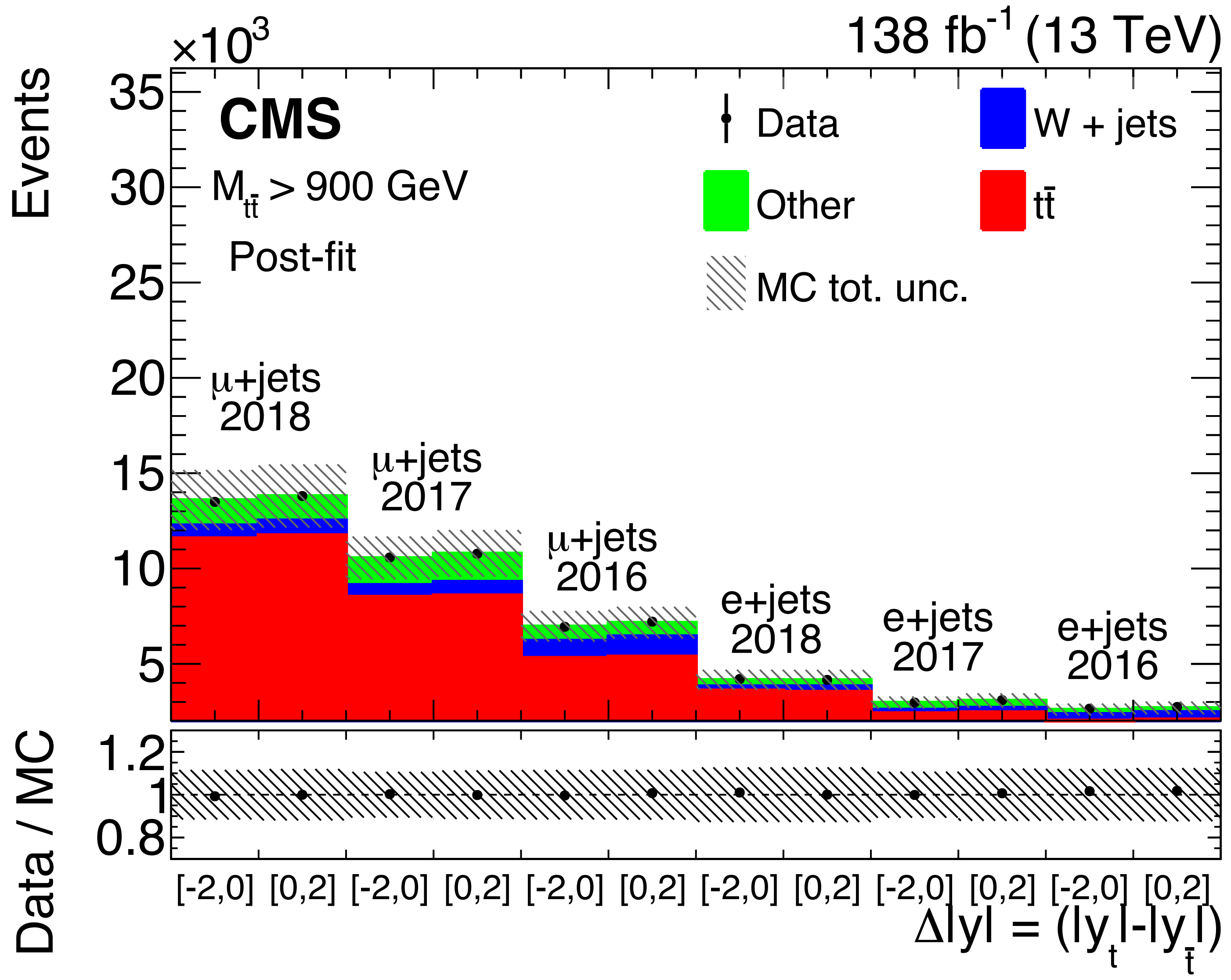


Events used in Unfolding









Charge Asymmetry in the Full phase space

- Unfolding with the Combine tool enables us to extract the A_C directly from the maximum likelihood fit that is performed, hence all error propagation is taken care of

$$A_C = \frac{N_{unf}(\Delta|y_{gen}| > 0) - N_{unf}(\Delta|y_{gen}| < 0)}{N_{unf}(\Delta|y_{gen}| > 0) + N_{unf}(\Delta|y_{gen}| < 0)}$$

$$N_{unf}(\Delta|y_{gen}| > 0) = r_{pos} \times \frac{N_{truth}(\Delta|y| > 0)}{\alpha\epsilon^{pos}}$$

$$N_{unf}(\Delta|y_{gen}| < 0) = r_{neg} \times \frac{N_{truth}(\Delta|y| < 0)}{\alpha\epsilon^{neg}}$$

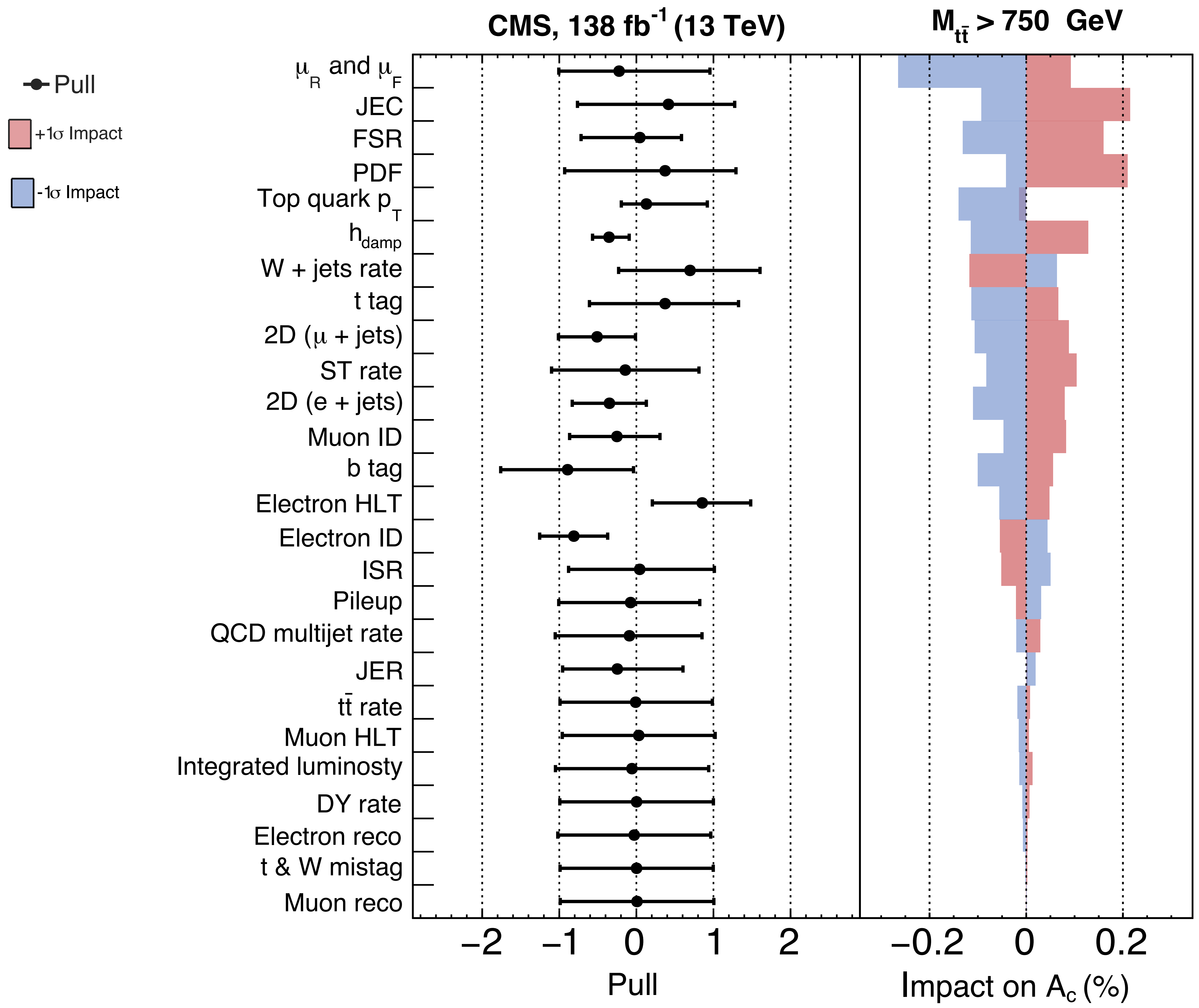
acceptance $\alpha\epsilon$ measured at generator level, corrects back from the fiducial phase space of a given channel to the full phase space :

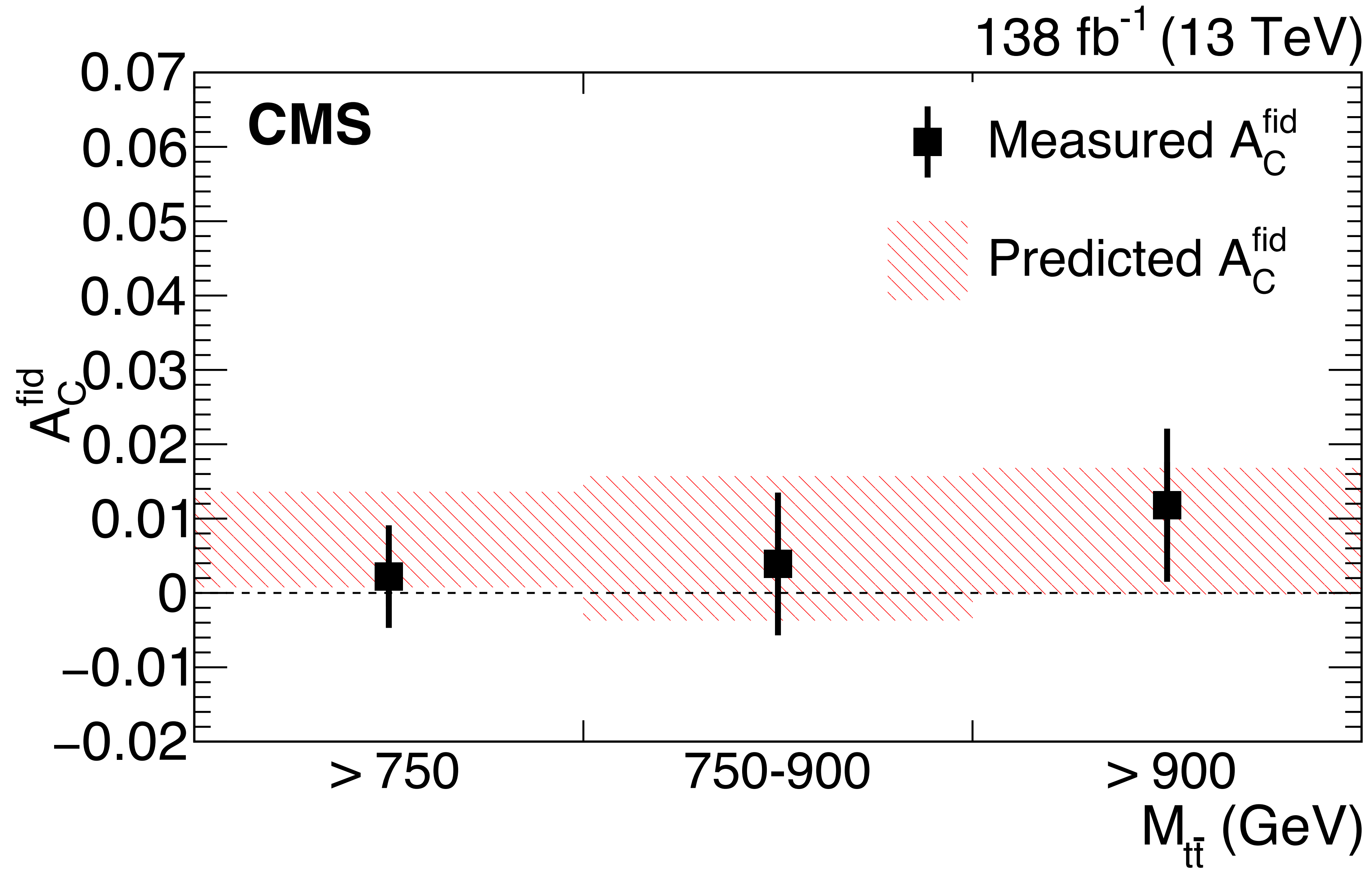
$$A_C^{full} = \frac{\alpha\epsilon^{neg} \times r_{pos} \times N_{truth}(\Delta|y| > 0) - \alpha\epsilon^{pos} \times r_{neg} \times N_{truth}(\Delta|y| < 0)}{\alpha\epsilon^{neg} \times r_{pos} \times N_{truth}(\Delta|y| > 0) + \alpha\epsilon^{pos} \times r_{neg} \times N_{truth}(\Delta|y| < 0)}$$

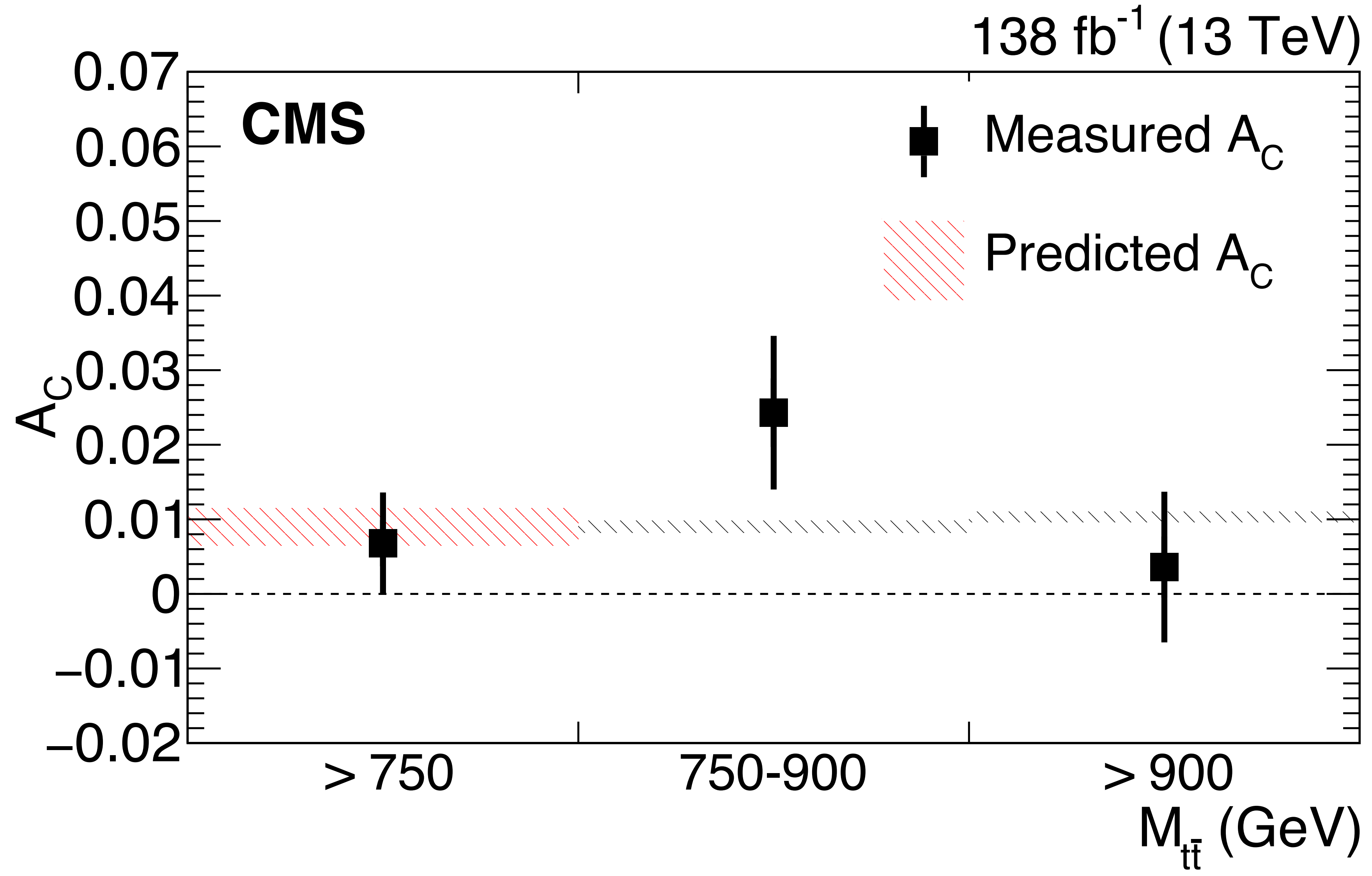
$$r_{pos} = \frac{\alpha\epsilon^{pos}}{\alpha\epsilon^{neg}} r_{neg} \times \frac{N_{truth}(\Delta|y| < 0)}{N_{truth}(\Delta|y| > 0)} \times \frac{1 + A_C^{full}}{1 - A_C^{full}}$$

Results

Full phase results can be compared to theory (*Phys. Rev. D* **98**, *014003*) values directly







MC stats are included using Barlow-Beeston lite method but not shown here

In summary

- https://arxiv.org/pdf/2208.02751.pdf
- We have presented the **first measurement of charge asymmetry in boosted ttbar l+jets events** with CMS data at √s=13 TeV using dedicated techniques for:
    - the hadronic decay of the top quark- using **substructure variables**
    - **non isolated leptons** in the leptonic decay of the top quark
- Maximum Likelihood unfolding used to extract the charge asymmetry in the **full phase space** and found it to be in agreement with theoretical values within uncertainty.
- We have unfolded to the full phase space $A_C^{full}(\,\%\,) = 0.69 \pm 0.44(\text{stat})^{+0.34}_{-0.42}(\text{syst}) = 0.69^{+0.65}_{-0.69}$, can be compared to NNLO in QCD perturbation with NLO EWK corrections $0.94^{+0.05}_{-0.07}\,\%$

Backup

Forward-Backward Asymmetry in top pair production at the Tevatron

- Investigation of the charge asymmetry in heavy quark production was performed at the Tevatron accelerator by CDF and D0 experiments.

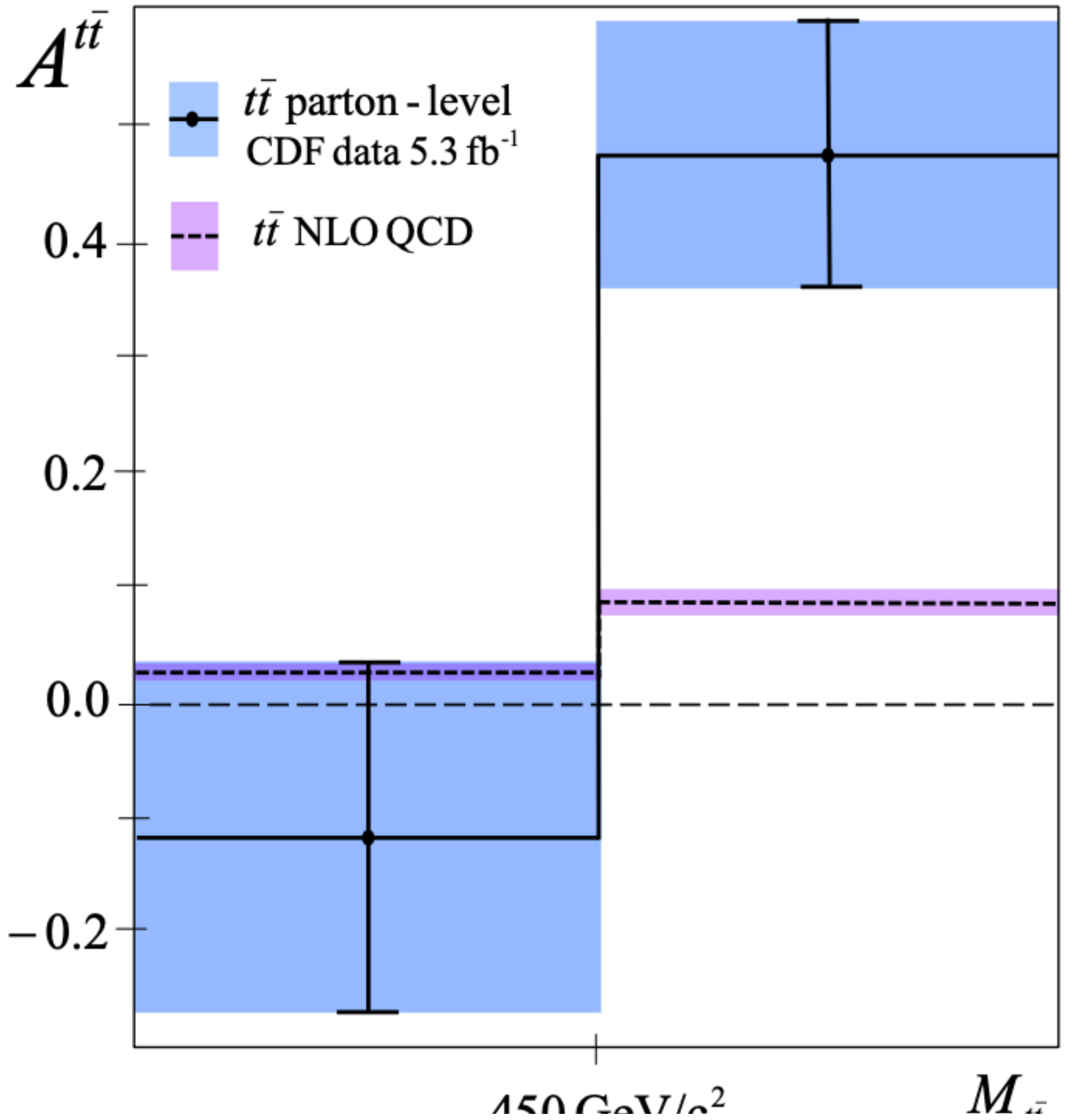
- Tevatron was a very suitable collider for studying $t\bar{t}$ charge asymmetry due to the dominant $q\bar{q} \rightarrow t\bar{t}$ production channel.

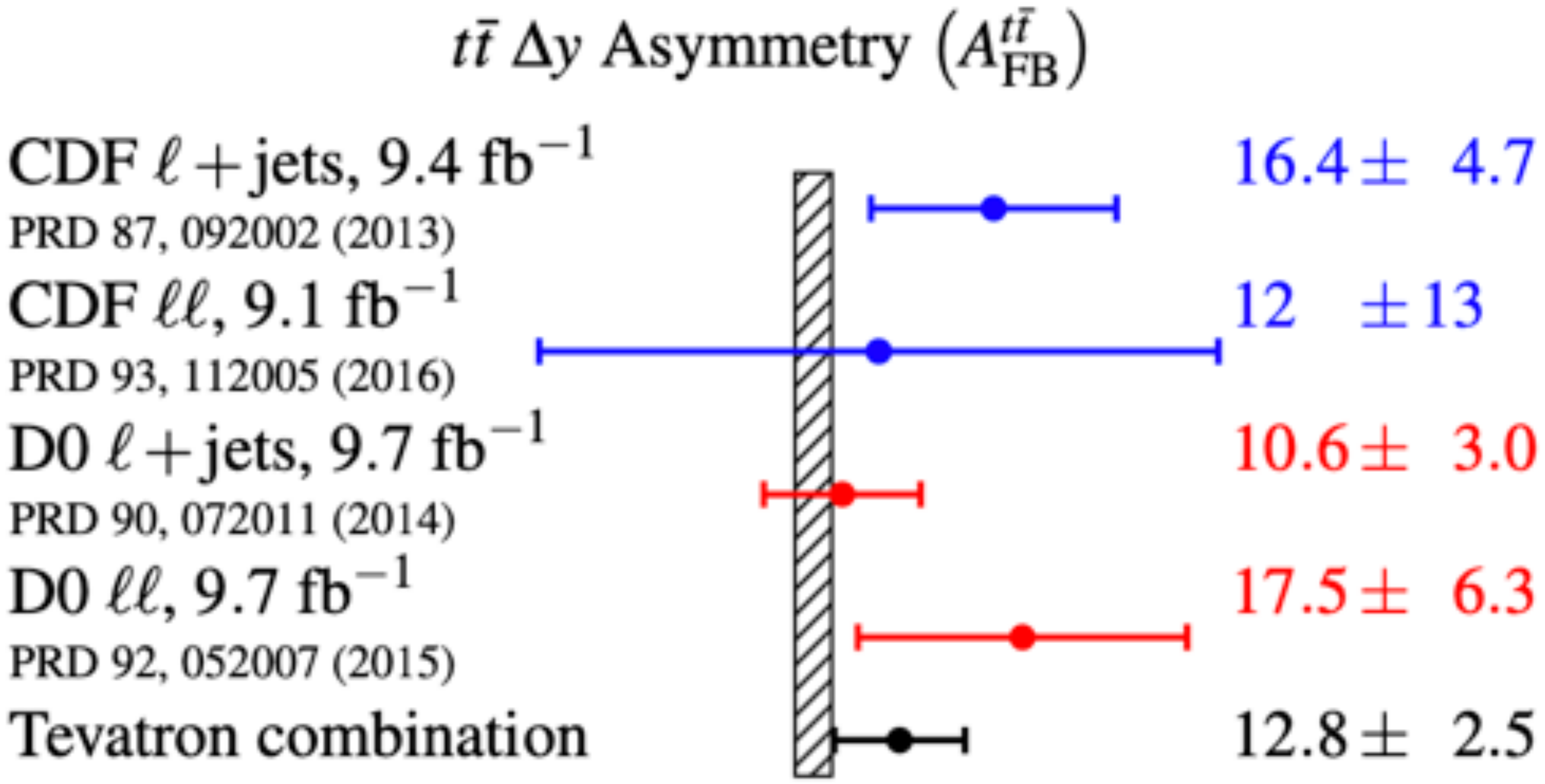
- Asymmetry, defined as:

$$A_{\rm FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},$$

- First results measured in D0 and CDF disagree with the MC@NLO based predictions, with most significant discrepancy above 3σ

Phys. Rev. D **83** (2011) 112003.





Phys. Rev. Lett. 120 (2018) 042001.

Baseline selection for e/μ + jets events

Muons

- HLT_Mu50_v*
- Exactly one muon
  - CutBasedGlobalHightPt
  - p_T > 55GeV and $|\eta| < 2.4$
- MET > 50 GeV; HT_{lep} > 150 GeV
- No isolation requirement
- 2D kinematic cut
- At least two AK4 (CHS) jets
  - p_T(jet1) >150GeV & p_T(jet2) >50 GeV; $|\eta| < 2.4$
  - >=1 b-jets are identified with DeepNN Jet Tight working point
- AK8 PUPPI jets with p_T > 400 GeV and $|\eta| < 2.4$
- Veto on events with second lepton p_T > 20 GeV, $|\eta| < 2.4$

Electrons

- HLT_Ele50_CaloIdVT_GsfTrkIdT_PFJet165_v* OR HLT_Ele115_CaloIdVT_GsfTrkIdT_v*
- Exactly one electron
  - cut-based TightID
  - p_T > 85GeV and $|\eta| < 2.4$
- MET > 120 GeV
- No isolation requirement
- 2D kinematic cut
- At least two AK4 (CHS) jets:
  - p_T(jet1) > 185GeV & p_T(jet2) > 50 GeV; $|\eta| < 2.4$
  - >=1 b-jets are identified with DeepNN Jet Tight working point
- AK8 PUPPI jets with p_T > 400 GeV and $|\eta| < 2.4$
- Veto on events with second lepton p_T > 20 GeV, $|\eta| < 2.4$