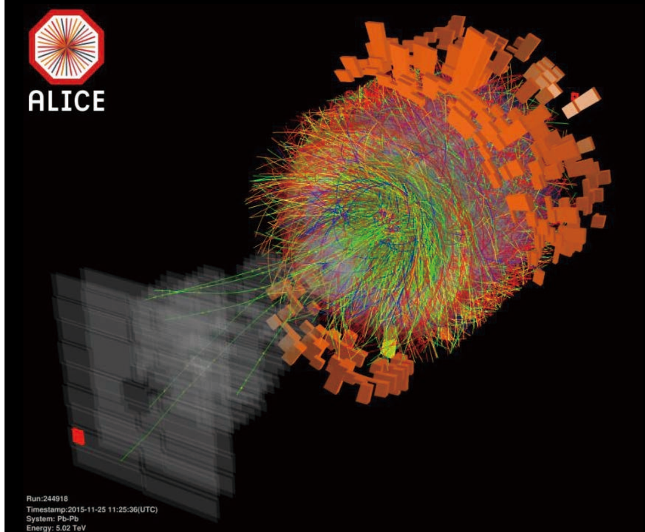
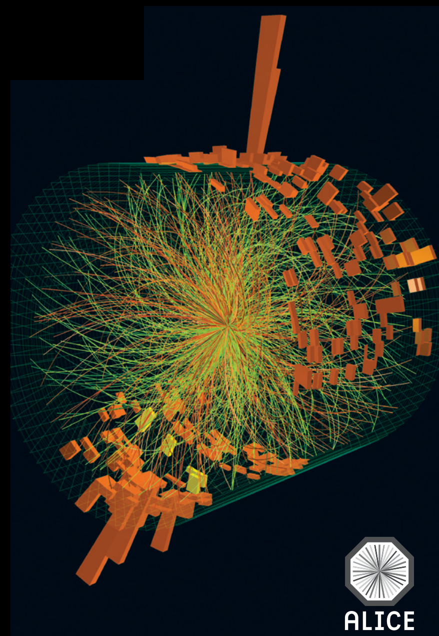
Jet physics in ALICE



Tatsuya Chujo
University of Tsukuba
(for the ALICE collaboration)

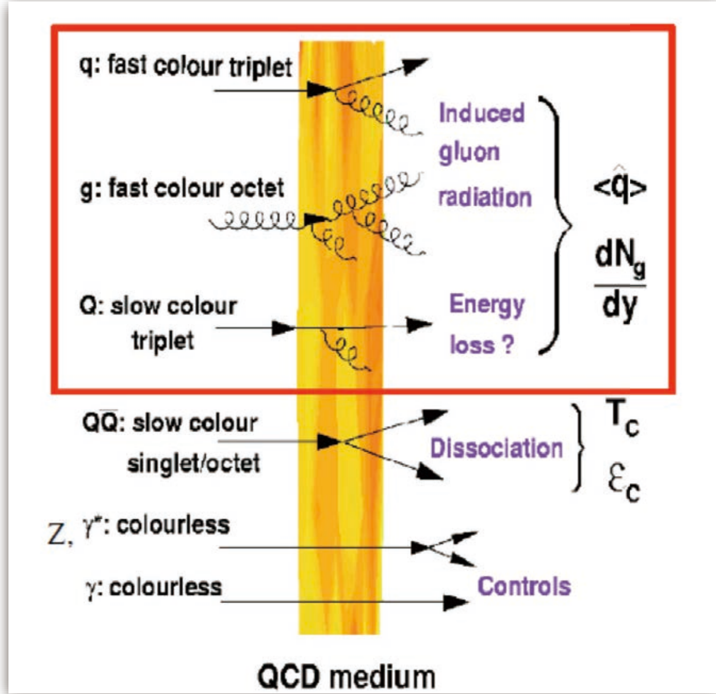


https://cds.cern.ch/record/2155668

UCLA 2019 Santa Fe Jets and Heavy Flavor Workshop
Jan. 28-30, 2019, UCLA, Los Angeles, USA

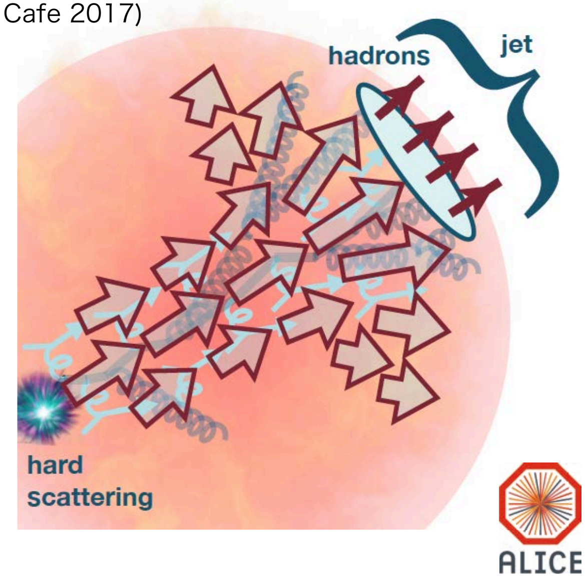
Hard probes in heavy-ion collisions

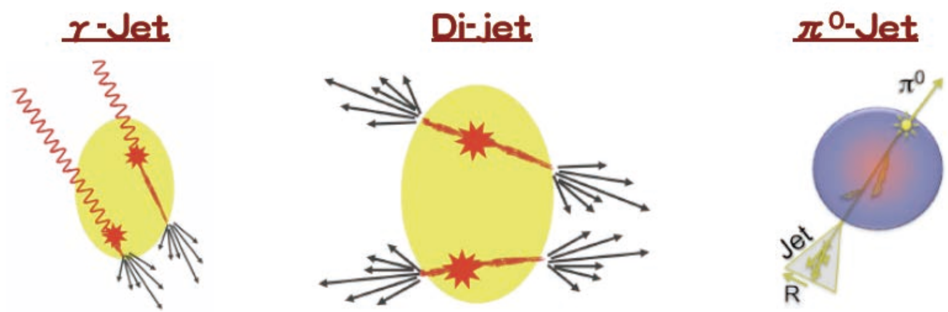
- **Hard probes:**
  - Originated at the parton hard scattering (large Q^2), prior to QGP formation time ($1/Q \ll 1$ fm/c)
  - Well calibrated (pQCD)
  - Jets: reflect a whole evolution of the system
- **Access to the medium properties:**
  - dE/dx of partons (g, q (uds, c, b)) & L dep.)
  - Large angle emissions
  - Jet tomography by different probes & techniques

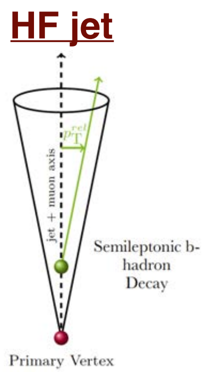


side by D. d'Enterria (slide at QGPWS, 2008)

Picture form Y. Tachibana (Heavy Ion Cafe 2017)

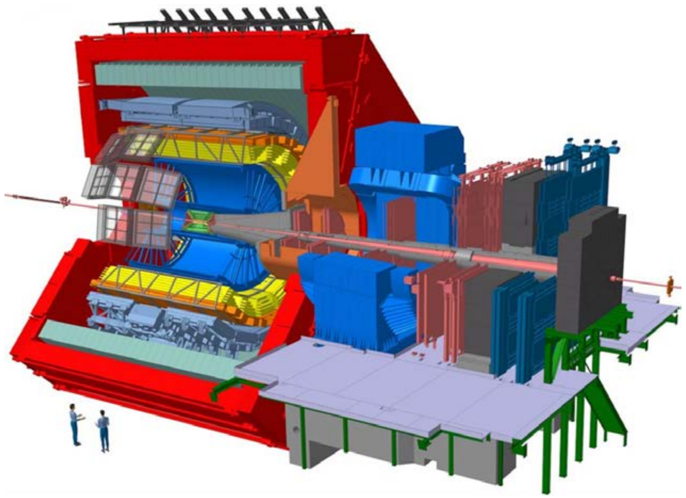


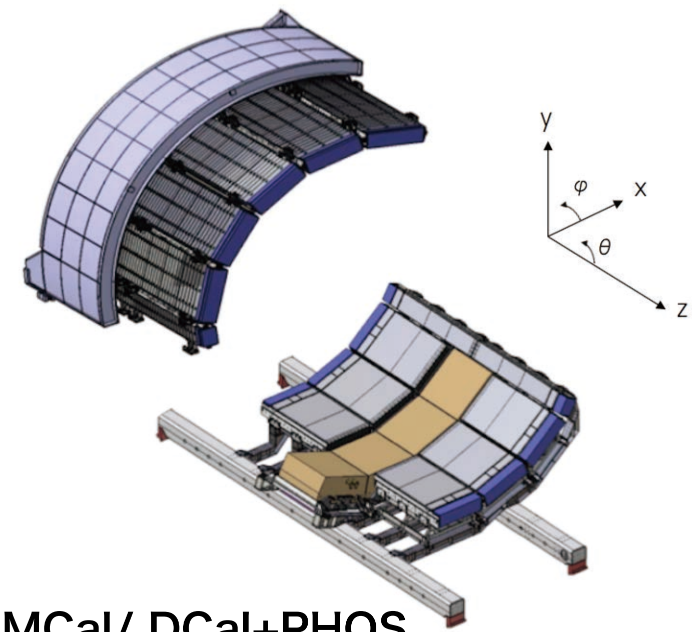




Jets in ALICE

- Jet reconstruction by tracking (TPC+ITS) + calorimetry
- Go to **low jet p_T and low constituent p_T** (> 0.15 GeV/*c* for charged) in large heavy-ion background
  - ✓ Detailed characterization of background fluctuations (JHEP 1203 (2012), 053)
  - ✓ Gamma and jet triggers by EMCal/DCal, PHOS for high p_T
- **Measurements:**
  - ✓ High p_T hadrons
  - ✓ Inclusive jet
  - ✓ Jet + hadron correlations (soft hadron, w/ PID)
  - ✓ Gamma-jet correlations, c/b taged jets, jet-jet
  - ✓ Jet substructure





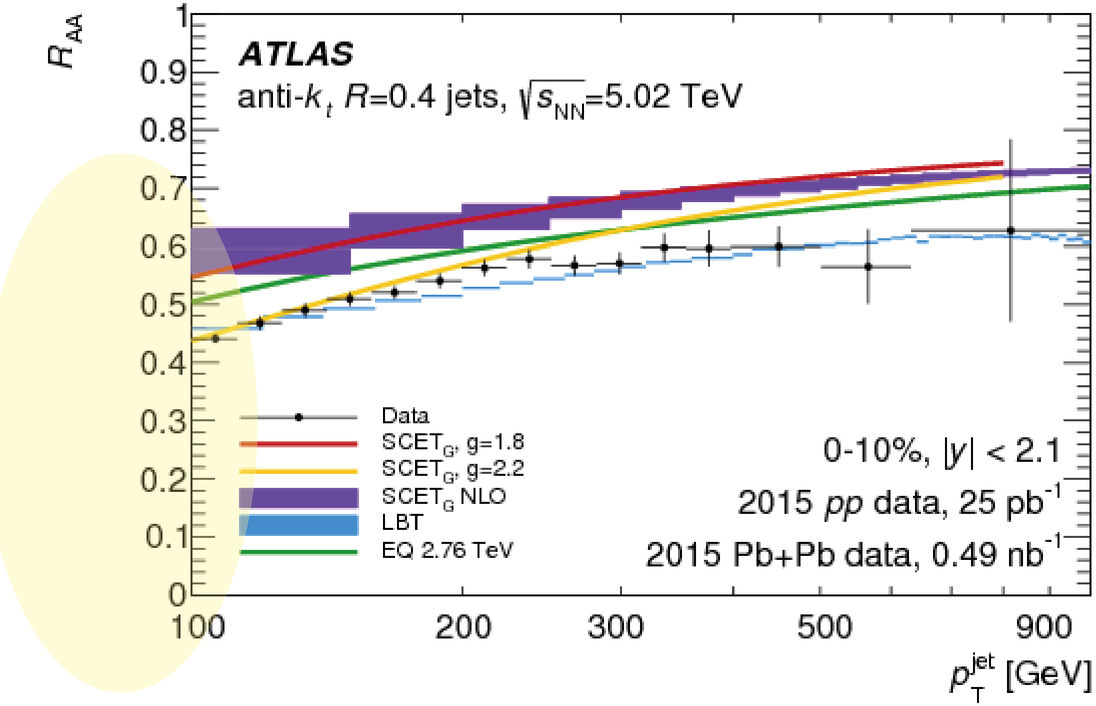
EMCal/ DCal+PHOS

Outline

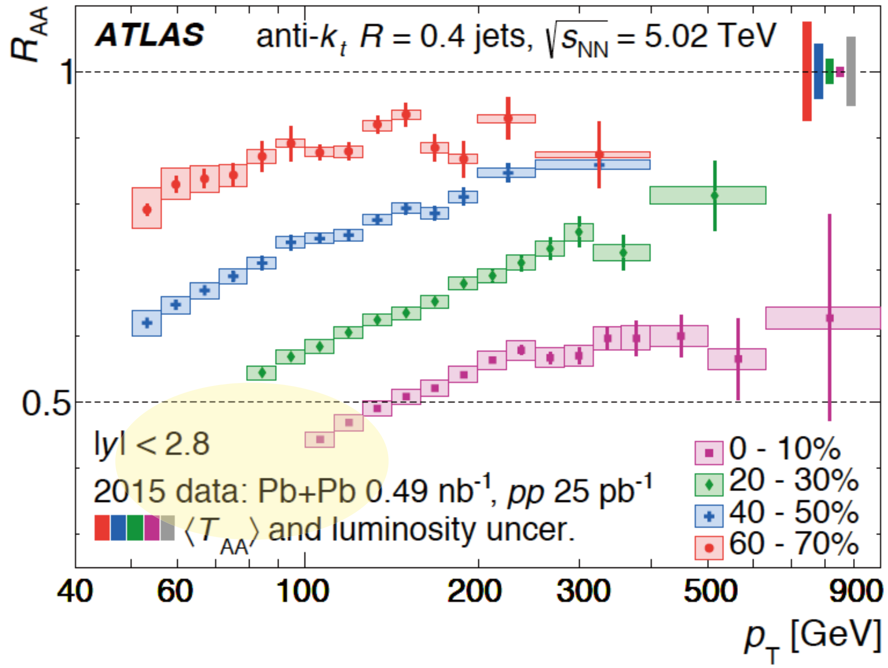
(1) Jet spectra and R_{AA}
(2) Jet substructure
(3) Gamma-jet
(4) Jet-hadron, hadron-jet
(5) Jet with PID (strangeness etc.)

(1) Jet spectra and R_{AA}

arXiv 1805.05424



arXiv:1805.05635



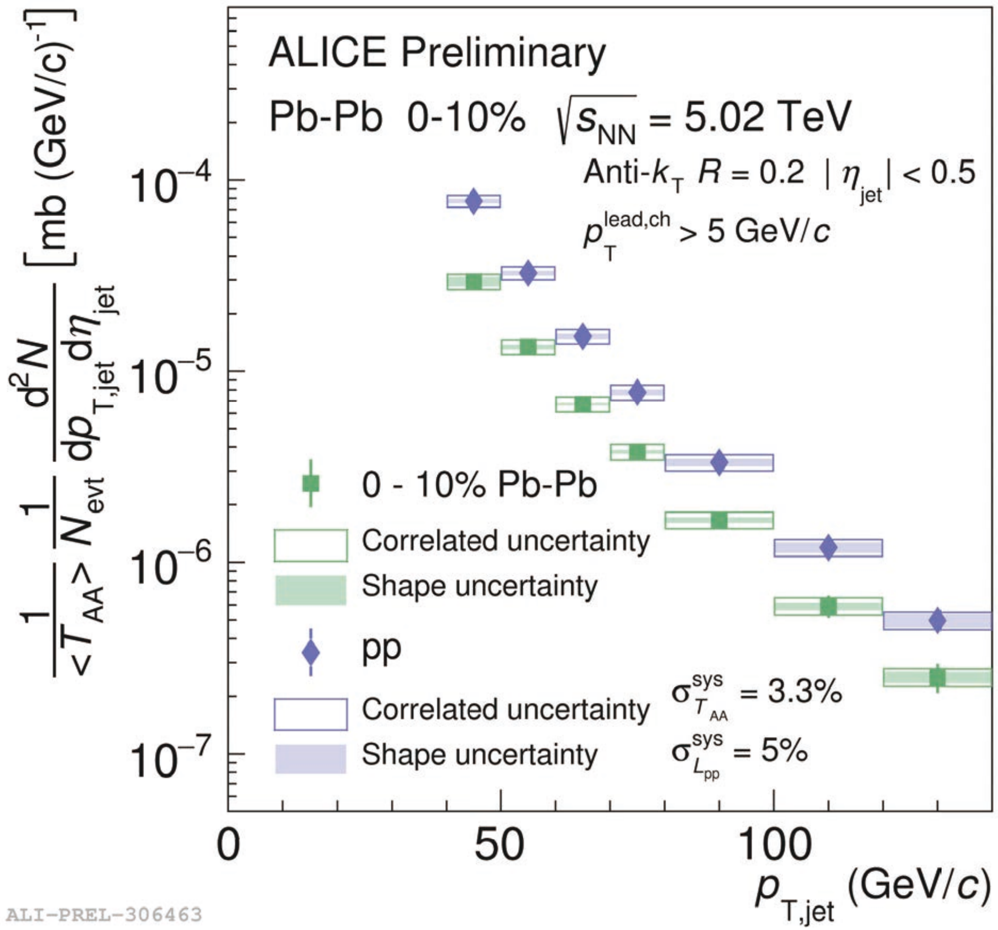
What can we learn from R_{AA} measurement of jet, beyond energy loss ?

ALICE:

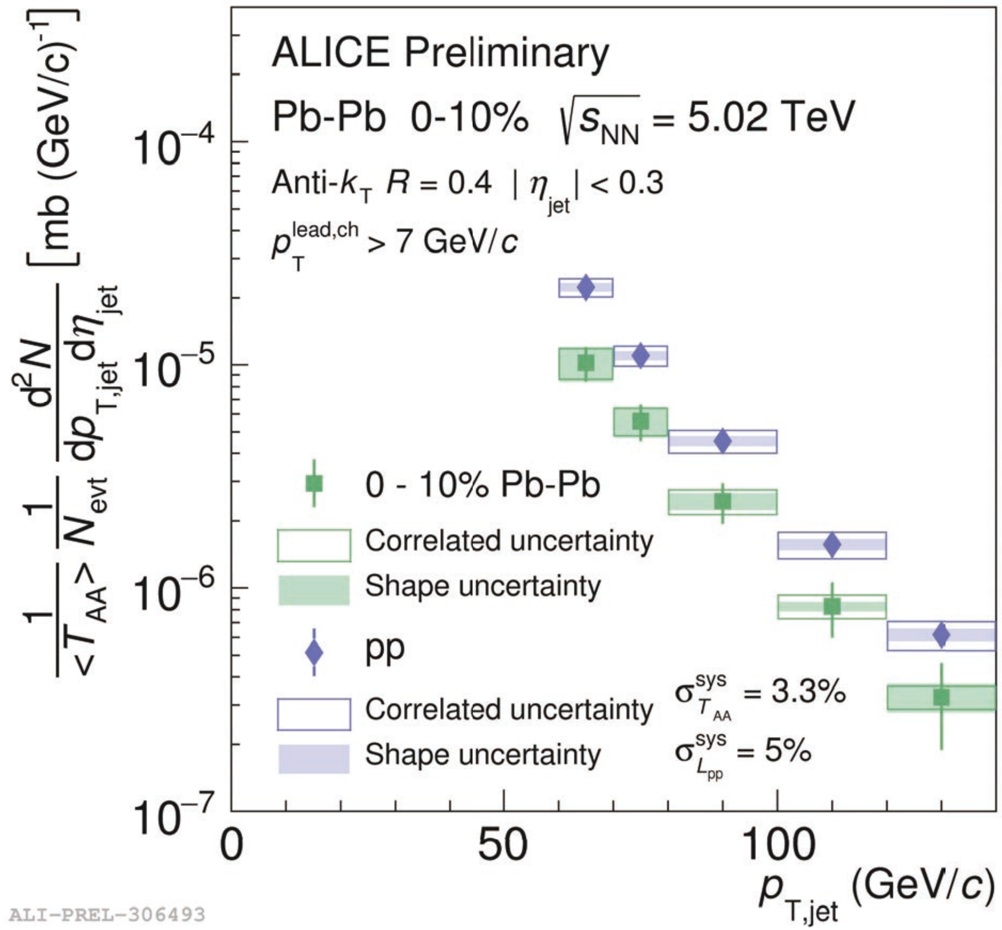
- Low p_T (< 100 GeV/c): p_T dependence of R_{AA}
- High p_T up to 200 GeV/c by using the current statistics
- Complementary to ATLAS/CMS

Full jets in pp and Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

R = 0.2



R = 0.4



Pb-Pb jet spectrum in 0-10% centrality
for $p_{T,jet}$ = 40-140 GeV/c

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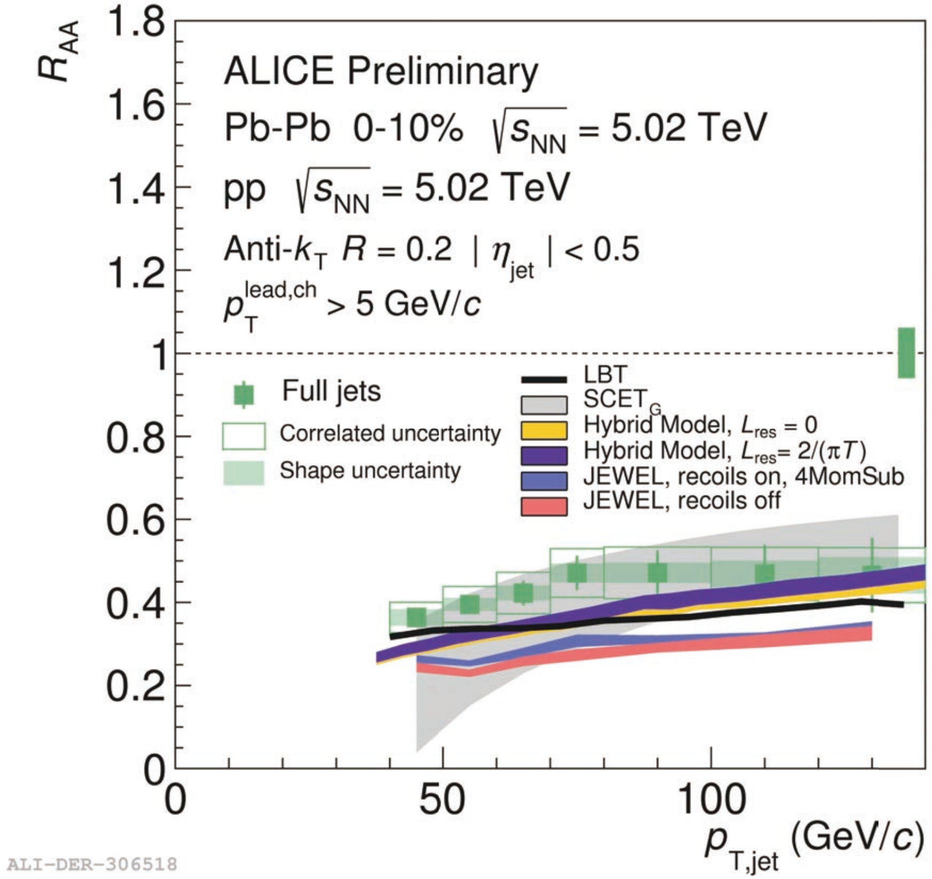
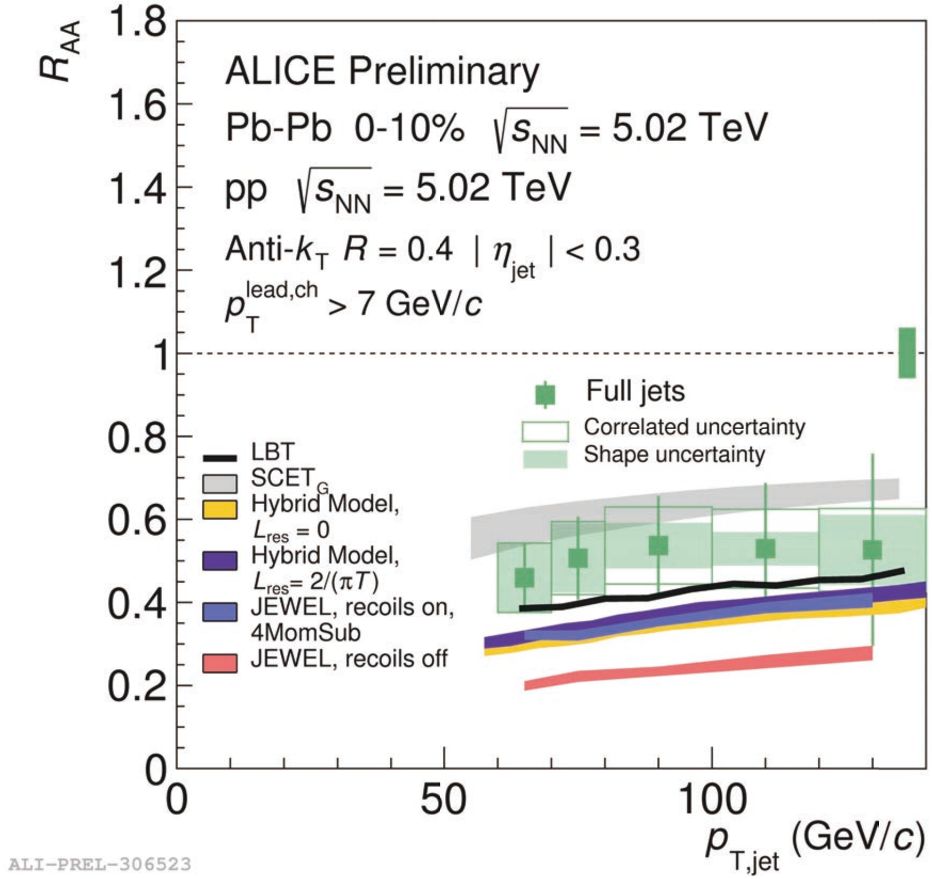
Full jets R_{AA}

R = 0.2



R = 0.4



- All models qualitatively describe the R_{AA}
- But quantitatively, it is not perfect
- Interesting to see JEWEL recoil on/off difference is larger for R=0.4

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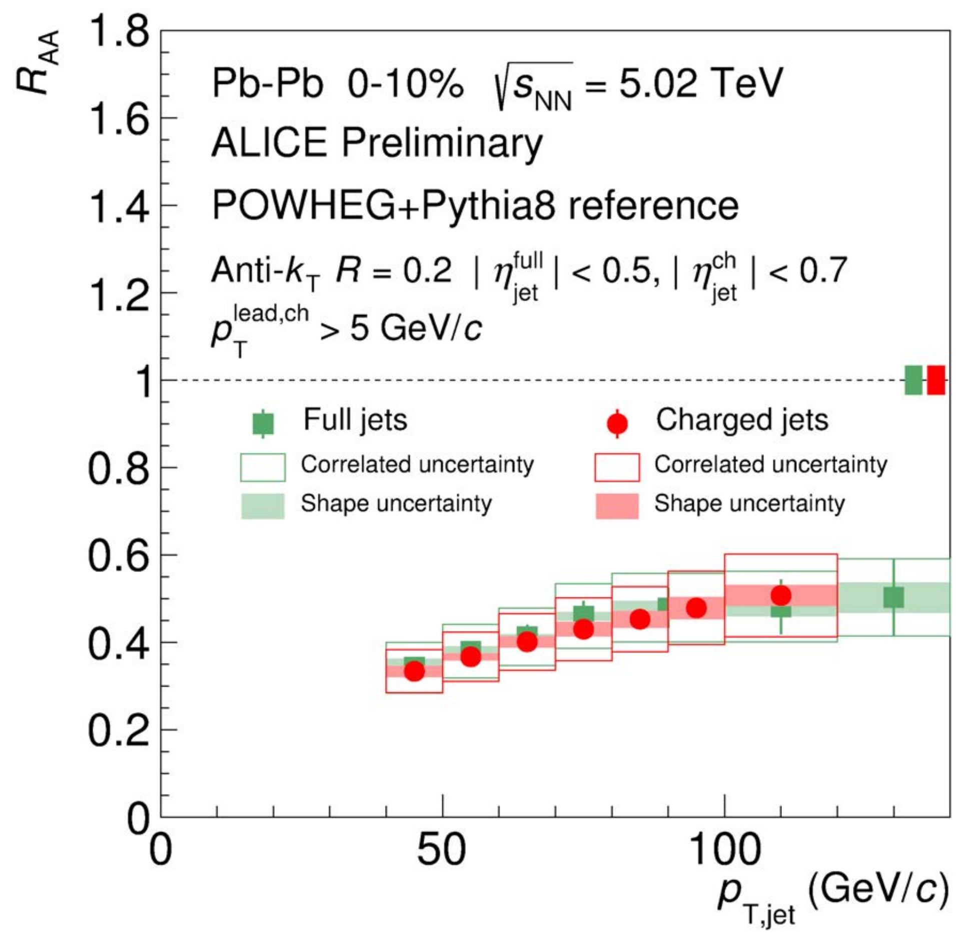
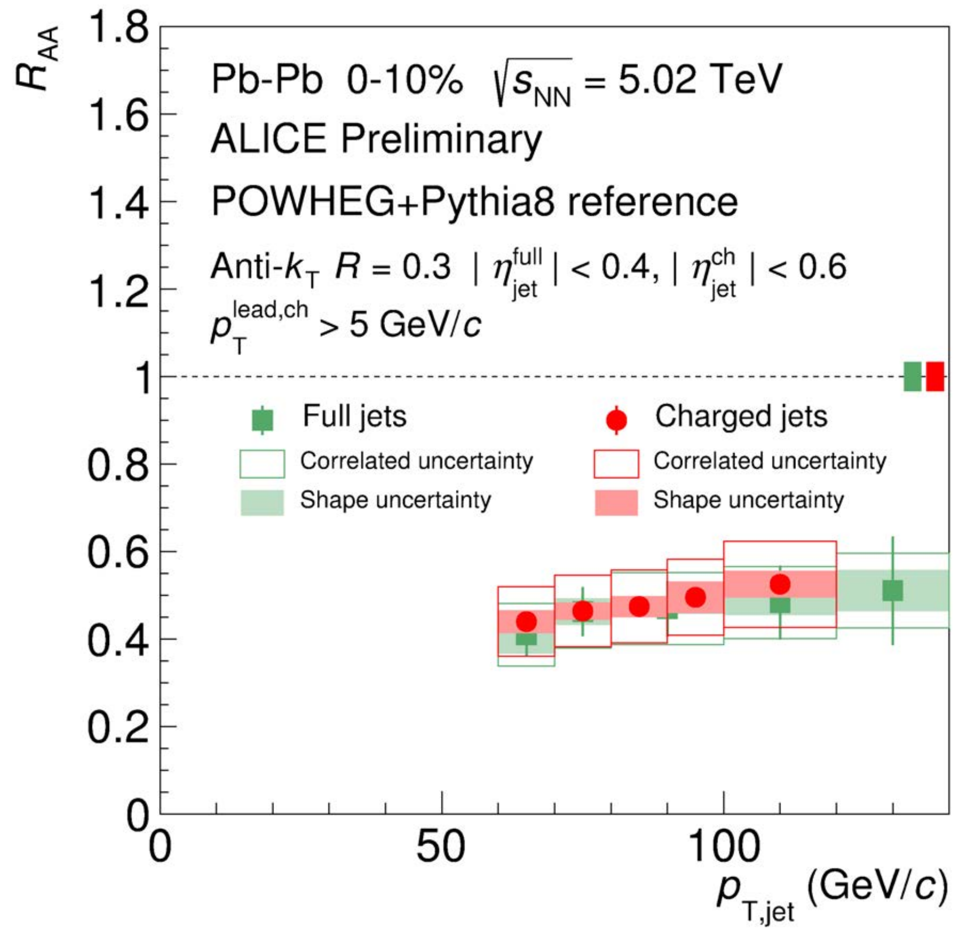
Charged vs. full jets

R = 0.2



R = 0.3



Charged particle jets and full jets are consistent

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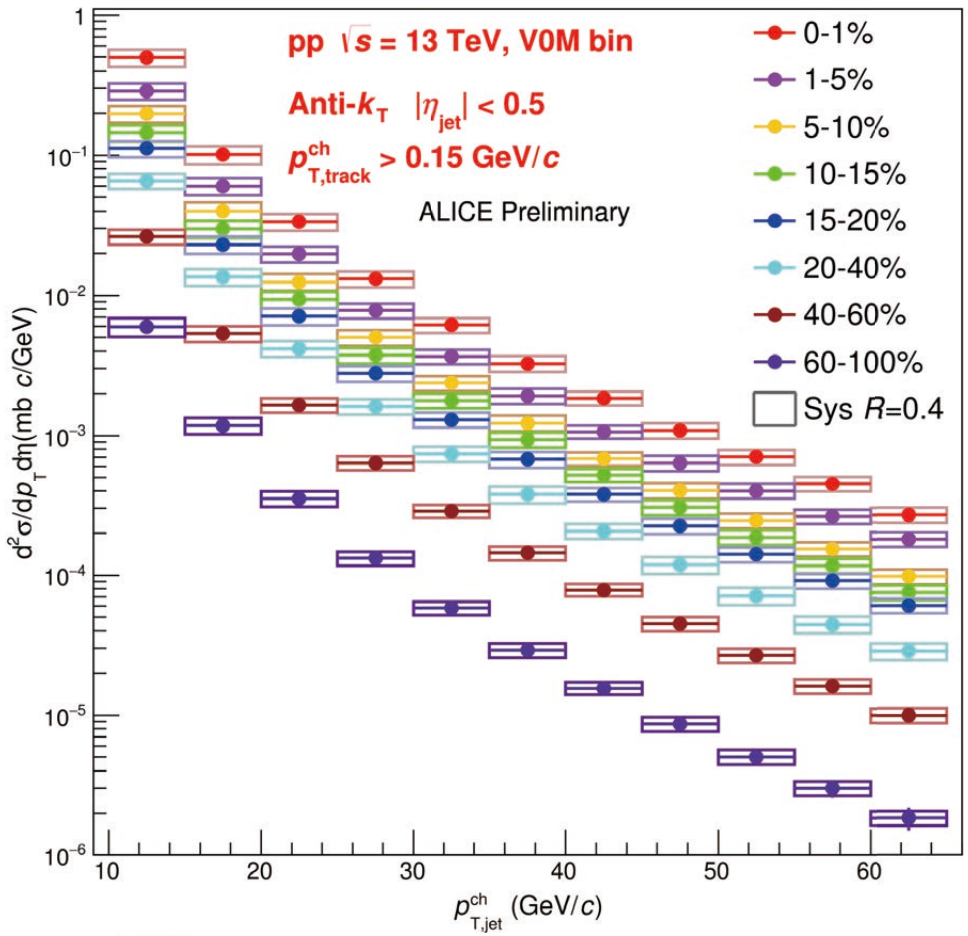
Multiplicity dep. charged jet in pp at $\sqrt{s}$ = 13 TeV



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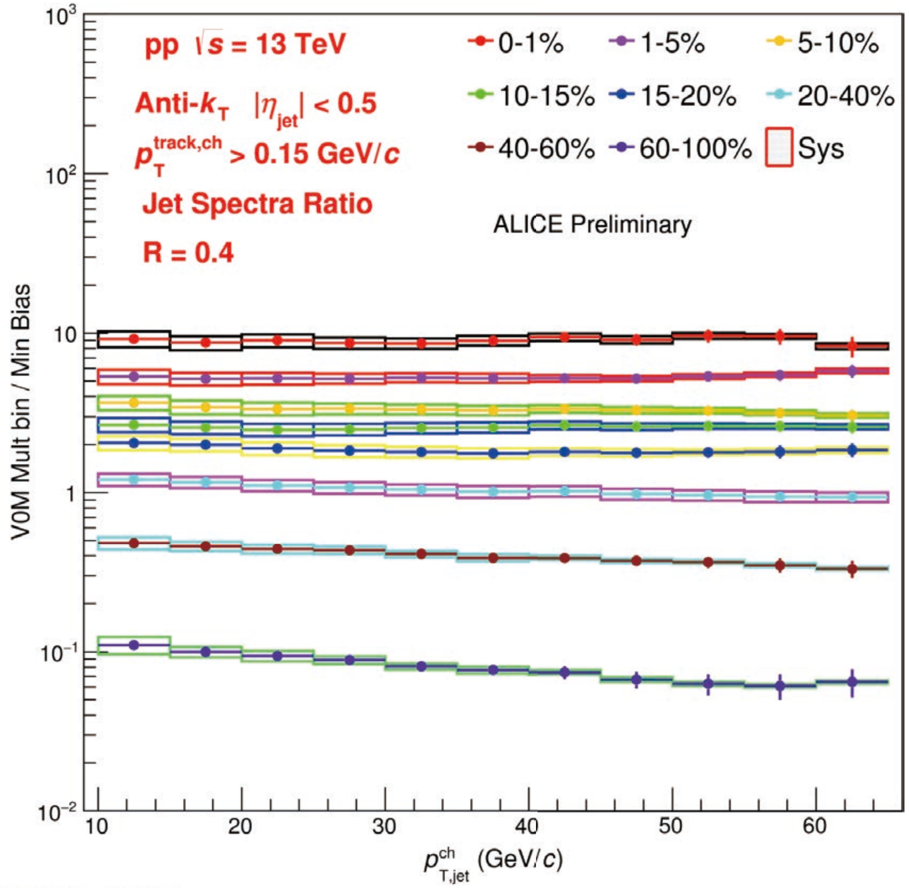


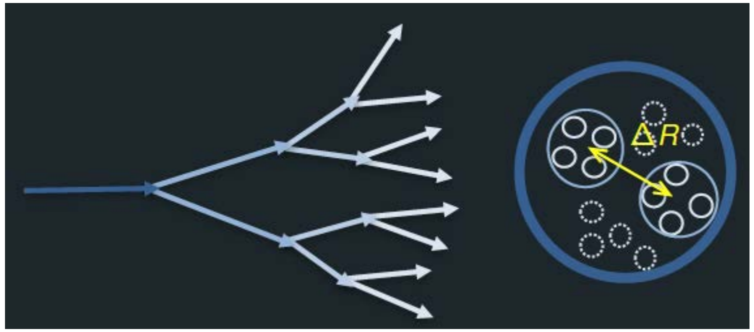
ALI-PREL-306699

- For high multiplicity, jet production yield is higher
- Yield ratio with respect to inclusive: no significant jet p_T dependence

(2) Jet substructure

Mapping jet substructure: Groomed jet

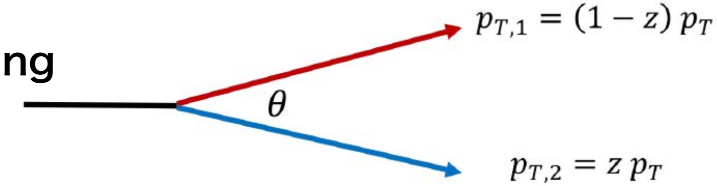
- **Iterative de-clustering to extract hard component of jet**
  - Recursively removing soft large angle radiation
  - Re-cluster found jet (e.g. with C/A) and unwind
  - Remove softer branch until SD condition fulfill

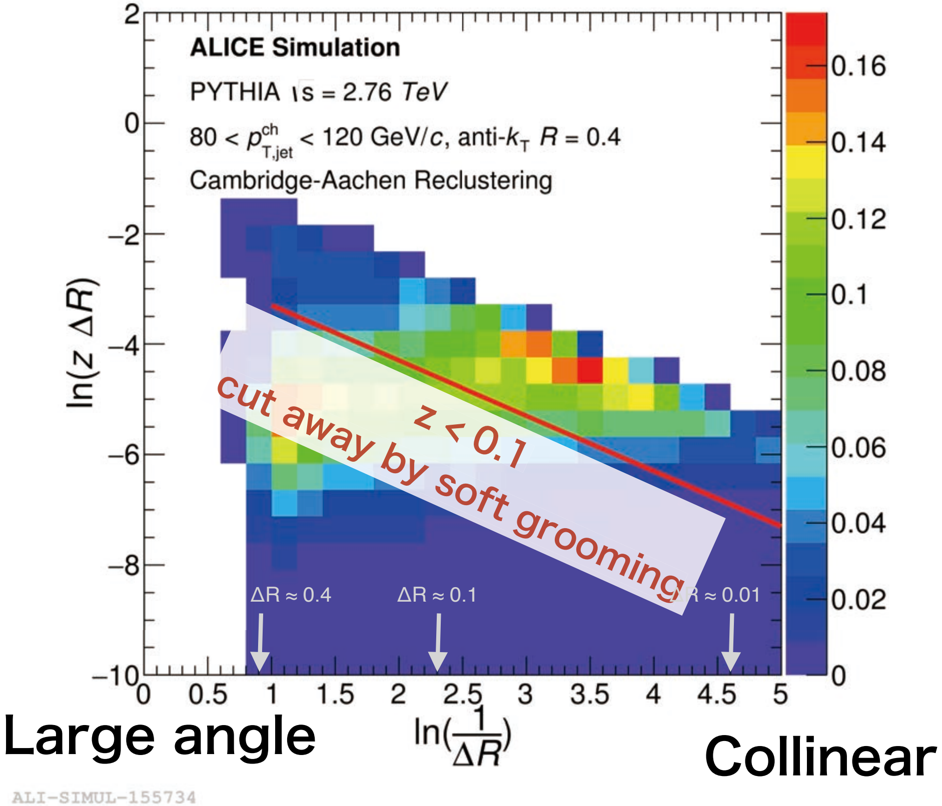


$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut}$$

– Each (sub)jet consists of 2 sub-jets

parton splitting



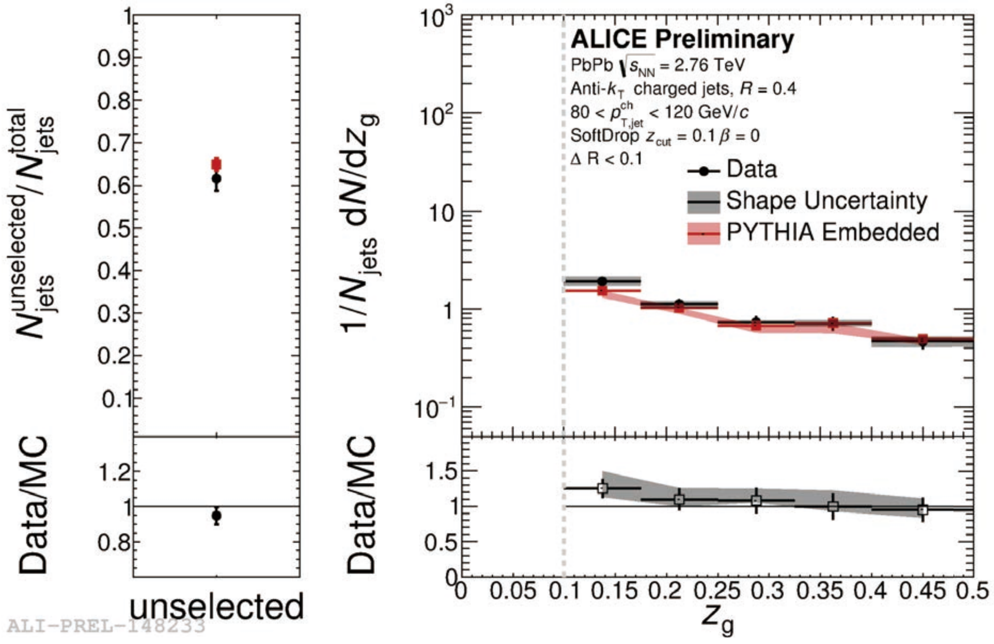


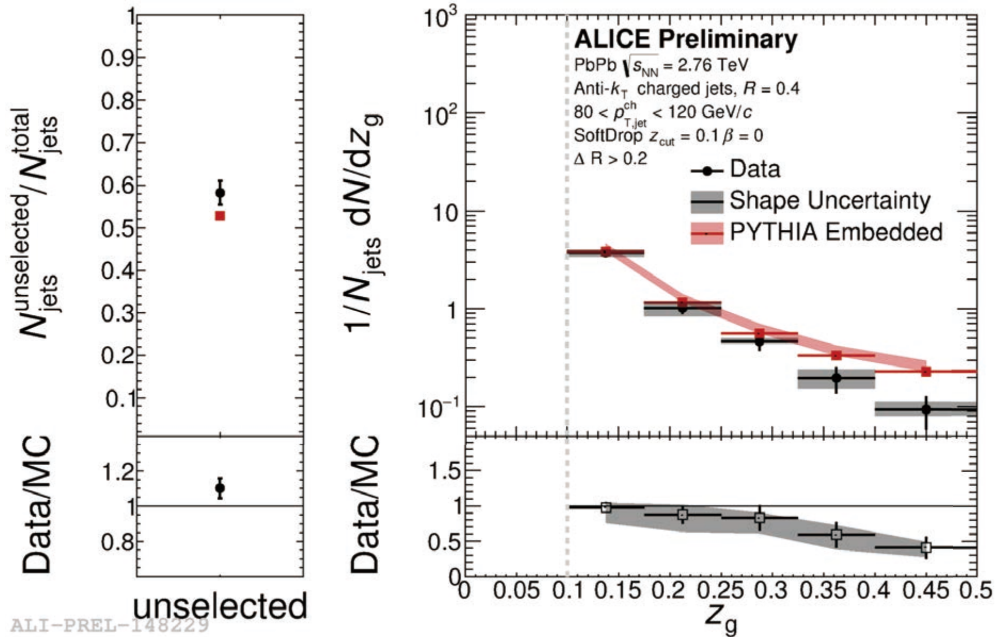
- **Lund diagram**
  - Phase space of all splittings
  - Momentum fraction vs. opening angle

- **Grooming**
  - Impose phase space cuts to enhance regions of interest
  - Soft drop: unwind, follow the largest p_T until $z > z_{cut} \cdot (\Delta R)^{\beta}$

Extreme angular limits of collimated and large angle splittings

$\Delta R < 0.1$ (small, collimated angle) **$\Delta R > 0.2$ (large angle)**



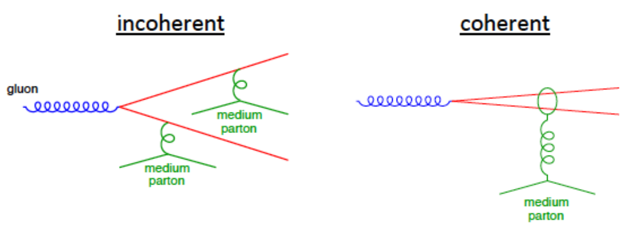


Slight enhancement of collimated first- splittings.

Suppression of large angle first (symmetric) splittings

In large angle limit, no evidence for excess of low *z* splittings

sensitive to coherence of energy loss



z_g: shared momentum fraction of the first groomed splitting

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

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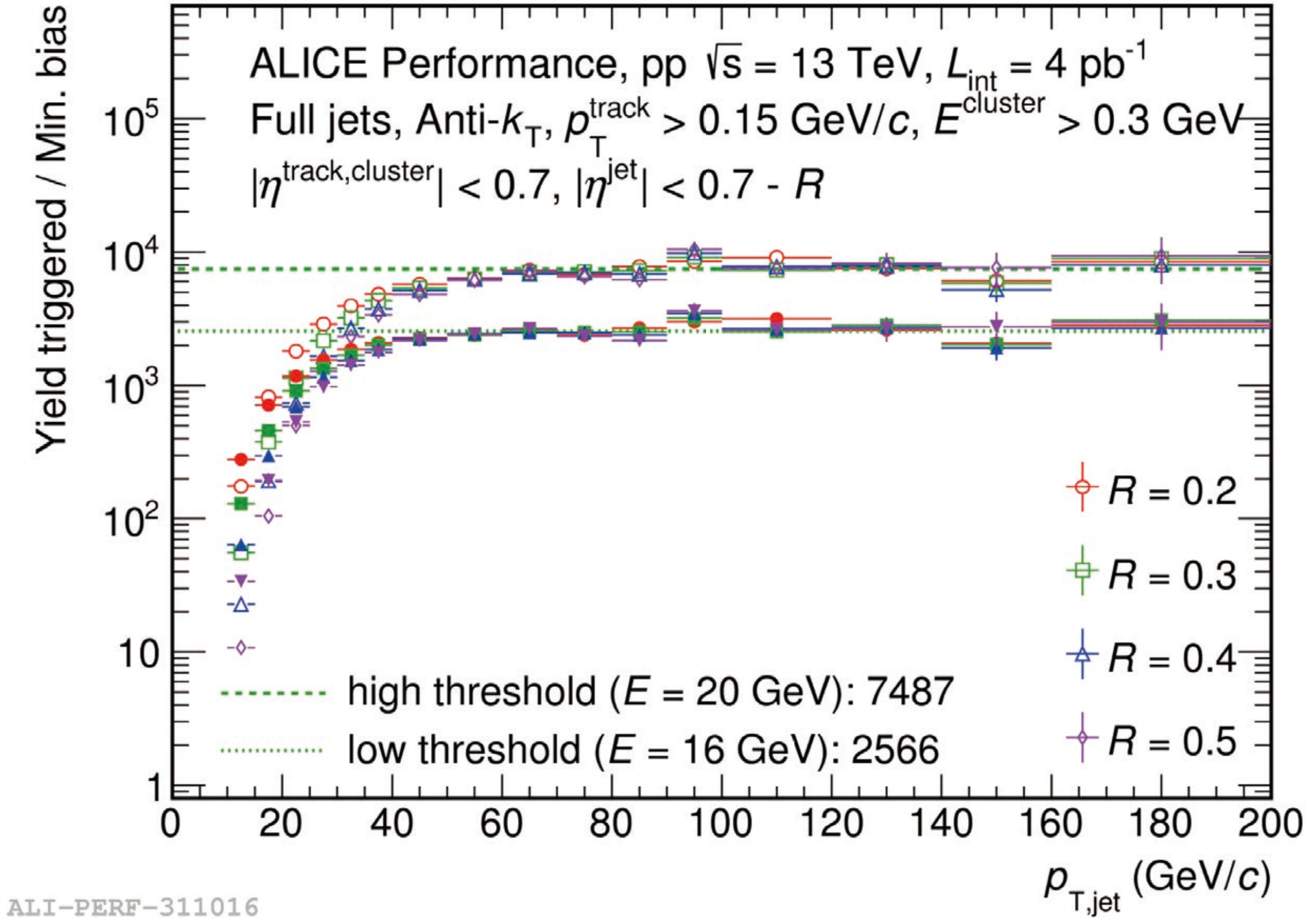
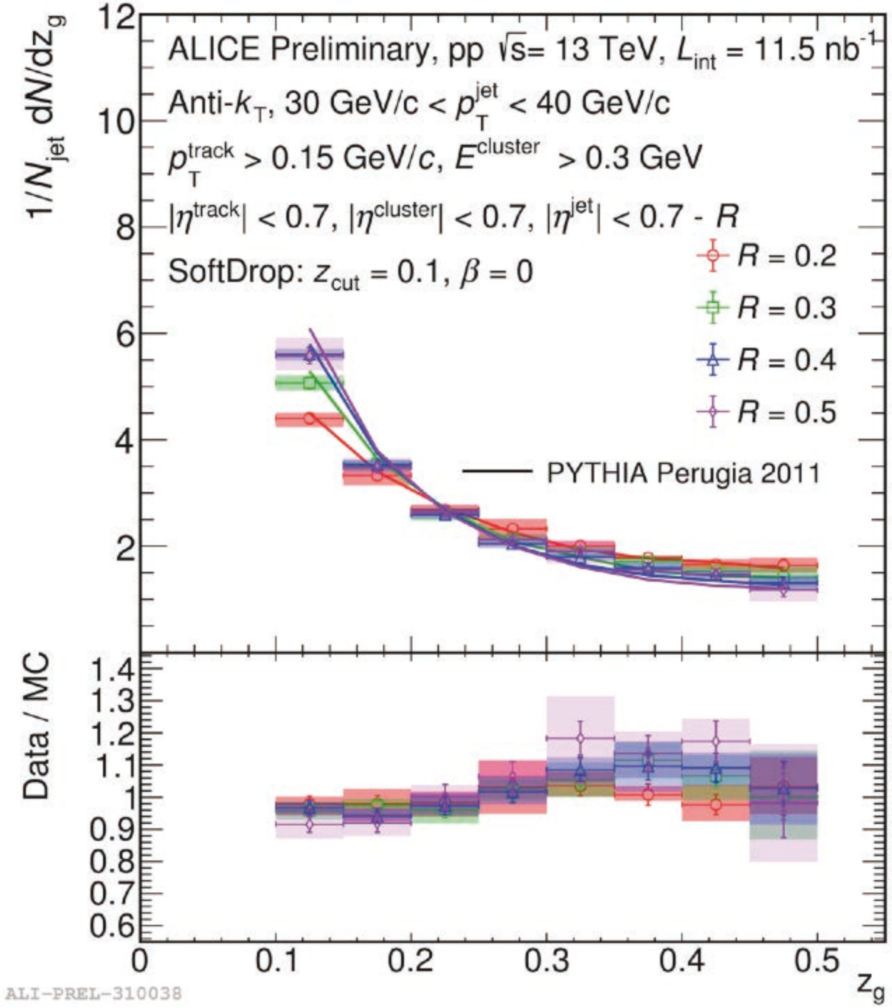
EMCal triggered data in pp at $\sqrt{s}$ =13 TeV



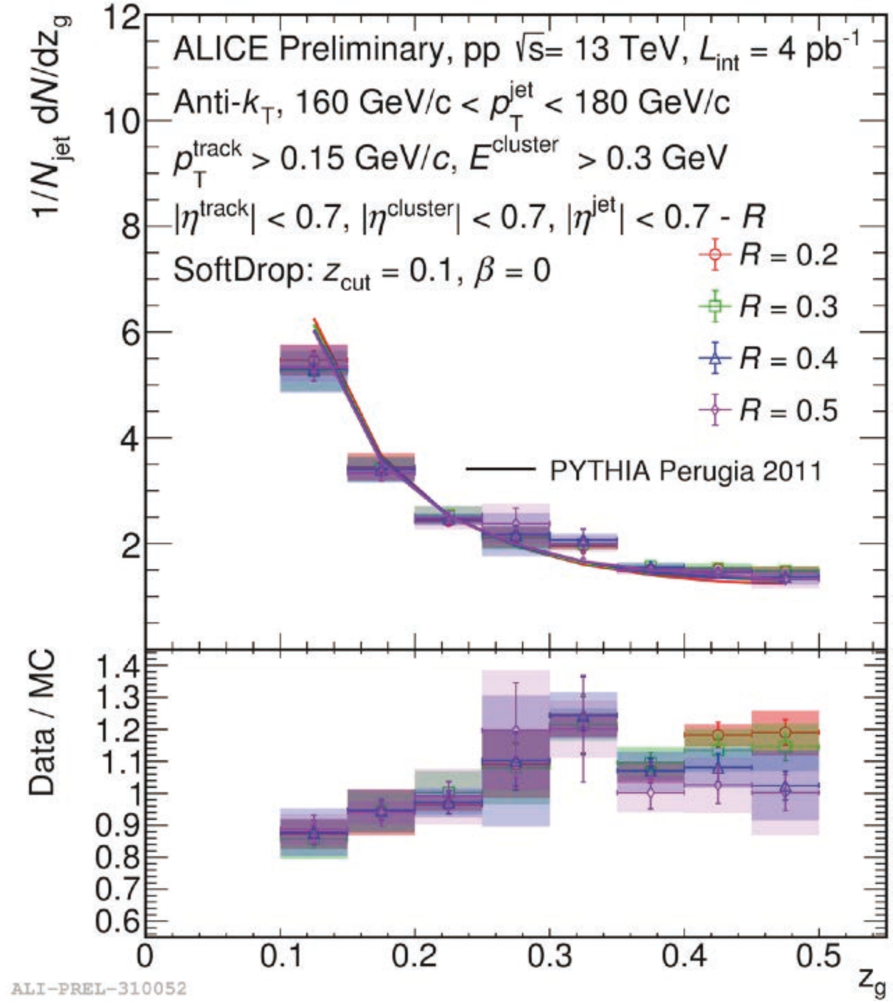
- **Utilized EMCal trigger for high-p_T jet up to 200 GeV/*c* for the first time!**
- Based on neutral energy in EMCal in a jet patch corresponding to $R \sim 0.3$
- No trigger bias region:
  - Low threshold: $p_T > 60$ GeV/*c*, High threshold: $p_T > 80$ GeV/*c*

z_g distribution in pp at $\sqrt{s}$ = 13 TeV

30 < p_T < 40 GeV/*c*



160 < p_T < 180 GeV/*c*



Low p_T (left): Shape different for small and large jet radii

- Trend towards more asymmetric splitting for larger *R*

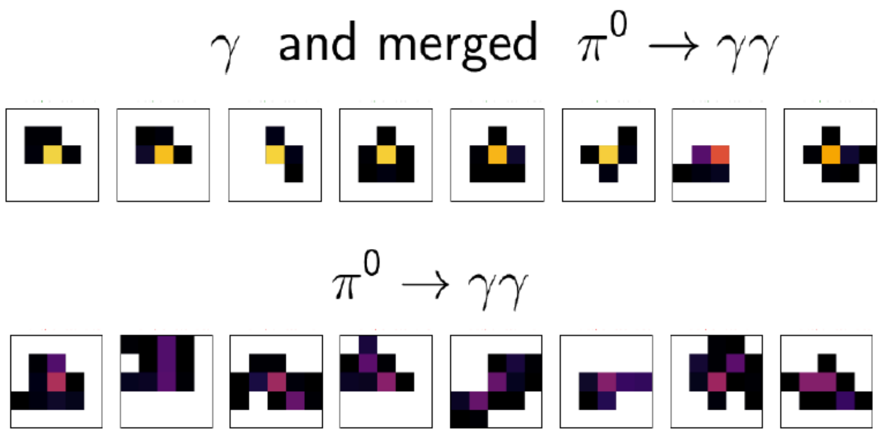
High p_T (right): z_g independent of *R*

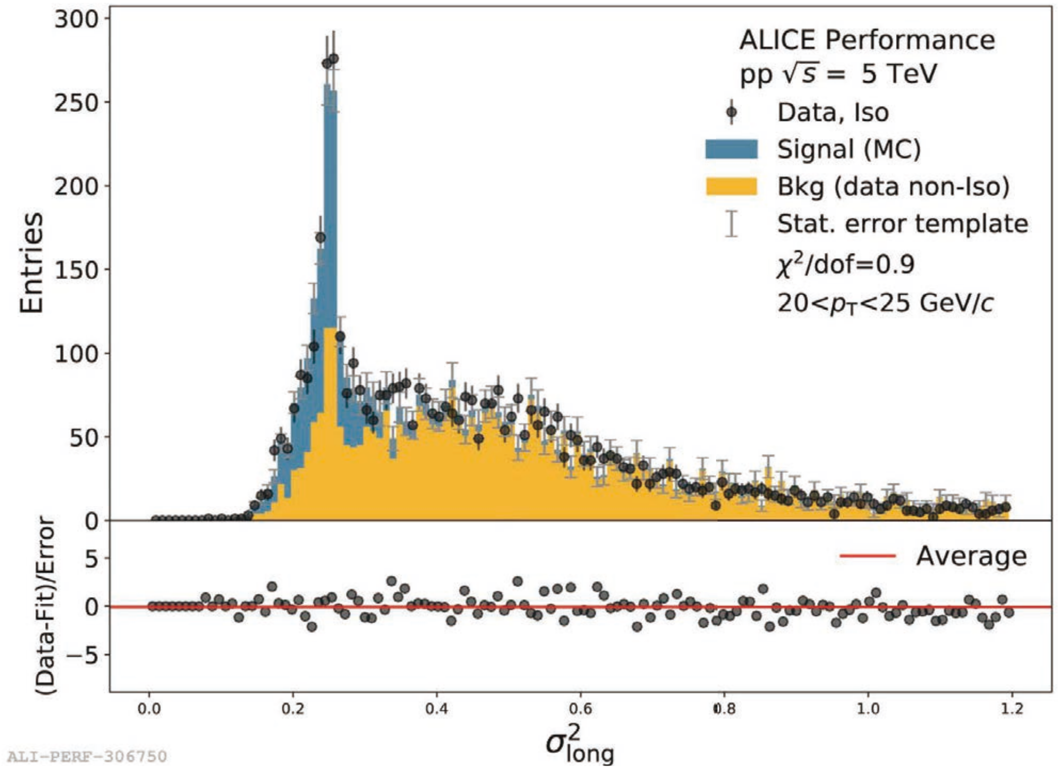
- Dominant part of the jet energy in core, small influence of large angle radiation

PYTHIA reproduces the trend at low p_T very well

ALICE

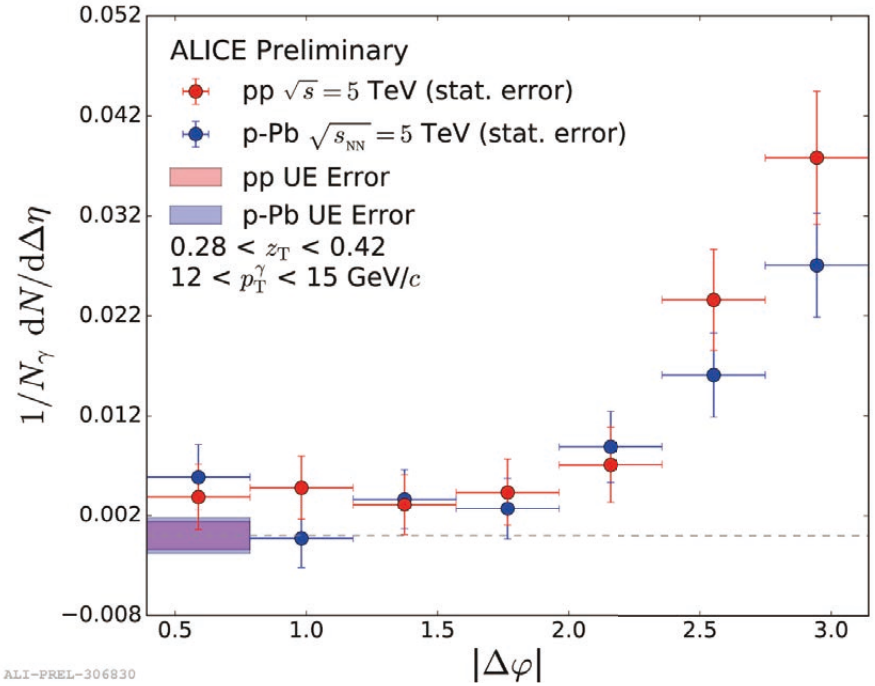
(3) Gamma-jet

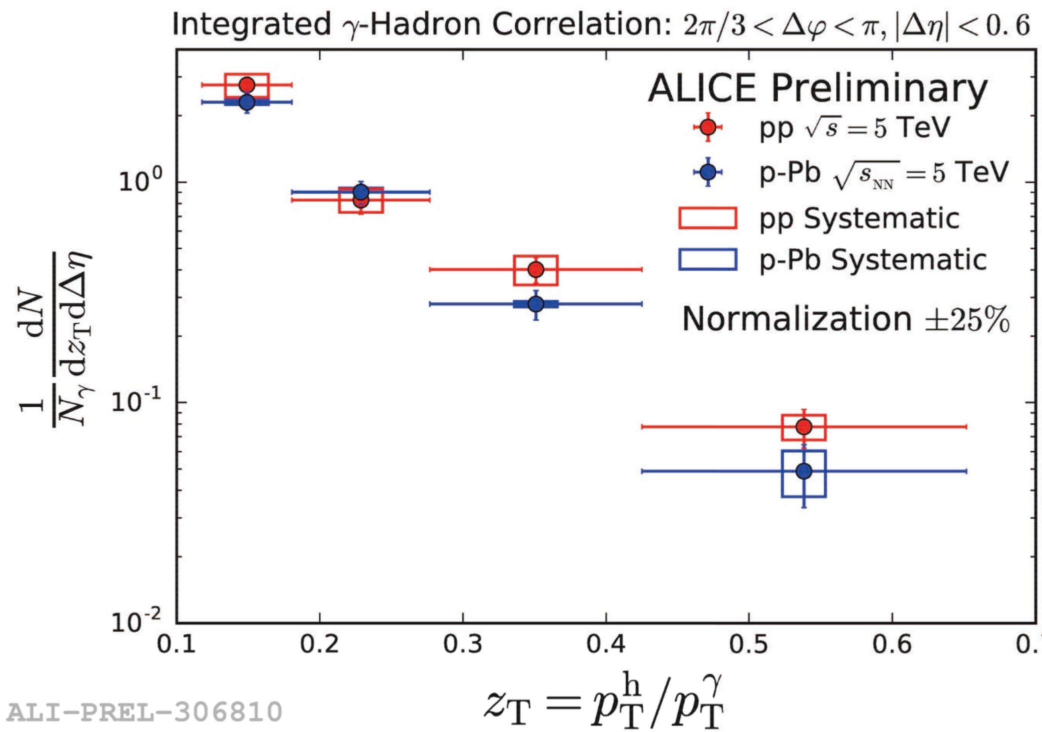




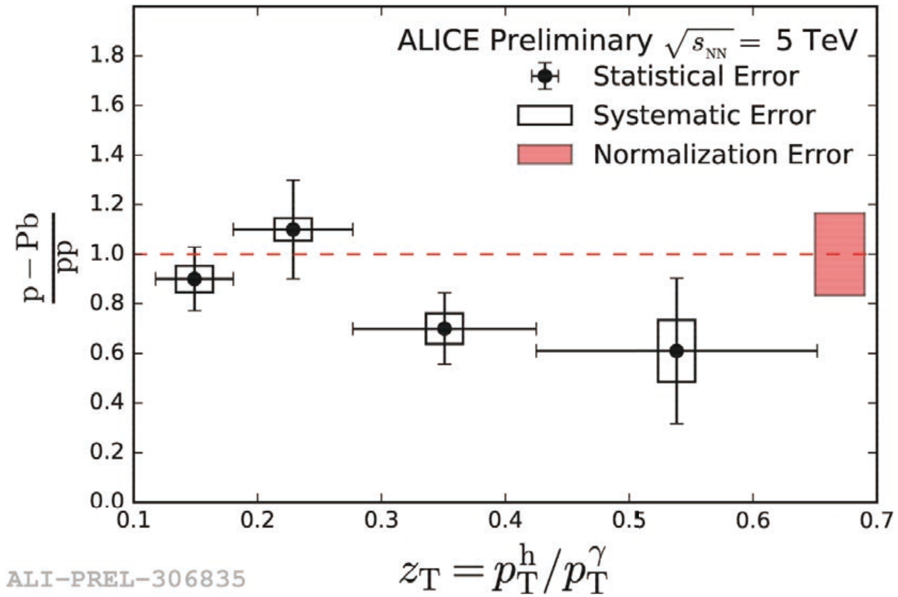
- Golden channel for energy loss, but rare probes
- Use ITS only track, and EMCal trigger in pp and p-Pb
- Photon measured in EMCal trigger, and applied isolation cut based on ITS tracks R=0.4 around photon candidates
- Set the benchmark for pp and p-Pb, look also the difference between pp and p-Pb at low Q^2 and low x region

γ -“hadron” in pp and p-Pb





- No significant difference between pp and p-Pb



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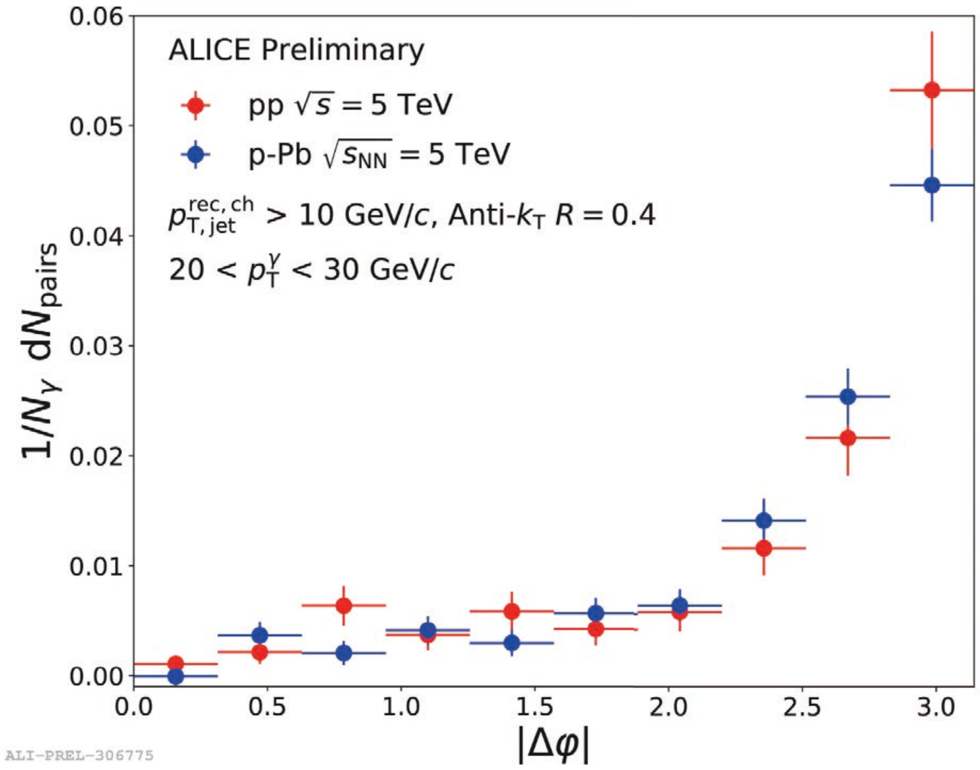
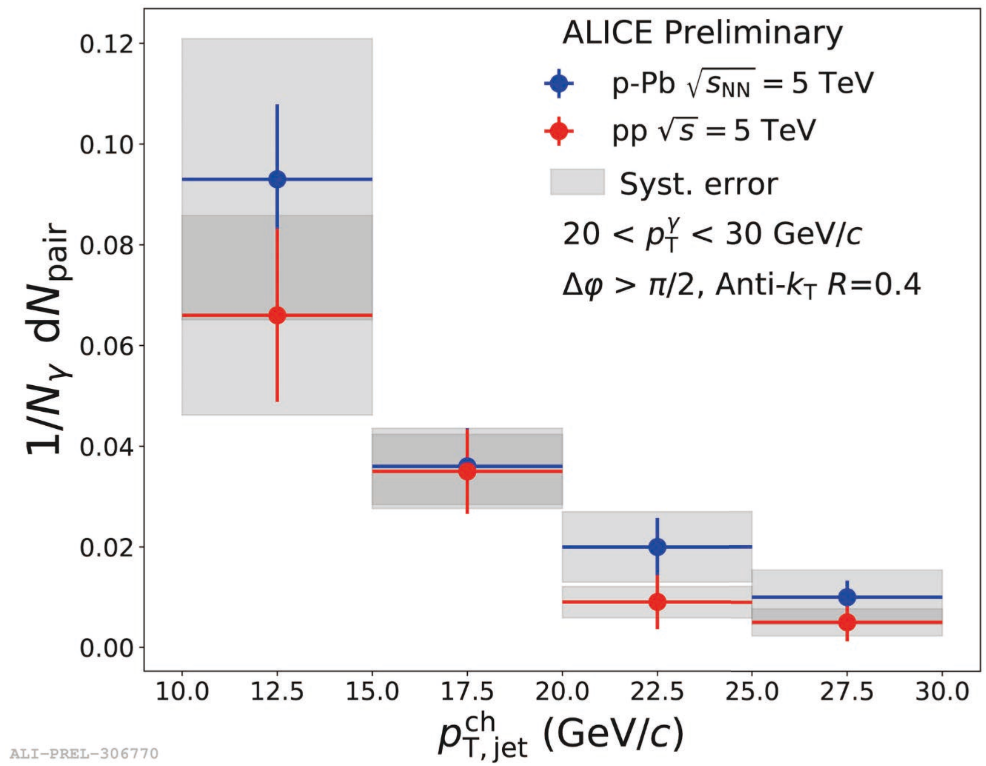
γ -“jet” in pp and p-Pb



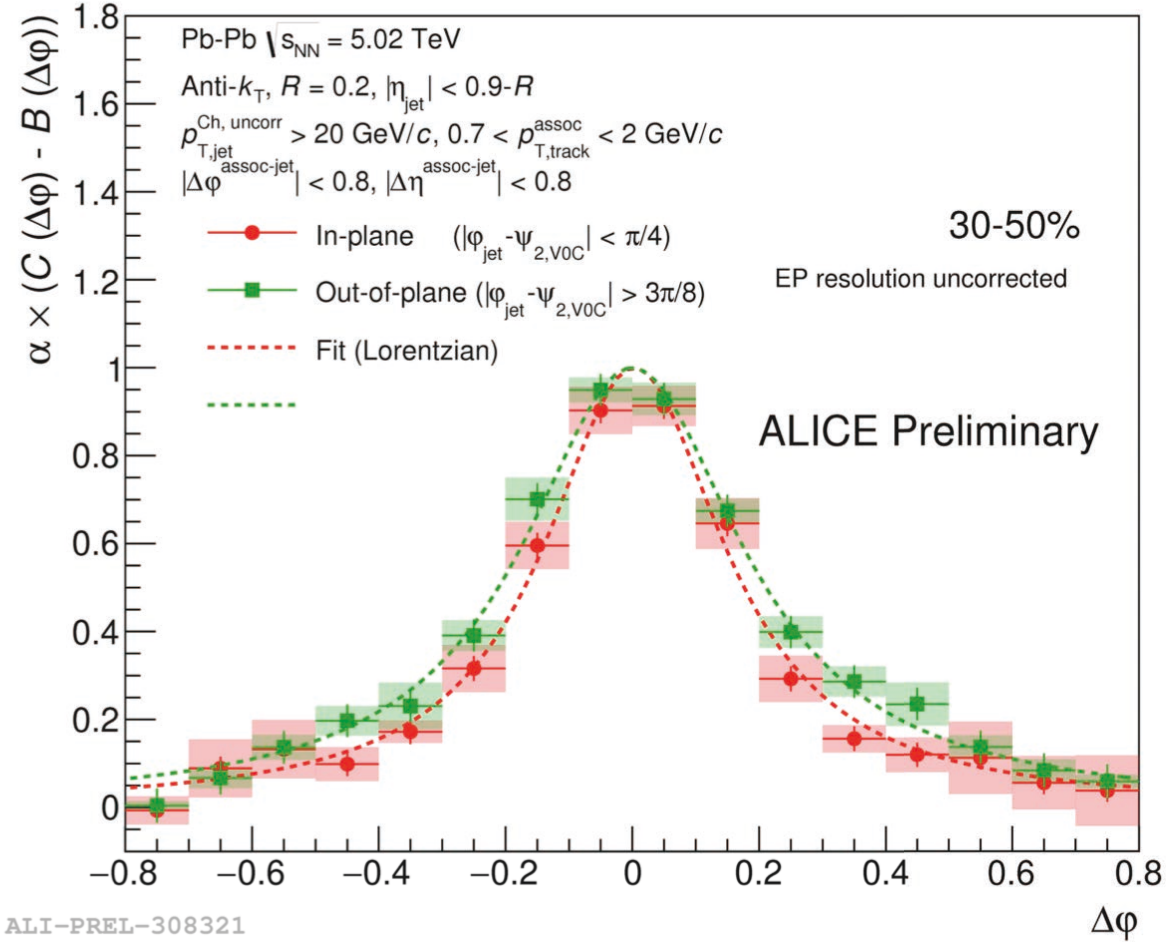


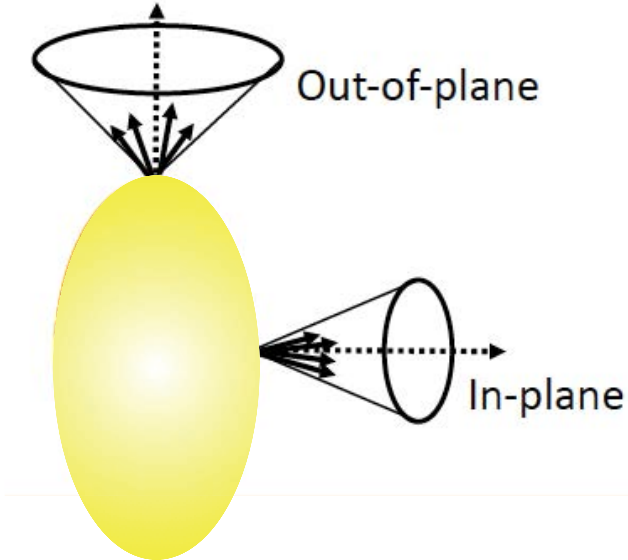
- No significant difference between pp and p-Pb

ALICE

(4) Jet-hadron & hadron-jet

Jet-hadron corr. in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV





A slightly wider distribution for out-of-plane in lower p_T associated tracks ($0.7 < p_T < 2$ GeV/c)

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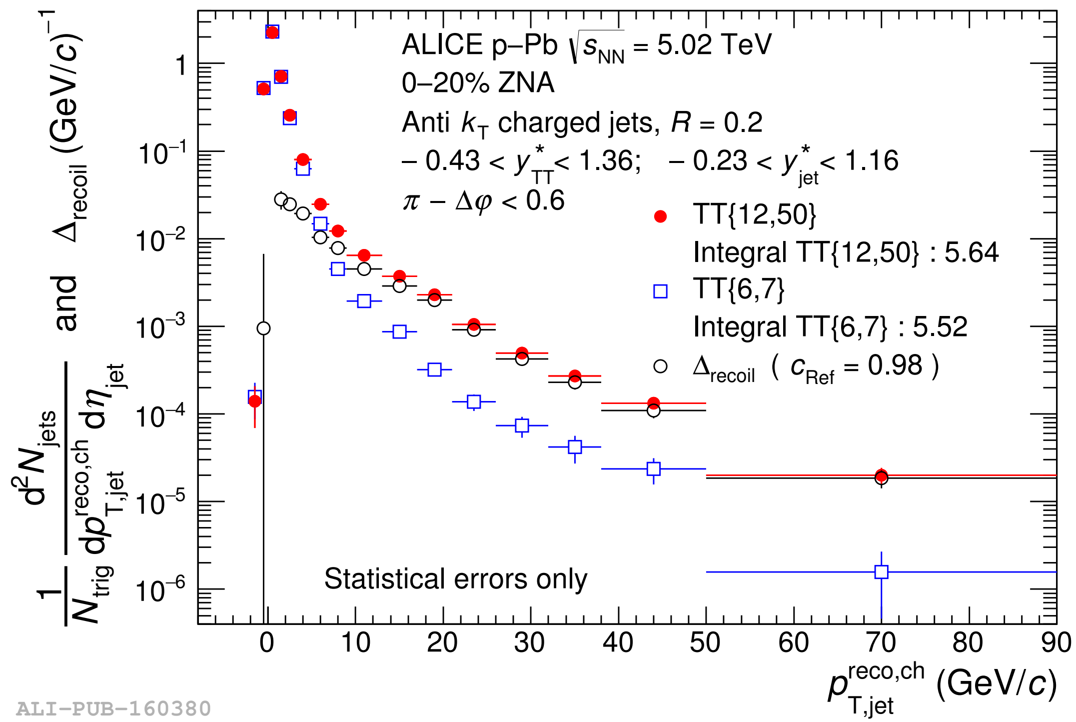
No jet quenching in p-Pb: recoil jet

- **Semi-inclusive recoil-jet distribution**
- Jet recoiling against a trigger high p_T hadron
- To subtract uncorrelated combinations:

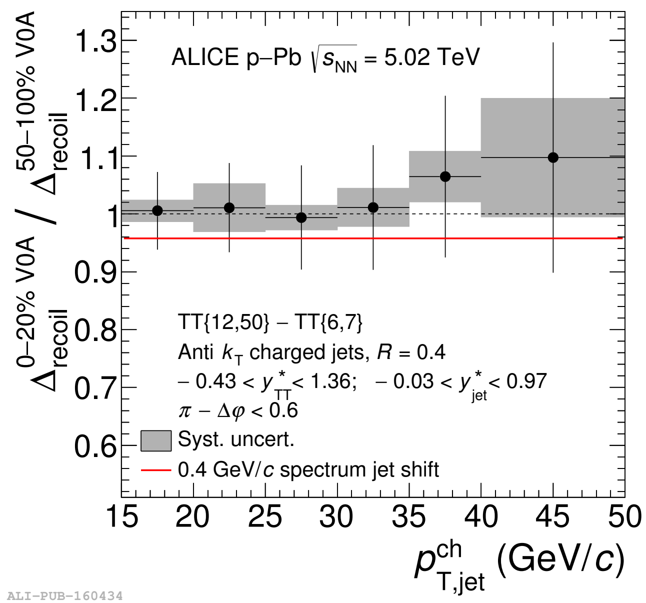
Δ_{recoil} = high p_T trigger (12-50 GeV/c)
- low p_T trigger (6-7 GeV/c)

- Self normalized coincidence

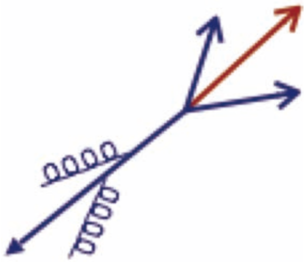
Phys. Lett. B 783 (2018) 95-113



Phys. Lett. B 783 (2018) 95-113



high p_T hadron trigger

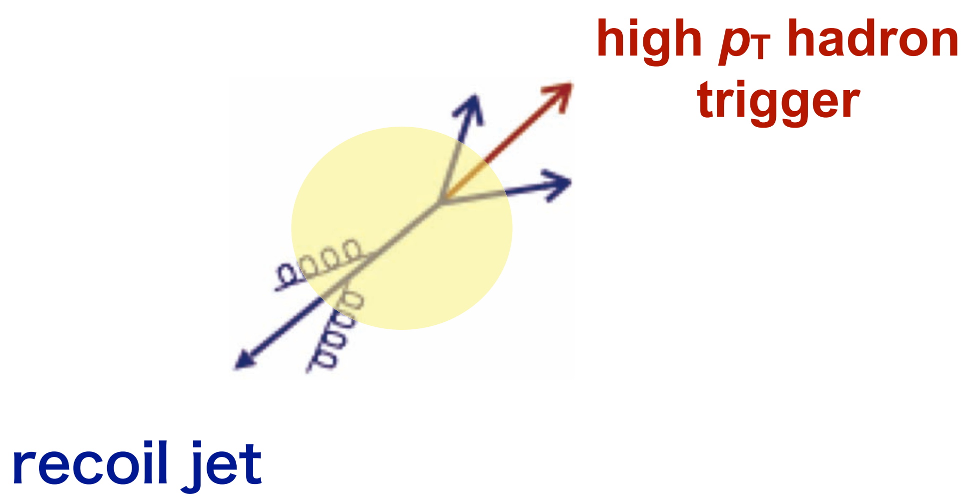


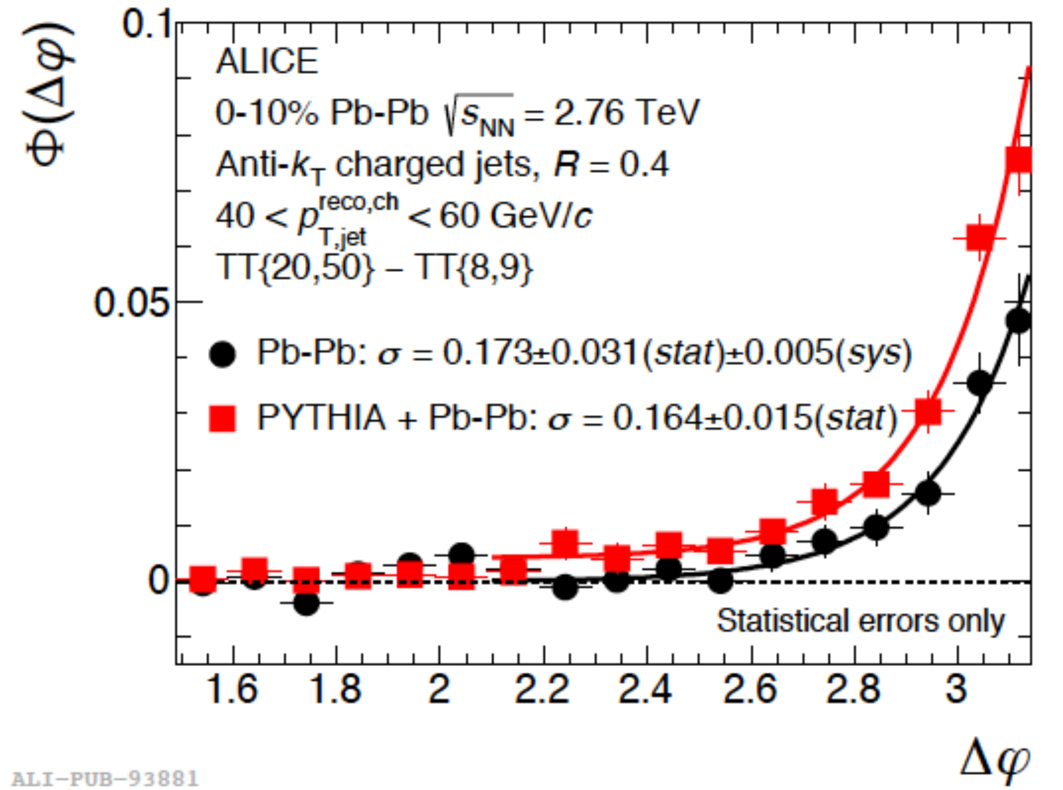
recoil jet

Divided central / peripheral:
no significant modification (ΔE < 0.4 GeV)

h-jet correlations in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

JHEP 09 (2015) 170

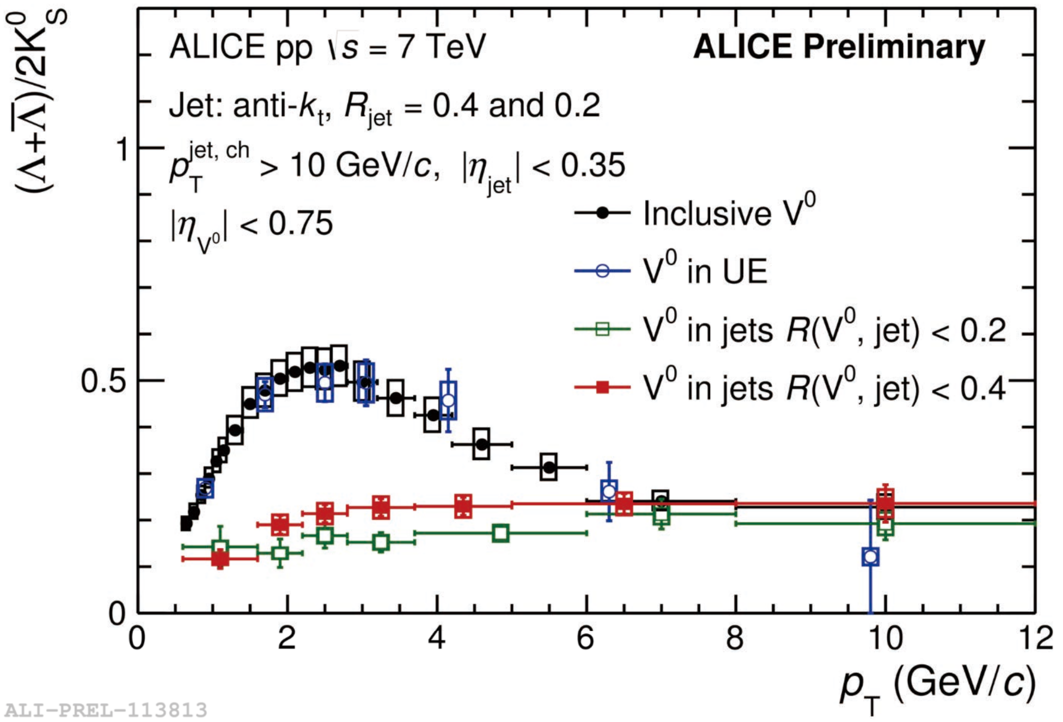


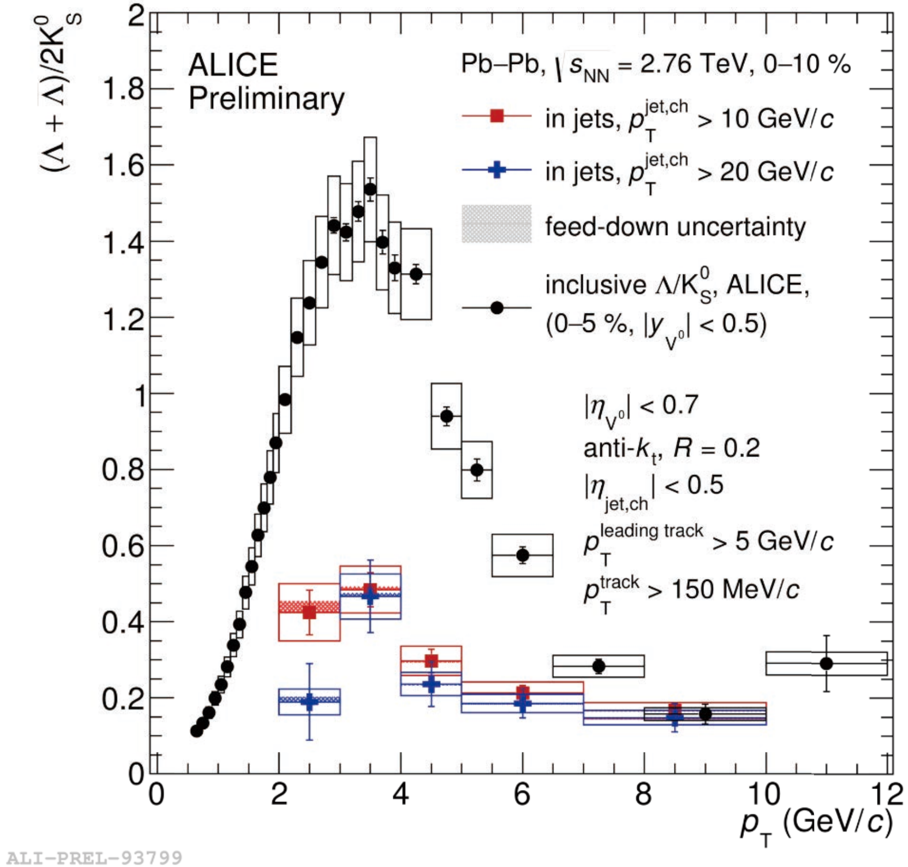


* Future: Also interesting to see the accoplanary for jet broadening, try to see large angle scattering (Molière scattering) with large data sample in Run-2 and Run-3

(5) Jet with PID

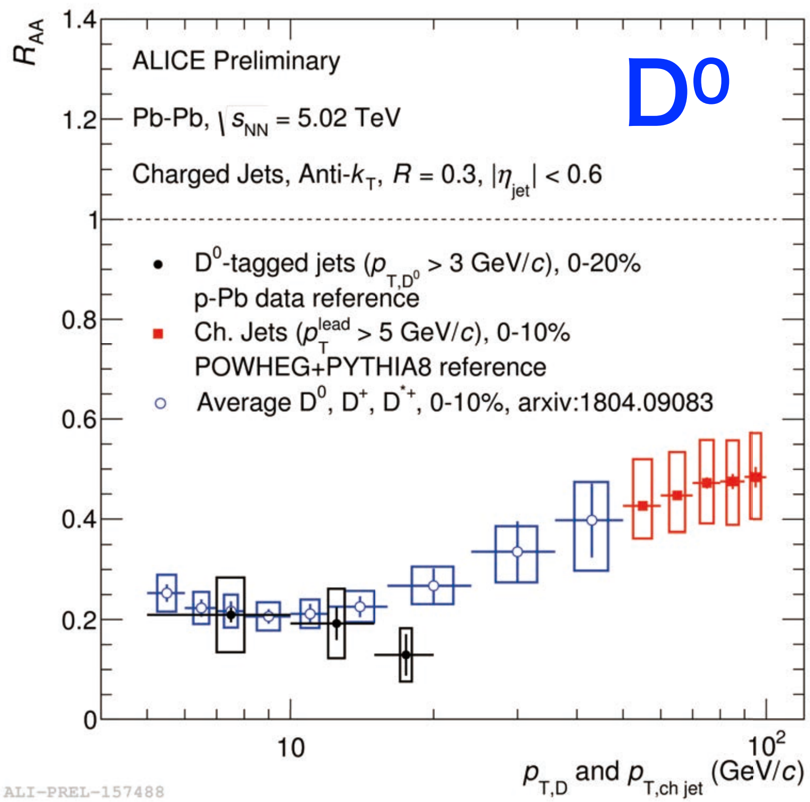
Λ, K^0, Ξ$^\pm$ production in jets in pp and Pb-Pb

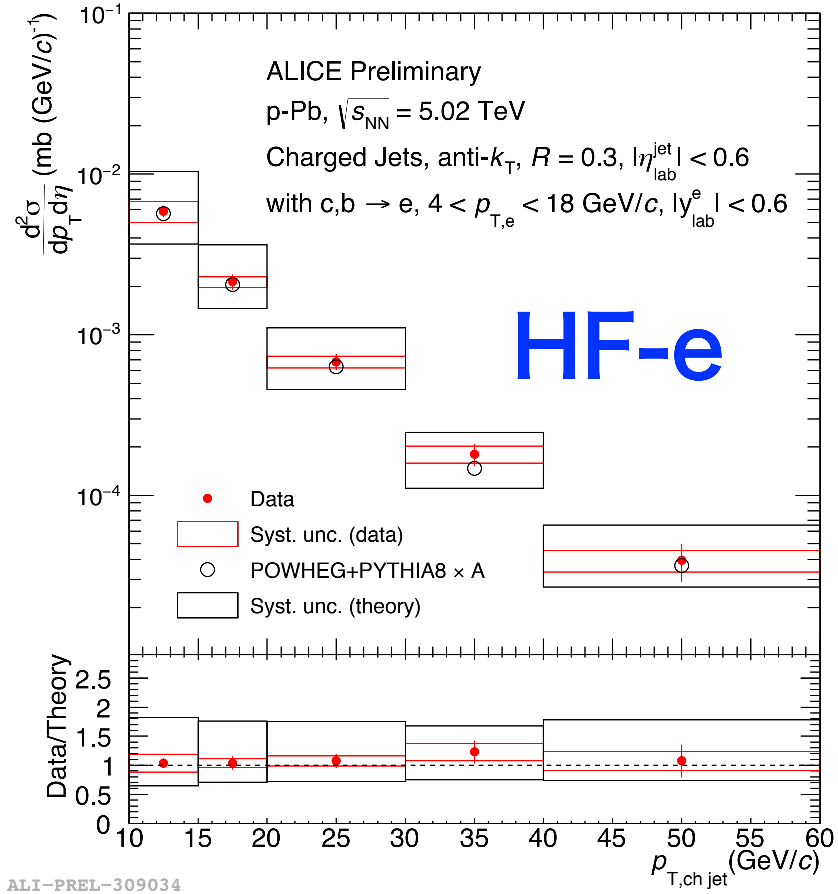


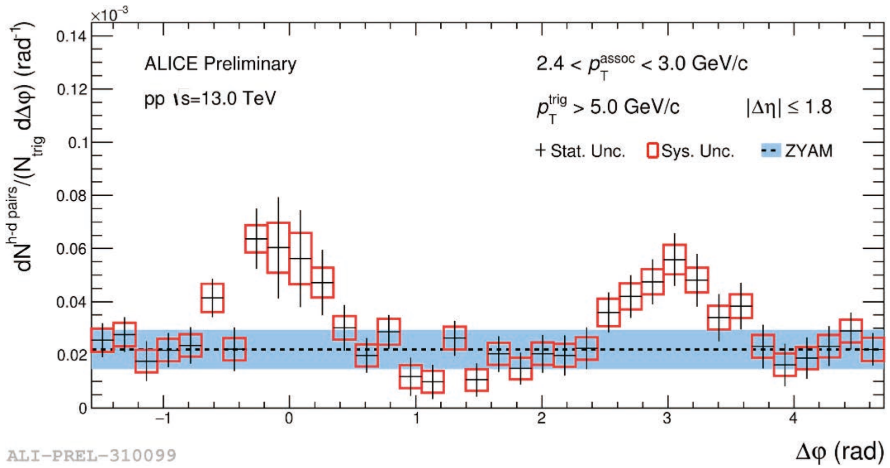


- Strangeness production in jets
- Reproduced inclusive Λ, K^0, Ξ$^\pm$
- Measured Λ, K^0, (Ξ$^\pm$) within jet (JE) and outside jet (UE)
- Clear difference in ratio for intermediate p_T
- Similar ratio in Pb-Pb, significant difference from inclusive

Other PID with jets



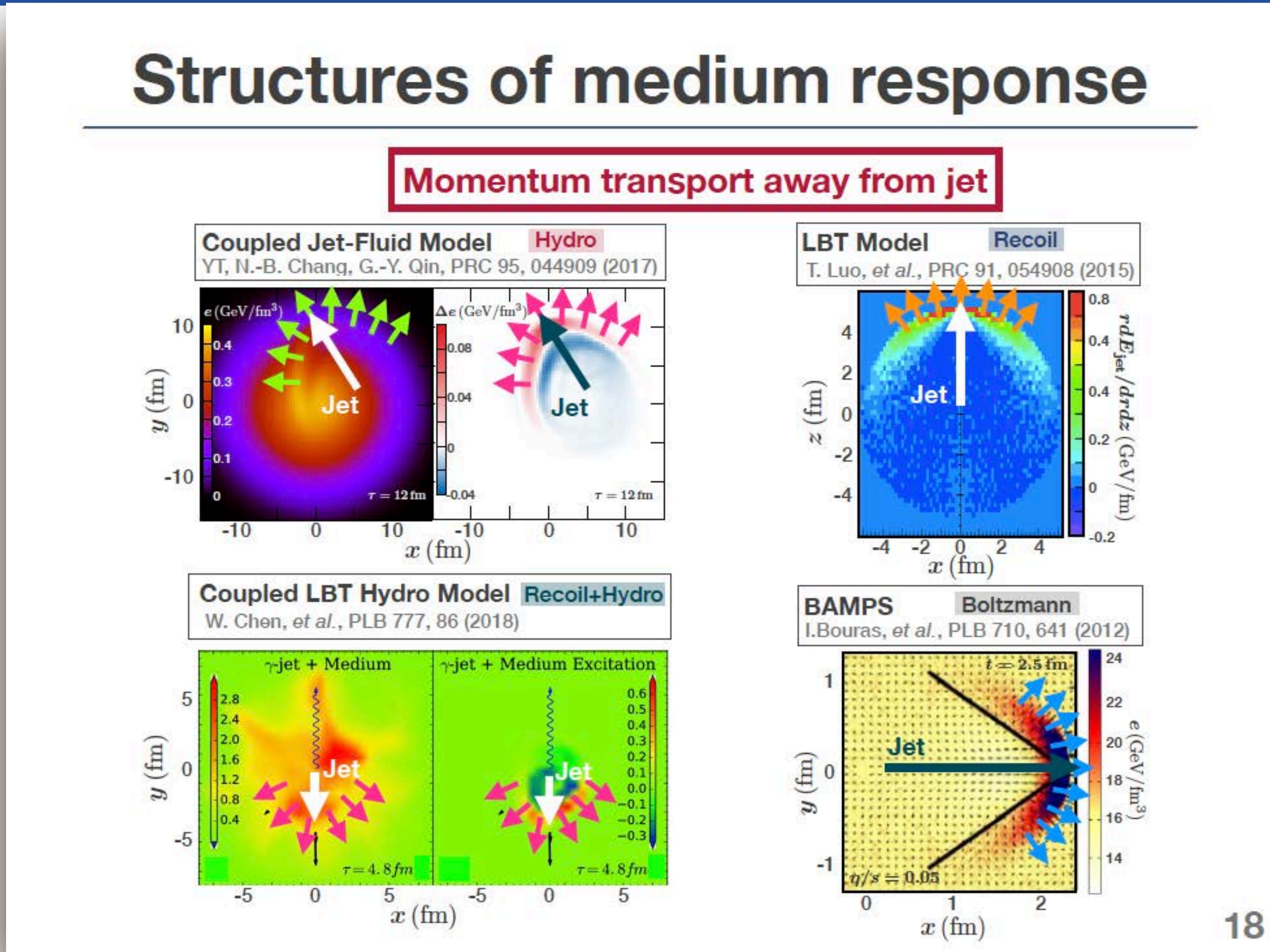




deuteron

Mach cone?

ALICE



Y. Tachibana (QM2018)

- In-medium thermalization (reheating, mach cone) ?
- Enhancement of particle emission around jet (recombination?)

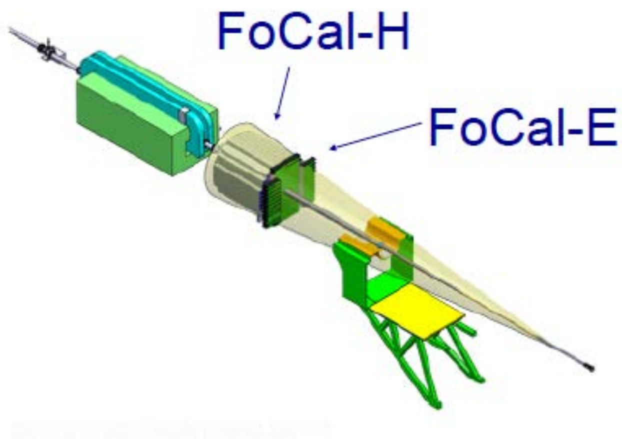
experimental observables

e.g.) ALICE: low p_T, PID, di-jet

Future upgrade proposal for forward γ and jet

FoCal = Forward Calorimeter:

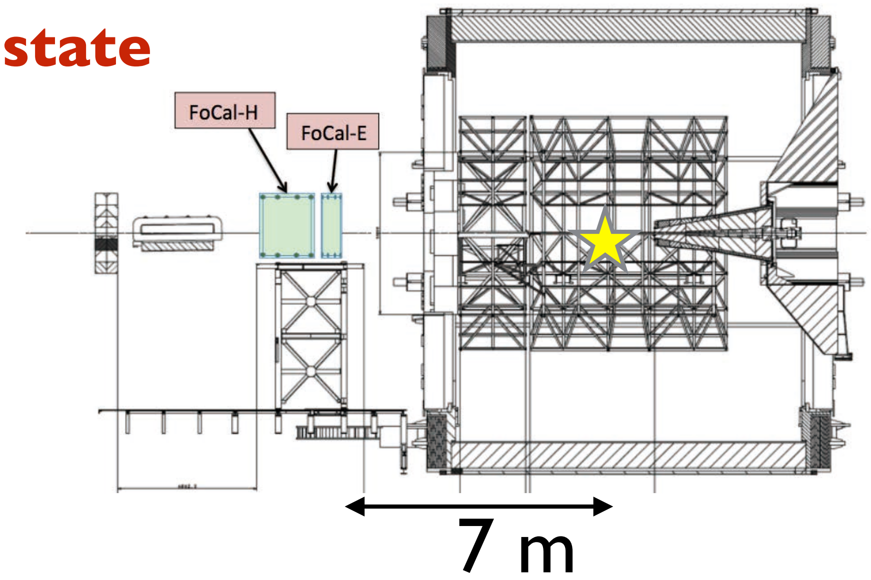
FoCal-E: EM Calorimeter
FoCal-H: Hadronic Calorimeter



- 7 m away from the interaction point
- Main challenge: separate γ/π^0 at high energy
- Si-W calorimeter, effective granularity ≈ 1mm²
- Upgrade proposal under discussion in ALICE for Run-4

$3.2 < \eta < 5.3$

- **p-Pb: investigating high-density initial state**
  - Direct photons
  - π^0
  - Di-hadron correlations (π^0-π^0)
  - Jets, quarkonia
- **pp: forward production, baseline**
  - (same as p-Pb)
- **Pb-Pb: medium density at forward y**
  - π^0 at $3.2 < \eta < 4.5$
    - Longitudinal evolution of medium
    - Provide jet quenching at forward rap., same region for J/ψ (muon arm)



Summary and outlook

Exploring parton energy loss with jets at LHC

- ***R_{AA}* of hadrons**: reaching at precision measurements
- **jet spectra**: new data using the new high interaction rate data in Pb-Pb
  - a hint of stronger broadening at lower p_T, central Pb-Pb
- **Groomed jets**:
  - Detailed picture of parton shower provided by Lund Plane
  - A tool to select substructures
  - Showed suppression of large angle splittings and slight enhancement of collinear splittings compared to embedded PYTHIA

- **Outlook**
  - Jet spectra →towards larger R and low jet p_T
  - Recoil jets, tagged jets (c, b) →jet-hadron, hadron-jet correlations w/ trigger
  - Groomed jets and jet sub-structure
  - Jet mass, Dijet-k_T
  - Di-jet, gamma-jet
  - Di-jet + soft hadron (PID)

Harvest of jet physics in ALICE !

ALICE

Thank you for your attention!