New perspectives in QCD with jet substructure

Grégory Soyez

IPhT, CEA Saclay, CNRS

GDR QCD, December 4 2017

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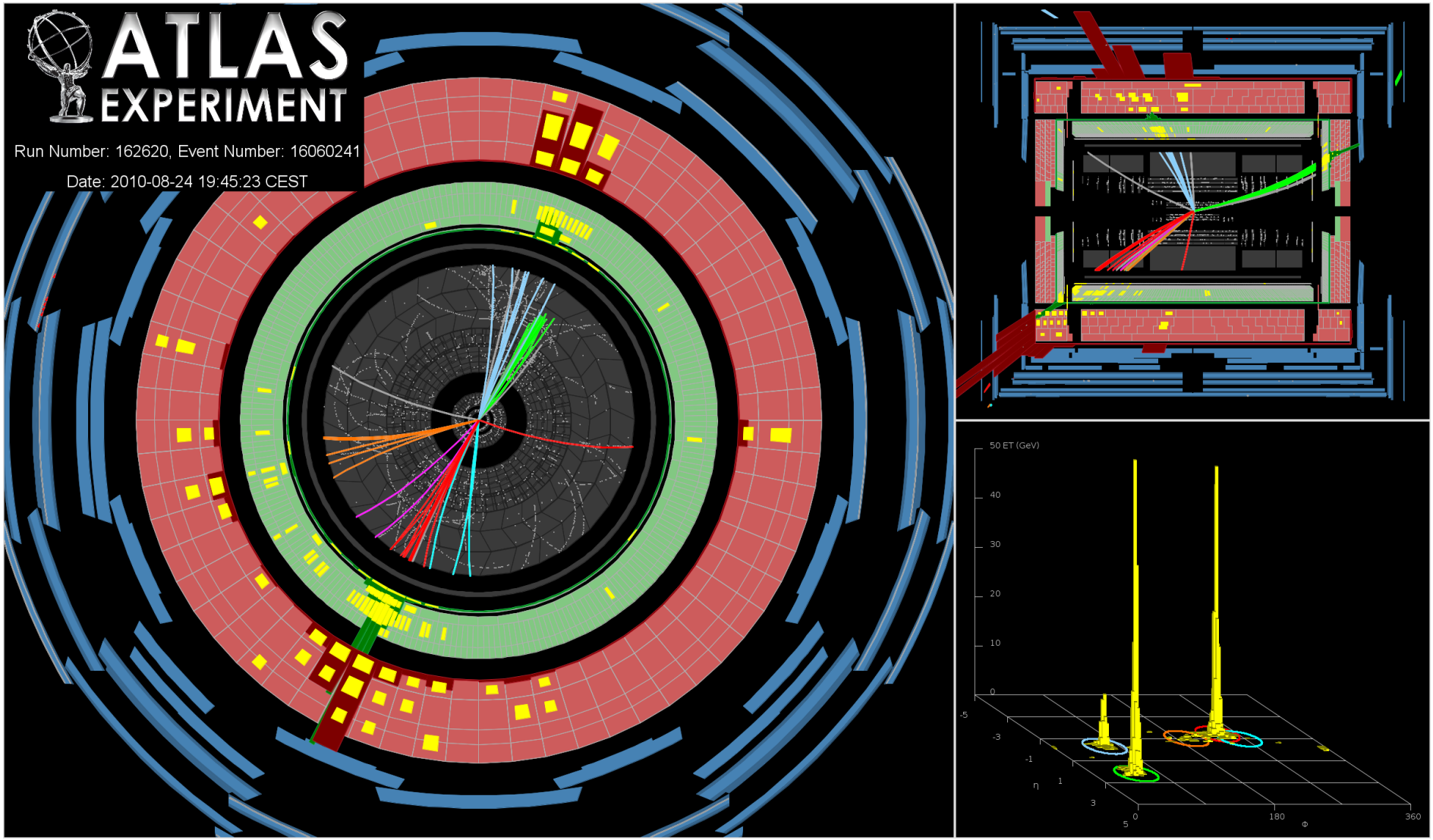
You could live a happy life by just knowing a few things

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


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

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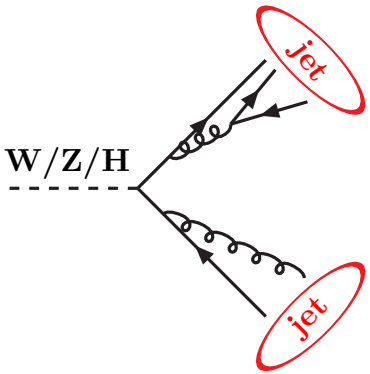
This talk: give you a hint of all these aspects

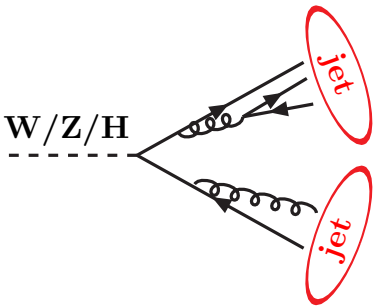
Boosted objects and searches

Boosted objects

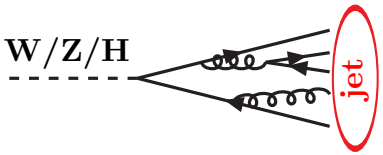
$p_t \lesssim m$



2 jets



$p_t \gg m$

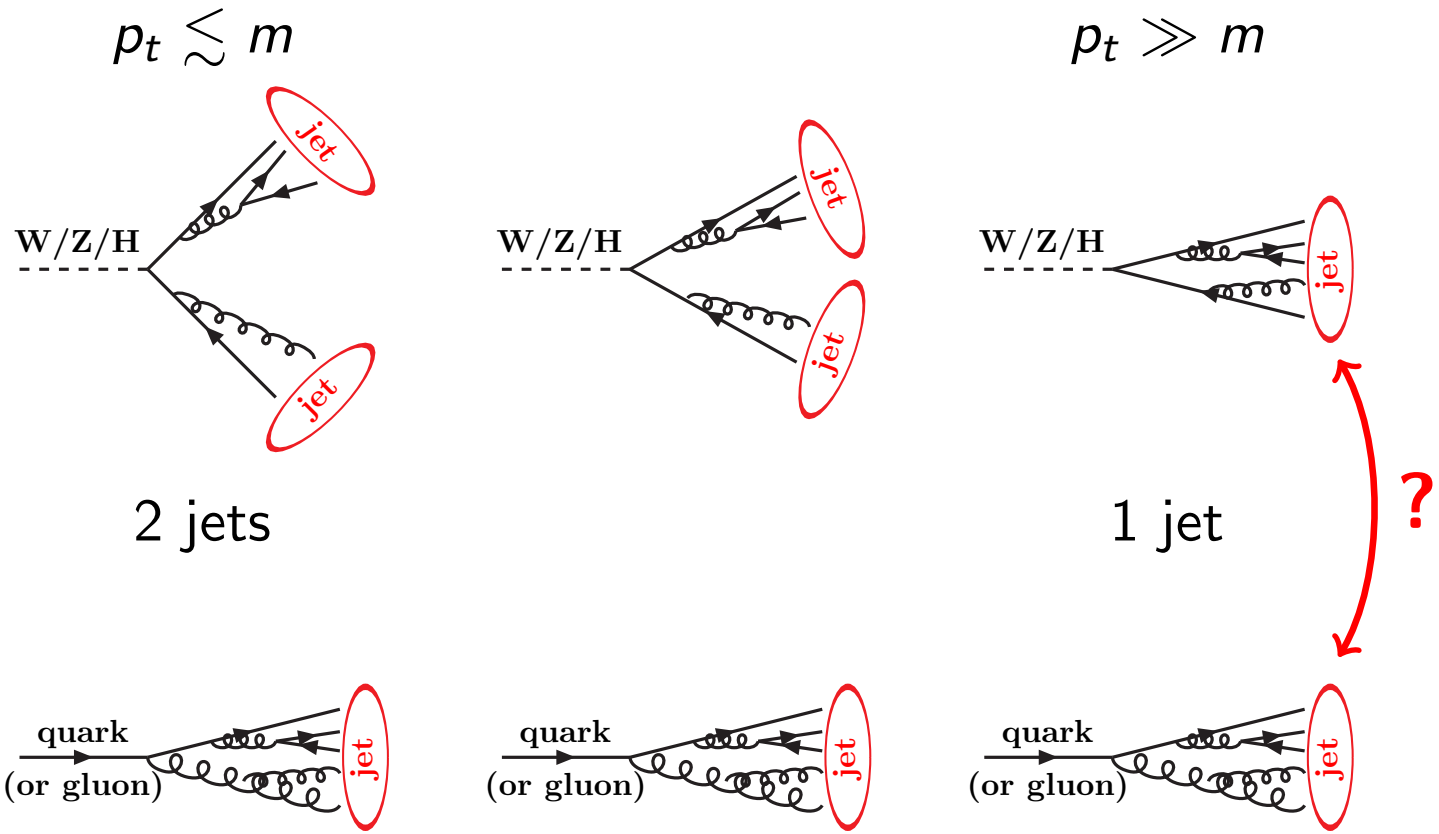


1 jet

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

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

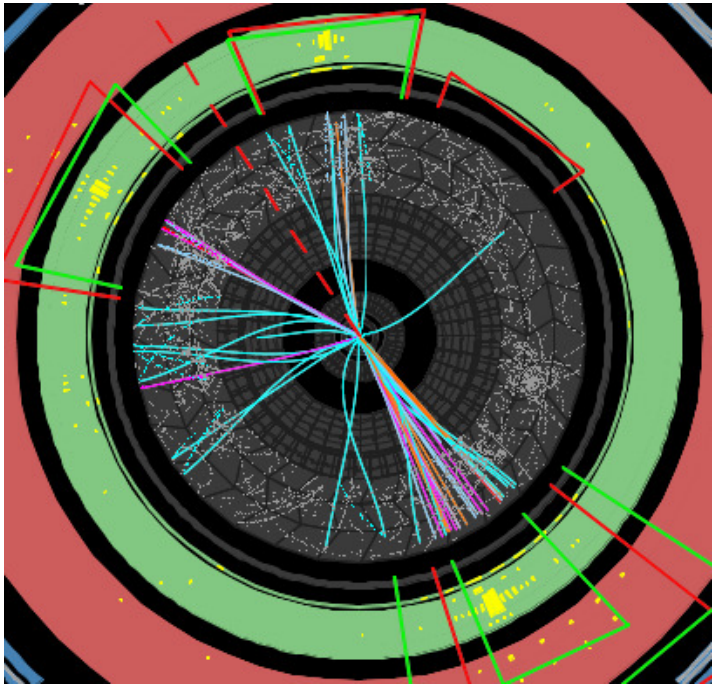
Boosted objects



use substructure to separate from QCD jets

Other examples

What jet do we have here?



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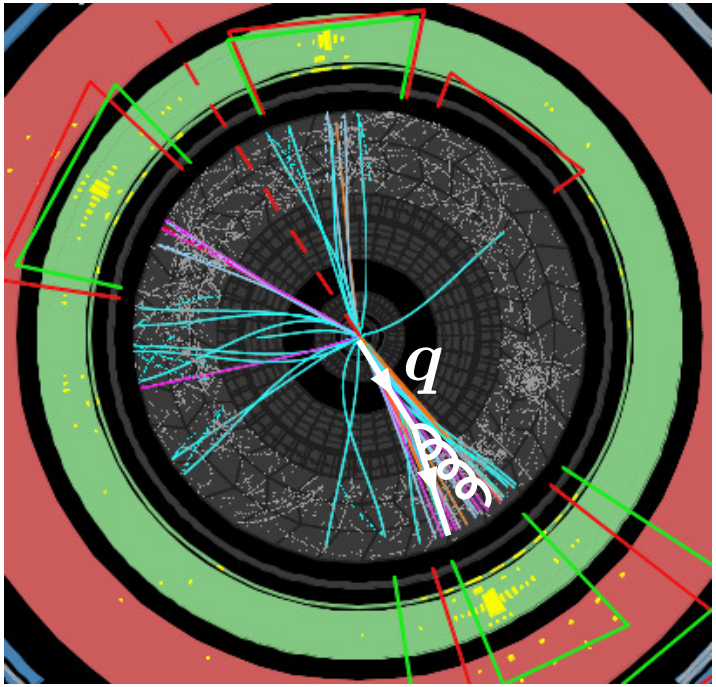
- a quark?



Other examples

What jet do we have here?

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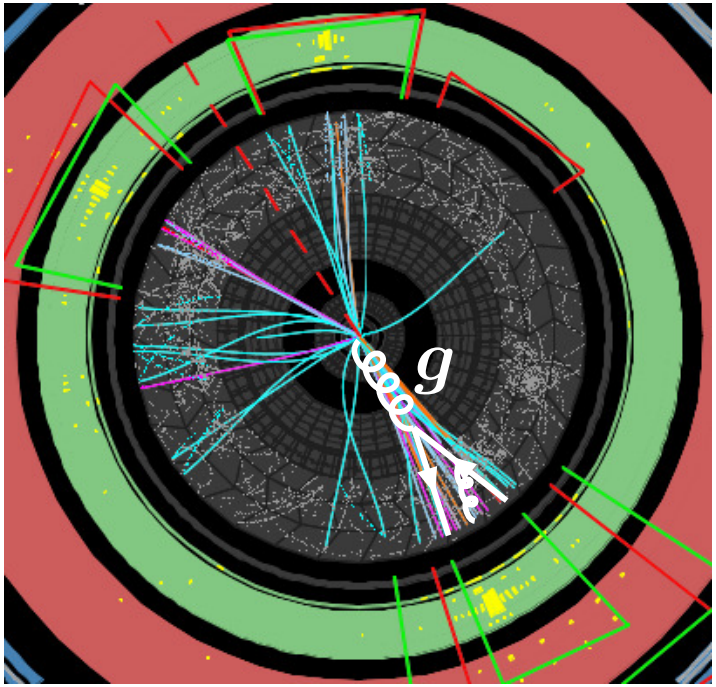
- a gluon?



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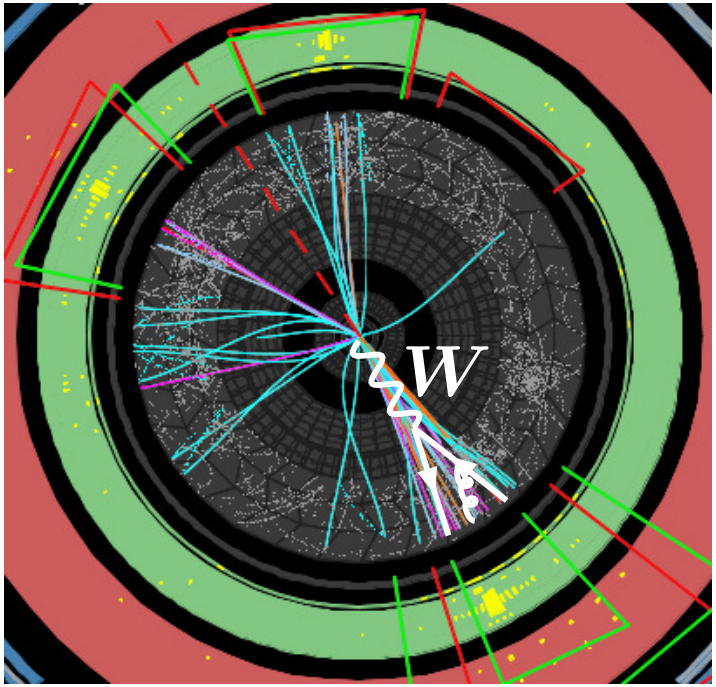

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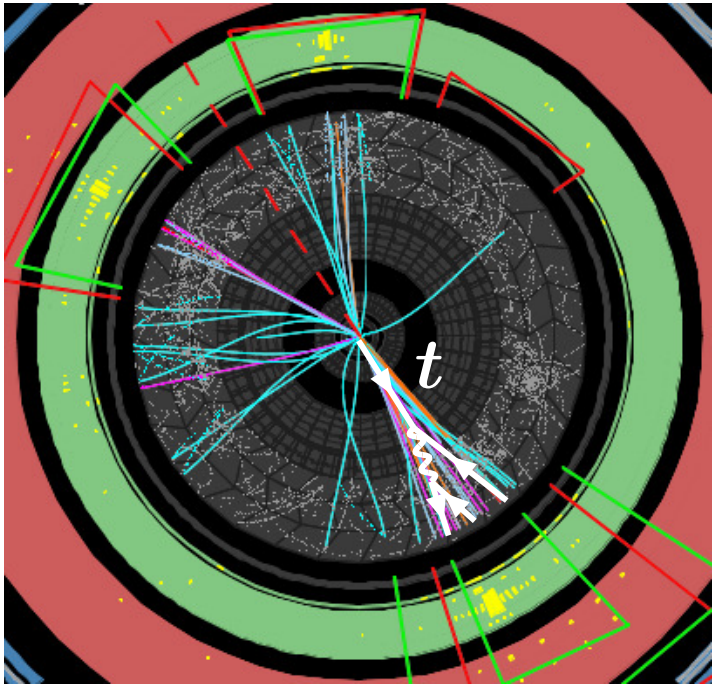

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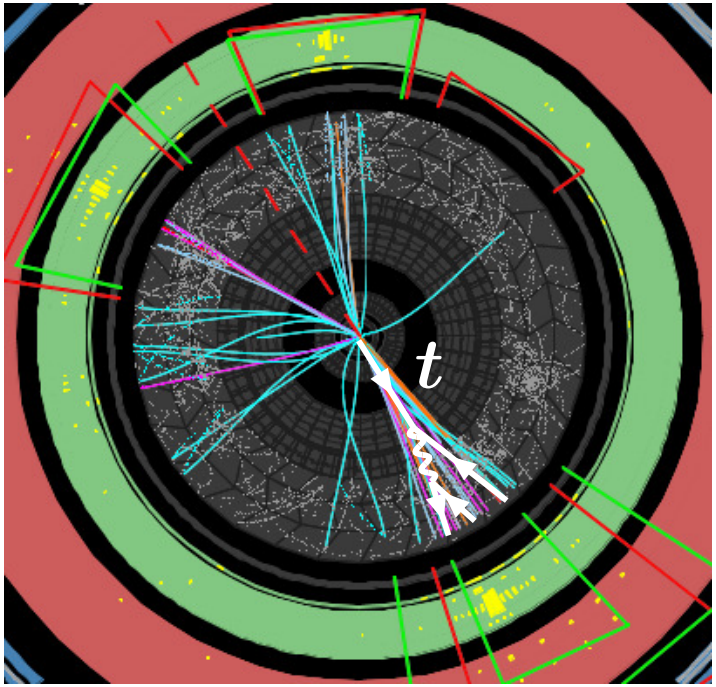

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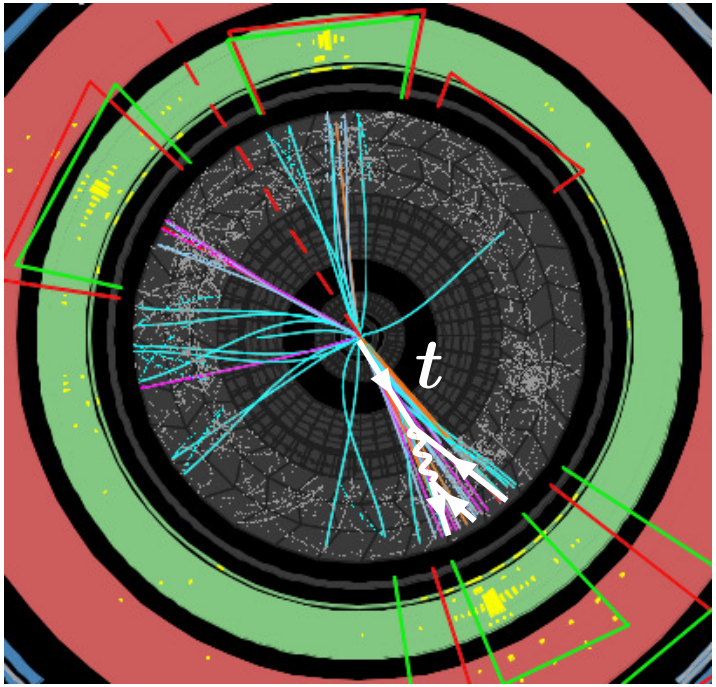
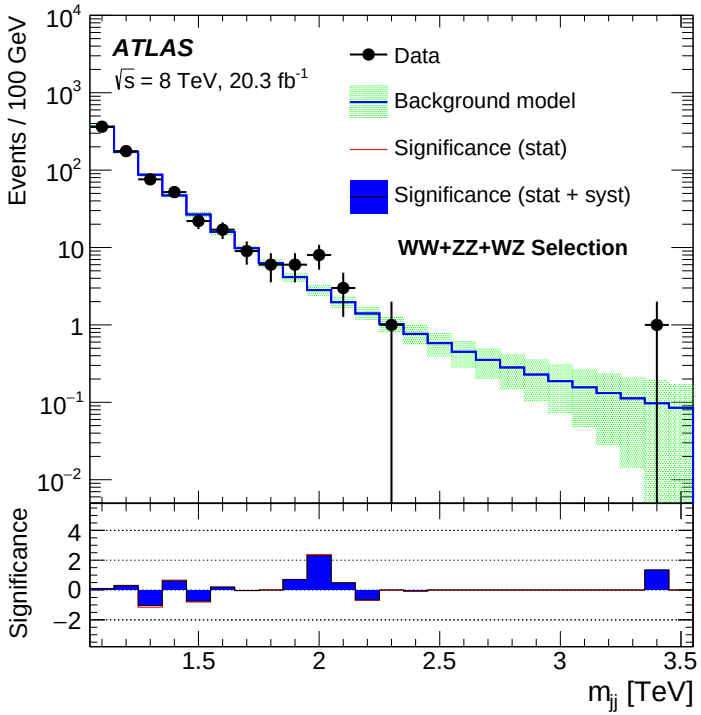
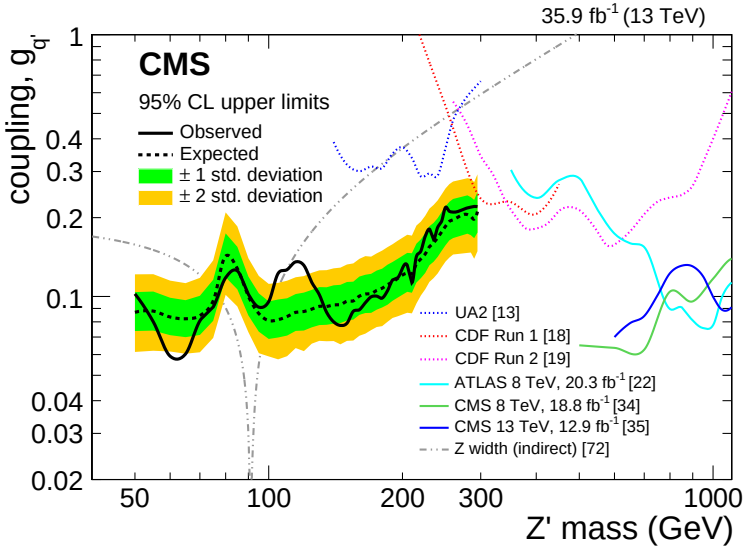


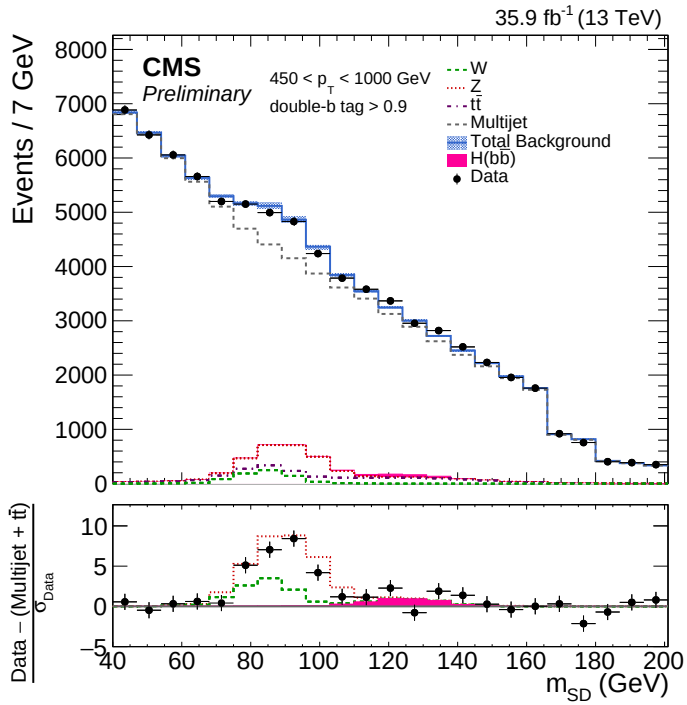
Many applications, all relevant to new physics searches:

- 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

Searches and measurements







↑ (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

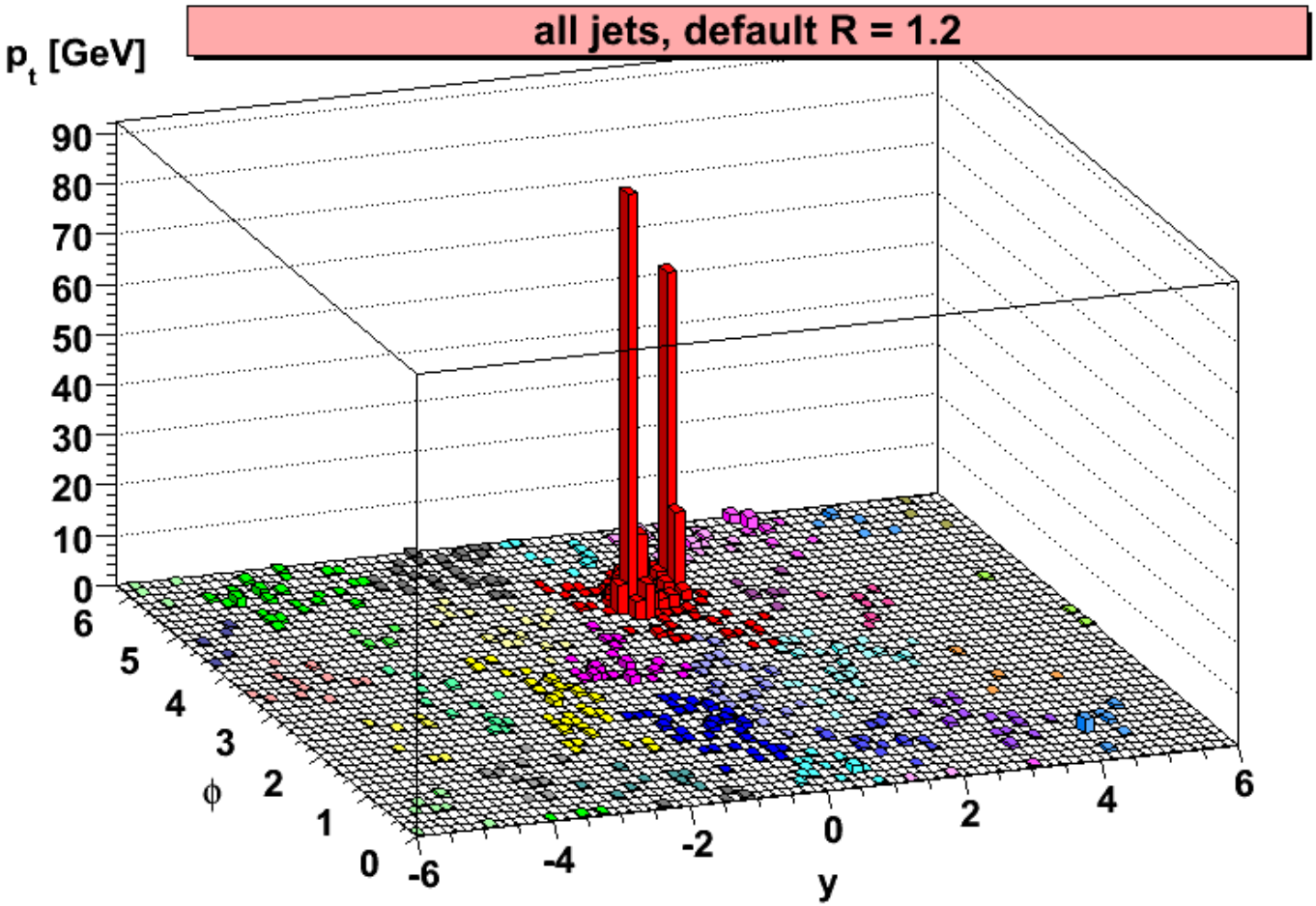
  N-subjettiness, energy-correlation functions, planar flow, ...

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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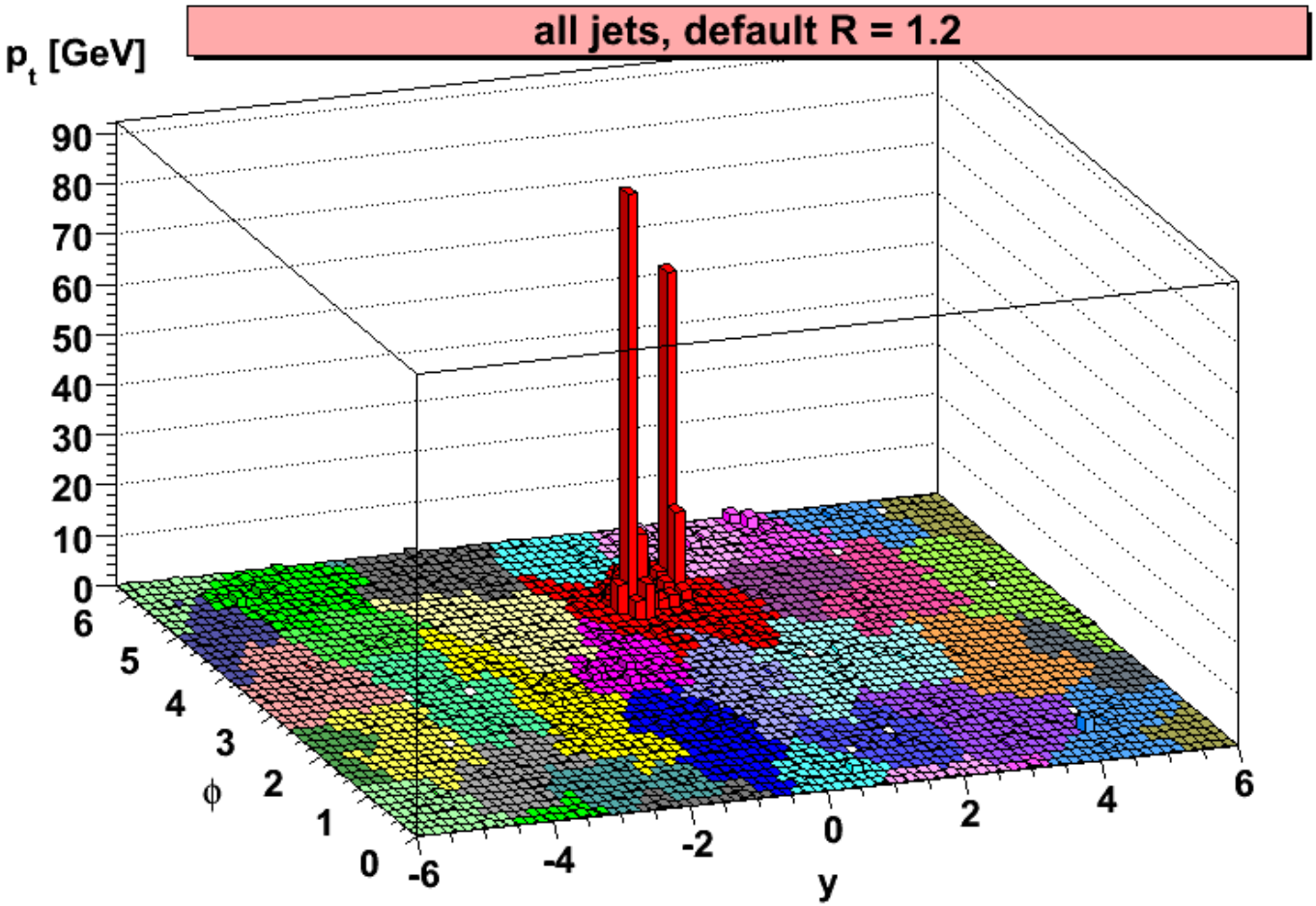

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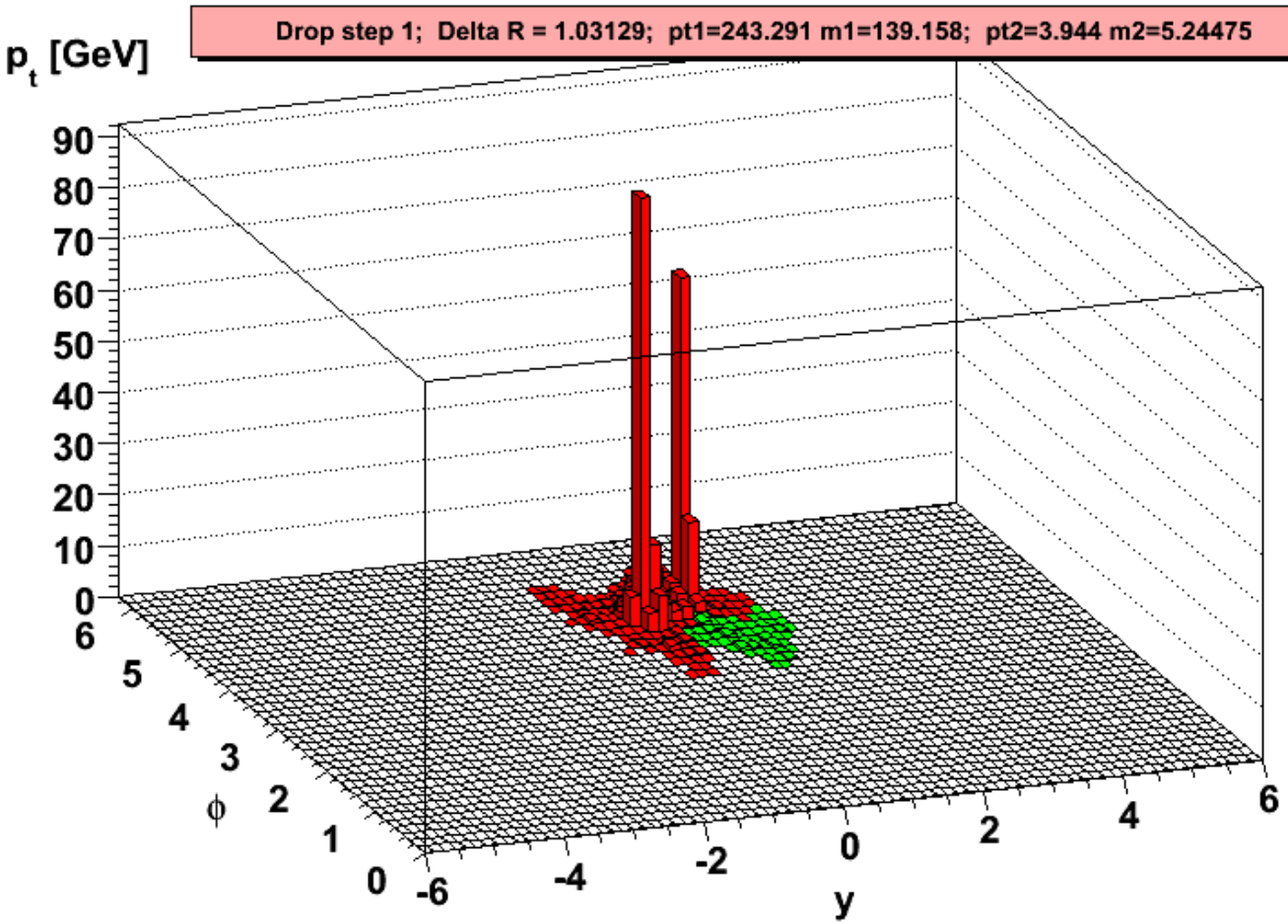

MassDrop

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

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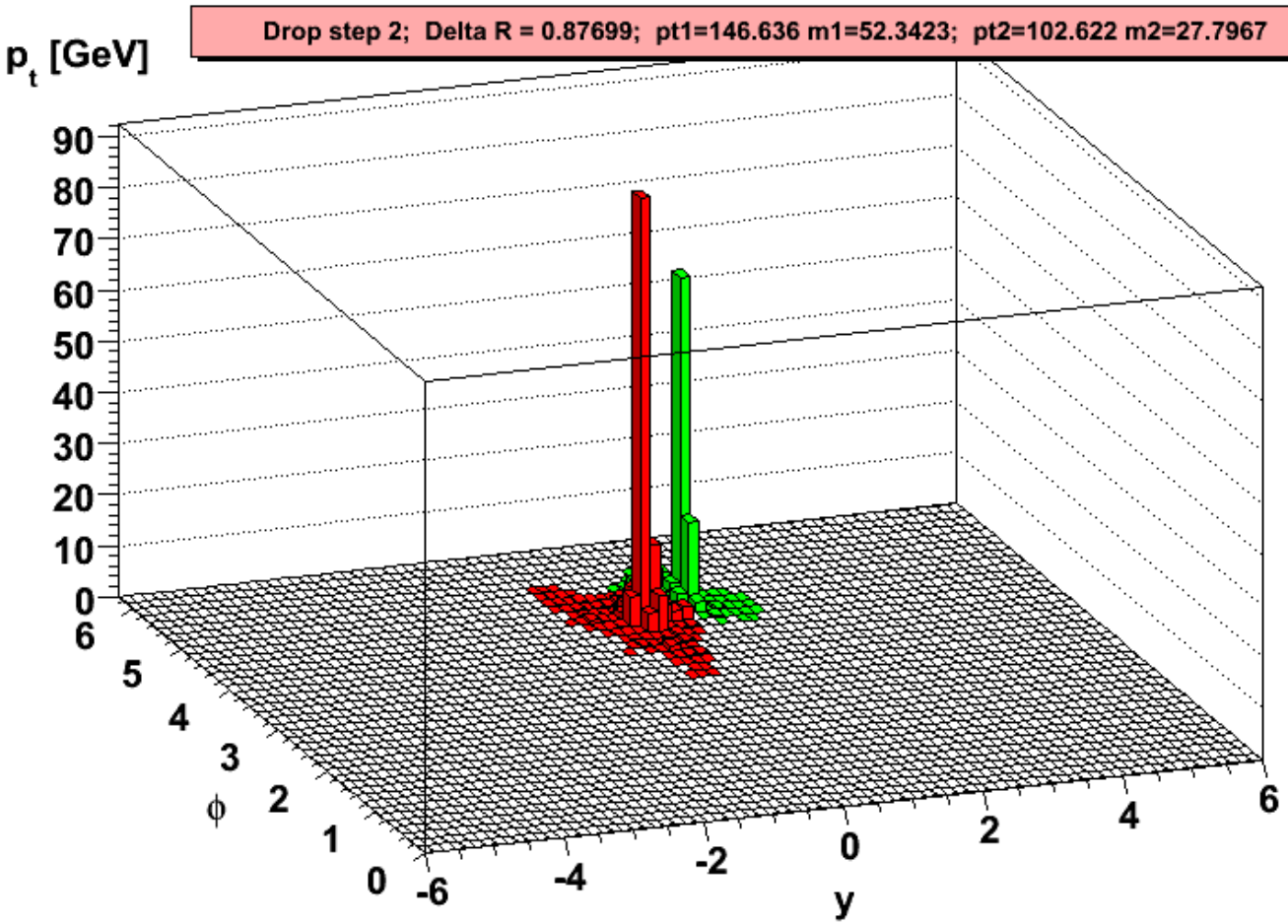

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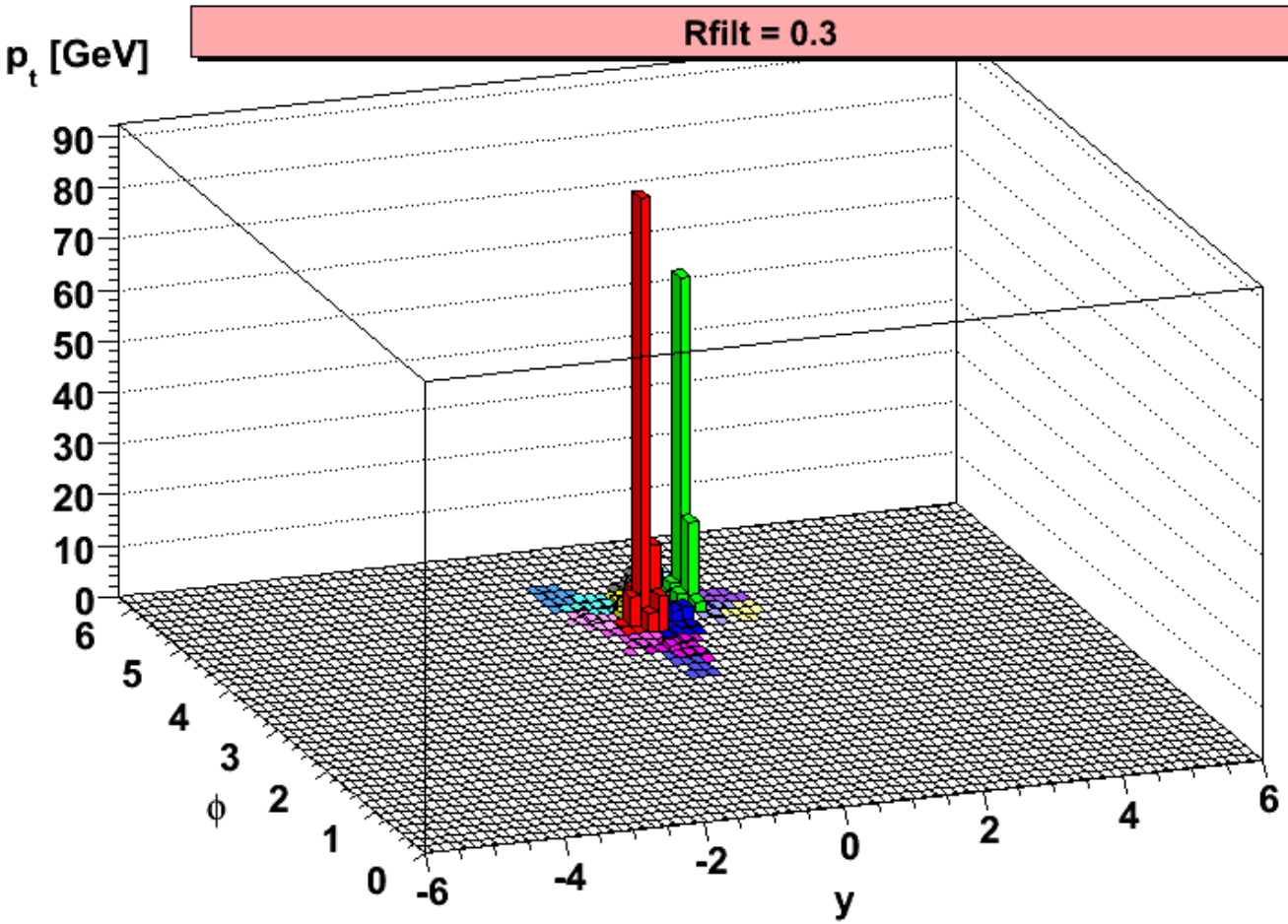

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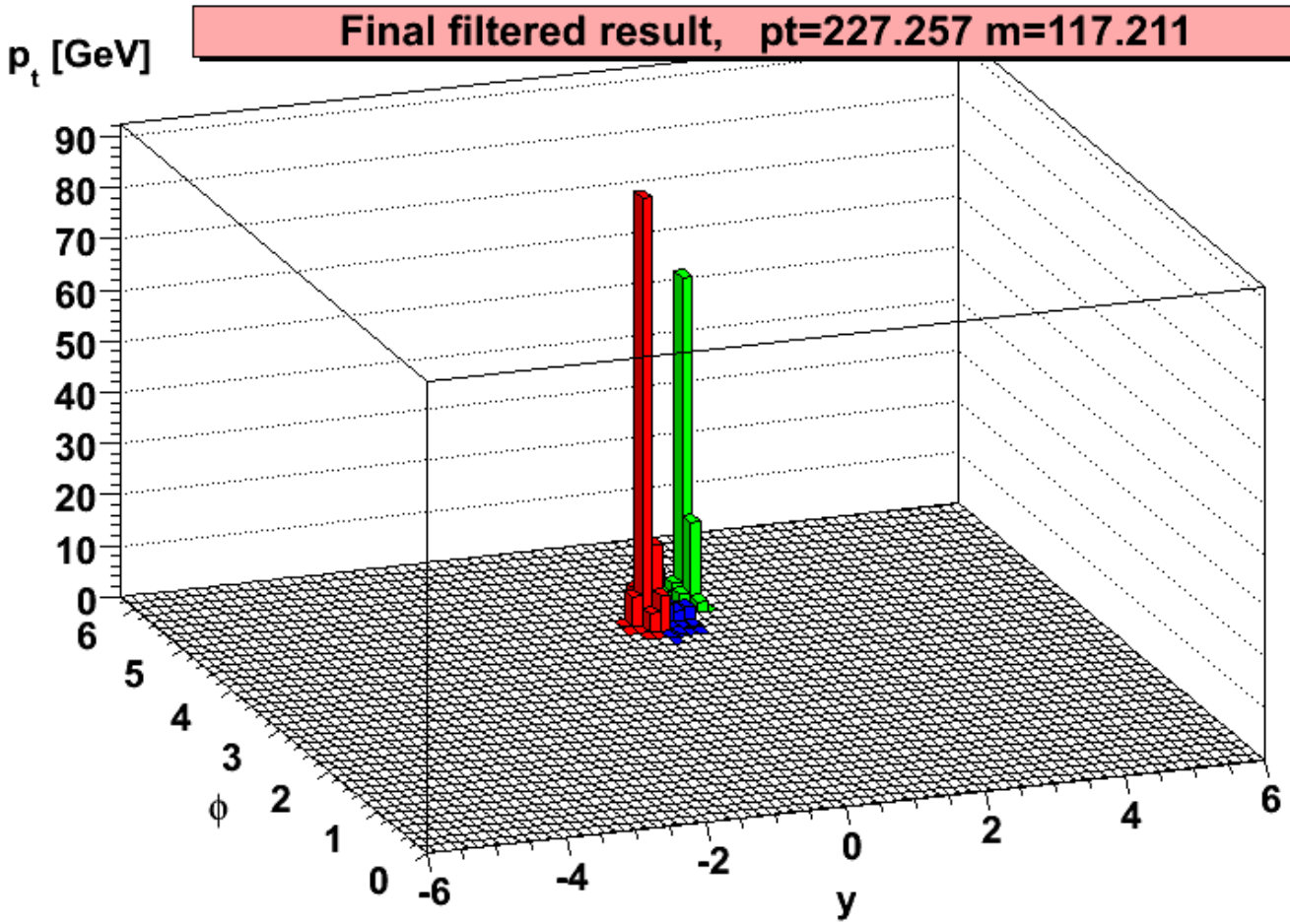

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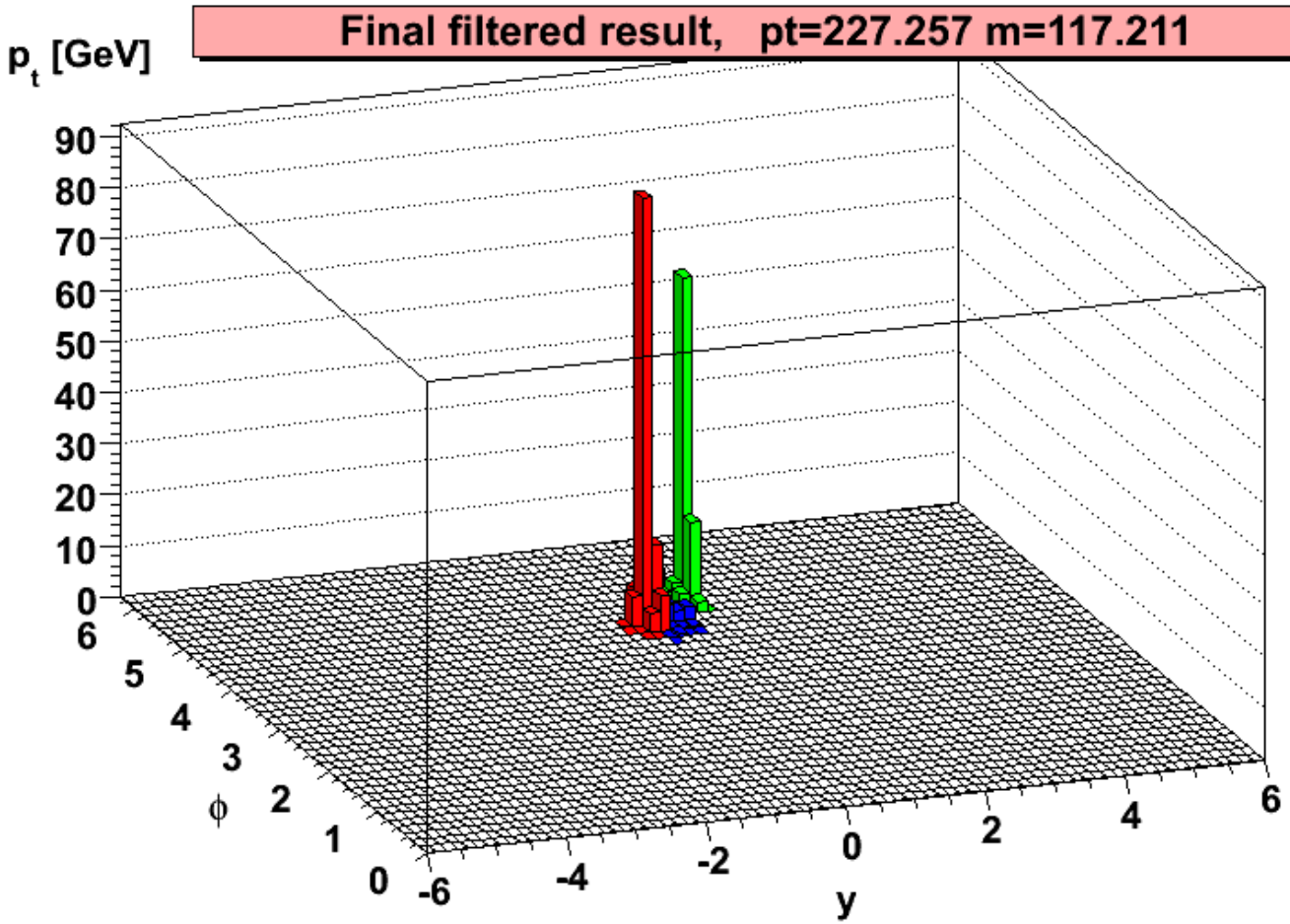

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Variant: **SoftDrop**: impose $z > z_{\text{cut}}\theta^{\beta}$ [A.Larkoski,S.Marzani,GS,J.Thaler,14]

Study radiation: N-subjettiness

Given N axes/prongs in a jet (axes)

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

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

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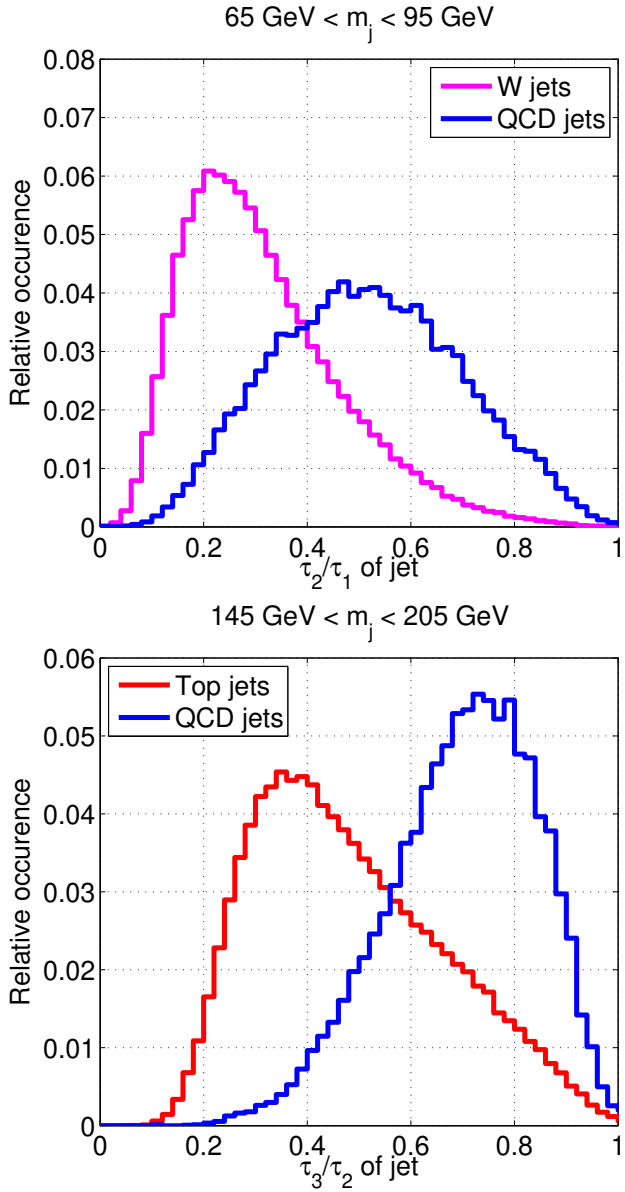
- Measures the radiation from N prongs
- $\tau_{N,N-1} = \tau_N / \tau_{N-1}$ discriminates N-prong v. QCD
- τ_{21} smaller for W than for QCD
- τ_{32} smaller for top than for QCD

Several alternatives similar to τ_N



Latest playground: deep learning

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:

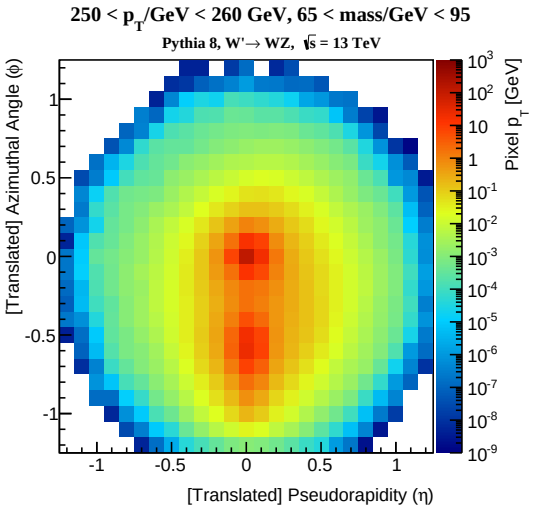
  Feed jet variables, jet constituents, jet images, ...

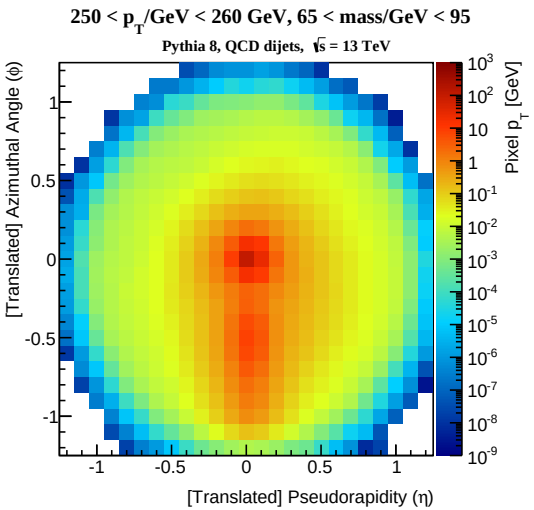
- Many applications:

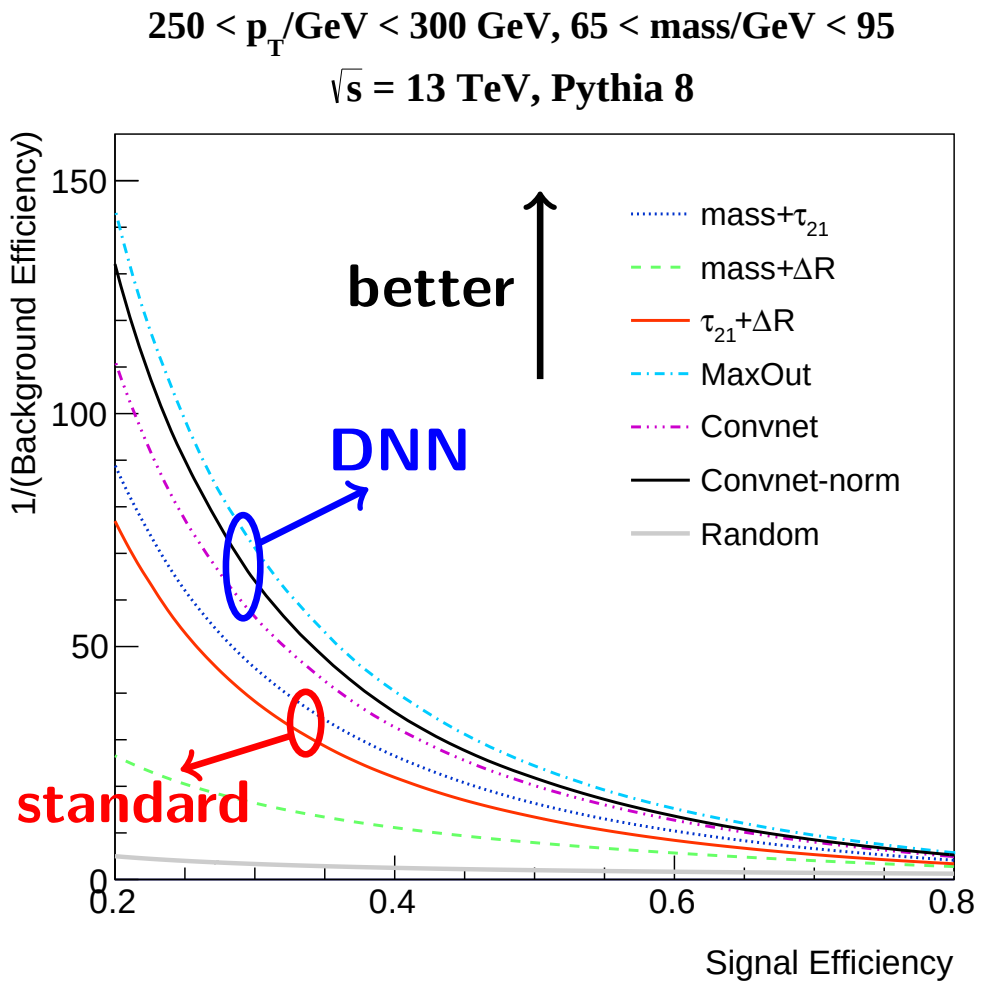
  q/g, b, W, H, t tagging, pileup-mitigation, detector sim, ...

Latest playground: deep learning

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







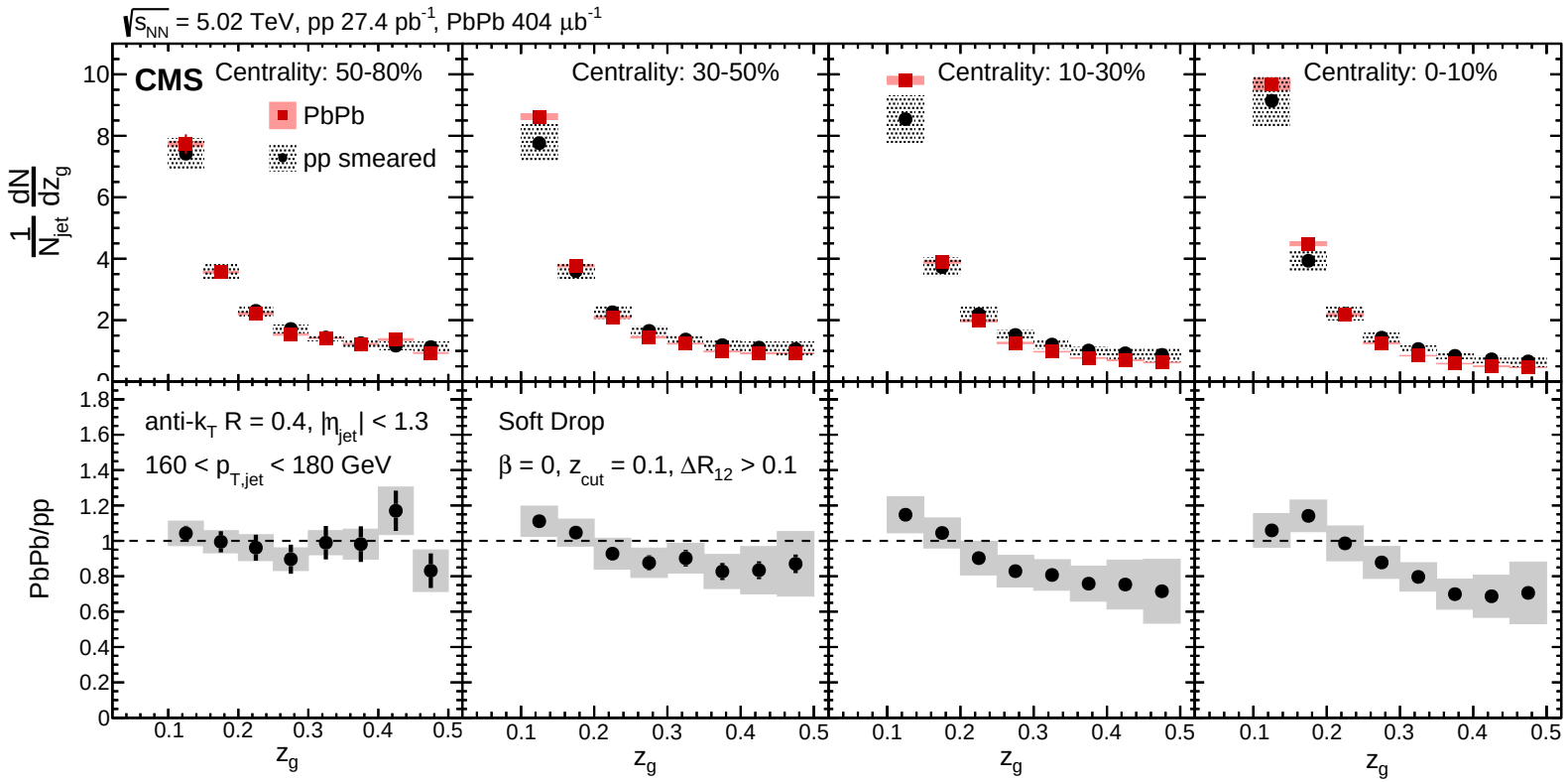
Improvement compared to standard approach

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

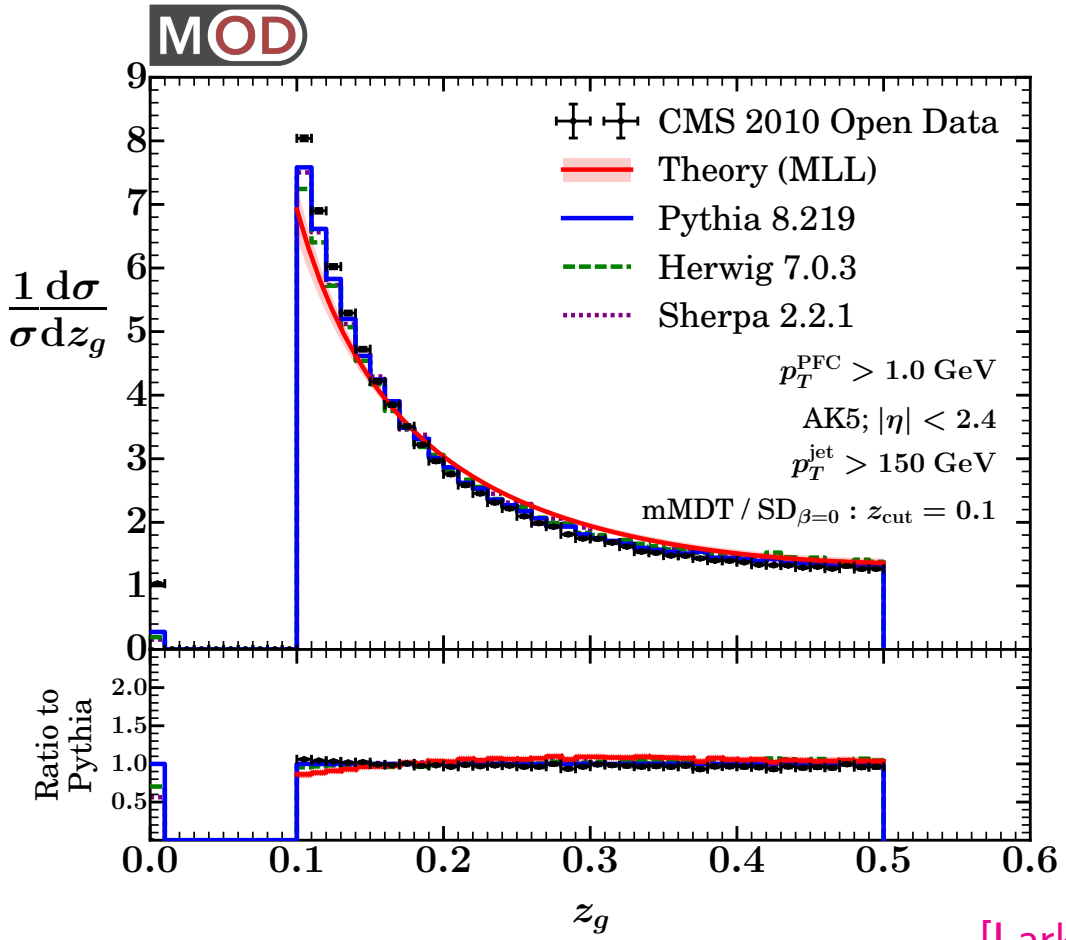
Measurement in *PbPb* shows quenching effects



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

Measuring the splitting function

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
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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
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- 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:

$$\text{Boosted jet} \Rightarrow p_t \gg m$$

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

$$\Rightarrow \text{expect } \log\rho \text{ coming with } \alpha_s$$

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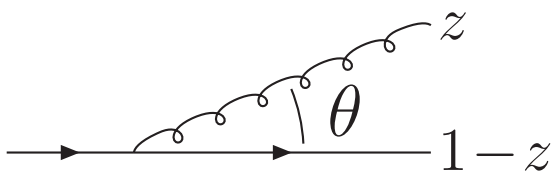
- Example: jet mass with one (soft-and-collinear) gluon emission

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



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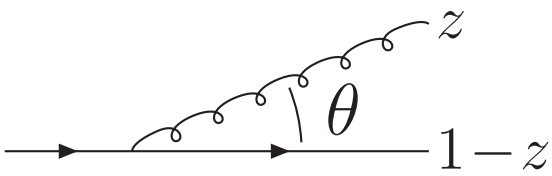

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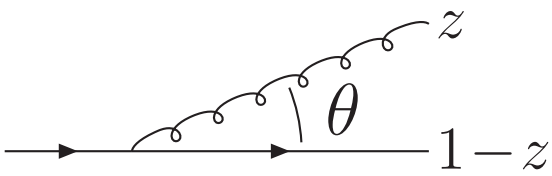

- mMDT jet mass again:

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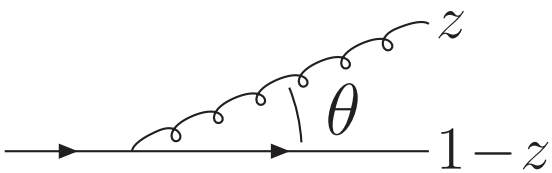

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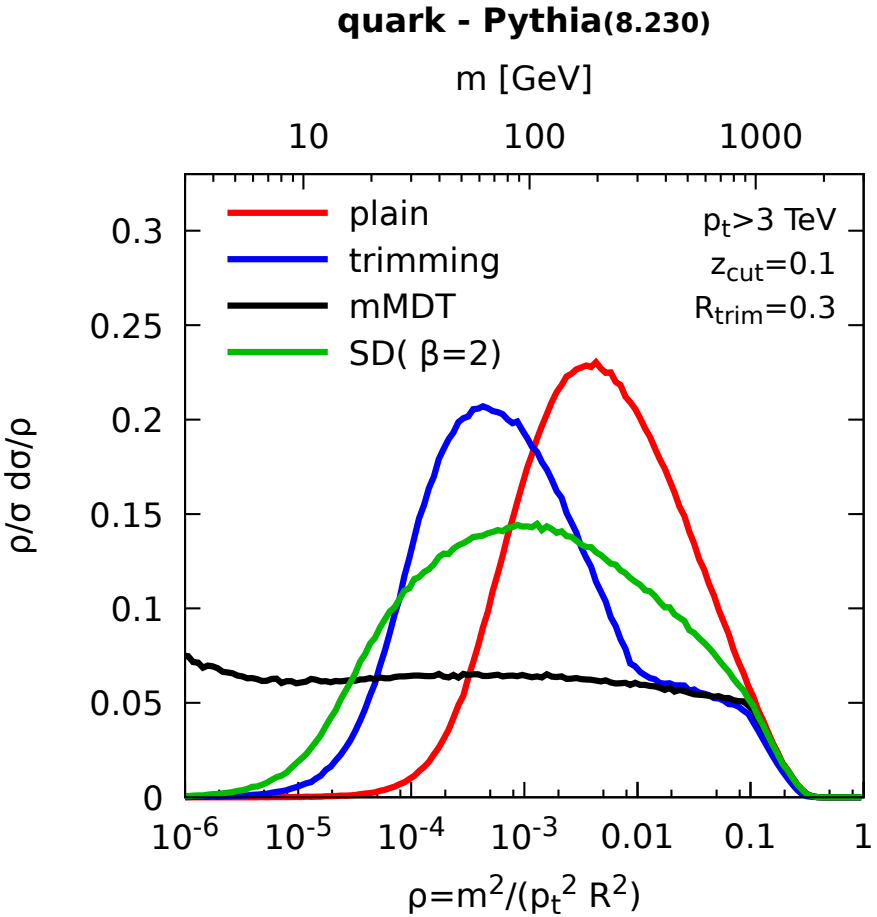
- all-order result (Leading-Log):

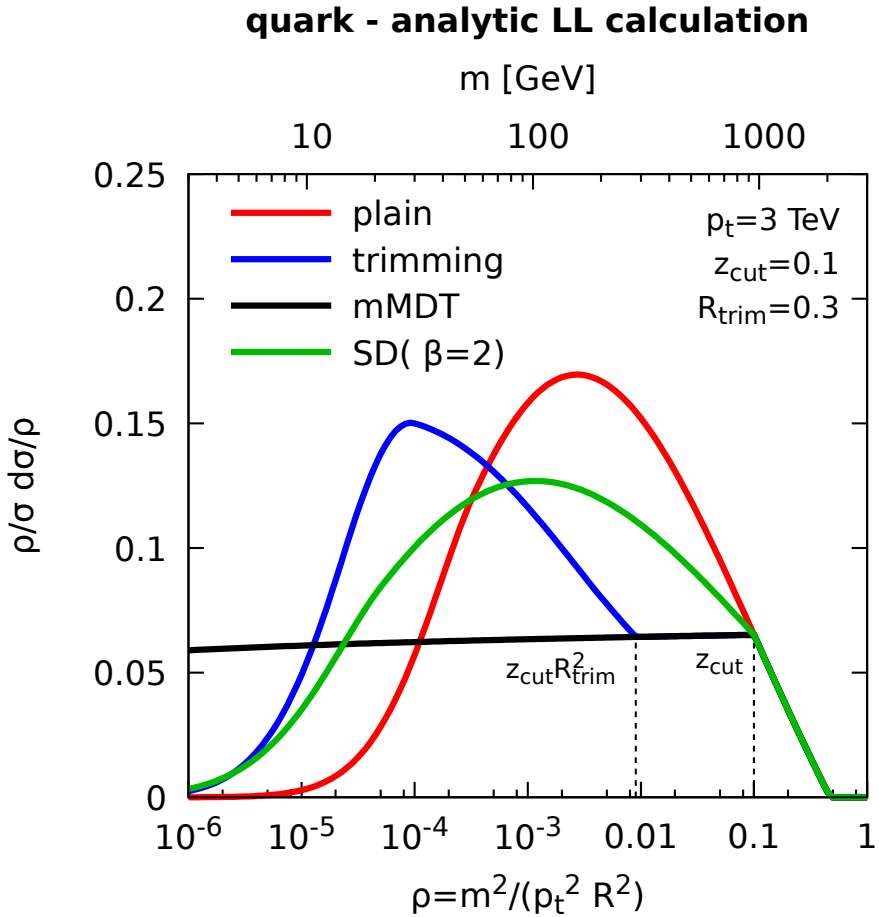
$$\text{Prob}_{\text{LL}}(<\rho) = \exp[-\text{Prob}_1(<\rho)]$$

Understanding substructure tools

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

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

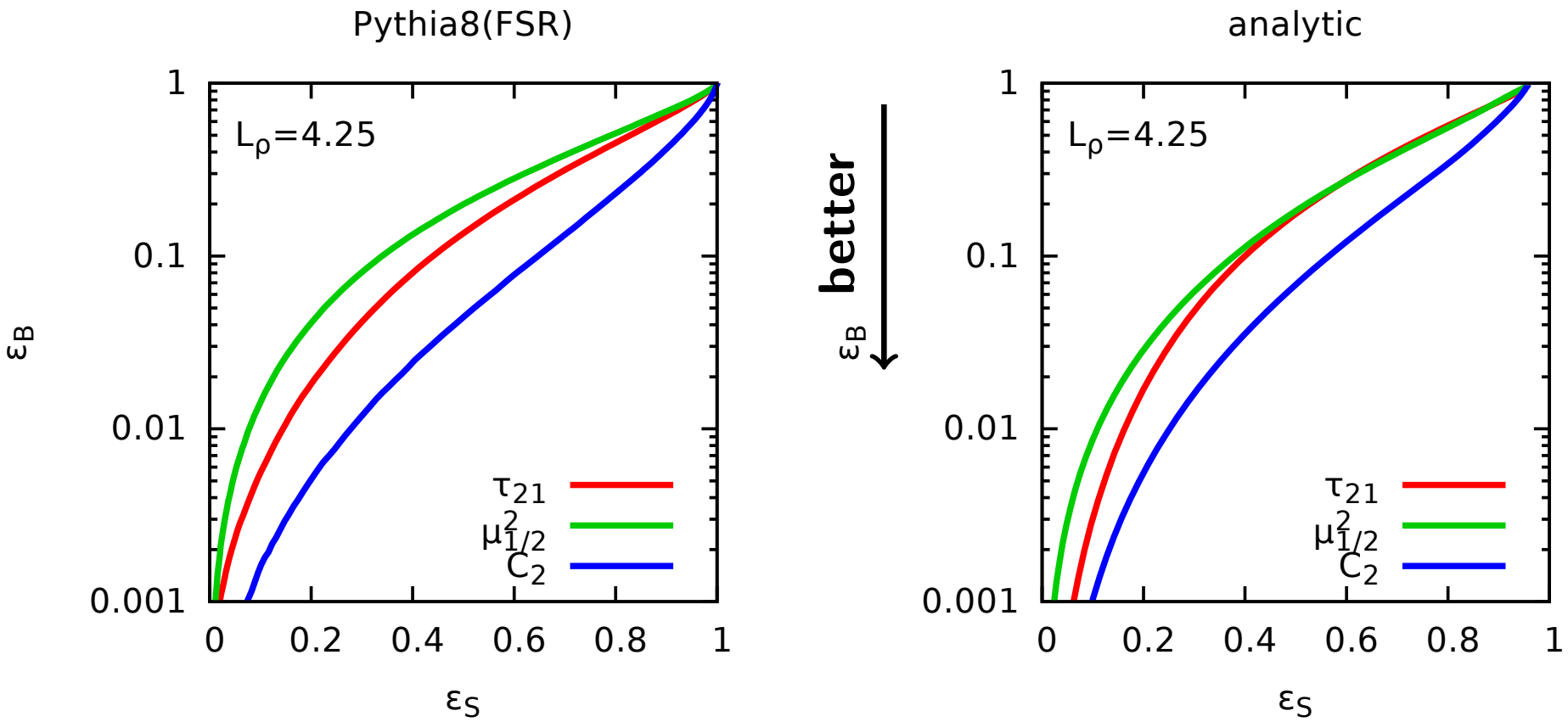




qualitative features reproduced and understood

Understanding substructure tools (cont'd)

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



qualitative features reproduced and understood

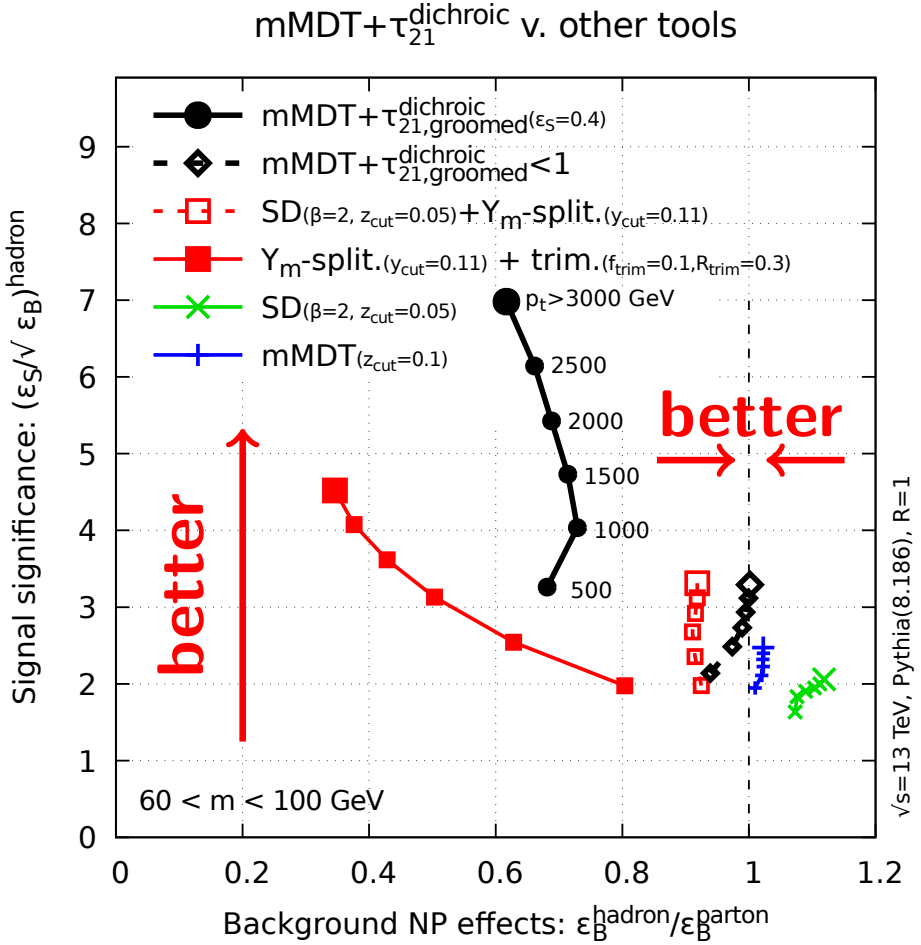
Improving substructure tools

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!



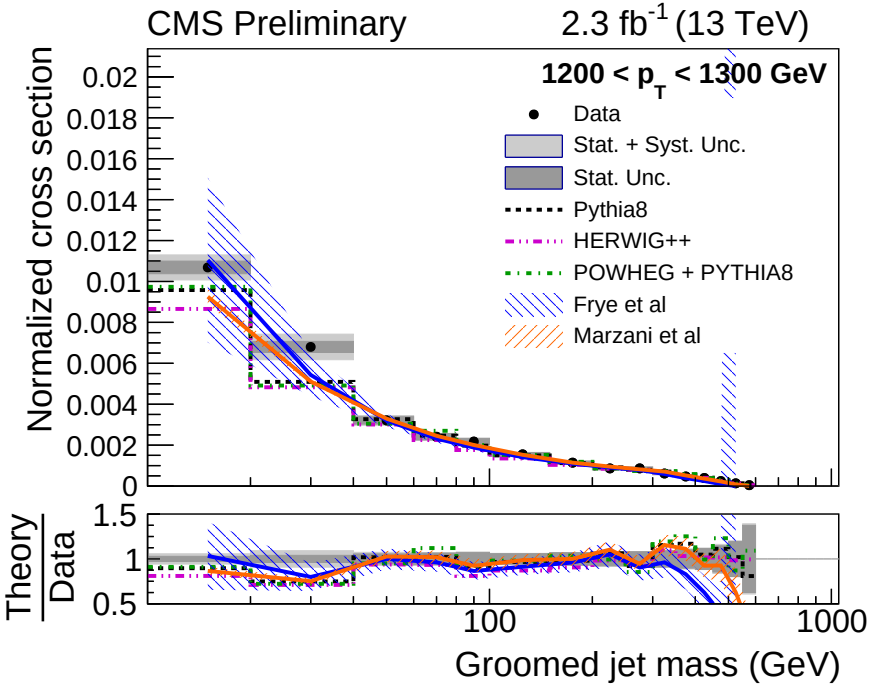
Precision physics

- 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

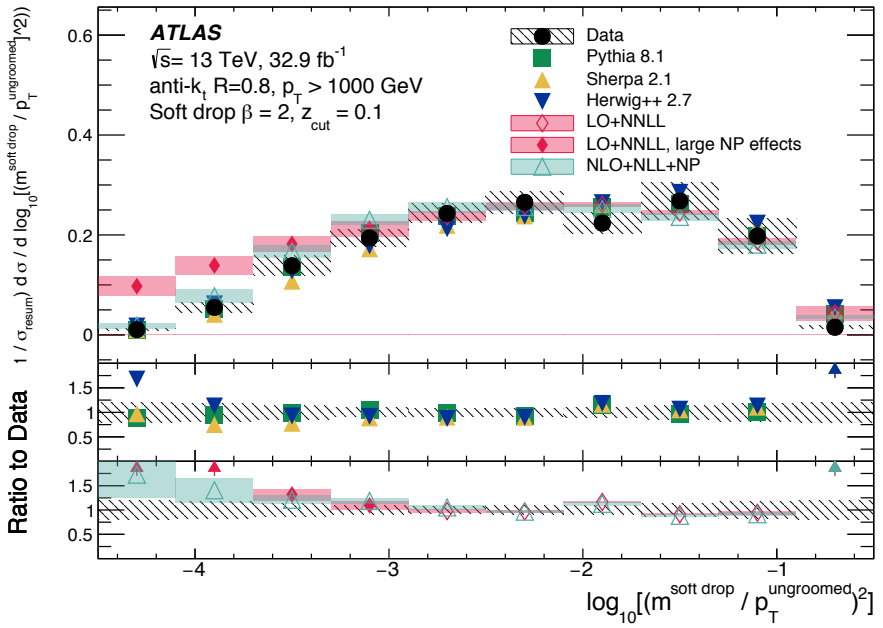
- Recent precise calculations of the mMDDT/SD jet mass:
  - NNLL+LO in SCET (Frye,Larkoski,Schwartz,Yan)
  - NLL+NLO in "standard QCD" (Marzani,Schunk,GS)

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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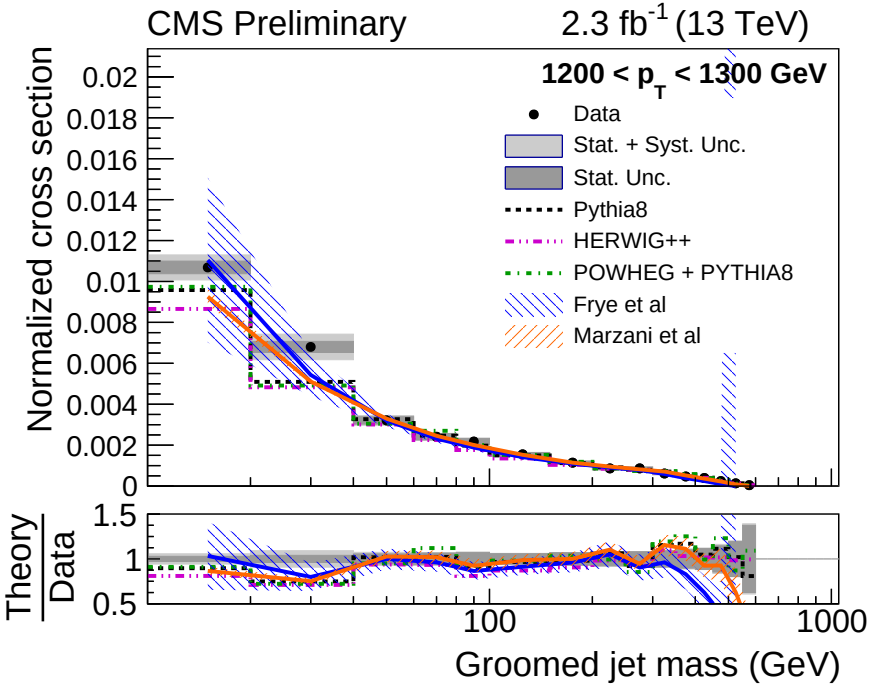

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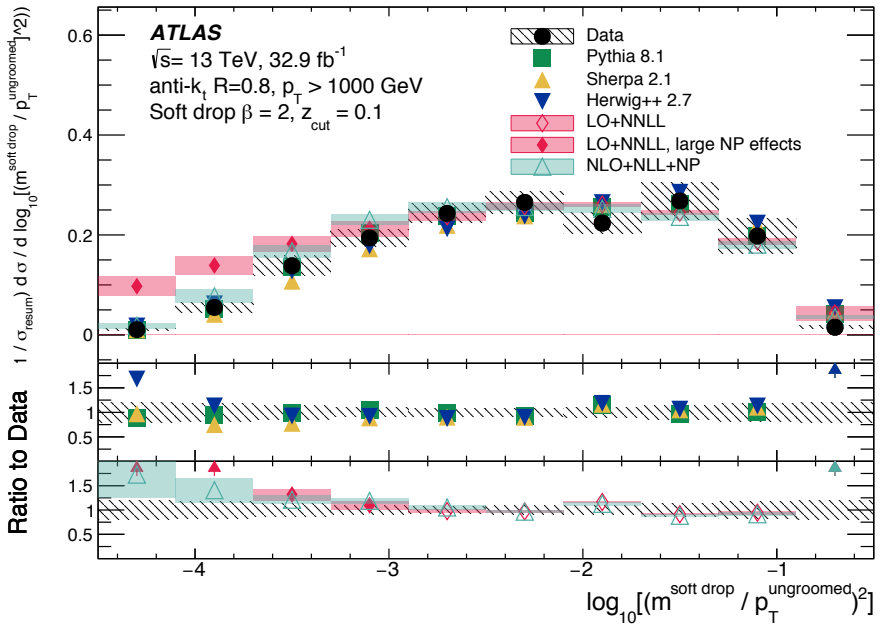

good overall agreement with the data

Precise observable with limited sensitivity to NP effects

$\Rightarrow$ **possibility to extract** α_s **(on-going study)**

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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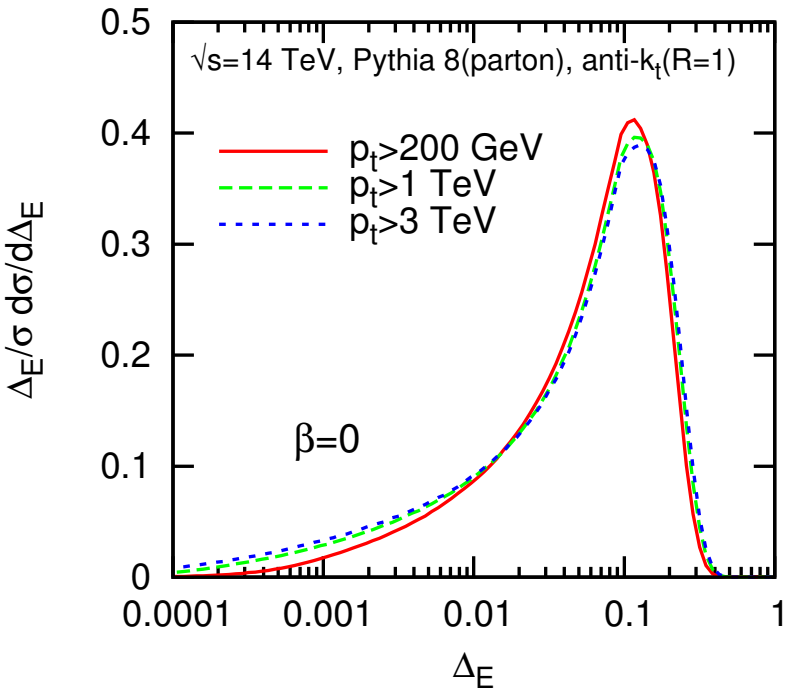
A series of interesting results
still many unknown to be explored

Curiosities (2/2): α_s independence

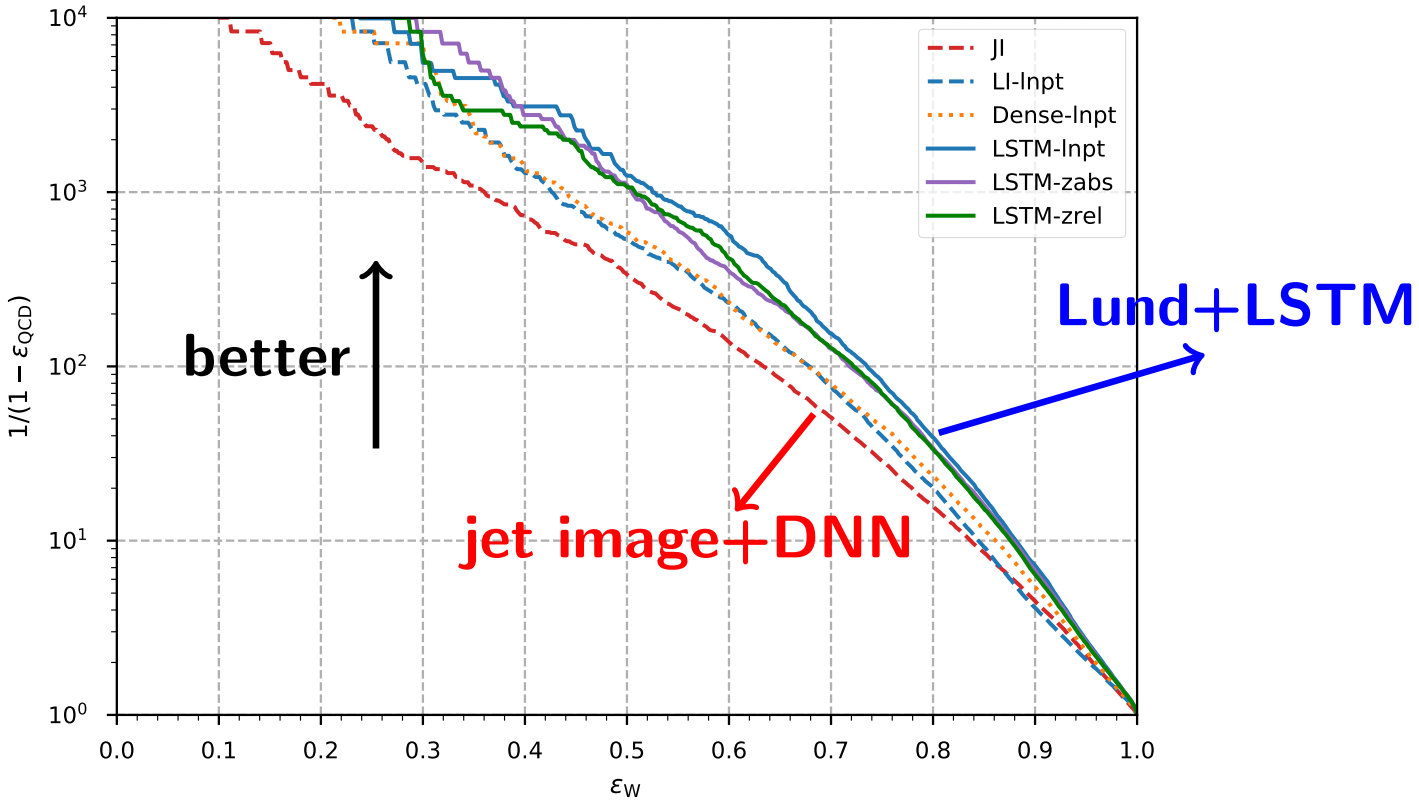


LL result: $\text{Prob}(<\Delta) = \frac{\log(z_{\text{cut}})+\frac{3}{4}}{\log(\Delta)+\frac{3}{4}}$

- 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 Δ distribution is **α_s-independent**

pQCD meets Machine Learning

[F.Dreyer,G.Salam,GS, soon]



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
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discussing latest progress in substructure

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July 16-20: BOOST 2018 in Paris
https://indico.cern.ch/e/boost2018