# ALICE Recent Highlights (a selection)

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2017 US LHC Users Association Meeting, Fermilab

# Fundamental question:

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, $\eta/s$, $\xi$, $\lambda_\pi$ ... | 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***

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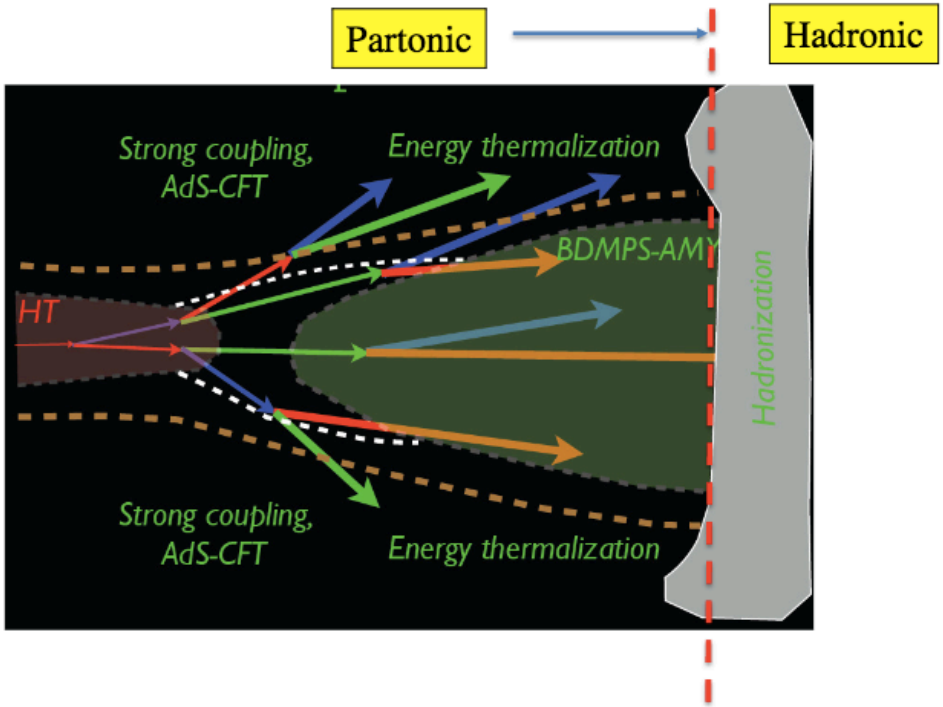
# Jets and substructure



# Jet Substructure

**Capture the dynamics of the jet shower,** characterize bulk of medium modifications to the shower

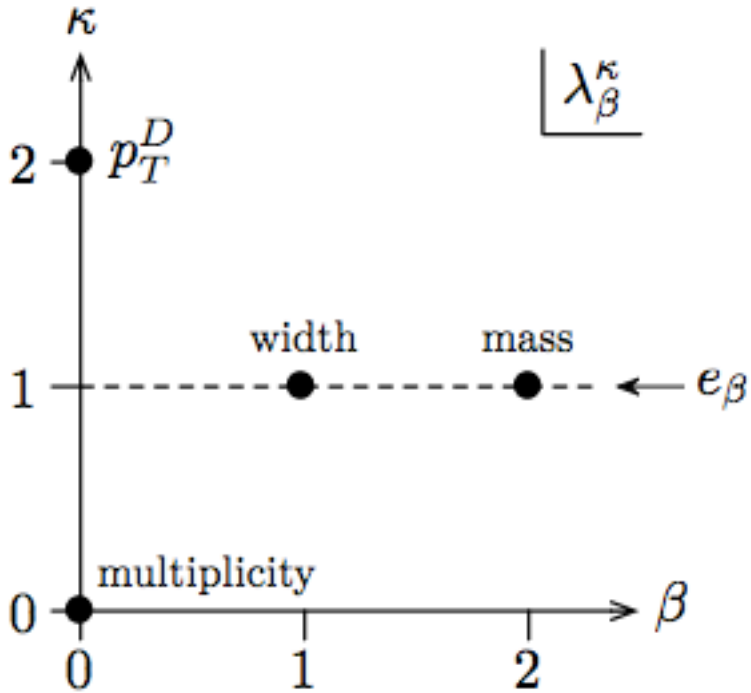
**Several fundamental physics points to investigate:**

-Identify possible change of the jet substructure due to the rare Moliere **scatterings off quark gluon degrees of freedom** in the medium or **hunting for the quasi-particle structure of hot QCD**

-Verify the effect of color coherence in medium or how the jet energy loss depends on the jet substructure

-Role of flavour hierarchy in medium

# Jet shapes: generalized angularities

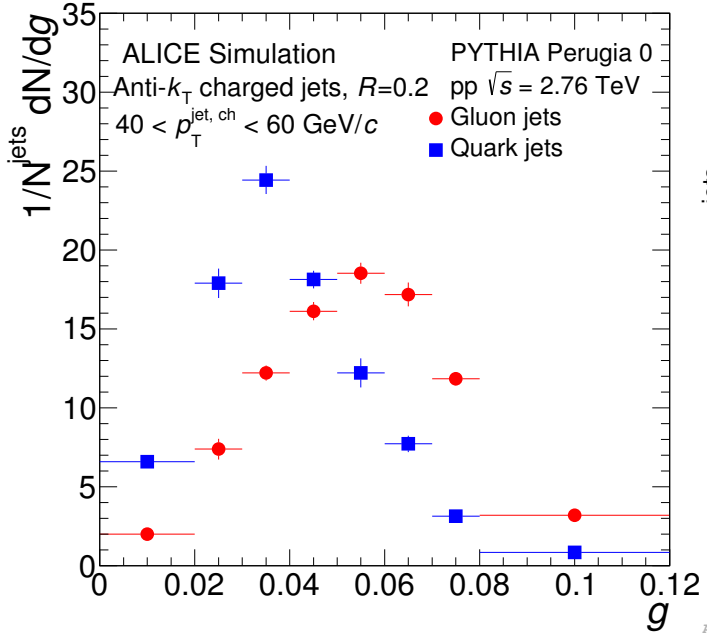


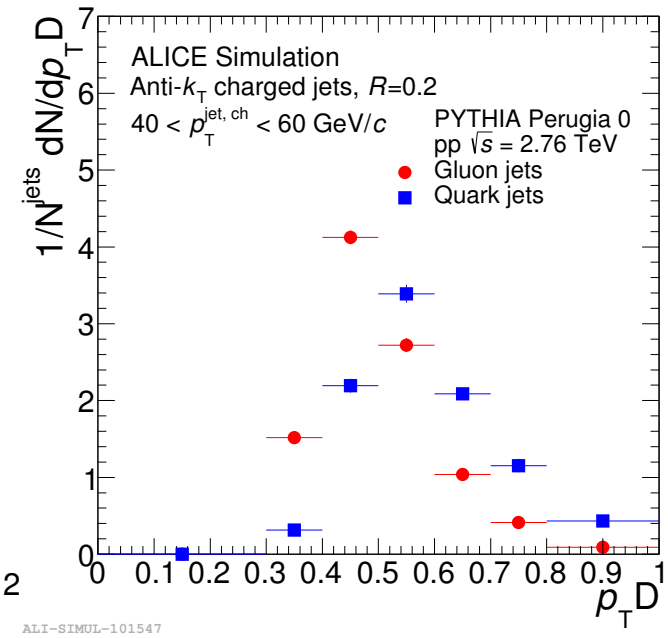

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{R_i}{R_0}\right)^\beta$$

*Diagram from Thaler et al*

**Exploring systematically the phase space of jet shapes**

# Jet shapes: generalized angularities

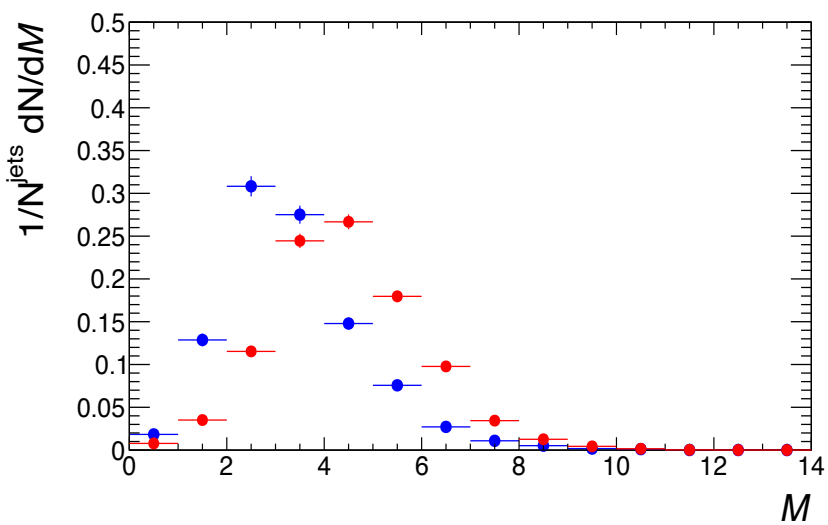



$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

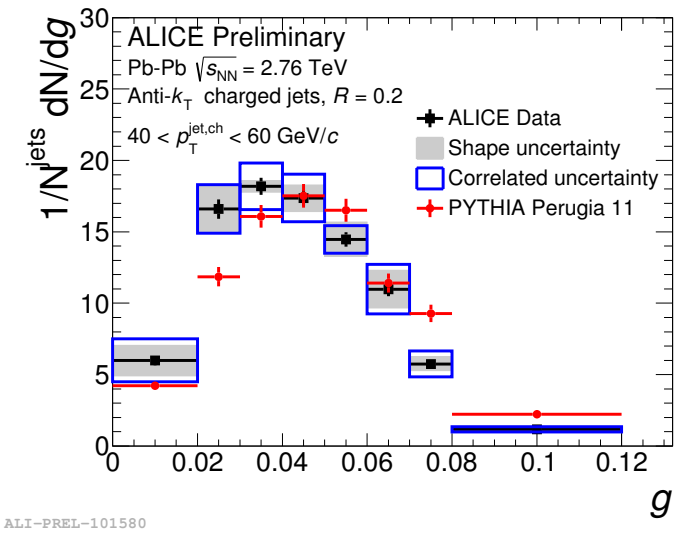
$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} |r_i|$$

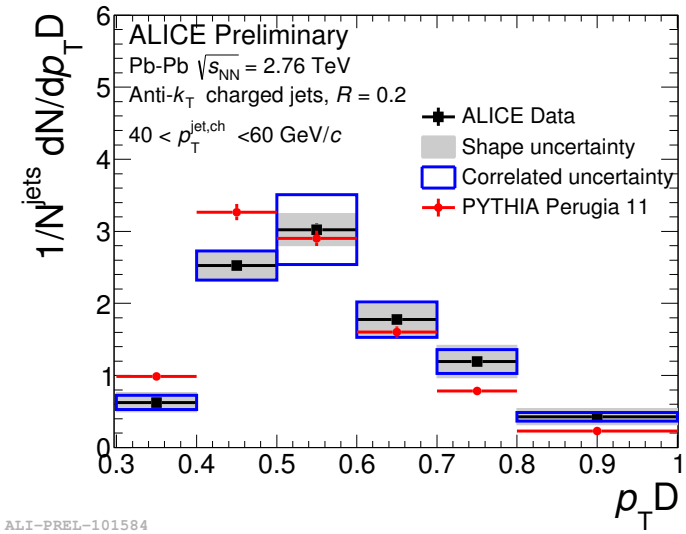
$$M = \sqrt{E^2 - p_T^2 - p_z^2}$$




**An accelerated shower (i.e. gluons compared to inclusive) leads to larger mass, higher angularities (broader) and smaller $p_T D$ (more constituents)**

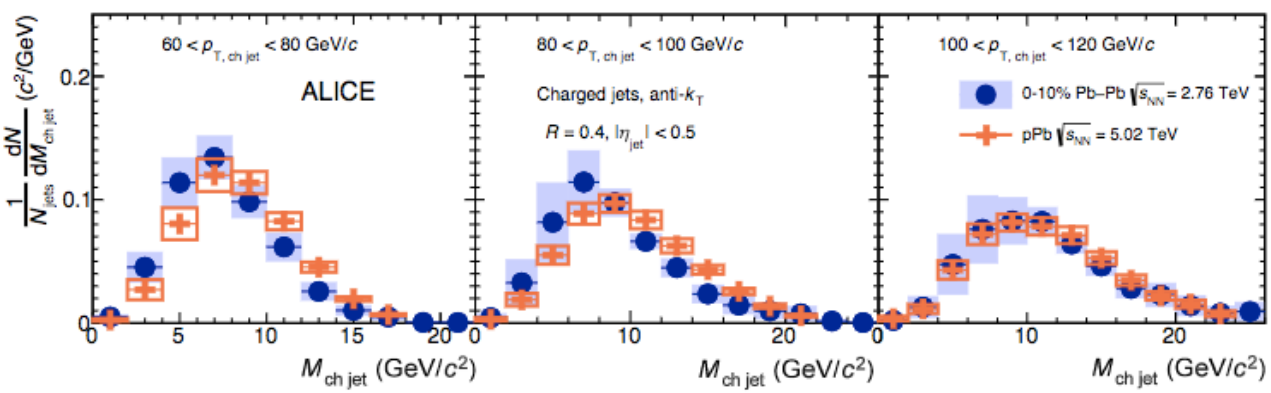
# Jet shapes: generalized angularities in Pb-Pb




**Picture qualitatively consistent with collimation of the jet core**

The parton shower seems to be harder and narrower than the pp reference

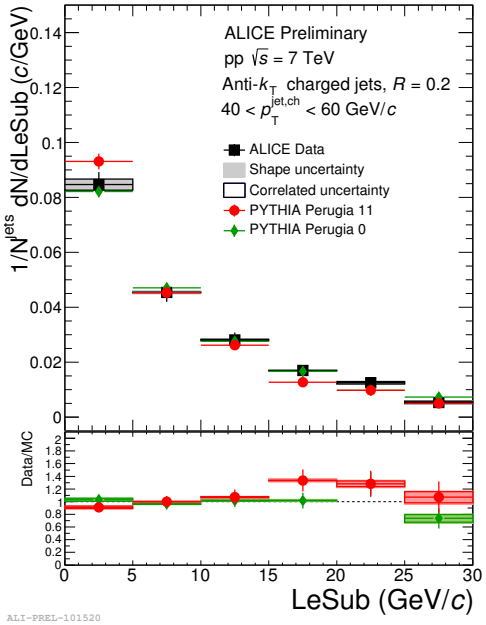


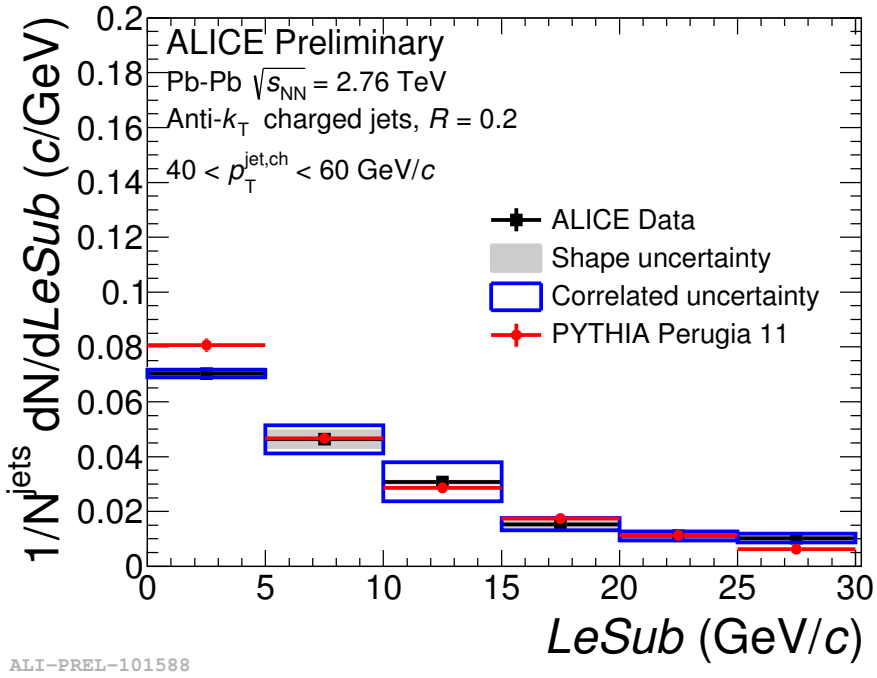

Small effects in the jet mass

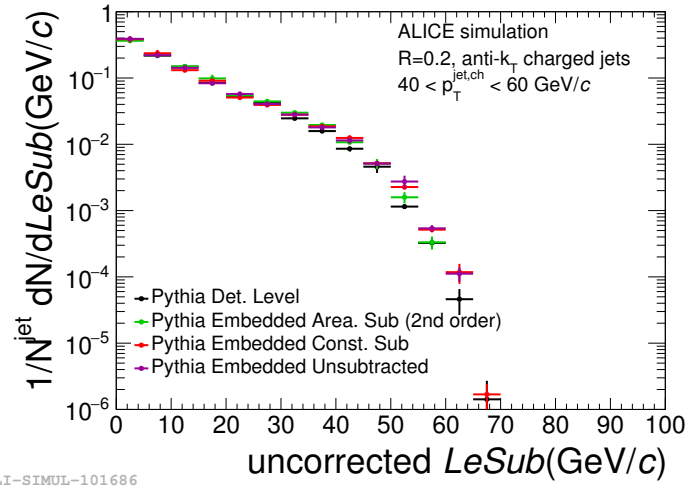
Mass ~ $p_T\theta^2$ while g ~ $p_T\theta$, both are measurements of jet broadening, but note that different $R$ are considered (here $R$ = 0.4 while $g$ measurement is $R$ = 0.2)

# LeSub

$$\text{LeSub} = p_T^{lead,\text{track}} - p_T^{\text{sublead,track}}$$



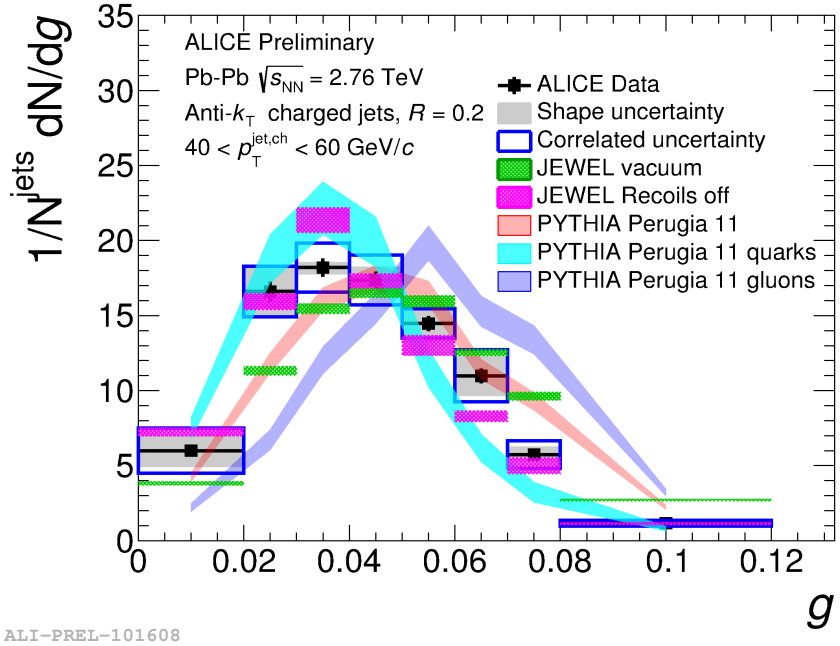



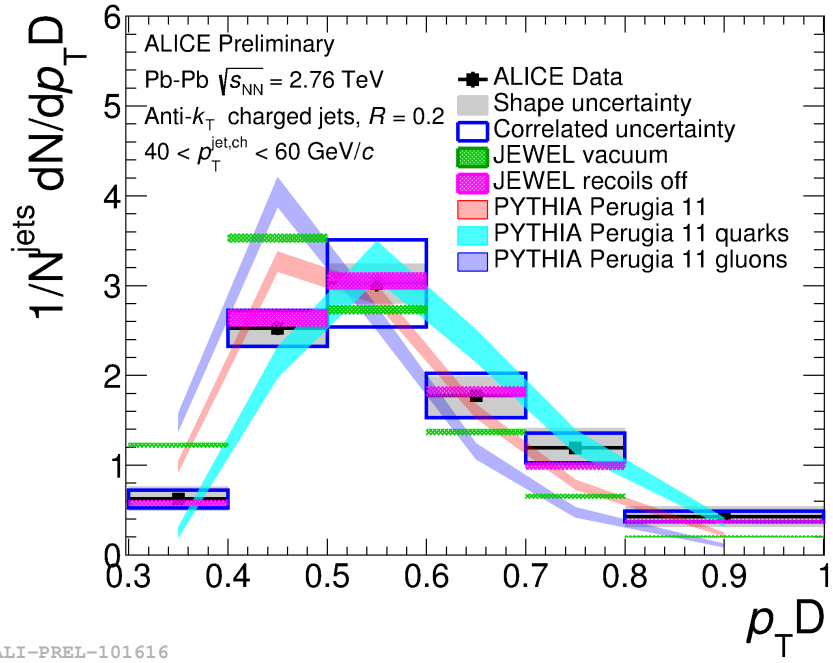




LeSub is not IRC safe but it has good properties like background invariance

**LeSub in Pb-Pb shows no deviations from the vacuum reference, indicating that the "hardish" part of the jet remains unmodified**

# Jet shapes: generalized angularities in Pb-Pb

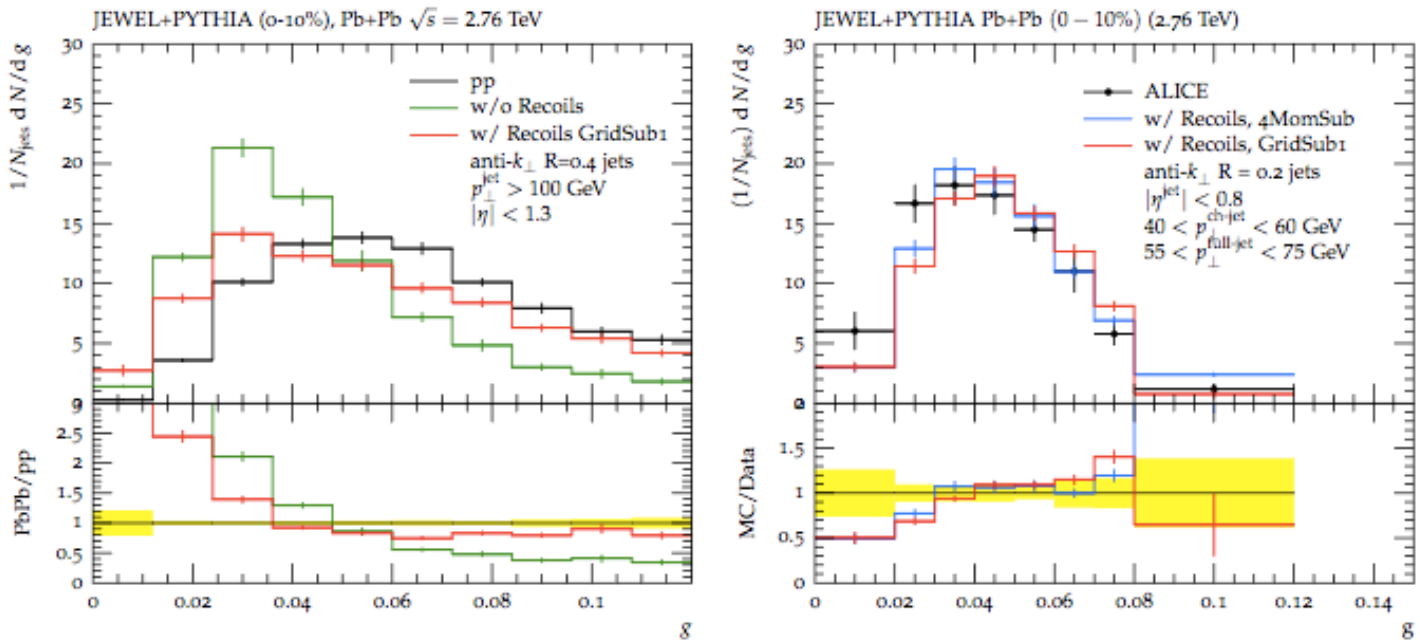



**Picture qualitatively consistent with collimation of the jet core**

Pb-Pb results in agreement with vacuum quark templates

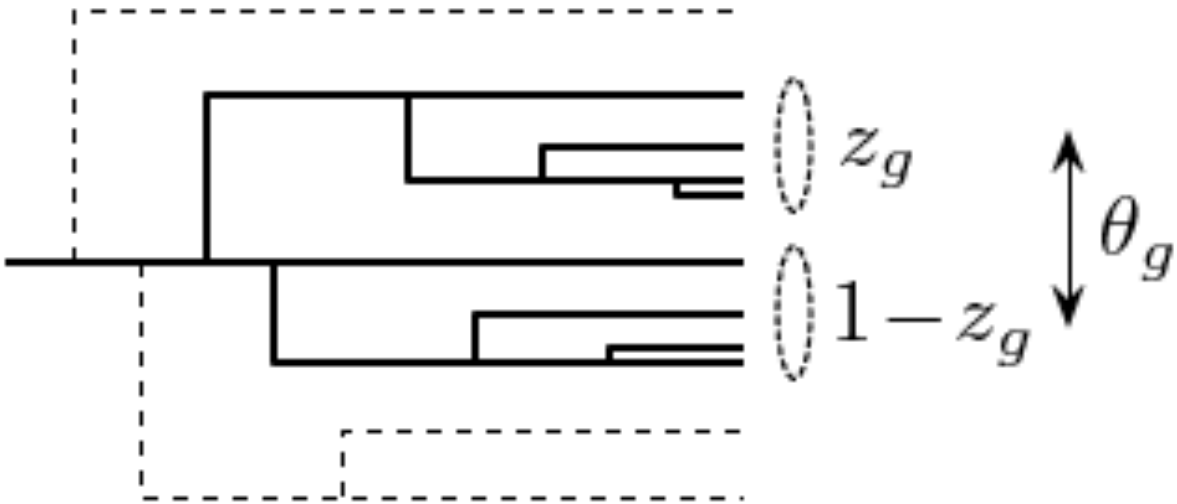
# Multiple effects contributing to the modification of the shape: medium response




*R. Kunnawalkam , K.Zapp, JHEP1707 (2017) 141*

Small effects in the shapes can be a compound effect of narrowing and re-population with jet-correlated background (medium response), as modelled by JEWEL

# Jet Substructure using clustering history



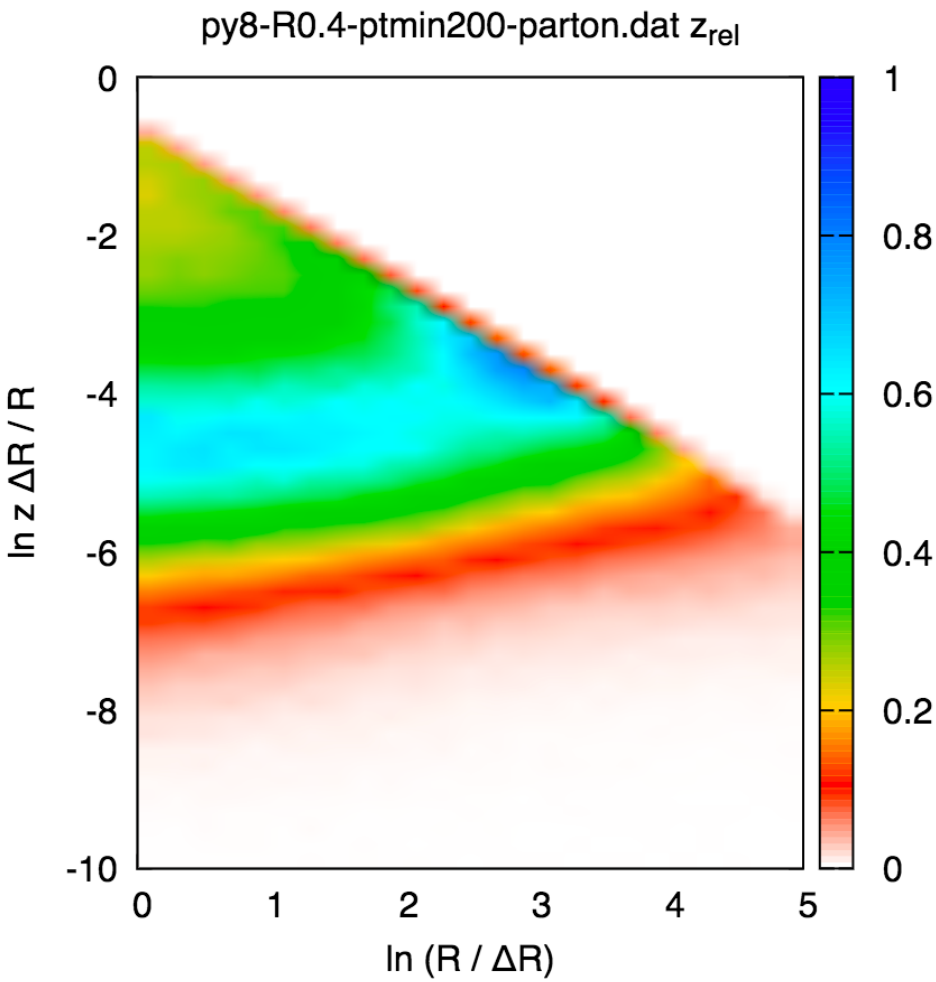

$$z > z_{\rm cut}\,\theta^{\beta}$$

**Move backwards through the clustering history grooming away branches according to a prescription.**

**Aim: Remove/signal out parts of the shower in a controlled way**

**Access parts of the shower where the theory is most reliable**

# Map of splittings



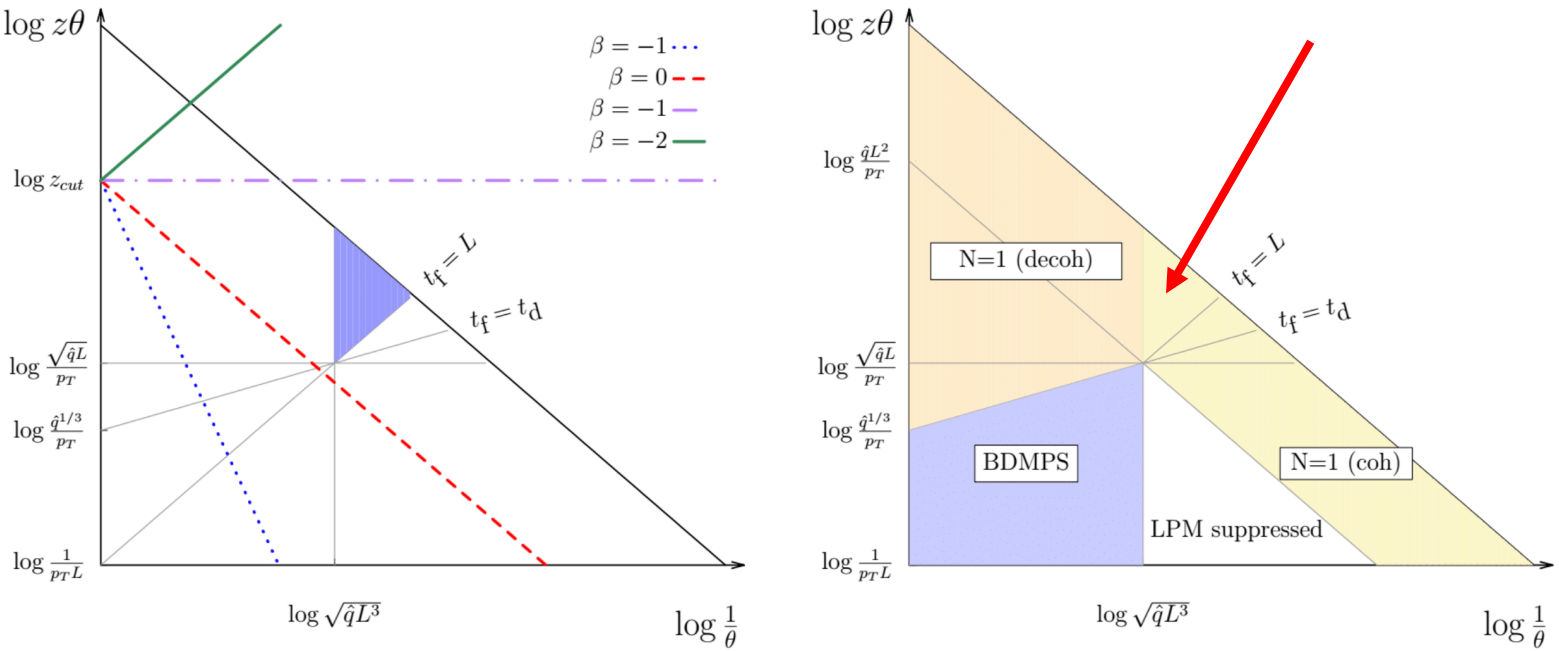

Register iteratively the kinematics of the hardest subjet in the Lund plot

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*

# Map of splittings




*K Tywoniuk et al, Jet substructure theory workshop*

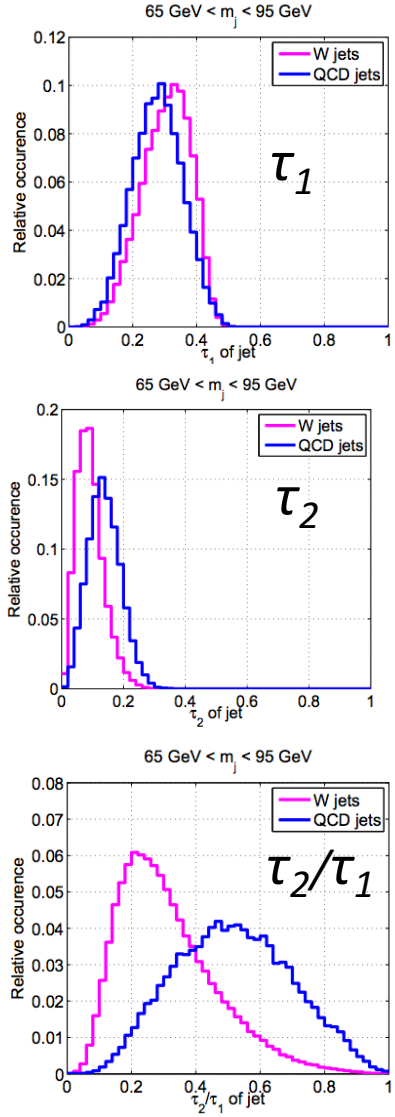
Different scales at work, interesting triangular region:

- **splitting produced in medium -> large $k_T^2$ so that $\tau_f < L < \tau_{dec}$**
- **coherent splitting: $\theta > \theta_C \sim \log(\sqrt{qhat L^3})$**
- **N=1 -> Moliere scattering off partonic degrees of freedom ~ $1/k_T^4$**

In ALICE, acceptance $\theta < \theta_C$

# $\Delta R$ and Nsubjettiness

W jets
QCD jets




*[J.Thaler et al,JHEP 1103:015,2011]*

$\Delta R$ and $\tau_2/\tau_1$ are calculated relative to the two antenna axes.

- $\Delta R$ -> $\eta$-$\varphi$ distance between axes.
- $\tau_2/\tau_1$ -> measures the two prongness of the jet.

-The Nsubjettiness, $\tau_N$ , jet shape (where $N$ can be any positive integer) is a measure of how $N$ pronged a jet's substructure is.

-Initially developed to tag jets from Higgs decays such as Higgs -> $W^+W^-$.

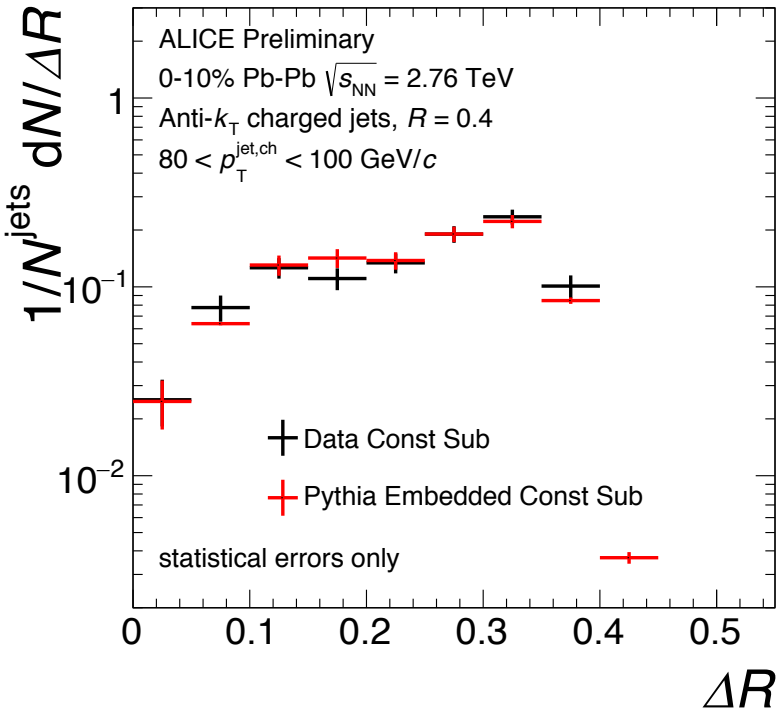
$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$

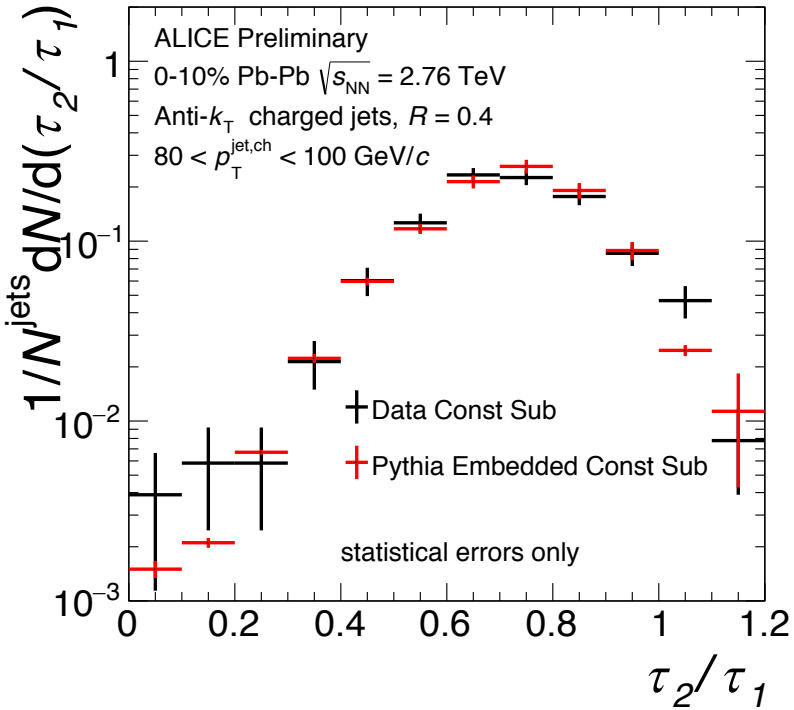
$\Delta R_{i,j}$ -> $\eta$-$\varphi$ distance between track i and subjet j
$p_{T,i}$ -> $p_T$ of $i^{th}$ jet constituent
$R_0$ Jet resolution parameter

| | |
|---|---|
| $\tau_N$ -> 0 | Jet has $N$ or fewer well defined cores |
| $\tau_N$ -> 1 | Jet has at least $N$+1 cores |
| $\tau_N/\tau_{N-1}$ -> 0 | Jet has $N$ cores |
| $\tau_2/\tau_1$ -> 0 | Jet is 2 pronged |

# Comparison of Embedded PYTHIA and Raw Inclusive Pb-Pb Data

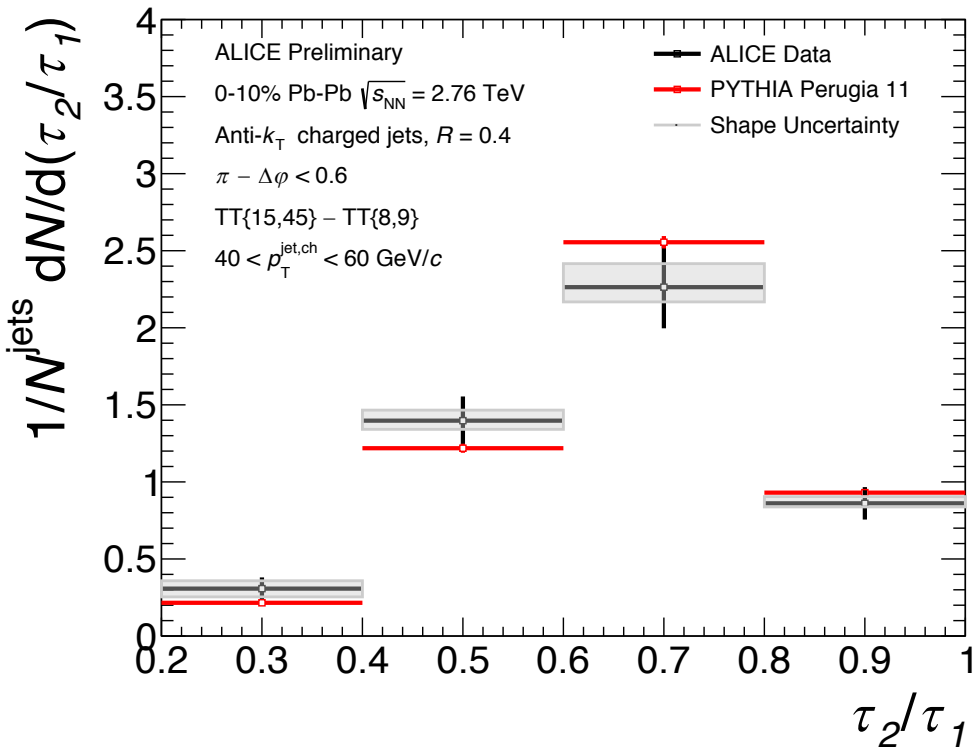
effectively grooming with $k_T$ declustering strategy




- Differences between the two distributions would point to quenching effects - small room for modifications.
- **If jets are decohered, we expect to see a suppression of rate of jets at large *ΔR***
- Large *ΔR* dominated by fake subleading subjets

# Fully Corrected Recoil Nsubjetiness in Pb-Pb

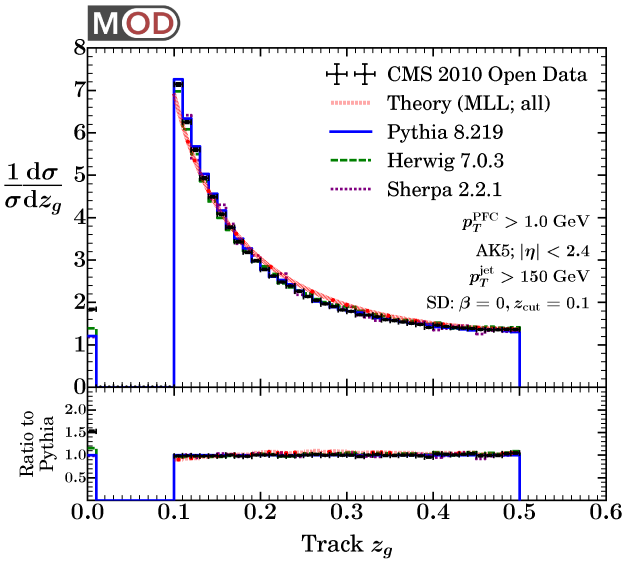



effectively grooming with $k_T$ declustering strategy

If there is a hard medium-induced splitting, can we detect it as an extra hard core in the jet substructure?

First attempt: study possible modification of the N-prongness measured with N-Subjettiness.

# Momentum imblance zg

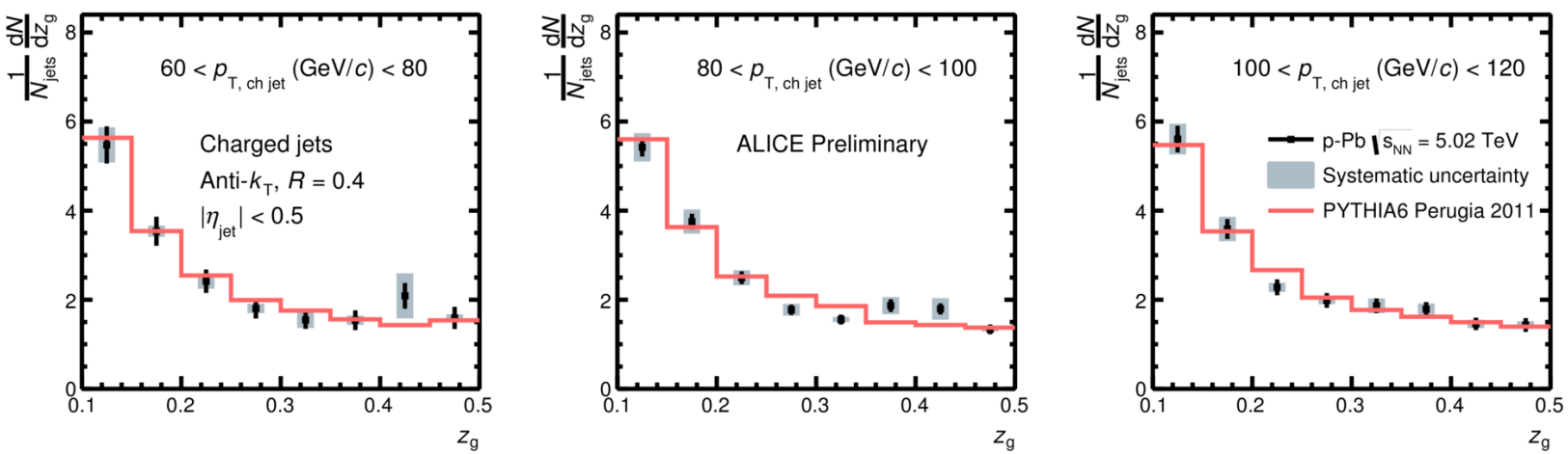



$$p(z_g) \approx \frac{2\frac{z_g}{1-z_g} + 2\frac{1-z_g}{z_g} + 1}{\frac{3}{2}(2z_{cut}-1) + 2log\frac{1-z_{cut}}{z_{cut}}}$$

**In pp: precision test of pQCD splitting functions**

**In PbPb: if color coherence is at work, medium is not expected to modify the imbalance of the subjet momentum**

**Also, sensitivity to the medium response in certain regions of phase space**

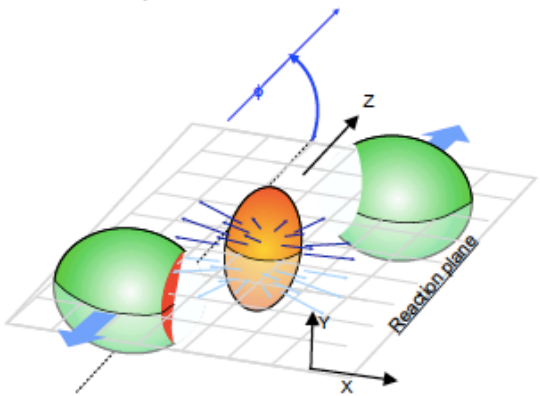



ALI-PREL-120123

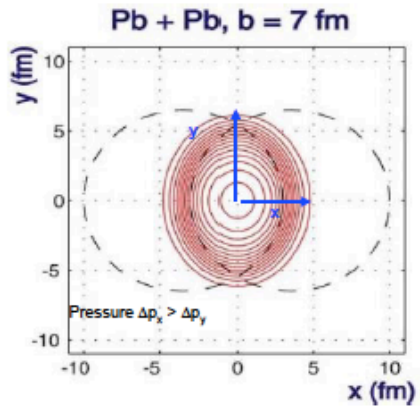
**ALICE pPb results, Pb-Pb analysis ongoing….**

# Flow

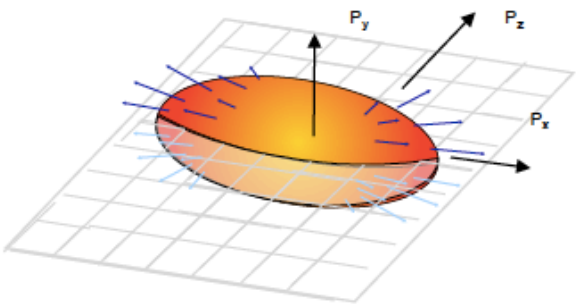
Spatial deformation




Azimuthal (ϕ)
pressure gradients



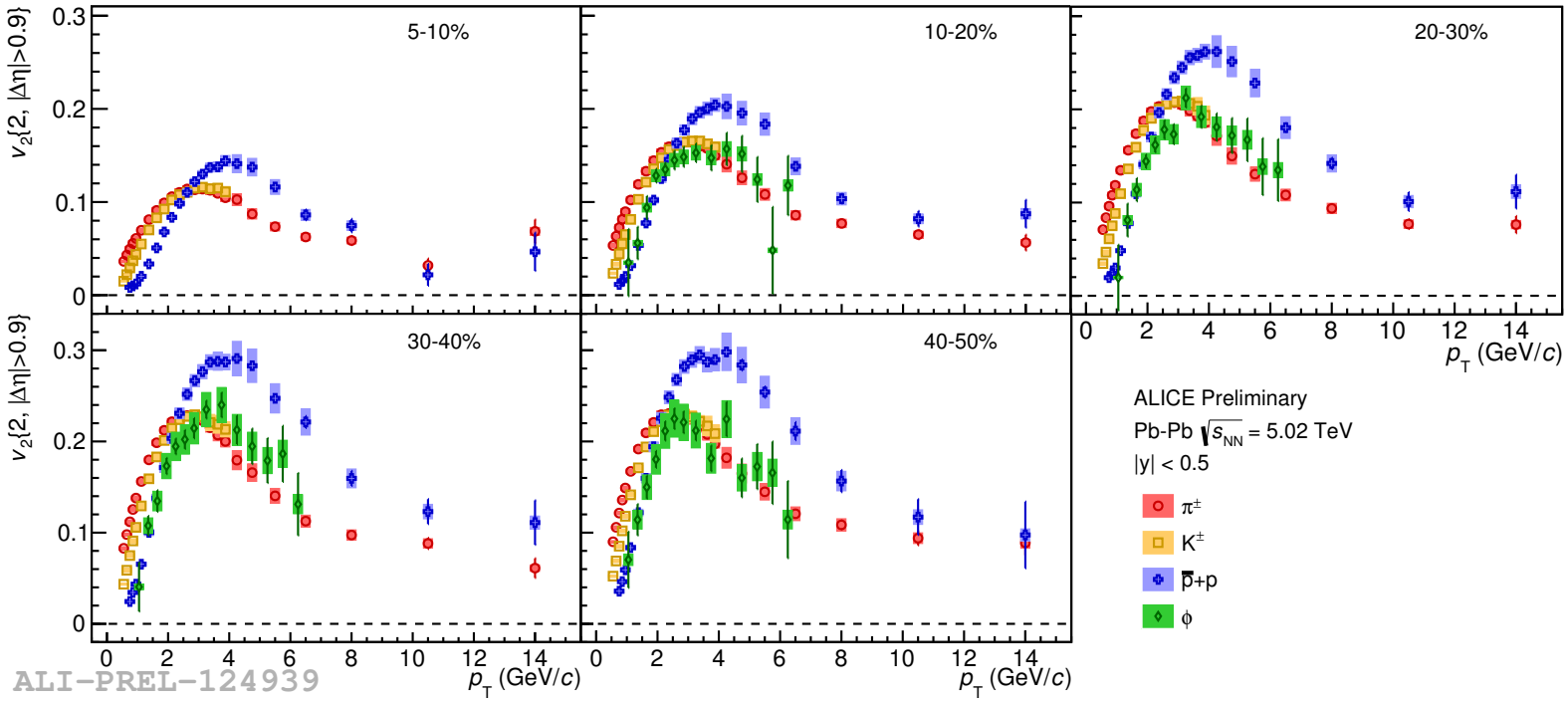

Anisotropic particle density




$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

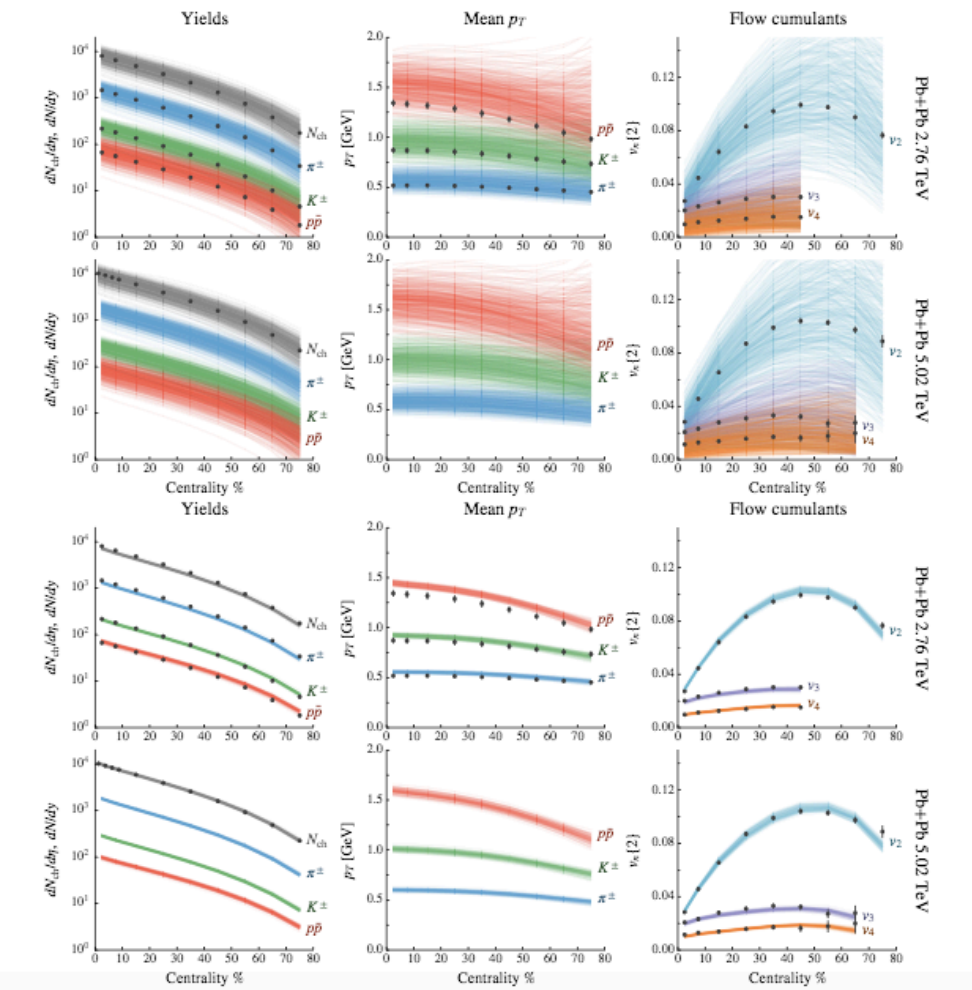
Anysotropy in coordinate space is transformed into momentum space by expansion

# Collective expansion and PID




**Thermalization pressure drives the expansion**
**Cornerstone in the interpretation of the heavy ion data**
**Particles move in a common velocity field**
**Momentum distribution ”blue-shifted”+ mass ordering**

# Transport properties: state of the art




Bayesian approach to constrain theory parameters

Theory parameters are Initial conditions, temperature dependent shear and bulk viscosities, thermalization time of the QGP, transition temperature from hydrodynamic evolution to microscopic evolution etc

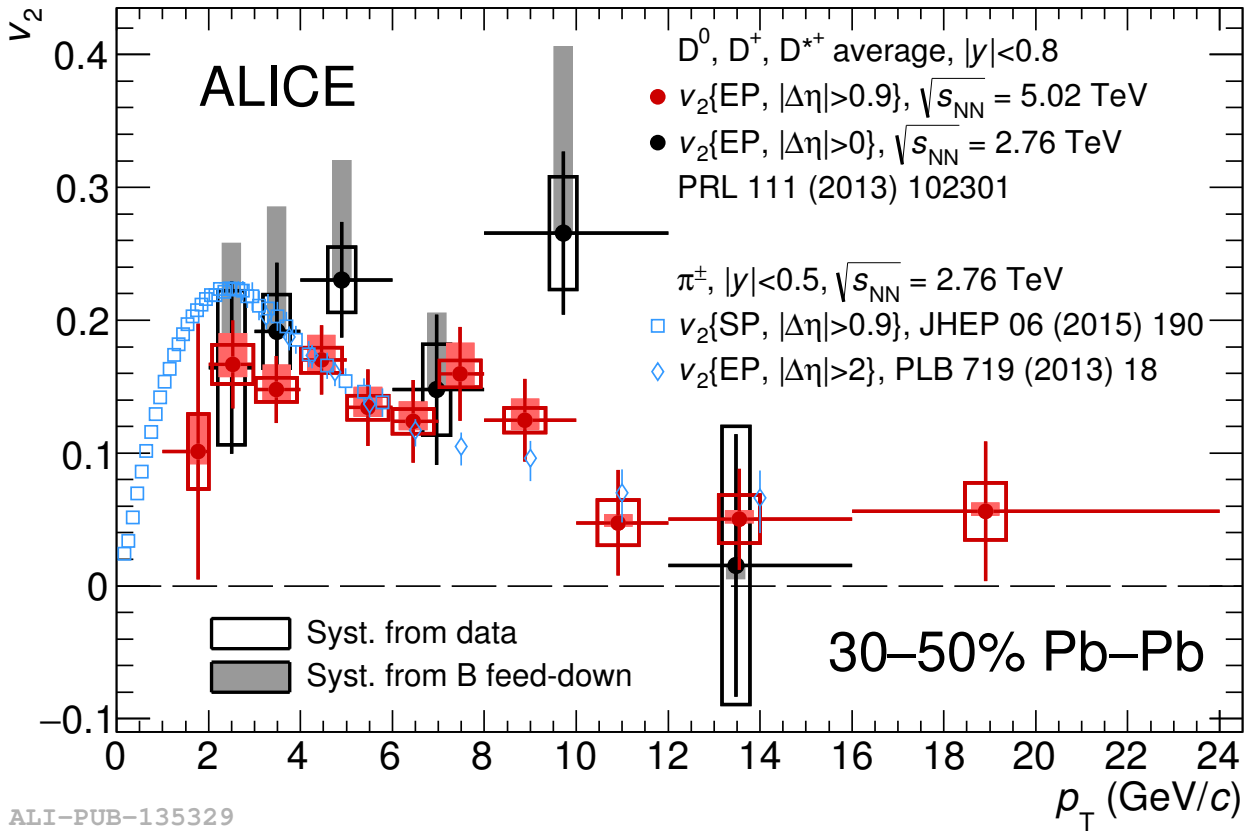
- Value of shear viscosity minimal, => **perfect liquid**, $\eta/s = 0.08^{+\cdots}_{-\cdots}$ **strongly coupled plasma.**

**No quasi-particles in a perfect liquid (up to what scale?)**

*J.E. Bernhard et al. , arXiv:1605.03954v2, fit to ALICE data.*

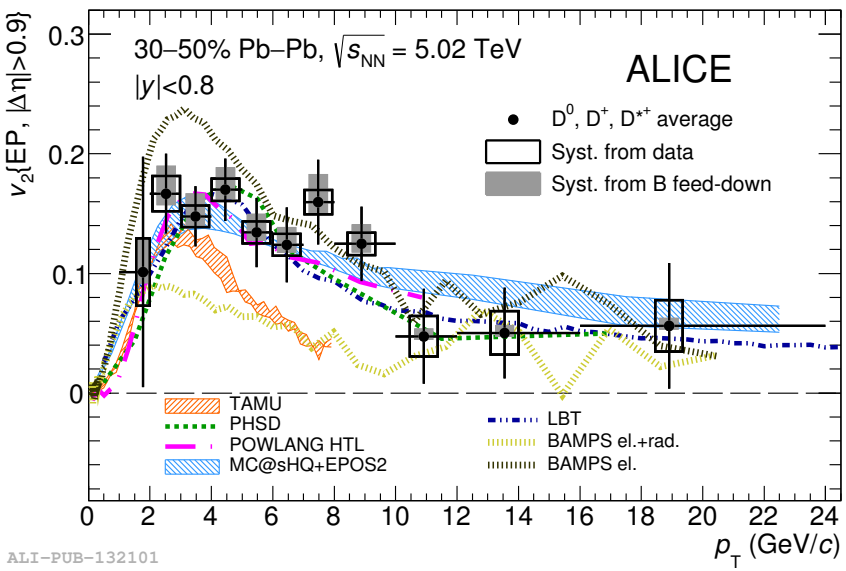
# Heavy Flavour transport

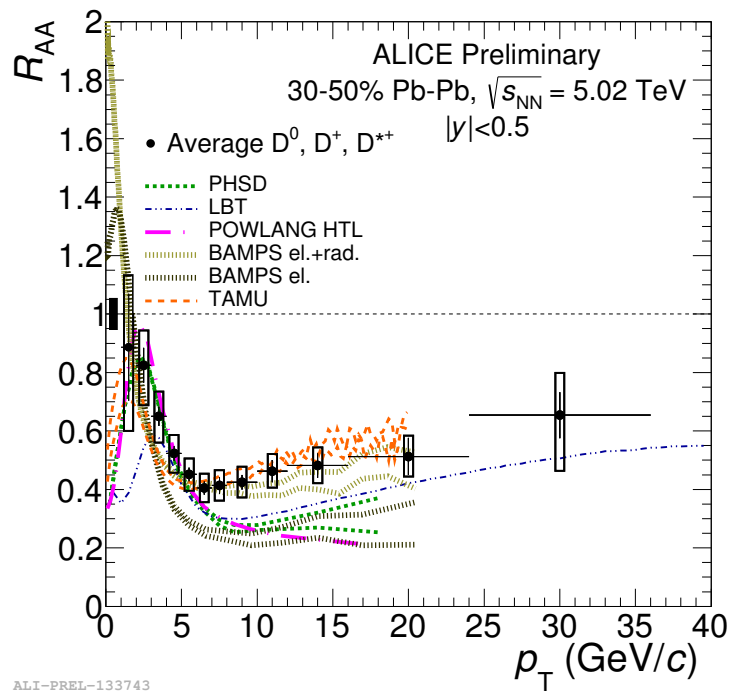
# Heavy Flavour and collective motion




**Participation of low $p_T$ charm in collective motion of the QGP**

# Heavy Flavour and collective motion



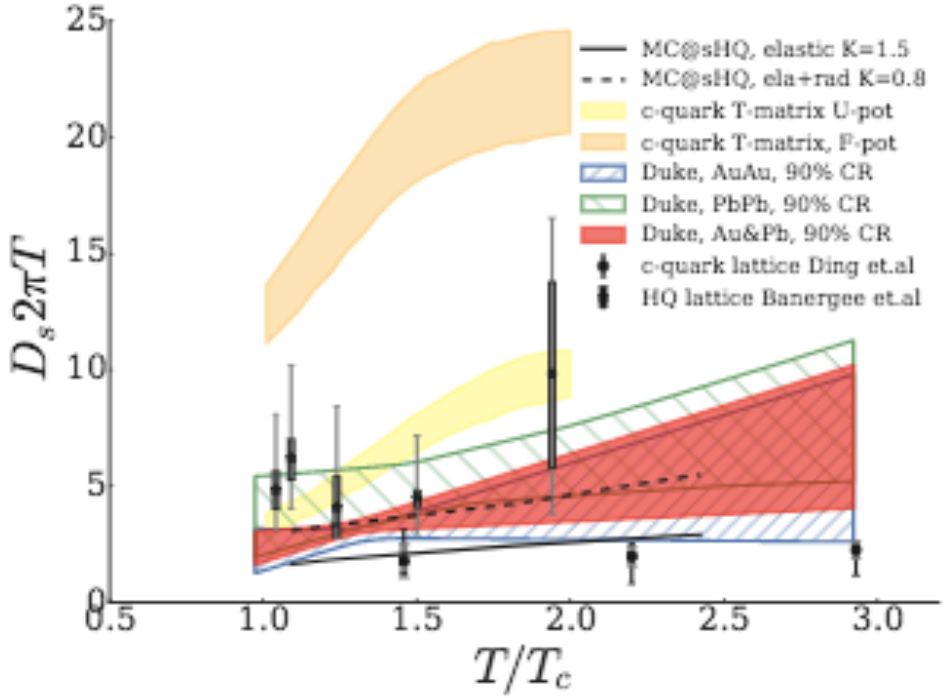




Models where charm quarks pick up collective flow via recombination and/or subsequent elastic collisions in expanding hydrodynamic medium do better at describing $R_{AA}$ and $v_2$ at low $p_T$

Data/model comparison allows the extraction of fundamental parameters like the diffusion coefficient and charm thermalization time

# Heavy Flavour transport: state of the art

*Yu.Xu et al, arXiv:1704.07800*

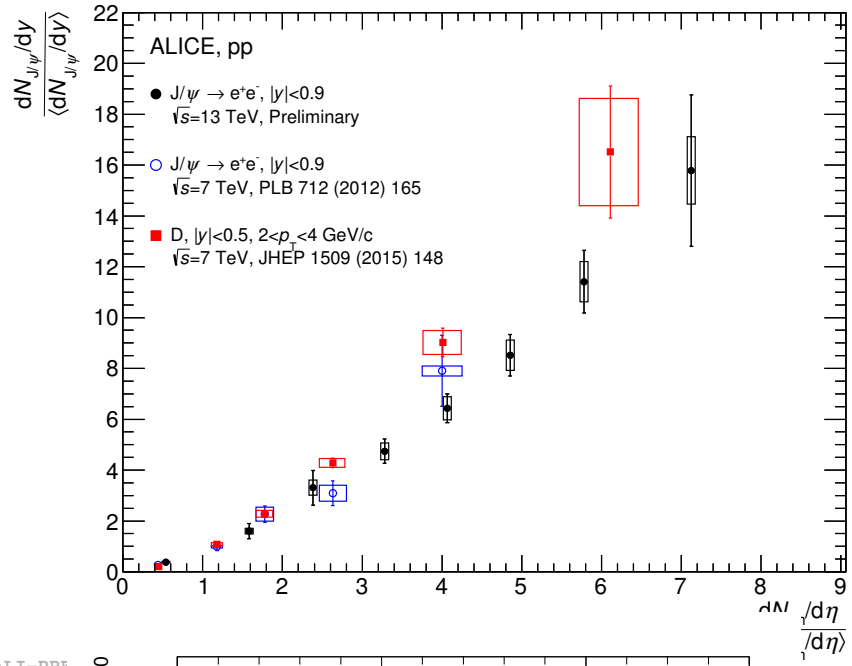



Bayesian analysis using ALICE data to calibrate model parameters to estimate temperature dependence of heavy quark diffusion coefficients

Test of QCD transport theory

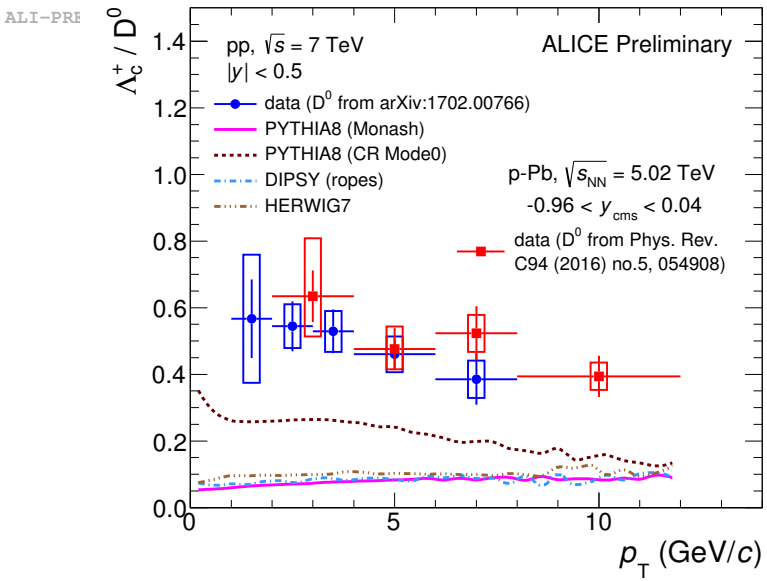
# Small systems

# Small systems: Hadronisation




**$J_{/\psi}$ production enhanced in high multiplicity pp collisions**

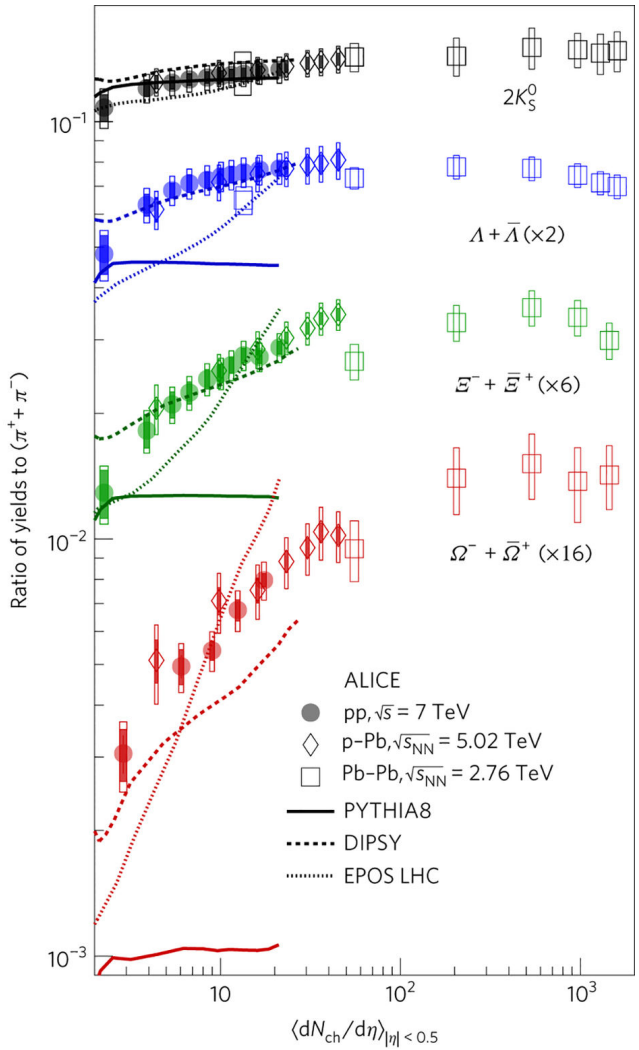
**Role of multiple parton interatctions (MPI)**




Ratio of charm baryons to D mesons not reproduced in event generators

**Role of color reconnections?**

# Small systems: Hadrochemistry




Smooth evolution of particle ratios with multiplicity

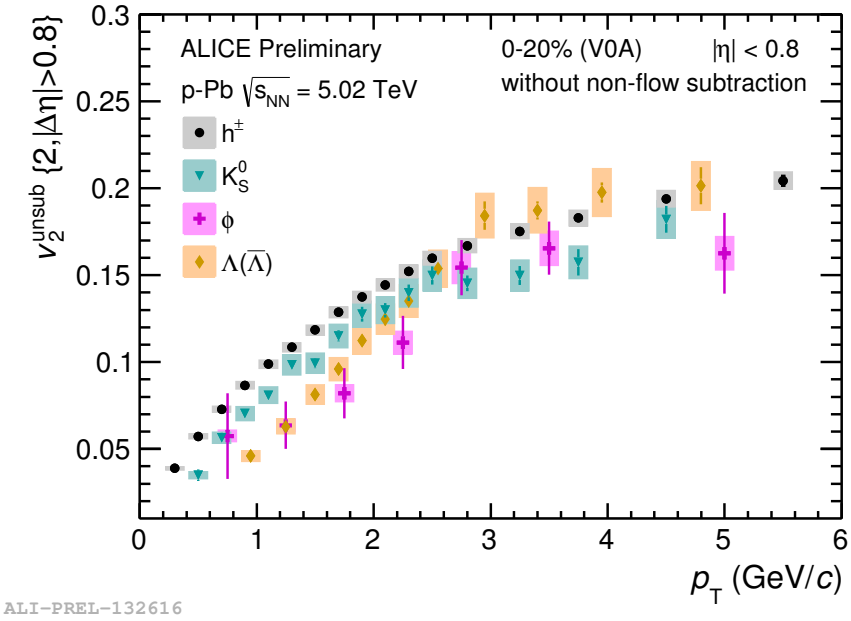
Not reproduced by pQCD models with independent string fragmentation

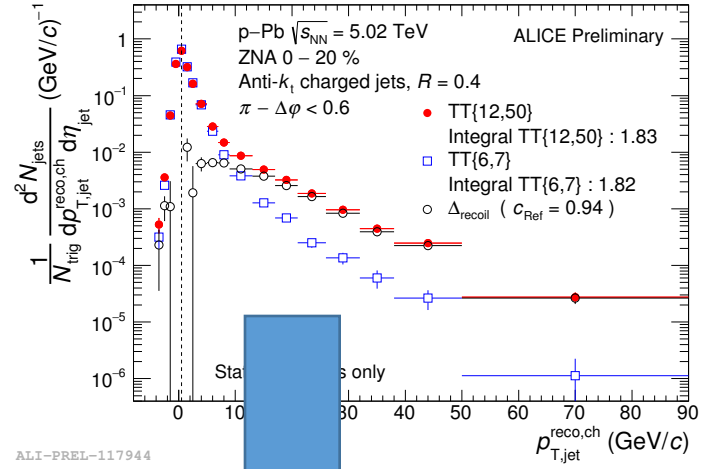
"Collectivity" introduced by string overlap and fusion needed to increase string tension and allow for heavier objects

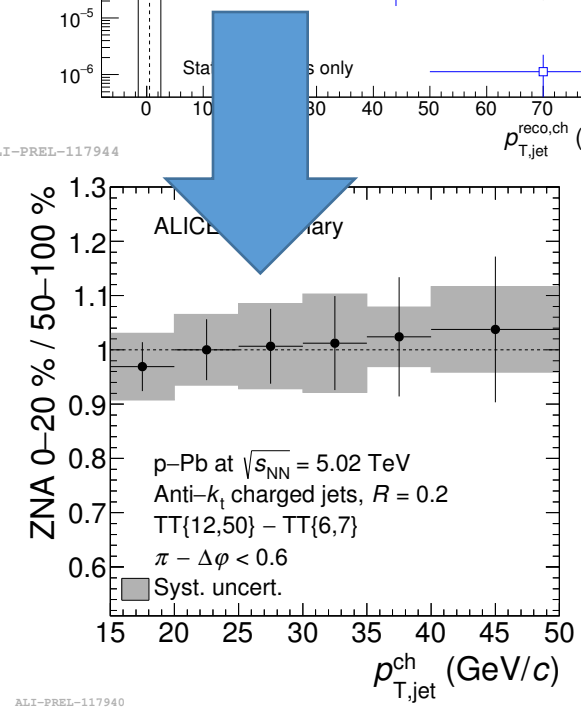
**Remnants of Heavy Ion Physics in high multiplicity pp or pPb collisions**

# Small systems: Flow and jet quenching

**Significant v2 (vn) and negligible quenching?**
**Role of initial state effects?**




Both jet quenching and flow are the result of the interactions with/between the constituents of the QGP

Seminclusive hadron-jet measurements to study hard procesess and constrain jet quenching in small system without relating event activity to geometry

# 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….

-Constraining equilibrium properties of QCD matter, advanced.
Differencial data provides great constraint to Bayesian approaches to model-data comparison.

-Efforts to understand transition between small systems and big systems, onset of critical phenomena, interplay between hard process and underlying event.

ALICE provides key data constrains to the three problems above

# **Run 2**: Collected (Goal)

| | pp, 5 TeV | pp, 13 TeV | p-Pb, 5 TeV | p-Pb, 8 TeV | Pb-Pb 5 TeV |
|---|---|---|---|---|---|
| $L_{int}$ | 112 $nb^{-1}$ (1 $pb^{-1}$) | 14 (50) $pb^{-1}$ | 3.4 $nb^{-1}$ | 21 $nb^{-1}$ | 250 $\mu b^{-1}$ (1 nb-1) |
| $N_{MB}$ | 128 (1000) M | 1.5 G (3.7 G) | 764 M | 70 M | 157M (250M) |
| $N_{HM}$ | N/A | 814 M (2.5 G) | N/A | 47 M | (200 M) |

**Data Taking in 2017**