ALICE Experiment - Highlights and Status

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for the ALICE Collaboration

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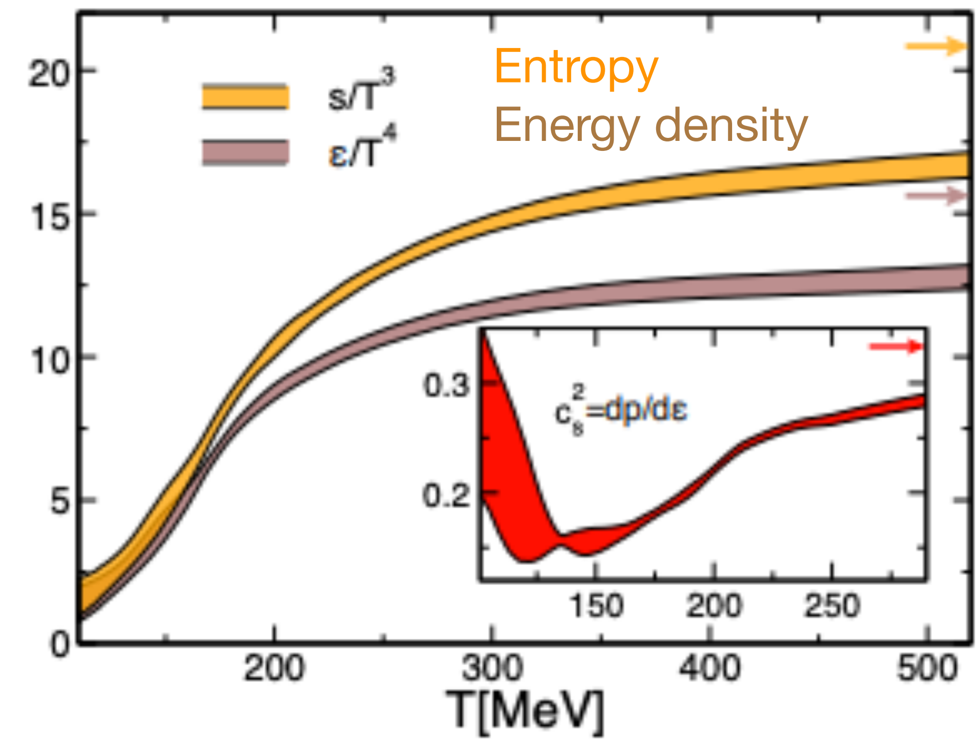
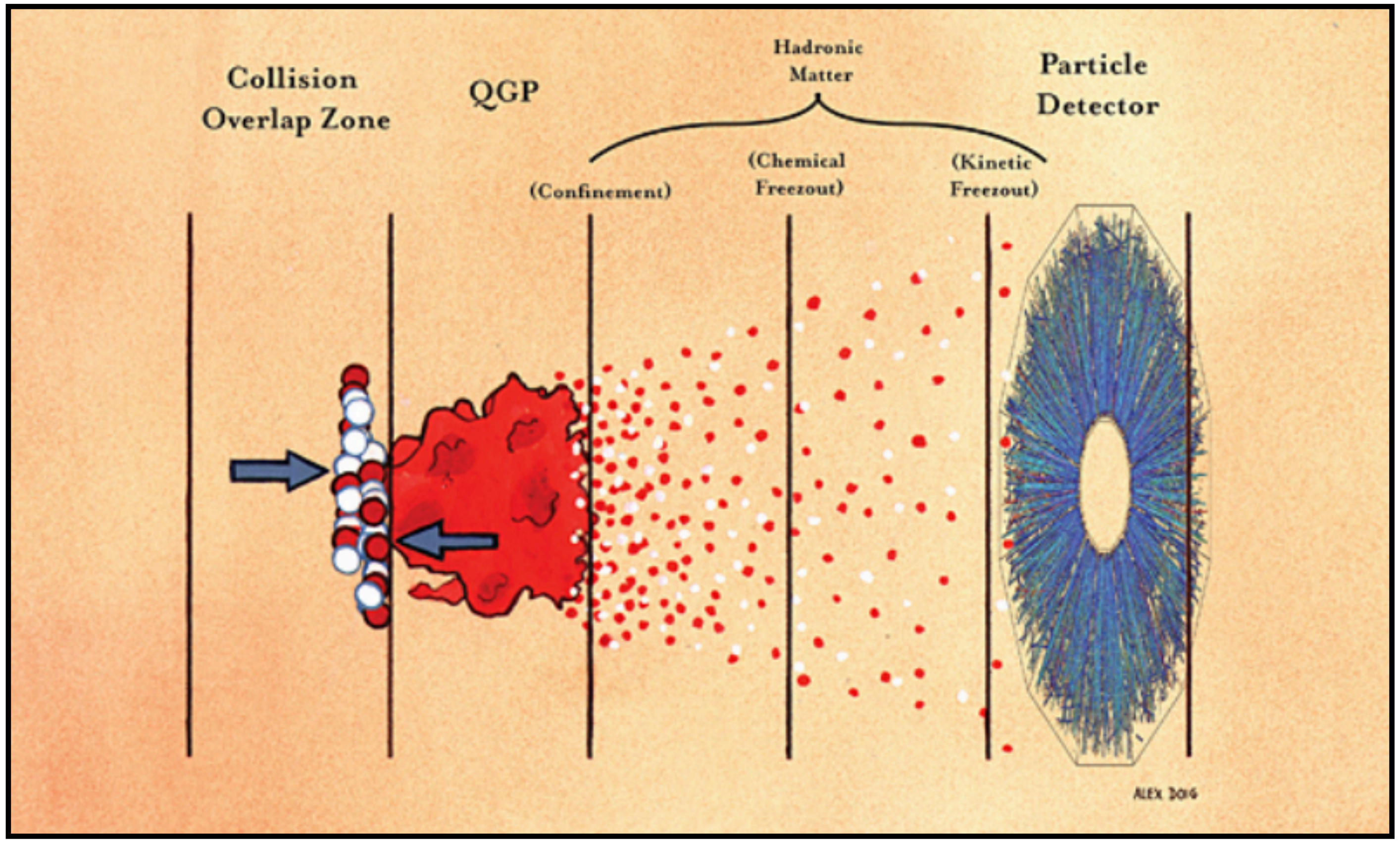
Heavy-ion collisions

- Explore the deconfined state of QCD matter
  -> **Quark Gluon Plasma**.
- Lattice QCD calculations indicate hadronic matter exhibits phase-transition at high temperature.
  - QGP -> QCD at high temperature and density.
- Measurements in heavy-ion collisions used to probe different stages of the evolution.



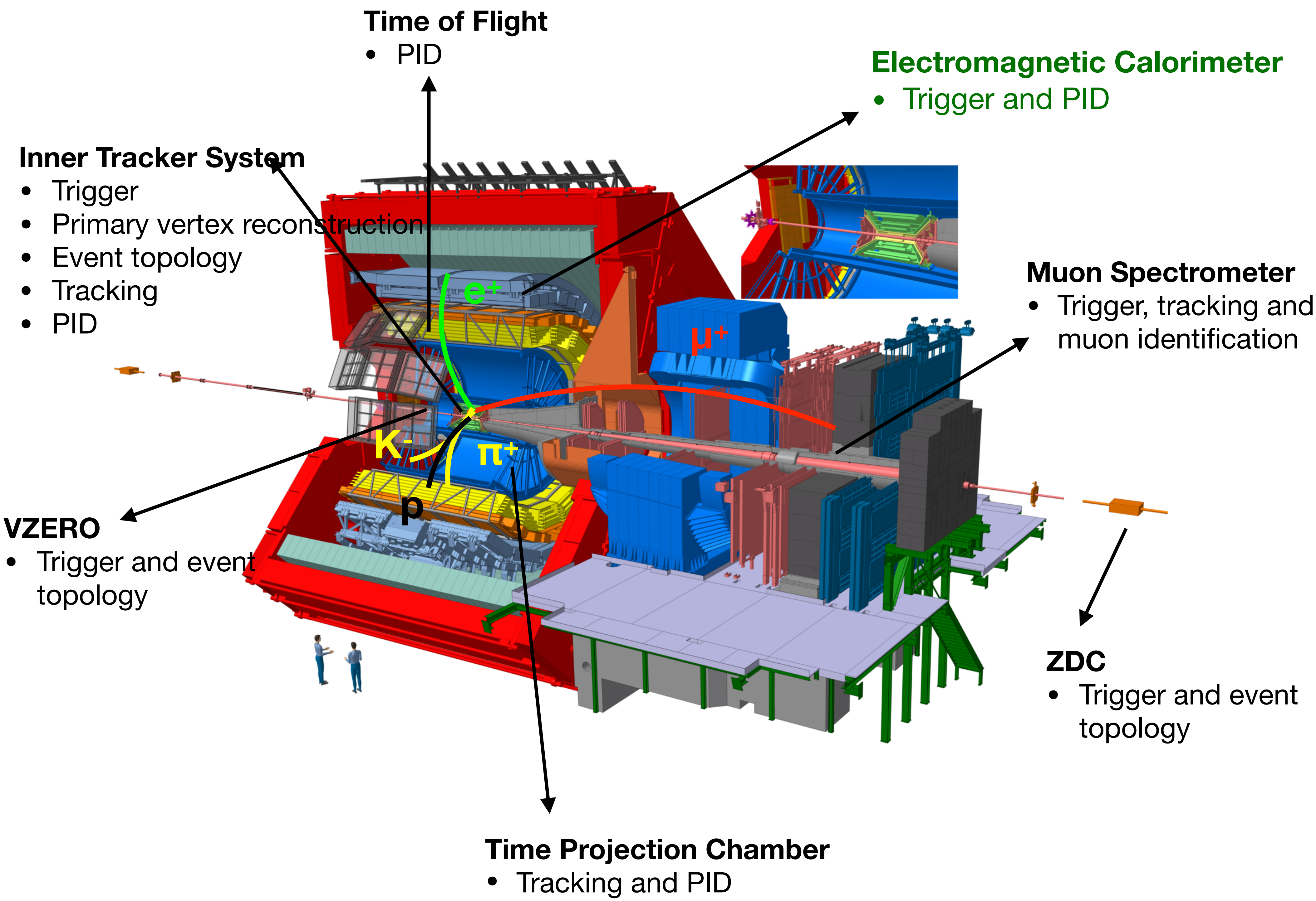
PLB 370 (2015) 99



1. Initial parton scattering processes
2. Thermalization and formation of QGP
3. Hydrodynamic expansion & cooling of QGP
4. Hadronization to hadron gas
5. Chemical freeze-out - inelastic collisions cease
6. Kinetic freeze-out - elastic collisions cease

ALICE detector

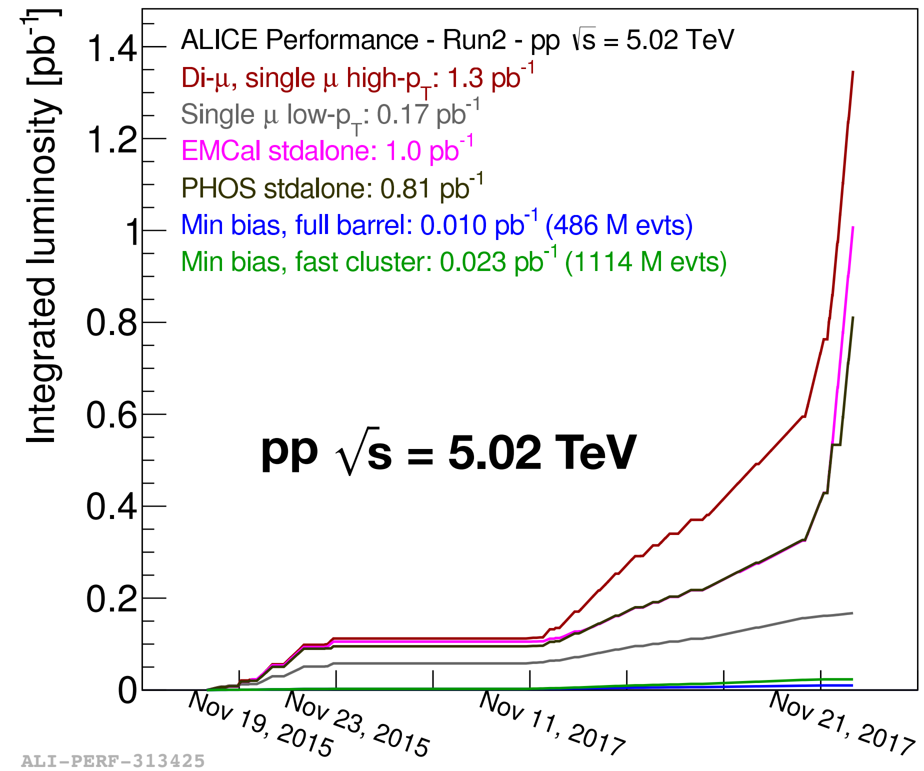
Central barrel coverage: |η| < 0.9
Muon spectrometer coverage: -4 < η < -2.5

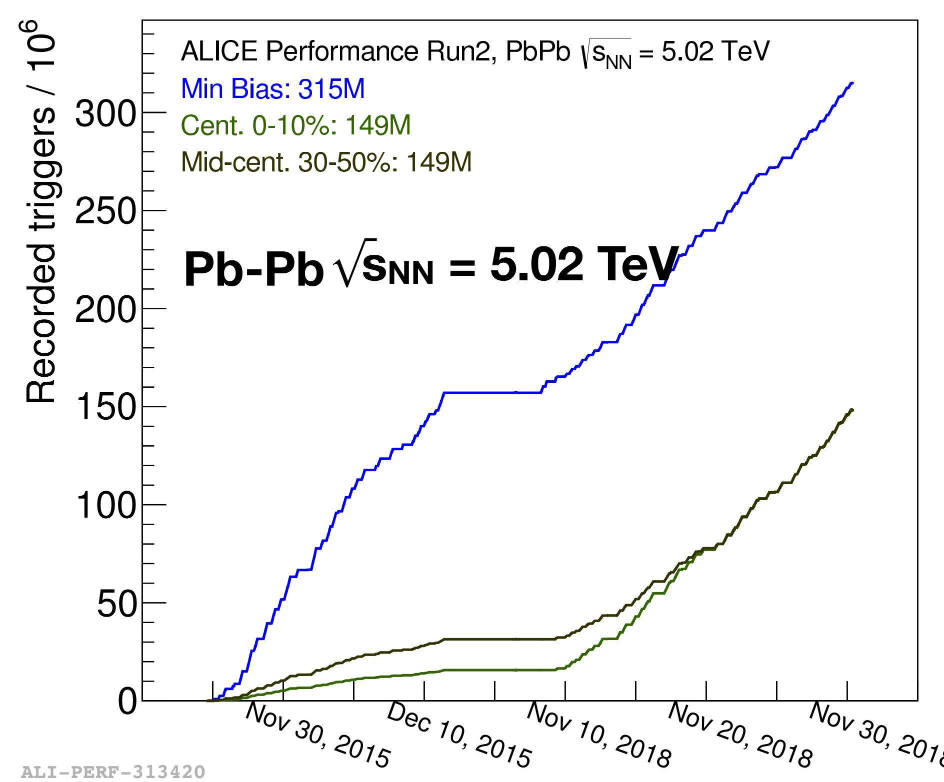


Run 2 data taking

Successful data taking in Run 2

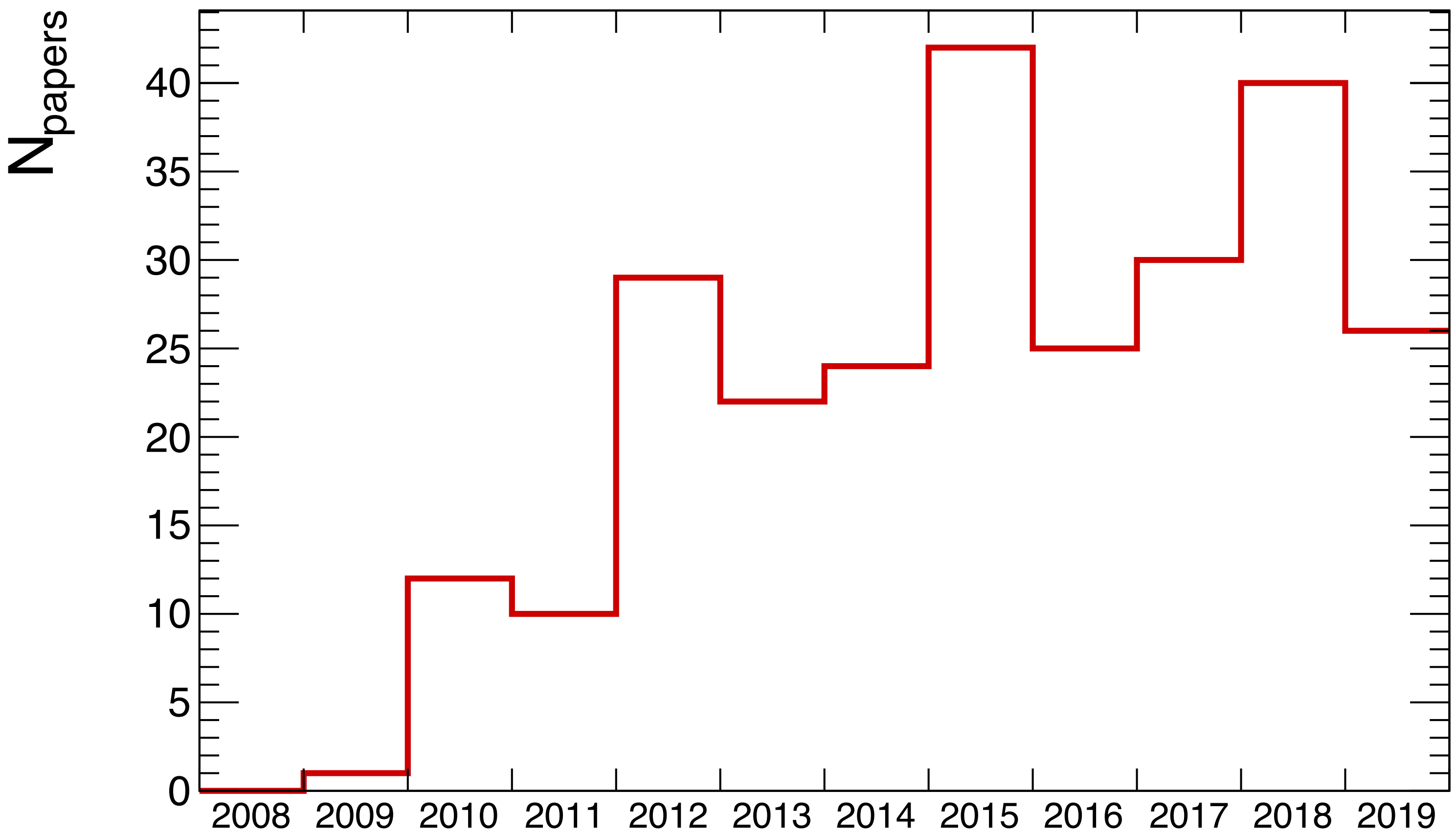
- pp @ 13 TeV: ~ 59 pb^{-1}
  - Using EMCal trigger to collect large statistics for rare probes
  - High multiplicity triggers
- pp @ 5 TeV: ~ 1.3 pb^{-1}
  - Reference data sample -> no QGP formation.
- Pb-Pb @ 5.02 TeV in 2018: ~ 0.9 nb^{-1}
  - 9 x larger sample of central collisions in 2018 compared to 2015.
- p-Pb @ 5 and 8 TeV: ~ 3nb^{-1}, ~ 25nb^{-1}
  - Study initial state effects
- Xe-Xe @ 5.14 TeV pilot run: ~ 0.3 μb^{-1}





ALICE physics output

- **Total No of papers : 262**
- 2 Nature Physics articles
  - Nature Physics 13 (2017) 535–539
  - Nature Physics 11 (2015) 811-814
- 27 papers submitted unto now in 2019

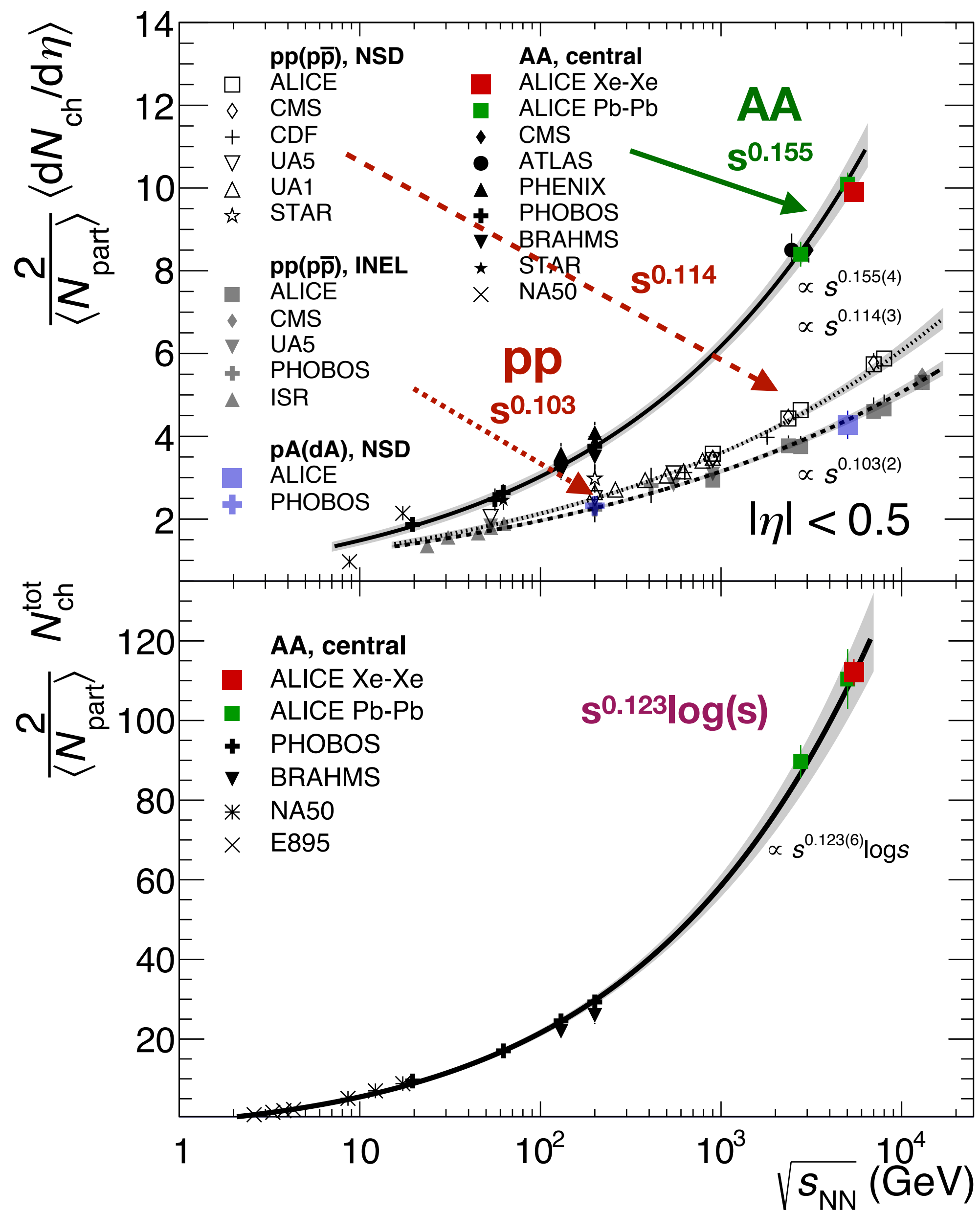


Highlights (biased selection)

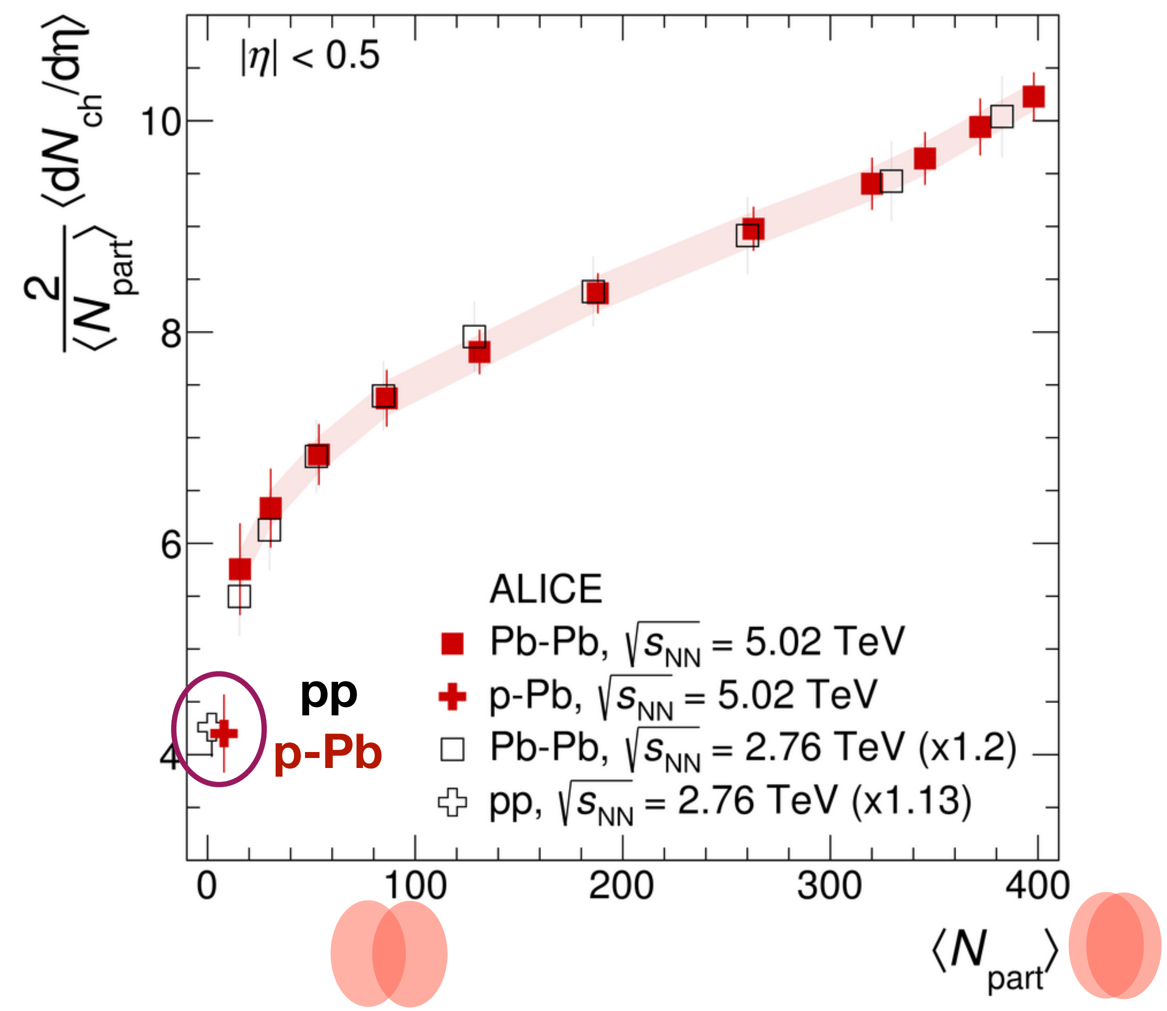
- Charge particle multiplicity and particle production
- Signatures of QGP in heavy-ion collisions
  - What about small systems (pp & p-Pb) at similar multiplicities?
- Probing QGP with heavy-quarks
- Probing QGP with jets
- Looking forward
- Summary & Conclusions

Charge-particle multiplicity

Particle production related to the initial parton and energy density.



PLB 790 (2019) 35
PRL 116 (2016) 222302

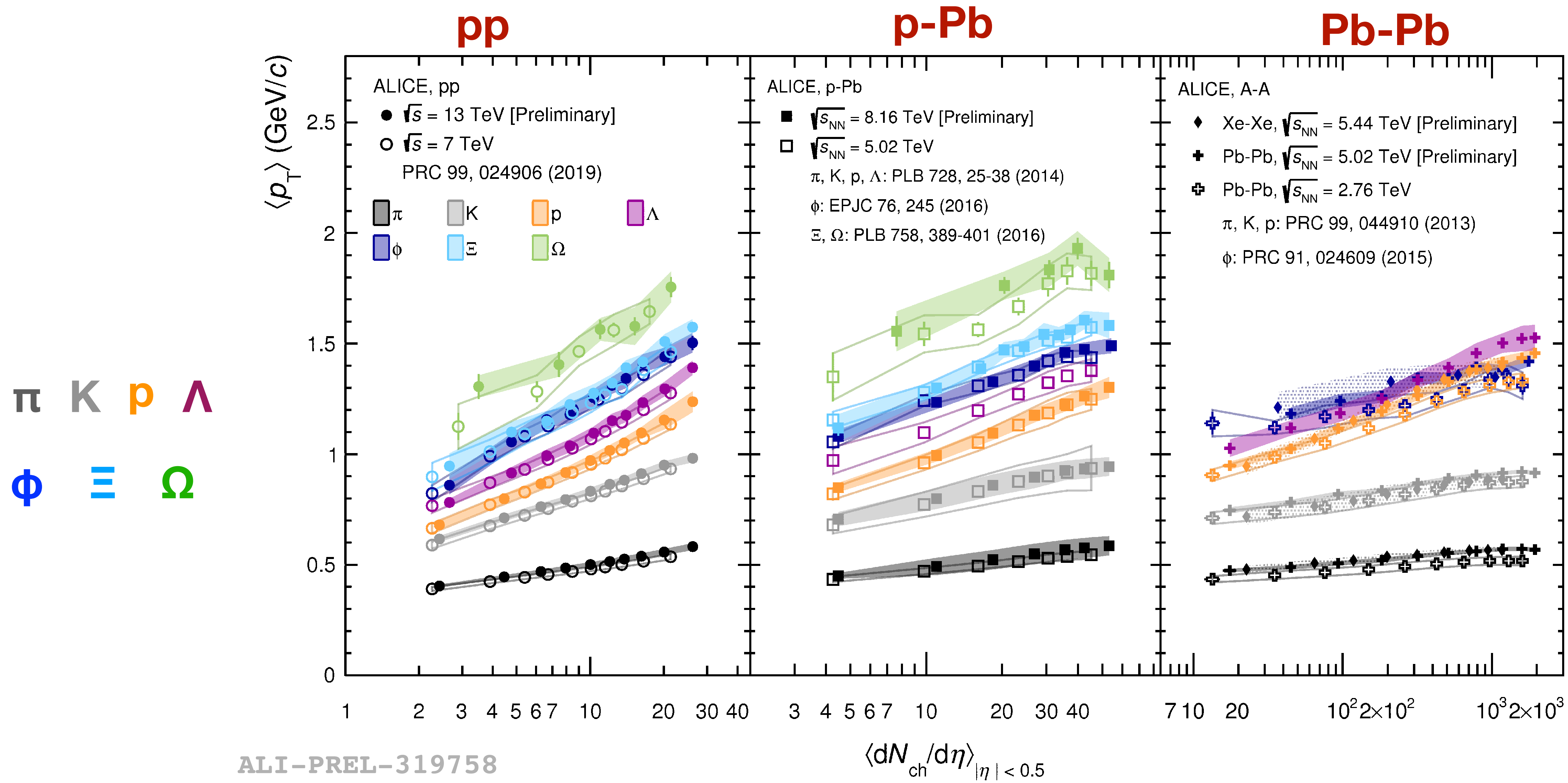


- Charge particle multiplicity in AA collisions shows a steeper rise vs $\sqrt{s}$ than pp and p-Pb (no universal scaling).
  - Follows similar trend as lower energy.
- dN/dη vs N participants shows a strong dependence.

Particle production in AA collisions driven by geometry (N_{part})

Particle production

Particle production vs multiplicity

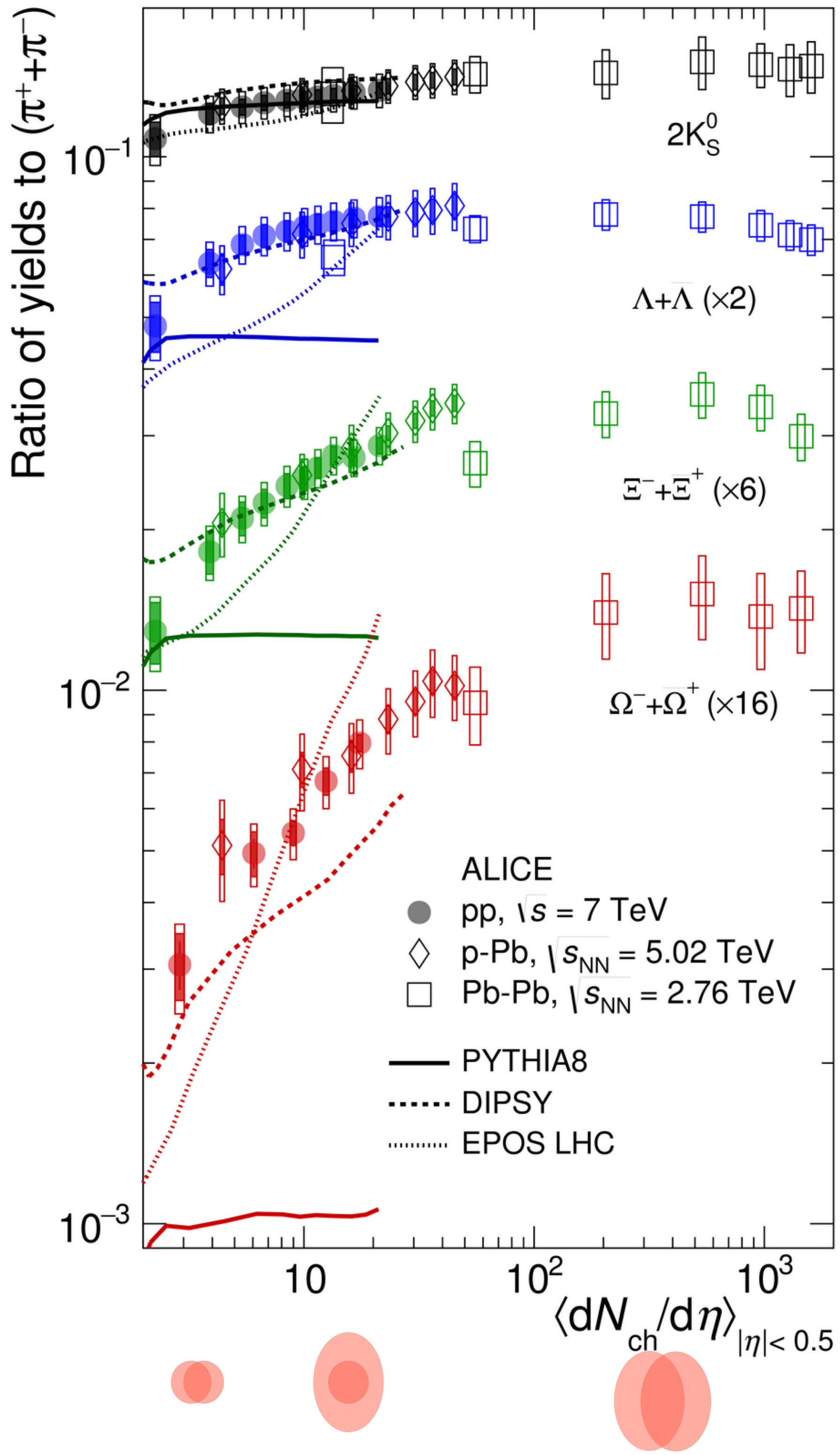


- Increase of <p_T> with multiplicity; with steeper increase for heavier particles (mass ordering).
  - **Signature of collective radial expansion.**
- **Trends similar in pp, p-Pb and Pb-Pb collisions**

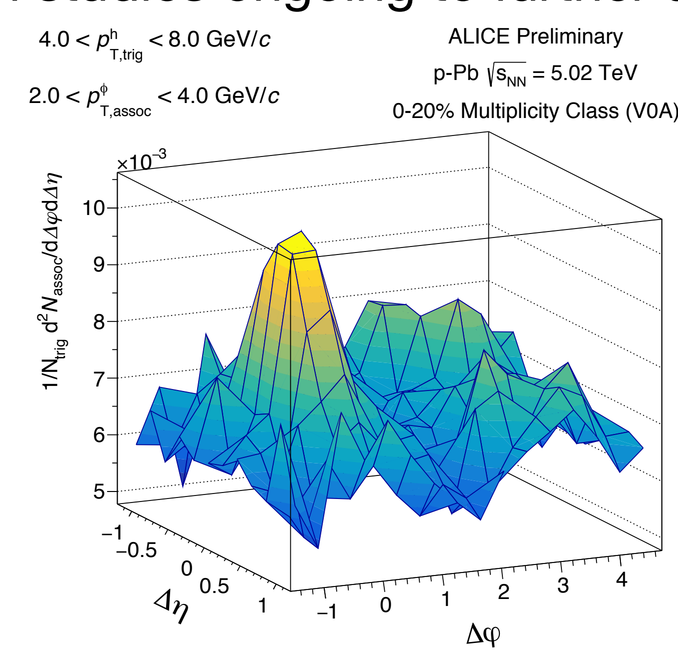
Collective radial expansion in high multiplicity pp & p-Pb collisions??

Strangeness enhancement

Nature Physics 13 (2017) 535

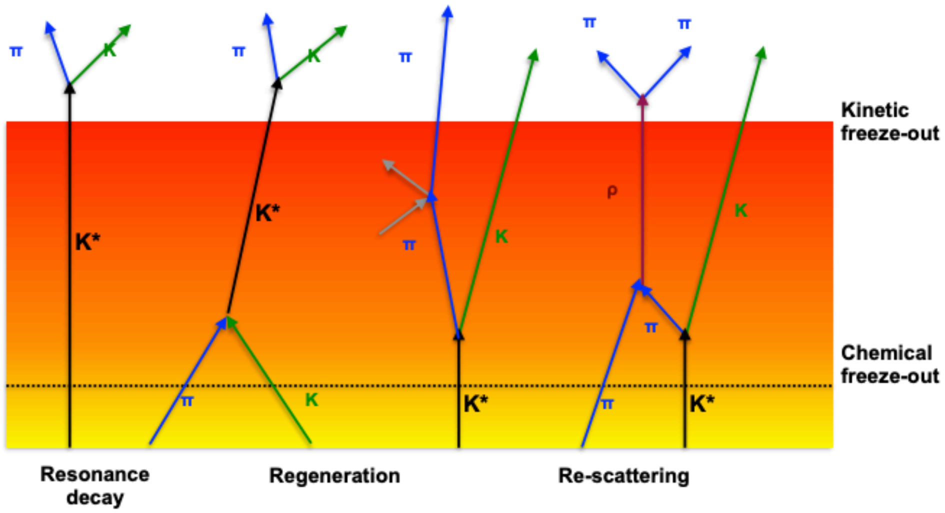


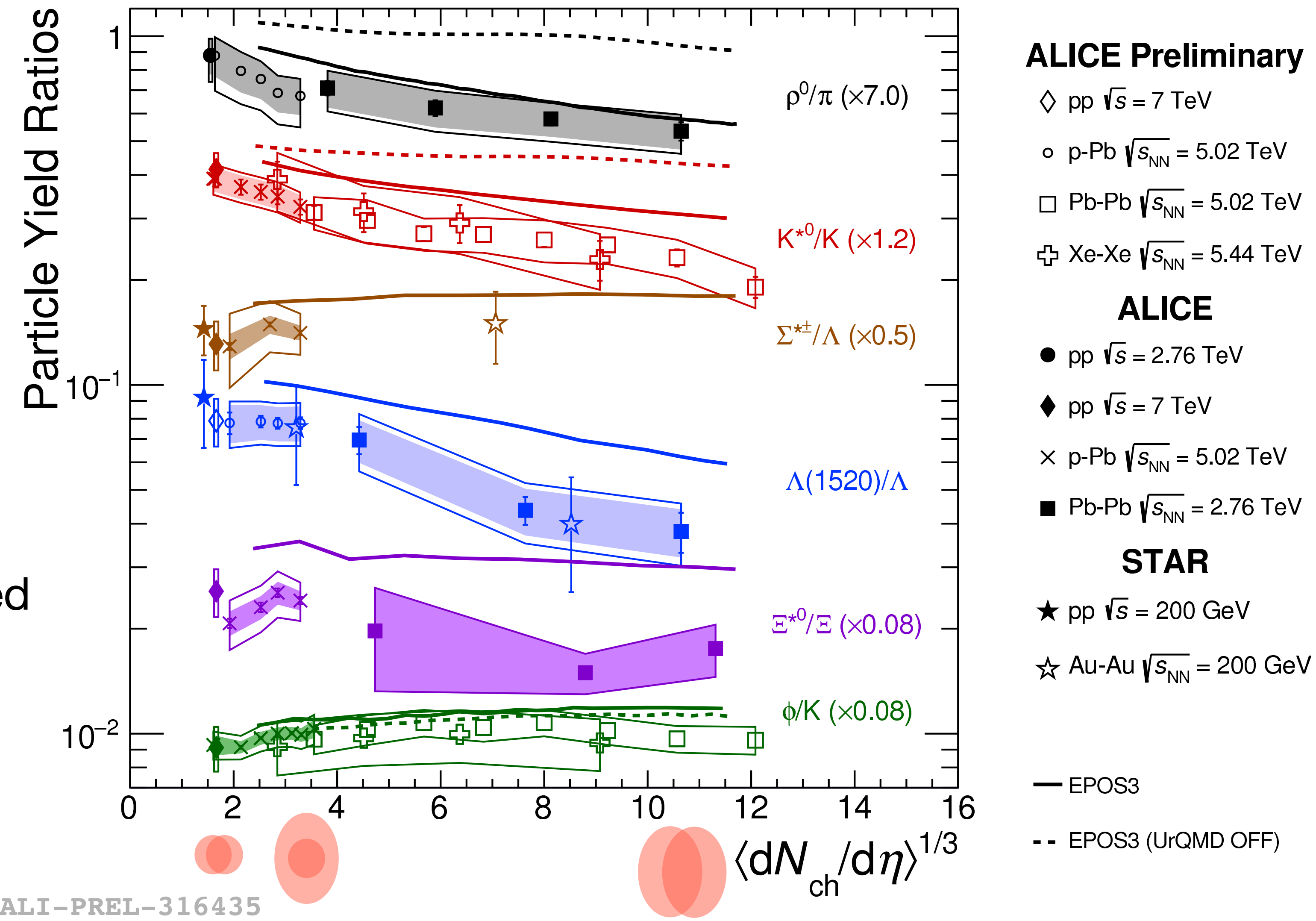
- Increase in the abundance of strange baryons —> effect increases with strangeness content.
  - **Signature of QGP in AA collisions.**
- **Relative abundance of strange quarks increases with multiplicity in small systems.**
  - **Values and evolution trend independent of collision systems or energy.**
- PYTHIA do not reproduce the data.
- Enhancement in small systems associated to jet production or soft processes?
  - ϕ-hadron correlation studies ongoing to further understand it



Resonance production

Resonance production vs multiplicity





Looking at hadronic phase: Yields modified by hadronic scattering after chemical freeze-out.

- Re-scattering of decay daughters scatter -> signal loss
- Regeneration: resonances formed in hadron scattering

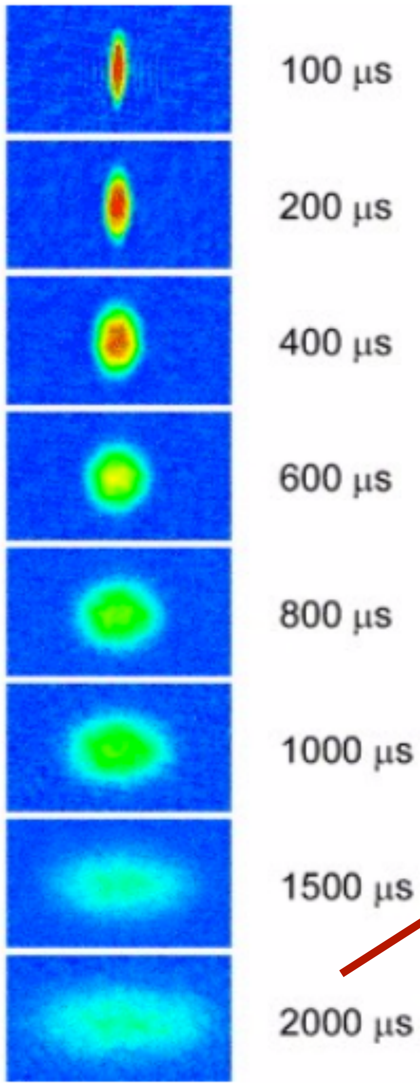
Lifetime(fm/c): τ_{ρ}(1.3) < τ_{K^*}(4.2) < τ_{Σ^*}(5.5) < τ_{Λ^*}(12.6) < τ_{Ξ^*}(21.7) < τ_{Φ}(46.2)

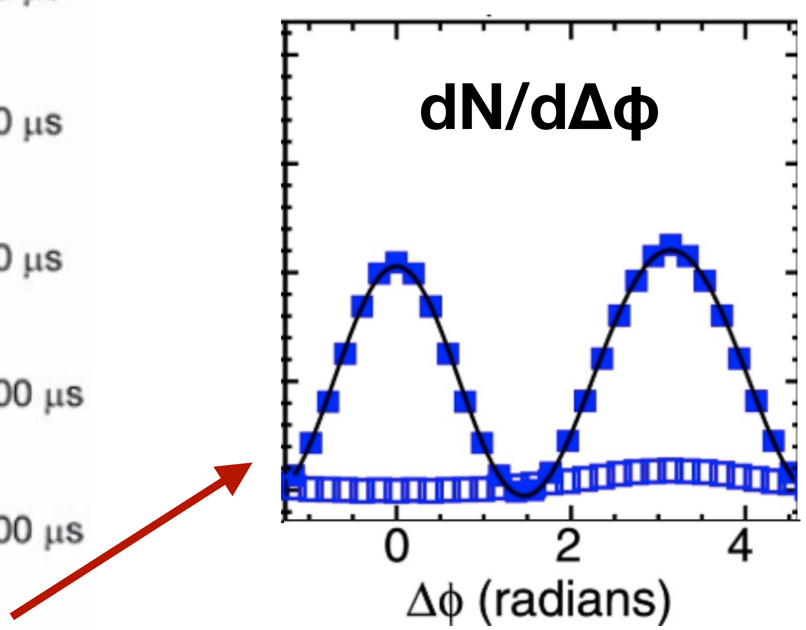
ρ, K*, Λ* reduced yield: final state scattering of decay particles

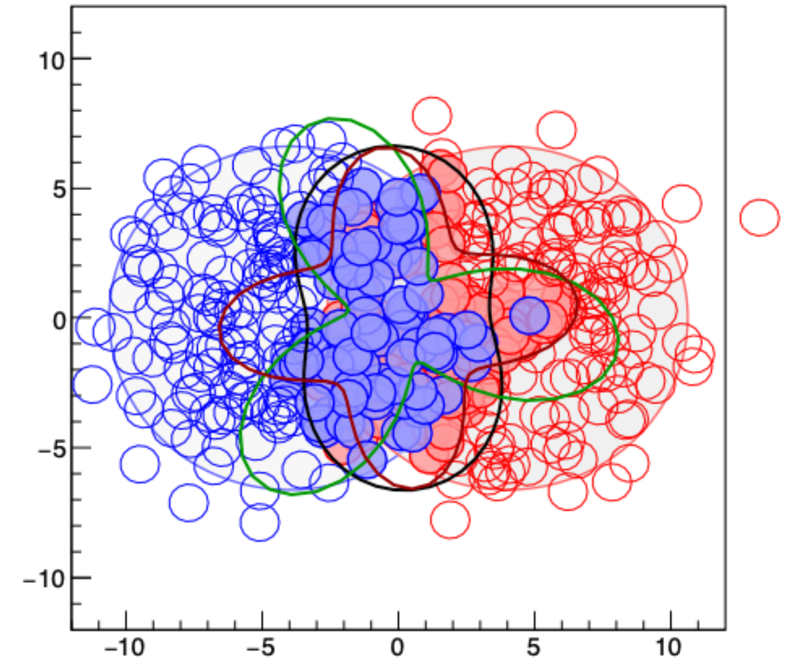
Φ, Ξ*: longer life time, yield constant

Collective flow

- Azimuthal distribution of particles in the plan perpendicular to beam axis -> sensitive to dynamics at the early stages of collision.
- Initial state spatial anisotropies are transferred into final state momentum anisotropies v_n by pressure gradients —> flow of the QGP







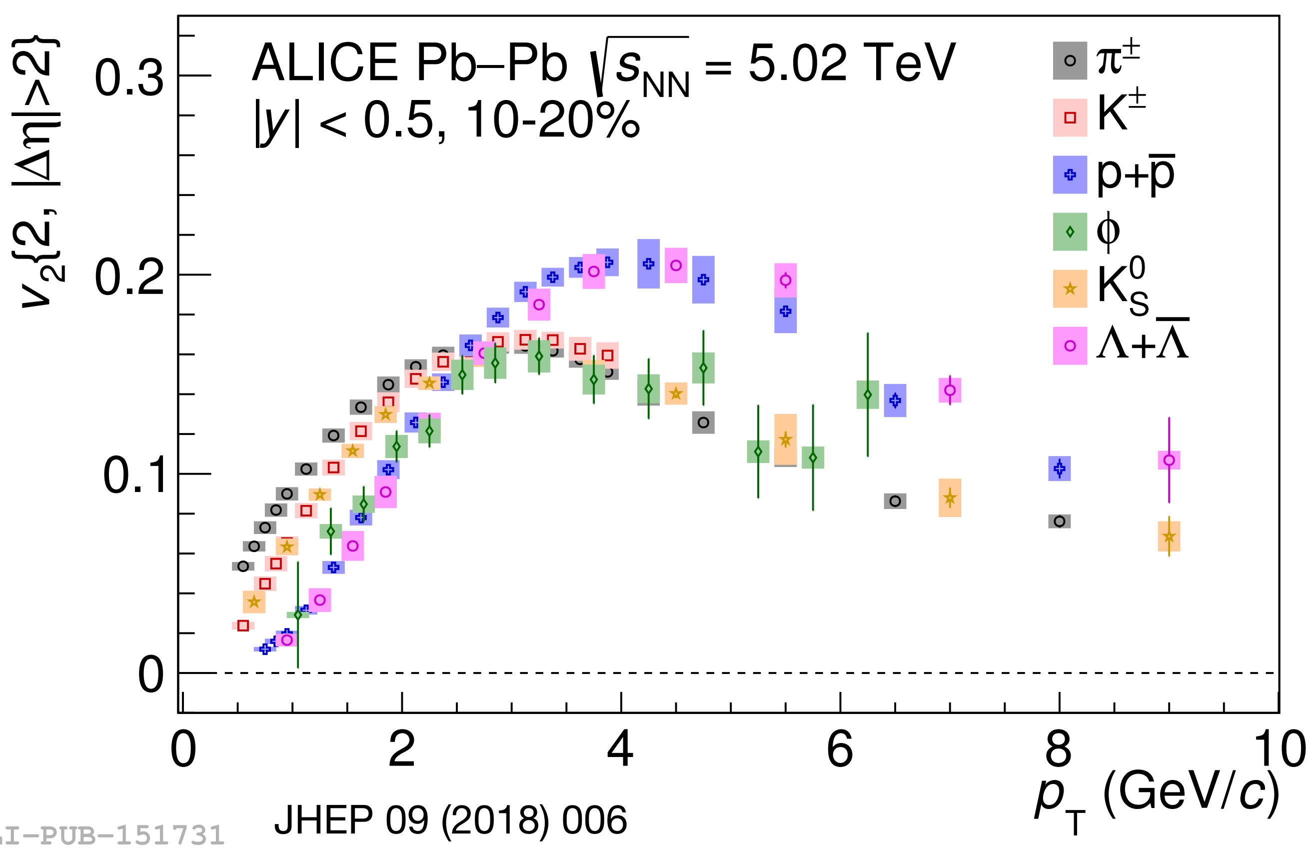
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos(\Delta\varphi) + 2v_2\cos(2\Delta\varphi) + 2v_3\cos(3\Delta\varphi) + \ldots$$

v_2: elliptic flow

Azimuthal anisotropy

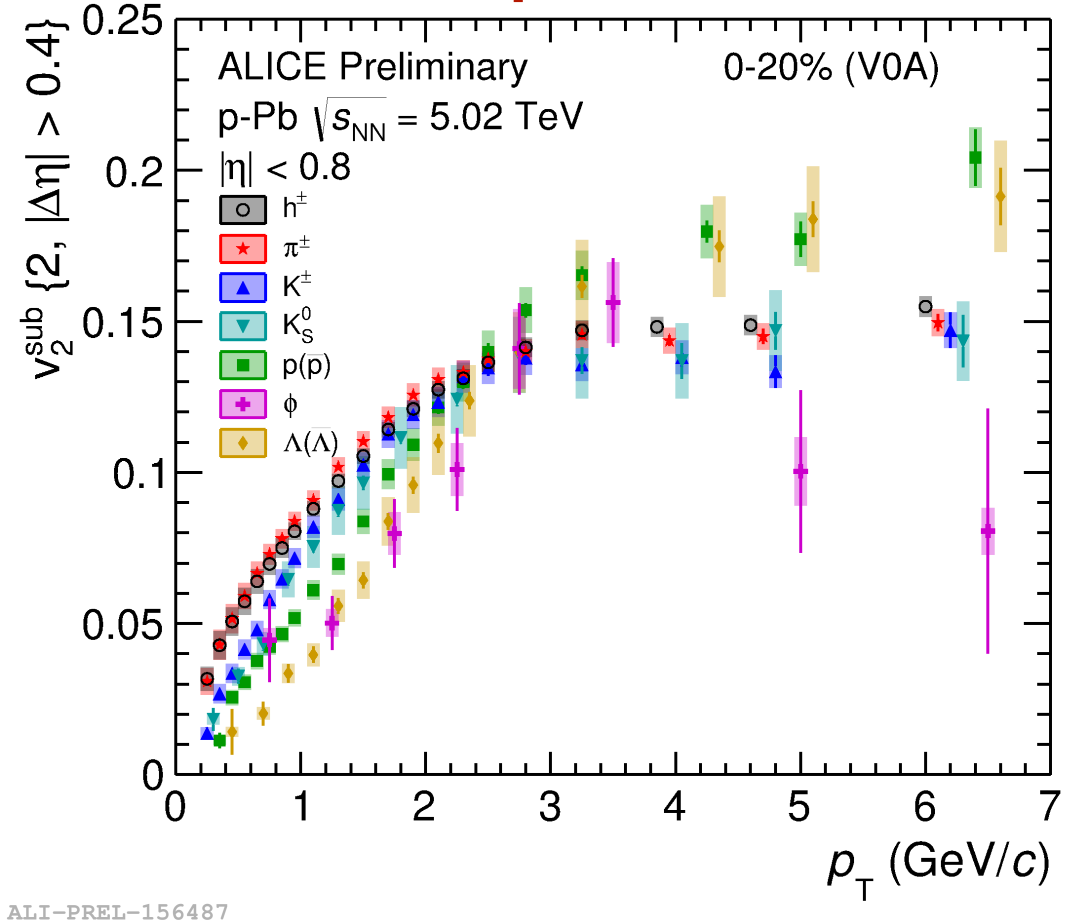
v_2 in Pb-Pb and p-Pb collisions

Pb-Pb



JHEP 09 (2018) 006

p-Pb



Pb-Pb:

- $p_T < 2$ GeV/c: hadron mass ordering -> **hydro-dynamic flow.**
- $p_T > 2.5$ GeV/c: baryons v_2 > mesons v_2 -> quark flow + recombination effects

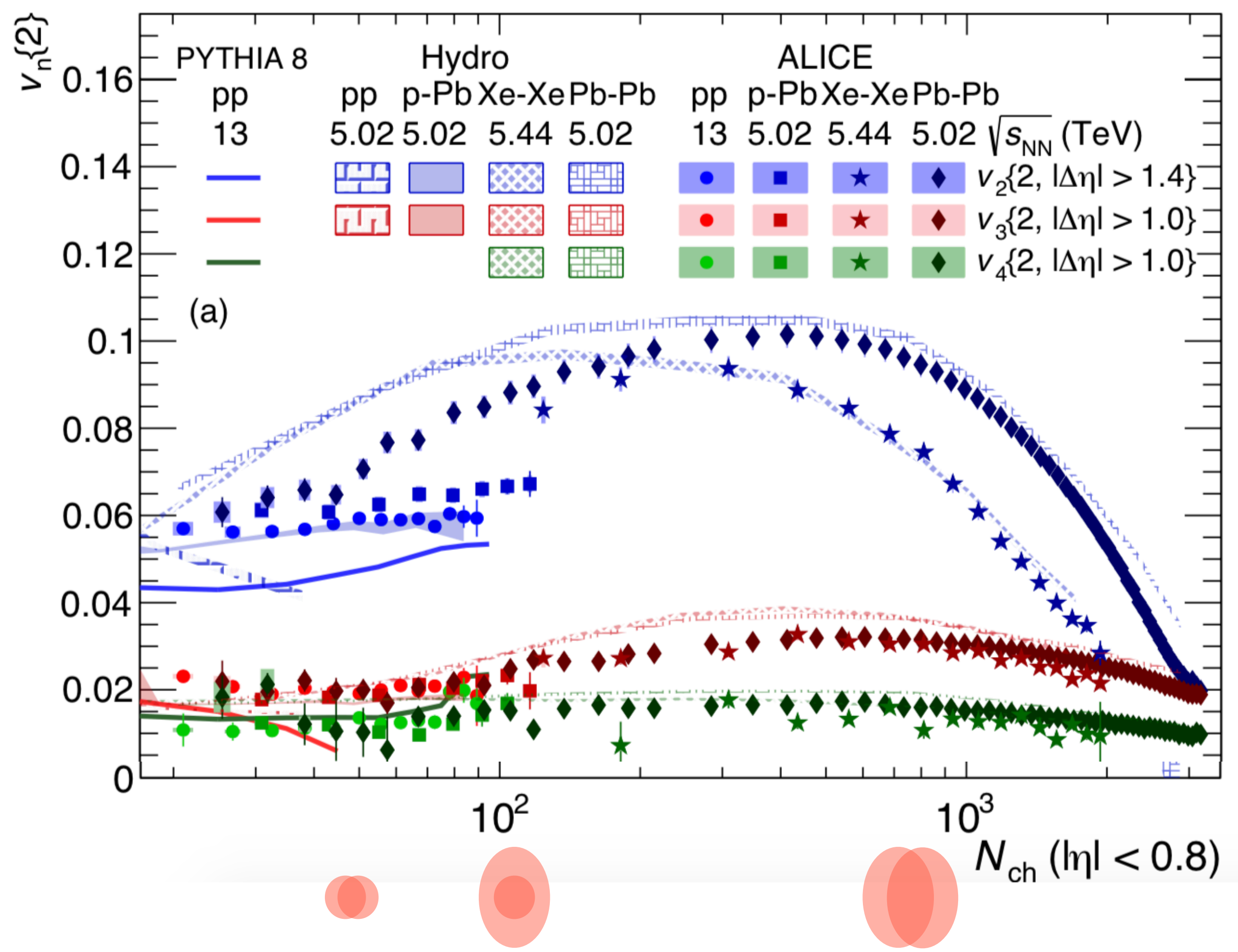
p-Pb:

- **Similar mass ordering observed in high multiplicity collisions.**
- **Medium in high-multiplicity p-Pb??**
- Some differences between systems observed.

Azimuthal anisotropy

v_n in pp, p-Pb, Xe-Xe and Pb-Pb collisions

$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos(\Delta\varphi) + 2v_2\cos(2\Delta\varphi) + 2v_3\cos(3\Delta\varphi) + \ldots$$



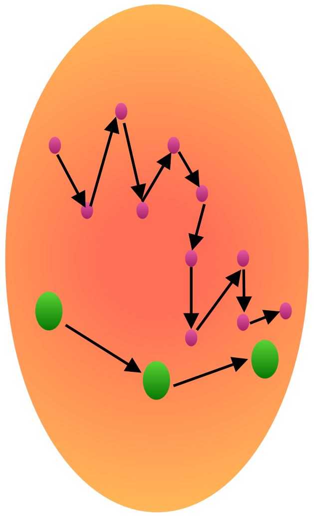
PRL 123 (2019) 142301

- **New technique to measure v_n**: multi-particle correlations in η ranges —> removes bias from non-flow.
- v_2, v_3 and v_4 in pp, p-Pb, Xe-Xe and Pb-Pb collisions **vs N_{ch}.**
- **Similar ordering of $v_2 > v_3 > v_4$ seen in all systems.**
- Weak multiplicity dependence of v_2 in pp and p-Pb.
- PYTHIA8 cannot describe the measurement in pp.

Probing QGP with Heavy-flavor

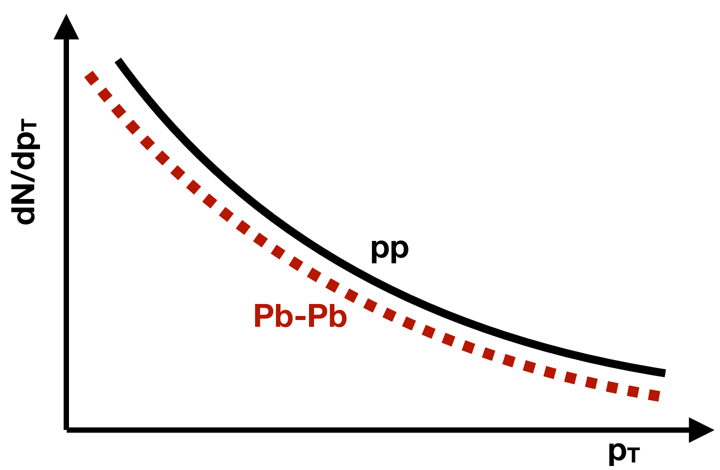
Heavy quarks (HQ): Charm and beauty quarks

- Massive - charm ~ 1 GeV/c^2
  beauty ~ 4 GeV/c^2

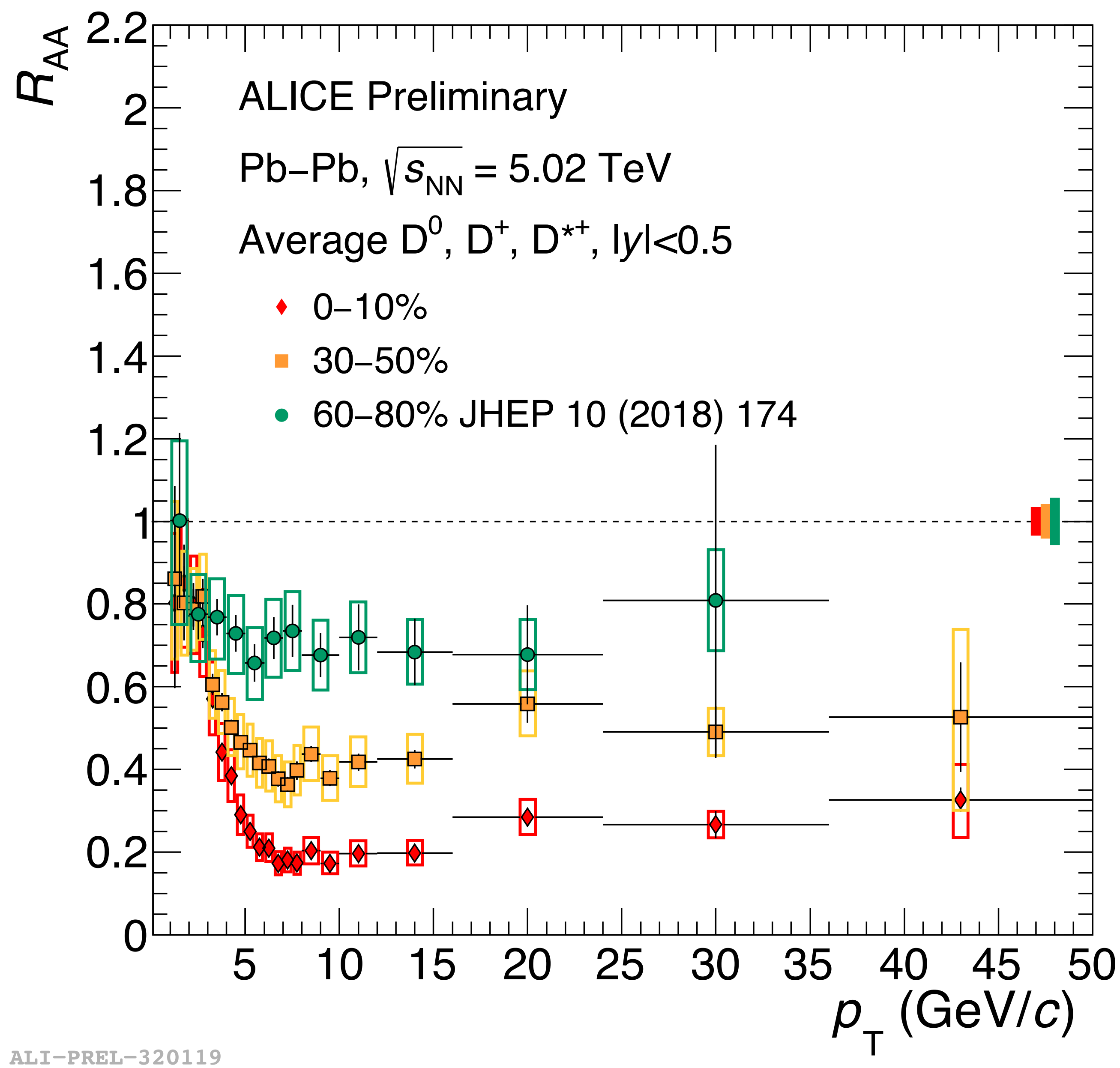


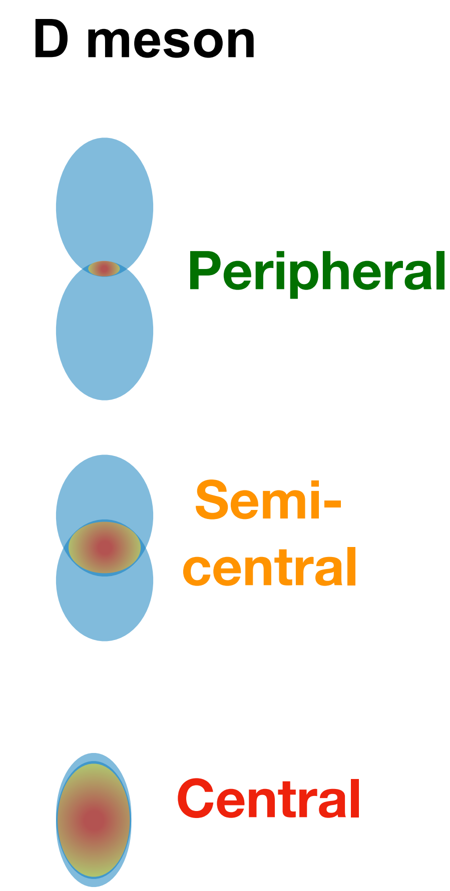
- Produced in hard scattering processes in the initial stages of the collisions before QGP is formed.
  charm ~ 0.07 fm/c, beauty ~ 0.02 fm/c
  QGP ~ 0.1-1 fm/c
  - Production well controlled and calculable with pQCD —> **Calibrated probe.**
- Undergoes elastic (collisional) and inelastic (radiational) collisions —> **sensitive to transport properties of QGP.**
- Lose less energy in QGP compared to light quarks.
- Not created or destroyed in the medium —> **identity is preserved** in the medium, thus tagged up to hadronization

Nuclear Modification Factor



$$R_{AA} = \frac{1}{< N_{coll} >} \frac{Y_{AA}}{Y_{pp}}$$





R_{AA} < 1 -> charm undergoes energy loss in QGP

R_{AA} (0-10%) < R_{AA} (30-50%) < R_{AA} (60-80%) at intermediate and high p_T

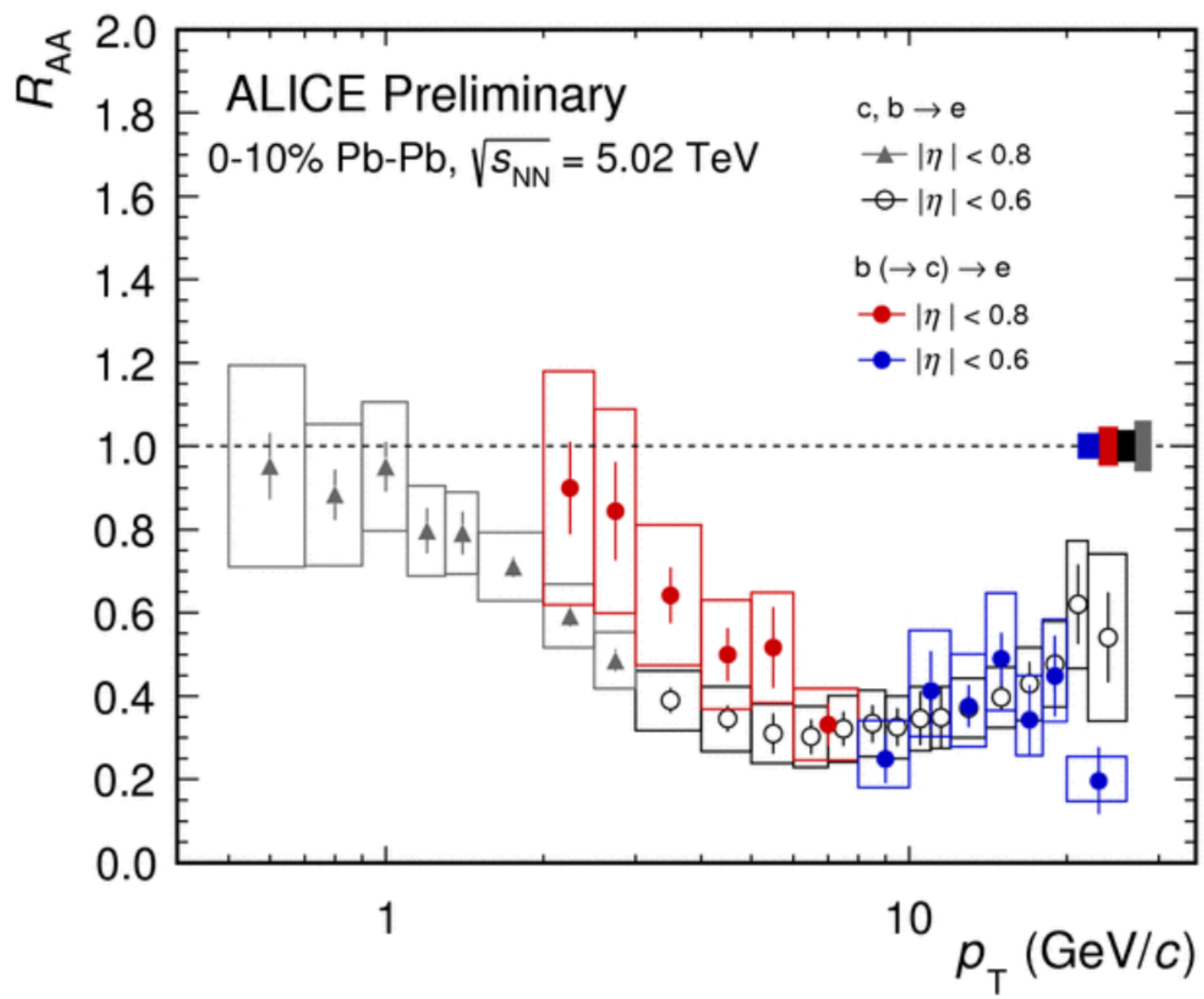
Hotter and denser medium in central Pb-Pb collisions compared to peripheral collisions.

Beauty in QGP

Study mass and flavor dependence of energy loss.

$$\Delta E(g) > \Delta E(uds) > \Delta E(c) > \Delta E(b) \overset{??}{<=>} R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

b->e
b+c->e



R_{AA} (b->e) > R_{AA}(b,c->e) for 2 < p_T < 6 GeV/c

Hint of beauty losing less energy than charm

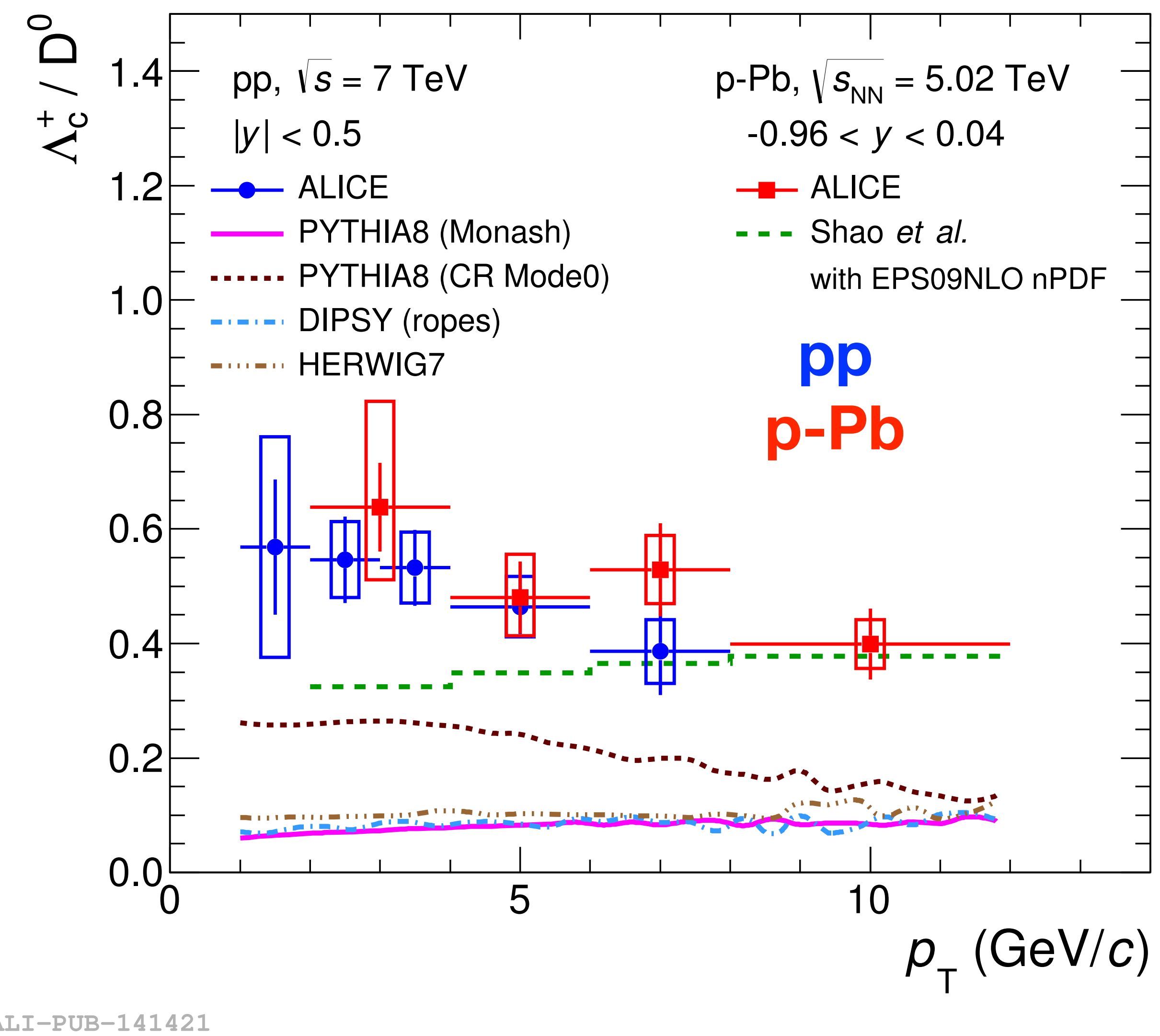
Heavy-quark hadronisation

Investigating hadronisation mechanisms with Λ^+_c

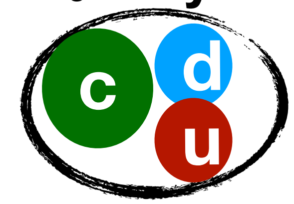
- Expected **enhancement of baryon over meson yield** in if **hadronization via coalescence**.
- Λ^+_c/D^0 measured.

Λ^+_c/D^0 vs p_T

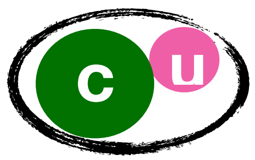
JHEP 04 (2018) 108



Λ_c baryon



D^0 meson



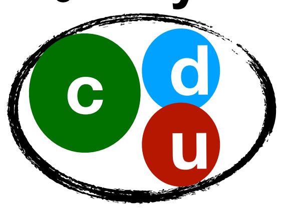
Λ^+_c/D^0 at LHC higher than the expectations based $e^+ e^-$

Heavy-quark hadronisation

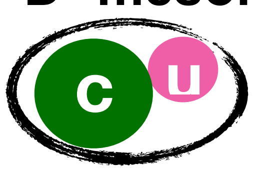
Investigating hadronisation mechanisms with Λ^+_c

- Expected **enhancement of baryon over meson yield** in if **hadronization via coalescence**.
- Λ^+_c/D^0 measured.

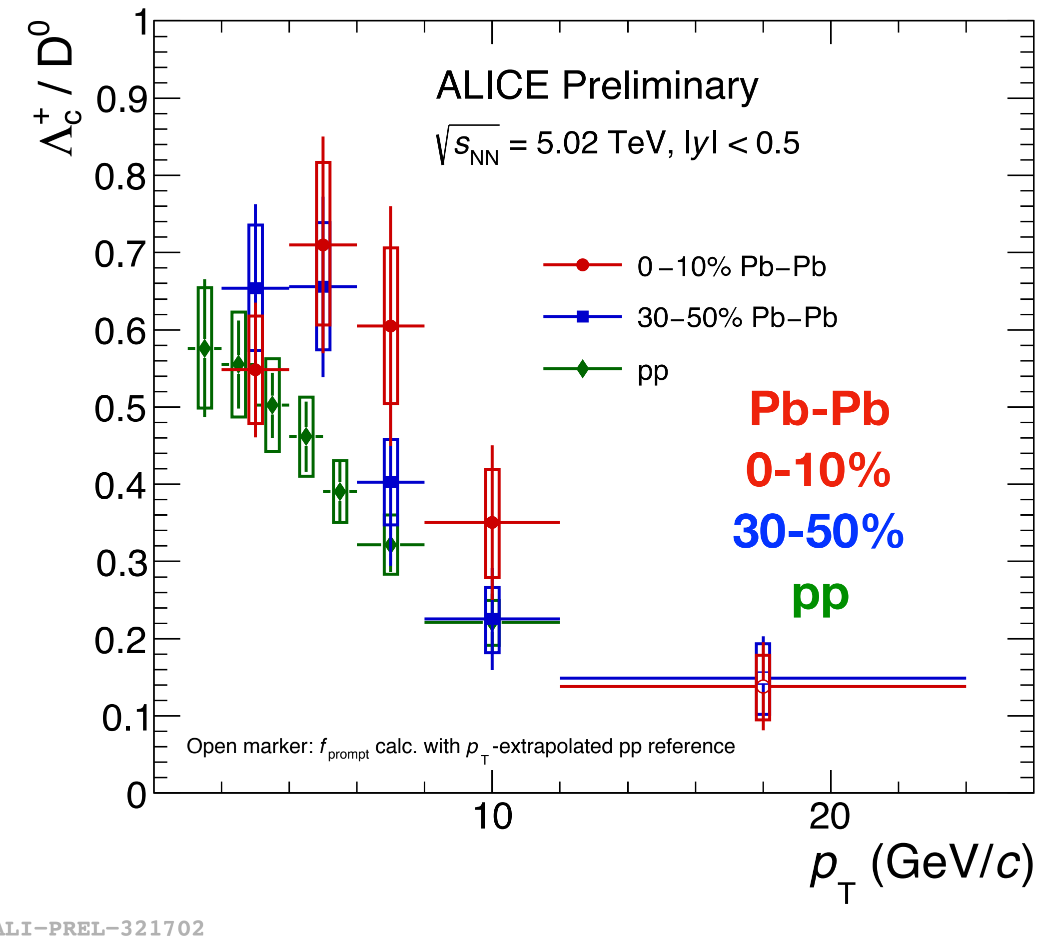
Λ_c baryon



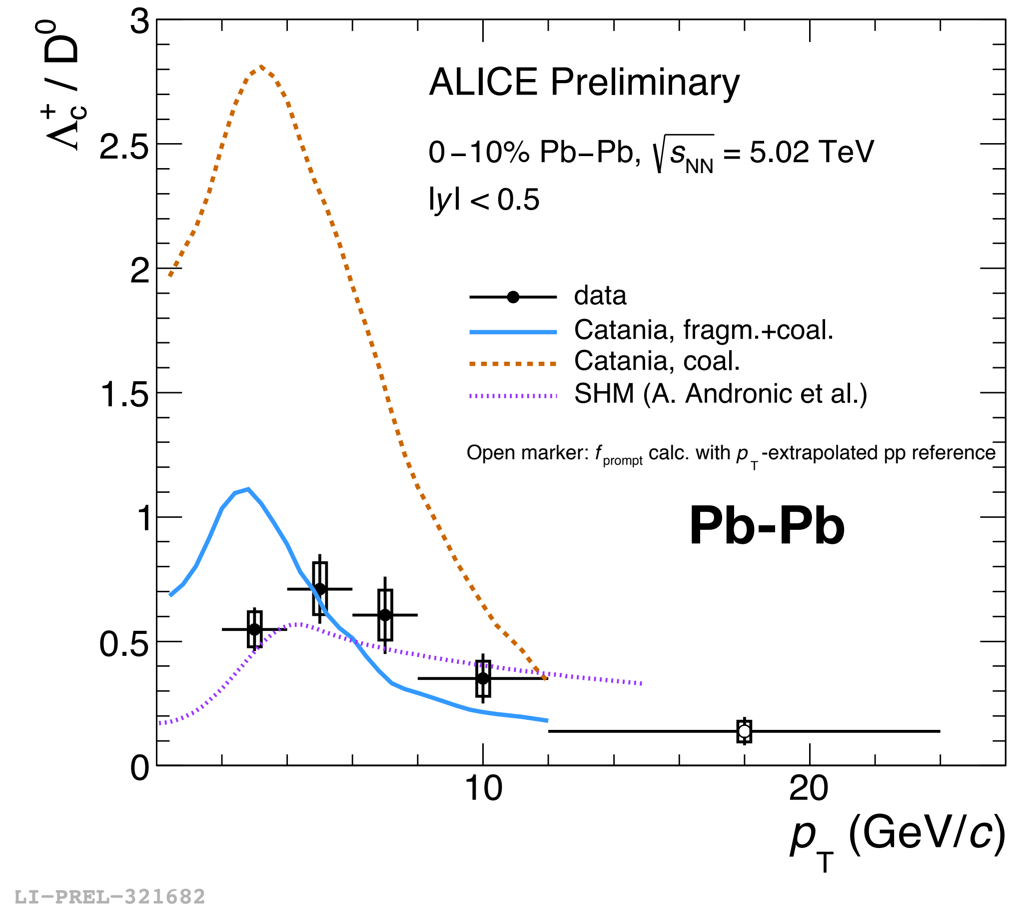
D^0 meson



Λ^+_c/D^0 vs p_T



Pb-Pb collisions

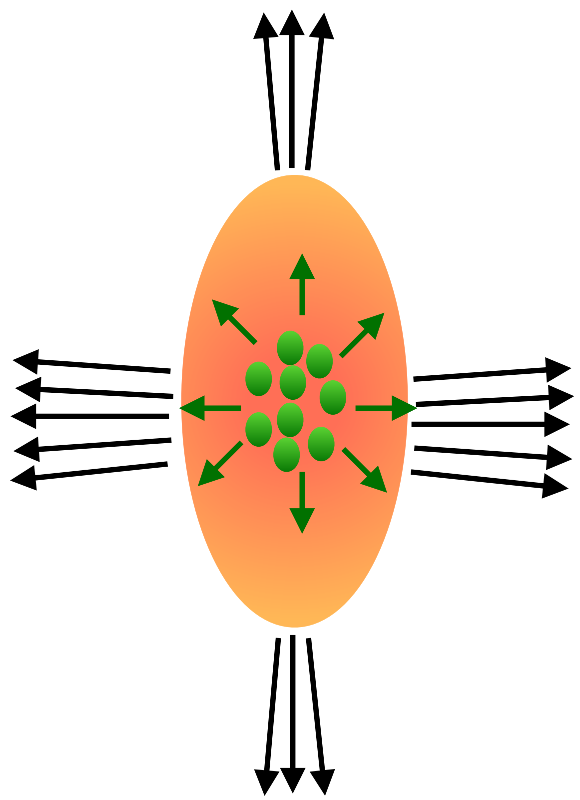


Λ^+_c/D^0 in Pb-Pb collisions higher than in pp and p-Pb collisions -> model calculations with fragmentation and coalescence is favored by data.

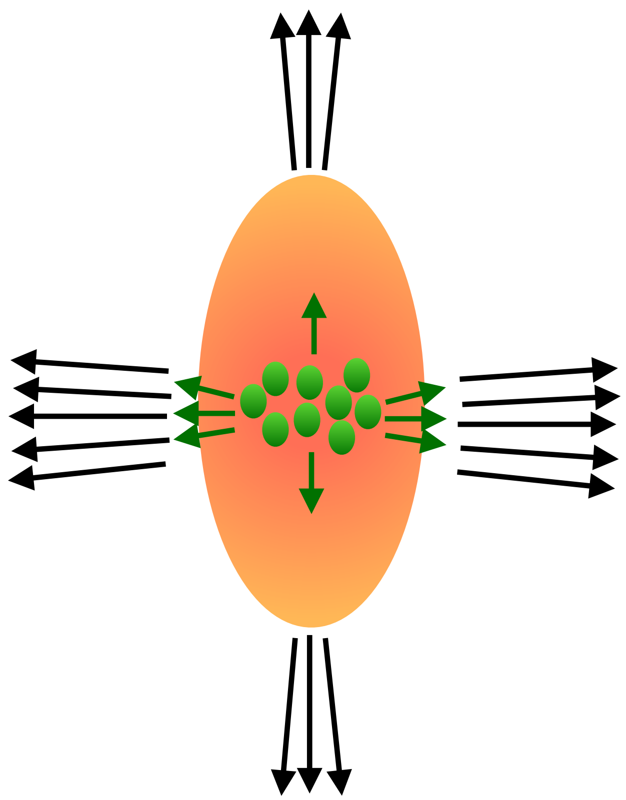
Heavy-quark collective flow

- Elliptic flow of light flavour hadrons at low p_T (< 2-3 GeV/*c*) explained by hydrodynamical models.
- Heavy quarks with large mass interact enough that they thermalize (equilibrate)?
  - Expected to take longer than light quarks

HQ production is
isotropic ($\boldsymbol{v_2}$ **= 0**) ??



HQ production is
anisotropic ($\boldsymbol{v_2}$ **!= 0**) ??



Heavy-quark collective flow

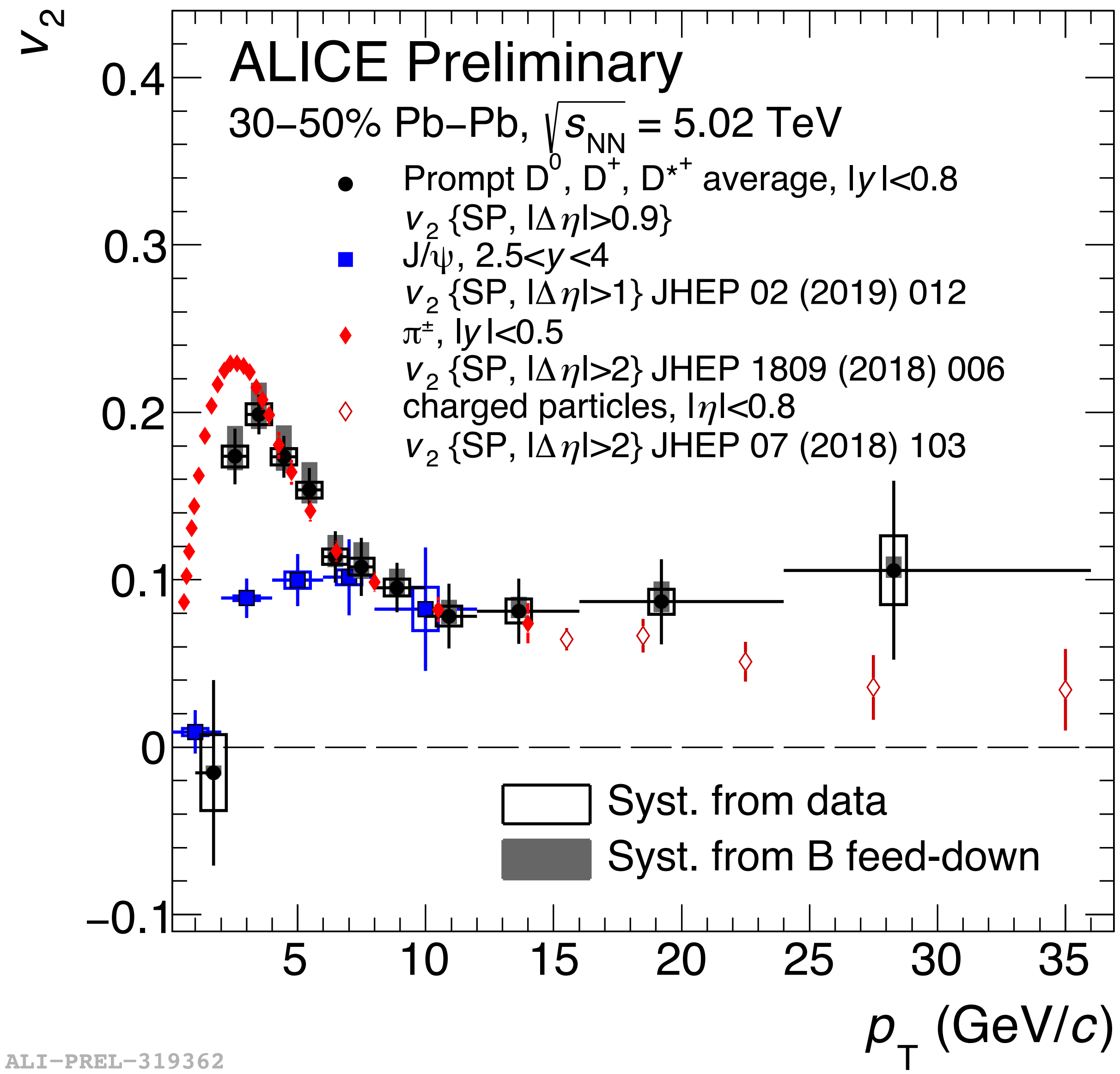
$v_2 = \langle \cos[2(\phi - \Psi_2)] \rangle$

Charm quark

Charged particles

D mesons

J/Ψ



- **Charm quarks interact strongly with the medium.**
- Charm quarks participate in the collective expansion of the medium
- D-meson v_2 possibly from charm quark flow + hadronisation via coalescence with the light-flavour quark

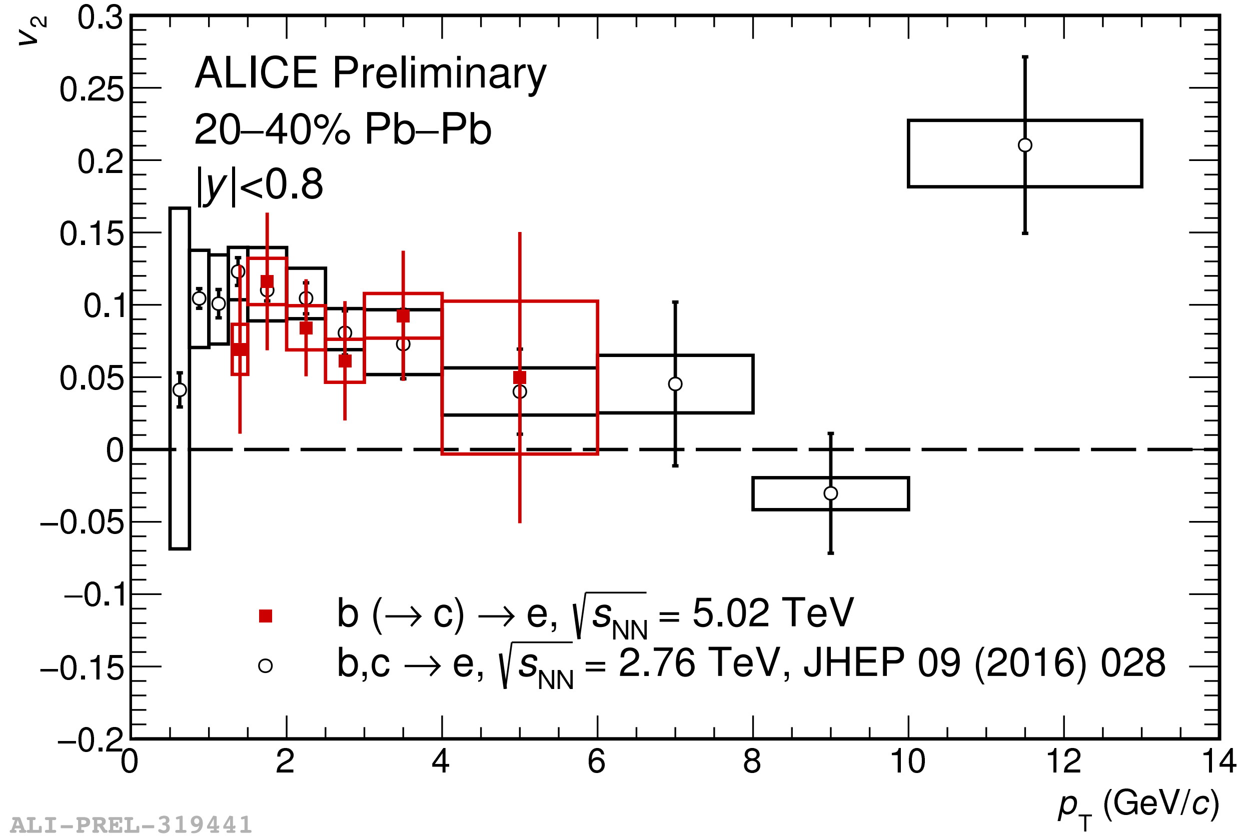
Heavy-quark collective flow

$v_2 = \langle \cos[2(\phi - \Psi_2)] \rangle$

Beauty quark

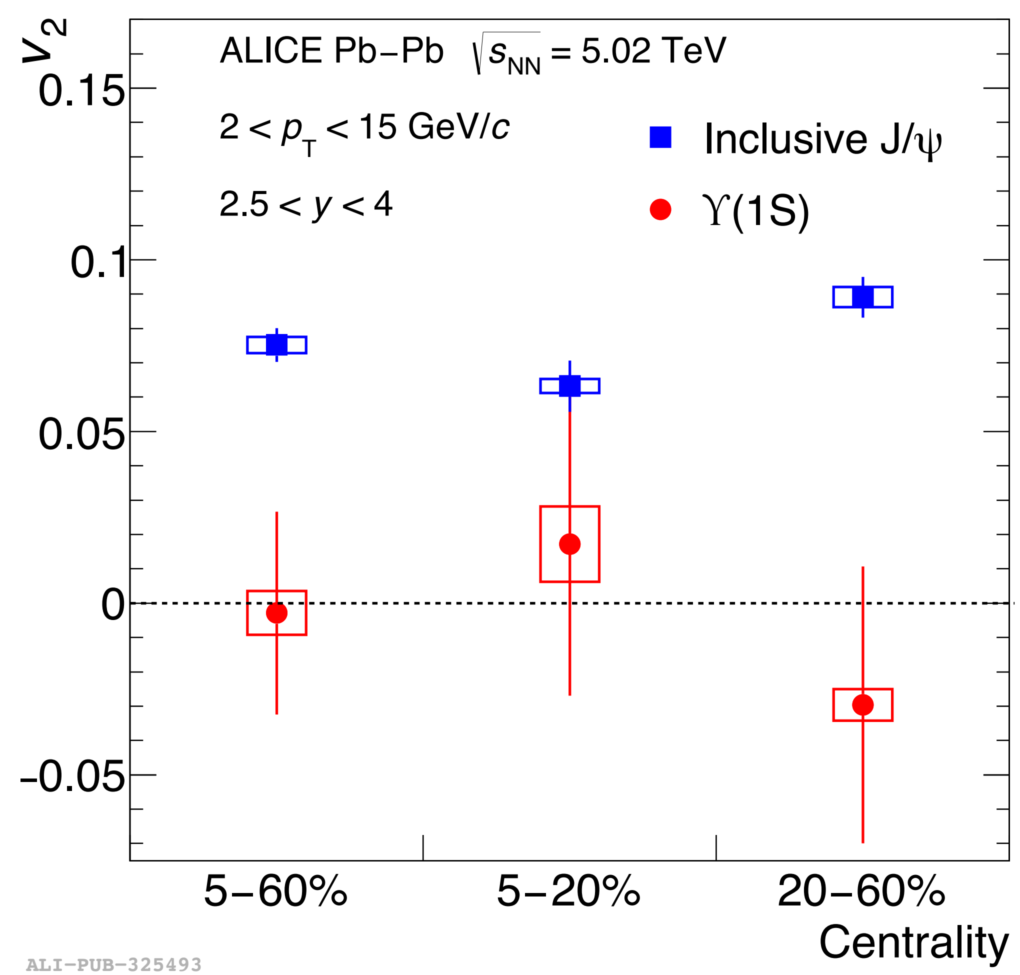
c, b ->e

b->e



J/Ψ

Υ



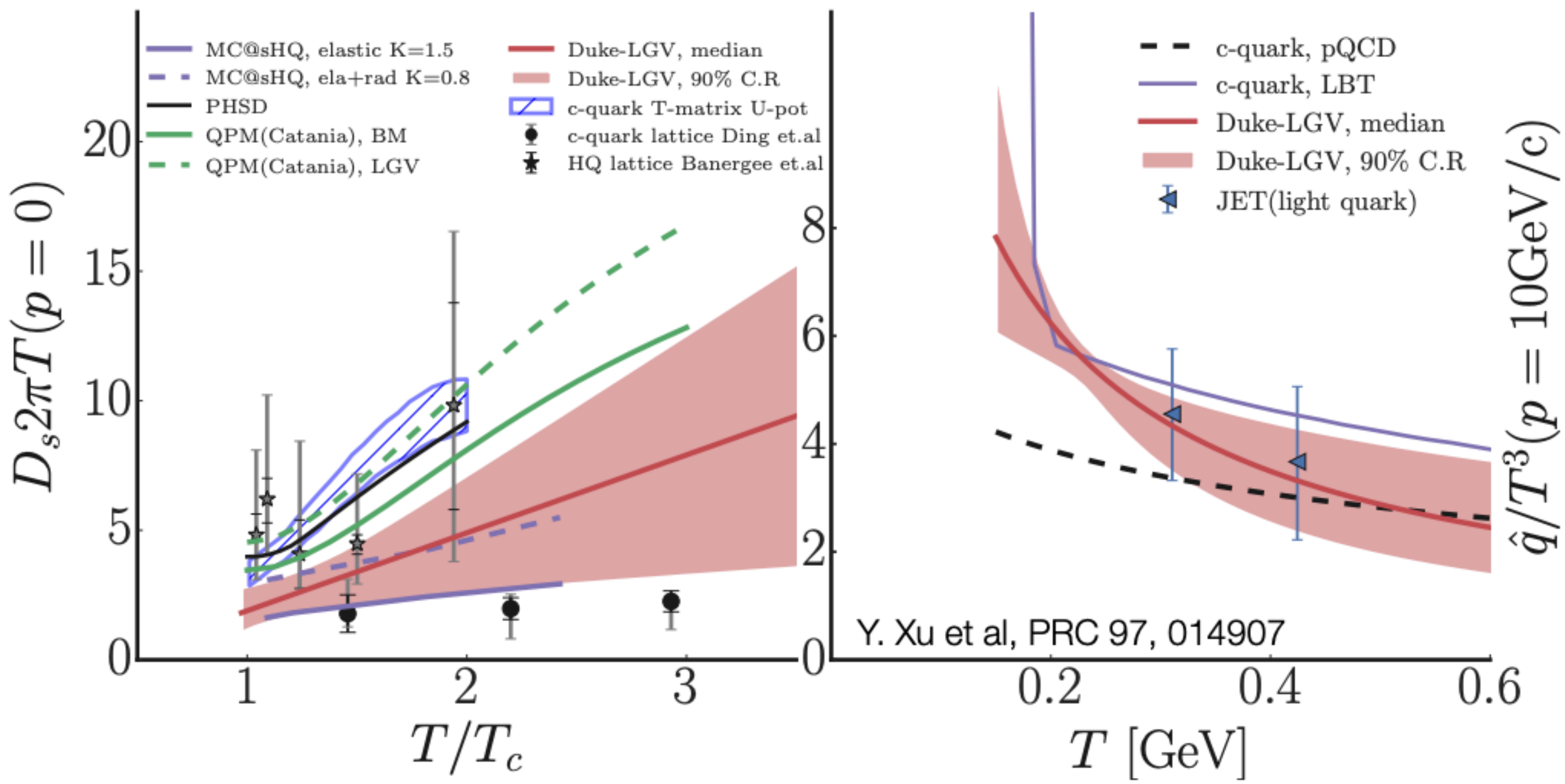
- **Open-beauty v_2 > 0, while bottomonia v_2 ~ 0**
  - Impact of collisional energy loss and coalescence on b->e?

Heavy-flavor transport coefficients

D meson R_{AA} and v_2 measurements provide constraints to models

Diffusion coefficients

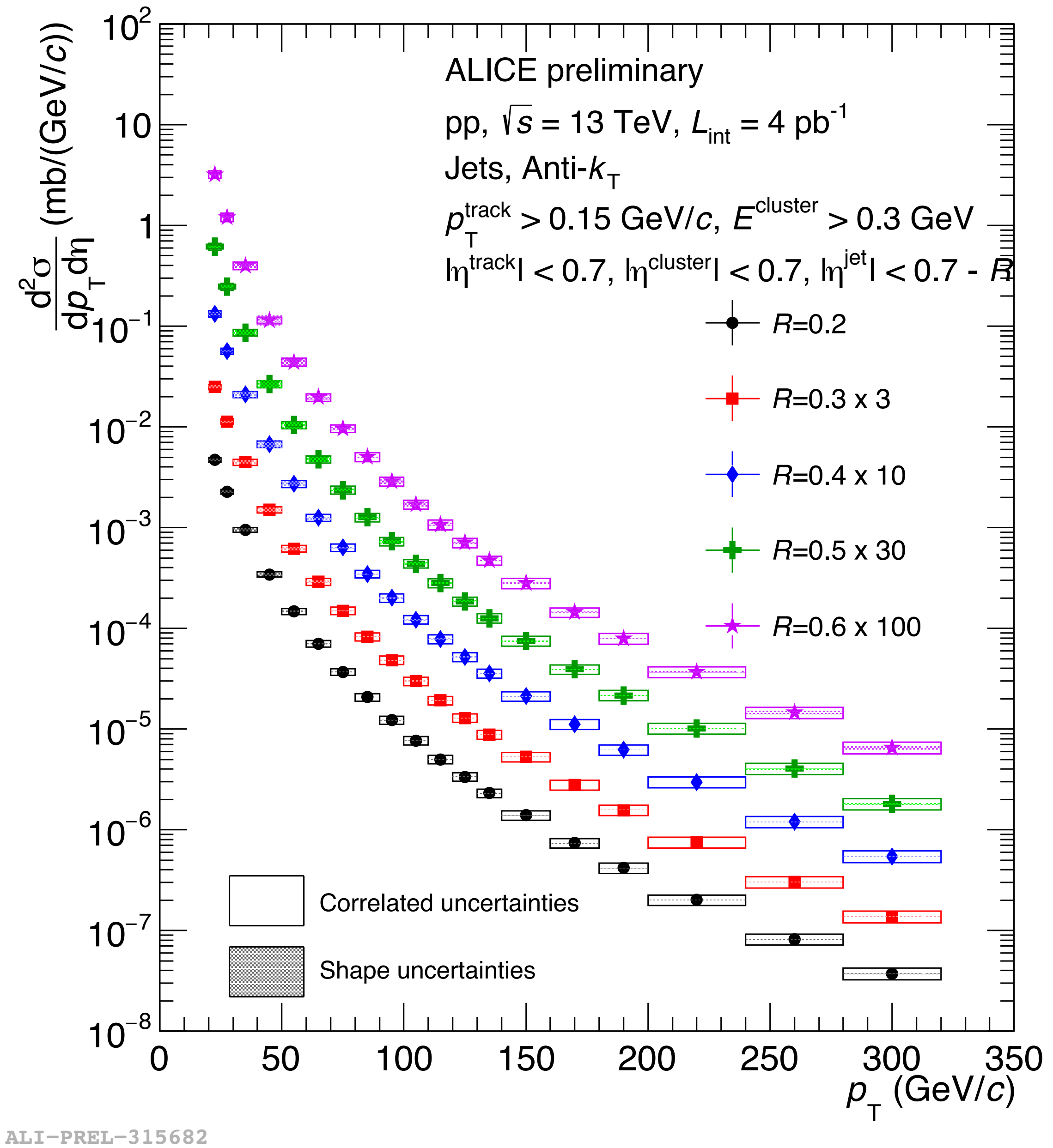
Transport coefficients



Constraints on T and p dependence of $\hat{q}$ and D_s

Probing QGP with jets

Jet cross-section in pp collisions

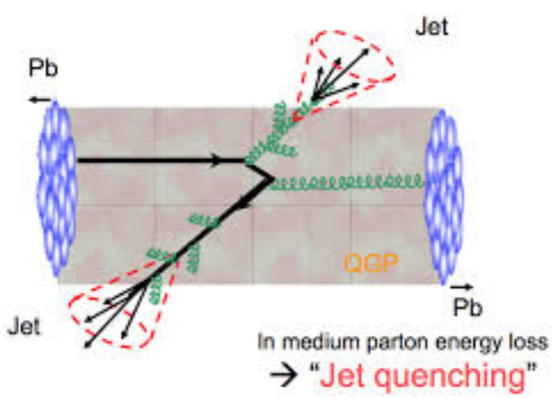


Jet cross-sections for different *R* -> study sensitivity to the jet transverse energy profile.

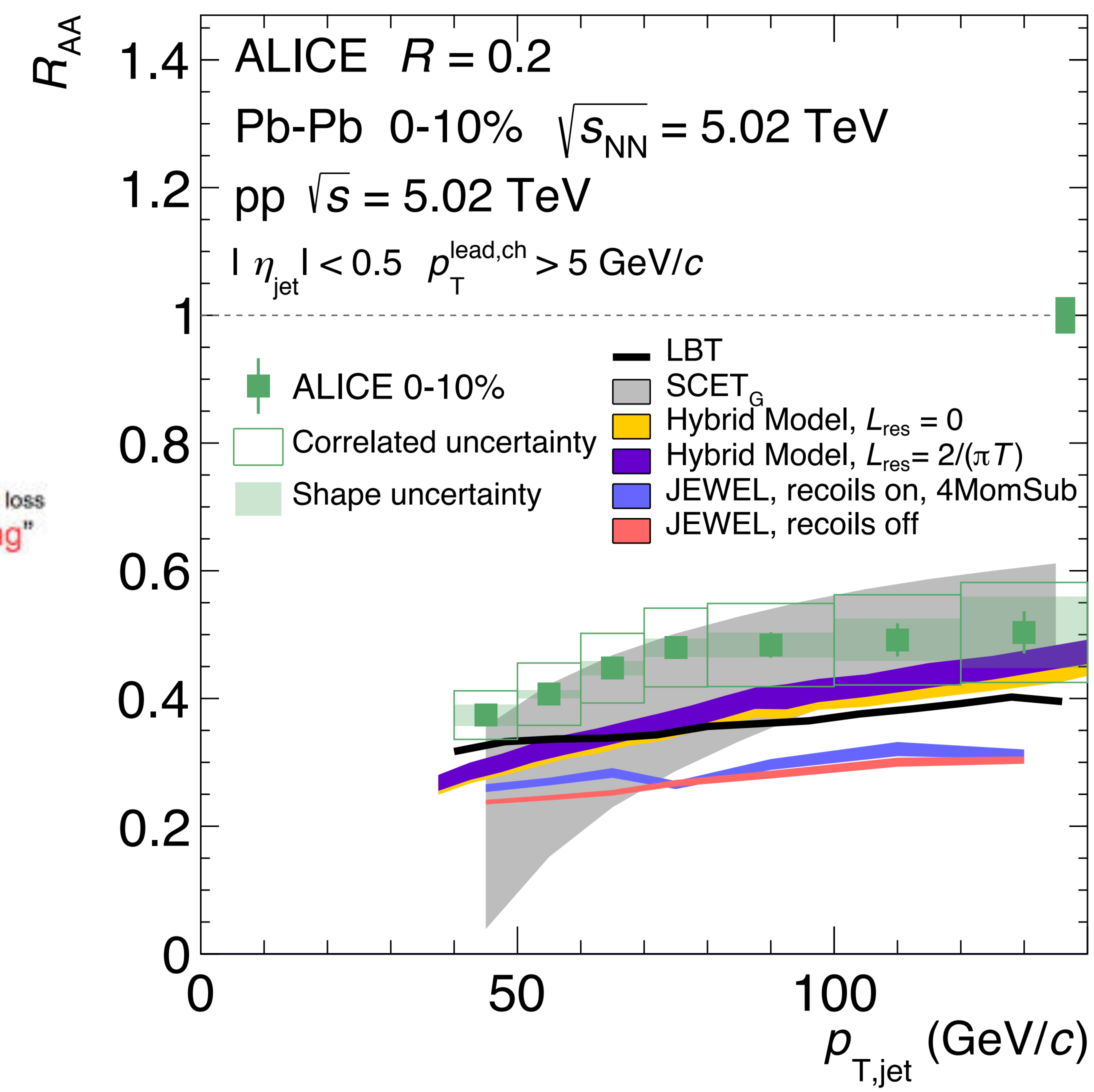
Probing QGP with jets

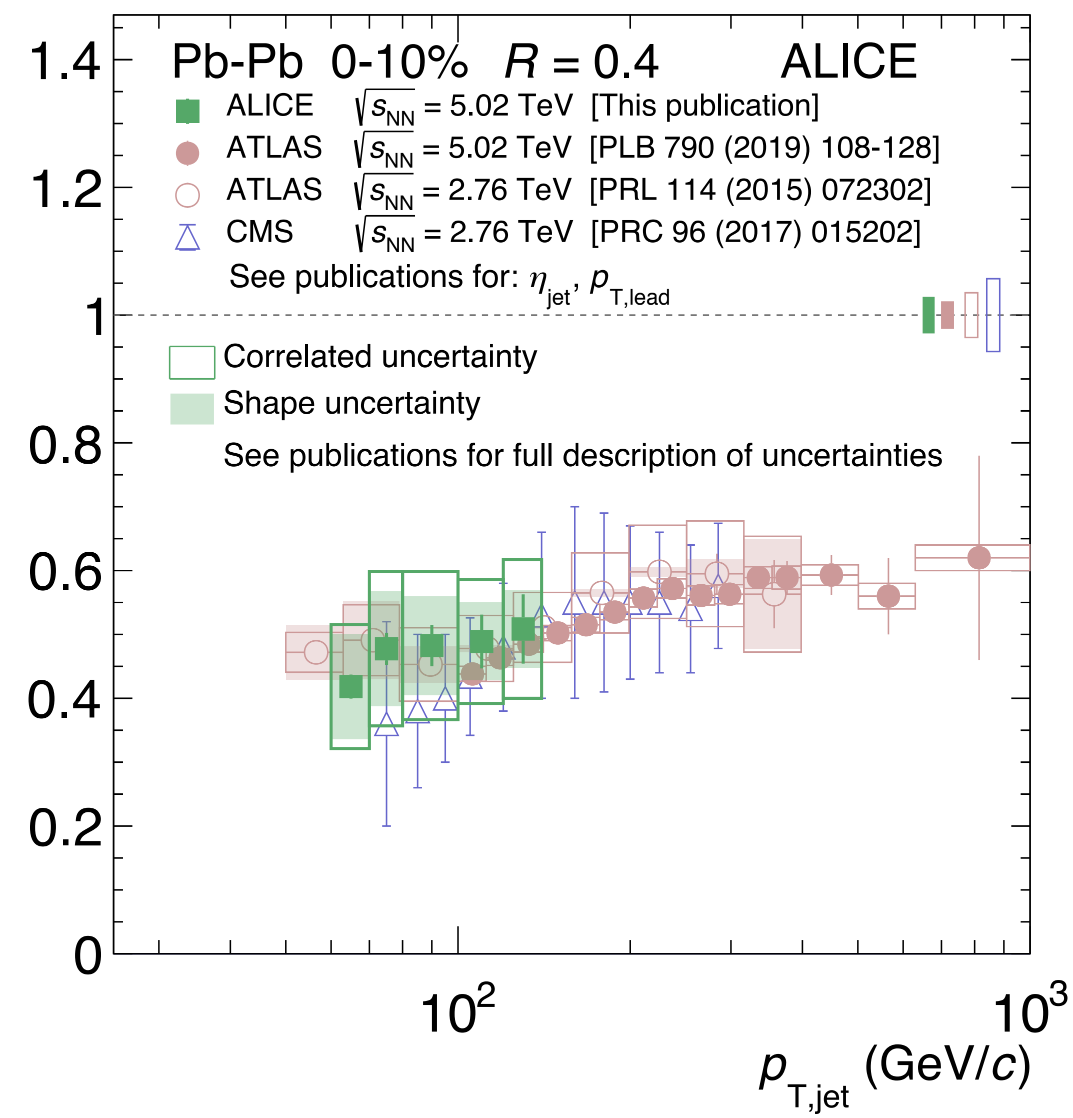
Jet quenching in Pb-Pb

$$R_{AA} = \frac{1}{<N_{coll}>} \frac{Y_{AA}}{Y_{pp}}$$



arXiv:1909.09718





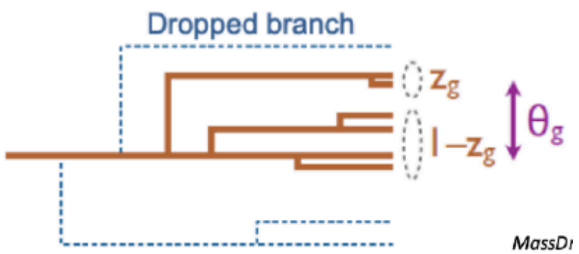
- Full jet R_{AA} for R = 0.2, 0.4 measured at low jet p_T down to 40 GeV/c.
- **Strong suppression of jet yield. No jet R dependence**
- **Models include jet-medium interactions —> predict similar tried as data.**

Jet substructure

Jet substructure sensitive to modifications in the medium.

Grooming jets with SoftDrop algorithm

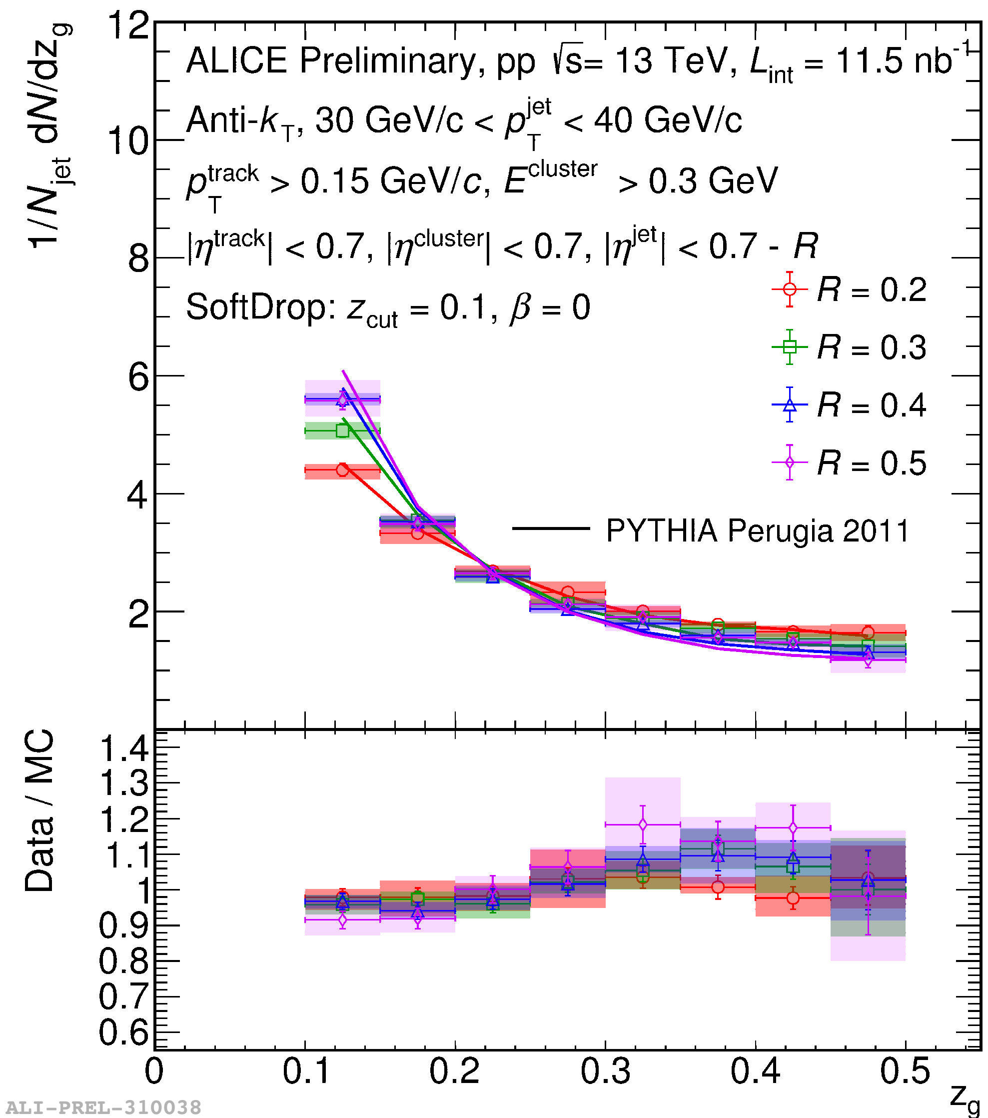
- Extract the hard components of a jet by recursively removing large-angle soft radiation to expose 2-prong structure in the jet.

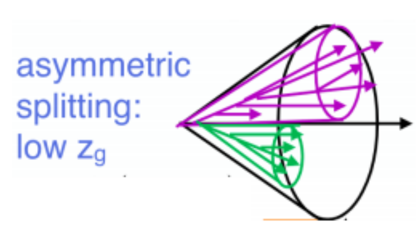


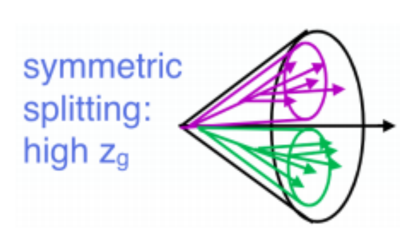
Groomed momentum fraction distributions;

pp:

- **Shape different for small and large jet radii at low p_T.**
- PYTHIA reproduces the trend very well.







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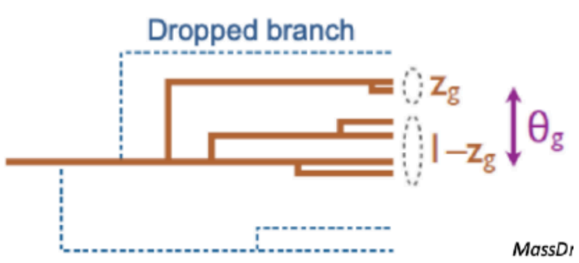

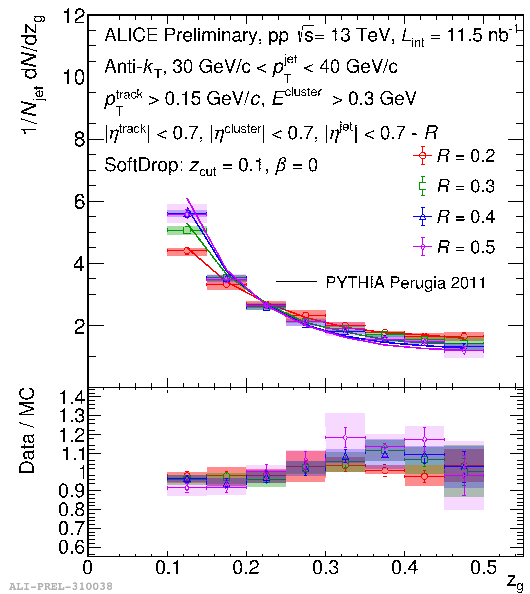

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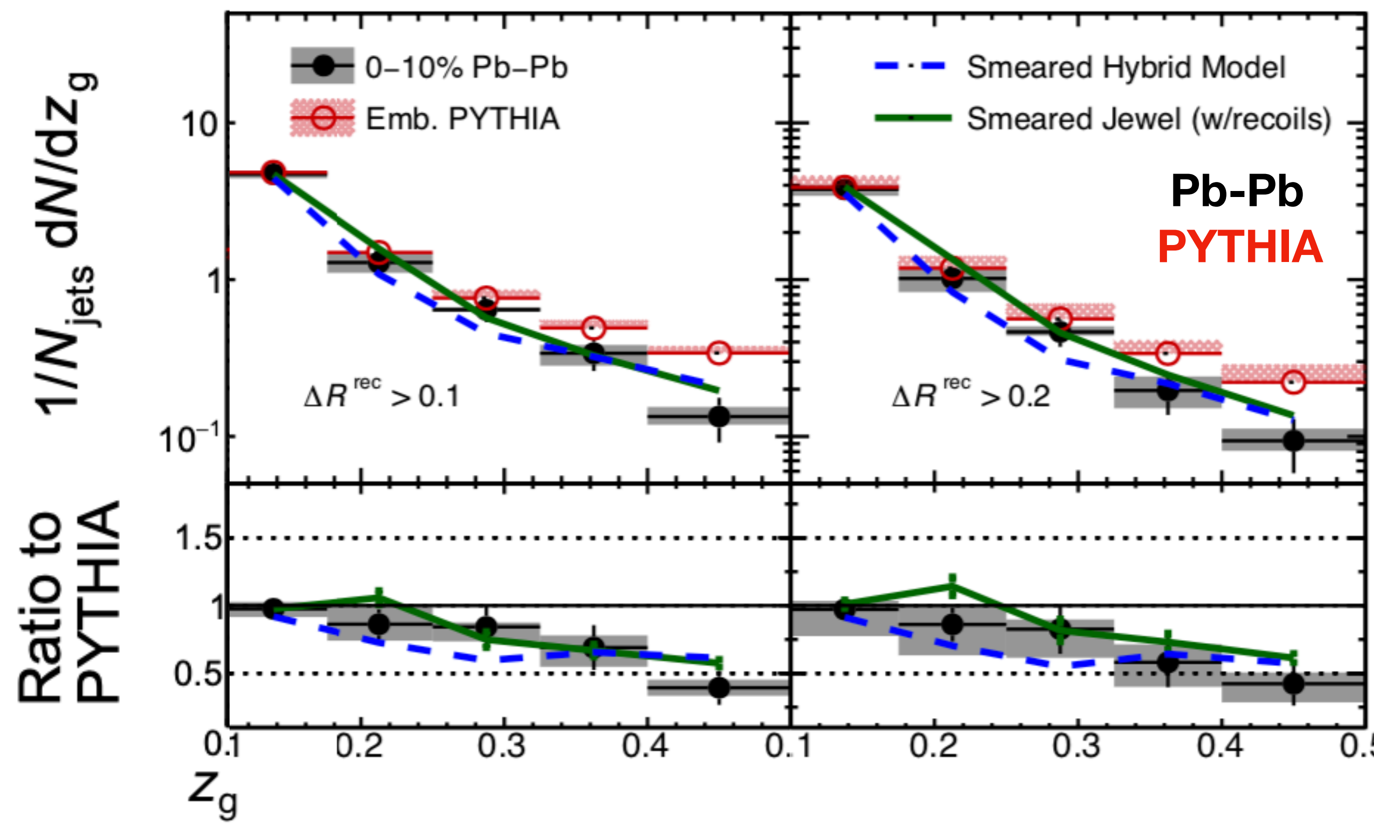
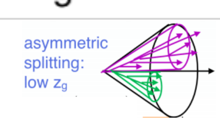
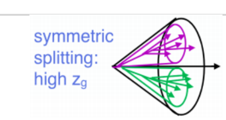




arXiv:1905.02512



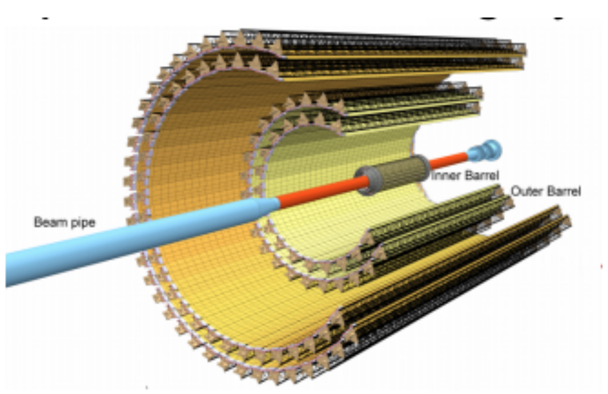
Pb-Pb:

- **Modification of Z_g in central Pb-Pb collisions w.r.t vacuum.**
- Suppression in the rate of symmetric splittings.
- Models capture the qualitative trend of data

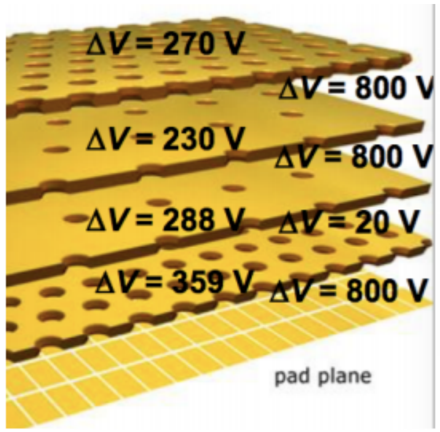
Looking forward

Major upgrade during LS2

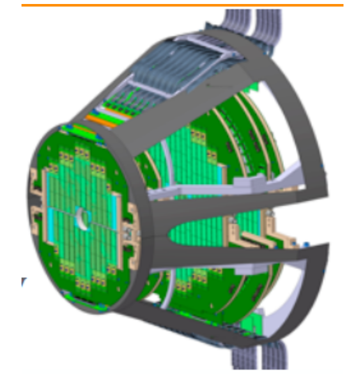
All pixel Inner Tracker System



GEM based TPC readout



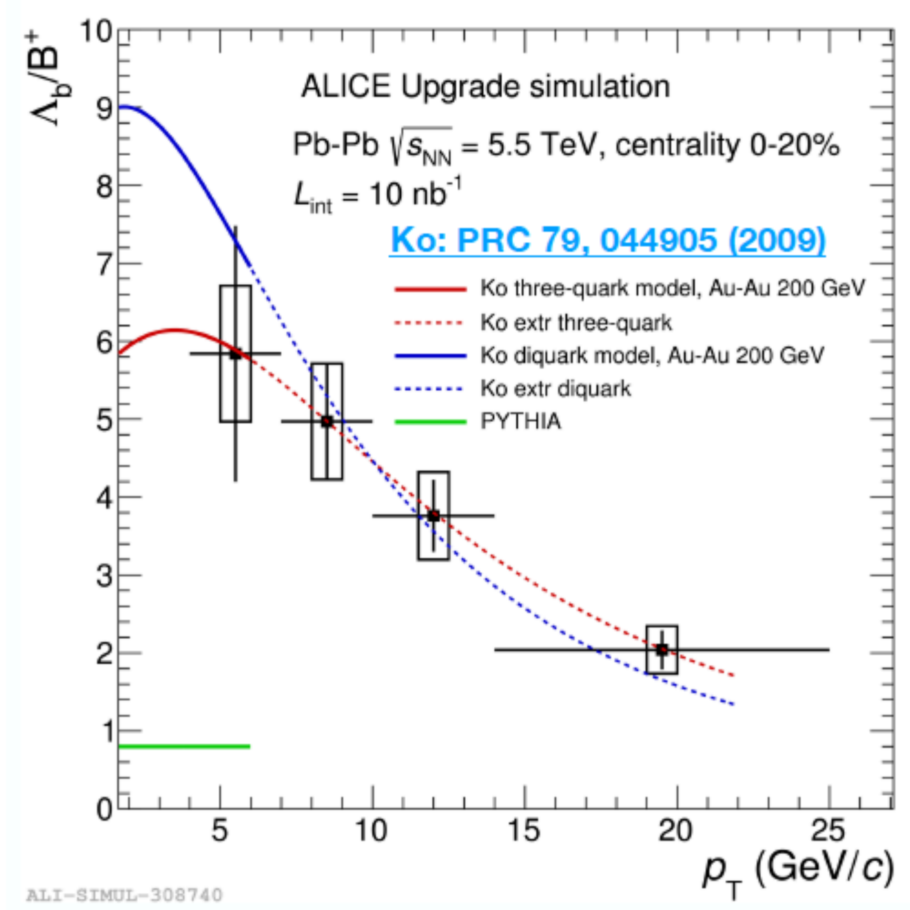
Pixel Muon Forward Tracker



- Faster interaction trigger
- New online-offline system

Run 3+4: x 100 higher statistics than Run 2

High precision measurements including beauty hadrons possible.



Conclusions

- Several new results from Run 2 data -> improving our understanding of the nature of QGP
  - v_n measurements in A-A collisions due to collective hydrodynamic flow of the medium.
  - Heavy-quarks and high p_T jets lose energy through interactions with QGP.
- QGP in small systems?? —> New puzzle.
- Exciting times in heavy-ion physics!!
- Looking forward for the restart in 2021
  - New detector components.
  - x 100 increase in statistics from Run 3 and 4.

Back-up