Search for Z’ → $t\bar{t}$ at LHC with the ATLAS Detector

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September 9, 2008

Outline

- Physics motivation
- W / Top reconstruction from jets
- Event selections
- Z' → ttbar search strategies
- Expected detection sensitivities
- Future plans

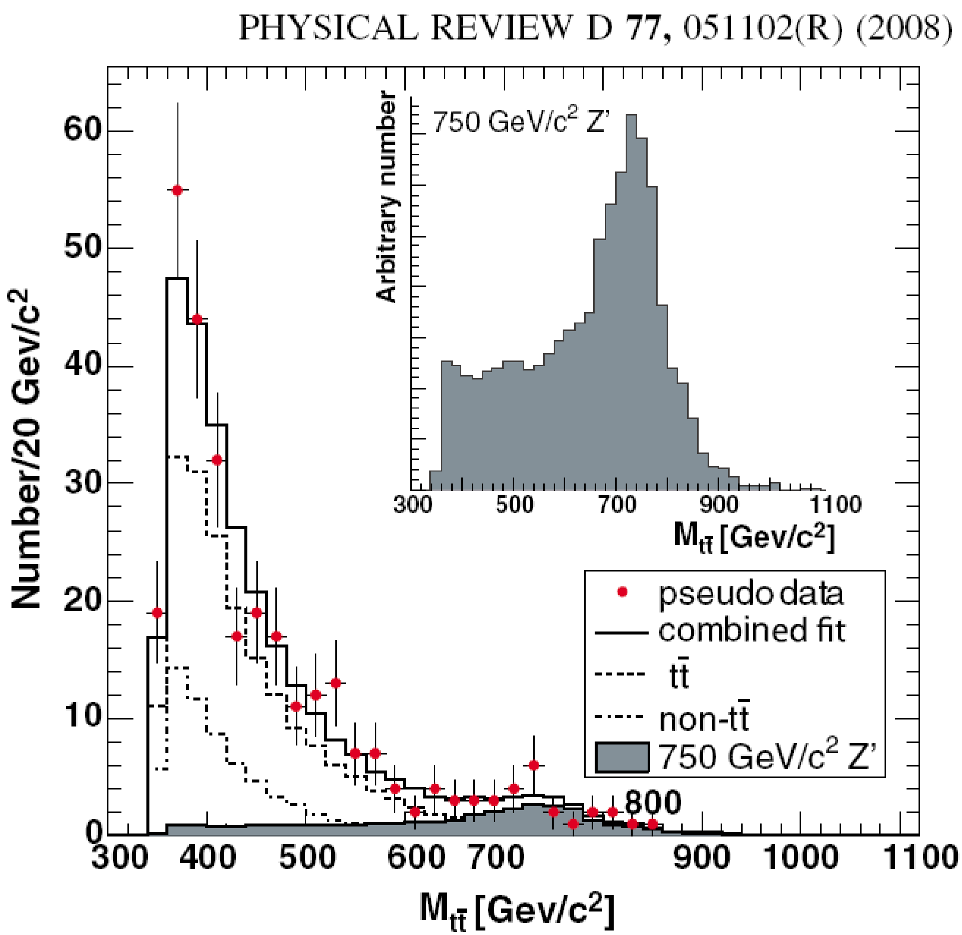
Physics Motivation

- There are many models predict the signatures with top-rich events. Z'→ ttbar has been used as the *benchmark* for such studies.

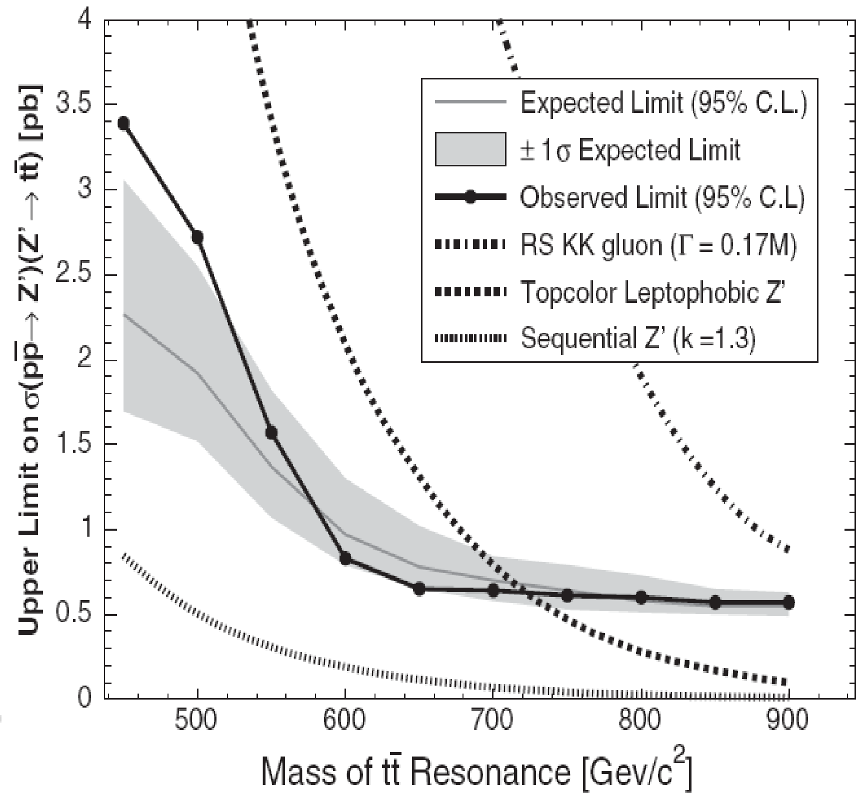
- Additional U(1)' gauge symmetries and associated Z' gauge boson are one of many motivated extensions of the SM (Ref: Paul Langacker, arXiv:0801.1345v2). Searches for Z' via leptonic decay productions (ee, $\mu\mu$) have been conducted at LEP and Tevatron (current limit: $M_{Z'}$ > 850 GeV from CDF, Ref: Phys. Rev. D70:093009, 2004).

- But, the searches through leptonic channels do not rule out the existence of a Z' resonance with suppressed decays to leptons, so called "leptophobic" Z'. Several models (RS Kaluza-Klein states of gluons, weak bosons and gravitons; Topcolor leptophobic Z'; Sequential Z' etc.) suggest that Z'-like state would decay predominantly to heavy quark-antiquark pairs, e.g. ttbar if the Z' mass is larger than 2 $M_{top.}$

Search for Z'→ $t\bar{t}$ at CDF



σ_{tt} = 7.8 ± 0.7 pb

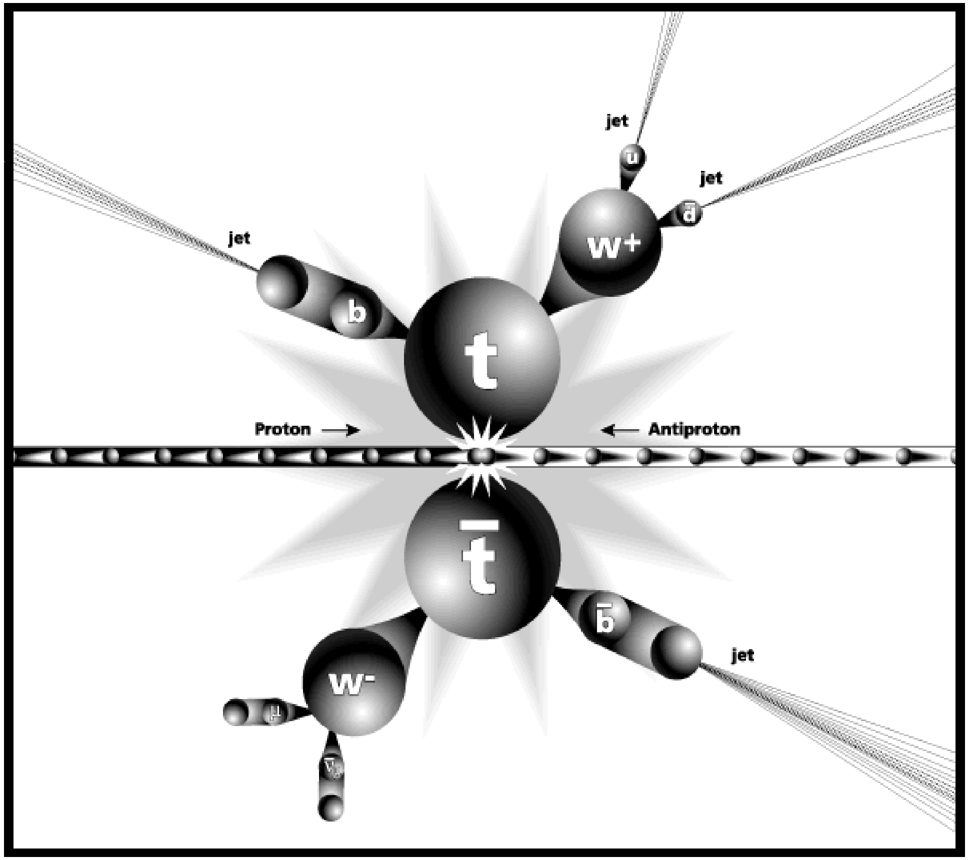


MC Samples Used in Our Study

- Signal: Z’ → ttbar → bbww → bbjjlν
  - Dataset: 6231, 20000 Events, M_Z’ = 1.0 TeV
  - Dataset: 6232, 19500 Events, M_Z’ = 1.5 TeV
  - Dataset: 6233, 20000 Events, M_Z’ = 2.0 TeV
  - Dataset: 6234, 19500 Events, M_Z’ = 3.0 TeV
- Major Backgrounds:
  - Ttbar: 5200(>=1 lep), 450100 Events
  - Ttbar: 5204(W hadronic decay), 97750 Events
  - Single Top: 5500(Wt,14950 Events), 5501(s-channel, 9750 Events), 5502(t-channel, 18750 Events)
  - W/Z+Jets (1.1 Million Alpgen Events)
  - Dijets: 5014(14500 Events), 5015 (381550 Events)

W and Top Reconstruction with jets final states

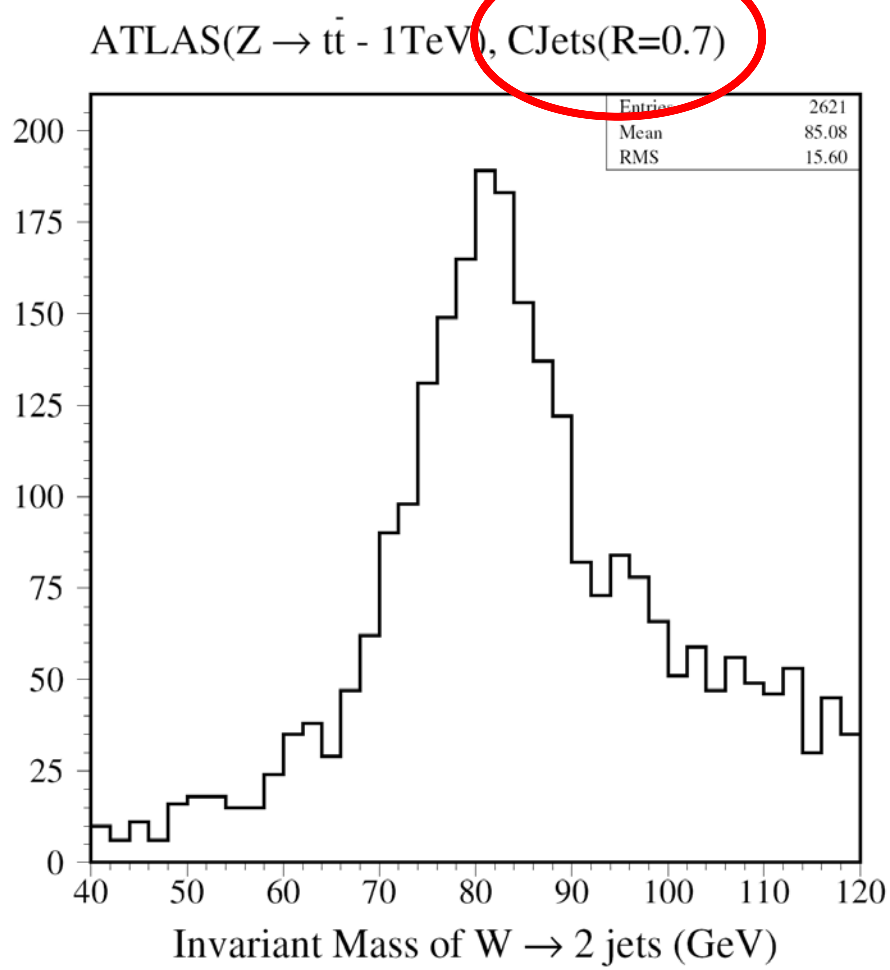
➔ With the increase of Z' mass, the energy of Top/W from Z' decay increase and the decay jets are boosted and located in a relative small region. In order to reconstruct Top/W efficiently, it's critical to use a suitable jet finding algorithm.

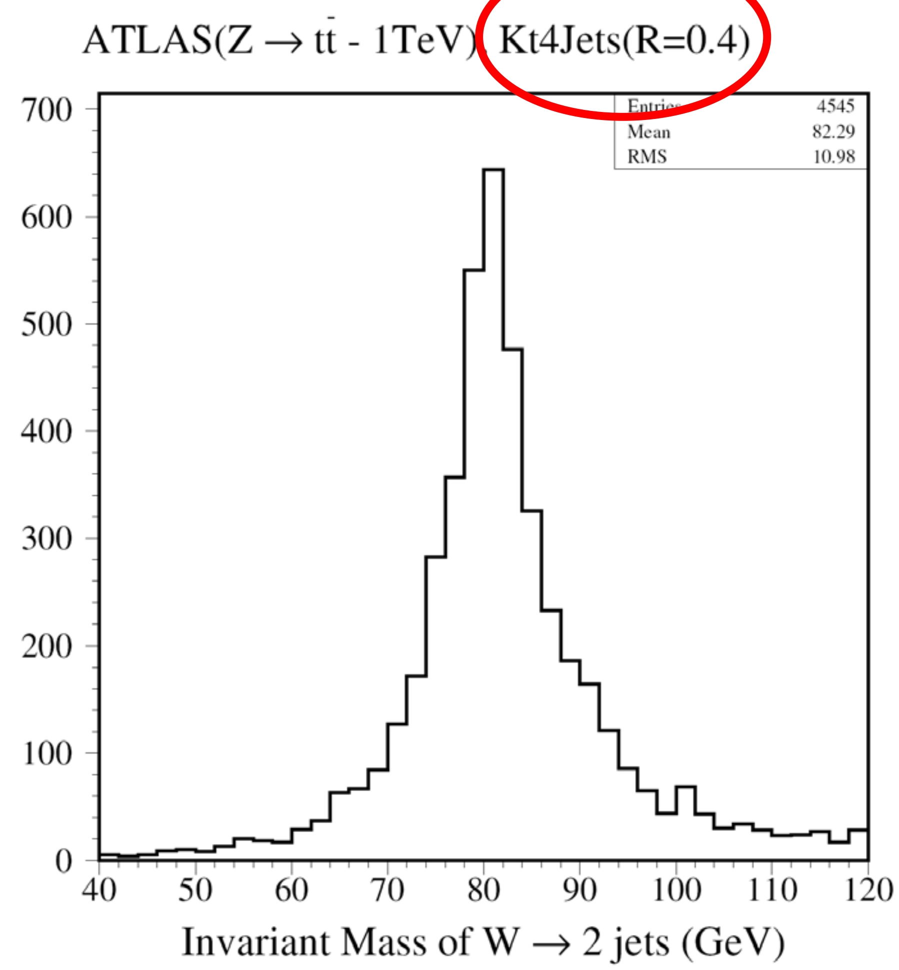


➔ATLAS employs two jet finding algorithms (Cone, Kt),

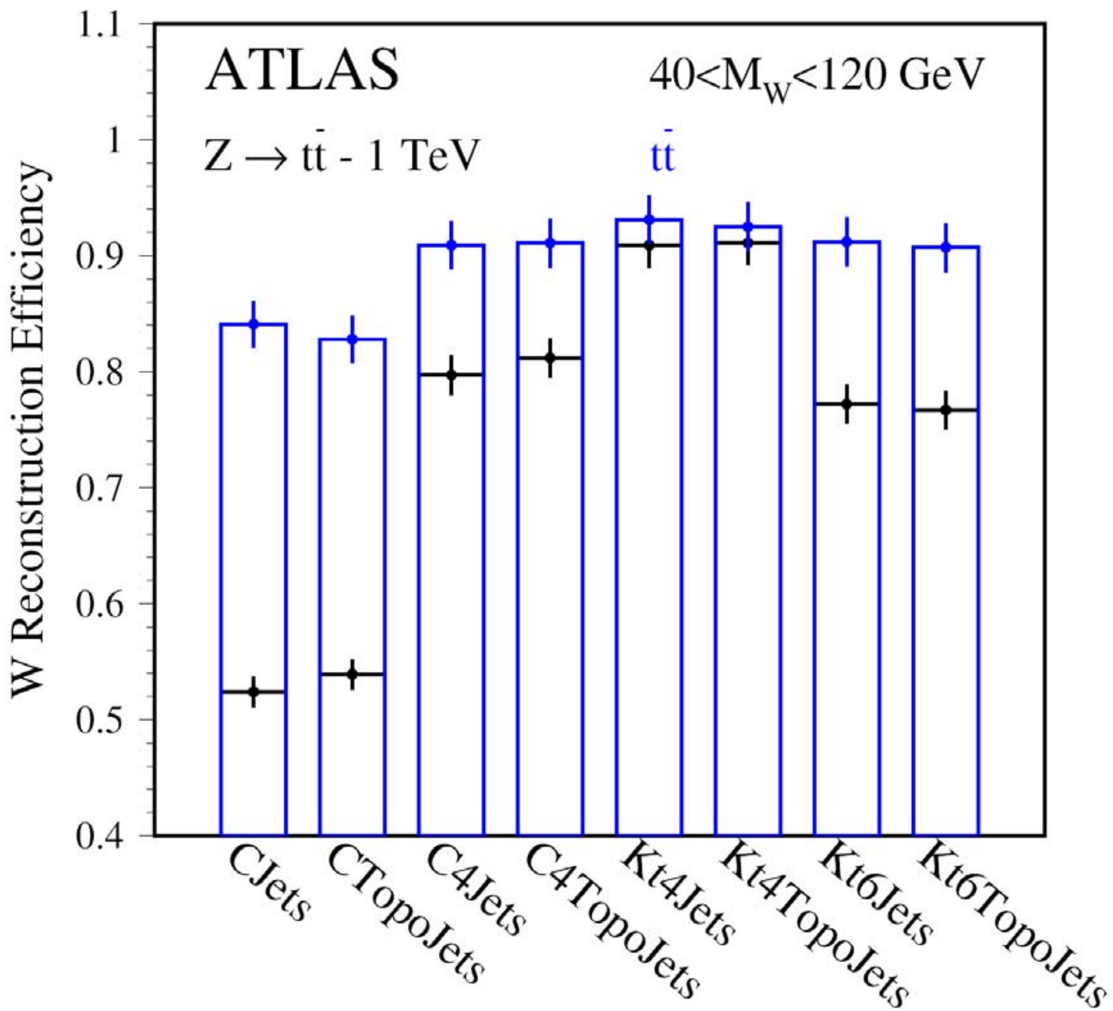
- CJets (R=0.7)
- CTopoJets (R=0.7)
- C4Jets (R=0.4)
- C4TopoJets (R=0.4)
- Kt4Jets (R=0.4)
- Kt4TopoJets (R=0.4)
- Kt6Jets (R=0.6)
- Kt6TopoJets (R=0.6)

W → jj Reconstruction

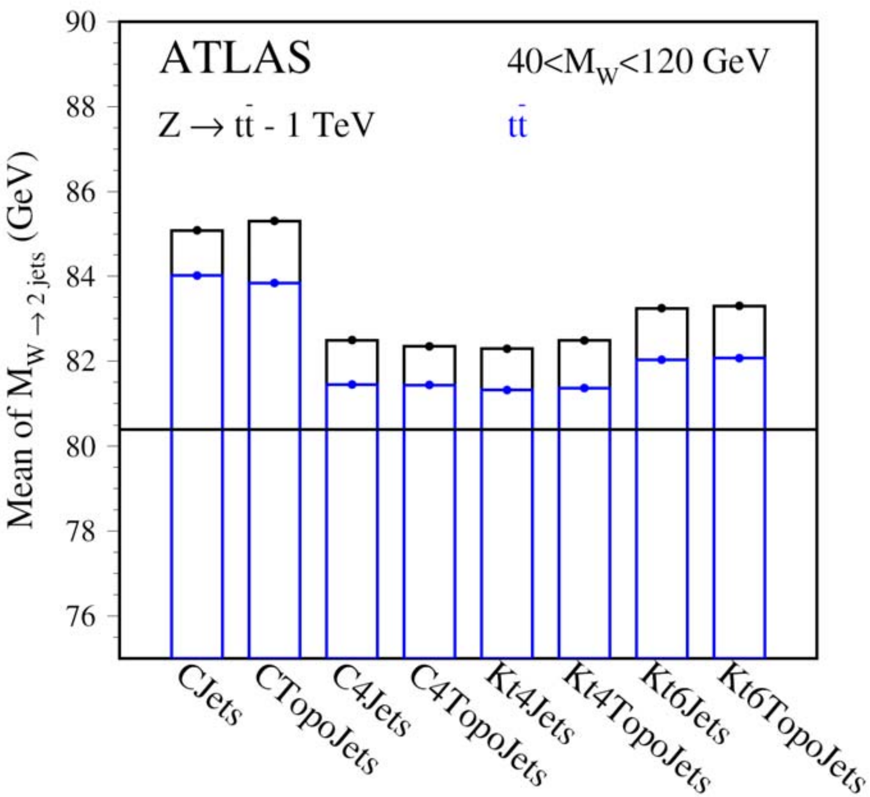


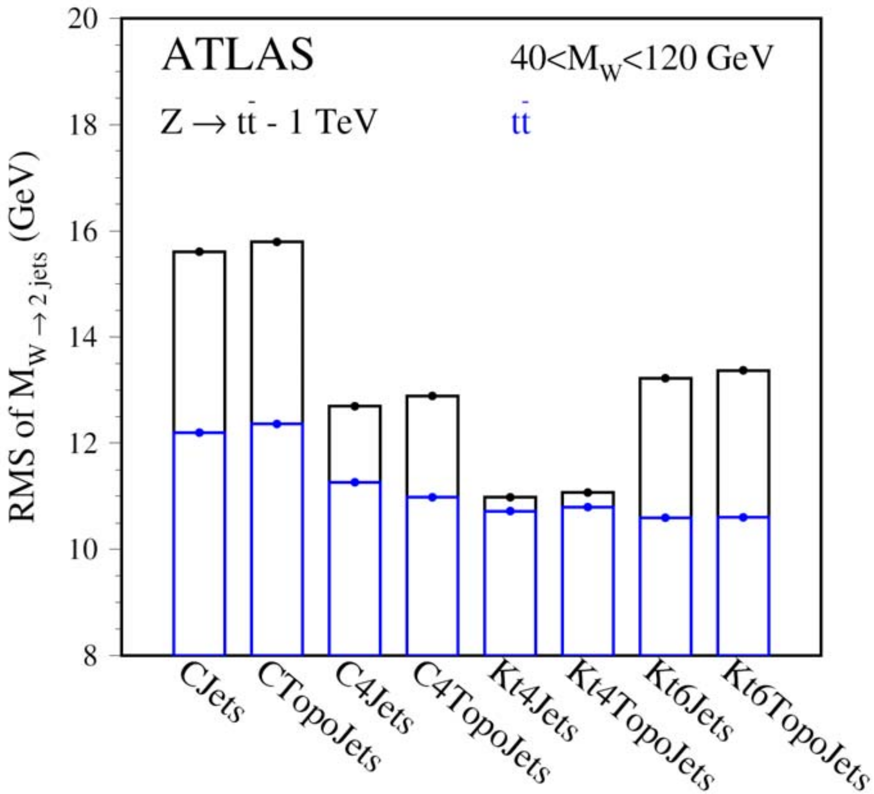


Efficiency of W → jj Reconstruction



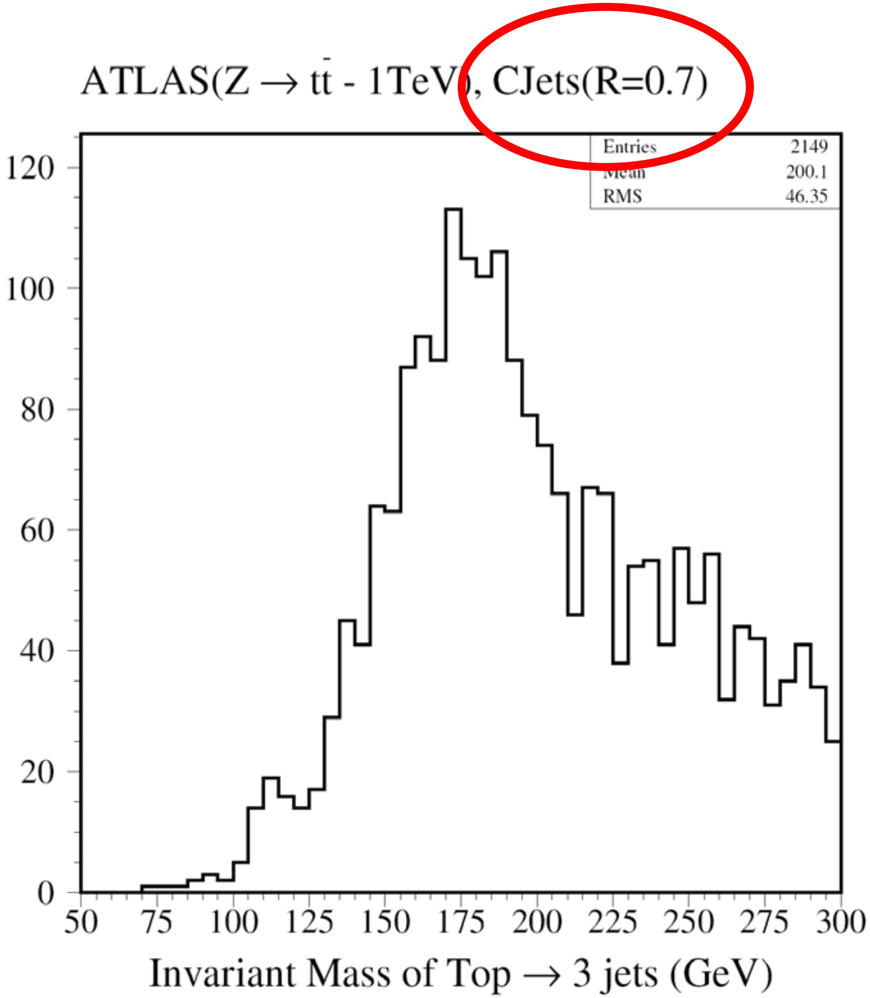
Mass Reconstruction of W → jj

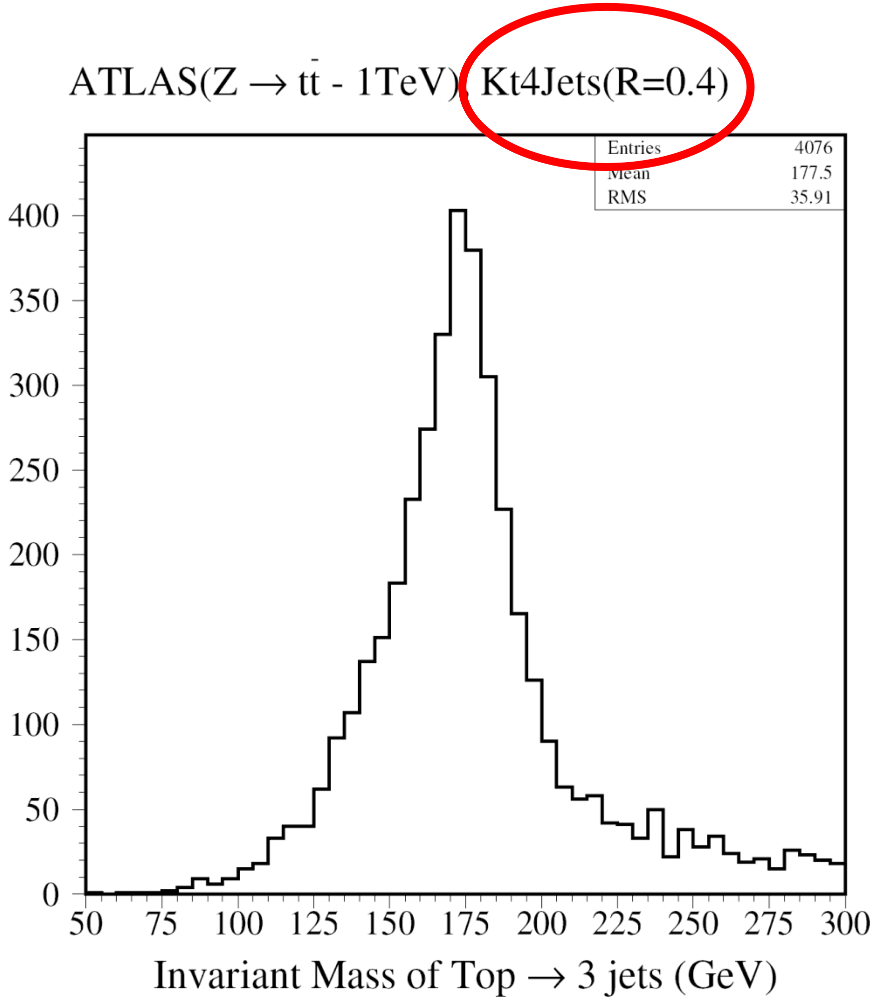




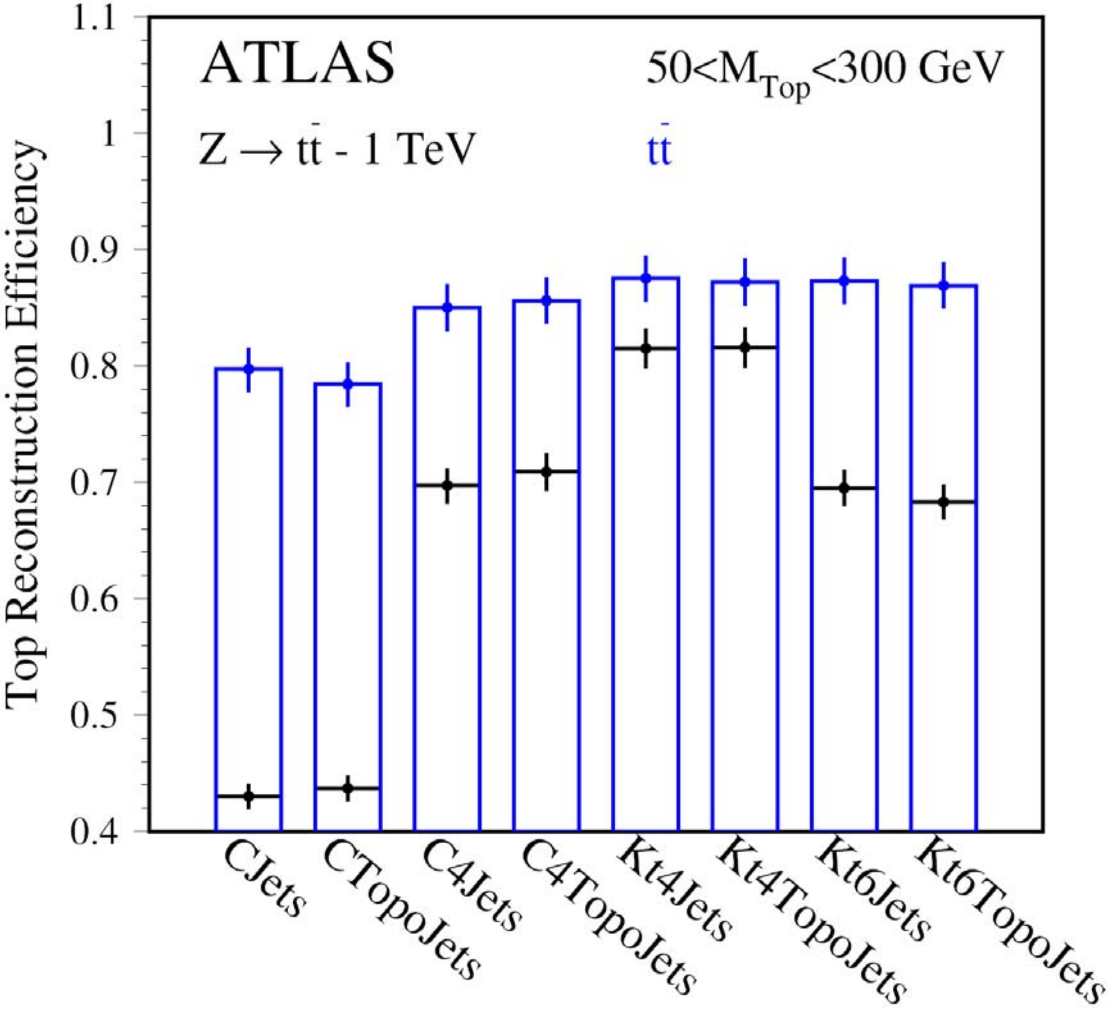
RMS of M_W ~ 11 GeV

Top → bW(→jj) Reconstruction

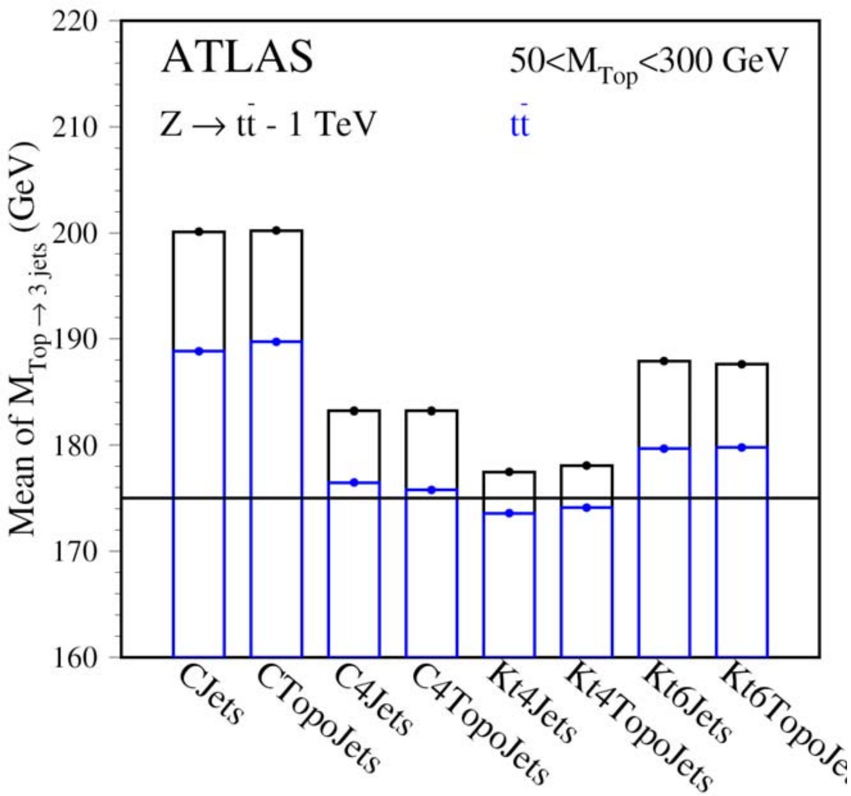


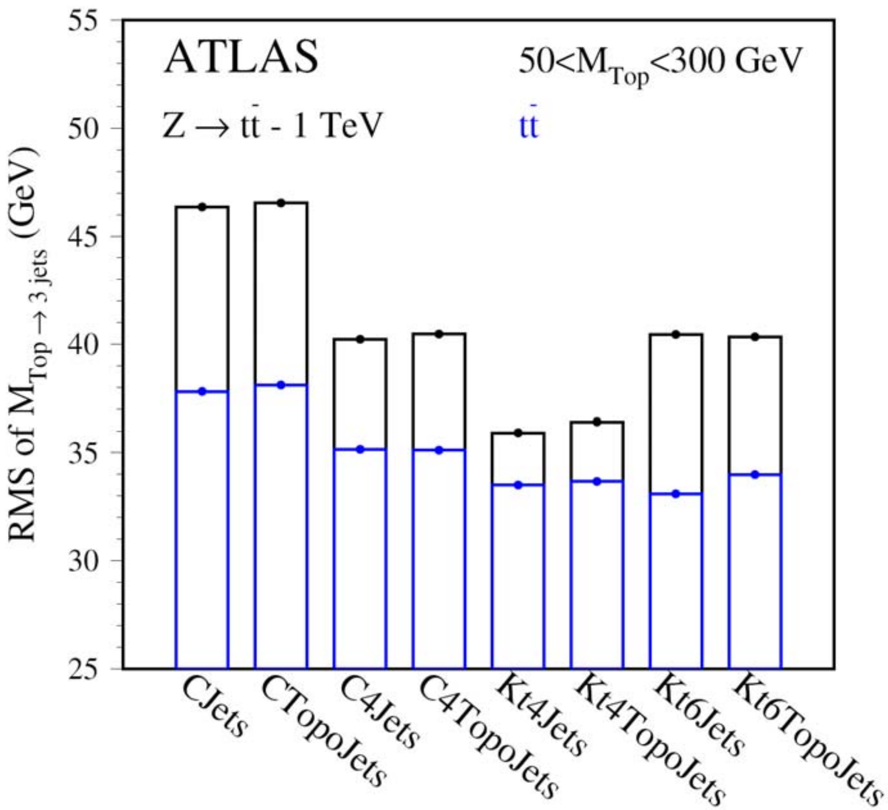


Eff. of Top → bjj Reconstruction



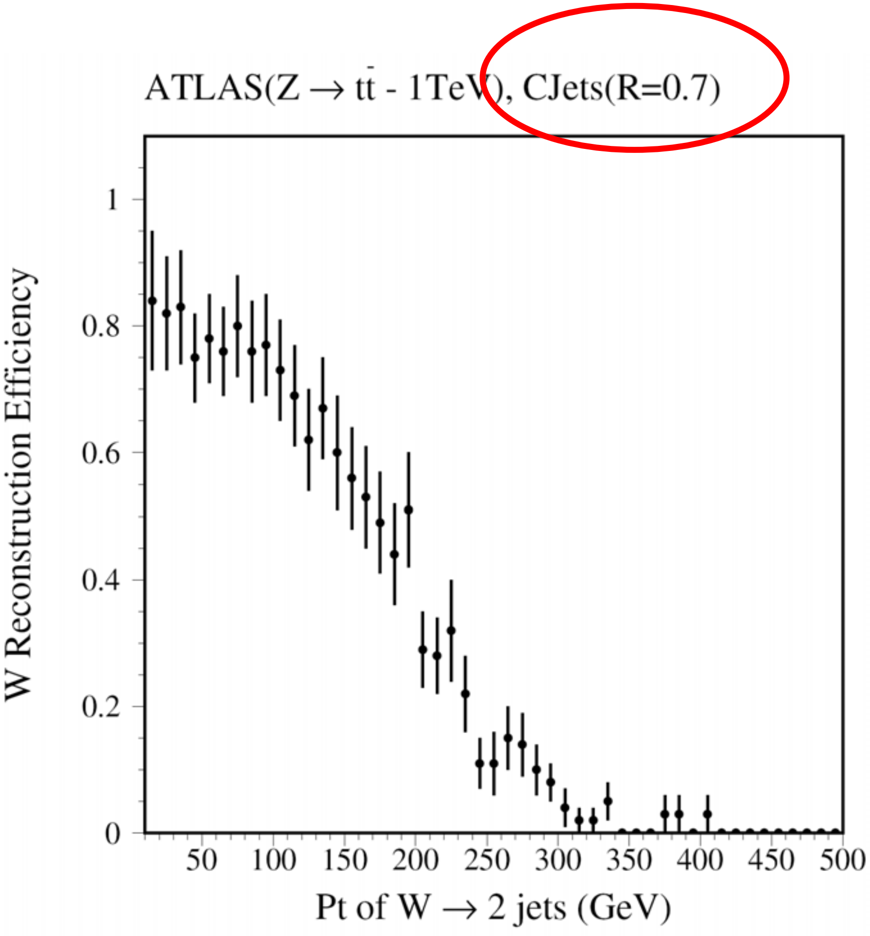
Mass Reconstruction of Top → bjj

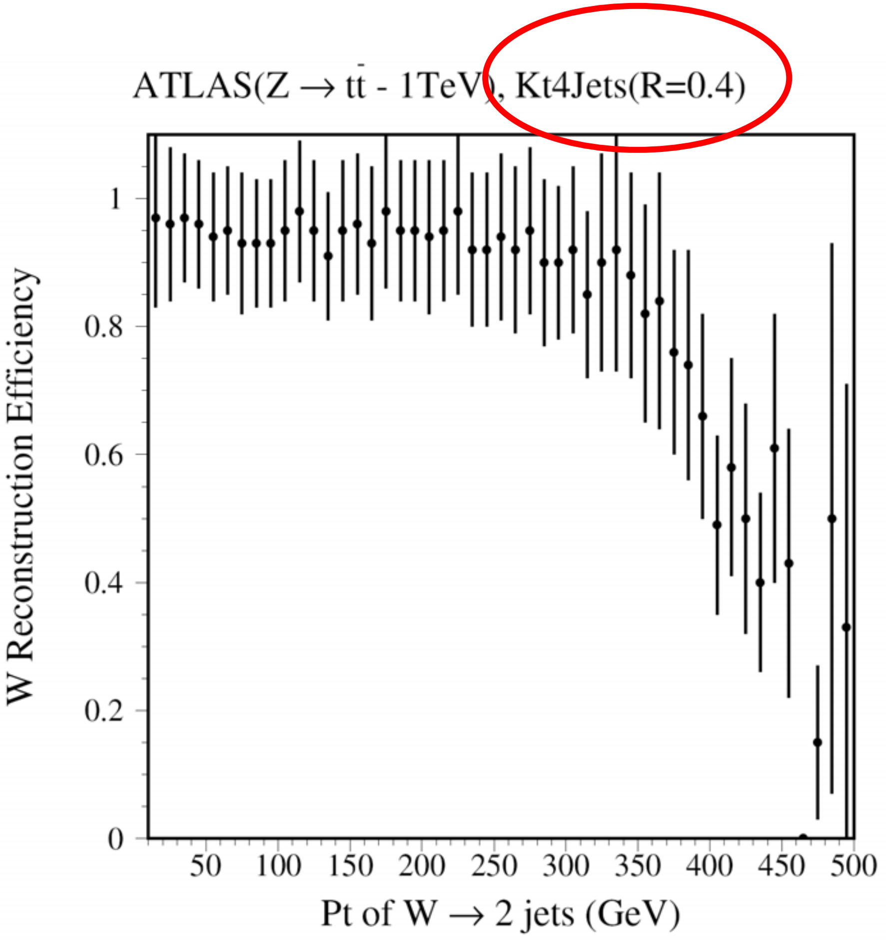




RMS of M_{Top} ~ 36 GeV

Efficiency of W Reconstruction vs. Pt





Analysis Strategy

- Event selection (to suppress most of background events):
  - Pre-selection cuts
  - With cut-based analysis
  - With BDT multivariate technique, trained decision trees using Z' with the combination of various mass (1, 1.5, 2, 3 TeV)

- Scan the "mass window" to find the most interest region (IR) in Mass(lep,jets) spectrum after selection, then enlarge or shrink mass window to optimize the "signal" sensitivity.

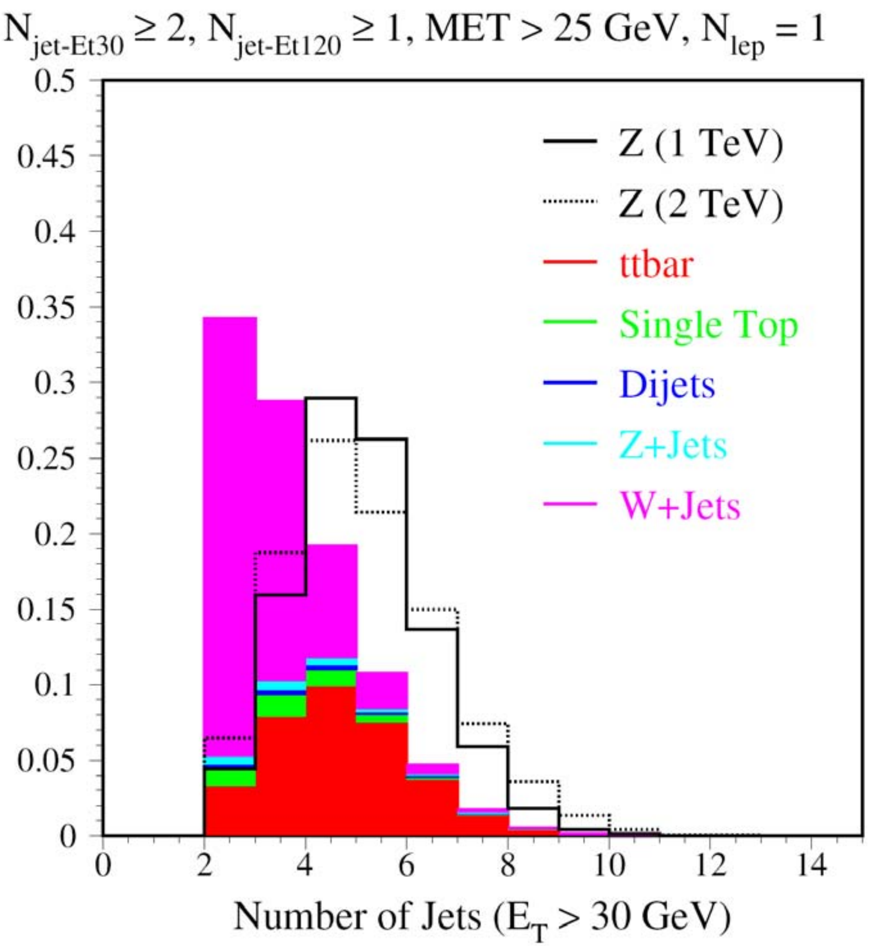
- To extract possible "signal" by fitting the background distributions.

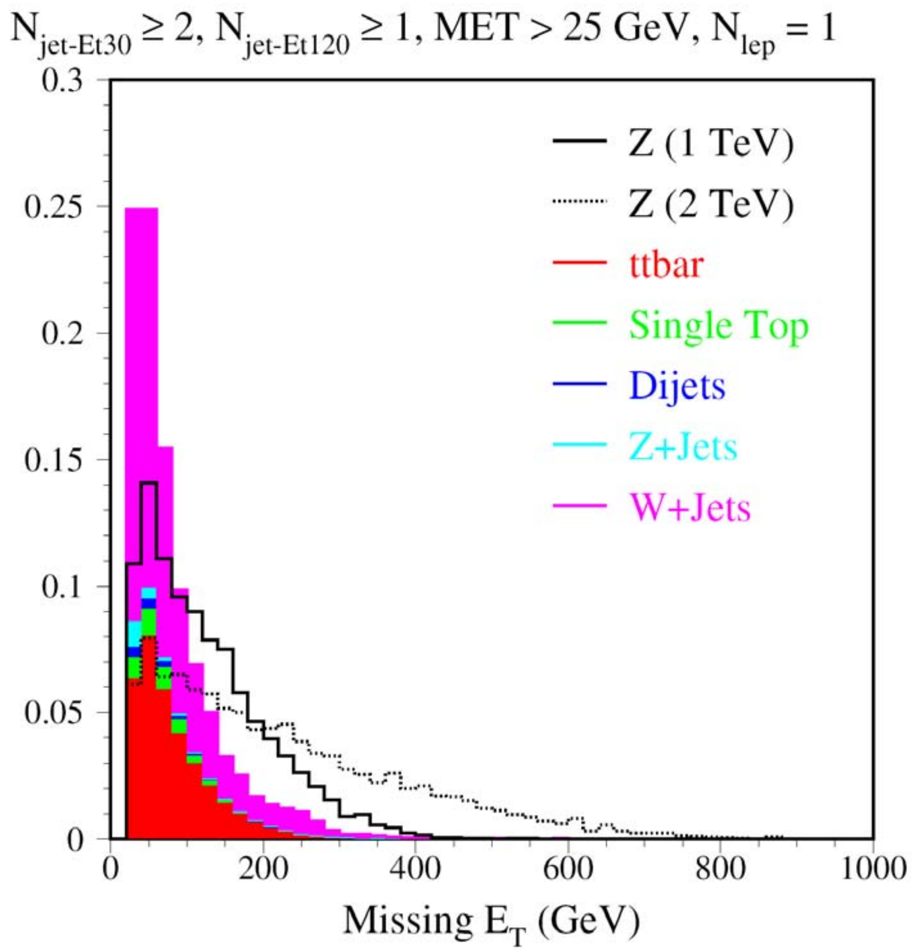
- If an interesting "signal" is found (e.g. $>3\sigma$), we will use Z' with estimated mass as signal to re-train BDT which could enhance the signal sensitivity if the signal does exist.

Event Pre-selection

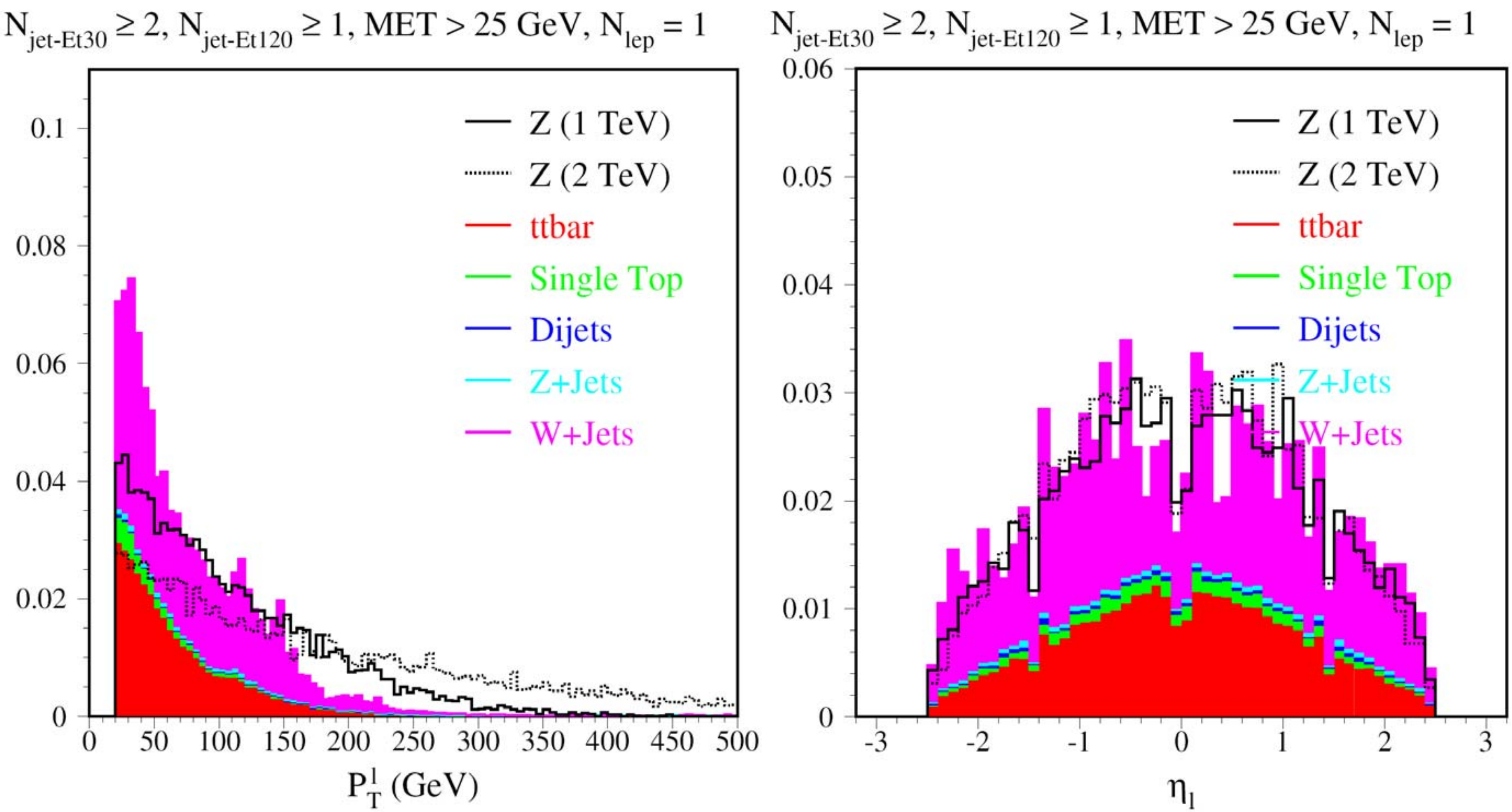
- At least 2 Jets with Et > 30 GeV
- At least 1 Jet with Et > 120 GeV
- Missing Transverse Momentum > 25 GeV
- Only one lepton (e or μ) with Pt > 20 GeV

Variable Distributions After Pre-selection
Number of Jets and MET

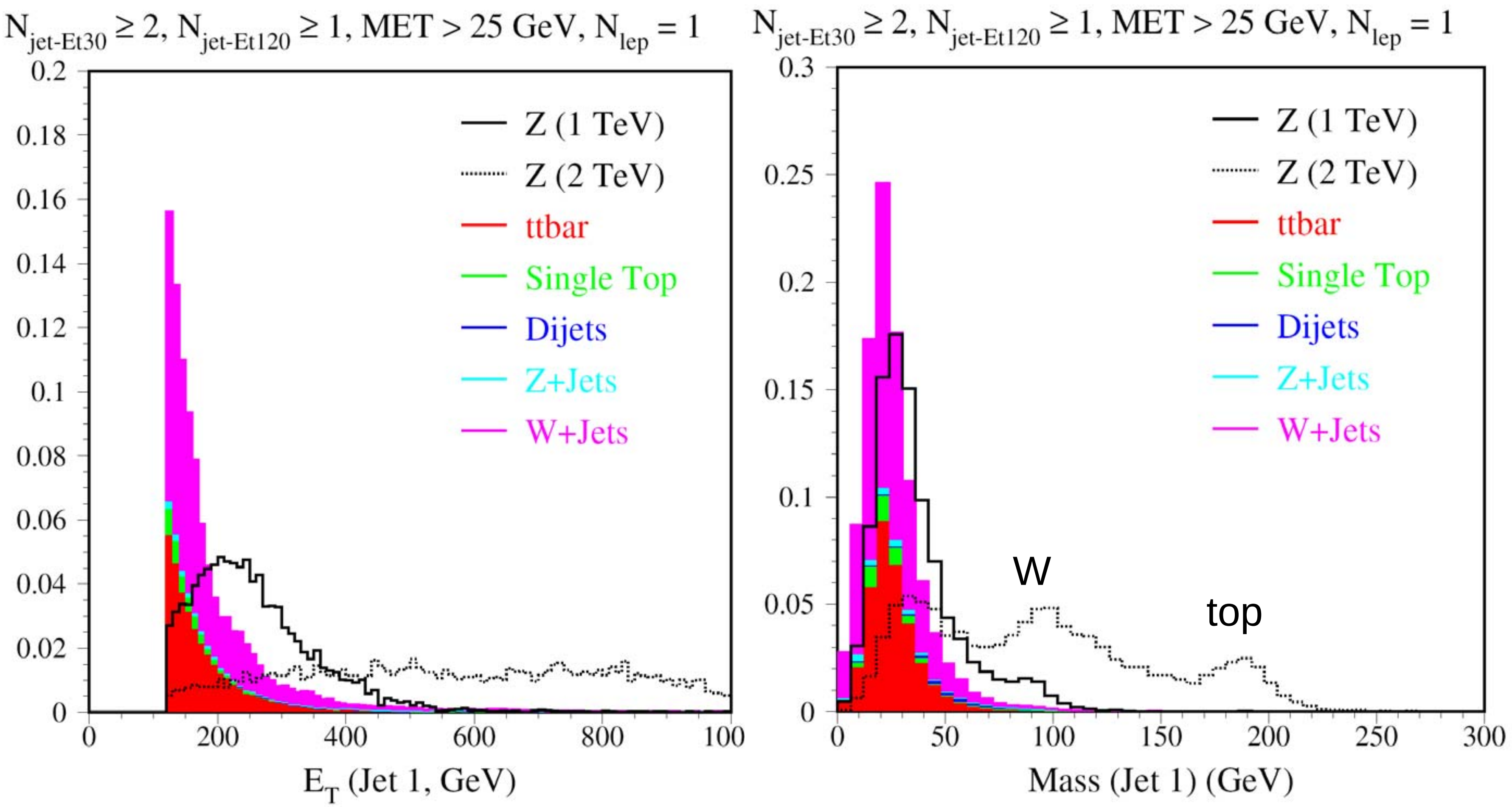




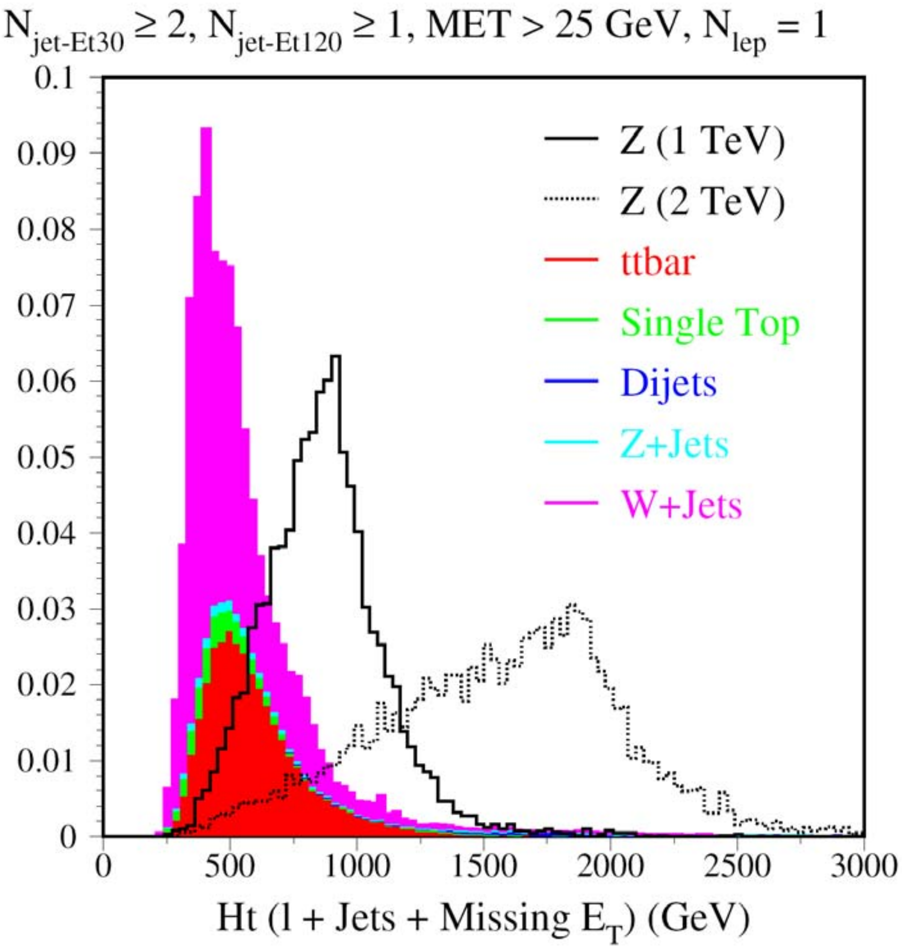
Lepton Pt and Eta

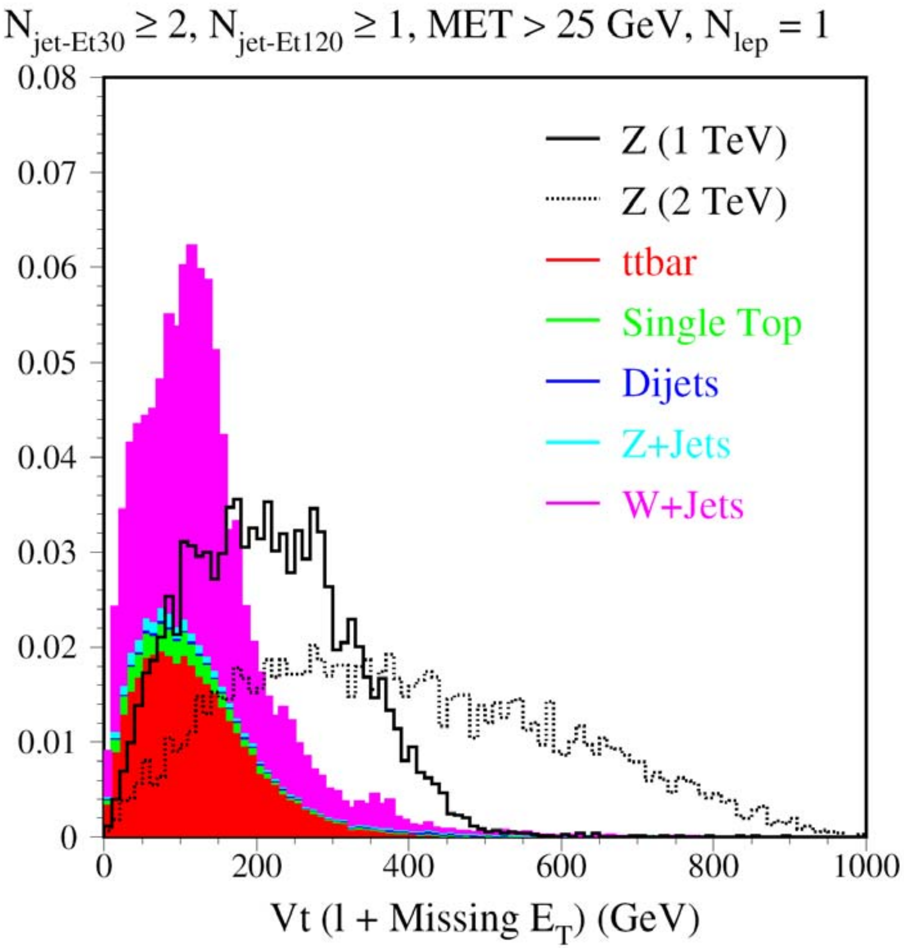


E_T & Mass of the 1st Energetic Jet

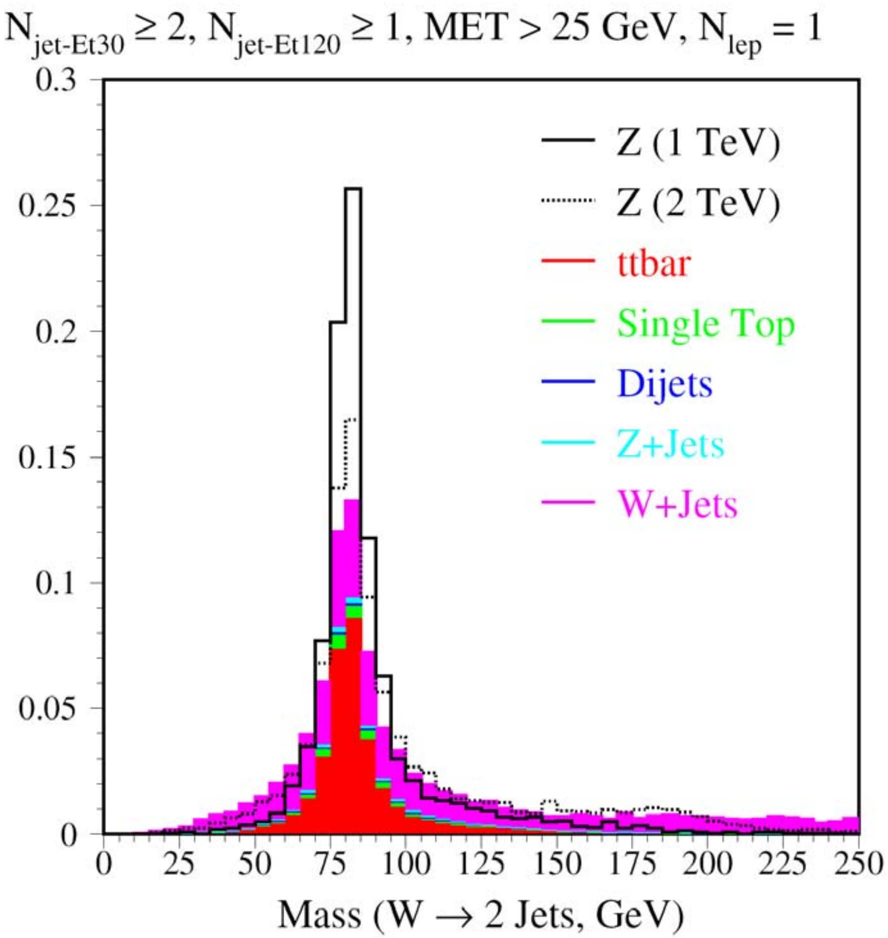


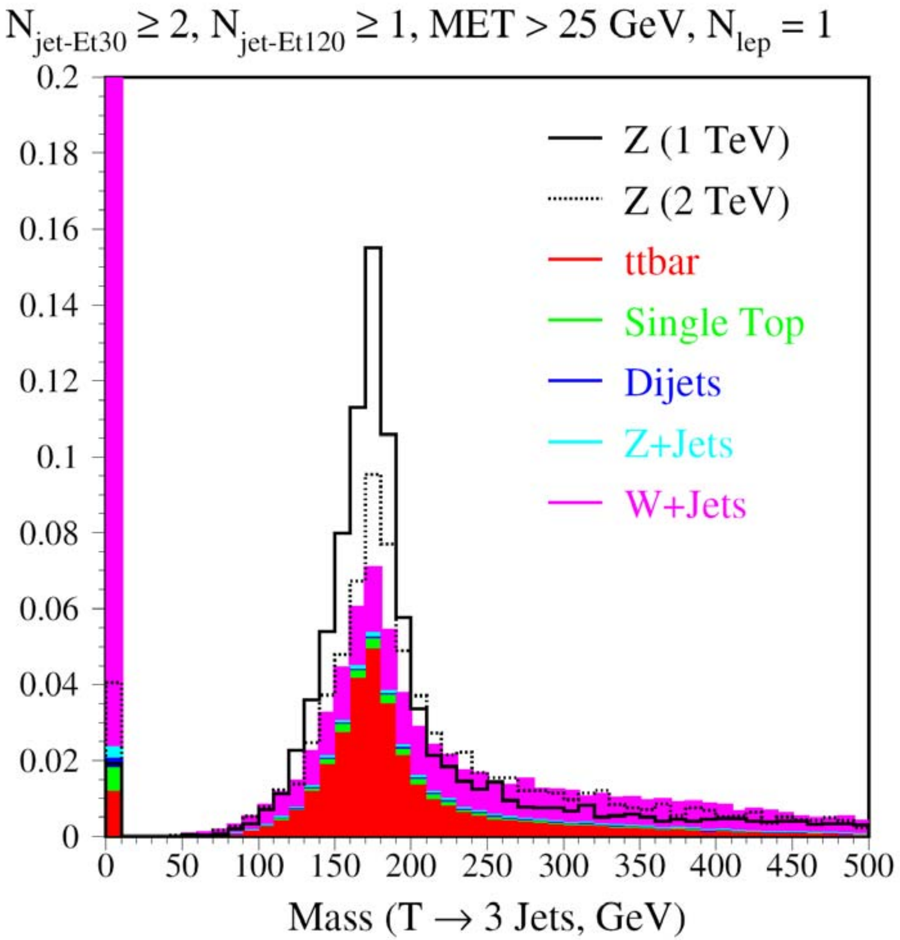
Distributions of H_T and V_T



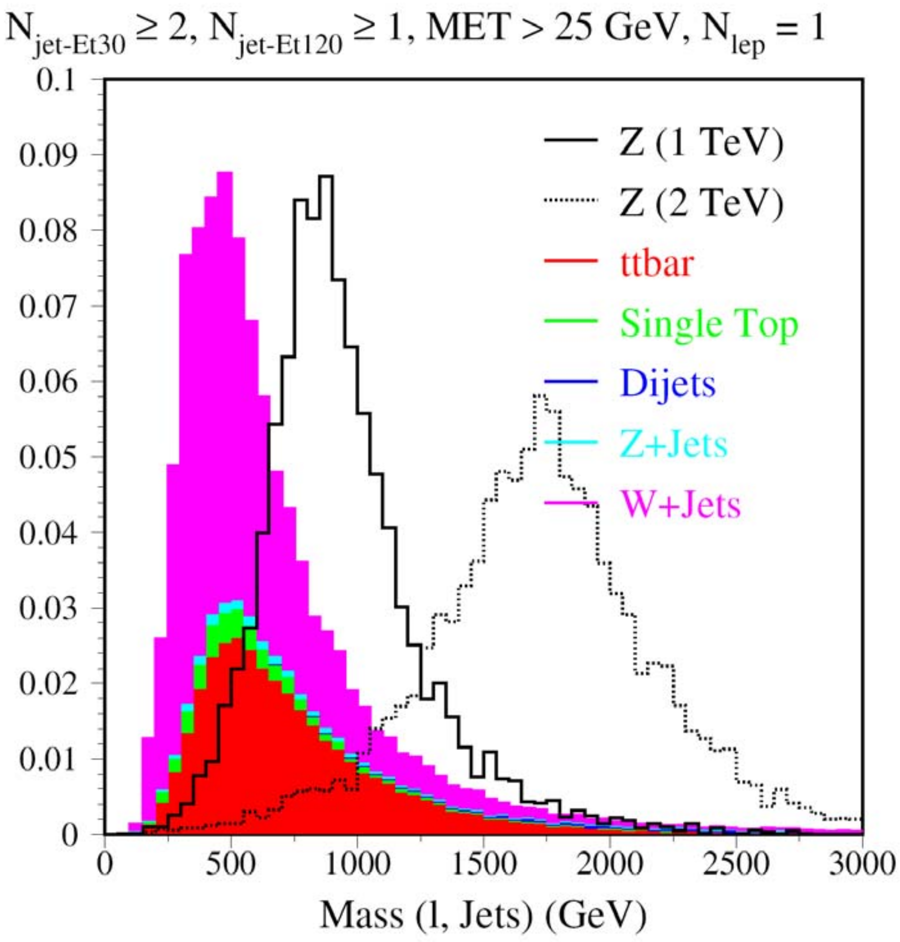


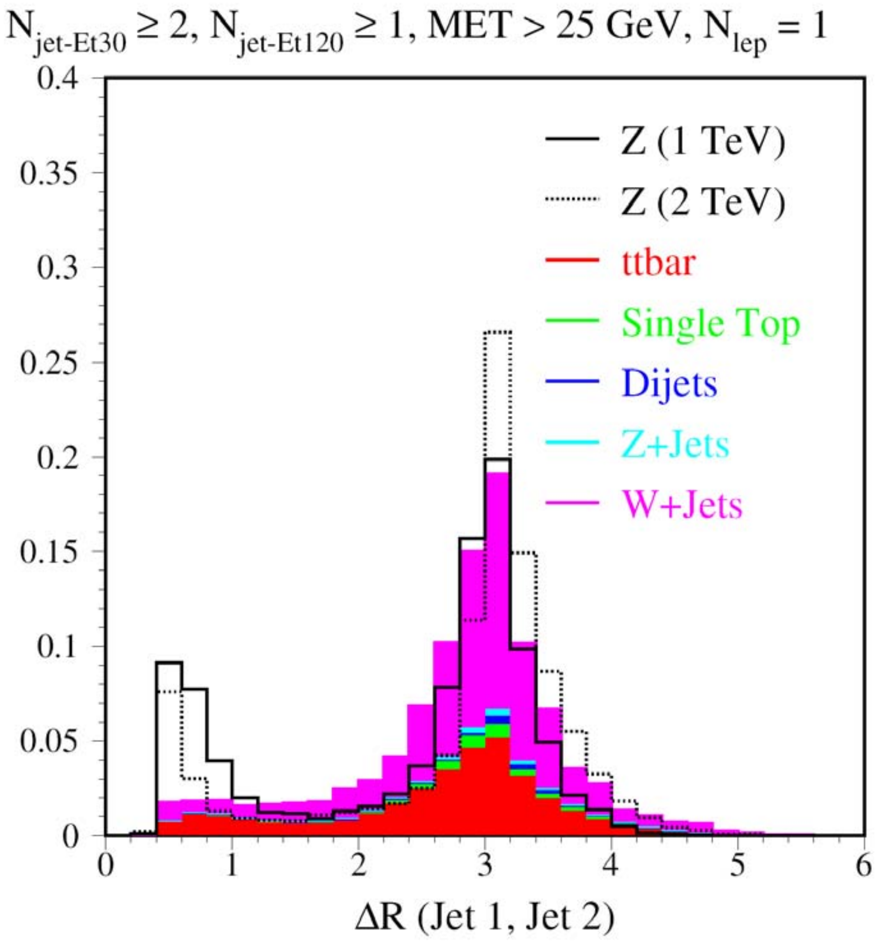
W and Top Mass



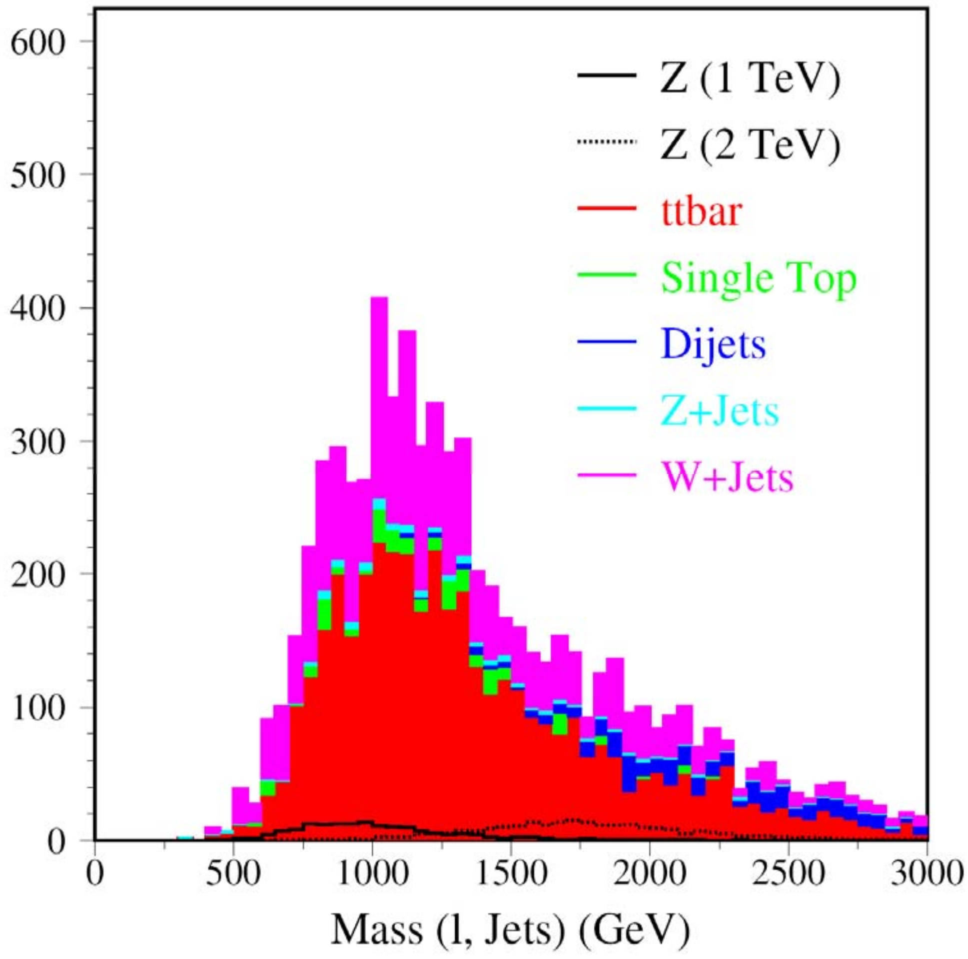


Mass(L,Jets) and ΔR(J1,J2)





Z' Selection with Straight Cuts (normalization to 1/fb)



- $40 \leqslant M_W \leqslant 120$ GeV
- $50 \leqslant M_{Top} \leqslant 300$ GeV
- Et(J1) > 200 GeV
- Ht(L,Jets,MET) > 800 GeV
- Vt(L,MET) > 150 GeV

➔**Z' Signal (assuming σ=1pb)**
- 170 from Mz' = 1.0 TeV
- 269 from Mz' = 1.5 TeV
- 261 from Mz' = 2.0 TeV
- 215 from Mz' = 3.0 TeV

➔**Backgrounds (7258)**
- 4188 from ttbar
- 247 from single top
- 500 from dijet
- 2189 from W+Jets
- 134 from Z + Jets

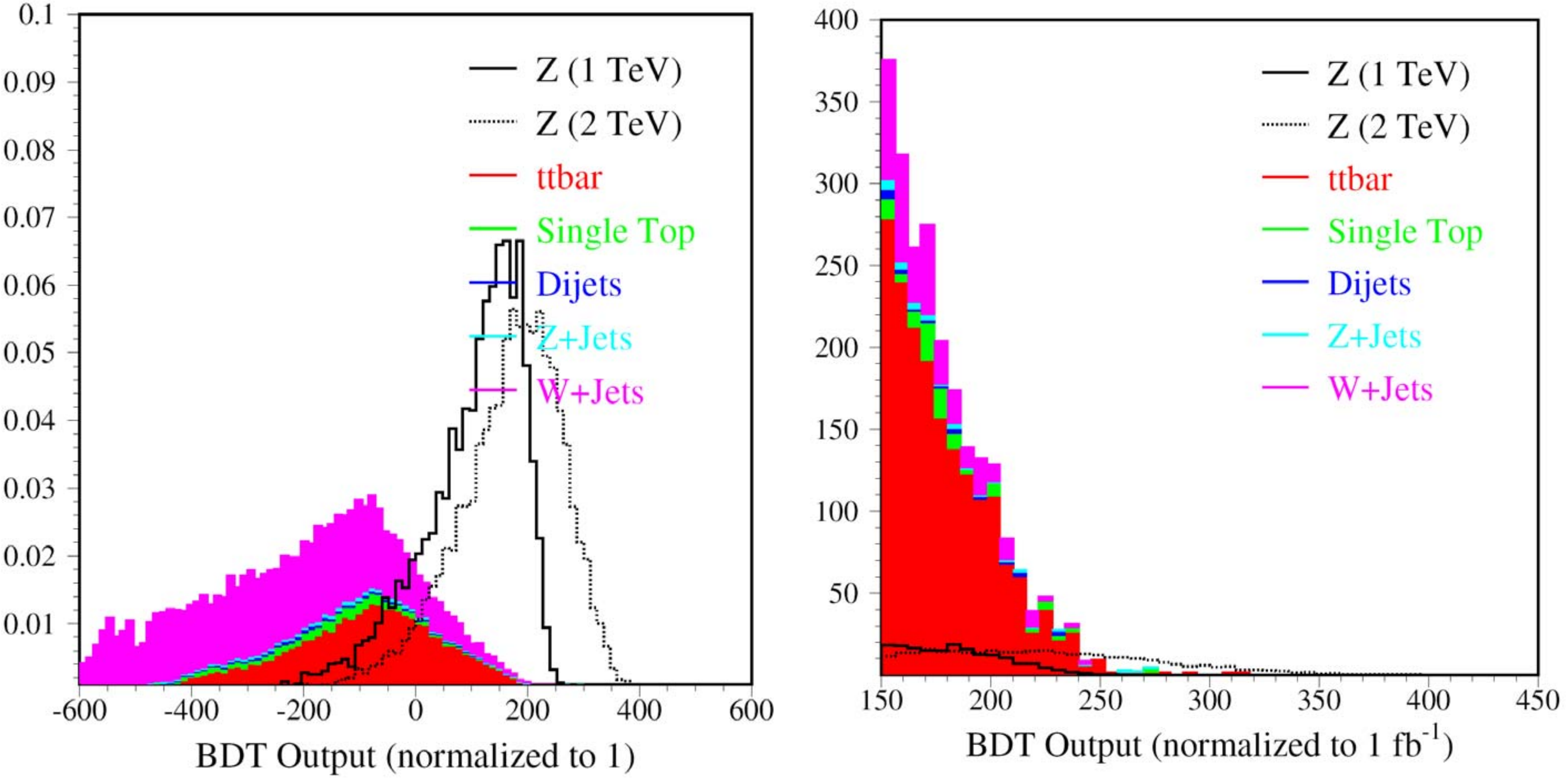
Z' Selection with BDT Analysis (A)

with 24 input variables for training

H.J. Yang et.al., NIM A555(2005)370, NIM A543(2005)577, NIM A574(2007)342

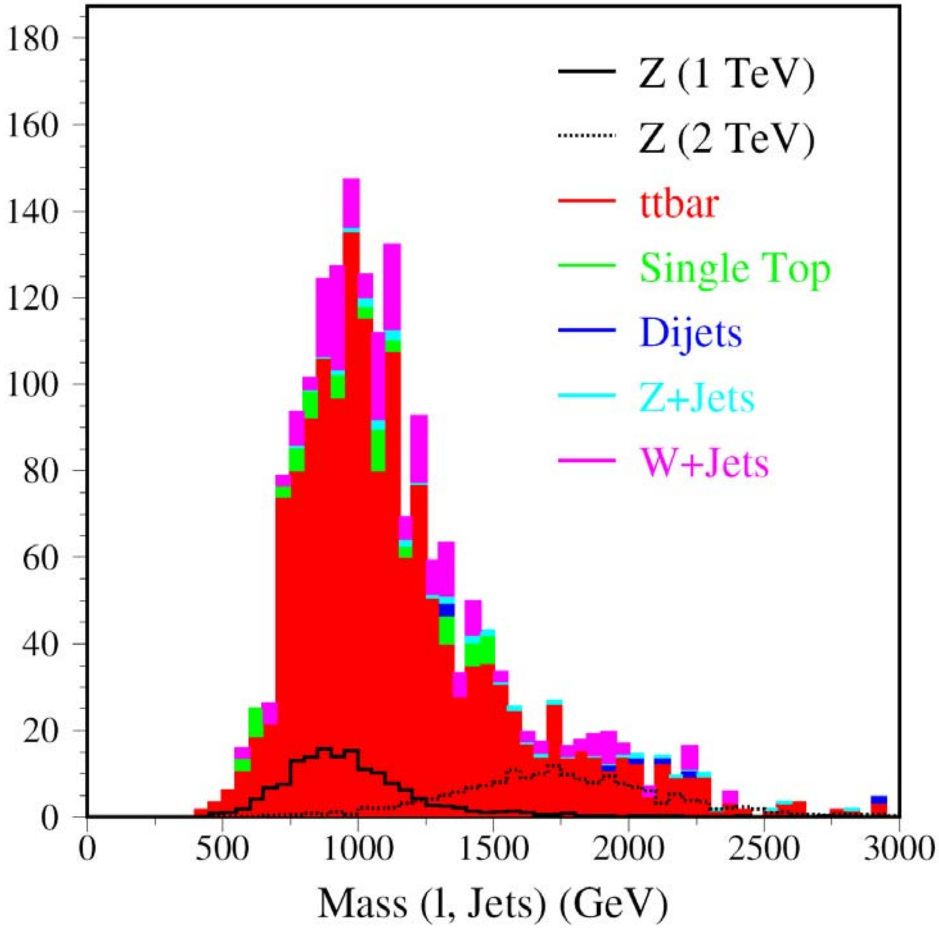
- P_t^L, N_{track}(R=0.2), $\sum P_t$(track) / E_t^L (R=0.2)
- N_{jet}(Et>30GeV), Size(J1), E_{em}(J1)
- E_t(J1), E_t(J2), E_t(L,MET), MET
- M(J1), M(Jets), M(Jets,L), M_t(L,MET)
- H_t(L,Jets), H_t(L,Jets,MET), V_t(L,MET)
- $\Delta\phi$(J1,J2), ΔR(J1,J2), ΔR(J1,J3)
- $\Delta\phi$(J1,L), $\Delta\phi$(J2,L), ΔR(J1,L), ΔR(J2,L)

BDT Analysis *Discriminator* (A)



Selected Events (1 fb^{-1})

$BDT \geq 150,\ 40 \leq M_W \leq 120,\ 50 \leq M_{Top} \leq 300$ GeV



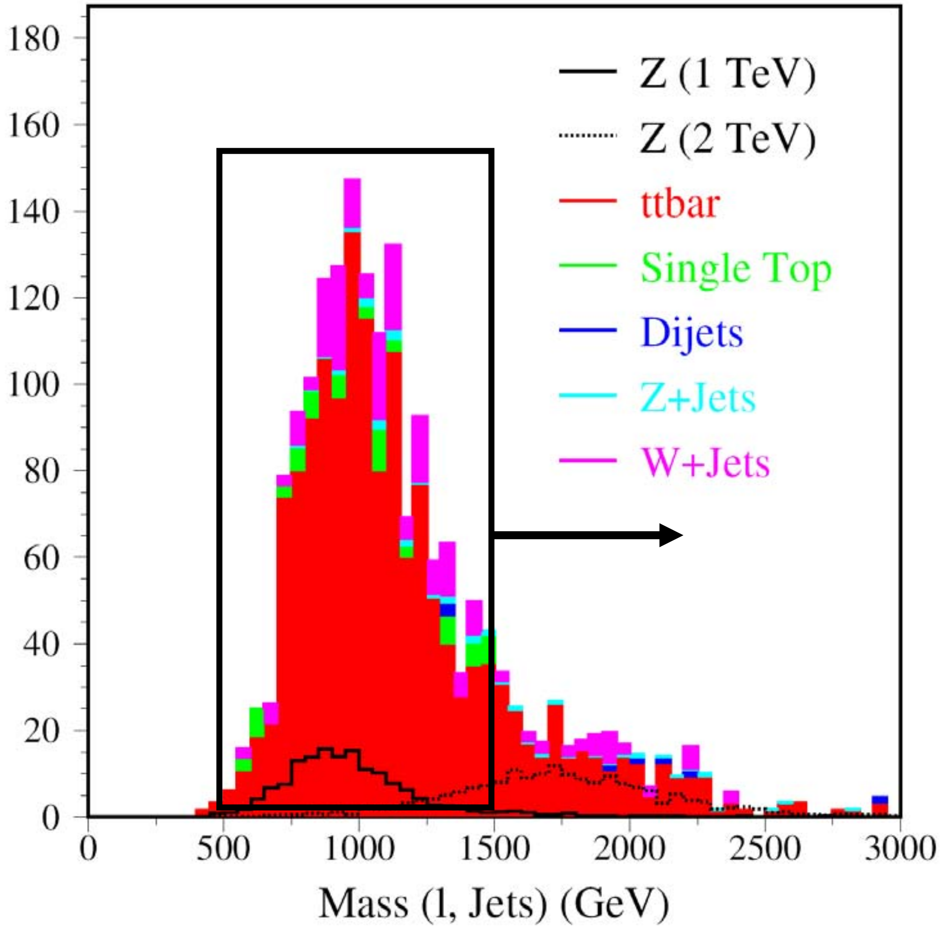
Signal (assuming σ=1 pb):
→ Z' (1.0 TeV) – 150.5 Events
→ Z' (1.5 TeV) – 215.2 Events
→ Z' (2.0 TeV) – 186.2 Events
→ Z' (3.0 TeV) – 124.9 Events

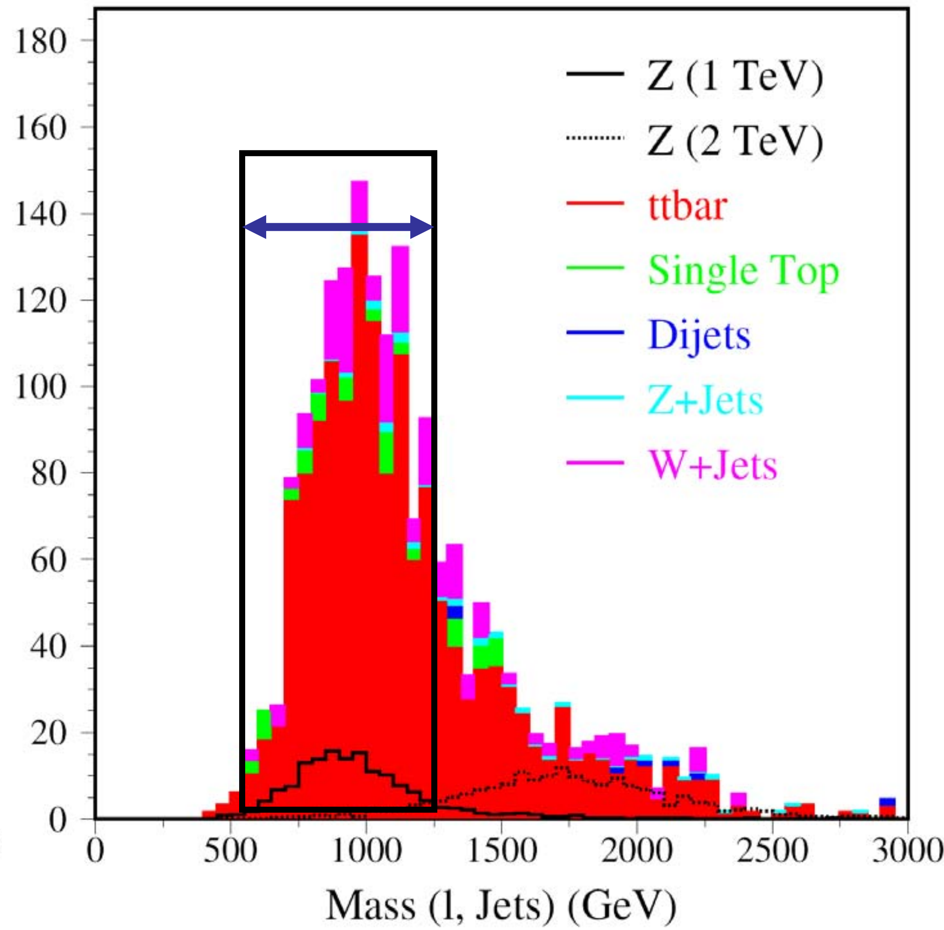
Backgrounds (1844):
→ Ttbar – 1536 Events (83.3%)
→ Single top – 65 Events(3.5%)
→ W+ Jets – 209 Events(11.3%)
→ Z + Jets – 24 Events(1.3%)
→ Dijets – 10 Events(0.54%)

Scan the Mass Window

Sliding mass window to find the IR

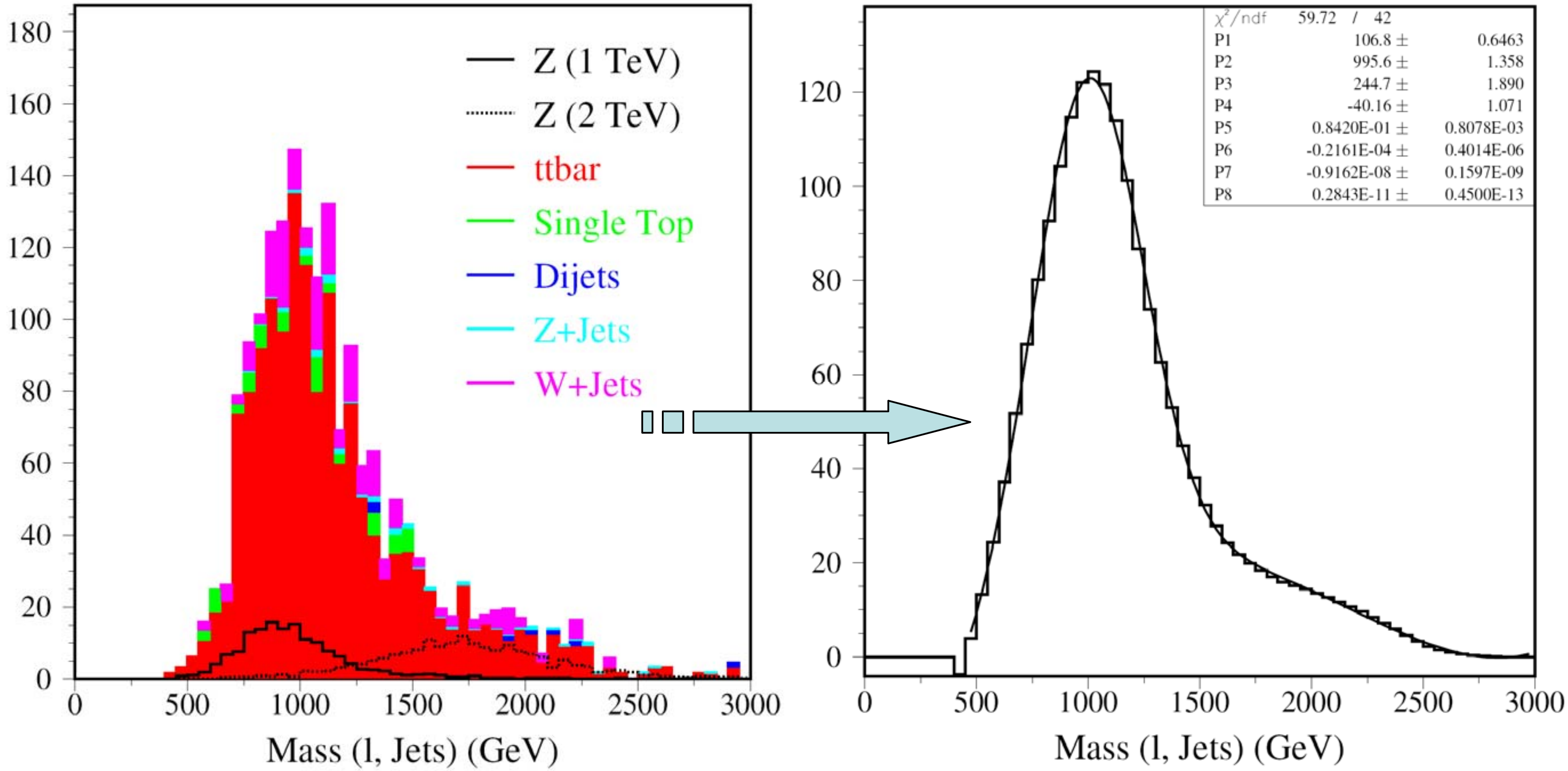
Opt. sensitivity by varying mass window



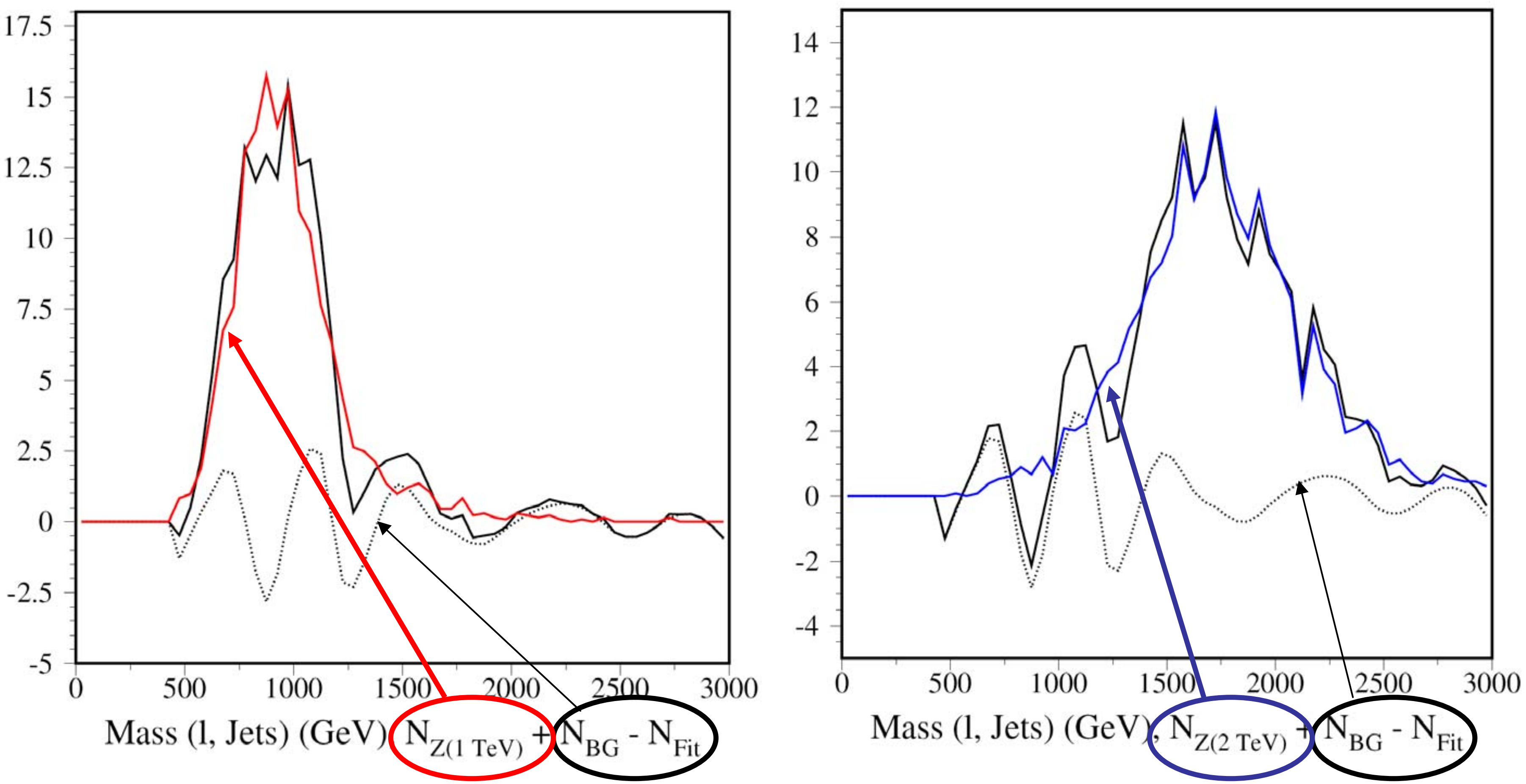


Fitting Background Events

1. Smooth background events; 2. Fit background using gaussian + polynomial



Extracting Signal by Subtracting Background From Fitting



Further BDT Training (B)

- If an interesting "signal" is found (>3σ), we will use Z' with estimated mass as signal to re-train BDT (**B**) which could enhance the signal sensitivity if it's real.

Assuming cross section of Z'→ ttbar is 1 pb & for 1 fb^{-1} int. lumi.

- Z'(1.0 TeV): Ns = 128.9, Nb = 3183, Nσ = 2.3 (Cuts)
  Ns = 129.0, Nb = 1186, Nσ = 3.75 (BDT-A)
  Ns = 123.3, Nb = 1076, Nσ = 3.76 (BDT-B)
- Z'(1.5 TeV): Ns = 99.0, Nb = 399.0, Nσ = 5.0 (Cuts)
  Ns = 106.0, Nb = 250.0, Nσ = 6.7 (BDT-A)
  Ns = 102.2, Nb = 135.2, Nσ = 8.8 (BDT-B)
- Z'(2.0 TeV): Ns = 22.4, Nb = 12.2, Nσ = 6.4 (Cuts)
  Ns = 41.7, Nb = 7.2, Nσ = 15.5 (BDT-A)
  Ns = 40.7, Nb = 3.1, Nσ = 23.0 (BDT-B)
- Z'(3.0 TeV): Ns = 39.1, Nb = 4.8, Nσ = 17.8 (Cuts)
  Ns = 50.8, Nb = 4.6, Nσ = 23.7 (BDT-A)
  Ns = 66.6, Nb = 3.1, Nσ = 38.0 (BDT-B)

5σ Discovery X-section for Z’ → $t\bar{t}$

Signal	SM-like cross section	$\sigma_{Z'} \times Br(Z' \to tt)$ (1fb^{-1})	$\sigma_{Z'} \times Br(Z' \to tt)$ (10fb^{-1})	$\sigma_{Z'} \times Br(Z' \to tt)$ (100fb^{-1})
Z’(1.0 TeV)	190 fb	> 1330 fb	> 420.6 fb	> 133 fb
Z’(1.5 TeV)	37 fb	> 570 fb	> 180.3 fb	> 57 fb
Z’(2.0 TeV)	10 fb	> 220 fb	> 69.6 fb	> 22 fb
Z’(3.0 TeV)	1 fb	> 130 fb	> 41.1 fb	> 13 fb

95% C.L. Limits for Z' → $t\bar{t}$

Signal	SM cross section	95% C.L. Ex. Limit ($1fb^{-1}$)	95% C.L. Ex. Limit ($10fb^{-1}$)	95% C.L. Ex. Limit ($100fb^{-1}$)
Z'(1.0 TeV)	190 fb	< 446 fb	< 139.5 fb	< 43.8 fb
Z'(1.5 TeV)	37 fb	< 196 fb	< 60.7 fb	< 18.8 fb
Z'(2.0 TeV)	10 fb	< 74 fb	< 24.6 fb	< 7.4 fb
Z'(3.0 TeV)	1 fb	< 45 fb	< 15 fb	< 4.5 fb

W / Top Mass Reconstruction

- Algorithm-A1, W→2 jets, Top→3 jets
- Algorithm-A2, W→1,2 jets, Top→1,2,3 jets
- Tight cuts: $60<M_w<100$ GeV, $125<M_{top}<225$ GeV

MC(1000 Events)	A1	A2	Ratio
ttbar	652	652	1.0
Z’ – 1TeV	660	687	1.04
Z’ – 1.5TeV	573	703	1.23
Z’ – 2 TeV	436	641	1.47
Z’ – 3 TeV	348	586	1.68

Further Working Plans

- In order to mimic real data for BDT training, we will try MC “Background+Signal” as “background” to train BDT using event re-weighting technique.

  (Ref: H.J.Yang et.al., JINST 3 P04004, 2008)
- Use BDT output (discriminator) distribution to fit “Background-only” or “Background+Signal” shapes for signal extraction.
- Build event shape variables (eg. event thrust, sphericity) and explore suitable combination algorithm to reconstruct W/Top from jets in one hemisphere which may help to increase reconstruction efficiency and to identify Z’ signal from background.
- Need to estimate systematic uncertainty for Z’ search.

Backup

This work is stimulated by the LHC new physics workshop in Jan. 2008 (Ann Arbor)

Where the most likely new physics signal would show up at LHC:

diboson and top-rich events

Current participants from U. of Michigan

- Hai-Jun Yang
- Bing Zhou
- Tiesheng Dai
- Zhengguo Zhao
- Claudio Ferretti

Search for Z’

- If there is a Z' with typical electroweak scale couplings to the ordinary fermions (ee, $\mu\mu$, eμ, $\tau\tau$, $q\bar{q}$, $t\bar{t}$), it should be observable at,
  - LHC for masses up to ~ 4 - 5 TeV (for 100/fb)
  - Tevatron for masses up to ~ 900 GeV (for ~10/fb)
- The latest results from CDF with 955 /pb data
  - ruled out Topcolor Z' below 720 GeV/c^2
  - the cross section of Z’-like state decaying to $t\bar{t}$ is less than 0.64 pb at 95% C.L. for $M_{Z'}$ above 700 GeV/c^2
  - **Ref: T. Aaltonen et.al., PRD 77, 051102(R) (2008)**.

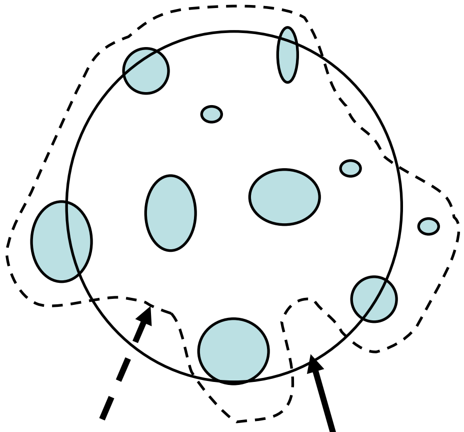
Physics Implications of Z’

- Additional U(1)' gauge symmetries and associated Z' gauge boson are one of the best motivated extensions of the SM, it would have profound implications for particle physics and cosmology. Possible implications of a Z' including,
  - an extended Higgs sector
  - extended neutralino sector
  - exotic fermions needed for anomaly cancellation
  - possible flavor changing neutral current effects
  - neutrino mass
  - possible Z' mediation of supersymmetry breaking
  - cold dark matter and electroweak baryogensis
  - **(Ref: Paul Langacker, arXiv:0801.1345v2)**

Jet Finder – Cone Algorithm

- Draw a cone (eg. R=0.4, 0.7) around a "seed" (Pt >1 GeV)
- Calculate sum ET, and ET-weighted position (jet center)
- Draw new cone at jet center and recalculate sum ET, ET-weighted position
- Re-iterate until stable

$$R_{ij} = \sqrt{\Delta\eta_{ij}^2 + \Delta\varphi_{ij}^2}$$

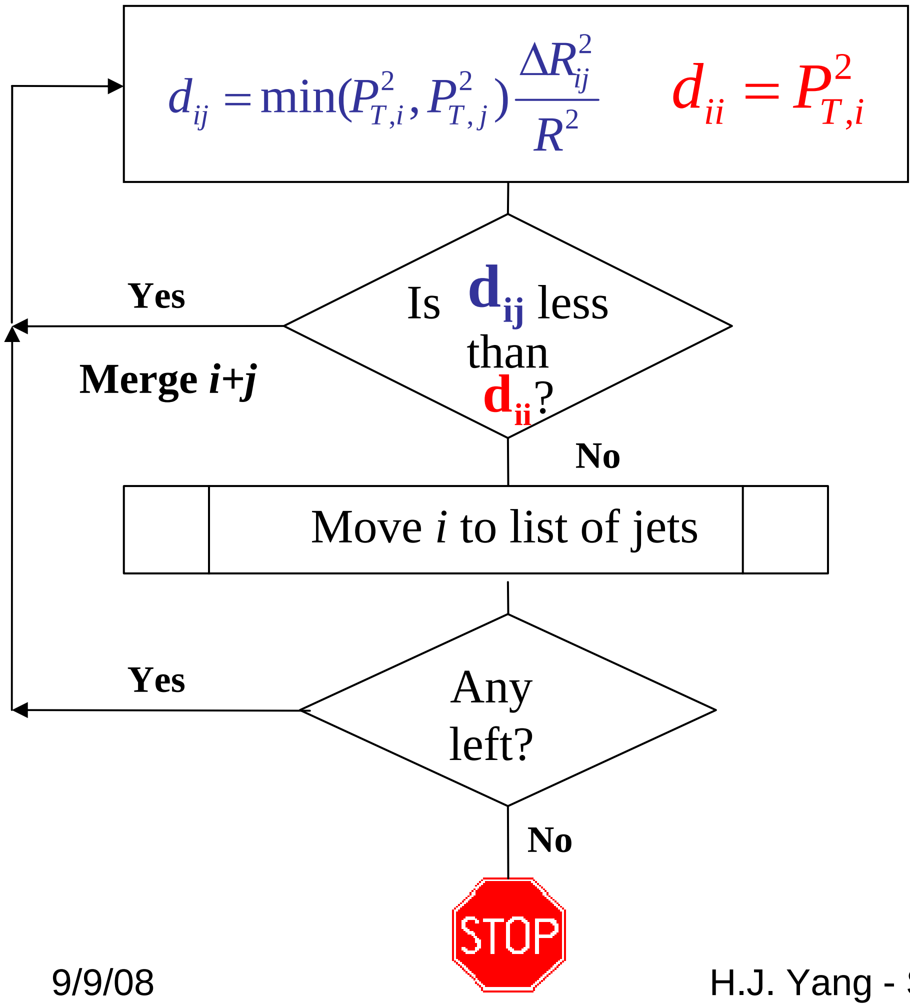


➔The cone jets always have well defined, smooth boundaries. However, it is possible with two equally energetic protojets located near opposite edges of the cone and nothing in the center of the cone.

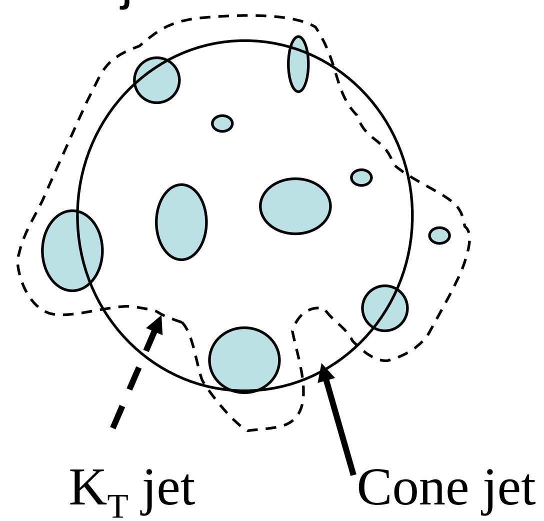
Jet Finder – Kt Algorithm

(**Ref: S.D.Ellis & D.E.Soper, PRD 48 (1993) 3160**)

$$R_{ij} = \sqrt{\Delta\eta_{ij}^2 + \Delta\varphi_{ij}^2}$$



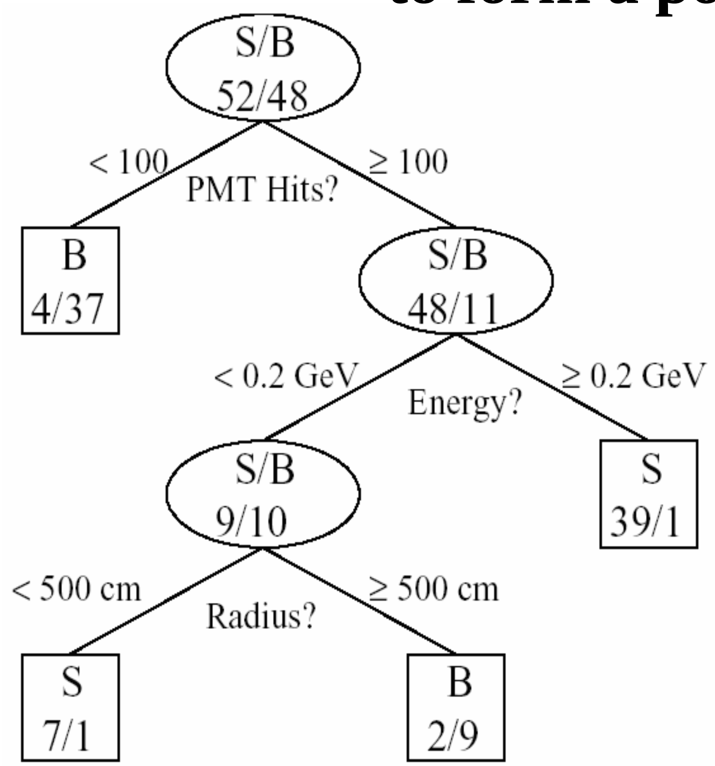
➔the lower Et protojet can be far from jet axis, up to a max separation R, while the higher Et protojet must be closer to the jet axis.



Boosted Decision Trees

➔Relative new in HEP – MiniBooNE, BaBar, D0(single top discovery), ATLAS
➔Advantages: robust, understand 'powerful' variables, relatively transparent, …

"A procedure that combines many weak classifiers to form a powerful committee"



- Split data recursively based on input variables until a stopping criterion is reached (e.g. purity, too few events)
- Every event ends up in a "signal" or a "background" leaf
- Misclassified events will be given larger weight in the next decision tree (boosting)

H. Yang et.al. NIM A555 (2005)370, NIM A543 (2005)577, NIM A574(2007) 342

A set of decision trees can be developed,

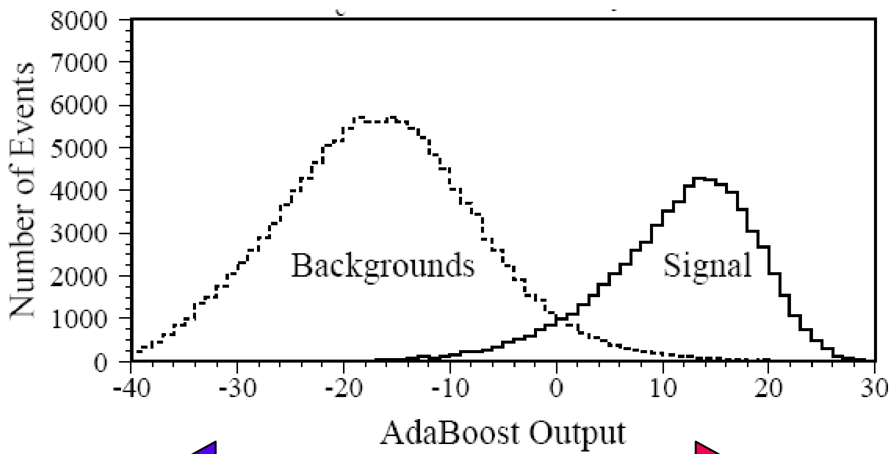
each re-weighting the events to enhance identification of backgrounds misidentified by earlier trees   (“boosting”)

For each tree, the data event is assigned

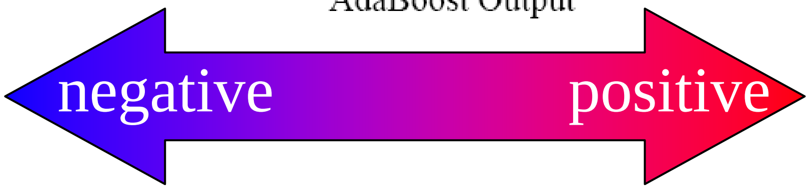
+1 if it is identified as signal,

- 1 if it is identified as background.

The total for all trees is combined into a “score”

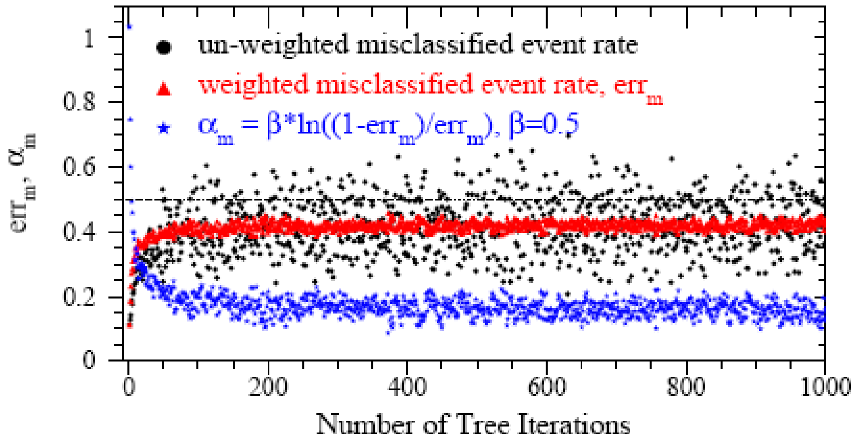


Background-like

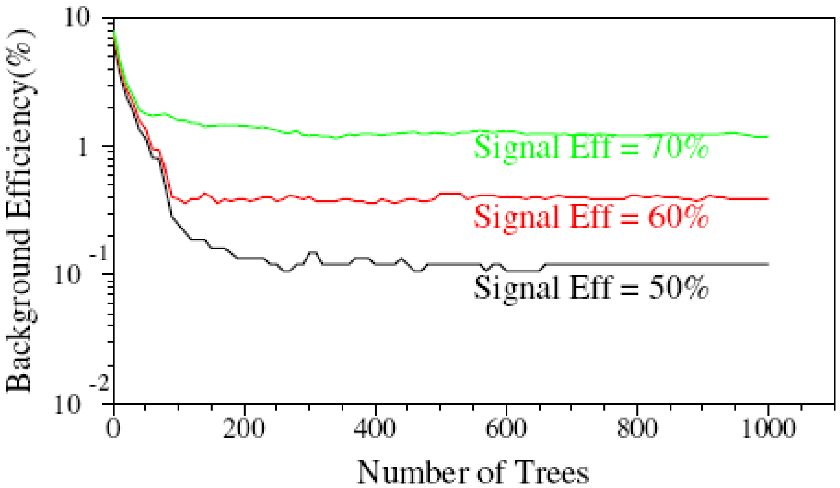


signal-like

Weak → Powerful Classifier



→ The advantage of using boosted decision trees is that it combines many decision trees, "weak" classifiers, to make a powerful classifier. The performance of boosted decision trees is stable after a few hundred tree iterations.



→ Boosted decision trees focus on the misclassified events which usually have high weights after hundreds of tree iterations. An individual tree has a very weak discriminating power; the weighted misclassified event rate err_m is about 0.4-0.45.

Ref1: H.J.Yang, B.P. Roe, J. Zhu, "*Studies of Boosted Decision Trees for MiniBooNE Particle Identification*", physics/0508045, Nucl. Instum. & Meth. A 555(2005) 370-385.

Ref2: H.J. Yang, B. P. Roe, J. Zhu, " *Studies of Stability and Robustness for Artificial Neural Networks and Boosted Decision Trees* ", physics/0610276, Nucl. Instrum. & Meth. A574 (2007) 342-349.

Major Achievements using BDT

- MiniBooNE neutrino oscillation search using BDT and Maximum Likelihood methods
  - Phys. Rev. Lett. 98 (2007) 231801
  - One of top 10 physics stories in 2007 by AIP
- D0 – discovery of single top using BDT, ANN, ME
  - Phys. Rev. Lett. 98 (2007) 181802
  - One of top 10 physics stories in 2007 by AIP
- BDT was integrated in CERN TMVA package
  - Toolkit for MultiVariate data Analysis
  - http://tmva.sourceforge.net/
- Event Weight training technique for ANN/BDT
  - H. Yang et.al., JINST 3 P04004 (2008)
  - Integrated in TMVA package within 2 weeks after my first presentation at CERN on June 7, 2007