First measurement of single top quark production cross-section in association with W boson at 13 TeV with CMS detector

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Measurement of the production cross section for single top quarks in association with W bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

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Abstract: A measurement is presented of the associated production of a single top quark and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV by the CMS Collaboration at the CERN LHC. The data collected corresponds to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$. The measurement is performed using events with one electron and one muon in the final state along with at least one jet originated from a bottom quark. A multivariate discriminant, exploiting the kinematic properties of the events, is used to separate the signal from the dominant $\mathrm{t\bar{t}}$ background. The measured cross section of $63.1 \pm 1.8\,\mathrm{(stat)} \pm 6.4\,\mathrm{(syst)} \pm 2.1\,\mathrm{(lumi)}$ pb is in agreement with the standard model expectation.

Keywords: Hadron-Hadron scattering (experiments), Top physics

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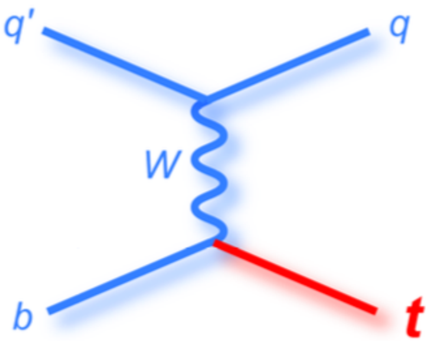
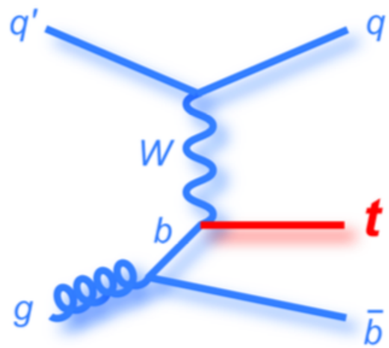
Outline

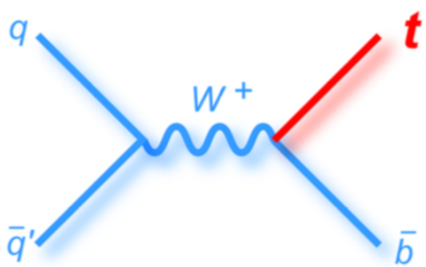
- ➢ Single top quark production at LHC
- ➢ Introduction & Motivation
- ➢ Cross section for top quark production at NNLO
- ➢ tW & tt interference and treatments
- ➢ Analysis signal & possible backgrounds
- ➢ Analysis Strategy, Object selection criteria & Status
- ➢ Results
- ➢ Summary & Outlook

Single top-quark production at LHC

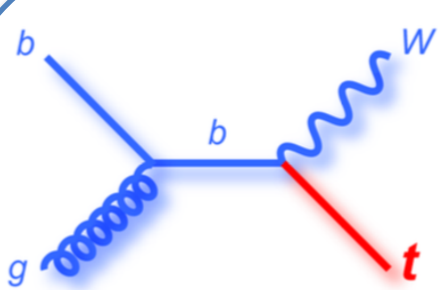


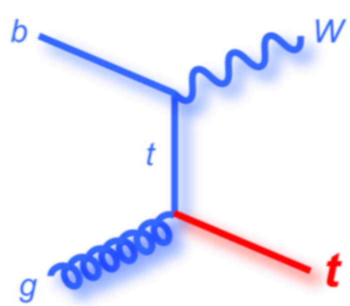


- t-channel: Dominant process at LHC.



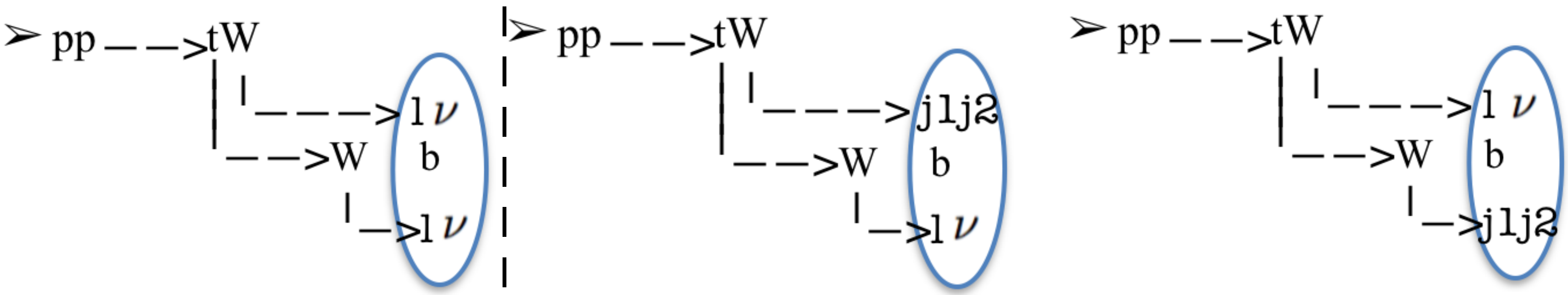
- s-channel: Least dominant process at LHC.





- Associated production of top quark & W boson (tW-channel): 2nd most dominant process at LHC.

Introduction & Motivation



Di-lepton (Clean Channel)

l can be electron or muon

Lepton+jets

- Both analyses are documented on the [tW Run2 twiki]
- Cross-section of Single top-quark production => |Vtb| matrix element of CKM matrix[1].
- Sensitive to non-SM couplings of Wtb vertex[1].
- Background to other searches (e.g. H->WW)

1) THE STANDARD MODEL AND THE TOP QUARK, Scott Willenbrock==>arXiv:hep-ph/0211067v3

Theoretical (experimental) cross sections (in pb) for top quark production at approximate NNLO.

Center of mass Energy	t-Channel (NNLO)	s-Channel (NNLO)	tW-Channel (NNLO)	tt~ (NNLO)
Tevatron (ppBar) 1.96TeV	$2.08^{+0.00}_{-0.04}\pm0.12$ ($3.04^{+0.54}_{-0.49}$)	$1.05^{+0.00}_{-0.01}\pm0.06$ ($1.29^{+0.26}_{-0.24}$)	0.22±0.08 (—)	$7.164^{+0.11+0.169}_{-0.20-0.122}$
LHC (pp) 7TeV[1,3,4]	$63.89^{+1.92+2.19}_{-1.25-2.19}$ (67.2±6.1)	$4.29^{+0.12}_{-0.1}\pm0.14$ (<26.5)	$15.74\pm0.4^{+1.1}_{-1.14}$ (16^{+5}_{-4})	$173.60^{+4.46}_{-5.85}\pm8.85$
LHC (pp) 8TeV[2,3,4]	$84.69^{+2.56+2.76}_{-1.68-2.76}$ (85±12)	$5.24^{+0.15}_{-0.12}\pm0.16$ (<11.5)	22.37±0.60±1.40 (23.4±5.4)	$247.74^{+6.26}_{-8.45}\pm11.47$
LHC (pp) 13TeV[3,4]	$216.99^{+6.62}_{-4.62}\pm6.16$ (219±1.5±32.9)	$10.32^{+0.29}_{-0.24}\pm0.27$	71.7±1.8±3.4	$815.96^{+19.37}_{-28.61}\pm34.38$ at NNLO+NNLL (772±60±62)

3.2 ~ 3.3

References:

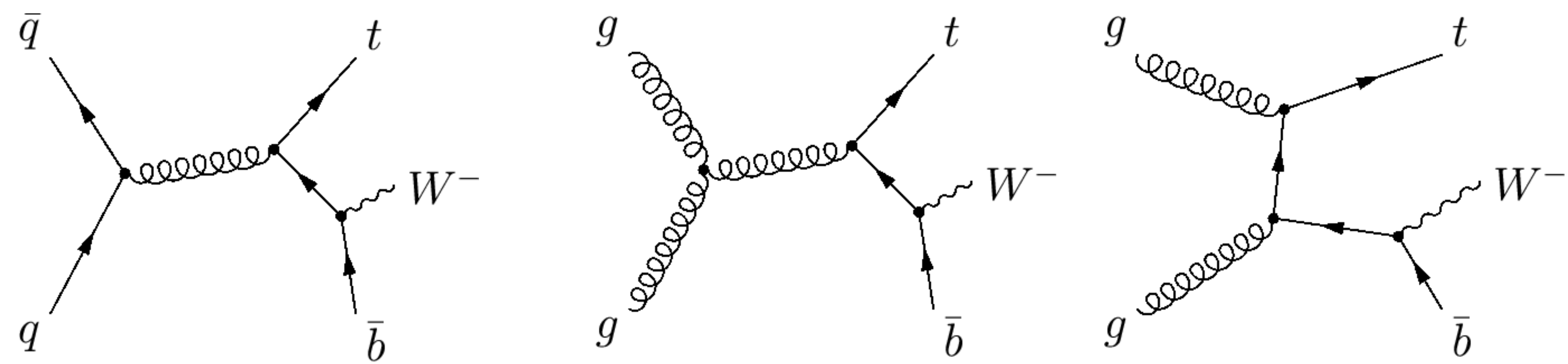
- [1]Evidence for Associated Production of a Single Top Quark and W Boson in pp Collisions at 7TeV, PRL 110, 022003 (2013).
- [2]Observation of the Associated Production of a Single Top Quark and a W Boson in pp Collisions at 8TeV, PRL 112, 231802 (2014)
- [3]https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec#Single_top_t_channel_cross_sect
- [4]https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO#Top_quark_pair_cross_sections_at

$t\bar{t}$ and tW

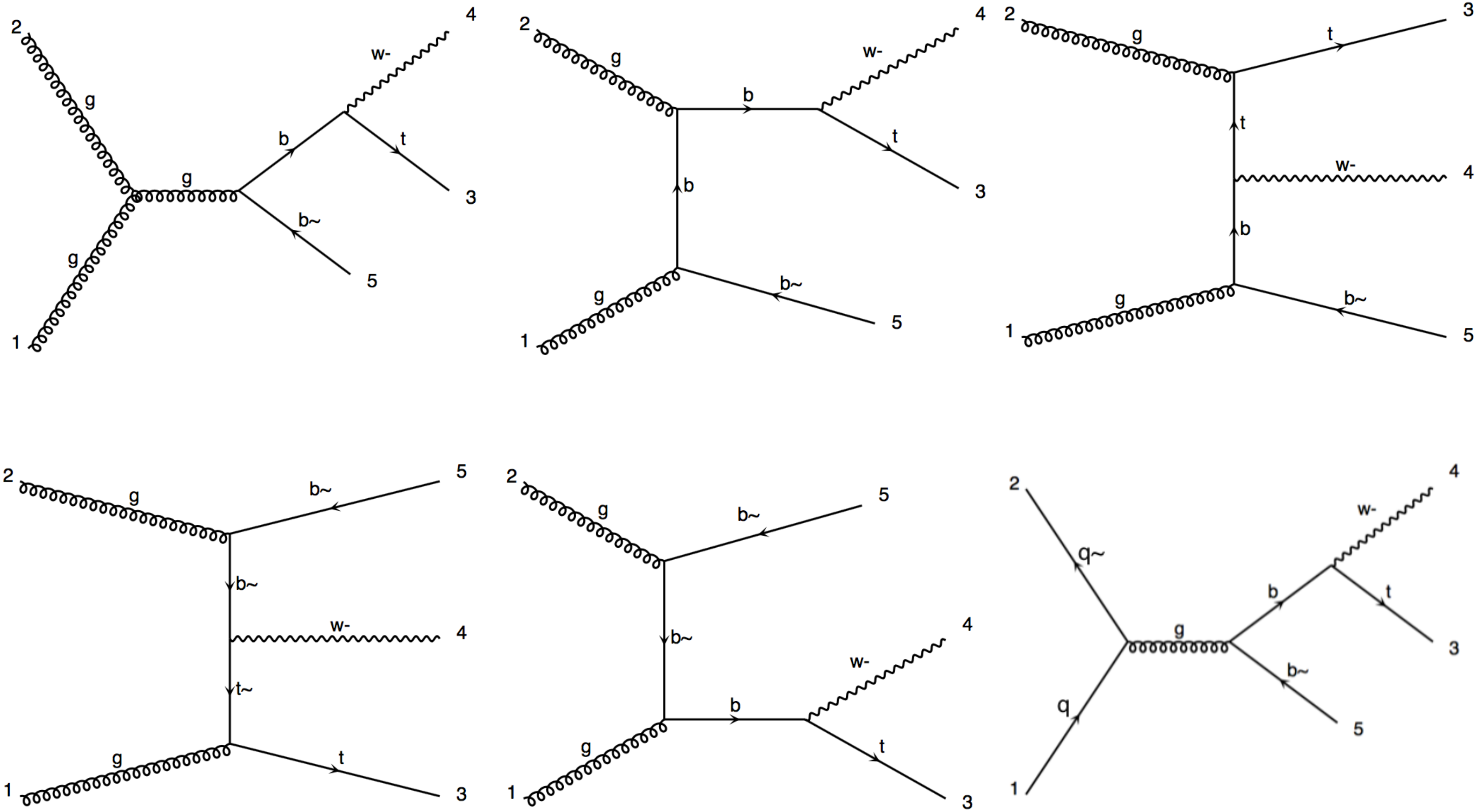
☞At LO the two processes are well defined and independent, but $t\bar{t}$ is still the dominant background

- Much larger cross section, and same final state if one b-jet is lost

☞***Challenge for tW-Channel:*** Interference at NLO level with top-quarks (tt~) pair production for extraction of tW signal.

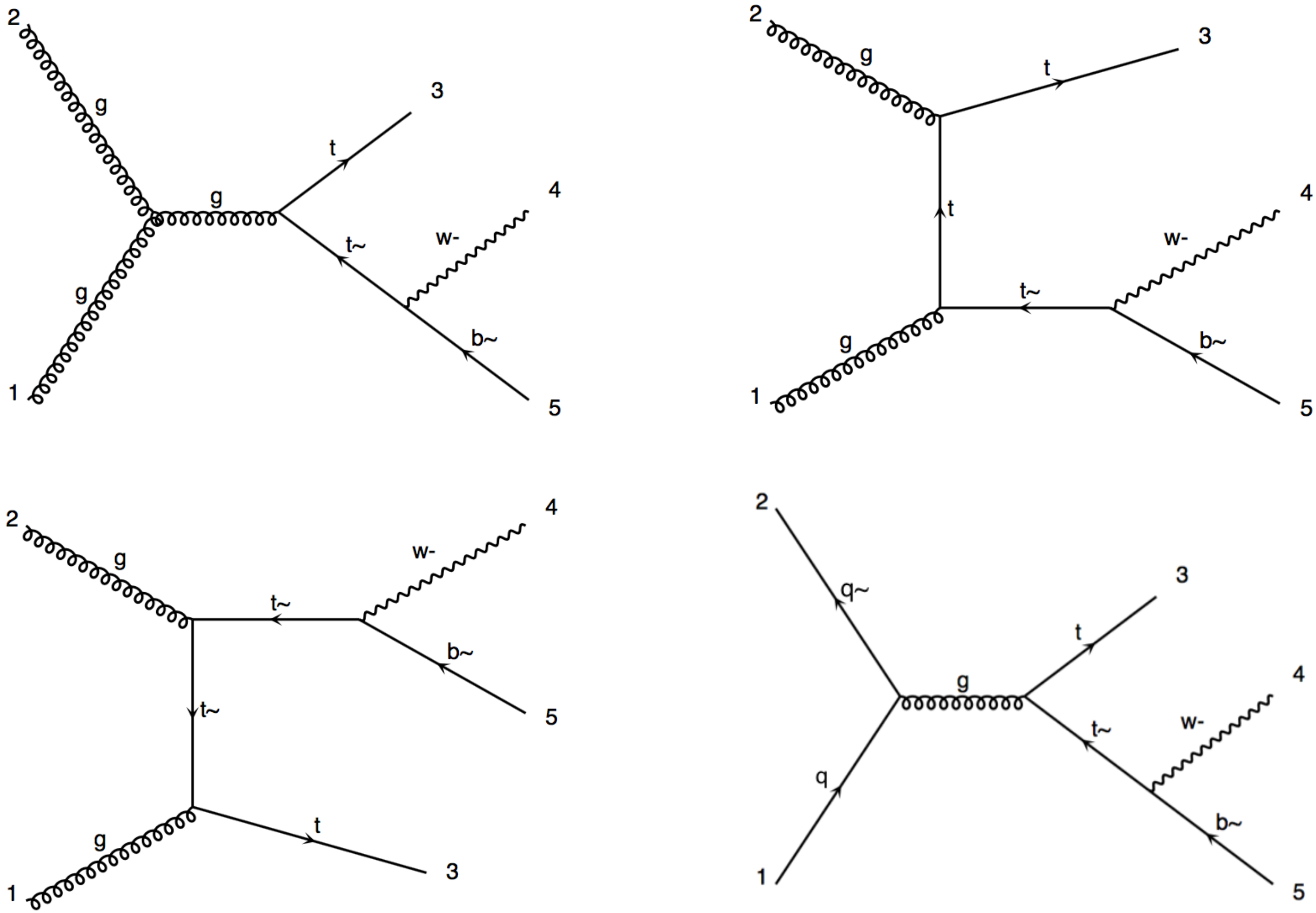


tW(NLO)



2 g g b w- 4 t 3 b~ 5 g 1
2 g b w- 4 t 3 b b~ 5 g 1
2 g t 3 t w- 4 b b~ 5 g 1
2 g b~ 5 b~ w- 4 t~ g t 3 1
2 g b~ 5 b~ w- 4 b t 3 g 1
2 q~ g b w- 4 t 3 b~ 5 q 1

tW(NLO-interference)



Treatments of $t\bar{t}$ and tW

- Theoretical difficulty overcome by Diagram Removal (DR)[1] & Diagram Subtraction (DS)[1].

$$\mathcal{M} = \mathcal{M}^{(tw)} + \mathcal{M}^{(tt\sim)}$$

$$|\mathcal{M}|^2 = |\mathcal{M}^{(tw)}|^2 + 2\mathrm{Re}\{\mathcal{M}^{(tw)}\mathcal{M}^{(tt\sim)*}\} + |\mathcal{M}^{(tt\sim)}|^2$$

- **Diagram Removal (DR)**: Removes doubly resonant diagrams in NLO Wt amplitudes.

$$|\mathcal{M}|^2 = |\mathcal{M}^{(tw)}|^2$$

- **Diagram Subtraction (DS)**: Implement a subtraction term to locally cancel the tt~ contribution to modify the NLO Wt cross section.

$$|\mathcal{M}|^2 = |\mathcal{M}^{(tw)} + \mathcal{M}^{(tt\sim)}|^2 - C^{SUB}$$

$$g + g \to W^- + t + \bar{b}$$

$$k_1 \quad k_2 \quad k_3$$

$$C^{SUB} = \frac{(m_t\Gamma_t)^2}{((k_1+k_2)^2 - m_t^2)^2 + (m_t\Gamma_t)^2}\,|\mathcal{M}^{t\bar{t}}(\mathbf{\Phi}_3')|^2$$

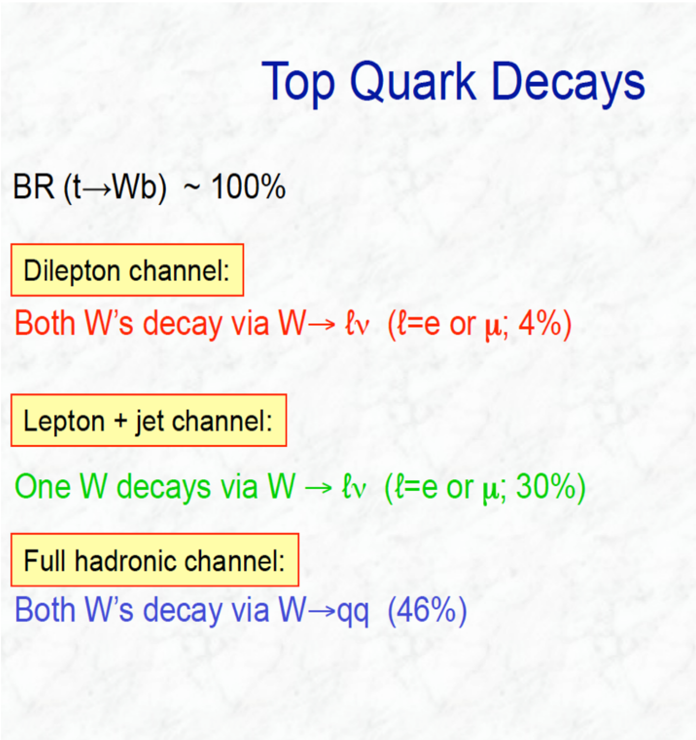
$\mathbf{\Phi}_3'$: 3-body phase space point obtained by reshuffling $\mathbf{\Phi}_3$ kinematics to get

$$(k_1 + k_3)^2 = m_t^2$$

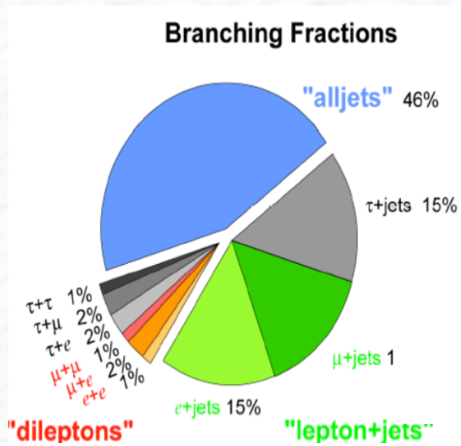
➢ ***DR-DS*** $= |\mathcal{M}^{(tw)}|^2 - [|\mathcal{M}^{(tw)} + \mathcal{M}^{(tt\sim)}|^2 - C^{SUB}] = 2\mathrm{Re}\{\mathcal{M}^{(tw)}\mathcal{M}^{(tt\sim)*}\}$

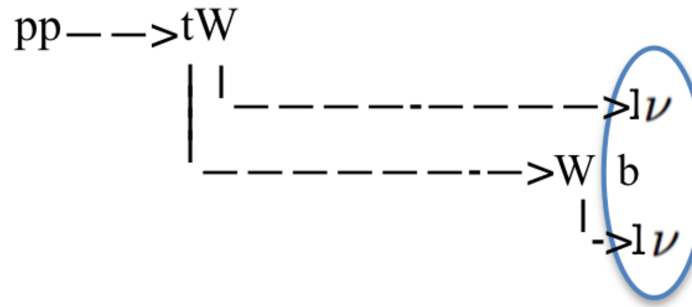
[1] Single-top hadroproduction in association with a W boson, Stefano Frixione, Eric Laenen, Patrick Motylinski and Chris White, Bryan R. Webber==> arXiv:0805.3067v1 [hep-ph]

Analysis Channel



Top quarks decay predominantly (~100%) to a W Boson and a b-quark.





Final state

Channel study consists:

eμ2νb, ee2νb, μμ2νb

- In final state we have 2 opposite charge leptons. Leptons include e,μ
- Additionally, we have 2 neutrinos, constitute Missing Energy
- Also b-jet

Possible Backgrounds

☞ $t\bar{t}$: $t\bar{t}$ $\longrightarrow$ WWbb $\longrightarrow$ 2l2ν2b & 1b is not detected.

☞ **Z+jets:** Z decays to e^+e^- or $\mu^+\mu^-$ & mis-measurement of jet energy causes the missing energy.

☞ **W+jets:** W decays leptonically & one of the jets fake as lepton.

☞ **ZZ:** One Z decays to e^+e^- or $\mu^+\mu^-$ & Second decays hadronically, but mis-measurement of jet energy causes the missing energy.

☞ **WZ:** (i) Either W decays hadronically & Z leptonically, but mis-measurement of jet energy causes the missing energy OR (ii) W decays leptonically & Z decays leptonically.

☞ **WW:** Both W decays leptonically.

☞ **Non W/Z:** Arise from processes with one prompt-lepton (decaying from a W or a Z boson) and one non-prompt lepton that passes the isolation and identification criteria.

Data Samples and triggers

- Analysis is performed over the complete 2016 dataset (35.9 fb^{-1})
- SingleElec, SingleMuon, DoubleElec, DoubleMuon and MuonEG primary datasets
- Run2016B-Run2016H (03Feb2017 ReReco)
- Using offical JSON: Cert_271036-284044_13TeV_ 23Sep2016ReReco_Collisions16_JSON.txt
- Trigger strategy as in TOP trigger twiki

Run B-G and MC	Run H
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v* HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v* HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Ele27_WPTight_Gsf v* HLT_IsoTkMu24_v* HLT_IsoMu24 v*	HLT_Ele27_WPTight_Gsf_v* HLT_IsoTkMu24_v* HLT_IsoMu24_v*

MC Datasets

- Monte Carlo samples of tW and $t\bar{t}$ used in the analysis

Sample	σ [pb]	Events
/TT_TuneCUETP8M2T4_13TeV-powheg-pythia8	831.8	77,229,341
/TT_TuneCUETP8M2T4_13TeV-powheg-pythia8 (_backup)	831.8	78,006,311
/TTTo2L2Nu_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8	831.8	79,092,400
/ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1 (_ext1-v1)	35.85	6,952,830
/ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1 (_ext1-v1)	35.85	6,933,094
/ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1	19.467	5,372,991
/ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1 (_ext1-v1)	19.467	3,256,650
/ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1 (_ext2-v2)	19.467	2,715,978
/ST_tW_antitop_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1	19.467	5,425,134
/ST_tW_antitop_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1 (_ext1-v1)	19.467	3,256,407
/ST_tW_antitop_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1 (_ext2-v1)	19.467	2,726,603

- Dileptonic ($t\bar{t}$) and “not fully hadronic” (tW) samples are used for BDT training, inclusive for background estimation and signal extraction
- Other backgrounds
  - DY: M50 and M10to50 amcatnloFXFX-pythia8
  - W+jets: madgraphMLM
  - ttV: amcatnloFXFX-pythia8
  - VV: pythia8

Di-lepton(eμ) Analysis Strategy

- HLT (Logical OR between single & double lepton triggers)
- At least two well identified, isolated leptons.
- Leptons must be with opposite charge (signal)
- m_{ll} > 20 GeV (Suppress low mass Resonances)

Pre-selection

☞Signal region: 1jet 1b-tag, 2jet 1b-tag, 2jet 2b-tag

➤ **Distinguish signal (tW) from background ($t\bar{t}$) :**

- Multivariate technique (MVA) => Boosted decision tree (BDT).

➢ Simultaneous Likelihood fit over the different regions to BDT discriminant to separate signal tW and dominant $t\bar{t}$ background.

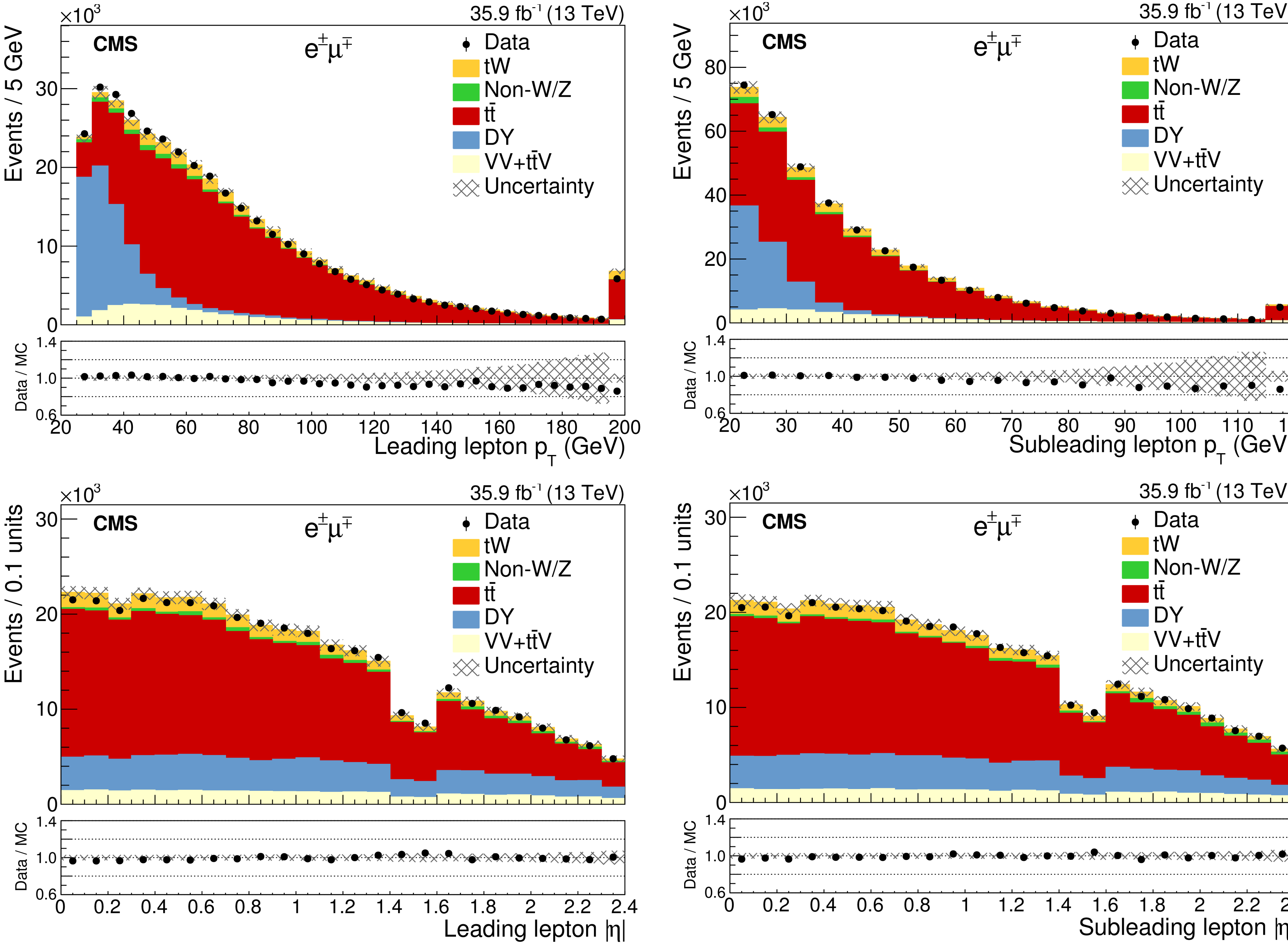
Selection Criteria-I ✓

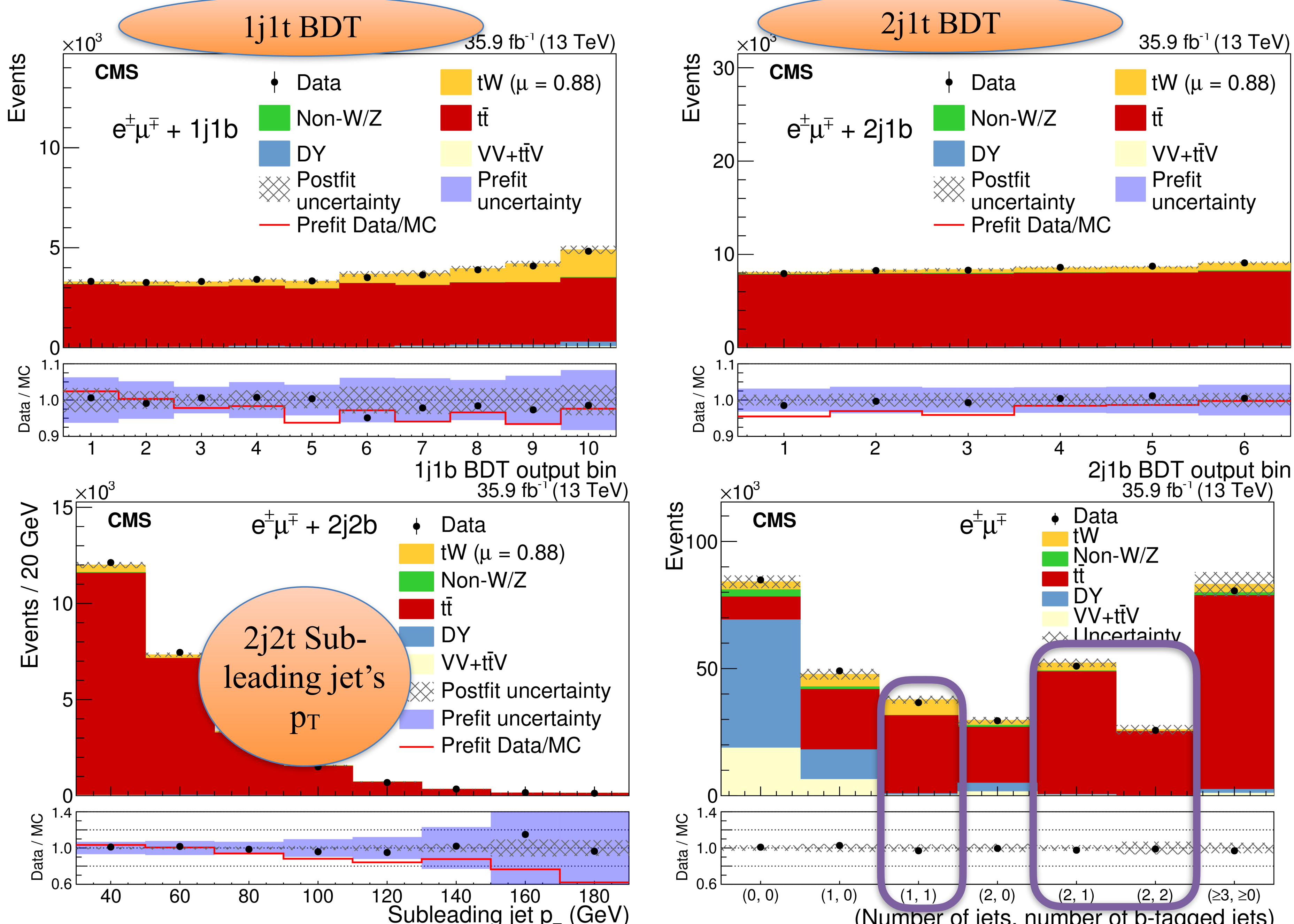
- *Event should have atleast one Tight Electron and one Tight muon*
  - **Electrons**
    - ☞ Cut based identification with **Tight** working points electronID
    - ☞ $\mathbf{P_T}$ > 20GeV, |**eta**| < 2.4
    - ☞ **Gap veto:** 1.4442 < |$\mathbf{eta}_{sc}$| < 1.566
  - **Muons**
    - ☞ **Tight** ID MuonID
    - ☞ $\mathbf{P_T}$ > 20GeV, |**eta**| < 2.4

Leading Lepton's P_t > 25GeV

- **Jets**
  - ☞L1Fastjet, L2, L3 JECs for MCs.
  - ☞MC's+L2L3Residual JECs for real data.
  - ☞$\mathbf{P_T}$ > 30GeV, |**eta**| < 2.4
  - ☞**Loose** ID JetID
  - ☞CSVv2M=0.8484 bTaggingLink
  - ☞jet-lepton cleaning dR < 0.4
- **Met**
  - ☞Used Type-I Corrected MET.
  - ☞Recommended Filters applied.

Data-MC comparison for several lepton kinematic variables at pre-selection level





- Signal strength extracted using a maximum likelihood fit to the shape of 1j1tBDT, 2j1tBDT,2j2t sub-leading jet's p_T

Summary & Outlook

- tW production cross-section paper has been published in JHEP (Cadi-line: TOP-17-018).

- Signal extraction and cross-sections are measured to be:

$$\mu = 0.88 \pm 0.02(stat.) \pm 0.09(syst.) \pm 0.03(lumi.)pb$$
$$\sigma_{tW} = 63.1 \pm 1.8(stat.) \pm 6.4(syst.) \pm 2.1(lumi.)pb$$
$$\sigma_{tW}(NNLO) = 71.7 \pm 1.8(scale) \pm 3.4(PDF)pb$$

- Main uncertainties: JES, lepton identification, tt modeling

THANK YOU