Measurement of the top-quark mass using t-channel single top events

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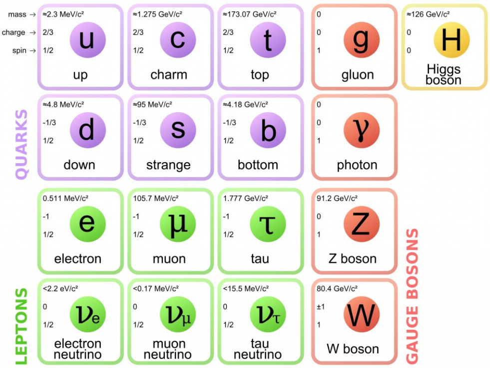
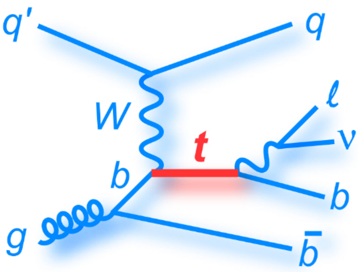
The Top quark

- Top quark is a most massive elementary particle in the standard model (SM)
- It has the largest coupling with the Higgs boson
- Top and antitop quark pair ($t\bar{t}$) production is the largest contributor to top quark events as well as to top mass measurement
  - Systematic uncertainty dominates over the statistical one (m_t=172.5$\pm$ 0.20 $\pm$0.98 GeV)



- t-channel process is the largest contributor to single top quark production
  - This process is cleaner compared to $t\bar{t}$ due to absence of color reconnection effects

t-channel process



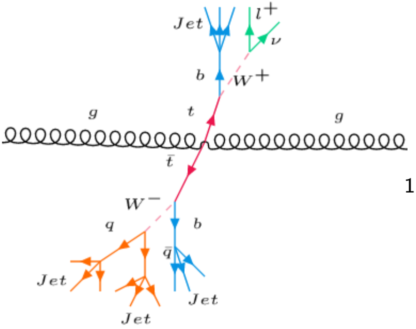
t-channel process
$\sigma = 216$ pb @ 13 TeV

- t-channel is an electroweak process and is considered as signal in our analysis
- This process has two or more jets of which one is b-tagged, coming from the top decay
- There is a light flavor jet recoiling against the top quark
- We also have an isolated electron and large missing transverse energy due to escaping neutrino

Parton

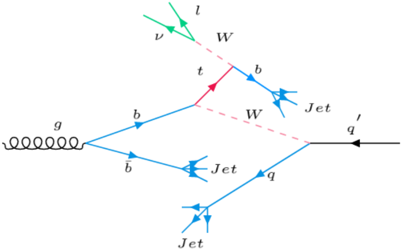
Advantage of t-channel single process

$t\bar{t}$ **process**



[1]

t-channel process



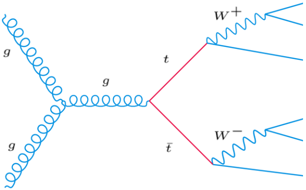
To the total systematic uncertainty (0.98 GeV) in the $t\bar{t}$ sample, color reconnection contributes at the 20-30% level

provides a statistically a independent sample, where color reconnection is less of worry

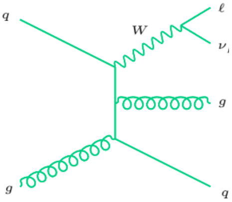
[1] arXiv:1812.10534

Background processes

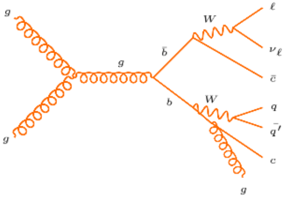
- The most significant background process is $t\bar{t}$ where one t undergoes the leptonic decay
- W+jets & Z+jets are the next dominant contributor followed by QCD multijet process
- Other two single top processes are also considered as background



$t\bar{t}$ process
$\sigma = 831$ pb



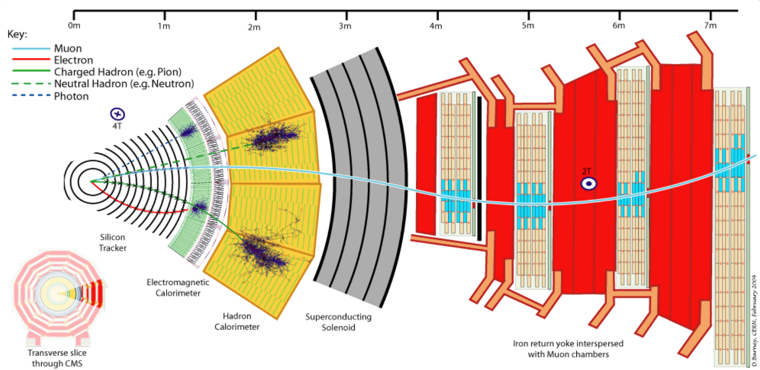
W+Jets process
$\sigma = 63$ nb



QCD multijet
$\sigma = 302$ nb

cross section

CMS Detector



- Silicon tracker has two parts: inner pixel and outer strip detector
- Electromagnetic calorimeter (ECAL) is made up of lead tungstate crystals
- Hadron calorimeter is comprised brass and plastic scintillators
- Outside the solenoid, there are gas ionizing detectors embedded in the steel flux return yoke to identify muons
- In our analysis, information from each sub-detector is used

cross view

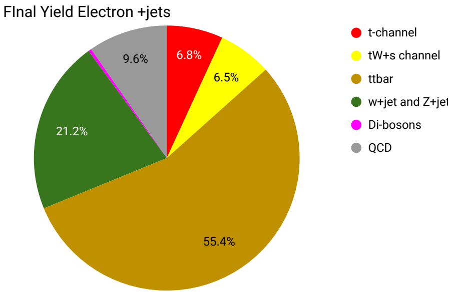
Data and simulated samples

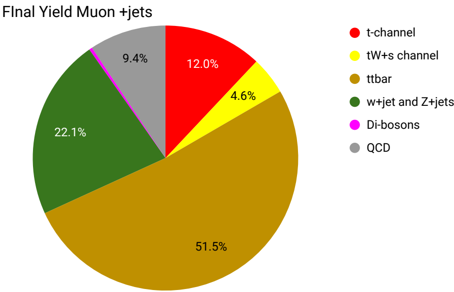
- Data sample collected by the CMS detector in proton-proton collisions at center-of-mass energy 13 TeV during 2016 is used; the corresponding luminosity is 35.9 fb^{-1}
- Signal process t-channel is generated using POWHEG generator
- Among background processes, tW channel and $\mathrm{t\bar{t}}$ process are also generated by POWHEG
- All other backgrounds are generated with aMC@NLO
- QCD is estimated by a data driven method
- PYTHIA8 is used to model the showering
- All generated events are passed through full simulation of the CMS detector using GEANT4

Event selection

- **Trigger:**
  μ: HLT_Iso(Tk)Mu24
  e: HLT_Ele32_eta2p1_WPTight_Gsf
- **Exactly 1 lepton:**
  μ: p_T >26 GeV, $|\eta|$<2.4, tight ID, $\mathrm{I_{rel}}$ <0.06 within ΔR=0.4
  e: p_T >35 GeV , $|\eta|$<2.1 , passes cut-based tight ID , EB-EE transition gap excluded,
  IP cuts: for $|\eta_{\mathrm{SC}}|$<=1.479 , $|\mathrm{d_{xy}}|$<0.05 cm and $|\mathrm{d_z}|$<0.10 cm , for $|\eta_{\mathrm{SC}}|$>=1.479 , $|\mathrm{d_{xy}}|$<0.10 cm and $|\mathrm{d_z}|$<0.20 cm
- **Veto events having another lepton:**
  p_T >10 (15) GeV , $|\eta|$<2.4 (2.5), loose (veto) ID, $\mathrm{I_{rel}}$ <0.2 for $\mu(e)$
- **2 -3 AK4PFJets with:**
  p_T >40 GeV, $|\eta|$<4.7, loose ID, $\Delta\mathrm{R_{(lep,jets)}}$) >0.4
  Summer16_25ns_v1 corrections applied
- **1- 2 b-tag with**
  $|\eta|$<2.4 passing CMVAv2 tight working point
- m_t^w > **50 GeV** Tagging cut flow anti k`T Rel.iso trigg

Event selection

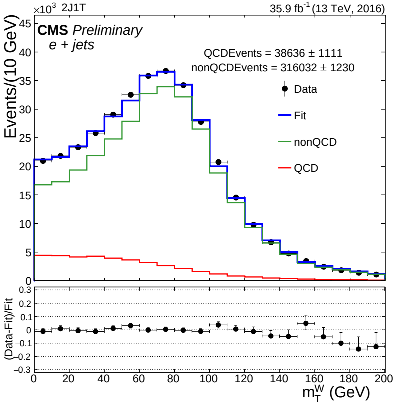




e + jets

μ **+ jets**

- QCD has high cross section but has a very low selection efficiency
- Require high stat. $\Rightarrow$ time consuming $\Rightarrow$data-driven estimate
  - Go to the sideband (anti-isolation)$\rightarrow$ Subtract nonQCD from this SB $\Rightarrow$ data-driven QCD template

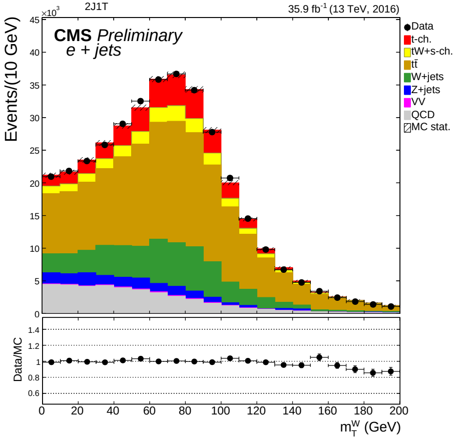


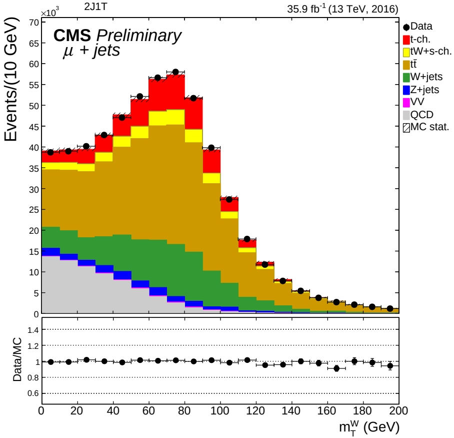
Data driven QCD fit

- Maximum likelihood fit to data in the signal region.
- $F(m_t^W) =$ $\mathrm{N_{QCD}} \times P(m_t^W) +$ $\mathrm{N_{nonQCD}} \times Q(m_t^W)$
- $\mathrm{P}(\not{p}_\mathrm{T})$ & $\mathrm{Q}(\not{p}_\mathrm{T})$ are QCD and nonQCD templates
- $\mathrm{N_{QCD}}$ and $\mathrm{N_{nonQCD}}$ are the corresponding yields

Met

Data-MC comparison after the fit

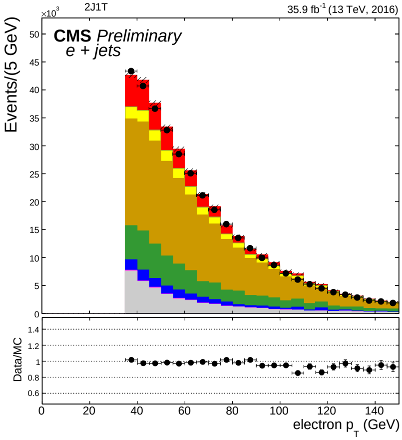


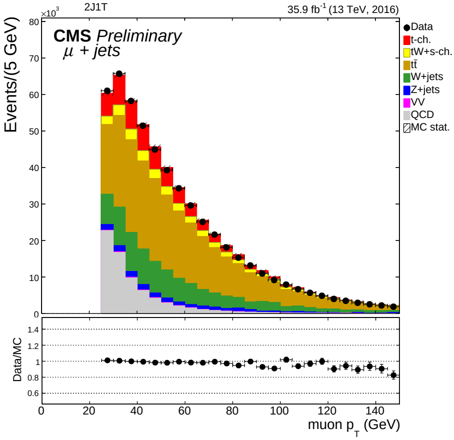


m_t^W distribution of e + jets final state

m_t^W distribution of μ + jets final state

Data-MC comparison after the fit (contd.)





Electron p_T distribution of e + jets final state

Muon p_T distribution of μ + jets final state More 3J1T

Fox-Wolfram moments in 2J1T region

- Describe correlation between jets based on event topology
- Calculated from all the selected jets in each event
- When there are two jets in the event, we get basic

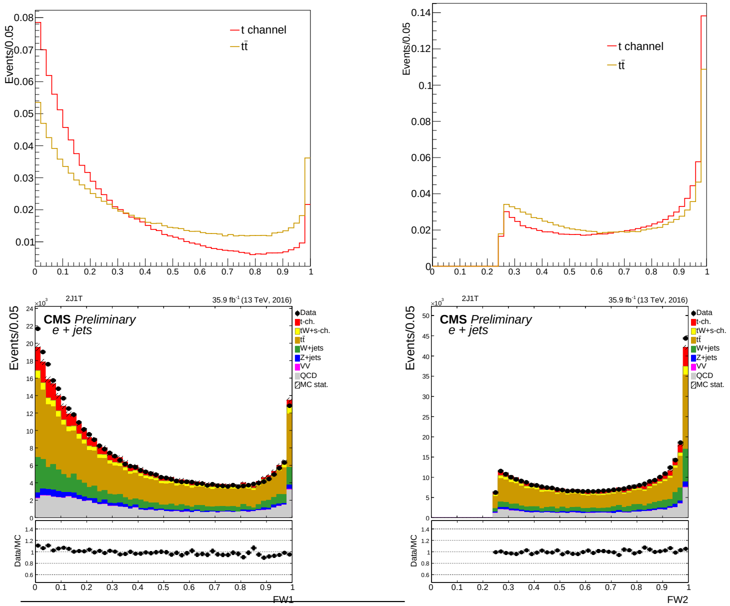
$$\mathrm{H}_l = \frac{1 + r^2 + 2r\mathrm{P}_l \cos\Omega_{12}}{(1+r)^2} \quad (1)$$

Here r is the ratio of p_T of the jets and Ω_{12} is angle between the jets

- First and second Fox-Wolfram moment for 2J1T region are:

$$\mathrm{H}_1 = \frac{1 + r^2 + 2r\cos\Omega_{12}}{(1+r)^2}$$
$$\mathrm{H}_2 = \frac{1 + r^2 + 2r(\cos^2\Omega_{12} - 1)}{(1+r)^2} \quad (2)$$

Fox-Wolfram moment distributions



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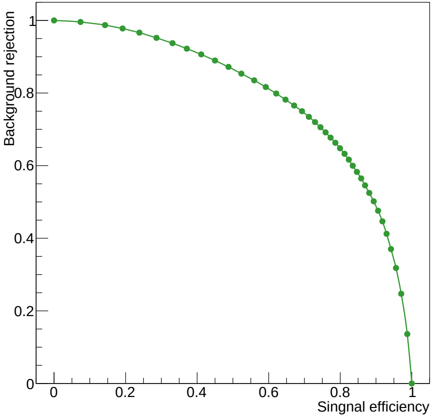
Performance of Fox-Wolfram moments in BDT

Rank	Variable	Separation
1	ΔR b/w b tag jet & untagged jet	2.097×10^{-1}
2	$\|\eta\|$ of untagged jet	2.047×10^{-1}
3	Sum of mass of both jet	1.676×10^{-1}
4	$\cos\theta^*, \theta$ is angle b/w elec & untagged jet	7.089×10^{-2}
5	m_t^W transverse mass of the W	4.792×10^{-2}
6	First Fox-Wolfram moment	2.985×10^{-2}
7	$\|\Delta R\|$ b/w electron and b tag jet	1.267×10^{-2}
8	Sum of P_T's of both jet	1.013×10^{-2}

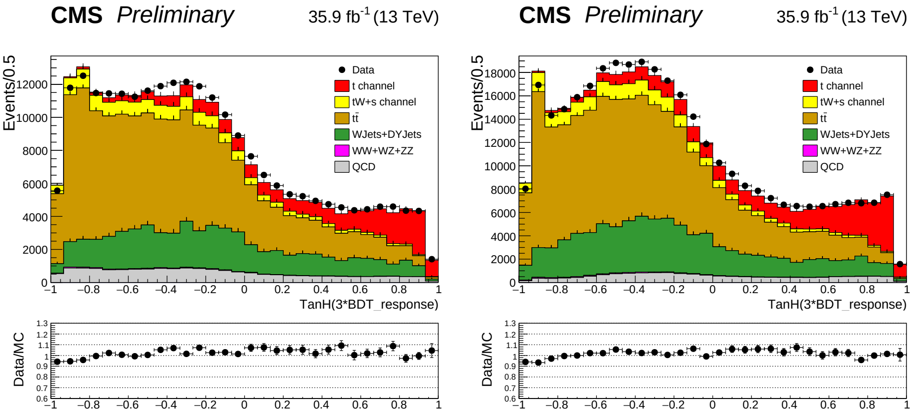
First Fox-Wolfram moment has best sensitivity among the three and is used in the BDT



ROC curve

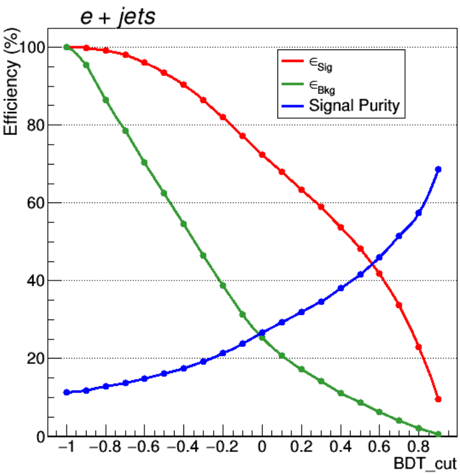
basic cor

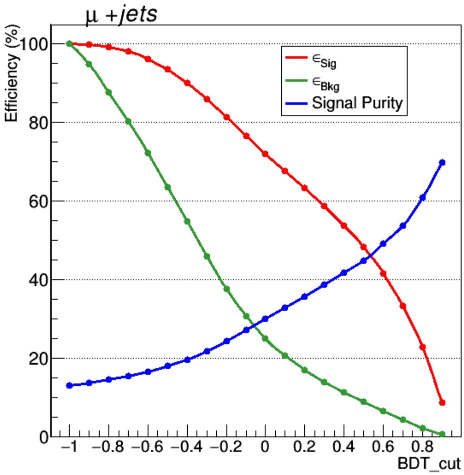
BDT Response



e + jets final state **μ + jets final state**

Purity, signal efficiency vs. multivariate discriminator





e + jets final state **μ + jets final state**

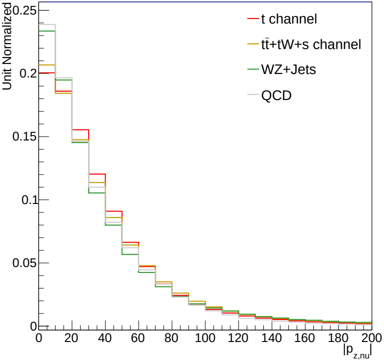
- Top quark mass is reconstructed using the available kinematic information of the event
- The longitudinal momentum of the neutrino is determined from the $\mathrm{m_W} = 80.4$ GeV constraint
- Using energy-momentum conservation we obtain a quadratic equation in $p_{z\nu}$ with following solutions

$$p_{z,\nu} = \left(\frac{\lambda^2 p_{z,\ell}}{p^2_{T,\ell}}\right) \pm \frac{\sqrt{(\lambda^2 p^2_{z,\ell} - p^2_{T,\ell}(\not{E}^2_T E^2_\ell - \lambda^2)}}{p^2_{T,\ell}}$$

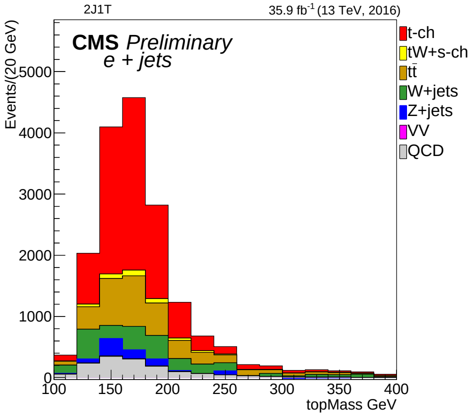
Discriminant $\rightarrow (\lambda^2 p^2_{z,\ell} - p^2_{T,\ell}(\not{E}^2_T E^2_\ell - \lambda^2)$

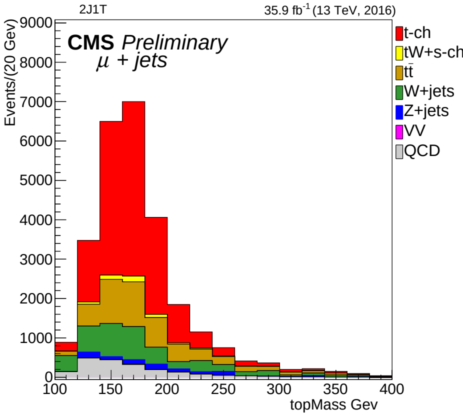
Here $\lambda = \frac{(m_W)^2}{2} + \vec{\not{E}}_T \cdot \vec{p}_{T,\ell}$

- Discriminant is -ve
  - Put $m_T^W = m_W$ and make discriminate zero
- Discriminant is +ve
  - choose the solution which have minimum $|p_z \nu|$



top quark mass after the BDT cut



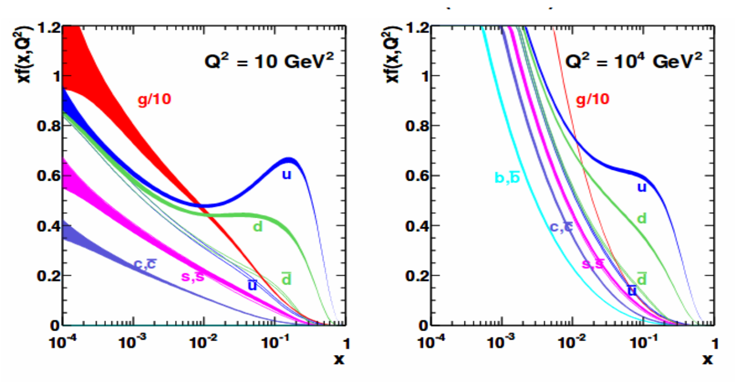


top quark mass distribution of e + jets final state after BDT cut

top quark mass distribution of μ + jets final state after BDT cut

Thank you

Parton Distribution

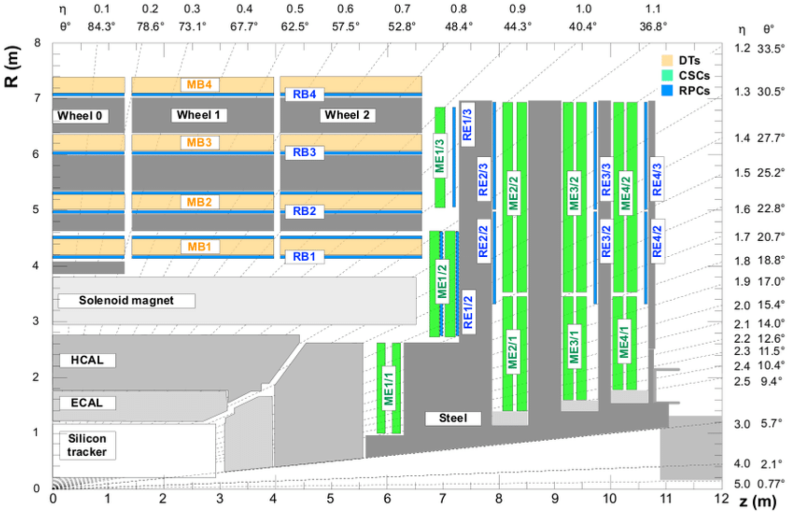


main

Jet reconstruction algorithm

- Iterative process to cluster particles based on "closeness"
- For each particle i, compute
  $$d_i = p_{T,i}^{2p}$$
- For each pair of particles i and j, compute
  $$d_{i,j} = min(p_{T,i}^{2p}, p_{T,j}^{2p})\frac{R_{i,j}^2}{R^2} \qquad R_{i,j}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$
- Find minimum of all $d_i, d_{i,j}$
  -If d_i is minimum, i is a jet and removed from list of particles
  -If $d_{i,j}$ is minimum, combine particles i and j
- Repeat process until all particles are part of a jet with $R_{i,j} < R$
- Parameter p governs the relative power of energy vs geometrical scales to distinguish the algorithms: 1=k_T, -1=Anti-k_T main

Coverage of CMS detector



Source :ResearchGate uploaded by Tamer Elkafrawy

Data and Simulated samples

Process	σ(.BR)[pb]	Genrators	Nevents
t-channel top	136.02 (NLO)	powheg-pythia8	67 m
t-channel antitop	80.95 (NLO)	powheg-pythia8	38 m
tw-channel top	35.6 (NLO)	powheg-pythia8	0.9 m
tw-channel antitop	35.6 (NLO)	powheg-pythia8	0.9 m
S channel top+antitop	10.32 (NLO)	aMC@NLO-pythia8	0.6 m
$t\bar{t}$	831.76 (NNLO)	aMC@NLO-pythia8	77 m
W($\rightarrow l\nu$)+0jets	49670 (NNLO)	aMC@NLO-pythia8	39 m
W($\rightarrow l\nu$)+1jets	8264 (NNLO)	aMC@NLO-pythia8	19 m
W($\rightarrow l\nu$)+2jets	2628 (NNLO)	aMC@NLO-pythia8	15 m
Z/γ($\rightarrow ll$)+jets	5765.4 (NNLO)	aMC@NLO-pythia8	19 m
WW($\rightarrow l\nu$)+jets	45.85 (NLO)	aMC@NLO-pythia8	3 m
WW($\rightarrow 2l2\nu$)+jets	12.178 (NLO)	powheg-pythia8	1 m
WZ($\rightarrow l\nu$)+jets	10.71 (NLO)	aMC@NLO-pythia8	14 m
WZ($\rightarrow 2l2\nu$)+jets	5.595 (NLO)	aMC@NLO-pythia8	15 m
ZZ($\rightarrow l\nu$)+jets	3.22 (NLO)	aMC@NLO-pythia8	9 m
QCD	302672.16 (LO)	pythia8	22 m

List of MC samples Scaled to $\mathcal{L}_{\text{int}} = 35.9\ \text{fb}^{-1}$

Run Period	Run Range	Dataset Name	Integrated Luminosity (fb^{-1})
Run B	273158 - 275376	/SingleElectron/Run2016B-03Feb2017_ver2-v2/MINIAOD	5.7
Run C	275657 - 276283	/SingleElectron/Run2016C-03Feb2017-v1/MINIAOD	2.6
Run D	276315 - 276811	/SingleElectron/Run2016D-03Feb2017-v1/MINIAOD	4.2
Run E	276831 - 277420	/SingleElectron/Run2016E-03Feb2017-v1/MINIAOD	4.0
Run F	277981 - 278808	/SingleElectron/Run2016F-03Feb2017-v1/MINIAOD	3.1
Run G	278820 - 280385	/SingleElectron/Run2016G-03Feb2017-v1/MINIAOD	7.6
Run H	281613 - 284044	/SingleElectron/Run2016H-03Feb2017_ver2-v1/MINIAOD /SingleElectron/Run2016H-03Feb2017_ver3-v1/MINIAOD	8.4 0.2
Total			35.9

List of data samples

Cut-flow table

Table: Cut flow for events with the muon final state.

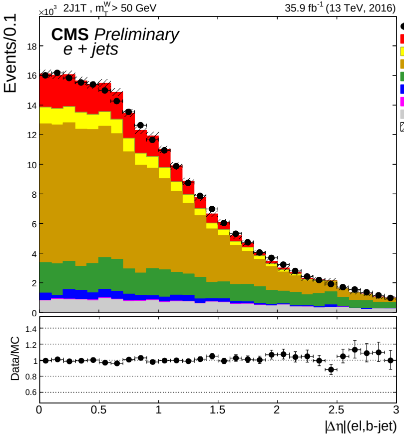
Cut	t-ch.	tW + s-ch.	$t\bar{t}$	W+jets	Z+jets	di-boson	QCD	Total MC	Data	Data/MC(%)
No cut	7779880	2672579	29766400	2213536000	206744000	2781417	1.08533e+10	15538630276	788340964	5.07
Trigger	522486	386189.3	4026120	310895500	44618700	576922.4	1.56252e+08	828871917.7	471040410	56.83
1 tight isolated μ	386696	284249.3	2836410	222101300	21587000	414429.4	2.32383e+07	493565384.7	259002854	52.48
Loose μ veto	384687	272944.3	2712020	221766800	12231200	387302.6	2.23960e+07	482532953.9	246130600	51.01
e veto	383160	246864.9	2444290	221603800	12129600	357592.4	2.23670e+07	481745307.3	245550723	50.97
2 jets	144898.2	89136.9	665306	6059963	544834	76369.4	1.31616e+06	15087927.5	8152312	54.03
1 b-tag	61109.8	32067.6	265547	100684.3	17725.1	2053.3	138056	715988.19	552720	77.20
$m_t^W > 50$ GeV	42180.6	16206.2	181050	68497.3	9156.2	1327.2	32844.4	318495.37	326800	93.04

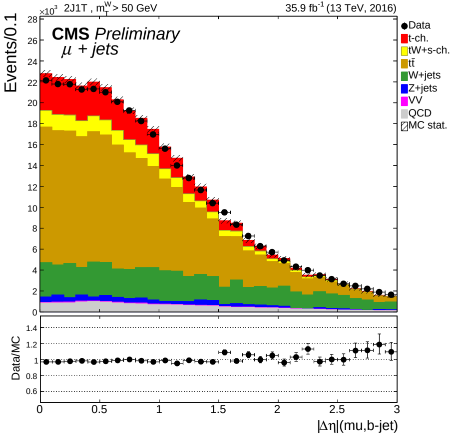
Table: Cut flow for events with the electron final state.

Cut	t-ch.	tW + s-ch.	$t\bar{t}$	W+jets	Z+jets	di-boson	QCD	Total MC	Data	Data/MC(%)
No cut	7717690	2673866	30895200	4.43e+09	2.08e+08	2783180	6.41e+11	6.46e+11	843398435	0.13
Trigger	309594	262230.3	2660710	2.91e+108	2.72e+07	353090.5	9.71e+07	4.19e+08	292170629	69.69
1 Tight isolated e	229830.3	201756.71	2019920	1.77e+08	1.42e+07	251417.7	1.21e+07	2.05e+08	117287424	56.94
Loose e veto	229067.5	192672.2	1920620	1.76e+08	5752430	228387.7	1.21e+07	1.97e+08	108316594	54.91
μ veto	227904.9	171837.61	1711180	1.76e+07	5709520	208425.8	1.21e+07	1.96e+08	107856987	54.83
2 Jets	86035.3	61974.68	456275	7036850	529504	48973.8	1356662.3	9576275	5918361	61.80
1 b-tag	36664.9	21965.62	182395	116990.6	16016.1	1331.1	28739.4	404102.7	359251	88.90
$m_t^W > 50$ GeV	15852.7	15108.48	128345	41333	7712.2	864	22334.5	271400	238295	87.80

main

Data-MC comparison plots 2J1T (contd.)

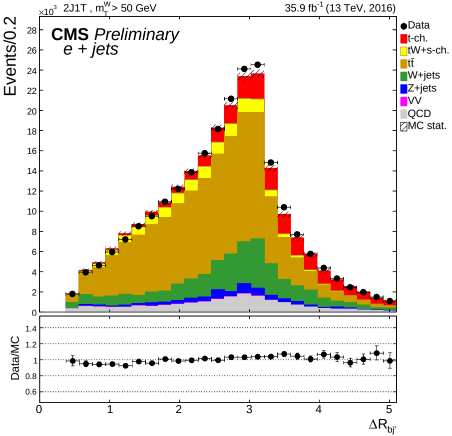




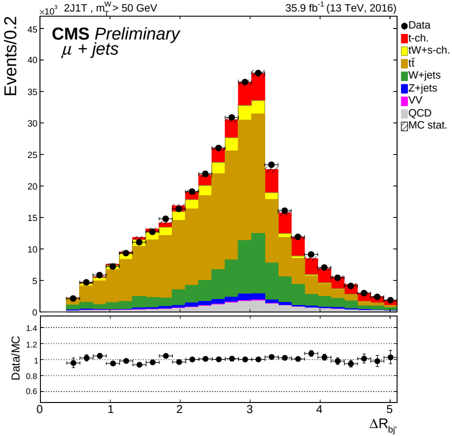
$|\Delta\eta|$ between the electronon and b tagged jet in e+jets final state

$|\Delta\eta|$ between the muon and b tagged jet in mu+jets final state main

Data-MC comparison plots 2J1T (contd.)

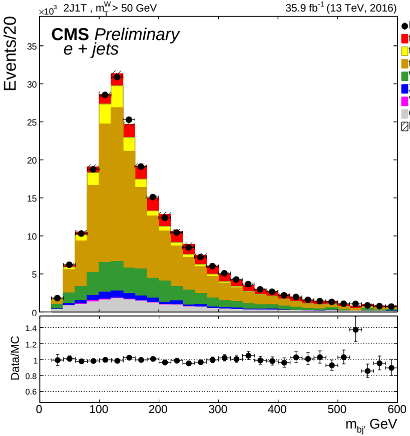


$|\Delta\mathrm{R}|$ **between the electron and b tagged jet in** e**+jets final state**



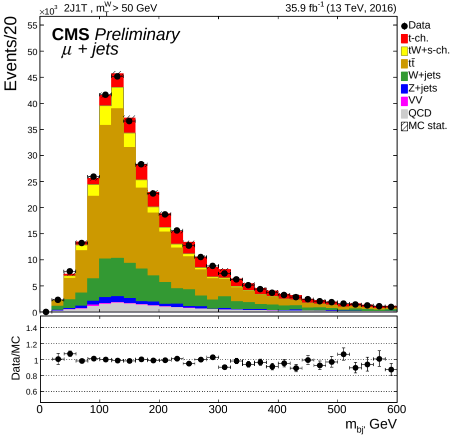
$|\Delta\mathrm{R}|$ **between the muon and b tagged jet in** *mu*+**jets final state** main

Data-MC comparison plots 2J1T (contd.)



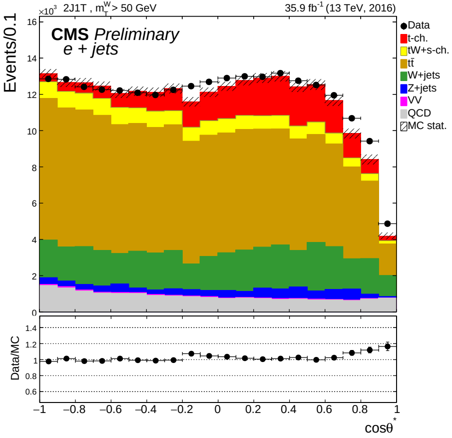
Invariant mass sum of the untagged and b tagged jet in e+jets final state

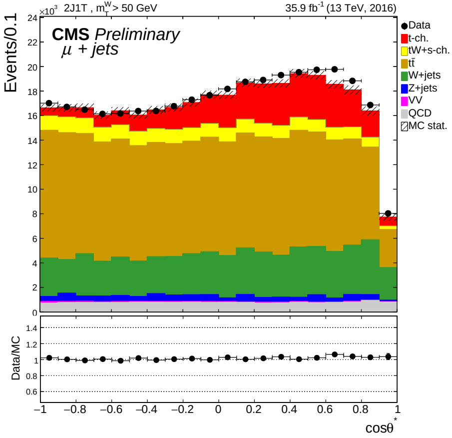
main



Invariant mass sum of the untagged and b tagged jet in μ+jets final state

Data-MC comparison plots 2J1T (contd.)

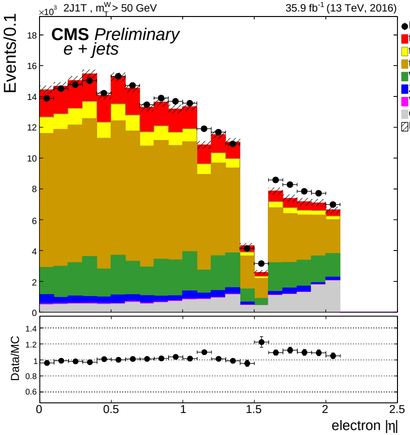


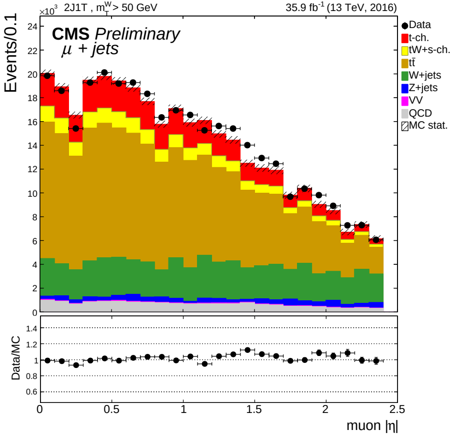


θ^* is the angle b/w the electron and untagged jet in the top quark frame main

θ^* is the angle b/w the muon and untagged jet in the top quark frame

Data-MC comparison plots 2J1T (contd.)

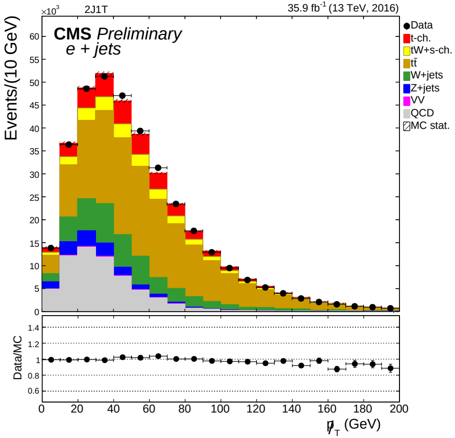


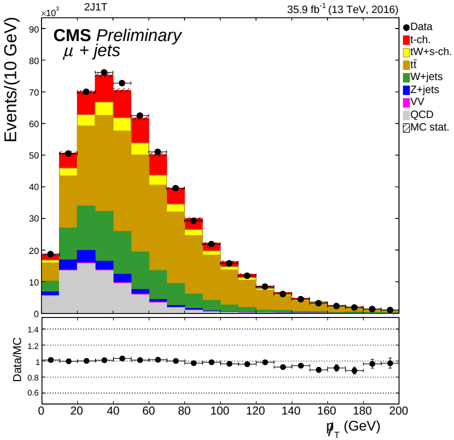


$|\eta|$ of the electron main

$|\eta|$ of the muon

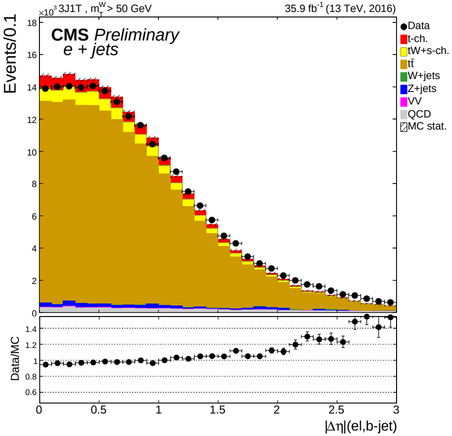
Data-MC comparison plots 2J1T (contd.)



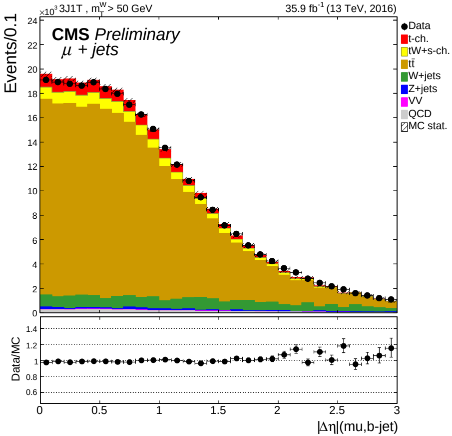


m_t^W transverse mass of W boson in e+jets final stat main

m_t^W transverse mass of W boson in μ+jets final stat

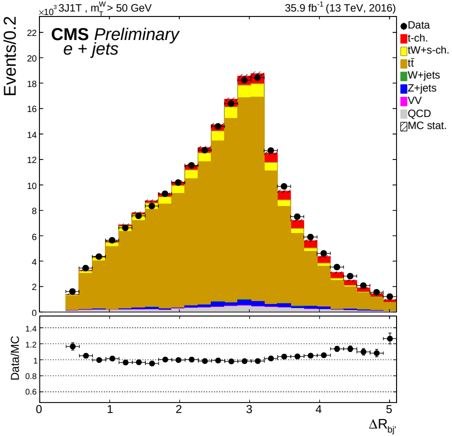


$|\Delta\eta|$ **between the electronon and b tagged jet in** e**+jets final state**

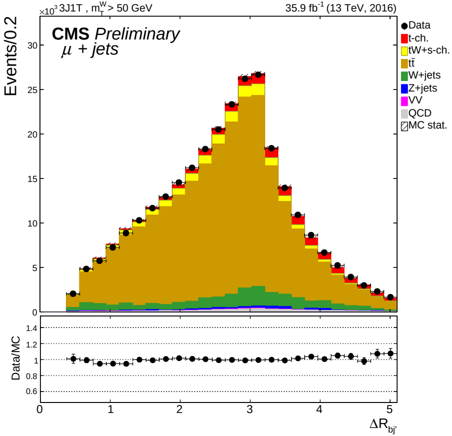


$|\Delta\eta|$ **between the muon and b tagged jet in** mu**+jets final state** main

Data-MC comparison plots 3J1T (contd.)

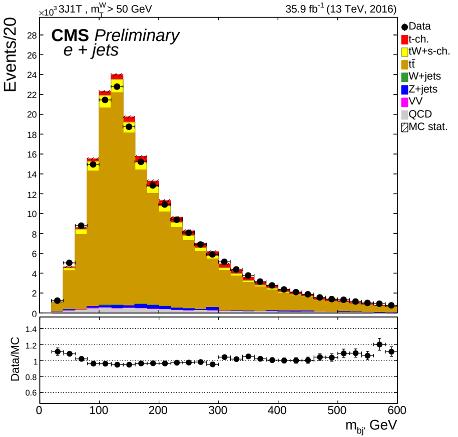


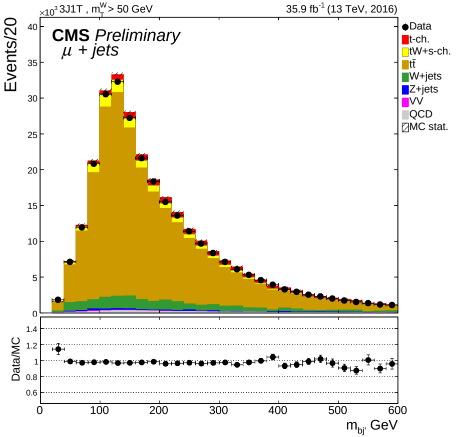
$|\Delta \mathrm{R}|$ **between the electron and b tagged jet in** e**+jets final state**



$|\Delta \mathrm{R}|$ **between the muon and b tagged jet in** mu**+jets final state** main

Data-MC comparison plots 3J1T (contd.)

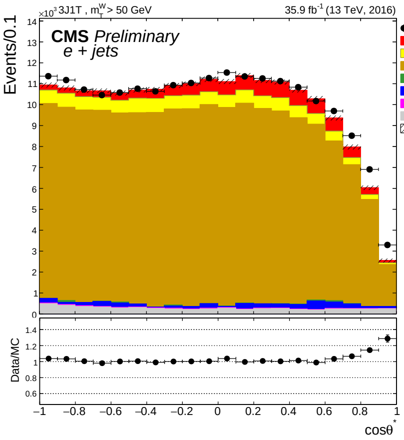


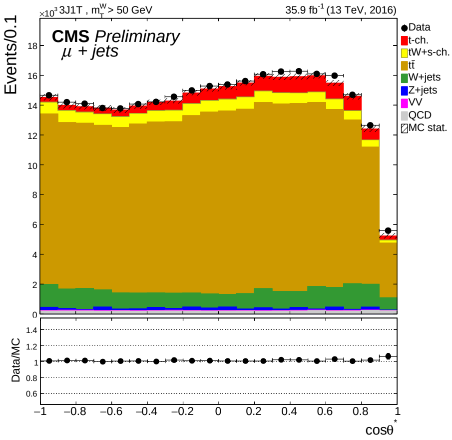


Invariant mass sum of the untagged and b tagged jet in e+jets final stat main

Invariant mass sum of the untagged and b tagged jet in μ+jets final stat

Data-MC comparison plots 3J1T (contd.)

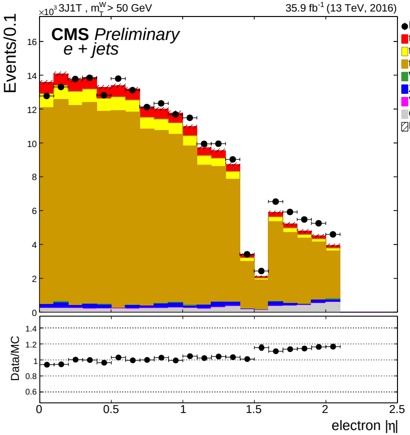




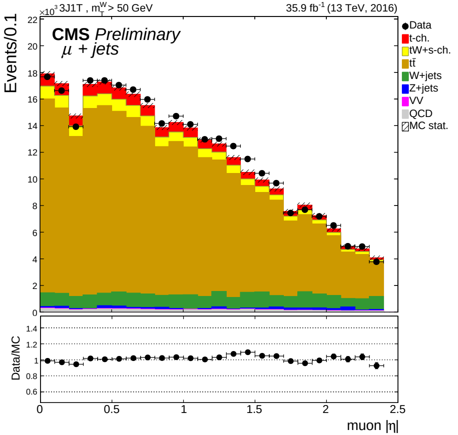
θ^* is the angle b/w the electron and untagged jet in the top quark frame main

θ^* is the angle b/w the muon and untagged jet in the top quark frame

Data-MC comparison plots 3J1T (contd.)



$|\eta|$ **of the electron** main



$|\eta|$ **of the muon**

Fox-Wolfram moments

- Describe correlation between jets using event geometry
- Calculated from all the selected jets in each event
- Moments are defined as the superposition of spherical harmonics $\mathrm{Y}_l^m \cos(\theta)$:

$$\mathrm{H}_l = \frac{4\pi}{2l+1} \sum_{i=-l}^{l} \left| \sum_{i=1}^{N} \mathrm{Y}_l^m(\Omega) \frac{|p_i|}{\sqrt{s}} \right|^2 \quad (3)$$

Here index i sums over all the jets and Ω_i is the angular distance from the assumed reference axis

- Using an additional theorem for spherical harmonics

$$\frac{4\pi}{2l+1} \sum_{i=-l}^{l} \mathrm{Y}_l^m(\Omega) \mathrm{Y}_l^{m*}(\Omega) = \mathrm{P}_l(\cos\Omega_{ij}) \quad (4)$$

We can rewrite main

$$\mathrm{H}_l = \sum_{i,j=-1}^{N} \frac{|\vec{p}_i||\vec{p}_j|}{s} \mathrm{P}_l(\cos\Omega_{ij}) \quad (5)$$

b-Tagging

- life time of the b quark is large
- Combined Secondary Vertex version 2 (CSVv2):
  - based on secondary vertex and track-based lifetime information
  - combining the variables such as vertex mass,number of tracks at vertex and inside a jet, 2D flight distance significance of the b-flavoured meson, ratio of energy carried by the tracks at the secondary vertex vs all tracks inside the jet etc
- combined MultiVariate Algorithm version 2 (cMVAv2):
  - Algorithm uses a Boosted Decision Tree (BDT)
  - taking as input the different algorithm outputs of CSVv2, a variant of CSVv2 using alternate vertex reconstruction, Jet Probability (JP), Jet B Probability (JBP)
  - Algorithm performs better compared to CSVv2
  - A tight threshold on the b-tagging discriminator value corresponds to mis-tag rate of 0.1% main

Relative isolation

$$I_{rel} = \frac{I^{\text{charged hadron}} + \max\left((I^{\gamma} + I^{\text{neutral hadron}} - I^{\text{pileup}}), 0\right)}{p_{T,\mu}} \quad (6)$$

where I is the energy deposit by the corresponding particle. main

Boosted decision trees

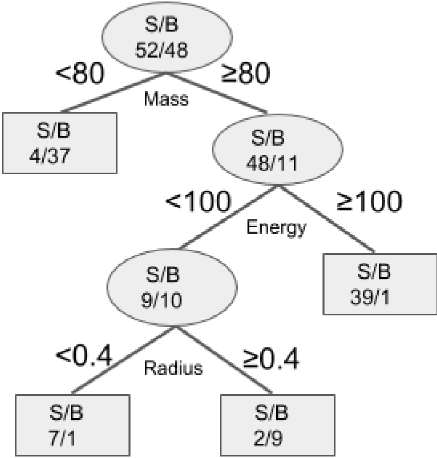
- An advanced multivariate technique to separate signal from backgrounds.
- From input variables find one for which a single cut gives the best improvement in signal purity:

$$P = \frac{\mathrm{S}}{\mathrm{S} + \mathrm{B}}$$

- The set of cuts defines the decision classifier

$$t(x) = \sum_{k=1}^{K} \alpha_k f_k(x)$$

- separation $< s^2 >$ of a variable x is given as an integral main b



$$< s^2 >= \frac{1}{2} \int \frac{(\hat{x}_S(x) - \hat{x}_B(x))^2}{(\hat{x}_S(x) + \hat{x}_B(x))} dx$$

Boosting

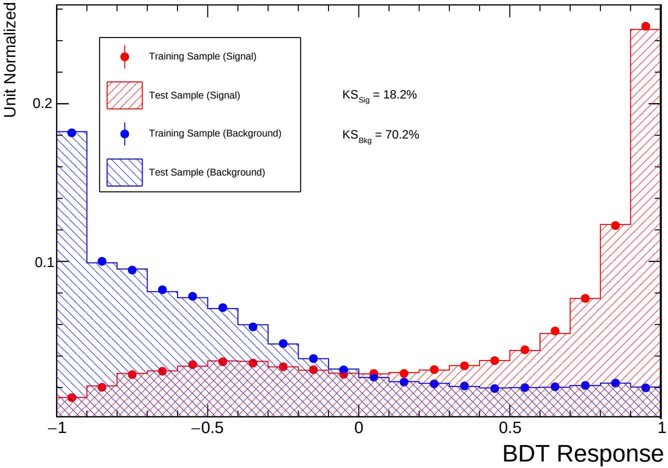
- First initialize the training sample T_1 using the original
  x_1, x_2, x_3 .....x_N Variables
  y_1, y_2, y_3 ......y_N event data Vector
  w_1^1, w_2^1, w_3^1... w_N^1 event weight

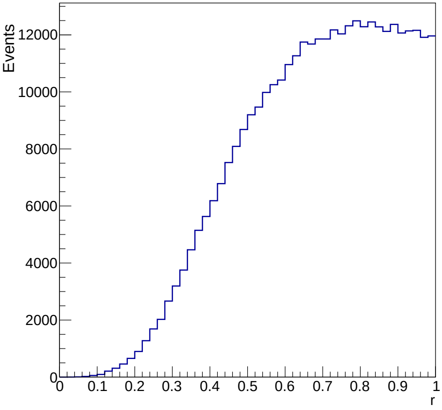
$$\sum_{i=1}^{n} w_i = 1 \tag{8}$$

- Then train the classifier $f_1(x)$ with a method that uses the event weights
- We will define an iterative procedure that gives a series of classifiers $f_1(x)$, $f_2(x)$,...
- The classifier at each iterative step is found from an updated training sample, in which the weight of event i is modified from step k to step $k+1$ according to

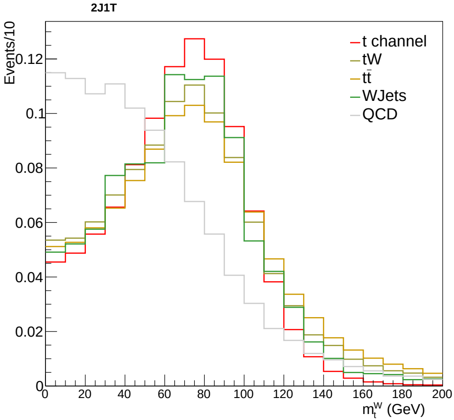
$$w = \frac{1 - f_{err}}{f_{err}} \quad \text{where} \quad \mathrm{f_{err}} = \frac{\#\text{misclassified event}}{\#\text{all event}} \tag{9}$$

Over training test



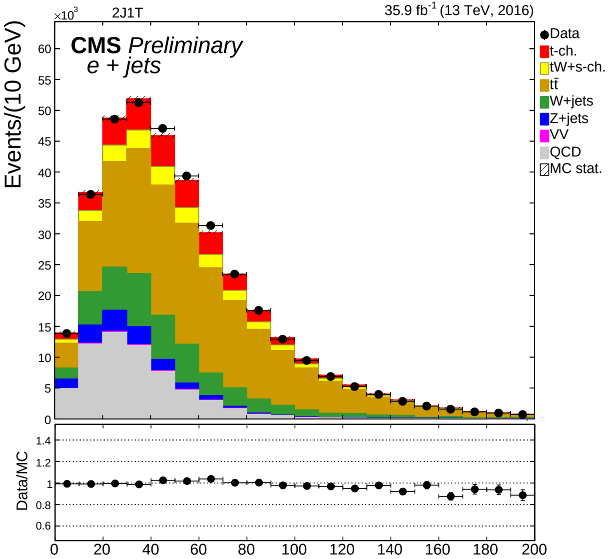


p_t **ratio of jets** main

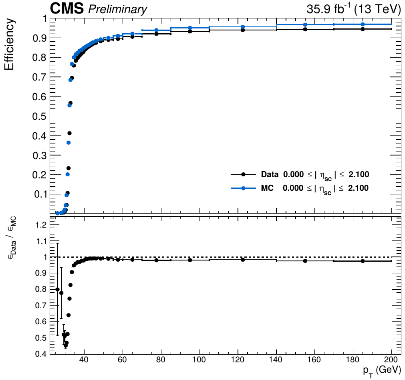


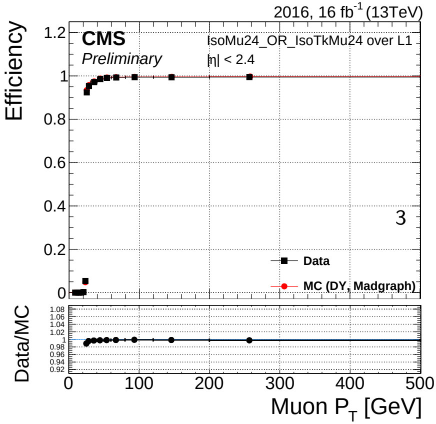
m_t^W **transverse mass of W boson**

Met distribution



Trigger efficiency





HLT_Ele32_eta2p1_WPTight

IsoTkMu24_OR_IsoTkMu24

[3] Electron trigger performance in CMS with the full 2017 data sample.

Tight and loose ID

- Electron tight ID
  - H/E $<$ 0.0414 (barrel), 0.0641 (endcap),
  - $\sigma_{\eta\eta} <$ 0.00998 (barrel), 0.0292 (endcap),
  - $|\Delta\eta i\eta|<$ 0.00308 (barrel), 0.00605 (endcap),
  - $|\Delta\phi i\eta|<$0.0816(barrel), 0.0394 (endcap),
  - $|\frac{1}{ESC}$ - $\frac{1}{p}|<$ 0.0129(barrel), 0.0129 (endcap),
  - Irel,corrPF$<$ 0.0588 (barrel), 0.0571(endcap).
  - expected missing inner hits $\leq$ 1 (barrel), 1 (endcap)
  - pass conversion veto $=$ yes (barrel), yes (endcap)
- Jet loose ID
  - Neutral Hadron Fraction $<$ 0.99
  - Neutral EM Fraction $<$ 0.99
  - Number of Constituents $>$ 1
  - Charged EM Fraction $<$ 0.99

main