Search for vector-like T quarks with oppositely-charged dilepton pairs and jets in p-p collisions at 13 TeV

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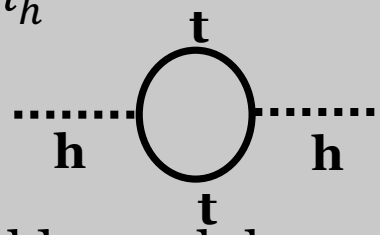
Introduction – Vector Like Quarks

- Candidates that could solve the hierarchy problem by stabilizing quantum corrections to the Higgs mass
- $$m_h^2 = m_{bare}^2 + \delta m_h^2$$

  Where δm_h^2 =



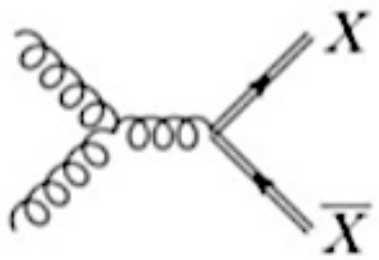
- Their contributions to the Higgs mass would cancel the corrections due to the top quark loop naturally
- Spin ½, non chiral, colored charged particles, heavier than t quark

$Q^{Ele.Charge}$	Decays
$T^{2/3}$	bW^+, tH, tZ
$B^{-1/3}$	tW^-, bH, bZ
$X^{5/3}$	tW^+
$Y^{-4/3}$	bW^-

		Isospin	Hypercharge
Singlets	T	1	2/3
	B	1	-1/3
Doublets	T, B	2	1/6
	T, X	2	7/6
	B,Y	2	-5/6
Triplets	T, B, X	3	2/3
	T, B, Y	3	-1/3

QCD Pair production

- Model-independent cross section



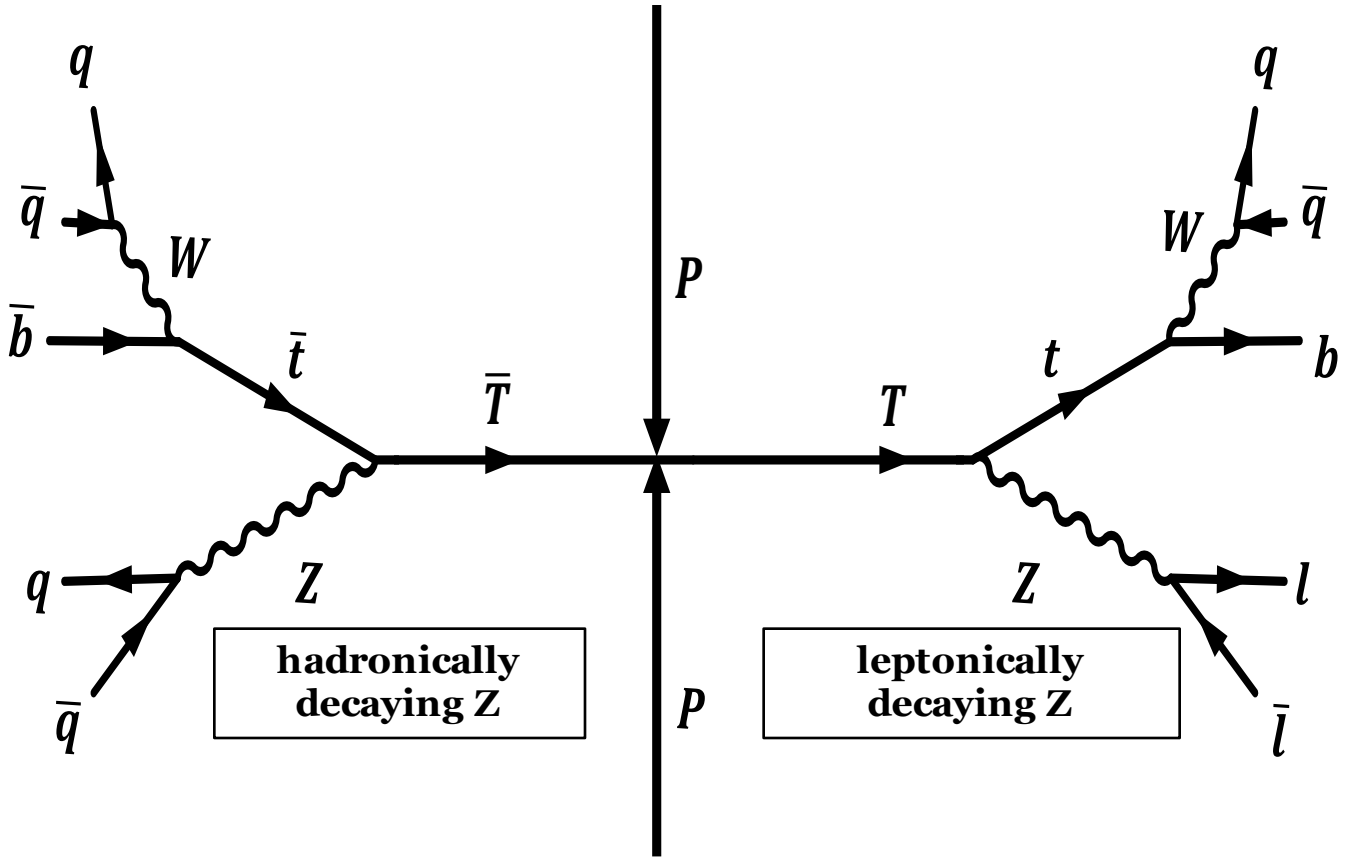
Introduction

- Search for VLQ TT Pairs with two leptons from Z boson decay

- TT → tZ + X
  Where X = tZ, tH, bW

Pre-Event Selection

- Opposite sign dilepton pair from Z
- Jets
  - ≥ 3 Ak4 jets
  - ≥ 1 b-tagged jets



Pair Produced TT decays into tZtZ , where one Z decays into l^+l^-

Introduction (Contd....)

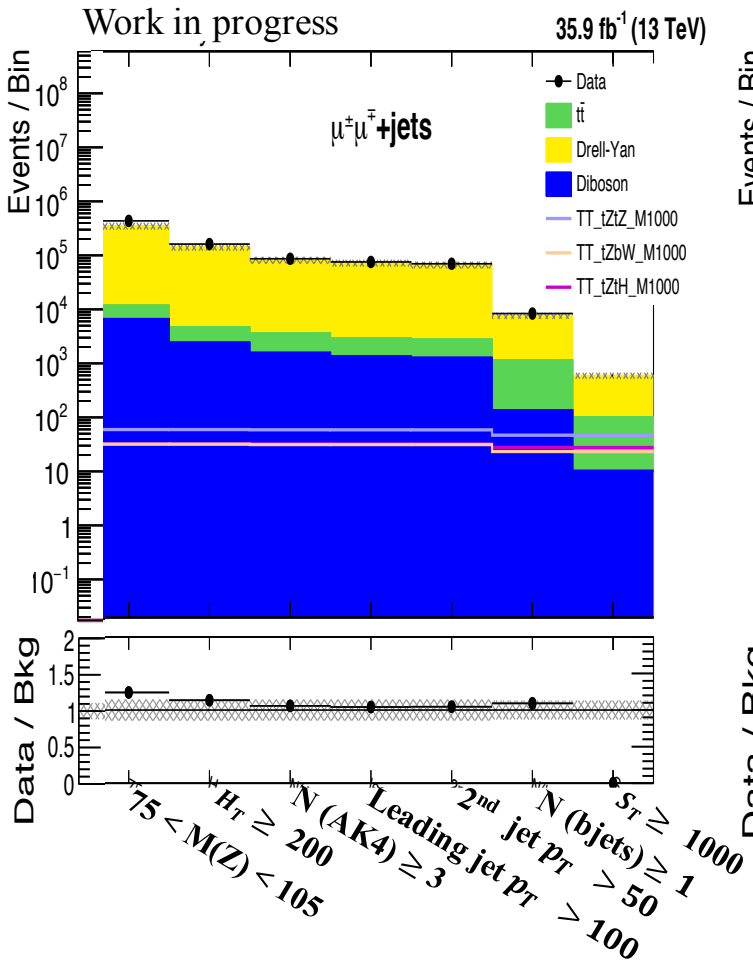
- Signal cross-sections : Pair-production cross-section at QCD NNLO
- Background cross-sections: NNLO, NLO, or measured (when available)
- Data : Collected in 2016 with at least a single lepton (35.9 fb^{-1})

Bkg	$\sigma(pb)$
Drell- Yan	1921.8
ttbar	831.76
Diboson	118.7
	46.74
	16.91

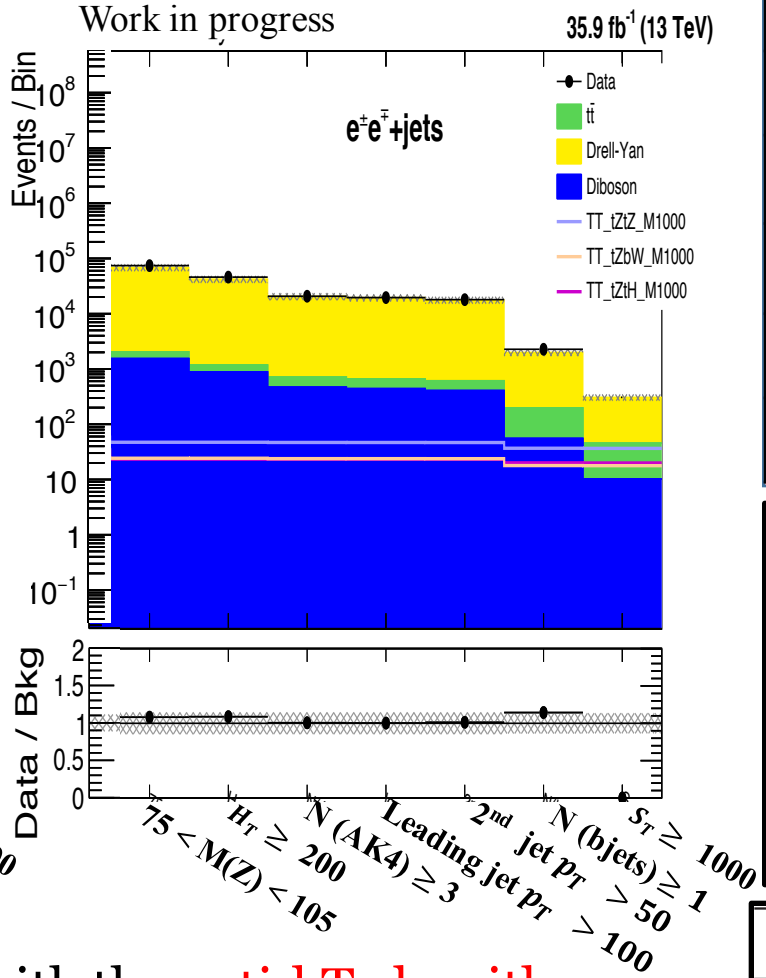
Pair-production TT cross section	
M (GeV)	$\sigma(pb)$
700	0.455
800	0.196
900	0.0903
1000	0.0440
1100	0.0224
1200	0.0118
1300	0.00639
1400	0.00354
1500	0.00200

Event Selection

Muon Channel



Electron Channel



Pre Selection Region	
Z boson mass	**75 < M(Z) < 105 GeV**
N (Z → l^+l^-)	**=1**
p_T(Z → l^+l^-)	**>100 GeV**
N (AK4)	**≥ 3**
H_T	**≥ 200 GeV**

Control region selection	
Leading AK4 jet p_T	> 100 GeV
2nd leading AK4 jet p_T	> 50 GeV
N(bjets)	≥ 1
S_T	≤ 1000 GeV

Signal region selection	
Leading AK4 jet p_T	> 100 GeV
2nd leading AK4 jet p_T	> 50 GeV
N(bjets)	≥ 1
S_T	≥ 1000 GeV

AK4 Jet ≡ A Jet clustered with the anti-kT algorithm with distance parameter R=0.4

$\mathbf{H_T} \equiv \sum_{all\ jets} \mathbf{P_T}$

$\mathbf{S_T} \equiv \sum_{all\ jets+leptons+MET} \mathbf{P_T}$

MET ≡ Missing Transverse Energy

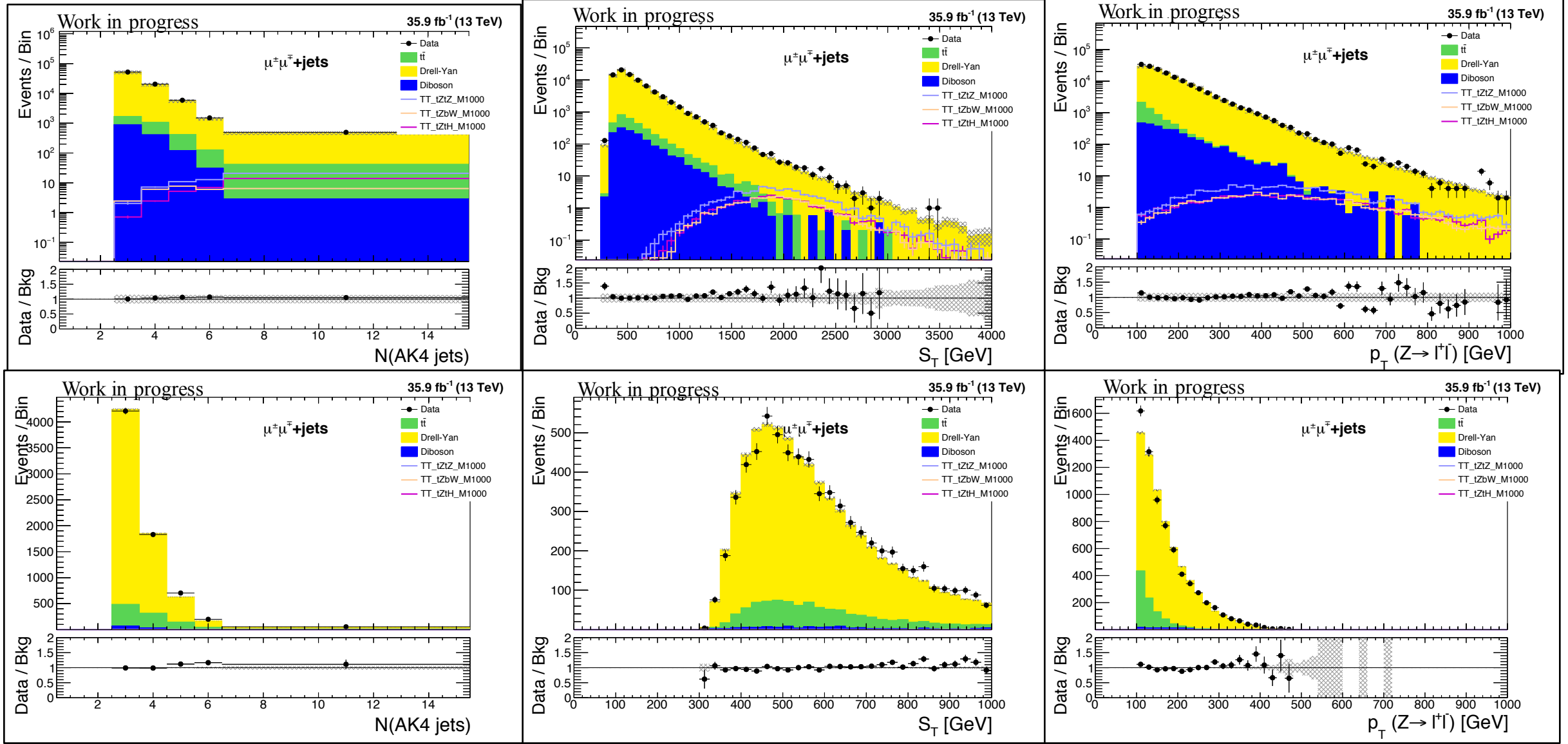
Pre Selection/ Control Regions

Muon Channel

NAK4 | S_T | Z-Pt

Pre-Selection

Control Region

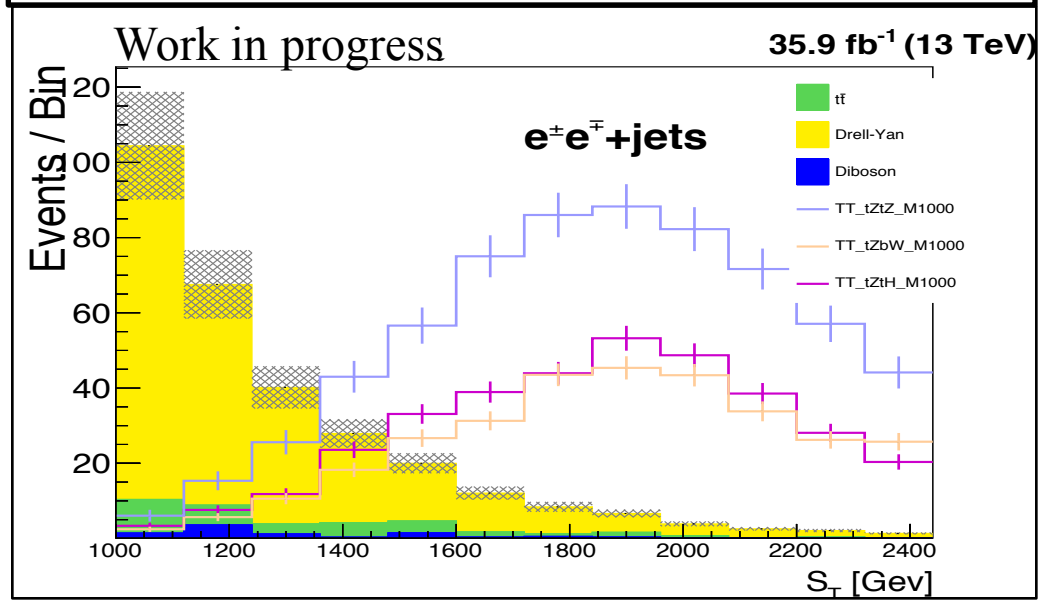


Signal Region

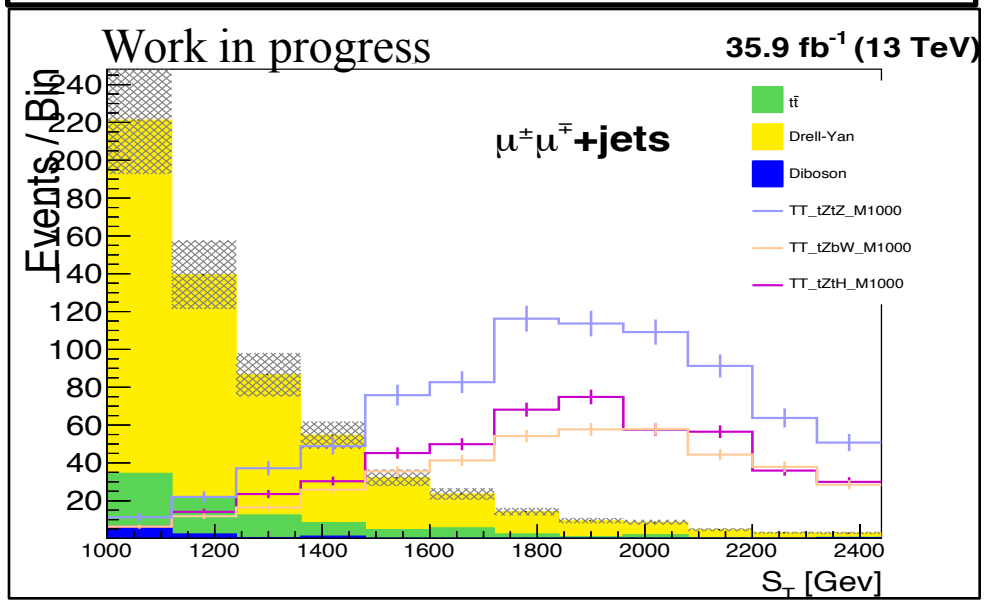
Sample (Integrated Lumi. $= 35.9\ fb^{-1}$)	Electron Channel	Muon Channel
DY	268.8 ± 2.1	532.8 ± 3.3
Top	29.9 ± 2.4	86.7 ± 4.2
Diboson	9.4 ± 2.1	9.7 ± 2.1
Total Bkg.	308.1 ± 3.8	629.2 ± 5.7
$T\bar{T} \to tZtZ$-M1000	35.2 ± 0.8	44.4 ± 0.9
$T\bar{T} \to tZbW$-M1000	16.8 ± 0.4	22.1 ± 0.5
$T\bar{T} \to tZtH$-M1000	18.3 ± 0.4	25.6 ± 0.5

*** Signal is normalized to 1 pb cross section for visualization**

S_T in Signal region (Electron)



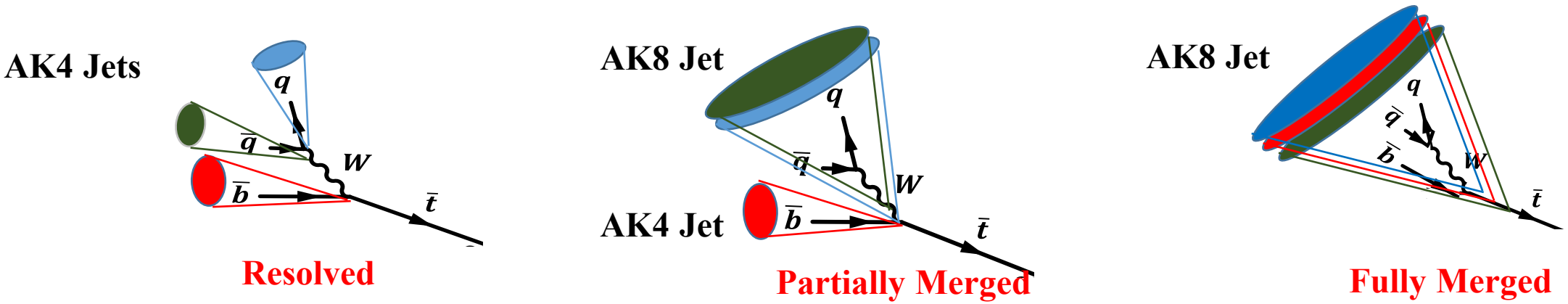
S_T in Signal region (Muon)



Analysis Strategy

- Search for hadronic top, Z, H candidates in events
- See how categorizing events according to n-tops, n-Z, n-H and n-b reduces the SM Bkg
- The **hadronically decaying objects** are reconstructed using,
  - **AK8** jets for **Partially merged** or **Fully merged** categories
  - **AK4** jets for **Resolved** categories
- **AK8 Jet** ≡ A Jet clustered with the anti-kT algorithm with distance parameter R=0.8

Resolved , Partially merged , Fully merged Categories



Analysis Strategy (n-top , n-Z ,n-H & n-b)

Category	top	Z	H
Resolved	$\sum_{3\ jets} \overrightarrow{P_T} > 100\ GeV$ $120 < \sum_{3\ jets} M < 240$ GeV	$\sum_{2\ jets} \overrightarrow{P_T} > 100\ GeV$ $70 < \sum_{2\ jets} M < 120$ GeV	$\sum_{2\ jets} \overrightarrow{P_T} > 100\ GeV$ $80 < \sum_{2\ jets} M < 160$ GeV
Partially Merged	W Tagged AK8 Jet $\sum_{2\ jets} \overrightarrow{P_T} > 150\ GeV$ $120 < \sum_{2\ jets} M < 240$ GeV		
Fully Merged	top Tagged AK8 Jet	Z Tagged AK8 Jet	H Tagged AK8 Jet
	n-top	n-Z	n-H

Top Jets
- JetPt < 400
- 105 < SoftDropMass <220
- $0 < \tau_3/\tau_2 < 0.81$

Z/W Jets
- JetPt < 200
- 65 < PrunedMass <105
- $0 < \tau_2/\tau_1 < 1$

H Jets
- JetPt < 300
- 105 < PrunedMass <135

- $0 < \tau_2/\tau_1 < 1$
- subjetCSV < 0.5426

Optimization of the Analysis

- signal - fitting the observed S_T spectrum to the combination of the SM backgrounds + a new physics signal
- The 95% limits are computed using Bayesian technique
- The categories are sorted in descending order of significance ($S / \sqrt{B}$)
- Select only categories with highest significances
- Combine categories with similar significances
- 4 such combined categories have been identified

	Category	$T\bar{T} \to tZ\,tZ$, $M_T = 1000$ GeV		
		Exp. Signal	Exp. Background	Significance
1	t1Z1H1b1	12.6 ± 0.7	105.4 ± 5.8	1.23
2	t1Z1H1b2	17.0 ± 0.8	31.8 ± 3.5	3.01
3	t1Z1H0b1	18.0 ± 0.8	141.8 ± 6.5	1.51
4	t1Z1H0b2	9.0 ± 0.6	14.4 ± 2.0	2.38
5	t0Z1H1b1	2.2 ± 0.3	56.9 ± 4.3	0.29
6	t0Z1H1b2	2.4 ± 0.3	12.5 ± 1.7	0.68
7	t0Z1H0b1	3.7 ± 0.4	126.9 ± 6.2	0.33
8	t0Z1H0b2	1.9 ± 0.3	14.3 ± 1.9	0.50
9	t1Z0H1b1	1.0 ± 0.2	19.3 ± 1.8	0.23
10	t1Z0H1b2	1.5 ± 0.2	6.0 ± 1.3	0.60
11	t1Z0H0b1	4.8 ± 0.4	66.0 ± 3.9	0.59
12	t1Z0H0b2	2.6 ± 0.3	8.3 ± 1.3	0.89
13	t0Z0H1b1	0.7 ± 0.2	50.1 ± 3.4	0.10
14	t0Z0H1b2	0.6 ± 0.1	12.2 ± 1.6	0.17
15	t0Z0H0b1	1.0 ± 0.2	242.9 ± 6.3	0.06
16	t0Z0H0b2	0.7 ± 0.2	28.3 ± 2.4	0.12

Optimization of the Analysis

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8	t0Z1H0b2	1.9 ± 0.3	14.3 ± 1.9	0.50
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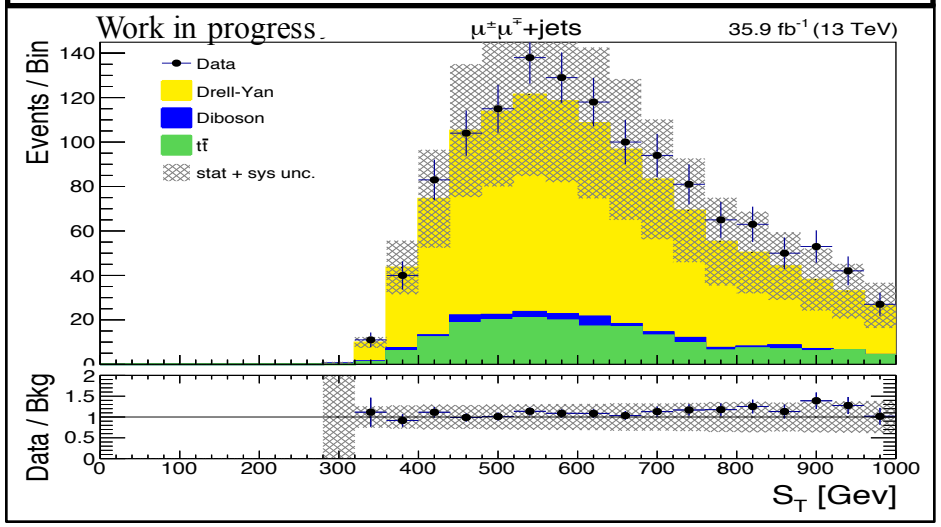
10	t1Z0H1b2	1.5 ± 0.2	6.0 ± 1.3	0.60
11	t1Z0H0b1	4.8 ± 0.4	66.0 ± 3.9	0.59
12	t1Z0H0b2	2.6 ± 0.3	8.3 ± 1.3	0.89
13	t0Z0H1b1	0.7 ± 0.2	50.1 ± 3.4	0.10
14	t0Z0H1b2	0.6 ± 0.1	12.2 ± 1.6	0.17
15	t0Z0H0b1	1.0 ± 0.2	242.9 ± 6.3	0.06
16	t0Z0H0b2	0.7 ± 0.2	28.3 ± 2.4	0.12

Cat A Cat B
Cat C Cat D

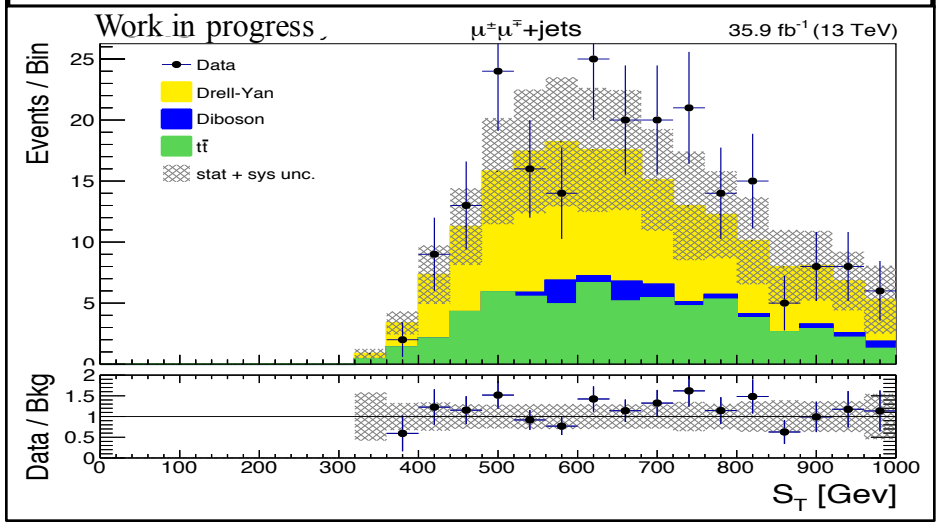
S_T distribution for Final Categories in Control Region (Muon Channel)

- Data/MC modelling in Control region

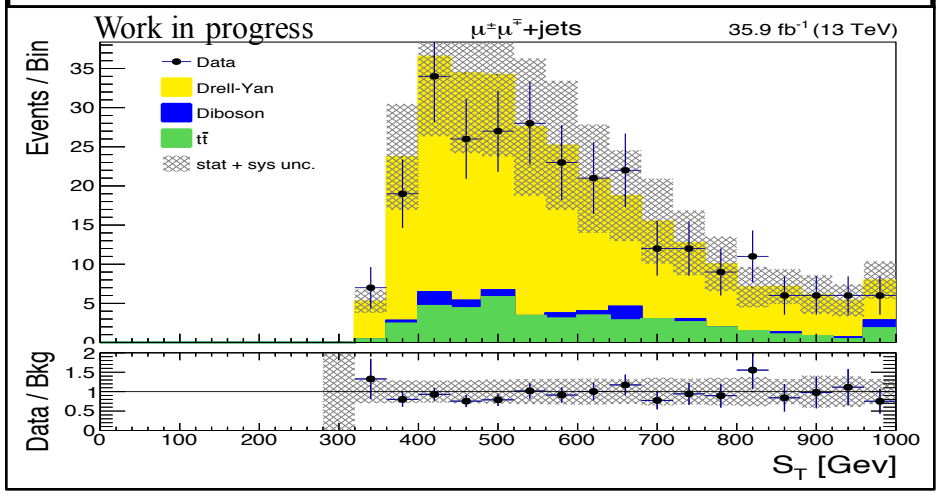
S_T dist^n of Cat A



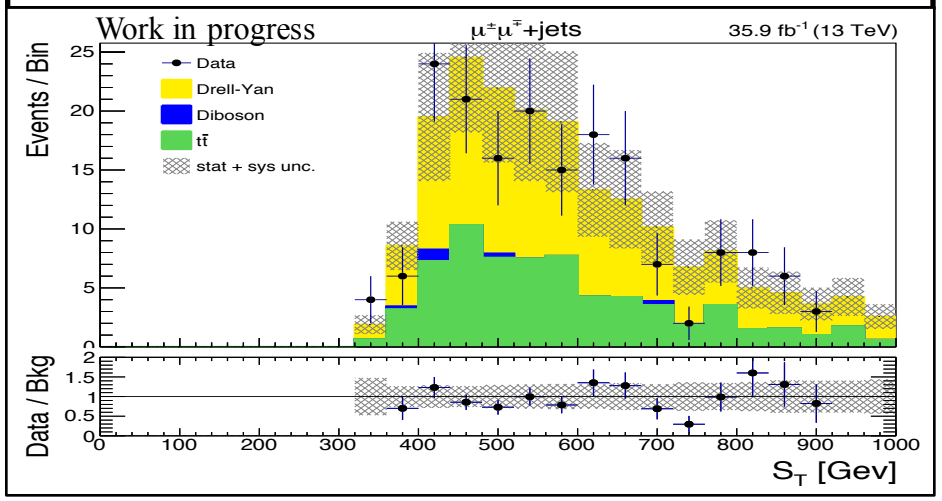
S_T dist^n of Cat B



S_T dist^n of Cat C



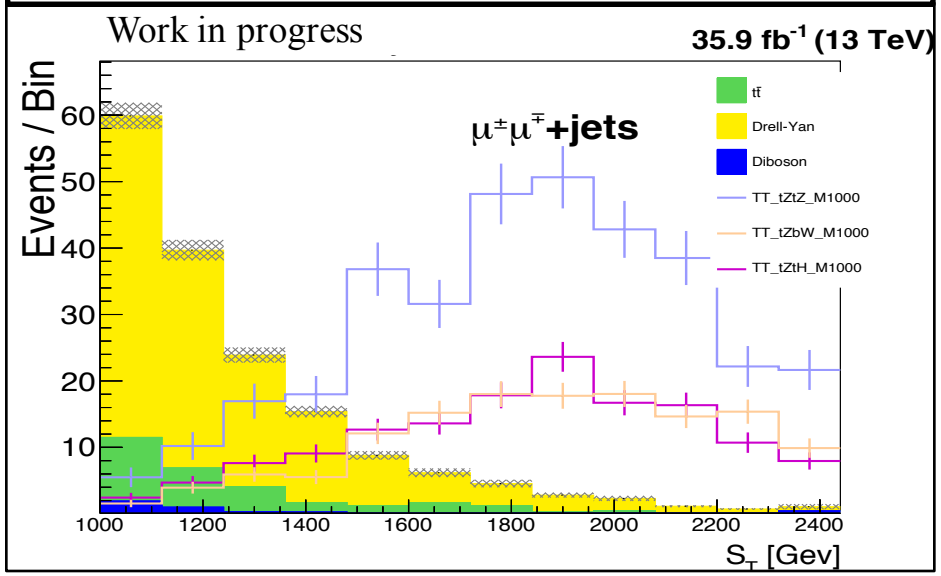
S_T dist^n of Cat D



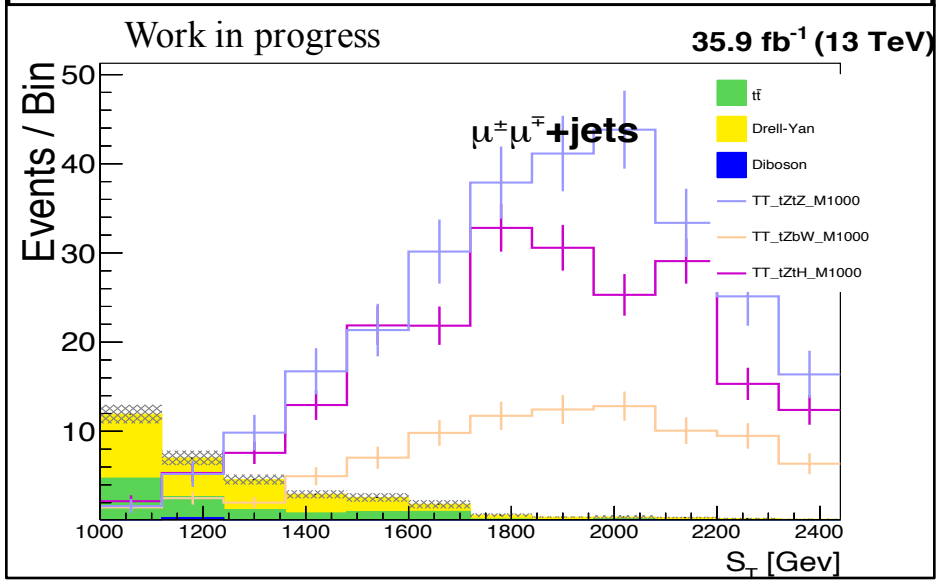
S_T distribution for Final Categories in Signal Region (Muon Channel)

*** Signal is normalized to 1 pb cross section for visualization**

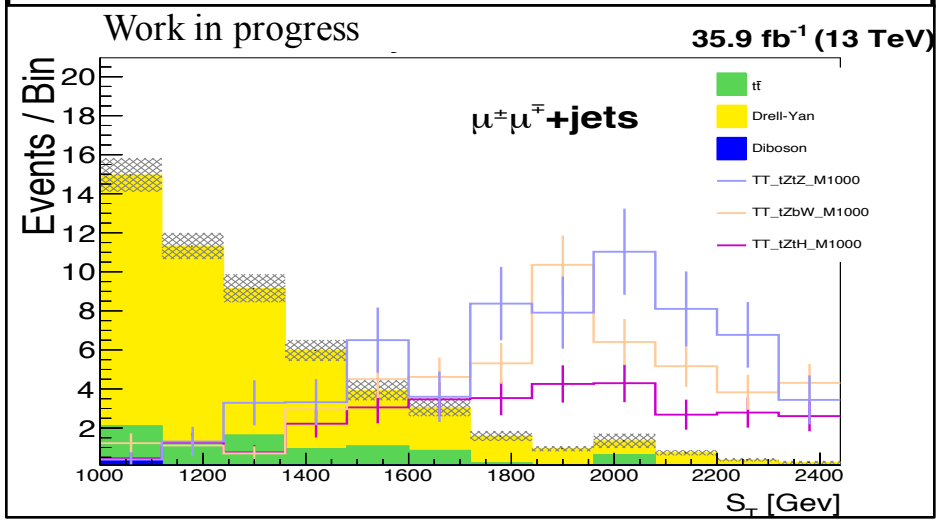
S_T dist^n of Cat A



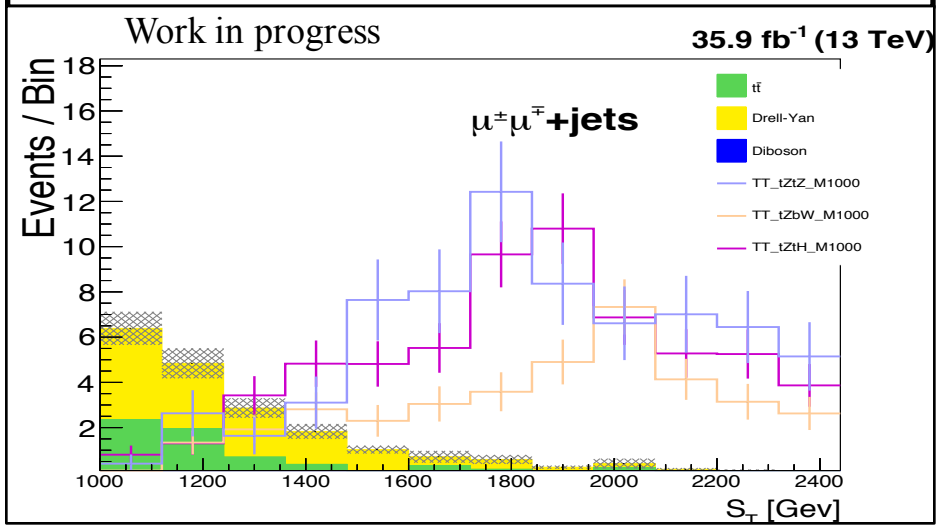
S_T dist^n of Cat B



S_T dist^n of Cat C

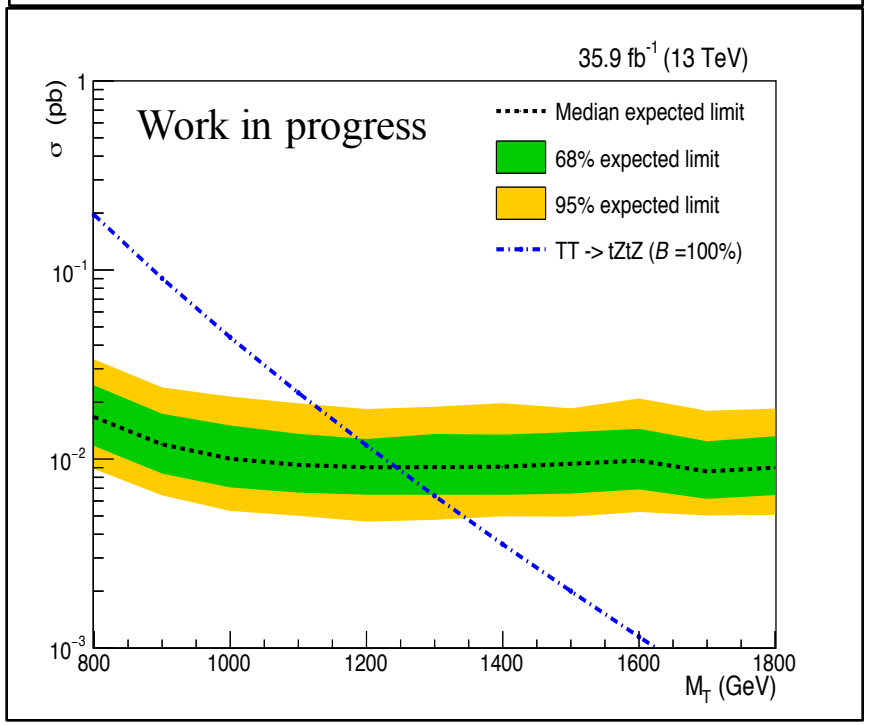


S_T dist^n of Cat D

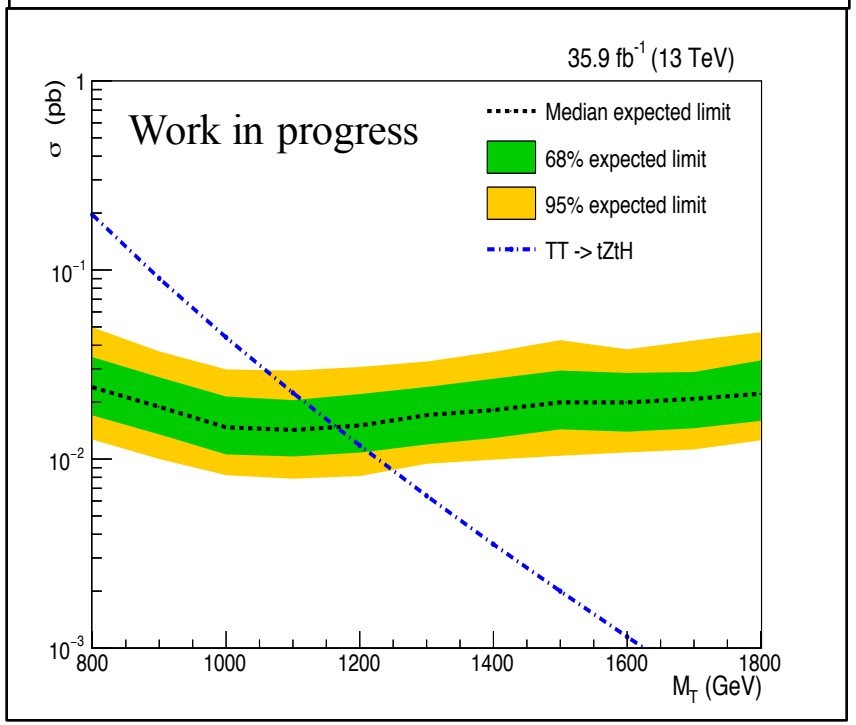


Expected Limits

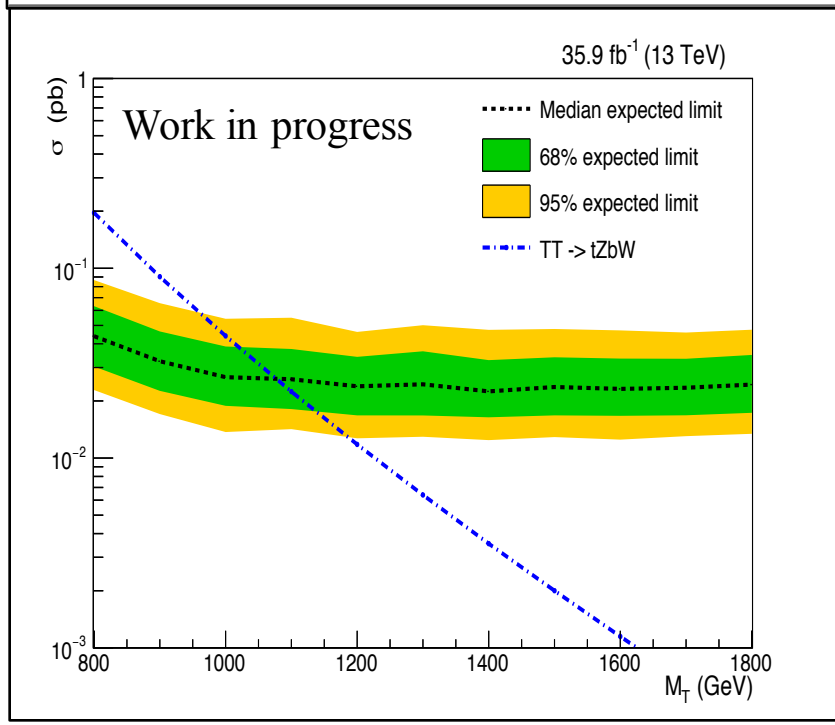
Expected limit for $T\bar{T} \rightarrow tZtZ$



Expected limit for $T\bar{T} \rightarrow tZtH$



Expected limit for $T\bar{T} \rightarrow tZbW$



- Expected limits are computed using Bayesian likelihood-based technique
- If data is consistent with SM Bkg T quark can be excluded with masses below,

(1) 1245 GeV (TT → tZtZ)
(2) 1165 GeV (TT → tZtH)
(3) 1065 GeV (TT → tZbW)

Summary

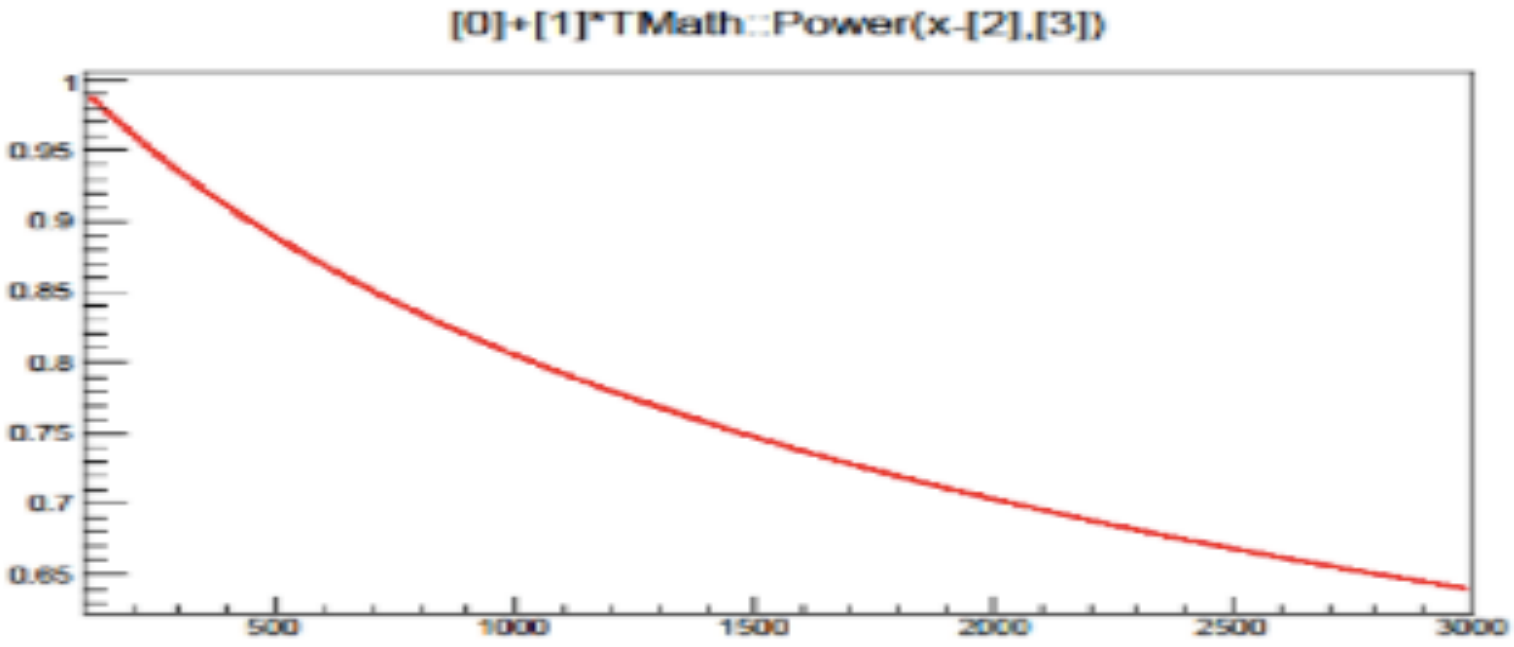
- Devised a efficient method to identify the hadronically decaying objects and thereby to optimize the search

- Planning to un-blind the signal region after pre approval

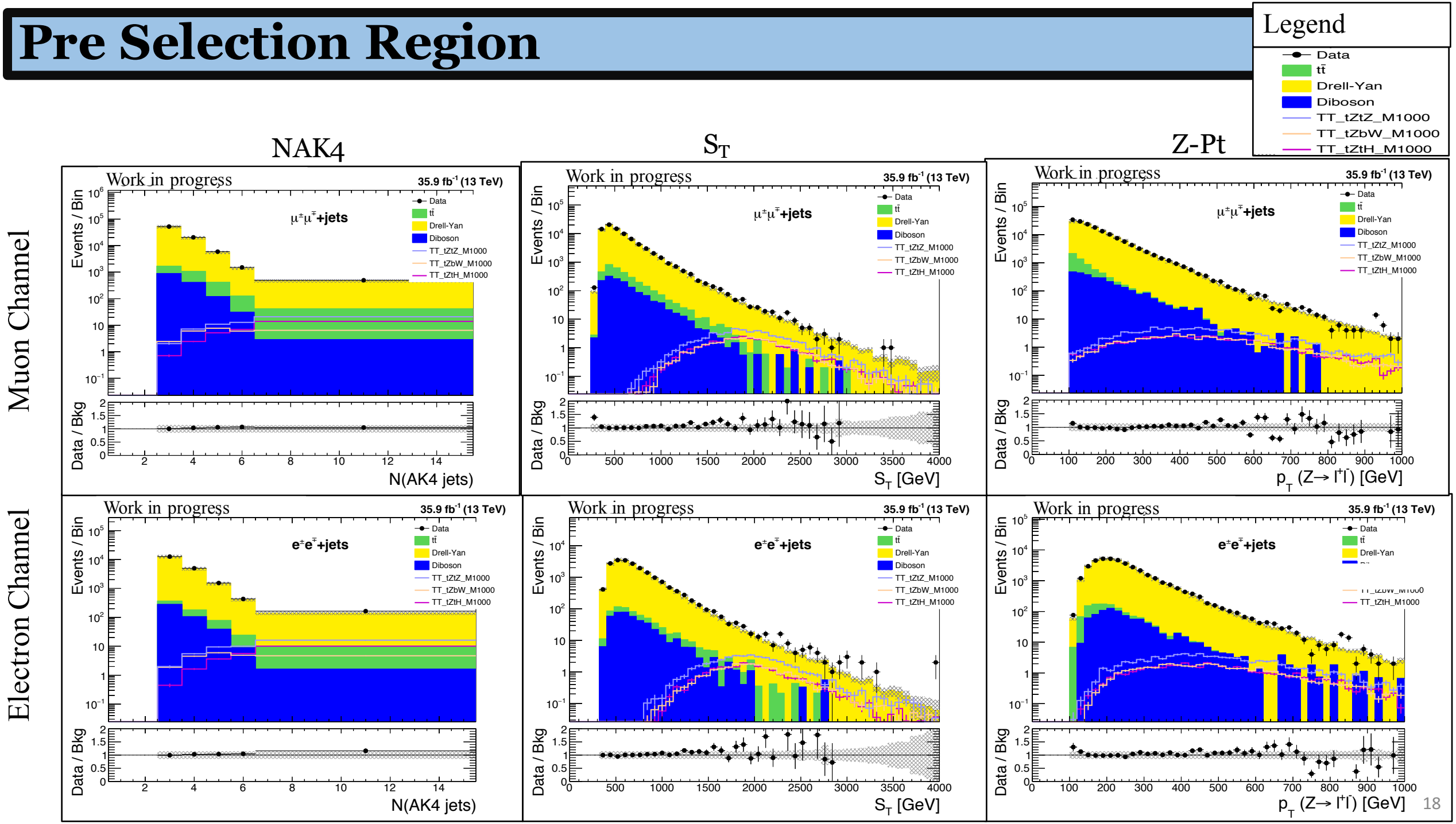
BackUp

Electroweak Corrections

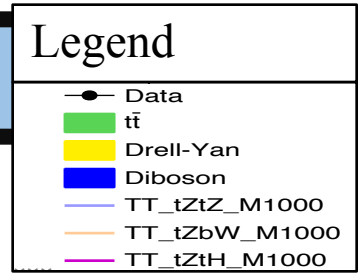
- AN2015_186_v9
- Corrections due to NLO electroweak contributions
- Applied to the event weight per event
- Increasingly important at high pt
- S. Kallweit et al., “NLO QCD+EWpredictions for V+jets including off-shell vector-boson decays and multijet merging”, arXiv:1511.08692.



Pre Selection Region

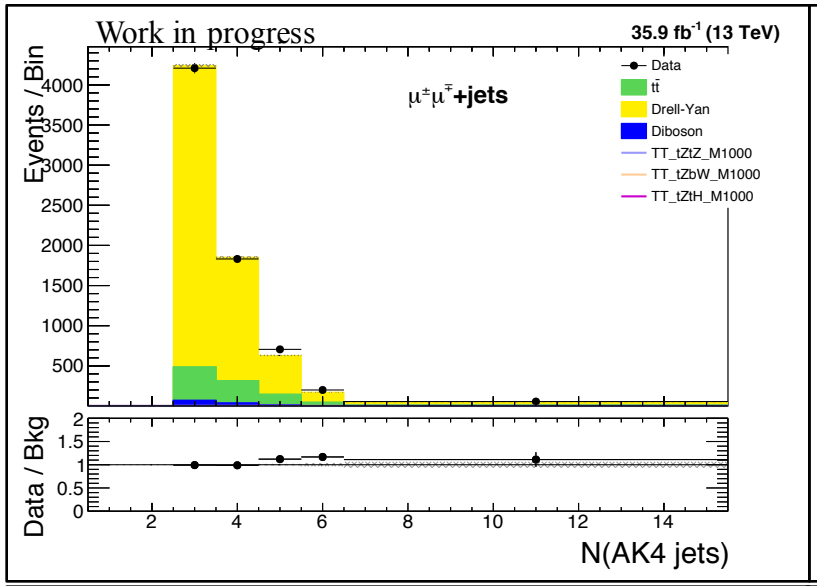


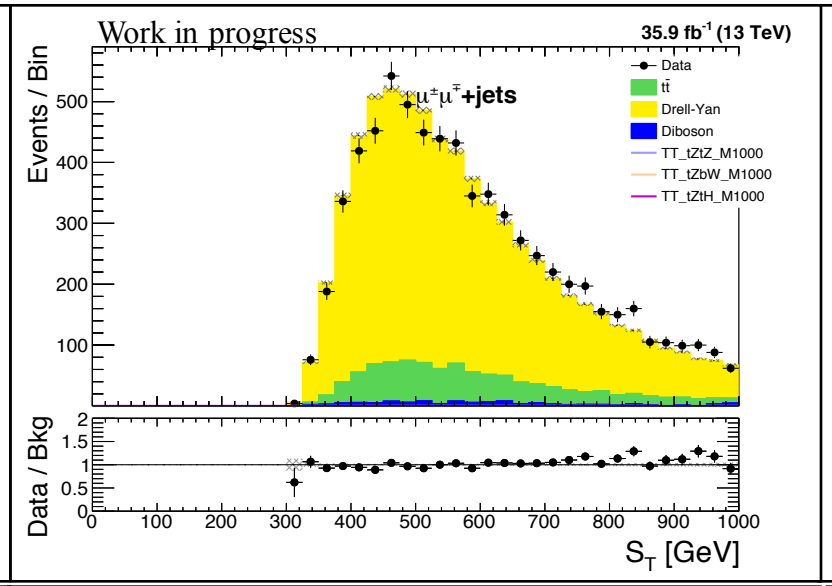
Control Region

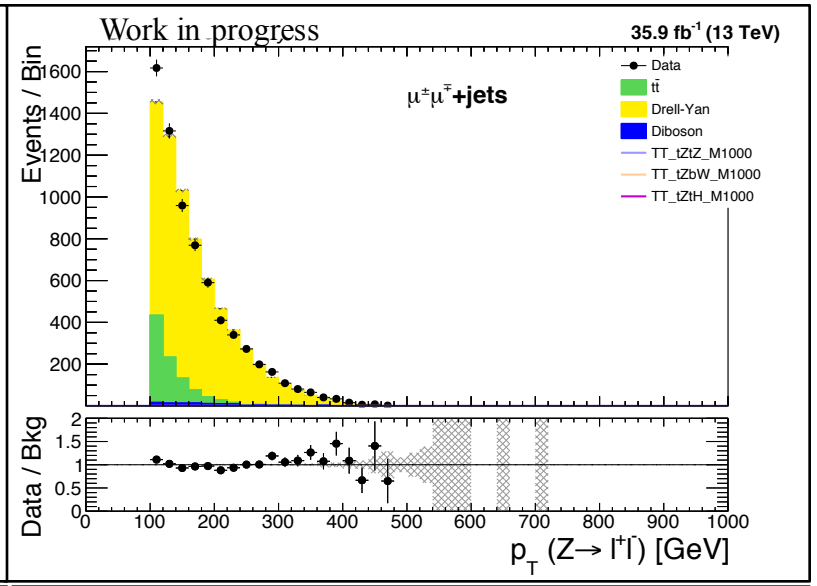


NAK4 | S_T | Z-Pt

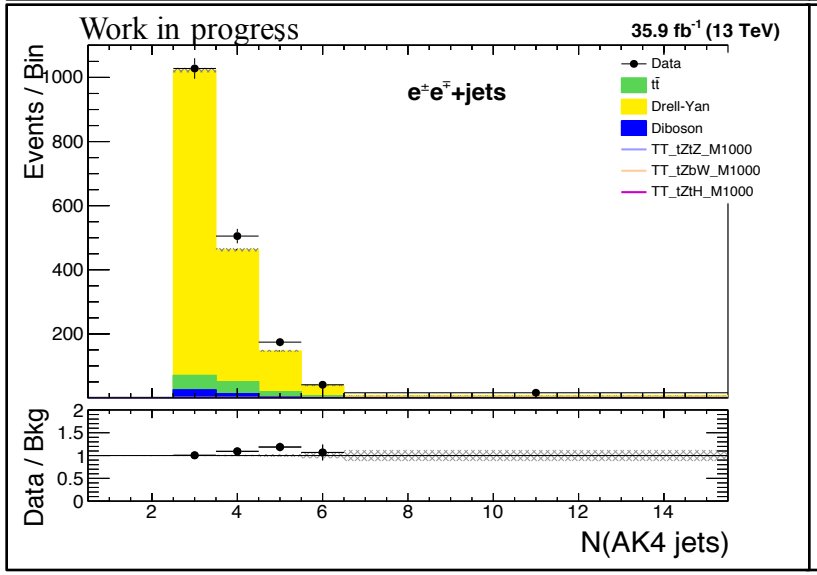
Muon Channel

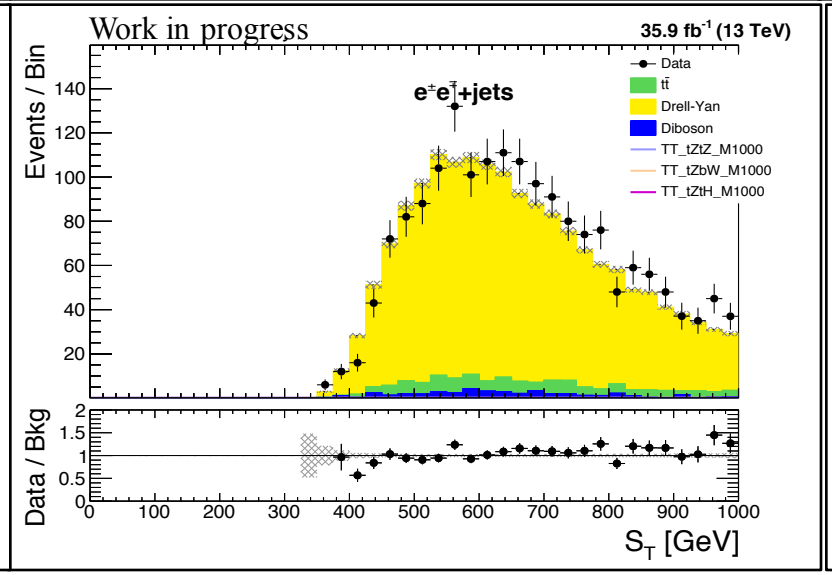


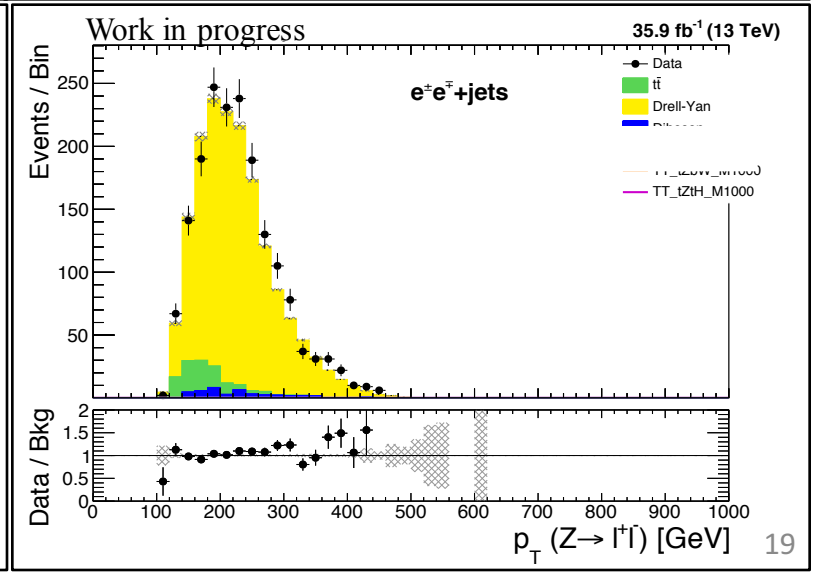




Electron Channel







Categorization using n-top , n-Z ,n-H & n-b

N-Top/ Z/ H candidates and N-btags

Sorting the events into 16 mutually exclusive categories

t1Z1H1b1	ntop≥1 nZ≥1 nH=1 nb=1
t1Z1H1b2	ntop≥1 nZ≥1 nH=1 nb≥ 2
t1Z1H0b1	ntop≥1 nZ≥1 nH= 0 nb=1
t1Z1H0b2	ntop≥1 nZ≥1 nH= 0 nb≥ 2
t0Z1H1b1	ntop= 0 nZ≥1 nH=1 nb=1
t0Z1H1b2	ntop= 0 nZ≥1 nH=1 nb≥ 2
t0Z1H0b1	ntop= 0 nZ≥1 nH= 0 nb=1
t0Z1H0b2	ntop= 0 nZ≥1 nH= 0 nb≥ 2
t1Z0H1b1	ntop≥1 nZ= 0 nH=1 nb=1
t1Z0H1b2	ntop≥1 nZ= 0 nH=1 nb≥ 2
t1Z0H0b1	ntop≥1 nZ= 0 nH= 0 nb=1
t1Z0H0b2	ntop≥1 nZ= 0 nH= 0 nb≥ 2
t0Z0H1b1	ntop= 0 nZ= 0 nH=1 nb=1
t0Z0H1b2	ntop= 0 nZ= 0 nH=1 nb≥ 2
t0Z0H0b1	ntop= 0 nZ= 0 nH= 0 nb=1
t0Z0H0b2	ntop= 0 nZ= 0 nH= 0 nb≥ 2

S_T distribution for Final Categories in Control Region (Electron Channel)

- Data/MC modelling in Control region

Fig : S_T dist^n of Cat A

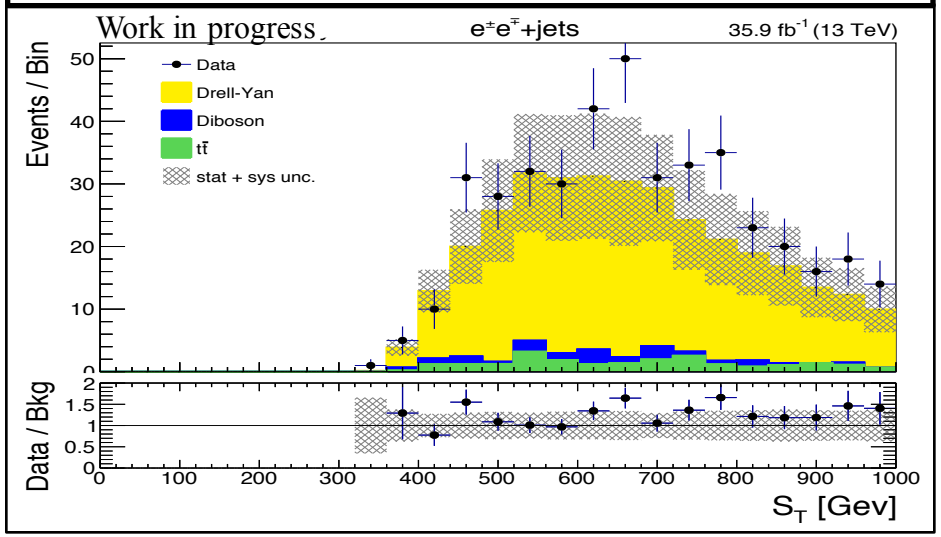


Fig : S_T dist^n of Cat B

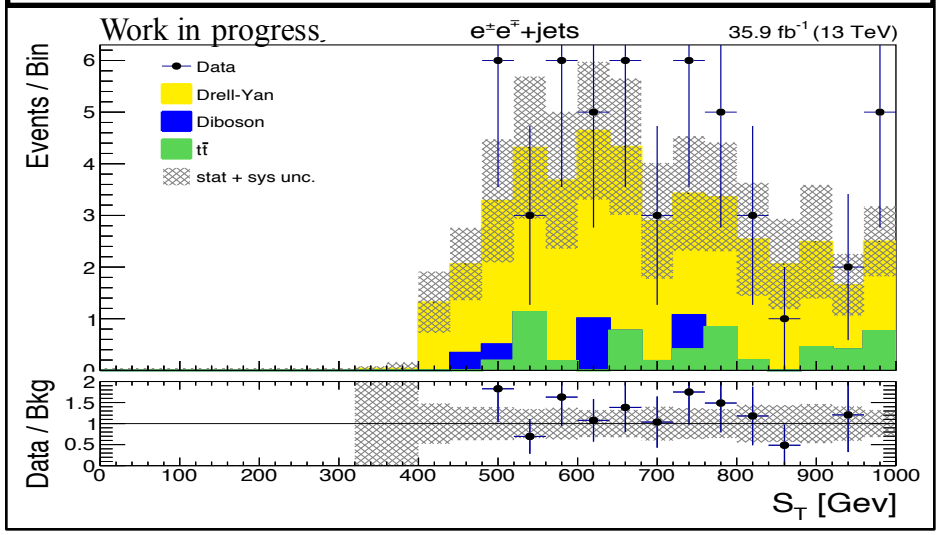


Fig : S_T dist^n of Cat C

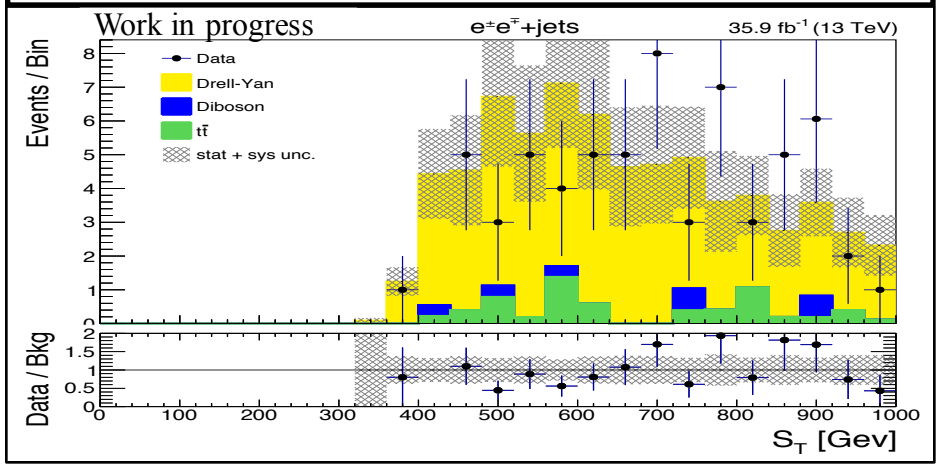
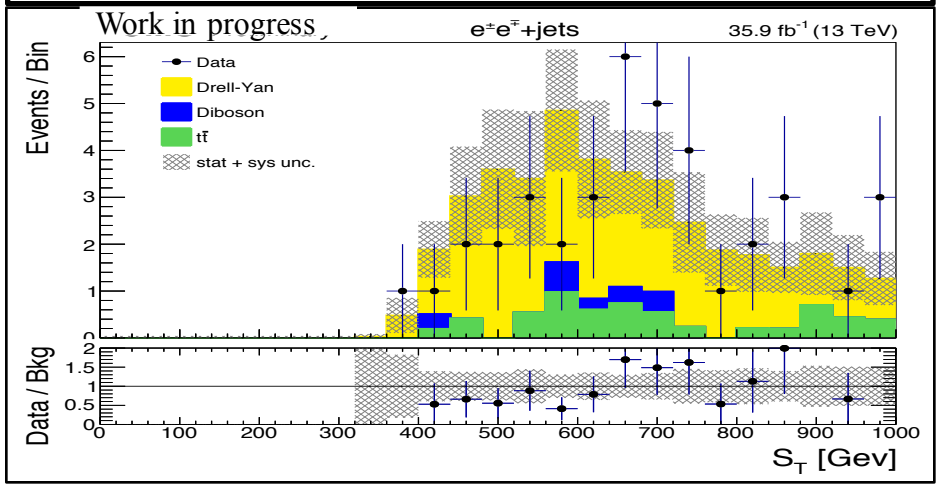


Fig : S_T dist^n of Cat D



S_T distribution for Final Categories in Signal Region (Electron Channel)

*** Signal is normalized to 1 pb cross section for visualization**

Fig : S_T dist^n of Cat A

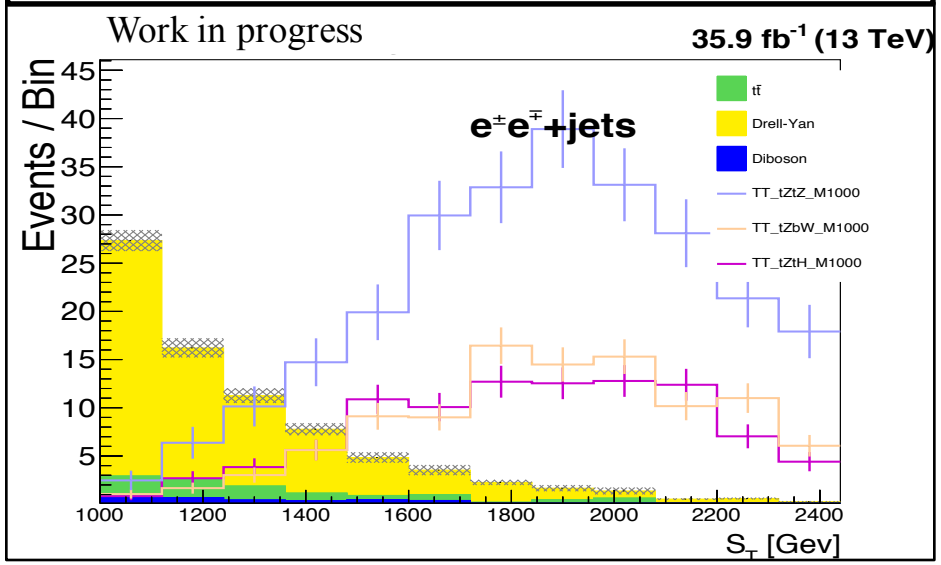


Fig : S_T dist^n of Cat B

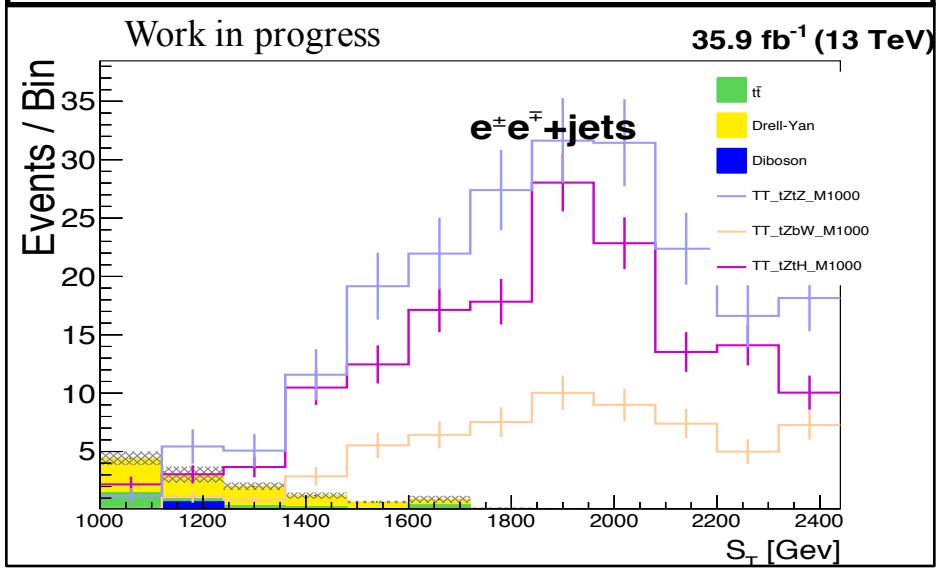


Fig : S_T dist^n of Cat C

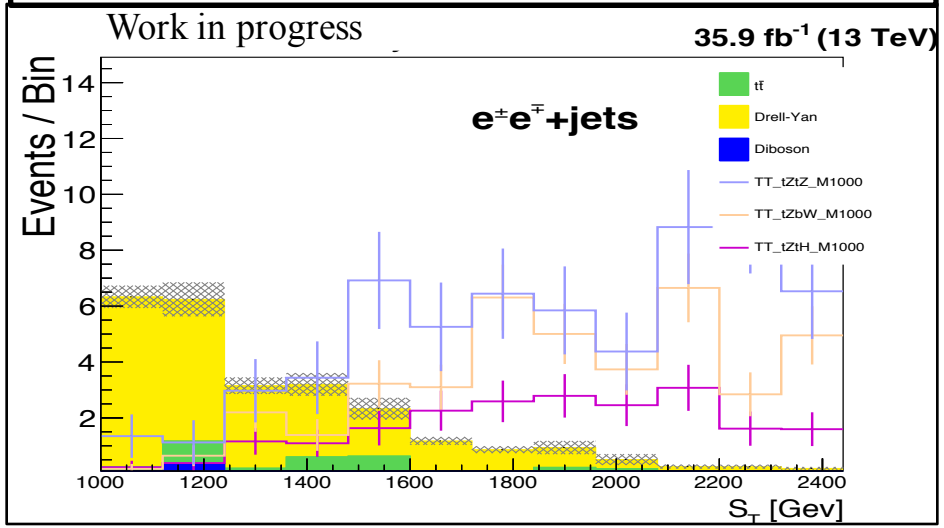
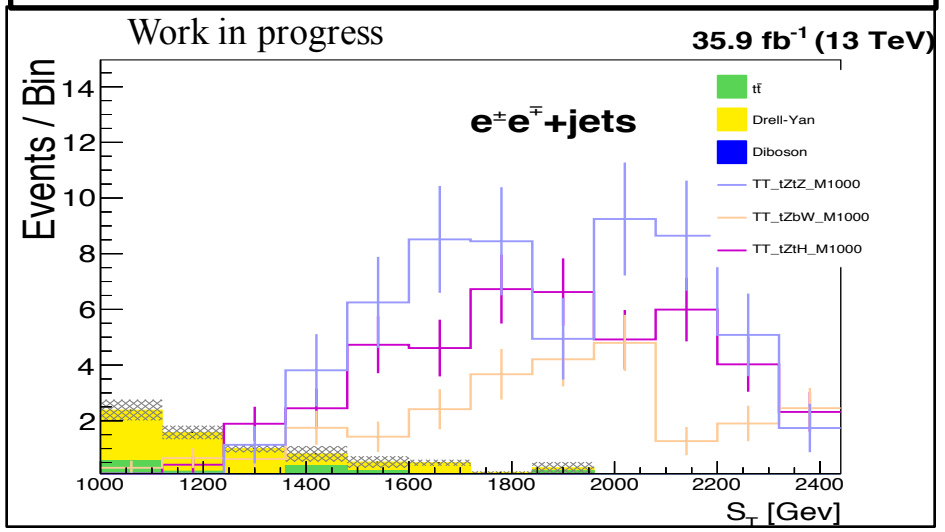


Fig : S_T dist^n of Cat D



Systematics

Normalization Uncertainties

Source	Uncertainty (%)
$t\bar{t}$ + jets	15
Drell-Yan	15
Diboson	15
Integrated Luminosity	2.6
Lepton ID + Isolation	3
Trigger Efficiency	1

Shape Uncertainties

Source	source
Jet Energy Scale	Jet Energy Resolution
Pileup	b tagging scale factor
W/Z/H-tagging	DY- Scale factor
Top tagging τ_3/τ_2	subjet b-tagging for H-tag
PDF	QCD scale

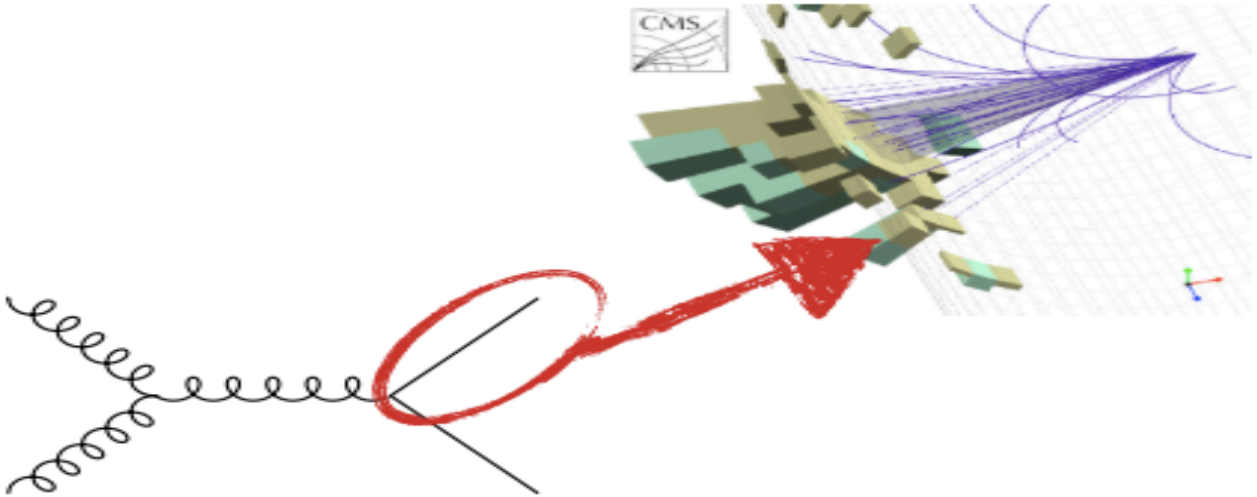
Expected Limits

- Expected limits are computed using Bayesian likelihood-based technique
- If data is consistent with SM Bkg T quark can be excluded with masses below,

(1) 1245 GeV (TT → tZtZ)
(2) 1165 GeV (TT → tZtH)
(3) 1065 GeV (TT → tZbW)

What is a jet?

- From a list of particles one can form **jets**, an object to reconstruct the shower of particles produced from a quark or gluon
- Each particle belonging to a jet is known as a **constituent**
  - Each has a 4-vector that can be used for further studies



$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\, \Delta R_{ij}^2 / R^2$$
$$d_{iB} = p_{ti}^{2p}\ .$$

$p = 1$ → kt algorithm (KT)

$p = 0$ → Cambridge Aachen algorithm (CA)

$p = -1$ → anti-kt algorithm (AK)

- Need a jet algorithm to collect the particles in this shower
- **"Clustering Algorithm"**
  - Iteratively find the two particles in the event which are closest in some distance measure and combine them
  - Combine two particles if $d_{ij} < d_{iB}$
    - Stop when $d_{ij} > d_{iB}$

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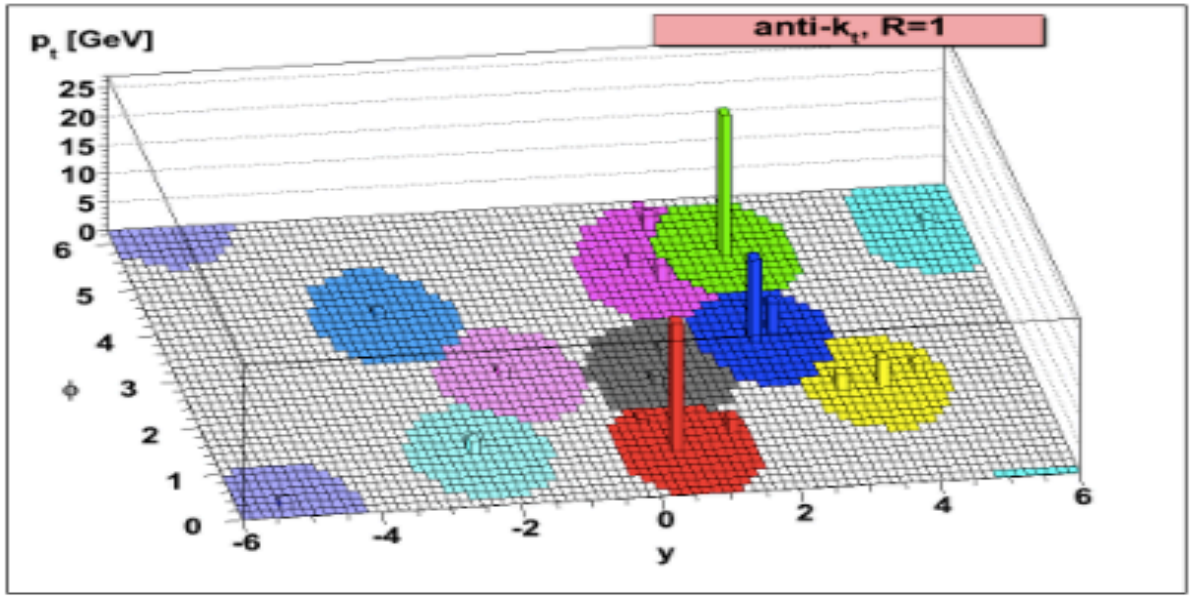
Jet properties

- Jet 4-vector = sum of all constituent particle 4-vectors
  - energy, pT, η, Φ
  - Jet mass $m = \sqrt{E^2 - p^2}$
  - Jet constituent multiplicities (PF)
    - ex. charged multiplicity
  - Jet constituent fractions
    - ex. charged hadron energy fraction
  - Jet area = area in η-Φ plane in which an infinitely soft particle will be clustered with the jet



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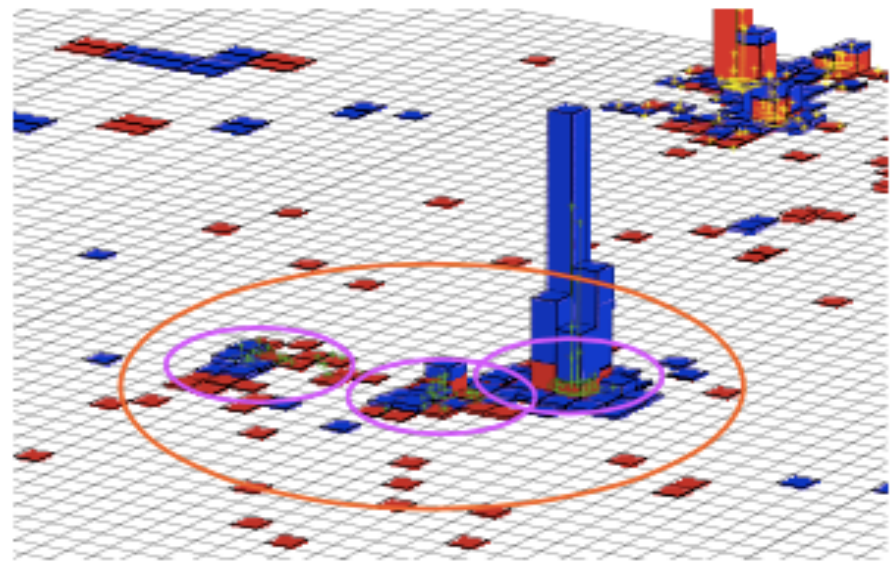
Jet substructure

- The internal structure of the jet constituents give us handles to discriminate between:
  - Noise jets
  - Quark jets
  - Gluon jets
  - b-jets
  - W-jets
  - Z-jets
  - t-jets
  - H-jets
  - PU jets



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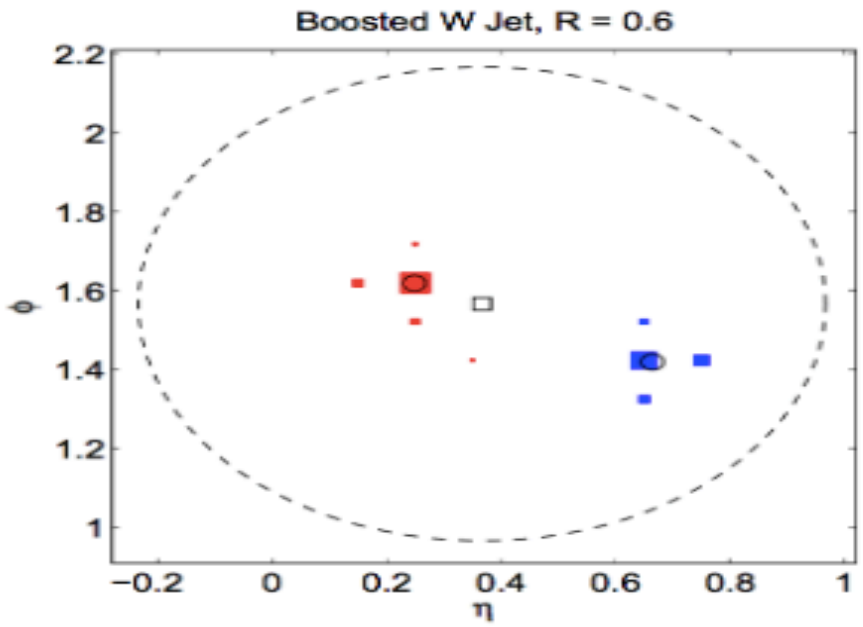
Topological Algorithms

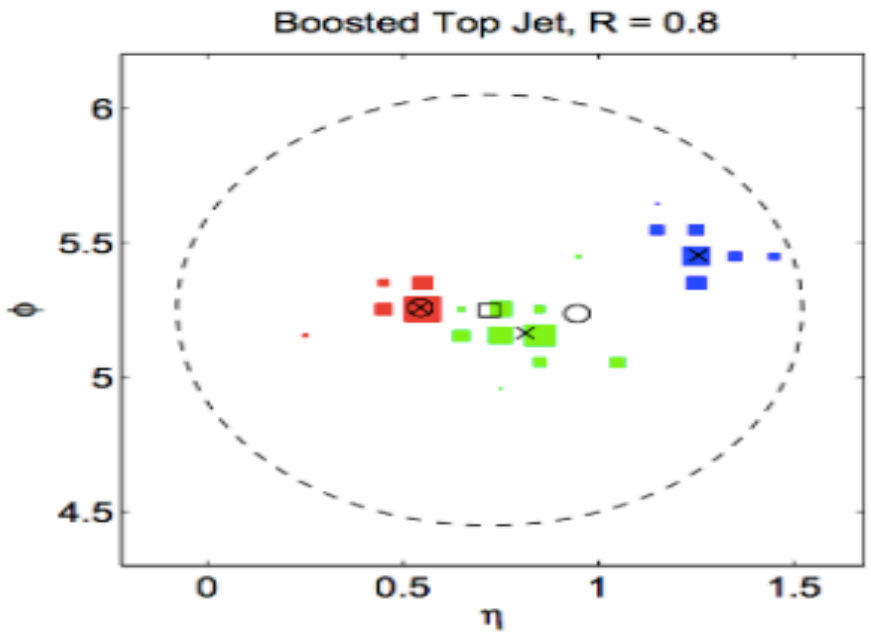
arXiv:1011.2268

- We know how many final state objects to expect from these decays
  - Can look inside the jet for the expected substructure
    - Top decays → 3 subjets
    - W/Z/H decays → 2 subjets
- A quantity called N-subjettiness is a measure of how consistent a jet is with a hypothesized number of subjets
  - Low τ_N → consistent with N (or fewer) subjets
  - Ratios used for additional discrimination

$$\tau_N = \frac{1}{\sum_i p_{T,i} \cdot R} \sum_i p_{T,i} \cdot \min(\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i})$$



□ 1 subjet hyp.
○ 2 subjet hyp.
× 3 subjet hyp.



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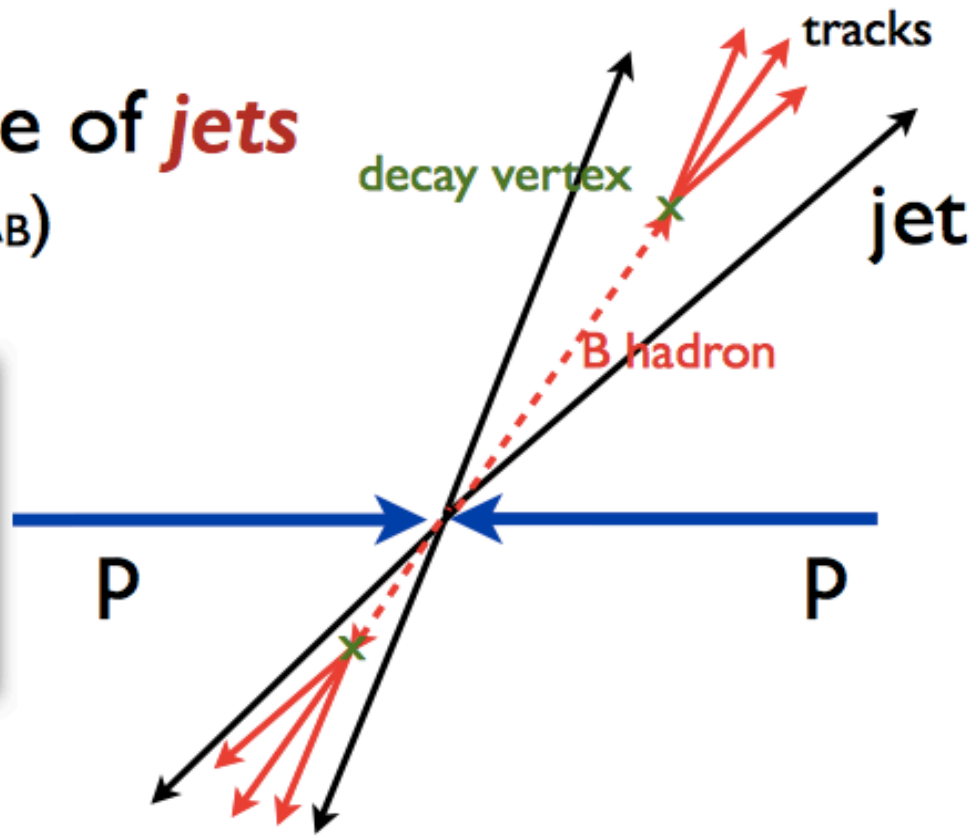
at hadron colliders (LHC)

B-hadrons are produced inside of *jets*

(b-quarks hadronize into B^+,B^-, B^0, B_s, Λ_B)

their *lifetime* (1.5ps) and the Lorentz boost lead to displaced decay vertices



b-tagging:

look for **displaced** tracks and vertices (secondary) within jets

why? for example Higgs→$b\bar{b}$ and many "new physics" scenarios

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b-tagging algorithms

- Impact Parameter based b-tagging:
  IP of one track in the jet ("track counting" TC algorithms, based on the IP significance of the 2nd most displaced track)
  or combination of all tracks in the jet ("jet probability")

- Secondary Vertex algorithms:
  SSV discriminators, based on the 3D SV flight distance

- combined methods using multivariate techniques (e.g. neural networks) to calculate one discriminator from many variables: CSVv2, cMVA

```
CSVv2M = 0.8484
```

- soft lepton tagging, exploiting B→lepton decays: limited BR to leptons, used for calibration purposes or combined with other variables

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