Jets at the LHC
(both pp and $PbPb$)

aka Jets of a new generation

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Plan

- Basic jet definitions
  - Motivation: the need for a jet definition
  - Situation today: meeting the 1990 requirements
- New directions (*selected topics*)
  - Jet substructure: filter UE, tag boosted objects
  - Subtracting soft background using jet areas
- New directions (*additional topics*)
  - Optimisation: kinematic dijet reconstruction
  - Dijet asymmetries: what room for quenching?
  - Tools: Towards FastJet 3.0

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- New directions (*additional topics*)
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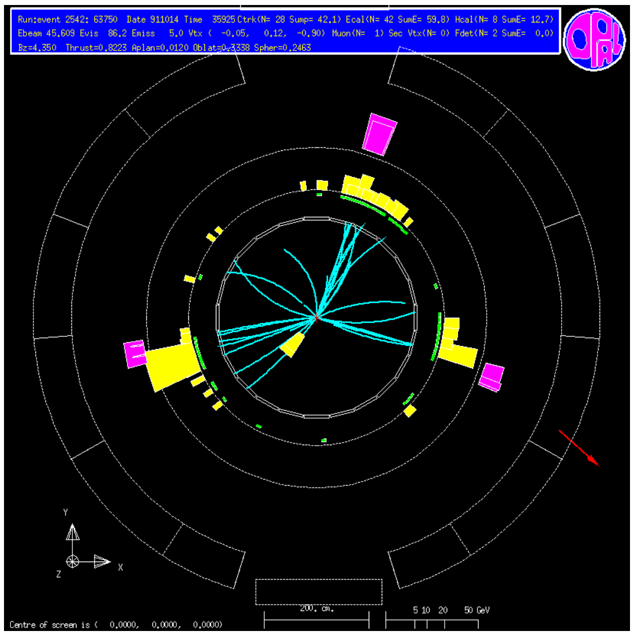
  - Dijet asymmetries: what room for quenching? [$PbPb$]
  - Tools: Towards FastJet 3.0 [pp, $PbPb$]

Jet definitions

“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons



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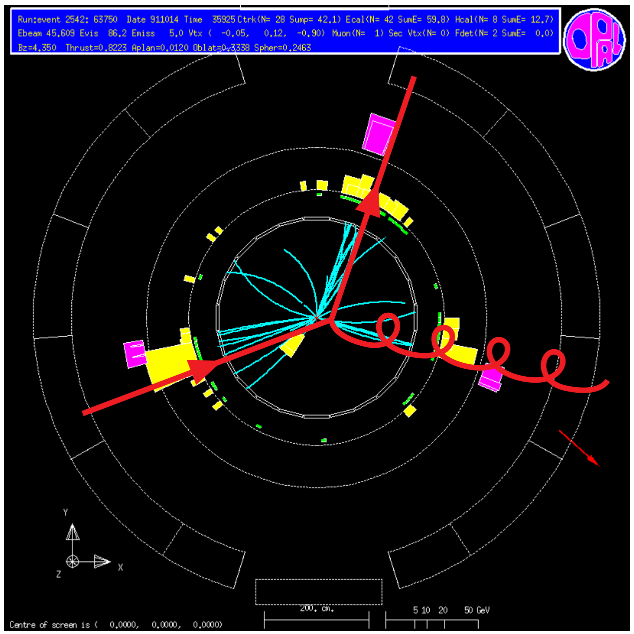

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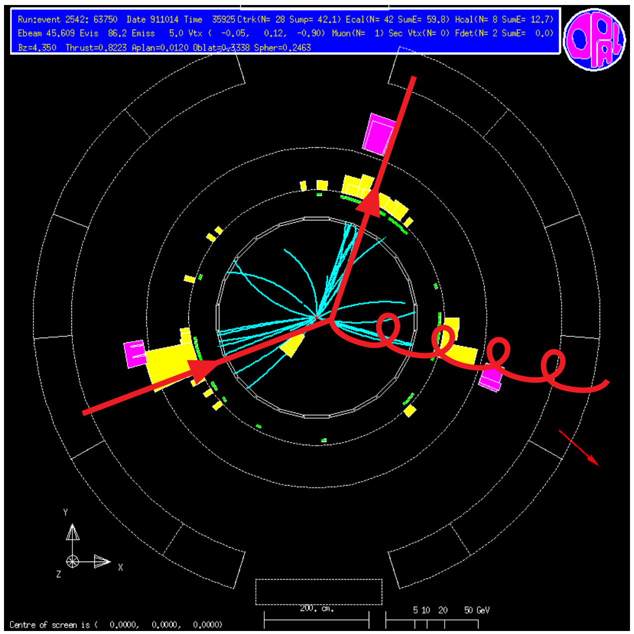

In practice: use a <u>jet definition</u>

particles $\{p_i\}$ $\xrightarrow[\textbf{definition}]{\textbf{jet}}$ jets $\{j_k\}$

algorithm: the recipe (insufficient!)

definition: algorithm + params

“Jet=hadron” too simplistic: What opening for “collimated”? NLO?

Jet algorithms: a big family

Recombination:

- k_t algorithm
- Cambridge/Aachen alg.
- anti-k_t algorithm

Cone:

- SISCone
- CDF JetClu
- CDF MidPoint
- D0 (run II) Cone
- PxCone
- ATLAS Cone
- CMS Iterative Cone
- PyCell/CellJet
- GetJet

Jet definitions: constraints

SNOWMASS accords (FermiLab, 1990)

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

20 years later, these are only recently satisfied!!!

Jet algorithms: the situation now

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Jet algorithms: the situation now

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Implementation:
FastJet
www.fastjet.fr

Cone:

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Inside jet definitions

- Recombination: successively recombine the closest pair

$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2)$$

  Stop at distance R

  - $p = 1$: k_t algorithm (very close to QCD)

    [Catani, Dokshitzer, Seymour, Webber, 93]

  - $p = 0$: Cambridge/Aachen (C/A) algorithm (substructure studies)

    [Dokshitzer, Leder, Moretti, Webber, 93]

  - $p = -1$: anti-k_t algorithm (circular/rigid jets)

    [Cacciari, Salam, GS, 08]

- Cone: $\approx$ flow of energy in a cone (of fixed R) centred on the cone centre: SISCone

  [Salam, GS, 07]

Finite perturbative cross-section: only consider infrared-and-collinear-safe algorithms

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  the default at the LHC [Cacciari, Salam, GS, 08]

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Finite perturbative cross-section: only consider infrared-and-collinear-safe algorithms

New generations

Challenges

Idea: set of solid algorithms: optimise their usage

- Handle pileup (in pp) and large UE (in $PbPb$)
- Tag boosted objects/Study substructure
- filter out UE contamination to jets
- optimize reconstruction

New generations
2. pileup subtraction using jet areas

[M.Cacciari,G.Salam, 07]

[M.Cacciari,G.Salam,GS, 08]

[M.Cacciari,J.Rojo,G.Salam,GS, 10]

Physics cases and scales

Typical applications: [GeV]

Case	$\rho = p_t/$unit area	σ =flucts	$\delta p_{t,\mathrm{jet}}(R = 0.4)$
Pileup in pp	10-20	3-5	5-10
$AuAu$ (RHIC)	80-100	8-12	40-50
$PbPb$ (LHC)	150-250	15-25	75-125

Central formula

$$p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{bkg}} A_{\text{jet}}$$

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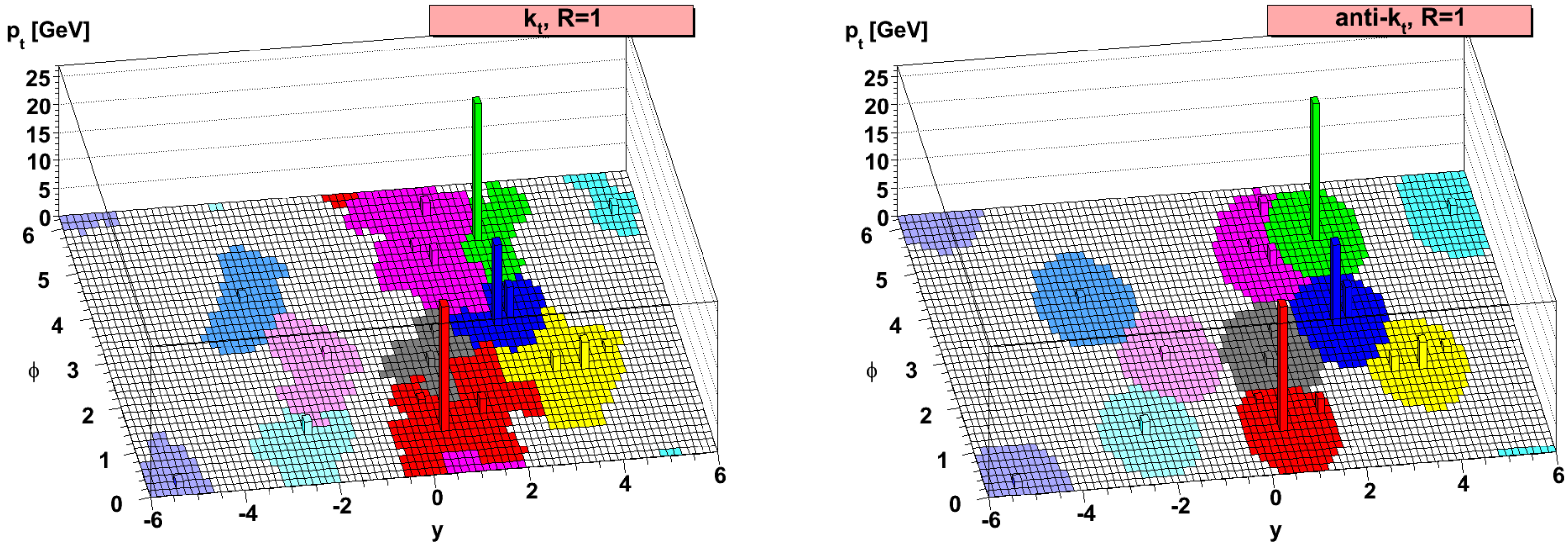
$$p_{t,\mathrm{jet}}^{(\mathrm{sub})} = p_{t,\mathrm{jet}} - \rho_{\mathrm{bkg}} A_{\mathrm{jet}}$$

- jet area:
  - defined to mimic the reaction to the background
  - implemented in FastJet
  - analytic handle

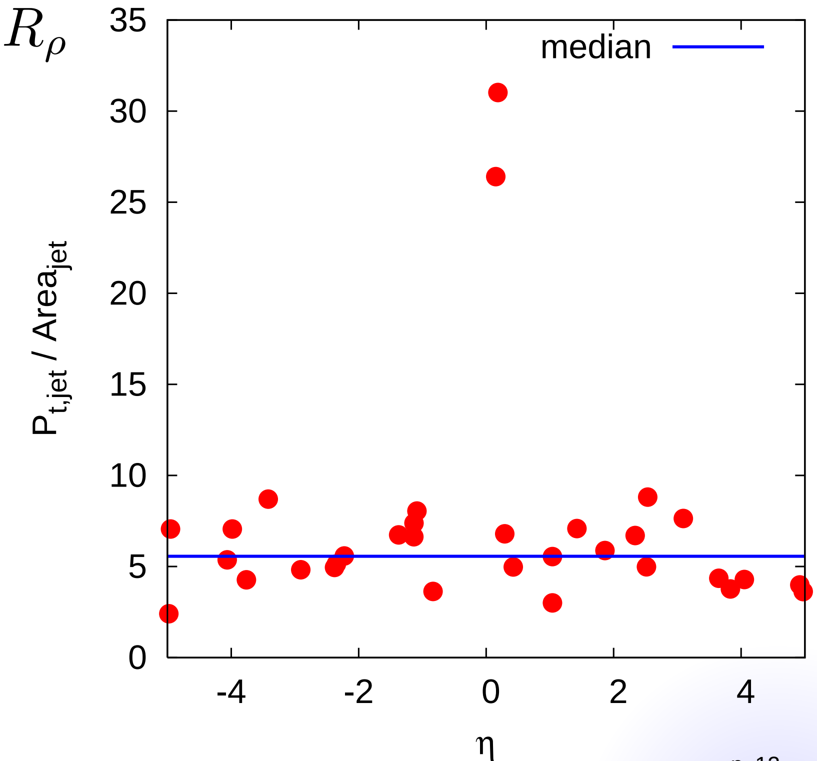


Central formula

$$p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{bkg}} A_{\text{jet}}$$

- jet area:
- ρ_{bkg}, the background p_t density per unit area
  - Cluster with k_t of C/A with "radius" R_ρ
  - Estimate ρ_{bkg} using

$$\rho_{\text{bkg}} = \underset{j \in \text{jets}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$



Subtraction uncertainties

1. Background fluctuations: (inside an event!)

$$p_{t,\text{jet}} = p_{t,\text{jet}}^{\text{hard}} + \rho_{\text{bkg}} A_{\text{jet}} \pm \sigma_{\text{bkg}} \sqrt{A_{\text{jet}}}$$

Hint: reduce A_{jet} *e.g.* using filtering

Subtraction uncertainties

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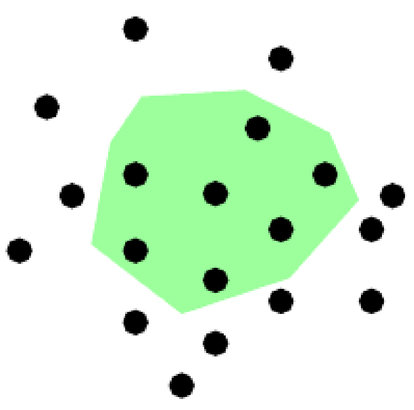
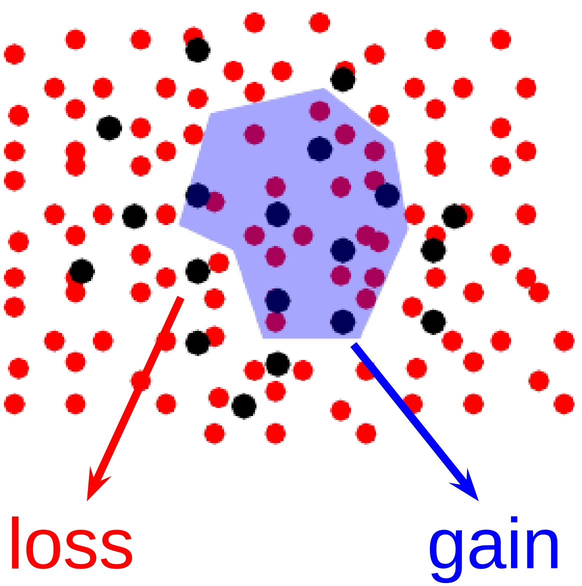
2. Back-reaction:

No background



With background



Hint: use anti-k_t (rigidity!)

Subtraction uncertainties

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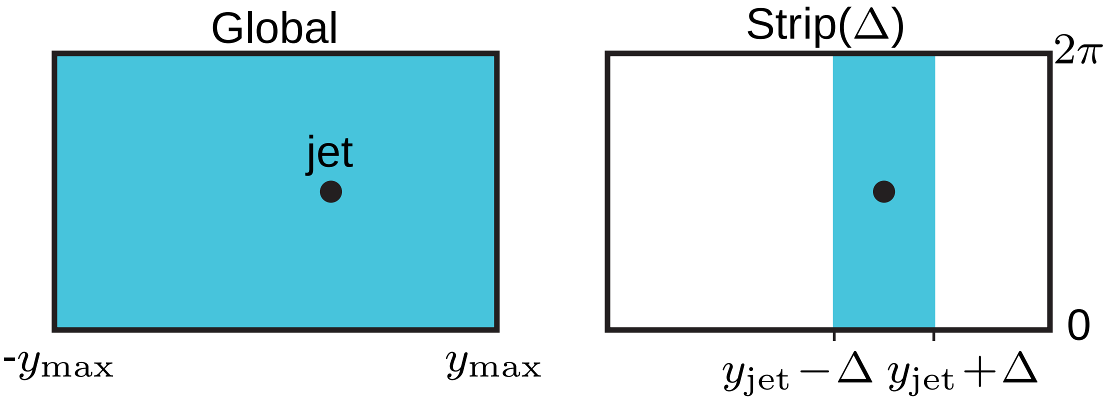
2. Back-reaction:

3. Background non-uniform (*e.g.* rap dependence)
   Use jets in a *local range* to estimate ρ_{bkg}

$$\rho_{\text{bkg}} = \underset{j \in \mathcal{R}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$



+ exclude the (*e.g.*) 2 hardest jets

Subtraction uncertainties

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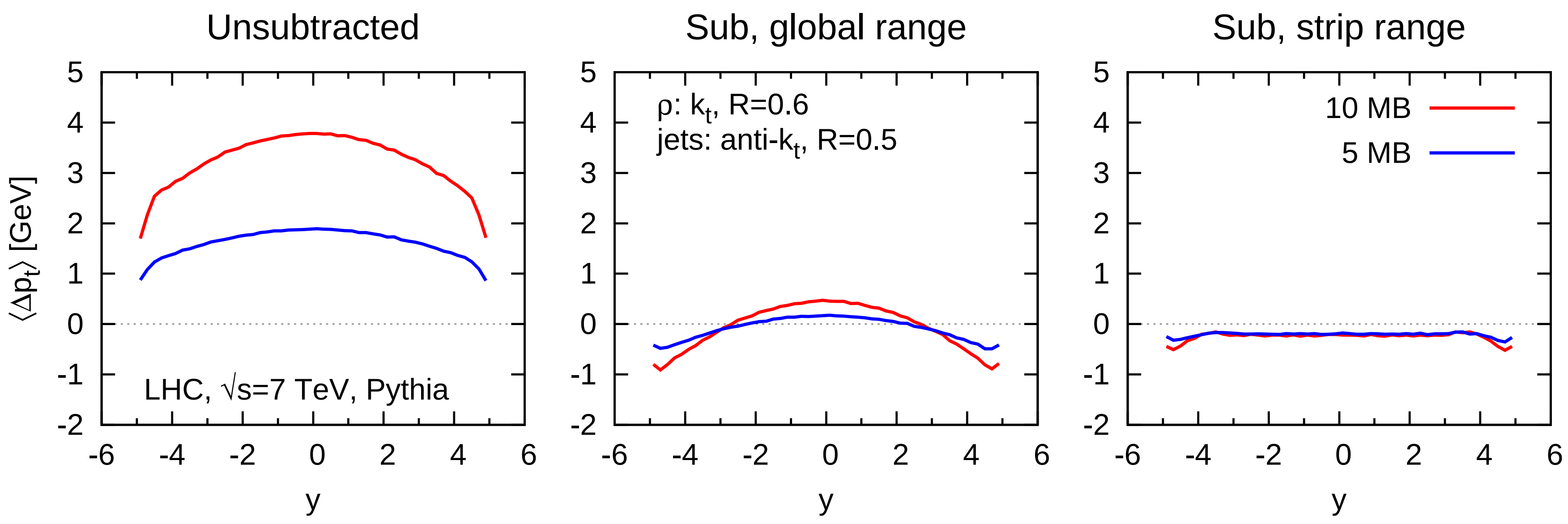

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Typical applications:

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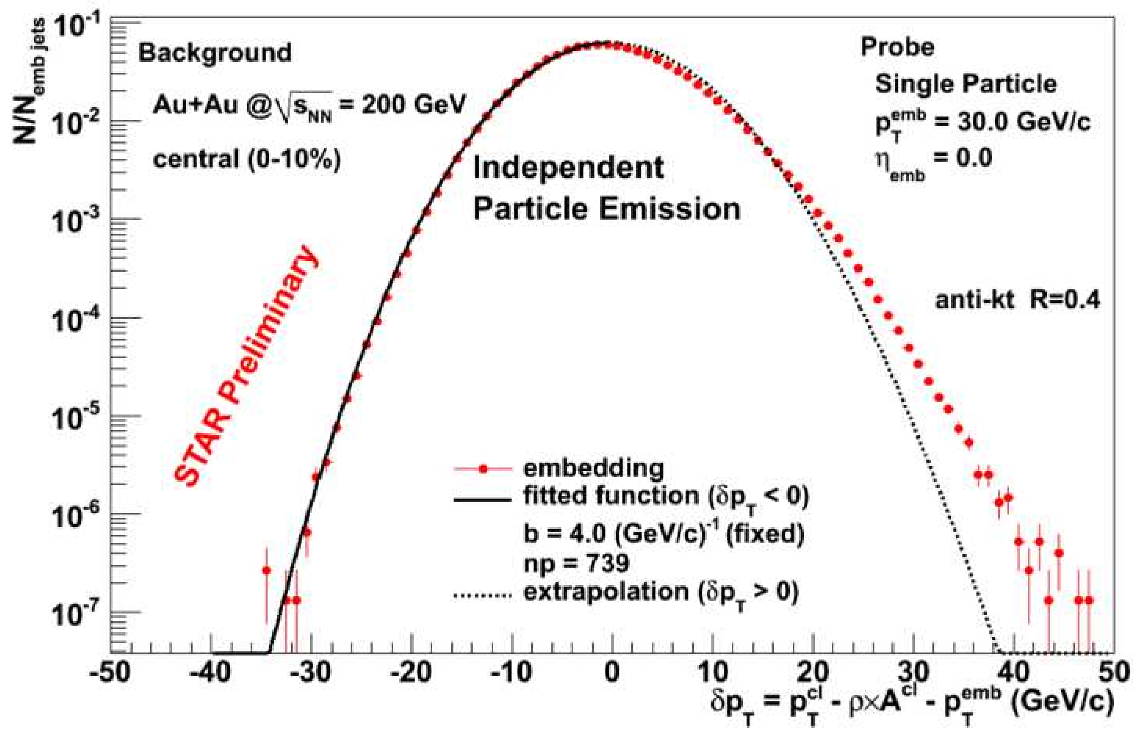
- After subtraction: $|\delta p_{t,\text{jet}}| \lesssim$1 GeV
- Left with fluctuations (and back-reaction)

Physics cases and scales

Typical applications:

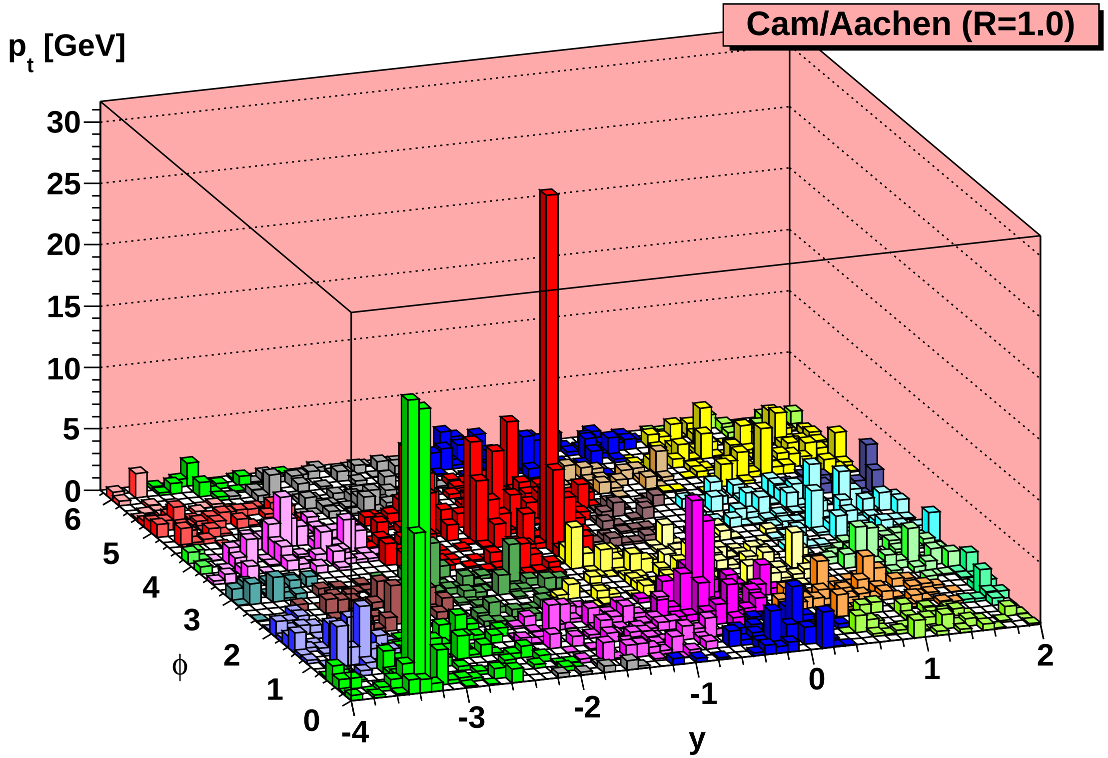
Case	0.4)
Pileup in pp	
$AuAu$ (RHIC)	
$PbPb$ (LHC)	



- After subtra
- Left with flu
- Can be studied *e.g.* by embedding “known jets into background data” ($\rightarrow$ unfolding)

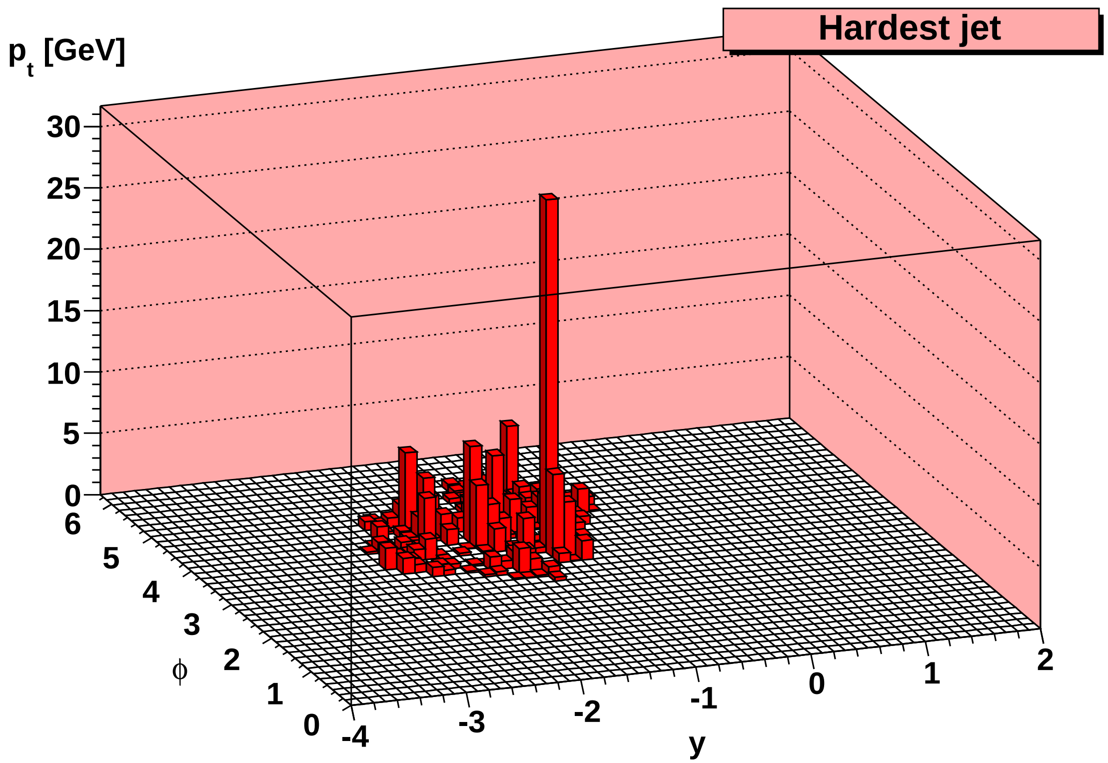
New generations
2. Jet substructure

Filtering



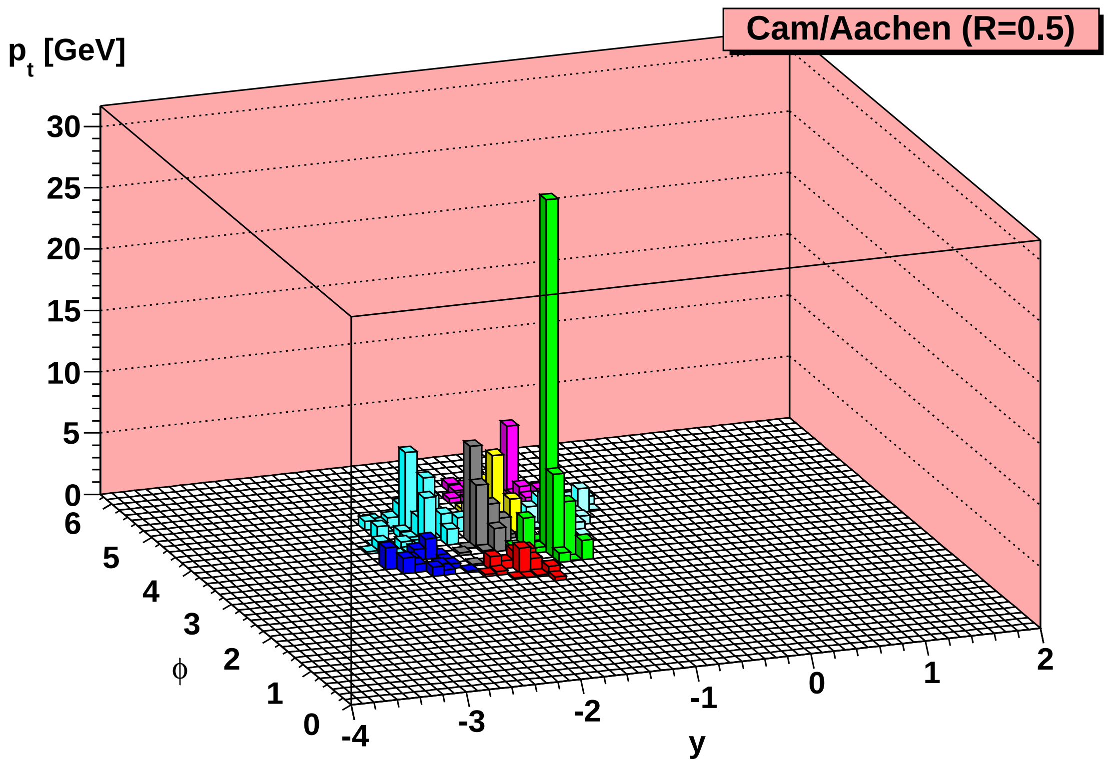
- cluster with Cambridge/Aachen(R)

Filtering



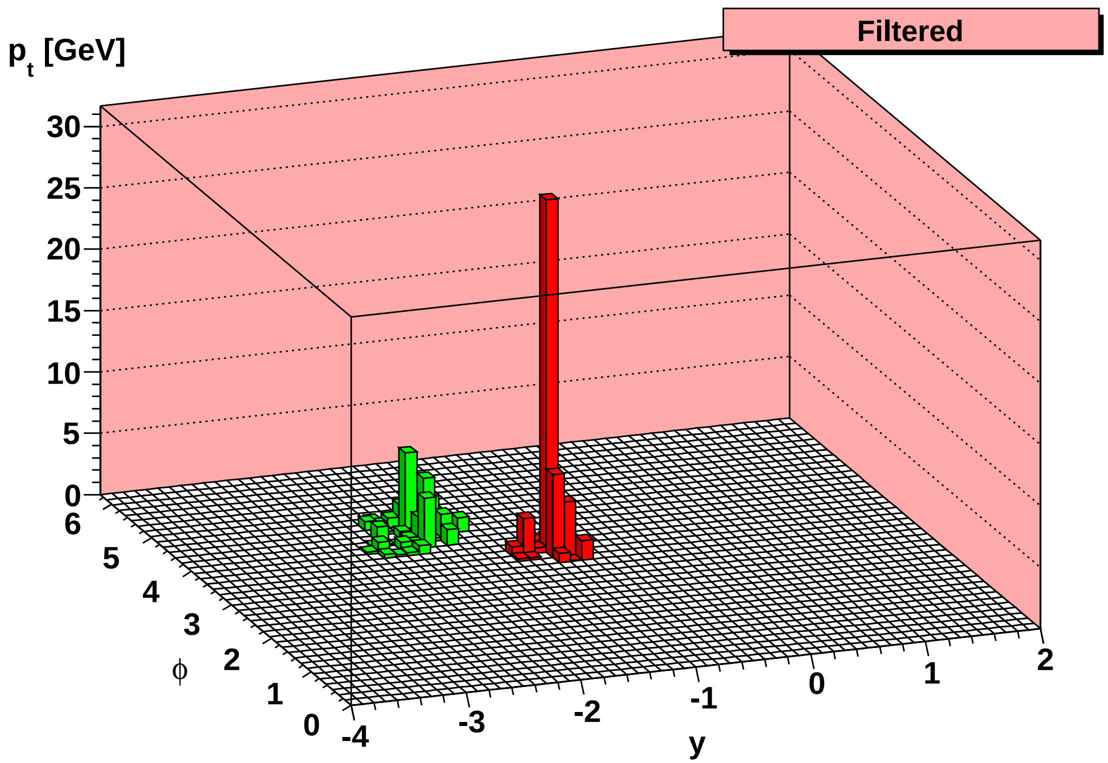
- cluster with Cambridge/Aachen(R)
- for each jet

Filtering



- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)

Filtering



- cluster with Cambridge/Aachen(R)
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  - recluster with Cambridge/Aachen(R/2)
  - keep the 2 hardest subjets

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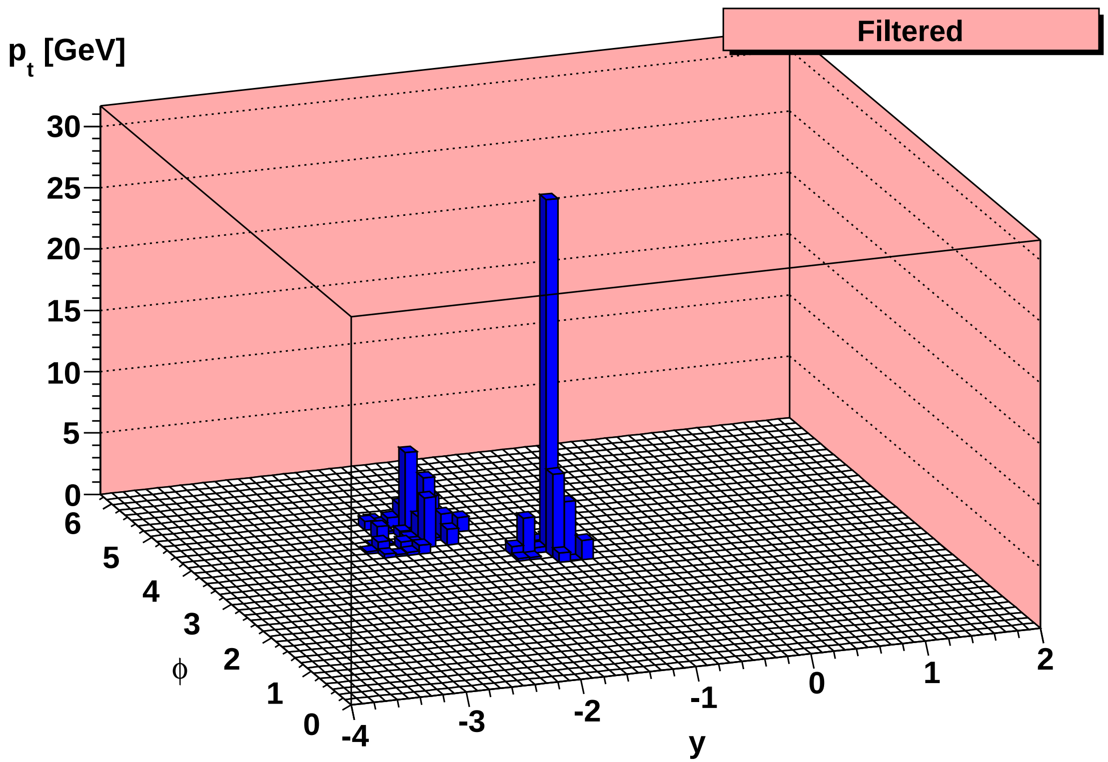

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Idea:

✓ keep perturb. radiation

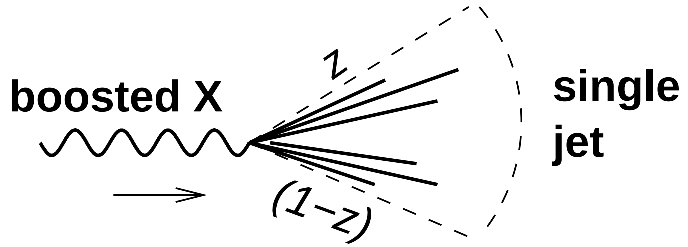
✓ remove UE

- Proven useful for boosted jet $H \to b\bar{b}$ tagging
  [J.Butterworth, A.Davison, M.Rubin, G.Salam, 08]
- Proven useful for kinematic reconstructions
  [M.Cacciari, J.Rojo, G.Salam, GS, 08]
- Similar: trimming [D.Krohn,J.Thaler,L-T.Wang,10]

Boosted object tagging

Problem:

boosted heavy object $\Rightarrow$ decays reconstructed in a single jet



$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

How to disantangle that from a QCD jet?

Idea: substructure *e.g.* look inside the jet

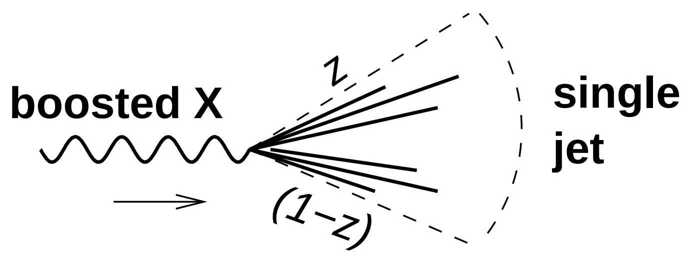
Various methods: mass drop, pruning, use Jade distances, asymmetry cuts,...

Applications: (examples)

- 2 decay products: $W \to q\bar{q}$, $H \to b\bar{b}$
- 3 decay products: $t \to qqb$, $\tilde{\chi} \to qqq$
- busier: $t\bar{t}H$

Example: boosted Higgs

[J.Butterworth, A.Davison, M.Rubin, G.Salam,08]



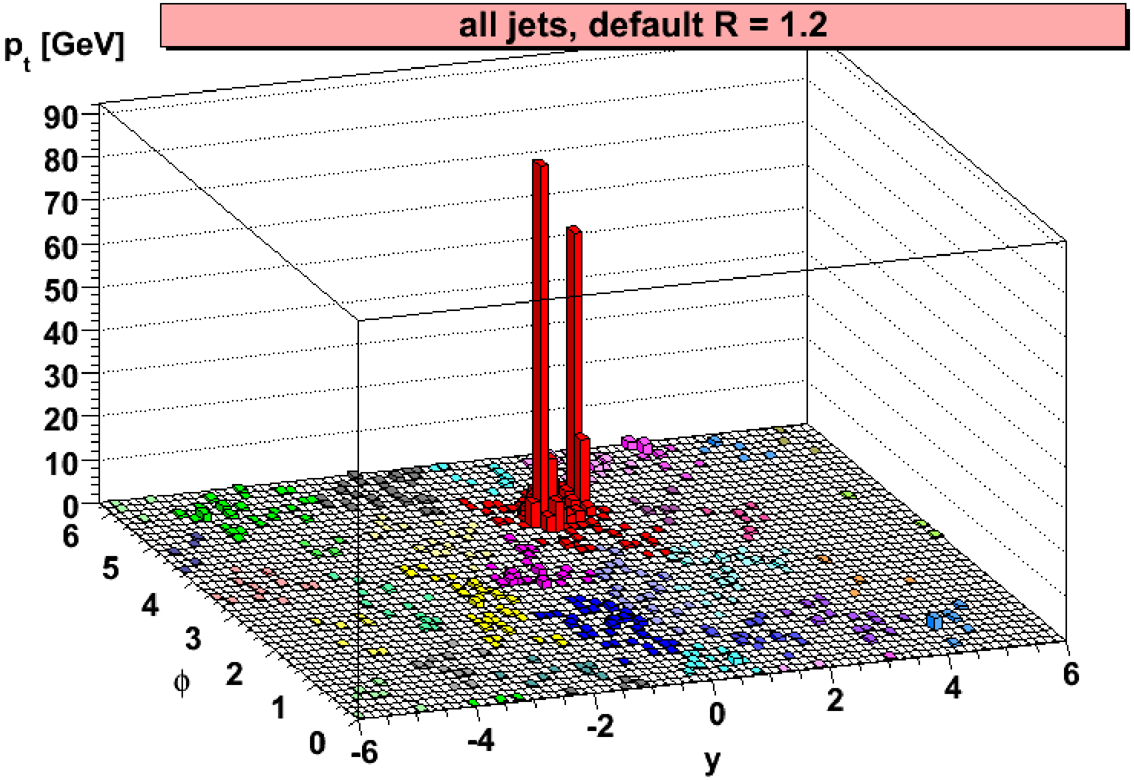
$$R \gtrsim \frac{m}{p_t}\frac{1}{\sqrt{z(1-z)}}$$

Method: start with a hard (C/A, radius R) jet j

1. Undo the last clustering $\to j_1, j_2$
2. If $\max(m_1, m_2) < 0.67m$, we have a mass drop, else back to 1
   idea: find the 2 b-jets, dynamically find R_{bb}
3. Require symmetric splitting $y_{12} \approx \frac{\min(z_1,z_2)}{\max(z_1,z_2)} > 0.09$, else go to 1
   idea: remove QCD asymmetric splittings
4. Require 2 b taggings
5. Filter *i.e.* uncluster down to $R_{\rm filt}$, keep the 3 hardest subjets
   idea: keep "hard" QCD radiations, reduce UE

Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Cluster C/A, R=1.2

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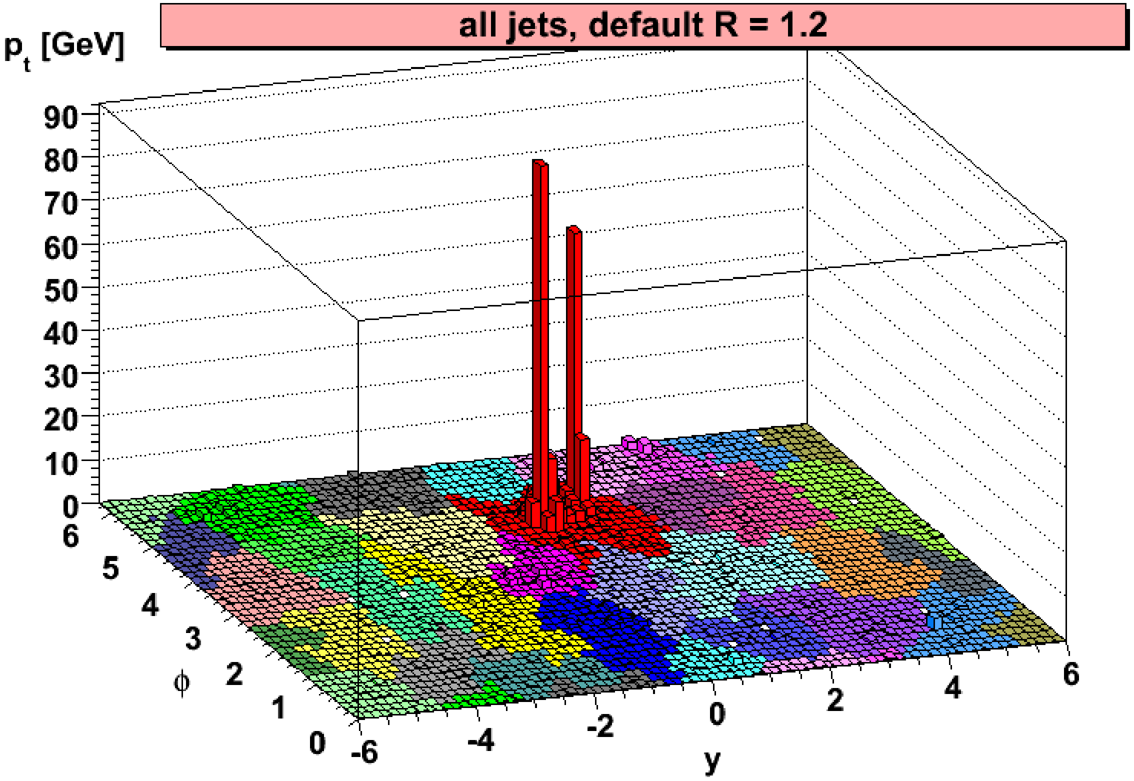

Show jets more clearly

Boosted Higgs: one event, effects on S/B

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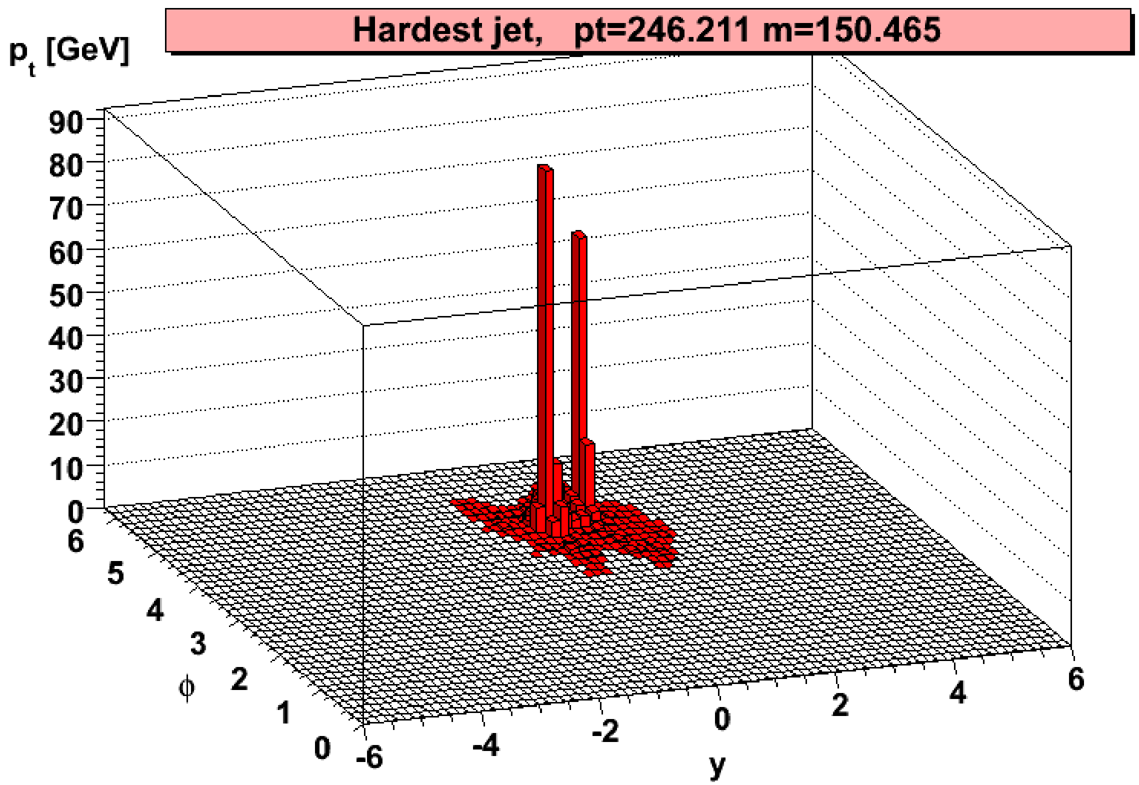
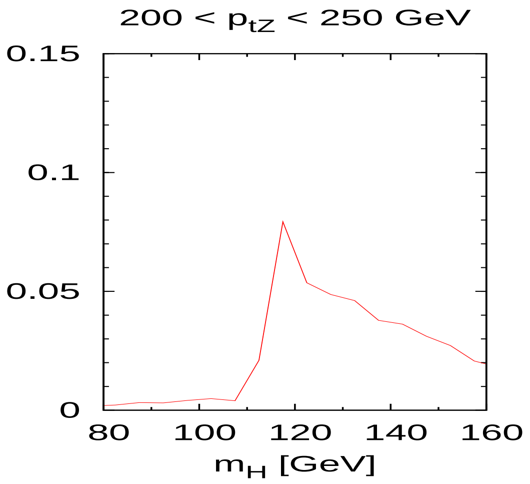
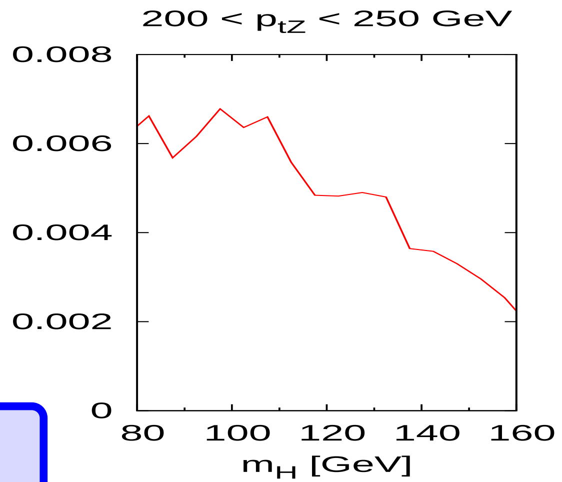


HZ Signal



Zbb Background



Hardest jet ($m = 150$ GeV)

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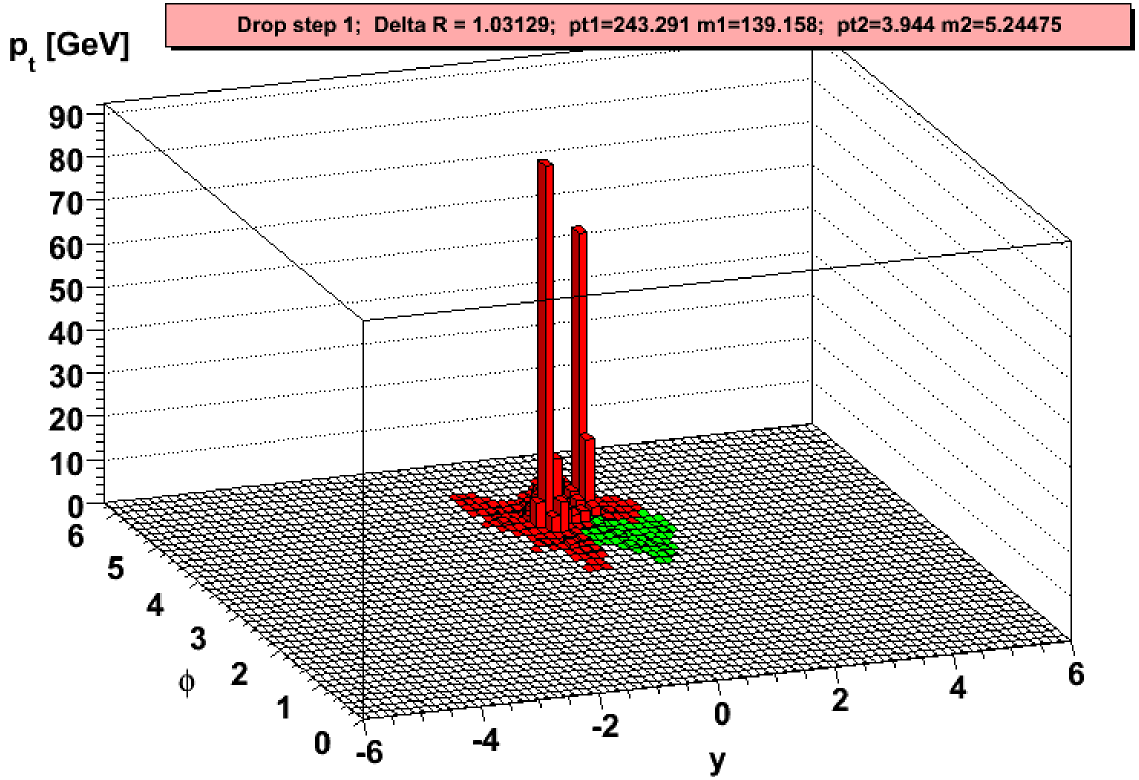

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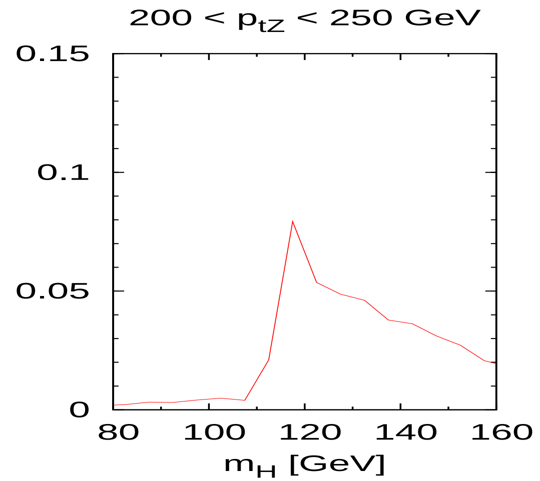

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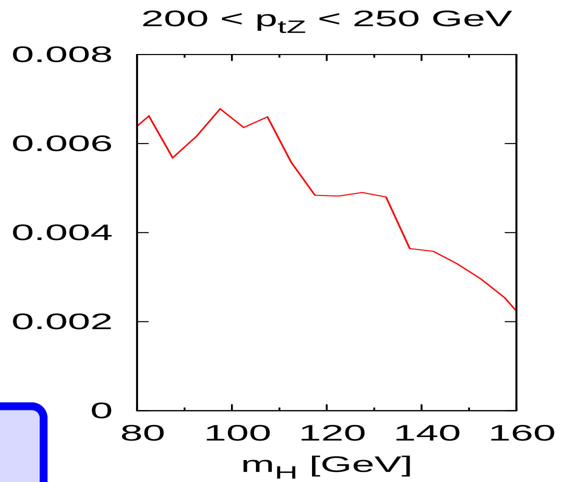

Split: $\frac{\max(m_1, m_2)}{m} = 0.92$, repeat ($m = 150$ GeV)

Boosted Higgs: one event, effects on S/B

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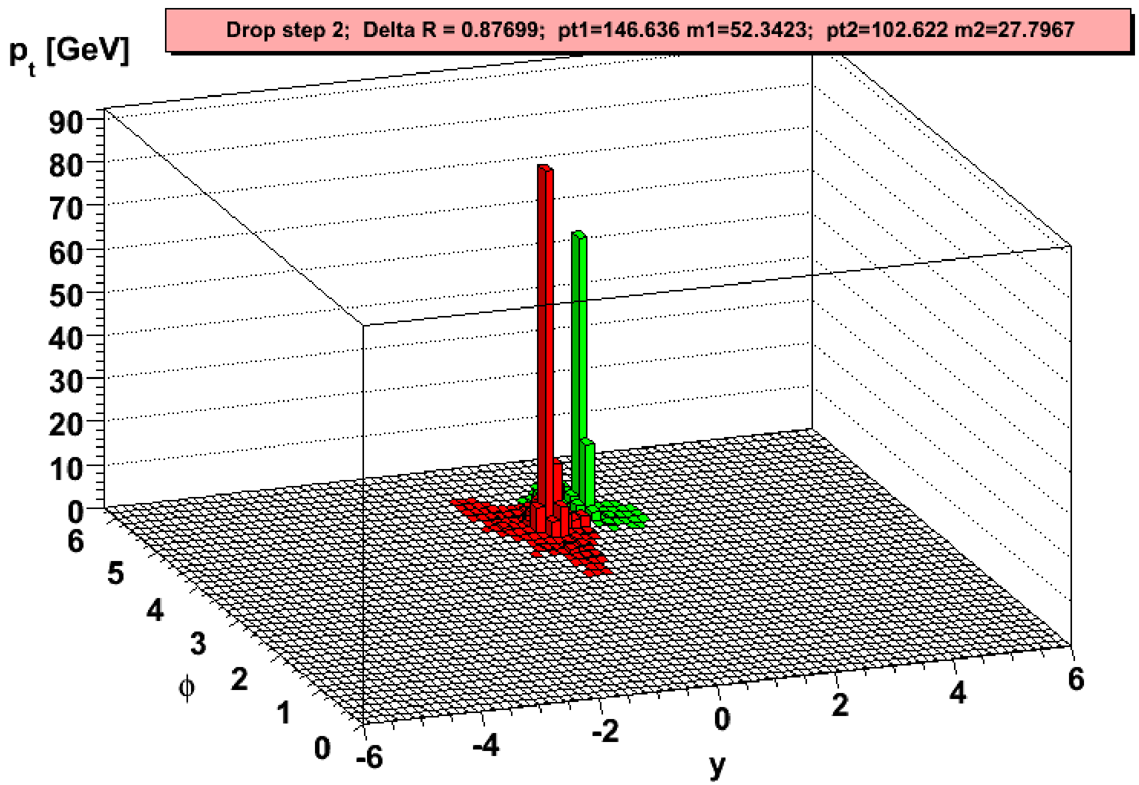

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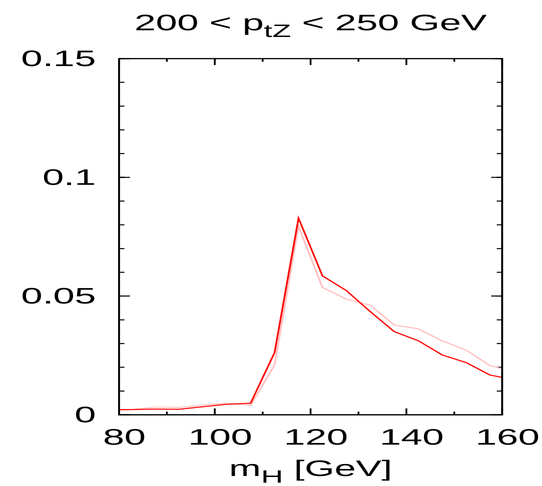

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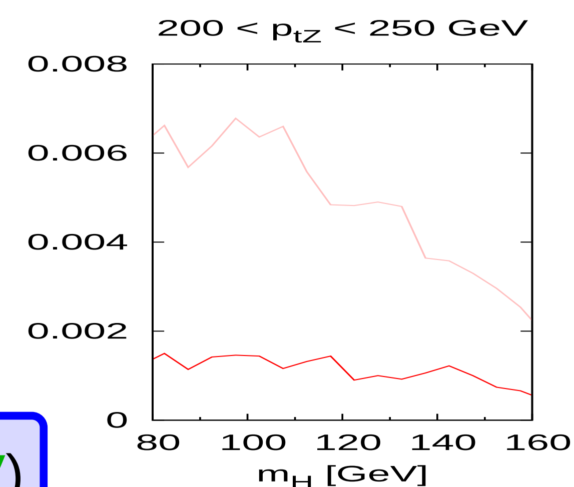

Split: $\frac{\max(m_1, m_2)}{m} = 0.37$, mass drop ($m = 139$ GeV)

Boosted Higgs: one event, effects on S/B

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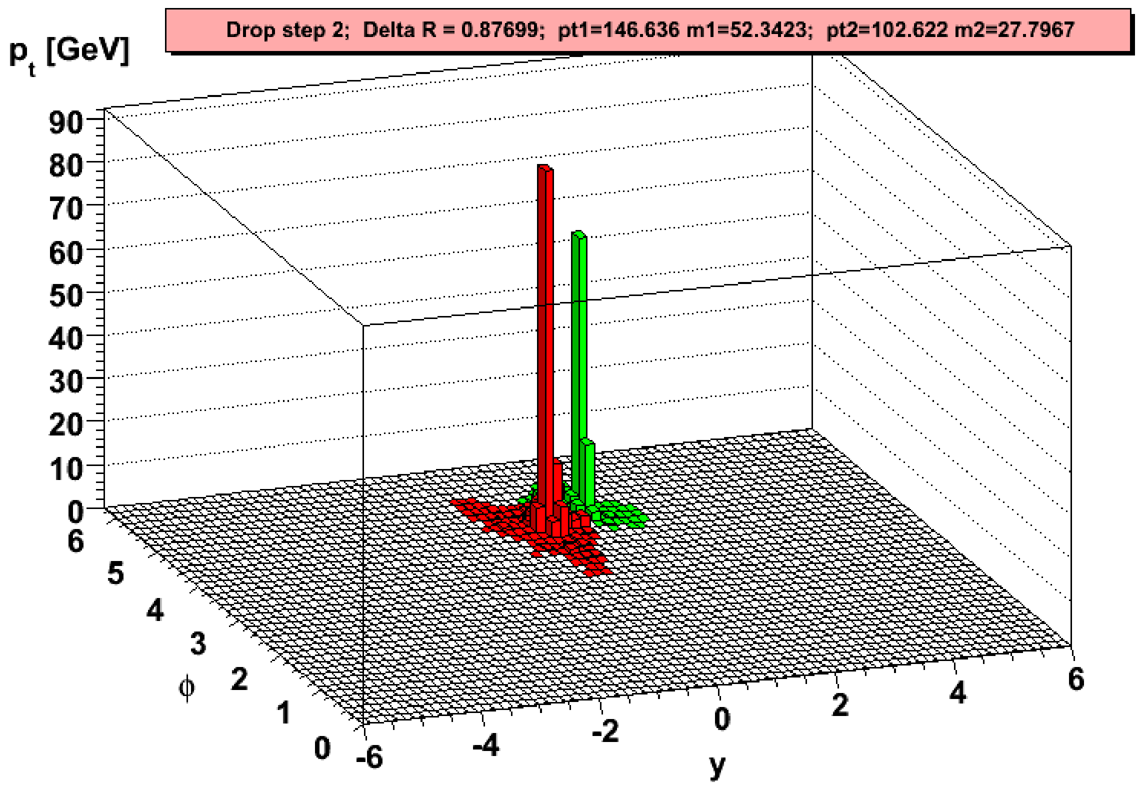

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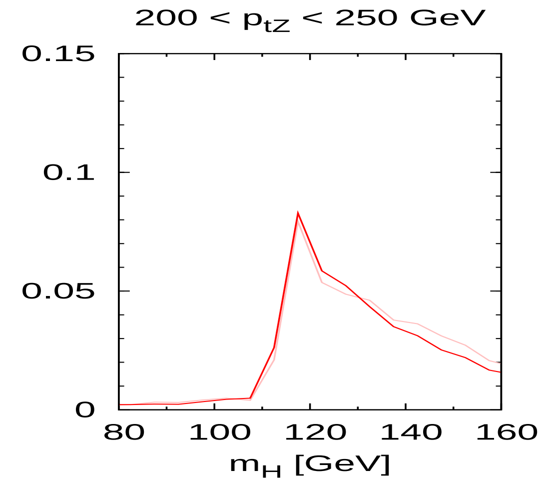

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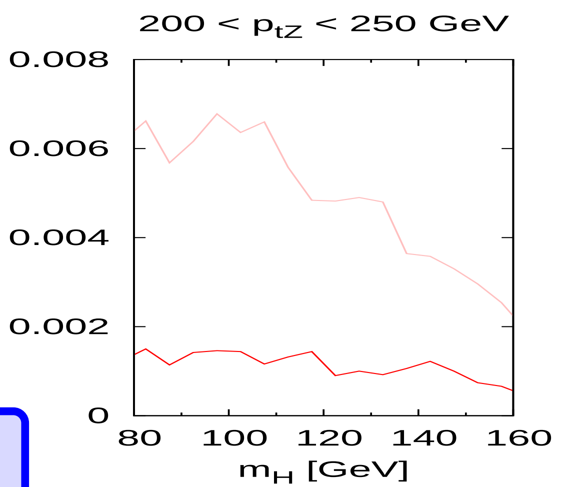
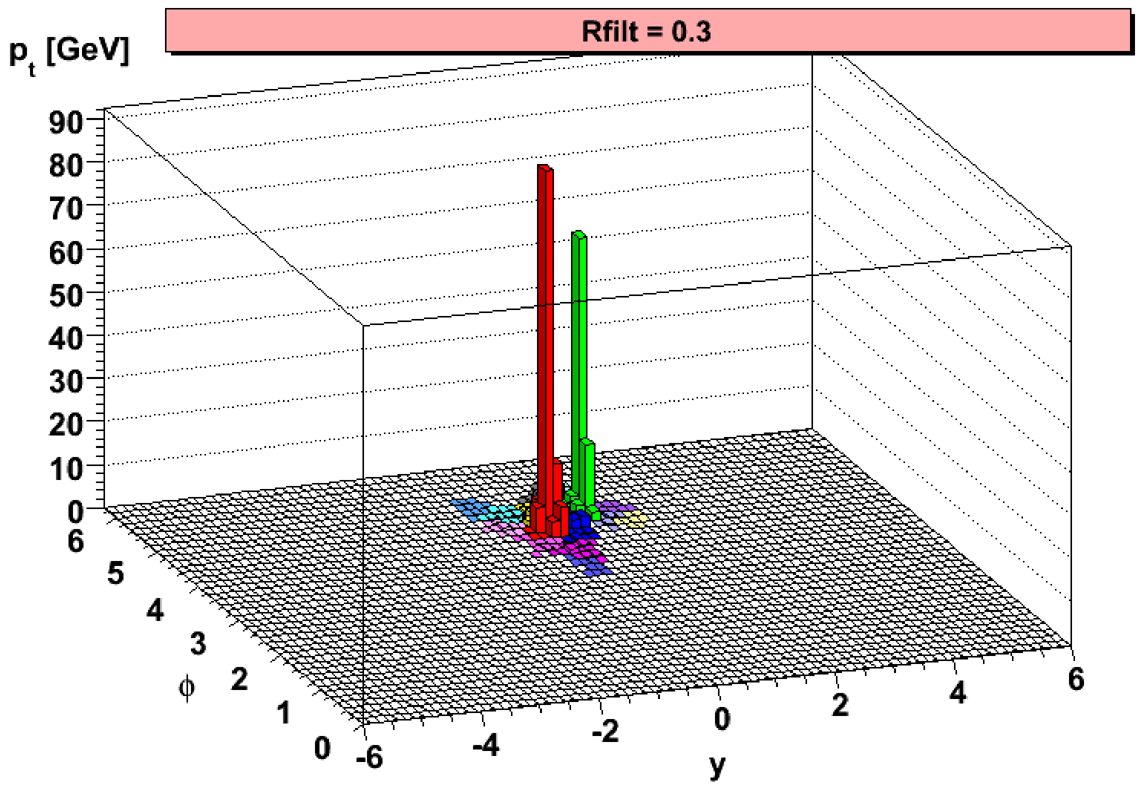


Split: $y_{12} = 0.7$, 2 b tags $\Rightarrow$ OK ($m = 139$ GeV)

Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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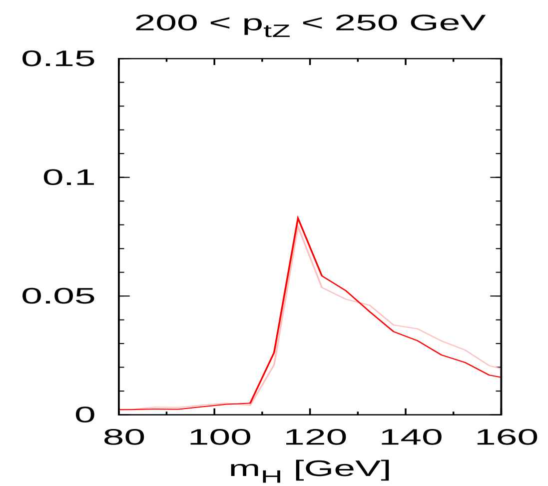
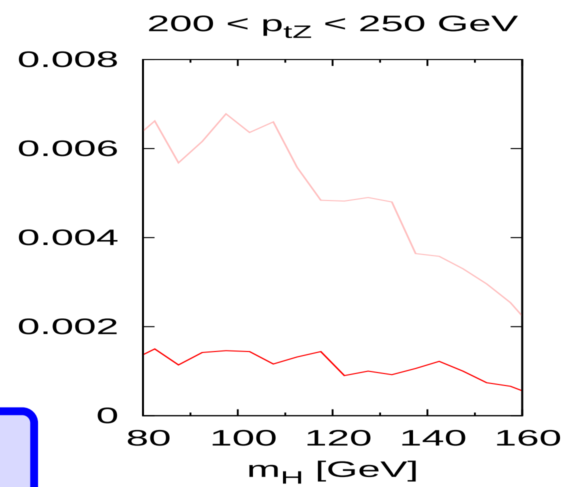


Zbb Background



Re-cluster: $R_{\text{filt}} = 0.3$

Boosted Higgs: one event, effects on S/B

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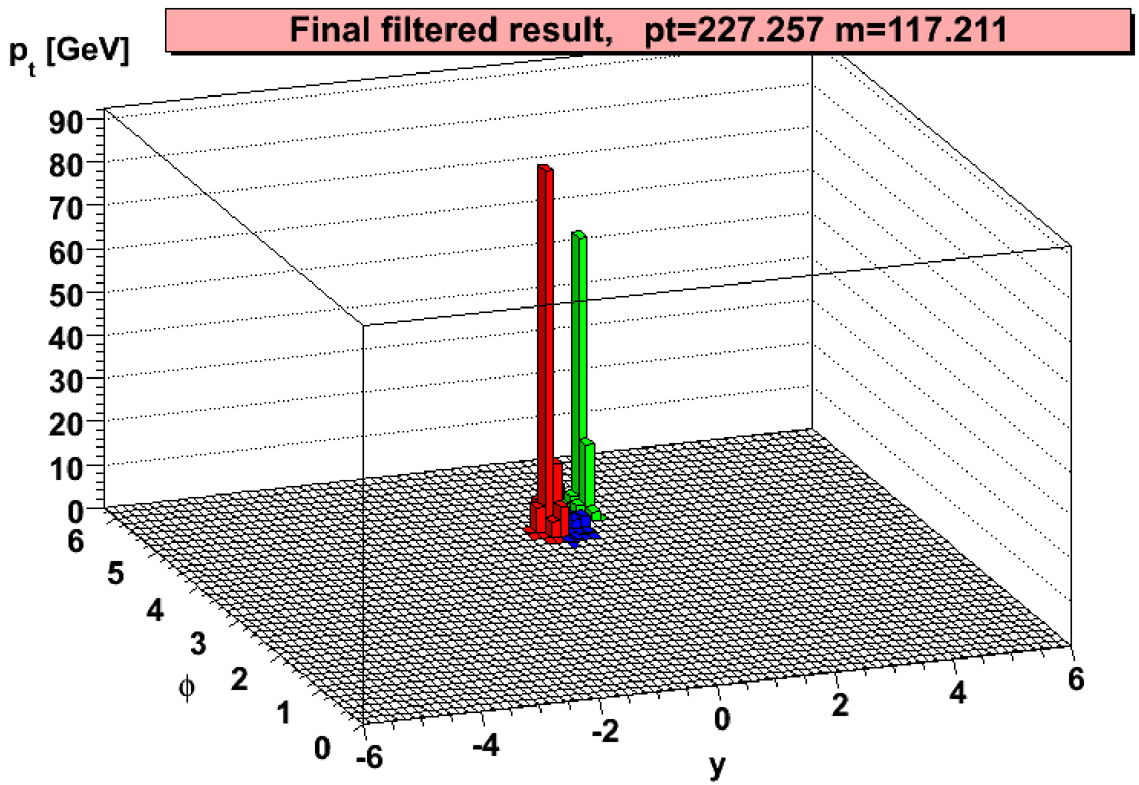

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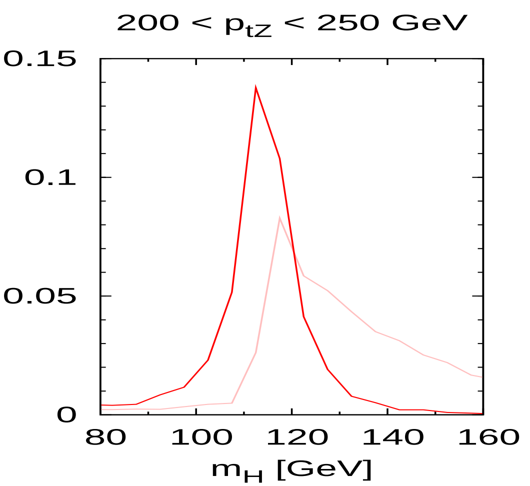

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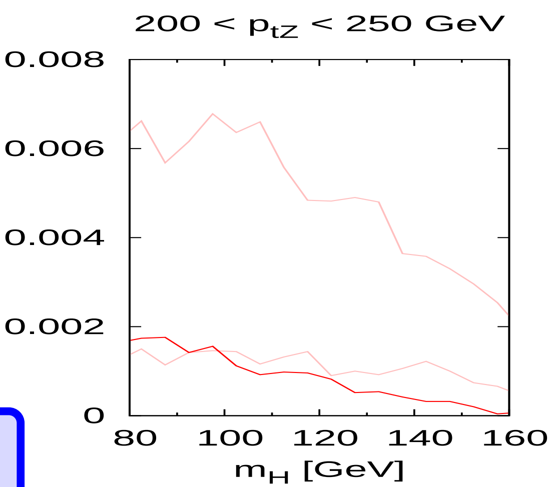
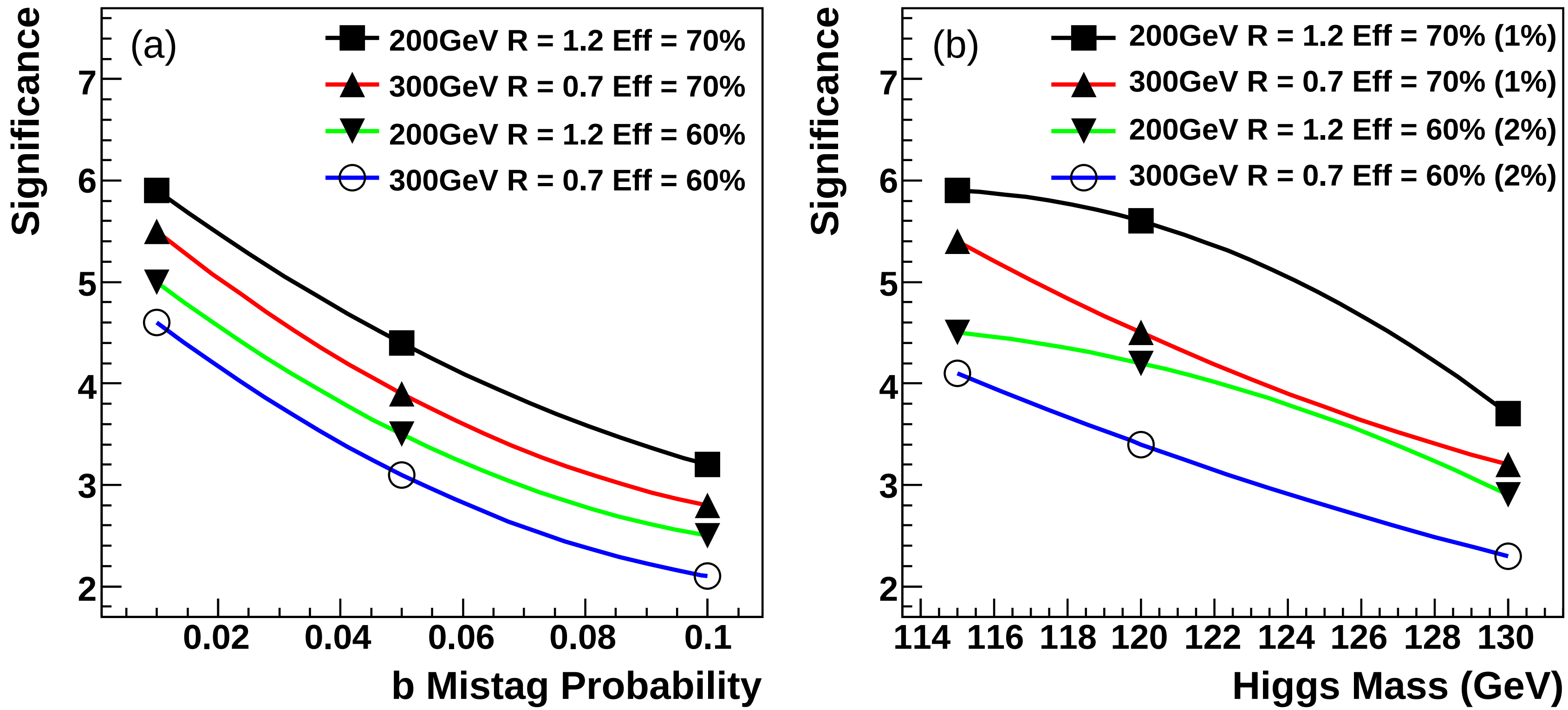


Filter: keep 3 hardets ($m = 117$ GeV)

Boosted Higgs: one event, effects on S/B



More than 3σ for most scenarios (30 fb^{-1})

Filter: keep 3 hardjets ($m = 117$ GeV)

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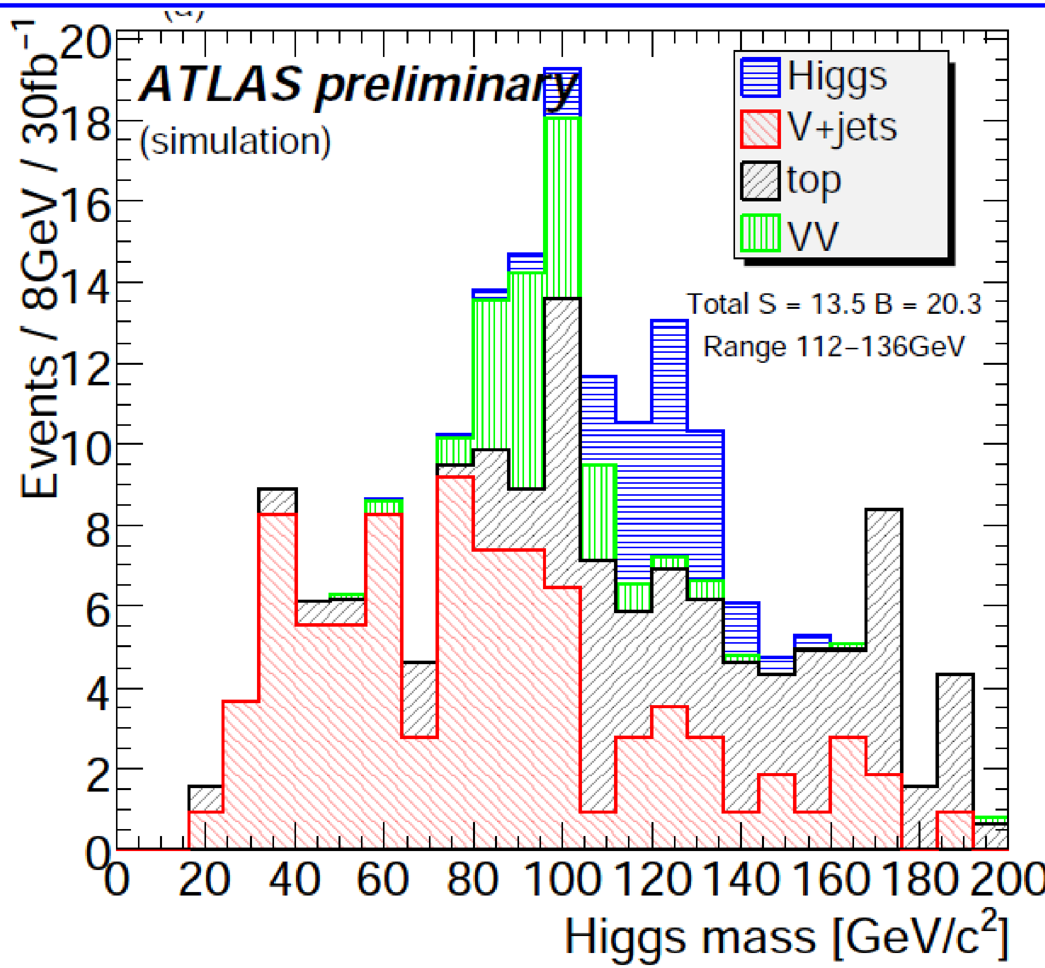


Under consideration in ATLAS (here $WZ \to l\nu b\bar{b}$, 30 fb^{-1})

Filter: keep 3 hardjets ($m = 117$ GeV)

Conclusions

- Finally a set of jet algs meeting the fundamental requirements
  i.e. Infrared-and-collinear-safe and fast

- Allows better/advanced usage of jets at the LHC
  - jet areas for background subtraction
  - jet substructure for boosted-objects tagging
  - UE-sensitivity using filtering/trimming

- Future: improve in those directions
- *e.g.* towards analytic understanding/optimisation

Additional topics:
Optimisation

[M.Cacciari,J.Rojo,G.Salam,GS, 08]

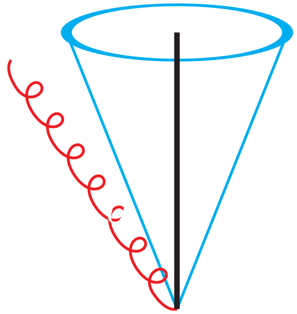
[M.Dasgupta,L.Magnea,G.Salam, 08]

[GS, 10]

Optimisation: underlying idea

Competition between

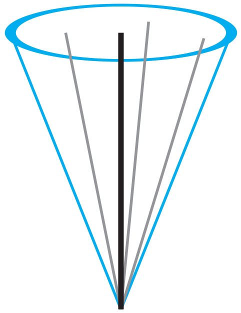
- catching perturbative radiation



Out-of-cone radiation:

$$\langle \delta p_t \rangle \propto -\int_R \frac{d\theta}{\theta} \sim -\log(1/R)$$

- not catching soft background radiation (underlying event)



$\langle \delta p_t \rangle \sim$ Soft contents $\propto$ jet area $\sim R^2$

the coefficients depend on the algorithm

Optimisation: underlying idea

Competition between

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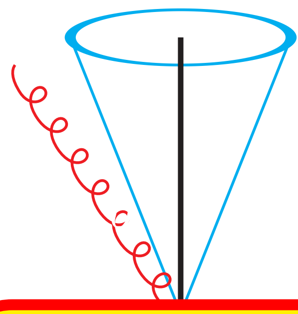
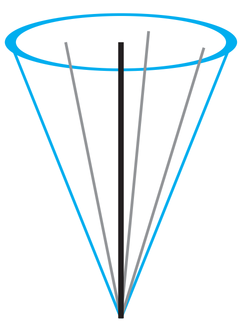


Out-of-cone radiation:

$$\langle \delta p_t \rangle \propto -\int_R \frac{d\theta}{\theta} \sim -\log(1/R)$$

What is the optimal jet definition (algo+R!)?

- not [illegible]



$\langle \delta p_t \rangle \sim$ Soft contents $\propto$ jet area $\sim R^2$

the coefficients depend on the algorithm

Framework

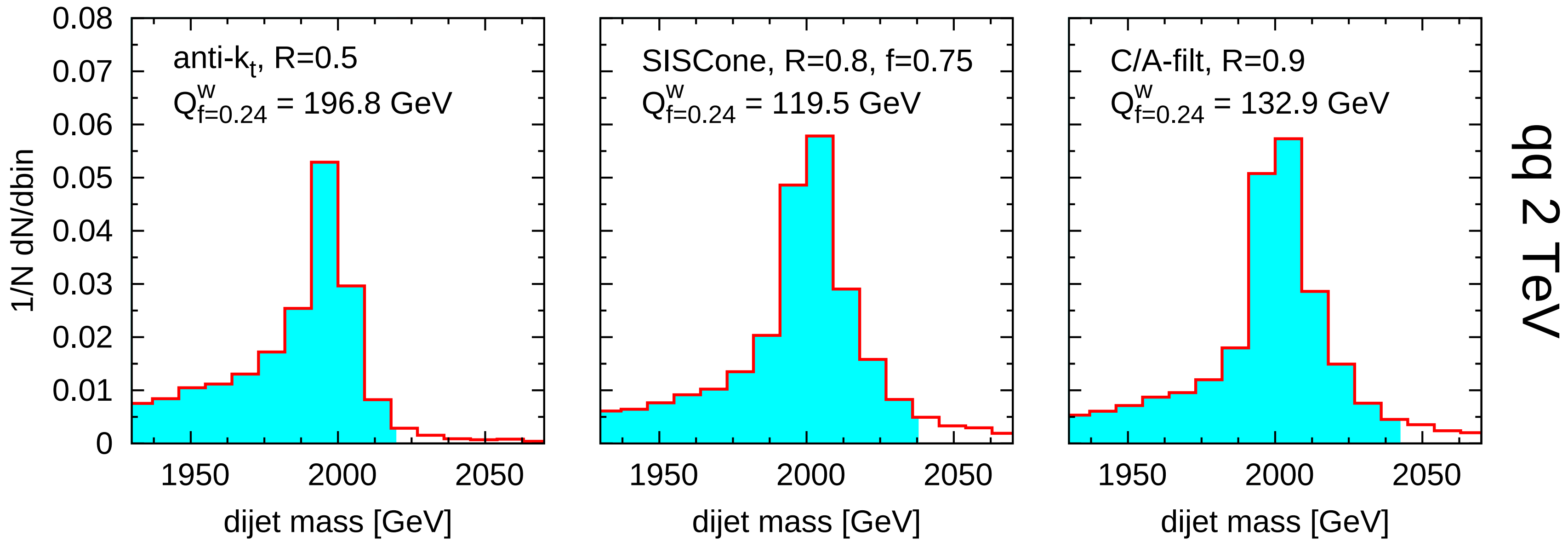
Example process to illustrate various effects:

$$Z' \to q\bar{q} \to 2 \text{ jets}$$

- $M_{Z'}$ can be varied (between 100 GeV and 4 TeV)
- Also valid for $H \to gg$ to study gluon jets
- Reconstruction method:
  - get the 2 hardest jets: j_1 and j_2
  - reconstruct the Z': $m_{Z'} = (j_1 + j_2)^2$

  Look how the mass peak is reconstructed
- Also $t\bar{t}$ with full hadronic decay for multijet tests

Observations



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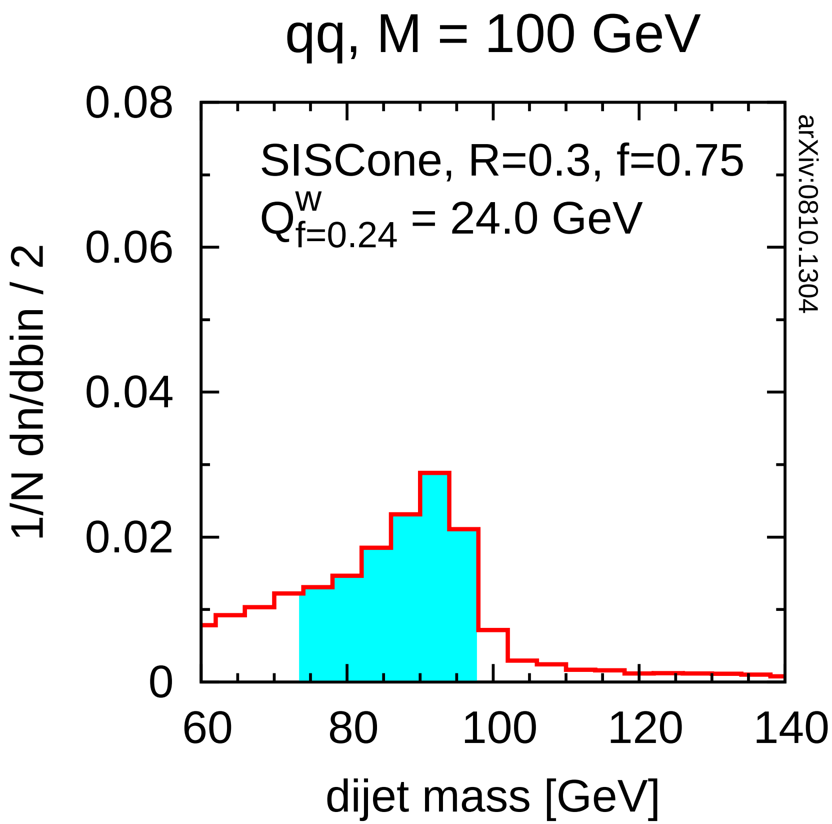
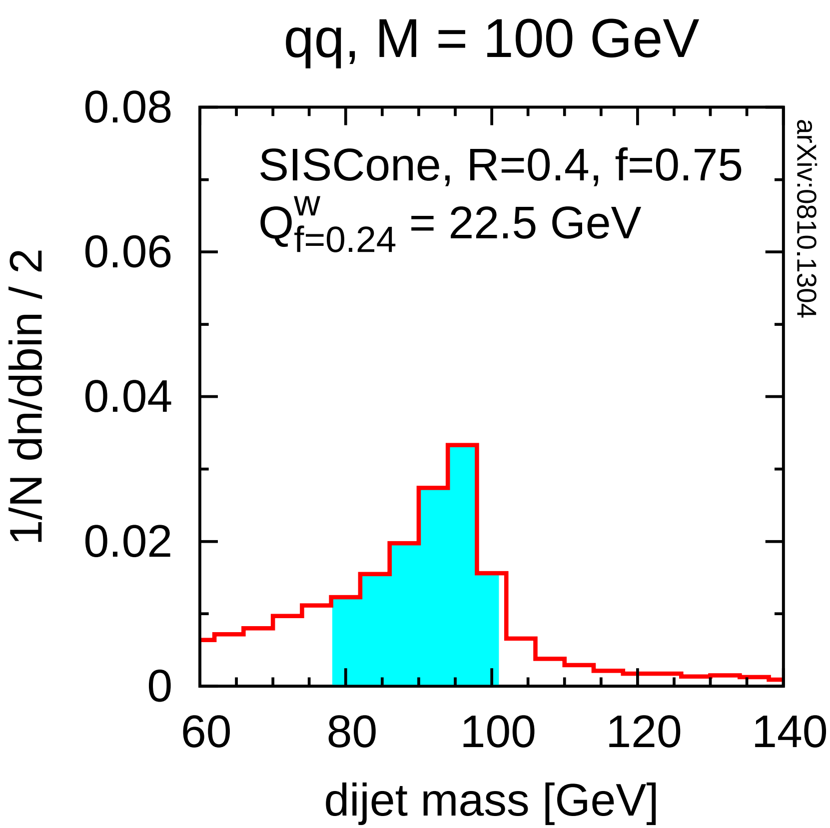


Histogram:

fixed mass, algorithm

Observations

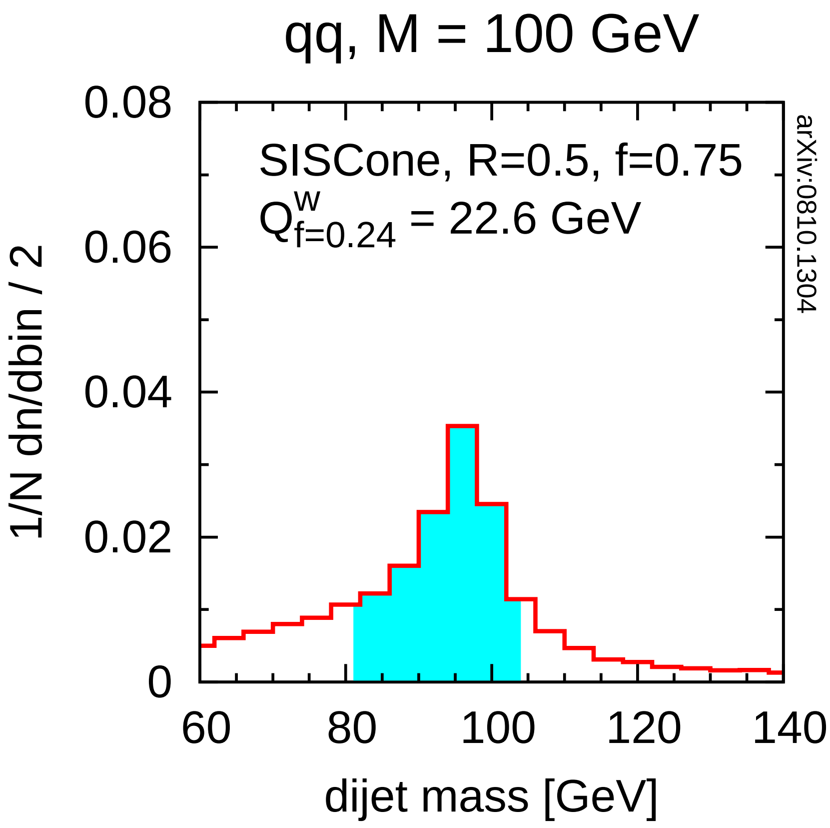


Histogram:

fixed mass, algorithm

vary R

Observations



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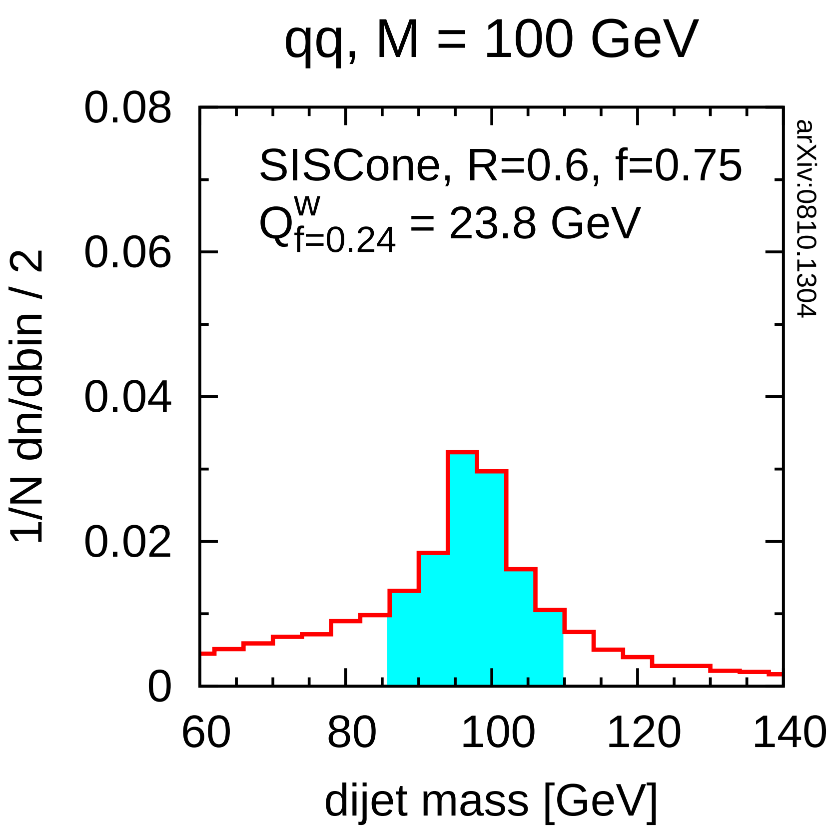

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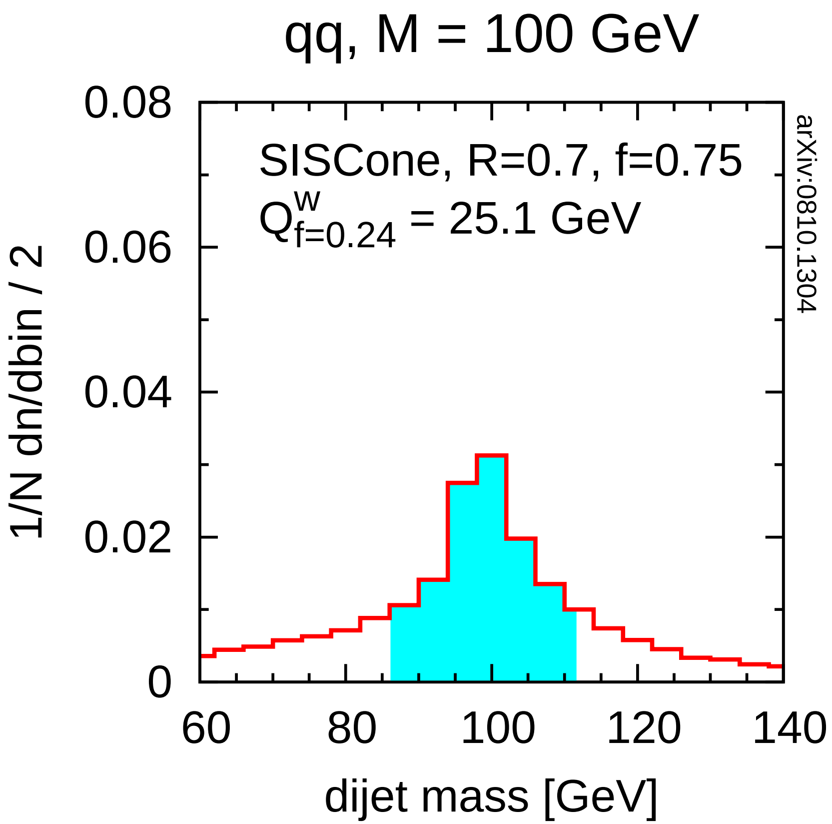

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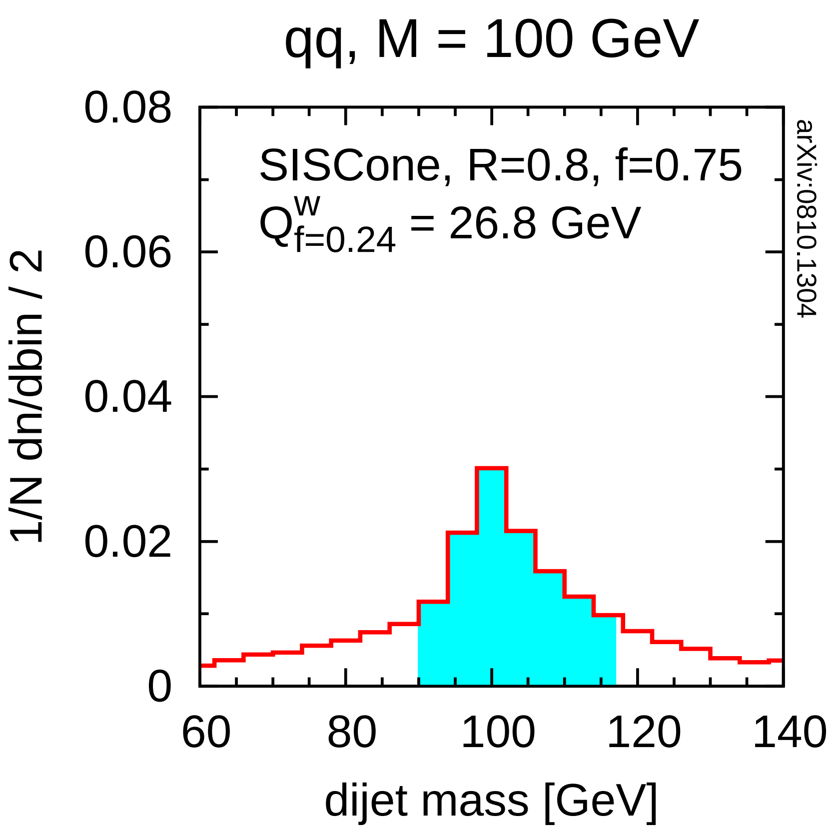

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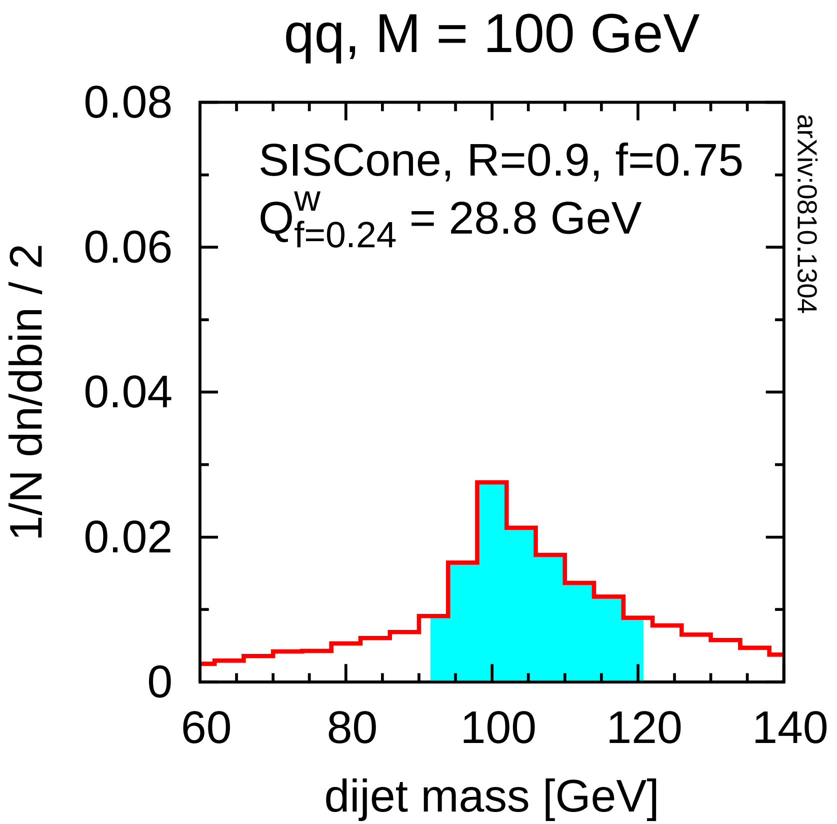

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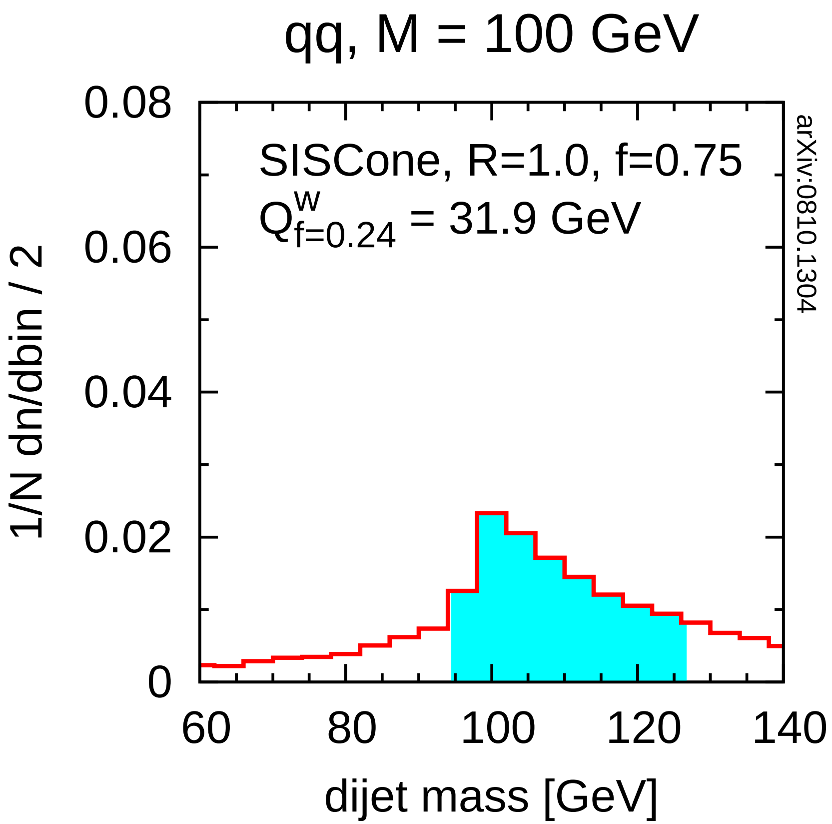

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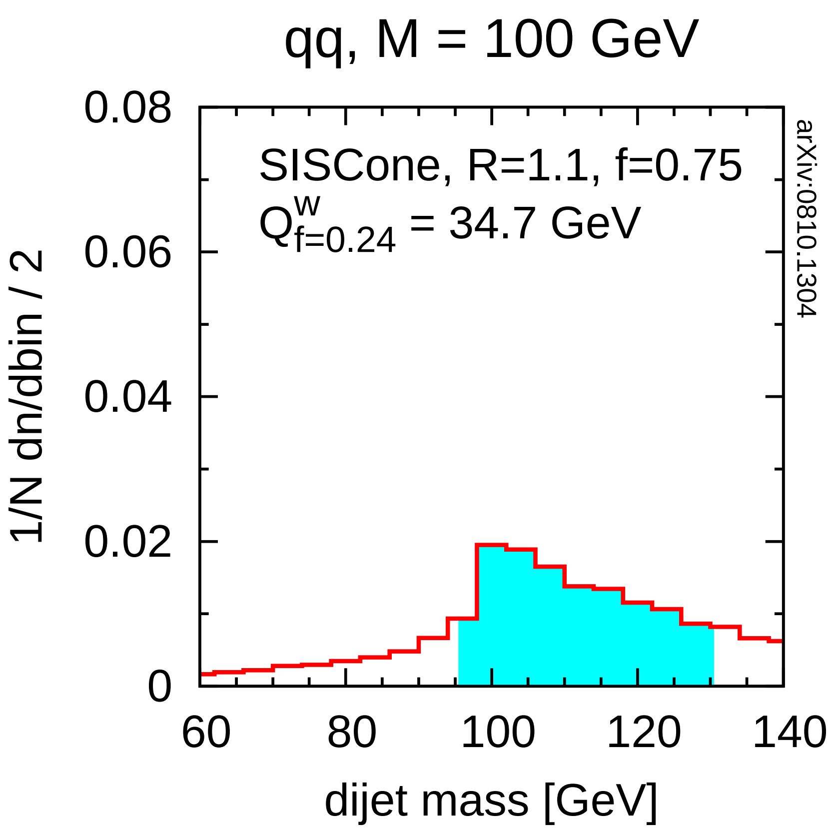

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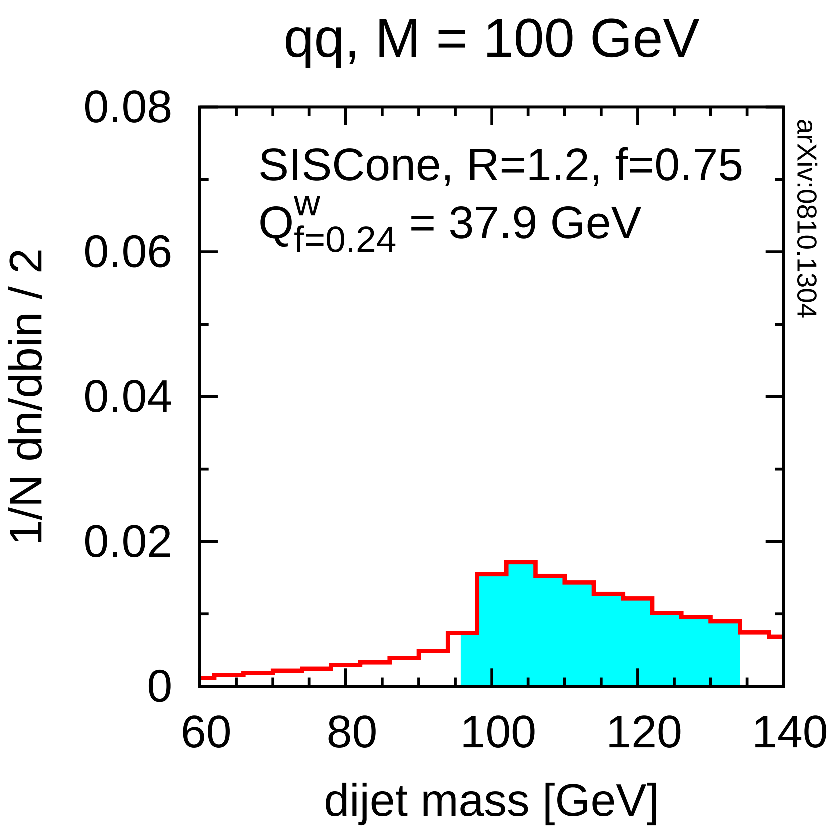

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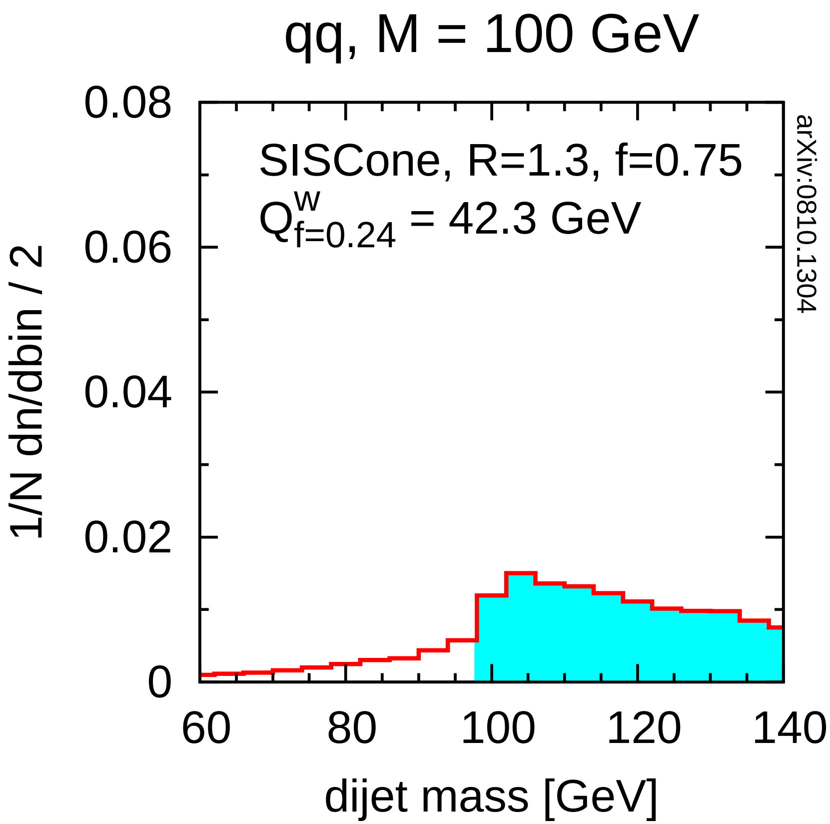

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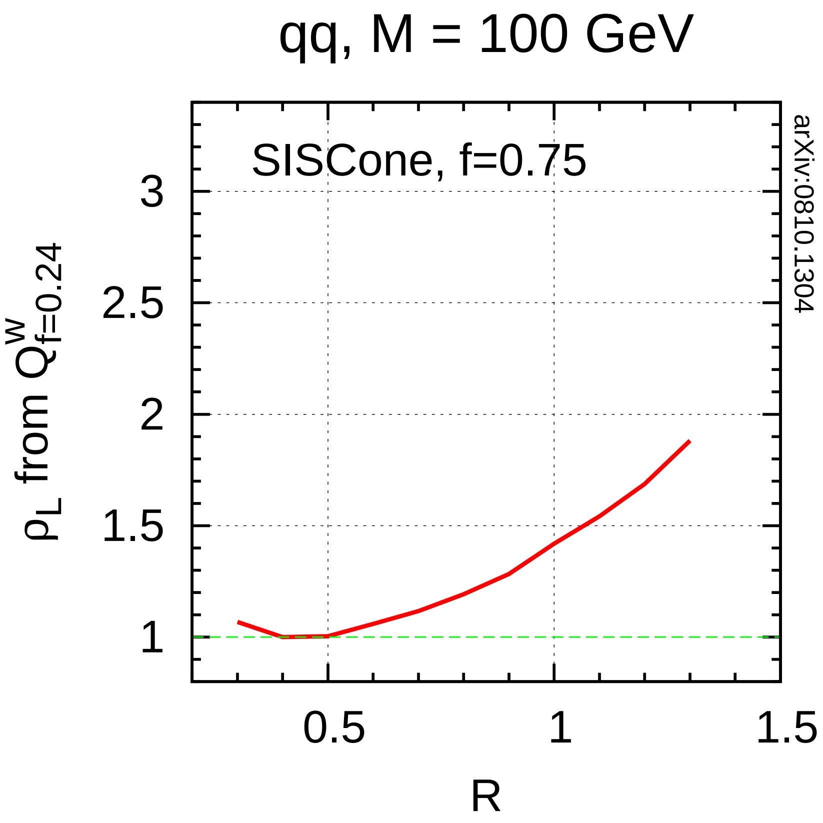
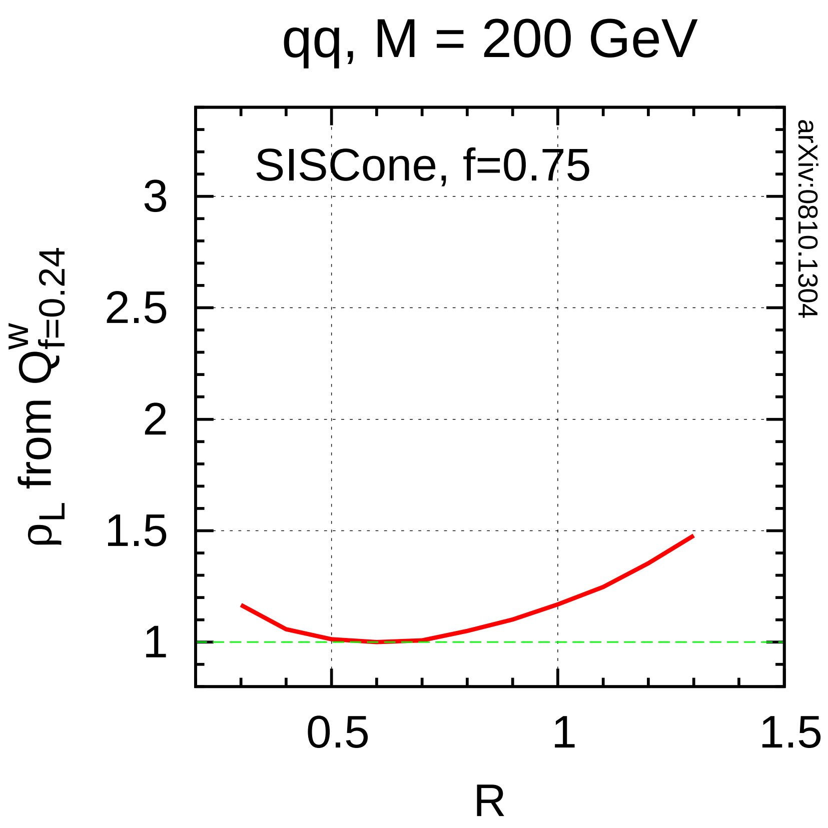


Width vs. R:

fixed algorithm

Observations

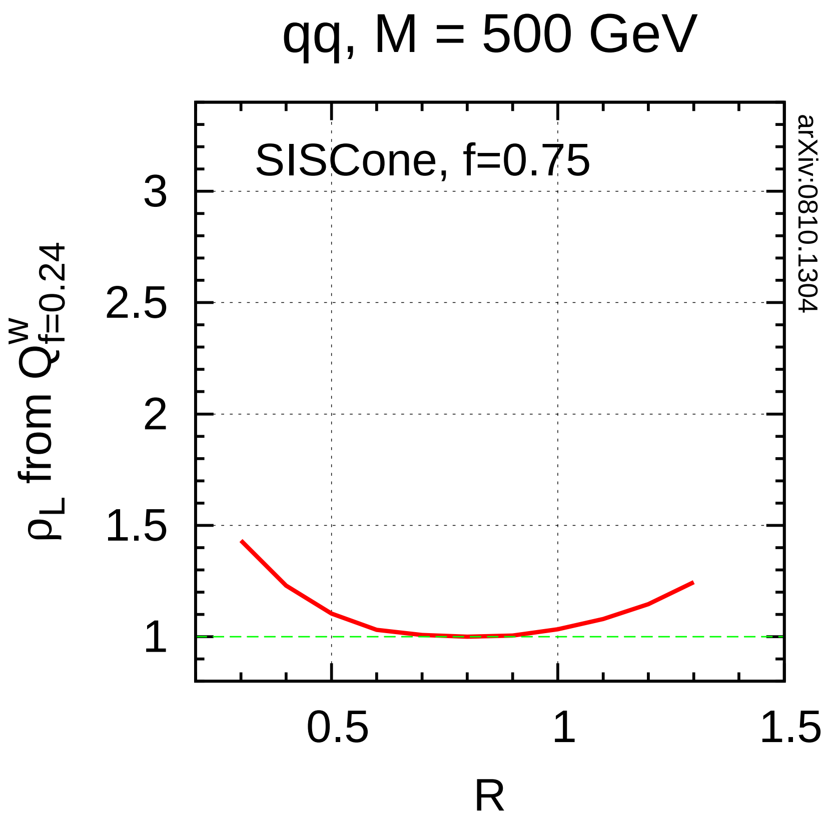


Width vs. R:

fixed algorithm

vary M

Observations



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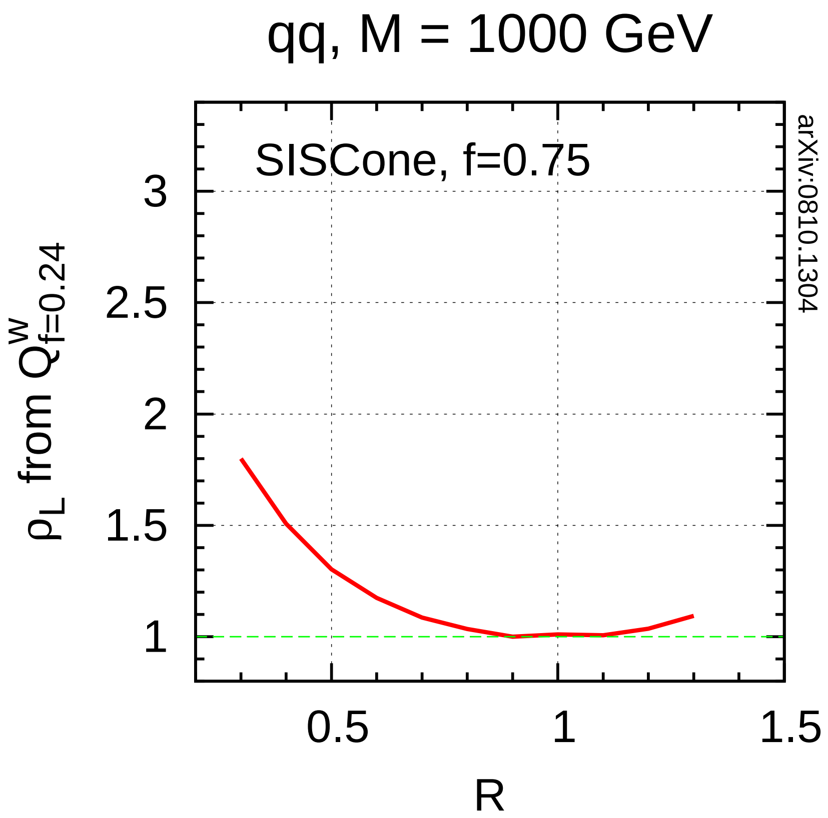
fixed algorithm

vary M

Observations



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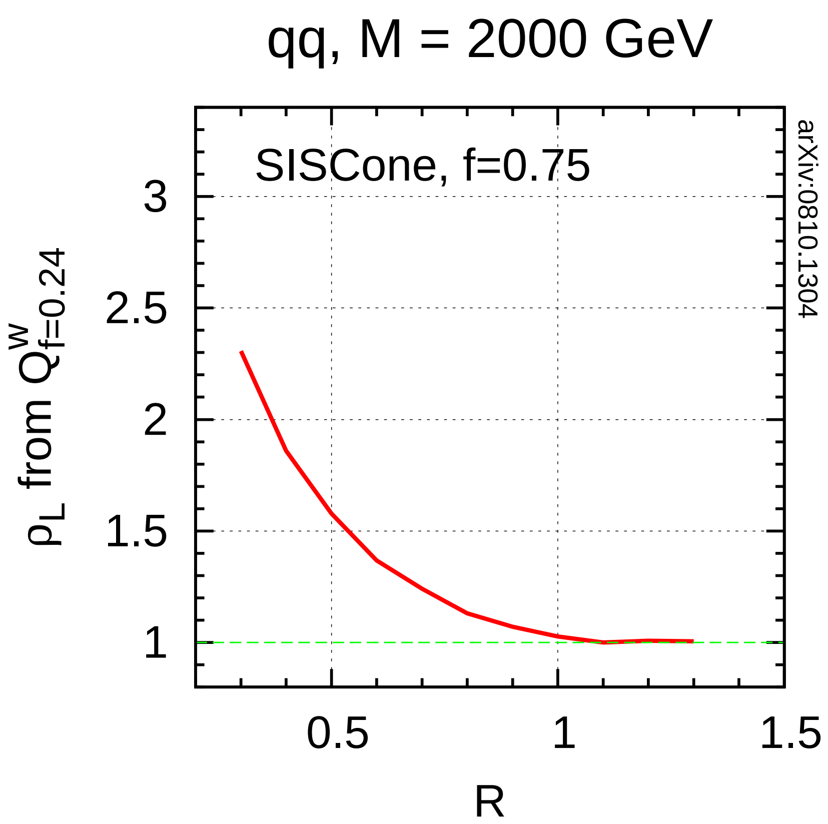


Width vs. R:

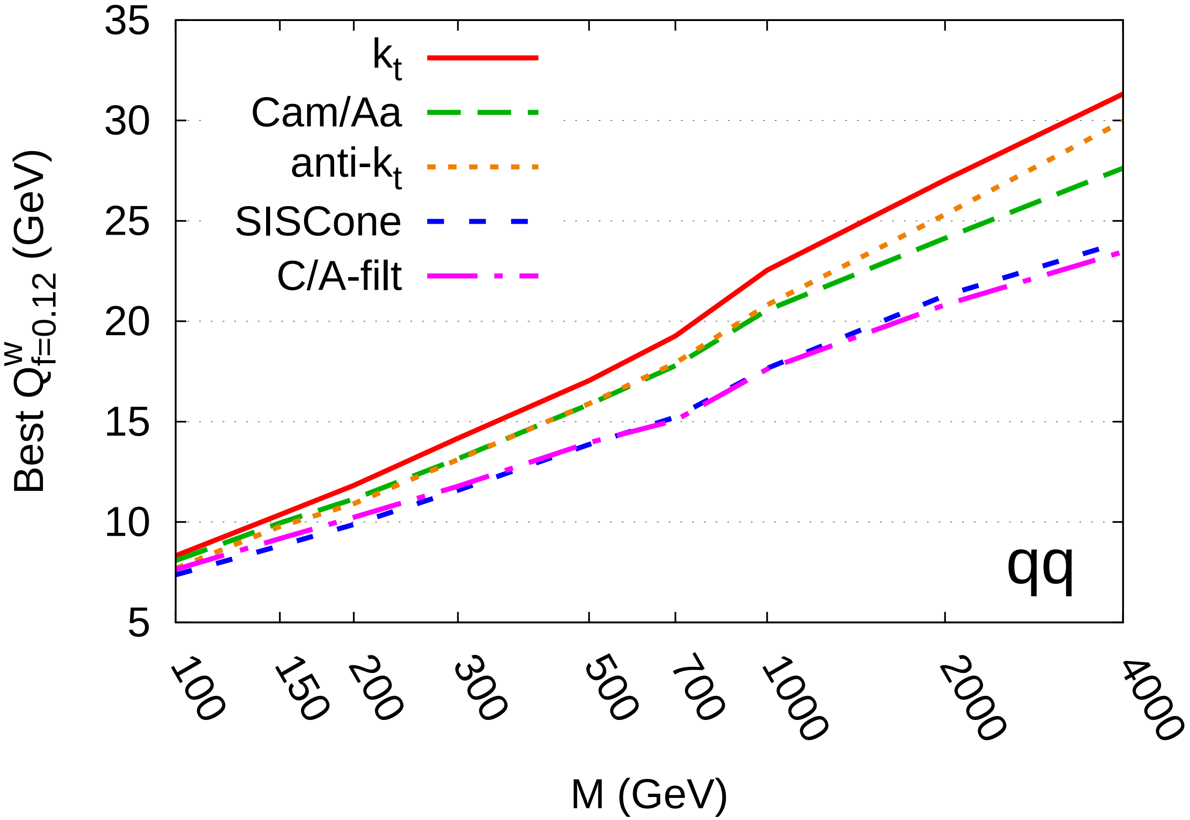
fixed algorithm

vary M

In summary:

- width vs. R: strong R dependence

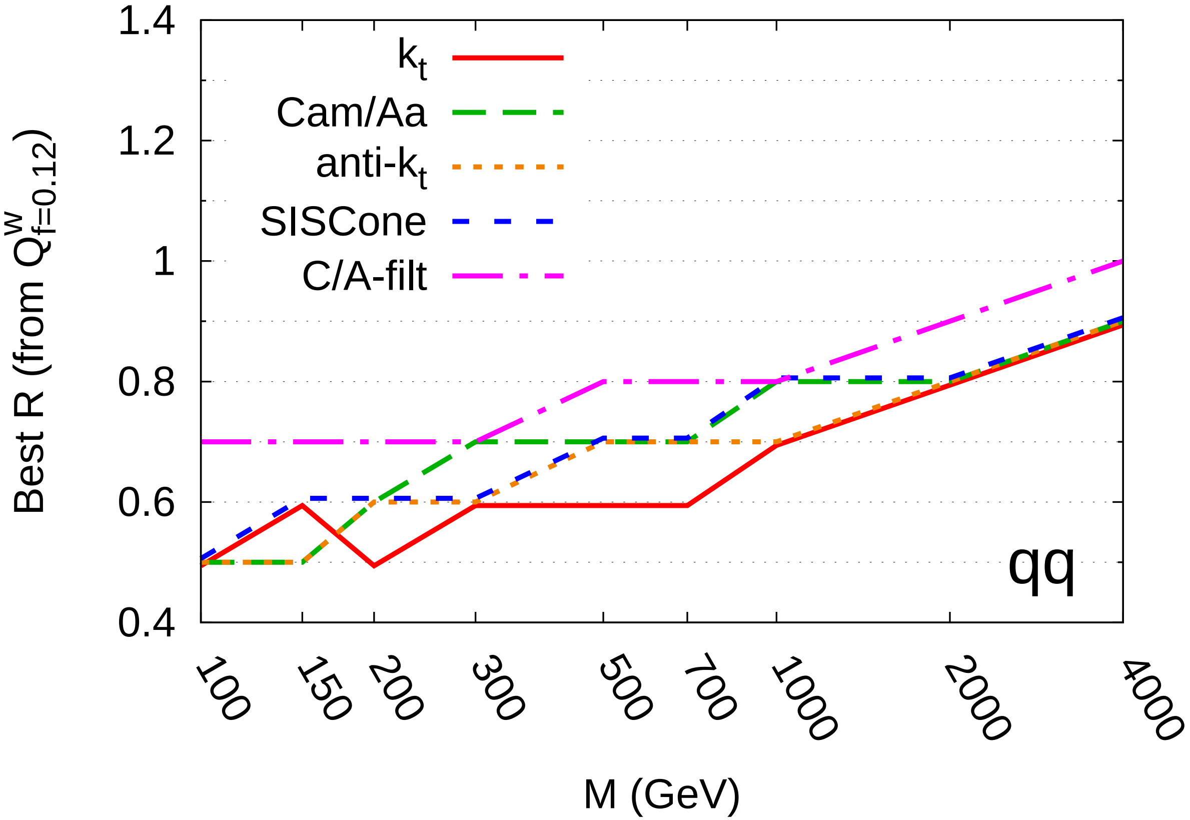
Observations



In summary:

- width vs. R: strong R dependence
- optimal width vs. M: SISCone, C/A(filt) preferred

Observations



In summary:

- width vs. R: strong R dependence
- optimal width vs. M: SISCone, C/A(filt) preferred
- optimal R vs. M: R_{best} increases with M

Towards analytics

Analytic computation of the histogram including:

- pert. final-state radiation: loss $\propto \alpha_s M \log(1/R)$
- pert. initial-state radiation: gain $\propto \alpha_s M R^2$ (+PDFs)
- UE contamination: gain $\propto \rho_{\mathrm{UE}} R^2$

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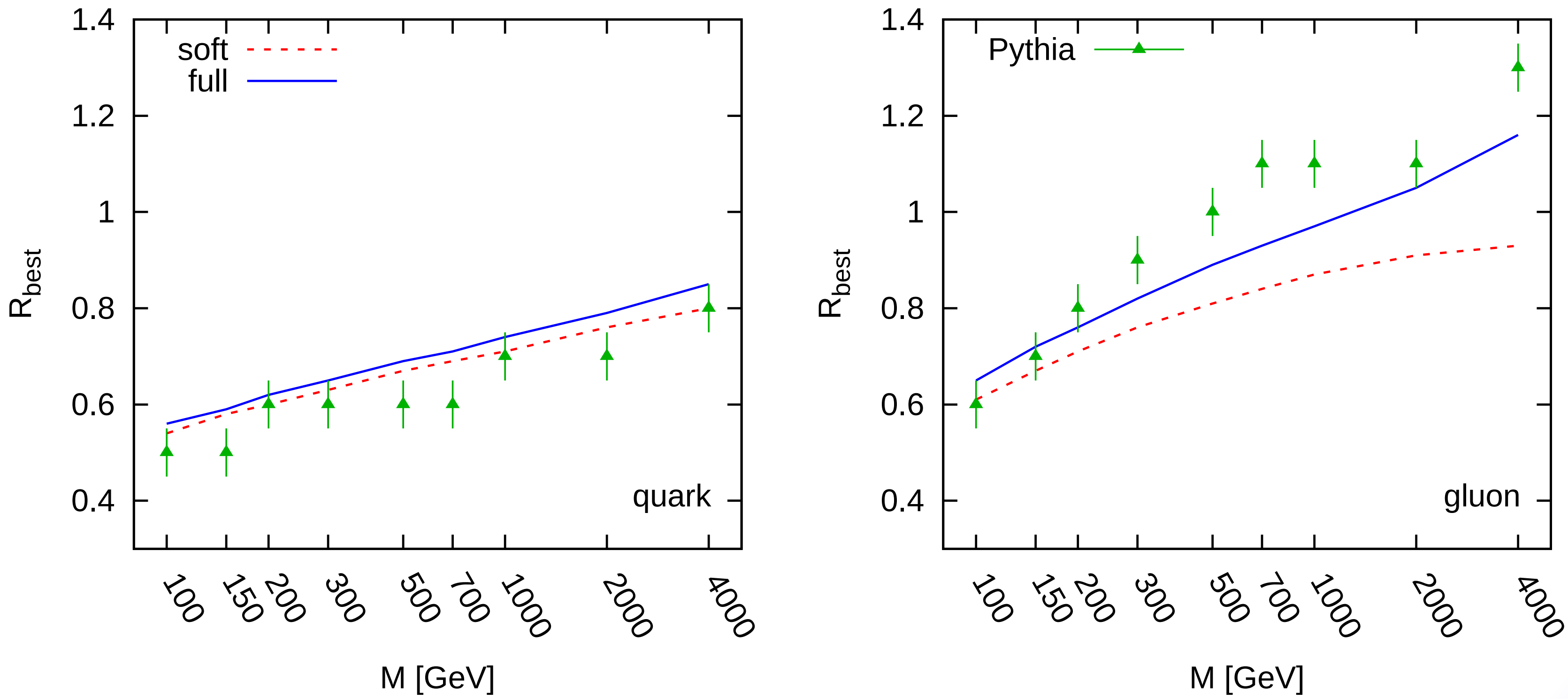


Additional topic:
the FastJet interface

Future of FastJet

FastJet 3.0 on its way (3.0alpha1 on January the 26th):

- Interface: a jet knows about its clustering, *e.g.*

```
clust_seq.constituents(jet);
```

  $\rightarrow$ `jet.constituents();`

- Generic additional info in PseudoJet: `jet.extra_info()`

- `Selector` for selecting objects in a list, *e.g.*

```
Selector jet_sel =
  SelectorMaxAbsRap(2.5) && SelectorPtMin(20);
jets = jet_sel(clust_seq.inclusive_jets());
```

- Improved bkgd subtraction: `BackgroundEstimator`

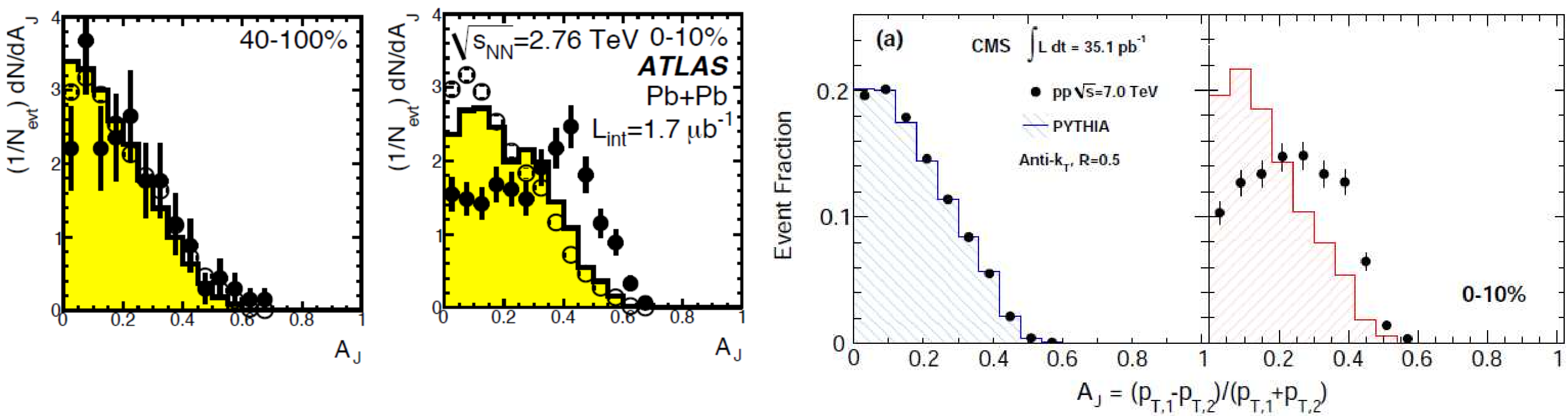
- FastJet tools *e.g.* `Filter`

Additional topic:
dijet asymmetries in $PbPb$

Fully reconstructed (and subtracted) jets in $PbPb$ coll.

$$A_J = \frac{p_{t,1} - p_{t,2}}{p_{t,1} + p_{t,2}}$$

Physics interpretation:
more frequent large A_J due to jet quenching



Quantitative interpretation?

Warning:

background fluctuations go in the same direction

might affect quantitative estimate of quenching effects!

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Ex.: Pythia+Gaussian smearing(width $\sigma_{\rm jet}$)