New perspectives in QCD with jet substructure

Grégory Soyez

IPhT, CEA Saclay, CNRS

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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 genersalised k_t algorithm)

- From all the objects to cluster, define the distances

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

- repeatedly find the minimal distance
  if d_{ij}: recombine i and j into $k = i + j$
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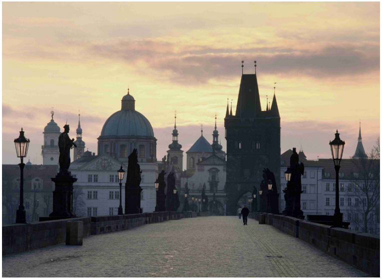
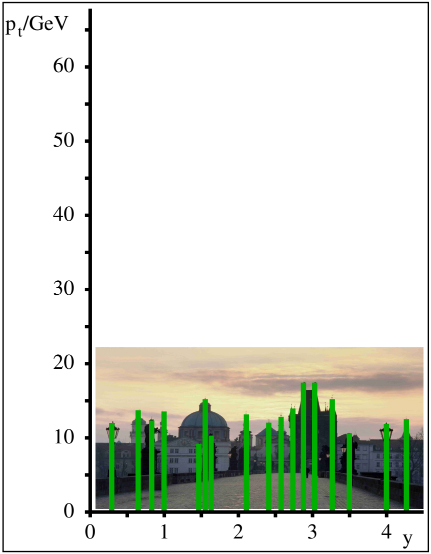
- Parameter p is (typically) one of
  - $p = 1$: k_t algorithm (closest to QCD)
    [Catani,Dokshitzer,Seymour,Weber,Ellis,Soper,1993]
  - $p = 0$: Cambridge/Aachen (geometrical distance)
    [Dokshitzer,Leder,Moretti,Webber,1997]
  - $p = -1$: anti-k_t (the LHC choice) [M.Cacciari,G.Salam,GS,2008]



Start with your favourite picture

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



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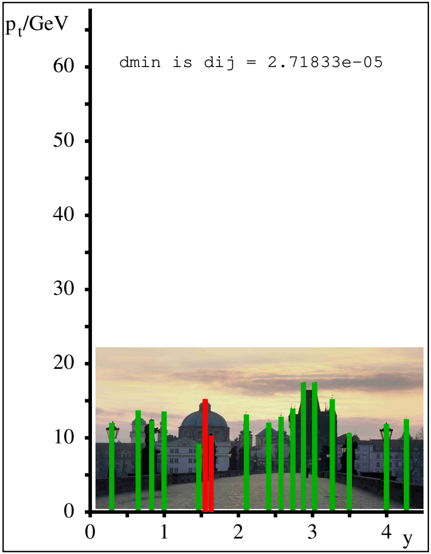

min is $d_{ij} = 2.7\,10^{-5}$

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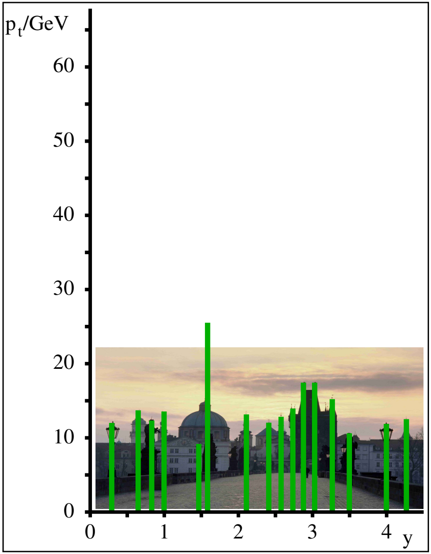

recombine them

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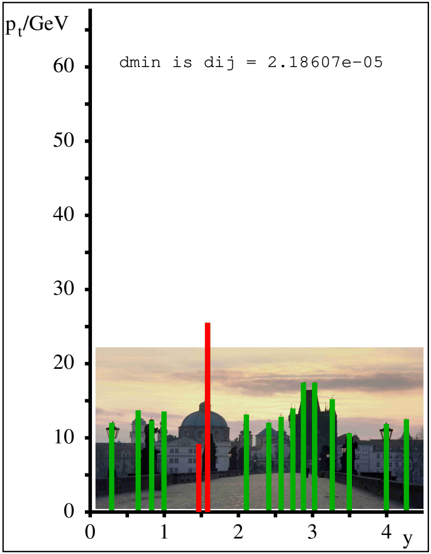

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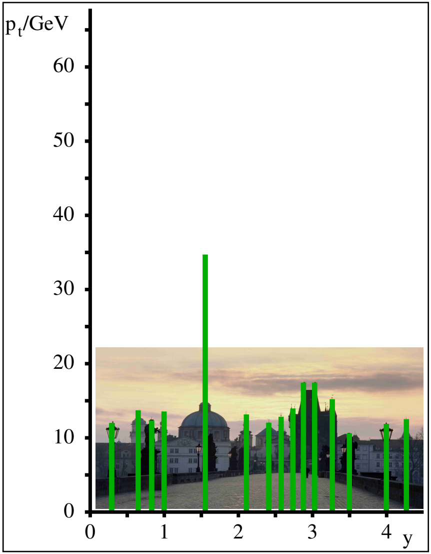

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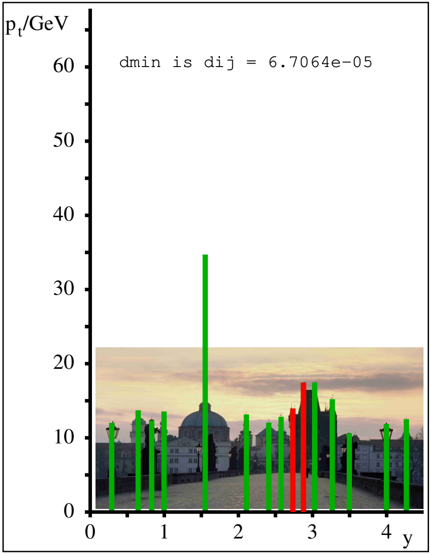

min is $d_{ij} = 6.7\,10^{-5}$

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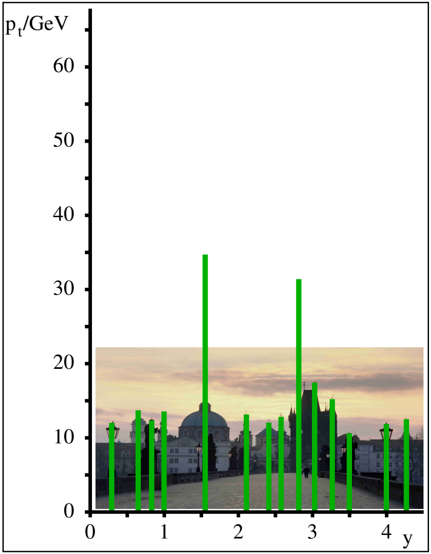

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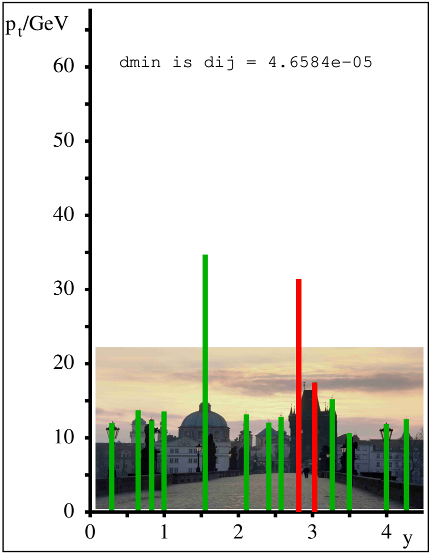
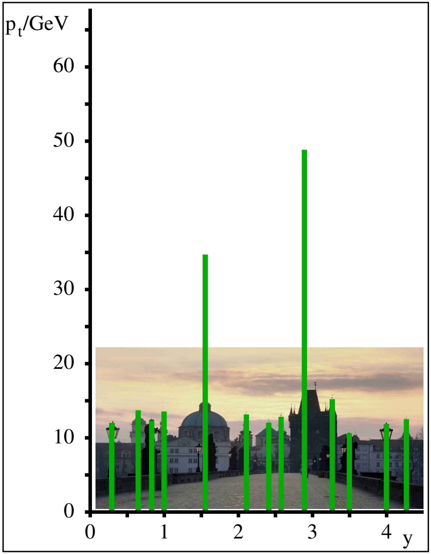


min is $d_{ij} = 4.7\,10^{-5}$



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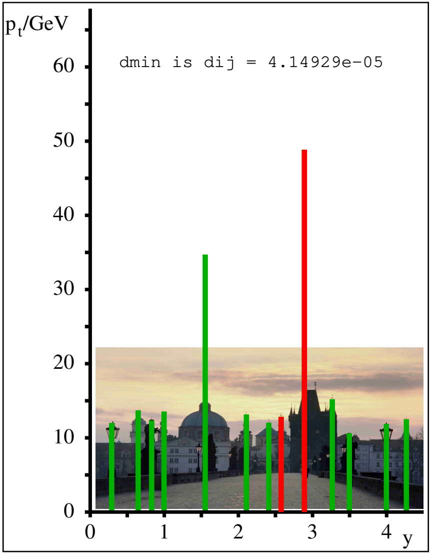

min is $d_{ij} = 4.1\,10^{-5}$

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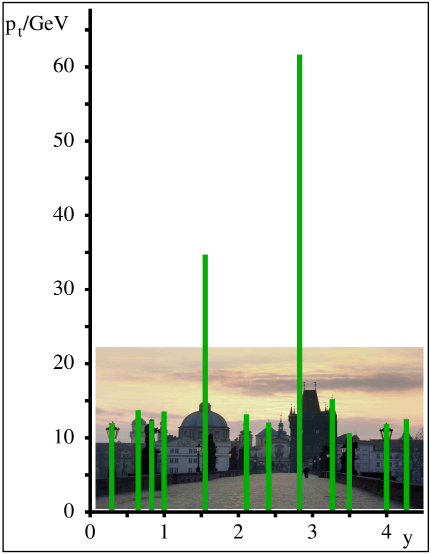

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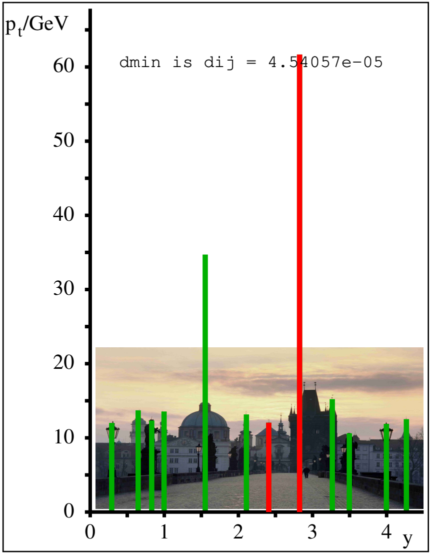
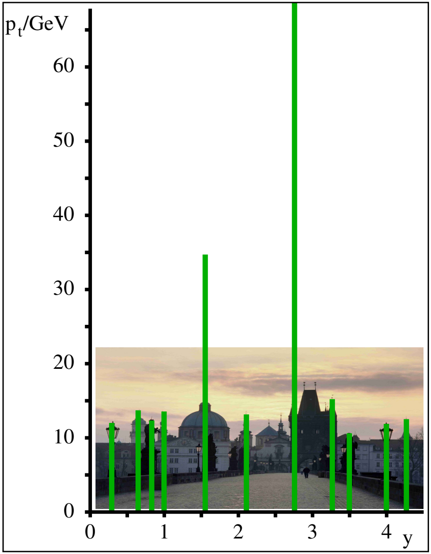


min is $d_{ij} = 4.5\,10^{-5}$



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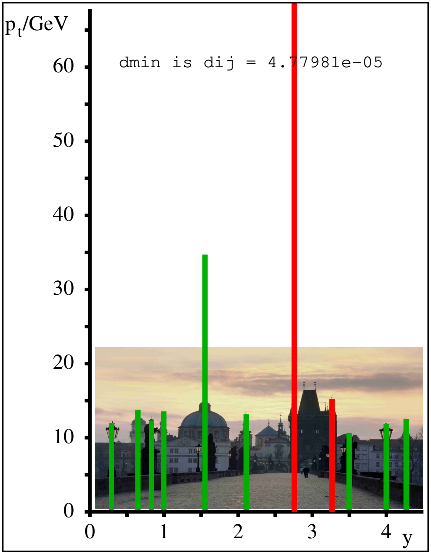
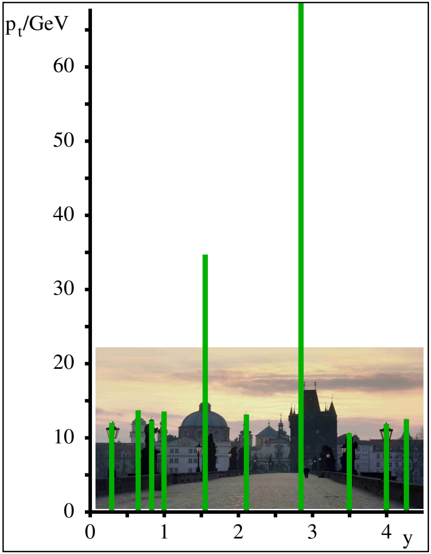


min is $d_{ij} = 4.8\,10^{-5}$



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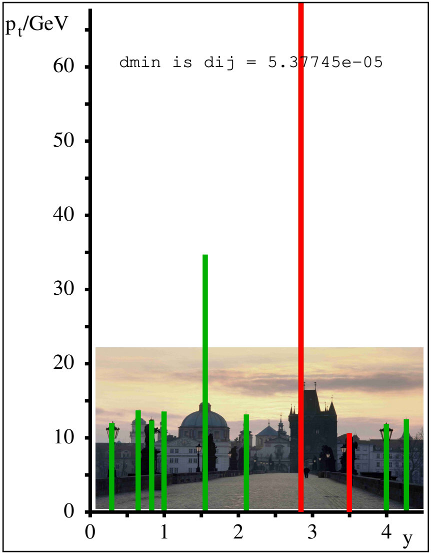
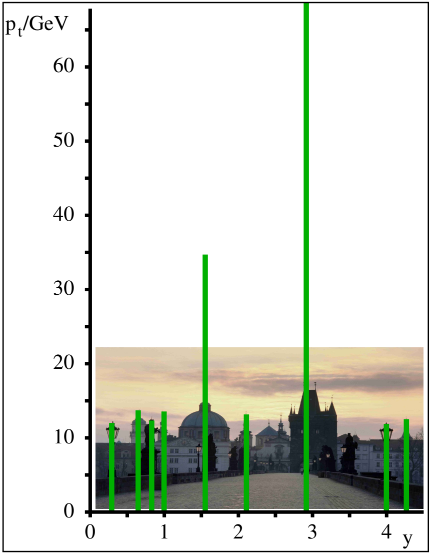


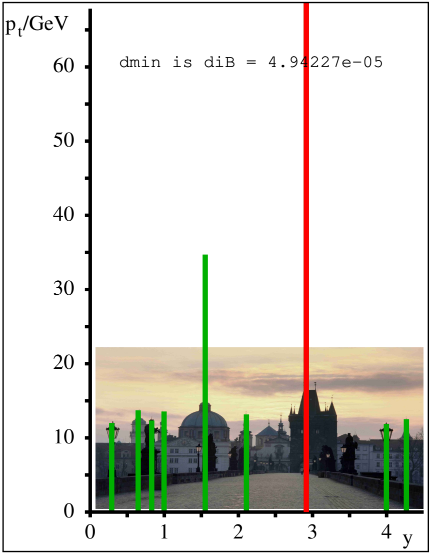
min is $d_{ij} = 5.4\,10^{-5}$

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



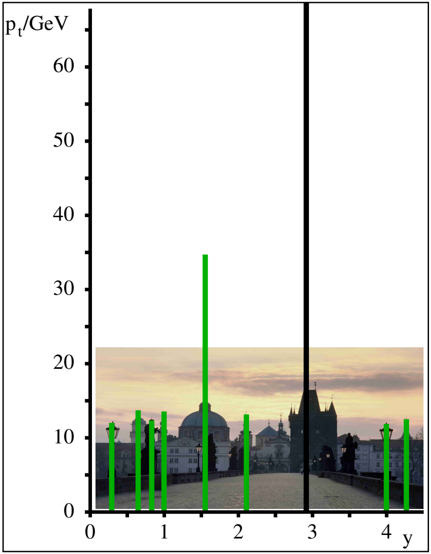
recombine them

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



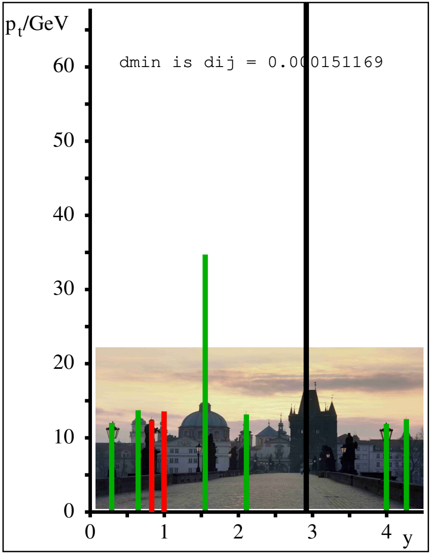
min is $d_{iB} = 4.9\,10^{-5}$

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



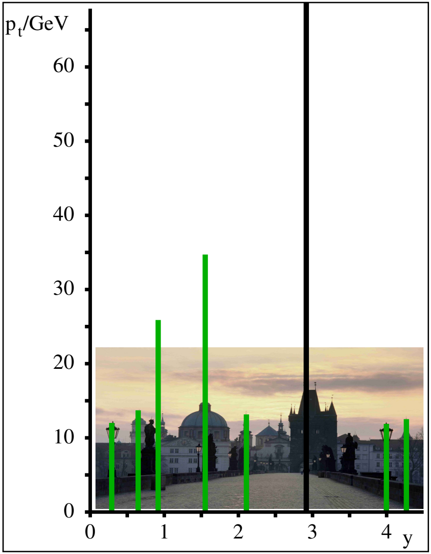
declare as a jet

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



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

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



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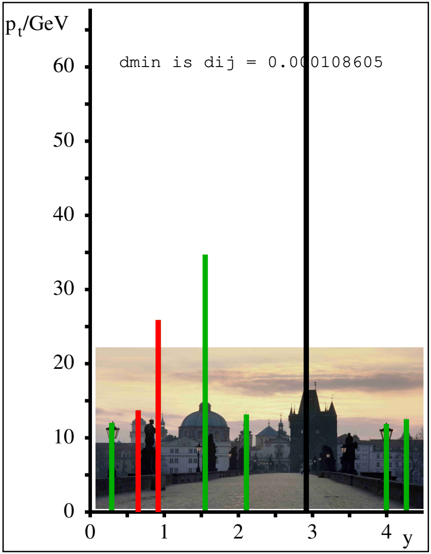

min is $d_{ij} = 1.1\,10^{-4}$

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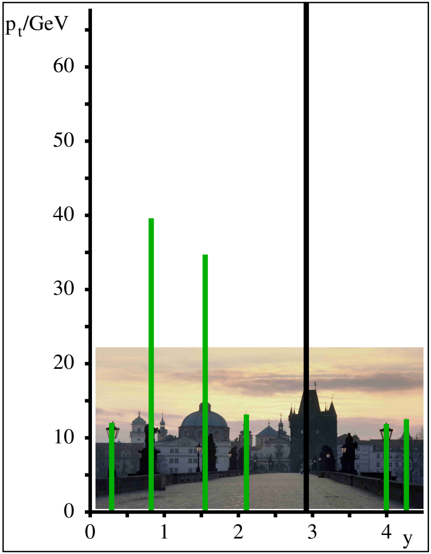

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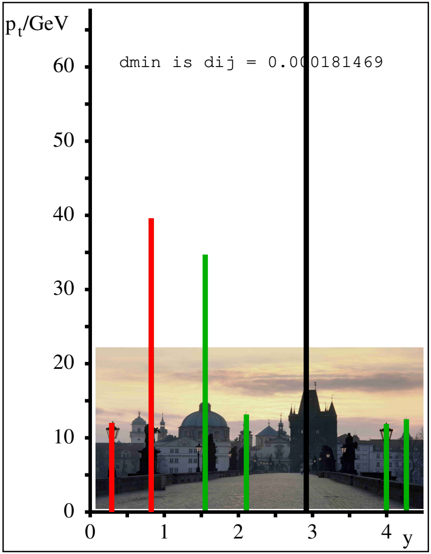

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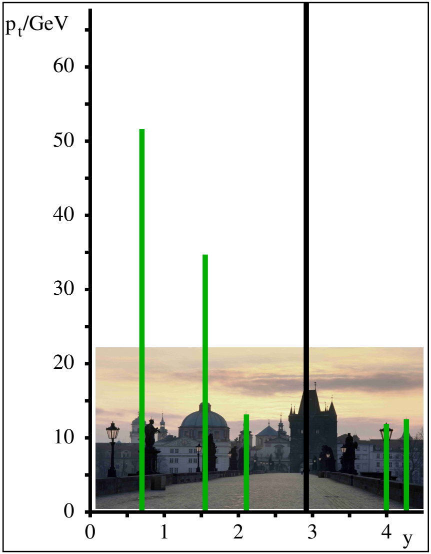

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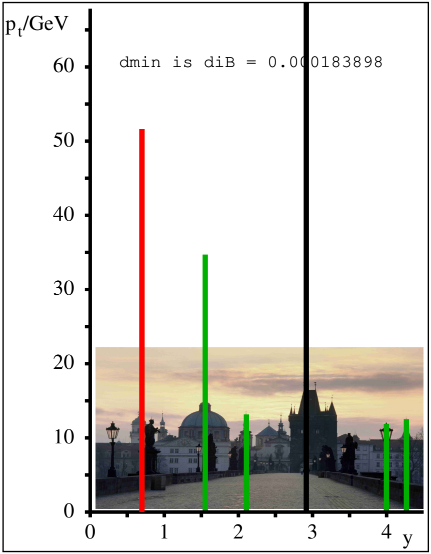
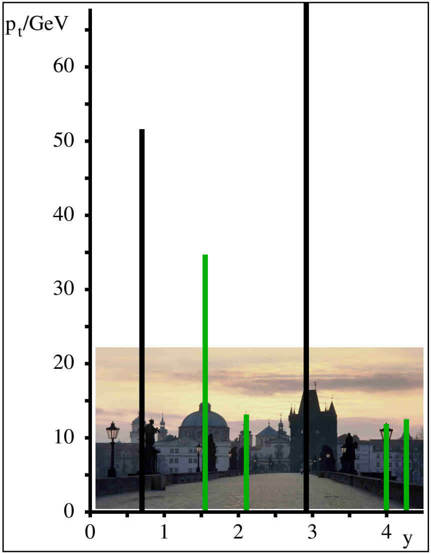


min is $d_{iB} = 1.8\,10^{-4}$

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



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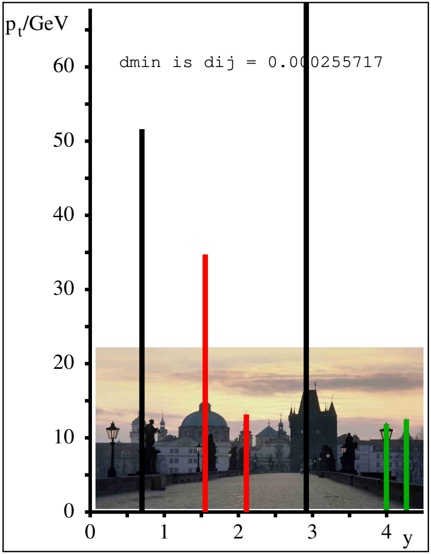
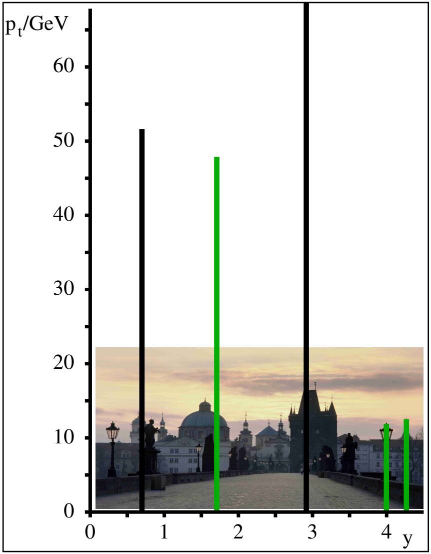


min is $d_{ij} = 2.6\,10^{-4}$

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



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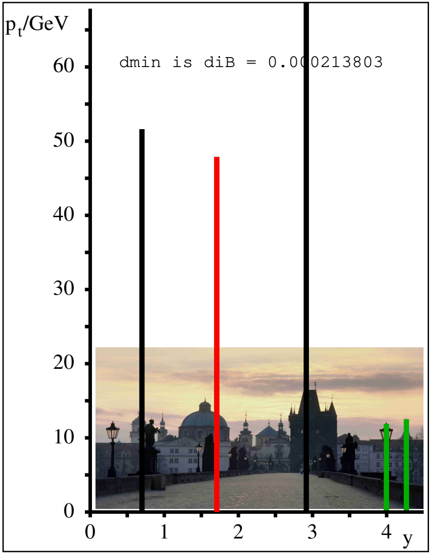

min is $d_{iB} = 2.1\,10^{-4}$

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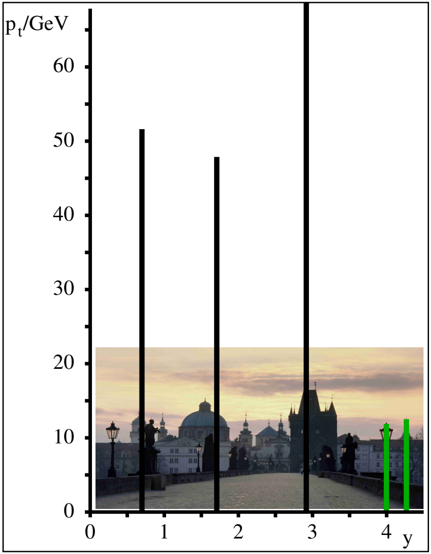
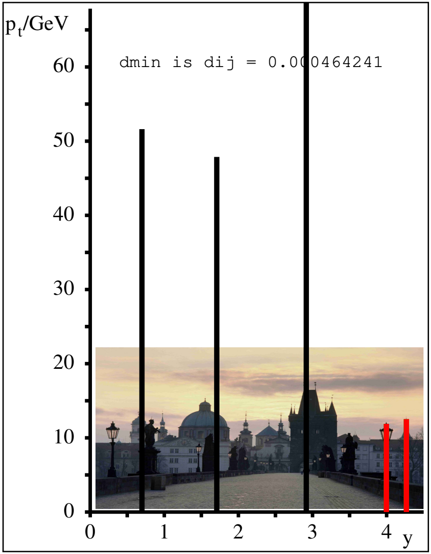


decclare as a jet

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



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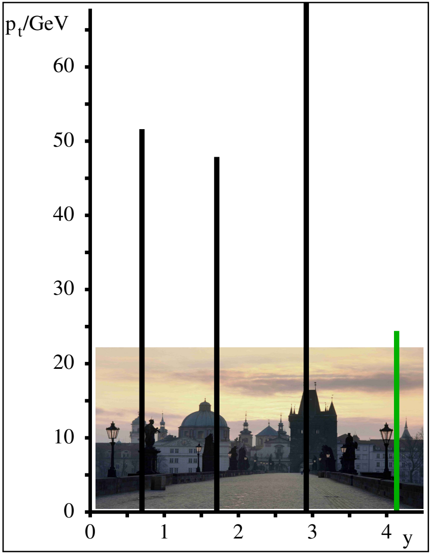

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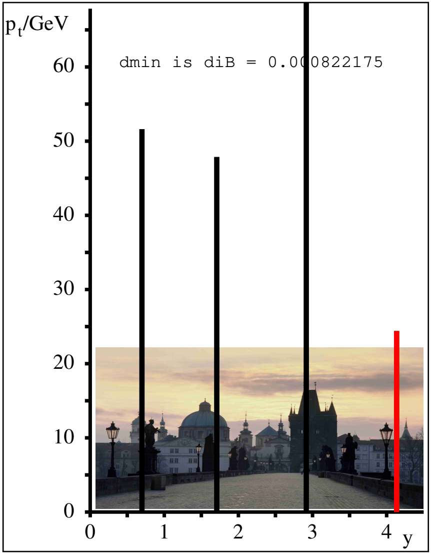

min is $d_{iB} = 8.2\,10^{-4}$

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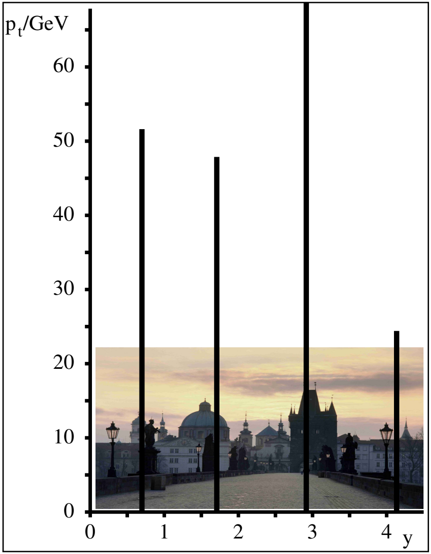

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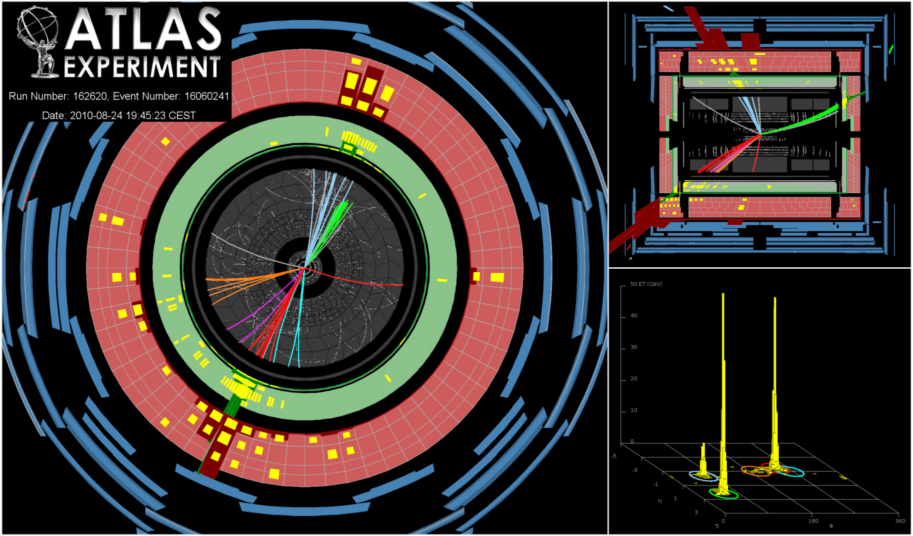
ATLAS
EXPERIMENT
Run Number: 162620, Event Number: 16060241
Date: 2010-08-24 19:45:23 CEST
50 ET (GeV)
40
30
20
10
0
η
Φ
-5
-3
-1
1
3
5
0
180
360

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

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Many useful/interesting aspects:

- boosted jet tagging (now a common search tool)
- entered the field of Heavy-Ion collisions
- rich QCD phenomenology
- precision calculations at the LHC
- many conceptual ideas

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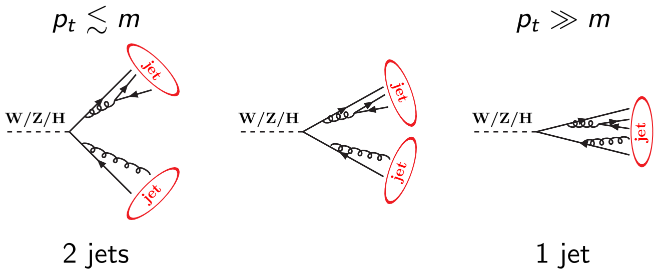
This talk: give you a hint of all these aspects

Boosted objects and searches

Boosted objects

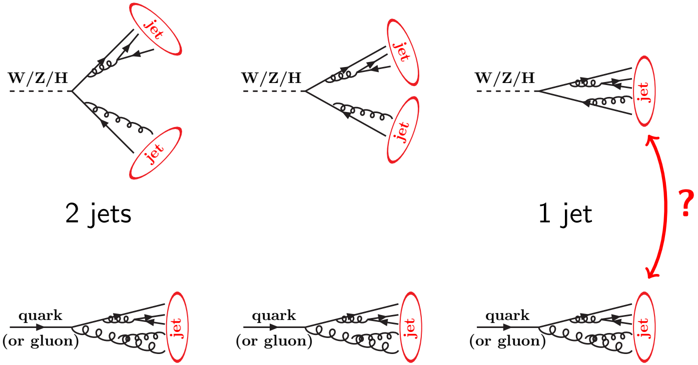


(massive) objects produced boosted (energy $\gg$ mass) are seen as 1 jet:

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

Boosted objects

$p_t \lesssim m$ $\qquad$ $p_t \gg m$

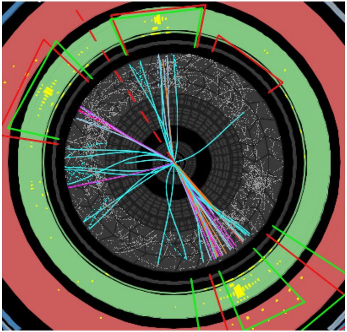


2 jets $\qquad$ 1 jet

use substructure to separate from QCD jets

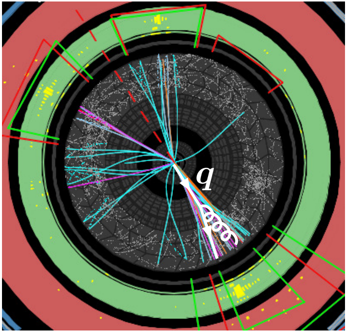
Other examples

What jet do we have here?



What jet do we have here?

- a quark?



Other examples

What jet do we have here?

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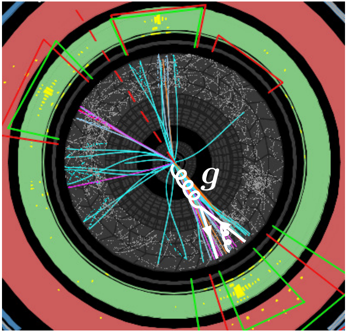
- a gluon?



Other examples

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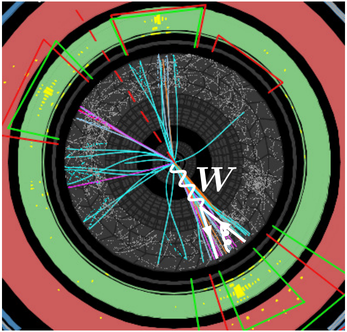

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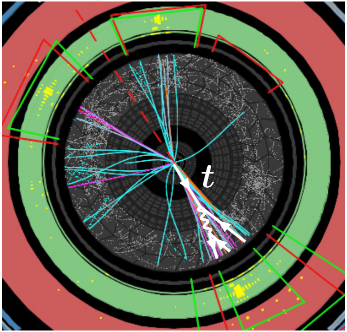

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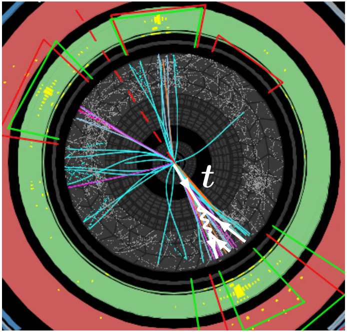
Source: ATLAS boosted top candidate



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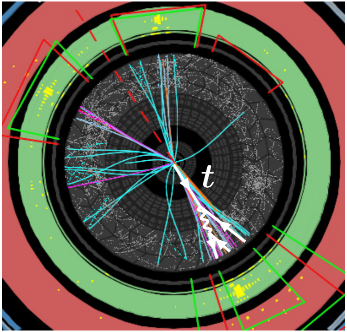
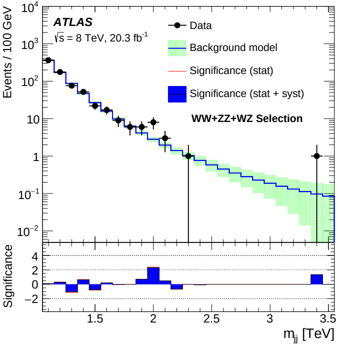
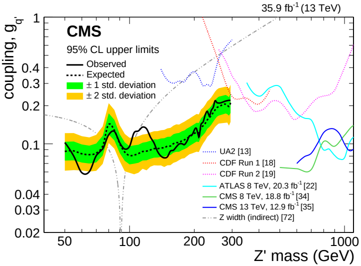
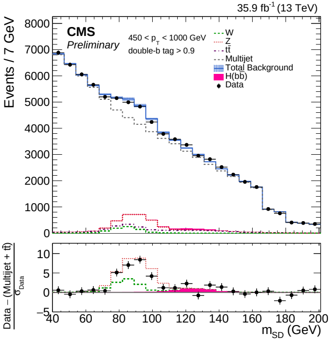


Many applications, all relevant to new physics searches:

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







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

↗ Search for $X \to q\bar{q}$
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,...)

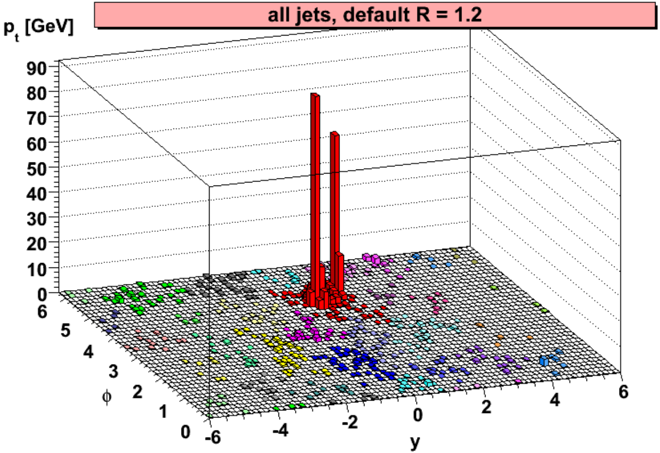
  filtering, trimming, pruning, Soft Drop, (m)MDT, ...

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

Requires both some creativity and some control over the underlying physics

Search hard components: mMDT/SD

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



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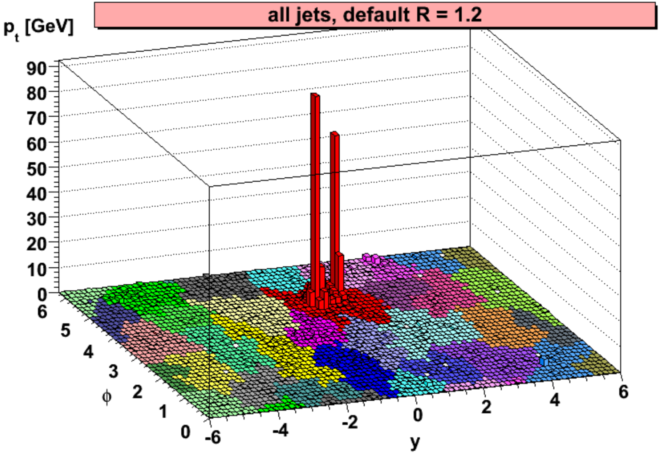

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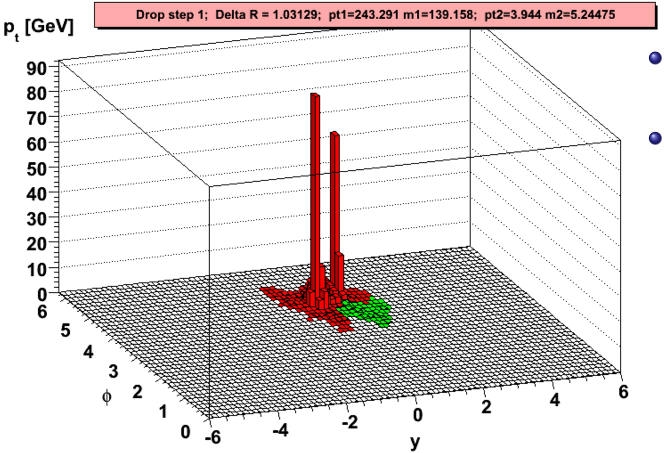
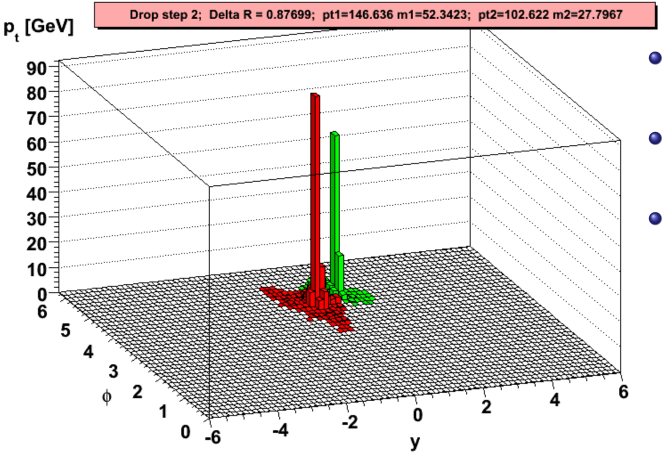


MassDrop

- undo the last clustering step
- $z = 0.016 < 0.1$ carry on

Search hard components: mMDT/SD

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



MassDrop

- undo the last clustering step
- $z = 0.016 < 0.1$ carry on
- $z = 0.41 > 0.1$ stop

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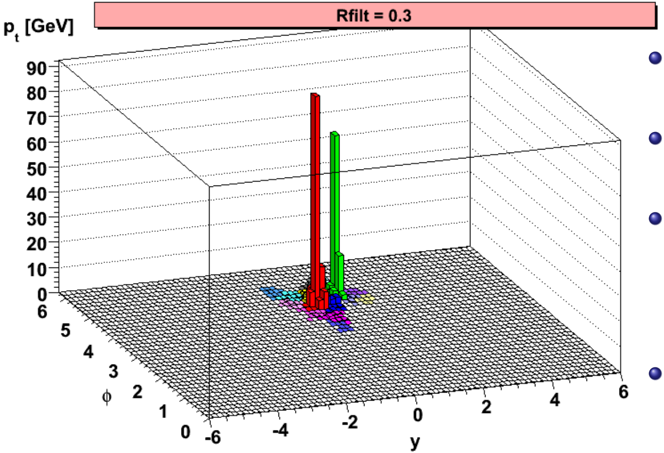

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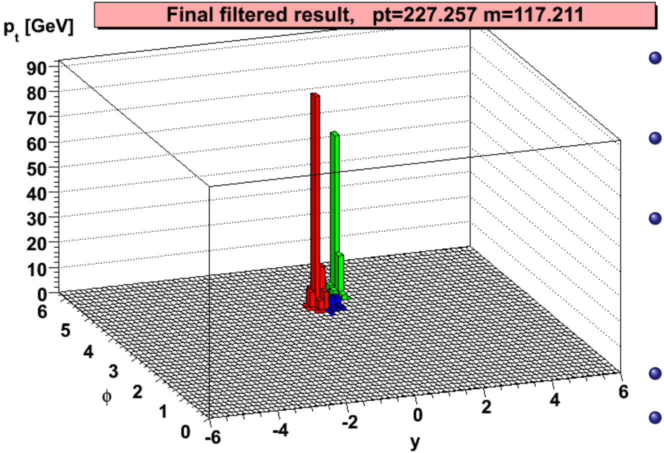

MassDrop

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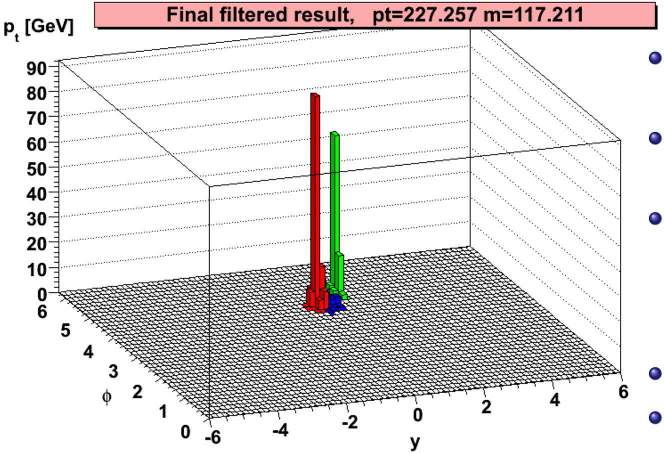
Filter

- recluster
- keep 3 hardest

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



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Filter

- 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]

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

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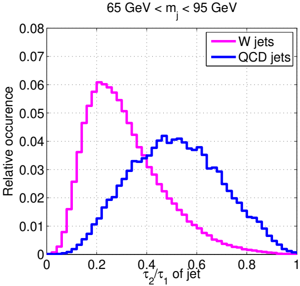
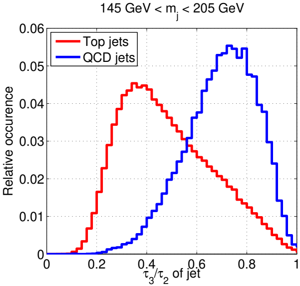
- Measures the radiation from N prongs
- $\tau_{N,N-1} = \tau_N / \tau_{N-1}$ discriminates N-prong v. QCD
- τ_{21} smaller for W than for QCD
- τ_{32} smaller for top than for QCD

Several alternatives similar to τ_N





Expanding in new directions

Machine Learning has become a major player

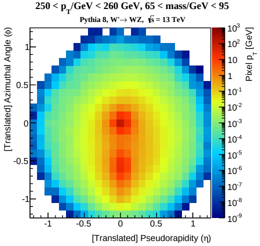
- Many architectures:

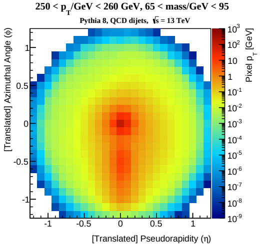
ANN	Artificial Neural Network
DNN	Dense Neural Network
CNN	Convolutional Neural Network
GANN	Generative Adversarial Neural Network
LSTM	Long Short-Term Memory Neural Network

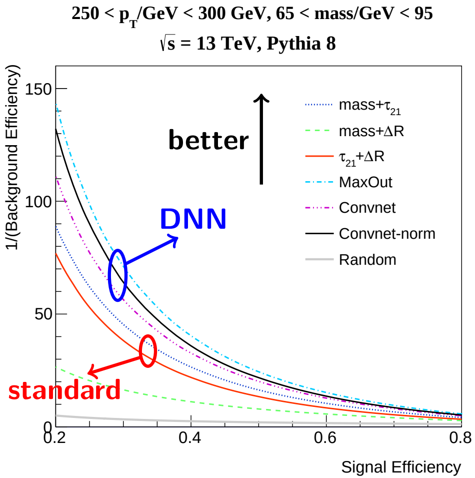
- Many approaches:
  Feed jet variables, jet constituents, jet images, ...
- Many applications:
  q/g, b, W, H, t tagging, pileup-mitigation, detector sim, ...

Latest playground: deep learning

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







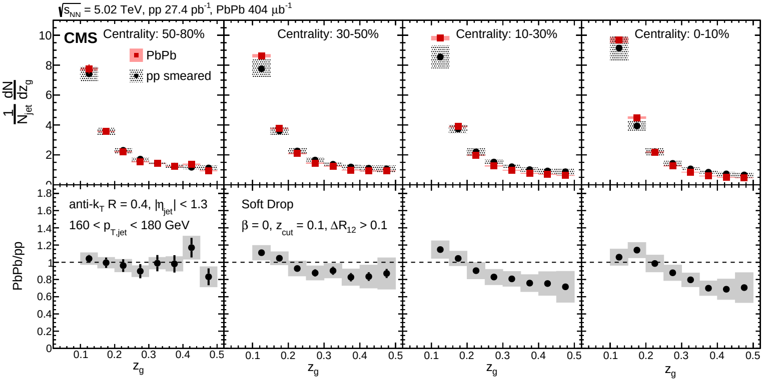
Improvement compared to standard approach

Expanding in new directions
Heavy-Ion collisions

Measuring the splitting function

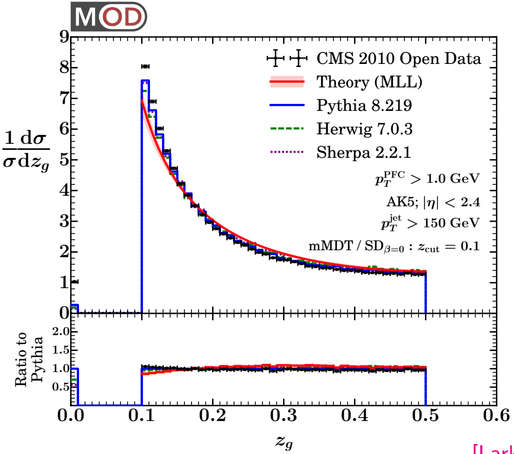
- Take a jet with large p_t
- apply mMDT $\rightarrow$ hard splitting
- $z_g \equiv$ mom fraction of that splitting

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

Substructure from first principles (1/2)

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

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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)

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  - 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	$\tau_{21}^{(\beta=2)}$, μ^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

Resummation's kingdom

- Main idea:

$$\text{Boosted jet} \Rightarrow p_t \gg m$$
$$\Rightarrow \rho \equiv \frac{m^2}{p_t^2 R^2} \ll 1$$
$$\Rightarrow \text{expect } \log\rho \text{ coming with } \alpha_s$$
$$\Rightarrow \text{need for all-order resummation}$$

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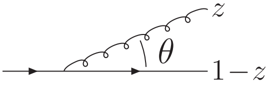
- Example: jet mass with one (soft-and-collinear) gluon emission

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



- (plain) jet mass again:

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

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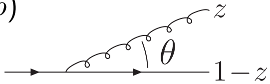

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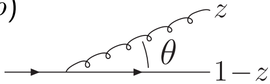

- mMDT jet mass:

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

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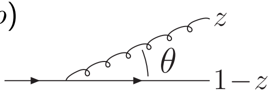

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$$\simeq \frac{\alpha_s C_R}{\pi}\left[\log(1/\rho)\log(1/z_{\text{cut}}) - \frac{1}{2}\log^2(1/z_{\text{cut}})\right]$$

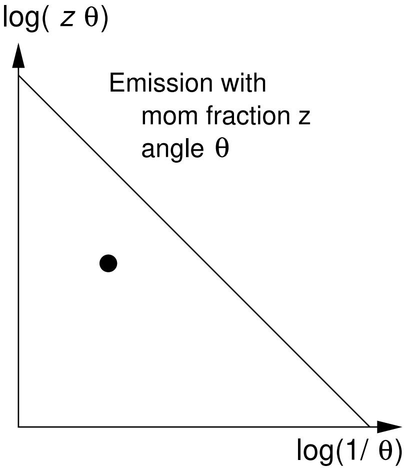
- all-order result (Leading-Log): for both the "plain" jet and mMDT

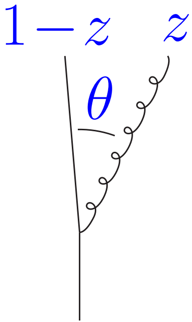
$$\text{Prob}_{\text{LL}}(<\rho) = \exp[-\text{Prob}_1(<\rho)]$$

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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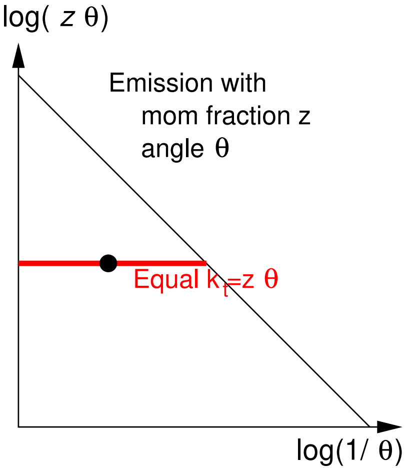

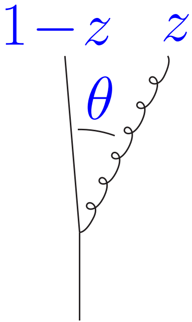

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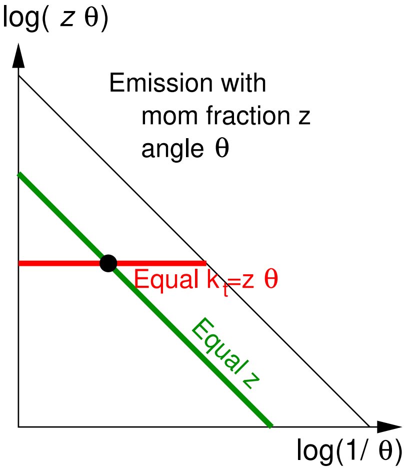

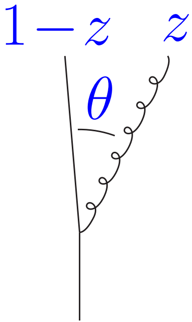

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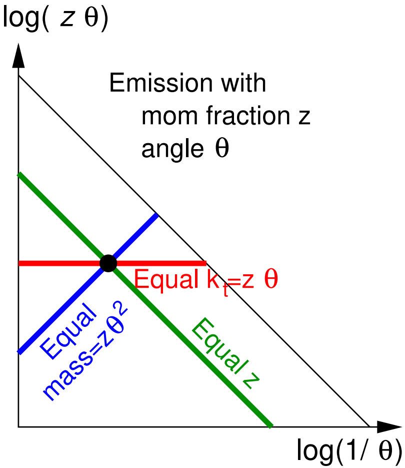

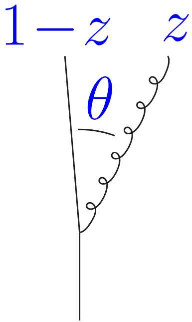

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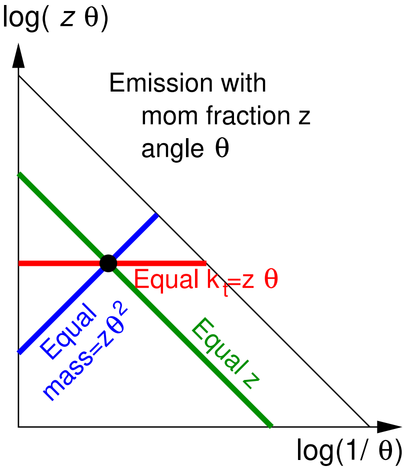


Observables in the soft-collinear limit

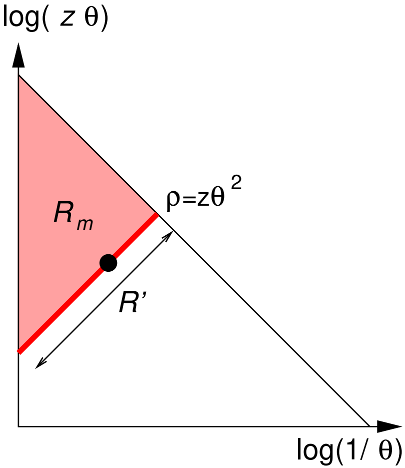
Jet "mass": $(z_1\theta_1^2 \gg z_2\theta_2^2 \gg \dots)$

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

N-subjettiness:

$$\tau_1 = \rho$$

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



(plain) jet mass spectrum at LL

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

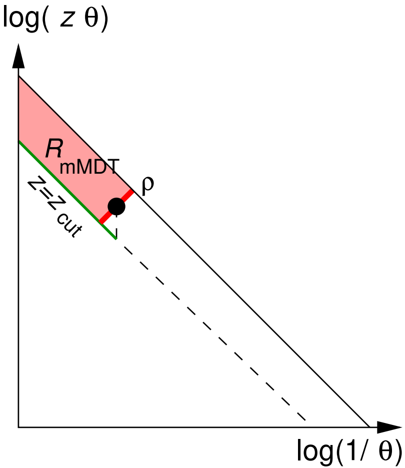
1. veto on larger-mass (Sudakov)

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

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)

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

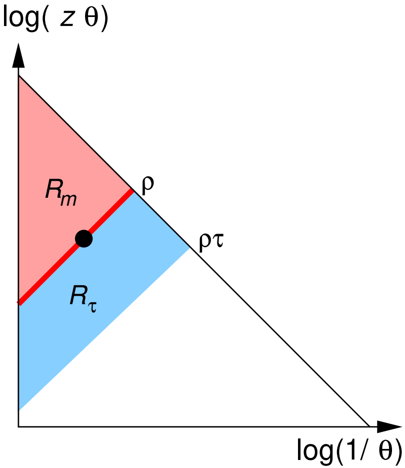
2. emission of given mass

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

Smaller R $\longrightarrow$ less bkg suppression
Smaller R' $\longrightarrow$ 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

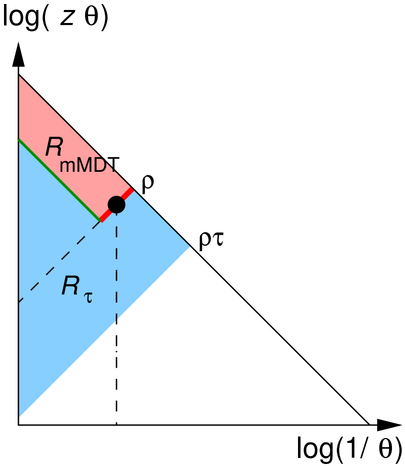
$$R_{\text{full}} \sim \frac{\alpha_s C_R}{2\pi} \log^2(1/\rho)$$

to

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

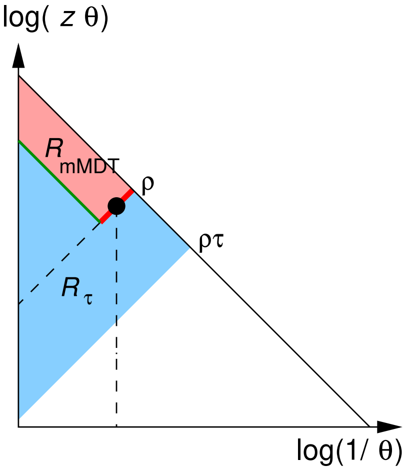
i.e. extra Sudakov suppression

[M.Dasgupta,L.Schunk,GS]



Ideally we would want:

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



Ideally we would want:

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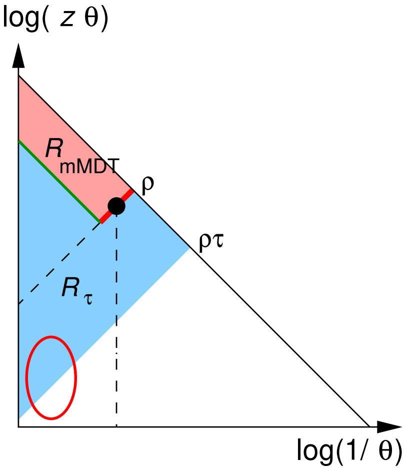
2. a small R' pre-factor
   (like for mMDT)

Achieved by Dichroic N-subjettiness:

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

[G.Salam,L.Schunk,GS]

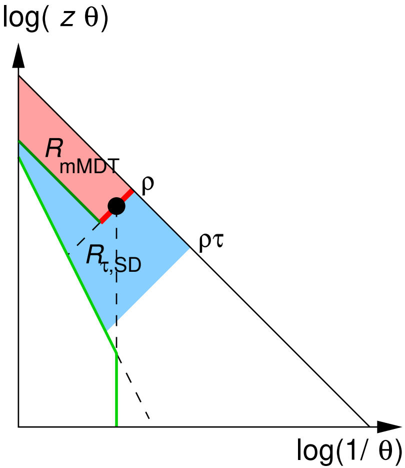
Anatomy of the phase-space (at Leading Log)



<u>WATH OUT:</u>

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

Anatomy of the phase-space (at Leading Log)



<u>SOLUTION:</u>
"groom" (remove) that region

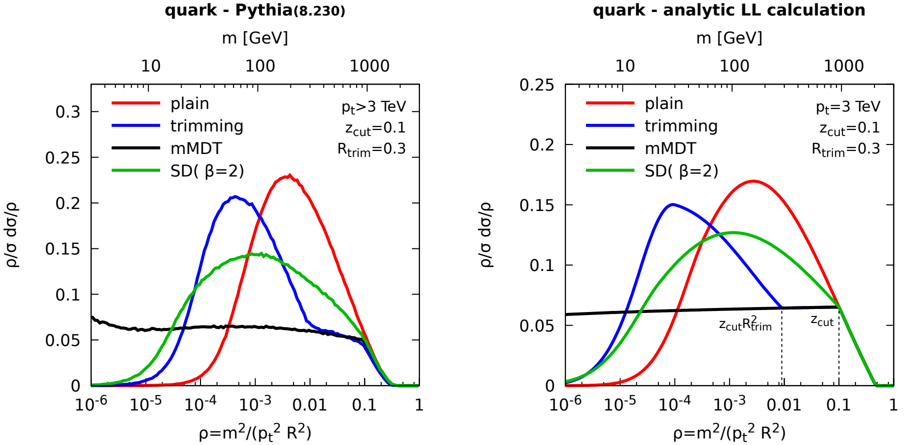
Can be done by "SoftDrop"

- smaller suppression
- better control

Understanding substructure tools

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

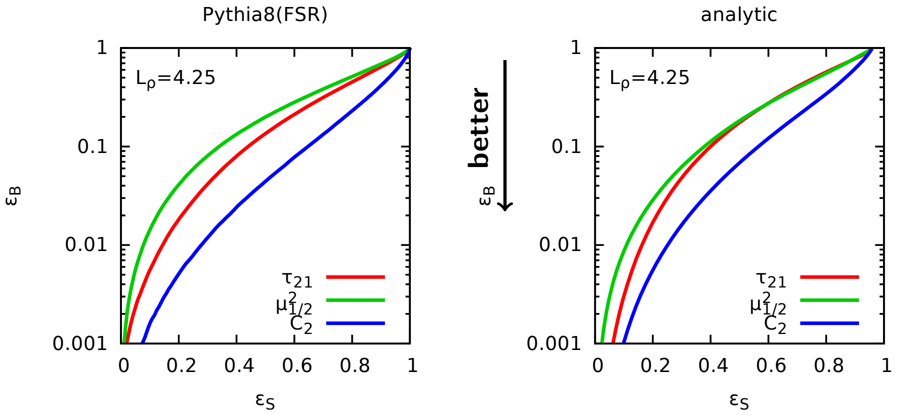
[A.Larkoski, S.Marzani, GS, J.Thaler, 14]



qualitative features reproduced and understood

Understanding substructure tools (cont'd)

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



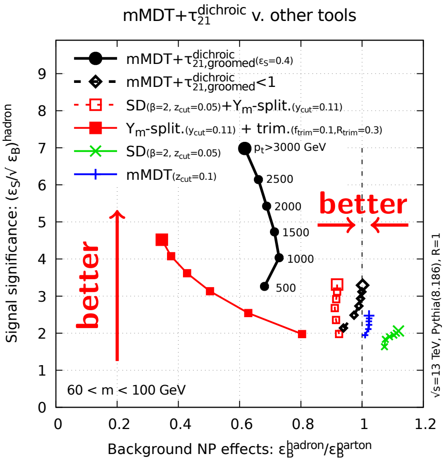
qualitative features reproduced and understood

Improving substructure tools

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

Examples:

- *Y*-splitter+groomong
  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

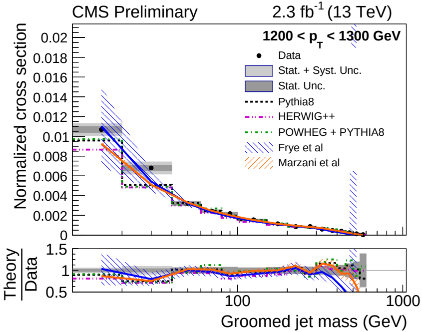
Precision physics

- tools like mMDT and Soft Drop cut soft radiation at large angles
  $\Rightarrow$ only sensitive to collinear branchings
  $\Rightarrow$ process-independent
  $\Rightarrow j$ in jj same as in Wj or Zj, ...
  $\Rightarrow$ small non-perturbative corrections
  $\Rightarrow$ amenable to precise calculations

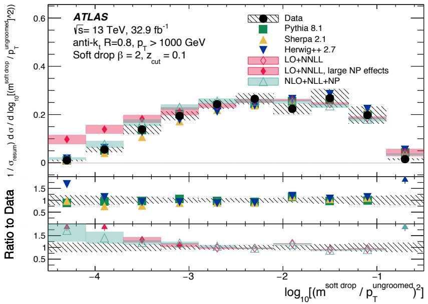
- Recent precise calculations of the mMDDT/SD jet mass:
  - NNLL+LO in SCET
    (Frye,Larkoski,Schwartz,Yan; assumes small z_{cut})
  - NLL+NLO in "standard QCD"
    (Marzani,Schunk,GS; includes (LL) finite z_{cut} for mMDT)

Measurements at the LHC:

CMS-PAS-SMP-16-010



ATLAS(CERN-EP-2017-231)



good overall agreement with the data

Precision physics

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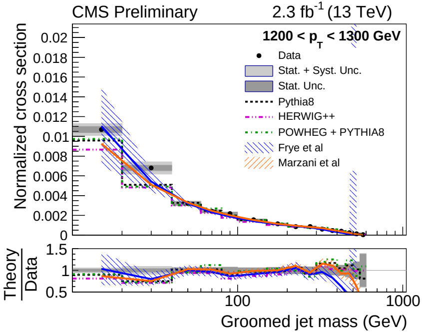

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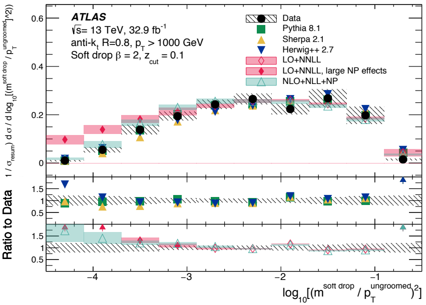

good overall agreement with the data

Precise observable with limited sensitivity to NP effects

⇒ **possibility to extract α_s** **(on-going study)**

Rich QCD phenomenology
Fun facts

Curiosities (1/2): Sudakov safety

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

- z_g not defined at $\mathcal{O}\left(\alpha_S^0\right)$ (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 $\mathcal{O}\left(\alpha_s^0\right)$
- some observables are ill-defined at any fixed order (see next slide)

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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 $\frac{dP}{de_\beta} \to 0$ in that limit (Sudakov exponential)

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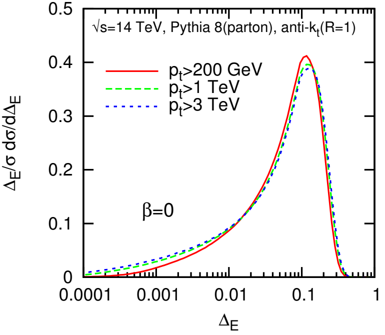
A series of interesting results
still many unknown to be explored

Curiosities (2/2): α_s independence

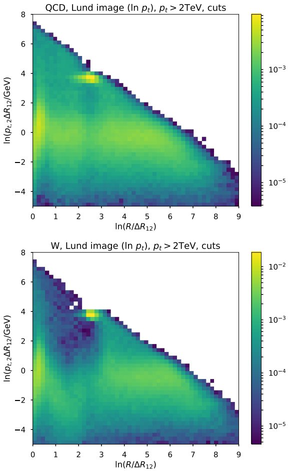


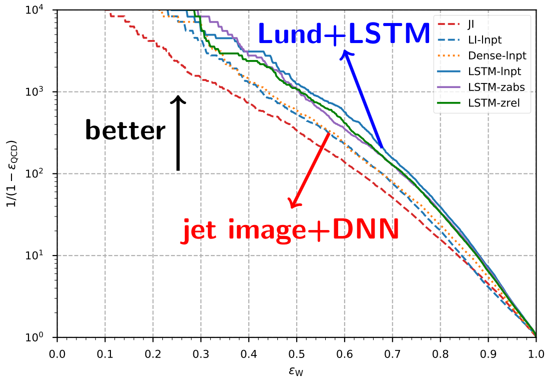
LL result: $\text{Prob}(<\Delta) = \frac{\log(z_{\rm cut})+\frac{3}{4}}{\log(\Delta)+\frac{3}{4}}$

- What are we looking at?
  - jet with momentum $p_{t,\rm jet}$
  - apply mMDT
  - after, $p_t = p_{t,\rm mMDT}$
  - measure $\Delta = \frac{p_{t,\rm jet} - p_{t,\rm mMDT}}{p_{t,\rm jet}}$ i.e. the lost p_t fraction
- Result:
  at LL and fixed coupling, the Δ distribution is α_s-**independent**

pQCD meets Machine Learning

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





QCD-motivated input to LSTM network shows great performance

Conclusions

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