Recent Highlights on Jet Physics in Heavy-ion Collisions with ALICE and New Developments

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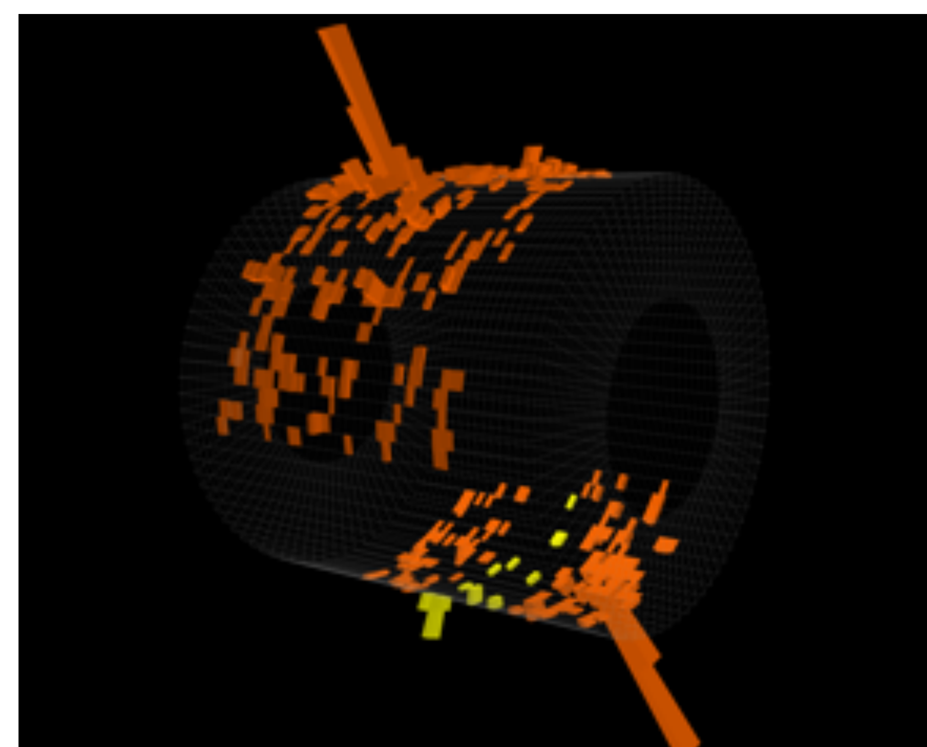
9th France-China Particle Physics Laboratory Workshop

March 30 — Apr. 1, 2016, Strasbourg, France

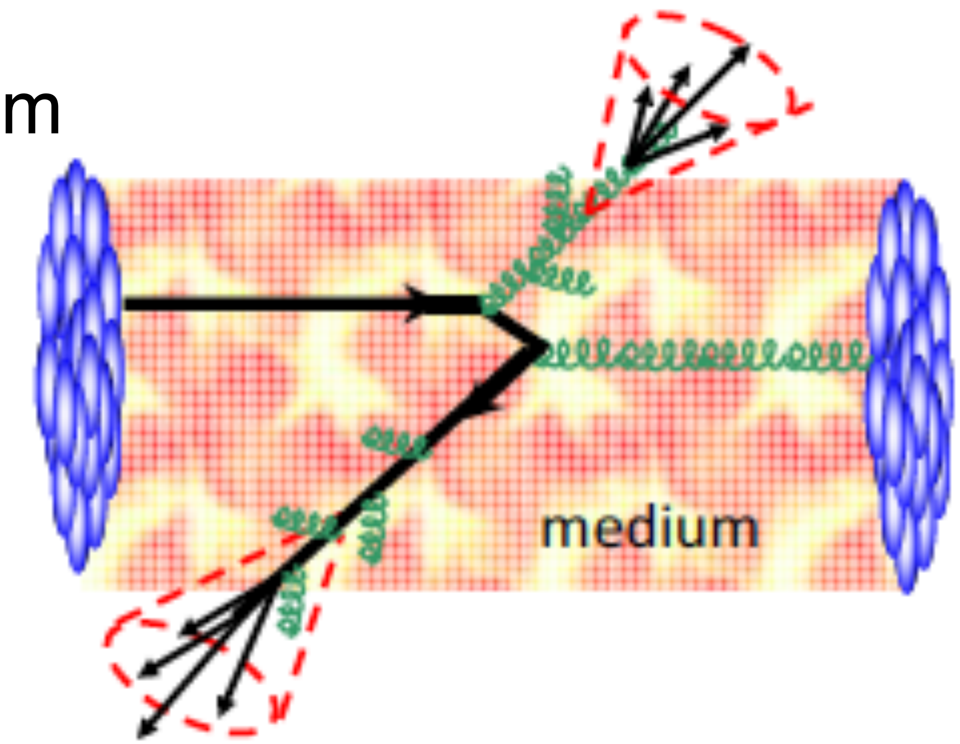
- **Introduction**
- **Inclusive and semi-inclusive productions**
- **Jet shapes**
- **Strangeness production in jets**
- **Conclusion**

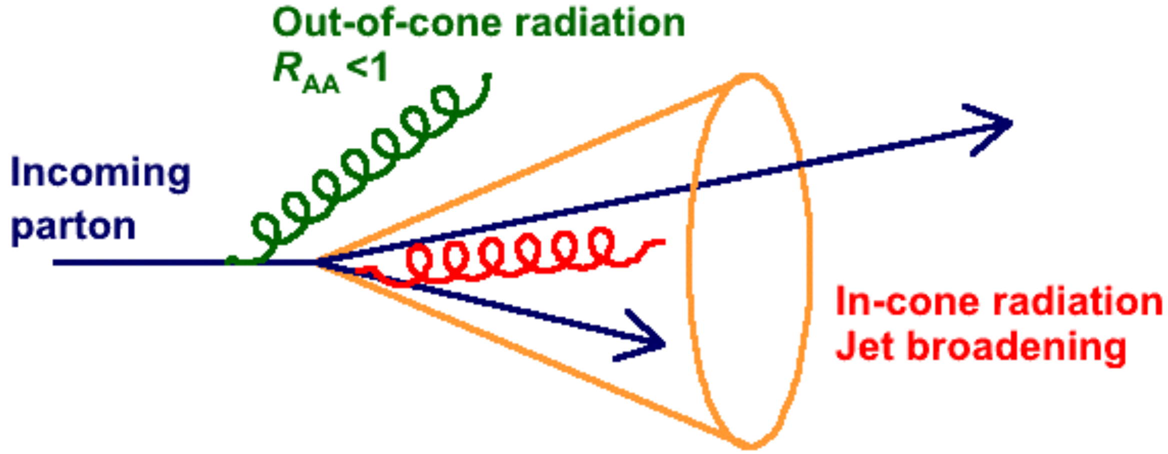


Jet Production in Heavy-Ion Collisions

- Jet: a spray of particles from hard parton fragmentation — get closer access to parton energy
- Hard partons — produced before the QCD medium forms, interact with the hot and dense medium

➡ Efficient probes for understanding the transport properties of the medium





$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

QCD medium

QCD vacuum

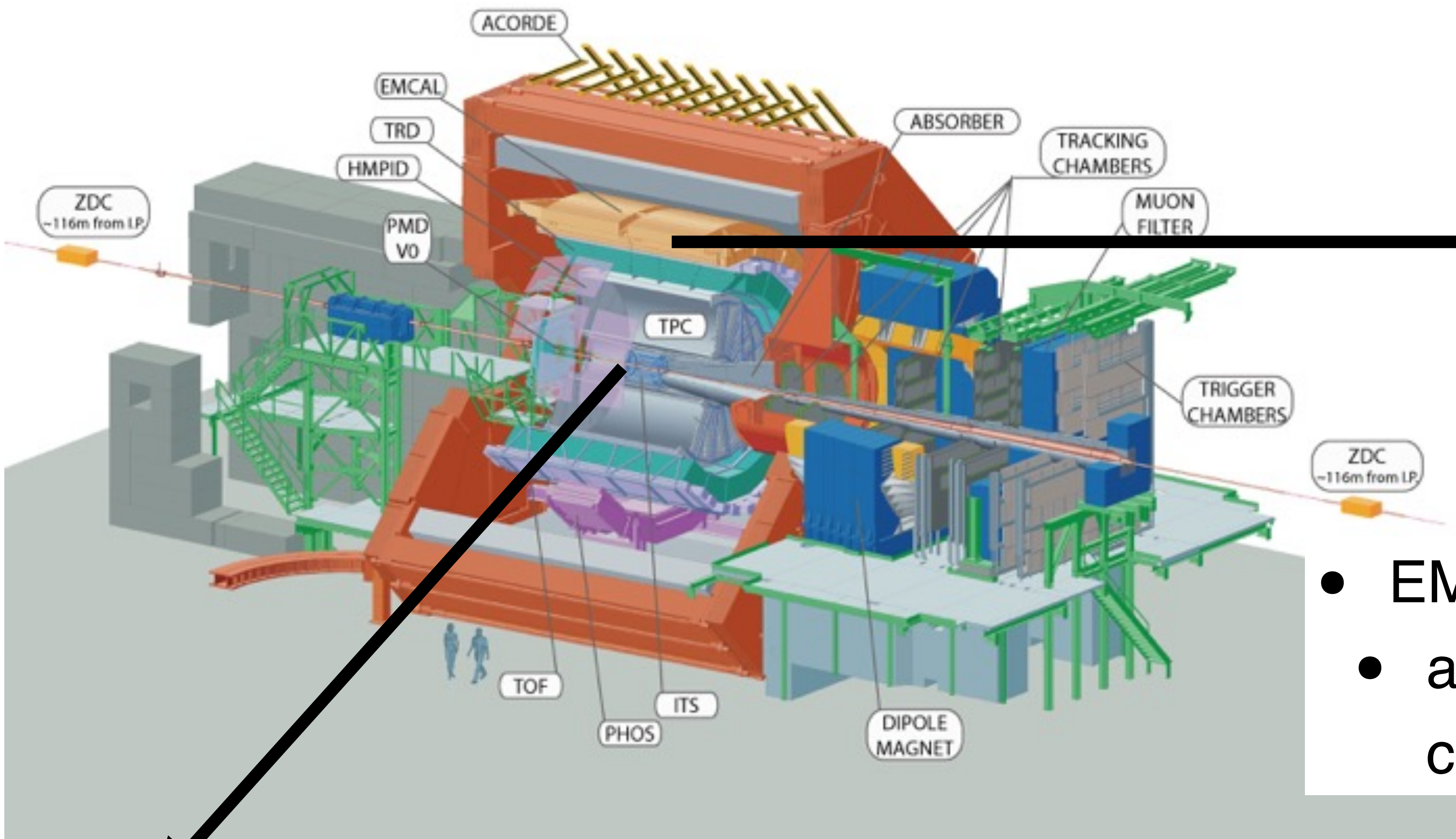
- Out-of-cone radiation: energy loss in jet cone — $R_{AA} < 1$

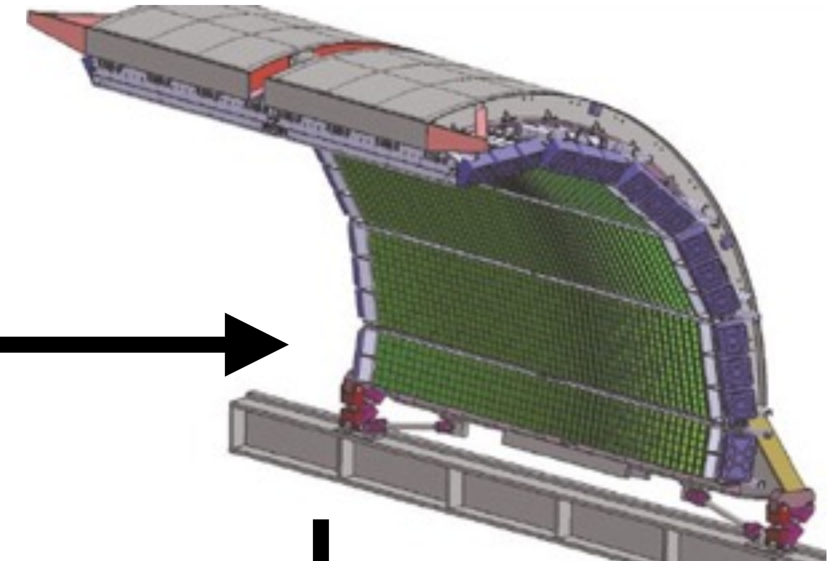
➡ Jet yield suppression, jet v_2, dijet or hadron–jet acoplanarity…

- In-cone radiation: medium modified fragmentation — $R_{AA} = 1$

➡ Jet shape broadening, modification of transverse energy profiles…

Jet Measurement with ALICE





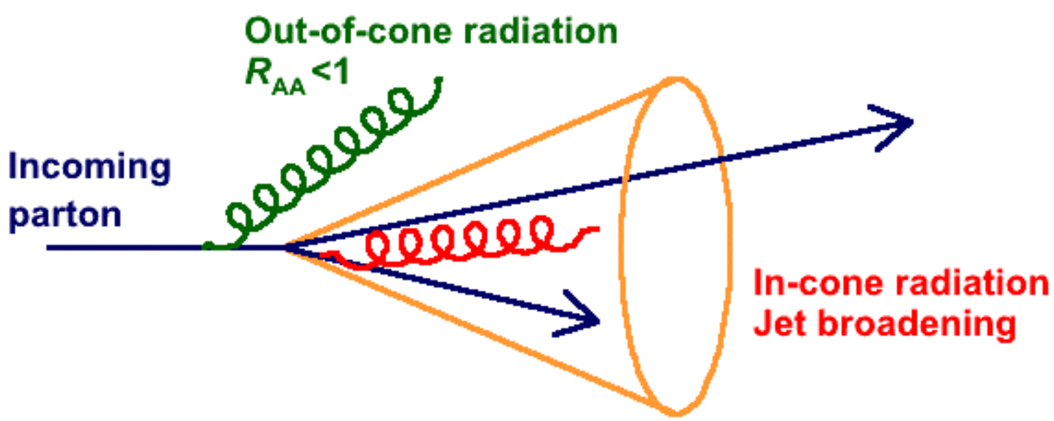
- EMCal: |η|<0.7, 1.4<ϕ<π
  - a Pb-scintillator sampling calorimeter

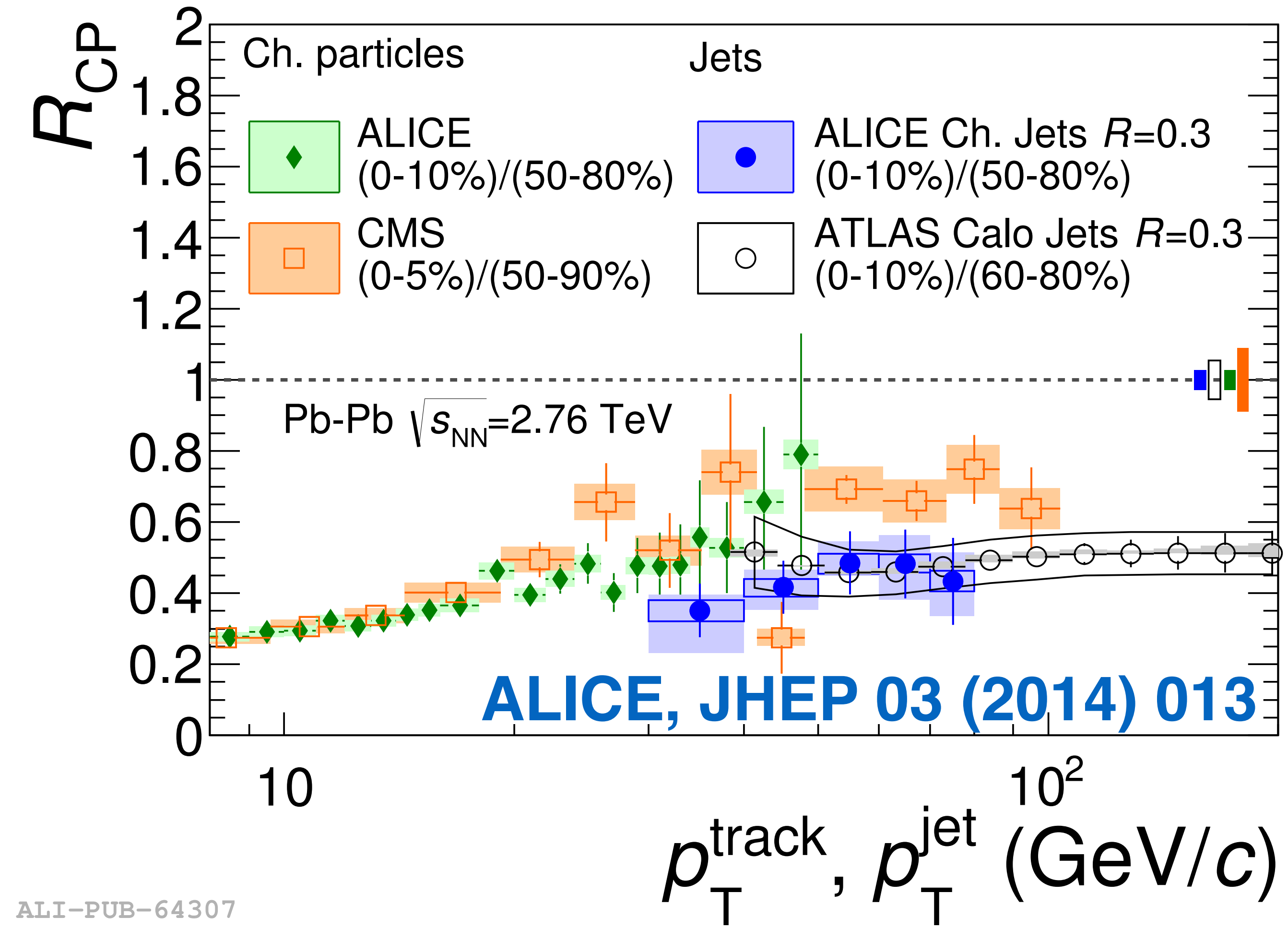
Charged-particle correction: prevents energy double counting

- Tracking: |η|<0.9, 0<ϕ<2π
  - TPC: gas drift detector
  - ITS: silicon detector

Charged constituents → JET ← Neutral constituents

Jet Yield Suppression





- ATLAS: calorimetric jets
- ALICE: charged-particle jets — more sensitive to the low-momentum fragments

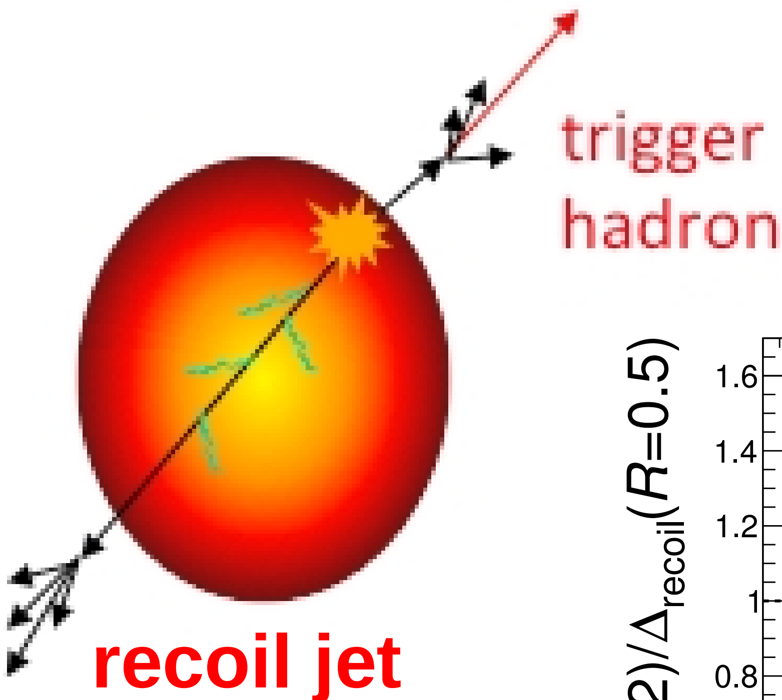
- Agreement between ALICE and ATLAS

➡ Contribution of low momentum jet fragments to jet energy is small

- R_{CP} of jets and single hadrons are compatible

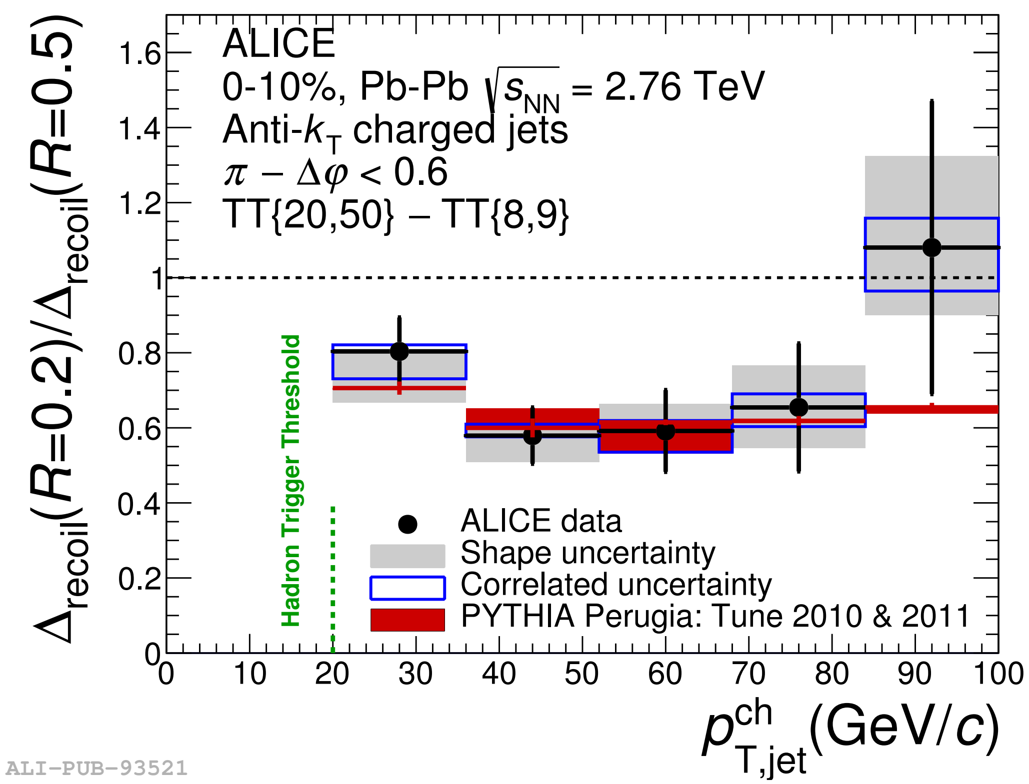
➡ Indication that the momentum is redistributed to larger angles

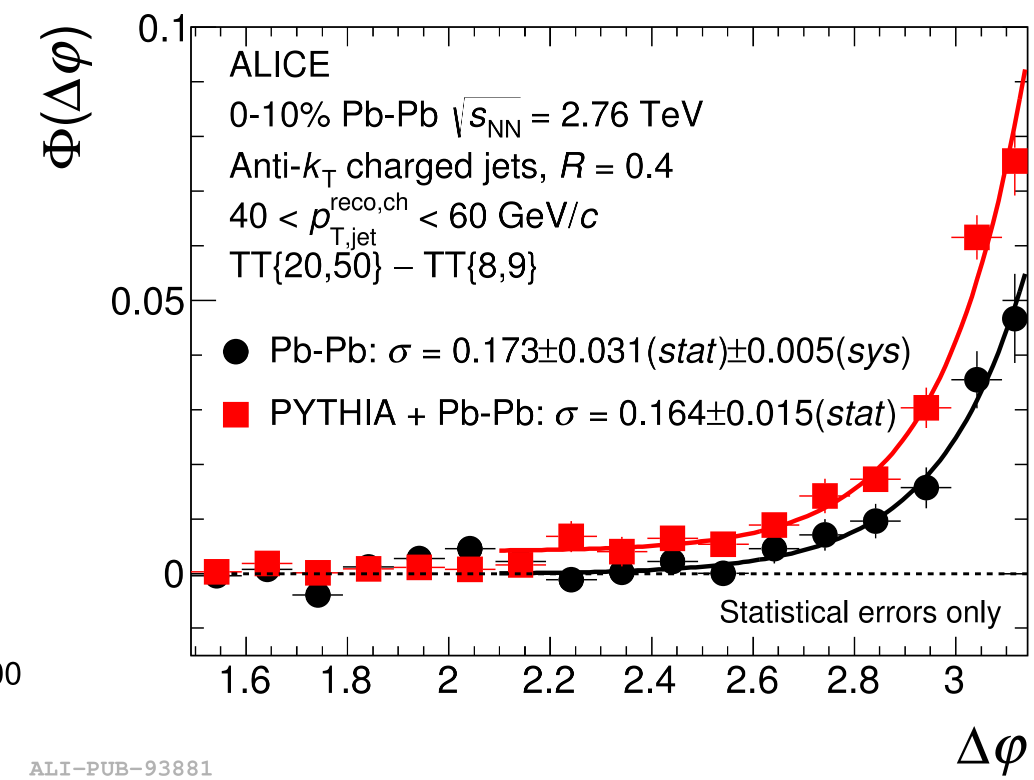
Semi-inclusive Recoil Jet



$$\Delta_{\mathrm{recoil}} = [1/N_{\mathrm{trg}} \mathrm{d}N/\mathrm{d}p_{\mathrm{T,jet}}]_{\mathrm{trg}} - [1/N_{\mathrm{ref}} \mathrm{d}N/\mathrm{d}p_{\mathrm{T,jet}}]_{\mathrm{ref}}$$

ALICE, JHEP 09 (2015) 170



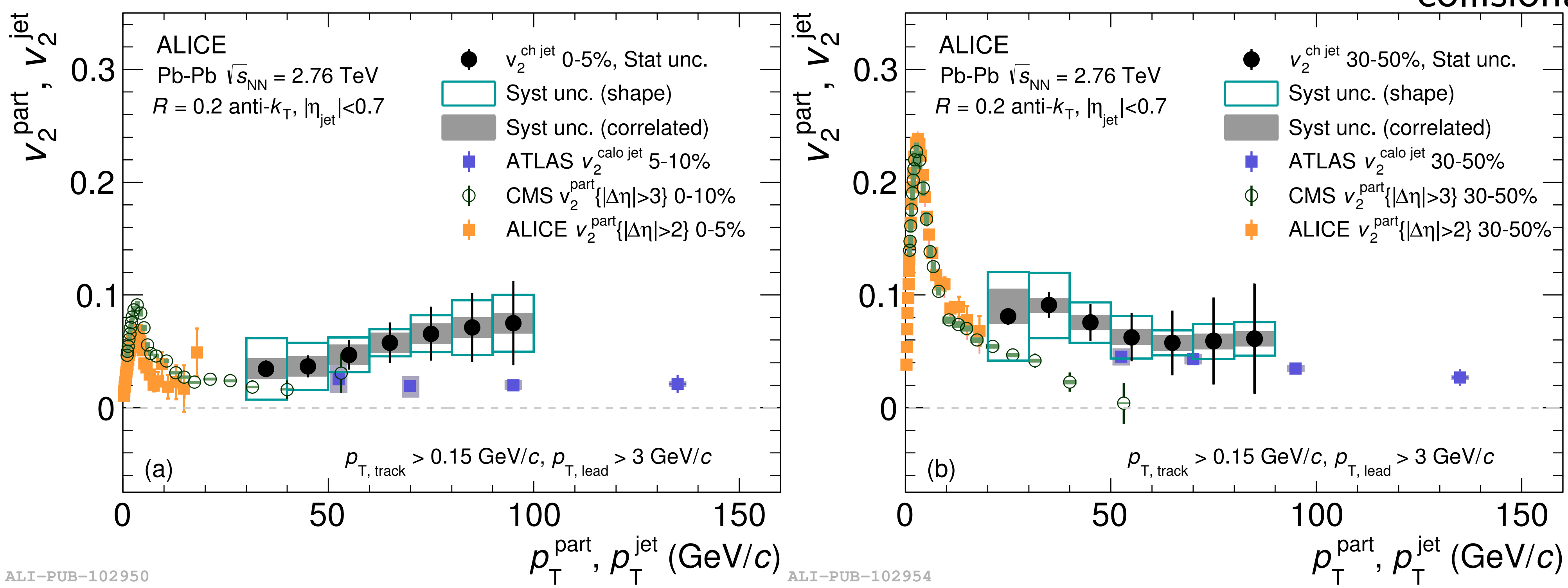


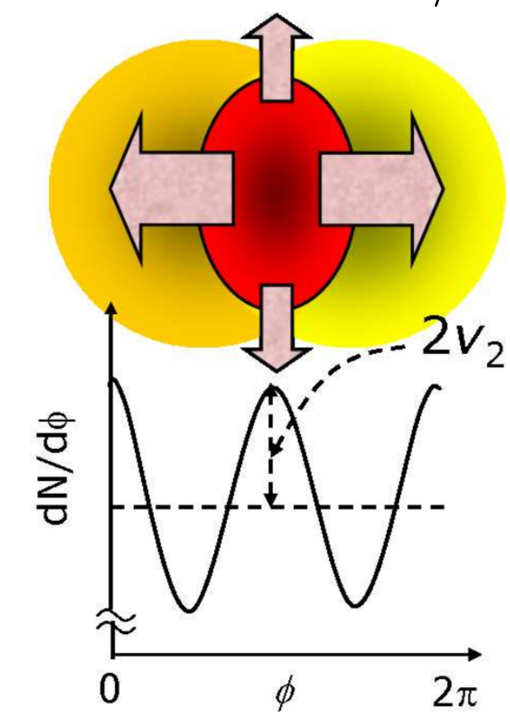
- Recoil-jet ratio — consistent with PYTHIA reference
  - ➡ Intra-jet energy profile is not changed significantly for $R < 0.5$
  - ➡ Significant in-medium radiation to angles > 0.5 rad
- Width of Φ(jet,trigger) — similar in Pb–Pb and pp collisions
  - ➡ No evidence for medium-induced acoplanarity

Jet Azimuthal Anisotropy

ALICE, arXiv:1509.07334

$\underbrace{\Delta E \propto L}_{\text{collisional}} \leftrightarrow \underbrace{\Delta E \propto L^2}_{\text{radiative}} \leftrightarrow \underbrace{\Delta E \propto L^3}_{\text{AdS/CFT}}?$





- Central collisions (0–5%): null-hypothesis can not be excluded (1.5~2σ)

➡ Initial-state fluctuations (?)

- Semi-central collisions (30–50%): non-zero v_2 (3σ effect)

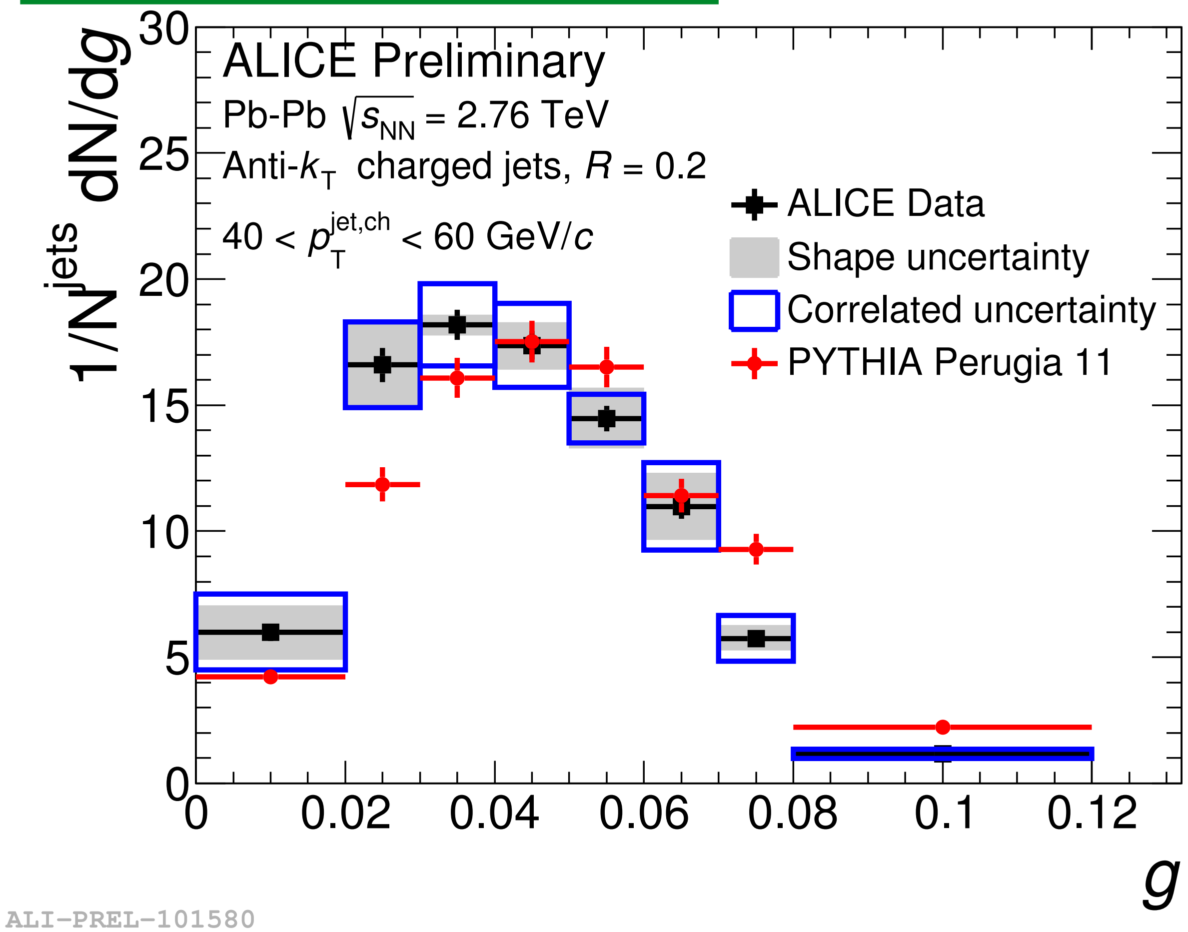
➡ Information of path-length dependence of parton in-medium energy loss

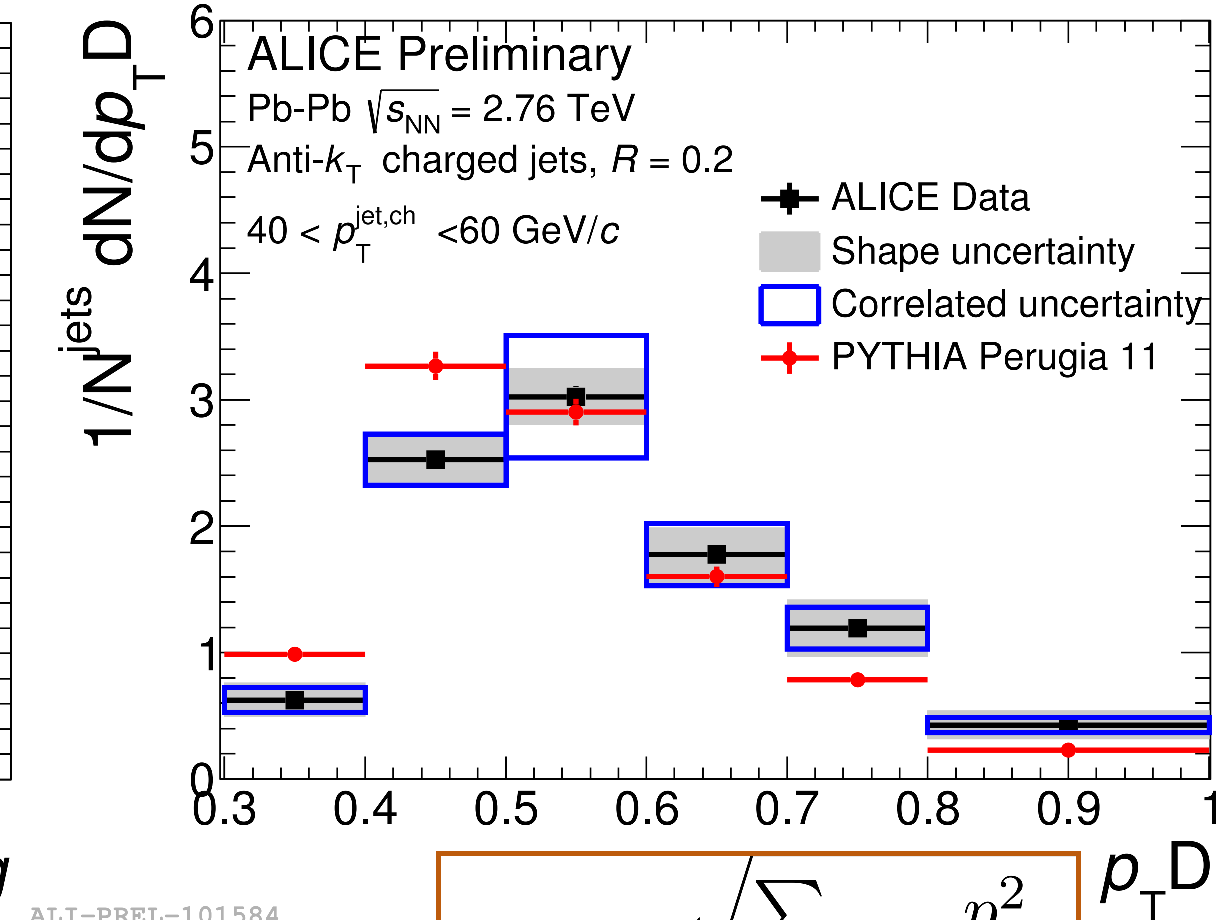
- Compatible with single particle and calo-jet v_2 at high p_T (with different energy scales)

➡ Large parton energy loss and that is sensitive to the collisions geometry

Jet Shapes

$$g = \sum_{i \in \text{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R(i, \text{jet})$$

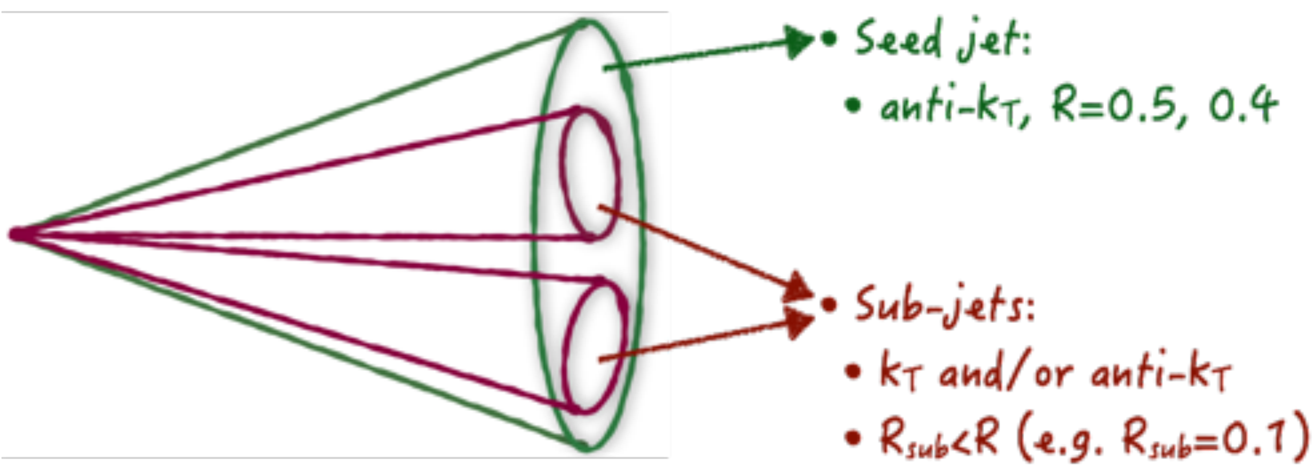




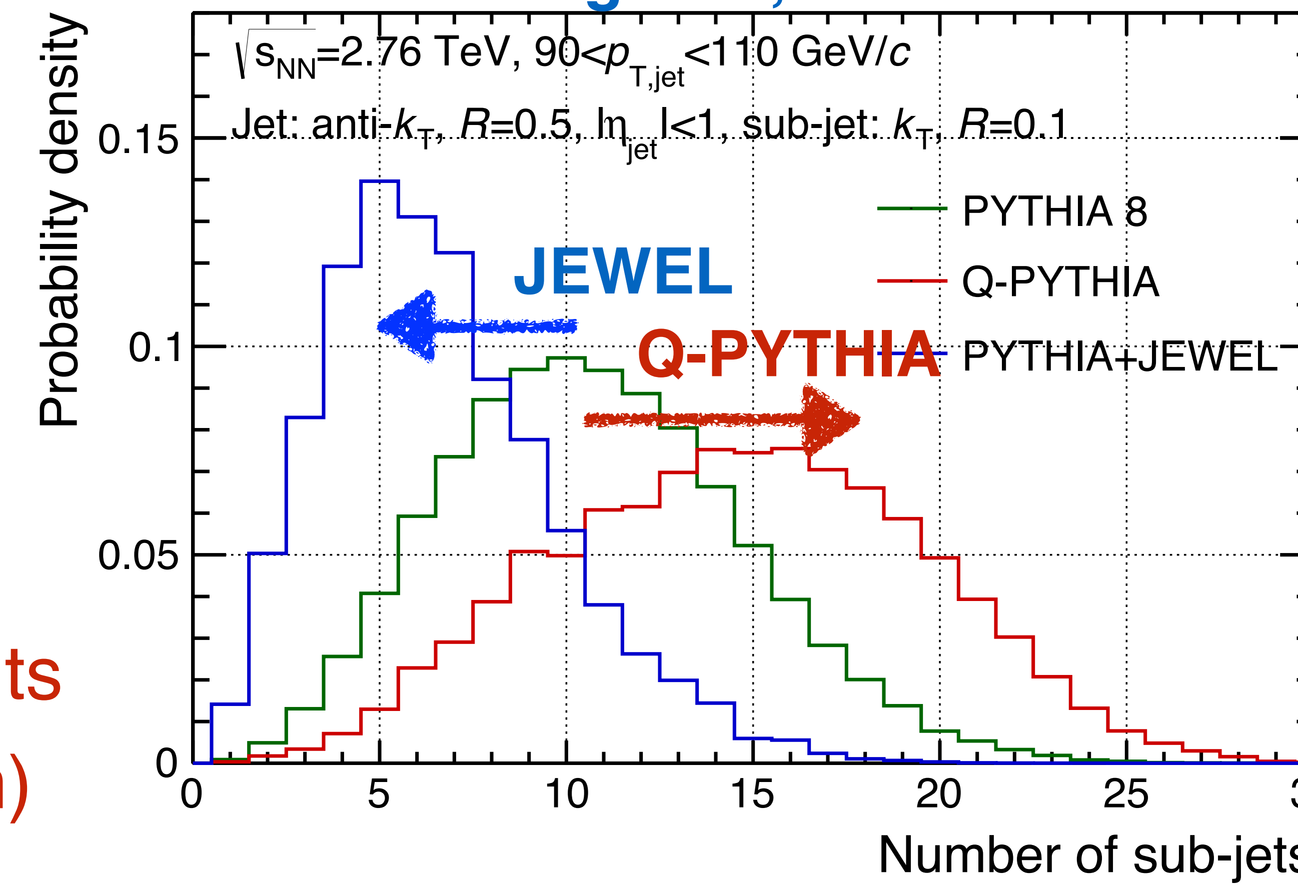
$$p_{\mathrm{T}}D = \frac{\sqrt{\sum_{i \in \text{jet}} p_{\mathrm{T},i}^2}}{p_{\mathrm{T,jet}}}$$

- Radial momentum (g) — p_{T}-weighted width of jet
  - g shifted to lower values in Pb–Pb data relative to PYTHIA — indication of more collimated jet cores in data
- $p_{\mathrm{T}}D$ — dispersion of jet constituents
  - $p_{\mathrm{T}}D$ shifted to large values relative to PYTHIA — indication of few jet constituents and large dispersion

Sub-jet Structure: Proposed Observable



X. Zhang et al, arXiv:1512.09255



- Sub-jets: re-clustering the constituents in a jet (possibly a different algorithm)
- Smaller radius/area — reduces the background fluctuations and pile-up
- Opening the degree of freedom in jets — details of fragmentation with decreased dependence on hadronic DOFs, provides sensitivity to details of the parton radiation/shower
- Different multiplicity of sub-jets in the two models — sub-jet production is sensitive to quenching mechanisms

Sub-jet Structure: Proposed Observable

X. Zhang et al, arXiv:1512.09255

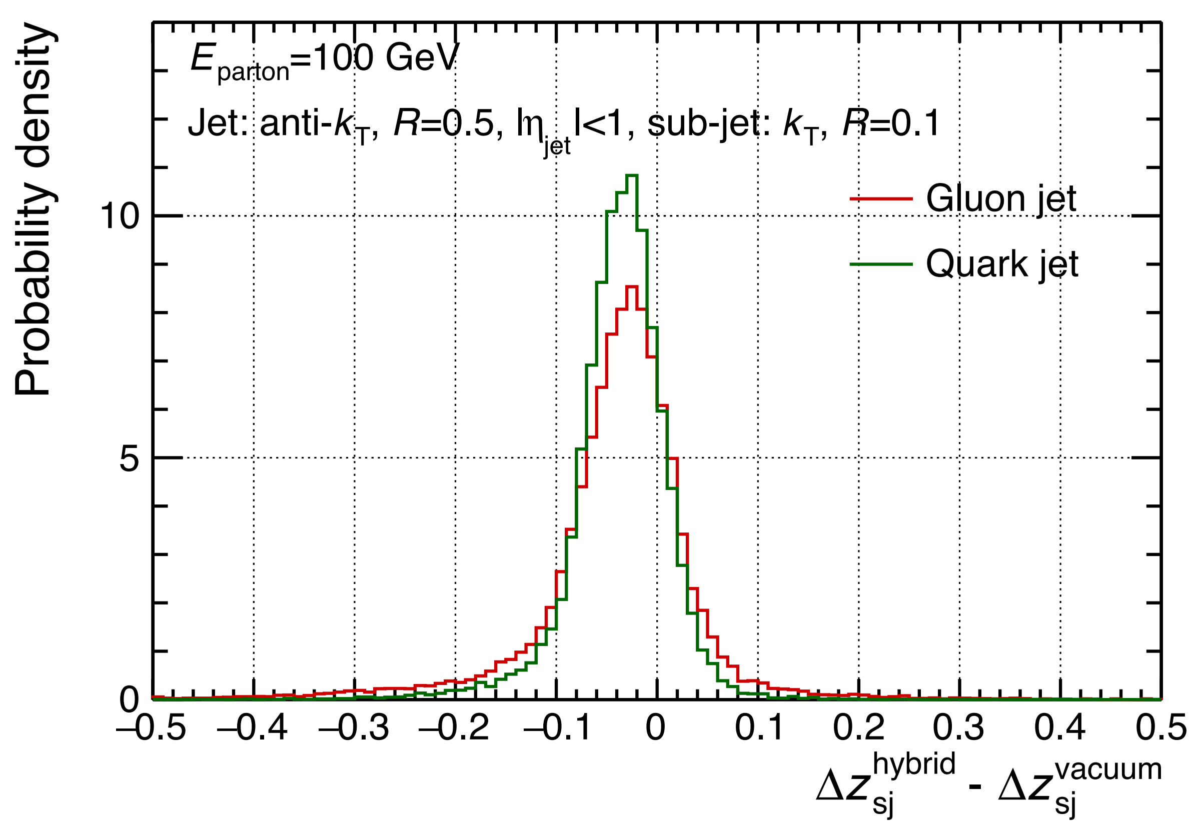
- The local background for the two sub-jets is (to a large extend) similar
  - use the p_T difference between the two leading sub-jets
- In the leading order (FastJet median background subtraction):

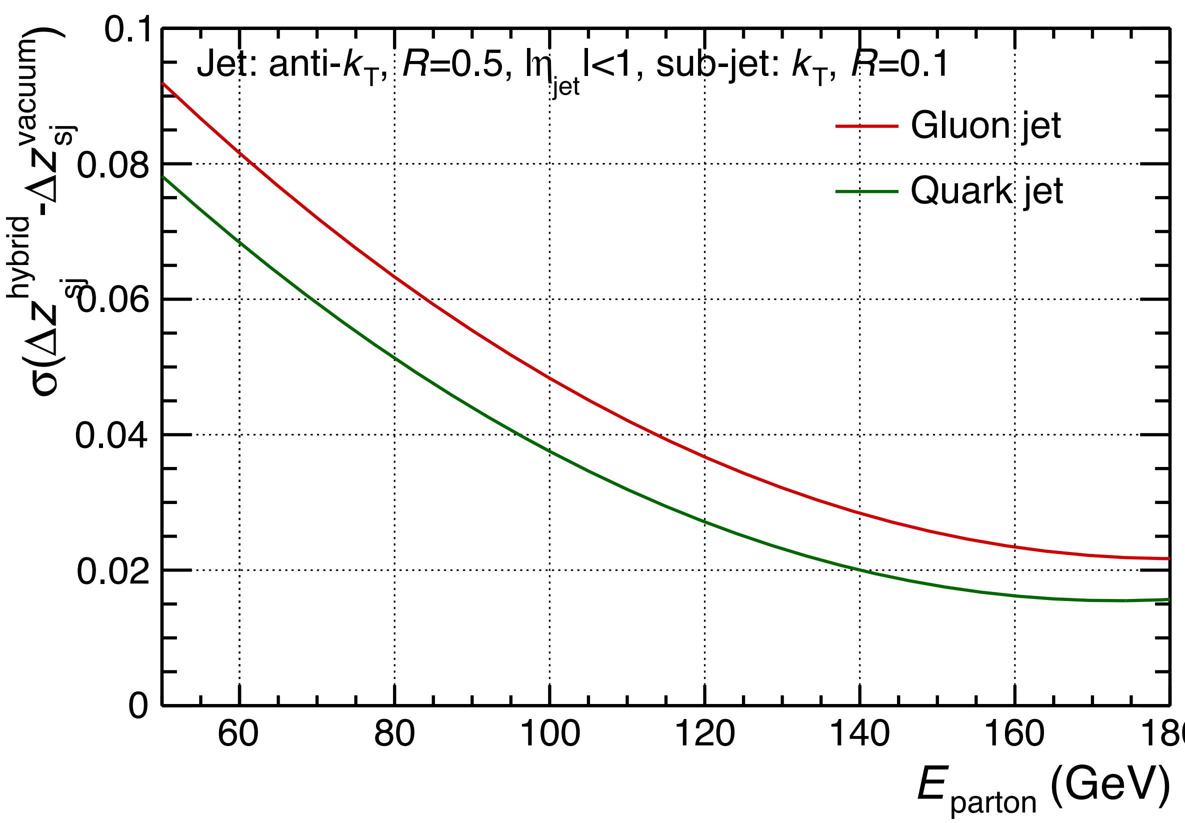
$$\Delta p_T^{sj12} = p_T^{sj1} - \rho^{BG} \times A^{sj1} \pm \delta^{BG}(A^{sj1}) - (p_T^{sj2} - \rho^{BG} \times A^{sj2} \pm \delta^{BG}(A^{sj2}))$$

Background terms cancel out for locally uniform background

Tests on a realistic LHC heavy-ion background show a promising behavior

$$\Delta_{\rm sj} = p_{\rm T,subjet}^{\rm 1st\ leading} - p_{\rm T,subjet}^{\rm 2nd\ leading}, \quad \Delta z_{\rm sj} = \Delta_{\rm sj}/p_{\rm T,jet}$$

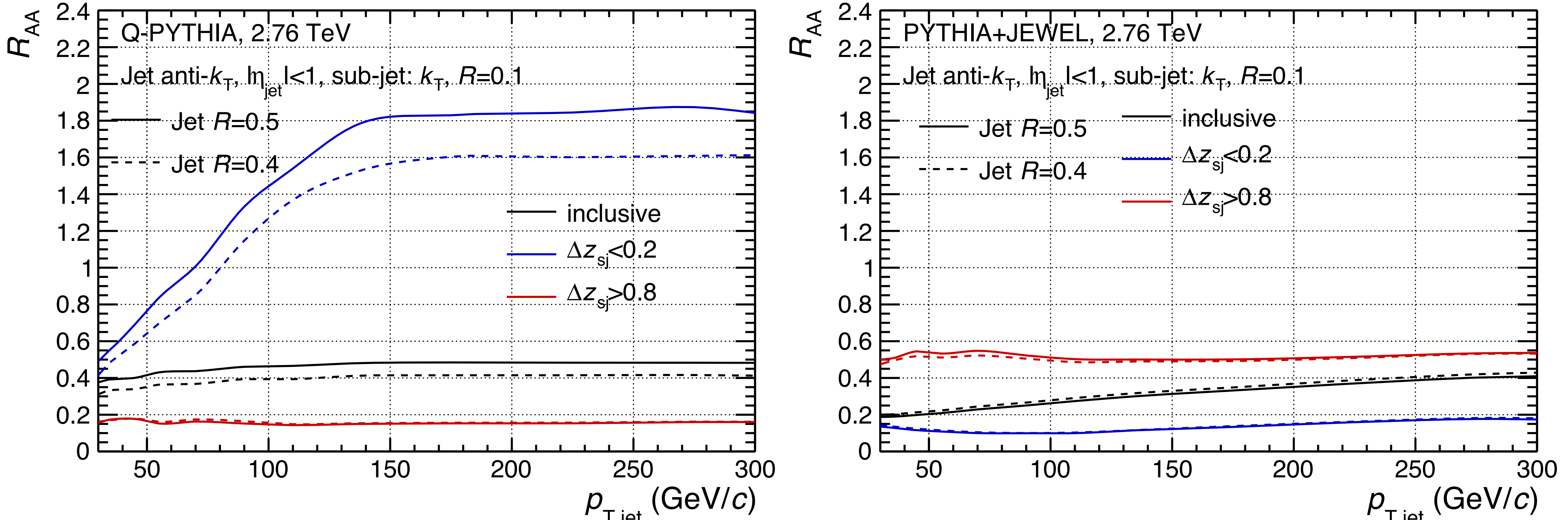




Sub-jet Structure: Proposed Observable

$$R_{AA}(\Delta z_{sj}) = \frac{d\sigma_{medium}/dp_T|_{\Delta z_{sj}}}{d\sigma_{vacuum}/dp_T|_{\Delta z_{sj}}}$$

X. Zhang et al, arXiv:1512.09255

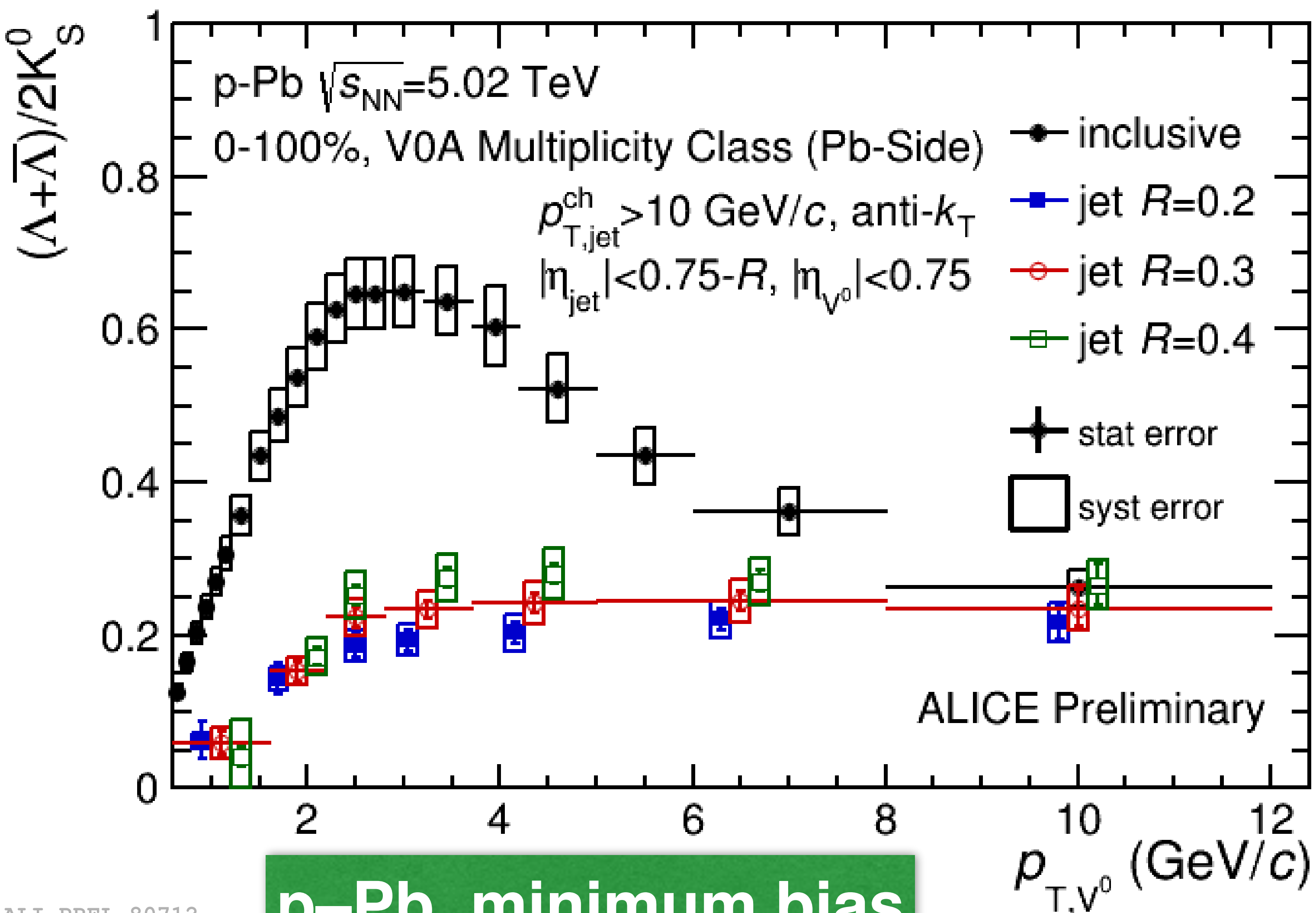


- A jet by jet selection on Δz_{sj} carries little experimental difficulties (both in pp and AA)
- Differences for Δz_{sj} selected jets with respect to inclusive R_{AA}:
  - For large Δz_{sj}: R_{AA} suppressed in Q-PYTHIA but enhanced in JEWEL
    - The opposite behavior for small Δz_{sj}
- Small R-jet dependence only for Q-PYTHIA

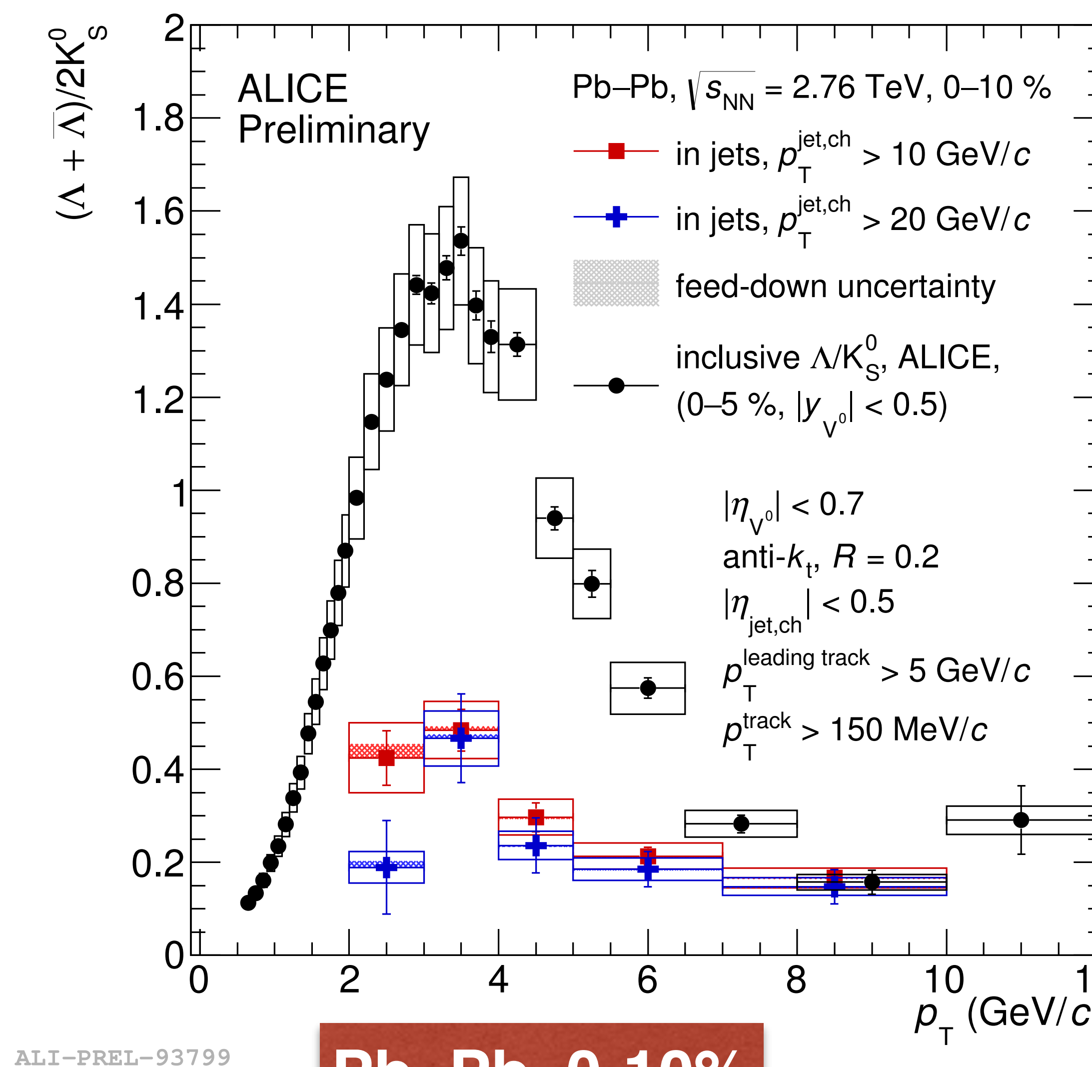
Note: These are shown as examples — different selections on sub-jet p_T difference possible - e.g. moments of the distributions, etc

Λ/K_S^0 Ratio in Jets

- The enhanced ratio of Λ/K_S^0 at inter-median p_T of inclusive V⁰s in p–Pb and Pb–Pb collisions relative to pp collisions is not present within the jet region
  - Baryon enhancement does not origin from modified jet fragmentation
  - Results independent on jet radii and disfavor the hard-soft recombination



p–Pb, minimum bias



Pb–Pb, 0-10%

Conclusion

- Inclusive and semi-inclusive jet measurements
  - ➡ Jet cores behavior as in vacuum
  - ➡ Significant amount of energy radiated at large angles
- Non-zero v_2 of single particles, charged jets and calorimetric jets
  - ➡ Large parton in-medium energy loss, sensitive to collision geometry up to high p_T
- Jet shapes: jets are more collimated and more p_T dispersion in Pb–Pb collisions
- Promising observable: sub-jet structure — sensitive to quenching details and robust against heavy-ion background
- Λ/K_S^0 ratio in jets: disfavor the soft-hard recombination mechanism

Backup

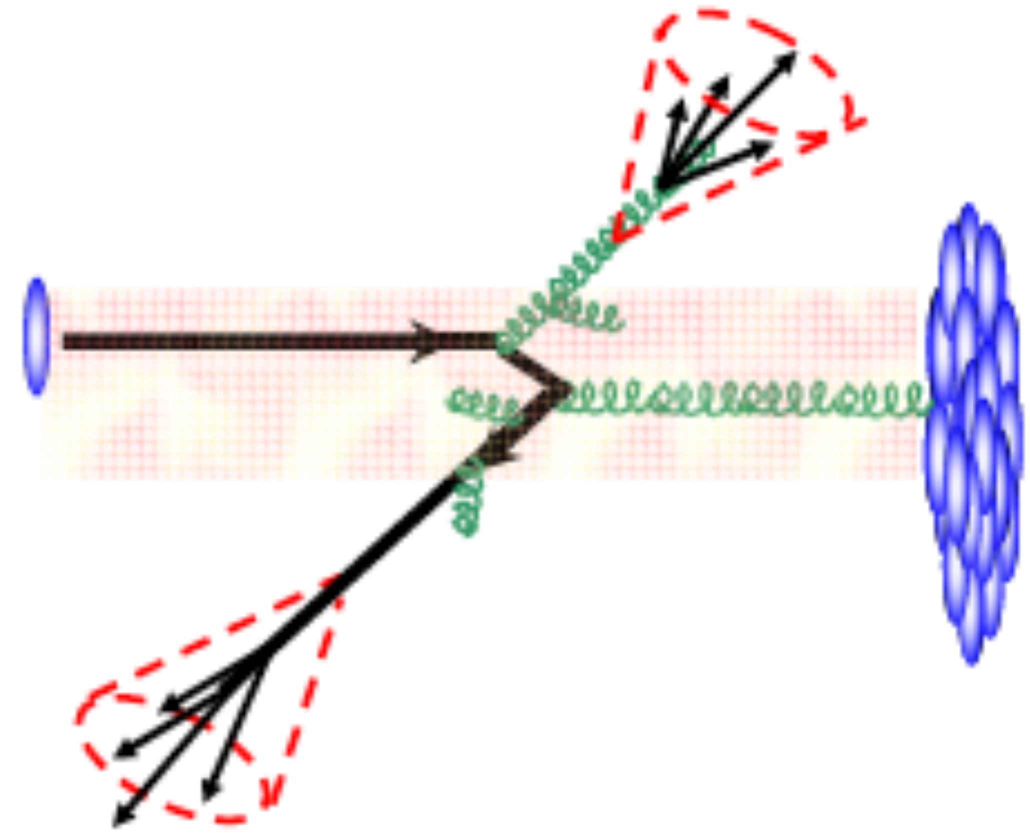
Jets in Small Systems

Study of cold nuclear matter

- Initial state effects:

➡ Color Glass Condensate (CGC)?

➡ nuclear modified Parton Distribution Function (nPDF)…



- Final state effects:

➡ parton scattering in cold nuclear matter…

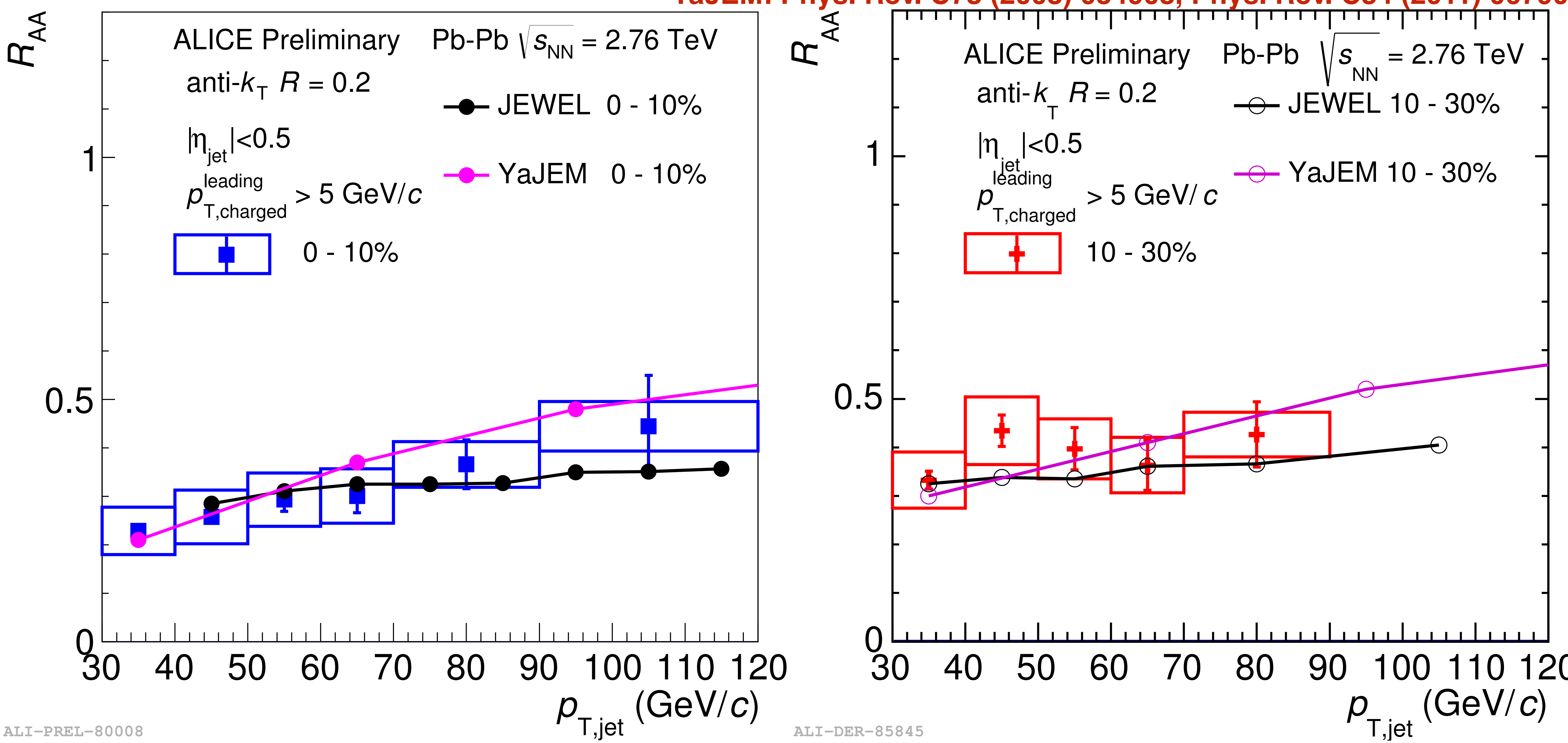
Baseline for heavy-ion collisions:

➡ disentangle the initial state effects from the hot and dense medium produced in the final state of the heavy-ion collisions

Comparison with Theoretical Models

JEWEL: JHEP 1303 (2013) 080, Eur. Phys. J. C74 (2014) 2762

YaJEM: Phys. Rev. C78 (2008) 034908, Phys. Rev. C84 (2011) 067902



- Good agreement between data and models within errors

➡ both models fitted to the single particle R_{AA}