Jet Substructure in Heavy Ion Collisions at ALICE

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Boost 2018, July, Paris

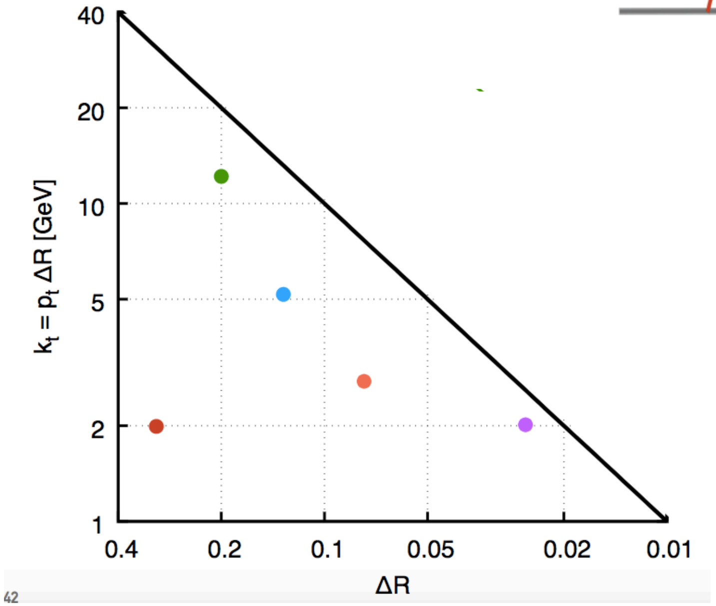
Fundamental question in the physics of heavy ion collisions:

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, $\eta/s\,,\xi\,,\tau_\pi\,\ldots$	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 microscopic 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

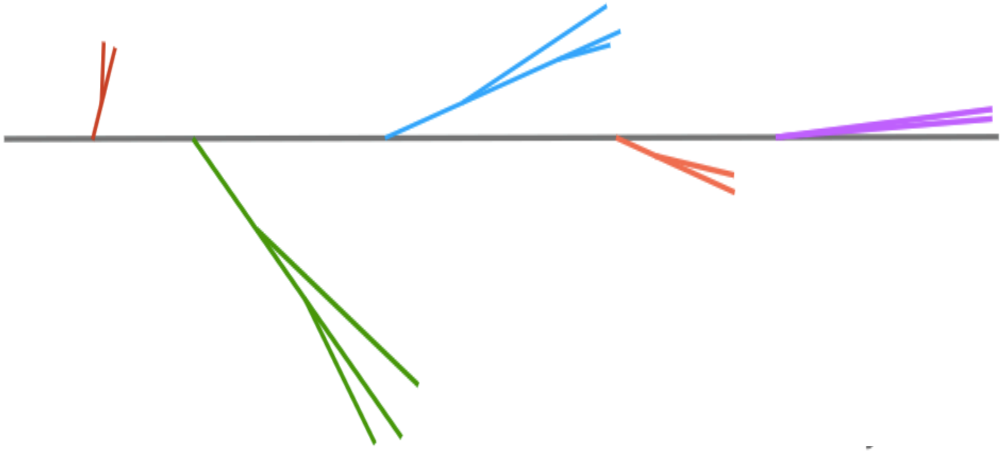
Slide taken from Urs Wiedemann, Workshop on the physics of HL-LHC, CERN

Jet substructure: map of splittings in vacuum



plot from G.Salam, QM18

(positive-slope diagonals are constant formation time t_f)



Unwind the CA clustering

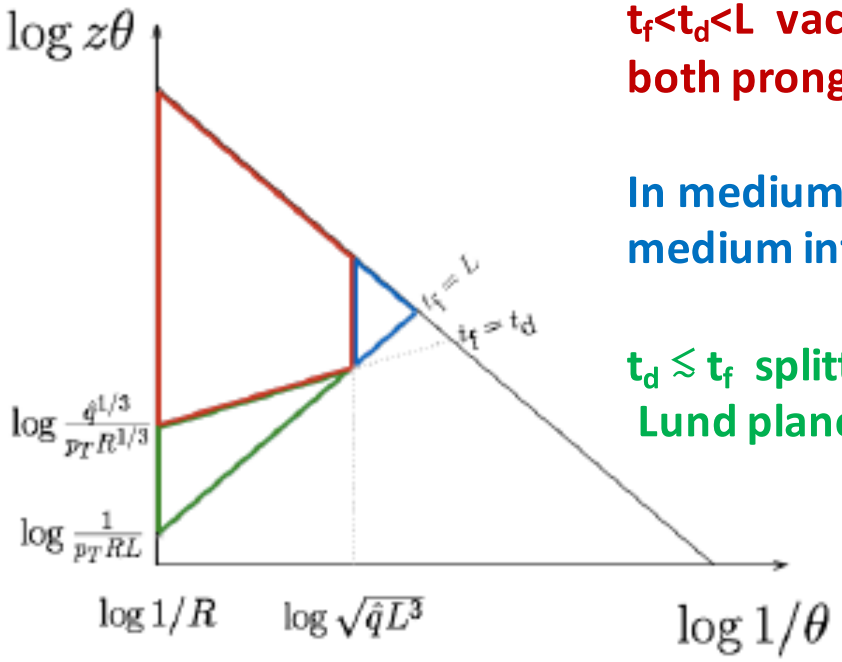
At each step, register the k_T, ΔR coordinates

Follow the hardest branch at each step

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

In vacuum, flat 2D density except for variation of the coupling with k_T
General observable, others can be derived from it

Map of splittings in medium



Multiple scales in medium:

$t_f < t_d < L$ vacuum splittings inside the medium, both prongs can lose energy independently

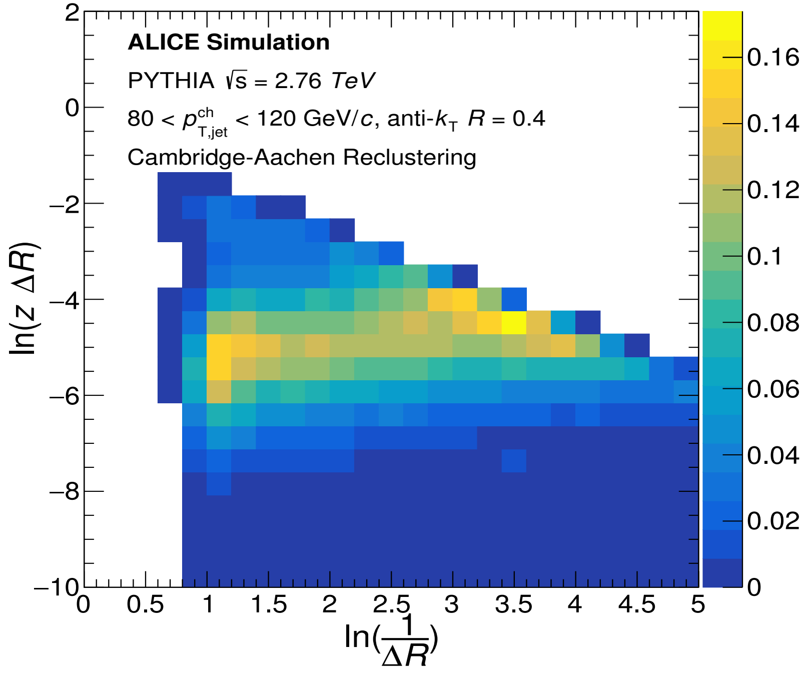
In medium splittings with $t_d > L$:not resolved by the medium interactions

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

K.Tywoniuk et al, Novel tools and observables for jet physics in heavy ion collisons, paper in preparation

Iterative declustering in the Pb-Pb environment

PYTHIA jets



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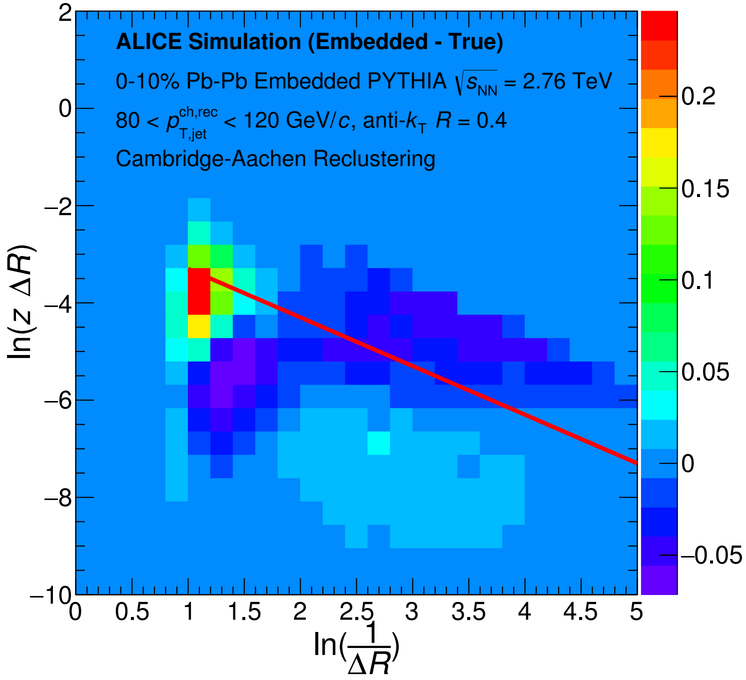
PYTHIA jets embedded into 0-10% central Pb-Pb events



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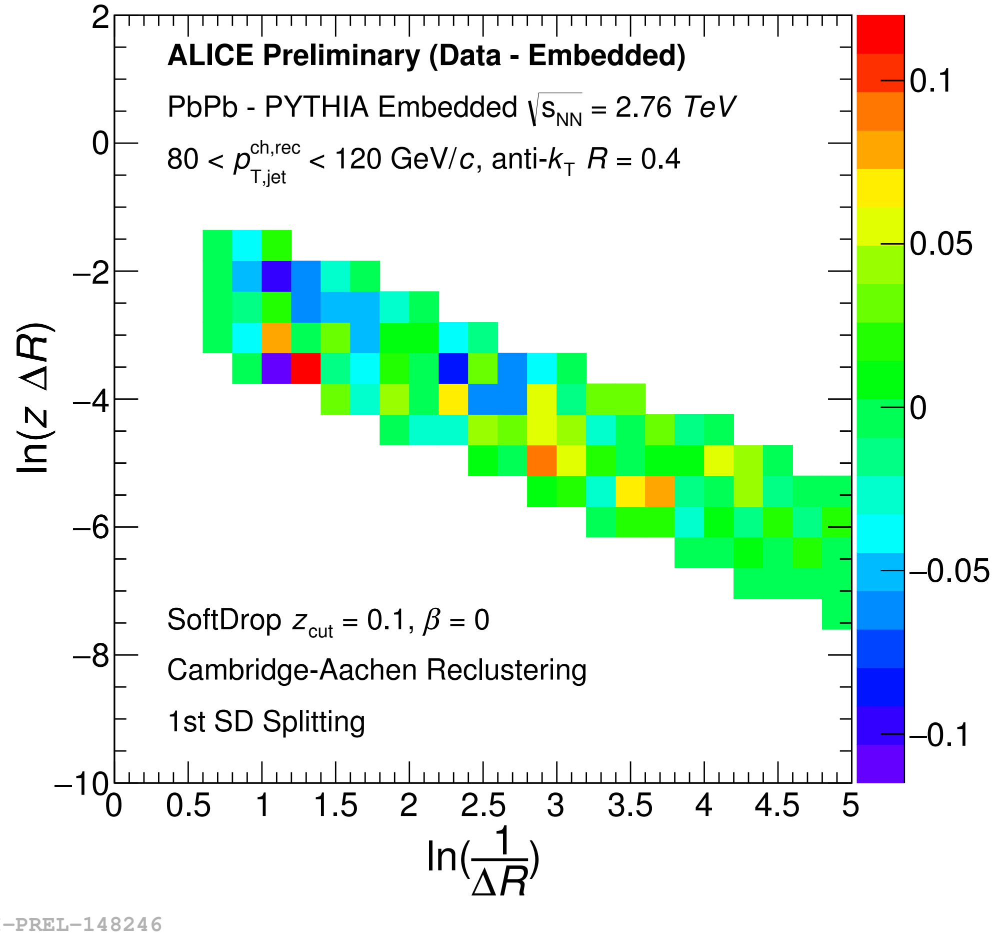
Fake splittings due to soft background from HI event occur at large angles θ ~R and low z

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

[0] M. Dasgupta et al. JHEP 1309 (2013) 029, Larkoski et al. JHEP 1405 (2014) 146

The splitting map in Pb-Pb

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



Plan to scan the map inspecting the ΔR projections in bins of scale k_T

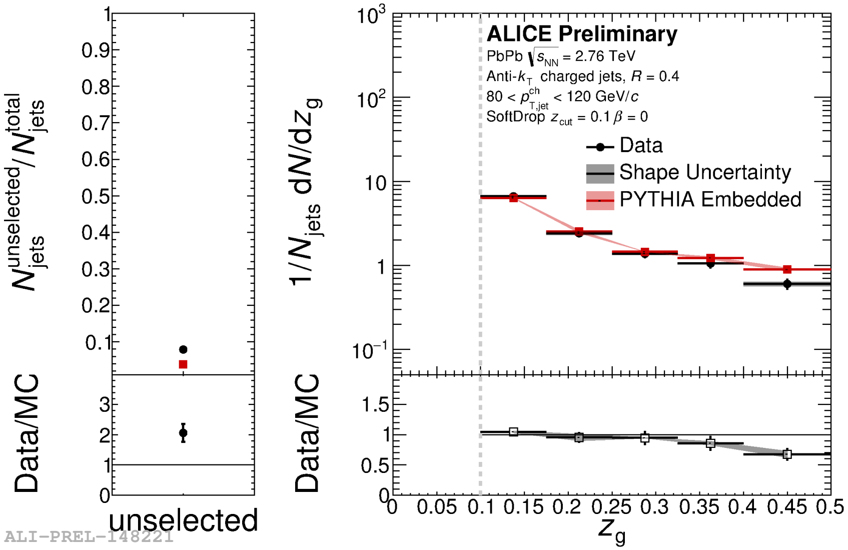
So far we have focused on the region defined by SD cuts z_{cut}>0.1, β=0

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

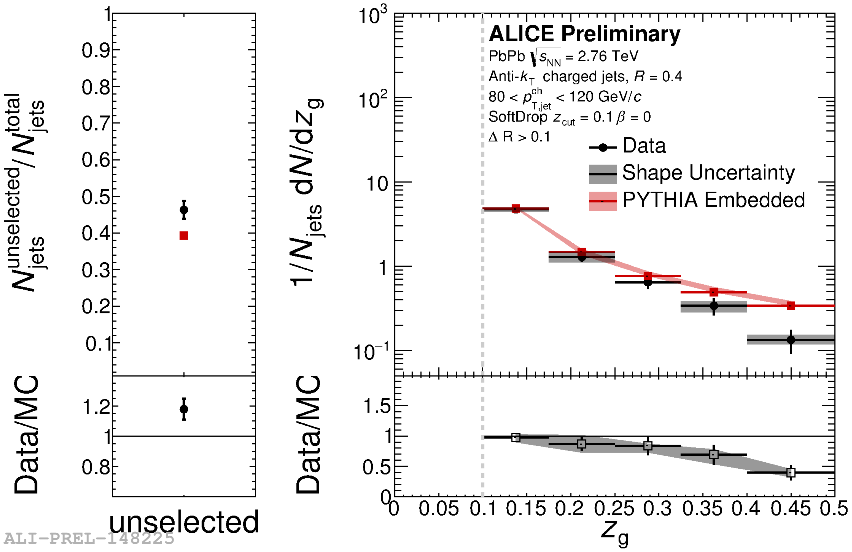
*pedestal background removal applied constituent subtraction, Berta et al, JHEP 1406 (2014) 092

The z_g distribution

$\Delta R > 0$



$\Delta R > 0.1$



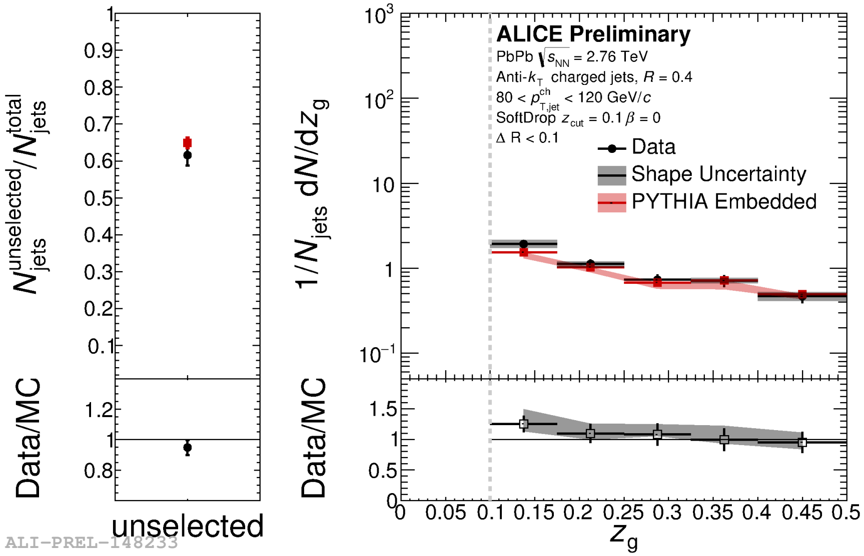
The observable is normalized to the total number of jets in the given momentum bin, not to the number of jets satisfying the SD cut.

Absolute normalization is crucial in order to interpret the results

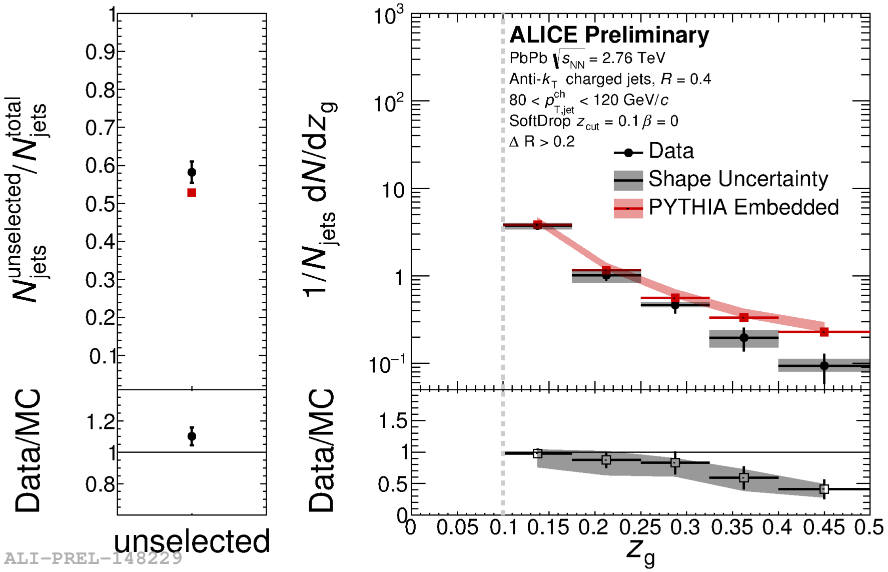
TPC tracking: no instrumental limitation in subjet separation
However expect ambiguity /mixing of subjets at small separation also at particle level

The z_g distribution: angular cutoff

$\Delta R < 0.1$



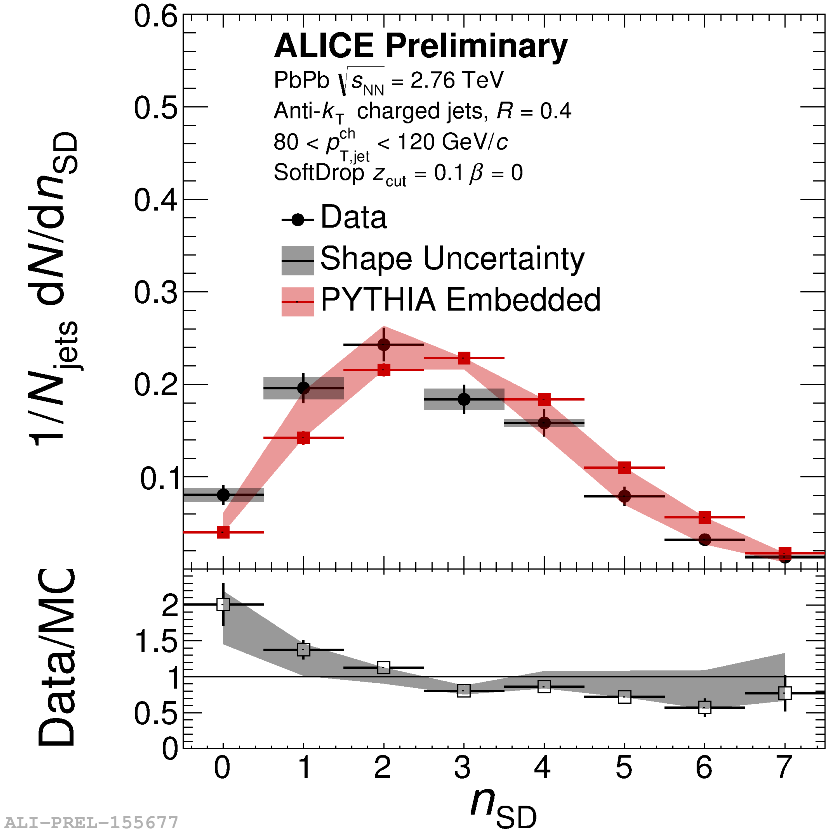
$\Delta R > 0.2$



When large-angle splittings are considered ($\Delta R > 0.2$), there is a net suppression of splittings at large z_g that is balanced by a 20% increase of unselected jets.

When large-angle splittings are vetoed ($\Delta R < 0.1$), a net enhancement of splittings passing the z_g cut is observed

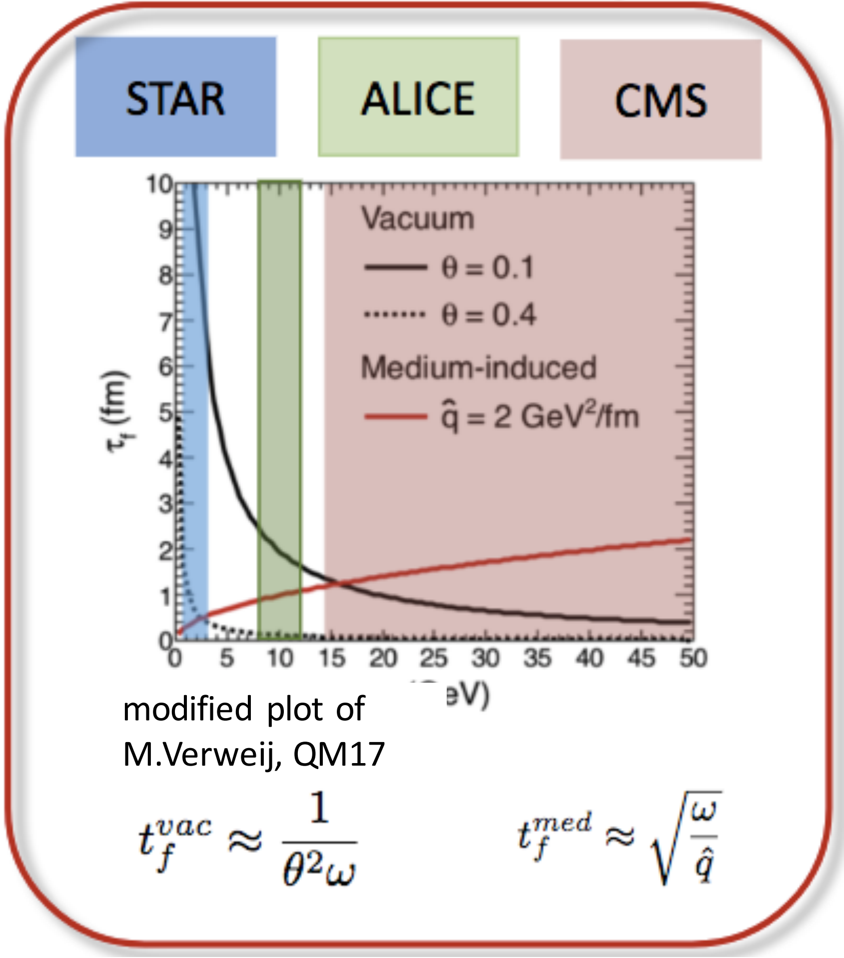
Counting the number of splittings that pass the SD cut



The density map of splittings is deformed in Pb-Pb relative to vacuum, but this deformation is not accompanied by an increase in the number of hard splittings selected by SD.

The role of formation time

Phase space covered by $z_g = 0.1$



modified plot of M.Verweij, QM17

$$t_f^{vac} \approx \frac{1}{\theta^2 \omega} \qquad t_f^{med} \approx \sqrt{\frac{\omega}{\hat{q}}}$$

At large angles/energies:

The un-modified vacuum splittings are suppressed

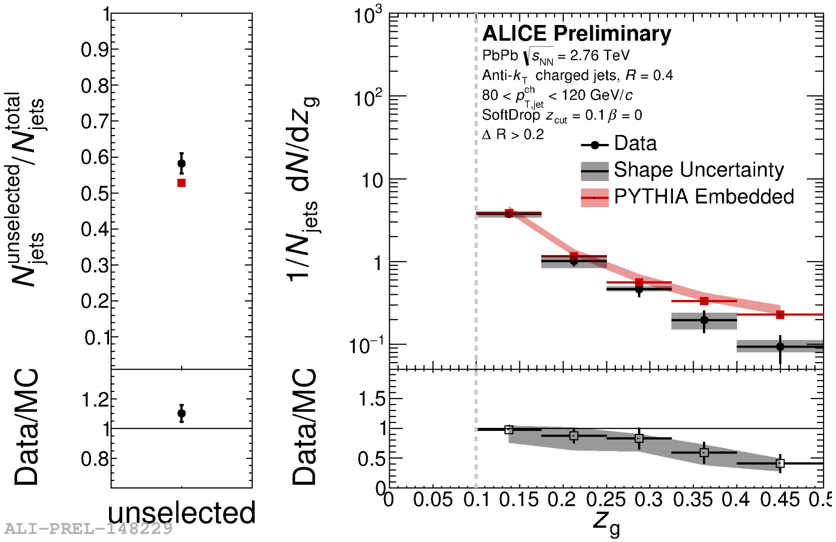
Thus more sensitive to medium-modified splittings

Color (de)coherence

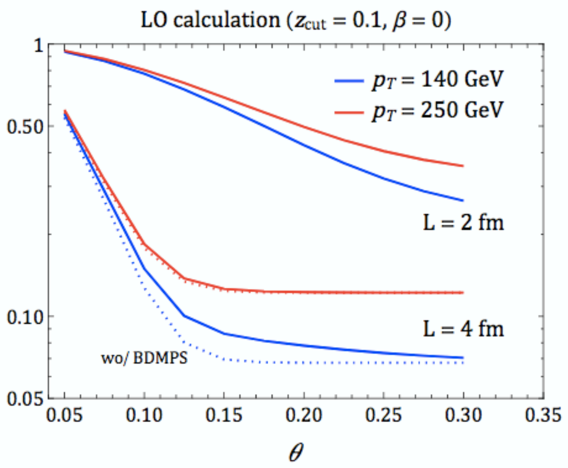
Is the jet substructure resolved by the medium? Or is the jet interacting with the medium as a single color charge?

What is the critical angle for the onset of incoherent radiation?

A modified z_g could point to subjets interacting independently with the medium



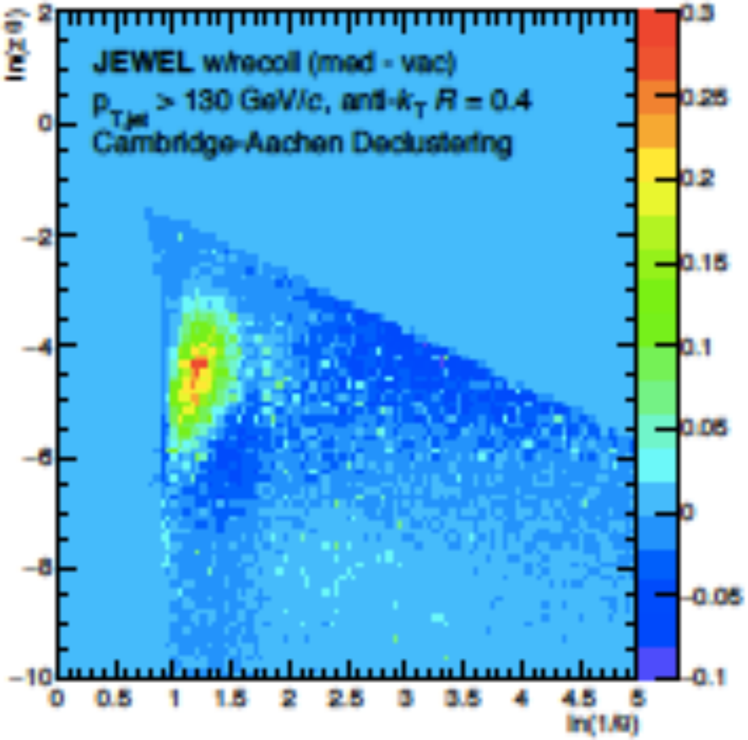
$$R^{2\text{-prong}} \equiv \frac{p_{AA}(r_g)}{p_{pp}(r_g)}$$



Yacine Mehtar-Tani et al, QM17 calculate a 50% suppression of the 2-prong probability at large angles. In our data, the suppression is of the order of 10%

The role of medium response?

JEWEL MC: Medium - Vacuum



K.Tywoniuk et al, Novel tools and observables for jet physics in heavy ion collisons, paper in preparation

The correlated background or medium response is the background that gets "excited by the jet" and ends up in the jet cone.[0]

As correlated bkg, it cannot be suppressed using standard techniques like event mixing or coincidence measurements.

The lack of increased number of SD splittings and the lack of excess of low z_g splittings in our data **don't show the presence of a medium response contribution**

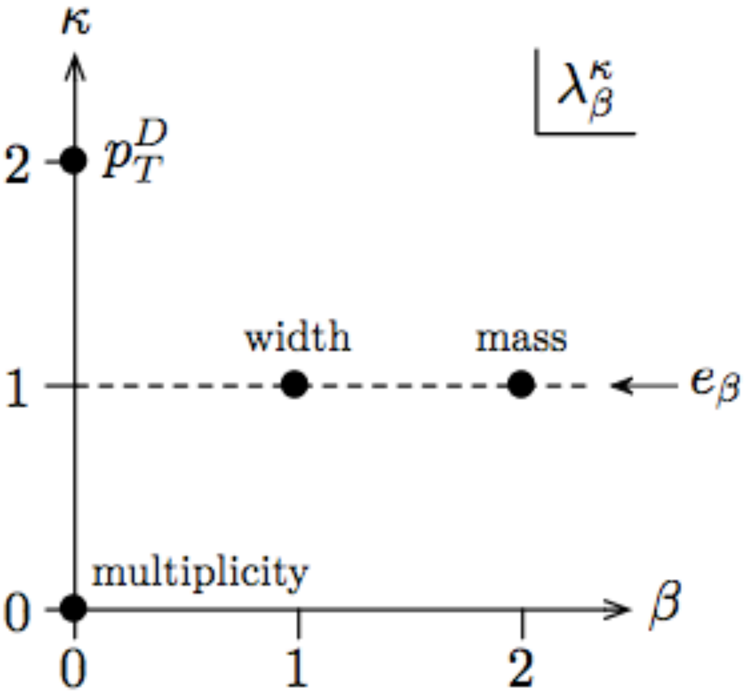
Next steps

- Systematic projections of the Lund map
- Use data as a reference. Currently we use Pythia (validated in pp collisions, see backup slides).
- Vary the pedestal background subtraction method. Currently constituent subtraction$_{[1]}$ is used. Easy to introduce the area-based method$_{[2]}$ in the iterative procedure.
- Explore semi-central collisions to suppress fake subleading subjets, to increase the significance of the signal at large ΔR

[1] P.Berta et al, JHEP 1406 (2014) 092
[2] G.Soyez et al, Phys.Rev.Lett 110 (2013) 16

- Other substructure studies in ALICE that did not exploit the clustering history of the jets and what we learnt from them

Generalized angularities

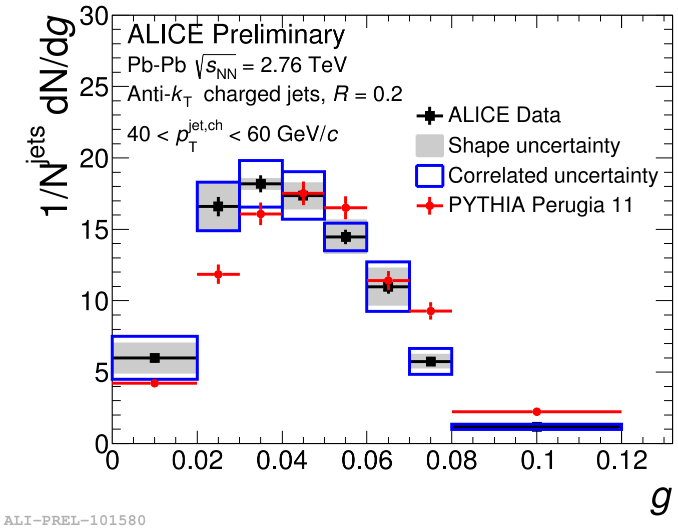


$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{R_i}{R_0} \right)^\beta$$

Diagram from Thaler et al

Exploring systematically the phase space of jet shapes

Generalized angularities in Pb-Pb



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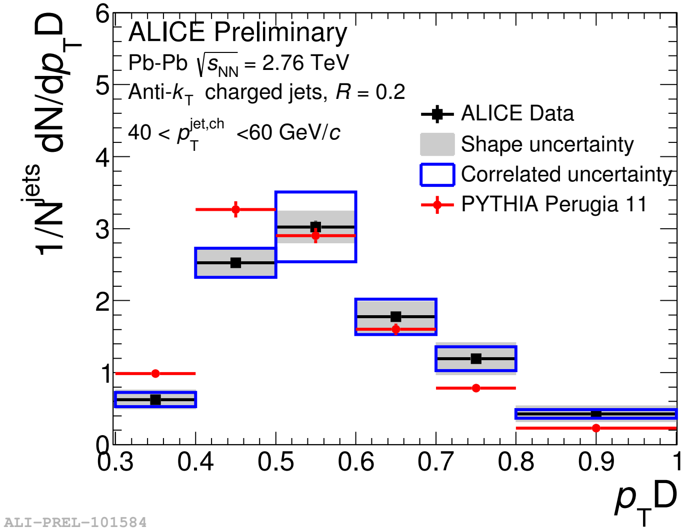
small-R jets



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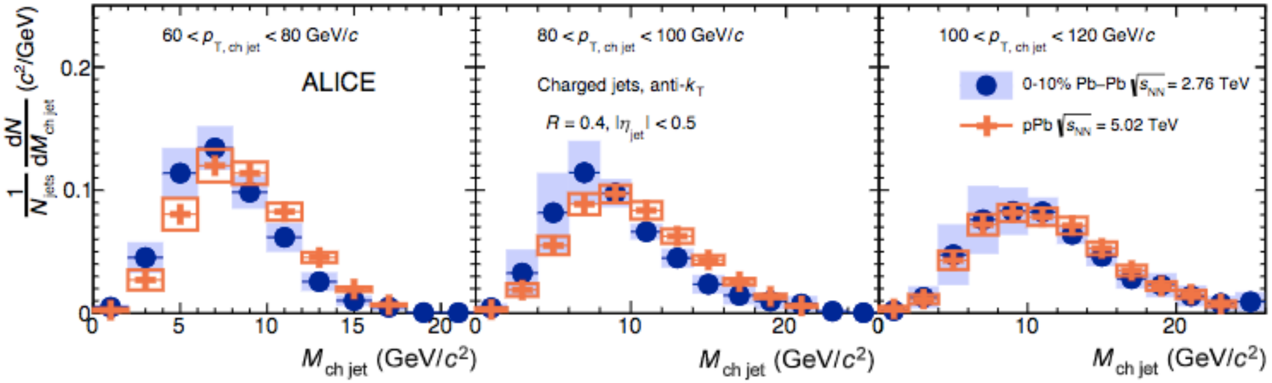
Picture qualitatively consistent with collimation of the jet core

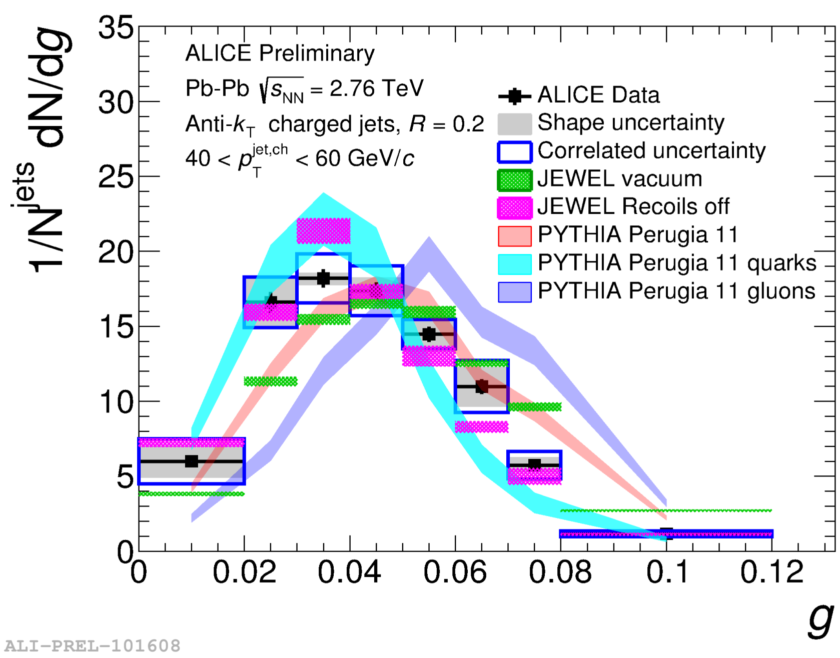
The jet core seems to be narrower and to fragment harder than the pp reference

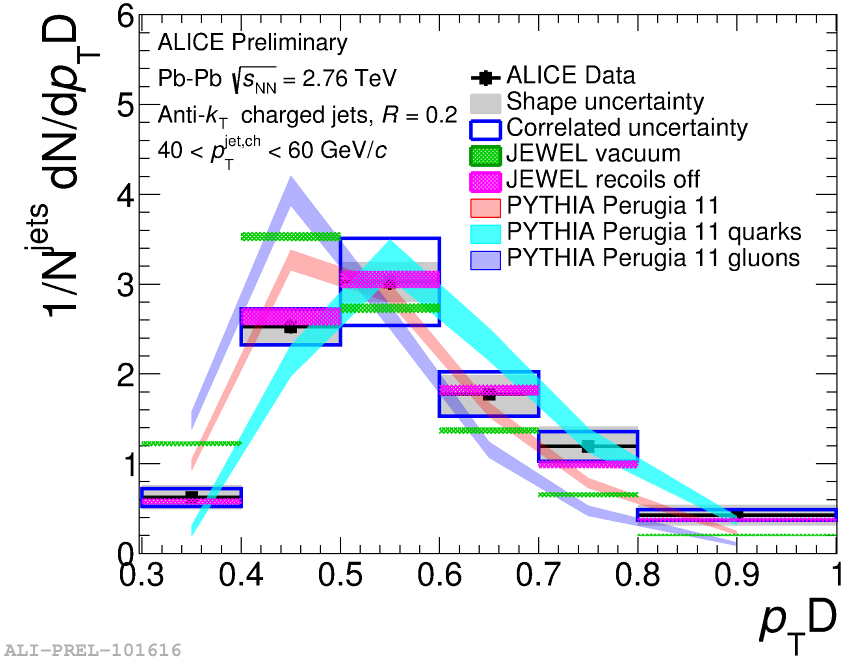


Small effects in the jet mass

Mass ~ $p_T\theta^2$ while g ~ $p_T\theta$, both are measurements of jet broadening, but note that different R are considered (here R = 0.4 while g measurement is R = 0.2)

Generalized angularities in Pb-Pb





Picture qualitatively consistent with collimation of the jet core

Pb-Pb results in agreement with vacuum quark templates,suggesting:

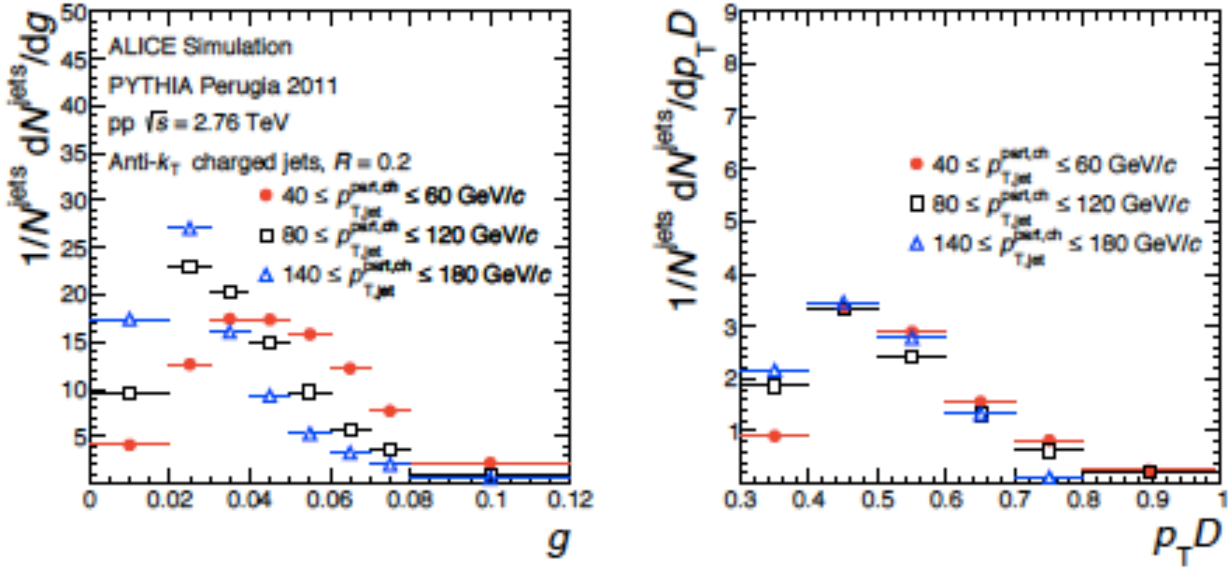
-modified fragmentation patter of all jets

-or, a selection of quark-like jet properties imposed by the medium

Momentum dependence and resolved substructure

$$g = \sum_{i\in\text{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R_{\mathrm{jet},i},$$

$$p_{\mathrm{T}}D = \frac{\sqrt{\sum_{i\in\text{jet}} p_{\mathrm{T},i}^{2}}}{\sum_{i\in\text{jet}} p_{\mathrm{T},i}}.$$



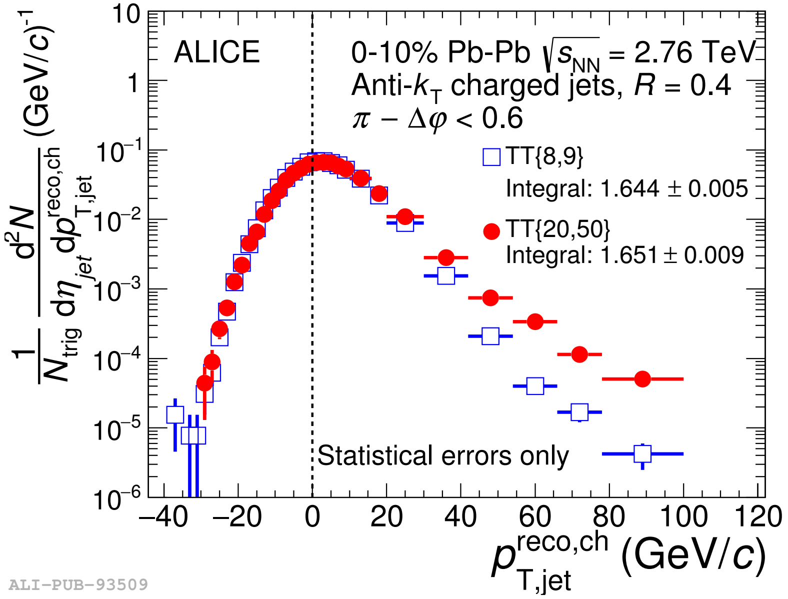
If a fraction X of the jet momentum is lost coherenly (jet interacts with the medium as a whole, substructure is not resolved), at given reconstructed jet p_{T}, jet shapes in Pb-Pb will be vacuum-like and corresponding to higher true jet p_{T}

In vacuum both g and $p_{\mathrm{T}}D$ decrease with the jet momentum

This simple picture is inconsistent whith the data: g/$p_{\mathrm{T}}D$ decrease/increase in medium relative to vacuum

This suggests that the jet substructure is resolved at the angular scales probed by our measurements (*R*=0.2)

Lower jet p_T accesible via recoil jet substructure: suppression of combinatorial background



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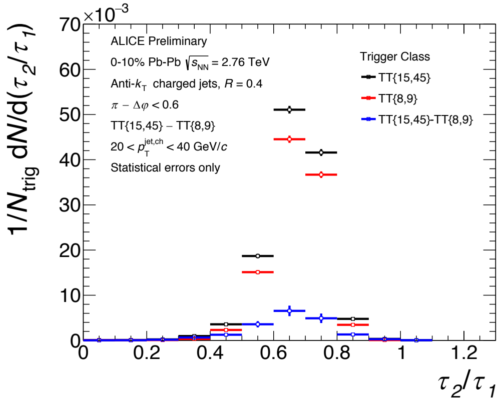
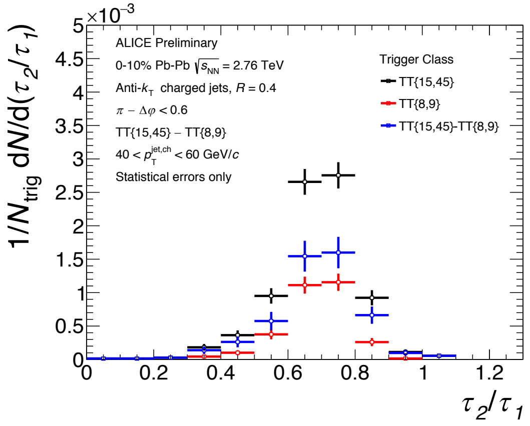
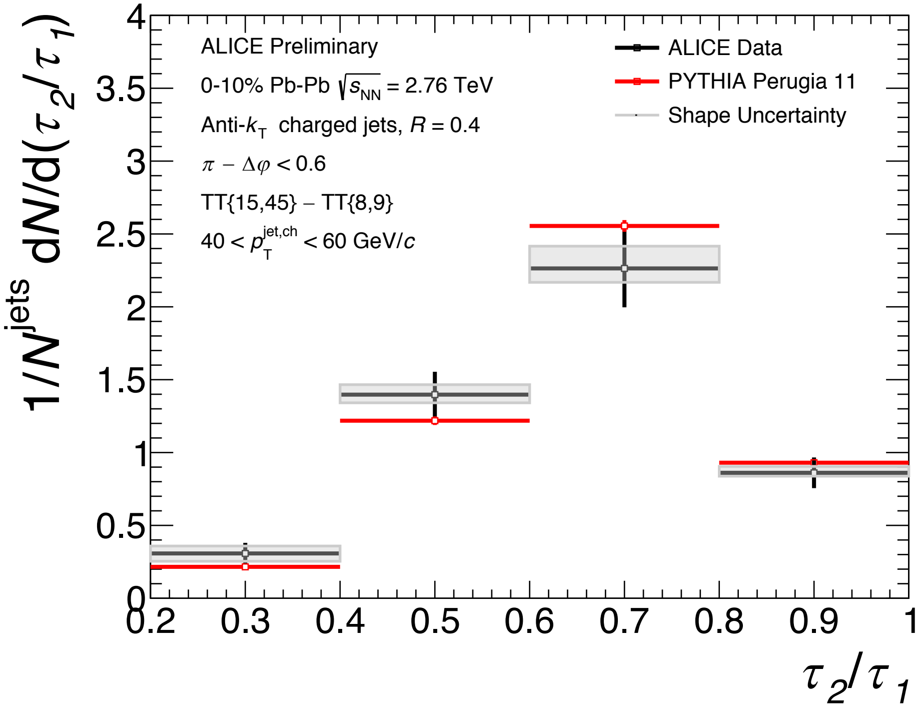




$$\text{Difference} = \left(\frac{1}{N_{\text{trig}}}\cdot\frac{dN_{\text{jet}}}{d(\text{shape})\,dp_{\text{T,jet}}}\right)_{\text{TT}_{\text{signal}}} - \left(\frac{1}{N_{\text{trig}}}\cdot\frac{dN_{\text{jet}}}{d(\text{shape})\,dp_{\text{T,jet}}}\right)_{\text{TT}_{\text{reference}}}$$

Fully Corrected Recoil Nsubjetiness(τ_2/τ_1) in Pb-Pb



Axes found unwinding k_T clustering (not optimal, but firs try in 2017)

Other axes are currently explored systematically, including CA+SD or CA+WTA

No modification of the 2-prongness of jets in medium relative to vacuum

Fundamental problem: a large k_T medium-induced radiation can be a signature of scattering off the weakly-coupled degrees of freedom within the strongly coupled medium (Moliere regime ~$1/k_T^4$).

If such hard radiation is produced, can it create an extra subjet prong in the jet and can we detect it as an increase of the 2-subjetiness?

Inspecting the Lund map looking for an increase of large k_T quanta is probably more direct?

Summary

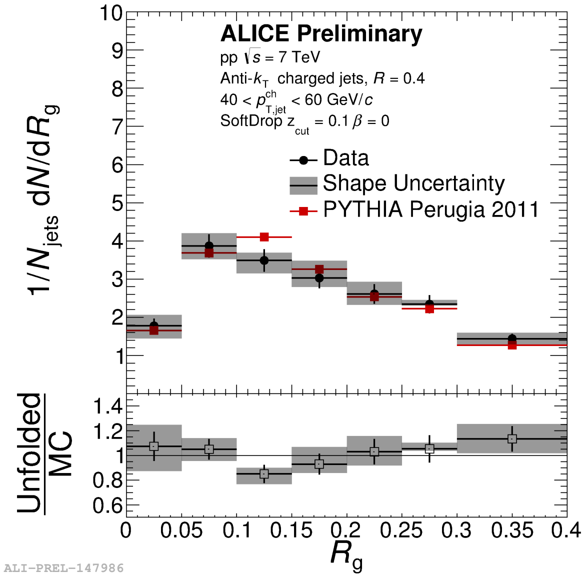
-Accessing microscopic properties of QCD matter via jet substructure, in reach.

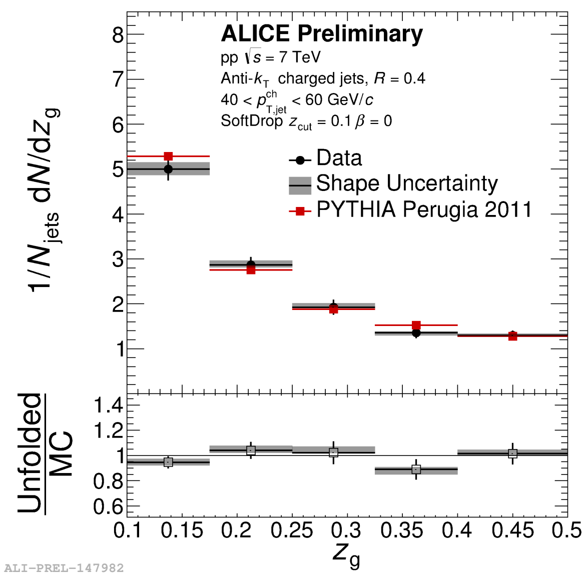
-Fundamental problems to explore: role of color coherence, change of degrees of freedom of the medium with the probing scale, quark/gluon hierarchy of energy loss …

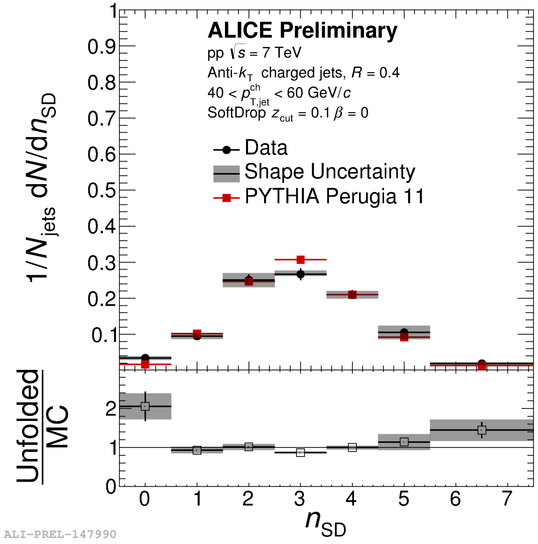
-Strong synergy between jet substructure in Heavy Ions and HEP community
An example: Novel tools and observables for jet physics in heavy-ion collisions
https://indico.cern.ch/event/625585/

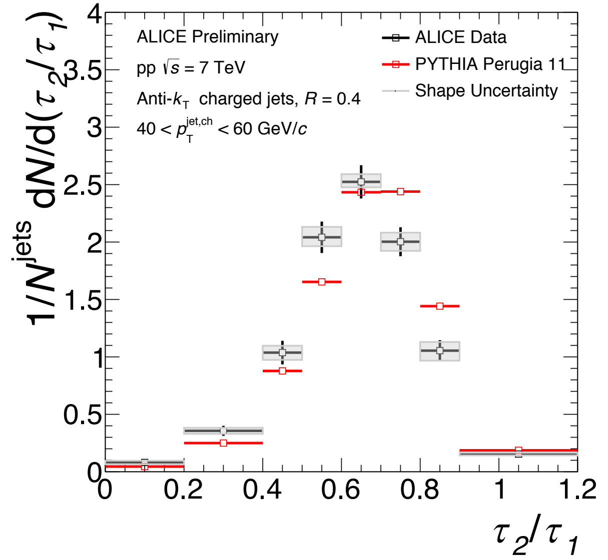
-Consensus on using the distribution of hadronic fragments in the Lund plane in order to make systematic comparisons between current and future jet quenching models/calculations
Possibility to isolate and test different physics effects in a "modular" way

The substructure measurement in pp





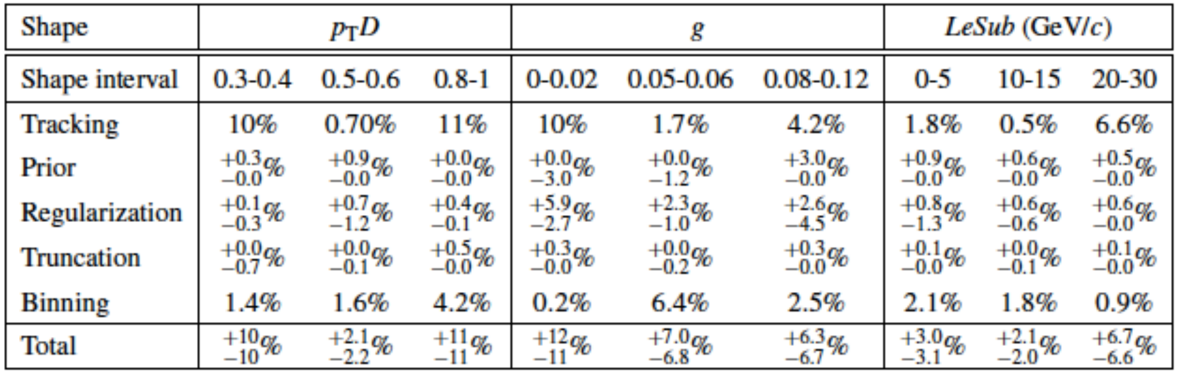




Fully corrected to particle level.

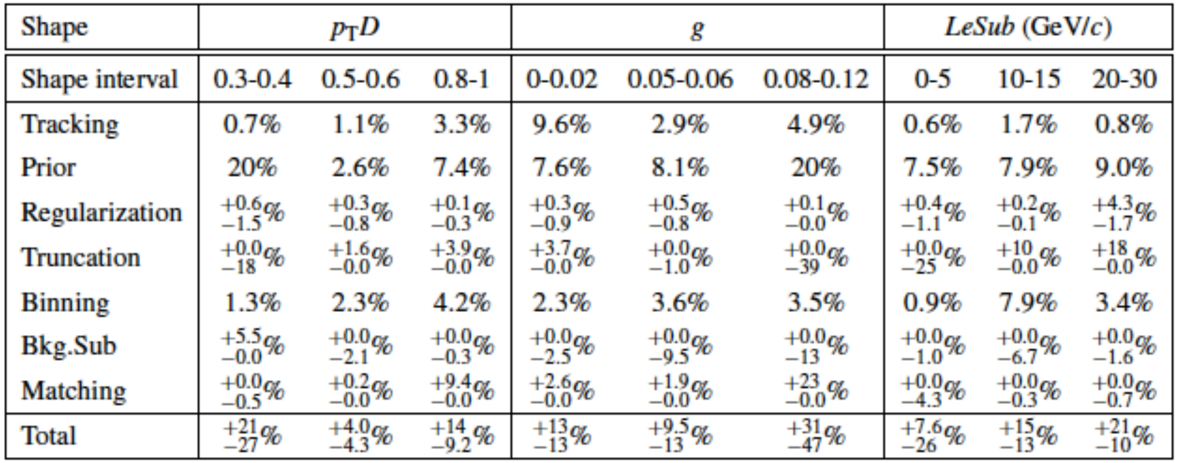
Instrumental effects are corrected via a 2-dimensional unfolding

An example of uncertainties in pp and PbPb jet shapes



Shape	$p_{\mathrm{T}}D$			g			*LeSub* (GeV/c)		
Shape interval	0.3-0.4	0.5-0.6	0.8-1	0-0.02	0.05-0.06	0.08-0.12	0-5	10-15	20-30
Tracking	10%	0.70%	11%	10%	1.7%	4.2%	1.8%	0.5%	6.6%
Prior	$^{+0.3}_{-0.0}\%$	$^{+0.9}_{-0.0}\%$	$^{+0.0}_{-0.0}\%$	$^{+0.0}_{-3.0}\%$	$^{+0.0}_{-1.2}\%$	$^{+3.0}_{-0.0}\%$	$^{+0.9}_{-0.0}\%$	$^{+0.6}_{-0.0}\%$	$^{+0.5}_{-0.0}\%$
Regularization	$^{+0.1}_{-0.3}\%$	$^{+0.7}_{-1.2}\%$	$^{+0.4}_{-0.1}\%$	$^{+5.9}_{-2.7}\%$	$^{+2.3}_{-1.0}\%$	$^{+2.6}_{-4.5}\%$	$^{+0.8}_{-1.3}\%$	$^{+0.6}_{-0.6}\%$	$^{+0.6}_{-0.0}\%$
Truncation	$^{+0.0}_{-0.7}\%$	$^{+0.0}_{-0.1}\%$	$^{+0.5}_{-0.0}\%$	$^{+0.3}_{-0.0}\%$	$^{+0.0}_{-0.2}\%$	$^{+0.3}_{-0.0}\%$	$^{+0.1}_{-0.0}\%$	$^{+0.0}_{-0.1}\%$	$^{+0.1}_{-0.0}\%$
Binning	1.4%	1.6%	4.2%	0.2%	6.4%	2.5%	2.1%	1.8%	0.9%
Total	$^{+10}_{-10}\%$	$^{+2.1}_{-2.2}\%$	$^{+11}_{-11}\%$	$^{+12}_{-11}\%$	$^{+7.0}_{-6.8}\%$	$^{+6.3}_{-6.7}\%$	$^{+3.0}_{-3.1}\%$	$^{+2.1}_{-2.0}\%$	$^{+6.7}_{-6.6}\%$

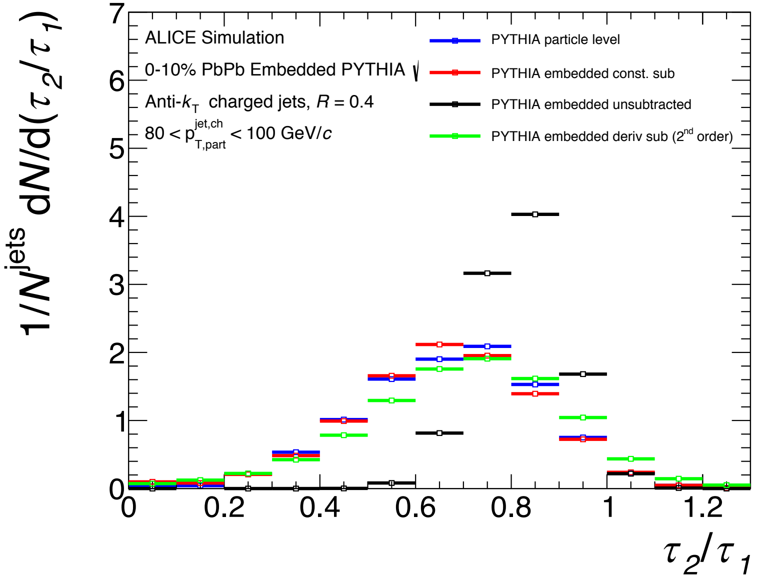
Table 1: Relative systematic uncertainties on the measured jet shapes in pp collisions for three selected jet shape intervals in the jet $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ range of 40–60 GeV/c.

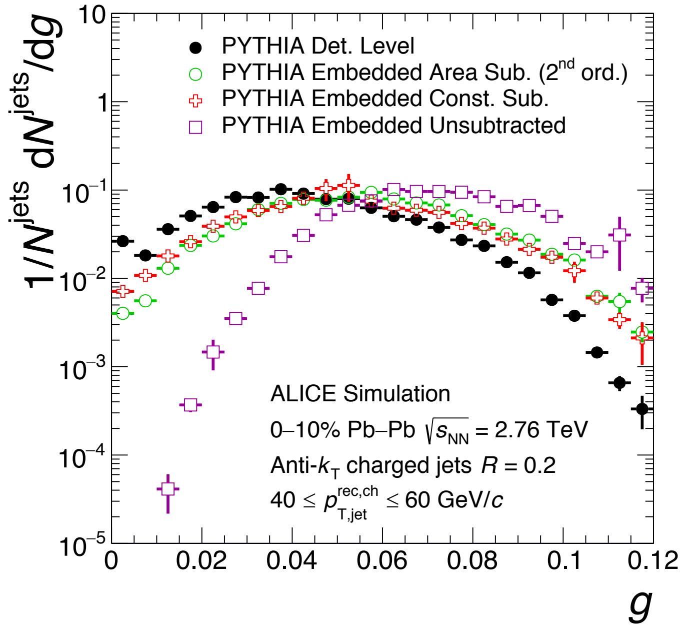


Shape	$p_{\mathrm{T}}D$			g			*LeSub* (GeV/c)		
Shape interval	0.3-0.4	0.5-0.6	0.8-1	0-0.02	0.05-0.06	0.08-0.12	0-5	10-15	20-30
Tracking	0.7%	1.1%	3.3%	9.6%	2.9%	4.9%	0.6%	1.7%	0.8%
Prior	20%	2.6%	7.4%	7.6%	8.1%	20%	7.5%	7.9%	9.0%
Regularization	$^{+0.6}_{-1.5}\%$	$^{+0.3}_{-0.8}\%$	$^{+0.1}_{-0.3}\%$	$^{+0.3}_{-0.9}\%$	$^{+0.5}_{-0.8}\%$	$^{+0.1}_{-0.0}\%$	$^{+0.4}_{-1.1}\%$	$^{+0.2}_{-0.1}\%$	$^{+4.3}_{-1.7}\%$
Truncation	$^{+0.0}_{-18}\%$	$^{+1.6}_{-0.0}\%$	$^{+3.9}_{-0.0}\%$	$^{+3.7}_{-0.0}\%$	$^{+0.0}_{-1.0}\%$	$^{+0.0}_{-39}\%$	$^{+0.0}_{-25}\%$	$^{+10}_{-0.0}\%$	$^{+18}_{-0.0}\%$
Binning	1.3%	2.3%	4.2%	2.3%	3.6%	3.5%	0.9%	7.9%	3.4%
Bkg.Sub	$^{+5.5}_{-0.0}\%$	$^{+0.0}_{-2.1}\%$	$^{+0.0}_{-0.3}\%$	$^{+0.0}_{-2.5}\%$	$^{+0.0}_{-9.5}\%$	$^{+0.0}_{-13}\%$	$^{+0.0}_{-1.0}\%$	$^{+0.0}_{-6.7}\%$	$^{+0.0}_{-1.6}\%$
Matching	$^{+0.0}_{-0.5}\%$	$^{+0.2}_{-0.0}\%$	$^{+9.4}_{-0.0}\%$	$^{+2.6}_{-0.0}\%$	$^{+1.9}_{-0.0}\%$	$^{+23}_{-0.0}\%$	$^{+0.0}_{-4.3}\%$	$^{+0.0}_{-0.3}\%$	$^{+0.0}_{-0.7}\%$
Total	$^{+21}_{-27}\%$	$^{+4.0}_{-4.3}\%$	$^{+14}_{-9.2}\%$	$^{+13}_{-13}\%$	$^{+9.5}_{-13}\%$	$^{+31}_{-47}\%$	$^{+7.6}_{-26}\%$	$^{+15}_{-13}\%$	$^{+21}_{-10}\%$

Table 2: Relative systematic uncertainties on the measured jet shapes in Pb–Pb collisions for three selected jet shape intervals in the jet $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ range 40–60 GeV/c.

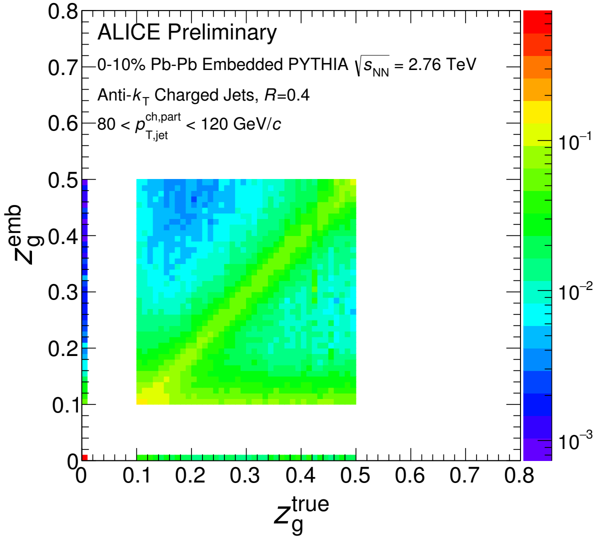
Pedestal subtraction performance in Pb-Pb





The subtraction is applied consistently to the data and the response,so unfolded results are to leading order invariant on the specific pedestal subtraction method.

The background response: fake subjets



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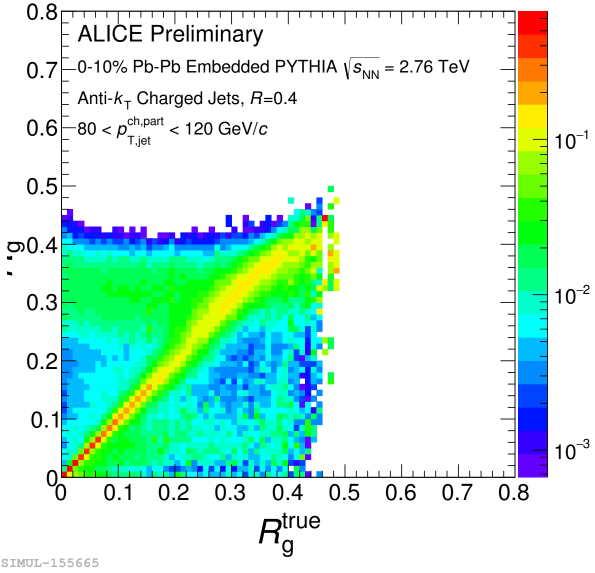

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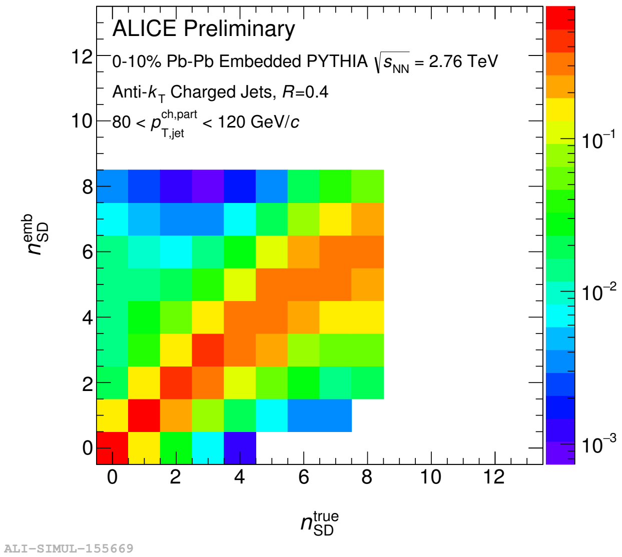
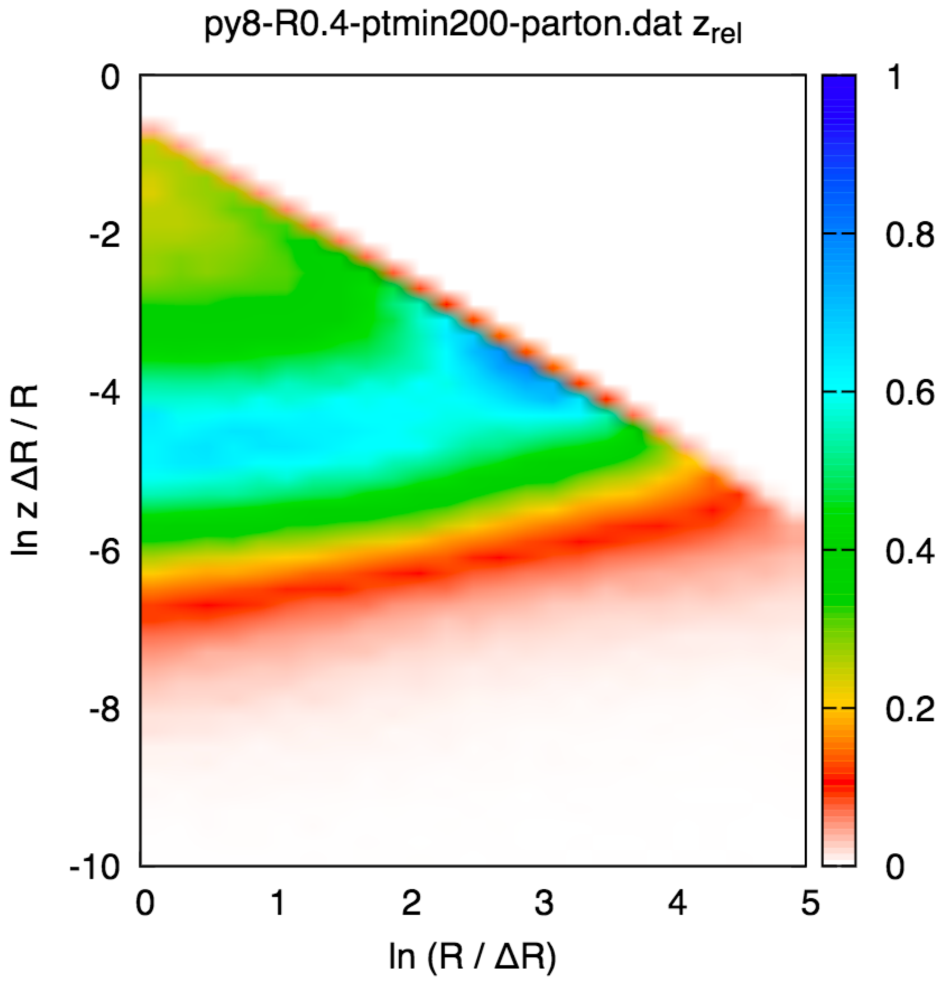


ALI-SIMUL-155669

Off-diagonal elements in the response render unfolding difficult in Pb-Pb (sensitivity to the underlying distribution is reduced)

Map of splittings



Register iteratively the kinematics of the hardest subjet in the Lund plot

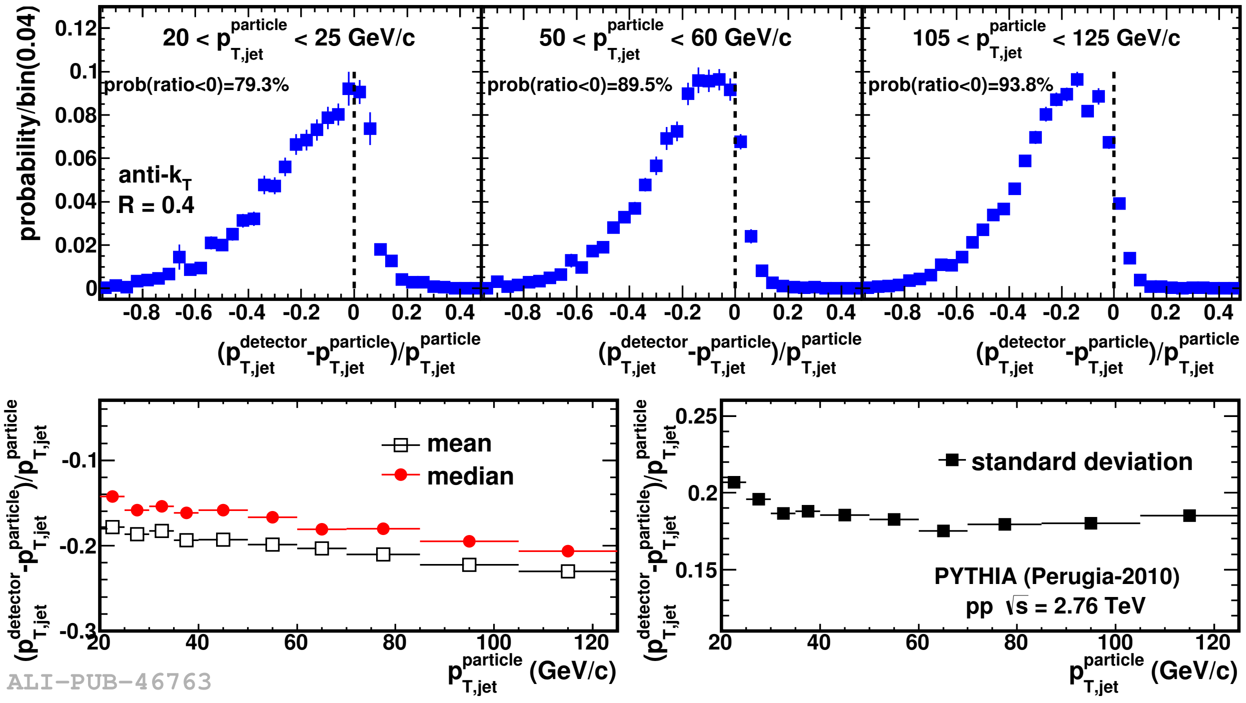
Can do the same in data!

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

G.Salam, Jet Substructure Theory workshop
https://gitlab.cern.ch/gsalam/2017-lund-from-MC

Instrumental response

Full jet response



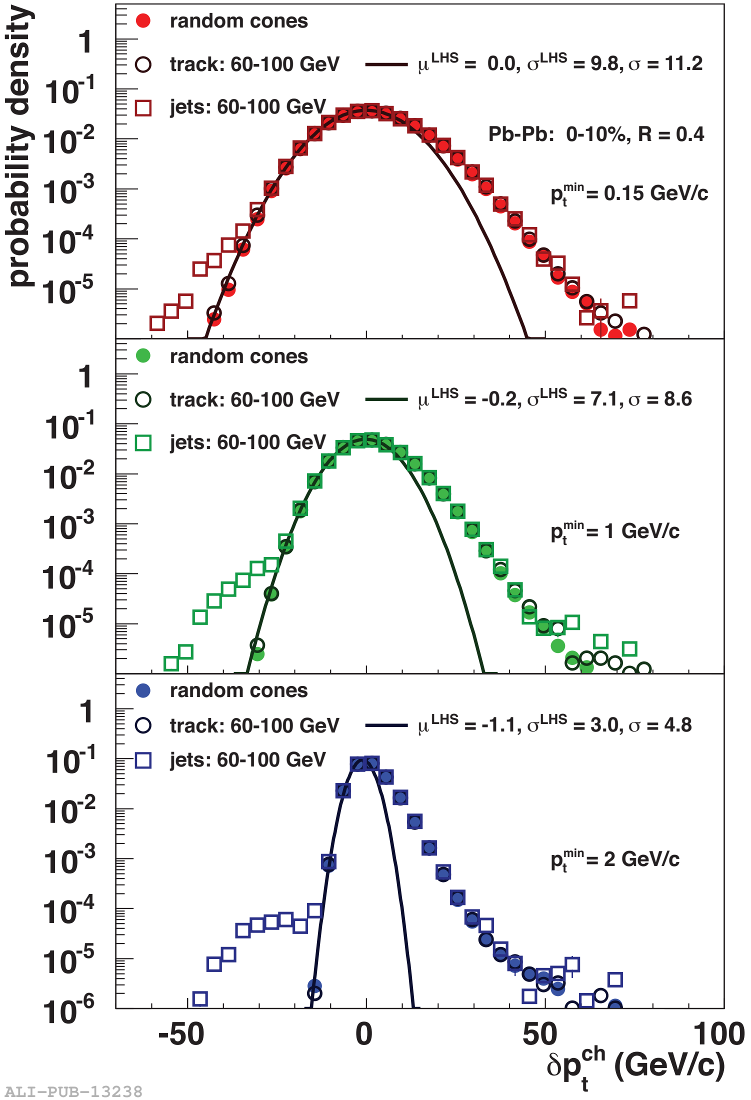
[ALICE, PLB722 (2013) 262]

Shift of the Jet Energy Scale (JES) ~20%

JES uncertainty is dominated by tracking efficiency uncertainty and is ~5%

JER (instrumental jet energy resolution) ~18% with mild jet p_T and R dependence

Background response: region-to-region fluctuations



[ALICE, JHEP03(2012)053]

$$\sigma(\delta p_T^{jet}) \propto R$$

$$\delta p_T = p_{T,jet}^{reco} - \rho \cdot A_{jet} - p_T^{part,embed}$$

We embed different probes into Pb-Pb events and estimate the background response through δp_T

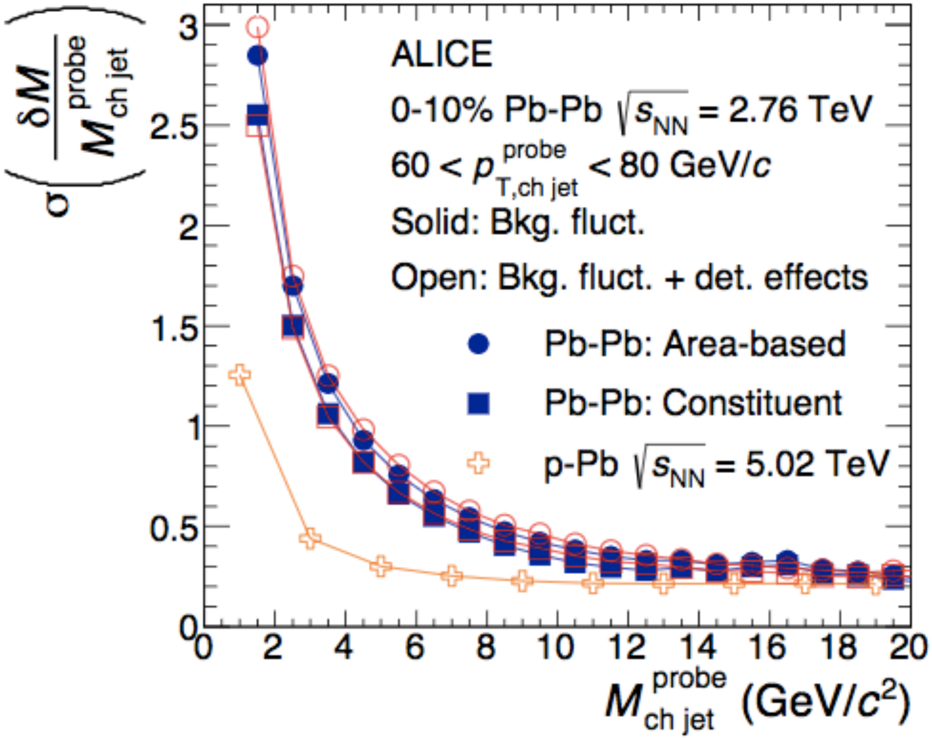
-Small dependence on the probe fragmentation pattern

-Small **back reaction** effects in the tails of the response due to jet splitting and jet merging

-Minimum constituent p_T cut-off reduces fluctuations

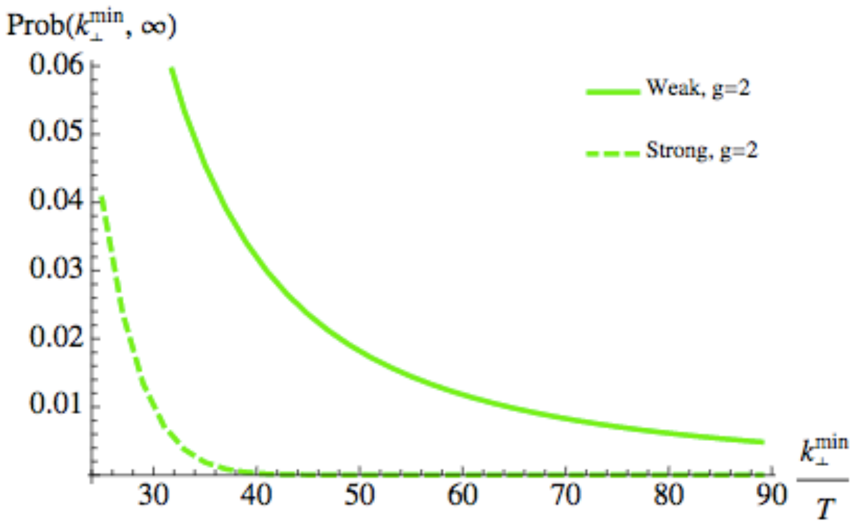
Residual background fluctuations correction via unfolding

Jet mass resolution



An example of jet shape resolution. Low mass probes have few constituents and are very sensitive to tracking inefficiency and background fluctuations. At higher mass, the resolution is better and around 25%.

Medium-induced broadening: rare large angle deflections



D'Eramo, Lekaveckas,Liu,Rajagopal, JHEP 1305 (2013) 0131

The equivalent of performing the Rutherford experiment in the QGP

Evolution of degrees of freedom with scale

Scale is the deflection angle of the parton in the medium

At large deflection angles ->emergence of weakly coupled degrees of freedom in the strongly coupled QGP

Experimentally:

- ○ inspect the tails of the azimuthal dijet correlation at very low jet p_T
- ○ large angle deflections of constituents within the jet ->need jet substructure large R
- ○ statistically hungry

Need more realistic calculations including finite energy corrections etc