Search for CP violation in top quark pair events

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Introduction

- Why CP violation (CPV) ?

  - it could bring new physics that may explain asymmetry of matter over anti-matter in our universe

- CPV in Standard Model (SM) effects can be accommodated is in the weak interactions of quarks and leptons (Cabibbo–Kobayashi–Maskawa matrix)

- The first experimental observation is a non-vanishing rate for the decay $K_L \to 2\pi$ (Christenson, Cronin, Fitch and Turlay, 1967)

$$Br(K_L \to 2\pi) = 3.00 \pm 0.04 \times 10^{-3}$$

- Barbar exp., Belle exp, LHCb measured CPV (CP asymmetry)

  eg. at LHCb, measured "$A_{cp} = D^0 \to K_S^0 K_S^0$ decay" in 2021 (Phys. Rev. D **104**, L031102)

- However, the level of CPV in the SM is insufficient to accommodate the observed matter-antimatter asymmetry in the universe

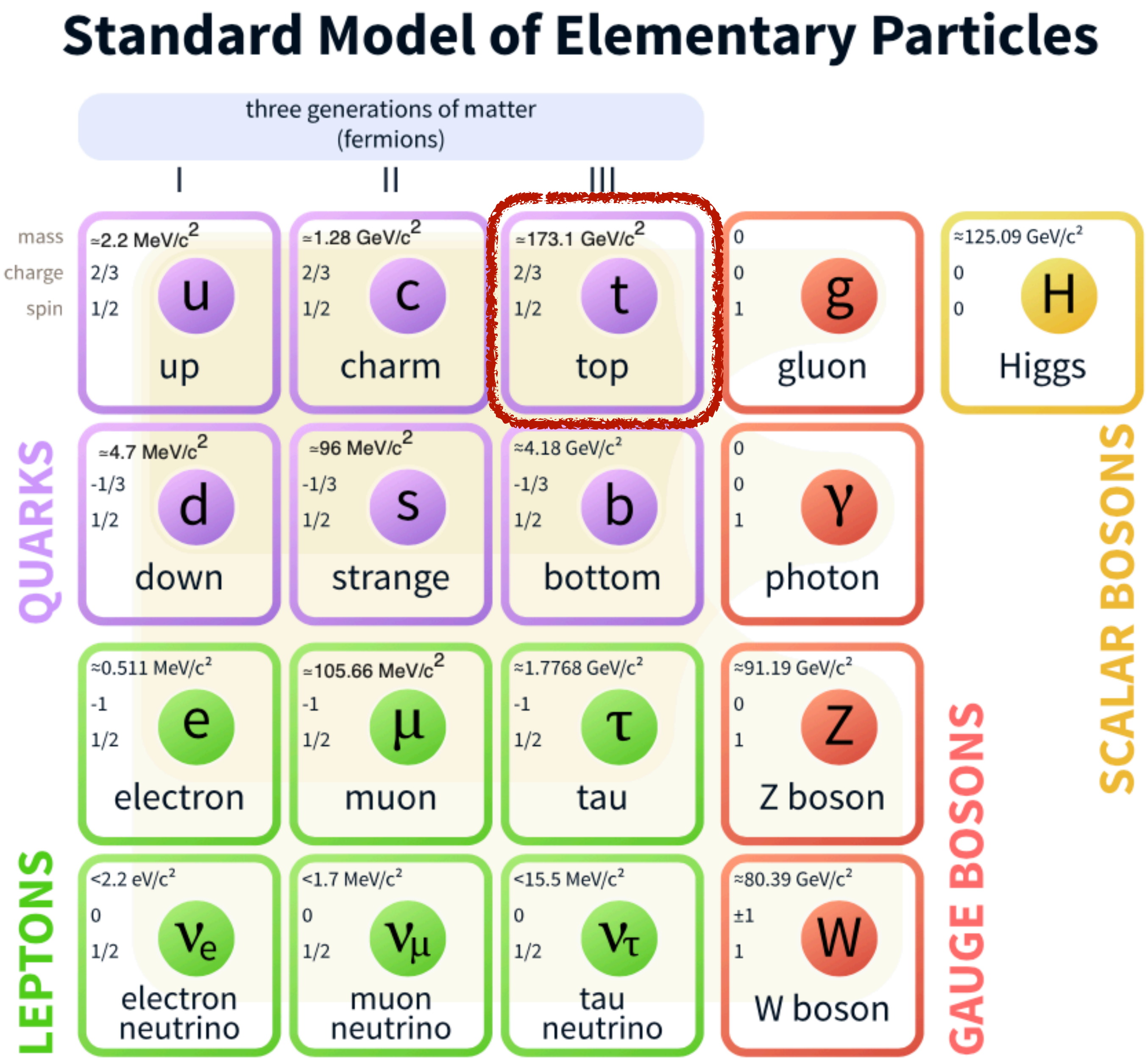
Introduction

- In the standard model, the CPV is not large enough, so different CPV sources and models are needed
  - Multi-Higgs doublet models
  - Supersymmetric models
  - Top dipole moments (CEDM)
  - etc…
- Within the CMS (especially Top group), efforts for CPV are going a lot

Title	Description	Journal
Search for CP violating top quark couplings in pp collisions at sqrt(s) = 13 TeV	Asymmetry & CEDM	https://arxiv.org/abs/2205.07434
Search for CP violation using ttbar events in the lepton+jets channel in pp collisions at sqrt(s) = 13 TeV	Asymmetry	https://arxiv.org/abs/2205.02314
Measurement of the top quark polarization and ttbar spin correlations using dilepton final states in proton-proton collisions at sqrt(s) = 13 TeV	CMDM & CEDM (EFT model)	PRD 100 (2019) 072002
Measurements of ttbar Spin Correlations and Top-Quark Polarization Using Dilepton Final States in pp Collisions at sqrt(s) = 8 TeV	CMDM & CEDM (EFT model)	PRD 93 (2016) 052007

Higgs with CPV are listed in backup slide

Introduction TOP Quarks



Standard Model of Elementary Particles

three generations of matter (fermions)

	I	II	III		
mass charge spin					
QUARKS	≈2.2 MeV/c^2 2/3 1/2 u up	≈1.28 GeV/c^2 2/3 1/2 c charm	≈173.1 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs
QUARKS	≈4.7 MeV/c^2 -1/3 1/2 d down	≈96 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≈0.511 MeV/c^2 -1 1/2 e electron	≈105.66 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	
				GAUGE BOSONS	

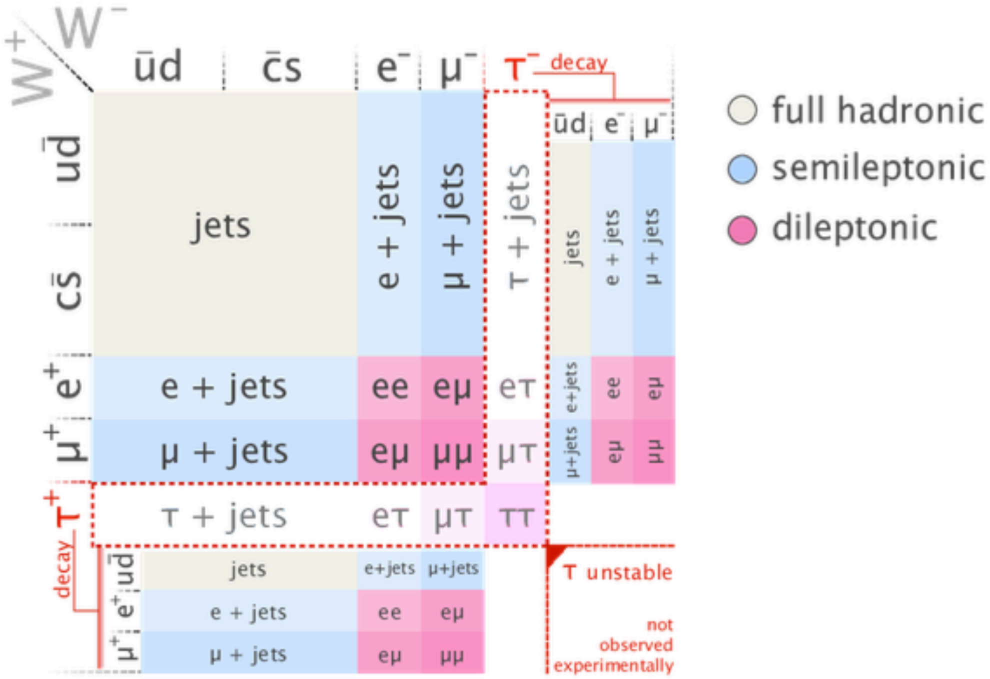
- In the SM, the top quark is the heaviest particle and it was discovered in 1995 by the D0 and CDF collaborations at the Tevatron

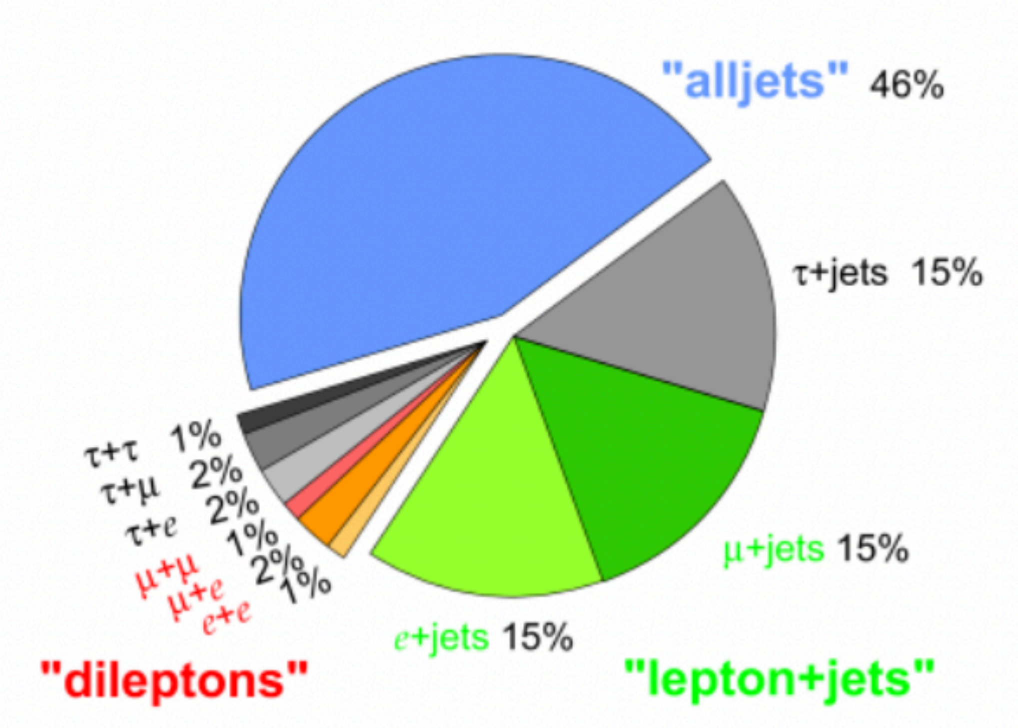
- Since the top quark has the heaviest mass, it can decay before its hadronization process

- It allows us to measure properties of the bare quark through the decay products

Introduction TOP Quarks

- According to CKM matrix, the top quark decays almost exclusively to a b-quark and a W boson, as the value of $|V_{tb}|$ is almost 1



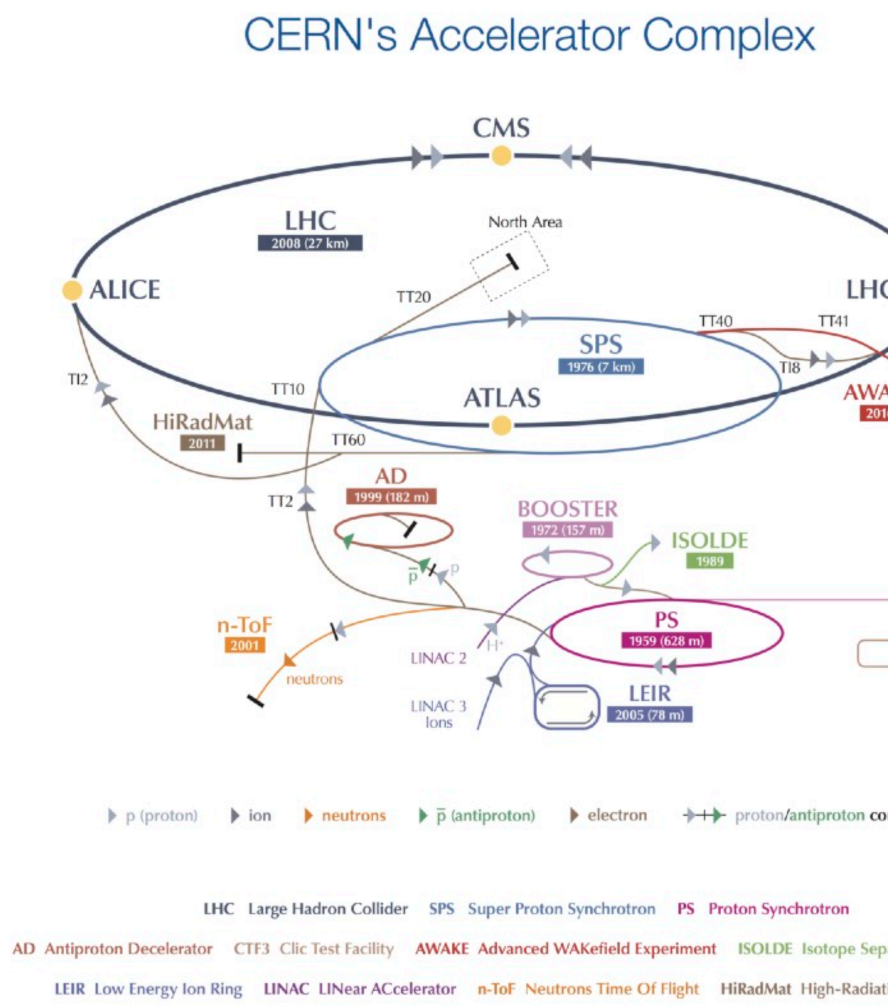


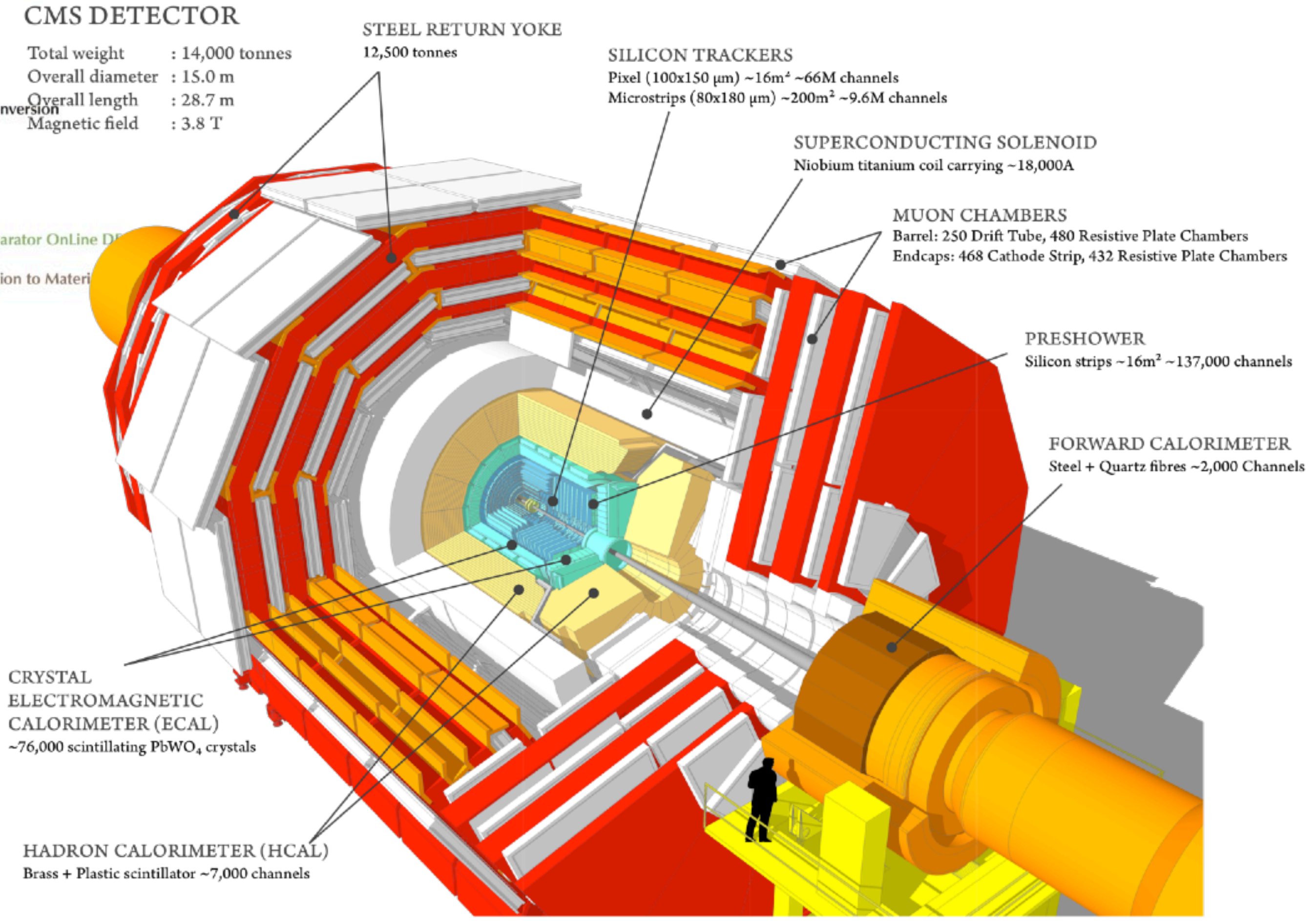
- Full hadronic channel : W bosons from ttbar are decaying to quark-antiquark pairs(branching ratio :45.7%)

- Semi leptonic channel : One W boson decays lepton and neutrino, another one decays hadronically(branching ratio : about 43.8%)

- Dileptonic channel W bosons are decaying to leptons and neutrinos(branching ratio : about 10.5%)

Overview of LHC and CMS





CEDM in Top quark (i)

- CPV for top quark in SM

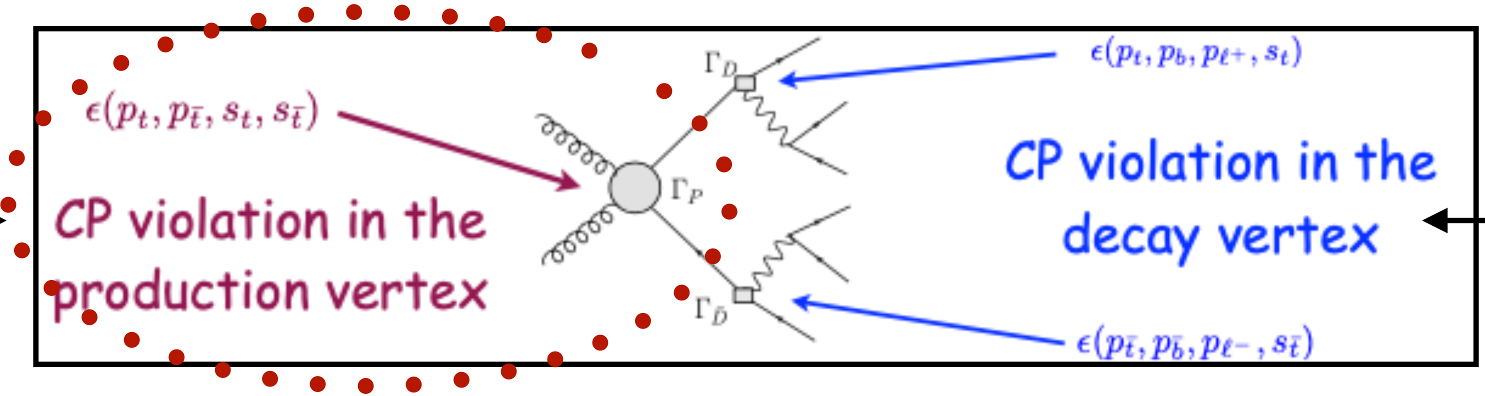
  - In the SM, CPV in the production and decay of top quark-antiquark (tt) pairs is predicted to be very small (if find out CPV in top quark, it would be evidence of new physics)

- CEDM (chromoelectric dipole moment)

  - CP violating new physics from top quarks can be occurred in the production and/or decay vertices

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

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



$\epsilon(p_t, p_{\bar{t}}, s_t, s_{\bar{t}})$

CP violation in the production vertex

CP violation in the decay vertex

$\epsilon(p_t, p_b, p_{\ell^+}, s_t)$

$\epsilon(p_{\bar{t}}, p_{\bar{b}}, p_{\ell^-}, s_{\bar{t}})$

$\mathcal{O}_6 = \epsilon(P, b - \bar{b}, \ell^+, \ell^-)$

CEDM

$$\mathcal{L}_{cdm} = -ig_s \frac{\tilde{d}}{2} \bar{t} \sigma_{\mu\nu} \gamma_5 t G^{\mu\nu}$$

$\tilde{d}$ is CEDM (CP-odd)

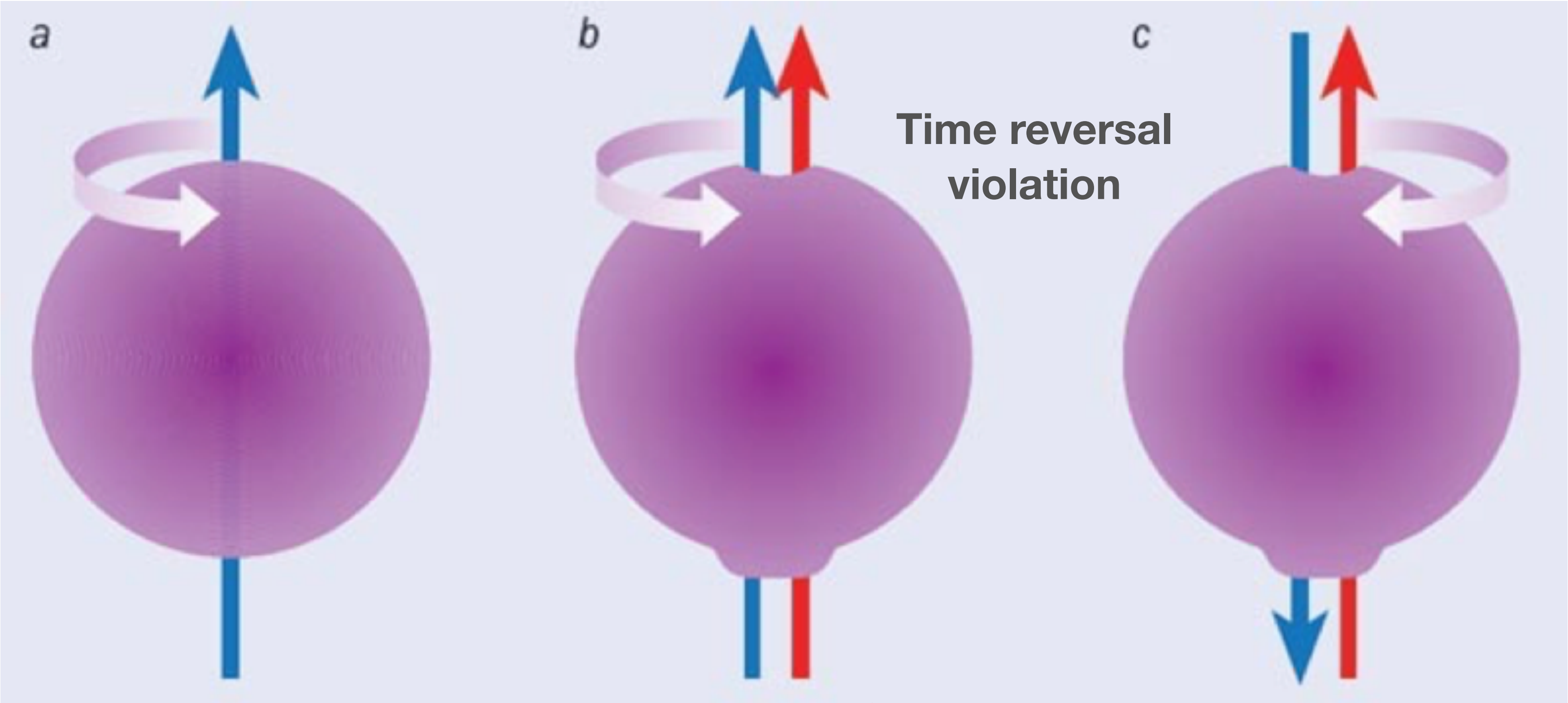
CEDM in Top quark (ii)

- Electrical dipole moment of the elementary particles shows electrical can shows the CP and T violations

  - For a spin 1/2 particle, the spin indicates an orientation

  - Then an electric dipole moment is a charge polarization in the direction of the spin

  - T reverses the spin but does not reverse the polarization. Then an electric dipole moment is a T-violating effect



↑ : Magnetic Dipole Moment ↑ : Electric Dipole Moment

- The upper limits on the electric dipole moments of the electron and neutrons

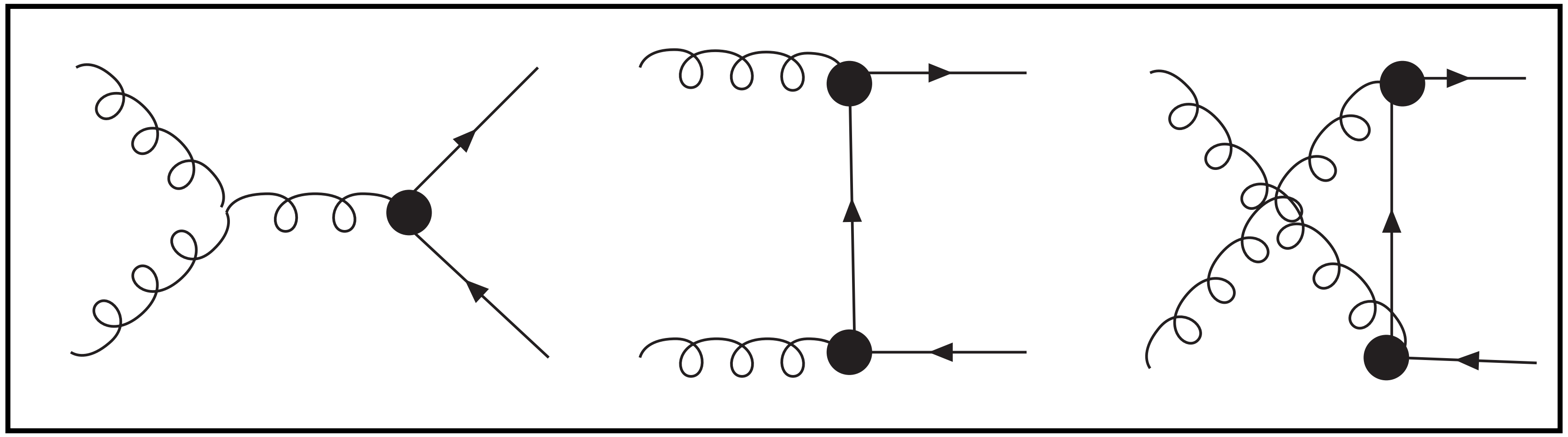
$$\boxed{\begin{array}{c} d_n < 0.3 \times 10^{-25} e\text{-}cm \\ d_e < 8.7 \times 10^{-29} e\text{-}cm \end{array}}$$

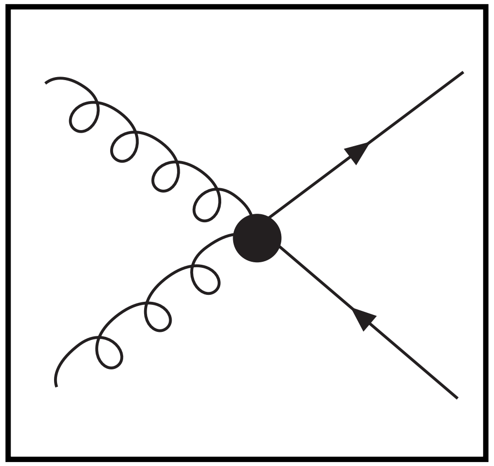
CEDM in Top quark (iii)

- We first study CP violation in the production vertex, taking the decay vertices to proceed as in the standard model

$$\mathcal{L}_{cdm} = -ig_s\frac{\boxed{\tilde{d}}}{2}\bar{t}\sigma_{\mu\nu}\gamma_5 t G^{\mu\nu}$$

- This Lagrangian modifies the standard model top-quark couplings to gluons as follows





$$gt\bar{t} \;\rightarrow\; -ig_s\frac{\lambda_a}{2}\left(\gamma_\mu + \boxed{\tilde{d}}\sigma_{\mu\nu}q^\nu\gamma_5\right)$$

$$ggt\bar{t} \;\rightarrow\; i\,\pi\,\alpha_s\,[\lambda^b,\lambda^c]\boxed{\tilde{d}}\sigma_{\mu\nu}\gamma_5.$$

https://arxiv.org/abs/0807.1295v3

CEDM in Top quark (iiii)

- Top-quark anomalous couplings

  - arise from the interference between the SM amplitude and the CP violating anomalous coupling :

$$
\begin{aligned}
|\mathcal{M}|^2_{CP} \;=\;& C_1(s,t,u)\, q\cdot(p_{\bar t}-p_t)\,\epsilon(p_t,p_{\bar t},p_D,p_{\bar D}) \\
&+\; C_2(s,t,u)\,\left(P\cdot p_t\,\epsilon(p_D,p_{\bar D},p_{\bar t},q)+P\cdot p_{\bar t}\,\epsilon(p_D,p_{\bar D},p_t,q)\right) \\
&+\; C_3(s,t,u)\,\left(P\cdot p_D\,\epsilon(p_{\bar D},p_t,p_{\bar t},q)+P\cdot p_{\bar D}\,\epsilon(p_D,p_t,p_{\bar t},q)\right)
\end{aligned}
$$

$P \equiv p_1 + p_2 \quad q \equiv p_1 - p_2 \longrightarrow$ the sum and difference of parton four-momenta

- example of di-muon channel :

$$p_D \to p_{\mu^+},\;\; p_{\bar D} \to p_{\mu^-}$$

$$\downarrow$$

$$\boxed{|\mathcal{M}|^2_{CP} \;=\; C_1(s,t,u)\,\mathcal{O}_1 \,+\, C_2(s,t,u)\,\mathcal{O}_2' \,+\, C_3(s,t,u)\,\mathcal{O}_3'}$$

$$
\begin{aligned}
\mathcal{O}_1 &= \epsilon(p_t,p_{\bar t},p_{\mu^+},p_{\mu^-}) \\
\mathcal{O}_2' &= (t-u)\,\epsilon(p_{\mu^+},p_{\mu^-},P,q) \\
\mathcal{O}_3' &= (t-u)\,\left(P\cdot p_{\mu^+}\,\epsilon(p_{\mu^-},p_t,p_{\bar t},q)+P\cdot p_{\mu^-}\,\epsilon(p_{\mu^+},p_t,p_{\bar t},q)\right)
\end{aligned}
$$

Physics Observable & Asymmetry

- Physics Observable

-Theory paper: 10.1103/PhysRevD.93.014020

- TOP-18-007 paper (Accepted by JHEP): https://arxiv.org/abs/2205.07434

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

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

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

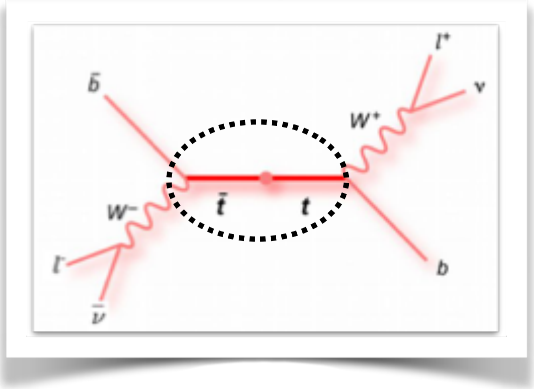
- Asymmetries :

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

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

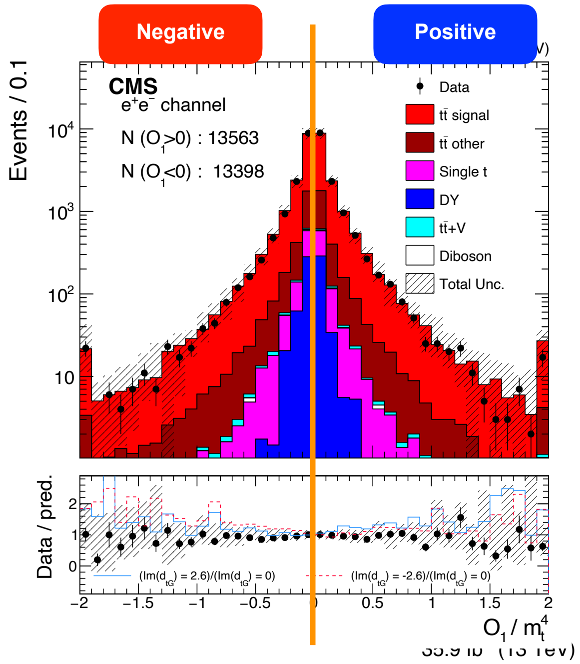
Analysis Procedure : TOP-18-007

- Selection of events top pair events in the di-lepton final state

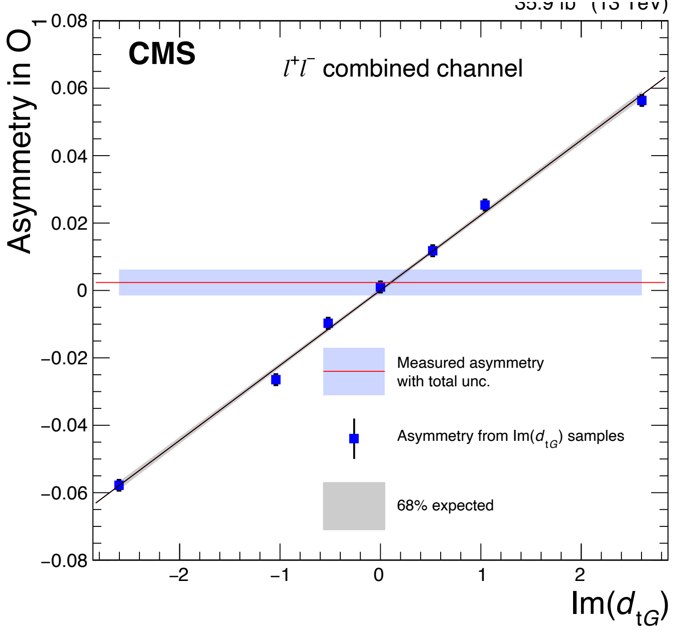


In the analysis, CMS 2016 data set(35.9 fb^{-1}) is used

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



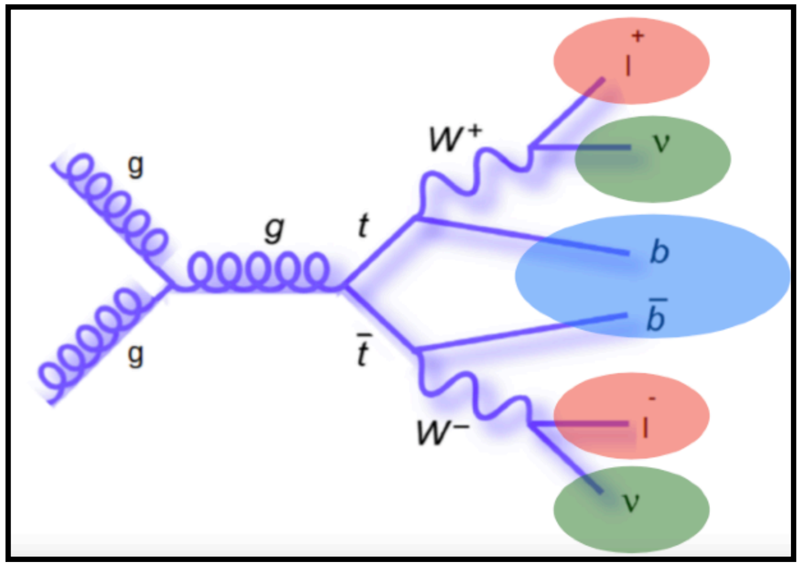
- Extraction of CEDM (O1 & O3)
  - Using the generated CP-violation events



Signals & Backgrounds

- Signal : $t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)$

  - 2 charged leptons (e^+e^- or $e^\pm\mu^\mp$ or $\mu^+\mu^-$) originating from W boson decays, but not from tau decays
  - 2 jets originating from the hadronization of b-quarks (b-jets)
  - large MET from undetected neutrinos



- Main backgrounds :
  - ttbar events with leptonically decaying tau leptons (ttbar other)
  - single top quarks produced in association with a W boson (tW)
  - Z/gamma* bosons produced with additional jets (Z+jet)
    - estimated using data driven method (everything else using simulation)

- Other backgrounds :
  - W boson production with additional jets (W+jets)
  - diboson events (WW, ZZ,WZ)
  - production of ttbar in association with W or Z boson (ttbar+W/Z)

Object Selection

- Object Selection

Muon
Tight ID
PFIso < 0.15
Leading Lepton pT > 25 GeV & Sub Leading Lepton pT > 20 GeV, |η| < 2.4
Rochester Correction

Electron
Cut-based Tight ID
Leading Lepton pT > 25 GeV & Sub Leading Lepton pT > 20 GeV, |η| < 2.4
Veto of transition region 1.4442 < | Super Cluster η | < 1.5660
Scale / Smear Correction

Jet
PFJetID Loose
pT > 30 GeV, |η| < 2.4
JEC (Summer16_23Sep2016V4)
JER (Spring16_25nsV10a (Spring16_25nsV10(central) + Summer16_25nsV1(systematic))

B-Tagging
CombinedSecondaryVertexv2
Medium Working Point (disc.> 0.8484)

MET
Type-1 Corrected MET
Phi Correction

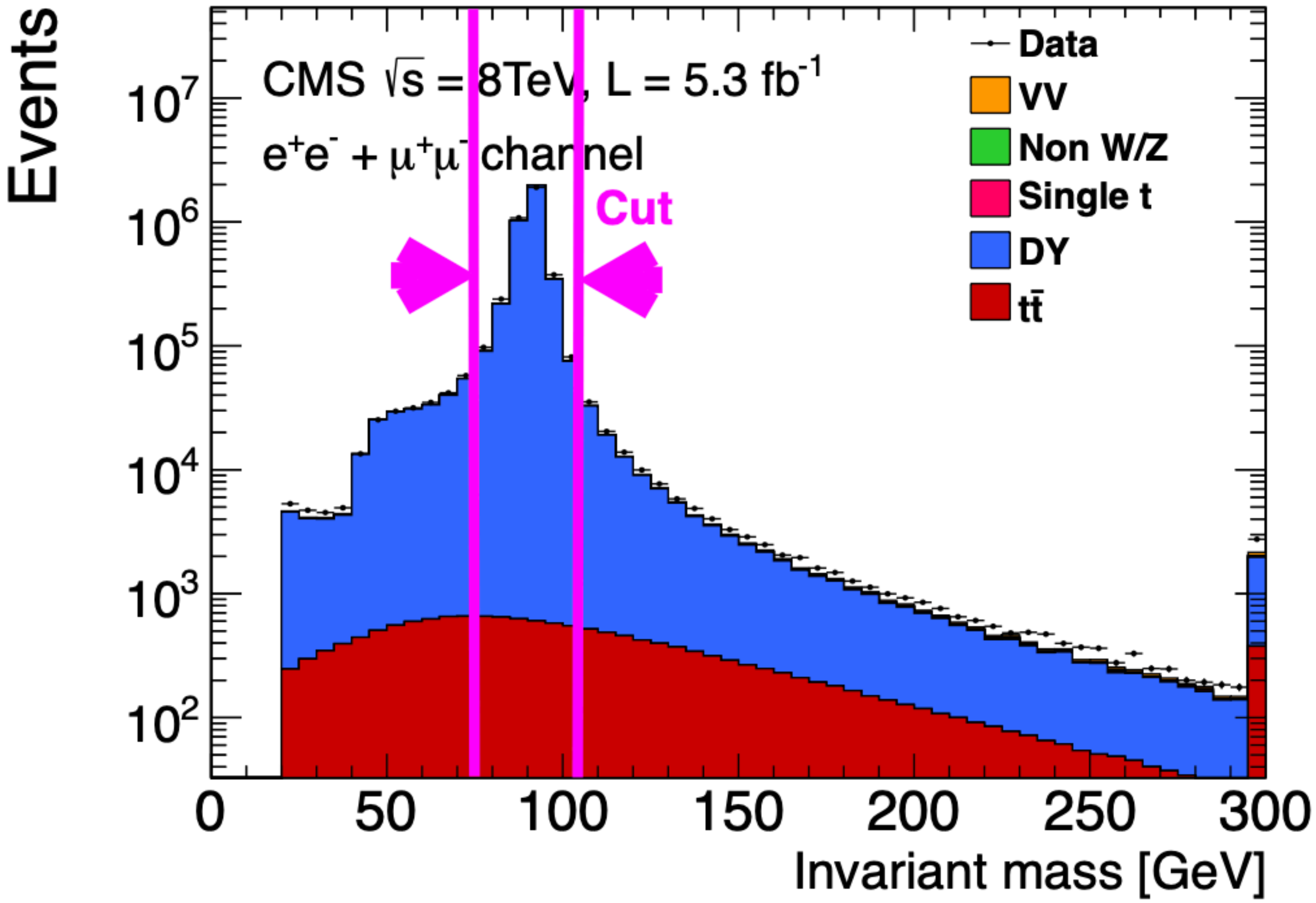
Event Selection

- **Event Selection**

Cut flow	Dimuon	Dielectron	Muon-electron
Trigger & MET Fileters [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 ≥ 2	O	O	O
MET > 40 GeV	O	O	-
Num. b-tagged Jet ≥ 1 (CSVv2, Medium working point)	O	O	O
Top Reconstruction (Kinematic solver)	O	O	O

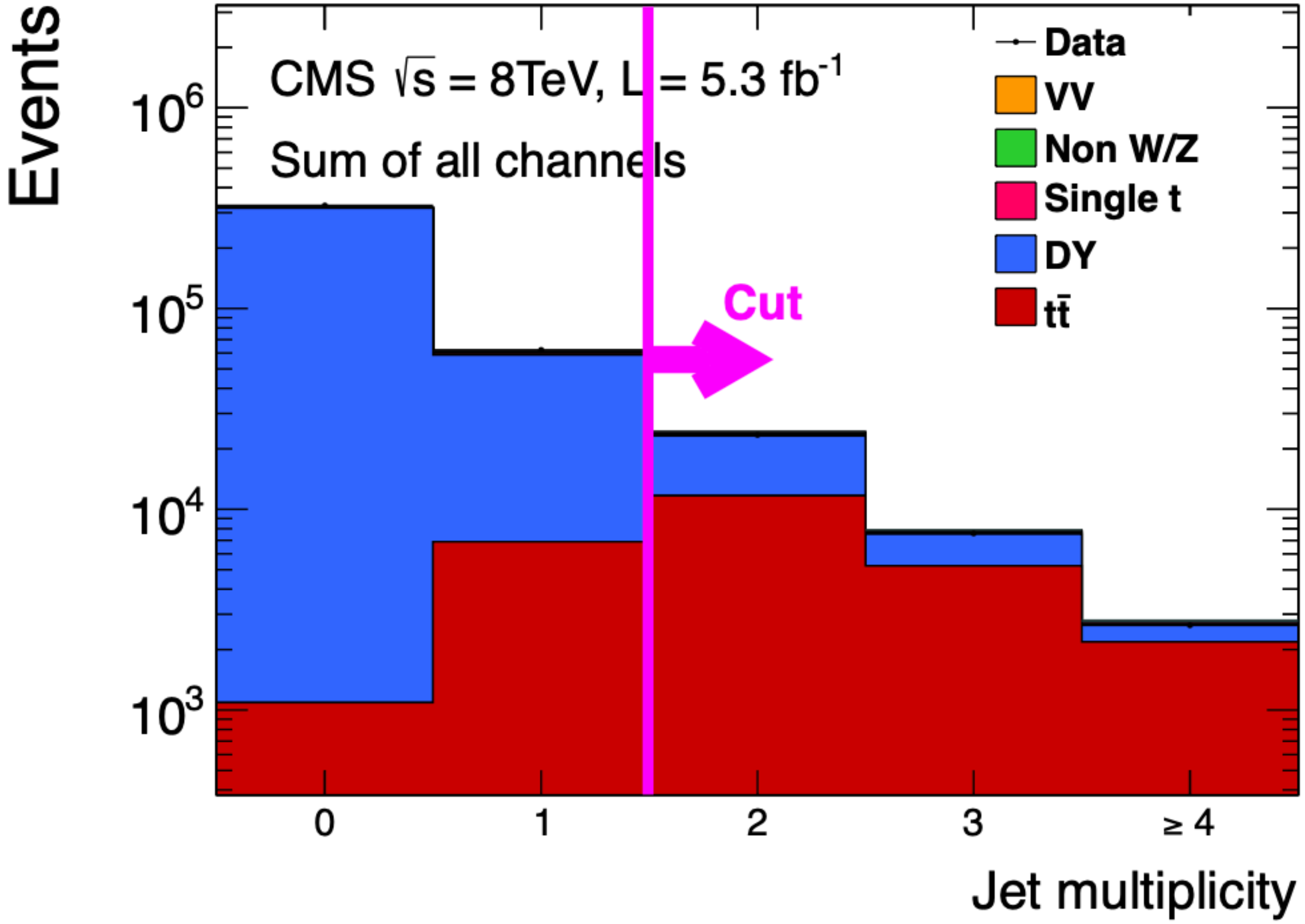
Event Selection

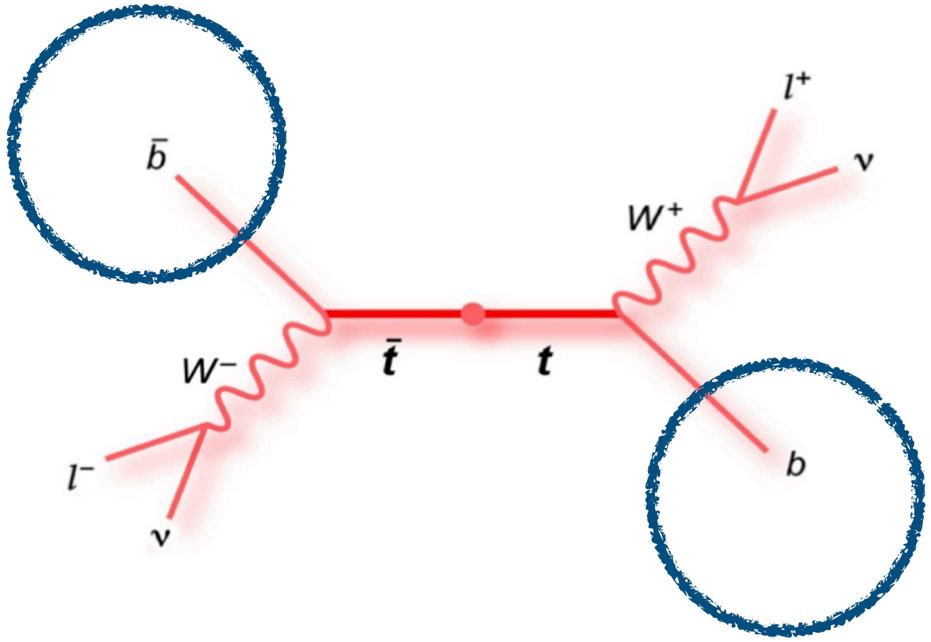
- Events with $76 < m_{ll} < 106\text{GeV}$ are rejected for the e^+e^- and $\mu^+\mu^-$ channels. This cut rejects around 90% of Z+jets events in those channels



Event Selection

- The $t\bar{t}$ final state includes two jets from the b quark hadronization

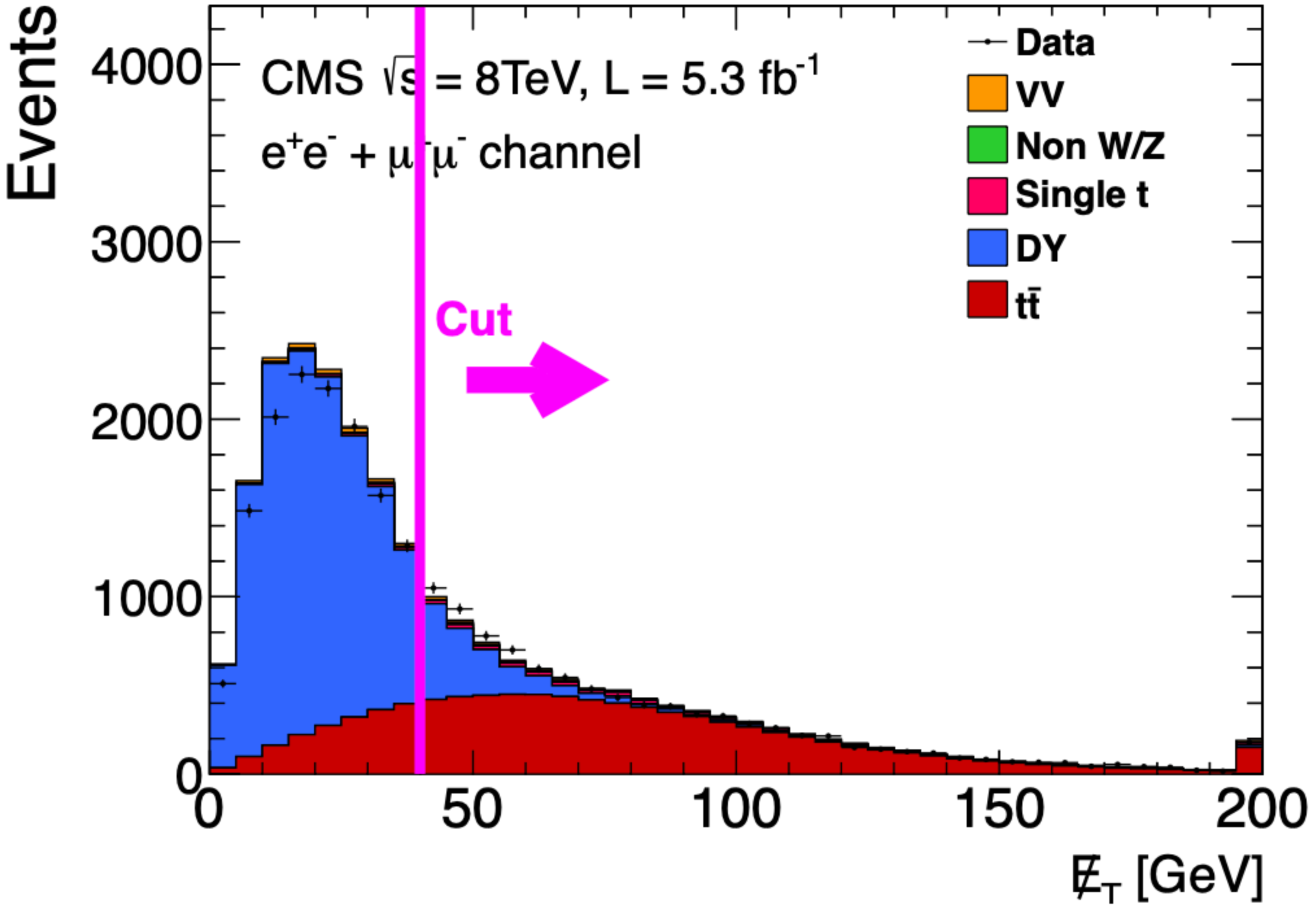




Event Selection

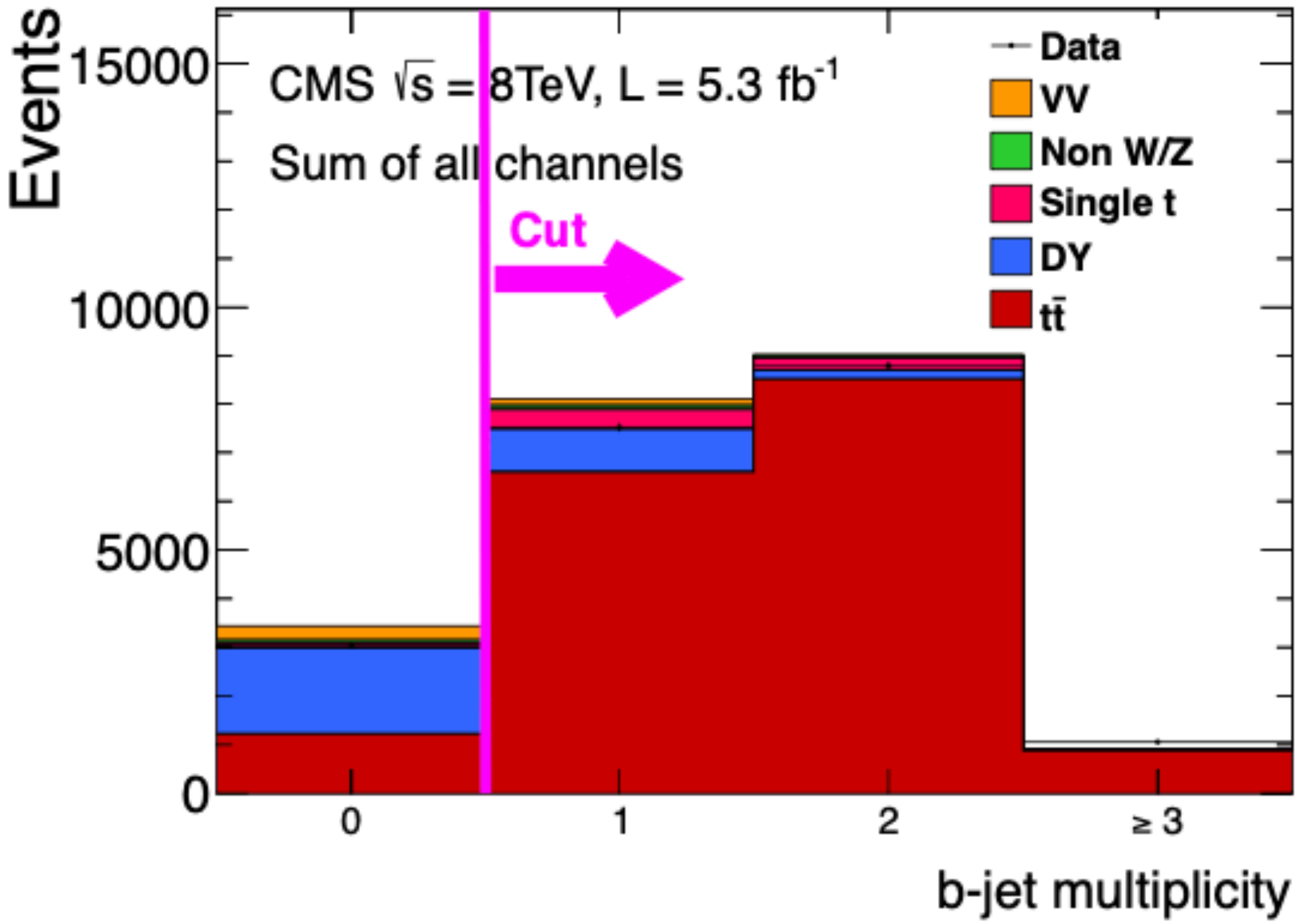
- Missing transeverse energy(MET) > 40GeV for the e^+e^- and $\mu^+\mu^-$ channels
  - This MET cut rejects more than 65% MC Drell-Yan events with a loss of signal efficiency of about 10% giving the best compromise between the signal efficiency and the signal over signal plus background

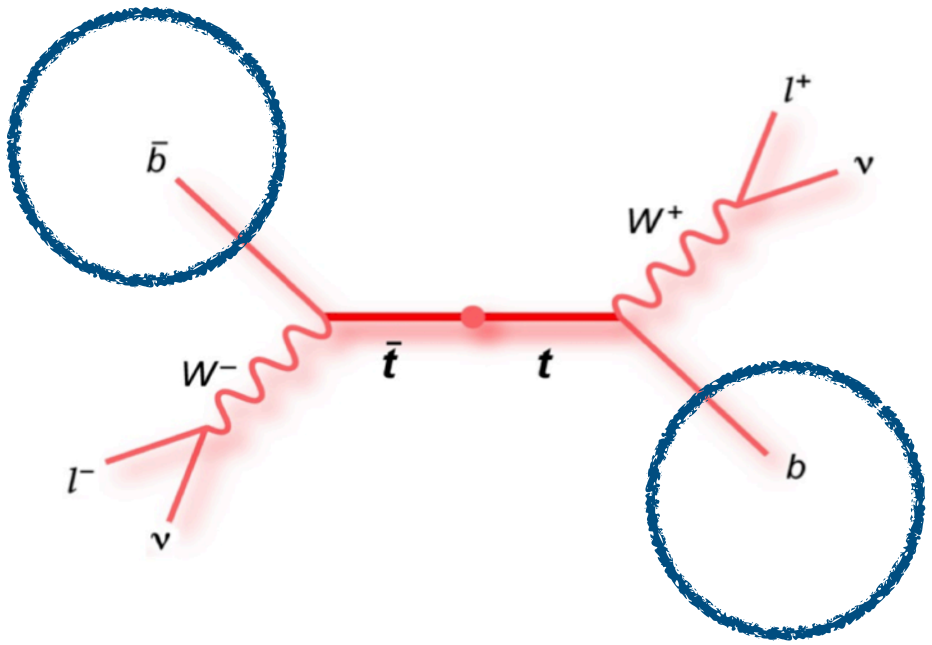
- This requirement is not applied in the μe channel



Event Selection

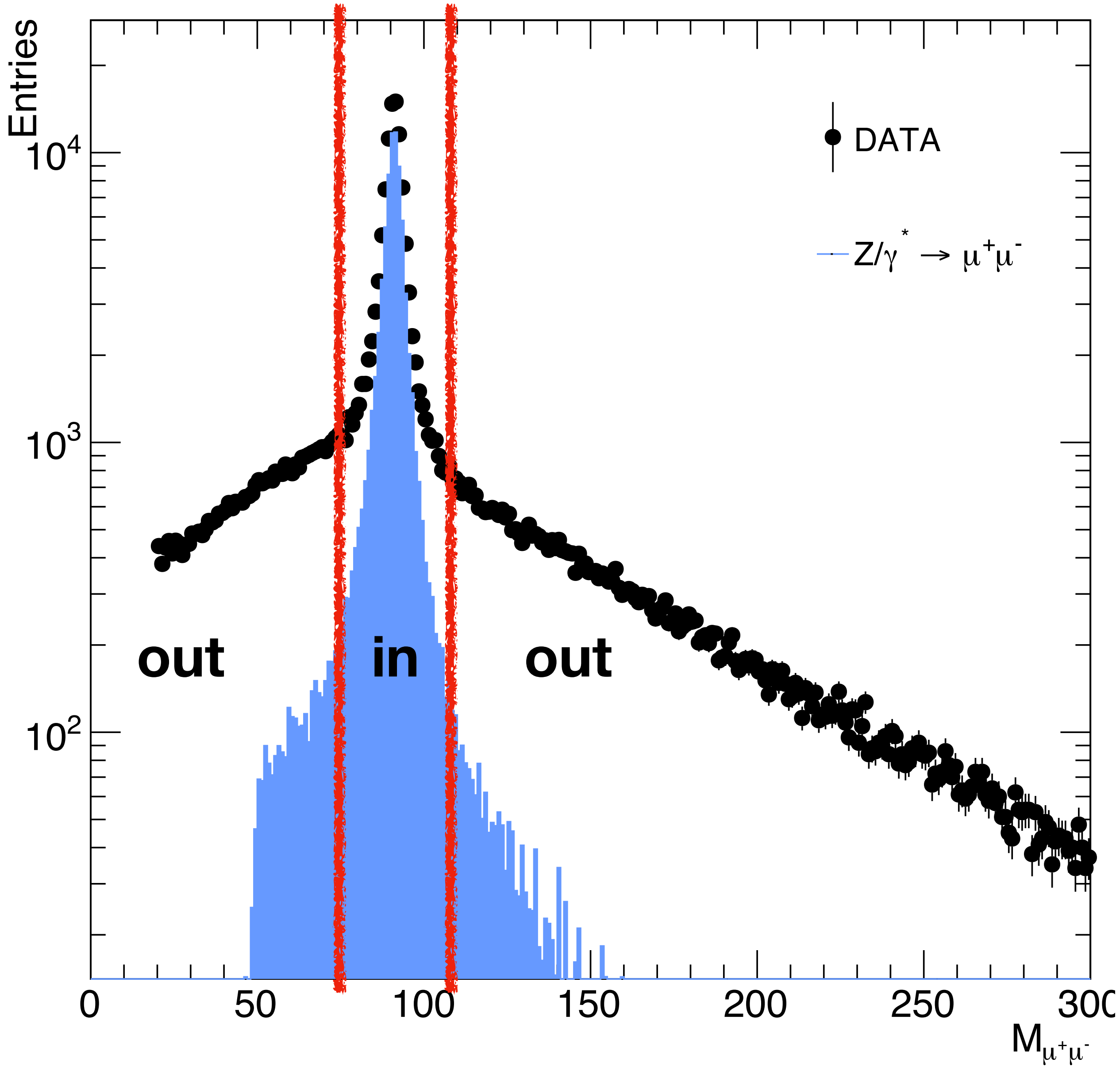
- To require at least one b-tagged jet is enough to reject most of the remaining Drell-Yan background maintaining a high number of signal events





Determination of Drell-Yan Background

- To determine DY background, we follow the method (Rout/in) suggested in [1,2,3].



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

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

- Since physics observables need the kinematic information of top quarks, we should reconstruct top quarks.

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

- In these equations, Missing Transverse Momentum is the important kinematic constraint to obtain the momenta of two neutrinos.

$$\boxed{\begin{aligned} \not{E}_x &= p_{\nu_x} + p_{\bar{\nu}_x} \\ \not{E}_y &= p_{\nu_y} + p_{\bar{\nu}_y} \end{aligned}}$$

$$\begin{aligned} E_\nu^2 &= p_{\nu_x}^2 + p_{\nu_y}^2 + p_{\nu_z}^2 + m_\nu^2 \\ E_{\bar{\nu}}^2 &= p_{\bar{\nu}_x}^2 + p_{\bar{\nu}_y}^2 + p_{\bar{\nu}_z}^2 + m_{\bar{\nu}}^2 \end{aligned}$$

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

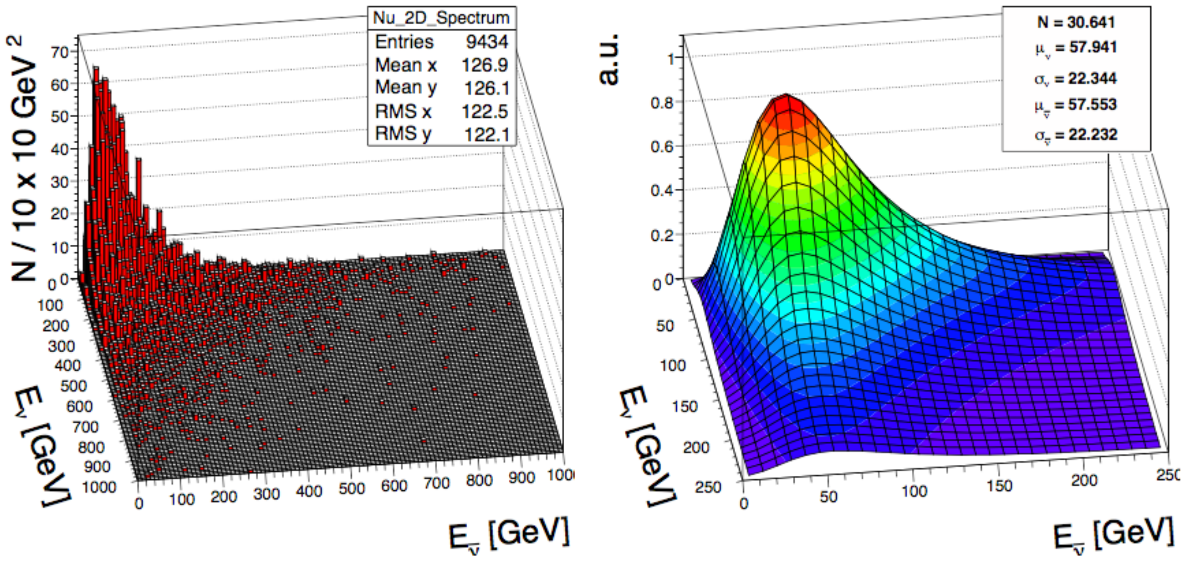
Reconstruction of Top Quarks

Standard Kinematic Solver

1. Input Object :
reconstructed jets, leptons, MET

2. Top mass Scan:
100-500 GeV

3. Weighted average:
Weight-> neutrino energy(gen.) 2D.
Find best solution.



Updated Kinematic Solver

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.

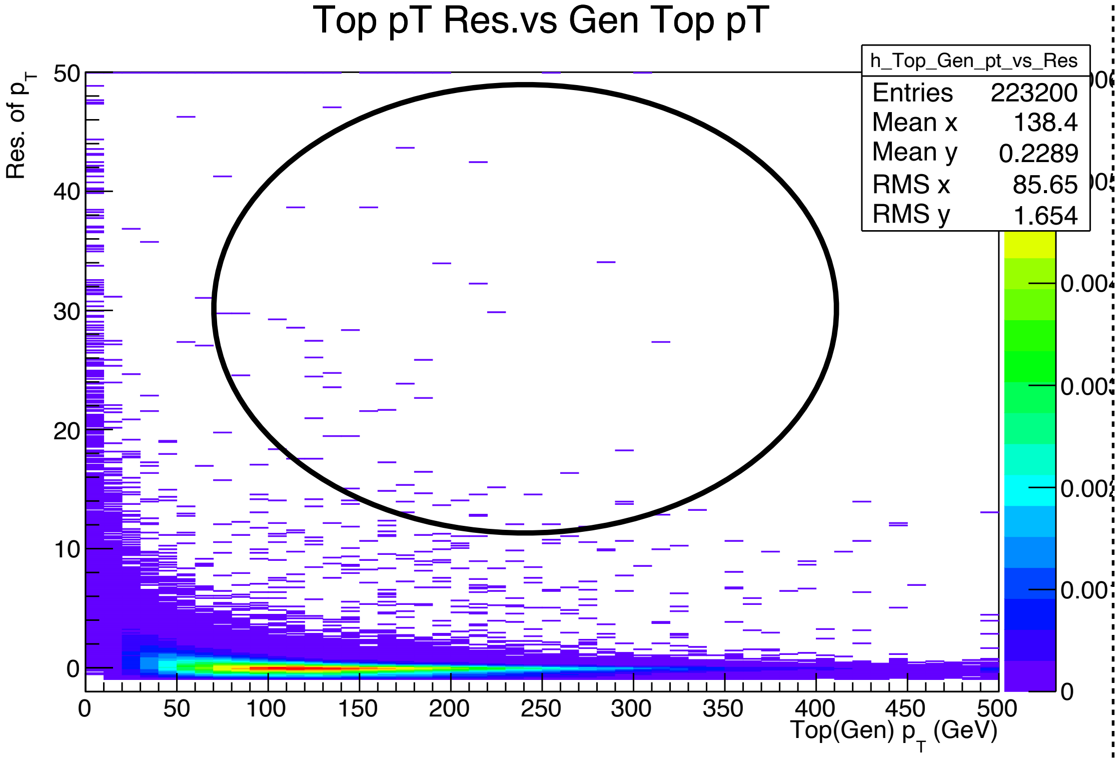
Reconstruction of Top Quarks

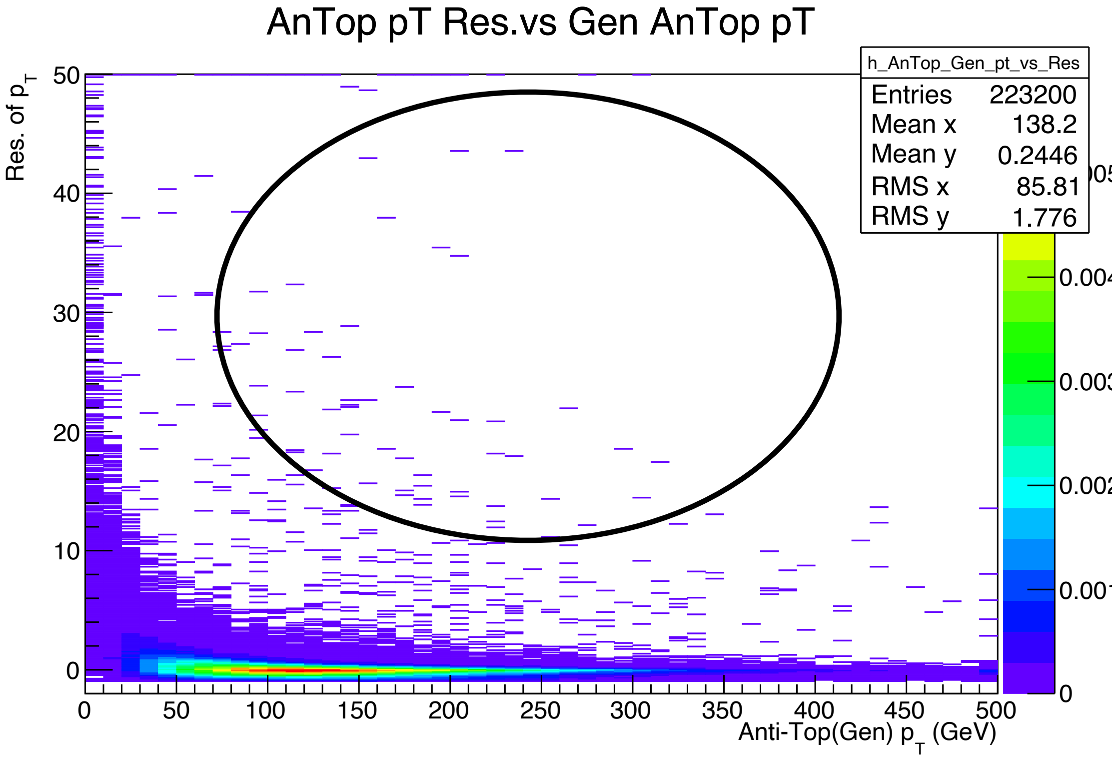
Dimuon

$$\text{Resolution of } p_T = \frac{(p_T\,\text{of Reco.} - p_T\,\text{of Gen.})}{(p_T\,\text{of Gen.})}$$

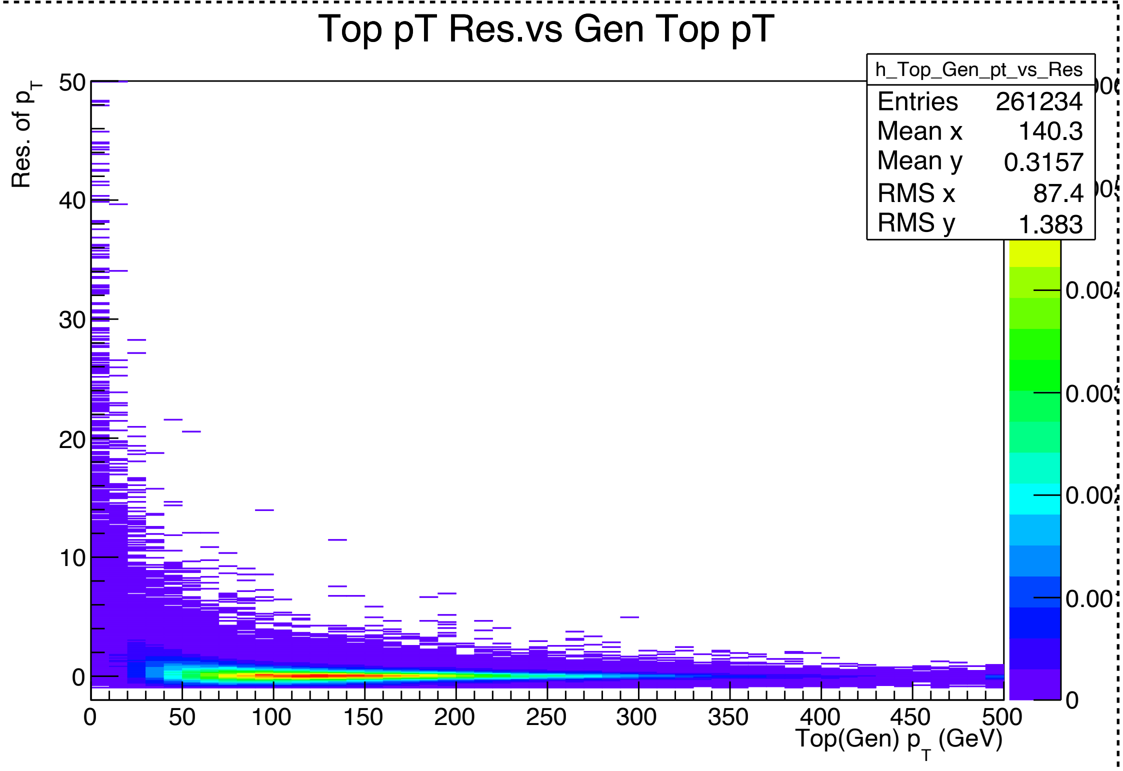
Solver | **Top pT** | **Anti-Top pT**

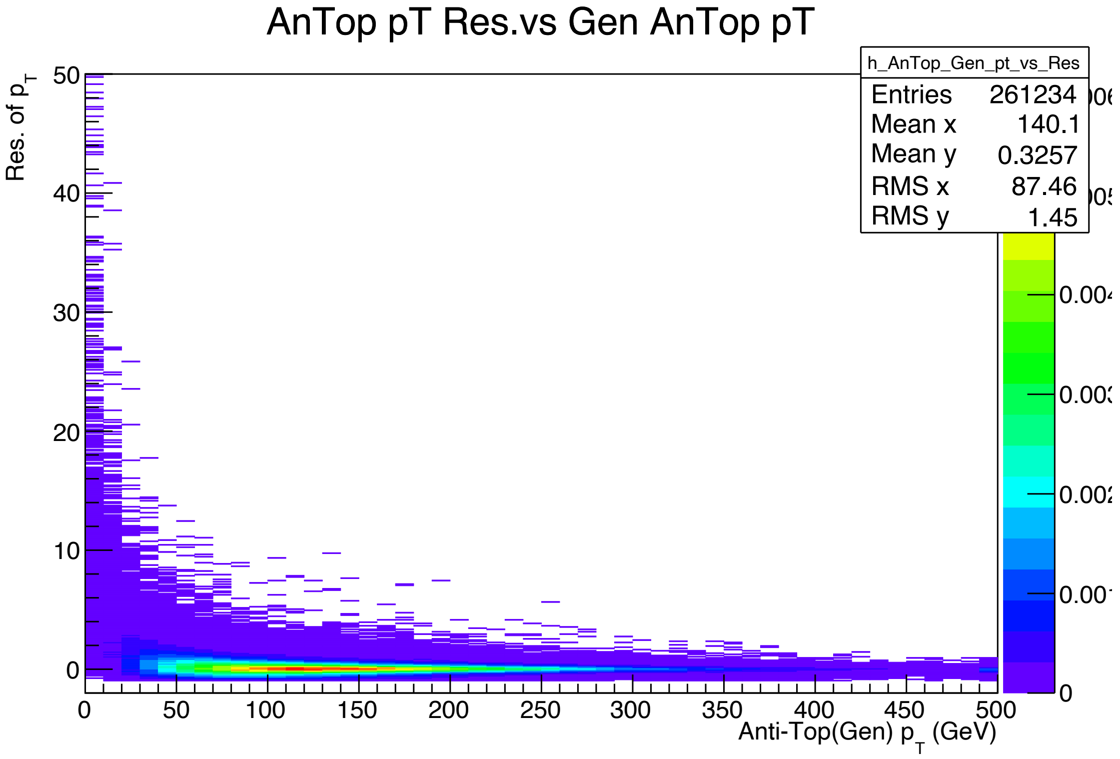
Old





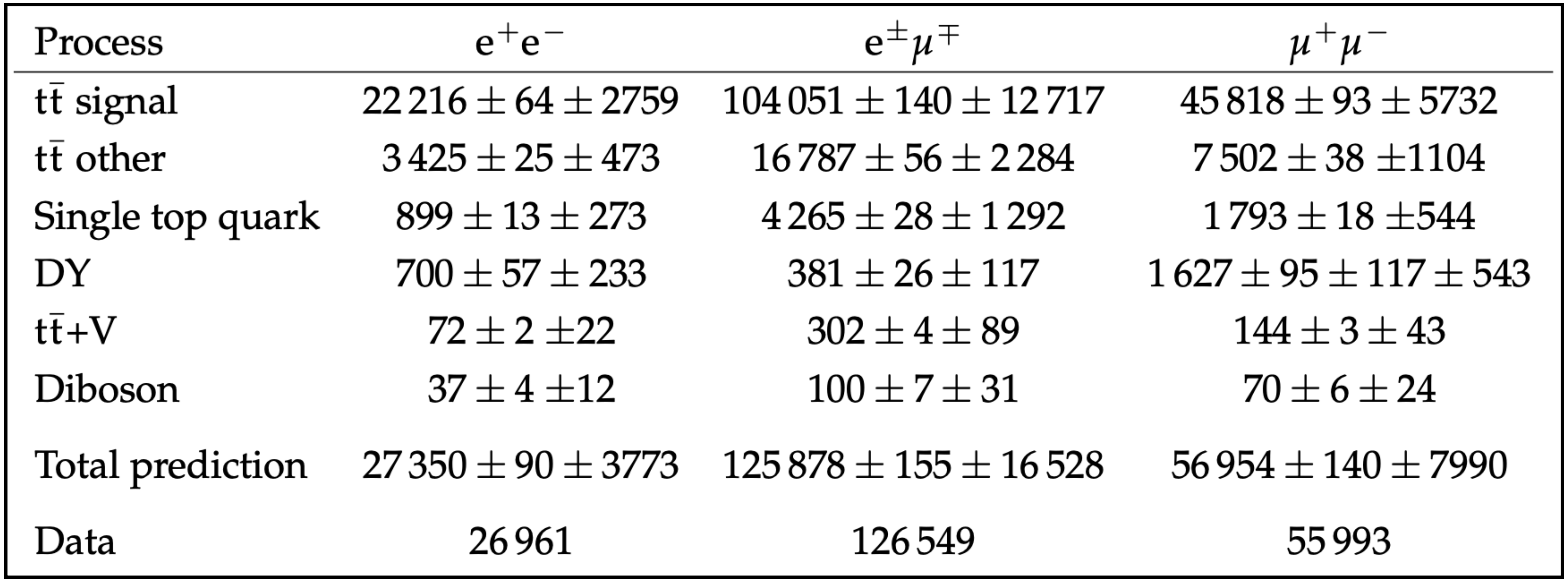
New





Event Yield

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

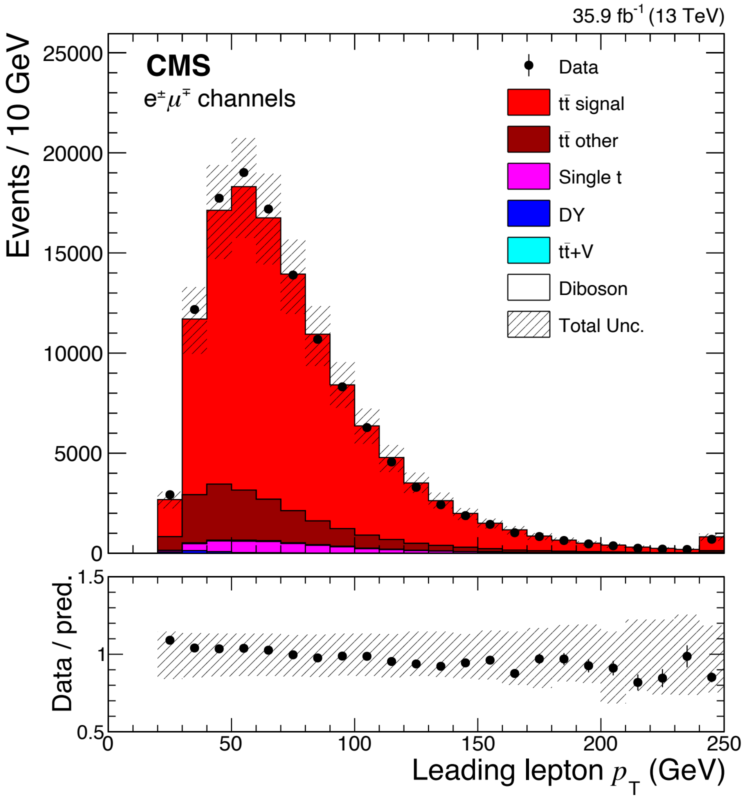


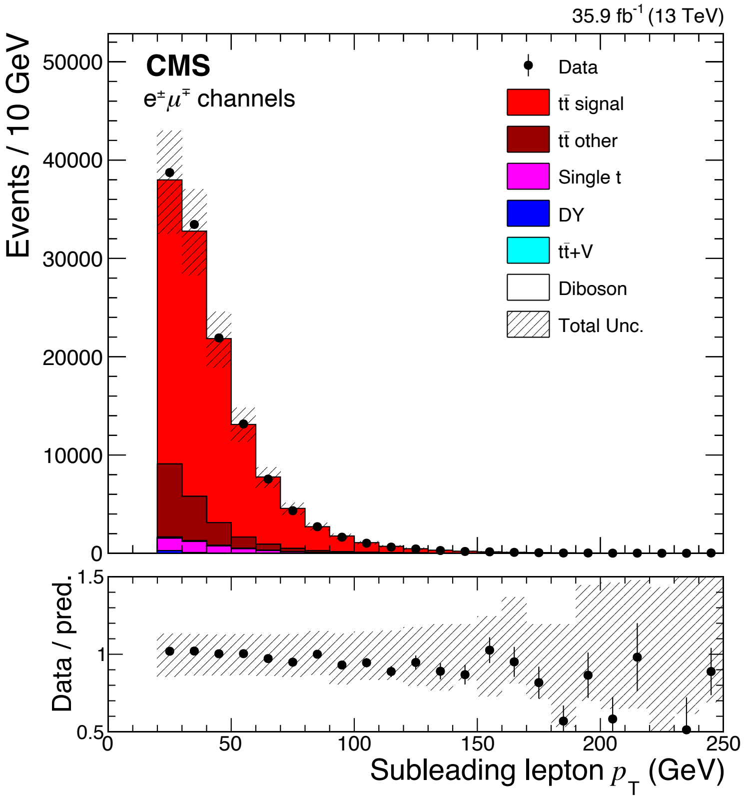
Process	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$
$t\bar{t}$ signal	$22\,216 \pm 64 \pm 2759$	$104\,051 \pm 140 \pm 12\,717$	$45\,818 \pm 93 \pm 5732$
$t\bar{t}$ other	$3\,425 \pm 25 \pm 473$	$16\,787 \pm 56 \pm 2\,284$	$7\,502 \pm 38 \pm 1104$
Single top quark	$899 \pm 13 \pm 273$	$4\,265 \pm 28 \pm 1\,292$	$1\,793 \pm 18 \pm 544$
DY	$700 \pm 57 \pm 233$	$381 \pm 26 \pm 117$	$1\,627 \pm 95 \pm 117 \pm 543$
$t\bar{t}$+V	$72 \pm 2 \pm 22$	$302 \pm 4 \pm 89$	$144 \pm 3 \pm 43$
Diboson	$37 \pm 4 \pm 12$	$100 \pm 7 \pm 31$	$70 \pm 6 \pm 24$
Total prediction	$27\,350 \pm 90 \pm 3773$	$125\,878 \pm 155 \pm 16\,528$	$56\,954 \pm 140 \pm 7990$
Data	26 961	126 549	55 993

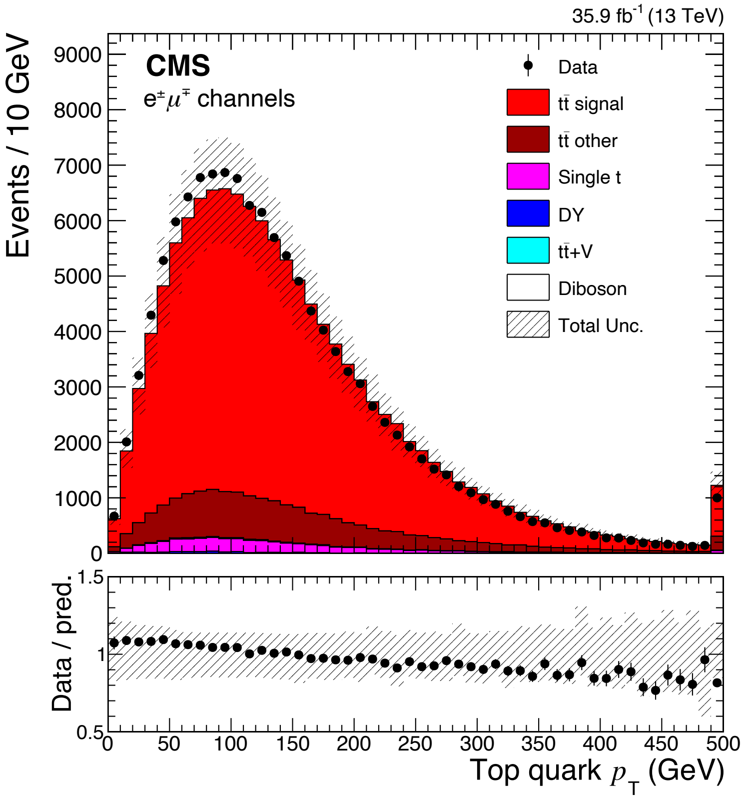
- The discrepancy between observed and simulated events is lower than ~3%.
  ($\mu^+\mu^-$: ~3% , e^+e^- : ~2.9%, $e^\pm\mu^\mp$: ~0.8%)

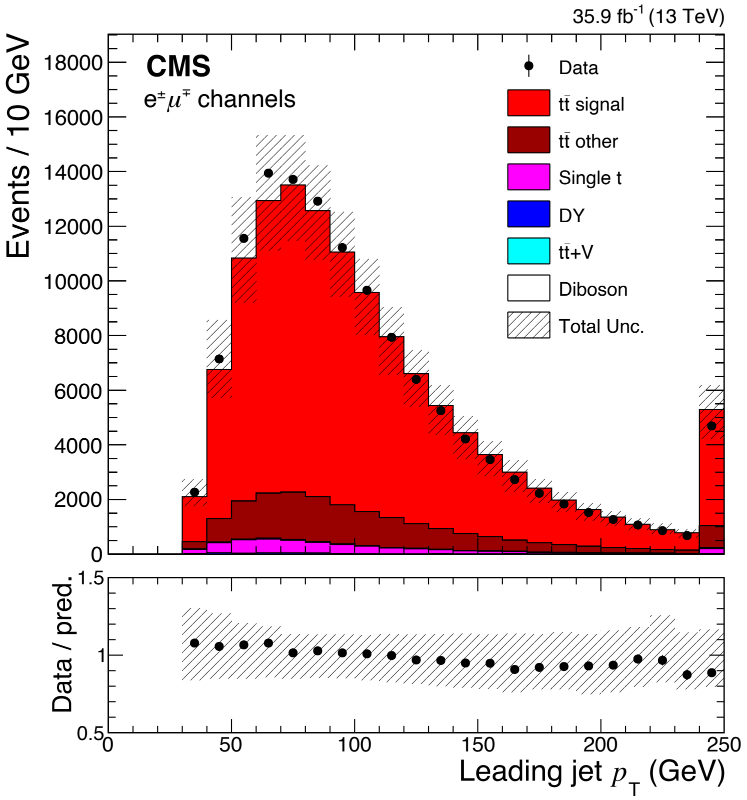
Kinematics of Object ($e^{\pm}\mu^{\mp}$)

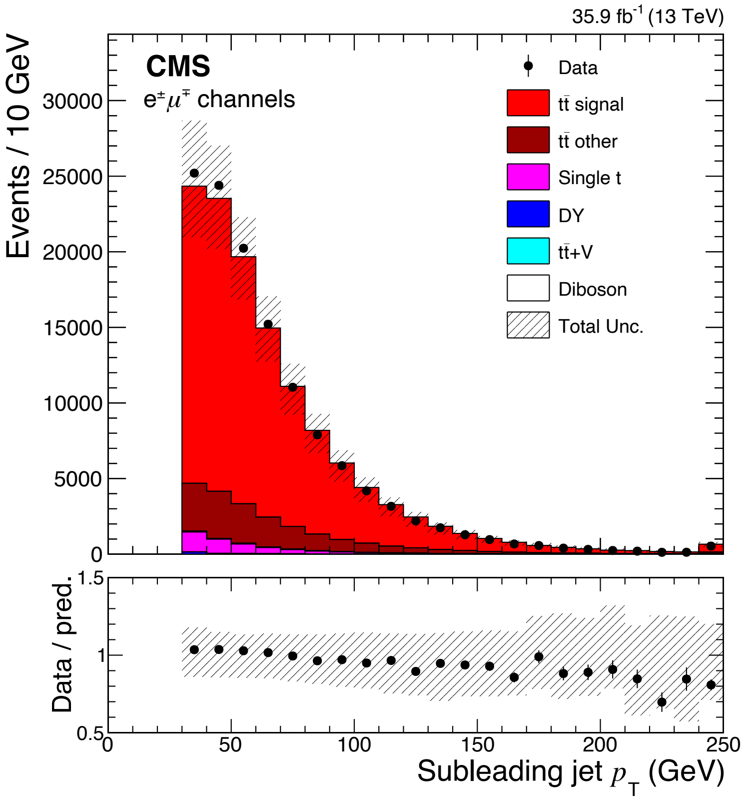
- p_T distribution of leading leptons, jets and top quarks

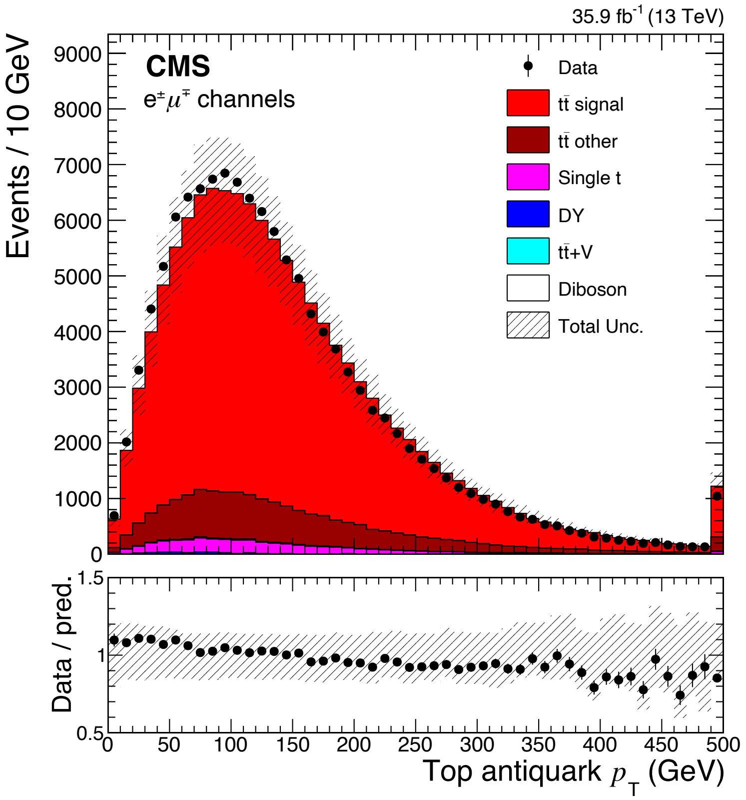






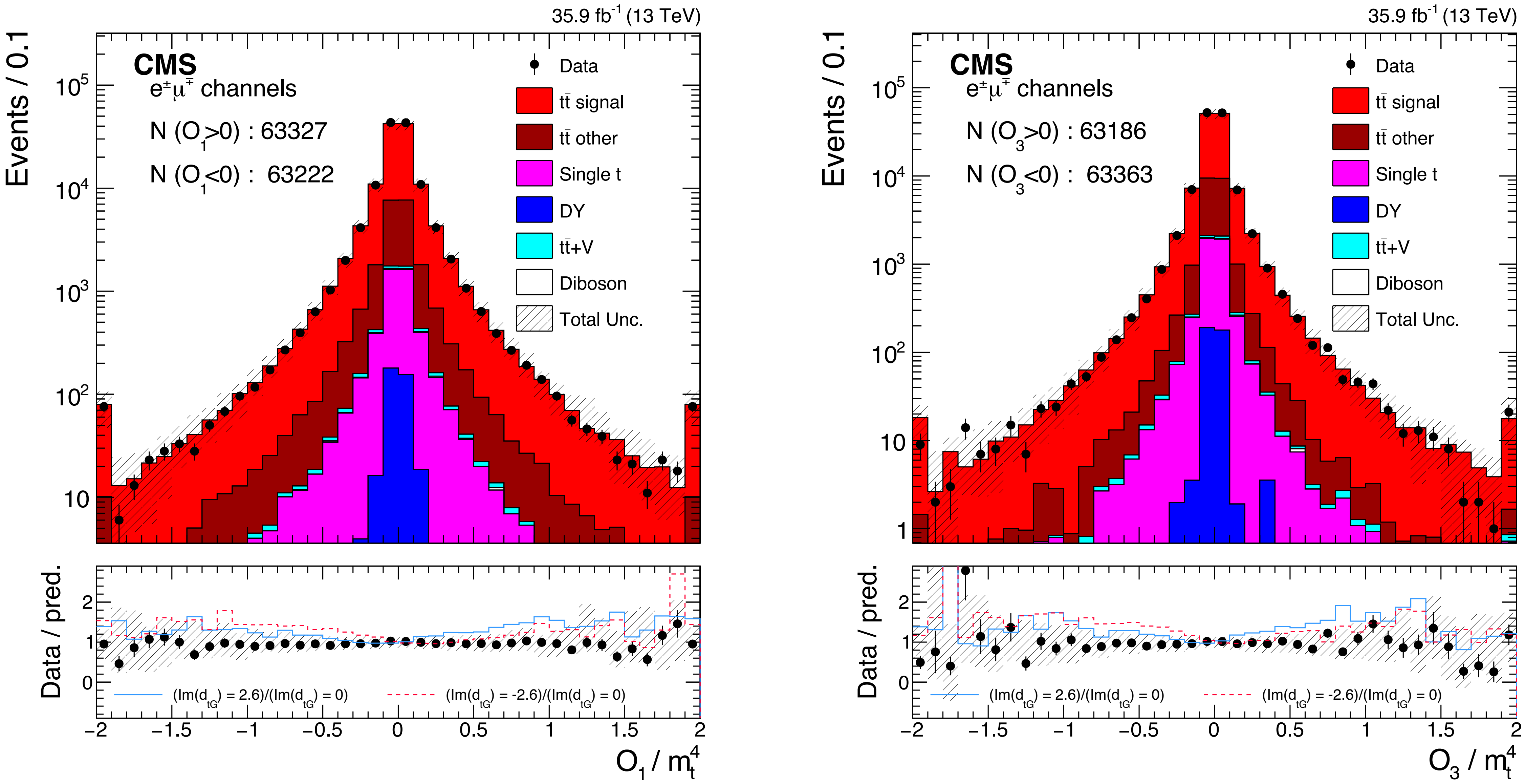






Distribution of O_1 and O_3 $(e^{\pm}\mu^{\mp})$

- Distribution of O_1 and O_3



We extracted asymmetries with maximum likelihood fit

Asymmetry Extraction (MLE)

- Often in HEP, we make a series of measurements and wish to deduce the value of a fundamental parameter (mass…)

- Or we might measure the efficiency for detecting such events as a function of momentum and then wish to derive a functional form

- $P(X|\alpha) \equiv$ Probability of measuring X on a given event
  - Suppose we make a series of measurements, yielding a set of X_i's.

  The likelihood function is defined as

$$\boxed{L = \prod_{i=1}^{N} P(X_i \,|\, \alpha)}$$

- The value of α that maximizes L is known as the Maximum Likelihood Estimator (MLE) of α, which we will denote as α^*

Asymmetry Extraction

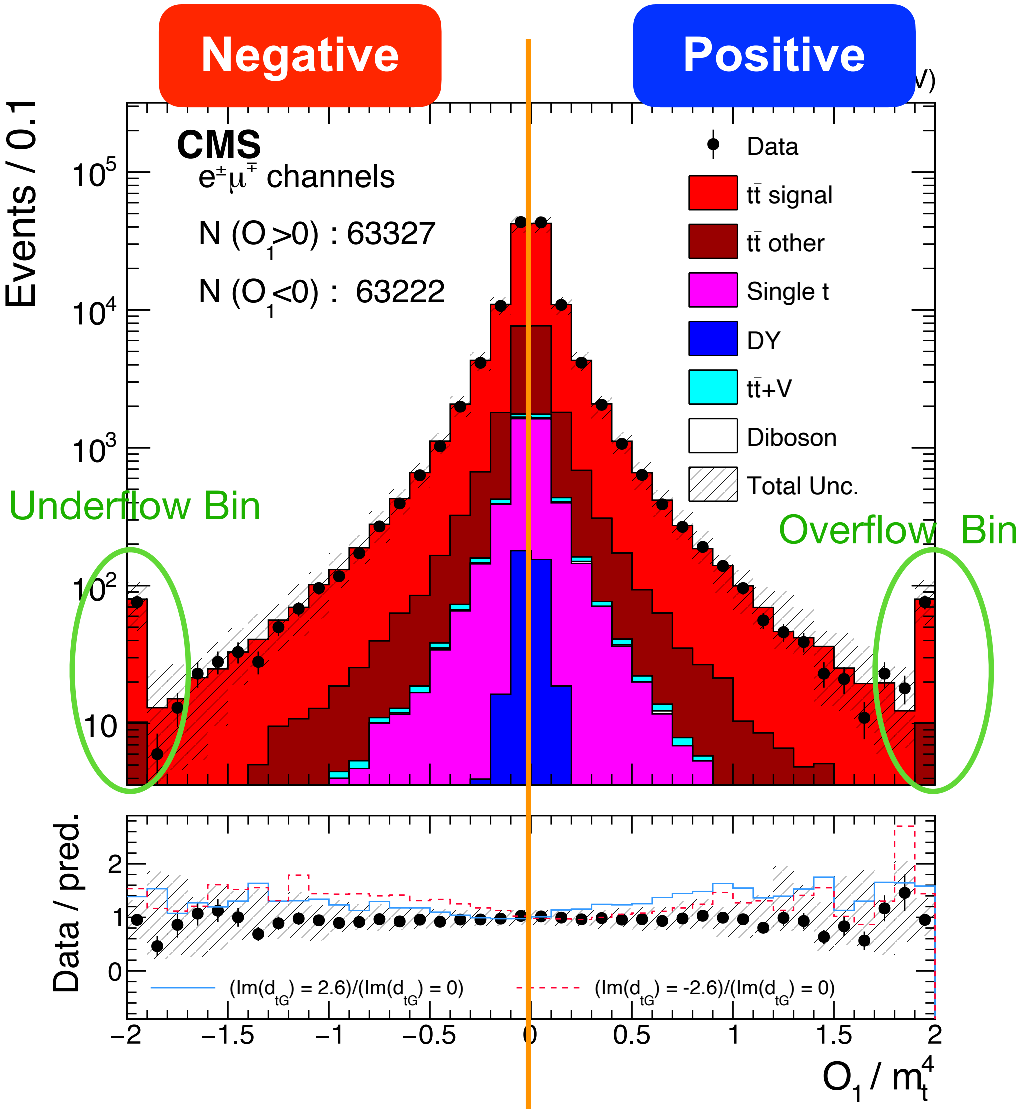
- Definition of the likelihood fit function

$$\mathcal{L}(A_i,\sigma_{t\bar{t}}) = \mathcal{P}(N_+^{\mathrm{obs}}, \underline{N_+^{\mathrm{pred}}}) \times \mathcal{P}(N_-^{\mathrm{obs}}, \underline{N_-^{\mathrm{pred}}})$$

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

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

made A and x-section float



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

	Asymmetry and uncertainty ($\times10^{-3}$)			
Observable	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	Combined
$A_{\mathcal{O}_1}$	8.8 ± 7.5	0.6 ± 3.4	6.9 ± 5.3	2.4 ± 2.8
$A_{\mathcal{O}_3}$	4.1 ± 7.5	-1.7 ± 3.4	6.1 ± 5.3	0.4 ± 2.8

Combination of Asymmetry

Best Linear Unbiased Estimator

$$\hat{y} = \Sigma\, \alpha_i\, y_i \longrightarrow \text{Linear Combination}$$

$$\Sigma\, \alpha_i = 1 \longrightarrow \text{Constrain}$$

$$\sigma^2 = \alpha^T \boxed{\mathbf{E}} \alpha \longrightarrow \text{Error Matrix}$$

$$\boxed{\mathrm{E} = \begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{pmatrix}_{stat.} + \begin{pmatrix} \sigma_1^2 & \rho_{1,2}\sigma_1\sigma_2 & \rho_{1,3}\sigma_1\sigma_3 \\ \rho_{1,2}\sigma_1\sigma_2 & \sigma_2^2 & \rho_{2,3}\sigma_2\sigma_3 \\ \rho_{1,3}\sigma_1\sigma_3 & \rho_{2,3}\sigma_2\sigma_3 & \sigma_3^2 \end{pmatrix}_{syst.}}$$

By the defintion, the weights that minimize the variance.

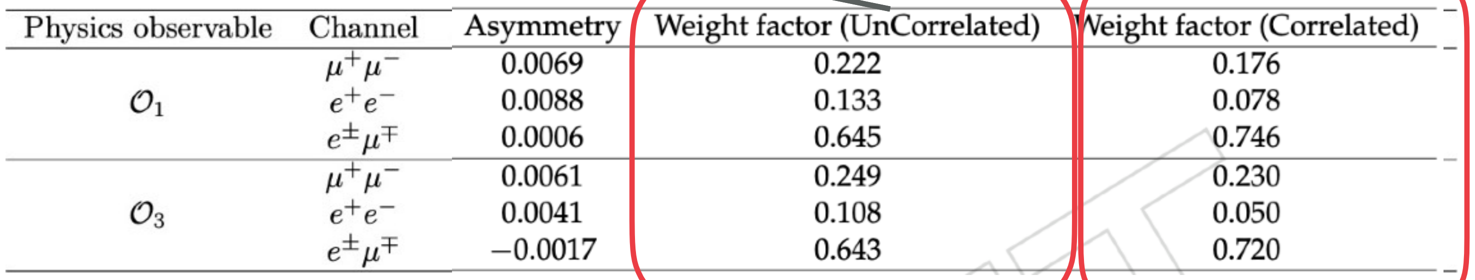
$$\boxed{\vec{\alpha} = \frac{E^{-1}\vec{u}}{\vec{u}^T E \vec{u}} \qquad u = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}}$$

Combination of Asymmetry

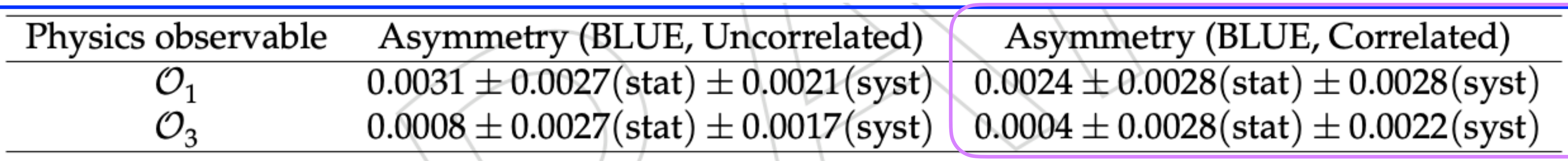
BLUE Method

All uncertainties are uncorrelated.

All uncertainties are correlated.
(Statistics,BGNorm, BGStat are uncorrelated, other unc. 100%)

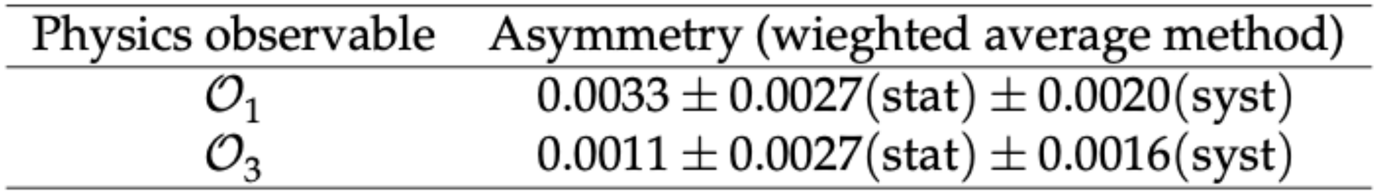


Physics observable	Channel	Asymmetry	Weight factor (UnCorrelated)	Weight factor (Correlated)
$\mathcal{O}_1$	$\mu^+\mu^-$	0.0069	0.222	0.176
	e^+e^-	0.0088	0.133	0.078
	$e^\pm\mu^\mp$	0.0006	0.645	0.746
$\mathcal{O}_3$	$\mu^+\mu^-$	0.0061	0.249	0.230
	e^+e^-	0.0041	0.108	0.050
	$e^\pm\mu^\mp$	−0.0017	0.643	0.720



Physics observable	Asymmetry (BLUE, Uncorrelated)	Asymmetry (BLUE, Correlated)
$\mathcal{O}_1$	$0.0031 \pm 0.0027(\text{stat}) \pm 0.0021(\text{syst})$	$0.0024 \pm 0.0028(\text{stat}) \pm 0.0028(\text{syst})$
$\mathcal{O}_3$	$0.0008 \pm 0.0027(\text{stat}) \pm 0.0017(\text{syst})$	$0.0004 \pm 0.0028(\text{stat}) \pm 0.0022(\text{syst})$

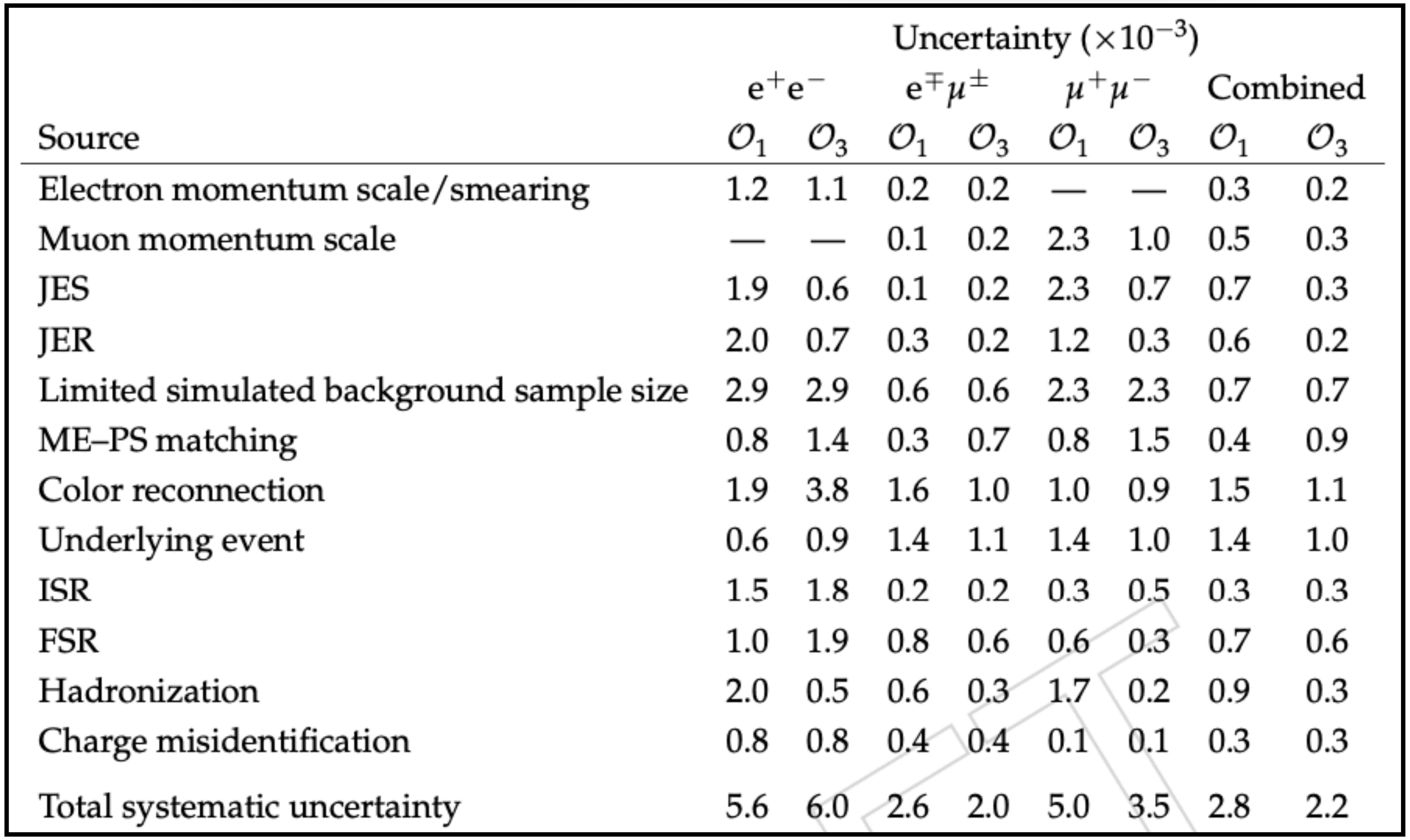
Weighted Method



Physics observable	Asymmetry (wieghted average method)
$\mathcal{O}_1$	$0.0033 \pm 0.0027(\text{stat}) \pm 0.0020(\text{syst})$
$\mathcal{O}_3$	$0.0011 \pm 0.0027(\text{stat}) \pm 0.0016(\text{syst})$

The results are compatible to each other. But we think the uncertainties with weighted average method are underestimated, since they are similar to the results for case of uncorrelated uncertainties using BLUE method.

Systematic Uncertainties



	Uncertainty ($\times 10^{-3}$)							
	e^+e^-		$e^{\mp}\mu^{\pm}$		$\mu^+\mu^-$		Combined	
Source	$\mathcal{O}_1$	$\mathcal{O}_3$	$\mathcal{O}_1$	$\mathcal{O}_3$	$\mathcal{O}_1$	$\mathcal{O}_3$	$\mathcal{O}_1$	$\mathcal{O}_3$
Electron momentum scale/smearing	1.2	1.1	0.2	0.2	—	—	0.3	0.2
Muon momentum scale	—	—	0.1	0.2	2.3	1.0	0.5	0.3
JES	1.9	0.6	0.1	0.2	2.3	0.7	0.7	0.3
JER	2.0	0.7	0.3	0.2	1.2	0.3	0.6	0.2
Limited simulated background sample size	2.9	2.9	0.6	0.6	2.3	2.3	0.7	0.7
ME–PS matching	0.8	1.4	0.3	0.7	0.8	1.5	0.4	0.9
Color reconnection	1.9	3.8	1.6	1.0	1.0	0.9	1.5	1.1
Underlying event	0.6	0.9	1.4	1.1	1.4	1.0	1.4	1.0
ISR	1.5	1.8	0.2	0.2	0.3	0.5	0.3	0.3
FSR	1.0	1.9	0.8	0.6	0.6	0.3	0.7	0.6
Hadronization	2.0	0.5	0.6	0.3	1.7	0.2	0.9	0.3
Charge misidentification	0.8	0.8	0.4	0.4	0.1	0.1	0.3	0.3
Total systematic uncertainty	5.6	6.0	2.6	2.0	5.0	3.5	2.8	2.2

- Dedicated ttbar sample : ISR, FSR, ME-PS matching, Color reconnection, Underlying Event, Hadronization
- Limited number of simulated BG events, JES, JER

  \- Especially, for Limited number of simulated BG events, if we can suppress the BG process, we can expect that the size of uncertainty can be reduce

Asymmetries vs dtG

- We used Madgraph5_aMC@NLO(v2.5.3) to generate CP violating event.

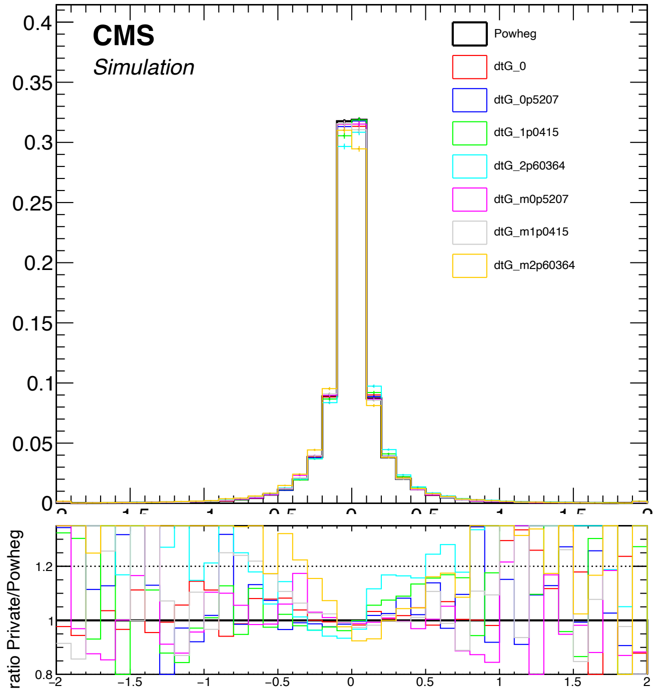
- And we followed all the standard procedure to generate CMS Monte Carlo events.

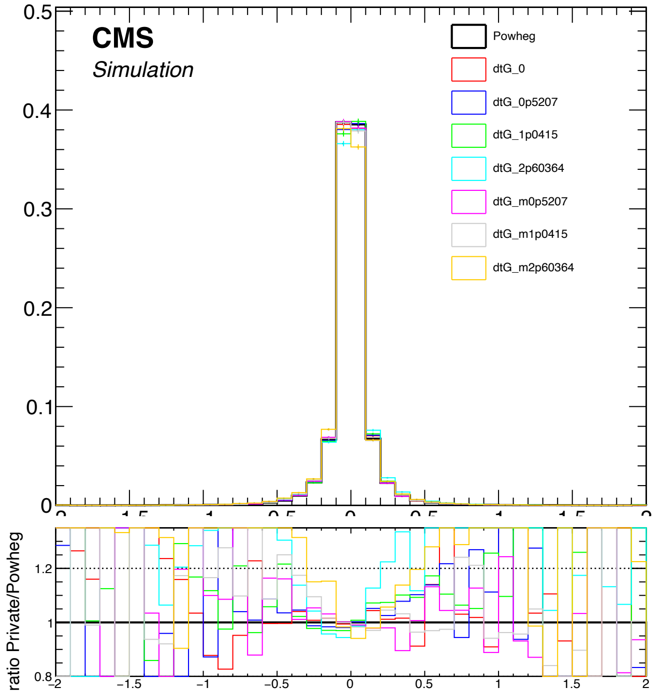
- d_{tG} Points (Dimensionless, 7 points)
  For each d_{tG} input, 3 million events were generated, and they contain top and anti-top quark pairs decaying into the dilepton final states.

d_{tG}	-2.6	-1.0	-0.5	0.0	0.5	1.0	2.6
Asymmetry (O1) (10^{-2})	**−5.9 ± 0.2**	**−2.5 ± 0.2**	**−1.1 ± 0.2**	**−0.0 ± 0.2**	**1.2 ± 0.2**	**2.5 ± 0.2**	**5.5 ± 0.2**
Asymmetry (O3) (10^{-2})	**−5.5 ± 0.2**	**−2.0 ± 0.2**	**−1.0 ± 0.2**	**−0.1 ± 0.2**	**1.1 ± 0.2**	**2.4 ± 0.2**	**5.4 ± 0.2**

Asymmetries vs dtG

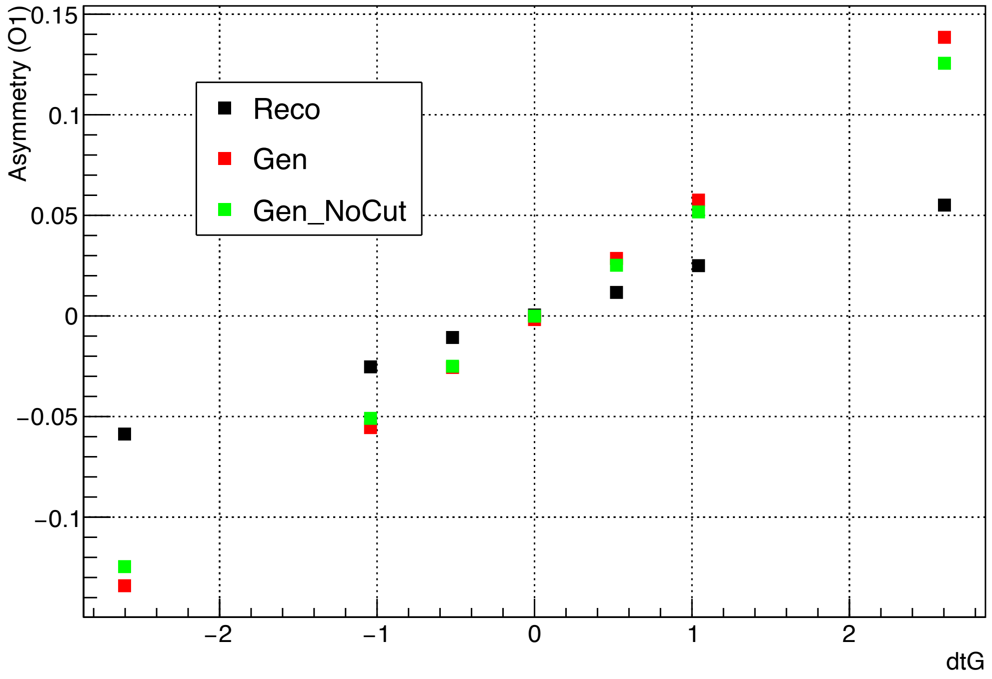
Muonelectron channel



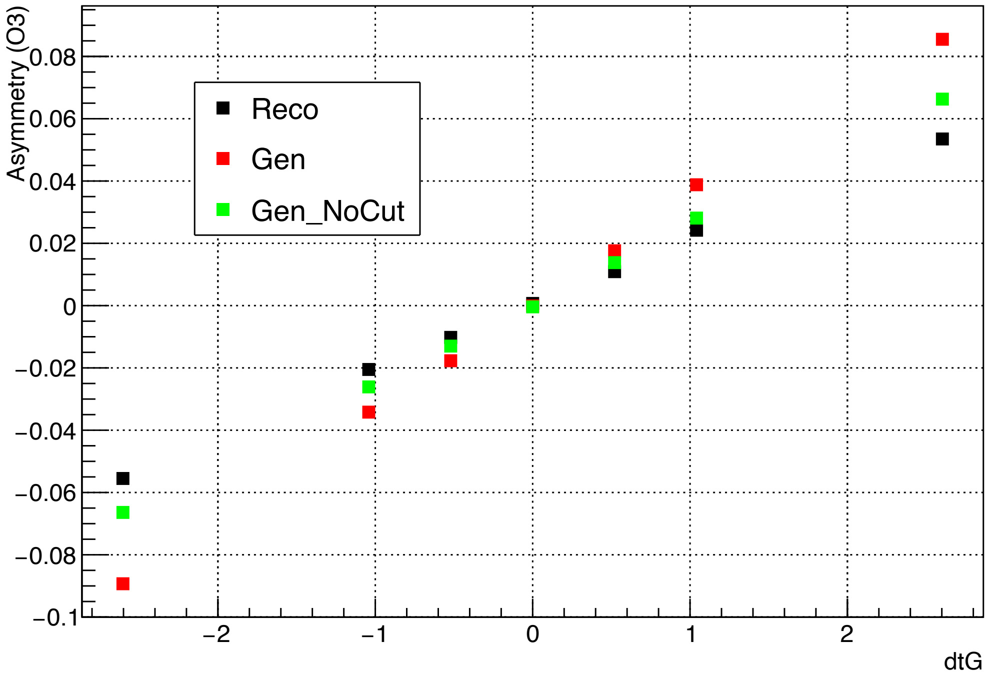


Combined channel

dtG vs Asym.



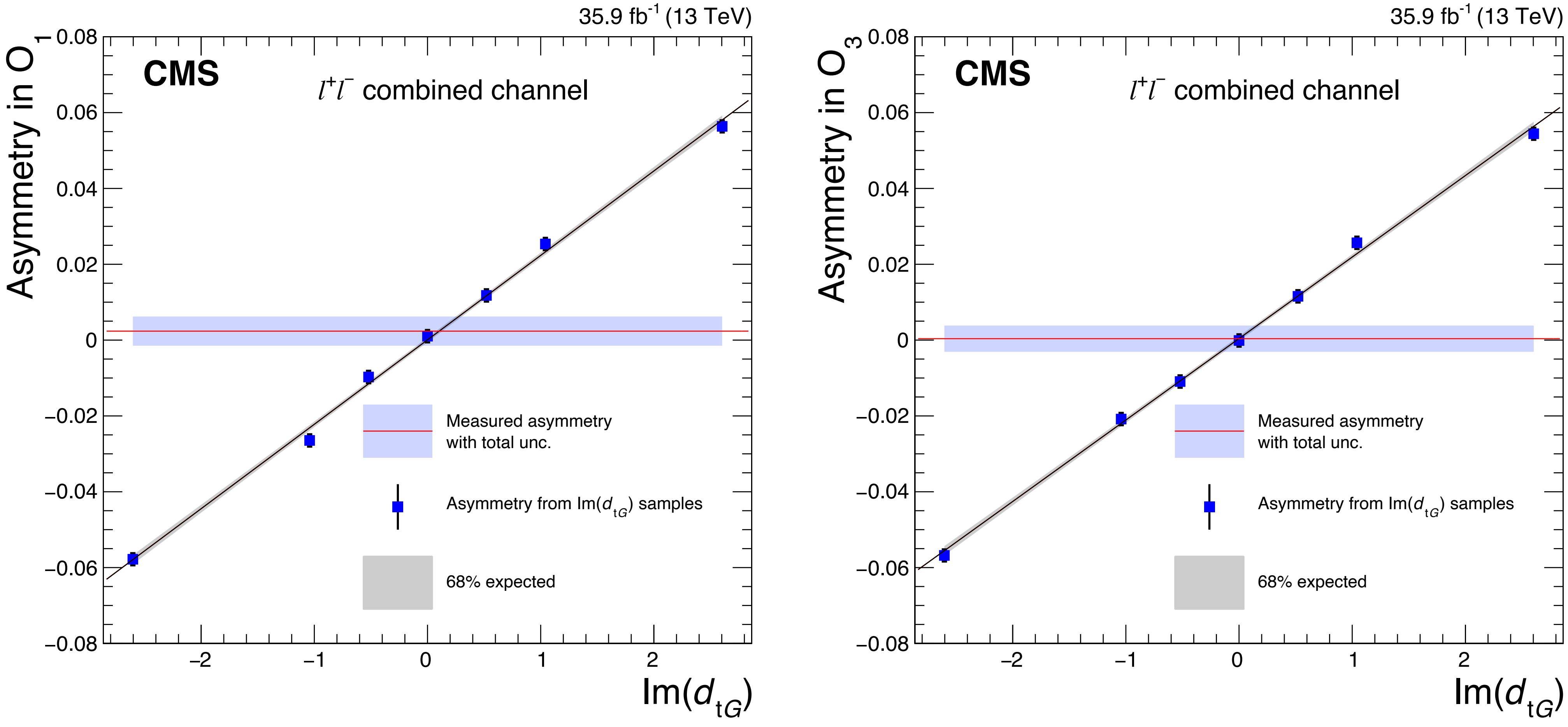
dtG vs Asym.



dtG and asymmetries have linear correlation.

Asymmetries vs dtG

Combined channel



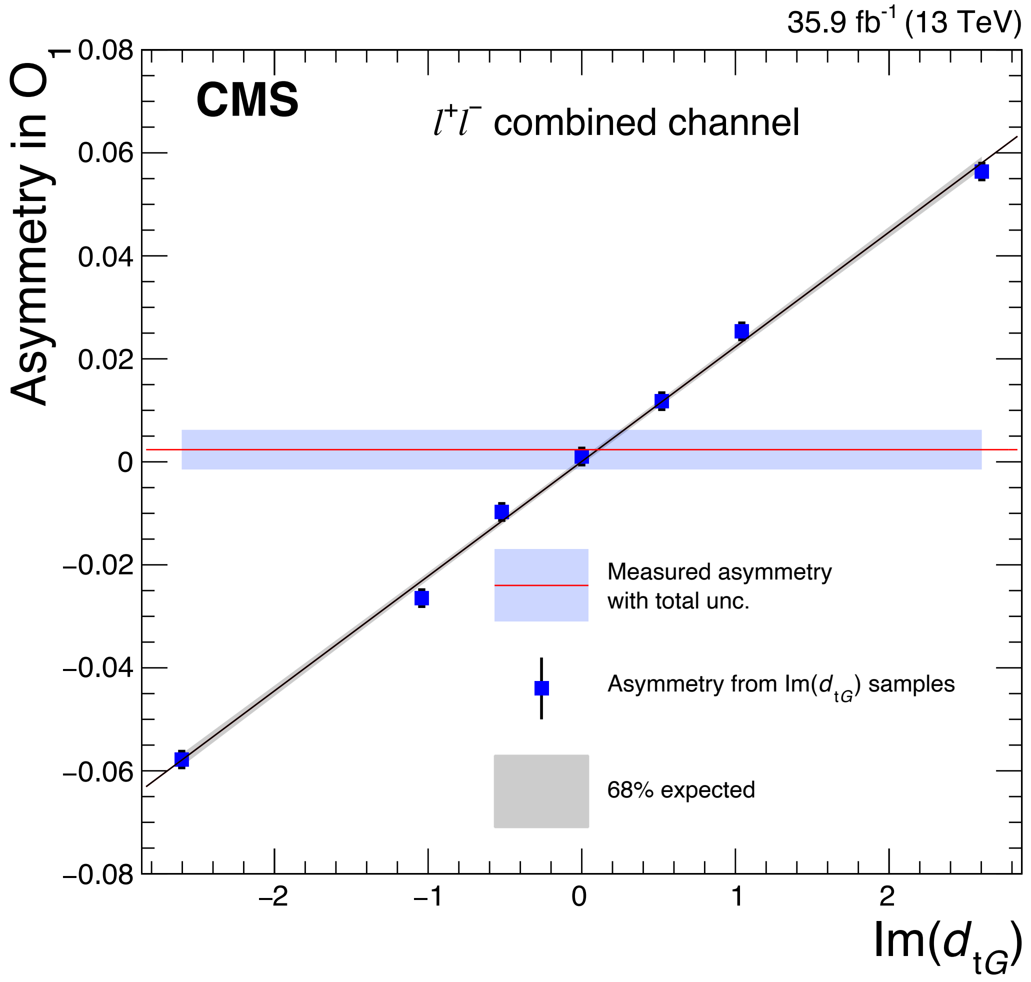
We will extract the CEDM with measured asymmetries.

Extraction of CEDM

$$Asymmetry = a \cdot d_t^G + b \quad \text{(eq.1)}$$

$$d_t^G = \frac{Asymmetry - b}{a} \quad \text{(eq.2)}$$

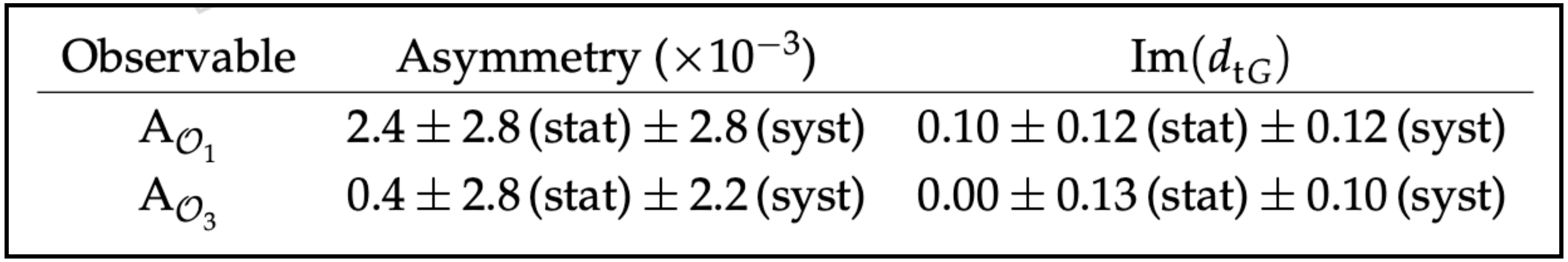
a , b can be obtained from linear fitting.



$$\Delta^2_{d_t^G} = \begin{pmatrix} \frac{\partial d_t^G}{\partial A} & \frac{\partial d_t^G}{\partial b} & \frac{\partial d_t^G}{\partial a} \end{pmatrix} \begin{pmatrix} \Delta_A^2 & 0 & 0 \\ 0 & \Delta_b^2 & \mathrm{cov}(b,a) \\ 0 & \mathrm{cov}(a,b) & \Delta_a^2 \end{pmatrix} \begin{pmatrix} \frac{\partial d_t^G}{\partial A} \\ \frac{\partial d_t^G}{\partial b} \\ \frac{\partial d_t^G}{\partial a} \end{pmatrix} \quad \text{(eq.3)}$$

Results (Asymmetry & CEDM)

- Asymmetries & CEDM



Observable	Asymmetry ($\times 10^{-3}$)	$\mathrm{Im}(d_{tG})$
$A_{\mathcal{O}_1}$	$2.4 \pm 2.8\,(\mathrm{stat}) \pm 2.8\,(\mathrm{syst})$	$0.10 \pm 0.12\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst})$
$A_{\mathcal{O}_3}$	$0.4 \pm 2.8\,(\mathrm{stat}) \pm 2.2\,(\mathrm{syst})$	$0.00 \pm 0.13\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst})$

- The measured asymmetries of observables are consistent with the SM prediction

- The CEDMs(Im(d_{tG})) we extracted are consistent with the SM prediction

Summary

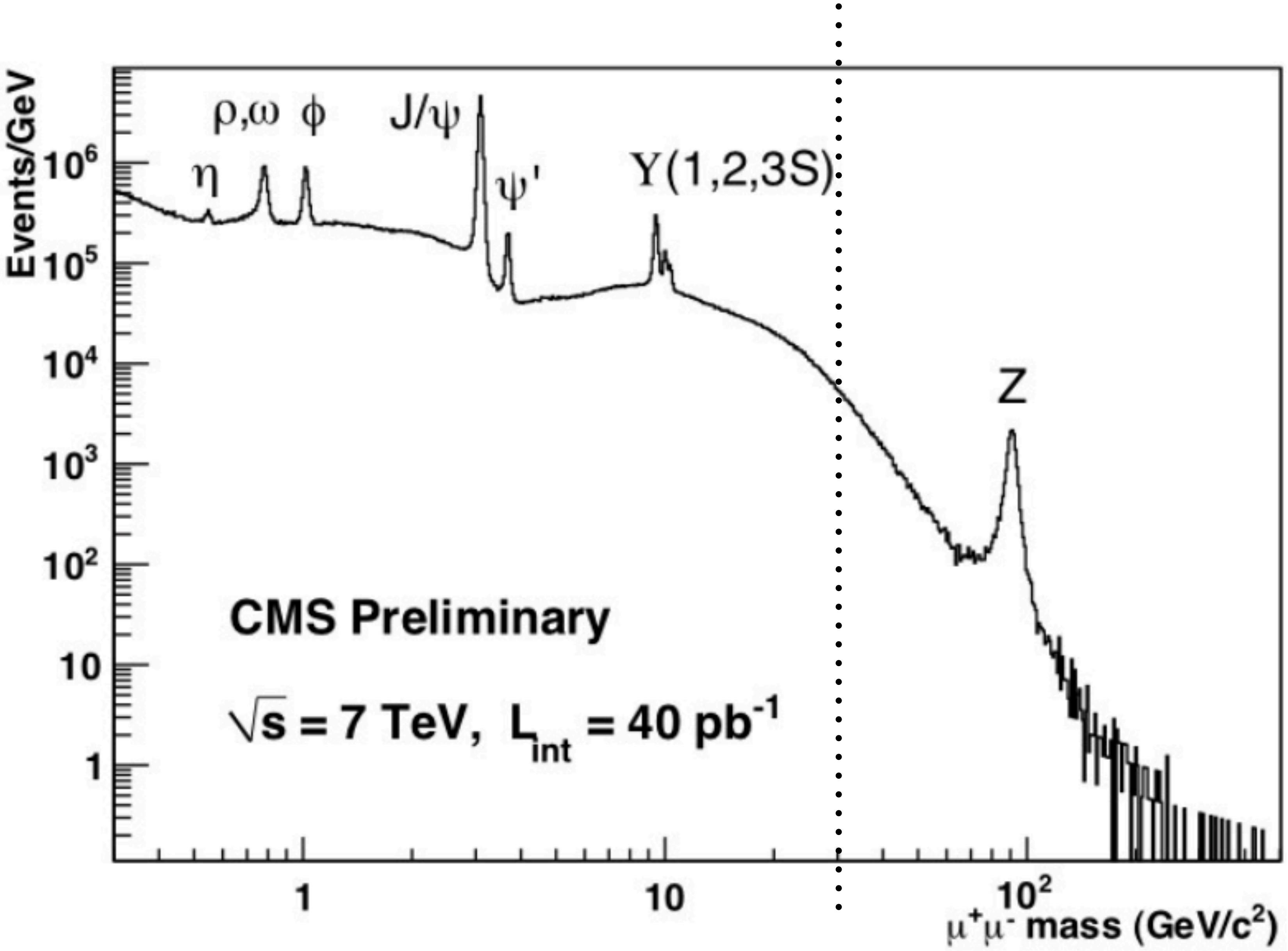
- CP violating asymmetries and CEDM of top quark have been presented

- 2016 data set (CMS, 35.9 fb^{-1}) was analyzed

- Measured asymmetries and CEDM are consistent with the Standard Model prediction within uncertainties

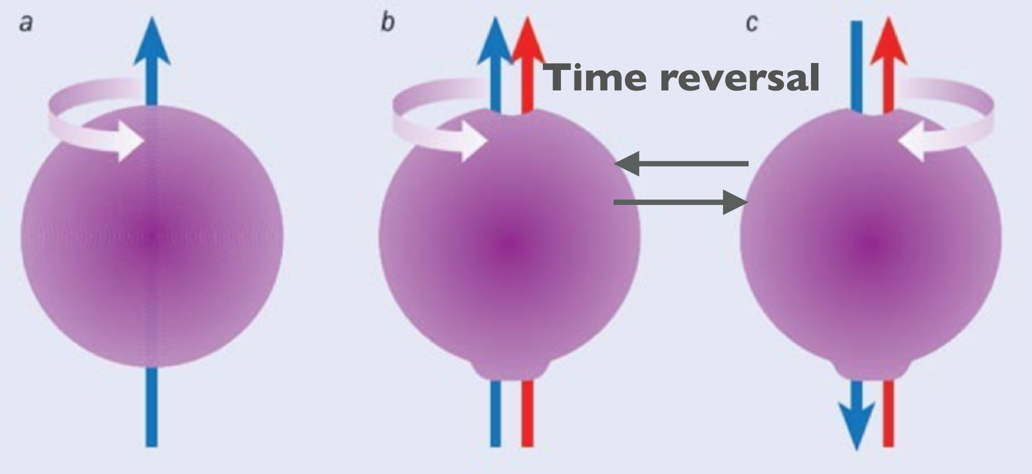
Backup

DY invariant mass



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)



↑ : Magnetic Dipole Moment

↑ : Electric Dipole Moment

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

d_t^g is CEDM

Form factors

$$C_1^s(s,t,u) = C_2^s(s,t,u) = C_3^s(s,t,u) = \frac{3}{2}\,\tilde{d}\,K_{bb}\,m_t\frac{(t-u)}{s^2}.$$

$$\begin{aligned}
C_1^{tu}(s,t,u) &= \frac{1}{48}\,\tilde{d}\,K_{bb}\,\frac{m_t}{s^2(t-m_t^2)^2(u-m_t^2)^2}\Big[9(t-u)^5 - 2(5s-36m_t^2)s(t-u)^3 \\
&\quad + s^2(s^2-22sm_t^2+144m_t^4)(t-u) + \frac{14m_t^2 s^4(s+8m_t^2)}{(t-u)}\Big] \\
C_2^{tu}(s,t,u) &= \frac{1}{48}\,\tilde{d}\,K_{bb}\,\frac{m_t}{s^2(t-m_t^2)^2(u-m_t^2)^2}\Big[9(t-u)^5 - 2(5s-9m_t^2)s(t-u)^3 \\
&\quad + s^2(s^2+46sm_t^2)(t-u)\Big] \\
C_3^{tu}(s,t,u) &= C_2^{tu}(s,t,u).
\end{aligned}$$

$$\begin{aligned}
C_1^{tu-s}(s,t,u) &= -\frac{3}{4}\,\tilde{d}\,K_{bb}\,\frac{m_t(t-u)}{s^2(t-m_t^2)(u-m_t^2)}\left(-4sm_t^2+s^2-(t-u)^2\right) \\
C_2^{tu-s}(s,t,u) &= -3\,\tilde{d}\,K_{bb}\,m_t\frac{t-u}{s^2} \\
C_3^{tu-s}(s,t,u) &= C_2^{tu-s}(s,t,u).
\end{aligned}$$

$$C_i(s,t,u) = C_i^s(s,t,u) + C_i^{tu}(s,t,u) + C_i^{tu-s}(s,t,u),$$

for $i = 1, 2, 3.$

$$K_{bb} \equiv (\pi^2\alpha_s^2 g^4)\left(2-\frac{m_t^2}{M_W^2}\right)^2\left(\frac{\pi}{m_t\Gamma_t}\right)^2\delta(p_t^2-m_t^2)\,\delta(p_{\bar{t}}^2-m_t^2).$$

T-odd correlation Physics Observables (also CP-odd)

Lorentz Scalar form of the triple product
(can be evaluated in any reference frame)

$$\begin{aligned}\tilde{\mathcal{O}}_1 &= \epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-})\\ \tilde{\mathcal{O}}_2 &= \tilde{q}\cdot(p_{\mu^+} - p_{\mu^-})\,\epsilon(p_{\mu^+}, p_{\mu^-}, p_b + p_{\bar{b}}, \tilde{q})\\ \tilde{\mathcal{O}}_3 &= \tilde{q}\cdot(p_{\mu^+} - p_{\mu^-})\,\epsilon(p_b, p_{\bar{b}}, p_{\mu^+} + p_{\mu^-}, \tilde{q}),\end{aligned}$$

CP Property

$$\tilde{\mathcal{O}}_1 = \varepsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) \xrightarrow{(b\bar{b})_{C.M.}} \propto \vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})$$

$$\xrightarrow{CP} -\vec{p}_{\bar{b}} \cdot (-\vec{p}_{\mu^-} \times -\vec{p}_{\mu^+}) = -\vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}).$$

Null-Test: vanish in the limit of CP conservation

$$A_{CP} = \frac{N_{events}(\vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}) > 0) - N_{events}(\vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}) < 0)}{N_{events}(\vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}) > 0) + N_{events}(\vec{p}_b \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}) < 0)}$$

OR

$$A_{CP} = \frac{N_{events}(\epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) > 0) - N_{events}(\epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) < 0)}{N_{events}(\epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) > 0) + N_{events}(\epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) < 0)}$$

Physics observable

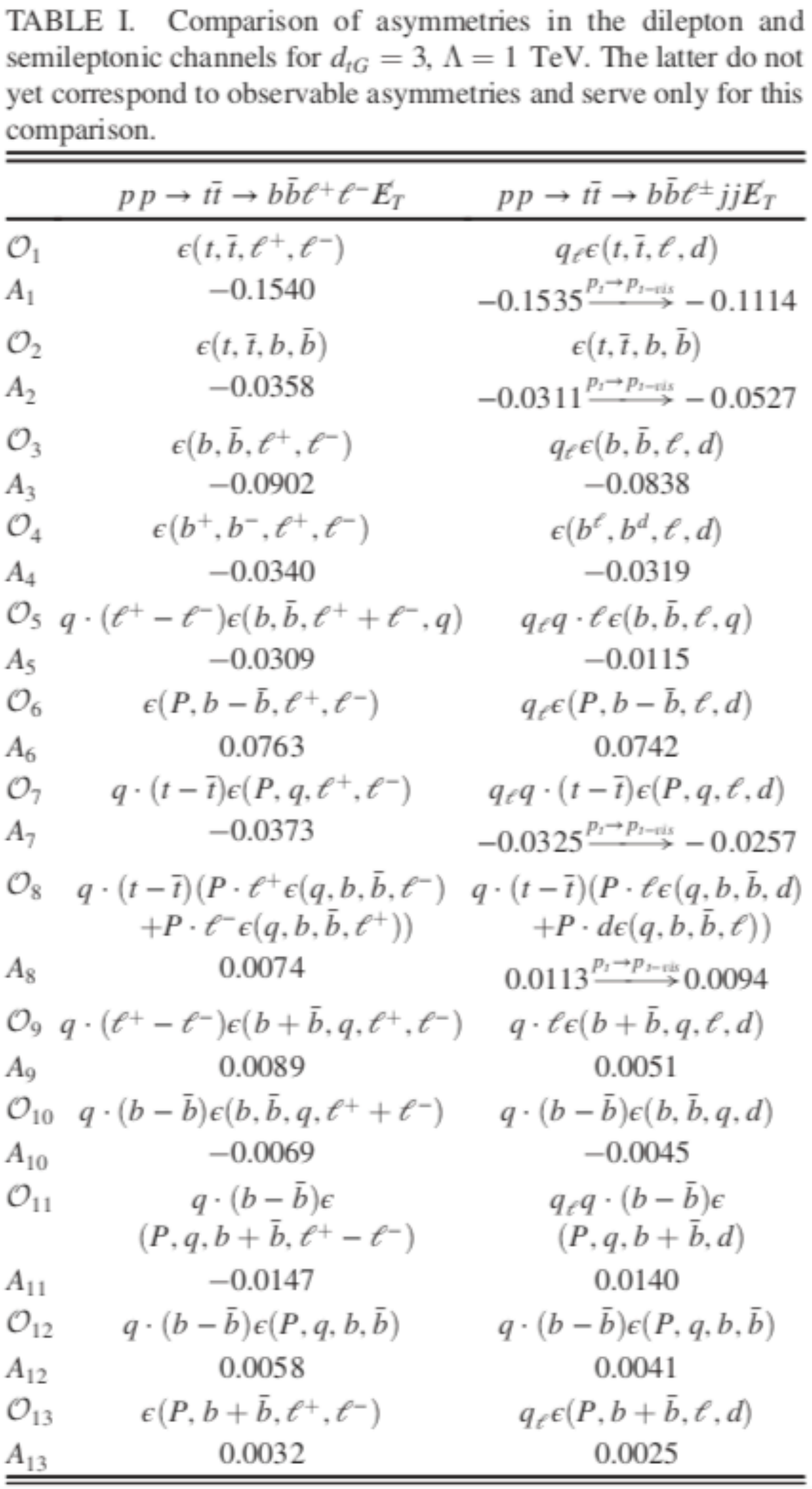


TABLE I. Comparison of asymmetries in the dilepton and semileptonic channels for $d_{tG} = 3$, $\Lambda = 1$ TeV. The latter do not yet correspond to observable asymmetries and serve only for this comparison.

	$pp \to t\bar{t} \to b\bar{b}\ell^+\ell^-\not{E}_T$	$pp \to t\bar{t} \to b\bar{b}\ell^\pm jj\not{E}_T$
$\mathcal{O}_1$	$\epsilon(t, \bar{t}, \ell^+, \ell^-)$	$q_\ell \epsilon(t, \bar{t}, \ell, d)$
A_1	-0.1540	$-0.1535 \xrightarrow{p_t \to p_{t\text{-vis}}} -0.1114$
$\mathcal{O}_2$	$\epsilon(t, \bar{t}, b, \bar{b})$	$\epsilon(t, \bar{t}, b, \bar{b})$
A_2	-0.0358	$-0.0311 \xrightarrow{p_t \to p_{t\text{-vis}}} -0.0527$
$\mathcal{O}_3$	$\epsilon(b, \bar{b}, \ell^+, \ell^-)$	$q_\ell \epsilon(b, \bar{b}, \ell, d)$
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	$-0.0325 \xrightarrow{p_t \to p_{t\text{-vis}}} -0.0257$
$\mathcal{O}_8$	$q \cdot (t - \bar{t})(P \cdot \ell^+ \epsilon(q, b, \bar{b}, \ell^-)$ $+P \cdot \ell^- \epsilon(q, b, \bar{b}, \ell^+))$	$q \cdot (t - \bar{t})(P \cdot \ell \epsilon(q, b, \bar{b}, d)$ $+P \cdot d\epsilon(q, b, \bar{b}, \ell))$
A_8	0.0074	$0.0113 \xrightarrow{p_t \to p_{t\text{-vis}}} 0.0094$
$\mathcal{O}_9$	$q \cdot (\ell^+ - \ell^-)\epsilon(b + \bar{b}, q, \ell^+, \ell^-)$	$q \cdot \ell \epsilon(b + \bar{b}, q, \ell, d)$
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

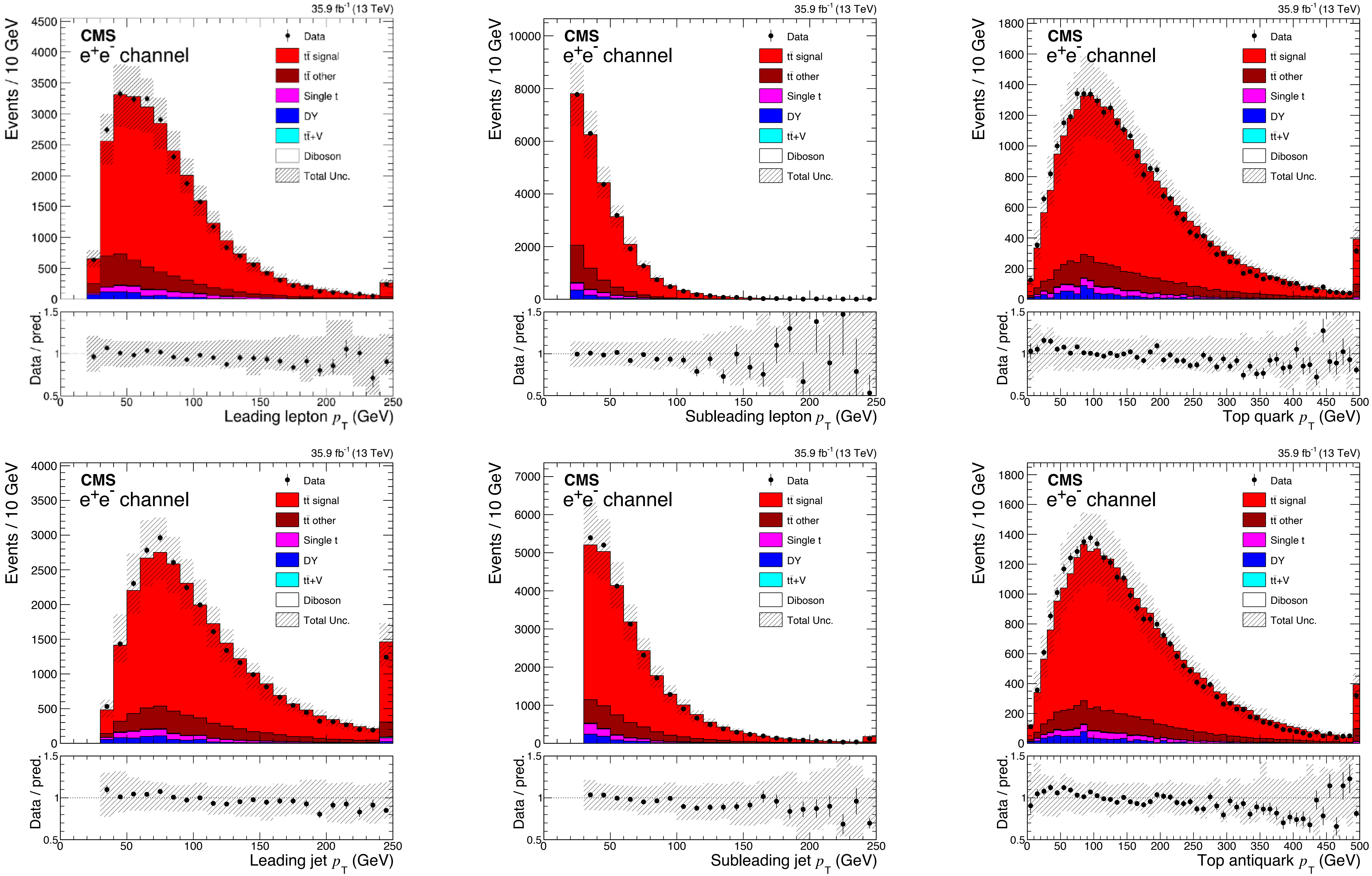
O1 and O3 are described in this theory paper.[1]

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

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

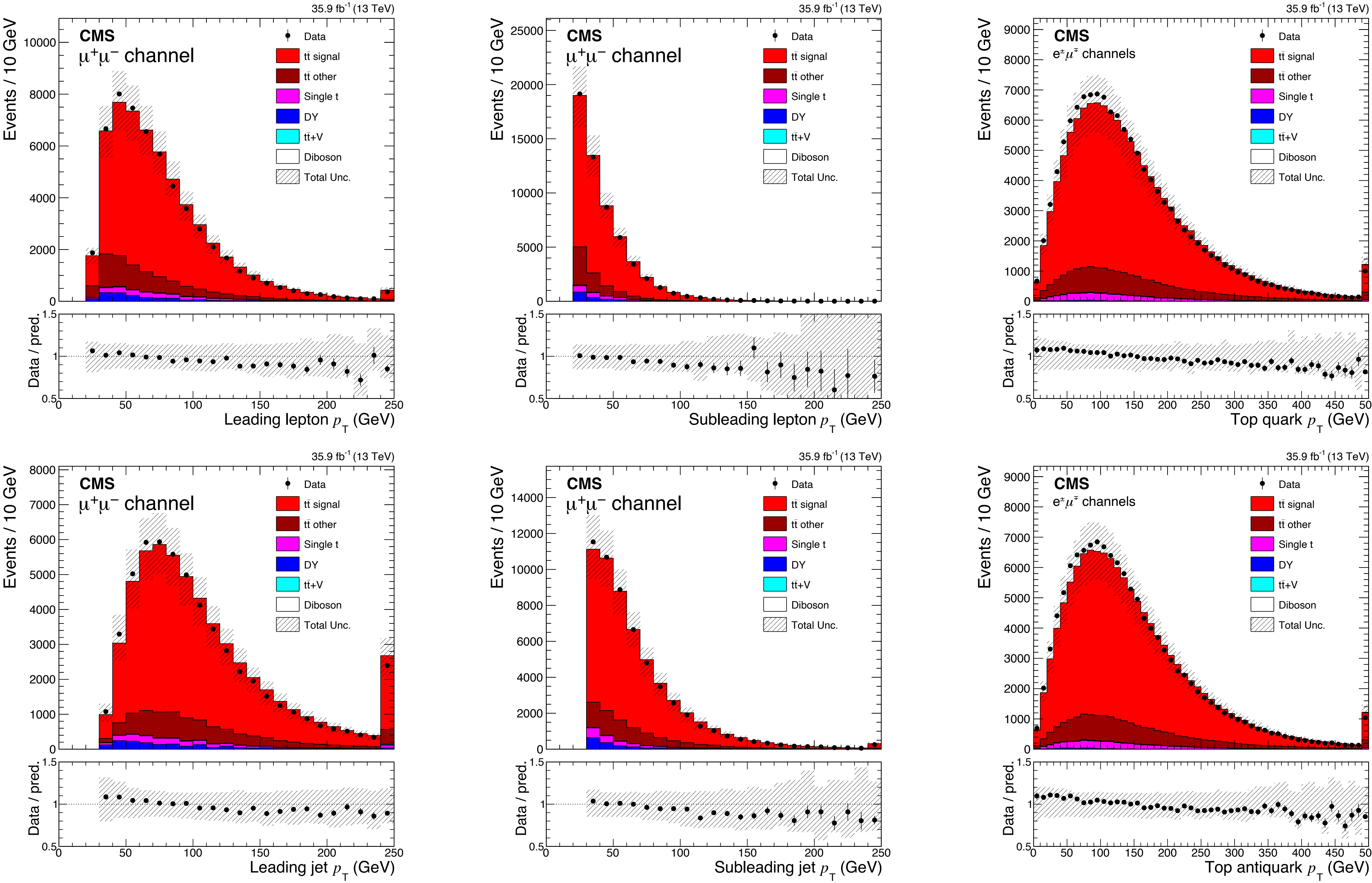
Kinematics of Object (e^+e^-)

- p_T distribution of leading leptons, jets and top quarks

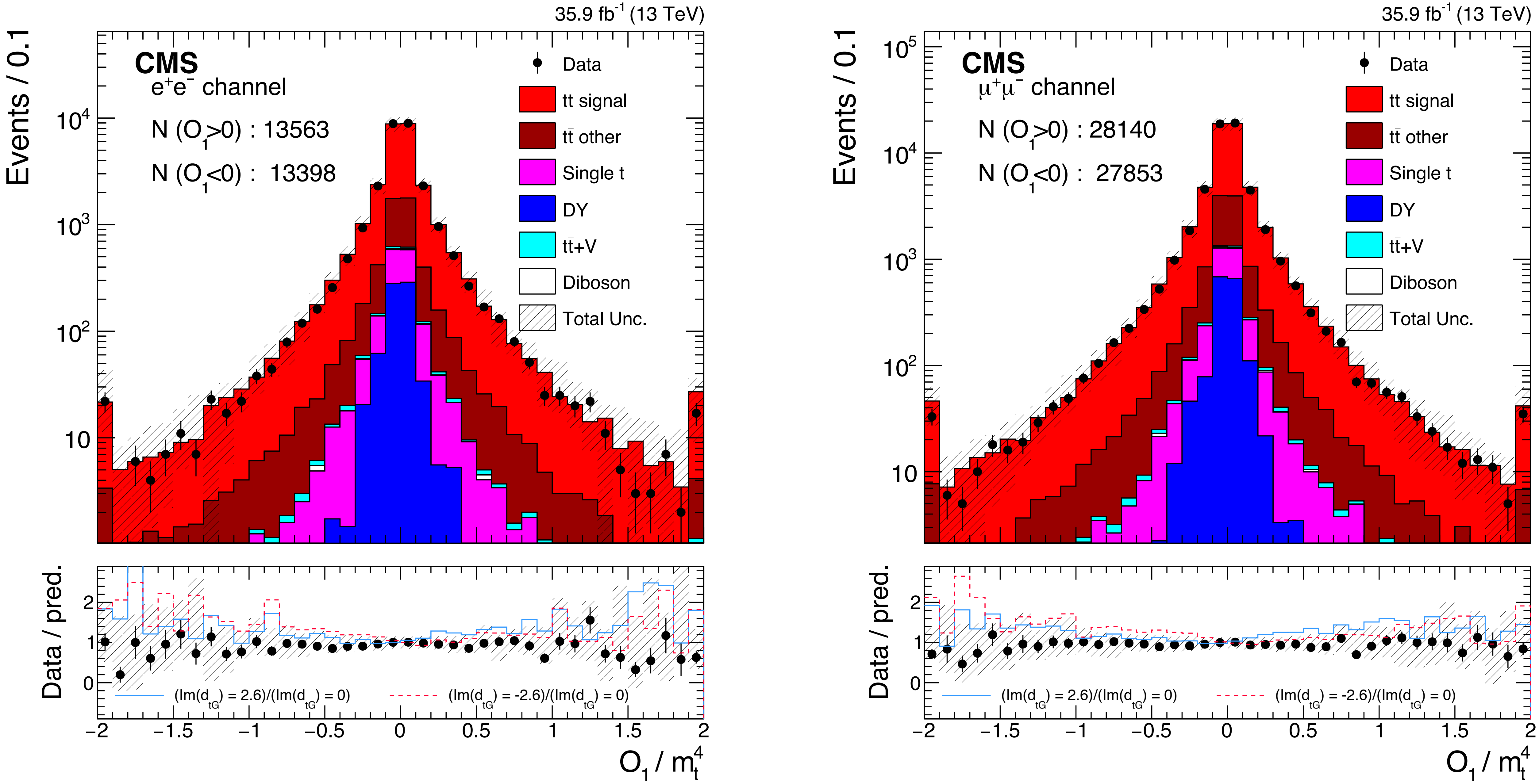


Kinematics of Object ($\mu^+\mu^-$)

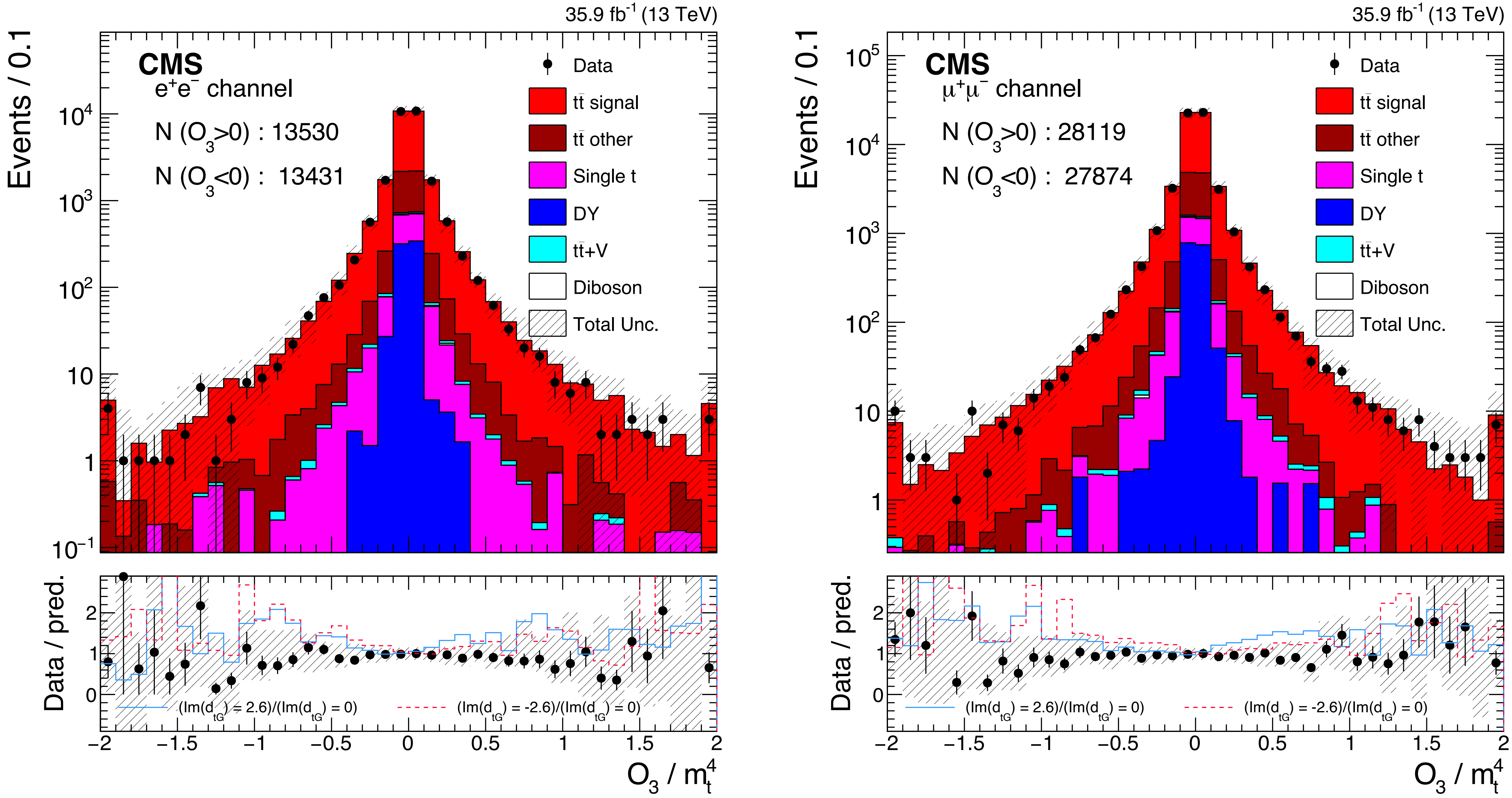
- p_T distribution of leading leptons, jets and top quarks



Dist. O1 (dielectron & dimuon)



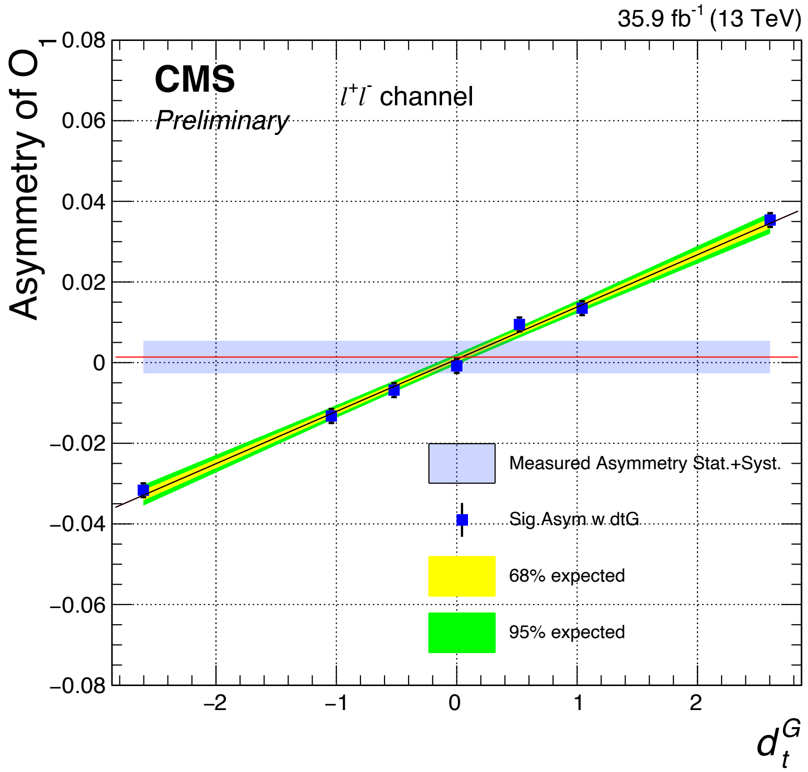
Dist. O3 (dielectron & dimuon)

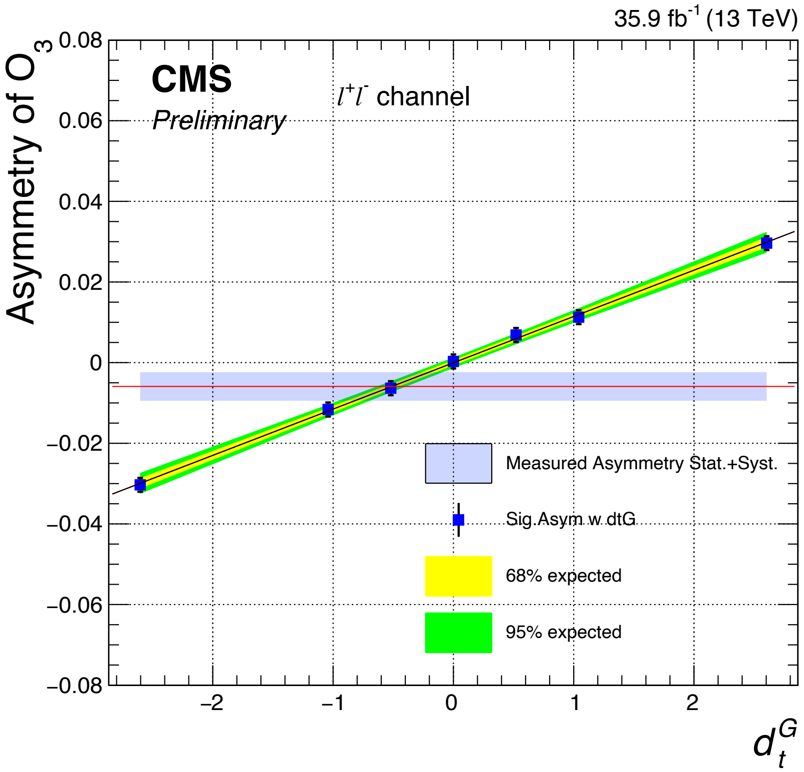


What we learned by TOP-18-007
Kinematic Solver (dtG vs Asym)

KinSolver | O1 | O3

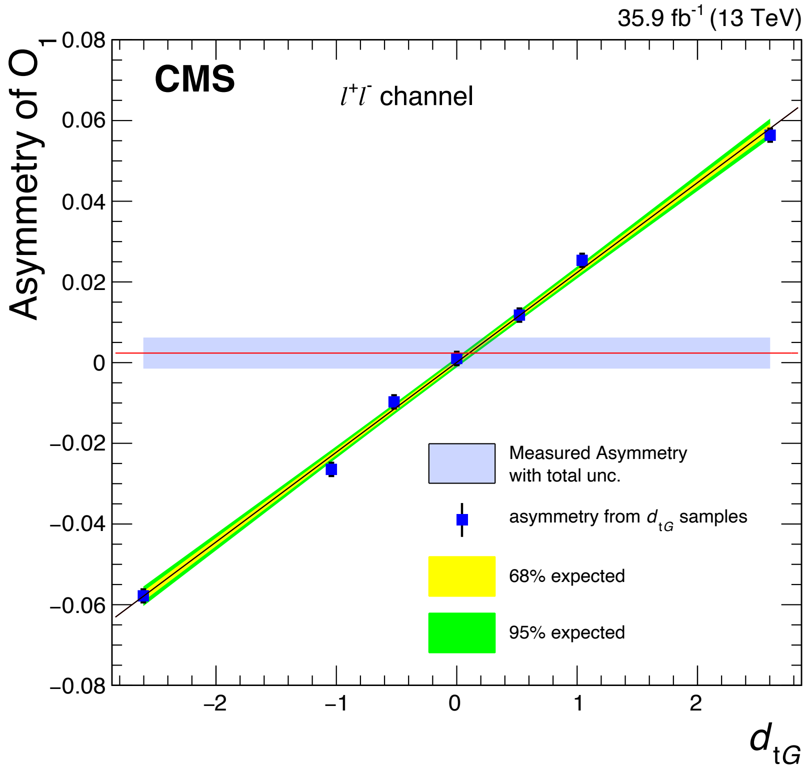
Old

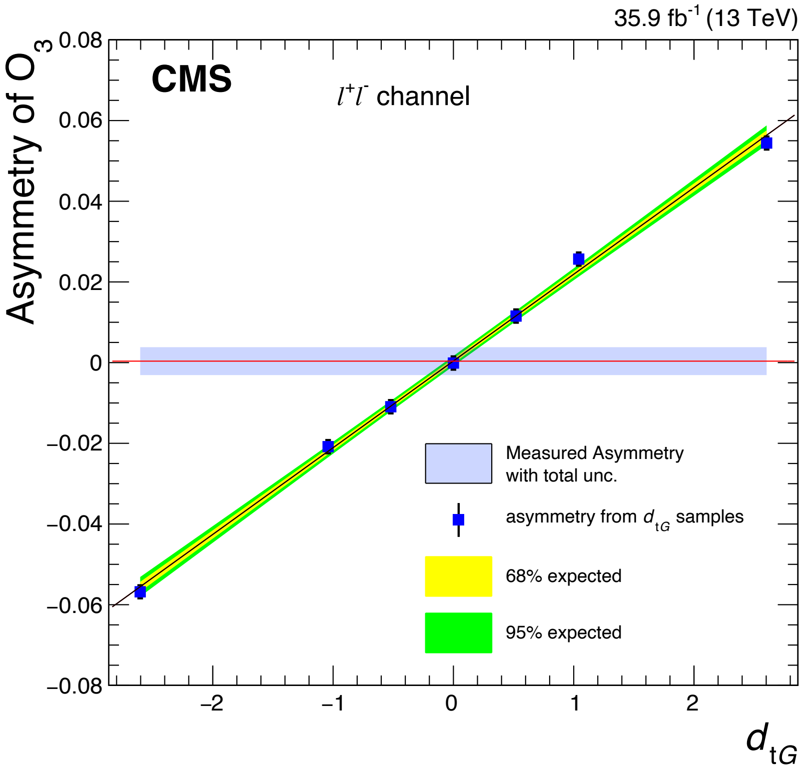




New kinematic solver has more sensitivity (dtG vs Asym.)

New



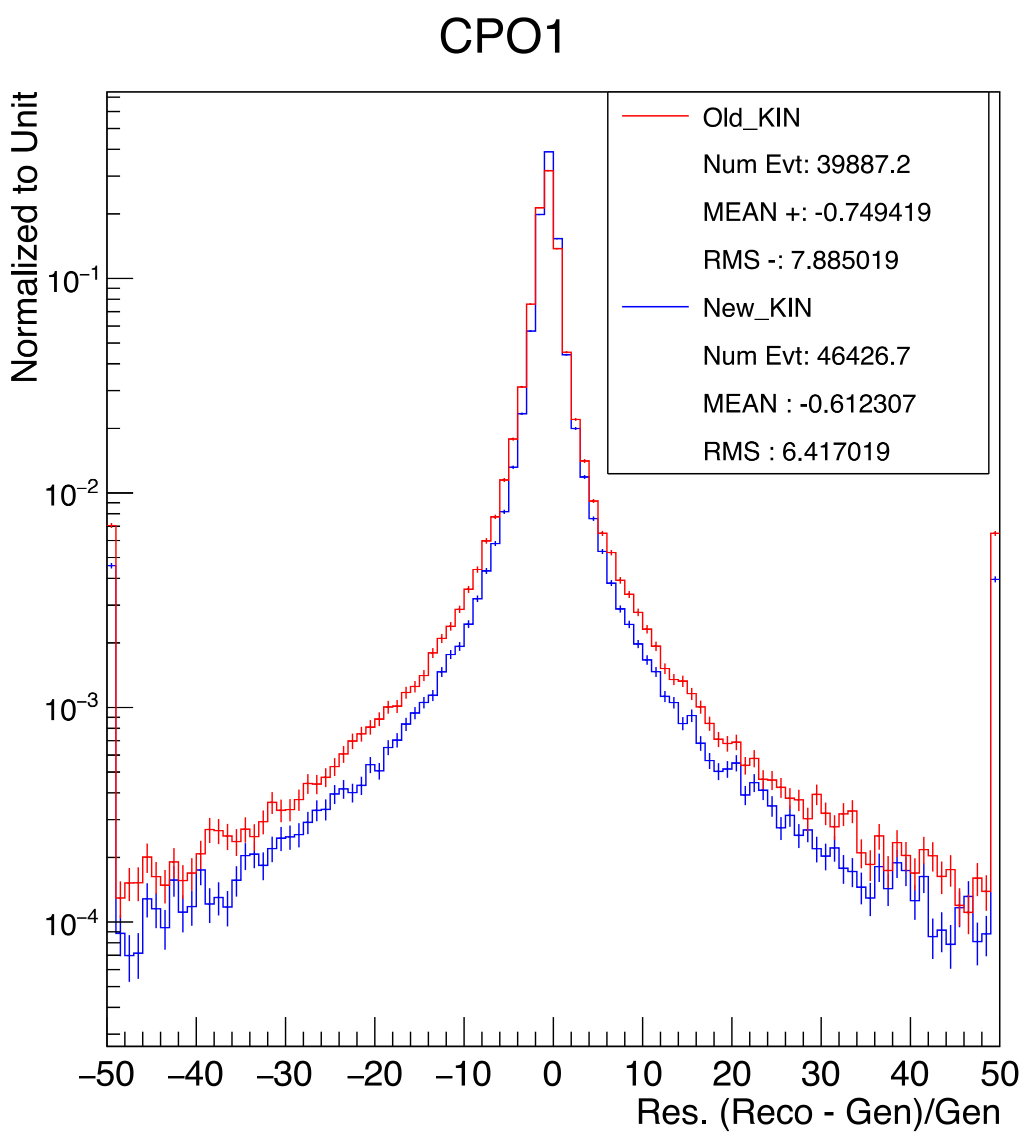


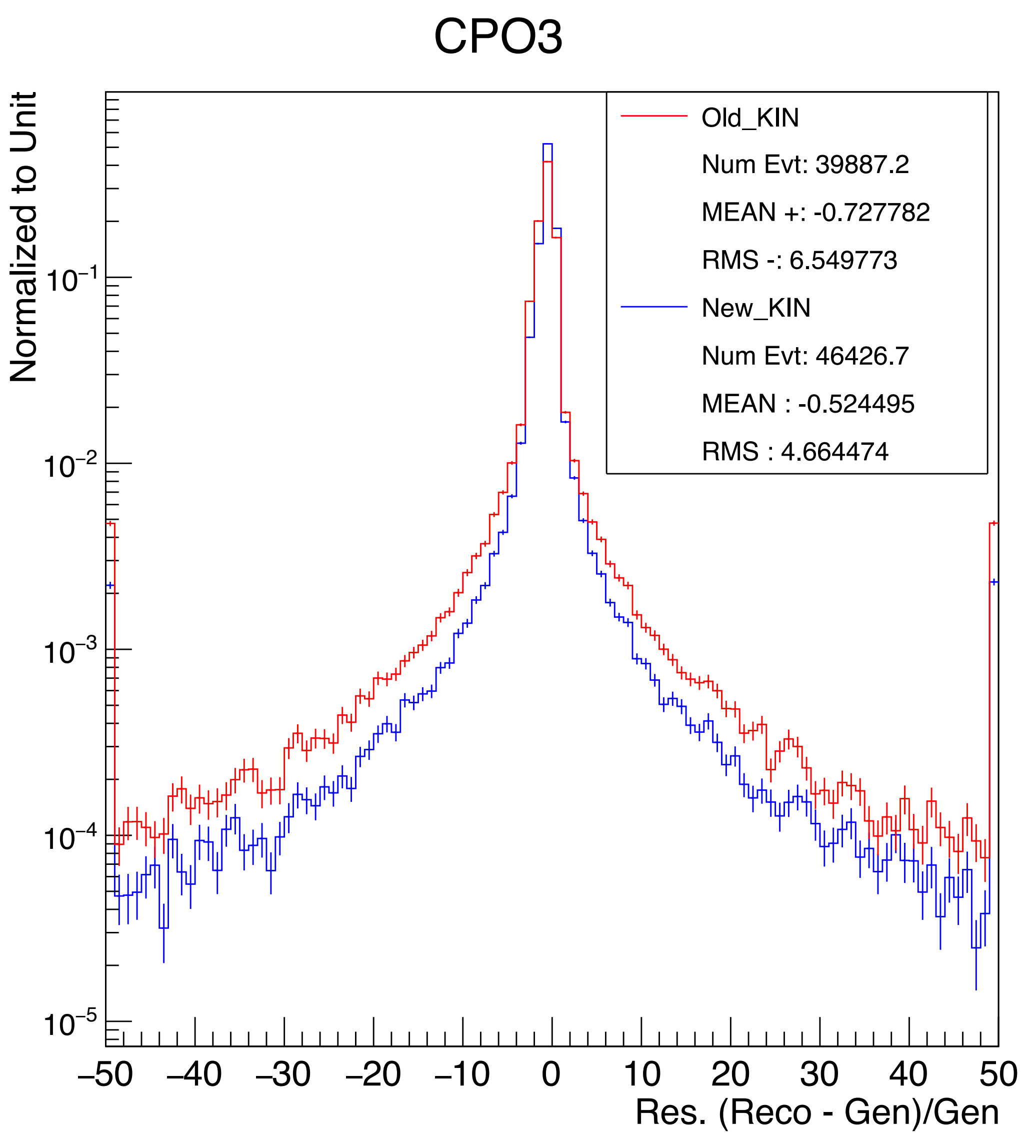
The reconstruction of top quarks are important.

Resolution of O1 and O3

Dimuon channel

$$\textbf{Resolution of } O_i = \frac{O_i\textbf{of Reco.} - O_i\textbf{of Gen.})}{(O_i\textbf{of Gen.})}$$

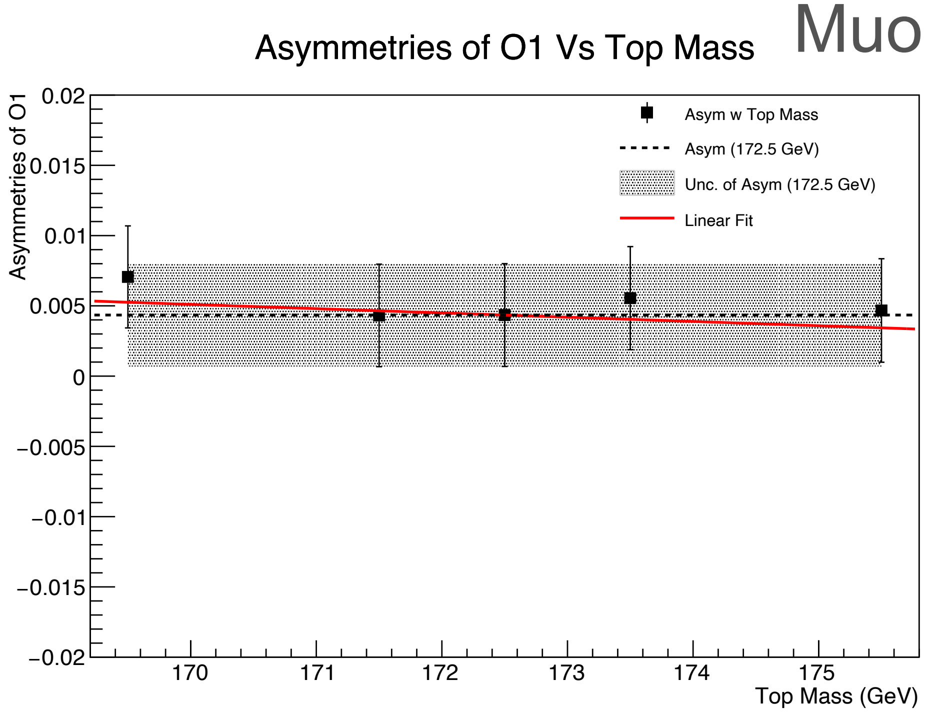

CPO1

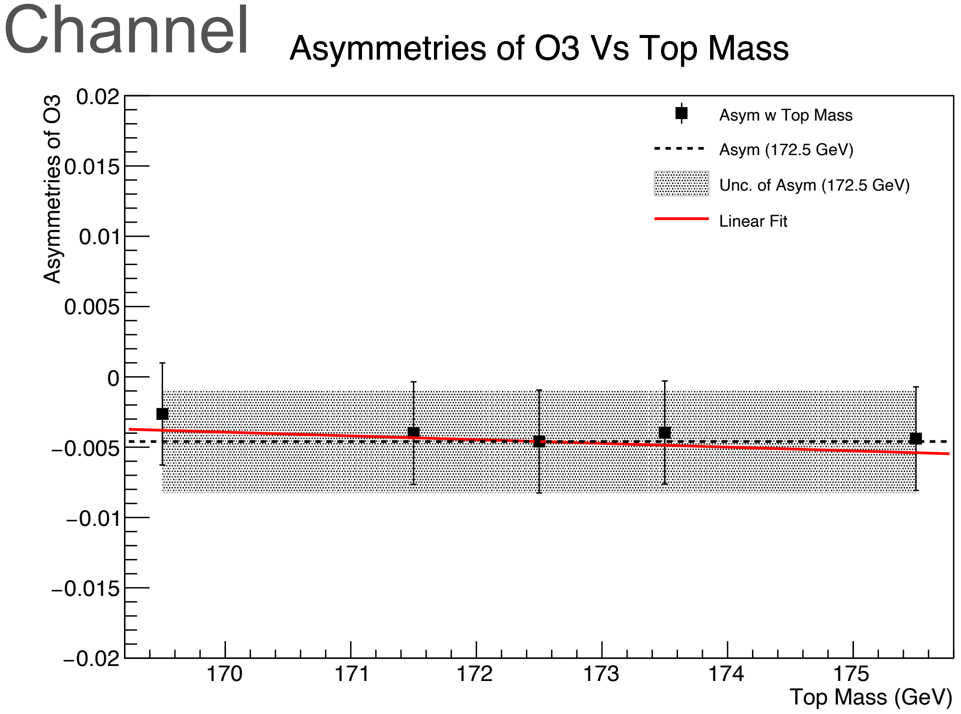

CPO3

Changed kinematic solver allows us more improved resolution of Observable.

Systematic Uncertainty (Top Mass Variation)

Muon-Electron Channel


Asymmetries of O1 Vs Top Mass


Asymmetries of O3 Vs Top Mass

Samples	**Top Mass Variation (GeV)**
TT_TuneCUETP8M2T4_mtop1695_13TeV-powheg-pythia8	3
TT_TuneCUETP8M2T4_mtop1715_13TeV-powheg-pythia8	1
TT_TuneCUETP8M2T4_13TeV-powheg-pythia8	0
TT_TuneCUETP8M2T4_mtop1735_13TeV-powheg-pythia8	1
TT_TuneCUETP8M2T4_mtop1755_13TeV-powheg-pythia8	3

Channel	**Variable**	**1-sig. up (Topmass)**	**1-sig. down (Topmass)**
Dimuon	O_1	0.0003	-0.0003
	O_3	0.0001	-0.0001
Dielectron	O_1	0.0003	-0.0003
	O_3	0.0003	-0.0003
Muon-electron	O_1	0.0003	-0.0003
	O_3	0.0003	-0.0003
Combined Channel	O_1	0.0001	-0.0001
	O_3	0.0002	-0.0002

Measured cross section

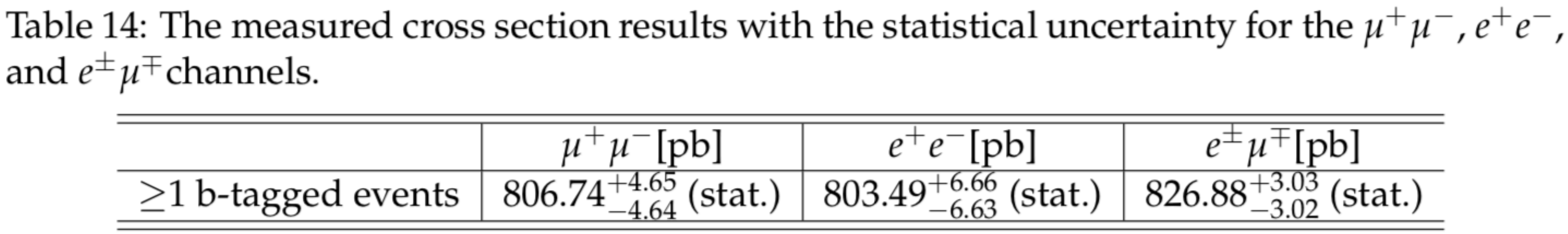


Table 14: The measured cross section results with the statistical uncertainty for the $\mu^+\mu^-$, e^+e^-, and $e^\pm\mu^\mp$ channels.

	$\mu^+\mu^-$[pb]	e^+e^-[pb]	$e^\pm\mu^\mp$[pb]
≥1 b-tagged events	$806.74^{+4.65}_{-4.64}$ (stat.)	$803.49^{+6.66}_{-6.63}$ (stat.)	$826.88^{+3.03}_{-3.02}$ (stat.)

Conversion of unit of CEDM

- Theory paper :10.1103/PhysRevD.93.014020

$$\mathcal{L} = \frac{g_s}{2}\bar{t}T^a\sigma^{\mu\nu}(a_t^g + i\gamma_5 d_t^g)tG_{\mu\nu}^a, \qquad (1)$$

$$d_t^g = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}(d_{tG}). \longrightarrow \boxed{\text{dimensionless CEDM}}$$

Since d_t^g has units of 1/Mass (GeV^{-1}), GeV^{-1} can be obtained by multiplying by (hbar c) in units of GeV-cm.

$$GeV^{-1} = 1.974 \times 10^{-14} \qquad gs = 1.2172$$

$$d_t^g = \frac{0.1137 \times 246GeV \times \sqrt{2}}{(1000GeV)^2} = 3.96 \times 10^{-5} GeV^{-1}$$

$$=> 3.96 \times 10^{-5} \times 1.974 \times 10^{-14} cm = 0.78 \times 10^{-18}/1.2172\ gscm$$

$$= 0.64 \times 10^{-18} gscm$$

CPV in Higgs Sector (CMS)

Title	Journal
Analysis of the CP structure of the Yukawa coupling between the Higgs boson and tau **leptons in proton-proton collisions at** sqrt(s) = **13 TeV**	Phys. Rev. Lett. 125 (2020) 061801
Search for a light charged Higgs boson decaying to a W boson and a CP-odd Higgs boson in final states with emumu or mumumu in proton-proton collisions at sqrt(s) =13 TeV	Phys. Rev. Lett. 123 (2019) 131802
Measurement of the top quark polarization and ttbar spin correlations using dilepton final states in proton-proton collisions at sqrt(s) = 13 TeV	PRD 100 (2019) 072002
Measurements of ttbarH production and the CP structure of the Yukawa interaction between the Higgs boson and top quark in the diphoton decay channel	Phys. Rev. Lett. 125 (2020) 061801