Jet Substructure and the Search for Z′ -> Zh/WW

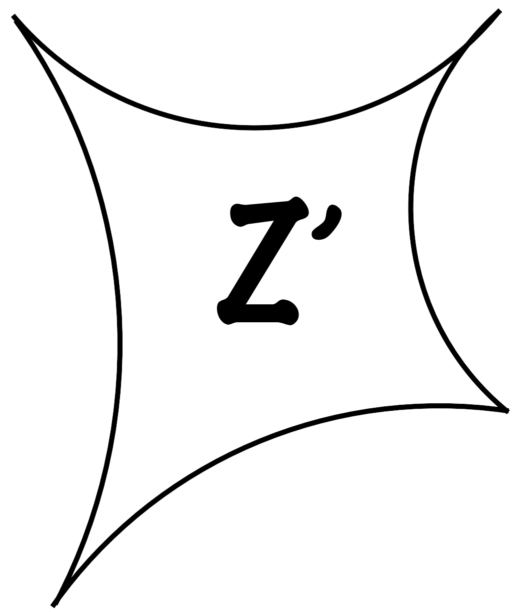
Minho Son
Yale University

w/ Andrey Katz and Brock Tweedie
- arXiv:1010.5253, arXiv:1011.4523, in progress

Z' is a strong contender for New Physics

Weakly coupled Z'
: Sequential Y, B-L , U(1) subgroup from Unif.

Little-Higgs type



Strongly Coupled Dynamics
: RS, Technicolor, Composite Higgs, etc

$\Rightarrow \quad Z' \longrightarrow WW/Zh/t\bar{t}$

...

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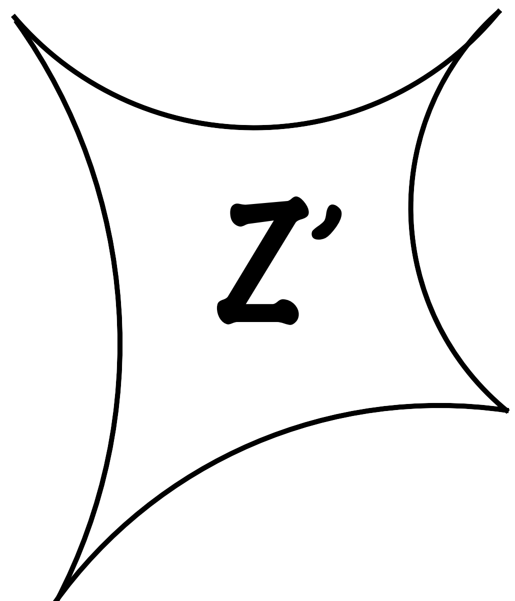


Strongly Coupled Dynamics
: RS, Technicolor, Composite Higgs, etc

$\Rightarrow Z' \longrightarrow WW/Zh/t\bar{t}$

...

+

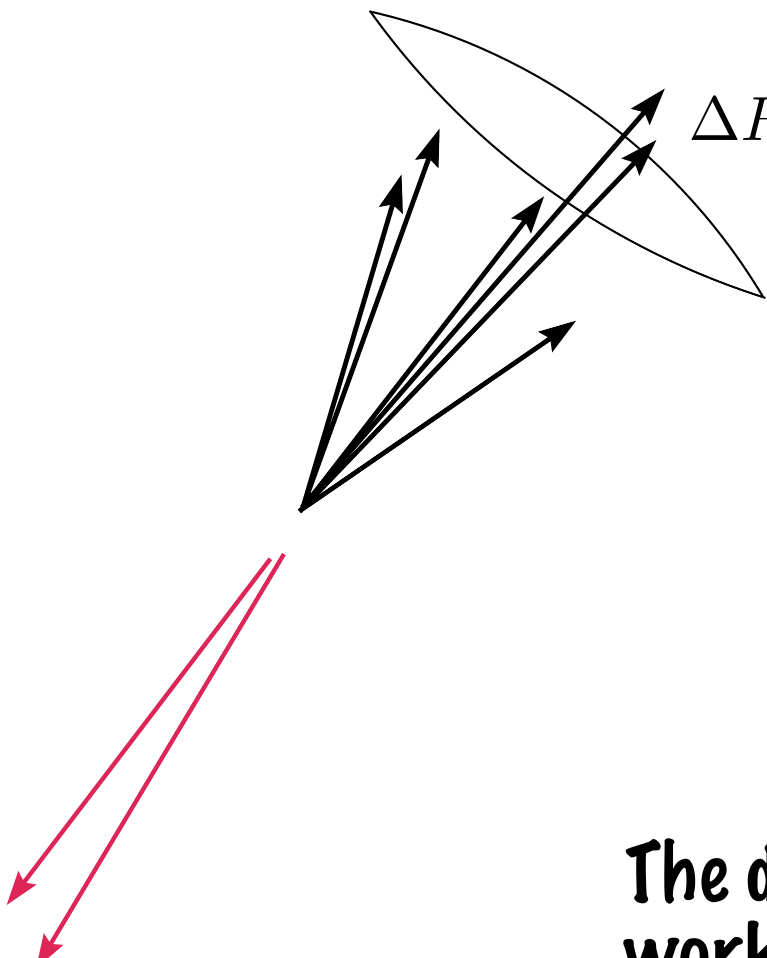
Direct/Indirect (EWPT) search

||

... is consistent with multi-TeV Z'

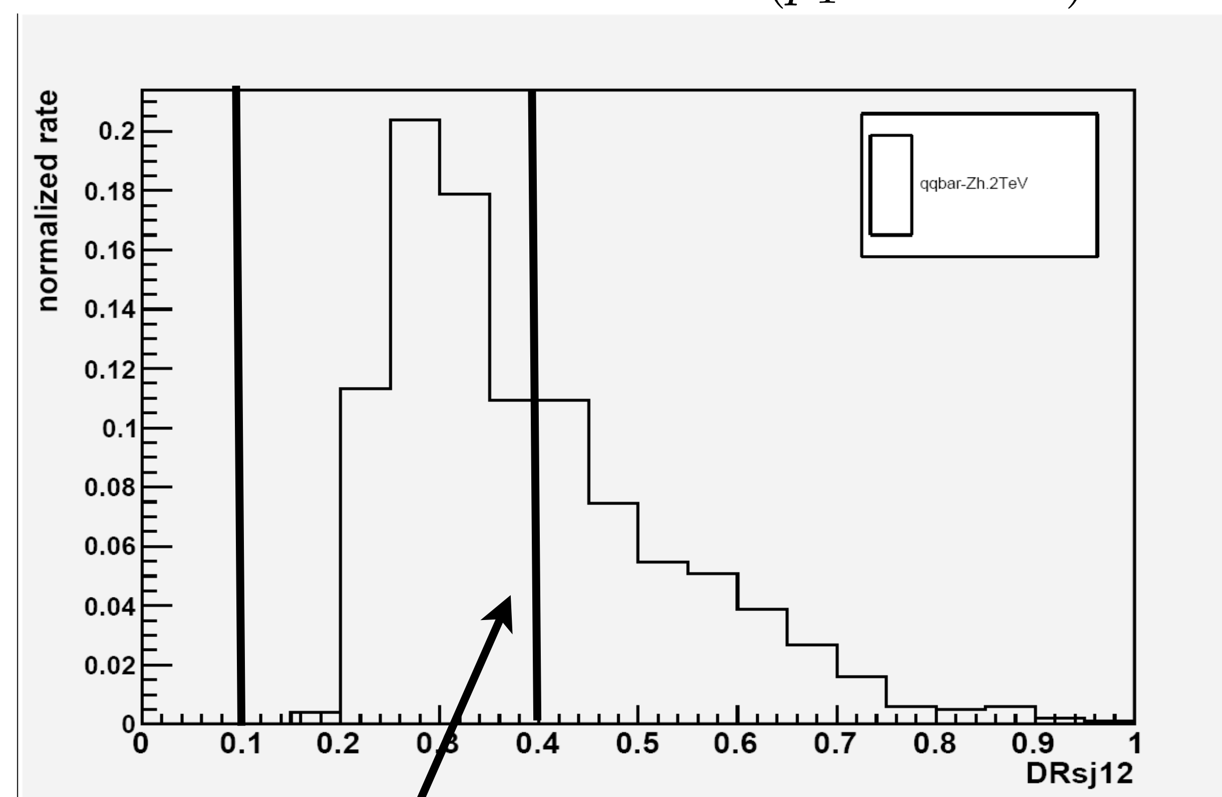
Multi-TeV Z′ decaying to Zh/WW results in

Merged jets (fat jets) !!



$$\Delta R \sim \frac{2\,m}{p_T}$$

$h(p_T \sim 1\text{TeV}) \to b\bar{b}$



The default LHC jet size does not work well with this physics

Typical Jet size ~ 0.4

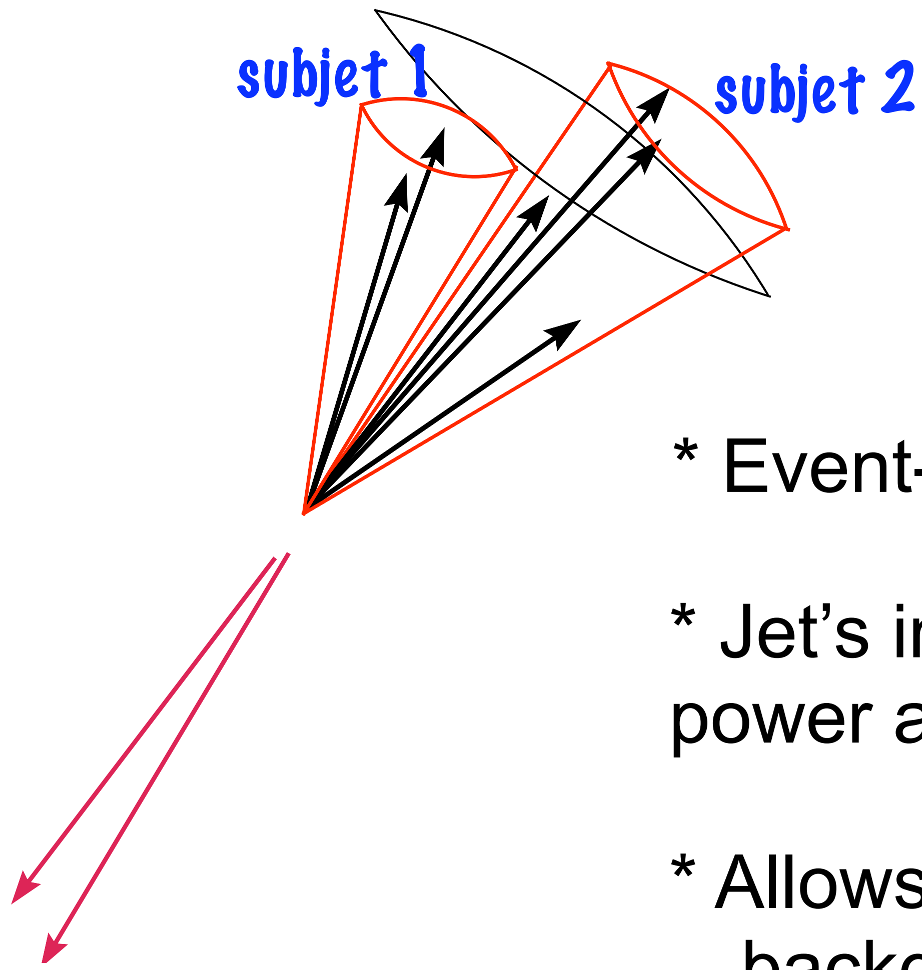
HCAL ~ 0.1

ECAL ~ 0.02

Tracker ~ 0.001

Jet Substructure

-> Take advantage of recently developed Jet Substructure Tech.



* Event-by-event subjet size optimizes mass resolution

* Jet's internal kinematics provides further discriminating power against QCD backgrounds

* Allows for nearly scale-free analysis with featureless background jet-mass spectrum

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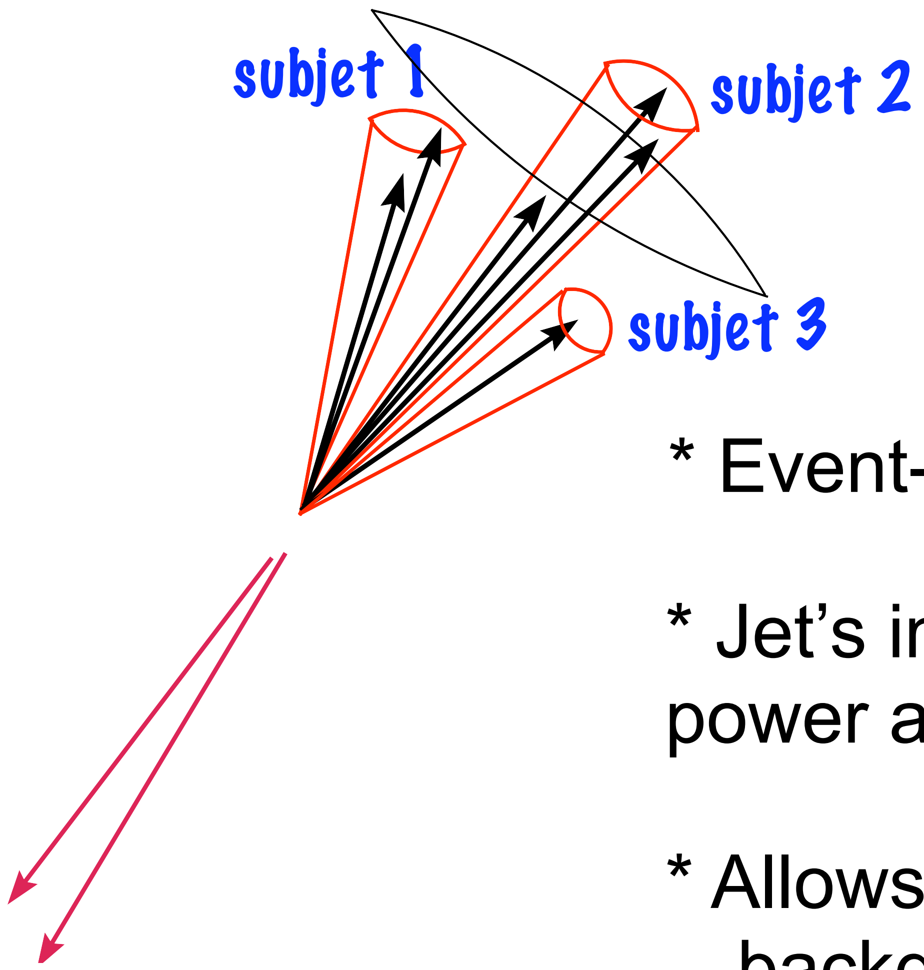

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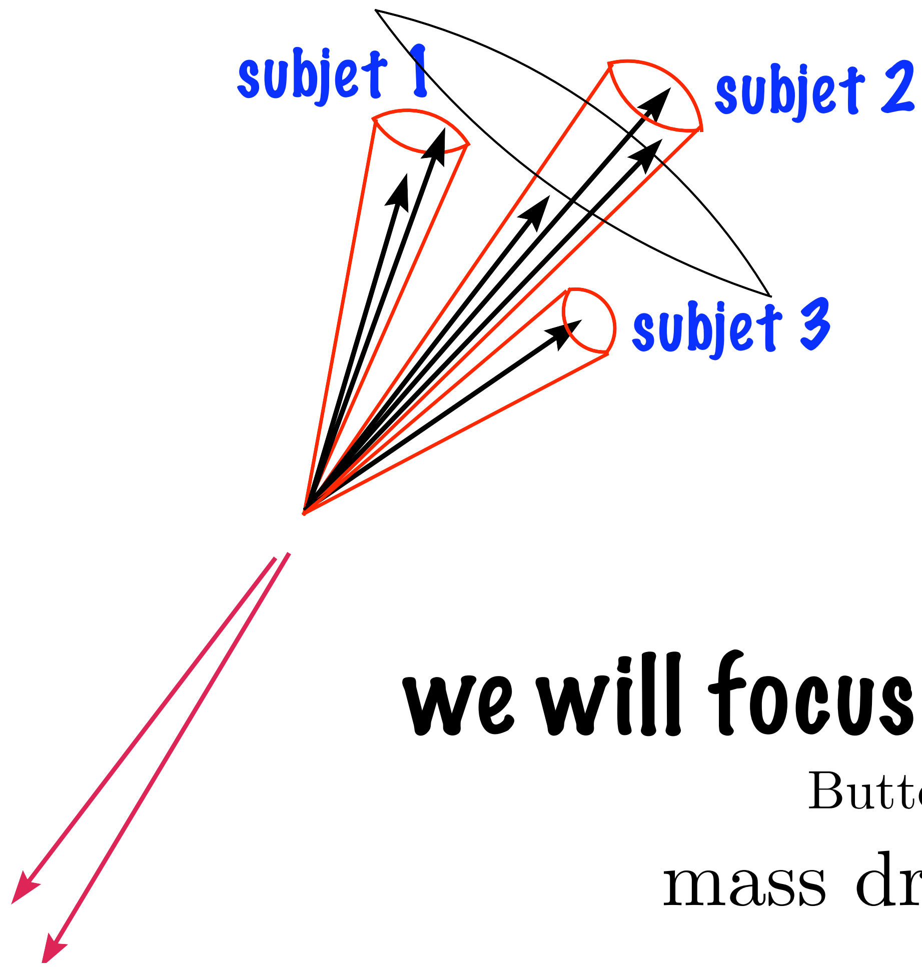


we will focus on BDRS style (C/A & filtering)

Butterworth, Davison, Rubin and Salam [PRL 100 (2008)]

mass drop/asym.

$$m_{sj}/m_j < 67\ \%$$

$$p_{t\,sj<}/p_{t\,sj>} > 9\ \%$$

** We stick to same values as original paper, but result is not highly sensitive
(also, mass-drop turns out to be strictly weaker than asym, and is redundant)

(see Zhenyu's talk)

We wish to address these issues

1. Mono/Dijet vs. Jet Substructure

2. Utility of quasi-hemispheric jet

3. Impact of possible detector effects at high pT

4. W/h-tag rates at high pT from jet substructure

5. Z' - search

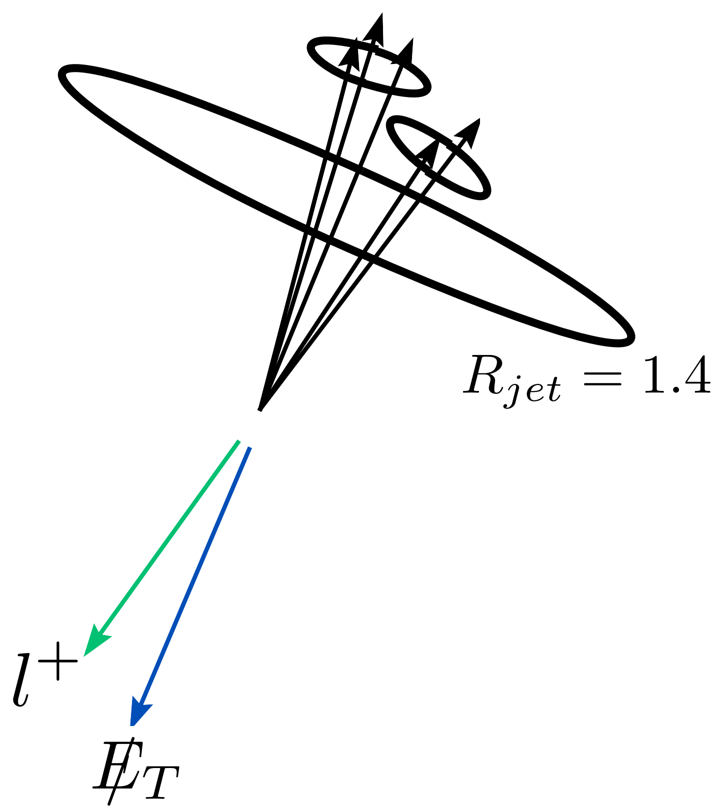
$$Z' \to Zh \to (l^+l^-)(b\bar{b})$$
$$\to (\nu\bar{\nu})(b\bar{b})$$
$$Z' \to W^+W^- \to (l\nu)(qq')$$

5-1. Investigate μ-based b-tagging

6. ISR/UE/Pile-up (if time is allowed)

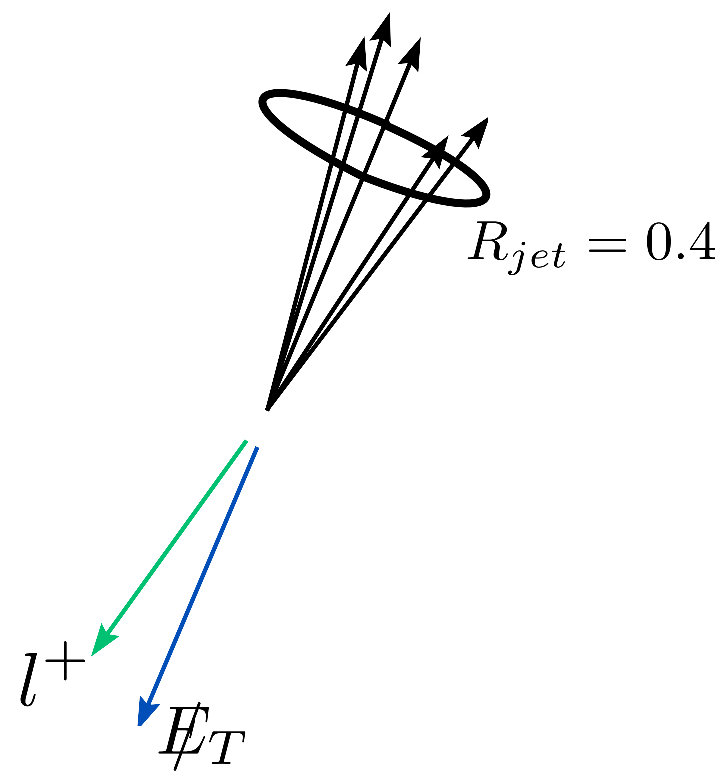
1. Mono/Dijet vs Jet Substructure

Jet Substructure



vs

Traditional jet-style



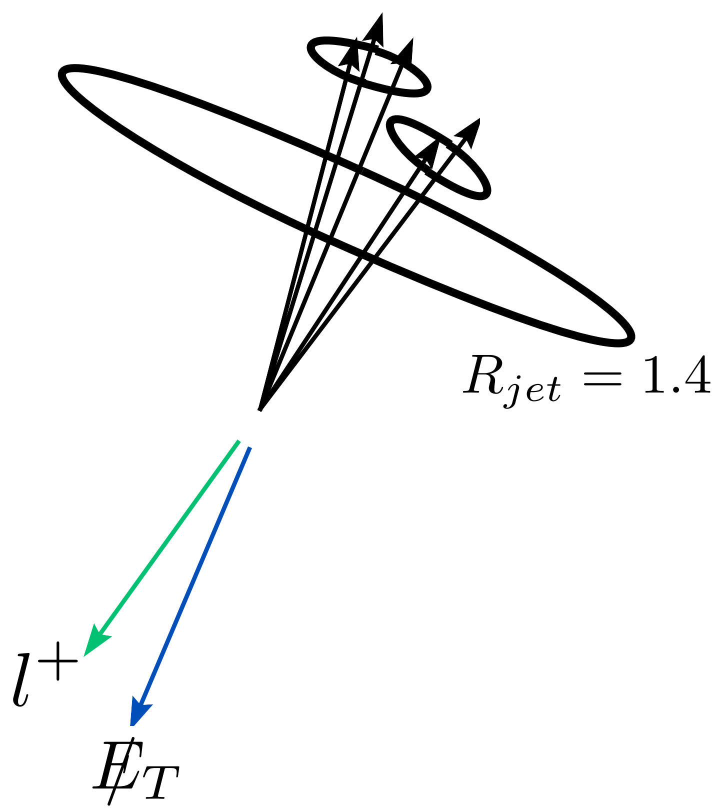
1. cluster into R = 1.4 C/A jet
2. Identify the hardest fat-jet
3. Decluster according to BDRS to two subjets

1. cluster into R =0.4 anti-kT jet
2. identify the hardest jet
3. look within DR=1.4 for the second jet that makes symmetric pairing (Dijet)
4. failing pairing, take only the leading jet (Monojet)

** no filtering/ no Pileup/no detector model for this comparison

1. Mono/Dijet vs Jet Substructure

Jet Substructure



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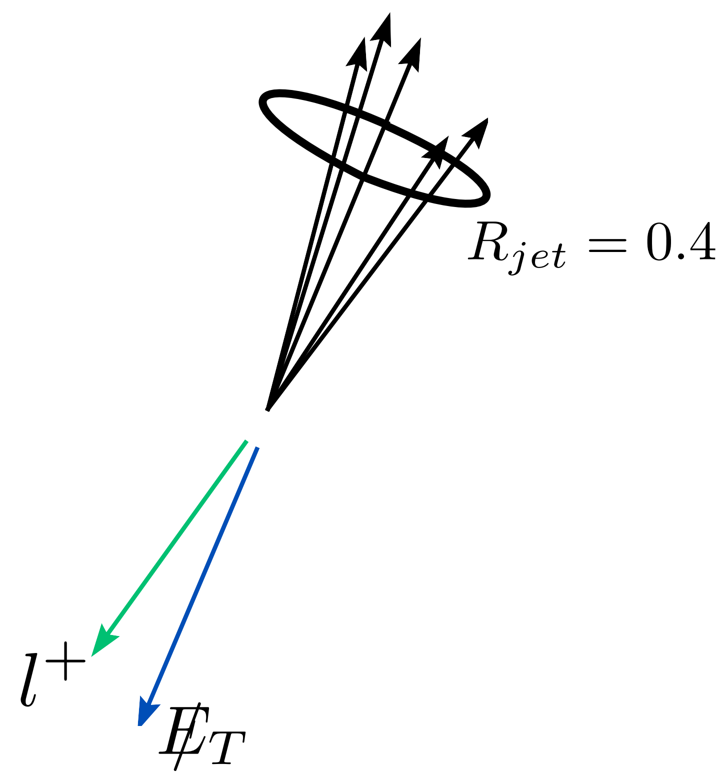
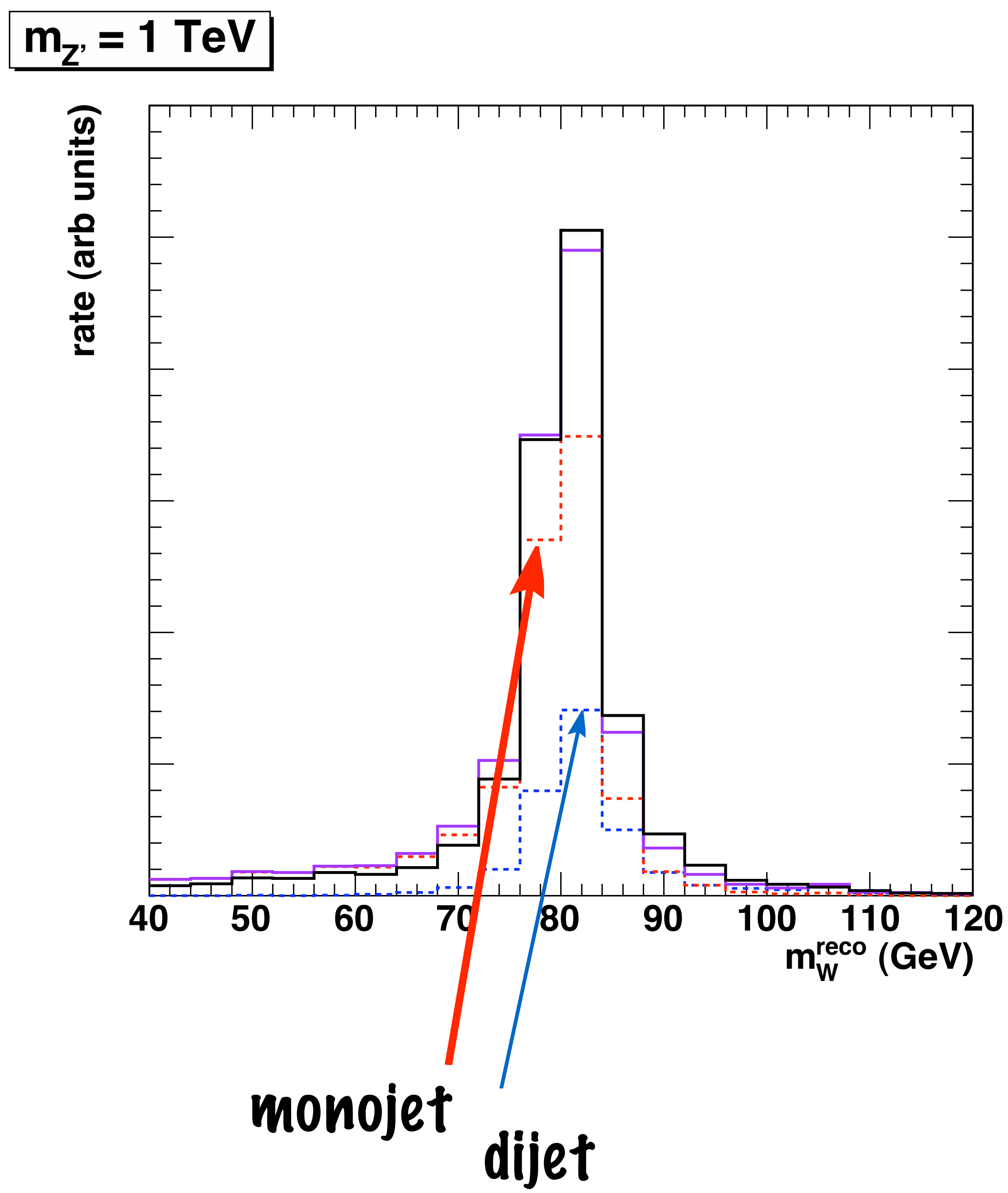
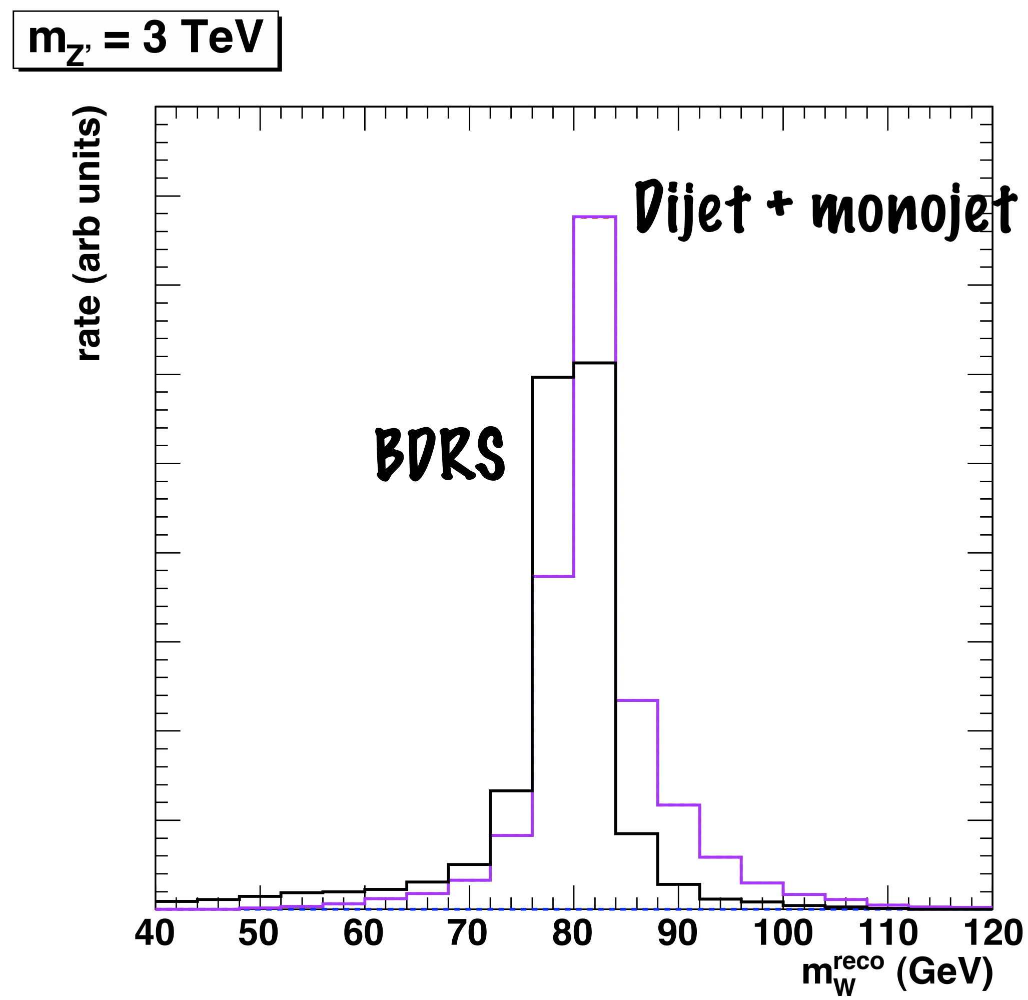


Z'->WW->(lv)(qq'), W+jets->(lv)+jets

1. Mono/Dijet vs Jet Substructure

Signal

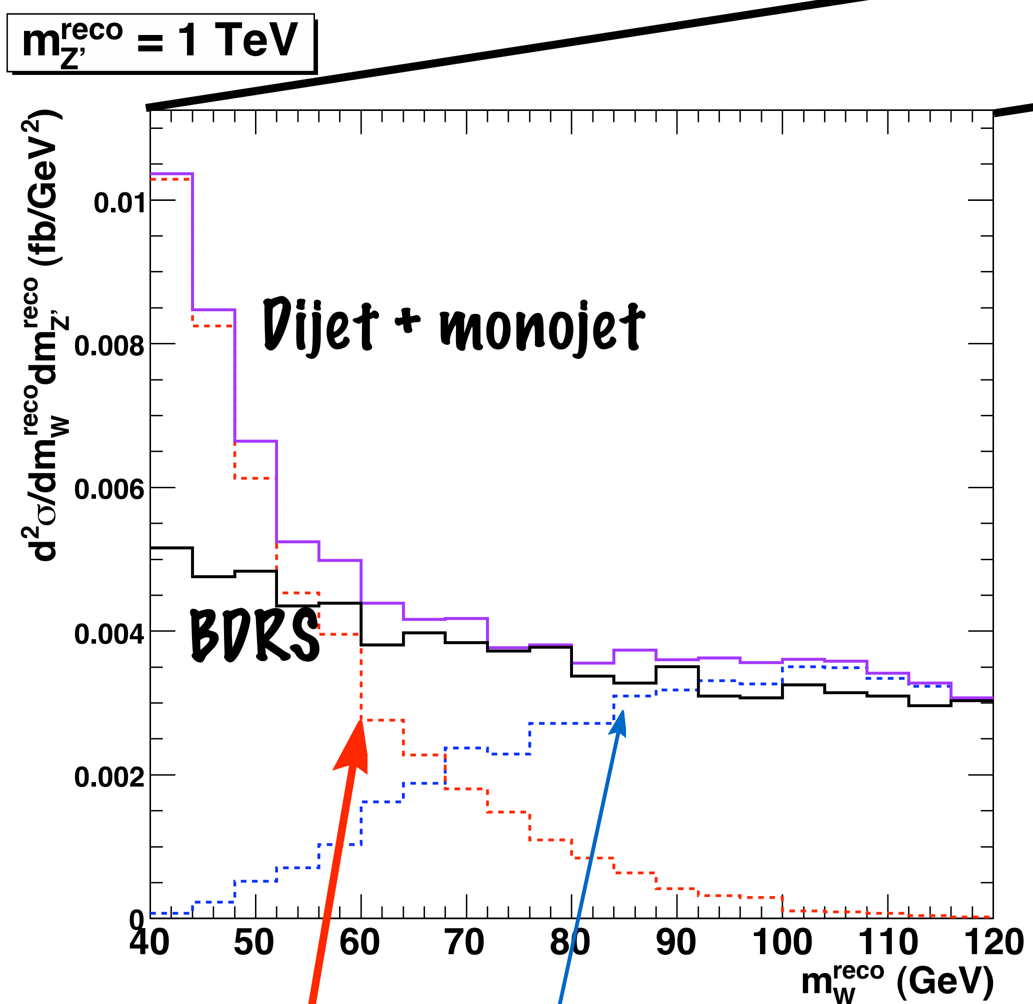


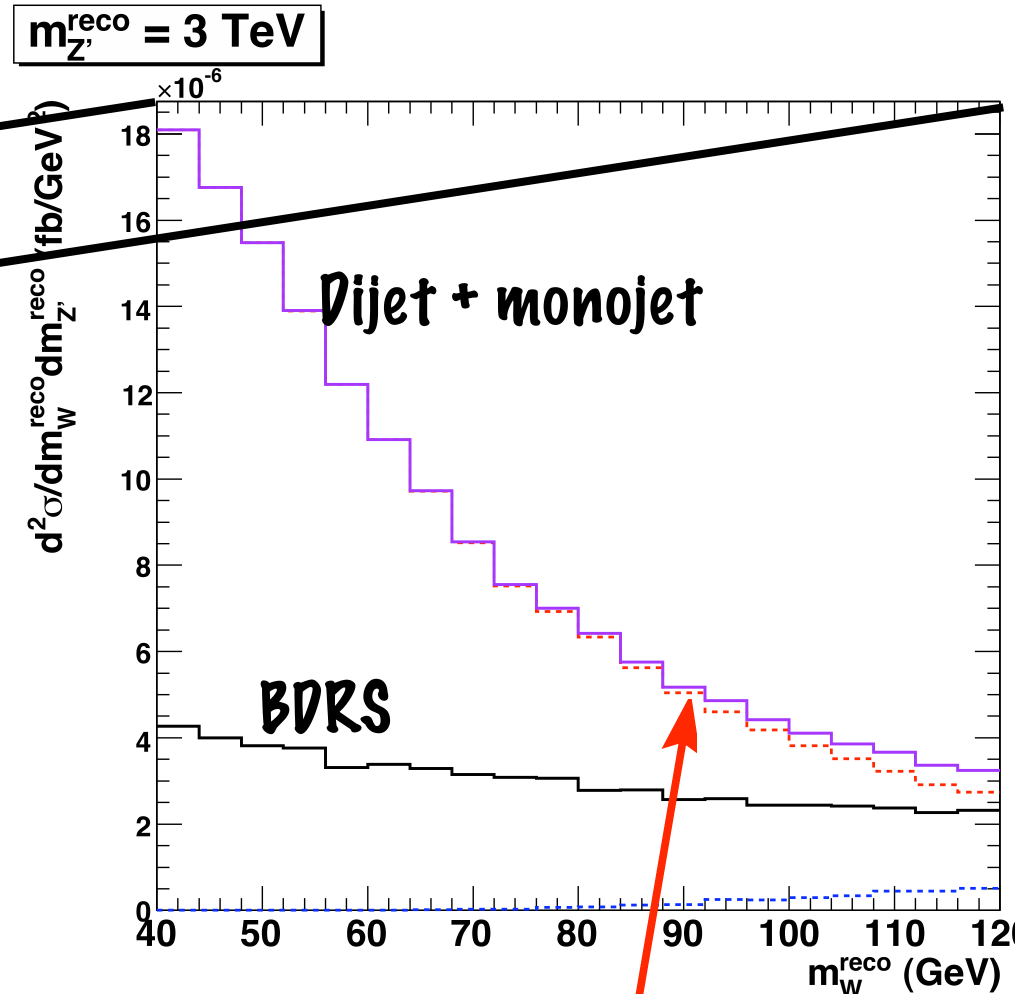


by Magraph/Event 4.4.32
fastjet-2.4.1

1. Mono/Dijet vs Jet Substructure

Background





Dijet introduces an artificial shape (or scale) near mW

Healthy amount of monojet compensates

Monojet dominates !!

by PYTHIA 6.4.11
fastjet-2.4.1

2. Utility of quasi-hemispheric jet

R_jet = 1.4

1. Remove a dimensionful scale in jet mass distribution, i.e. $(\sim R_{jet} \times p_T)$

   : flattens sidebands

2. Single analysis works uniformly for all mZ' ≳ 400 GeV

3. Seeing in Color

J. Gallicchio, M. Schwartz arXiv : 1001.5027

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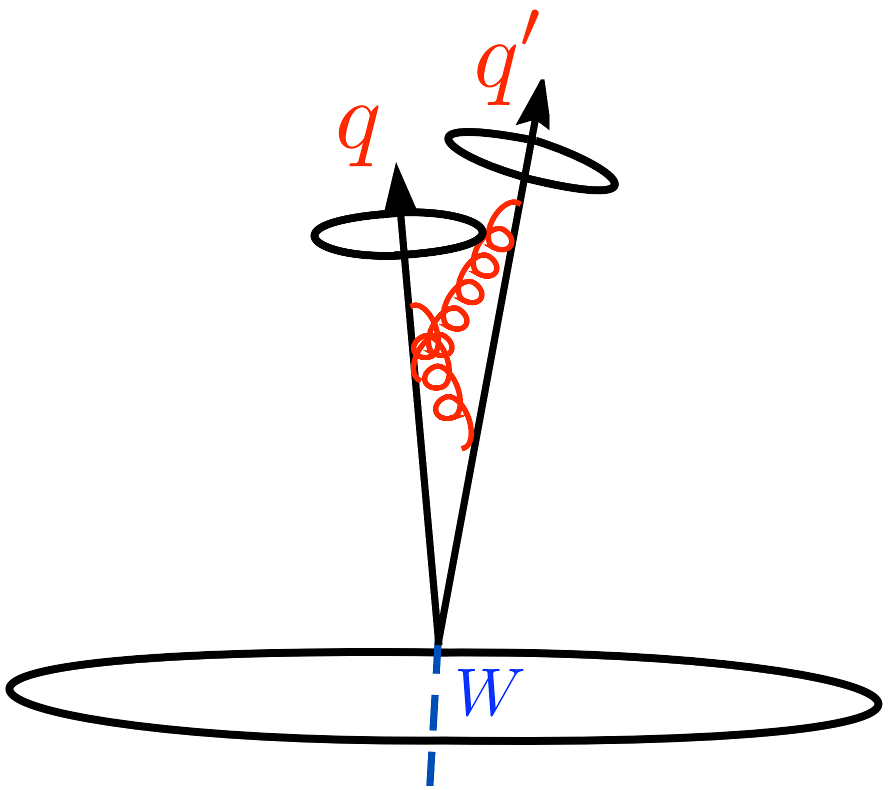
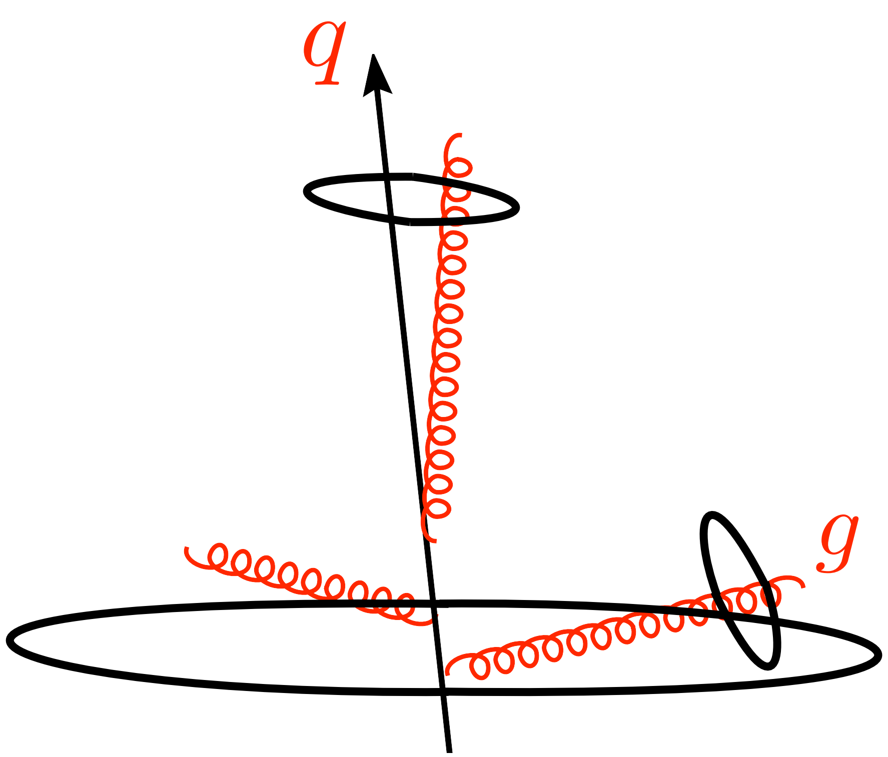


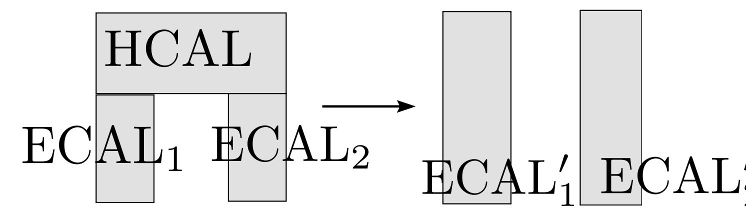


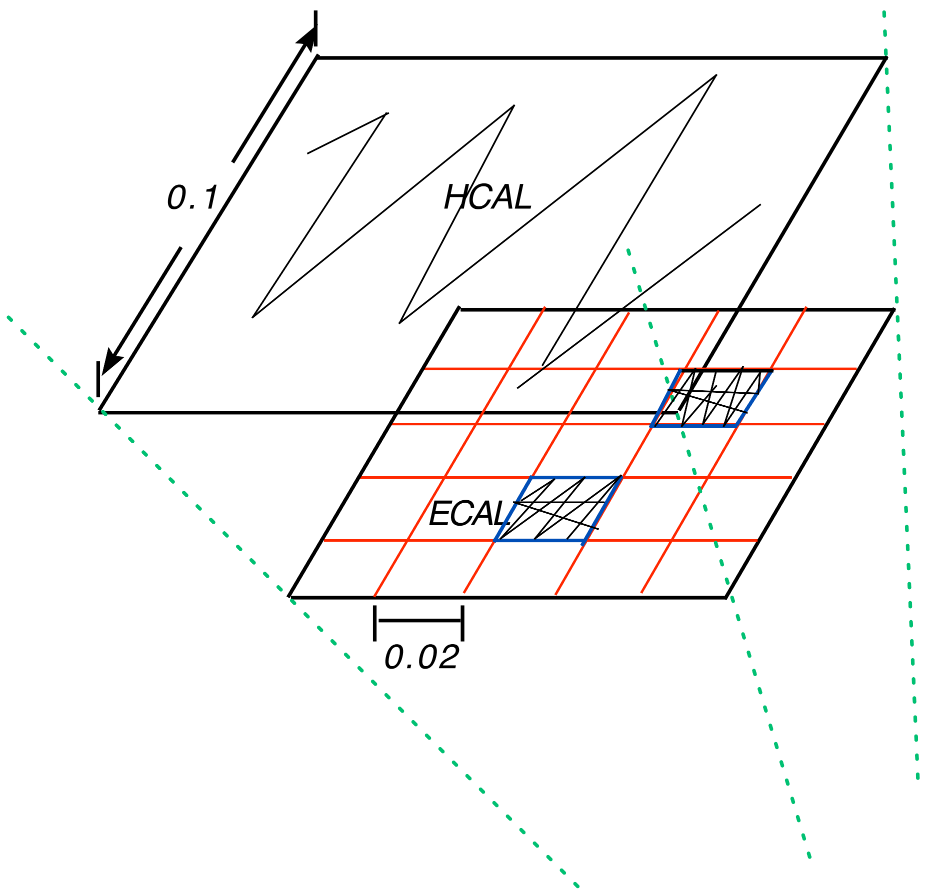
(see Zhenyu's talk)

3. Simple detector Model

1. γ and non-isolated electrons into ECAL/all hadrons into HCAL

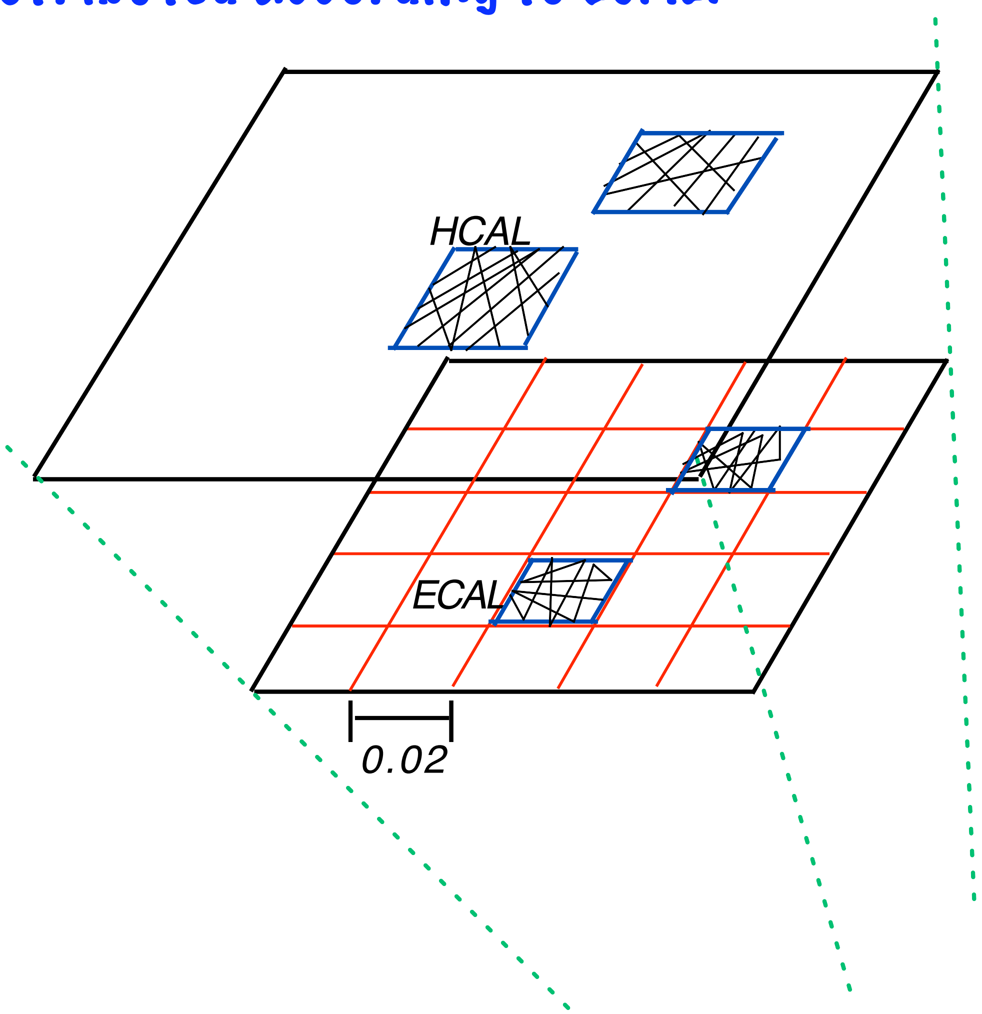
2. muons and isolated electrons are kept as tracks



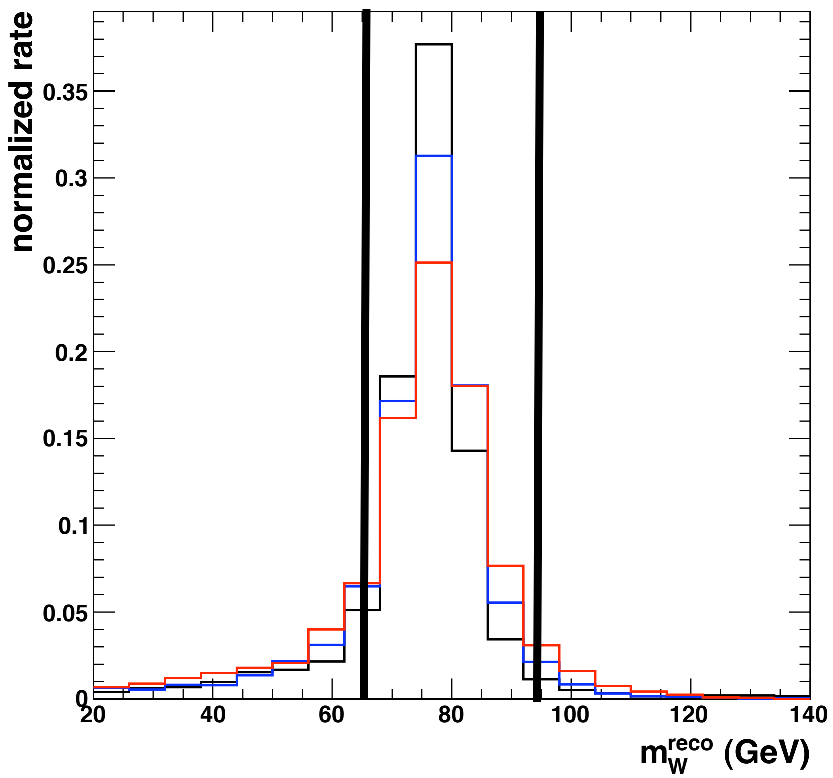


ECAL is rescaled to match full ECAL + HCAL energy
(i.e. HCAL is re-distributed according to ECAL)

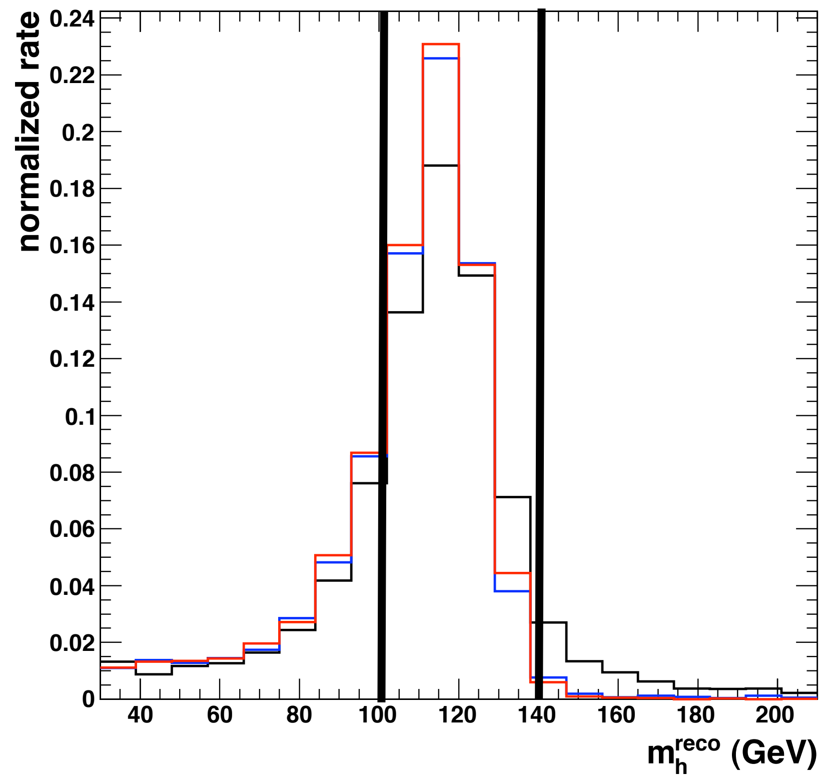
ECAL to trace jet energy flow



4. W/h Tag-Rates from Jet Substructure



$$65 \le m_W^{\rm reco} \le 95 \text{ GeV}$$



$$100 \le m_h^{\rm reco} \le 140 \text{ GeV}$$

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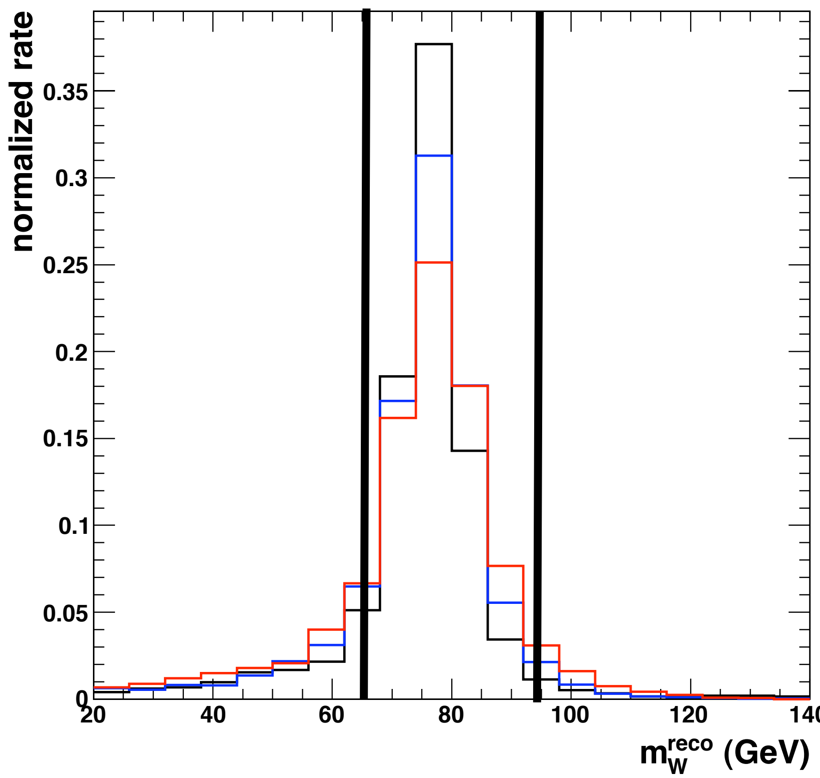
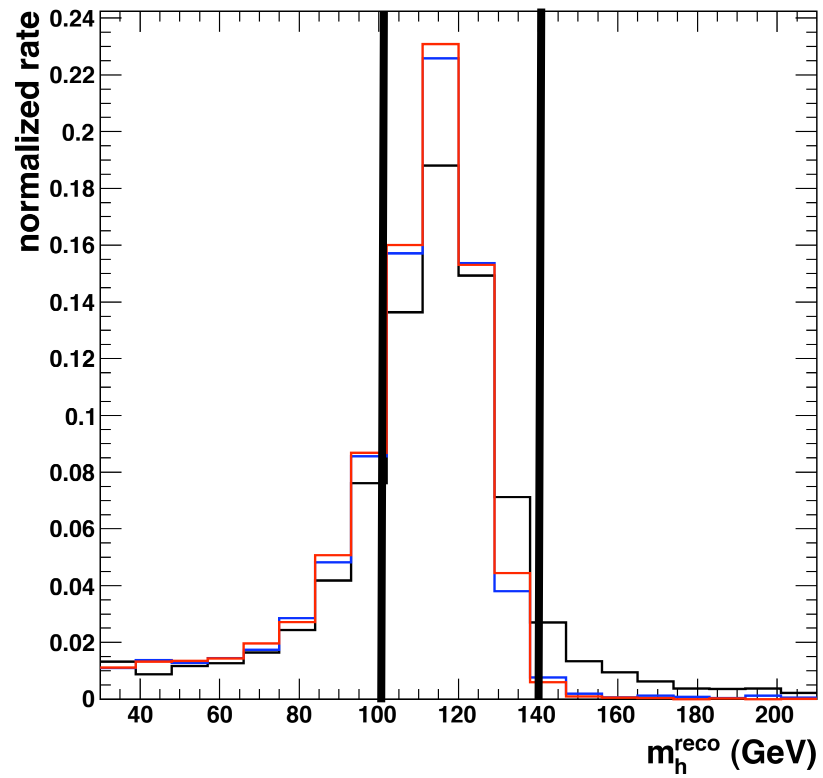


$65 \leq m_W^{\rm reco} \leq 95$ GeV



$100 \leq m_h^{\rm reco} \leq 140$ GeV

Signal →

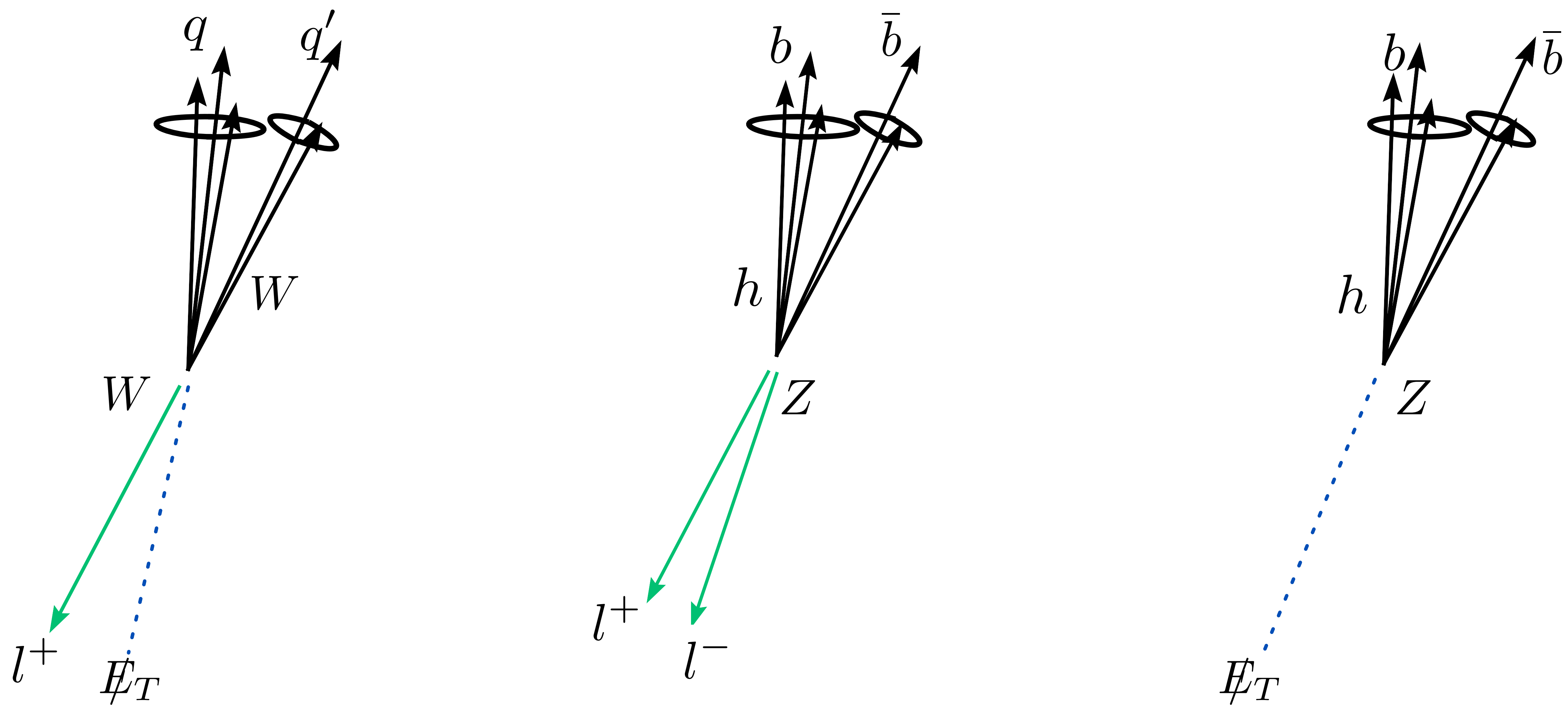
Background →

	$p_T \simeq 500$ GeV	$p_T \simeq 1000$ GeV	$p_T \simeq 1500$ GeV
W	76%	77	72
h	59	61	62
quark $\to W$	6.5%	6.5	5.9
quark $\to h$	6.8	5.6	5.8
gluon $\to W$	10.4	8.3	7.4
gluon $\to h$	10.5	8.8	7.4

5. Z'-Search

: We investigate three promising channels (for light Higgs w/ mH = 120 GeV)

$Z' \to W^+W^- \to (l\nu)(qq')$ $Z' \to Zh \to (l^+l^-)(b\bar{b})$ $Z' \to Zh \to (\nu\bar{\nu})(b\bar{b})$



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Assumptions:

1. MET balances leading (energy-smeared) objects

$$WW \to (l\nu)(qq') : \not{E}_t = -\left(\Sigma\, p_T(\mathrm{sj}) + p_T(l)\right)$$

$$Zh \to (\nu\bar{\nu})(b\bar{b}) : \ \not{E}_t = -\Sigma\, p_T(\mathrm{sj})$$

2. neutrino has the same Eta as lepton's

$$WW \to (l\nu)(qq') : \ p_{L\,\nu} = \frac{\not{E}_t}{p_{T\,l}}\, p_{L\,l}$$

3. Lepton's pT dominates sub-leading jet (to suppress ttbar bkgs in WW-(lv)(qq'))

$$p_T(l) \geq 2\, p_T(j_2)$$

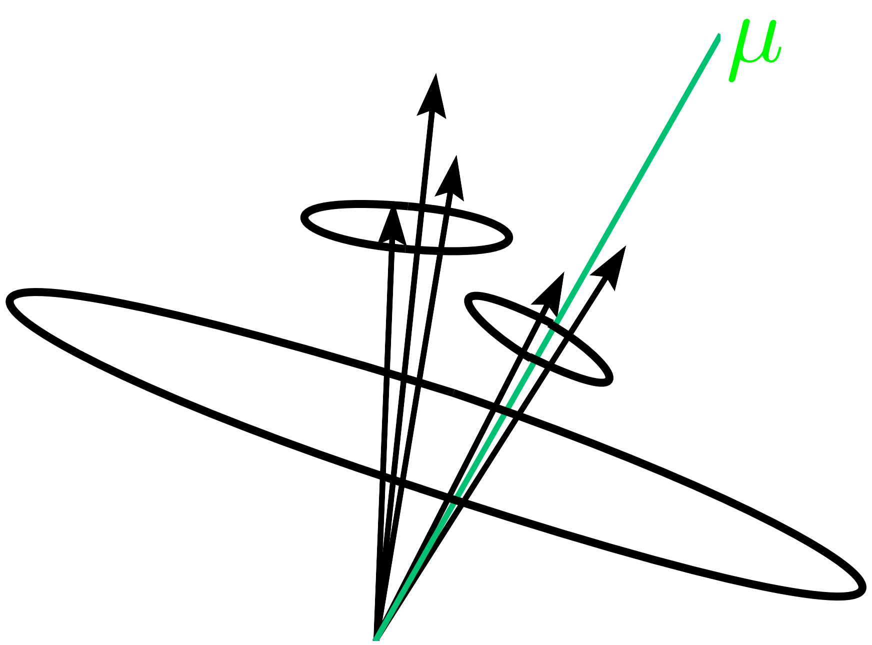
4. b-Tagging: muon-Tag in b-jet

b-tagging

trad. b-tagging may quickly degrade at high pT

⟶ Is there more robust form of b-tagging ?

We investigate μ-based b-tagging



$$\mathcal{B}(b \to \mu\nu\, X) = 11\ \%$$
$$\mathcal{B}(b \to c \to \mu\nu\, X) = 10\ \%$$

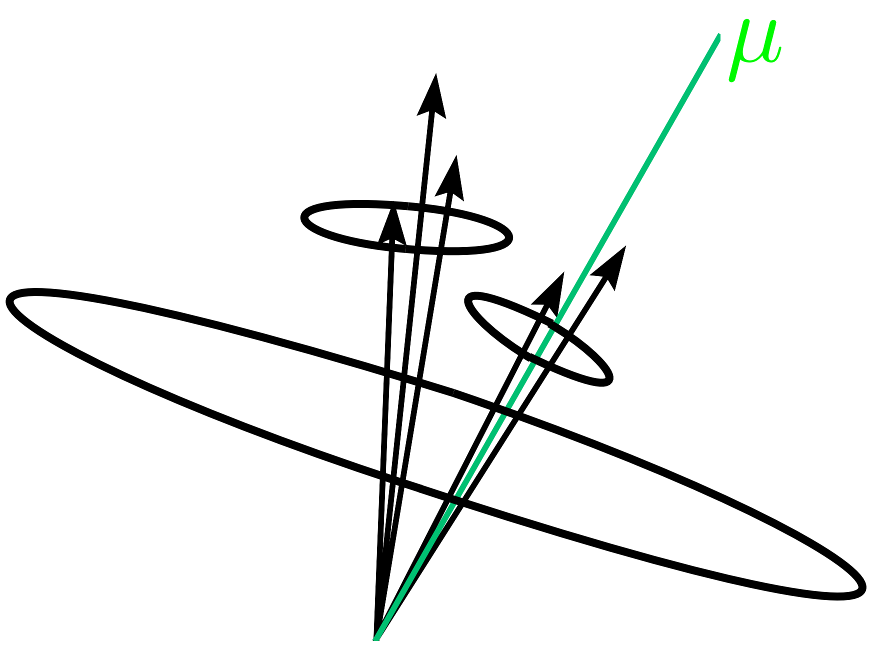
μ-Tag Criterion

: # $\mu \geq 1$

for 35 % of time muon is tagged

mistag-rate < 5%

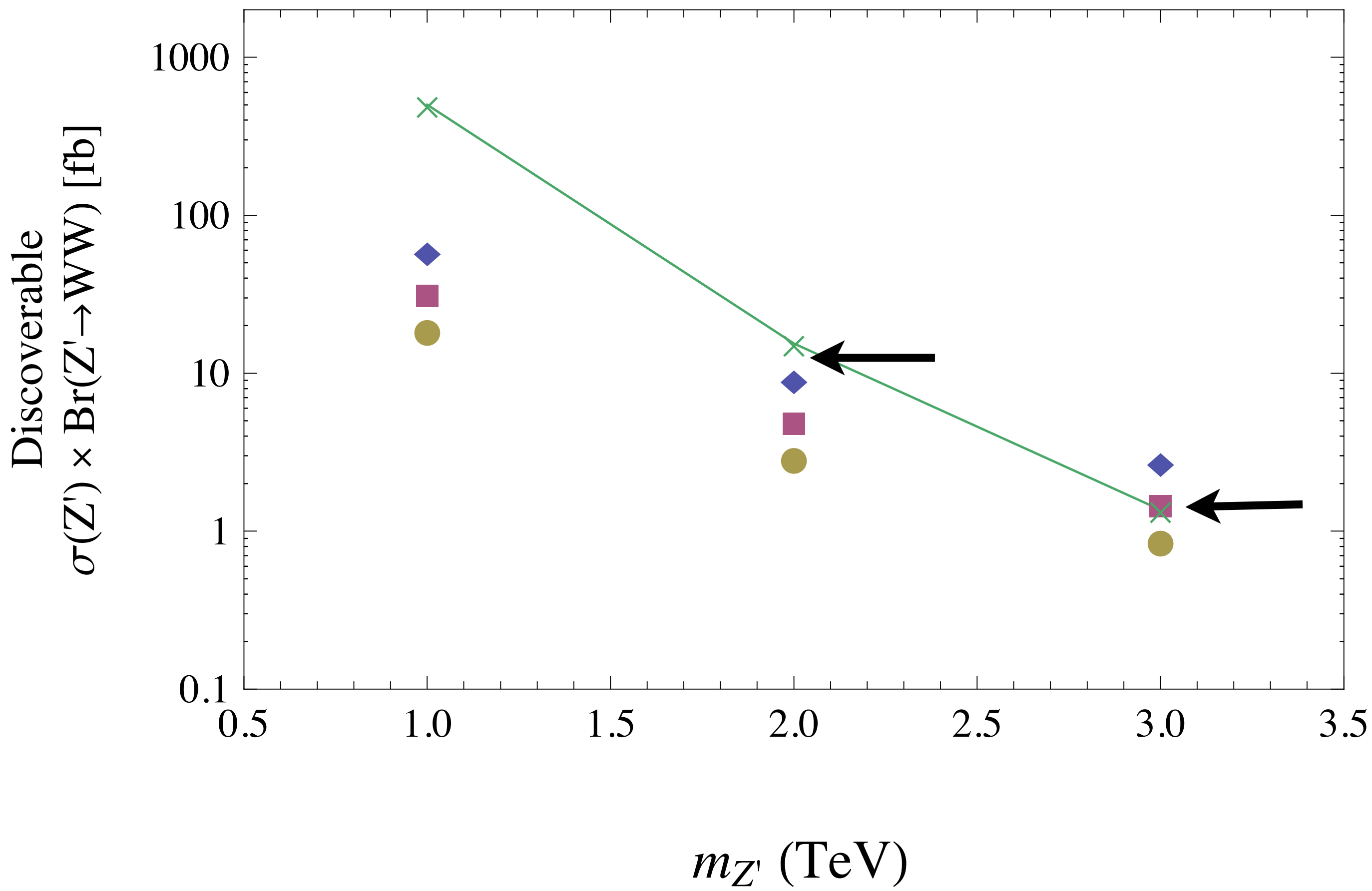
: roughly pT-independent



Discovery Reach at LHC w/ 14 TeV

$Z' \to W^+W^- \to (l\nu)(qq')$

w/ $N_s > 10$



◆ : 30 fb^{-1}
■ : 100 fb^{-1}
● : 300 fb^{-1}
× : $S/B = 1$

← : Warped RS

K. Agashe et. al [arXiv : 0709.0007]

$\sigma \times BR \sim 15(1.5)$ fb for 2(3) TeV

$m_{Z'}^{\text{reco}} = [m_{Z'} - 15\%, m_{Z'} + 15\%]$

$p_T > m_{Z'}/3$

3 TeV Z' from Warped RS is discoverable with about 100/fb

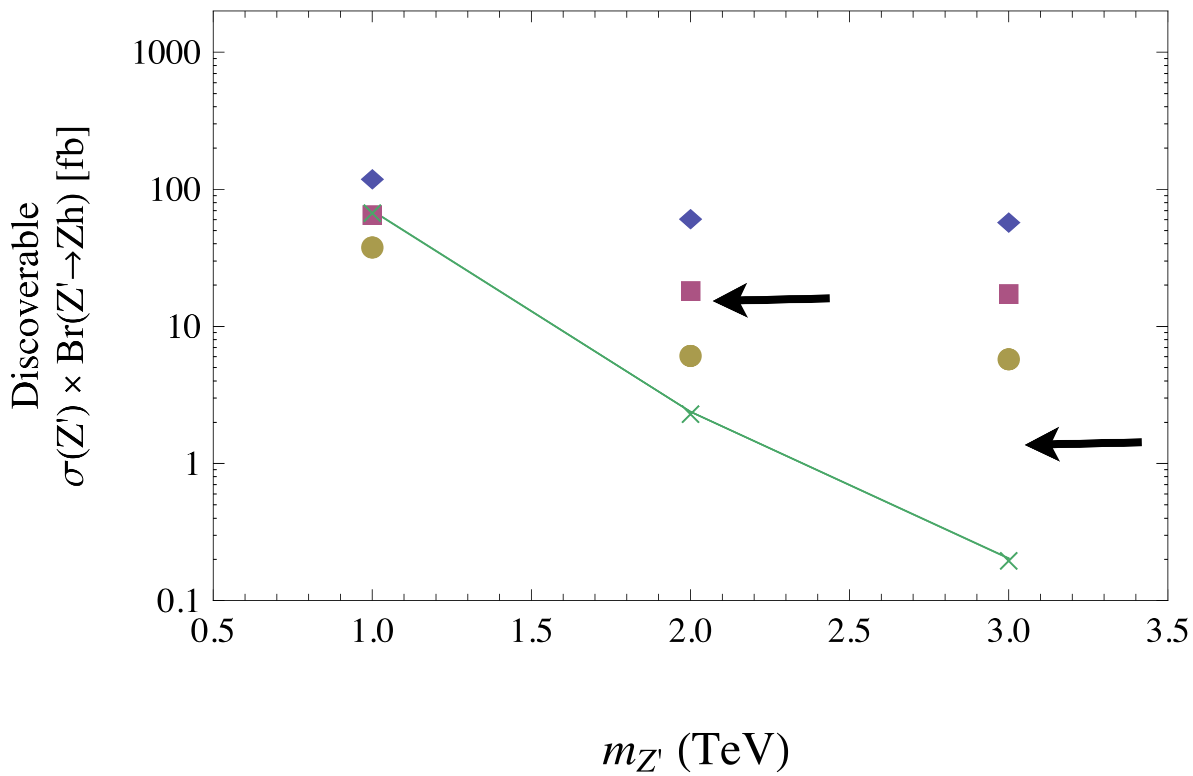
Discovery Reach at LHC w/ 14 TeV

$Z' \to Zh \to (l^+l^-)(b\bar{b})$

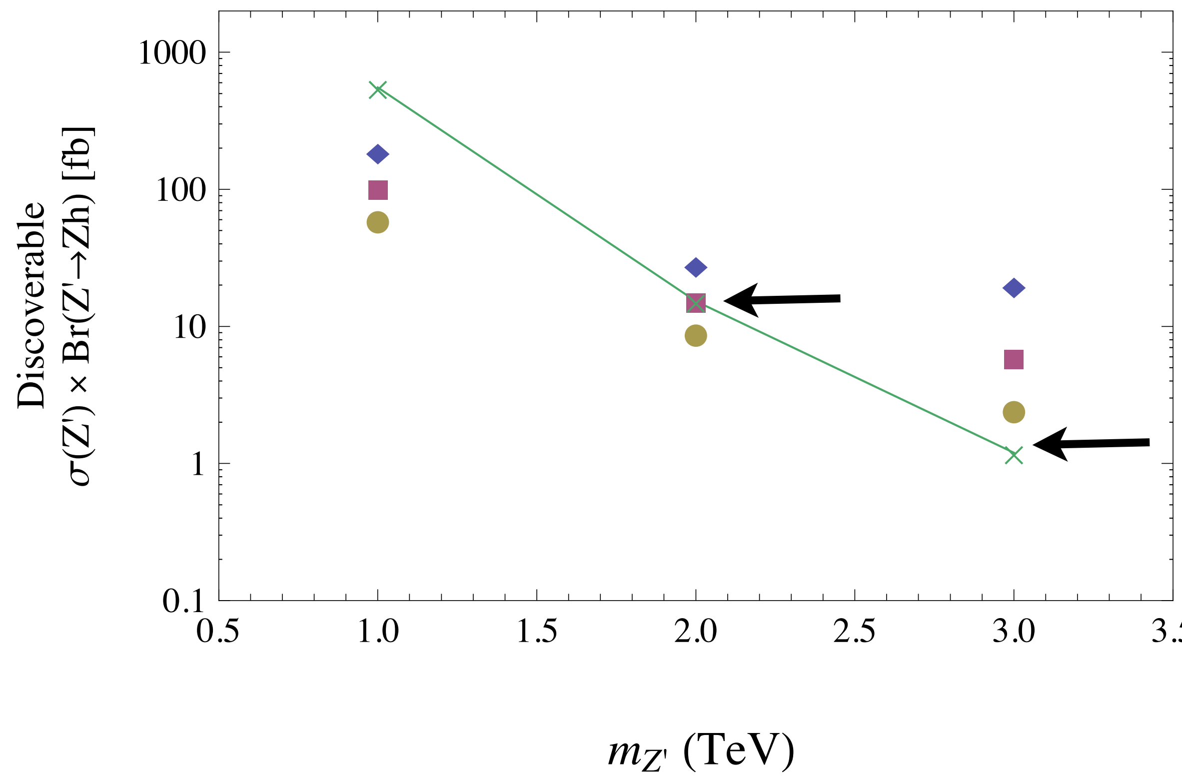
w/ $N_s > 10$

♦ : $30\ \text{fb}^{-1}$
■ : $100\ \text{fb}^{-1}$
● : $300\ \text{fb}^{-1}$
× : $S/B = 1$

$\mu - \text{tagged}$



no b − tagging



$m_{Z'}^{\text{reco}} = [m_{Z'} - 15\%, m_{Z'} + 15\%]$

$p_T > m_{Z'}/3$

b-tagging is most important at sub-TeV masses, where bkgs are still substantial and also trad. b-tagging tech. would operate well

3 TeV Z' from Warped RS would require a bit less than 400/fb

Discovery Reach at LHC w/ 14 TeV

$$Z' \to Zh \to (\nu\bar{\nu})(b\bar{b})$$

w/ $N_s > 10$

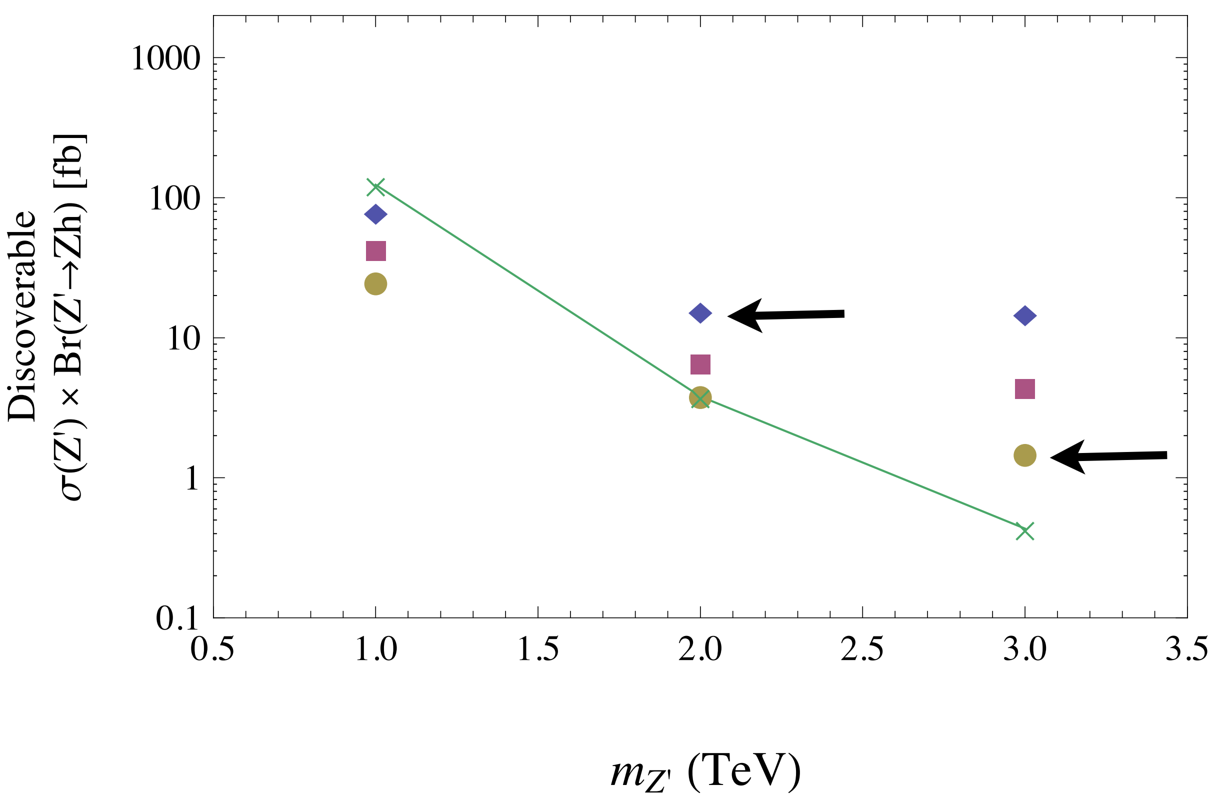
◆ : $30\ \text{fb}^{-1}$

■ : $100\ \text{fb}^{-1}$

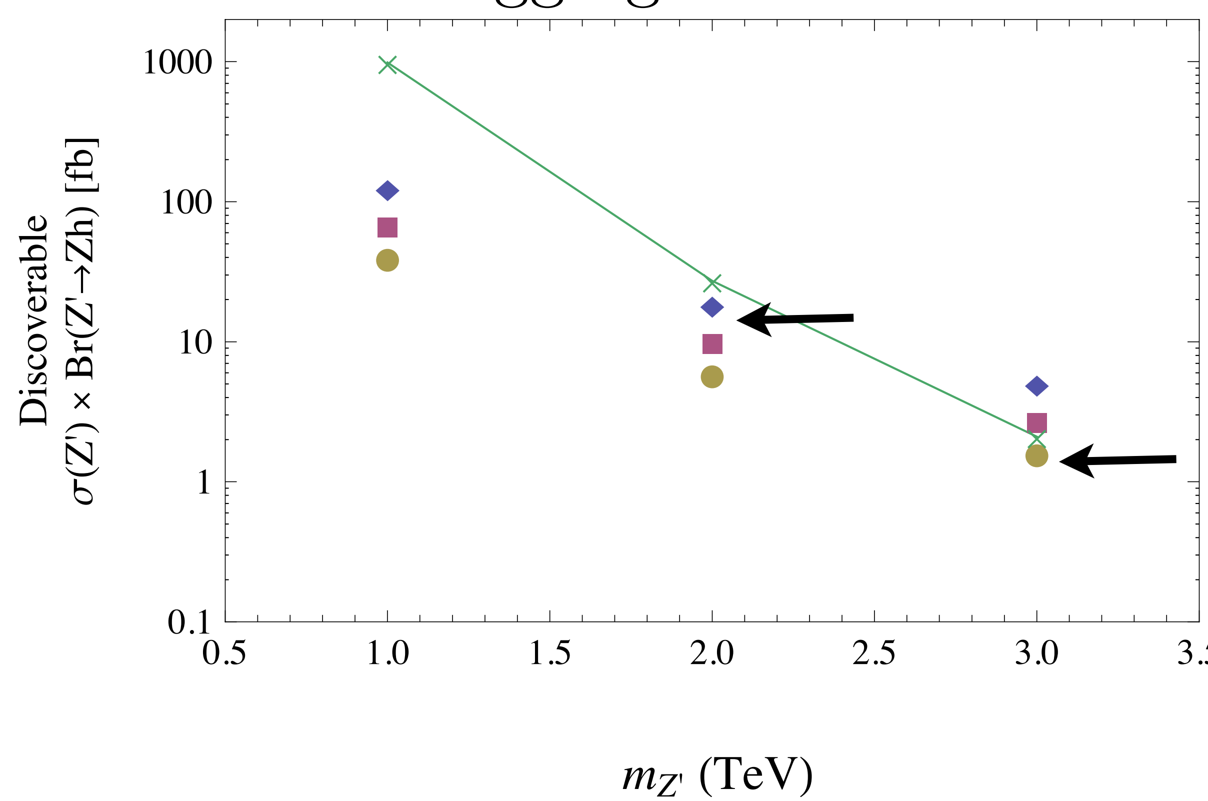
● : $300\ \text{fb}^{-1}$

× : $S/B = 1$

$\mu -$ tagged



no b $-$ tagging



$$m_{Z'}^{\text{reco}} = [m_{Z'} - 30\%, m_{Z'} + 10\%]$$

3 TeV Z' from Warped RS is discoverable with about 300/fb
**** tradeoff: broader (transverse) mass peak**

Summary

BDRS-based substructure tech. help significantly in identification of hadronic W/Z/h w/ high pT

1. correct jet size event-by-event basis
2. bkgs jet-mass spectrum is made flatter/featureless
3. some global color discrimination
4. Works for any Z' mass above ~400 GeV

Appl. to Z'-Zh/WW shows promising results

1. 3 TeV Z' from warped RS via WW mode w/ ~ 100/fb
2. Zh w/ h-bb may also be doable before super-LHC
3. Invisible Z mode previously under-utilized, but appears comeptitive with leptonic Z mode
4. Mu-based b-tag can help, but non-tagged analysis can perform better for high mass (esp. (ll)(bb))

Backup

Pileup and Filtering

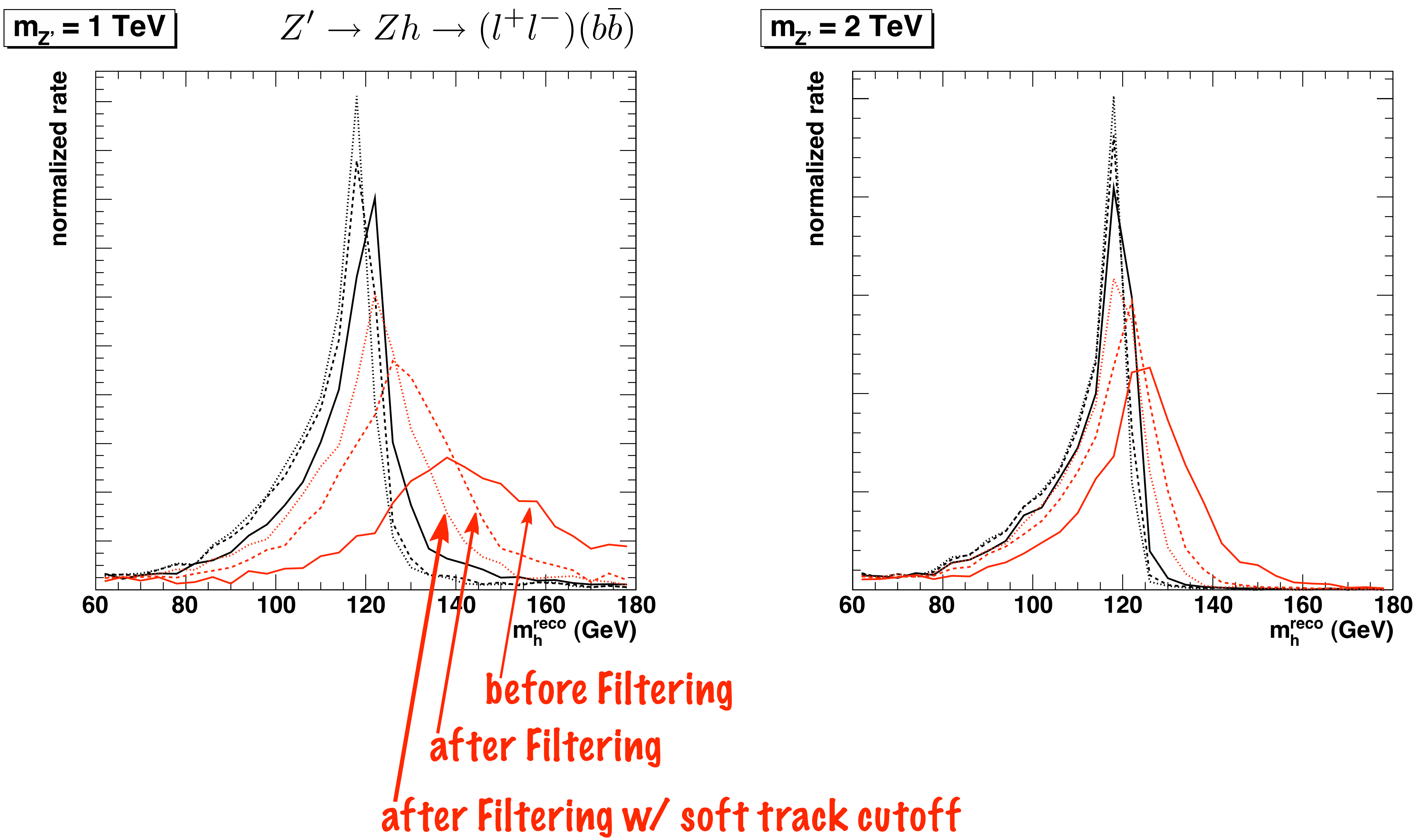
: approx. 20 min-bias pileup collisions superimposed on each Z' candidate event

Signal

Black lines : without PU

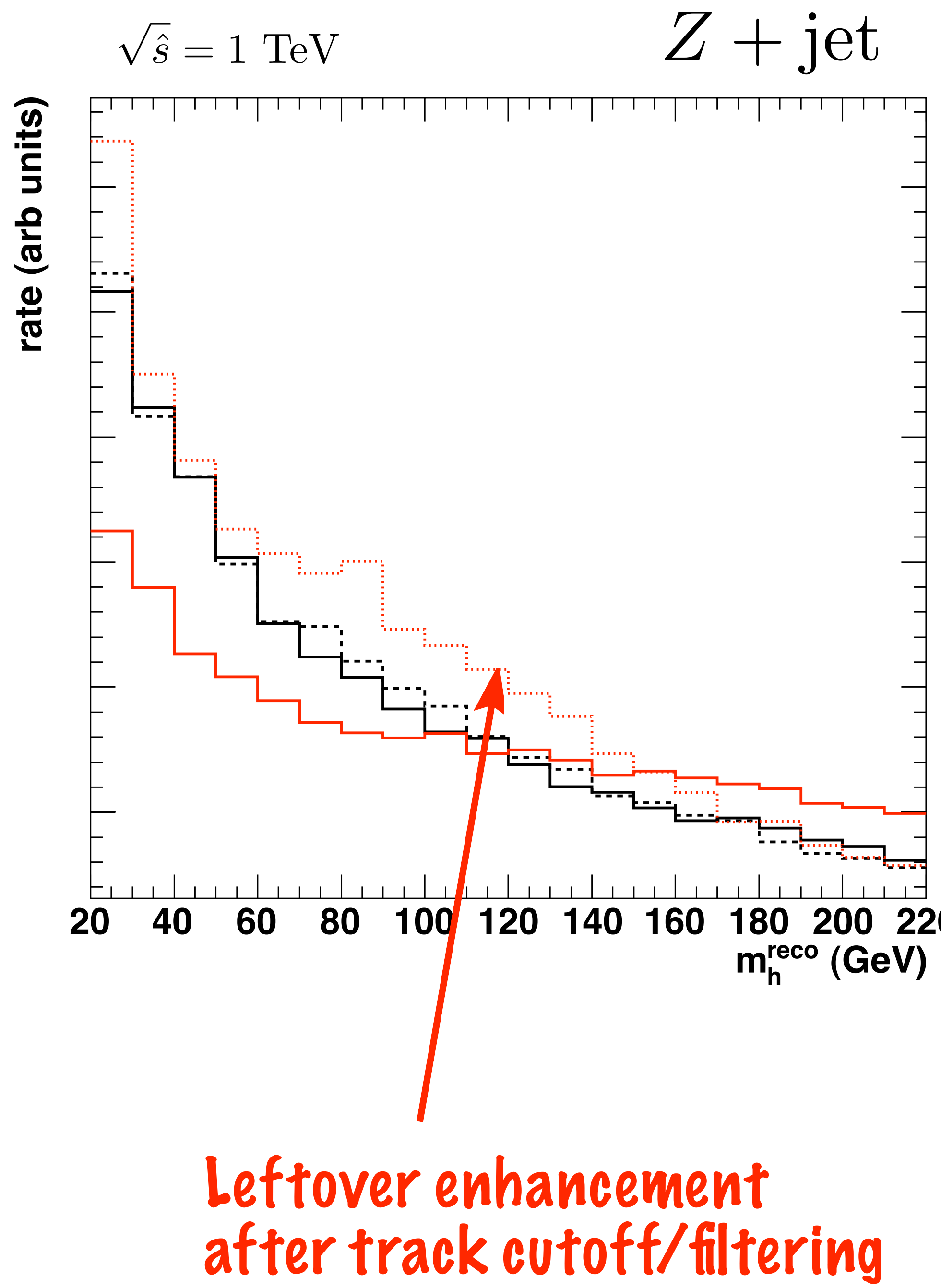
Red lines : with PU

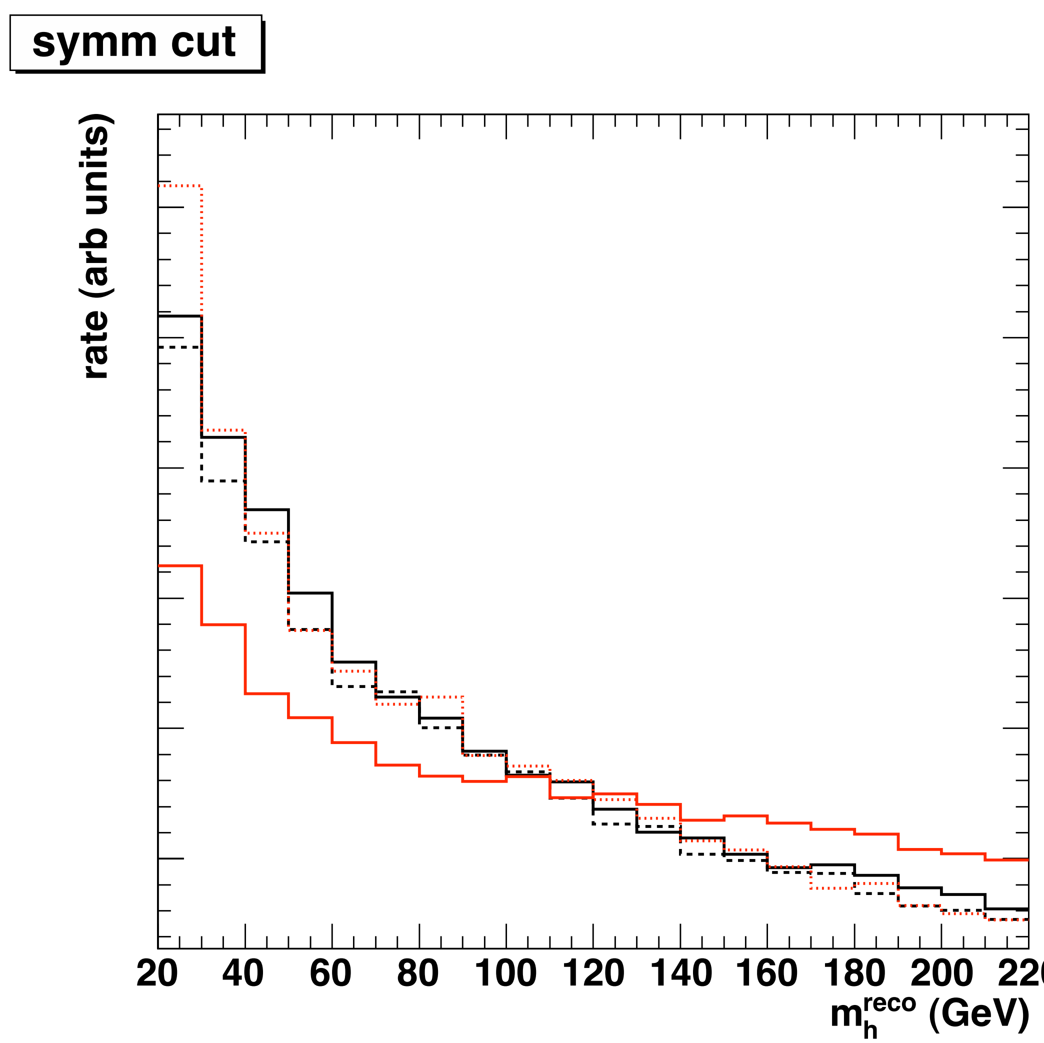
$Z' \rightarrow Zh \rightarrow (l^+l^-)(b\bar{b})$



(i.e. remove all charged particles w/ pT < 1 GeV: will not reach HCAL)

Background

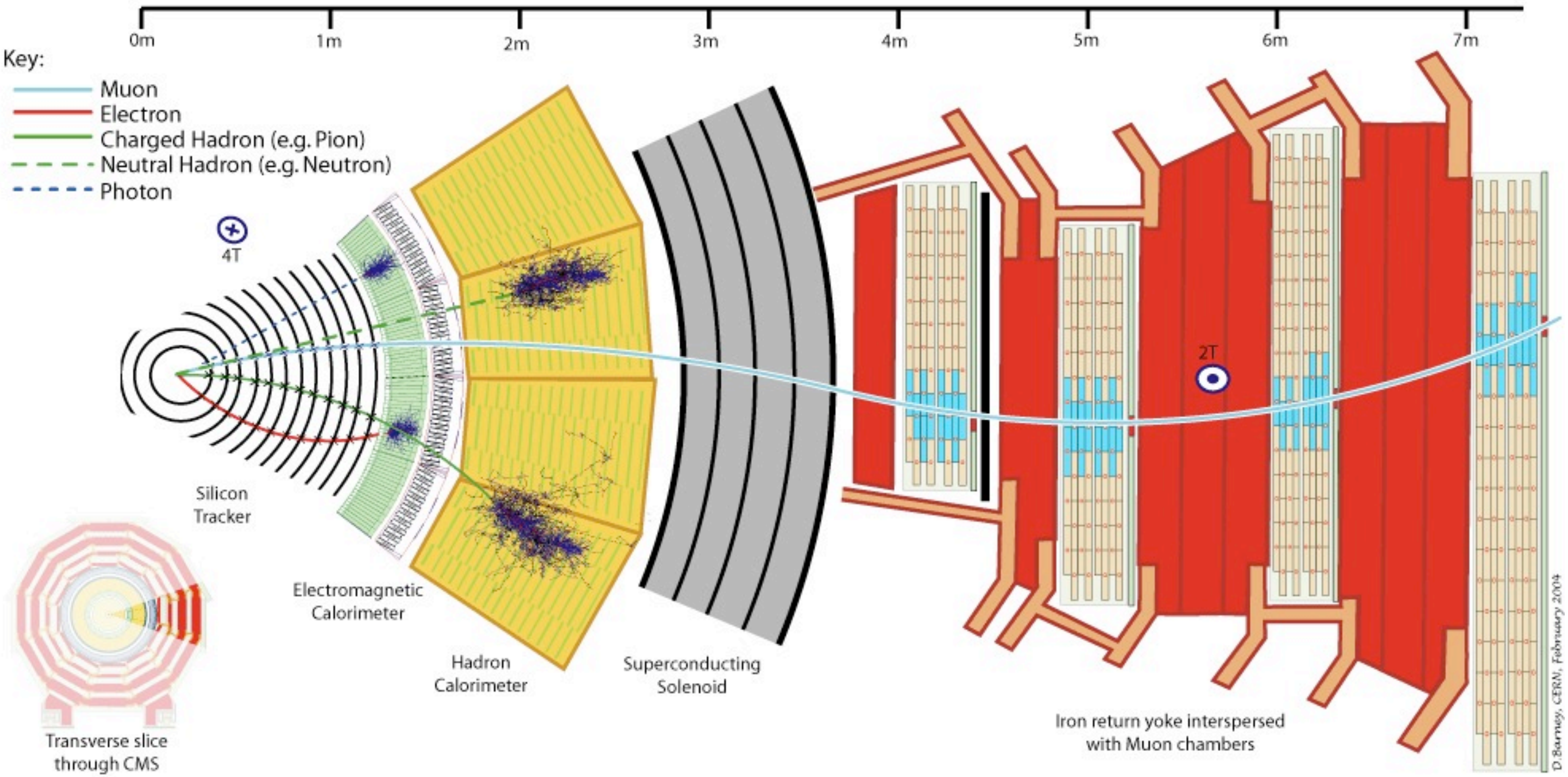




Post-filtering symmetry cut

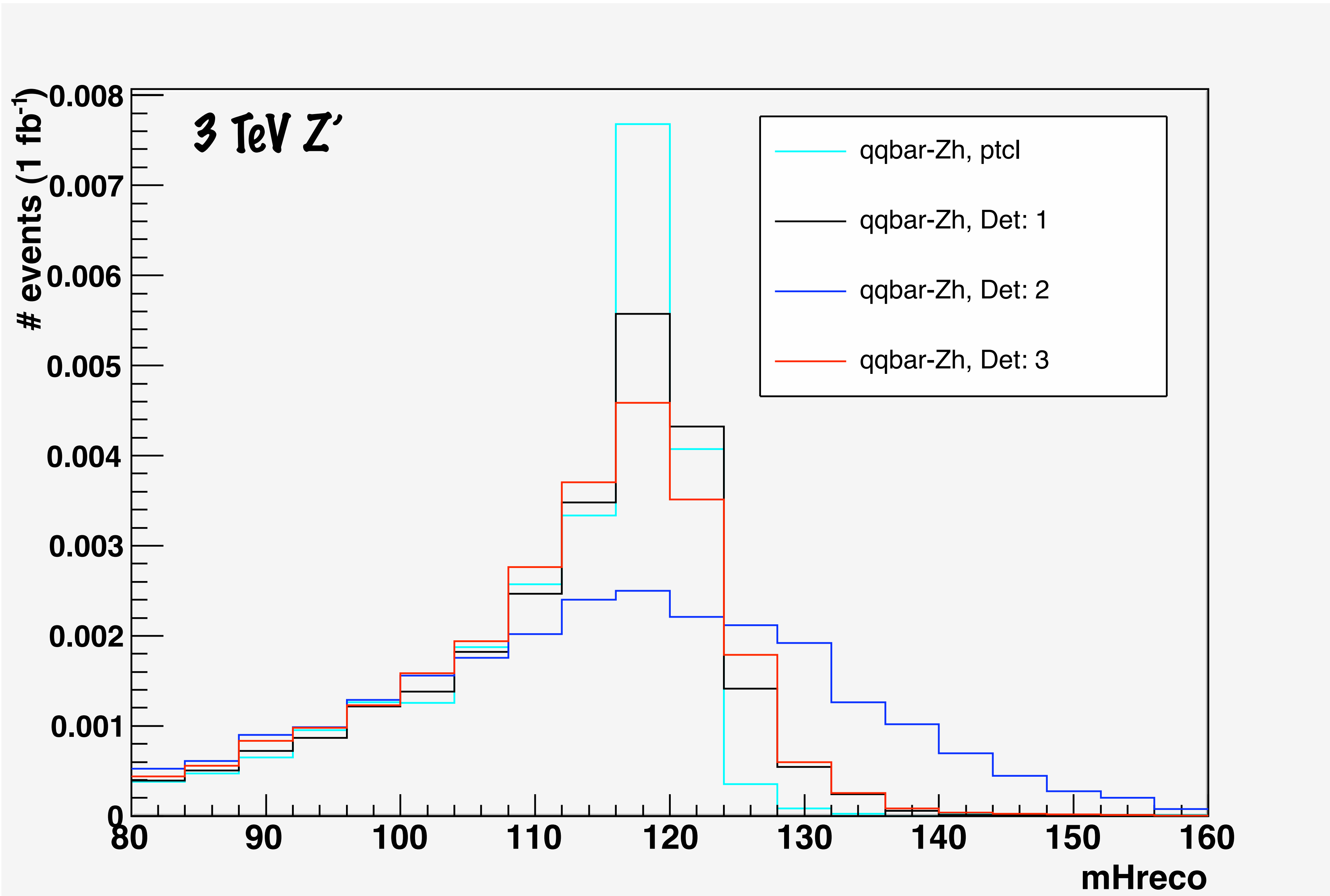
$: \; p_T(\text{filtered subjet \#2})/p_T(\text{filtered jet}) > 0.1$

Detectorize



$$\text{ATLAS}\ :\ 2.3\,\text{m}/2\,\text{T}$$

$$\text{CMS}\ :\ 1.8\,\text{m}/4\,\text{T}$$



Detector model 1: use tracker, ECAL and HCAL

Detector model 2: ignore tracker, use only ECAL and HCAL

Detector model 3: as above Det. model 2 with ECAL rescaled to match full ECAL + HCAL energy
(ECAL as tracker of jet energy flow)
E.g.