Measurement of High p_T boosted jets

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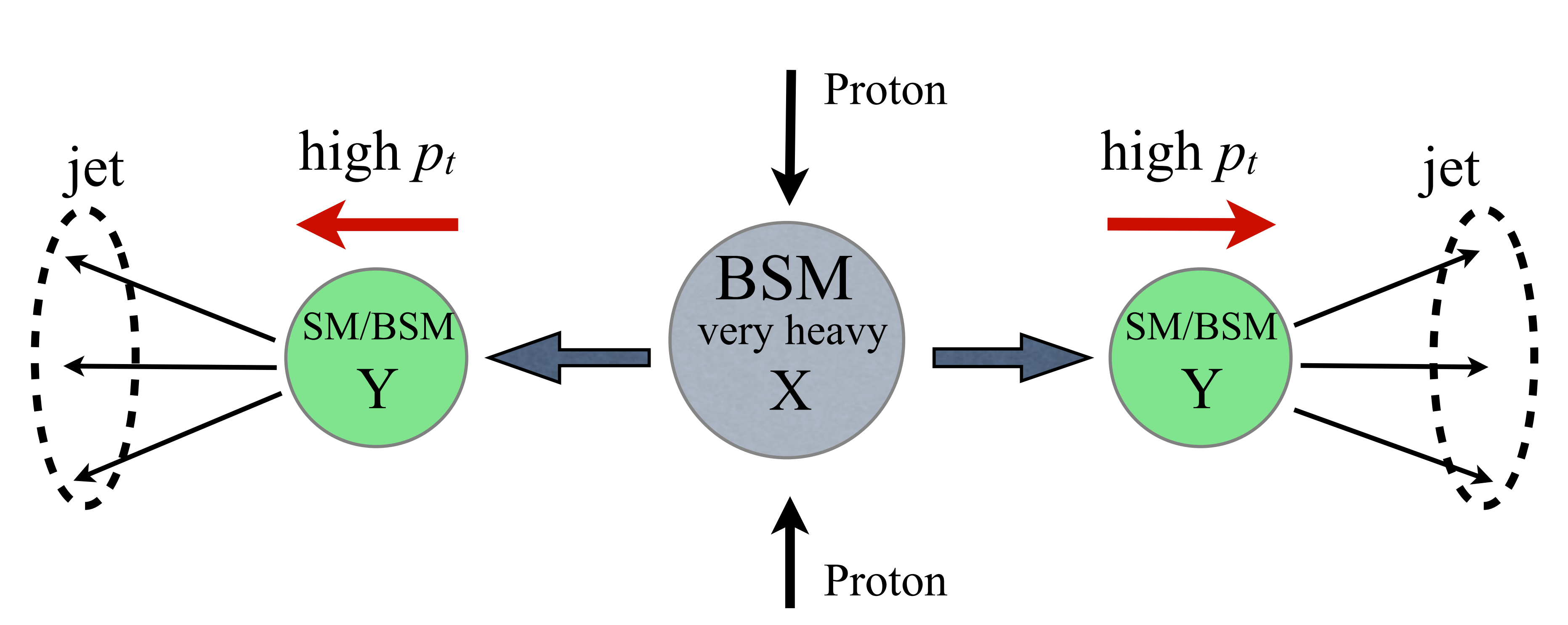
Outline

- High pT jets
- How to tag: Theoretical developments
- Validation in data
- Application to probe various physics channels
- Summary

High p_T Jets

pT>200 GeV

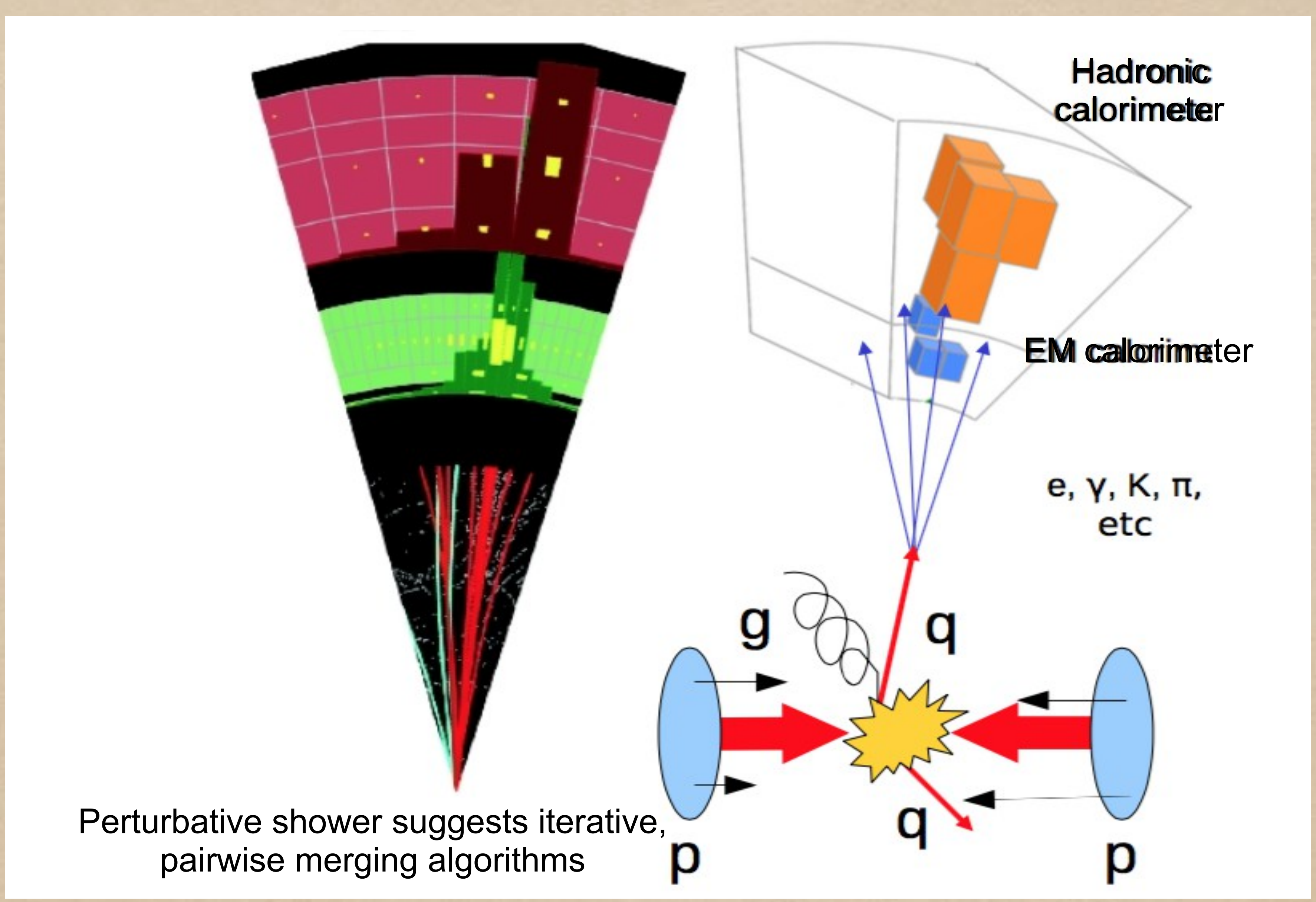
1901.10342



Boosted Resonances in New Physics Searches

Jets

Jets are collimated energetic particles



Perturbative shower suggests iterative,
pairwise merging algorithms

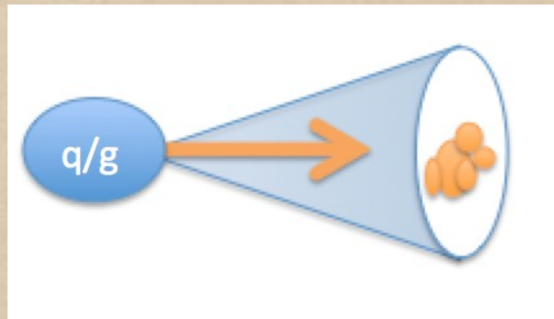
Reconstruction of Jets

IR and Collinear safe, invariant under boost,

Jet algorithm

$$d_{ij} = min(k_{t,i}^{2p}, k_{t,j}^{2p})\frac{\Delta R_{ij}}{R}$$

$$\Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$



Inputs: 4 momentum/cell energy,
Value of R, the jet size parameter

Talk by, T. Chujo, A. Mukherjee,

p=-1, AntiKT jets, semi irregular jets, Hardest energy clustered first

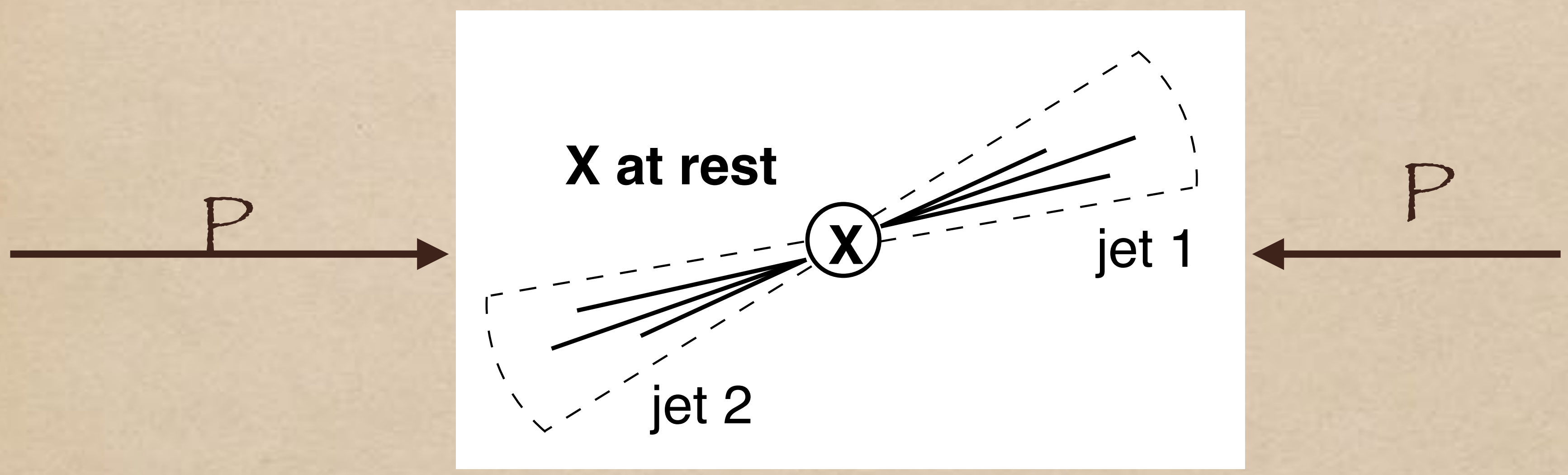
p=1, KT jets, irregular jets, softest energy clustered first

p=0, C/A jets, only geometrical locations of clustered.

Jet properties, XSection

Talk by, Suman Chatterjee

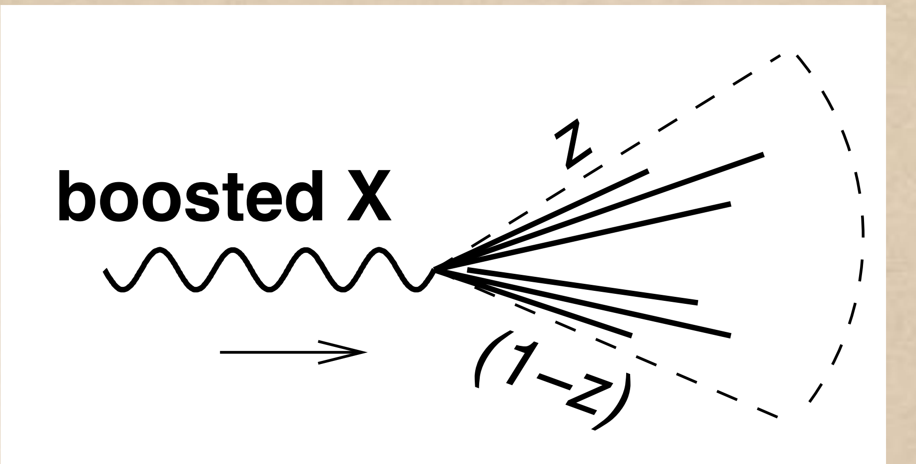
Jets From Resonance



PP -> X -> q q

Two quarks are reconstructed as jets,
X can also be reconstructed

High pT(Boosted) Jet(1)



Single Jet

With a boost jets overlap, not very usual in SM,
in NP searches it happens

High pT region: X is boosted, boost factor, $\gamma \sim E/m$

decay products are collimated,

both jets are in a single jet(FatJet)

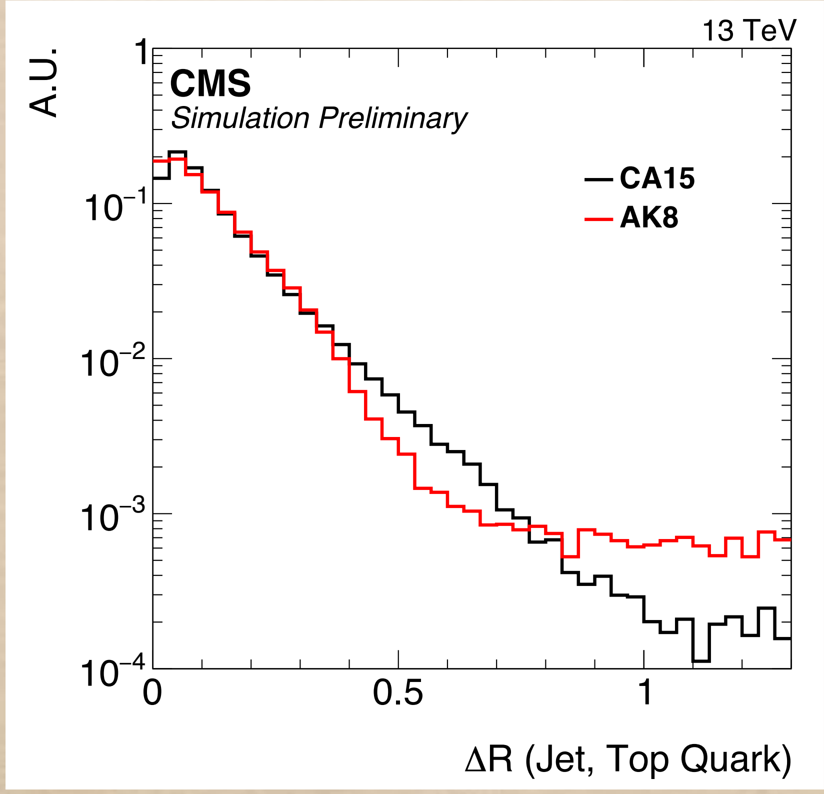
$R \sim 2m/pT$,

if m=mW, R=0.7, pT ~230 GeV,

for m=mt, pT ~ 500 GeV

Boosted Jets(2)

With a boost, jets overlap, not very usual in SM, in NP searches it happens



'Jets overlaping' may be helpful to get rid of SM backgrounds

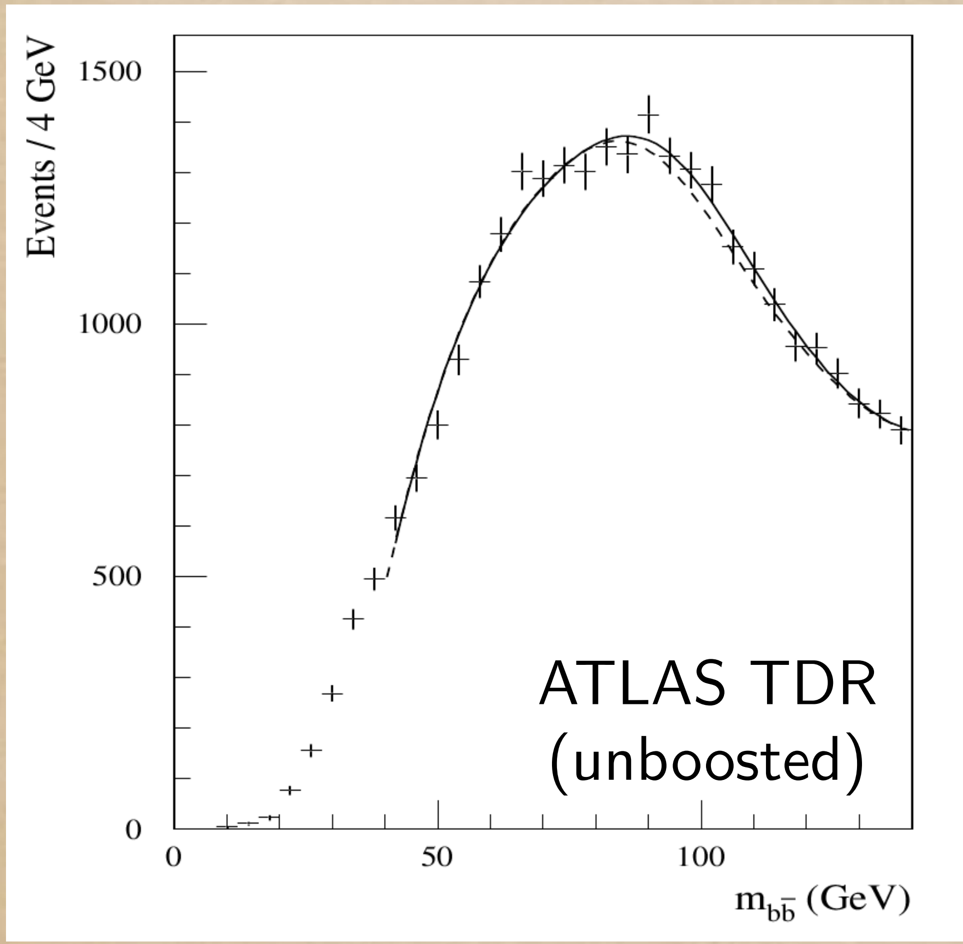
Boosted Jets(3)

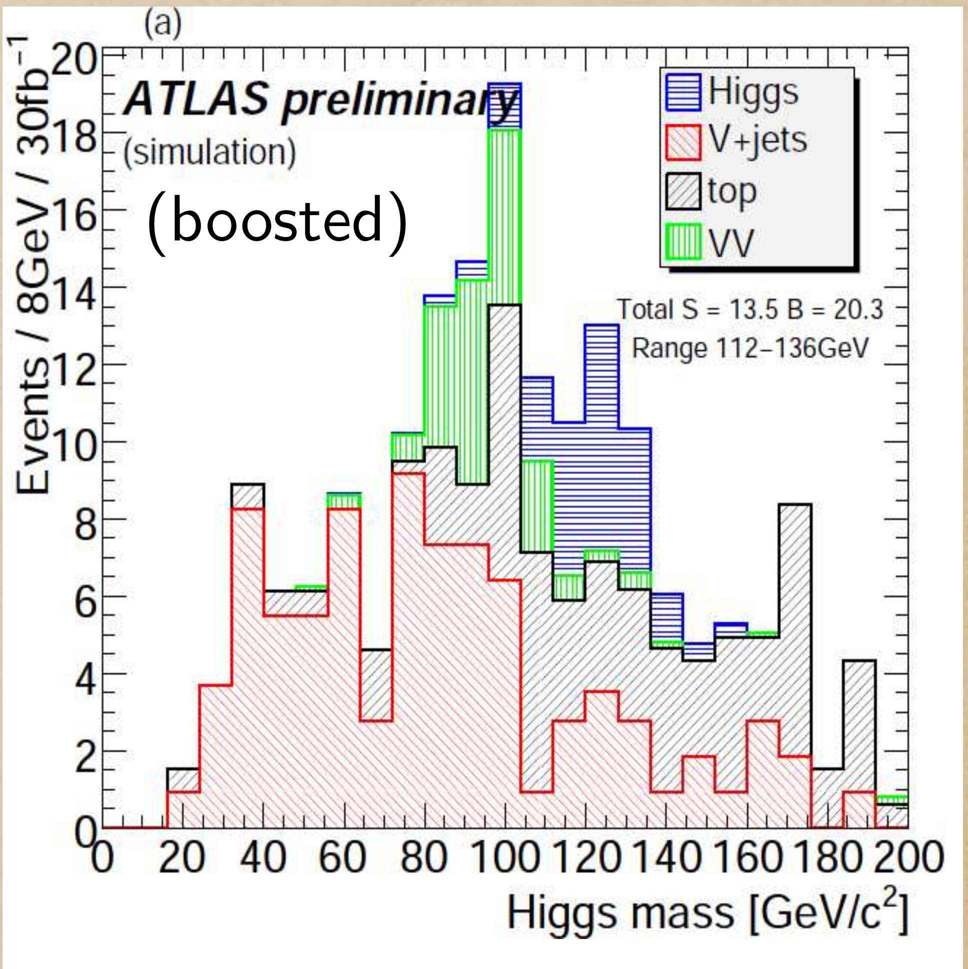
NP heavy particles decay to boosted W, Z, t.

- Leptonic mode is easy to tag, but presence of largeMET, not easy to reconstruct parent mass.
- Hadronic events, larger in rates, reconstructible
- In High energy and high pT regime, may be a good fraction of events are clustered
- Backgrounds may be less, as it falls faster in pT,
- Combinatorics is better

Example: Higgs reconstruction(1)

Search for Higgs, W/Z+H, H → bb



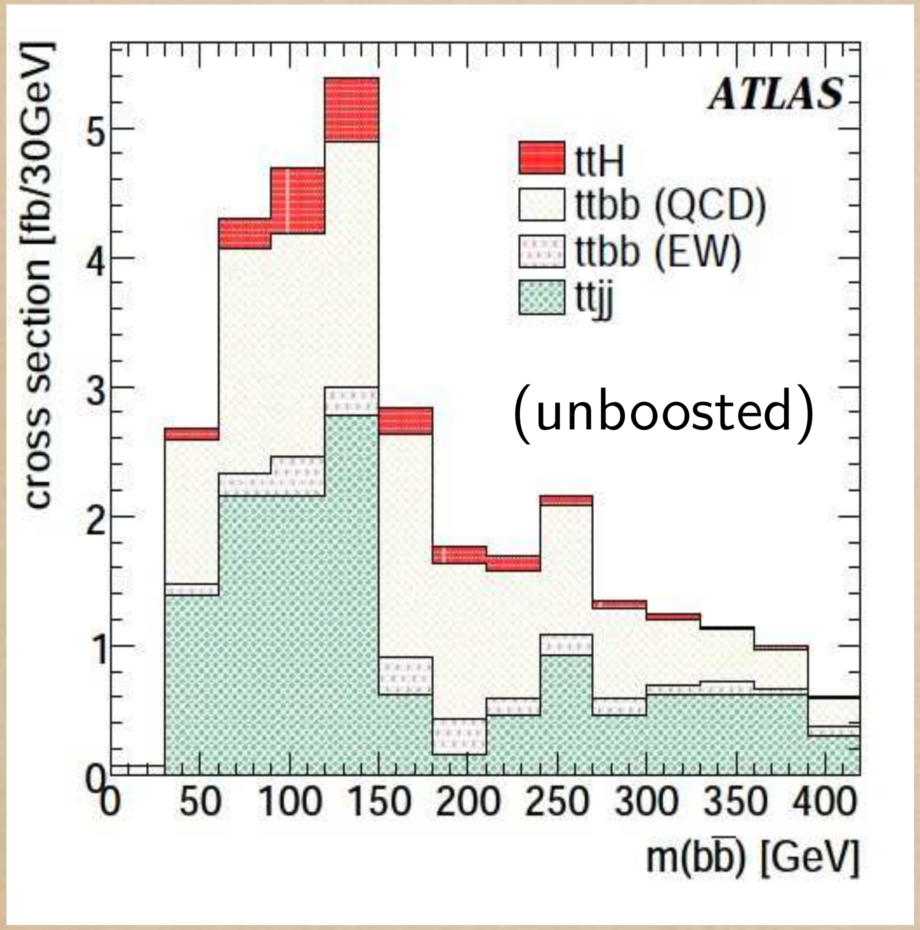


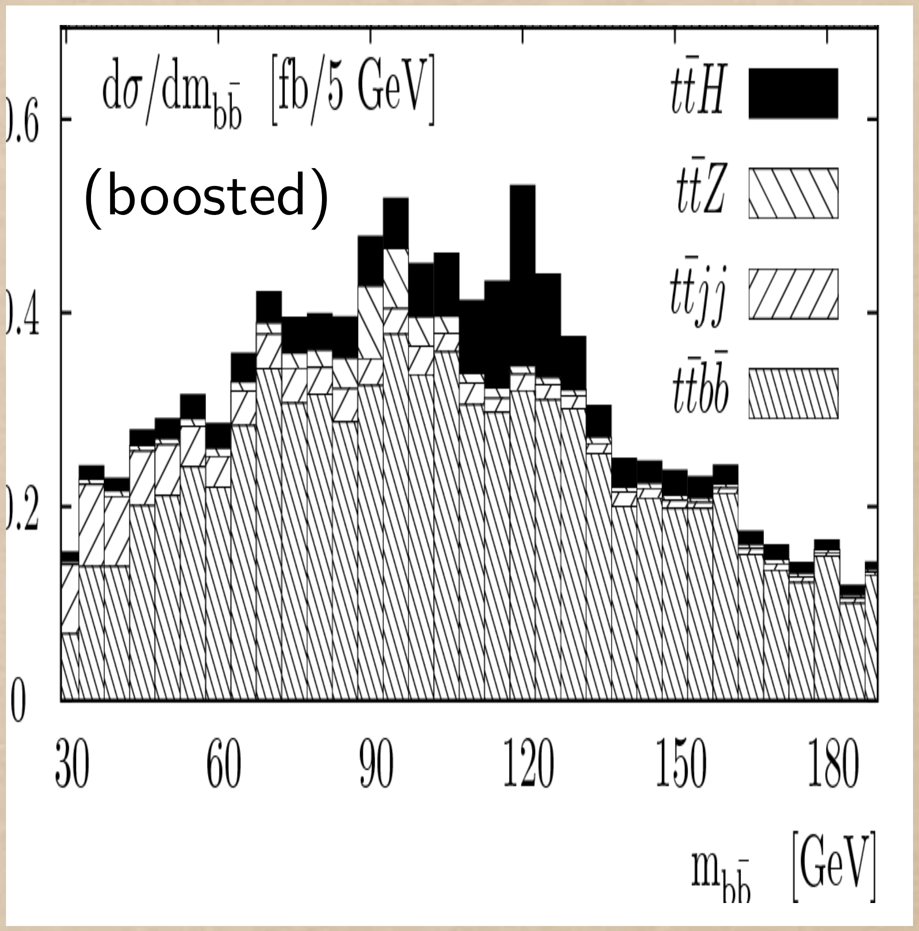
pTh>200 GeV

Butterworth, Davidson, Rubin, Salam,'08

Example: Higgs reconstruction(2)

Search for Higgs ttH, H → bb





pTh>200 GeV

Butterworth, Davidson, Rubin, Salam,'08

Boosted Jets: Exciting

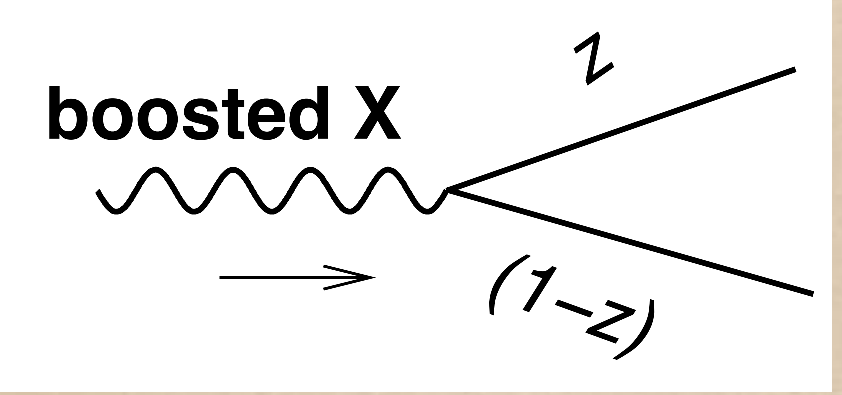
Un cluster, Jet profiles, and cut

- First Proposed by Seymour for Ws, '93
- Butterworth, cox, Forshaw,'02
- More improved, and used it for H->bb reconstruction by Butterworth, Davison, Rubin, Salam(BDRS),'08

Top quarks reconstruction: Thaler+Wang, Kaplan, Reherman, Schwartz, Tweedie(JHtagger)

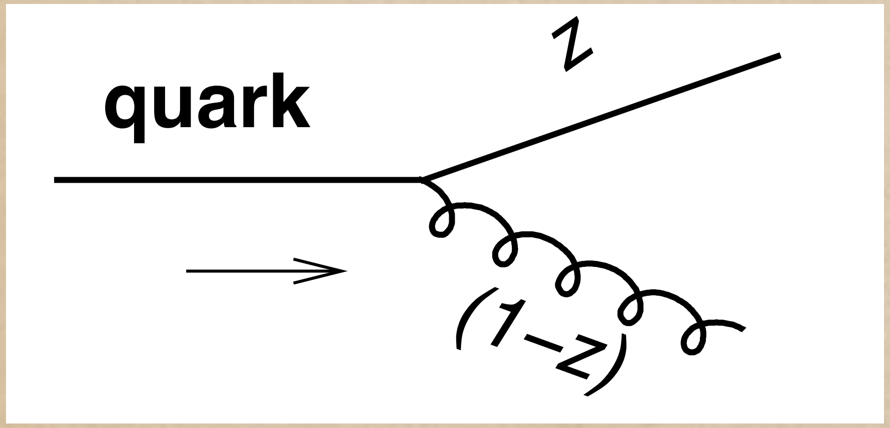
Soft Divergence

Talk by A. Mukherjee



Probability of Higgs splitting:

$$P(z) \propto 1$$



Probability of quark splitting:

$$P(z) = \frac{1+z^2}{1-z}$$

A cut on z, removes divergence in background
Selection of Z can also help to increase $S/\sqrt{B}$

Jet Observables

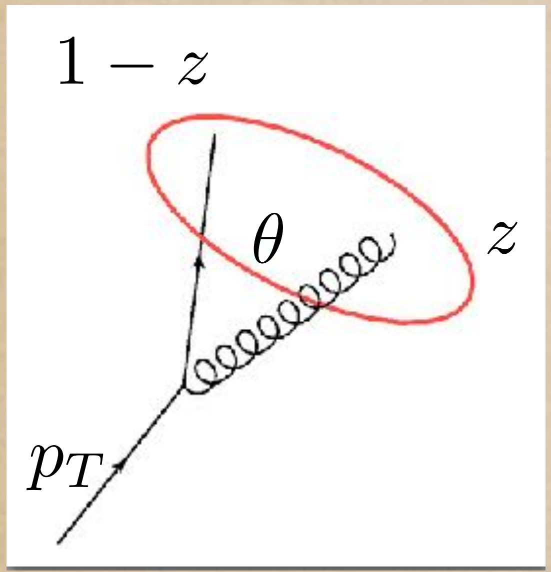
Jet mass(1)

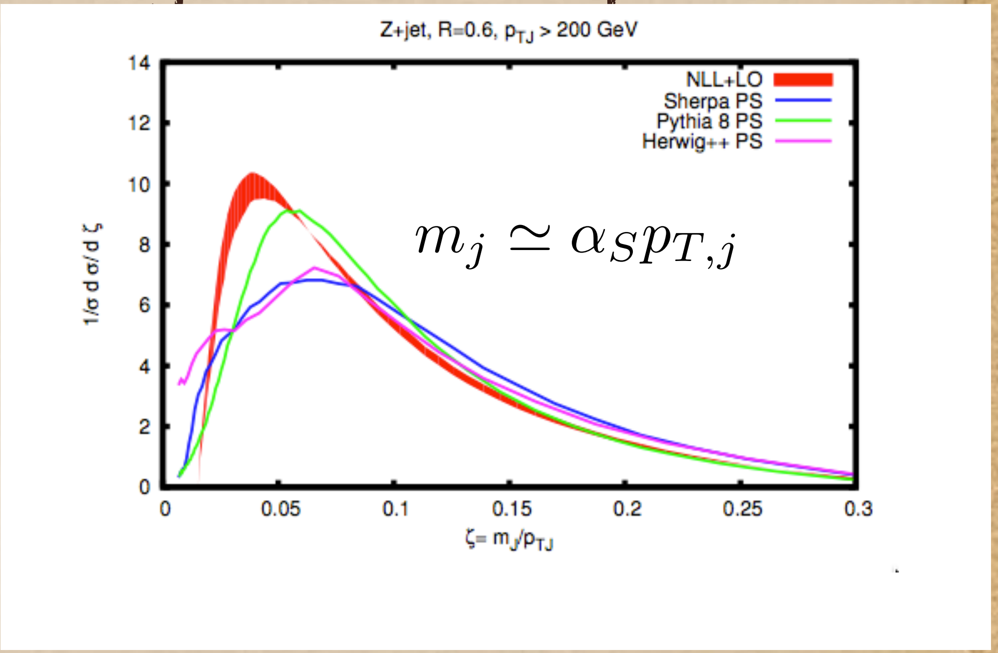
Jet is not massless

Jet mass can be used as one of the jetObservable

$$m^2 = 2.p_q.p_g \simeq z(1-z)\theta^2 p_T^2$$

Mass grows with pT

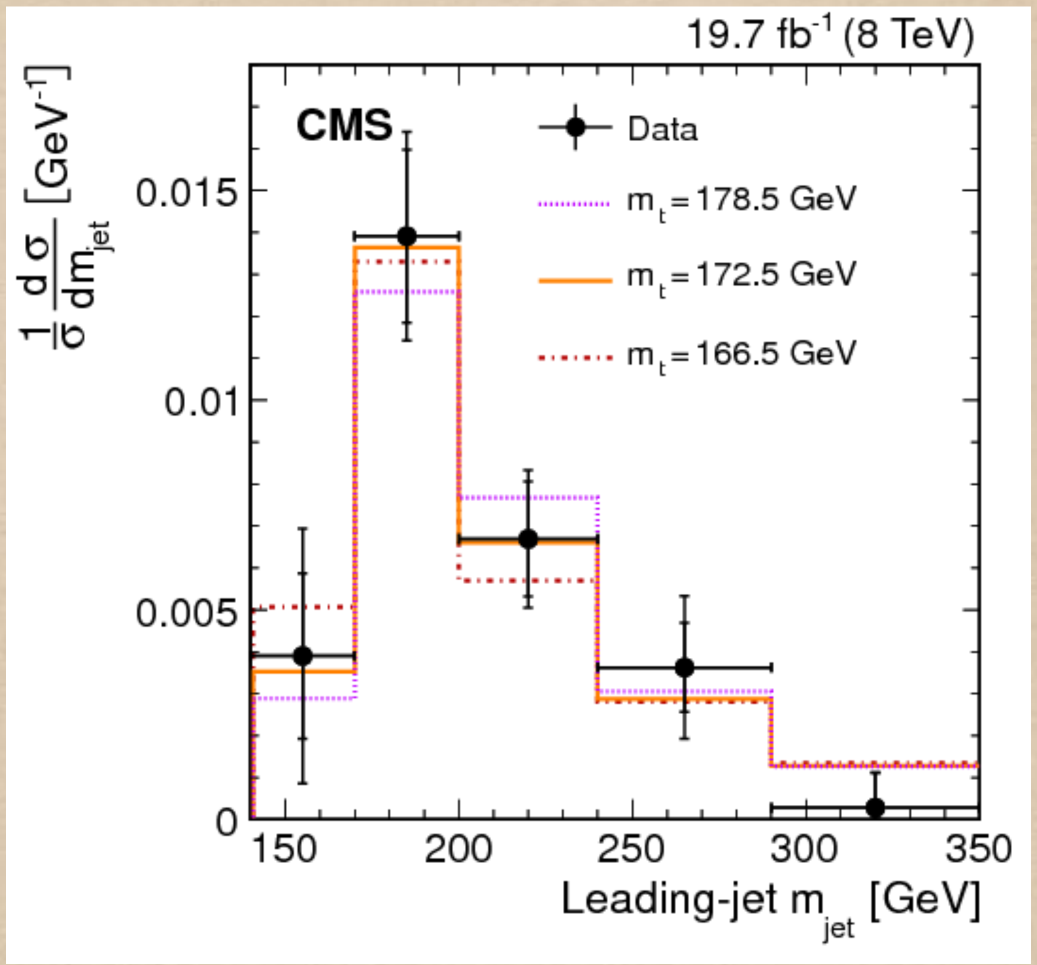




- Signal jet should have a mass peak near the resonance.
- But the pert and non-pert emissions broadens and shift the peak .
- UE and PU also increases the jet mass
- QCD jets acquire mass through parton showering

jet with pT ~1 TeV, m ~mW/mZ

Jet Mass(2)



Ungroomed, R=1.2, pT>200 GeV

- Jet mass can be used as a basic observable of Jet.
- Mass is sensitive to energy distribution in the jet, can also be thought of as a jet shape variable

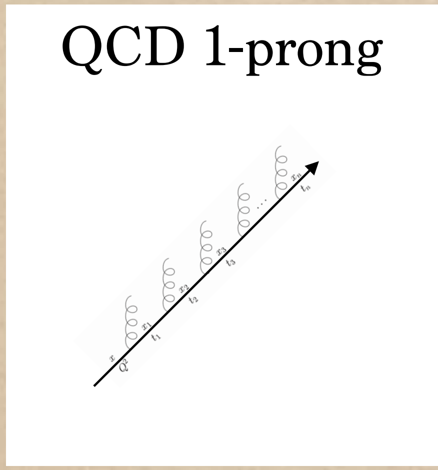
Jet Charge is also used another observable

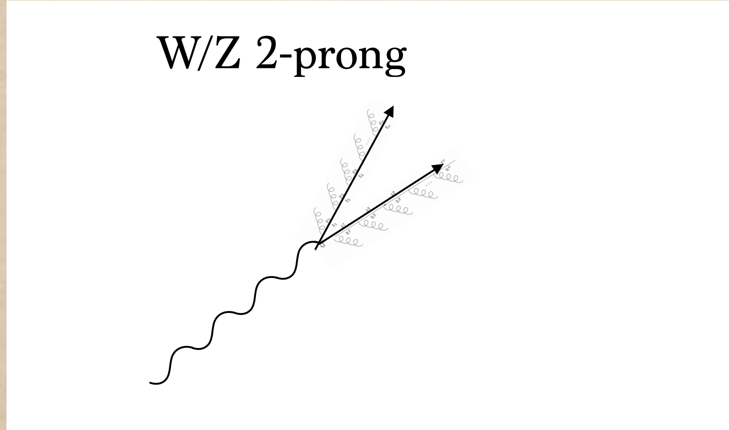
Jet Charge (rev p 170)

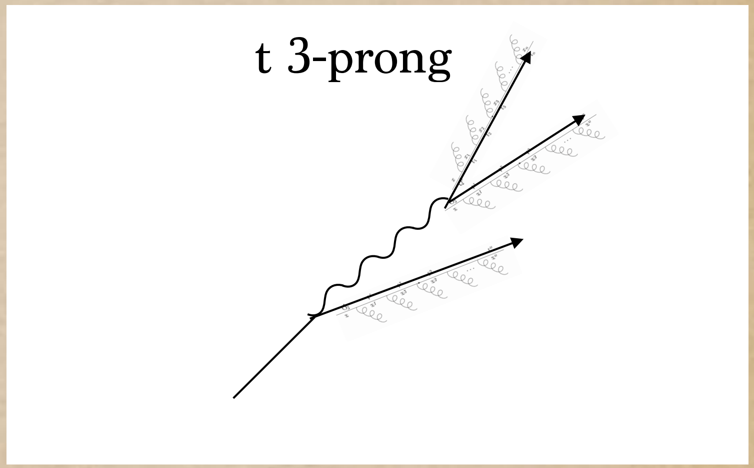
Beyond the Jet mass: JetSubstructure

Beyond the jet mass, study the internal structure and exploit it: jet substructure

- Clean the jets removing the soft radiation, find subjets
- Identify the kinematic features of hard decays and select them







Jet Substructure: Profile of Jets

Jet Substructure

Goal: To study the internal kinematic properties of jets to distinguish signal and background like jets .

Large number of methods are available which can be categorised in three subgroups.

Prong Finders: Prongs in jets

Radiation Constraints: Color connection

Groomers: FatJets

Jet Substructure

Prong Finders: Look for multiple hard cores in a jet, reducing the contamination from QCD jets, 'pronginess'.e.g. QCD jet 1 hard core, W/Z/H give two cores and top jets three pronged.

Color constraints: Color connection between sub jets are exploited. jets from W/Z/H will have less soft radiation than from QCD jets. Similarly, quark initiated jets will have less contamination than gluon initiated jets. Various jets shapes are used to quantify the effect of contamination, and then separate out the signal and background jets.

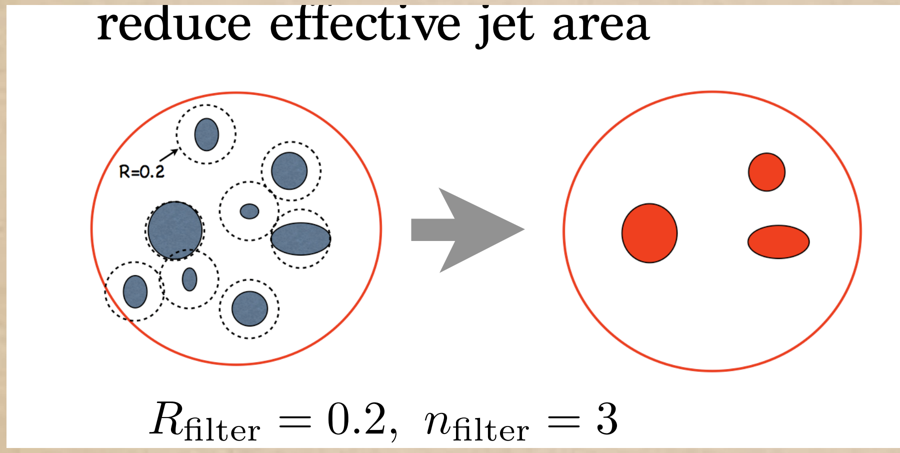
Groomers: Use Large jet radius to capture all jets inside a single jet, FatJet. Because of large radius, jets are sensitive to UE and PU. Grooming tools are used to mitigate the impact of these soft effects. from QCD jets, 'pronginess'.e.g. QCD jet 1 hard core, W/Z/H give two cores and top jets three pronged.

Various techniques are developed

Grooming

Filtering

Butterworth, Davison, Rubin, Salam(BDRS)',08



- Jets are using AntiKT
- Subjets are using C/A with R_{filt}=0.3,
- three subjects are retained

Trimming

Krohn, Thaler,Wang',09

- jets are using AntiKT R=1.0
- re-clustered using AntikT, with R_{trim}=0.2,
- subjects are retained, if Z^{cut}=0.03

$$p_{T,j} > Z^{cut} p_{T,j}$$

Pruning

It is applied during the formation of jets. S.D.Ellis, Vermilion, Walsh Salam, '09

Applied dynamically, to suppress the small and larger distance using two cuts Z_{cut} and Dcut.

Pruning vetoes recombinations, between i and j , if geometrical distance between them larger than D and one of the objects is less than Zcut; Dcut=0.5, Zcut~=0.1

Mass Drop

BDRS

It is in the category of prong finders and grooming

Form a jet and with C/A algorithm.
Undoes the last step $p_{i+j} \to p_i + p_j$

Mass drop $max(m_i, m_j) < \mu_{cut} \quad m_{I+j}$

Splitting is sufficiently symmetric $Min(p_{t,i}^2, p_{t,j}^2)\Delta R_{ij}^2 > y_{cut} \quad m_{i+j}^2$

If satisfies, keep both i and j, otherwise keep only the massive one

Iterate it, till all are declusters, stable subjects are obtained
mMDT: modified mass drop

Tool: HEPtoptagger

pT based grooming: JHToptagger

Soft Drop

Larkowski, Marzani, Soyez, Thaler', 1402.2657

Soft drop de-clustering removes wide angle soft radiation from a jet in order to mitigate the effects of contamination from ISR, UE, PU.

For a given jet radius, R_0 with only two constituents, the soft drop procedure remove softer ones,

$$\frac{min(p_{T_i}, p_{T_j})}{p_{T_i} + p_{T_j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R} \right)^{\beta}$$

The above equation fails for wide angle emission, the grooming is Controlled by Zcut and β.(i=1,j=2), Zcut determines the strength of fractional pT selection, and β is set to greater than 0, to soften the collinear radiation. This procedure can be extended for jets with more than two constituents, using pairwise recursive algorithm.

Useful in PU removal

N subjettiness

N-subjettines is a jet shape variable that discriminates jets according to the number N of subjets.

Jets from top decay are expected to have three regions,QCD

jets have one one two regions.

A set of axes $a_1, a_2....a_N$ is introduced , jet shape variable is defined as

$$\tau_N^{(\beta)} = \sum_i p_{Ti} \min(\Delta R^{\beta}_{ia_1} ... \Delta R^{\beta}_{ia_N})$$

The axes, K can be chosen in several ways. e.g..

kT axes, minimal axes..

$$\tau_{N,N-1} = \frac{\tau_N}{\tau_{N-1}}$$ is a good discriminator,.

$\tau_{21} < \tau_{cut}$ Discriminate W/Z/H jets against QCD jets

$\tau_{32} < \tau_{cut}$ Discriminate top jets against QCD jets

Shower Deconstruction

The aim of the method is to determine whether the Subjets pattern is compatible with a Parton shower profile, typical of a top quark.

Sopper, Spannowsky, 1102.3480, 1211,3140.

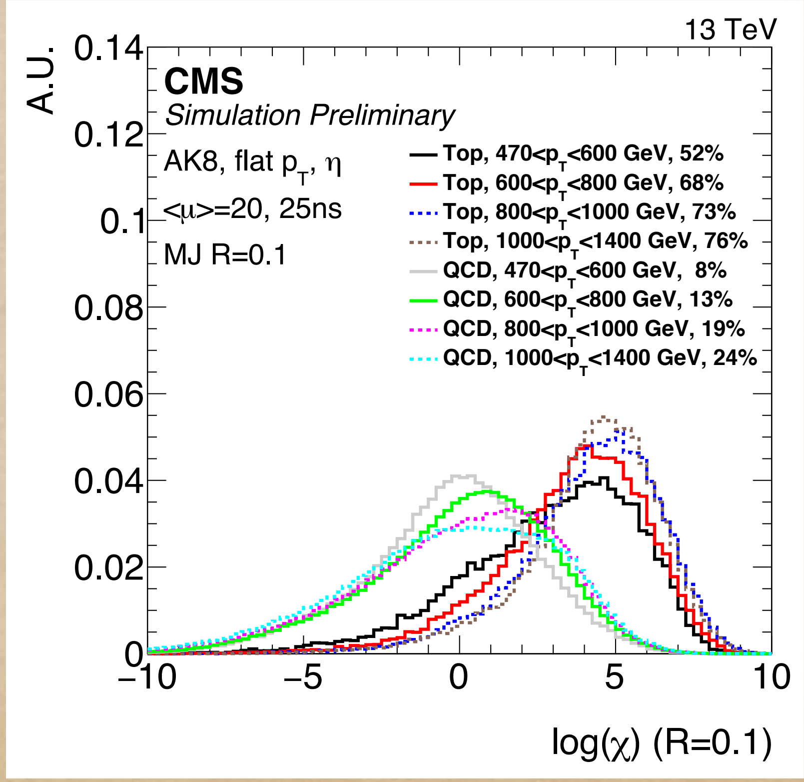
Initial jet is reclustered with R=0.2 or 0.1, $p_N = (p_1, p_2, p_3, ...p_N)$

The signal and Background likelihood are estimated calculating the probabilities that a simplified Parton shower Monte Carlo would generate p_N according to the signal and background hypothesis.

$$\chi(p_N) = \frac{P(p_N|S)}{P(p_n|B)}$$

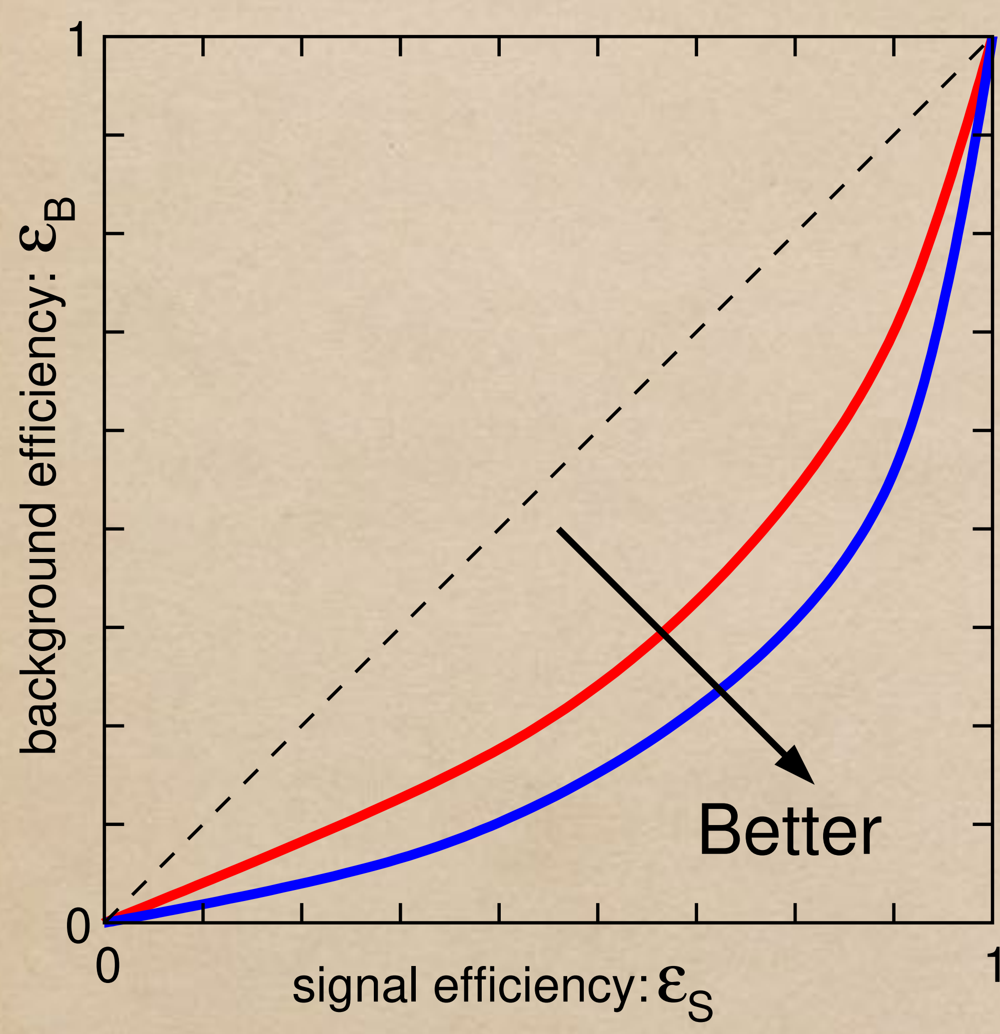
High values correspond to signal from top quark decay

CPU intensive



Performance

Receiver Operating Chracteristic(ROC)

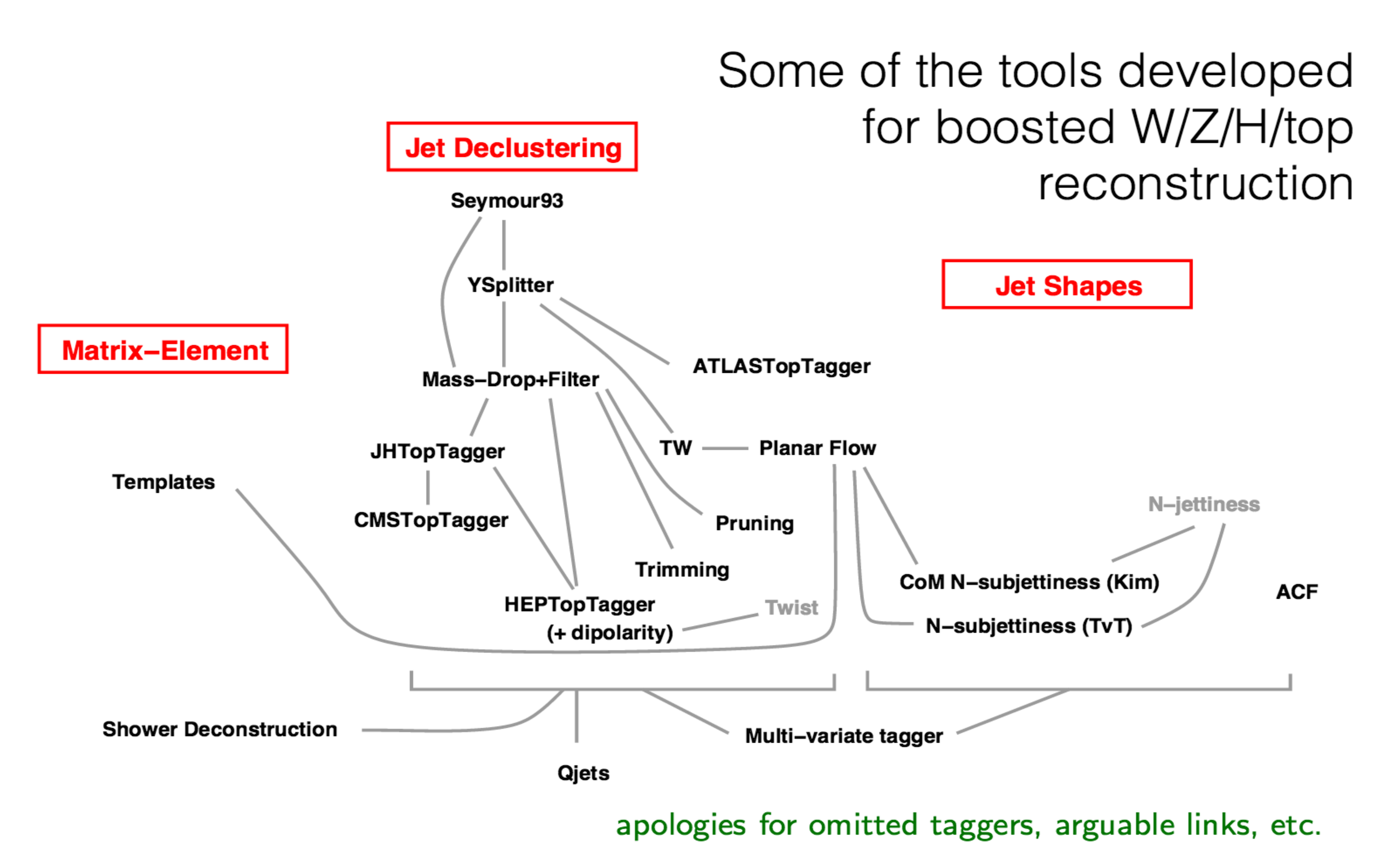


Algorithm IR and collinear safe

Little sensitive to model dependent non perturbative effects, hadronisation, UE,Detector effects, PU.

Many more..

Q Jets, Energy Correlation Functions (ECF), Y Splitter…



Slide from G.P. Salam's talk

Jet tagging

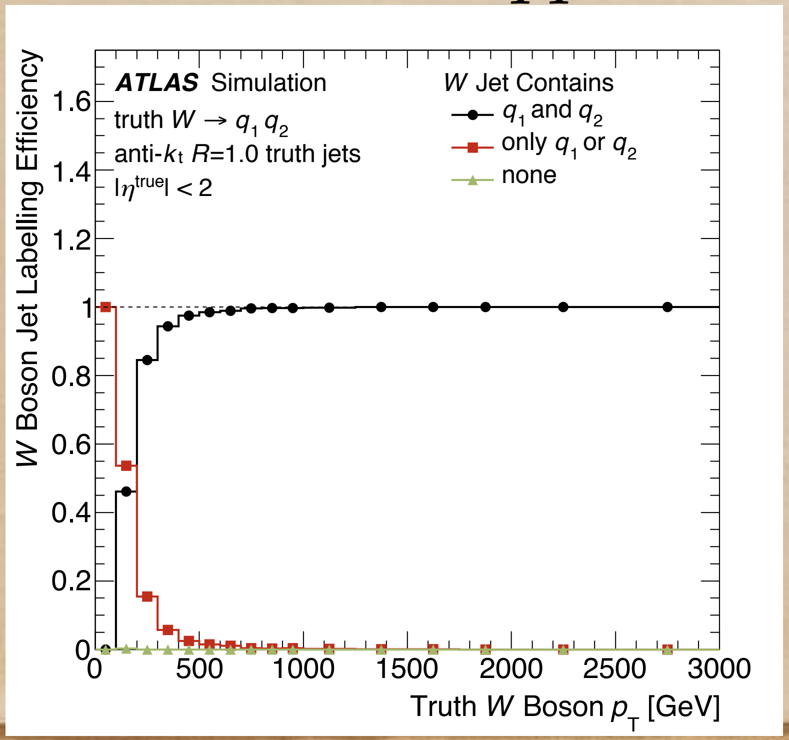
Labelling of the jet with the particle which initiated it - Jet tagging, of particular interest W and top tagging

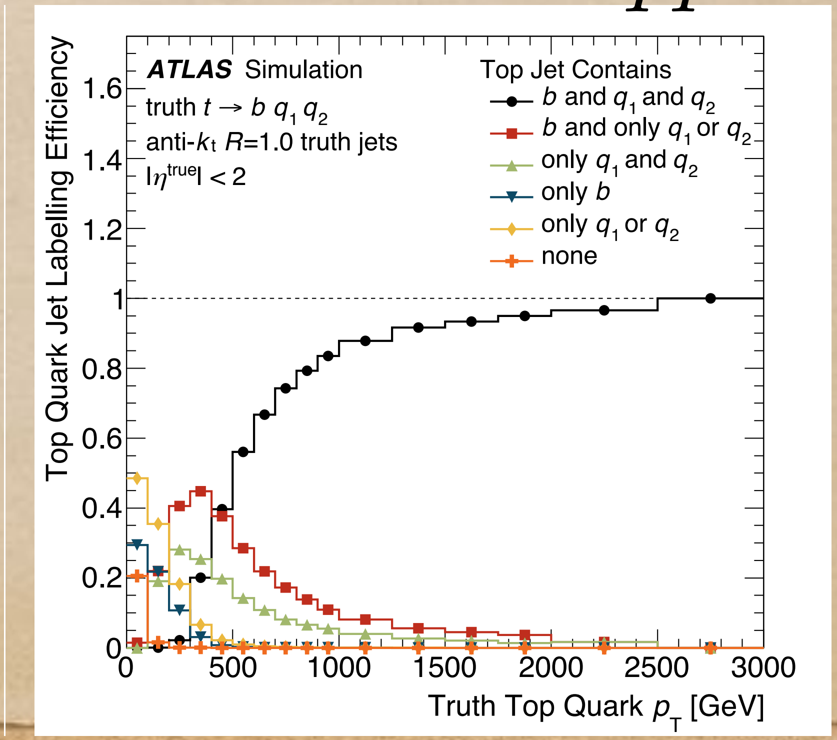
- Reconstructed jets are matched: $\Delta R(j_{true}, j_{reco}) < 0.75$
- Truth jets are matched truth W/top $\Delta R(j_{true}, \text{particle}) < 0.75$
- The partonic decay products of W/top are matched with reconstructed jet

A jet is tagged if the parent particle and its decay products are: $\Delta R < 0.75 \times R_{jet}$

$W \to q\bar{q}'$

$t \to bW \to bq\bar{q}'$





HEP Top Tagger

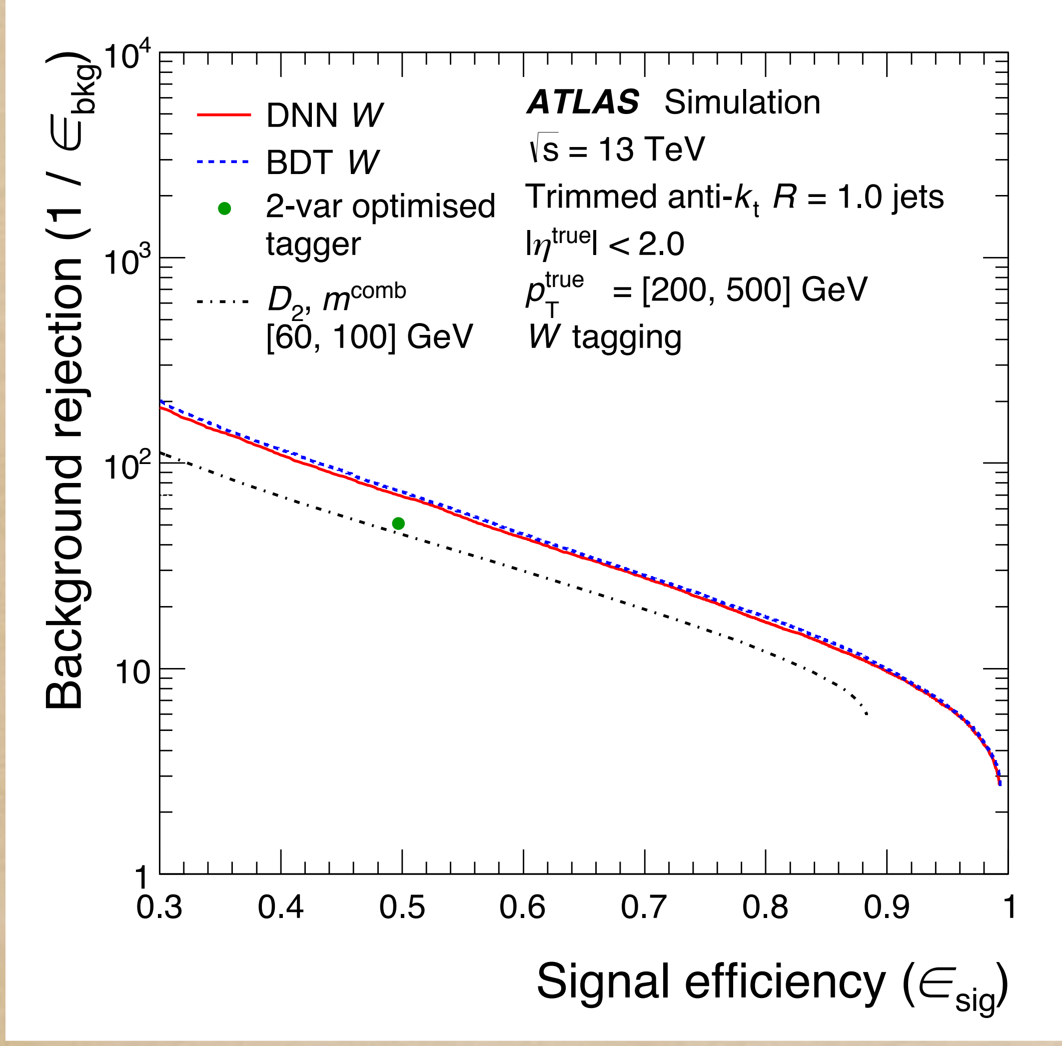
W/top tagging

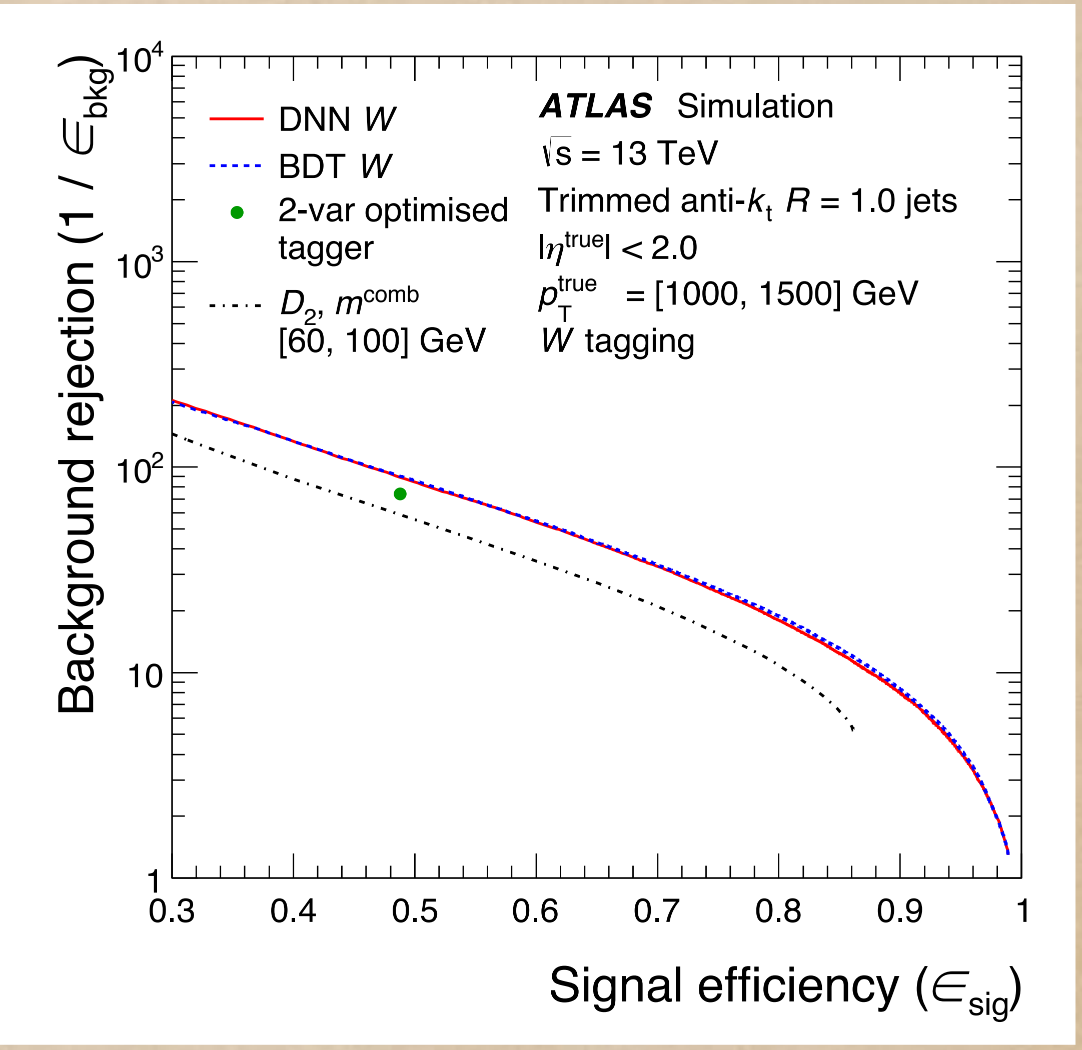
- For W/top tagging, many variables or correlations, Jet moments are used for tagging.
- All these Jet moments are given input for multivariate analysis (DNN, MVA)

Observable	Variable	Used for	References
Calibrated jet kinematics	p_{T}, m^{comb}	top,W	[44]
Energy correlation ratios	e_3,C_2,D_2	top,W	[50, 54]
N-subjettiness	τ_1,τ_2,τ_{21} τ_3,τ_{32}	top, W top	[55, 56]
Fox–Wolfram moment	R_2^{FW}	W	[57, 58]
Splitting measures	z_{cut} $\sqrt{d_{12}}$ $\sqrt{d_{23}}$	W top, W top	[59, 60]
Planar flow	$\mathcal{P}$	W	[61]
Angularity	a_3	W	[62]
Aplanarity	A	W	[58]
KtDR	$KtDR$	W	[63]
Qw	Q_w	top	[59]

1808.07858, ATLAS Collab

W tagging





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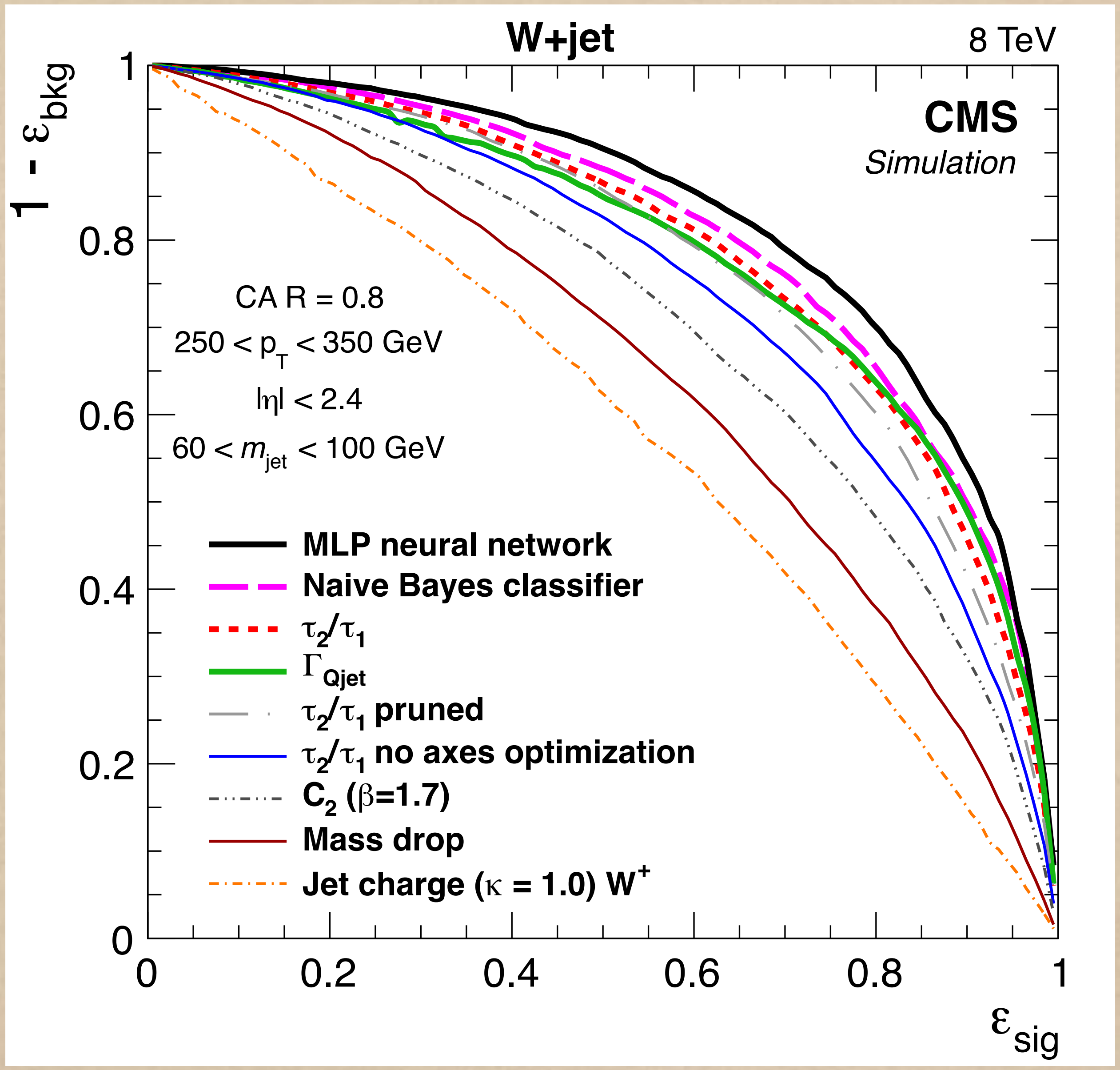
ATLAS Collab

W tagging in CMS



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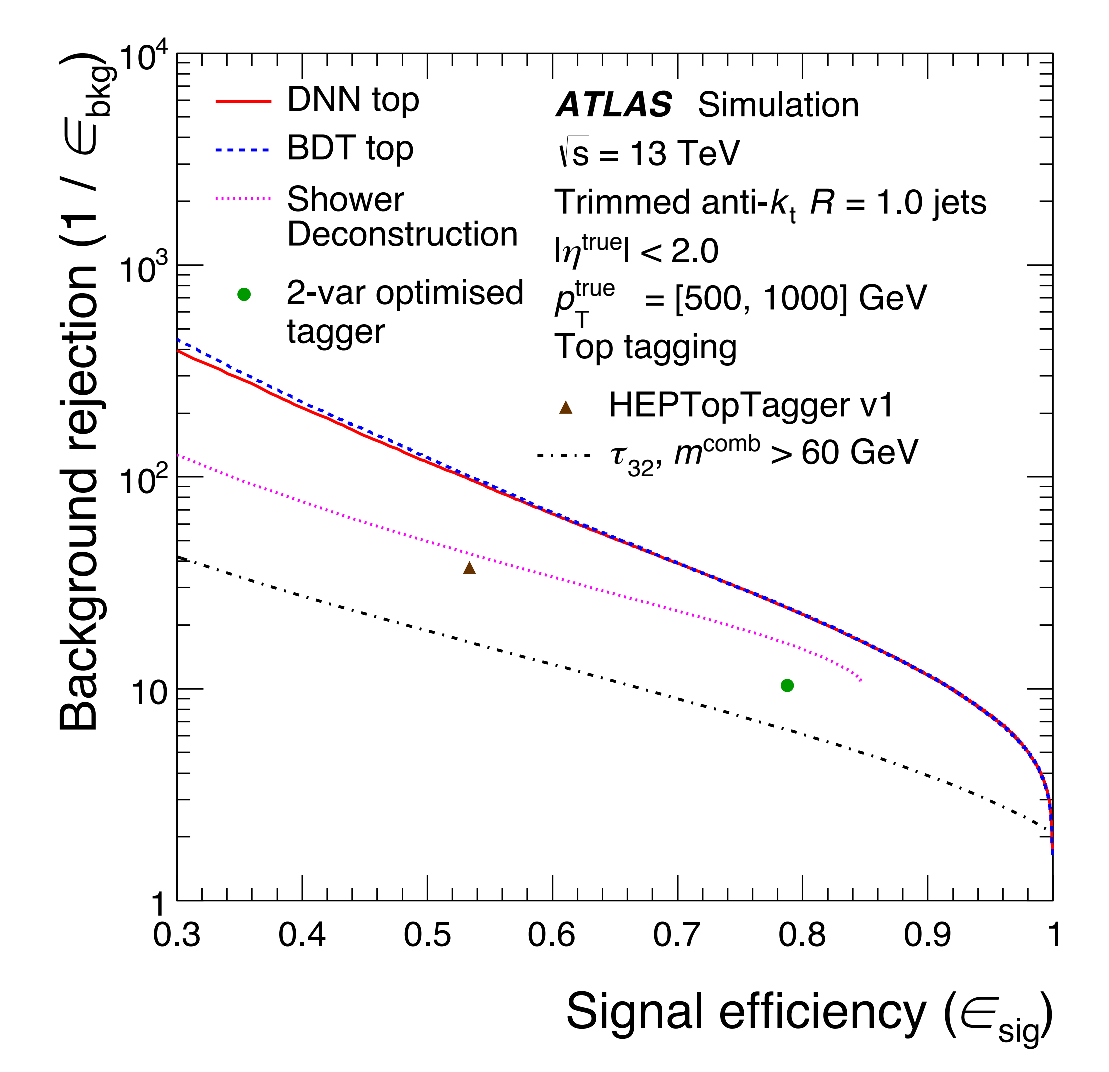
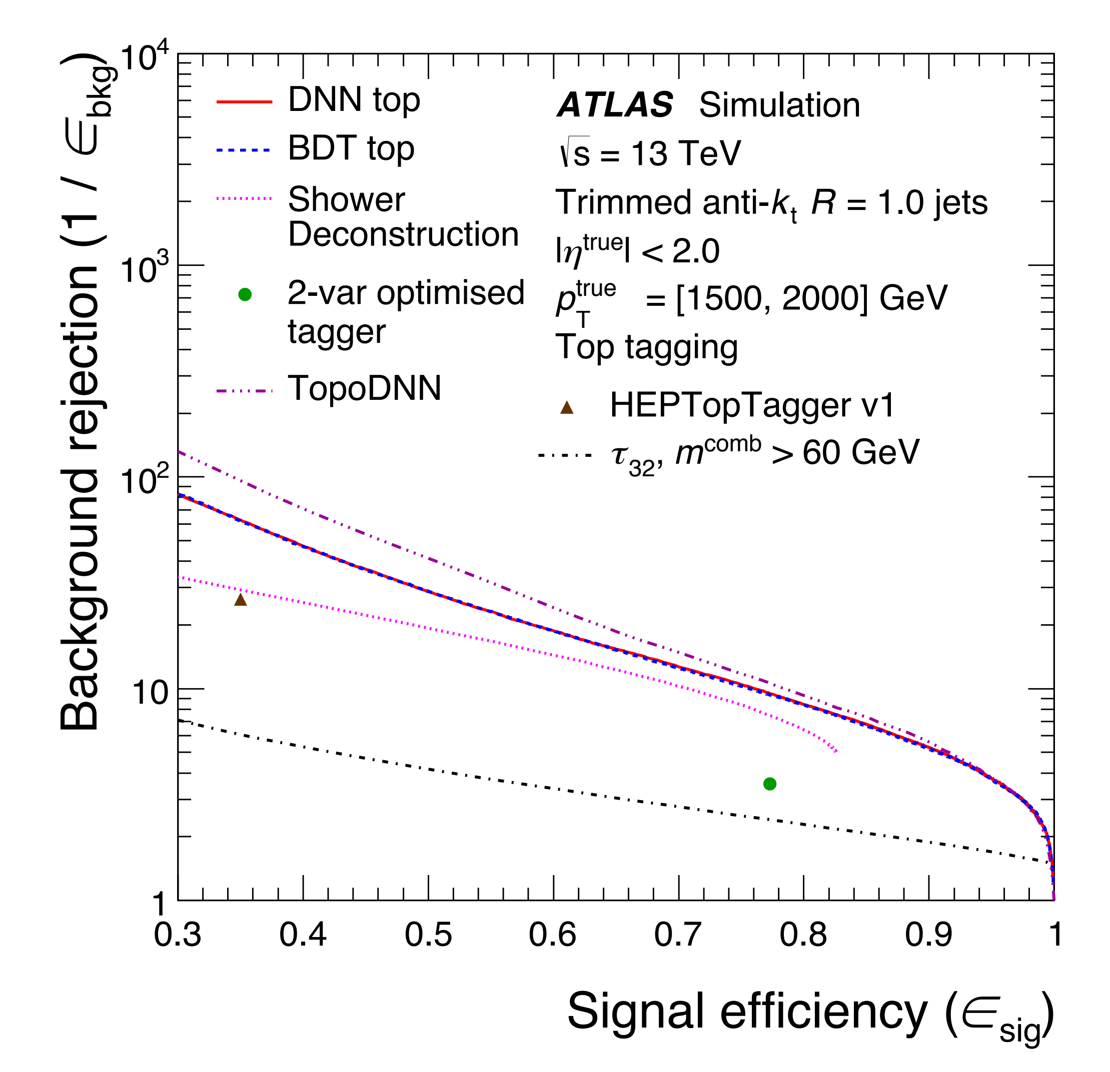
CMS Collab

Top Tagging:ATLAS





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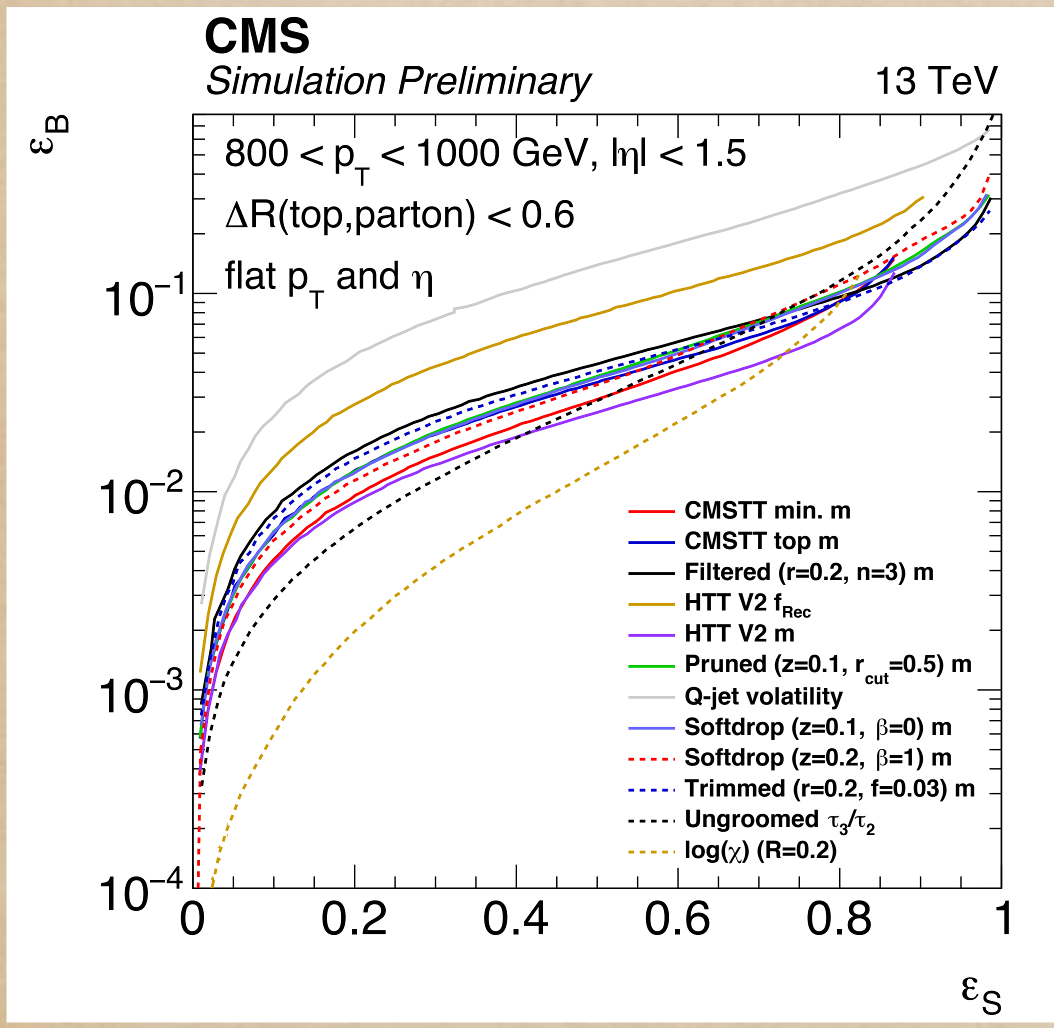
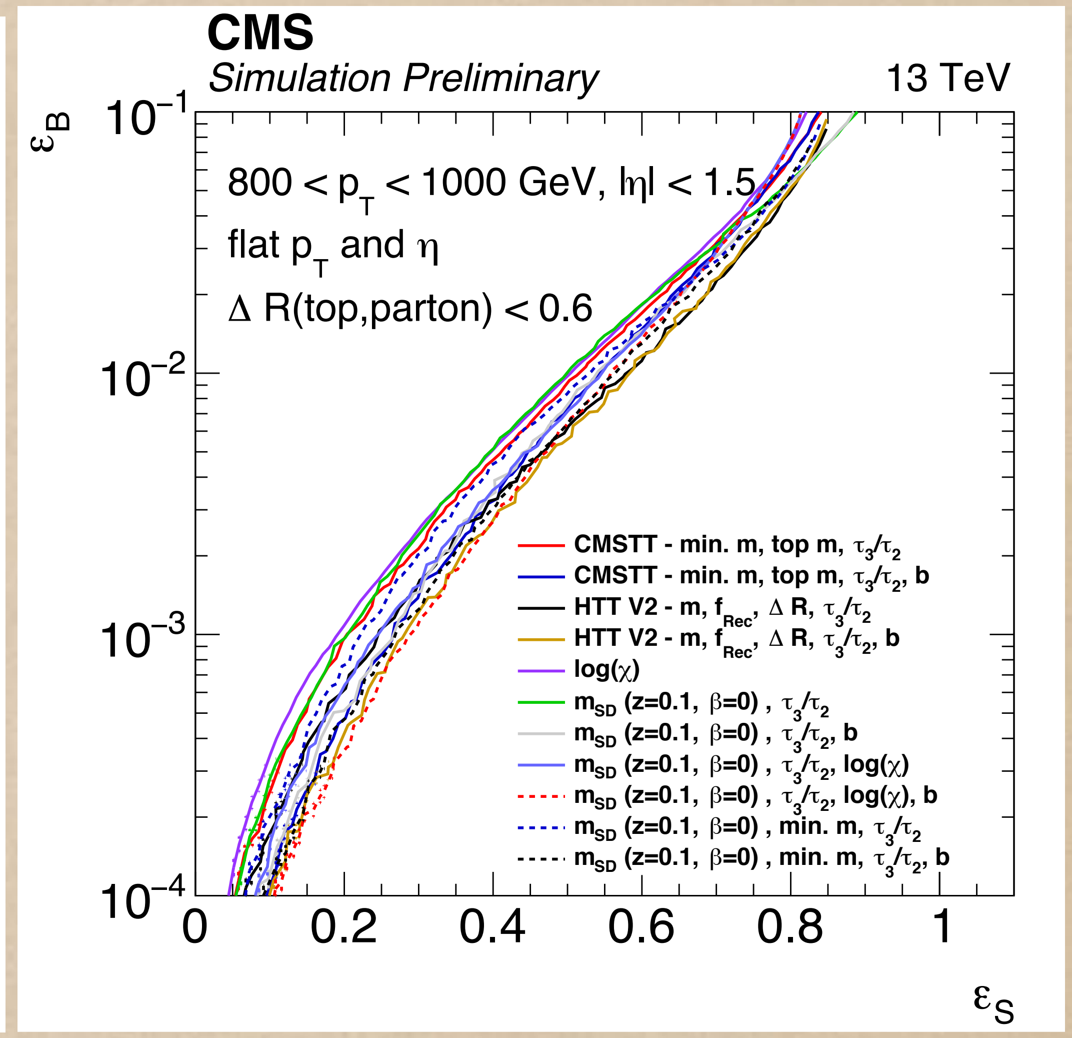
ATLAS Collab

Top Tagging: CMS





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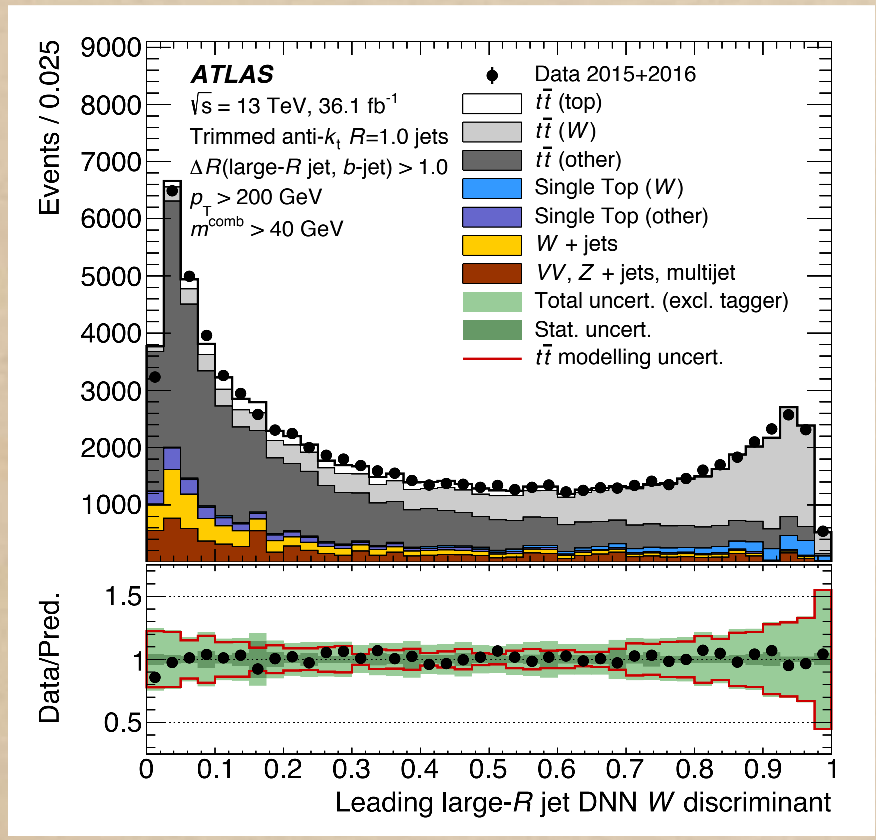
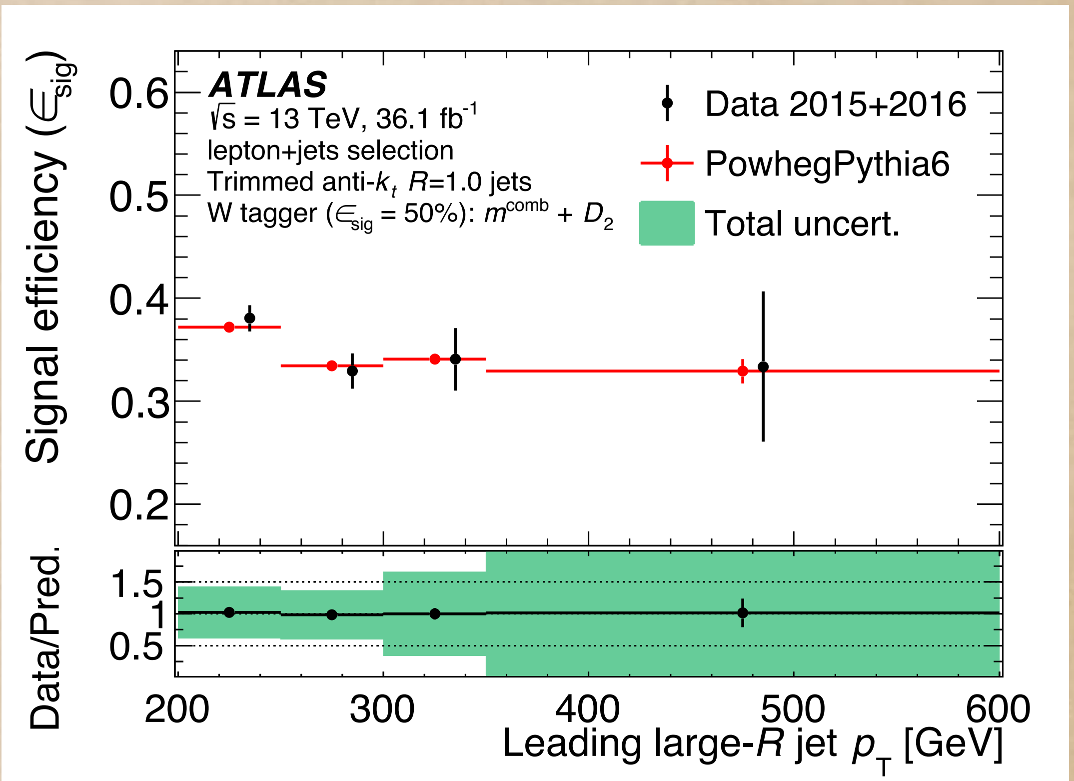
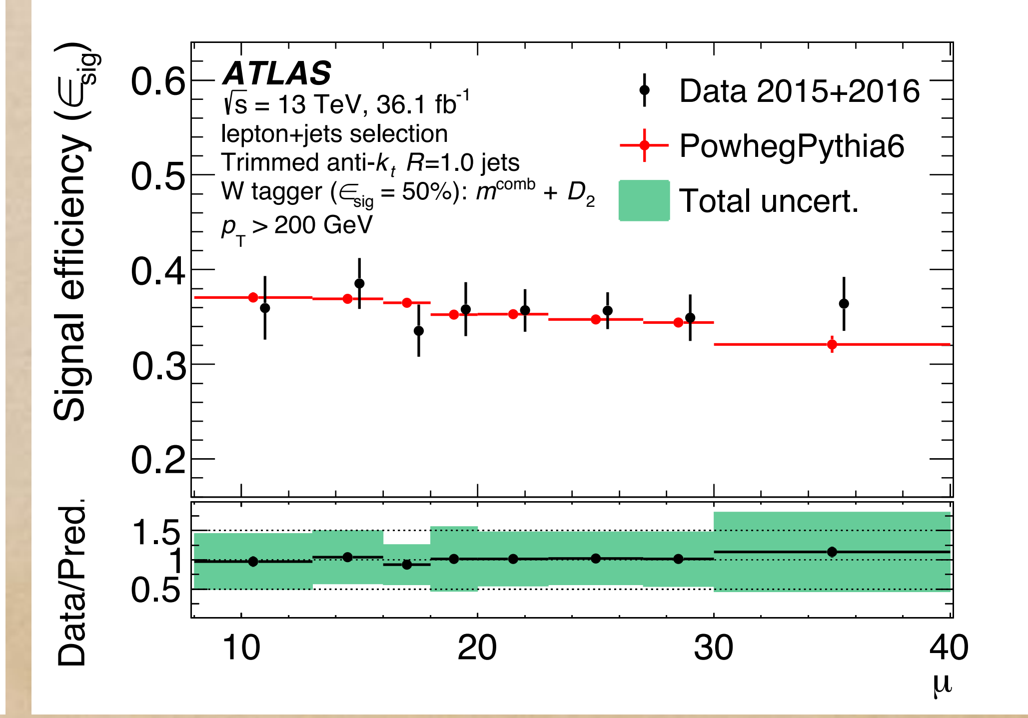
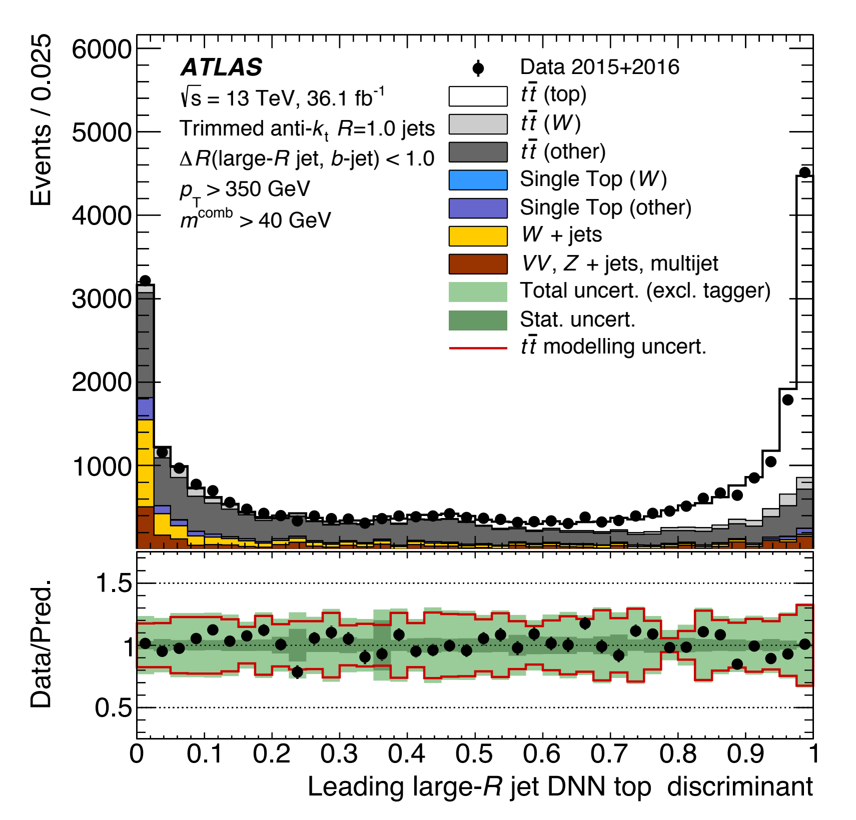
W Tagging: Data

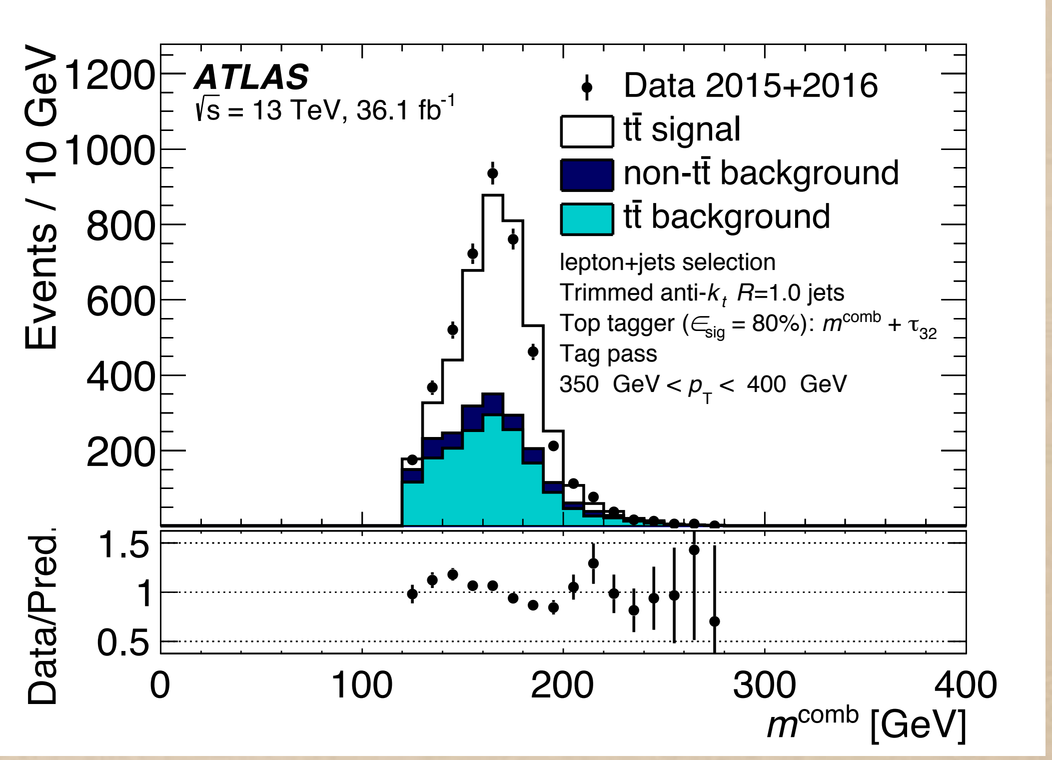


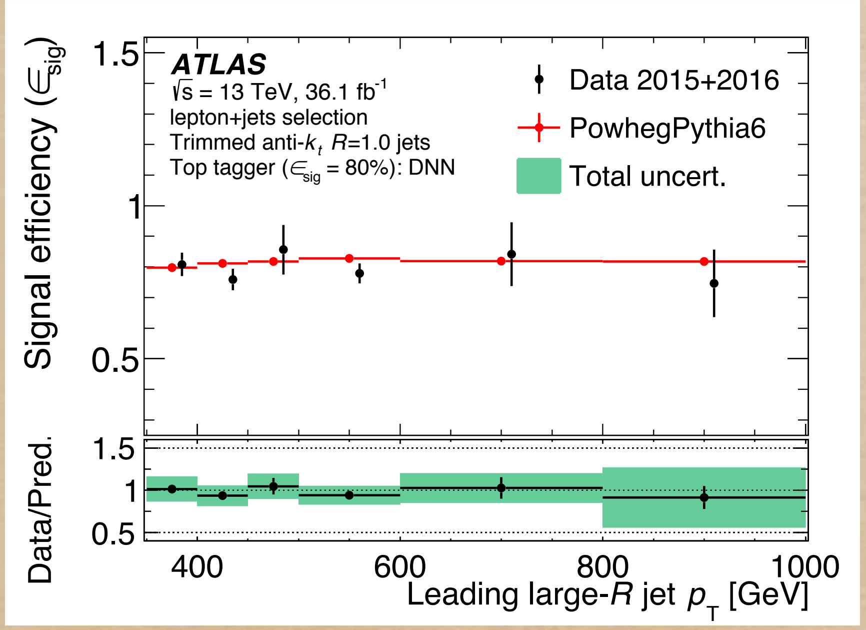


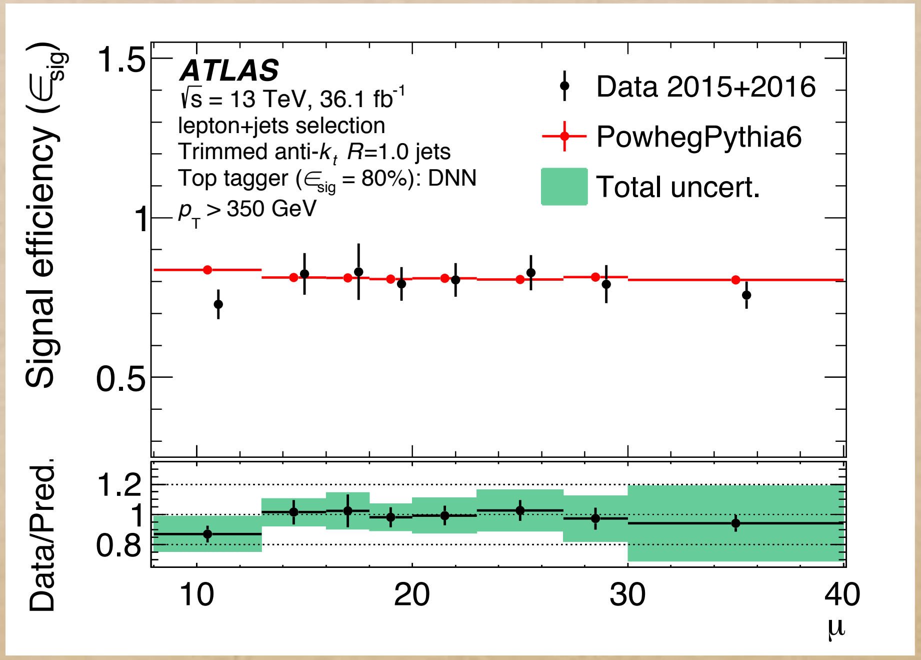


Top Tagging validation

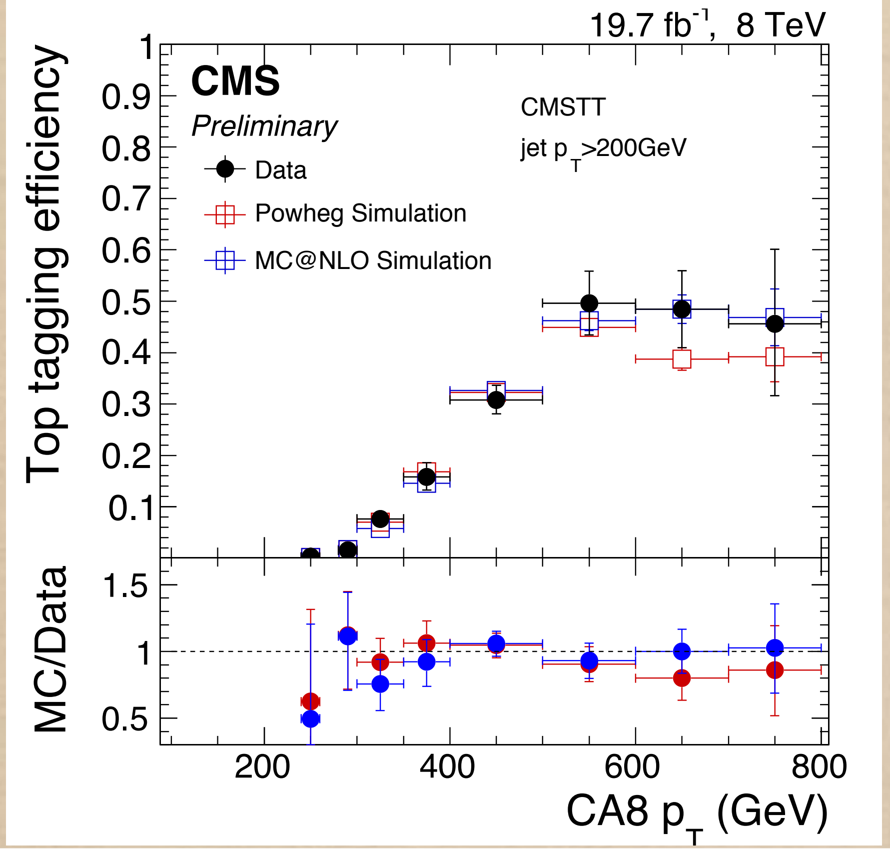


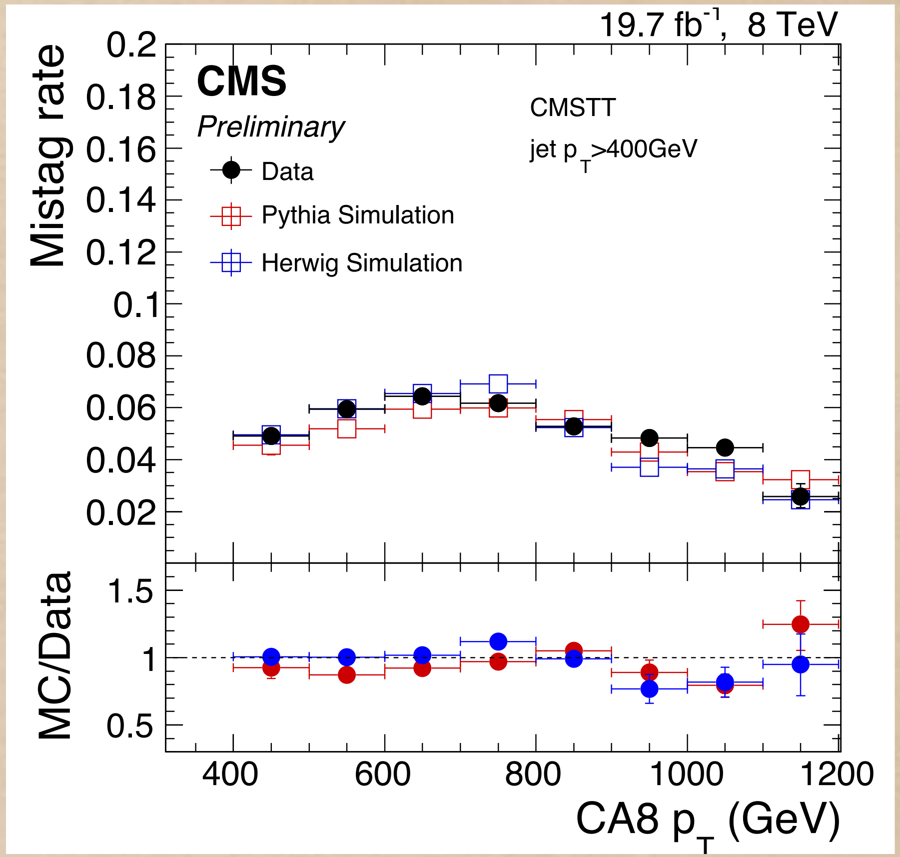


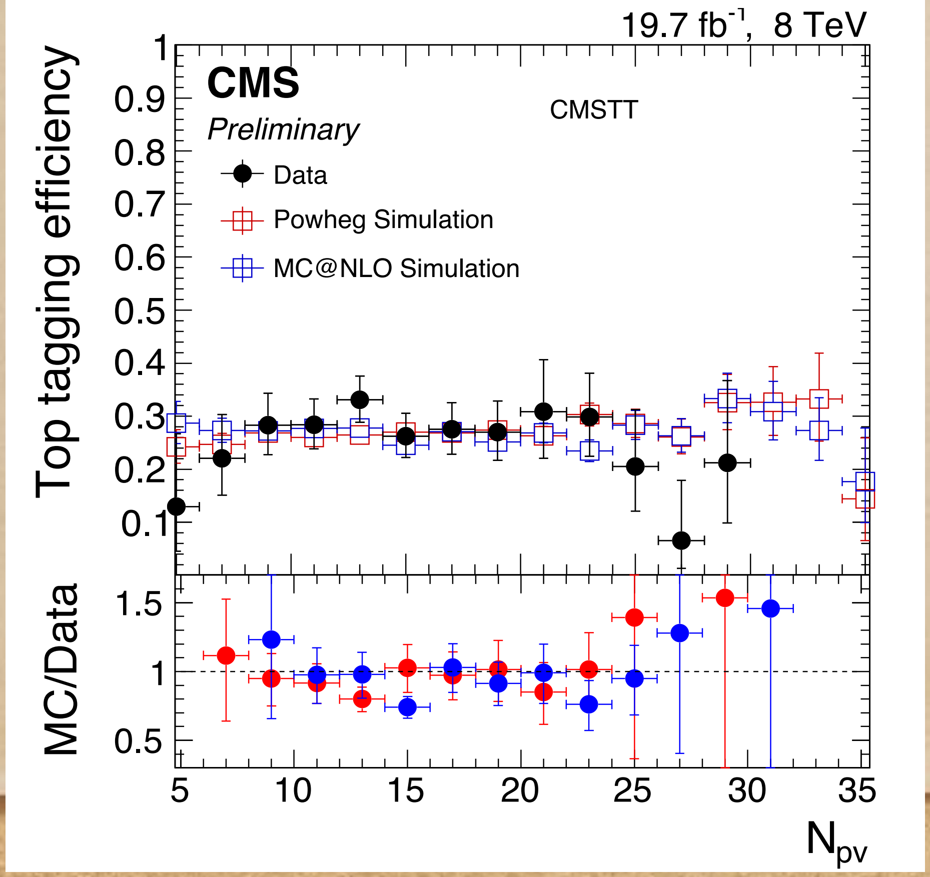


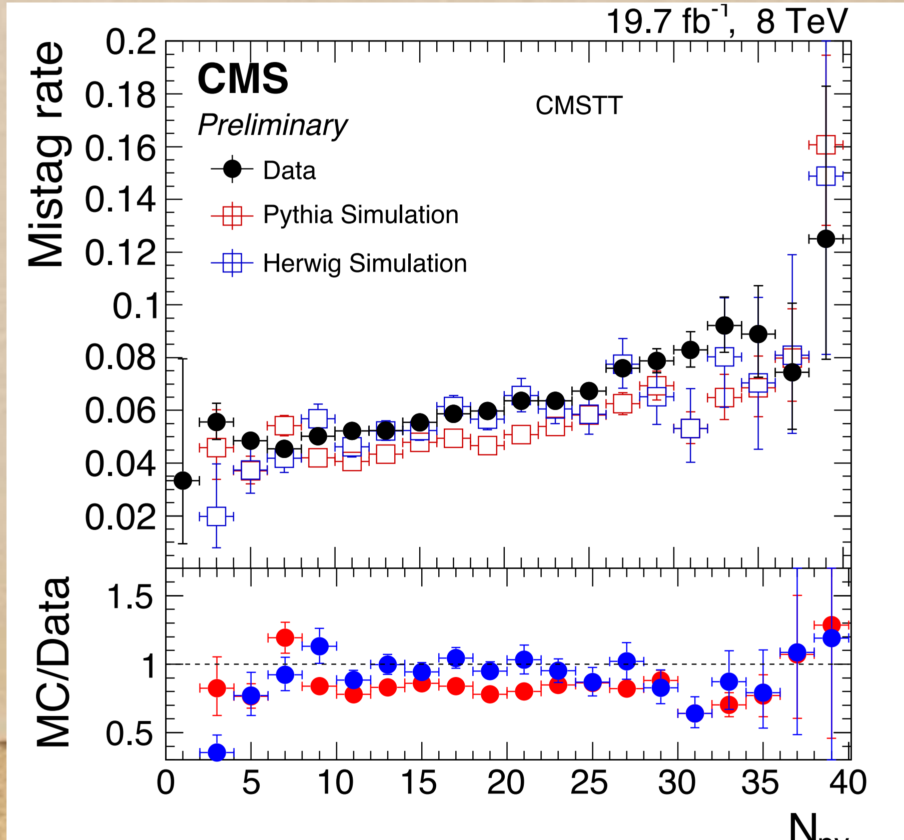


CMS Toptagging : Validation







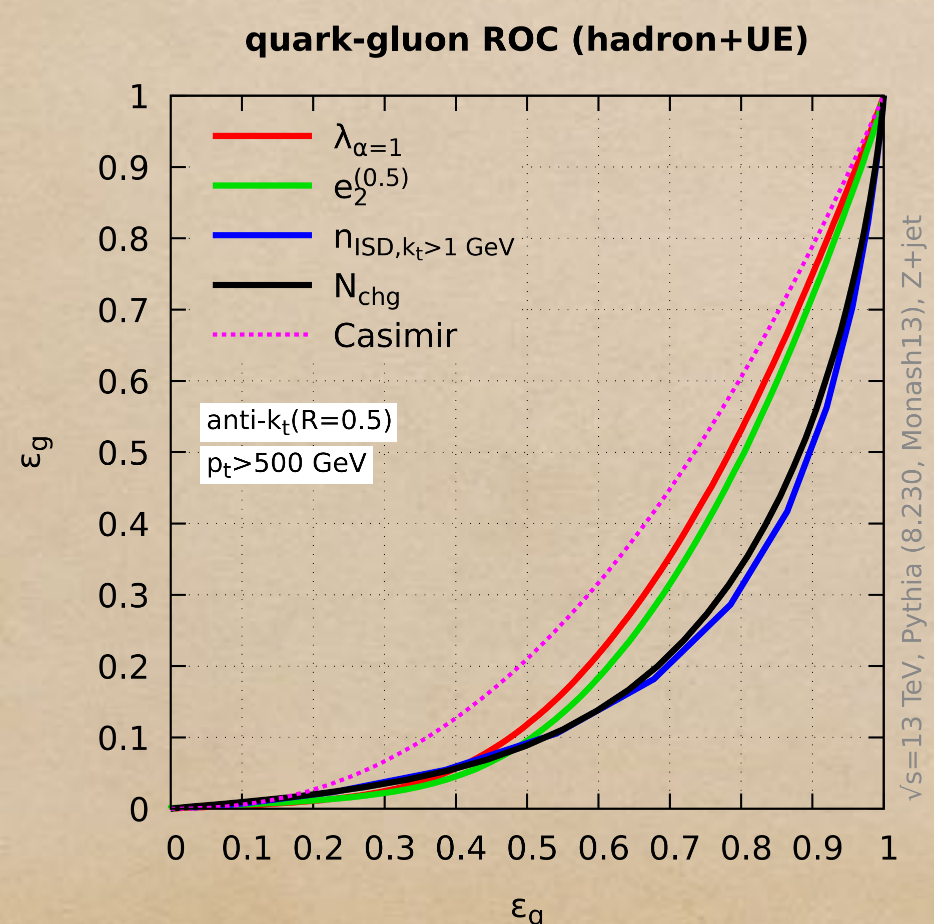


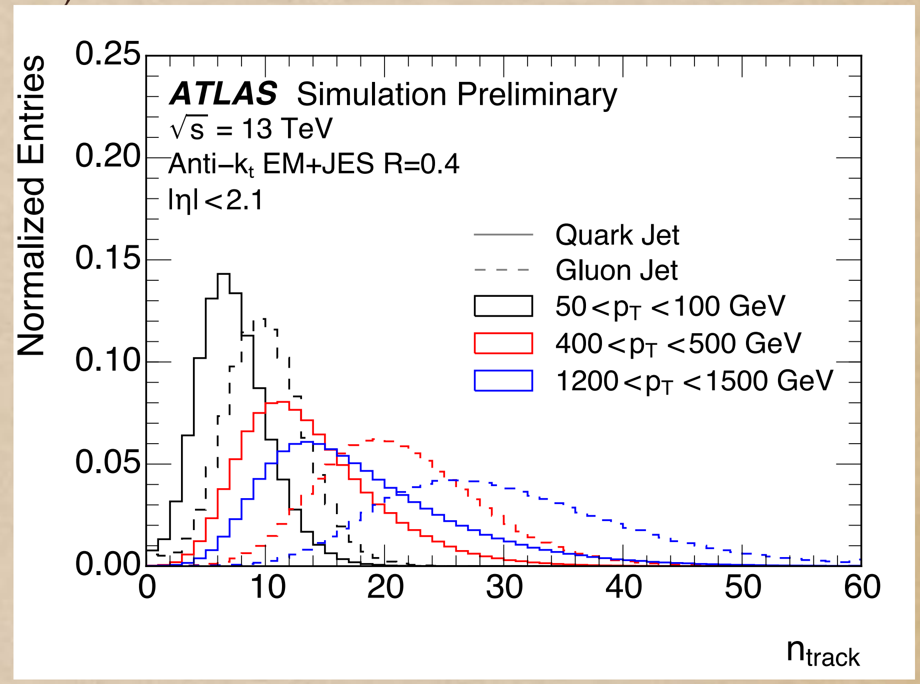
quark/gluon Discrimination

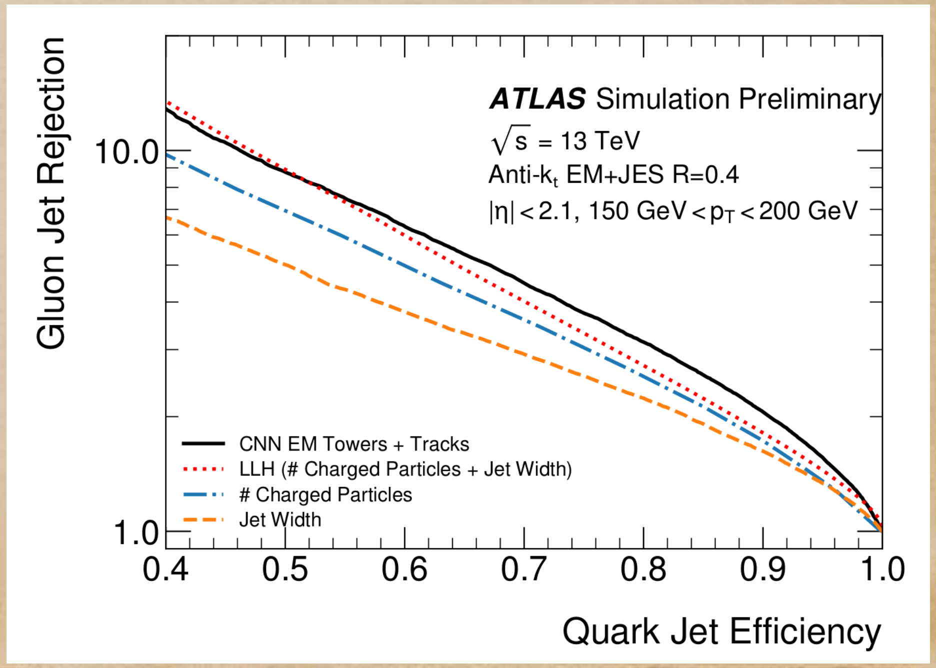
Higgs, NP (SUSY cascade), top mostly decks to quark jets.

QCD backgrounds are dominantly gluon jets

Jet shapes: angularities and
energy correlation functions,
Multiplicity based observables, Soft Drop







Higgs Searches

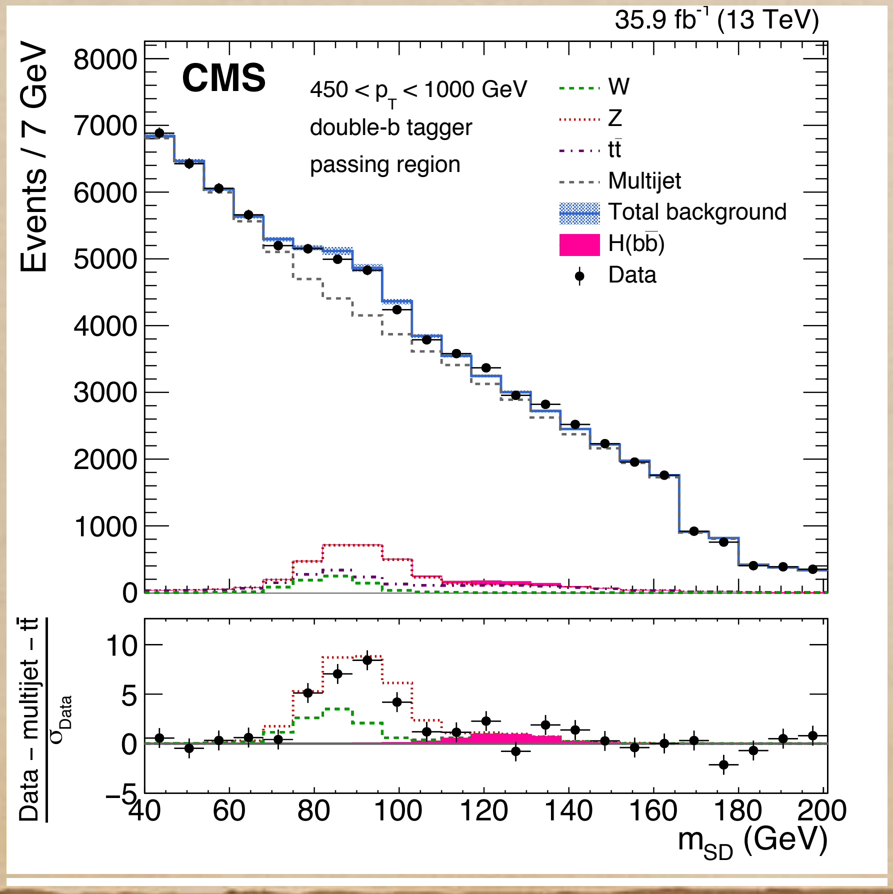
PP-> W/Z+H, $H \to b\bar{b}$

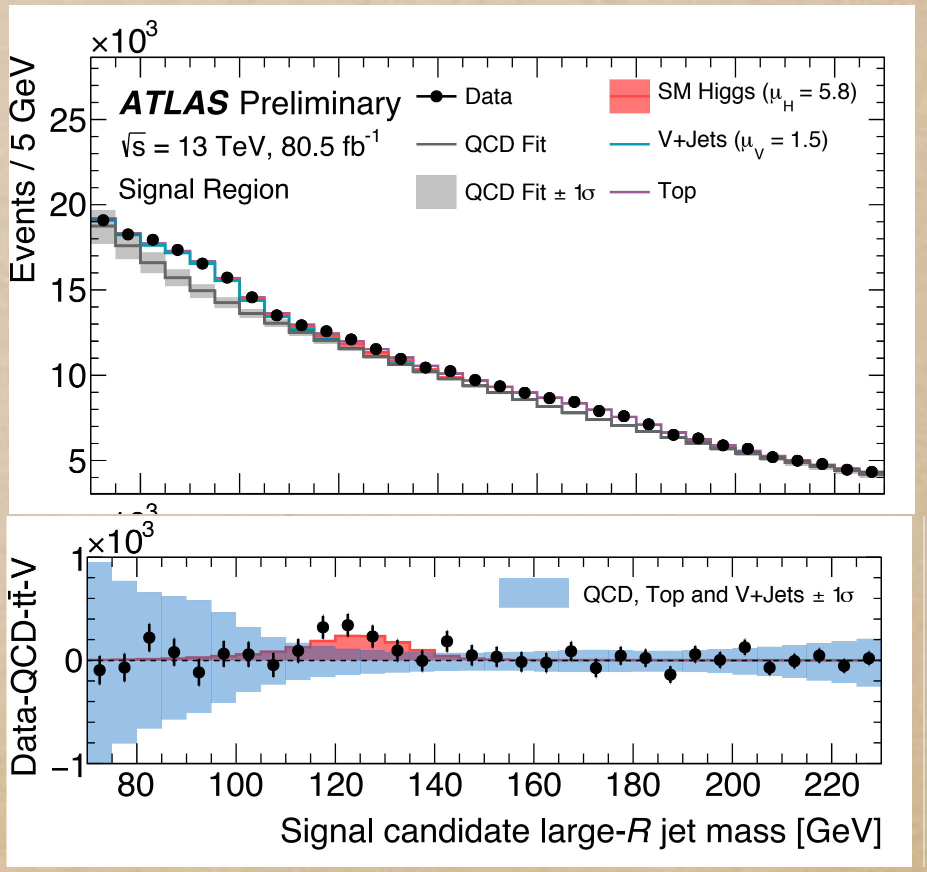
It was difficult channel to find Higgs, it was never considered for low luminosity option, because of Huge SM background.
But it is also important to study this decay mode, as its gives highest contribution to decay width

BDRS, PRL, '08

Jet Substructure level analysis helped to study this channel

SD+ECF

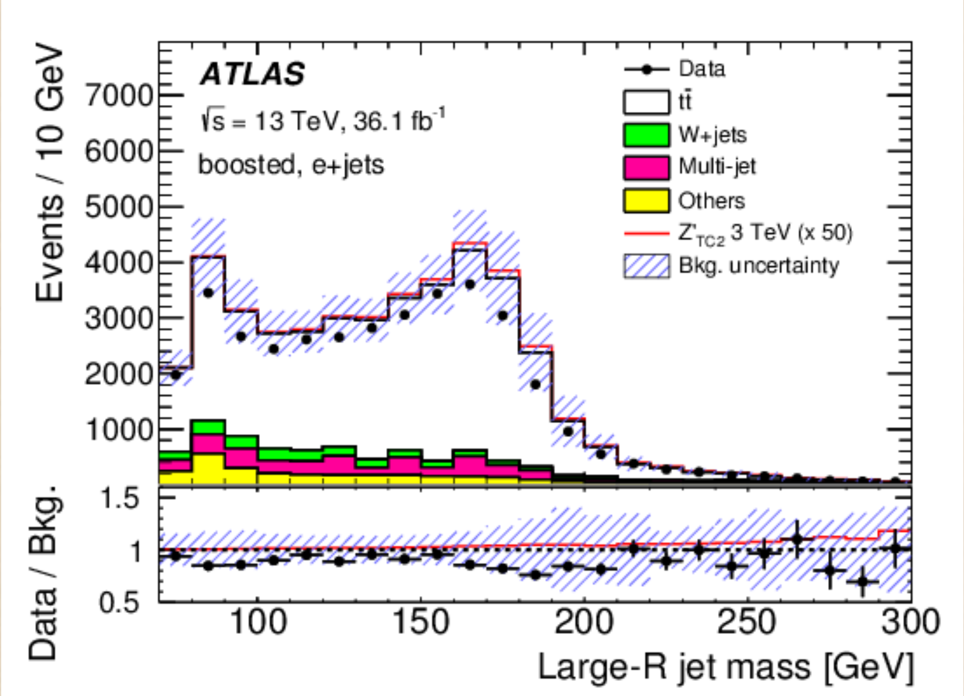


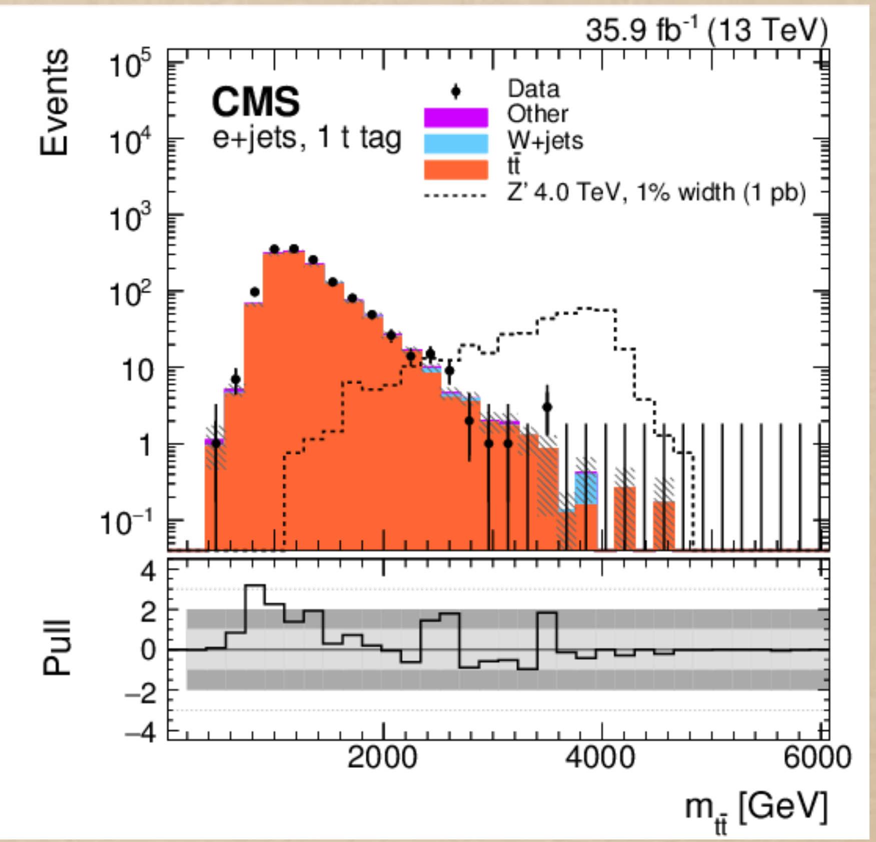


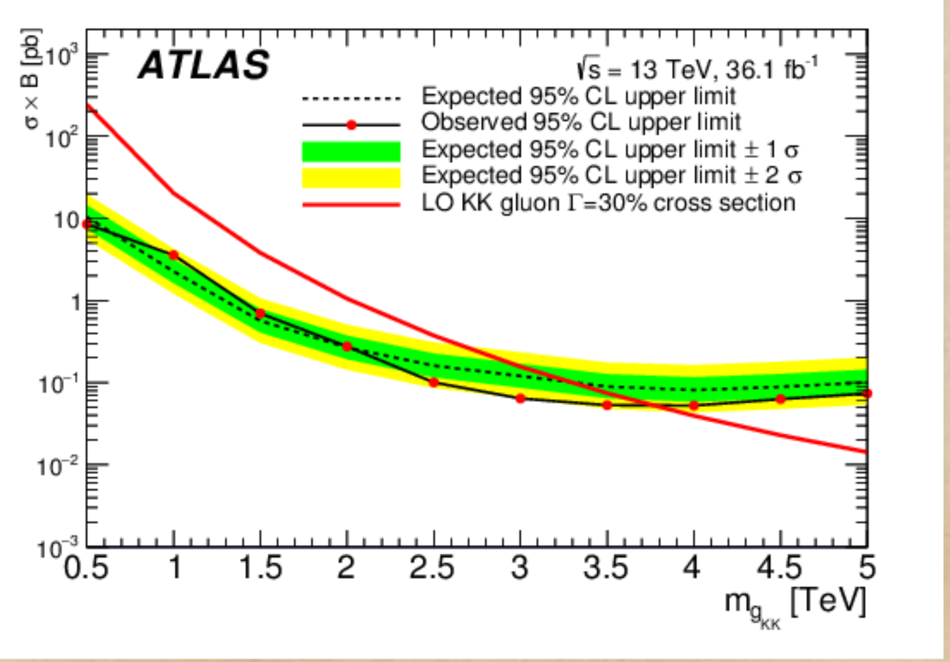
New Physics Searches

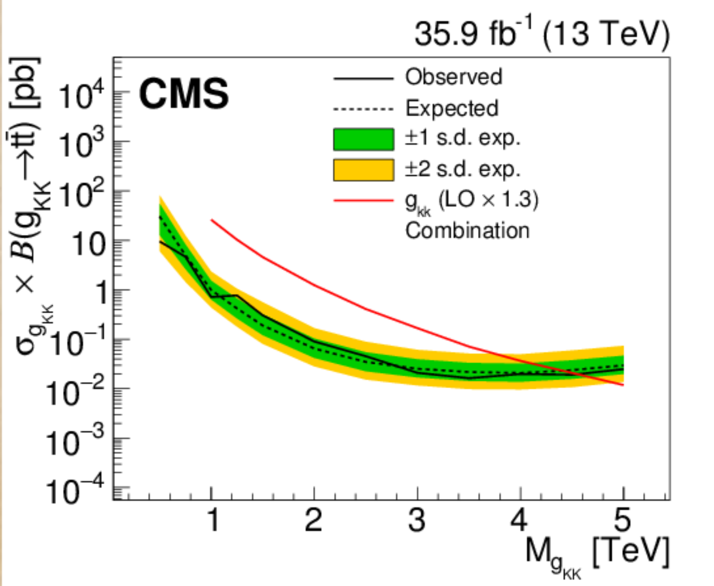
Heavy resonance searches

$$PP \to Z', g_{KK}, G_{KK} \to t\bar{t}$$









Charged Higgs Search

2HDM model predicts charged Higgs

$m_{H^-} >> m_t + m_b \Rightarrow H^- \to \bar{t}b$

$PP \to tbH^- \Rightarrow t\bar{t}b\bar{b};$

- Huge Background from SM top pair production
- Signal sensitivity is too low for the mass range 400 - 1000 GeV
- Mass reconstruction poor, for combinatorial problem

Top quark from Charged Higgs decay is boosted. Mass reconstruction is better

Better boosted top construction

Signal sensitivity is improved. Possible to observe at 300/fb

Aravind H Vijay, MG, PRD, '2018(1803.06986)

Boosted top quark polarization

- Top quark is polarised..decided by the interaction vertex
- Polarisation measurement provides hints about the possible modification on interaction vertex.

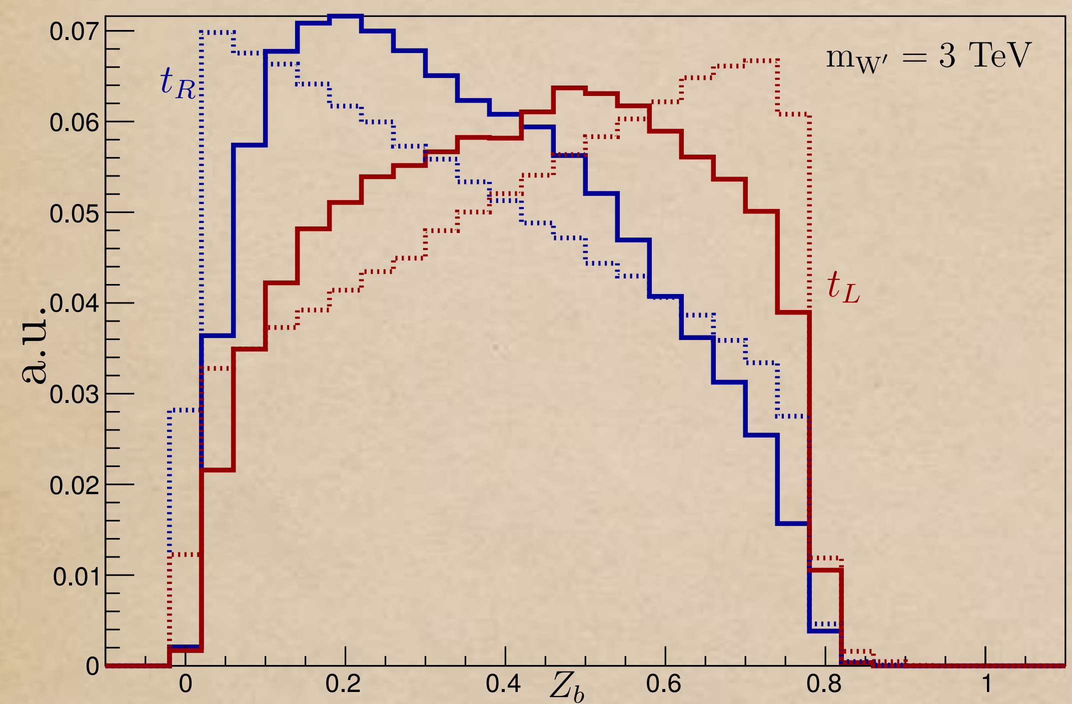
$t^- \rightarrow b\ell^-\nu$ Leptonic decay mode is used

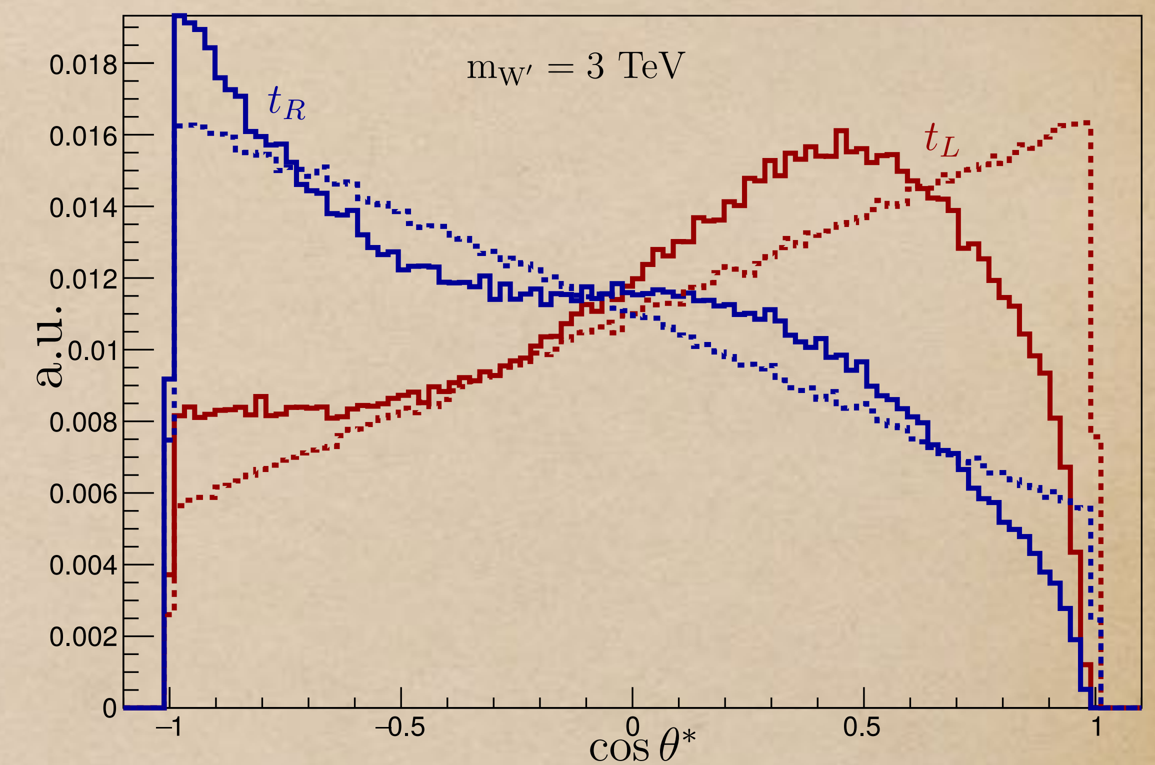
- Top quark from resonance decay, is boosted, lepton is not isolated $W' \rightarrow tb; m_{W'} \sim 1-3\ TeV$

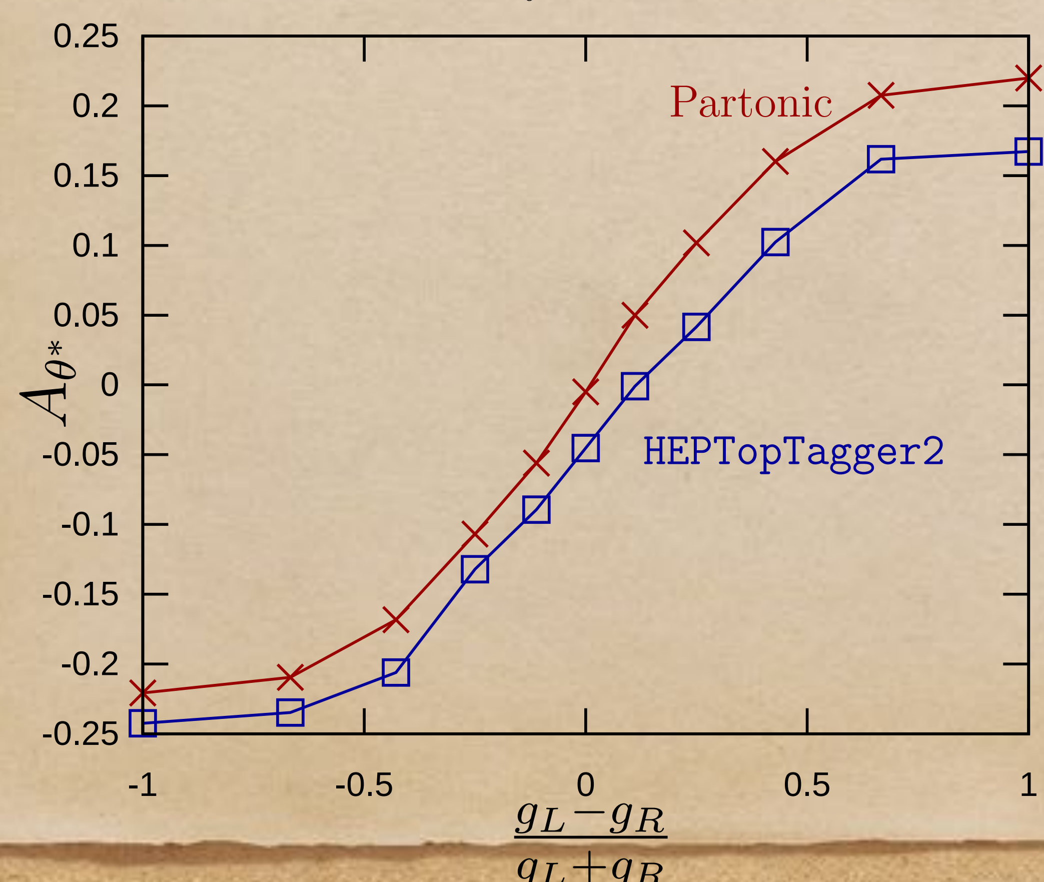
- t -> b q q, hadronic decay mode is considered, and subjets are identified, energy fractions, angular correlation are used to extract polarisation to identify left and right handed top quarks

Boosted top quark polarization

$$pp \to W' \to tb$$







Aravind H Vijay, R.Godbole, MG, J. Lahiri,
C. Kaur, S.Sharma
in progress

Summary

Understanding High pT jets are essential for NP searches

Various Techniques to tag High pT jets are discussed

Taggers validated using data

Techniques developed are used in the context of NP Searches, in particular parent mass reconstruction

Very busy area, use of ML

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Thank you