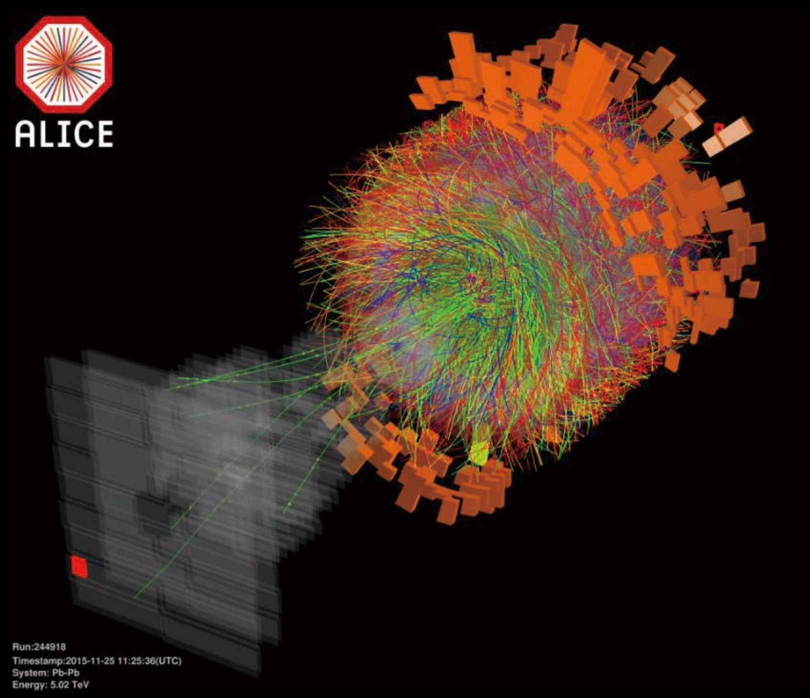
Recent jet results and future directions in ALICE



Tatsuya Chujo

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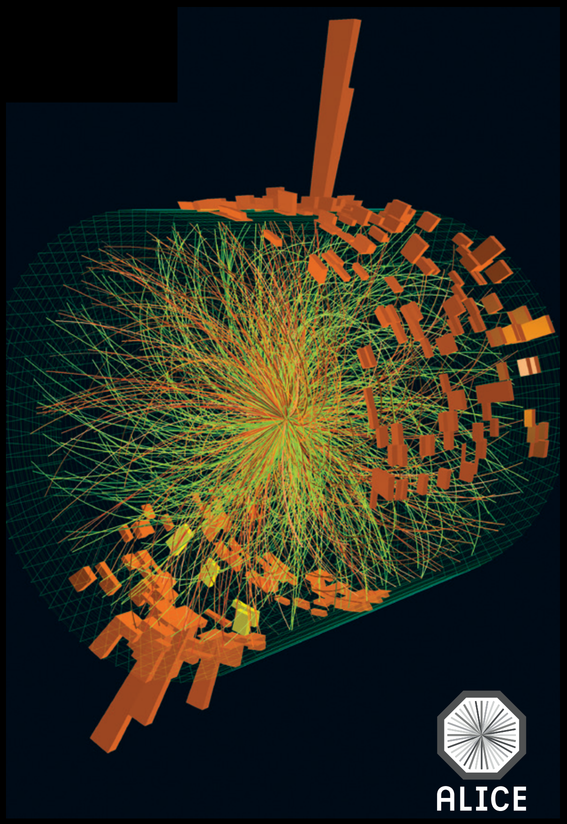
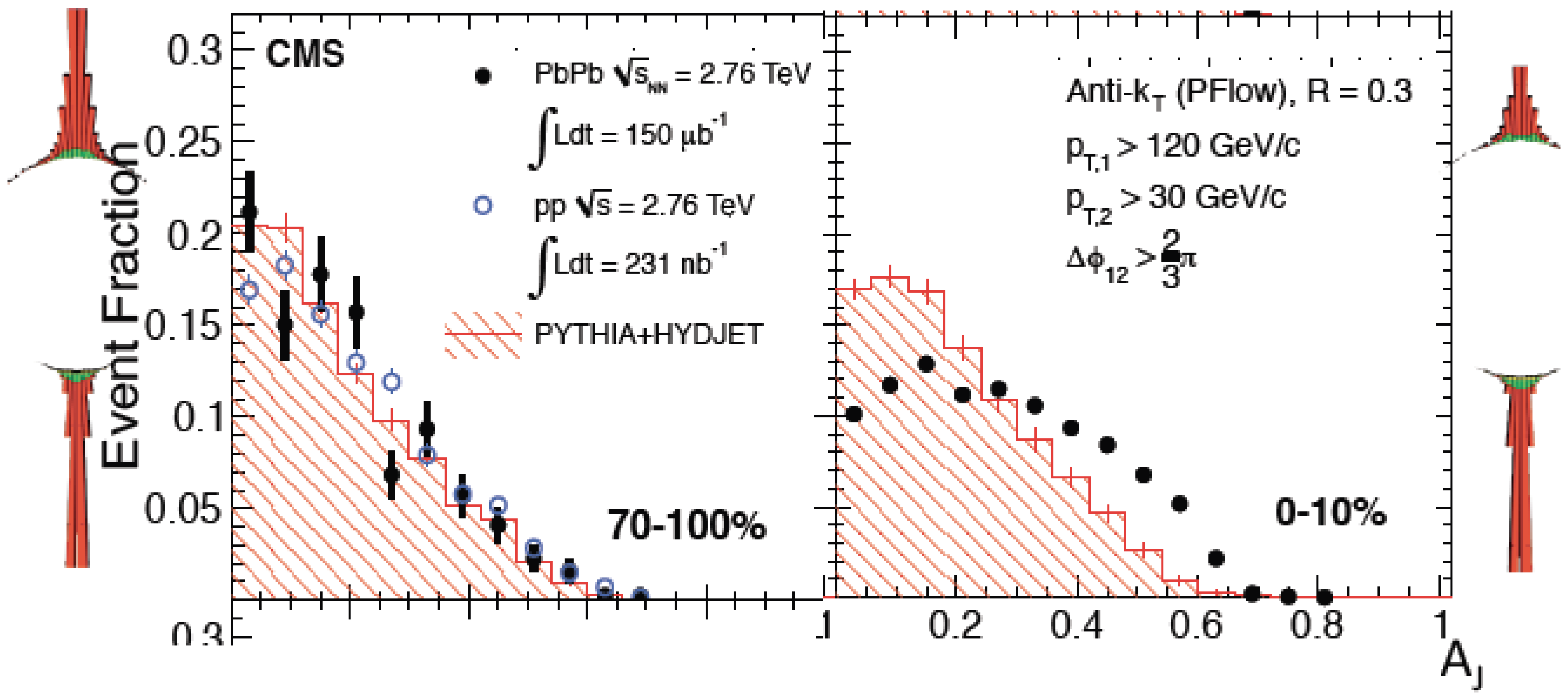


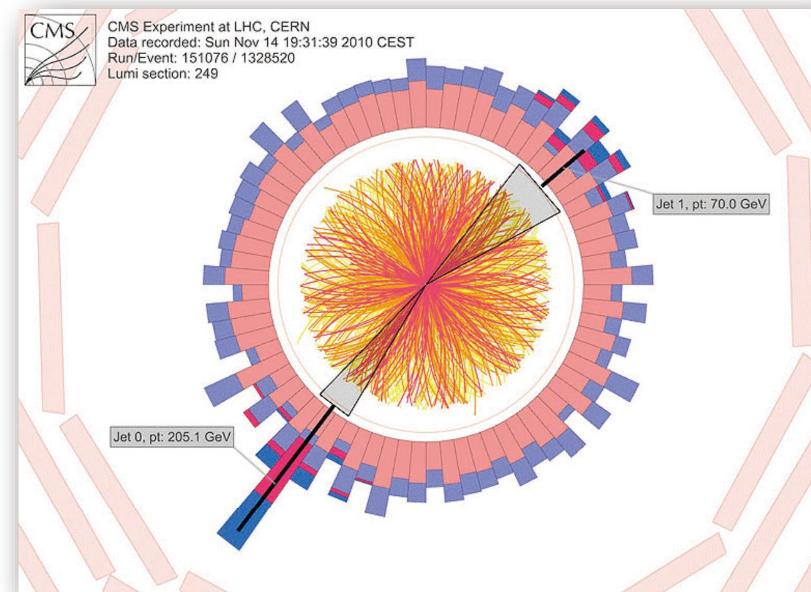
https://cds.cern.ch/record/2155668

Heavy Ion Cafe
June 22-23, 2019, Sophia University, Tokyo

Jet quenching at LHC

CMS, PRC 84, 024906 (2011)





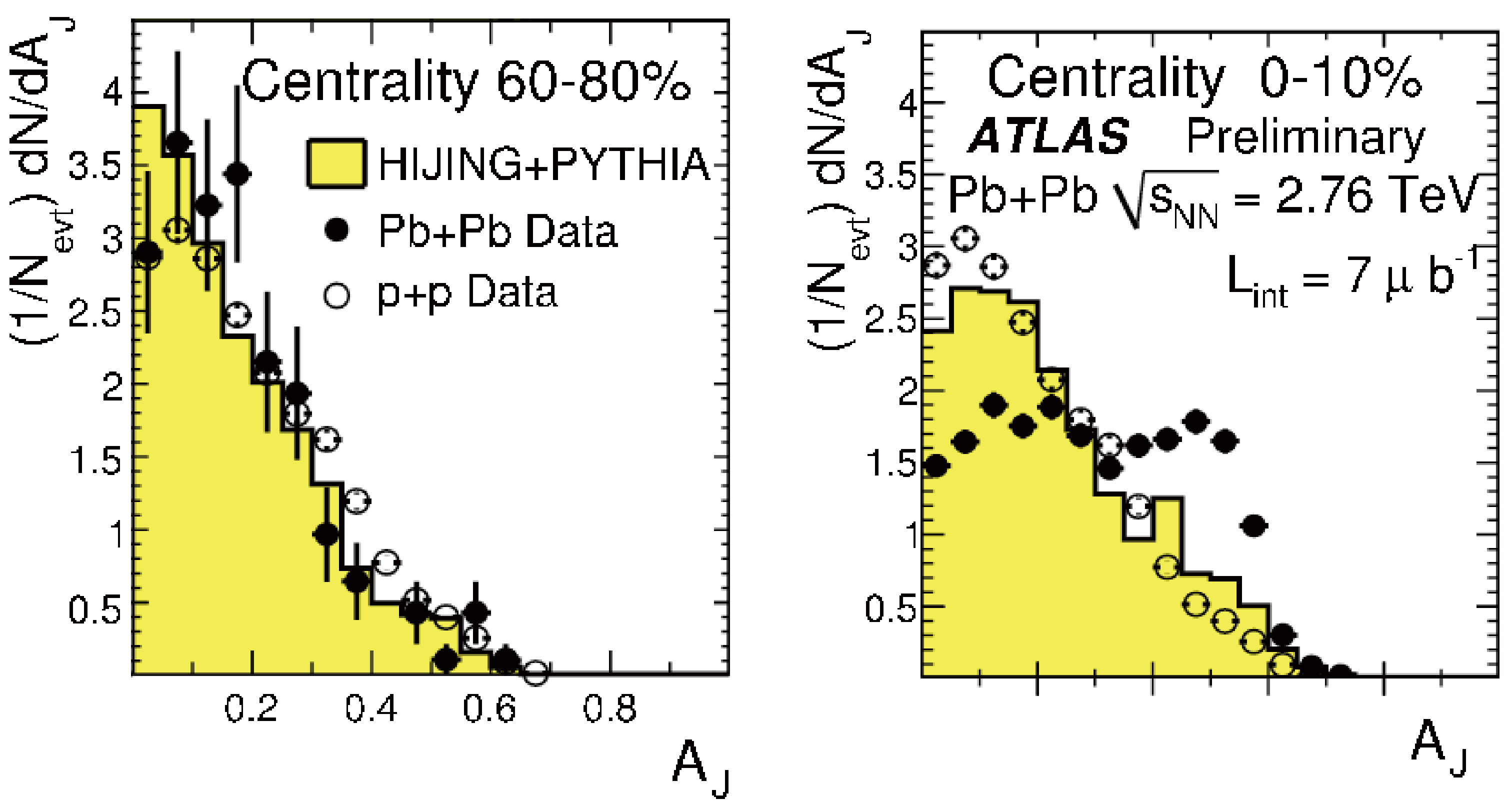
1) Large energy imbalance is observed in central Pb-Pb.

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$p_{T,1}$: leading jet

$p_{T,2}$: sub-leading jet

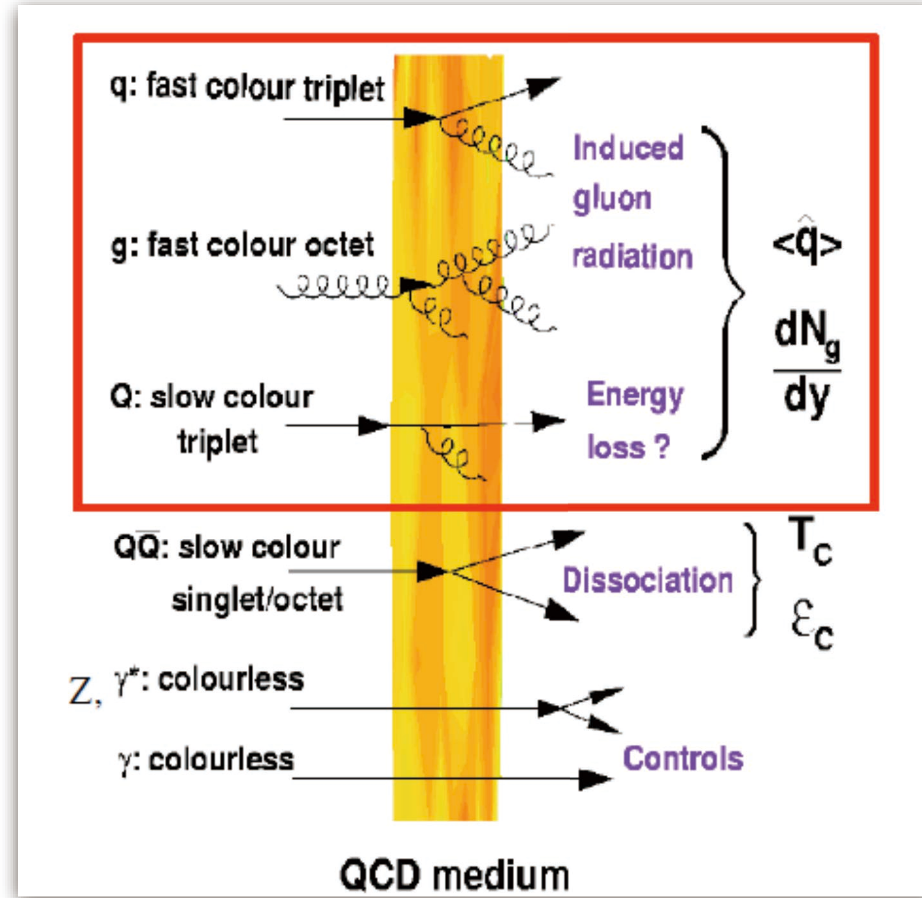
ATLAS, PRL, 105 (2010) 252303



2) Large A_J : low momentum particle (< 4 GeV/c) emitted at large angle on away side.

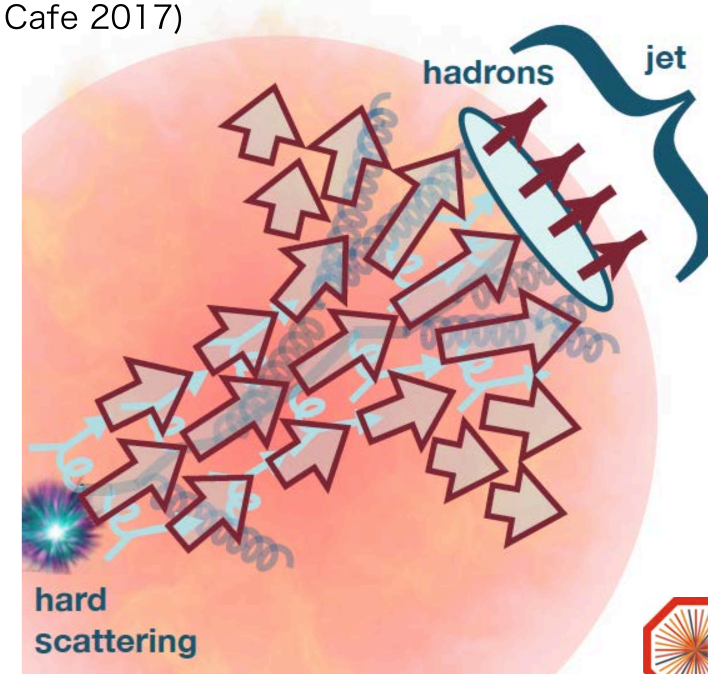
Hard probes in heavy-ion collisions

- **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

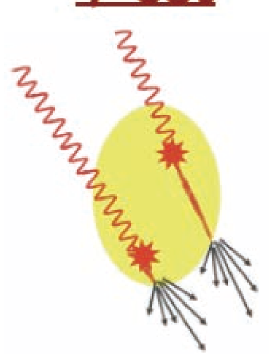


side by D. d'Enterria (slide at QGPWS, 2008)

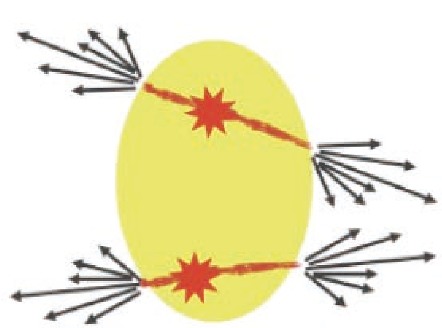
Picture form Y. Tachibana (Heavy Ion Cafe 2017)



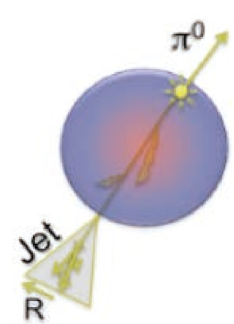
γ-Jet



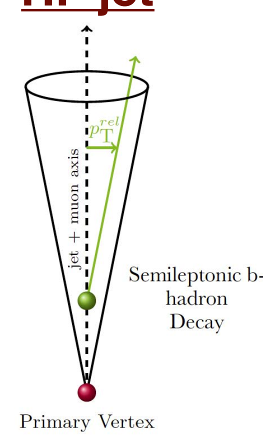
Di-jet



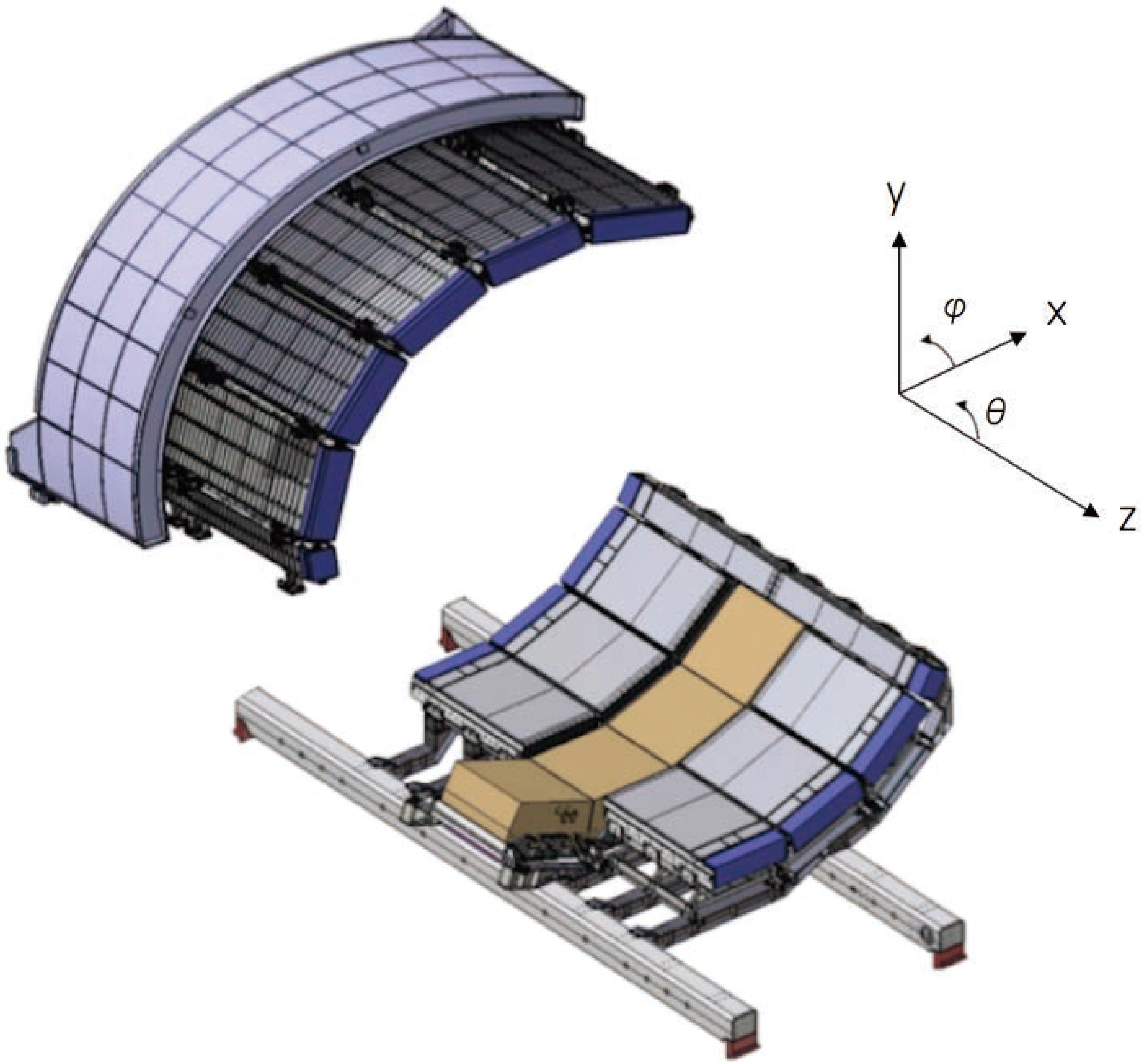
π⁰-Jet

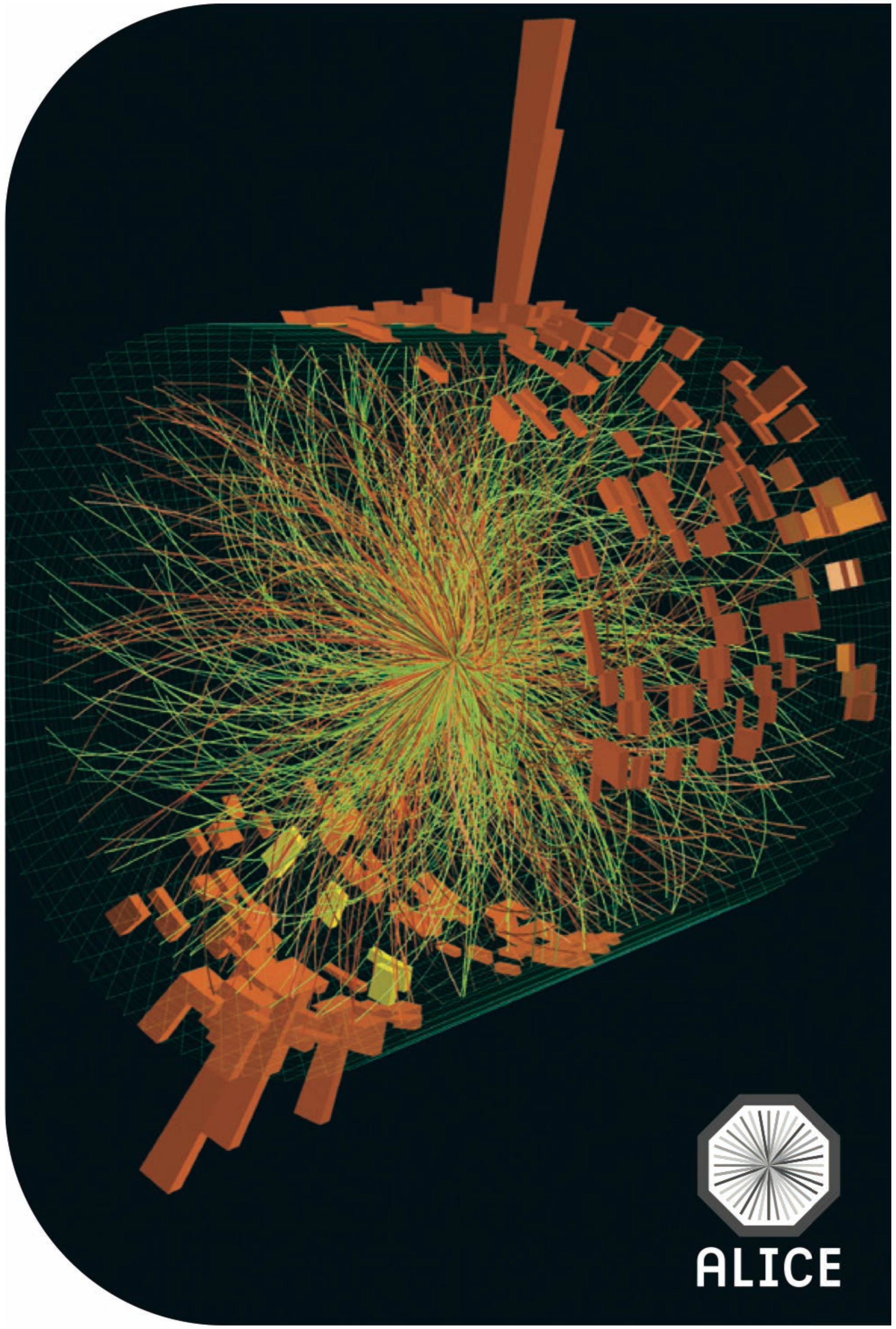


HF jet



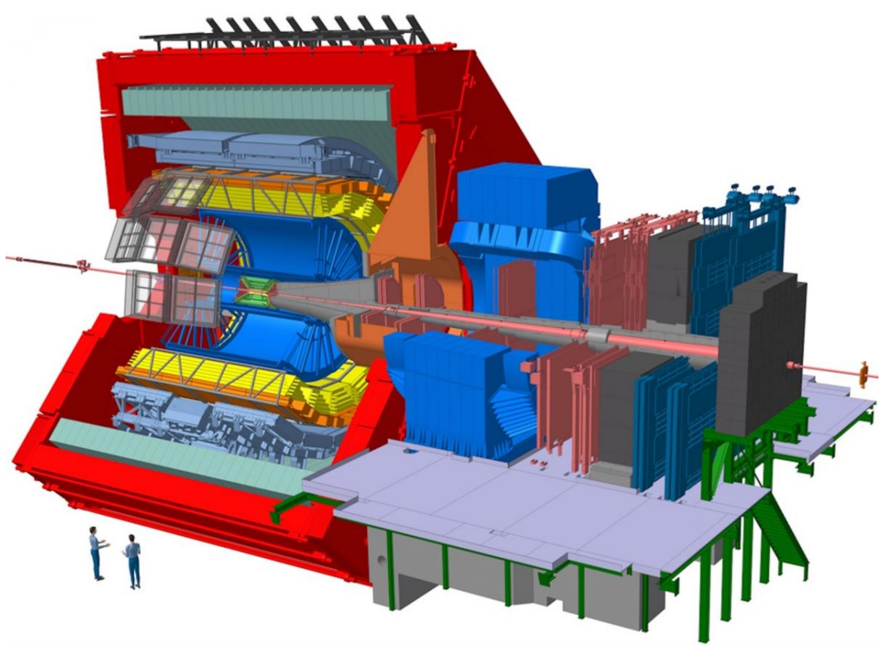
New detector in ALICE Run-2

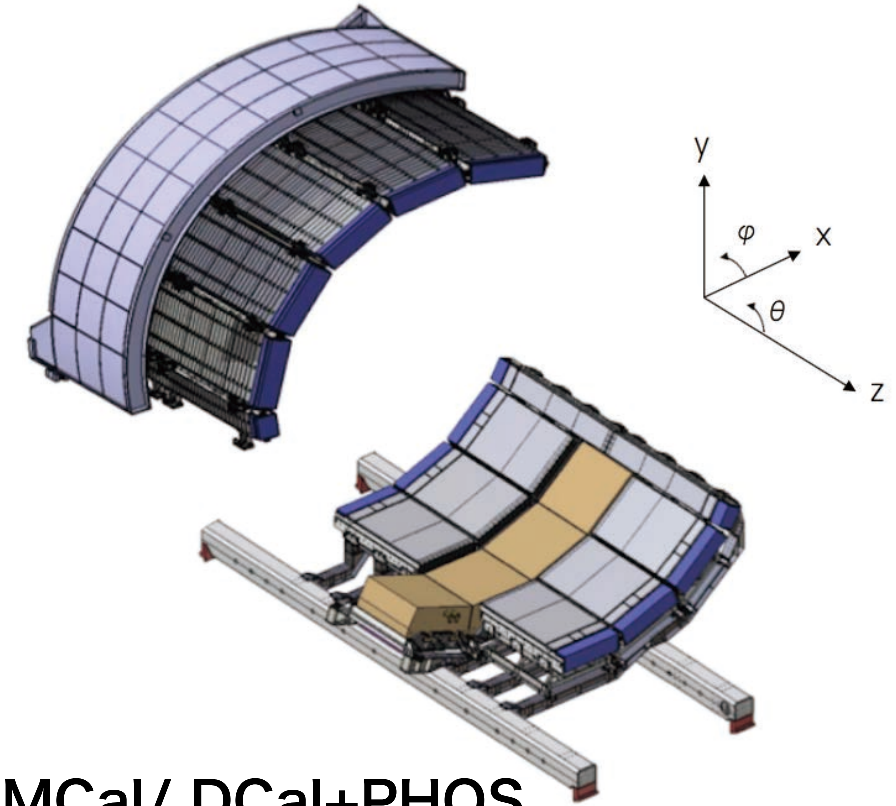




Jets in ALICE

- 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

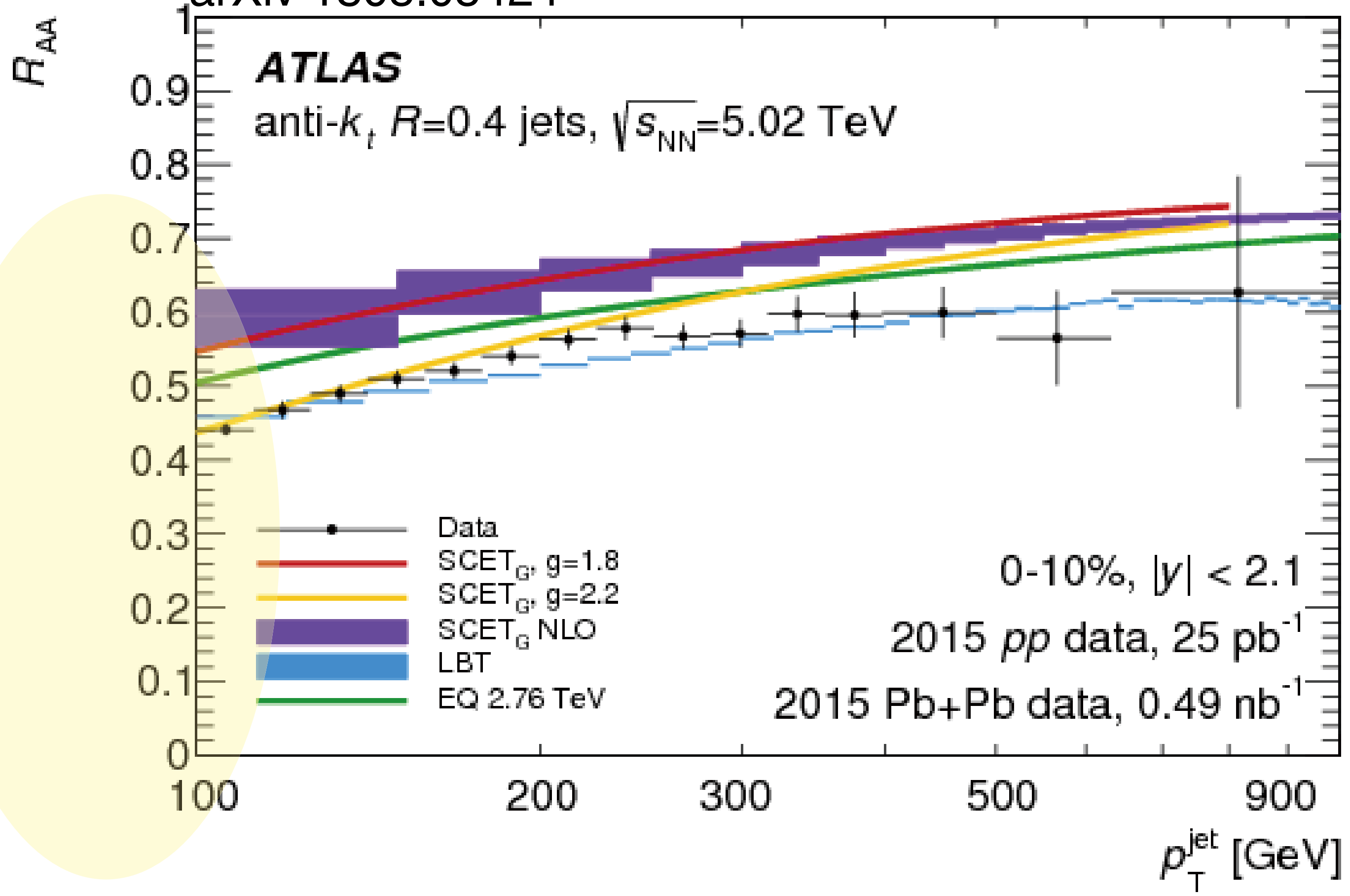
- **Part-1: Jet results from ALICE**
  (1) Jet spectra and R_{AA}
  (2) Jet substructure
  (3) Gamma-jet
  (4) Jet-hadron, hadron-jet
  (5) Jet with PID (strangeness etc.)
- **Part-2: Open questions and future directions**

(1) Jet spectra and R_{AA}

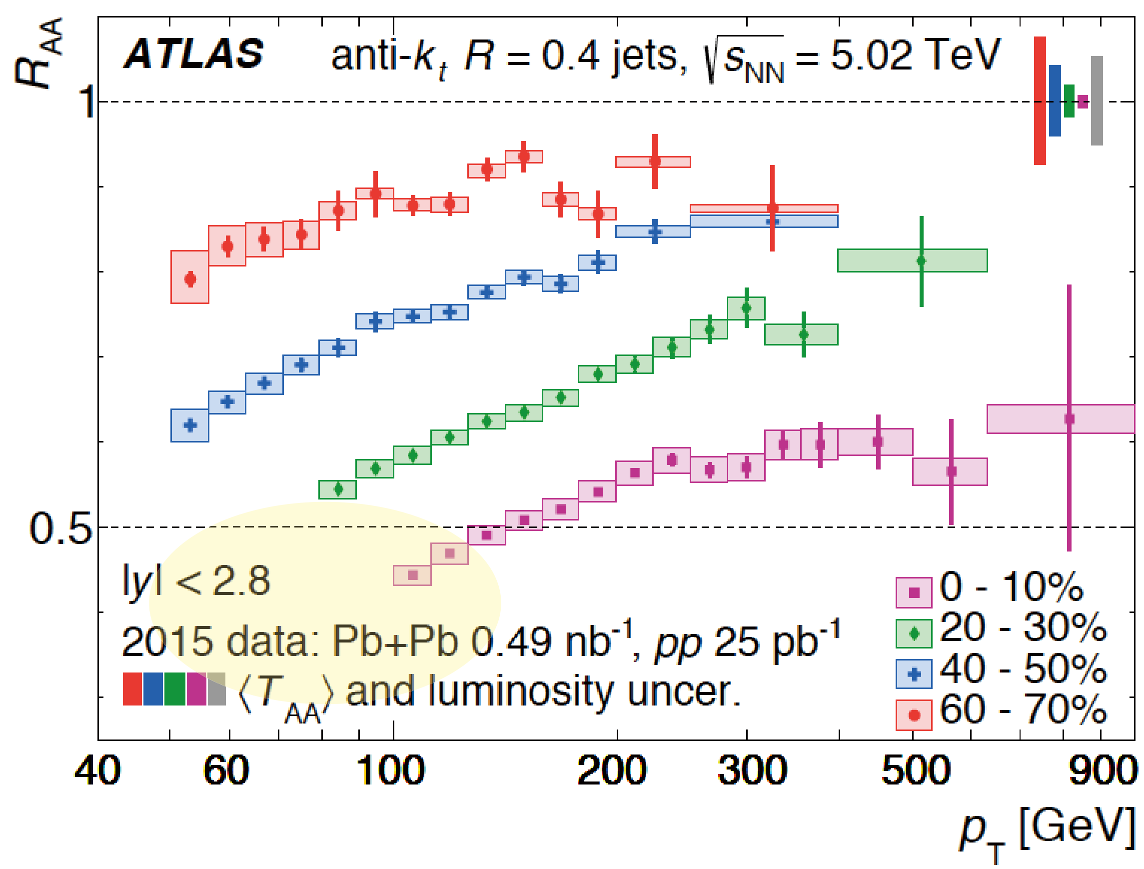
(1) Jet spectra and jet R_{AA}

$$R_{\mathrm{AA}} = \frac{\text{"hot/dense QCDmedium"}}{\text{"QCD vacuum"}} = \frac{dn_{\mathrm{AA}}/dp_{\mathrm{T}}dy}{\langle N_{\mathrm{binary}} \rangle \cdot dn_{\mathrm{pp}}/dp_{\mathrm{T}}dy}$$

arXiv 1805.05424



arXiv:1805.05635



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

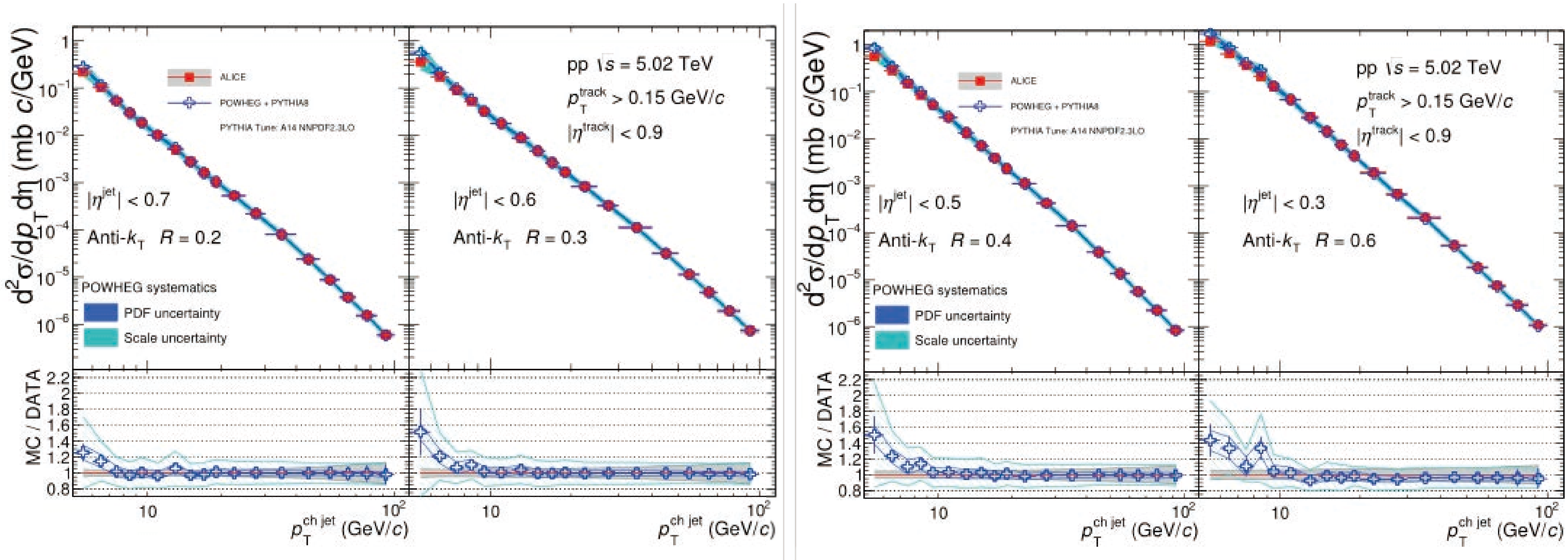
ALICE:

- 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

ALICE

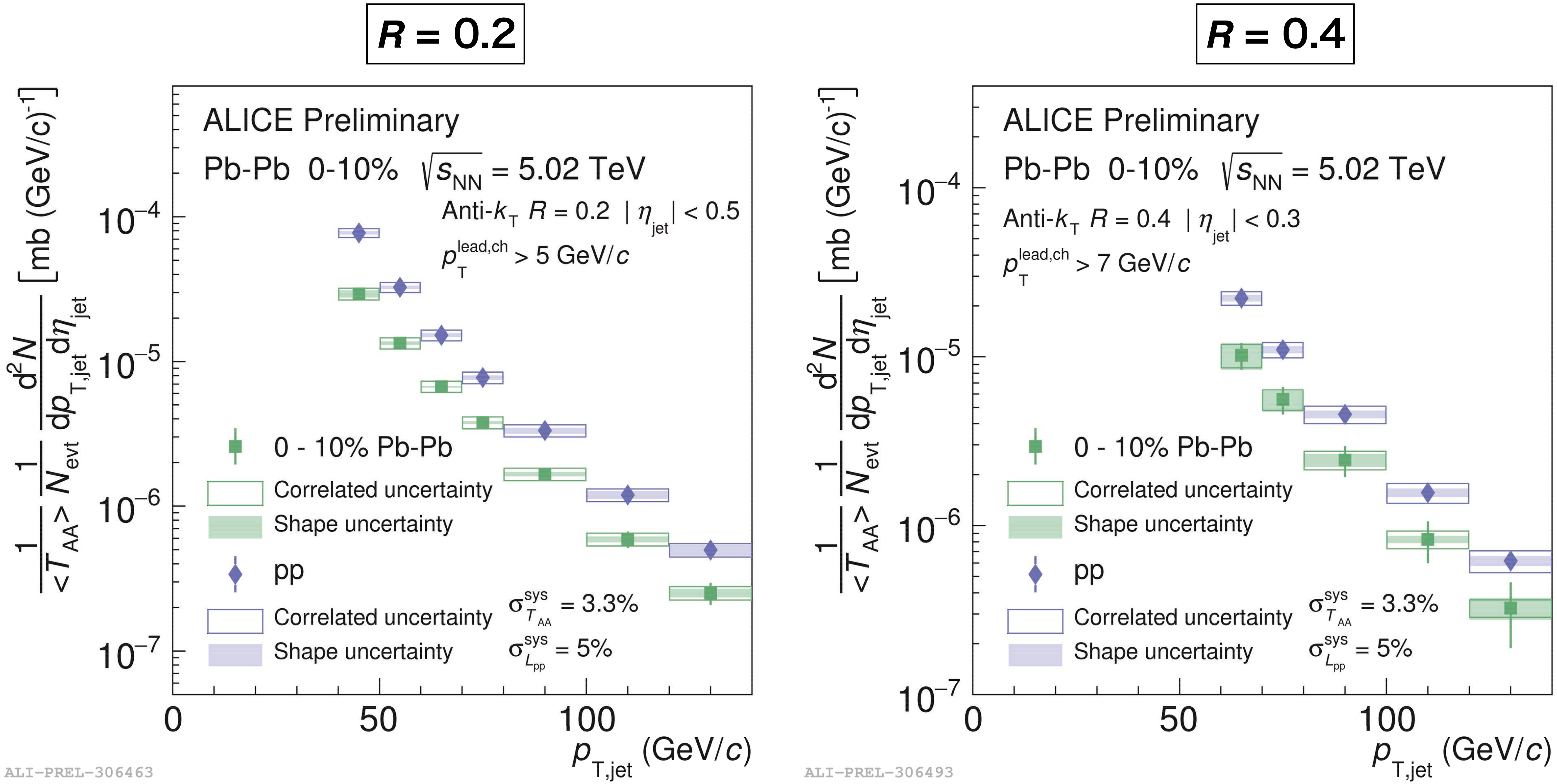
Inclusive charged jet production arXiv:1905.02536

R. Hosokawa



- Submitted to arXiv https://arxiv.org/abs/1905.02536
- Comparison to a NLO pQCD-based model prediction (POWHEG+Pythia8)
- Good agreement within large theoretical uncertainty
  - Higher-order (NNLO) calculation will improve scale uncertainties in pQCD calculation
  - Further understanding of non-perturbative effects (e.g. Underlying events) will also be crucial for low p_T region

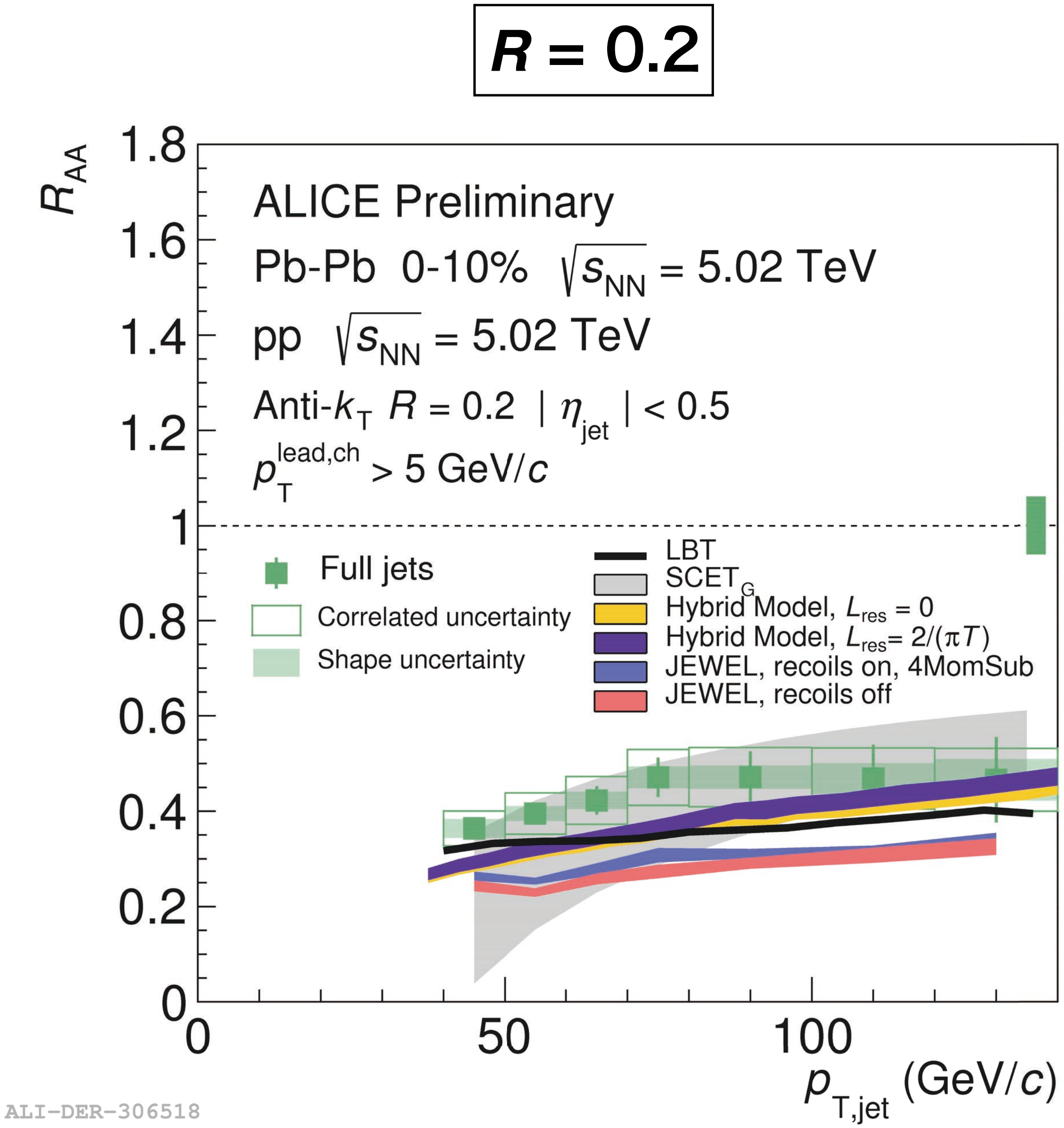
Full jets in pp and Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

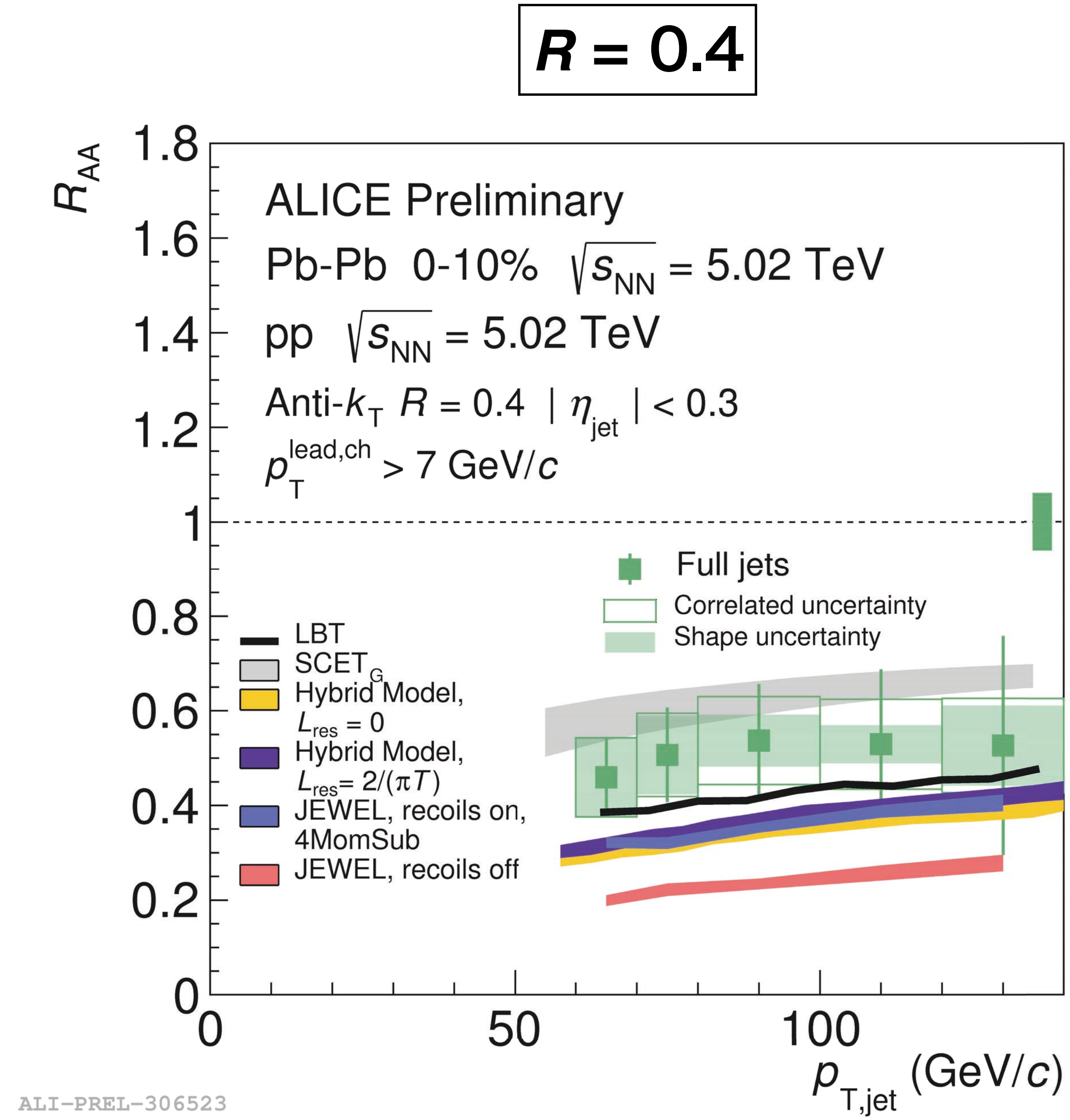


Pb-Pb jet spectrum in 0-10% centrality
for $p_{T,jet}$ = 40-140 GeV/c

ALICE

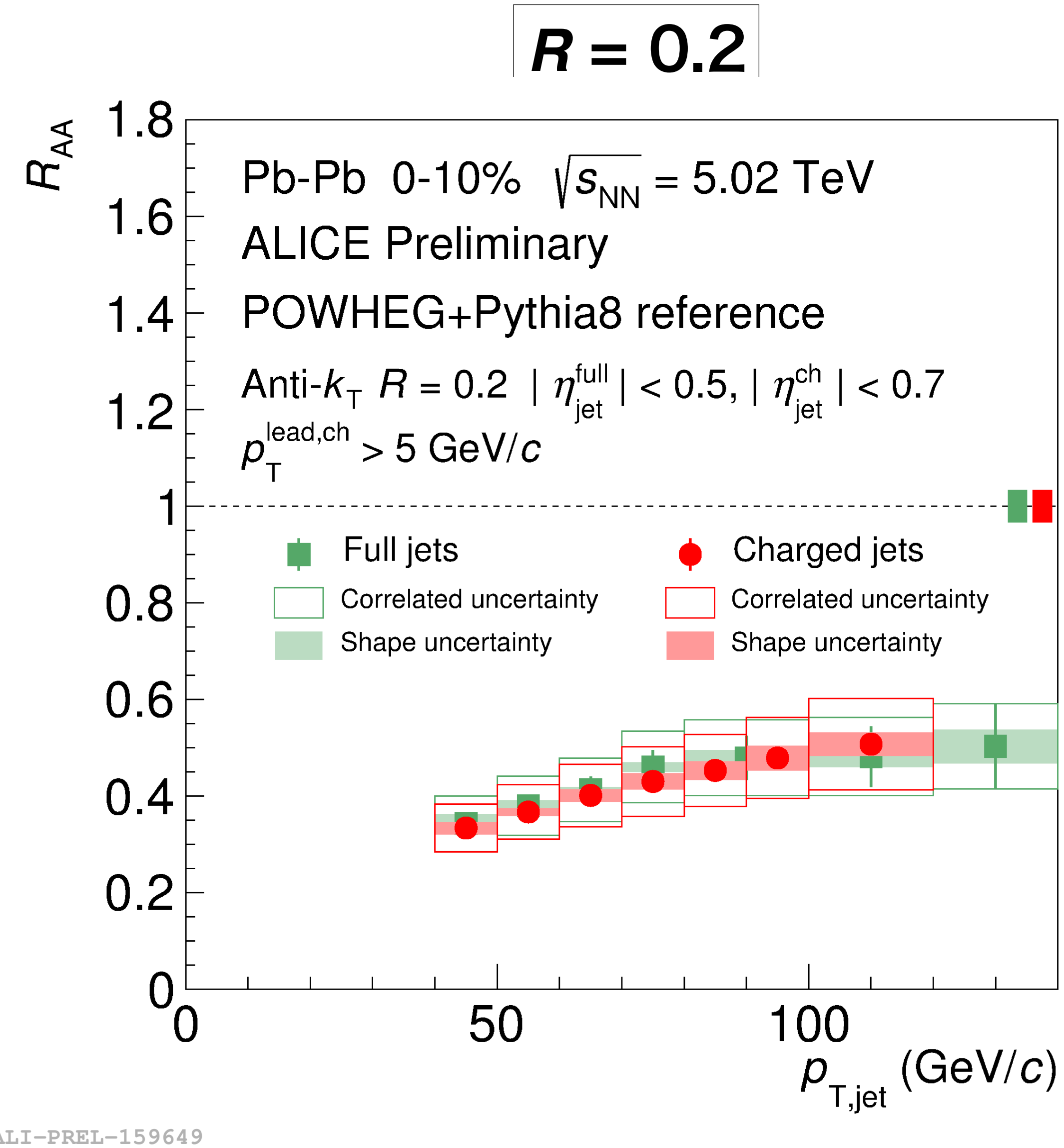
Full jets R_{AA}

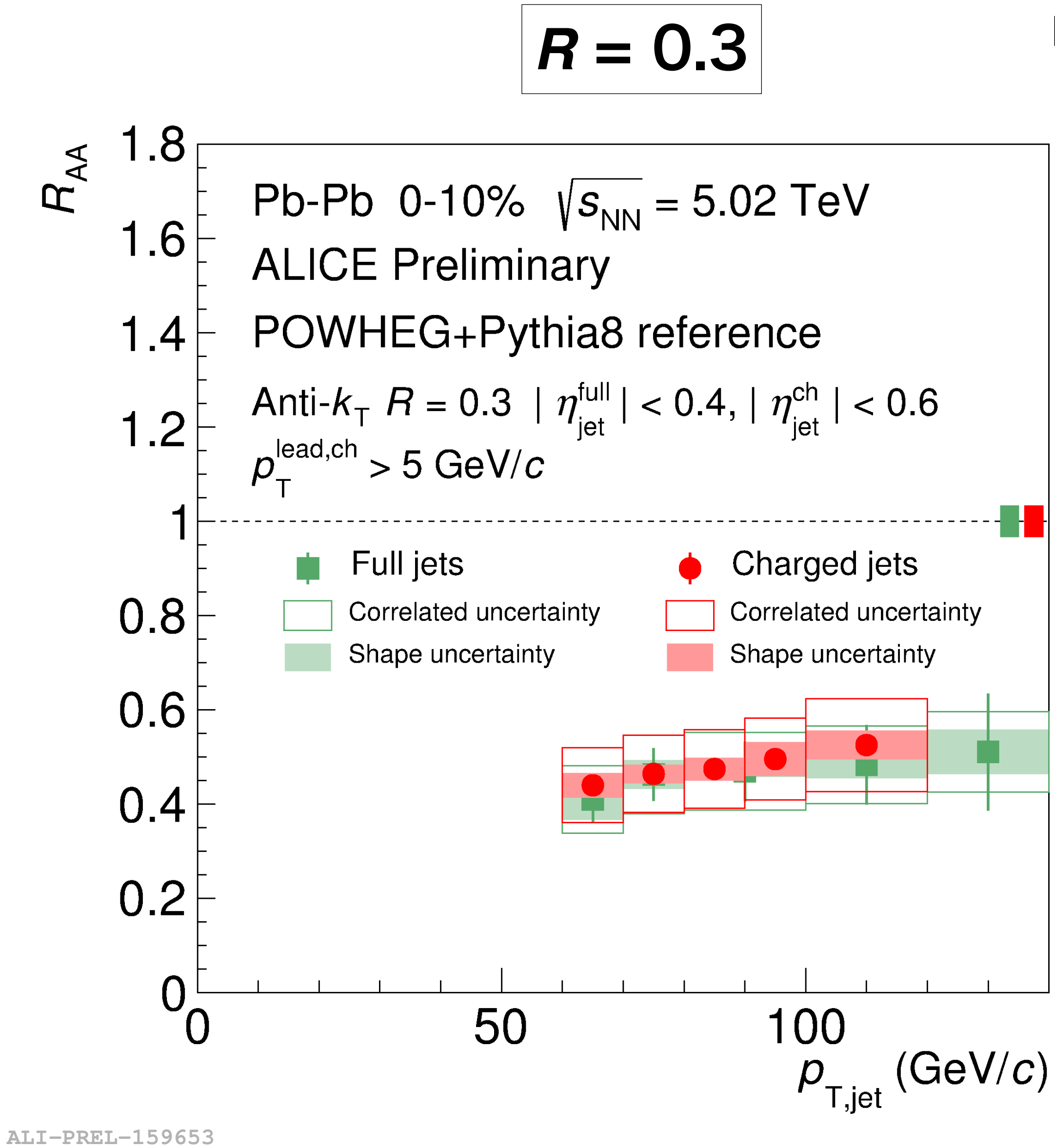




- All models qualitatively describe the R_{AA}
- But quantitatively, it is not perfect
- Interesting to see JEWEL recoil on/off difference is larger for R=0.4

H. Yokoyama





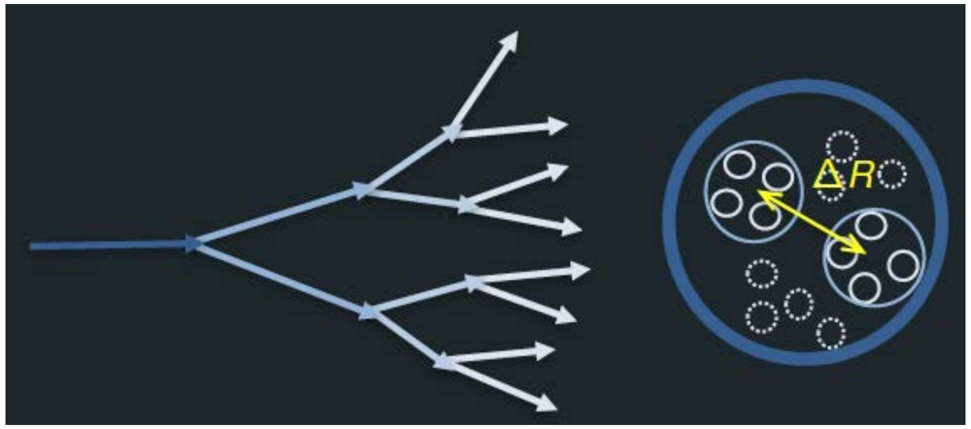
- Strong suppression of jet in Pb-Pb central.
- p_T dependence especially for R=0.2 at lower p_T
- Little R dependence
- Charged particle jets and full jets are consistent

✦ Future direction: ML based jet reconstruction in Pb-Pb at low p_T and larger R.

ALICE

(2) Jet substructure

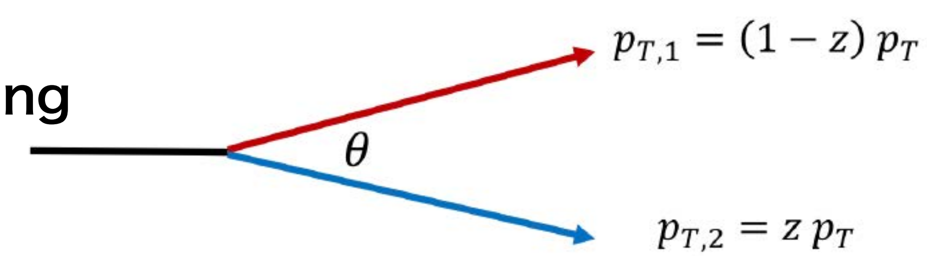
- **Iterative de-clustering to extract hard component of jet**
  - Recursively removing soft large angle radiation
  - Re-cluster found jet (e.g. with C/A) and unwind
  - Remove softer branch until SD condition fulfill



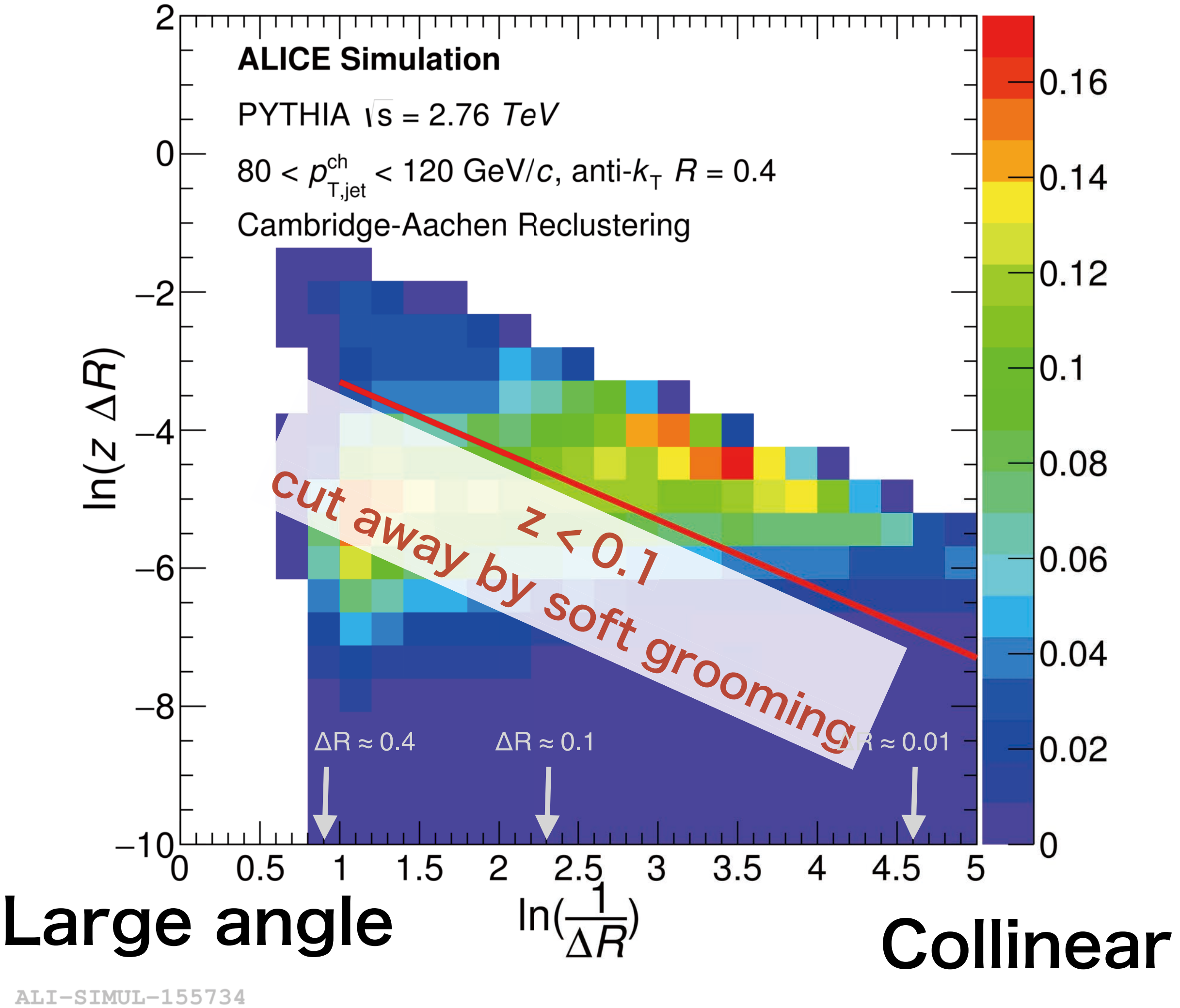
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut}$$

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

parton splitting



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



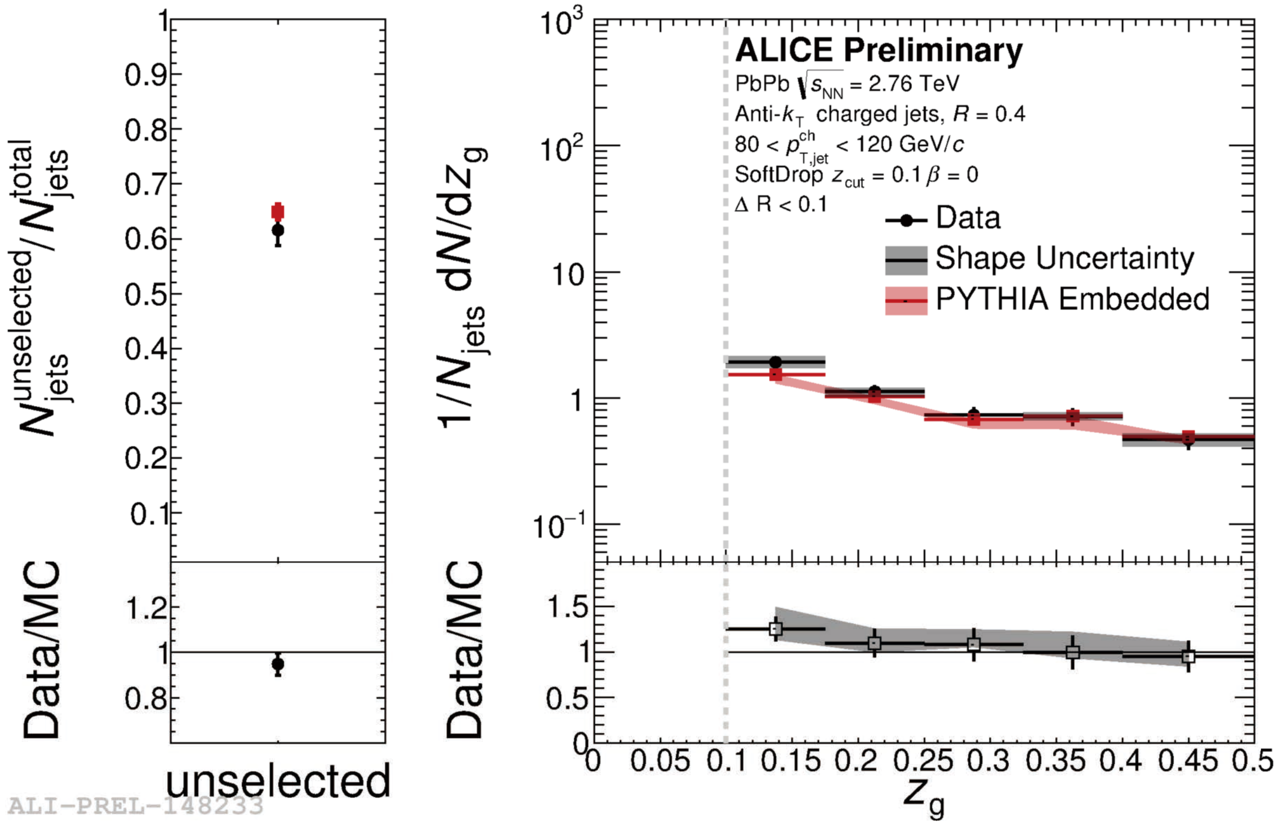
- **Grooming**
  - Impose phase space cuts to enhance regions of interest
  - Soft drop: unwind, follow the largest p_T until $z > z_{cut} \cdot (\Delta R)^{\beta}$

Groomed jet (z_g distributions)

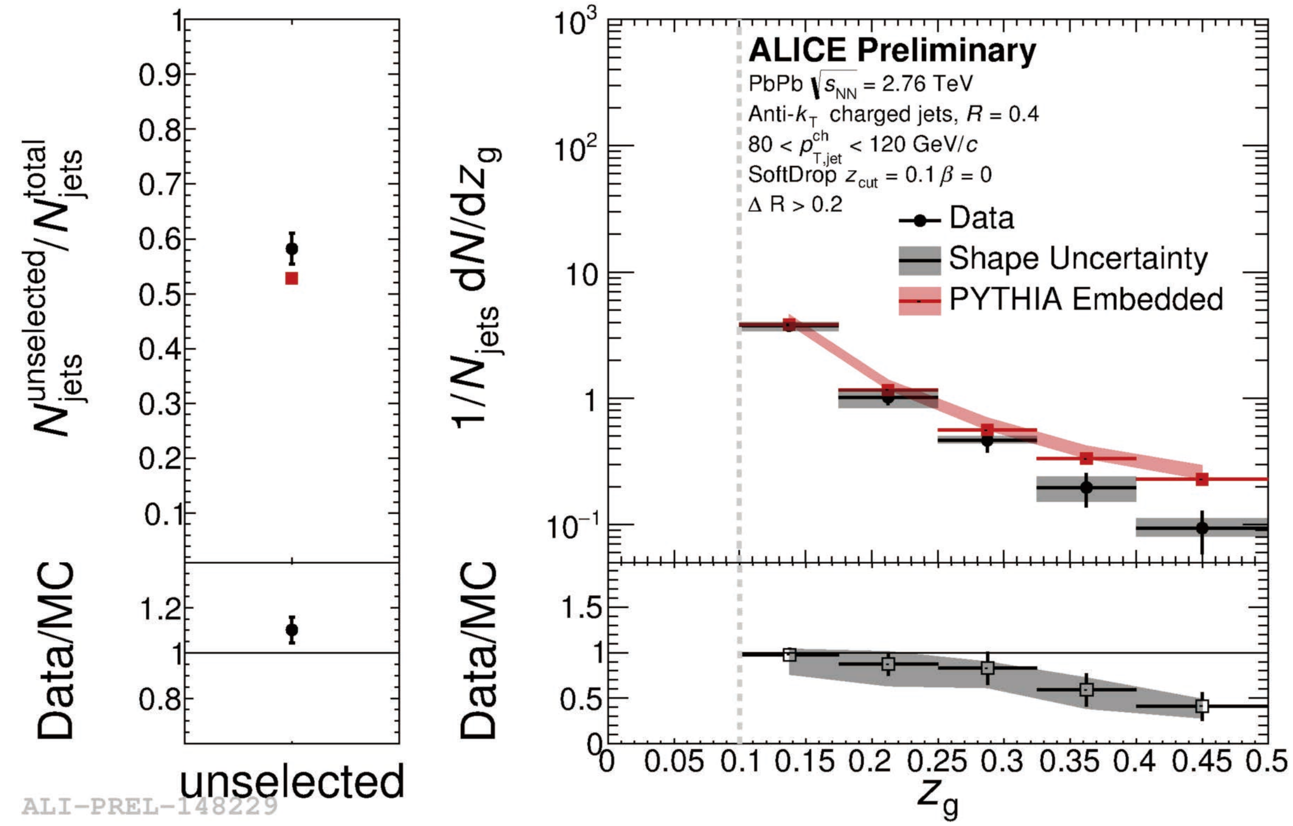
arXiv:1905.02512

Extreme angular limits of collimated and large angle splittings

$\Delta R < 0.1$ (small, collimated angle)



$\Delta R > 0.2$ (large angle)

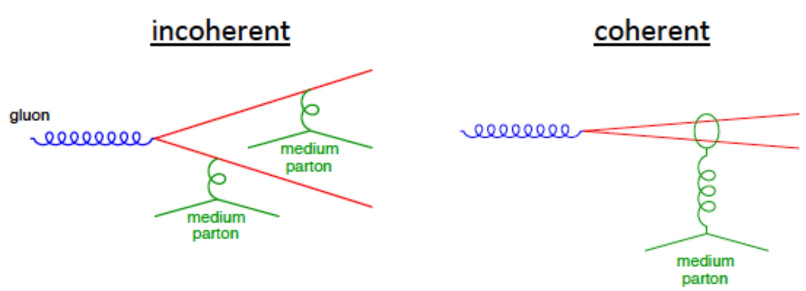


Slight enhancement of collimated first- splittings.

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

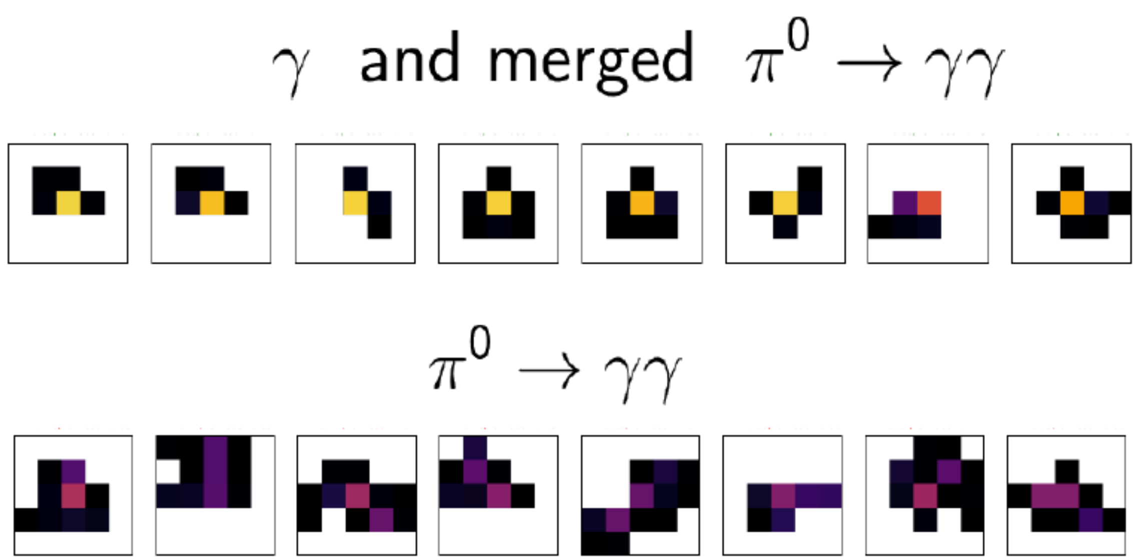


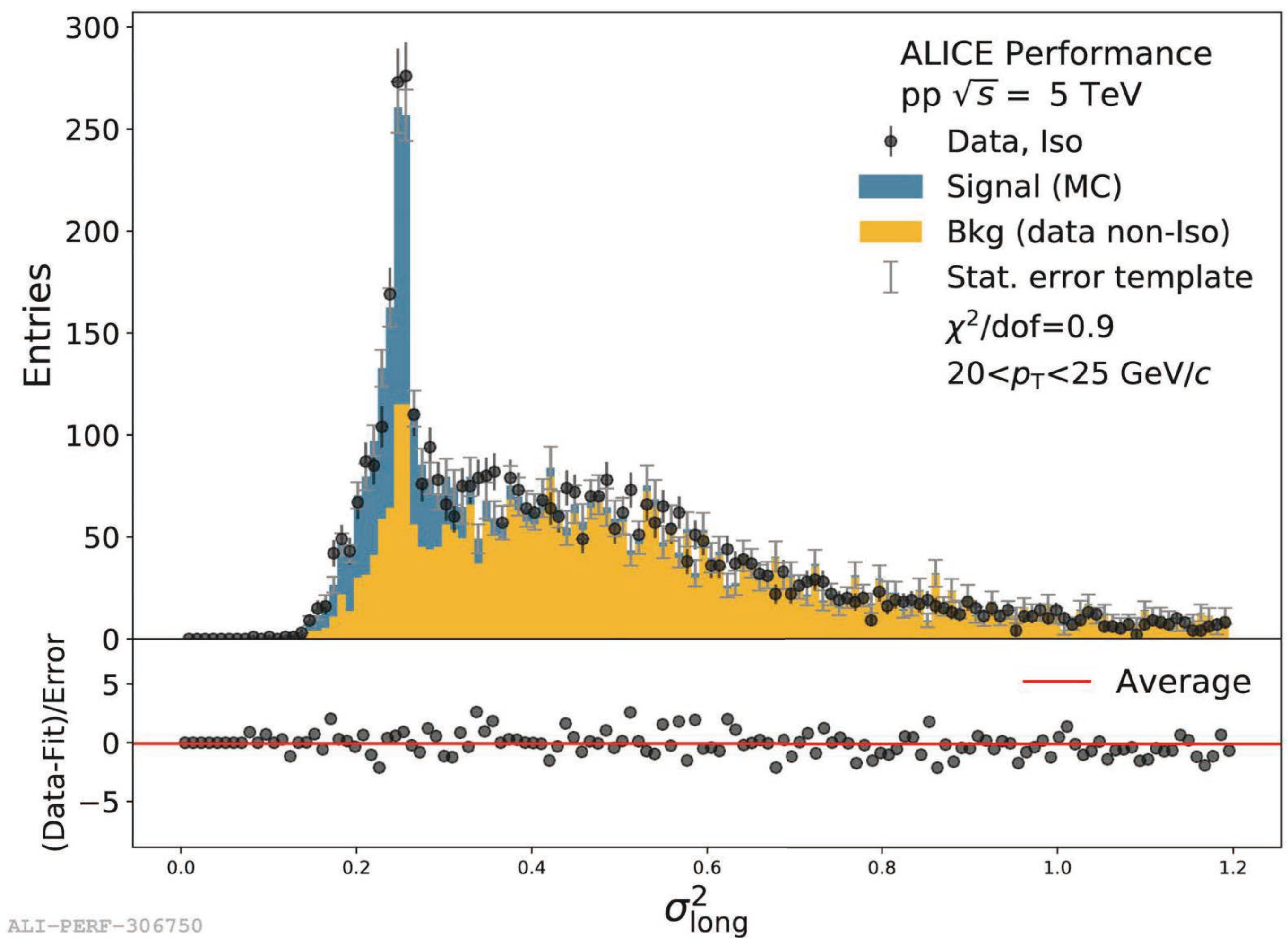
z_g: shared momentum fraction of the first groomed splitting

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

(3) Gamma-jet

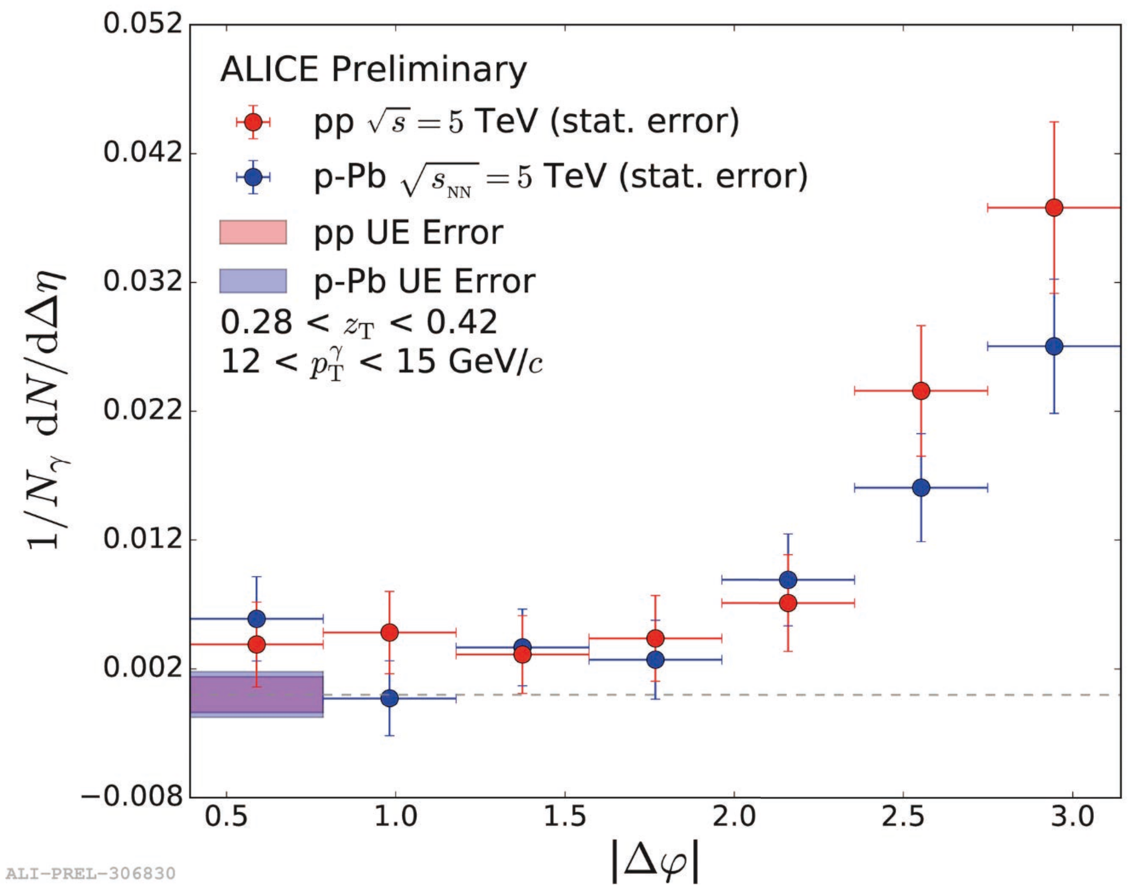
Isolated γ in pp and p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

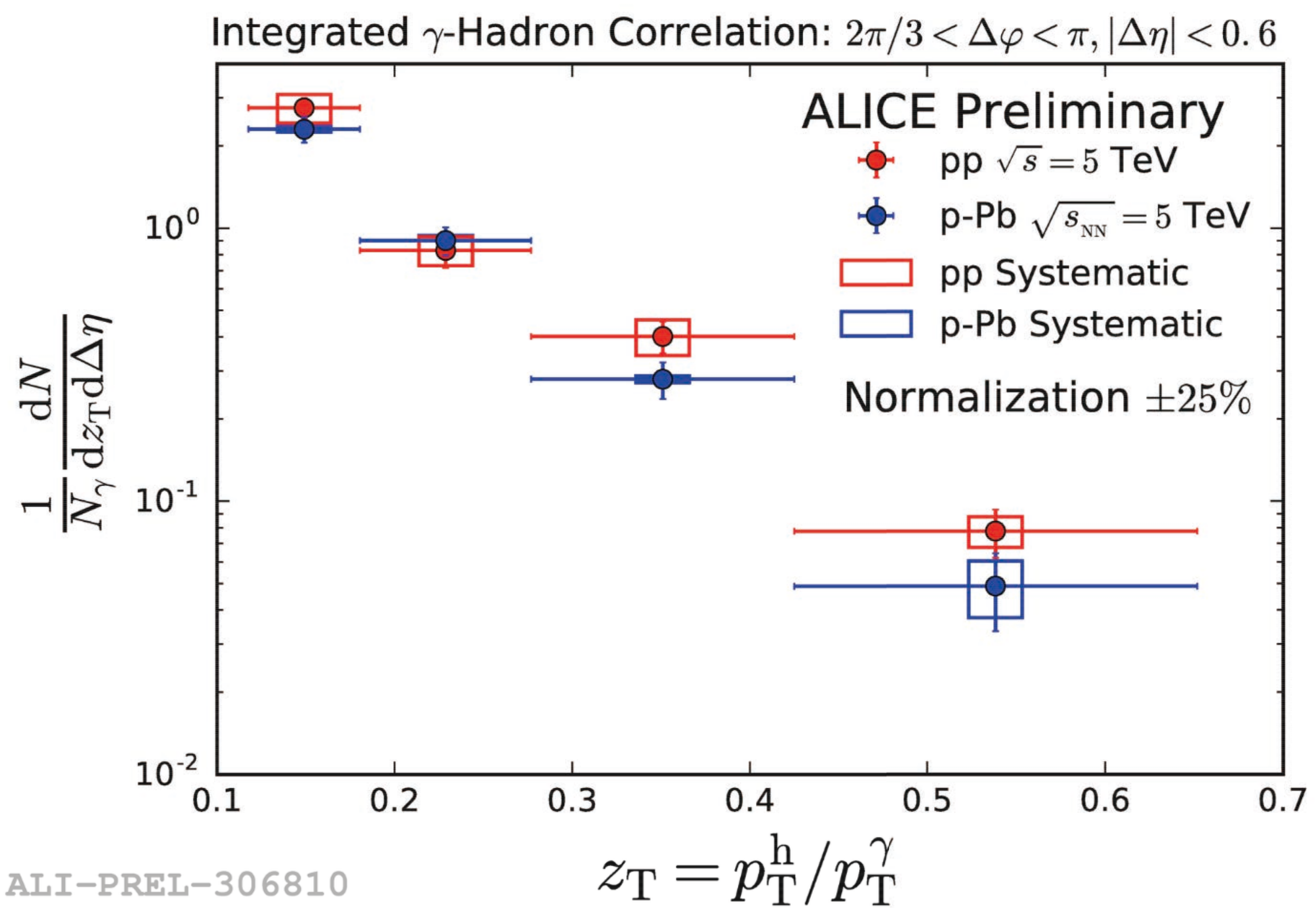




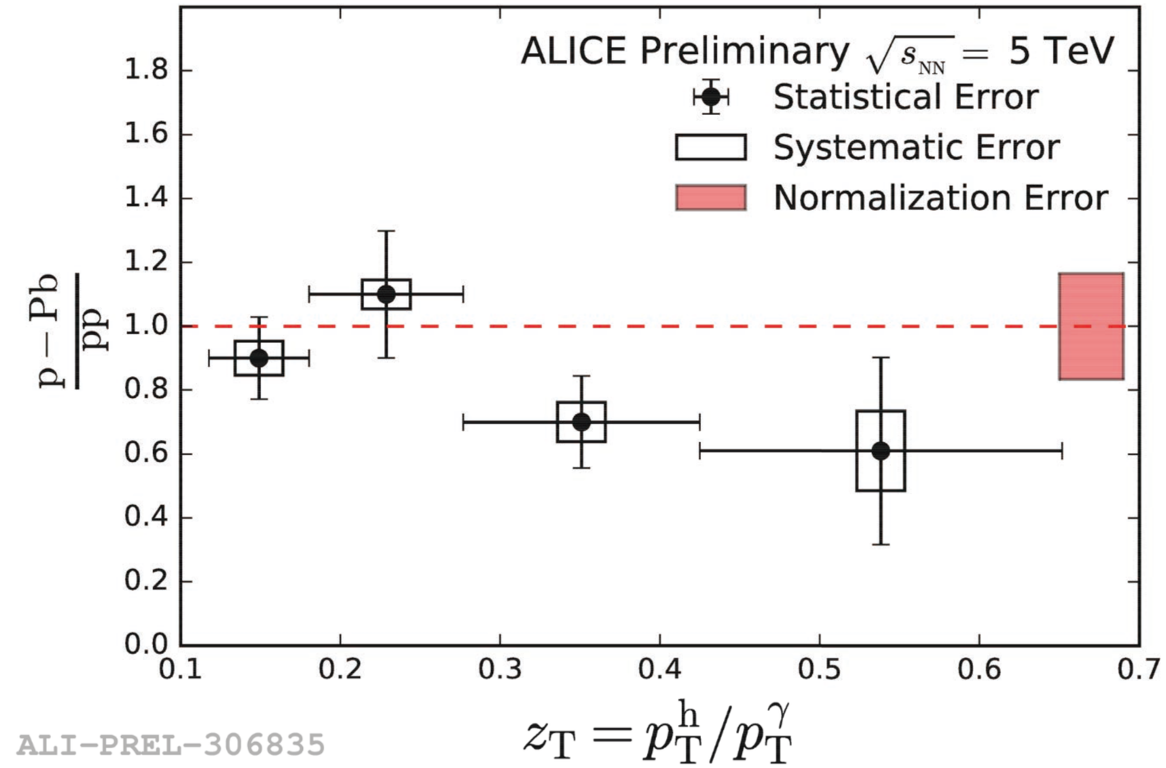
- Golden channel for energy loss, but rare probes
- Use ITS only track, and EMCal trigger in pp and p-Pb
- Photon measured in EMCal trigger, and applied isolation cut based on ITS tracks *R*=0.4 around photon candidates
- Set the benchmark for pp and p-Pb, look also the difference between pp and p-Pb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

γ -"hadron" in pp and p-Pb



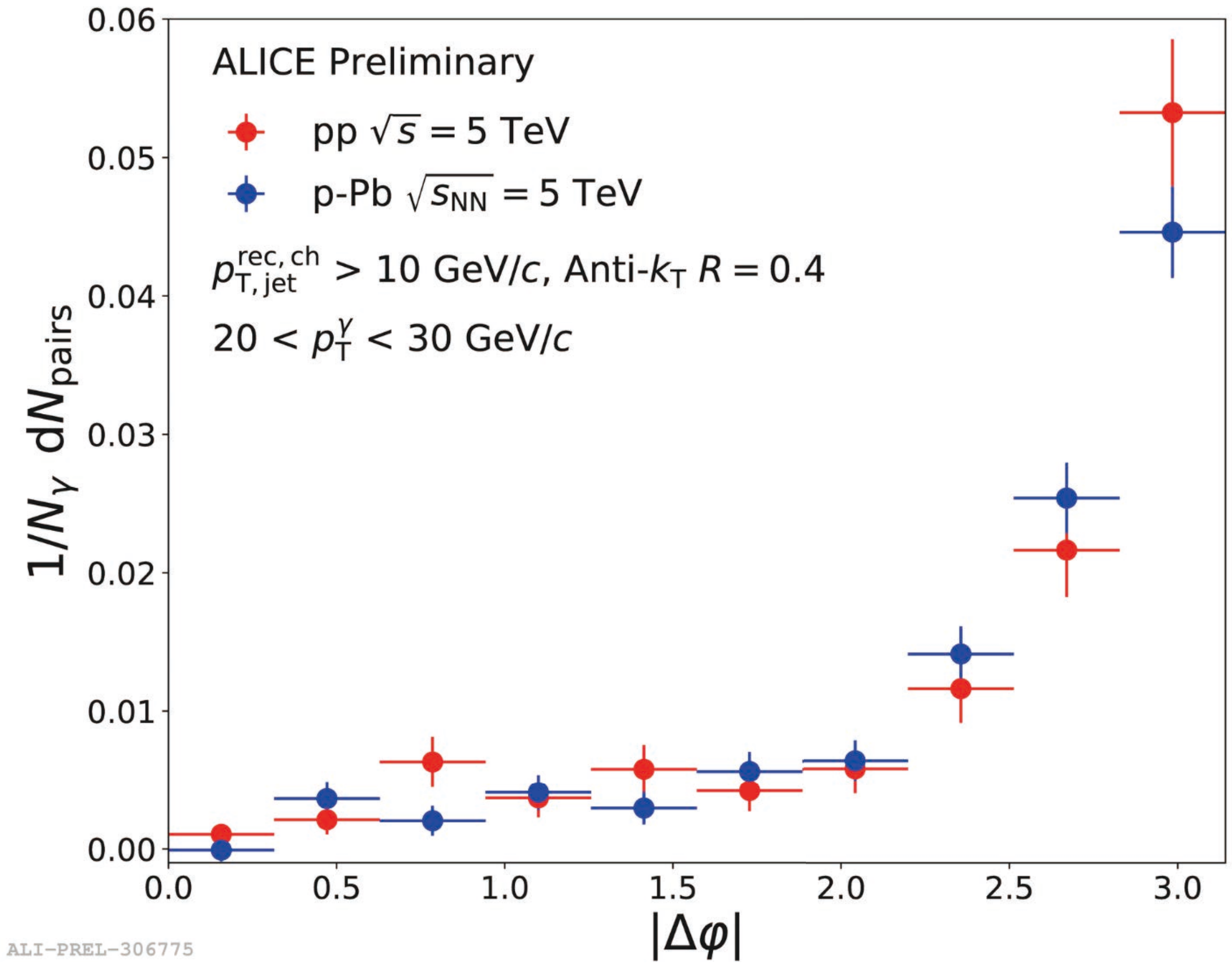


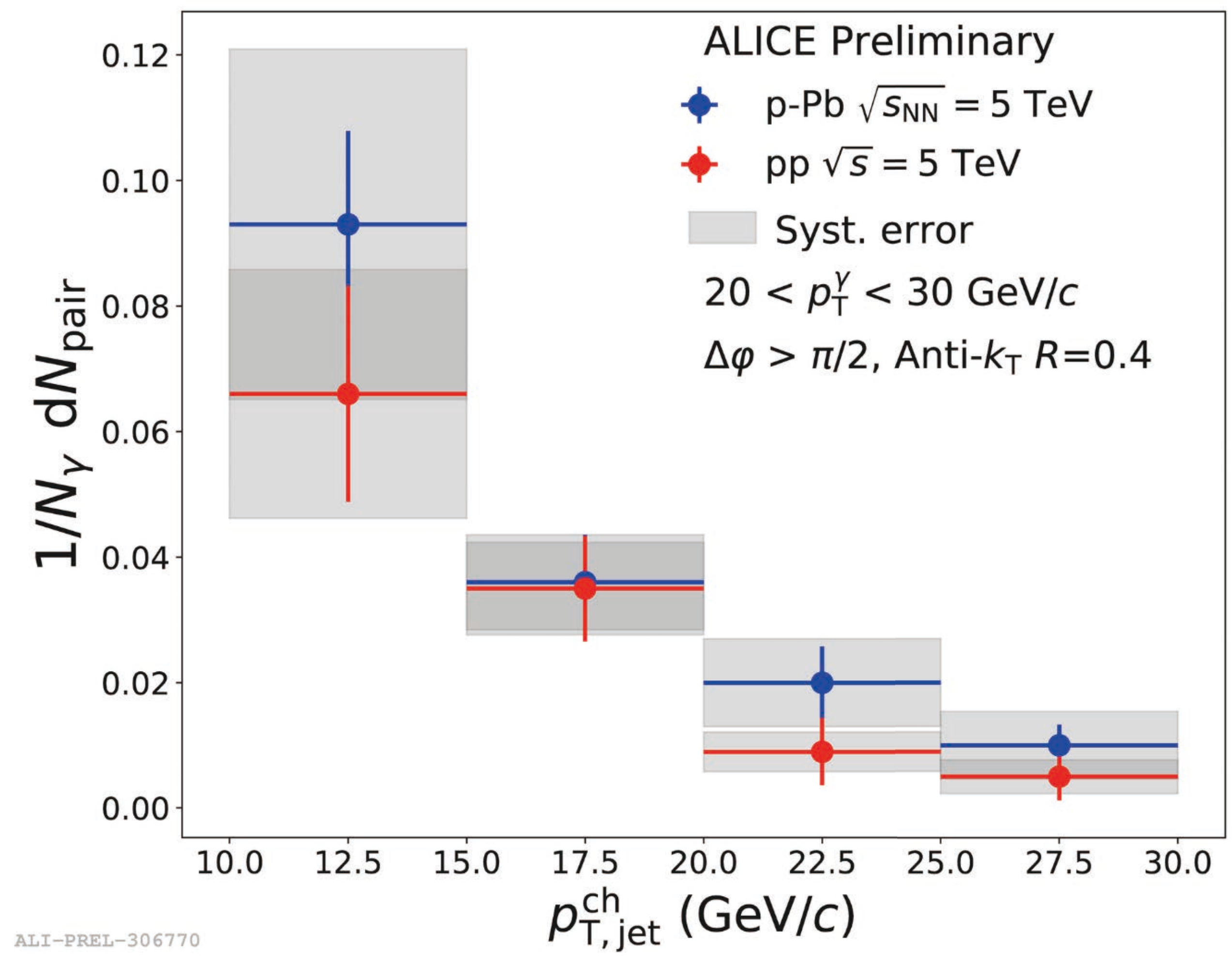
- No significant difference between pp and p-Pb



ALICE

γ -“jet” in pp and p-Pb

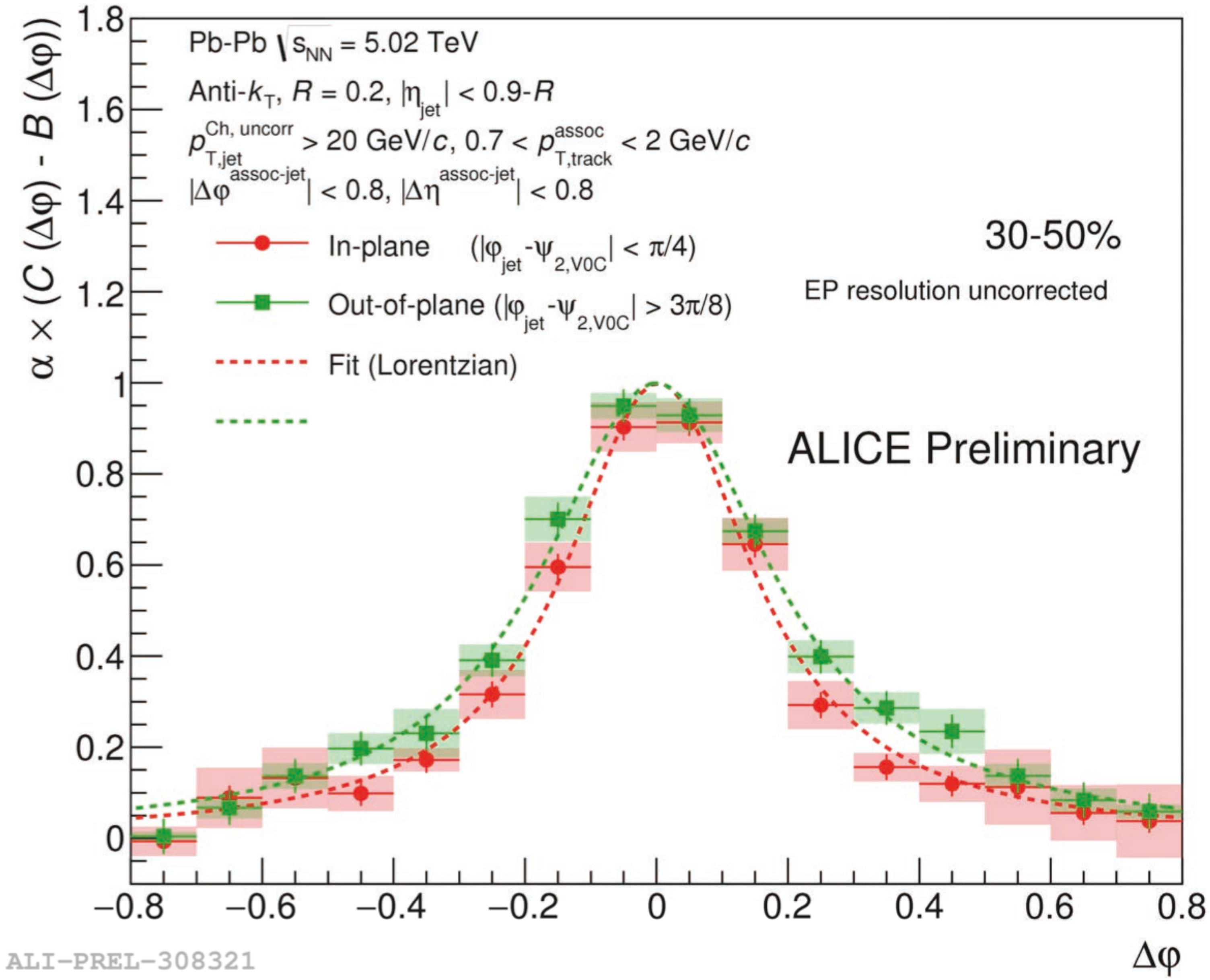


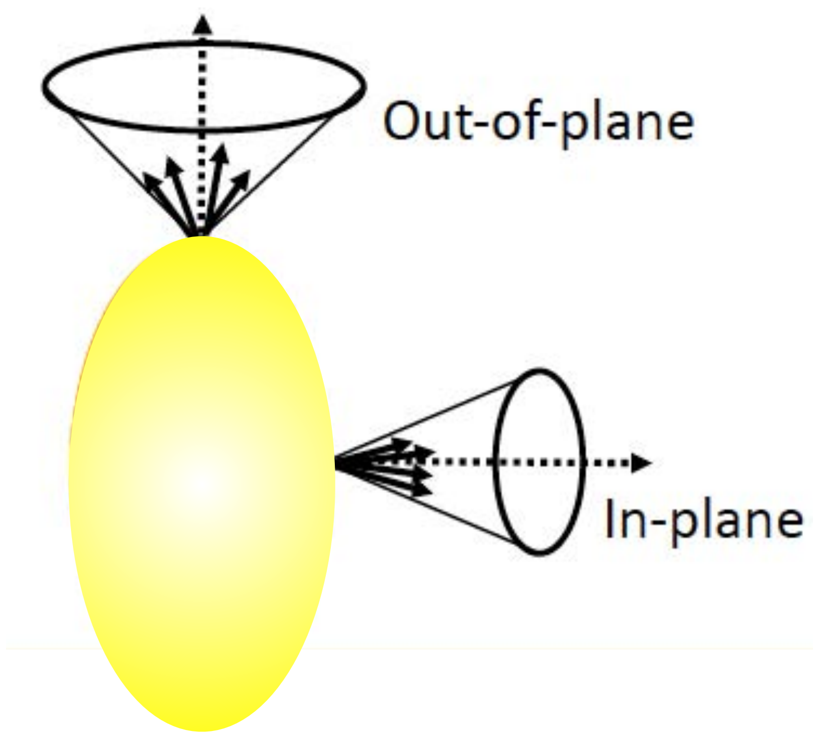


- No significant difference between pp and p-Pb

(4) Jet-hadron & hadron-jet

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





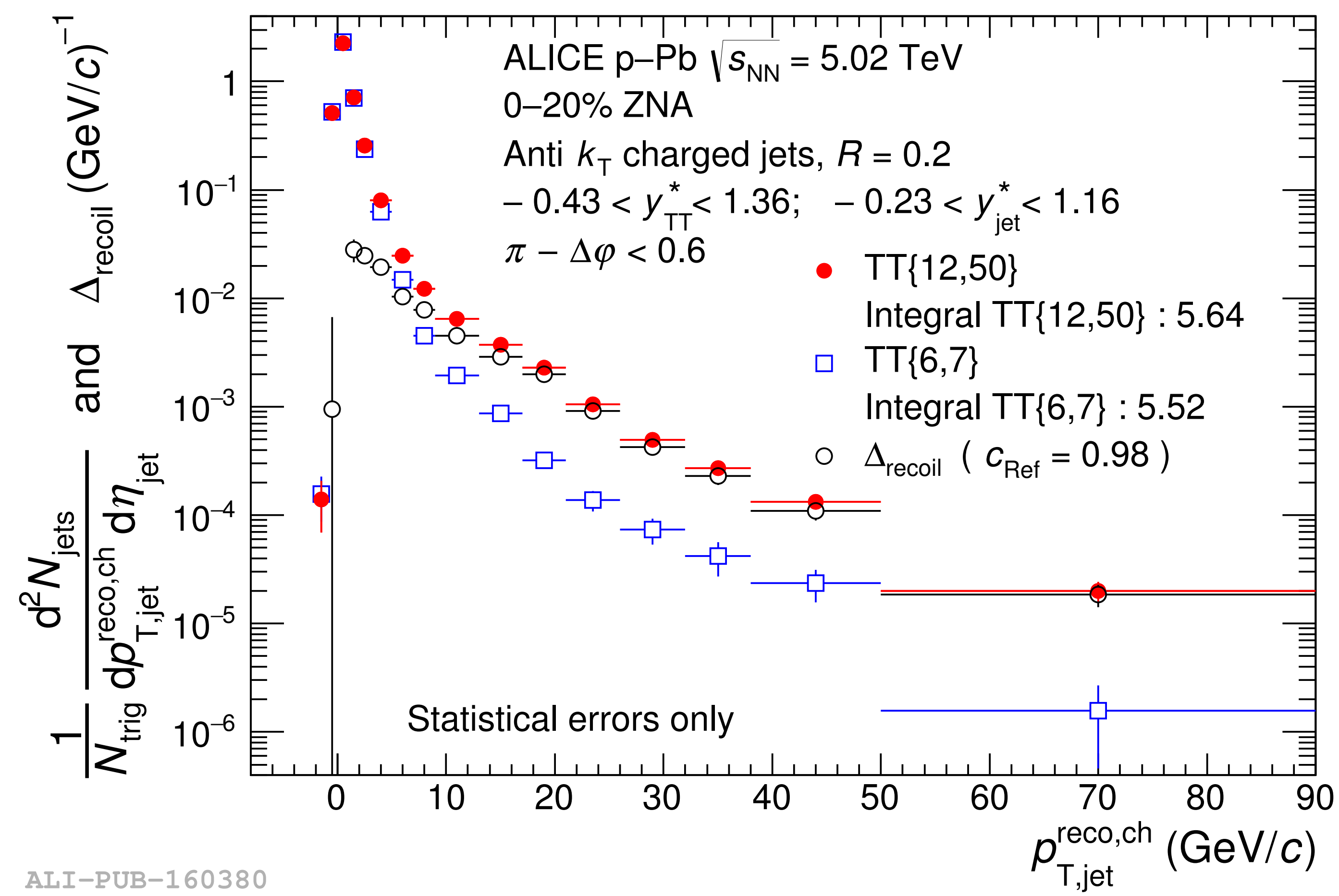
A slightly wider distribution for out-of-plane in lower p_T associated tracks (0.7 < p_T < 2 GeV/c)

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

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

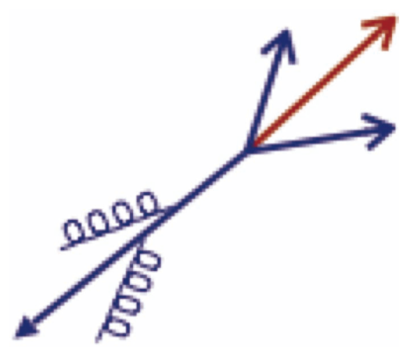
Δ_{recoil} = high p_T trigger (12-50 GeV/c)
- low p_T trigger (6-7 GeV/c)

- Self normalized coincidence

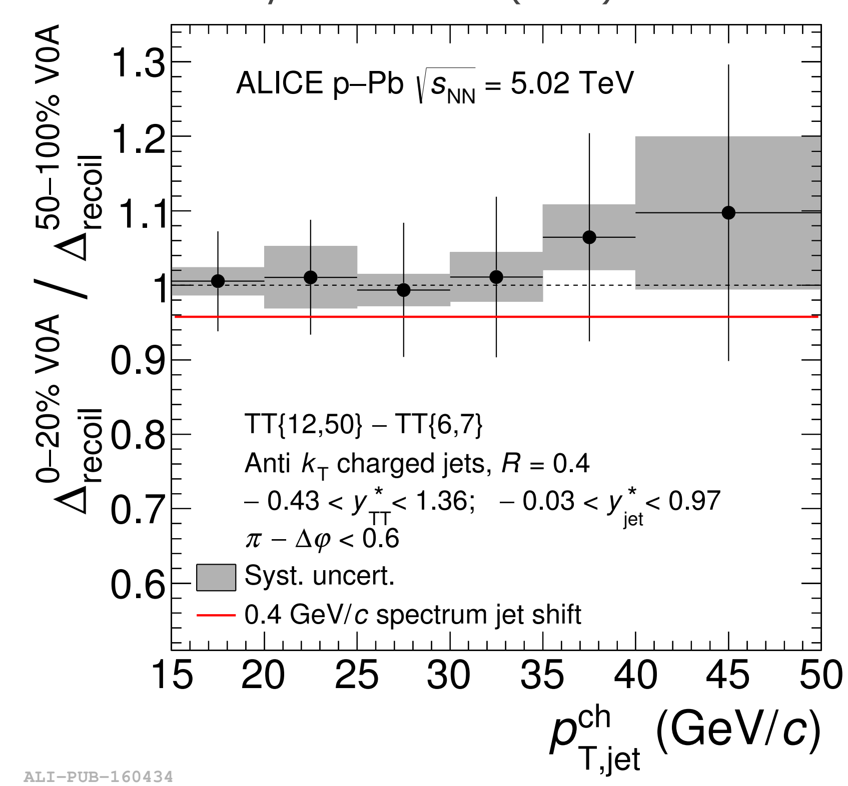


Phys. Lett. B 783 (2018) 95-113

high p_T hadron trigger

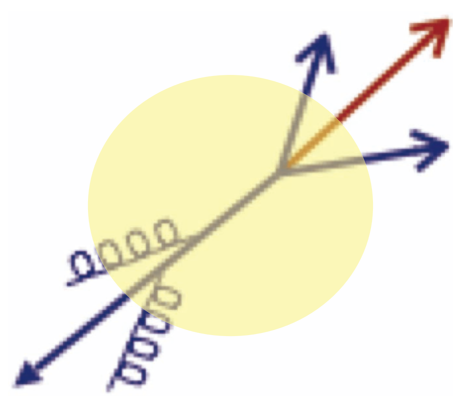


recoil jet



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

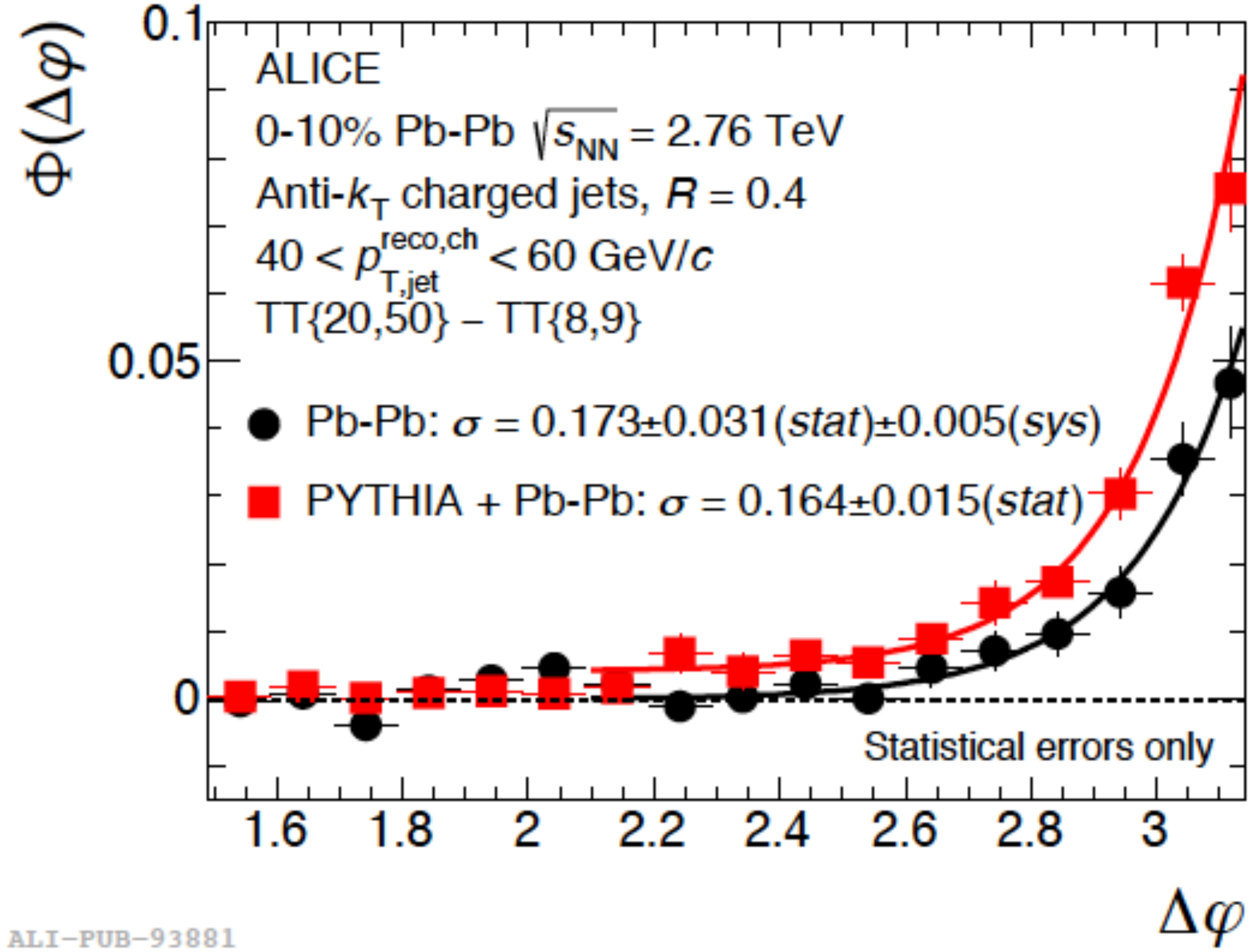
h-jet correlations in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV



high p_T hadron trigger

recoil jet

JHEP 09 (2015) 170

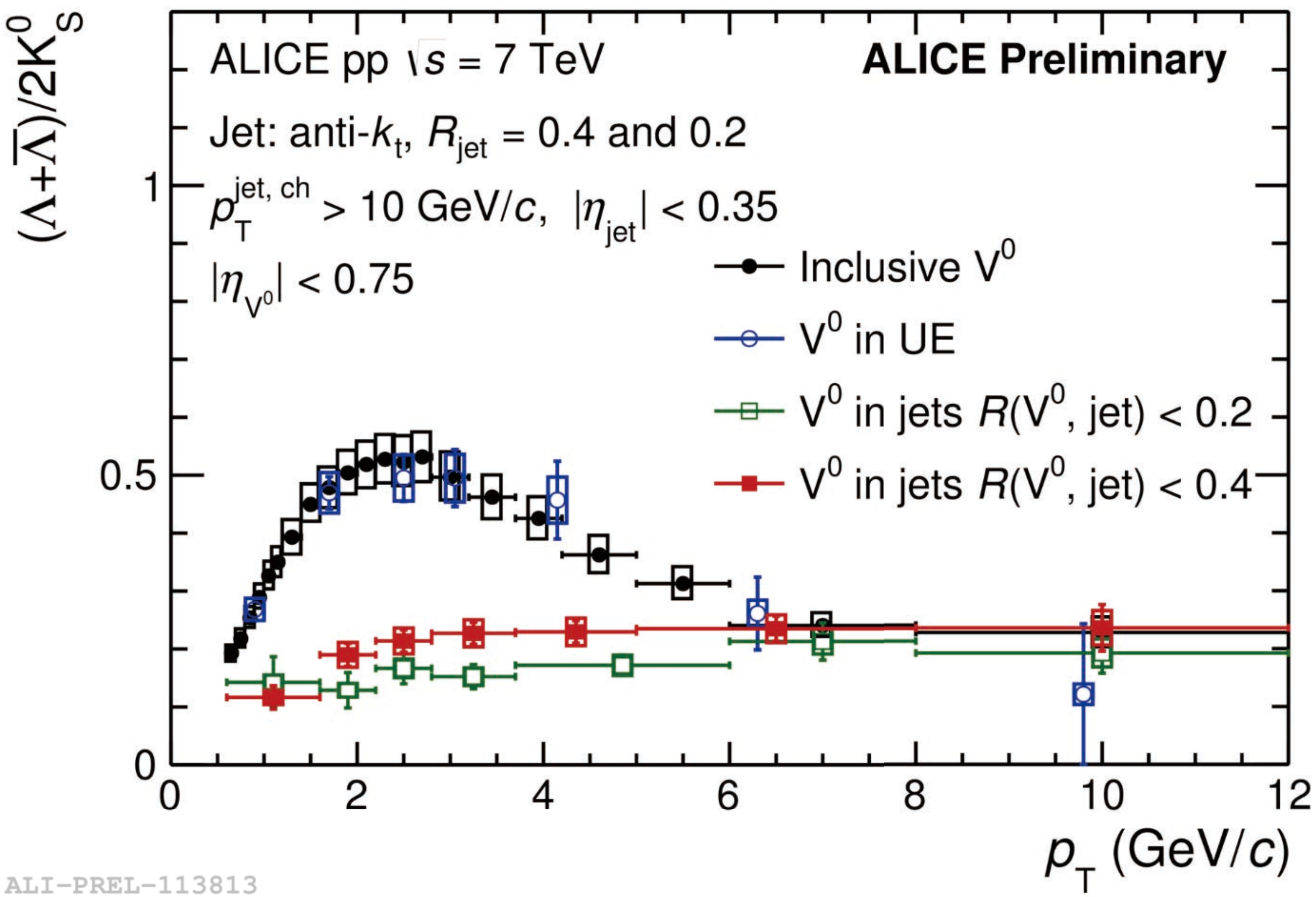


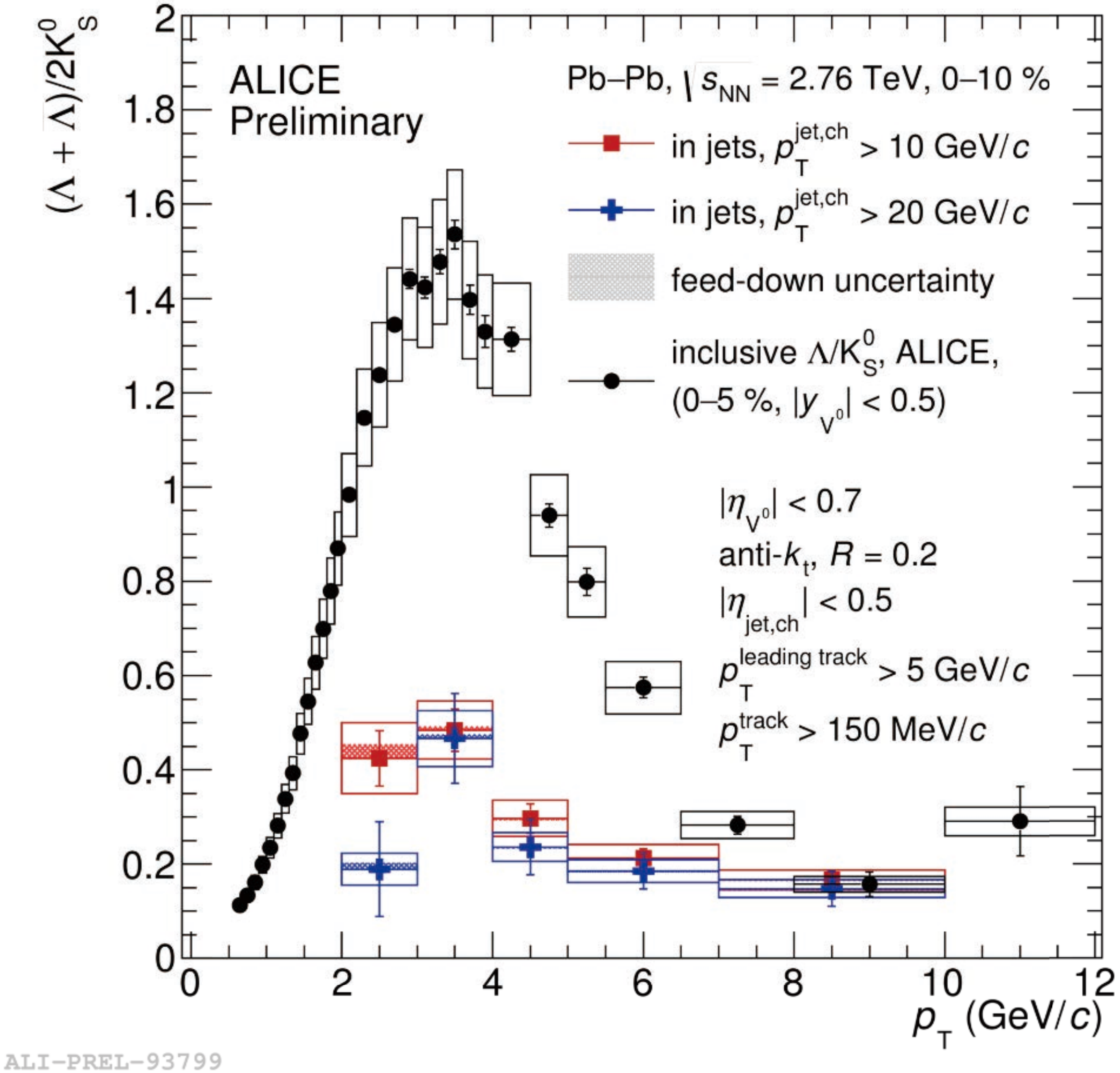
* Future: Also interesting to see the accoplanary for jet broadening, try to see large angle scattering (Molière scattering) with large data sample in Run-2 and Run-3

ALICE

(5) Jet with PID

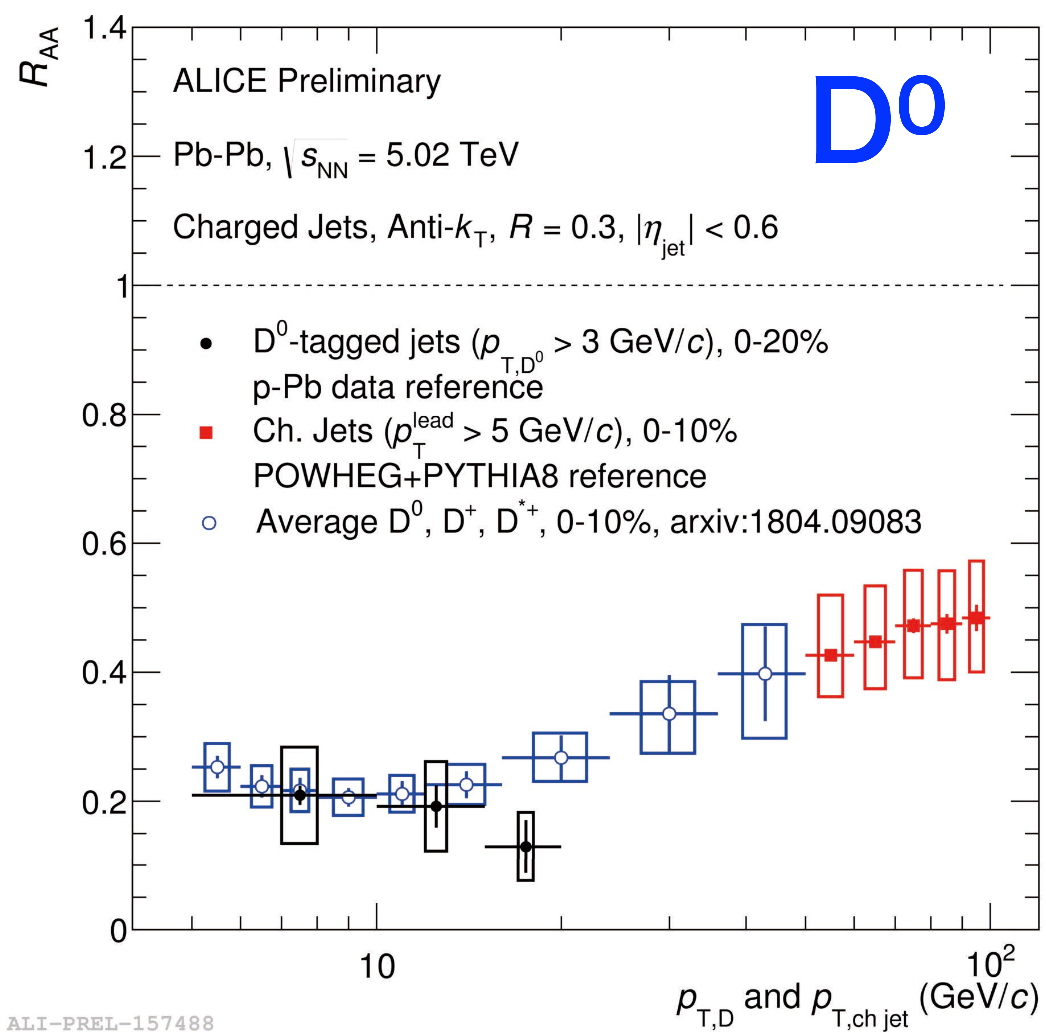
Λ, K⁰, Ξ± production in jets in pp and Pb-Pb

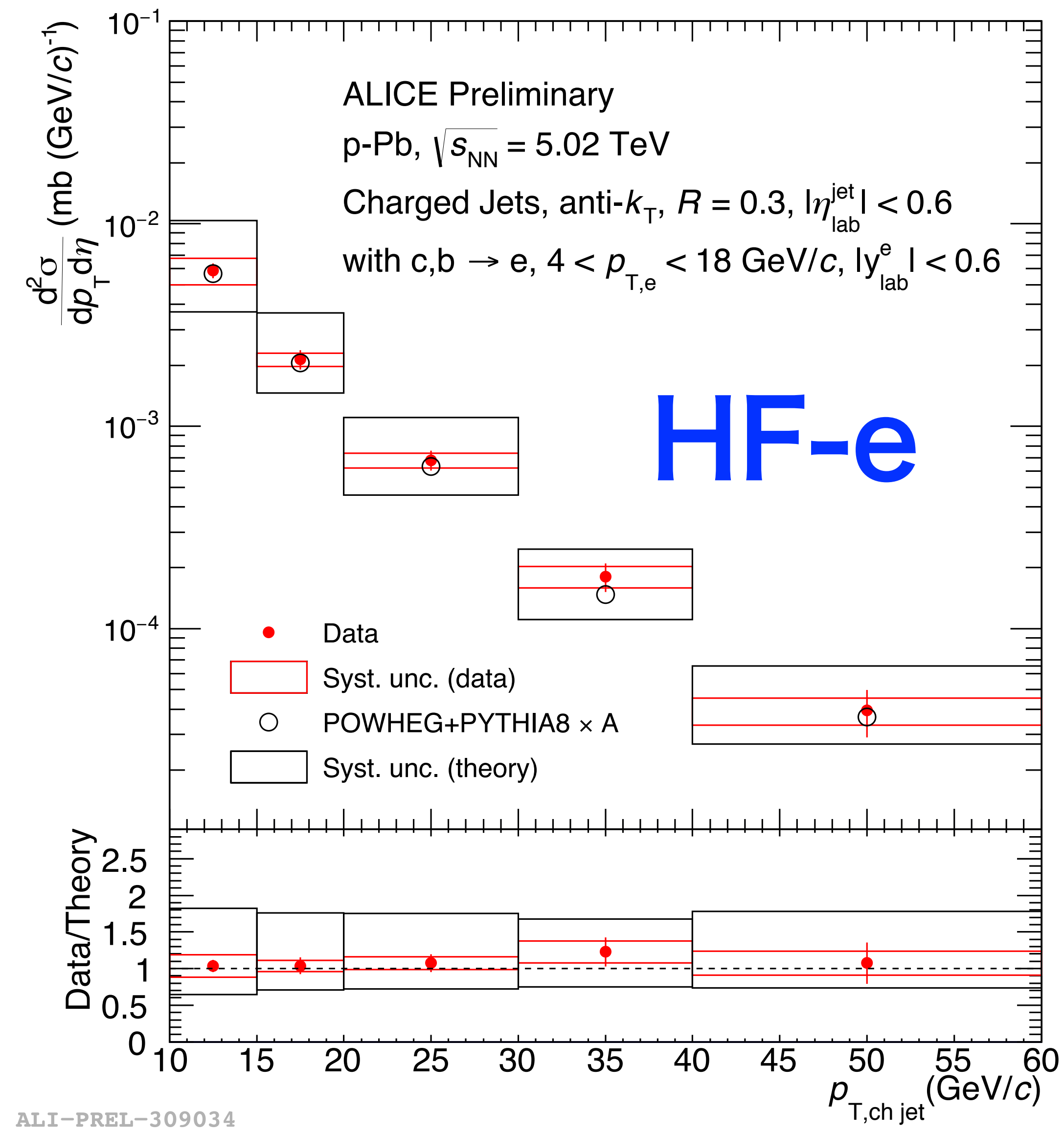


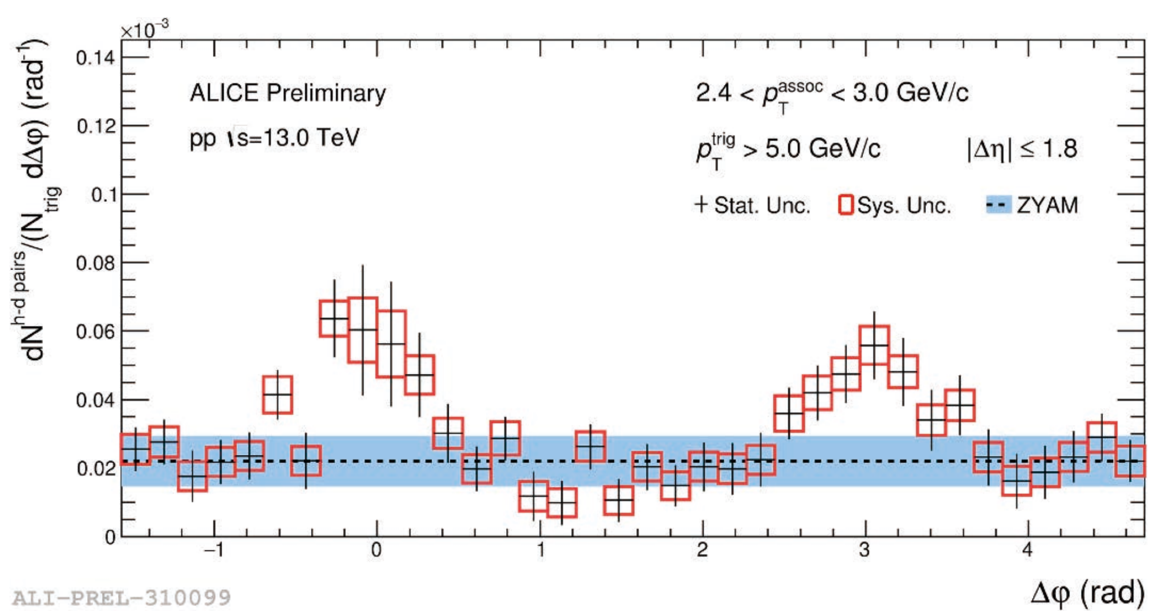


- Strangeness production in jets
- Reproduced inclusive Λ, K⁰, Ξ±
- Measured Λ, K⁰, (Ξ±) within jet (JE) and outside jet (UE)
- Clear difference in ratio for intermediate p_T
- Similar ratio in Pb-Pb, significant difference from inclusive

Other PID with jets



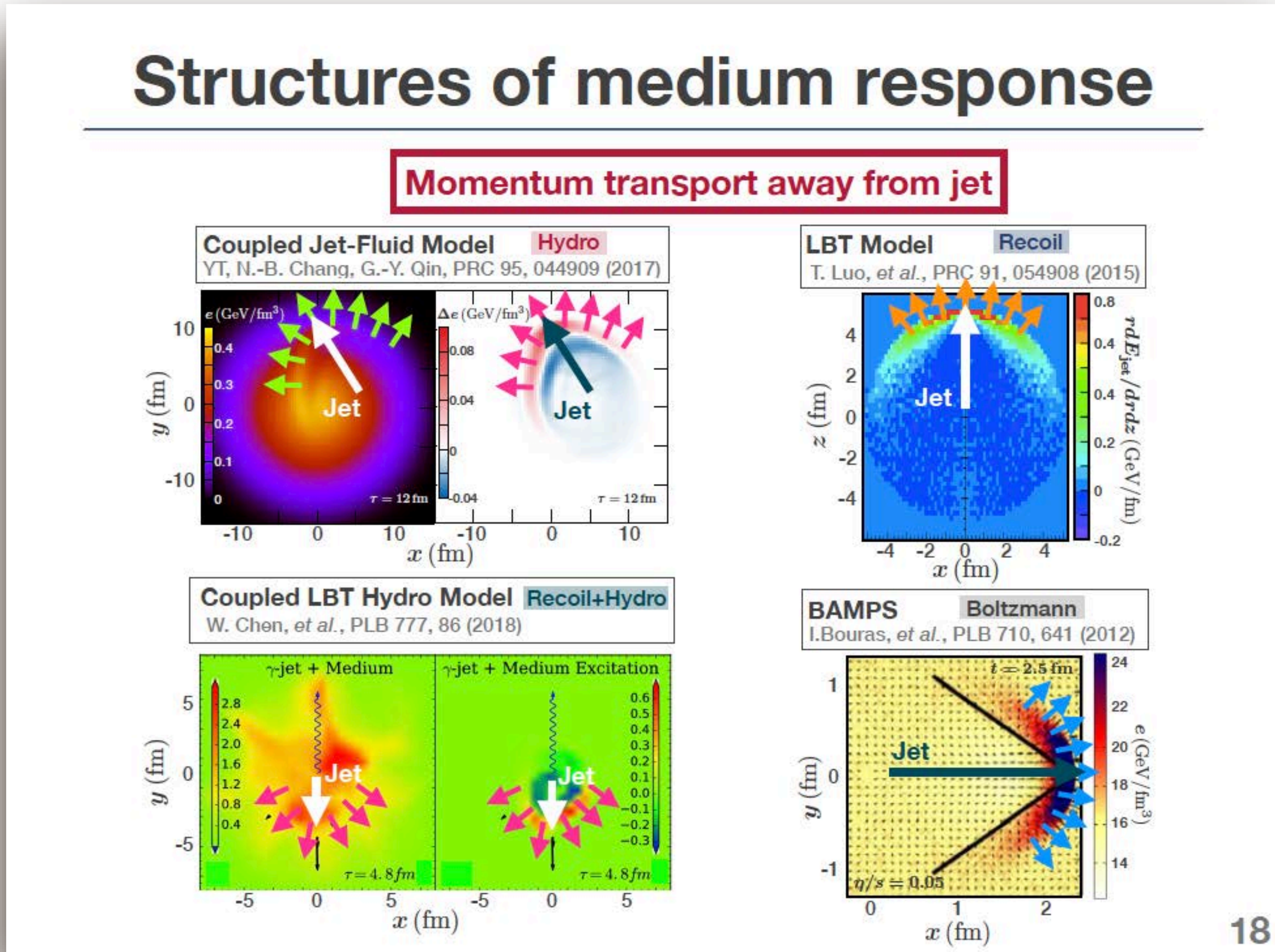




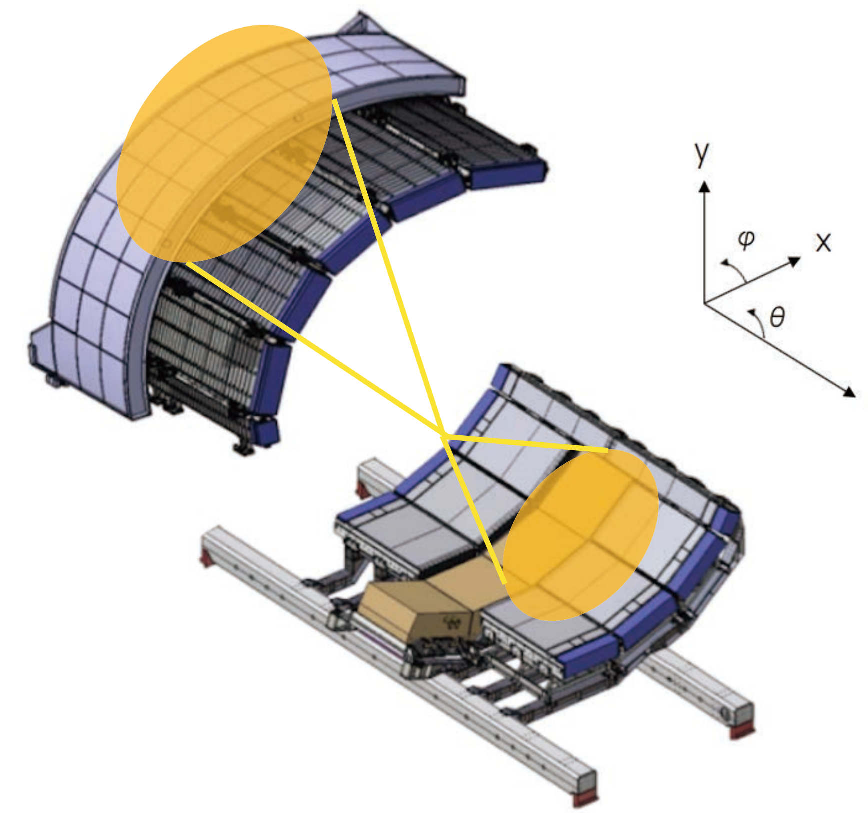
deuteron

Open questions

Q1) Mach cone?



Y. Tachibana (QM2018)



- **ALICE: low p_T with PID & di-jet**

- In-medium thermalization (reheating, mach cone) ?
- Enhancement of particle emission around jet (recombination?)
- Unexplored medium properties: EOS, c_s etc.

experimental observables

Q2) No jet quenching in small system?

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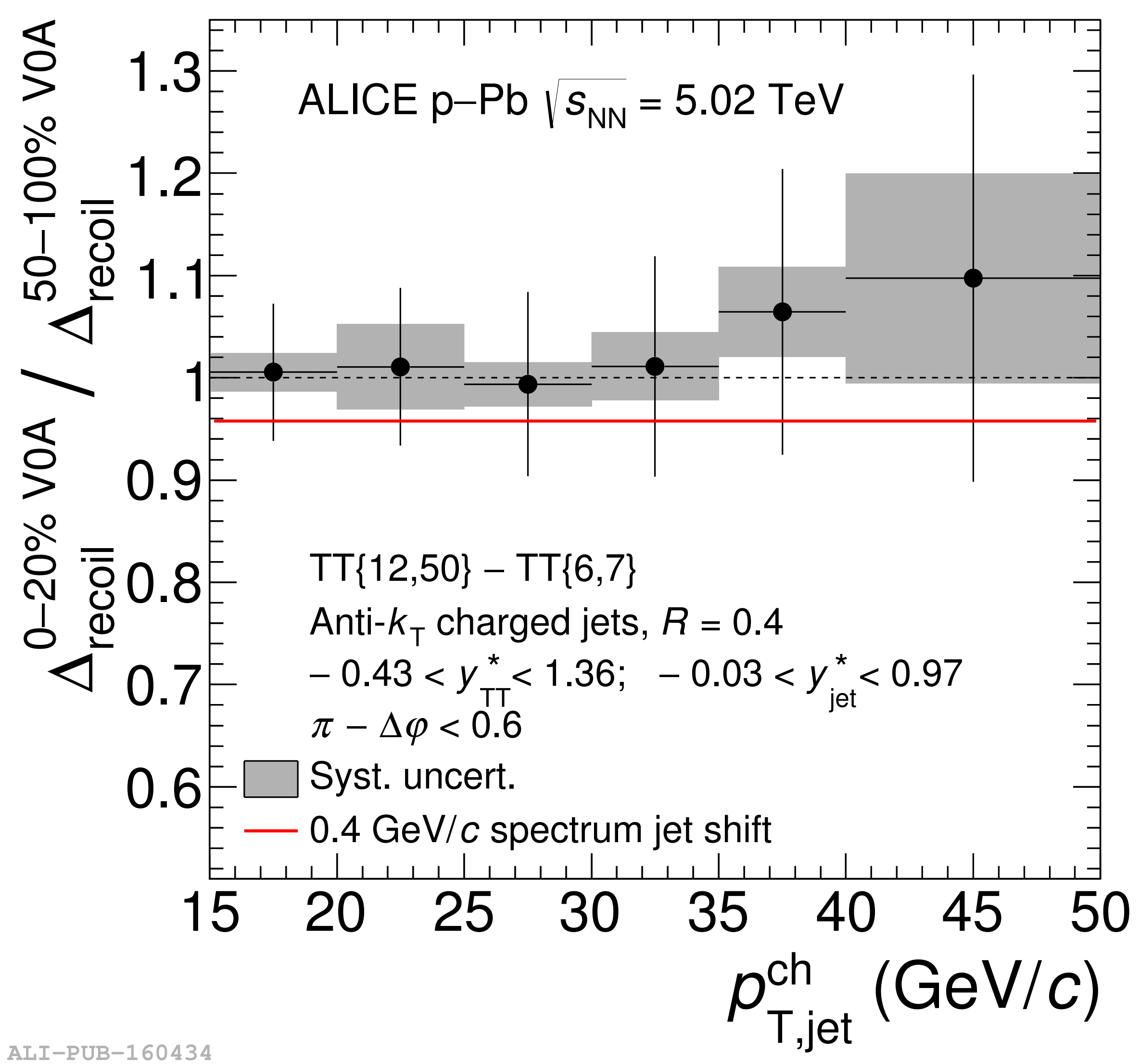


"Jet quenching" is not observed in high multiplicity event in pp and p-Pb at LHC energy.

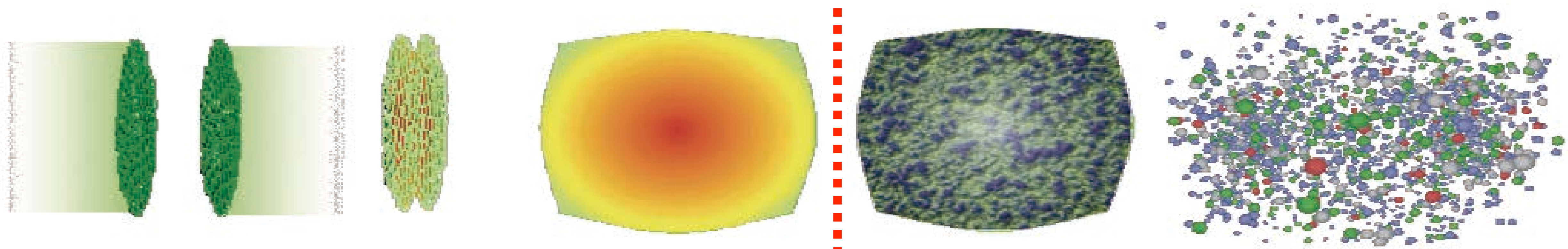
↓

ALICE

High statistics "high multiplicity" triggered data in pp 13 TeV Run-2 data is on-going.

Q3) How QGP is thermalized so quickly ?

Unknown !

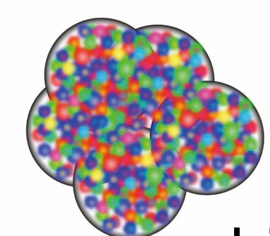


CGC ? | collisions | Glasma ? | QGP | hadron gas

Courtesy of S. Bass

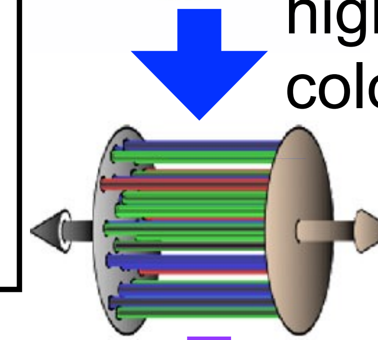
t = -1 fm | t = 0 fm | t= 0.6 fm/c | t= 20 fm/c | **t**

- **What is the initial condition?**
- **Why so rapidly thermalized (t=0.6 fm/c)?**
  - **Instability of strong color field ?**
- **No clear evidence for CGC as an initial condition yet.**
- **initial condition ⇔ CGC strong color fields ⇔ thermalized QGP**



CGC

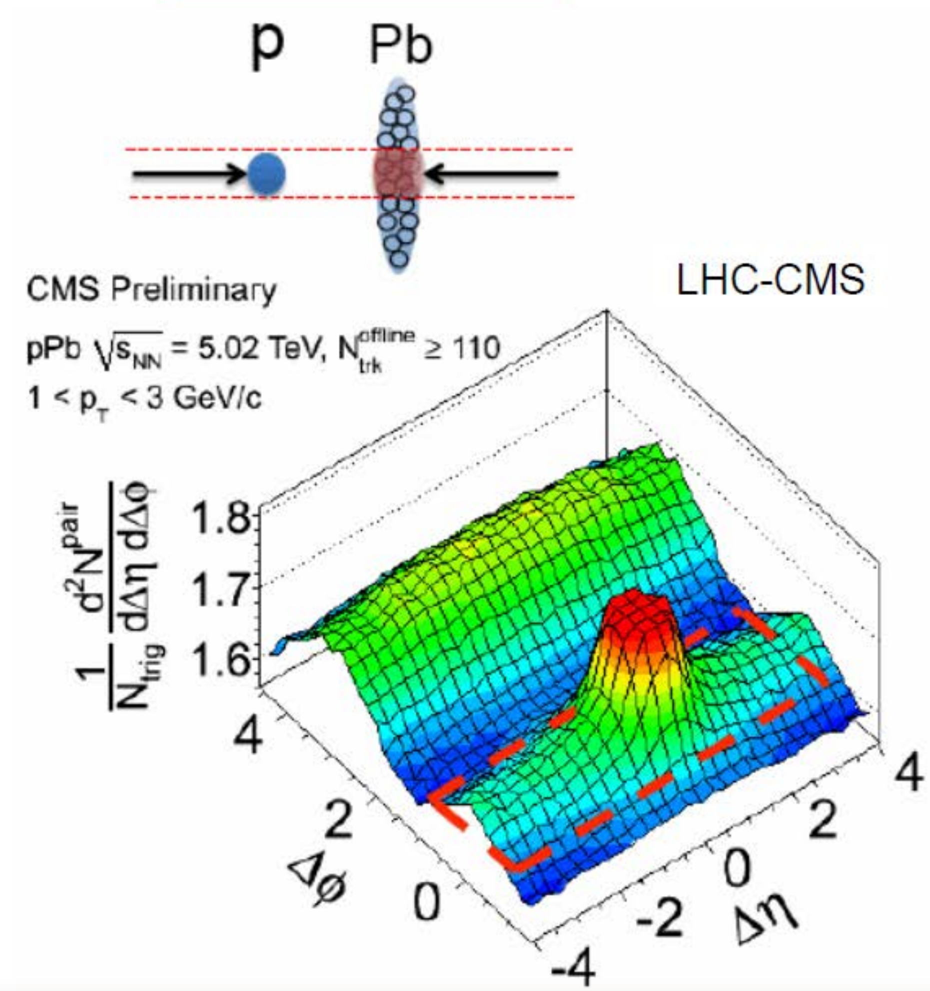
high density color field



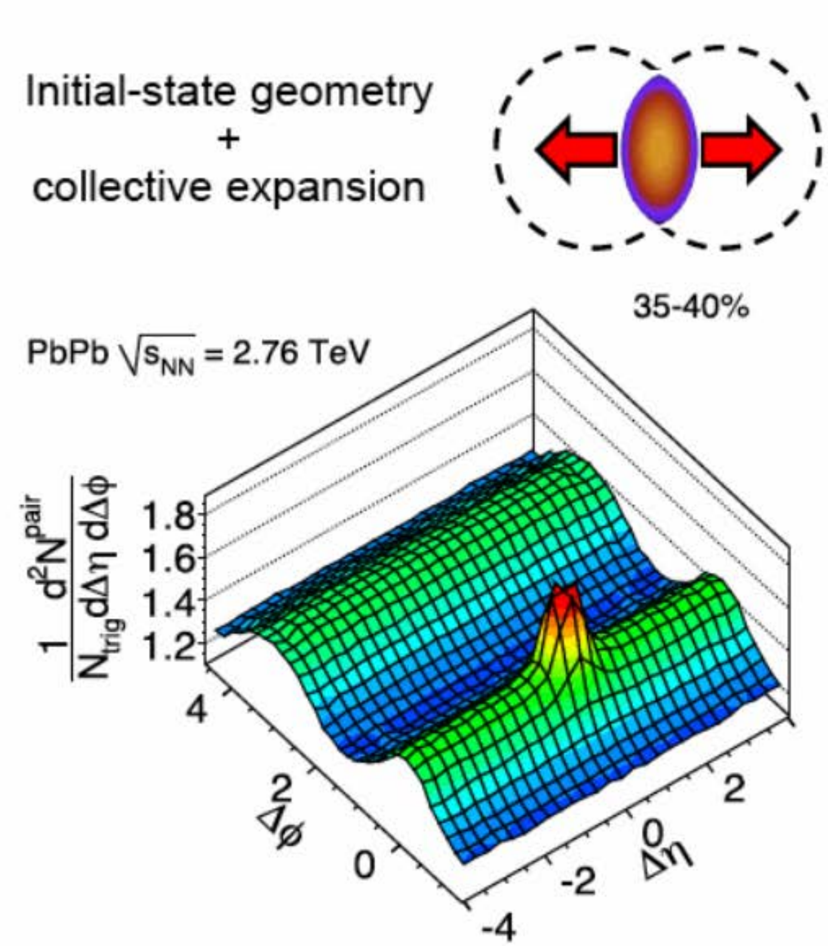
QGP rapid thermalization?

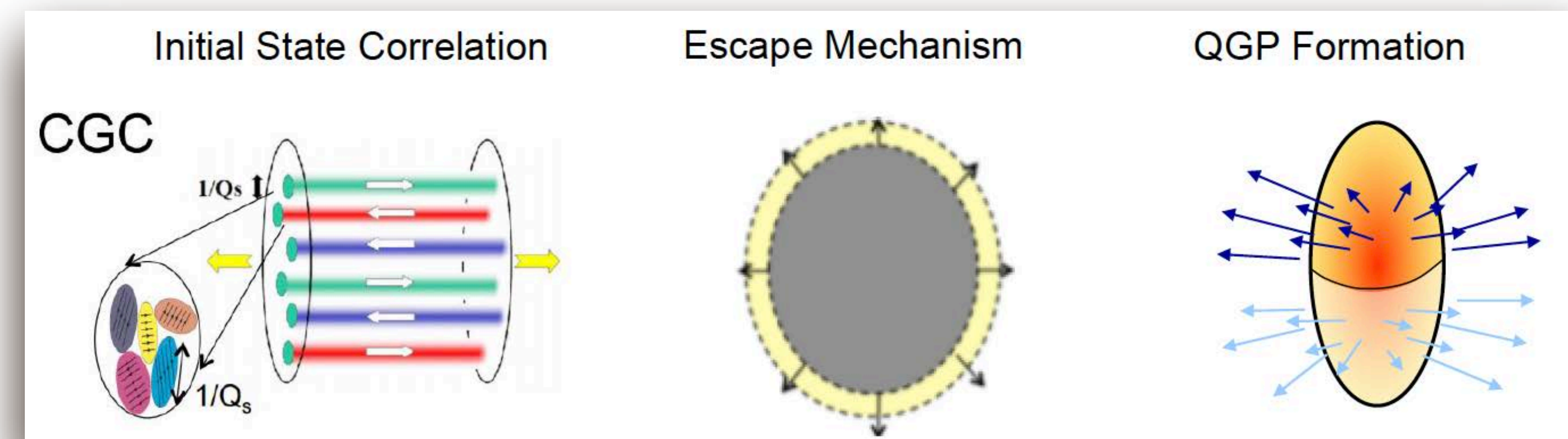
Q4) Origin of ridge, collectivity in small system?

p+A collisions



A+A collisions





Yen-Jie Lee, heavy ion town meeting (2018)

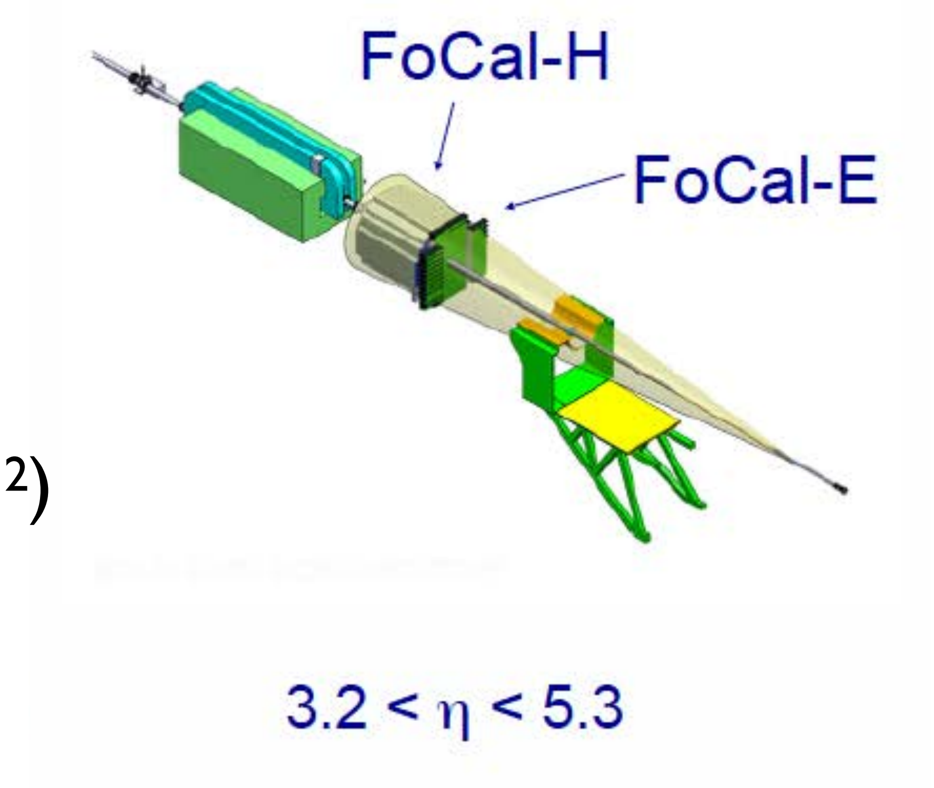
ALICE FoCal

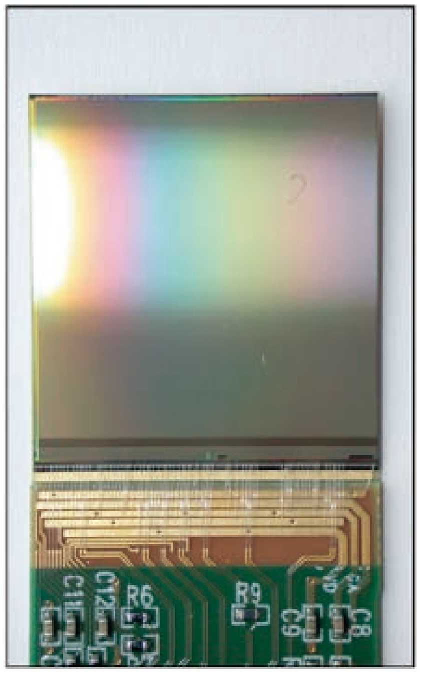
FoCal = Forward Calorimeter:

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

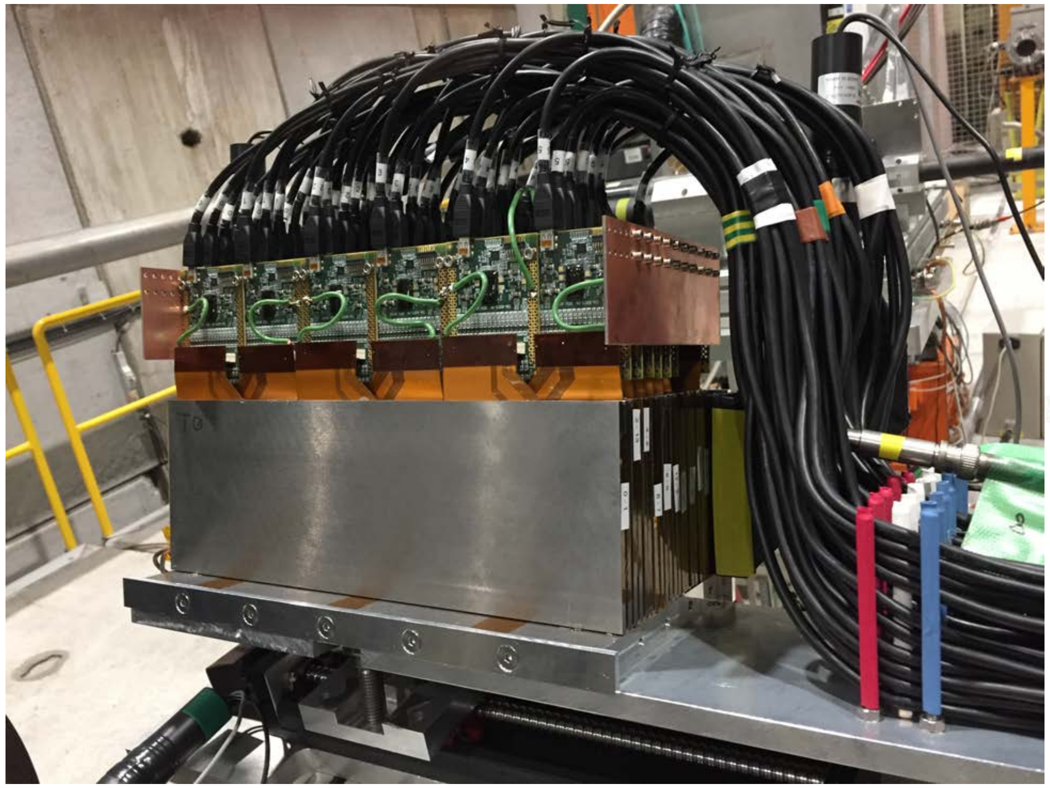
- ~7 m away from the interaction point
- main challenge: separate γ/π^0 at high energy
- Si-W calorimeter (hybrid Si: pad $1 cm^2$ & MAPS $30 \mu m^2$)
- Considered as an ALICE upgrade for Run-4

- **Look for CGC effects at small-x (~10^{-5})**
- **Origin of Quark Gluon Plasma**
  - main observables: Direct photons, π^0, π^0-π^0 correlations

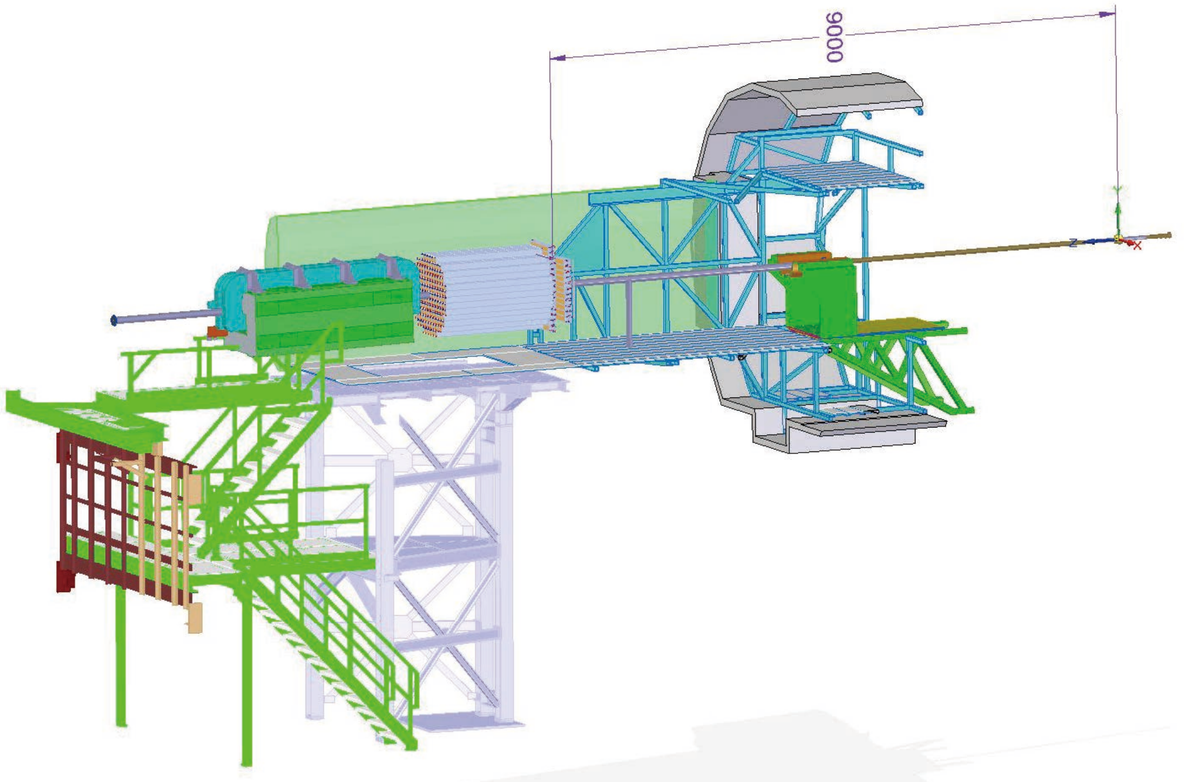


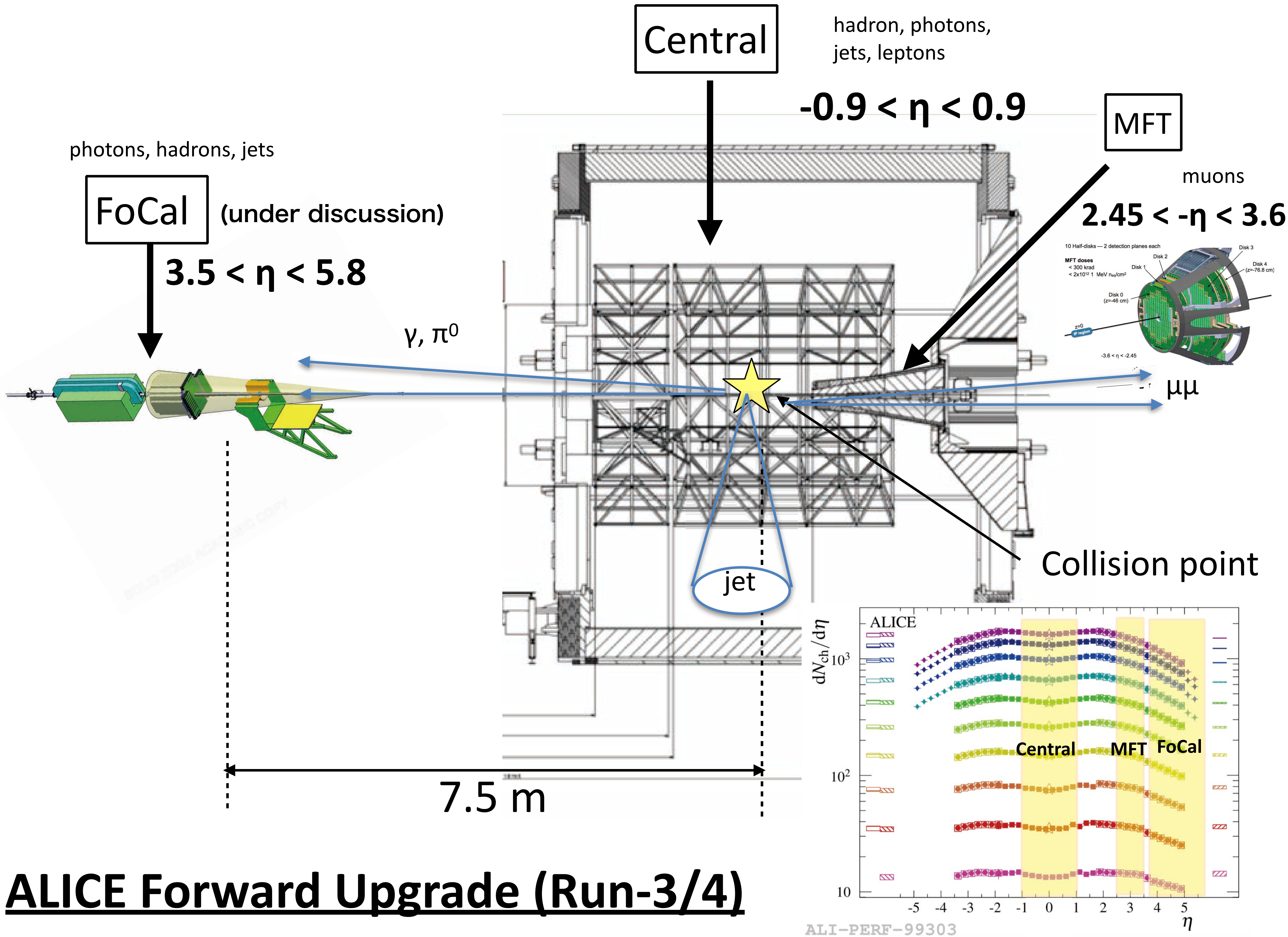


MAPS detector



mini-FoCal (PAD)





ALICE Forward Upgrade (Run-3/4)

Summary and outlook

Exploring parton energy loss with jets at LHC

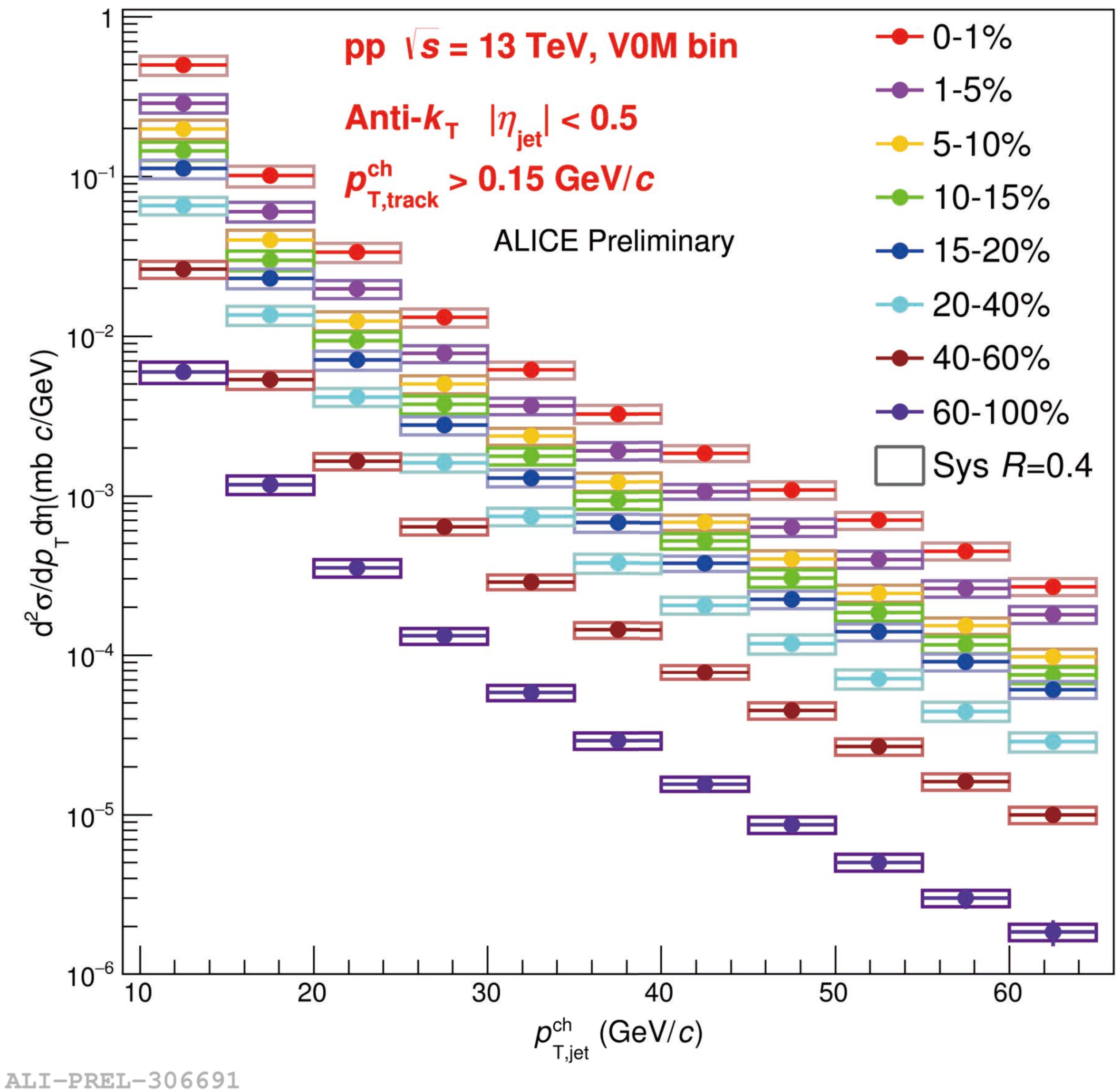
- **Jet spectra:**
  - towards larger R and low jet p_T
- **Groomed jets**:
  - Showed suppression of large angle splittings and slight enhancement of collinear splittings compared to embedded PYTHIA
- γ **-jet:** no difference between pp and p-Pb
- **Jet-hadron correlations:** a hit of broadening for out-of-plan for soft particles.
- **Jet with PID:** with strangeness, (c,b) tagged jets

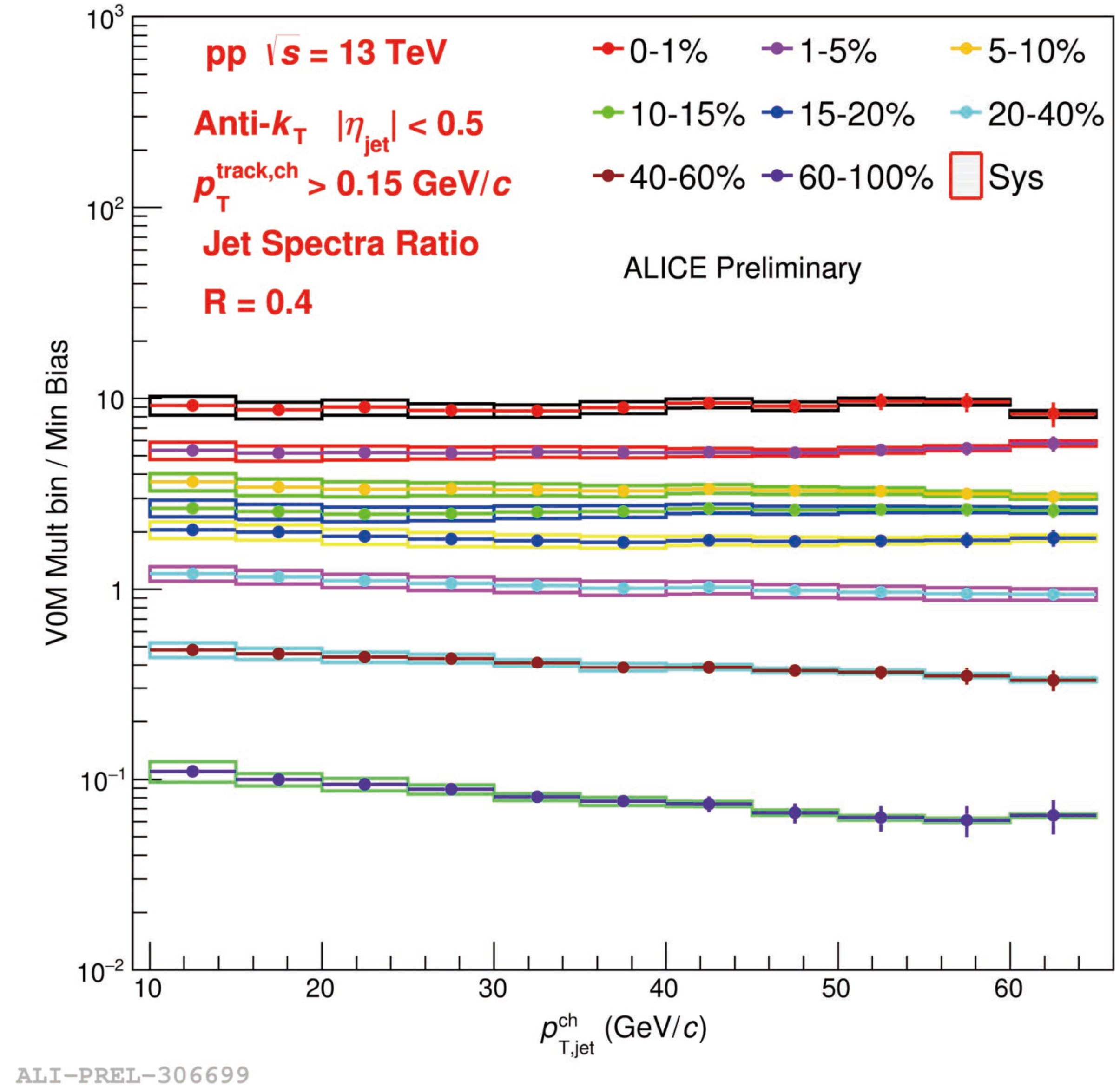
- **Outlook**
  - Jet spectra →towards larger R and low jet p_T, ML technique?
  - Jet tomography, mach cone search
  - “FoCal” for ALICE Run-4 upgrade: access to the initial conditions of QGP.

Harvest of jet physics in ALICE !
stay tuned on QM2019

Thank you for your attention!

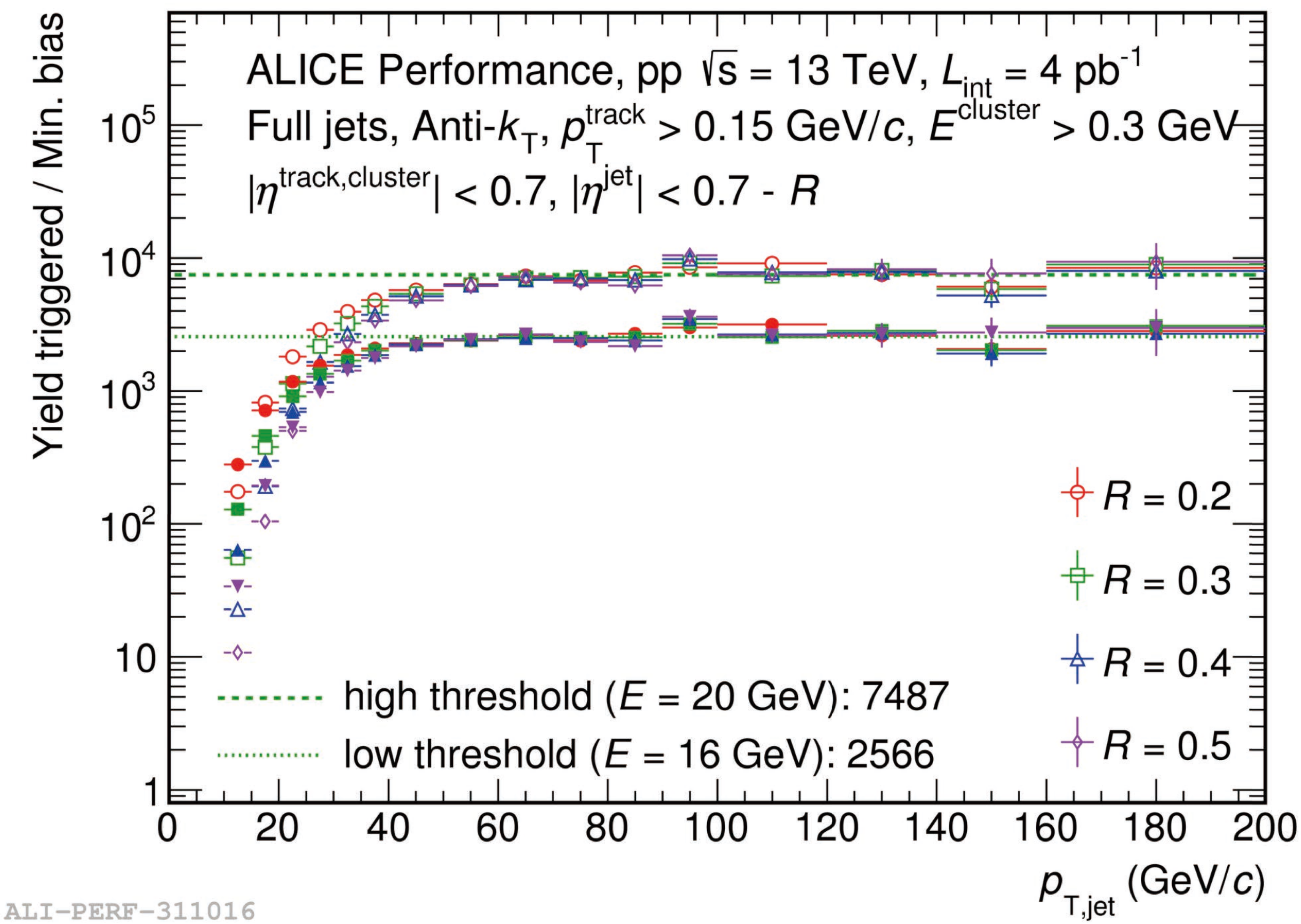
Multiplicity dep. charged jet in pp at $\sqrt{s}$ = 13 TeV





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

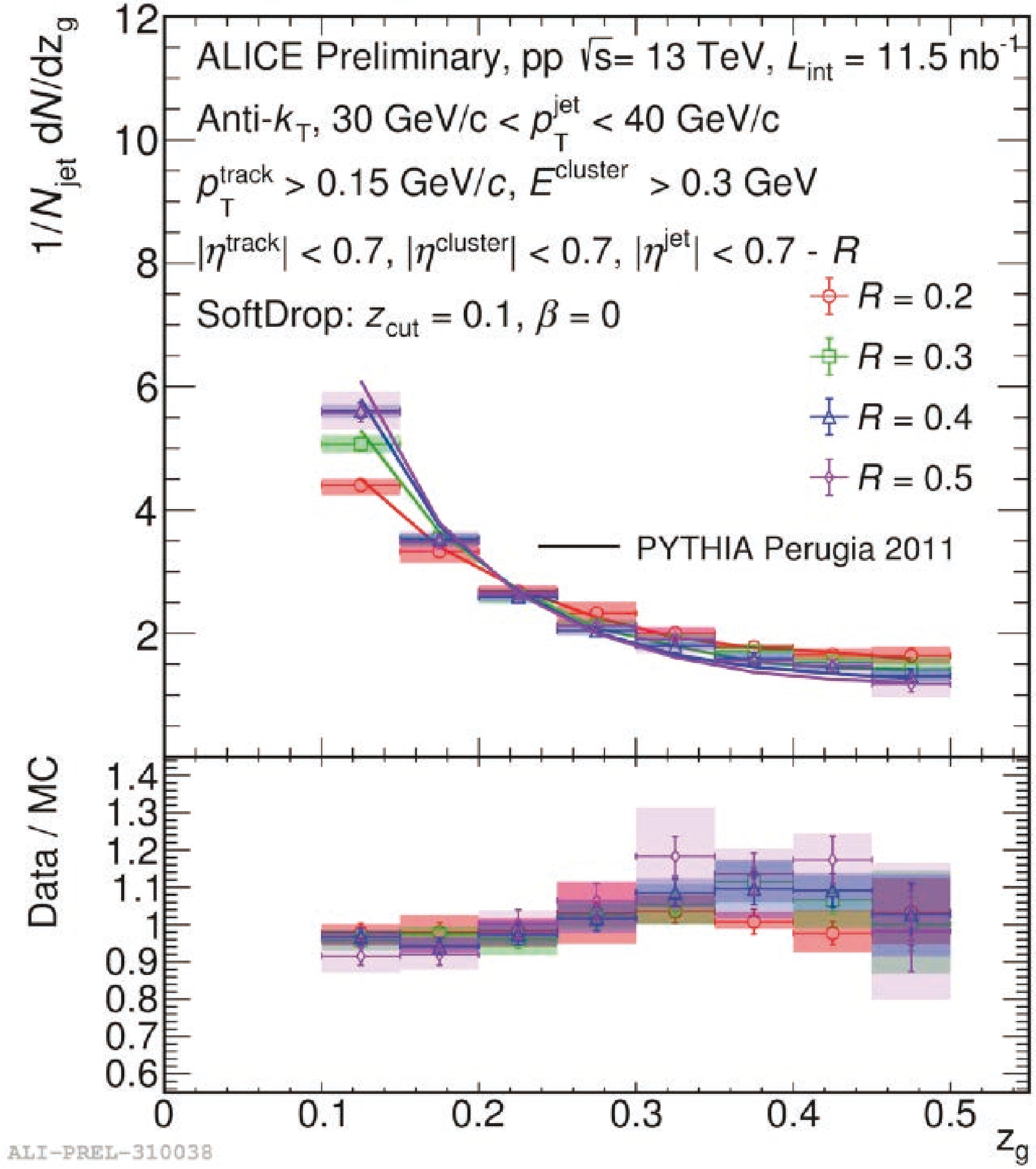
EMCal triggered data in pp at $\sqrt{s}$ =13 TeV



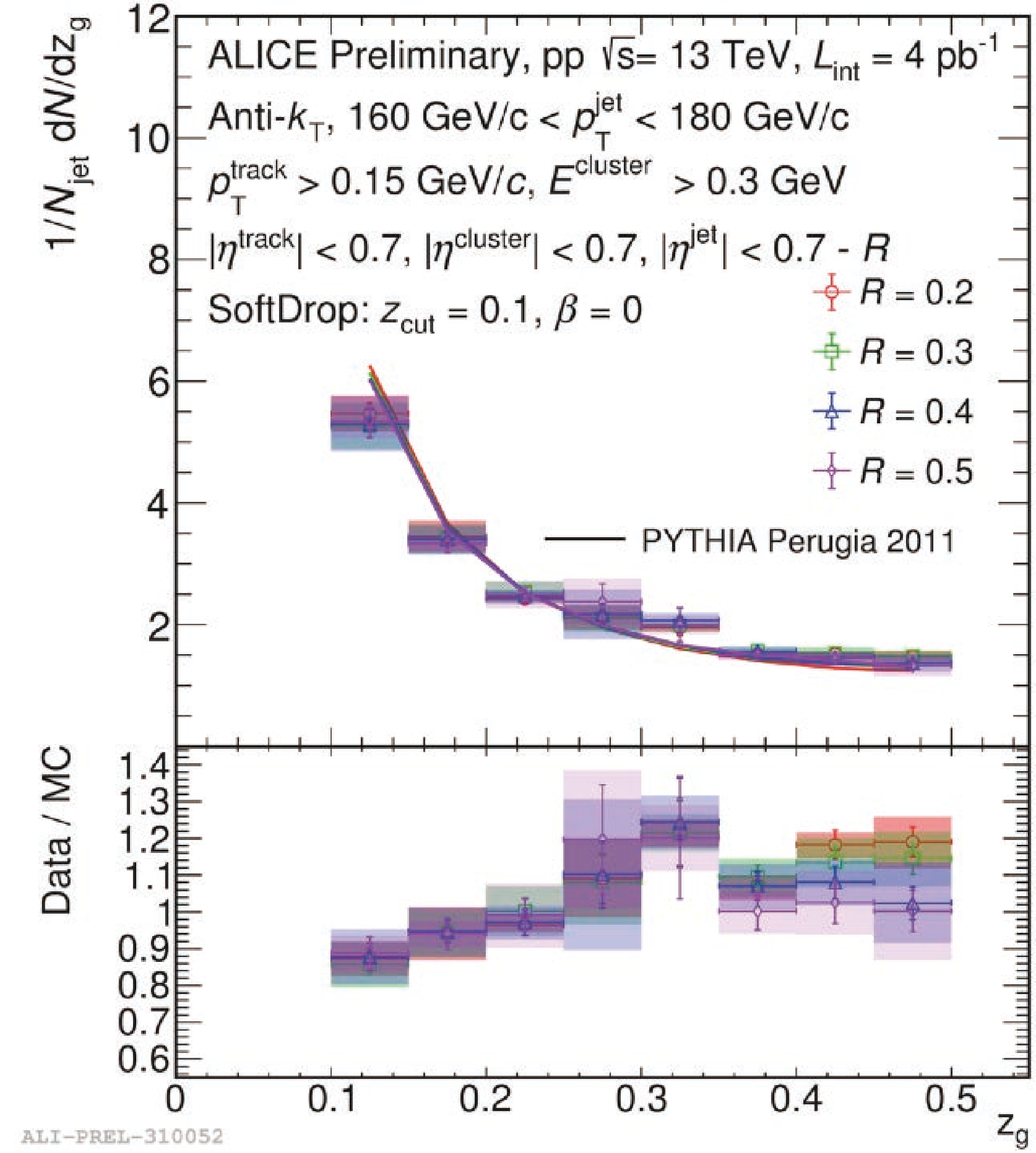
- **Utilized EMCal trigger for high-p_T jet up to 200 GeV/*c* for the first time!**
- Based on neutral energy in EMCal in a jet patch corresponding to $R \sim 0.3$
- No trigger bias region:
  - Low threshold: $p_T > 60$ GeV/*c*, High threshold: $p_T > 80$ GeV/*c*

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