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

(CMS-PAS-TOP-18-007)

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on behalf of the **CMS Collaboration**

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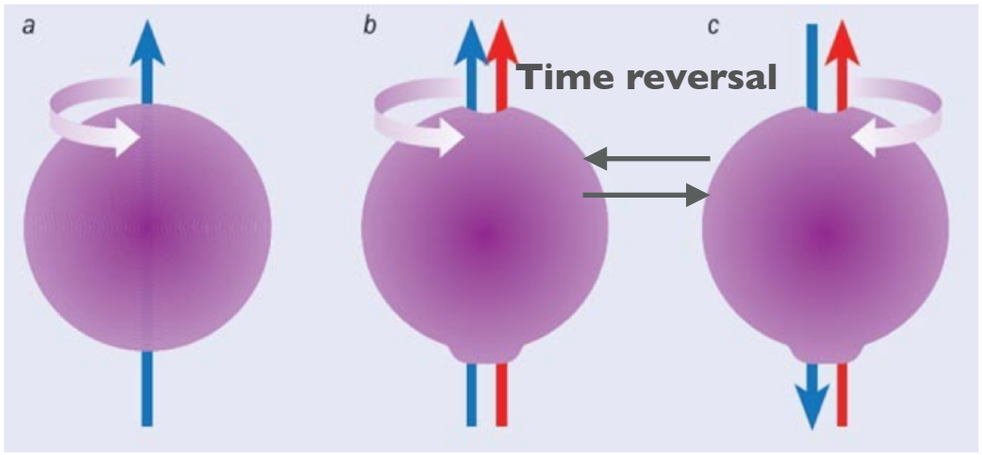
CMS Highlight @ LHC-TOP-WG Meeting

Introduction

- CP violation (CPV) is a candidate to explain the matter-antimatter but it has not been observed beyond the expectation of the SM

- In the SM, CPV in the production and decay of top quark pairs is predicted to be very small
- Search the new source of CPV using top quark pair events in the dilepton channels; chromoelectric dipole moment, CEDM



: Magnetic Dipole Moment

: Electric Dipole Moment

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

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：

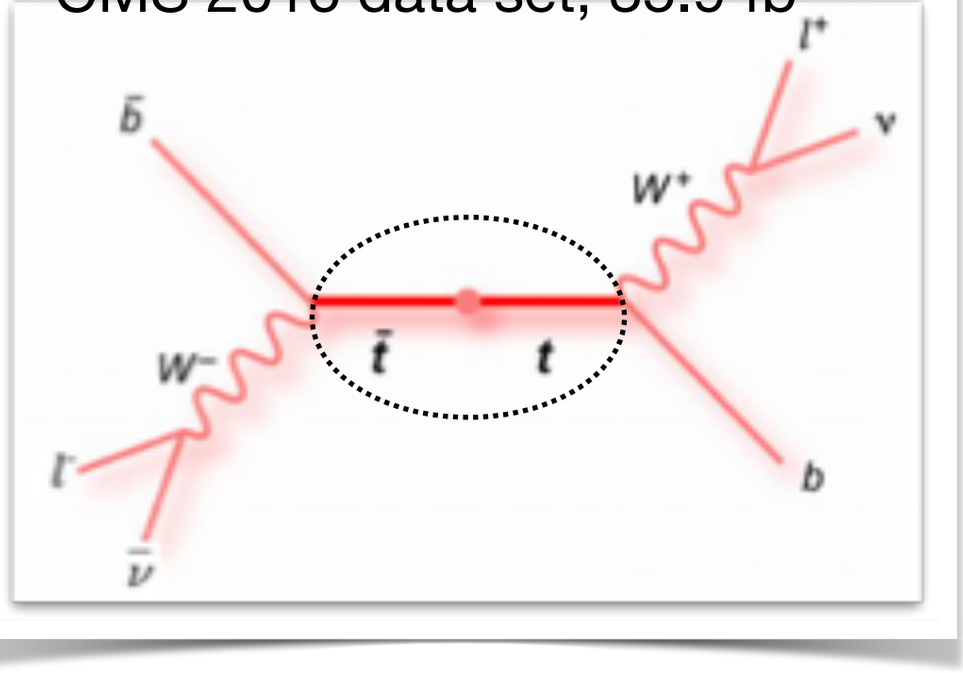
$$A_i \equiv \frac{N_{events}(\mathcal{O}_i > 0) - N_{events}(\mathcal{O}_i < 0)}{N_{events}(\mathcal{O}_i > 0) + N_{events}(\mathcal{O}_i < 0)} \quad i = 1 \text{ or } 3$$

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

Analysis Procedure

- **The main goal of this analysis**
  Extraction the asymmetry and CEDM in top pair events in the dilepton final state

CMS 2016 data set, 35.9 fb^{-1}

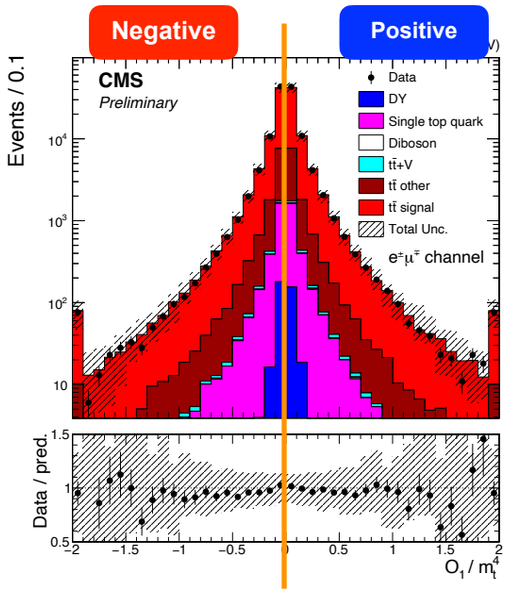


- Selection of events top pair events in the dilepton final state

- DY contribution estimated ($R_{out/in}$)

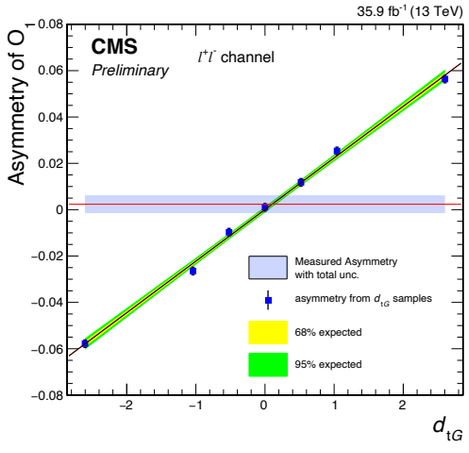
- Reconstruction of top quarks

- Calculate O1 and O3



Extraction of Asymmetry of O1 & O3
Using a maximum likelihood fit

Extraction of CEDM
Using the generated CP-violation events



Object & Event Selection

- **Object Selection**

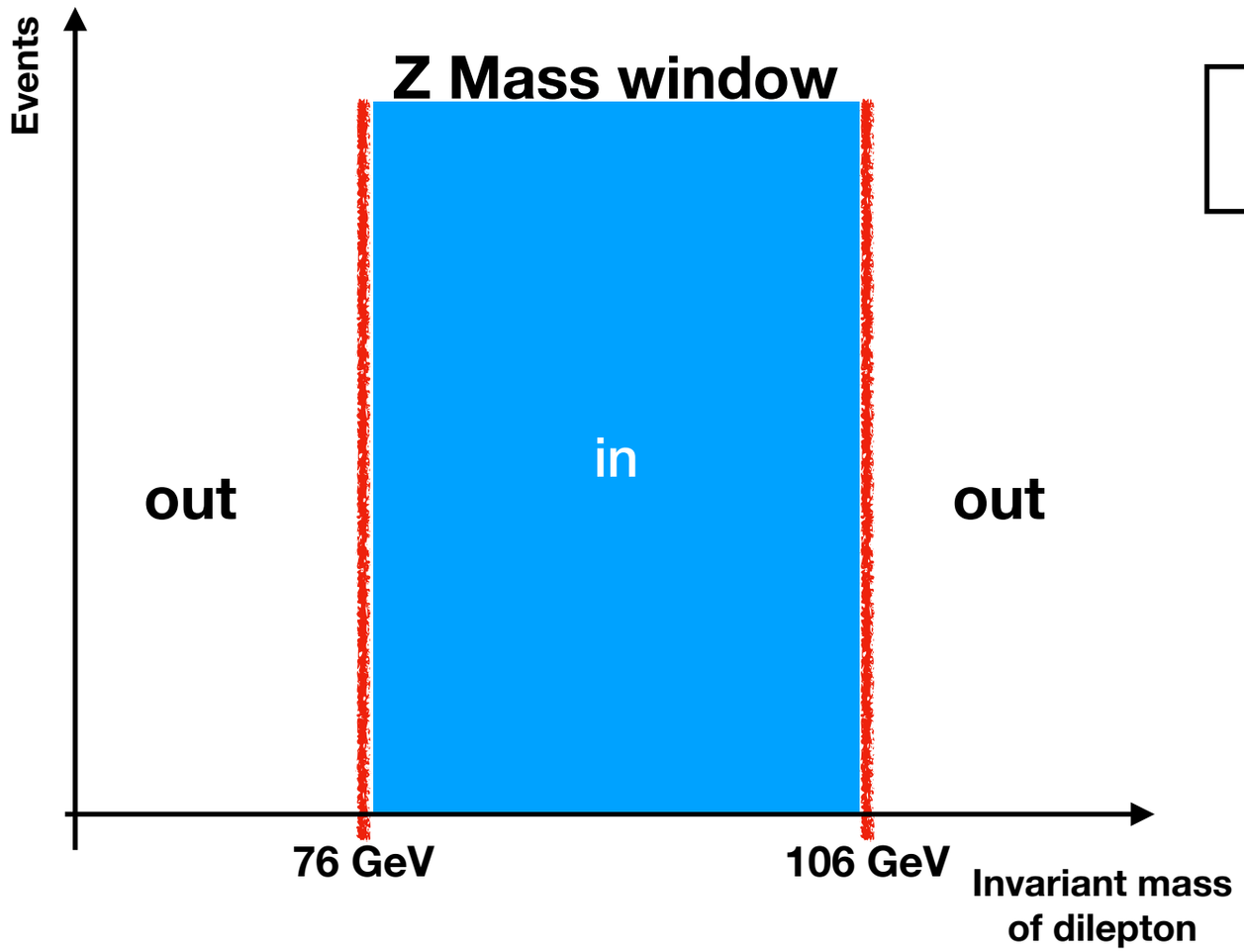
Requirement	Muon	Electron	Jet
ID & Isolation	Tight ID PFIso < 0.15 (Tight)	Tight (Cut Based)	PF Loose
Kinematic Requriement	$\|\eta\| < 2.4$ Leading lepton $p_T > 25$ GeV & Sub-leading Lepton $p_T > 20$ GeV		$p_T > 30$ GeV, $\|\eta\| < 2.4$
b-tagging	-		Medium (CSVv2)

- **Event Selection**

Cut flow	Dimuon & Dielectron	Muon-electron
Trigger & MET filters	O	O
Lepton requirement & M_{ll}> 20 GeV & Third lepton veto	O	O
Z mass veto (76 GeV < M_{ll} <106 GeV)	O	-
Num. of Jet ≥ 2	O	O
MET > 40 GeV	O	-
Num. b-tagged Jet ≥ 1 (CSVv2, Medium W.P.)	O	O
Top reconstruction (Kinematic solver)	O	O

Determination of Drell-Yan Background

- To determine DY background, we follow the method ($R_{out/in}$) suggested in [1,2,3].



$$N_{out}^{l^+l^-,data} = R_{out/in}^{l^+l^-}(N_{in}^{l^+l^-,data} - 0.5 \cdot k_{ll} \cdot N_{in}^{e\mu,data})$$

$$\text{where } ll = \mu\mu \text{ or } ee,\ R_{out/in} = \frac{N_{DY\,MC}^{out}}{N_{DY\,MC}^{in}}$$

$$\text{for } k_{ll},\ k_{ee} = \sqrt{\frac{N_{in}^{e^+e^-}}{N_{out}^{\mu^+\mu^-}}},\ k_{\mu\mu} = \sqrt{\frac{N_{in}^{\mu^+\mu^-}}{N_{out}^{e^+e^-}}}$$

	$\mu^+\mu^-$	e^+e^-	$e^\pm\mu^\mp$
SF	1.1	1.1	1.2

[1] E. P. J. Cuevas, J. R. Gonzalez, “Measurement of the Top-Quark Pair Production Cross Section in the Dilepton Channel with 35.9 fb−1 of 13 TeV data using the Cut and Count Method”, CMS Note 2017/039, 2017

[2] W. Andrews and et al., “A Method to Measure the Contribution of DY → l+l− to a di-lepton + MET Selection”, CMS Note 2009/023, 2009.

[3] S. Chenarani and et al., “Measurement of the cross-section for tW production in dilepton final states at 13 TeV using 2016 data”, CMS Note 2017/132, 2017.

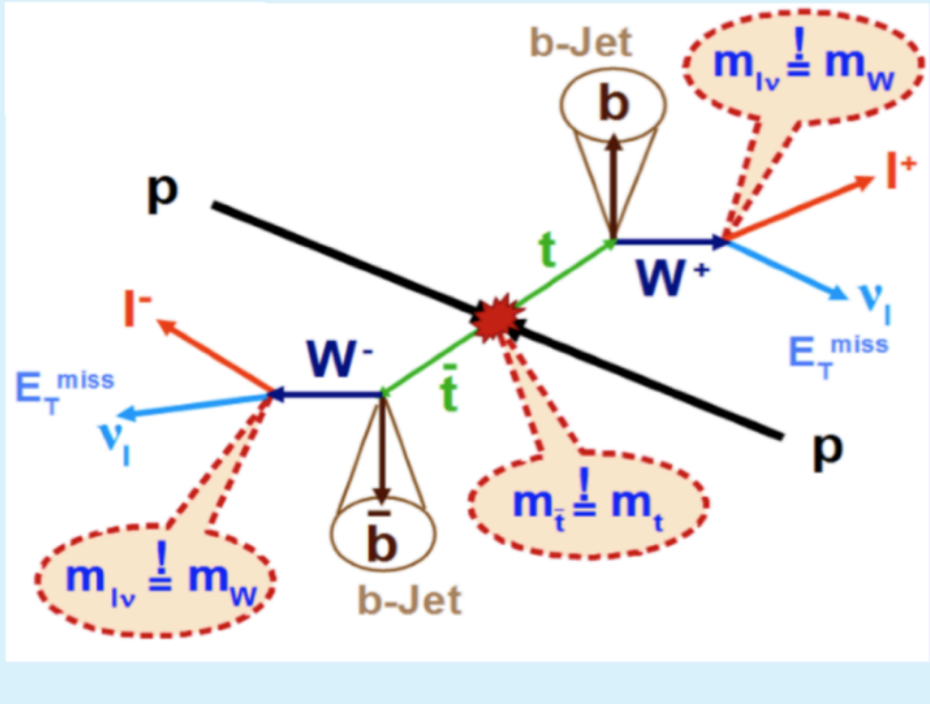
Reconstruction of Top Quarks

kinematic reconstruction

inputs: 2 jets, 2 leptons, MET

constraints:
- m_t, m_{tbar} → 2
- m_{W+}, m_{W-} → 2
- $P_T(\vec{\nu} + \vec{\bar{\nu}})$ = MET →2

unknowns:
$\vec{\nu}$, $\vec{\bar{\nu}}$ → 6



- reconstruct event 100 times and smear inputs by their resolution:
  - top mass fixed to 172.5 GeV
  - w mass smeared according to gen-level W mass distribution
  - take weighted average of solutions for all smearings
  - weights defined according to gen-level m_{lb} distribution

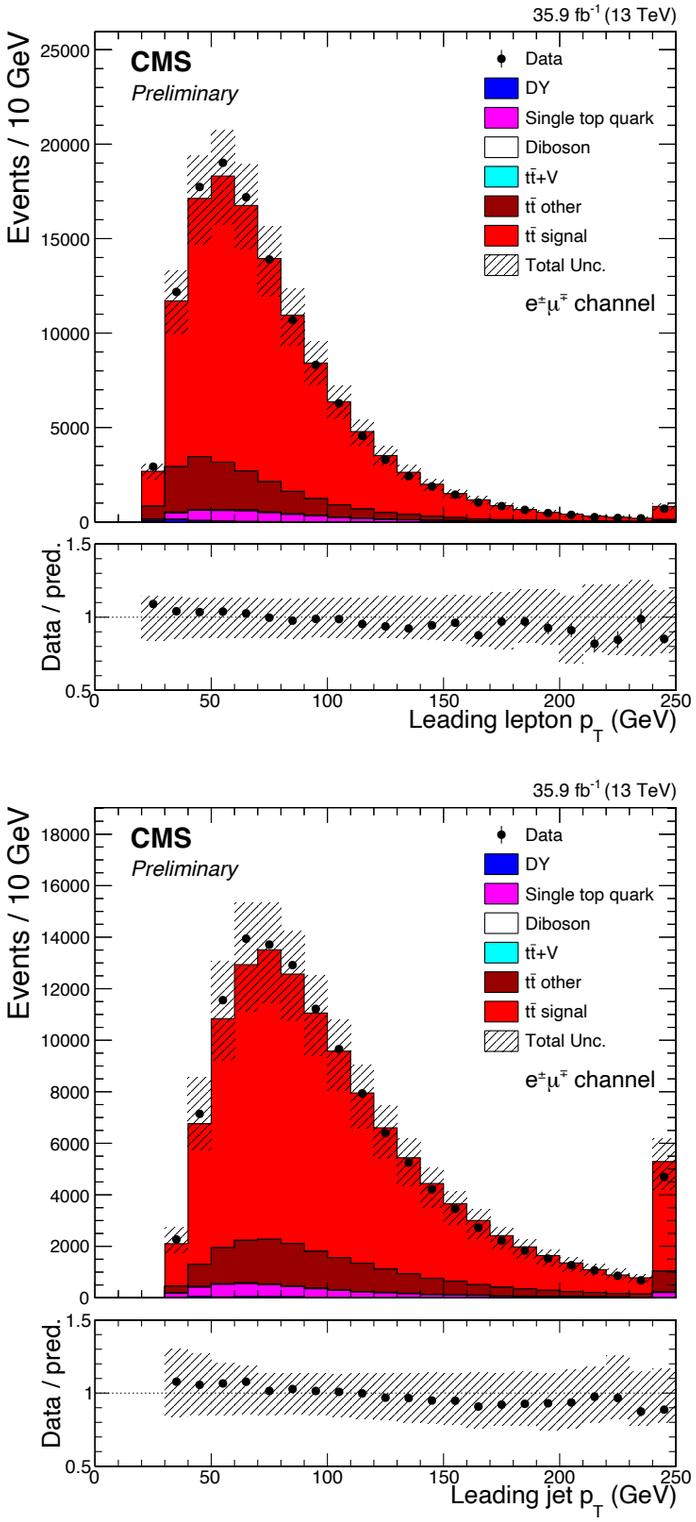
$$p^{top}_{x,y,z} = \frac{1}{w}\sum_{i=0}^{100} w_i \cdot \left(p^{top}_{x,y,z}\right)_i$$

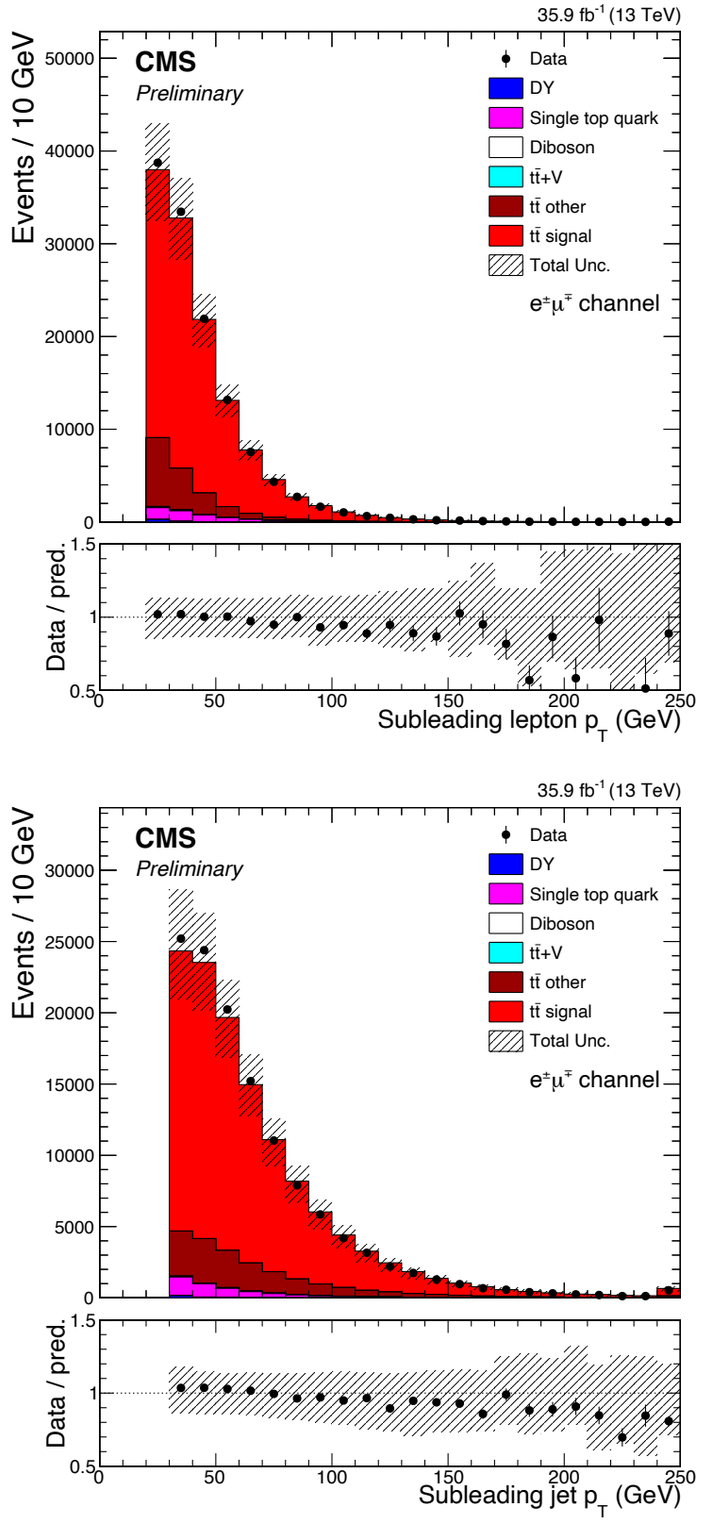
20/03/18

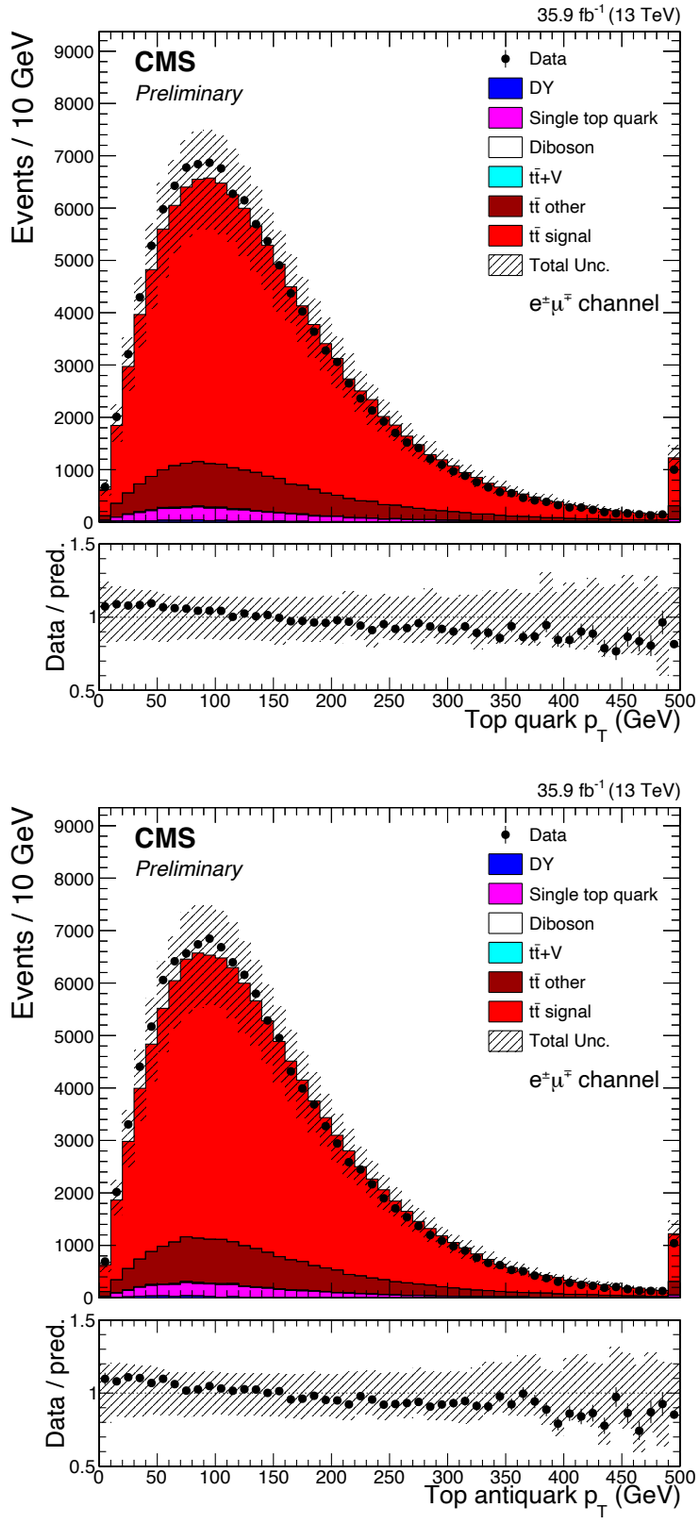
Slide courtesy by Mykola Savitskyi

Kinematics of Object ($e^{\pm}\mu^{\mp}$)

- p_T distribution of leading leptons, jets and top quarks







Event Yield

- Simulated and observed event yields with their statistical uncertainties for the three dilepton channels.

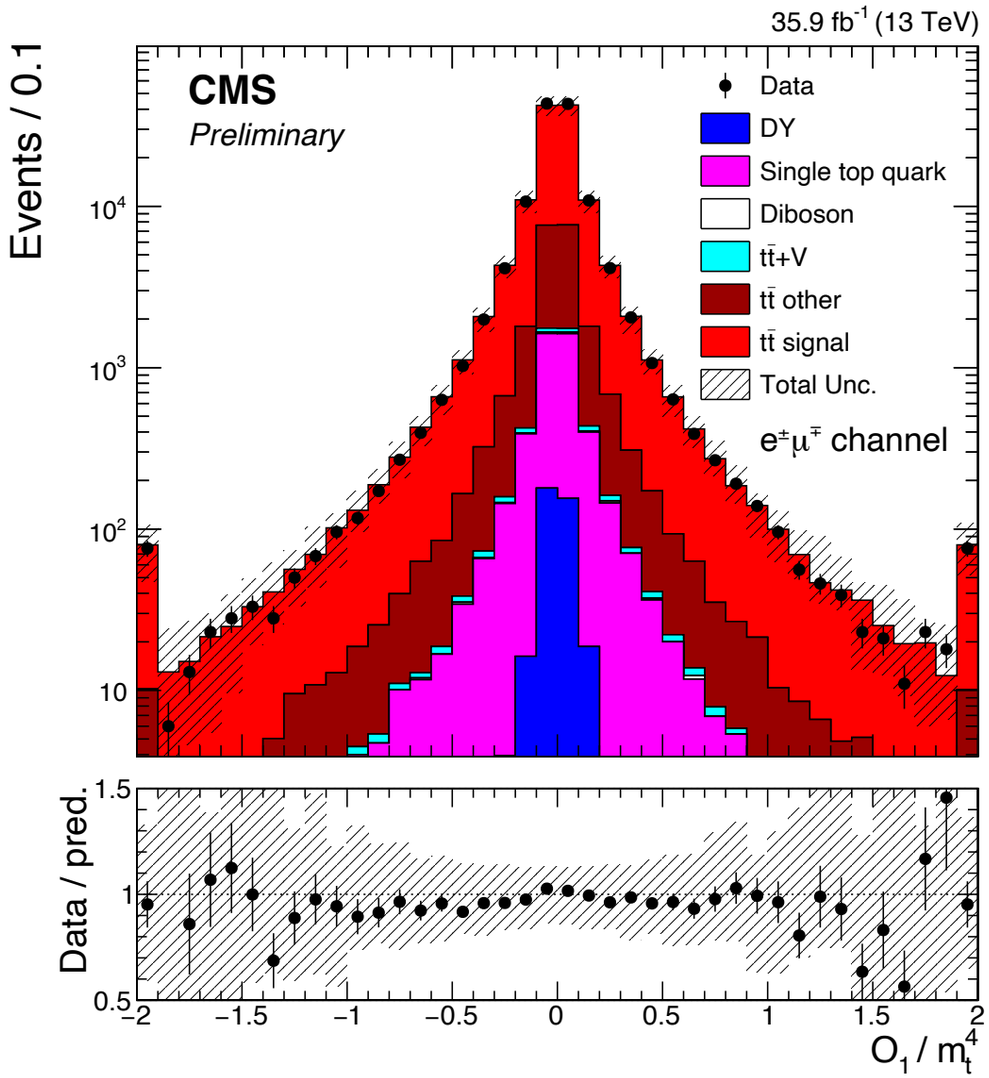
- **Only statistical uncertainty**

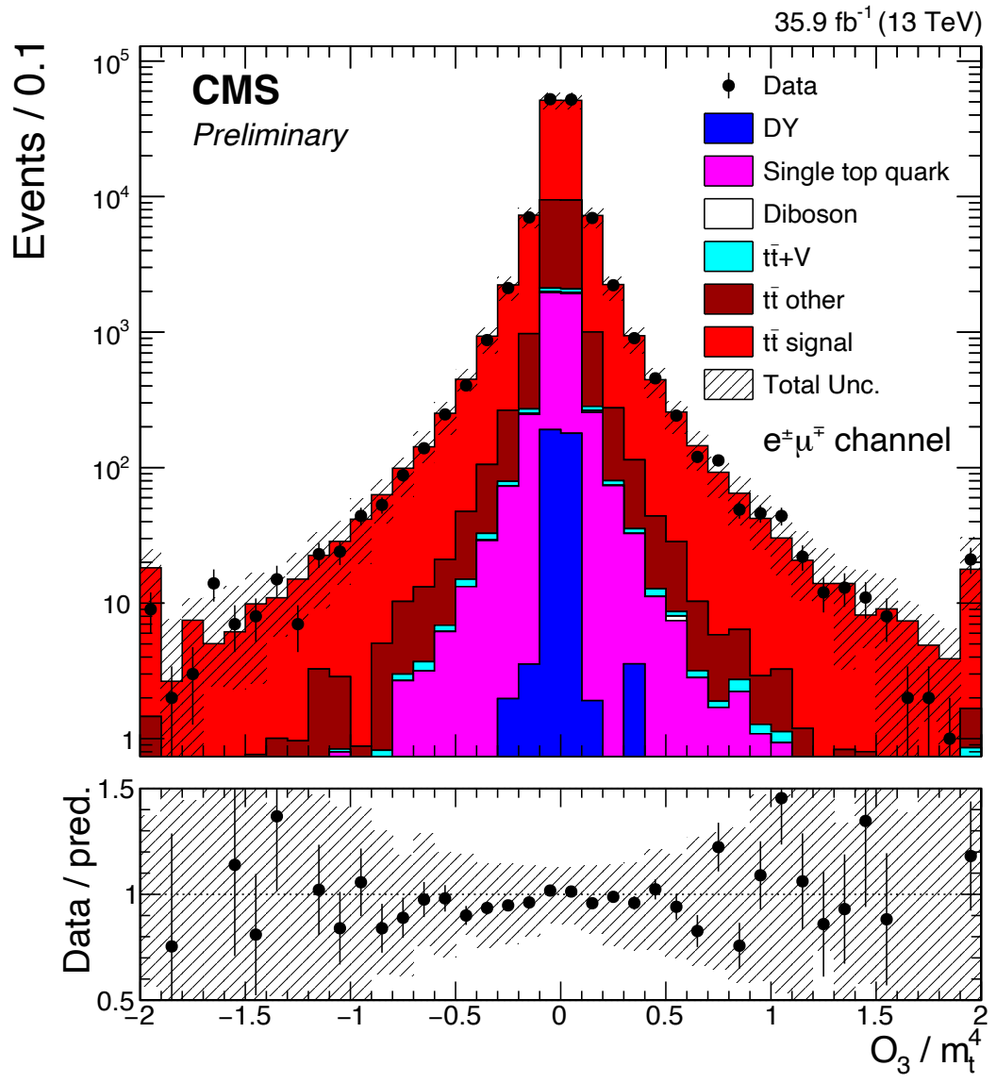
Process	$\mu^+\mu^-$	e^+e^-	$e^\pm\mu^\mp$
DY	1627 ± 95	700 ± 57	381 ± 26
Single top quark	1793 ± 18	899 ± 13	4265 ± 28
$t\bar{t}$+V	144 ± 3	72 ± 2	302 ± 4
Diboson	70 ± 6	37 ± 4	100 ± 7
$t\bar{t}$ other	7502 ± 38	3425 ± 25	16787 ± 56
$t\bar{t}$ signal	45818 ± 93	22216 ± 64	104051 ± 140
Total prediction	56954 ± 140	27350 ± 90	125878 ± 155
Observed data	55993	26961	126549

- The discrepancy between observed and simulated events is lower than ~3%.
($\mu^+\mu^-$: ~3% , e^+e^- : ~2.9%, $e^\pm\mu^\mp$: ~0.8%)

Distribution of O_1 and O_3 $(e^{\pm}\mu^{\mp})$

- Distribution of O_1 and O_3





We extracted asymmetries with maximum likelihood fit

Asymmetry Extraction

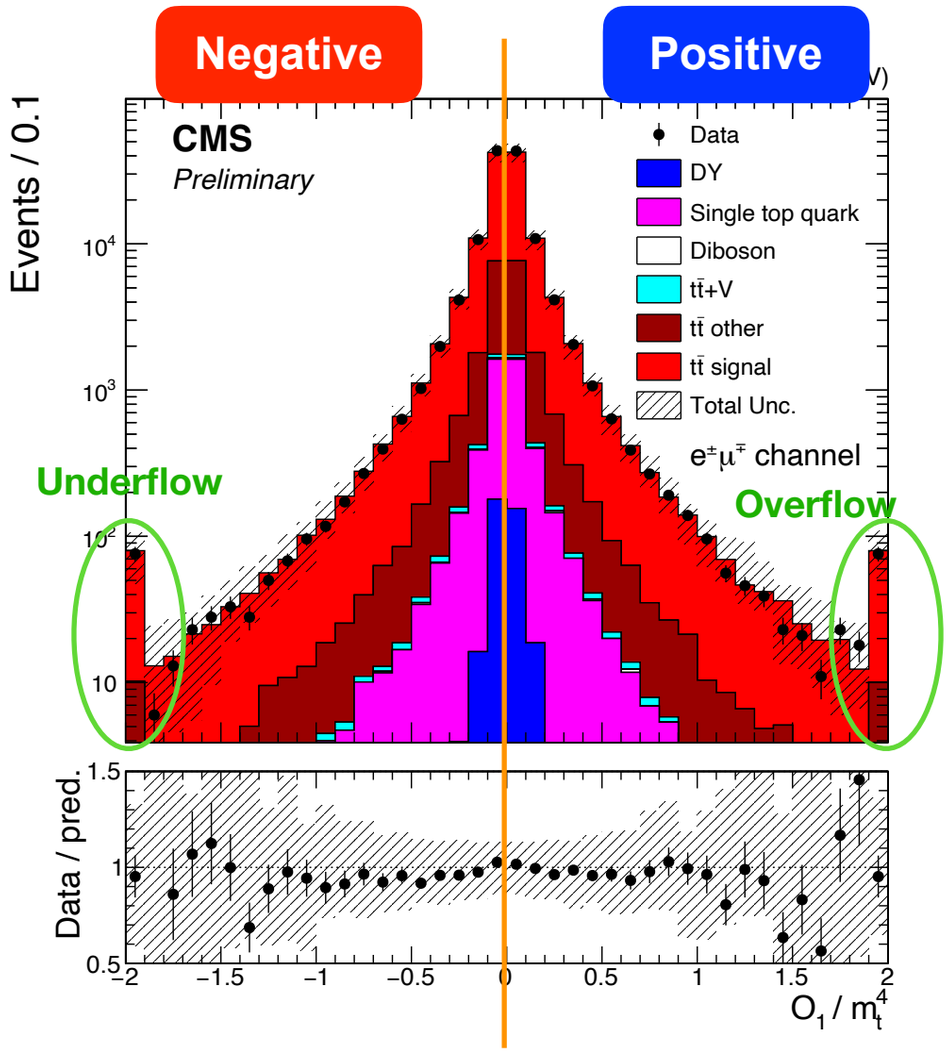
- Definition of the likelihood fit function

$$\mathcal{L}(\mathrm{A}_i, \sigma_{t\bar{t}}) = \mathcal{P}(N_+^{\mathrm{obs}}, N_+^{\mathrm{pred}}) \cdot \mathcal{P}(N_-^{\mathrm{obs}}, N_-^{\mathrm{pred}})$$

$$N_\pm^{\mathrm{pred}} = N^{\mathrm{t\bar{t}}} \frac{1 \pm A_i}{2} + N^{\mathrm{bkg}} f_\pm^{\mathrm{bkg}},$$

$$N^{\mathrm{t\bar{t}}} = L \cdot \mathcal{B} \cdot \varepsilon_{\mathrm{sig}} \cdot \sigma_{\mathrm{t\bar{t}}}$$

made A and x-section float



- By minimizing the negative log-likelihood function, we extract asymmetry

Sources of Systematic Uncertainties

- Basically, we considered two types of systematic uncertainties

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
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
Jet ϕ Resolution	Underlying event
Charge Mis identification (Leptons)	Top mass
Different response of b/b-bar quark jet	-

Additional systematic uncertainty sources (next slide)

Dilution Study: Additional Sys. Uncertainty

- Dilution factor is important in our analysis. Physics observables to test CP violation are the determinant of 4X4 Matrix which consists of 4-vectors of top quarks, b-quark jets and leptons.

  If either the 4-vectors or the order of component of determinant(O_i) is changed, the sign of the physics observable O_i is also changed. So it will affect the asymmetry.

$$\mathcal{O}_1 = \epsilon(p_t, p_{\bar{t}}, p_{l+}, p_{l-})$$
$$\mathcal{O}_3 = \epsilon(p_b, p_{\bar{b}}, p_{l+}, p_{l-})$$

$$A_i \equiv \frac{N_{events}(\mathcal{O}_i > 0) - N_{events}(\mathcal{O}_i < 0)}{N_{events}(\mathcal{O}_i > 0) + N_{events}(\mathcal{O}_i < 0)}$$

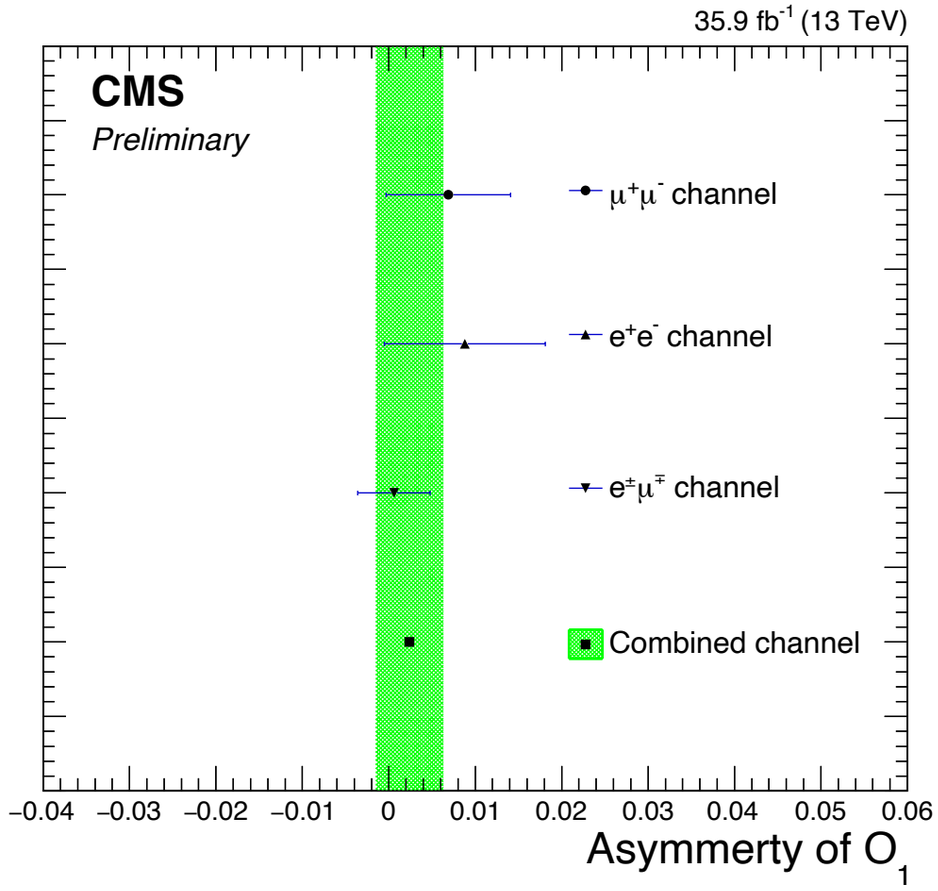
- Jet ϕ Resolution (Angular Resolution)
  - Shifted phi of jets by ϕ Resolution

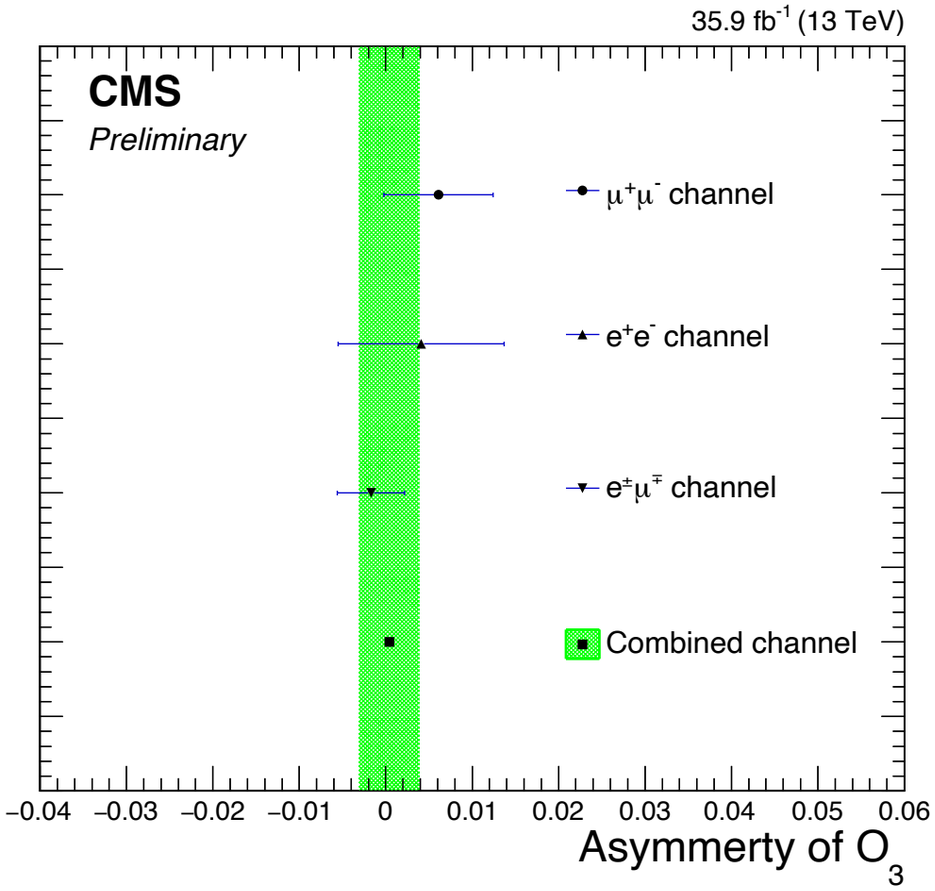
- Charge Mis-Identification
  - One lepton charge mis-identification
  - Two lepton charge mis-identification

- b & b-bar quark Jet Different Response
  - Applied b& b-bar quark jet difference to MC simulation

Asymmetries

- Asymmetry



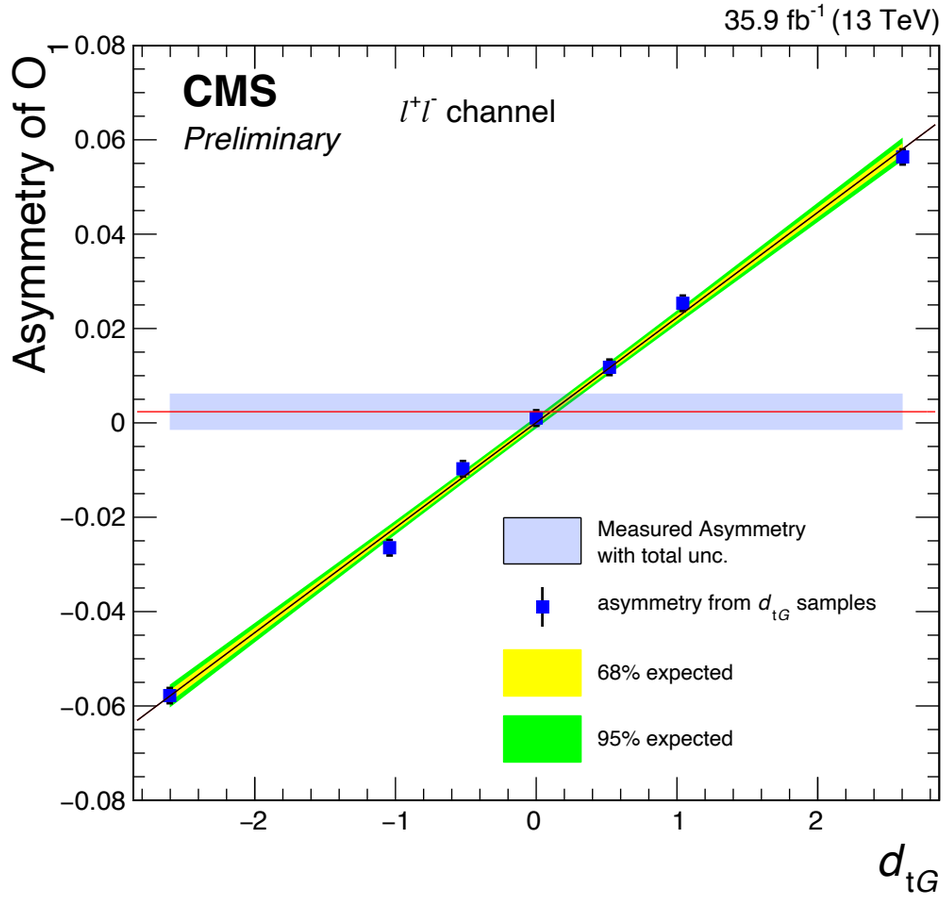


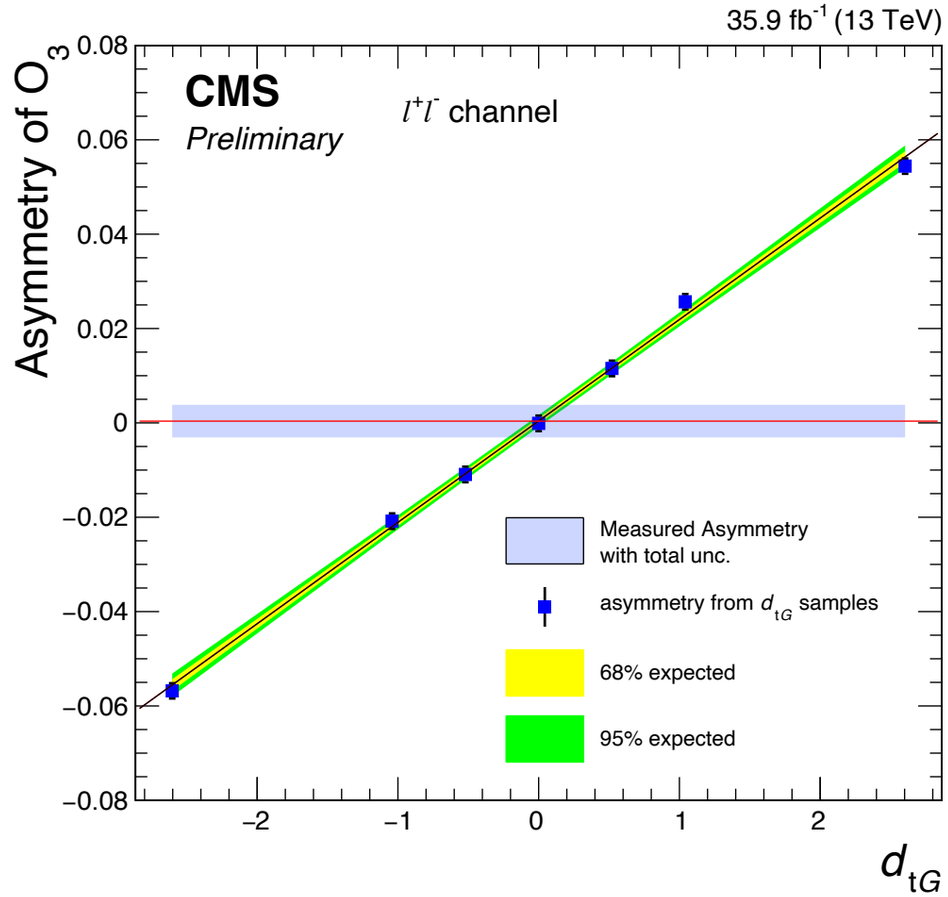
-Dominant Systematic Sources : Color-reconnection, Underlying event

- Asymmetry of combined channel is estimated by using best linear unbiased estimator (BLUE) method
- **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 & Plan

- CP violating asymmetries and CEDM of top quark have been presented
- 2016 data set (CMS, 35.9 fb^{-1}) was analyzed
- Measured Asymmetries for combined channel are
  $2.4 \pm 2.8(\text{stat}) \pm 2.8(\text{syst}) \times 10^{-3}$ and $0.4 \pm 2.8(\text{stat}) \pm 2.2(\text{syst}) \times 10^{-3}$
- 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
- We have a plan for using Run 2 Full data set

Backup

Physics Observable

TABLE I. Comparison of asymmetries in the dilepton and semileptonic channels for $d_{tG} = 3$, $\Lambda = 1$ TeV. The latter do not yet correspond to observable asymmetries and serve only for this comparison.

	$pp \to t\bar{t} \to b\bar{b}\ell^+\ell^- E_T$	$pp \to t\bar{t} \to b\bar{b}\ell^\pm jj E_T$
$\mathcal{O}_1$	$\epsilon(t,\bar{t},\ell^+,\ell^-)$	$q_\ell \epsilon(t,\bar{t},\ell,d)$
A_1	-0.1540	$-0.1535 \xrightarrow{p_t \to p_{t-vis}} -0.1114$
$\mathcal{O}_2$	$\epsilon(t,\bar{t},b,\bar{b})$	$\epsilon(t,\bar{t},b,\bar{b})$
A_2	-0.0358	$-0.0311 \xrightarrow{p_t \to p_{t-vis}} -0.0527$
$\mathcal{O}_3$	$\epsilon(b,\bar{b},\ell^+,\ell^-)$	$q_\ell \epsilon(b,\bar{b},\ell,d)$
A_3	-0.0902	-0.0838
$\mathcal{O}_4$	$\epsilon(b^+,b^-,\ell^+,\ell^-)$	$\epsilon(b^\ell,b^d,\ell,d)$
A_4	-0.0340	-0.0319
$\mathcal{O}_5$	$q\cdot(\ell^+-\ell^-)\epsilon(b,\bar{b},\ell^++\ell^-,q)$	$q_\ell q\cdot\ell\epsilon(b,\bar{b},\ell,q)$
A_5	-0.0309	-0.0115
$\mathcal{O}_6$	$\epsilon(P,b-\bar{b},\ell^+,\ell^-)$	$q_\ell \epsilon(P,b-\bar{b},\ell,d)$
A_6	0.0763	0.0742
$\mathcal{O}_7$	$q\cdot(t-\bar{t})\epsilon(P,q,\ell^+,\ell^-)$	$q_\ell q\cdot(t-\bar{t})\epsilon(P,q,\ell,d)$
A_7	-0.0373	$-0.0325 \xrightarrow{p_t \to p_{t-vis}} -0.0257$
$\mathcal{O}_8$	$q\cdot(t-\bar{t})(P\cdot\ell^+\epsilon(q,b,\bar{b},\ell^-)$ $+P\cdot\ell^-\epsilon(q,b,\bar{b},\ell^+))$	$q\cdot(t-\bar{t})(P\cdot\ell\epsilon(q,b,\bar{b},d)$ $+P\cdot d\epsilon(q,b,\bar{b},\ell))$
A_8	0.0074	$0.0113 \xrightarrow{p_t \to p_{t-vis}} 0.0094$
$\mathcal{O}_9$	$q\cdot(\ell^+-\ell^-)\epsilon(b+\bar{b},q,\ell^+,\ell^-)$	$q\cdot\ell\epsilon(b+\bar{b},q,\ell,d)$
A_9	0.0089	0.0051
$\mathcal{O}_{10}$	$q\cdot(b-\bar{b})\epsilon(b,\bar{b},q,\ell^++\ell^-)$	$q\cdot(b-\bar{b})\epsilon(b,\bar{b},q,d)$
A_{10}	-0.0069	-0.0045
$\mathcal{O}_{11}$	$q\cdot(b-\bar{b})\epsilon$ $(P,q,b+\bar{b},\ell^+-\ell^-)$	$q_\ell q\cdot(b-\bar{b})\epsilon$ $(P,q,b+\bar{b},d)$
A_{11}	-0.0147	0.0140
$\mathcal{O}_{12}$	$q\cdot(b-\bar{b})\epsilon(P,q,b,\bar{b})$	$q\cdot(b-\bar{b})\epsilon(P,q,b,\bar{b})$
A_{12}	0.0058	0.0041
$\mathcal{O}_{13}$	$\epsilon(P,b+\bar{b},\ell^+,\ell^-)$	$q_\ell \epsilon(P,b+\bar{b},\ell,d)$
A_{13}	0.0032	0.0025

O1 and O3 are described in this theory paper.[1]

According to theory paper, O1 and O3 are very sensitive.

[1] https://journals.aps.org/prd/pdf/10.1103/PhysRevD.93.014020

Triggers & MET Filters

- MET Filters :

  -Primary vertex filter
  -Beam halo filter
  -HBHE noise fiter
  -HBHEiso noise filter
  -ee badSC noise filter (Applied only to data)
  -badMuon filer
  -badCharged hadron filter

- Triggers

	Data	MC
$\mu\mu$	HLT_IsoMu24_v*, HLT_IsoTrkMu24_v* (B to H) HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v*, HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v* (B to G) HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*, HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v* (H)	HLT_IsoMu24_v*, HLT_IsoTkMu24_v*, HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v*, HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v*
ee	HLT_Ele27_WPTight_Gsf_v*, HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v* (B to H)	HLT_Ele27_WPTight_Gsf_v* HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
$e\mu$	HLT_IsoMu24_v*, HLT_IsoTkMu24_v*, HLT_Ele27_WPTight_Gsf_v* (B to H) HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*, HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v* (B to G) HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*, HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v* (H)	HLT_IsoMu24_v*, HLT_IsoTkMu24_v*, HLT_Ele27_WPTight_Gsf_v*, HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*, HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*

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

Determination of Drell-Yan Background

- To determine DY background, we've follow the method which was suggested in [1,2,3].

- For the estimation of DY background outside the dilepton invariant mass window ($76 < M_{ll} < 106$ GeV/c^2) in data, it is necessary to derive the ratio of DY events outside to inside the dilepton invariant mass window, $R_{out/in}$.

$$N_{out}^{l^+l^-,data} = R_{out/in}^{l^+l^-}(N_{in}^{l^+l^-,data} - 0.5 \cdot k_{ll} \cdot N_{in}^{e\mu,data})$$

where $ll = \mu\mu$ or ee, $R_{out/in} = \frac{N_{DY\,MC}^{out}}{N_{DY\,MC}^{in}}$ for k_{ll}, $k_{ee} = \sqrt{\frac{N_{in}^{e^+e^-}}{N_{out}^{\mu^+\mu^-}}}$, $k_{\mu\mu} = \sqrt{\frac{N_{in}^{\mu^+\mu^-}}{N_{out}^{e^+e^-}}}$

	$\mu^+\mu^-$	e^+e^-	$e^\pm\mu^\mp$
SF	1.1	1.1	1.2

[1]E. P. J. Cuevas, J. R. Gonzalez, "Measurement of the Top-Quark Pair Production Cross Section in the Dilepton Channel with 35.9 fb−1 of 13 TeV data using the Cut and Count Method", CMS Note 2017/039, 2017

[2]W. Andrews and et al., "A Method to Measure the Contribution of DY → l+l− to a di-lepton + MET Selection", CMS Note 2009/023, 2009.

[3]S. Chenarani and et al., "Measurement of the cross-section for tW production in dilepton final states at 13 TeV using 2016 data", CMS Note 2017/132, 2017.

Reconstruction of Top Quarks

- There are eight equations describing the kinematics of ttbar dilepton events.

$$
\begin{aligned}
\not{E}_x &= p_{\nu_x} + p_{\bar{\nu}_x} \\
\not{E}_y &= p_{\nu_y} + p_{\bar{\nu}_y} \\
E_\nu^2 &= p_{\nu_x}^2 + p_{\nu_y}^2 + p_{\nu_z}^2 + m_\nu^2 \\
E_{\bar{\nu}}^2 &= p_{\bar{\nu}_x}^2 + p_{\bar{\nu}_y}^2 + p_{\bar{\nu}_z}^2 + m_{\bar{\nu}}^2
\end{aligned}
$$

$$
\begin{aligned}
m_{W^+}^2 &= (E_{\ell^+} + E_\nu)^2 - (p_{\ell_x^+} + p_{\nu_x})^2 \\
&\quad -(p_{\ell_y^+} + p_{\nu_y})^2 - (p_{\ell_z^+} + p_{\nu_z})^2 \\
m_{W^-}^2 &= (E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\ell_x^-} + p_{\bar{\nu}_x})^2 \\
&\quad -(p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\ell_z^-} + p_{\bar{\nu}_z})^2 \\
m_t^2 &= (E_b + E_{\ell^+} + E_\nu)^2 - (p_{b_x} + p_{\ell_x^+} + p_{\nu_x})^2 \\
&\quad -(p_{b_y} + p_{\ell_y^+} + p_{\nu_y})^2 - (p_{b_z} + p_{\ell_z^+} + p_{\nu_z})^2 \\
m_{\bar{t}}^2 &= (E_{\bar{b}} + E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}_x} + p_{\ell_x^-} + p_{\bar{\nu}_x})^2 \\
&\quad -(p_{\bar{b}_y} + p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\bar{b}_z} + p_{\ell_z^-} + p_{\bar{\nu}_z})^2
\end{aligned}
$$

- Details of reconstruction method

1. Input Object :
reconstructed jets, leptons, MET

2. Input to kinematic reconstruction :
- Correction for detector effects:
Jet & lepton energies smeared
- Directional smearing

3. Top Mass Fixed: 172.5 GeV

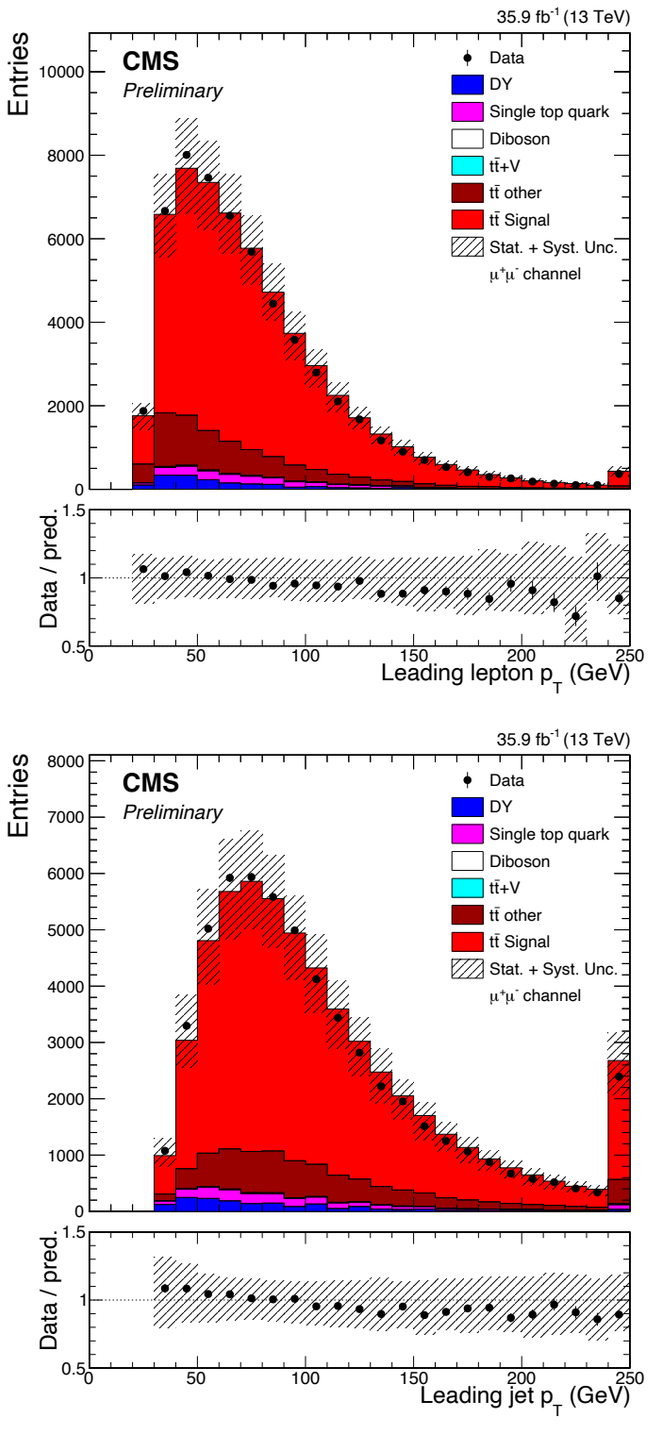
4. W mass on the reco level is smeared according to the true W mass distribution.

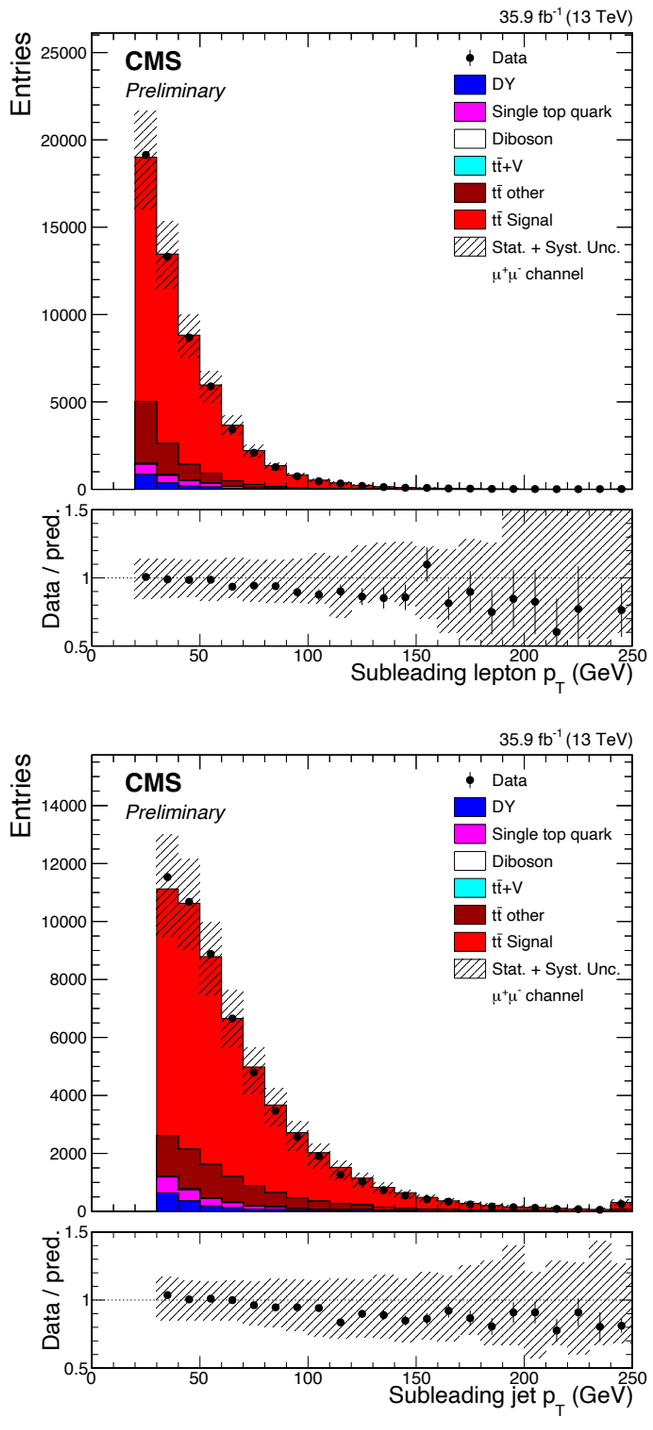
5. Combinatorics solved: ONLY the Lepton-Jet combination with the largest sum of solution weights according to true m(bl) spectrum is taken

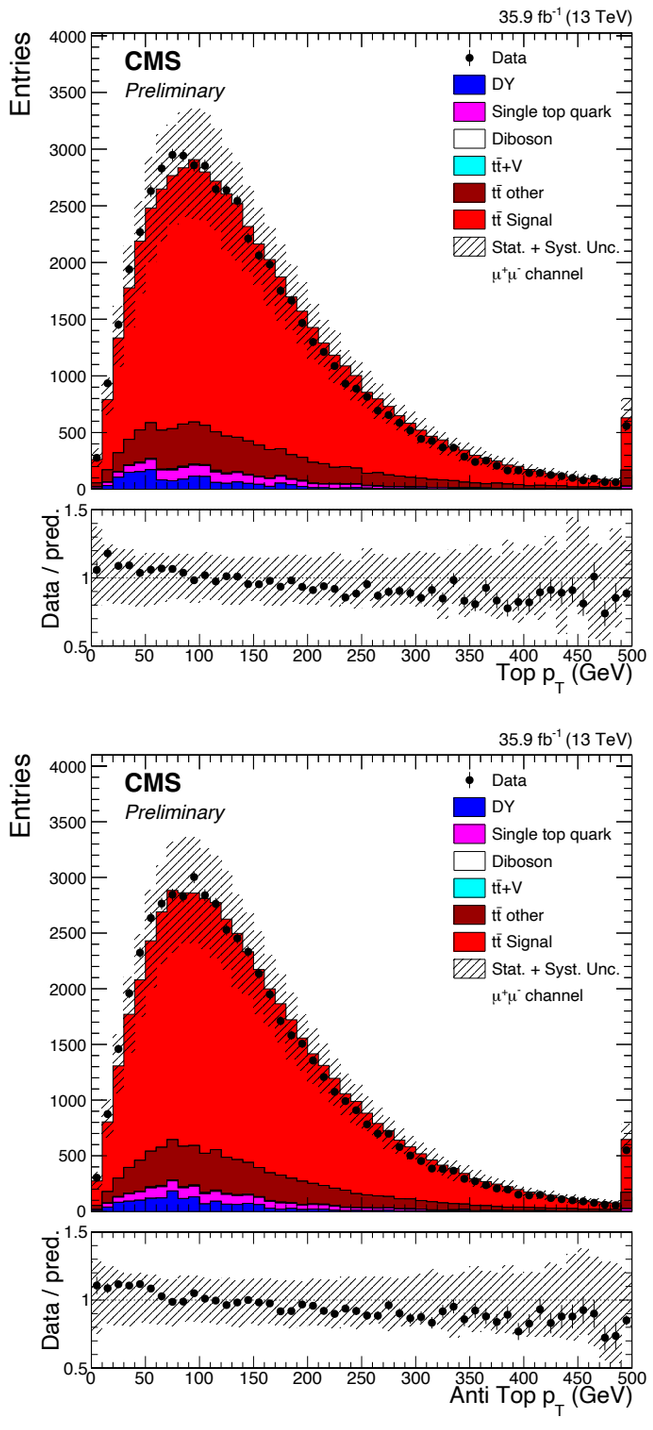
6. Solution ambiguities: solution with smallest m(tt) is taken.

7. weighted average solution is taken.

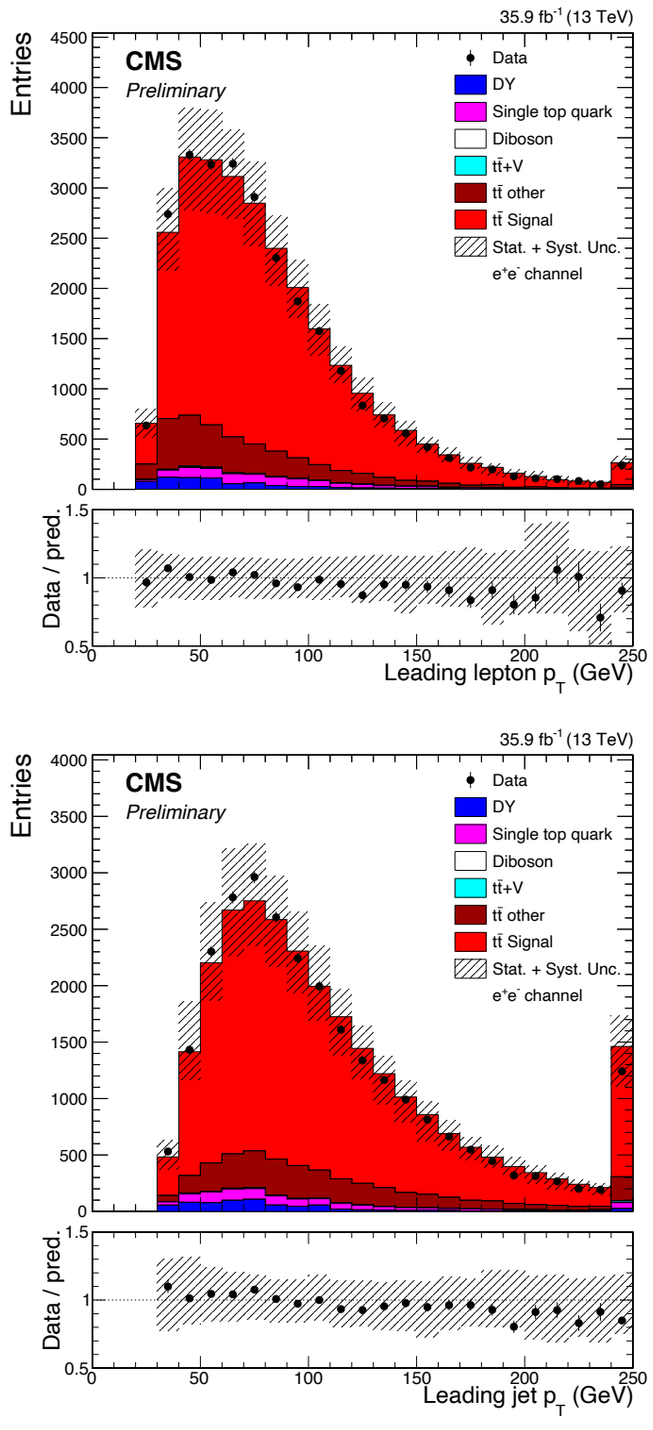
Kinematics of Object ($\mu^+\mu^-$)

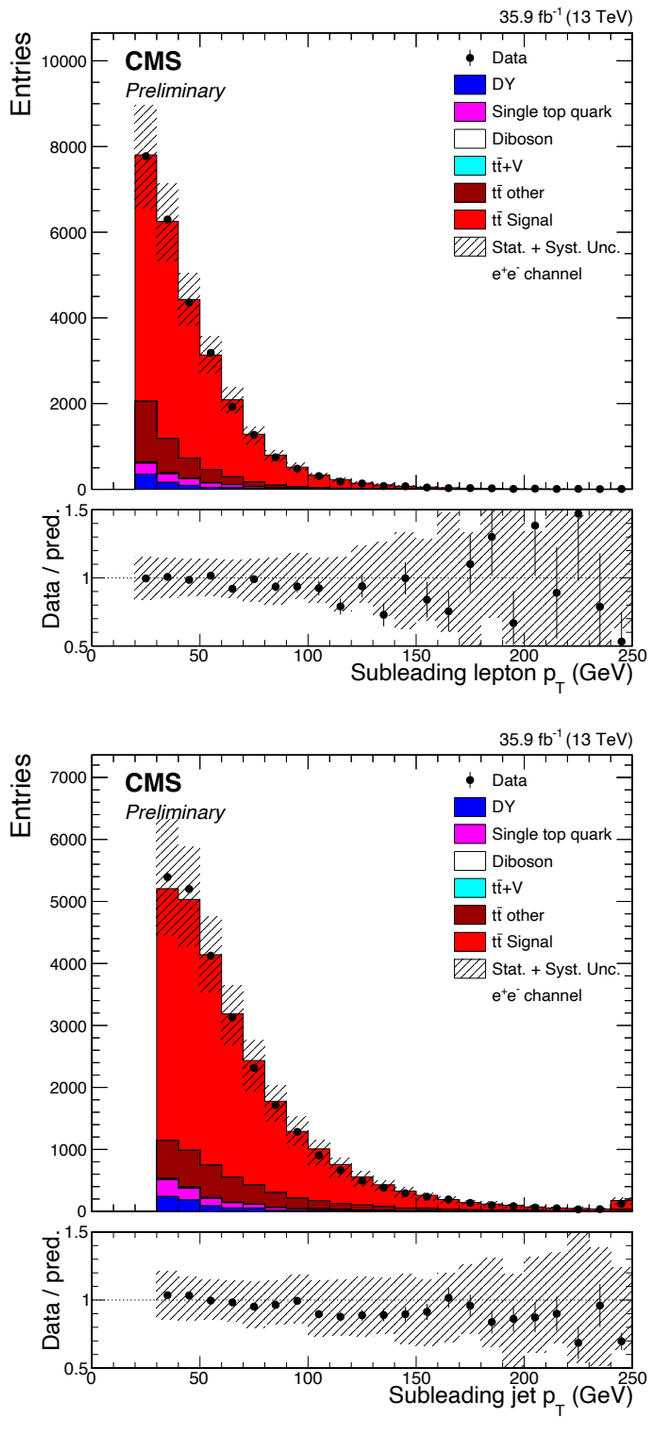


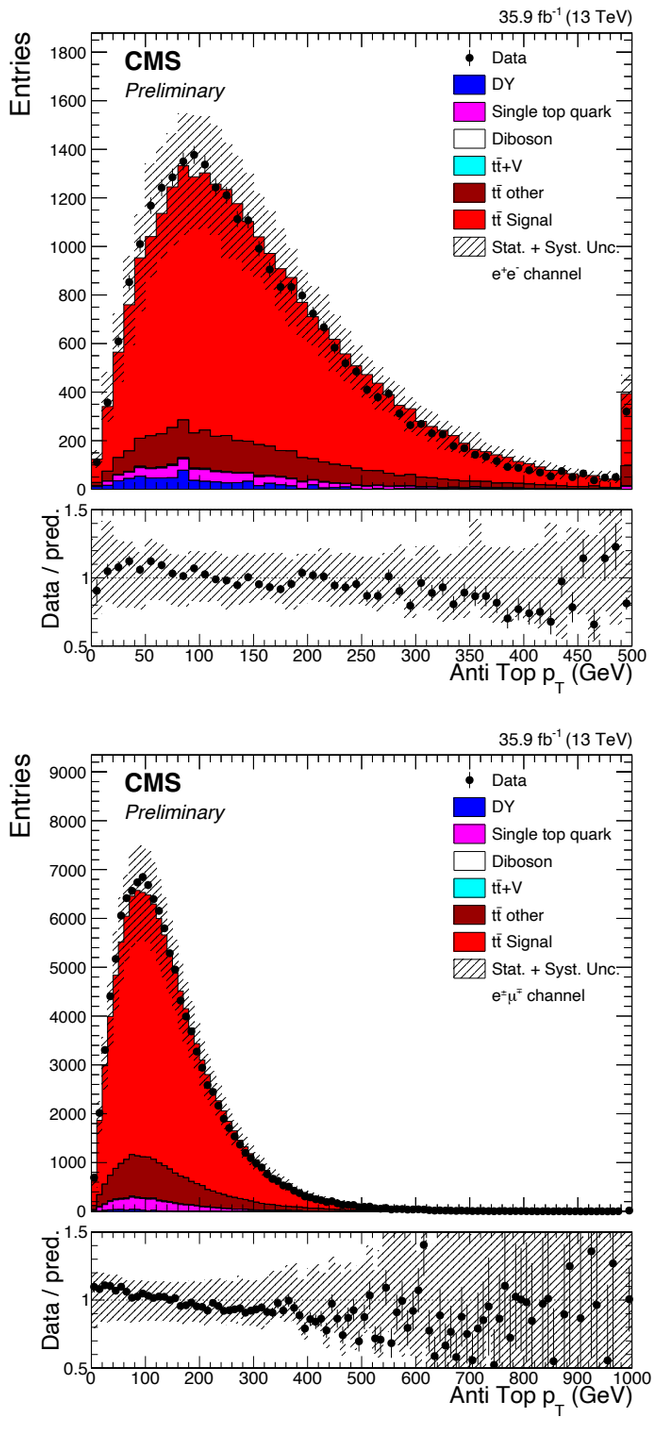




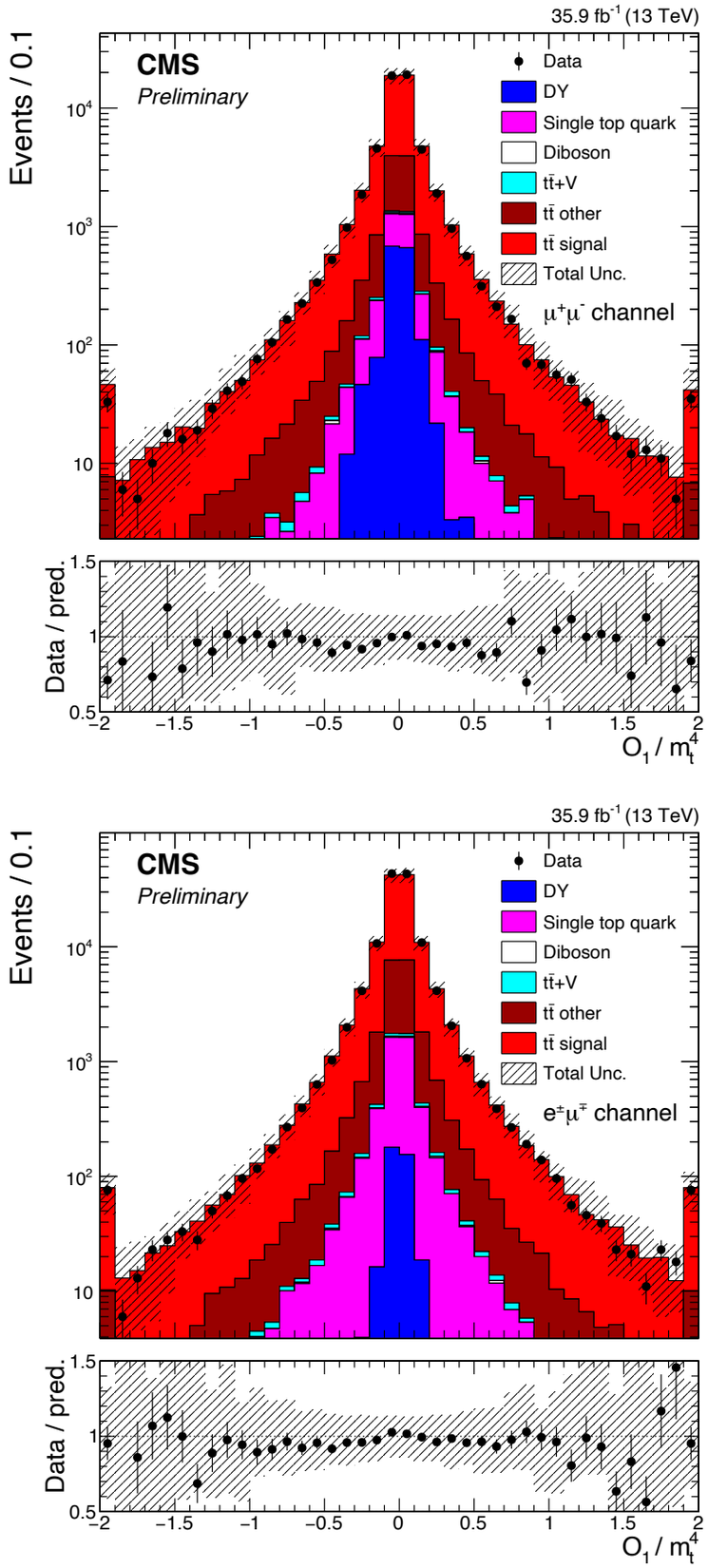
Kinematics of Object (e^+e^-)

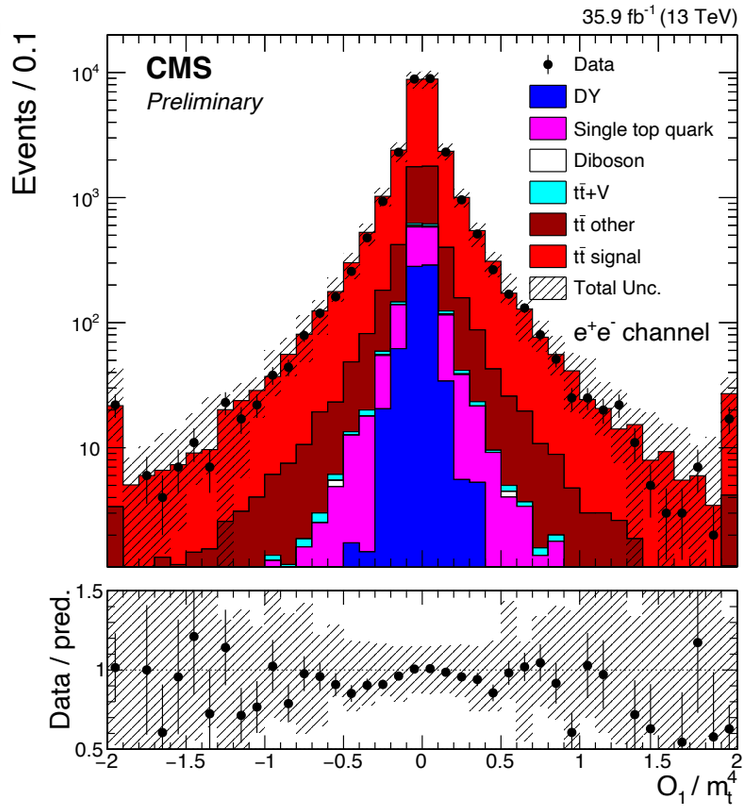




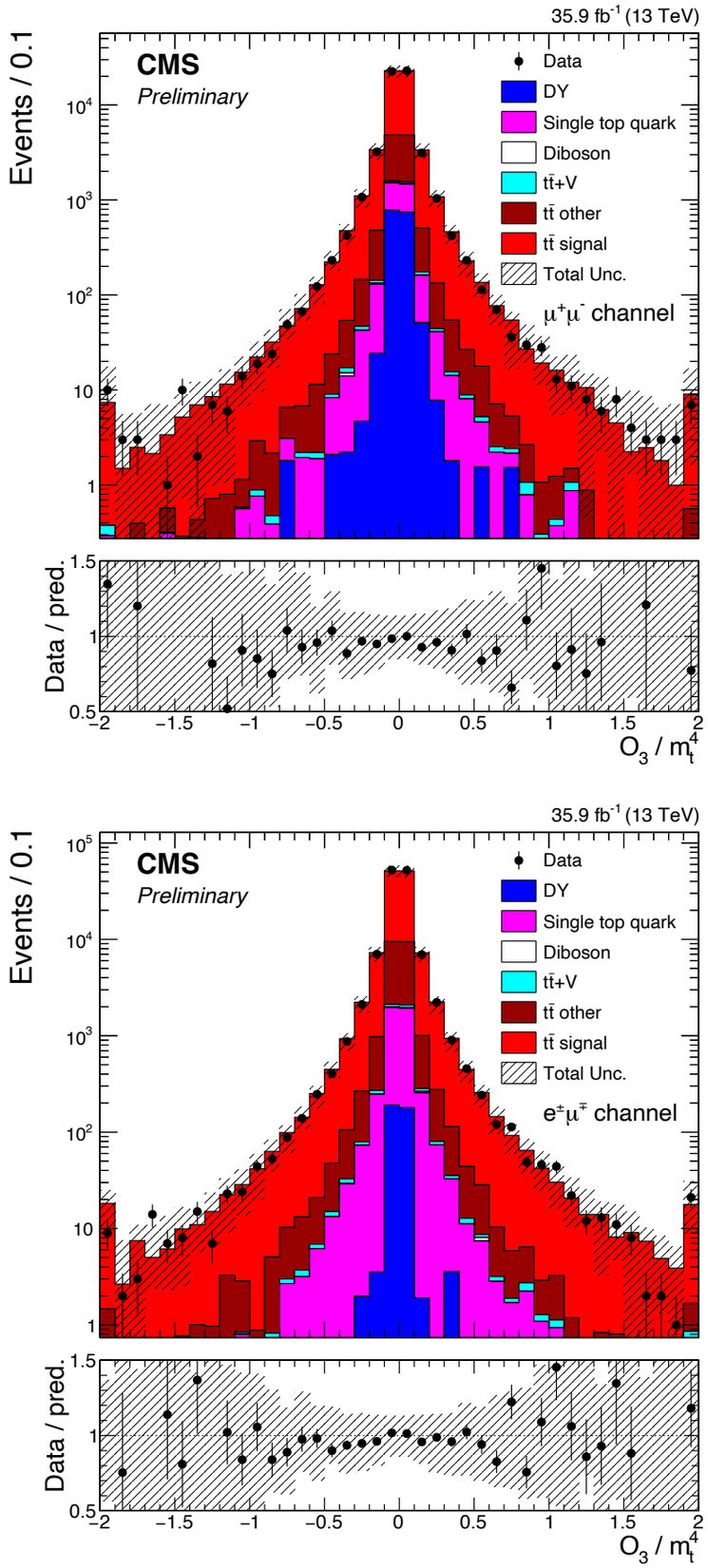


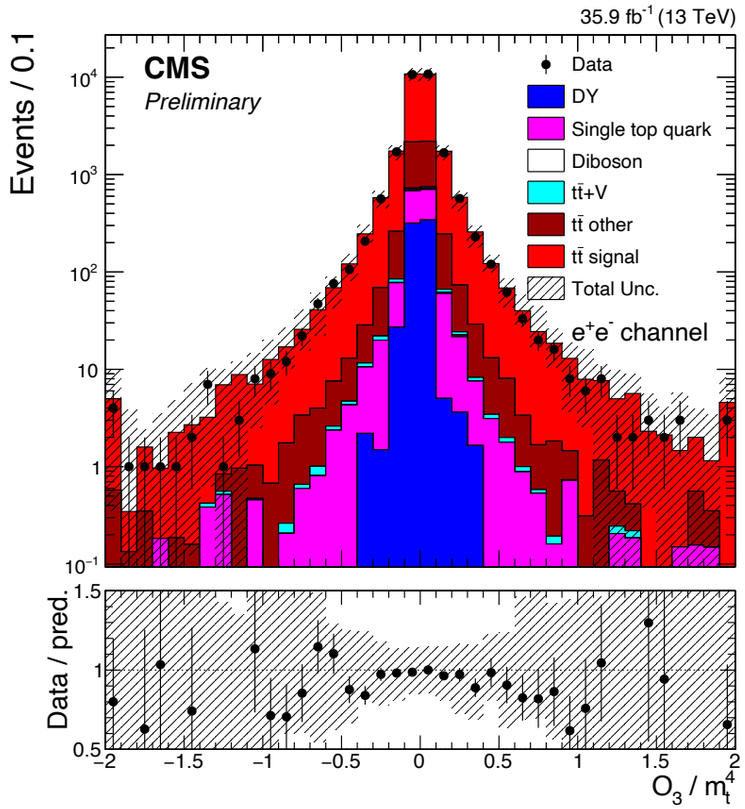
Distribution of O1





Distribution of O3





Dilution Study (Charge Mis-Id.)

For Positive Area

1. Only one mis-identified charge of lepton

(We got same sign leptons, Veto Event)

- N_p = # of events in positive Area
- f = charge mis-Id probability (Lep)
- f′ = charge mis-Id probability (An-Lep)
- $P_{mis\text{-}id} = (1-f')\times f + (1-f)\times f'$
- $N_{veto} = N_p * P_{mis\text{-}id}$
- $N_p' = N_p - N_{veto}$
- $N_{total}' = N_{total} - N_{veto}$

2. Mis-identified charge of two leptons

(Changing sign of O_i)

- N_p = # of events in positive Area
- f = charge mis-Id probability (Lep)
- f′ = charge mis-Id probability (An-Lep)
- $P_{mis\text{-}id} = f'\times f$
- $N_{p\to m} = N_p * P_{mis\text{-}id}$
- $N_p' = N_p - N_{p\to m}$
- $N_m' = N_m + N_{p\to m}$

- In case of only one charge mis-identification, if one lepton charge is mis-identified, the charge of the other lepton is correctly identified. This event contains same charge of leptons, so that it is rejected. The number of vetoed events is $N_{veto} = N_p * P_{mis\text{-}id}$
- For mis-identification of the charges of two leptons, we evaluated how many events in the positive area moved to the negative area.
- We did the same procedure for negative area.

Charge Mis-Identification

Channel	Case	Uncertainty ($\times 10^{-3}$)	
Dimuon	**Only one charge mis-identified lepton**	$\Delta A(O_1)$	$\Delta A(O_3)$
	Positive area	**0.1**	**0.1**
	Negative area	**-0.1**	**-0.1**
	Two charge mis-identified lepton		
	Positive area	**0.1**	**0.1**
	Negative area	**-0.1**	**-0.1**
Dielectron	**Only one charge mis-identified lepton**		
	Positive area	**1.0**	**1.0**
	Negative area	**-1.0**	**-1.0**
	Two charge mis-identified lepton		
	Positive area	**1.0**	**1.0**
	Negative area	**-1.0**	**-1.0**
Muon-Electron	**Only one charge mis-identified lepton**		
	Positive area	**0.4**	**0.4**
	Negative area	**-0.4**	**-0.4**
	Two charge mis-identified lepton		
	Positive area	**0.1**	**0.1**
	Negative area	**-0.1**	**-0.1**

Difference Response to b and bbar-quark jets

- Our analysis can be affected by a different response of the calorimeter to quark and antiquark jets, because the four-vectors for b/$\bar{b}$-quark jets participate in the contractions of the Levi-Civita tensor and the kinematic top quark reconstruction.

- K^- and K^+ mesons are the dominant fragments of b/$\bar{b}$-quarks, which fly to the calorimeter and interact with its absorbers. Furthermore, they have different inelastic nuclear cross sections. As a result, the different contents of K^- and K^+ mesons from the fragmentations of b/$\bar{b}$-quarks lead the calorimeter to respond to b/$\bar{b}$-quark jets differently.

- The calorimeter responses to b/bbar-quark jets are modeled with no difference in MC, while such a difference is present in data.

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

Table 3: Systematic uncertainties of asymmetries of $\mathcal{O}_1$, as detailed in the text.

Source	Uncertainty ($\times 10^{-3}$) $\mu^+\mu^-$ up	$\mu^+\mu^-$ down	e^+e^- up	e^+e^- down	$e^\pm\mu^\mp$ up	$e^\pm\mu^\mp$ down	Combined up	Combined down
Muon energy	2.3	−2.3	–	–	0.1	−0.1	0.5	−0.5
Electron scale and smearing	–	–	1.2	−1.2	0.2	−0.2	0.3	−0.3
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
Limited number of simulated BG events	2.3	−2.3	2.9	−2.9	0.6	−0.6	0.7	−0.7
ME–PS matching	0.8	−0.8	0.8	−0.8	0.3	−0.3	0.4	−0.4
Color reconnection	1.0	−1.0	1.9	−1.9	1.6	−1.6	1.5	−1.5
Underlying event	1.4	−1.4	0.6	−0.6	1.4	−1.4	1.4	−1.4
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
Hadronization	1.7	−1.7	2.0	−2.0	0.6	−0.6	0.9	−0.9
Charge misidentification	0.1	−0.1	0.8	−0.8	0.4	−0.4	0.3	−0.3
Total systematic uncertainty	5.0	−5.0	5.6	−5.6	2.6	−2.6	2.8	−2.8

Table 4: Systematic uncertainties of asymmetries of $\mathcal{O}_3$, as detailed in the text.

Source	Uncertainty ($\times 10^{-3}$) $\mu^+\mu^-$ up	$\mu^+\mu^-$ down	e^+e^- up	e^+e^- down	$e^\pm\mu^\mp$ up	$e^\pm\mu^\mp$ down	Combined up	Combined down
Muon energy	1.0	−1.0	–	–	0.2	−0.2	0.3	−0.3
Electron scale and smearing	–	–	1.1	−1.1	0.2	−0.2	0.2	−0.2
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
Limited number of simulated BG events	2.3	−2.3	2.9	−2.9	0.6	−0.6	0.7	−0.7
ME–PS matching	1.5	−1.5	1.4	−1.4	0.7	−0.7	0.9	−0.9
Color reconnection	0.9	−0.9	3.8	−3.8	1.0	−1.0	1.1	−1.1
Underlying event	1.0	−1.0	0.9	−0.9	1.1	−1.1	1.0	−1.0
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
Hadronization	0.2	−0.2	0.5	−0.5	0.3	−0.3	0.3	−0.3
Charge misidentification	0.1	−0.1	0.8	−0.8	0.4	−0.4	0.3	−0.3
Total systematic uncertainty	3.5	−3.5	6.0	−6.0	2.0	−2.0	2.2	−2.2

BLUE method is used to combine the asymmetries for threes channels

Limited statistics of background (BG) models

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

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

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

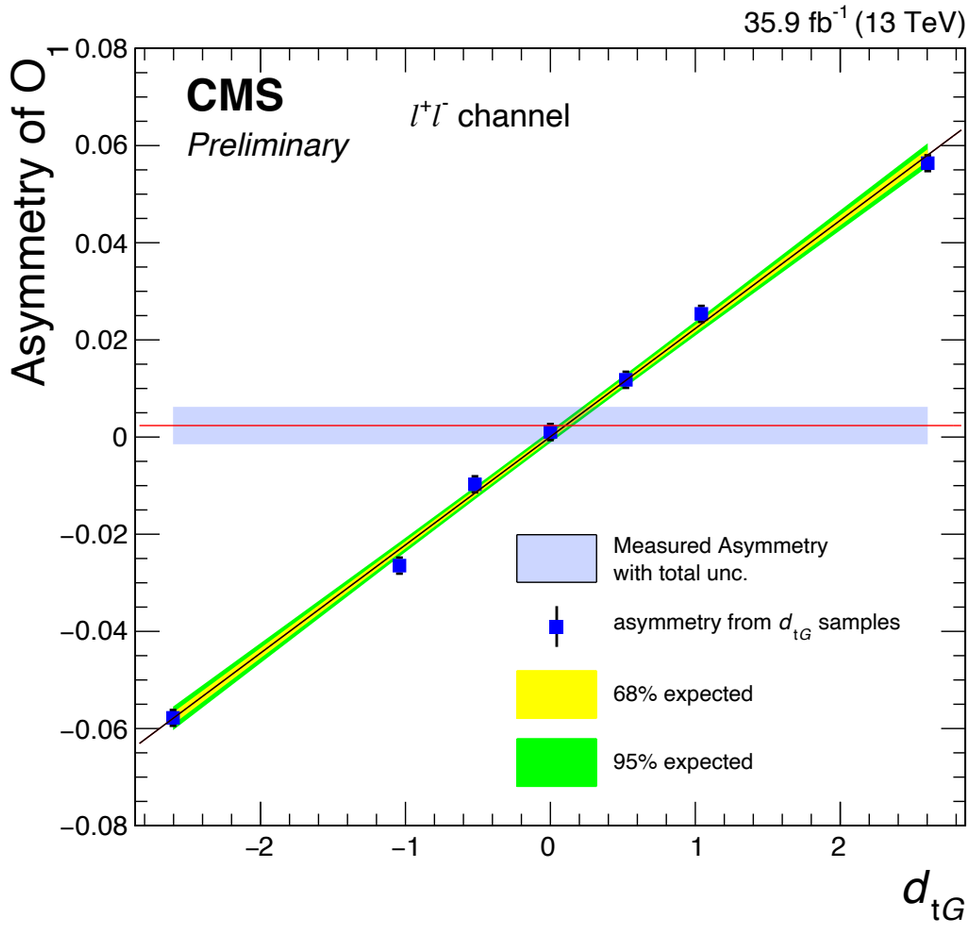
Gaussian constraints.

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

$$Gaus(N_{neg}^{bkg} | \mu_{neg}, \sigma_{neg}) Gaus(N_{pos}^{bkg} | \mu_{pos}, \sigma_{pos})$$

- 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.

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

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

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

a , b can be obtained from linear fitting.

Comparison Result with Spin Correlation

TOP-18-007 (1-sigma unc.)

Obs	d_{tG}	$\hat{d}_t$
O1	0.103+-0.175	0.006 +- 0.011
O3	-0.002+- 0.163	-0.000 +- 0.010

TOP-18-006 (95% CL.) [1]

Coupling	95% CL	Theoretical unc.	χ^2	Coefficients
$\hat{\mu}_t$	$-0.014 < \hat{\mu}_t < 0.004$	± 0.001	7	C_{kk}, C_{nn}, $C_{rk}+C_{kr}$, D
$\hat{d}_t$	$-0.020 < \hat{d}_t < 0.012$	—	9	B_2^r, B_1^n, $C_{nr}-C_{rn}$, $C_{nk}-C_{kn}$
$\hat{c}_{--}$	$-0.040 < \hat{c}_{--} < 0.006$	± 0.001	7	B_2^r, B_1^n, $C_{nr}-C_{rn}$, $C_{nk}-C_{kn}$
$\hat{c}_{-+}$	$-0.009 < \hat{c}_{-+} < 0.005$	—	11	B_1^n, B_2^n, B_1^{r*}, $C_{nk}+C_{kn}$
$\hat{c}_{VV}$	$-0.011 < \hat{c}_{VV} < 0.042$	± 0.004	7	C_{kk}, C_{nn}, $C_{rk}+C_{kr}$, D
$\hat{c}_{VA}$	$-0.044 < \hat{c}_{VA} < 0.027$	± 0.003	9	B_2^k, B_2^r, C_{kk}, $C_{nr}+C_{rn}$
$\hat{c}_{AV}$	$-0.035 < \hat{c}_{AV} < 0.032$	± 0.001	6	B_1^{k*}, B_2^{k*}, B_1^{r*}, B_2^{r*}
$\hat{c}_1$	$-0.09 < \hat{c}_1 < 0.34$	± 0.04	7	C_{kk}, C_{nn}, $C_{rk}+C_{kr}$, D
$\hat{c}_3$	$-0.35 < \hat{c}_3 < 0.21$	± 0.02	9	B_2^k, B_2^r, C_{kk}, $C_{nr}+C_{rn}$
$\hat{c}_1-\hat{c}_2+\hat{c}_3$	$-0.17 < \hat{c}_1-\hat{c}_2+\hat{c}_3 < 0.15$	± 0.01	6	B_1^{k*}, B_2^{k*}, B_1^{r*}, B_2^{r*}

TOP-18-007 (95% CL.)

CADI	(Observable)	$\hat{d}_t$
TOP-18-007	O1	$-0.014 < \hat{d}_t < 0.027$
	O3	$-0.019 < \hat{d}_t < 0.019$

CADI	$\hat{d}_t$
TOP-18-006	$-0.020 < \hat{d}_t < 0.012$

Our results are consistent with TOP-18-006.

Our Intervals of $\hat{d}_t$ are lager than TOP-18-006 (about 20~30%).

[1] http://dx.doi.org/10.1103/PhysRevD.100.072002