Search for CP violating anomalous top quark coupling in proton-proton collisions at $\sqrt{s}$ = 13 TeV

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on behalf of the **CMS Collaboration**

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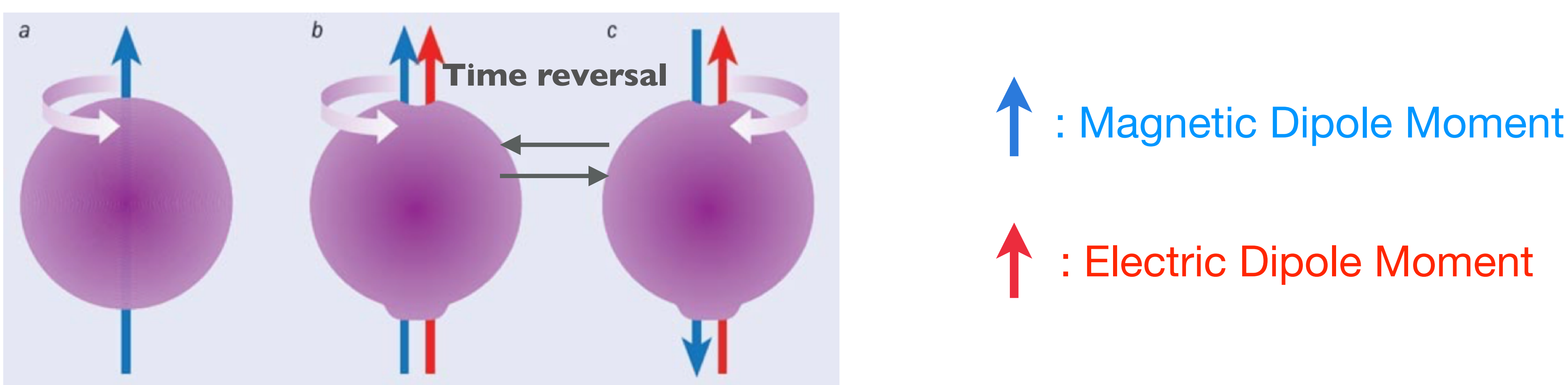
Introduction

- CP violation is a candidate to explain the matter-antimatter but it has not been observed beyond the expectation of the SM. (we need additional source)
- In the SM, CPV in the production and decay of top quark pairs is predicted to be very small
- Search the new source of CP violation using Top-quark pair events in the dilepton channels. (chromoelectric dipole moment ,CEDM)



$$\boxed{\mathscr{L} = \frac{g_s}{2}\bar{t}T^a\sigma^{\mu\nu}(a_t^g + i\gamma_5\, d_t^g\,)tG^a_{\mu\nu}}$$

d_t^g is CEDM

Physics Observable & Asymmetry

- Physics Observable :

-Theory paper: 10.1103/PhysRevD.93.014020

$$\mathcal{O}_1 = \epsilon(p_t, p_{\bar{t}}, p_{l^+}, p_{l^-}) = \begin{vmatrix} E_t & p_{tx} & p_{ty} & p_{tz} \\ E_{\bar{t}} & p_{\bar{t}x} & p_{\bar{t}y} & p_{\bar{t}z} \\ E_{l^+} & p_{l^+x} & p_{l^+y} & p_{l^+z} \\ E_{l^-} & p_{l^-x} & p_{l^-y} & p_{l^-z} \end{vmatrix}$$

$$\mathcal{O}_3 = \epsilon(p_b, p_{\bar{b}}, p_{l^+}, p_{l^-}) = \begin{vmatrix} E_b & p_{bx} & p_{by} & p_{bz} \\ E_{\bar{b}} & p_{\bar{b}x} & p_{\bar{b}y} & p_{\bar{b}z} \\ E_{l^+} & p_{l^+x} & p_{l^+y} & p_{l^+z} \\ E_{l^-} & p_{l^-x} & p_{l^-y} & p_{l^-z} \end{vmatrix}$$

- **These physics observables have CP-odd correlation, and allow us to test CP violation in top-quark pair events**

- Asymmetries :

$$A_i \equiv \frac{N_{events}(\mathcal{O}_i > 0) - N_{events}(\mathcal{O}_i < 0)}{N_{events}(\mathcal{O}_i > 0) + N_{events}(\mathcal{O}_i < 0)} \quad i = 1 \text{ or } 3$$

- **Allow to infer the CEDM of top quark (linearly correlated)**

Analysis Procedure

- **The main goal of this analysis :**
  In this analysis, we are to extract the asymmetry and CEDM in top pair events in the dilepton final state **(2016 CMS data set, 35.9 fb^{-1})**

- **Event selection (2016 data set, 35.9 fb^{-1}):**
  - Two isolated leptons with opposite charges ($\mu^+\mu^-, e^+e^-,$ and $e^\pm\mu^\mp$)
  - # of jet > 1
  - # of b-tagged jet (CSVv2, medium working point.) ≥ 1
  - Reconstruction of Top quarks

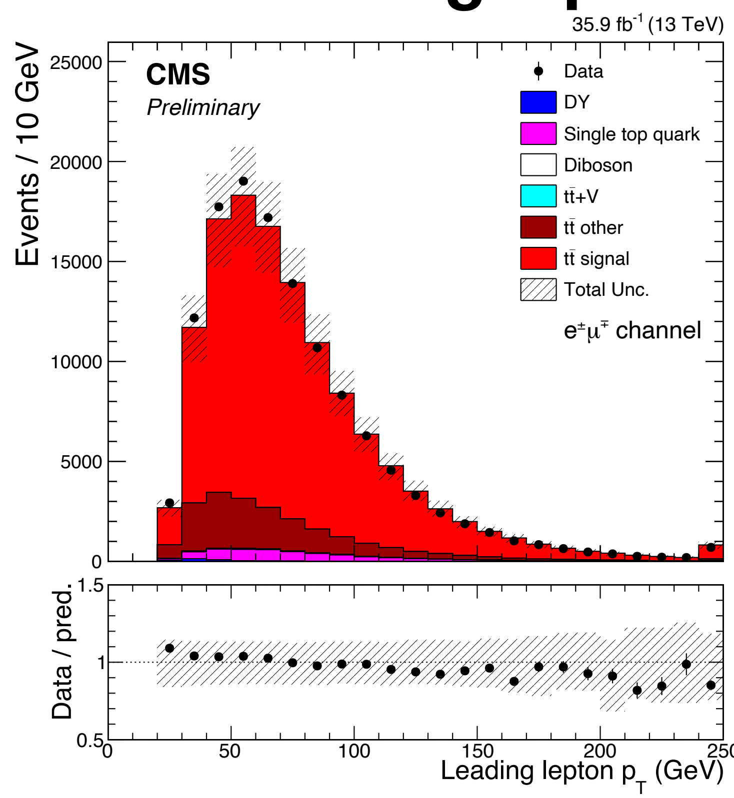
- **Extraction of Asymmetry:**
  Using a maximum likelihood fit

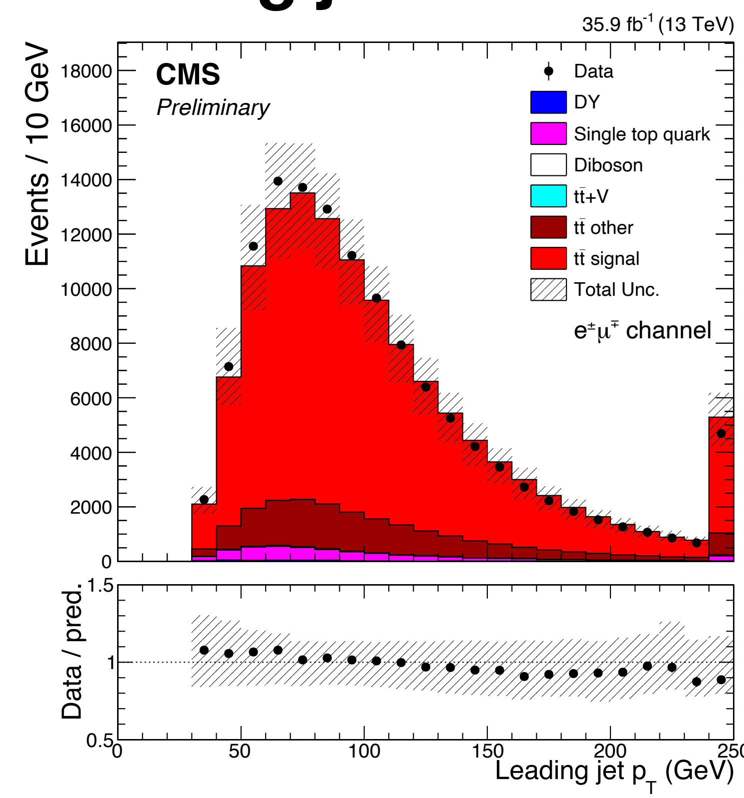
- **Extraction of CEDM:**
  Using the generated CP-violation events, CEDM can be measured.

[1] more details are in the backup slide(p)

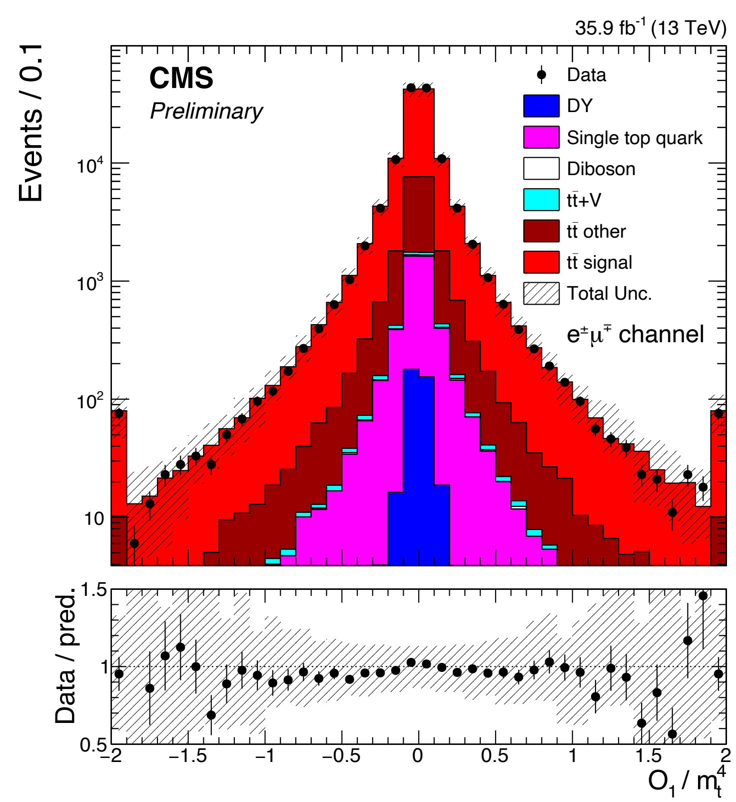
Kinematics of object & physics observables ($e^{\pm}\mu^{\mp}$ channel)

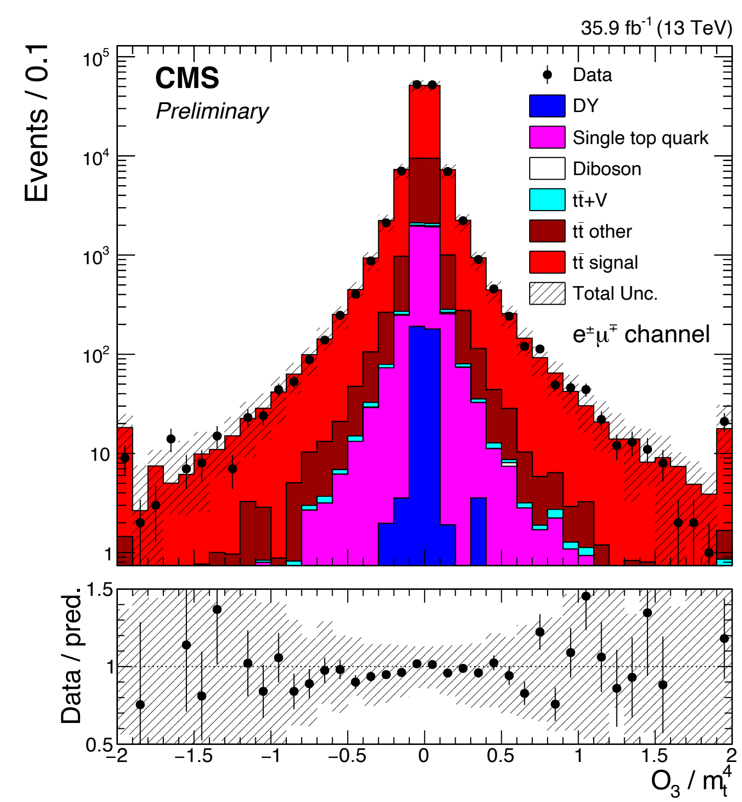
- **p_T distribution of leading lepton and leading jet**





- **Distribution of O_1 and O_3**





Asymmetries

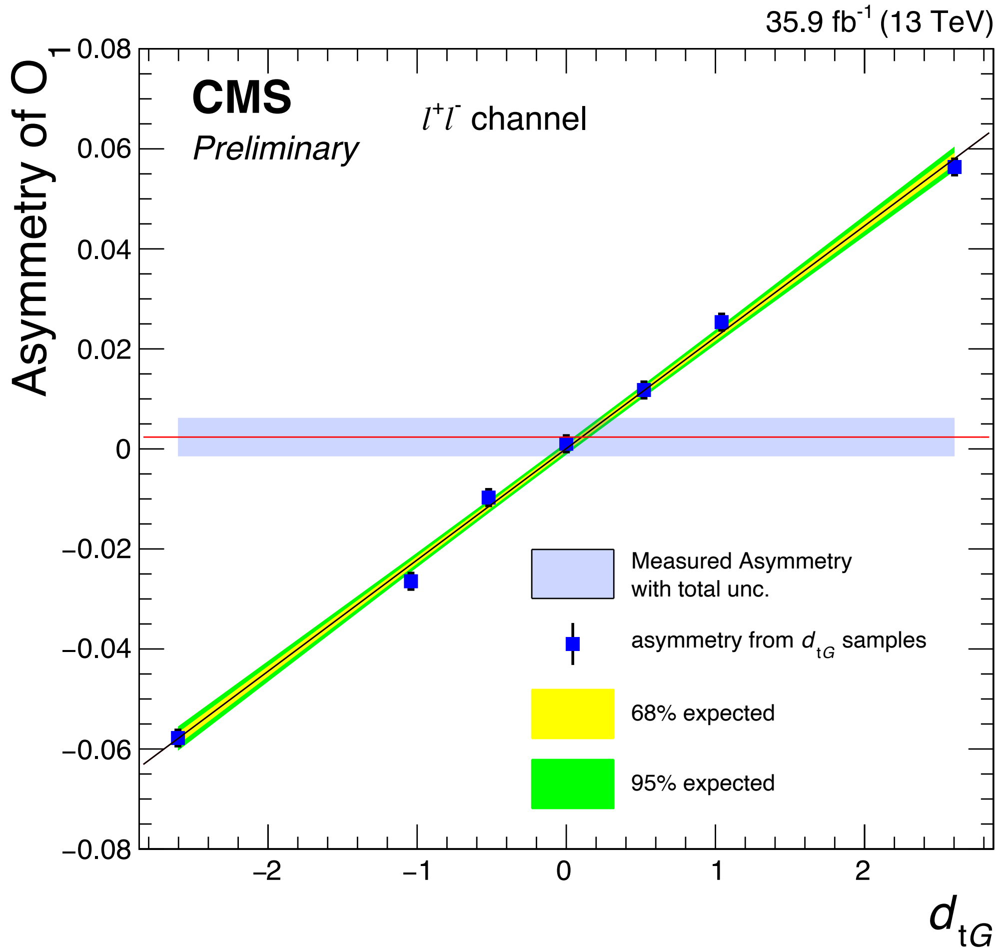
	Asymmetry and uncertainty ($\times 10^{-3}$)	
Channel	$\mathcal{O}_1$	$\mathcal{O}_3$
$\mu^+\mu^-$	$6.9 \pm 5.3(\text{stat}) \pm 5.0(\text{syst})$	$6.1 \pm 5.3(\text{stat}) \pm 3.5(\text{syst})$
e^+e^-	$8.8 \pm 7.5(\text{stat}) \pm 5.6(\text{syst})$	$4.1 \pm 7.5(\text{stat}) \pm 6.0(\text{syst})$
$\mu^\pm e^\mp$	$0.6 \pm 3.4(\text{stat}) \pm 2.6(\text{syst})$	$-1.7 \pm 3.4(\text{stat}) \pm 2.0(\text{syst})$
Combined	$2.4 \pm 2.8(\text{stat}) \pm 2.8(\text{syst})$	$6.1 \pm 5.3(\text{stat}) \pm 3.5(\text{syst})$

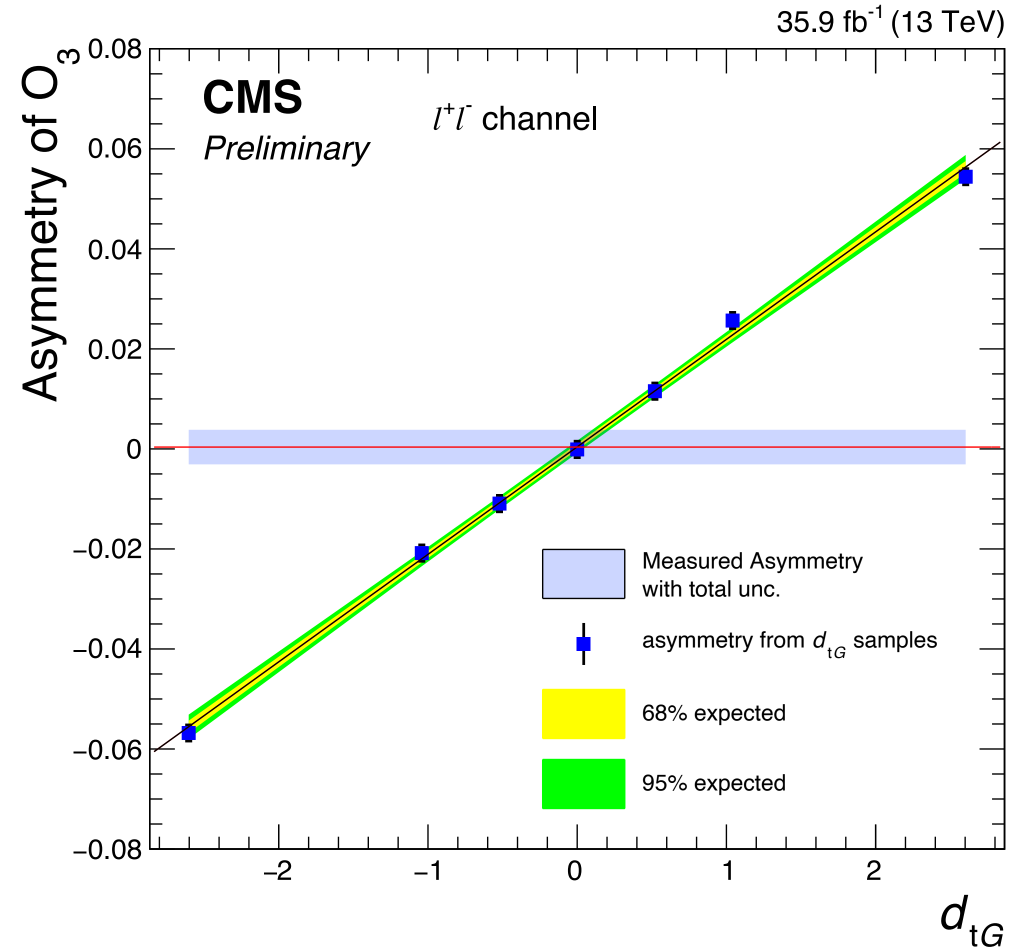
Dominant Systematic Sources : ME-PS matching, ISR, FSR, Color-reconnection, JES, JER, Limited stat. of BG models.

- **The measured asymmetries are consistent with the Standard Model prediction** within statistical and systematical uncertainties

Extraction of CEDM

- Asymmetry and CEDM have linear correlation





- CEDM is extracted by exploiting its correlation with the asymmetry
  - $Asymmetry = a \cdot d_{tG} + b$; using the linear fit result, we can extract the CEDM

Physics observable	d_{tG}	CEDM (10^{-18} $g_s \cdot$ cm)
$\mathcal{O}_1$	$0.10 \pm 0.12(\text{stat}) \pm 0.12(\text{syst})$	$0.58 \pm 0.69(\text{stat}) \pm 0.70(\text{syst})$
$\mathcal{O}_3$	$-0.00 \pm 0.13(\text{stat}) \pm 0.10(\text{syst})$	$-0.01 \pm 0.72(\text{stat}) \pm 0.58(\text{syst})$

- The CEDMs we extracted are consistent with the SM prediction

Summary

- CP violating asymmetries and CEDM of top quark have been presented
- 2016 data set (CMS, 35.9 fb^{-1}) was analyzed
- Measured CEDMs are $0.58 \pm 0.69(\text{stat}) \pm 0.70(\text{syst}) \times 10^{-18} g_s \cdot \text{cm}$ and $-0.01 \pm 0.72(\text{stat}) \pm 0.58(\text{syst}) \times 10^{-18} g_s \cdot \text{cm}$
- Measured asymmetries and CEDM are consistent with the Standard Model prediction within uncertainties

Backup

Configuration & Setup

- CMSSW version : **CMSSW_8_0_26_patch1**
- Lumi : **35.9 fb^{-1}**
- Global Tag : 80X_dataRun2_2016SeptRepro_v7(DATA)
  80X_mcRun2_asymptotic_2016_TrancheIV_v8(MC)
- Json : **Official Golden** (Cert 271036-284044_13TeV_23Sep2016ReReco_Collisions16_JSON)
- Data Sets

Channel	Data Set
Dimuon	Single(Double)Muon/Run2016(B-H)-03Feb2017*/MINIAOD
Dielectron	SingleElectron(DoubleEG)/Run2016(B-H)-03Feb2017 ver2-v2/MINIAOD
Muon-Electron	SingleMuon(Electron)/Run2016(B-H)-03Feb2017*/MINIAOD MuonEG/Run2016(B-H)-03Feb2017*/MINIAOD

- MC Samples :

	Sample name
TTJets	/TT_TuneCUETP8M2T4_13TeV-powheg-pythia8/RunIISummer16MiniAODv2-PUMoriond17_(backup)_80X_mcRun2_asymptotic_2016_TrancheIV_v6-v1
DY 10to50	/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6(ext1)-v1/
DY 50	/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6_ext1-v2/
WW	/WW_TuneCUETP8M1_13TeV-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-(ext1)-v1/
WZ	/WZ_TuneCUETP8M1_13TeV-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-(ext1)-v1/
ZZ	/WZ_TuneCUETP8M1_13TeV-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-(ext1)-v1/
ST_tW_top	/ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6_ext1-v1
ST_tW_antitop	/ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6_ext1-v1/
TTbar_WJetToLNu	/TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6_ext1-v3/MINIAODSIM
TTbar_WQQ	/TTWJetsToQQ_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-v1/MINIAODSIM
TTbar_ZToLLNuNu	/TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6_ext1-v1/MINIAODSIM
TTbar_ZQQ	/TTZToQQ_TuneCUETP8M1_13TeV-amcatnlo-pythia8/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-v1/MINIAODSIM

Data & Samples

- Data : The 2016 dataset is collected at 13 TeV with CMS detector. Integrated luminosity is 35.9 fb^{-1} .

- MC Samples:

Signal	TTBar Events	Powheg & Pythia8
Background	DrellYan	MadgraphMLM
	Diboson	Pythia8
	SingleTop	Powheg & Pythia8
	TTV	amc@NLO

Object & Event Selection

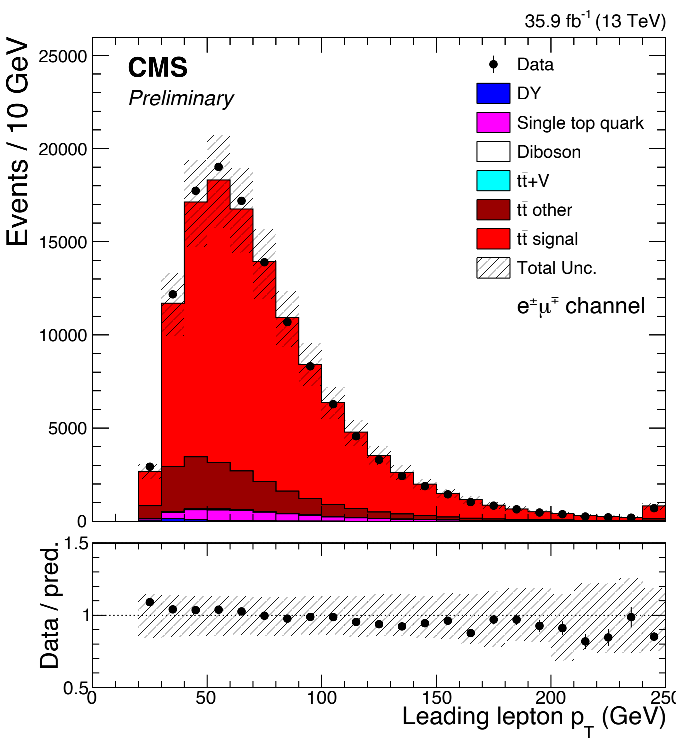
- **Object Selection**

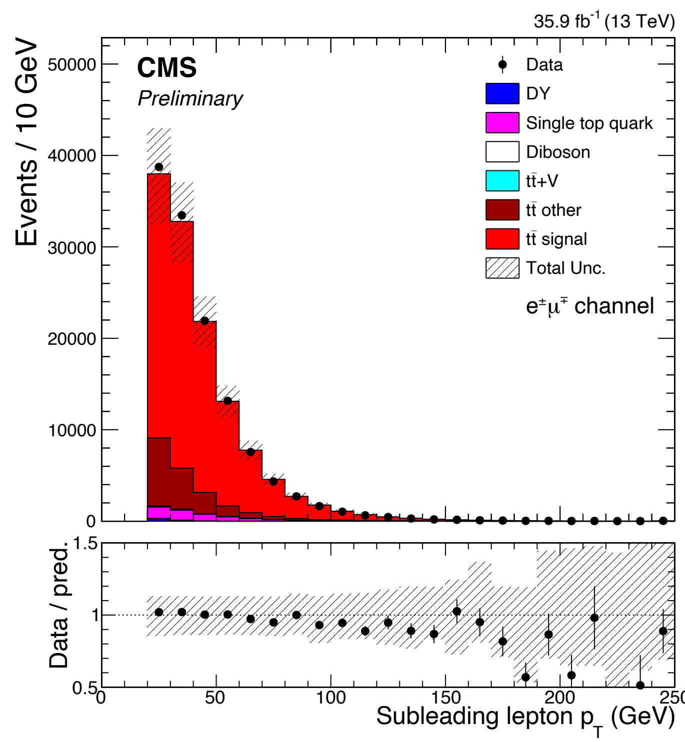
Requirement	Muon	Electron	Jet
ID & Isolation	Tight ID PFIso < 0.15 (Tight)	Tight (Cut Based)	PF Loose
Kinematic Requrienment	$\lvert\eta\rvert < 2.4$ Leading Lepton pT > 25 GeV & Sub Leading Lepton pT > 20 GeV		pT > 30 GeV, $\lvert\eta\rvert < 2.4$

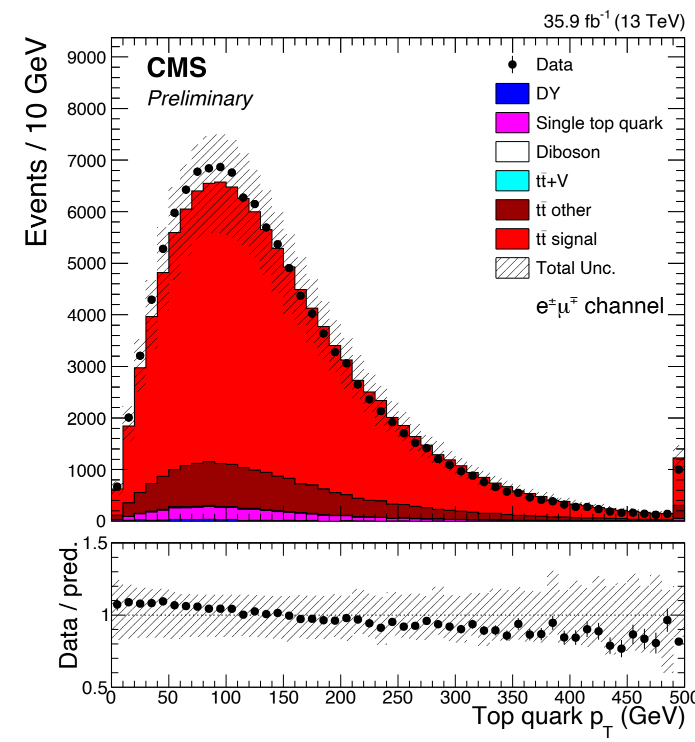
- **Event Selection**

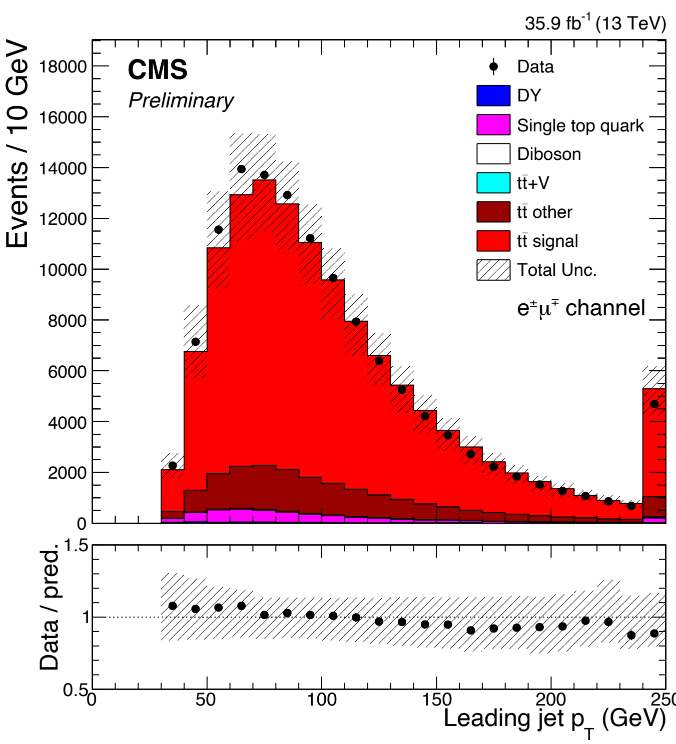
Cut flow	Dimuon	Dielectron	Muon-electron
Trigger & MET Filters [1]	O	O	O
Lepton requirement & M_{ll}> 20 GeV & Third Lepton Veto	O	O	O
Z Mass Veto (76 GeV < M_{ll} <106 GeV)	O	O	-
# of Jet > 1	O	O	O
MET > 40 GeV	O	O	-
Num. b-tagged Jet ≥ 1	O	O	O
Top Reconstruction (Kinematic solver)	O	O	O

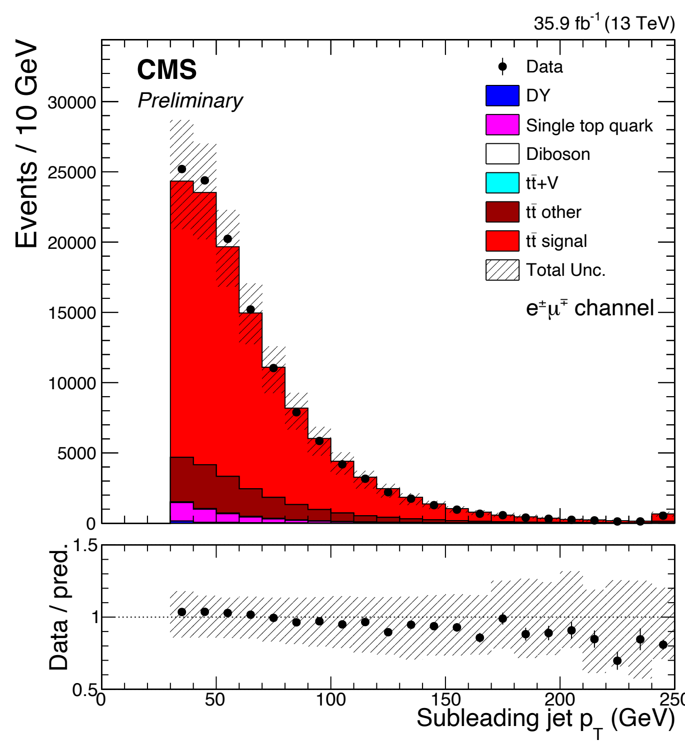
Distributions of Object (Muonelecton)

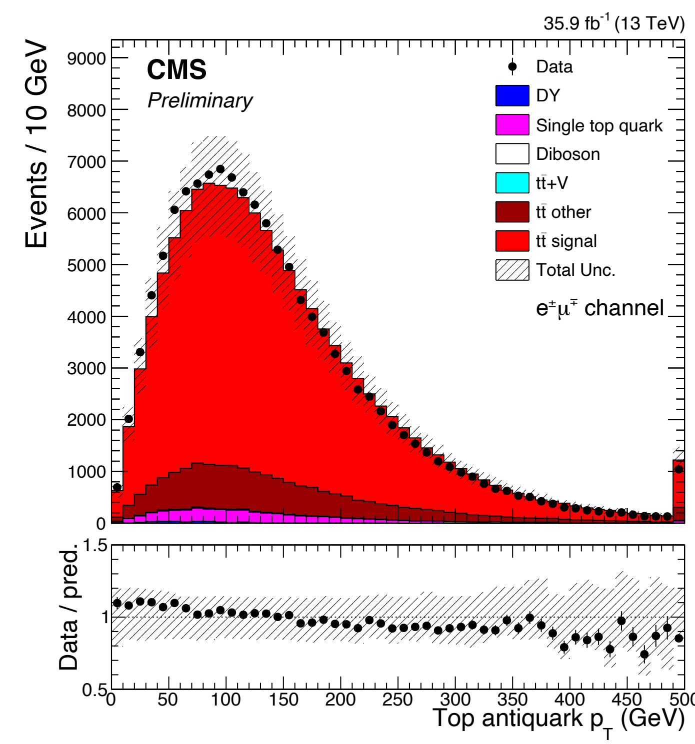




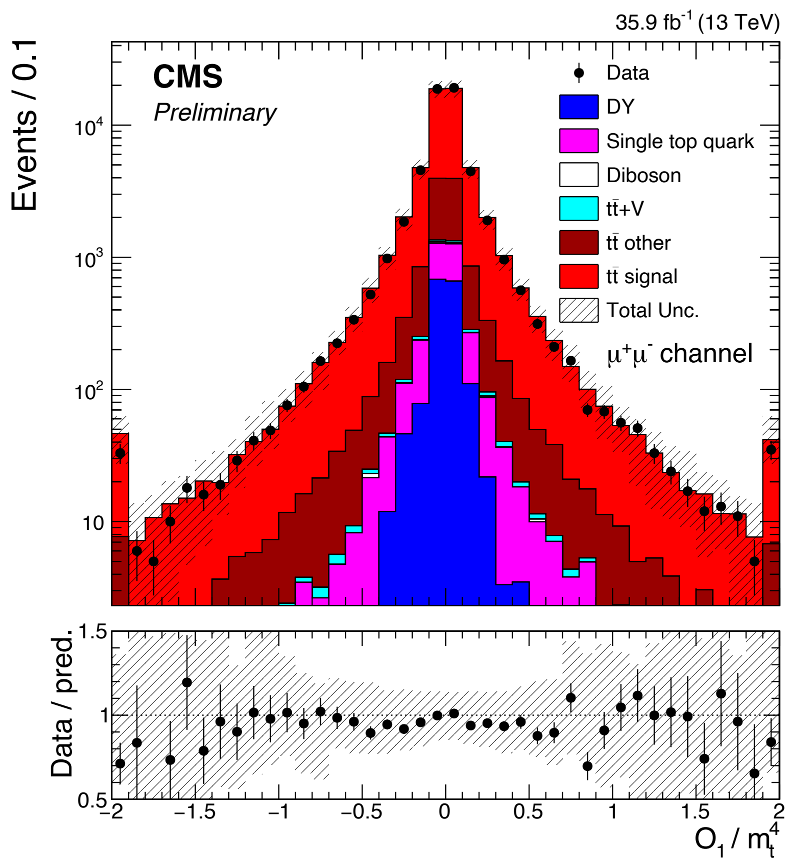


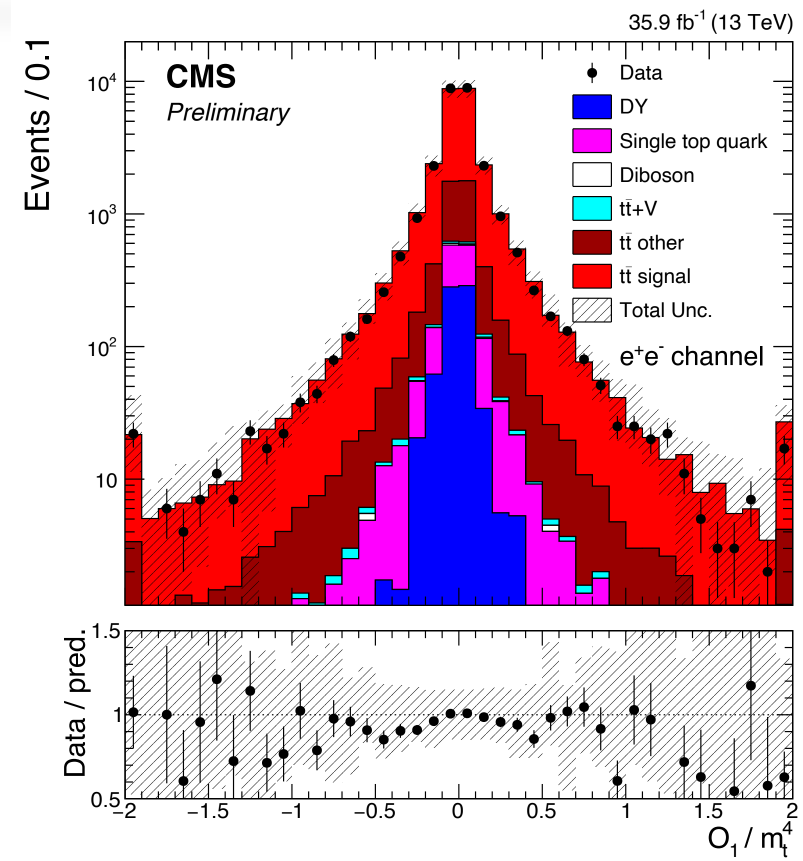


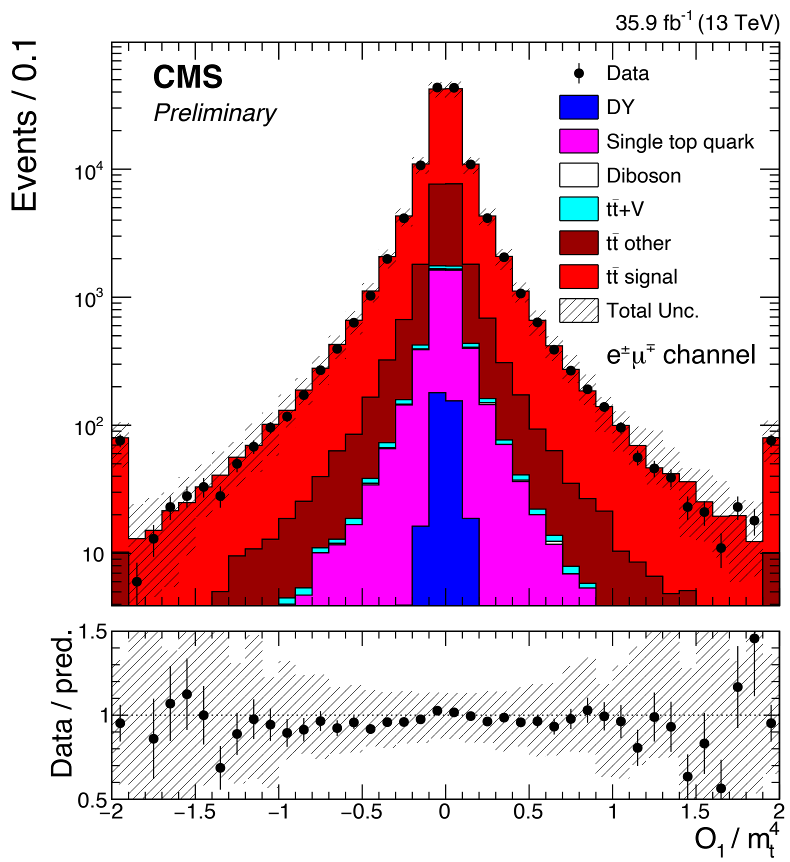




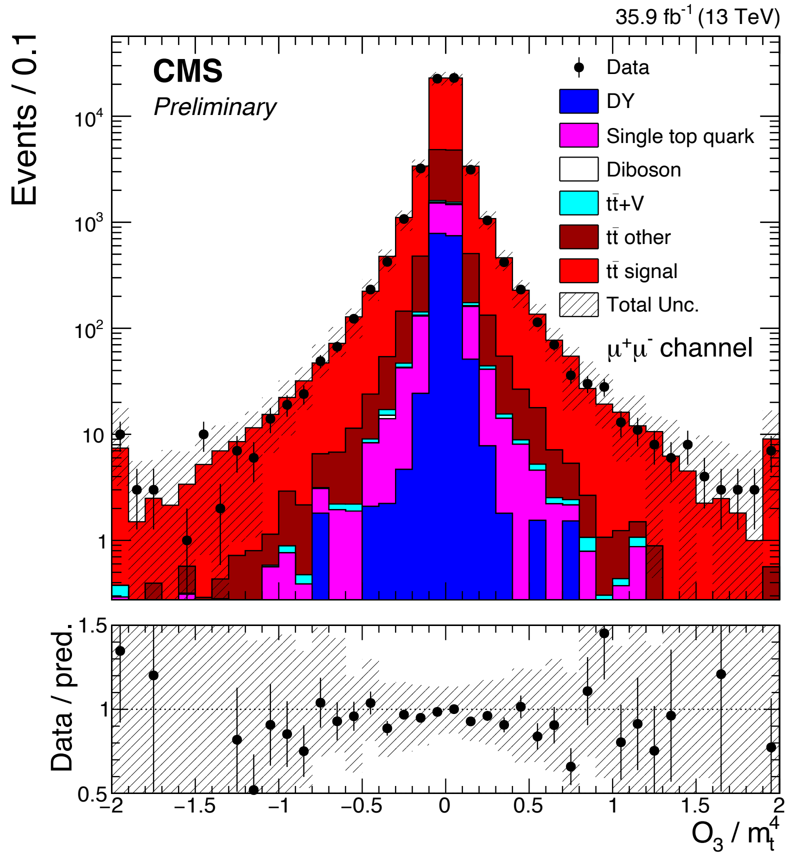
Distribution of O1

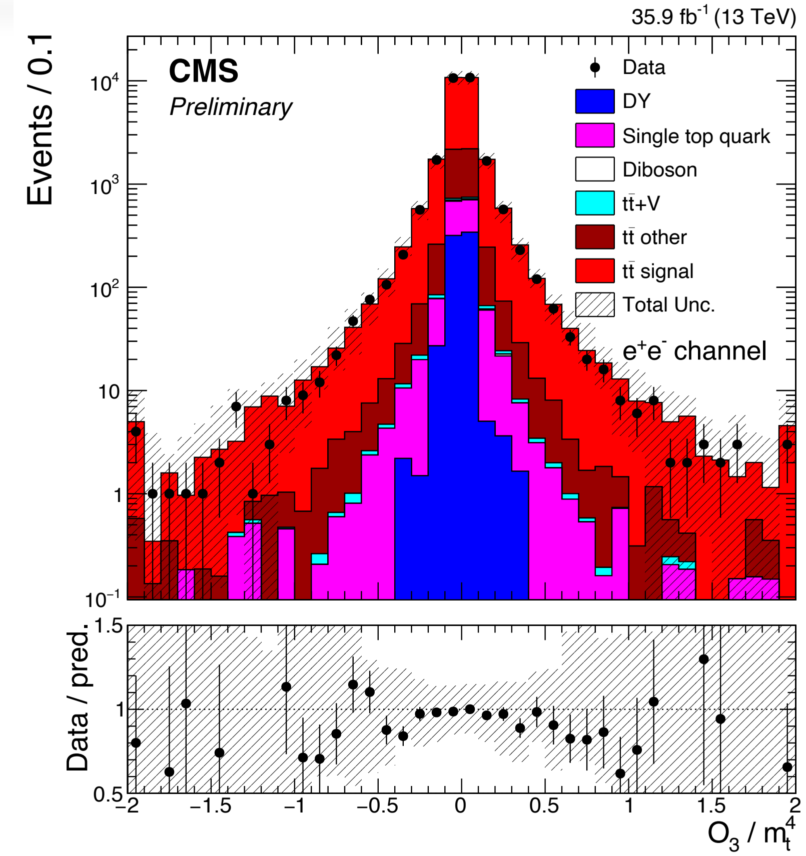


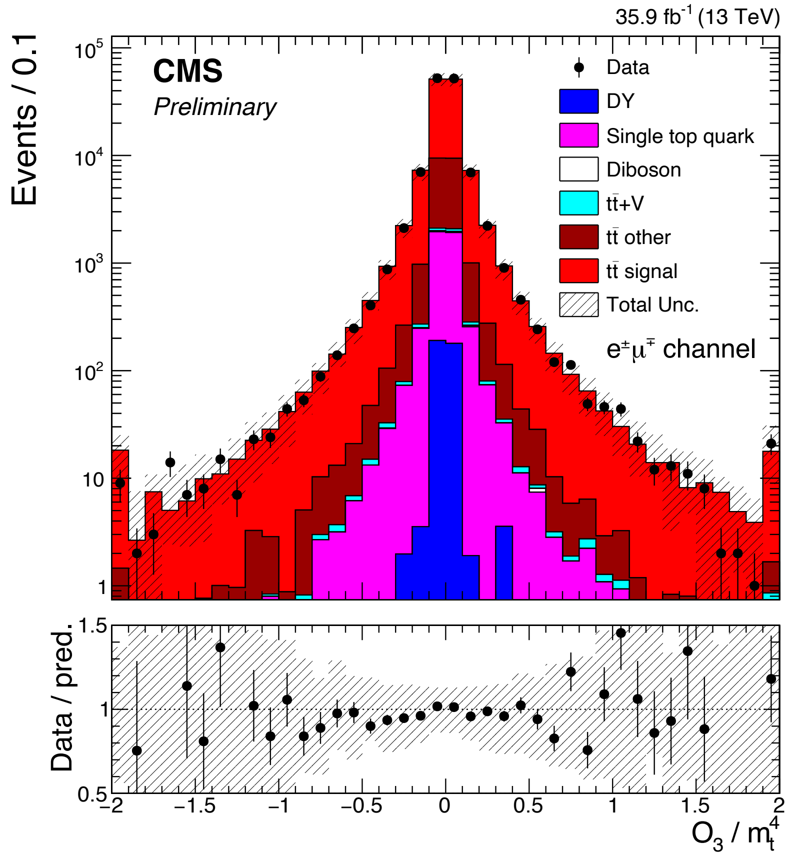




Distribution of O3







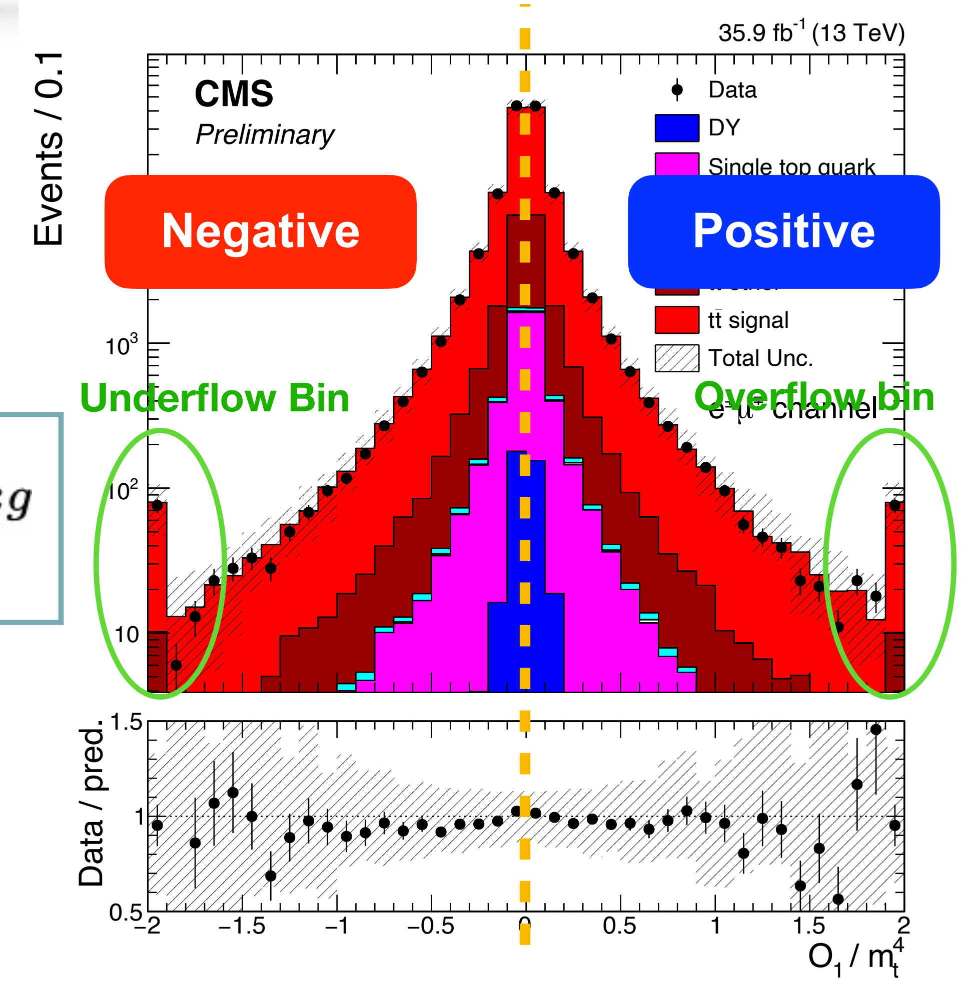
Asymmetry extraction using the maximum likelihood fit

$$\mathcal{L}(A_{\mathcal{O}_i}, \sigma_{t\bar{t}}) = \prod_k \mathcal{P}(N_k^{obs}, N_k^{pred})$$

$$\boxed{N_k^{pred} = N_t^{t\bar{t}} \frac{1+A_{\mathcal{O}_i}}{2} f_k^{\mathcal{O}_i>0} + N_t^{t\bar{t}} \frac{1-A_{\mathcal{O}_i}}{2} f_k^{\mathcal{O}_i<0} + N^{bkg} f_k^{bkg}}$$

where $N_t^{t\bar{t}} = \mathcal{L} \cdot Branching\ Ratio \cdot \epsilon_{sig} \cdot \sigma_{t\bar{t}}$

made A and x-section float



$$f_k^{O_i>0} = 1 \text{ for the positive region and } 0 \text{ for the negative region}$$

$$f_k^{O_i<0} = 1 \text{ for the negative region and } 0 \text{ for the positive region}$$

f_k^{bkg} is the fraction of the number of event in the positive or negative region in total backgrounds.

$$\boxed{-\log\mathcal{L}(A_{O_i}, \sigma_{t\bar{t}}) \simeq \sum_k (-N_k^{obs} \log N_k^{pred} + N_k^{pred})}$$

Sources of Systematic Uncertainties

- Basically, we've followed the recommendation from TOP Systematic Uncertainties. [1]

Experimental uncertainties	Modeling uncertainties
Luminosity uncertainty	Parton Distribution Function
Pileup reweighting	Factorization & Renormalization
Jet energy scale uncertainty	ME-PS matching scale
Jet energy resolution uncertainty	Color Reconnection
Muon momentum correction	Top p_T reweighting[2]
Electron energy scale and smearing	*b*-fragmentation
Lepton ID and Isolation scale factors	Semileptonic Branching Ratio of B hadron
Unclustered energy of MET	Hadronization model
b-quark jet tag scale factor	ISR
Limited statistics of background (BG) models	FSR
-	Underlying event
-	Top Mass

[1]https://twiki.cern.ch/twiki/bin/view/CMS/TopSystematics

[2]We didn't apply the top p_T reweighting to the entire analysis. However, we want to check what extent the top p_T reweighting affects the asymmetry.

Measured Asymmetries

Physics observable	Asymmetry and Uncertainty ($\times 10^{-3}$) $\mu^+\mu^-$	e^+e^-	$e^\pm\mu^\mp$	combined channel
$\mathcal{O}_1$	6.9 ± 5.3	8.8 ± 7.5	0.6 ± 3.4	2.4 ± 2.8
$\mathcal{O}_3$	6.1 ± 5.3	4.1 ± 7.5	-1.7 ± 3.4	0.4 ± 2.8

O_1

	Uncertainty ($\times 10^{-3}$)							
	$\mu^+\mu^-$		e^+e^-		$e^\mp\mu^\pm$		combined channel	
Source	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$
ME-PS matching	0.8	-0.8	0.8	-0.8	0.3	-0.3	0.4	-0.4
ISR	0.3	-0.3	1.5	-1.5	0.2	-0.2	0.3	-0.3
FSR	0.6	-0.6	1.0	-1.0	0.8	-0.8	0.7	-0.7
Underlying event	1.4	-1.4	0.6	-0.6	1.4	-1.4	1.4	-1.4
Color Reconnection	1.0	-1.0	1.9	-1.9	1.6	-1.6	1.5	-1.5
Hadronization	1.7	-1.7	2.0	-2.0	0.6	-0.6	0.9	-0.9
JES	2.3	-2.3	1.9	-1.9	0.1	-0.1	0.7	-0.7
JER	1.2	-1.2	2.0	-2.0	0.3	-0.3	0.6	-0.6
Muon Energy	2.3	-2.3	–	–	0.1	-0.1	0.5	-0.5
Electron scale/smearing	–	–	1.2	-1.2	0.2	-0.2	0.3	-0.3
Normalization of background	0.1	-0.1	0.3	-0.3	0.0	-0.0	0.0	-0.0
Limited number of background Monte Carlo events	2.3	-2.3	2.9	-2.9	0.6	-0.6	0.7	-0.7
Charge misidentification	0.1	-0.1	0.8	-0.8	0.4	-0.4	0.3	-0.3
Total Syst	5.0	-5.0	5.6	-5.6	2.6	-2.6	2.8	-2.8

O_3

	Uncertainty ($\times 10^{-3}$)							
	$\mu^+\mu^-$		e^+e^-		$e^\mp\mu^\pm$		combined channel	
Source	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$
ME-PS matching	1.5	-1.5	1.4	-1.4	0.7	-0.7	0.9	-0.9
ISR	0.5	-0.5	1.8	-1.8	0.2	-0.2	0.3	-0.3
FSR	0.3	-0.3	1.9	-1.9	0.6	-0.6	0.6	-0.6
Underlying event	1.0	-1.0	0.9	-0.9	1.1	-1.1	1.0	-1.0
Color Reconnection	0.9	-0.9	3.8	-3.8	1.0	-1.0	1.1	-1.1
Hadronization	0.2	-0.2	0.5	-0.5	0.3	-0.3	0.3	-0.3
JES	0.7	-0.7	0.6	-0.6	0.2	-0.2	0.3	-0.3
JER	0.3	-0.3	0.7	-0.7	0.2	-0.2	0.2	-0.2
Muon Energy	1.0	-1.0	–	–	0.2	-0.2	0.3	-0.3
Electron scale/smearing	–	–	1.1	-1.1	0.2	-0.2	0.2	-0.2
Normalization of background	0.1	-0.1	0.0	-0.0	0.0	-0.0	0.0	-0.0
Limited number of background Monte Carlo events	2.3	-2.3	2.9	-2.9	0.6	-0.6	0.7	-0.7
Charge misidentification	0.1	-0.1	0.8	-0.8	0.4	-0.4	0.3	-0.3
Total Syst	3.5	-3.5	6.0	-6.0	2.0	-2.0	2.2	-2.2

Limited statistics of background (BG) models

$$\mathcal{L}(A_{\mathcal{O}_i}, \sigma_{t\bar{t}}) = \prod_k \mathcal{P}(N_k^{obs}, N_k^{pred})$$

$$N_k^{pred} = N_t^{t\bar{t}} \frac{1 + A_{\mathcal{O}_i}}{2} f_k^{\mathcal{O}_i > 0} + N_t^{t\bar{t}} \frac{1 - A_{\mathcal{O}_i}}{2} f_k^{\mathcal{O}_i < 0} + \boxed{N^{bkg} f_k^{bkg}}$$

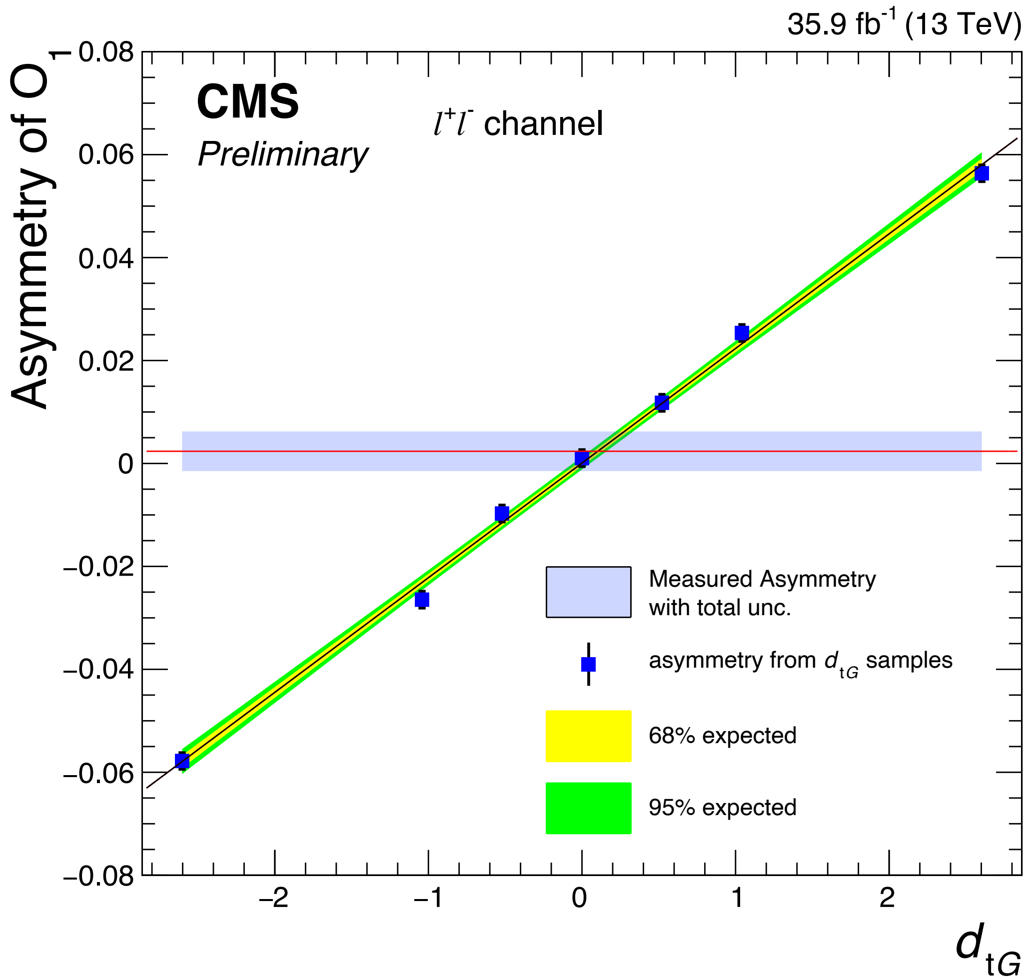
$$where\ N_t^{t\bar{t}} = \mathcal{L} \cdot Branching\ Ratio \cdot \epsilon_{sig} \cdot \sigma_{t\bar{t}}$$

Gaussian constraints.

$$\mathcal{L}(A_{\mathcal{O}_i}, \sigma_{t\bar{t}}) = \prod_k \mathcal{P}(N_k^{obs}, N_k^{pred}) = \prod_k Pois(N_k^{obs} | A_{\mathcal{O}_i}, \sigma_{t\bar{t}}, N_{neg}^{bkg}, N_{pos}^{bkg})$$
$$\boxed{Gaus(N_{neg}^{bkg} | \mu_{neg}, \sigma_{neg}) Gaus(N_{pos}^{bkg} | \mu_{pos}, \sigma_{pos})}$$

- Background Monte Carlo samples are generated with the limited numbers of events. Therefore, the total number of background events has fluctuations on the basis of the statistical uncertainty.
- The fluctuations of asymmetries by the limited statistics of background models are investigated by setting the numbers of the background events in the negative and positive regions as the nuisance parameters.

Extraction of CEDM



- We generate CP violating tt events decaying to the dilepton channels.
- These samples were generated with several d_{tG} values.

$$Asymmtry = a \cdot d_{tG} + b$$

$$\boxed{d_{tG} = \frac{Asymmetry - b}{a}} \longrightarrow$$

$$\Delta^2_{d_{tG}} = \begin{pmatrix} \frac{\partial d_{tG}}{\partial A} & \frac{\partial d_{tG}}{\partial b} & \frac{\partial d_{tG}}{\partial a} \end{pmatrix} \begin{pmatrix} \Delta^2_A & 0 & 0 \\ 0 & \Delta^2_b & \mathbf{cov}(b,a) \\ 0 & \mathbf{cov}(a,b) & \Delta^2_a \end{pmatrix} \begin{pmatrix} \frac{\partial d_{tG}}{\partial A} \\ \frac{\partial d_{tG}}{\partial b} \\ \frac{\partial d_{tG}}{\partial a} \end{pmatrix}$$

a , b can be obtained from linear fitting.