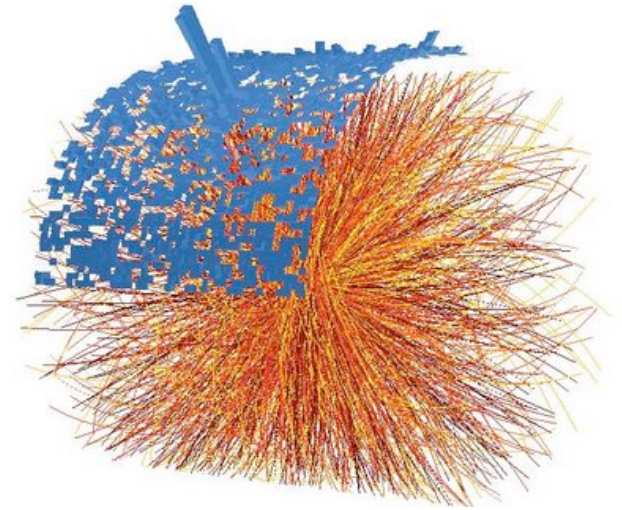
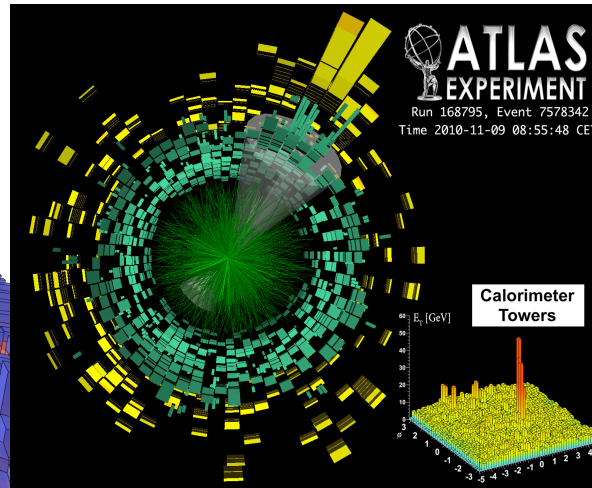
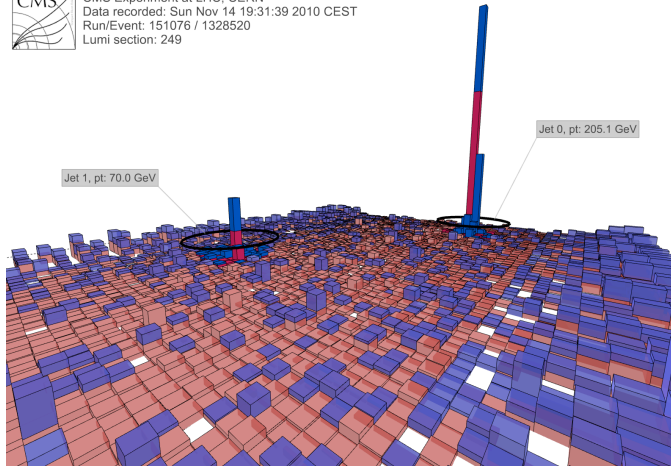
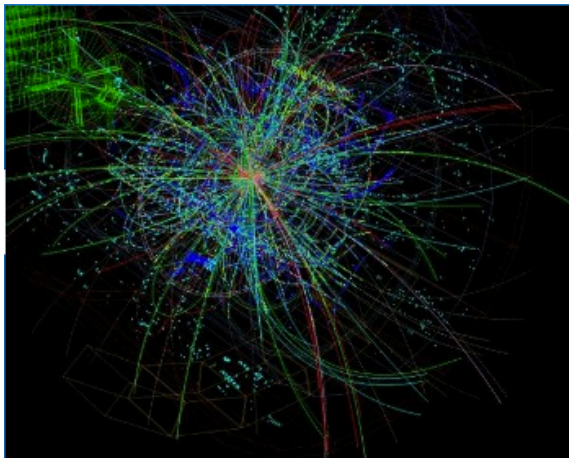


CMS  
CMS Experiment at LHC, CERN  
Data recorded: Sun Nov 14 19:31:39 2010 CEST  
Run/Event: 151076 / 1328520  
Lumi section: 249



# JETS

Elena Bruna (INFN Torino)

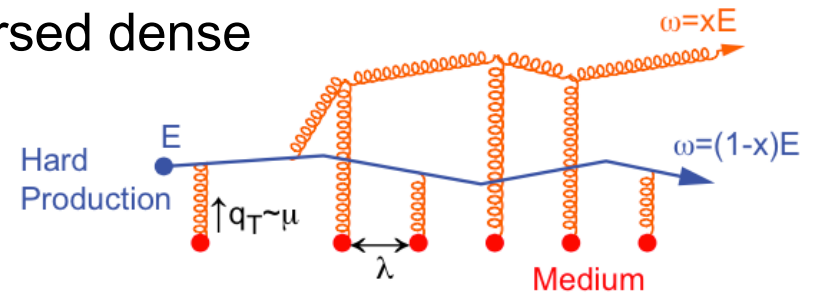


Incontro sulla fisica con ioni pesanti a  
LHC

26-27 May 2015 *Accademia delle Scienze*  
Europe/Rome timezone

# Hard probes in the medium

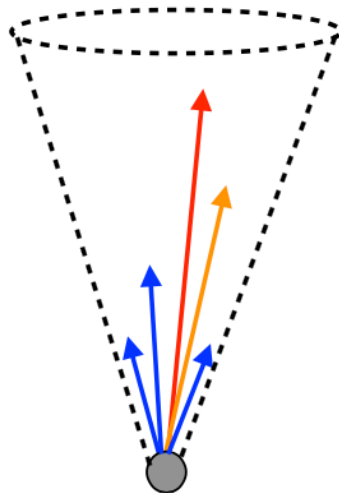
Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium ~ “Gluon Bremsstrahlung”



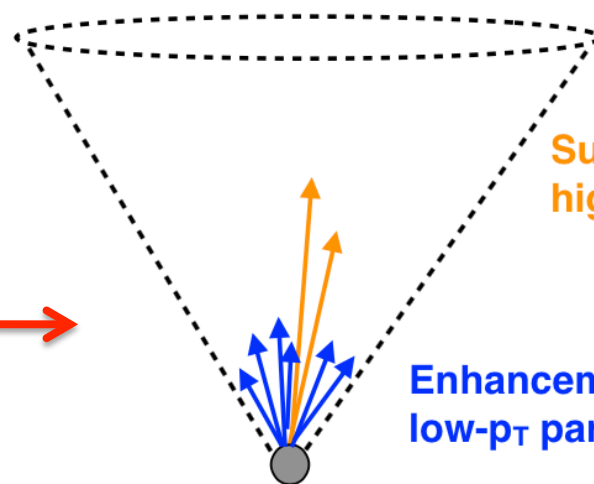
Effect:

- Softening of high- $p_T$  particles
- Modification of the Jet Structure/Fragmentation Function

Jets in vacuum



Jets in medium



**Jet broadening**

Suppression of high- $p_T$  particles

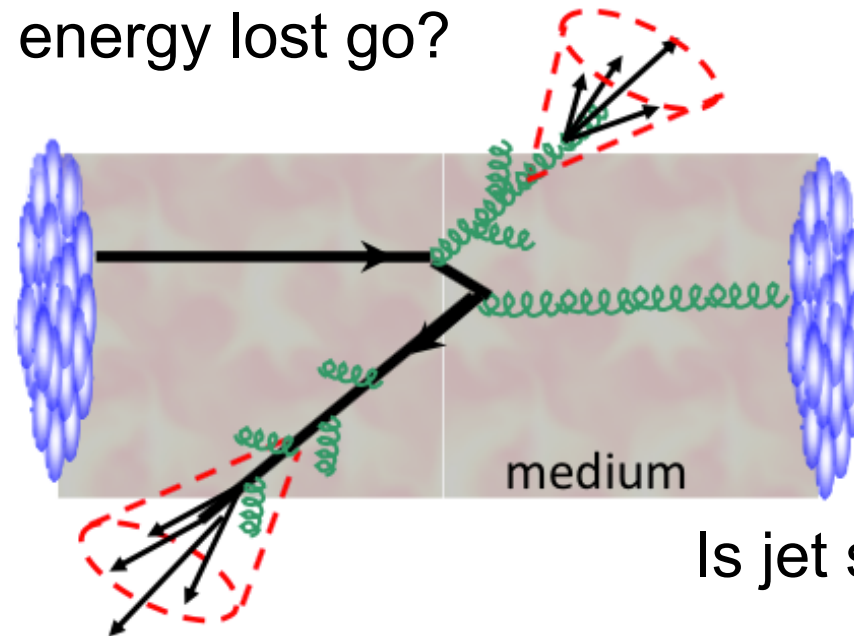
Enhancement of low- $p_T$  particles

**Quenching effects?**

# Jets in QGP: questions to be answered

Can lost energy be recovered with jet reconstruction?

Where does the energy lost go?



Is jet structure modified?

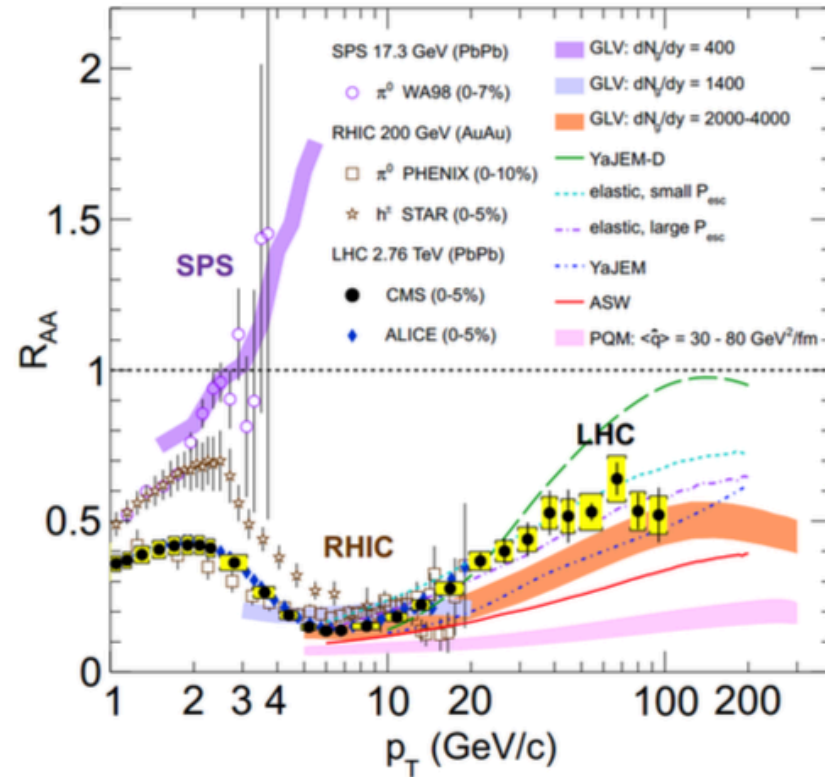
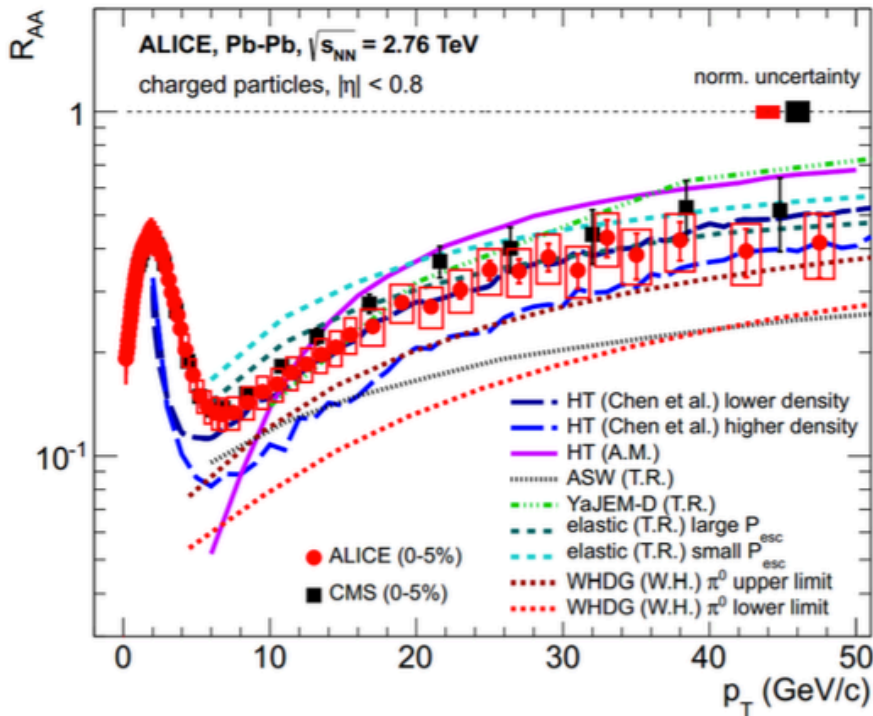
Flavour dependence?  
Jet hadrochemistry?

Are there initial state effect?

# High $p_T$ charged particles



ALICE, PLB 720, (2013) 52

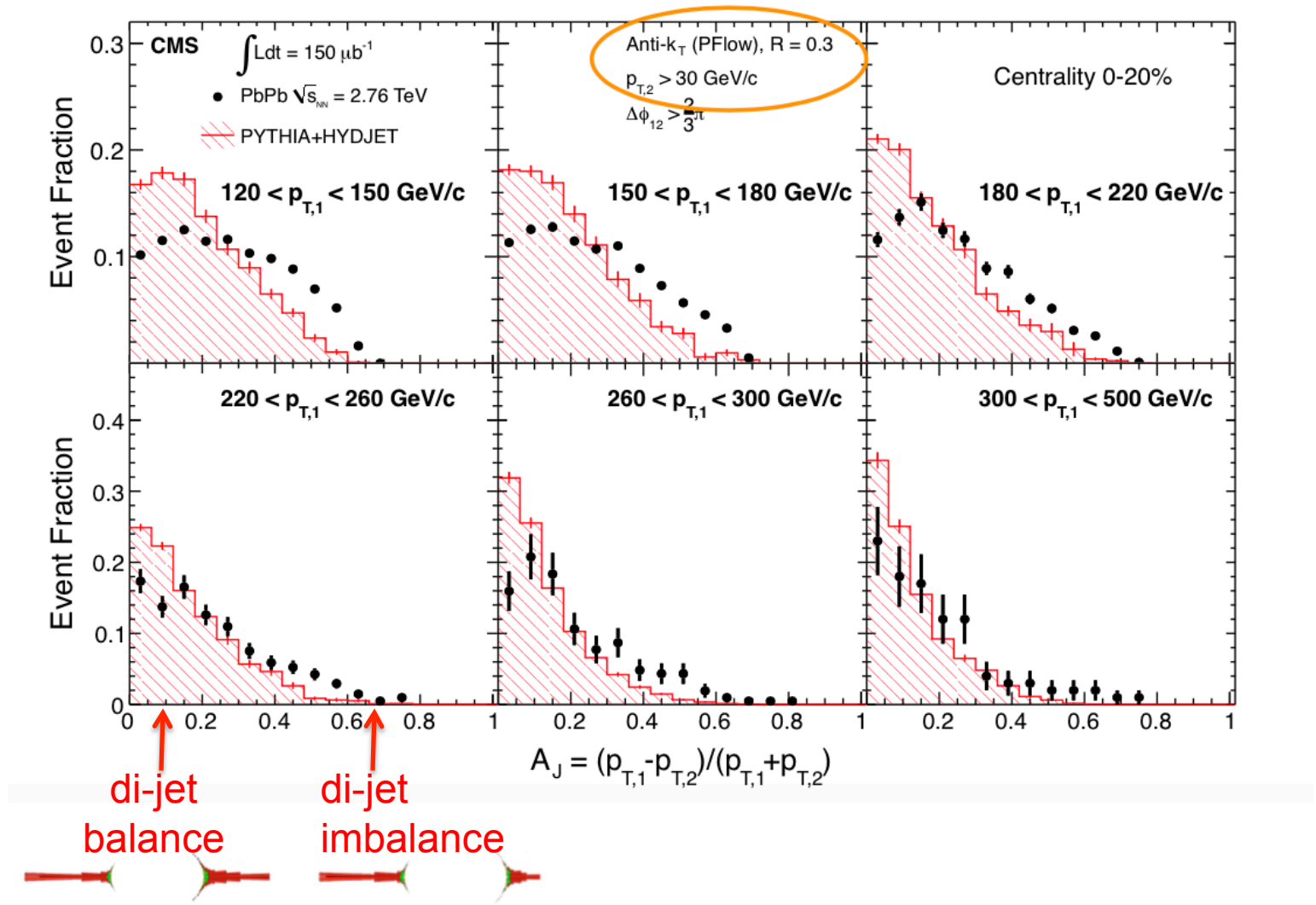


## Jet core detected via leading hadrons

$R_{AA}$  increases with  $p_T$ , seen for several models.

More measurements to constrain models and understand jet quenching  
 → Particle correlations, reconstructed jets

# Full jets at the LHC

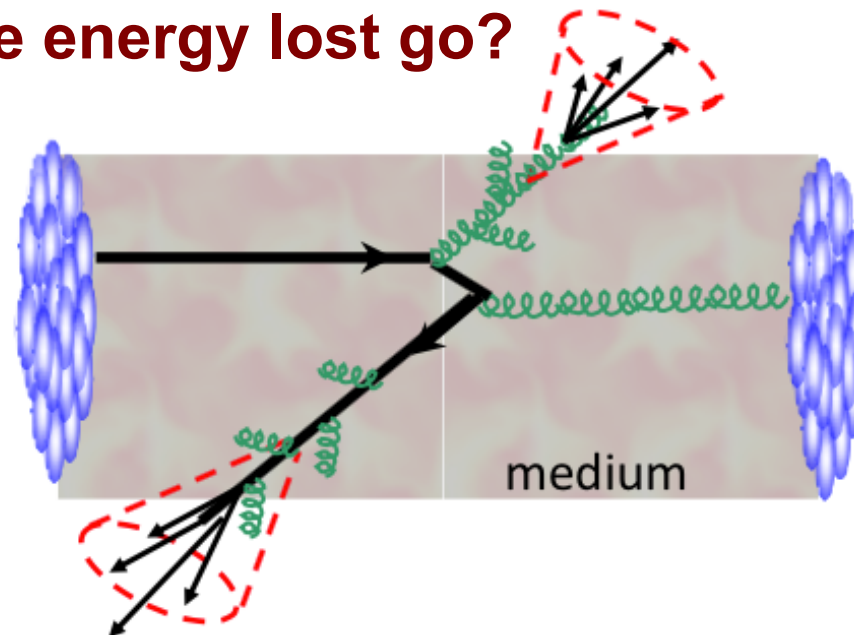


Di-jet asymmetry/imbalance in Pb-Pb collisions at the LHC

# Jets in QGP: questions to be answered

Can lost energy be recovered with jet reconstruction?

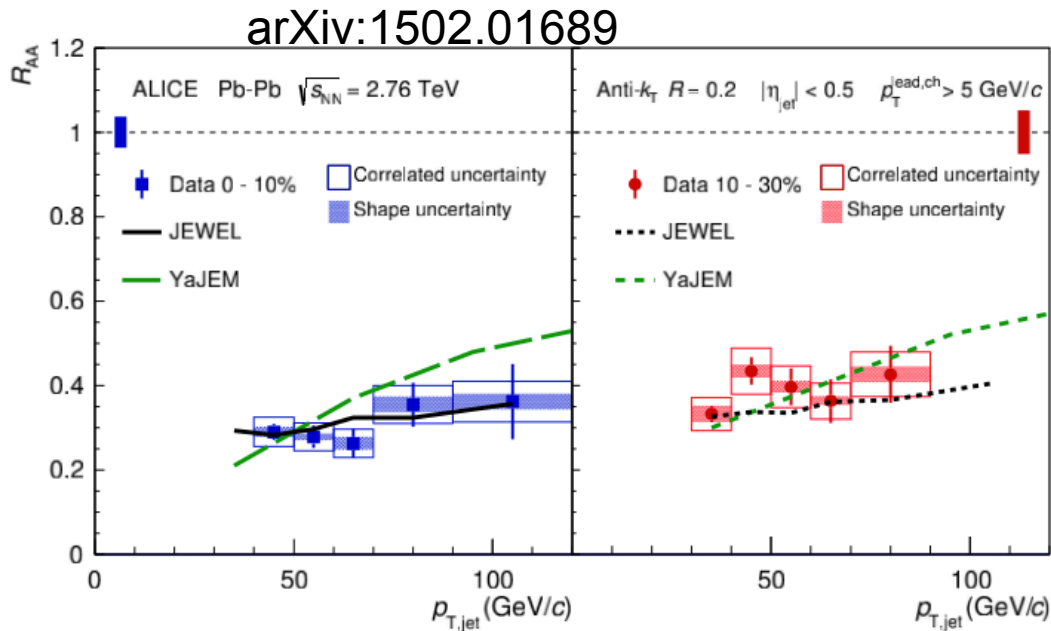
Where does the energy lost go?



Momentum and energy is conserved even for quenched jets

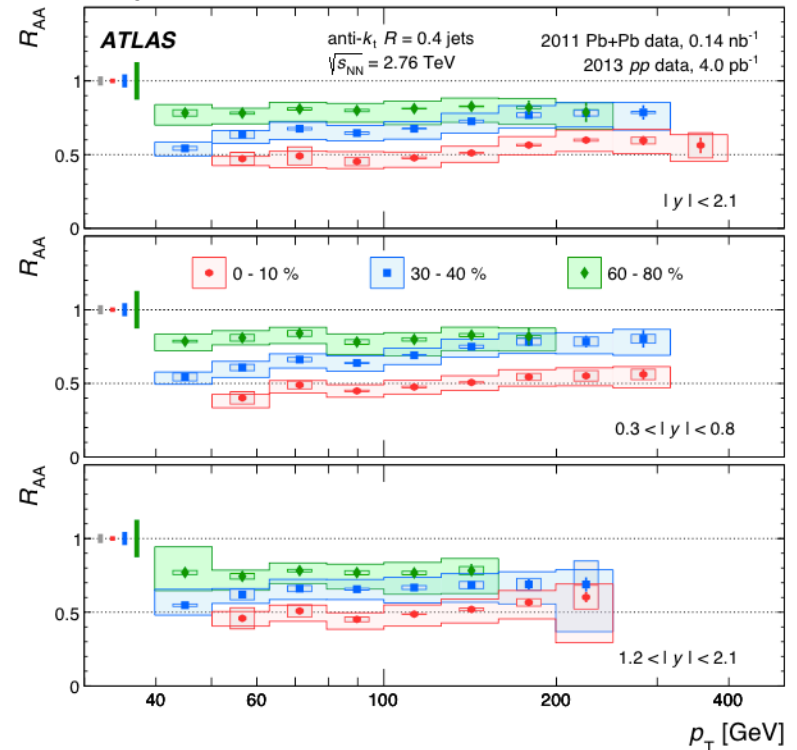
If full jet reconstruction in heavy-ion collisions is unbiased  $R_{AA}=1$   
 if  $R_{AA}<1$ : either some jets are absorbed or part of the lost energy is outside the jet cone ...

# Jet $R_{AA}$



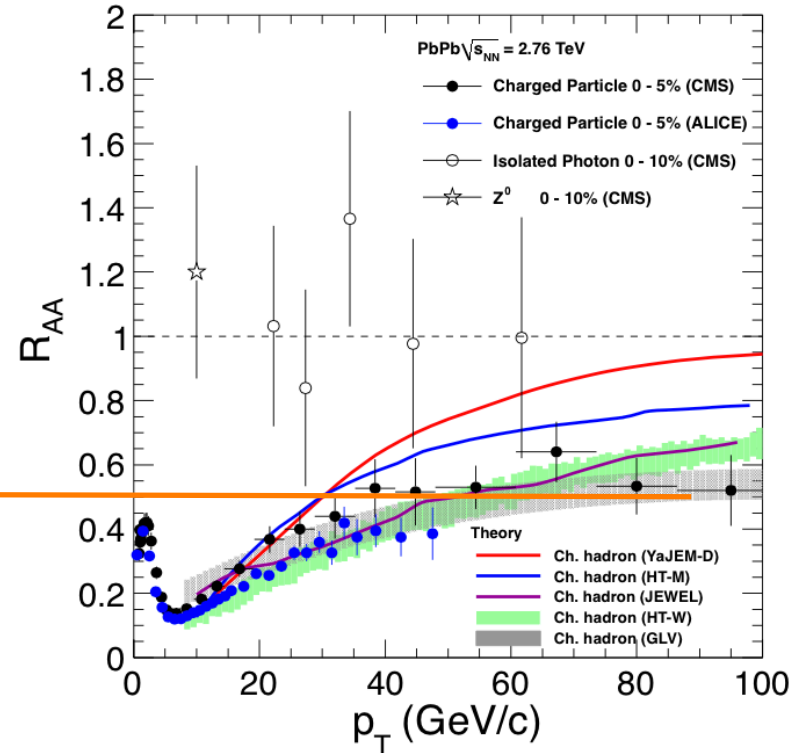
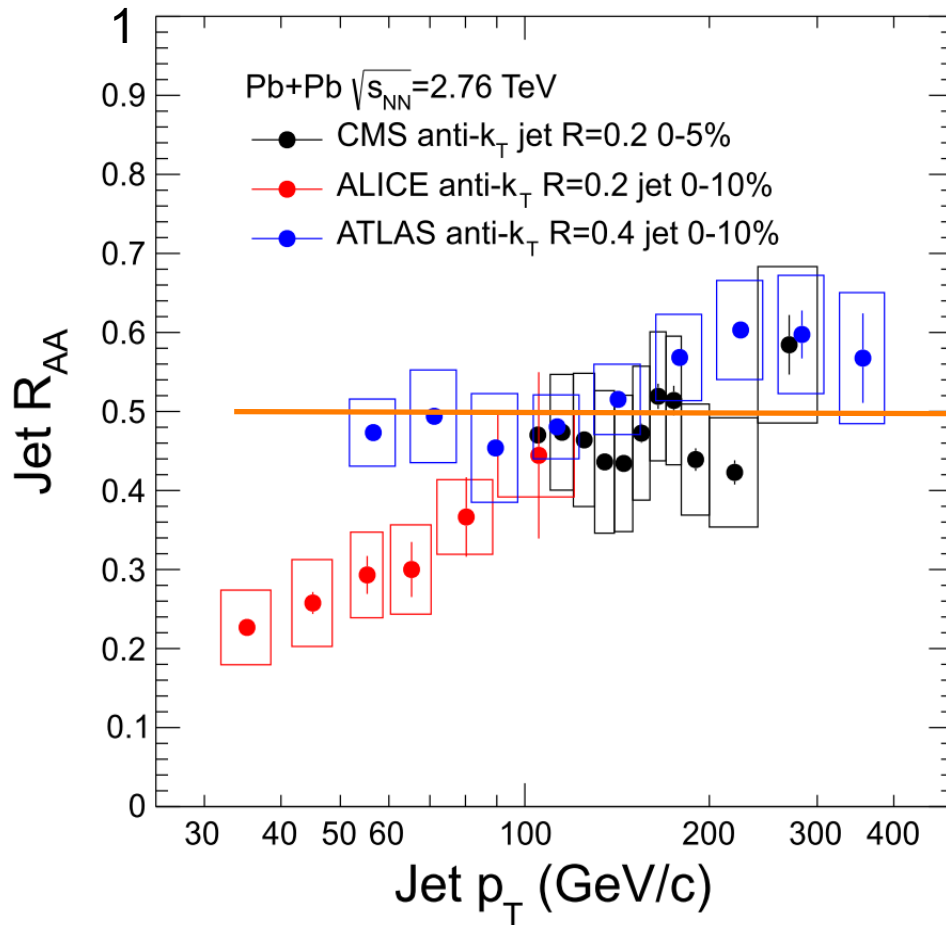
**Suppression in fair agreement with expectations** from two jet quenching model calculations.

Phys. Rev. Lett. 114 (2015) 072302



**Weak dependence on jet rapidity**  
 Quark/gluon fraction and slope of the jet  $p_T$  spectra change with  $y$

# Jets vs hadrons: $R_{AA}$ suppression

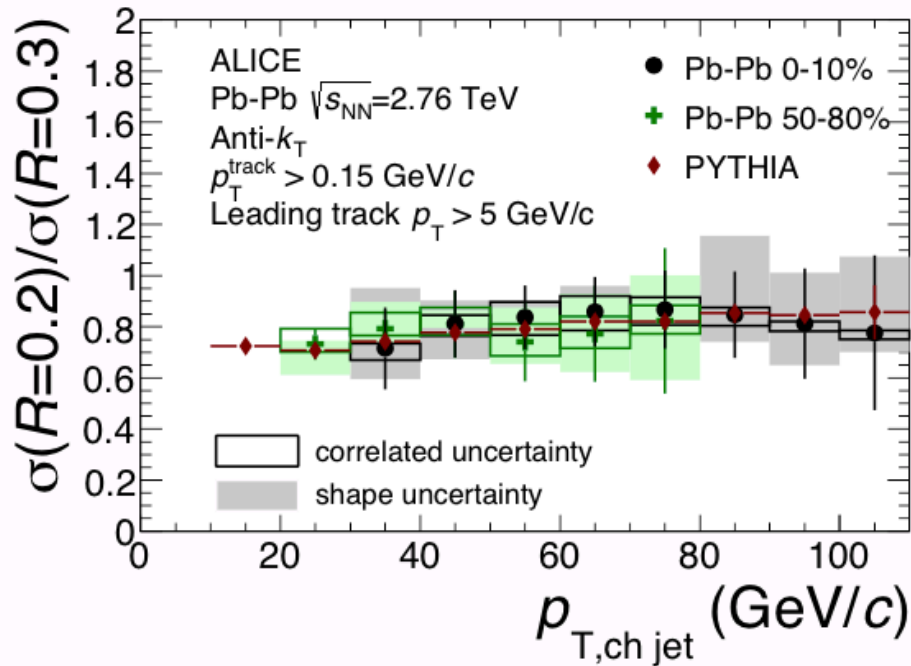


**Similar limiting value  $R_{AA} \sim 0.4-0.5$**   
both for full jets and charged hadrons

Not much energy recovered when opening the cone from  $R \sim 0.2$  to larger  $R$



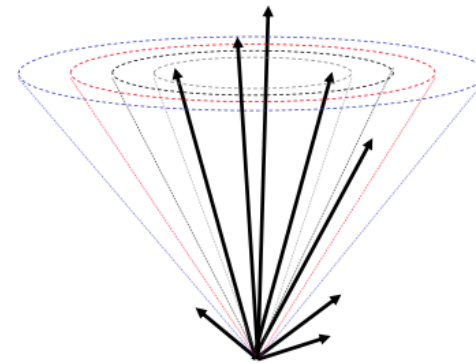
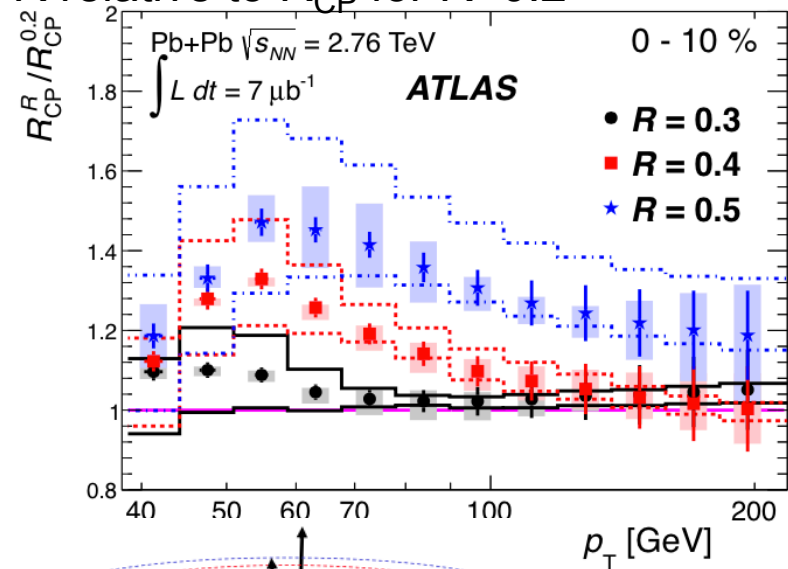
# Can lost energy be recovered within jet R?



Ratio of jet cross-section  $R=0.2/R=0.3$  is sensitive to broadening in the jet structure

Pb-Pb jet structure consistent with vacuum jets; **no significant jet broadening (within  $R=0.3$ ) observed!**

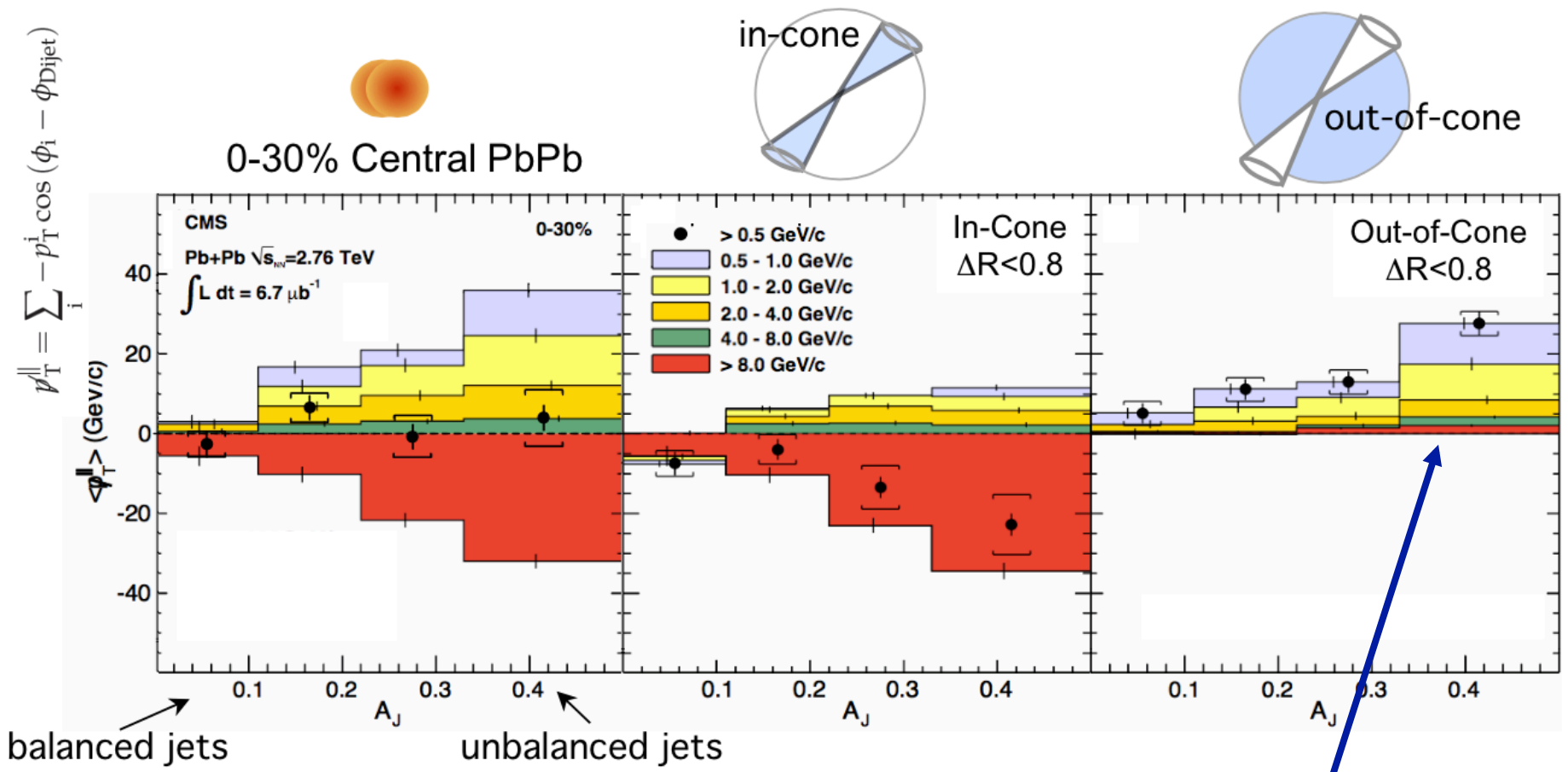
$R_{CP}$  (central/peripheral) for different jet R relative to  $R_{CP}$  for  $R=0.2$



$$R_{CP}^{(R=0.5)} / R_{CP}^{(R=0.2)} > 1$$

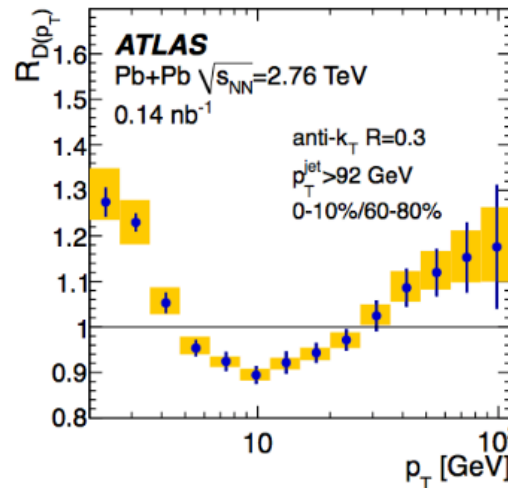
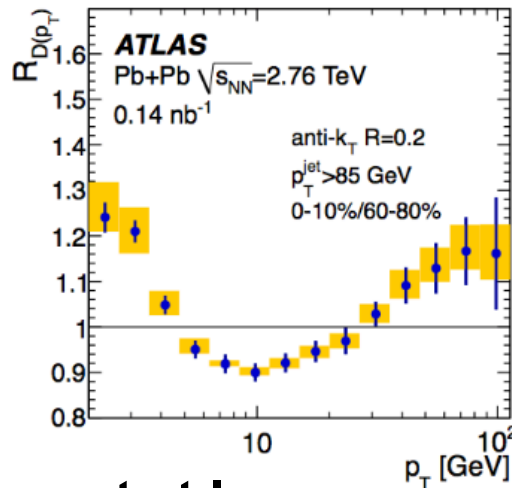
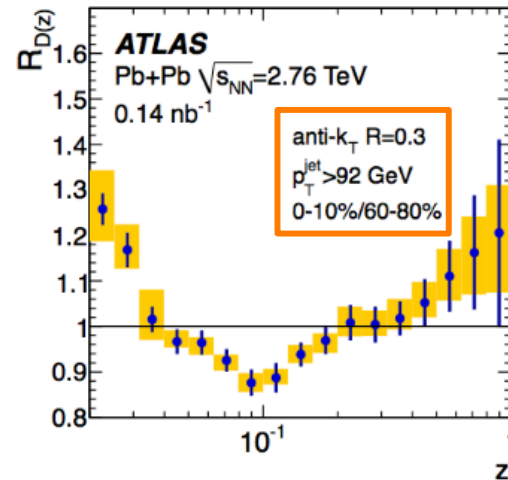
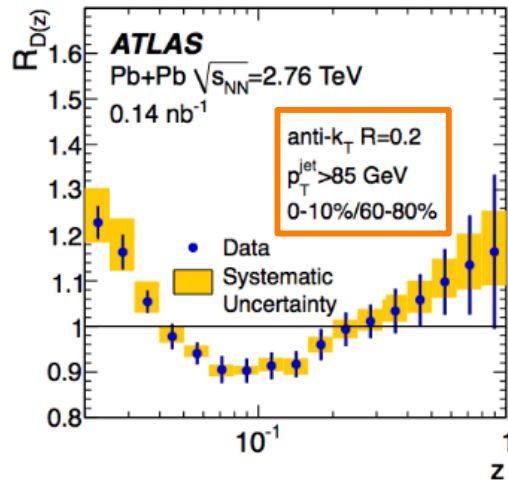
**Partial recovery of lost energy**, change in jet shape with respect to the pp reference

# Where does the energy lost go?



The momentum difference in the di-jet is balanced by **low  $p_T$  particles at large angles** relative to the away side jet axis

# Is the jet structure modified?

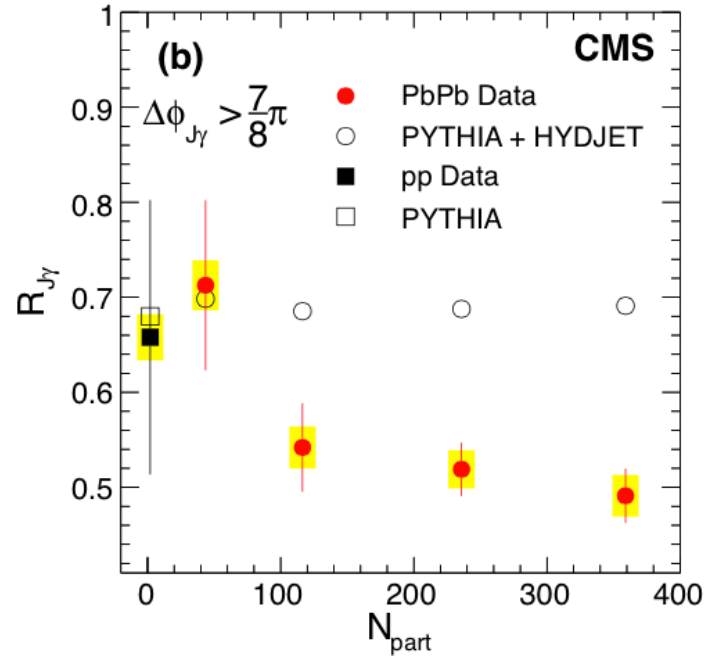
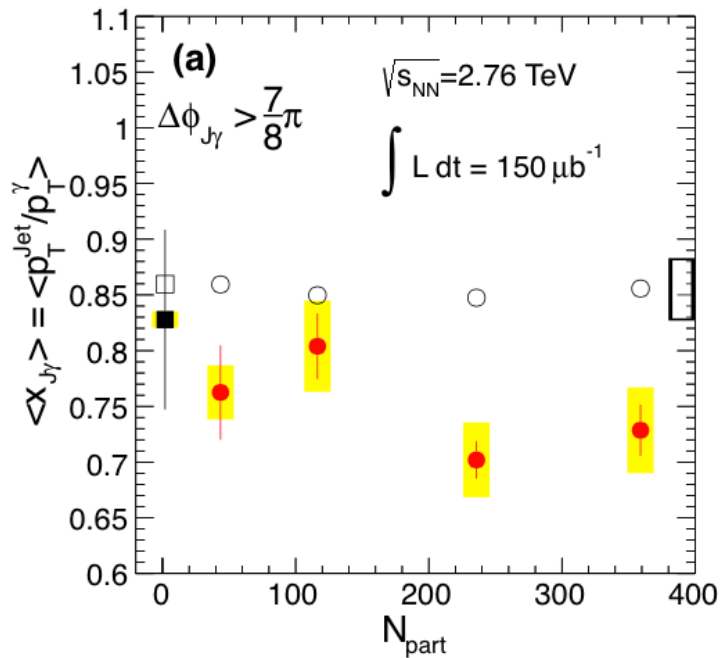


Enhancement at low  $z$

Suppression at intermediate  $z$

**No suppression at high  $z$ !** Different quark/gluon contributions?

# Coincidence measurements: $\gamma$ -jet



$p_T^\gamma > 60 \text{ GeV}$   
 $p_T^{\text{jet}} > 30 \text{ GeV}$

$R_{J\gamma}$  = fraction  
of  $\gamma$  with jet  
partner

**Large quenching effects with an associated jet above 30 GeV/c**  
Consistent with jets measurements?  
Quark vs gluon energy loss?

# Jet Hadrochemistry



High-multiplicity p-Pb vs Pb-Pb: many similarities

- Double ridge
- $v_2 > 0$
- Enhanced  $\Lambda/K^0_s$

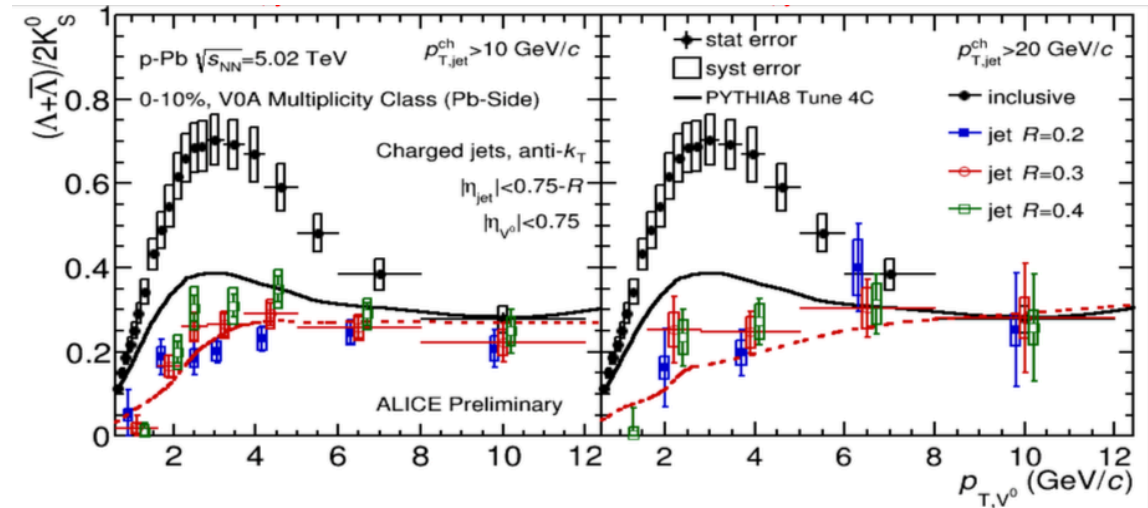
Physics origin?

Radial flow

Coalescence/recombination  
vs fragmentation

Hadrochemistry in jets:

Measure baryon/meson in jets and compare it to bulk



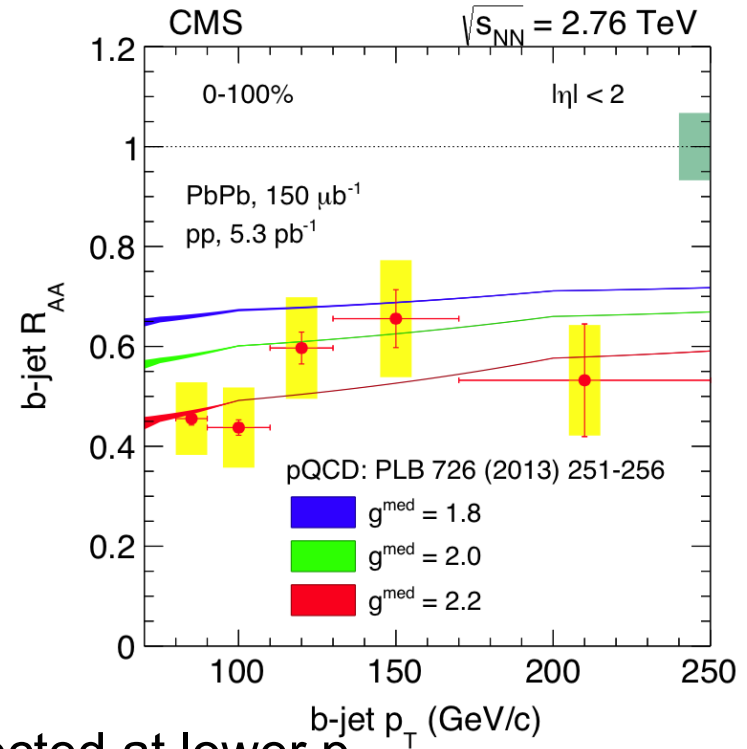
**ALICE high-multiplicity p-Pb:  $\Lambda/K^0_s$  in jets lower than inclusive and compatible with PYTHIA**

# Mass dependence of energy loss with jets



CMS:  
 b-tagged jets  
 $80 < p_T^{\text{jet}} < 250 \text{ GeV}/c$   
 (via displaced secondary vertices)

**Similar suppression as inclusive jets**

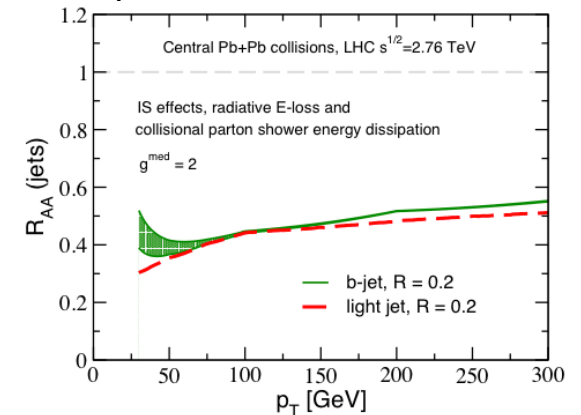


**Mass-dependent effect** on energy loss expected at lower  $p_T$

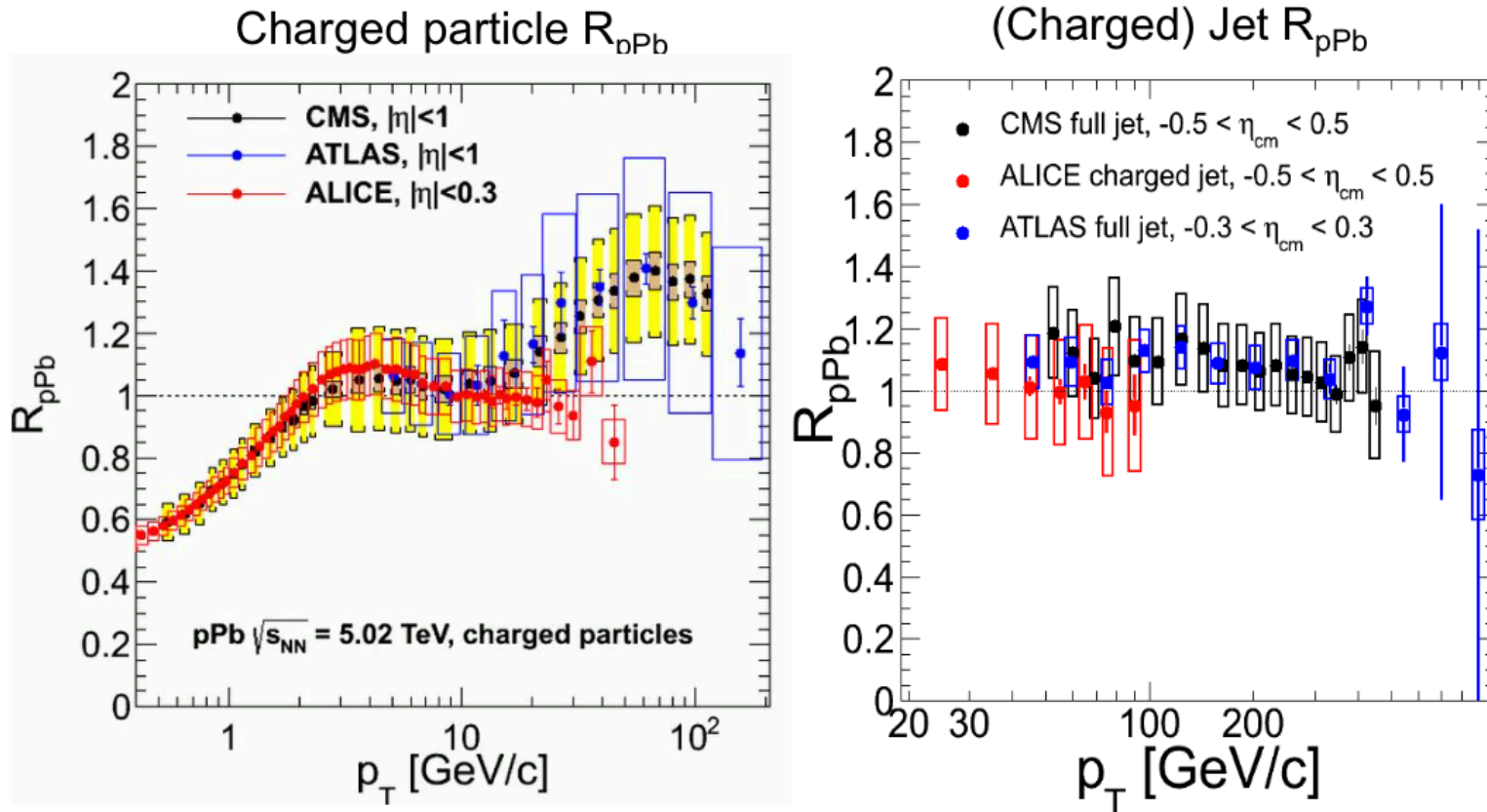
→ ALICE will go down to  $\sim 30 \text{ GeV}/c$

Inclusive jets mainly from gluons at LHC energies.

→ Contribution of b-jets from gluon splitting?



# Initial state effects?



Tension at high- $p_T$  for charged hadrons  $\rightarrow$  need pp reference at 5.02 TeV!  
**No sizeable deviation from unity for jet  $R_{pPb}$**   $\rightarrow$  study fragmentation functions

Jets can be used to study nPDF ( $\eta_{dijet}$  probes different  $x_{pPb}$ )

# Towards a consistent “quenching” picture

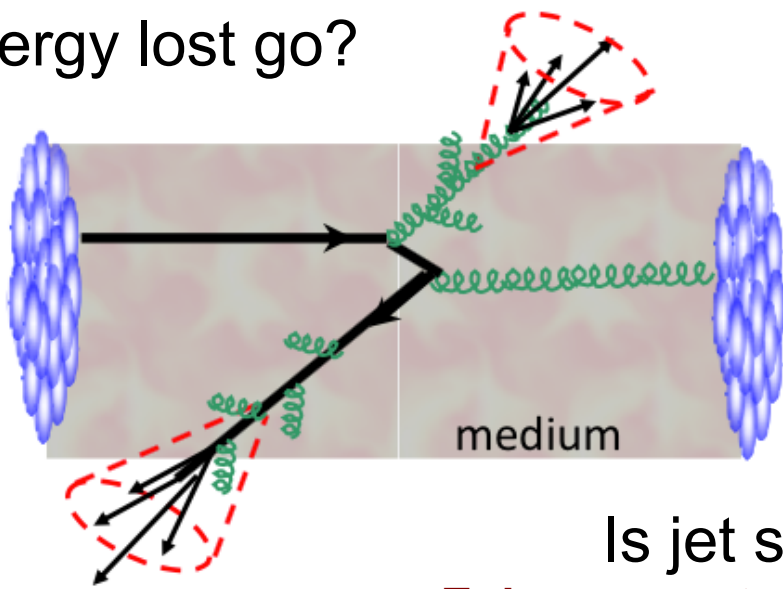
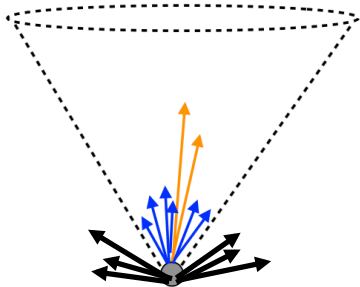


Can lost energy be recovered with jet reconstruction?

**Energy not fully recovered within  $R=0.2-0.5$**

Where does the energy lost go?

**Large angles!**



Is jet structure modified?

**Enhancement of low- $p_T$  particles in jets**  
**Shapes modified**

Flavour dependence?

Jet hadrochemistry?

Are there initial state effect?

**Baryon/meson in pPb jets similar to vacuum jets**  
**B-jet suppression at high- $p_T$  similar to inclusive**

**Jets in pPb: probe nPDF**



# Towards a consistent “quenching” picture



Jets/hard probes can be used to ask and answer fundamental questions about the nature of the QGP

**Jet measurements in Pb-Pb at LHC in Run 2 and 3 will quantitatively help constraining pQCD quenching models**

Complementary measurements:

RHIC: explores smaller energy loss at early times

LHC: larger energy loss at early times

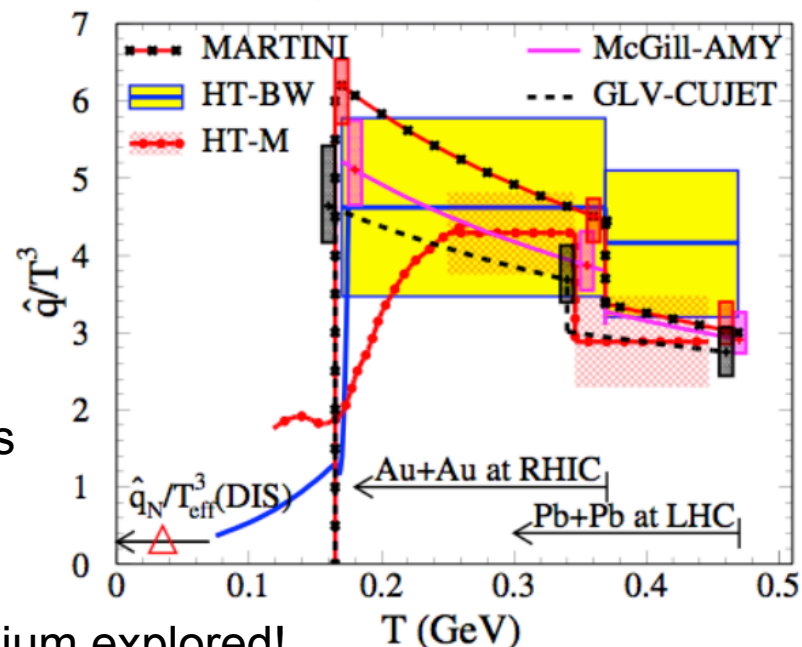
(larger angles).

Different regions of weak vs strong coupling medium explored!

ALICE can explore low jet  $p_T$  where medium effects can be studied

**More differential jet measurements:** jet mass, sub-jets, coincidence (h+jet, jet-hadron, ...), shape measurements to study q/g contribution, redistribution of lost energy. Exploit biases to measure quenching!

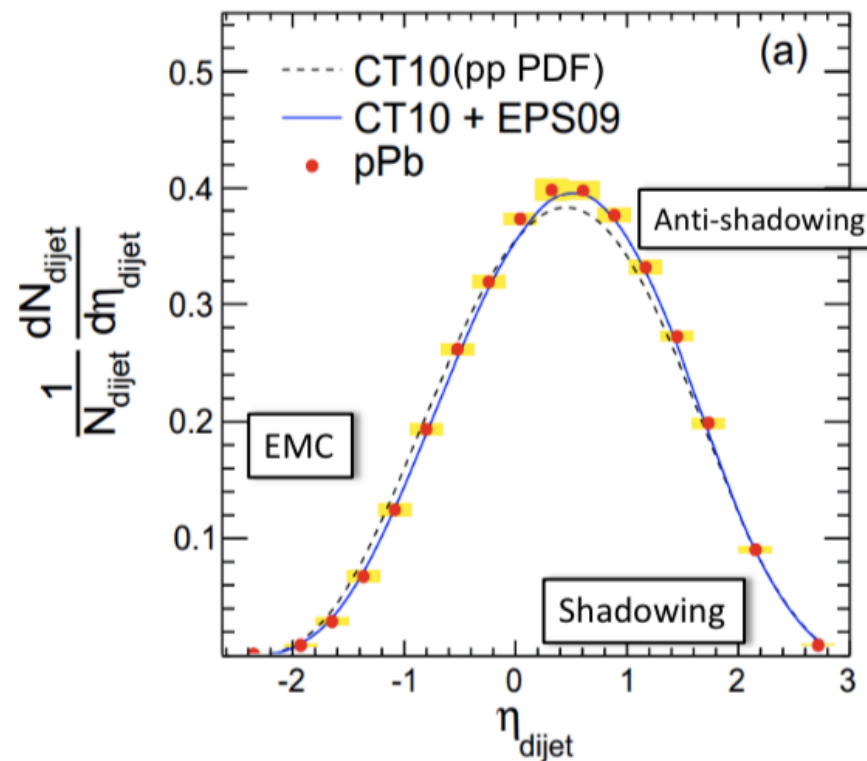
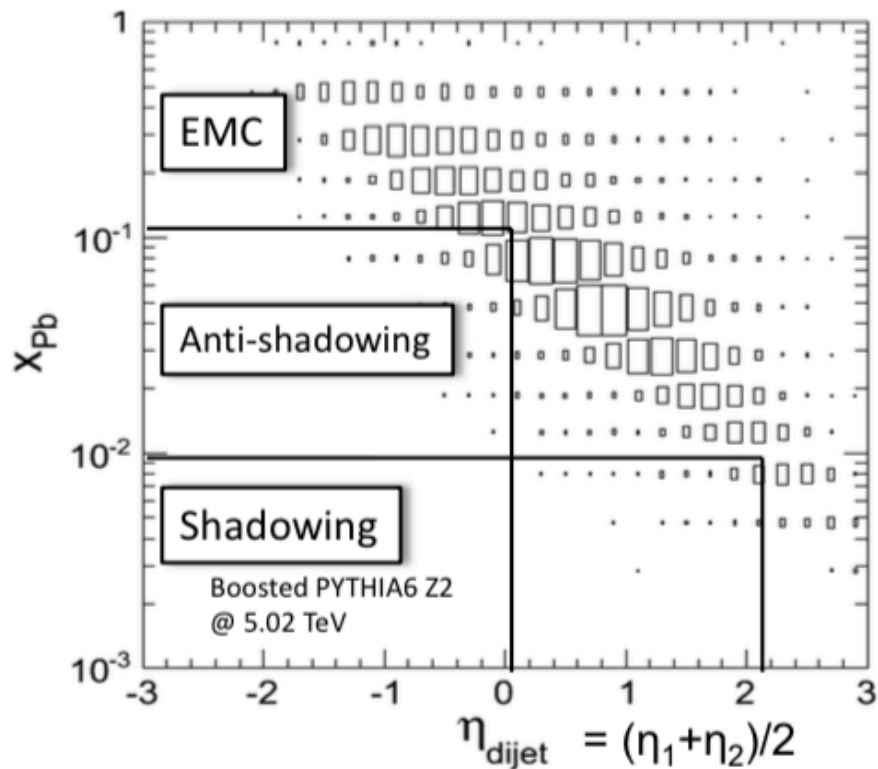
**Map of transport coefficient  $\hat{q}$  vs temperature**  
JET Collaboration (based on hadron  $R_{AA}$ )



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# Extra

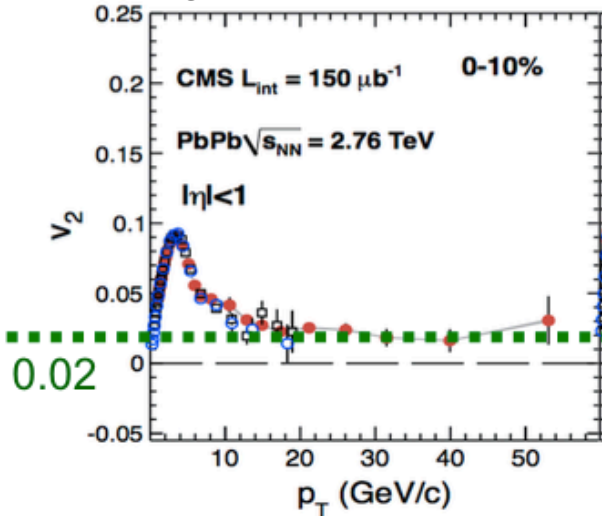
# Di-jets to study nPDF in pPb



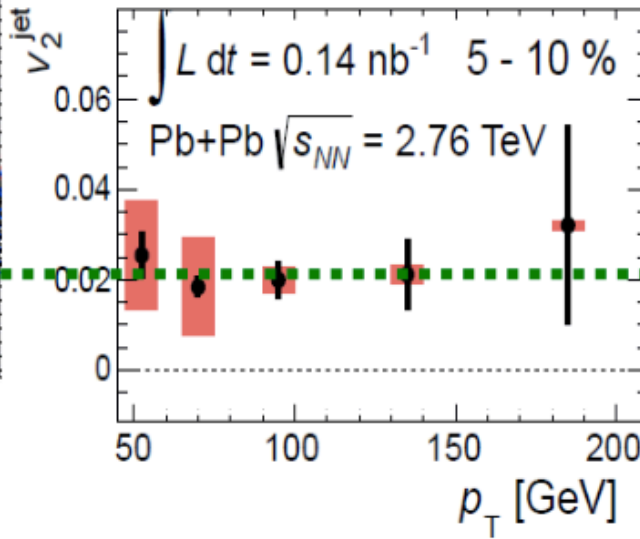
# Jets vs hadrons: $v_2$



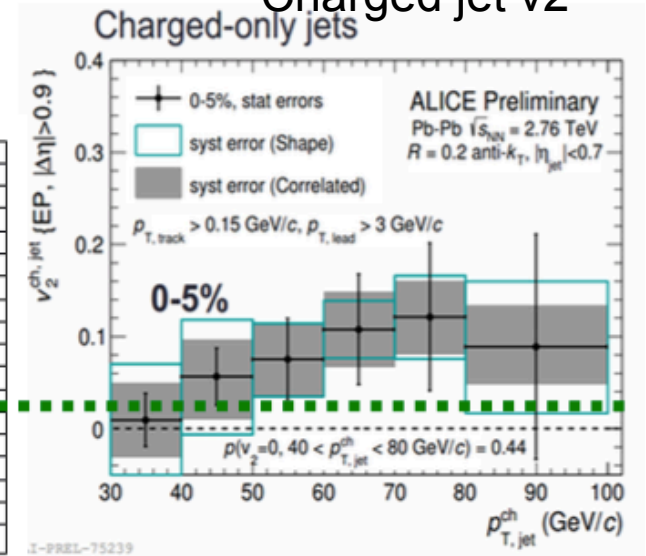
CMS 0-10%  
High  $p_T$  track  $v_2$



ATLAS 5-10%  
Jet  $v_2$



ALICE 0-5%  
Charged jet  $v_2$



Jet and high- $p_T$  track  $v_2$ : non zero  $v_2$  up to high  $p_T$   
Larger  $v_2$  from ALICE

Non zero  $v_2$ : modulation due to path-length dependent energy loss