Jet substructure topics

Les Houches 2023

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Jets@LesHouches

Jet studies at Les Houches has been very productive!

1. **LH15** featured a systematic studies of q/g discrimination exploiting MC studies of angularities
   a. limitations in modelling gluon radiation were discovered
   b. follow-up study featured analytic predictions as well
2. **LH17** concentrated on two aspects of jet substructure
   a. measurements & precision: towards strong coupling extraction
   b. more reliable tools: understanding performance and robustness
3. **LH19** the gluon turns 40: studies across four decades in energy
   a. Non-perturbative corrections to jet mass distribution and tuning
   b. ML to probe higher-order effects in parton showers
   c. q/g tagging in VBF/VBS
   d. Tagging gluon PDFs at high *x*.

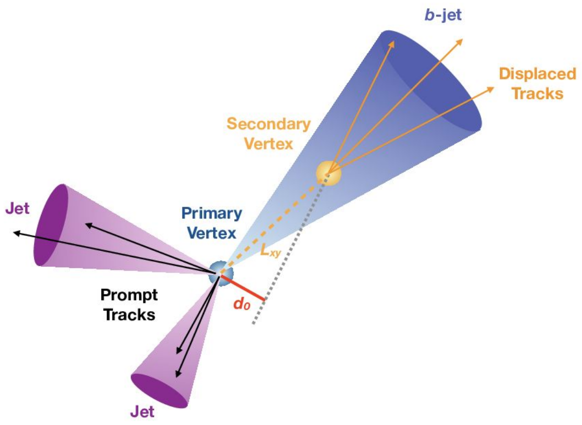
Some ideas for Jets@LesHouches 2023

1. **Heavy flavour jets**
2. **Jet substructure measurements, modelling, uncertainties**
3. **Jet substructure modeling and machine learning**

ÉCOLE DE PHYSIQUE DES HOUCHES

Heavy Flavour Jets

- jets containing heavy flavours (charm and beauty) are central to the LHC Higgs program
- important for QCD studies too: PDFs, fragmentation etc.
- they are identified exploiting B hadron lifetime: displaced vertices
- from theory viewpoint, m_b & m_c set perturbative scales: high accuracy (NNLO) QCD calculations Z+b/c jet now exist

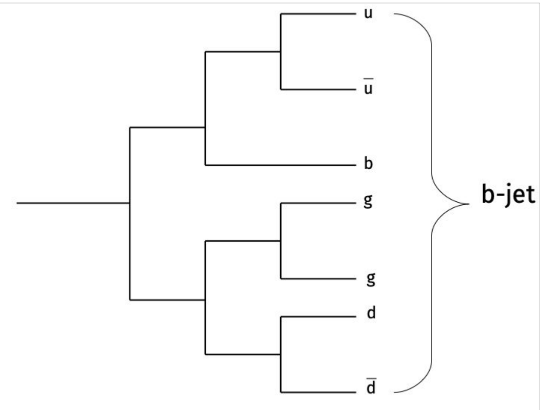


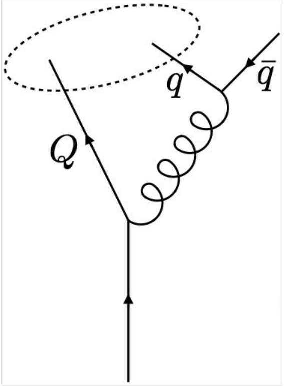
Experiment vs Theory

- Experimental procedure:
  - cluster jets using the anti-k_t algorithm
  - run *b* (*c*)-tagging

- Theory calculation:
  - compute real and virtual
  - cluster jets using an IRC safe (flavour) algorithm

BUT counting the flavour of an anti-k_t jet is NOT IRC Safe beyond NLO!





splitting of a soft gluon can affect jet flavour

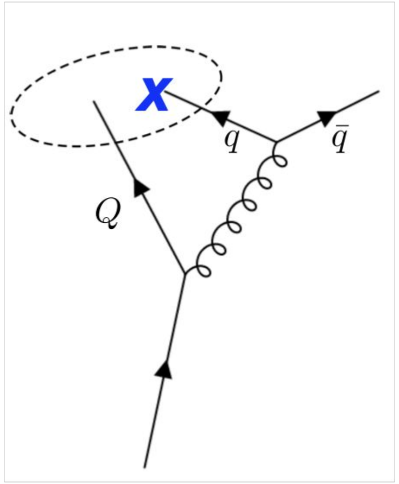
Banfi Salam Zanderighi (2006)

BSZ flavour algorithm

- flavour-sensitive metric that reflects the absence of soft quark singularities
- it is IRC safe because it tends to recombine together the problematic soft pair
- however the use of BSZ in experimental analysis is far from straightforward:
  - obviously, it’s not anti-k_t
  - it requires knowledge of the flavour at each step of the clustering
- Comparison between theory and experiments requires to unfold the experimental data to the theory calculation performed with BSZ
- it would be better to identify a common procedure in order to avoid this unfolding step

3+1* new ideas in the past year

- use Soft Drop to remove soft quarks

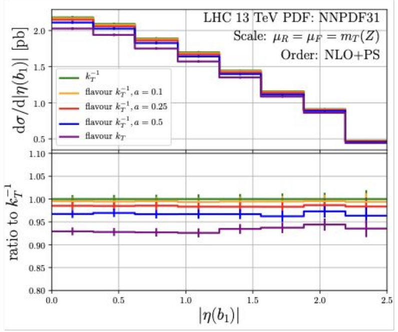


- needs JADE as reclusters, known to fail at three loops

Caletti, Larkoski, SM, Reichelt (2022)

- define a flavour algorithm that resembles anti-k_t

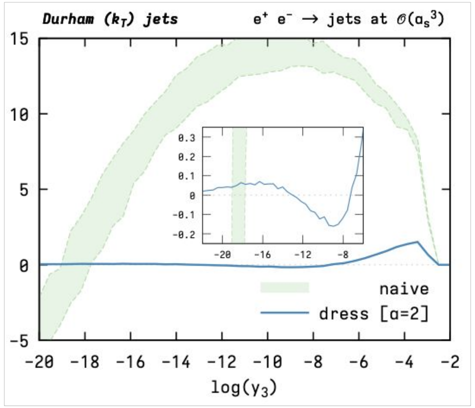
$$d_{ij}^{(F)} \equiv d_{ij} \times \begin{cases} \mathcal{S}_{ij}\,, & \text{if both } i \text{ and } j \text{ have non-zero flavour of opposite sign,} \\ 1\,, & \text{otherwise.} \end{cases}$$



- flavour-dependent metric, still needs some (small) unfolding

Czakon, Mitov, Poncelet (2022)

- construct a flavour dressing for a given jet



- needs flavour information of many (all?) particles in an event

Gauld, Huss, Stagnitto (2022)

** Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2023)*

Proposal for a Les Houches study

- Les Houches provides us with a unique opportunity to compare and validate these new algorithms
- Questions we can try and answer
  - IRC safety … to which order?
  - Behaviour in PS and sensitivity to hadronisation effects
  - Interplay between what can be computed and measured: unfolding etc
  - Kinematic properties: similarities and differences wrt to standard anti-kt jets
  - Can such algorithms be used to defined “gluon->bb” or H->bb jets? In experiment we identify jets containing two b-hadrons and use them as calibration sample for double-b-taggers.
  - Can such algorithm distinguish also “gluon” jets from “quarks” (one ”flavour” to rule them all)?
  - …

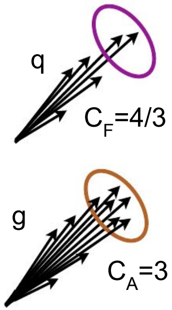
Jet substructure physics

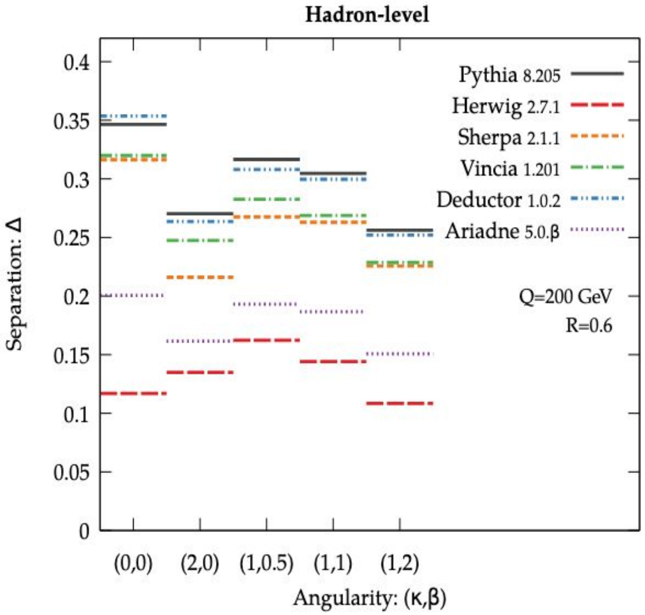
- Physics with jet substructure measurements
  - Precision tests of QCD: Softdrop jet mass with NLO+NLL+NP, …
  - Properties of QCD: QGP, Dead cone effect, …
  - SM parameters: AlphaS, top quark mass, EFT, …
- Physics enabled by good jet substructure modelling
  - Training of neural networks to identify jets from q/g/b/W/Z/H/top
  - Higgs physics: boosted H pT, kappa2V with H(bb)-tagging, VBF with q/g-tag …
  - BSM searches: Z'/X → WW/HH/tt, VBF, …
  - Gluon PDF measurement with quark/gluon tagging (idea)
- Over the past years huge development to better exploit jet substructure
  - Better detector reconstruction/calibrations/uncertainty
  - Better observables
  - Better calculations and MC techniques
- Opportunity at Les Houches: Take stock of developments quantitatively and develop recommendations

Jet substructure of quark/gluon jets: modelling

- Les Houches 2015 study of quark-gluon systematics: https://arxiv.org/abs/1605.04692

  Large spread in predicted discrimination power of quark/gluon discriminating observables, many generator features studied





Angularities

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$$

$$z_i \equiv \frac{p_{Ti}}{\sum_{j \in \text{jet}} p_{Tj}}$$

Jet substructure of quark/gluon jets: measurements

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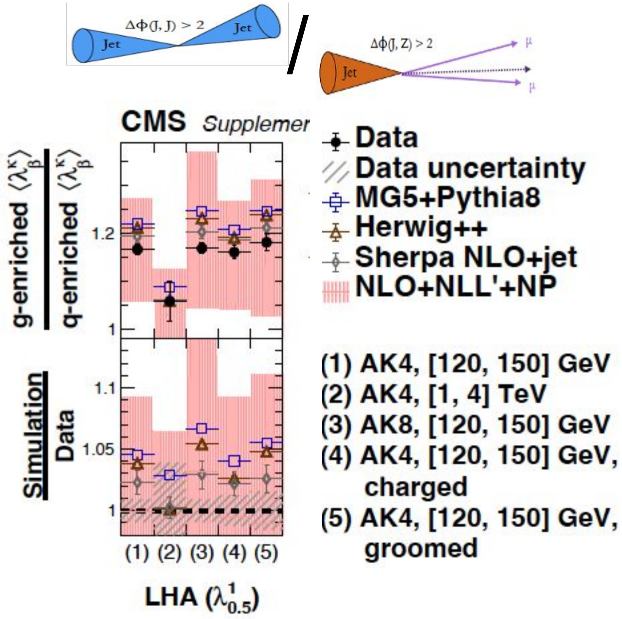
- Since then, many new measurements (and generator developments): LHCJetSubstructureMeasurements



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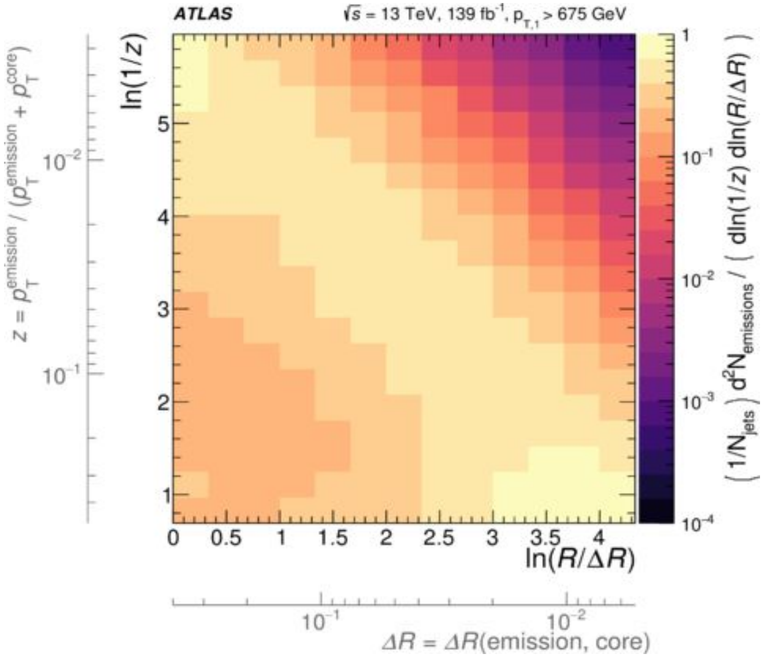

[2004.03540]

Jet substructure of quark/gluon jets: machine learning

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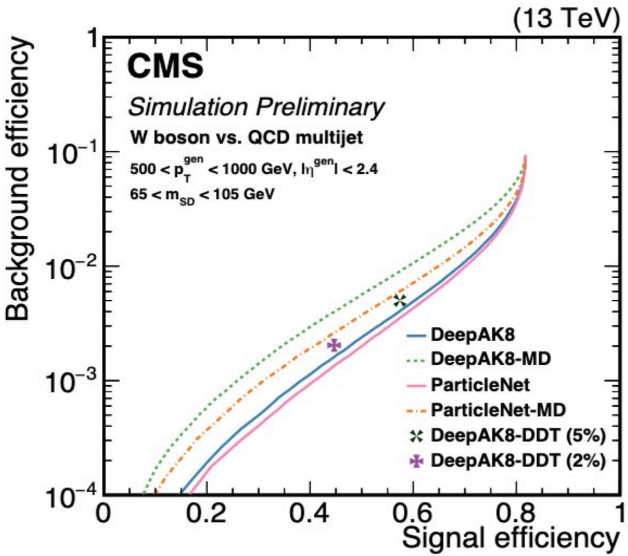
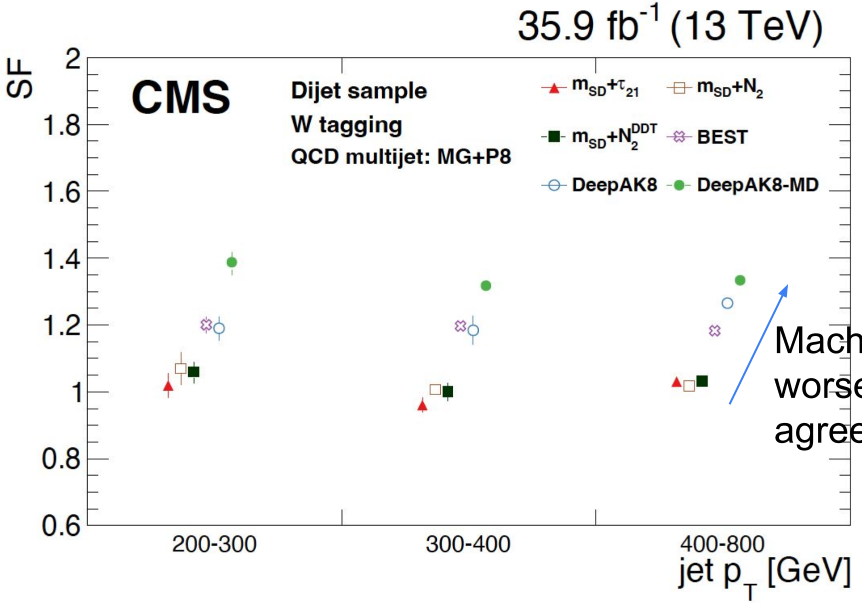
  Large spread in predicted discrimination power of quark/gluon discriminating observables, many generator features studied
- Since then, many new measurements (and generator developments): LHCJetSubstructureMeasurements
- Experiments use ML-based jet taggers (quark, gluon, bottom, charm, W, Z, H, top), partially correlated with measured jet substructure observables.



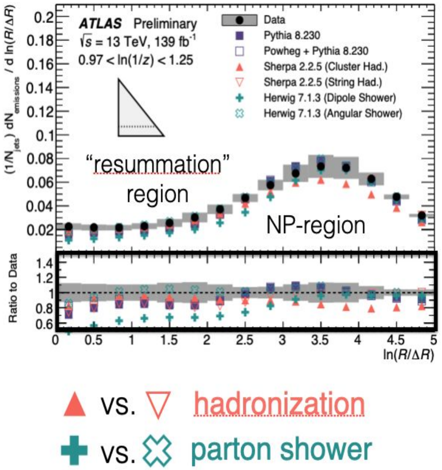


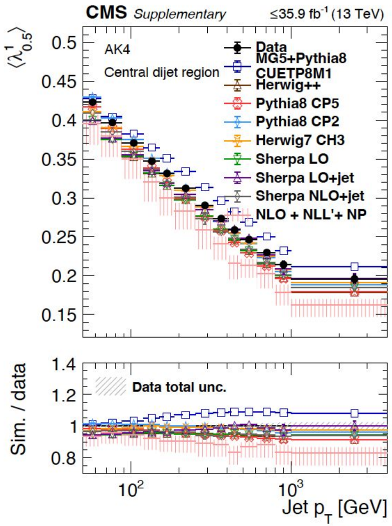
Machine learning worsens data/MC agreement

Jet substructure measurements and modelling

Questions for discussion/study:

- How well do the most recent generators and shower/hadronization models perform at describing these measurements? How compared to the CMS/ATLAS/ALICE/LHCb “defaults”?
- Do measurements of different sets of observables (e.g. Lund plane vs. angularities) give a consistent picture?
- What pp generator setups give a good description of quark/gluon discrimination power?
(resolving the large spread among generators and data/MC disagreements observed in the past)





5 recent measurements in Rivet (out of many more):
CMS_2021_I1920187 angularities in Z+jet and multijets
ATLAS_2020_I1790256 lund plane in multijets
ATLAS_2019_I1772062 softdrop observables in multijets
ATLAS_2019_I1740909 jet fragmentation observables
ATLAS_2019_I1724098 jet substructure observables in ttbar, multijets
CMS_2018_I1690148 jet substructure observables in ttbar

Jet substructure measurements and modelling

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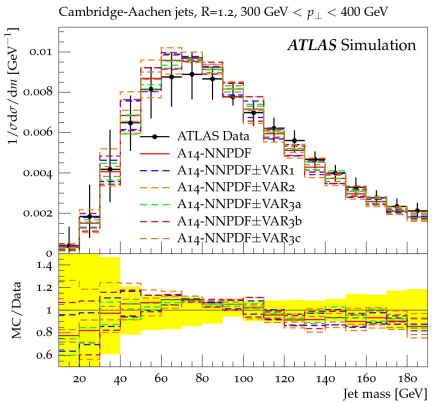
  (resolving the large spread among generators and data/MC disagreements observed in the past)
    - Related: Important ingredient to measuring quark/gluon jet substructure: quark/gluon composition in dijet, Z+jet, ttbar
      To what extend fixed-order prediction of sample composition limits understanding of quark/gluon discrimination measurements?
    - Related: Can we turn this around and measure gluon PDF making use of precise prediction of q/g jet substructure?

- How to deal with remaining data/MC disagreements?
    - Can recent generator development improve agreement?
    - Tuning of MC generators to match jet substructure observables (without destroying other observables)?
    - Lund-plane-reweighting?
    - Carry out a new measurement?



Jet substructure uncertainties

Questions for discussion/study:

- Recommendations for uncertainties on shower/hadronization models describing jet substructure?
    - Best sets of variations of shower/hadronization-models/parameters? (Not just Pythia/Herwig)
    - Go away from “conservative envelopes” to reduce uncertainties to match statistics/precision of LHC?
    - How to incorporate the bounds from existing jet substructure measurements? Exclude variation not matching the measurements? Can we reduce variations in phase-space/samples covered by measurements? (an example is scale-variations, where our constraints from data are sometimes stronger than the factor 2 variations, but sometimes the opposite)

Jet substructure and machine learning

Questions for discussion/study:

- How much state-of-the-art ML-taggers are correlated to the observables/phasespace in the measurements of substructure we already have?
- How to deal with the uncertainty on the part not-obviously correlated with well understood observables?

Interested in these topics?

- if you have other ideas for projects, they are more than welcome!
- out of the list just presented, some topics are very “jetty”, other ones can naturally be of interests for MC, PDFs, ML experts,
- experience teaches us that the best strategy for LH is to concentrate on a couple of projects
- this way can have enough people to actively work here in LH and make good progress
- details and refinement can be done after, if we want to publish a write-up, but we think it is crucial that we leave LH already with a good story to tell

Interested in these topics?

Join the slack channels!

flavoured-jets

jss-measurements

jss-and-ML

¡boostamos!