Jet measurements in small systems relevant for medium modifications

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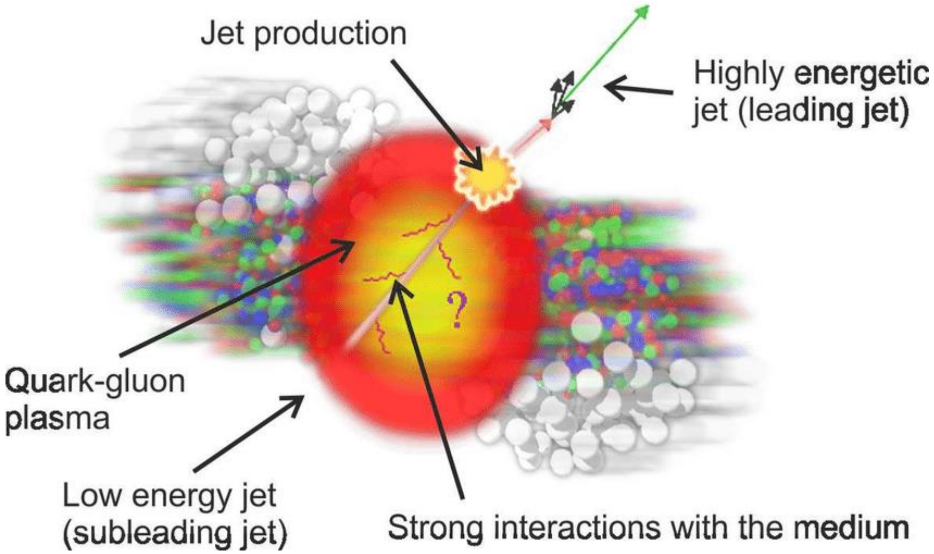
Attila Rádl
on behalf of ALICE, ATLAS and CMS Collaboration
Eötvös University, Wigner RCP

Outline

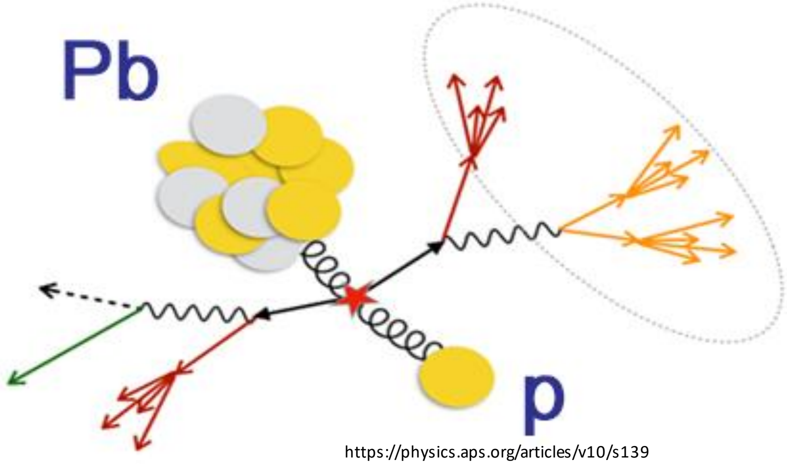
- Signatures and hard probes for quark-gluon plasma
- Observations in small size final states
  - Constraints on jet quenching based on latest measurements
  - Collective behavior in several systems
  - Dijet correlations and per-event yields

QGP medium with hard probes

- Quark Gluon Plasma (QGP): unique state of matter formed in heavy ion collisions
- Wide range of signatures in dense system
  - Suppression of jet spectra due to the energy loss in strongly interacting medium
  - Azimuthal anisotropies (collective flow)
- Smaller systems: benchmark for the interpretation of the heavy ion collision observations
  - Intermediate system: p-Pb collisions
  - Smallest: p-p collisions with high multiplicity



https://www2.lbl.gov/Science-Articles/Archive/sabl/2008/Feb/jets.html



https://physics.aps.org/articles/v10/s139

Jet suppression

- Modified particle p_T spectrum due to energy loss, observables of interest:
  - Nuclear modification factor
  - Per-jet charged particle yield
- Significant difference between heavy-ion and small systems
- Jet quenching in nuclear modification factor measurements

Measurements in Pb-Pb or p-Pb collisions

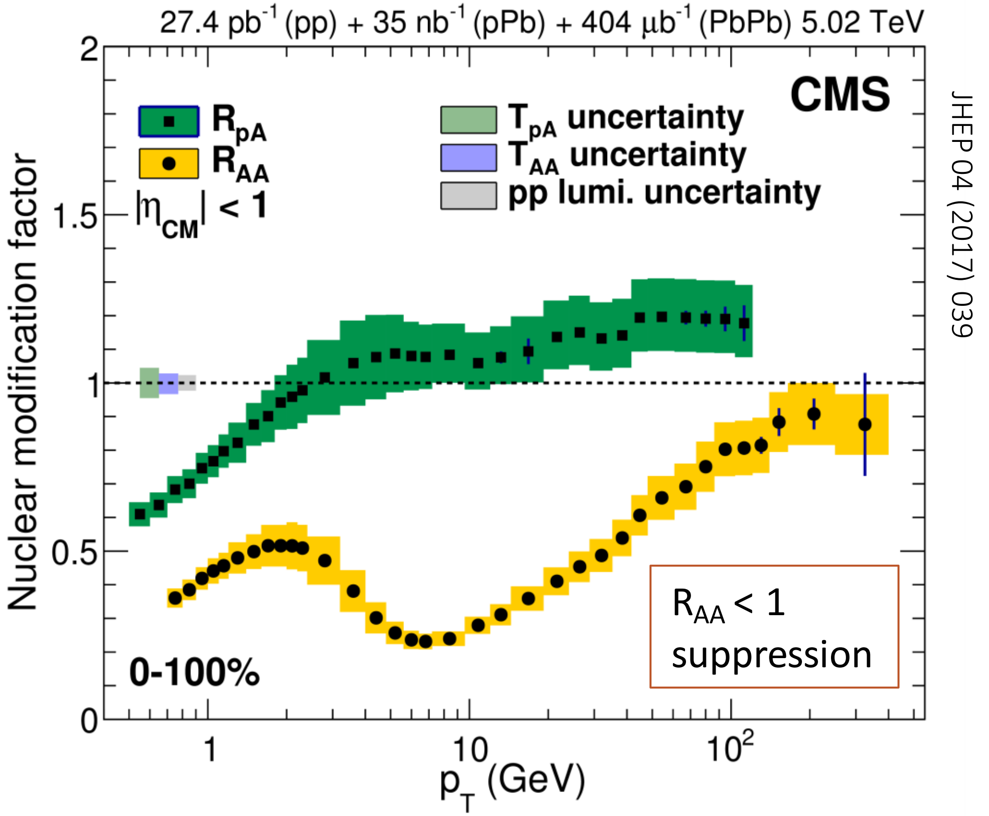
$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T} = \frac{dN^{AA}/dp_T}{T_{AA}\, d\sigma^{pp}/dp_T}$$

Nr of binary NN collisions

p-p reference

No quenching in p-Pb collisions at $p_T > 2$ GeV

Clear sign of suppression in Pb-Pb events



$R_{AA} < 1$ suppression

Latest results from ATLAS

- Ratio between per-jet (jet p_T > 60 GeV) charged particle yields

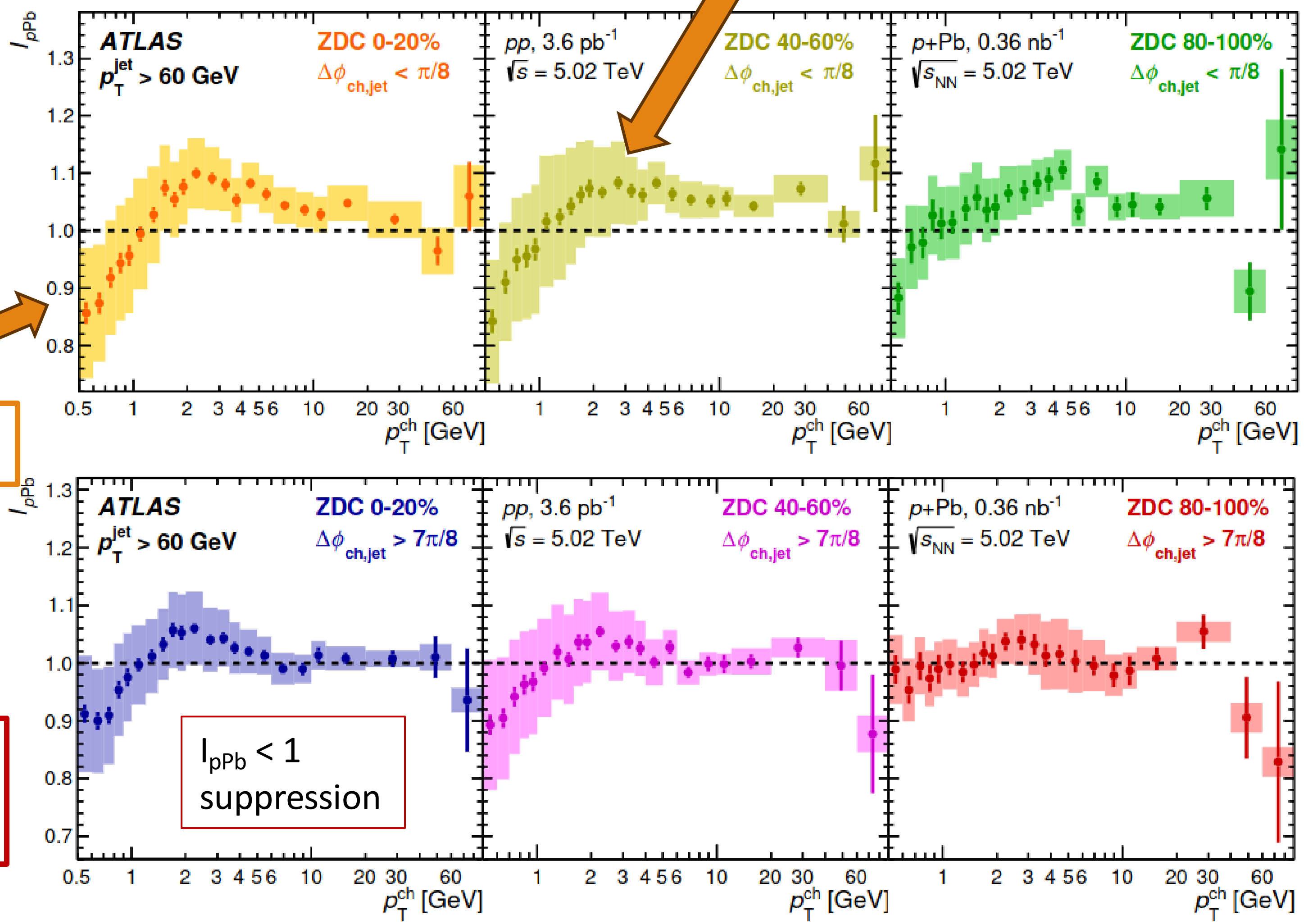
$$I_{pPb} = Y_{pPb} / Y_{pp}$$

5% centrality independent enhancement at near side

Hint of depletion at p_T < 1 GeV

- Away-side hadrons from fragmentation p_T ~ 60 GeV

p_T^{ch} > 1 GeV
compatible with I_{pPb}~1



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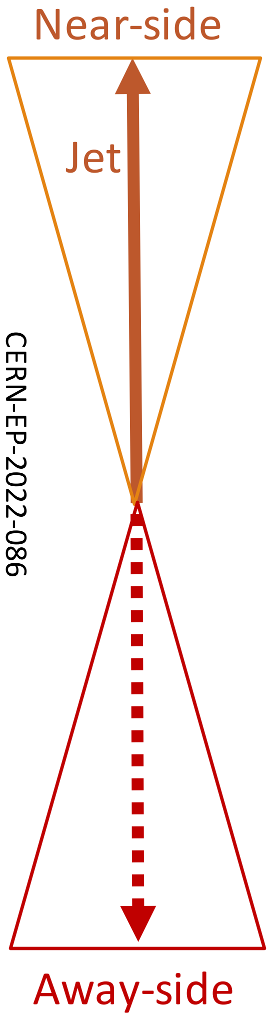
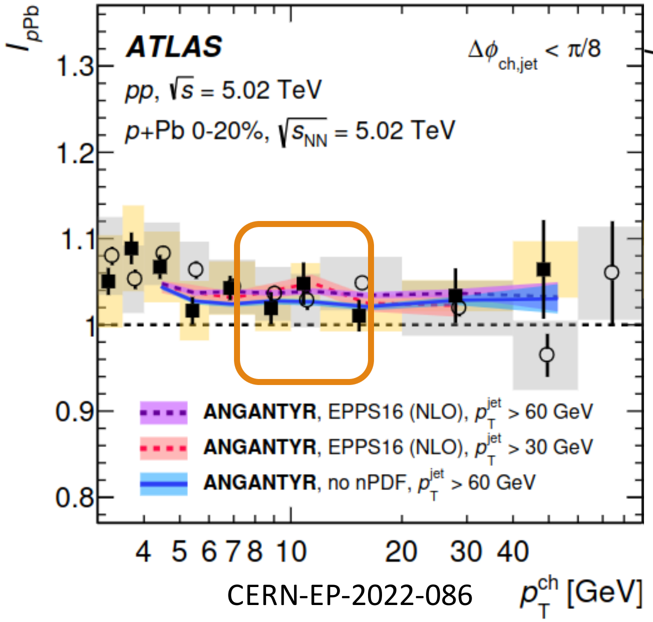


Jet quenching constraints

- Combined measurements with jet p_T > 30 GeV
- Focusing on the central collisions
- Similar trend for both sides
- Results are compared with Angantyr and AMPT (A MultiPhase Transport model) generator predictions
  - p_T^{ch} > 4.5 GeV: no UE subtraction is required
  - Running with or without final-state effects

Near-side



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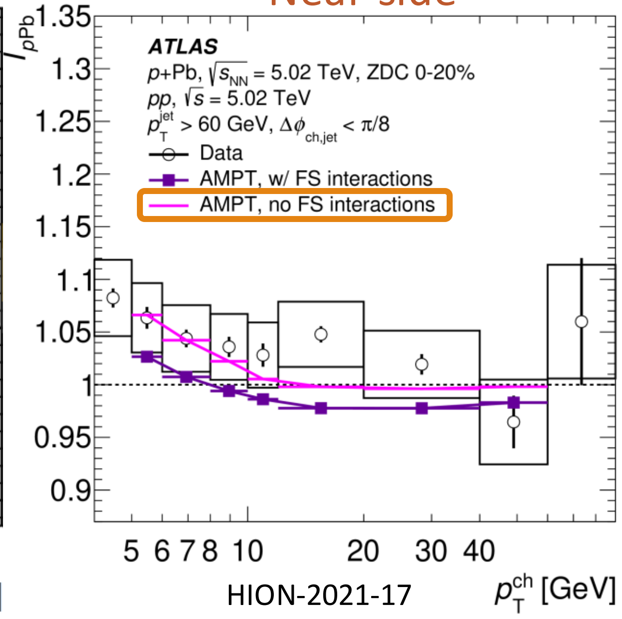
Near-side



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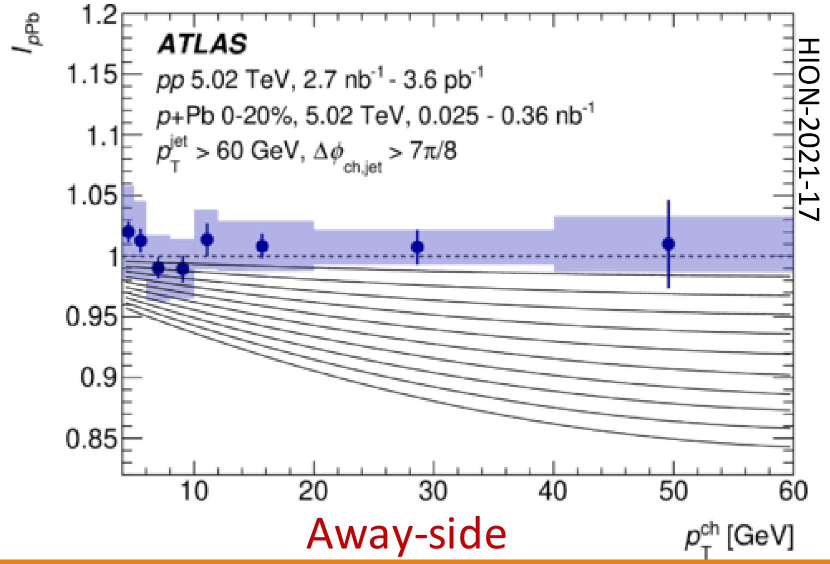
Small near-side enhancement, also predicted by Angantyr

AMPT without final state interactions show good agreement



Away-side

No sign of jet quenching in $z = p_T^{ch} / p_T^{jet} = 0.05\text{-}1.0$

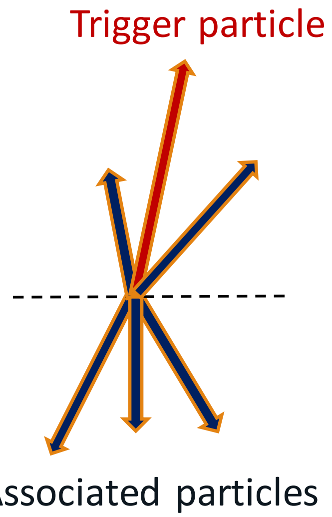
Final state anisotropies

- Two-particle angular correlations in high-energy collisions

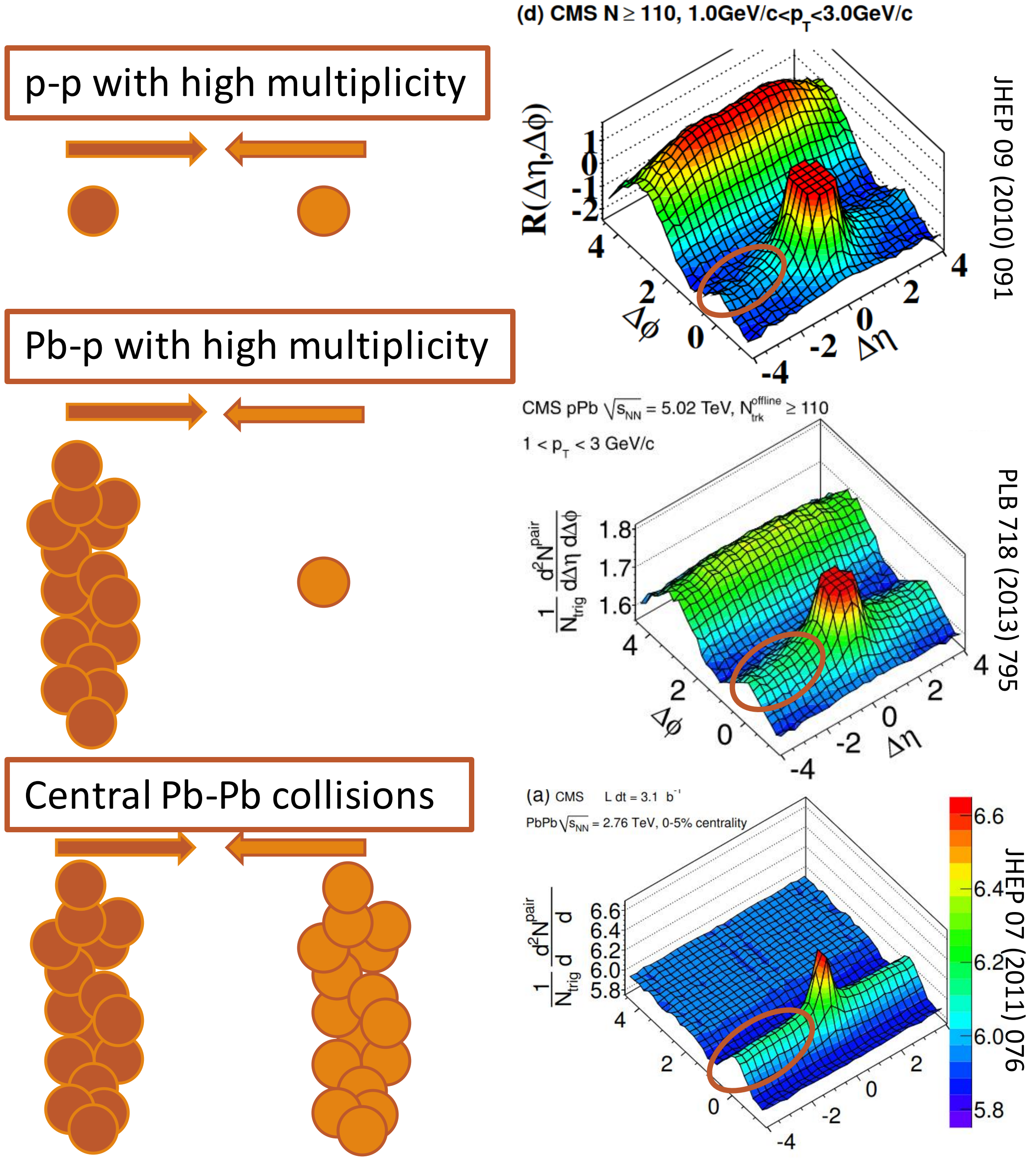
Jet particle correlation function

$$\frac{1}{N_{trig}}\frac{d^2 N_{assoc}}{d(\Delta\eta)\,d(\Delta\phi)} = \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Random combinatorial background



- short range collective effects observed in all systems
- Ridge structure: hint of long range correlations



Elliptic flow determination

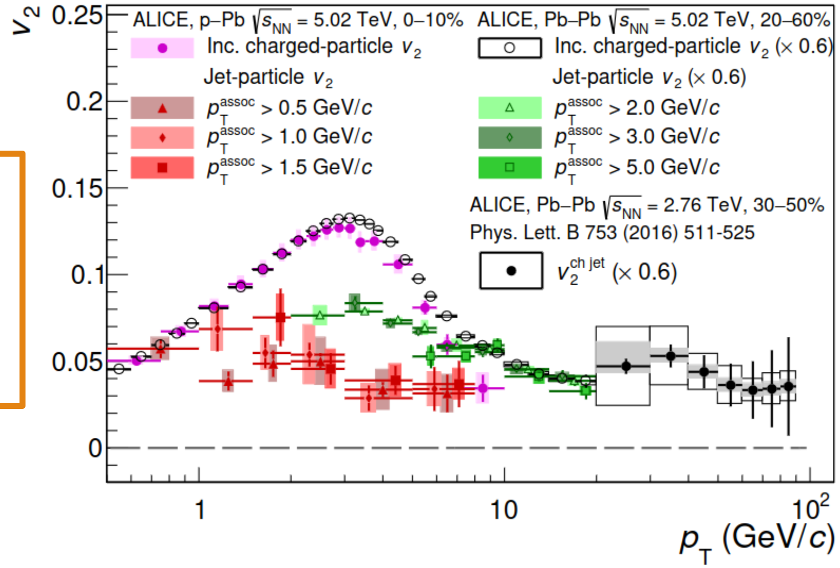
- Fourier expansion of the particle-pair projected azimuthal correlations

$$\frac{dN_{pair}}{d(\Delta\phi)} \propto 1 + 2\sum v_{n\Delta} \cos(n\Delta\phi)$$

v_2 elliptic flow

- Specific kinematic constraints on trigger and associated particle pairs
- Harmonics (v_n) interpreted as flow observables
  - Measured vs trigger particle p_T
  - Low-p_T regime: UE-UE dominated
  - High-p_T : more HS-UE pairs

v_2 increases up to 3 GeV, and decreases continuously as the jet physics regime is reached



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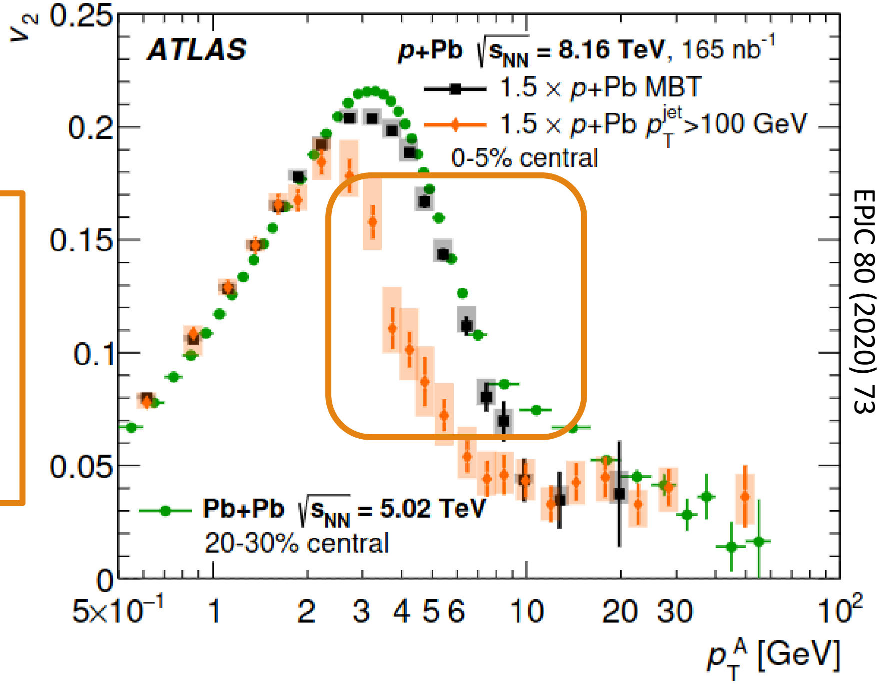
Significant difference between minimum bias and jet triggered events at intermediate p_T: different HS-UE contribution



EPJC 80 (2020) 73

ALICE results compared to AMPT

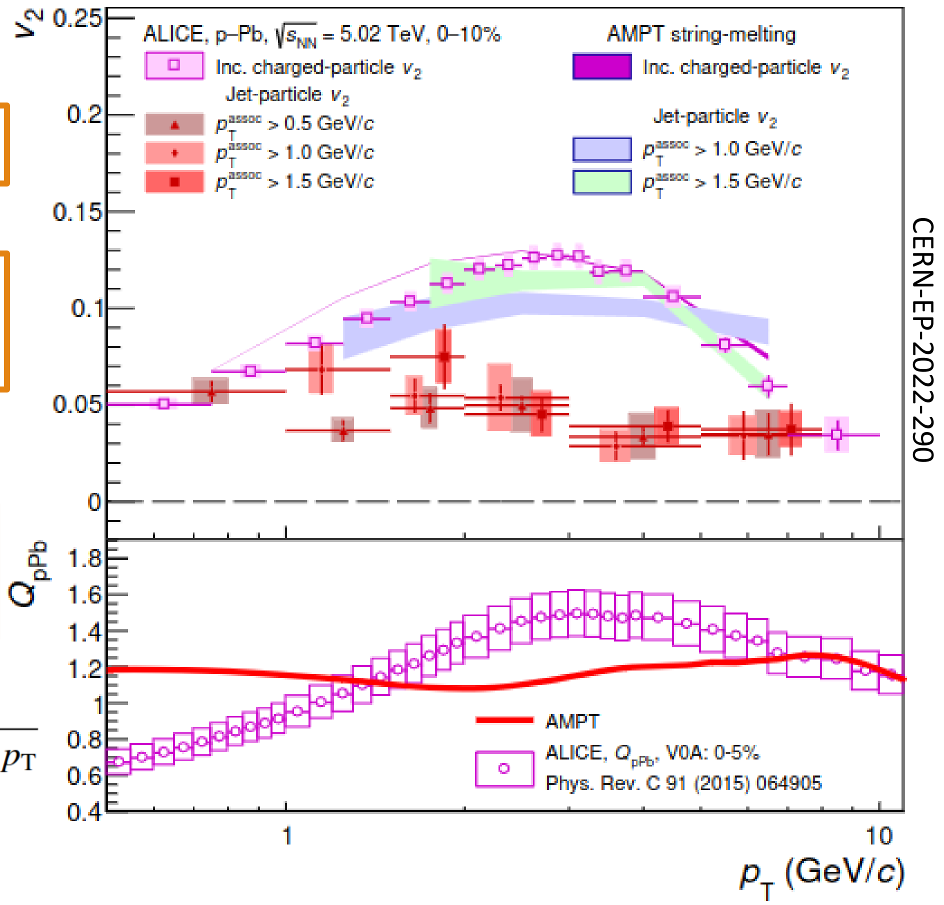
- $v_2 > 0$ without jet quenching in high multiplicity p-Pb?
- Inclusive charged particles show different trend
- AMPT predictions with string melting also included
  - All strings converted to q and anti-q
  - Elastic scattering between these partons responsible for long-range correlations

Predicted $v_2 > 0$

v_2 for jet particles is below the model predictions

Modification factor described at high-p_T

$$Q_{pPb}(p_T;\mathrm{cent}) = \frac{dN^{pPb}_{\mathrm{cent}}/dp_T}{\langle N^{\mathrm{Glauber}}_{\mathrm{coll}}\rangle dN^{pp}/dp_T}$$



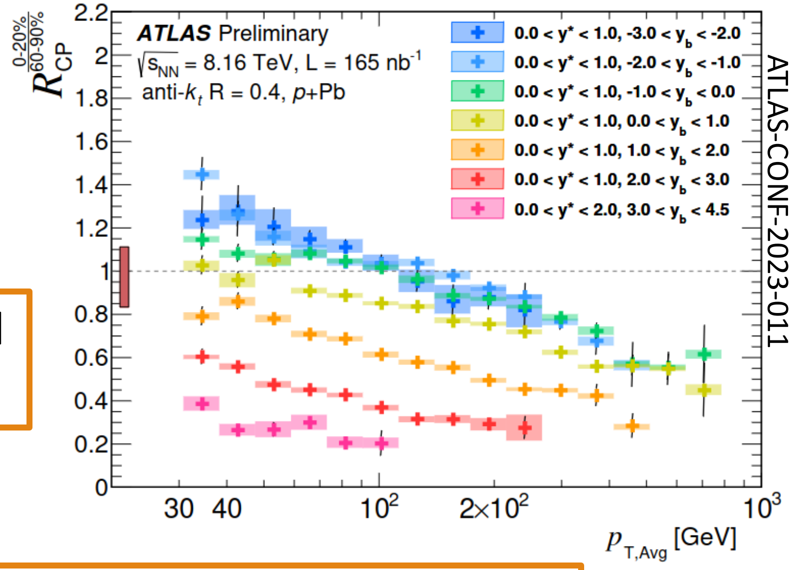
Initial spatial anisotropy → Partons escape more likely along the shorter axis of the volume → Azimuthal anisotropies not from hydrodynamic flow

Dijets in small systems

- Properties of dijets measured in photonuclear and p-Pb and p-p collisions
  - Angular correlations
  - Per-event dijet yields

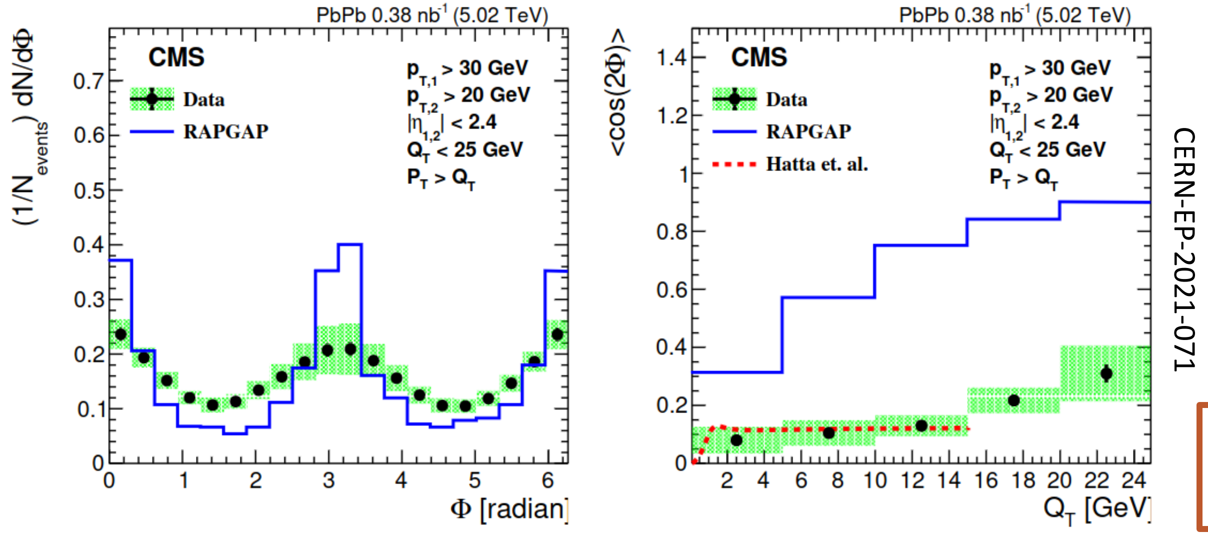
$$R_{CP}^{\frac{0-20\%}{60-90\%}}(p_{T,Avg}, y_b, y^*) = \frac{\frac{1}{\langle T_{AB}^{0-20\%}\rangle}\frac{1}{N_{evt}^{0-20\%}}\frac{d^3N_{dijet}^{0-20\%}}{dp_{T,Avg}dy_b dy^*}}{\frac{1}{\langle T_{AB}^{60-90\%}\rangle}\frac{1}{N_{evt}^{60-90\%}}\frac{d^3N_{dijet}^{60-90\%}}{dp_{T,Avg}dy_b dy^*}}$$

Central / peripheral dijet yield

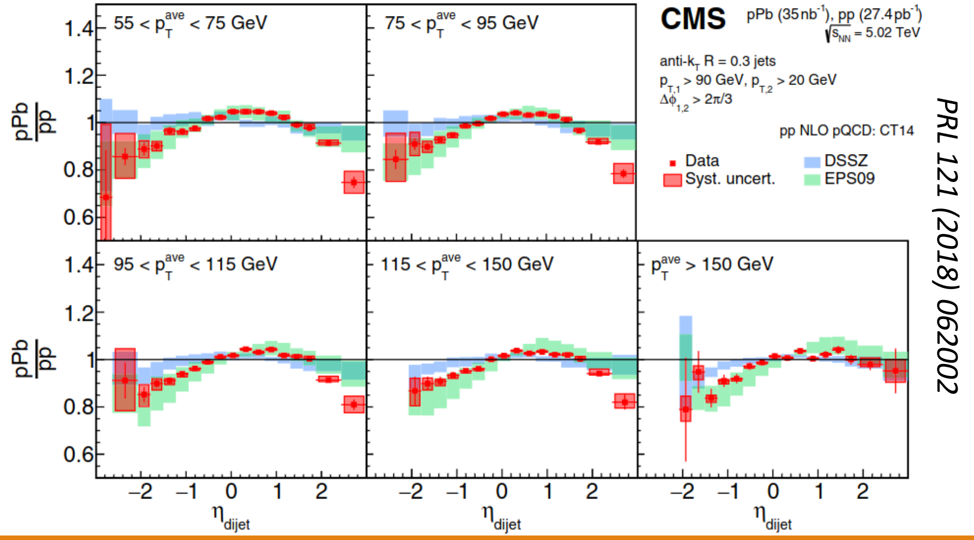


Modifications in dijet yield vs pseudorapidity compared to p-p reference system (shadowing)

Non-trivial angular correlations in ɣ-Pb dijet event



Q_T: vector sum of two jets

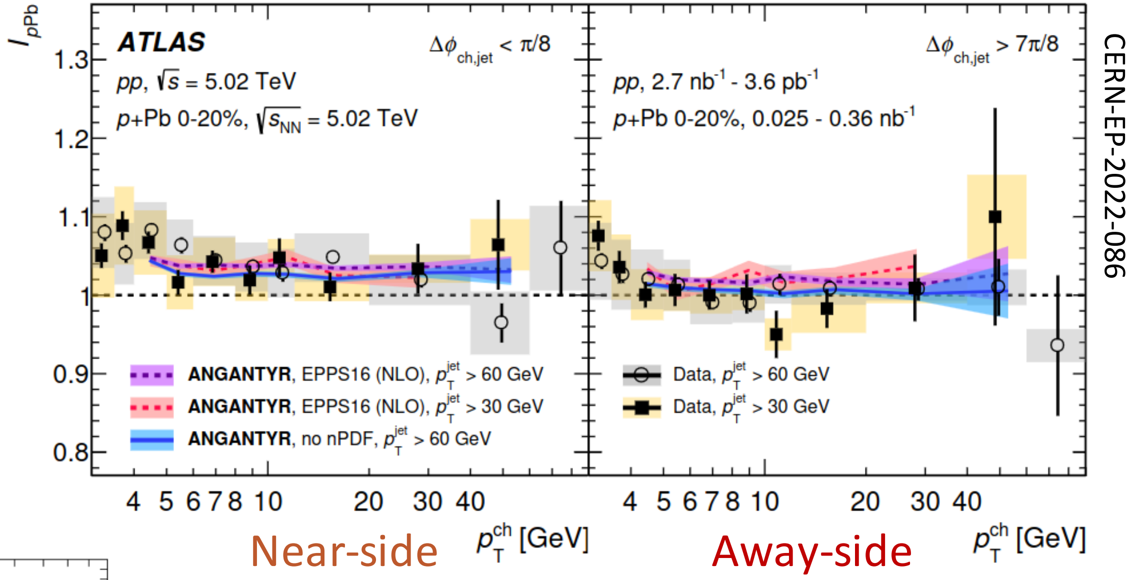


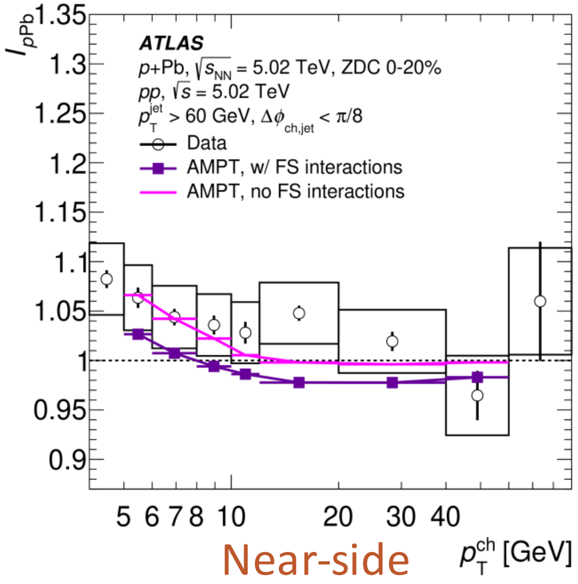
Overview

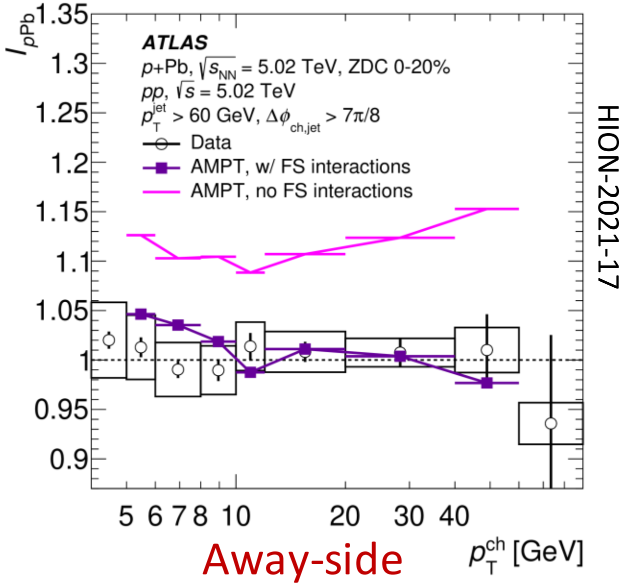
- Hard probes can be used to explore the behavior of small systems
- Long-range angular correlations observed in heavy ion, but also in high multiplicity p-Pb and p-p collisions
- Elliptic flow $v_2 > 0$ in various measurements as in heavy-ion collisions
  - But no sign of jet quenching
  - Latest results: string melting model (in AMPT) suggests positive v_2 without hydrodynamical flow effects
- Modifications in dijet yields, and unexpected angular correlations are measured in photonuclear and p-Pb collisions
- Run-3 heavy ion runs provide unique opportunity: O-O collisions (details in backup) and increased p-Pb luminosity
  - Further understanding of the initial state is expected

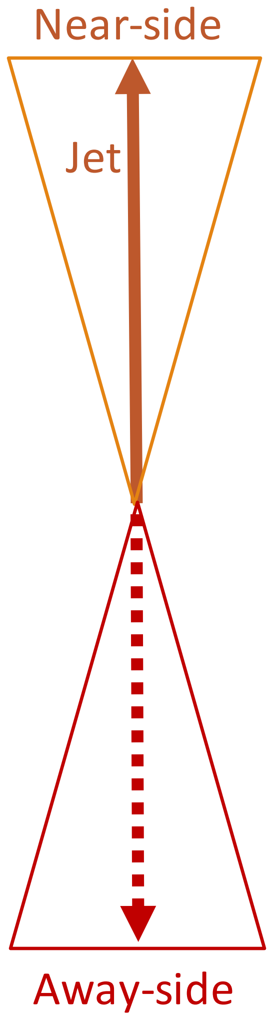
Backup

Jet quenching constraints from ATLAS measurements



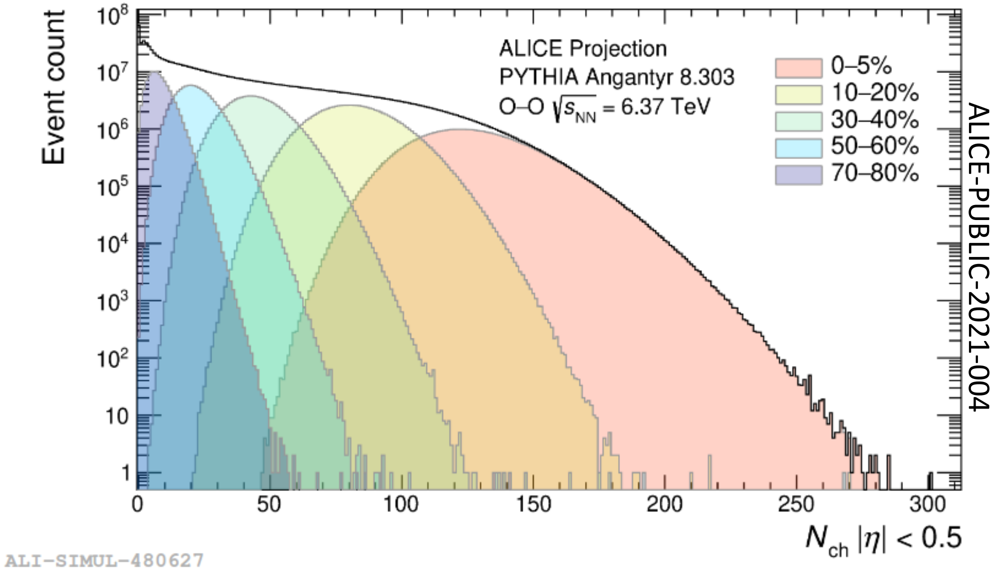




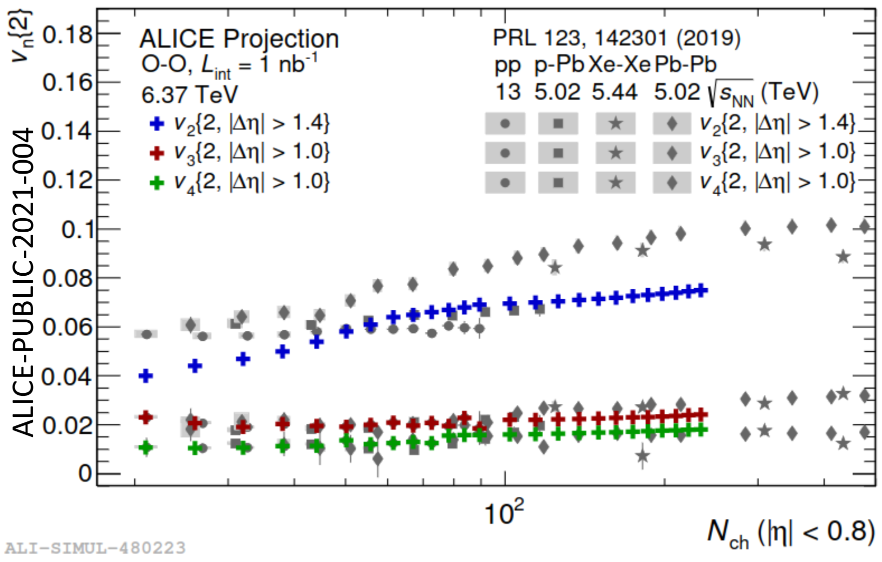


Oxygen run at the LHC

- Alternative intermediate system: O-O collisions
  - Broad covered final state multiplicity
  - Geometrically small system, but large fluctuations expected
  - Further investigation of the missing jet quenching
  - Flow effects can also be studied to explore the intermediate multiplicity range between p-p, p-Pb and Pb-Pb systems
- Short run is proposed at the LHC
  - 6.37 TeV cm energy with ~1 nb^{-1} delivered data



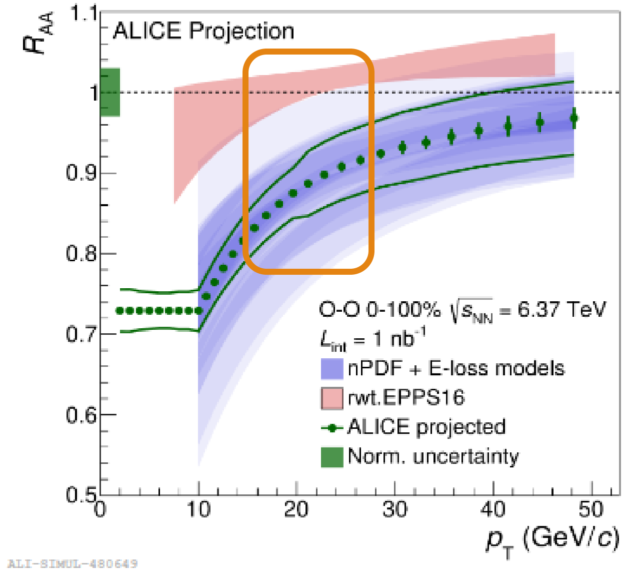
Projections of the O-O run results

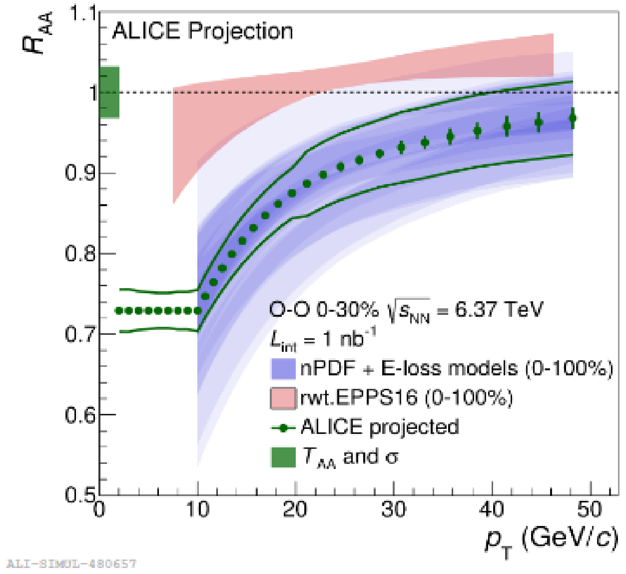


- Foreseen correlation measurements over large variety of final state multiplicities

Connection between the fluctuation dominant and the geometry dominant region

Statistical precision < 1.5% up to 50 GeV





ALICE-PUBLIC-2021-004

- Search for energy loss measuring the nuclear modification factors
- The possibility of observing a reduction in R_{AA} depends on the size of the effect

$20 < p_T < 25$ GeV
Uncertainties are the smallest for the predictions

References

- CMS Collaboration "Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV", JHEP 04 (2017) 039
- ATLAS Collaboration "Transverse momentum and process dependent azimuthal anisotropies in $\sqrt{s_{NN}}$ = 8.16 TeV p+Pb collisions with the ATLAS detector", EPJC 80 (2020) 73
- ATLAS Collaboration "Strong constraints on jet quenching in centrality-dependent p+Pb collisions at 5.02 TeV from ATLAS", CERN-EP-2022-086
- ALICE Collaboration "Azimuthal anisotropy of jet particles in p-Pb and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV ", CERN-EP-2022-290
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- ATLAS Collaboration "Measurement of the centrality dependence of the dijet yield in p+Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV p+Pb with the ATLAS detector", ATLAS-CONF-2023-011
- CMS Collaboration "Azimuthal correlations within exclusive dijets with large momentum transfer in photon-lead collisions", CERN-EP-2021-071
- CMS Collaboration "Constraining gluon distributions in nuclei using dijets in proton-proton and proton-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV", PRL 121 (2018) 062002