Dalian University

Searching for Heavy Charged Higgs with Jet Substructure

Based on JHEP02(2012)074 [arXiv:1111.4530 hep-ph]

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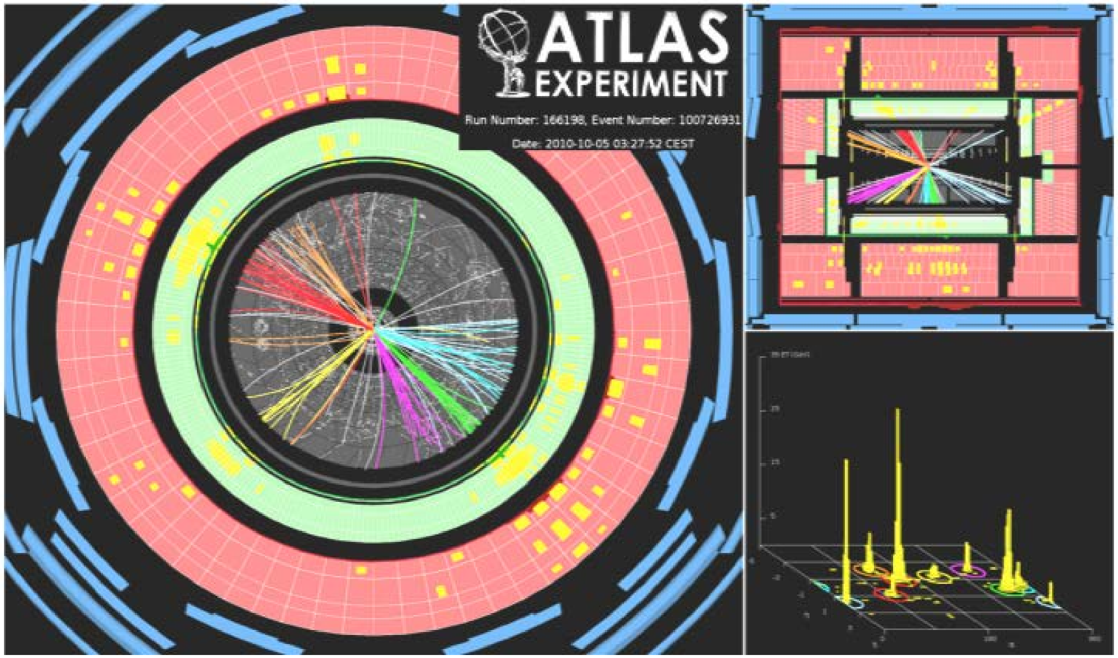
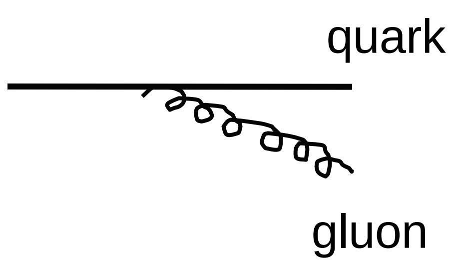
Workshop on Higgs and Beyond the Standard Model at the LHC
June 24~June 28 2013, ICTP, Trieste, Italy

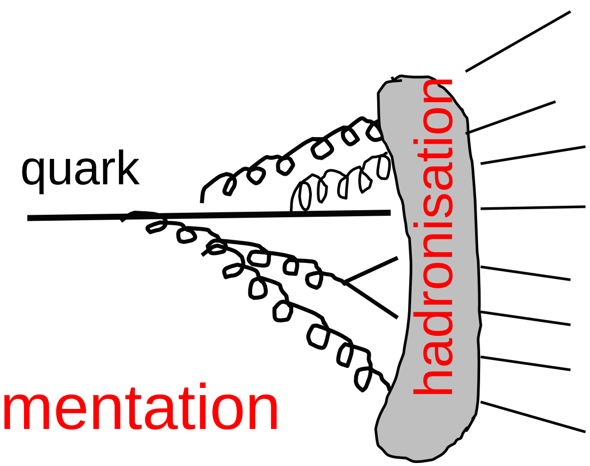
Outline

- Jet algorithm and Jet substructure
- Heavy charged Higgs search with jet substructure
- Summary

I. Jet Algorithms and Jet Substructure





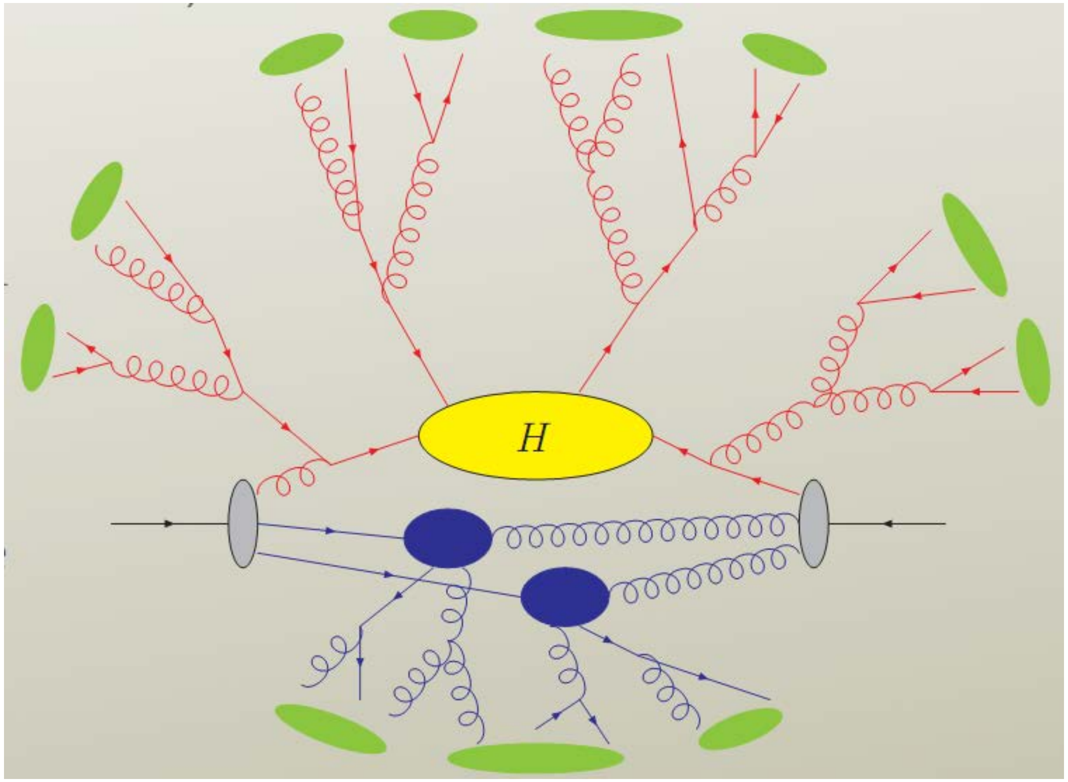


Why do we see jets? Parton fragmentation

Jet Definition

- Which?

- How?



Jet Algorithms

Cone Algorithm

UAI,JetCLU,SISCone….

Based on fixed geometry
Idea: Put cone along dominatant direction of flow direction

Recombination Algorithm

Jade,Kt, Cambrige-Aachen, Anti-Kt….

Idea: Undo branching

For a review, 0906.1833

1. Calculate the distance d_{ij} between all pairs of pseudo-jets and the beam distance d_{iB} for each pseudo-jet.
2. Find the minimum in the list of d_{ij} and d_{iB}.
3. If the minimum is d_{ij}, recombine i and j into a new particle and then return to step 1.
4. If it is d_{iB}, define it as a final-state jet and remove it from the jet list. Return to step 1.
5. Iterate this process until the original list is empty, i.e., all peudo-jets have been clustered to jets.

The d_{ij} and d_{iB} in most popular sequential recombine algorithms for use at the LHC can be parameterized as:

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

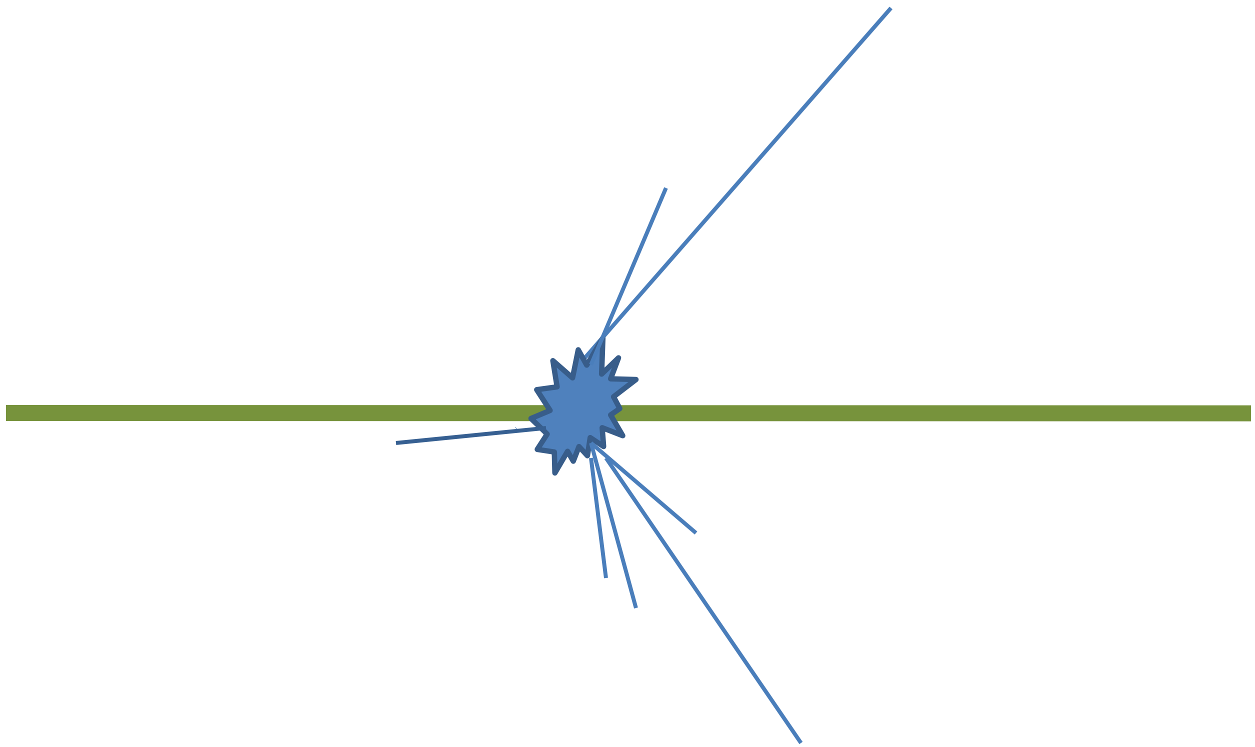
$$d_{iB} = p_{ti}^{2p},$$

P is a parameter, 1 for kt, -1 for anti-kt, 0 for CA

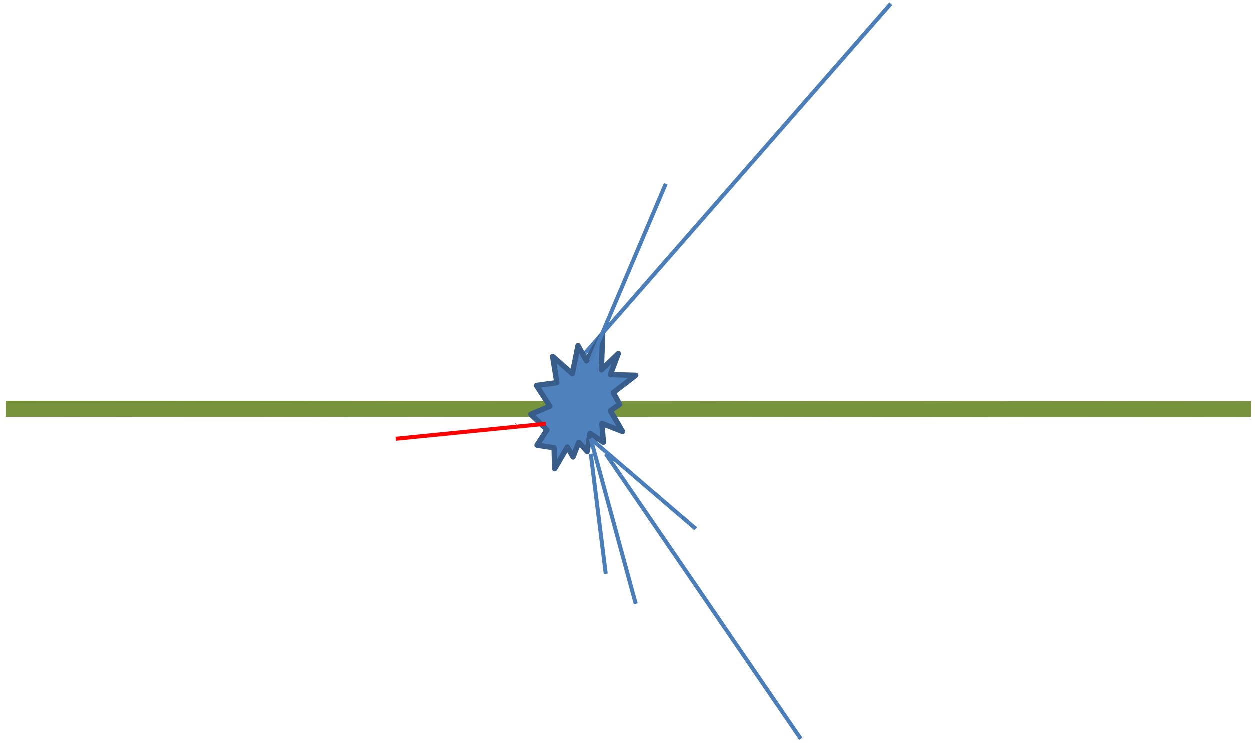
Remarks

- There is no standard jet algorithms. The jet algorithm and the parameters could be chosen flexibly.
- All these algorithms are infrared-safe and collinear safe.
- The anti-kt algorithms gets circular jets area which act much like an idealized cone-based algorithm, while the kt and CA get irregular jets area.
- The kt and CA algorithms incline to combine the harder pseudo-jets or pseudo-jets with a large separation in the later, so it is expected that the combination in the last step is the reverse of the main QCD branching or the 2-body decay of a massive particle. So decluster can be used in CA and kt in substructure study.

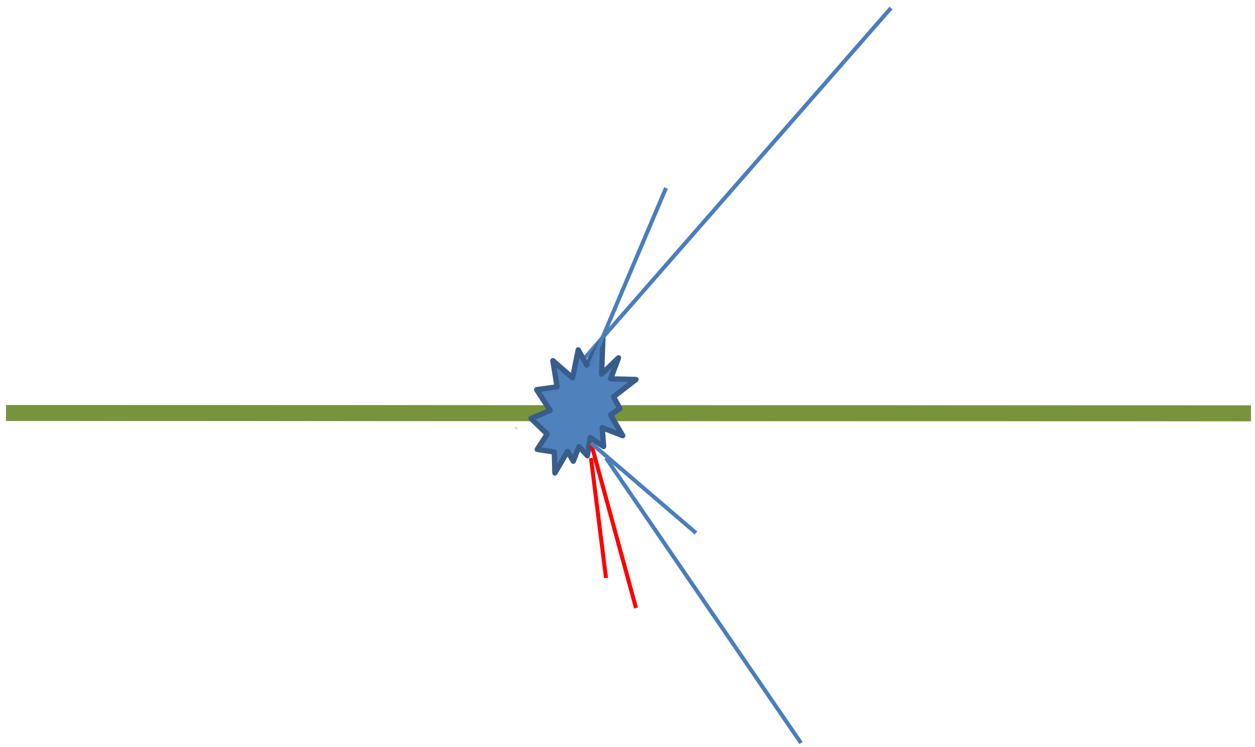
Cartoon for the Kt algorithm



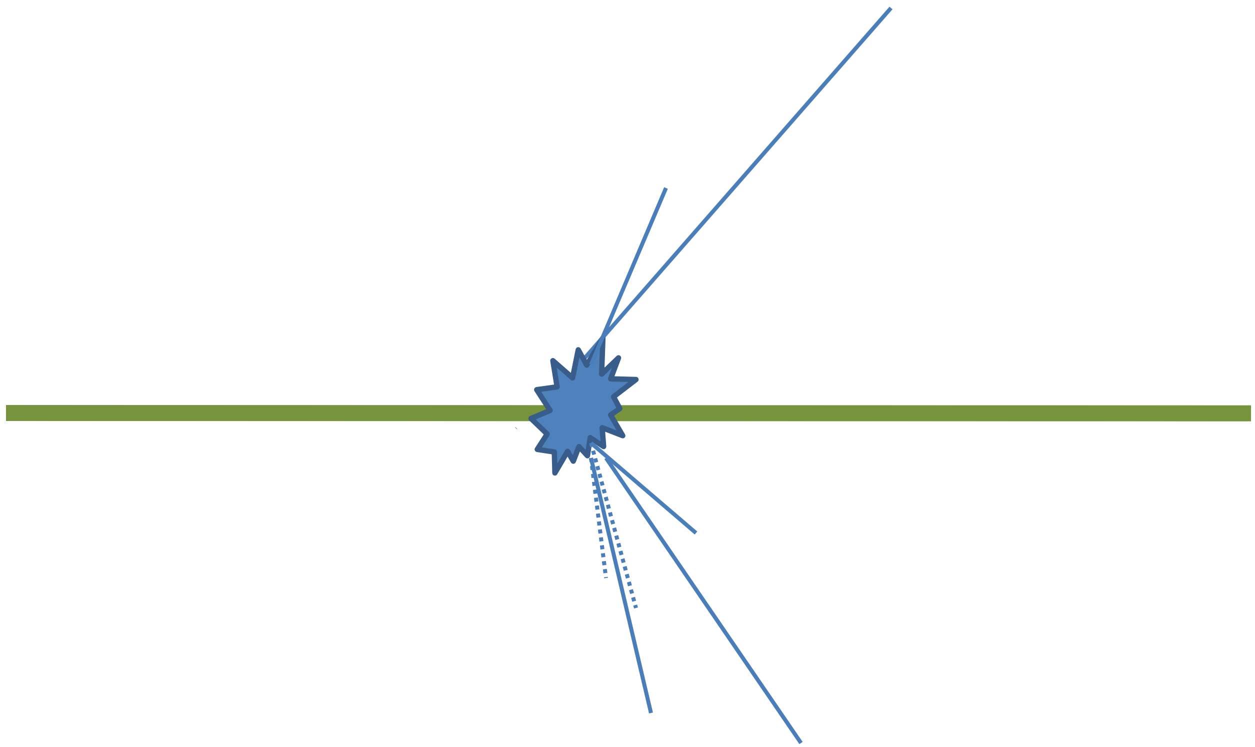
Cartoon for the Kt algorithm



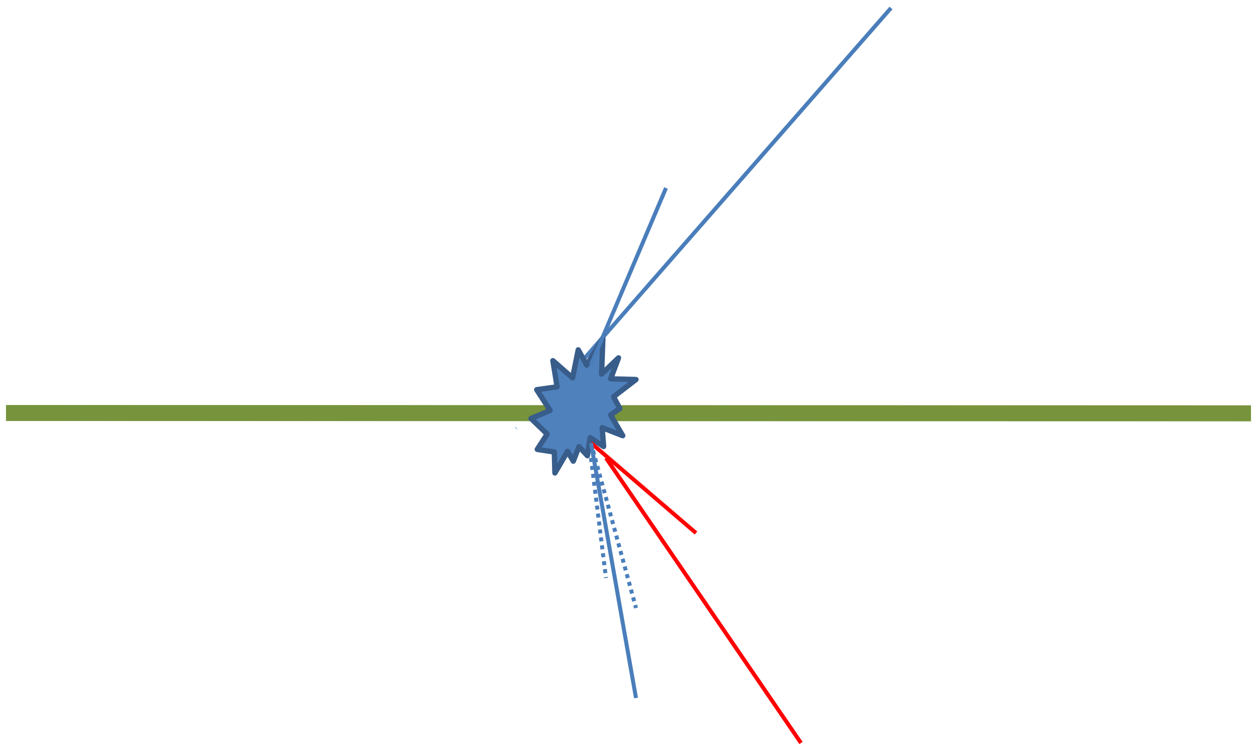
Cartoon for the Kt algorithm



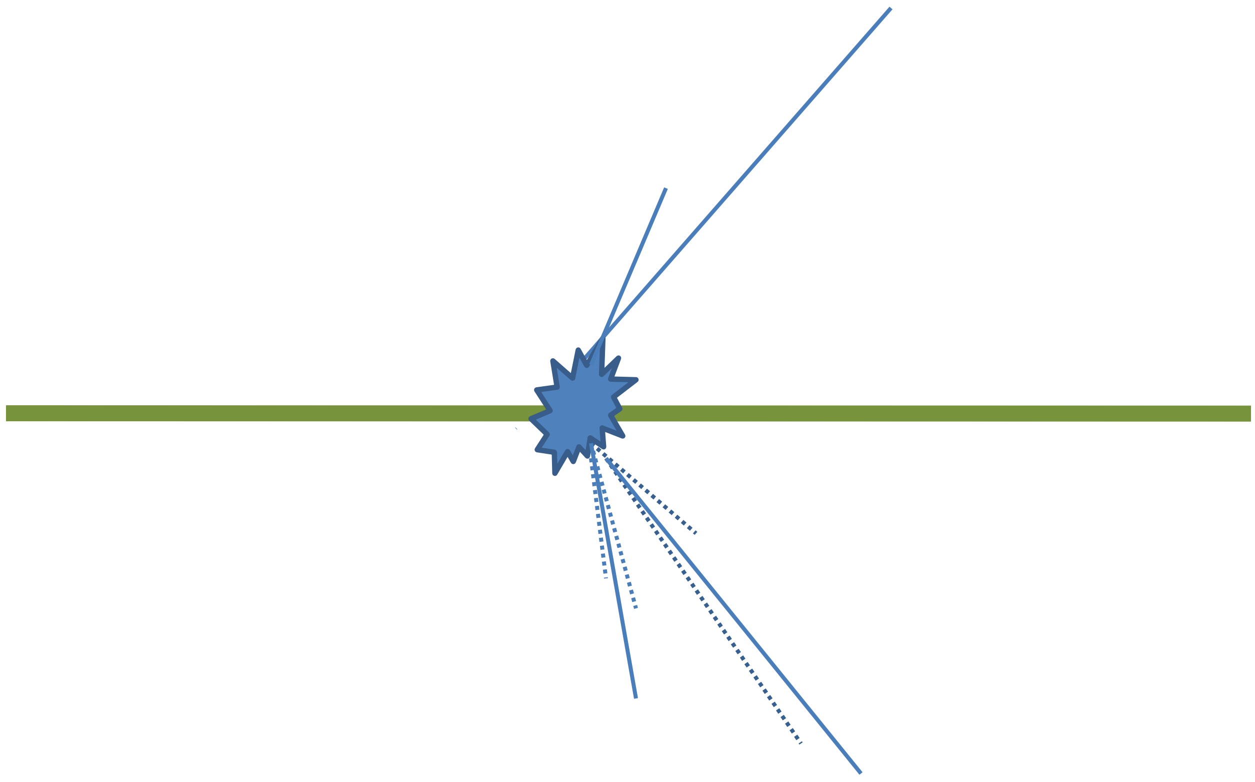
Cartoon for the Kt algorithm



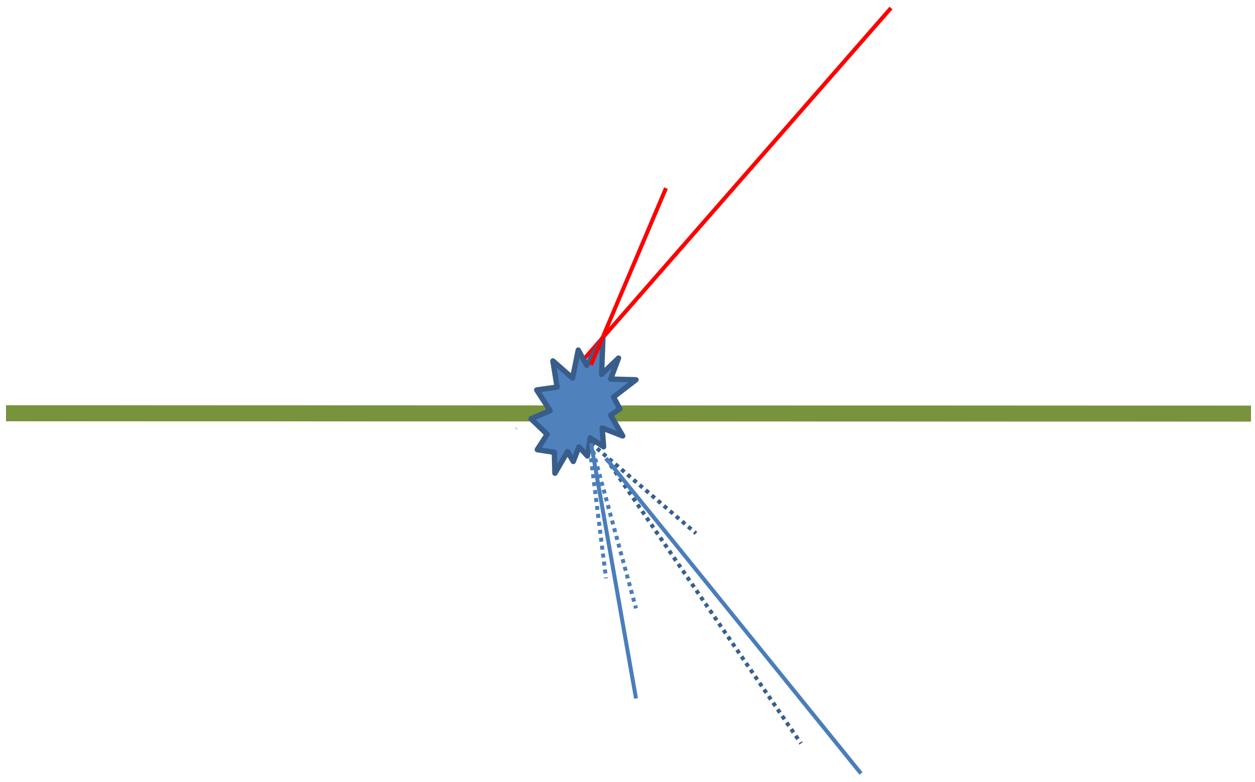
Cartoon for the Kt algorithm



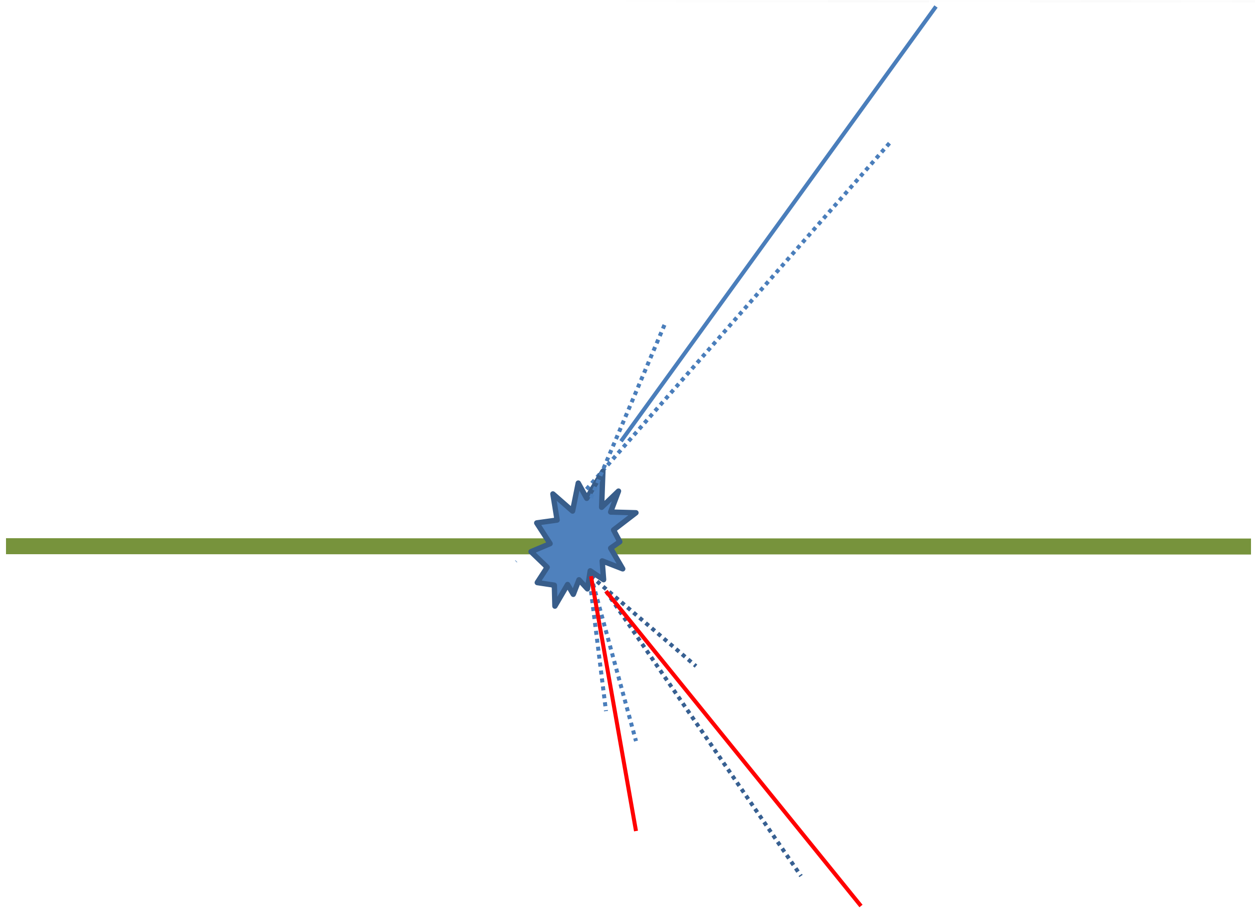
Cartoon for the Kt algorithm



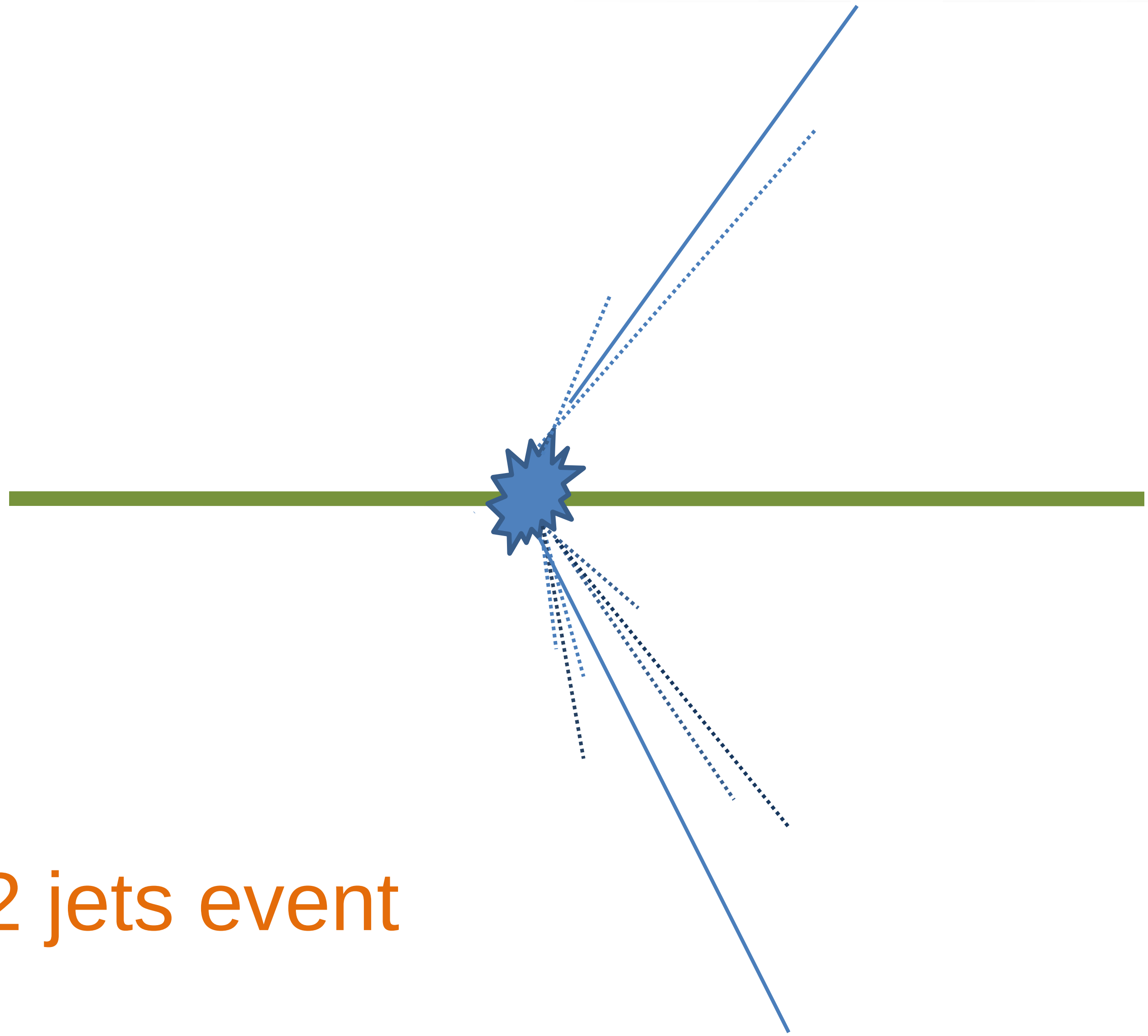
Cartoon for the Kt algorithm



Cartoon for the Kt algorithm



Cartoon for the Kt algorithm

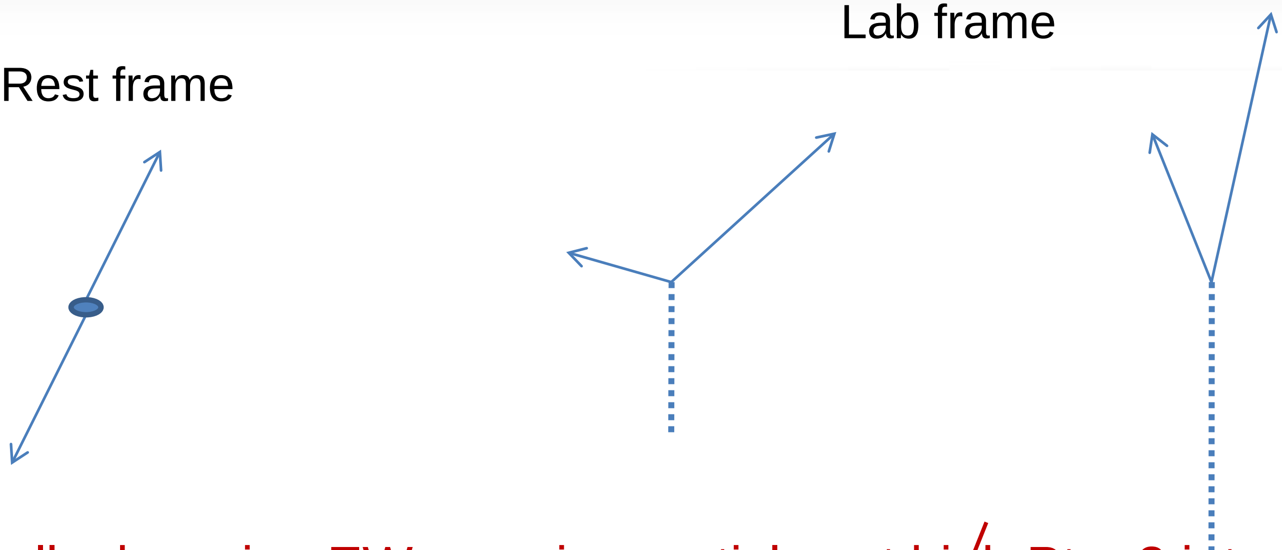


A 2 jets event

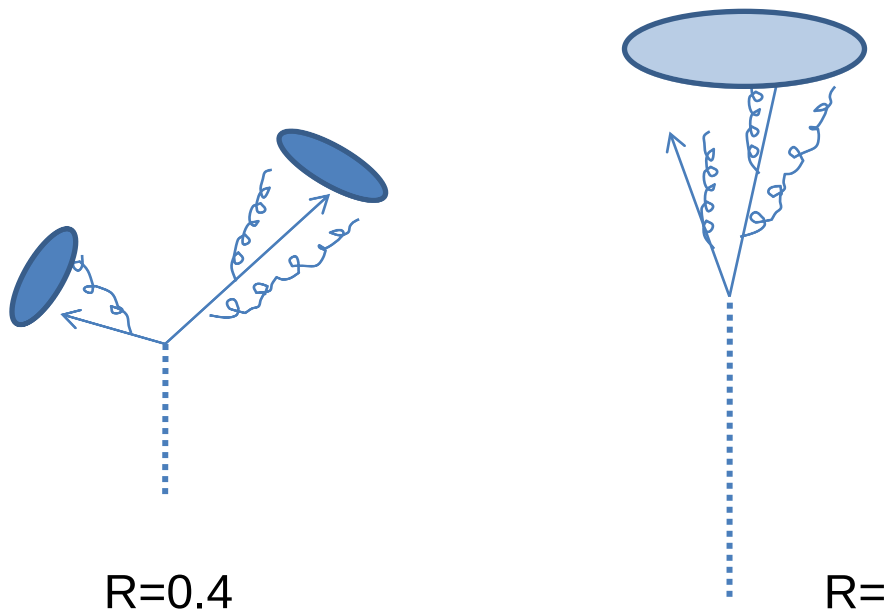
Boosted Massive Particles

Lab frame

Rest frame



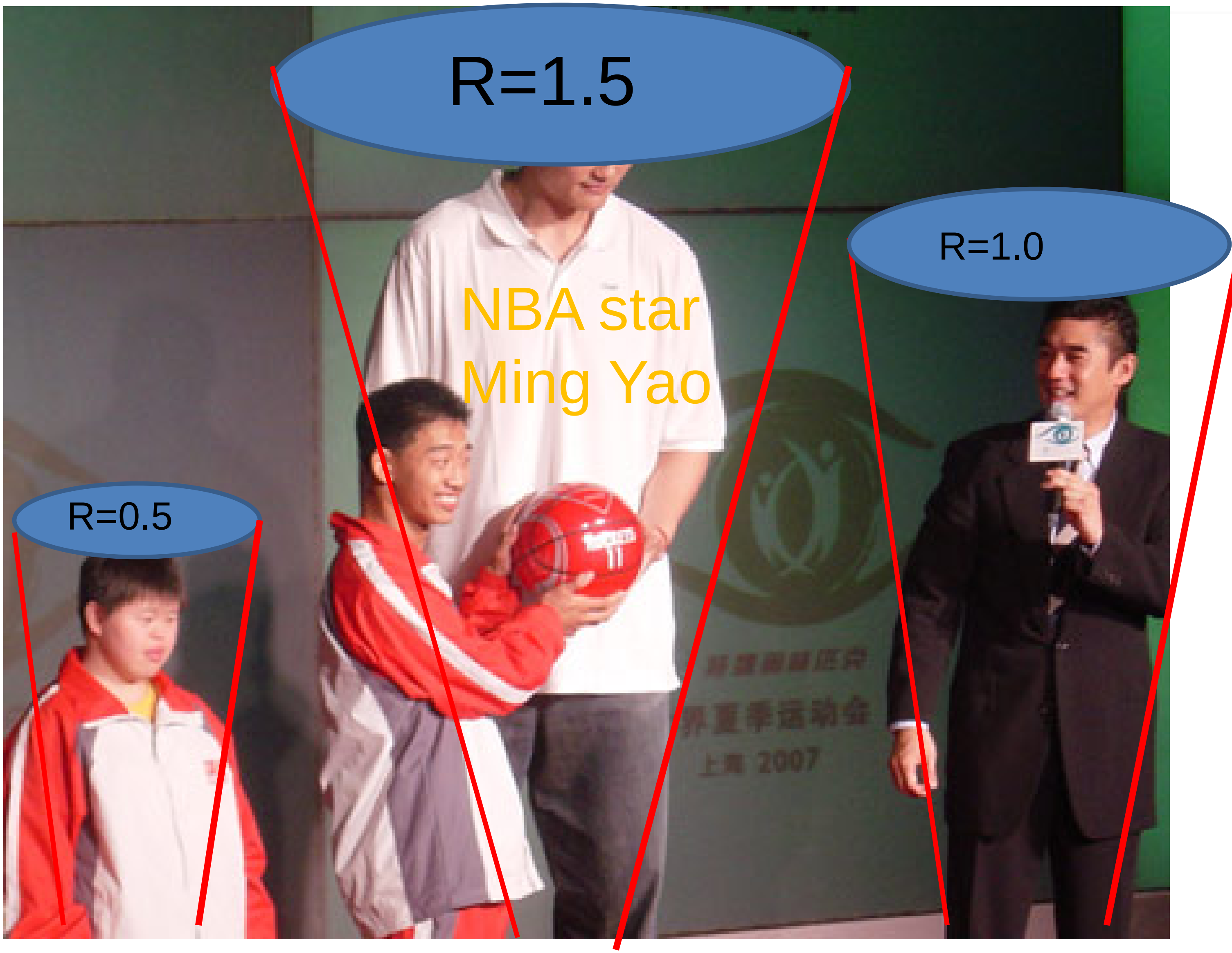
Hadronically decaying EW massive particles at high Pt = 2 jets



R=0.4

R=0.7

Cone size



Fat Jet

- Cone size should be chosen flexibly for physical intention.
- Boosted massive hadronically decaying objects is common at the LHC. M_Z/TeV
- Fat jet is useful to capture hadronical decay of the highly boosted massive particle. *W*, *H*, *t*
- Generally, mass discriminator is not enough!

In order to separate signal, one have to anatomize the Jet Substructure and reconstruct delicate kinematical variables on subjets !

Brief history of Jet Substructure

- Michael H. Seymour *Searches for new particles using cone and cluster jet algorithms: A Comparative study*, Jun 1993, Z. Phys. C62(1994) 127-138
- Butterworth, Cox, Forshaw, Jan 2002 *WW scattering at the CERN LHC*, Phys. Rev. D65 (2002) 096014
- Butterworth, Davison, Rubin, Salam, Feb 2008, *Jet substructure as new Higgs search channel at the LHC*, Phys.Rev.Lett.100(2008) 242001.
- Kaplan, Rehermann, Schwartz and Tweedie, ``*Top Tagging: A Method for Identifying Boosted Hadronically Decaying Top Quarks,''* Phys. Rev. Lett.101(2008) 142001
- Grooming： Filtering ,Trimming, Pruning ,
- Higgs–tagger, top-tagger, W-tagger …..
- Jet shape ……

………………

For a review, 1201.0008

JH Top Tagger

1. Four momenta of particles is clustered with a large cone size R (CA algorithm are used in original paper)

2. The last cluster is undone to get two objects j_1 and j_2. If the p_T ratio of the softer jet j_2 over the original jet j is too small, i.e., $p_{T_{j_2}}/p_{T_j} < \delta_p$, throw the softer j_2 and go on to decluster on the harder one.

3. The declustering step is repeated until two separated hard objects are found. If any criterion below are satisfied, the event is failed: 1) both objects are softer than δ_p

   (2) the two objects are too close, $\Delta\eta + \Delta\phi < \delta_r$ (3)the original jet is considered irreducible.

4. Declustering repeatedly on these two subjets will result in 2,3, or 4 hard objects.

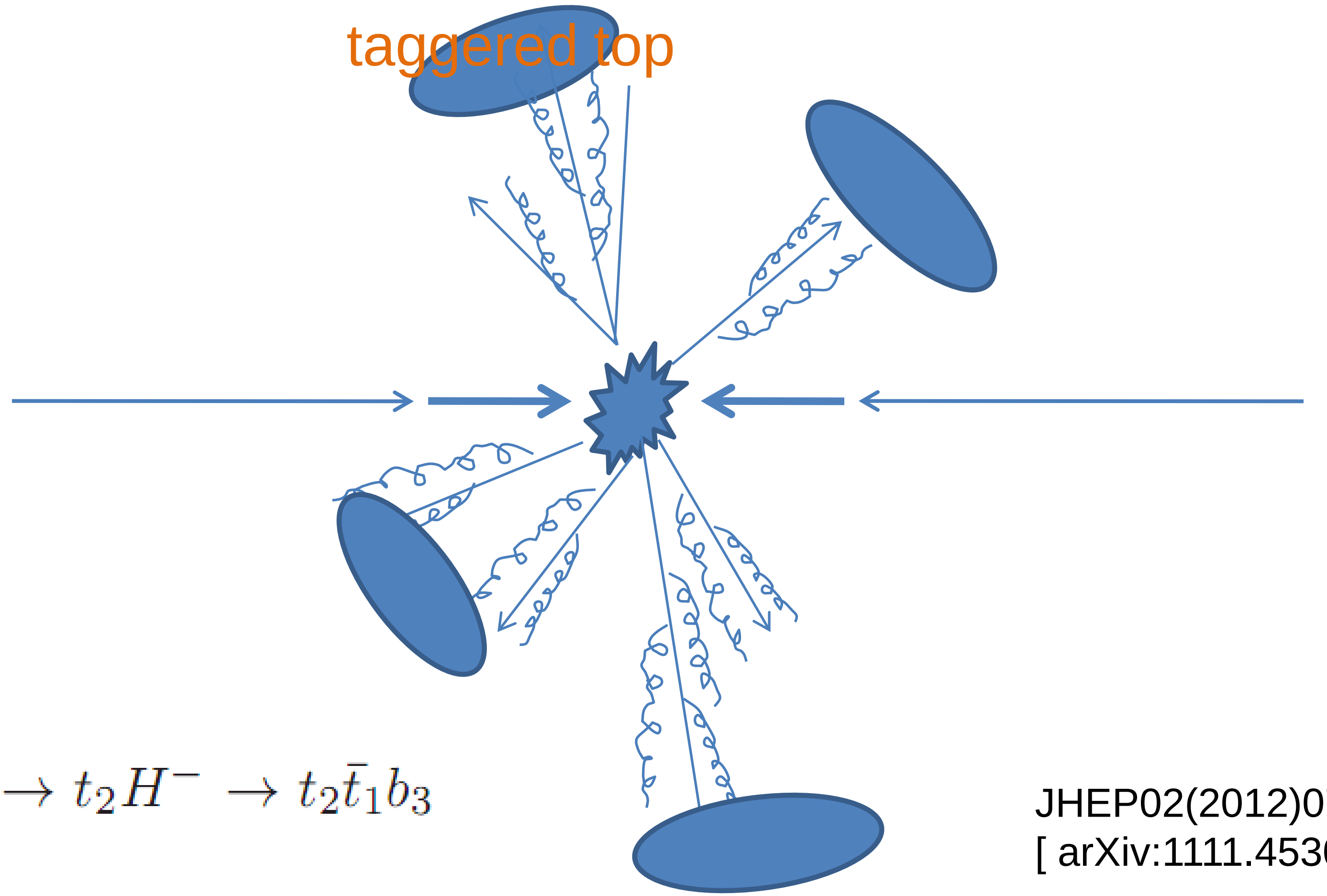
5. The case with 3 or 4 subjets are kept. And then require the these subjets that the total mass should be near m_t, the mass of two subjets should be in the m_W window, W helicity angle θ_t should be consistent with a top decay[2].

The parameters involved in the method can be optimized event by event [12]. In our study, these parameters are fixed as below:

$$\delta_p = 0.19 \qquad \delta_r = 0.1 \qquad |\theta_t| < 0.65\ . \tag{2.3}$$

II. Heavy charged Higgs search with jet substructure

We study the full hadronic decay mode of heavy charged Higgs. It is the first study along this line.



$$pp \to gb \to t_2 H^- \to t_2 \bar{t}_1 b_3$$

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[arXiv:1111.4530]

Hybrid-R Reconstruction Method

1. CA jet algorithm with a large cone and top tagger to capture the highly boosted top t_1. Form a jet list J_0 .
2. Recluster the pseudo-jets in the event with a small cone (anti-kt R=0.4) and then get a new jet list L_0 .
3. If a small-size jet is within the larger cone of the direction of the tagged top jet, remove it and then form a new jet list L_1 .
4. We identify the most energetic jet in L_1 as the b_3 jet. The unused jets in the jet list form L_2 .
5. We require there are at lest 3 jets in the list L_2. Reconstruct the second top and W by $\chi^2 = \frac{|m(j_1,j_2)-m_W^{\mathrm{PDG}}|^2}{\sigma_W^2} + \frac{|m(j_1,j_2,j_3)-m_t^{\mathrm{PDG}}|^2}{\sigma_t^2}$

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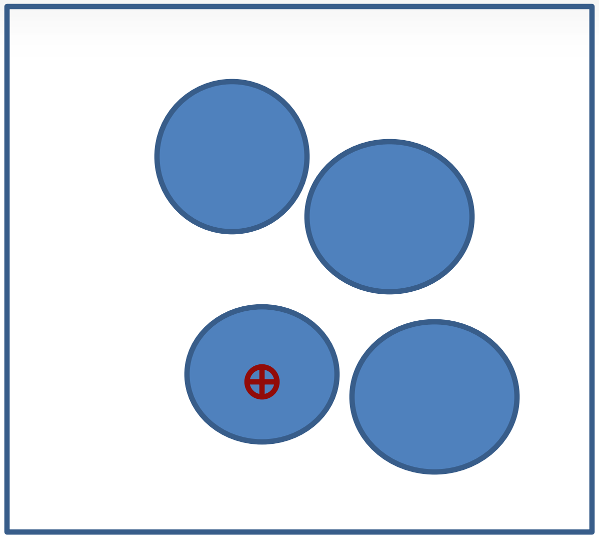
1



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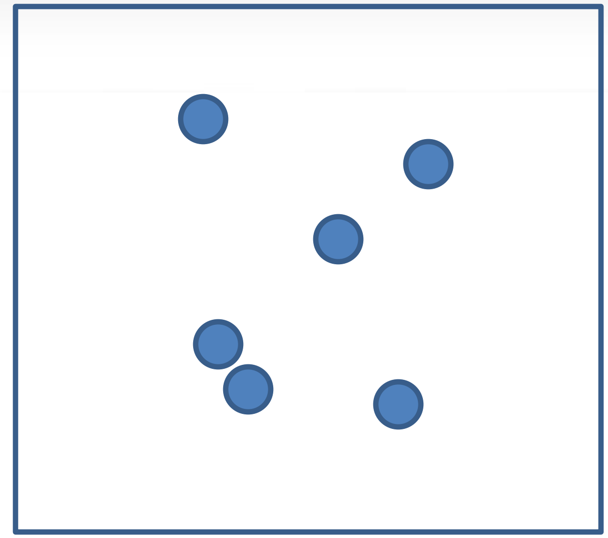

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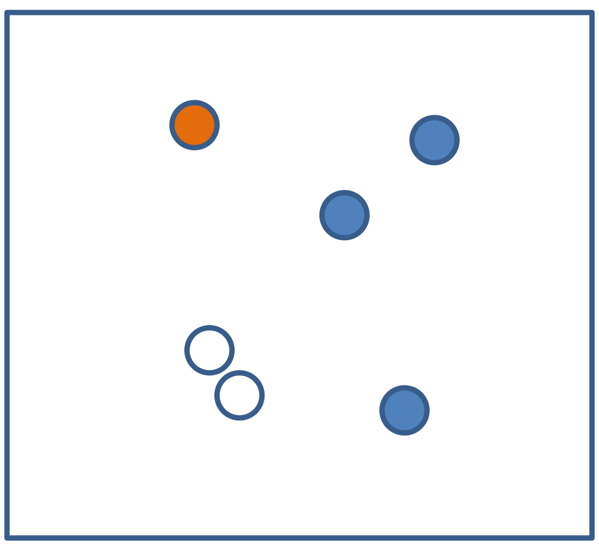

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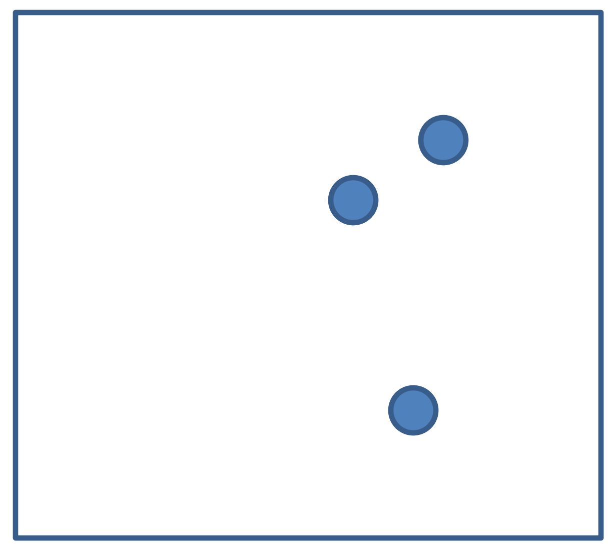


Parton level supports

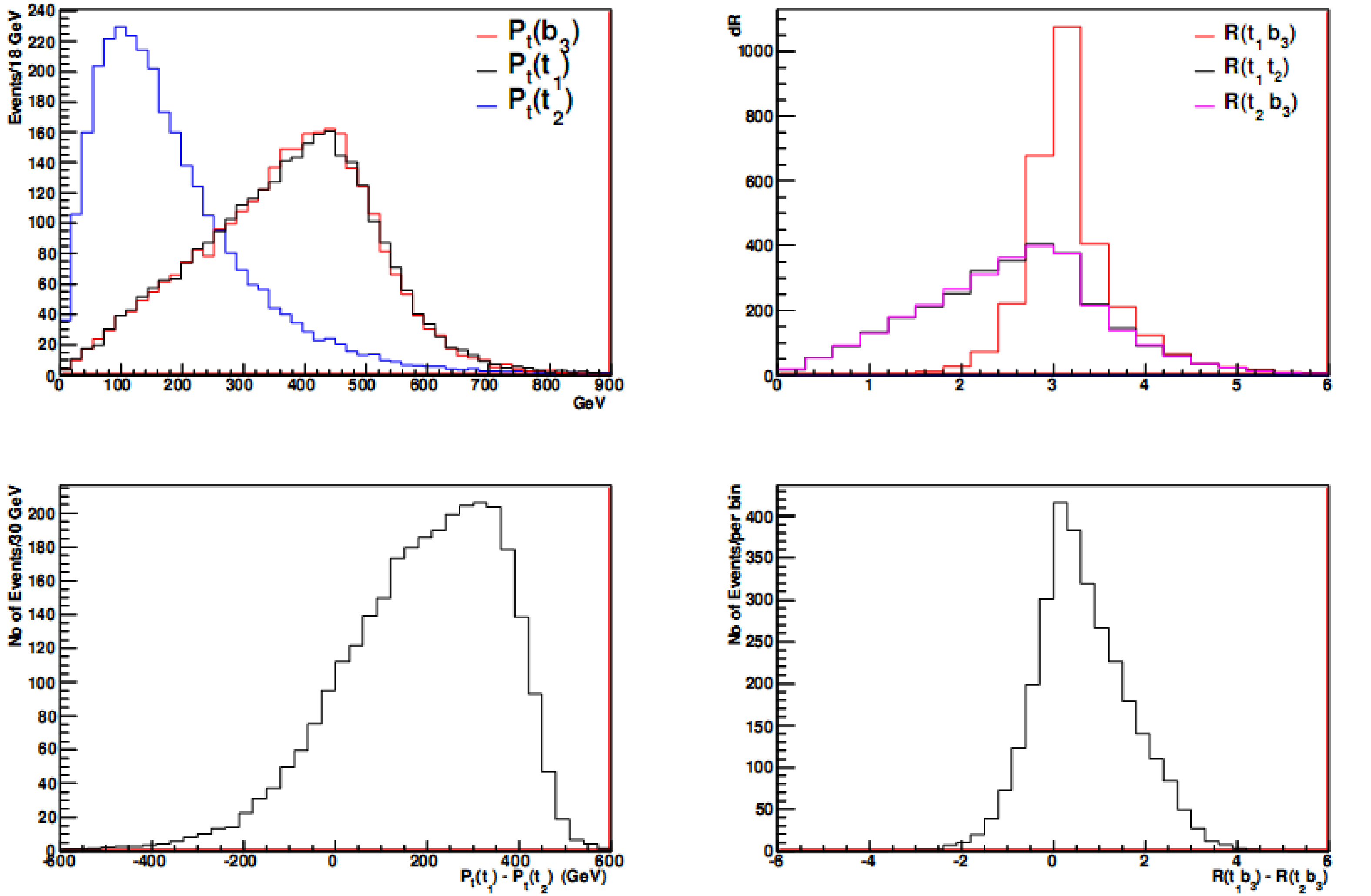


Figure 1: The transverse momenta and the angle separation are exposed at parton level with $m_{h^\pm} = 1.0$TeV. The transverse momentum difference between t_1 and t_2 and the angle separation difference between $R(t_1 b_3)$ and $R(t_2 b_3)$ are also shown.

R size vs. mass distribution

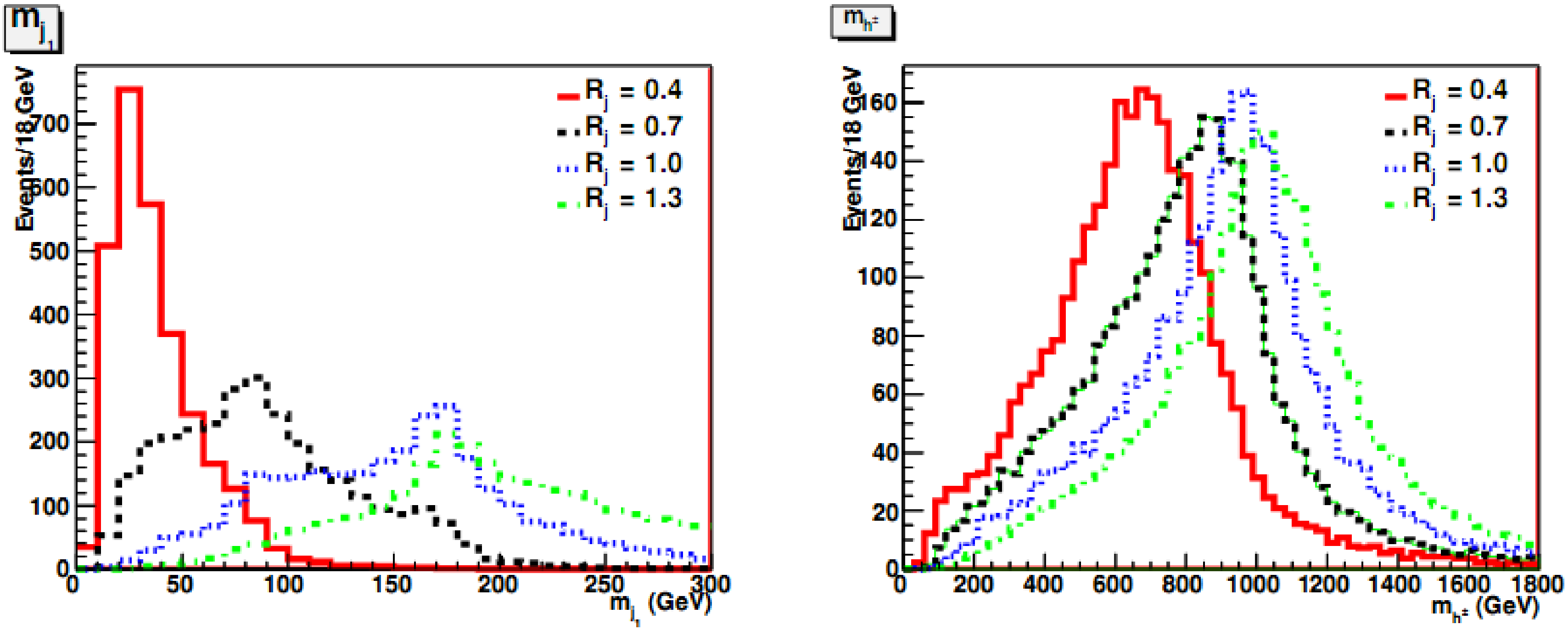


Figure 2: The mass distribution of the leading massive jet and the reconstructed charged Higgs boson mass are shown with the case $m_{h^\pm} = 1\text{TeV}$. The dependence on the angle separation parameter R in the anti-k_t algorithm is also exposed. To be more realistic, the detector effects have been taken into account by using PGS4.

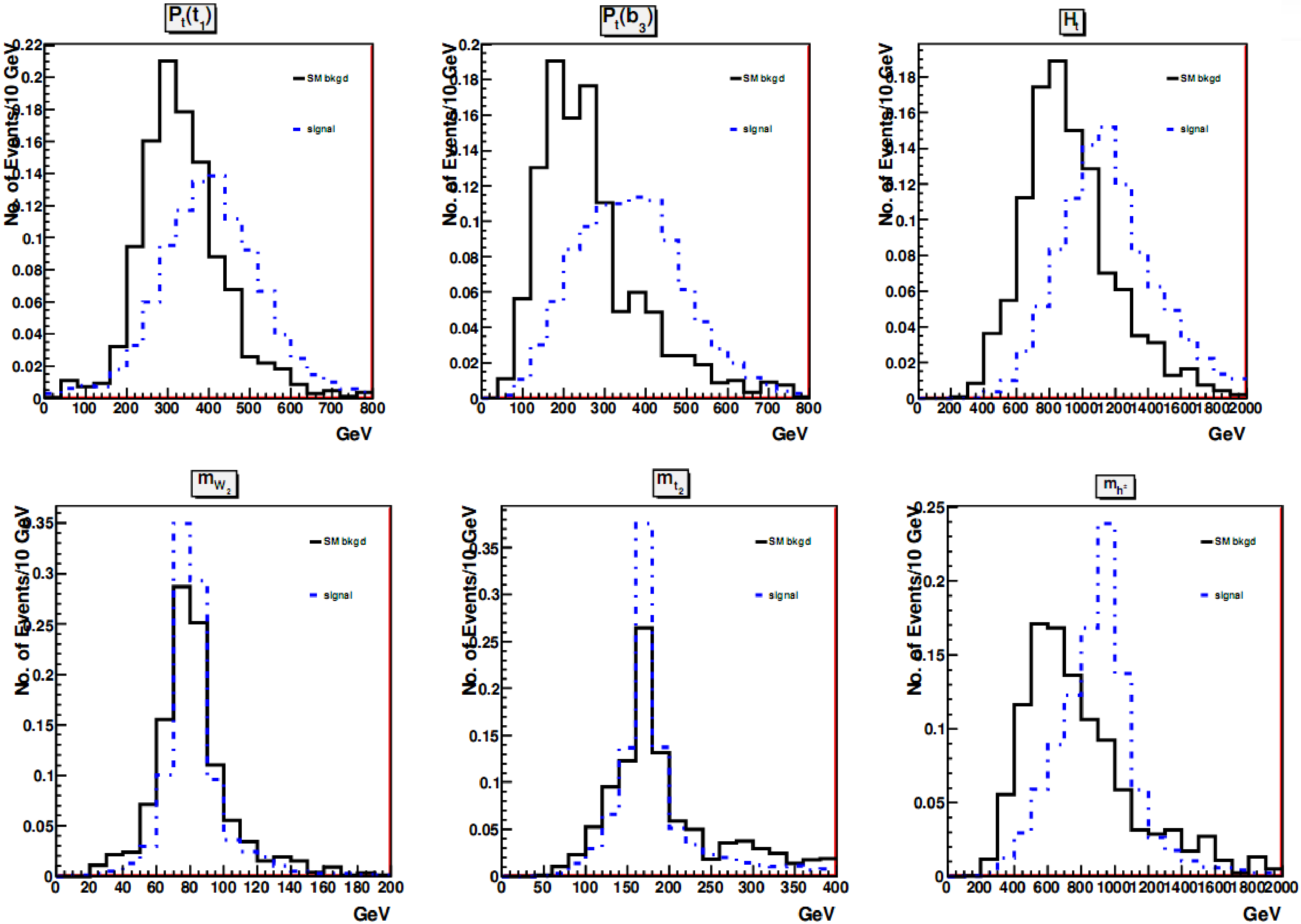
R	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
k_t algorithm	16%	22%	25%	28%	29%	29%	28%	27%
CA algorithm	13%	19%	24%	27%	29%	30%	30%	30%

Table 1: The efficiency of top tagger in k_t and CA algorithms along with the variation of angle separation parameter R are tabulated. The charged Higgs boson mass is assumed to be 1.0 TeV.

R	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
k_t algorithm	25%	27%	28%	28%	27%	26%	24%	22%
CA algorithm	23%	27%	29%	30%	30%	30%	30%	29%

Table 2: The efficiency of top tagger in k_t and CA algorithms along with the variation of angle separation parameter R are tabulated. The charged Higgs boson mass is assumed to be 1.5 TeV.

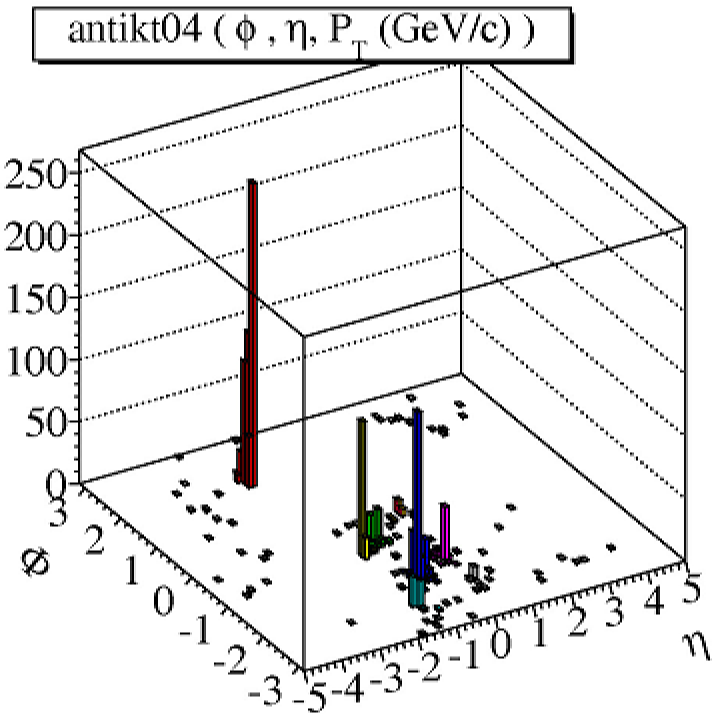
Analysis Results

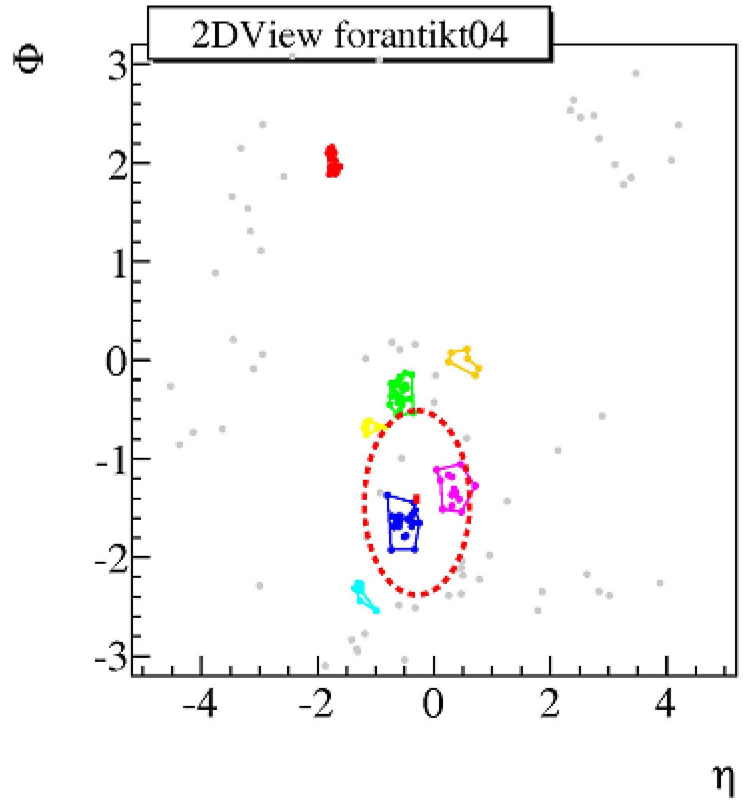


	signal $m_{h^\pm} = 1$ TeV	$t\bar{t}$ + jets	QCD $n_j \geq 4$
Cross Section x Br (pb)	0.053	553	9186.8
After JH tagger & $H_T > 400$GeV	29%	7%	4.8×10^{-3}
Two b-taggings	10%	4.2×10^{-4}	4.8×10^{-7}
The number of jets in jet list L_0, $n_j \geq 6$	10%	3.7×10^{-4}	3.4×10^{-7}
$H_T > 700$GeV & $C > 0.3$	9.6%	2.1×10^{-4}	3.0×10^{-7}
The leading jet $E(j_1) > 350$GeV	8.9%	1.6×10^{-4}	2.5×10^{-7}
The second leading jet $E(j_2) > 250$GeV	7.9%	1.3×10^{-4}	2.2×10^{-7}
$p_T(b_3) > 300$ GeV & $p_T(t_1) > 300$ GeV	5.3%	4.5×10^{-5}	7.7×10^{-8}
$\lvert m_{W_2} - m_W^{\mathrm{PDG}} \rvert < 20$ GeV & $\lvert m_{t_2} - m_t^{\mathrm{PDG}} \rvert < 30$ GeV	3.1%	2.6×10^{-5}	2.3×10^{-8}
$\lvert m_{h^\pm} - m_{h^\pm}^{\mathrm{assumed}} \rvert < 200$ GeV	2.5%	1.5×10^{-5}	1.5×10^{-8}
Events in 100 fb^{-1}	133	830	13.8

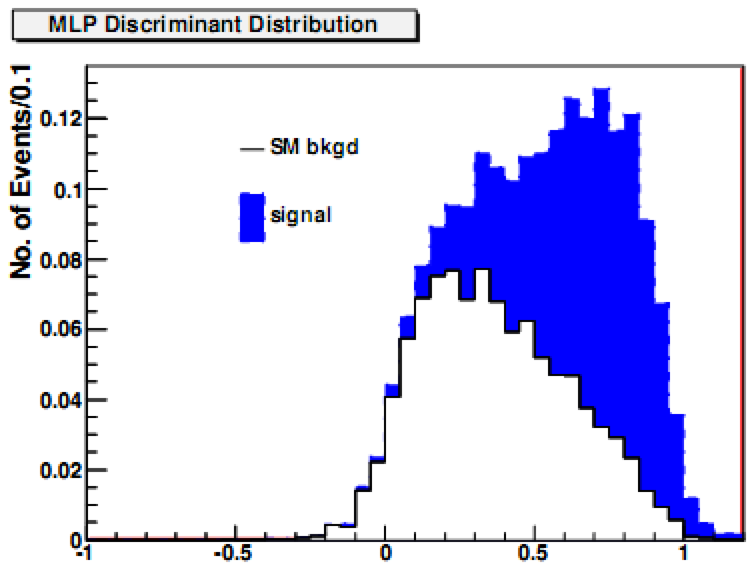
	signal $m_{\pm} = 1.5$ TeV	$t\bar{t}$ + jets	QCD $n_j \geq 4$
Cross Section x Br (pb)	0.007	553	9186.8
After JH tagger & $H_T > 400$GeV	29%	3%	3.3×10^{-3}
Two b-taggings	10%	1.8×10^{-4}	3.3×10^{-7}
The number of jets in jet list L_0, $n_j \geq 6$	9.3%	1.7×10^{-4}	2.5×10^{-7}
$H_T > 1050$GeV& $C > 0.3$	8.3%	5.5×10^{-5}	8.9×10^{-8}
The leading jet $E(j_1) > 525$GeV	7.7%	4.4×10^{-5}	7.3×10^{-8}
The second leading jet $E(j_2) > 375$GeV	6.8%	3.4×10^{-5}	5.4×10^{-8}
$p_T(b_3) > 450$ GeV & $p_T(t_1) > 450$ GeV	4.4%	9.2×10^{-6}	8.5×10^{-9}
$\lvert m_{W_2} - m_W^{\rm PDG}\rvert < 20$ GeV $\lvert m_{t_2} - m_t^{\rm PDG}\rvert < 30$ GeV	2.5%	4.6×10^{-6}	4.3×10^{-9}
$\lvert m_{h^\pm} - m_{h^\pm}^{\rm assumed}\rvert < 200$ GeV	1.8%	1.9×10^{-6}	1.8×10^{-10}
Events in 100 fb^{-1}	13	105	0.2

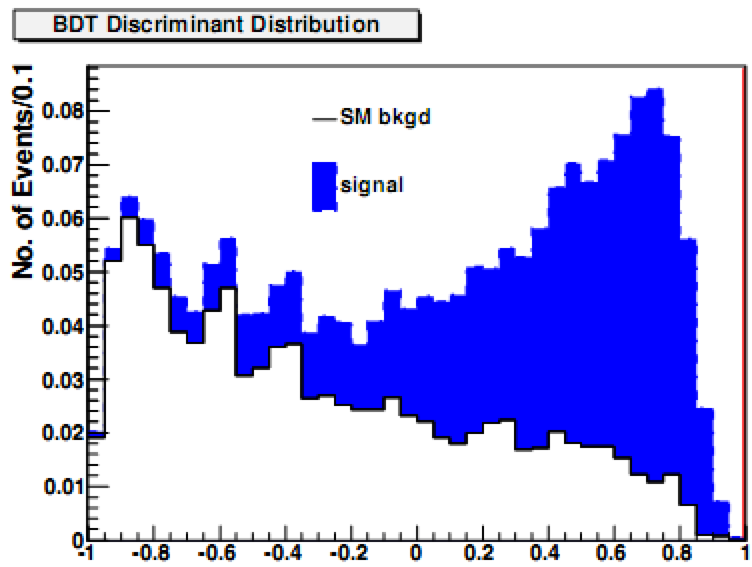
One typical signal event

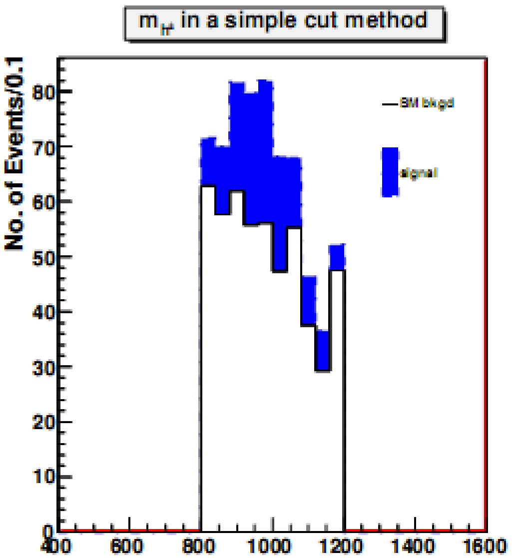


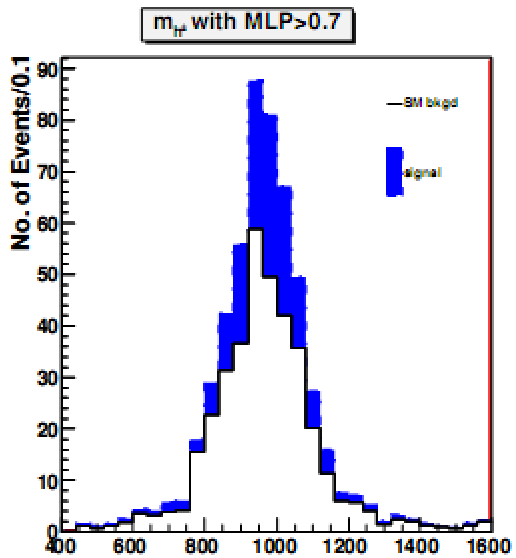


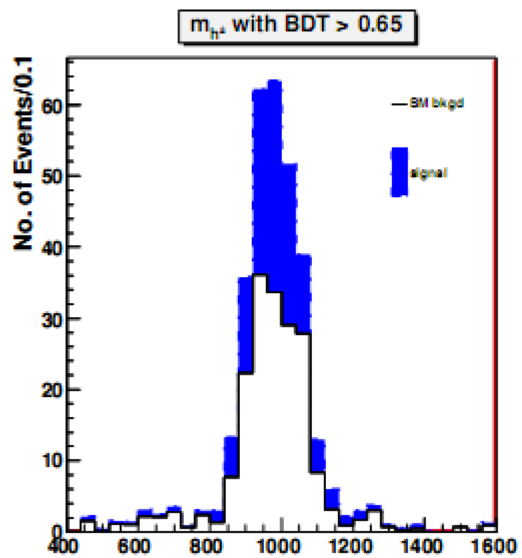
	signal $m_{\pm} = 1.0$ TeV	$t\bar{t}$ + jets	QCD $n_j \geq 4$
After simple cuts	2.5%	1.5×10^{-5}	1.5×10^{-8}
After NN cut ($NN > 0.6$)	5.5%	2.0×10^{-5}	3.0×10^{-8}
After BDT cut ($BDT > 0.5$)	5.7%	2.1×10^{-5}	3.2×10^{-8}



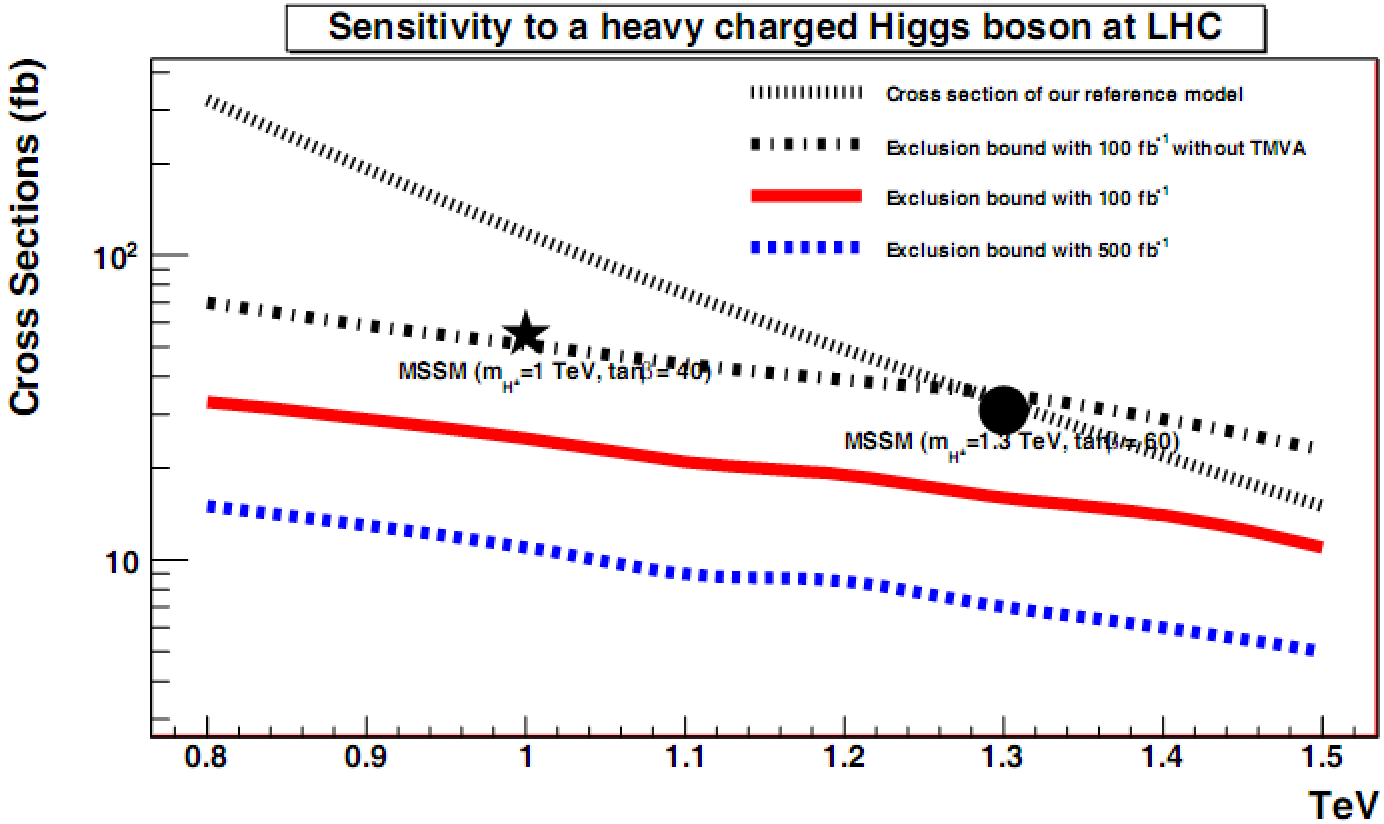



$m_{H^\pm}$ in a simple cut method
No. of Events/0.1
SM bkgd
signal


$m_{H^\pm}$ with MLP>0.7
No. of Events/0.1
SM bkgd
signal


$m_{H^\pm}$ with BDT > 0.65
No. of Events/0.1
SM bkgd
signal

$m_{H^\pm}$ (TeV)	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
σ (fb)	324	192	118	75	49	33	22	15
$\frac{S}{\sqrt{B}}$ (with two b taggings & TMVA)	19.4	13.3	9.5	7.0	5.1	4.0	3.1	2.6
lower bound on σ (fb)	33	29	25	21	19	16	14	11
$\frac{S}{\sqrt{B}}$ (with two b taggings without TMVA)	9.3	6.5	4.6	3.4	2.5	1.9	1.5	1.3
lower bound on σ (fb)	70	59	51	44	39	35	29	23



IV Summary

- Jet Substructure is helpful to identify highly boosted massive particles or to tell the jet origin.
- We proposed a hybrid-R method with top-tagger. By studying the full hadronic mode of $pp \to H^{\pm}t \to ttb$, we find that this method can greatly reduce the combinatorics and can successfully reduce background down to a controlled level.
- The sensitivity of LHC to the heavy charged Higgs is also studied.


Thank You!

Backup

- Theory: Two Higgs Doublet Model

Five physical Higgs particles A, h, H, $H^{\pm}$

- Charged Higgs Search:

1. For $m_{H^{\pm}} < m_t$, search for $t \to H^+ b$ in top pair decay. Tevatron set a limit for charged Higgs mass up to ~ 160.

2. At LHC, the main production mechanism $gb \to tH^-$.

Previous studies for charged Higgs search mainly focus on

$$gb \to tH^- \to t\tau\bar{\nu}$$

$$gb \to tH^- \to t\bar{t}b \to bqq\tau(had)\nu bb$$

$$gb \to tH^- \to t\bar{t}b \to bqqbl\nu b$$

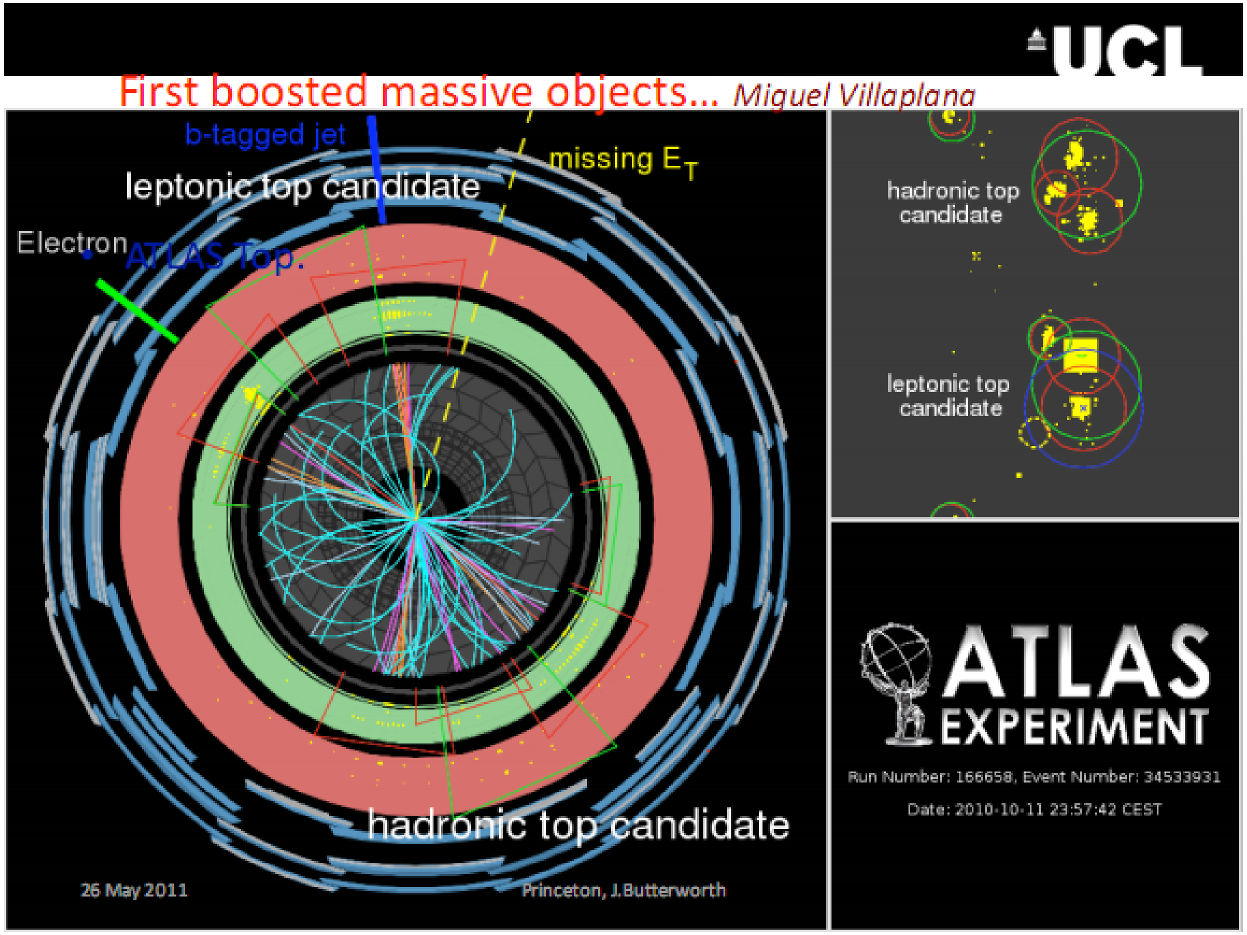
- Detector acceptance cuts are chosen as $p_T(j) > 20$ GeV, $|\eta|(j) < 2.5$.
- A cut on the number of jets in the jet list L_0, $n_j \geq 6$.
- A cut on the H_T, $H_T > \frac{7}{10} M_{H^\pm}$, and the centrality, $C > 0.3$.
- A cut on the leading energetic jet in the jet list L_0, $E(j_1) > \frac{7}{20} M_{H^\pm}$.
- A cut on the second leading energetic jet in the jet list L_0, $E(j_1) > \frac{1}{4} M_{H^\pm}$.

- A large p_T requirement on t_1 jet captured by the top-tagger and on the supposed b_3 in hybrid-R reconstruction method, i.e. $p_T(b_3) > \frac{3}{10} M_{H^\pm}$ and $p_T(t_1) > \frac{3}{10} M_{H^\pm}$.
- Cuts are chosen for the mass bumps in the t_2 reconstruction, i.e., $|m_{W_2} - m_W^{\rm PDG}| < 20$ GeV and $|m_{t_2} - m_t^{\rm PDG}| < 30 GeV$.
- The charged Higgs boson mass window is chosen as $|m_{h^\pm} - m_{h^\pm}^{\rm assumed}| < 200$ GeV.

Refine the jet resolution

- Filtering: break jet into subjets on angular scale R_{filt}, take n filtered hardest subjets.
- Trimming: break jet into subjets on angular scale R_{trim}, take all subjets with $P_{t,sub}>\varepsilon P_{t,jet}$
- Pruning: If the subjets about to be recombined have $\Delta R>R_{prune}$ and $\min(P_{t1},P_{t2})< \varepsilon(P_{t1}+P_{t2})$, discard the softer one.

There are many boosted massive objects at the LHC, which inspire the study of jet substructure.



small cone vs. large cone

perturbative fragmentation 

non-perturbative fragmentation 

underlying event & pile up 

multi-hard-parton 

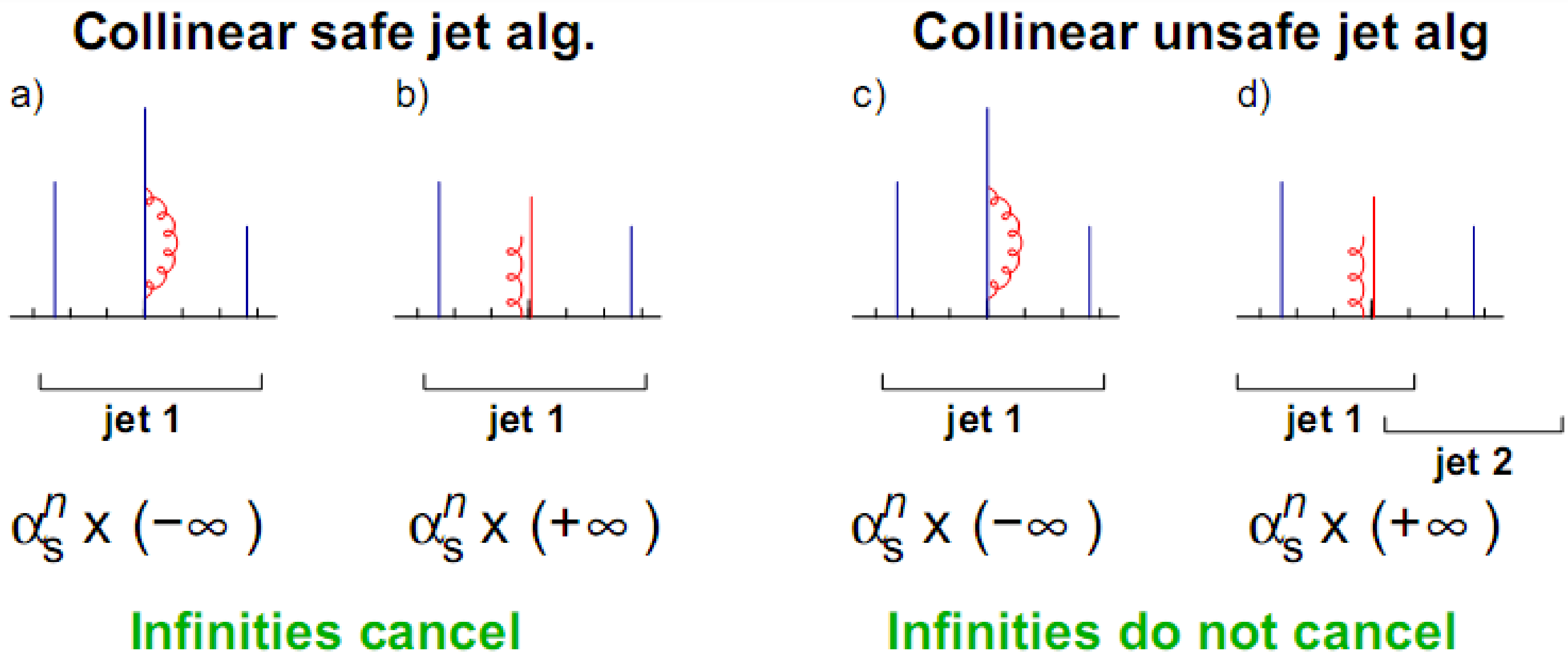


Illustration for collinear safety (left) and collinear unsafety in an IC-PR algorithm(right)