Jet substructure in pp and heavy ion collisions (discussion of some results, mostly from ALICE)

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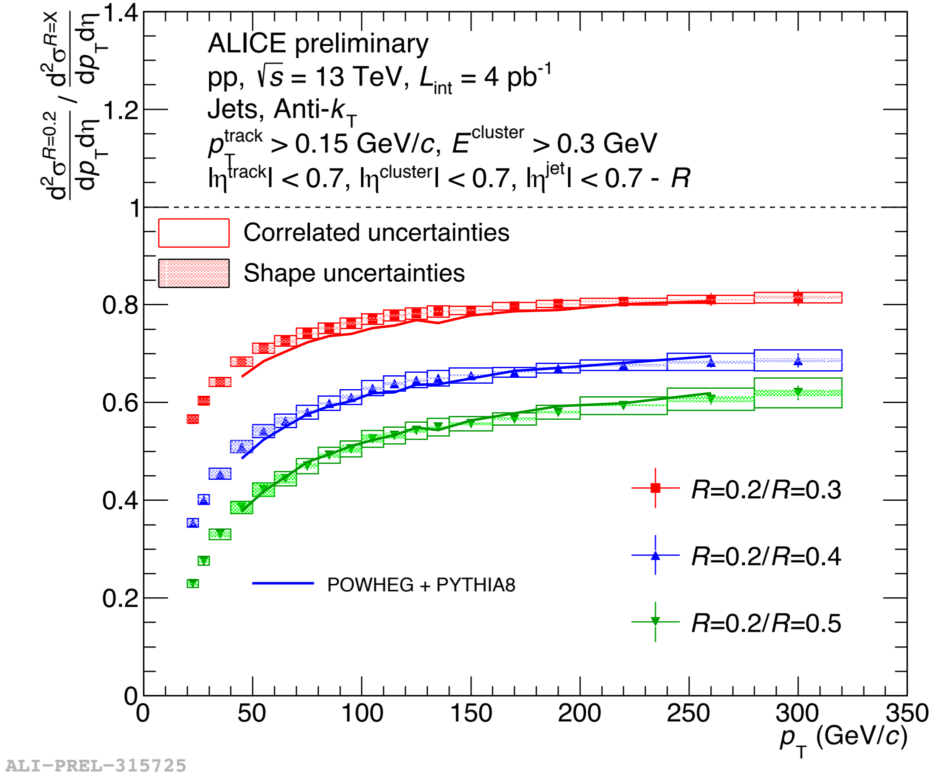
Heavy Ion Meeting, Orsay June 2019

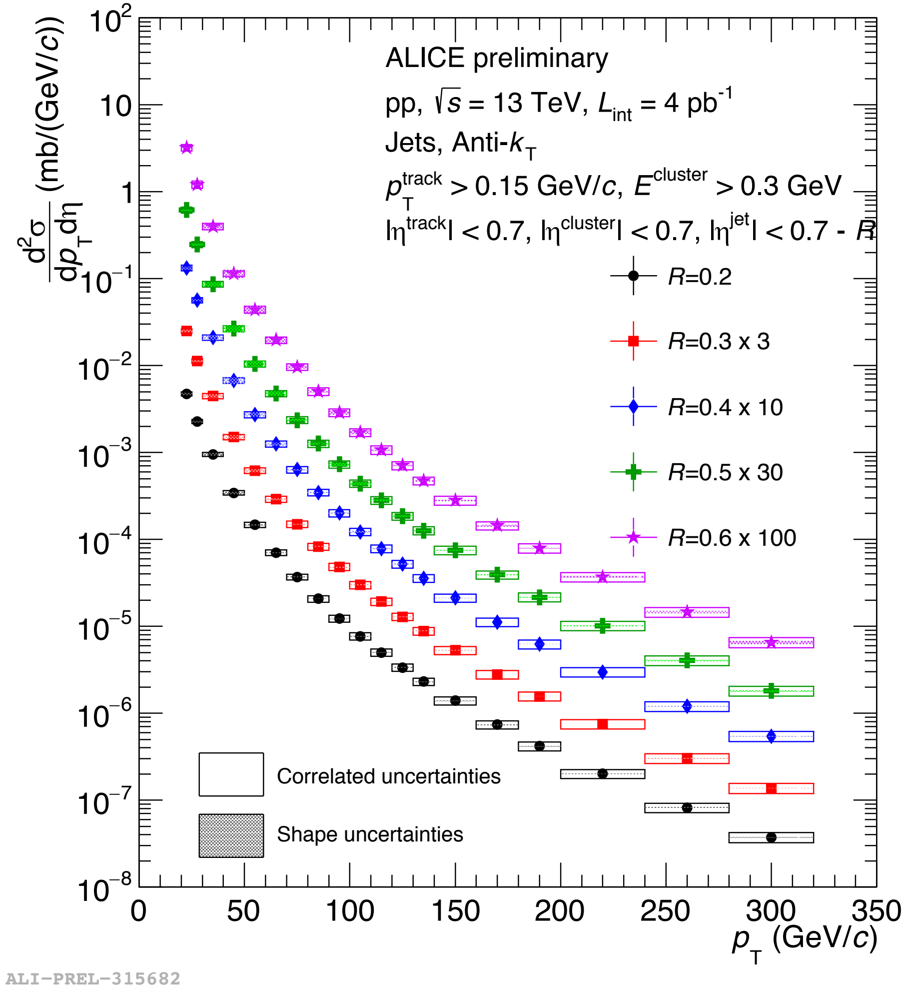
Jet substructure plays a main role in LHC analysis, for instance in q/g discrimination or tagging of boosted objects.
It allows to access fundamental properties of QCD and to pose differential constrain to perturbative and non-perturbative theoretical components

Jet substructure in Heavy ion Collisions: access the high-temperature phase of QCD to investigate how macroscopic properties of matter arise from QCD interactions

Jets are well-calibrated, Rutherford-like probes of the dense QCD medium created in heavy ion collisions. Modification of their yields and radiatio pattern in dense medium compared to vacuum ->microscopic description of the QGP

Jet yields and ratios of cross sections for different resolution R

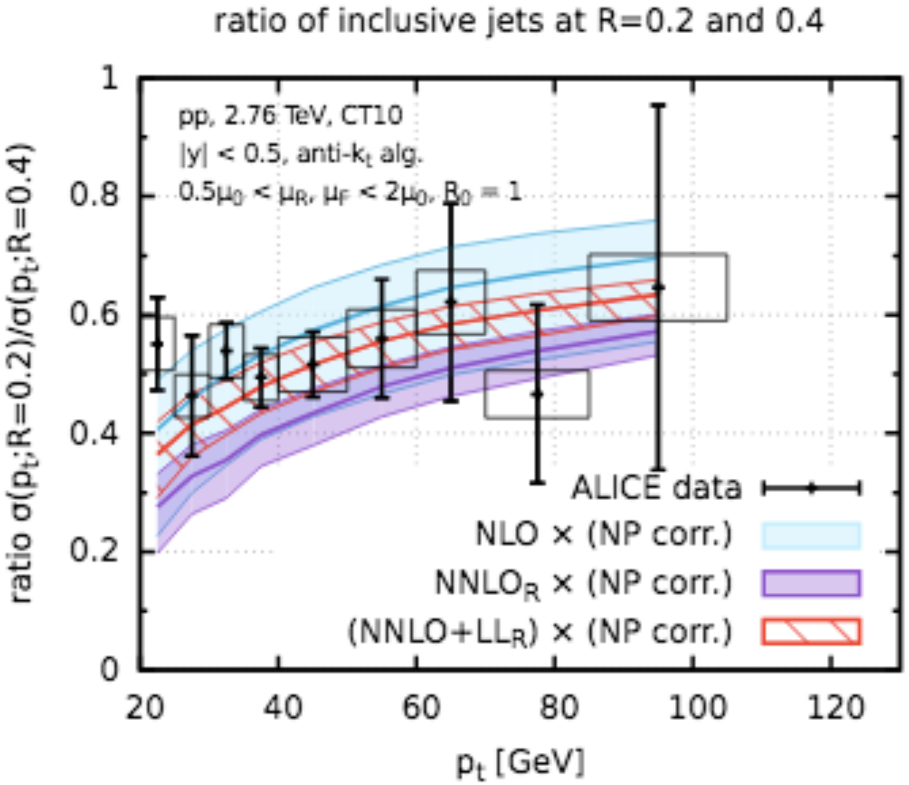


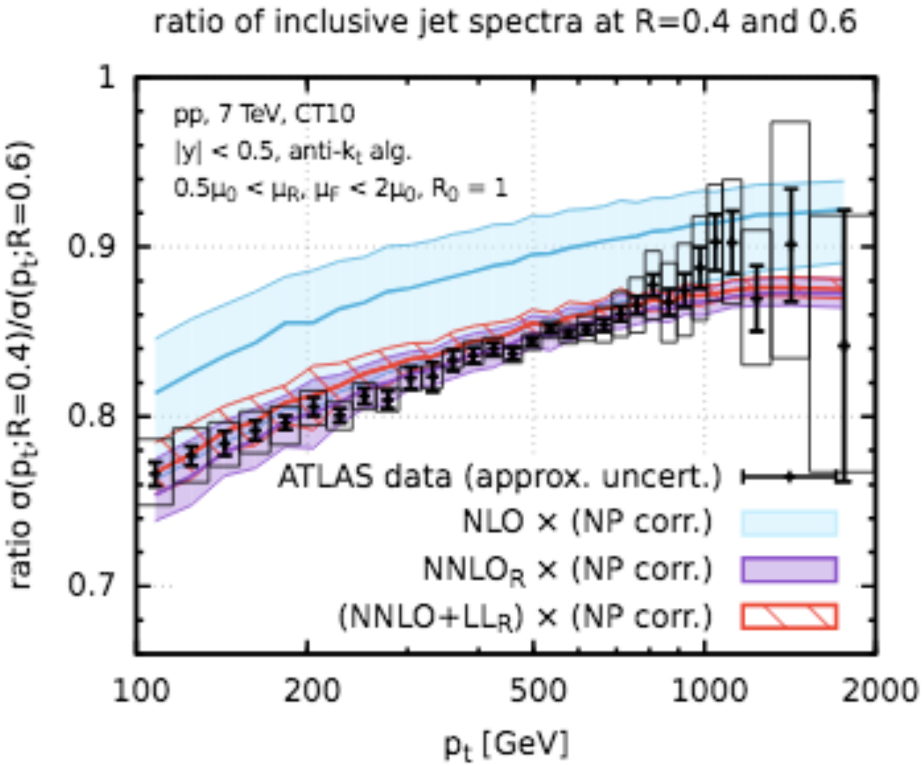


Wide kinematic reach at the LHC, from few GeV to the TeV scale

Ratios of Xsections for different R are sensitive to the jet transverse energy profile

Comparison to fixed-order calculations





Dasgupta, Dreyer,Salam,Soyez, **JHEP 1606 (2016) 057**

(new data@13 TeV, previous page, will pose stronger constrain)

Jet grooming

Trimming

- Take jet with radius R
- Reclusters components into smaller subjets with radius $R_{sub} < R$
- Keep subjets that satisfy $p_{t,\,sub} > z_{cut}\, p_{t,\,jet}$

Pruning

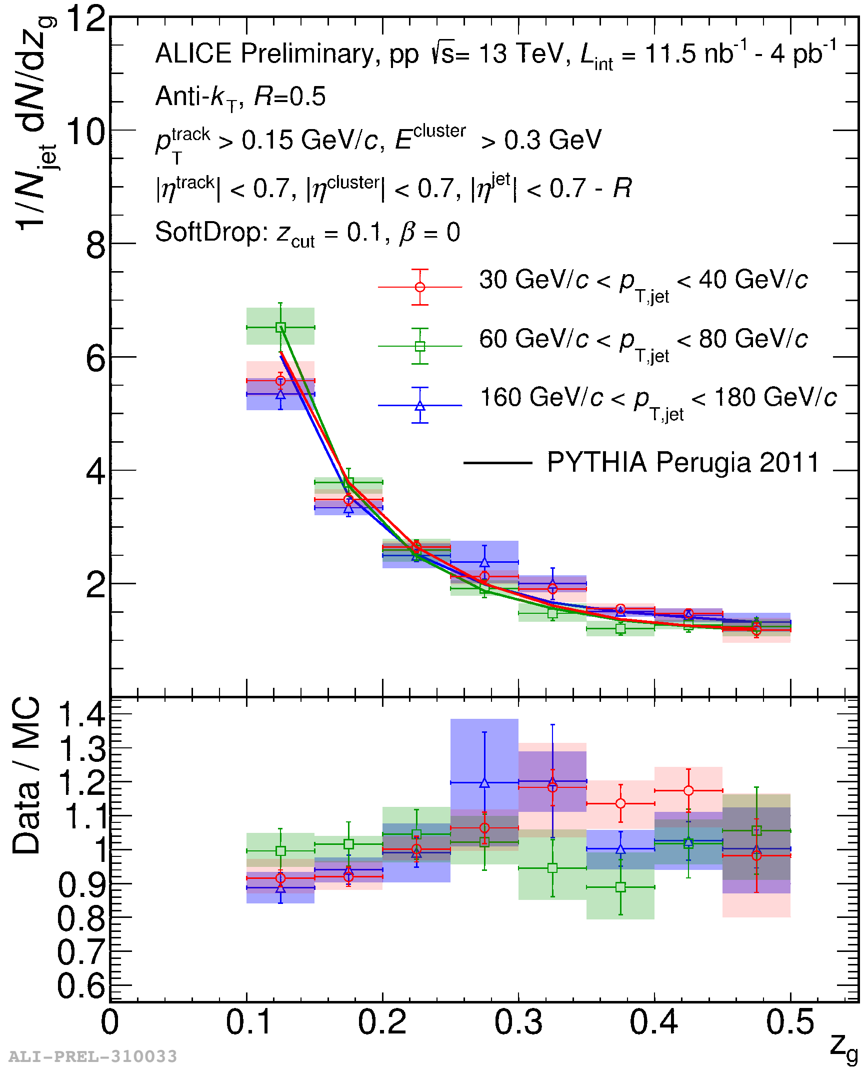
- Define pruning radius $R_{prun} = R_{cut} * 2\, m / p_t$
- For every step of clustering $j_1 + j_2 \rightarrow j_{12}$, check:
  - Wide-angle: $\Delta R_{12} > R_{prun}$
  - Soft: $\min(p_{t1}, p_{t2}) < z_{cut}\, p_{t,\,jet}$
- If either condition fails, eliminates softer subjet
- If both pass, continue clustering

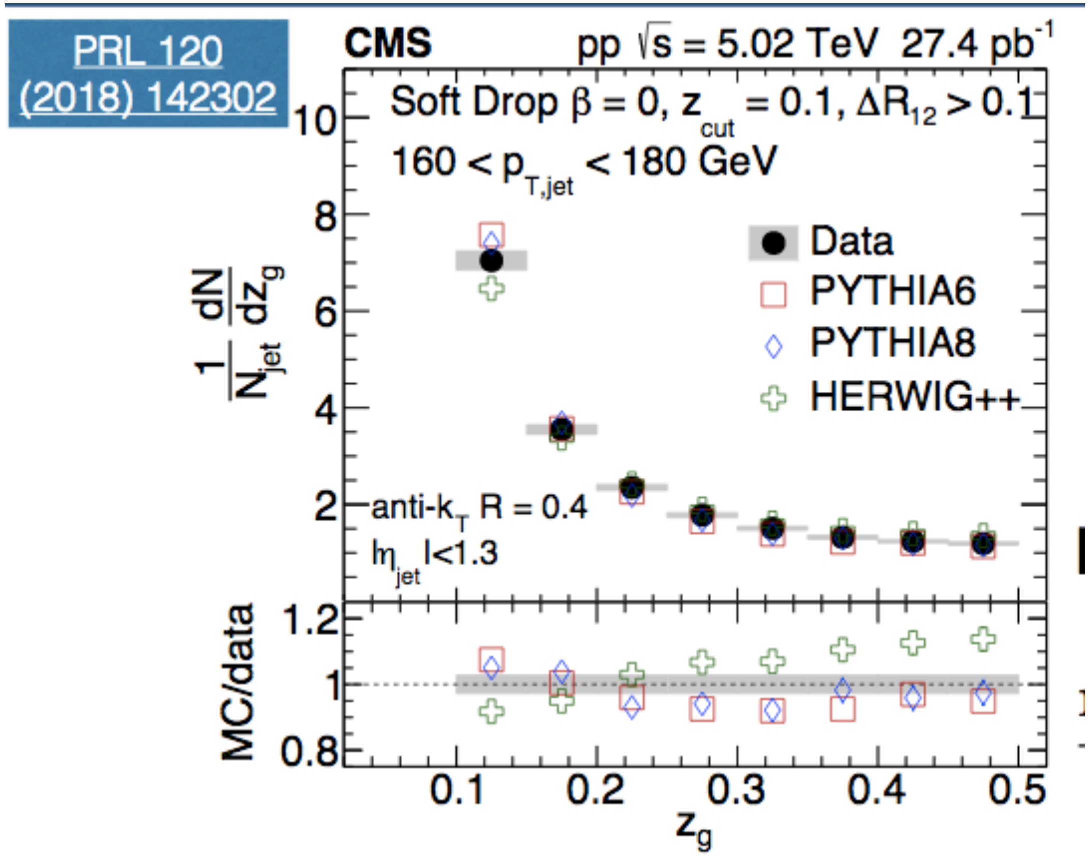
SoftDrop (or mMDT)

- Decluster jet $j_{12} \rightarrow j_1 + j_2$
- Check condition $\min(p_{t1}, p_{t2})/p_{t,jet} > z_{cut}(\Delta R_{12}/R)^{\beta}$
  - z_{cut}, β: tunable values
- If condition fails, the softer subjet is removed
- If passes, stops recursion
- For $\beta=0$, it is mMDT

AIM: Limit contamination of QCD background in a controlled way while retaining the bulk of perturbative radiation ->interesting idea to export to HI!

The 2-prong momentum imbalance, z_g, exposed by grooming

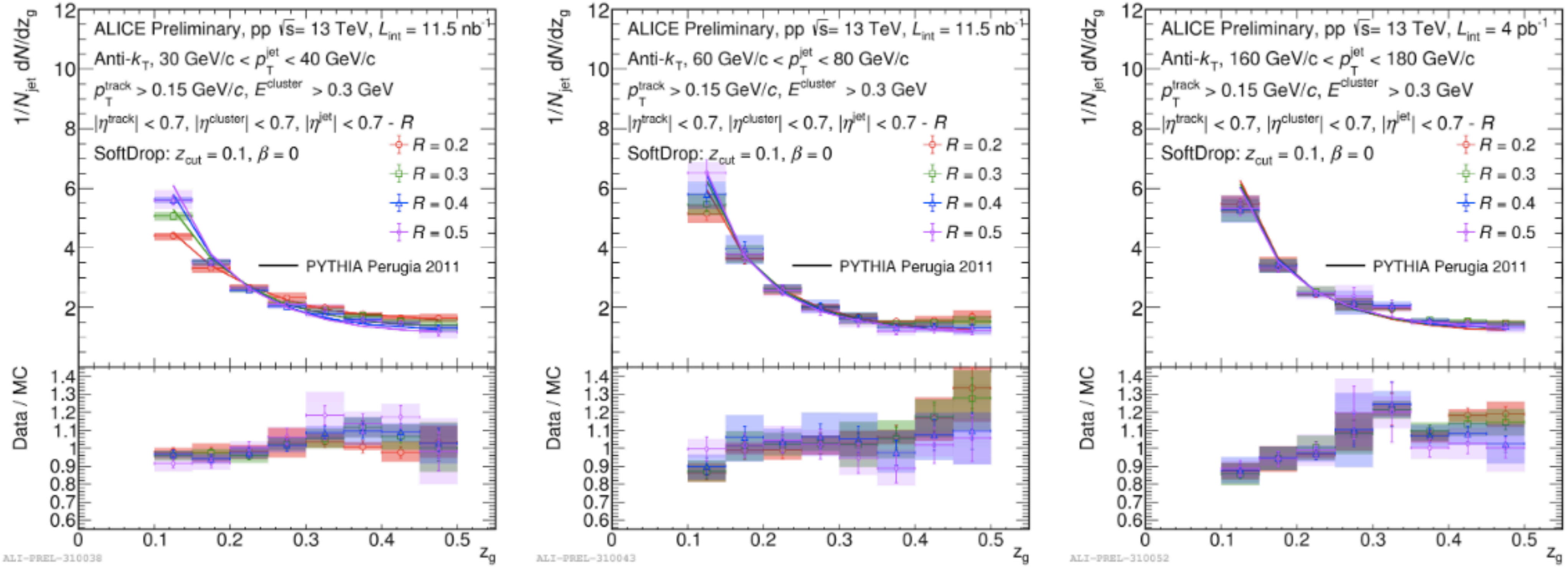




The z_g in vacuum is directly linked to the Altarelli-Parisi splitting function

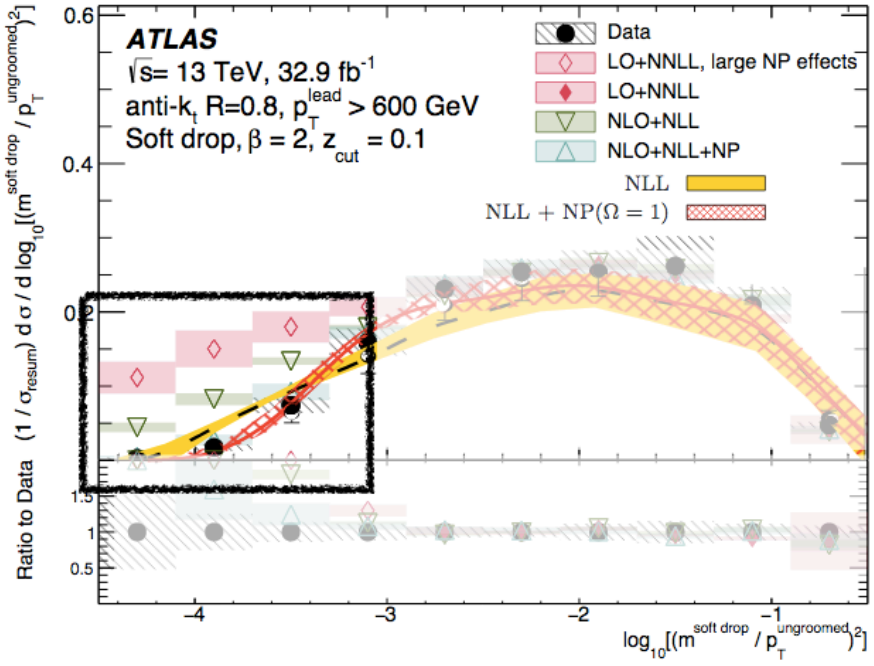
No jet p_T dependence observed, as expected if measurement of the QCD z kernel

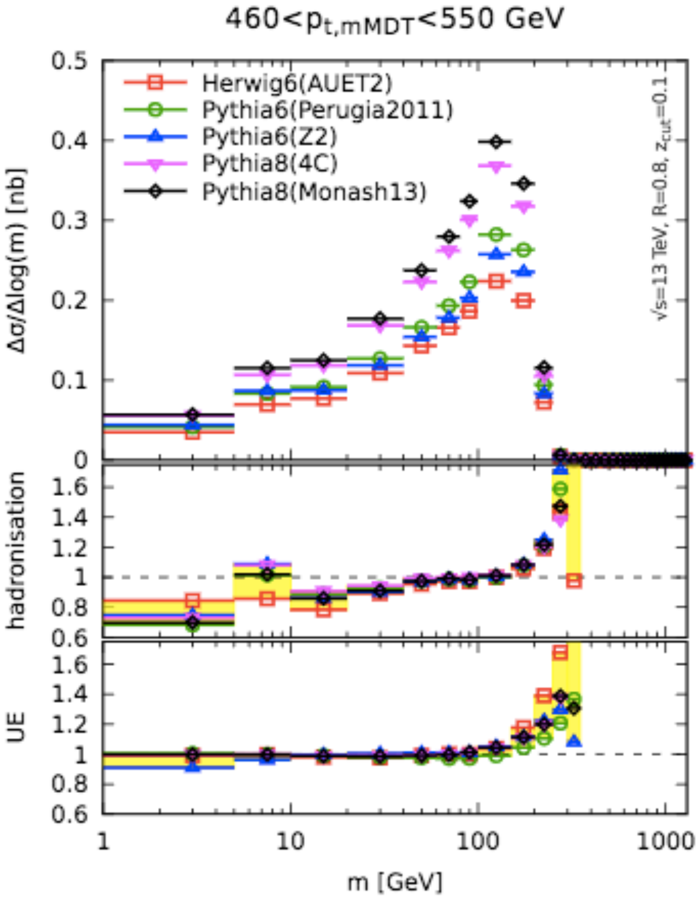
The 2-prong momentum imbalance, z_g , exposed by grooming



At low jet p_T, jets are broader, and at larger R one picks more soft prongs that the CA reclusterer combines last.

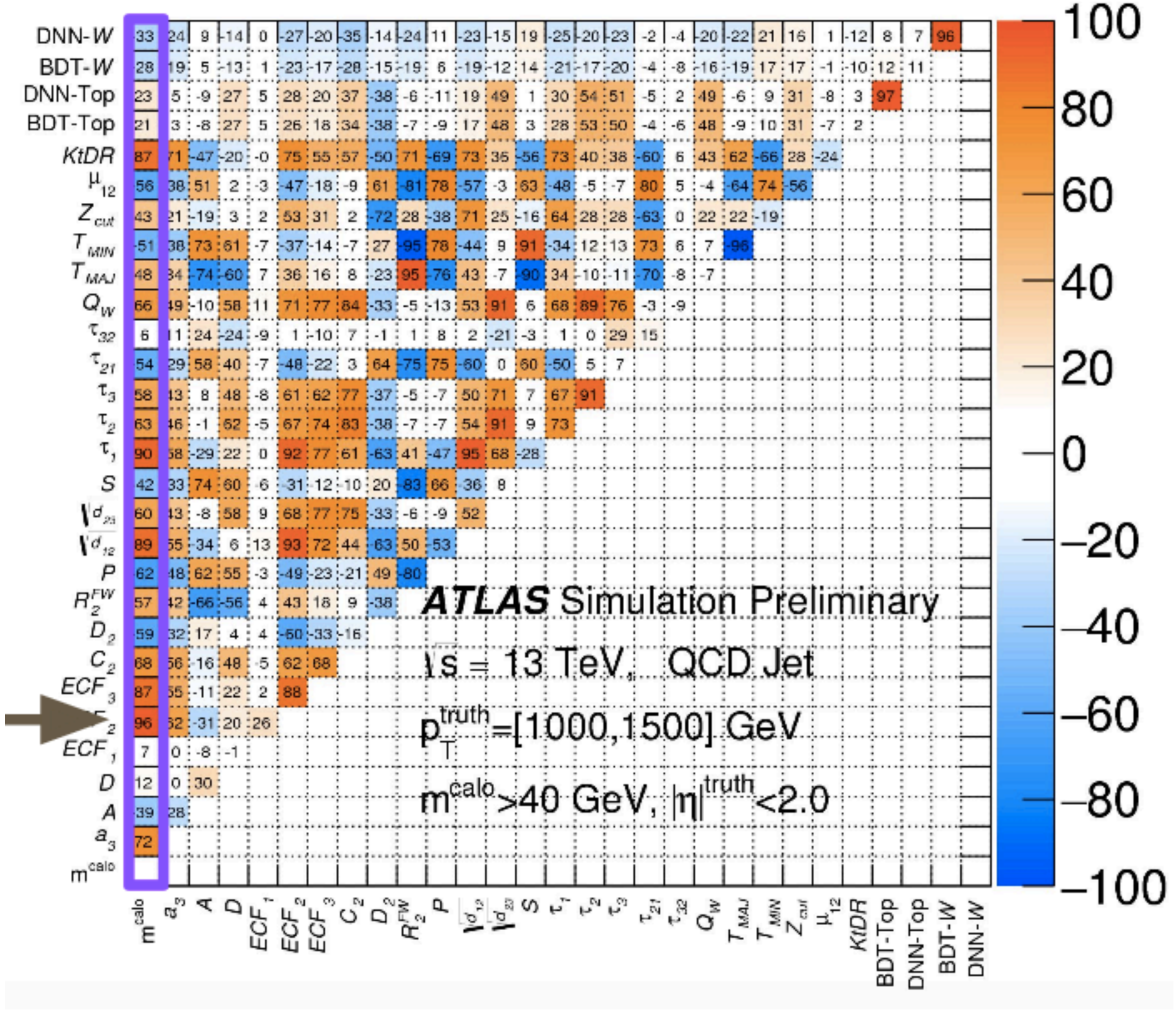
The groomed jets mass





Large region in mass where NP effects (yellow bands, right plot) are negligible
->strong constrain to perturbative aspects of parton showers

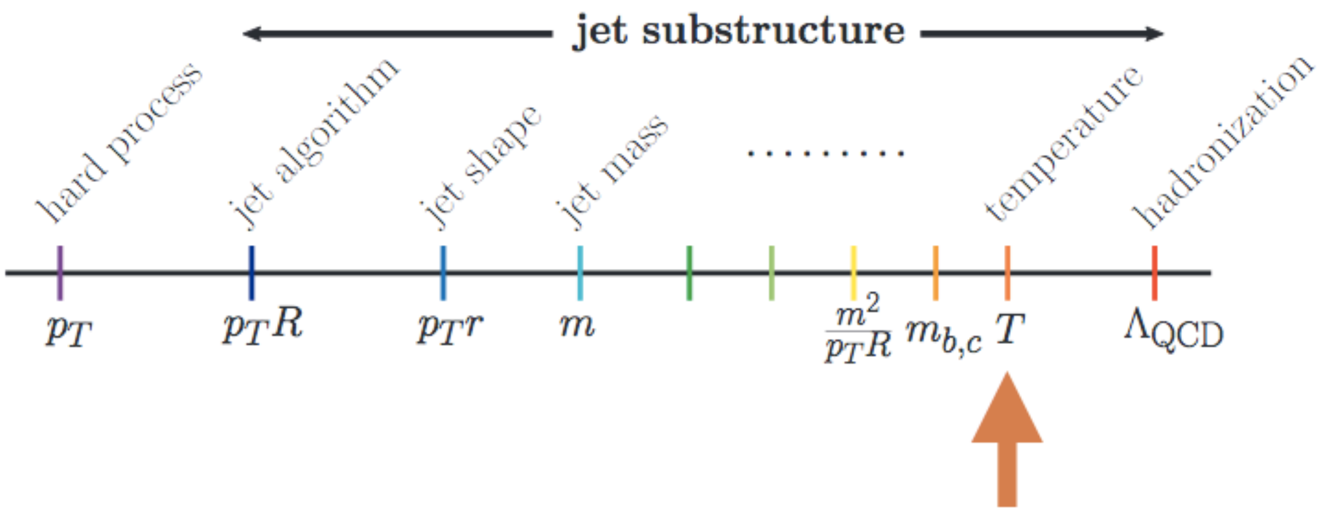
Plethora of jet substructure observables, many strongly correlated



Difficult to find a jet shape that is not correlated/anticorrelated with the jet mass

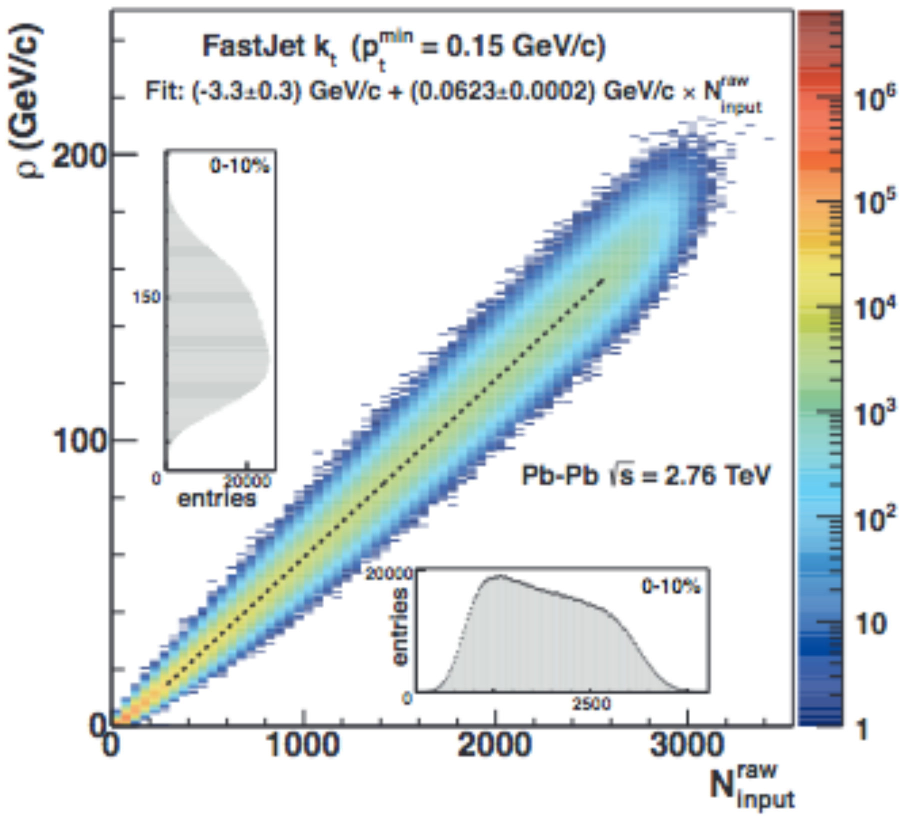
In order to extract maximal information (ie about jet quenching), the more uncorrelated the set of observables, the better

Jets in Heavy Ion Collisions a multi-scale problem

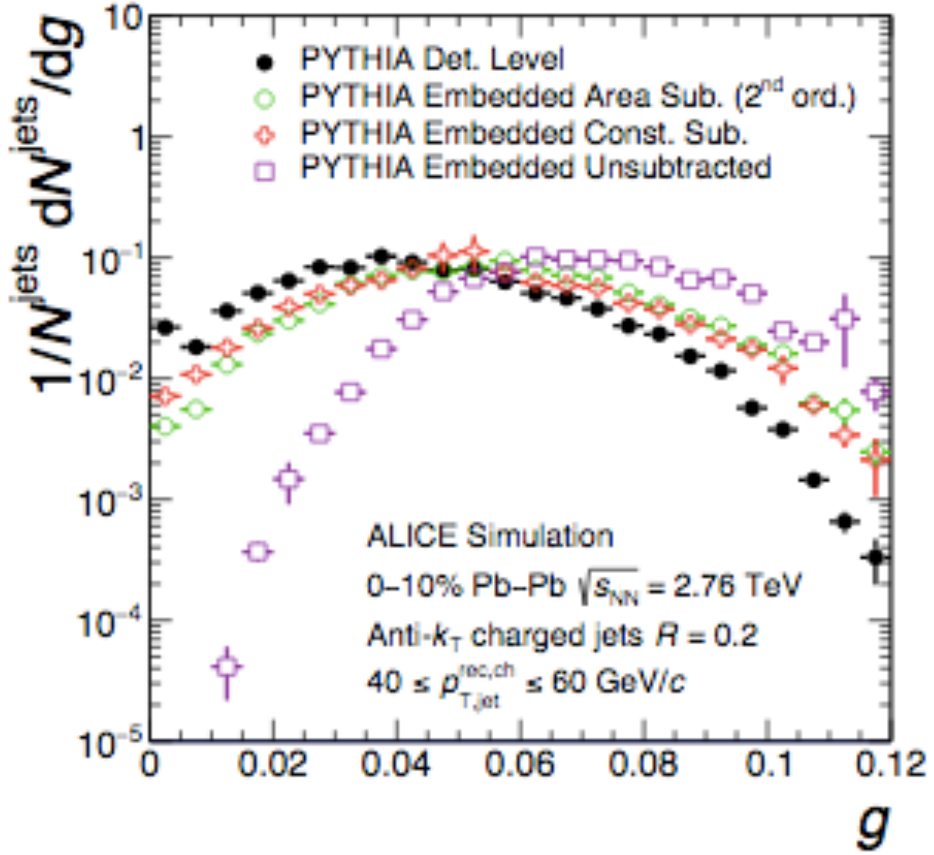


Large pedestal background to subtract

Large uncorrelated background per unit area

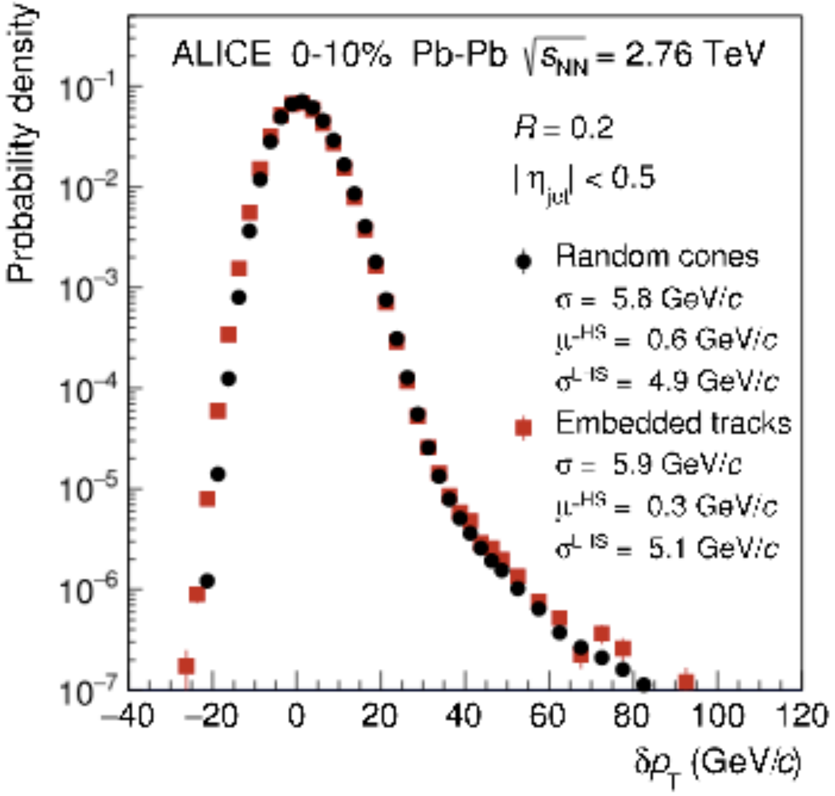


Pythia events embedded into Pb-Pb data

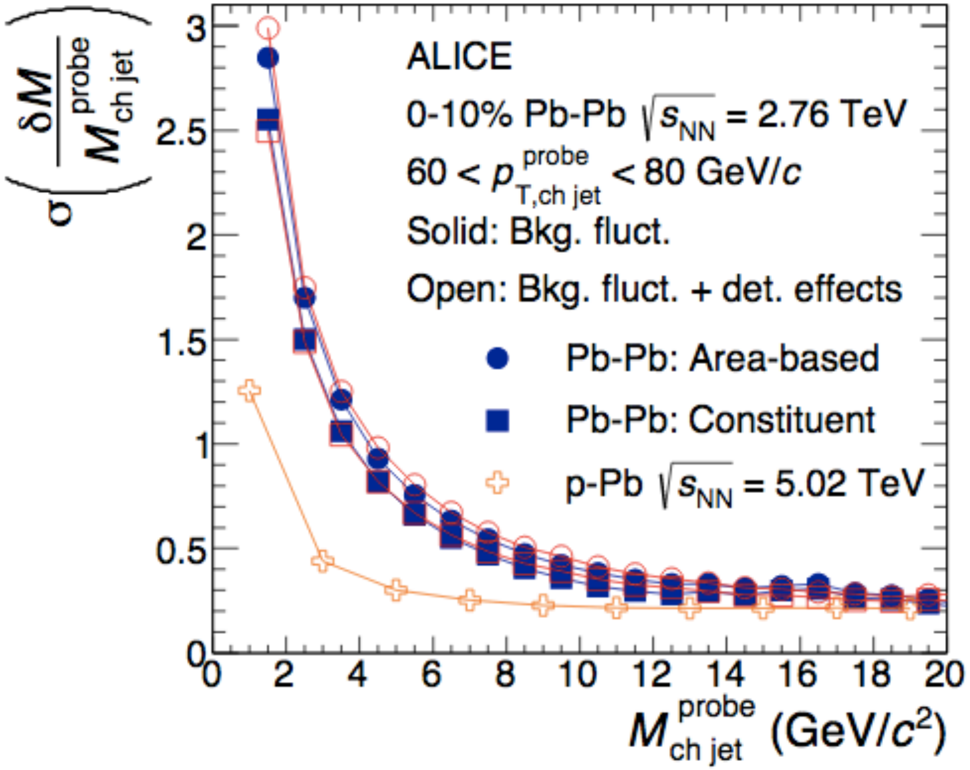


Jet energy and shape irresolution to unfold

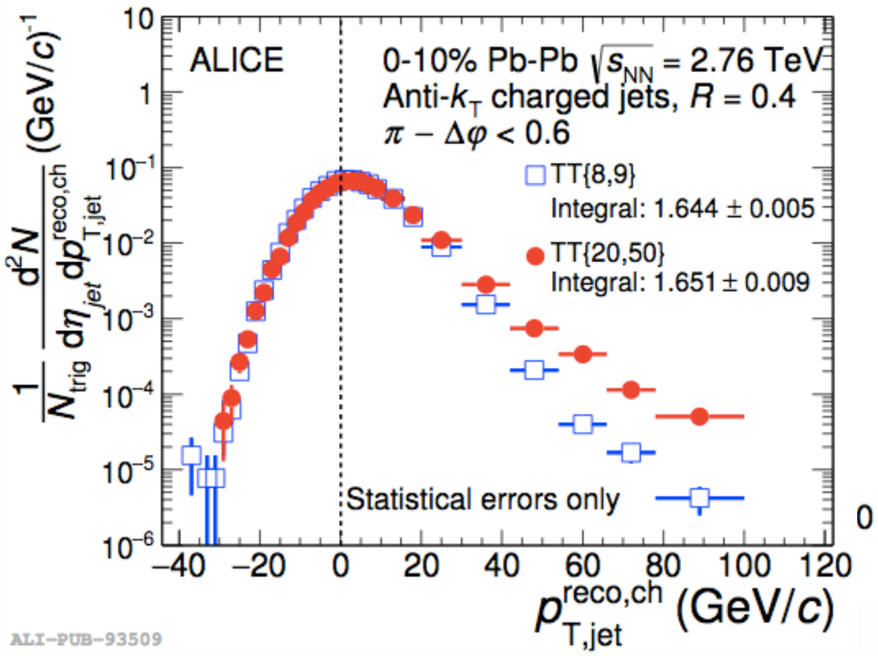
Smearing of the jet p_T due to the background fluctuations



Smearing of the jet mass by background fluctuations and detector effects



Large combinatorial background to suppress

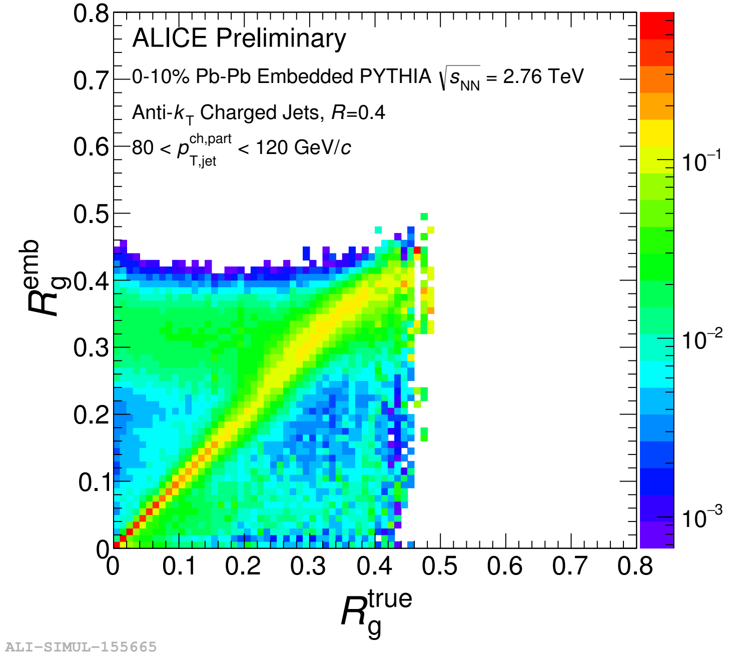


ALICE, JHEP09(2015)170

Large fake jet contribution limits inclusive jet measurements at low jet p_T/large R

Data-driven techniques based on semi-inclusive coincidence measurements can be applied to subtract combinatorial background. Jet event mixing, ML are other approaches under exploration

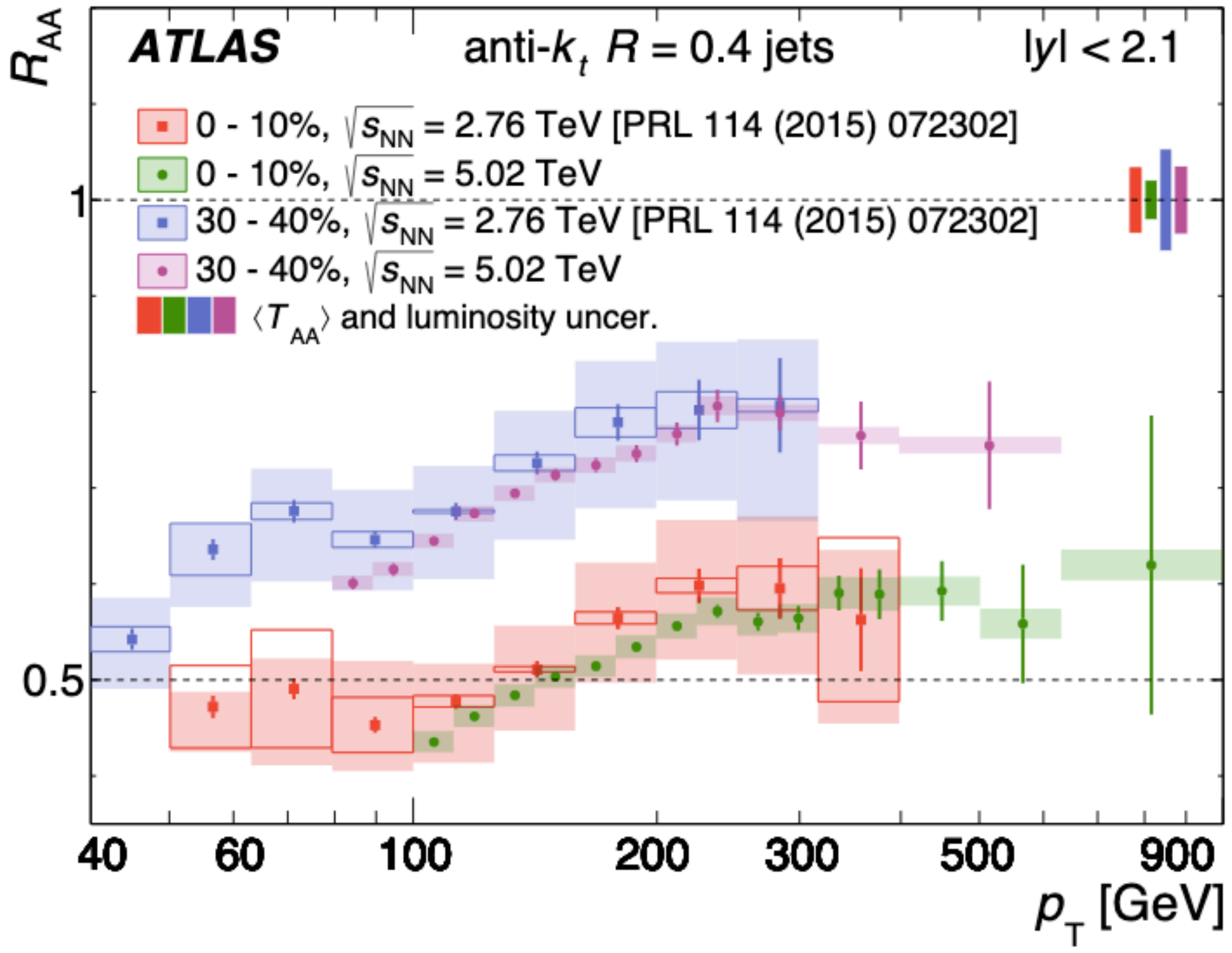
Background and detector response of the splitting aperture angle



The uncorrelated background generates combinatorial subleading prongs at large angles (where area is maximal)

Off-diagonalities render the unfolding very hard

Jet disappearance

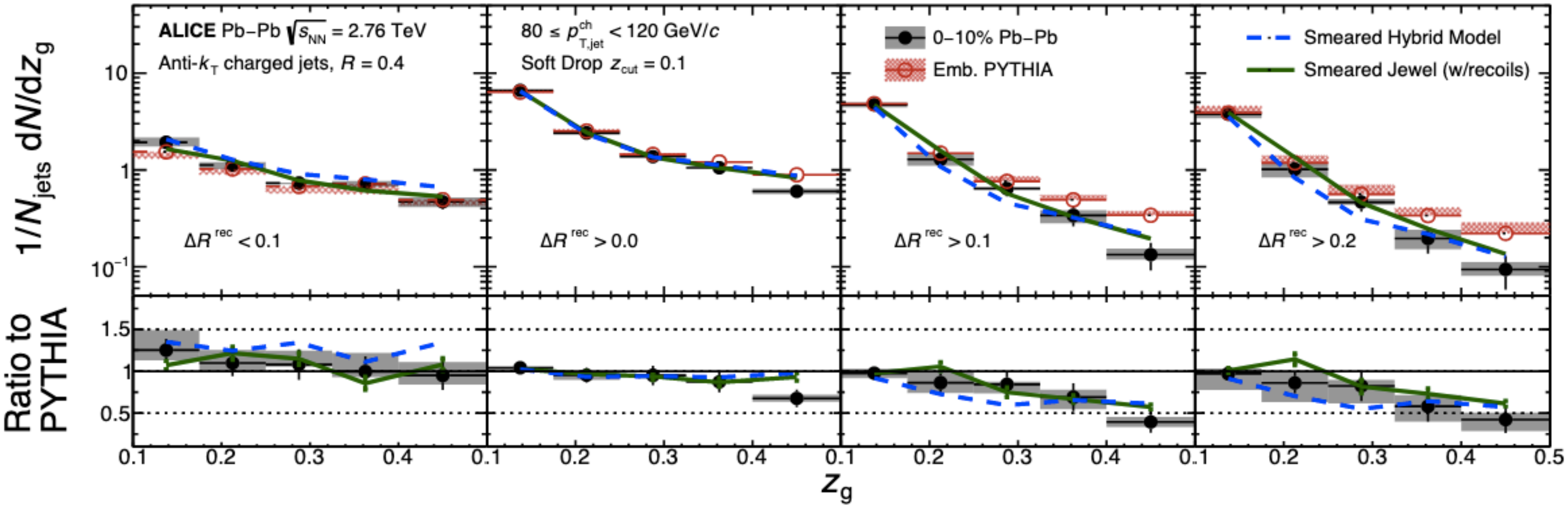


Medium is opaque to jets up to the TeV scale

Surprising given the difference between the shower length and the medium length!

Now, let's try to understand how energy loss depends on the jet substructure

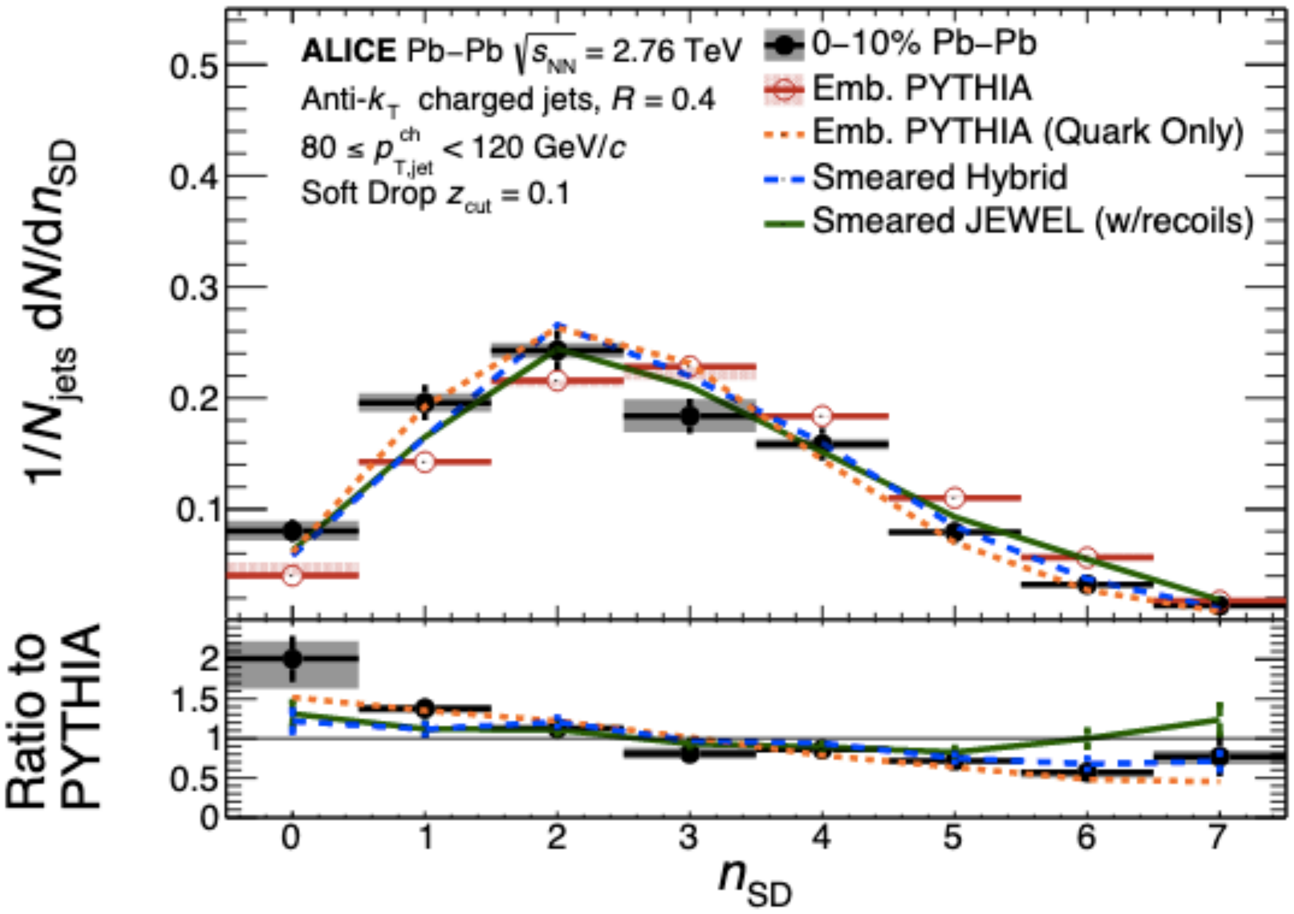
The 2-prong momentum imbalance, z_g



Apperture angle dependence of z_g in medium compared to vacuum (smeared) reference

At large angles ΔR > 0.2, suppression of symmetric splittings
At small angles ΔR < 0.1, enhancement of splittings
No observed enhancement of splittings passing the SD cut in medium relative to vacuum
Increased number of untagged jets in medium

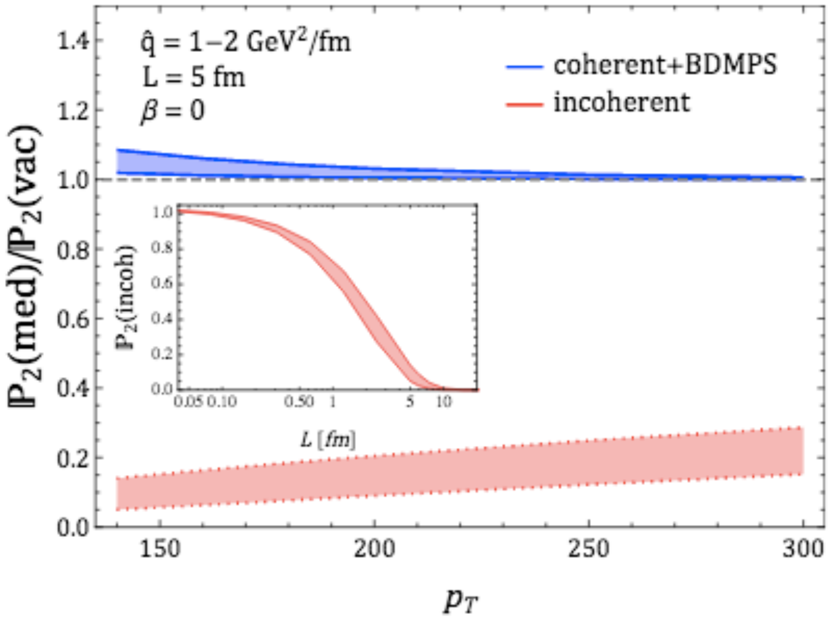
The number of hard prongs in the shower



The nSD counts the number of prongs that pass the mass drop condition as the jet is iteratively declustered

Data indicates less number of prongs in medium than in vacuum (also in agreement with the more quark-like fragmentation shown by the angularities)

Is color coherence driving the suppression of the 2-prong splittings?



Yacine Methar-Tani and Konrad Tywoniuk, JHEP 1704 (2017) 125

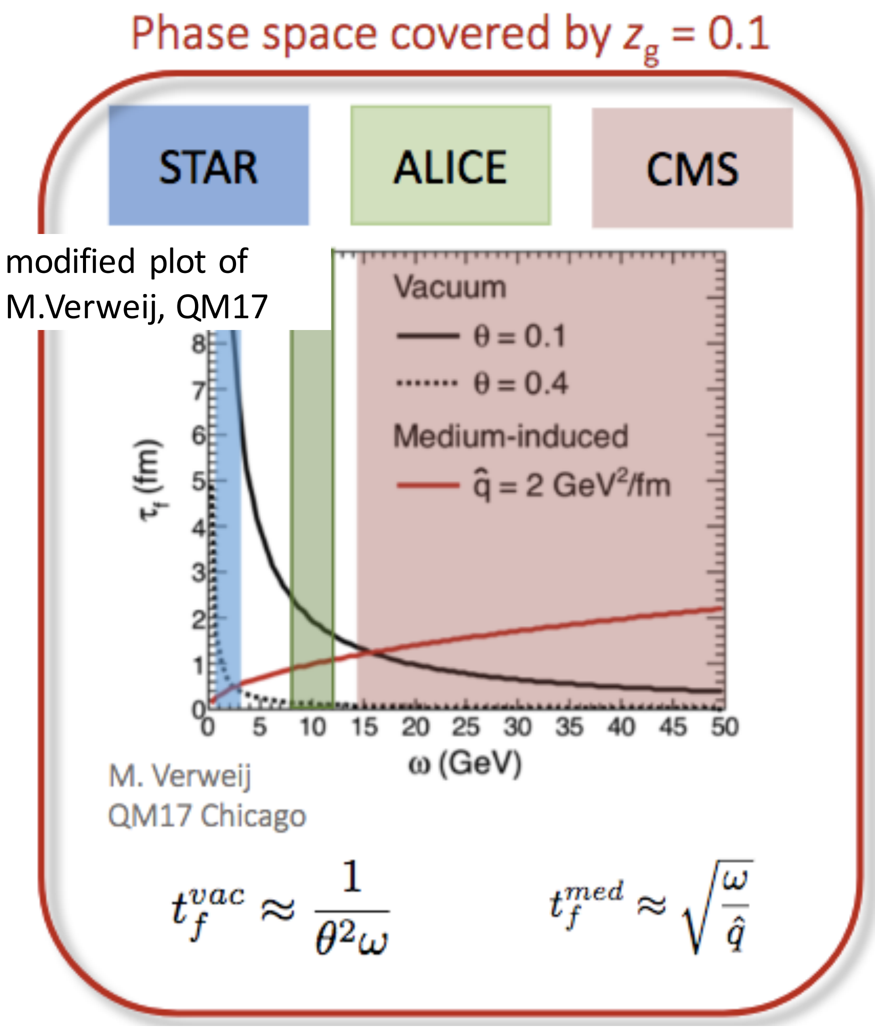
Coherent limit:
small-angle prongs* are resolved as a single color charge

Incoherent limit:
large angle prongs* are resolved by the medium independently and thus more quenched

However: the data trends of the z_g are described by two models that represent the totally incoherent case; this suggests that the driving mechanism is something simpler like formation time or kinematic biases.

*compared to the medium resolution power or correlation length

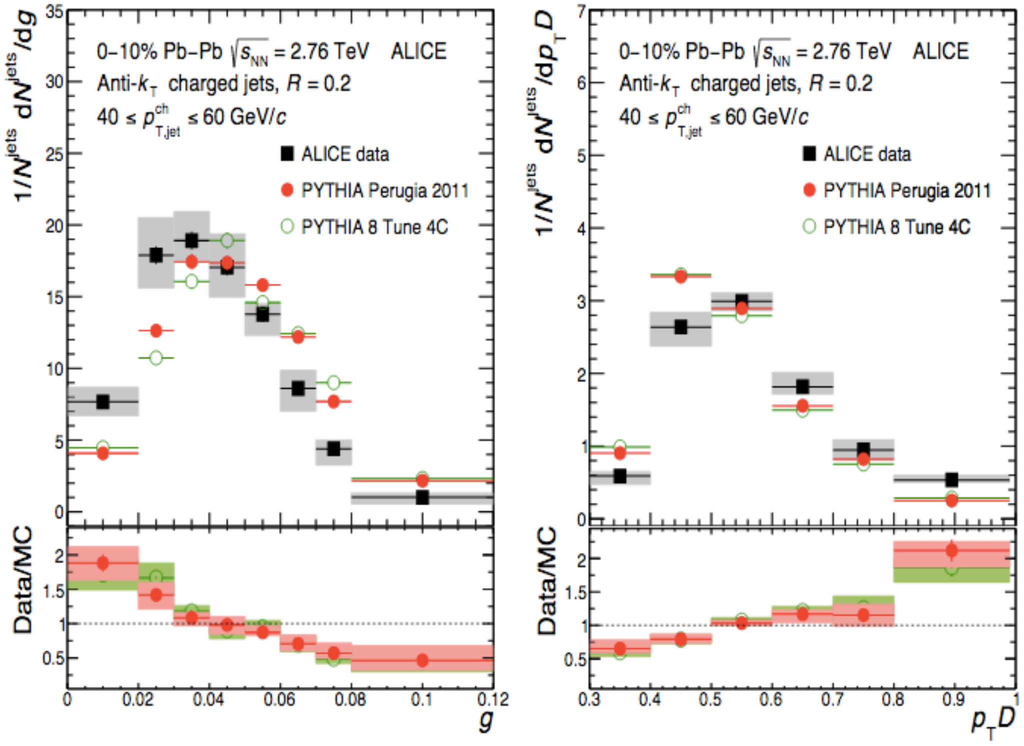
If it is not color coherence what dictates the suppression of splittings at large angle, is it driven by formation time effects?

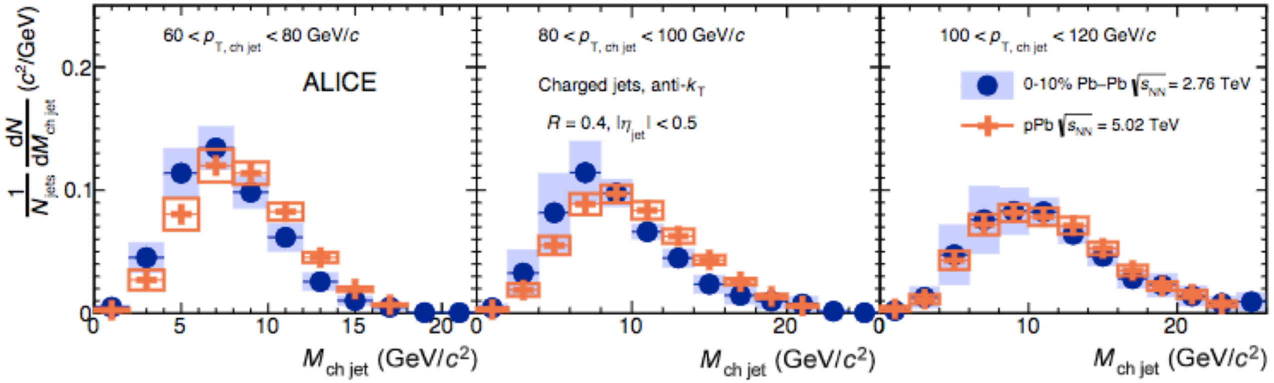


At large angles/energies:
The un-modified vacuum splittings
are suppressed
Thus more sensitive to medium-modified
splittings

Or is it a kinematic effect?
By selecting large angle splittings we bias towards higher Q^2 structures that are more quenched?

Generalized angularities in Pb-Pb: mass, $p_T D$, girth…

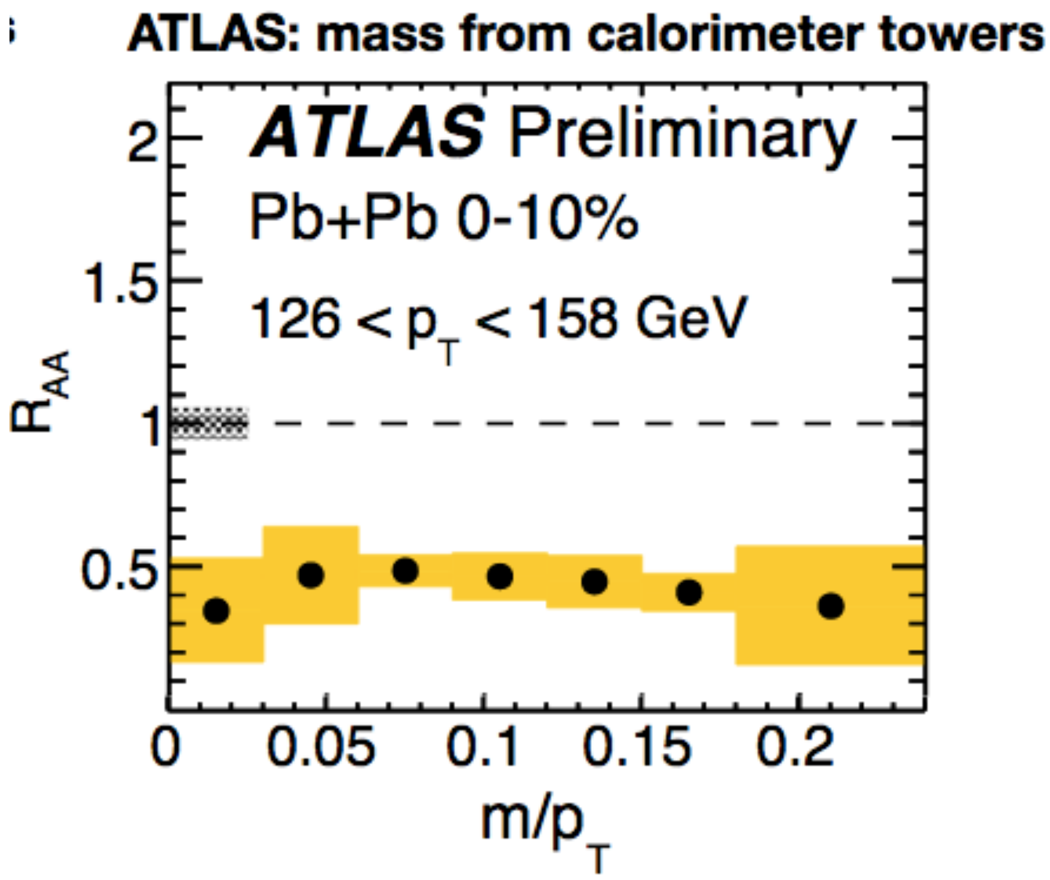




Picture qualitatively consistent with collimation of the jet core

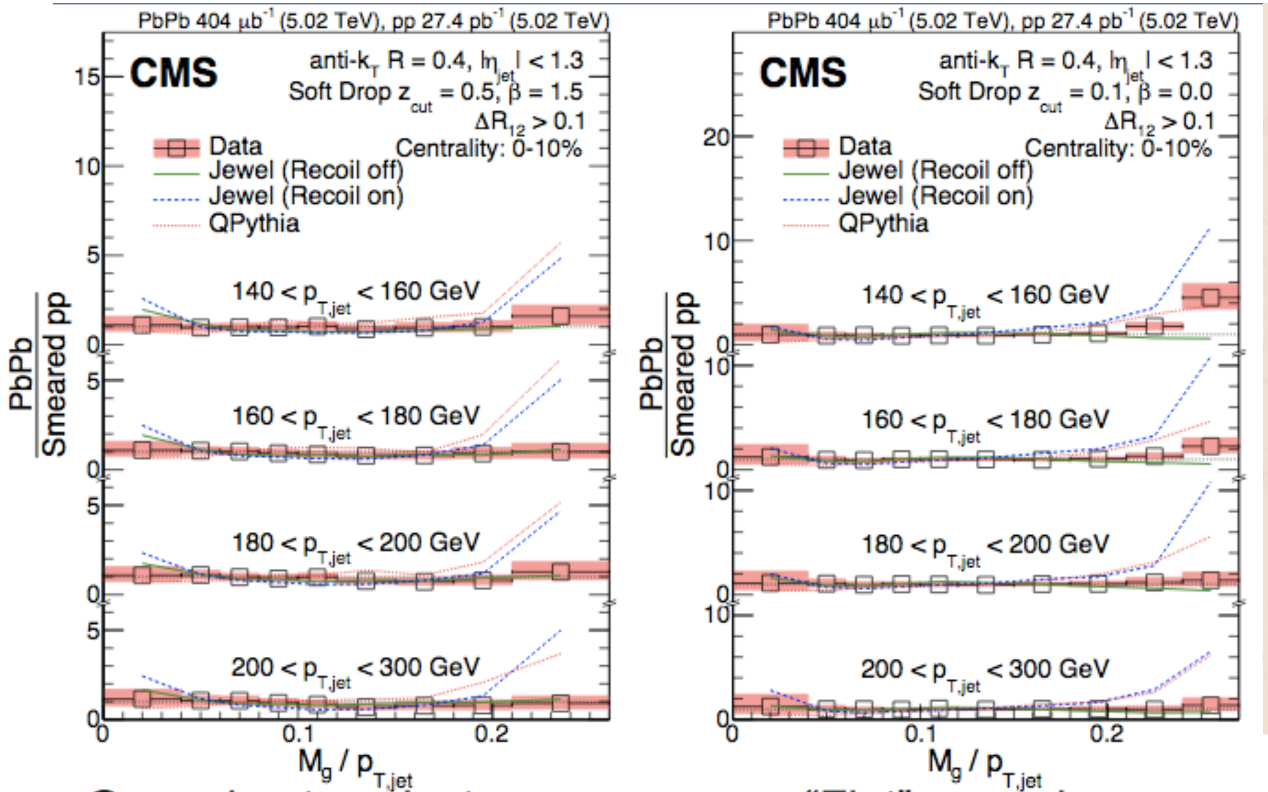
The jet core seems to be narrower and to fragment harder than the pp reference

Generalized angularities in Pb-Pb: mass, pTD, girth…



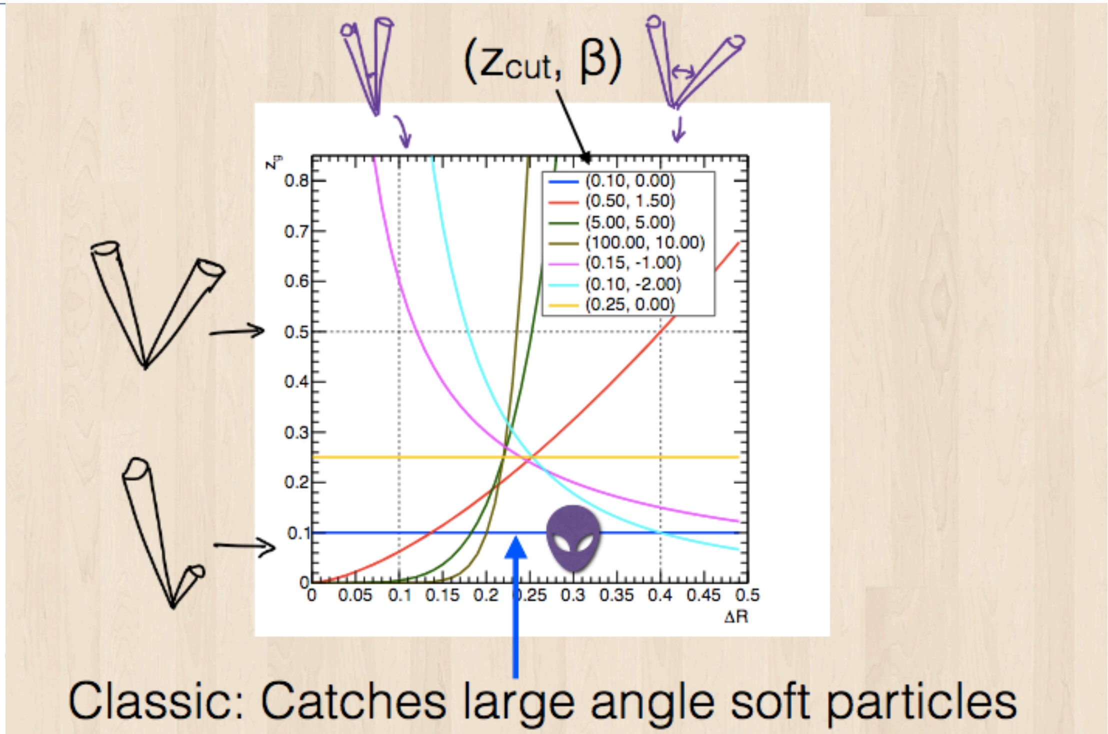
No apparent dependence of the energy loss on the jet mass is observed

Groomed mass for different grooming settings



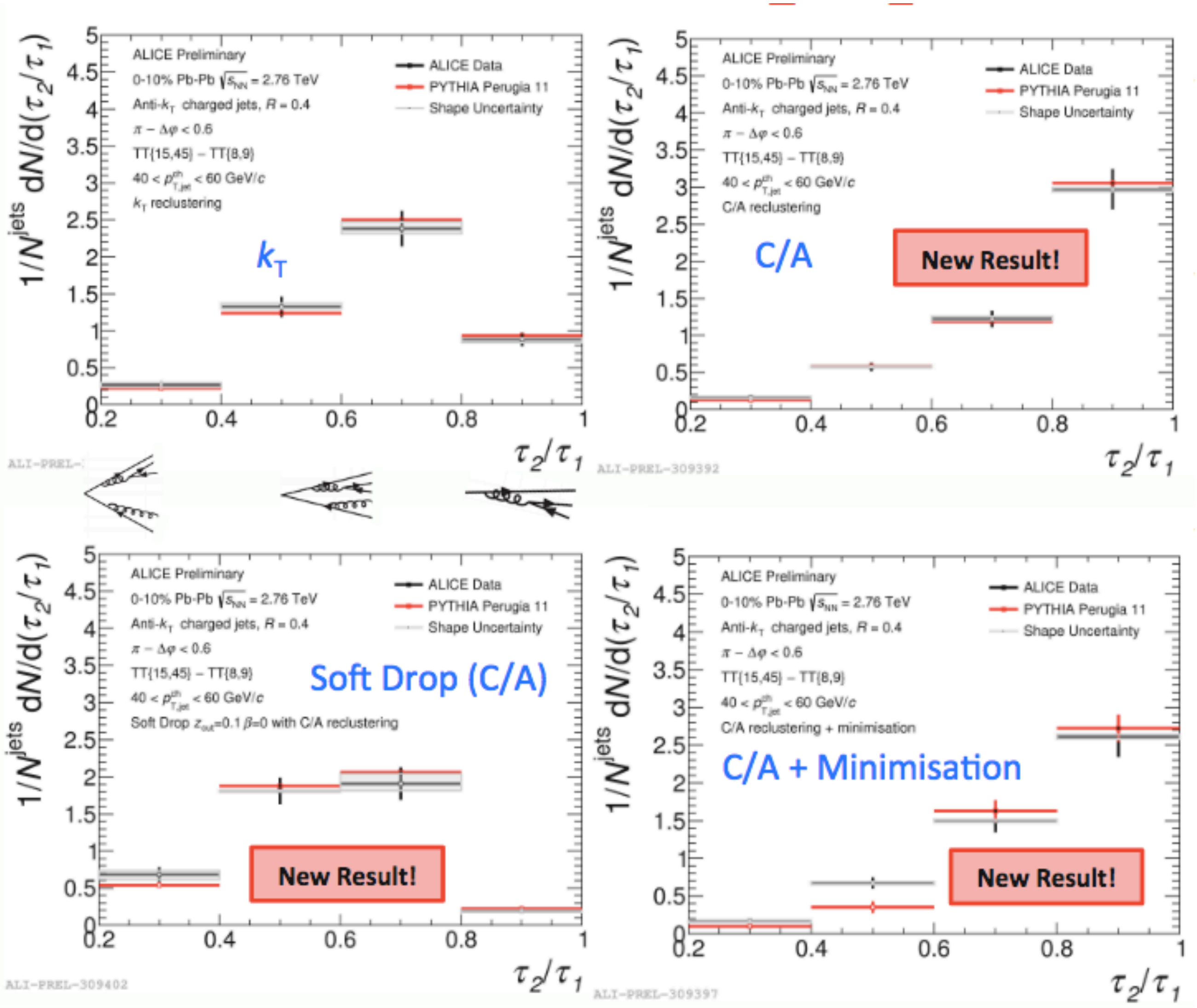
Grooming to select core

“Flat” grooming



Interesting exploration of the phase space of emissions
Some effects observed at the tails

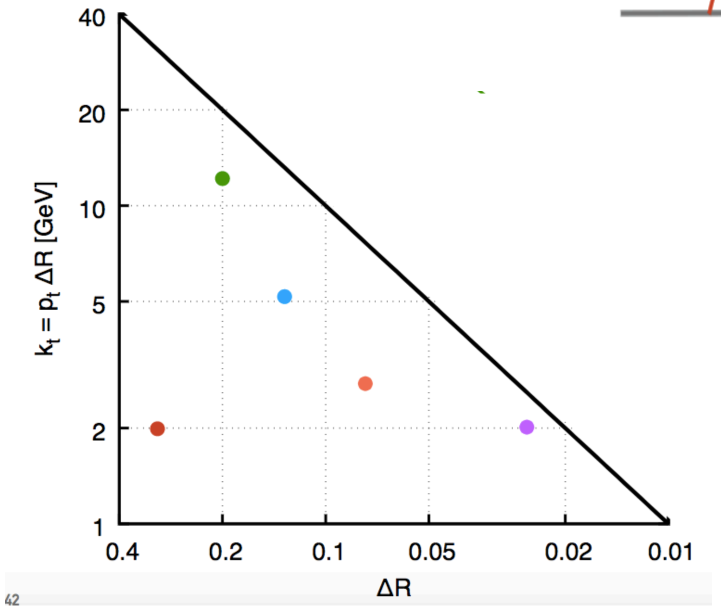
The 2-subjettiness: extra medium-induced prongs?

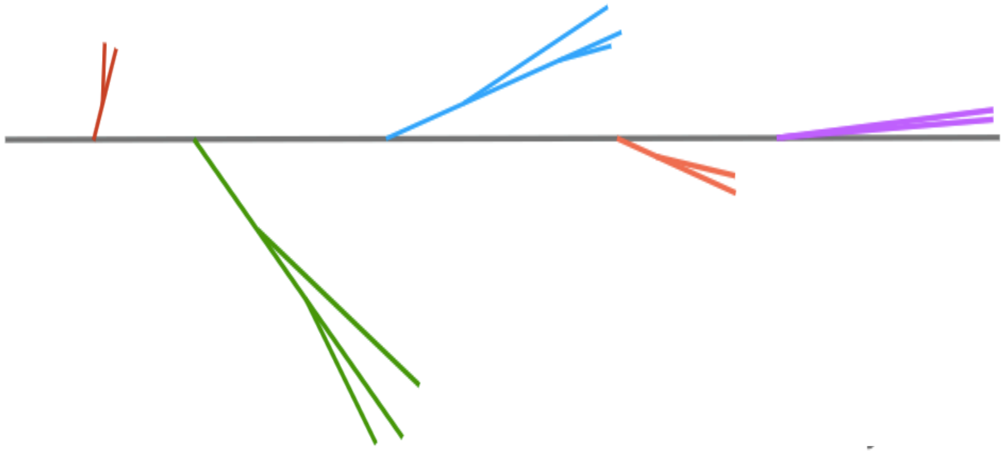


$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$

The way radiation is aligned relative to the chosen prong axes (a very different set of splittings was considered) does not change in medium relative to vacuum

The map of splittings in vacuum, the Lund plane





Unwind the CA clustering

At each step, register the k_T, ΔR coordinates

Follow the hardest branch at each step

plot from G.Salam, QM18

$$\boxed{d^2P = 2\frac{\alpha_s(k_\perp)C_R}{\pi}dln(z\theta)dln(\frac{1}{\theta})}$$

In vacuum, flat 2D density except for variation of the coupling with scale k_T

General observable, others can be derived from it

The Lund plane in vacuum

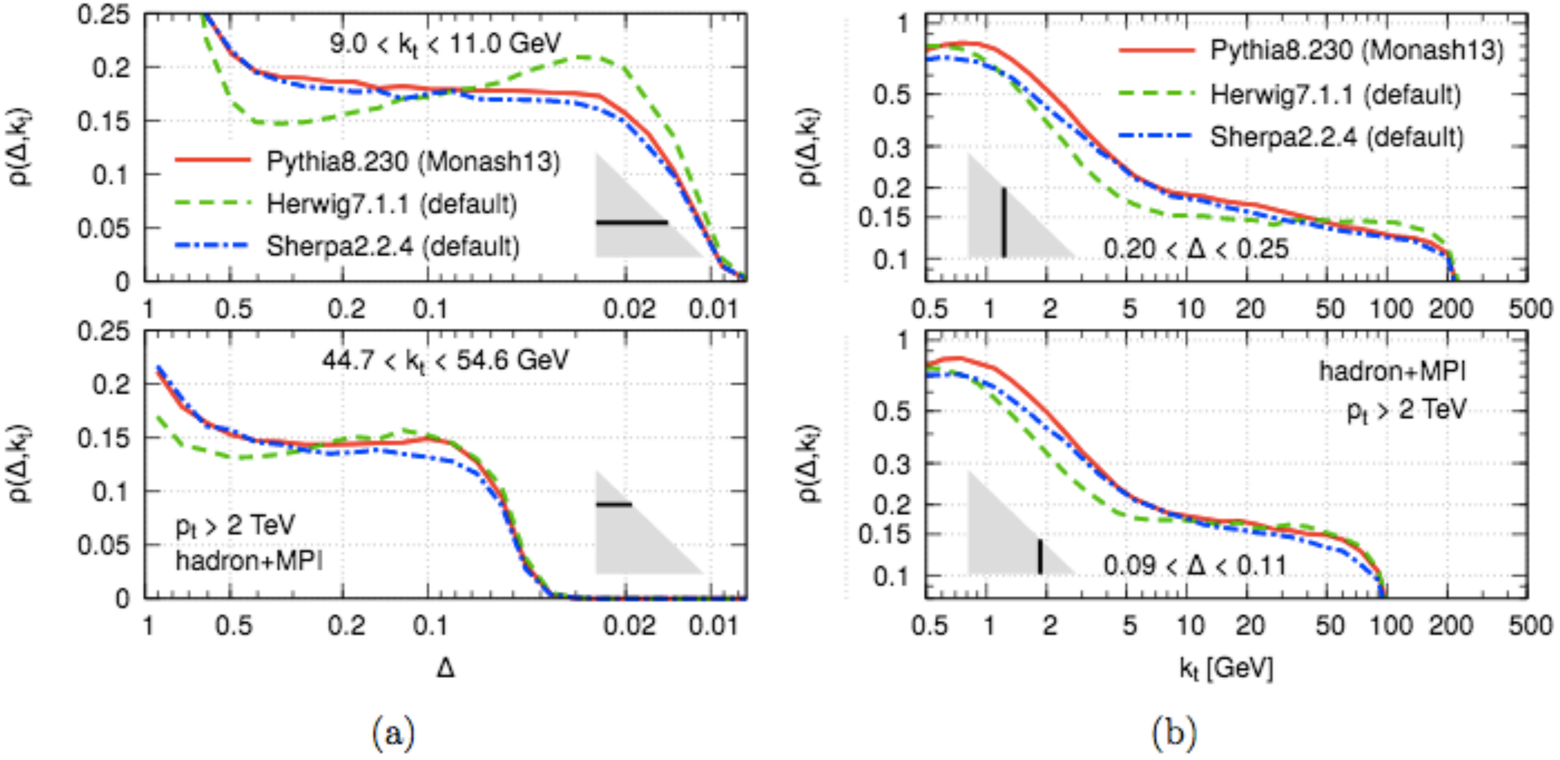
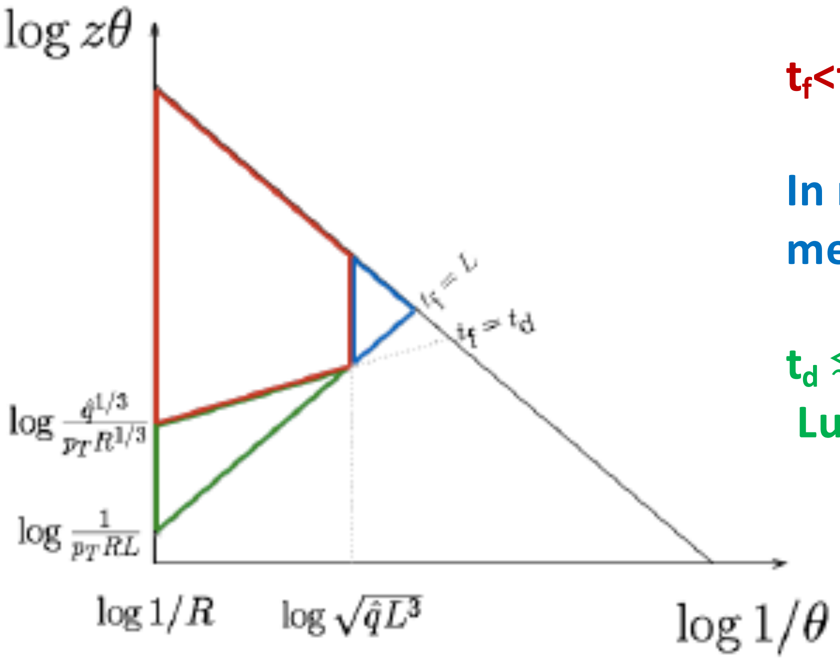


Figure 3: Emission density along slices of the Lund plane, at fixed k_t (top) and Δ (bottom), comparing three event generators.

Similar scanning of the pp data should be done (and is ongoing ☺)

Dreyer et al,JHEP 1812 (2018) 064

Map of splittings in medium



Multiple scales in medium:

$t_f<t_d<L$ vacuum splittings inside the medium

In medium splittings with $t_d>L$:not resolvd by the medium interactions

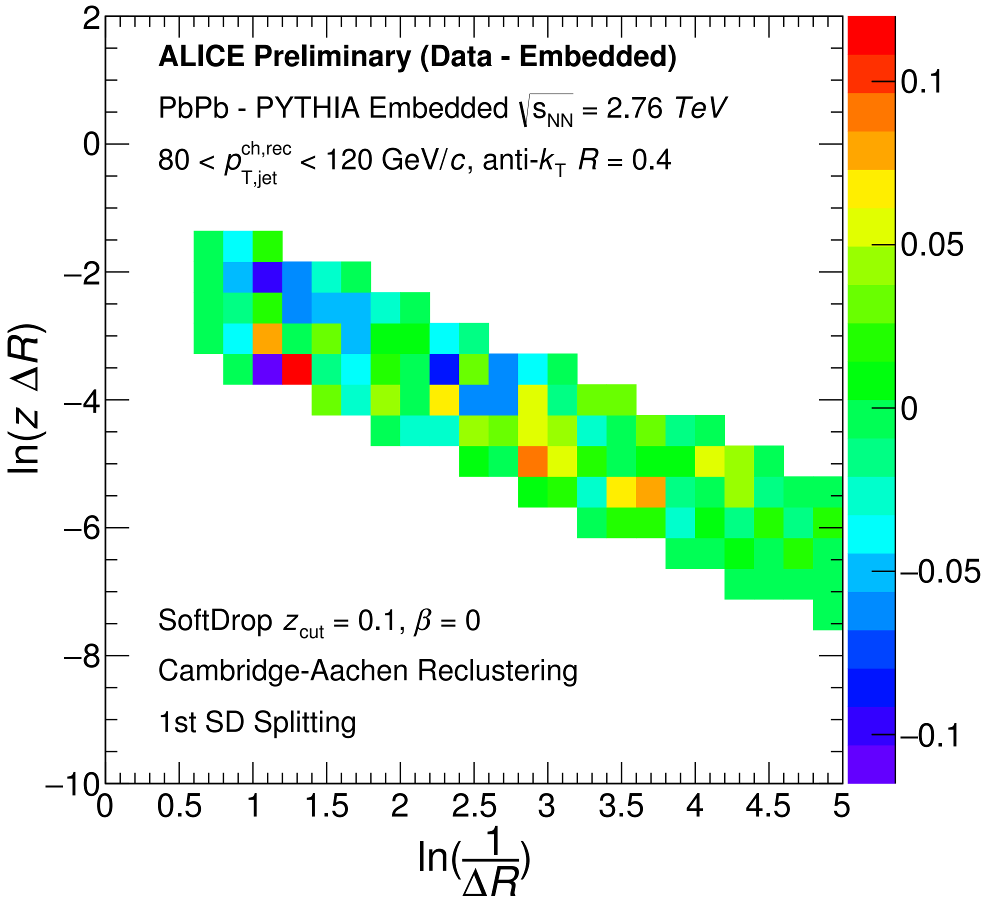
$t_d \lesssim t_f$ splitting kinematics dominated by medium effects
Lund plane not filled with the pQCD uniform probability

The density of splittings in heavy ion collisions is not expected to be constant in the Lund plane, medium-induced radiation follows different “rules” compared to vacuum radiation

K.Tywoniuk et al, Novel tools and observables for jet physics in heavy ion collisons,
https://arxiv.org/pdf/1808.03689.pdf

The splitting map in Pb-Pb

Probability density difference: Data - PYTHA embedded into Pb-Pb events



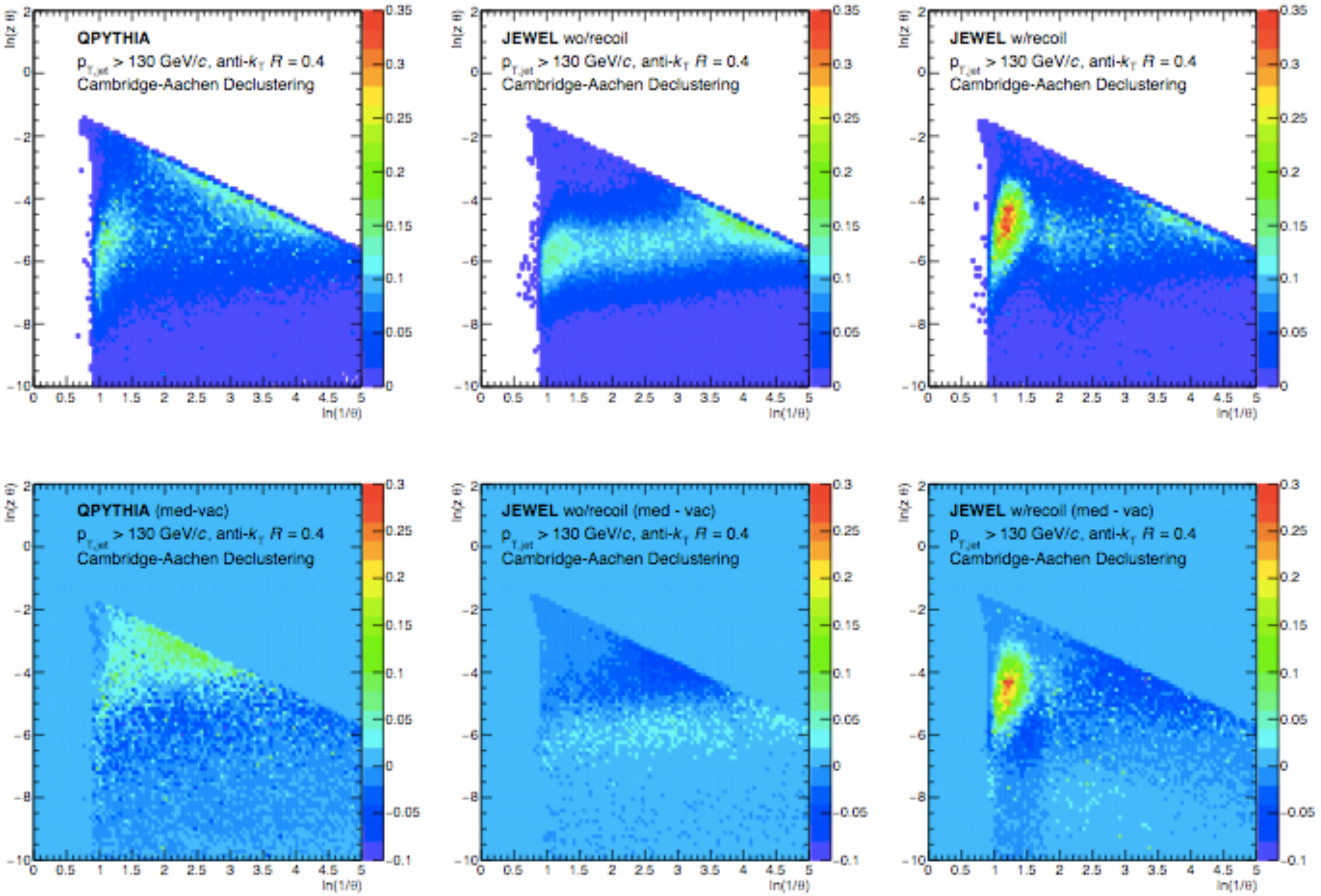
ALI−PREL−148246

So far we have focused on the region defined by SD cuts z_{cut}>0.1, β=0

Hint of suppression/enhancement of large/small angle splittings in data relative to the vacuum reference

Very low statistics! to be improved with recent Pb-Pb 2018 run data

The splitting map in PbPb: models



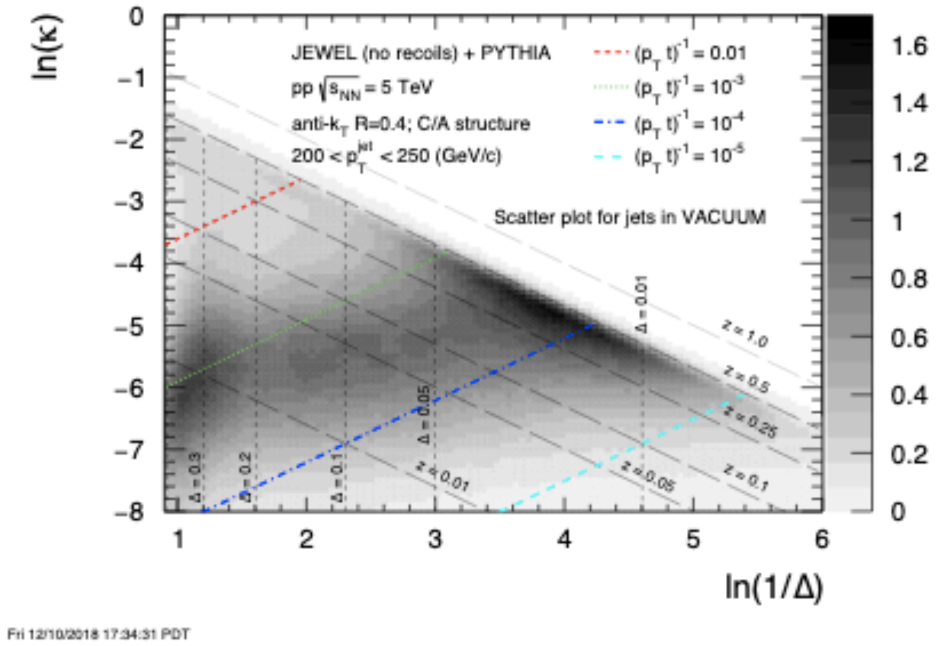
QPYTHIA is a MC that modifies the Sudakov form factor with an enhanced medium splitting function, leading to a strong intrajet broadening -> increased density of splittings at high k_T

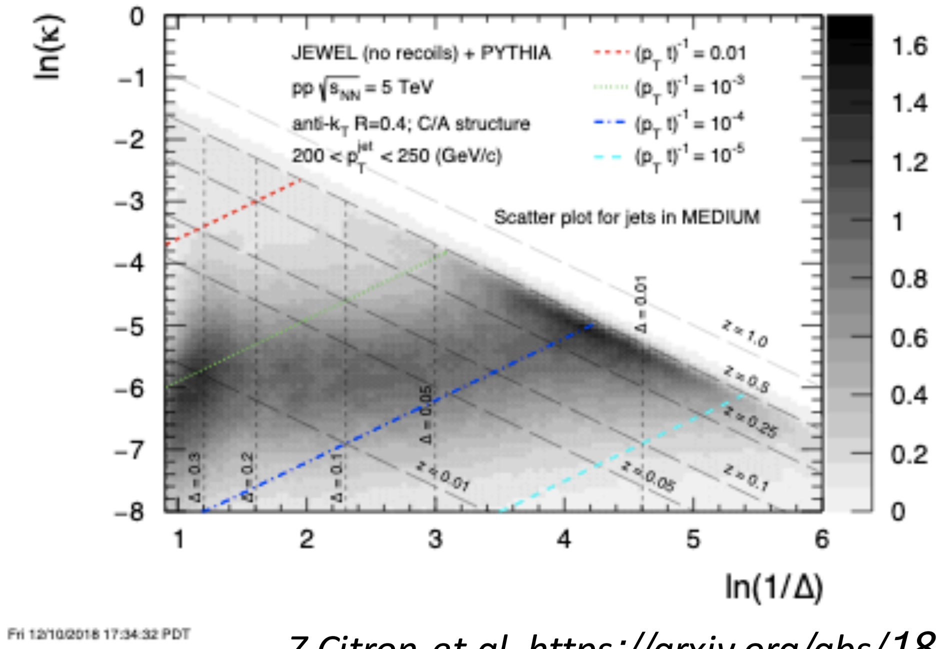
JEWEL recoils populate the large-angle side of the map

Possibility to visualize and isolate the different elements of the theory

https://arxiv.org/pdf/1808.03689.pdf

The splitting map in Pb-Pb, projections





Z.Citron et al, https://arxiv.org/abs/1812.06772

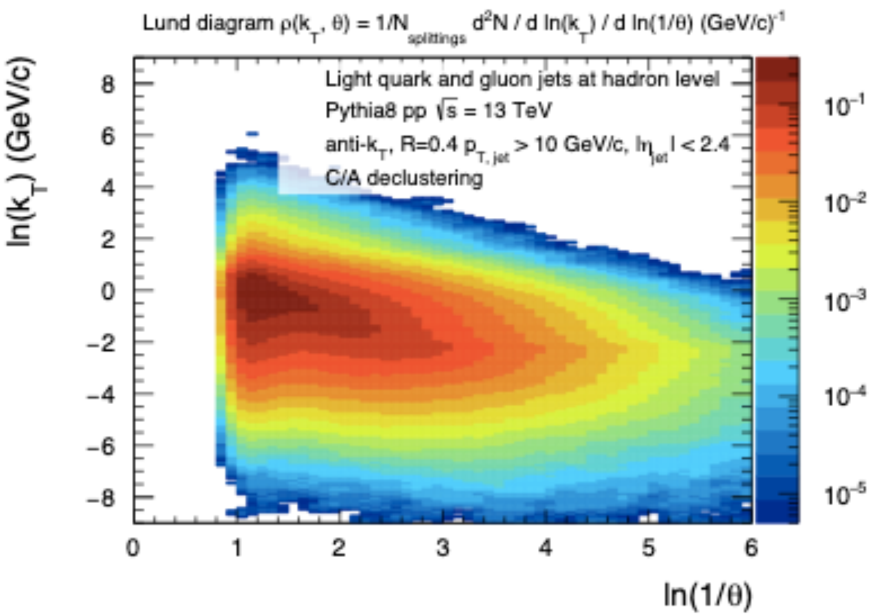
Higher statistics will allow for a detailed scan of the Lund plane.

Slicing in formation time will allow to select early splittings that are fully produced and decohered in the medium, and to reduce the unmodified vacuum component of radiation

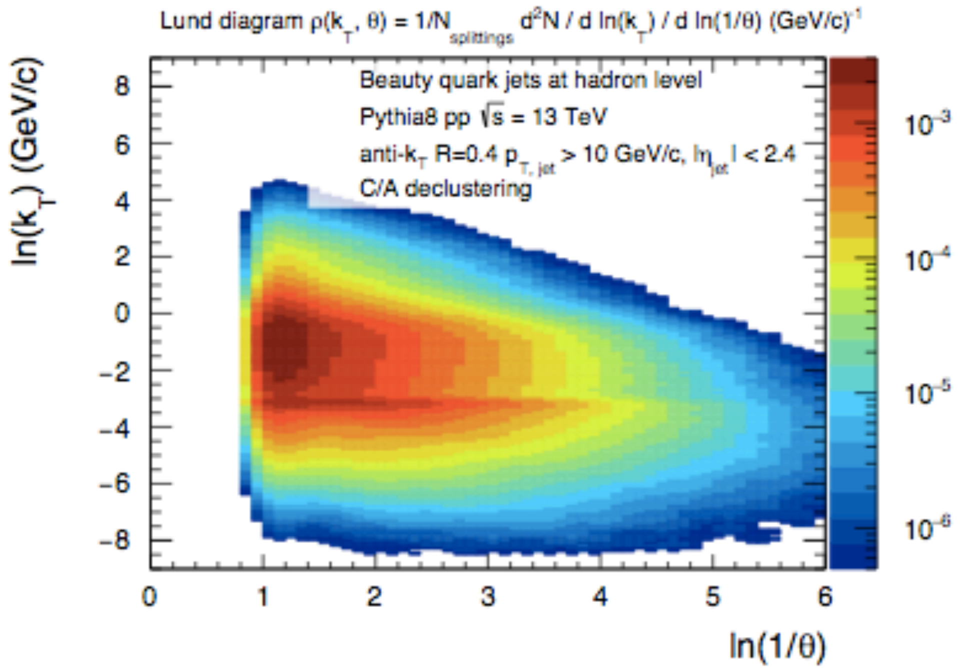
Projections onto scale k_T axis for fine bins of angle are forseen, in order to measure broadening and to look for Rutherford-like scatterings.

Other applications of the Lund map: exposing he dead cone effect

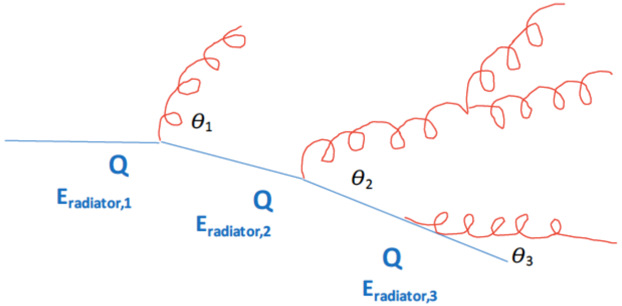
Hadron level inclusive jets



Hadron level B jets



L.Cunqueiro, M.Ploskon, Phys.Rev.D99 (2019)no.7.

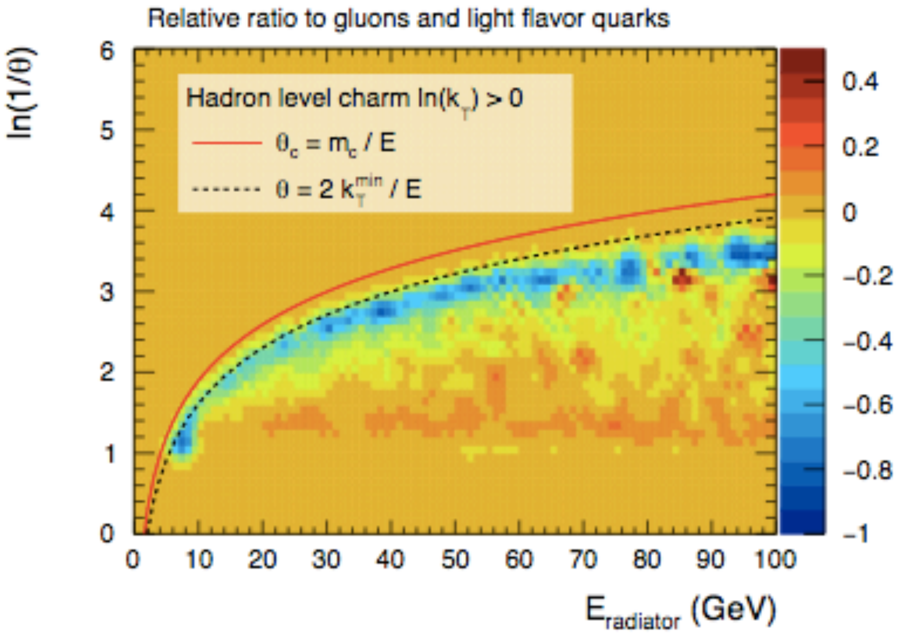


Iterative declustering following the chunk that cotains the HF hadron

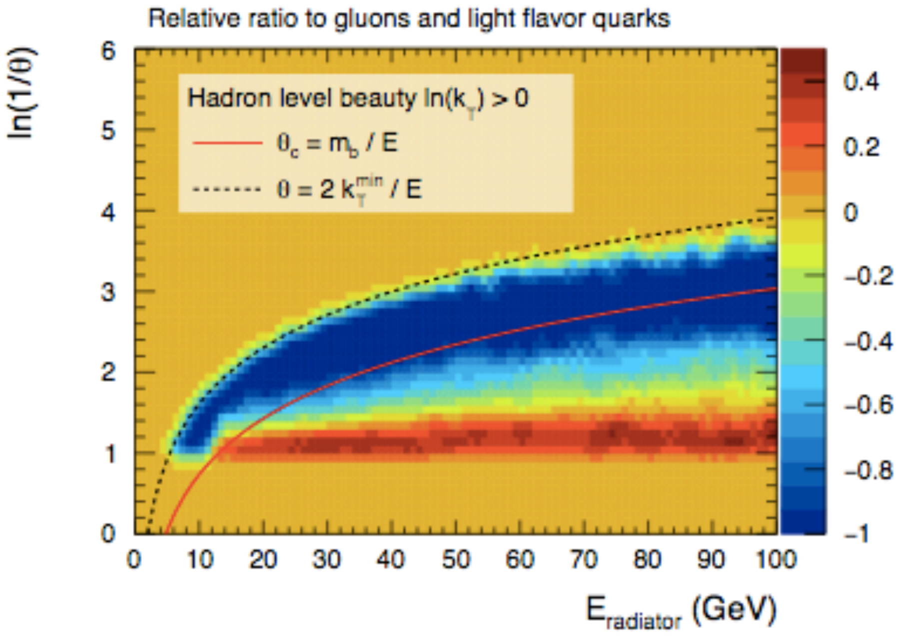
Already by eye, without further analysis, one can see that the angle distributions are different for heavy and light partons, the low angle reach is more limited for the heavy flavors

Other applications of the Lund map: exposing he dead cone effect

charm



beauty



$$Q = \frac{P^Q(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

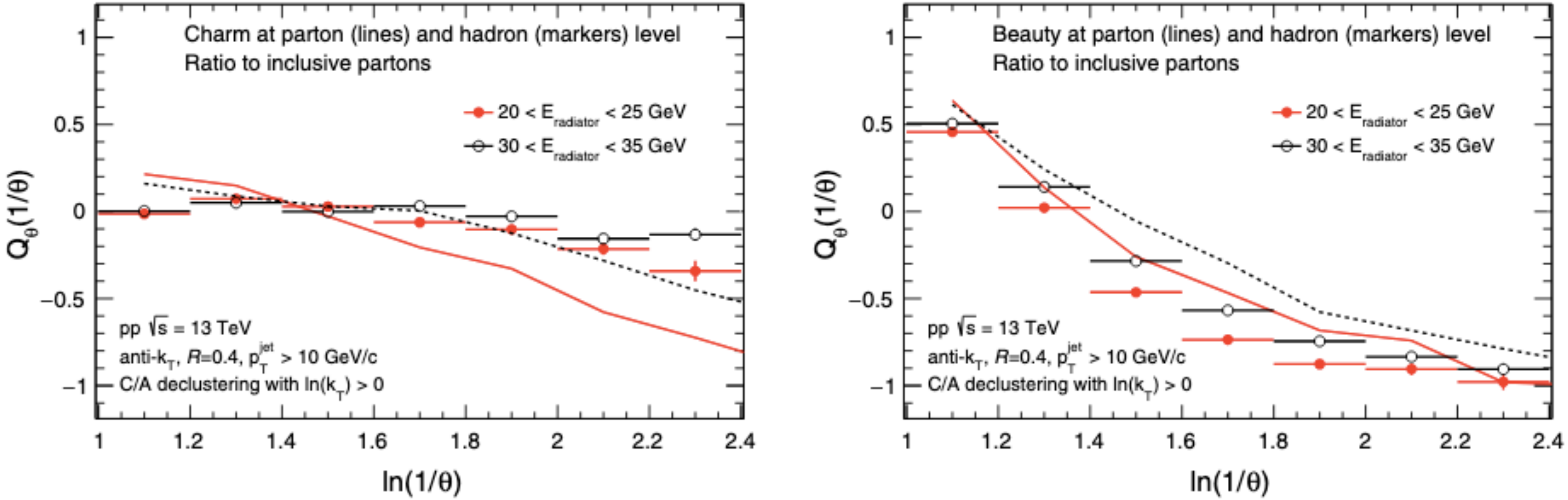
At hadron level the effects are smeared but not washed out

As expected: the higher $E_{radiator}$ is, the dead cone effects appear at smaller angles.

For D jets, the effects appear at measurable angles of ~0.1 rad for radiator energies of 10-30 GeV

For B jets, one can go higher in radiator energy and still have effects at angles of the order of 0.1 rad

Other interesting applications of the Lund plane, exposing the dead cone at colliders



Dead cone effect accessible experimentally even for charm jets

$$Q_\theta = \frac{P^Q(1/\theta) - P^{inc}(1/\theta)}{P^{inc}(1/\theta)}, E_{radiator} \in (E_{min}, E_{max})$$

The ideal measurement will require fully reconstructed heavy flavours, access to low energy subjets of about 10-20 GeV and a detector that allows to resolve subjets at angular distances of 0.1 radians.

Summary

-Accessing microscopic properties of QCD matter via jet substructure, in reach.

-Strong sinergy between jet substructure in Heavy Ions and HEP community
Plethora of jet tools to explore: grooming, iterative reclustering….

-Searches of medium-induced signal by the scanning of the Lund plane ongoing

-New possibilities will be opened with the measurement of large R-jet substructure

Thanks!

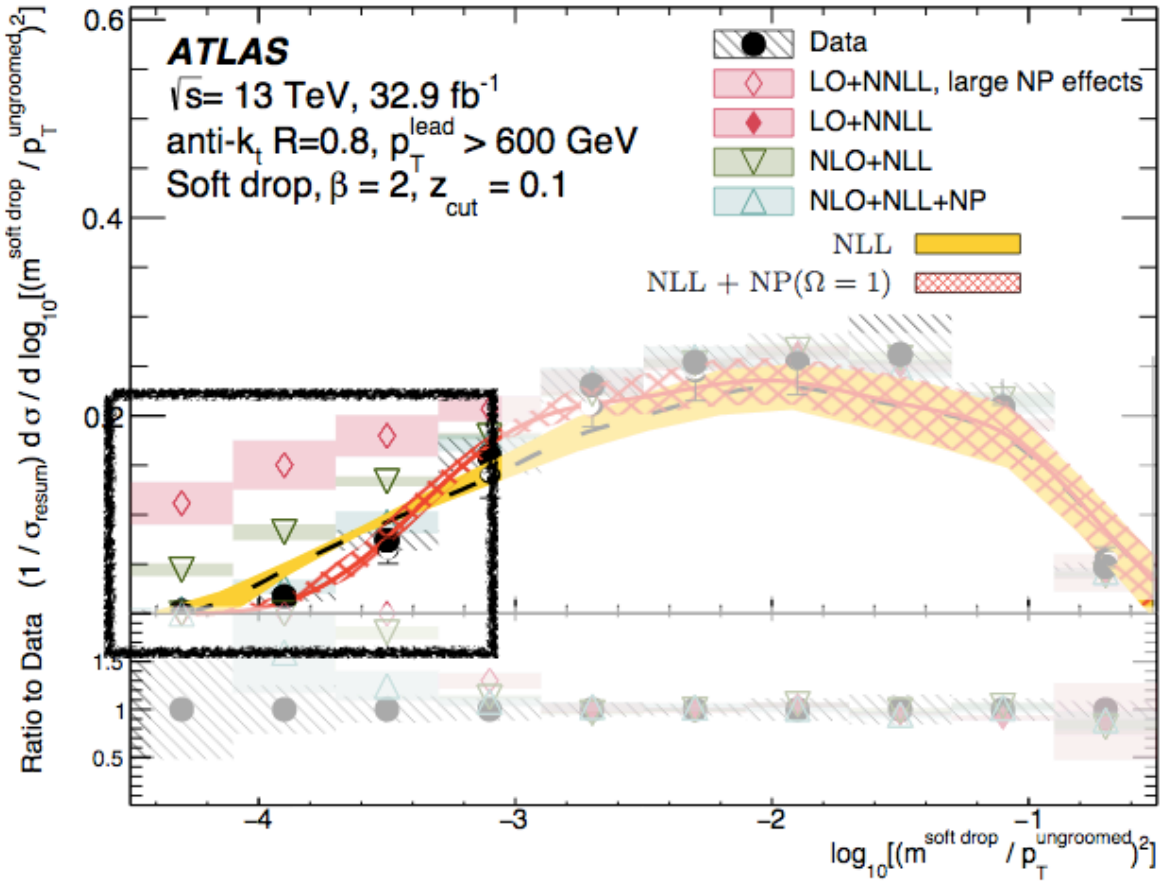
How to look inside a jet?

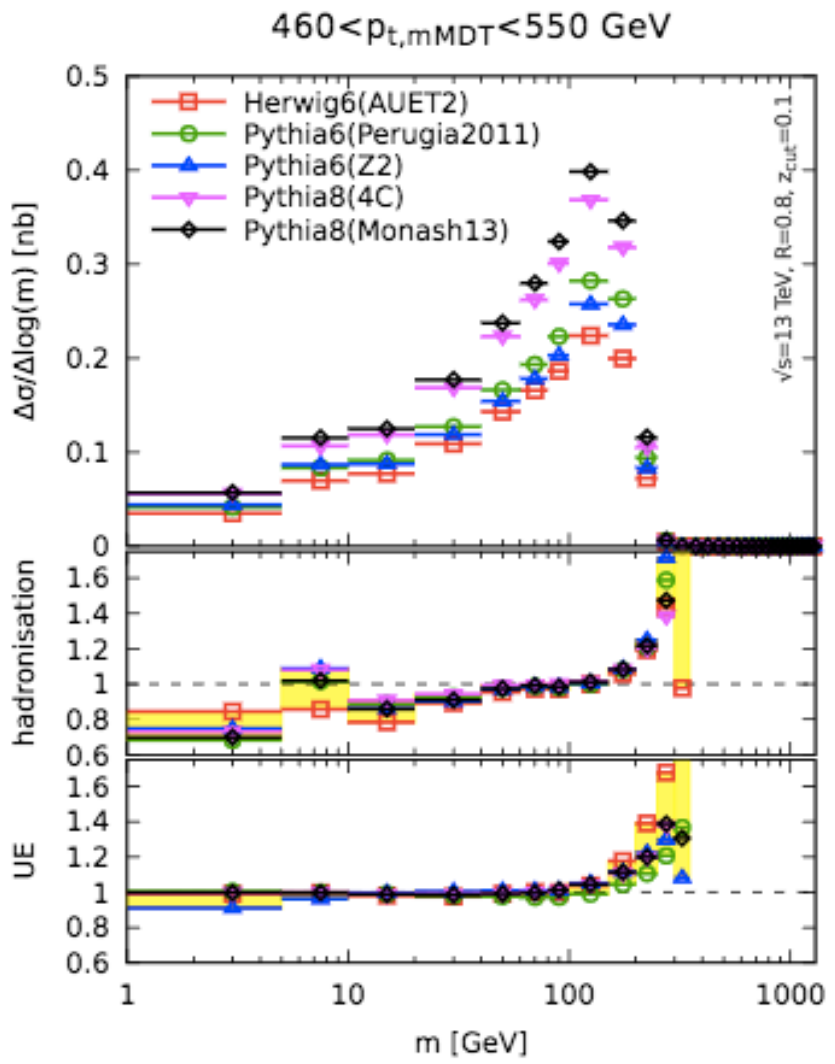
-Define jet shape variables: a function of the jet consitutents.
Examples: jet mass, angularity, pTD (generalized angularities), FF…

-Recluster the jet constituents with a hierarchical algorithm.
Unwind the clustering history of the jet to access the jet tree
Examples: n-subjettiness, zg, nSD,…groomed shapes in general…

Jet substructure pays a main role in LHC analysis, for instance in q/g discrimination or tagging of boosted objects.
In heavy ion collisions, we use it to probe the microscopic structure of QCD matter in AA

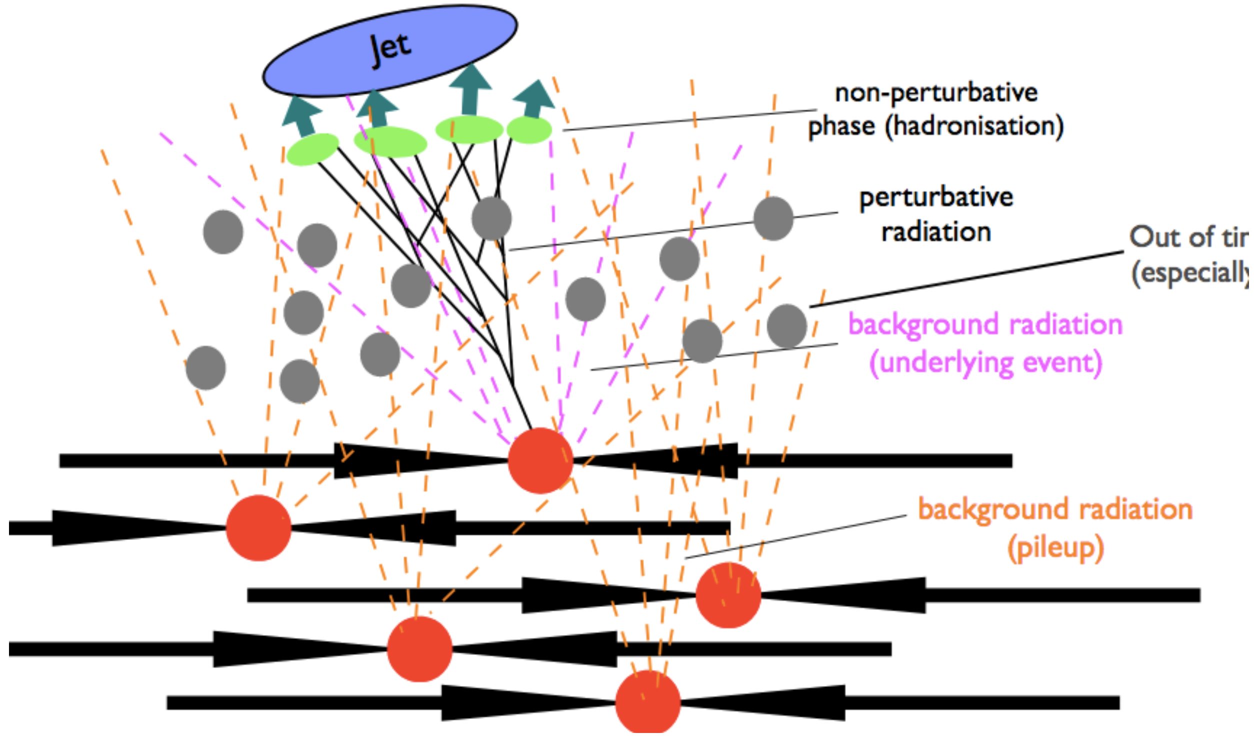
Jet shapes: differential constrain





Large region in mass where NP effects (yellow bands, right plot) are negligible
->great constrain to perturbative aspects of parton showers

Pileup subtraction



$$\Delta p_t = \boxed{\rho A \pm (\sigma\sqrt{A})}$$

Particles that are uncorrelated to the hard scattering will contaminate the jet.

The jet momentum can be adjusted, the jet area is the background susceptibility

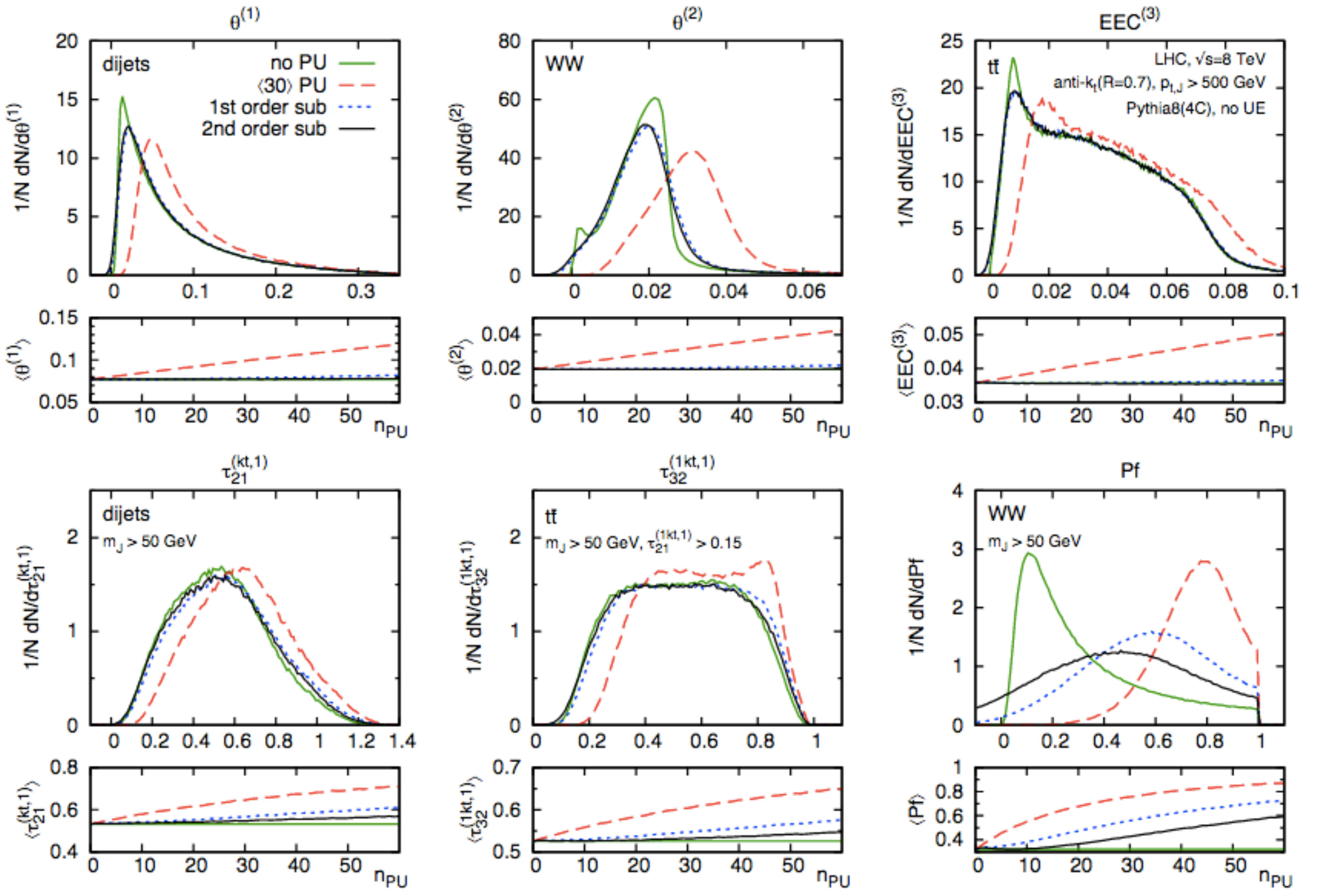
The area-based equation below can be extended to shapes, to perform a zero-biased background subtraction, simultaneous in jet pt and shape

Salam,Cacciari et al

Other methods modify the event by removing particles according to some prescription. Not bias-free.

Constituent Subtraction (Berta, Spousta, Miller, Leitner, 1403.3108)
SoftKiller(MC, Salam, Soyez, 1407.0408)
PUPPI (Bertolini, Harris, Low, Tran, unpubl.)
...

Pileup subtraction



The event pileup is characterised by $\boldsymbol{\rho}$ and $\boldsymbol{\rho}_m$ Ghost particles are added uniformly in the acceptance, each mimicking a pileup-like component in a region of area A_g.The sensitivity of the shape to bkg is determined by calculating its derivatives with respect to the transverse momentum and mass of the ghosts. The value of the shape is then extrapolated by a Taylor series to zero pileup.

Soyez, Salam et al
Phys.Rev.Lett. 110 (2013) no.16, 162001

Jet grooming

Trimming

- Take jet with radius R
- Reclusters components into smaller subjets with radius $R_{sub} < R$
- Keep subjets that satisfy $p_{t,\,sub} > z_{cut}\, p_{t,\,jet}$

Pruning

- Define pruning radius $R_{prun} = R_{cut} * 2\, m / p_t$
- For every step of clustering $j_1 + j_2 \rightarrow j_{12}$, check:
  - Wide-angle: $\Delta R_{12} > R_{prun}$
  - Soft: $\min(p_{t1}, p_{t2}) < z_{cut}\, p_{t,\,jet}$
- If either condition fails, eliminates softer subjet
- If both pass, continue clustering

SoftDrop (or mMDT)

- Decluster jet $j_{12} \rightarrow j_1 + j_2$
- Check condition $\min(p_{t1}, p_{t2})/p_{t,jet} > z_{cut}(\Delta R_{12}/R)^{\beta}$
  - z_{cut}, β: tunable values
- If condition fails, the softer subjet is removed
- If passes, stops recursion
- For β=0, it is mMDT

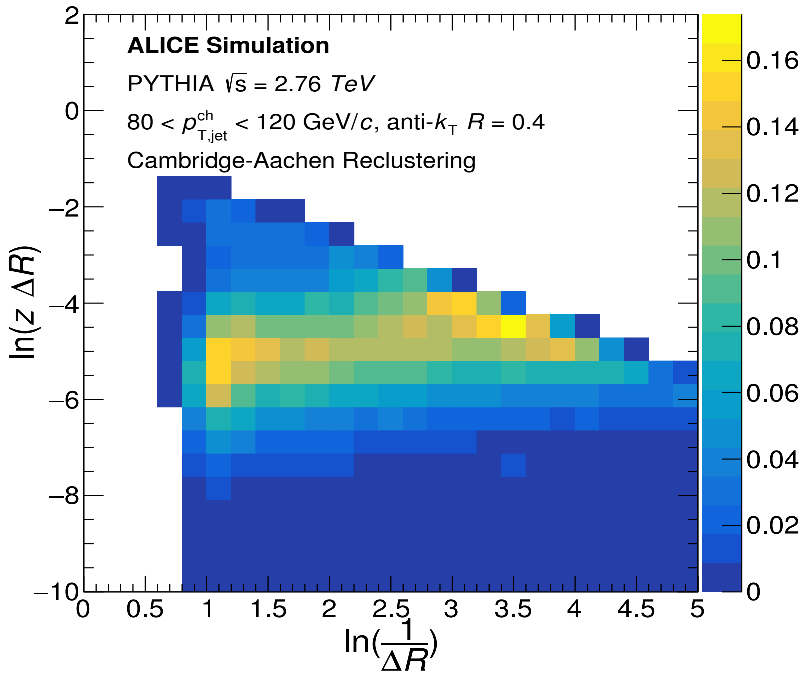
AIM: Limit contamination of QCD background in a controlled way while retaining the bulk of perturbative radiation ->interesting idea to export to HI!

Several fundamental questions to answer

- Can we probe the partonic degrees of freedom within the strongly-coupled QGP? Do we have access to the Moliere regime? Can we detect scatterings off quasi-particles via large angle deflection of jets/constituents?
- Is color coherence at work and what are the critical angles?
- Is flavour hierarchy respected in medium?
- Related to the 3 previous points: how does energy loss depend on the jet substructure?
- Can we experimentally isolte specific aspects of the in-medium shower that are under better theoretical control?

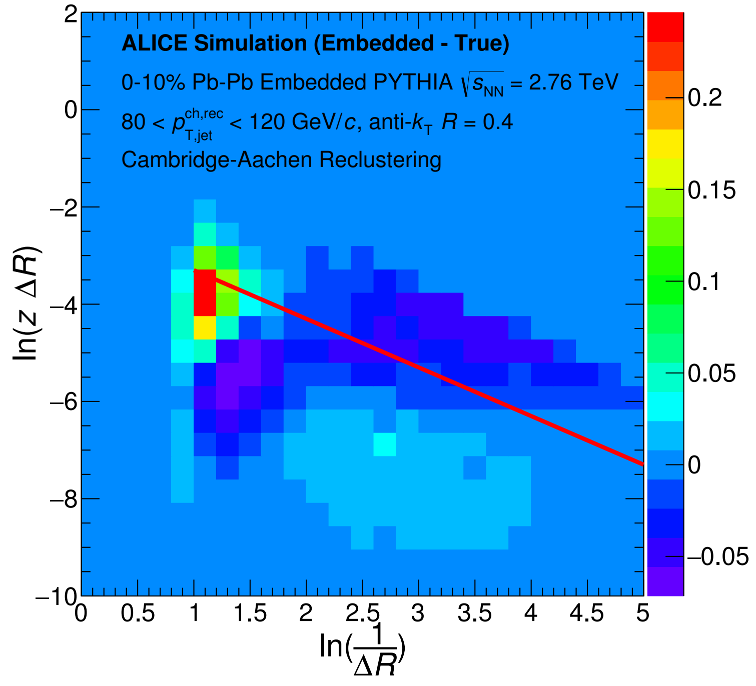
Map different contributions: uncorrelated background

PYTHIA jets



ALI-SIMUL-161454

PYTHIA jets embedded into 0-10% central Pb-Pb events

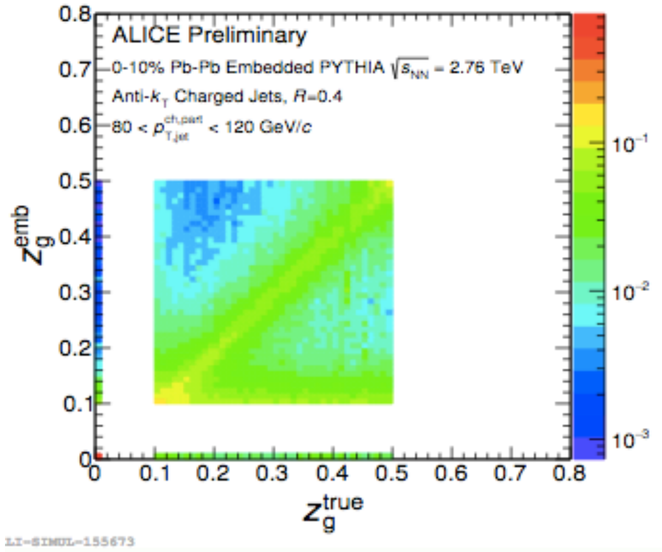


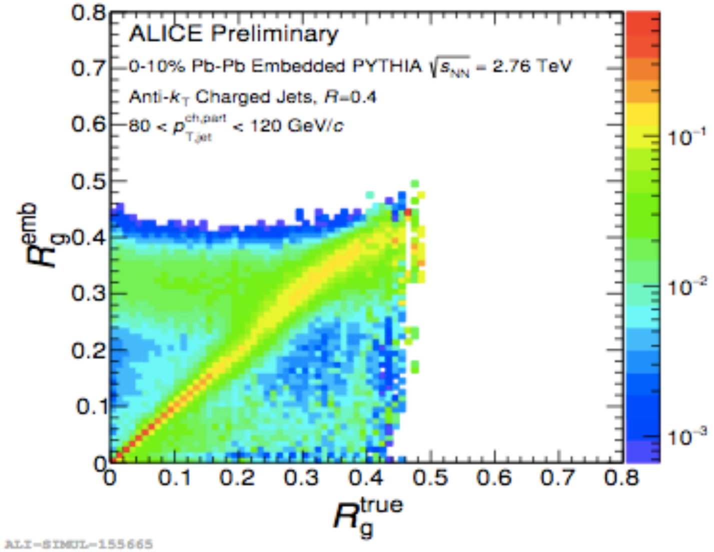
ALI-SIMUL-154411

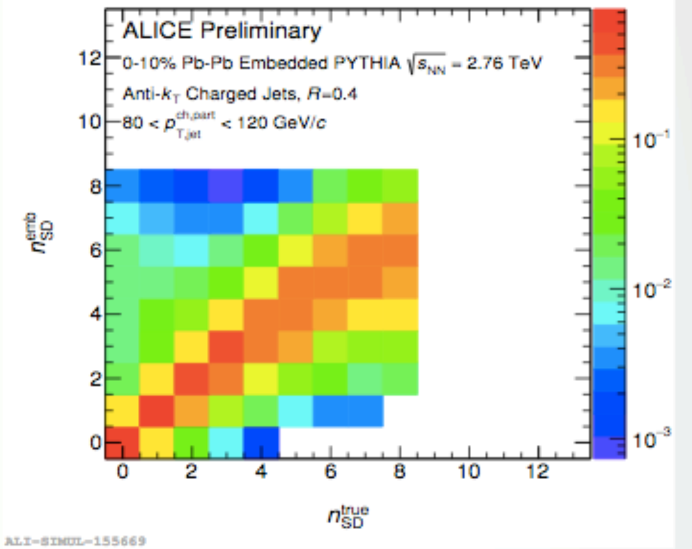
Fake splittings appear at large angles θ ~R and lowish z

They contribute to the groomed signal (above red line representing SD condition z_{cut}> 0.1, β=0)

Fake splittings







- Uncorrelated background **adds splittings** at **low z_g**.
- Fake splittings **appear** at **large R_g** due to the background.
- n_{SD} appears relatively robust to the presence of background.

Fundamental question in the physics of heavy ion collisions:

How do collective phenomena and macroscropic properties of matter arise from the elementary interactions of a non-abelian quantum field theory?

Opportunities	Tools	Status
Constraining equilibrium properties of QCD matter (eos, η/s , ξ , τ_π ...	Flow and fluctuation measurements in AA	advanced
Measuring medium properties with hard auto-generated probes ($\hat{q}$, $\hat{e}$, T), ...	Quarkonia, R_{AA}'s , photons	in progress
Accessing microscropic structure of QCD matter in AA	Jet substructure, heavy flavor transport	in reach
Controlling initial conditions	pA (light AA) runs, npdf global fits, small-x	in reach
Testing hydrodynamization and thermalization	Combined jet and flow analyses	strategy t.b.d.
Understanding "heavy-ion like behavior" in small systems (pp, pA)	Flow, hadrochemistry, jets	recent surprises

Slide stolen from Urs Wiedemann, Workshop on the physics of HL-LHC

Jet shapes: generalized angularities

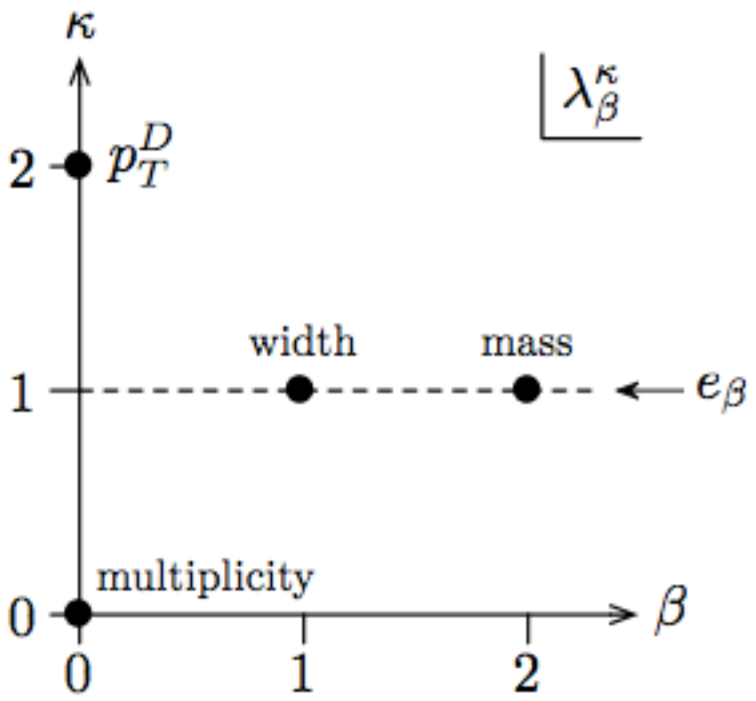
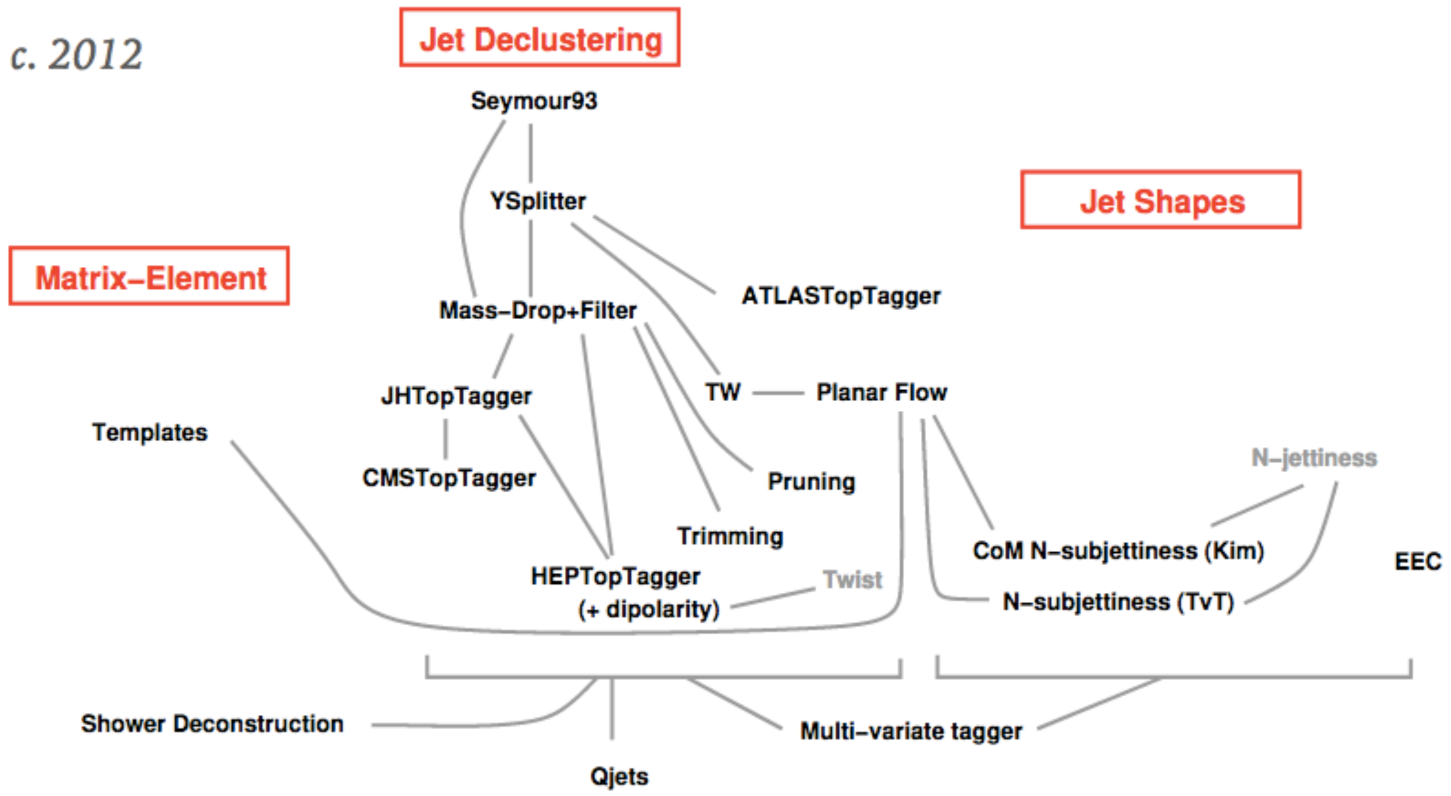


Diagram from Thaler et al

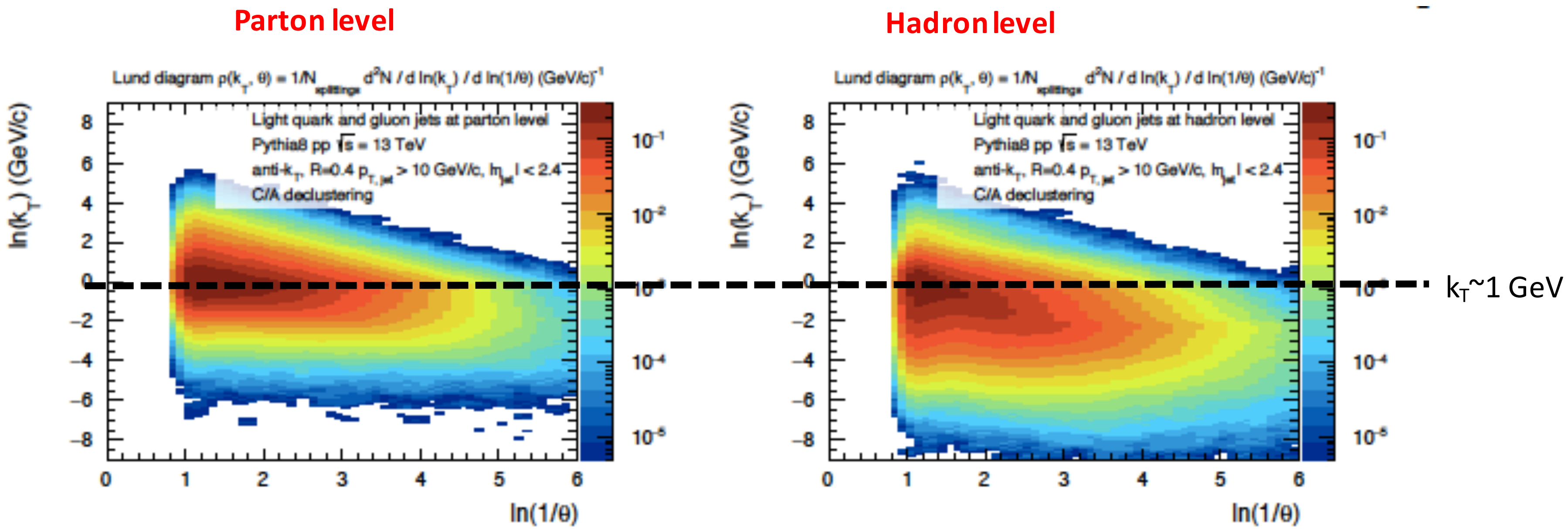
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{R_i}{R_0} \right)^\beta$$

Exploring systematically the phase space of jet shapes

Plethora of techniques



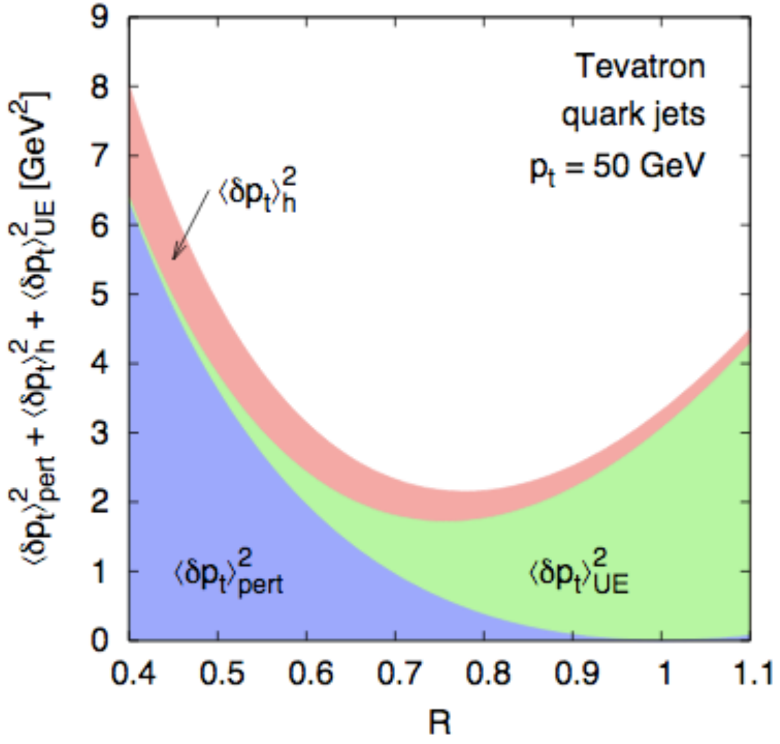
Map different contributions: hadronization



L.Cunqueiro, M.Ploskon, https://arxiv.org/pdf/1812.00102.pdf

Non-perturbative effects can be removed/isolated by cutting at $\ln(k_T)$>/< 0

The perturbative and non-perturbative components of the jet



	Dependence of jet $\langle \delta p_t \rangle$ on			
	'partonic' p_t	colour factor	R	$\sqrt{s}$
perturbative radiation	$\sim \alpha_s(p_t)\, p_t$	C_i	$\ln R + \mathcal{O}(1)$	–
hadronization	–	C_i	$-1/R + \mathcal{O}(R)$	–
underlying event	–	–	$R^2 + \mathcal{O}(R^4)$	s^ω

Dasgupta, Magnea, Salam **JHEP 0802 (2008) 055**