Measurement of the charge asymmetry in top pair production at $\sqrt{s}$ = 13 TeV with the CMS experiment

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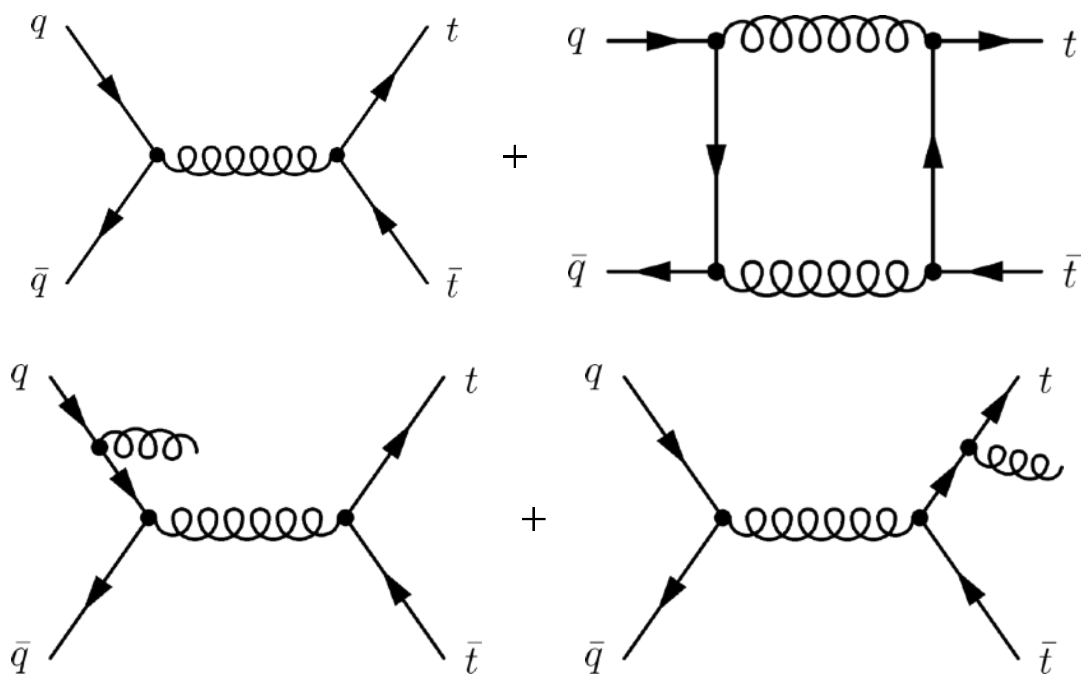
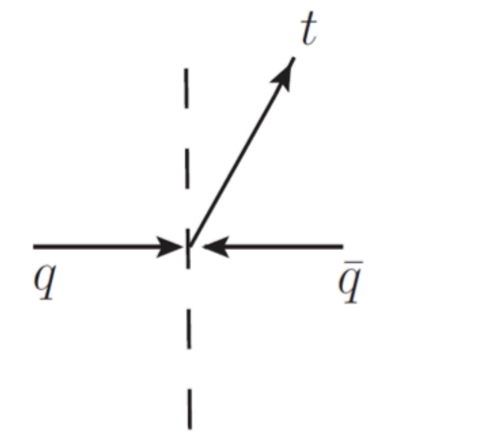
Charge asymmetry in top pair prodcution

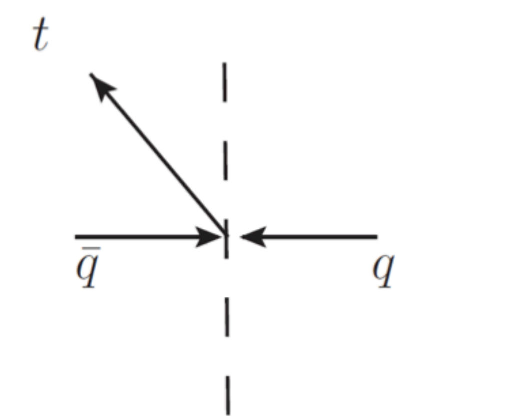
Positive contribution

Negative contribution





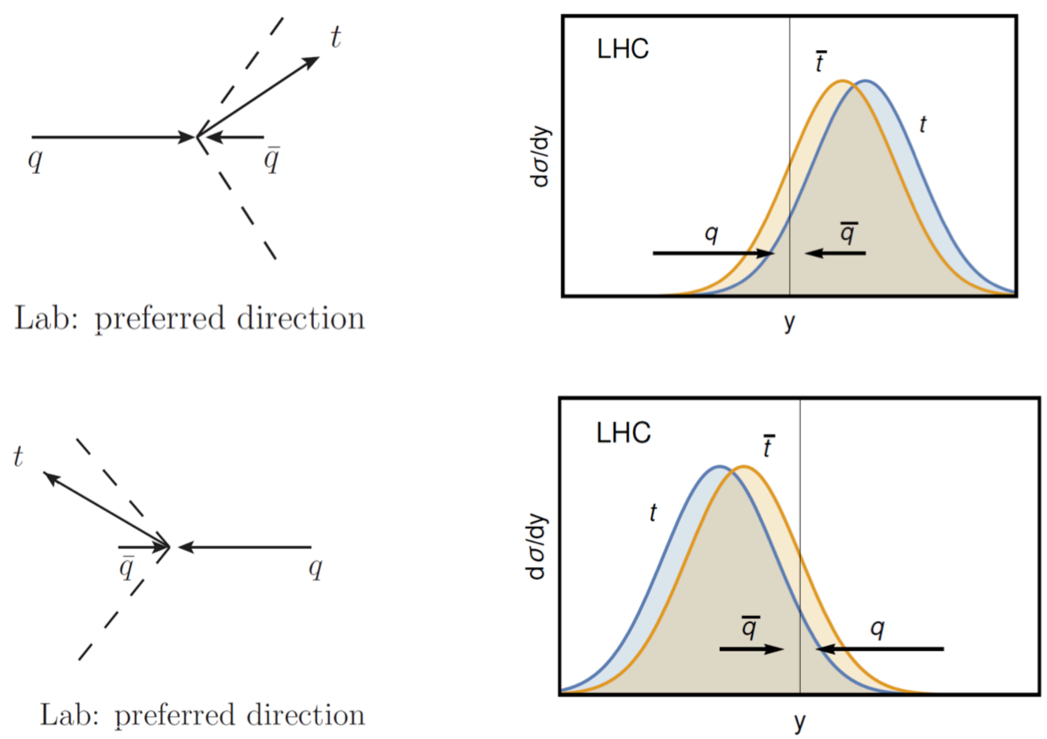
CM: preferred direction

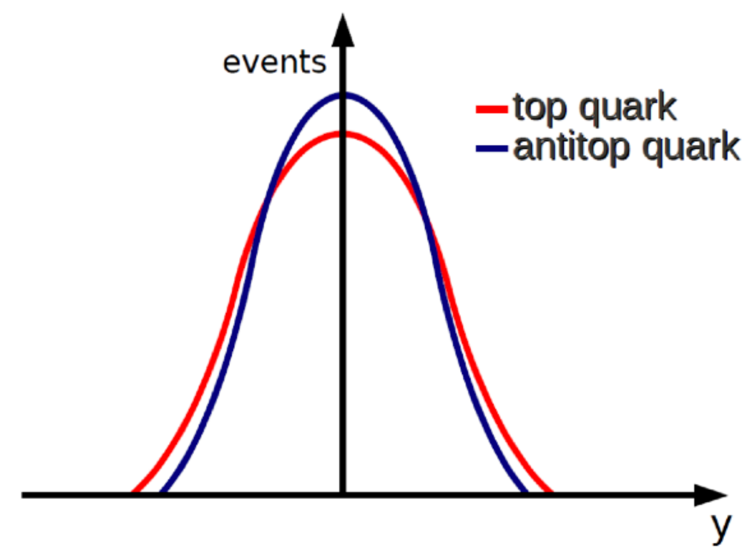


CM: preferred direction

- Top quarks in pair production have a preferential direction
  - No asymmetry with LO and $gg \to t\bar{t}$ production
  - Expected in higher order diagrams
    - Asymmetry with $q\bar{q} \to t\bar{t}$ and $qg \to t\bar{t}Q$
    - We can test the NLO/NNLO SM physics

Top pair charge asymmetry in LHC

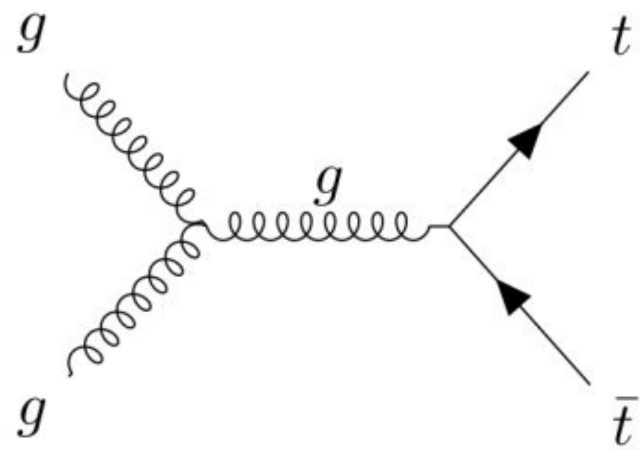


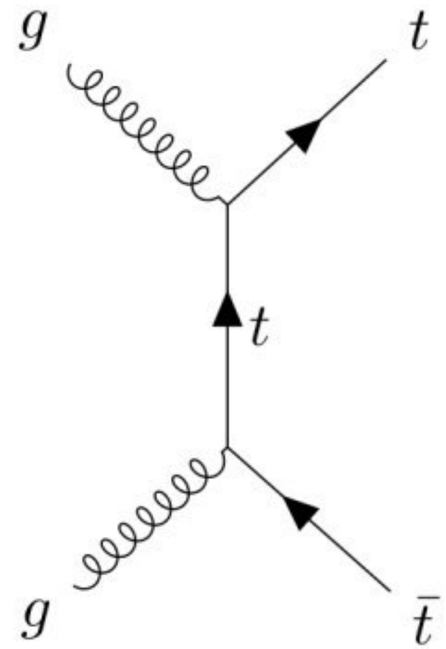


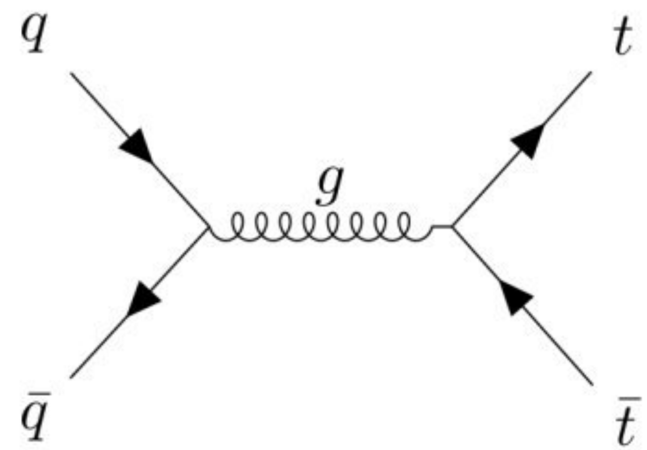
- The valence quarks in protons have larger energy than other quarks
  - We can expect the forward-center asymmetry in the top pair production at LHC.
- Suppressed by a large fraction of $gg \to t\bar{t}$ events at LHC.
  - Very small amount of the asymmetry is measurable.
  - But in the new physics model, we expect additional contribution to the asymmetry [1]
    - Axigluon, Z`, colour-triplet scalar, etc

[1]J.A. Aguilar-Saavedra, D. Amidei, A. Juste, and M. Pérez-Victoria,
"Asymmetries in top quark pair production at hadron colliders " Rev. Mod. Phys. **87**, 421

Top pair production



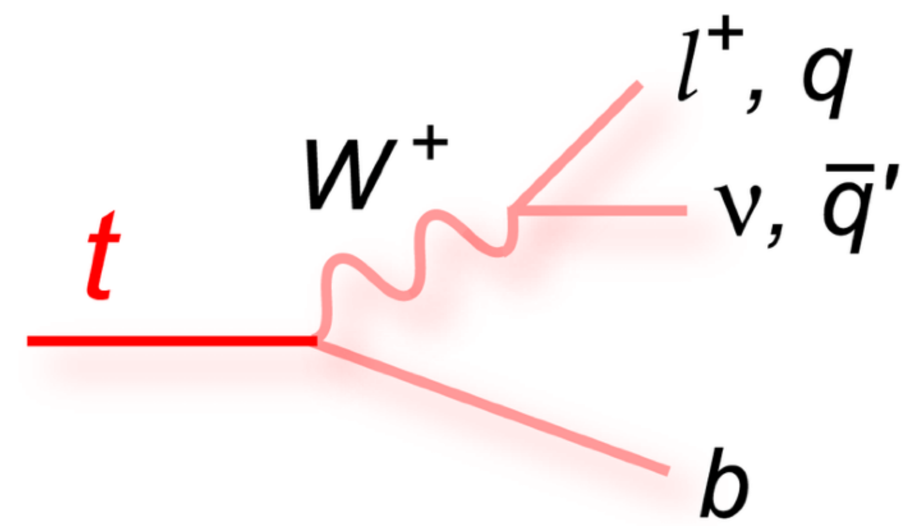


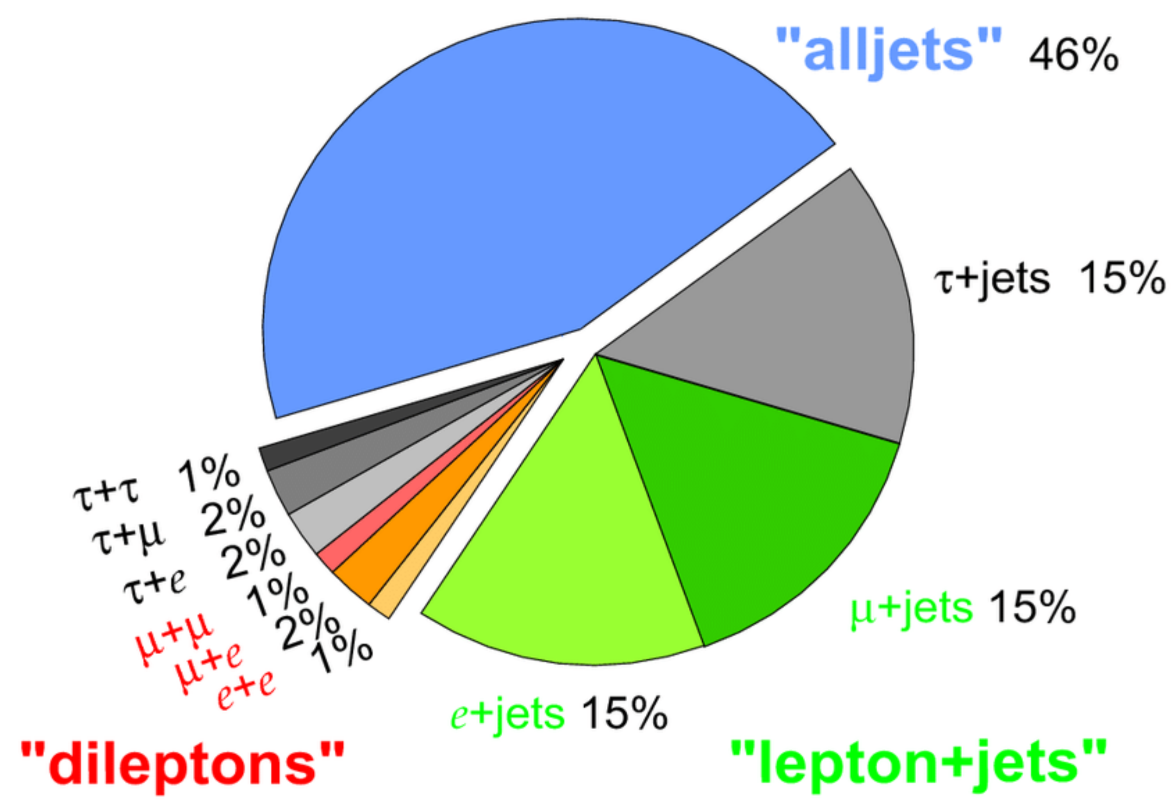


- The top quark is the most massive particle in the Standard Model
  - 172.52±0.14(stats.)±0.30(syst.) GeV
- One of the most promising productions in the LHC
  - Mediated by strong interaction
  - $\sigma_{t\bar{t}} = 923.6^{+22.6+22.8}_{-22.8-22.8}$ pb @ 13 TeV p-p collision

Final states of Top pair production

- Most of tops decay to b quark with emitting W boson
- Hadronic or Leptonic top quark
  - How W boson decays
  - Decay modes including τ in their final state are ignored
- Fully hadronic channel : 46%
- Dilepton channel : 4 %
- Lepton+jets channel : 30 %





Goal of the Analysis

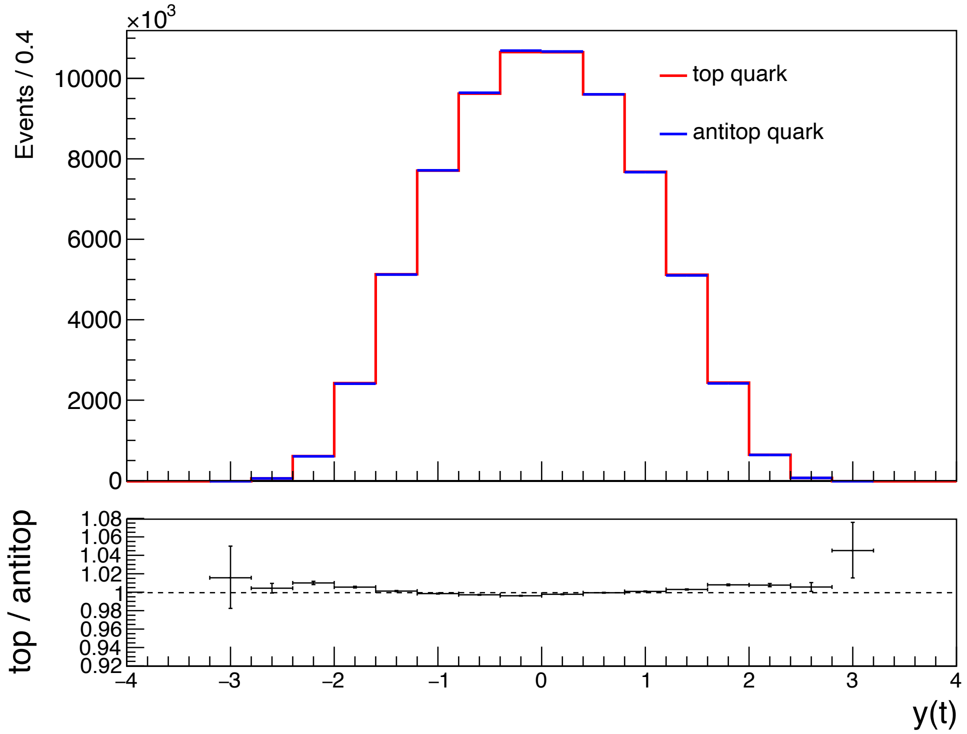
- Inclusive and differential measurement of the charge asymmetry with the CMS experiment

  - With single lepton final state of top pair production

  - Observable : charge asymmetry

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

    - $\Delta|y| = |y_t| - |y_{\bar{t}}|$, y_t : rapidity of top



  - Differential measurement as a function of Invariant mass of the top pair system ($M_{t\bar{t}}$)

  - New physics models' contribution is dominant in high mass region of top pair system and make a significant difference from SM prediction

Dataset

- Data : CMS Run 2 Data (137.6 fb^{-1})
  - 13 TeV proton-proton collision data, collected in 2016 - 2018

		2016preVFP	2016postVFP	2017	2018
integrated luminosity		$19.5fb^{-1}$	$16.81fb^{-1}$	$41.48fb^{-1}$	$59.83fb^{-1}$
L1 Menu	e+jets channel	SingleElectron	SingleElectron	SingleElectron	EGamma
	μ+jets channel	SingleMuon	SingleMuon	SingleMuon	SingleMuon

  - Data quality is checked with the CMS data certification group with considering detector conditions

- MC Samples are simulated
  with POWHEG + Pythia or MadGraph + Pythia for generator,
  GEANT4 for detector response simulation

- Signal MC : semi-leptonic decaying $t\bar{t}$

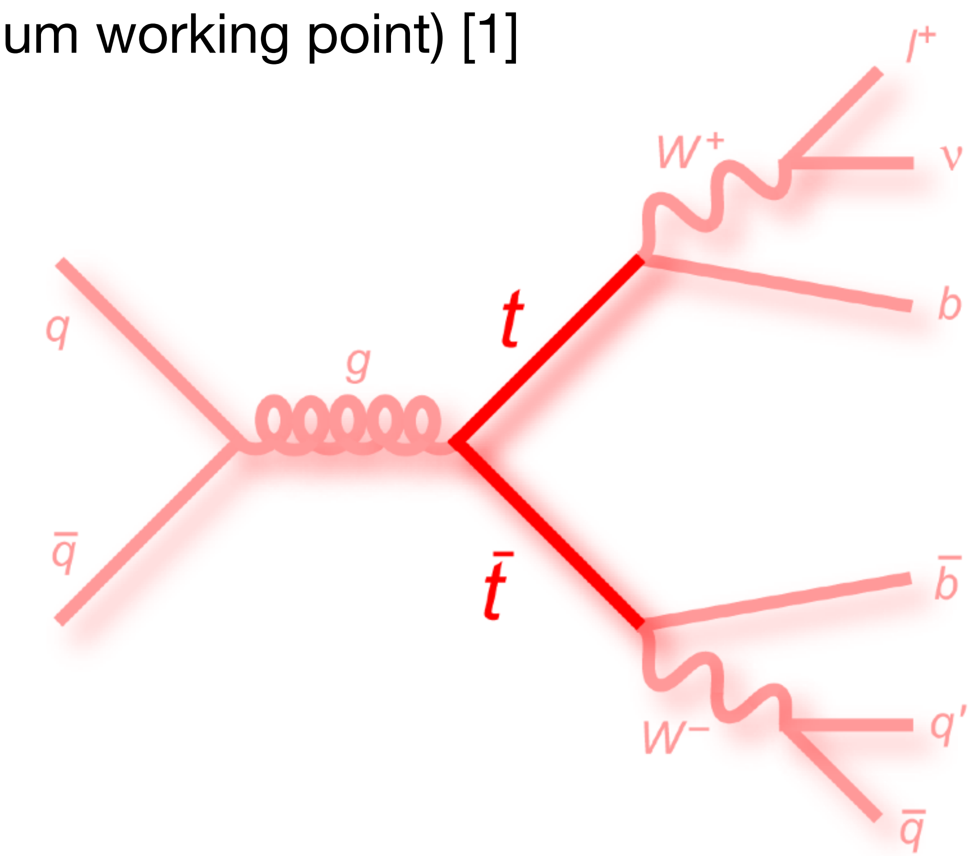
- Background MC
  - $t\bar{t}$ (di-leptonic & hadronic decaying), single top, Z/W+Jets, WW, WZ, ZZ, QCD

- MC samples are corrected with following scale factors
  - Pileup / Trigger efficiency / Lepton ID / Electron reconstruction / Muon isolation / b-tagging efficiency / Jet energy scale / Jet energy resolution

Object Selection

- Electron
  - Tight Identification
  - $p_T > 34$ GeV / $|\eta| < 2.4$
    (except $1.4442 < |\eta_{SC}| < 1.566$)
- Muon
  - Tight Identification and Isolation
  - $p_T > 30$ GeV / $|\eta| < 2.4$
- Veto Leptons
  - Loose Identification
  - e : $p_T > 15$ GeV / $|\eta| < 2.4$
  - μ : $p_T > 10$ GeV / $|\eta| < 2.4$

- Jets
  - Clustered with anti-k_t algorithm(Δ R < 0.4)
  - Loose identification
  - $p_T > 30$ GeV / $|\eta| < 2.4$
  - Isolated from selected lepton (Δ R < 0.4)
  - b-tagging with CMS DeepJet algorithm (medium working point) [1]



[1]Bols, E. and Kieseler, J. and Verzetti, M. and Stoye, M. and Stakia, A., "Jet flavour classification using DeepJet" JINST 15.12

Event Selection

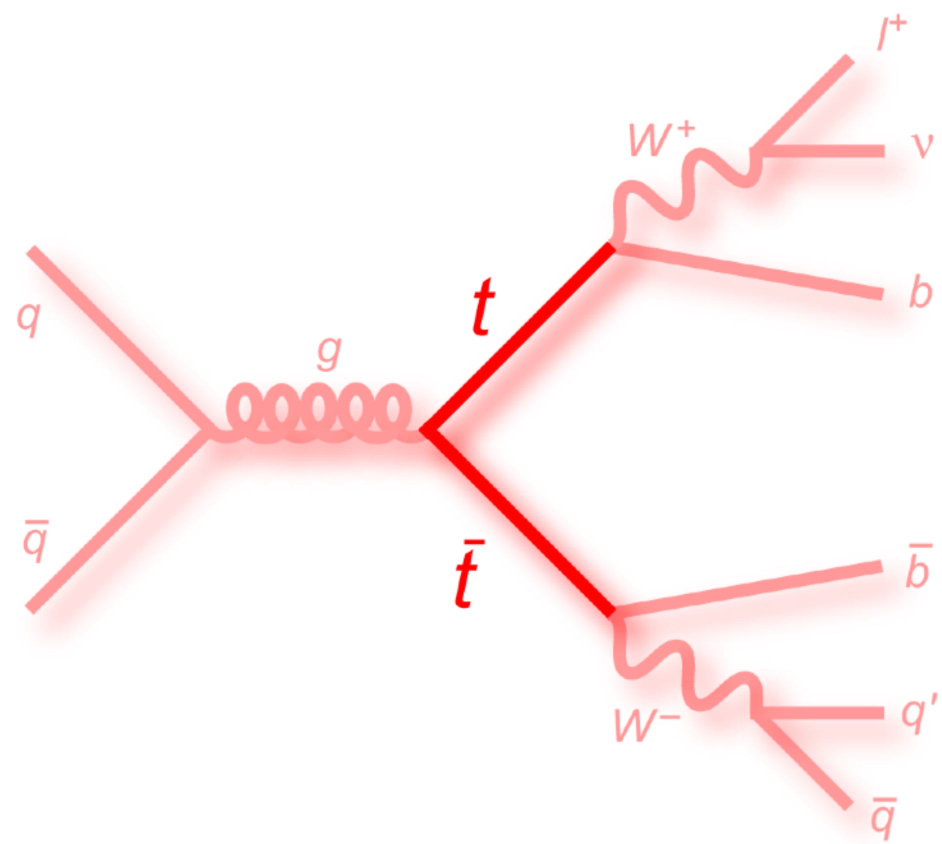
- High Level Trigger

Year	e+jets channel	μ+jets channel
2016	HLT_Ele27_WPTight_Gsf	HLT_IsoMu24 or HLT_IsoTkMu24
2017	HLT_Ele32_WPTight_Gsf_L1DoubleEG	HLT_IsoMu27
2018	HLT_Ele32_WPTight_Gsf	HLT_IsoMu24

  - e+jets : Single Electron with tight ID
  - μ+jets : Single Isolated muon

- Primary Vertex
  - At least 4 objects need to be associated with the primary vertex in $|z|$ < 24 cm from the interaction point

- Matching for finals state objects
  - Exactly **one lepton** without veto leptons
  - At least **4 jets** for event reconstruction
  - At least **1 b-tagged jets**



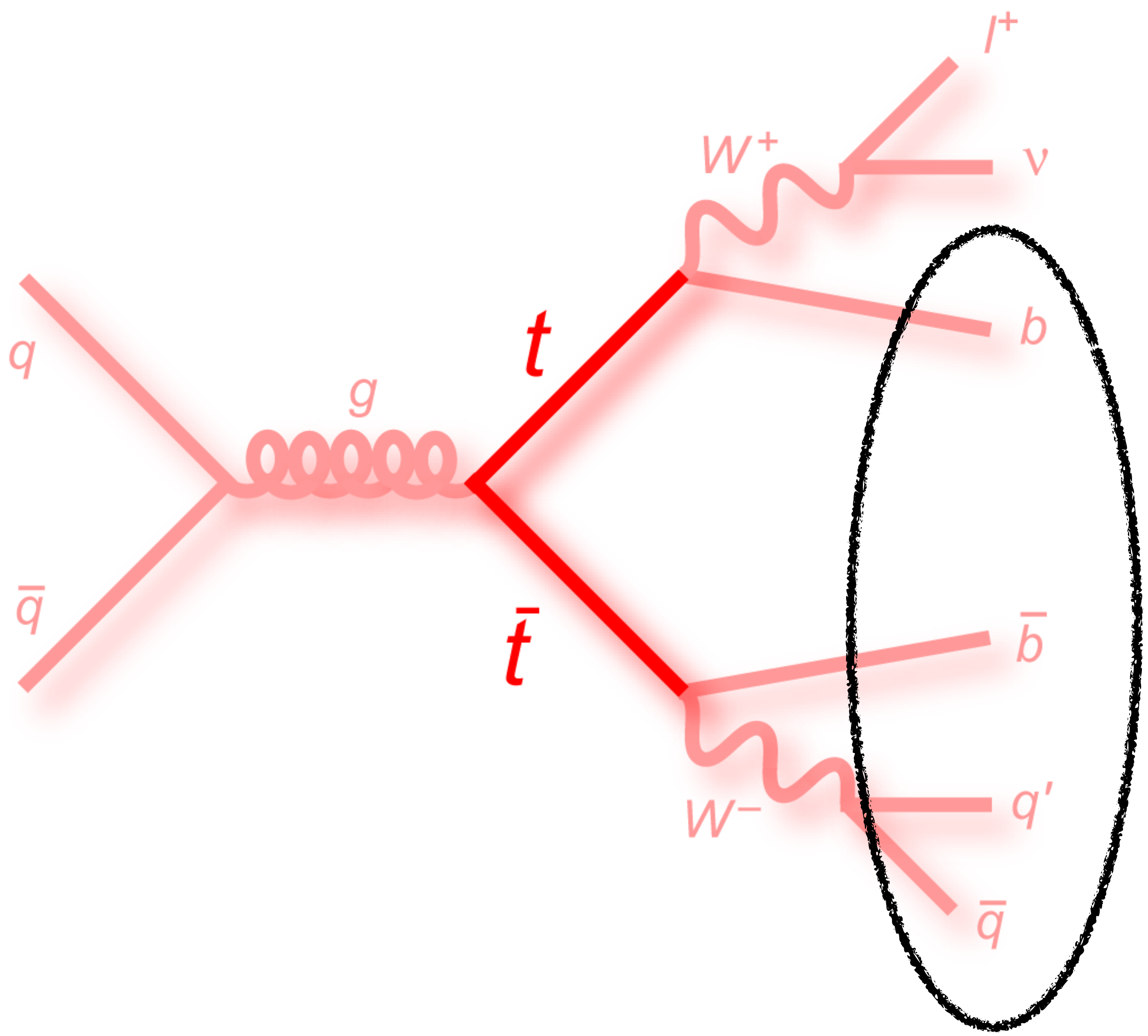
Solution of Neutrino Momentum

$$P_{T,\nu} = \not{E}_{p_T} \; ; \quad p^{\pm}_{z,\nu} = \frac{\mu p_{z,l}}{p^2_{T,l}} \pm \sqrt{\frac{\mu^2 p^2_{z,l}}{p^4_{T,l}} - \frac{E^2_l p^2_{T,\nu} - \mu^2}{p^2_{T,l}}} \; ; \; \mu = \frac{m^2_W}{2} + p_{T,\nu} p_{T,l} \, cos(\Delta\phi)$$

- Assumption
  - Transverse momentum of neutrino is the reconstructed missing transverse energy
  - W boson decays to the lepton and the neutrino
    - Mass of W boson is fixed value : 80.385 GeV
- When the solution is complex number
  - Charged lepton has been measured precisely
  - Mismatch of missing transverse energy with the transverse momentum of neutrino
    - Adjust the value of $P_{T,\nu}$ on the transverse plane as little as possible to make real solution

Event reconstruction

$$\Sigma\Delta R = \Delta R(t_{had}^{gen}, t_{had}^{reco}) + \Delta R(t_{lep}^{gen}, t_{lep}^{reco}) + \Delta R(W_{had}^{gen}, W_{had}^{reco}) + \Delta R(W_{had}^{gen}, W_{had}^{reco})$$

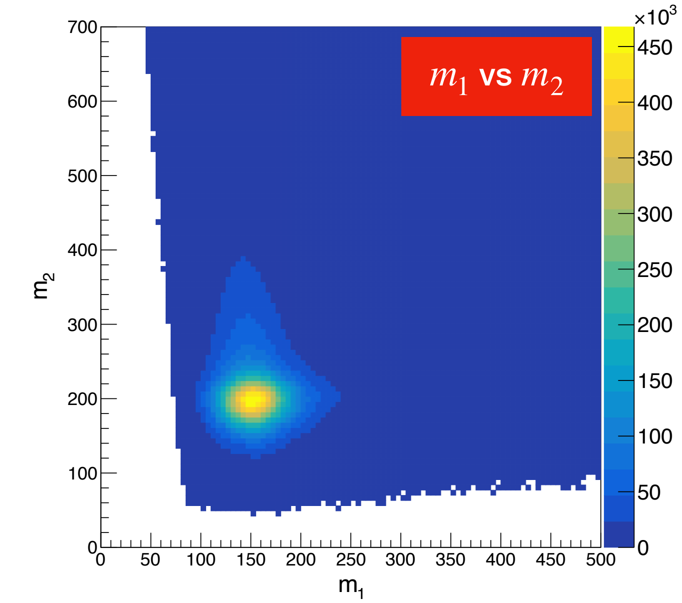


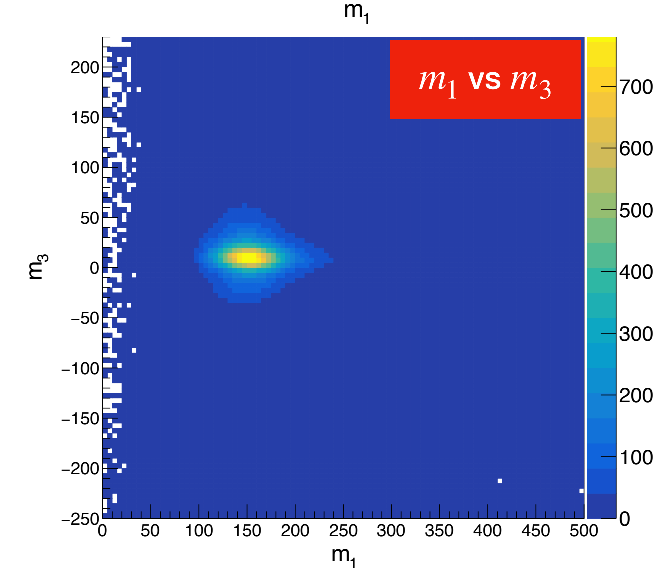
- Possible hypothesis
  - 2 ν solutions
  - Permutation of Jets
    - $\frac{N_{jets}!}{(N_{jets}-4)!}$
- Choose the best hypothesis within the event
  - Minimising $\Sigma\Delta R$ between generator and reconstruction level objects
- Only available on the signal MC

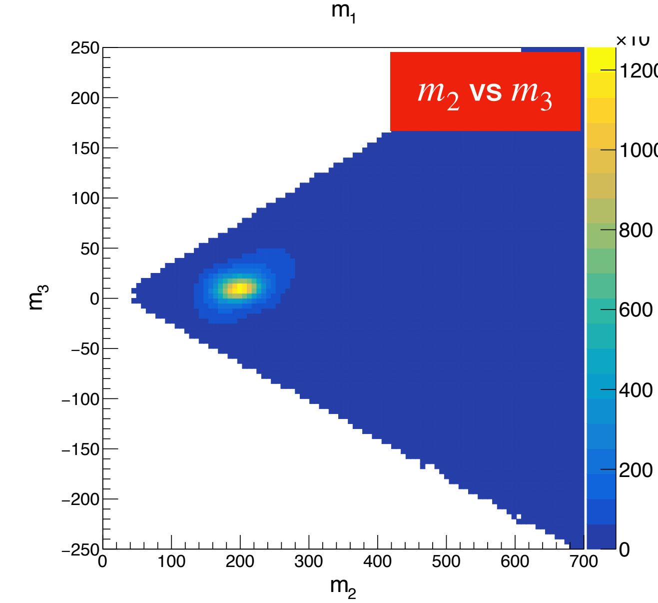
Likelihood based reconstruction

- Construct likelihood λ
  - $\lambda = L_1(m_1)L_2(m_2)L_3(m_3)$
  - The hypothesis with the smallest value of $-log(\lambda)$ is chosen as the solution
- m_1, m_2, m_3 : rotated mass from the minimum distance based reconstruction
  - Introduced to resolve the correlation between masses of the reconstructed **top quarks** and **hadronic decaying W boson**

$$\begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix} = \begin{pmatrix} 1.00 & -0.06 & -0.01 \\ 0.06 & 0.93 & 0.37 \\ -0.02 & -0.37 & 0.93 \end{pmatrix} \begin{pmatrix} m_{t,lep} \\ m_{t,had} \\ m_{W.had} \end{pmatrix}$$

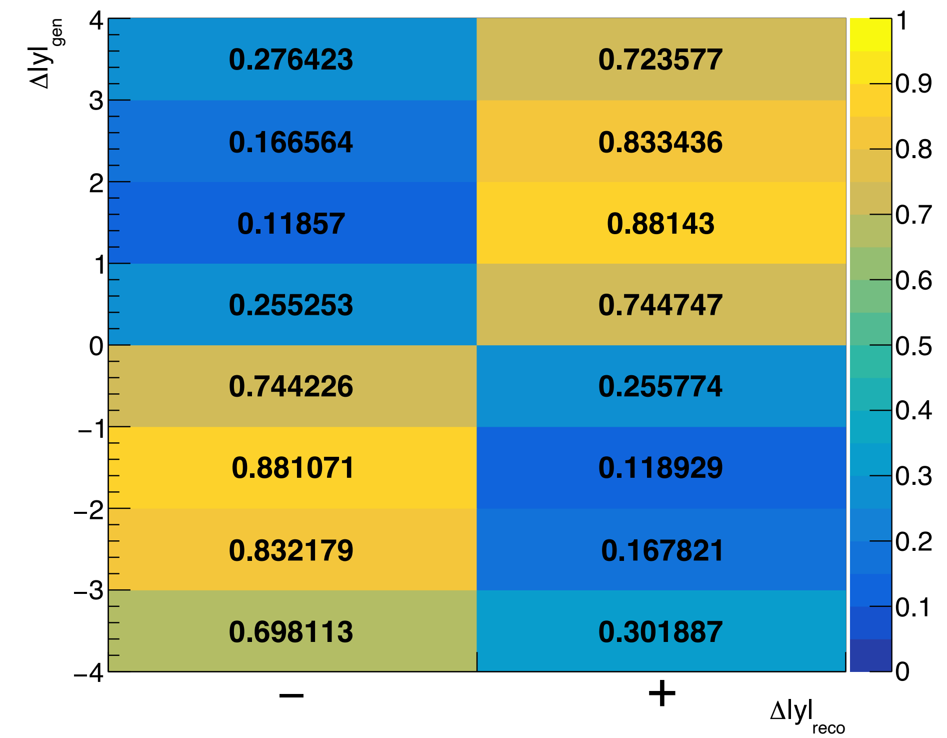


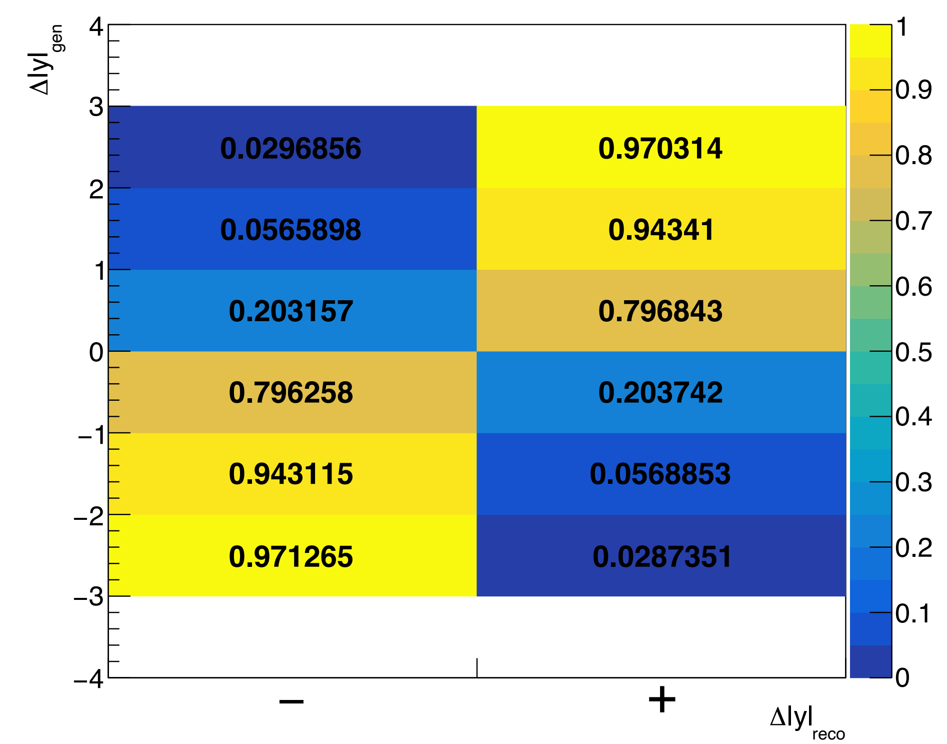




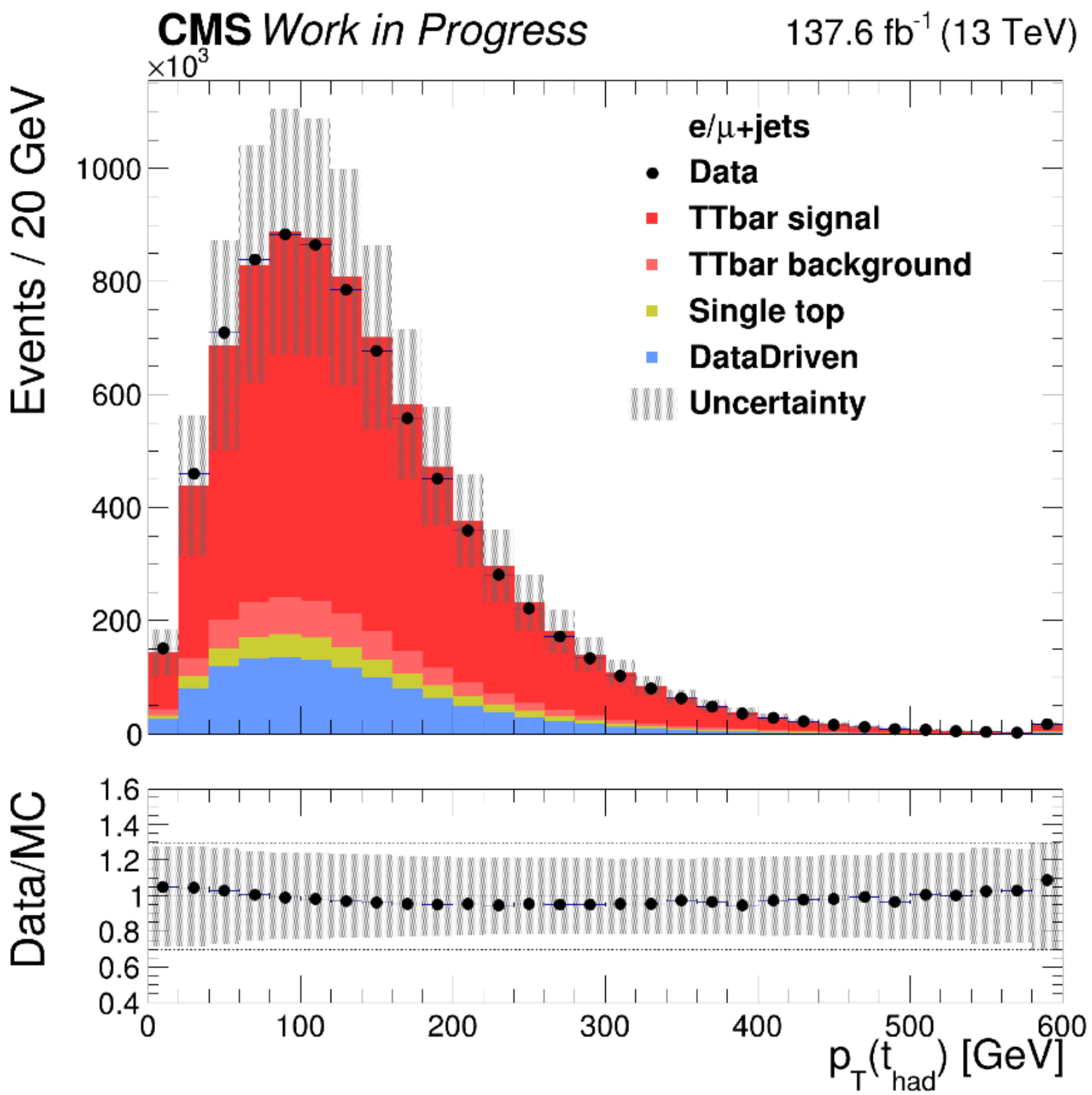
Recontruction Performance

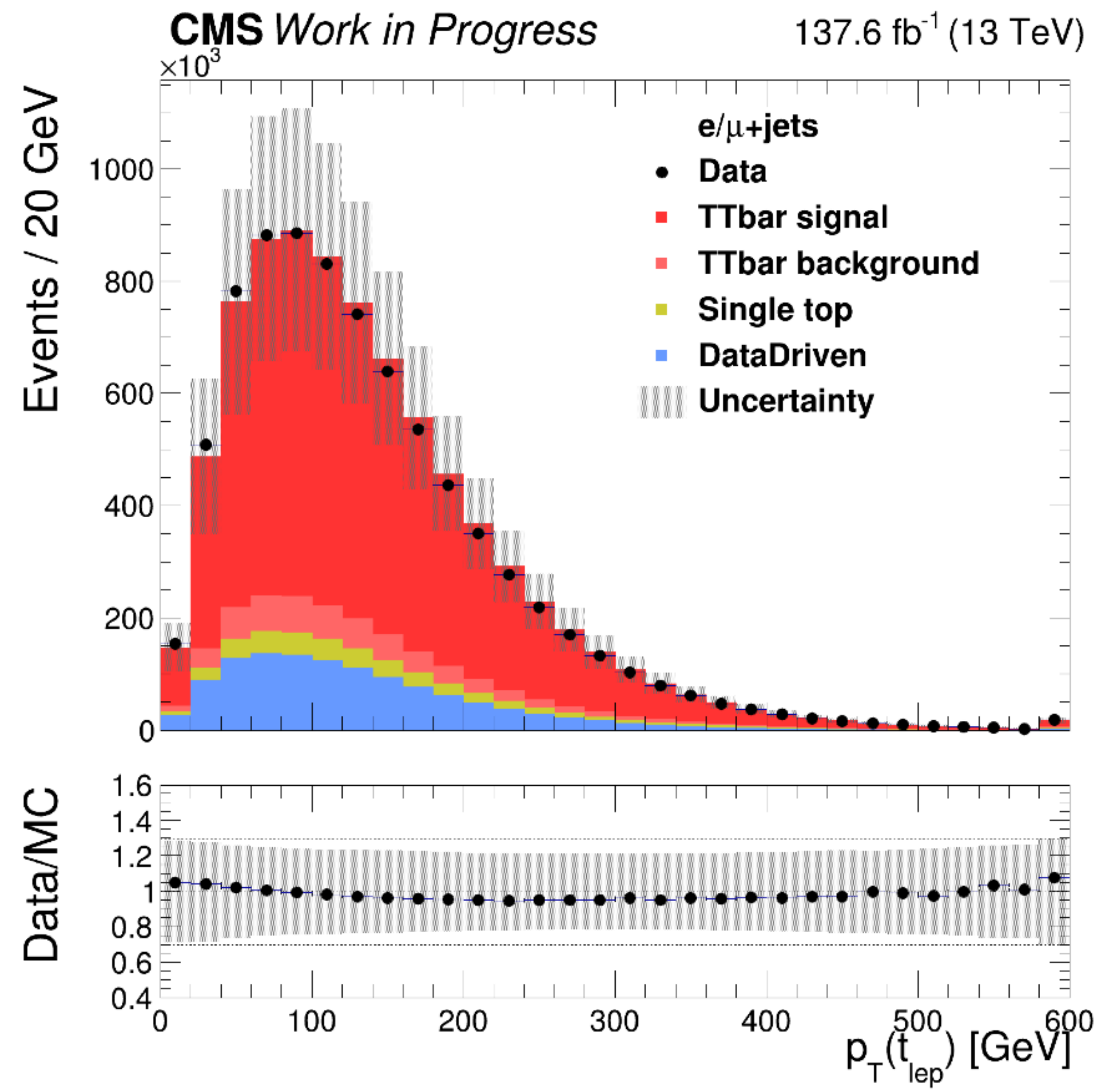
- The reconstruction performance is tested by comparing the $\Delta|y|$ between generator and reconstruction level
- The plots on the right side shows the probability that $\Delta|y|$ is correctly assigned
  - Normalised by the generator level bin
  - Top : the performance with all reconstructed events
  - Bottom : the events with the final state objects which is out of the acceptance ($p_T < 30$ GeV and $|\eta| > 2.4$)





pT distribution of the reconstructed tops





- Included uncertainties
  - Statistical and Experimental systematic uncertainties
- DataDriven background replaces QCD / Diboson / V+Jets

Inclusive Measurement

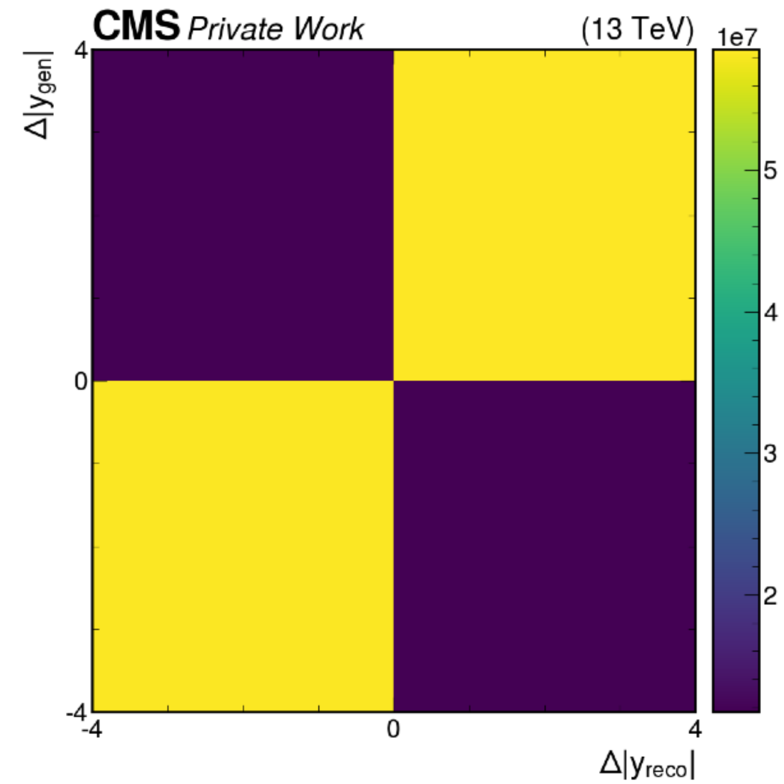
- The target of the analysis is the measurement of the charge asymmetry A_C

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

- Counting number of events for the bin matters in measurement of the A_C

- The unfolding method is required to make a correct counting of number of events for the multiple bin

Concept of the unfolding



- The measured data in reconstruction level is distorted and contaminated
  - $\vec{x} = R\overrightarrow{\mu} + \vec{b}$
  - R : Distortion with the hadronisation process and detector resolution, analysis method
  - $\vec{b}$: Contamination with the background processes
- Unfolding can simply performed with the inversion of the response matrix with subtraction of the background contribution
  - $\overrightarrow{\mu} = R^{-1}(\vec{x} - \vec{b})$
  - The computation for obtaining R^{-1} matters

Likelihood based unfolding

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

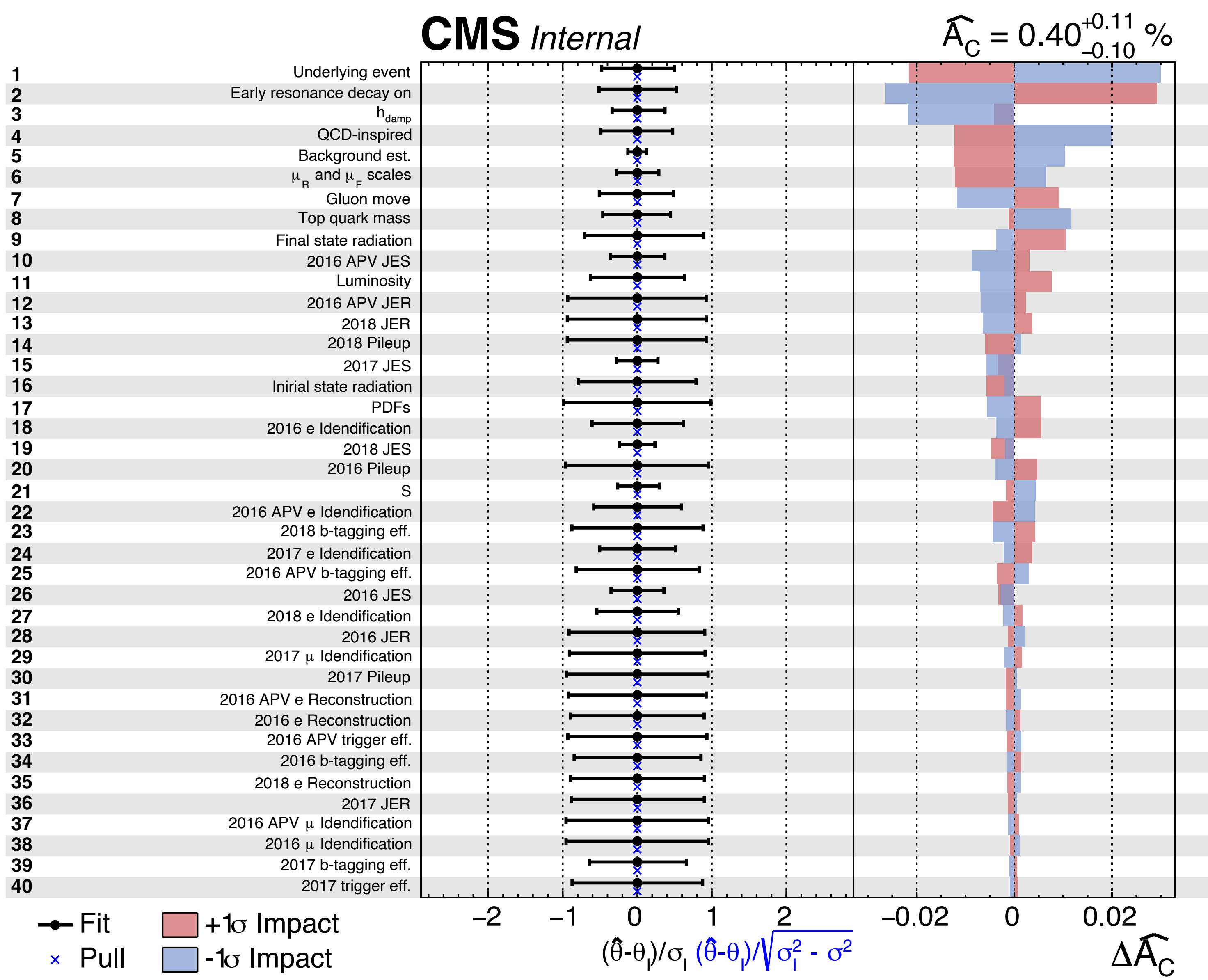
- $Poiss(n; \mu)$: probability of observing n events when μ are expected
  - A_{ij} : response matrix
  - $\overrightarrow{\delta_u}$: Nuisance parameter
  - $\mu_i = r_i N_{gen,i}$: Number of signal in bin i
  - b_j : number of background in bin j
- $N(\overrightarrow{\delta_u})$: constraints for the nuisance parameter (normalisation and shape)

Parameterised singal strength

$$r_{pos} = S\frac{N_{tot}}{N_{pos}}(1 + A_C) \quad r_{neg} = S\frac{N_{tot}}{N_{neg}}(1 - A_C)$$

- The unfolding is performed with the CMS Higgs Combine Tool software package [1]
- 2 bins for the inclusive measurement
  : $\Delta|y| > 0$ and $\Delta|y| < 0$
- The unfolding with the package supports to make a rate parameter as function of the parameters
  - A_C is set as the parameter of interest (POI),
    whereas the S is treated as one of the nuisance parameter
  - The parameter is calculated on the full phase space
  - Direct extraction of A_C from the framework

Unfolded result with the Asimov dataset



- The unfolding is performed with the Asimov dataset
  - $S = 1.0,\ A_C = 0.40\,\%$
- For the inclusive measurement, the estimated error is $^{+0.11}_{-0.10}\%$

Summary

- We tested the measurement of the charge asymmetry in top pair production with CMS Run 2 13TeV pp collision data (137.6 fb^{-1})
- The likelihood-based unfolding is performed to achieve the measurement for the charge asymmetry on the full phase space with the CMS Combine Tool