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Jets ~~and Heavy Flavour~~ Physics in the vacuum and in the medium

Matteo Cacciari

LPTHE Paris
Université Paris Diderot

Jets can be a golden observable to study the properties of the vacuum and of the medium

- Hard probes
- Huge kinematic range
- Definable at will*
- Calculable*
- LHC detectors highly optimized for their measurement
- Plenty of measurements and calculations, both in pp and in HI collisions

General advice

Very recent 1705.01974:

Review of Jet Measurements in Heavy Ion Collisions

Megan Connors, Christine Nattrass, Rosi Reed, Sevil Salur

I strongly urge the reading of at least its

"Section IV. Discussion and the path forward"

Selected quotes from 1705.01974

*"We think that **it is critical to quantitatively understand the impact of measurement techniques** on jet observables in order to make meaningful comparisons to theory. We encourage the developments in new observables but urge caution – new observables may not have as many benefits as they first appear to when their biases and sensitivities to the medium are better understood."*

*"**One of the dangers we face is that many observables are created by experimentalists**, which often yields observables that are easy to measure such as AJ, but that are not particularly differential with respect to constraining jet quenching models."*

"Theorists should not neglect the discussion of the experimental techniques, and experimentalists should make a greater effort to highlight potential impacts of the techniques to suppress and subtract the background on the measurement."

"If initial studies of a particular observable reveal that it is either not particularly sensitive to the properties of the medium, or that it is too sensitive to experimental technique, we should stop measuring that observable."

*"**An agreement for the treatment of the background in heavy ion collisions experimentally and theoretically is required as it is part of the definition of the observable.** Theorists and experimentalists need to understand each other's techniques and find common ground, to define observables that experimentalists can measure and theorists can calculate."*

"Observables that are impossible to measure are not useful, nor is it useful to measure observables that are impossible to calculate or are insensitive to the properties of the medium."

Additional advice

- Measure the same observable, in the same kinematic regime, in at least two different experiments

- For experimentalists: give details of background subtraction. Characterise the background itself. Perform same measurement with different background subtraction techniques

- For theorists: consider effect of background (subtraction) on observable

Recent focus has been on **jet substructure**, i.e. looking at a jet's internal structure

- Boosted massive particle tagging
- quark/gluon jet discrimination
- Modification of jet structure by interaction with medium
- .....

This talk will be about....

0802.0247	Mass Drop Tagger	Butterworth, Davison, Rubin, Salam
1307.0007	modified Mass Drop Tagger	Dasgupta, Fregoso, Marzani, Salam
1402.2657	Soft Drop (= mMDT for β=0)	Larkoski, Marzani, Soyez, Thaler
1502.01719	Groomed momentum fraction z_g	Larkoski, Marzani, Thaler
CMS-PAS-HIN-16-006	Measurement of z_g in HI	CMS collab.
1704.03046	Measurement of z_g in HI	STAR collab.
1704.05066 and 1704.05842	z_g in vacuum with CMS Open Data	Larkoski, Marzani, Thaler, Tripathee, Xue
1608.07283	Calculation of z_g in medium	Chien, Vitev
1610.08930	Calculation of z_g in medium	Mehtar-Tani, Tywoniuk

How to ‘look’ inside a jet?

- Use the clustering history of a ‘physical’ sequential recombination clustering algorithm
- Study jet shape-variables sensitive to specific distributions of radiation inside the jet
- Literally ‘look’ at the distribution of radiation inside the jet (machine-learning techniques)
- .....

The structure of a jet is usually obscured by soft, large-angle noise (underlying event, pileup,...)

Grooming and **background subtraction** go hand in hand in 'cleaning it up' and facilitating the **tagging** of the relevant features

(aim: limit contamination from background while retaining bulk of perturbative radiation)

(Boosted) jet studies at the LHC

Lily Asquith, summary talk at BOOST 2015

Boost is about:

1. Tagging high pT objects (SM and BSM)
2. Improving measurements (pileup, mass resolution etc)

ATLAS and CMS have taken different approaches to these things from day one.

ATLAS:
AKT4 CA12 split-fitered (BDRS)
AKT10 trimmed (R3/R2)
N-subjettiness WTA
JVT/ ρ
D2

CMS:
AKT5 CA8 pruned (p510)
CA15 HTT
N-subjettiness one-pass
Puppi
Soft drop

Essentially none of these tools existed as late as seven years ago

jet algorithms
groomers/taggers/jet shapes
background subtraction tools

Glossary

What	i.e.	When	Ref.
AKT	Anti-kt algorithm	2008	0802.1189
CA	Cambridge/Aachen algorithm	1999	9907280
BDRS	mass-drop tagger, includes filtering	2008	0802.2470
trimmed	Trimming, tagger/groomer	2009	0912.1342
pruned	Pruning, tagger/groomer	2009	0903.5081
HTT	HepTopTagger	2009	0910.5472
N-subjettiness	jet shape function, used in tagging	2010	1011.2268
WTA	Winner-Take-All (recombination scheme)	2013	1310.7584
one-pass	choice of axis for N-subjettiness	2010	
JVT	Jet Vertex Tagger (used in pileup subtr.)	2014	
ρ	background density (used in pileup subtr.)	2007	0707.1378
D2	jet shape function, used in tagging	2014	1409.6298
PUPPI	particle-by-particle pileup subtr.	2014	1407.6013
Soft Drop	tagger/groomer	2014	1402.2657

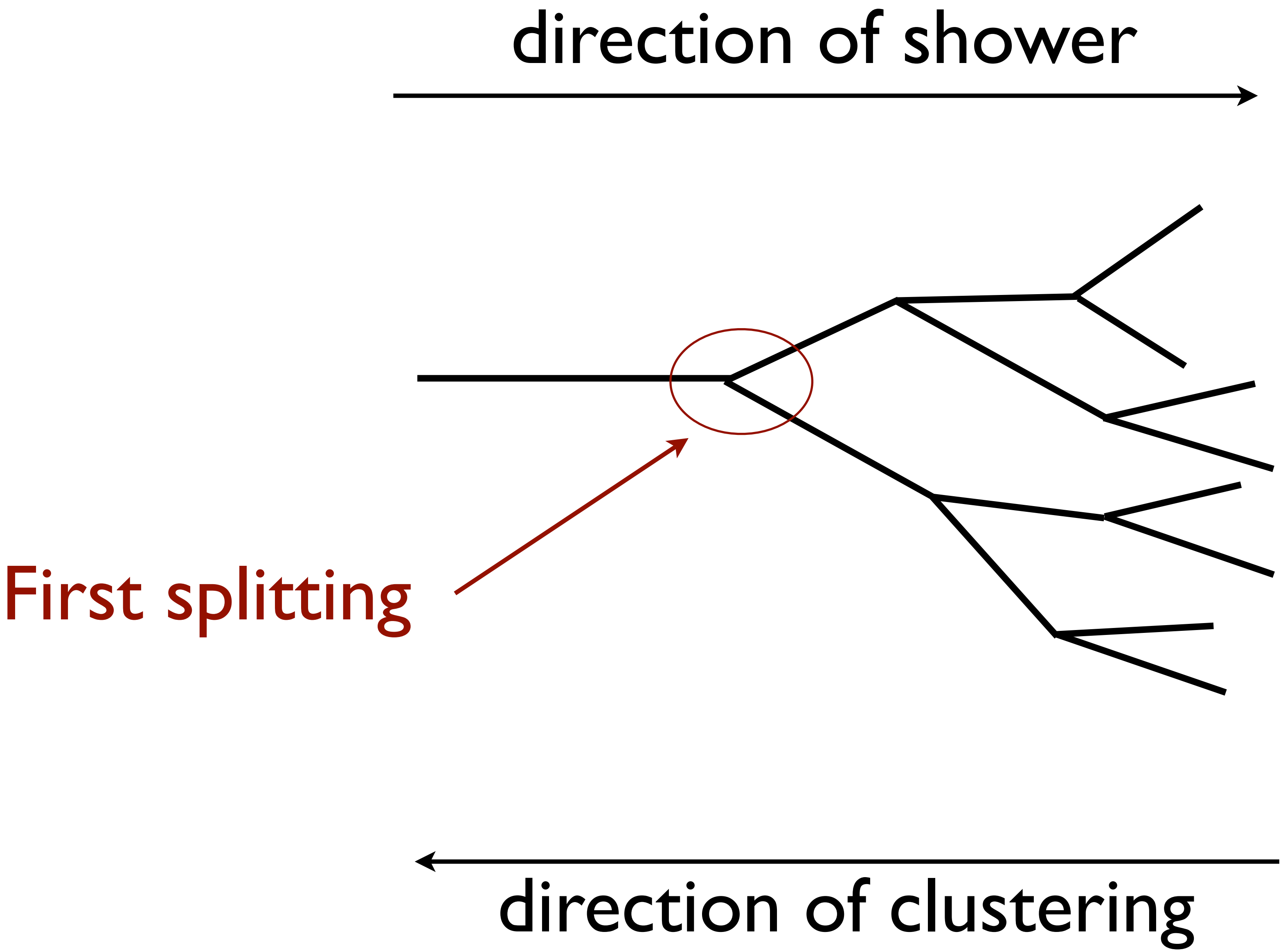
Tagging and Grooming

The substructure of a jet can be exploited to

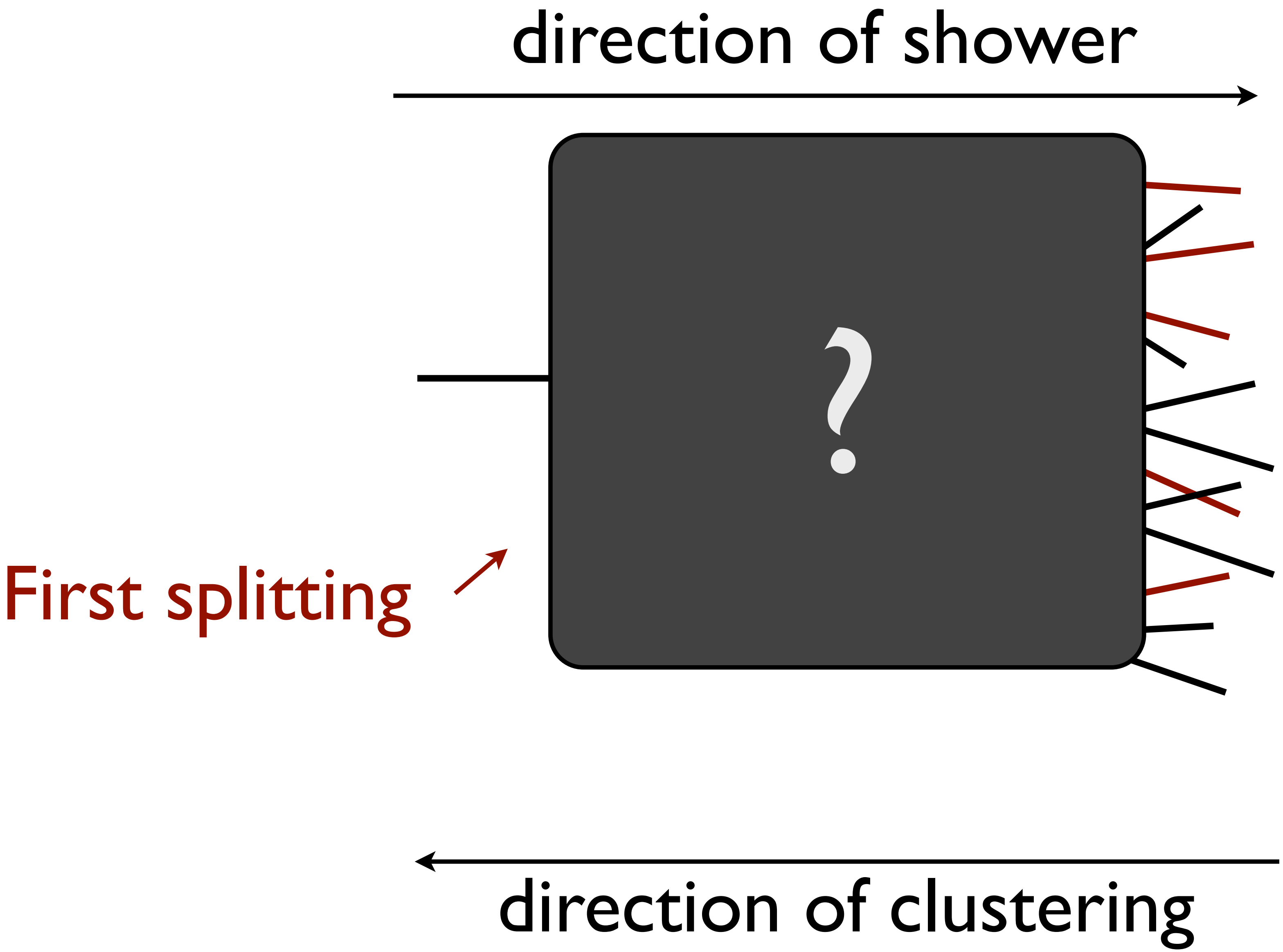
- *remove background contamination from the jet or its components, while keeping the bulk of the perturbative radiation, and without affecting overall jet production rates (often generically denoted as* ***grooming****)*
    - *First examples: filtering, trimming, pruning*
- ***tag*** *a particular structure inside the jet, e.g. a massive particle decaying or a specific parton splitting*
    - *First examples: Higgs (2-prong decay), top (3-prong decay)*

This can lead to the ability to reconstruct a 'relevant splitting'

Parton shower: in theory....



Parton shower: in practice



What jet algorithm to use

One can try finding the relevant splitting using the k_t algorithm (just decluster last step), but the presence of large-angle soft noise in subjets can **degrade signal efficiency**

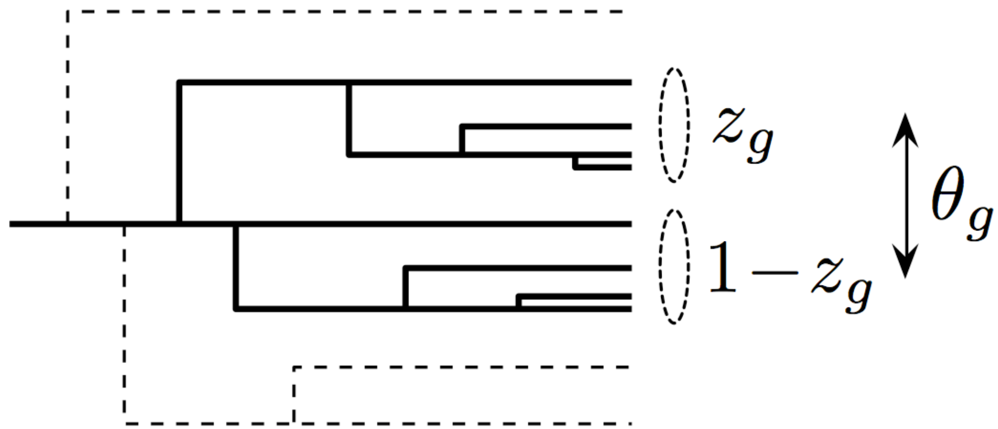
Cambridge/Aachen behaves better since it adapts to the angular distance of the relevant subjets. However, one needs to **iteratively decluster** in order to find the right splitting

Soft Drop declustering

Larkoski, Marzani, Soyez, Thaler, 2014

Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^\beta$

i.e. (for $\beta>0$) remove large-angle soft radiation from a jet of radius R_0

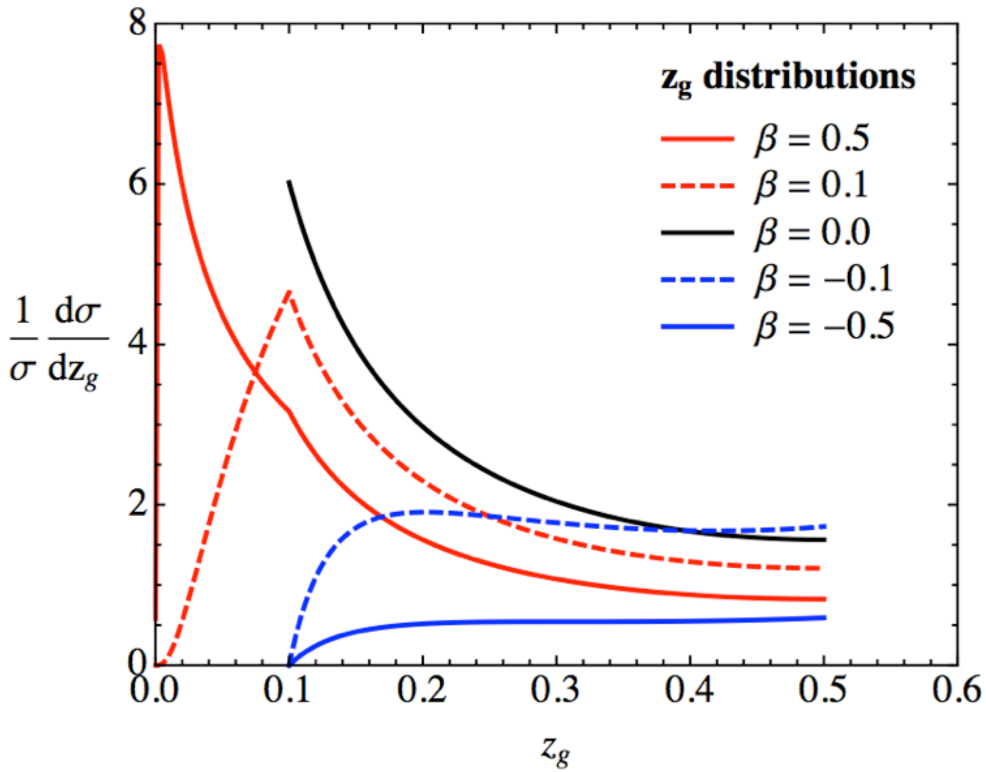


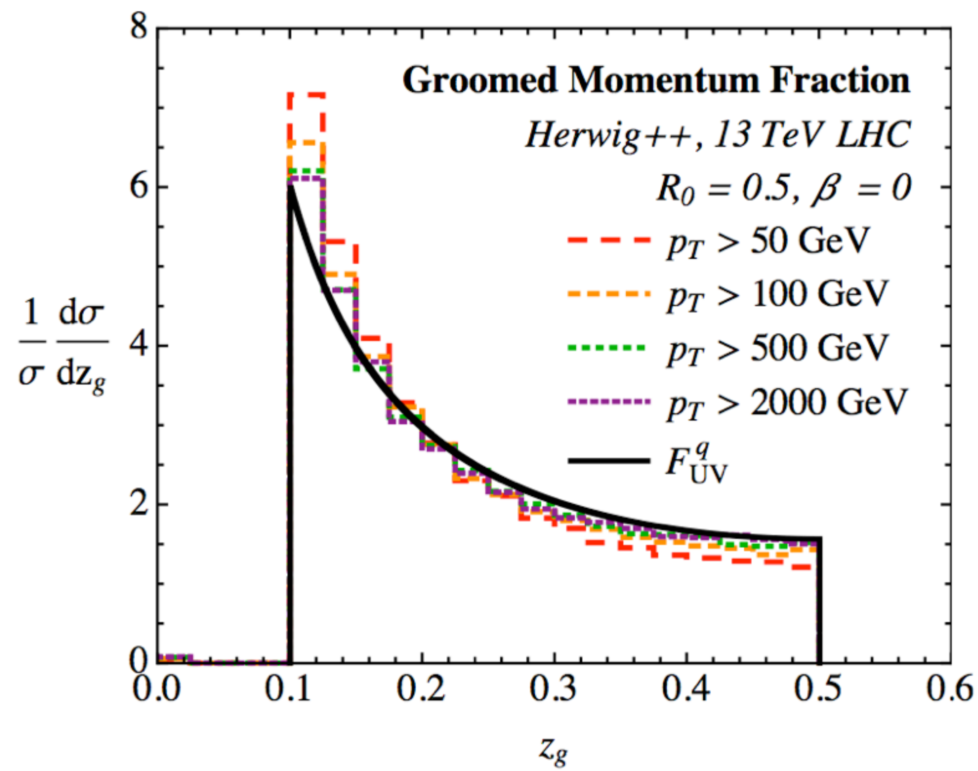
1. Break the jet *j* into two subjets by undoing the last stage of C/A clustering. Label the resulting two subjets as j_1 and j_2
2. If the subjets pass the soft drop condition (i.e. they are both sufficiently hard) then deem j to be the final soft-drop jet
3. Otherwise, redefine *j* to be equal to the subjet with larger p_T and iterate the procedure from point 1
4. If *j* is a singleton and can no longer be declustered, then one can either remove *j* from consideration ("tagging mode") or leave *j* as the final soft-drop jet ("grooming mode")

z_g distribution

Its "physical" interpretations aside (hardest splitting, AP splitting function, etc), z_g is first and foremost a **well defined observable that is calculable** in QCD

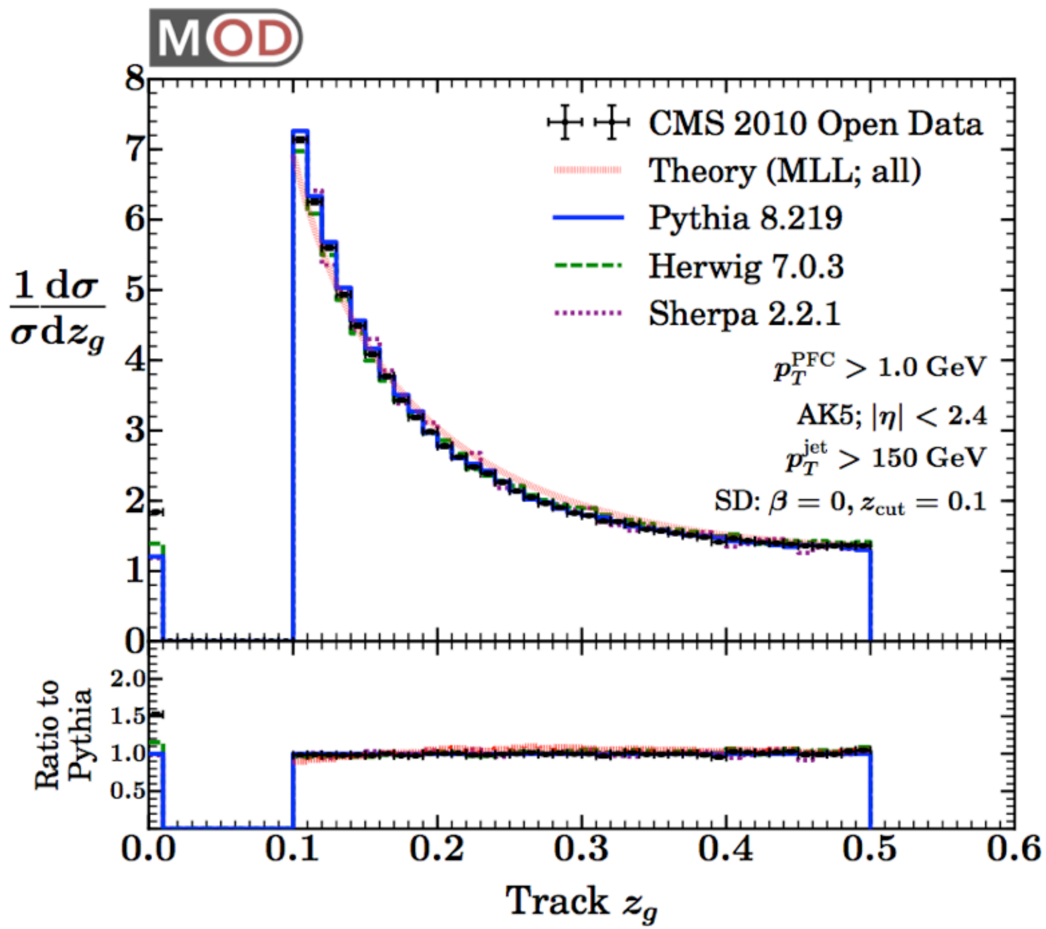
[Larkoski, Marzani, Thaler, 1502.01719]





Comparisons of measurements and predictions constitute a legitimate test of the theory (or of the approximations made)

z_g in CMS pp Open Data



Both Monte Carlos and analytical predictions agree well with data

This particular variable seems to be **particularly robust theoretically, and with small hadronisation corrections** (not true in all cases)

Of course, this ups the game: one probably can't content oneself with observing a 'fair' agreement (e.g. in the HI case)

Substructure in HI

Generic **experimental characterisation of jets in HI** collisions, even in the absence of universally valid theoretical descriptions, can and should be a **priority**

Measurements exist for

- Longitudinal fragmentation functions
- Radial distributions
- Splitting functions
- Other jet shapes
- ....

See Marta Verweij's review at QM17

Ideally, a coherent, motivated and well defined (small) set of distributions and shapes is agreed upon, and measurements and predictions are systematically improved and refined

z_g in HI collisions

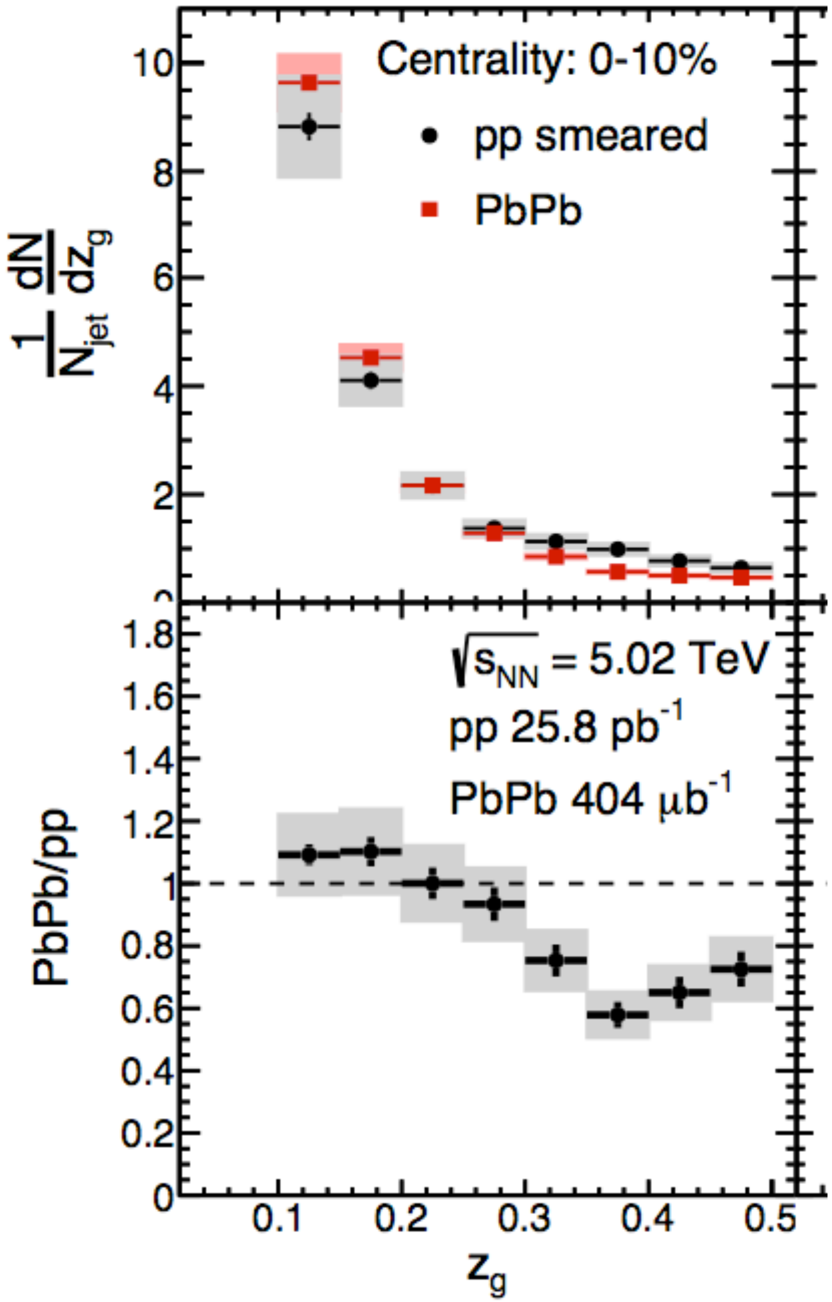
For the purpose of this talk, let us concentrate on the z_g distribution, that 'passes our cuts' of being a well defined, measurable, calculable and robust observable

Recent measurements from CMS (CMS-PAS-HIN-16-006) and STAR (1704.03046), in both cases using Soft Drop with z_{cut}=0.1 and β=0 (but background subtraction procedures differ)

First predictions (at least) from Chien and Vitev (1608.07283), and Mehtar-Tani and Tywoniuk (1610.0893)

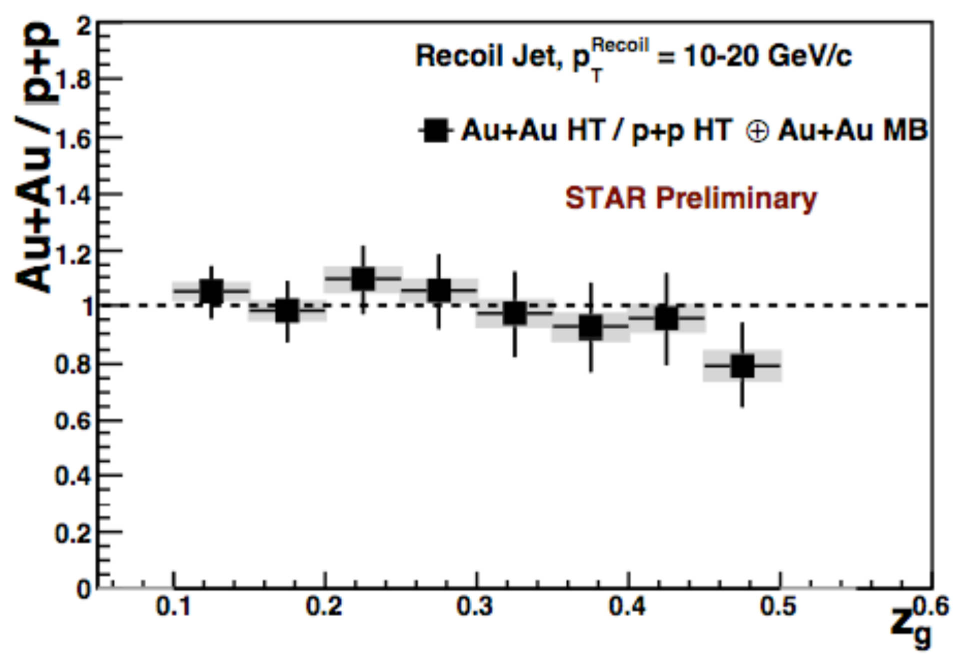
z_g in HI collisions - measurements

CMS



Apparent conflict, but very different kinematics and phase space of radiation could explain the difference.
Need to compare to theory in both cases for clean appraisal.

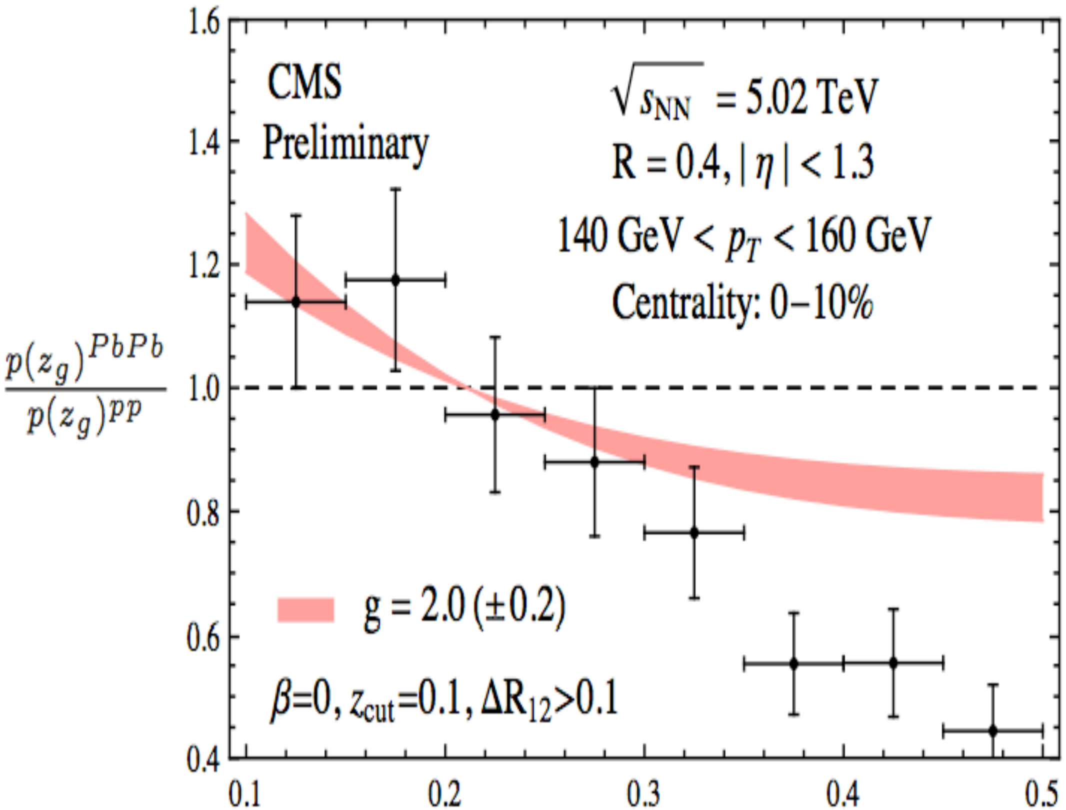
STAR



z_g in HI collisions - predictions

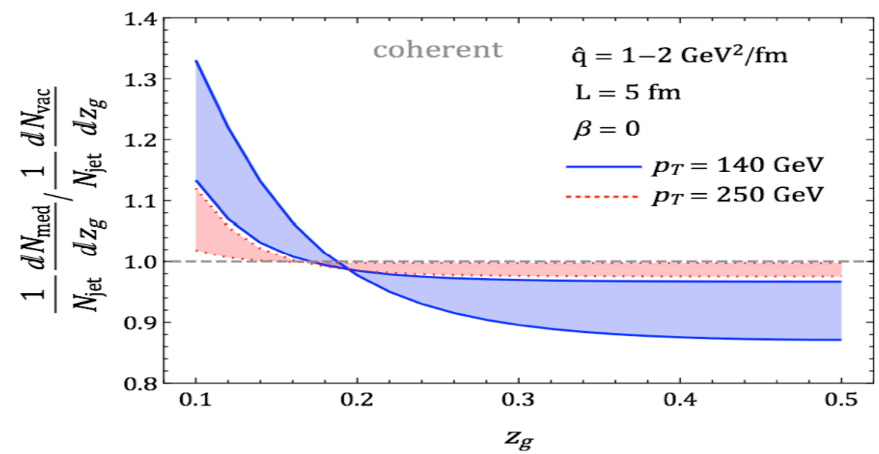
Chien-Vitev

Medium modified splitting function



Mehtar Tani-Tywoniuk

Coherent jet energy loss



Obviously more work to do. Especially if the observable is considered 'robust' and hence quite good agreement can be expected

Conclusions

- Jet substructure techniques are quite young in general, and even younger in HI. There is likely room for improvement

- To avoid fragmenting the field, and make progress efficient, we should
  - Introduce only jet substructure techniques motivated by analytical arguments, not simply MC testing, nsure that they enjoy a **good analytical calculability**
  - Provide a **public implementation** (e.g. in the FastJet contrib project, **`http://fastjet.hepforge.org/contrib`**, public repository for third-party contributions)
  - Choose robust and meaningful observables for measurement and calculation

- Once a few promising observables have been identified, we should **stick to them**, multiply measurements and refine calculations, rather than jump to the "next new thing"

Backup