Hadronization from the QGP in the Light and Heavy Flavour sectors

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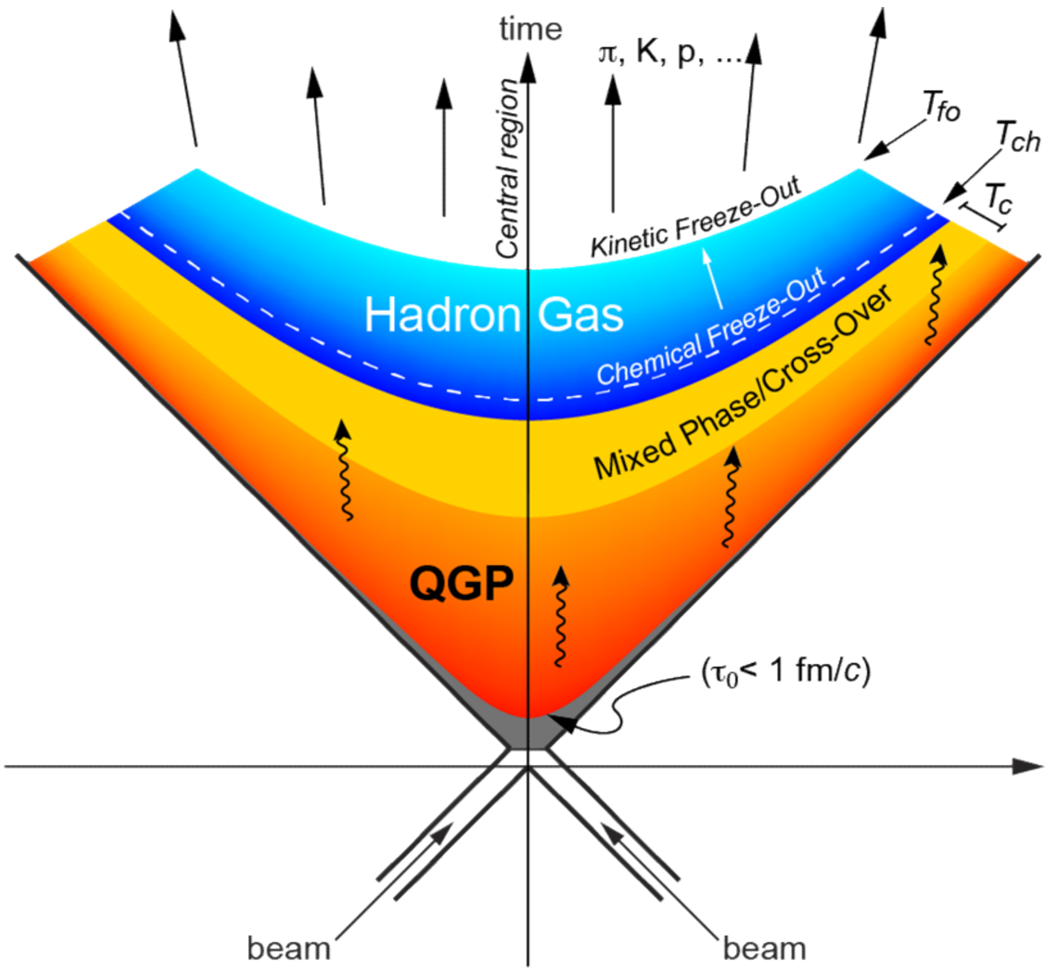
Heavy-ion collision evolution

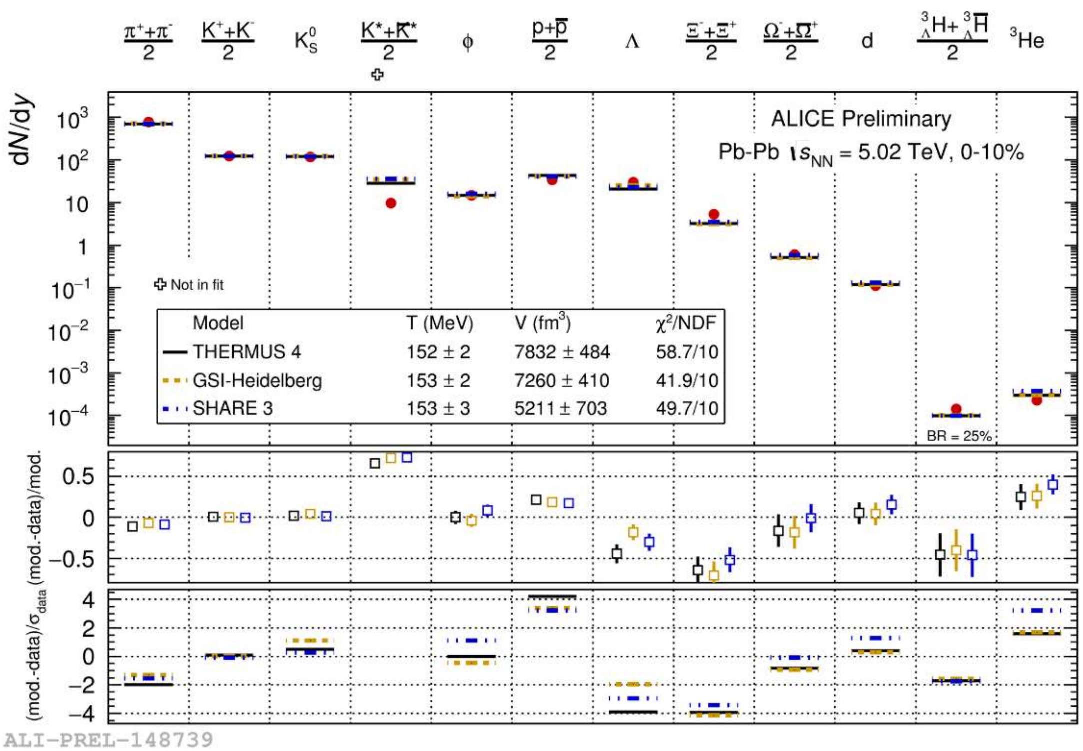


- Hadronization of the QGP medium at the pseudo-critical temperature
  - Transition from a deconfined medium composed of quarks, antiquarks and gluons to color-neutral hadronic matter
  - The partonic degrees of freedom of the deconfined phase convert into hadrons, in which partons are confined
- No first-principle description of hadron formation
  - Non-perturbative problem, not calculable with QCD

→ Hadronisation from a QGP may be different from other cases in which no bulk of thermalized partons is formed

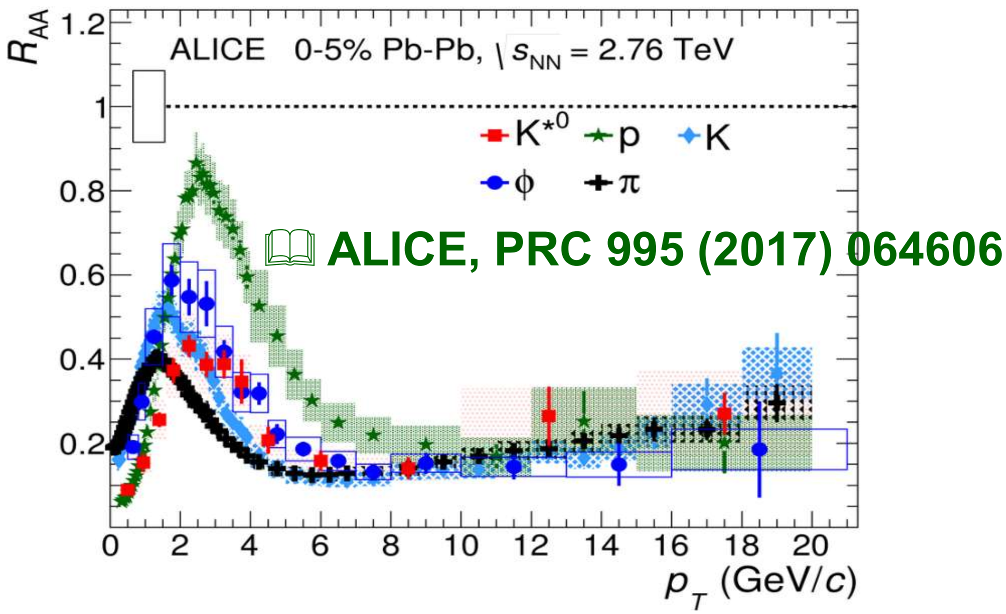
Hadron abundances

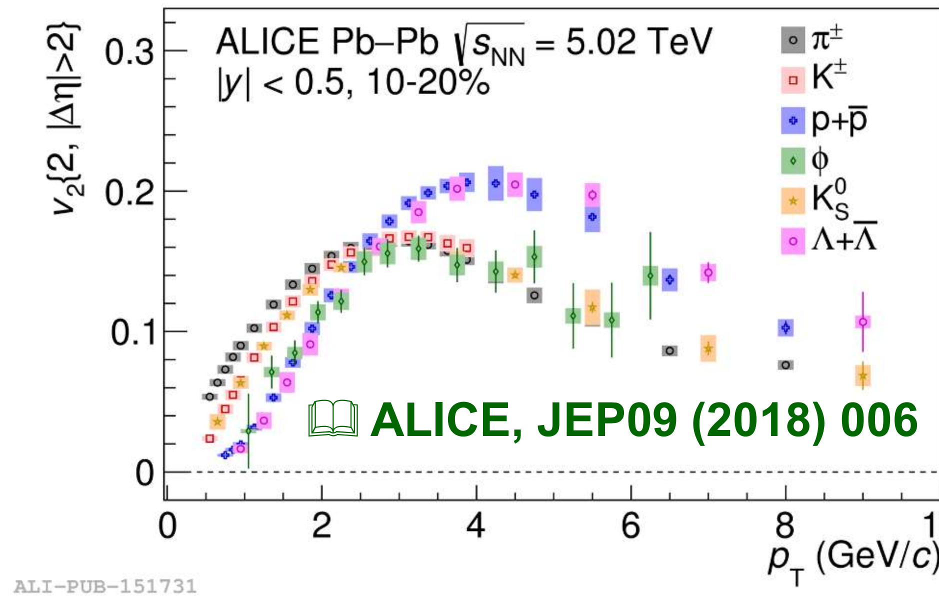
- Hadron yields (dominated by low-p_T particles) well described by statistical hadronization model
  - ⇨ Abundances follow expectations for hadron gas in chemical and thermal equilibrium
  - ⇨ Yields depend on hadron masses (and spins), chemical potentials and temperature



- Questions not addressed by the statistical hadronization approach:
  - ⇨ How the equilibrium is reached?
  - ⇨ How the transition from partons to hadrons occurs at the microscopic level?

Hadron R_{AA} and v_2 vs. p_T





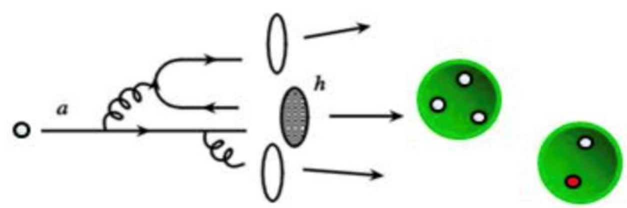
- Low p_T (<~2 GeV/c) :
  - ⇨ Thermal regime, hydrodynamic expansion driven by pressure gradients
  - ⇨ Mass ordering
- High p_T (>8-10 GeV/c):
  - ⇨ Partons from hard scatterings → lose energy while traversing the QGP
  - ⇨ Hadronisation via fragmentation → same R_{AA} and v_2 for all species
- Intermediate p_T:
  - ⇨ Kinetic regime, not described by hydro
  - ⇨ Baryon / meson grouping of v_2
  - ⇨ Different R_{AA} for different hadron species
    - ✓ ***Inconsistent with hard partons + energy loss + universal fragmentation***

Independent fragmentation

- Inclusive hadron production at large Q^2:
  - ⇨ Factorization of PDFs, partonic cross section (pQCD), fragmentation function

$$\sigma_{pp\to hx} = PDF(x_a, Q^2)PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z, Q^2)$$

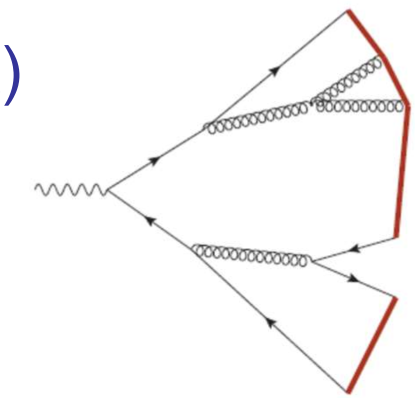
- Fragmentation functions $D_{q\to h}$ are phenomenological functions to parameterise the non-perturbative parton-to-hadron transition
  - ⇨ z = fraction of the parton momentum taken by the hadron h
  - ⇨ Do not specify the hadronisation mechanism
- Parametrised on data and assumed to be "universal"



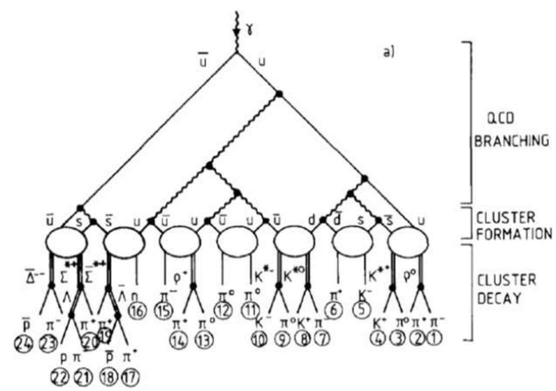
- In A-A collisions:
  - ⇨ Energy-loss of hard-scattered partons while traversing the QGP
  - ⇨ Modified fragmentation function $D_{q\to h}(z)$ by "rescaling" the variable z
    - ✓ ***Would affect all hadron species in the same way***

Hadronisation: string models

- On a microscopic level hadronisation of jets modeled with:
  - ⇨ Perturbative evolution of a **parton shower** with DGLAP down to a low-virtuality cut-off Q_0
  - ⇨ Final stage of parton shower interfaced to a non perturbative hadronization model
- **String fragmentation** (e.g. Lund model in PYTHIA)
  - ⇨ Strings = colour-flux tubes between q and $\bar{q}$ end-points
  - ⇨ Gluons represent kinks along the string
  - ⇨ Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs



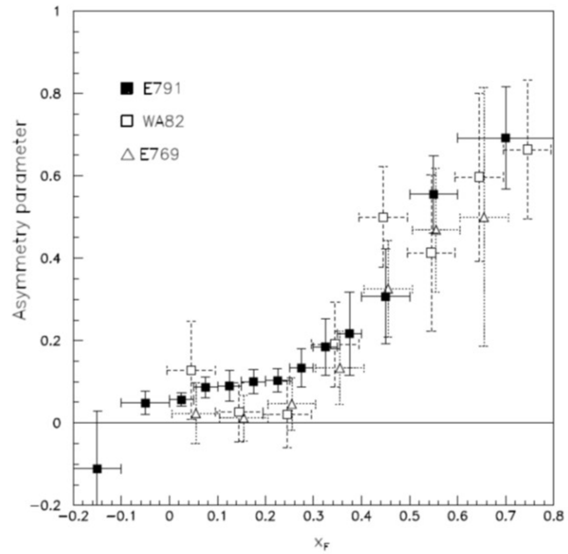
- **Cluster decay** in HERWIG
  - ⇨ Shower evolved up to a softer scale
  - ⇨ All gluons forced to split into $q\bar{q}$ pairs
  - ⇨ Identify colour-singlet clusters of partons following color flow
  - ⇨ Clusters decay into hadrons according to available phase space

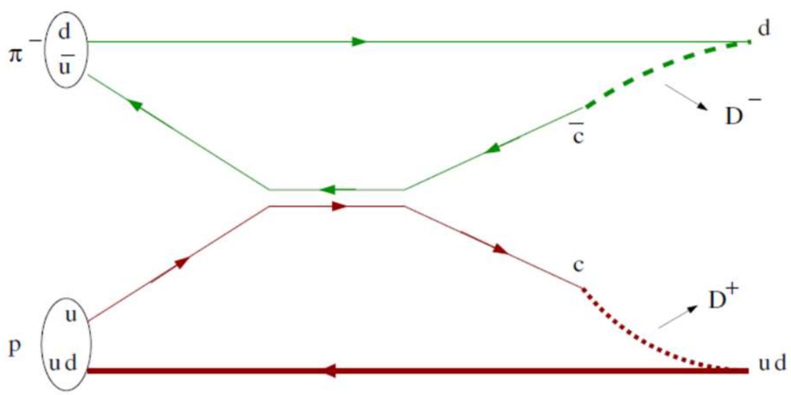


Leading particle effect

E791, PLB 371 (1996) 157

$$A(x_F) = \frac{\left(\frac{d\sigma}{dx_F}\right)^{D^-} - \left(\frac{d\sigma}{dx_F}\right)^{D^+}}{\left(\frac{d\sigma}{dx_F}\right)^{D^-} + \left(\frac{d\sigma}{dx_F}\right)^{D^+}}$$



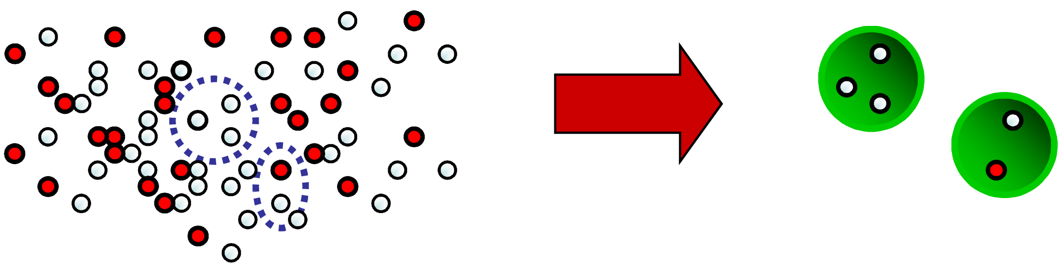


- Measurements of charm production in pion-nucleon collisions
- At **large x_F** : favoured production of hadrons sharing valence quarks with beam hadrons
  - ⇨ D^- ([$\bar{c}d$], leading meson shares the d quark with the π^- projectile) favored over D^+ [$c\bar{d}$]
  - ⇨ Break-up of independent fragmentation

→ A reservoir of particles leads to significant changes in hadronisation

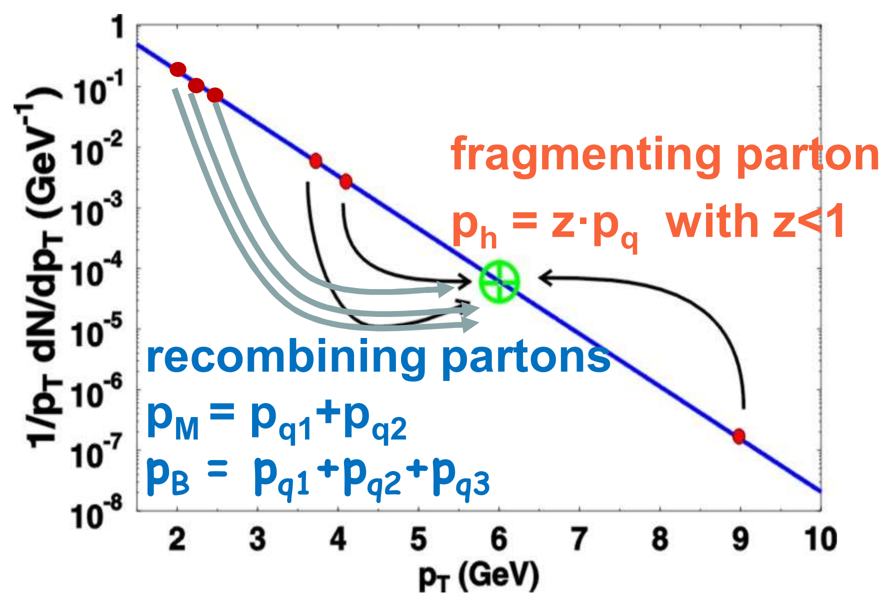
Hadronisation in medium

- Phase space at the hadronization is filled with partons
  - ⇨ Single parton description may not be valid anymore
  - ⇨ No need to create $q\bar{q}$ pairs via splitting / string breaking
  - ⇨ Partons that are "close" to each other in phase space (position and momentum) can simply **recombine** into hadrons



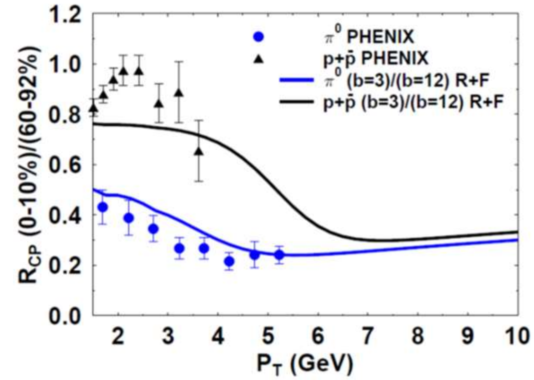
📖 Greco et al., PRL 90 (2003) 202302
📖 Fries et al., PRL 90 (2003) 202303
📖 Hwa, Yang, PRC 67 (2003) 034902

- Recombination vs. fragmentation:
  - ⇨ Competing mechanisms
  - ⇨ Recombination naturally enhances baryon/meson ratios at intermediate p_T



Coalescence/recombination

- 2003: hadronisation via **recombination** of quarks from a thermalized QGP provides a <u>simple explanation of unexpected features</u> of RHIC data:
  - Different R_{AA} of π and p
  - Apparent scaling of identified particle v_2 with number of constituent quarks



VOLUME 90, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 23 MAY 2003

Parton Coalescence and the Antiproton/Pion Anomaly at RHIC

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(Received 28 January 2003; published 22 May 2003)

Coalescence of minijet partons with partons from the quark-gluon plasma formed in relativistic heavy ion collisions is suggested as the mechanism for production of hadrons with intermediate transverse momentum. The resulting enhanced antiproton and pion yields at intermediate transverse momenta give a plausible explanation for the observed large antiproton to pion ratio. With further increasing momentum, the ratio is predicted to decrease and approach the small value given by independent fragmentations of minijet partons after their energy loss in the quark-gluon plasma.

DOI: 10.1103/PhysRevLett.90.202302 PACS numbers: 25.75.Dw, 12.38.Bx, 25.75.Nq

PHYSICAL REVIEW C **67**, 034902 (2003)

Scaling behavior at high p_T and the p/π ratio

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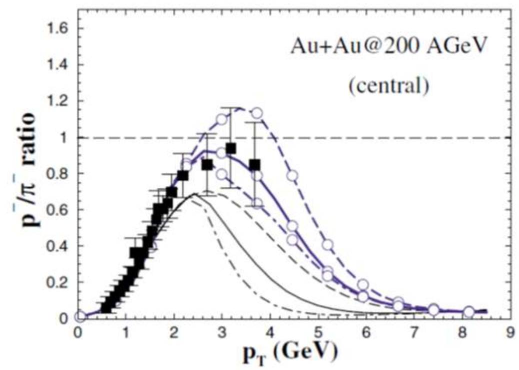
(Received 7 November 2002; published 10 March 2003)

We first show that the pions produced at high p_T in heavy-ion collisions over a wide range of high energies exhibit a scaling behavior when the distributions are plotted in terms of a scaling variable. We then use the recombination model to calculate the scaling quark distribution just before hadronization. From the quark distribution, it is then possible to calculate the proton distribution at high p_T, also in the framework of the recombination model. The resultant p/π ratio exceeds one in the intermediate-p_T region where data exist, but the scaling result for the proton distribution is not reliable unless p_T is high enough to be insensitive to the scale-breaking mass effects.

DOI: 10.1103/PhysRevC.67.034902 PACS number(s): 25.75.Dw, 24.85.+p



VOLUME 90, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 23 MAY 2003

Hadronization in Heavy-Ion Collisions: Recombination and Fragmentation of Partons

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(Received 28 January 2003; published 22 May 2003)

We argue that the emission of hadrons with transverse momentum up to about 5 GeV/c in central relativistic heavy ion collisions is dominated by recombination, rather than fragmentation of partons. This mechanism provides a natural explanation for the observed constant baryon-to-meson ratio of about one and the apparent lack of a nuclear suppression of the baryon yield in this momentum range. Fragmentation becomes dominant at higher transverse momentum, but the transition point is delayed by the energy loss of fast partons in dense matter.

DOI: 10.1103/PhysRevLett.90.202303 PACS numbers: 25.75.Dw, 24.85.+p

VOLUME 91, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2003

Elliptic Flow at Large Transverse Momenta from Quark Coalescence

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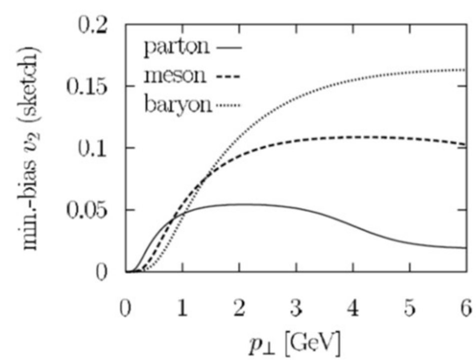
(Received 7 February 2003; published 27 August 2003)

We show that hadronization via quark coalescence enhances hadron elliptic flow at large $p_\perp$ relative to that of partons at the same transverse momentum. Therefore, compared to earlier results based on covariant parton transport theory, more moderate initial parton densities $dN/d\eta(b=0) \sim 1500$–3000 can explain the differential elliptic flow $v_2(p_\perp)$ data for Au + Au reactions at $\sqrt{s} = 130$ and $200A$ GeV from BNL RHIC. In addition, $v_2(p_\perp)$ could saturate at about 50% higher values for baryons than for mesons. If strange quarks have weaker flow than light quarks, hadron v_2 at high $p_\perp$ decreases with relative strangeness content.

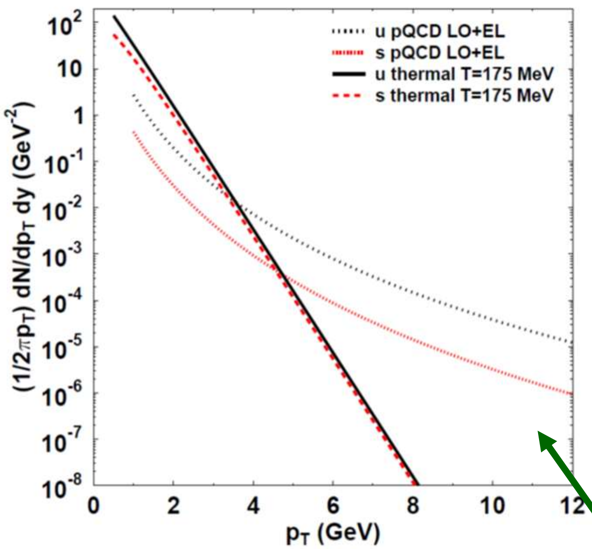
DOI: 10.1103/PhysRevLett.91.092301 PACS numbers: 12.38.Mh, 24.85.+p, 25.75.Ld



Hadronisation via quark coalescence

- **Instantaneous coalescence** approach:
  - ⇨ Formalism originally developed for light-nuclei production from coalescence of nucleons on a freeze-out hypersurface

    📖 **Scheibl and Heinz, PRC 59 (1999) 1585**
  - ⇨ Extended to describe meson and baryon formation from the quarks of a hadronising a QGP through 2→1 and 3→1 recombination processes



- Projection of parton states into hadron states:
  - ⇨ Phase space at hadronisation filled with partons
  - ⇨ Very rapid freeze-out → instantaneous recombination on infinitely thin hypersurface
  - ⇨ Quarks are dressed (constituent quarks)
  - ⇨ Gluons are split into quark-antiquark pairs (no dynamical gluons)
  - ⇨ Coalescence probability via Wigner function

parton distributions **Hadron Wigner function**

$$\frac{dN_{meson}}{dp_T} \propto \int f_q(x_q, p_q) f_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) f_W(x_a, x_{\bar{q}}; p_q, p_{\bar{q}})$$

Coalescence: "connections"

- Coalescence can occur not only for soft partons (thermal) but also for partons from mini-jets (parton showers)

  📖 **Greco et al., PRC68 (2003) 034904** 📖 **Hwa, Yang, PRC70 (2004) 024905**

  ⇨ Recombination with thermal+thermal and thermal+shower proposed to describe the species dependent Cronin enhancement in p-A

  📖 **Hwa, Yang, PRL93 (2004) 082302**

- Coalescence can be seen as a "dense" limit of hadronization, as opposed to single parton fragmentation

  ⇨ Points in common with **cluster hadronization** model of HERWIG

  ⇨ Hybrid approach using parton showers from pQCD jets + hadronisation with recombination of nearby quarks and string fragmentation provides hadron spectra compatible with PYTHIA

  📖 **Han, Fries, Ko, PRC 93 (2016) 045207**

- Coalescence and statistical hadronization model

  ⇨ The recombination mechanism connects a thermal parton phase with the observed thermal hadron phase

  ⇨ Recombination can be seen as the microscopic manifestation of statistical hadron production 📖 **Fries et al., PRC 68 (2003) 044902**

Energy conservation

- Only 3 components of 4-momentum conserved in the 2→1 and 3→1 instantaneous coalescence processes
  - ➪ Energy mismatch in the formation of the bound state should be balanced by the interactions with other particles of the medium
  - ➪ Small effect at intermediate p_T (>1.5 GeV/c) but relevant at low p_T
- Energy conservation can be obtained introducing finite width distributions of quark masses

📖 **Zimanyi et al, JPG31 (2005) 711**

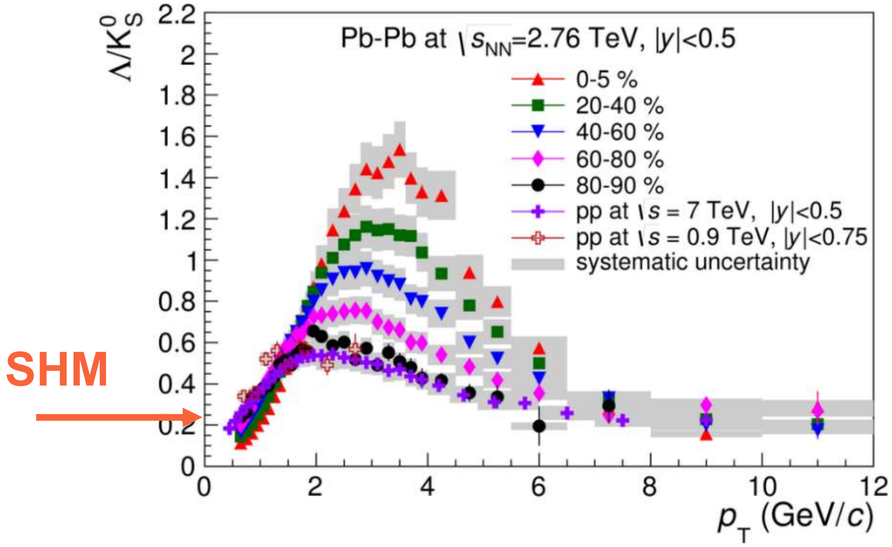
- **Resonance recombination model**
  - ➪ Alternative dynamical realization of the coalescence approach
  - ➪ Hadronization proceeds via formation of resonant states when approaching the (pseudo)critical temperature
    - ✓ ***Heavy-light quark interactions in the QGP mediated by broad bound states ($c\bar{q}$ and $s\bar{q}$) motivated by lattice QCD results***
    - ✓ ***Resonance formation/dissociation rate from Boltzmann equation***
  - ➪ Features:
    - ✓ ***Conserve energy in the hadron formation process***
    - ✓ ***Recover the equilibrium limit of hadron distributions***
    - ✓ ***Embody space-momentum correlations using quark phase-space distributions from transport calculations***

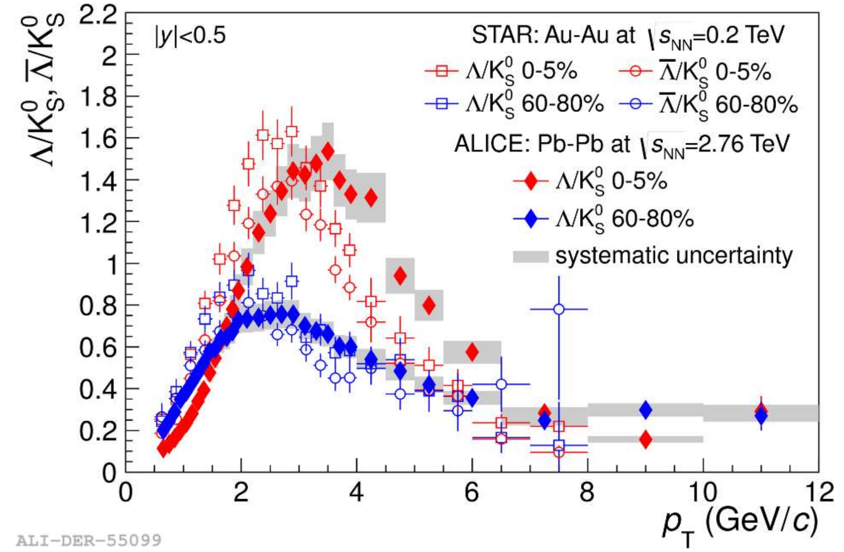
📖 **Ravagli, Rapp, PLB655 (2007) 126**

📖 **Ravagli et al. PRC79 (2009) 064902**

Particle ratios

Baryon/meson ratios

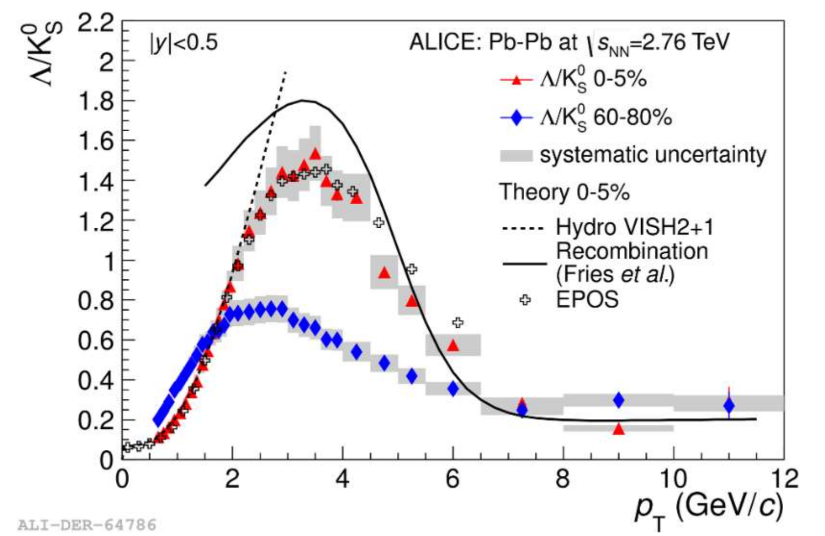




- Peak more pronounced and shifted to higher p_T with increasing centrality
- p_T integrated Λ/K^0 ratio does not change with centrality
- Peak position shifted to higher p_T with increasing $\sqrt{s_{NN}}$
- Hydrodynamics describes the data for p_T<2 GeV/c
- Recombination describes the shape at intermediate p_T

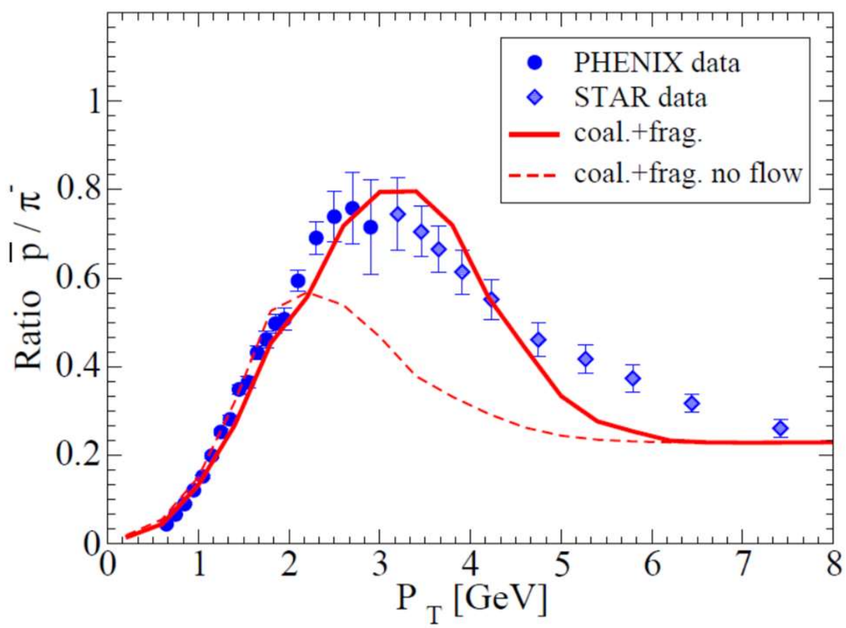
📖 **STAR, PRL 108 (2012) 072301**

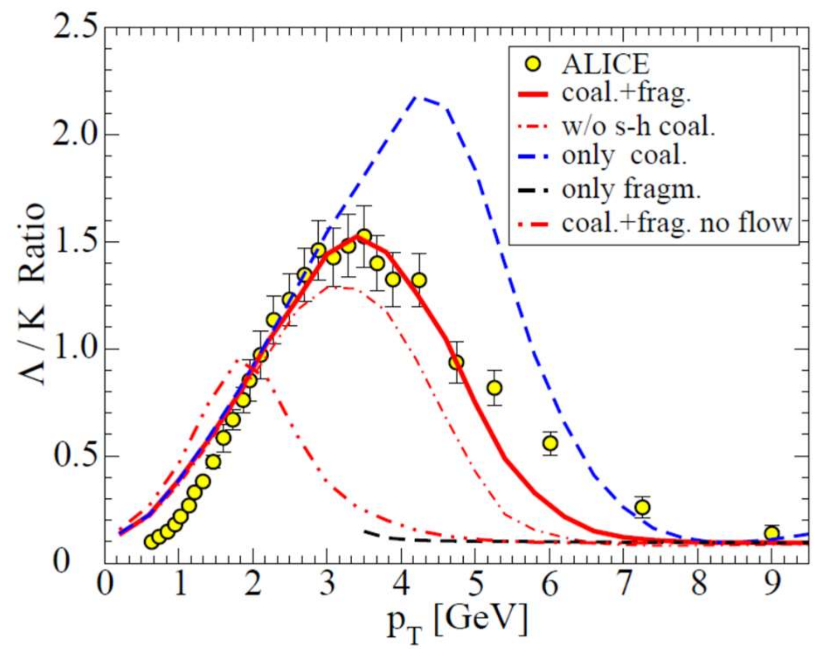
📖 **ALICE, PRL 111 (2013) 222301**



Baryon/meson ratios

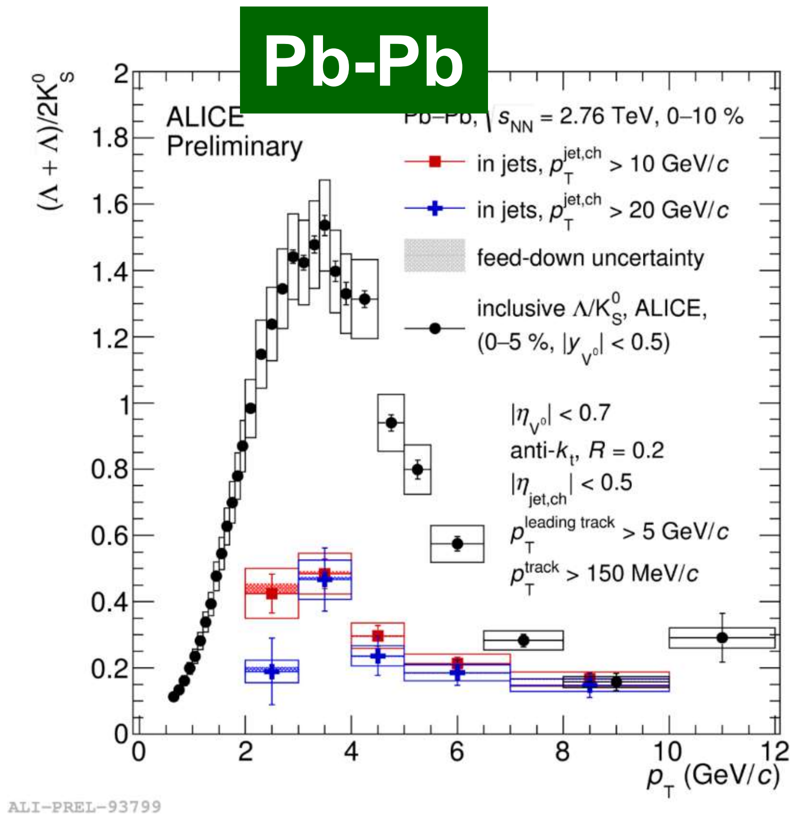
- Different modelling ingredients needed for a quantitative description of the data:
  - ➩ Coalescence (dominant at low p_T) + fragmentation (dominant at high p_T)
  - ➩ Radial flow of partons (from blast-wave)
  - ➩ Recombination of thermal soft partons with mini-jet partons
  - ➩ Contribution of resonance decays
- Still lack of baryon yield in the p_T region where fragmentation starts to be dominant

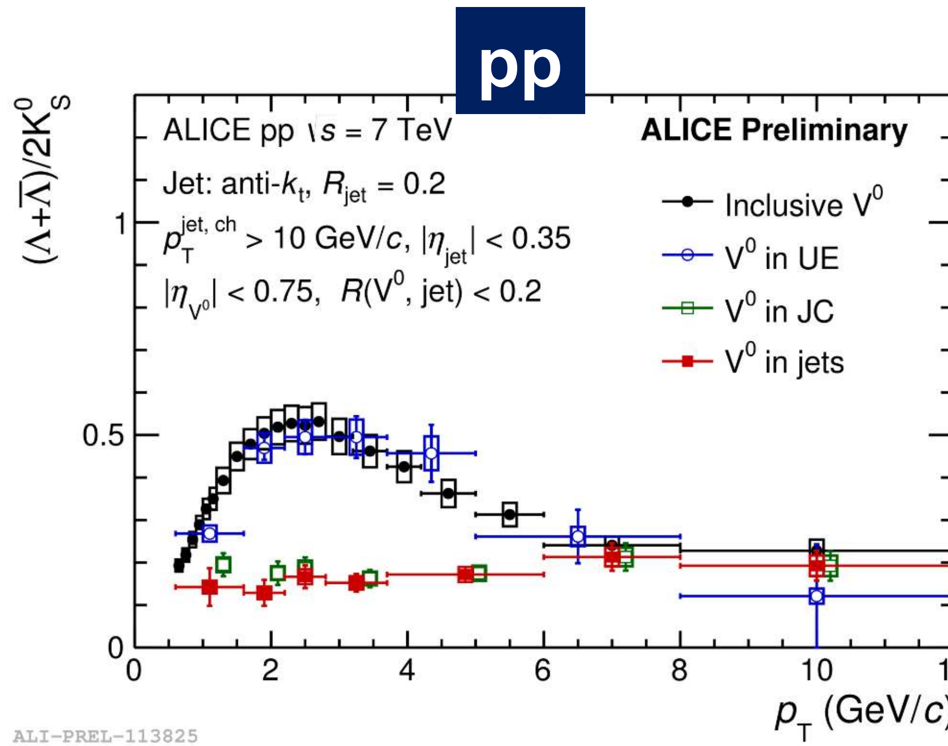




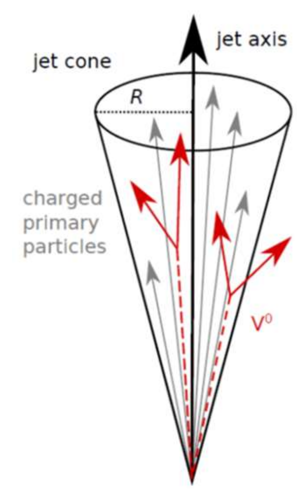
🕮 **Minissale et al., PRC92 (2015) 054904**

Λ/K^0 in jets and bulk





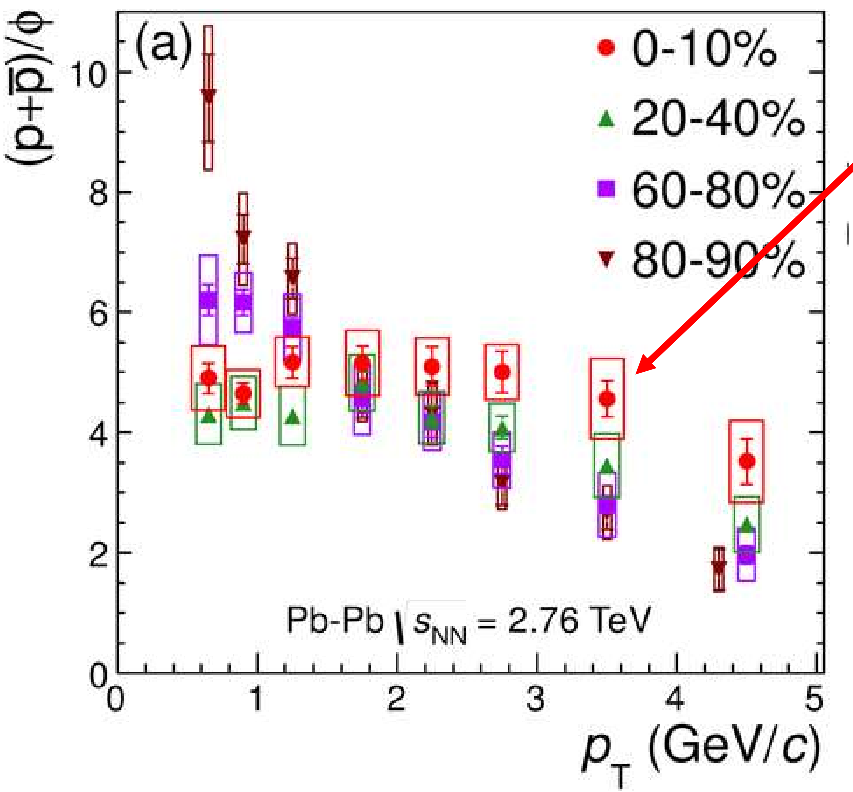
- Baryon/meson ratios different in-jet and out-of-jet
  - ⇨ Baryon enhancement mostly from the bulk
    - ✓ ***Connected to collective expansion and hadronisation of bulk***
  - ⇨ Ratio of Λ/K^0 in-jet is similar in pp and Pb-Pb
    - ✓ ***Fragmentation of the jet not modified by the medium***



Proton/Φ ratio at low p_T

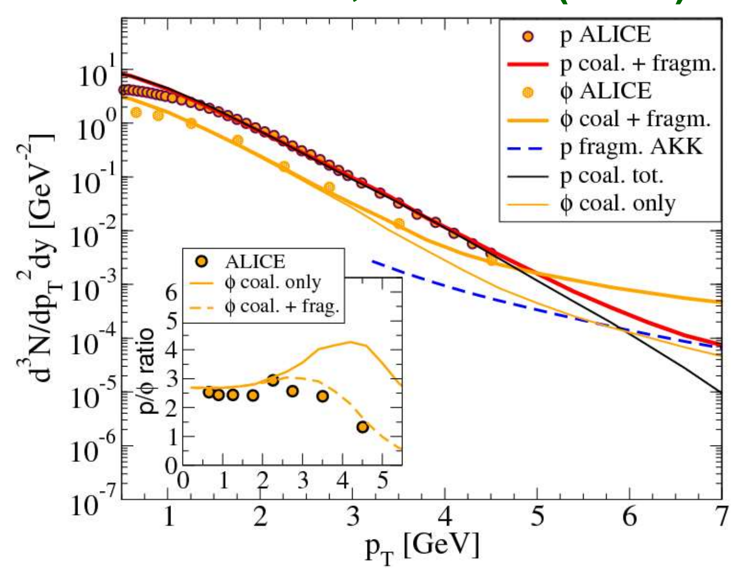
- Proton and Φ: similar mass and different quark content

📖 **ALICE, PRC 91 (2015) 024609**



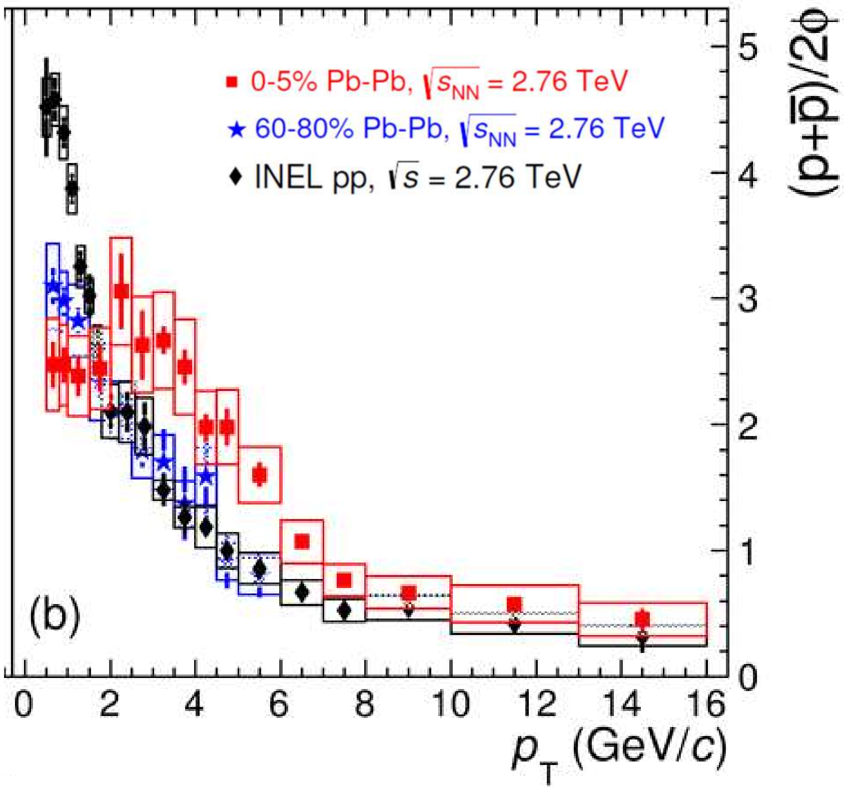
- Flat p/ Φ ratio for **central collisions** and p_T<5 GeV/c
  - ⇨ Shape of p_T distribution determined by particle mass, as in hydrodynamics
  - ⇨ Flat p/Φ ratio at low p_T also in models with hadronization via recombination

📖 **Minissale et al., PRC 92 (2015) 054904**



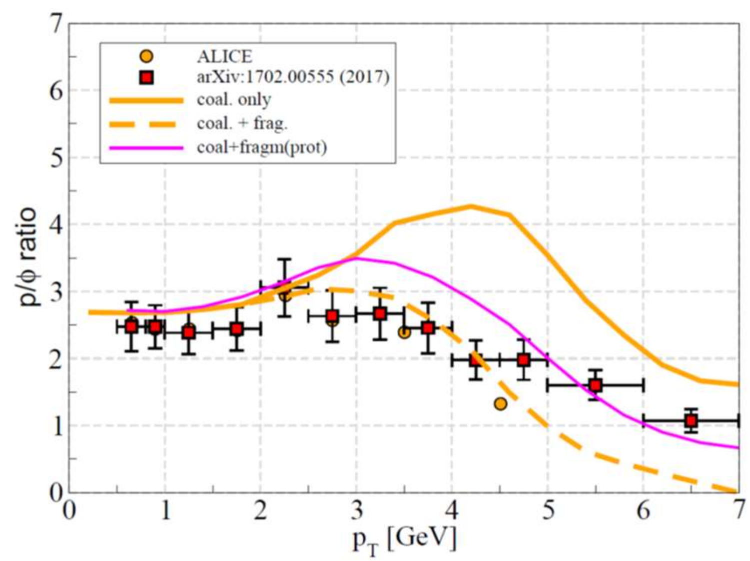
Proton/Φ ratio up to higher p_T

📖 ALICE, PRC 995 (2017) 064606



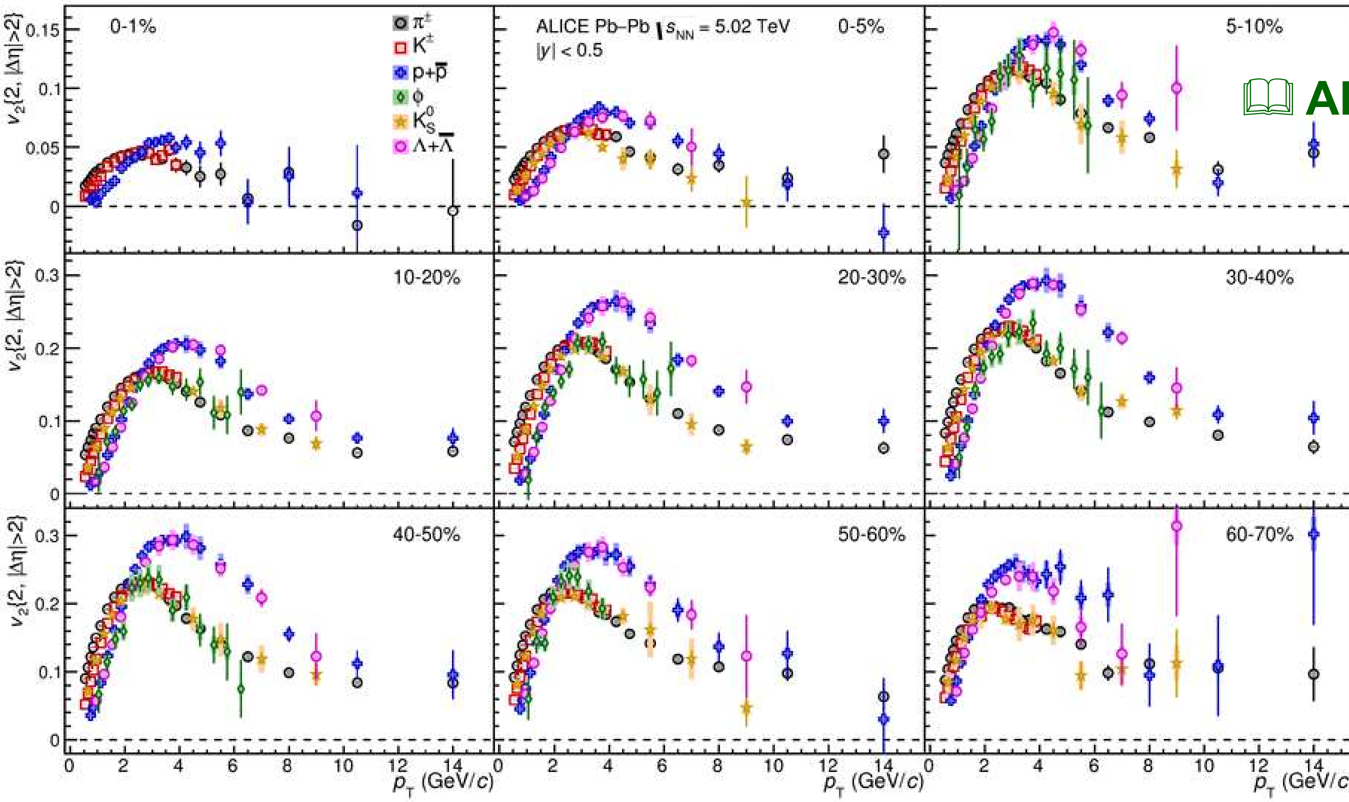
- Change of p and Φ p_T shapes from pp to peripheral and central Pb-Pb
- At high p_T (>6-7 GeV/c) :
  - ⇨ p/Φ ratio drops and becomes compatible with that in pp
    - ✓ ***Indication for parton fragmentation in vacuum for p_T>8-10 GeV/c***
  - ⇨ Captured by recombination model

📖 Minissale et al., PRC 92 (2015) 054904



Elliptic flow

Identified hadron v_2

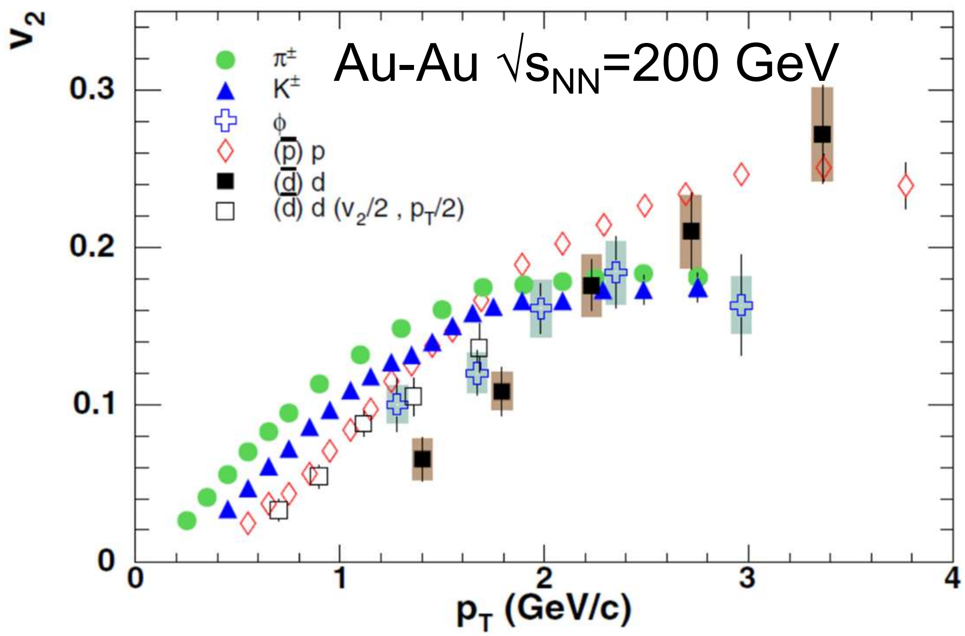


ALICE, JEP09 (2018) 006

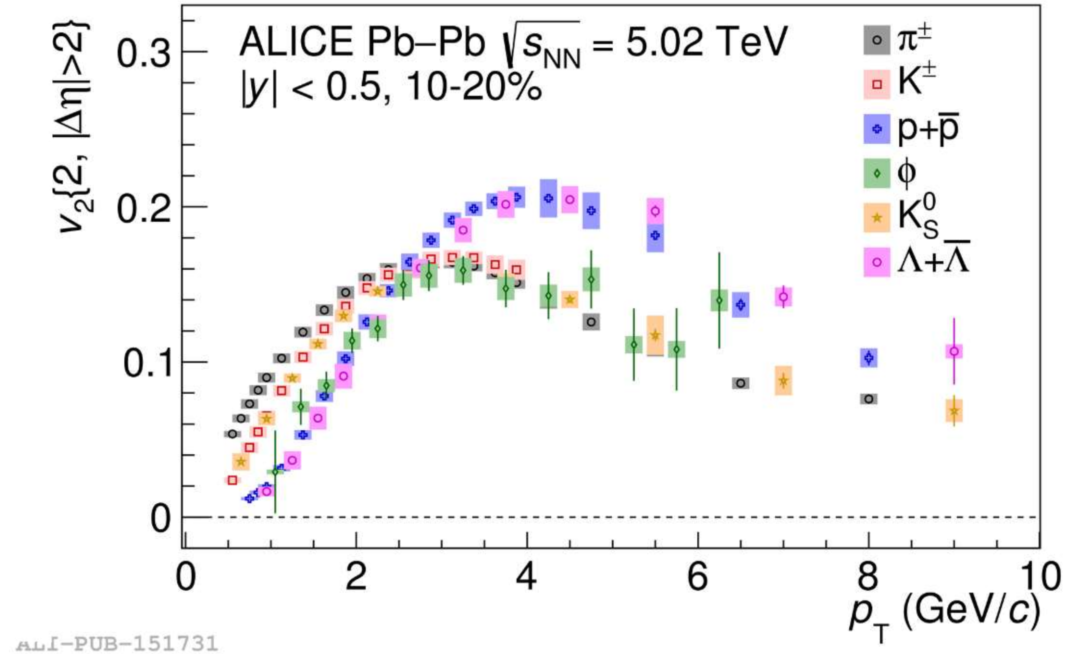
- Mass ordering for p_T<2-3 GeV/c as predicted by hydrodynamics
  - ⇨ Interplay between radial and anisotropic flow
- Grouping by number of constituent quarks for 3<p_T<8 GeV/c
  - ⇨ Supports hypothesis of particle production via coalescence
- Pion and proton v_2 are compatible for p_T>10 GeV/c
  - ⇨ Path length dependent energy low + independent fragmentation

Φ meson v_2

📖 **PHENIX, PRL99 (2007) 052301**



📖 **ALICE, JEP09 (2018) 006**



- Φ meson v_2: further test of mass ordering and particle type scaling
  - ⇨ Φ meson v_2 follows proton v_2 (similar **mass**) at **low p_T** and meson v_2 (same number of **constituent quarks**) at **higher p_T**
  - ⇨ Trend at intermediate p_T as expected from coalescence

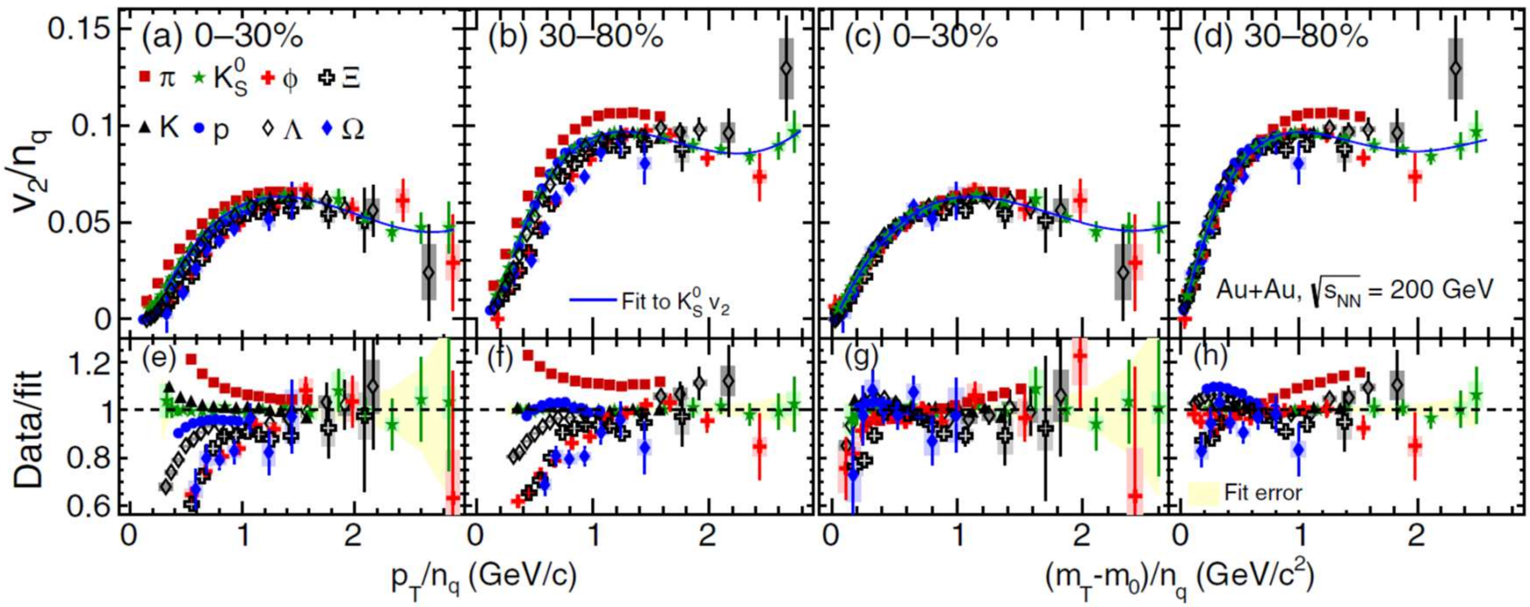
Constituent quark scaling of v_2?

- Expectation from naïve quark coalescence model with collinear momenta of the coalescing quarks:

$$v_{2,M}(p_T) \approx 2v_{2,q}\left(\frac{p_T}{2}\right) \qquad v_{2,B}(p_T) \approx 3v_{2,q}\left(\frac{p_T}{3}\right)$$

- Deviations expected due to:
  - ⇨ Resonance decays
    - ✓ ***Affect mostly pions*** 📖 **Greco, Ko, PRC 70 (2004) 024901**
  - ⇨ Quark momentum distributions in hadrons
    - ✓ ***Makes it possible for quarks with different momenta to coalesce***
  - ⇨ Hadronic binding energy
  - ⇨ Interactions in the hadronic phase
  - ⇨ Space-momentum correlations
  - ⇨ Baryon number transport 📖 **Dunlop et al., PRC 84 (2011) 044914**
    - ✓ ***Relevant for $\sqrt{s_{NN}}$ lower than RHIC top energy***
  - ⇨ High phase space density of quarks
    - ✓ ***Relevant at LHC energies?*** 📖 **Singha, Nasim, PRC 93 (2016) 034908**

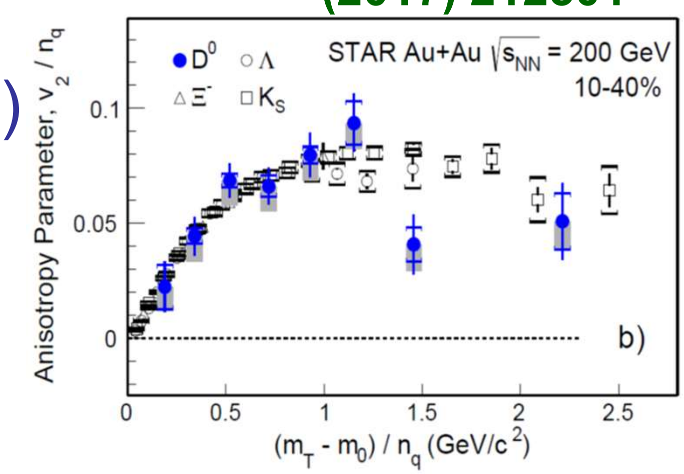
Constituent quark scaling at RHIC



📖 STAR, PRL116 (2016) 062301

📖 STAR, PRL118 (2017) 212301

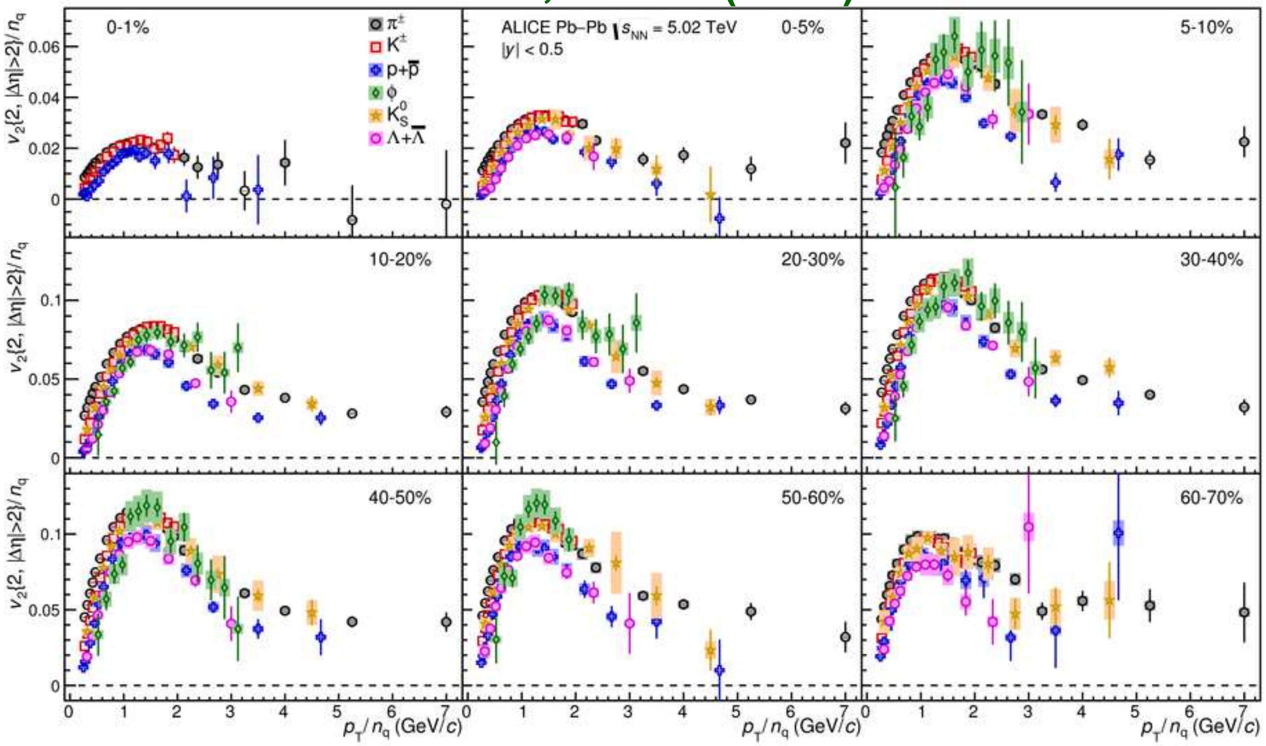
- Scaling of v_2 with number of constituent holds within ±10% (including charm mesons)
  - ⇨ Suggestive of thermalized medium with **partonic degrees of freedom**
- Scaling vs. KE_T/n_q better than vs. p_T/n_q
  - ⇨ Described in resonance recombination model



📖 Ravagli. Rapp, PLB655 (2007) 126

Constituent quark scaling at LHC

📖 **ALICE, JEP09 (2018) 006**



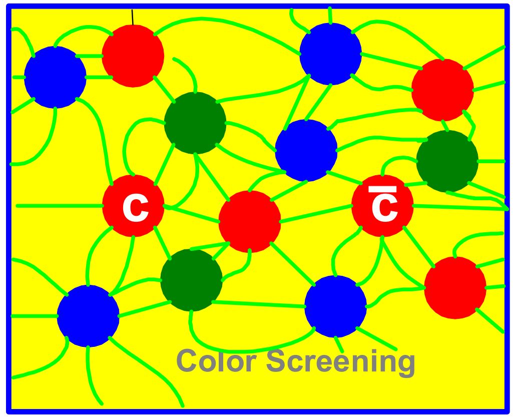
- Violation from the exact scaling by ±20% at LHC energies
  - ➩ Larger deviations w.r.t. RHIC energies
- Deviations from naïve scaling were in any case expected
  - ➩ Not a "stand-alone" signature for hadronization via recombination

Heavy flavours

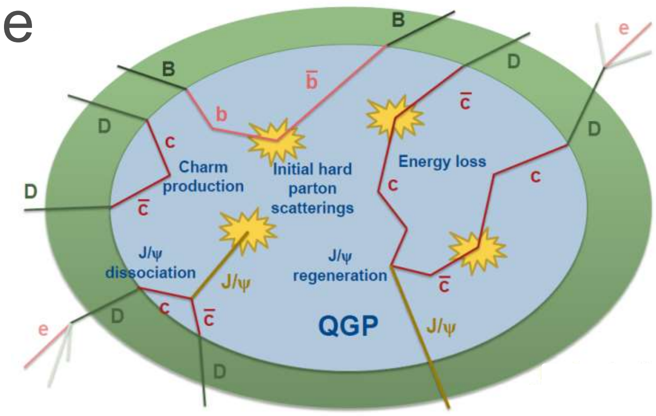
Quarkonia

- Quarkonium production in A-A collisions:
  - ⇨ Quarkonium **dissociation** in the QGP due to colour screening of the $q\bar{q}$ potential
    - ✓ ***Different quarkonium states melt at different temperatures, depending on their binding energy → sequential suppression***

📖 **Matsui, Satz, PLB178 (1986) 416**
📖 **Digal et al., PRD64 (2001) 094015**

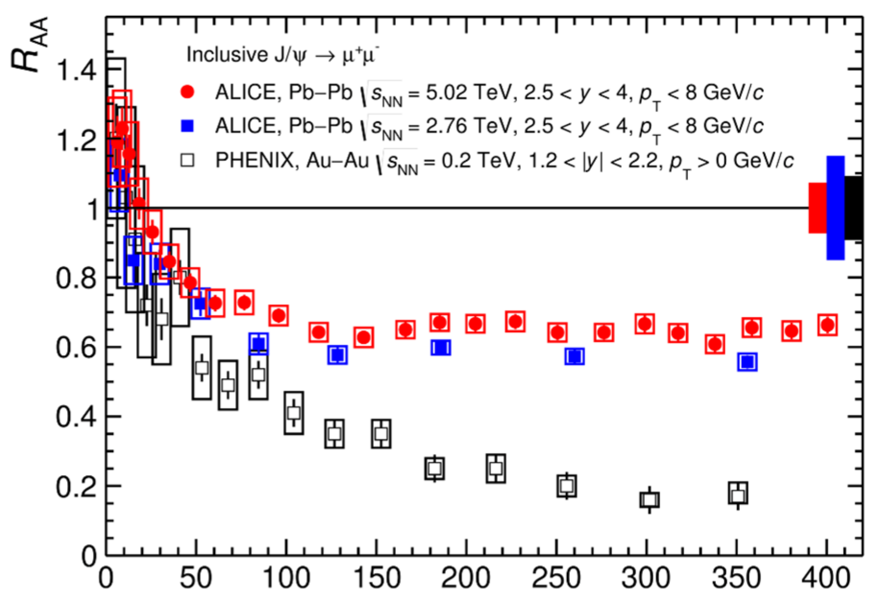


  - ⇨ Quarkonium production can occur also via **quark (re)combination / regeneration** in the QGP or at the phase boundary
    - ✓ ***Charm and beauty production cross section increase with √s → higher recombination contribution with increasing √s***
    - ✓ ***Smaller recombination contribution for bottomomium than for charmonium***



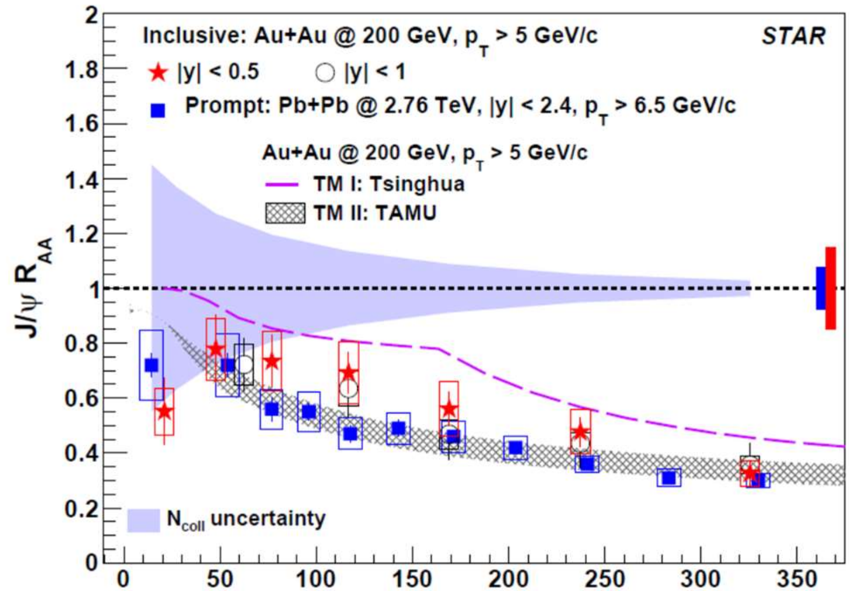
📖 **Braun-Munzinger, Stachel, PLB 490 (2000) 196**
📖 **Thews et al., PRC 63 (2001) 054905**

J/ψ R_{AA} vs. $\sqrt{s_{NN}}$



📖 **ALICE, PLB766 (2017) 212**

📖 **PHENIX, PRC84 (2011) 05912**



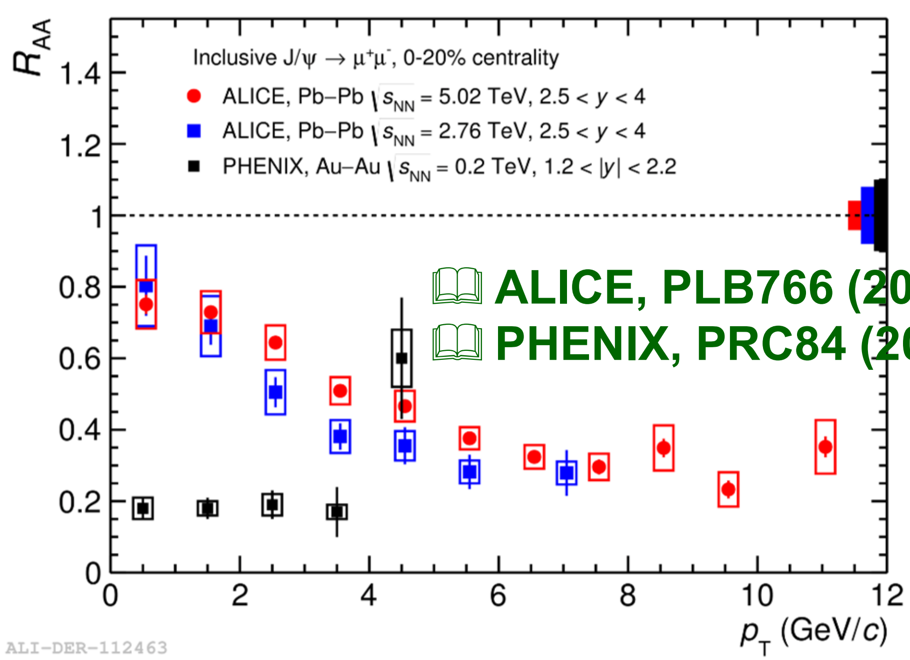
📖 **STAR, arXiv:1905.13669**

📖 **CMS, EPJ C77 (2017) 252**

- Low p_T
  - ⇨ **Less suppression at LHC** ($\sqrt{s}$=**2.76**, **5.02** TeV) than at RHIC ($\sqrt{s}$=**200** GeV)
  - ⇨ Larger charm cross section with increasing √s → larger regeneration contribution
- High p_T
  - ⇨ **Hint for more suppression at LHC** ($\sqrt{s}$=**2.76** TeV) than at RHIC ($\sqrt{s}$=**200** GeV)
  - ⇨ Higher temperature reached at higher √s → larger dissociation rate

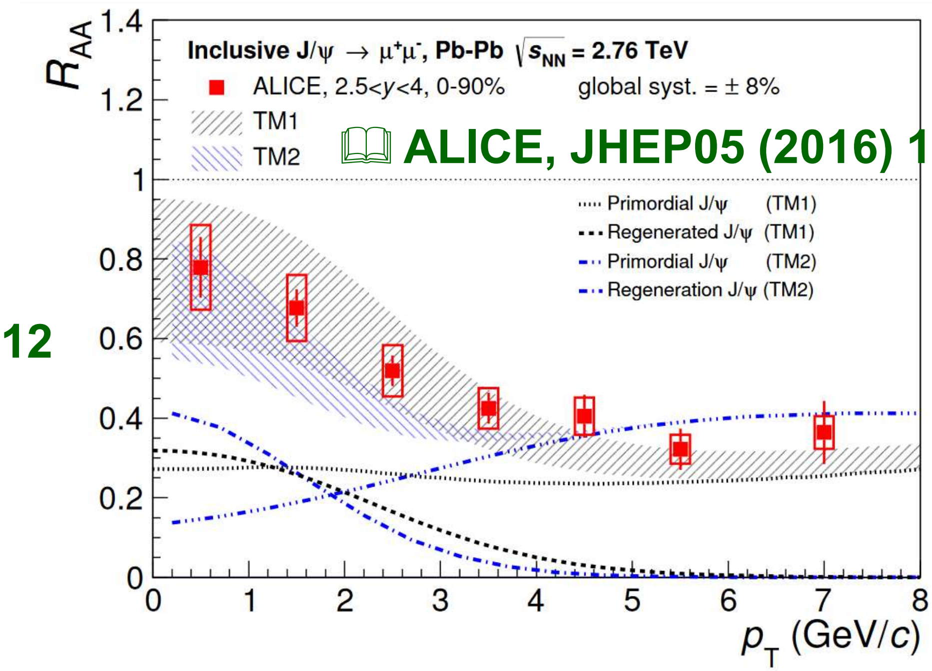
→ as expected in a scenario with dissociation + $c\bar{c}$ recombination

J/ψ R_{AA} vs. p_T



📖 **ALICE, PLB766 (2017) 212**

📖 **PHENIX, PRC84 (2011) 05912**



📖 **ALICE, JHEP05 (2016) 179**

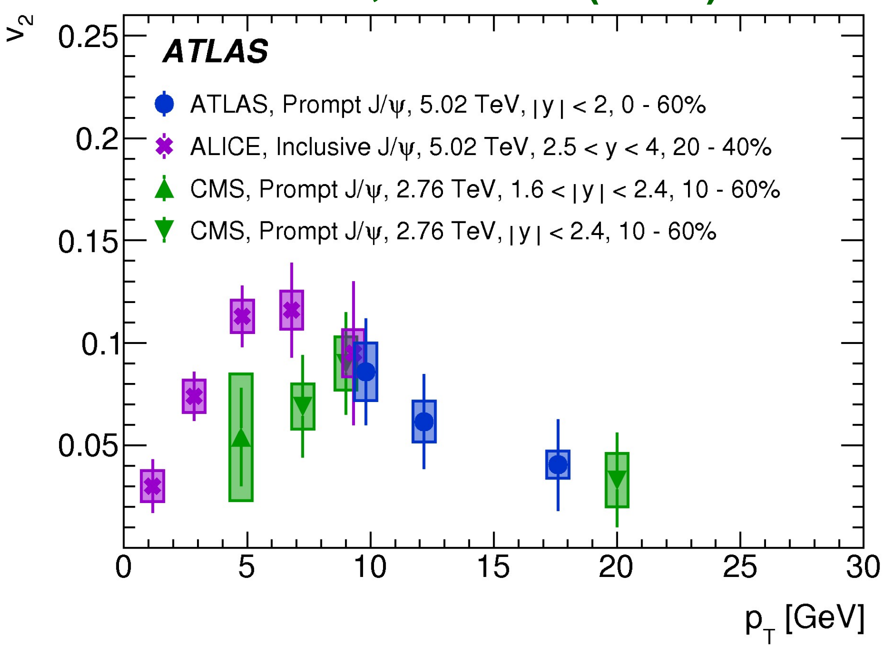
- p_T differential J/ψ R_{AA}
  - ➪ **Less suppression at low p_T** than at high p_T
  - ➪ Different p_T dependence of J/ψ R_{AA} at RHIC and LHC
- Described by transport models with dissociation and recombination
  - ➪ About 50% of low p_T J/ψ from recombination
  - ➪ Recombination negligible at high p_T

📖 **TM1: Zhao, Rapp, NPA859 (2011) 114**

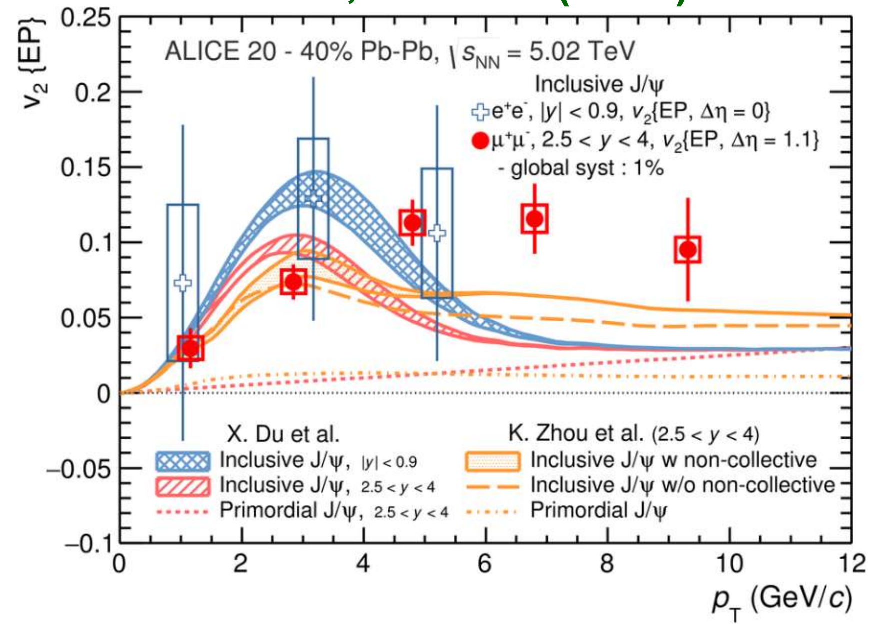
📖 **TM2: Zhou et al., PRC89 (2014) 054911**

J/ψ v_2

📖 ATLAS, EPJC78 (2018) 784



📖 ALICE, PRL119 (2017) 242301

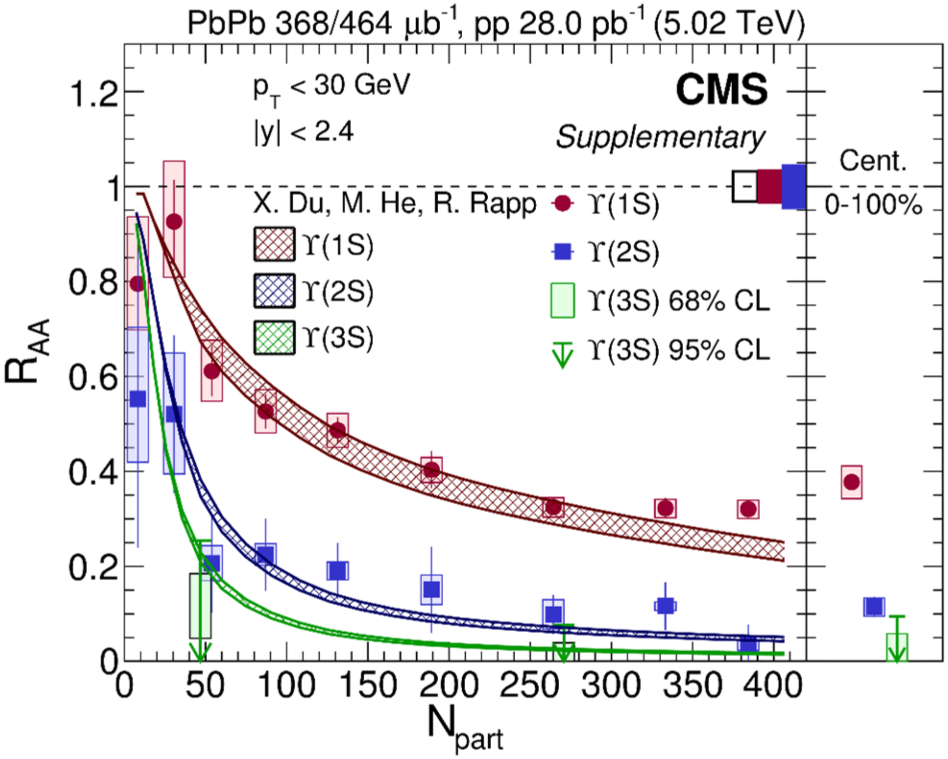


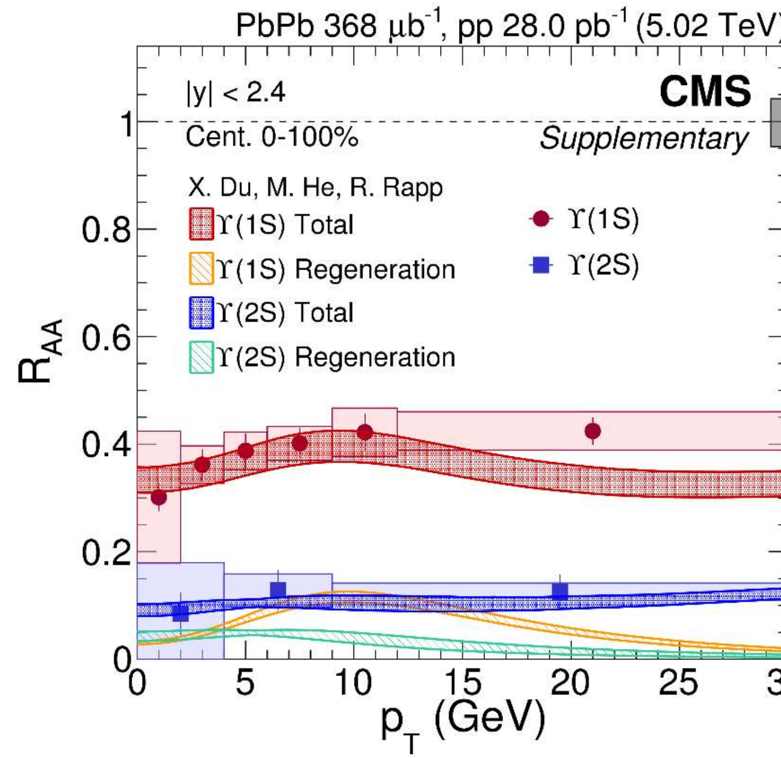
- Significant J/ψ elliptic flow observed at the LHC
  - ⇨ Confirms the contribution of J/ψ production from recombination
- J/ψ v_2 at intermediate p_T (>6 GeV/c) not described by transport models
  - ⇨ J/ψ v_2 of similar magnitude in this p_T range observed in p-Pb colllisions
  - ⇨ Same (unknown) origin?

📖 Du, Rapp NPA943 (2015) 147

📖 Zhou et al., PRC89 (2014) 054911

Bottomonium R_{AA}



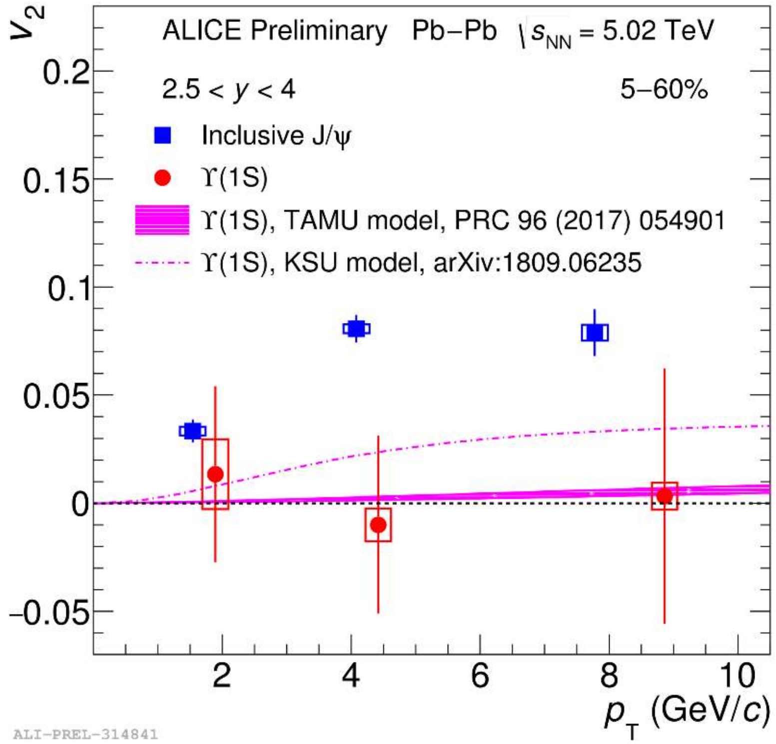


- Sequential suppression pattern: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
  - ⇨ Ordered by binding energy, as expected from dissociation in QGP
- Described by transport models
  - ⇨ Small contribution from $b\bar{b}$ recombination
  - ⇨ Presence of open-bottom bound states when approaching the (pseudo)critical temperature allow for a better description of the data

📖 **CMS, PLB790 (2019) 270**

📖 **Du et al., PRC96 (2017) 054901**

Υ not flowing



- Elliptic flow of Υ compatible with zero
  - ⇨ Smaller than J/ψ v_2
- A small v_2 was predicted by transport model simulations
  - ⇨ Small contribution from $b\bar{b}$ recombination
  - ⇨ Longer relaxation times for b quarks as compared to charm quarks
  - ⇨ Regeneration occurs at earlier times for bottomonium than for charmonium

📖 **Du et al., PRC96 (2017) 054901**

Open HF hadrons

Hadronization of heavy quarks via recombination with light quarks from the medium expected to modify:

- **Momentum distributions**
  - ⇨ HF hadrons pick-up the radial and elliptic flow of the light quark
  - ⇨ In simple quark coalescence formalism: quarks with different mass coalesce if have similar **velocities**, not momenta

    📖 **Lin, Molnar, PRC 68 (2003) 044901**
    📖 **Greco, Ko, Rapp, PLB 595 (2004) 202**

- **Relative abundances** of meson and baryon species
  - ⇨ Enhanced production of **baryons** relative to mesons
    - ✓ ***Sensitive also to the existence of [ud] diquarks in the QGP***

      📖 **Oh et al., PRC79 (2009) 044905**
      📖 **Ghosh at al., PRD 90 (2014) 054018**
      📖 **He, Rapp et al. arXiv:1905.9216**

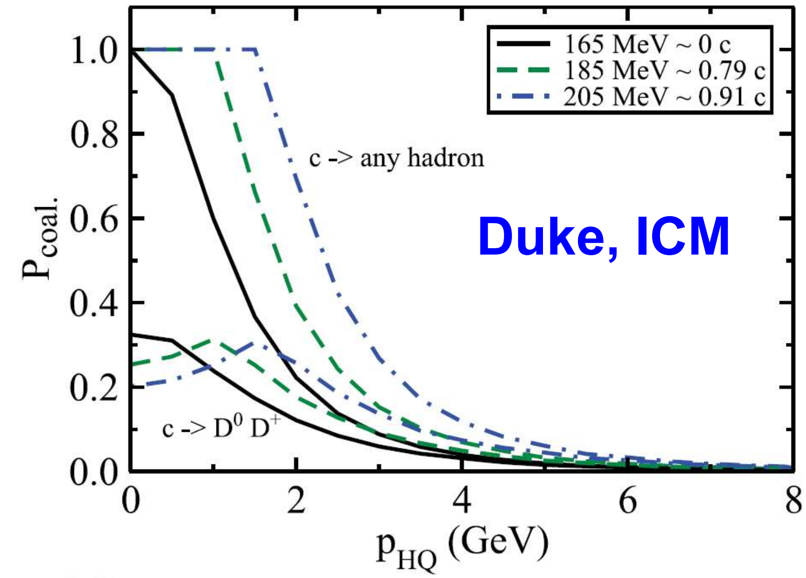
  - ⇨ **Strange** quarks abundant in the QGP → enhance D_s (B_s) yield relative to non-strange mesons

    📖 **Kuznetsova, Rafelski, EPJ C51 (2007) 113**
    📖 **Andronic et al., PLB659 (2008) 149**

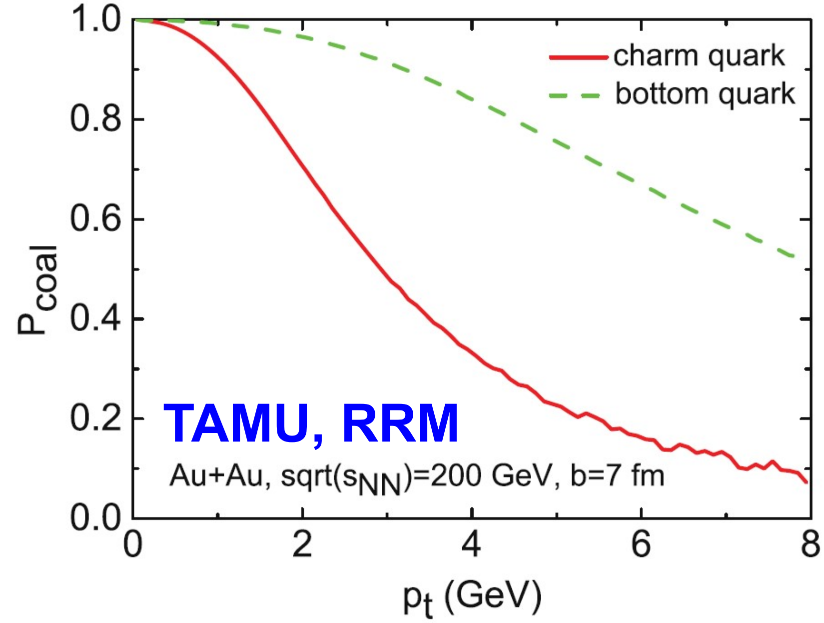
Hadronization in HF transport models

- Recombination + fragmentation
- Different recombination approaches:
  - Instantaneous coalescence used in most models (PHSD, Duke, Catania …)
  - Resonance Recombination Model in TAMU
  - String formation between heavy quark and a thermal light quark from the bulk in POWLANG

📖 **Beraudo et al., EPJ C75 (2015) 121**

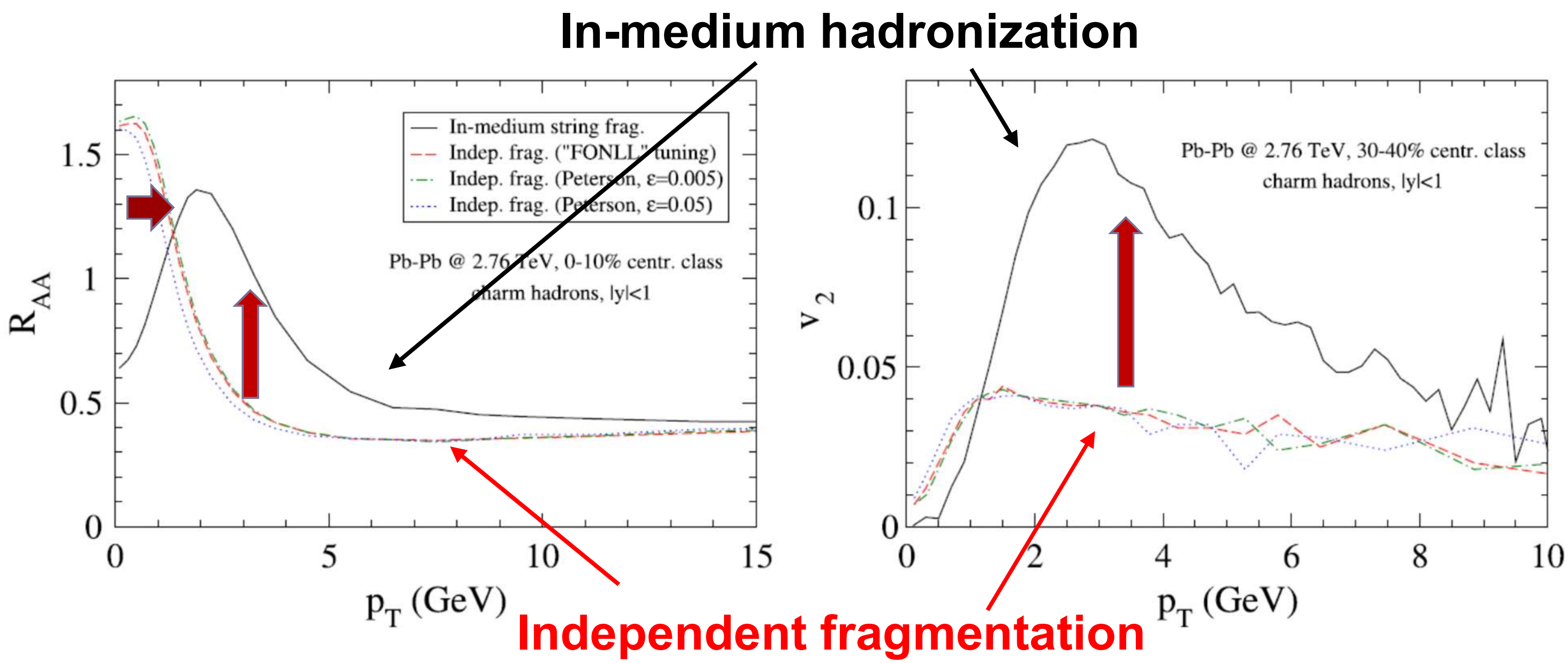


- Recombination for heavy flavours relevant up to higher momenta than for light flavours
  - At comparable momenta, the velocity of heavy quarks is smaller than that of light quarks, thus facilitating recombination with comoving thermal partons
- Recombination for beauty extends up to higher p_T with respect to charm



Charm R_{AA} and v_2 phenomenology

- Heavy-quark hadronization mechanism is an important ingredient to the phenomenology of heavy flavour R_{AA} and v_2
- Recombination with light quarks enhances R_{AA} and v_2 at intermediate p_T 🕮 **Van Hees et al., PRC73 (2006) 034907**
  - ⇨ Needed to describe the data at low and intermediate p_T
  - ⇨ D-meson v_2 and radial flow peak in R_{AA}



🕮 **Rapp et al., NPA 979 (2018) 21**

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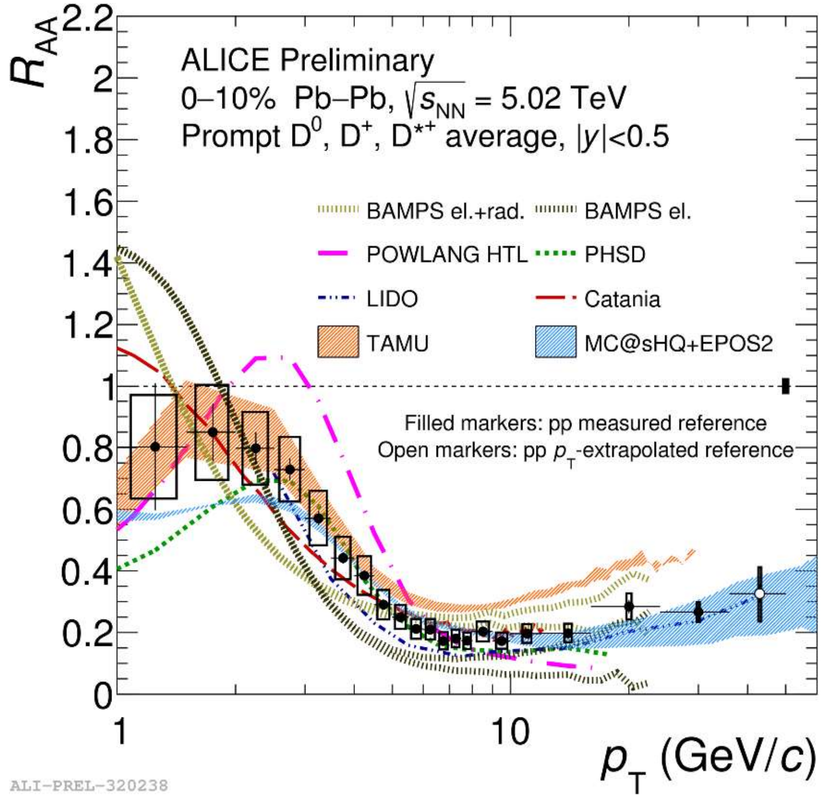
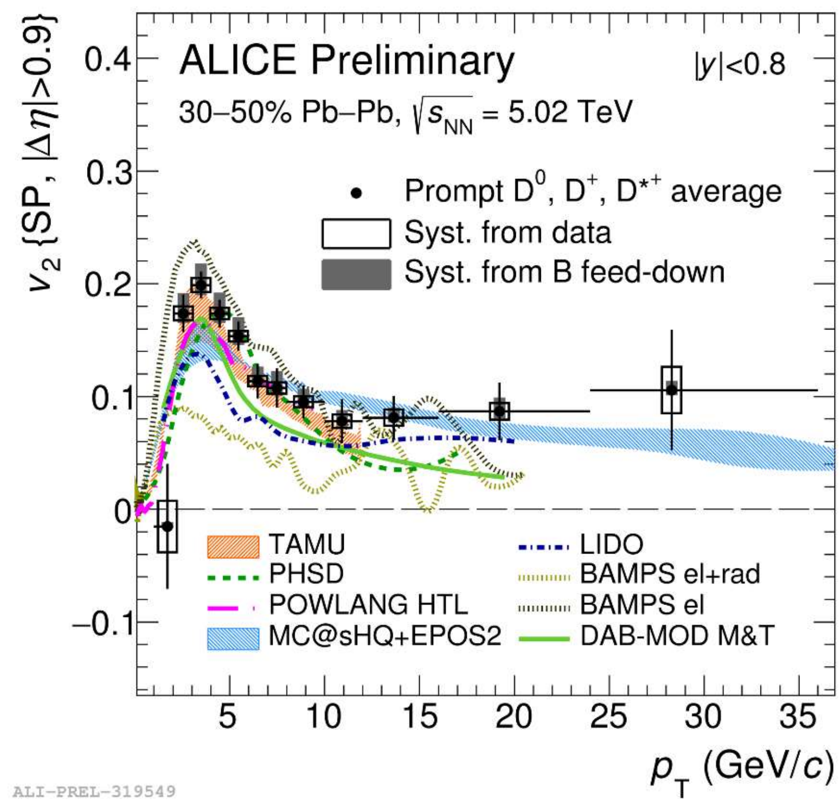
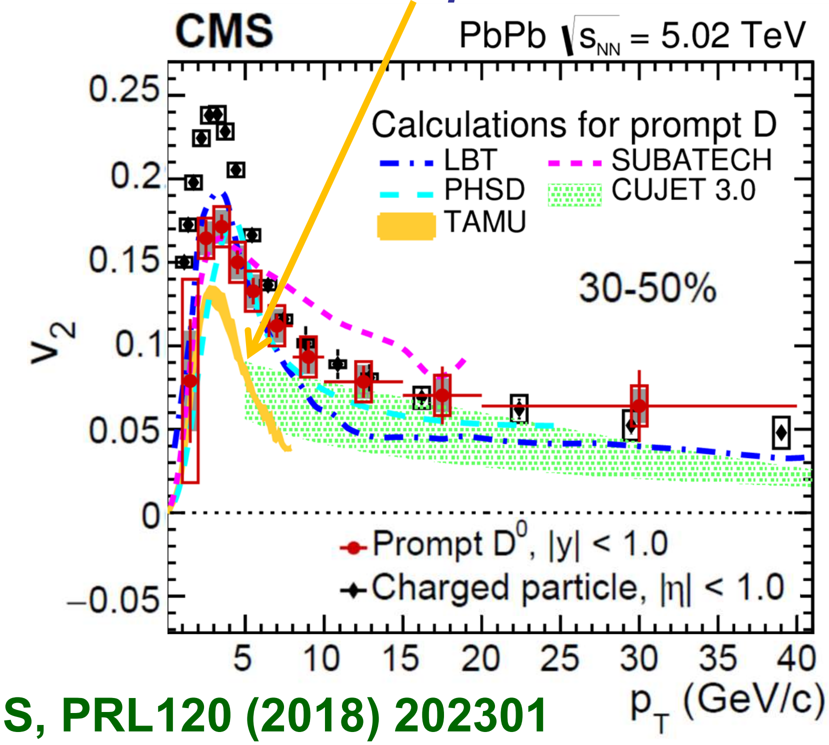


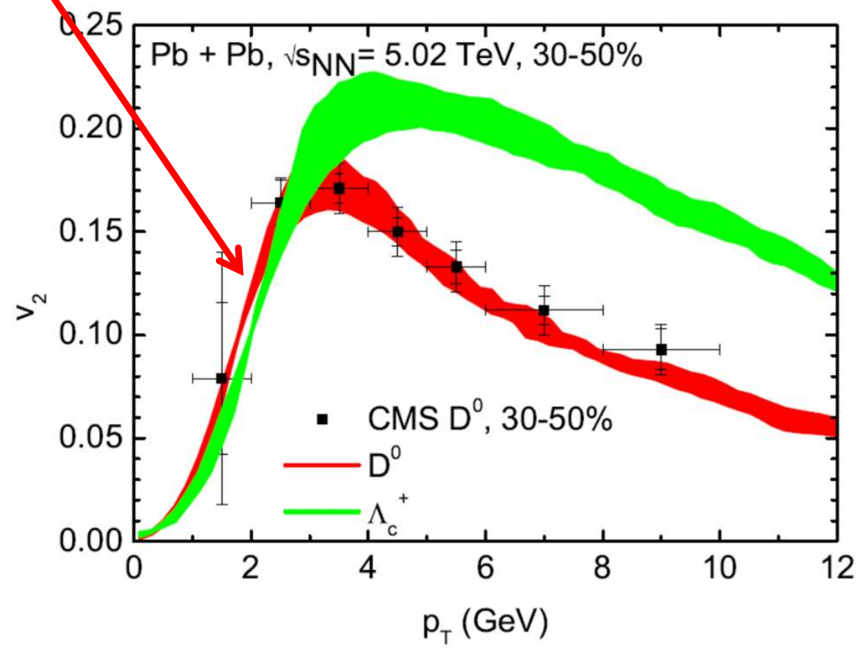


Charm R_{AA} and v_2 phenomenology

- Heavy-quark hadronization mechanism is an important ingredient to the phenomenology of heavy flavour R_{AA} and v_2
- Different aspects of the hadronization modelling have significant impact on the results
  - ⇨ E.g. Improved space-momentum correlations between c quarks and underlying hydro medium in latest TAMU calculations
    - ✓ ***Larger reach in p_T of the recombination contribution***
    - ✓ ***Better description of the measured D-meson v_2 up to higher p_T***

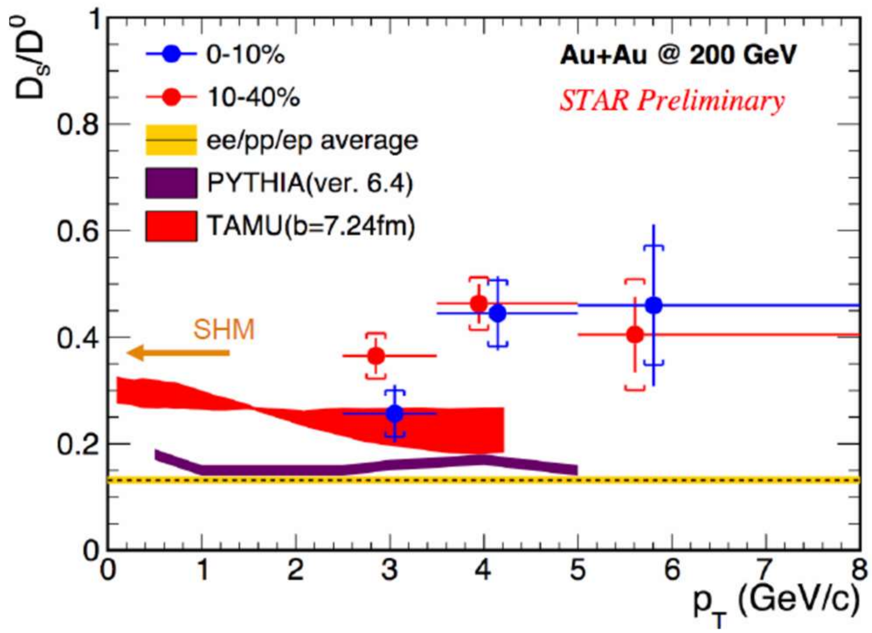


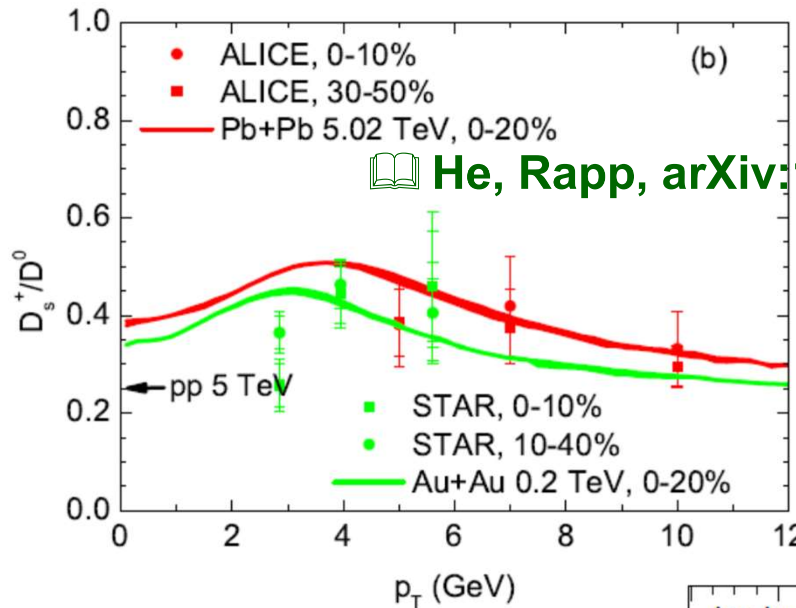
📖 **CMS, PRL120 (2018) 202301**



📖 **He, Rapp, arXiv:1905.09216**

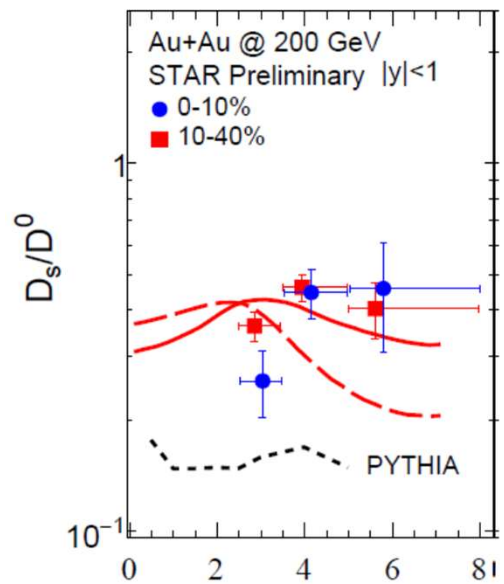
Charm-chemistry: D_s/D^0 at RHIC





📖 He, Rapp, arXiv:1905.09216

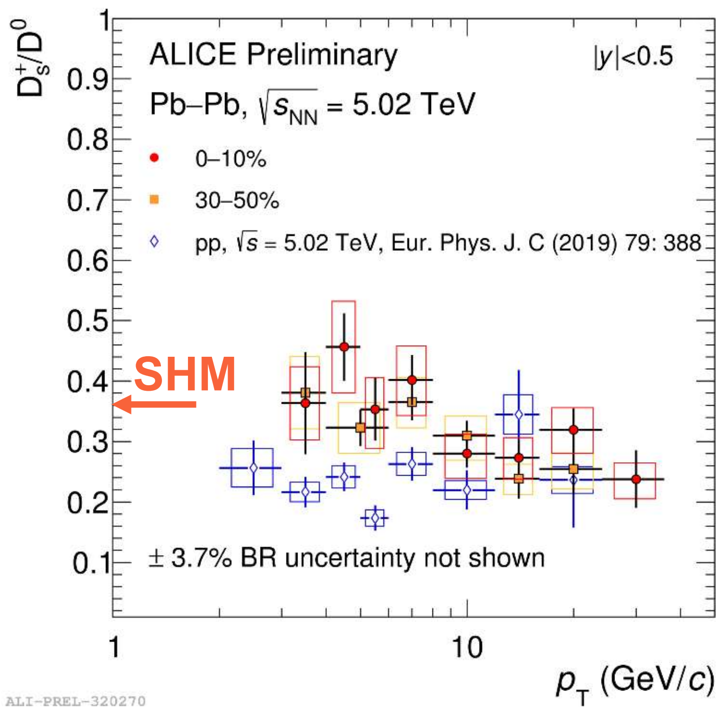
- D_s/D^0 ratio enhanced at low p_T as compared to pp
- Measured value compatible with Statistical Hadronizaion Model
- Described by models with charm quark recombination
  - ⇨ TAMU with improved space-momentum correlations between c quarks and underlying hydro medium
  - ⇨ Zhao model with and without sequential coalescence
    - ✓ ***D_s forming at higher temperature with respect to D^0***

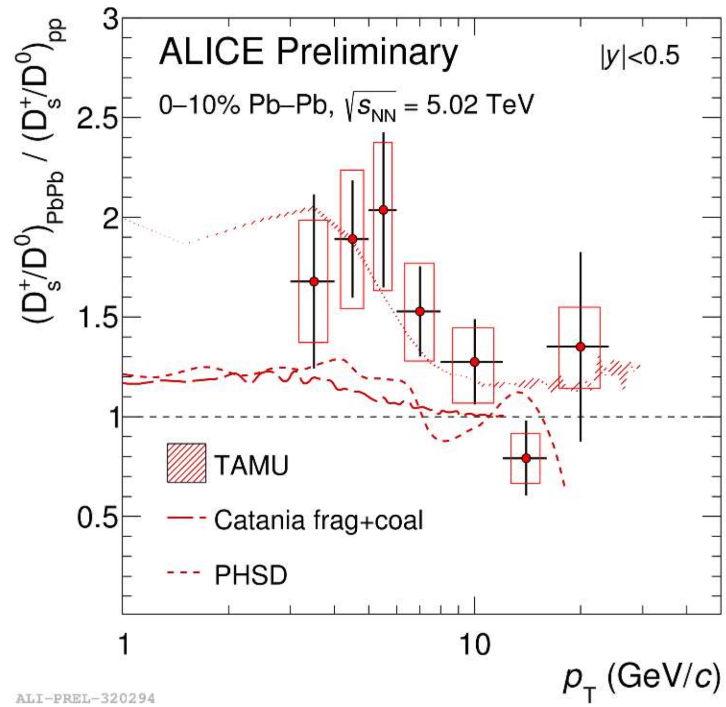


P. Zhuang, Tue 14.00

📖 Zhao et al., arXiv:1805.10858

Charm-chemistry: D_s/D^0 at LHC

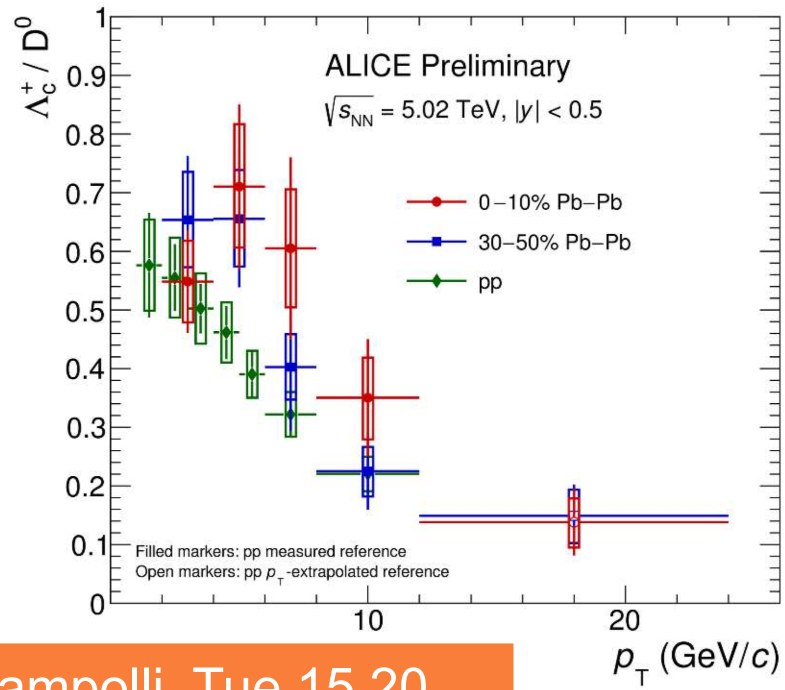


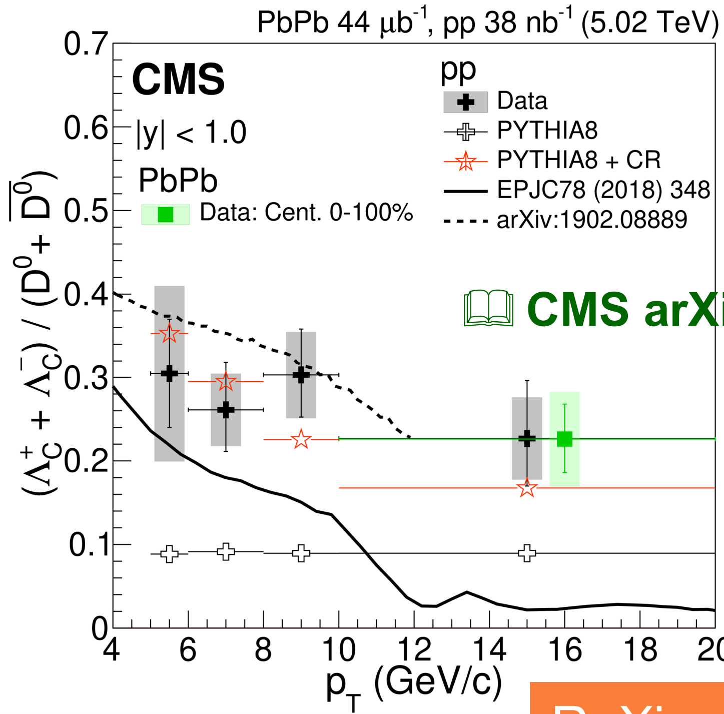


- Enhanced D_s/D^0 at low p_T with respect to pp
  - ⇨ D_s/D^0 at low p_T consistent with Statistical Hadronization Model
- Compatible with pp results at high p_T (>10 GeV/c)
- Qualitatively as expected in a scenario with strangeness enhancement in the QGP and hadronization via recombination
  - ⇨ Magnitude of D_s/D^0 enhancement relative to pp different in different models

📖 Catania: EPJC78 (2018) 348 📖 TAMU: PLB735 (2014) 445 📖 PHSD: PRC93 (2016) 034906

Baryon-to-meson: Λ_c / D^0





📖 CMS arXiv:1906.03322

C. Zampolli, Tue 15.20

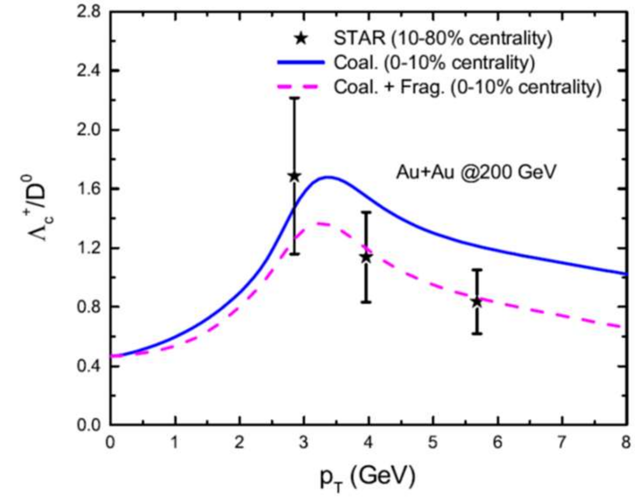
R. Xiao, Tue 14.20

- Λ_c/D^0 enhanced at low p_T (<6 GeV/c) with respect to pp
- Λ_c/D^0 consistent with pp results at high p_T (>10 GeV/c):
  - ⇨ Λ_c/D^0 in pp higher than in e^+e^- and not fully understood
    - ✓ ***Described by PYTHIA with color reconnection***
    - ✓ ***Described by FONLL + statistical hadronisation with excited charm-baryon states***

📖 Christiansen, Skands, JHEP 08 (2015) 003 📖 Rapp, arXiv:1902.08889

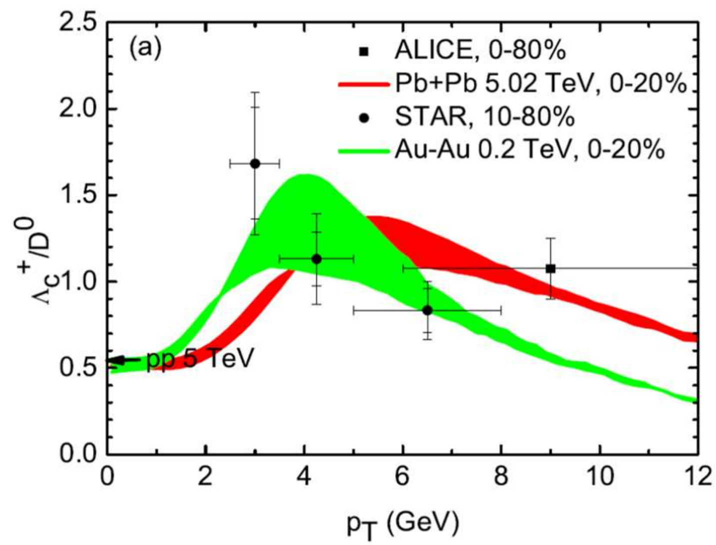
Λ_c / D^0 at RHIC vs. models

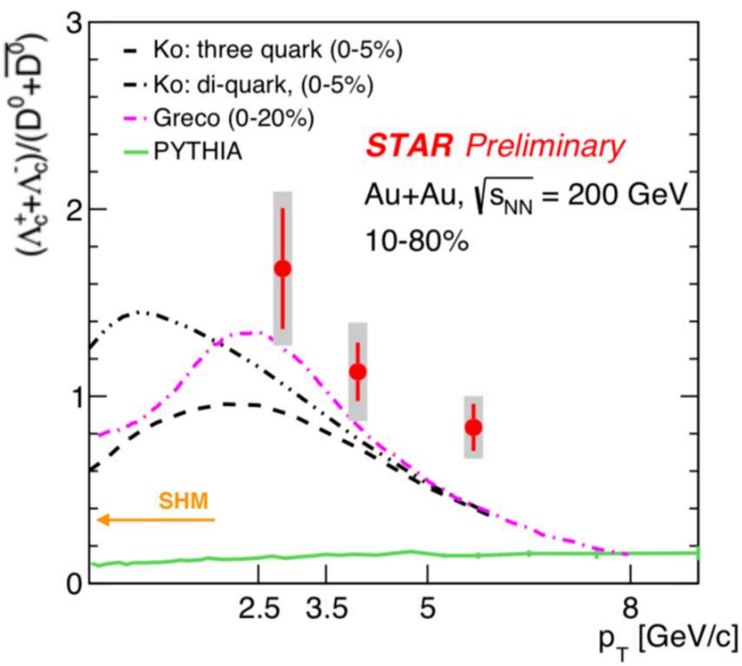
- Λ_c/D^0 ~ 1 at low p_T (<6 GeV/c)
  - ⇨ Enhanced with respect to PYTHIA
  - ⇨ Λ_c/D^0 larger than expectation from statistical hadronisation model
- Consistent with models with charm quark hadronization via coalescence

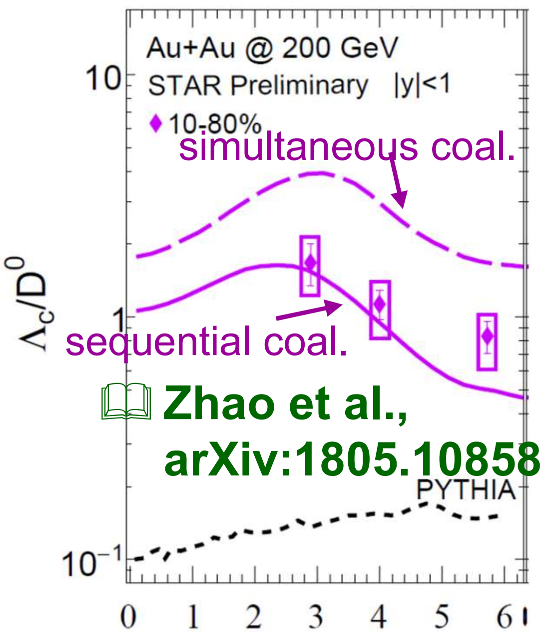


📖 **Cho et al., arXiv:1905.09774**

📖 **He, Rapp, arXiv:1905.09216**







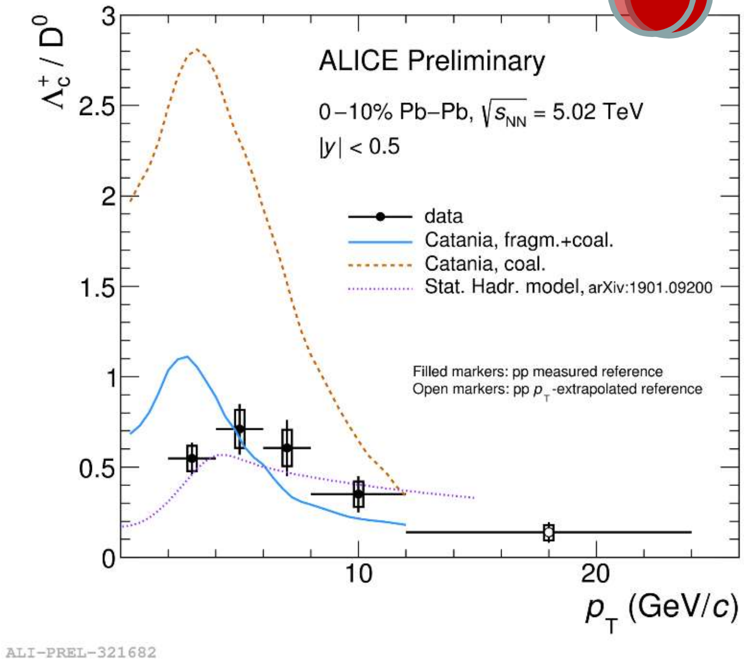
📖 **Zhao et al., arXiv:1805.10858**

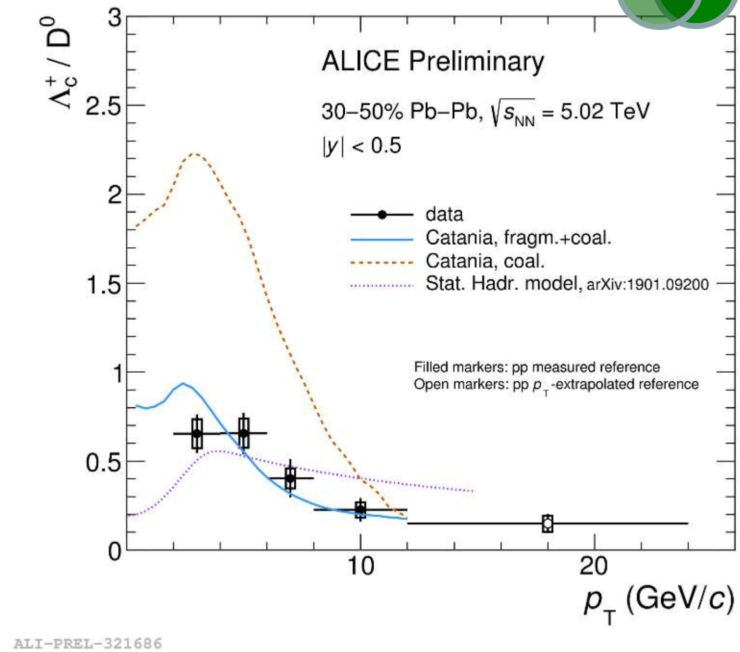
📖 **Ko et al., PRC79 (2009) 044905**

📖 **Plumari et al., EPJC78 (2018) 348**

Λ_c / D^0 at LHC vs. models

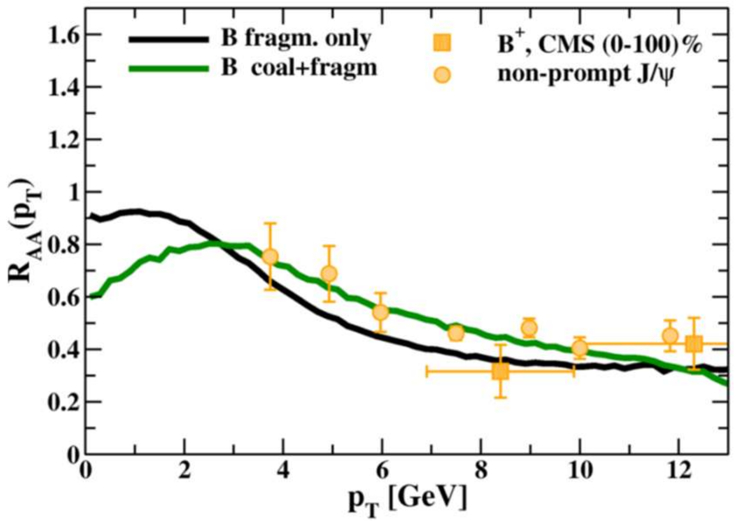
- Λ_c/D^0 ~ 0.7 at low p_T (<6 GeV/c)
  - ⇨ Enhanced with respect to pp (LHC) and PYTHIA
- Measured ratio described by:
  - ⇨ Statistical hadronisation model with core+corona
    - 🕮 **Andronic et al., arXiv:1901.09200**
  - ⇨ Transport model with hadronization via coalescence+fragmentation
    - 🕮 **Plumari et al., EPJC78 (2018) 348**



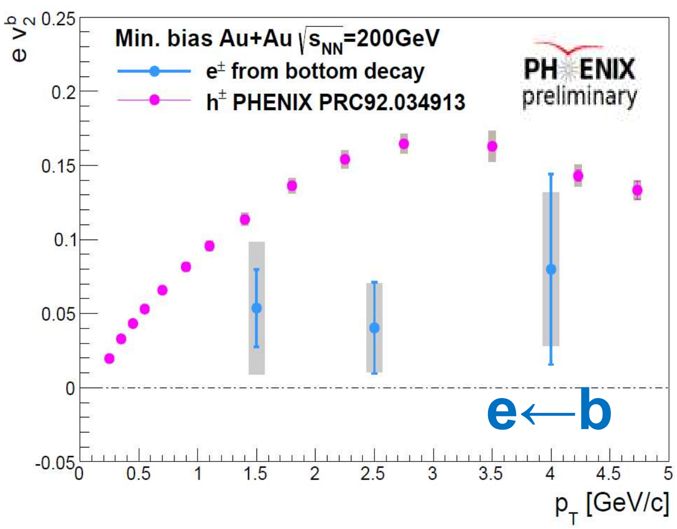


Open beauty: R_{AA} and v_2

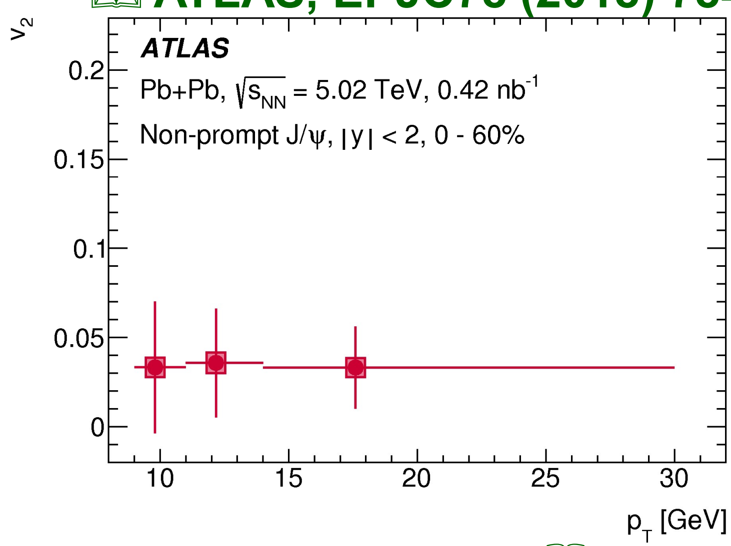
V. Minissale, Tue 15.00

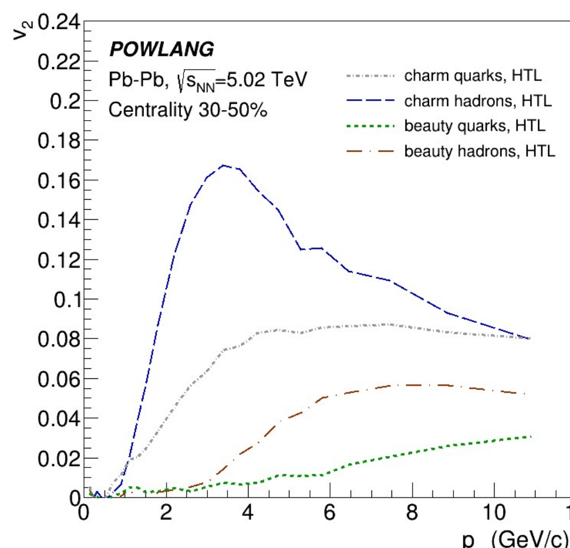


- B-meson R_{AA} in Catania's model better described with coalescence+fragmentation
- Hint of v_2 >0 for $e^{\pm}$ and J/ψ from beauty
  - ⇨ Magnitude transport model predictions
    - ✓ ***Smaller v_2 of b quarks with respect to c quarks***
    - ✓ ***Recombination for beauty important up to higher p_T than for charm***
    - ✓ ***Large mass difference between coalescing b and light quark → B meson v_2 slowly rising with p_T***



📖 ATLAS, EPJC78 (2018) 784

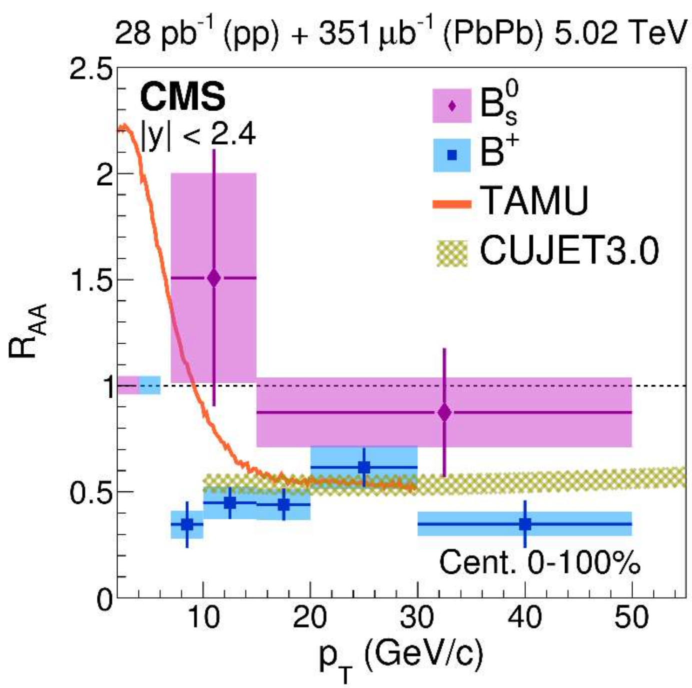


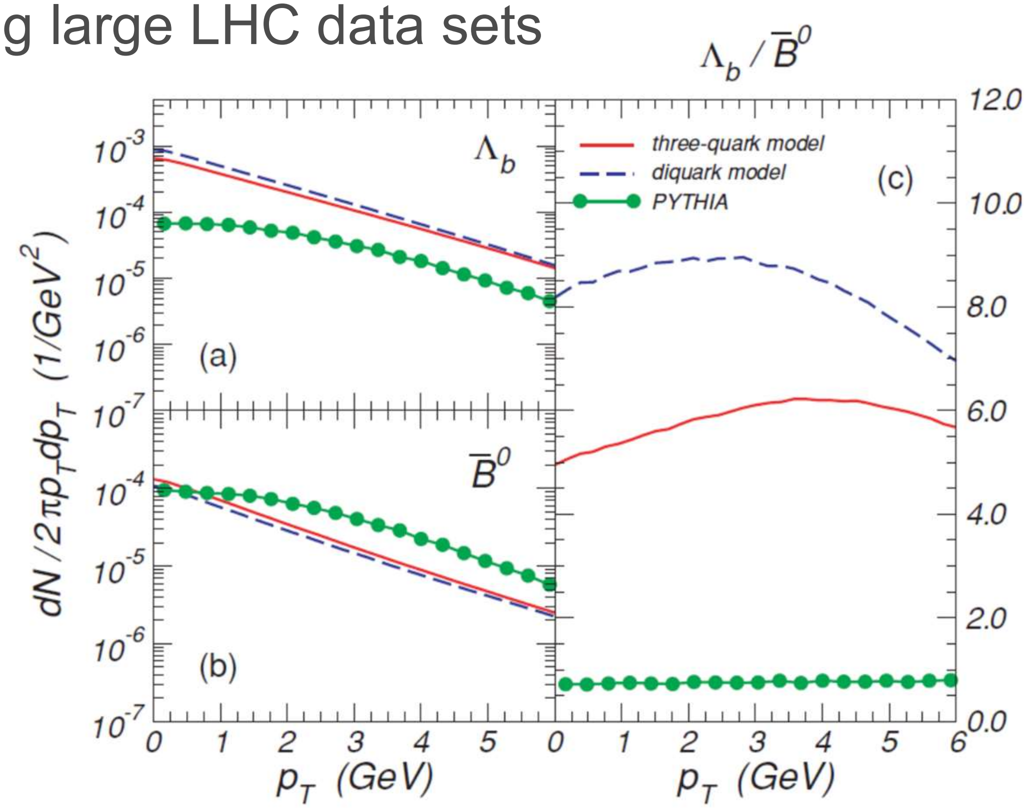


📖 Beraudo et al., JHEP02 (2018) 043

Beauty-chemistry

- B_s and B^+ mesons measured in Pb-Pb collisions at the LHC
  - ⇨ Uncertainties too large to allow to conclude on the B_s / B^+ enhancement expected from recombination
- Baryon enhancement with flatter p_T shape and reaching higher p_T predicted from recombination in the beauty sector
  - ⇨ Look forward to the upcoming large LHC data sets





📖 **CMS: arXiv:1810.03022**

📖 **Oh et al, PRC79 (2009) 044905**

Summary and perspectives

- Lot of progress, but a fully satisfying theoretical description of hadronisation is still missing
  - ⇨ Different phenomenological approaches valid in different momentum regions
- Light flavour production at intermediate p_T
  - ⇨ Transition from thermal (hydro) to kinetic regime
  - ⇨ Opens a window on hadronization mechanism?
  - ⇨ Quark coalescence captures many features of the data
    - ✓ ***Modelling of several aspects needed for a quantitative description***
- Heavy flavours
  - ⇨ Clear signs of recombination in J/ψ and open charm results
  - ⇨ Assessing the role of recombination in hadronization relevant for:
    - ✓ ***Proper comparison of the B, D and π R_{AA} to get insight into the colour charge and quark mass dependence of parton in-medium energy loss***
    - ✓ ***Extraction of medium transport coefficients via data-to-model comparison***
- Outlook:
  - ⇨ Multi-charmed hadrons, Λ_b , B_c can provide further insight into QGP hadronization
    - ✓ ***Might become accessible with future large A-A data sets***
  - ⇨ Hadronisation in (high-multiplicity) p-A (d-A) and pp collisions
    - ✓ ***Link between color-reconnection in string models and recombination?***

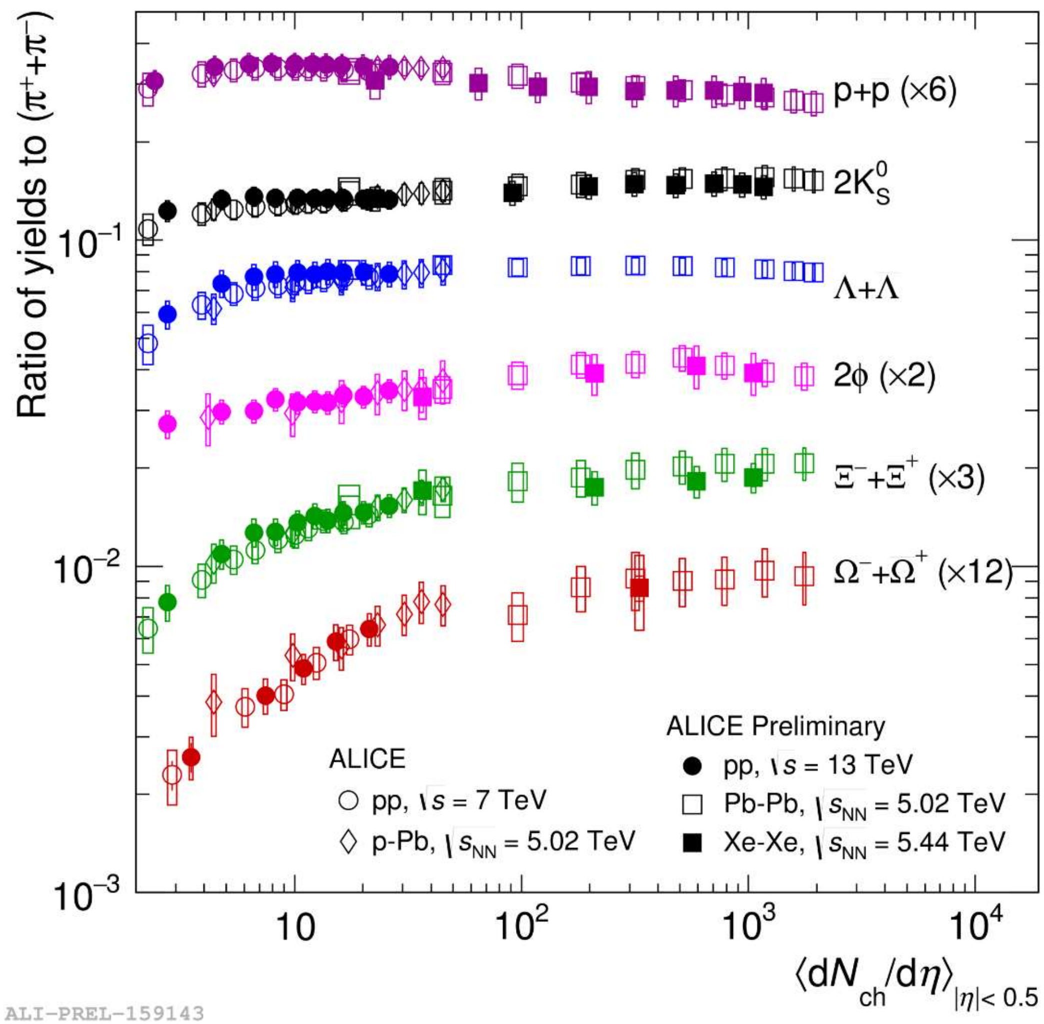
S. Cho, Tue 14.40

Thank you for the attention!

And many thanks to:
A. Andronic, R. Arnaldi, A. Beraudo, L. Bianchi, A. Dainese, V. Greco, M. Puccio, R. Rapp, A. Rossi, C. Terrevoli for sharing with me ideas, slides, plots, discussions

Backup

Strangeness enhancement



- Particle ratios measured in pp collisions show a violation of universal fragmentation
  - ⇨Challenge for pp event generators
- Smooth evolution with multiplicity from small to large collision systems

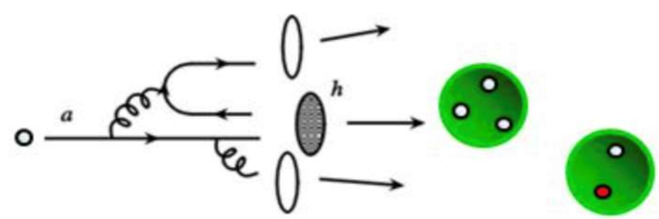
ALICE, Nature Physics 13 (2017) 535

Independent fragmentation

- Inclusive hadron production at large Q^2:
  - ⇨ Factorization of PDFs, partonic cross section (pQCD), fragmentation function

$$\sigma_{pp\to hx} = PDF(x_a, Q^2)PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z, Q^2)$$

- Fragmentation functions $D_{q\to h}$ are phenomenological functions to parameterise the non-perturbative parton-to-hadron transition
  - ⇨ Do not specify the hadronisation mechanism
- Microscopically:
  - ⇨ The outgoing high-energy parton is not a color singlet and has a color string attached
  - ⇨ The breaking of the string creates $q\bar{q}$ pairs producing a jet of particles, which share the energy of the initial parton

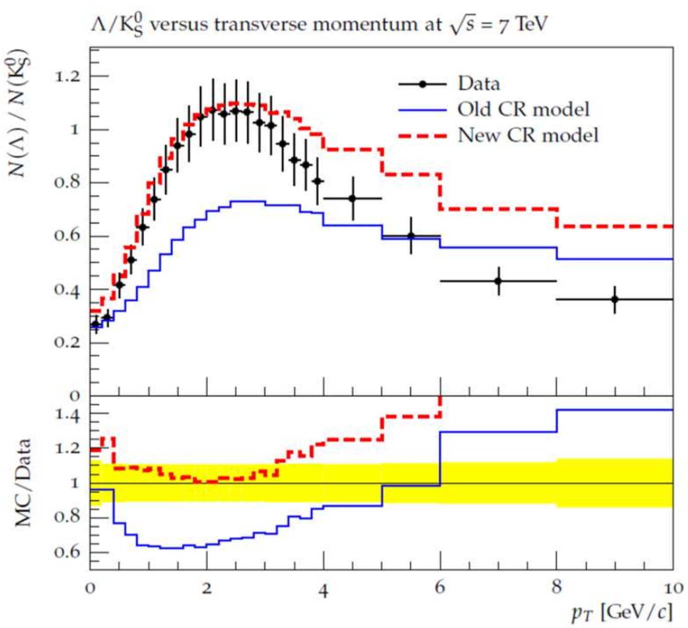


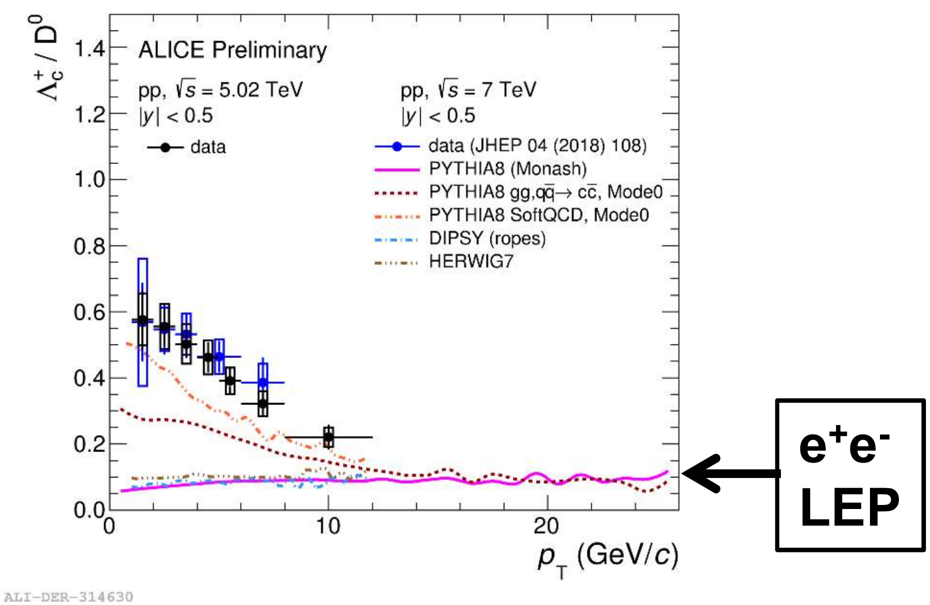
- In A-A collisions:
  - ⇨ Energy-loss of hard-scattered partons while traversing the QGP
  - ⇨ Modified fragmentation function $D_{q\to h}(z)$ by "rescaling" the variable z
    - ✓ ***Would affect all hadron species in the same way***

String formation and fragmentation

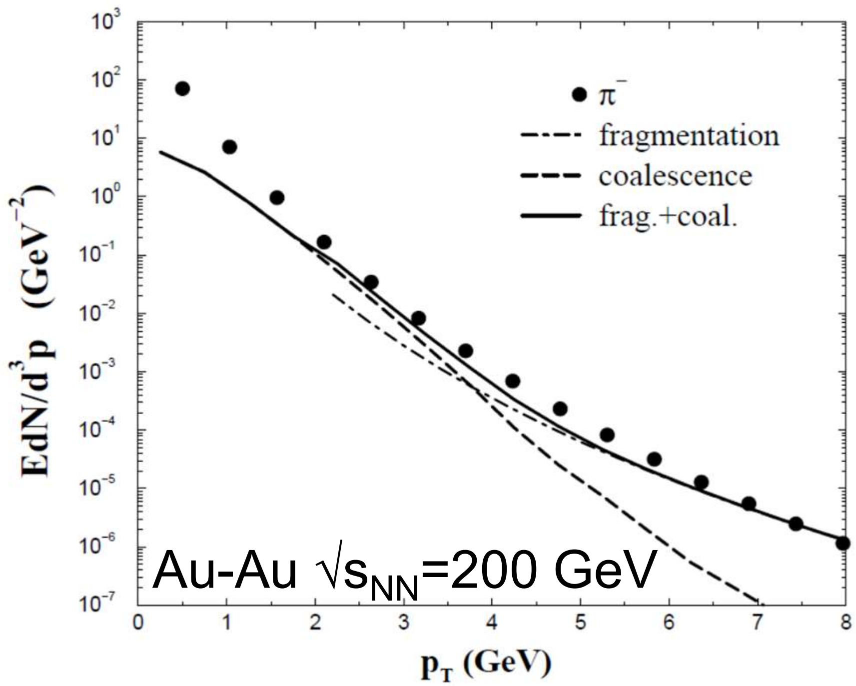
- Description of hadronic final state requires a cocktail of different physics effects (MPI, ropes, beam remnants, decays …)
- E.g.: need to define between which partons the strings are formed
  - ⇨ Leading-color approximation describes results from e^+e^- collisions
  - ⇨ Colour-reconnection (string topologies beyond leading color) relevant in pp collisions, especially at LHC energies (MPI)
  - ⇨ E.g.: a colour-connection mechanism with 3-leg string junctions can improve the description of baryon production in pp collisions at the LHC

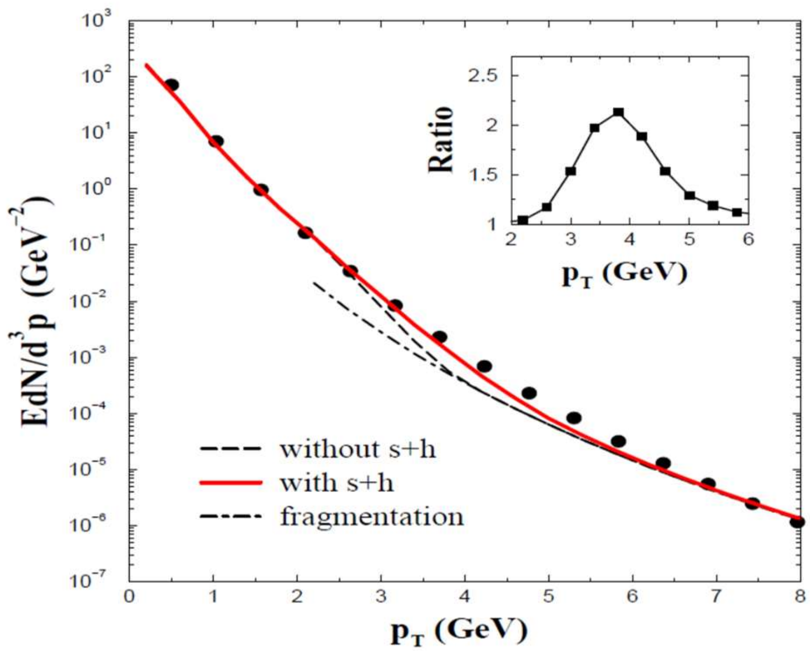
📖 **Christiansen, Skands, JHEP 08 (2015) 003**





Pion spectra from coalescence





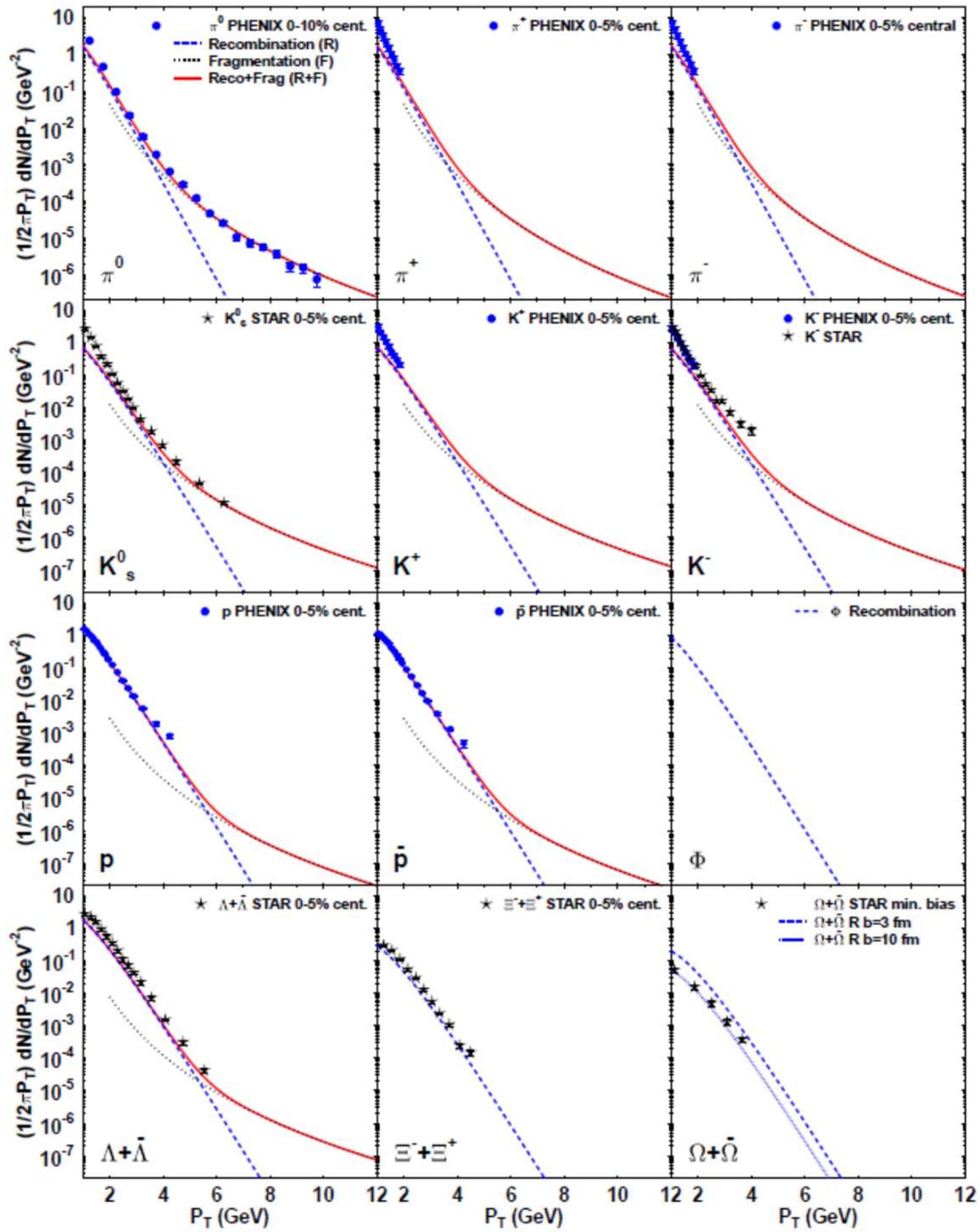
- Directly produced pions
  - ⇨ No resonance decays
- Model components:
  - ⇨ Thermal+minijets parton spectra
  - ⇨ Coalescence+fragmentation

- Pion spectrum after resonance decays
  - ⇨ Resonance decays dominant at low p_T
  - ⇨ Recombination of partons from mini-jets with thermal partons (s+h) relevant at intermediate p_T

📖 **Greco et al., PRC 68 (2003) 034904**

Hadron spectra from coalescence

- Model vs. data for central Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- Two-component model:
  - ⇨ Thermal (exponential) parton spectra with radial flow hadronizing via coalescence
  - ⇨ Power law (pQCD) spectra from hard scatterings + in medium energy loss hadronizing via fragmentation



📖 **Fries et al., PRC 68 (2003) 044902**

Baryons vs. mesons

- Baryon formation enhanced in recombination with respect to string fragmentation
  - ⇨ No need to create two $q\bar{q}$ pairs from the QCD vacuum
- Probability of meson (baryon) formation proportional to single parton distribution squared (cubed)

$$\frac{dN_{meson}}{dp_T} \propto \int f_q(x_q, p_q)^2 f_W(x_1, x_2; p_1, p_2) \qquad \frac{dN_{baryon}}{dp_T} \propto \int f_q(x_q, p_q)^3 f_W(x_1, x_2, x_3; p_1, p_2, p_3)$$

  - ⇨ Meson spectrum from recombination determined by $f_q(p_T/2)$
  - ⇨ Baryon spectrum from recombination determined by $f_q(p_T/3)$
  - ⇨ Enhances baryon/meson ratios at intermediate p_T
  - ⇨ Kinematic properties of the hadron spectrum due to radial flow extend to higher p_T for baryons as compared to mesons

Coalescence: remarks

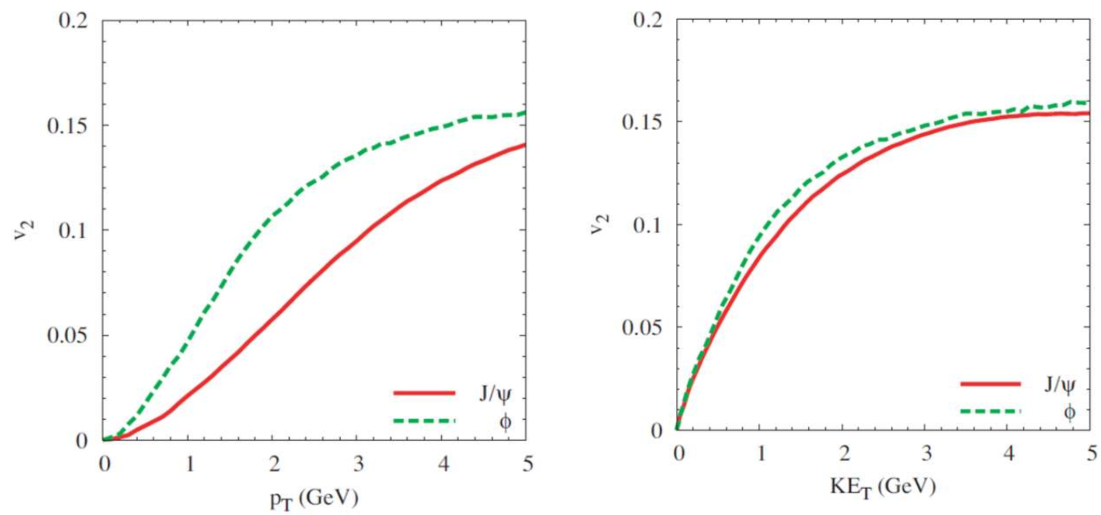
- 4-momentum not conserved in instantaneous coalescence
  - ⇨ Energy mismatch in the formation of a bound state from interacting particles should be balanced by other particles of the medium
  - ⇨ Small effect at intermediate p_T (>~1.5 GeV/c) but relevant at low p_T
    - ✓ ***If recombination is the dominant mechanism at intermediate p_T, it is reasonable to expect that it extends also to small p_T***
  - ⇨ Energy conservation can be obrainted with finite width distributions of parton mass
    📖 Zmanyi et al, JPG31 (2005) 711
- Entropy decreases in the individual 2→1 and 3 → 1 coalescence processes
  - ⇨ However, before coalescence the gluons are converted to $q\bar{q}$ pairs, increasing the number of degrees of freedom in the QGP
- Coalescence can occur not only for soft partons (thermal) but also for partons from mini-jets (parton showers)

  📖 Greco et al., PRC68 (2003) 034904 **📖 Hwa, Yang, PRC70 (2004) 024905**
  - ⇨ Recombination with thermal+thermal and thermal+shower proposed to describe the species dependent Cronin enhancement in p-A

    📖 Hwa, Yang, PRL93 (2004) 082302

Resonance recombination model

- Hadronization proceeds via formation of resonant states when approaching the (pseudo)critical temperature
  - ➩ Heavy-light quark interactions in the QGP mediated by broad bound states ($c\bar{q}$ and $s\bar{q}$) motivated by lattice QCD results
  - ➩ Resonance formation/dissociation rate from Boltzmann equation
- Features:
  - ➩ Conserve energy in the hadron formation process
  - ➩ Recover the equilibrium limit of hadron distributions
  - ➩ Embody space-momentum correlations using quark phase-space distributions from transport calculations
  - ➩ KE_T scaling of v_2



🕮 **Ravagli, Rapp, PLB655 (2007) 126**
🕮 **Ravagli et al. PRC79 (2009) 064902**

Elliptic flow from coalescence

- Assumptions:
  - ⇨ Recombination of quarks with same velocity
  - ⇨ Universal partonic v_2
  - ⇨ Coalescence is a rare process, i.e. moderate parton phase space density
    - ✓ ***Intermediate p_T interval***
  - ⇨ Effective parton density independent of φ
- Constituent quark scaling:

$$v_{2,M}(p_T) = 2v_{2,q}(p_T/2)\frac{1}{1+2v_{2,q}^2(p_T/2)}$$

$$v_{2,B}(p_T) = 3v_{2,q}(p_T/3)\frac{1+v_{2,q}^2(p_T/3)}{1+6v_{2,q}^2(p_T/3)}$$

⇨

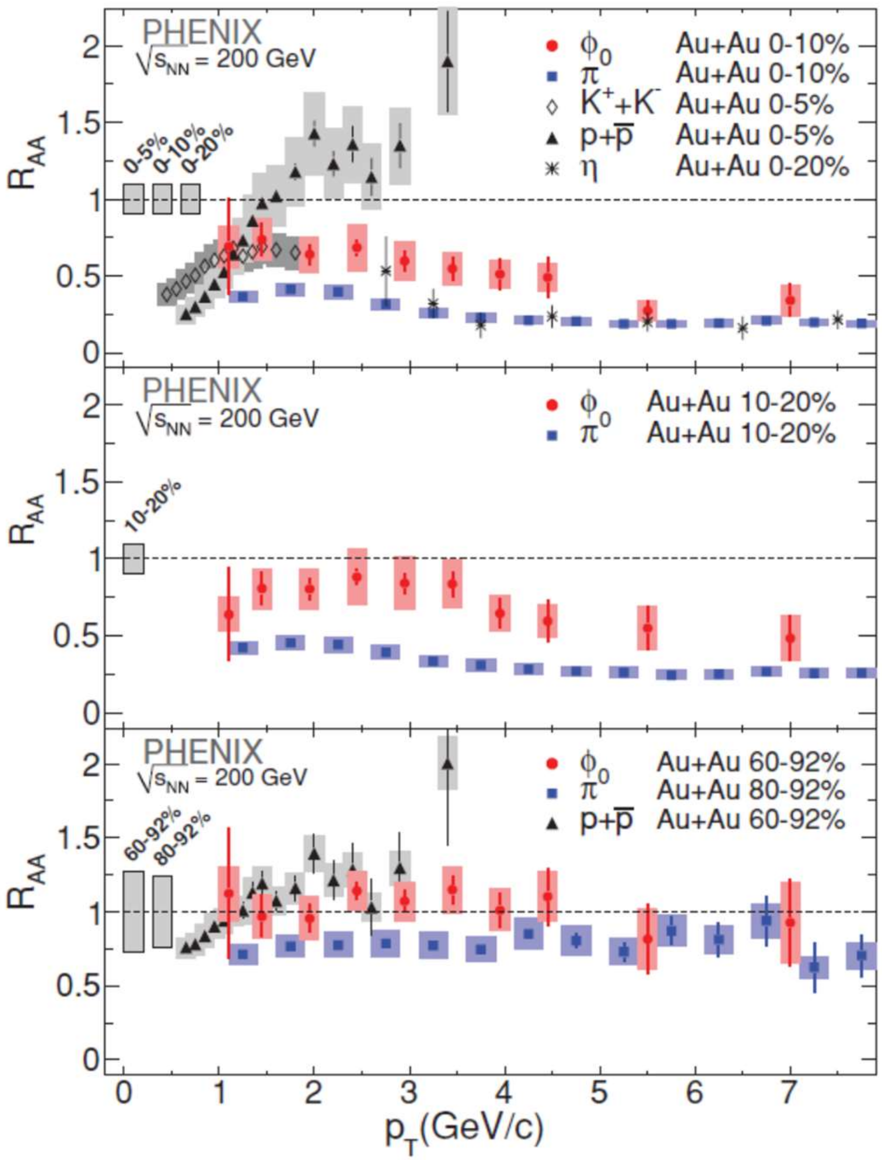
$$v_{2,M}(p_T) \approx 2v_{2,q}\left(\frac{p_T}{2}\right)$$

$$v_{2,B}(p_T) \approx 3v_{2,q}\left(\frac{p_T}{3}\right)$$

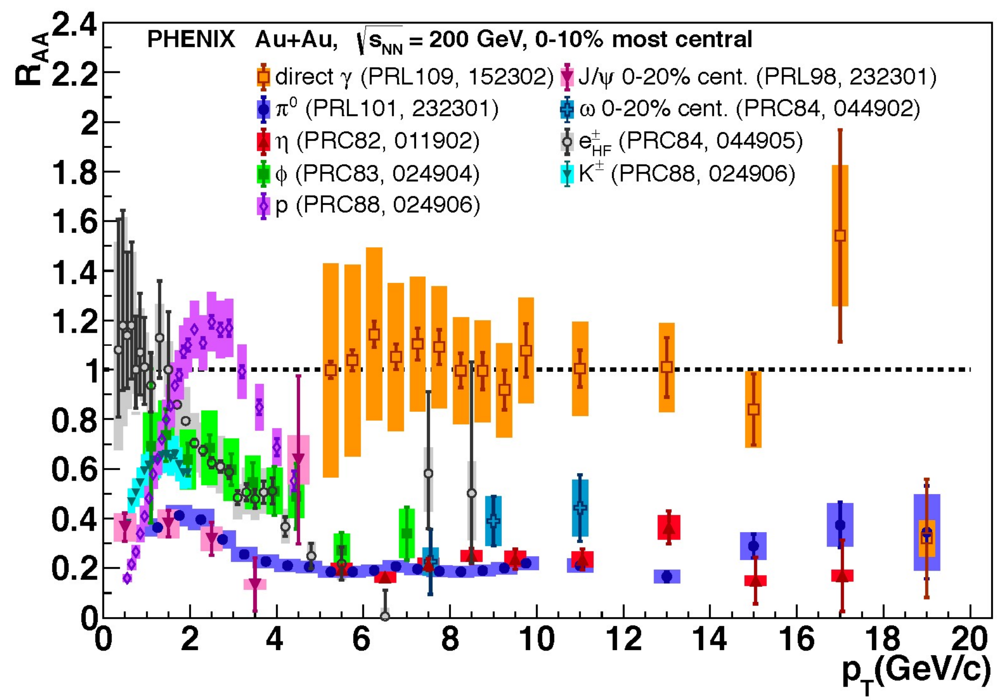
📖 **Molnar, Voloshin, PRL91 (2003) 092301**
📖 **Pratt, Pal, PRC71 (2005) 014905**

Identified hadron R_{AA} at RHIC

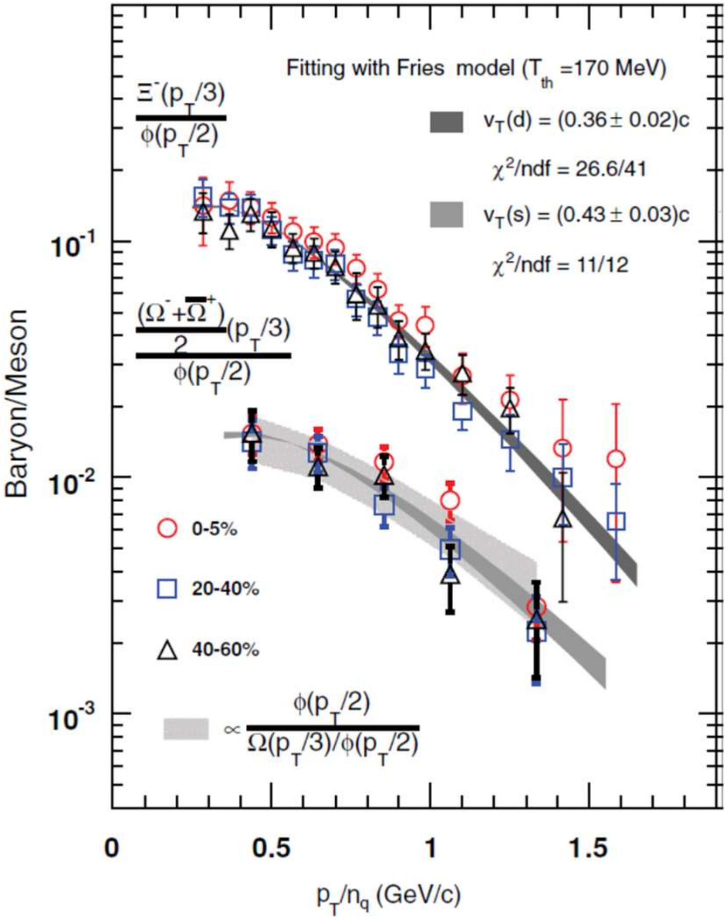
📖 **PHENIX, PRC 83 (2011) 024909**



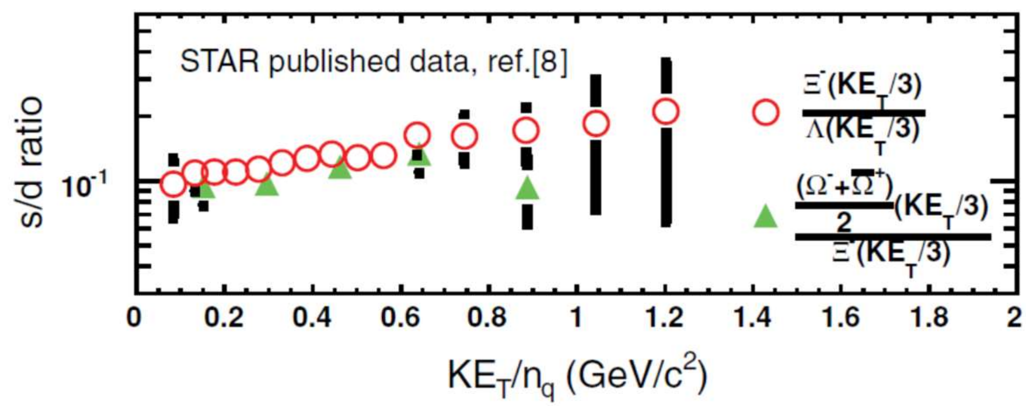
- Different suppression pattern for Φ mesons, kaons, protons, pions and η mesons
- Pattern qualitatively similar to the one observed at the LHC



Ω/Φ and Ξ/ Φ



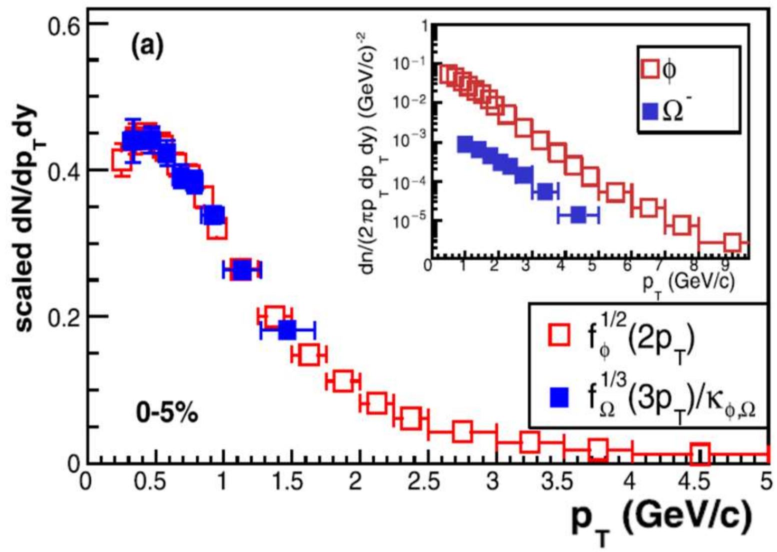
- Multi-strange hadrons:
  - ➩ Small hadronic interaction cross sections
  - ➩ Information on partons at hadronization
- Constituent quark number scaling of p_T spectra:
  - ➩ Φ spectrum from recombination ~ $f_s(p_T/2)^2$
  - ➩ Ω spectrum from recombination ~ $f_s(p_T/3)^3$
  - ➩ $\Omega(p_T/3)/\Phi(p_T/2)$ provides access to strange quark distributions
  - ➩ $\Xi(p_T/3)/\Phi(p_T/2)$ provides access to light quark distributions

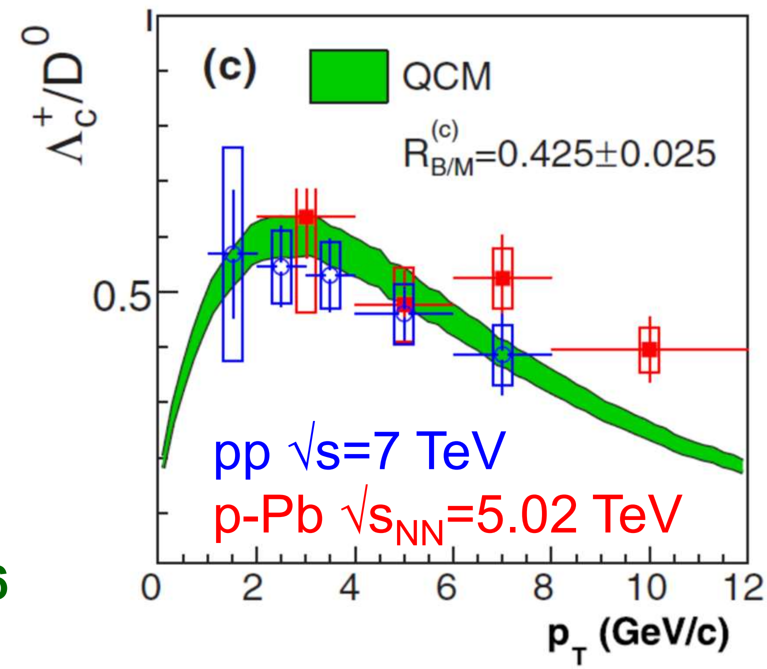


📖 **Chen et al., PRC78 (2008) 034907**
📖 **STAR, PRC93 (2016) 021903(R)**

Quark number scaling of p_T spectra

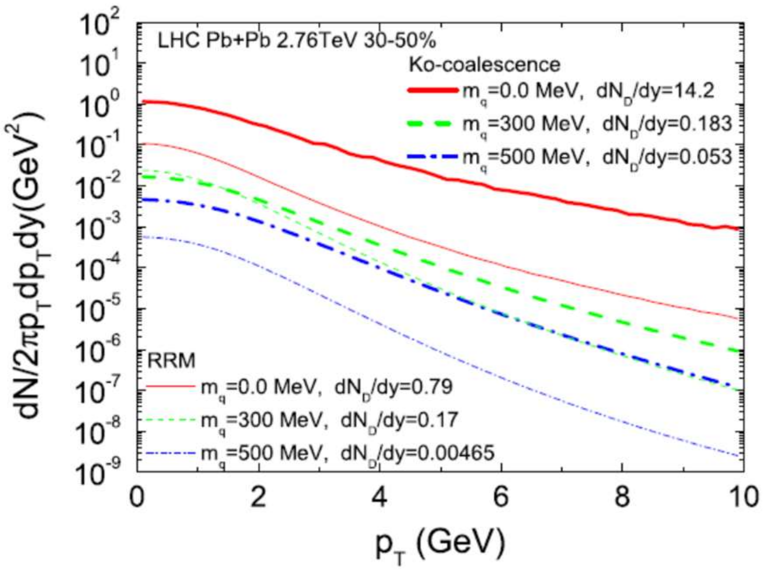
- Quark number scaling of p_T spectra:
  - ⇨ Observed scaling:
    - ✓ ***Φ p_T spectrum ~ $f_s(p_T/2)^2$***
    - ✓ ***Ω p_T spectrum ~ $f_s(p_T/3)^3$***
  - ⇨ Holds also in pp and p-Pb at LHC energies and high multiplicity
  - ⇨ Extract p_T spectra of s, u, d quarks
  - ⇨ Compute hadron p_T spectra using quark distributions and coalescence
  - ⇨ Captures features of the measured hadron spectra in pp and p-Pb collisions
- Extended to charm quarks:
  - ⇨ Extract c quark p_T spectra from D*
  - ⇨ Reproduces the measured p_T shape of Λ_c/D^0 ratios in pp and p-Pb collisions at the LHC

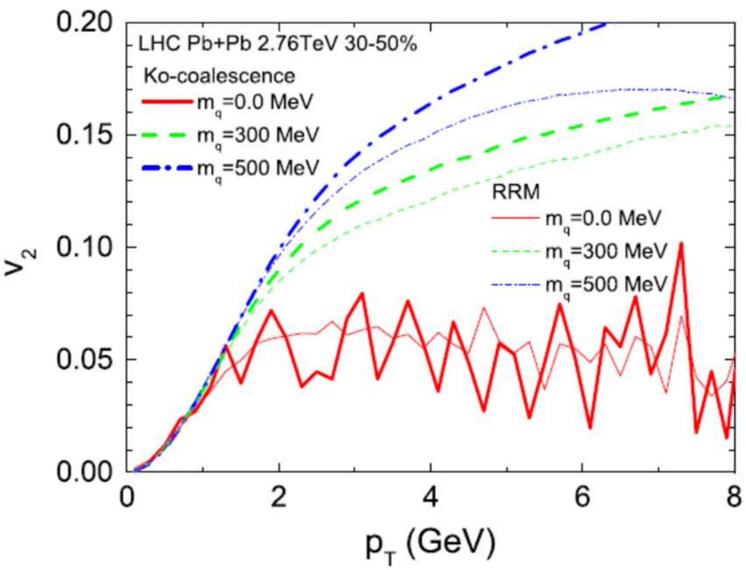




📖 **Song et al., PLB774 (2017) 516**
📖 **Li et al., PRC97 (2018) 064915**

Instantaneous coalescence vs. Resonance Recombination





- Test the two hadronization approaches starting from same charm and light quark spectra
- Similar results on D-meson yield only for m_q=300 MeV
- Softer spectra and smaller v_2 in RRM
  - ⇨ ICM combines charm and light quarks with parallel momenta
  - ⇨ RRM allows fo significant momentum smearing

📖 **Rapp et al., NPA 979 (2018) 21**

Charm hadrochemistry

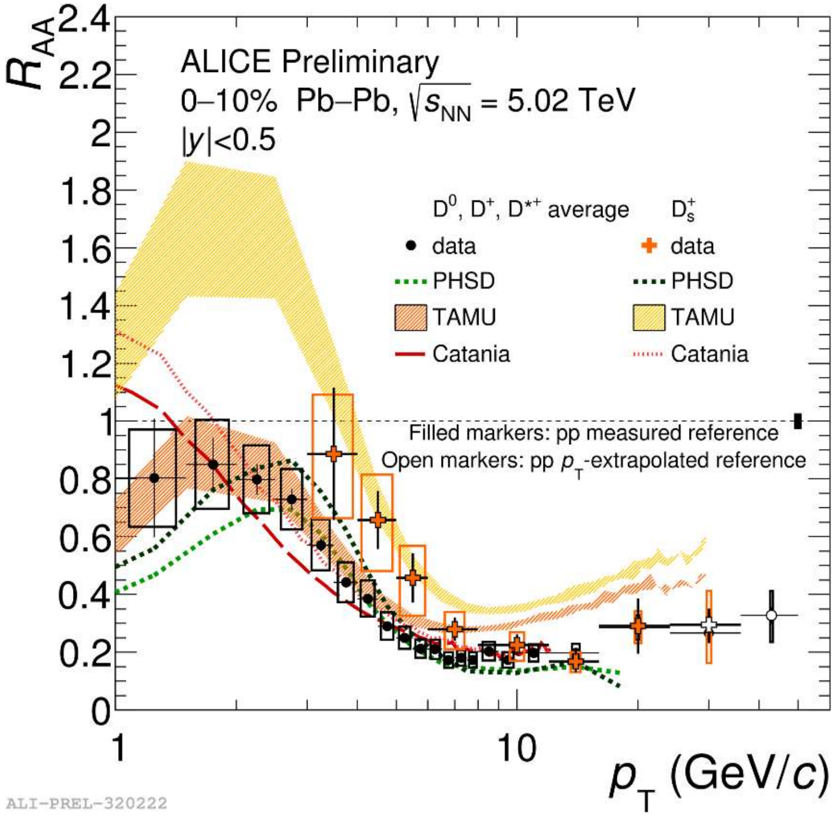
- Hadronization via recombination expected to modify the charm hadron abundances relative to pp case

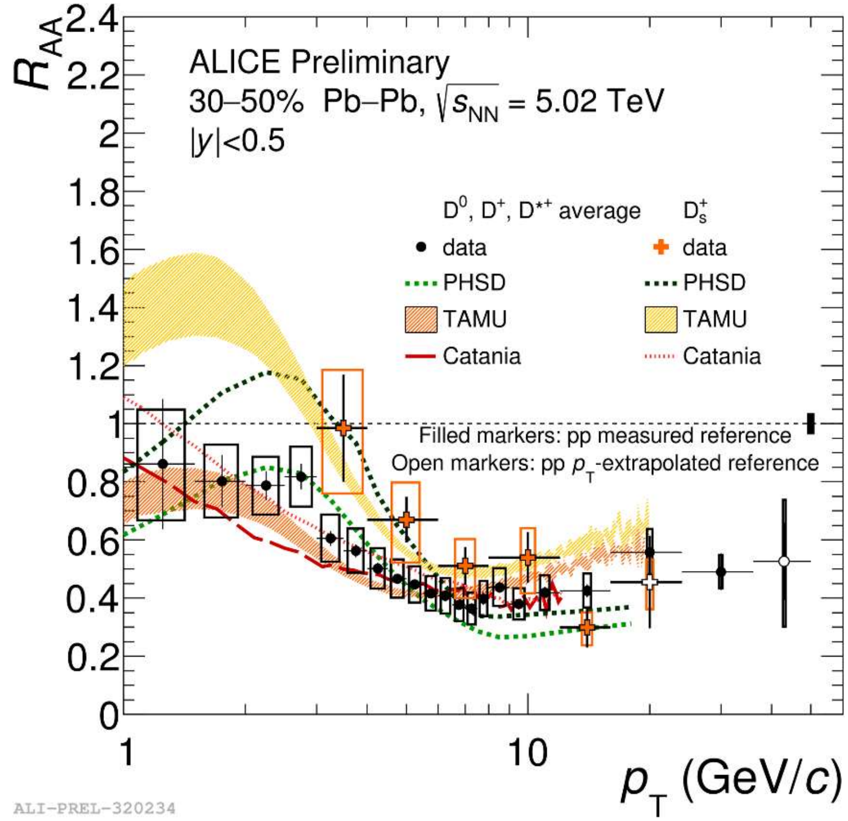
Particle	e^+e^-	PYTHIA	Thermal model	Coalescence (w/o diquark)	Coalescence (with diquark)
$f(c \rightarrow D^0)$	0.542	0.607	0.435	0.348	0.282
$f(c \rightarrow D^+)$	0.225	0.196	0.205	0.113	0.091
$f(c \rightarrow D_s^+)$	0.092	0.121	0.179	0.113	0.123
$f(c \rightarrow \Lambda_c^+)$	0.057	0.076	0.118	0.288	0.378
Ratio	**e^+e^-**	**PYTHIA**	**Thermal model**	**Coalescence (w/o diquark)**	**Coalescence (with diquark)**
D^+/D^0	0.41	0.32	0.47	0.32	0.32
D_s^+/D^0	0.17	0.20	0.41	0.32	0.44
Λ_c^+/D^0	0.11	0.13	0.27	0.83	1.34

📖 Oh et al, PRC79 (2009) 044905

📖 Andronic et al, J. Phys G35 (2008) 104155

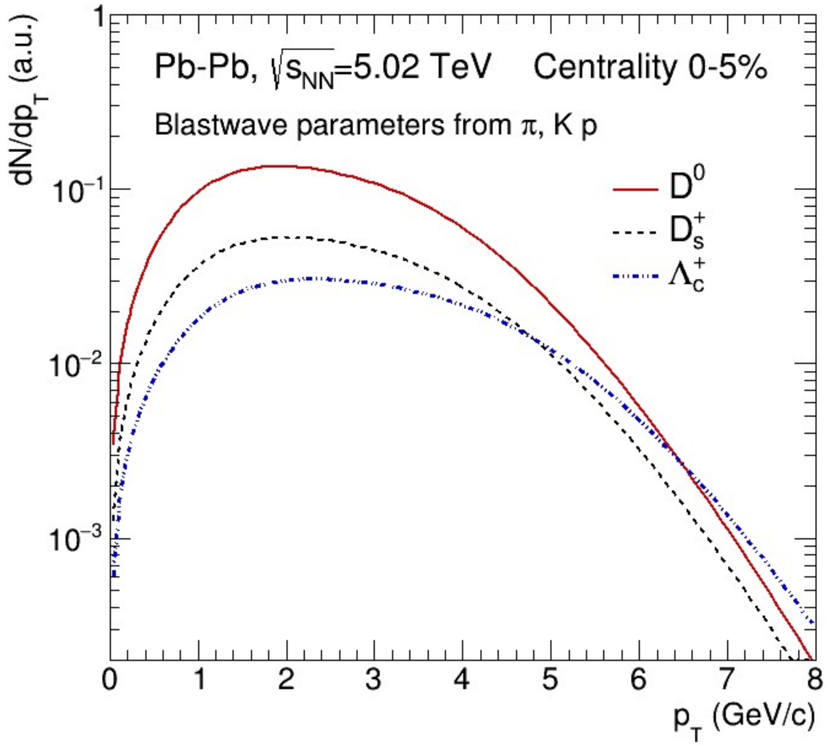
D_s R_{AA} at the LHC

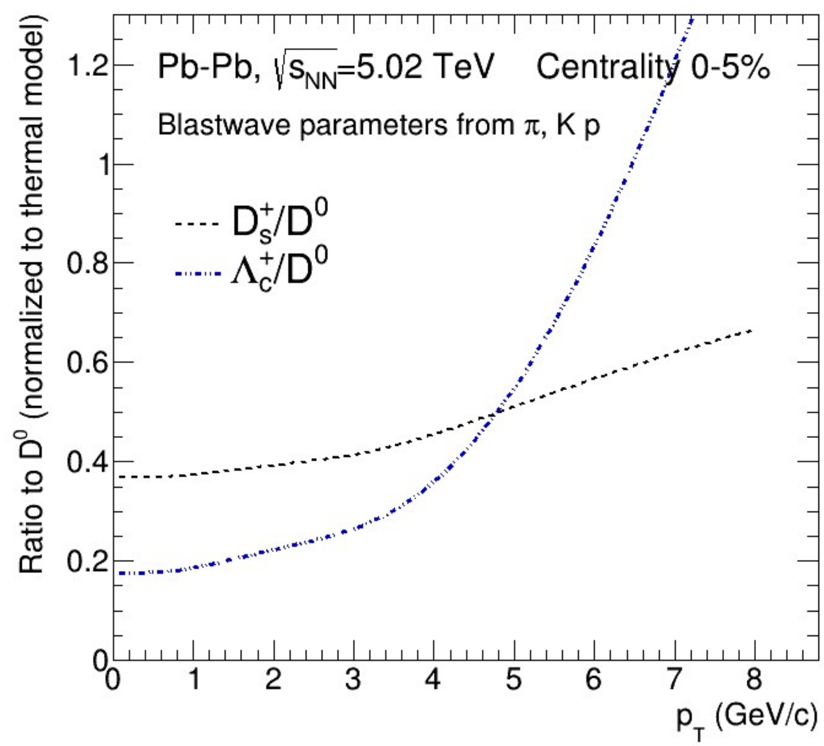




- D_s less suppressed than non-strange D mesons at low p_T
- R_{AA} of D_s and non-strange D mesons compatible at high p_T (>10 GeV/c)
- Qualitatively as expected in a scenario with strangeness enhancement in the QGP and hadronization via recombination

Charm: thermal + blast wave

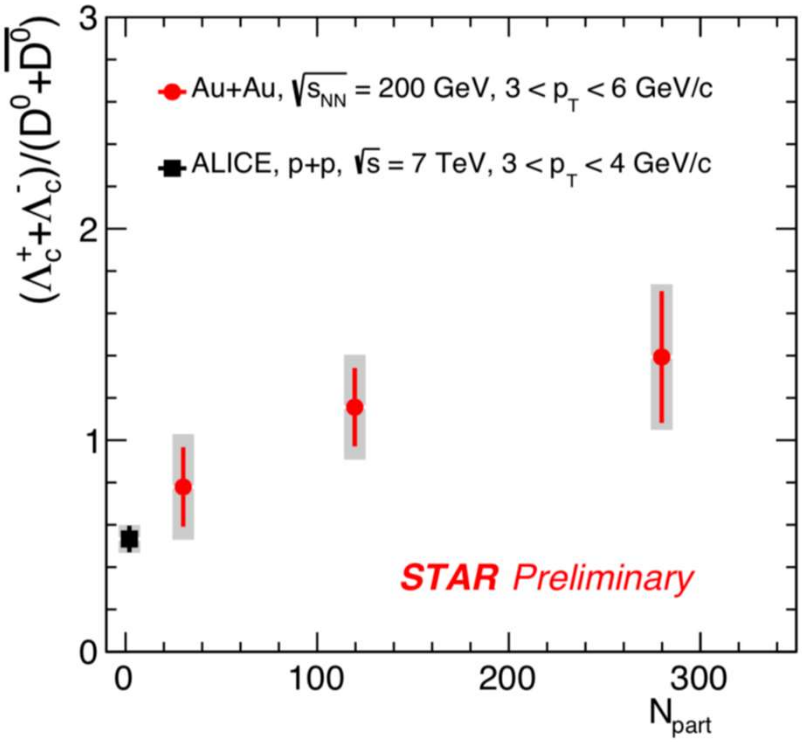




- Thermal model abundances from Oh et al.
- Blast wave parameters from pion, kaon, proton measurements by ALICE

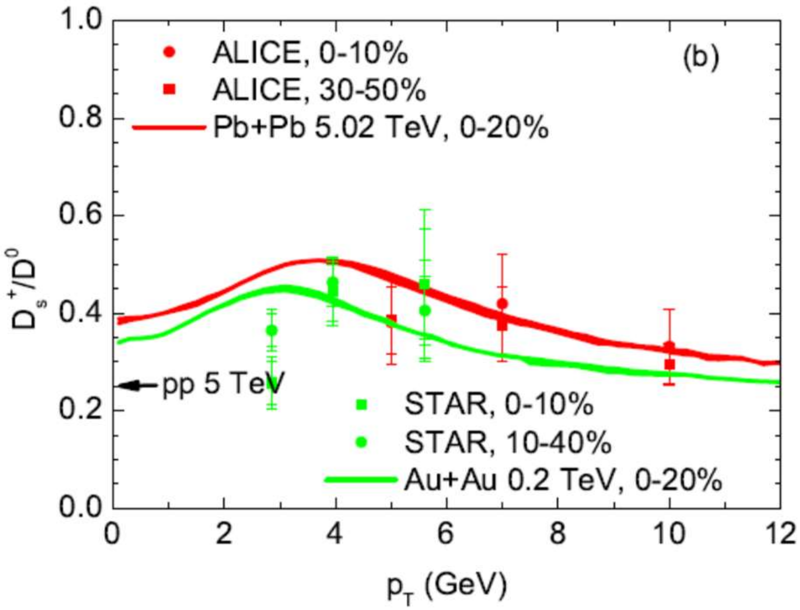
📖 **Oh et al, PRC79 (2009) 044905**

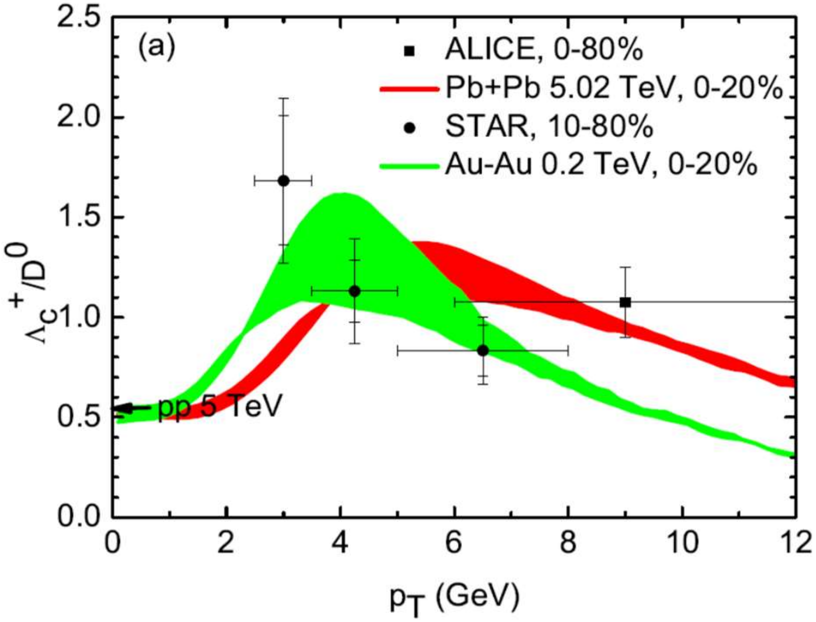
Λ_c / D^0 at RHIC



- Λ_c/D^0 at low/intermediate p_T increases from peripheral to central events
  - ⇨ Value in peripheral collisions slightly higher than the one measured in pp collisions at the LHC, even though compatible within uncertainties

Charm hadrochemistry from TAMU

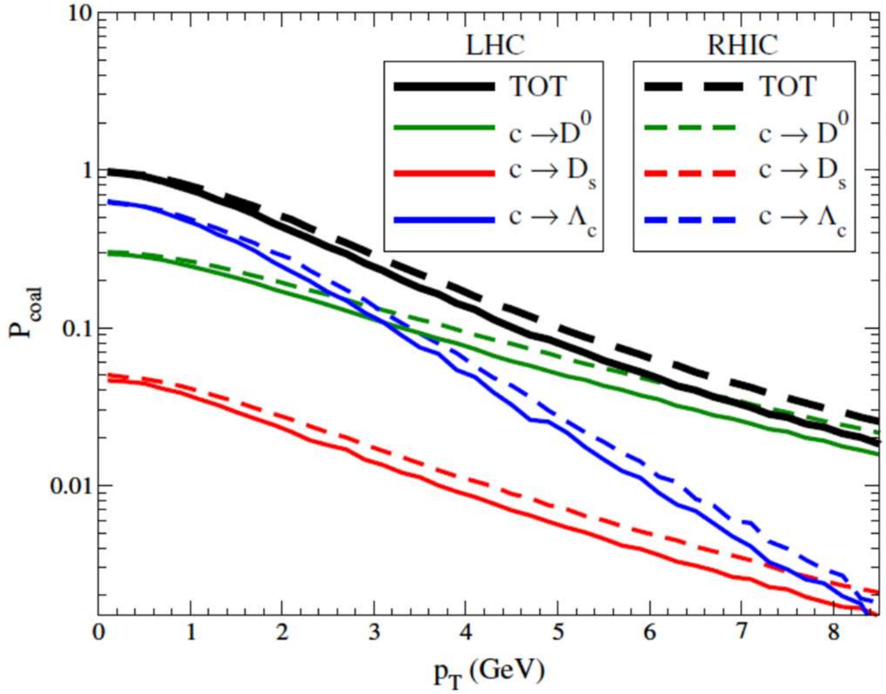




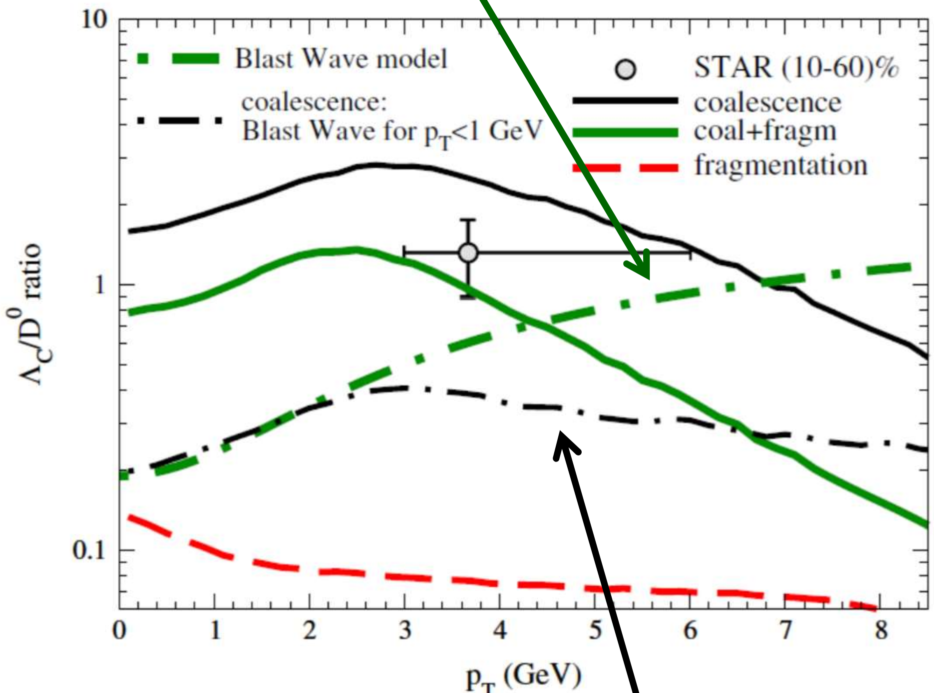
- Charm quark transport in hydrodynamic medium
- Generalized resonance recombination model
  - ⇨ Extended to 3-body case to treat hadronization into baryons
  - ⇨ Improved space-momentum correlations between c quarks and underlying hydro medium
  - ⇨ Improved charm-hadron chemistry with baryon states beyond PDG

📖 **He, Rapp, arXiv:1905.09216**

Charm baryons from Catania



Thermal spectra of Λ_c and D^0



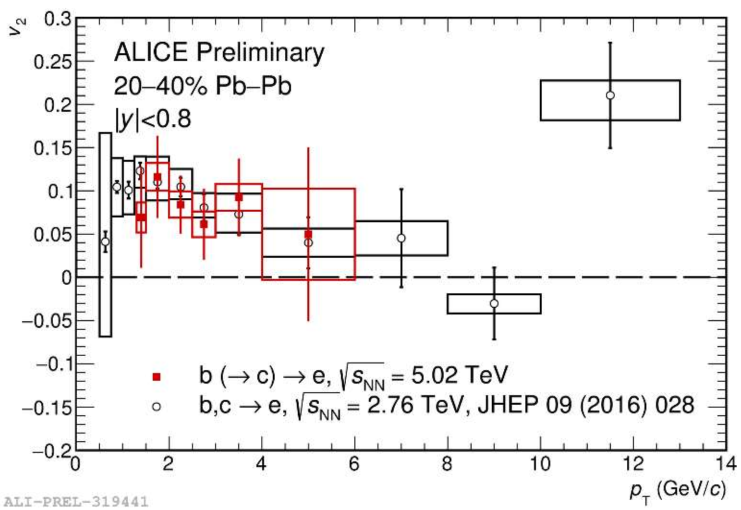
- Coalescence probability decreases with increasing p_T
  - ⇨ At high p_T fragmentation takes over
- Al low p_T the probability of udc quarks to coalescence into a Λ_c is higher than that of $c\bar{u}$ to form a D^0

Coalascence+fragmentation with Wigner function tuned to reproduce thermal model ratio at low p_T

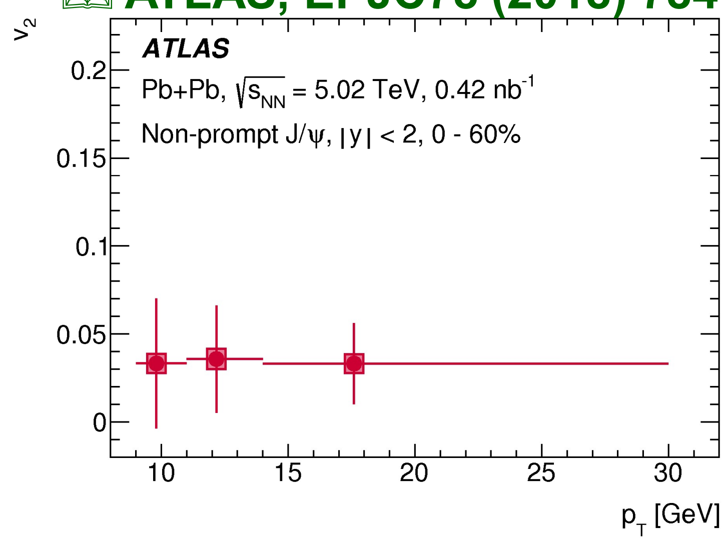
📖 **Plumari et al., EPJC78 (2019) 348**

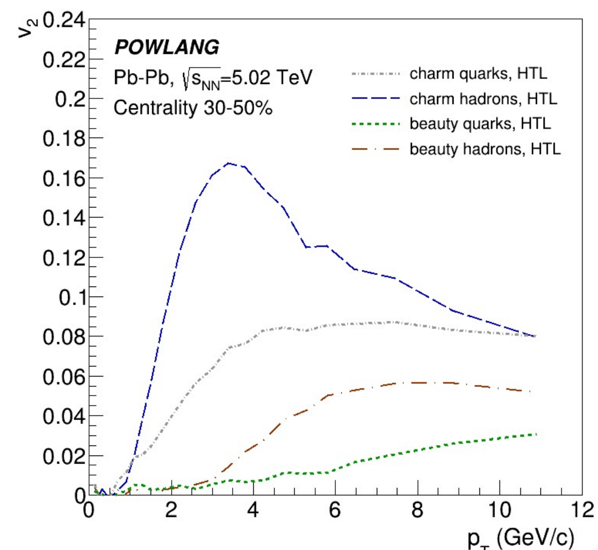
Open beauty v_2

- Hint of v_2 >0 for electrons and J/ψ from beauty-hadron decays
- Magnitude of v_2 consistent with transport model prediction
  - ⇨ Smaller v_2 of b quarks with respect to charm quarks
  - ⇨ Recombination for beauty important up to higher p_T than for charm
  - ⇨ Large mass difference between the coalescing b and light quark → v_2 of B meson slowly rising with p_T



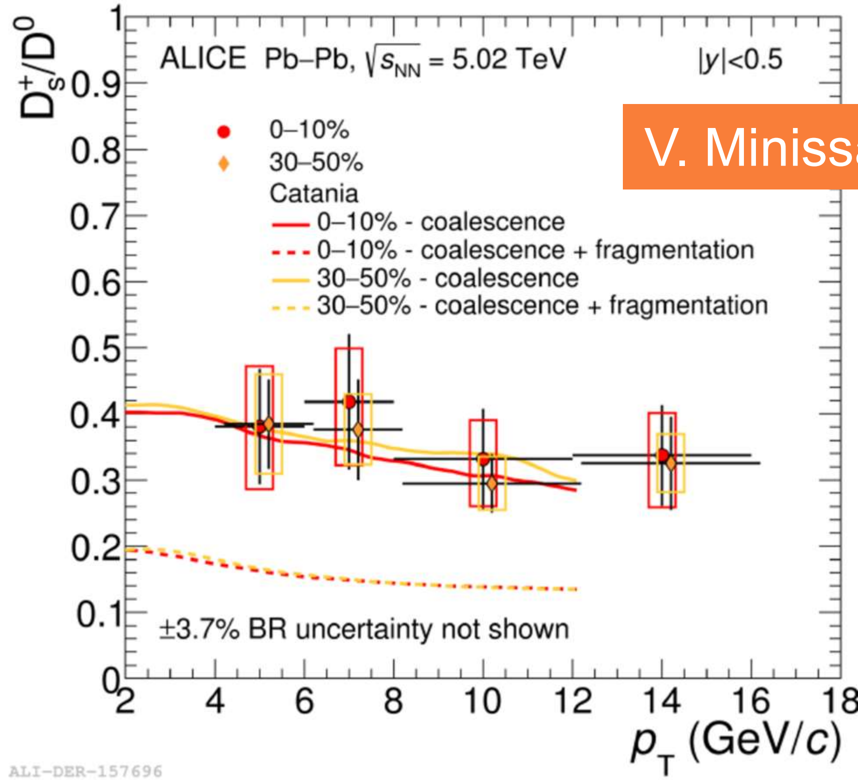
📖 **ATLAS, EPJC78 (2018) 784**





📖 **Beraudo et al., JHEP02 (2018) 043**

D_s / D^0 from Catania



V. Minissale, Tue 15.00

- Data close to the coalescence only prediction
- The coalescence+fragmentation calculation underestimates the measured ratio