Heavy-quarks in the QGP data and modelling

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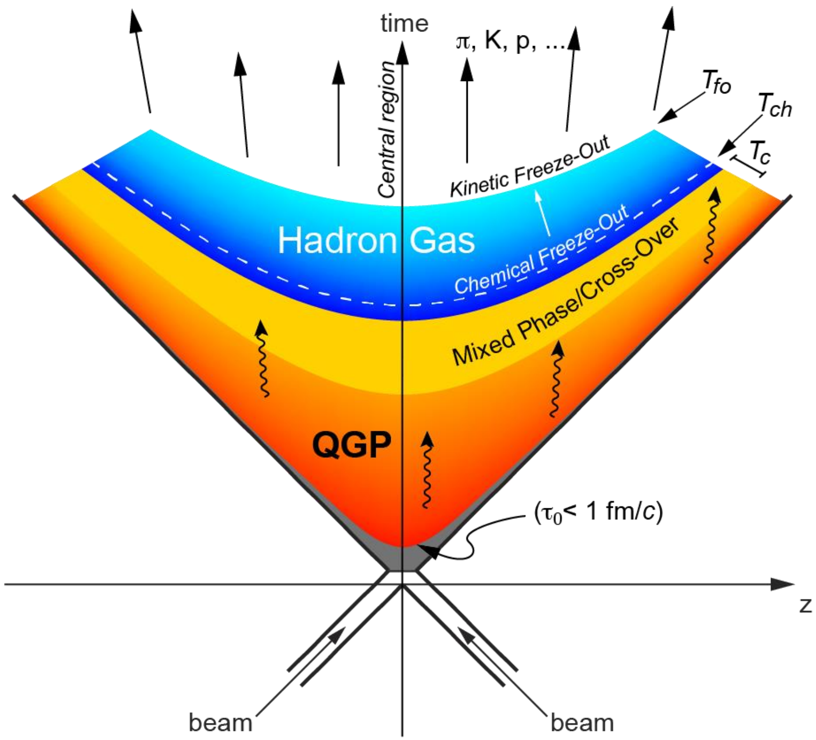
Heavy Quark hadroproduction from collider to astroparticle physics
Mainz, October 4th 2019

Space-time evolution of heavy-ion collisions



Time

Kinetic freeze-out | t~10 fm/c

Chemical freeze-out

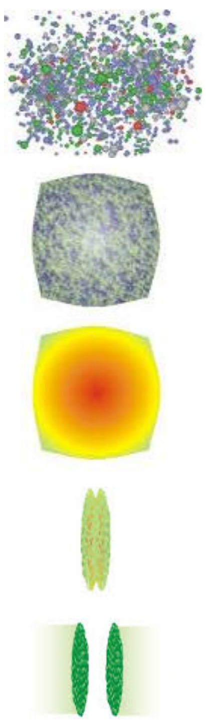
Hadronization

QGP hydrodynamic evolution

t~1 fm/c

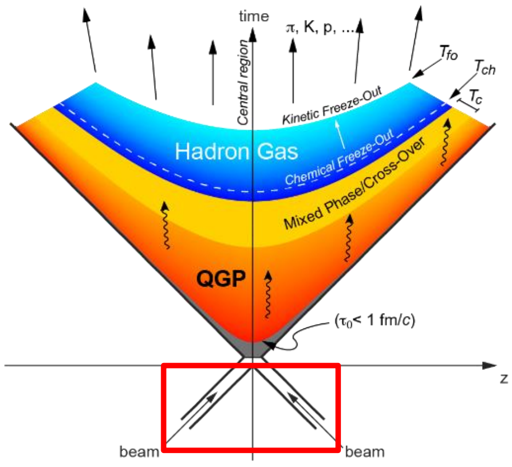
Pre-equilibrium

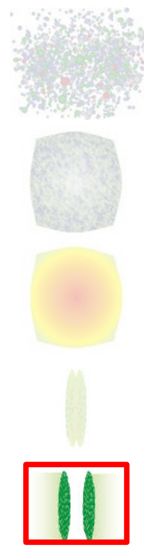
Collision | t=0 fm/c



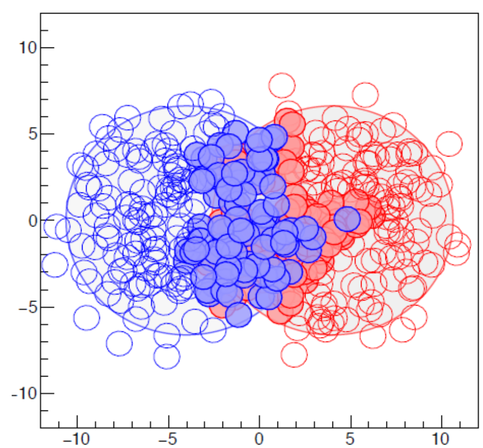
- QGP lifetime ~ a few fm/c
- Expansion under strong pressure gradients
- Transition to hadrons when temperature drops below critical value

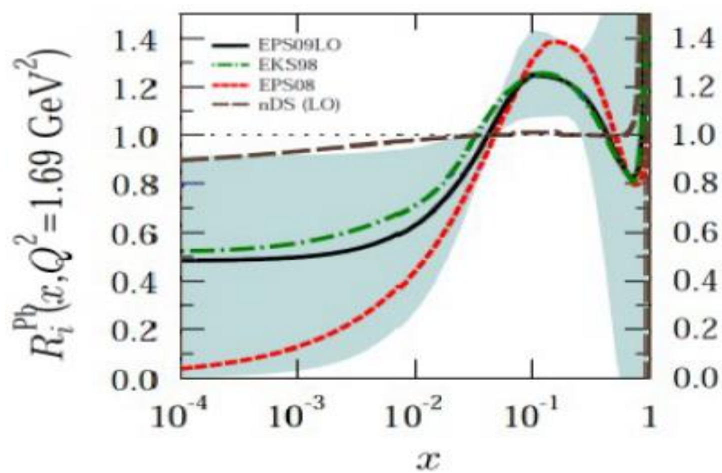
Initial state



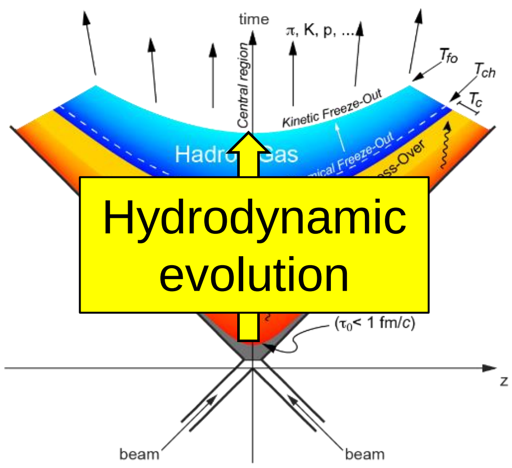


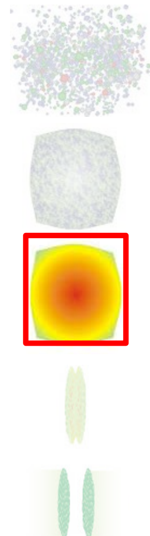
- What is the structure of the colliding objects?
  - ⇨ Spatial and momentum distribution of incoming partons
  - ⇨ Modification of the **PDFs in bound nucleons** (nPDF)
  - ⇨ Gluon saturation at small Bjorken-x / Color Glass condensate
  - ⇨ k_T broadening



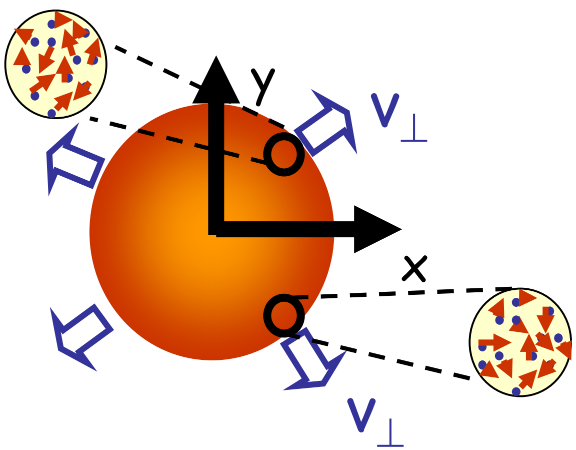


Collective expansion

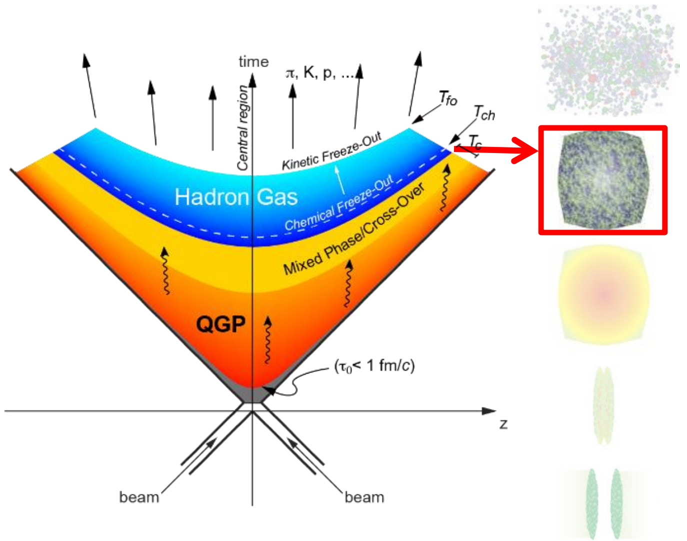




- System undergoes a **rapid expansion**
  - After collision: high-density QGP droplet in vacuum
  - Strong **pressure gradient** from center to boundary
  - Particles (quarks and gluons in the QGP phase and hadrons in the hadronic phase) get pushed by this pressure gradient
  - ***FLOW = Collective motion*** superimposed **on top of the *thermal* motion**
- Expanding medium can be described macroscopically with **hydrodynamical** models
  - Valid from the equilibration (hydrodynamization) time (<~1 fm/c) to the thermal-freeze out
    - ✓ ***Need model for initial state and freeze-out***
  - Deduce conclusions on initial conditions, Equation of State… by data comparison



Hadronization

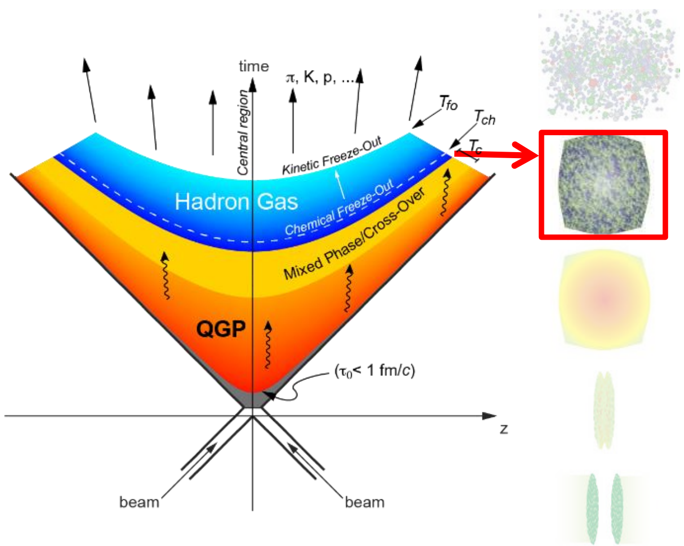


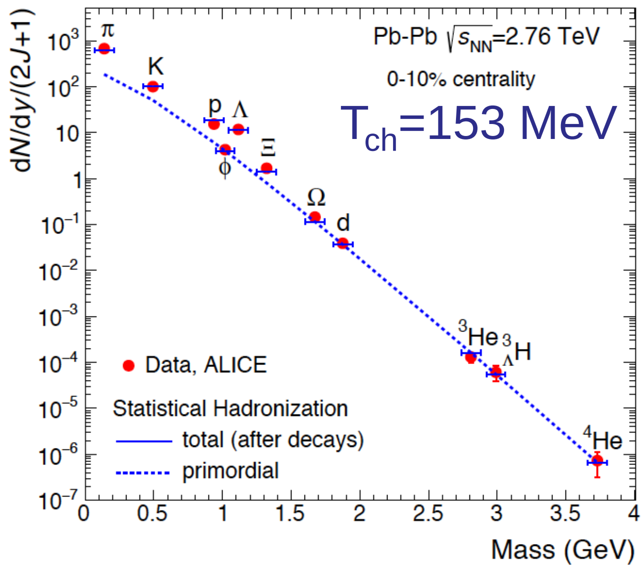
- Hadronization of the QGP medium at the pseudo-critical temperature
  - ⇨ Transition from a deconfined medium composed of quarks, antiquarks and gluons to color-neutral hadronic matter
  - ⇨ The partonic degrees of freedom of the deconfined phase convert into hadrons, in which partons are confined
- 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

“Chemical” composition

📖 Andronic et al. Nature 561 (2018) 321





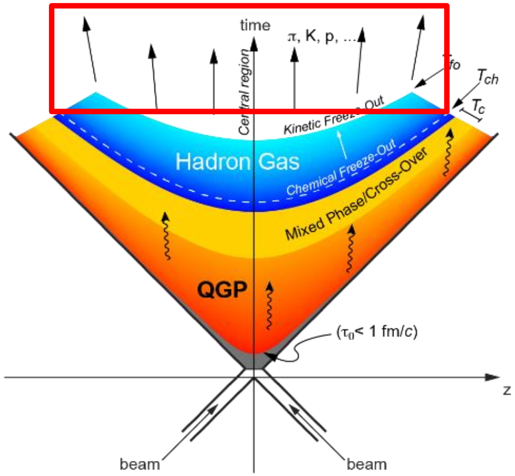
- At the **chemical freeze-out**
  - ⇨ Inelastic collisions cease
  - ⇨ Abundances of different hadron species fixed
- Hadron yields (dominated by low-p_T particles) described by statistical/thermal models
  - ⇨ Abundances follow expectation for hadron gas in chemical and thermal equilibrium
  - ⇨ Yields depend on hadron masses and spins, chemical potentials and temperature:

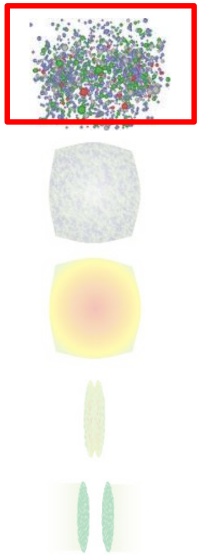
$$\frac{dN}{dy} \sim e^{-m/T_{ch}}$$

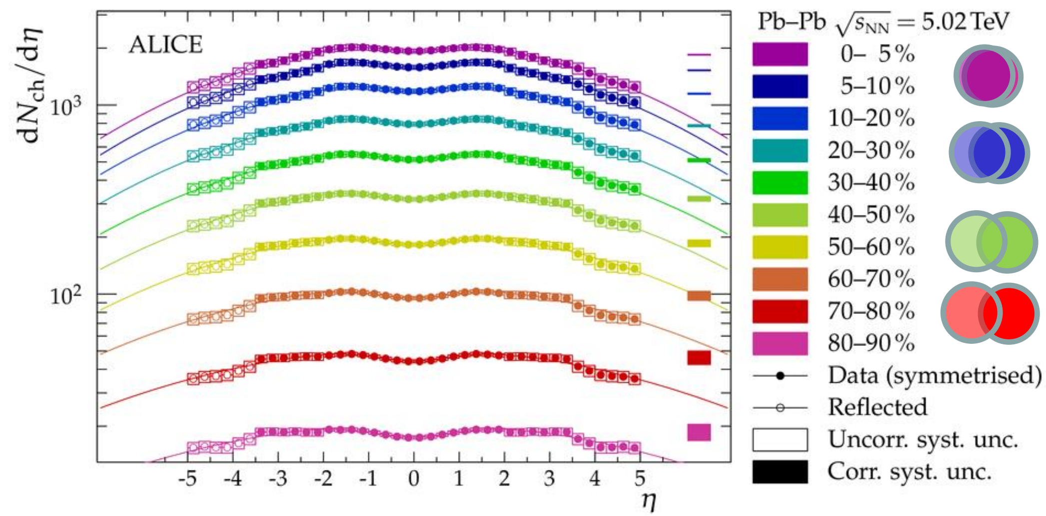
  - ⇨ Estimate **temperature**, baryochemical potential at the **chemical freeze-out**

Final state: the "bulk"

~**21000** particles produced in central Pb-Pb @ $\sqrt{s_{NN}}$=5.02 TeV







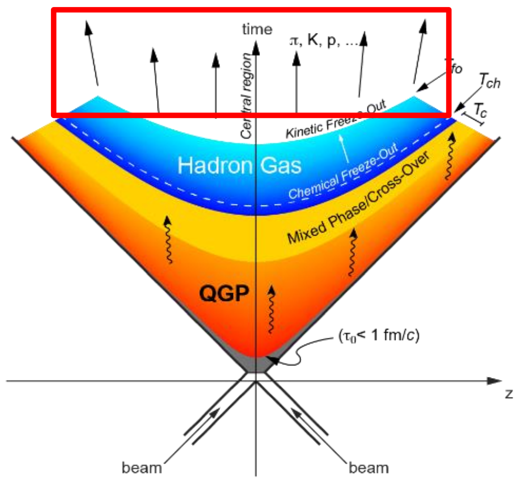
📖**ALICE, PLB 772 (2017) 567**

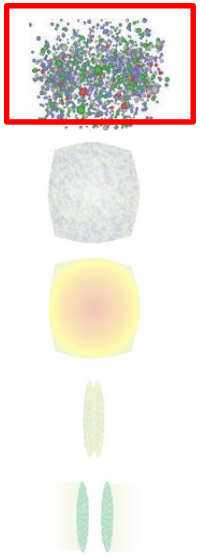
- Multiplicity of produced particles depends on collision geometry
  - ⇨ Decreases from central to peripheral collisions
- Large energy density in the created "fireball":
  - ⇨ **ε~12 GeV/fm³** at τ=1 fm/c in central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

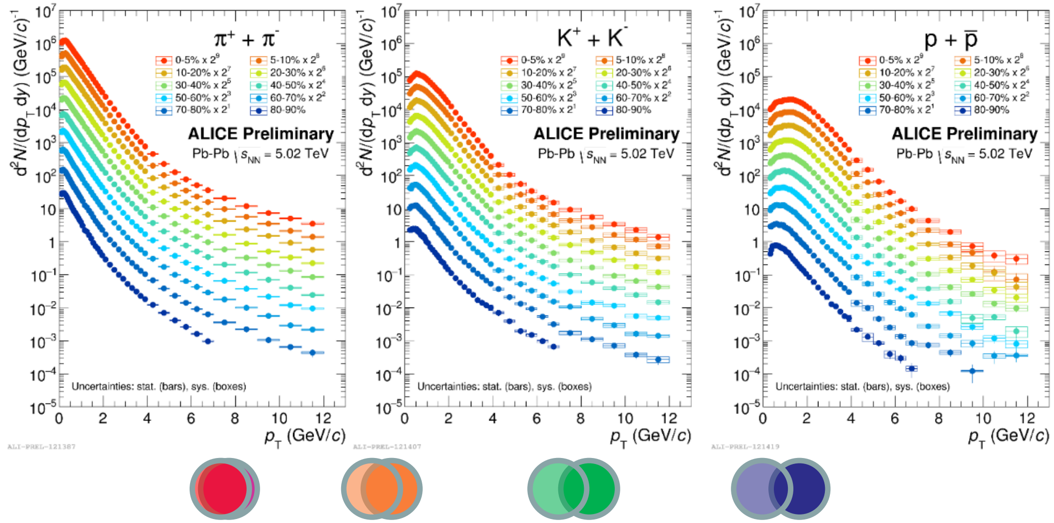
📖**ALICE, PRC 94 (2016) 034903**

Flowing "bulk" of soft particles

~**21000** particles produced in central Pb-Pb @ $\sqrt{s_{NN}}$=5.02 TeV







- Particle momentum spectra frozen at the **kinetic freeze-out**
  - ➯ Even at LHC energy, 95% of produced particles have p_T<2 GeV/c
  - ➯ Bulk of particle production associated with **"soft" physics** in non-perturbative regime of QCD
- Hardening of spectral shapes with increasing centrality and particle mass
  - ➯ Spectra "pushed" to higher p_T by the *common velocity field* $v_\perp$ **(radial flow)**
  - ➯ Described by **hydrodynamic expansion** of the medium with velocity β_T~0.5-0.6c at freeze-out temperature T_{kin}~100 MeV

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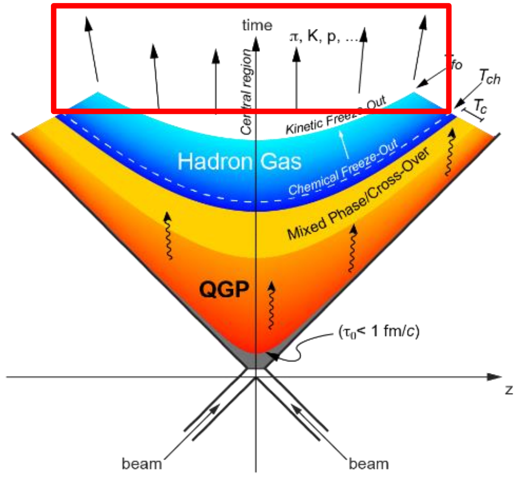

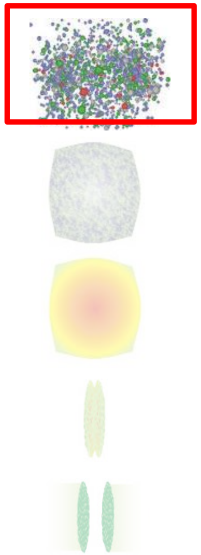

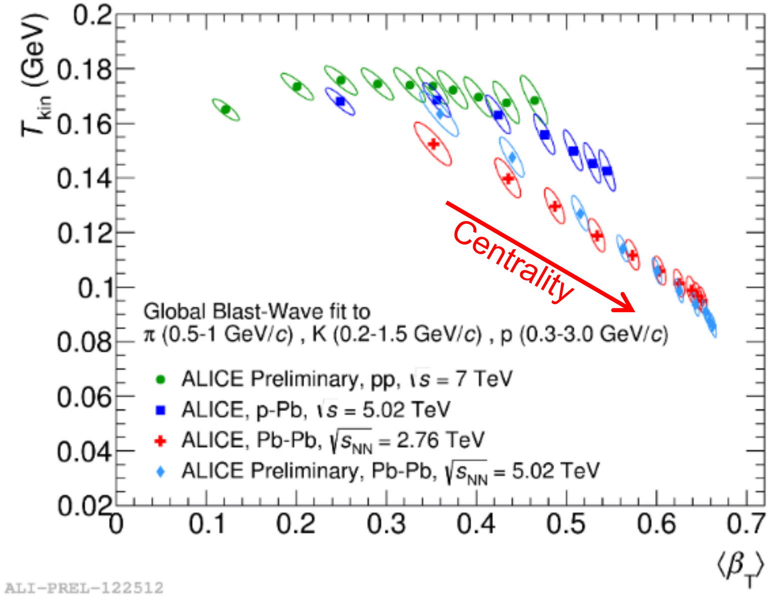

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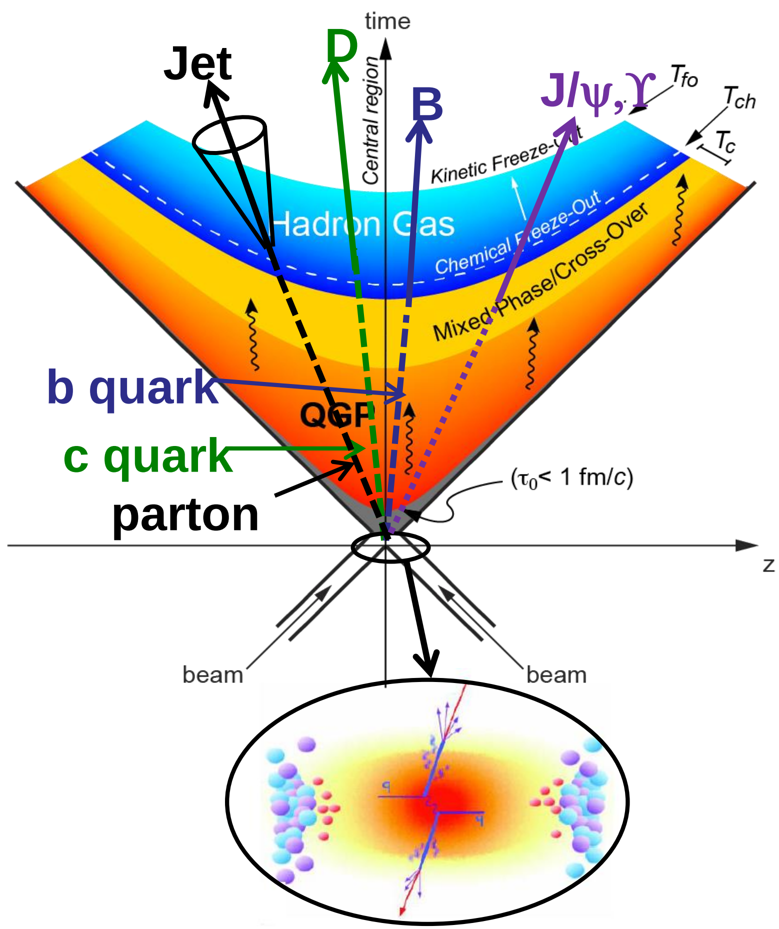
Hard probes of the QGP medium



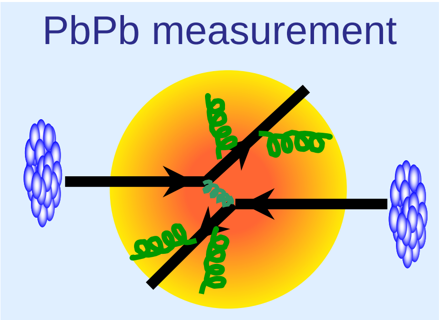
- Produced at the **very early stage** of the collision in partonic scattering processes with large momentum transfer
  - Produced out-of-equilibrium
- Traverse the hot and dense medium interacting with its constituents
  - The hard-scattered parton interacts with the medium constituents -> **energy loss** through:
    - ✓ ***Elastic collisions***
    - ✓ ***Gluon radiation***
  - Energy loss depends on:
    - ✓ ***Medium density***
    - ✓ ***Path-length in the medium***
    - ✓ ***Parton species (gluon vs. quark) and mass***
- **Unique probes** of the properties of the QGP
  - **Tomography of the medium**

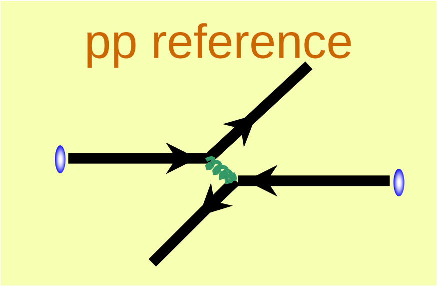
Nuclear modification factor

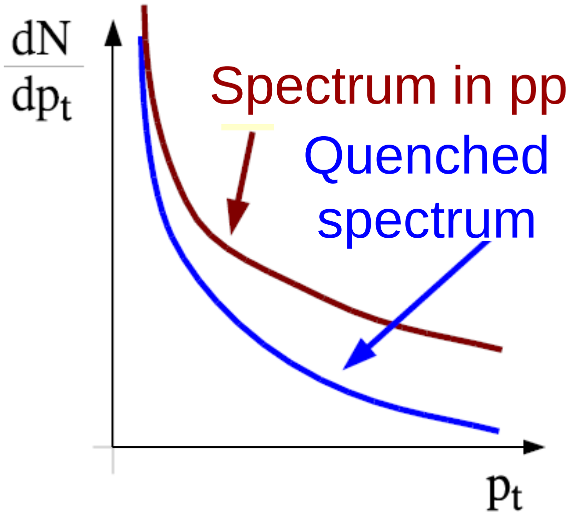
- Hadrons and jets from the hadronization of hard partons are unique probes of the QGP
- Observable: **nuclear modification factor**

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

  - ⇨ Hard processes in nuclear collisions expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
  - ⇨ If **no nuclear effects** are present → $\mathbf{R_{AA}=1}$
  - ⇨ **QGP** can modify the yield and distributions of final state hadrons and jets → $\mathbf{R_{AA}\neq 1}$
  - ⇨ Parton in medium **energy loss** → jet quenching → $\mathbf{R_{AA}<1}$ at high p_T
- But also cold nuclear matter effects (e.g. nuclear modification of PDF) may lead to $R_{AA}\neq 1$
  - ⇨ Need **control experiments**: medium-blind probes (photons, Z, W bosons) + p-A collisions

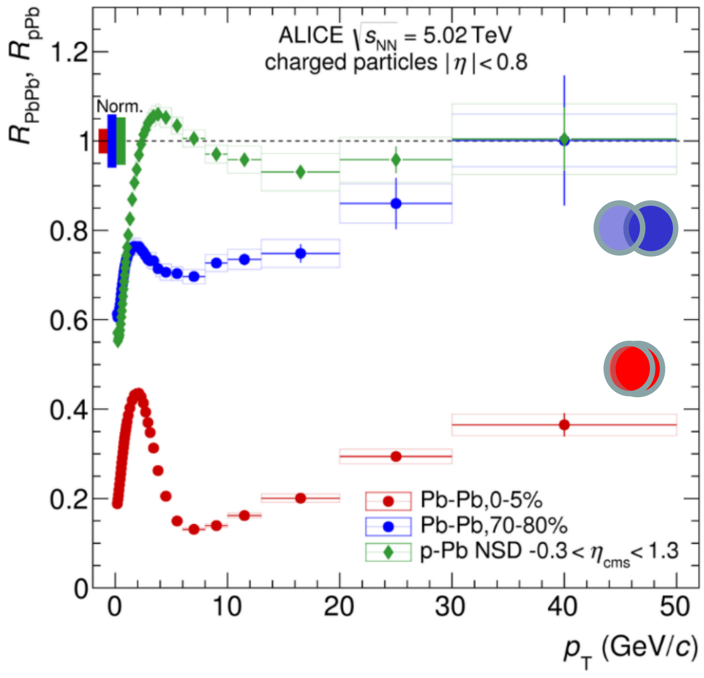


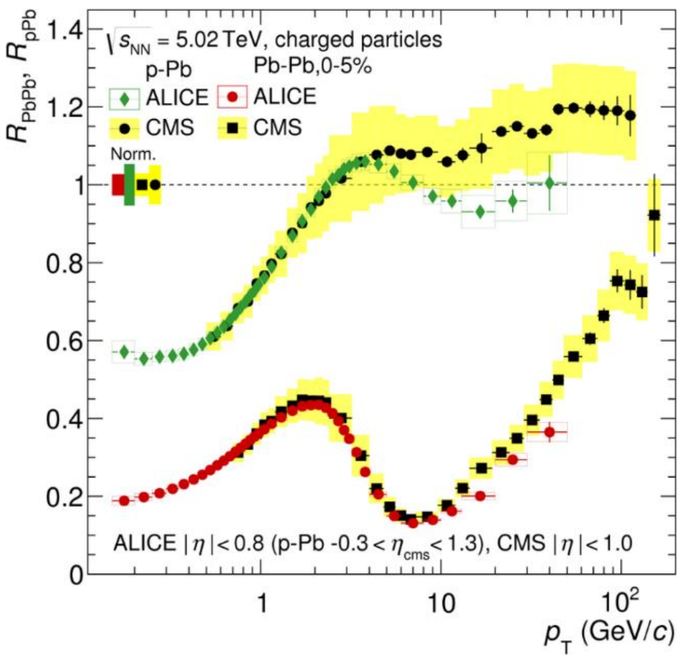




R_{AA} of hadrons

- Charged hadron yield at high p_T suppressed in Pb-Pb collisions (R_{AA}<1)
  - ⇨ Suppression decreases from **central** to **peripheral** collisions
    - ✓ ***Smaller path length, lower medium density in peripheral collisions***





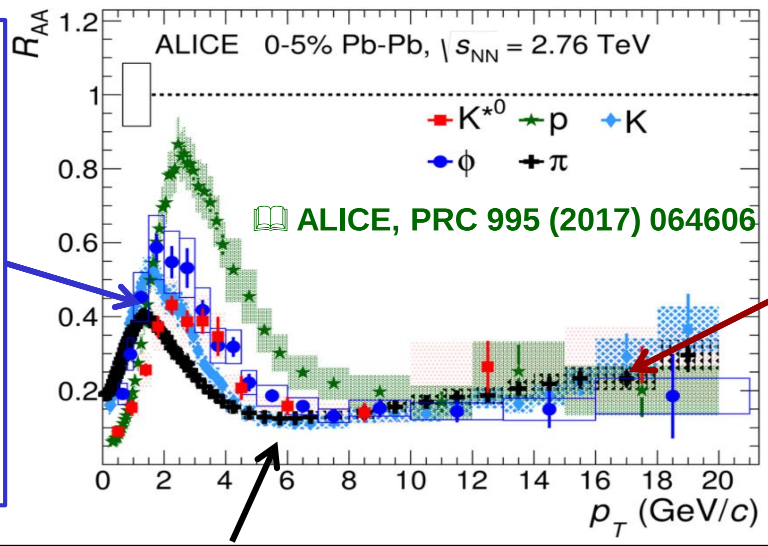
📖**CMS, JHEP 04 (2017) 039**

📖**ALICE, JHEP 11 (2018) 013**

- No evidence of jet quenching in p-A collisions
  - ⇨ R_{pPb}~1 in **p-Pb collisions**
  - ⇨ Suppression in A-A collisions due to hot and dense medium

Identified hadron R_{AA}

Low-p_T (<~2 GeV/c) :
- Thermal regime
- Hydrodynamic expansion driven by pressure gradients
- Radial flow peak, mass ordering

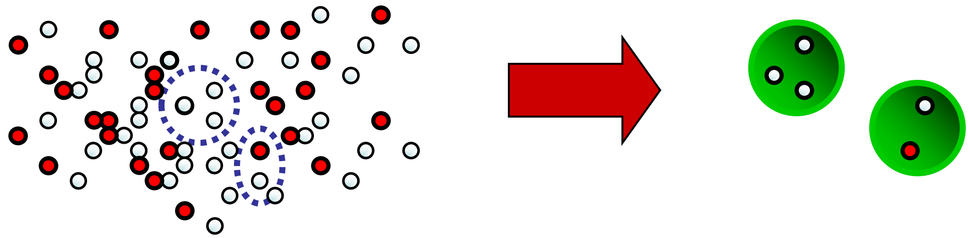


High-p_T (>10 GeV/c) :
- Partons from hard scatterings
- Lose energy while traversing the QGP
- Hadronisation via fragmentation → same R_{AA} for all species

Intemediate-p_T (ca. $3<p_T<8$ GeV/c) :
- Kinetic regime (not described by hydro)
- Different R_{AA} for different hadron species
  - Inconsistent with hard partons + energy loss + universal fragmentation
- Features described with in-medium **hadronization via quark recombination**

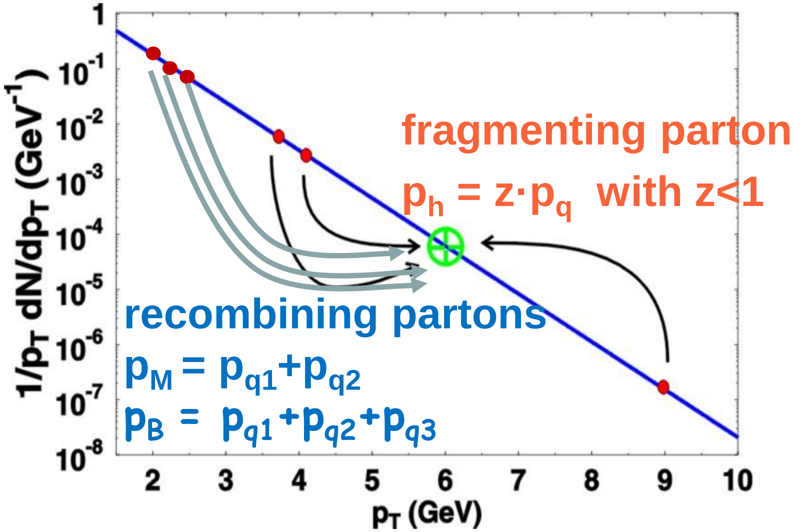
Hadronisation in medium

- 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



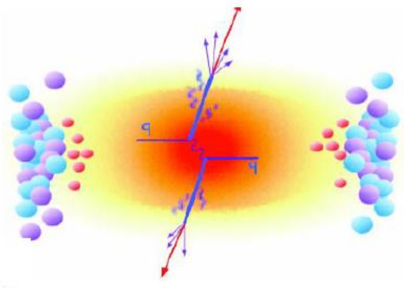
📖 Greco et al., PRL 90 (2003) 202302
📖 Fries et al., PRL 90 (2003) 202303
📖 Hwa, Yang, PRC 67 (2003) 034902

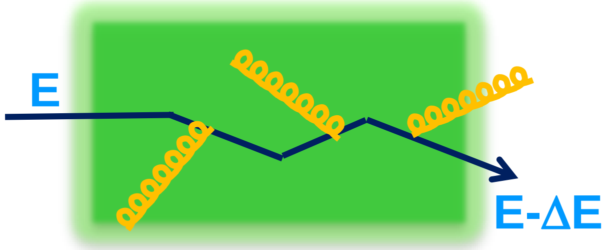
- Recombination vs. fragmentation:
  - ⇨ Competing mechanisms
  - ⇨ Recombination naturally enhances baryon/meson ratios at intermediate p_T

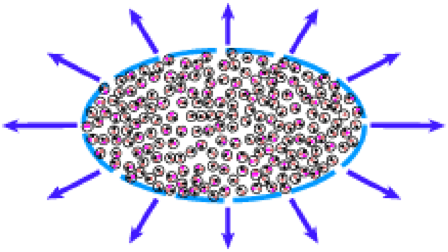


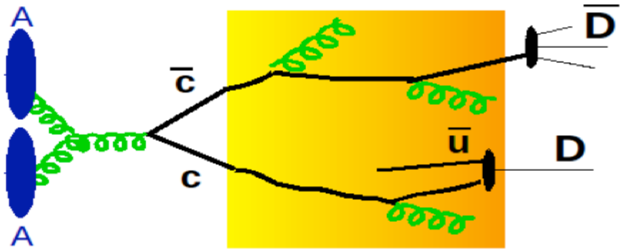
Heavy quarks in the QGP

- Produced in the early stages of the collision in hard-scattering processes
  - ⇨ Initial production calculable with pQCD
  - ⇨ Produced out of equilibrium
  - ⇨ Thermal production in the QGP negligible
- Interaction of heavy quarks with the QCD medium constituents
  - ⇨ **Energy loss:**
    - ✓ ***Elastic collisions*** *with the medium constituents (-> collisional energy loss)*
    - ✓ ***Gluon radiation***
  - ⇨ **Momentum gain due to the "push" from medium collective expansion**
    - ✓ *Do low-p_T heavy quarks* ***thermalize in the medium?***
  - ⇨ **In-medium hadronization**
    - ✓ *Hadronization via* ***(re)combination*** *of the charm quark with a (light) quark from the medium ?*



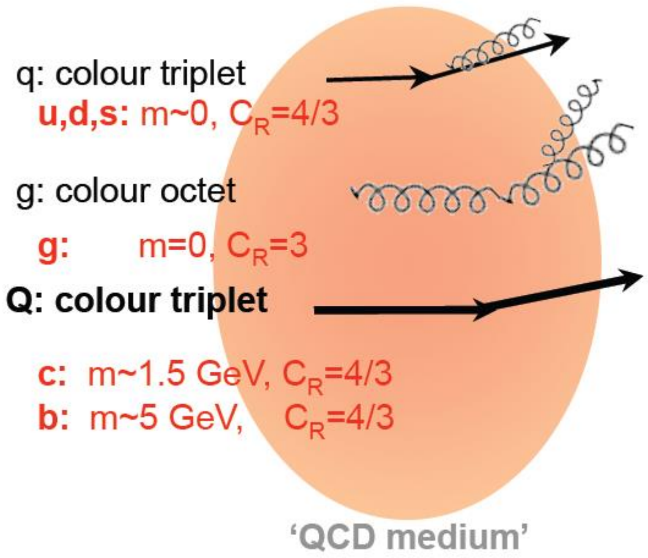






Heavy-quark energy loss

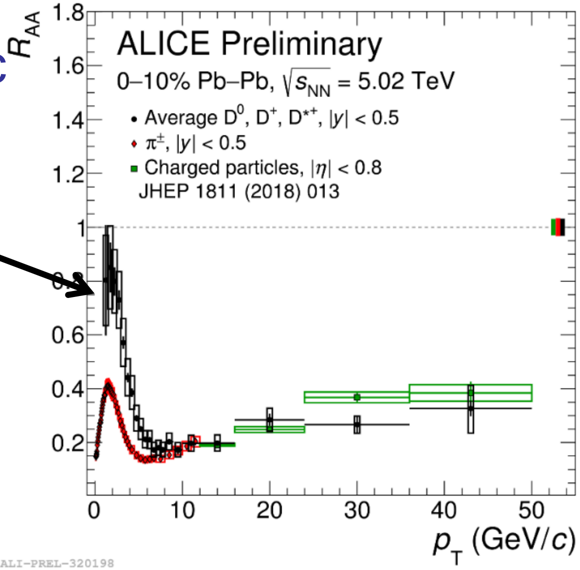
- In-medium energy loss ΔE depends on:
  - ⇨ Properties of the medium (density, temperature, mean free path, …) -> **transport coefficients**
  - ⇨ Path length in the medium
  - ⇨ Properties of the parton (**colour charge, mass**) traversing the medium
    - ✓ ***Casimir coupling factor***
      -> C_R = 3 for gluons
      -> C_R = 4/3 for quarks
    - ✓ ***Mass of the quark***

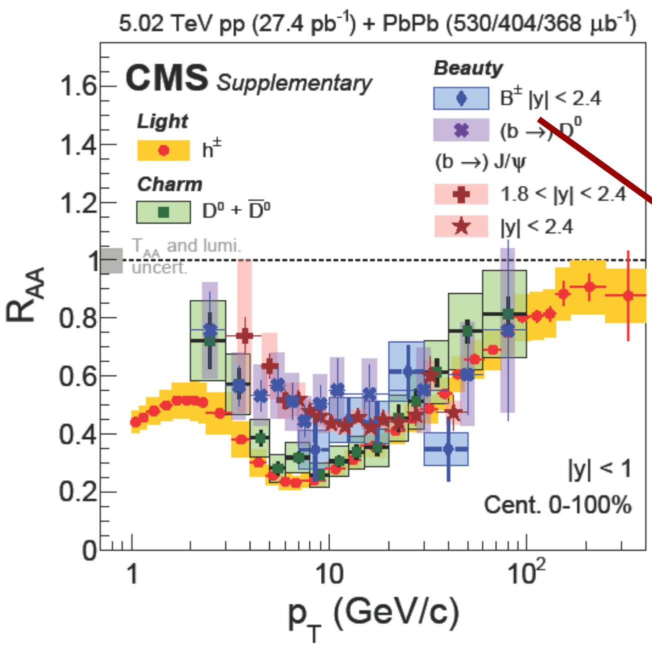


- Expectation: hierarchy in energy loss: $\boxed{\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b}$
- Should be reflected in a R_{AA} hierarchy: $\boxed{R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)}$

Charm vs. beauty vs. light flavours

- **D-meson R_{AA}** larger than **pion R_{AA}** for p_T< 8 GeV/c
- Captured by models including
  - ⇨ Energy loss hierarchy ($\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$)
  - ⇨ Different p_T shapes of produced partons
  - ⇨ Different fragmentation functions of gluons, light and charm quarks

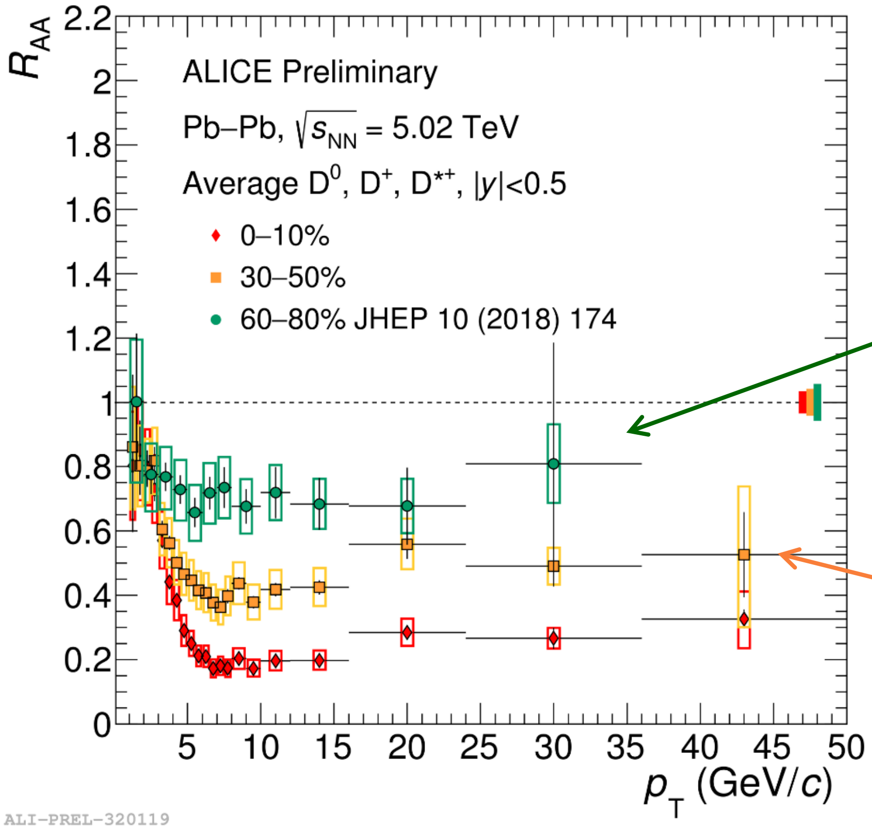




- Beauty via non-prompt D^0, non-prompt J/ψ and $B^{\pm} \rightarrow J/\psi\ K^{\pm}$
- **R_{AA}(beauty)>R_{AA}(charm)** for p_T<20 GeV/c
  - ⇨ As expected from **quark-mass dependence** of energy loss
- R_{AA} of beauty, charm and light merging at p_T~20 GeV/c

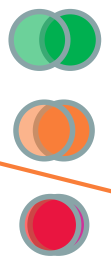
📖CMS, arXiv:1810,11102 📖CMS, PRL 119 (2017) 152301
📖CMS, EPJC 78 (2018) 509 📖CMS, PLB 782 (2018) 474 📖ALICE, JHEP 10 (2018) 174

Centrality (system size) dependence



$\langle N_{part} \rangle$ ~ 24

- Comparable to central O-O collision (N_{part}~30)
- Only slightly smaller than central Fe-O collision ($\langle N_{part} \rangle$~45-50)



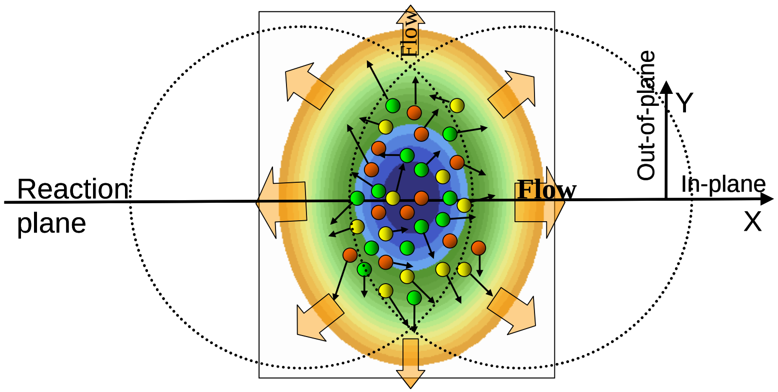
$\langle N_{part} \rangle$ ~ 100

- Much larger than O-O and Fe-O collisions

- Suppression at high p_T decreases from central to peripheral collisions
  - ⇨ Smaller in-medium path length (smaller size of the fireball) and lower medium density in peripheral collisions

Heavy-quark elliptic flow

- Initial geometrical anisotropy in non-central heavy-ion collisions
  - The impact parameter selects a preferred direction in the transverse plane



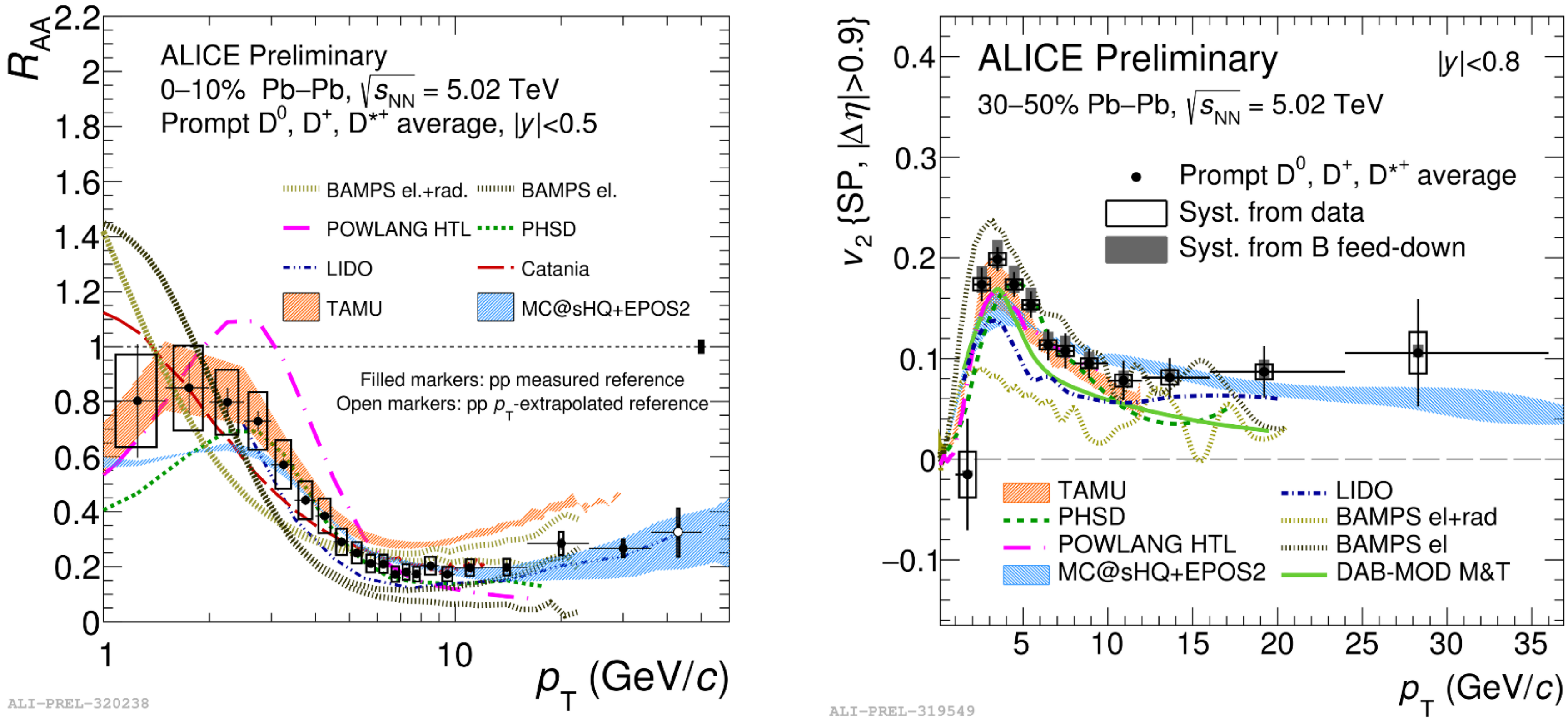
- Re-scatterings among produced particles convert the initial geometrical anisotropy into an observable momentum anisotropy
  - Anisotropies for **low-p_T** particles due to collective motion (**flow**)
  - Heavy quarks "pushed" by the flow of the medium
- In addition, anisotropic patterns induced (also at **high p_T**) by **path-length dependent energy loss** in an almond-shaped medium
  - Longer path length → larger energy loss for particles exiting out-of-plane
- Observable: Fourier coefficients of the particle azimuthal distribution, in particular 2nd harmonic v_2, called **elliptic flow**

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left\{1 + 2v_2\cos\left[2\left(\varphi - \Psi_{RP}\right)\right] + ...\right\}$$

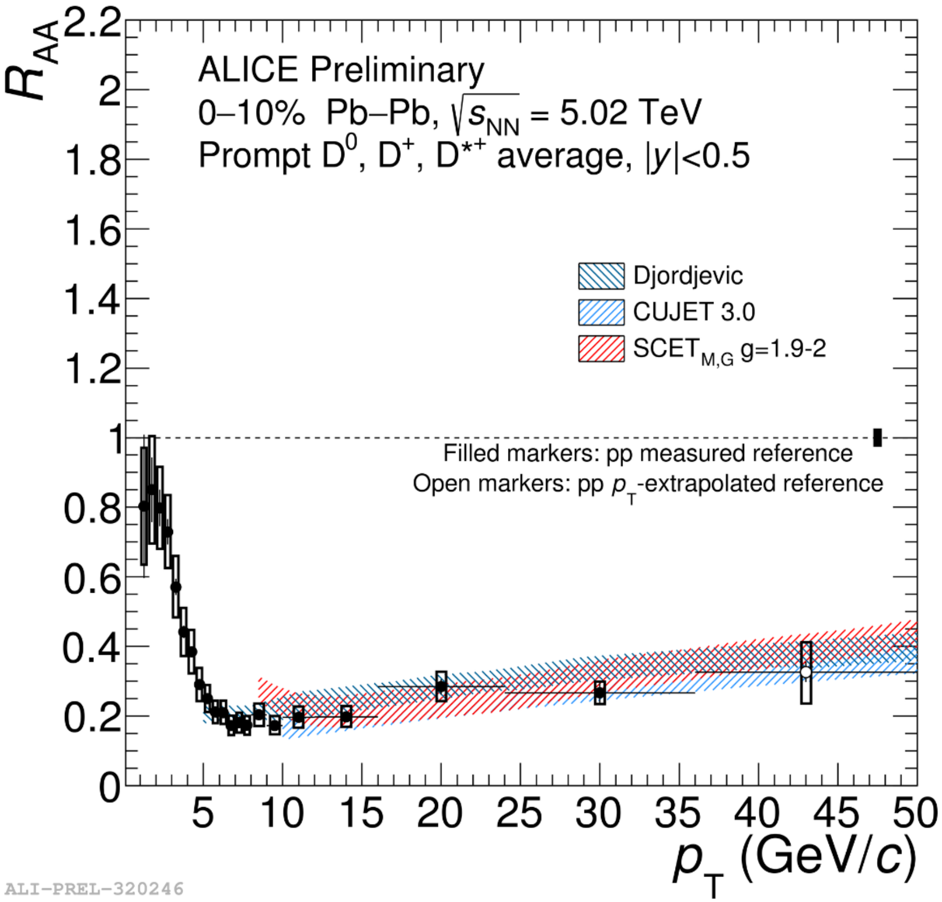
$$v_2 = \left\langle \cos\left[2\left(\varphi - \Psi_{RP}\right)\right]\right\rangle$$

Charm R_{AA} and v_2 phenomenology

- Simultaneous comparison of R_{AA} and v_2 to models can constrain QGP properties and the description of charm-quark interaction and diffusion in the medium
  - ⇨ Interplay of CNM effects, collisional and radiative energy loss, hadronisation via coalescence and fragmentation and realistic underlying medium evolution required to describe data



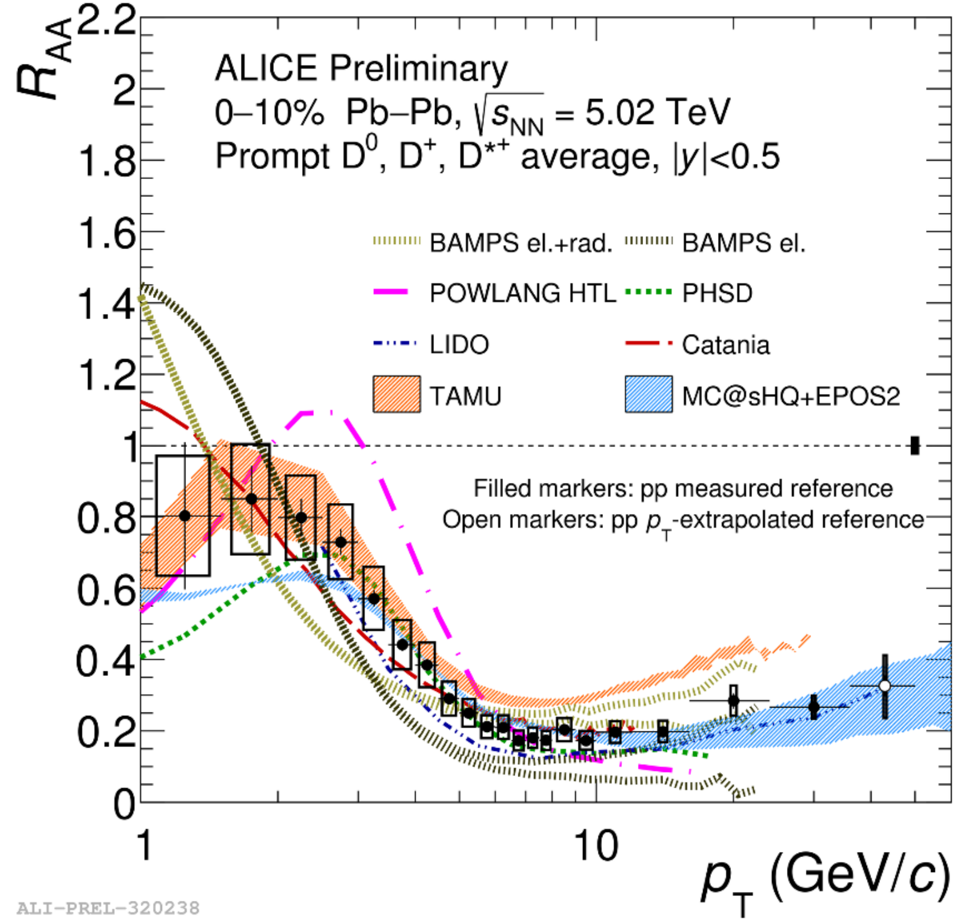
Two regimes



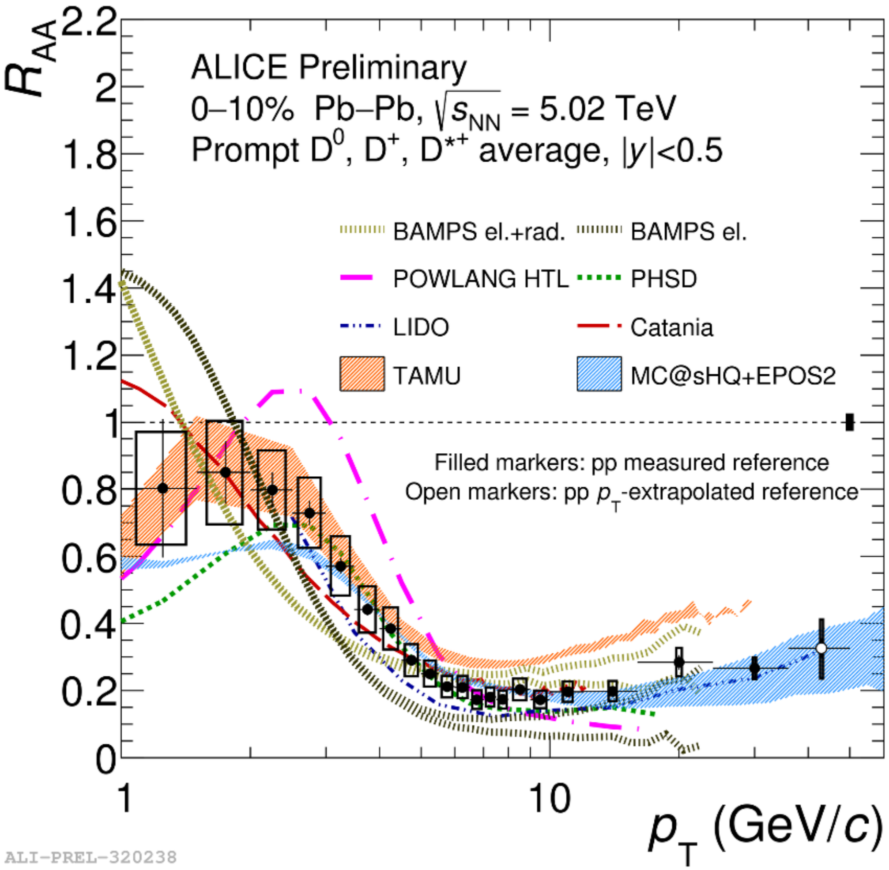
- High p_T (>~10 GeV/c)
  - Dominant effect: **energy loss** of charm and beauty quarks in the medium
    - ✓ ***Radiative energy loss*** *expected to dominate*
    - ✓ *"Early" signal: most of energy loss in the hottest (most dense) stages of the fireball*
  - Goal: study **colour charge** and **quark mass** dependence of in-medium energy loss
  - Relevant transport coefficient: $\hat{q}$

Two regimes

- Low p_T (<~5 GeV/c)
  - ⇨ Interplay of several effects:
    - ✓ ***Energy loss (collisional)***
    - ✓ ***Radial flow "push"***
    - ✓ ***Hadronization via recombination***
    - ✓ ***Nuclear PDFs***
  - ⇨ Goal: study how (if) heavy quarks **reach the equilibrium** with the medium
  - ⇨ Relevant transport coefficient: D_s (spatial diffusion coefficient)



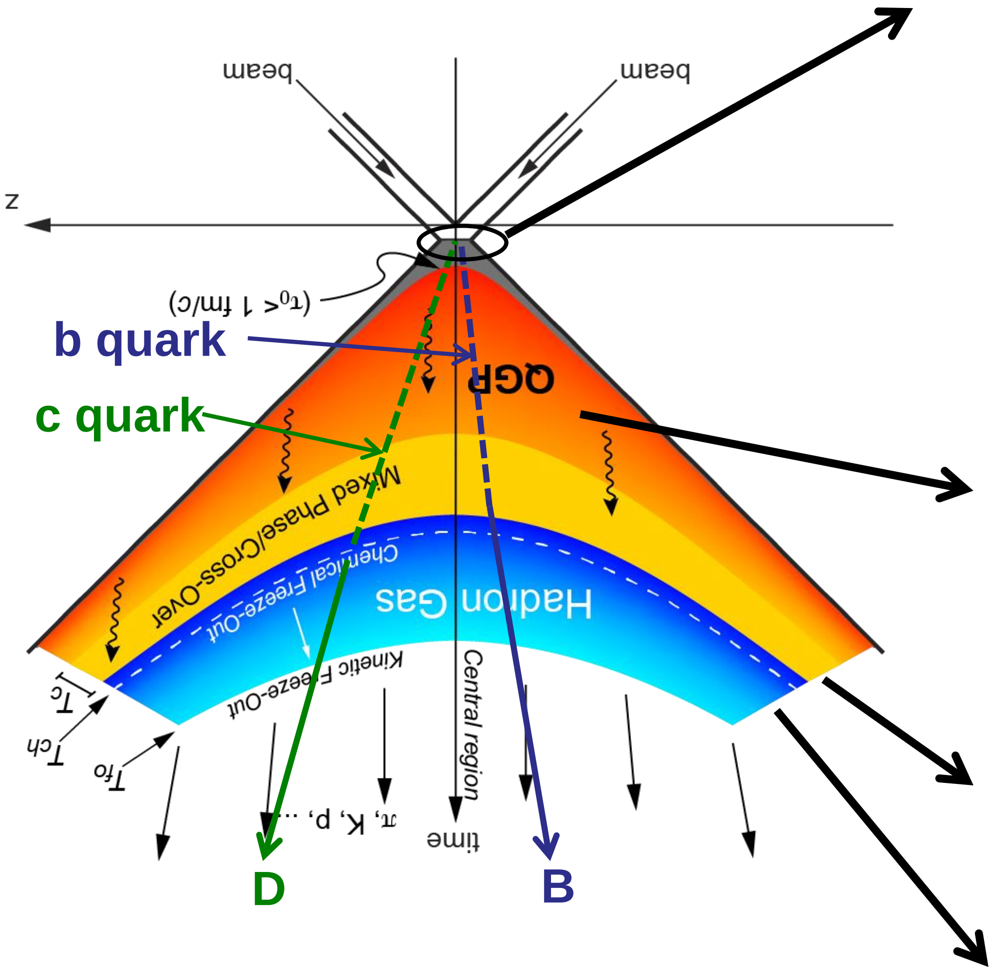
Low p_T: approach to equilibrium



- Description of heavy-flavour observables at all p_T's requires a setup allowing to deal with:
  - ⇨ Partons produced off equilibrium
  - ⇨ Interact with expanding medium
  - ⇨ Thermalization time longer than that of light flavours and comparable to fireball lifetime
    - ✓ ***Heavy quarks preserve memory of their interaction history → gauge their interaction strength with the QGP***
  - ⇨ HF can provide insight on how particles would (asymptotically) approach equilibrium

→ Transport models

Transport setup



- Initial production
  - ⇨ pQCD + possible "cold" (initial) nuclear effects: nPDF, k_T broadening
- Background medium
  - ⇨ Hydrodynamics: T(x), u^{μ}(x), needed for local value of transport coefficients
- Heavy quark dynamics in the medium
  - ⇨ Interactions with medium constituents, transport coefficients
- Hadronization
  - ⇨ Fragmentation in vacuum, coalescence
- Hadronic phase

Transport models: ingredients

Model	Heavy-quark production	nPDFs	Medium modelling	Quark-medium interactions	Hadronization	Hadron phase
Transport models						
BAMPS [28, 38, 76]	MC@NLO	No	Boltzmann parton 3+1D	Boltzmann pQCD coll+rad	frag	no
Cao *et al*/Duke [83, 84, 212]	MC@NLO	EPS09	Hydro 2+1D viscous	Langevin coll +pQCD rad	frag+ reco	yes
MC@sHQ+EPOS [45, 73, 74]	FONLL	EPS09	Hydro 3+1D (EPOS)	Boltzmann pQCD coll+rad	frag+ reco	no
PHSD [40, 51]	PYTHIA* tuned to FONLL	EPS09	off-shell parton transport	off-shell trans DQPM coll	frag+ reco	yes
POWLANG [36, 48, 124]	POWHEG	EPS09	Hydro 2+1D viscous	Langevin pQCD coll	string- reco	no
TAMU [65, 77, 126]	FONLL	EPS09	Hydro 2+1D ideal	Langevin T-mat coll	frag+ reco	yes

Heavy quark transport

- Space-time evolution of heavy quark phase space distribution function f_Q described in kinetic theory by **Boltzmann equation**
- For large quark masses and moderate temperatures:
  - ⇨ Typical momentum transfers in scatterings between heavy quarks and medium constituents (heat bath) are small
  - ⇨ Heavy quarks undergo soft and incoherent collisions -> **Brownian motion**
- Boltzmann equation reduces to **Fokker-Plank equation**:

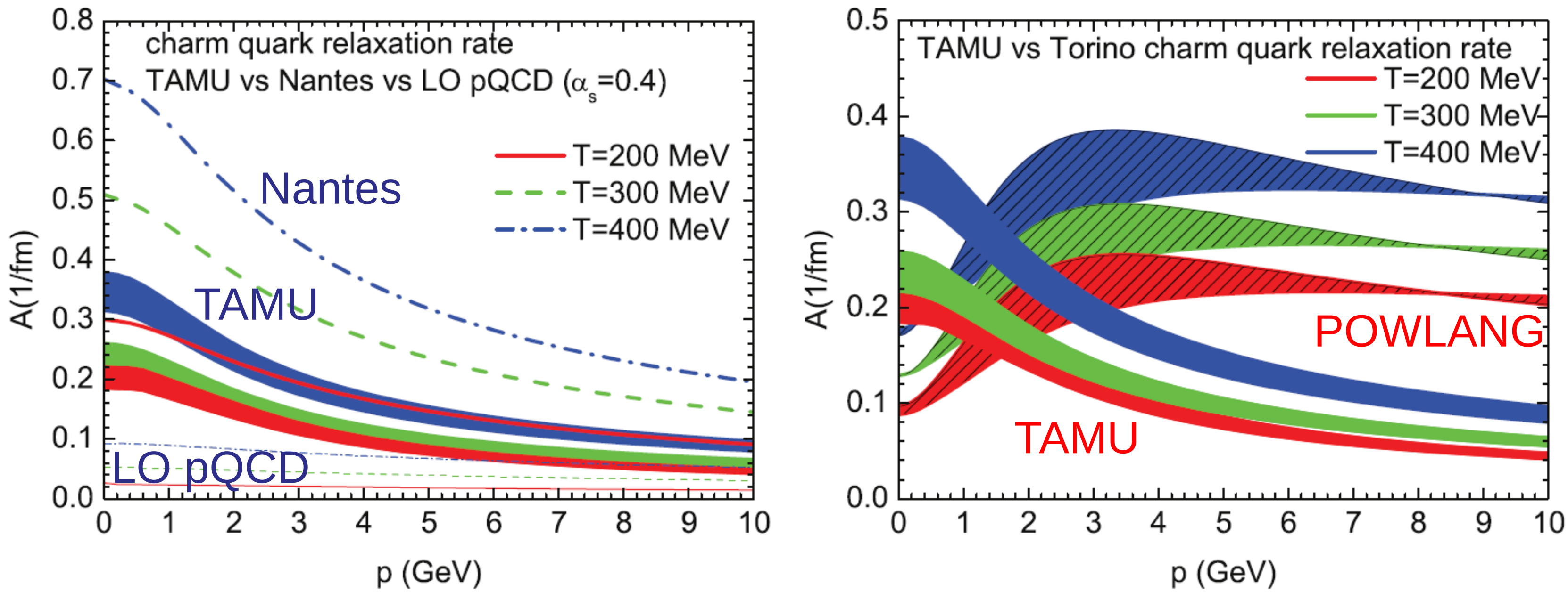
$$\frac{\partial}{\partial t} f_Q(t,\mathbf{p}) = \frac{\partial}{\partial p^i}\left\{ A^i(\mathbf{p}) f_Q(t,\mathbf{p}) + \frac{\partial}{\partial p^j}\left[B^{ij}(\mathbf{p}) f_Q(t,\mathbf{p})\right]\right\}$$

  - ⇨ Key ingredients are the transport parameters A and B
  - ⇨ In case of a medium in equilibrium, they simplify to **three transport coefficients** which are “a priori” independent among each other

$$A_i(\vec{p}\,) = A(p) p_i, \longrightarrow \textbf{FRICTION}$$

$$B_{ij}(\vec{p}\,) = B_0(p) P_{ij}^{\perp}(\vec{p}\,) + B_1(p) P_{ij}^{\parallel}(\vec{p}\,) \longrightarrow \textbf{MOMENTUM BROADENING}$$

Transport coefficients



- Friction coefficient = heavy quark relaxation rate
  - ⇨ Depend on temperature and heavy-quark momentum
  - ⇨ Different models use different approaches to compute A(p,T)
    - ✓ ***Larger friction coefficient than results from LO pQCD calculations***
    - ✓ *POWLANG (Torino, pQCD-inspired): different momentum dependence as compared to MC@sHQ (Nantes, also pQCD inspired) and TAMU (T-matrix approach constrained to lattice QCD)*
    - ✓ *TAMU: stronger coupling near T_c (due to non-perturbative forces, remnants of the confining force above T_c -> formation of resonances)*

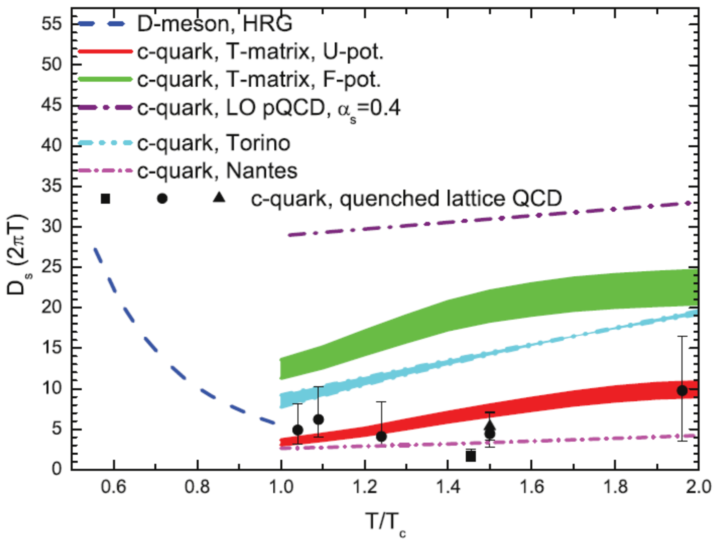
Spatial diffusion coefficient

- Brownian motion of heavy quarks in QGP governed by the coupling of heavy quarks to the medium
  - ⇨ Injecting a particle at x=0 and t=0, the mean squared position at time t is:

$$\left\langle x^2(t) \right\rangle = 6 D_s t$$

- D_s = **spatial diffusion coefficient**
  - ⇨ Encodes the **transport properties** of the medium
    - ✓ ***Coupling strength of heavy quarks with the medium***
    - ✓ ***Small values of D_s → strong coupling***
  - ⇨ Can be calculated in Lattice QCD
  - ⇨ Related to heavy-quark friction coefficient:

$$D_s \propto \frac{T}{m_Q A(p=0)}$$



- Scaling D_s by the thermal wavelength of the medium λ_{th}=1/(2πT) → dimensionless quantity proportional to η/s (viscosity/entropy)

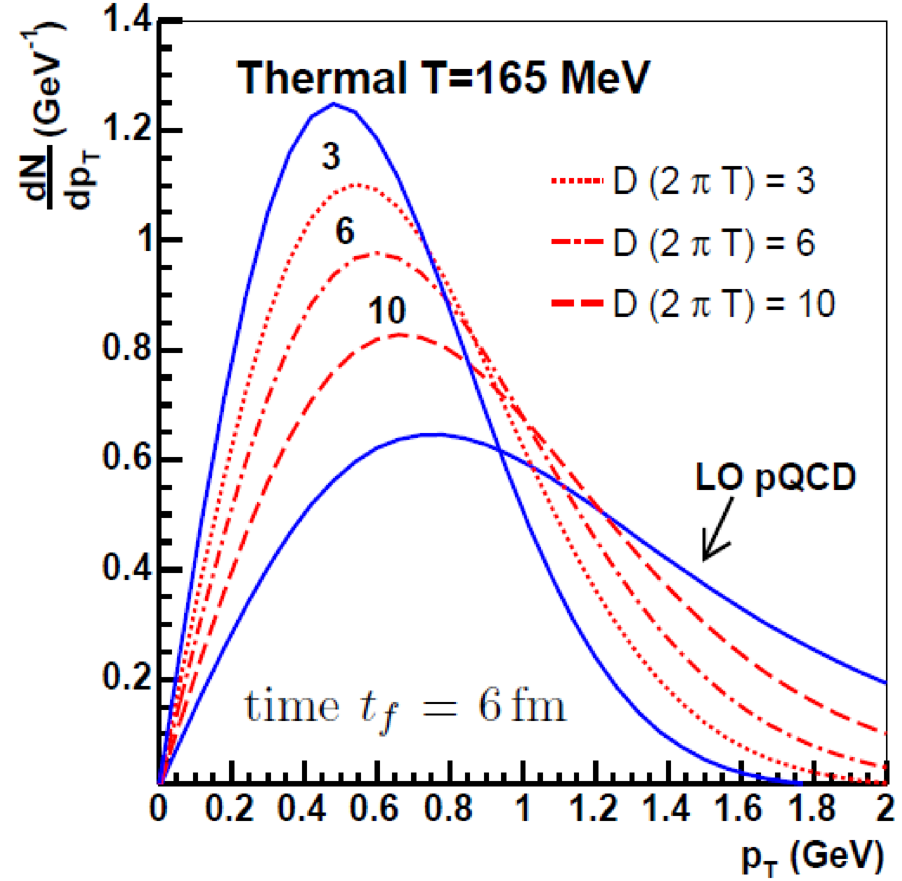
Relaxation time

- Spatial diffusion coefficient related to the relaxation time of heavy quarks in the medium:

$$\tau_Q = \frac{m_Q}{T} D_s \propto \frac{1}{A(p=0)}$$

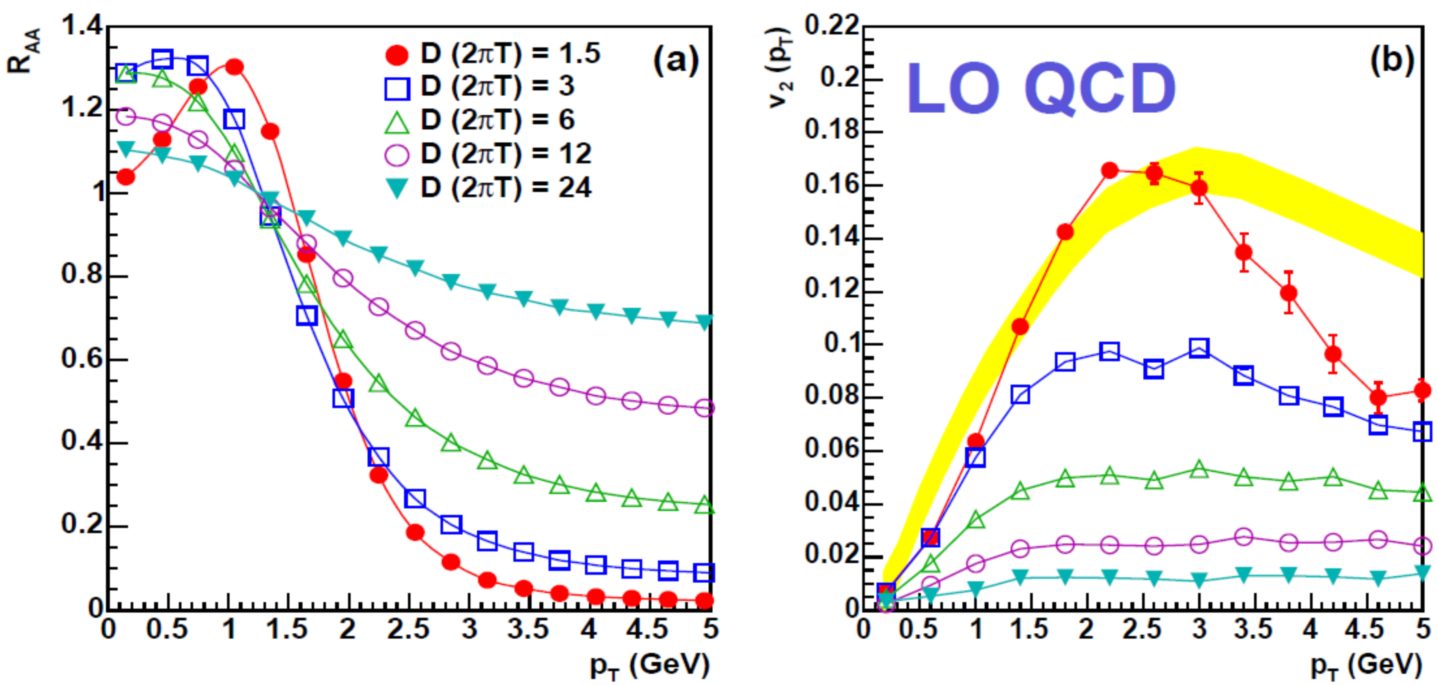
  - ⇨ If relaxation time <~ expansion rate of the medium → heavy quarks will "follow" the medium → large flow of charm
  - ⇨ If relaxation time >> expansion rate of the medium → heavy quark will not follow the medium → small flow of charm

Moore and Teaney, PRC71 (2005) 064904



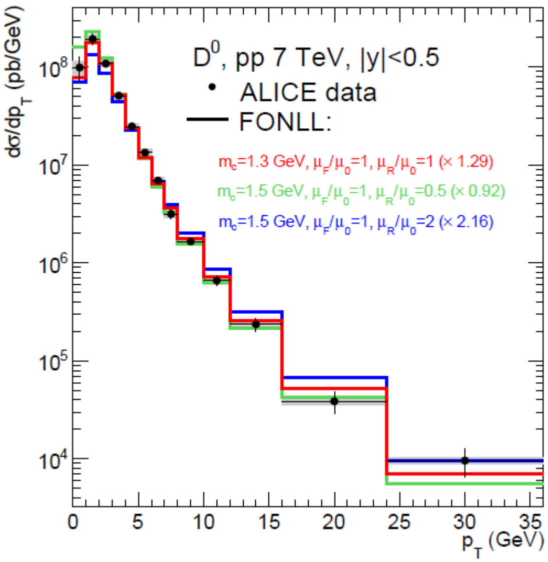
Extracting transport coefficients

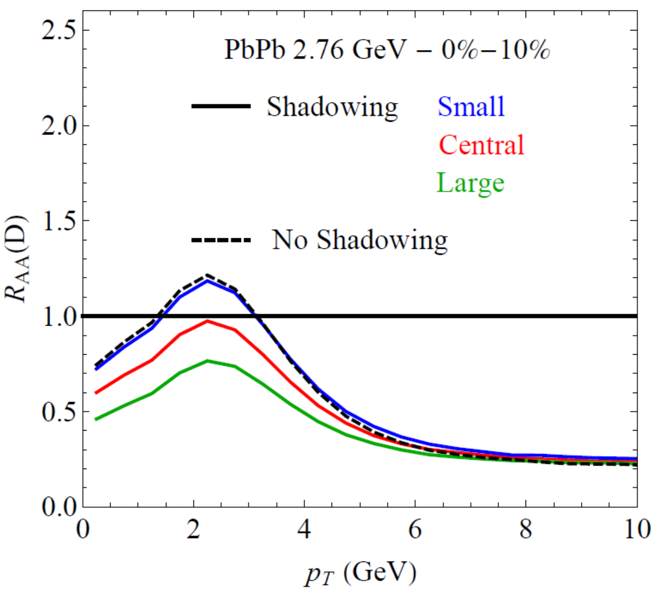
- R_{AA} and v_2 from low to high p_T generated by interactions of heavy quarks with the same underlying QGP medium
  - ⇨ Models should describe both of them simultaneously
- Extract D_s from data-to-model comparison
  - ⇨ Large D_s → long relaxation time → high R_{AA} and small elliptic flow



📖 **Moore and Teaney, PRC71 (2005) 064904**

Initial spectra

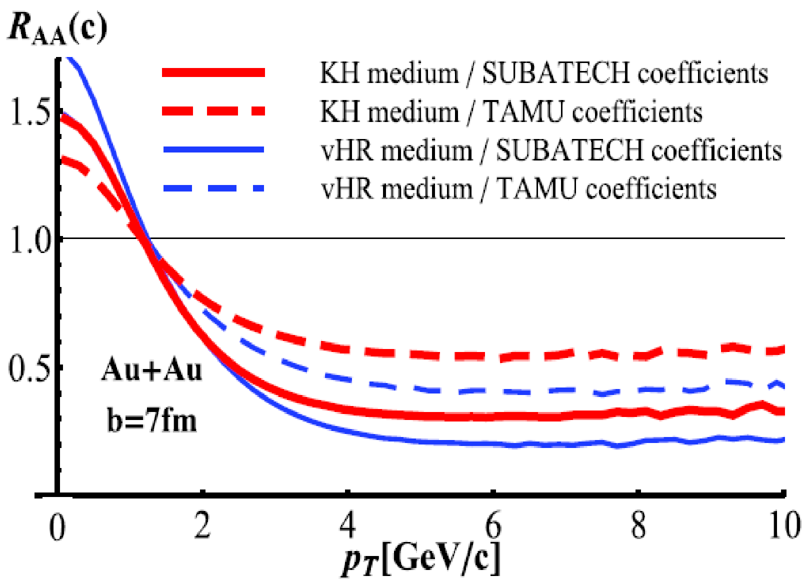


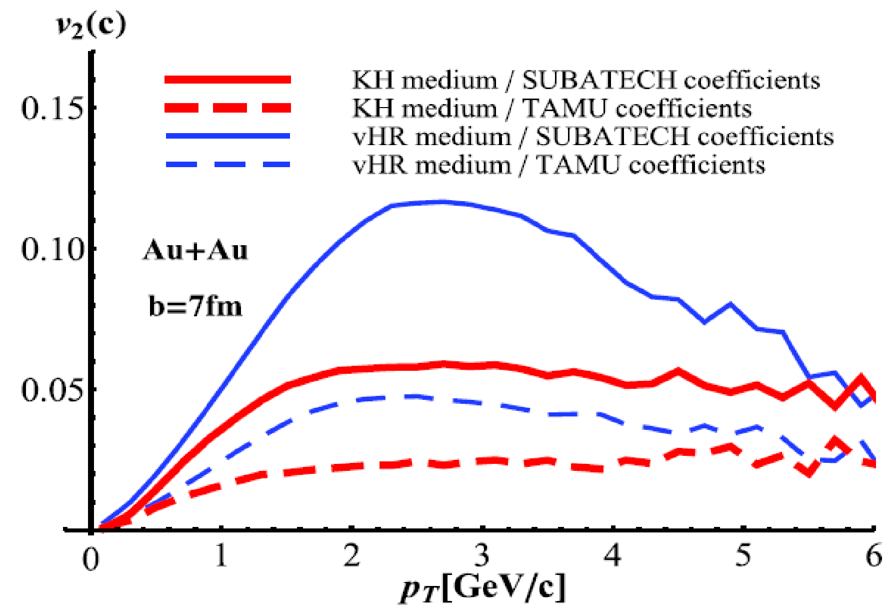


- Spectrum of produced charm quarks has an impact on the R_{AA} computed with models
- Most models use a spectrum of produced quarks from pQCD calcullations/event generators (FONLL, POWHEG)
  - ⇨ FONLL calculations with m_c=1.3 and "central" values for μ_F and μ_R give a good description of the data at LHC energies
- Important to include nuclear modification of PDFs (shadowing)
  - ⇨ Reduction of the yield and R_{AA} at low p_T

📖 **EMMI, Rapid Reaction Task Force, NPA 979 (2018) 21**

Hydrodynamic model of the bulk



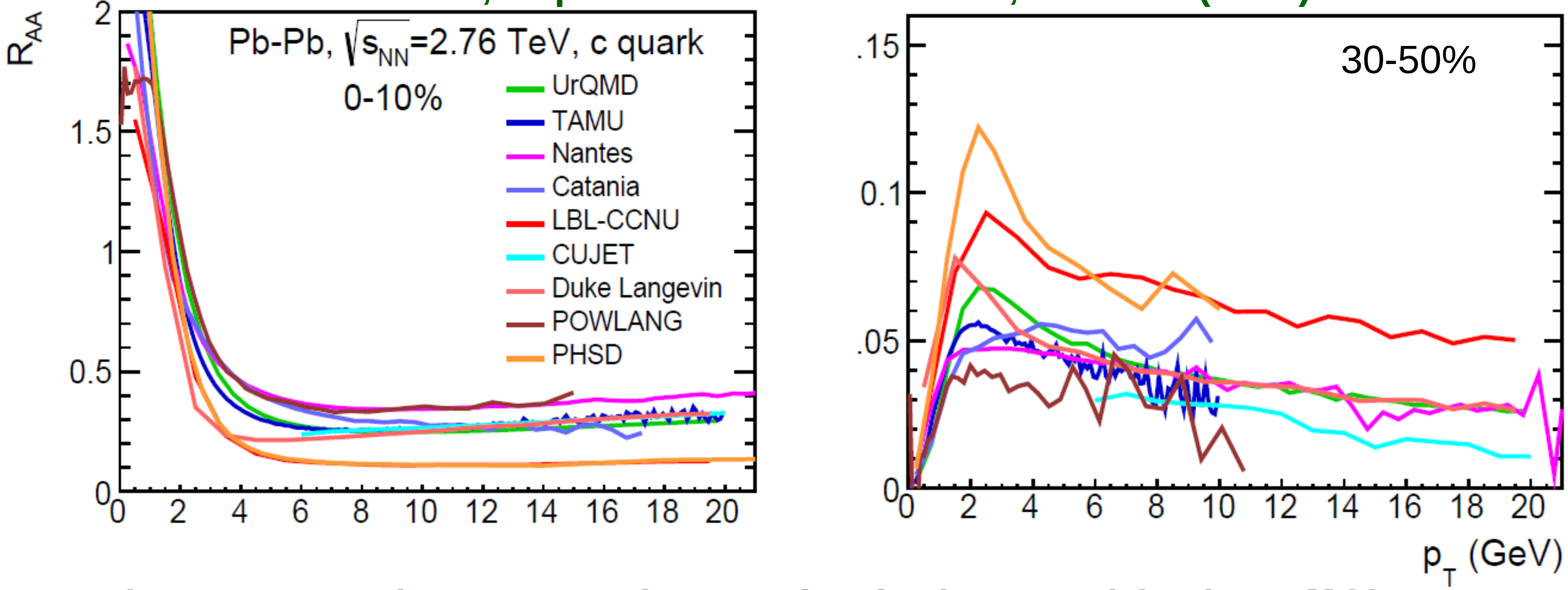


- Compare two hydrodynamical models tuned to described Au-Au data at √s=200 GeV
  - ⇨ "Soft" **Kolb-Heinz** hydro vs. more explosive **van Hees-Rapp**
- Heavy quark physics not decoupled from light quark physics
  - ⇨ Crucial to have precision tuning of the bulk evolution model to light-flavour data

📖 **Gossiaux et al., arXiv:1102.1114**

Hydrodynamic model of the bulk

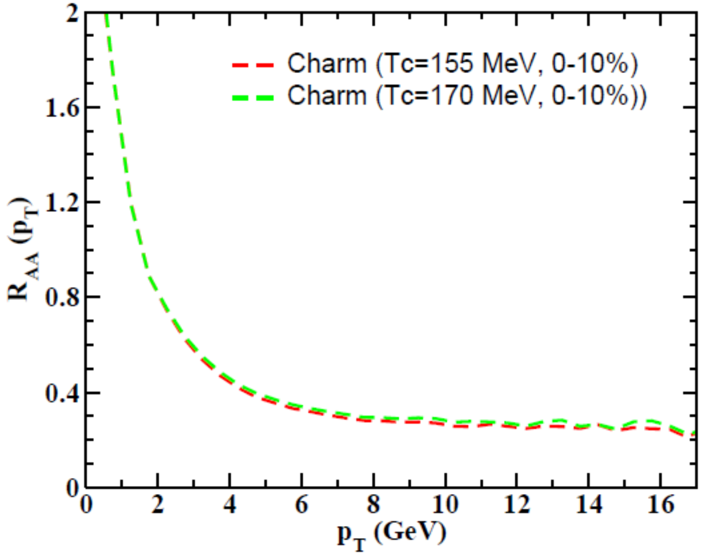
📖 EMMI, Rapid Reaction Task Force, NPA 979 (2018) 21

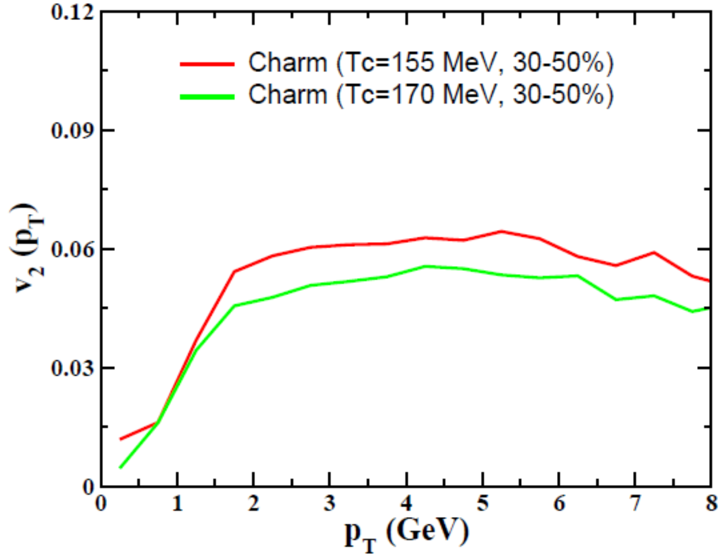


- Charm quark R_{AA} and v_2 calculations with the **different evolution models** and **same transport coefficients**
  - ⇨ All bulk evolutions tuned on soft observables
  - ⇨ Significant difference in v_2 (and R_{AA}) from the bulk descriptions
- Heavy quark physics not decoupled from light quark physics
  - ⇨ Crucial to have precision tuning of the bulk evolution model to light-flavour data

Hadronization temperature

📖 **EMMI, Rapid Reaction Task Force, NPA 979 (2018) 21**



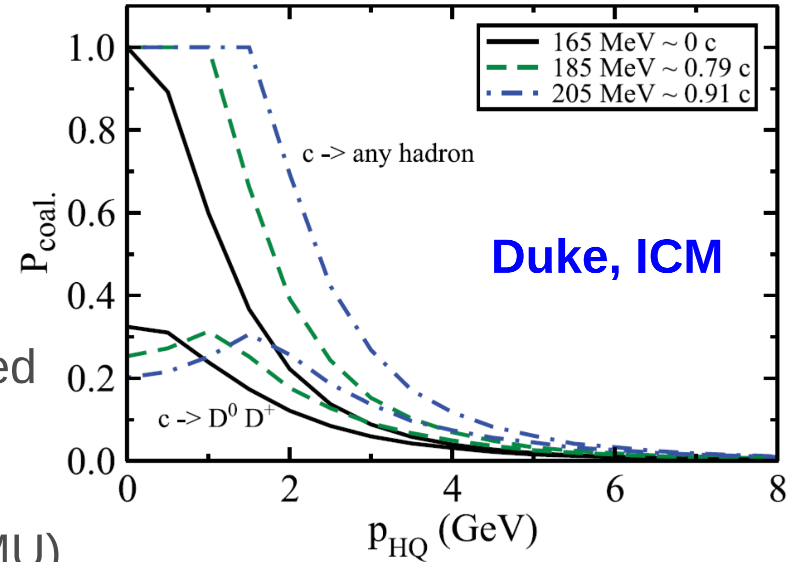


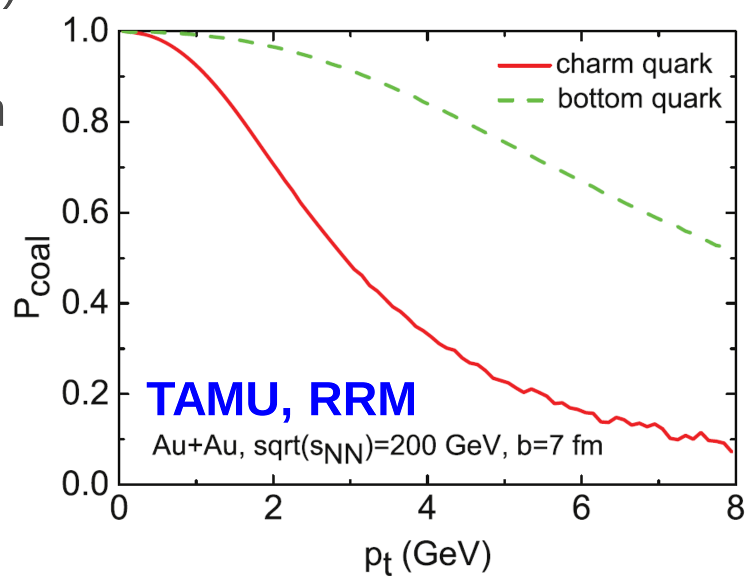
- Bulk evolution models differ also for the temperature T_c at which the QGP evolution ends
  - ⇨ Little effect on R_{AA}
    - ✓ *Energy loss (density-driven) mostly in the **early stages** of the fireball*
  - ⇨ Significant (~20%) increase of v_2 when the QGP lasts longer
    - ✓ *Charm elliptic flow is a **“late” signal**: the transfer of v_2 from the bulk to heavy quarks is most effective when the fireball v_2 is large, i.e. in the later phases of the evolution*

Hadronization mechanism

Two competing mechanisms:

- Independent fragmentation
  - ⇨ Fast partons hadronize in vacuum
- In-medium hadronization
  - ⇨ Instantaneous **coalescence** model, based on Wigner function (MC@sHQ, Catania, Duke, PHSD)
  - ⇨ **Resonance recombination** model (TAMU)
  - ⇨ **In-medium string formation** between heavy quark and a thermal light quark from the bulk (POWLANG)
- Recombination for heavy flavours relevant up to higher momenta than for light flavours
- Recombination for beauty extends up to higher p_T with respect to charm

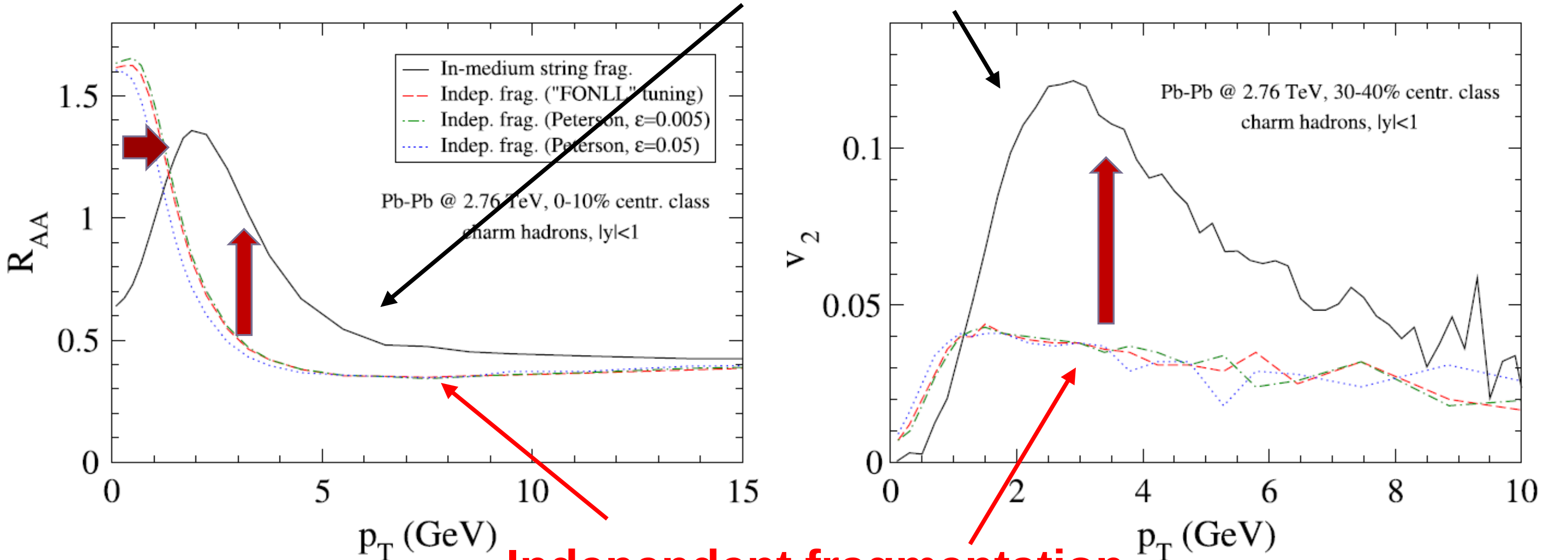




Hadronization: R_{AA} and v_2

- 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}

In-medium hadronization

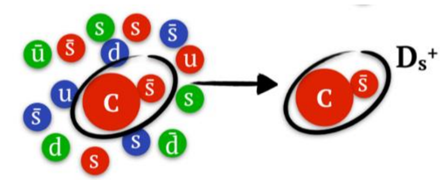


Independent fragmentation

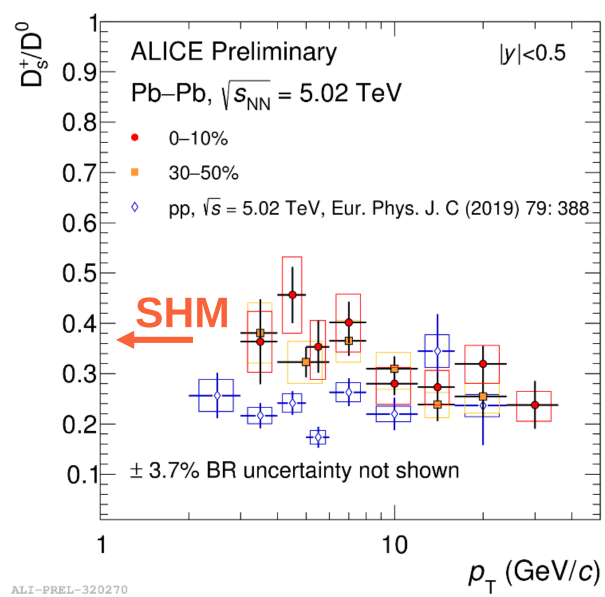
📖 **Rapp et al., NPA 979 (2018) 21**

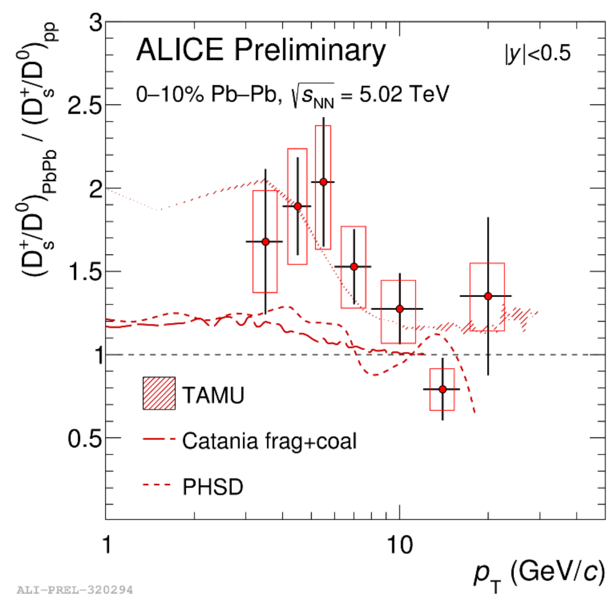
Charm hadrochemistry: D_s

- Hadronization of heavy quarks via recombination with light quarks from the medium expected to **modify relative abundances** of meson and baryon species
  - ⇨ Strange quarks abundant in the QGP
  - ⇨ Enhance D_s (B_s) yield relative to non-strange mesons



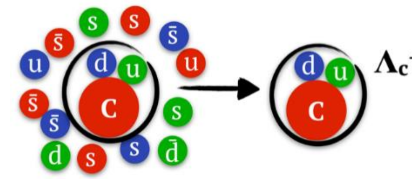
- D_s/D^0 ratio:
  - ⇨ Enhanced at low p_T as compared to pp
  - ⇨ Compatible with pp for p_T>10 GeV/c
  - ⇨ Captured by models with strangeness enhancement in QGP and hadronization via recombination



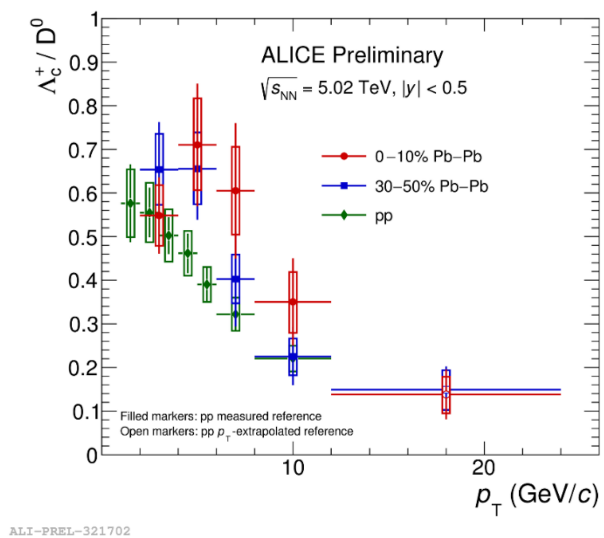


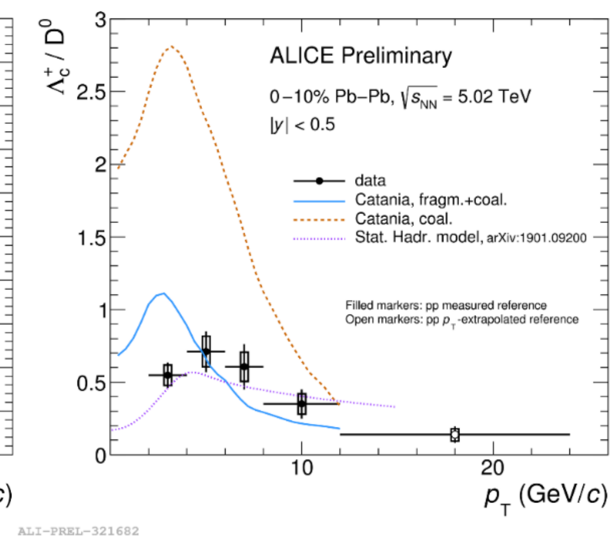
Charm hadrochemistry: Λ_c

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

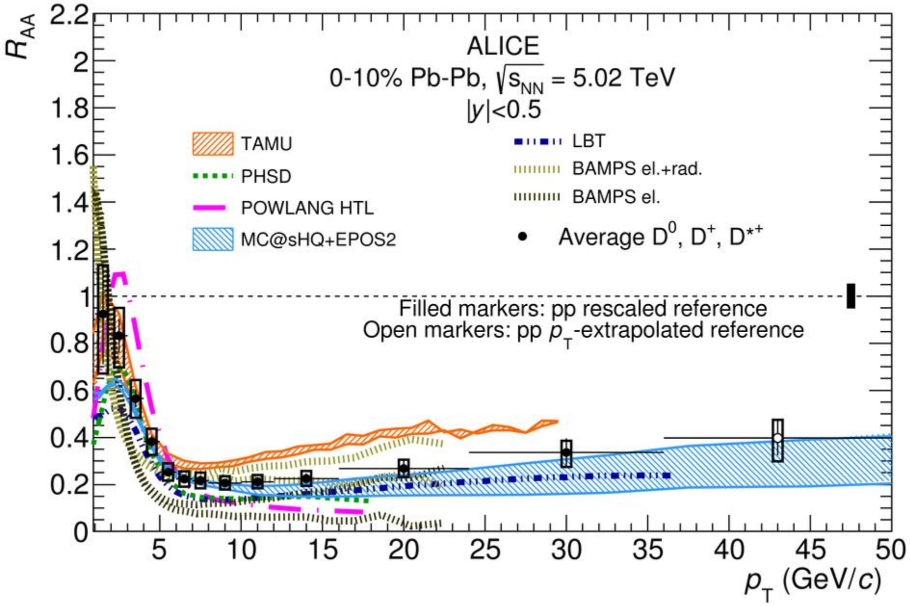


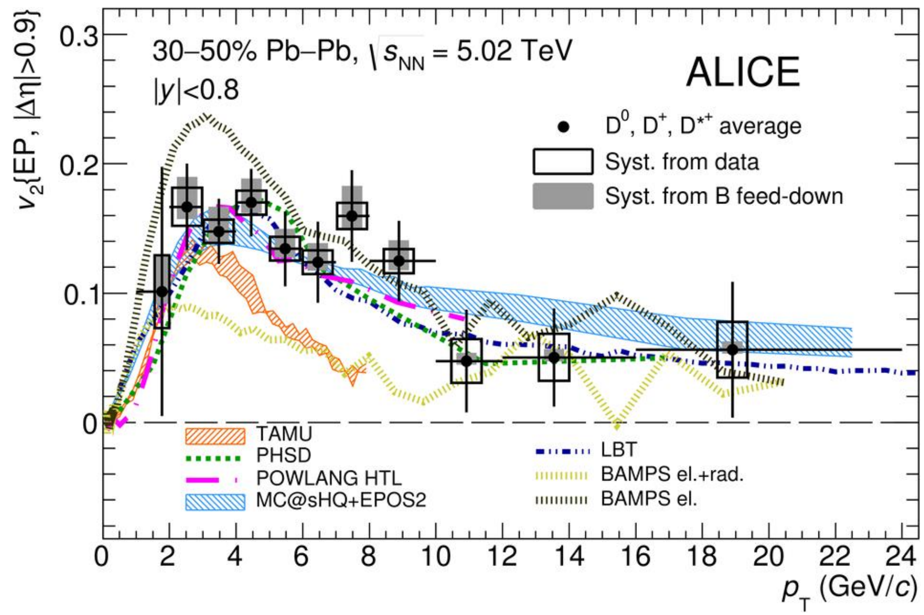
- Λ_c/D^0 ratio:
  - ⇨ Enhanced at low p_T with respect to pp
  - ⇨ Compatible with pp for p_T>10 GeV/c
  - ⇨ Consistent with a scenario of baryon enhancement due to hadronization via recombination
- Open question:
  - ⇨ Λ_c/D^0 in pp higher than in e^+e^-, not fully understood





Spatial diffusion coefficient





- Challenging for models to describe R_{AA} and v_2 at all p_T's
- Estimation of spatial diffusion coefficient: **D_s=1.5-7** at T_c
  - ⇨ From models that describe the measured v_2 for p_T<8 GeV/c
  - ⇨ Compatible with the values from lattice QCD

Calculation	Effects	$2\pi T D_s$	χ^2/ndf
BAMPS-el [47]	coll.	1–2	1.9
BAMPS-el+rad [47]	coll., rad.	6–10	6.73
LBT [49]	coll., rad., reco.	2–6	0.75
MC@sHQ [46]	coll., rad., reco.	1.5–4.5	0.46
PHSD [45]	coll., rad., reco.	4–9	0.81
POWLANG [48]	coll., reco.	7–18	0.52
TAMU [41]	coll., reco.	4–10	4.12

ALICE, PRL 120 (2018) 102301
ALICE, JHEP10 (2018) 174

Summary and remarks

- HF phenomenology in heavy-ion collisions provides a unique opportunity to extract QGP transport coefficients
  - ⇨ Close connection between theory, phenomenology and experiment
- Significant uncertainties on the extraction of the transport coefficients from the “other” modelling components
  - ⇨ Bulk evolution, hadronization, CNM effects …
- For astroparticle application:
  - ⇨ Models capture sufficiently well the features of the data
  - ⇨ Can be used as “effective” models to estimate possible QGP effects on charm and beauty production in cosmic-ray interactions in atmosphere
  - ⇨ QGP effects should be small
    - ✓ ***A central Fe-O collision should produce a system with similar size as a peripheral (60-70%) Pb-Pb collision***
  - ⇨ Not all models can compute predictions at forward rapidity (in the center-of-mass frame)

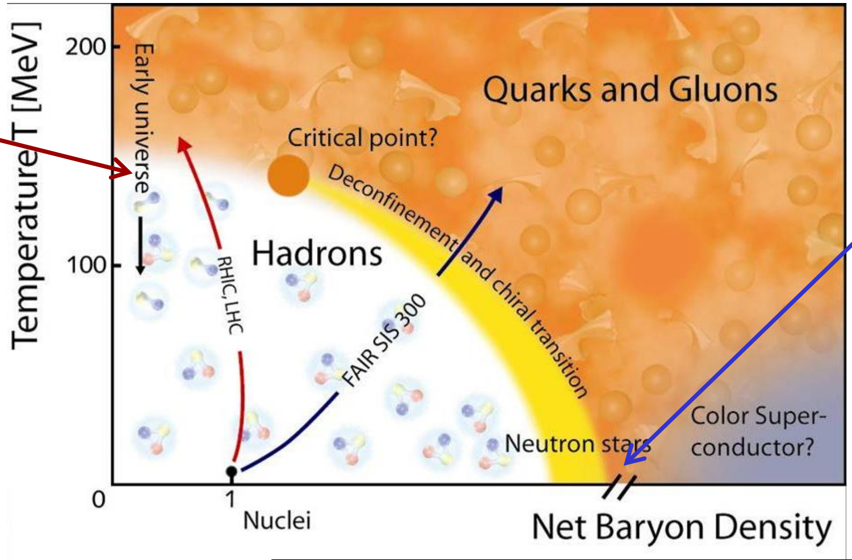
Backup

Heavy-ion collisions and QCD

- Goal: study the properties of strongly-interacting matter at extreme conditions of temperature and energy density
  - ⇨Explore the rich **phase diagram of QCD** matter
  - ⇨Transition to a state where quarks and gluons are deconfined (**Quark Gluon Plasma**, QGP)

Vanishing net-baryon density

- Lattice QCD: cross-over from hadrons to QGP at **T_C≈150 MeV** → ε_C≈0.5 GeV/fm^3
- **Early universe**: QGP-hadron transition at t~10^{-6} s after the Big Bang



Large net-baryon density

- Lattice QCD: challenging at finite μ_B
- Quark matter in the core of **neutron stars**?

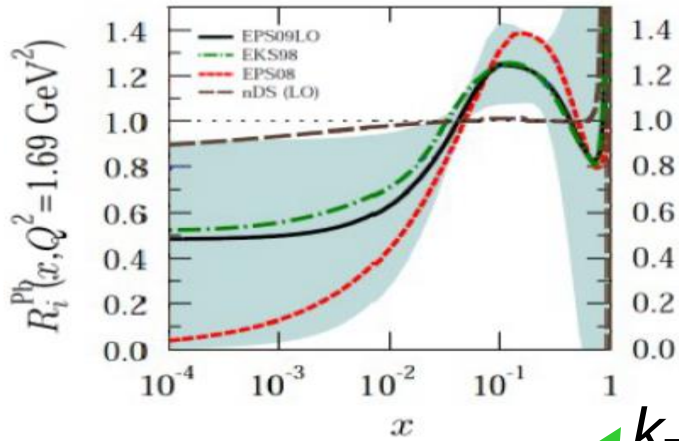
Insight into high-n_B QCD matter via **Gravitational Waves** from neutron star merging

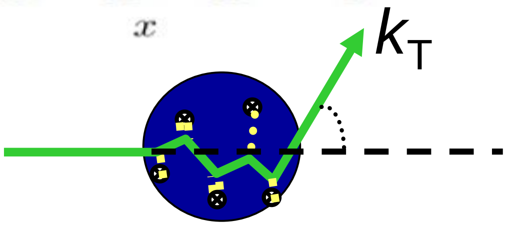
📖**Bazavov et al, PRD90 (2014) 094503**
📖**Borsanyi et al, JHEP 1009 (2010) 073**

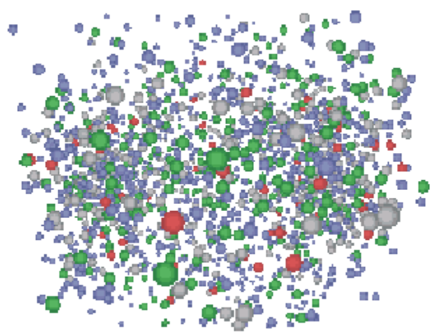
📖**Baym et al., arXiv:1707.04966**

Cold nuclear matter effects: p-Pb collisions

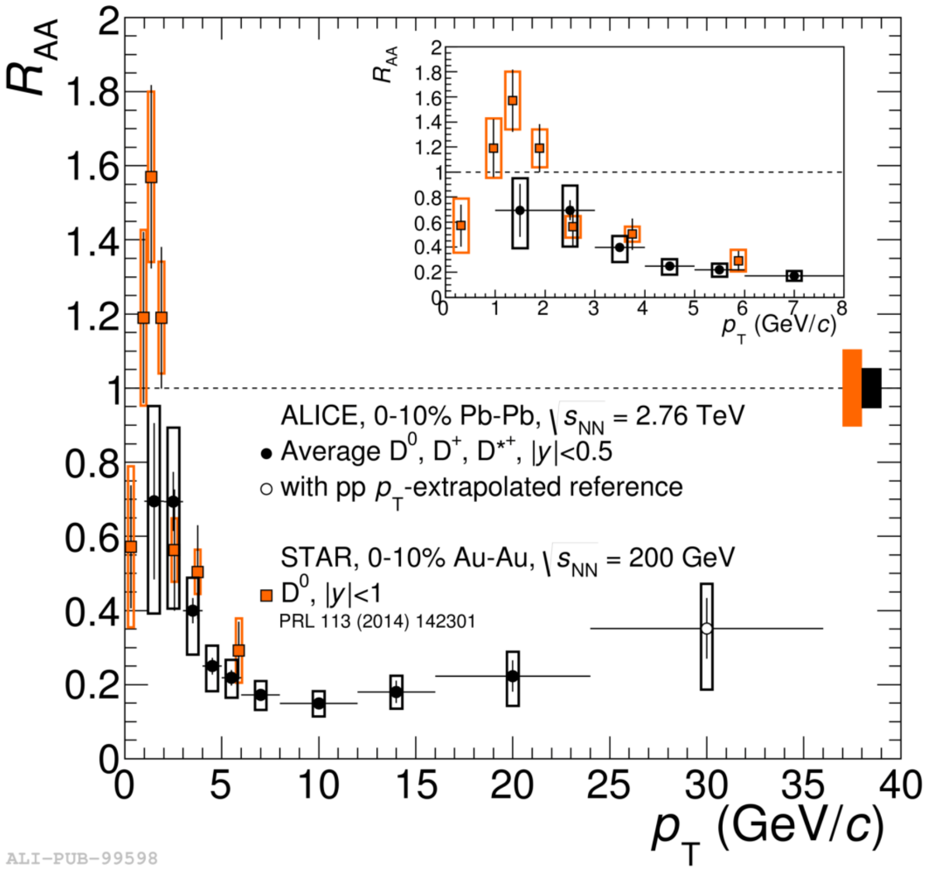
- GOAL: assess the role of **cold nuclear matter** (CNM) **effects**
  - ➪ **Initial-state** effects:
    - ✓ ***Nuclear modification of the PDFs*** → ***shadowing*** *at low Bjorken-x is the dominant effect at LHC energies*
    - ✓ ***Initial-state energy loss***
    - ✓ ***k_T broadening*** → *due to multiple collisions of the parton before the hard scattering*
  - ➪ **Final-state** effects
    - ✓ ***Final-state energy loss***
    - ✓ ***Interactions with the particles produced in the collision*** → *collective expansion?* → *Mini QGP?*
- Crucial for interpretation of Pb-Pb results







D-meson R_{AA}: LHC vs. RHIC

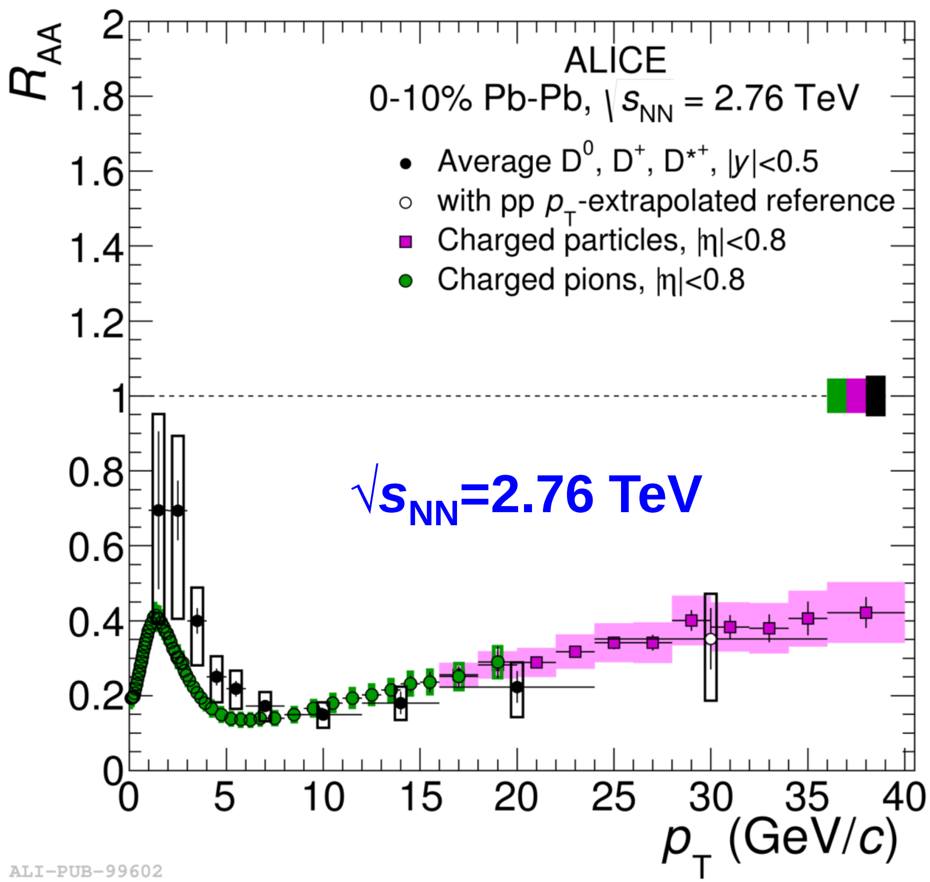


ALICE, JHEP1603 (2016) 081
STAR, PRL 113 (2014) 142301

- D-meson R_{AA} factor at $\sqrt{s_{NN}}$=0.2 and 2.76 TeV
  - Similar R_{AA} for p_T >3 GeV/c
  - Maybe different trend at lower p_T
- Many effects are different at different collision energies:
  - Different p_T shape of produced charm quarks / pp reference
  - Different shadowing
  - Different radial flow
  - Different medium density and energy loss
- Some theoretical models can describe both measurements reasonably well

R_{AA}: D mesons vs. pions

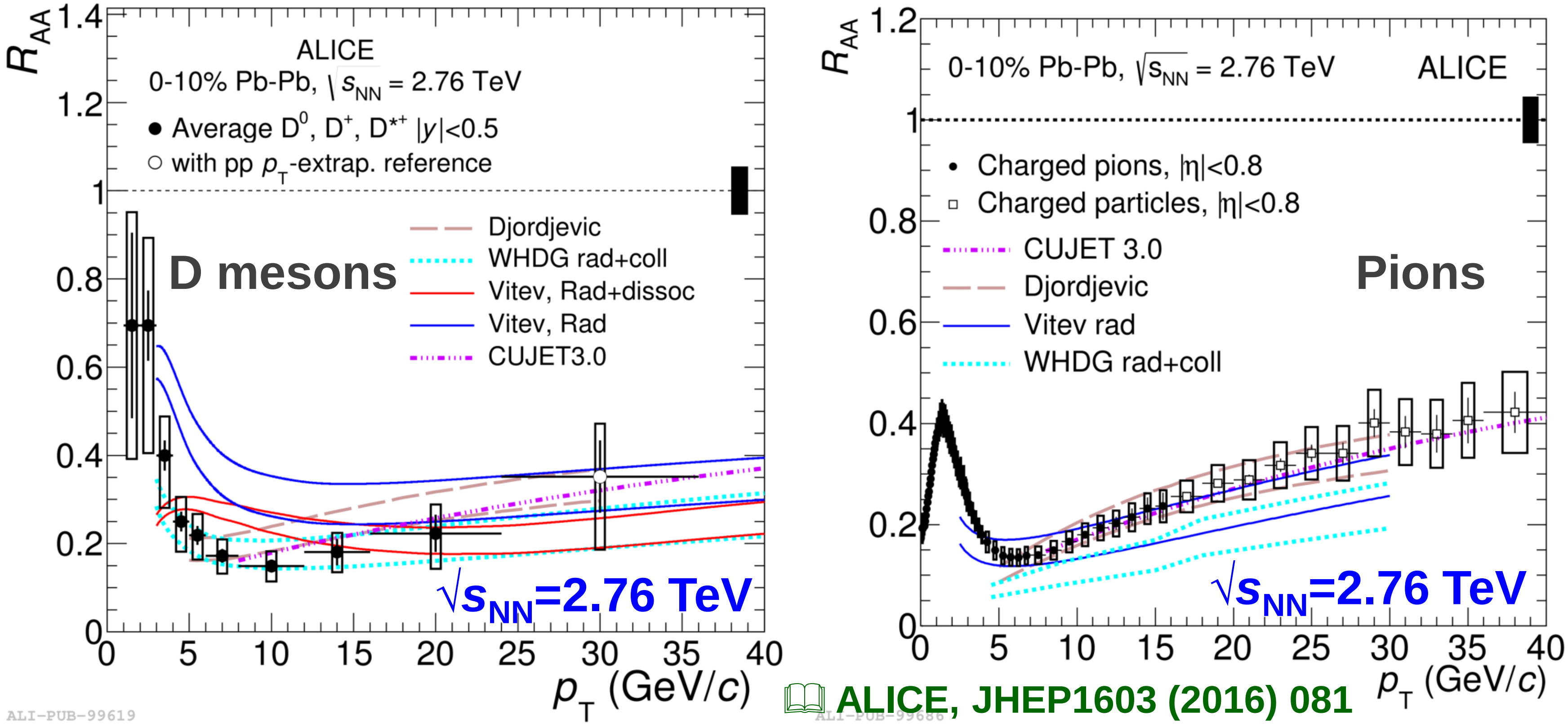
- Expectation: $\boxed{\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b}$
- Is this reflected in a R_{AA} hierarchy: $\boxed{R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)}$?



ALICE, JHEP1603 (2016) 081

- D-meson and pion R_{AA} compatible within uncertainties
- Described by models including
  - Energy loss hierarchy ($\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$)
  - Different p_T shapes of produced partons
  - Collisional and radiative energy loss
  - Different fragmentation functions of gluons, light and charm quarks

R_{AA}: D mesons vs. pions



ALICE, JHEP1603 (2016) 081

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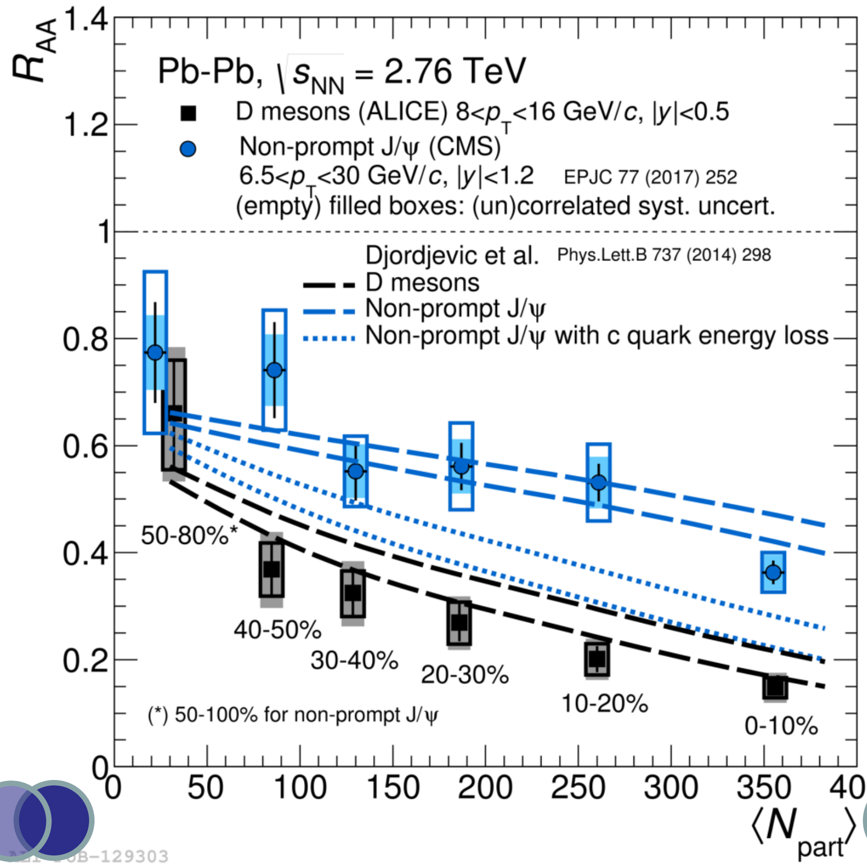
R_{AA}: D mesons vs. J/ψ from B

- Expectation: $\boxed{\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b}$
- Is this reflected in a R_{AA} hierarchy: $\boxed{R_{AA}(\pi) < R_{AA}\ (D) < R_{AA}(B)}$?

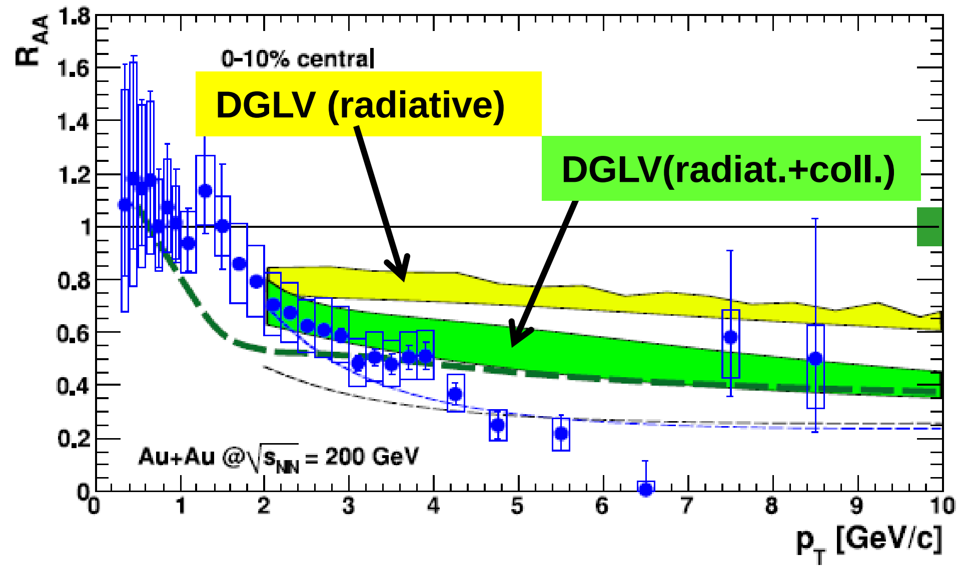


- Clear indication for R_{AA}(B)>R_{AA}(D)
  - ⇨ Consistent with the expectation $\Delta E_c > \Delta E_b$
  - ⇨ Described by models including quark-mass dependent energy loss

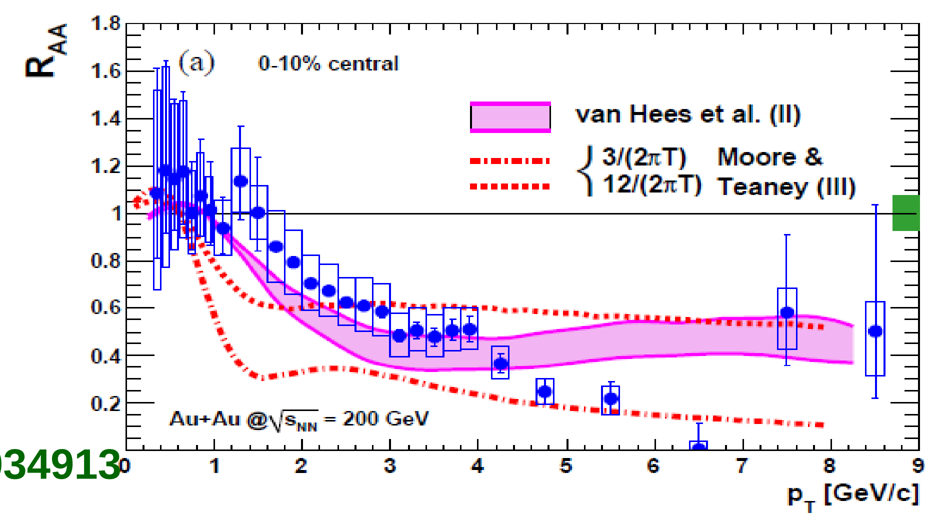
📖 **ALICE, JHEP 1511 (2015) 205**
📖 **CMS, EPJC77 (2017) 252**

High p_T: energy loss calculations

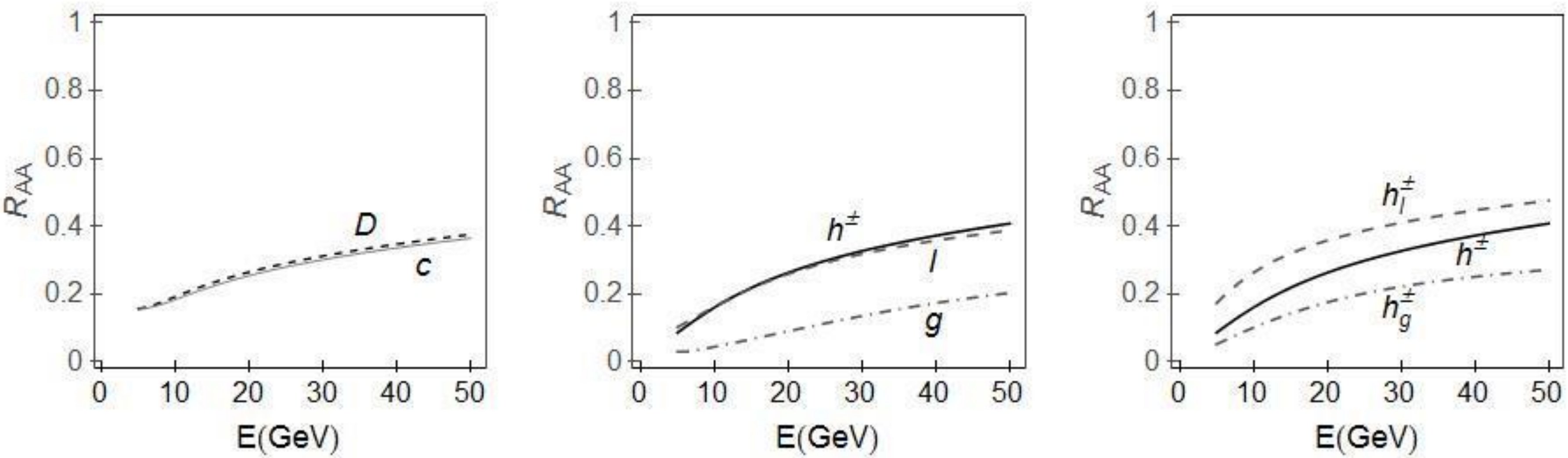
- pQCD calculations of (radiative) energy loss
  - ⇨ Early RHIC results for HFE showed larger suppression than what expected from hadron R_{AA}
  - ⇨ Difficult to describe R_{AA} of light hadrons and HFE within a “radiative only” energy loss scenario
  - 🕮 **Armesto et al., arXiv:0907.0667**



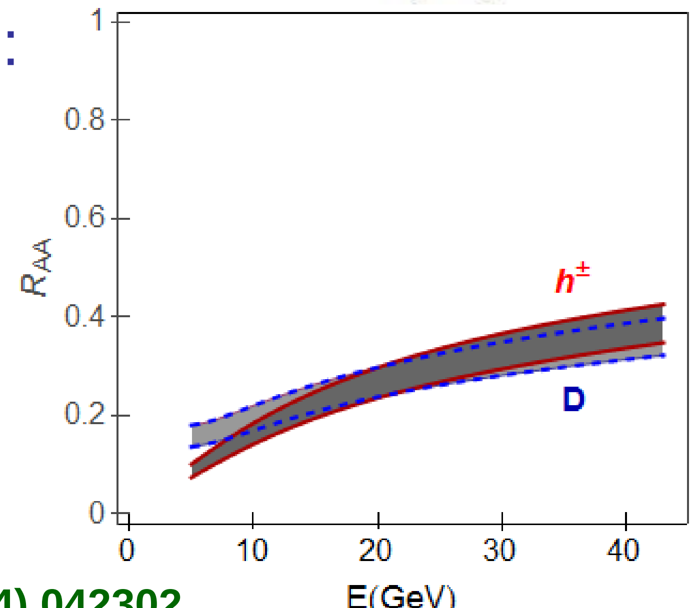
- Described by models including:
  - ⇨ Collisional energy loss
  - ⇨ In-medium formation and dissociation of resonances
    - 🕮 **Wicks et al., NPA784 (2007) 426**
    - 🕮 **Van Hees et al., PRC 73 (2006) 034913**
    - 🕮 **Adil, Vitev, PLB 649 (2007) 139**



Energy loss and fragmentation

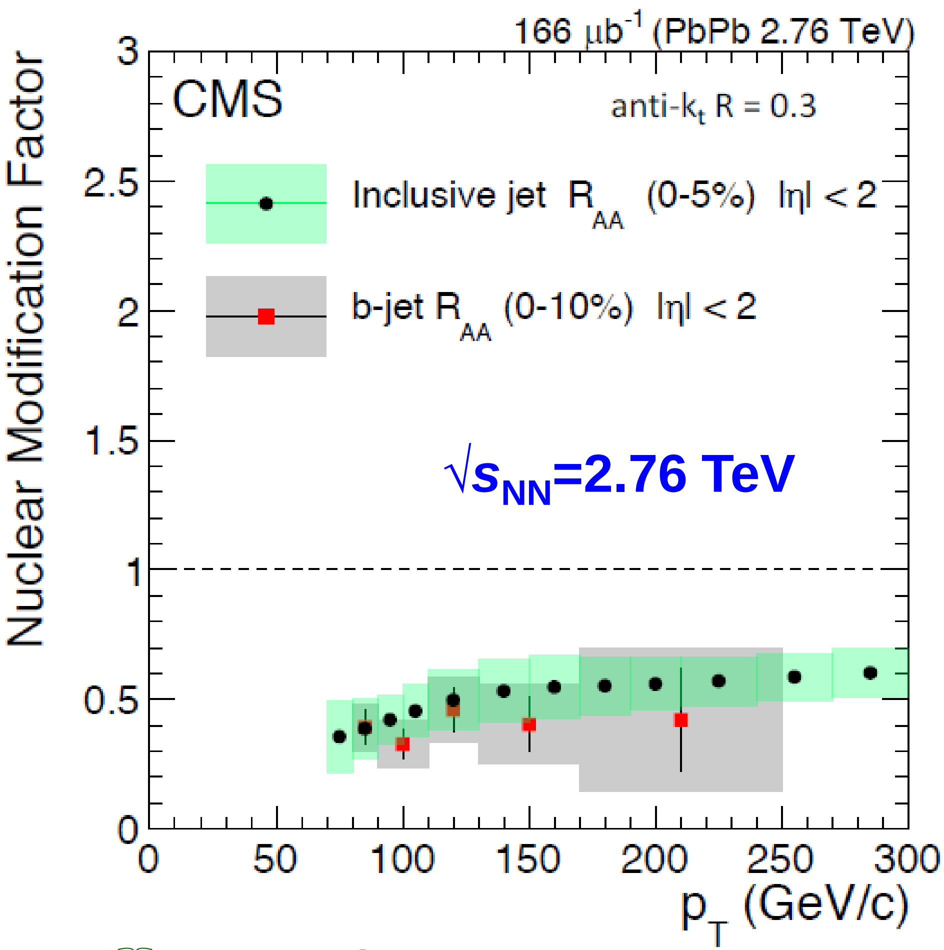


- Color-charge dependent energy loss:
  - ⇨ $\Delta E_g > \Delta E_{u,d,s}$
- Parton level R_{AA}:
  - ⇨ Gluons more suppressed than quarks
- Effect of softer gluon fragmentation:
  - ⇨ Hadron $R_{AA} \approx$ light quark R_{AA}
- In the charm sector:
  - ⇨ D-meson $R_{AA} \approx$ c quark R_{AA}



📖 **Djordjevic, PRL 112 (2014) 042302**

Flavour dependence at high-p_T?



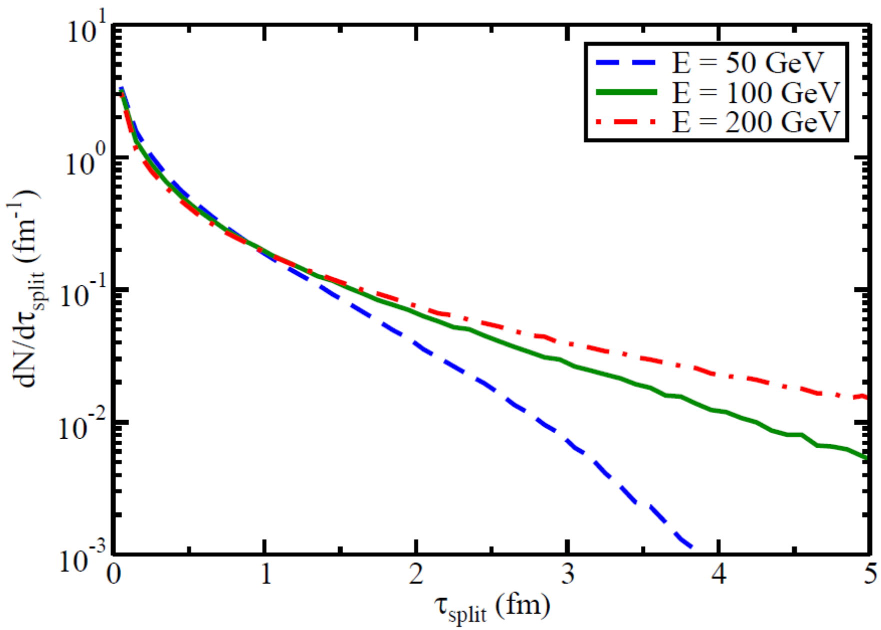
📖 **CMS, arXiv:1609.05383**

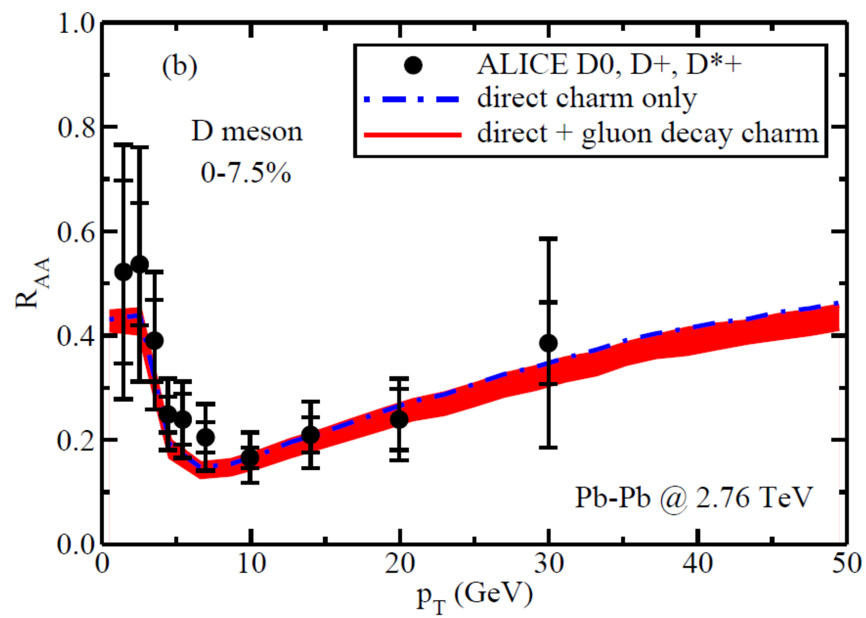
📖 **CMS, PRL 113 (2014) 132301**

- Same suppression for b-jets and inclusive jets at high p_T
  - ⇨Within (large) uncertainties
- Quark mass effect on energy loss negligible at high p_T
- What about colour charge effect?
  - ⇨For high-p_T $b\bar{b}$ pairs from gluon splitting the early stages of the medium are probed by the parent gluon
    - ✓ ***R_{AA} determined by gluon energy loss?***

Gluon splitting

- Gluon splitting contribution to heavy quark production relevant for interpretation the R_{AA}
  - ⇨ In-medium gluon energy loss before the splitting
  - ⇨ Key factor is the lifetime of the gluon before it splits
- PYTHIA based estimations of gluon lifetime
  - ⇨ Short lifetime compared to QGP formation time → small effect on the D-meson R_{AA} 📖 **Cao et al., arXiv:1511.04009**





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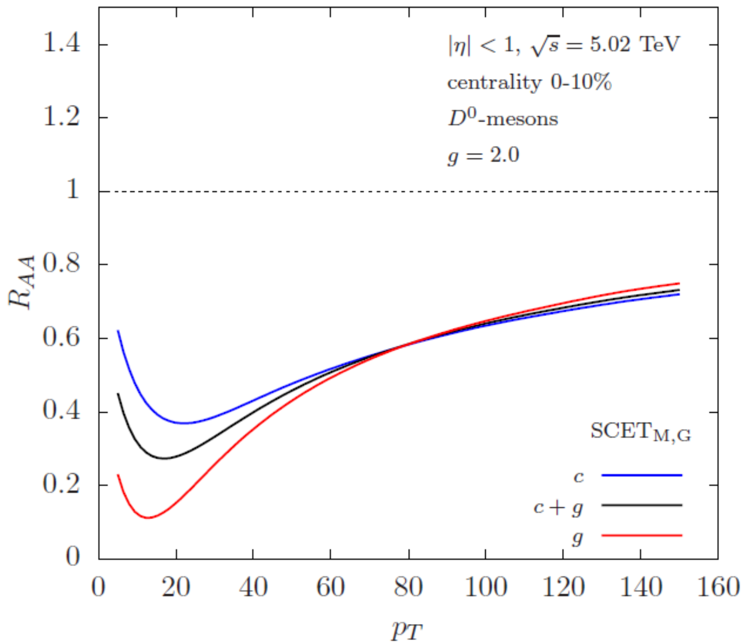
- Soft-Collinear Effective Theory
  - ⇨ Splitting functions of partons in vacuum and in QCD matter
  - ⇨ Different R_{AA} for p_T<50 GeV/c
    - ✓ ***Effect more pronounced for B mesons***
  - ⇨ Note: at low p_T the model still needs some improvements

📖 **Kang et al., arXiv:1610.02043**



Einstein relation

- In non-relativistic limit of momentum independent transport coefficients:

$$\gamma \equiv A(p) = \text{const} \qquad D_p \equiv B_0(p) = B_1(p) = \text{const}$$

  - The solution of Fokker-Plank equation for large times is:

$$f_Q(t, p) = \left(\frac{2\pi D_p}{\gamma}\right)^{3/2} \exp\left(-\frac{\gamma \vec{p}^{\,2}}{2D_p}\right)$$

  - Asymptotically the solution tends to a thermal distribution
- Einstein relation, aka **fluctuation-dissipation theorem**:

$$D_p = m_Q \gamma T$$

  - **Relation between friction and momentum diffusion coefficients** -> imprint the temperature of the heat bath to heavy quarks
- In practice, the Einstein relation is not satisfied by the calculated coefficients A(p), B_1(p) and B_2(p)
  - To ensure that heavy quark distributions converge to correct equilibrium distributions, Einstein relation is enforced
    - ✓ ***E.g. by expressing B_2(p) through A(p)***

Heavy flavour transport

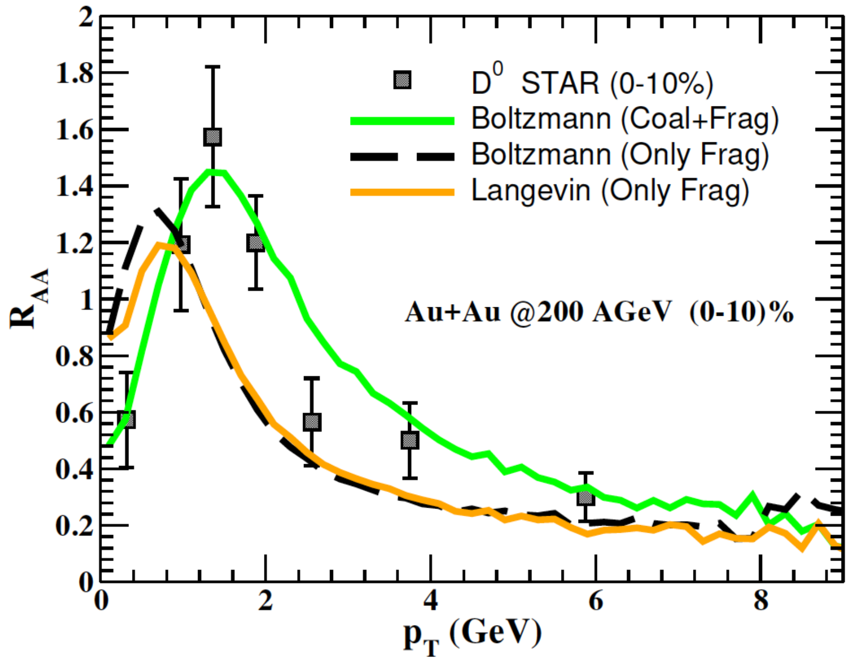
- Space-time evolution of heavy quark phase space distribution function f_Q described in kinetic theory by **Boltzmann equation**:

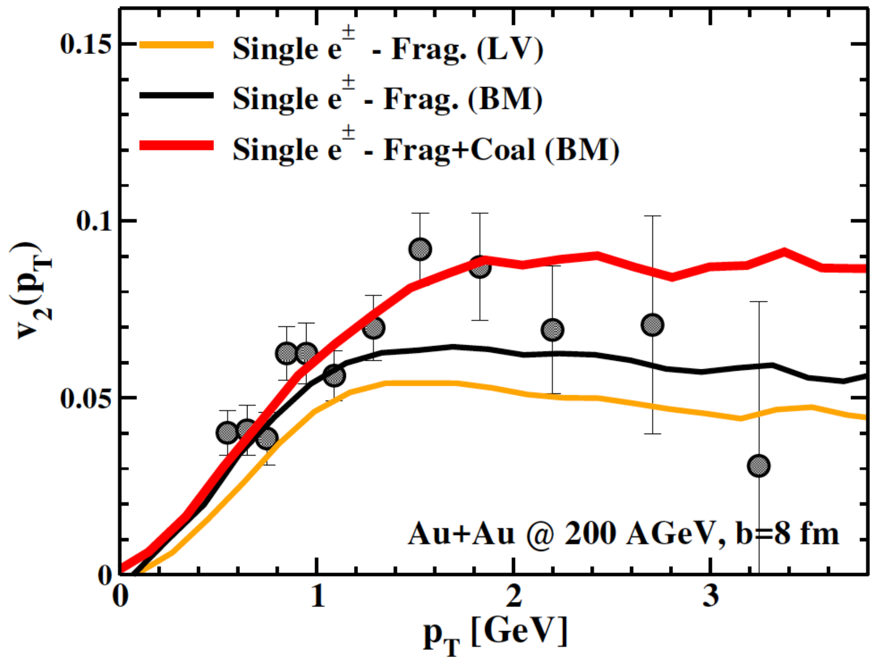
$$\left[\frac{\partial}{\partial t} + \frac{\vec{p}}{E_p}\frac{\partial}{\partial \vec{x}} + \vec{F}\frac{\partial}{\partial \vec{p}}\right] f_Q(t, \vec{x}, \vec{p}) = C[f_Q]$$

  - ⇨ E_p = on-shell heavy quark energy
  - ⇨ F = force induced by an external (mean) field
  - ⇨ $C[f_Q]$ = collision integral (2→2 processes)
    - ✓ *Dilute medium: can be calculated using particle cross sections*
    - ✓ *Dense medium: formulation in terms of scattering probabilities*
    - ✓ *Challenging to include radiative processes due to interference effects between successive scatterings*

- In a static medium in equilibrium at temperature T, f_Q approaches the Boltzmann distribution $f_Q \propto \exp[-E_p/T]$
  - ⇨ The Boltzmann equation makes heavy quarks relax to a thermal distribution at the same temperature of the medium

Boltzmann vs. Langevin





- Smaller drag coefficient in Langevin than in Boltzmann to have the same RAA
  - ⇨ But then v_2 is lower with Langevin than with Boltzmann
- Almost no difference between Langevin and Boltzmann for beauty

📖 **Das et al., PRC90 (2014) 04491**
📖 **Scardina et al., arXiv:1707.05452**

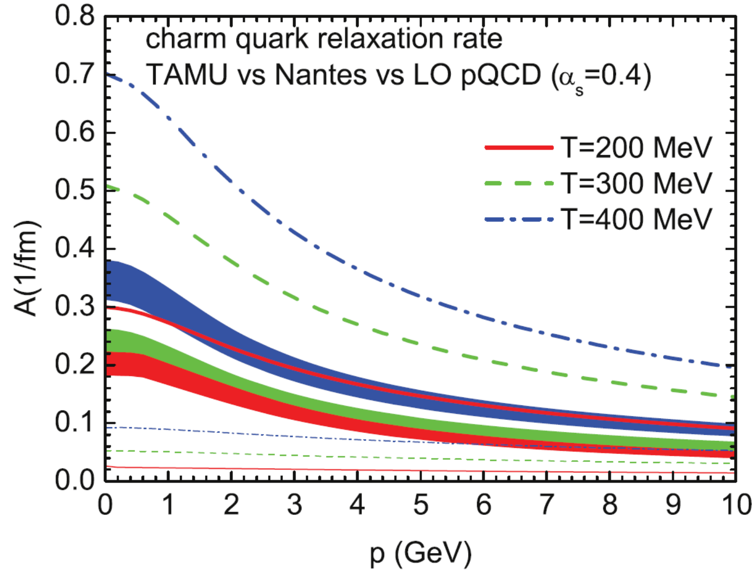
Friction coefficient, D_s and $\hat{q}$

- Conversion from heavy quark friction coefficient to $\hat{q}$:

$$\hat{q} \propto \frac{T E_p^2 A(p)}{p}$$

📖 **Gubser, Nucl. Phys. B 790 (2008) 175**

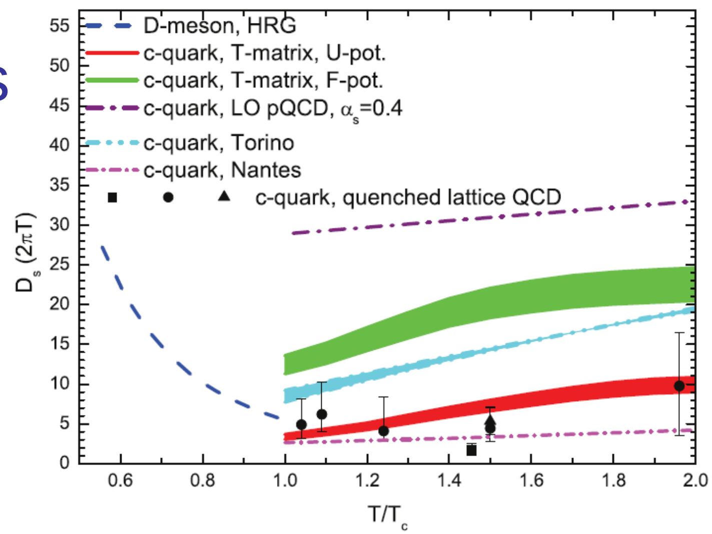
⇨ In MC@sHQ, which describes the high-p_T R_{AA}:
  - ✓ ***$A(p=10$ GeV$) = 0.25$-0.3 fm^{-1} at $T=300$-400 MeV***
  - ✓ ***$\hat{q} \approx 2.5 \pm 1.1$ Gev^2/fm at $T=350$ MeV***



- Spatial diffusion coefficient depends on A(p) at low momentum:

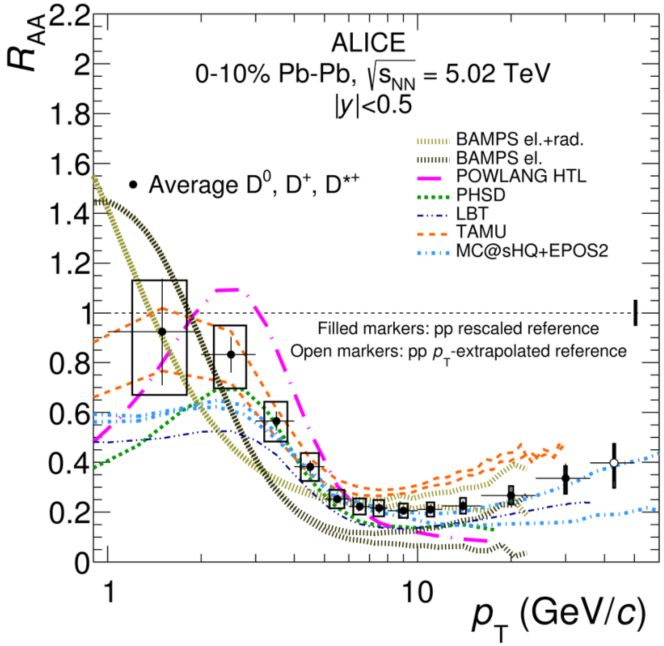
$$D_s \propto \frac{T}{m_Q A(p=0)}$$

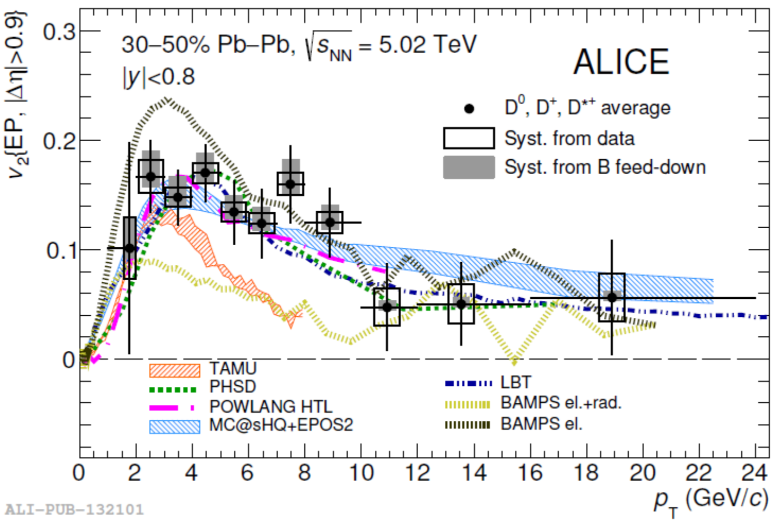
⇨ Different physics mechanisms and approximation schemes than what is relevant for $\hat{q}$



📖 **Prino, Rapp, J. Phys. G43 (2016) 093002**

Collisional vs. radiative





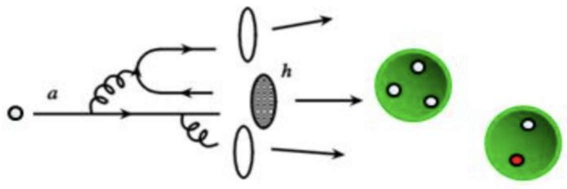
- TAMU approach with only elastic interactions describes the measured D-meson R_{AA} and v_2 up to $p_T \approx 5$ GeV/c and has significant deviations at higher p_T
  - ⇨ First (rough) estimate of the momentum region in which the elastic interaction dominate the charm quark coupling with the medium
- BAMPS results for v_2 indicate that elastic collisions are more effective in building v_2 at low p_T
  - 📖 **ALICE, PRL 120 (2018) 102301**
  - 📖 **ALICE, JHEP10 (2018) 174**

Independent fragmentation

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

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

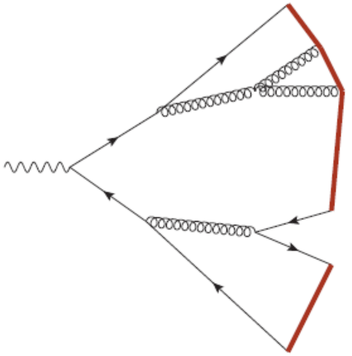
- Fragmentation functions $D_{q\rightarrow h}$ are phenomenological functions to parameterise the non-perturbative parton-to-hadron transition
  - ⇨ z = fraction of the parton momentum taken by the hadron h
  - ⇨ Do not specify the hadronisation mechanism
- Parametrised on data and assumed to be "universal"



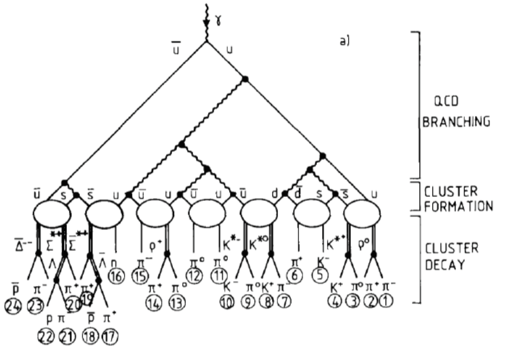
- In A-A collisions:
  - ⇨ Energy-loss of hard-scattered partons while traversing the QGP
  - ⇨ Modified fragmentation function $D_{q\rightarrow h}(z)$ by "rescaling" the variable z
    - ✓ ***Would affect all hadron species in the same way***

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



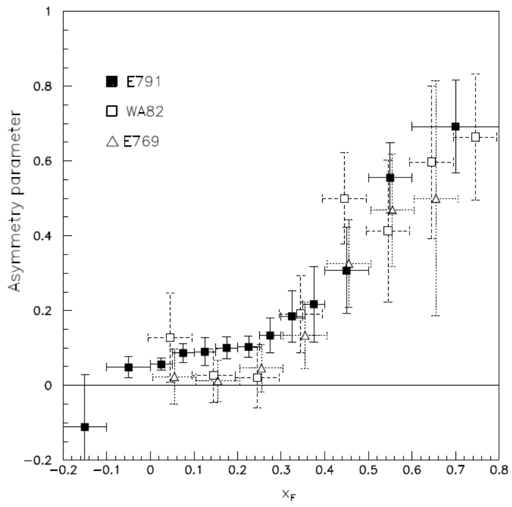
- **Cluster decay** in HERWIG
  - ⇨ Shower evolved up to a softer scale
  - ⇨ All gluons forced to split into $q\bar{q}$ pairs
  - ⇨ Identify colour-singlet clusters of partons following color flow
  - ⇨ Clusters decay into hadrons according to available phase space

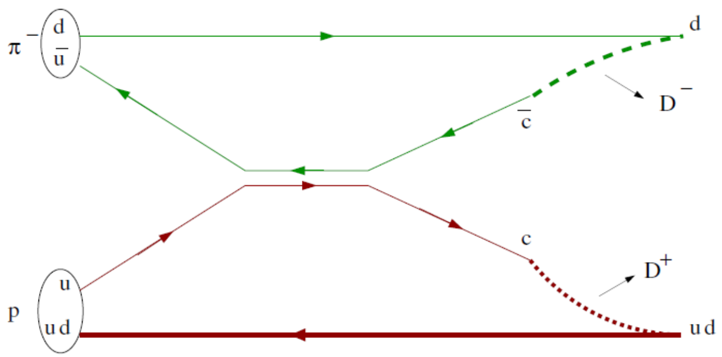


Leading particle effect

E791, PLB 371 (1996) 157

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





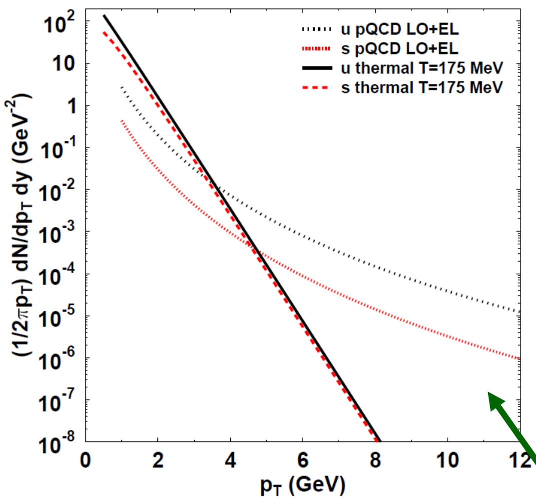
- Measurements of charm production in pion-nucleon collisions
- At **large x_F** : favoured production of hadrons sharing valence quarks with beam hadrons
  - D^- ($[\bar{c}d]$, leading meson shares the d quark with the π^- projectile) favored over D^+ $[c\bar{d}]$
  - Break-up of independent fragmentation

→ A reservoir of particles leads to significant changes in hadronisation

Hadronisation 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



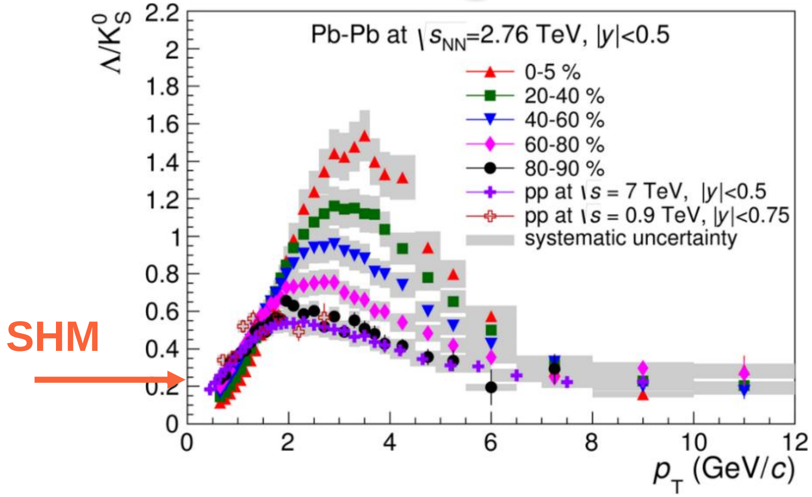
- Projection of parton states into hadron states:
  - ⇨ Phase space at hadronisation filled with partons
  - ⇨ Very rapid freeze-out → instantaneous recombination on infinitely thin hypersurface
  - ⇨ Quarks are dressed (constituent quarks)
  - ⇨ Gluons are split into quark-antiquark pairs (no dynamical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

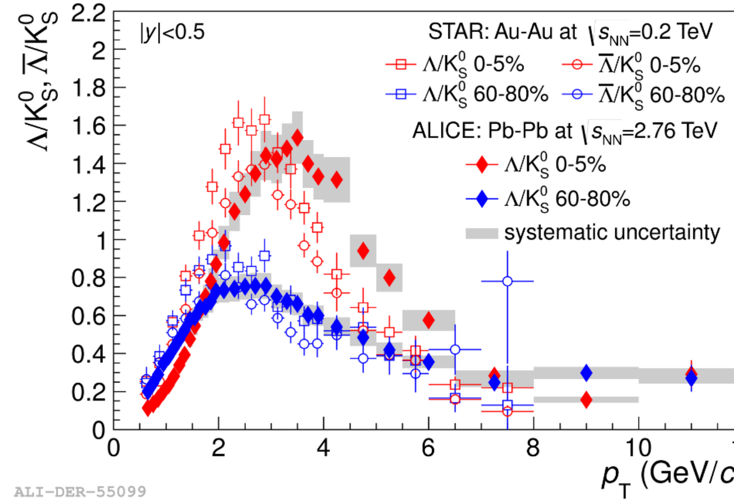
parton distributions

Hadron Wigner function

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

Baryon/meson ratios

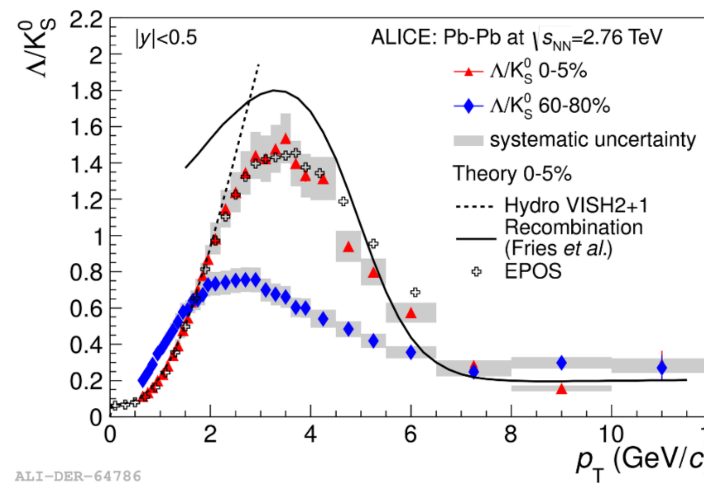




- Peak more pronounced and shifted to higher p_T with increasing centrality
- p_T integrated Λ/K^0 ratio does not change with centrality
- Peak position shifted to higher p_T with increasing $\sqrt{s_{NN}}$
- Hydrodynamics describes the data for p_T<2 GeV/c
- Recombination describes the shape at intermediate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

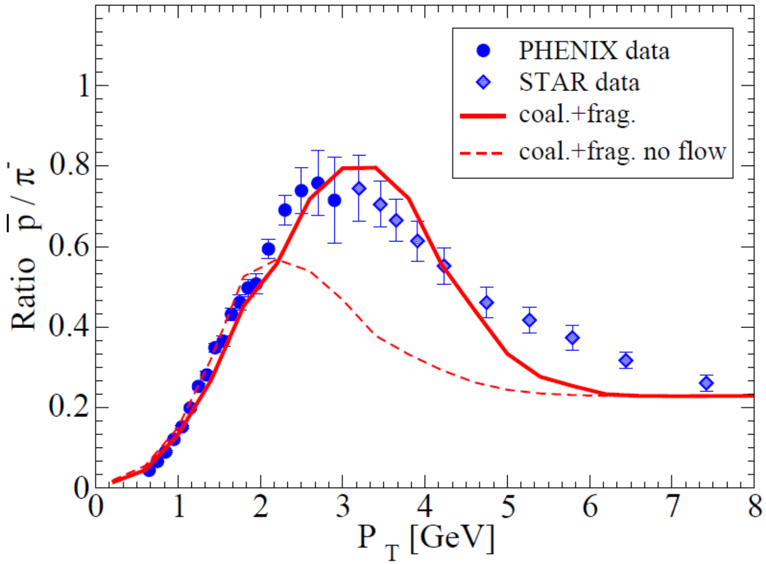
📖 **STAR, PRL 108 (2012) 072301**

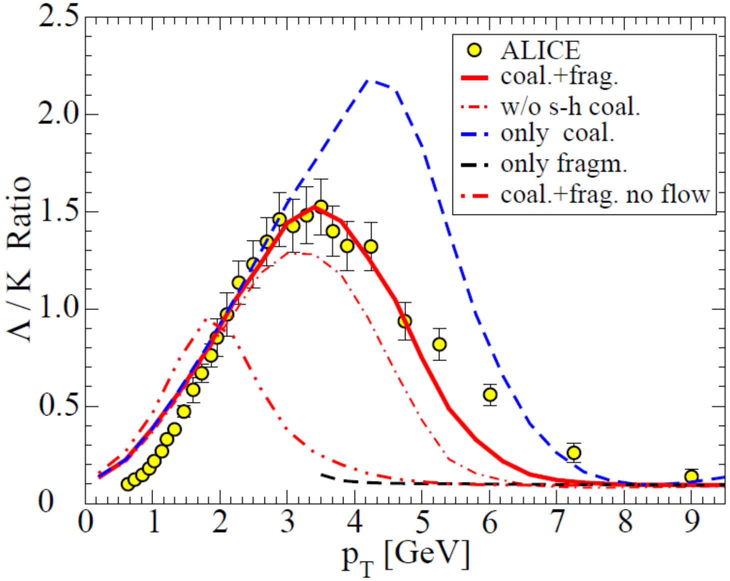
📖 **ALICE, PRL 111 (2013) 222301**



Baryon/meson ratios

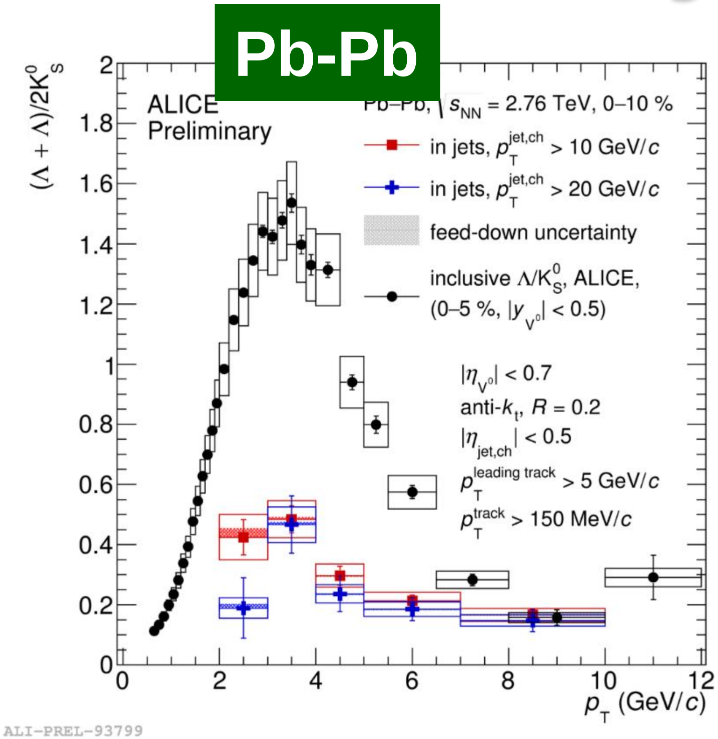
- Different modelling ingredients needed for a quantitative description of the data:
  - ⇨ Coalescence (dominant at low p_T) + fragmentation (dominant at high p_T)
  - ⇨ Radial flow of partons (from blast-wave)
  - ⇨ Recombination of thermal soft partons with mini-jet partons
  - ⇨ Contribution of resonance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

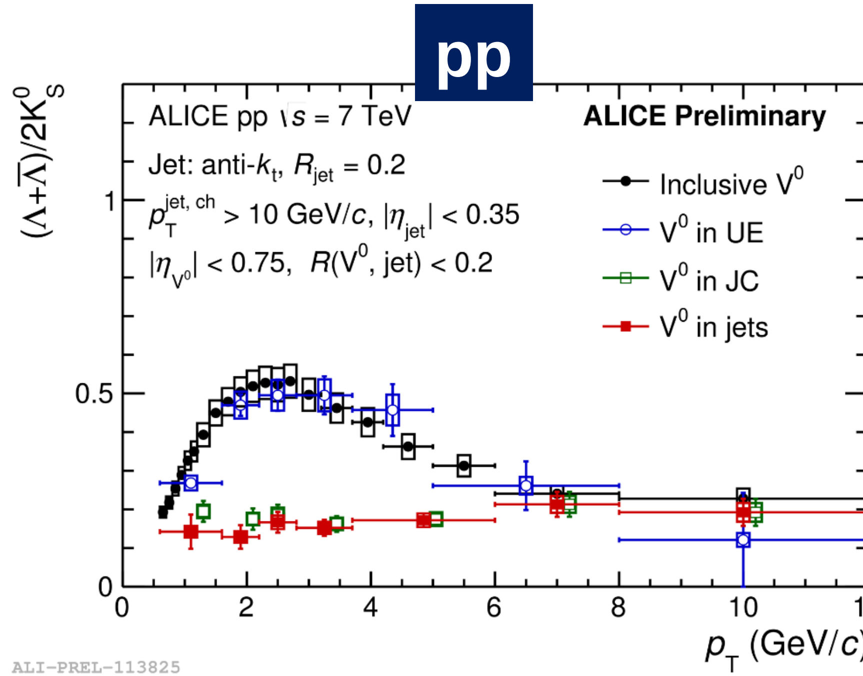


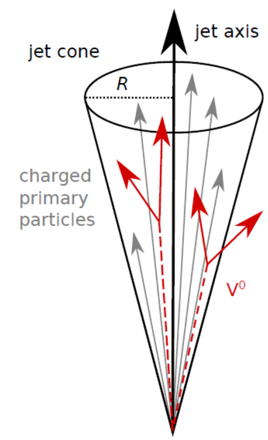


📖 **Minissale et al., PRC92 (2015) 054904**

Λ/K⁰ in jets and bulk





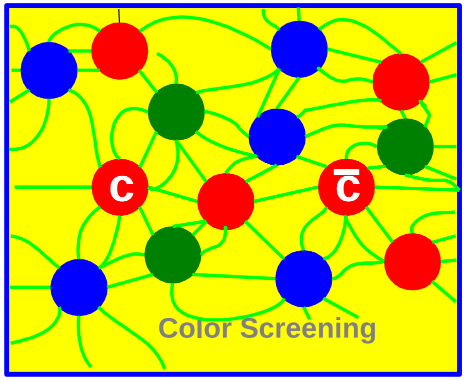


- Baryon/meson ratios different in-jet and out-of-jet
  - ⇨ Baryon enhancement mostly from the bulk
    - ✓ ***Connected to collective expansion and hadronisation of bulk***
  - ⇨ Ratio of Λ/K⁰ in-jet is similar in pp and Pb-Pb
    - ✓ ***Fragmentation of the jet not modified by the medium***

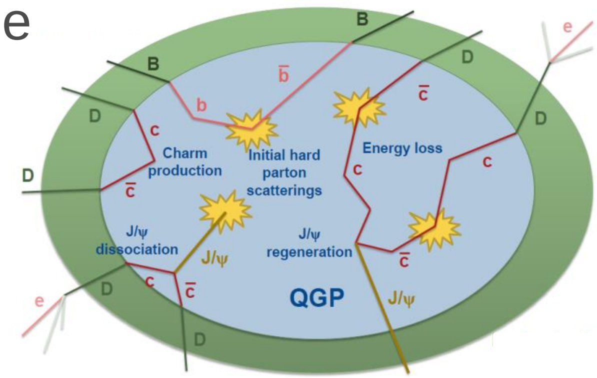
Quarkonia

- 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**

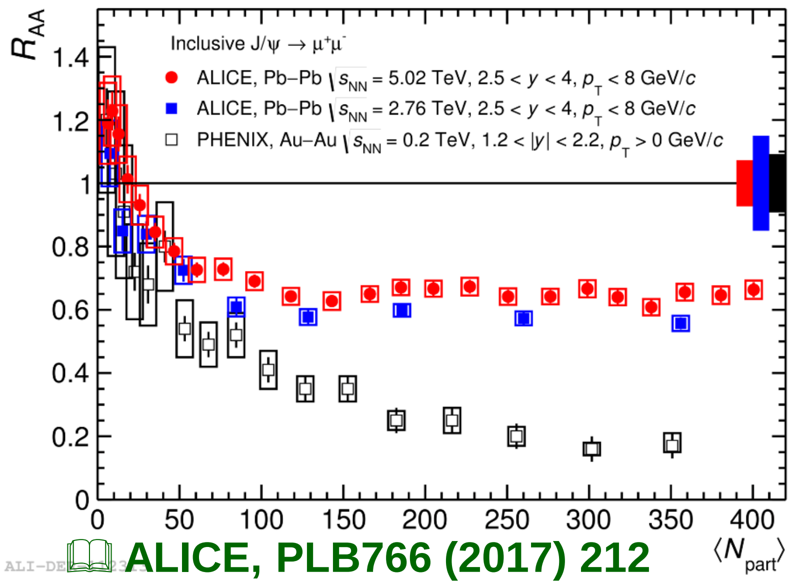


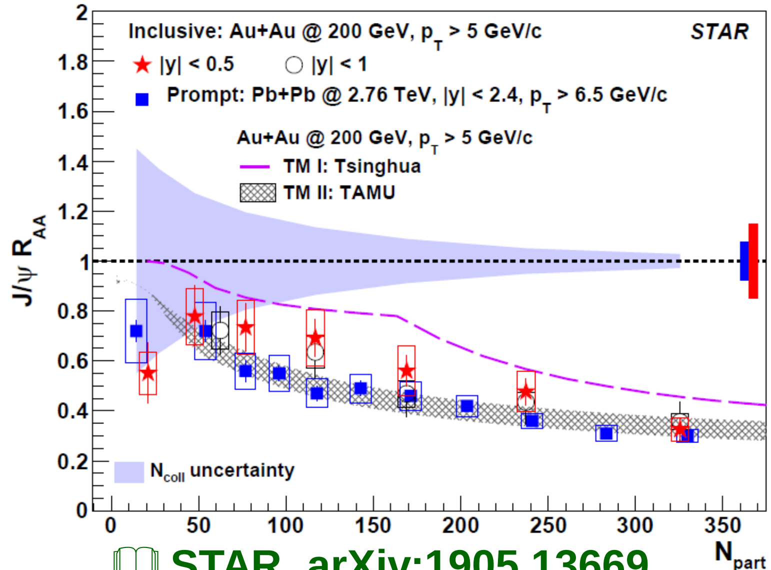
  - ⇨ Quarkonium production can occur also via **quark (re)combination / regeneration** in the QGP or at the phase boundary
    - ✓ ***Charm and beauty production cross section increase with $\sqrt{s}$ → higher recombination contribution with increasing $\sqrt{s}$***
    - ✓ ***Smaller recombination contribution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



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

J/ψ R_{AA} vs. $\sqrt{s_{NN}}$





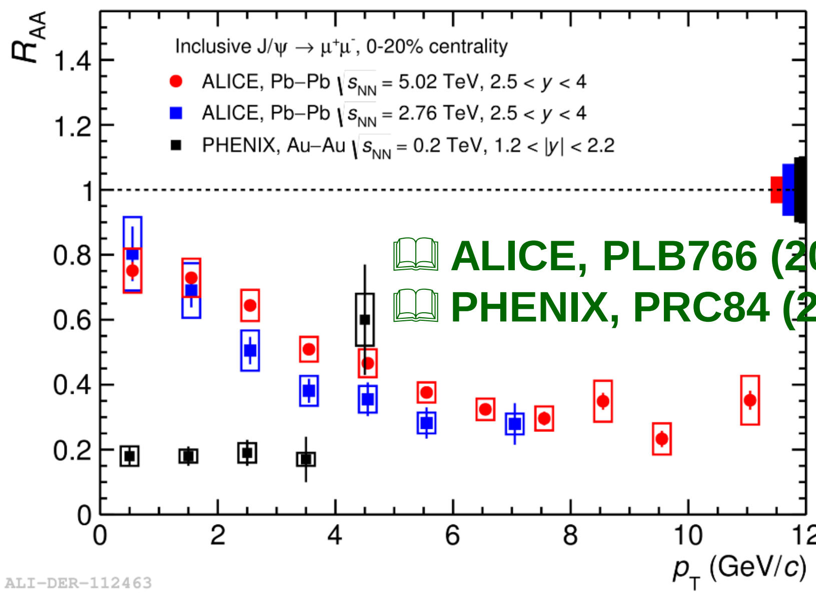
📖 ALICE, PLB766 (2017) 212
📖 PHENIX, PRC84 (2011) 05912

📖 STAR, arXiv:1905.13669
📖 CMS, EPJ C77 (2017) 252

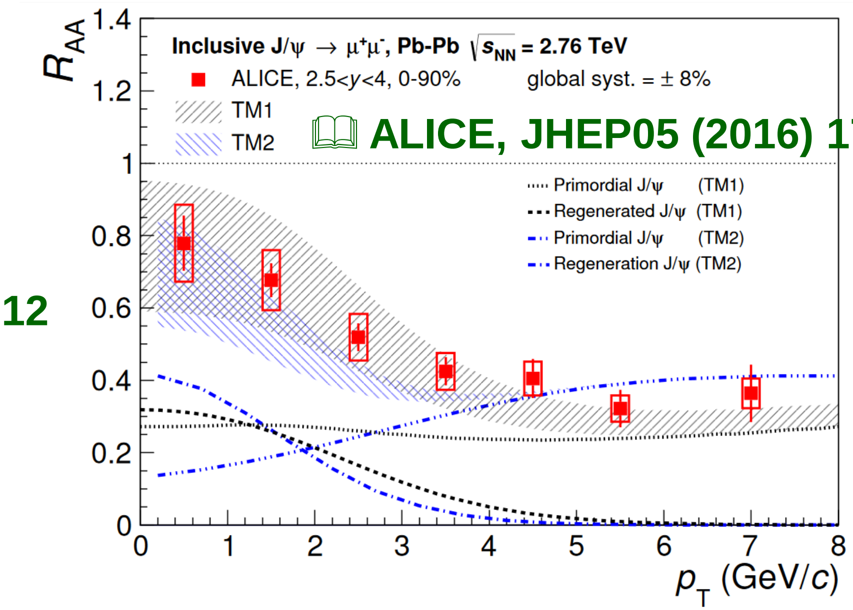
- Low p_T
  - ⇨ **Less suppression at LHC** ($\sqrt{s}$=**2.76**, **5.02** TeV) than at RHIC ($\sqrt{s}$=**200** GeV)
  - ⇨ Larger charm cross section with increasing $\sqrt{s}$ → larger regeneration contribution
- High p_T
  - ⇨ **Hint for more suppression at LHC** ($\sqrt{s}$=**2.76** TeV) than at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



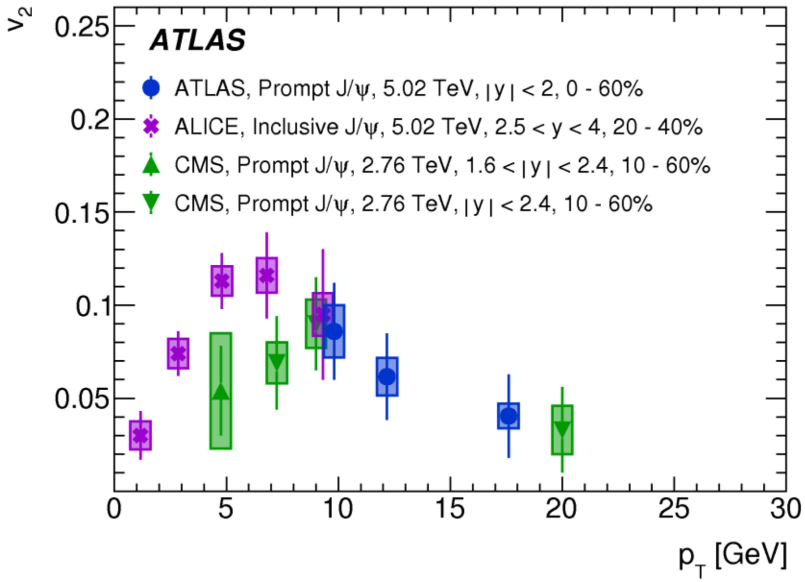
📖 ALICE, JHEP05 (2016) 179

- 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

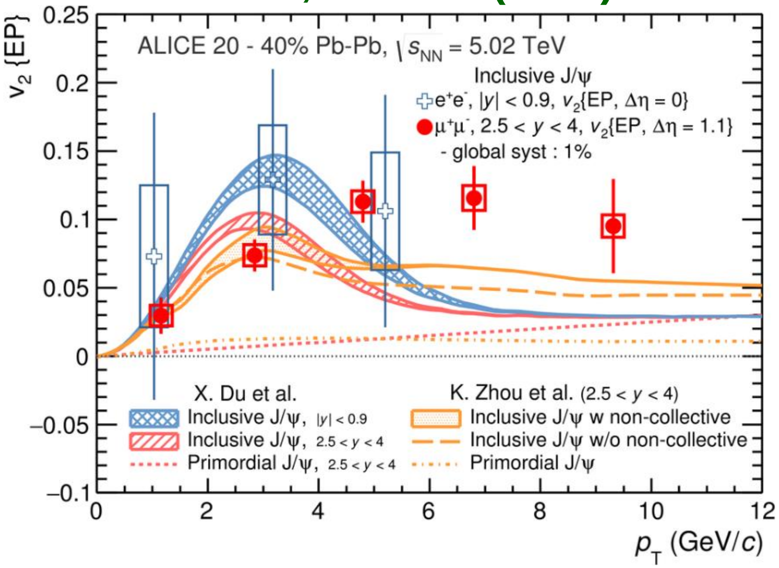
📖 **TM1: Zhao, Rapp, NPA859 (2011) 114**
📖 **TM2: Zhou et al., PRC89 (2014) 054911**

$J/\psi\ v_2$

📖 **ATLAS, EPJC78 (2018) 784**



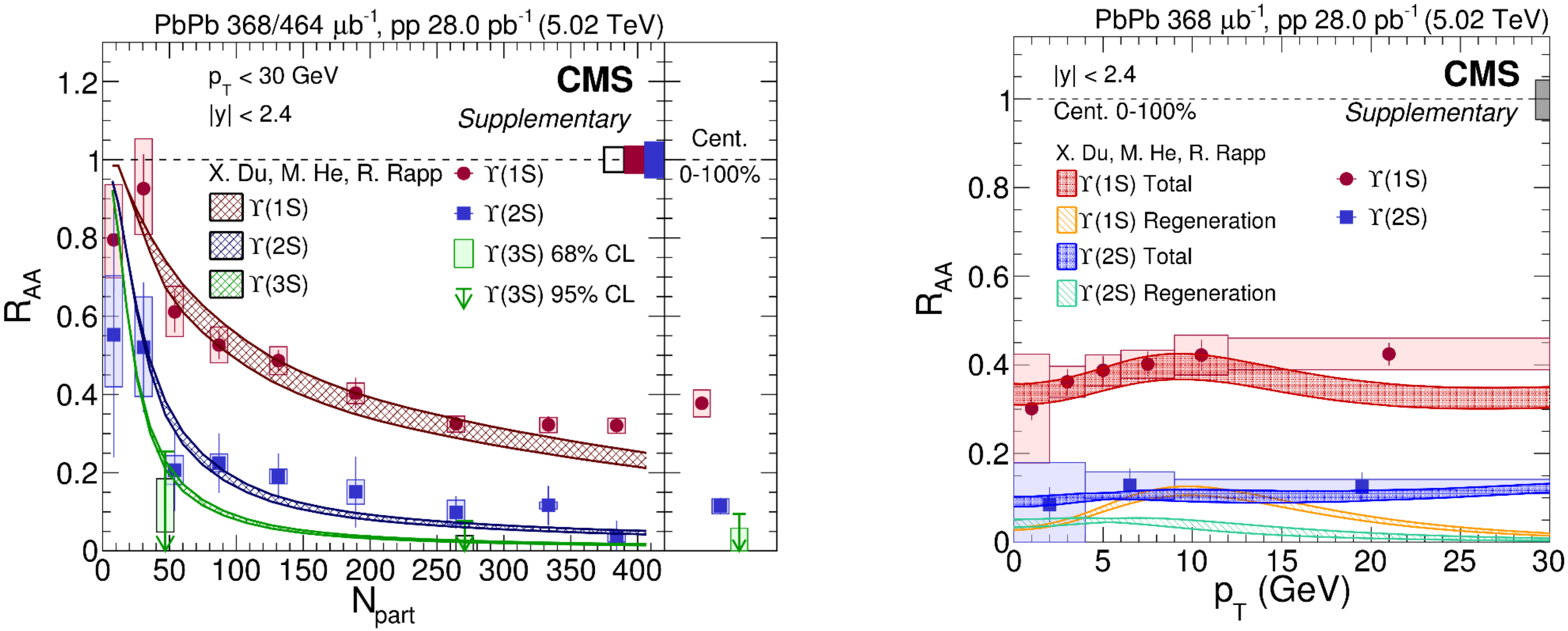
📖 **ALICE, PRL119 (2017) 242301**



- 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**

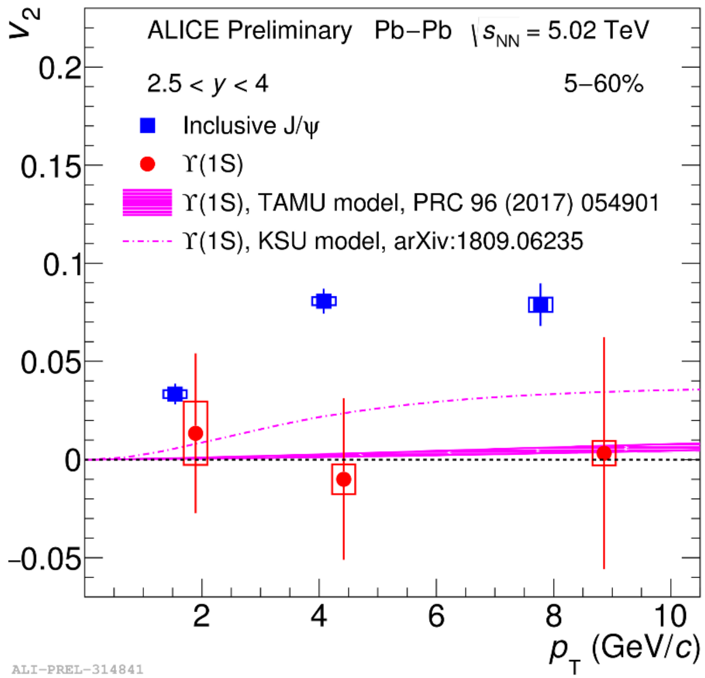
Bottomonium R_{AA}



- 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***

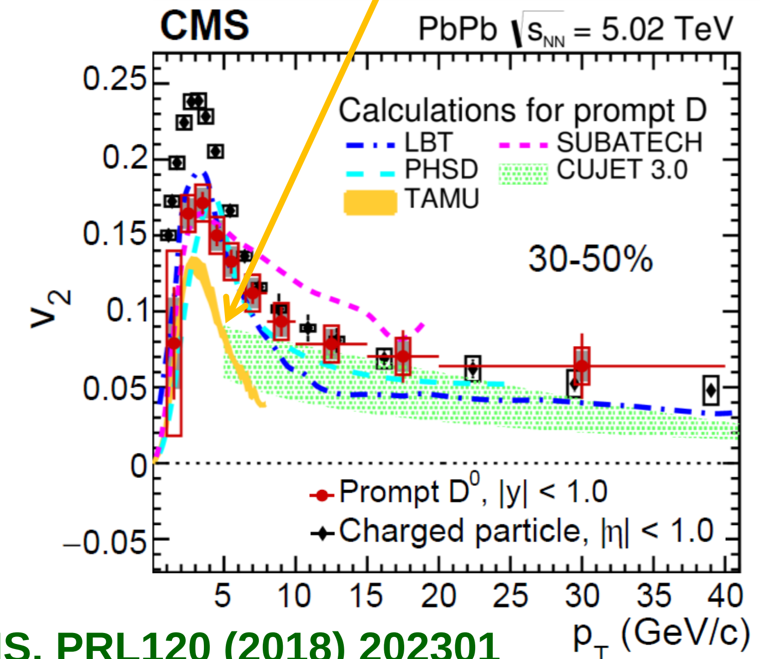
📖 **Oh et al., PRC79 (2009) 044905**
📖 **Ghosh at al., PRD 90 (2014) 054018**
📖 **He, Rapp et al. arXiv:1905.9216**

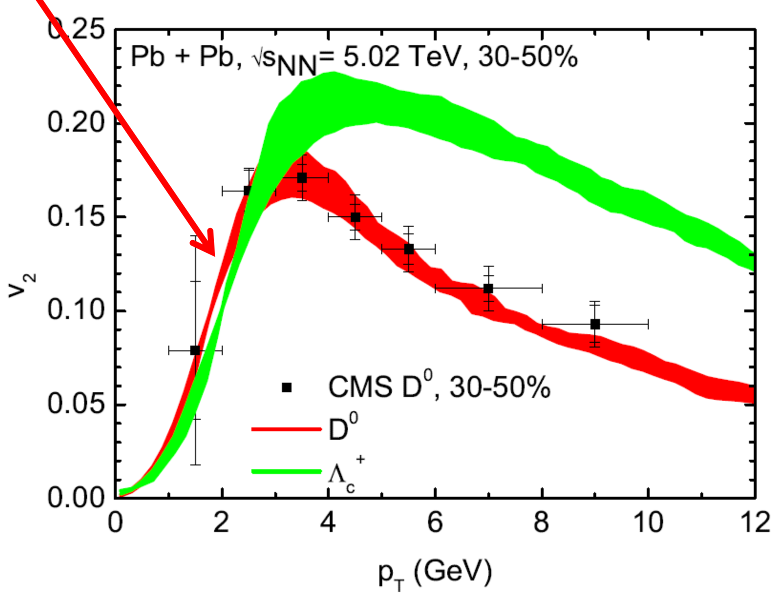
  - ⇨ **Strange** quarks abundant in the QGP → enhance D_s (B_s) yield relative to non-strange mesons

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

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***

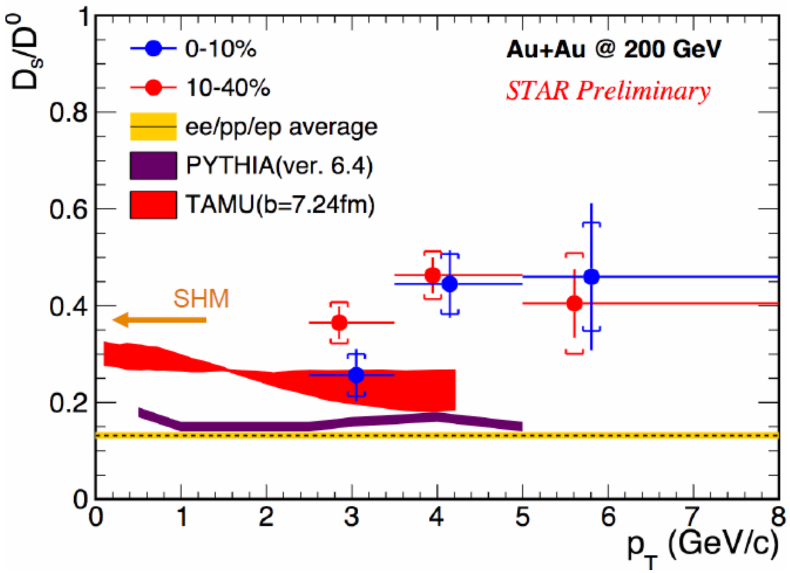


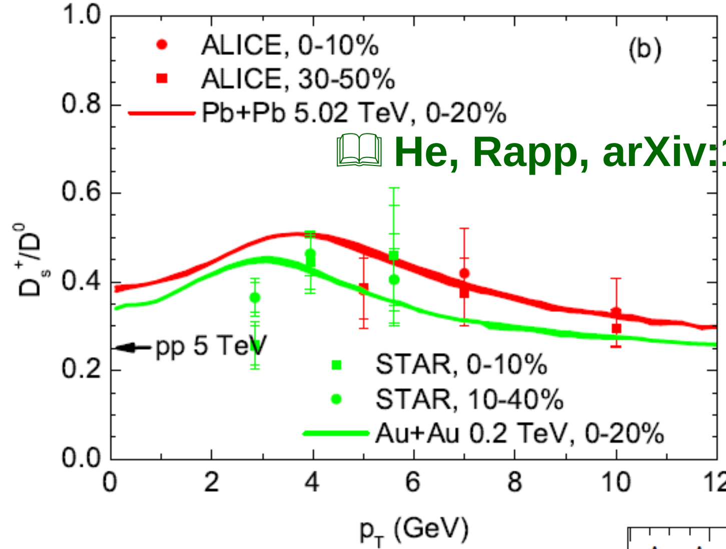


📖 **CMS, PRL120 (2018) 202301**

📖 **He, Rapp, arXiv:1905.09216**

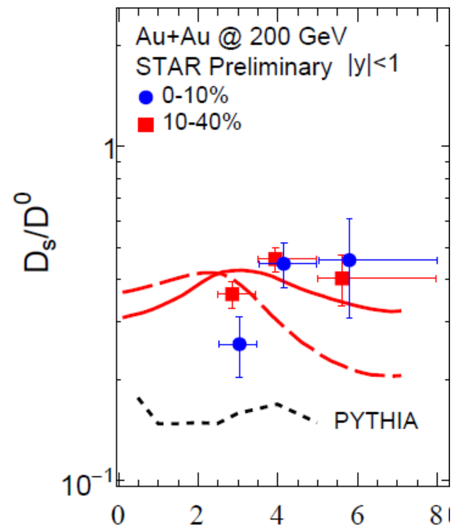
Charm-chemistry: D_s/D^0 at RHIC





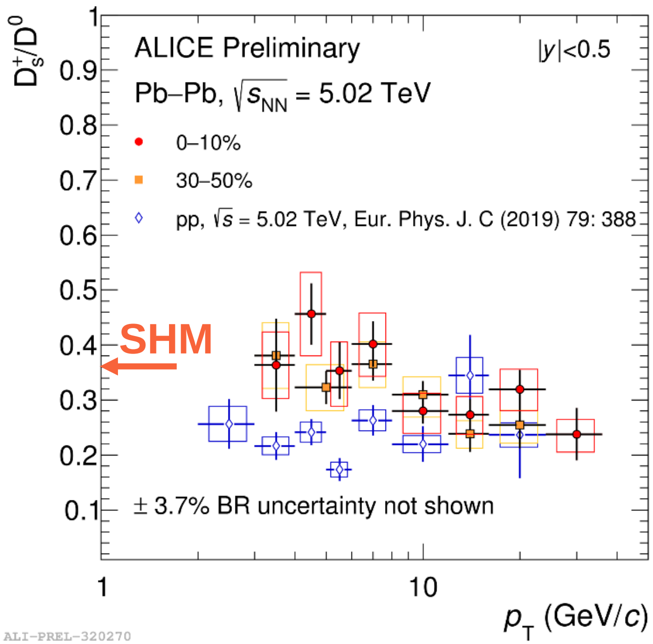
📖 **He, Rapp, arXiv:1905.09216**

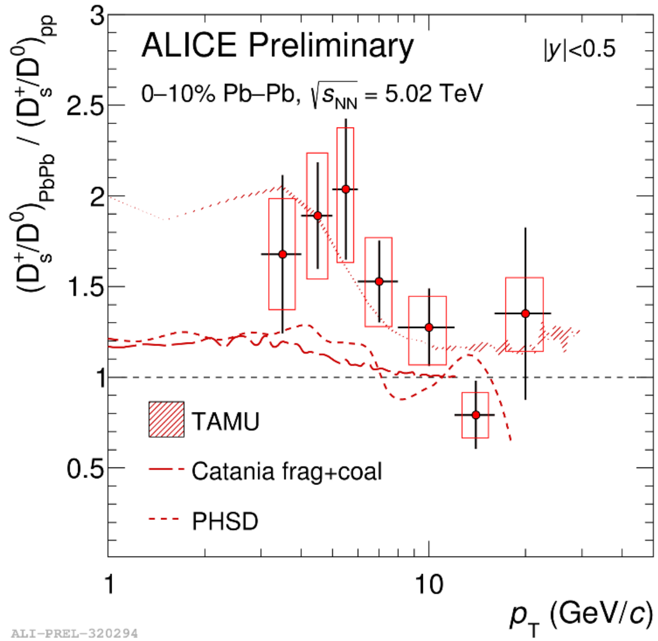
- D_s/D^0 ratio enhanced at low p_T as compared to pp
- Measured value compatible with Statistical Hadronizaion Model
- Described by models with charm quark recombination
  - ⇨ TAMU with improved space-momentum correlations between c quarks and underlying hydro medium
  - ⇨ Zhao model with and without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



📖 **Zhao et al., arXiv:1805.10858**

Charm-chemistry: D_s/D^0 at LHC

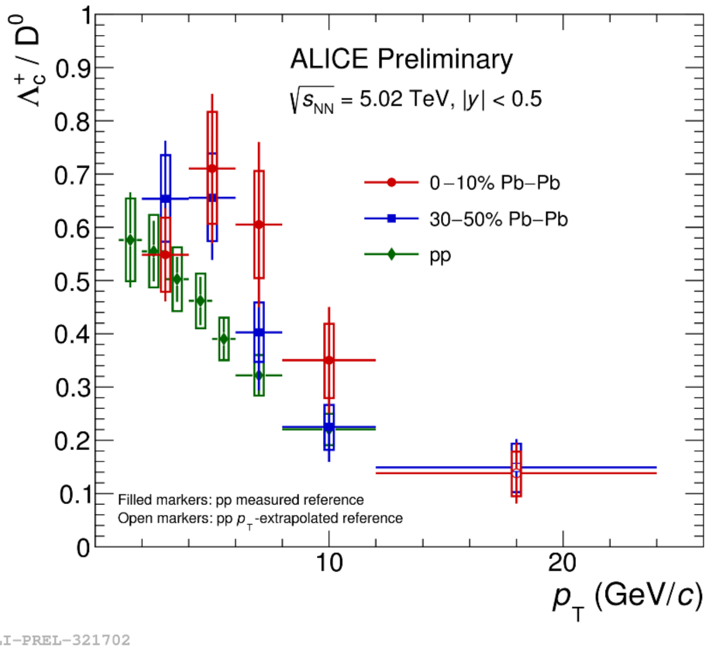


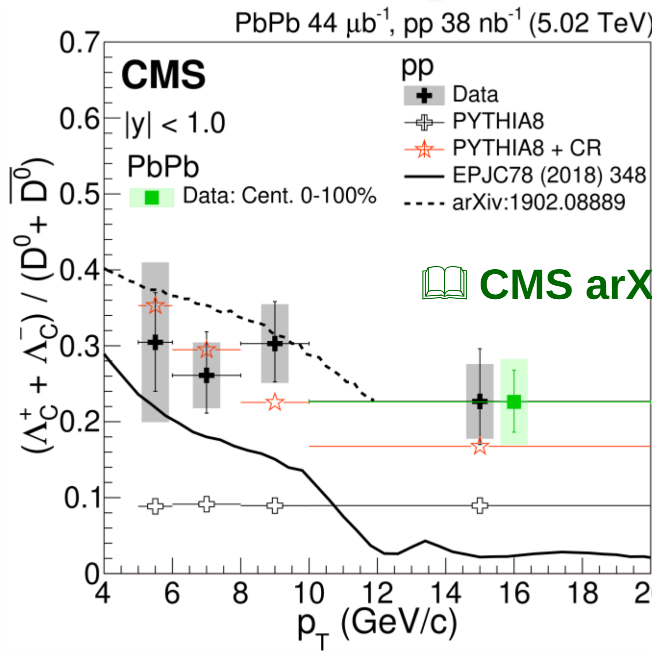


- Enhanced D_s/D^0 at low p_T with respect to pp
  - ⇨ D_s/D^0 at low p_T consistent with Statistical Hadronization Model
- Compatible with pp results at high p_T (>10 GeV/c)
- Qualitatively as expected in a scenario with strangeness enhancement in the QGP and hadronization via recombination
  - ⇨ Magnitude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





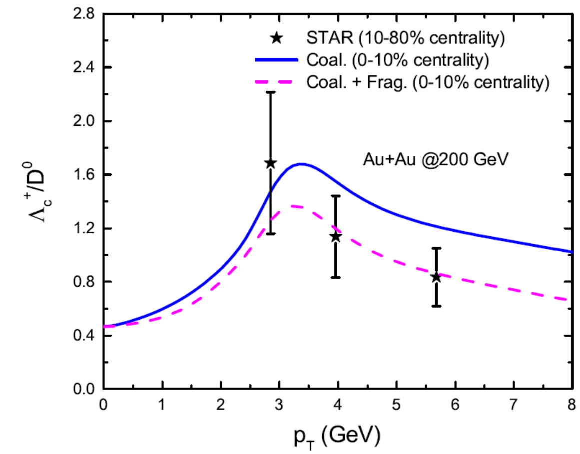
📖 CMS arXiv:1906.03322

- 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**

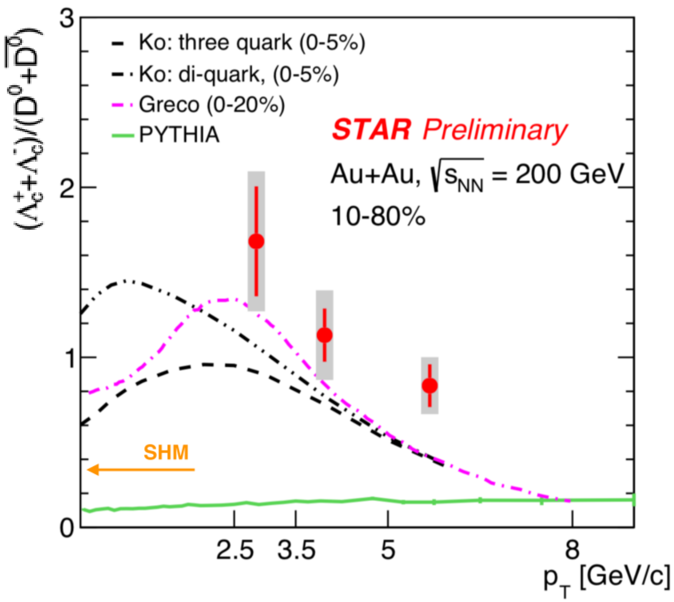
Λ_c / D^0 at RHIC vs. models

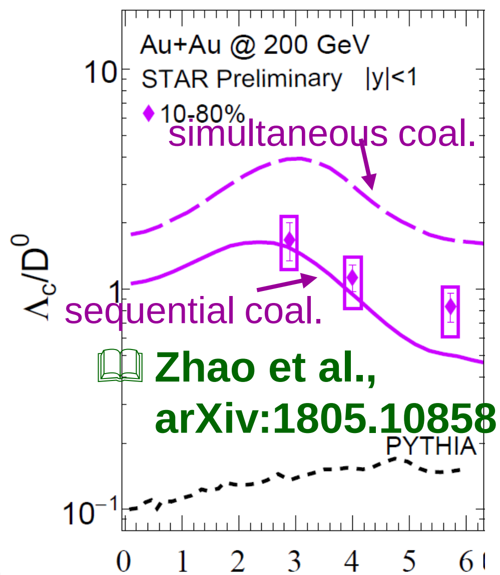
- Λ_c/D^0 ~ 1 at low p_T (<6 GeV/c)
  - ⇨ Enhanced with respect to PYTHIA
  - ⇨ Λ_c/D^0 larger than expectation from statistical hadronisation model
- Consistent with models with charm quark hadronization via coalescence



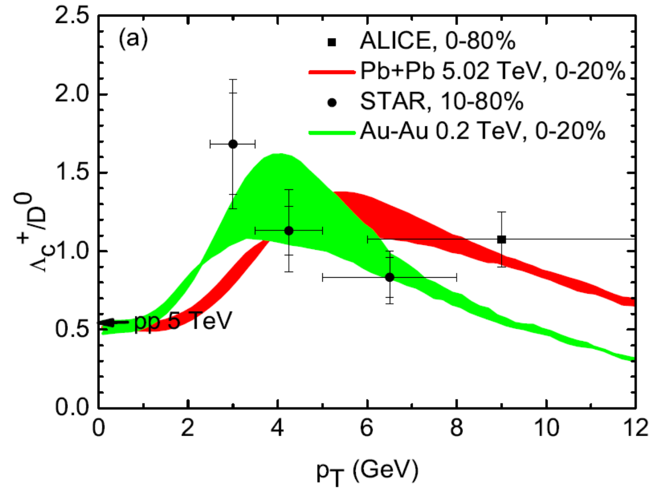
📖 Cho et al., arXiv:1905.09774

📖 He, Rapp, arXiv:1905.09216





📖 Zhao et al., arXiv:1805.10858

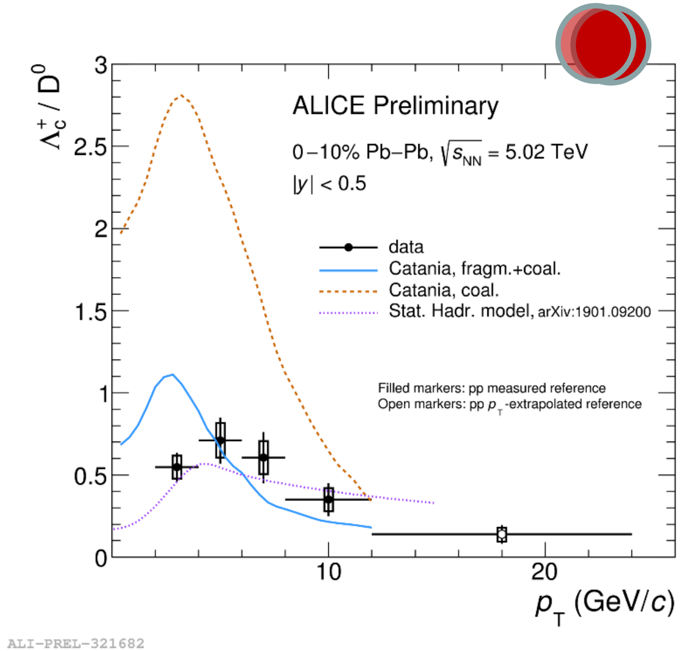


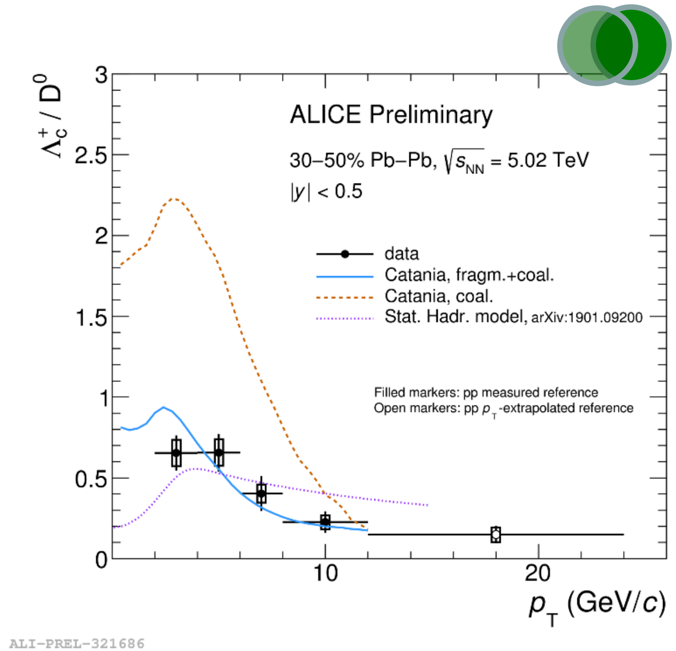
📖 Ko et al., PRC79 (2009) 044905

📖 Plumari et al., EPJC78 (2018) 348

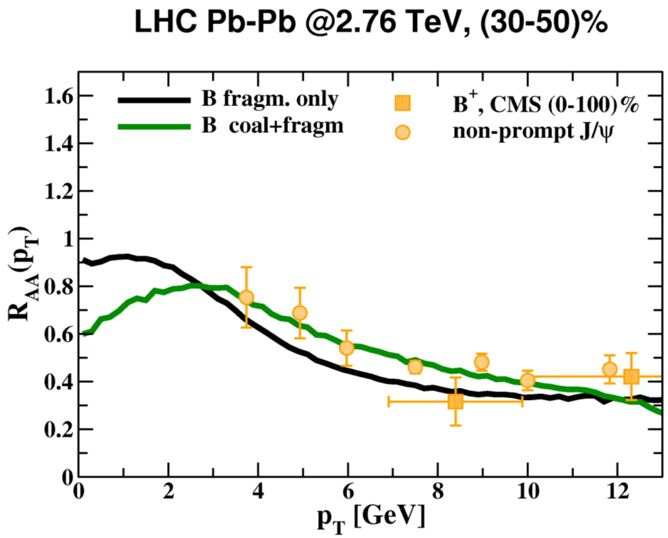
Λ_c / D^0 at LHC vs. models

- 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

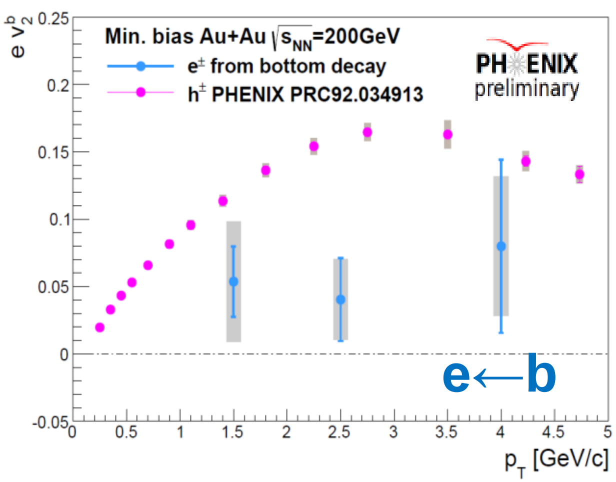




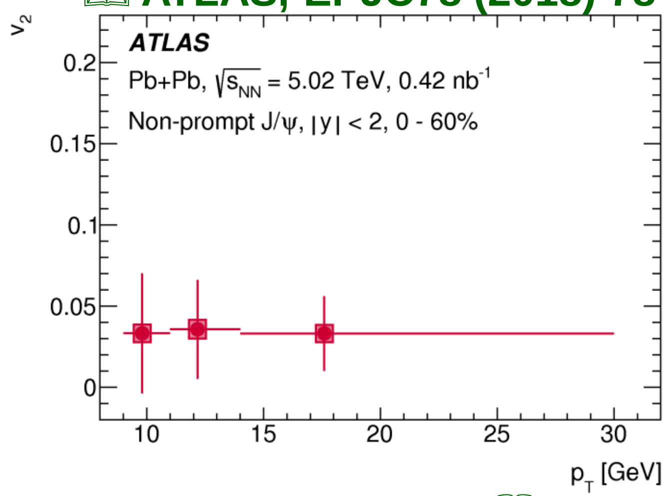
Open beauty: R_{AA} and v_2

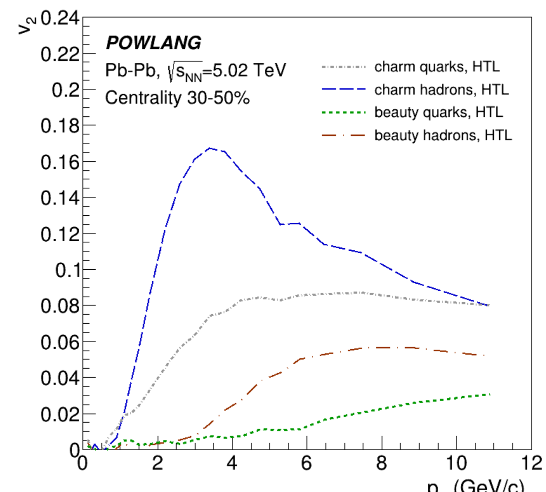


- B-meson R_{AA} in Catania's model better described with coalescence+fragmentation
- Hint of v_2 >0 for e± and J/ψ from beauty
  - ⇨ Magnitude transport model predictions
    - ✓ ***Smaller v_2 of b quarks with respect to c quarks***
    - ✓ ***Recombination for beauty important up to higher p_T than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



📖 **ATLAS, EPJC78 (2018) 784**

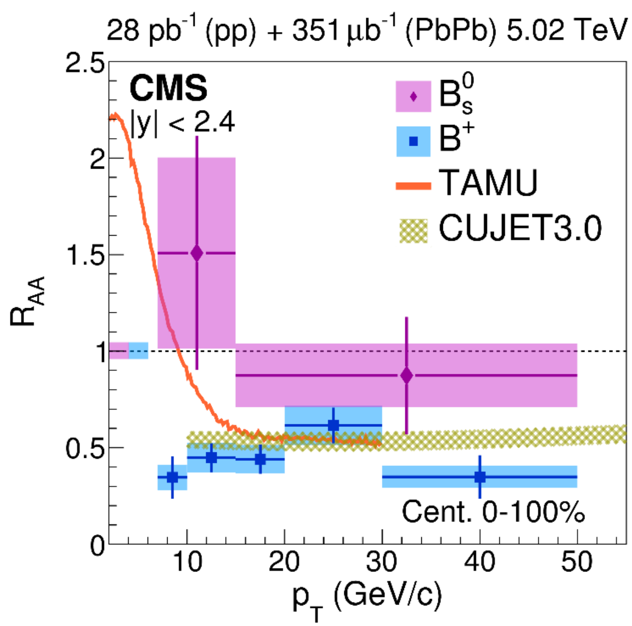


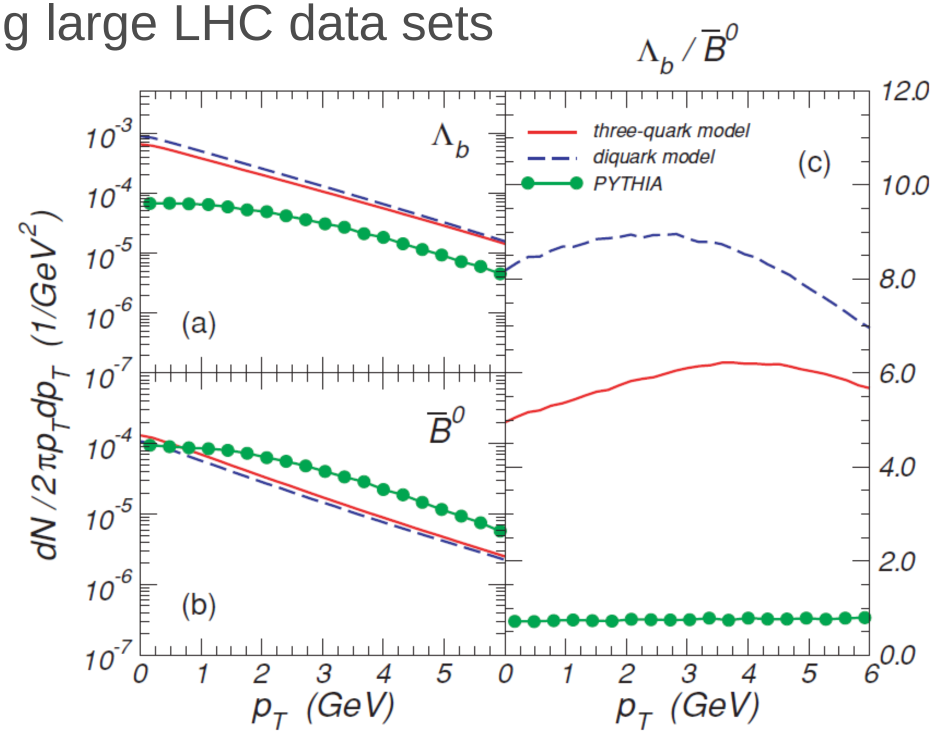


📖 **Beraudo et al., JHEP02 (2018) 043**

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



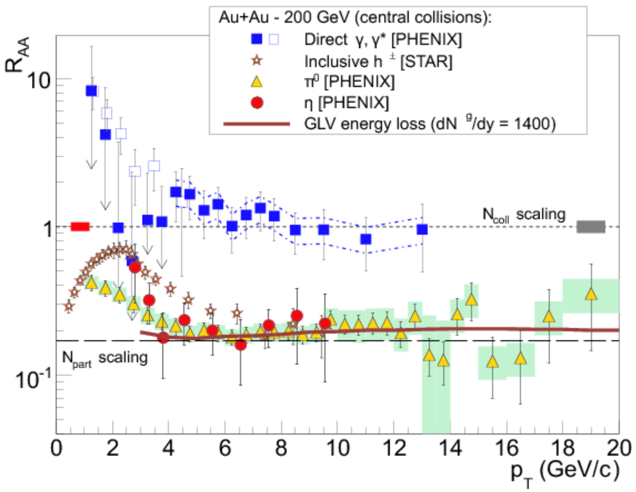


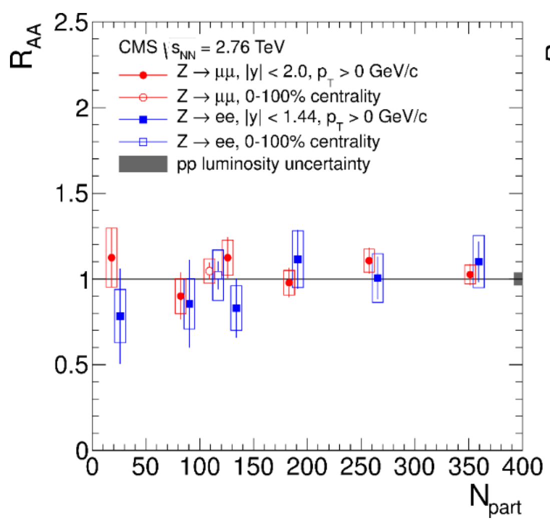
📖 **CMS: arXiv:1810.03022**

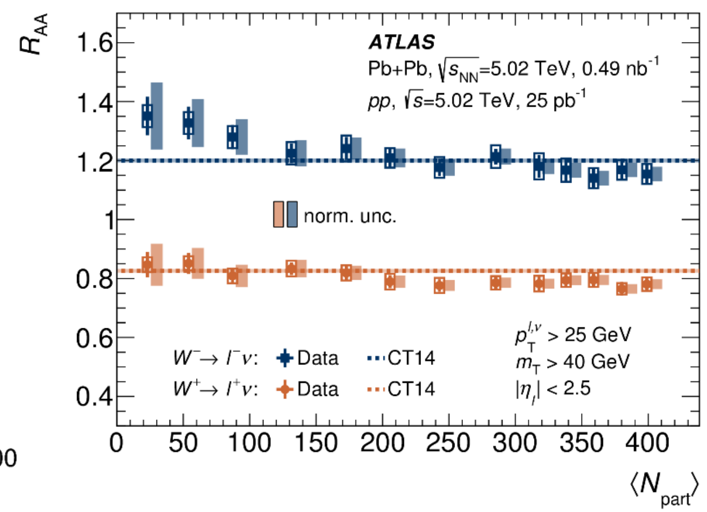
📖 **Oh et al, PRC79 (2009) 044905**

Medium blind probes: γ, W, Z^0

- Control experiment: no suppression for photons, W and Z^0 bosons
  - ⇨ Production of particles w/o color charge not modified by the QGP medium
  - ⇨ NOTE: R_{AA} of $W^{\pm}$ expected to deviate from unity due to isospin effect in Pb-Pb collisions
    - ✓ ***Enhancement of W^- and suppression of W^+ relative to pp***







📖D'Enterria, Betz, Springer Lecture Notes in Physics (LNP), 2009

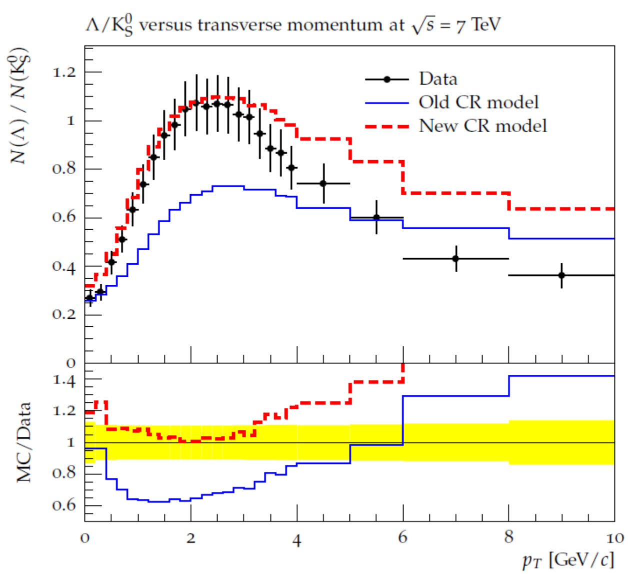
📖CMS, JHEP 03 (2015) 022

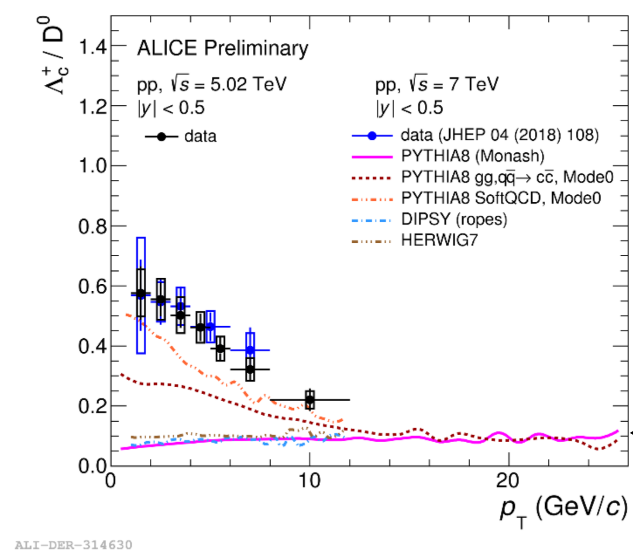
📖ATLAS, arXiv:1907.10414

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**





e^+e^- LEP

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

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:

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

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

⇨

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

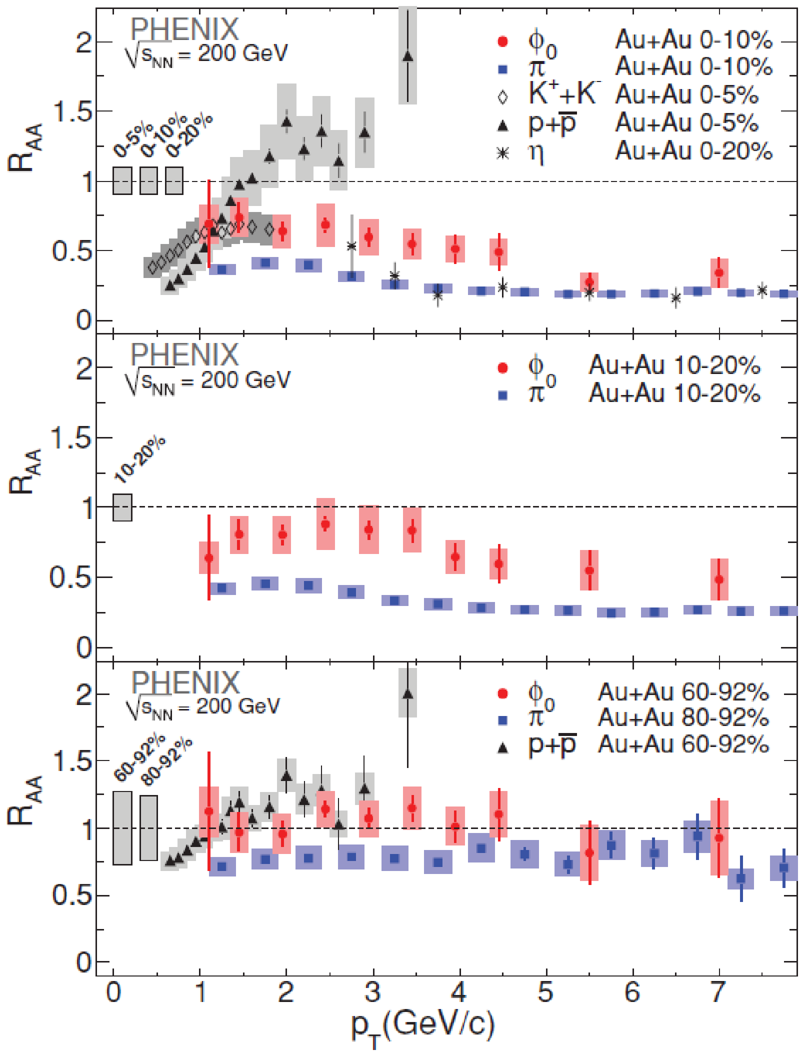
$$v_{2,B}(p_T) \approx 3v_{2,q}\left(\frac{p_T}{3}\right)$$

📖 **Molnar, Voloshin, PRL91 (2003) 092301**

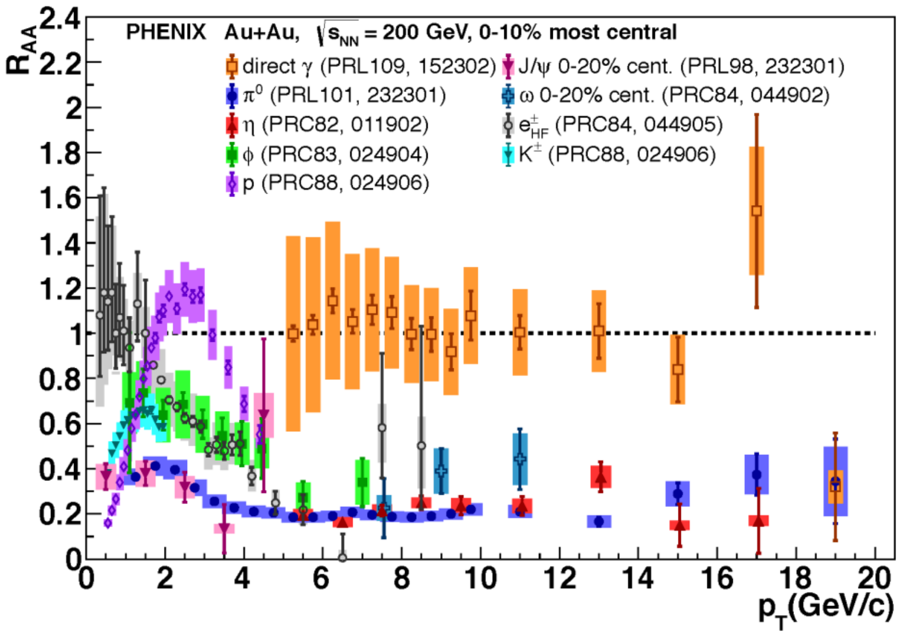
📖 **Pratt, Pal, PRC71 (2005) 014905**

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



Charm hadrochemistry

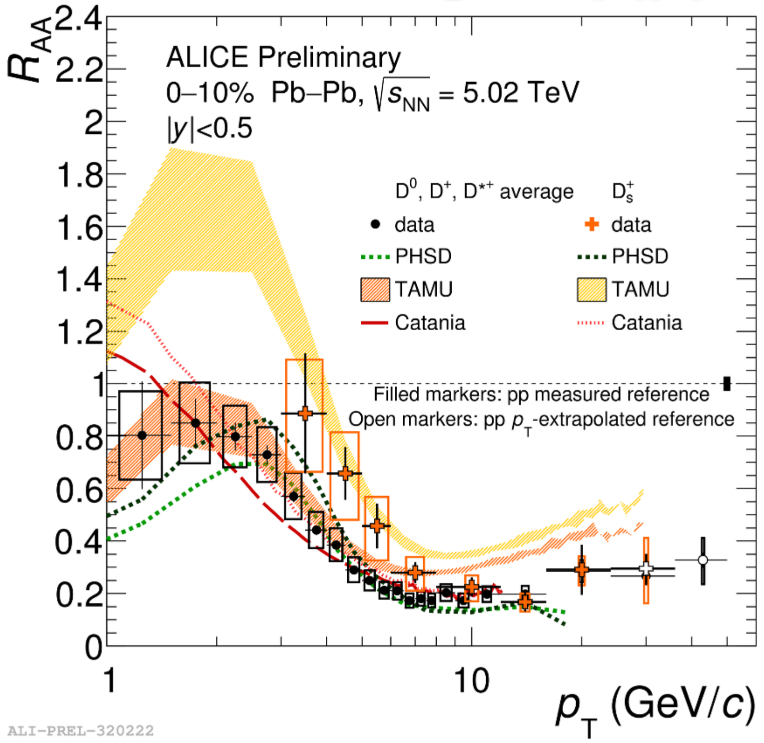
- Hadronization via recombination expected to modify the charm hadron abundances relative to pp case

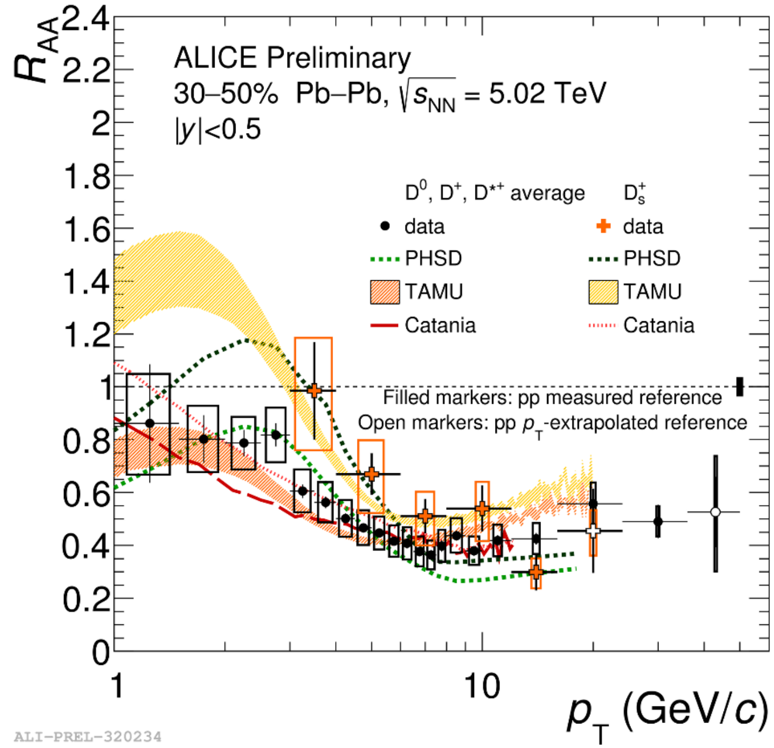
Particle	e^+e^-	PYTHIA	Thermal model	Coalescence (w/o diquark)	Coalescence (with diquark)
$f(c \to D^0)$	0.542	0.607	0.435	0.348	0.282
$f(c \to D^+)$	0.225	0.196	0.205	0.113	0.091
$f(c \to D_s^+)$	0.092	0.121	0.179	0.113	0.123
$f(c \to \Lambda_c^+)$	0.057	0.076	0.118	0.288	0.378
Ratio	**e^+e^-**	**PYTHIA**	**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

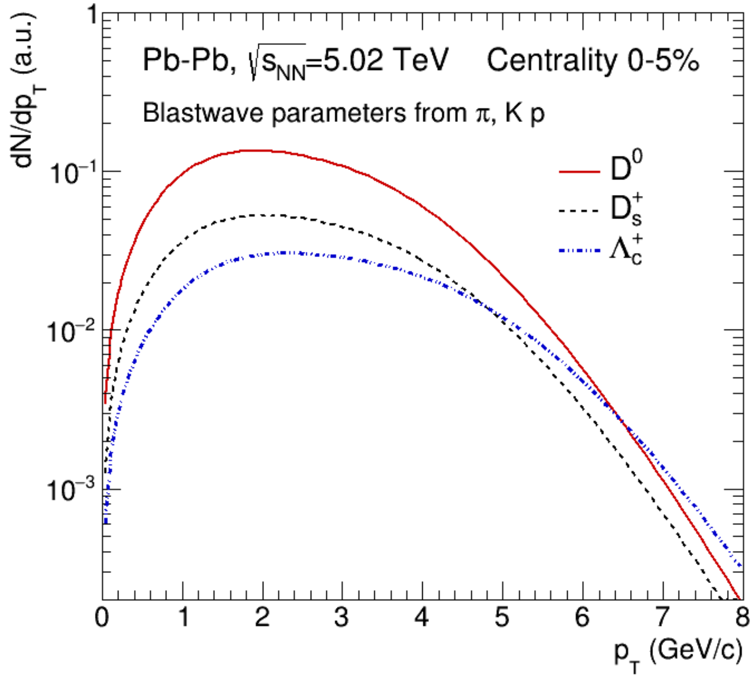
D_s R_{AA} at the LHC

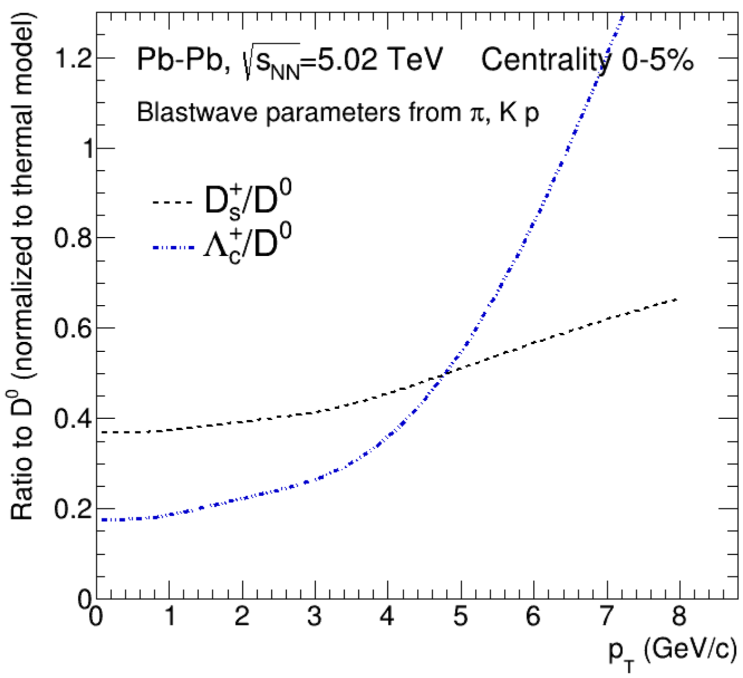




- D_s less suppressed than non-strange D mesons at low p_T
- R_{AA} of D_s and non-strange D mesons compatible at high p_T (>10 GeV/c)
- Qualitatively as expected in a scenario with strangeness enhancement in the QGP and hadronization via recombination

Charm: thermal + blast wave

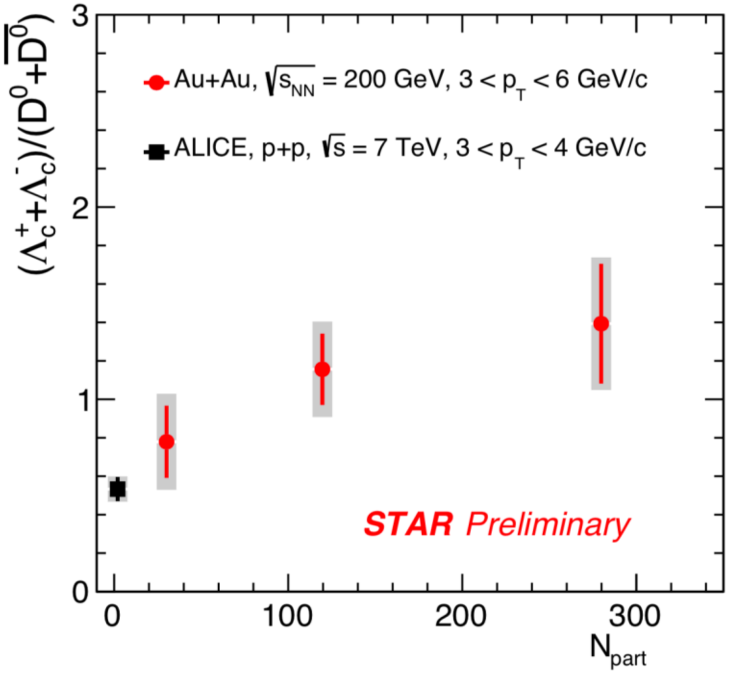




- Thermal model abundances from Oh et al.
- Blast wave parameters from pion, kaon, proton measurements by ALICE

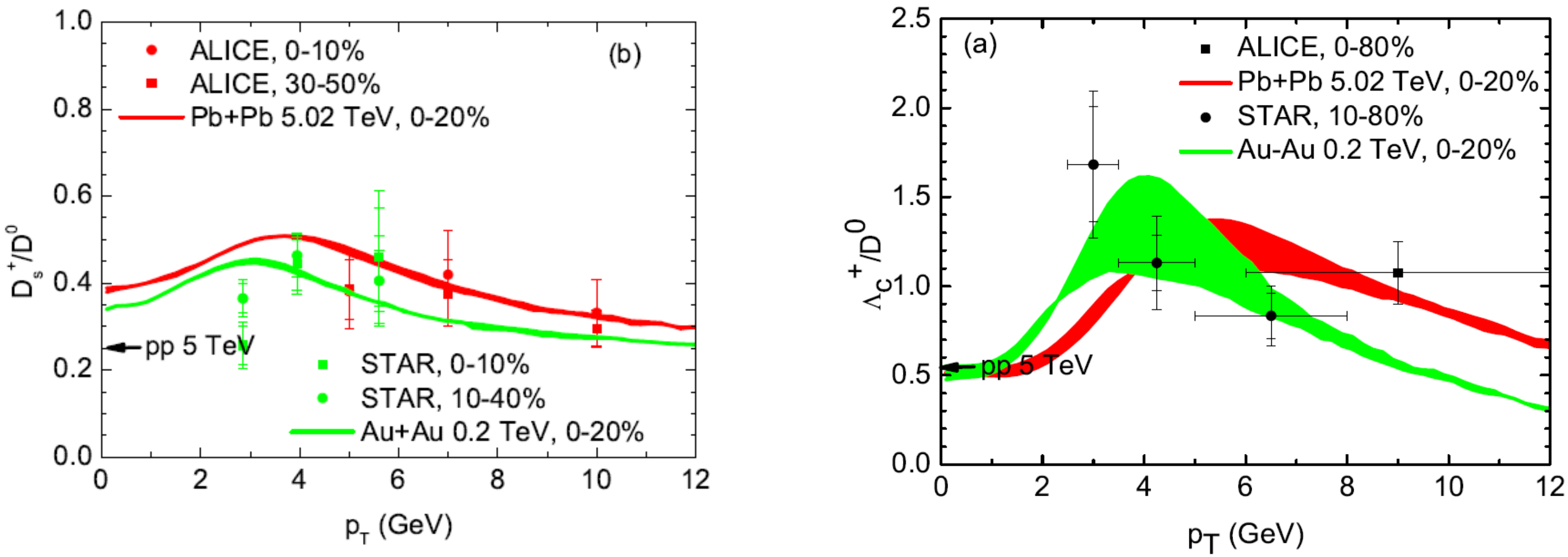
Oh et al, PRC79 (2009) 044905

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

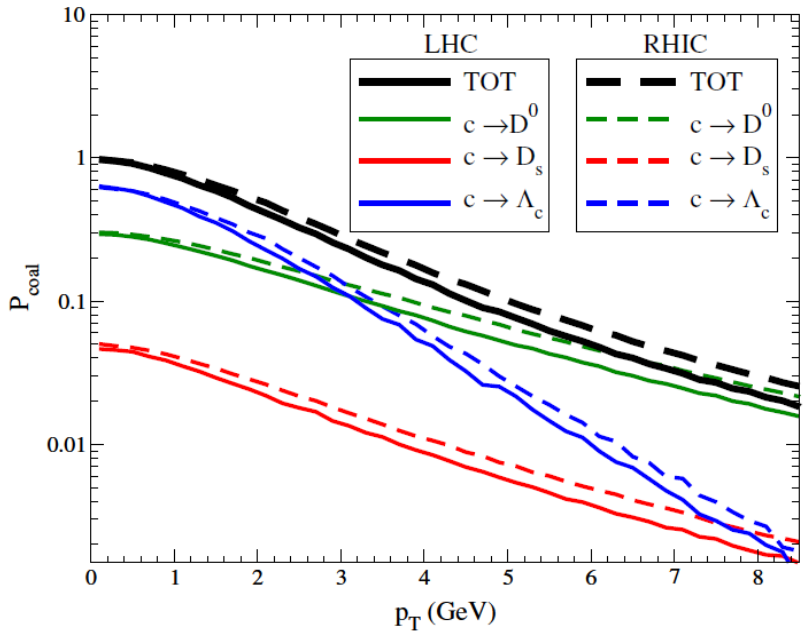
Charm hadrochemistry from TAMU



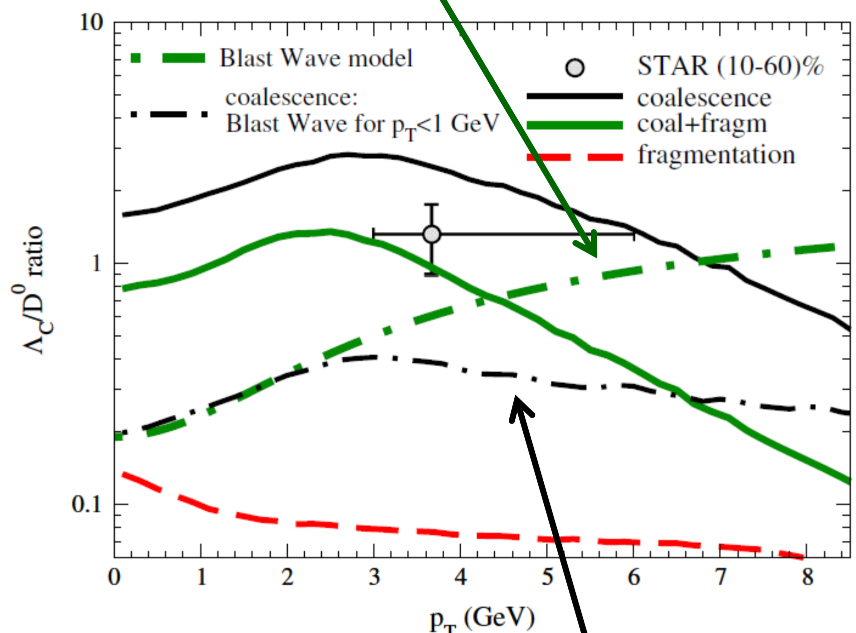
- Charm quark transport in hydrodynamic medium
- Generalized resonance recombination model
  - ⇨ Extended to 3-body case to treat hadronization into baryons
  - ⇨ Improved space-momentum correlations between c quarks and underlying hydro medium
  - ⇨ Improved charm-hadron chemistry with baryon states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

He, Rapp, arXiv:1905.09216

Charm baryons from Catania



Thermal spectra of Λ_c and D^0



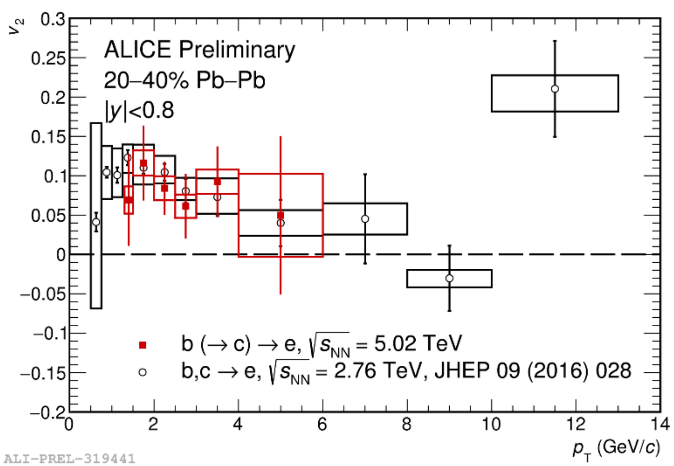
- Coalescence probability decreases with increasing p_T
  - ⇨ At high p_T fragmentation takes over
- Al low p_T the probability of udc quarks to coalescence into a Λ_c is higher than that of $c\bar{u}$ to form a D^0

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

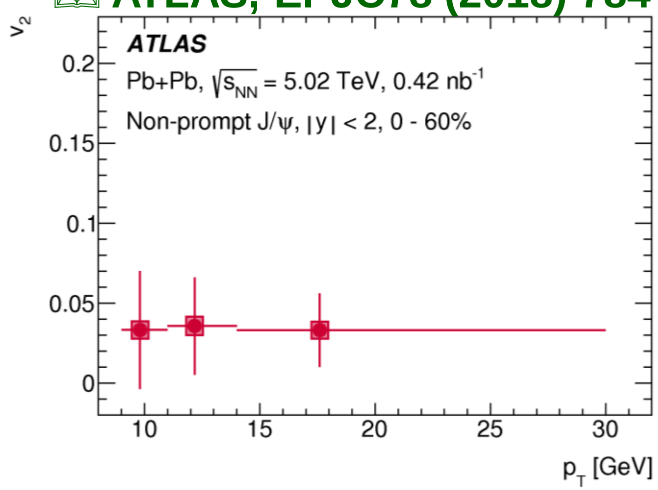
📖 **Plumari et al., EPJC78 (2019) 348**

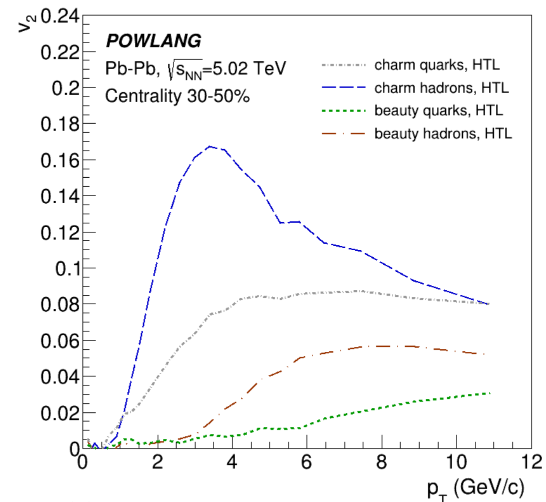
Open beauty v_2

- 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



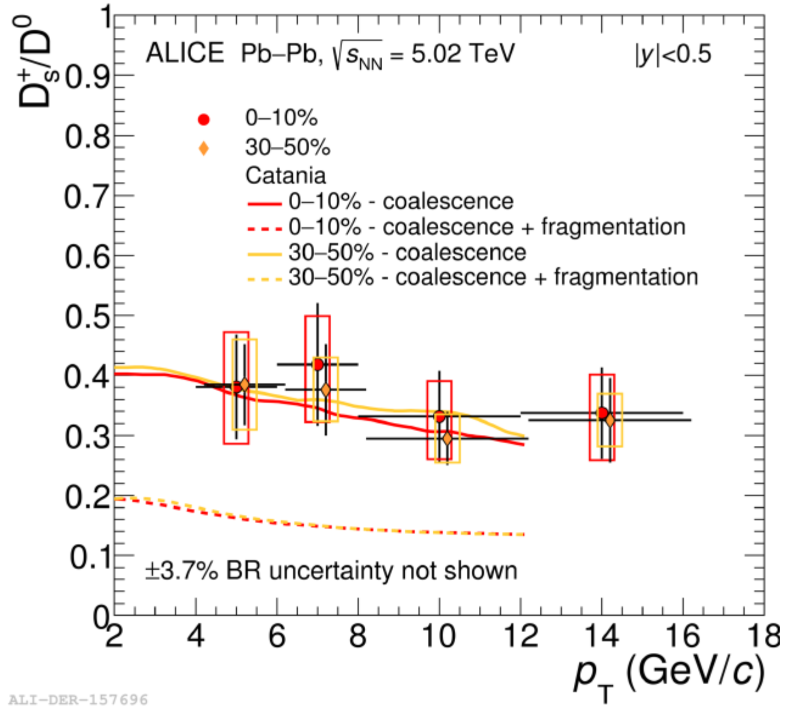
📖 **ATLAS, EPJC78 (2018) 784**





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

D_s / D^0 from Catania



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