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Jet substructure : theory developments and challenges

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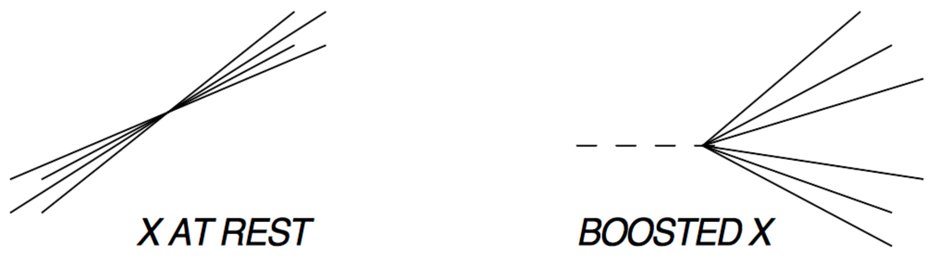
University of Manchester

ATLAS SM workshop, London, 6th September 2018

Outline

- Introduction and basics
- Some key theory issues
- Selective review of recent developments
- Prospects and challenges

Basic ideas



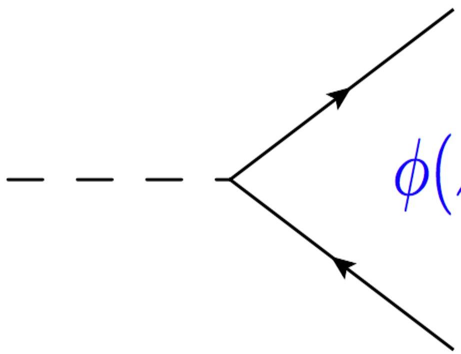
Key idea : for tagging a particle with mass M exploit boosted regime i.e. $P_T >> M$.

$$\theta^2 = \frac{M^2}{p_T^2 z(1-z)}$$

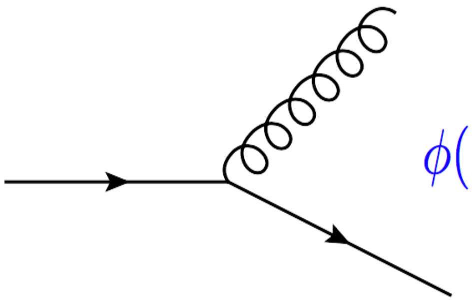
Either from going to high p_T or from decay of heavy new particle

Hadronic decays reconstructed in single “fat” jet.
Use our knowledge of QCD jets to distinguish this from background.

Basic ideas



$$\phi(z) \propto 1$$



$$\phi(z) \propto \frac{1+z^2}{1-z}$$

- Exploit the asymmetric nature of QCD splittings. Produce jets with single hard core or prong versus 2 pronged W/Z/H and 3 pronged t.

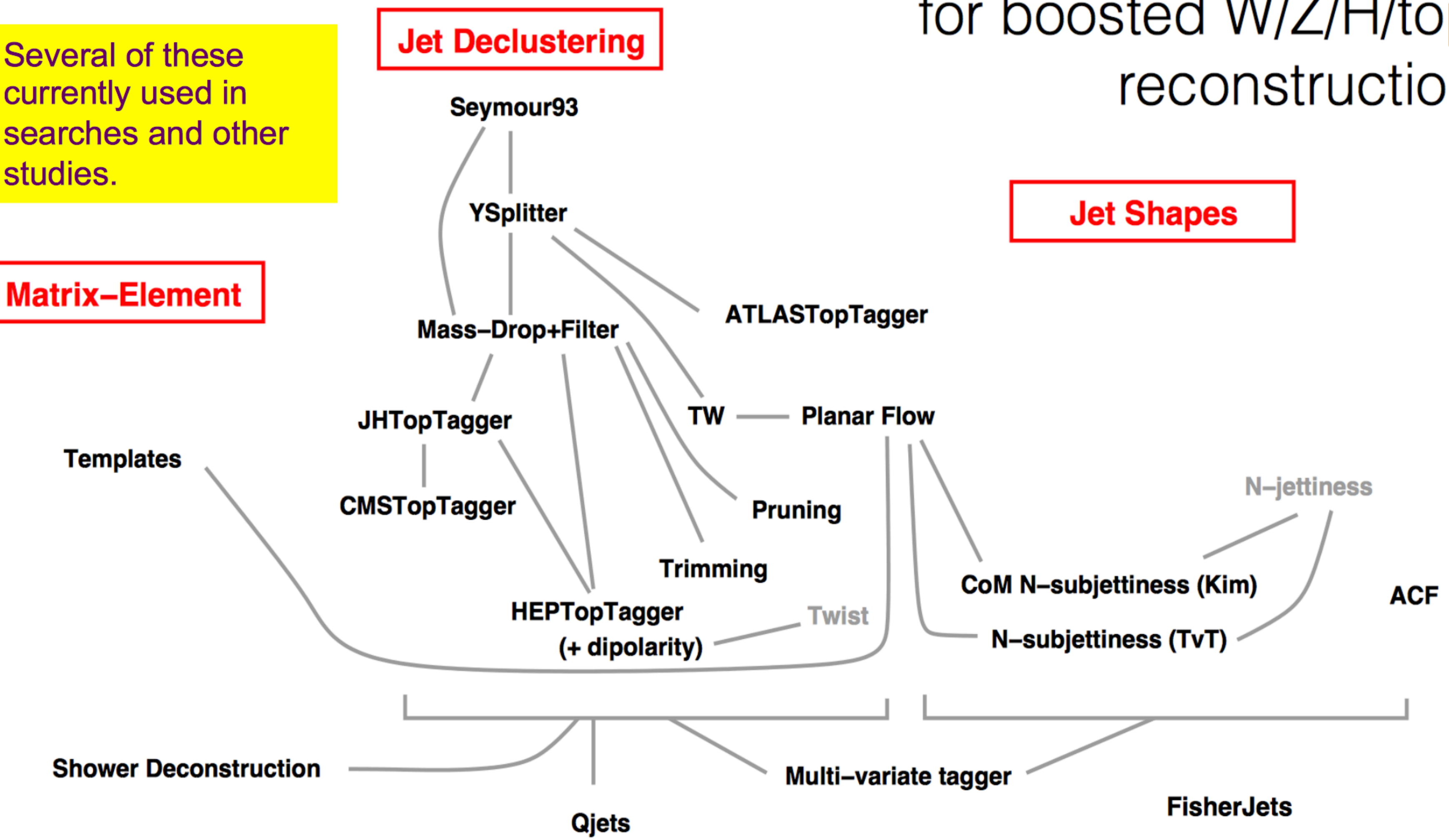
- Colour singlet nature of W/Z/H suppressing soft large angle radiation.

Pioneering work in 1991 by Seymour and 2008 by Butterworth, Davison, Rubin and Salam

Lots of tools

Some of the tools developed for boosted W/Z/H/top reconstruction

Several of these currently used in searches and other studies.



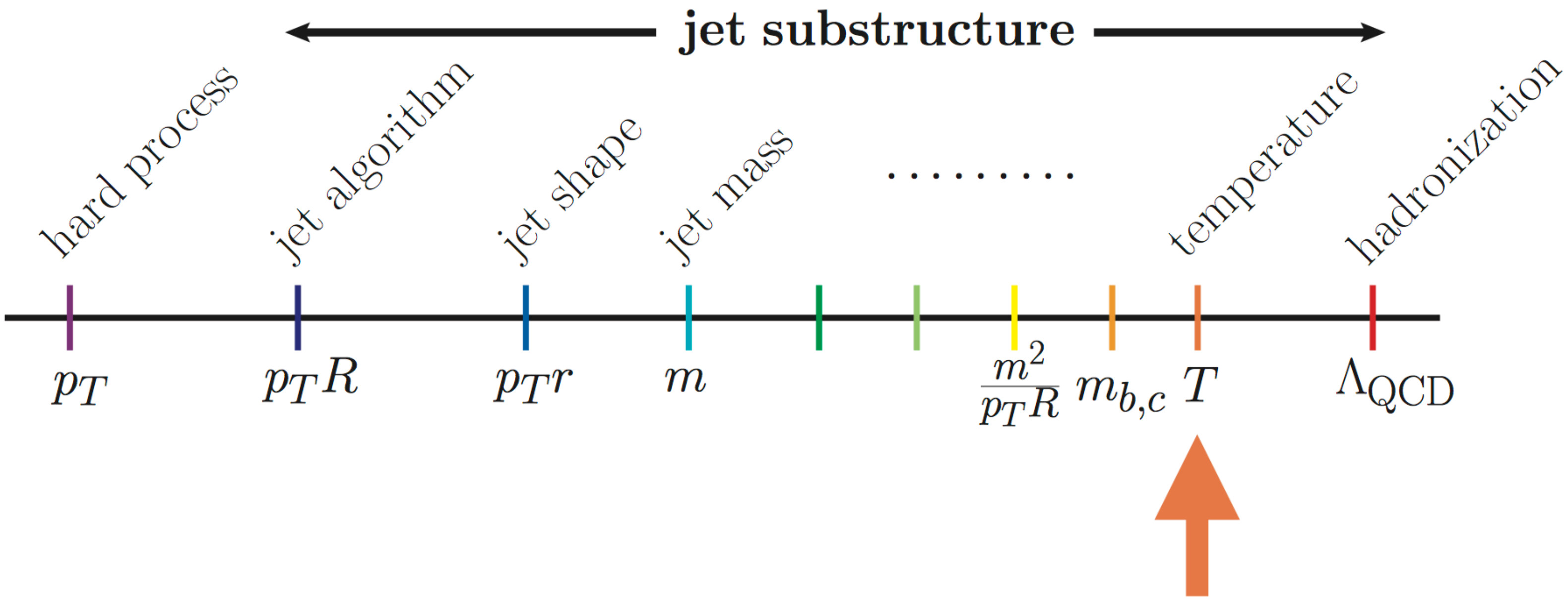
Open questions

- Why so many tools to exploit a few physics principles?
- Do we understand the physics behind tool performance?
- How robust are various tools? E.g. does performance change with kinematics and parameters?

How to decide which tools to use in searches and data/theory comparisons? Look to guidance from theory?

Theory Issues

A multiscale problem



Taken from talk by J. Thaler at Boost 2017

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Large logarithms

Higher order pQCD calculations are standard way to obtain better precision but are not used here.

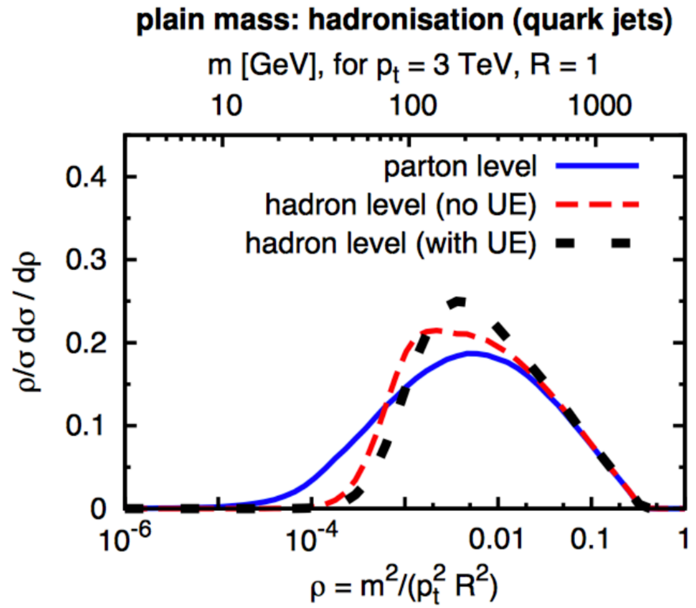
$$\frac{1}{\sigma}\frac{d\sigma}{dm_j^2} \sim \frac{1}{m_j^2}\frac{C_i\alpha_s}{\pi}\ln\left(\frac{R^2p_t^2}{m_j^2}\right)$$

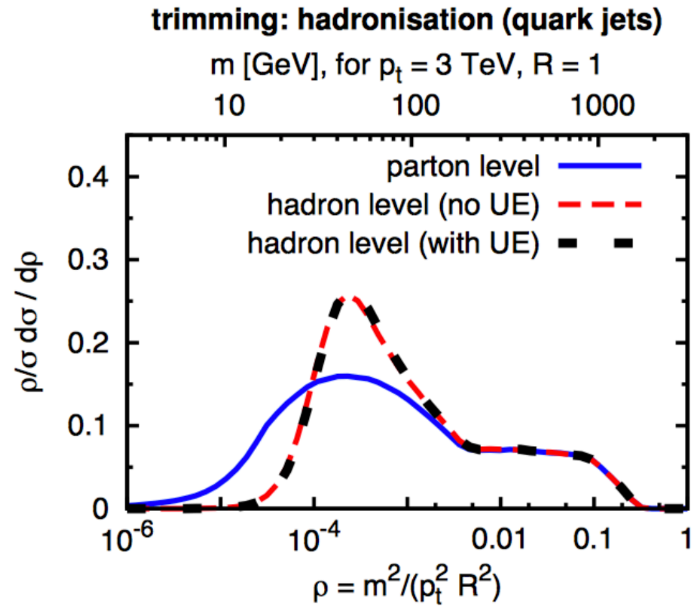
$p_t >> m_j$

Affect convergence of perturbation theory

- Large logarithms in boosted regime. Fixed-order is of limited use.
- Parton showers offer a limited accuracy resummation of logarithms.
- More precise analytic resummation now possible for some observables e.g. mMDT/SoftDrop jet masses.

Non-perturbative effects





Are these important in the TeV region? Consider that a 1 GeV gluon inside an R=1 3 TeV jet can produce a jet mass of 55 GeV.

$$m_j^2 \sim \Lambda p_T R^2$$

NP bumps visible but where NP = Non-Perturbative!

Models for hadronisation and UE but no first principles theory.

Main approaches

- Develop substructure taggers using rough intuition and study performance with **Monte Carlo methods.**

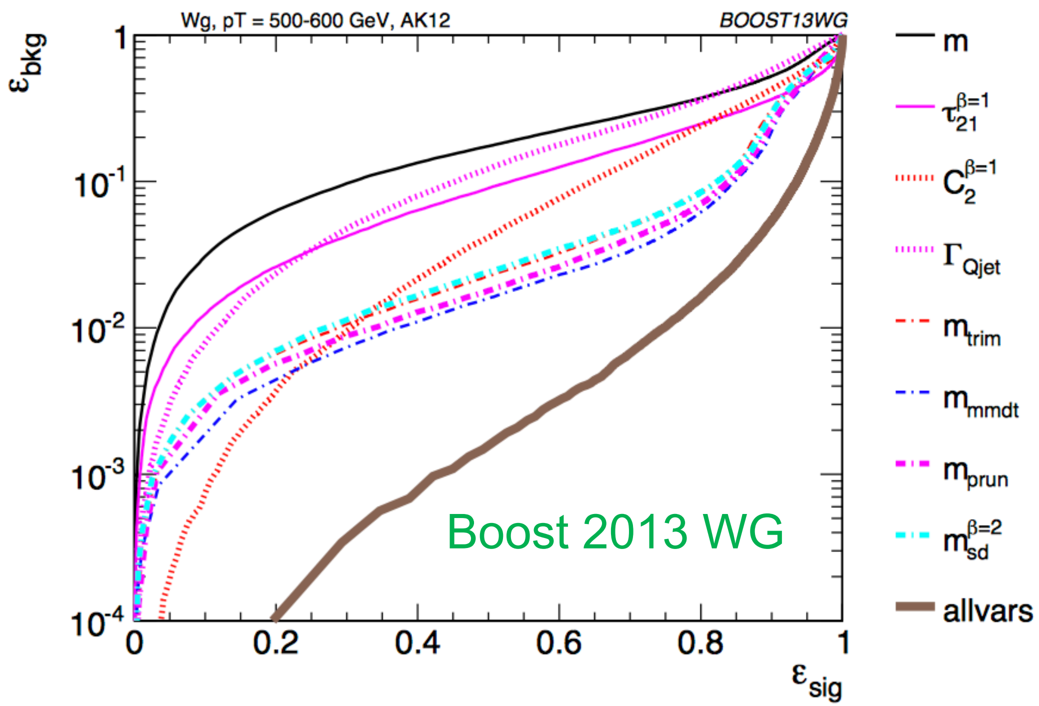
- Look for some guidance from perturbative QCD theory - **analytic resummation**.

- Exploit recent advances **in machine learning** to develop more performant tools.

All offer advantages but its crucial to recognise the limitations in each case.

Performance in MC studies

Imagine these same results with large uncertainty bands



Estimating uncertainties depends on assumptions about shower accuracy. At LL level 50-100% is possible.

Simplest most common approach is to use MC results.
But gives no idea about uncertainties or insight into origin of gains. Complete reliance on MC models.

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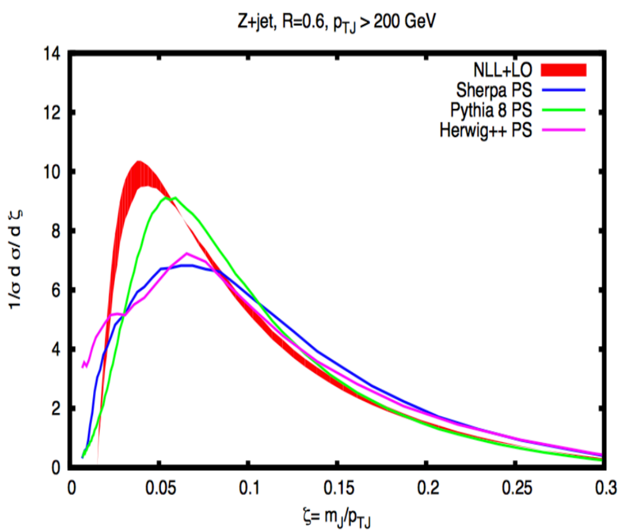
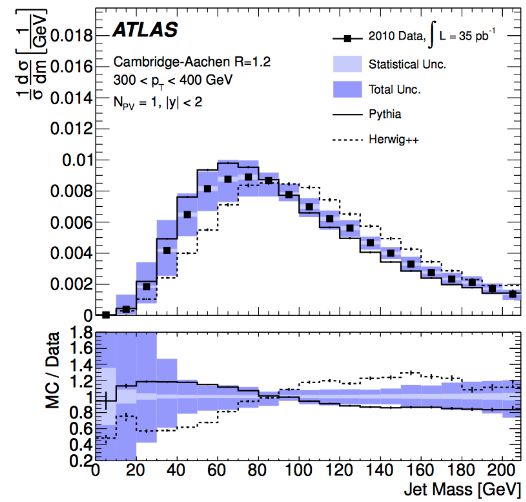
Issues with showers



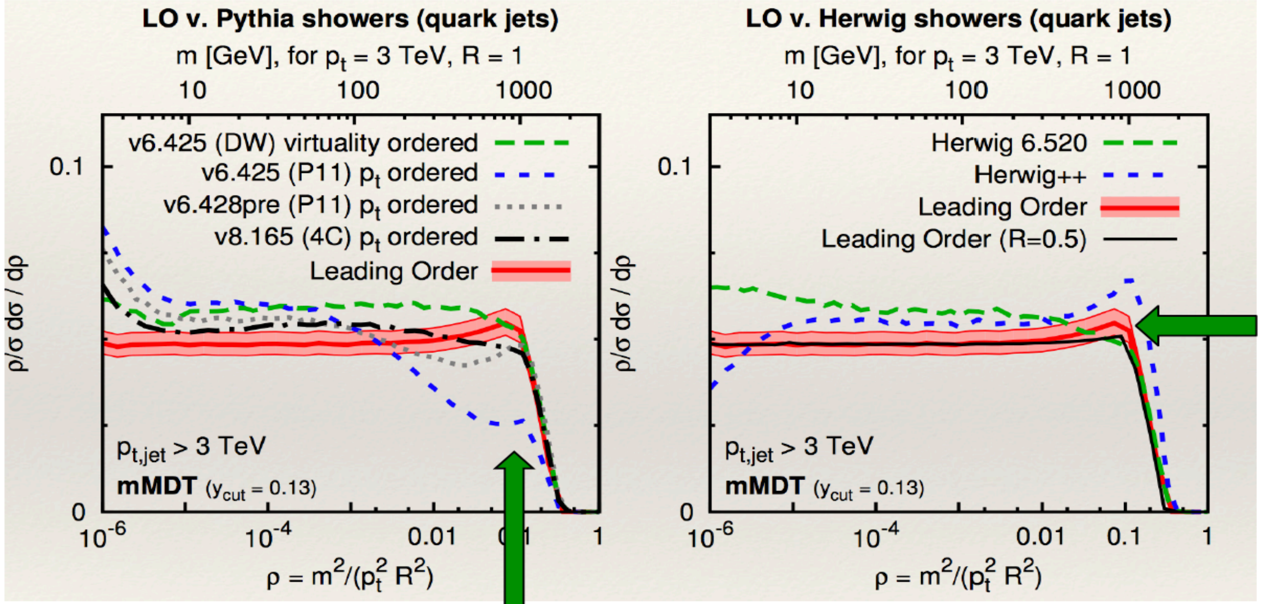
Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky 201



ATLAS collaboration 2012

- Shower predictions often show **a substantial spread**.
- At high p_t > 1 TeV the above differences would be large for 100 GeV or more in jet mass.

Limitations of showers



Bump at larger masses not in most showers

Pythia 6 p_t ordered fails

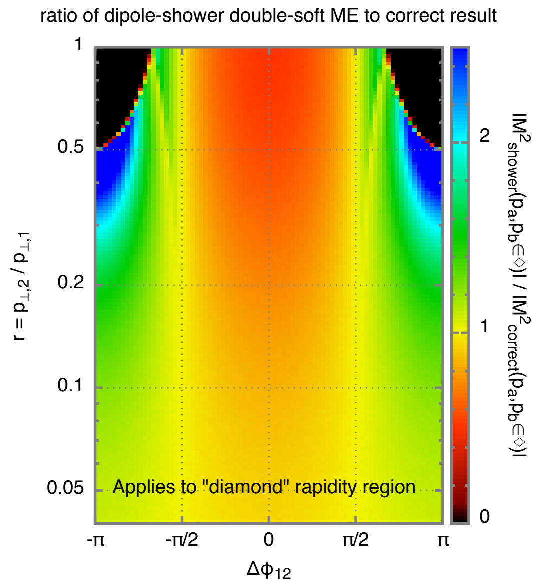
Jet masses with "mass drop" tagger

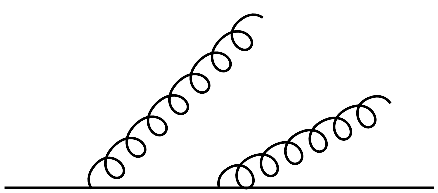
Different MC showers don't always agree.

Showers don't always produce relevant features and can contain flaws.

Shower versus QCD matrix elements

MD, Dreyer, Hamilton, Monni, Salam 2018



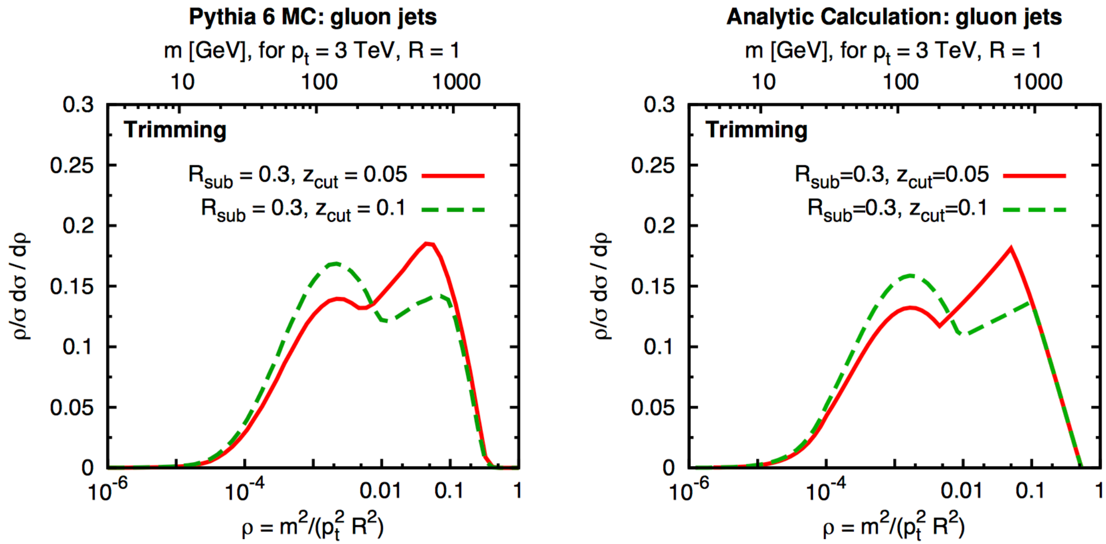


Pythia and Dire Shower two emission matrix element fails to reproduce known QCD results in logarithmically enhanced regions.

A concern for methods that exploit pattern of correlation between emissions e.g. machine learning based approaches?

Jet substructure from analytics

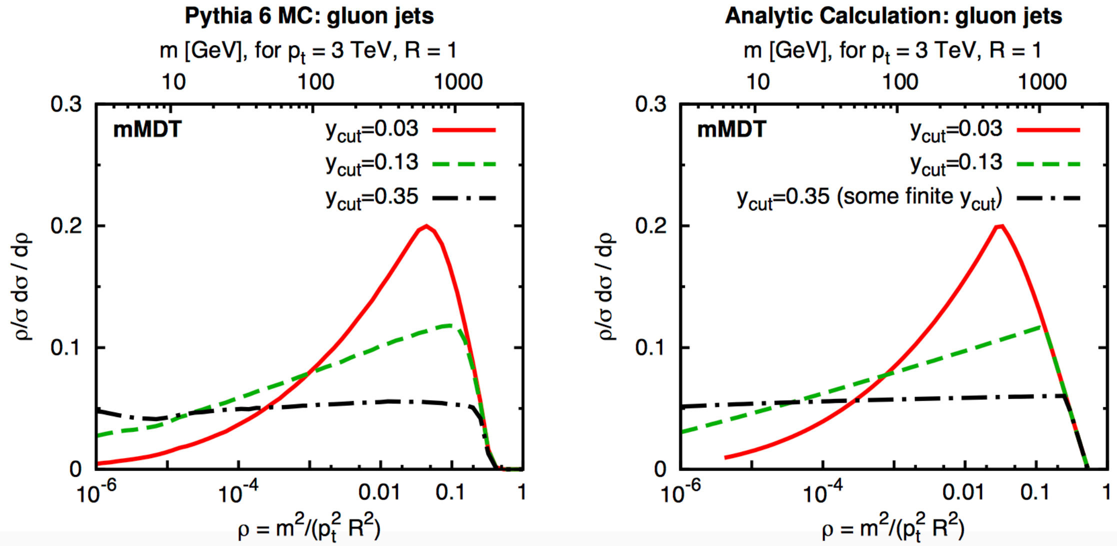
Dasgupta, Fregoso, Marzani and Salam 2013



- Since 2013 analytical calculations for substructure observables developed.
- Based on perturbative QCD resummed calculations.
- Give considerable insight into taggers and their features.

Jet substructure and analytics

Dasgupta, Fregoso, Marzani and Salam 2013



Analytical considerations led to deeper understanding but also development of more robust tools like mMDT/SoftDrop.

- Flat background distribution possible - better for data driven studies.
- High precision (NLL/NNLL) calculations possible for the first time for hadron collider jet masses.

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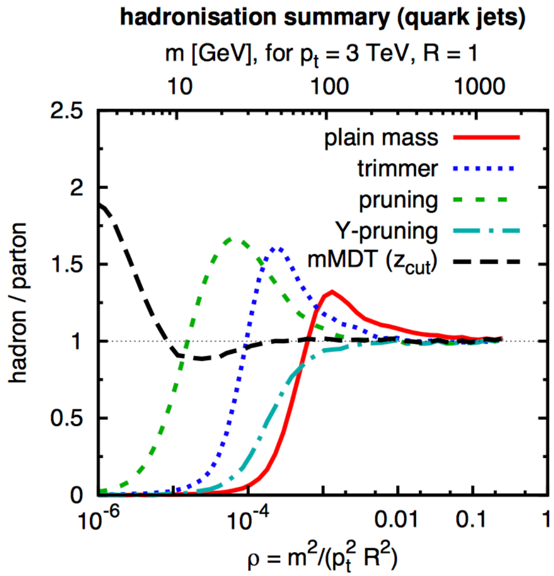
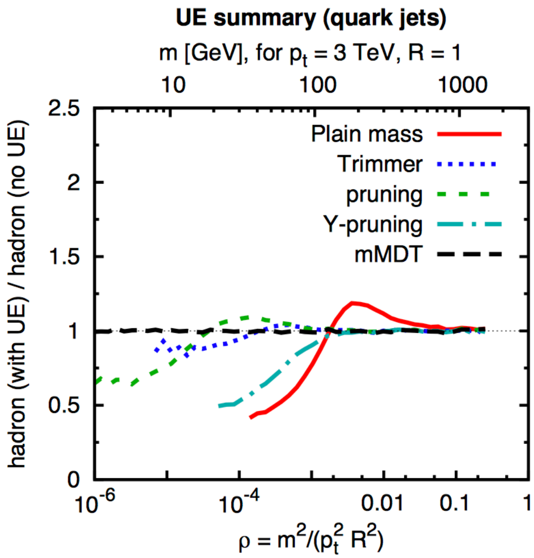
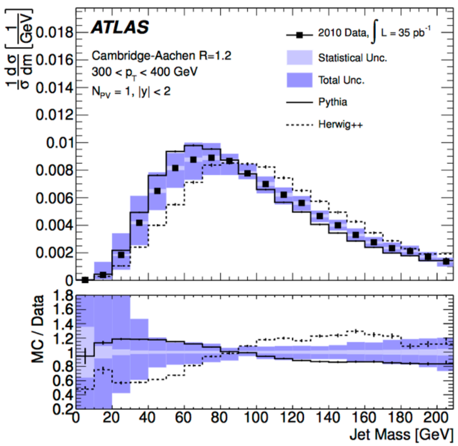
Jet substructure and analytics

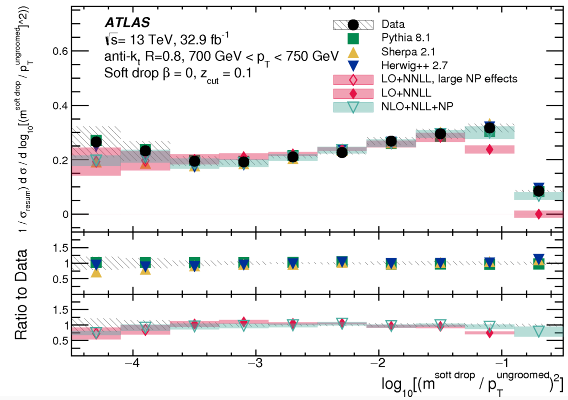




mMDT Soft/Drop **more resilient by design to non-perturbative effects** than e.g. trimming. Theoretical preference for tools like this.

Improved phenomenology for jet observables





Frye, Larkoski, Schwartz, Yan, 2016

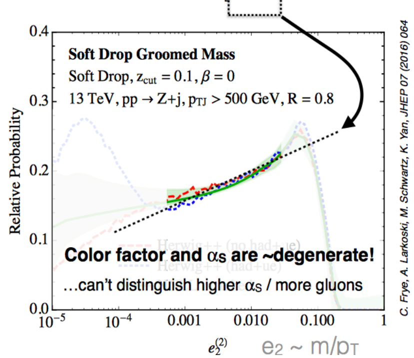
- Now possible to compare data with theory calculations directly for some jet observables.
- **Can still only be done for a few observables**. Important to widen the set of observables in longer term.
- But not an essential prerequisite for all substructure tools e.g. for searches.
- **MC independent analytic studies remain important to design robust tools.**

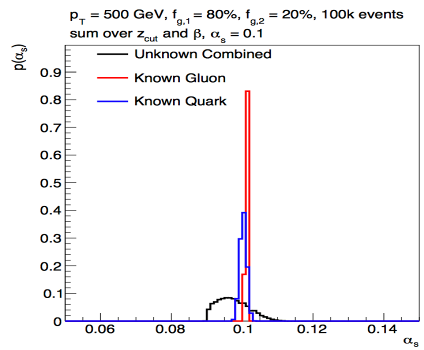
Recent Progress

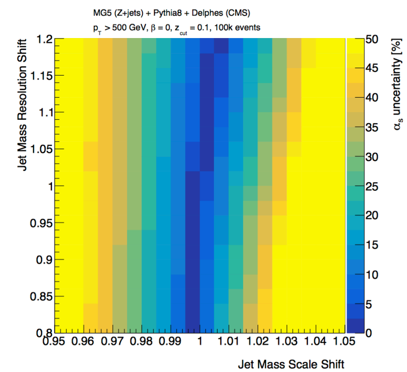
(WITH APOLOGIES FOR MANY OMISSIONS)

Strong coupling from substructure?

$$\frac{e_2^{(2)}}{\sigma}\frac{d\sigma}{de_2^{(2)}} \approx -\frac{\alpha_s C_i}{\pi}\left[\log(z_{\rm cut}) - B_i\right] \exp\left[-\frac{\alpha_s C_i}{\pi}\left[\log(z_{\rm cut}) - B_i\right]\log(e_2^{(2)})\right]$$





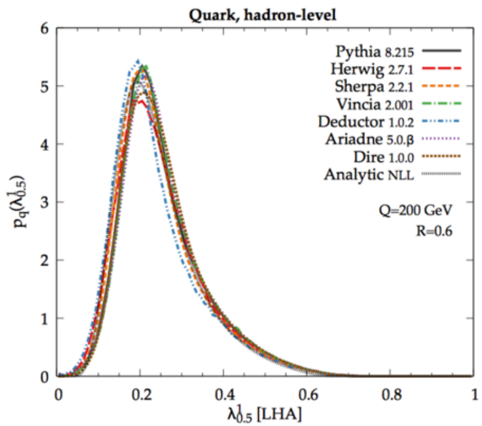


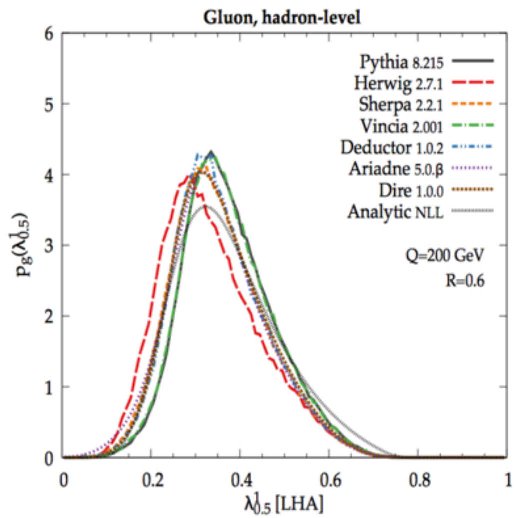
- Can we benefit from the precision calculations, small NP effects and measurements of groomed masses/angularities?
- Limiting factor is leading degeneracy with quark/gluon fraction due to Casimir scaling. Sensitivity to pdfs or need to fit quark-gluon fraction.
- 2017 Les Houches working group conclusion was that extraction of α_s to within ~ 10% is a realistic possibility with current data.

B. Nachman at BOOST 2018

Current world average $\alpha_s(M_Z)$ 0.1183 with ~ 1% uncertainty!

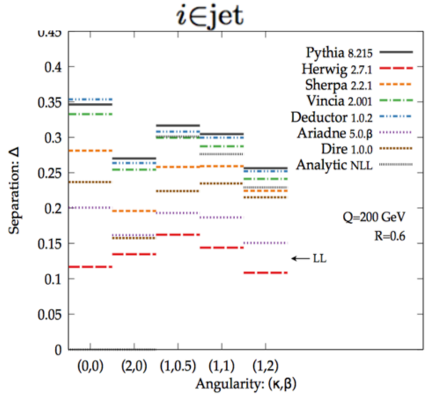
Quark/gluon discrimination





Gras et. al 2017

$$\lambda^{\kappa}_{\beta} = \sum_{i \in \text{jet}} z_i^{\kappa} \theta_i^{\beta},$$



$$\Delta = \frac{1}{2}\int d\lambda \, \frac{(p_q(\lambda) - p_g(\lambda))^2}{p_q(\lambda) + p_g(\lambda)} = 1 - 2\int d\lambda \, \frac{p_q(\lambda)\, p_g(\lambda)}{p_q(\lambda) + p_g(\lambda)}.$$

Focus on LHA with $\kappa = 1, \beta = 0.5$

Wide spread between generators for gluon jets. Call for LHC measurements of angularities to tune event generators and constrain gluon jets.

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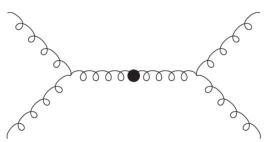
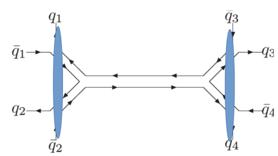
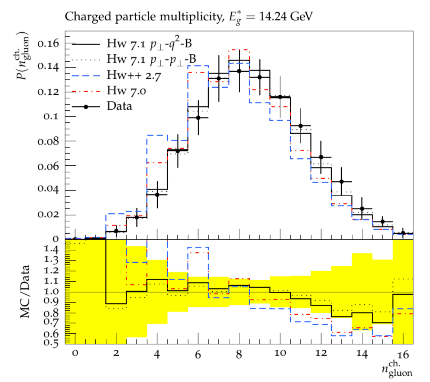
Improvements in HERWIG

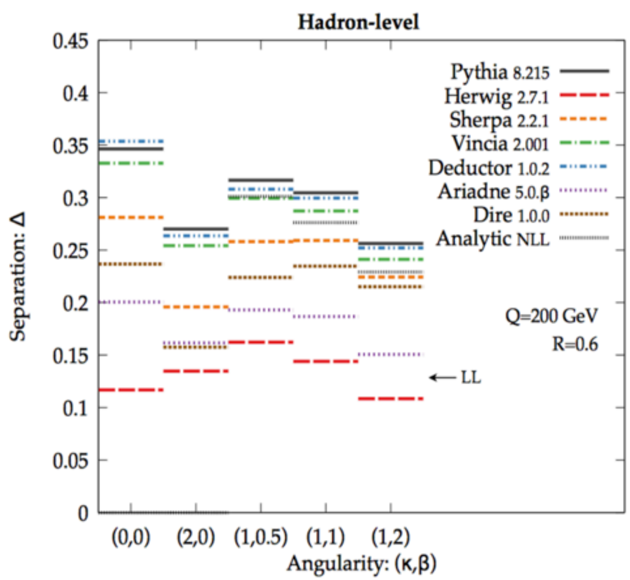


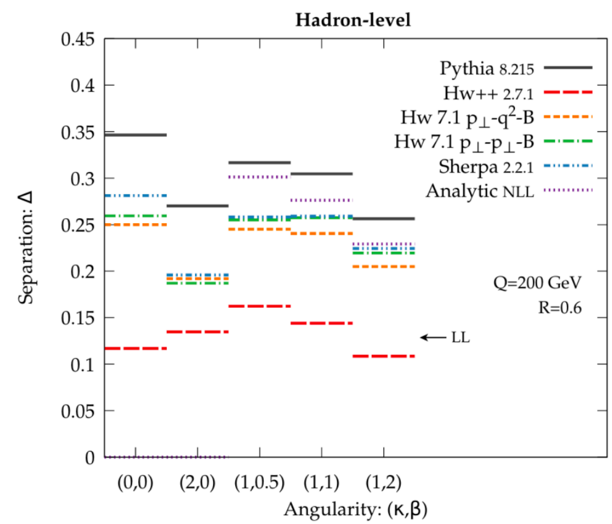


Improved colour reconnection model



OPAL data for gluon jet charged multiplicity. Not used for tuning before!

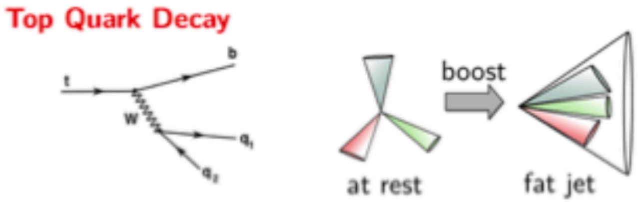




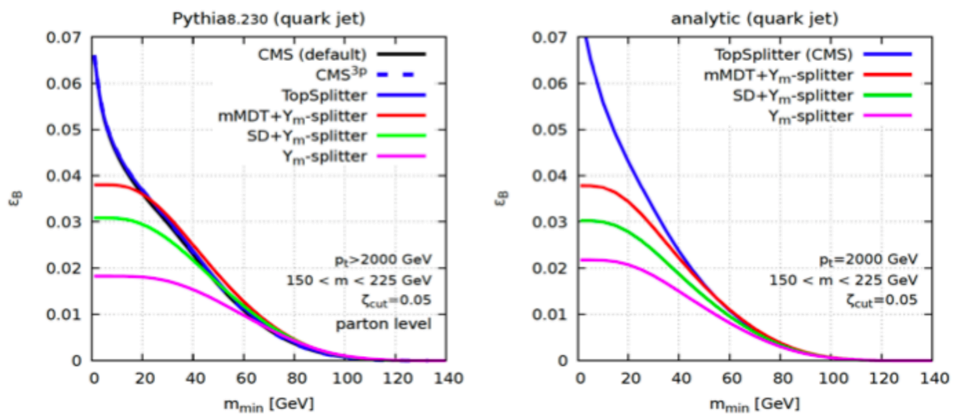
- Herwig is now more optimistic when it comes to distinguishing q/g jets.
- Spread of predictions is reduced.

Richardson, Reichelt, Siodmok 2017

Analytics for top tagging



Dasgupta, Guzzi,
Rawling and Soyez 2018



Recent progress showing CMS tagger is IRC unsafe and designing new method TopSplitter

Three pronged substructure and coloured signal. Harder problem than W/Z/H. **Can we get analytical control?**

Analytic understanding excellent for top taggers on background jets. Also reasonable for signal jets but some improvements possible.

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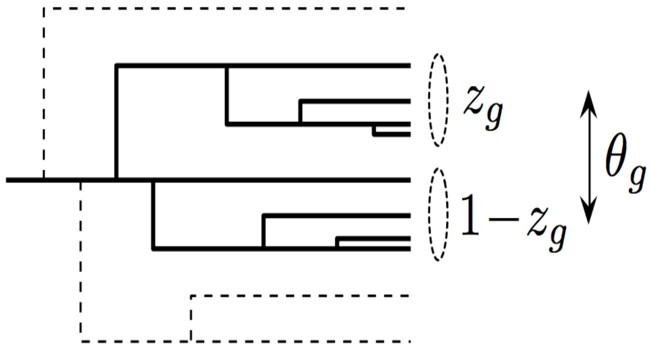
Extending theory reach?



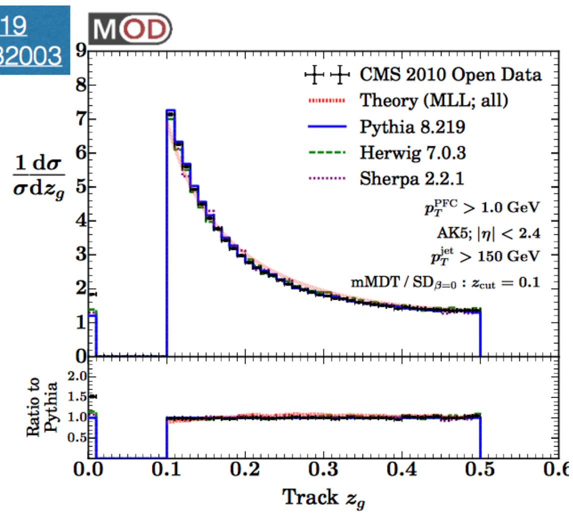
$$z = \frac{\min(p_{t,i}, p_{t,j})}{p_{t,i} + p_{t,j}}$$

Decluster until find

$$z > z_{\text{cut}}$$

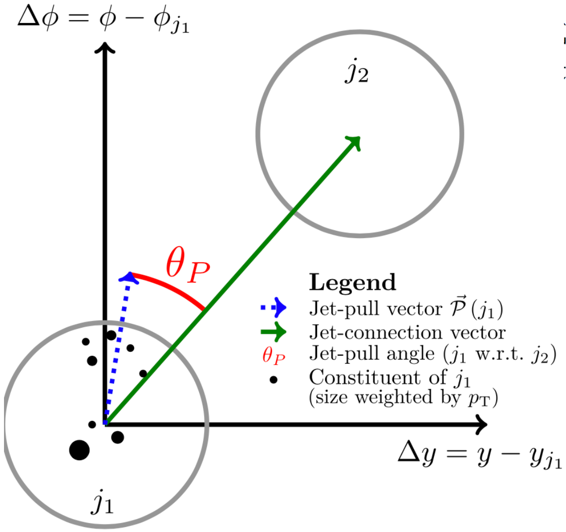
Applies to mMDT/SoftDrop jets.

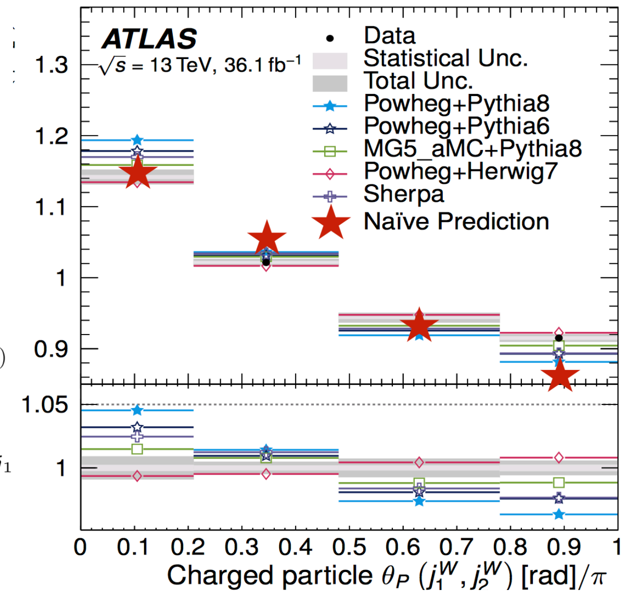
PRL 119 (2017) 132003



Collinear unsafe but Sudakov safe observable. Resummation produces finite result. Do we understand corrections and uncertainties?

Extending theory reach?





Steeper than data

Shape will change with:

Running coupling

Soft wide angle is more likely than hard collinear

Convolving with W boost

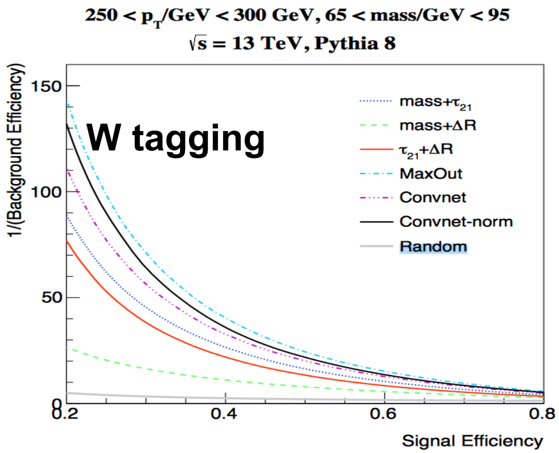
θ_{12} isn't fixed
Higher boosts = smaller θ_{12}
= closer subjets

arXiv: 1001.5027, 1805.02935
see also: 1506.05629

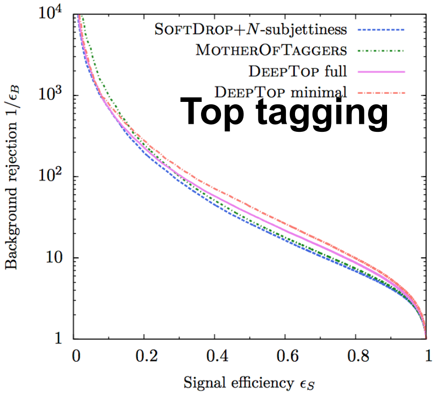
Presented by A. Larkoski at Boost 2018

Pull angle as measured by ATLAS. IRC unsafe but Sudakov safe variable. First theory results emerging. **But still work to do.**

Deep learning methods



De Oliveira, Kagan, Mackey, Nachman, Schwartzmann 2016



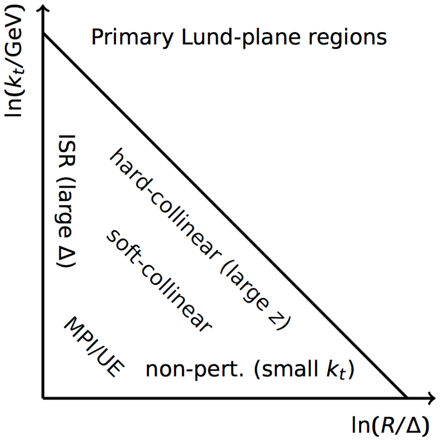
Kasieczka, Plehn, Russell. Schell 2016

- **Very active area. Perfect playground for ML approaches**. Wide range of methods used
- Often **substantially better than manually constructed observables** for performance
- Do we pay a price? **What features are learnt? Are they well modelled by showers, detector simulations?**

Learning from the Lund plane

Lund diagrams in the $(\ln z\theta, \ln\theta)$ plane are a very useful way of representing emissions.

Dreyer, Salam, Soyez
2018



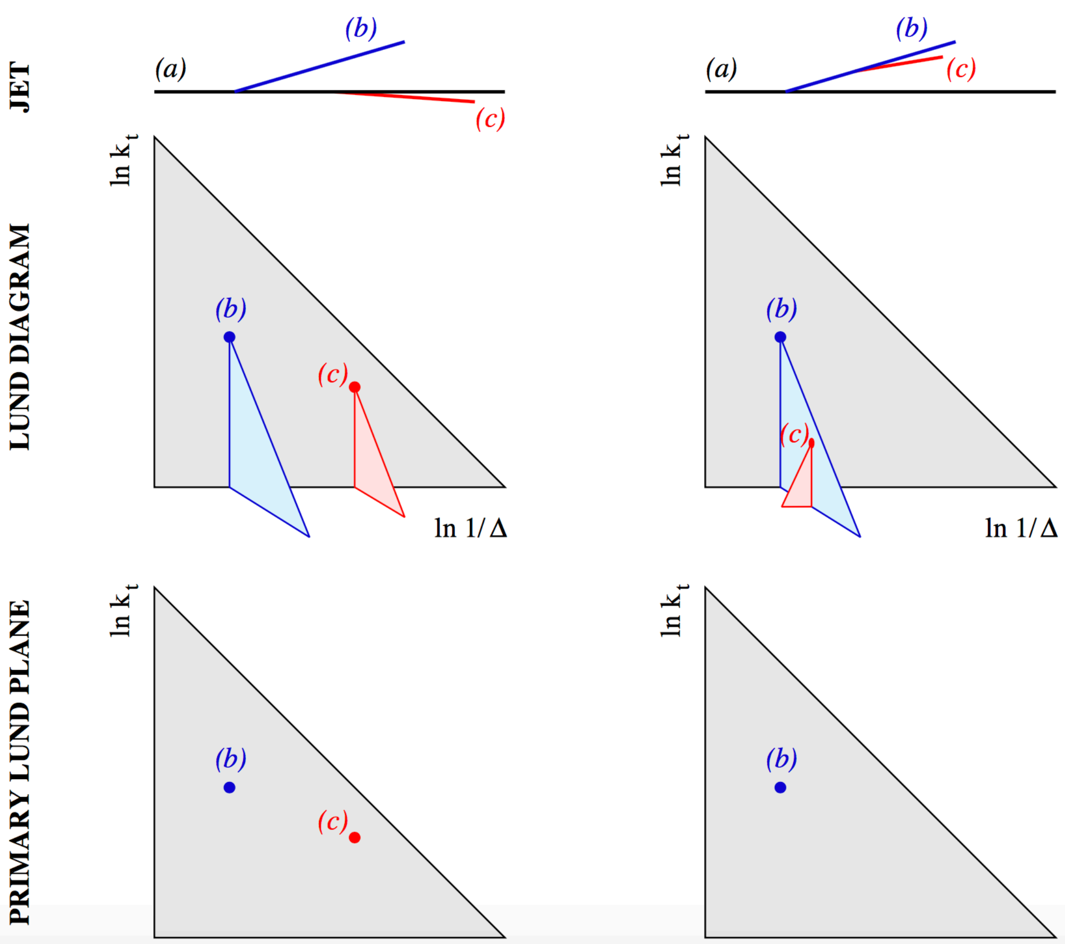
Separation of different physics effects inluding non-pert.

Density of emissions in primary Lund plane well understood theoretically.

At the heart of analytic approaches and parton showers. Can be used as an input to ML.

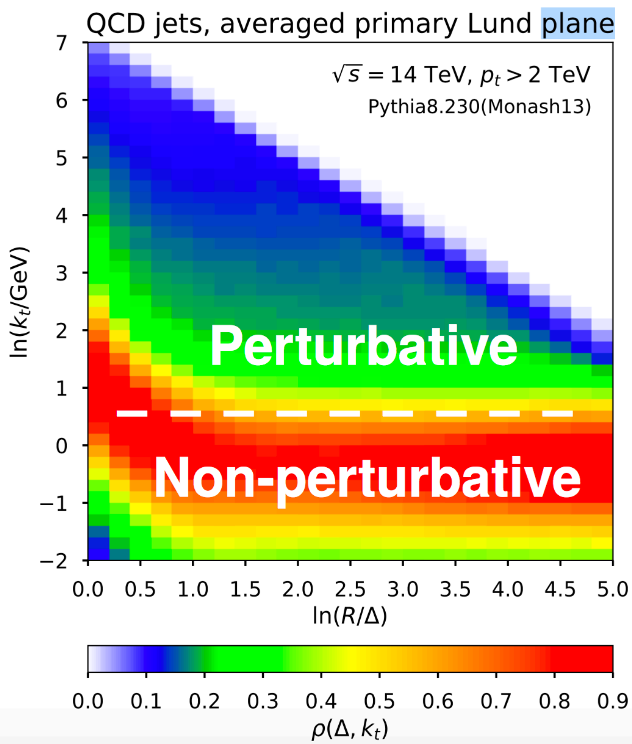
Bridges the gap between Deep learning and “Deep thinking” approaches?

Learning from the Lund plane



Dreyer, Salam, Soyez, 2018

QCD jets in Lund plane



Dreyer, Salam, Soyez, 2018

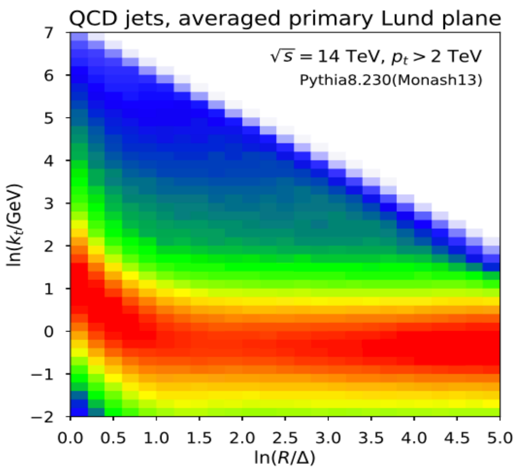
ln(k_t/GeV)

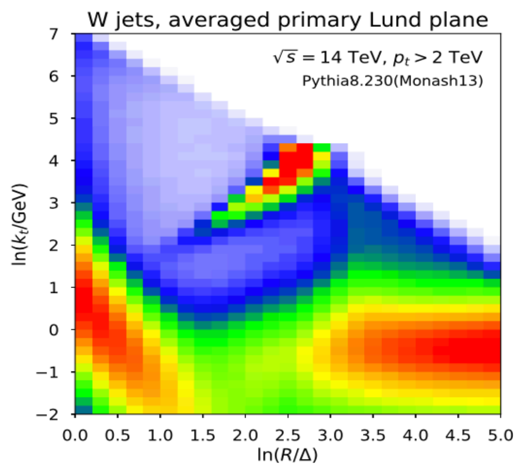
In the soft collinear region

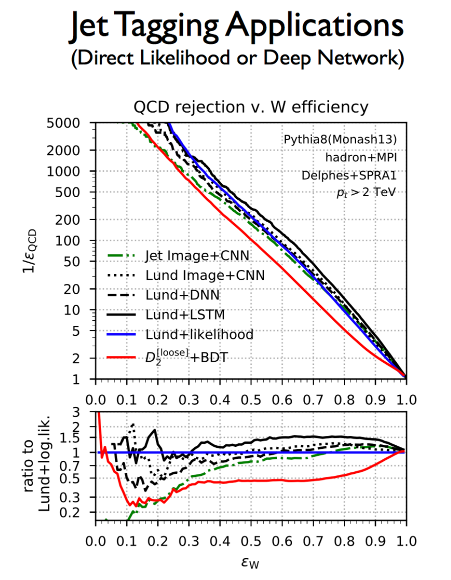
$$\rho \sim 2C_F \frac{\alpha_s(k_t)}{\pi}$$

Well understood theoretically. Applications include constraining event generator models, input to machine learning, manually designing optimal observables and direct measurements

W tagging







Used both log-likelihood and machine learning approach.

Dreyer, Salam, Soyez, 2018

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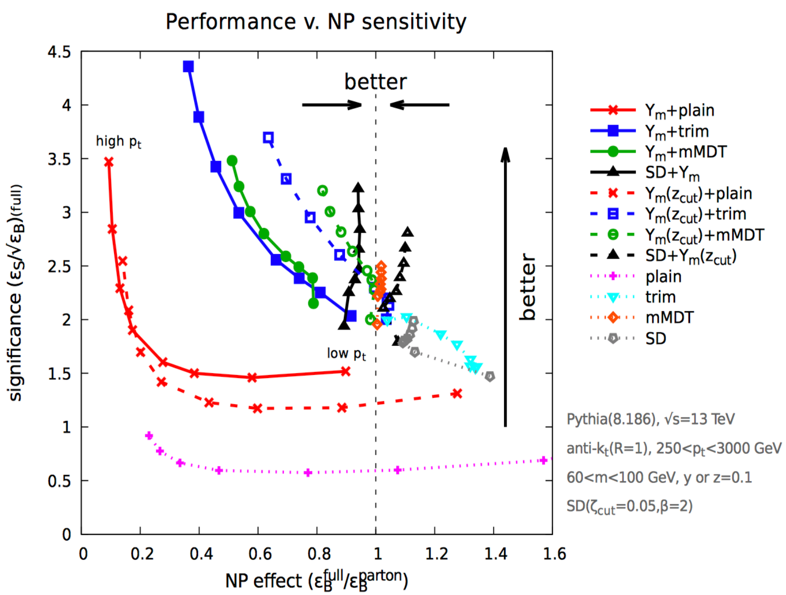
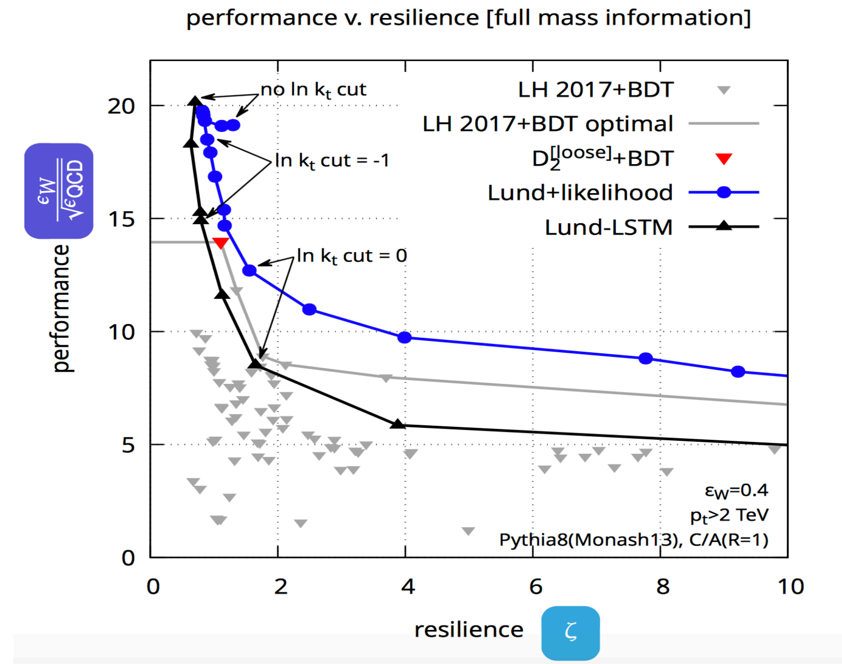
Final thoughts : performance v resilience



Dasgupta, Powling, Schunk, Soyez 2016



Dreyer, Salam, Soyez, 2018

To what extent do we want to rely on our knowledge of QCD at 1 GeV for TeV scale physics?

Prospects

We **need** and should look forward to

- **Further improvements in Monte Carlo event generators** (more about MC in Keith's talk).

- **Widening the scope of analytic calculations** both for precise comparisons to data but also for understanding and developing new tools.

- **Continued exploitation of machine learning advances** potentially with input from theory insight.

- **Experimental measurements** to support all of the above will be critical.

Note also crucial exploitation of jet substructure in heavy-ion collisions : reviewed in arXiv 1808.03689