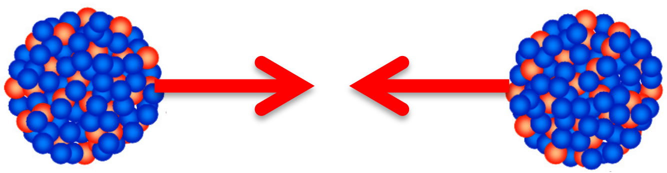
An Overview of Heavy-Ion Physics in Small Collision Systems at the LHC

A. G. Knospe
The University of Houston
on behalf of ALICE, ATLAS, CMS, & LHCb

31 July 2019

Introduction

- Why study small systems?
  - Baseline for A–A (vacuum processes, “cold nuclear matter”)
  - Study “turn-on” of collective effects
  - Could there be a QGP?
- Modelling



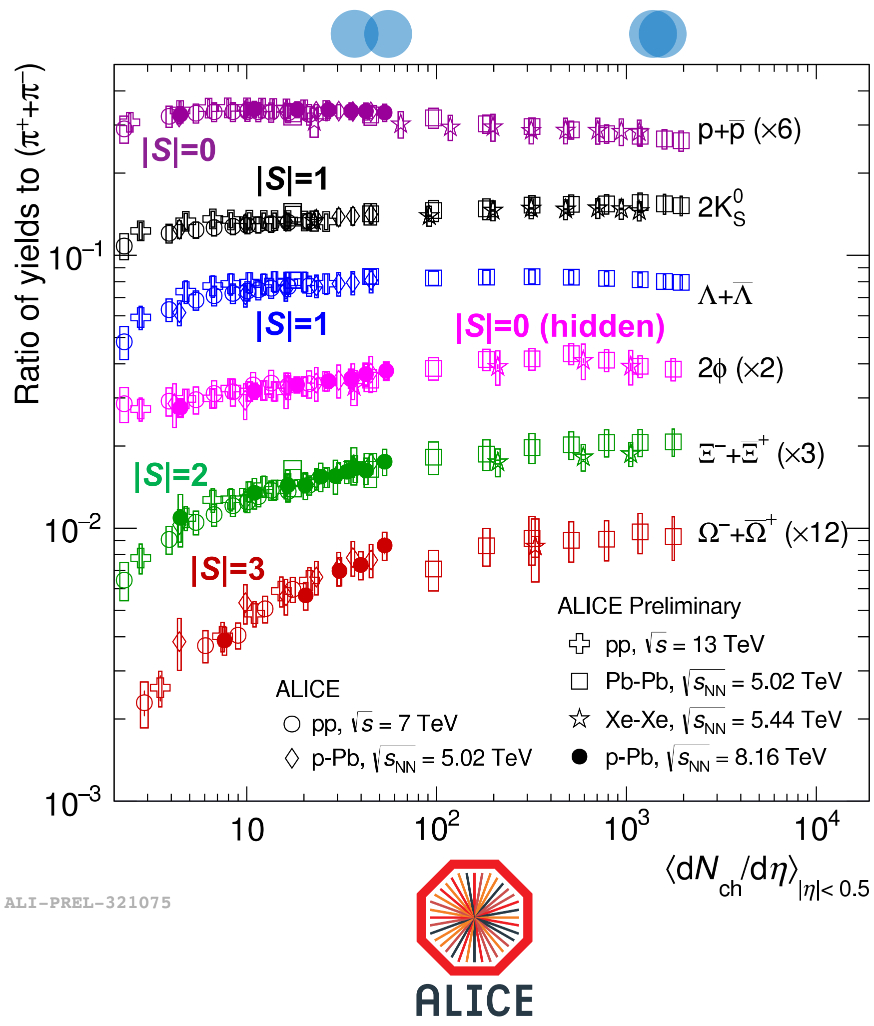
pp Models
Single hard scatterings
vacuum processes
+ multiparticle interactions
color reconnection, color ropes, …

A–A Models
QGP, hydrodynamics (radial & elliptic flow), statistical models

- *Disclaimer: there are of course many more results than what I show here.*

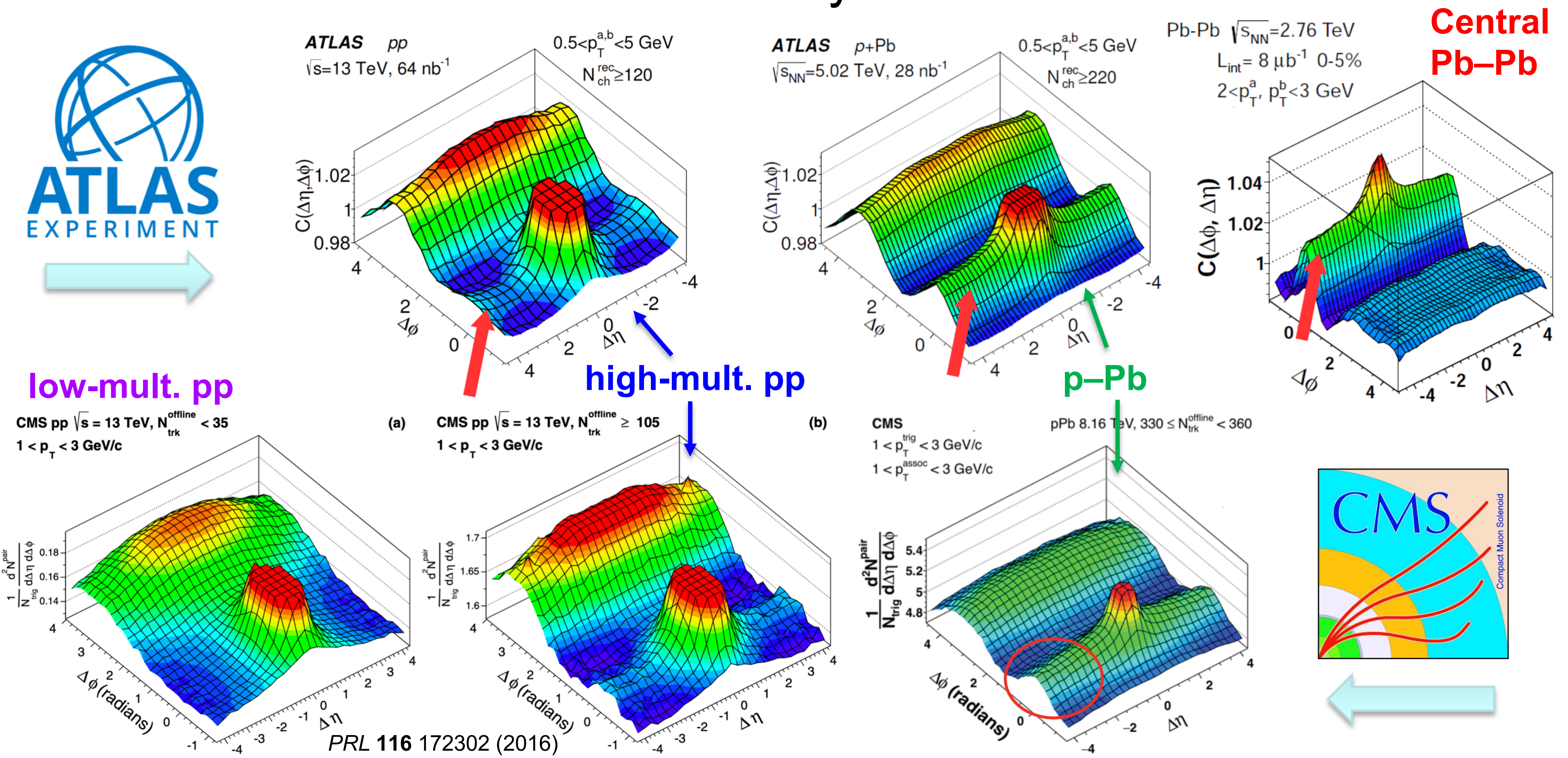
Strangeness Production

- Smooth evolution of particle production with charged-particle multiplicity across pp, p–Pb, Xe–Xe, and Pb–Pb collisions
  - No energy dependence
  - Hadron chemistry is driven by the multiplicity (system size)
- Increase of strange-particle production for small systems, saturation around thermal-model values for large systems
  - Magnitude of strangeness enhancement increases with strange-quark content



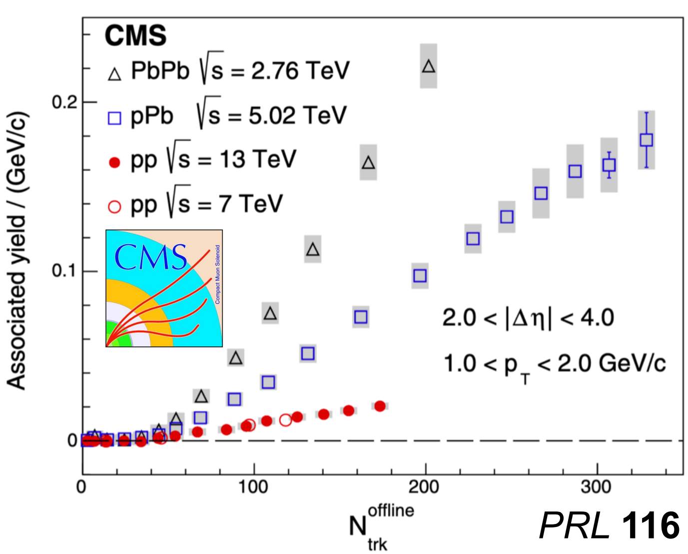
Ridge

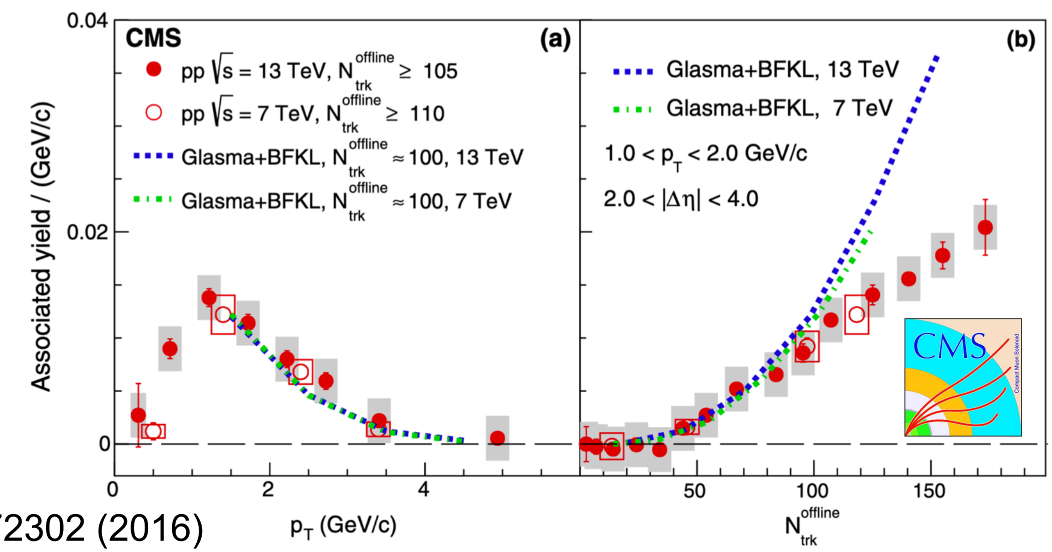
- Near-side, long-range correlations observed in Pb–Pb, p–Pb, and pp collisions
- Extends over at least 4 units of η
- Collective behavior in small systems?



Ridge

- Near-side, long-range yields:
  - Negligible for N_{trk} < 40, then ~linear increase
  - Collision system: for given multiplicity $Y_{pp} < Y_{pPb} < Y_{PbPb}$
- Yields described by Glasma model for N_{trk} < 100
  - Gluon saturation, initial collimated gluon emission
  - No collision energy dependence
  - Model overestimates associated yields at high multiplicity

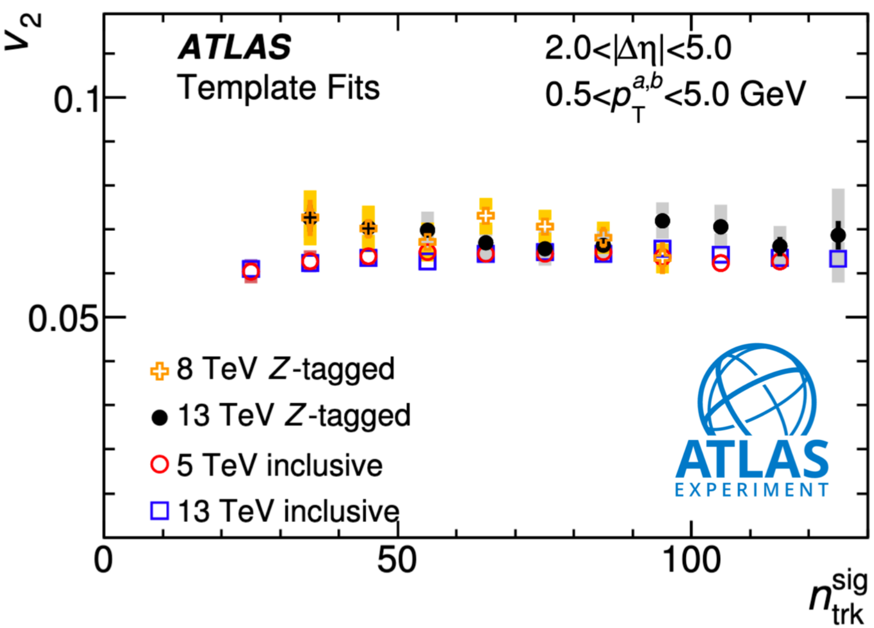


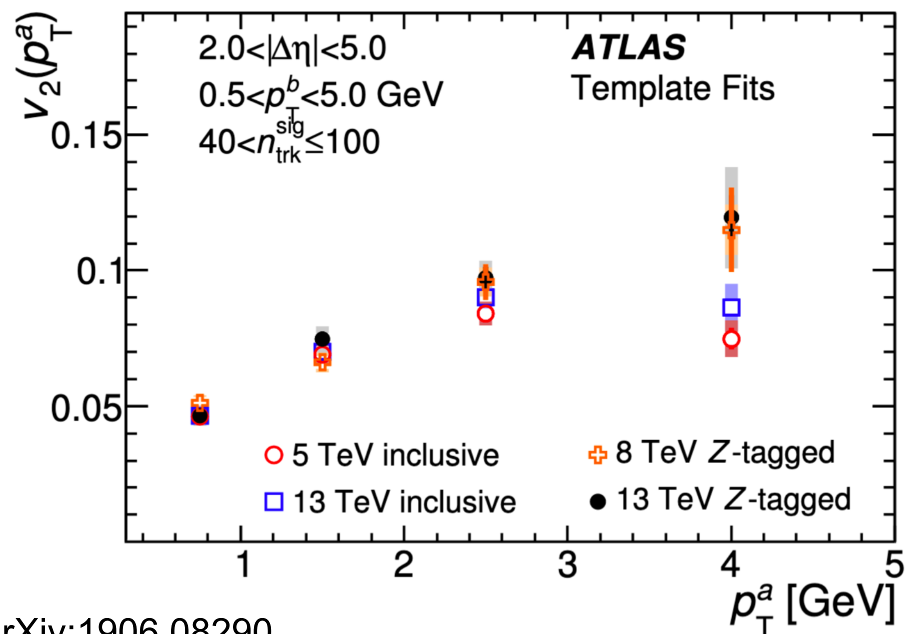


PRL **116** 172302 (2016)

Ridge in Z-Tagged Events

- ATLAS studied ridge in Z-tagged pp collisions
  - Presence of Z → hard scattering in event (high Q^2)
  - Proposal: presence of Z → smaller impact parameter (*b*) → smaller initial eccentricity → smaller v_2 (*cf.* inclusive pp sample)
  - Template fits remove back-to-back dijets, corrections for pileup
  - No significant difference between results in Z-tagged and inclusive events: presence of hard scattering does not affect ridge formation

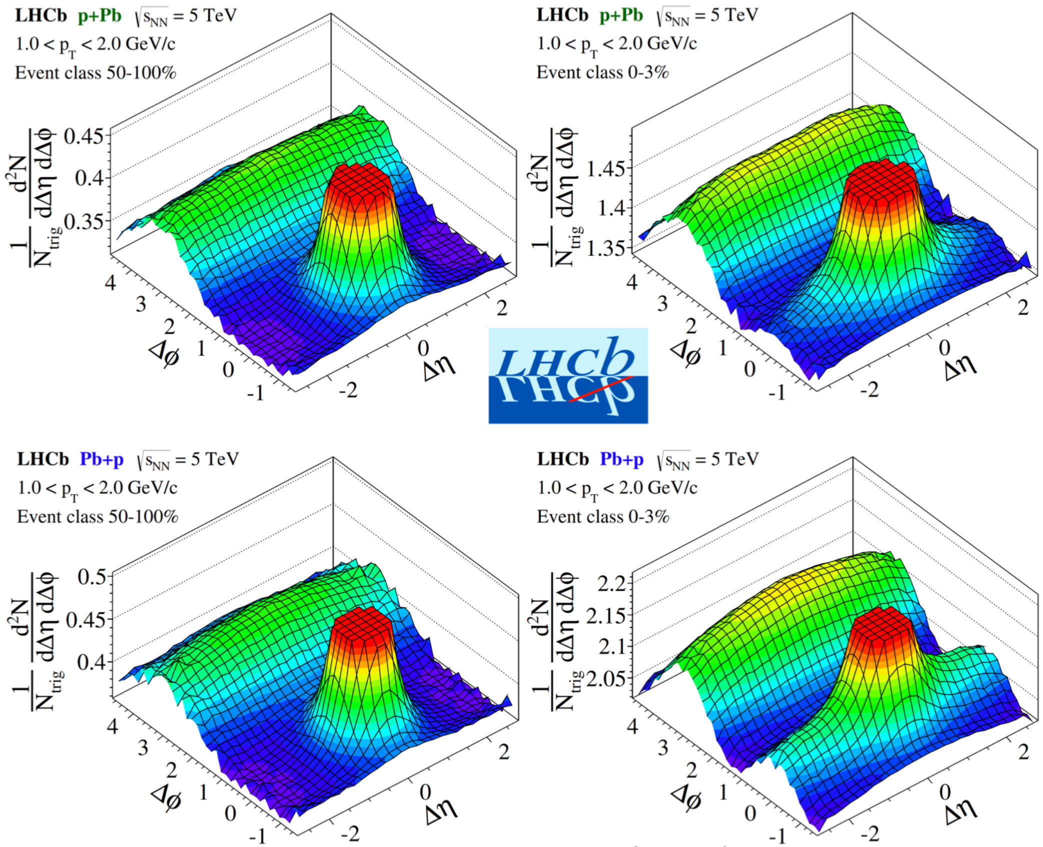




arXiv:1906.08290

Forward/Backward Ridge

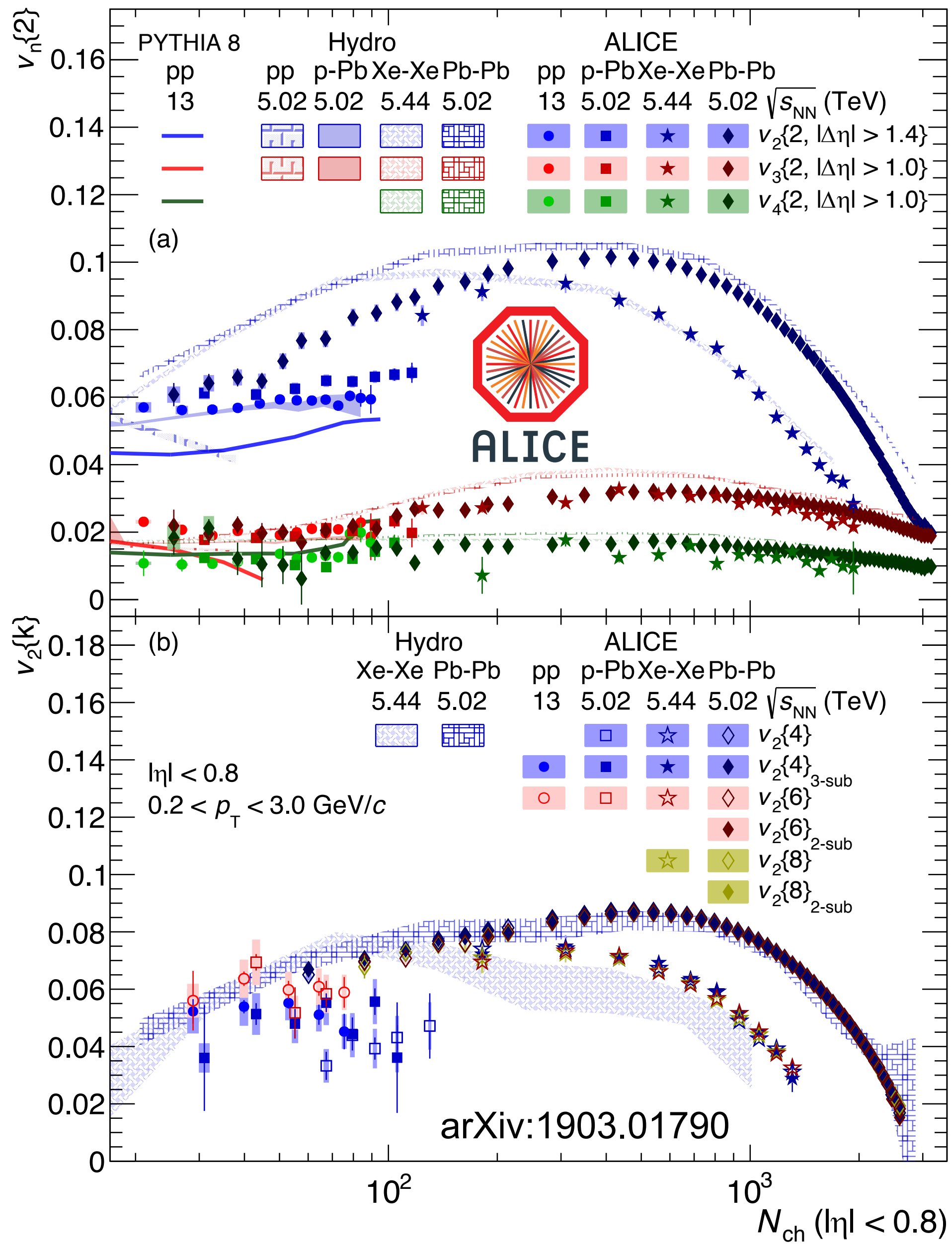
- Ridge also observed at forward & backward rapidity (p- and Pb-going directions)
- Size of near-side ridge increases with multiplicity
- Structures at forward and backward rapidities have similar magnitudes for similar multiplicities



PLB **762** 473 (2016)

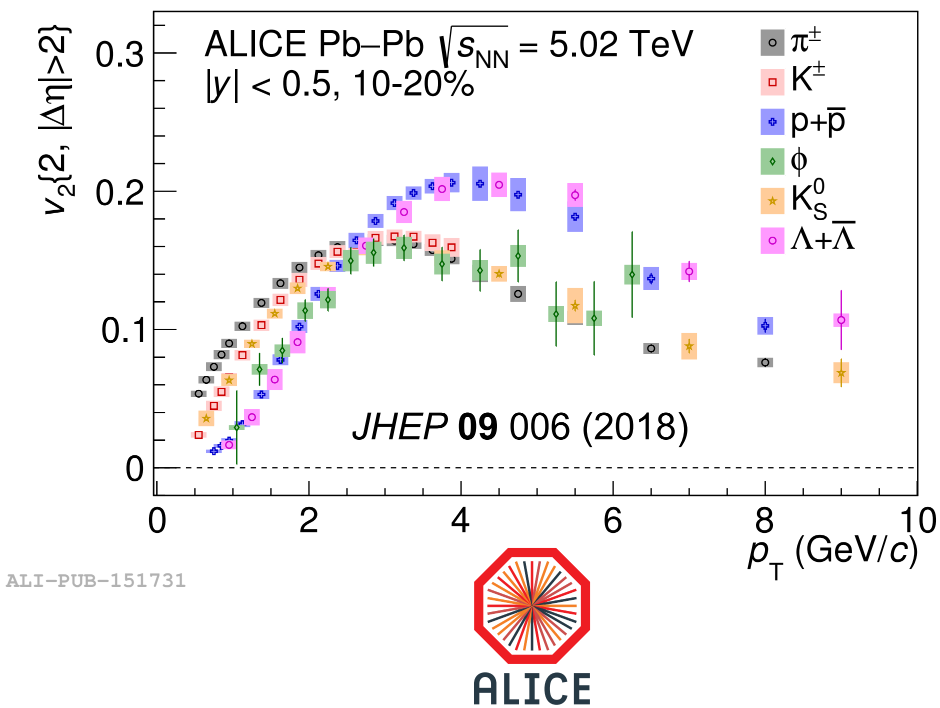
v_n Measurements

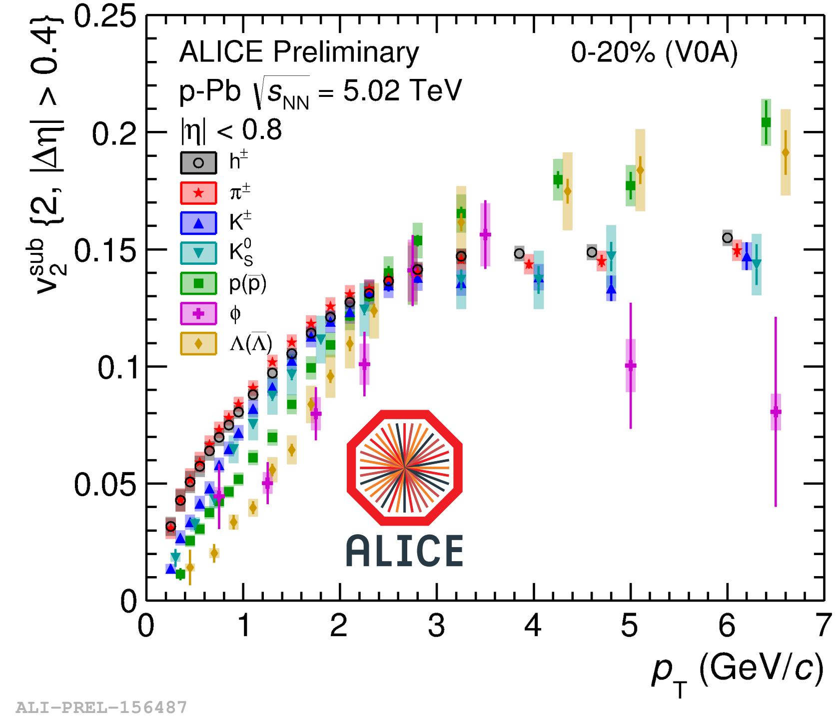
- A–A Collisions
  - Strong N_{ch} dependence
  - Ordering: $v_2 > v_3 > v_4$ (except for highest N_{ch})
    - Expected due to collision geometry (v_2), fluctuations (v_3, v_4)
  - Hydrodynamic calculations describe data well except for v_2 at low N_{ch}
- Small Systems
  - Weak N_{ch} dependence (similar values to A–A)
  - Ordering: $v_2 > v_3 > v_4$
  - Multi-particle results ($v_2\{4\}$ & $v_2\{6\}$) less influenced by non-flow
  - Results cannot be explained by non-flow effects alone (PYTHIA)



v_2 of Identified Hadrons

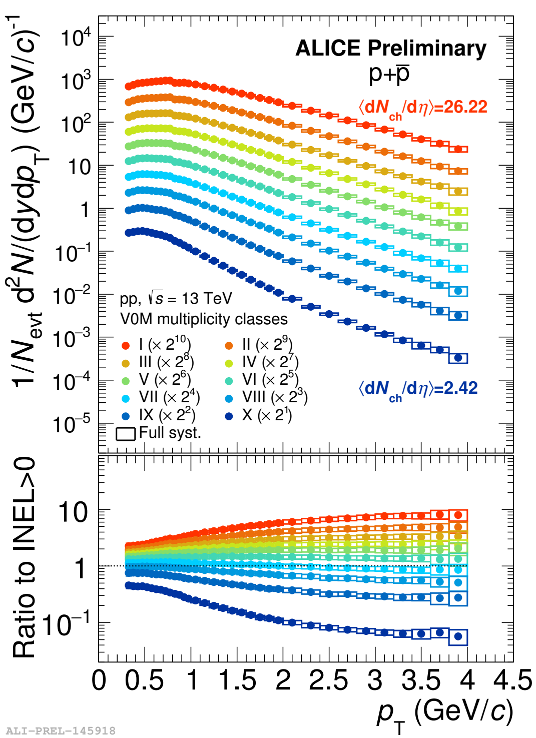
- A–A collisions
  - Mass ordering of v_2 for low p_T
  - Baryon-meson grouping for high p_T
- Indications of similar behavior in p–Pb



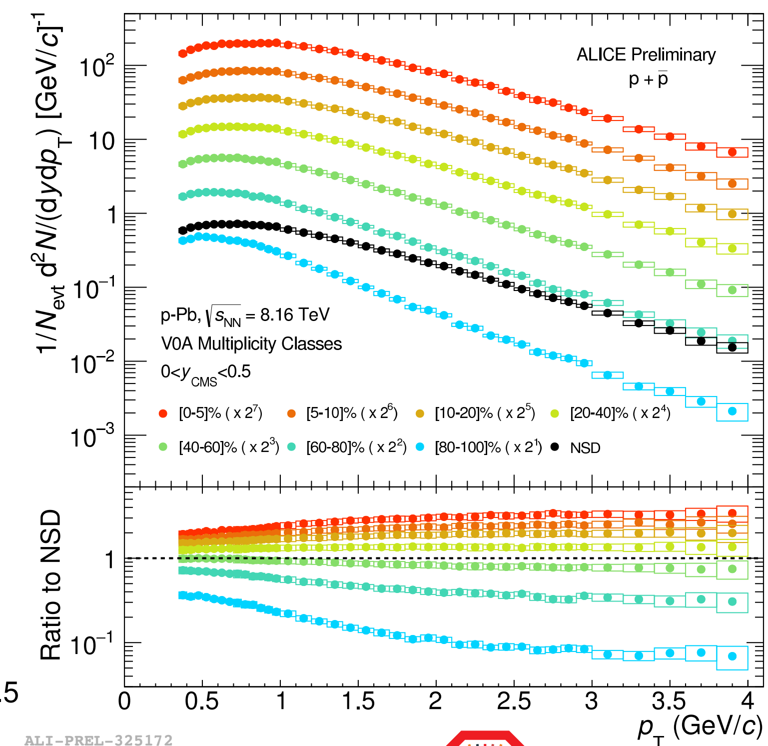


Evolution of p_T Spectra

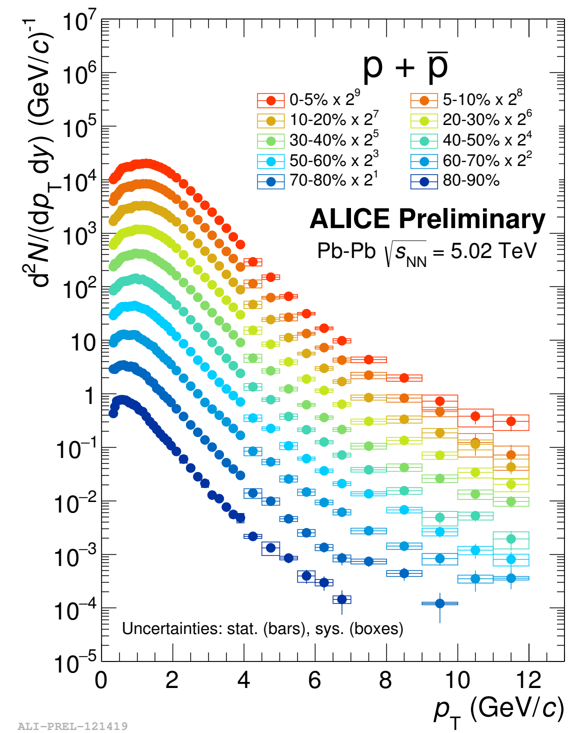
- Hadron p_T spectra become harder with increasing multiplicity ($\langle p_T \rangle$ increases)
- Qualitative similarities for pp, p–Pb, and Pb–Pb
- pp & p–Pb: modification mostly for $p_T < 3$ GeV/c



pp



p–Pb

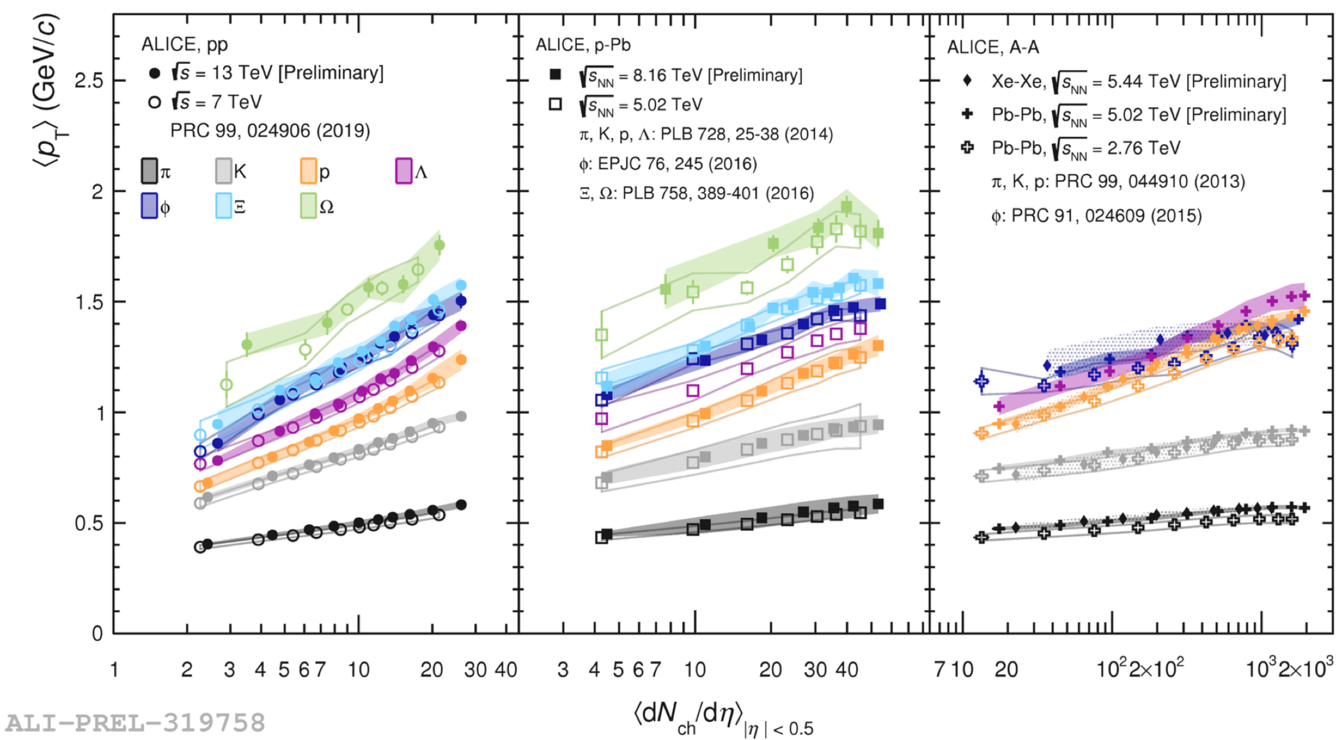


Pb–Pb

ALICE

Mean Transverse Momentum

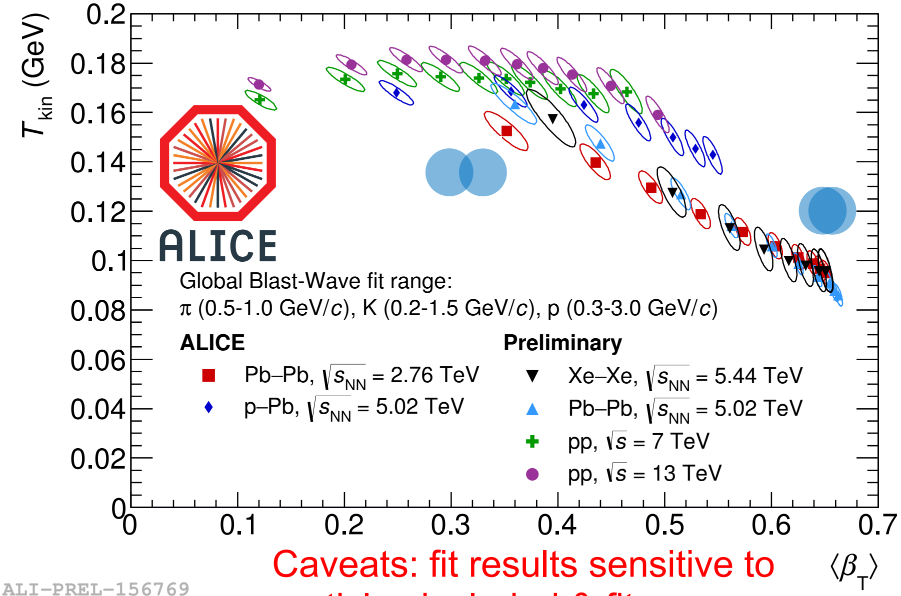
- A–A collisions: mass ordering of $\langle p_T \rangle$ (see p and ϕ)
  - Consistent with hydrodynamic flow
- Small Systems:
  - Mesons (K*, ϕ) have greater $\langle p_T \rangle$ than baryons w/ similar masses
  - More rapid increase in $\langle p_T \rangle$ with multiplicity
  - $\langle p_T \rangle$ values in high-mult. pp & p–Pb reach those seen in Pb–Pb



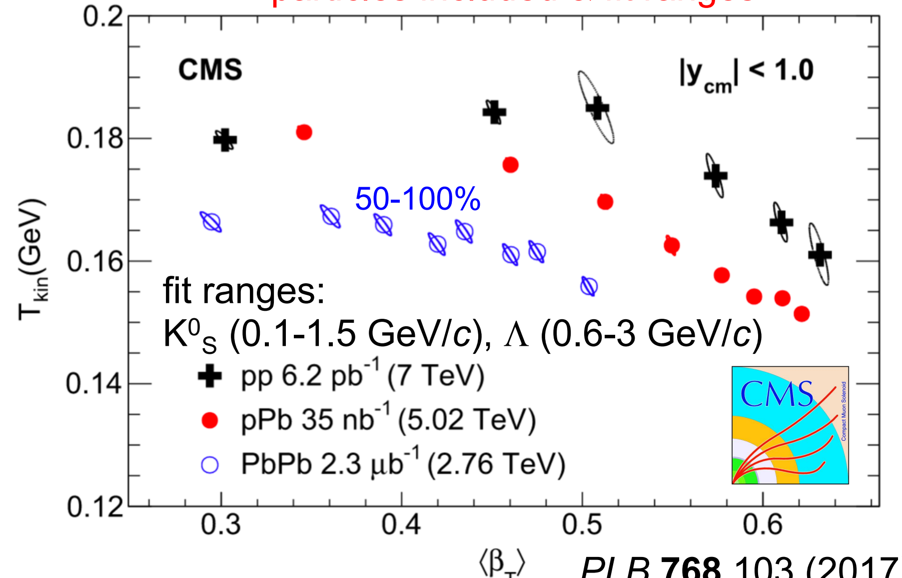
See also:
CMS *PLB* **768** 103 (2017)

Blast-Wave Fits

- Simultaneous blast-wave fits of p_T spectra
  - ALICE: π, $K^{\pm}$, & p
  - CMS: K^0_S & Λ
- A–A collisions
  - T_{kin} decreases, flow velocity $\langle\beta_T\rangle$ increases w/ centrality
- Small systems
  - Large increase of $\langle\beta_T\rangle$ w/ mult.
  - Higher T_{kin} values than A–A
  - Similar multiplicities: $\langle\beta_T\rangle$ (and $\langle p_T\rangle$) greater in smaller systems
- Change of $\langle p_T\rangle$ vs. multiplicity qualitatively consistent with expanding fluid, but MPIs and/or color reconnection are possible explanations in small systems



Caveats: fit results sensitive to particles included & fit ranges

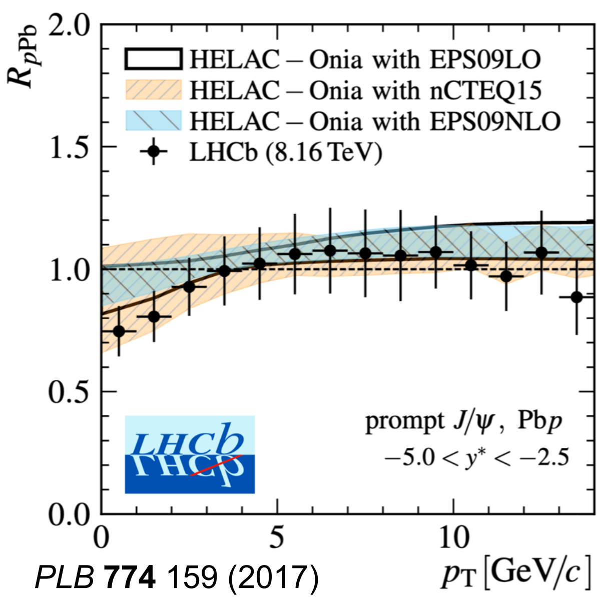


PLB **768** 103 (2017)

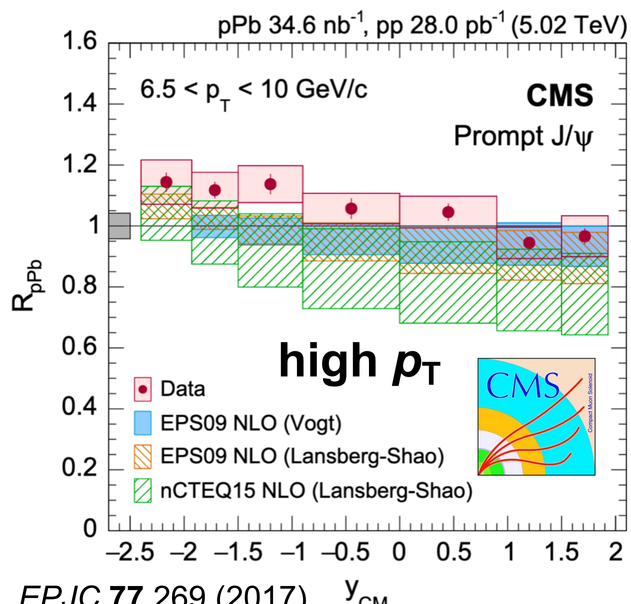
J/ψ in p–Pb

- Prompt J/ψ from initial hard scatterings
  - Modification due to initial-state effects (gluon density in nucleus, initial-state energy loss) or final-state effects (co-movers)
- Low p_T: suppression of prompt J/ψ
- High p_T: R_{pPb} consistent with unity
  - Possible weak decrease from backward to forward y
  - Suppression in Pb–Pb not due to cold nuclear matter effects
- R_{pPb} in good agreement with model predictions

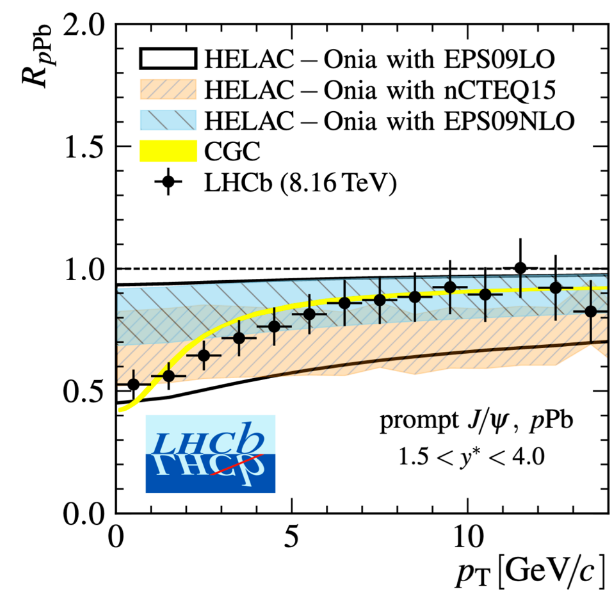
Pb (high *x*) ← → **p (low *x*)**



PLB **774** 159 (2017)



EPJC **77** 269 (2017)

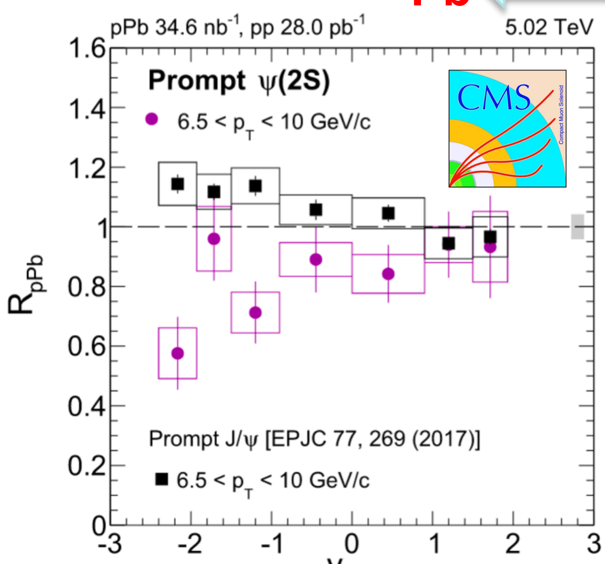


Also: ATLAS *EPJC* **78** 171 (2018); ALICE *EPJC* **78** 466 (2018)

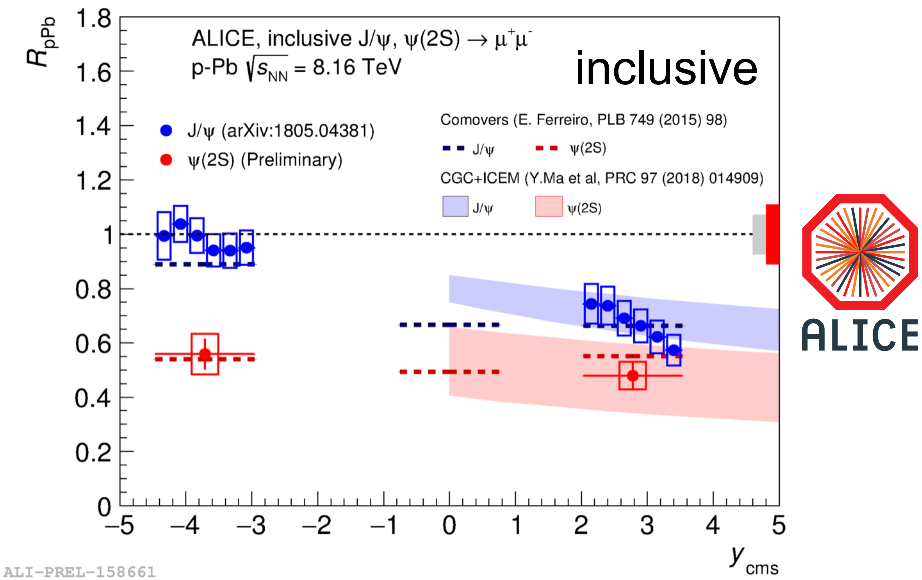
ψ(2S) in p–Pb

- More suppression of ψ(2S) compared to ground state
  - Different nuclear effects on J/ψ vs. ψ(2S)
  - Decent agreement with GCG + color evaporation model (in p-going direction), co-movers
  - Co-movers expected to affect ψ(2S) more than J/ψ, this difference greater in Pb-going direction
    - Observed suppression pattern consistent w/ final-state effect

Pb ⟵ ⟶ p

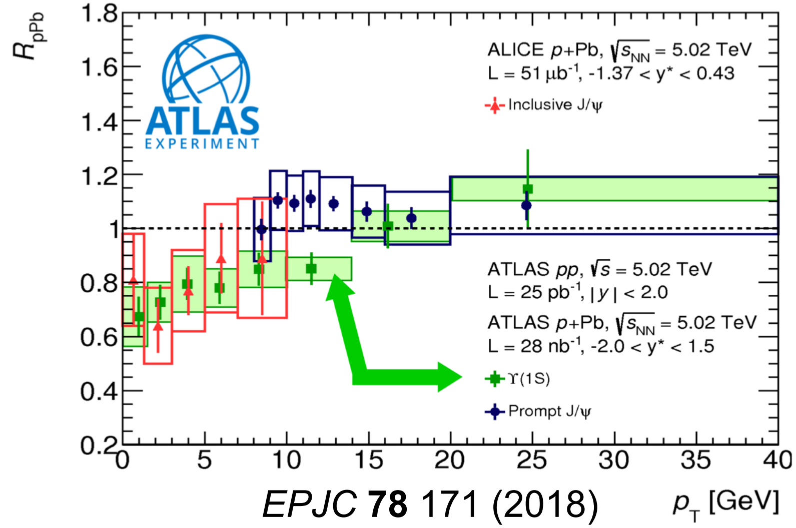


PLB **790** 509 (2019)

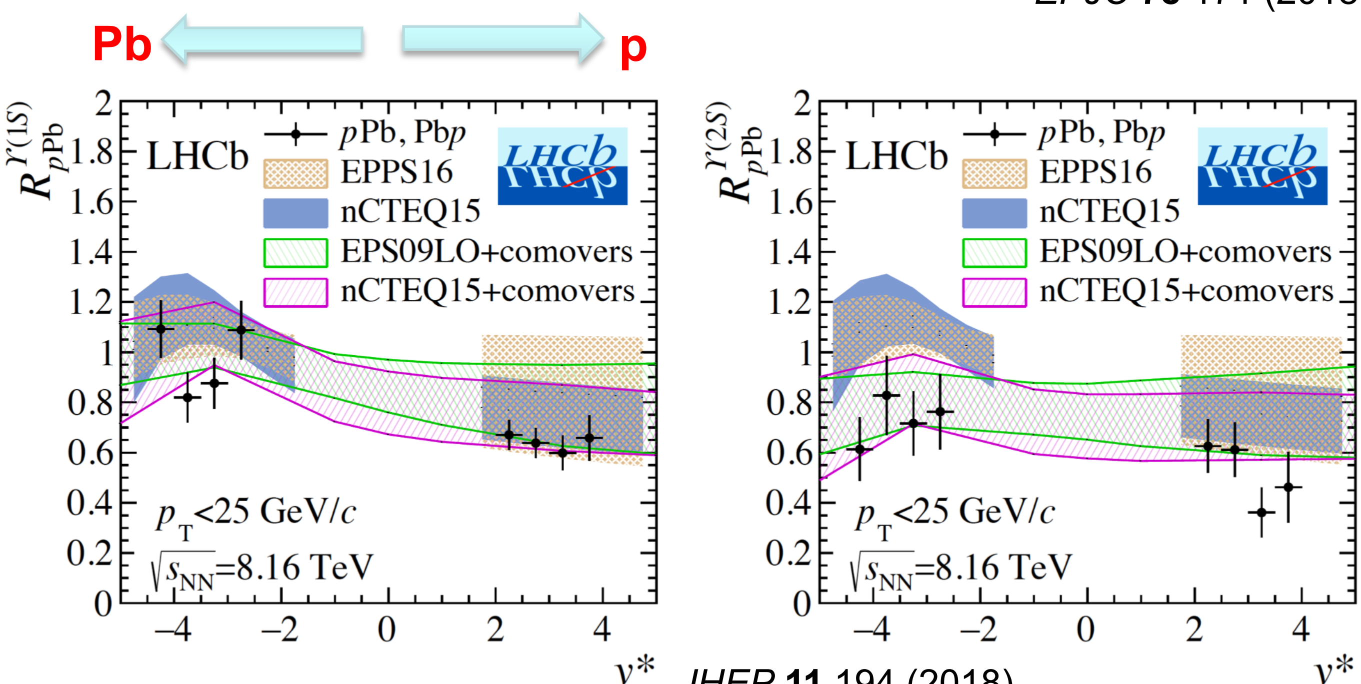


Υ(nS) Suppression

- Υ(1S) suppressed at low p_T
- Υ(2S) suppressed w.r.t Υ(1S)
- Suppression in forward (p-going) direction w.r.t. backward
  - Consistent w/ two predictions with nPDFs



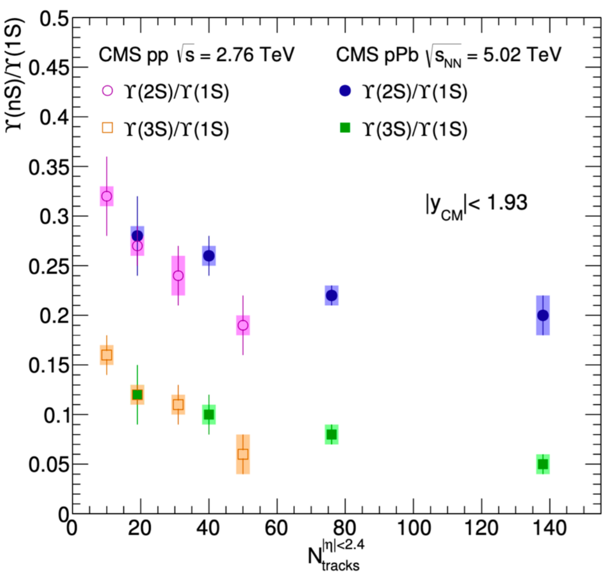
EPJC **78** 171 (2018)

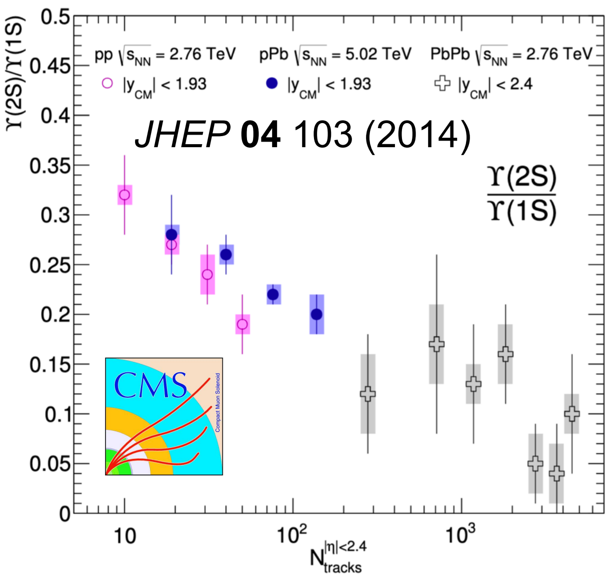


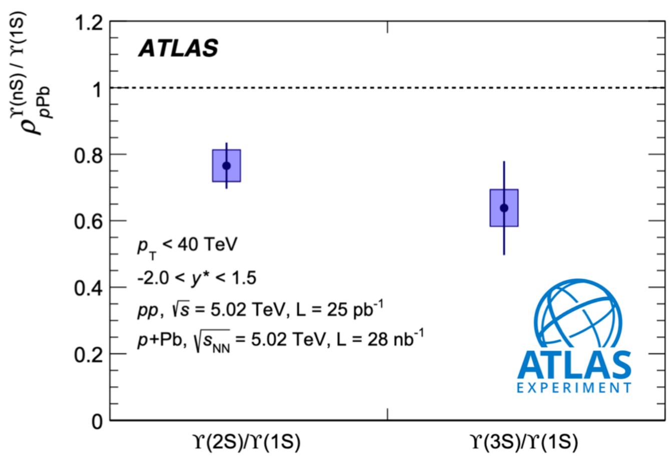
JHEP **11** 194 (2018)

Υ(nS) Suppression

- Υ(2S) & Υ(3S) suppressed w.r.t Υ(1S)
- More suppression with increasing multiplicity
- Final-state suppression mechanisms that affect excited Υ states more than ground state?
- Υ suppression pattern quite similar to situation for J/ψ and ψ(2S)



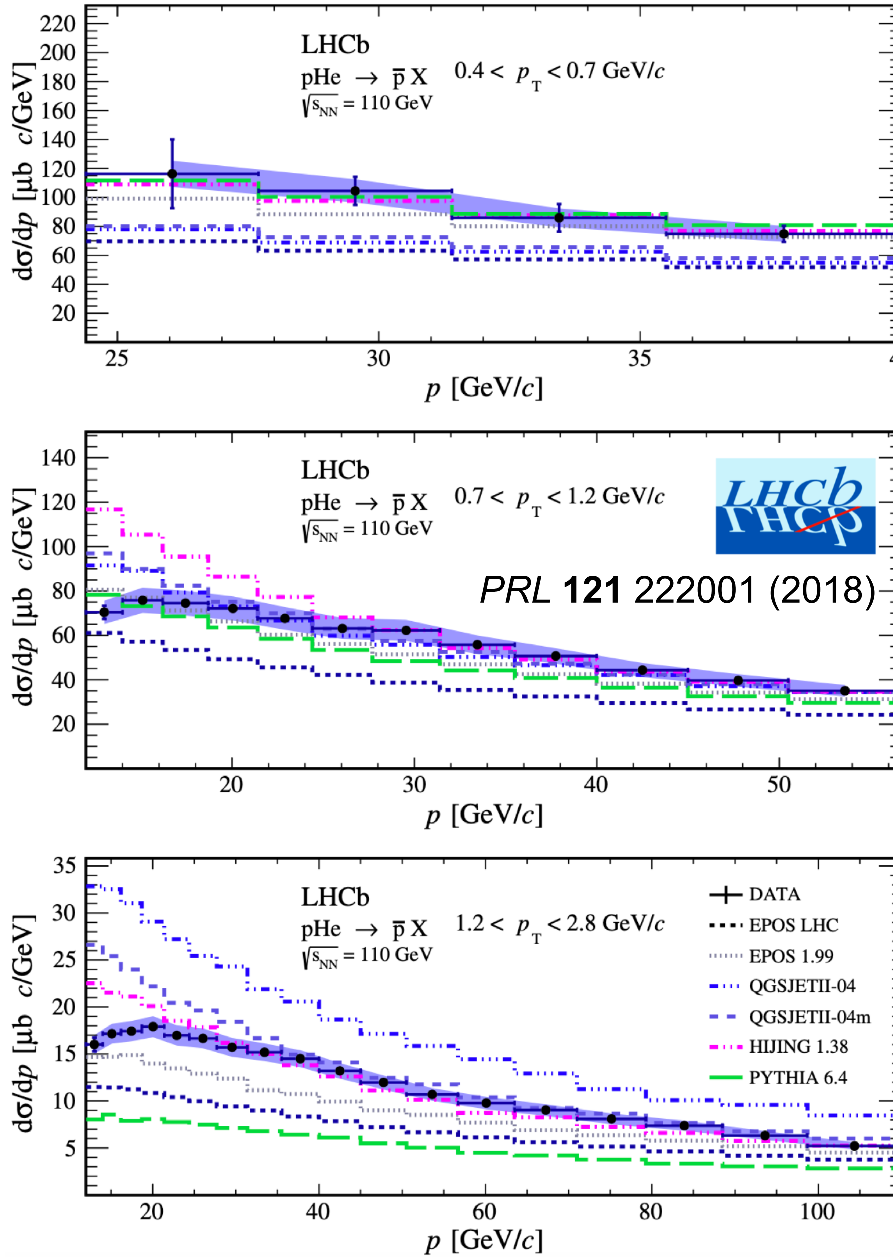




EPJC **78** 171 (2018)

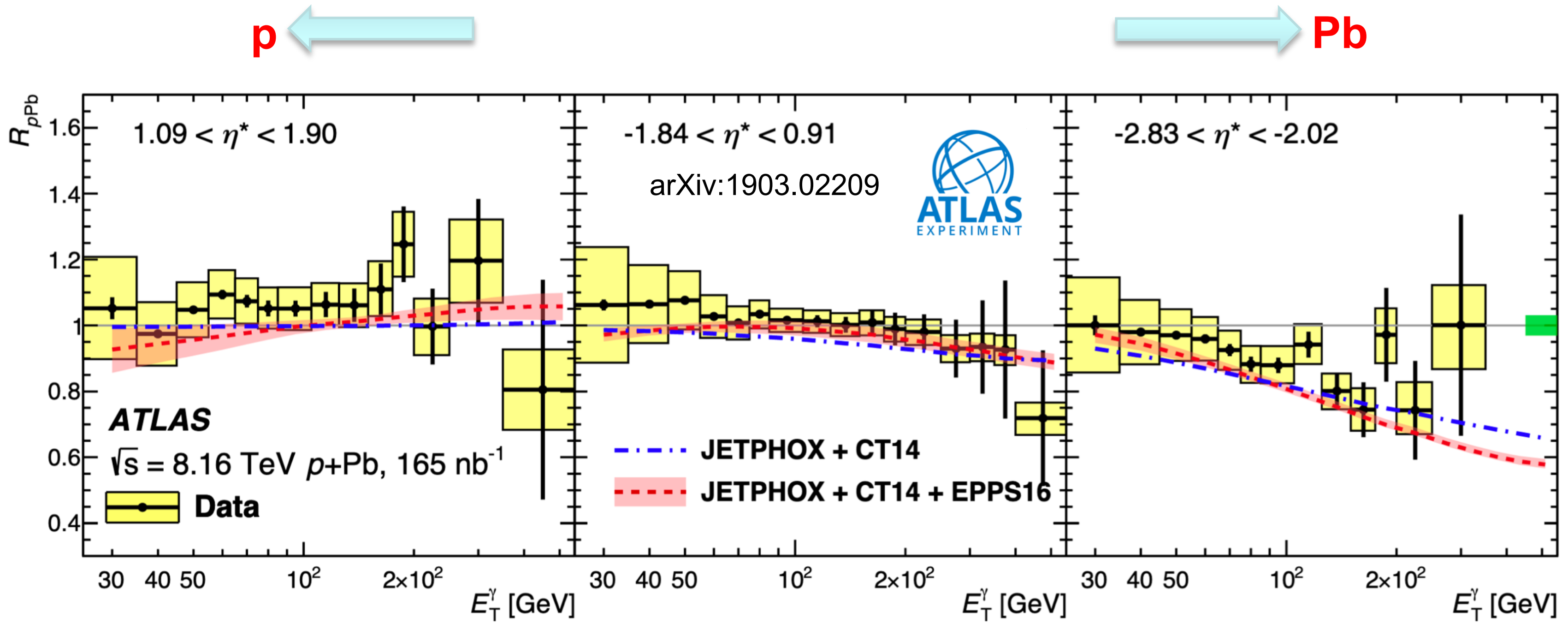
p–He Collisions at LHCb

- SMOG system
  - Low-density noble gas injected into VELO vessel (~100x higher pressure than LHC vacuum)
  - Allows LHCb to operate in fixed-target mode
- Measurements of $\bar{p}$ yields in p–He collisions
  - Uncertainties smaller than spread among various theoretical models
  - Will help shed light on $\bar{p}$ excess observed by AMS-02 and PAMELA: do those $\bar{p}$ come from cosmic-ray interactions with interstellar medium, or from Dark Matter annihiliation?
- ALICE studies of $\bar{d}$ and $^{3}\overline{\text{He}}$ also useful for Dark Matter searches



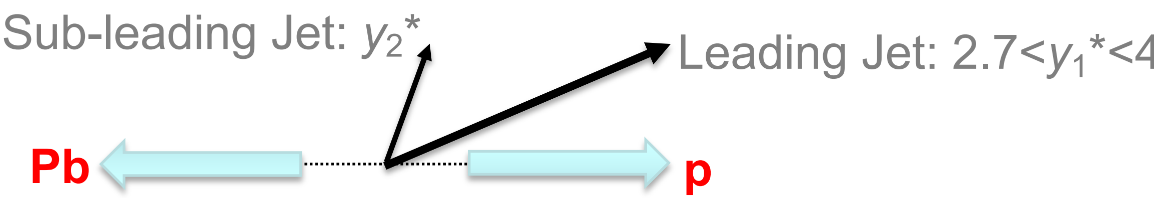
Direct Photons

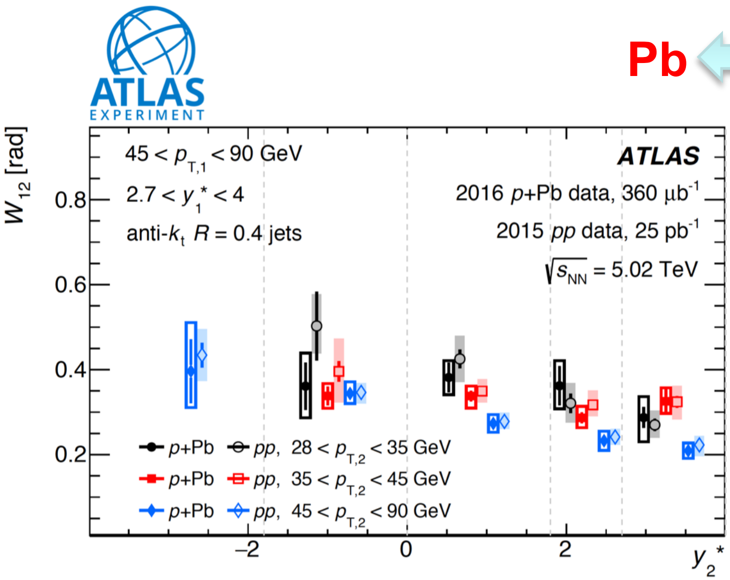
- R_{pPb} of isolated direct γ:
  - Consistent with unity at positive η
  - Modest modification in Pb-going direction (more d quarks)
  - Data consistent with modification of PDFs, disfavor initial-state energy loss

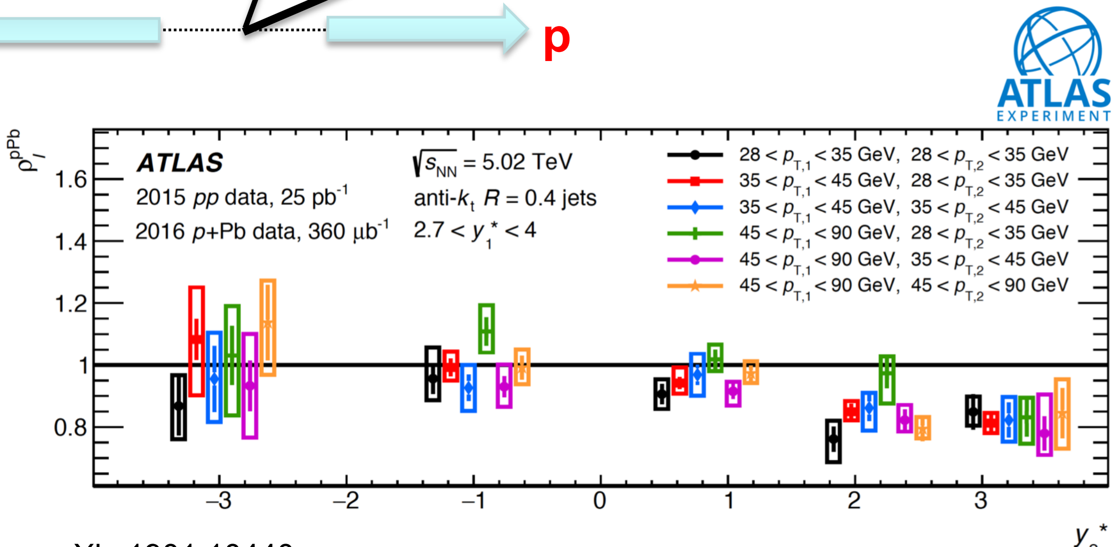


Dijet Correlations

- Shapes of dijet angular correlation distributions and conditional yields are sensitive to gluon saturation at low x_A
- Azimuthal correlation functions:
  - Wider for dijets with large rapidity separation
  - No significant broadening from pp→p–Pb
- Conditional yields suppressed by ~20% for forward-forward dijets
  - Can constrain nuclear effects in low-*x* region (*e.g.* saturation)







arXiv:1901.10440

Conclusions

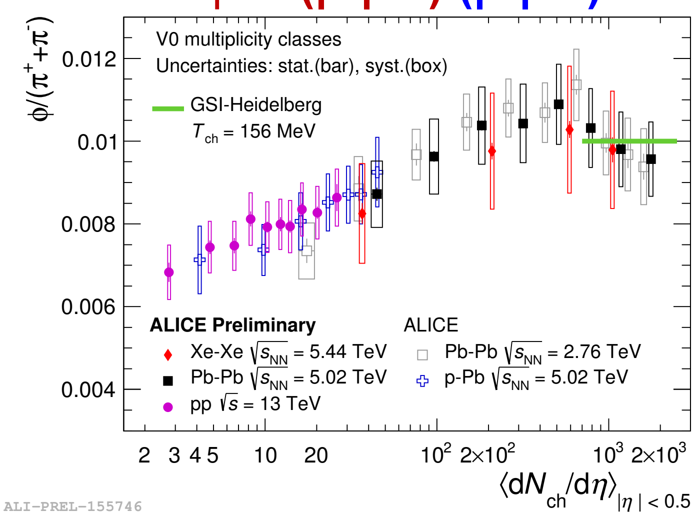
- Strangeness production evolves smoothly with multiplicity
  - No energy or collision-system dependence
  - Magnitude of enhancement increases with strangeness content
  - Small systems: rope hadronization, core-corona effects?
- Near-side ridge in small systems
- v_2 in small systems not explained by non-flow effects alone
- p_T spectral shapes:
  - Increasing $\langle p_T \rangle$ and $\langle \beta_T \rangle$ with multiplicity (MPIs, color reconnection, flow?)
  - Mass ordering of $\langle p_T \rangle$ in central A–A → violated in small systems (different trends for baryons vs. mesons?)
- Quarkonia
  - Suppression at low p_T
  - Excited states more suppressed than ground states (final-state effects)
  - Multiplicity dependence of Υ(nS) suppression
- Measurements of $\bar{p}$ production in p–He collisions will illuminate the excess observed by PAMELA and AMS-02

Additional Material

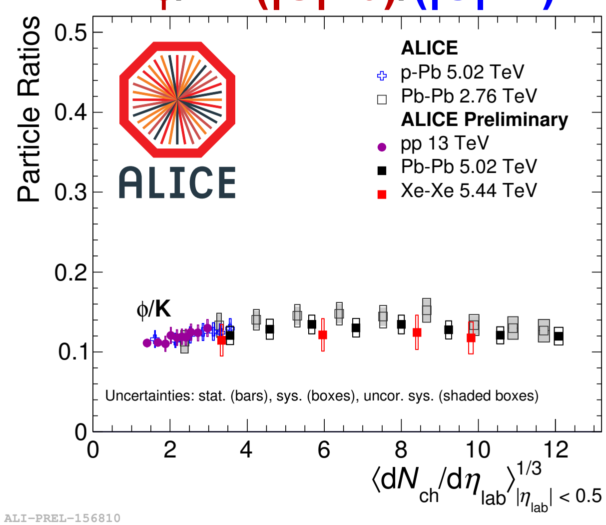
Hadrochemistry: ϕ

- The ϕ meson ($s\bar{s}$) is a key probe in studying strangeness production
  - Does ϕ evolve as S=0 particle, or as if it had open strangeness?
- Large systems: ϕ production described by thermal models
- Small systems: increase in ϕ/π ratio with multiplicity
  - Inconsistent with simple canonical suppression
  - Qualitatively explained by rope hadronization (DIPSY) and core/corona (EPOS)
    - Connected to strong color fields/high density
- Ratios ϕ/K and Ξ/ϕ fairly flat across wide multiplicity range
  - The ϕ has "effective strangeness" of 1–2 units

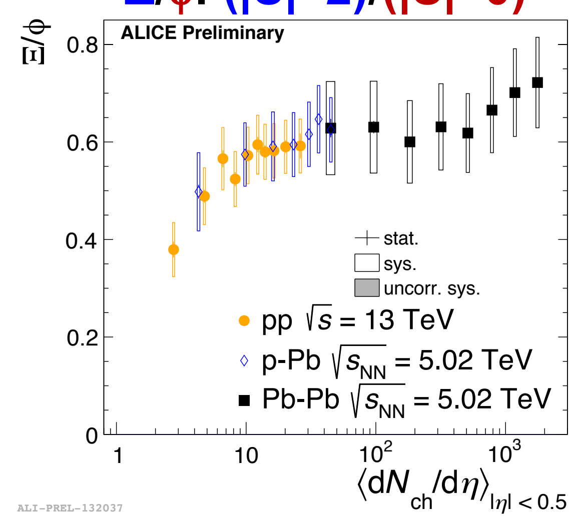
ϕ/π: (|S|=0)/(|S|=0)



ϕ/K: (|S|=0)/(|S|=1)

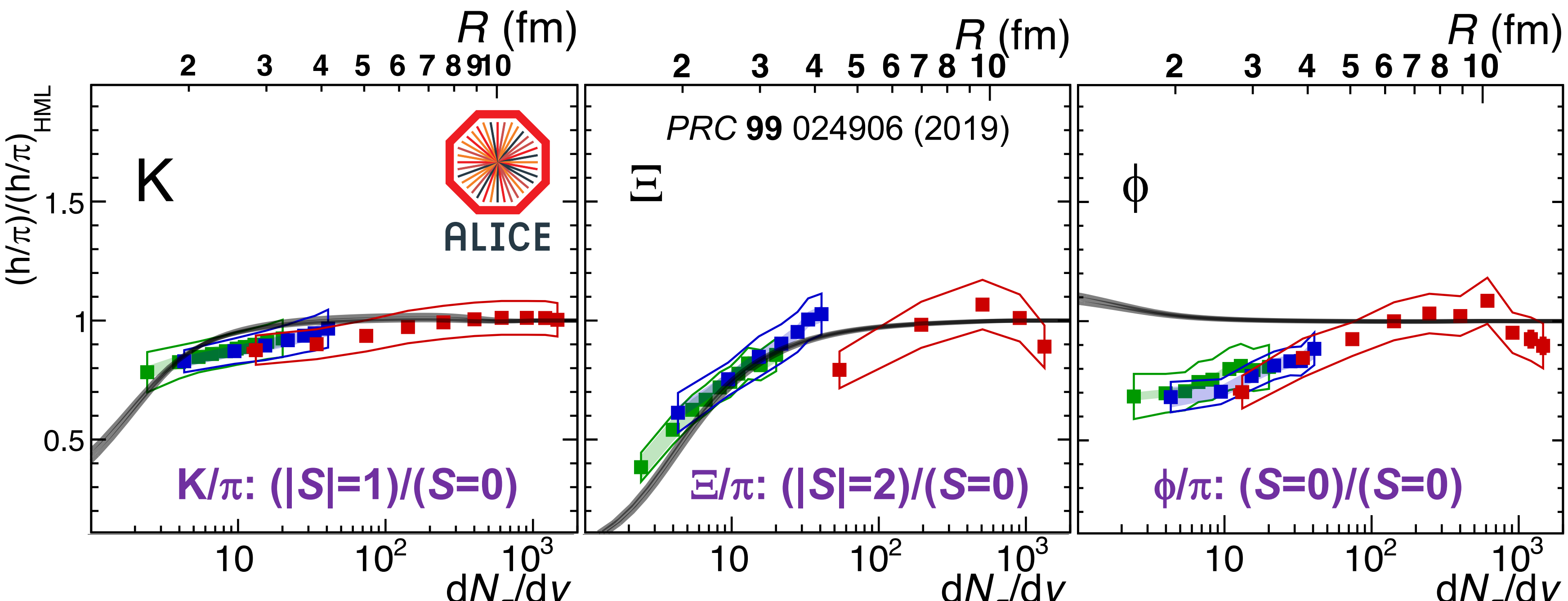


Ξ/ϕ: (|S|=2)/(|S|=0)



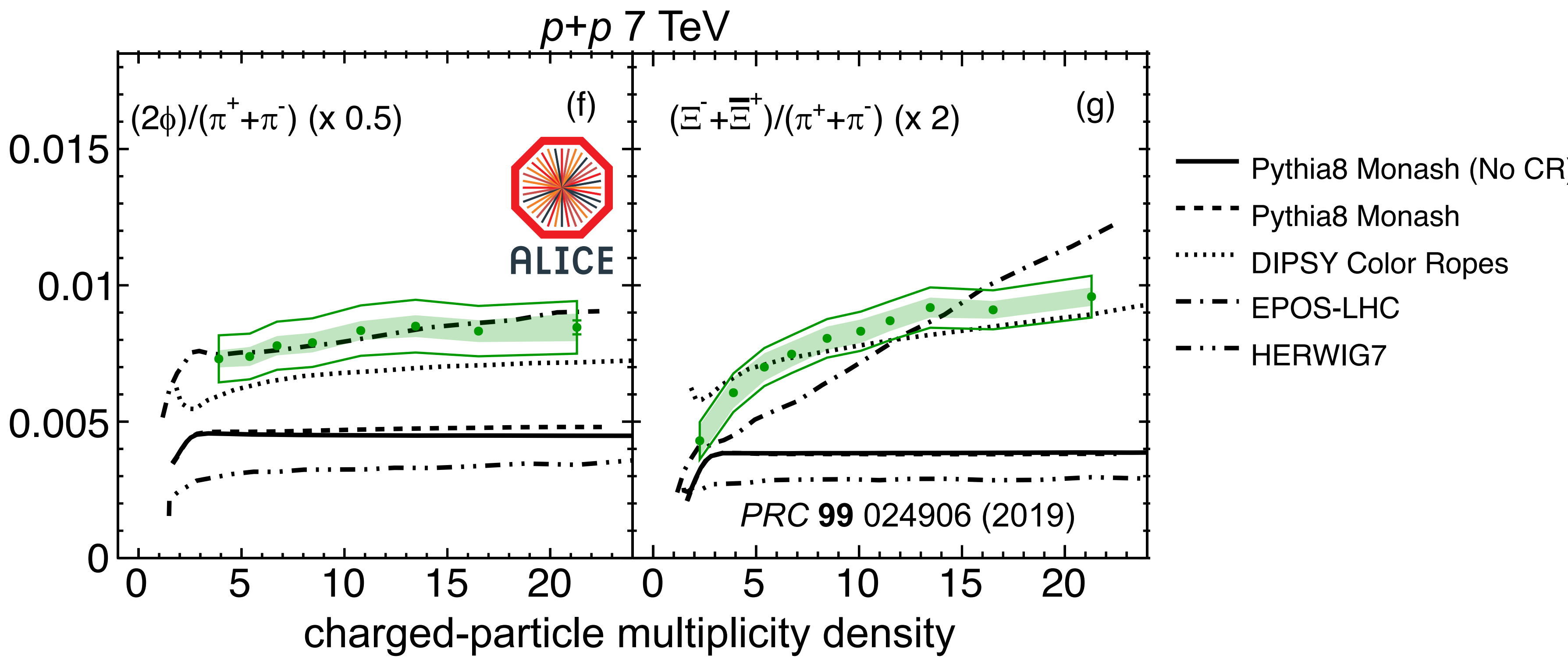
Canonical Suppression

- Small systems: particles with open strangeness subject to canonical suppression, while ϕ is not
- ALICE observes increase in ϕ/π with multiplicity in pp
  - Not expected for simple canonical suppression
  - Does system drop out of equilibrium?



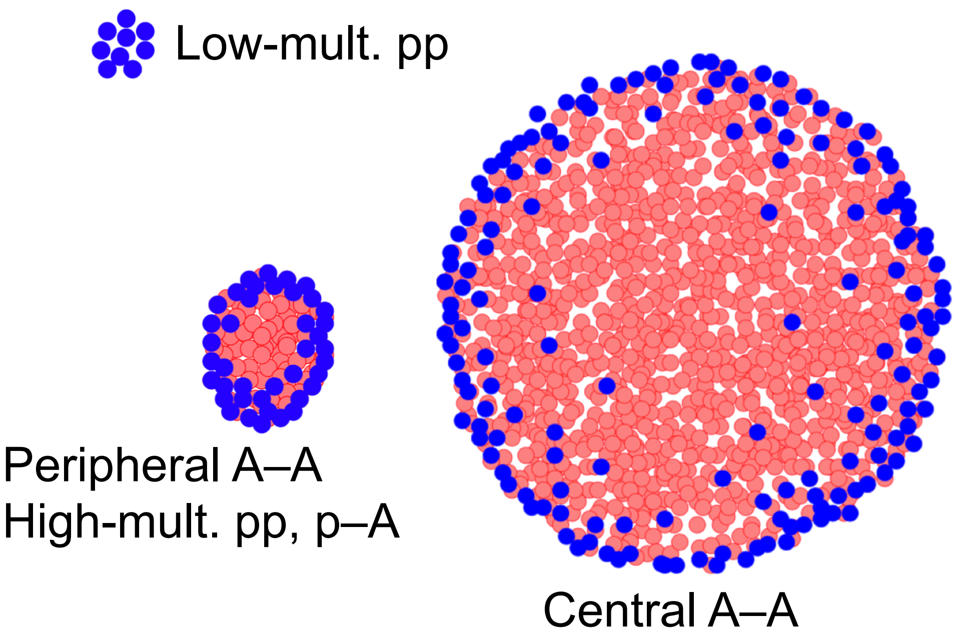
Rope Hadronization

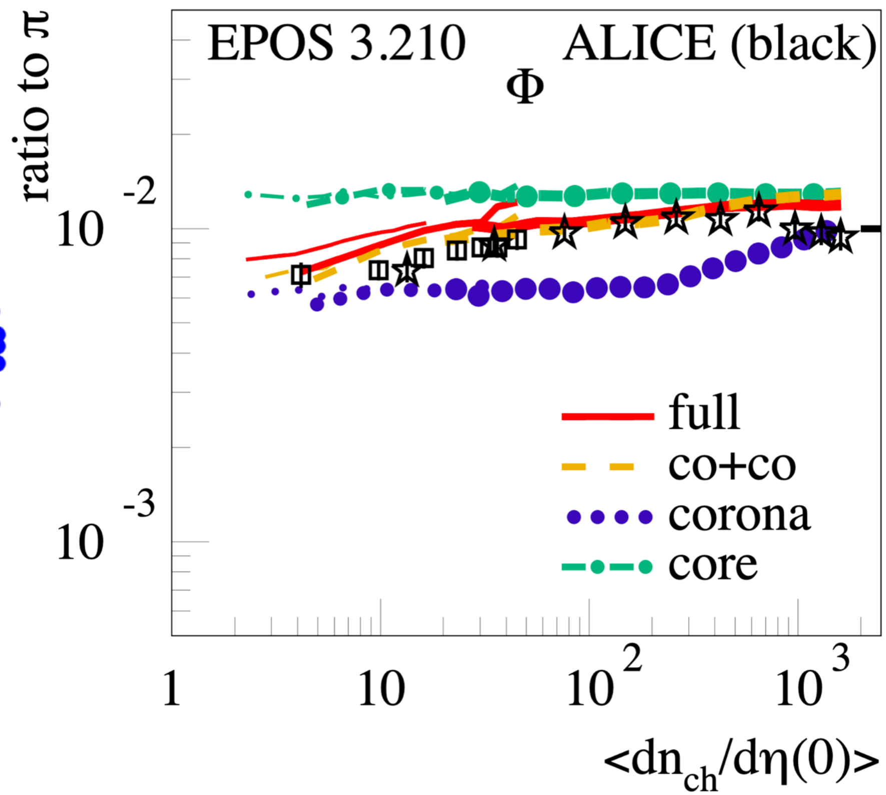
- Groups of overlapping strings fragment with higher effective string tension
  - Enhances strange-particle production
  - Enhancement of ϕ similar to open-strangeness hadrons
  - DIPSY (color ropes) qualitatively describes increase of ϕ/π with multiplicity



Core/Corona Effects

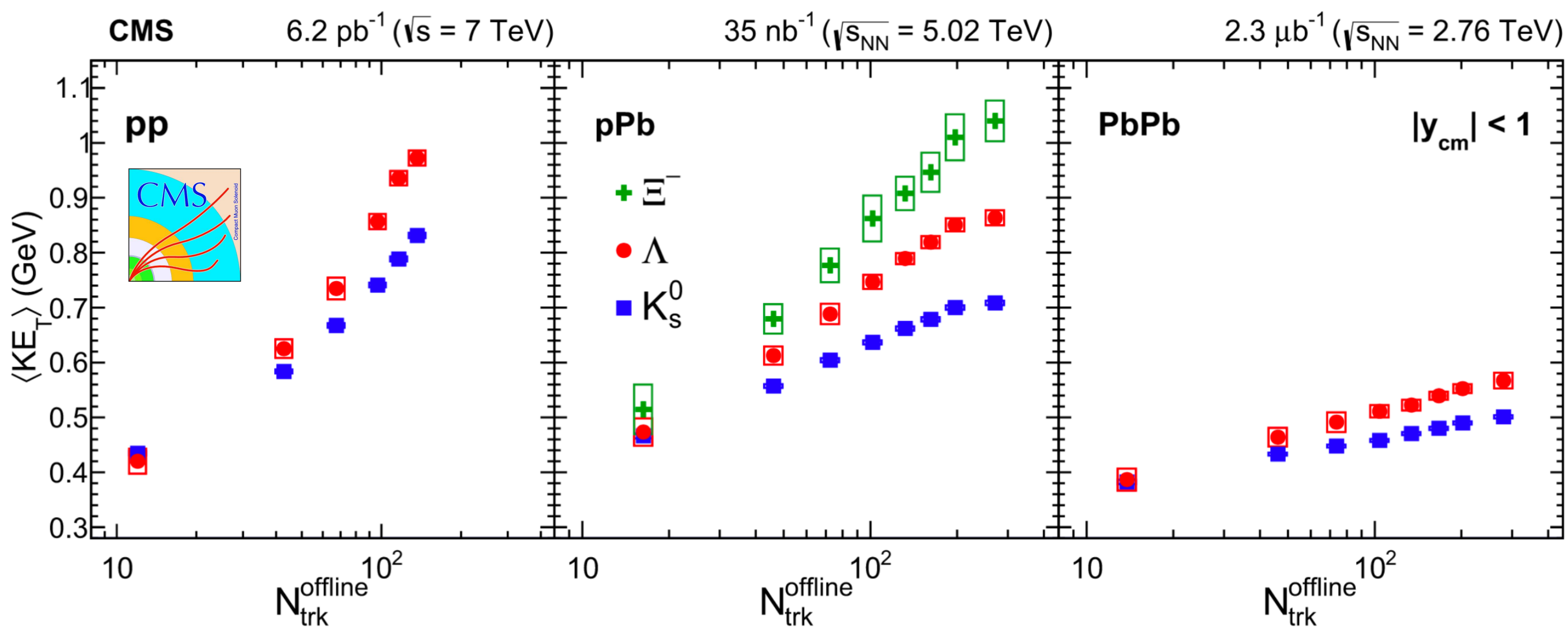
- EPOS: describes pp, p–A, and A–A collisions with common framework
  - Collision divided into a core (QGP) and a corona of jets
  - Core evolves hydrodynamically
  - Hadronic phase with re-scattering and regeneration (UrQMD)





Mean Transverse Momentum

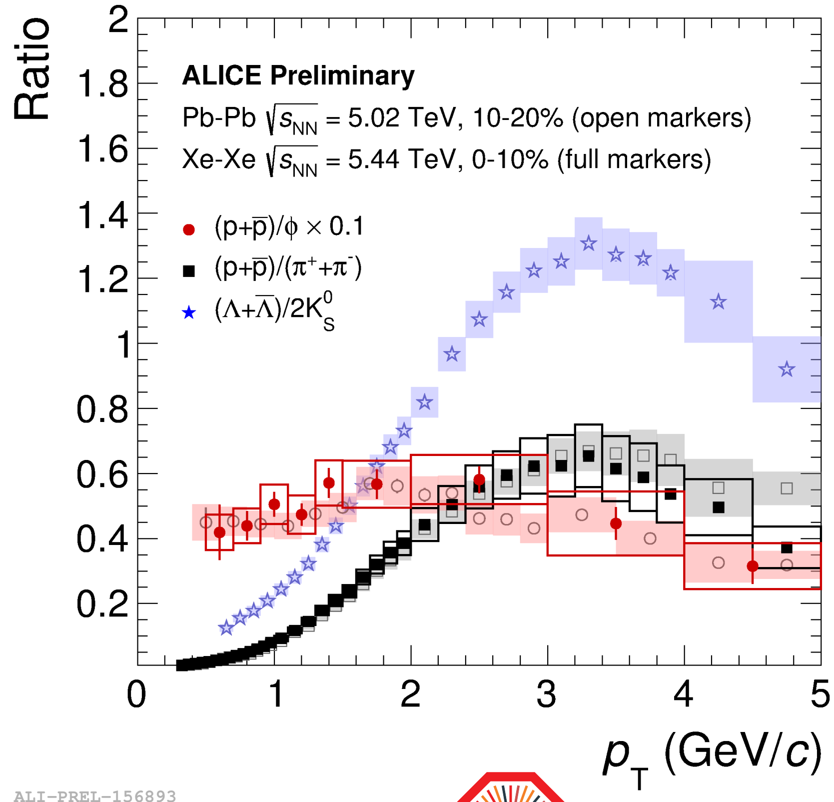
- A–A collisions: mass ordering of $\langle p_T \rangle$ (see p and ϕ)
  - Consistent with hydrodynamic flow
- Small Systems:
  - Mesons (K*, ϕ) have greater $\langle p_T \rangle$ than baryons w/ similar masses
  - More rapid increase in $\langle p_T \rangle$ with multiplicity
  - $\langle p_T \rangle$ values in high-mult. pp & p–Pb reach those seen in Pb–Pb



CMS *PLB* **768** 103 (2017)

Baryon-to-Meson Ratios

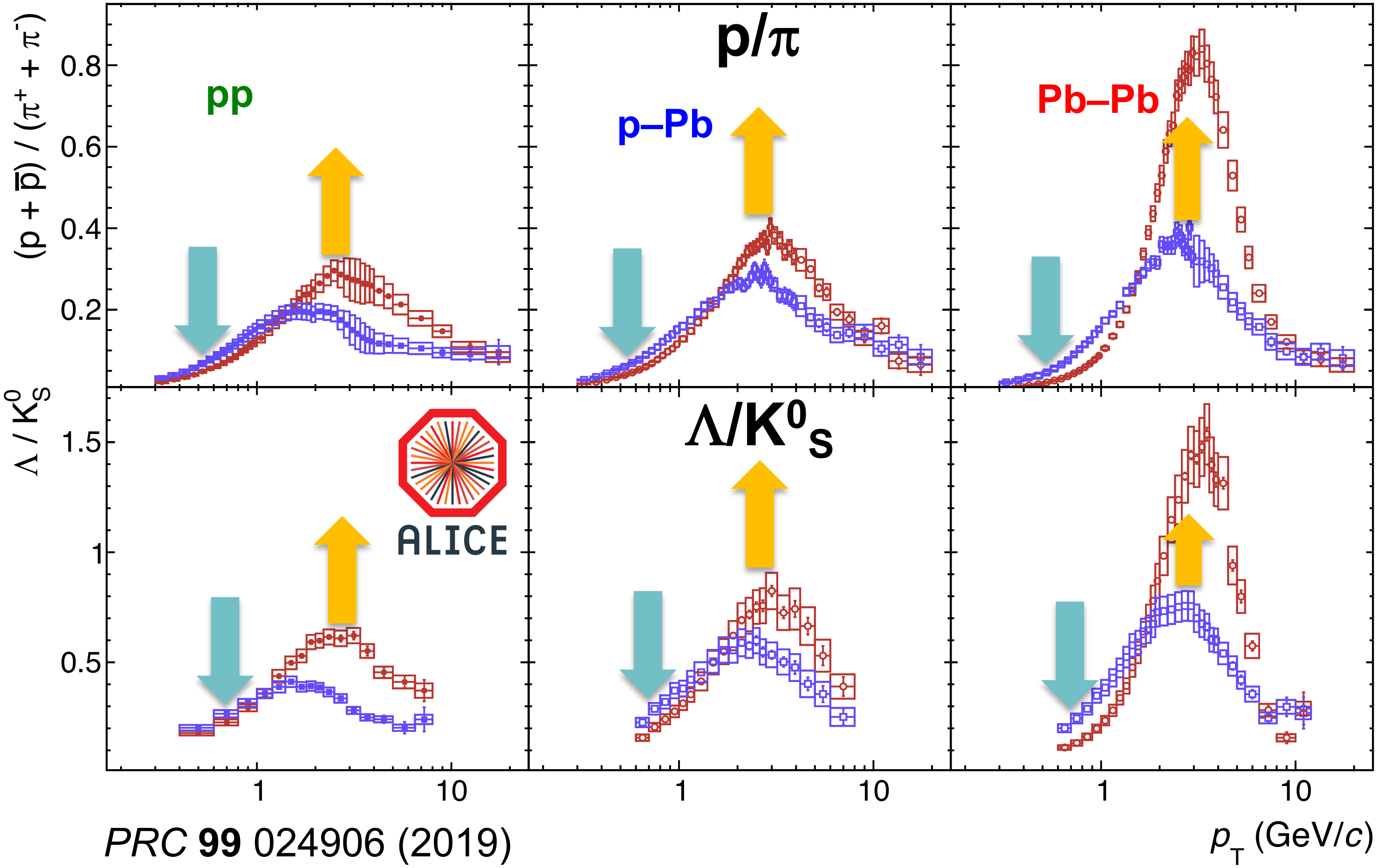
- Baryon-to-meson ratios vs. p_T allow us to study the interplay of hydrodynamics and recombination
- Compare Xe–Xe & Pb–Pb: consistent results for similar multiplicities
- p/ϕ ratio is useful: baryon and meson with almost the same mass
  - Flat with p_T → consistent with hydrodynamic behavior, but can also be described by some recombination models [V. Greco et al, *PRC* **92** 054904 (2015)]



ALICE

Baryon/Meson Ratios

- From low multiplicity (peripheral) to high multiplicity (central):
  - Baryon/Meson ratios depleted at low p_T
  - Enhanced at intermediate p_T
- Qualitative similarities between pp, p–Pb, & Pb–Pb

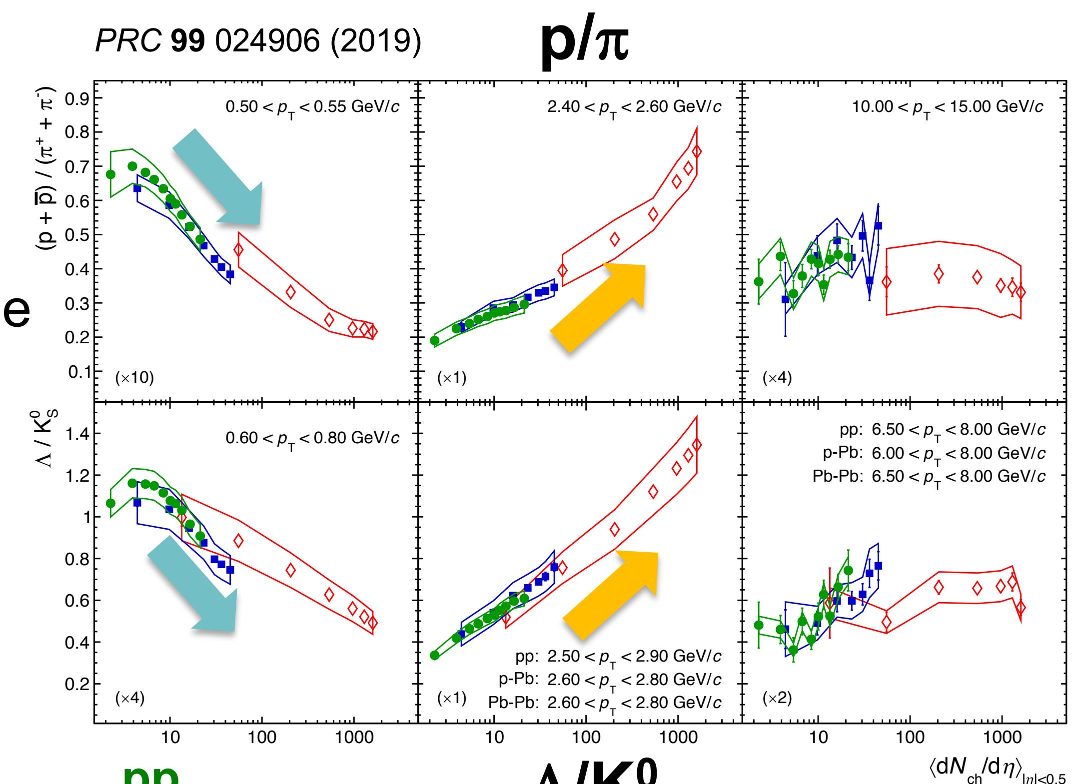


PRC **99** 024906 (2019)

Baryon/Meson Ratios

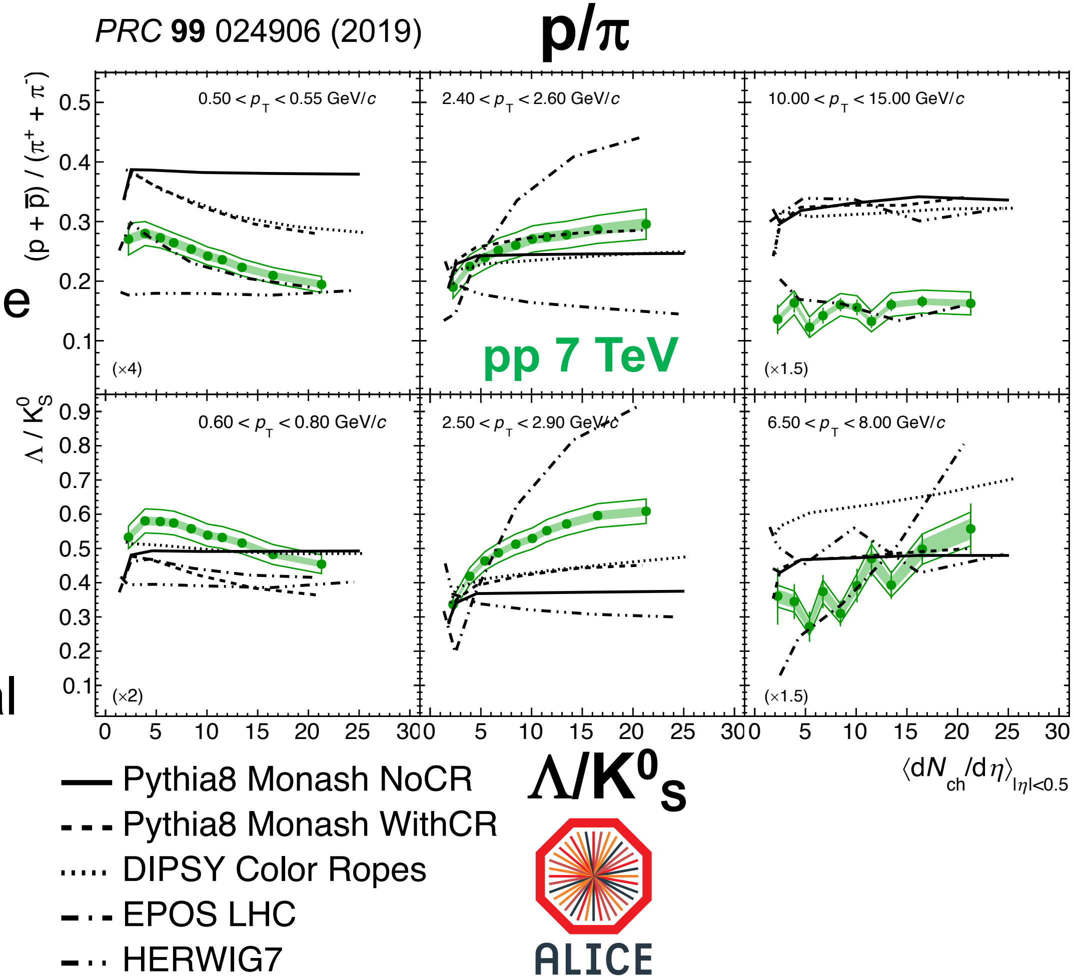
- Baron/meson ratios in different p_T regions:
  - Low-p_T depletion and intermediate-p_T enhancement
- Similar behavior for the three systems

PRC **99** 024906 (2019)

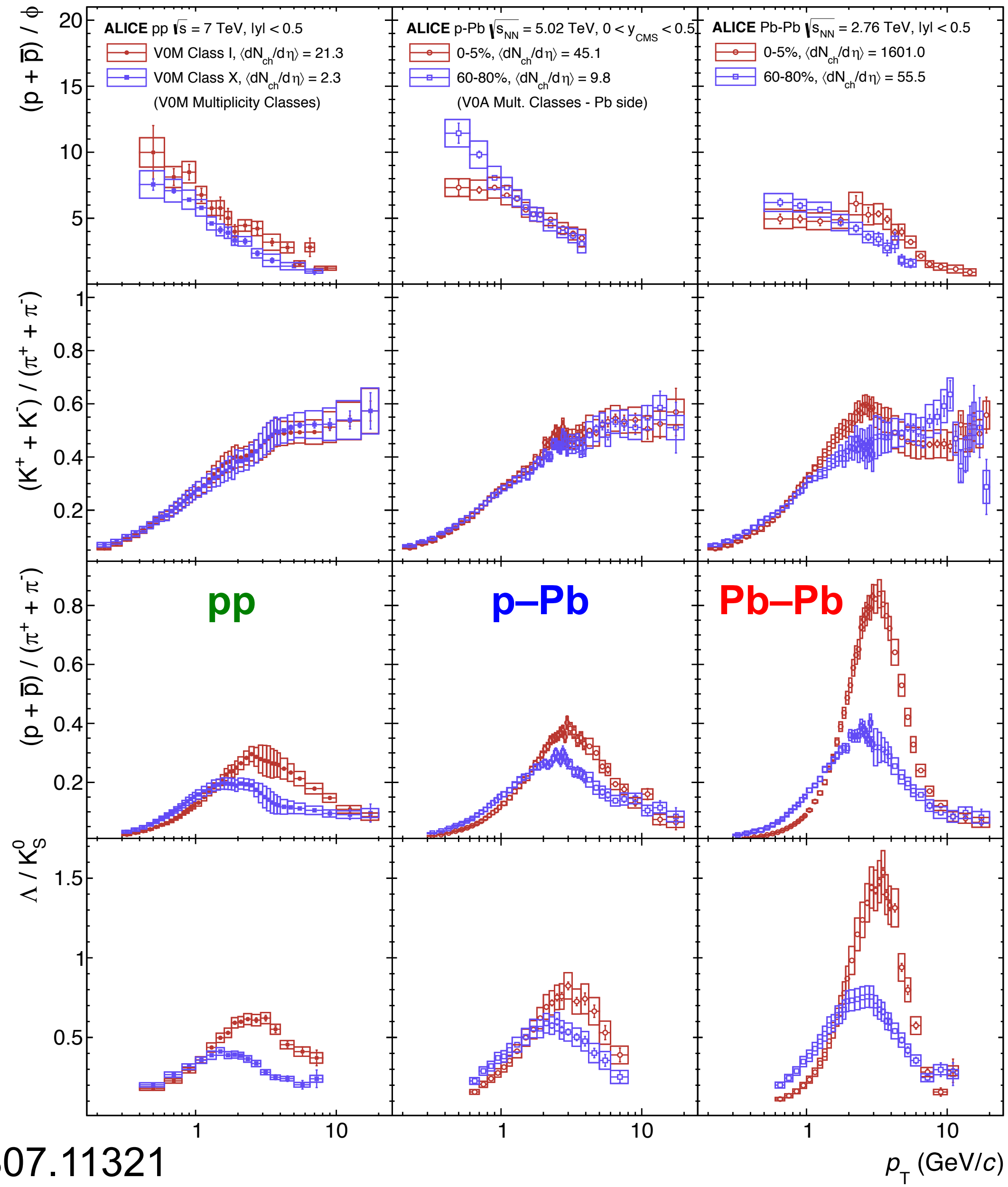


Baryon/Meson Ratios

- Baron/meson ratios in different p_T regions:
  - Low-p_T depletion and intermediate-p_T enhancement
- Similar behavior for the three systems
- Trend in pp described qualitatively by color reconnection (PYTHIA) and color ropes (DIPSY); over-predicted by collective radial expansion in EPOS

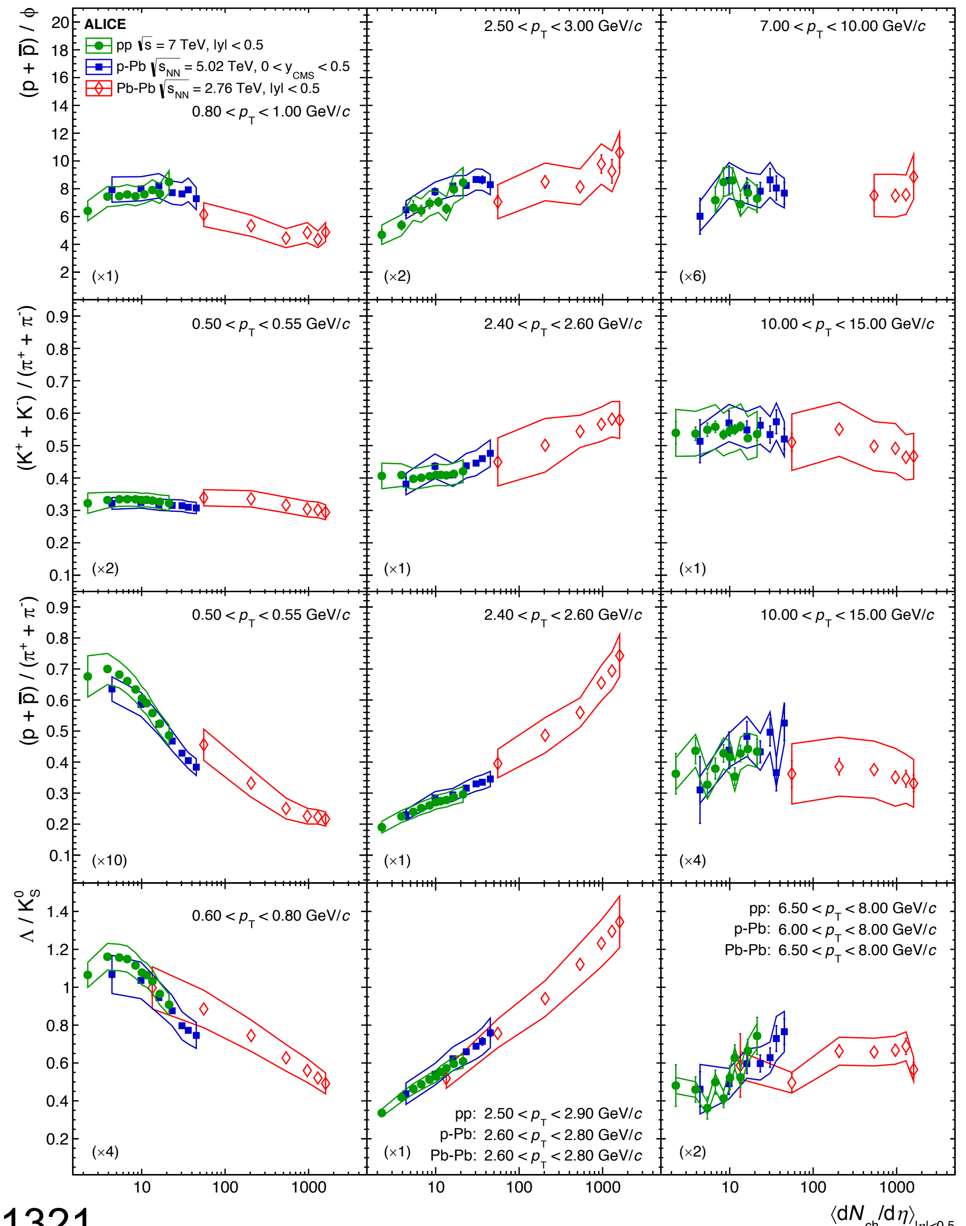


Baryon/Meson Ratios



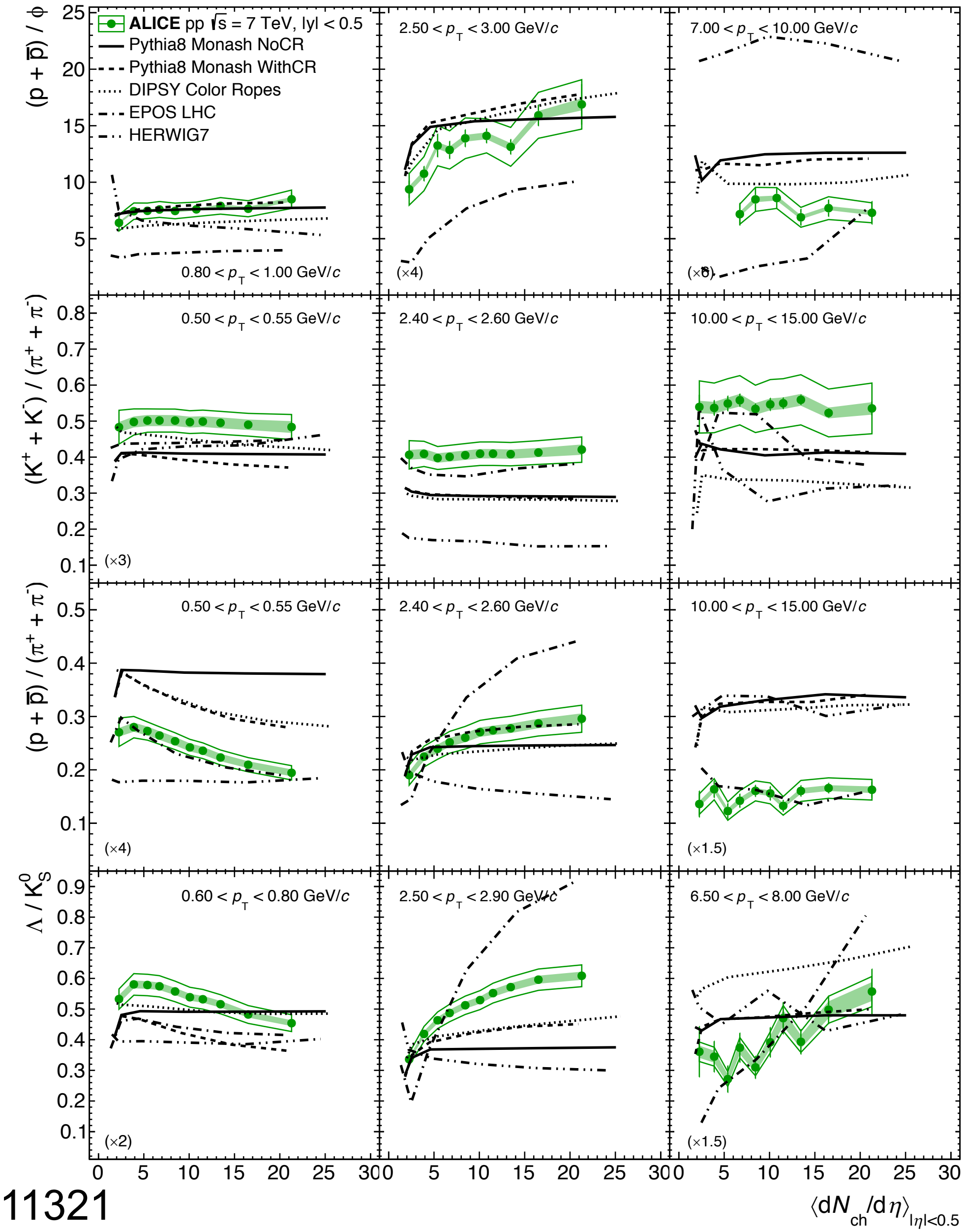
arXiv:1807.11321

Baryon/Meson Ratios



arXiv:1807.11321

Baryon/Meson Ratios

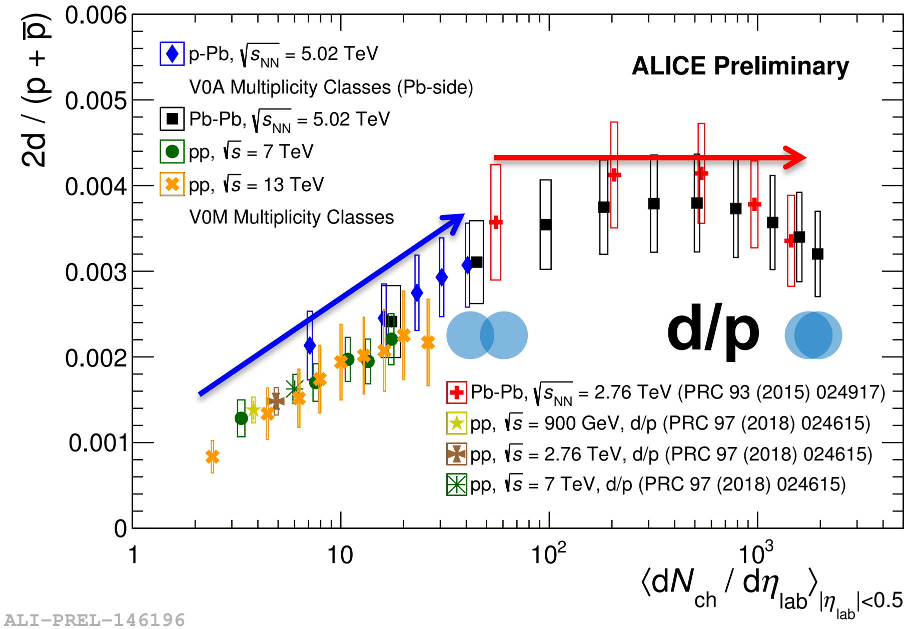


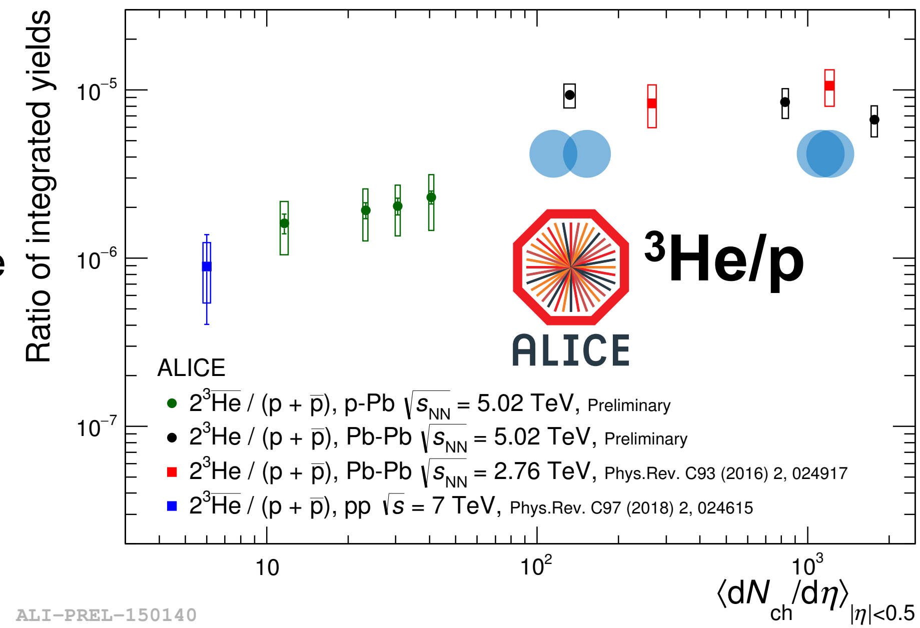
ALICE

arXiv:1807.11321

Nuclei

- Thermal models
  - Hadrons emitted in statistical equilibrium with chemical freeze-out temperature T_{ch}
  - Yields proportional to $\exp(-m/T_{ch})$
- Coalescence
  - Nuclei formed by baryons close in phase space after kinetic freeze-out
  - Nuclei may break up and re-form during hadronic phase
- Deuterons:
  - Coalescence in small systems and thermal production in A–A
  - Smooth transition between systems
  - Production controlled by system size
- ^{3}He: factor of 5 difference in ^{3}He/p ratio from p–Pb to Pb–Pb
  - But also a large gap in multiplicity
  - More data needed…





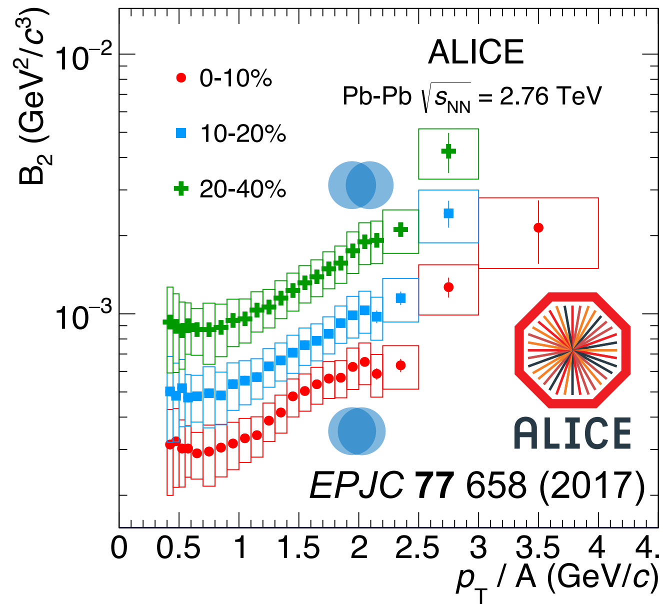
Deuteron Coalescence

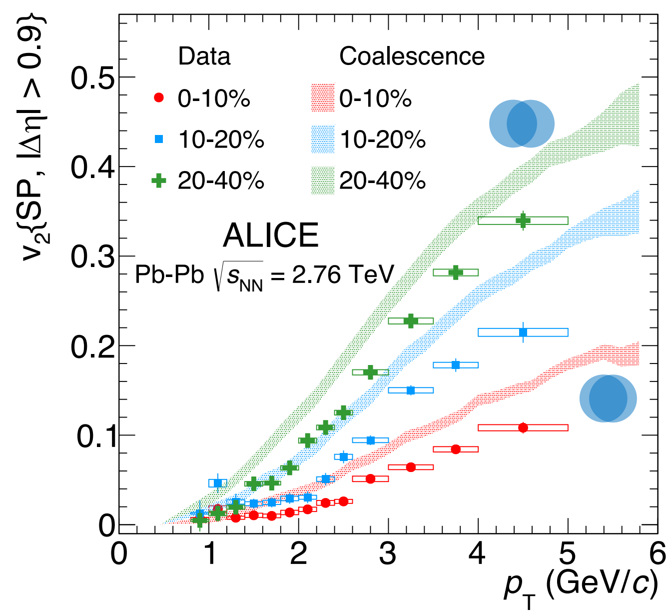
- Coalescence parameter for nucleus *i* with mass number *A*:

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

$$B_2 = \frac{E_d \frac{d^3 N_d}{dp_d^3}}{\left(E_p \frac{d^3 N_p}{dp_p^3} \right)^2}$$

- Simple coalescence
  - Flat $B_2(p_T)$
  - Simple relationship between d & p v_2:
    - $v_2^d(p_T^d) = 2 v_2^p(2p_T^p)$
- Simple coalescence does not describe ALICE deuteron measurements in Pb–Pb
  - Describes lower energy A–A data
  - B_2 flatter for smaller collision systems



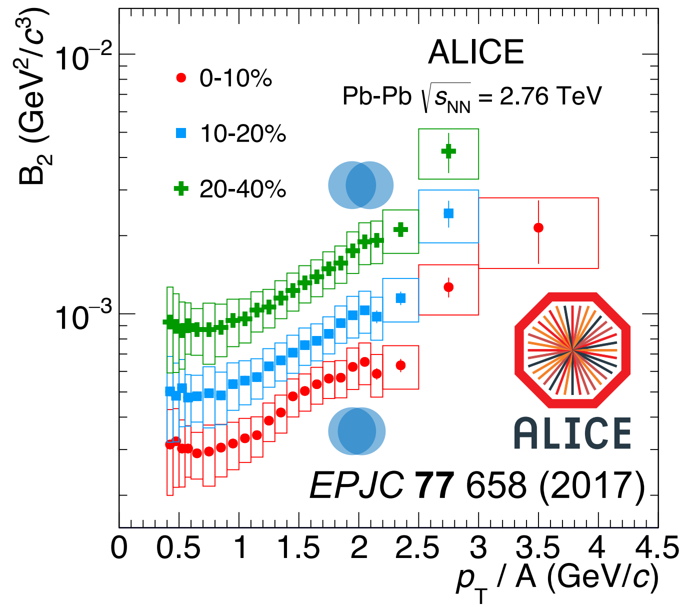


Deuteron Coalescence

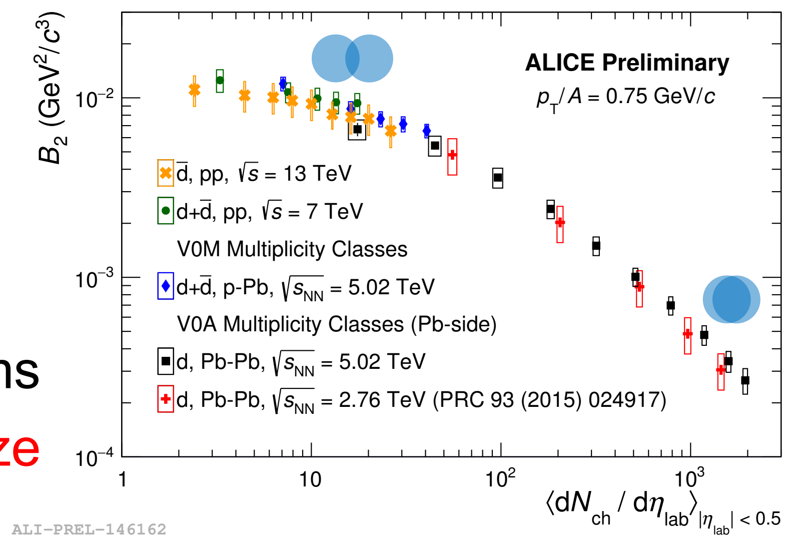
- Coalescence parameter for nucleus *i* with mass number *A*:

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

$$B_2 = \frac{E_d \frac{d^3 N_d}{dp_d^3}}{\left(E_p \frac{d^3 N_p}{dp_p^3} \right)^2}$$



- Simple coalescence
  - Flat $B_2(p_T)$
  - Simple relationship between d & p v_2:
    - $v_2^d(p_T^d) = 2 v_2^p(2 p_T^p)$
- Simple coalescence does not describe ALICE deuteron measurements in Pb–Pb
  - Describes lower energy A–A data
  - B_2 flatter for smaller collision systems
  - B_2 evolves smoothly with system size

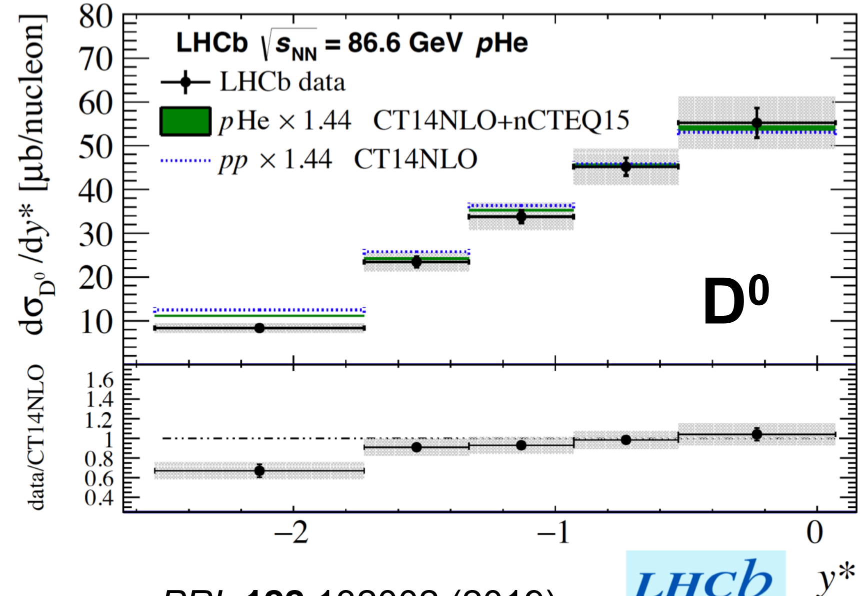


Charm (Fixed Target)

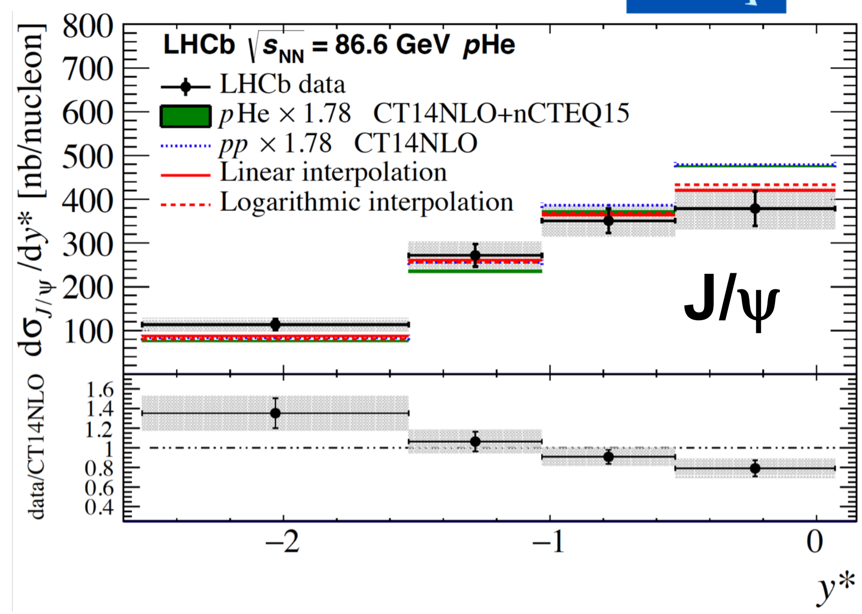
- LHCb: first measurement of charm production in fixed-target mode at LHC
  - D^0 and prompt J/ψ in p–He and p–Ar collisions
- Does the proton contain intrinsic charm?
- Production cross-sections compared to calculations without intrinsic (valence-like) charm contribution
  - No effect seen
  - Proves large Bjorken *x*:

Since $x \simeq \frac{2m_c}{\sqrt{s_{NN}}} e^{-y*}$,

large *x* → negative *y**

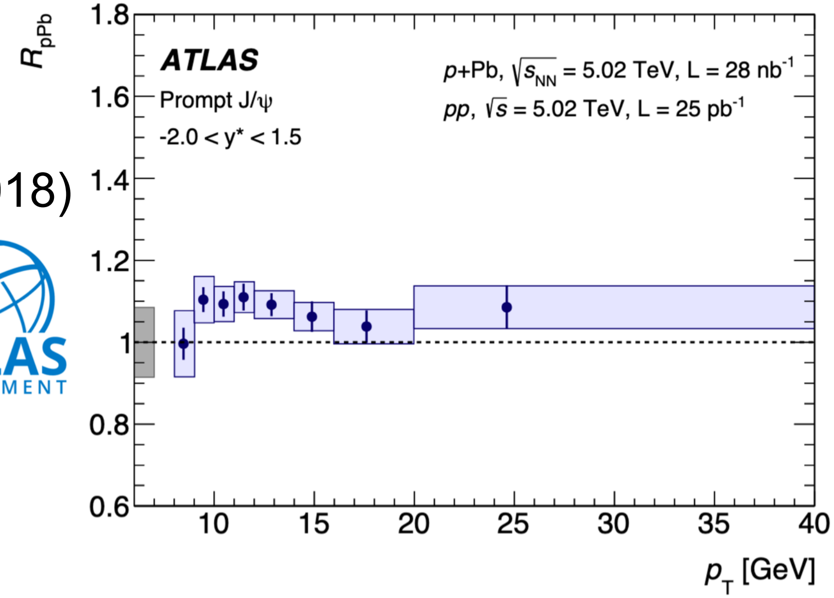


PRL **122** 132002 (2019)



Mid-Rapidity J/ψ R_{pPb}

EPJC **78** 171 (2018)



EPJC **78** 466 (2018)