Using the ϕ meson to study particle production

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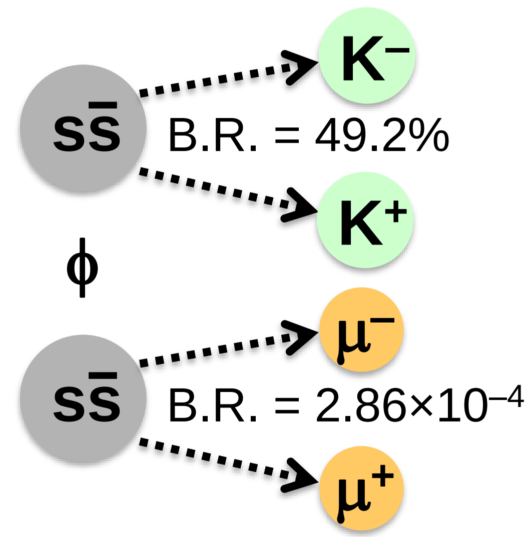
on behalf of the ALICE Collaboration

15 June 2018

Introduction

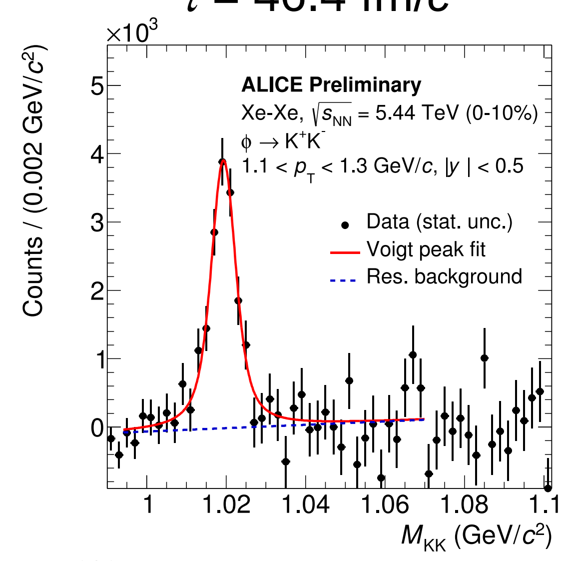
- Properties of ϕ
  - Vector meson
  - Hidden strangeness
  - Mass similar to p and Λ
  - Lifetime
    - Long-lived w.r.t. fireball & resonances
    - Short-lived w.r.t. many common hadrons
- Reconstruction
  - Usually: invariant-mass analysis with $K^{-}K^{+}$ decay channel
- In this presentation:
  - Yields of ϕ vs. system size & energy
  - Strangeness enhancement
  - p_T spectra of ϕ and particle production



m = 1019 MeV/c^2

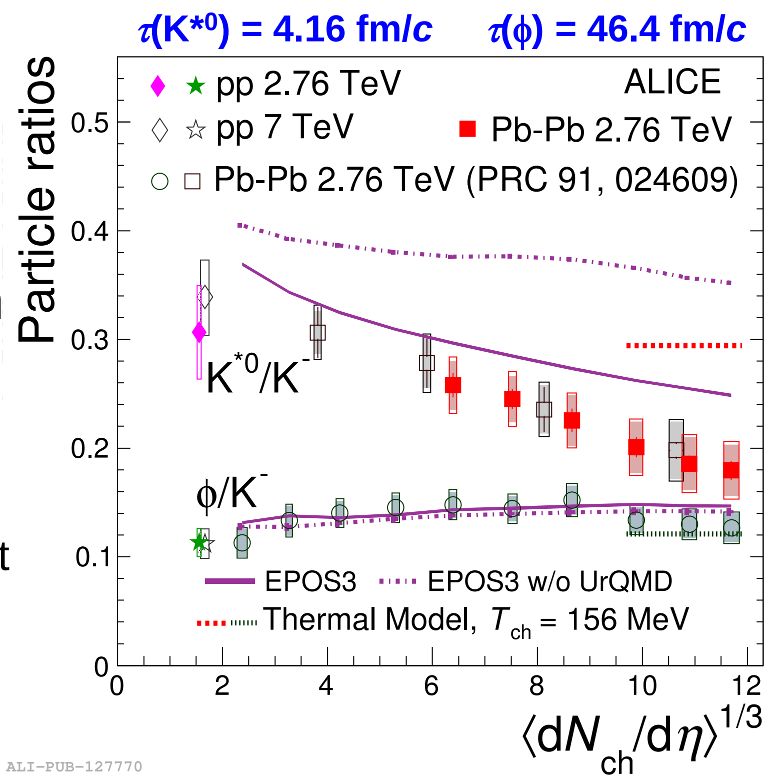
Γ = 4.25 MeV /c^2

τ = 46.4 fm/c



ϕ vs. Other Resonances

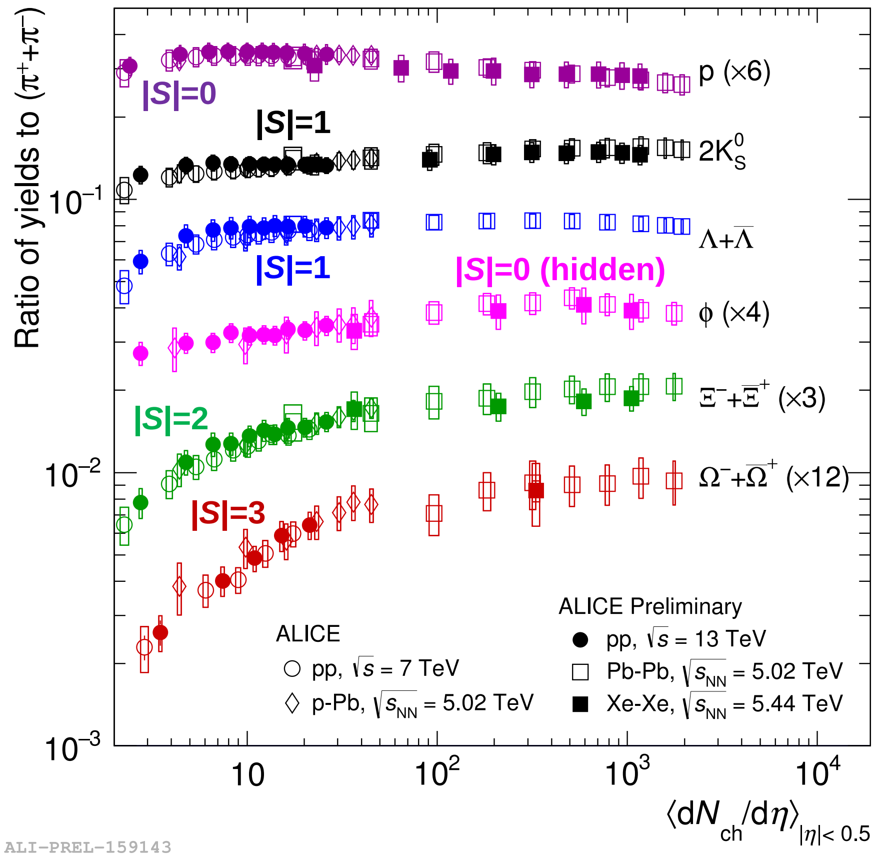
- Short-lived resonances suppressed in central Pb–Pb collisions w.r.t. pp & thermal models: see K^{*0}/K, ρ^0/π, $\Lambda(1520)/\Lambda$
- But ϕ is not suppressed
  - Lives longer than other resonances & many estimates of fireball lifetime
- EPOS describes resonance suppression trends fairly well
  - Uses UrQMD to model hadronic phase
  - Turn off UrQMD:
    - Suppression of short-lived resonances not reproduced;
    - Not much change for ϕ
- Conclusions:
  - At the very least, re-scattering and regeneration are balanced…
  - But given its lifetime, it seems that ϕ decays after hadronic phase and is not affected by re-scattering and regeneration.



PRC **95** 064606 (2017)

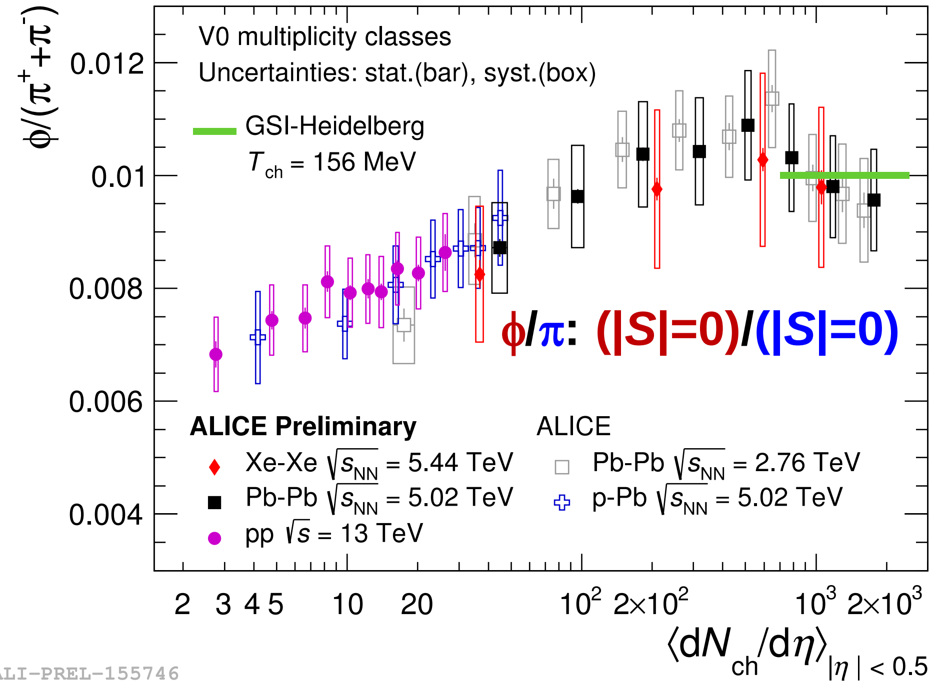
Strangeness Production

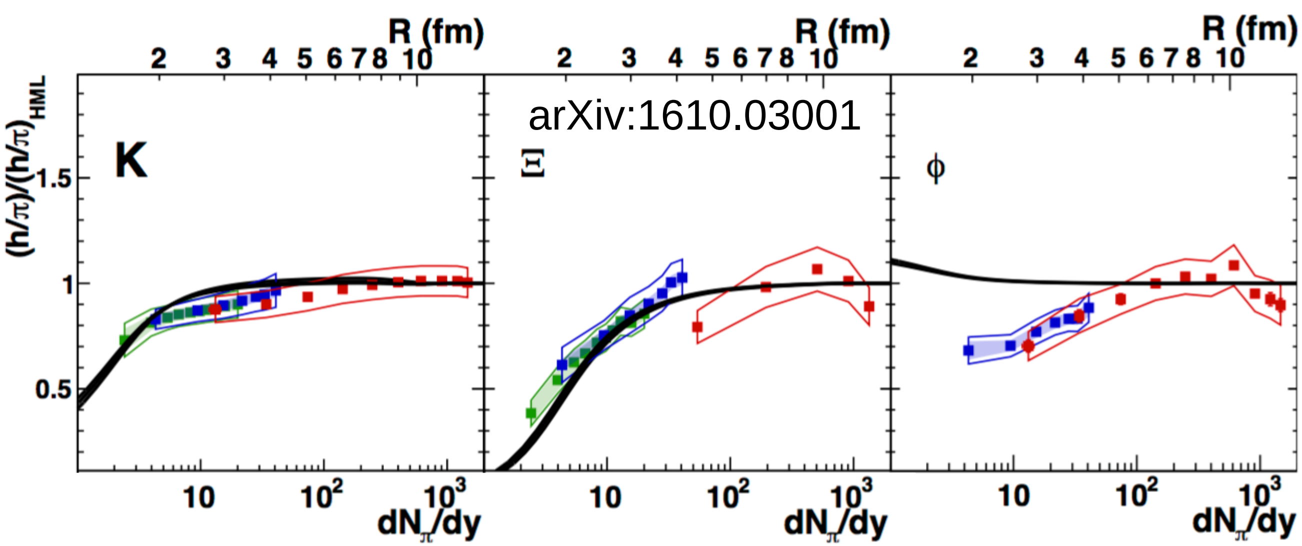
- Smooth evolution of particle production with multiplicity
  - Hadron chemistry is driven by the multiplicity (system size)
- Enhancement for small systems, saturation around thermal-model values for large systems
  - Magnitude of strangeness enhancement increases with strange-quark content
- The ϕ is a key probe:
  - Particles with open strangeness are subject to canonical suppression in small systems, while ϕ is not.



Hadron Chemistry: ϕ/π

- Large systems: ϕ production described by thermal models
- Small systems: increase in ϕ/π ratio with multiplicity
  - Not expected for simple canonical suppression
  - Favors non-equilibrium production (γ_s<1) production of ϕ or all strange particles

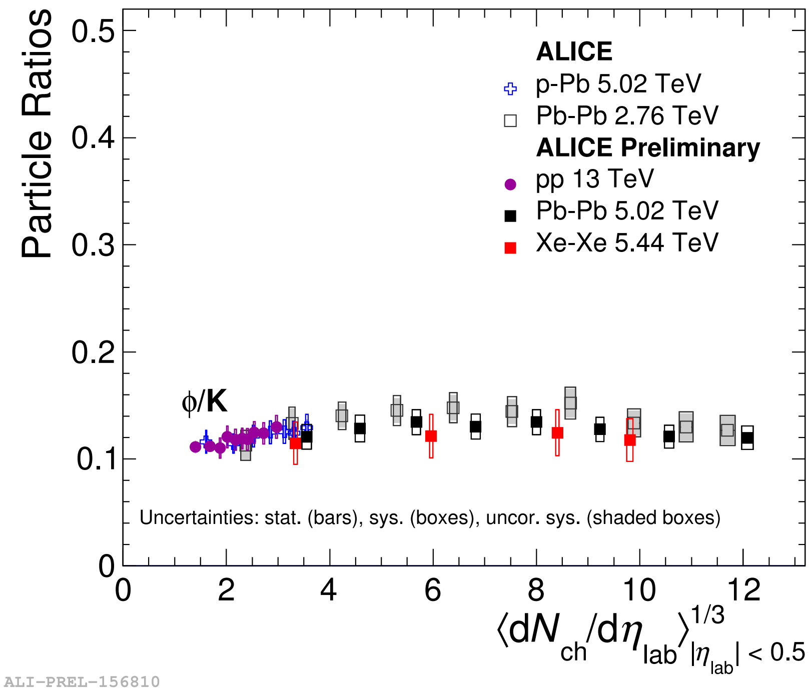




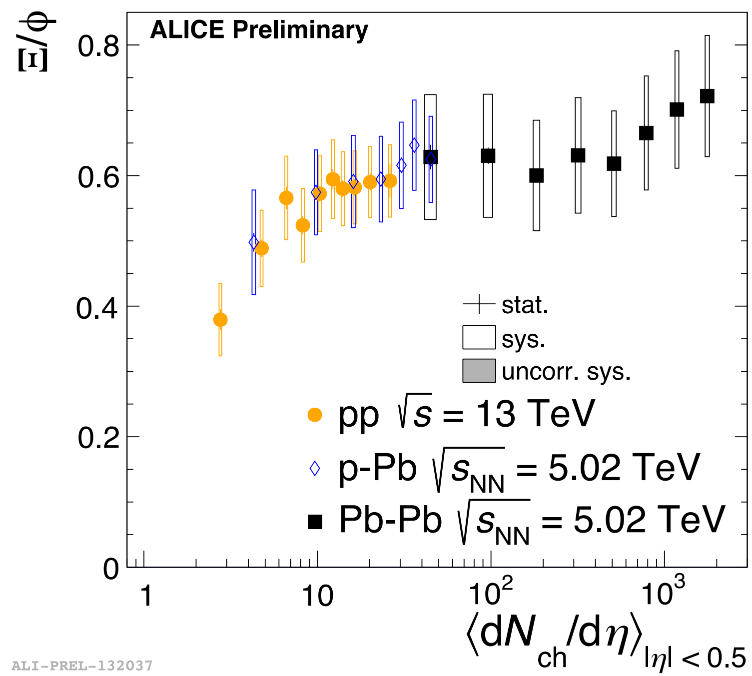
Hidden & Open Strangeness

- Ratios ϕ/K and Ξ/ϕ fairly flat across wide multiplicity range
  - The ϕ has "effective strangeness" of 1–2 units.
  - Yields of ϕ evolve similarly to particles with open strangeness.
  - Hint of different evolution for ϕ and Ξ at very low multiplicity.

ϕ/K: (|S|=0)/(|S|=1)



Ξ/ϕ: (|S|=2)/(|S|=0)



Hidden & Open Strangeness

- Ratios ϕ/K and Ξ/ϕ fairly flat across wide multiplicity range
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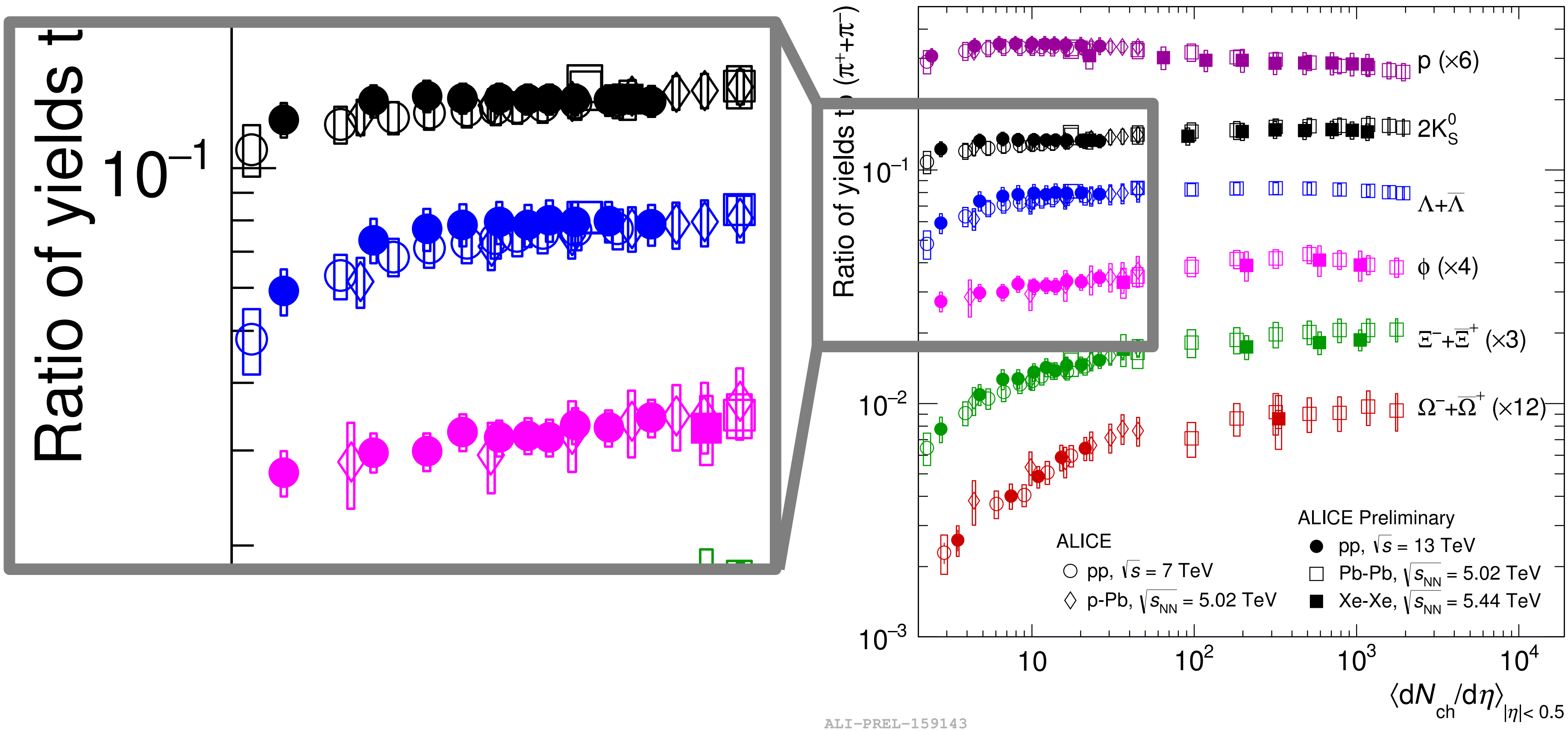
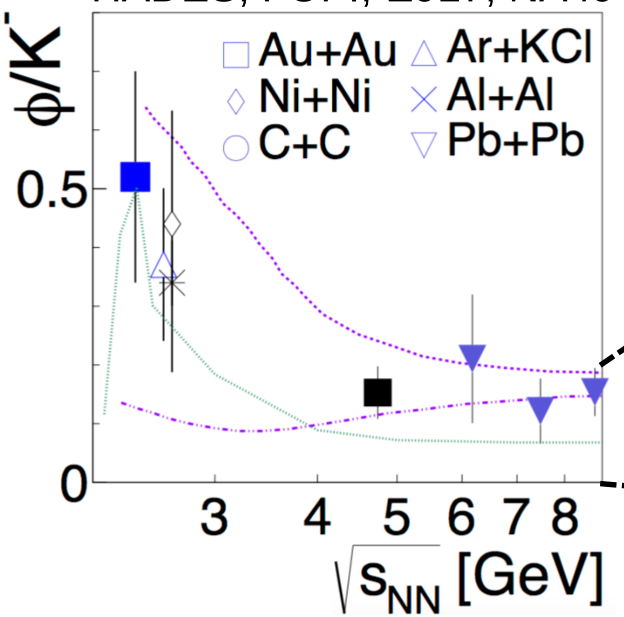
  - Yields of ϕ evolve similarly to particles with open strangeness.
  - Hint of different evolution for ϕ and Ξ at very low multiplicity.
- Very low multiplicity pp: Is there a stronger increase for Λ/π in than K/π and ϕ/π? Need ϕ/π in pp at 7 TeV.



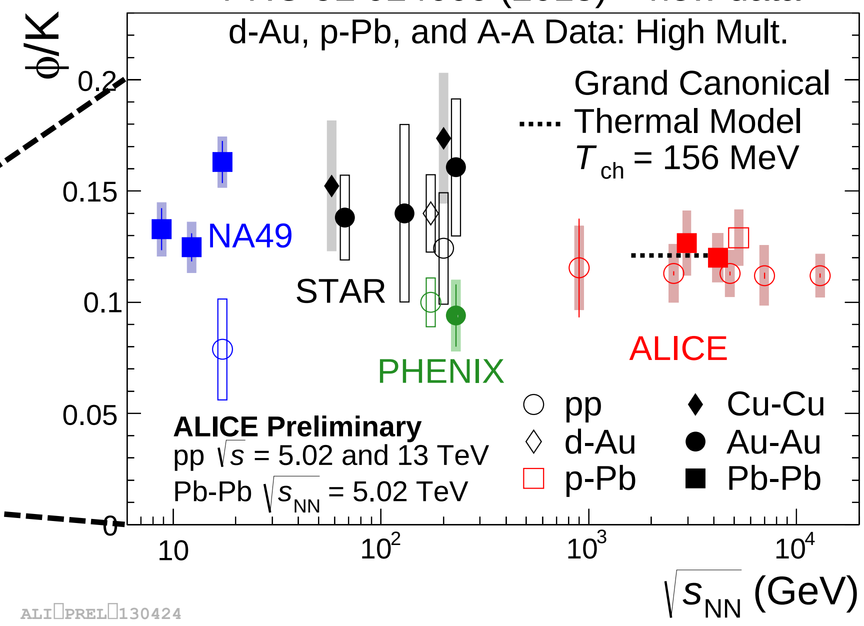
Energy Dependence

- Ratio ϕ/K fairly flat in A–A over 3 orders of magnitude in energy
- Large increase for low energies: can be explained by statistical model with strangeness correlation radius $R_C \approx 2.2$ fm
  - Strangeness conserved in small volume → K suppressed, but ϕ not affected
  - Supports standard picture of canonical suppression

HADES, FOPI, E917, NA49



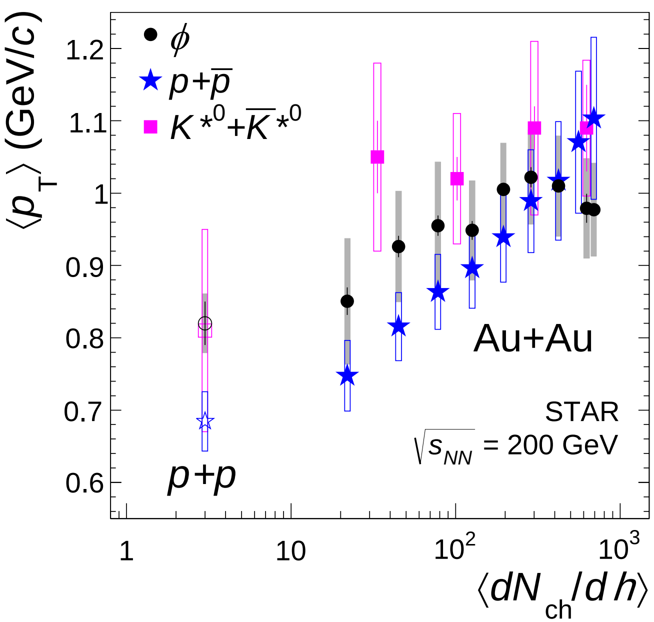
PRC **91** 024609 (2015) + new data

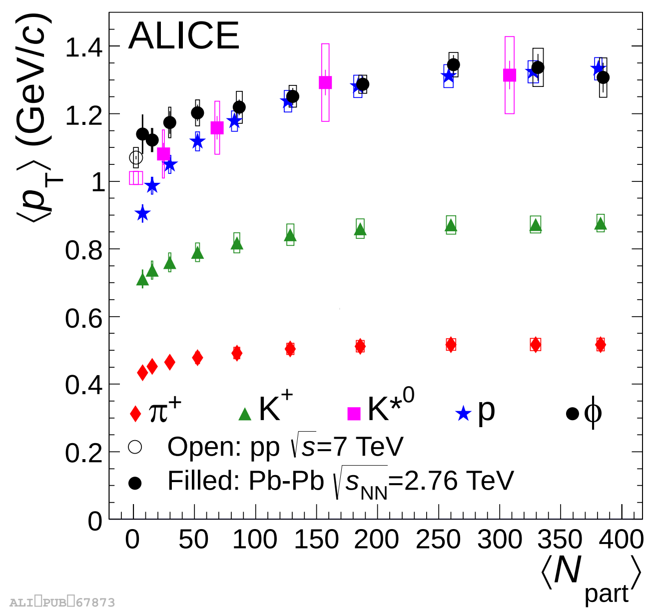


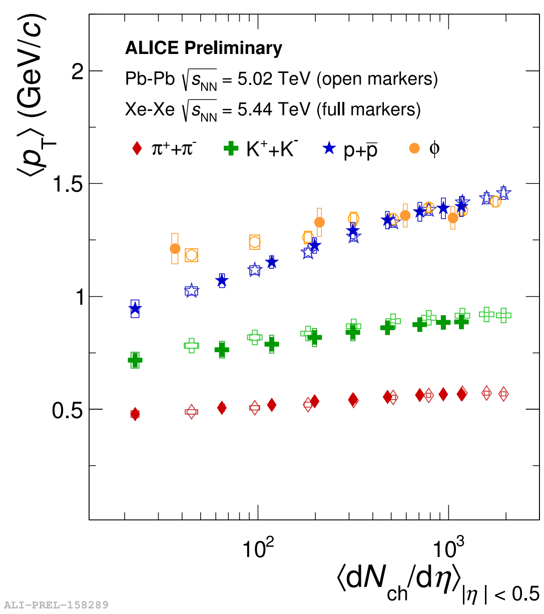
arXiv:1703.08418
PLB **778** 403-407 (2018)

Mean Transverse Momentum

- Mass ordering of $\langle p_T \rangle$ in central A–A
  - $\langle p_T \rangle$ for p and ϕ similar → expected from hydro (similar masses)
- Mass ordering only approximate for peripheral A–A





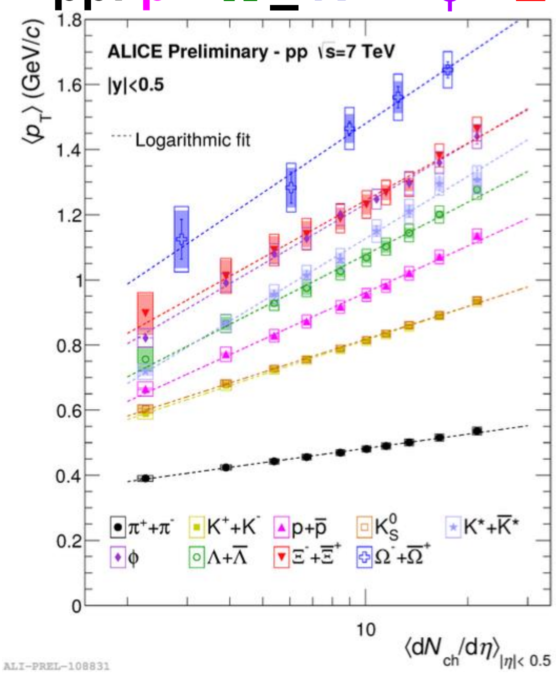


Mean Transverse Momentum

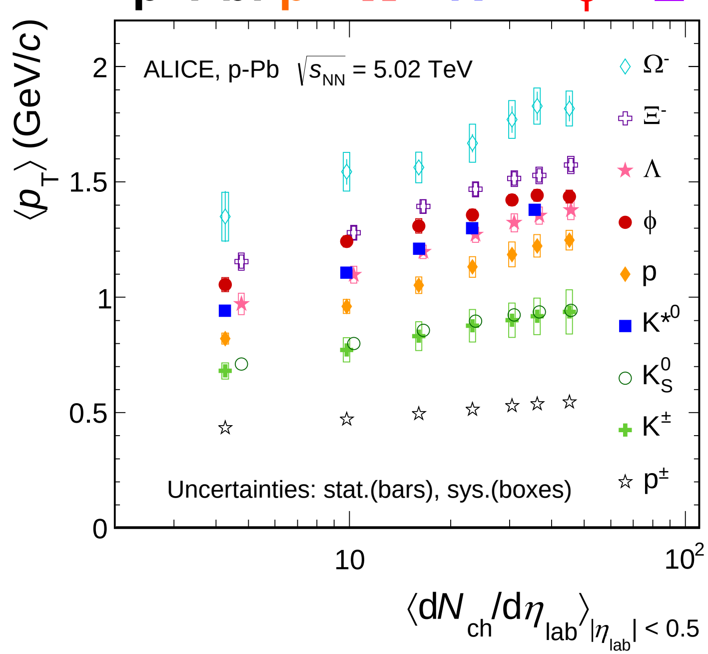
- Mass ordering of $\langle p_T \rangle$ in central A–A
  - $\langle p_T \rangle$ for p and ϕ similar → expected from hydro (similar masses)
- Mass ordering only approximate for peripheral A–A, p–Pb, and pp
  - Resonances different from long-lived particles? Baryon/meson difference?

$\langle p_T \rangle$ ordering:

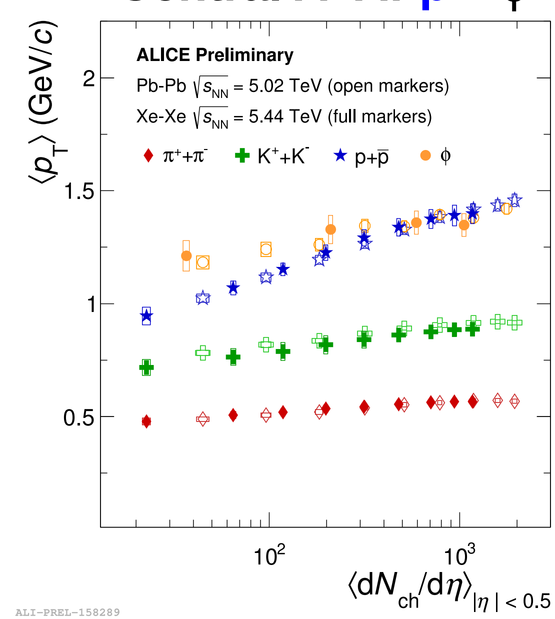
pp: p < Λ ≤ K^{*0} < φ ≈ Ξ



p–Pb: p < Λ ≈ K^{*0} < φ < Ξ

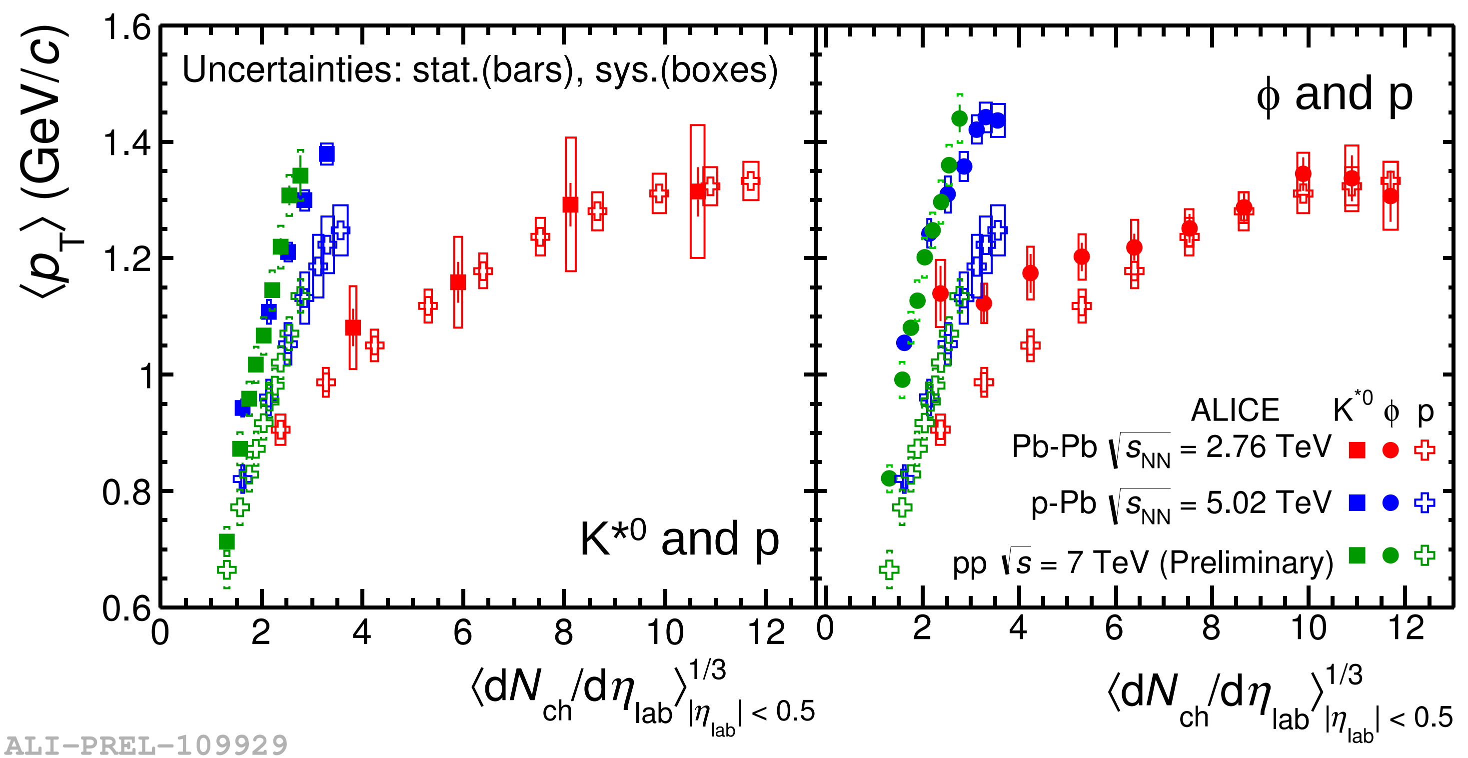


Central A–A: p ≈ φ



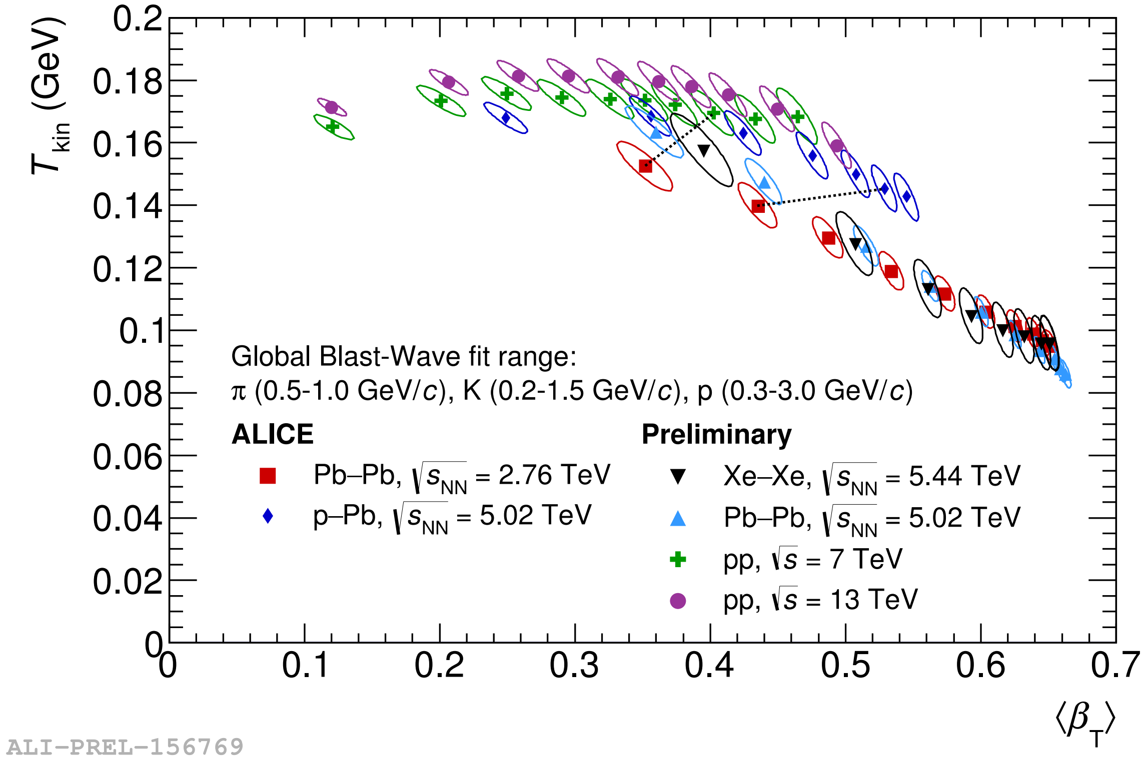
Mean Transverse Momentum

- Mass ordering of ⟨p_T⟩ in central A–A
  - ⟨p_T⟩ for p and ϕ similar → expected from hydro (similar masses)
- Mass ordering only approximate for peripheral A–A, p–Pb, and pp
  - Resonances different from long-lived particles? Baryon/meson difference?
- ⟨p_T⟩ of of K^{*0}, p, and ϕ:
  - pp and p–Pb follow same trends vs. multiplicity, different trend for Pb–Pb
  - Reach or exceed central Pb–Pb values in high multiplicity pp & p–Pb



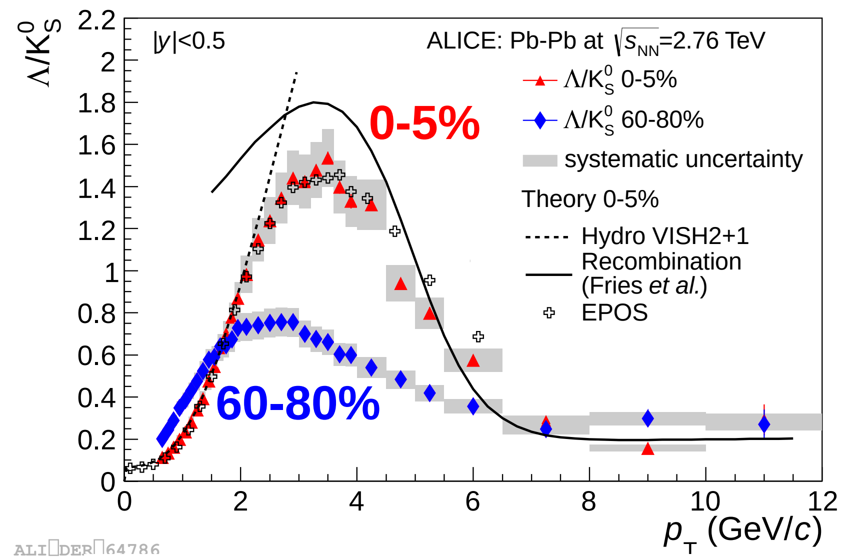
Blast-Wave Fits

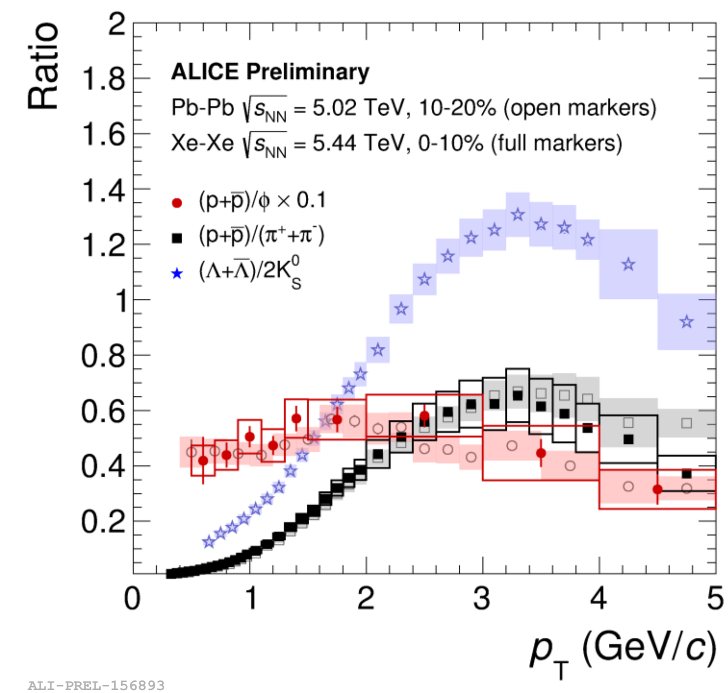
- Simultaneous blast-wave fits of $\pi^{\pm}K^{\pm}p$ p_{T} spectra
- A–A results follow different trend than pp and p–Pb
- For similar multiplicities: $\langle \beta_{\mathrm{T}} \rangle$ (and $\langle p_{\mathrm{T}} \rangle$) greater in smaller systems
- Consistent with behavior of ϕ



Baryon-to-Meson Ratios

- Pb–Pb Λ/K^0_S ratio:
  - Low-p_T rise described by hydrodynamics (VISH 2+1)
  - Recombination qualitatively describes enhancement
  - EPOS consistent with measured enhancement → radial flow
- p/ϕ ratio is useful: baryon and meson with almost the same mass
  - Flat with p_T → consistent with hydrodynamic expectation





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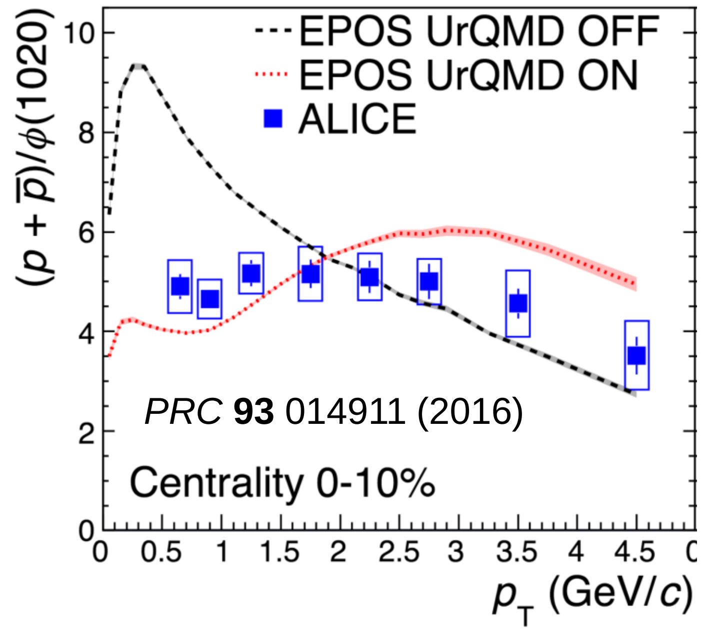
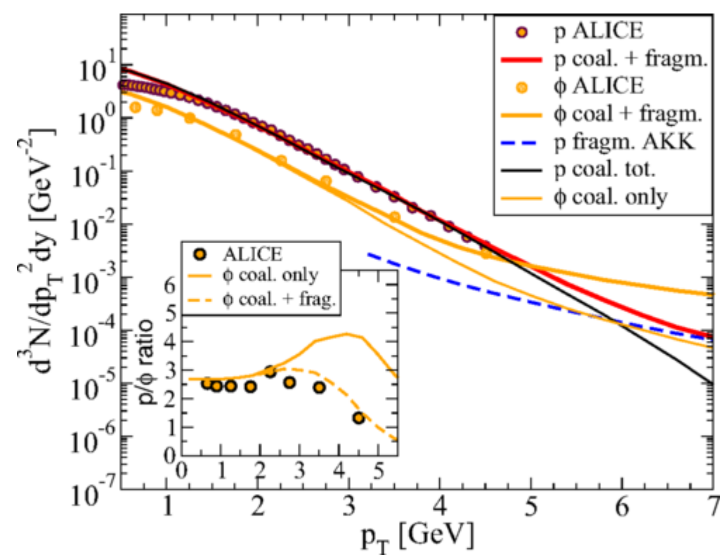
  - Recombination qualitatively describes enhancement
  - EPOS consistent with measured enhancement → radial flow
- p/ϕ ratio is useful: baryon and meson with almost the same mass
  - Flat with p_T → consistent with hydrodynamic expectation
  - Fair description by EPOS
  - Can also be described by some recombination models

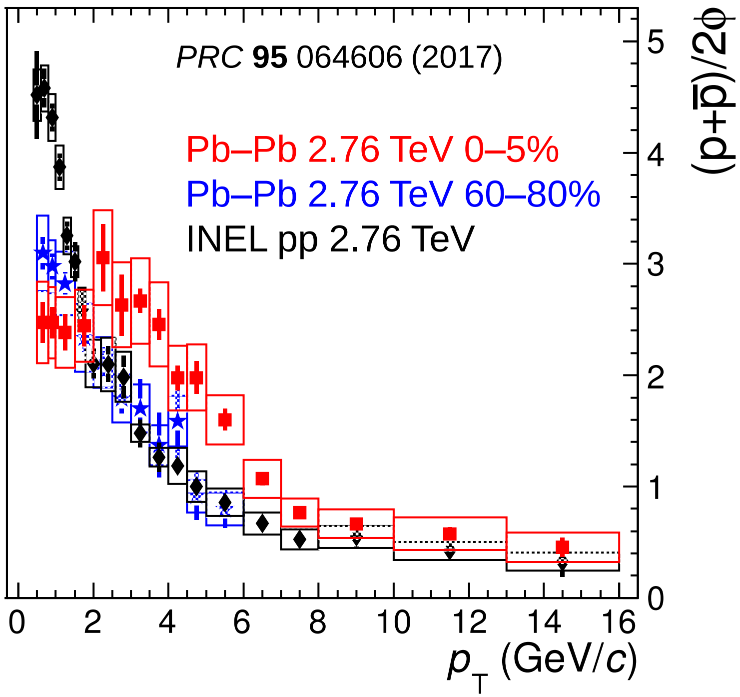




PRC **92** 054904 (2015)

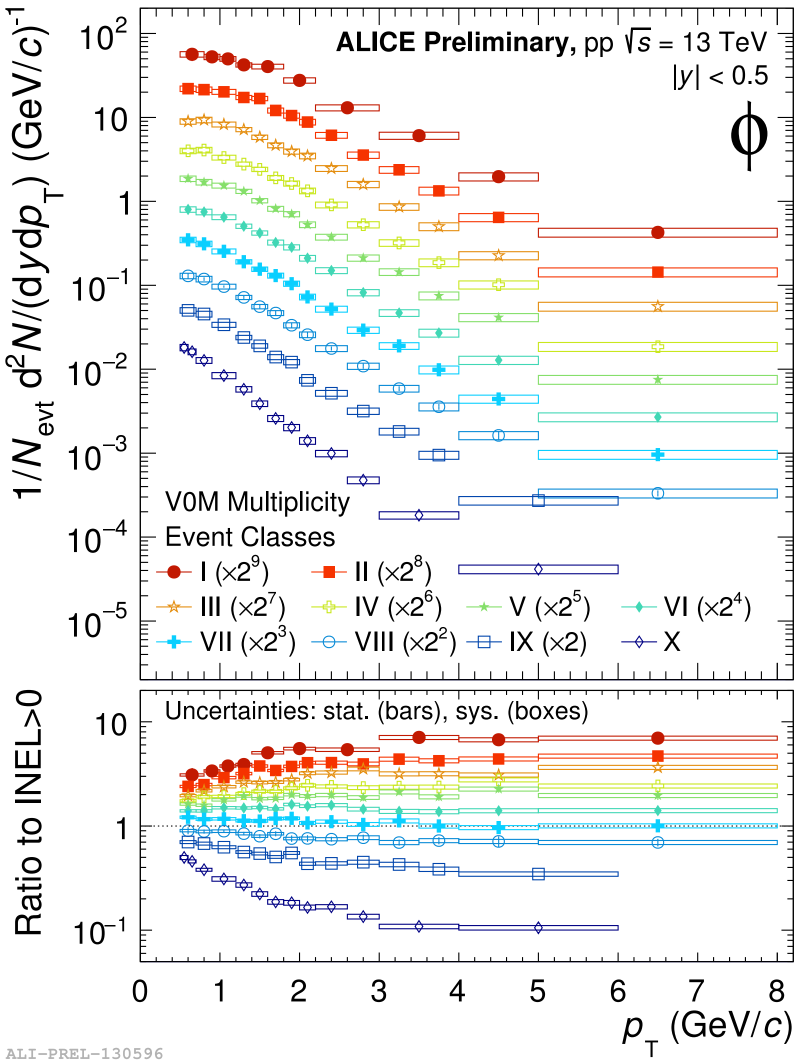
Baryon-to-Meson Ratios

- Extend p/ϕ measurement to high p_T
  - Flat in p_T for p_T<4 GeV/c
    - Hydrodynamics or recombination
  - Drop-off towards high p_T, Pb–Pb consistent w/ pp
    - Jets, fragmentation



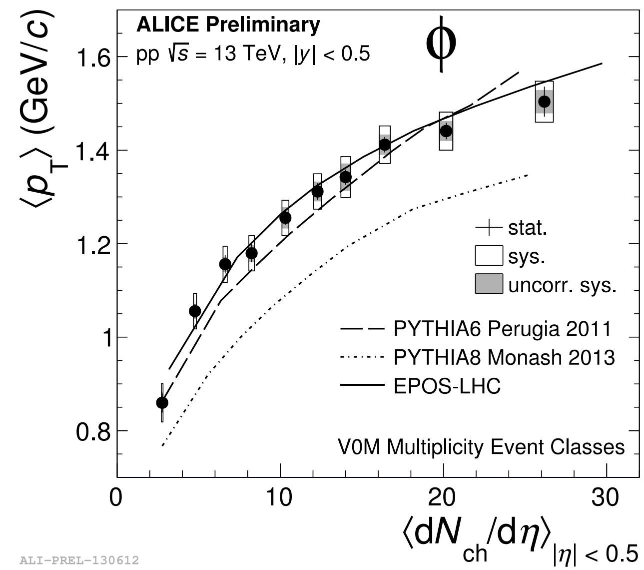
p_T Spectra in pp

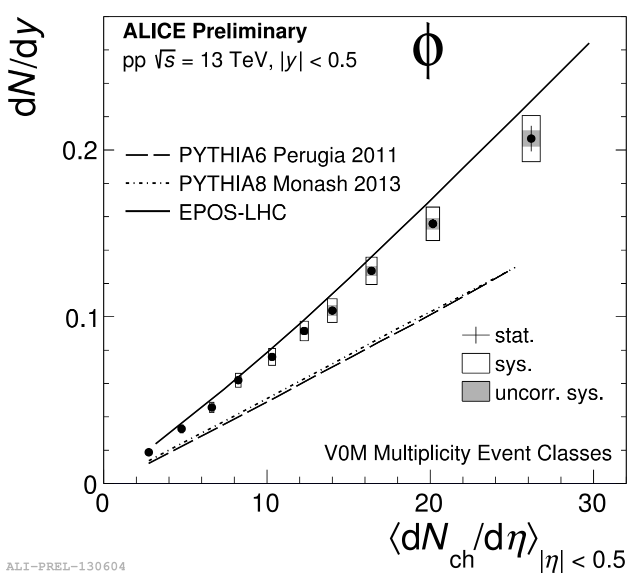
- p_T spectra harden in pp collisions with increasing multiplicity
- Ratio to INEL>0 flat for p_T >4 GeV/c
  - Spectral shape independent of multiplicity → jets, fragmentation
- Same behavior seen for other light-flavor particles and for ϕ at other energies

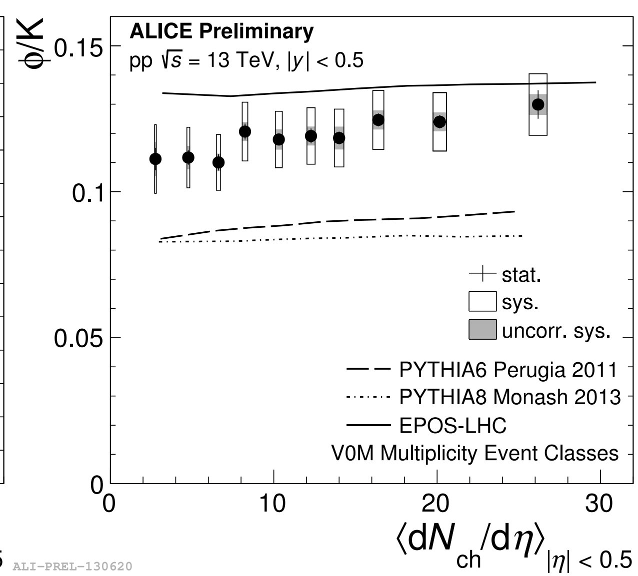


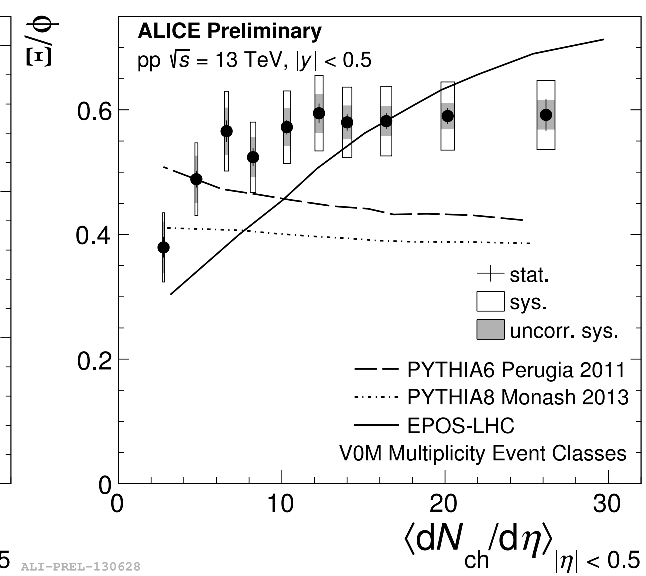
pp Model Comparisons

- $\langle p_T \rangle$: PYTHIA 6 & EPOS-LHC describe ϕ values
- Yield: EPOS-LHC better than PYTHIA at describing yields
  - Similar behavior for strange baryons
- Ratio ϕ/K: Flat-ish for all models, EPOS reproduces values better
- Ratio Ξ/ϕ: EPOS-LHC has increasing trend, PYTHIA does not reproduce the ratio



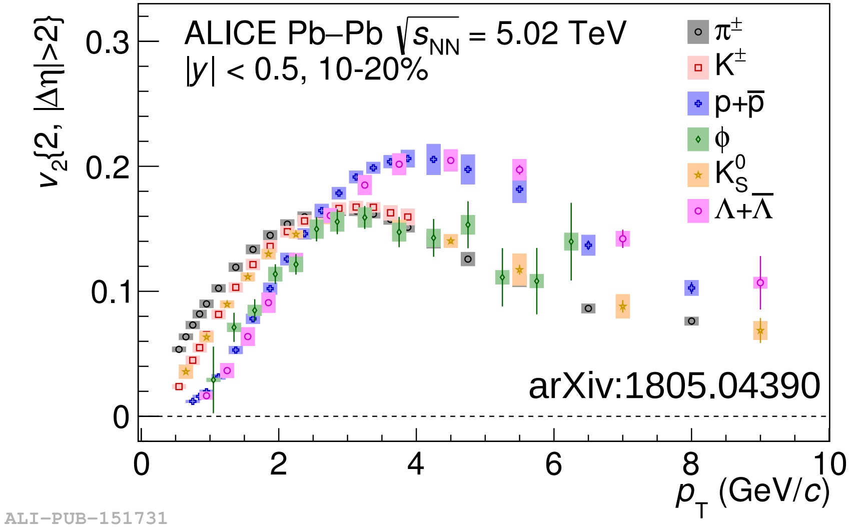


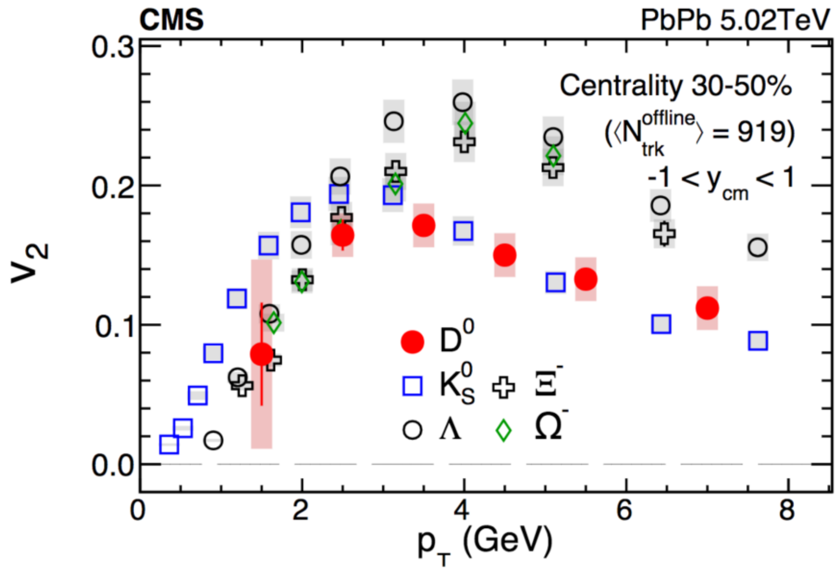




Elliptic Flow

- v_2 of identified hadrons in Pb–Pb
  - Low p_T: mass ordering: $v_2^p \approx v_2^\phi \approx v_2^\Lambda$
  - Hight p_T: baryon-meson splitting
  - Also for other centralities, lower energies
  - The ϕ is a key probe for verifying this.
- See also D^0 meson flow (CMS)
  - $m(D^0)$=1.865 GeV/c^2
  - Baryon-meson splitting at high p_T
  - Consistent with mass ordering at low p_T, but large uncertainties





arXiv:1804.09767

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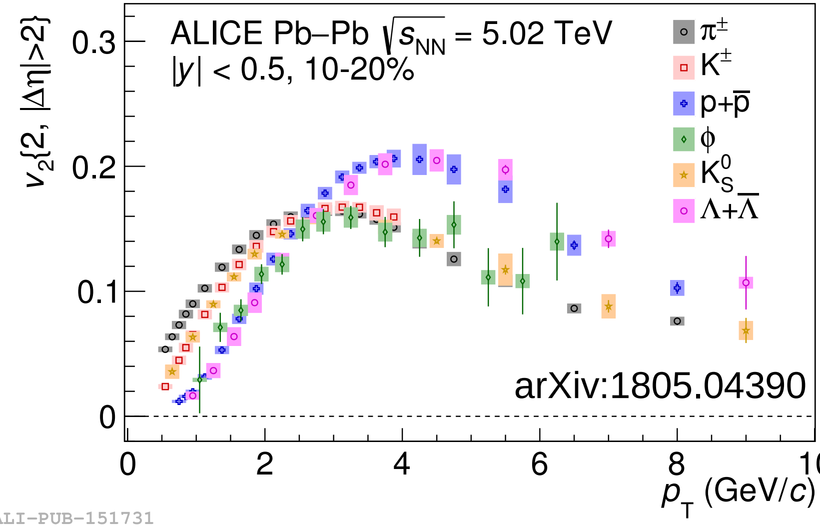
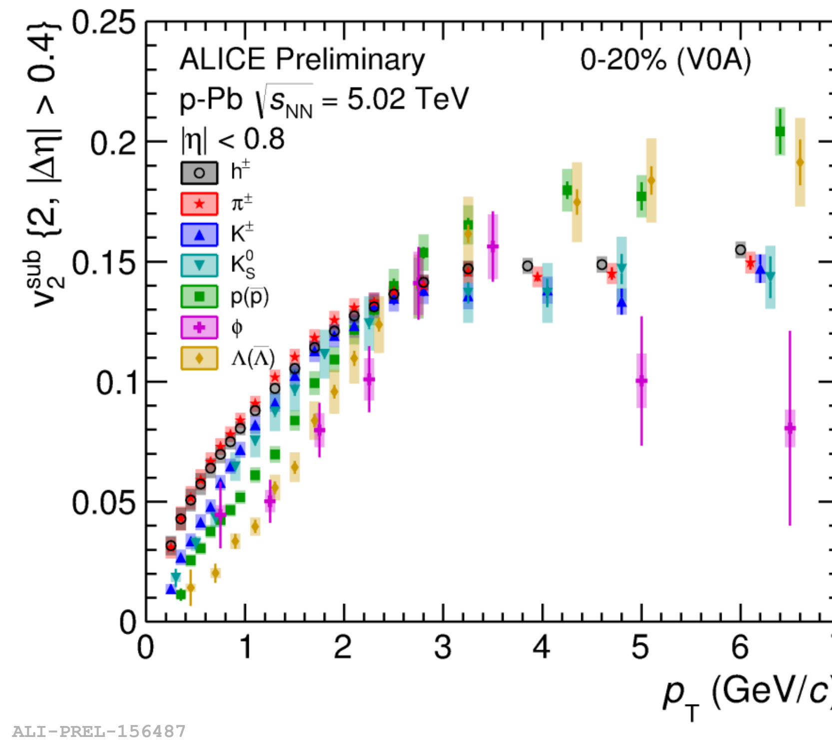
  - Baryon-meson splitting at high p_T
  - Consistent with mass ordering at low p_T, but large uncertainties
- In p–Pb
  - Mass ordering and baryon-meson splitting, becomes less pronounced for lower multiplicities
  - The ϕ may break mass ordering, but large uncertainties



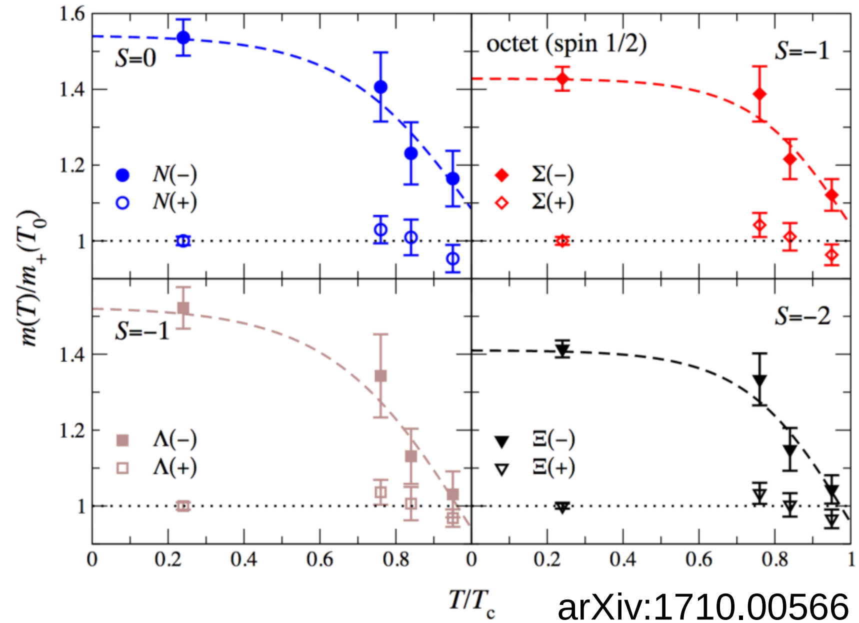


Conclusions

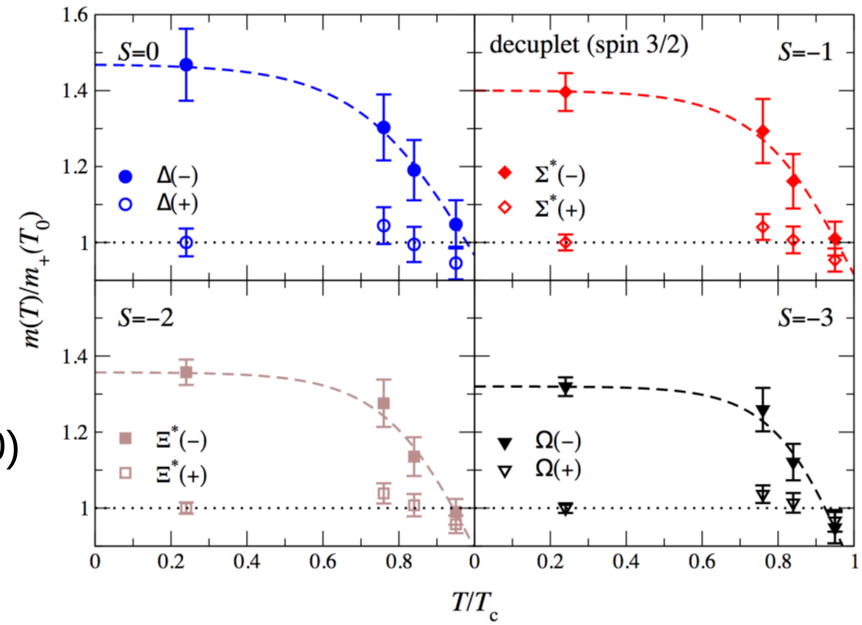
- **Yields & strangeness enhancement**
  - Thermal production of ϕ in A–A
  - Small systems:
    - Trend for ϕ inconsistent w/ simple canonical suppression.
    - The ϕ seems to have "effective strangeness" of 1–2
    - Do Λ & Ξ yields drop off faster than K & ϕ for very low-multiplicity collisions?
- **Shapes of p_T spectra**
  - Hydro-like behavior in central A–A
    - Mass ordering of $\langle p_T \rangle$, flat p/ϕ for p_T<4 GeV/c
  - Can also be described by (some) recombination models.
    - Any new measurements to help distinguish between hydro and recombination?
  - Violations of $\langle p_T \rangle$ mass ordering in smaller systems
  - At high p_T, shapes do not depend on coll. system or multiplicity

Parity Doubling

- FASTSUM Collaboration calculates mass degeneracy for (opposite-parity) chiral partners around T_C.
  - Positive-parity masses independent of temperature.
  - Negative-parity masses decrease with increasing temperature.
- Candidates in the octet:
  - Λ: $J^P = {}^1/_2{}^+$: measured many times
  - $\Lambda(1405)$: $J^P = {}^1/_2{}^-$: difficult to measure, decays to $\Sigma\pi$
- Candidates in the decuplet:
  - $\Xi(1530)$: $J^P = {}^3/_2{}^+$: measured in pp, p–Pb, and Pb–Pb
  - $\Xi(1820)$: $J^P = {}^3/_2{}^-$: (difficult) measurement in progress in pp in ΛK channels
  - Potential to measure mass shift, width broadening, or change in $\Xi(1820)/\Xi(1530)$ ratio with system size



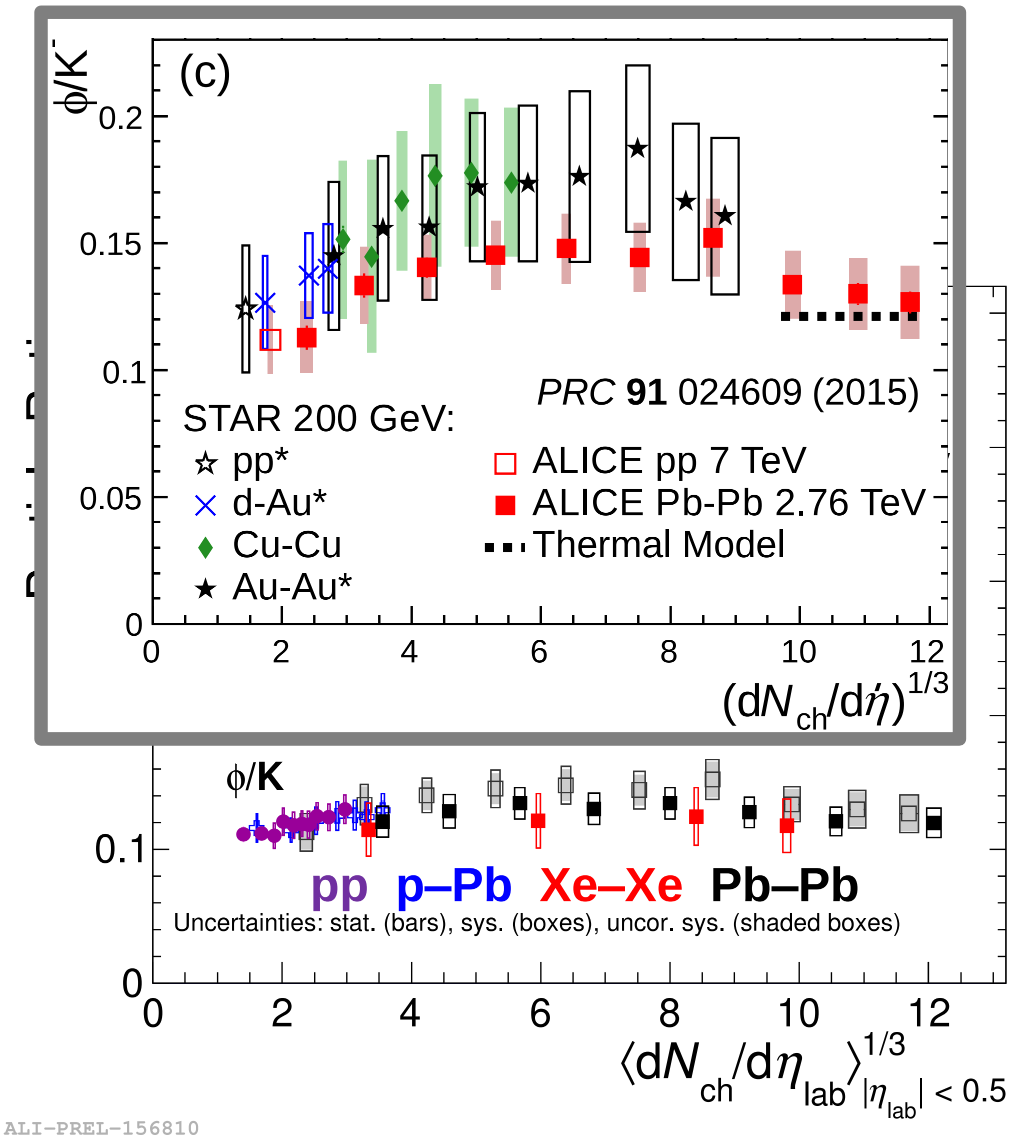
arXiv:1710.00566



Additional Material

Energy Dependence

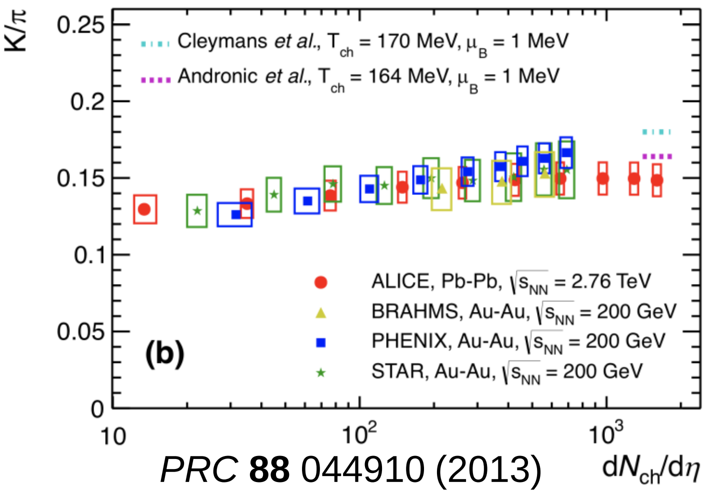
- Possible weak decrease in ϕ/K ratio with energy in A–A
- May be connected to
  - Decrease in ϕ/π from 200 GeV → 2.76 TeV
  - Increase in K/π from 2.76 TeV → 5.02 TeV



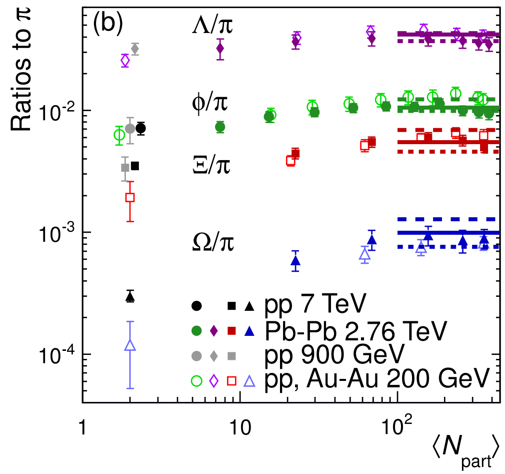
K/π, φ/π, and φ/K

Au–Au 200 GeV → Pb–Pb 2.76 TeV

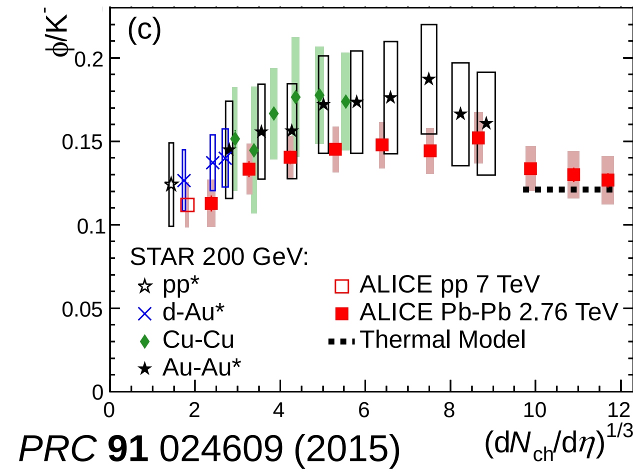
K/π: possible small decrease



φ/π: decrease



φ/K: hint of decrease



Pb–Pb 2.76 TeV → Pb–Pb 5.02 TeV

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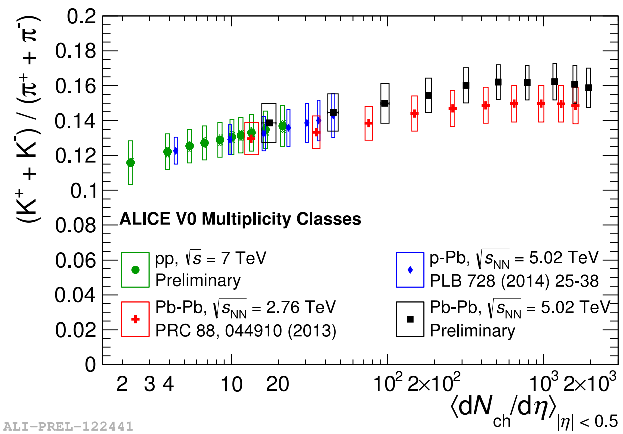
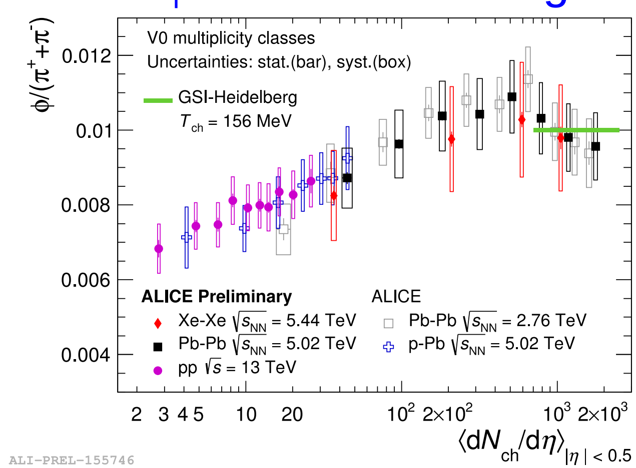


φ/π: no clear change



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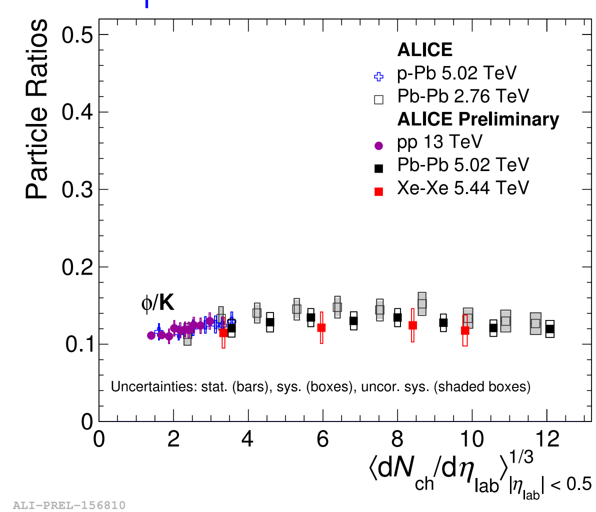
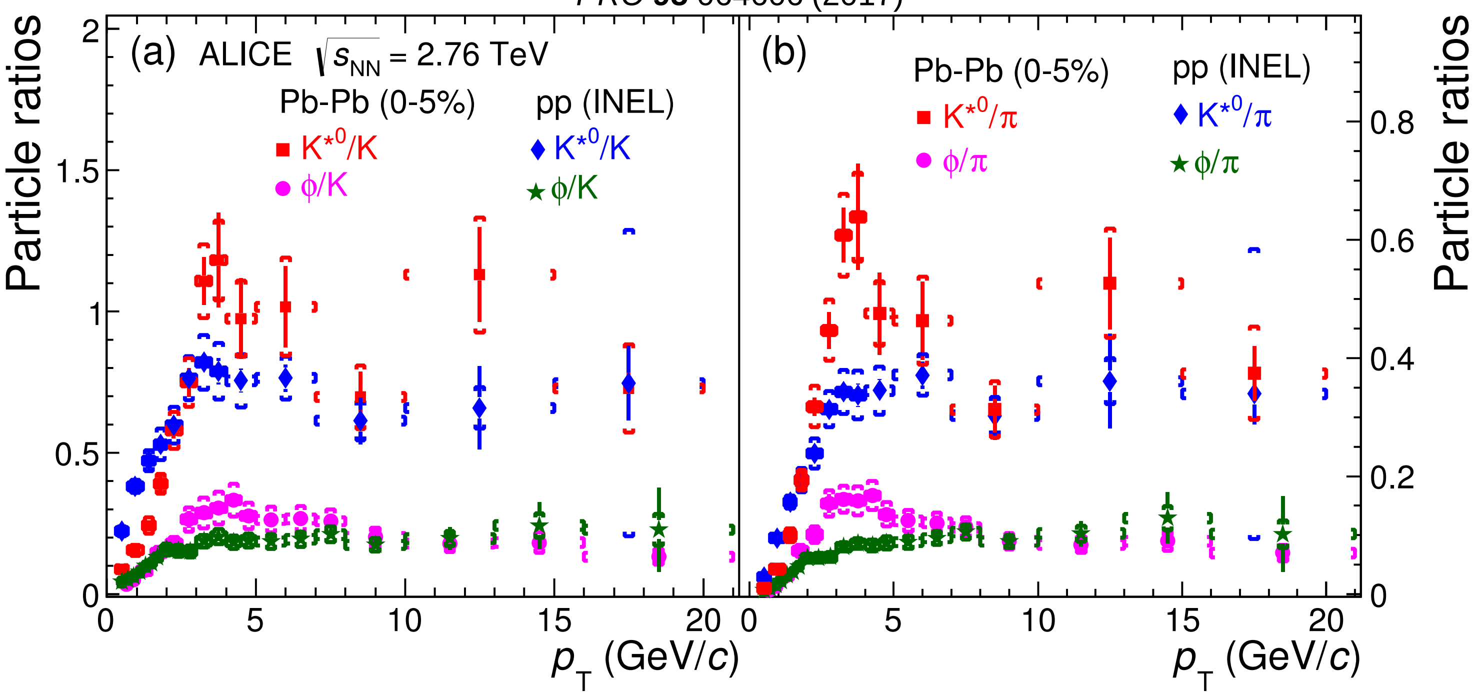


Particle Ratios vs p_T

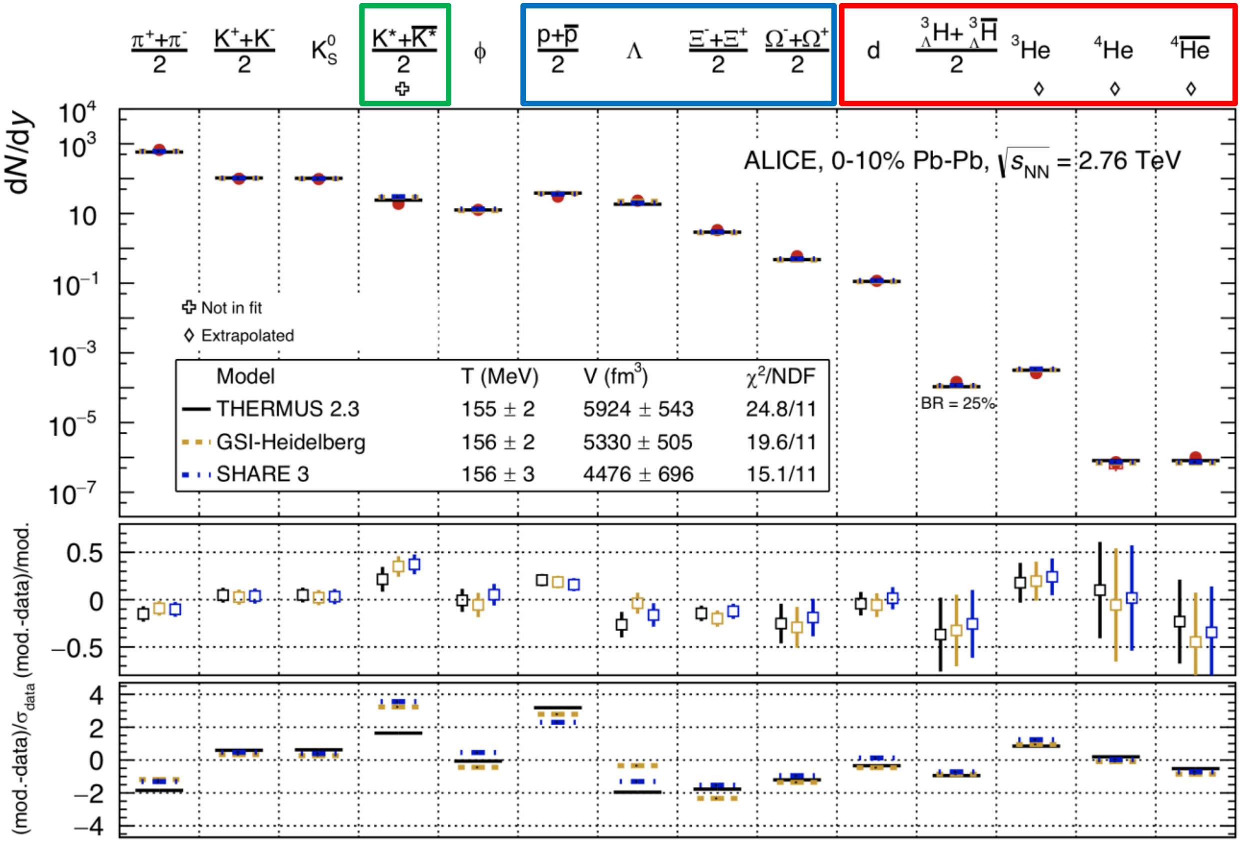
- Ratios of K^{*0} & ϕ to π & K
- At high p_T: Pb–Pb consistent w/ pp
  - Fragmentation

PRC **95** 064606 (2017)



Thermal Models

- Most light-flavor hadron yields described fairly well by thermal models with single chemical freeze-out temp. (T_{ch}=156±3 MeV for Pb–Pb at 2.76 TeV)
- Even (anti)nuclei and hyper-nuclei are described
- Short-lived resonances (e.g., K^{*0}) deviate due to re-scattering effects (excluded from fit)
- However, some tension for protons and (multi)strange baryons



Additional effects needed?
Baryon annihilation, interacting hadron gas, incomplete hadron spectrum?

Nucl. Phys. A **971** 1-20 (2018)
THERMUS: Wheaton *et al.*, *Comput. Phys. Commun.* **180** 84 (2009)
GSI-Heidelberg: Andronic *et al.*, *PLB* **673** 142 (2009)
SHARE: Petran *et al.*, *Comput. Phys. Commun.* **185** 2056 (2014)

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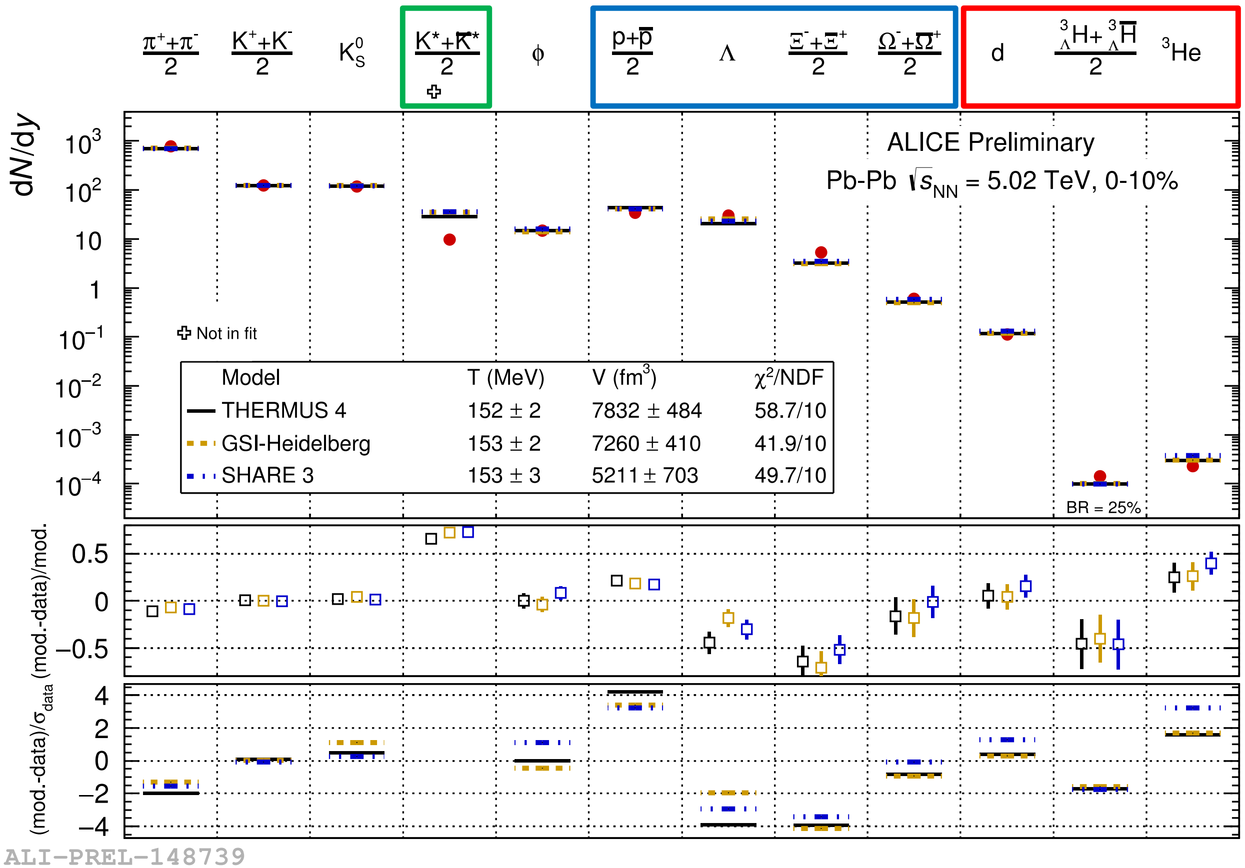
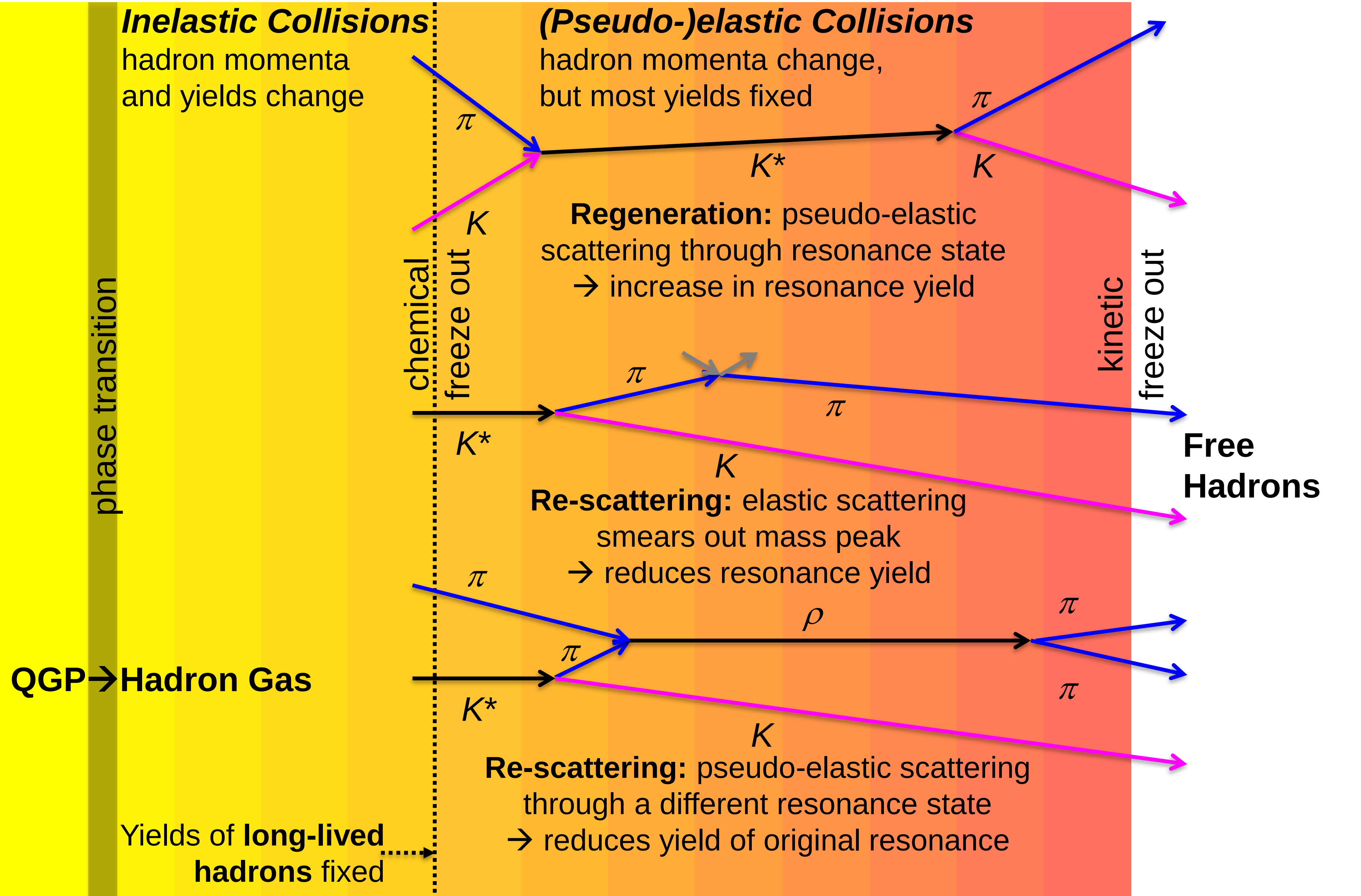


Additional effects needed?
Baryon annihilation, interacting hadron gas, incomplete hadron spectrum?

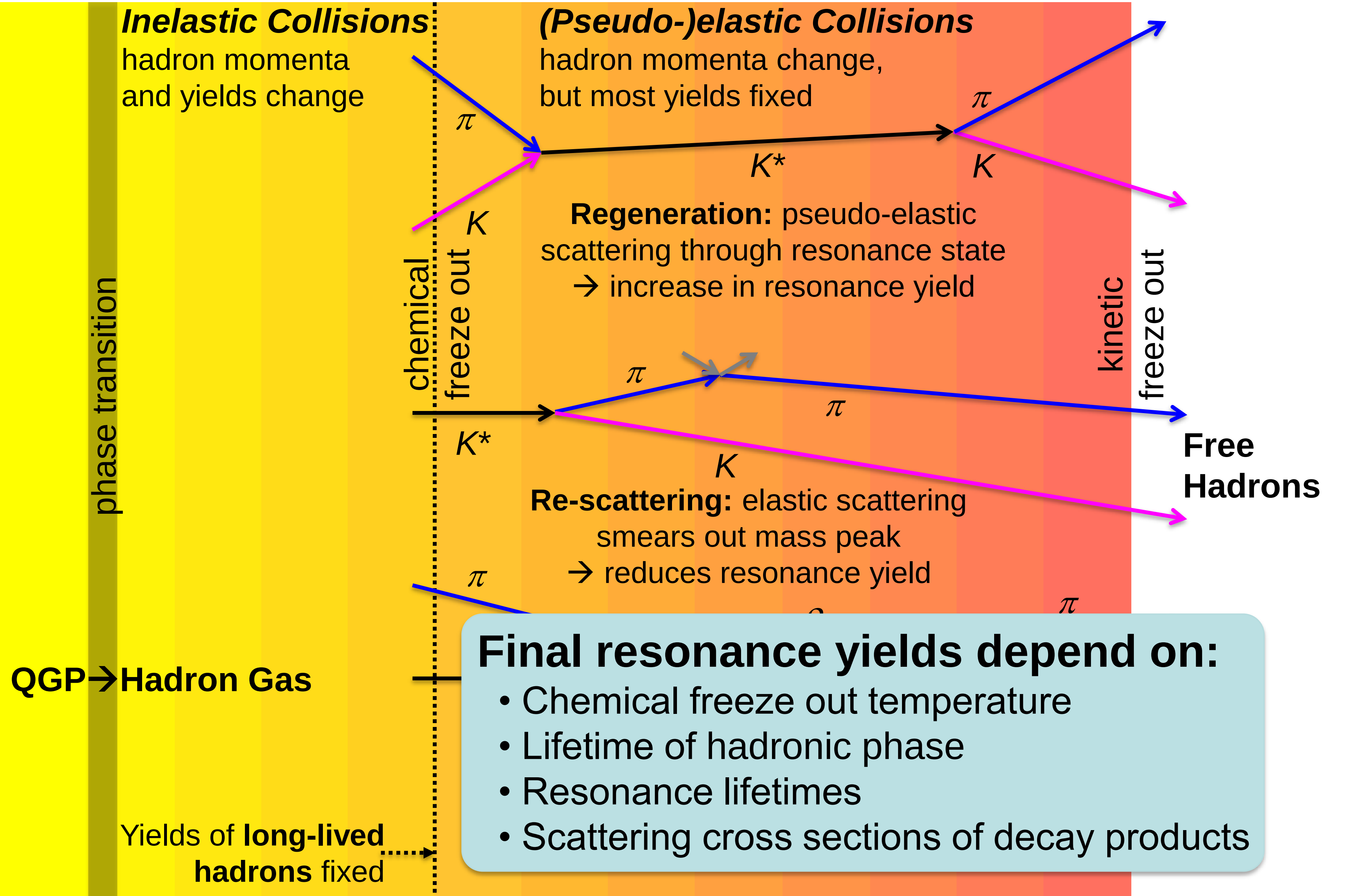
Similar behavior seen for
Pb–Pb at 5.02 TeV:
T_{ch}=153±3 MeV
Lower temperature driven by increase in system size

THERMUS: Wheaton *et al.*, *Comput. Phys. Commun.* **180** 84 (2009)
GSI-Heidelberg: Andronic *et al.*, *PLB* **673** 142 (2009)
SHARE: Petran *et al.*, *Comput. Phys. Commun.* **185** 2056 (2014)

Resonances


phase transition
Inelastic Collisions
hadron momenta
and yields change
(Pseudo-)elastic Collisions
hadron momenta change,
but most yields fixed
π
K
K*
π
K
chemical
freeze out
Regeneration: pseudo-elastic
scattering through resonance state
→ increase in resonance yield
kinetic
freeze out
π
π
K*
K
Free
Hadrons
Re-scattering: elastic scattering
smears out mass peak
→ reduces resonance yield
π
ρ
π
π
π
K*
K
QGP→Hadron Gas
Re-scattering: pseudo-elastic scattering
through a different resonance state
→ reduces yield of original resonance
Yields of long-lived
hadrons fixed

Resonances



Final resonance yields depend on:

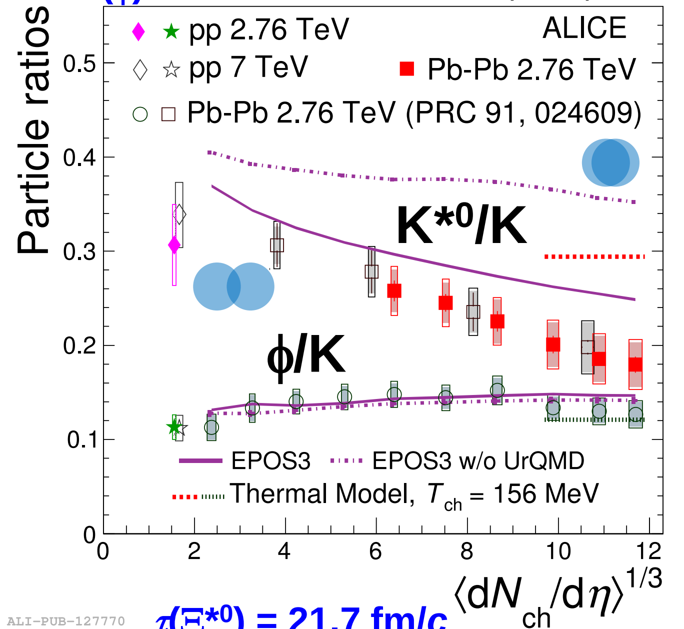
- Chemical freeze out temperature
- Lifetime of hadronic phase
- Resonance lifetimes
- Scattering cross sections of decay products

Resonance Suppression

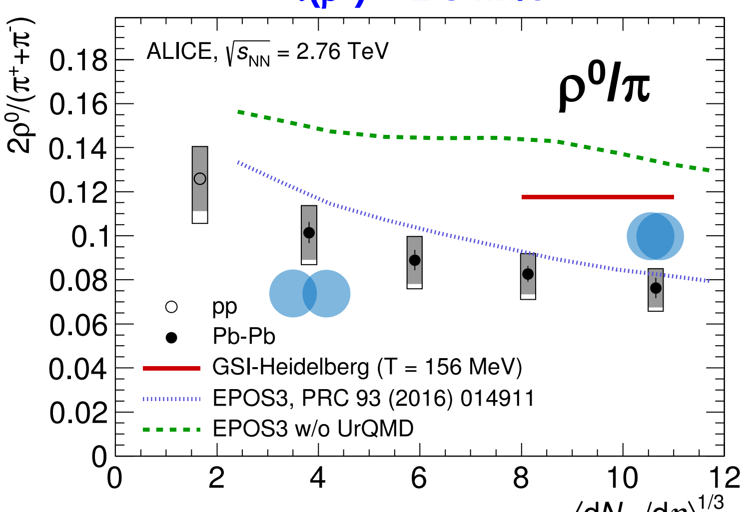
- Suppression of K^{*0} w.r.t. pp and thermal model values
  - Re-scattering of decay products in hadronic medium
  - Hint of K^{*0} suppression in high-mult. pp and p–Pb
- No ϕ suppression: lives longer, decays outside fireball
- Similar suppression of ρ^0 & $\Lambda(1520)$
- Possible weak suppression of Ξ^{*0} w.r.t. pp collisions
- Ratios do not depend on energy (RHIC→LHC) or collision system (same for p–Pb and Xe–Xe)
- Suppression trends qualitatively described by EPOS
  - Includes scattering effects modeled with UrQMD

$\tau(K^{*0})$ = 4.16 fm/c
$\tau(\phi)$ = 46.2 fm/c

PRC **95** 064606 (2017)

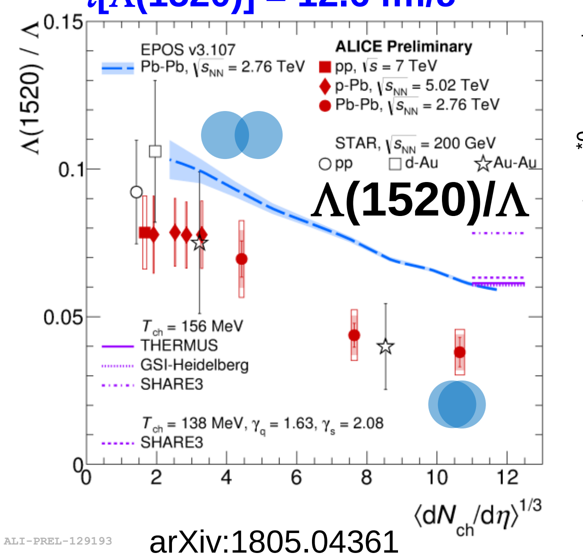


$\tau(\rho^0)$ = 1.3 fm/c



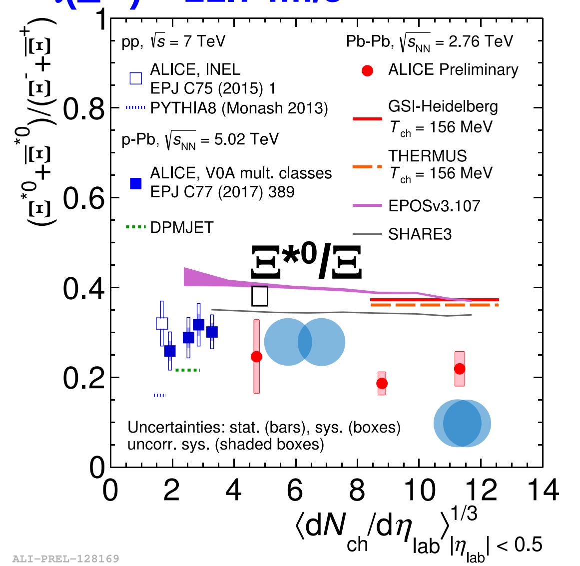
arXiv:1805.04365

$\tau[\Lambda(1520)]$ = 12.6 fm/c

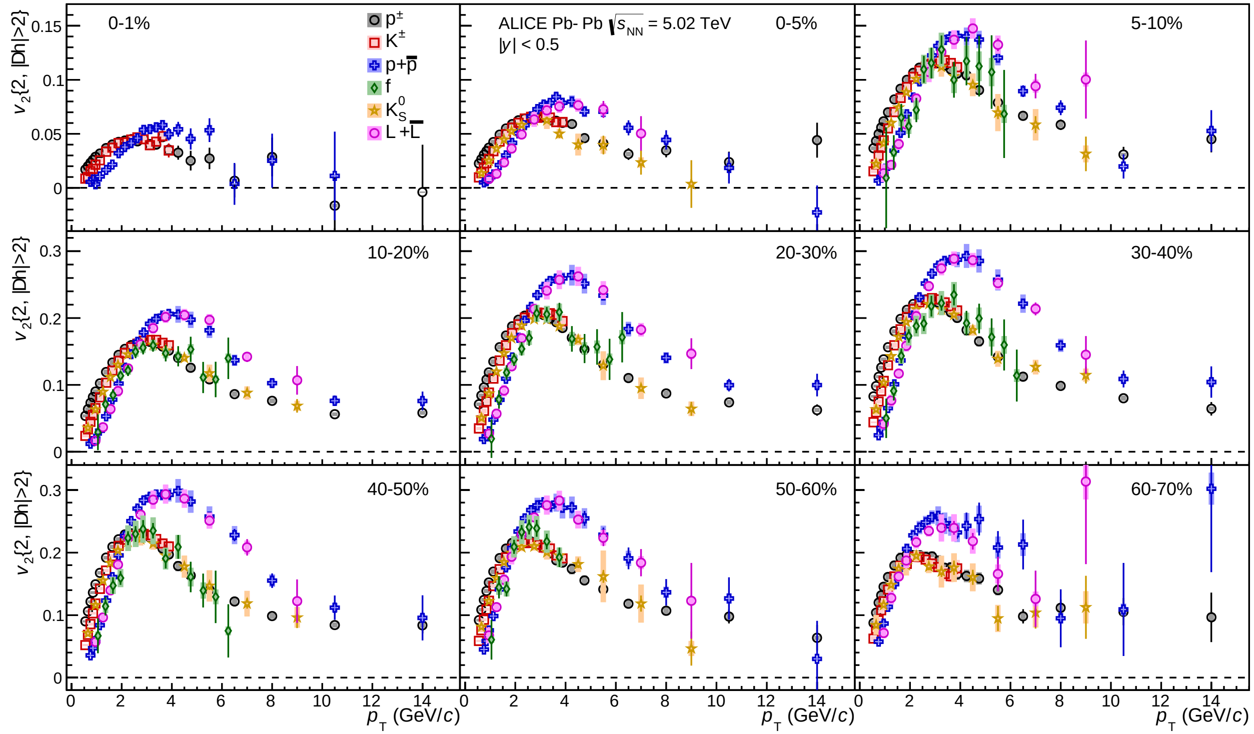


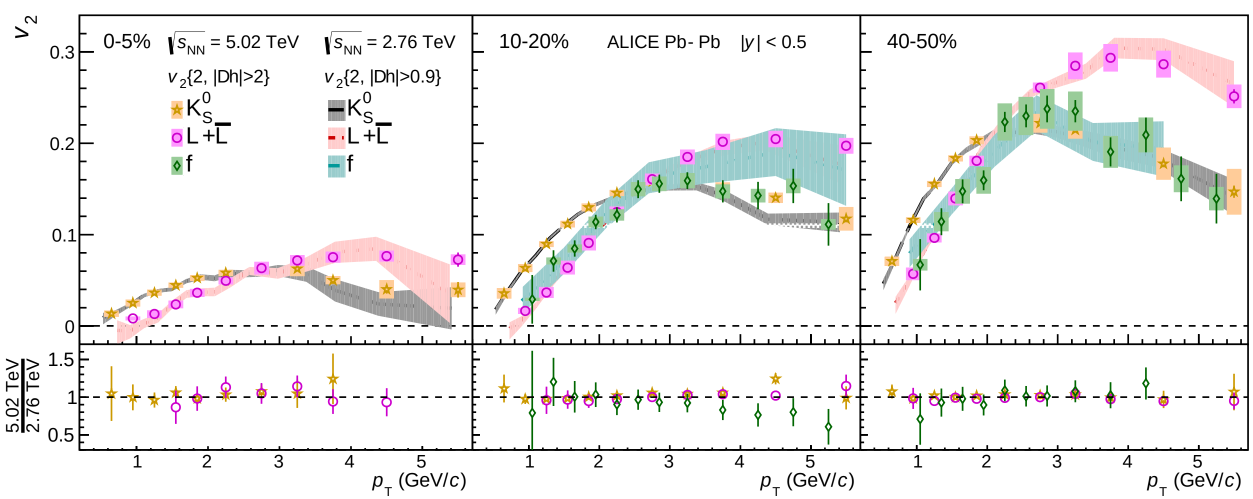
arXiv:1805.04361

$\tau(\Xi^{*0})$ = 21.7 fm/c

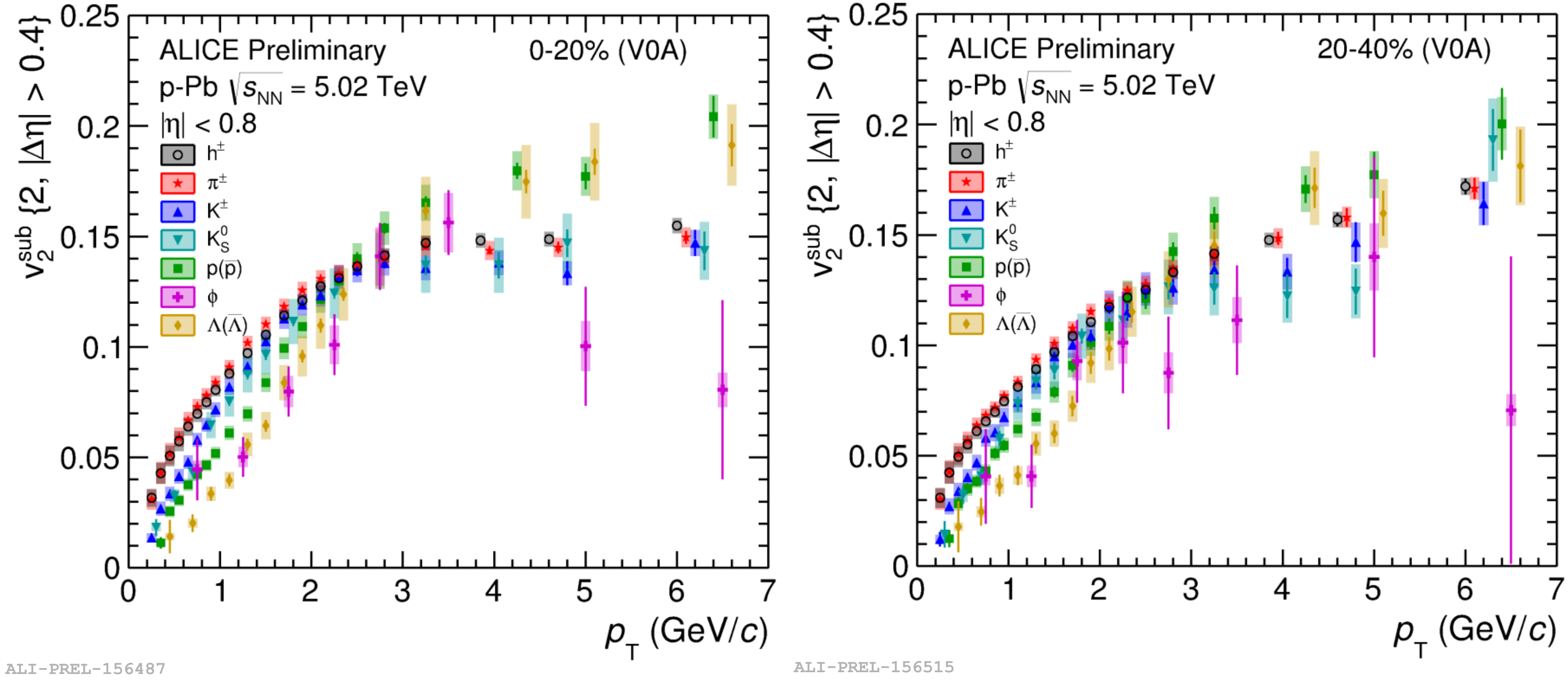


Elliptic Flow: Pb–Pb



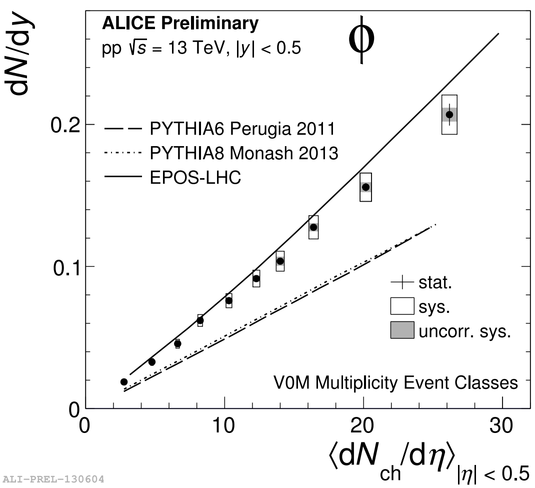


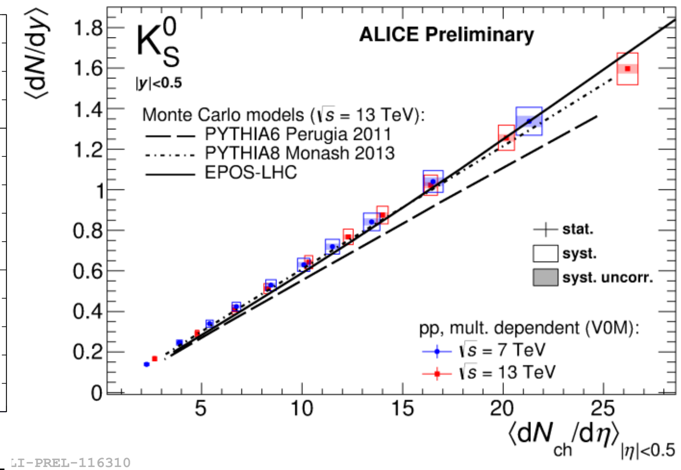
Elliptic Flow: p–Pb

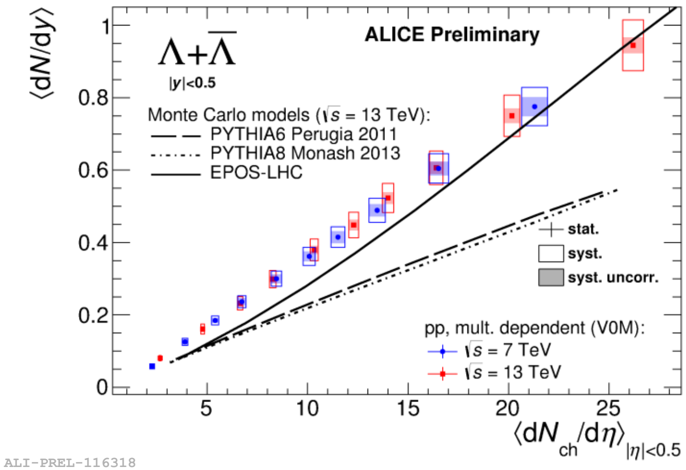


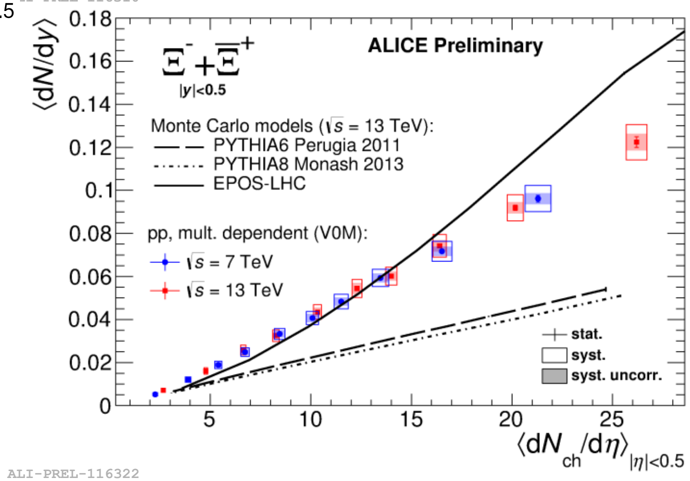
More Model Comparisons

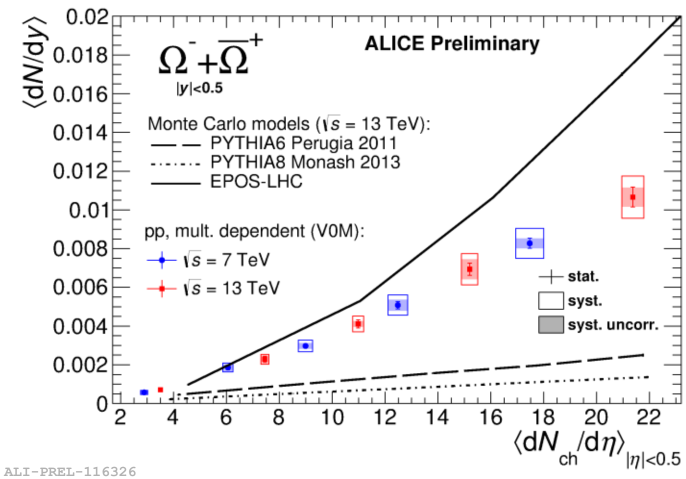
Knospe











Nuclear Modification Factor