Studying jet formation in the medium with help of correlation and jet shape observables

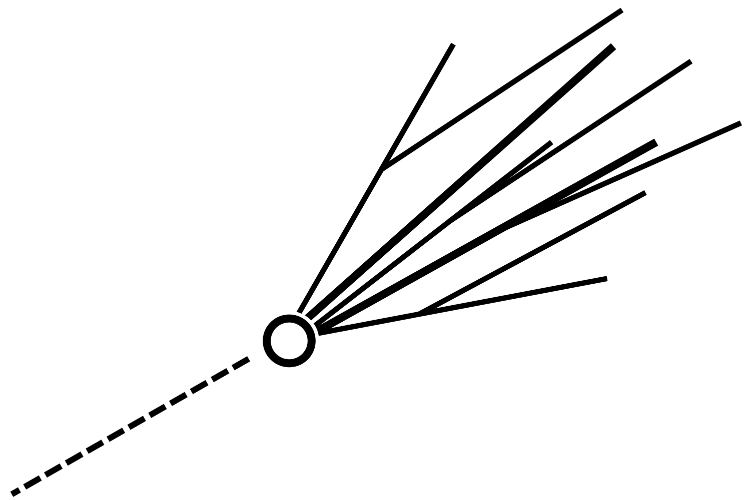
Eliane Epple
for the ALICE collaboration

Thu, 29.3.2018

Jet Physics in the Medium

Jet in Vacuum

created in a hard scattering event
back-to-back with parton/γ/Z-Boson
highly virtual parton fragmenting
and then hadronizing into measurable
particles



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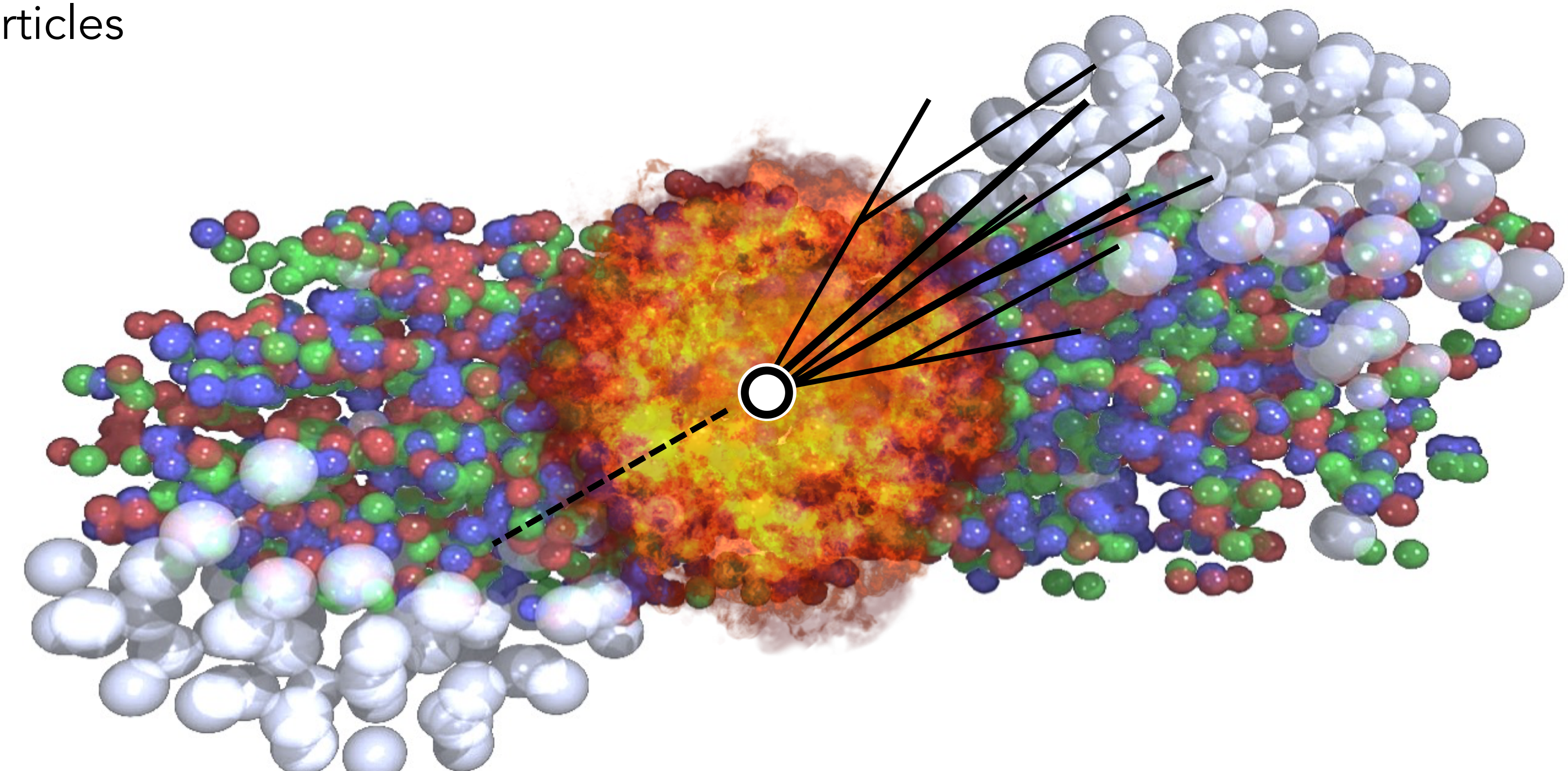
- modification of recoil angle
- modification of energy profile of the jet. Softening/broadening?
- collisional/radiative parton energy loss



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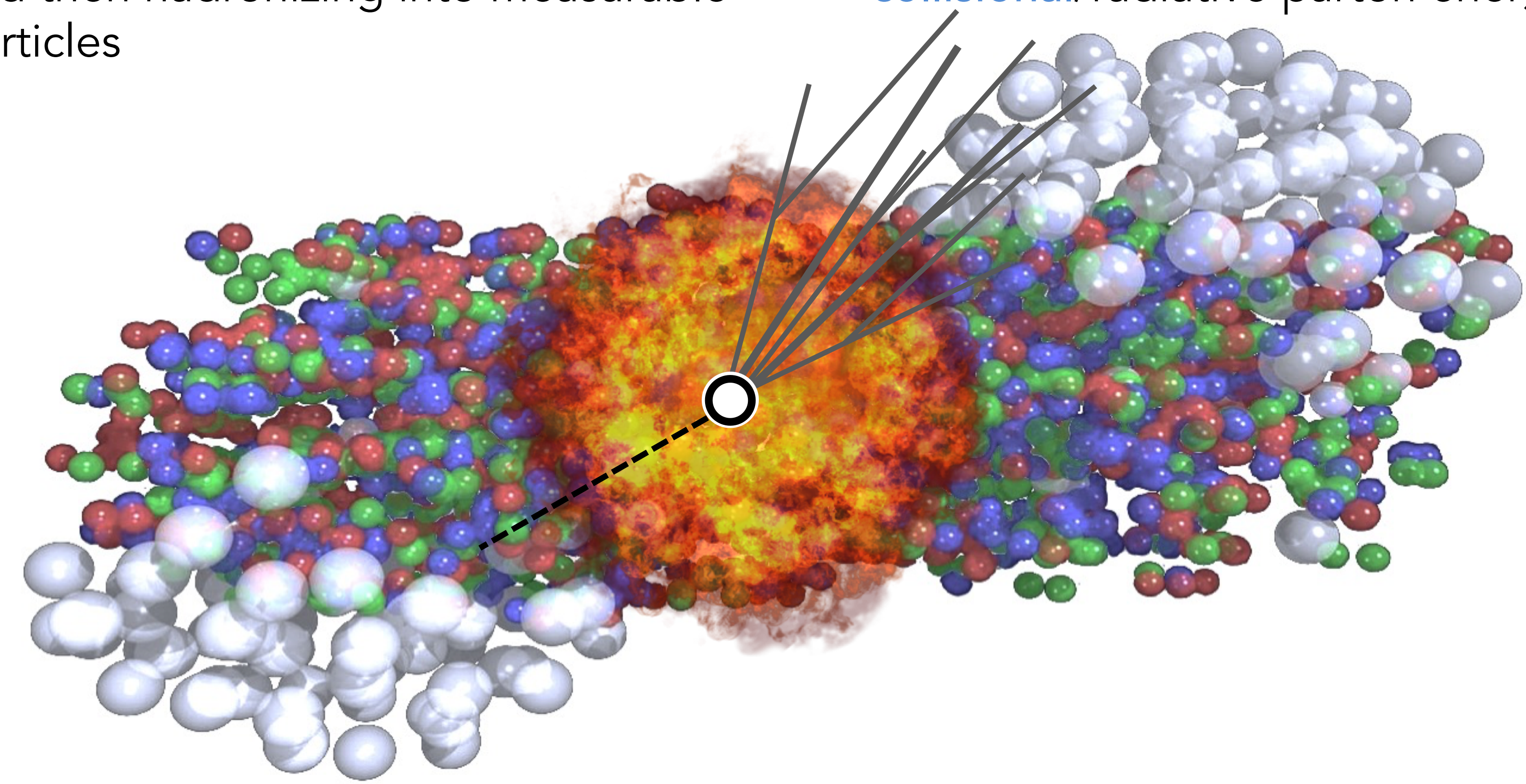

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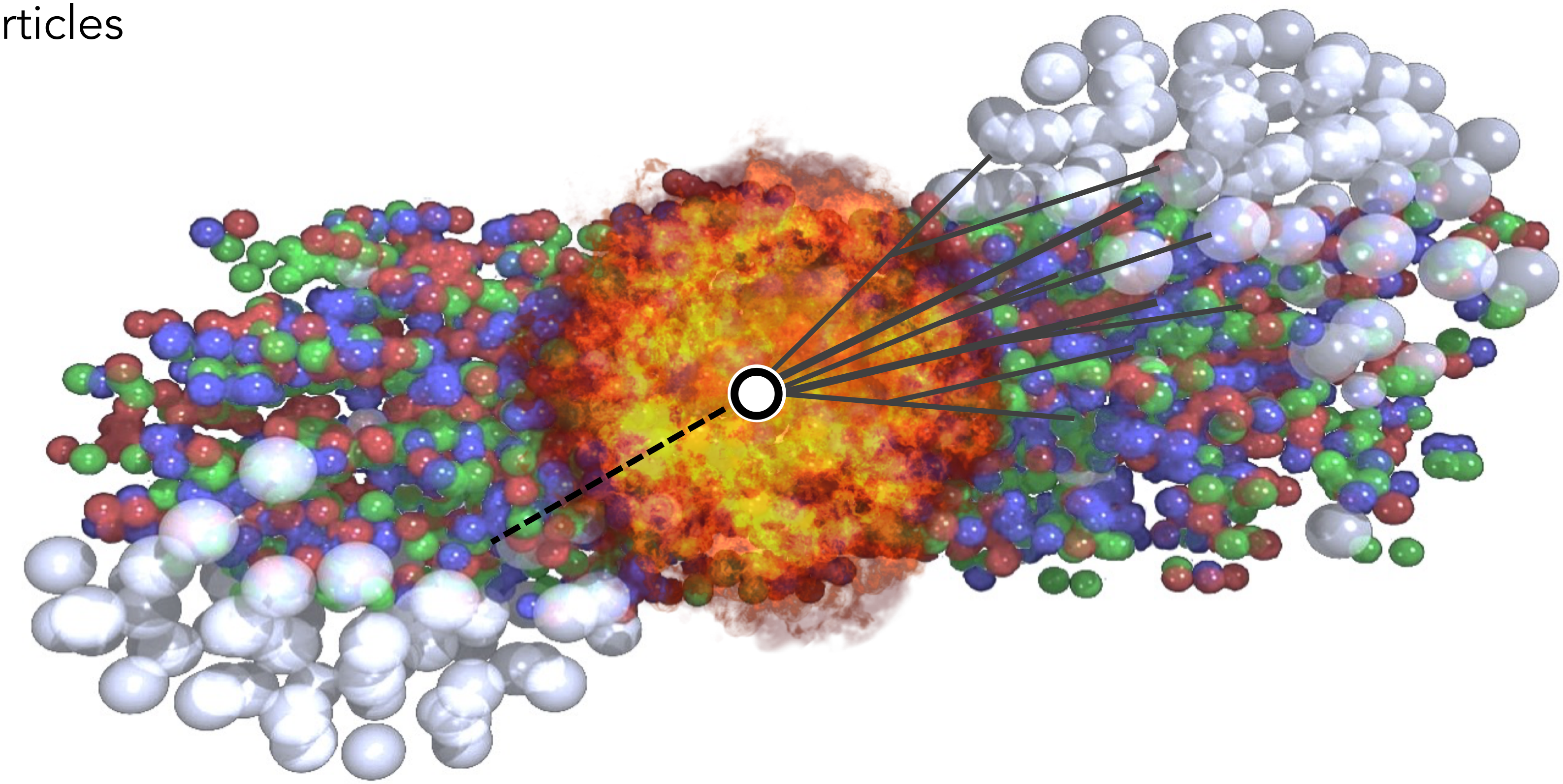

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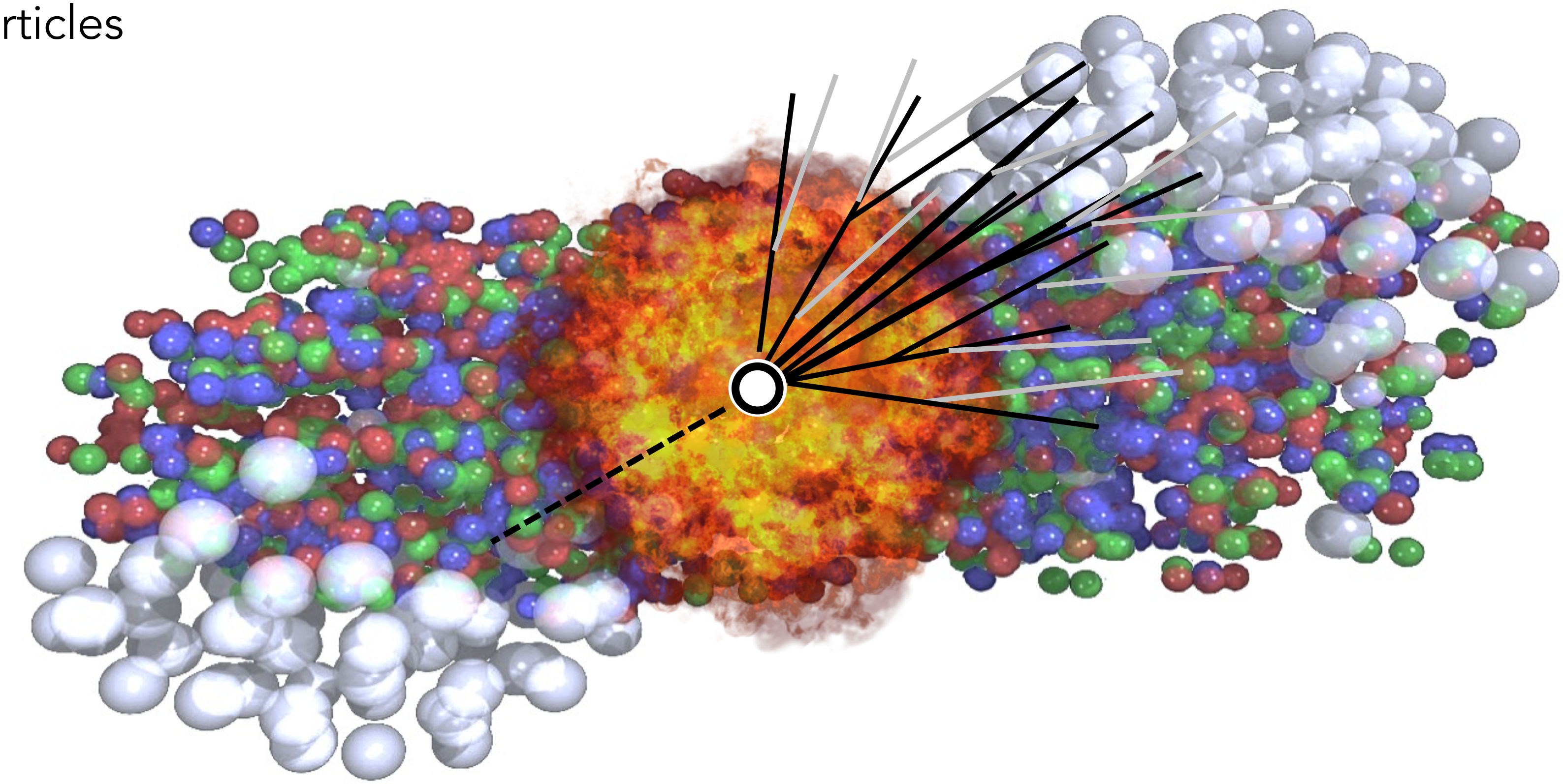
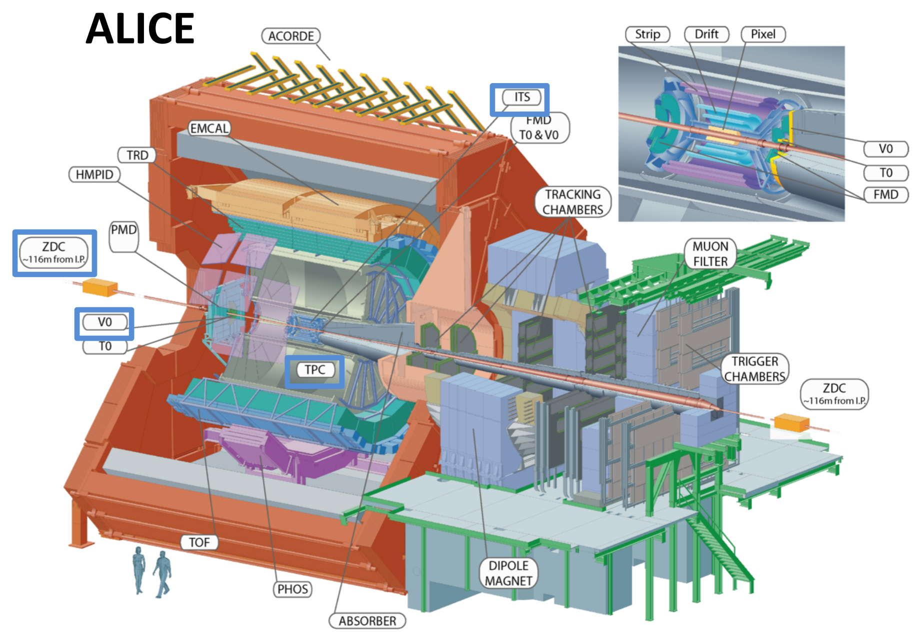


Experiment

TPC (Time projection chamber)
3D gas drift chamber
ITS (Inner Tracking System)
Si pixel, drift, and strip detectors
EMCal
Pb-scintillator sampling calorimeter



Measured Systems

p-Pb at 5.02 TeV

pp at 0.9, 2.76, 5.02, 7, 8, 13 TeV

Pb-Pb 2.76, 5.02 TeV

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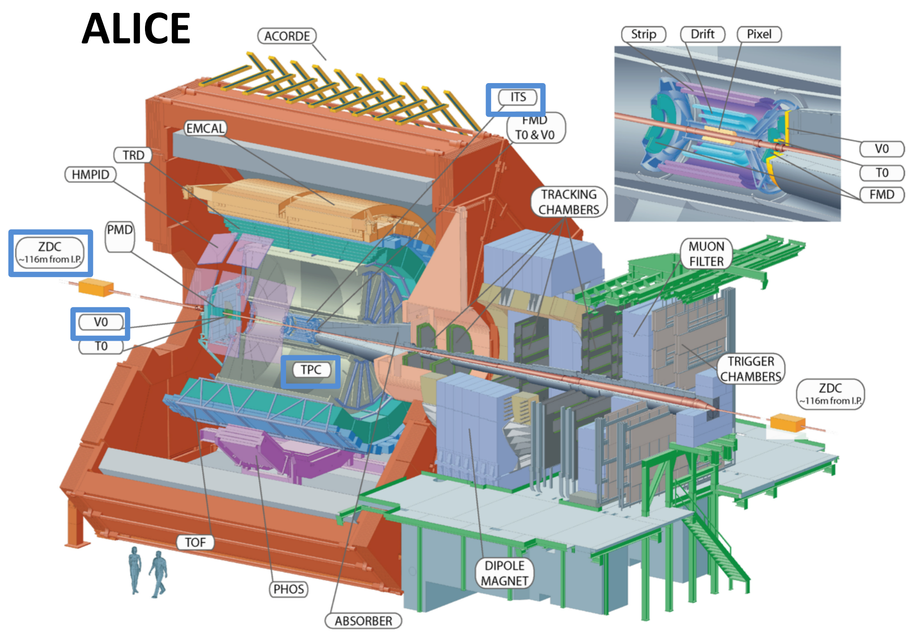

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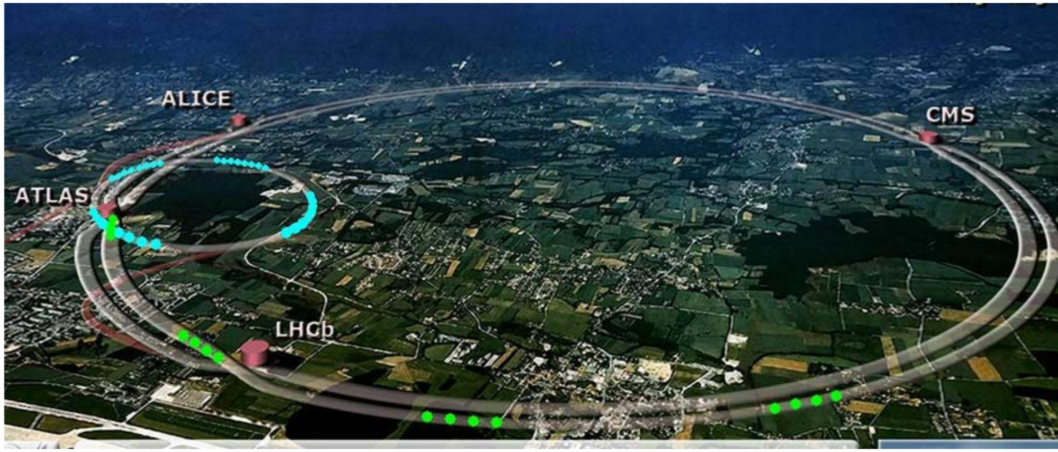


Results I Will Focus on

π^0-hadron correlations pp and Pb-Pb

How is the jet fragmentation modified by the medium

Jet Mass measurements in p-Pb and Pb-Pb

Is there a shift of measured jet masses due to hot QCD medium effects?

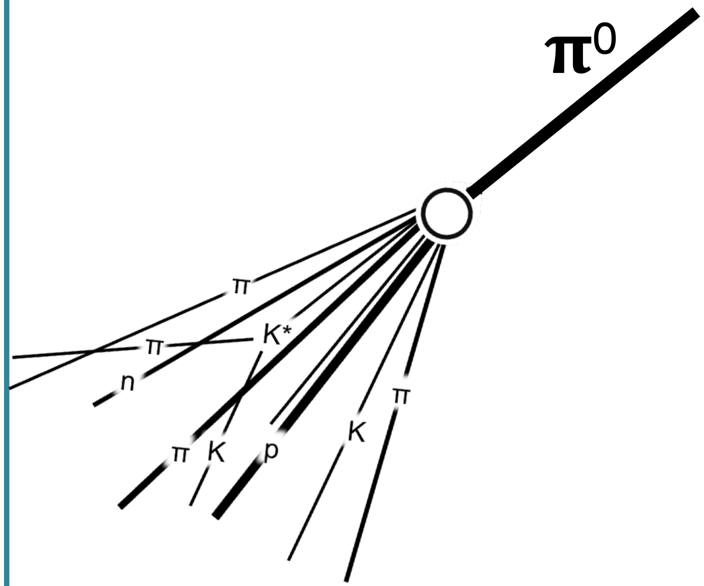
Jet shape measurement in pp and Pb-Pb

How are the cores of jets modified in the medium?

π^0-hadron correlations pp and PbPb

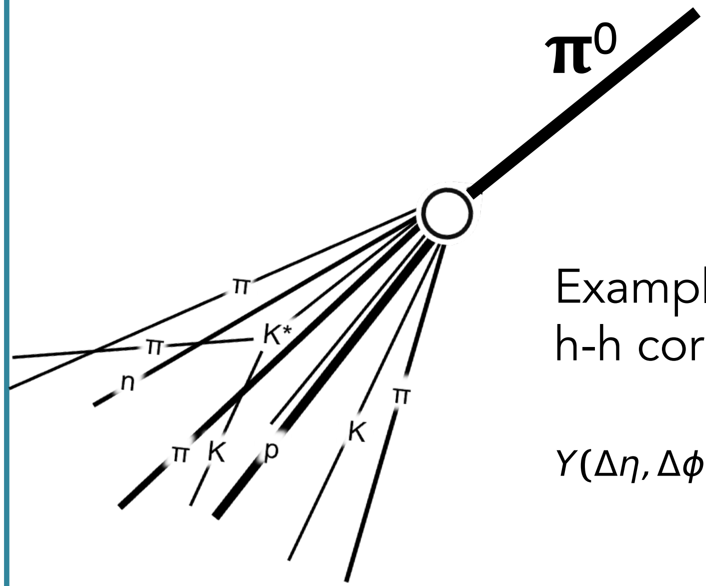
ALICE Collaboration, J. Adam et al.,
Phys. Lett., B 763, (2016) 238

π^0-hadron Correlations



We measure:
pp & Pb-Pb 2.76 TeV
8 < p^{trig} < 16 GeV/c
0.5 < p^{assoc} < 10 GeV/c

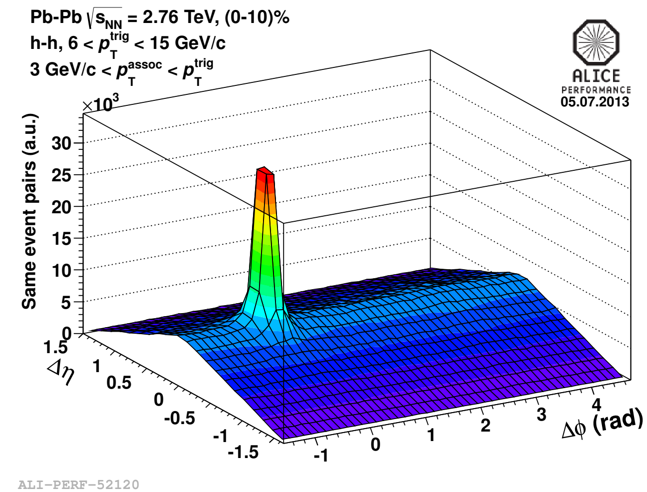
π^0-hadron Correlations

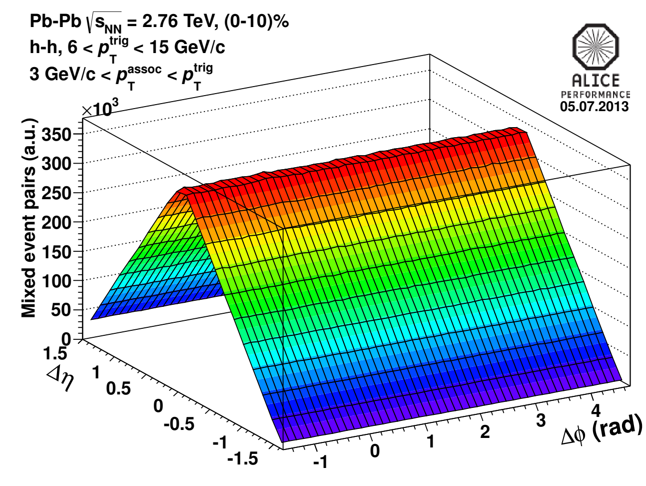


Example from
h-h correlations

$$Y(\Delta\eta, \Delta\phi) = \frac{1}{N^{trig.}} \frac{d^2 N^{trig.-h}}{d\Delta\eta d\Delta\phi}$$

$$C(\Delta\phi, \Delta\eta) = \frac{1}{N_{trig.}} \frac{d^2 N^{\gamma-h}_{same}/d\Delta\phi d\Delta\eta}{d^2 N^{\gamma-h}_{mix}/d\Delta\phi d\Delta\eta} \cdot \alpha$$





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π^0-hadron Correlations

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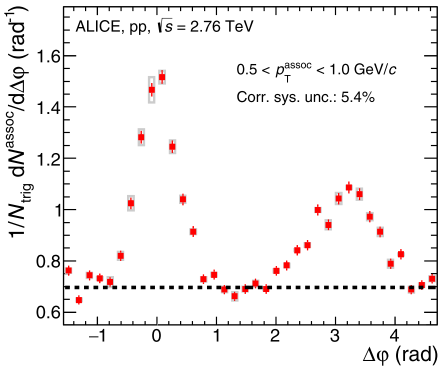

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ALICE Collaboration, J. Adam et al., *Phys. Lett., B* 763, (2016) 238

π^0-hadron Correlations

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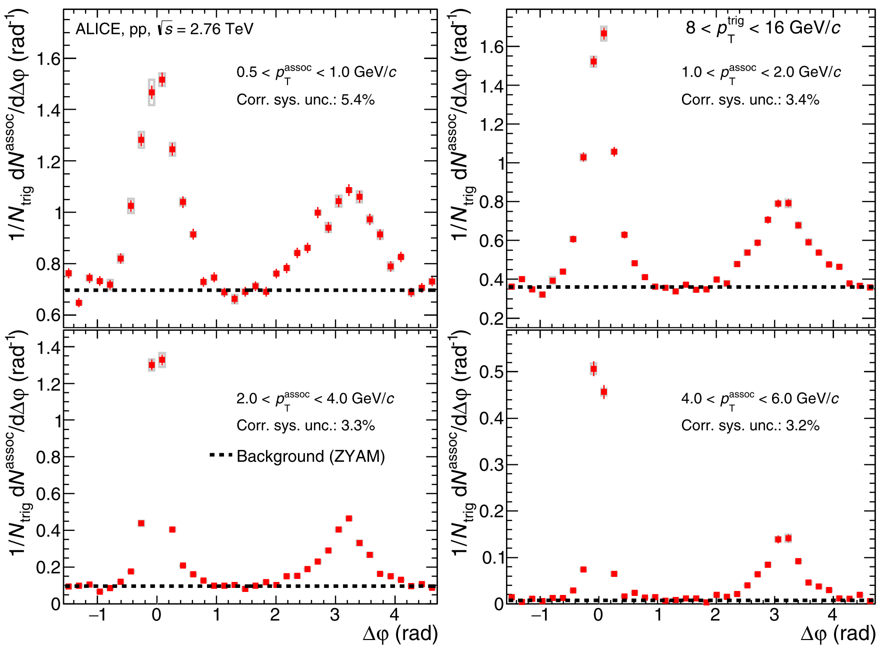
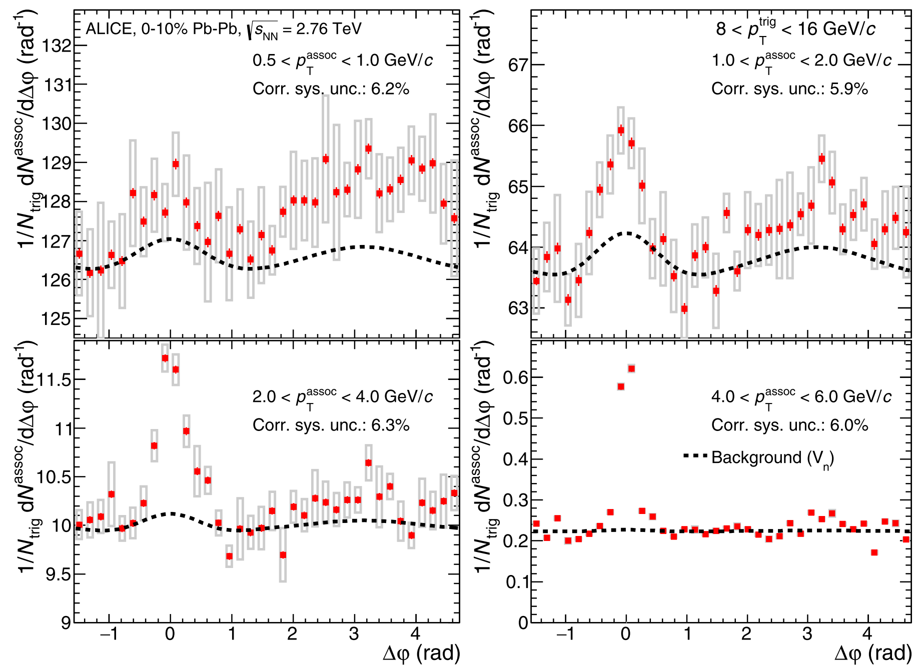


0-10% Pb-Pb



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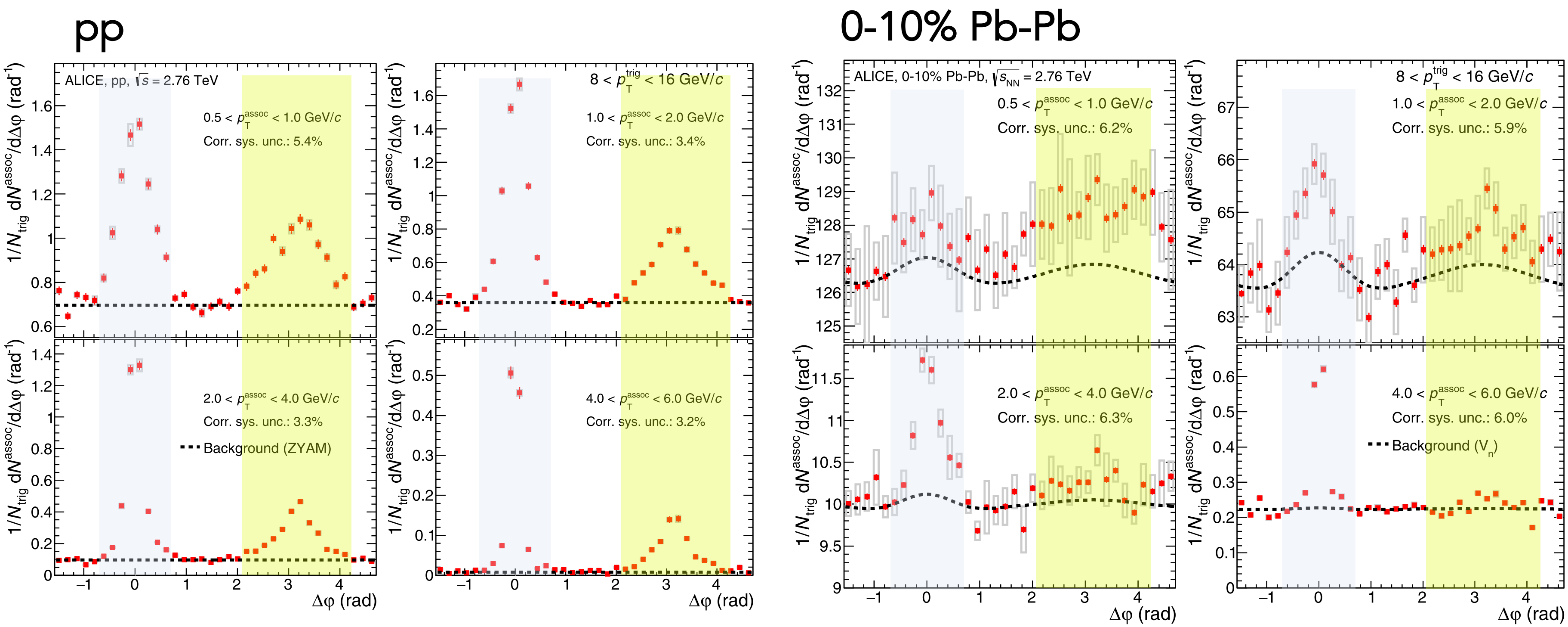
ALICE Collaboration, J. Adam et al., ***Phys. Lett.*****, *B* 763, (2016) 238**

π^0-hadron Correlations



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Near Side Signal

Away Side Signal

ALICE Collaboration, J. Adam et al., *Phys. Lett., B* 763, (2016) 238

Associated Hadron Yield

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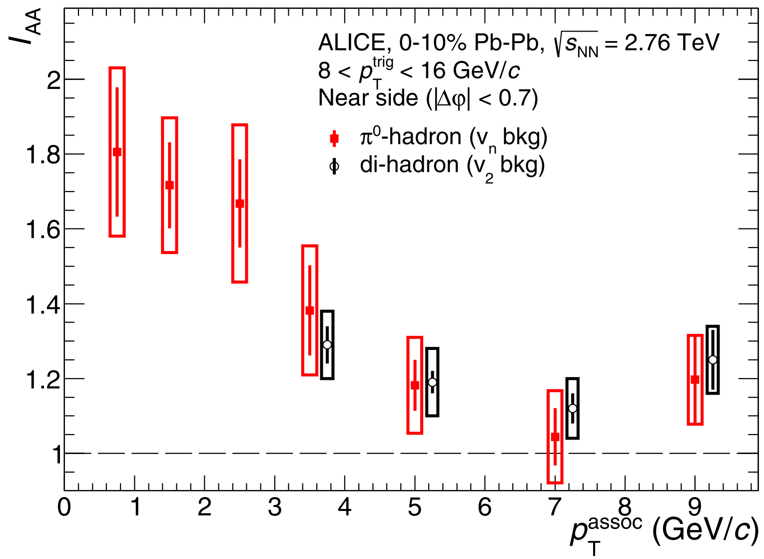

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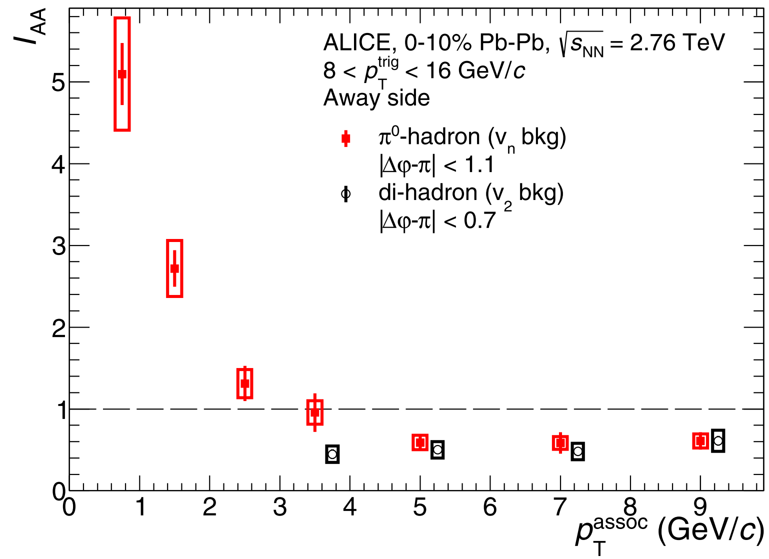

$$I_{AA} = \int_X J_{AA}(\Delta\varphi)\mathrm{d}\Delta\varphi \Big/ \int_X J_{pp}(\Delta\varphi)\mathrm{d}\Delta\varphi\,,$$

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ALICE Collaboration, J. Adam et al., *Phys. Lett.*, B 763, (2016) 238

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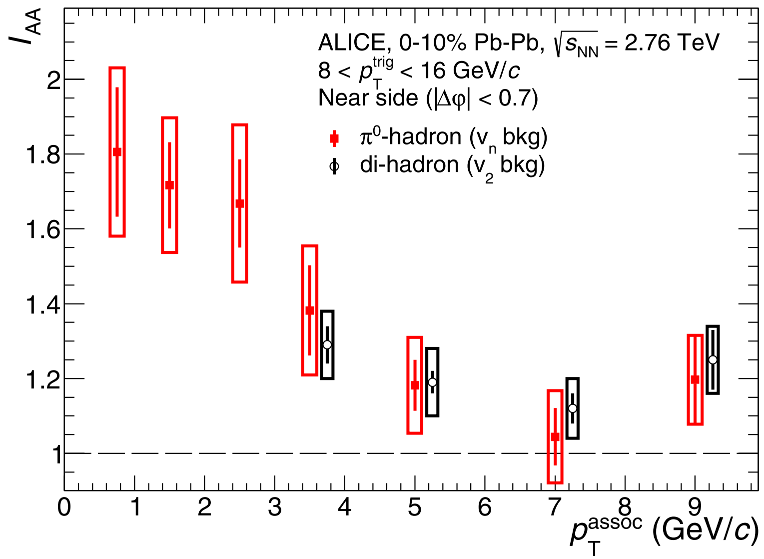

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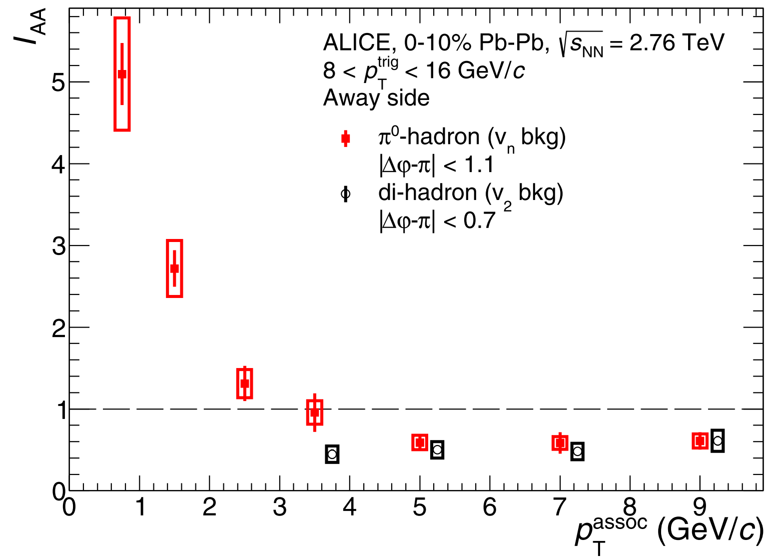

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Enhancement at the **near side** in Pb-Pb
- Medium response to the jet
- Modified fragmentation function?
- Change of q/g jet fraction?

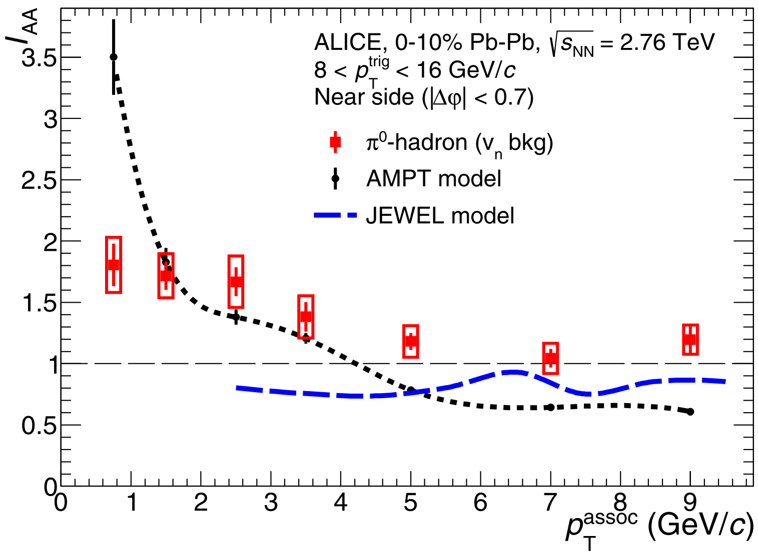
High-p_T suppression at the **away side**
- parton energy loss in-medium

Low-p_T enhancement at the **away side**
- Soft gluon radiation/medium response

Associated Hadron Yield

ALICE Collaboration, J. Adam et al., *Phys. Lett.*, B 763, (2016) 238

Near Side Signal



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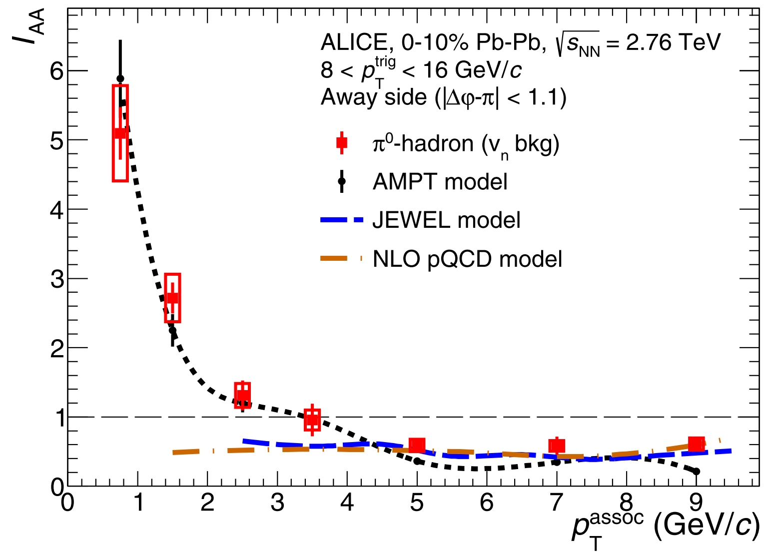
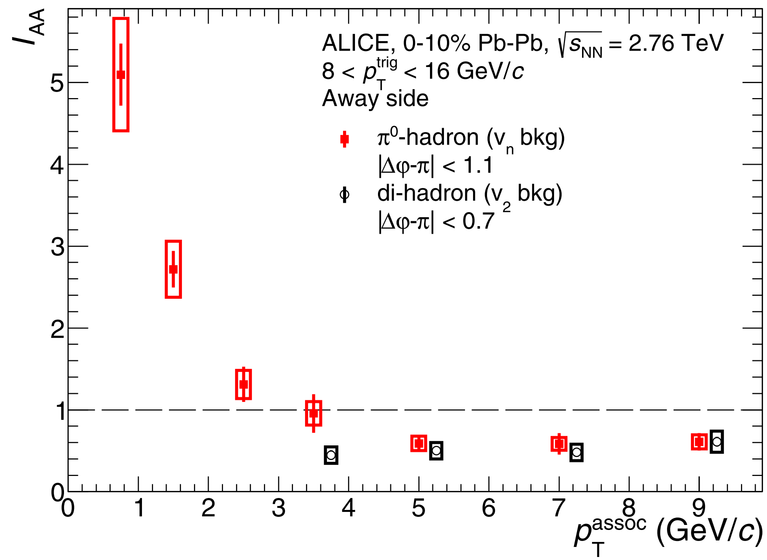


$$I_{AA} = \int_X J_{AA}(\Delta\varphi)\mathrm{d}\Delta\varphi \Big/ \int_X J_{pp}(\Delta\varphi)\mathrm{d}\Delta\varphi\,,$$

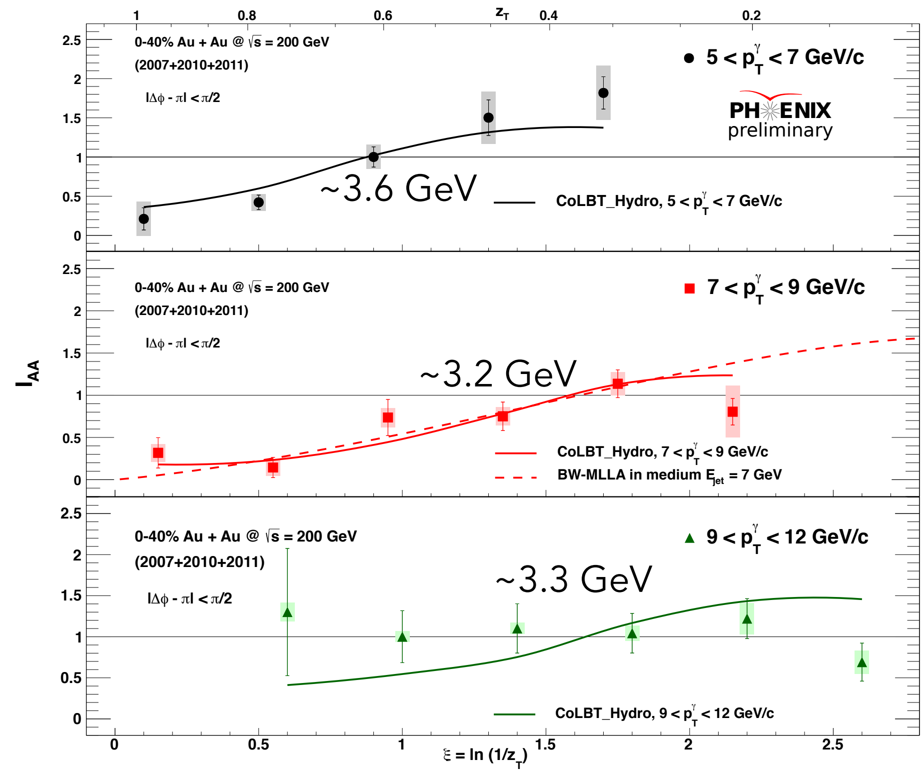
All models can describe the suppression at high p_T for the away side.
The increase at low p_T is only described by **AMPT**.
For **AMPT**, however, the suppression at the near and away side is much too strong.

In Context

ALICE Collaboration, J. Adam et al.,
Phys. Lett., B 763, (2016) 238



PHENIX Collaboration, J. Osborn et al.,
Nuclear Physics A 00 (2017) 1–4



Low-p_T enhancement also seen by PHENIX.
Enhancement there also starts at about 3.5 GeV
Same p_T region where ALICE sees the enhancement.

$$z_T = \frac{p_T^h}{p_T^{Trigger}}$$

Intra-jet Distributions I

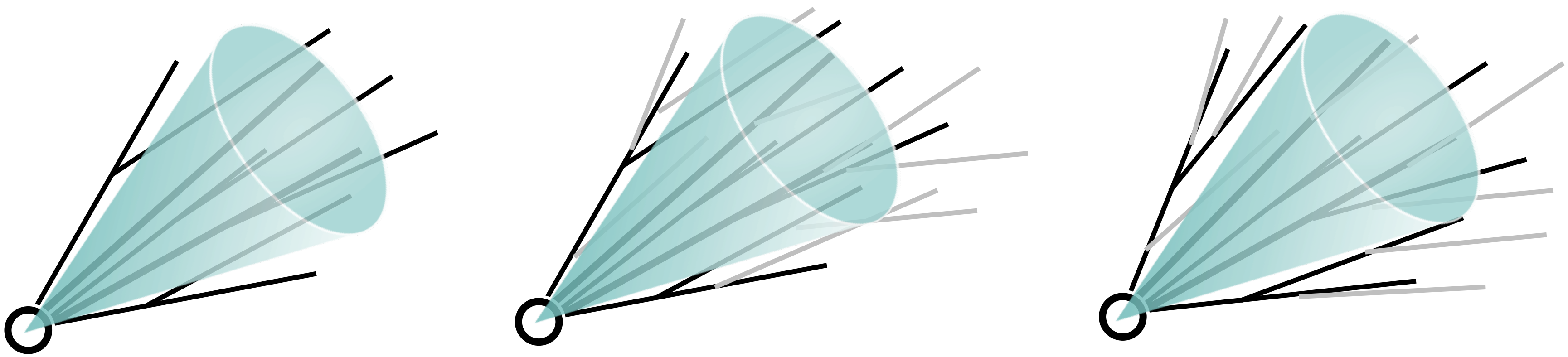
Jet Mass

ALICE Collaboration, S. Acharya et al.,
Phys. Lett., B 776, **(2018)** ***249***

Jet Mass

Jet mass is a measure of the spread of the jet and is linked to the virtuality of the initial parton

$$M = \sqrt{E^2 - p^2}$$



Measure jet mass in a given cone **R**

In Medium
If the profile broadens due to soft gluon radiation measured mass will increase

In Medium
If the profile broadens so much that large fraction of radiation is outside the cone, mass as well as p_T will decrease

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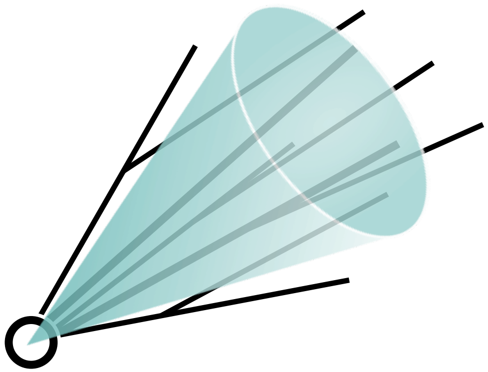

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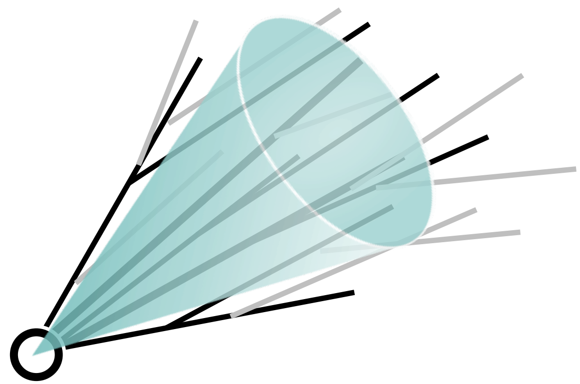

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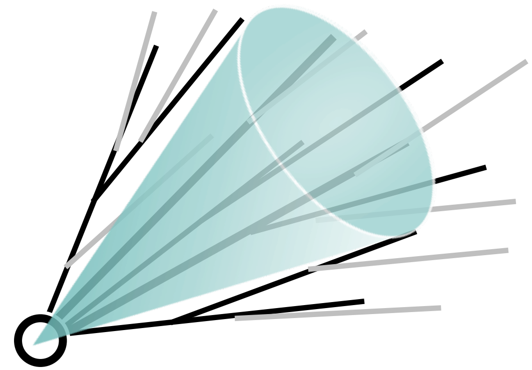


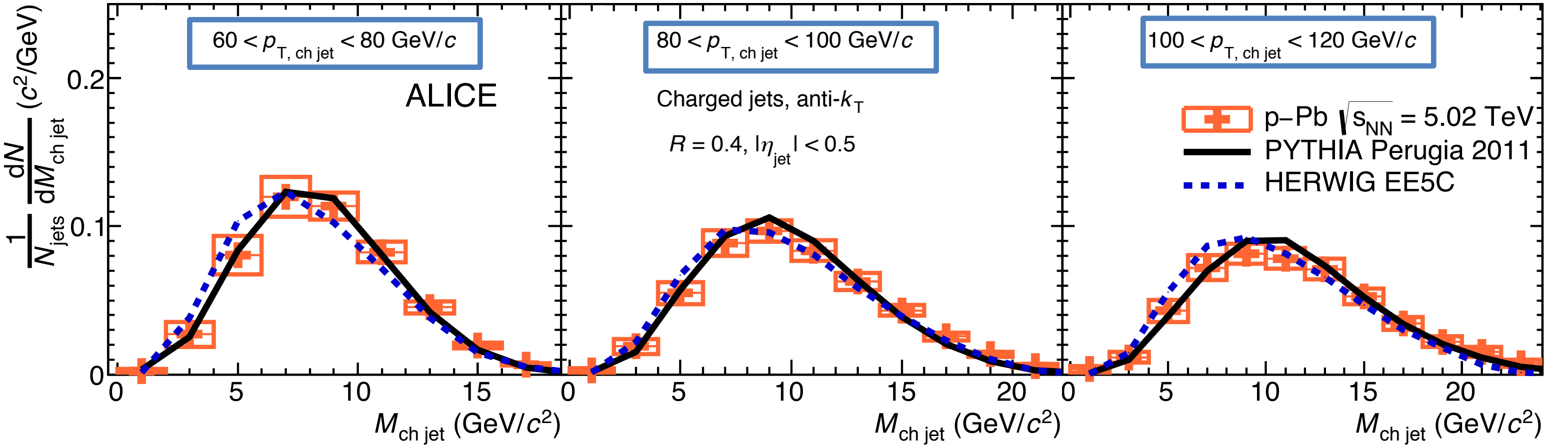
In Medium
If the profile broadens so much that large fraction of radiation is outside the cone, mass as well as p_T will decrease

We measure:
p-Pb 5.02, Pb-Pb 2.76 TeV
Anti-k_T jet algorithm,
resolution parameter R = 0.4,
$|\eta_{jet}| < 0.5$,
p_T = 60 - 120 GeV/c

Jet Mass Results

p-Pb, 5.02 TeV

ALICE Collaboration, S. Acharya et al., *Phys. Lett., B 776, (2018) 249*



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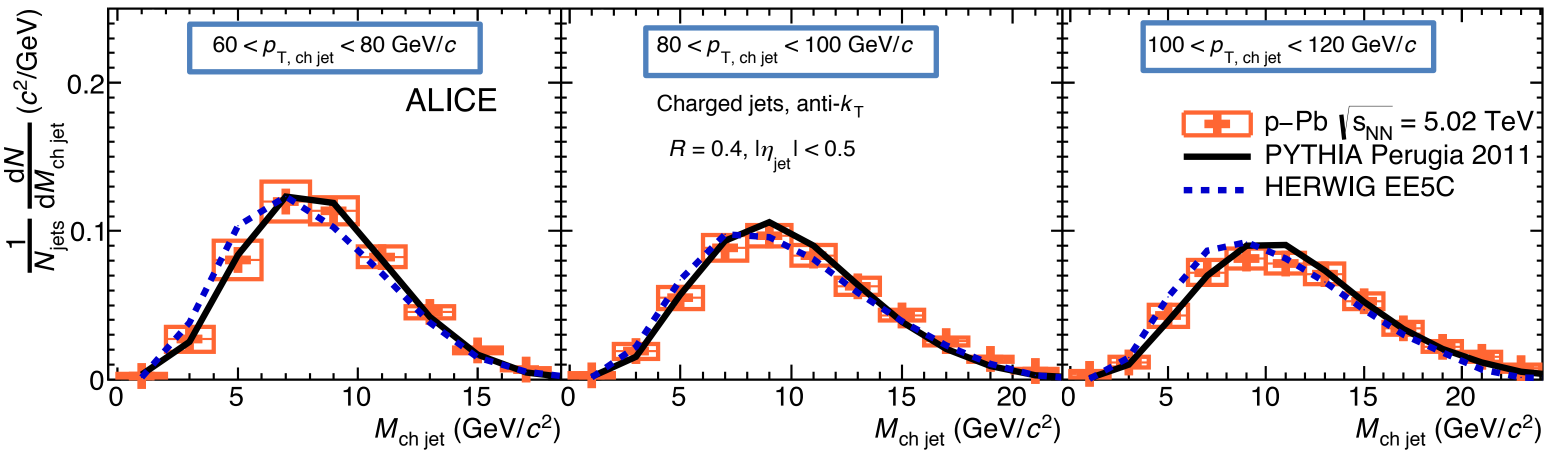
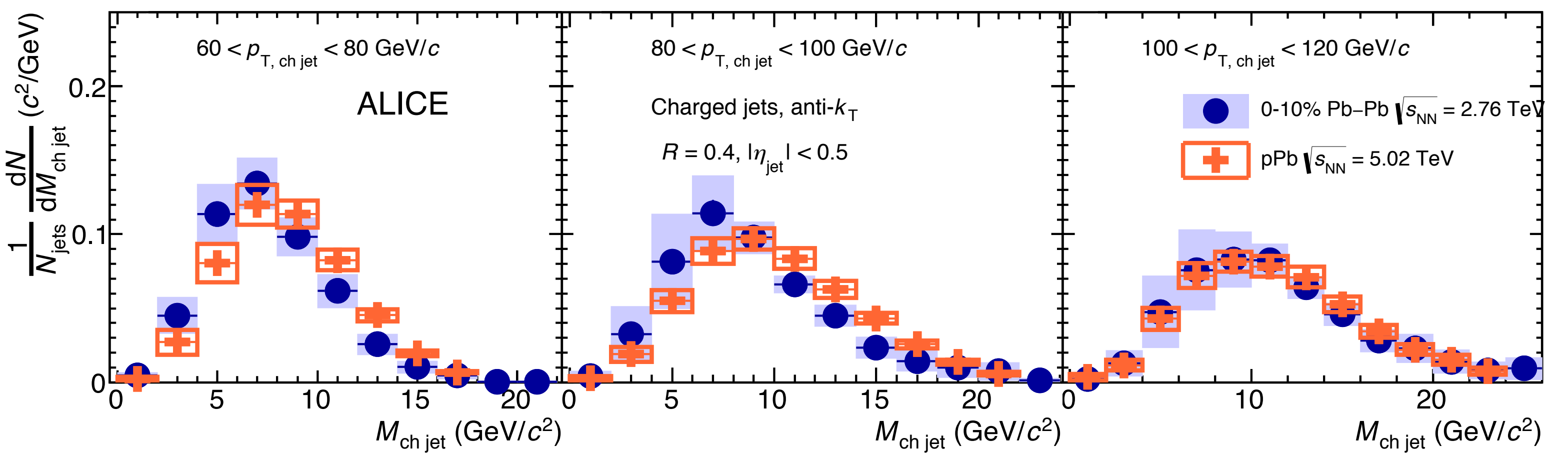


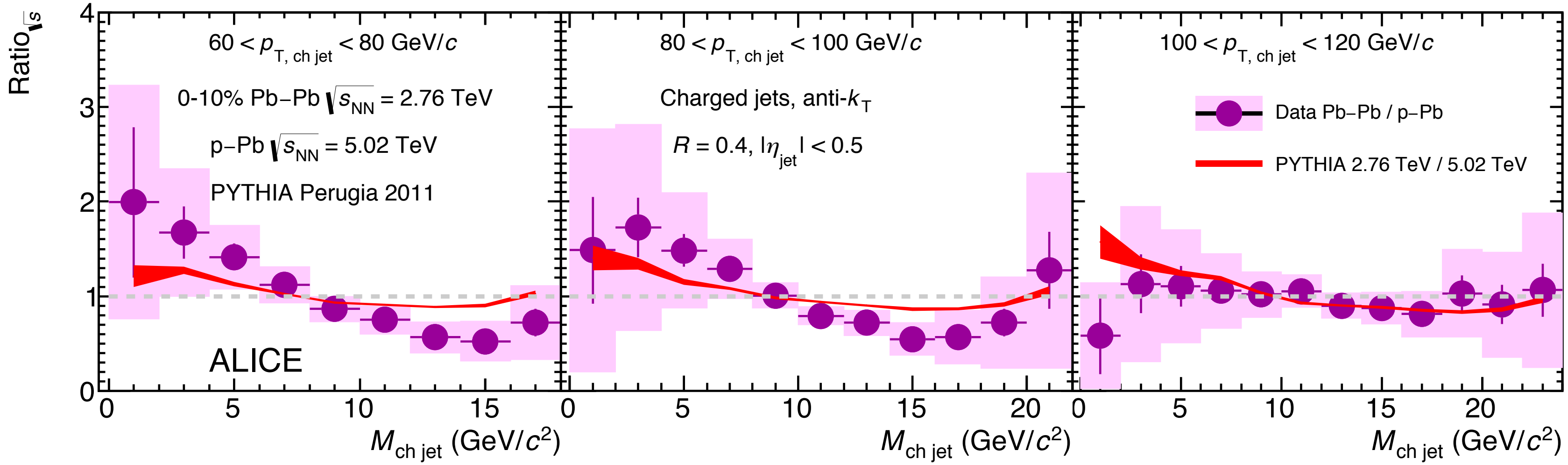
pPb, 5.02 TeV and PbPb 2.76 TeV



Jet mass in PbPb seems shifted to slighty lower values compared to pPb

Jet Mass Interpretation

ALICE Collaboration, S. Acharya et al., *Phys. Lett., B 776, (2018) 249*



To see effects of:

- different q/g ratio at different collision energies
- effect of different shapes of the underlying jet p_T spectrum

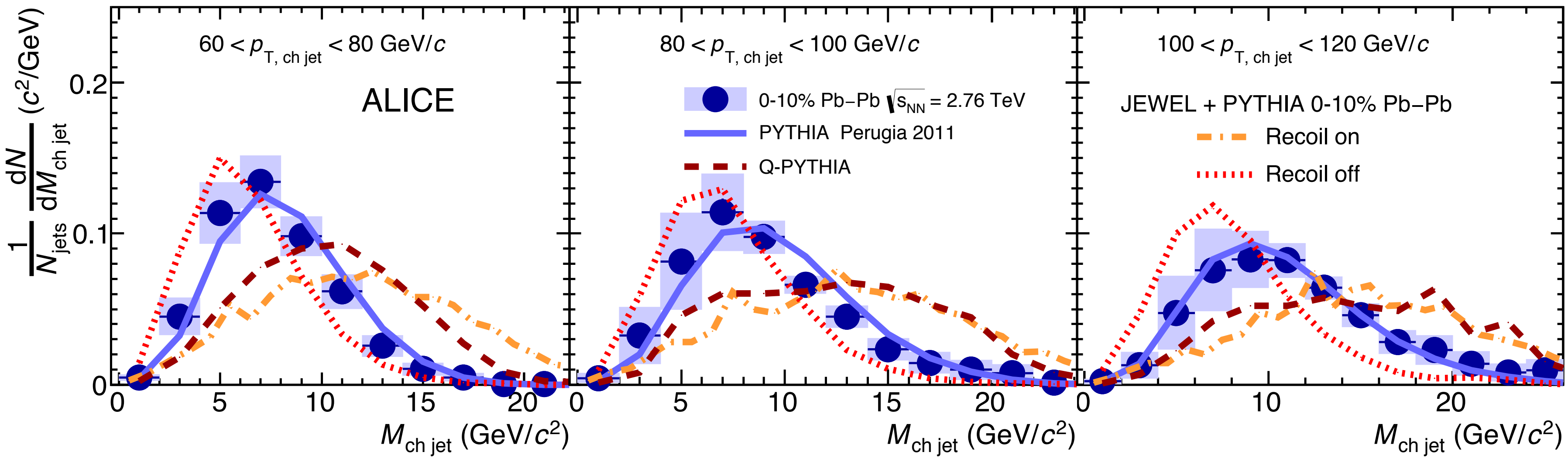
The PYTHIA ratio is compared to the Pb-Pb/p-Pb ratio

Observed effect is compatible with PYTHIA, no significant shift observed due to medium.
The soft radiation outside the cone doesn't alter the relation between p_T and mass of the parton

Jet Mass Interpretation

ALICE Collaboration, S. Acharya et al., *Phys. Lett.*, B 776, (2018) *249*

Pb-Pb results compared to models
How well do they describe the in medium shower shape evolution?



PYTHIA	result without jet quenching
Q-PYTHIA	modifies the splitting functions of PYTHIA resulting in medium-induced gluon radiation following the multiple soft scattering approximation
JEWEL	computation of scattering of leading parton with medium constituents. Gives a microscopic description of the transport coefficient $\hat{q}$. "Recoil on" keeps additional track of momenta of recoiling scattering centers

Quenching models do not describe measured jet mass

Intra-jet distributions II

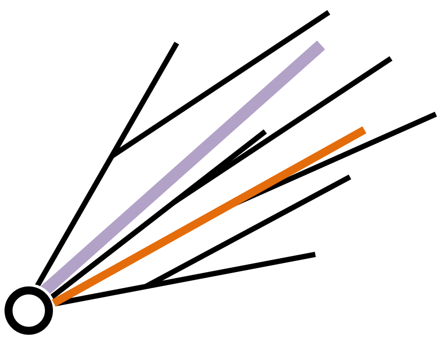
Jet Shapes of Small Jets

Jet Shapes of Small Jets

difference between leading and sub-leading track momentum

LeSub

$$LeSub = \boxed{p_{\mathrm{T,track}}^{lead}} - \boxed{p_{\mathrm{T,track}}^{sublead}}$$

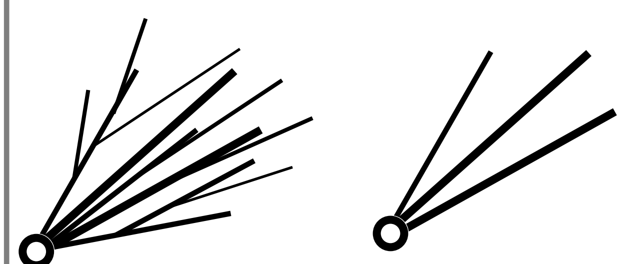


momentum dispersion

$\mathrm{p_T D}$

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

A measure for the hardness of the fragmentation. Small value for many constituents. Large value for fewer constituents



$\mathrm{p_T D} \sim 0$ $\mathrm{p_T D} \sim 1$

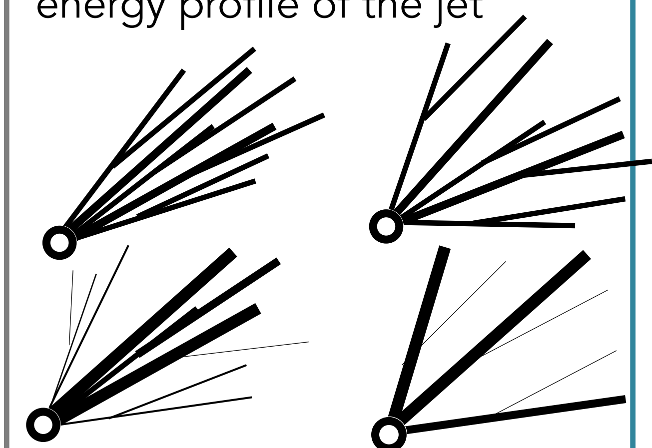
first radial moment or angularity

g

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

use momentum and distance to jet axis of each constituent

A measure for the radial energy profile of the jet



small g large g

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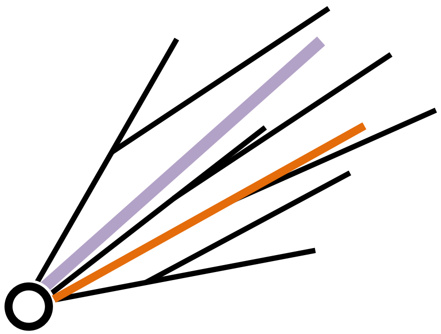

We measure:
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Anti-k_T jet algorithm,
resolution param. R = 0.2
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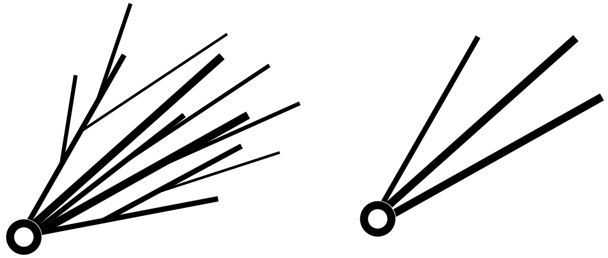

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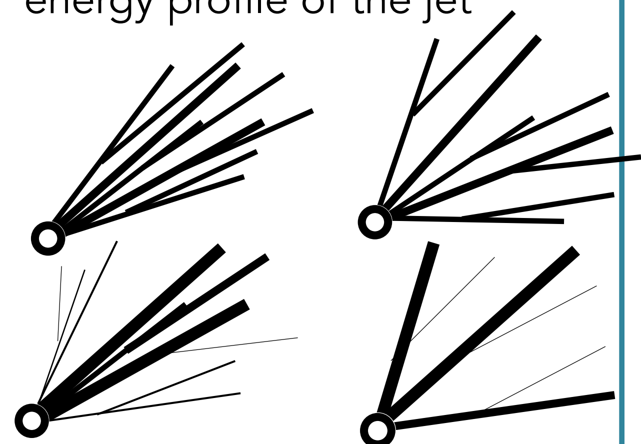
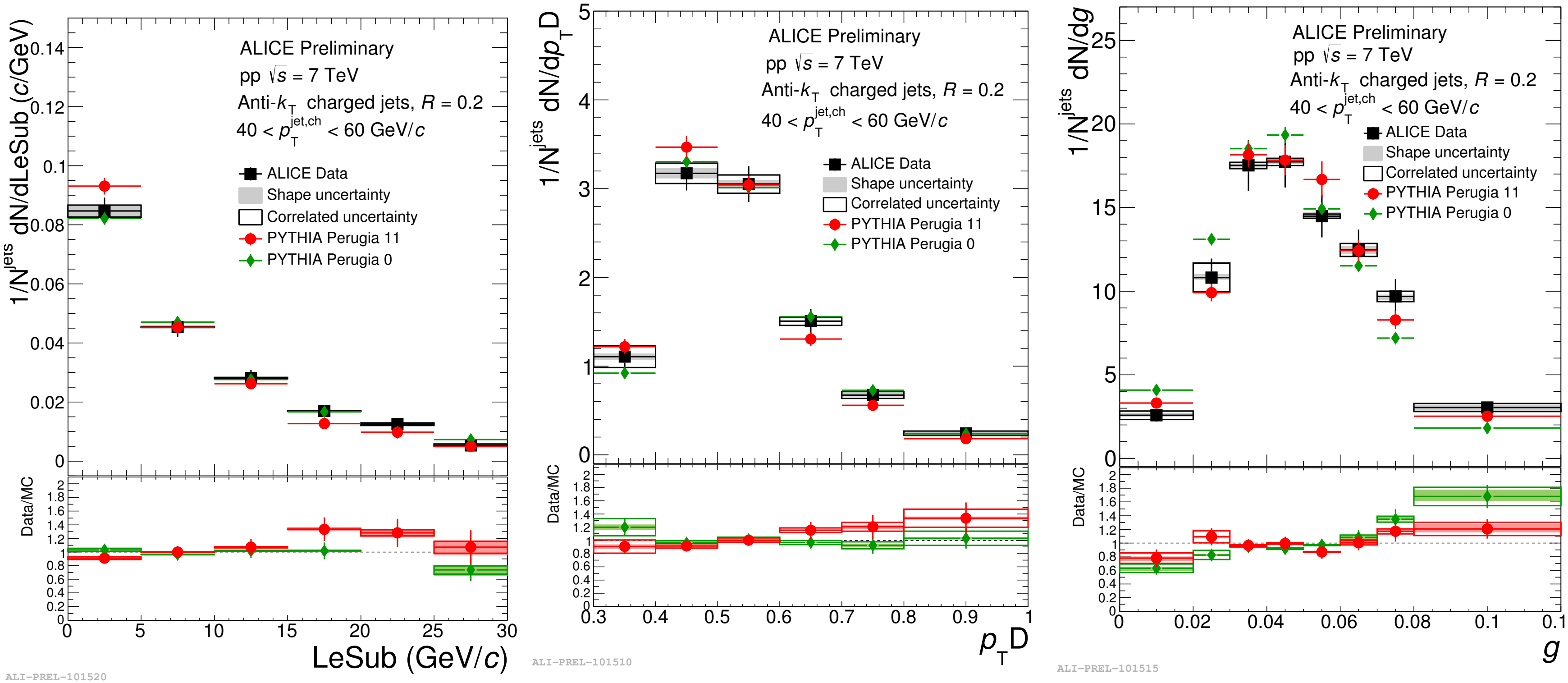


small g large g

Jet Shapes of Small Jets

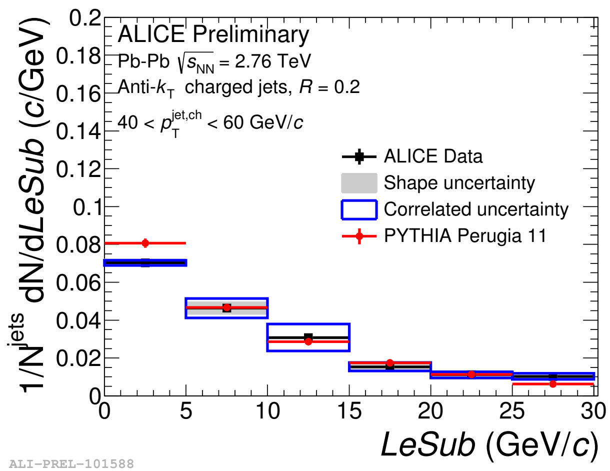
pp collisions

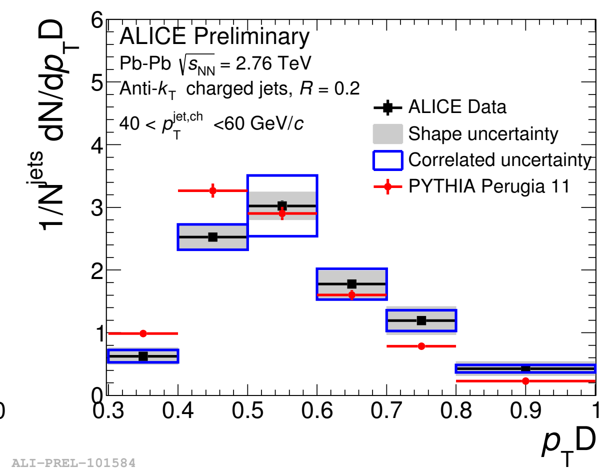


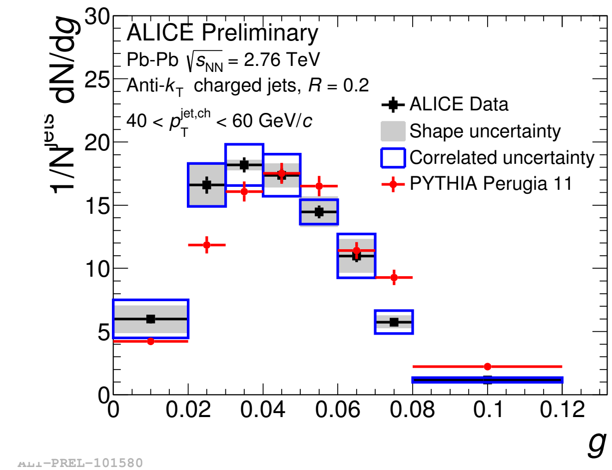
PYTHIA in agreement with data within 20%

Jet Shapes of Small Jets

Pb-Pb collisions







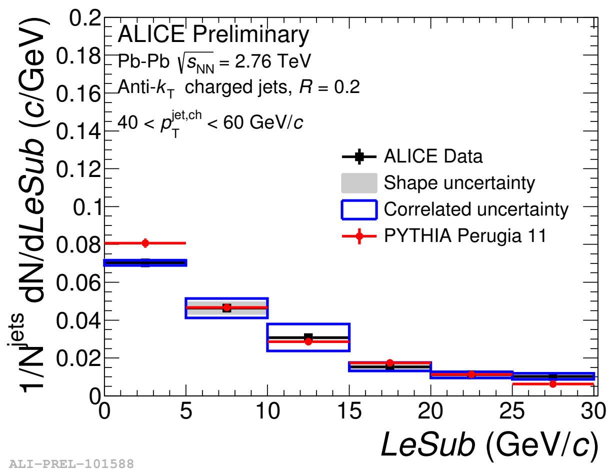
no significant modification

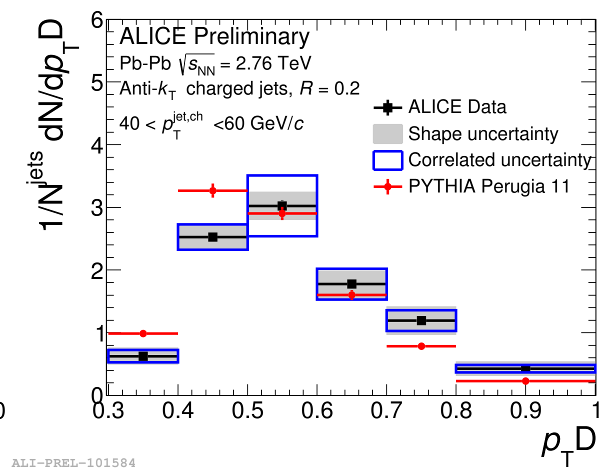
momentum dispersion is shifted to higher values

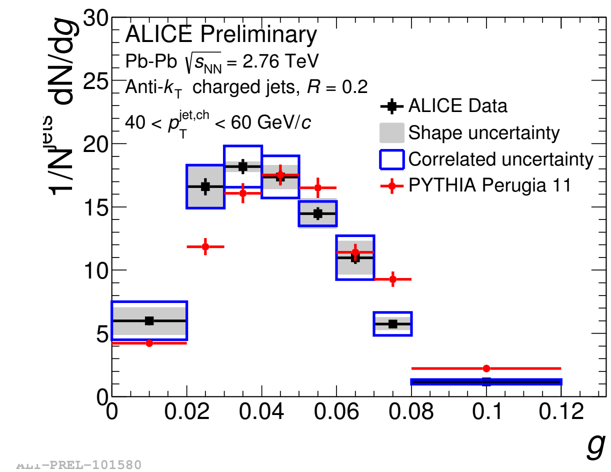
radial moment is shifted to lower values

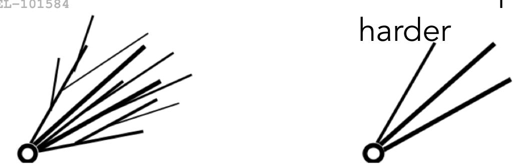
Jet Shapes of Small Jets

Pb-Pb collisions









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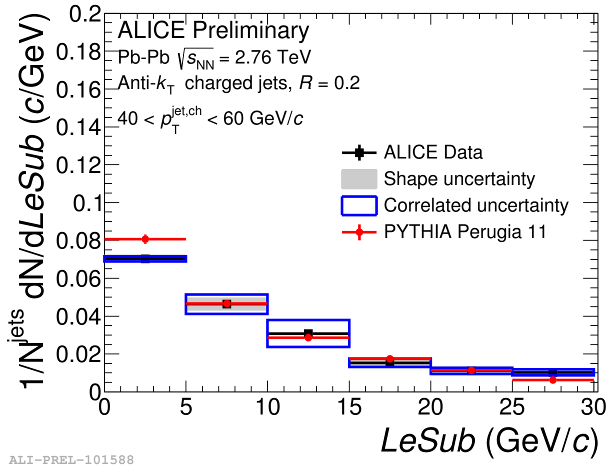
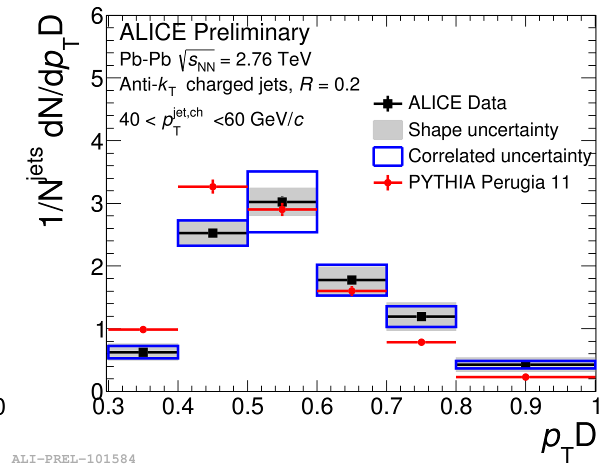
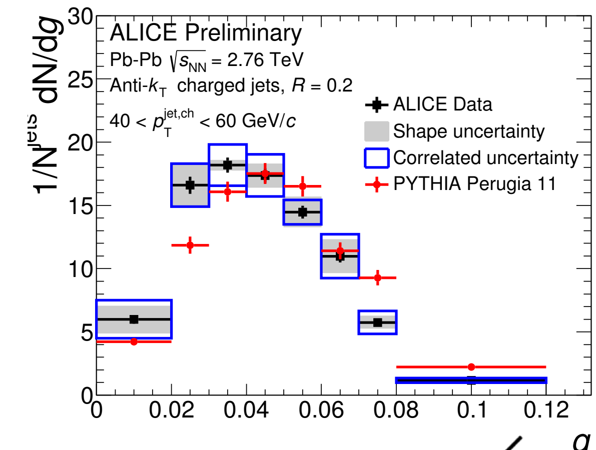
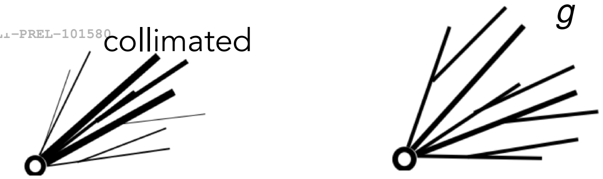
Jet Shapes of Small Jets

Pb-Pb collisions









no significant modification

momentum dispersion is shifted to higher values

radial moment is shifted to lower values

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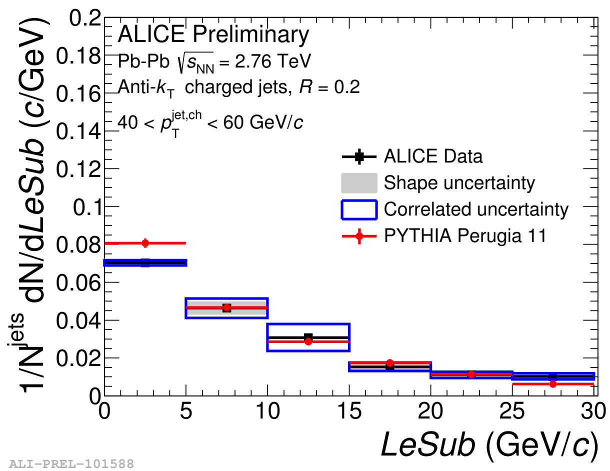
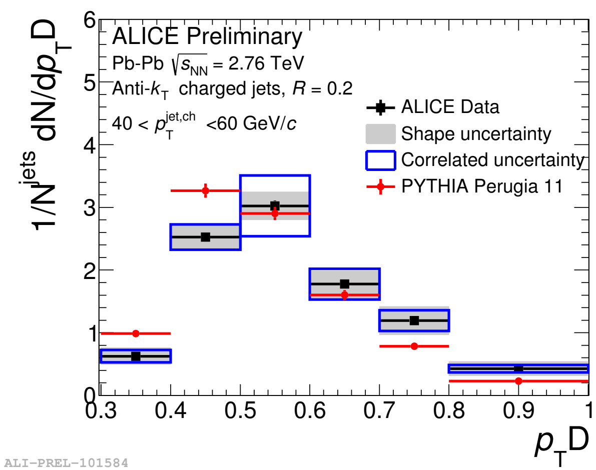
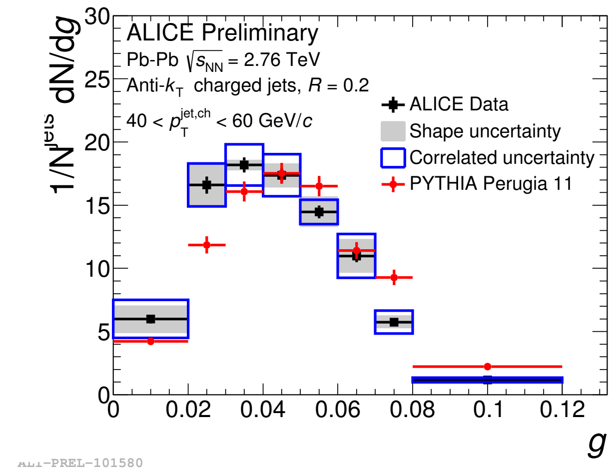






no significant modification

momentum dispersion is shifted to higher values

radial moment is shifted to lower values

The results of R=0.2 jet shapes indicate that jet cores in Pb–Pb are more collimated and harder than those in PYTHIA at the same energy.
Soft particles emitted outside R=0.2

Summary

π^0-hadron correlations pp and Pb-Pb

How is the jet fragmentation modified in the medium?

- Enhancement of low-p_T associated hadrons at the near and away side in Pb-Pb.
- The yield of high-p_T ass. hadrons (>3.5 GeV) is suppressed at the away side.

Jet Mass measurement in p-Pb and Pb-Pb

Is there a shift of measured jet masses due to hot QCD medium effects?

- No significant mass shift observed due to medium.
- It seem the soft radiation outside the cone doesn't alter the relation between p_T and mass of the parton.
- Quenching models can not describe measured jet mass.

Jet shape measurement in pp and Pb-Pb

How are the cores of jets modified in the medium?

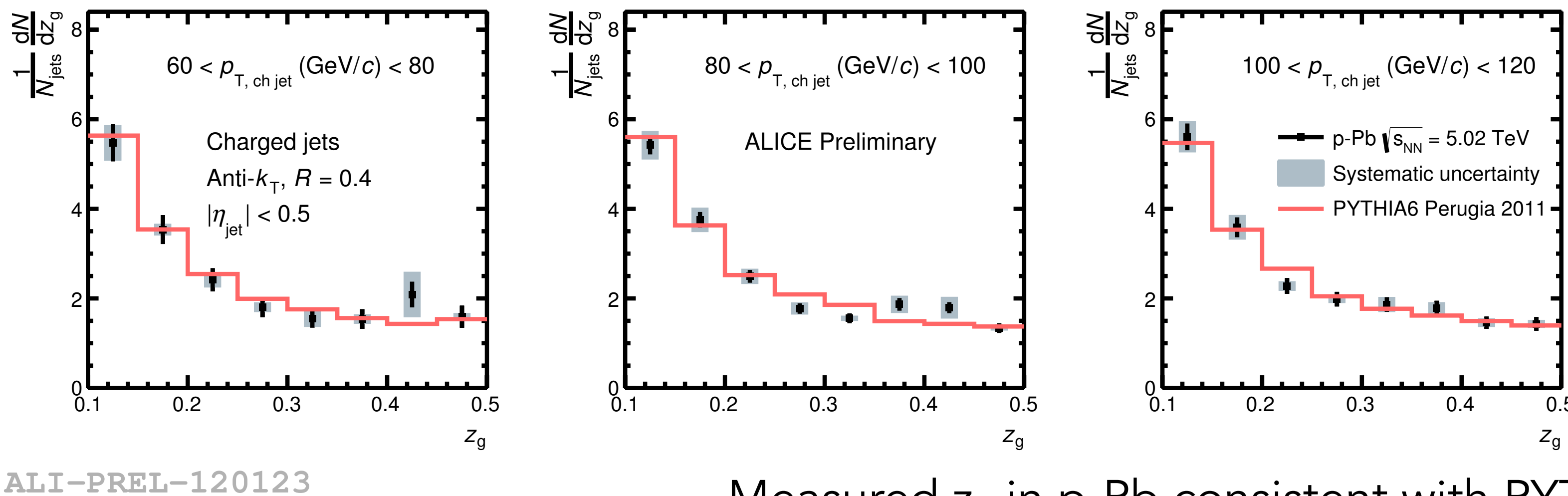
The results of R=0.2 jet shapes indicate that jet cores in Pb–Pb are more collimated and harder than those in PYTHIA at the same energy.

Outlook - Results to Come

Jet substructure
using Soft Drop (removal of soft subjets)
to determine momentum distribution of
hard subjets $\beta = 0$ and $z_{cut} = 0.1$

shared momentum fraction

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}},$$



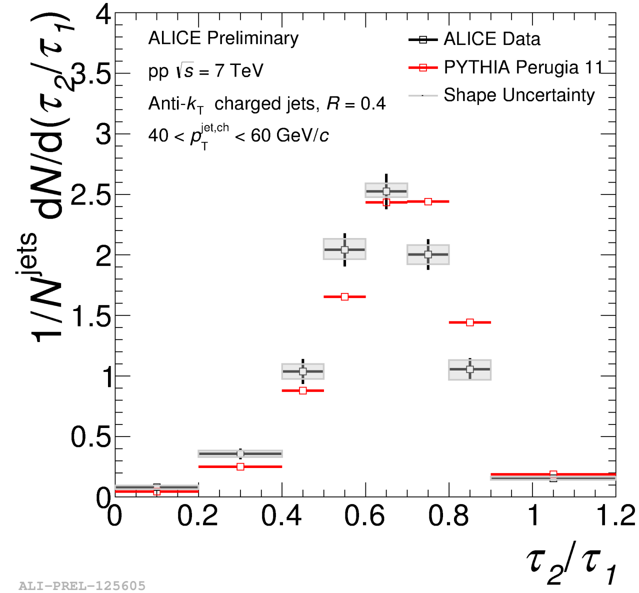
We measure:
p-Pb 5.02 TeV
Anti-k_T jet algorithm,
resolution parameter R = 0.4,
$|\eta_{jet}| < 0.5$,
p_T = 60 - 120 GeV/c

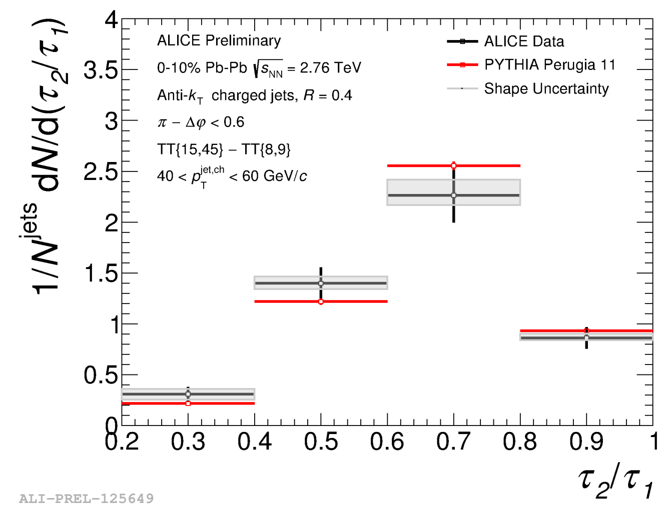
Measured z_g in p-Pb consistent with PYTHIA. Previously observed modifications in z_g not due to cold nuclear matter effects.

Outlook - Results to Come

Nsubjetiness of jets in Pb-Pb collisions
Ratio of 2-Subjettiness to 1-Subjettiness (τ_2/τ_1) measures two-prongness of the jet

Interpretation
τ_N ~0, N or fewer cores
τ_N ~1, N+1 or more cores
Thus:
τ_2/τ_1 tells us about 2-cores
If (τ_2/τ_1 ~0) parton has split into two resolvable subjets



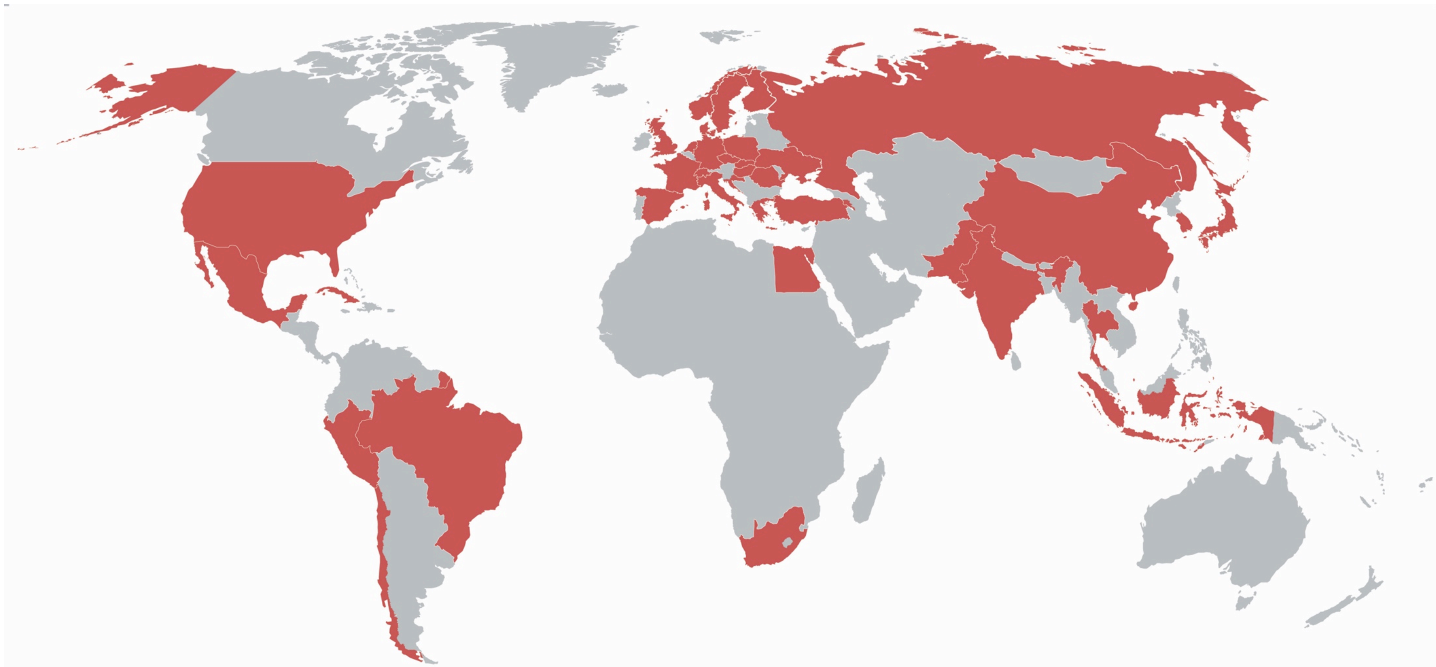


consistent with PYTHIA

We measure:
Pb-Pb 2.76 TeV
Anti-k_T jet algorithm,
resolution parameter R = 0.4,
$|\eta_{jet}|$ < 0.5,
p_T = 40 - 60 GeV/c

Thanks to the ALICE Collaboration

37 Countries, 154 Institutes and over 1500 members



Special thanks to the **Jet working group** and **Gamma working group** with about 30 members each.