# Top Taggers

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Würzburg 11/2014

# Fat jets

## Boosted particles at the LHC

1994 boosted $W \to 2$ jets from heavy Higgs [Seymour]

1994 boosted $t \to 3$ jets [Seymour]

2002 boosted $W \to 2$ jets from strongly interacting $WW$ [YSplitter: Butterworth, Cox, Forshaw]

2006 boosted $t \to 3$ jets from resonances [Agashe, Belyaev, Krupovnickas, Perez, Virzi]

2008 boosted $H \to b\bar{b}$ [BDRS Higgs tagger: Butterworth, Davison, Rubin, Salam]

2008 boosted $t \to 3$ jets from resonances [JH/CMS tagger: Kaplan, Rehermann, Schwartz, Tweedie]

2009 boosted $t \to 3$ jets in Higgs production [HEPTopTagger: TP, Salam, Spannowsky]

2009 boosted $t \to 3$ jets from resonances [Template Tagger: Almeida, Lee, Perez, Sterman, Sung, Virzi]

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2010 first meta analysis review [BOOST proceedings, Ed: Karagoz, Spannowsky, Vos]

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2011 N-Subjettiness [Thaler, van Tilburg]

2011 Shower Deconstruction [Soper, Spannowsky]

2011 pedagogical review (partly basis for this talk) [TP, Spannowsky]

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2014 BDRS tagger with 427 citations, BOOST 2009-2014 done

# Jet Algorithms

## Definition of jets

- jet–parton duality $\Leftrightarrow$ what are partons in detector?
- need algorithm to reconstruct what was one parton [IR save recombination algos]
- crucial for any LHC analysis [ILC analyses without jets?]
- extension to $b$ and $t$ perturbative QCD problem

## Different measures [FASTJET: Cacciari, Salam, Soyez]

- define jet–jet and jet–beam distance [exclusive with resolution $y_{\text{cut}}$]

$$
\begin{array}{lll}
k_T & y_{ij} = \dfrac{\Delta R_{ij}}{R} \min\left(p_{T,i}, p_{T,j}\right) & y_{iB} = p_{T,i} \\
\text{C/A} & y_{ij} = \dfrac{\Delta R_{ij}}{R} & y_{iB} = 1 \\
\text{anti-}k_T & y_{ij} = \dfrac{\Delta R_{ij}}{R} \min\left(p_{T,i}^{-1}, p_{T,j}^{-1}\right) & y_{iB} = p_{T,i}^{-1} \; .
\end{array}
$$

- (1) find minimum $y^{\text{min}} = \min_{ij}(y_{ij}, y_{iB})$
  (2a) if $y^{\text{min}} = y_{ij}$ merge subjets $i$ and $j$, back to (1)
  (2b) if $y^{\text{min}} = y_{iB}$ remove $i$ from subjets, go to (1)
- theoretical and experimental trade-off decisions
- fat jets: use clustering history

# Analysis: $Z' \to t\bar{t}$

## LHC target $m_{Z'} \gtrsim 1.5$ TeV

- purely leptonic decays rate limited
- semi-leptonic approximate reconstruction of neutrino 4-vector:

  massless neutrino
  2D missing energy vector
  top or $W$ mass constraints
- purely hadronic decays deemed not useful

## Many taggers [Hopkins/CMS tagger, HEPTopTagger, template tagger, shower deconstruction]

- hadronic top identification and reconstruction
- jet separation challenging for heavy $Z'$
- combination of calo and tracker great
- usually combined with $b$-tag

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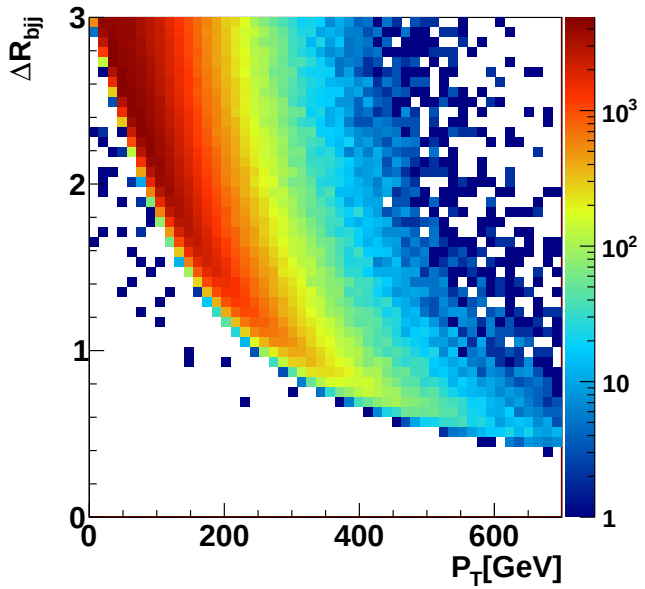
## Validation and systematics

- tagging easier for higher boost, $p_{T,t} > 600$ GeV
- Standard Model events at lower $p_{T,t} < 400$ GeV

$\Rightarrow$ $p_T$ range main challenge



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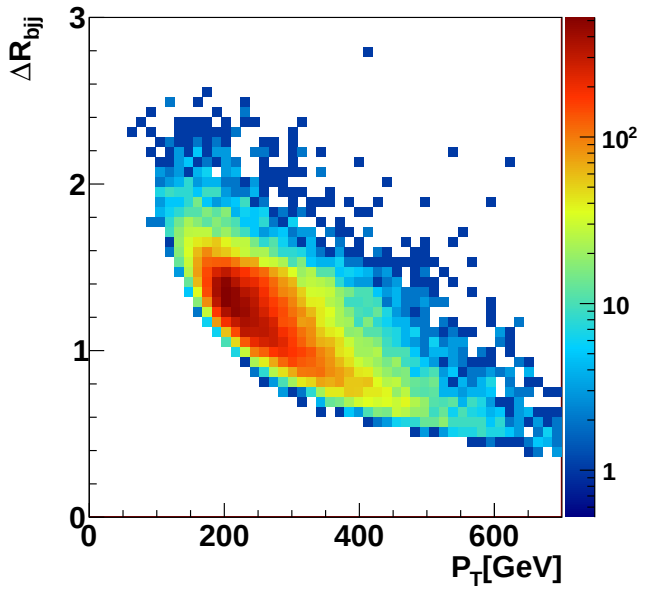


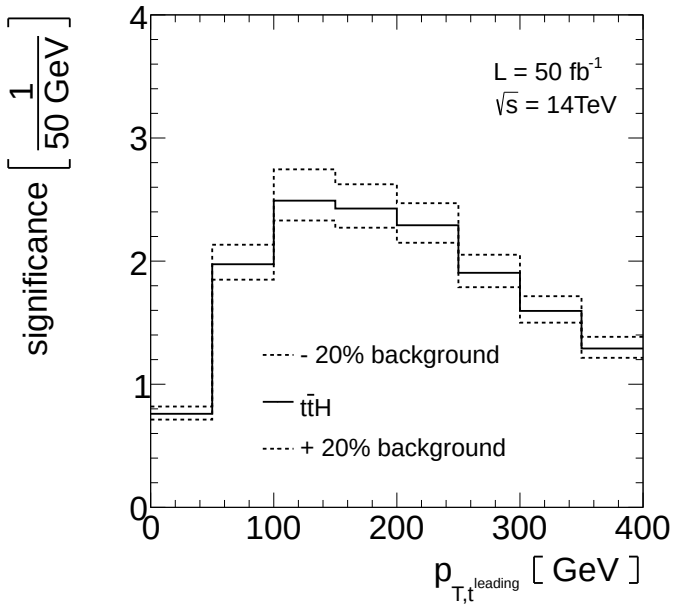
# Analysis: $t\bar{t}H, H \to b\bar{b}$

## Sad story of $t\bar{t}H, H \to b\bar{b}$ [CMS-TDR]

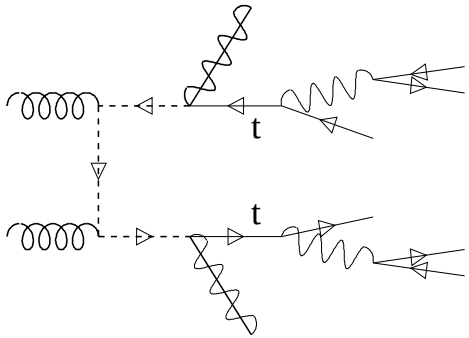
- trigger: $t \to bW^+ \to b\ell^+\nu$
  reconstruction and rate: $\bar{t} \to \bar{b}W^- \to \bar{b}jj$
- continuum background $t\bar{t}b\bar{b}, t\bar{t}jj$ [weighted by b-tag]
- 1– combinatorics: $m_H$ in $pp \to 4b_{tag}\ 2j\ \ell\nu$
  2– kinematics: peak-on-peak
  3– systematics: $S/B \sim \mathcal{O}(0.1)$

## Tagger [TP, Salam, Spannowsky; MadMax: TP, Schichtel, Wiegand]

- boost solving combinatorics [buckets]
- significance known to be in boosted regime
- side band in $m_{bb}$ possible
- fun: fat Higgs jet + fat top jet [similar $HH \to b\bar{b}b\bar{b}$]



# Analysis: top partners

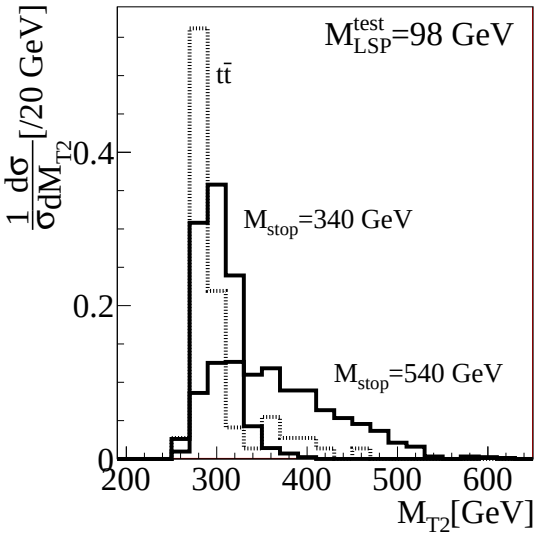



## Stop pairs including reconstruction [TP, Spannowsky, Takeuchi, Zerwas]

- stop crucial for hierarchy problem
  comparison to other top partners [Meade & Reece]
- hadronic: $\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0\ \bar{t}\tilde{\chi}_1^0$
- stop mass from $m_{T2}$ endpoint [like sleptons or sbottoms]

$$m_{T2}(\hat{m}_\chi) = \min_{\not{p}_T = q_1 + q_2} \left[ \max_j\ m_{T,j}(q_j; \hat{m}_\chi) \right] \overset{!}{<} m_{\tilde{t}}$$

$\Rightarrow$ hadronic search as easy as $b\bar{b} + \not{E}_T$



# N-Subjettiness

## N-Jettiness to count subjets inside fat jet [Thaler, van Tilburg]

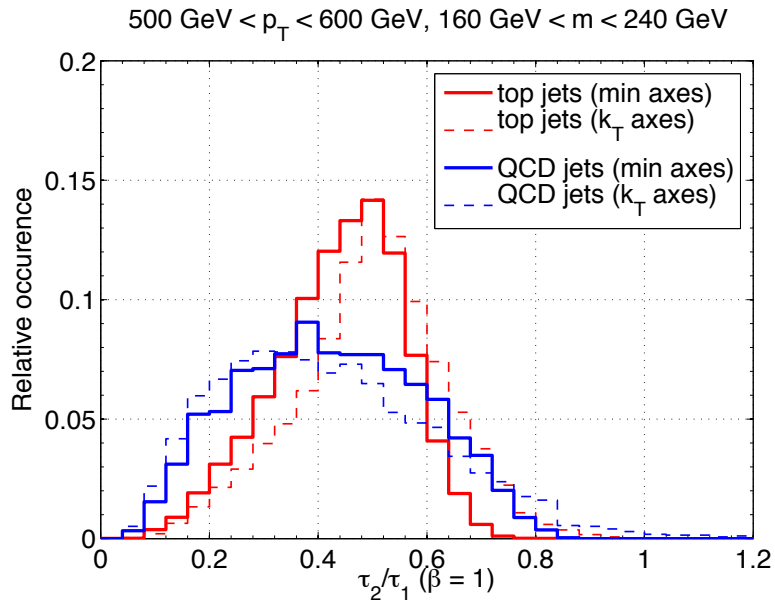
- how many subjets do the calo entries correspond to?
- event shape using $N$ subjet directions $\hat{n}_j$ $[\beta > 0]$

$$\tau_N = \frac{1}{\sum_{\alpha \in \text{jet}} p_{T,\alpha} R_0^\beta} \sum_{\alpha \in \text{jet}} p_{T,\alpha} \min_{k=1,\ldots,N} (\Delta R_{k,\alpha})^\beta$$

- choice of reference axes

  1- from subjet algorithm
  2- from minimization of $\tau_N$

- $\tau_N \to 1$ means many calo entries away from $N$ axes
  $\tau_N \to 0$ means perfect matching
- systematics cancelled in ratios
  $\tau_{N+1}/\tau_N$ with dip for $N+1$ subjets



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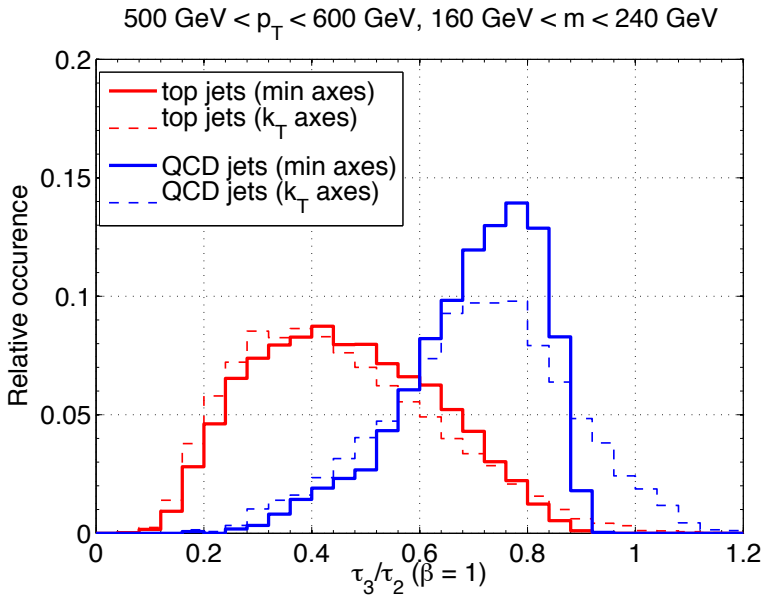

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## Tagger

- simple selection

$$m_{\text{fat jet}} = 160 \ldots 240 \;\; \text{GeV} \qquad \frac{\tau_3}{\tau_2} < 0.6$$

- multi-variate in $N$ and $\beta$ with some improvement

$\Rightarrow$ easily added to any other tagger

# HEPTopTagger

## Mass drop algorithm [TP, Salam, Spannowsky, Takeuchi]

1– C/A fat jet, $R = 1.5$ and $p_T > 200$ GeV [FastJet limitation]

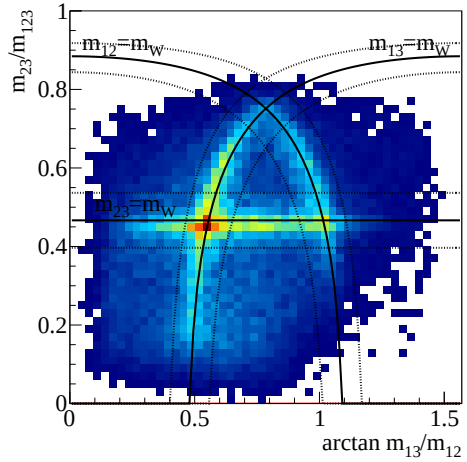
2– mass drop, cutoff $m_{\text{sub}} > 30$ GeV

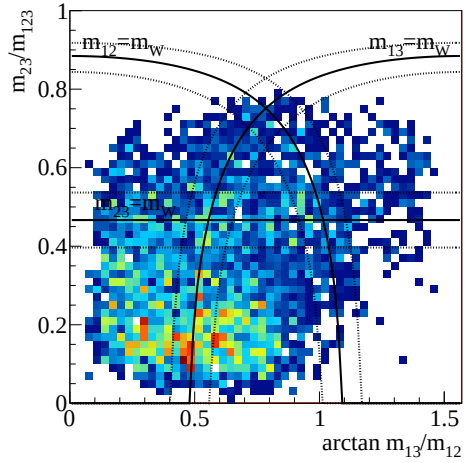
3– filtering leading to hard substructure triple

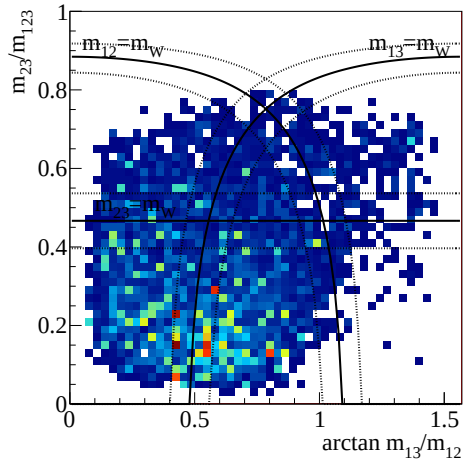
4– top mass window $m_{123} = [150, 200]$ GeV

5– A-shaped mass plane cuts as function of $m_W/m_t$

6– consistency condition $p_T^{(\text{tag})} > 200$ GeV



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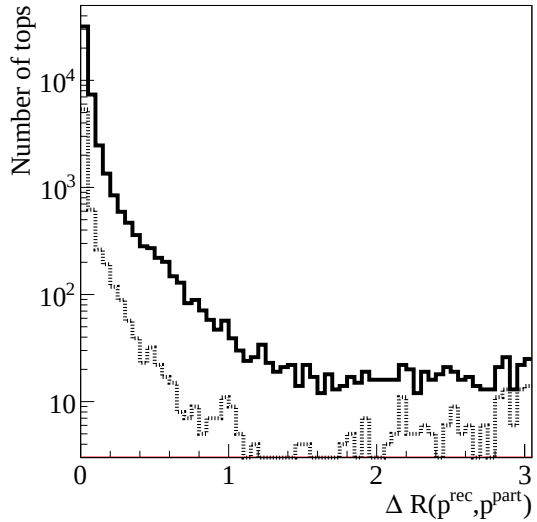
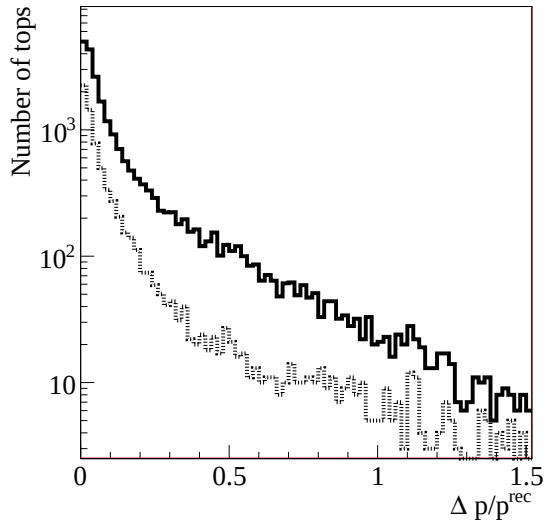
## Top reconstruction

– direction less critical

– energy requiring calibration



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## Improvements for upcoming run

– signal efficiency

– background sculpting

– $p_T$ range

– resonance reconstruction

# ATLAS Analysis

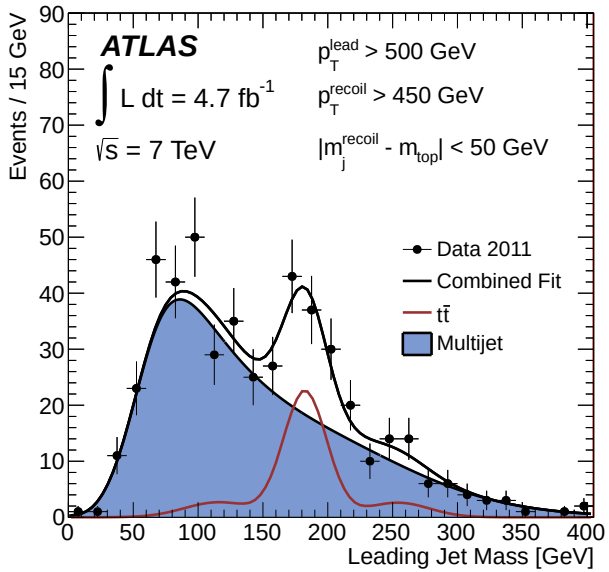
## ATLAS resonance search [CERN-PH-EP-2012-291, ATLAS-CONF-2013-084]

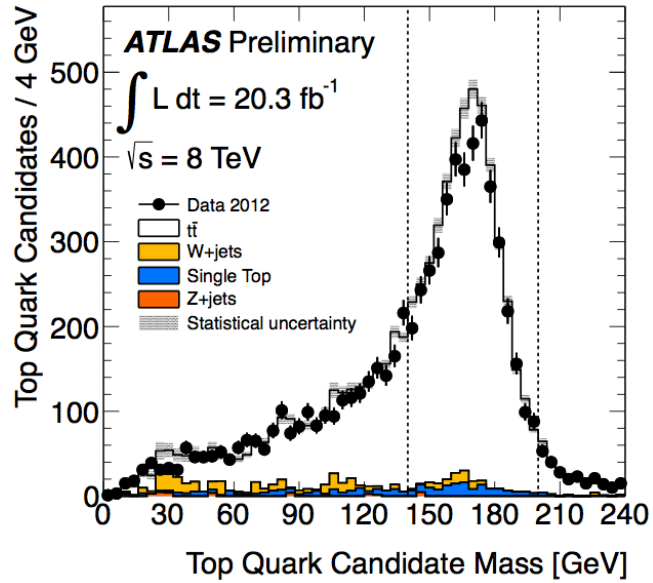
- resonances decaying to $t\bar{t}$ [mass 1.0-1.5 TeV]
- $Z'$ or KK gluon only different in width, $\Gamma_{Z'} < \Gamma_G$
- semi-leptonic searches done before

$\Rightarrow$ mostly test of top taggers

## Test of subjet methods [Kasieczka, Schätzel, Anders, ask Andre Schöningp]

- starting with lots of jet calibration
- also add *b*-tag in/around fat jet
- fat jet and top masses in data [background region]



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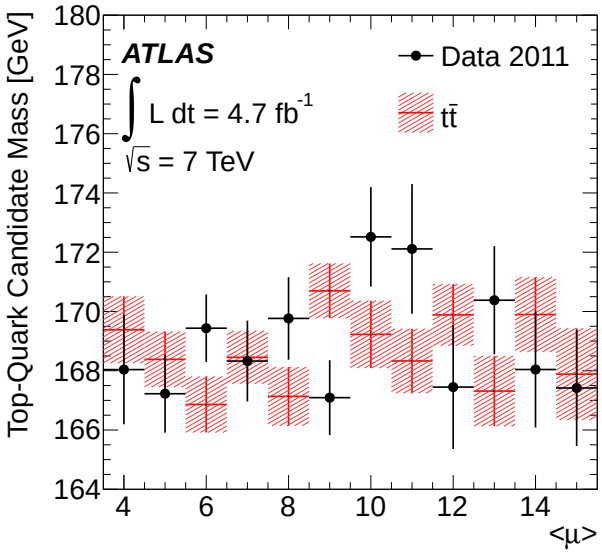


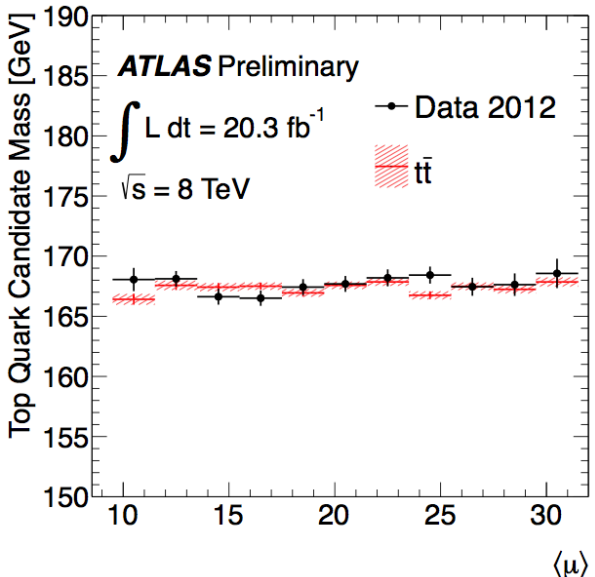

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$\Rightarrow$ subjet methods established

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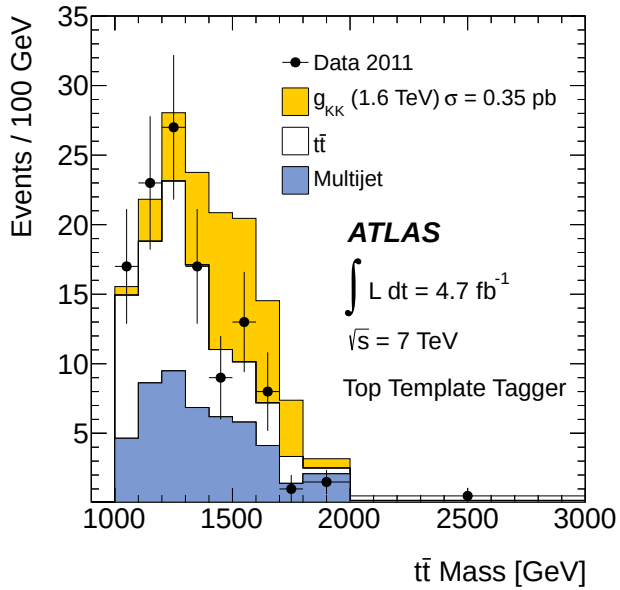
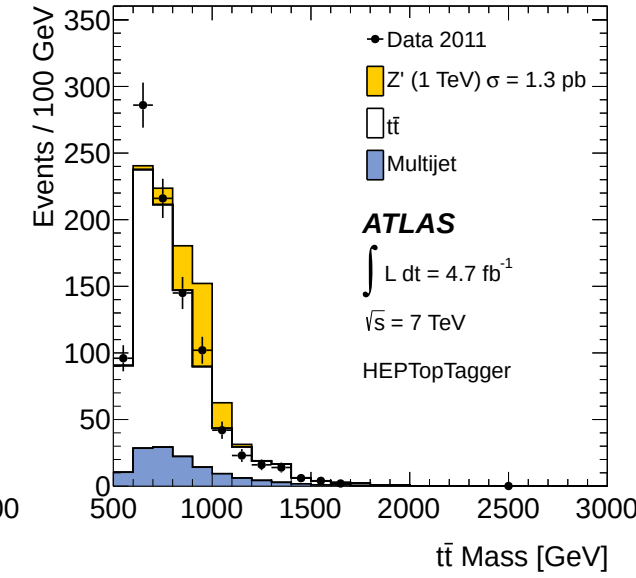
## Resonance search

- $m_{tt}$ from TemplateTagger and HEPTopTagger



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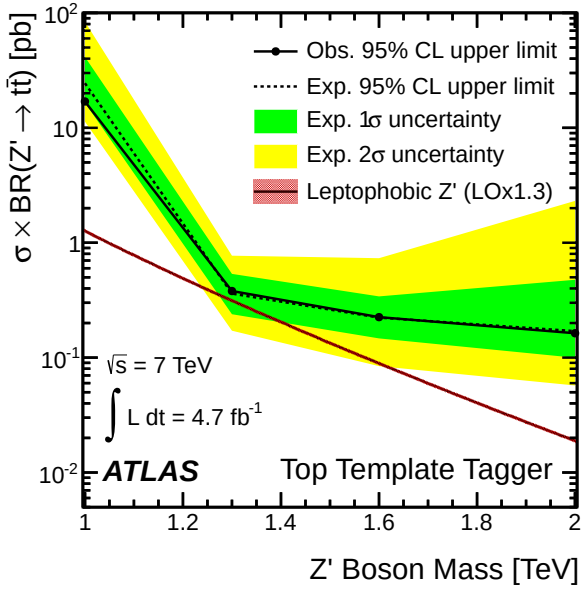


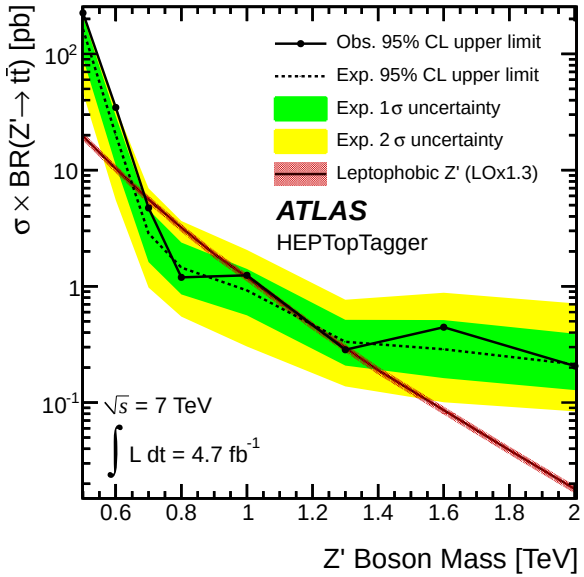

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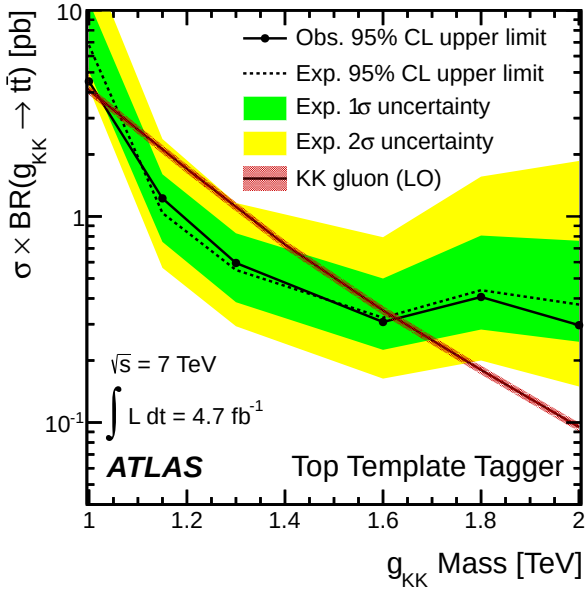


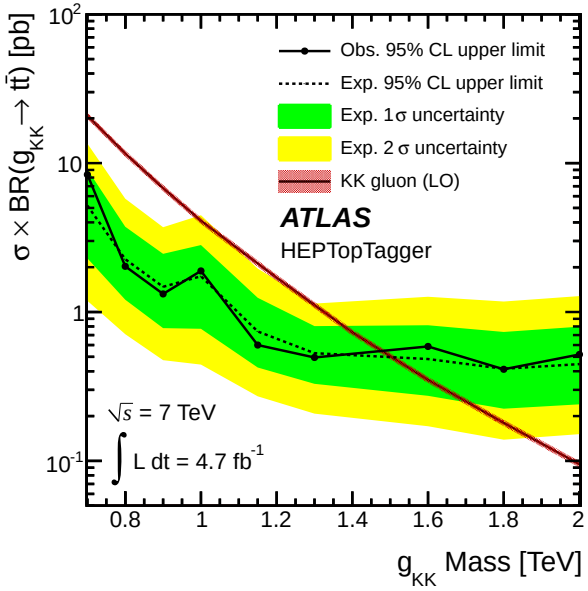

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## Resonance search

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- limit on $Z'$
- limit on KK gluon

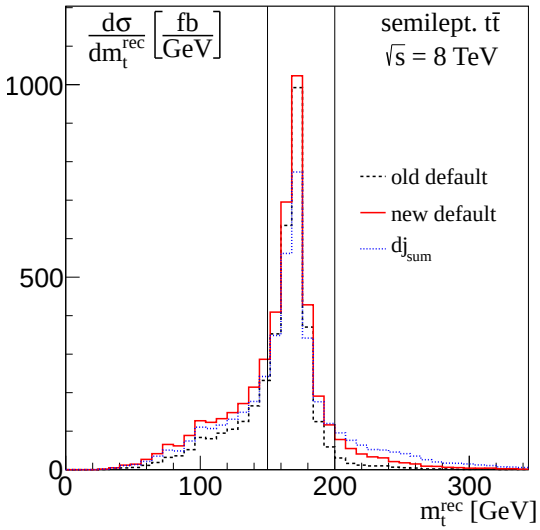
$\Rightarrow$ it actually works!

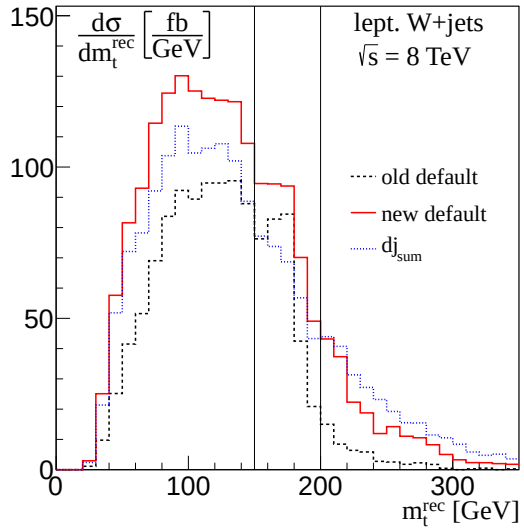
# Better HEPTopTagger

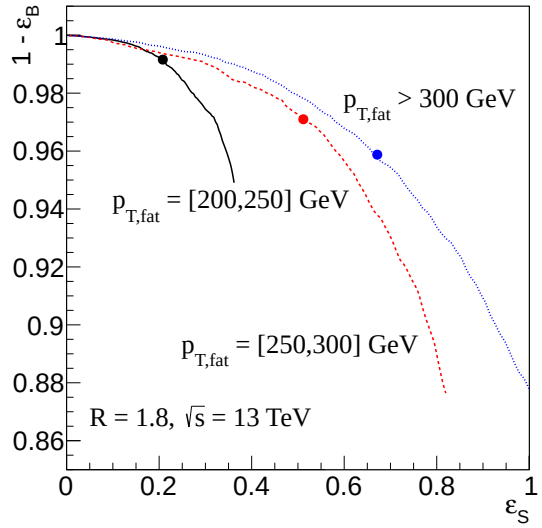
## Improved algorithm [TP, Spannowsky, Takeuchi; Anders, Bernaciak, Kasieczka, TP, Schell]

- increase size $R = 1.8$
- change in cut order $3 \leftrightarrow 4$
- alternative triplet selection

  maximal $dj_{\text{sum}} = \sum p_{T,i} p_{T,j} (\Delta R_{ij})^4$
  triplet of hardest subjets
- BDT $\{m_{13}, m_{23}, m_{123}, (m_W/m_t)^{(\text{rec})}\}$ [on semilep sample]



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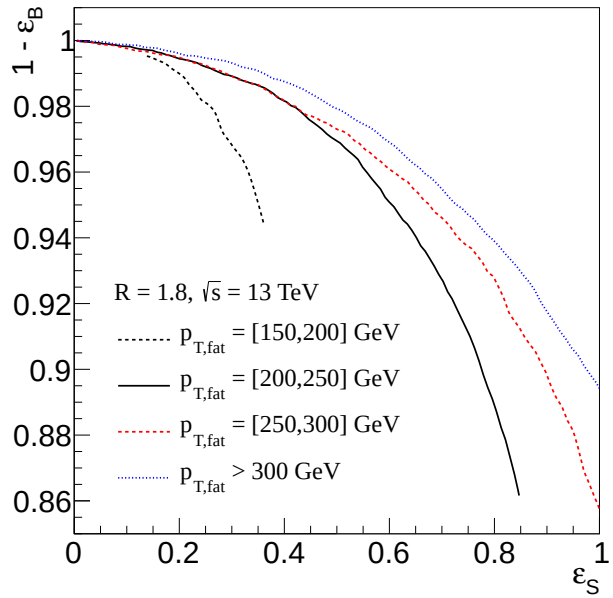
## Towards low $p_T$ [Anders, Bernaciak, Kasieczka, TP, Schell]

- focus on $p_T = [150, 200]$ GeV
- target type-2 tags [two hardest subjets matched]
- correlations via Fox–Wolfram moments

$$H_\ell^U = \sum_{i,j} \frac{1}{N^2} P_\ell(\cos \Omega_{ij})$$

- $\{m_{13}, m_{23}, m_{123}, (m_W/m_t)^{(\text{rec})}, \text{FWMs}\}$



# MultiR HEPTopTagger

## Extended algorithm [Kasieczka, TP, Salam, Schell, Strebler (prelim)]

- optimal $R_{\text{min}}$

  large to include all decay jets
  small to avoid combinatorics, ISR, pile-up
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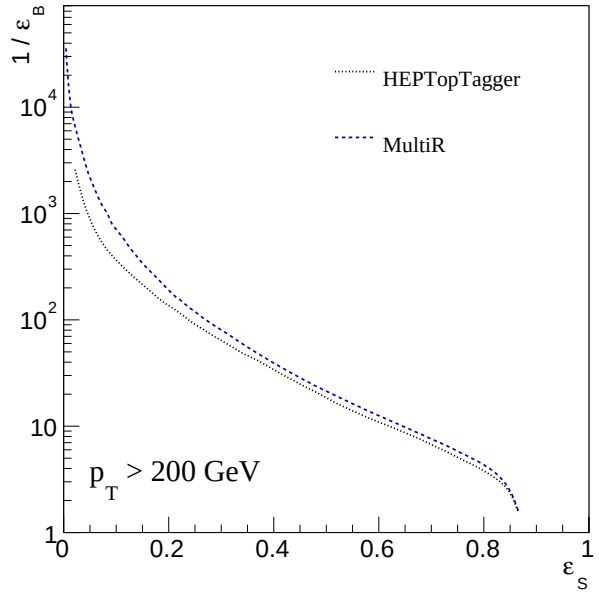
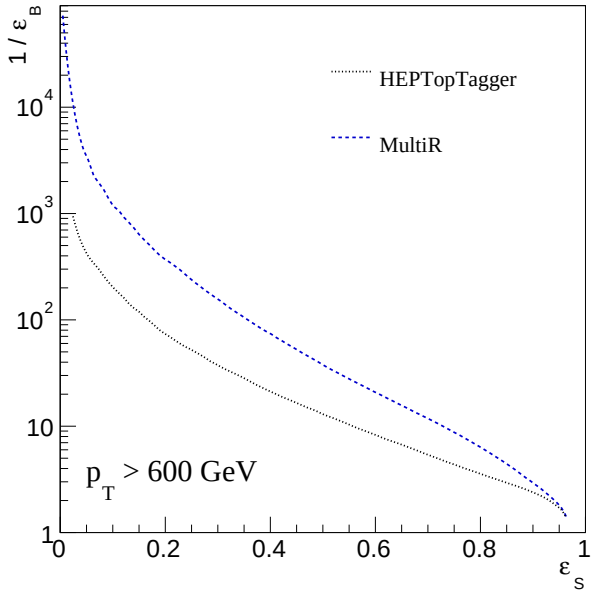
- $\{m_{123}^{(R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}\}$ $[f_W = \min|m_{ij}/m_{123} - m_W/m_t|]$



# MultiR HEPTopTagger

## Extended algorithm [Kasieczka, TP, Salam, Schell, Strebler (prelim)]

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## Combined with N-Subjettiness [DESY group]

- fixed multiR working point
- also include rejected events $[R_{\text{filt}} = 0.2,\ N_{\text{filt}} = 5]$
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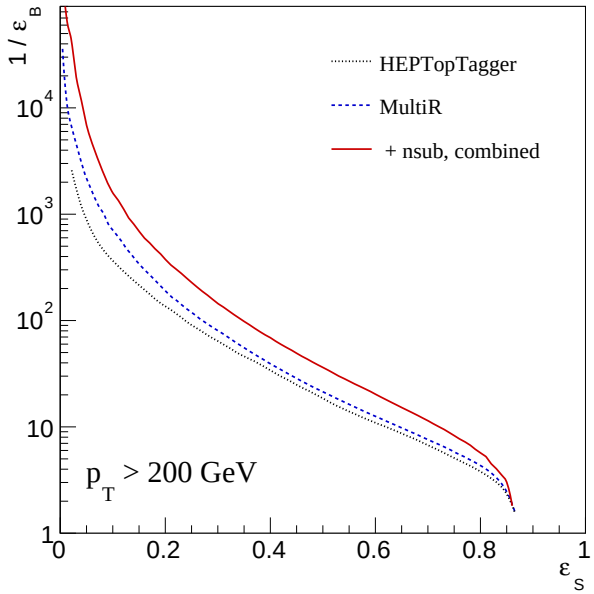

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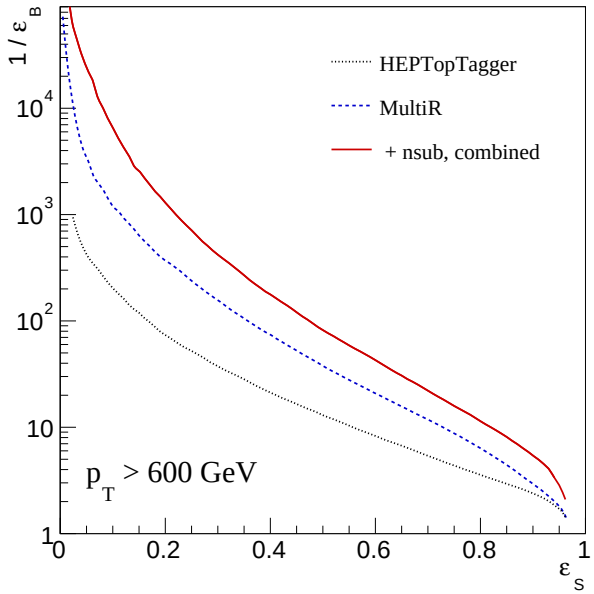
$\Rightarrow$ stay tuned for HEPTopTagger2.0



# Taggers beyond cuts

## Best clustering history

- BDRS-like taggers asking for mass drop in best clustering history
- deterministic means conceptionally simple
- limited in efficiency
- limited in observables

## Beyond single clustering history

- shower deconstruction: Sudakov weighting
- Qjets weighted by [Ellis, Hornig, Roy, Krohn, Schwartz]

$$\omega_{ij} = \exp\left[-\alpha \frac{y_{ij} - y_{ij}^{\min}}{y_{ij}^{\min}}\right]$$

  then using distributions like $\langle m^2 \rangle - \langle m \rangle^2$
- Jet Sampling applying Qjets and weights to full event [Kahawala, Krohn, Schwartz]

$\Rightarrow$ few convincing studies around, maybe because of $W$ tagging?

# Shower Deconstruction

## Remember matrix element method [Tevatron]

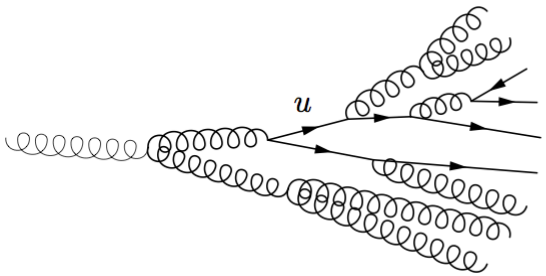
- measured fully exclusive cross section: $d\sigma$
  computed matrix element squared: $|\mathcal{M}|^2(m_t)$
- direct comparison to determine $m_t$
- Neyman–Pearson: log likelihood ratio best test statistic [minimum false positive]

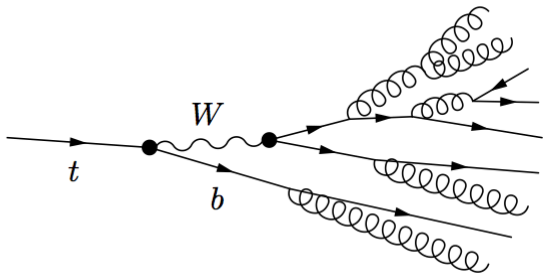
$$q(\vec{r}) = -\sigma_{\text{tot},s}\ \mathcal{L}\ + \ln\left(1 + \frac{d\sigma_s(\vec{r})}{d\sigma_b(\vec{r})}\right) \equiv -\sigma_{\text{tot},s}\ \mathcal{L}\ + \ln\chi$$

- combinatorics by adding likelihoods

## Same for subjets [Soper, Spannowsky]

- background from QCD splittings [parton shower]
  signal from hard decays
  Sudakovs for non–splitting
- compute LLR for signal and background assumption as ‘top-ness’ measure



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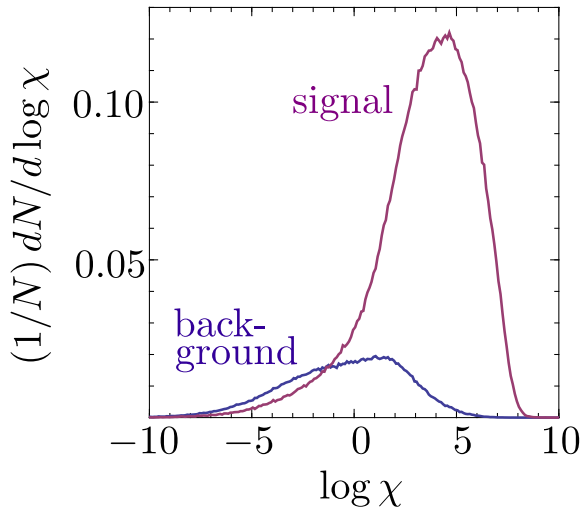
## Implementation [1211.3140]

- look at microjets inside fat jet $[R_{k_T} = 0.2, p_T < 5 - 10\ \text{GeV}, N = 9]$
- approximate parton shower as description [shower time, analytic computation]
- compute $\chi$ for signal/background hypothesis
  $\chi > 0$ for 68% (14%) for S (B)

$\Rightarrow$ tagger with $\chi_{\text{min}}$

- combined with MEM to Event Deconstruction



# Resonance Searches and FSR

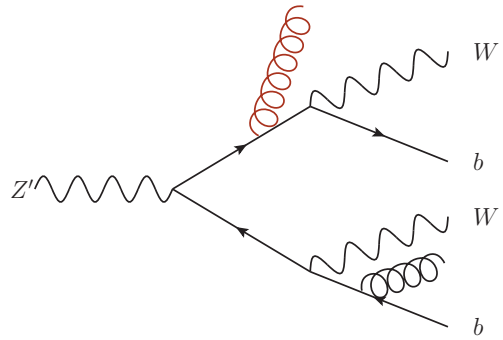
## Shower/Event Deconstruction setup [Soper, Spannowsky]

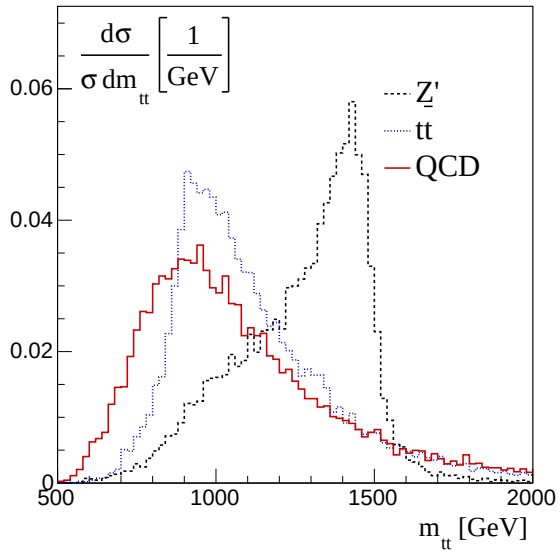
- signal: $Z' \to t_h \bar{t}_h$, $m_{Z'} = 1.5$ TeV, $\Gamma_{Z'} = 65$ GeV
- background: QCD di-jets, SM $t_h \bar{t}_h$,
- no detector simulation
- fat jets $p_T > 400$ GeV, $|y| < 2.5$

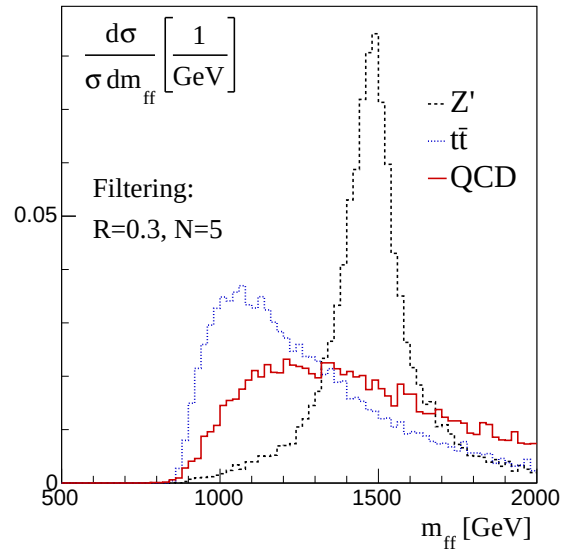
## Final state radiation

- use reconstructed 4-momentum of tagged top
- tail in $m_{tt}^{(\text{rec})}$ from tagged momentum and FSR

$\Rightarrow$ use 4-momentum of fat jet: $\{m_{tt}, p_{T,t}, m_{jj}^{(\text{filt})}, p_{T,j}^{(\text{filt})}\}$



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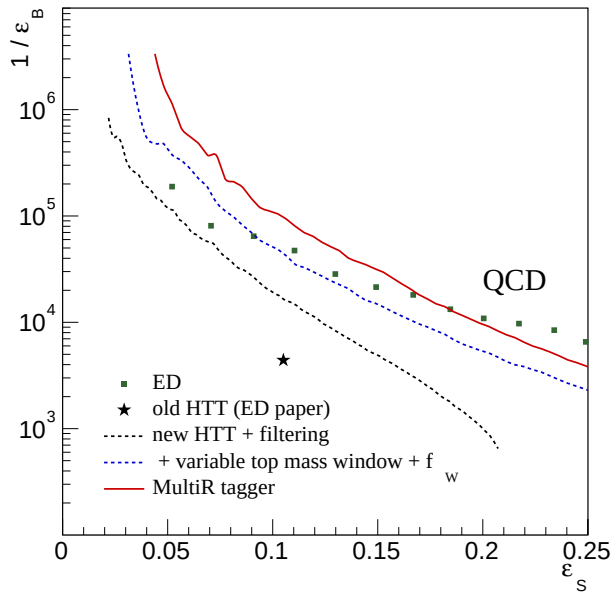
## Preliminary comparison with HEPTopTagger2.0

- multiR $\{m_{tt}, p_{T,t}, m_{jj}^{(\text{filt})}, p_{T,j}^{(\text{filt})}, m_{123}^{(\text{min},R_{\text{min}})}, m_{123}^{(\text{max},R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}\}$
- N-Subjettiness still missing
- high efficiencies still a challenge [NN instead of BDT?]
- definite tools progress



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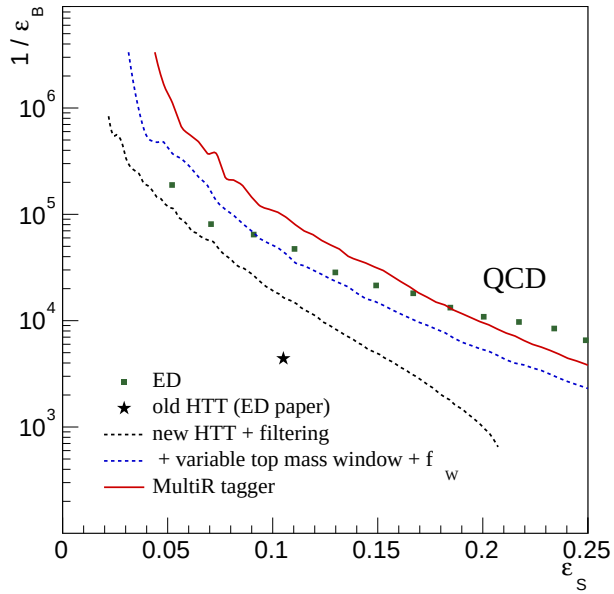


## Open theory questions

- more and more algorithms/variables included
- less and less perturbative QCD
- multivariate analyses standard

$\Rightarrow$ Do we (does Gavin) know what we are doing?

# Outlook

## Fat Jets are...

...turning jet physics into a cool topic

...a fast–moving and happy field

...bringing together experiment and theory

...an opportunity for young people to have impact

...always honoring good ideas

## Sorry for not discussing...

...template taggers

...wavelet taggers

...your favorite tagger

## Thank you to...

...former and current ATLAS–Heidelberg

...all groups working with and on taggers

*Lectures on LHC Physics*, Springer, arXiv:0910.4182 updated under `www.thphys.uni-heidelberg.de/~plehn/`