

# New perspectives in QCD with jet substructure

Grégory Soyez

IPhT, CEA Saclay, CNRS

University of Vienna, January 16 2018

## Jets are routine QCD objects

- ubiquitous in collider physics
- around since 40 years
- used in at least 60% of LHC analyses

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You could live a happy life by just knowing a few things

Concepts:

- Jets are proxies to hard partons produced in collisions
- infrared-and-collinear safe
- capture collimated parton cascades from hard scale  $Q$  to  $\mathcal{O}(1 \text{ GeV})$

Practically:

- obtained by running a clustering algorithm
- the LHC uses the anti- $k_t$  algorithm
- FastJet covers covers all your numerical needs for clustering

# The anti- $k_t$ (and generalised $k_t$ algorithm)

- From all the objects to cluster, define the distances

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

- repeatedly find the minimal distance
  - if  $d_{ij}$ : recombine  $i$  and  $j$  into  $k = i + j$
  - if  $d_{iB}$ : call  $i$  a jet

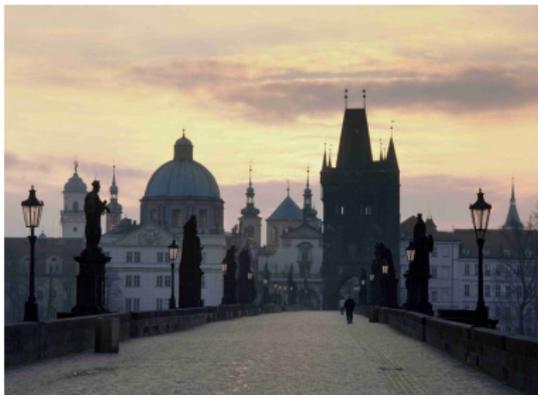
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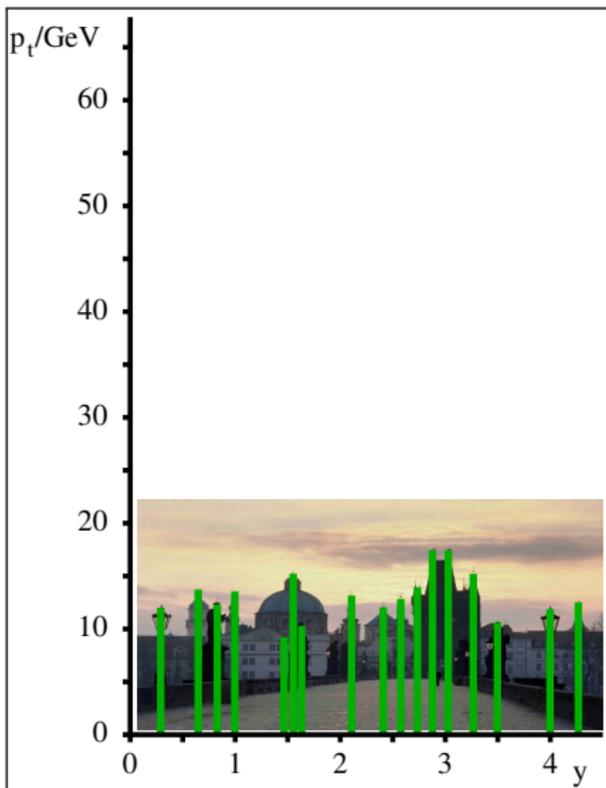
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  - if  $d_{iB}$ : call  $i$  a jet
- Parameter  $p$  is (typically) one of
  - ▶  $p = 1$ :  $k_t$  algorithm (closest to QCD)  
[Catani,Dokshitzer,Seymour,Weber,Ellis,Soper,1993]
  - ▶  $p = 0$ : Cambridge/Aachen (geometrical distance)  
[Dokshitzer,Leder,Moretti,Webber,1997]
  - ▶  $p = -1$ : anti- $k_t$  (the LHC choice) [M.Cacciari,G.Salam,GS,2008]

# Clustering in action: anti- $k_t$ ( $R = 0.7$ )



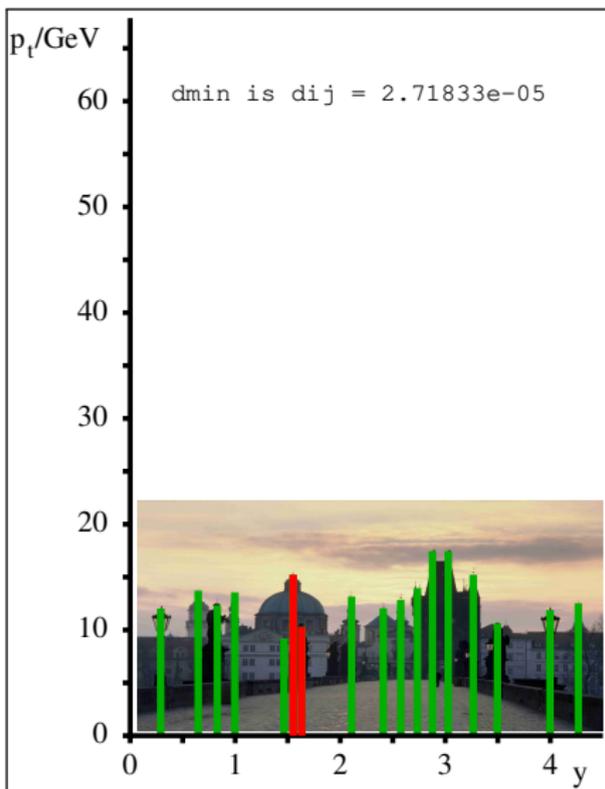
Start with your  
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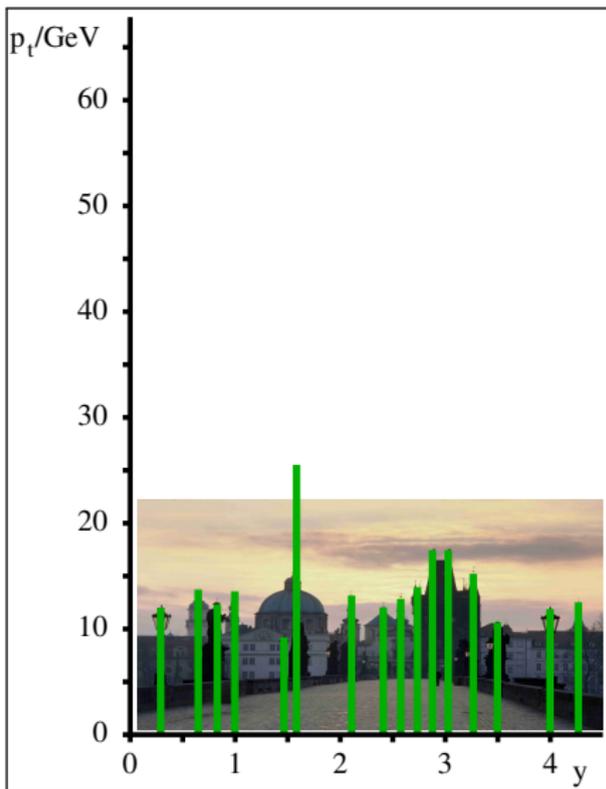
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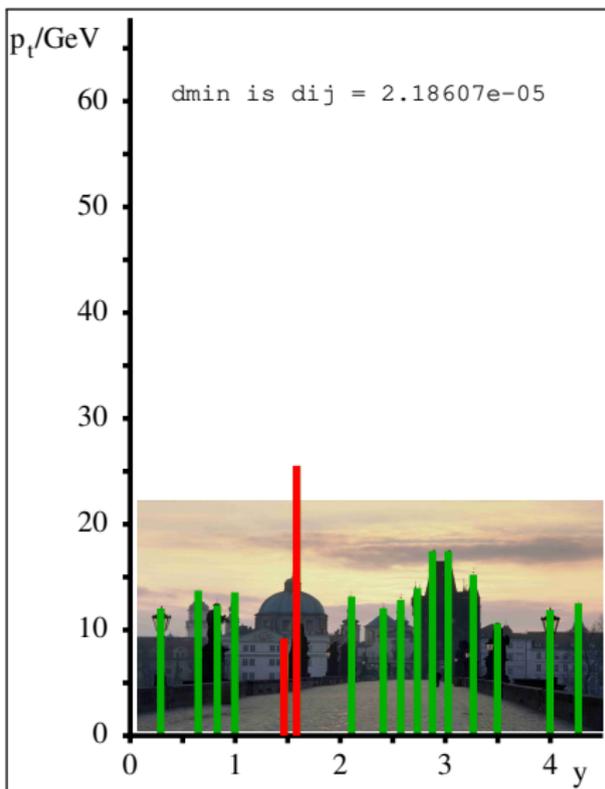
min is  $d_{ij} = 2.7 \cdot 10^{-5}$

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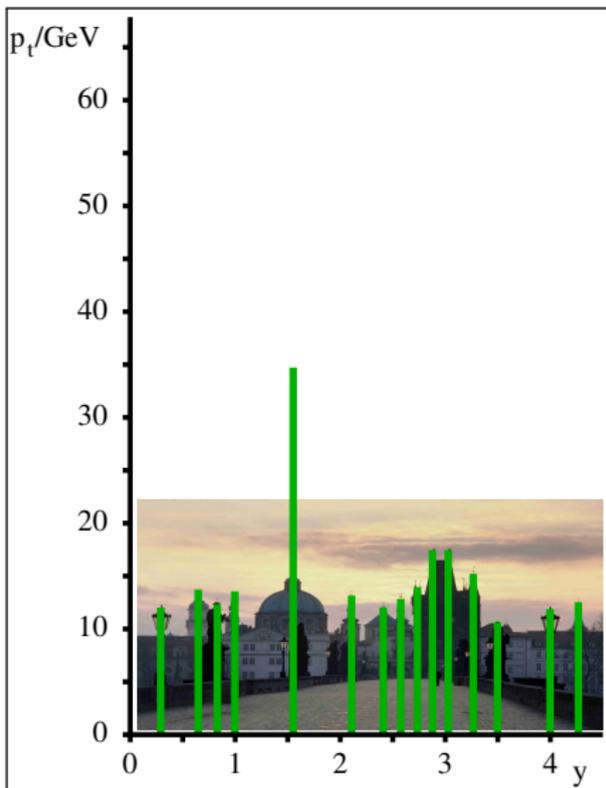
recombine them

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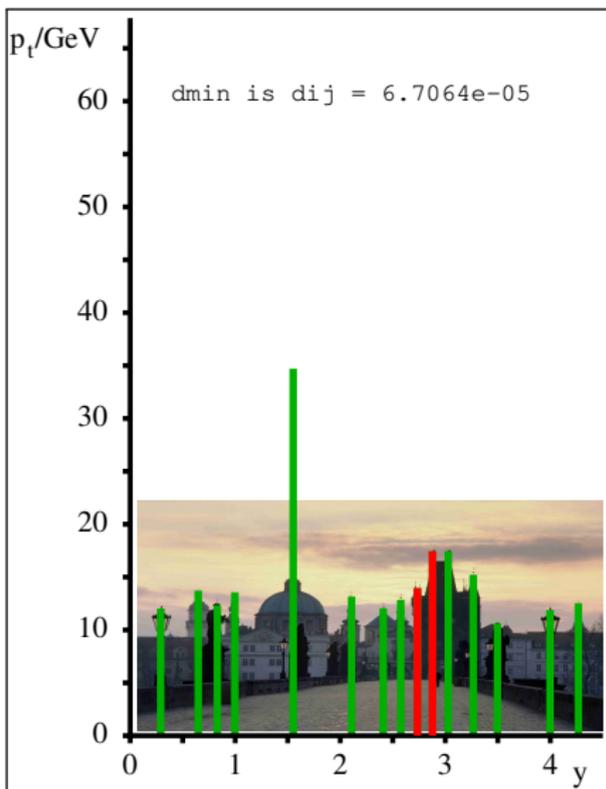
min is  $d_{ij} = 2.2 \cdot 10^{-5}$

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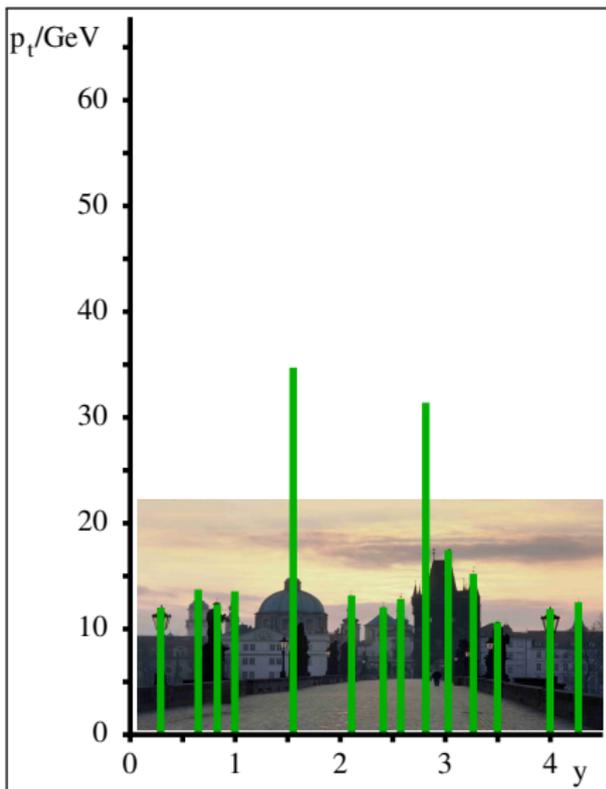
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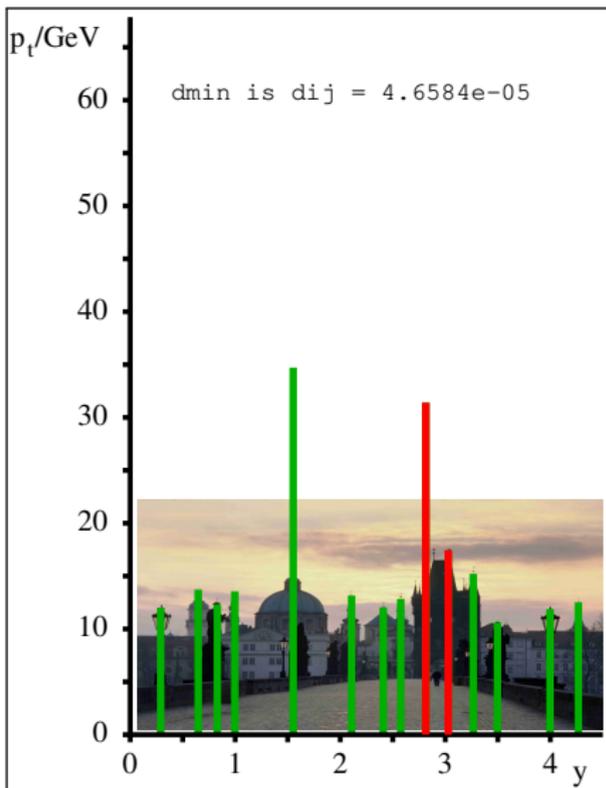
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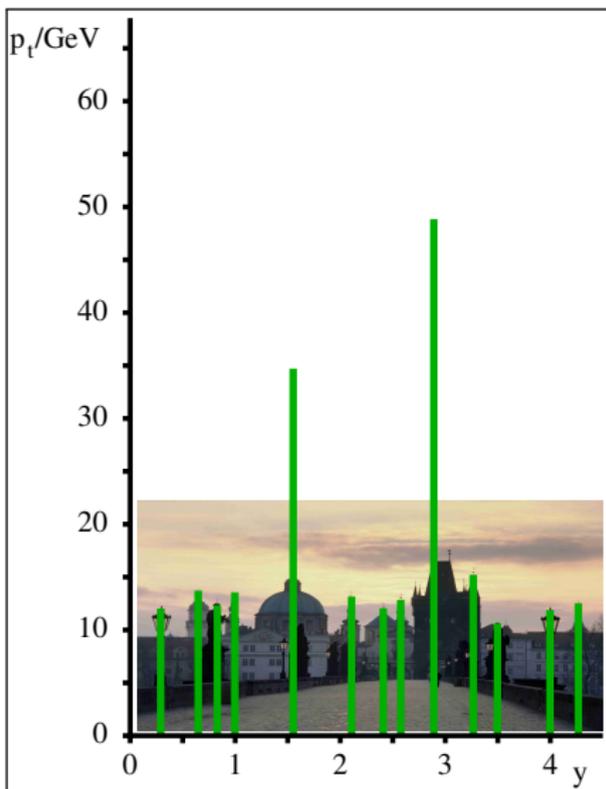
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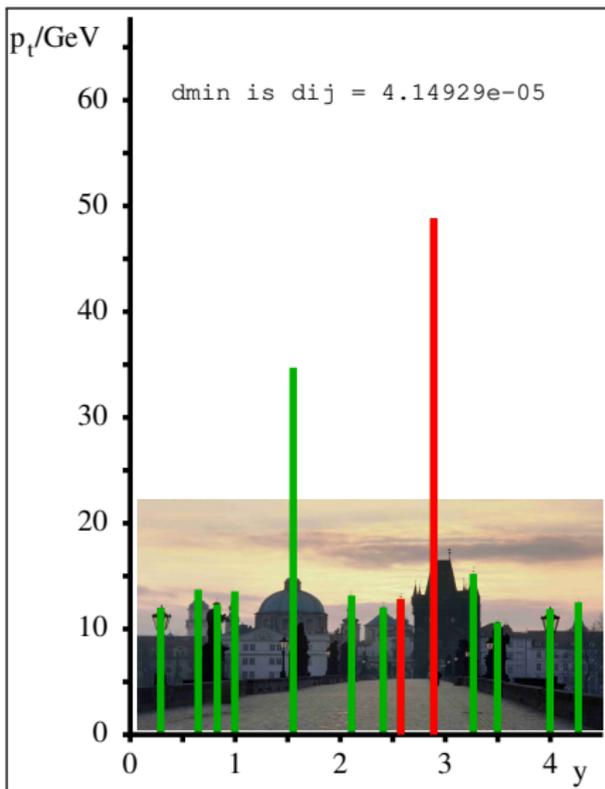
$\min$  is  $d_{ij} = 4.7 \cdot 10^{-5}$

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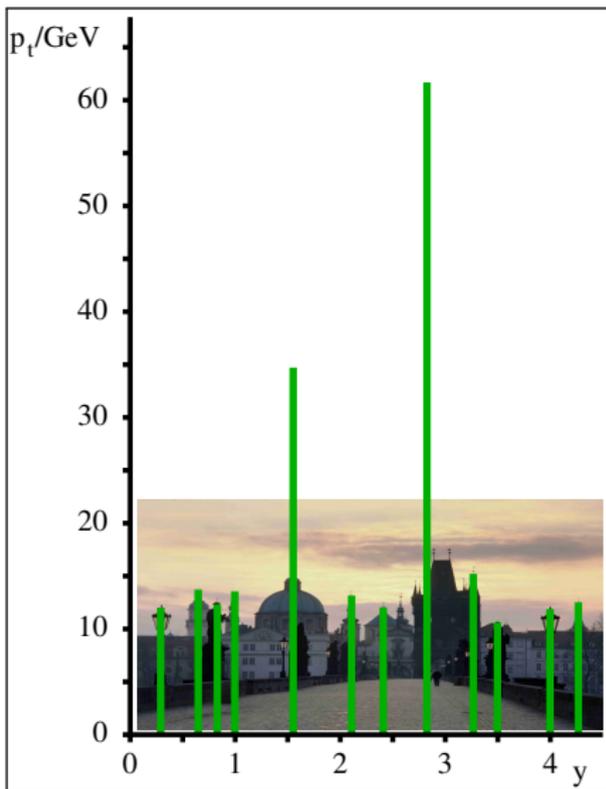
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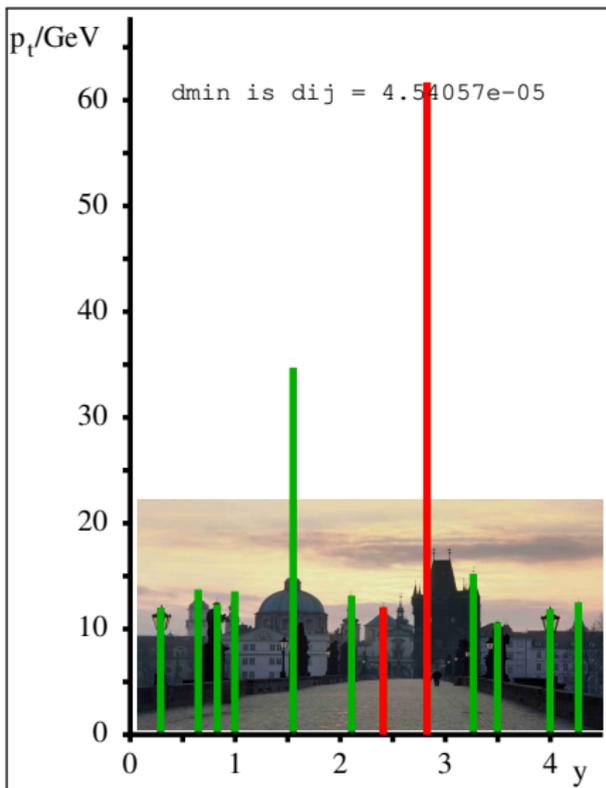
min is  $d_{ij} = 4.1 \cdot 10^{-5}$

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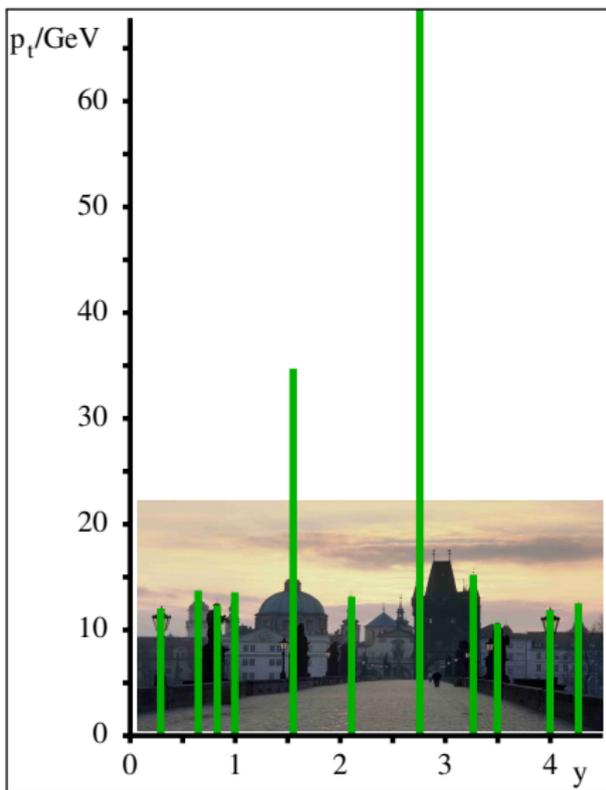
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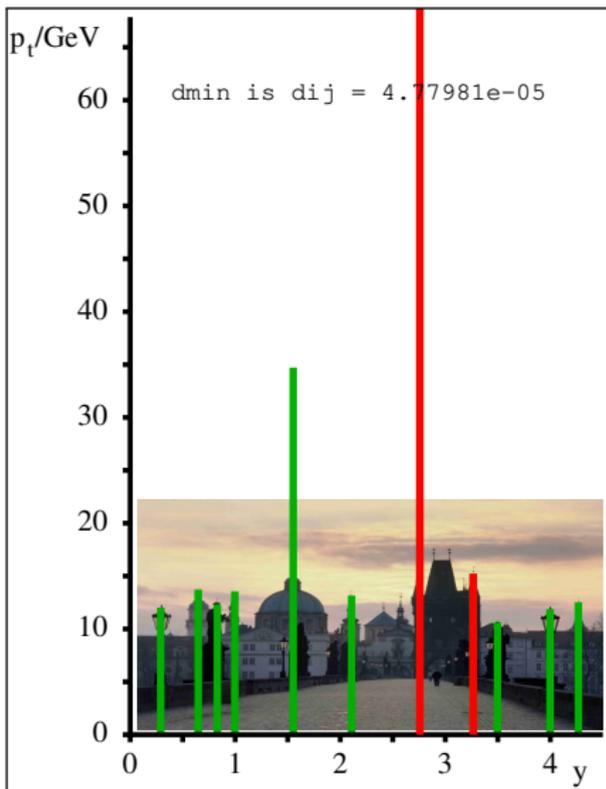
min is  $d_{ij} = 4.5 \cdot 10^{-5}$

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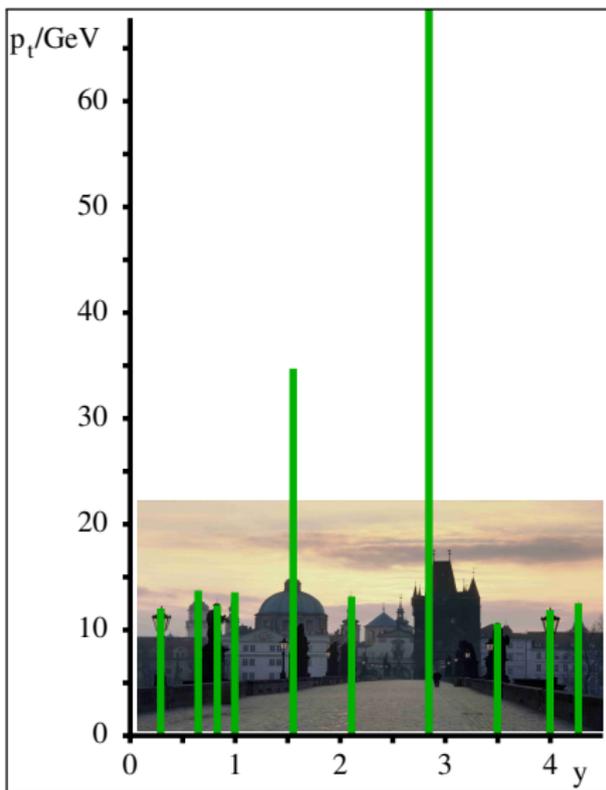
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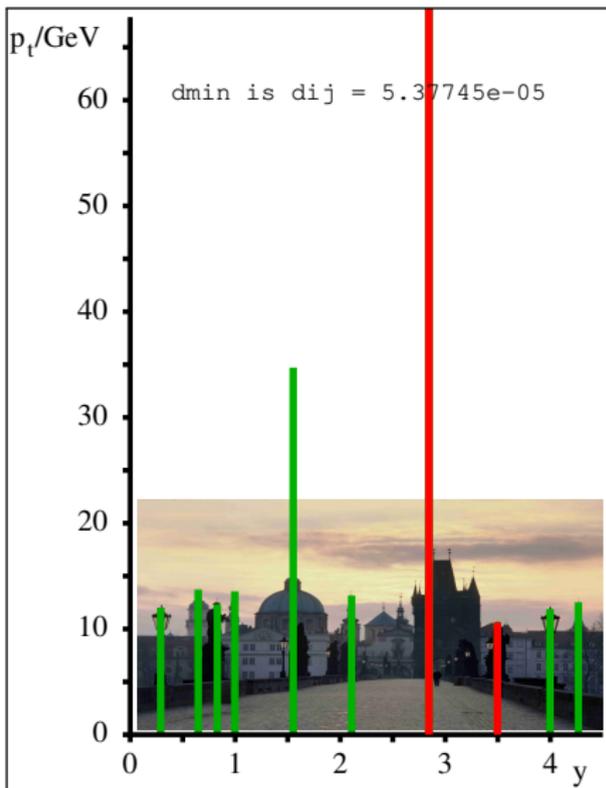
min is  $d_{ij} = 4.8 \cdot 10^{-5}$

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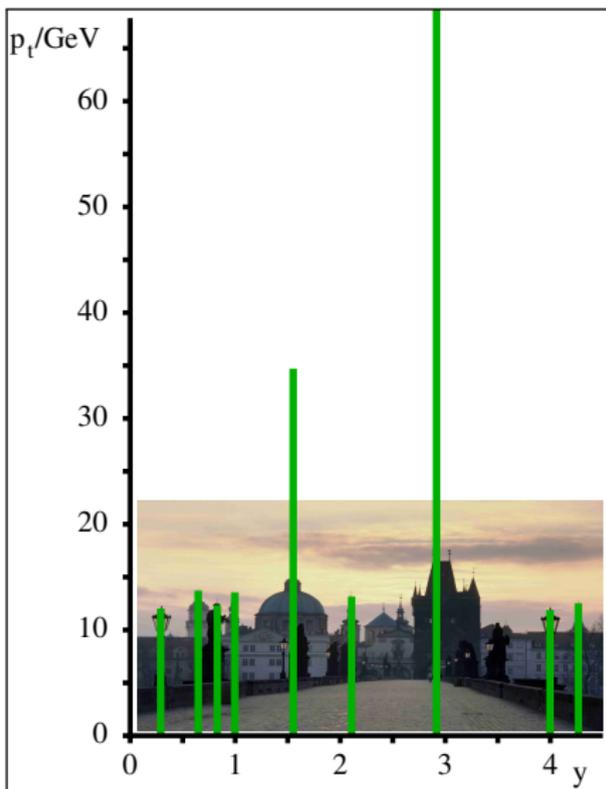
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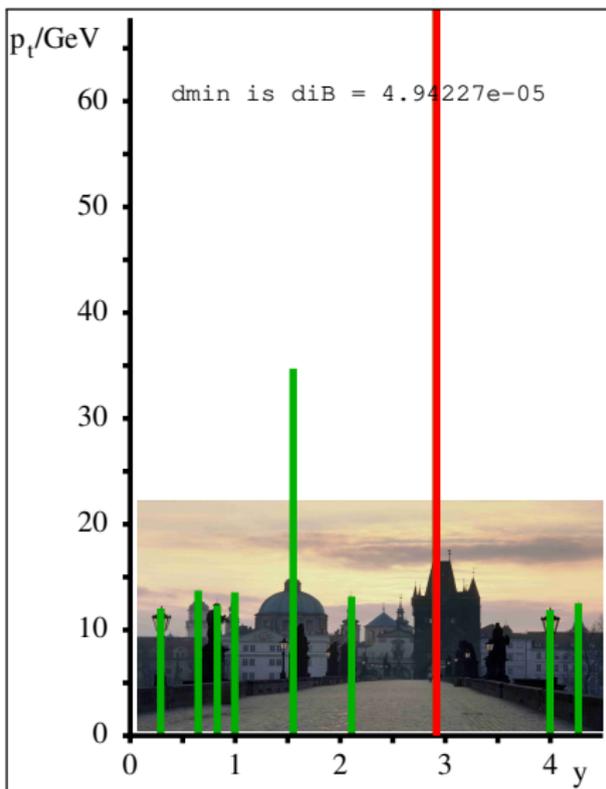
min is  $d_{ij} = 5.4 \cdot 10^{-5}$

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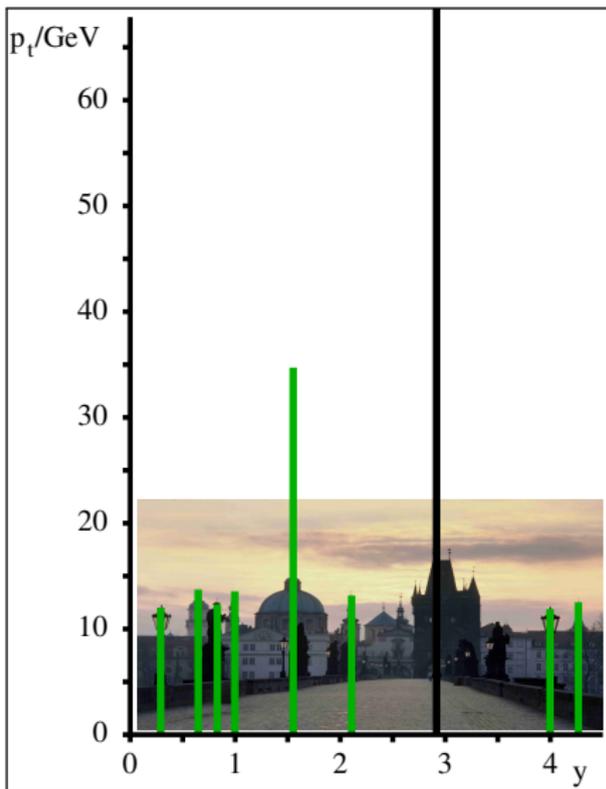
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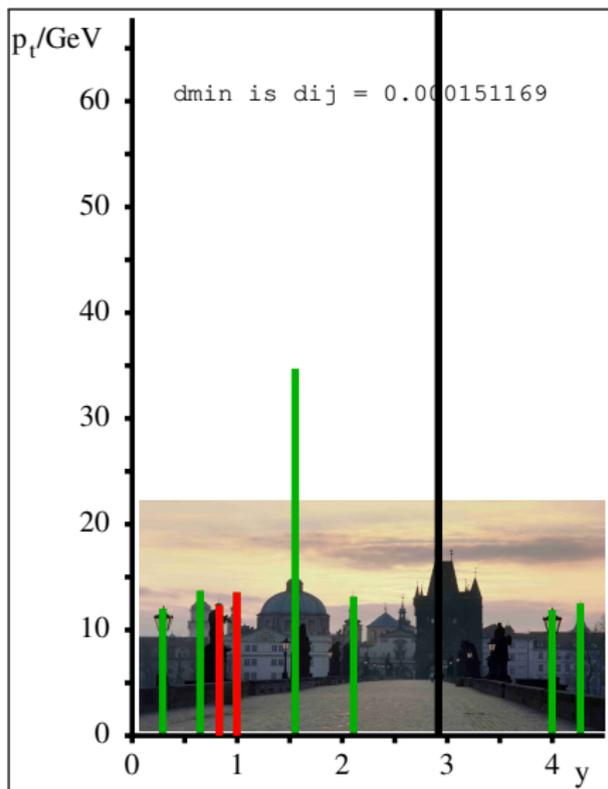
min is  $d_{iB} = 4.9 \cdot 10^{-5}$

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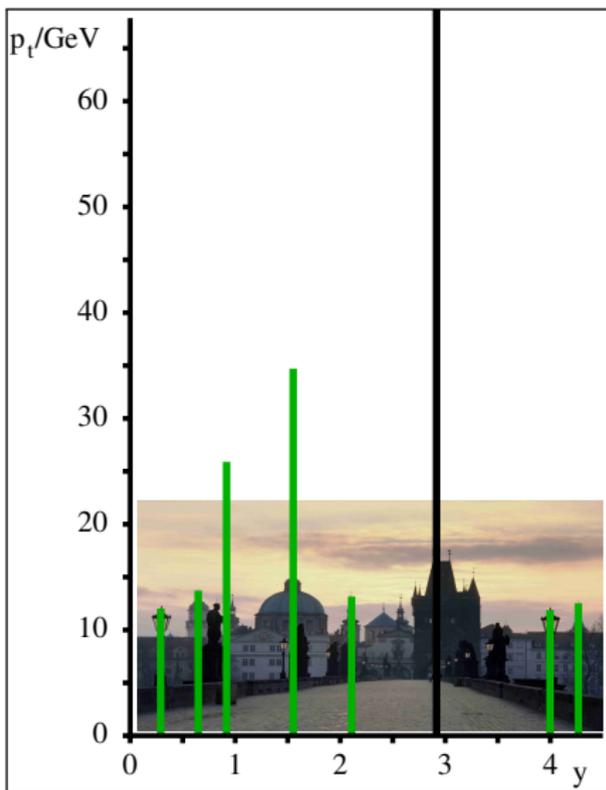
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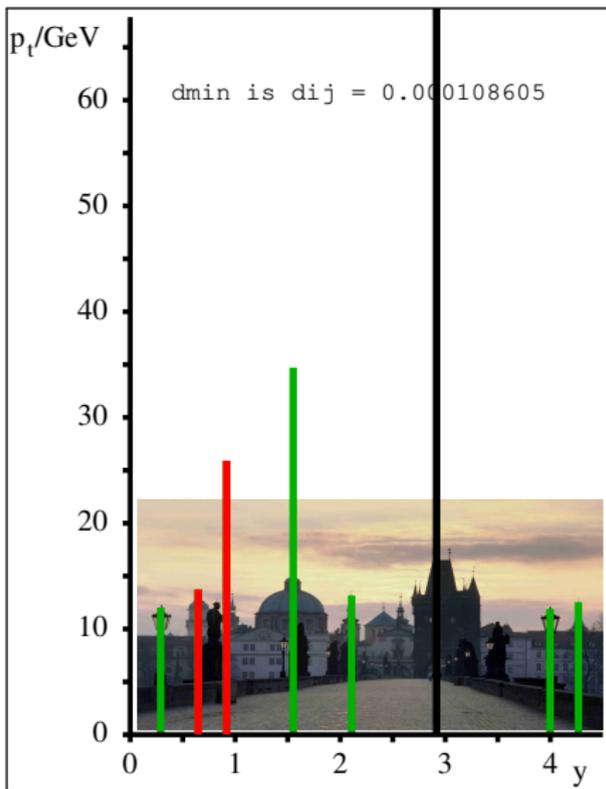
min is  $d_{ij} = 1.5 \cdot 10^{-4}$

# Clustering in action: anti- $k_t$ ( $R = 0.7$ )



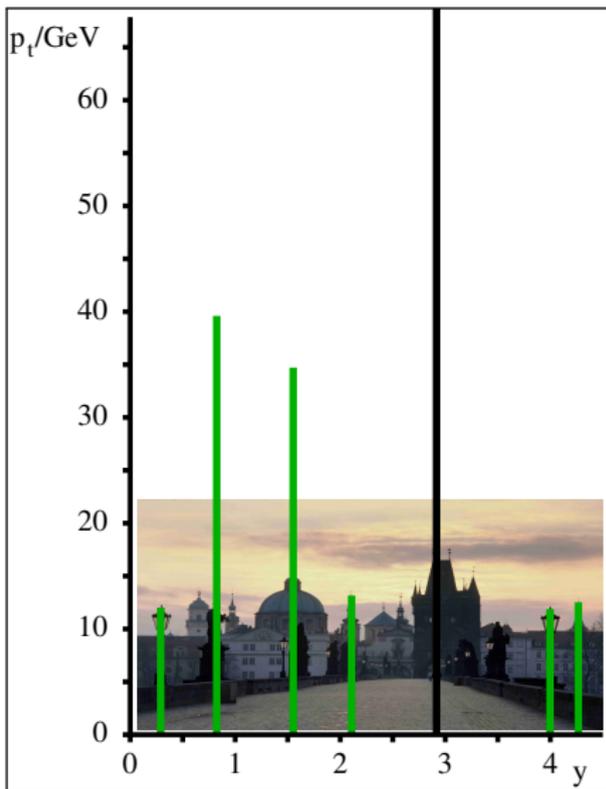
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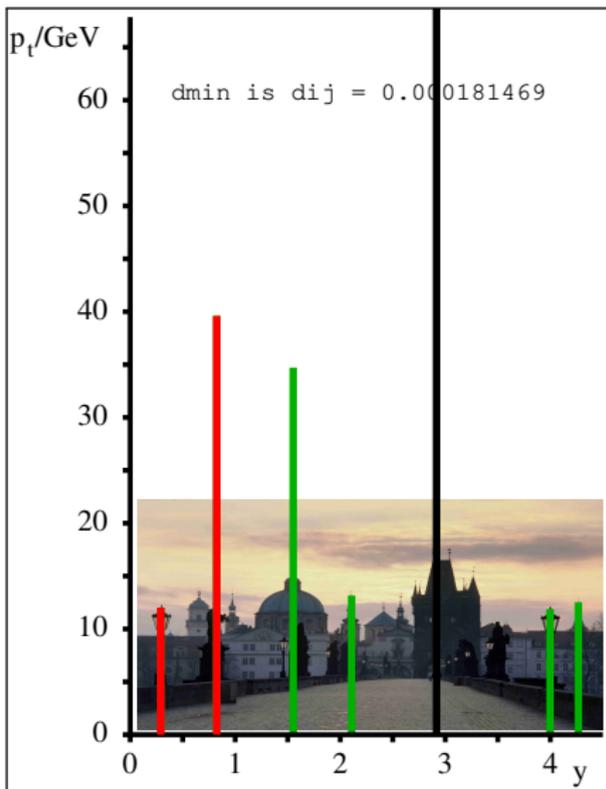
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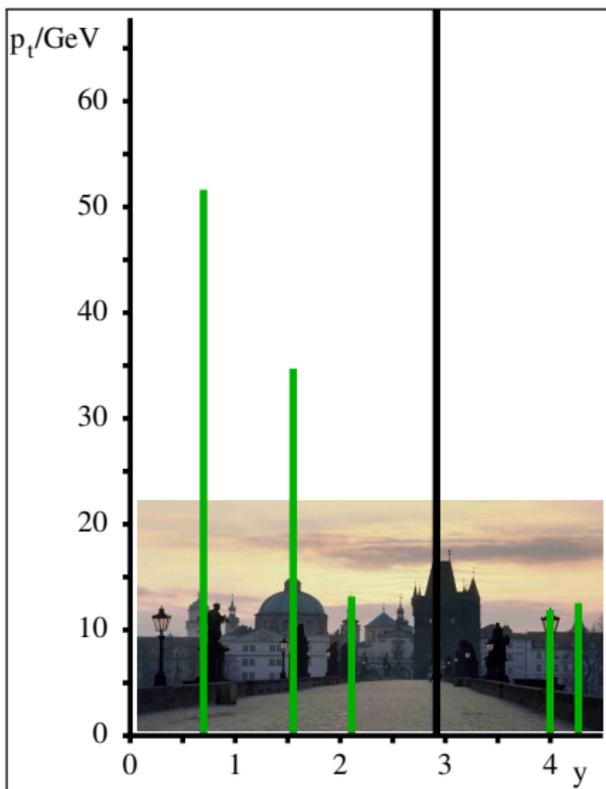
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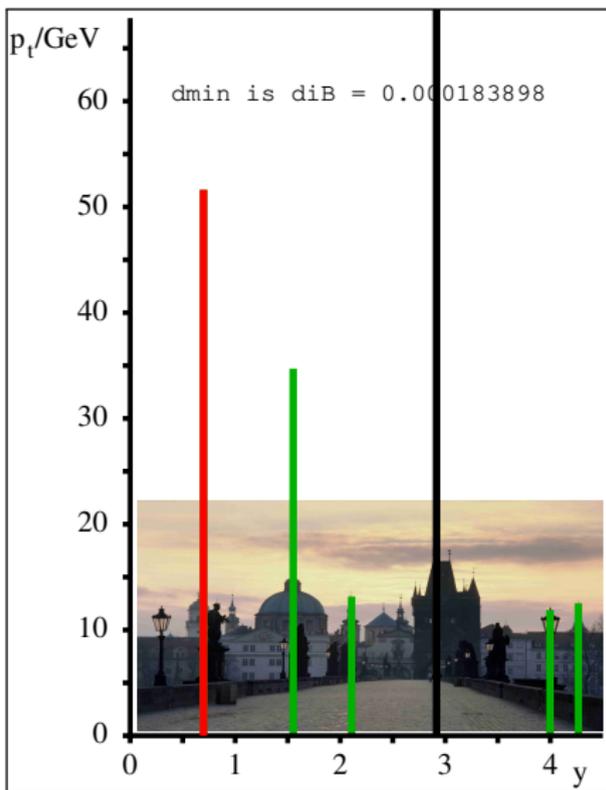
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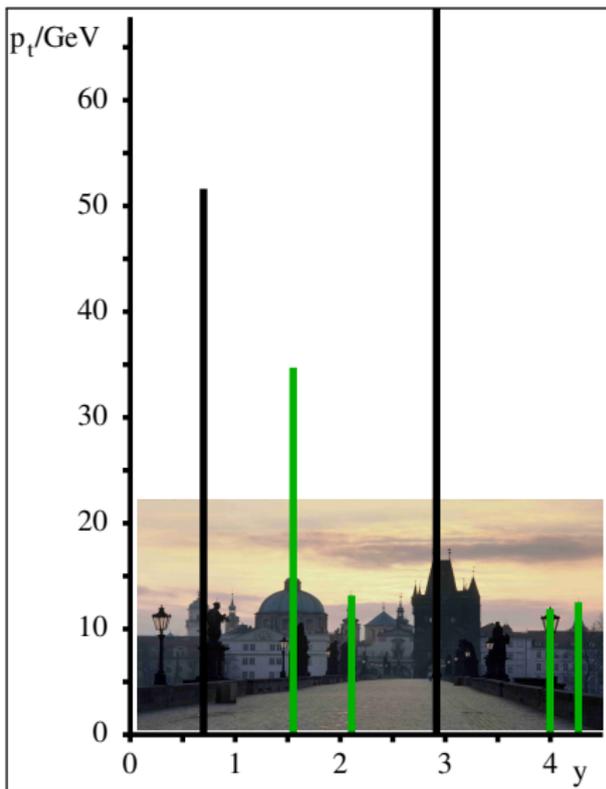
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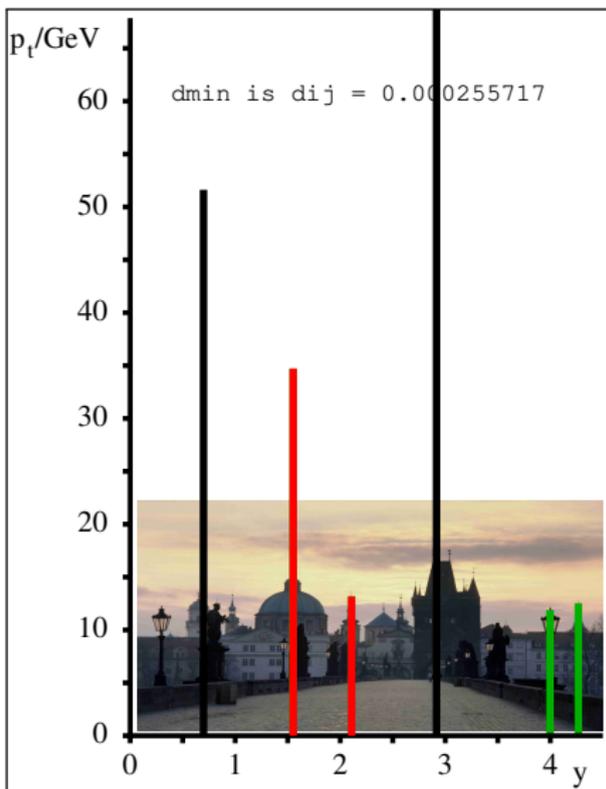
$$\min \text{ is } d_{iB} = 1.8 \cdot 10^{-4}$$

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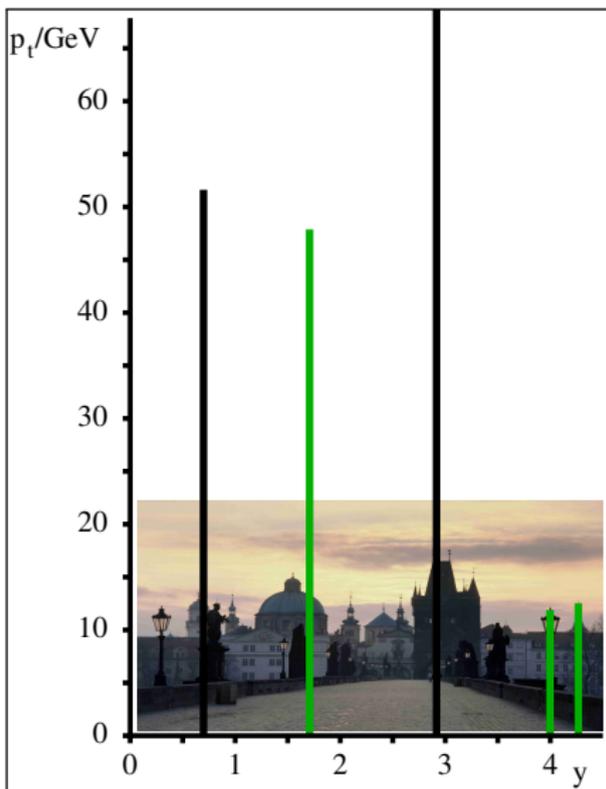
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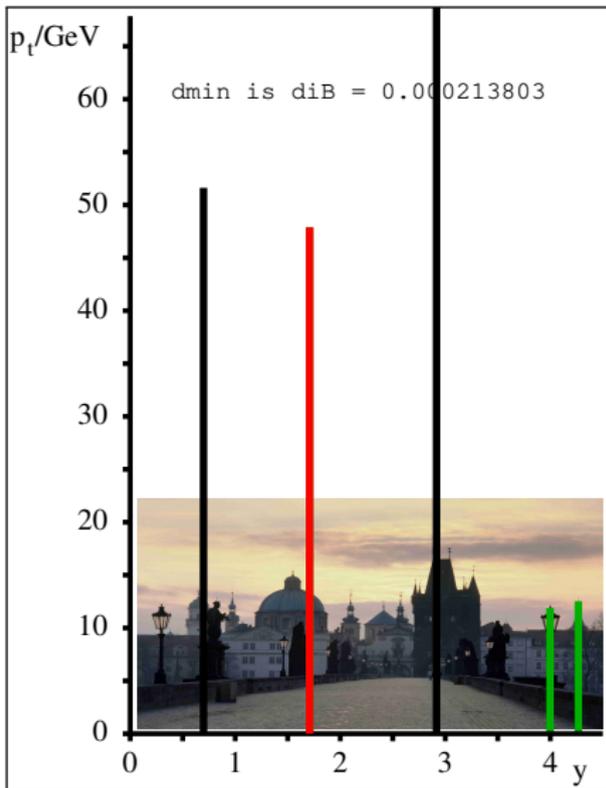
min is  $d_{ij} = 2.6 \cdot 10^{-4}$

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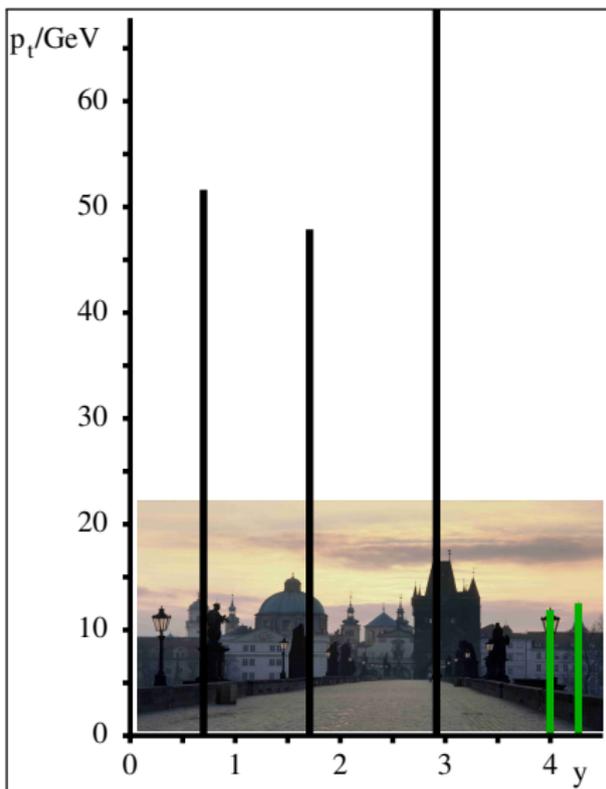
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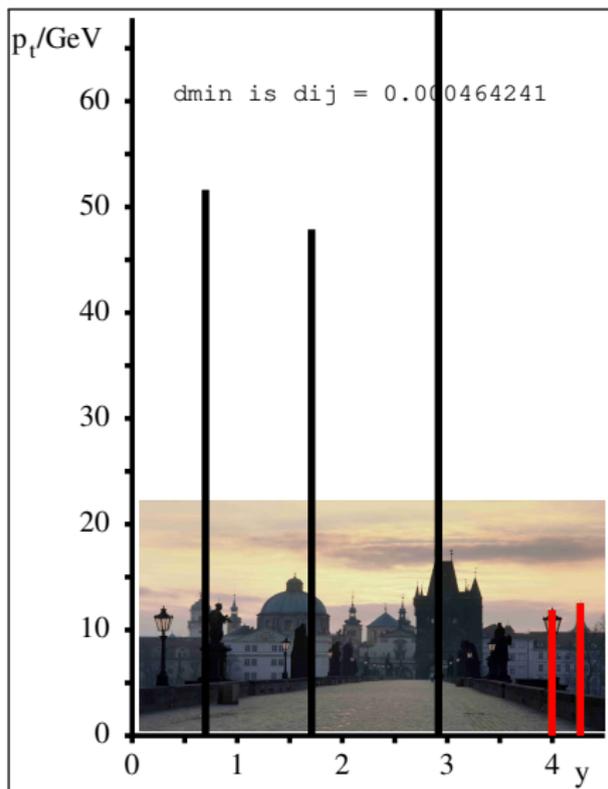
$$\min \text{ is } d_{iB} = 2.1 \cdot 10^{-4}$$

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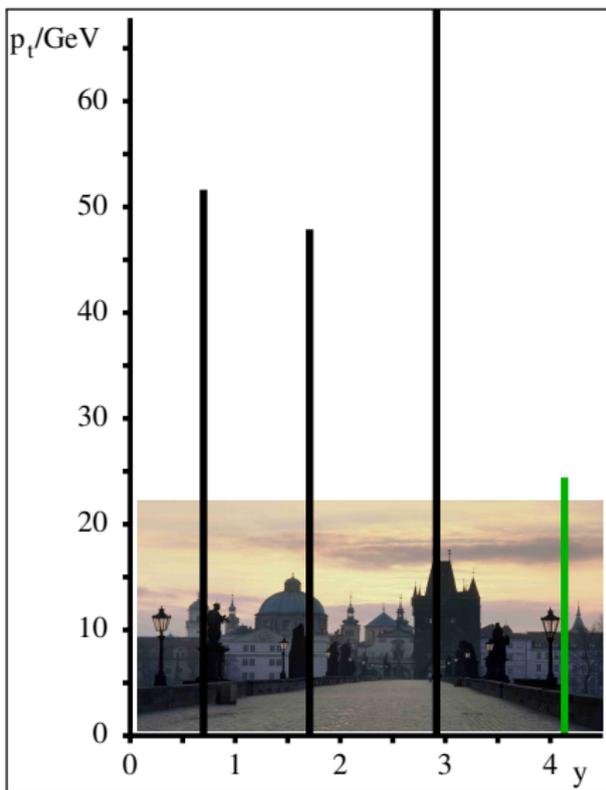
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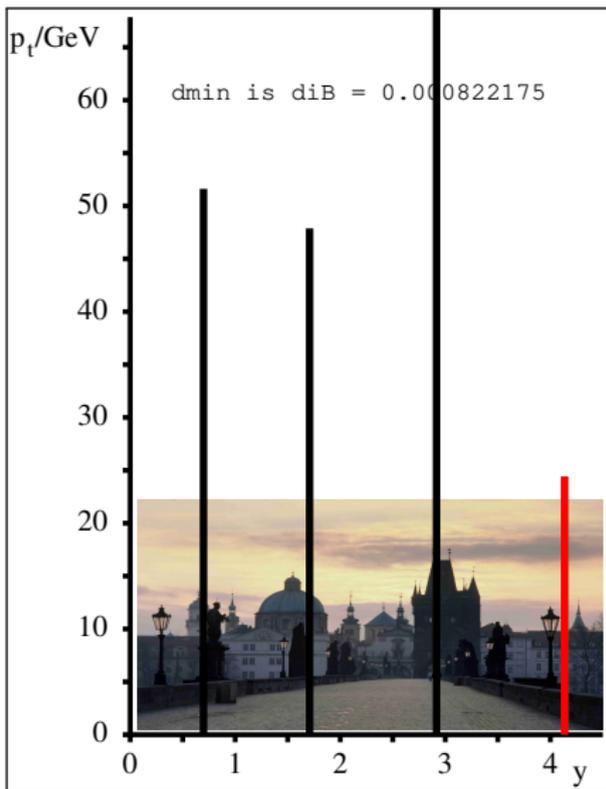
min is  $d_{ij} = 4.6 \cdot 10^{-4}$

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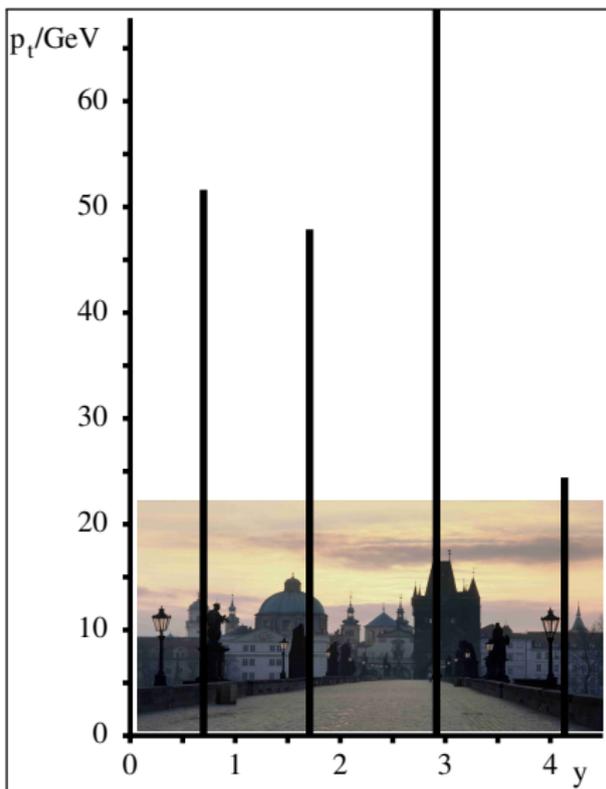
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$$\min \text{ is } d_{iB} = 8.2 \cdot 10^{-4}$$

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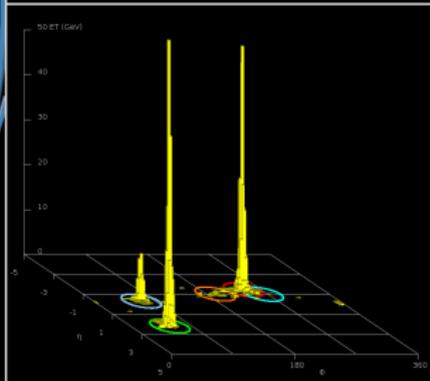
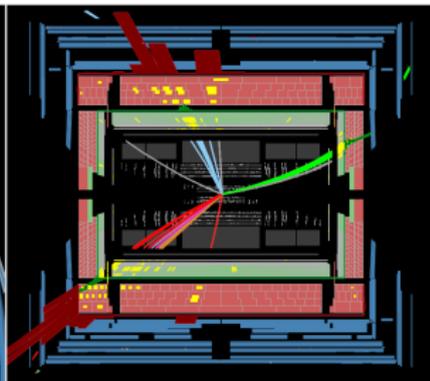
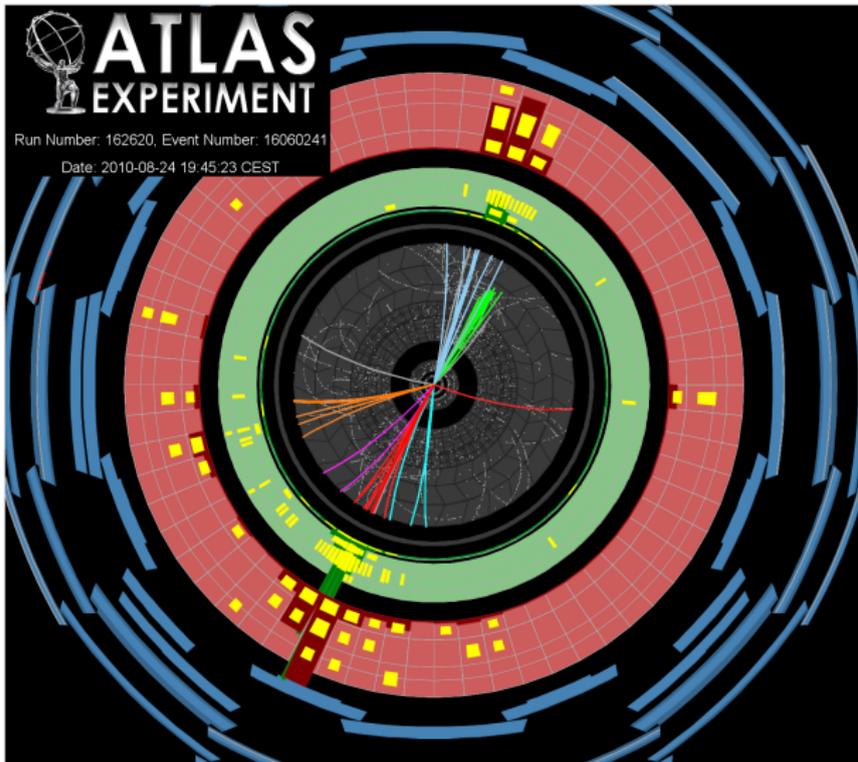


declare as a jet

# ATLAS EXPERIMENT

Run Number: 162620, Event Number: 16060241

Date: 2010-08-24 19:45:23 CEST



Substructure means looking at the internal dynamics of jets  
(as opposed to consider jets as monolithic objects)

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- rich QCD phenomenology
- precision calculations at the LHC
- many conceptual ideas

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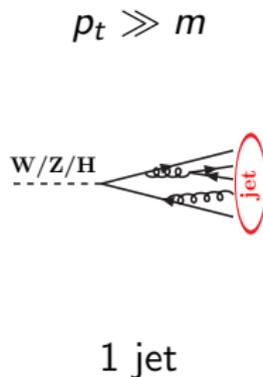
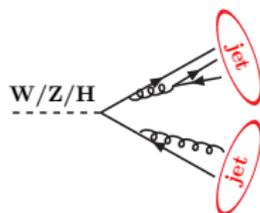
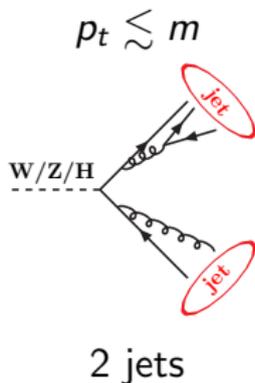
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**This talk: give you a hint of all these aspects**

# Boosted objects and searches

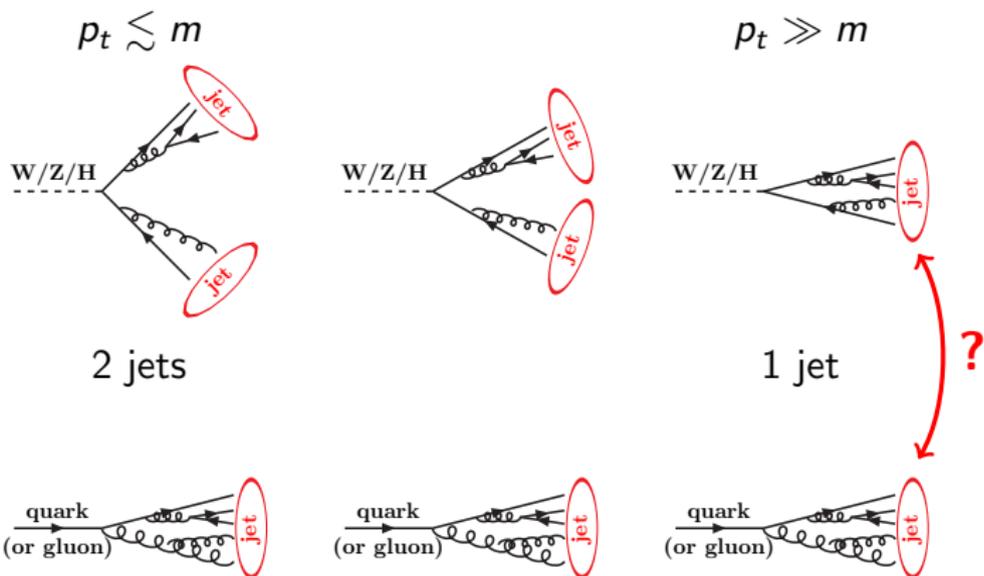
# Boosted objects



(massive) objects produced boosted (energy  $\gg$  mass) are seen as 1 jet:

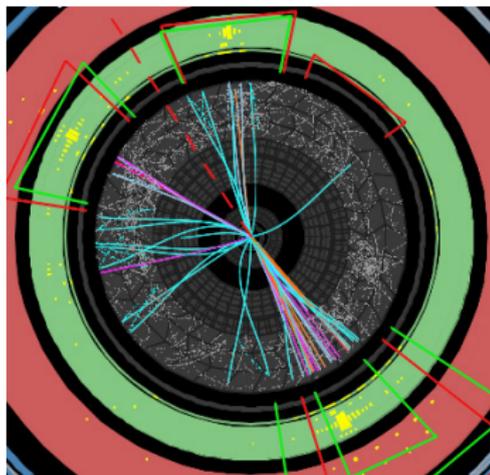
$$\theta_{q\bar{q}} \sim \frac{m}{p_t}$$

# Boosted objects



**use substructure to separate from QCD jets**

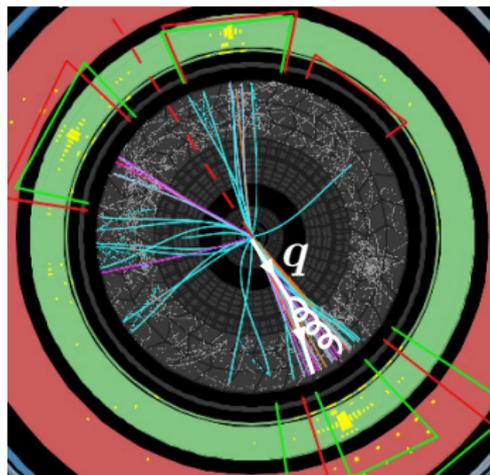
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# Other examples

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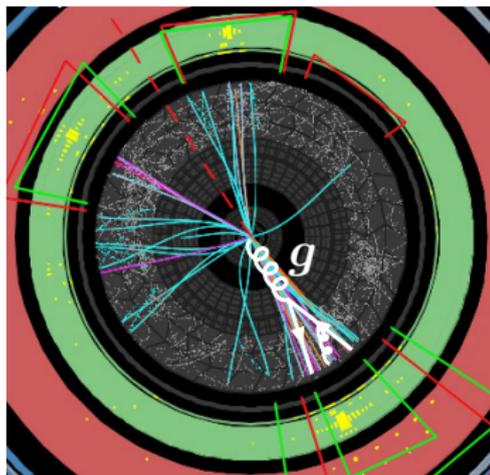
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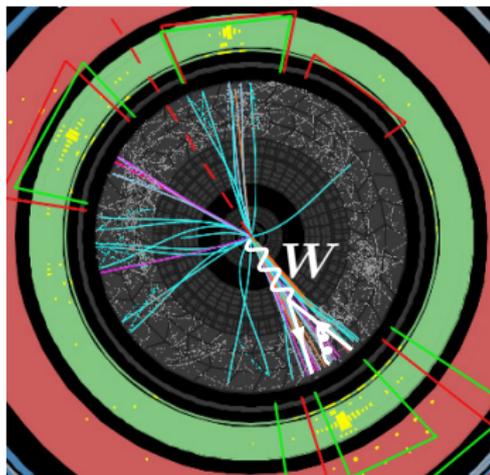
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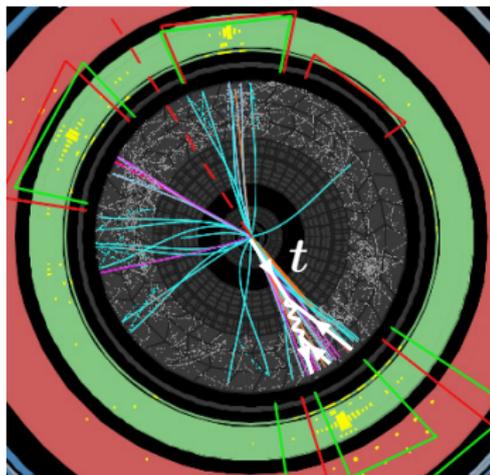
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- a  $W/Z$  (or a Higgs)?



# Other examples

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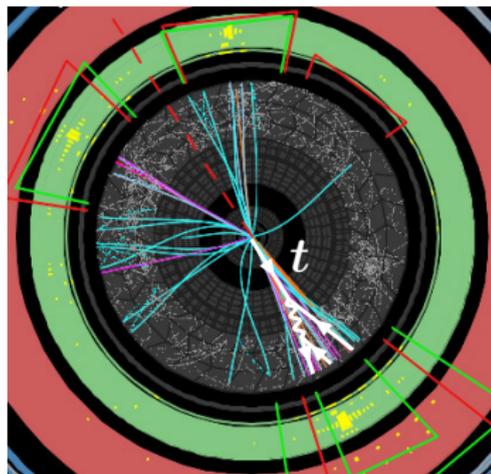


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Source: ATLAS boosted top candidate

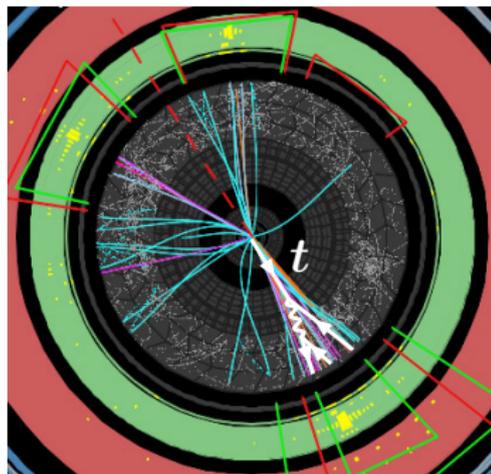


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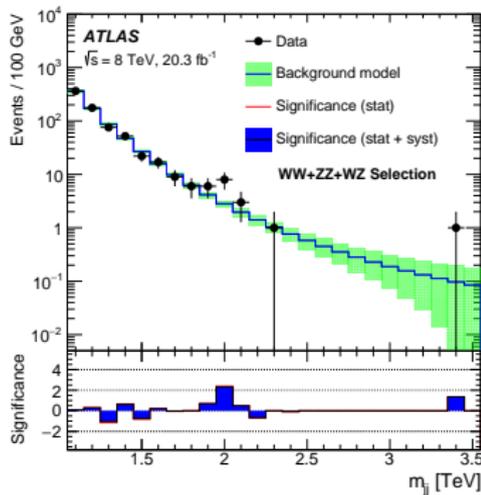
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Many applications, all relevant to new physics searches:

- 2-pronged decay:  $W/Z \rightarrow q\bar{q}$ ,  $H \rightarrow b\bar{b}$
- 3-pronged decay:  $t \rightarrow qqb$ ,  $\tilde{\chi} \rightarrow qqq$
- quark-gluon discrimination
- more exotic signatures

# Searches and measurements

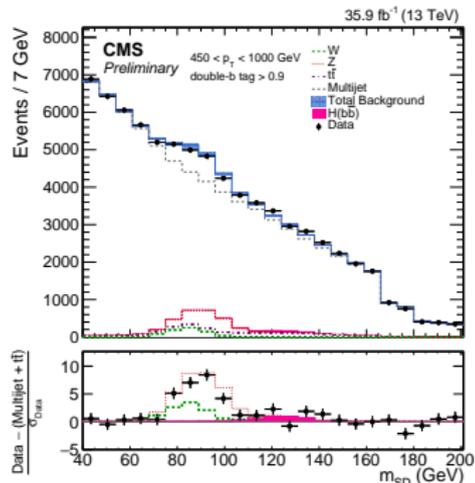
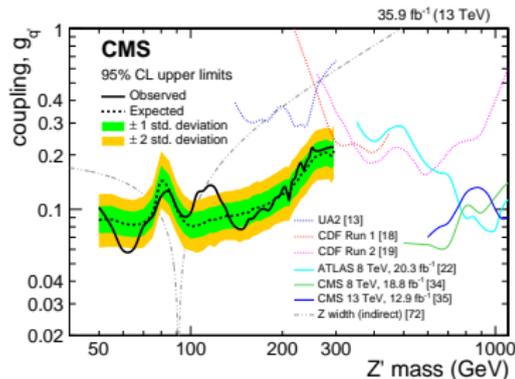


↑ (now-gone) di-boson excess (end of Run-I)

↗ Search for  $X \rightarrow q\bar{q}$

Region inaccessible otherwise

→ Clear  $Z$  peak, hint of a  $H$  peak



# Conceptual ideas

# Like a kid in a candy store

Compared to standard jets, substructure uses a **large toolkit**

- all kinds of jet algorithms

anti- $k_t$ , Cambridge/Aachen (ang-ordered),  $k_t$ , generalised  $k_t$ , winner-takes-all recomb., ...

- tools to find peaks in jets

(modified) mass-drop, Soft Drop, trimming, JHTopTagger, ...

- tools to quantify radiation patterns in jets

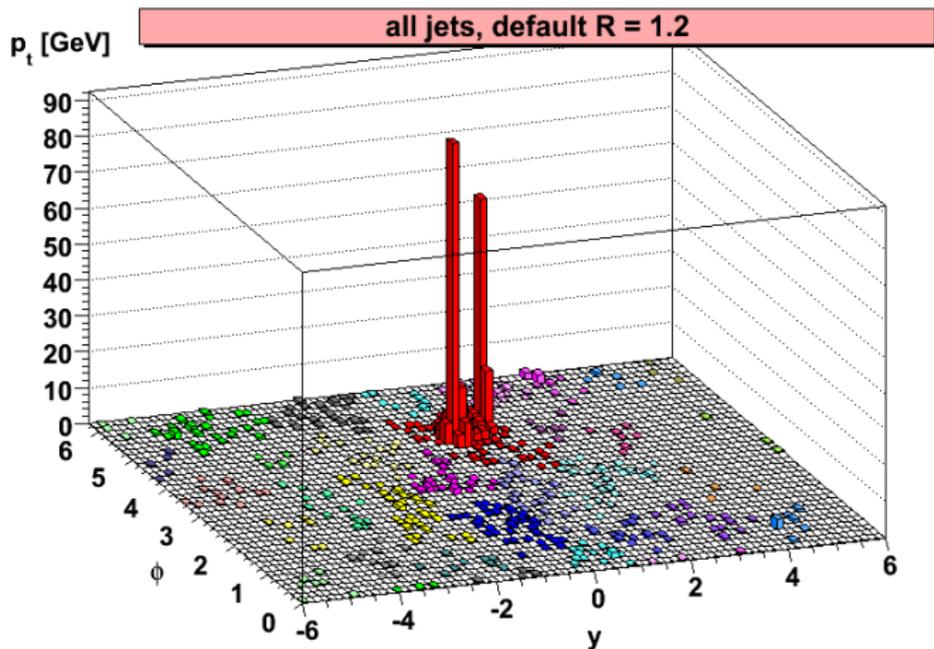
$N$ -subjettiness, energy-correlation functions, planar flow, ...

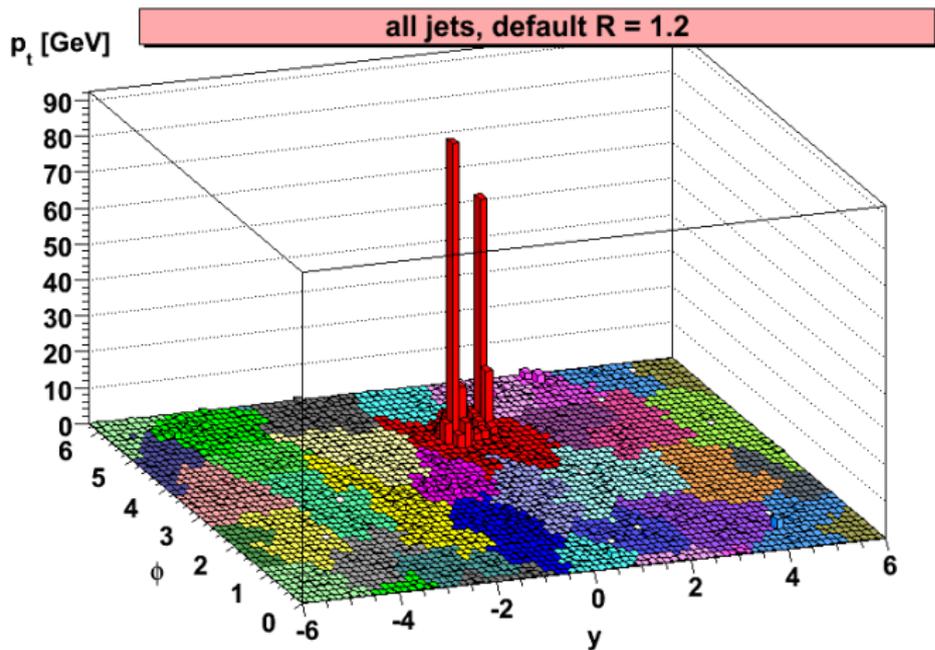
- tools to limit sensitivity to soft-large-angle radiation (UE, PU,...)

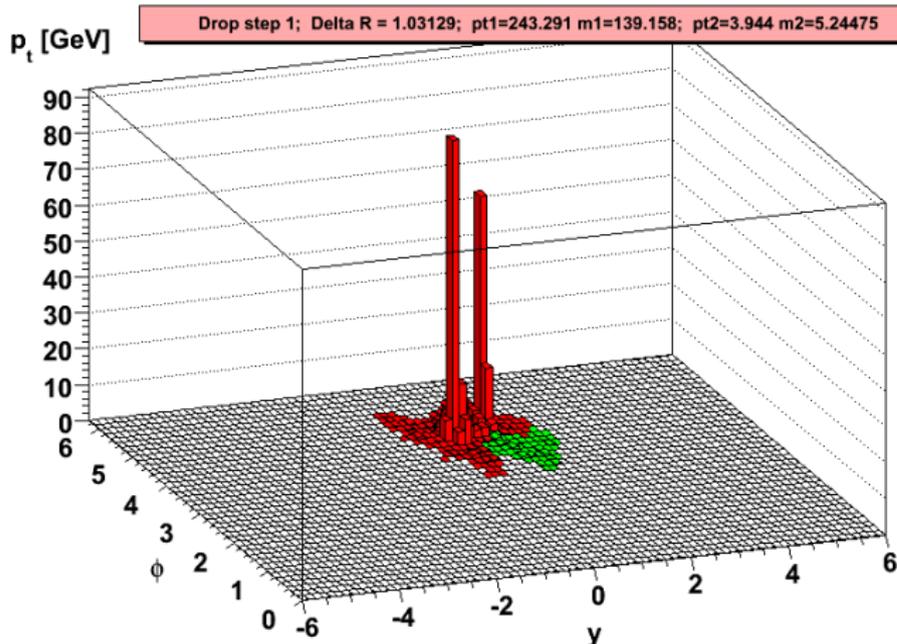
filtering, trimming, pruning, Soft Drop, (m)MDT, ...

Active field for developing/studying new tools , combining them,...

Requires both some creativity and some control over the underlying physics

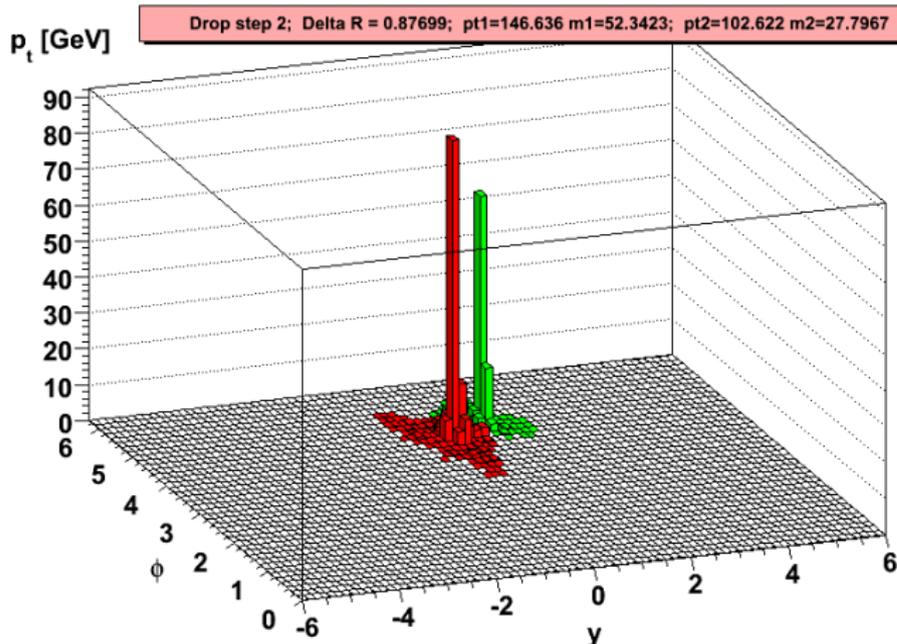






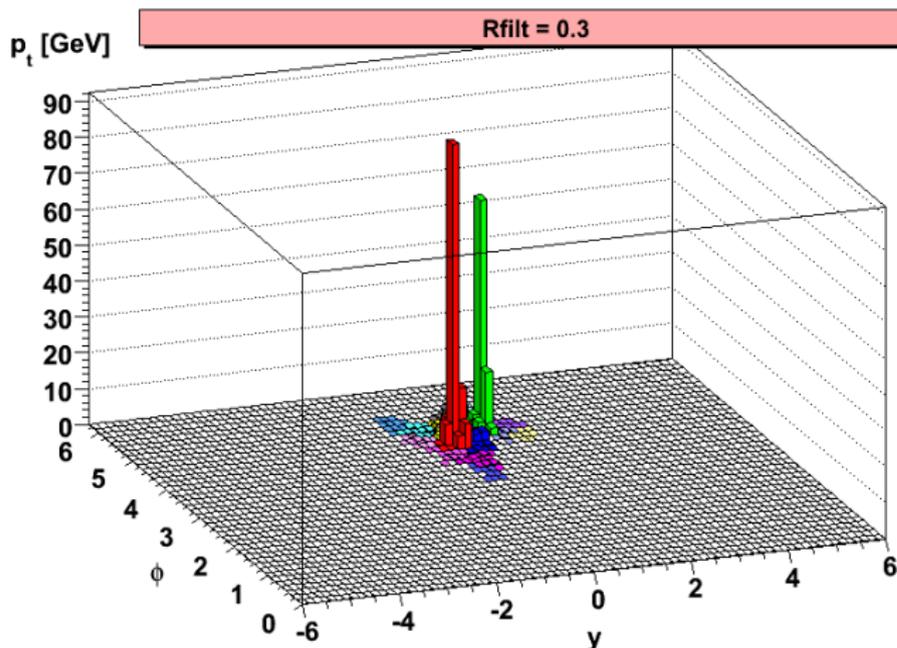
## MassDrop

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- $z = 0.016 < 0.1$   
carry on



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- $z = 0.41 > 0.1$   
stop

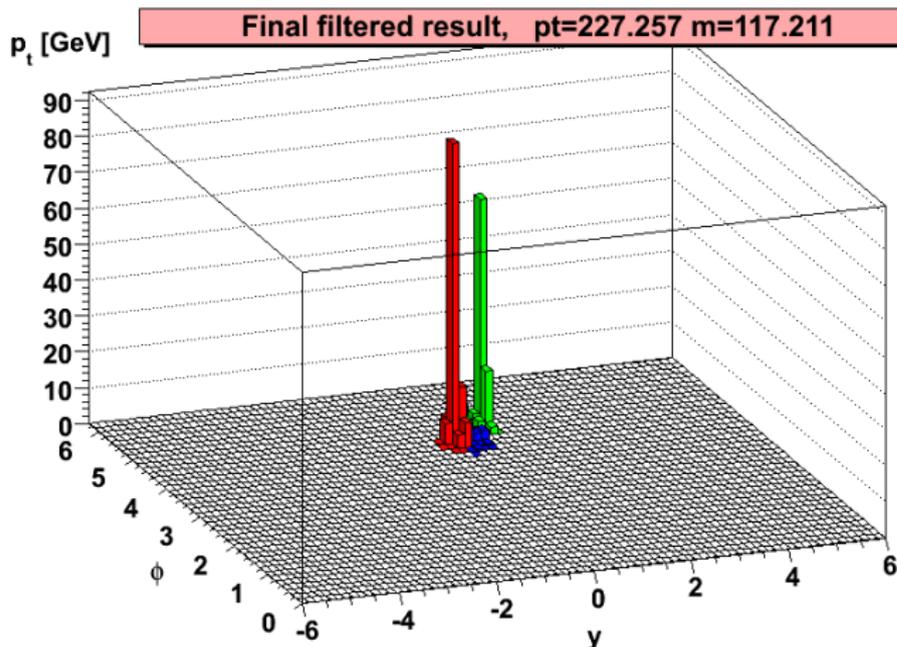


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## Filter

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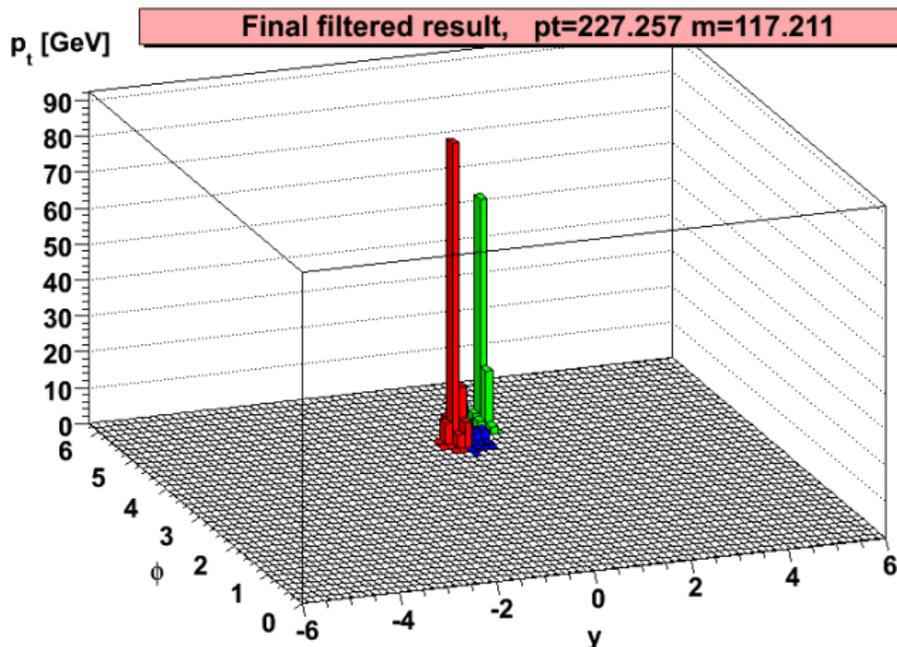


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- recluster
- keep 3 hardest

Variant: **SoftDrop**: impose  $z > z_{\text{cut}}\theta^\beta$

[A.Larkoski,S.Marzani,GS,J.Thaler,14]

# Study radiation: $N$ -subjettiness

Given  $N$  axes/prongs in a jet (axes)

[ $\neq$  options, e.g.  $k_t$  subjets]

$$\tau_N^{(\beta)} = \frac{1}{p_T R^\beta} \sum_{i \in \text{jet}} p_{t,i} \min(\theta_{i,a_1}^\beta, \dots, \theta_{i,a_n}^\beta)$$

# Study radiation: $N$ -subjettiness

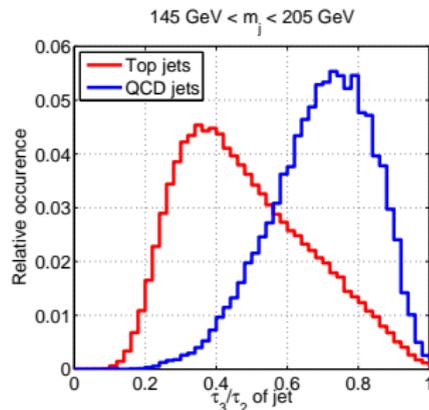
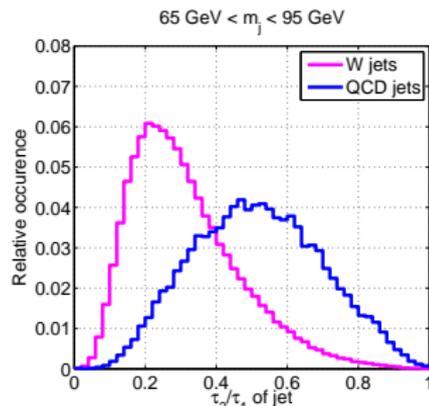
Given  $N$  axes/prongs in a jet (axes)

[ $\neq$  options, e.g.  $k_t$  subjets]

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- Measures the radiation from  $N$  prongs
- $\tau_{N,N-1} = \tau_N / \tau_{N-1}$  discriminates  $N$ -prong v. QCD
- $\tau_{21}$  smaller for  $W$  than for QCD
- $\tau_{32}$  smaller for top than for QCD

Several alternatives similar to  $\tau_N$



# Expanding in new directions

## Machine Learning has become a major player

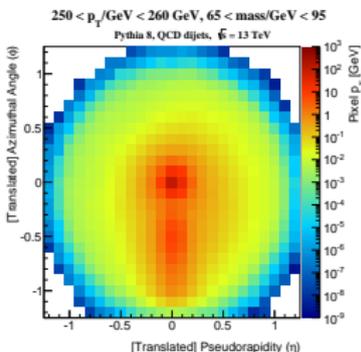
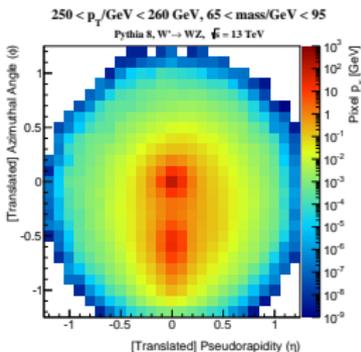
- Many architectures:
  - ANN Artificial Neural Network
  - DNN Dense Neural Network
  - CNN Convolutional Neural Network
  - GANN Generative Adversarial Neural Network
  - LSTM Long Short-Term Memory Neural Network
- Many approaches:

Feed jet variables, jet constituents, jet images, ...
- Many applications:

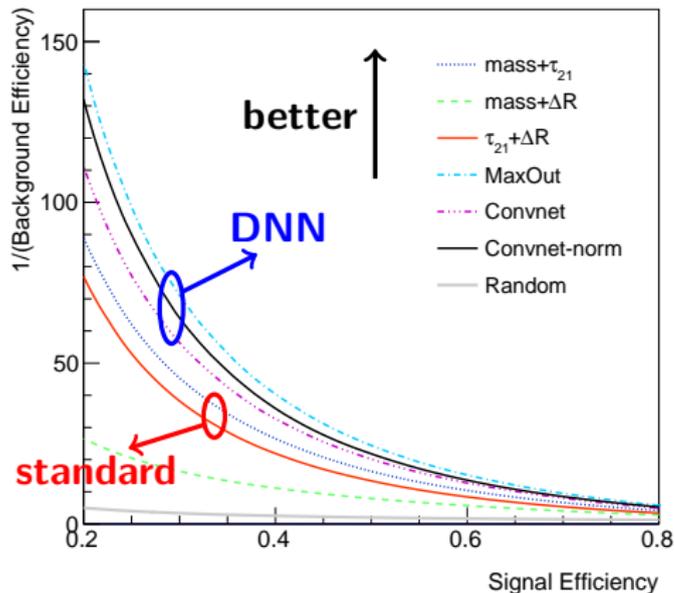
$q/g$ ,  $b$ ,  $W$ ,  $H$ ,  $t$  tagging, pileup-mitigation, detector sim, ...

# Latest playground: deep learning

## Example 1: jet image for $W$ vs. QCD jets using Convolutional/Dense NN



250 <  $p_T$ /GeV < 300 GeV, 65 < mass/GeV < 95  
 $\sqrt{s} = 13$  TeV, Pythia 8



Improvement compared to standard approach

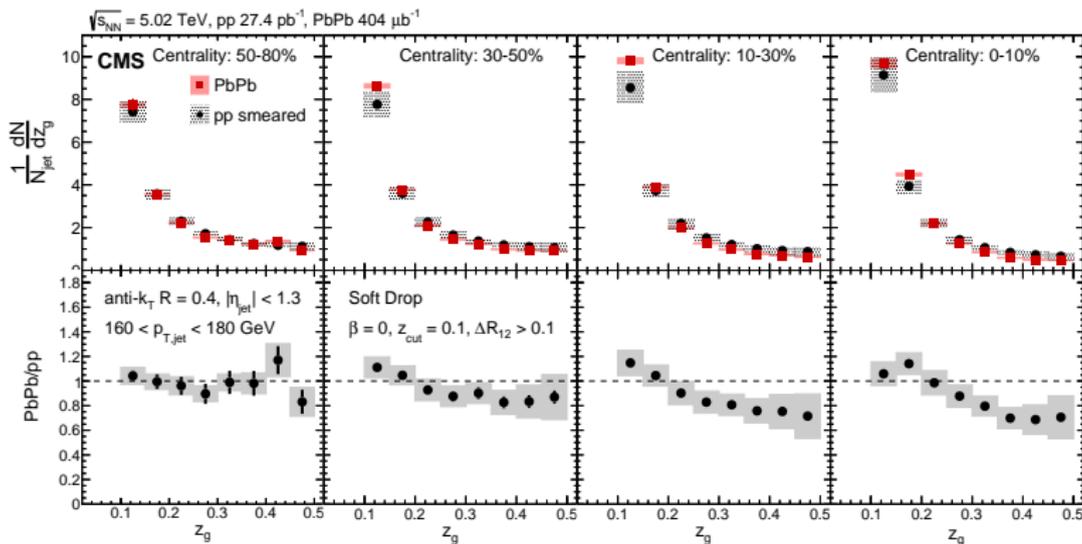
# Expanding in new directions

## Heavy-Ion collisions

# Measuring the splitting function

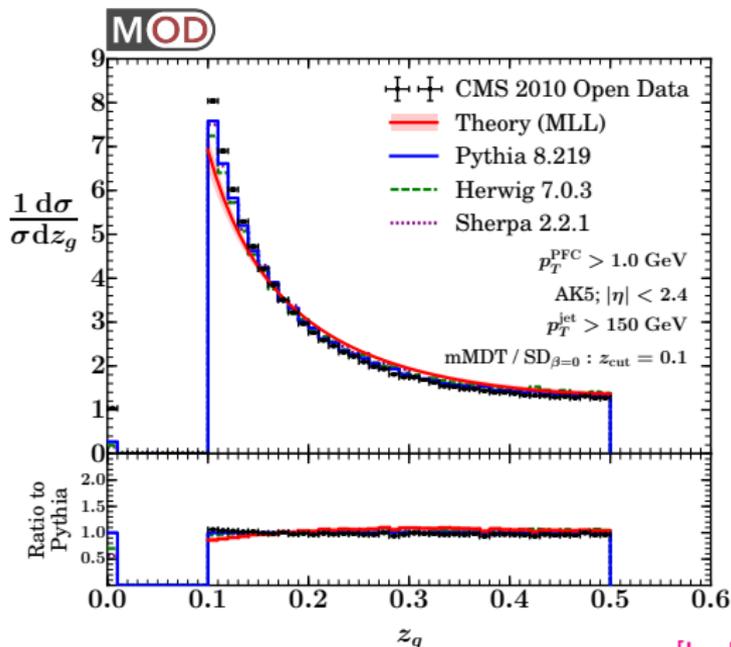
- Take a jet with large  $p_t$
- apply mMDT  $\rightarrow$  hard splitting
- $z_g \equiv$  mom fraction of that splitting

Measurement in *PbPb* shows quenching effects



Expect more to come in the (near) future...

## First “analysis” using CMS Open Data



- Open data is a heated debate
- many interesting possibilities (incl. substructure)

[Larkoski,Marzani,Thaler,Thipathee,Xue,17]

# Rich QCD phenomenology

For a long time, it was thought that  
the complexity of substructure techniques implies throwing the  
ability to make analytic calculations

# Substructure from first principles (1/2)

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Main benefits of a first-principles understanding:

- ▶ understanding the dynamics at play in jet kinematics (example later)
- ▶ understand similarities and differences between methods  
e.g. trimming, prunng, mMDT similar at large mass, differ at low mass
- ▶ adjust substructure tools for better performance (e.g. *modified* MDT)
- ▶ understand parametric dependence, e.g.  $p_t$  (without generators)
- ▶ highlight a trade-off between performance and model-independence

# Substructure from first principles (2/2)

- Several interesting directions (all overviewed below)
  - ▶ Understanding how the methods work
  - ▶ Building improved tools
  - ▶ Precision QCD at the LHC
  - ▶ Funny structures in pQCD

# Substructure from first principles (2/2)

- Several interesting directions (all overviewed below)

- ▶ Understanding how the methods work
- ▶ Building improved tools
- ▶ Precision QCD at the LHC
- ▶ Funny structures in pQCD

- Substantial progress in understanding substructure, e.g.:

	peak finder	radiation
$W/Z/H$	mMDT, trimming, pruning Dasgupta,Fregoso,Marzani,Salam,13 SoftDrop Larkoski,Marzani,GS,Thaler,14	$\tau_{21}^{(\beta=2)}, \mu^2, D_2^{(\beta=2)}$ Dasgupta,Schunk,GS,15 $D_2^{(\beta)}$ Larkoski,Moult,Neill,15-16
top	CMSTopTagger, Y-splitter Dasgupta,Guzzi,Rawling,GS,soon	next task Cacciari,Napoletano,GS,Stagnitto,18-20

- Main idea:

Boosted jet  $\Rightarrow p_t \gg m$

$$\Rightarrow \rho \equiv \frac{m^2}{p_t^2 R^2} \ll 1$$

$\Rightarrow$  expect  $\log \rho$  coming with  $\alpha_s$

$\Rightarrow$  need for all-order resummation

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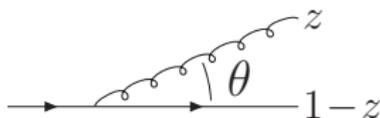
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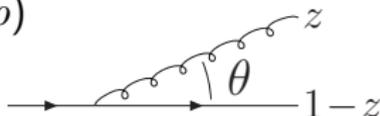
- Example: jet mass with one (soft-and-collinear) gluon emission

$$\begin{aligned} \text{Prob}_1(> \rho) &\simeq \int_0^1 \frac{d\theta^2}{\theta^2} \frac{dz}{z} \frac{\alpha_s C_R}{\pi} \Theta(z\theta^2 > \rho) \\ &\simeq \frac{\alpha_s C_R}{2\pi} \log^2(1/\rho) \end{aligned}$$



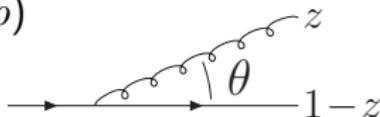
- (plain) jet mass again:

$$\begin{aligned}\text{Prob}_1^{(\text{plain})}(> \rho) &\simeq \int_0^1 \frac{d\theta^2}{\theta^2} \frac{dz}{z} \frac{\alpha_s C_R}{\pi} \Theta(z\theta^2 > \rho) \\ &\simeq \frac{\alpha_s C_R}{2\pi} \log^2(1/\rho)\end{aligned}$$



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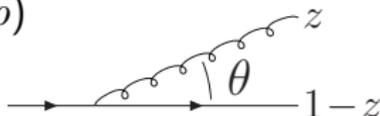


- mMDT jet mass:

$$\begin{aligned}\text{Prob}_1^{(\text{mMDT})}(> \rho) &\simeq \int_0^1 \frac{d\theta^2}{\theta^2} \frac{dz}{z} \frac{\alpha_s C_R}{\pi} \Theta(z\theta^2 > \rho) \Theta(z > z_{\text{cut}}) \\ &\simeq \frac{\alpha_s C_R}{\pi} \left[ \log(1/\rho) \log(1/z_{\text{cut}}) - \frac{1}{2} \log^2(1/z_{\text{cut}}) \right]\end{aligned}$$

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- all-order result (Leading-Log): for both the “plain” jet and mMDT

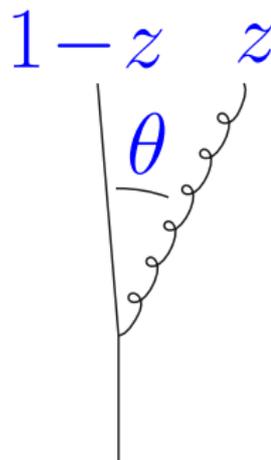
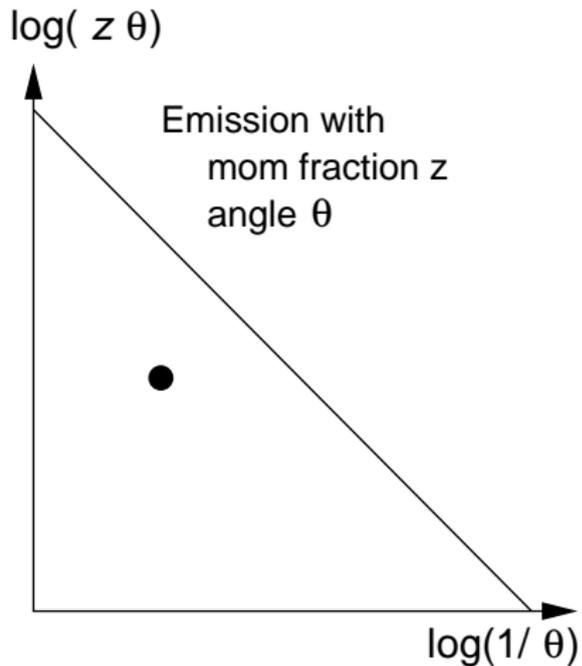
$$\text{Prob}_{\text{LL}}(< \rho) = \exp[-\text{Prob}_1(< \rho)]$$

# Rich QCD phenomenology

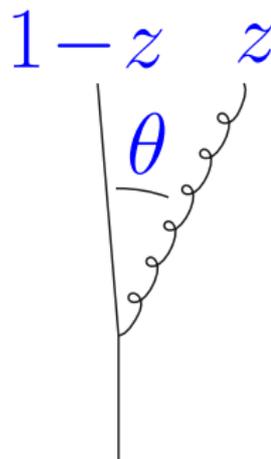
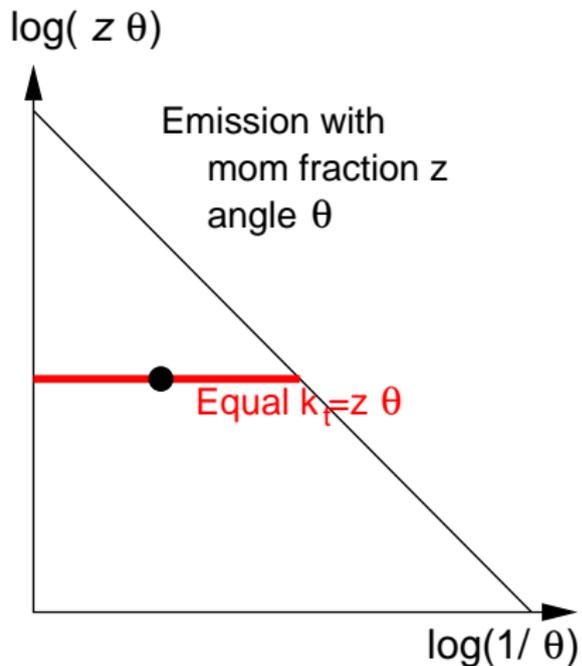
## Explicit examples at LL

- ▶ Understanding jet substructure: revisited jet mass (plain and mMDT)
- ▶ Understanding jet substructure:  $N$ -subjettiness
- ▶ Designing new tools: *Dichroic*  $N$ -subjettiness

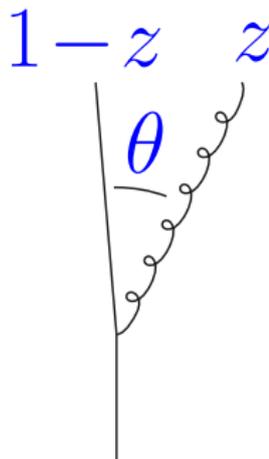
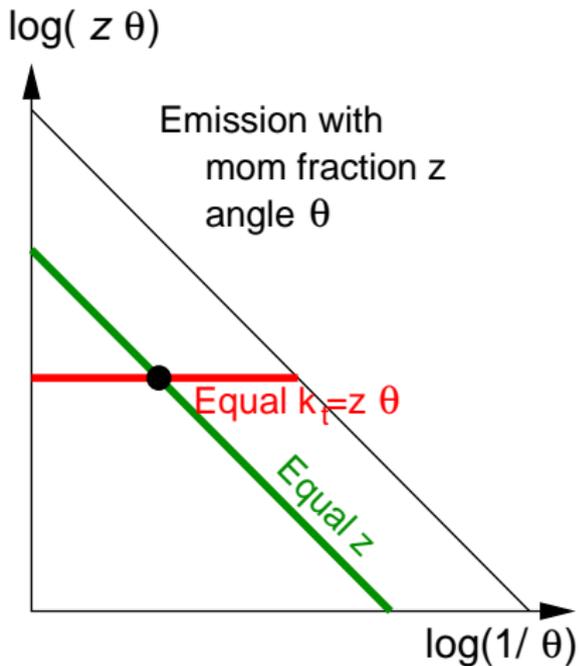
# Anatomy of the phase-space (at Leading Log)



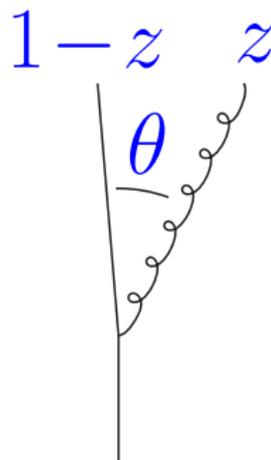
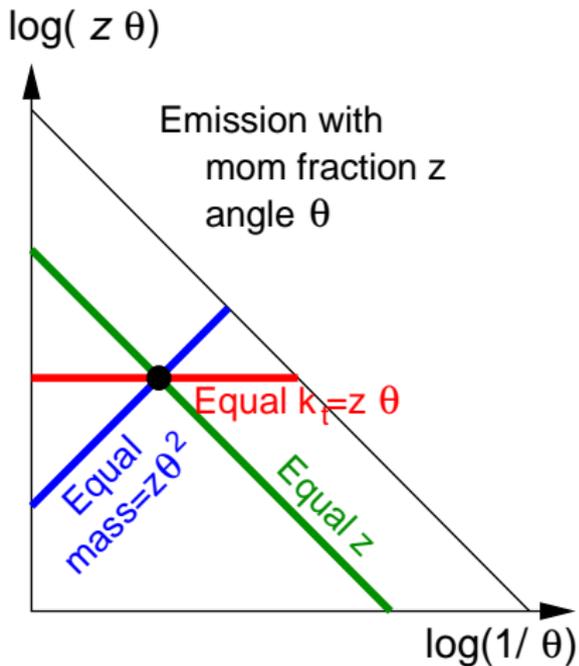
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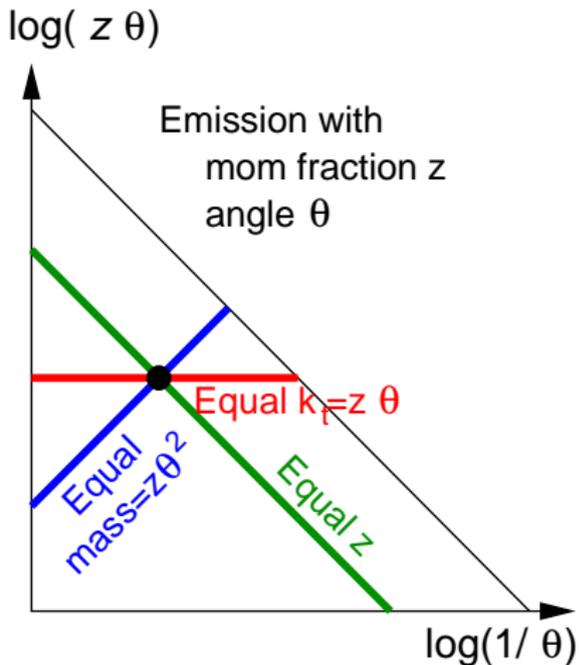
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## Observables in the soft-collinear limit

Jet "mass":  $(z_1\theta_1^2 \gg z_2\theta_2^2 \gg \dots)$

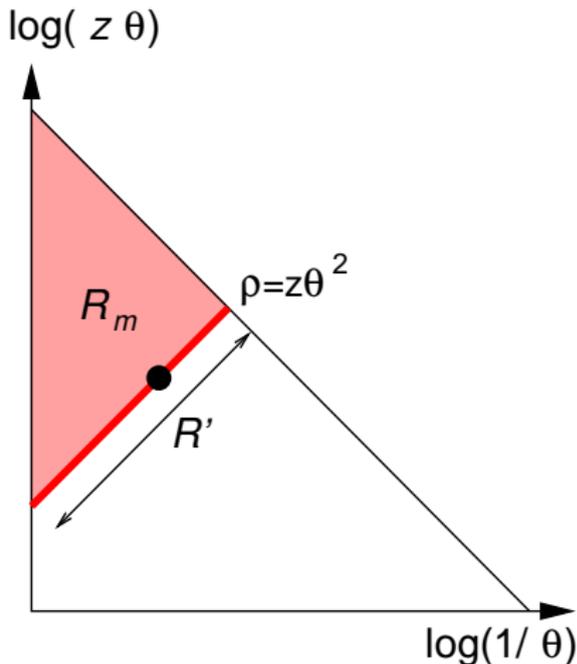
$$\rho \equiv \frac{m^2}{p_t^2 R^2} = \sum_{i \in \text{jet}} z_i \theta_i^2 \approx z_1 \theta_1^2$$

$N$ -subjettiness:

$$\tau_1 = \rho$$

$$\tau_2 = \sum_{i=2}^n z_i \theta_i^2 \approx z_2 \theta_2^2$$

# Anatomy of the phase-space (at Leading Log)



## (plain) jet mass spectrum at LL

$$\frac{\rho}{\sigma} \frac{d\sigma}{d\rho} = R'_{\text{plain}} \exp(-R_{\text{plain}})$$

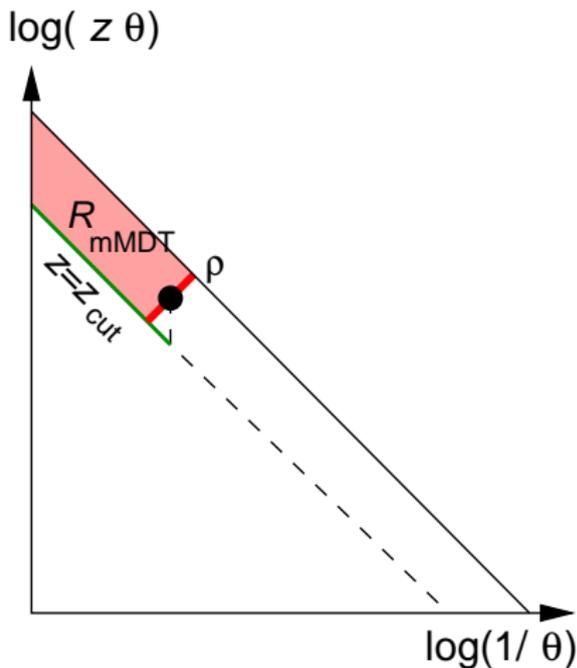
- 1 veto on larger-mass (Sudakov)

$$R_{\text{plain}} \simeq \frac{\alpha_s C_R}{2\pi} \log^2(1/\rho)$$

- 2 emission of given mass

$$R'_{\text{plain}} \simeq \frac{\alpha_s C_R}{\pi} \log(1/\rho)$$

# Anatomy of the phase-space (at Leading Log)



## (mMDT) jet mass spectrum at LL

$$\frac{\rho}{\sigma} \frac{d\sigma}{d\rho} = R'_{\text{mMDT}} \exp(-R_{\text{mMDT}})$$

- 1 veto on larger-mass (Sudakov)

$$R_{\text{mMDT}} \sim \frac{\alpha_s C_R}{\pi} \log(1/\rho) \log(1/z_{\text{cut}})$$

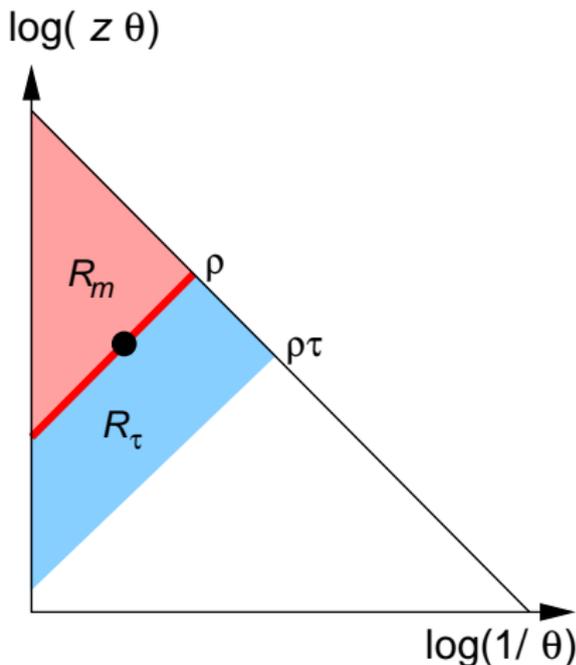
- 2 emission of given mass

$$R'_{\text{mMDT}} \sim \frac{\alpha_s C_R}{\pi} \log(1/z_{\text{cut}})$$

Smaller  $R \rightarrow$  less bkg suppression  
Smaller  $R' \rightarrow$  more bkg suppression

[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam]

# Anatomy of the phase-space (at Leading Log)



jet mass with a cut  $\tau_{21} < \tau$ :

$$\left. \frac{\rho}{\sigma} \frac{d\sigma}{d\rho} \right|_{<\tau} = R'_{\text{full}} \exp(-R_{\text{full}} - R_{\tau})$$

The Sudakov is (roughly) changed from

$$R_{\text{full}} \sim \frac{\alpha_s C_R}{2\pi} \log^2(1/\rho)$$

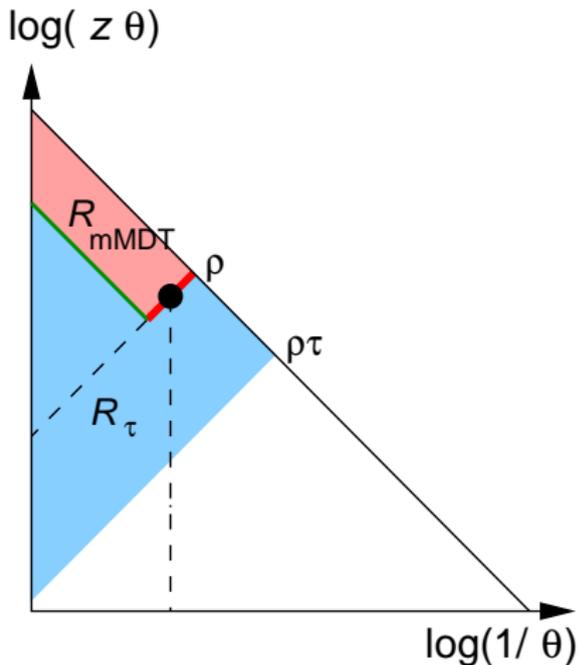
to

$$R_{\text{full}} + R_{\tau} \sim \frac{\alpha_s C_R}{2\pi} \log^2(1/\rho\tau)$$

i.e. **extra Sudakov suppression**

[M.Dasgupta, L.Schunk, GS]

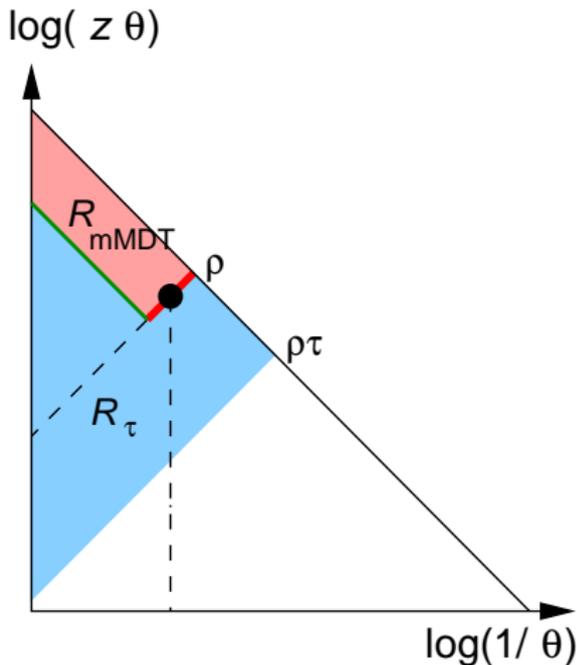
# Anatomy of the phase-space (at Leading Log)



Ideally we would want:

- 1 a large  $R$  Sudakov  
(like for  $N$ -subjettiness)
- 2 a small  $R'$  pre-factor  
(like for mMDT)

# Anatomy of the phase-space (at Leading Log)



Ideally we would want:

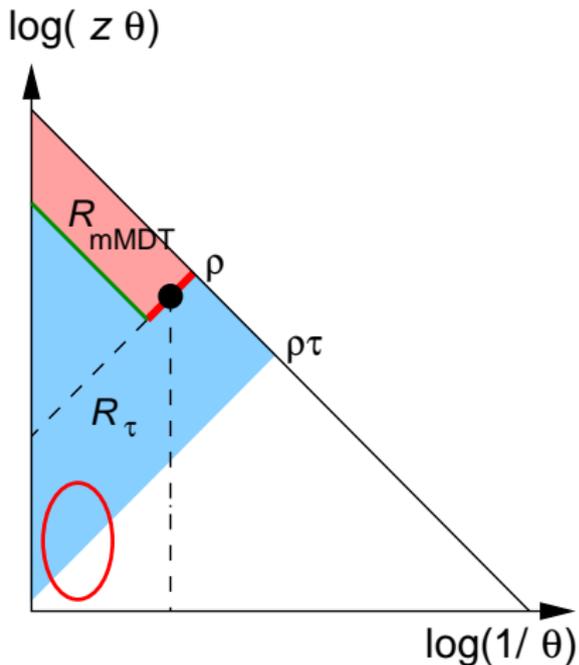
- 1 a large  $R$  Sudakov  
(like for  $N$ -subjettiness)
- 2 a small  $R'$  pre-factor  
(like for mMDT)

Achieved by Dichroic  $N$ -subjettiness:

$$\tau_{21}^{(\text{dichroic})} = \frac{\tau_2^{(\text{plain})}}{\tau_2^{(\text{mMDT})}}$$

[G.Salam,L.Schunk,GS]

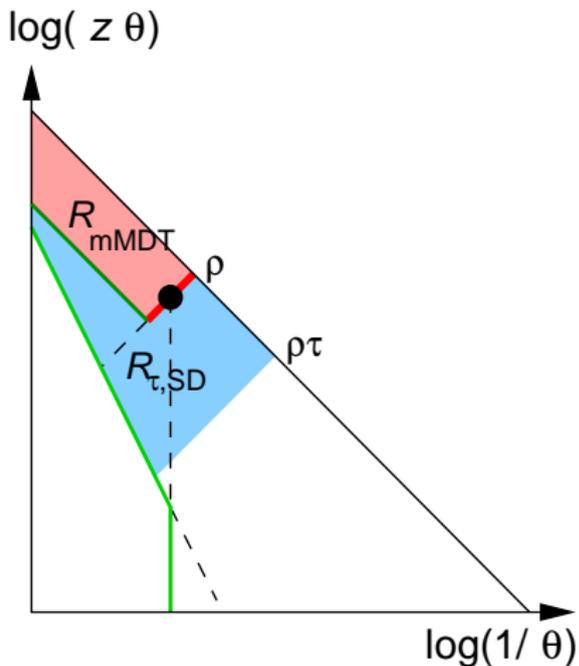
# Anatomy of the phase-space (at Leading Log)



WATH OUT:

sensitivity to soft-large-angle  
i.e. UE, pileup, hadr., NGLs  
 $\Rightarrow$  poor control

# Anatomy of the phase-space (at Leading Log)



## SOLUTION:

“groom” (remove) that region

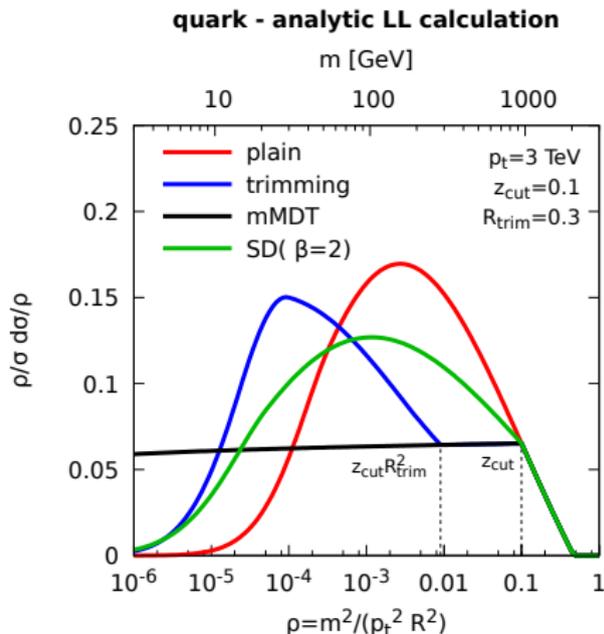
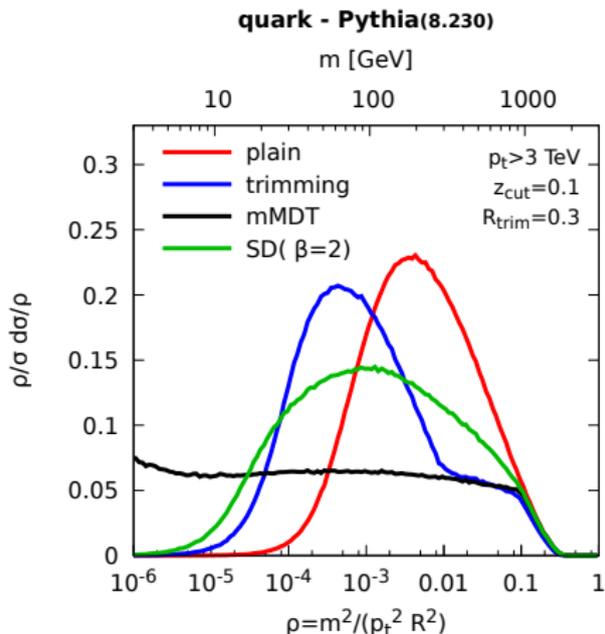
Can be done by “SoftDrop”

- smaller suppression
- better control

# Understanding substructure tools

[M.Dasgupta, A.Fregoso S.Marzani, G.Salam, 13]

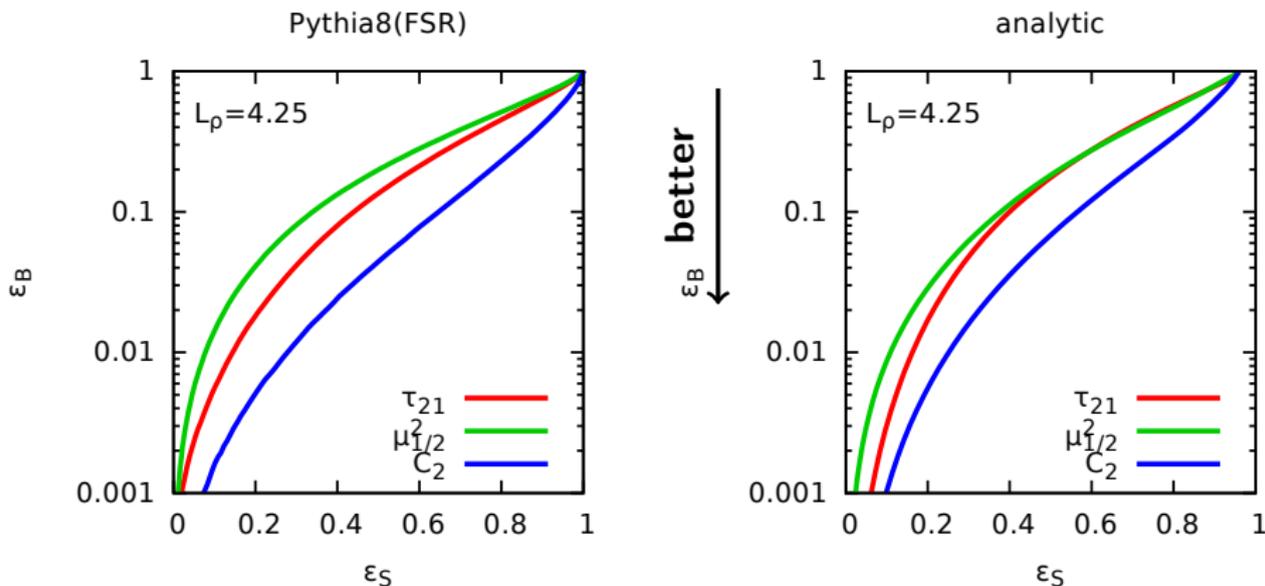
[A.Larkoski, S.Marzani, GS, J.Thaler, 14]



qualitative features reproduced and understood

# Understanding substructure tools (cont'd)

[M.Dasgupta, L.Schunk, GS, 15]



qualitative features reproduced and understood

# Improving substructure tools

More recently: **use acquired understanding to develop improved tools**

Examples:

- **Y-splitter+grooming**

Dasgupta, Powling, Schunk, GS, 16

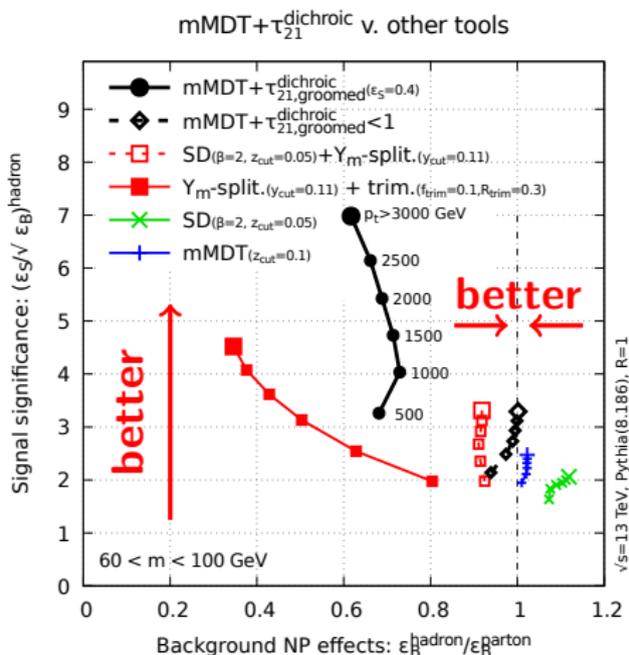
- **New angles on ECFs**

Moult, Necib, Thaler, 16

- **Dichroic  $N$ -subjettiness**

Salam, Schunk, GS, 16

Certainly more of these in the future!



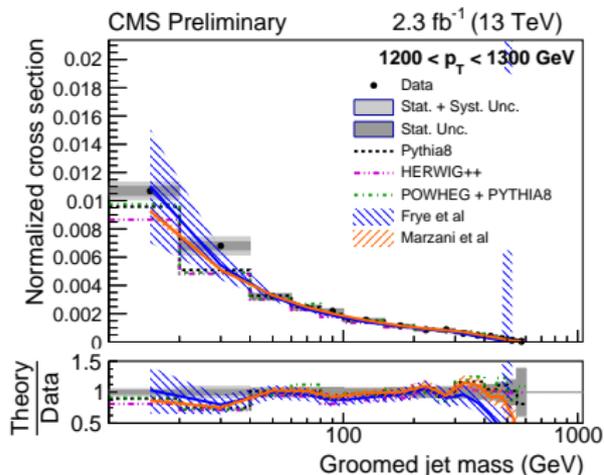
# Rich QCD phenomenology

## Towards precision physics

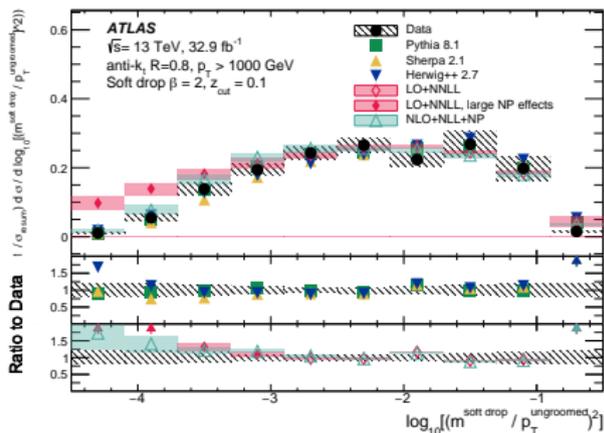
- tools like mMDT and Soft Drop cut soft radiation at large angles
  - ⇒ only sensitive to collinear branchings
    - ⇒ process-independent
      - ⇒  $j$  in  $jj$  same as in  $Wj$  or  $Zj$ , ...
    - ⇒ small non-perturbative corrections
    - ⇒ amenable to precise calculations
- Recent precise calculations of the mMDDT/SD jet mass:
  - ▶ NNLL+LO in SCET  
(Frye,Larkoski,Schwartz,Yan; assumes small  $z_{\text{cut}}$ )
  - ▶ NLL+NLO in “standard QCD”  
(Marzani,Schunk,GS; includes (LL) finite  $z_{\text{cut}}$  for mMDT)

## Measurements at the LHC:

CMS-PAS-SMP-16-010



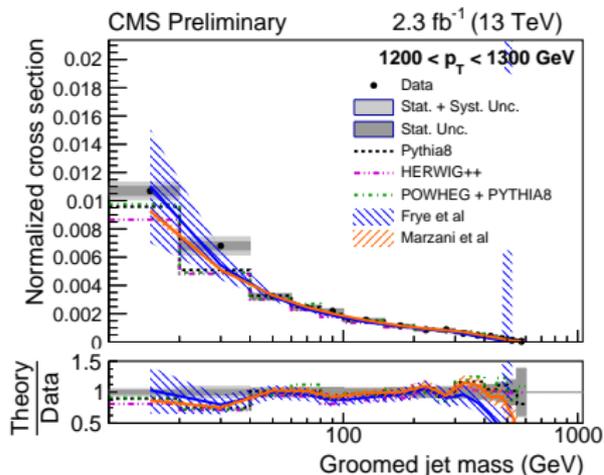
ATLAS(CERN-EP-2017-231)



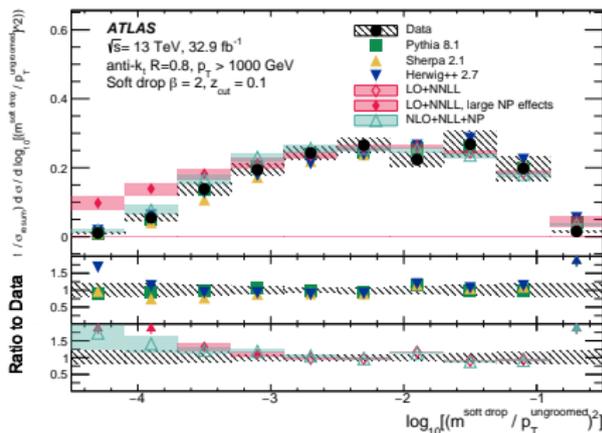
good overall agreement with the data

## Measurements at the LHC:

CMS-PAS-SMP-16-010



ATLAS(CERN-EP-2017-231)



good overall agreement with the data

Precise observable with limited sensitivity to NP effects

⇒ **possibility to extract  $\alpha_S$**  (on-going study)

# Rich QCD phenomenology

## Fun facts

# Curiosities (1/2): Sudakov safety

Some observables are ill-defined in fixed-order pQCD:

- $z_g$  not defined at  $\mathcal{O}(\alpha_S^0)$  (only 1 particle in the jet)
- many ratios  $v_2/v_1$  (like  $\tau_{21} = \tau_2/\tau_1$ ) have  $v_2 = v_1 = 0$  at  $\mathcal{O}(\alpha_S^0)$
- some observables are ill-defined at any fixed order (see next slide)

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**but can still be computed perturbatively thanks to resummation**

Example:  $r = e_\alpha/e_\beta$  with  $e_\alpha = \sum_{i \in \text{jet}} z_i \theta_{i,\text{jet}}^\alpha$

We can write

$$\frac{dP}{dr} = \int de_\alpha de_\beta \frac{dP}{de_\alpha} \frac{dP}{de_\beta} \delta(r - e_\alpha/e_\beta)$$

Idea: the dangerous case  $e_\beta = 0$  is absent because  $\frac{dP}{de_\beta} \rightarrow 0$  in that limit (Sudakov exponential)

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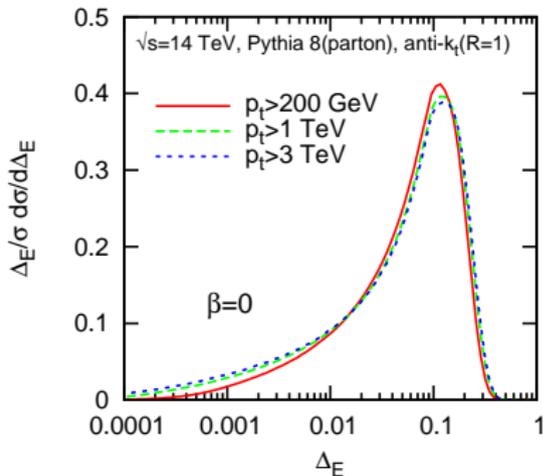
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A series of interesting results  
still many unknown to be explored

# Curiosities (2/2): $\alpha_s$ independence



$$\text{LL result: Prob}(\Delta < \Delta) = \frac{\log(z_{\text{cut}}) + \frac{3}{4}}{\log(\Delta) + \frac{3}{4}}$$

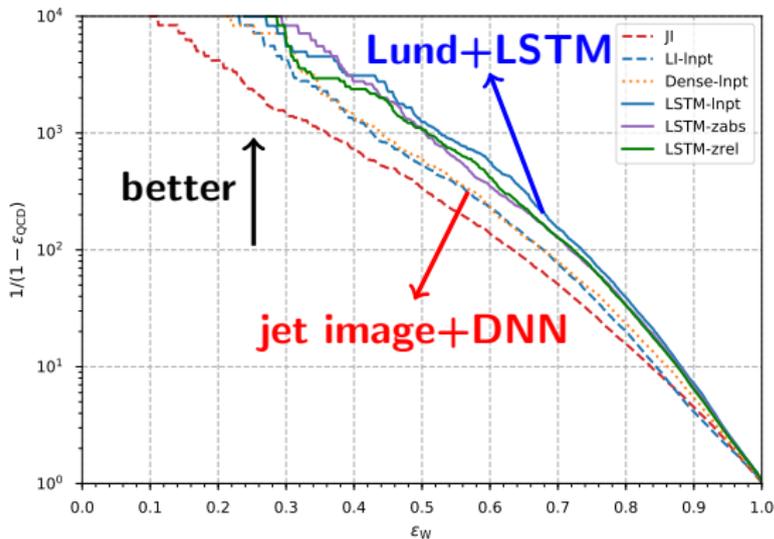
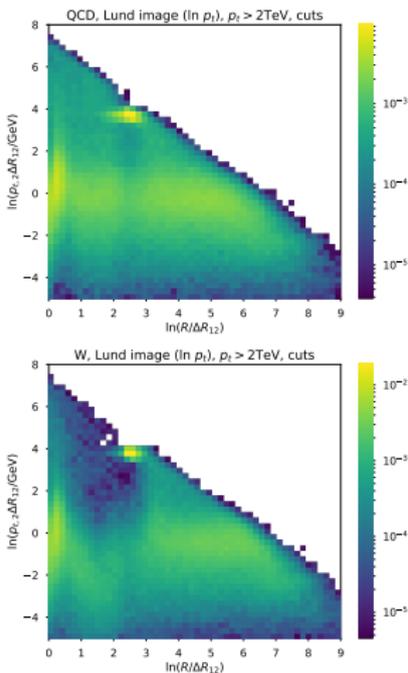
- What are we looking at?

- ▶ jet with momentum  $p_{t,\text{jet}}$
- ▶ apply mMDT
- ▶ after,  $p_t = p_{t,\text{mMDT}}$
- ▶ measure  $\Delta = \frac{p_{t,\text{jet}} - p_{t,\text{mMDT}}}{p_{t,\text{jet}}}$   
i.e. the lost  $p_t$  fraction

- Result:

at LL and fixed coupling, the  $\Delta$  distribution is  $\alpha_s$ -independent

[F.Dreyer,G.Salam,GS, in progress]



**QCD-motivated input to LSTM network shows great performance**

## Jet substructure has gained a lot of importance in the past decade

- Important tool for LHC physics
- exciting pQCD phenomenology
  - ▶ understanding and development of tools
  - ▶ precision pheno at the LHC
  - ▶ interesting structure emerging
- Expansion towards new horizons:
  - ▶ heavy-ion hard probes
  - ▶ machine learning

BOOST Annual meeting  
around 100 theorists and experimentalists  
discussing latest progress in substructure

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**July 16-20: BOOST 2018 in Paris**

<https://indico.cern.ch/e/boost2018>

