Heavy-ion physics

Francesco Prino
INFN – Sezione di Torino

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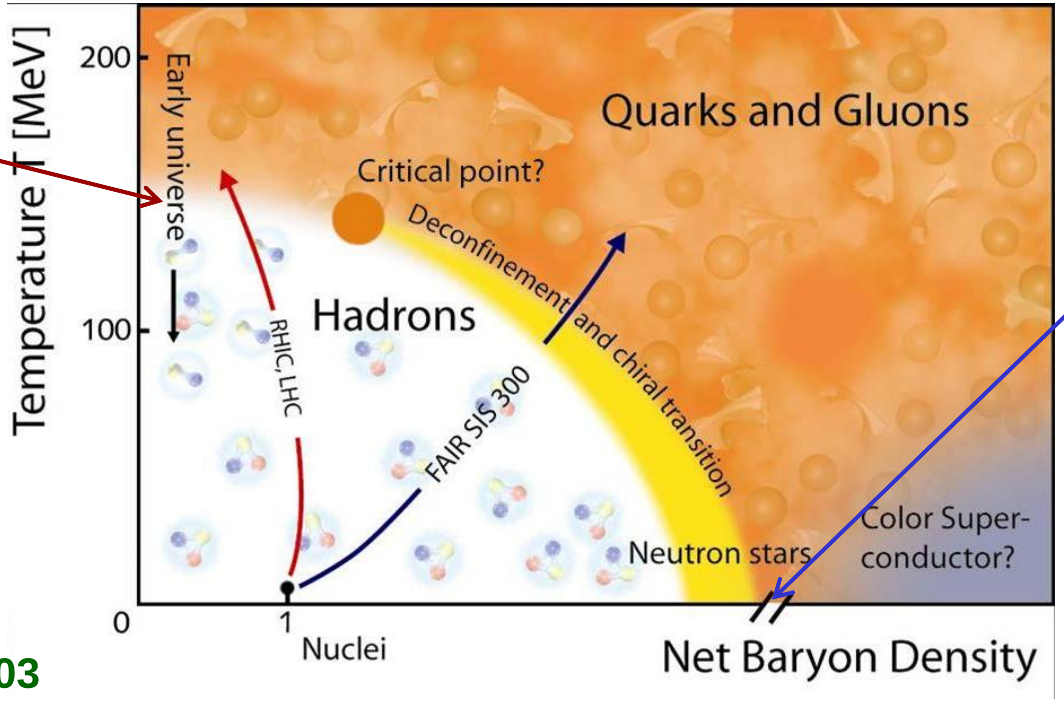
Heavy-ion collisions and QCD

- 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≈145-160 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

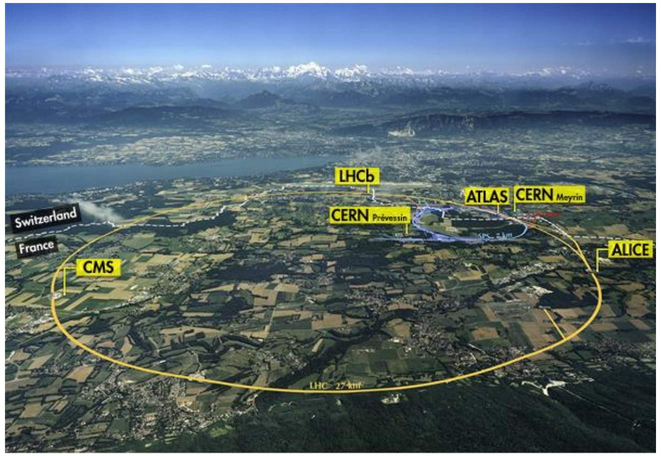
📖 **Bazavov et al, PRD90 (2014) 094503**
📖 **Borsanyi et al, JHEP 1009 (2010) 073**
📖 **Baym et al., arXiv:1707.04966**

Heavy-ion collisions and QCD

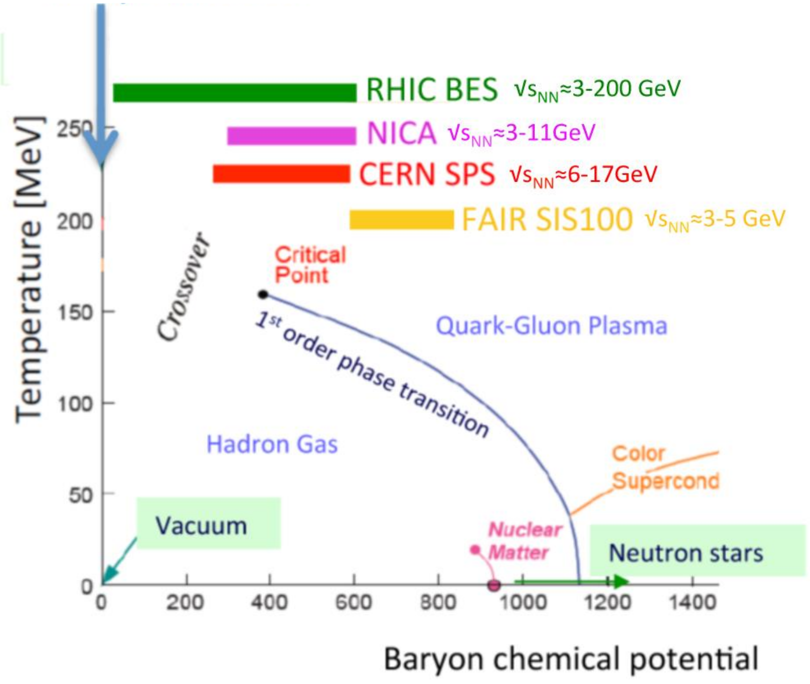
- Heavy-ion collision at different energies allow us to explore different regions of the QCD phase diagram

High energy frontier: LHC, RHIC top energy

- All the four main LHC experiments have a heavy ion program
- sPHENIX experiment in preparation at RHIC

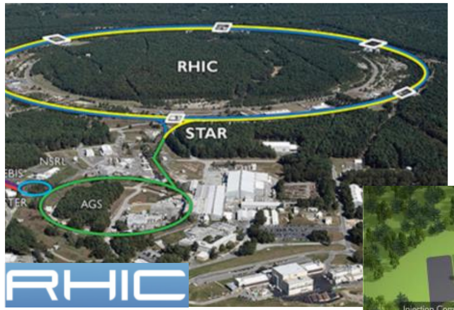


LHC, RHIC (top energy)

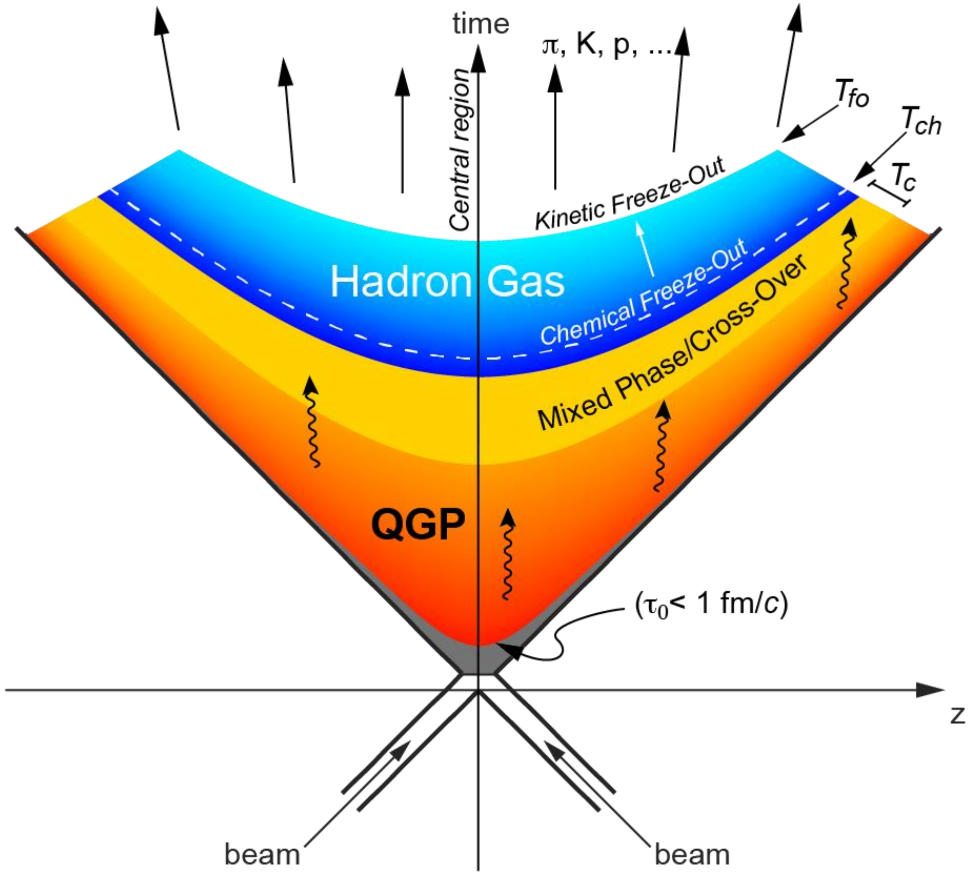


Low energy frontier:

- RHIC and SPS beam energy scan
- Future facilities: FAIR, NICA



Space-time evolution



Time

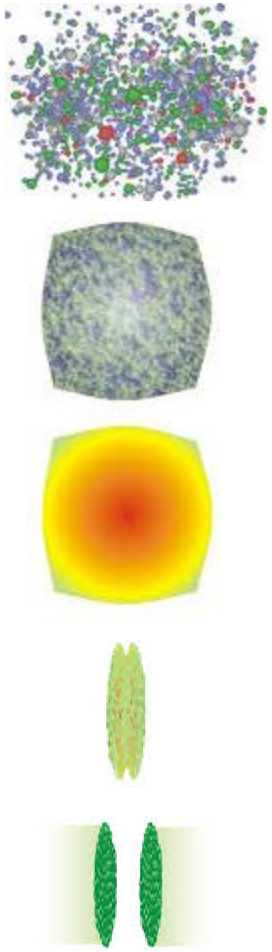
Kinetic freeze-out — t~10 fm/c

Chemical freeze-out
Hadronization

QGP hydrodynamic evolution

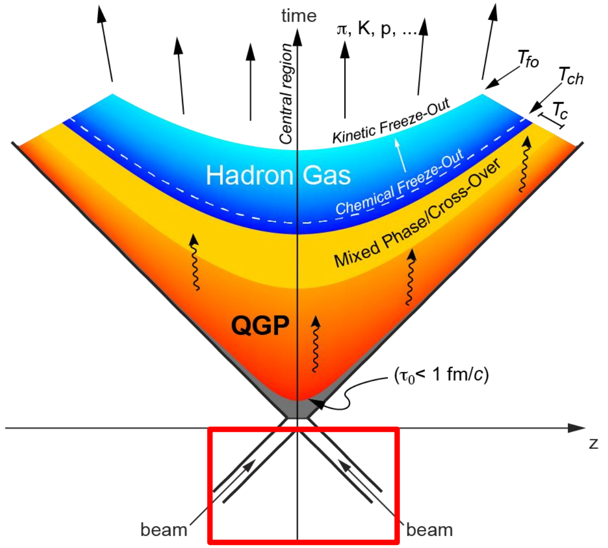
Pre-equilibrium — t~1 fm/c

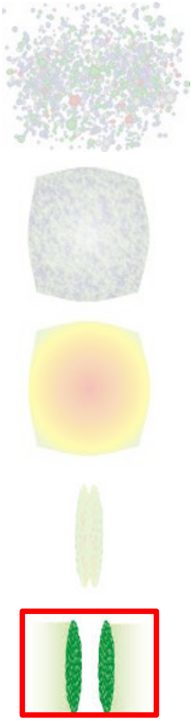
Collision — t=0 fm/c



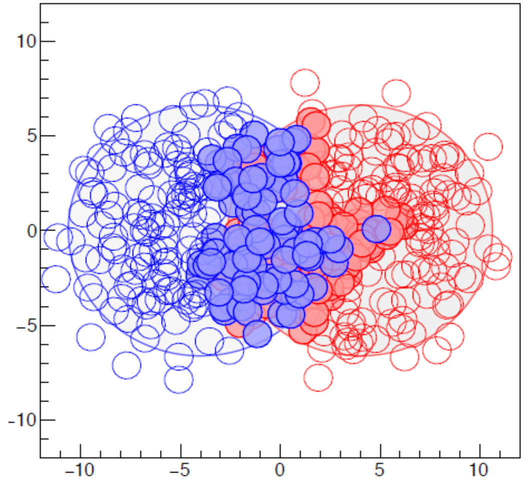
- QGP lifetime ~ a few fm/c
- Expansion under strong pressure gradients
- Transition to hadrons when the temperature drops below the critical value

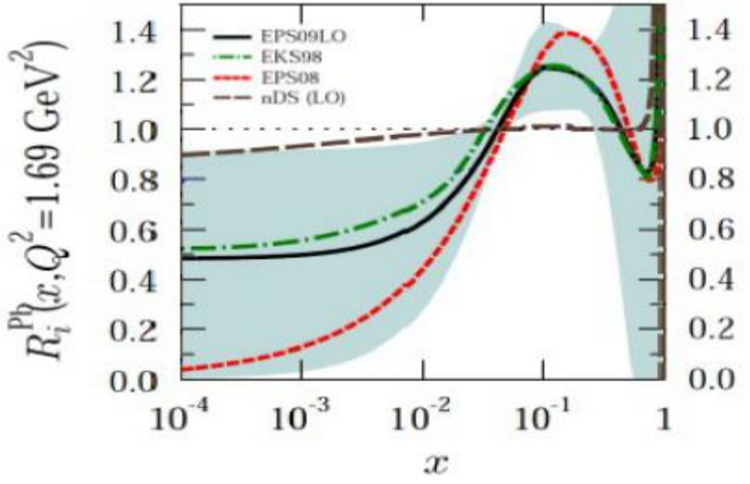
Initial state





- 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

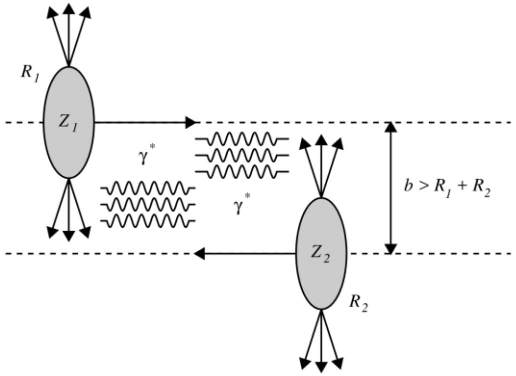


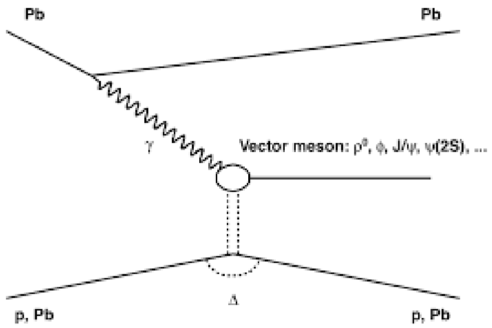


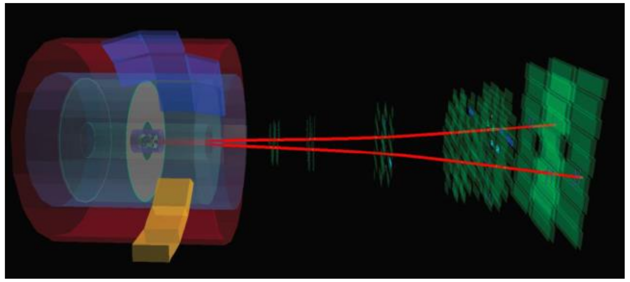
- Insight into initial state via:
  - ⇨p-A collisions
  - ⇨Ultra-peripheral A-A collisions
- Future measurements in e-A interactions at electron-ion collider

Initial state: Ultra Peripheral Collisions

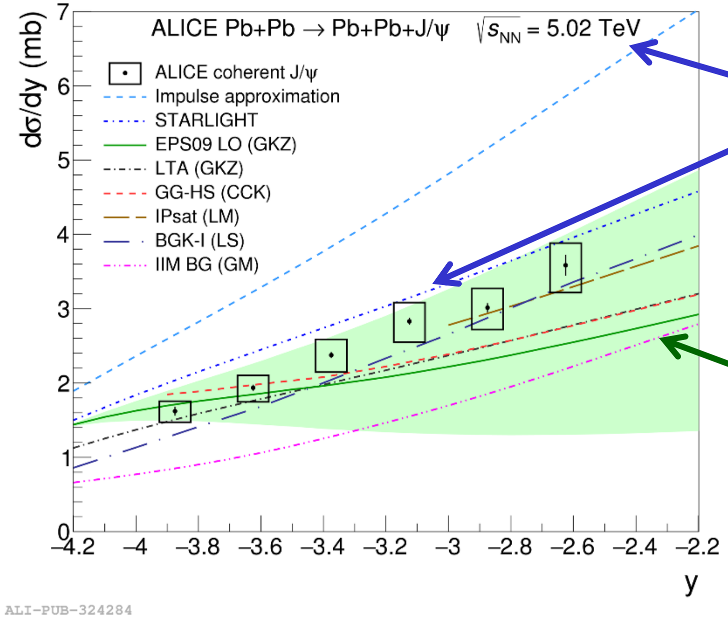
- Collisions with impact parameter b > 2R
  - ⇨ Hadronic interactions suppressed
- Coherent J/ψ photoproduction
  - ⇨ γ coupling coherently to the nucleus
  - ⇨ Low J/ψ p_T, target nucleus not breaking up
  - ⇨ Sensitive to gluon PDFs at low Bjorken-x (~10^{-2}-10^{-5}) → **shadowing** region







Poster by T. Herman



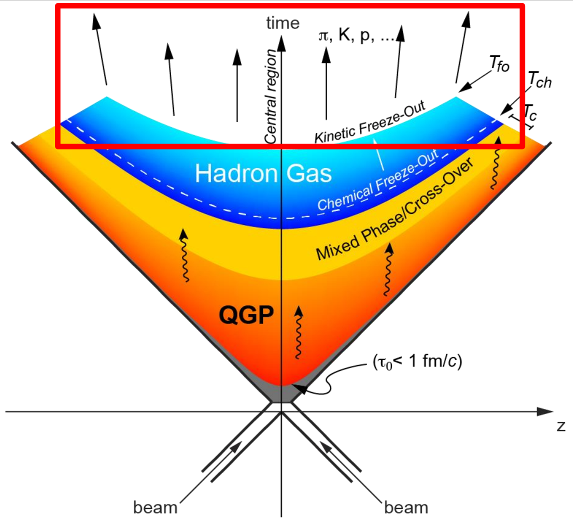
Models without gluon shadowing overpredict the data

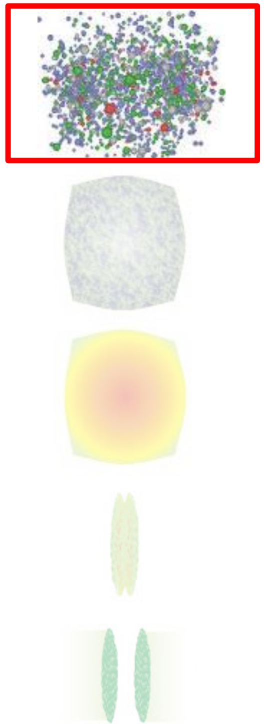
Moderate shadowing in the nucleus necessary to describe the measurements

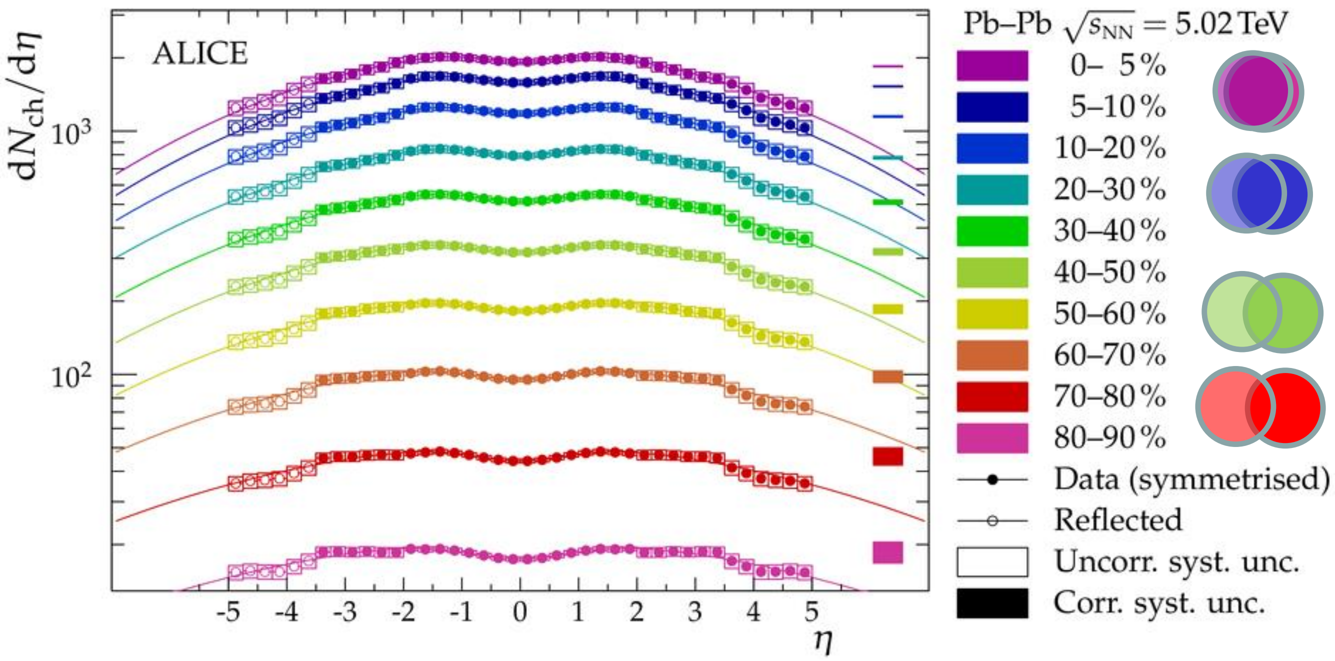
📖 **ALICE, arXiv:1904.06272**

Final state: the "bulk"

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







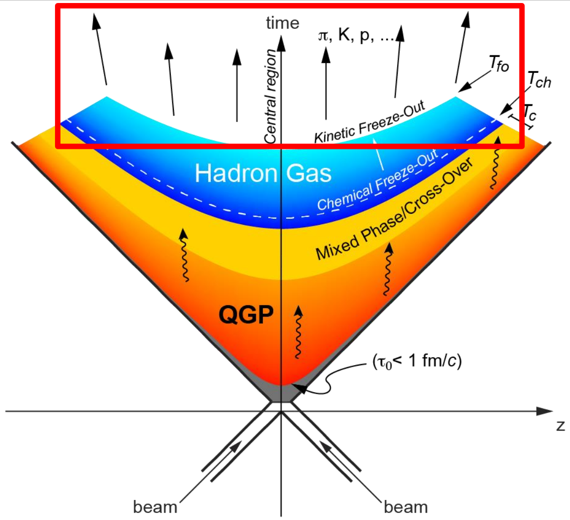
📖 **ALICE, PLB 772 (2017) 567**

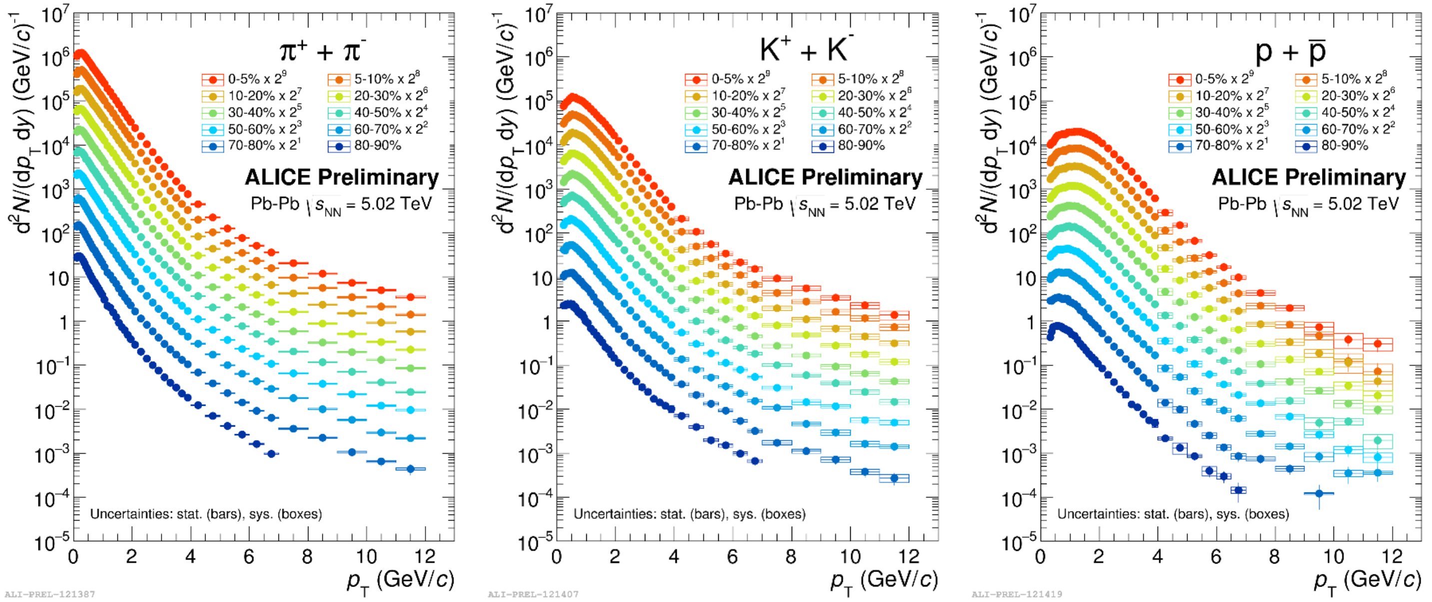
- Multiplicity of produced particles depends on collision geometry
  - ⇨ Decreases from central to peripheral collisions
- Large energy density in the created "fireball":
  - ⇨ **ε~12 GeV/fm³** at τ=1 fm/c in central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

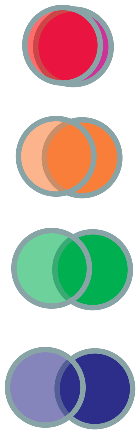
📖 **ALICE, PRC 94 (2016) 034903**

The flowing "bulk" of soft particles

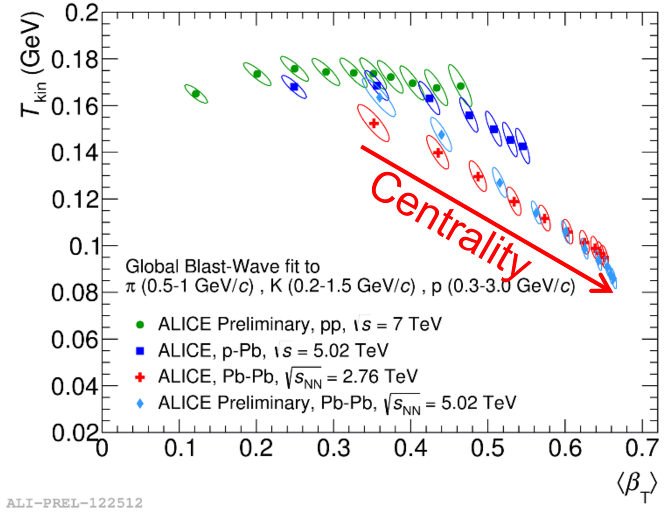
~**21000** particles produced in central Pb-Pb @ $\sqrt{s_{NN}}$=5.02 TeV



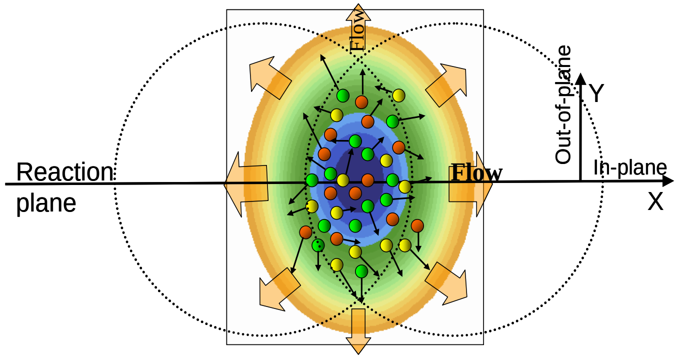




- Particle momentum spectra frozen at the **kinetic freeze-out**
  - ⇨ Even at LHC energy, 95% of produced particles have p_T<2 GeV/c
  - ⇨ Bulk of particle production associated with **"soft" physics** in non-perturbative regime of QCD
- Hardening of the spectral shapes with increasing centrality and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

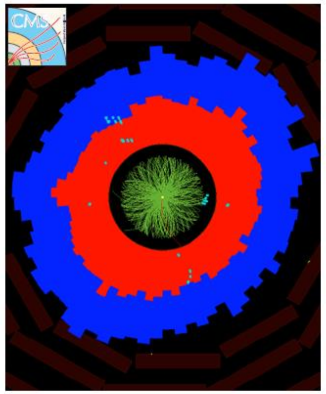


Anisotropic transverse flow

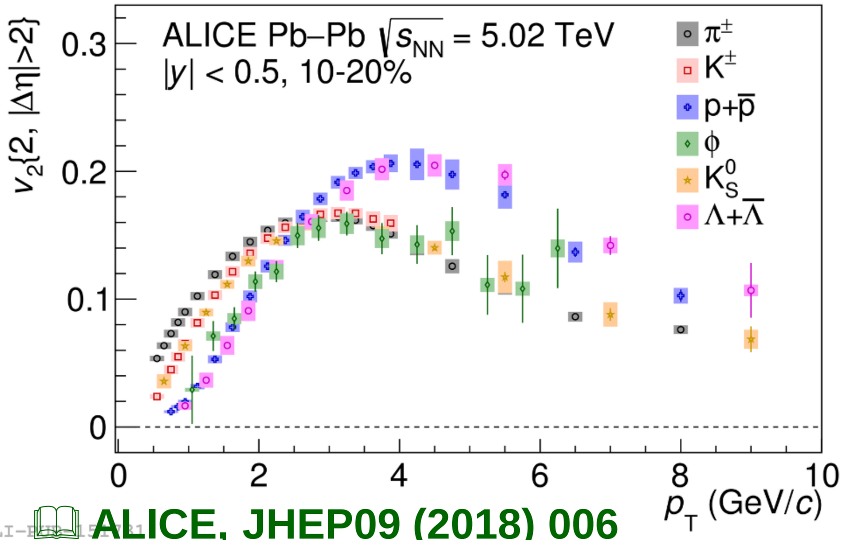


- Initial geometrical anisotropy in non-central collisions
  - ⇨ Impact parameter selects preferred direction in the transverse plane
- Hydrodynamical evolution converts the initial geometrical anisotropy into an observable final-state particle momentum anisotropy:

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos[n(\varphi - \Psi_{RP})]\right\}$$

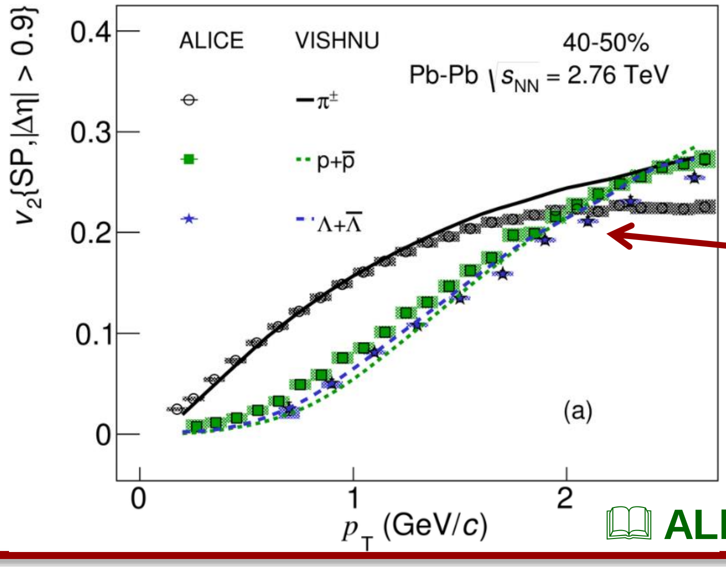


⇨ Fourier coefficient v_2 = **elliptic flow**



ALI-PUB-151881

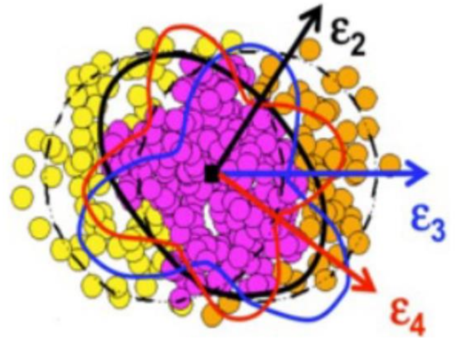
📖 **ALICE, JHEP09 (2018) 006**

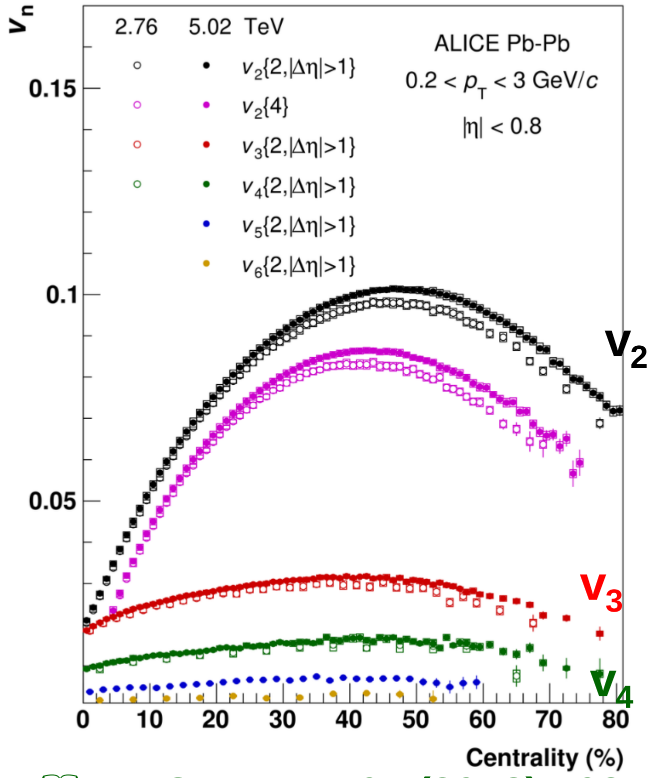


📖 **ALICE, JHEP06 (2015) 190**

- Measured v_2 at low p_T described by **hydrodynamics**
- Mass ordering originating from collective radial flow velocity

Anisotropic transverse flow





📖 ALICE, JHEP07 (2018) 103

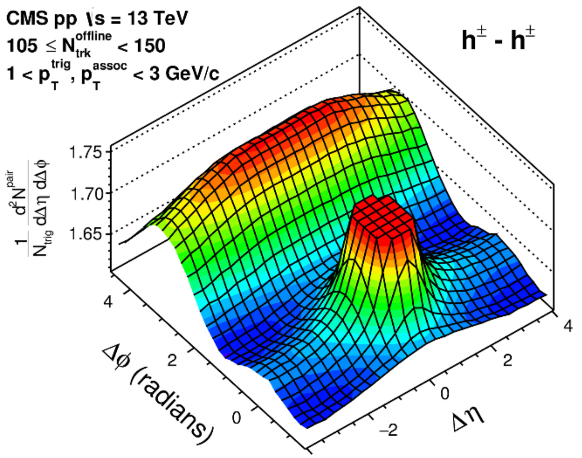
- Fluctuations and lumpiness of initial geometry (participant nucleons)
  - ⇨ Fluctuations and lumpiness in initial energy density profile
  - ⇨ Development of higher harmonics in anisotropic flow (v_3, v_4 ...)

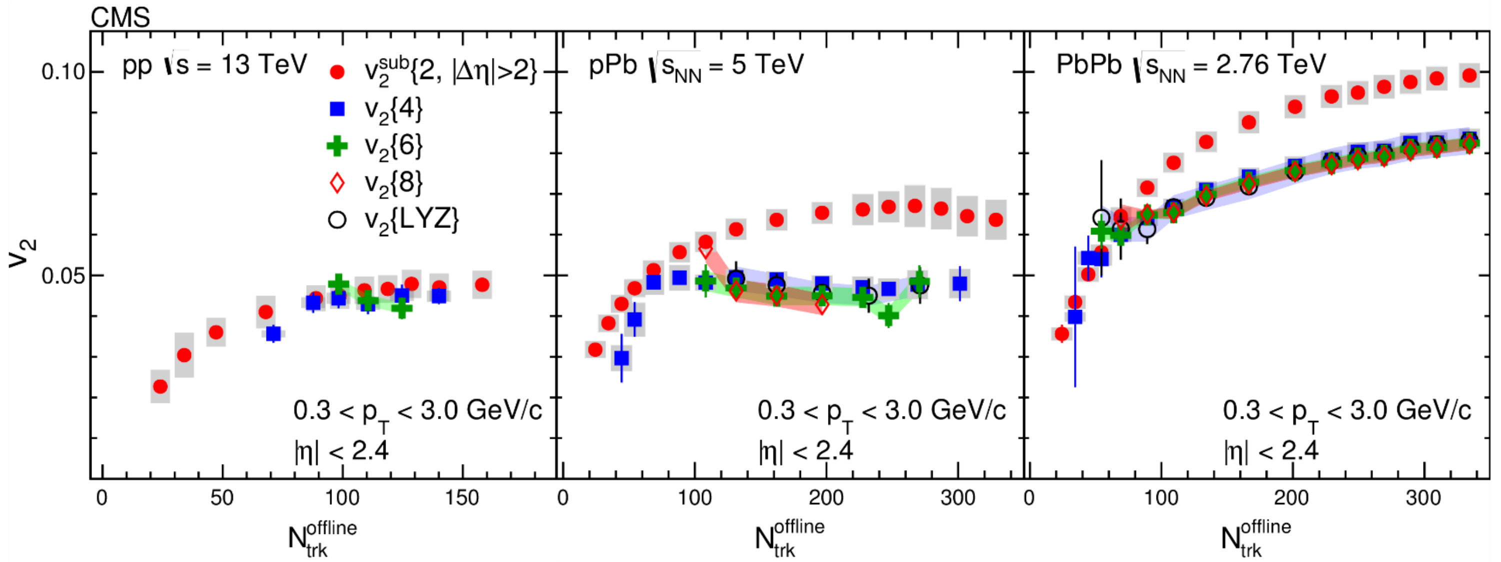
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos\left[n(\varphi - \Psi_{RP})\right]\right\}$$

  - ⇨ Semi-central and peripheral collisions
    - ✓ ***Dominant effect from initial geometry (v_2 > other harmonics)***
  - ⇨ Central collisions
    - ✓ ***Fluctuations of initial nucleon positions are important ($v_3 \sim v_2$)***
- Connection between initial-state fluctuations and final-state particle v_n sensitive to QGP properties such as shear and bulk viscosity 📖 **Scott Moreland et al., arXiv:1808.02106**
- QGP produced in the collision is **strongly coupled**
  - ⇨ Quarks and gluons form a collective medium that flows as a relativistic fluid with exceptionally **low viscosity/entropy ratio**

Collectivity in small collision systems

- Long-range angular correlations observed in high-multiplicity pp and p-Pb → **ridges**
  - ⇨ Similar features as those observed in Pb-Pb and interpreted as due to collective flow
- Origin of ridges in small collision systems still unclear:
  - ⇨ Initial state momentum correlations (Color Glass Condensate) ?
  - ⇨ Collectively expanding medium (QGP droplet) ?
    - ✓ ***Few (~5-6) interactions among particles needed for hydro to work***
    - ✓ ***Where does the hydro picture break down?***

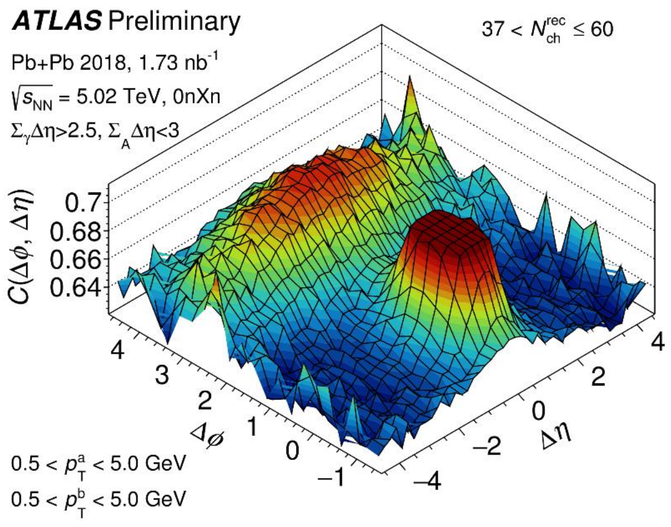


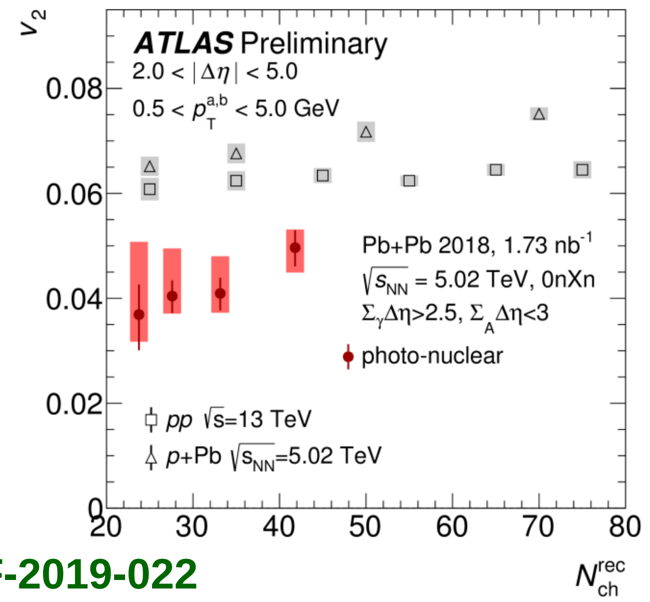


📖 **CMS, PLB765 (2017) 193**

Ridge in γ-A and e^+e^- collisions

- Photo-nuclear events in ultra peripheral Pb-Pb collisions
  - ⇨ Finite v_2 observed in 2-particle correlations
  - ⇨ Smaller than that in pp and p-Pb at similar multiplicity

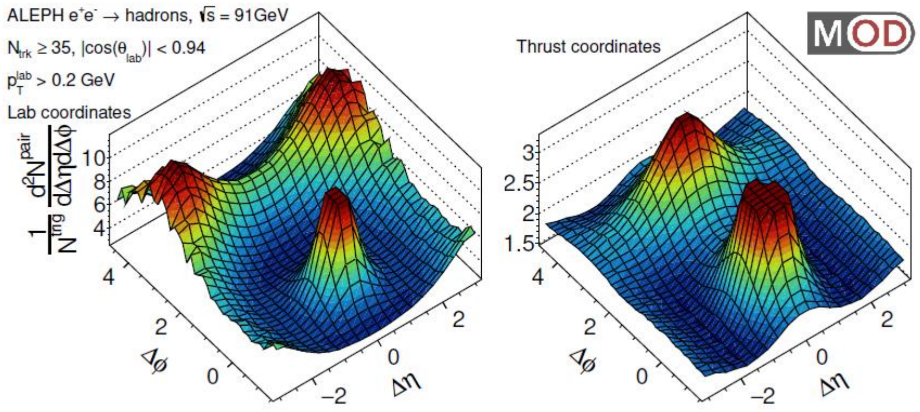




📖 **ATLAS-CONF-2019-022**

- No sign of ridges from reanalysis of ALEPH e^+e^- data

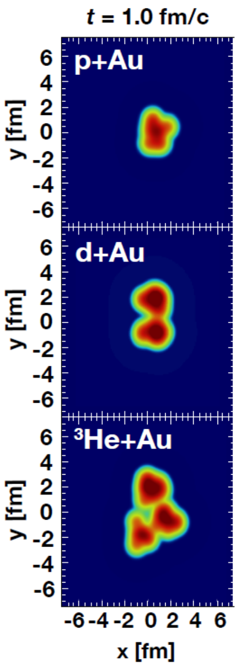
- What is the smallest droplet of matter showing these phenomena?

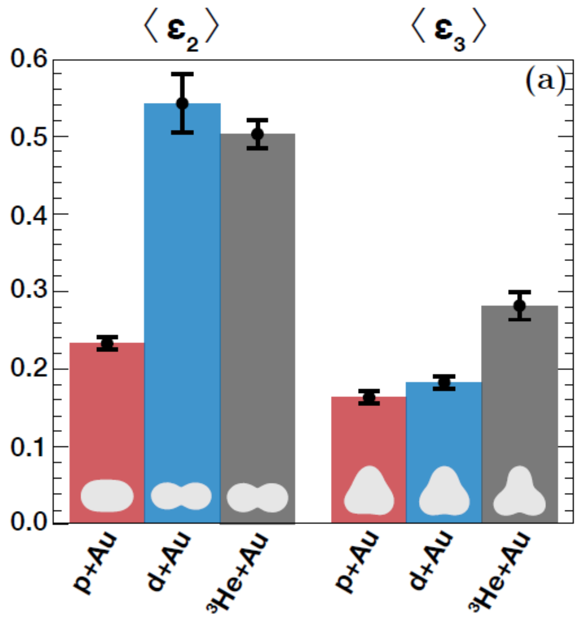


📖 **Badea et al., arXiv:1906.00489**

Quark-Gluon droplets engineered

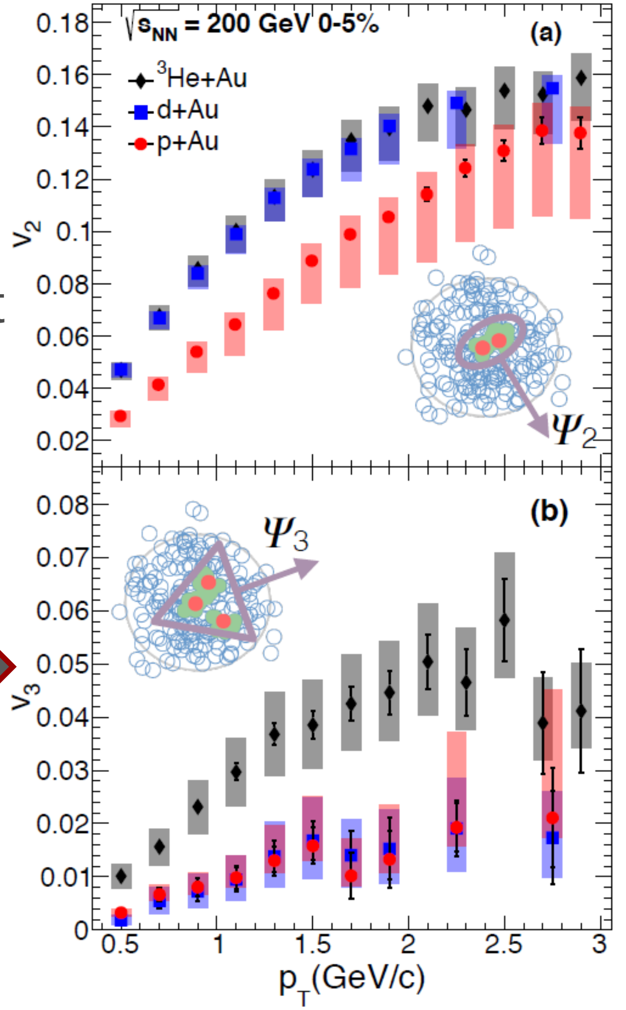
- Exploit RHIC versatility: projectile geometry scan
  - ⇨ **p-Au** fluctuation driven, **d-Au** and **^{3}He-Au** geometry driven
- Initial-state anisotropy ε_n imprinted on final-state particle v_n
  - ⇨ Captured by hydrodynamic expansion
  - ⇨ Models of initial-state momentum correlation cannot reproduce the effect





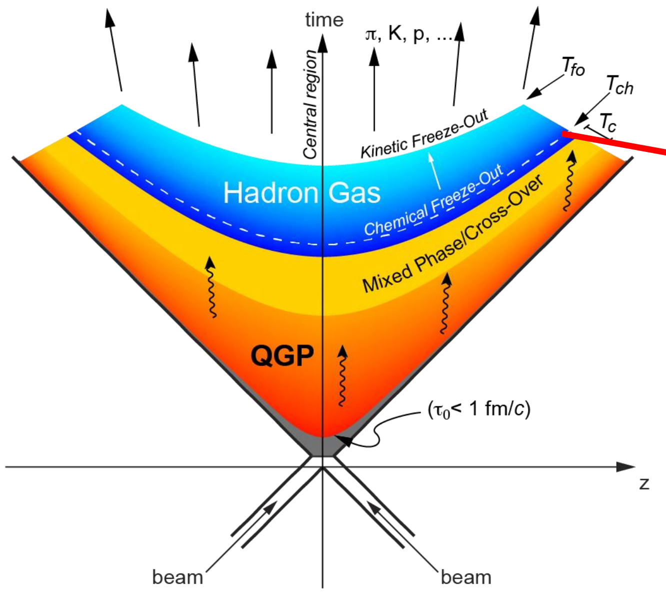
$$v_2^{\mathrm{p-Au}} < v_2^{\mathrm{d-Au}} \approx v_2^{^3\mathrm{He-Au}}$$

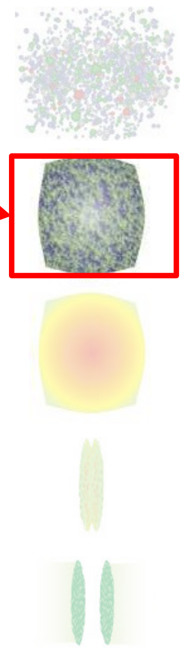
$$v_3^{\mathrm{p-Au}} \approx v_3^{\mathrm{d-Au}} < v_3^{^3\mathrm{He-Au}}$$



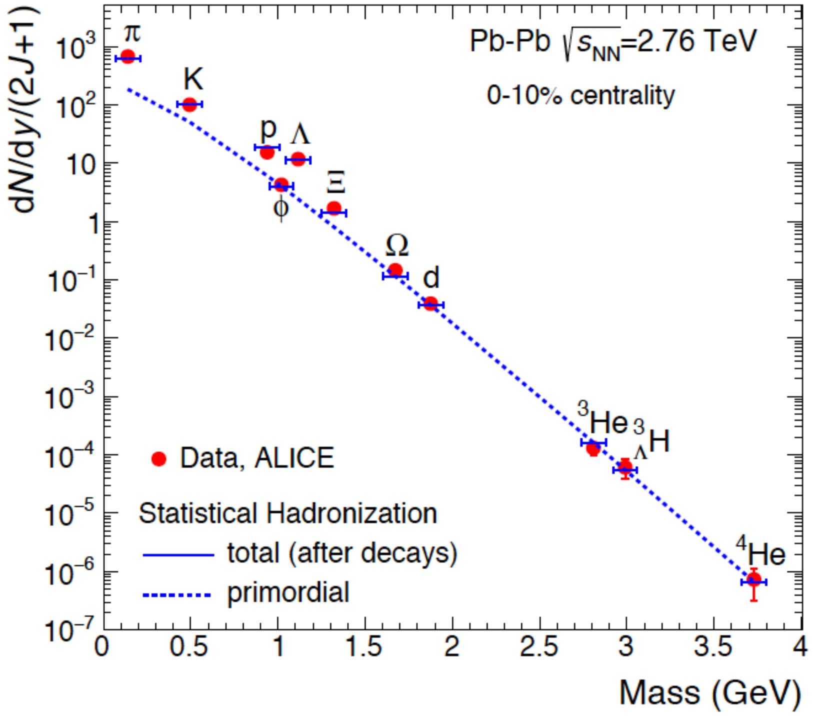
📖 PHENIX, Nature Physics 15 (2019) 214

“Chemical” composition





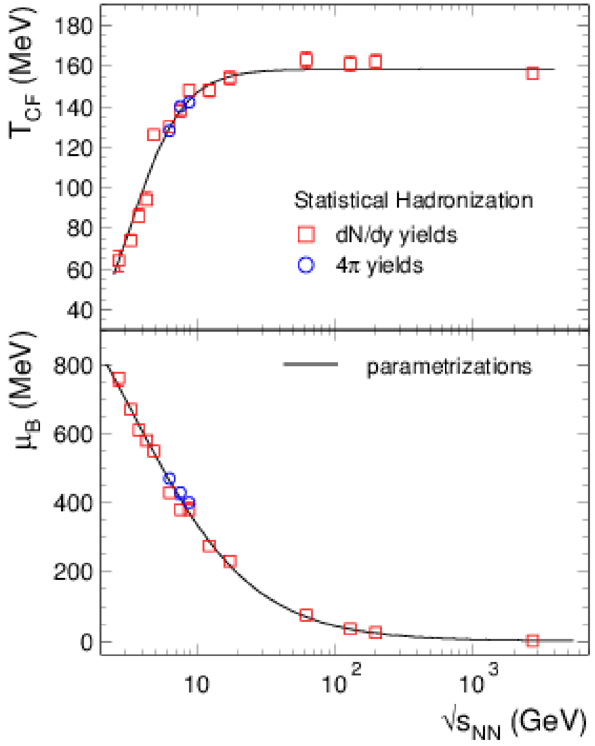
Andronic et al. Nature 561 (2018) 321



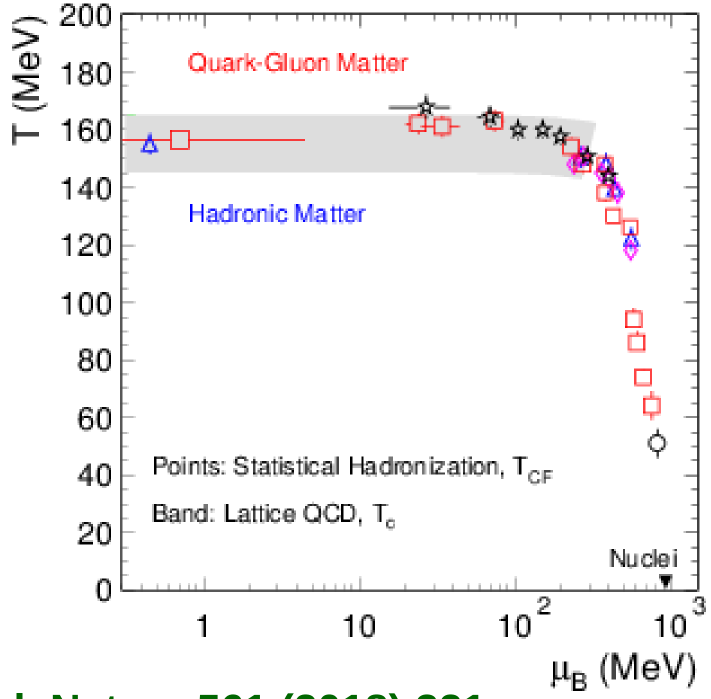
- At the **chemical freeze-out**
  - ⇨ Inelastic collisions cease
  - ⇨ Abundances of different hadron species fixed
- Hadron yields (dominated by low-p_T particles) described by statistical/thermal models
  - ⇨ Abundances follow expectations for hadron gas in chemical and thermal equilibrium
  - ⇨ Yields 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**

Mapping the phase diagram

- Statistical hadronization analysis of hadron yields at different collision energies
  - ➪ **Chemical freeze-out temperature** increases with $\sqrt{s_{NN}}$ at low energies and saturates at T_{ch}~155-160 MeV at top SPS energy
  - ➪ At high $\sqrt{s_{NN}}$: T_{ch} very **close to the QGP phase boundary** temperature from lattice QCD
  - ➪ **Baryo-chemical potential** decreases with $\sqrt{s_{NN}}$ and vanishes at LHC energies

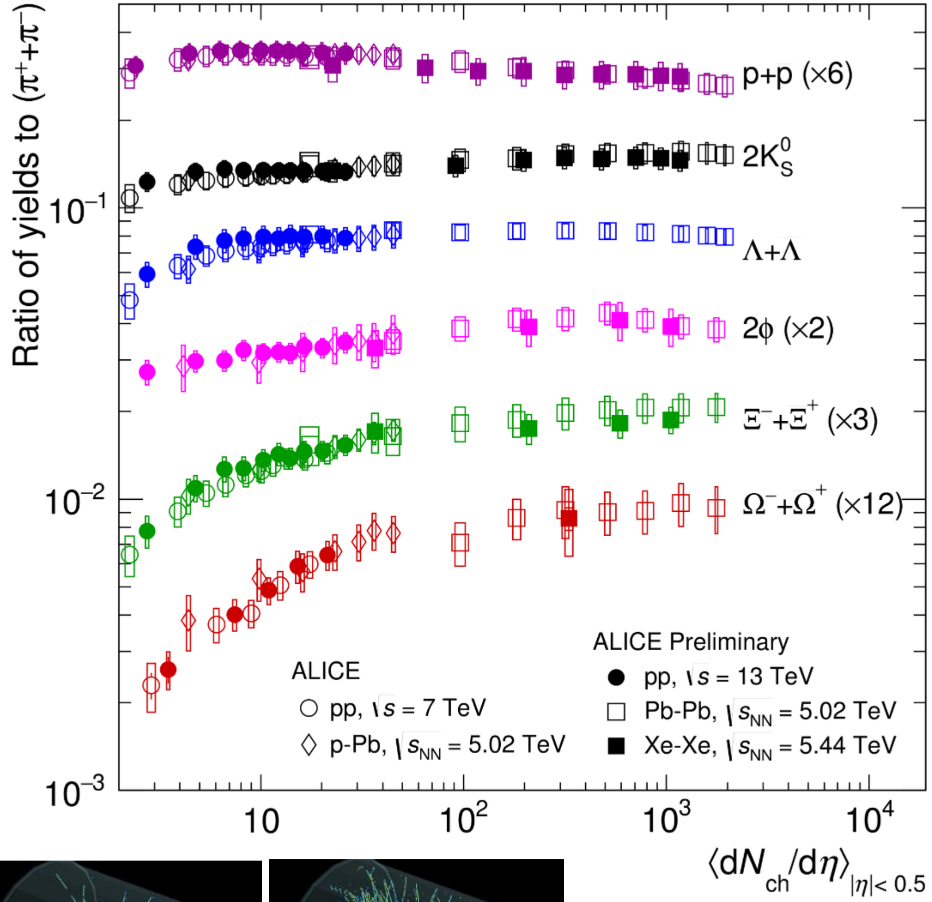


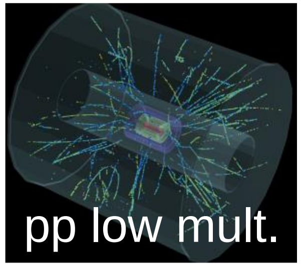
Use the (T_{ch},μ_B) pairs from statistical-hadronization analysis at each $\sqrt{s_{NN}}$ to map a diagram of the chemical freeze-out conditions

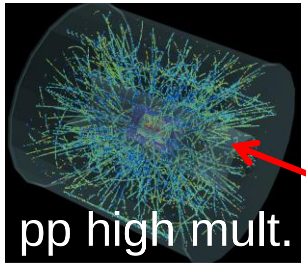


📖 Andronic et al. Nature 561 (2018) 321

Strangeness production vs. multiplicity





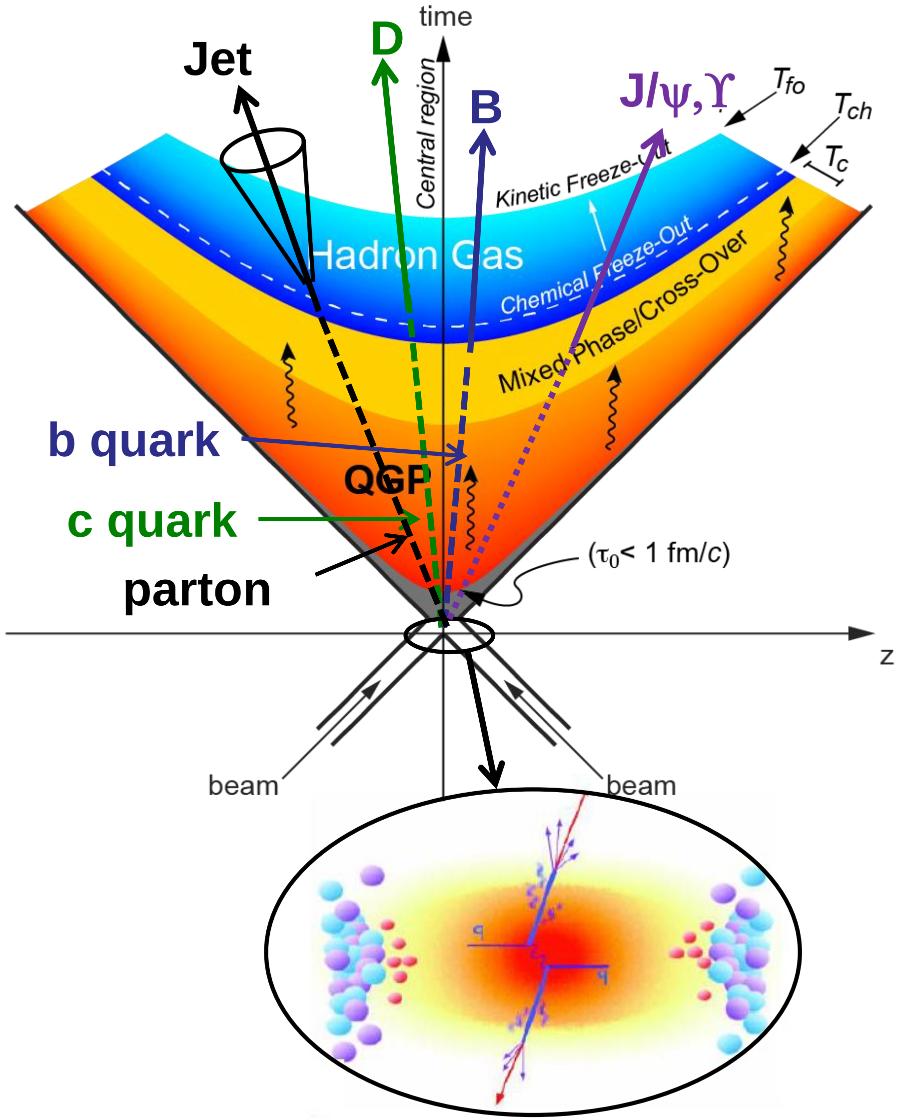


Similar multiplicity as in peripheral Pb-Pb

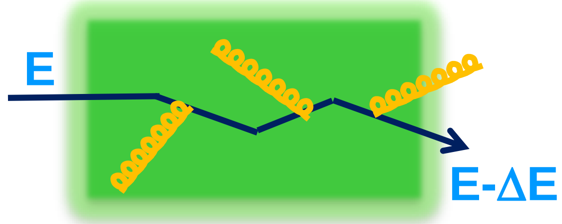
- Smooth evolution of hadrochemistry with multiplicity from small to large collision systems
- Significant enhancement of strange to non-strange particle production with multiplicity
  - ⇨ Strangeness production increases with multiplicity in pp and p-Pb collisions
    - ✓ ***Effect related to strangeness content rather than mass***
  - ⇨ Plateau reached in Pb-Pb collisions at the value expected from statistical hadronisation model with gran-canonical formulation
- Challenge for pp event generators

ALICE, Nature Physics 13 (2017) 535

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***



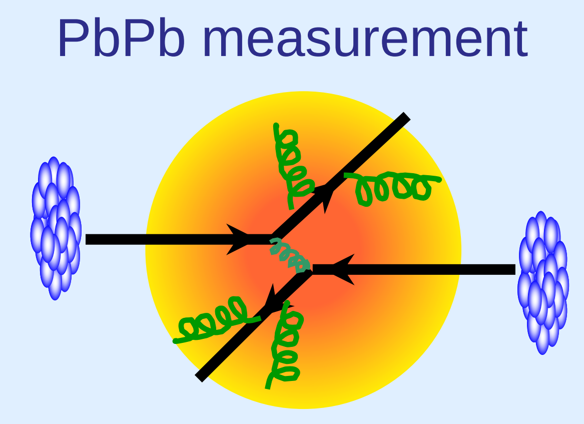
- **Unique probes** of the properties of the QGP
  - ⇨ **Tomography of the medium**

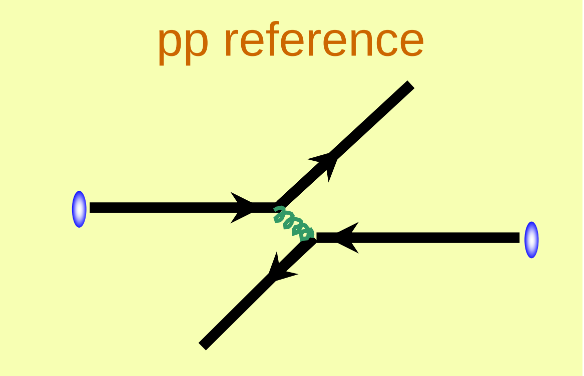
Nuclear modification factor

- Hard processes in nuclear collisions
  - Expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
- Observable: **nuclear modification factor**

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

  - If **no nuclear effects** are present -> $\mathbf{R_{AA}=1}$
  - **QGP** can modify the yield and distributions of the final state hadrons and jets -> $\mathbf{R_{AA} \neq 1}$
    - ✓ ***E.g.: in-medium energy loss causes suppression of yield at high p_T (jet quenching) relative to pp collisions where no medium is present***

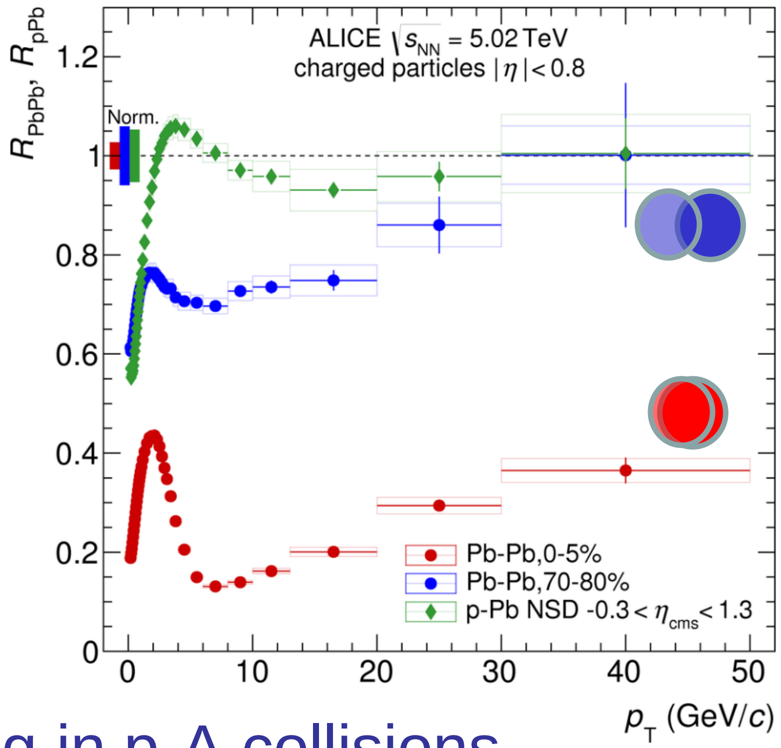


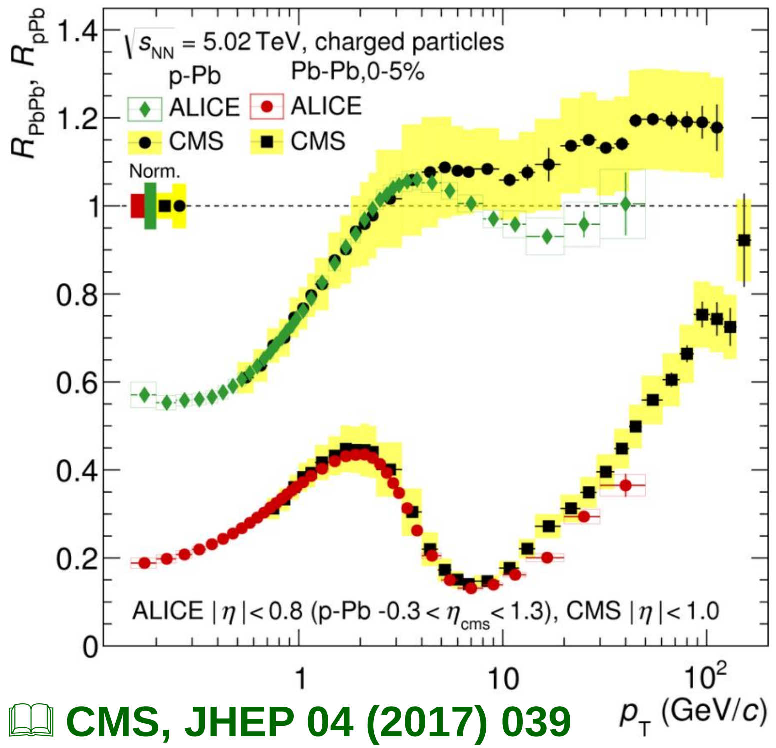


- But also cold nuclear matter effects (e.g. nuclear modification of PDF) may lead to $R_{AA} \neq 1$
- Need **control experiments**: medium-blind probes (photons, Z, W bosons) + p-A collisions

Nuclear modification factor: 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***



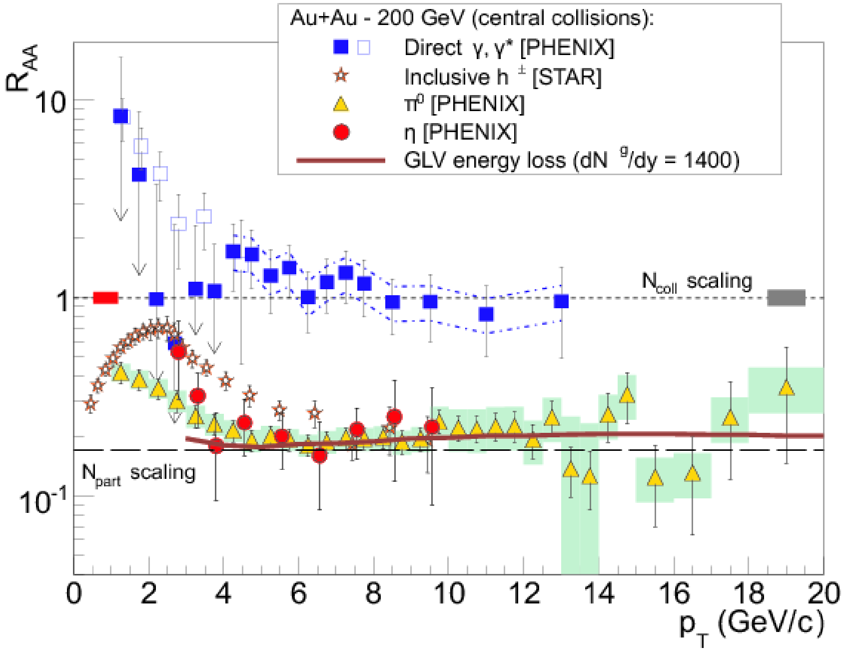


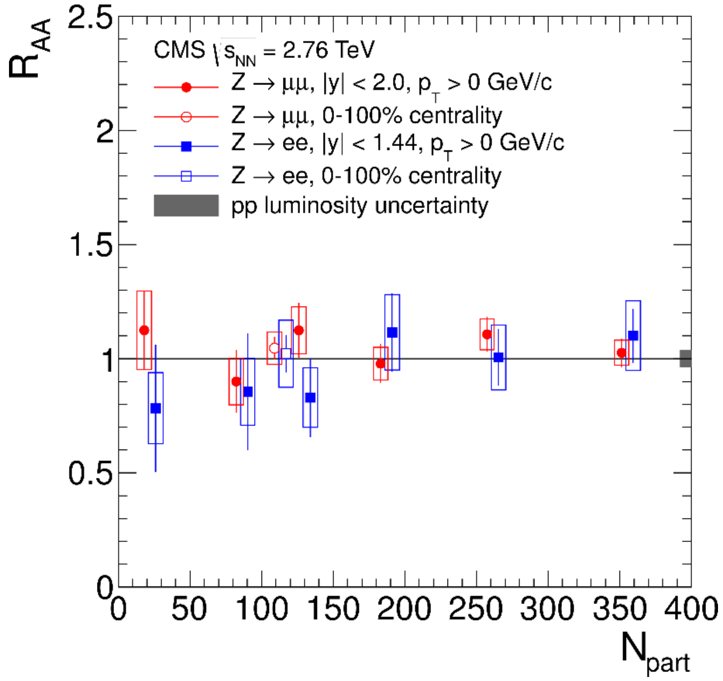
- No evidence of jet quenching in p-A collisions
  - ⇨ R_{pPb}~1 in **p-Pb collisions**
  - ⇨ Suppression in A-A collisions due to hot and dense medium
- Open question: **collectivity in p-A without energy loss**
  - ⇨ When does energy loss turn on?

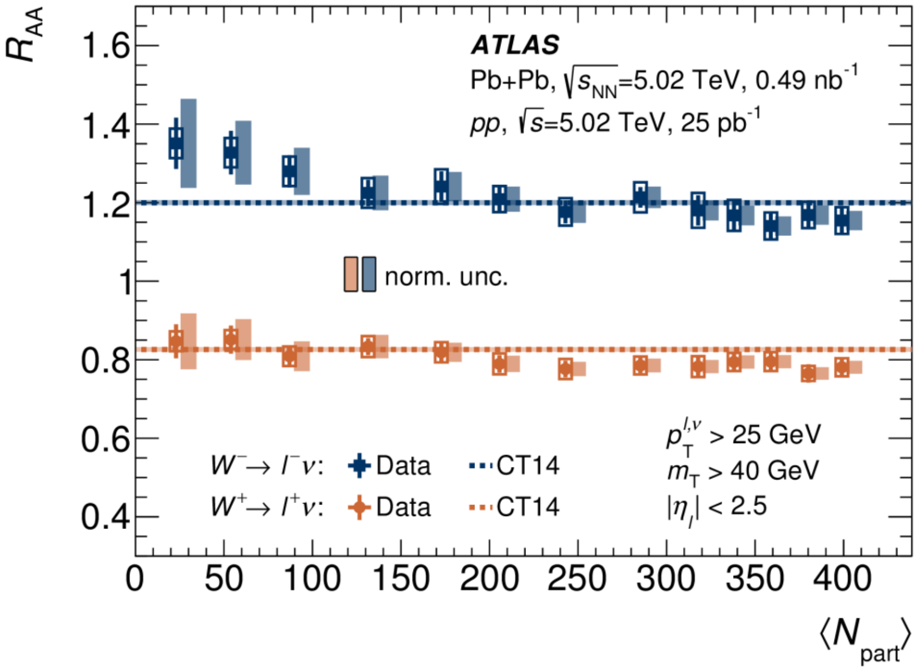
📖 **CMS, JHEP 04 (2017) 039**
📖 **ALICE, JHEP 11 (2018) 013**

Medium blind probes: γ, W and 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***







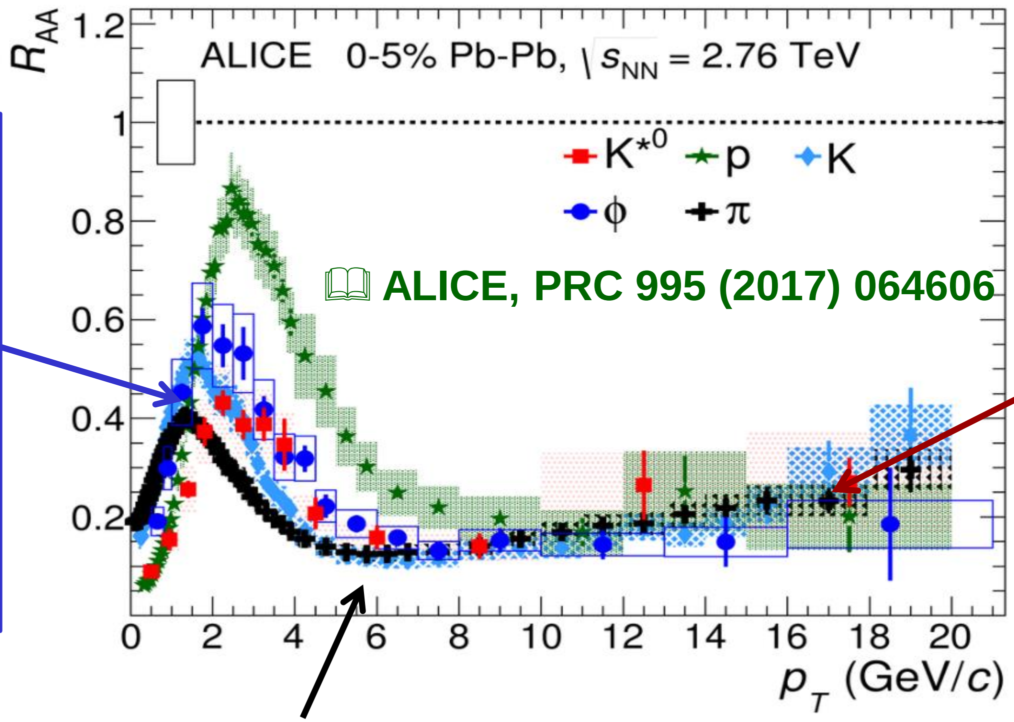
📖 **D'Enterria, Betz, Springer Lecture Notes in Physics (LNP), 2009**

📖 **CMS, JHEP 03 (2015) 022**

📖 **ATLAS, arXiv:1907.10414**

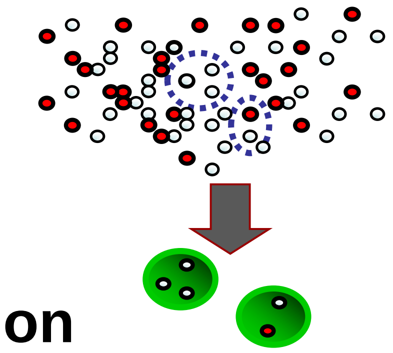
Identified hadron R_{AA}

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



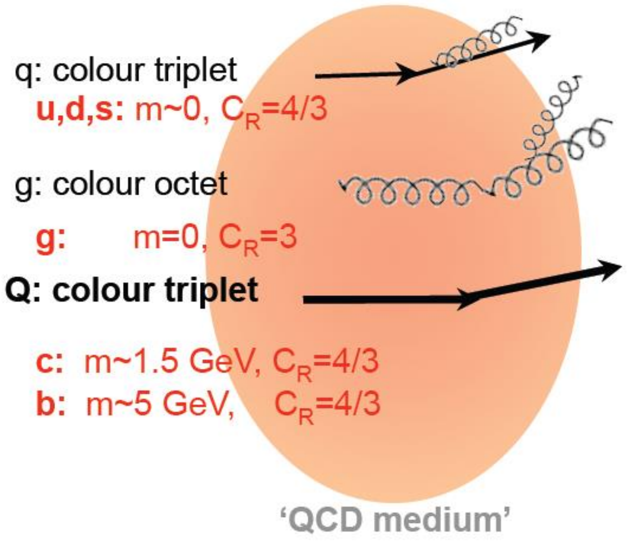
High-p_T (>10 GeV/c) :
- Partons from hard scatterings
- Lose energy while traversing the QGP
- Hadronisation via fragmentation → same R_{AA} for all species

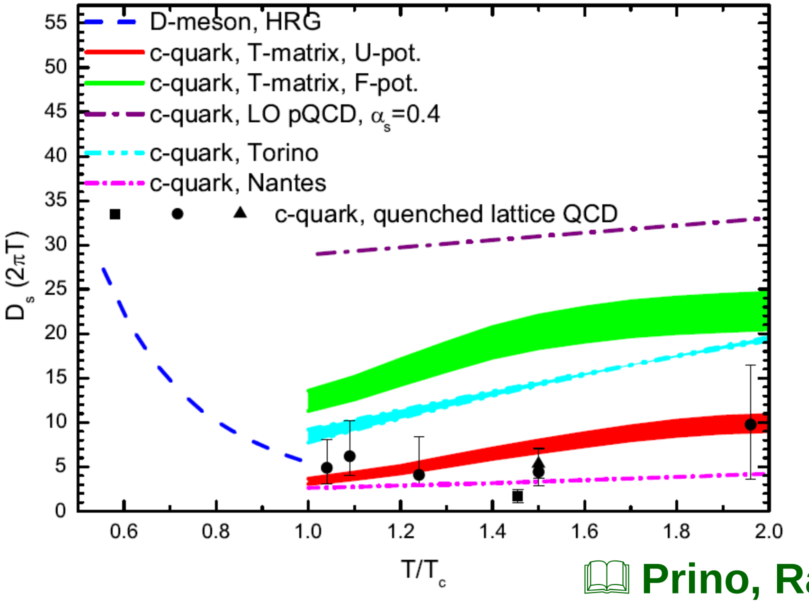
Intemediate-p_T (ca. 3<p_T<8 GeV/c) :
- Kinetic regime (not described by hydro)
- Different R_{AA} for different hadron species
  - Inconsistent with hard partons + energy loss + universal fragmentation
- Features described with in-medium **hadronization via quark recombination**



Open heavy-flavour hadrons

- 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



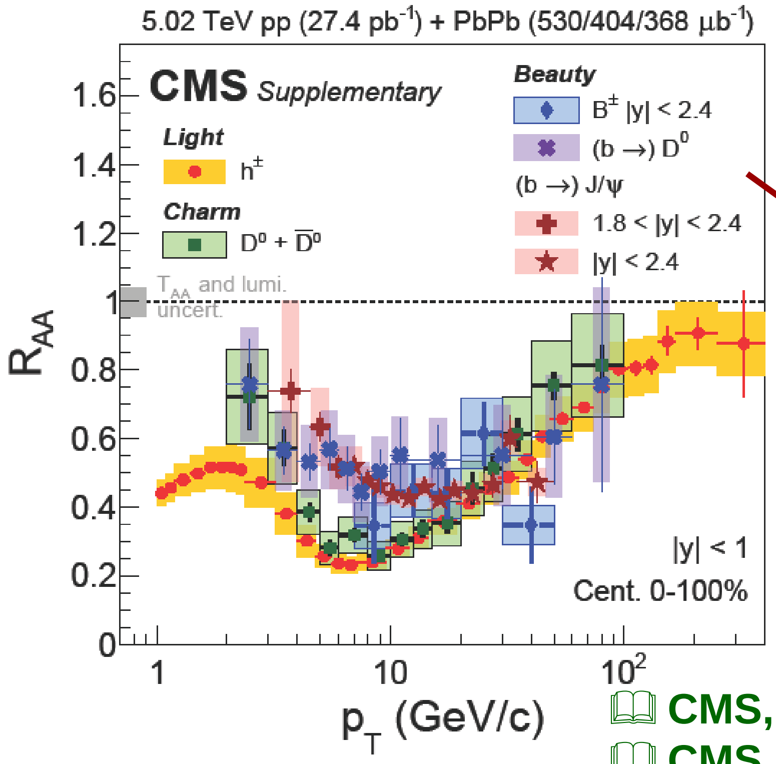


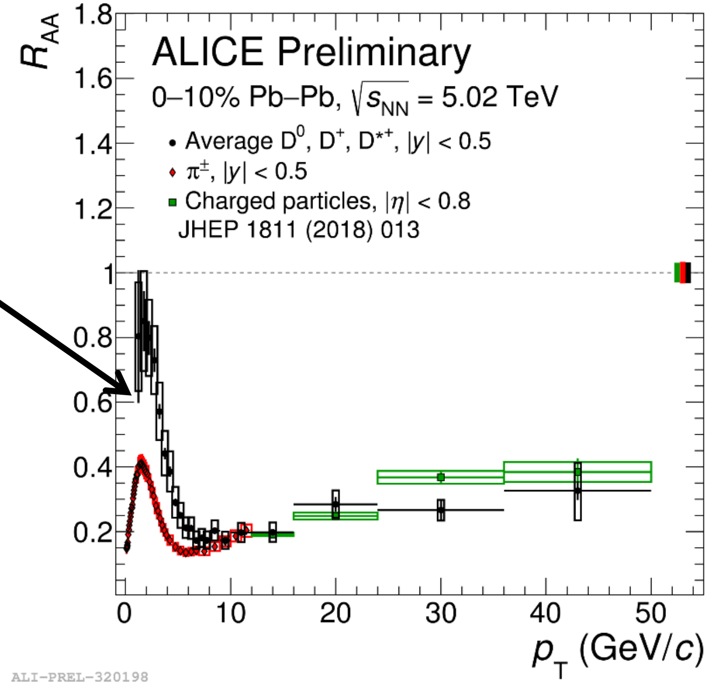
- Charm and beauty hadrons:
  - ⇨ Produced in hard-scattering processes at all p_T
  - ⇨ Test **colour charge and mass dependence of energy loss**
  - ⇨ Sensitive to transport properties of the QGP (e.g. **diffusion coefficient**)

📖 Prino, Rapp, JPG43 (2016) 093002

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

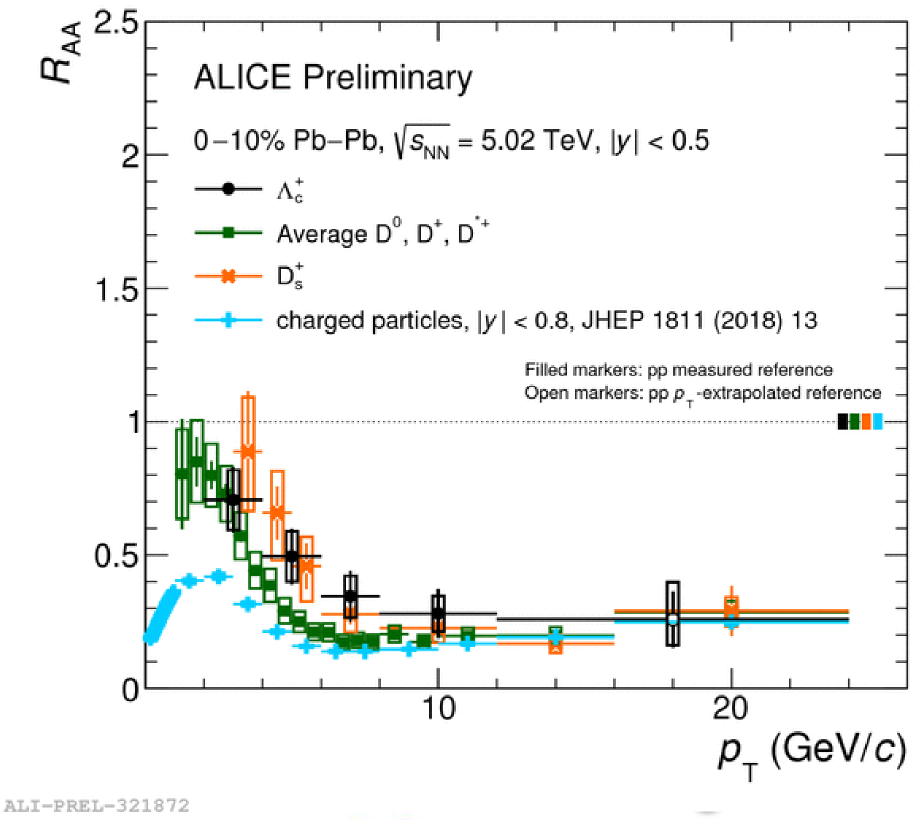


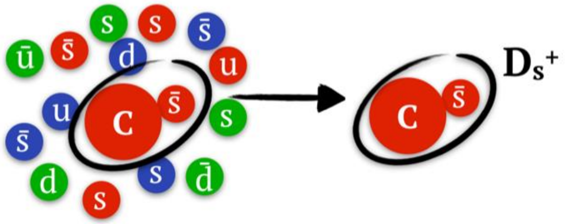


- Beauty via non-prompt D^0, non-prompt J/ψ and $B^{\pm} \rightarrow J/\psi K^{\pm}$
- Indication for **R_{AA}(beauty)>R_{AA}(charm)** for p_T<20 GeV/c
  - ⇨ As expected from **quark-mass dependence** of energy loss
- R_{AA} of beauty, charm and light merging at p_T~20 GeV/c

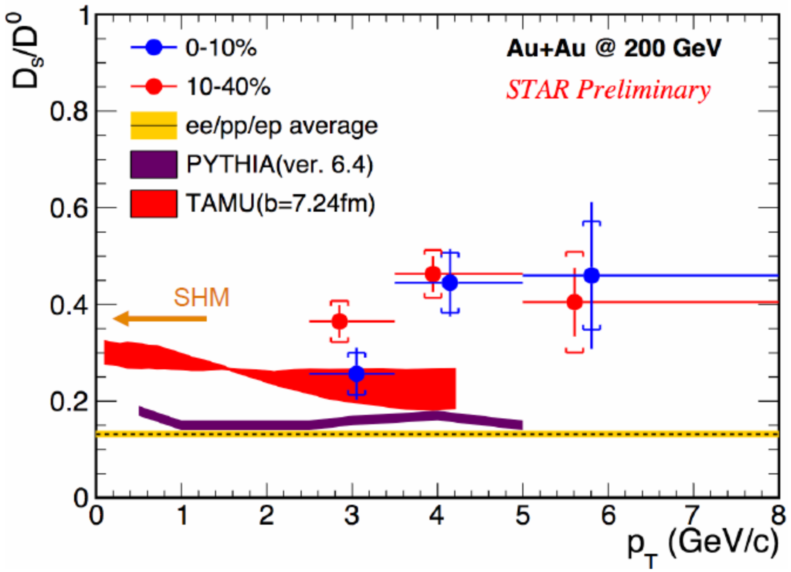
📖 CMS, arXiv:1810,11102 📖 CMS, PRL 119 (2017) 152301
📖 CMS, EPJC 78 (2018) 509 📖 CMS, PLB 782 (2018) 474 📖 ALICE, JHEP 10 (2018) 174

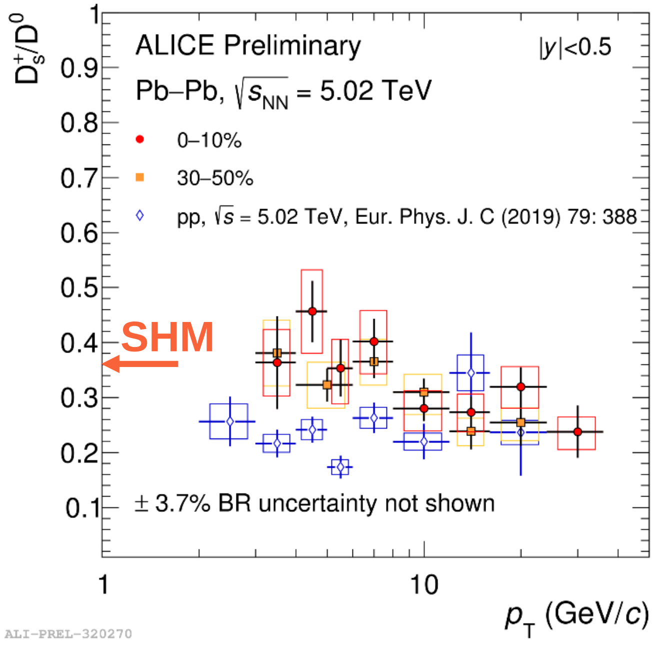
Charm hadrochemistry in A-A: D_s





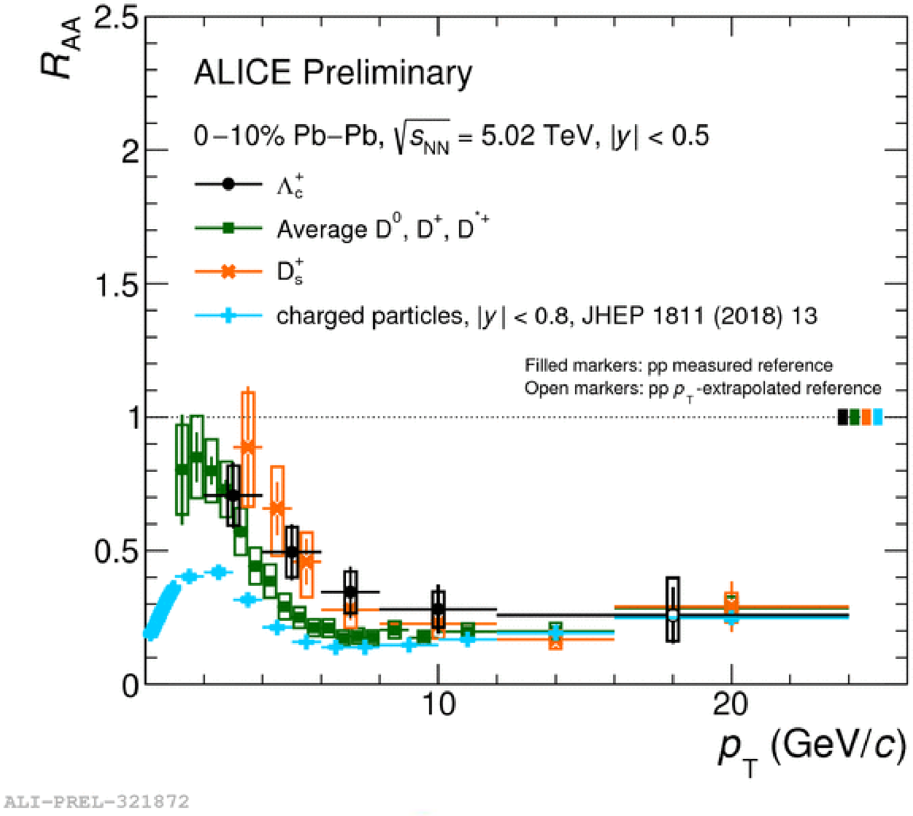
- D_s/D^0 ratio:
  - ⇨ Enhanced at low p_T as compared to pp
    - ✓ ***Measured ratio consistent with expectation from Statistical Hadronization Model***
  - ⇨ Compatible with pp for p_T>10 GeV/c
- As expected in a scenario with strangeness enhancement in the QGP and hadronization via quark recombination

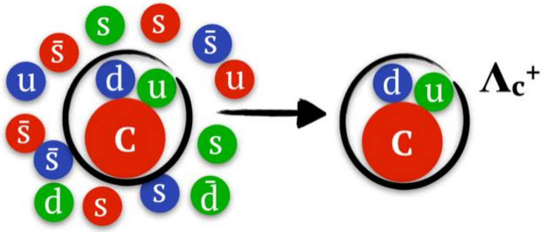


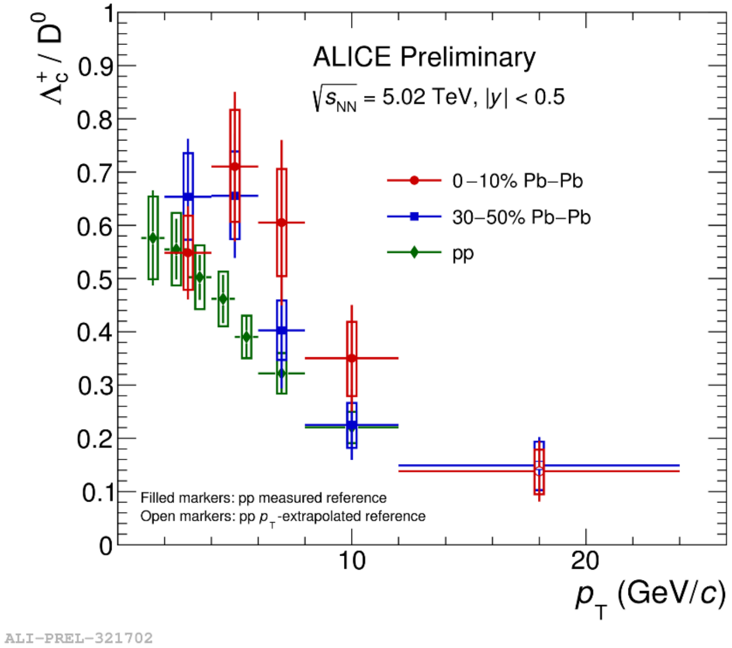


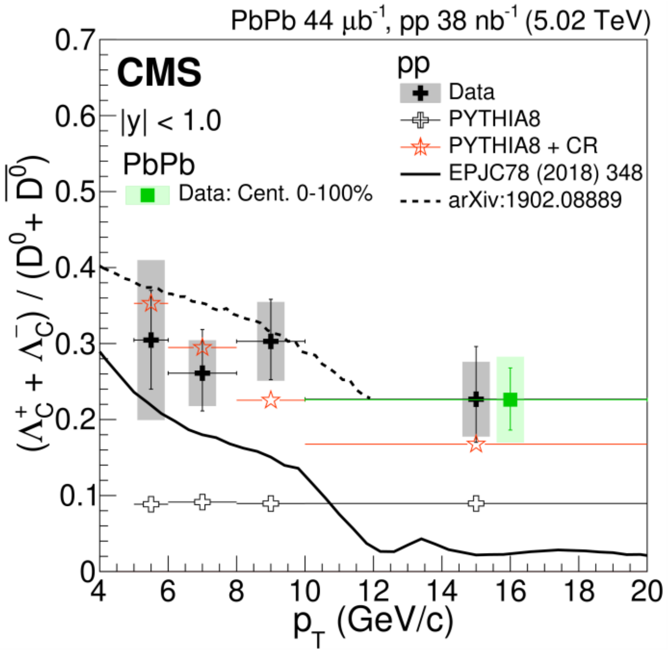
Charm hadrochemistry in A-A: Λ_c

- Λ_c/D^0 ratio:
  - ⇨ Enhanced at low p_T (<6 GeV/c) with respect to pp
  - ⇨ Compatible with pp results for p_T>10 GeV/c
- Consistent with a scenario of baryon enhancement due to charm quark hadronization via recombination
- Open question:
  - ⇨ Λ_c/D^0 in pp higher than in e^+e^-, not fully understood





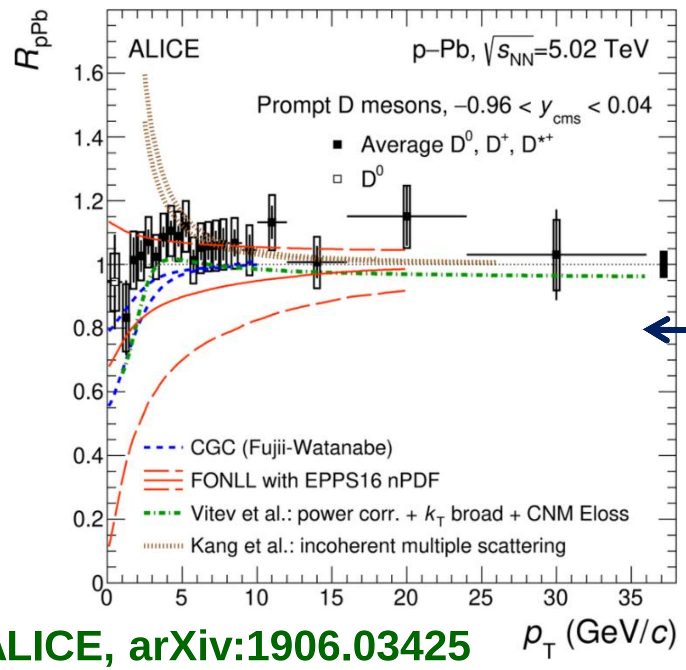




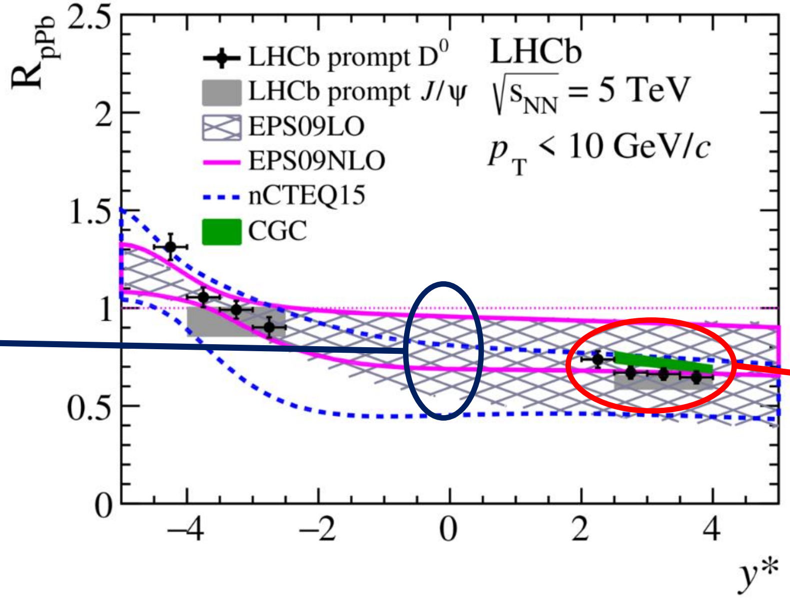
CMS arXiv:1906.03322

Charm in p-Pb: cold nuclear matter effects

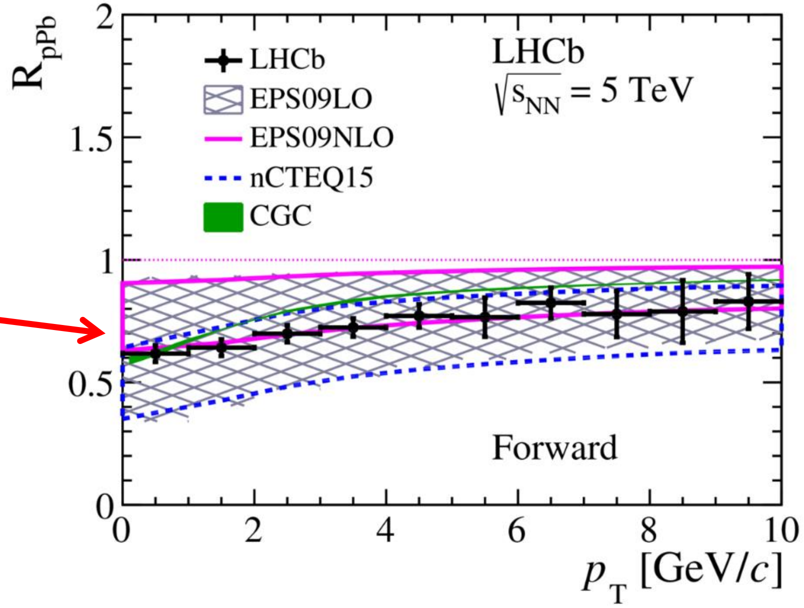
- No modification observed in p-Pb collisions beyond expected cold nuclear matter effects
  - ⇨ Suppression observed in A-A collisions is a final state effect due to interactions with the QGP
- Very precise D-meson data in p-Pb collisions down to p_T=0 in different rapidity regions
  - ⇨ Potential to constrain nuclear PDFs 📖 **Eskola et al., arXiv:1906.02512**
- Assessment of cold nuclear matter effects important for the estimation of QGP transport coefficients



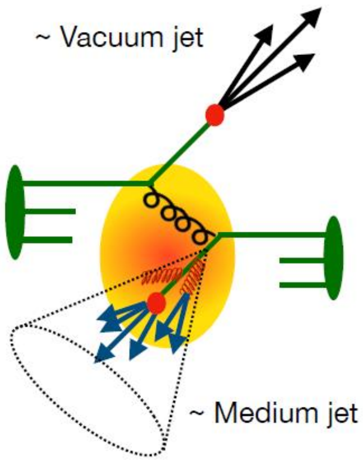
📖 **ALICE, arXiv:1906.03425**

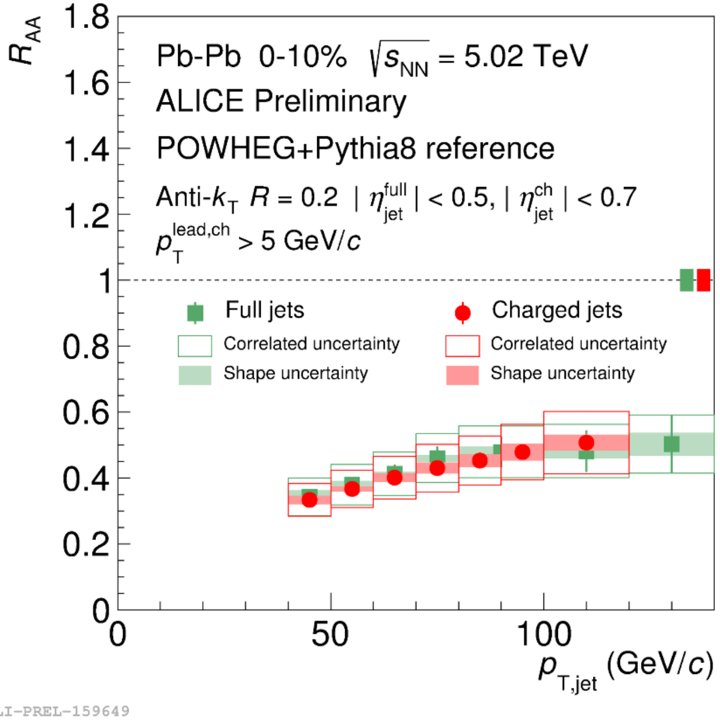


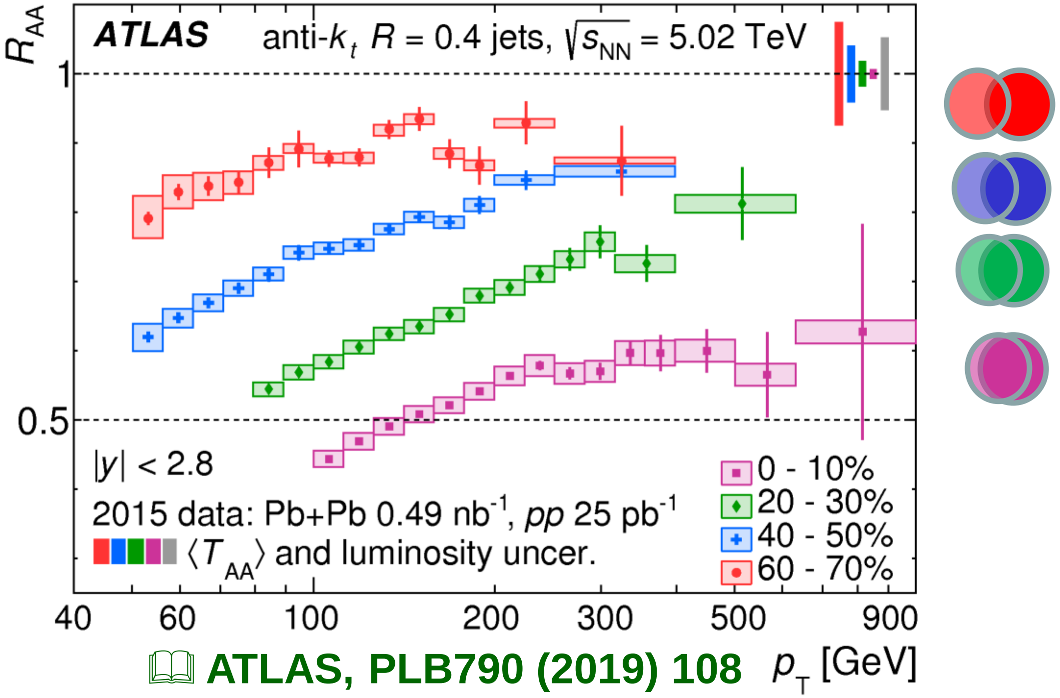
📖 **LHCb, JHEP 10 (2017) 090**



Jet R_{AA}

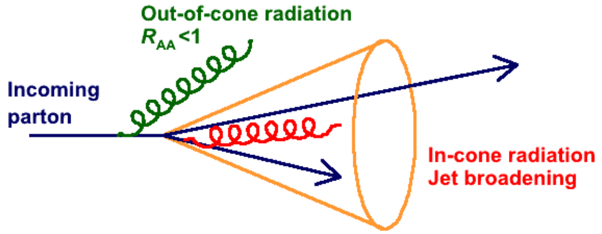




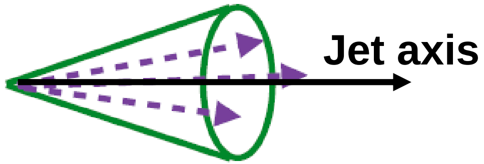


📖 **ATLAS, PLB790 (2019) 108**

- Jet yield at the LHC suppressed from 50 GeV to 1 TeV
  - ⇨ Hard-scattered quarks and gluons evolve as parton showers that propagate through the hot and dense medium
  - ⇨ Part of energy of parton shower transferred outside the jet cone through interactions with QGP (→ soft radiation at large angles)
- Suppression decreases from central to peripheral collisions

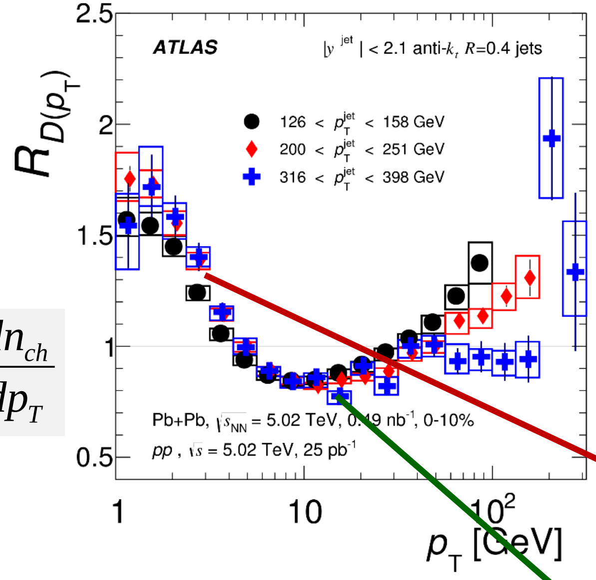


Jet fragmentation



$$R_{D(p_T)} = \frac{D(p_T)_{PbPb}}{D(p_T)_{pp}}$$

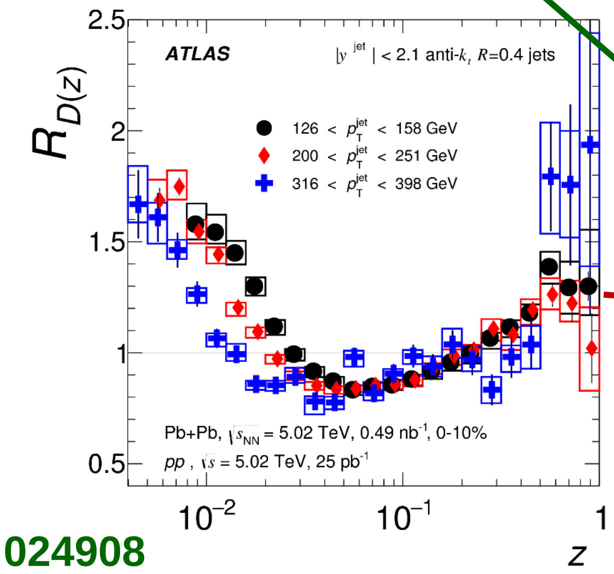
$$D(p_T) = \frac{1}{N_{jet}} \frac{dn_{ch}}{dp_T}$$



$$R_{D(z)} = \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

$$D(z) = \frac{1}{N_{jet}} \frac{dn_{ch}}{dz}$$

$$z = \frac{p_T^{track} \cos \Delta r}{p_T^{jet}}$$

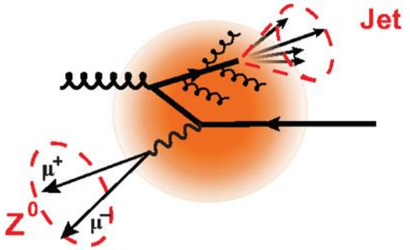


- Distributions of particle momenta within the jet modified in Pb-Pb collisions with respect to pp
  - ⇨ Jet fragmentation affected by in-medium energy loss
  - ⇨ Magnitude of modification decreases from central to peripheral collisions
- Excess of particles with p_T<4 GeV/c
  - ⇨ Energy lost transmitted to soft particles within and around the jet
- Suppression of particles at intermediate p_T
- Enhancement of particles carrying a large fraction z of the jet transverse momentum
  - ⇨ Higher quark-jet / gluon-jet fraction in Pb-Pb than in pp?

📖 **ATLAS, PRC 98 (2018) 024908**

EW boson – jet correlations

- Z^0-jet associations:
  - ⇨ Z^0 does not interact strongly in the QGP
  - ⇨ Z^0 momentum not modified by the medium
  - ⇨ Access to hard-scattered parton momentum



- Angular distribution of jets with respect to Z^0 via $\Delta\phi_{jZ}$:

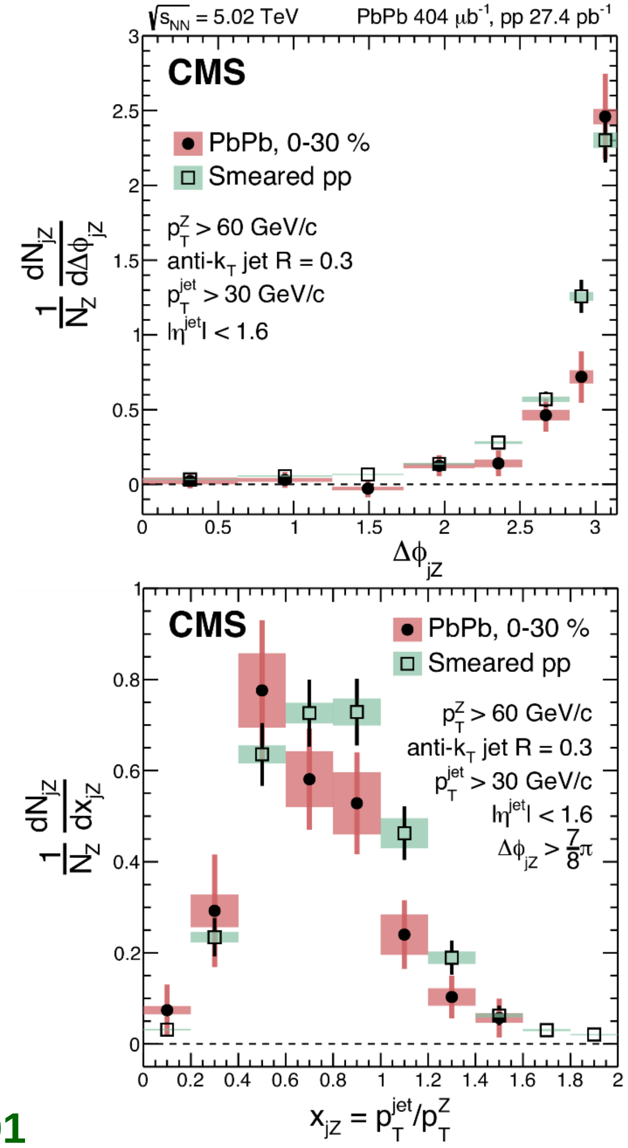
$$\Delta\phi_{jZ} = \left|\phi_{jet} - \phi_Z\right|$$

  - ⇨ No significant difference in $\Delta\phi_{jZ}$ between pp and Pb-Pb

- Momentum balance quantified by x_{jZ}:

$$x_{jZ} = \frac{p_T^{jet}}{p_T^Z}$$

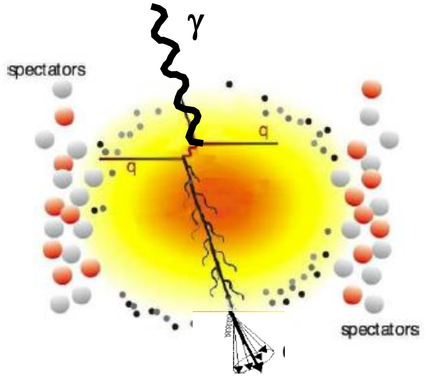
  - ⇨ Shift of x_{jZ} distributions in Pb-Pb as compared to pp
  - ⇨ p_T imbalance due to parton in-medium energy loss



📖 **CMS, PRL119 (2017) 082301**

Photon-jet correlations

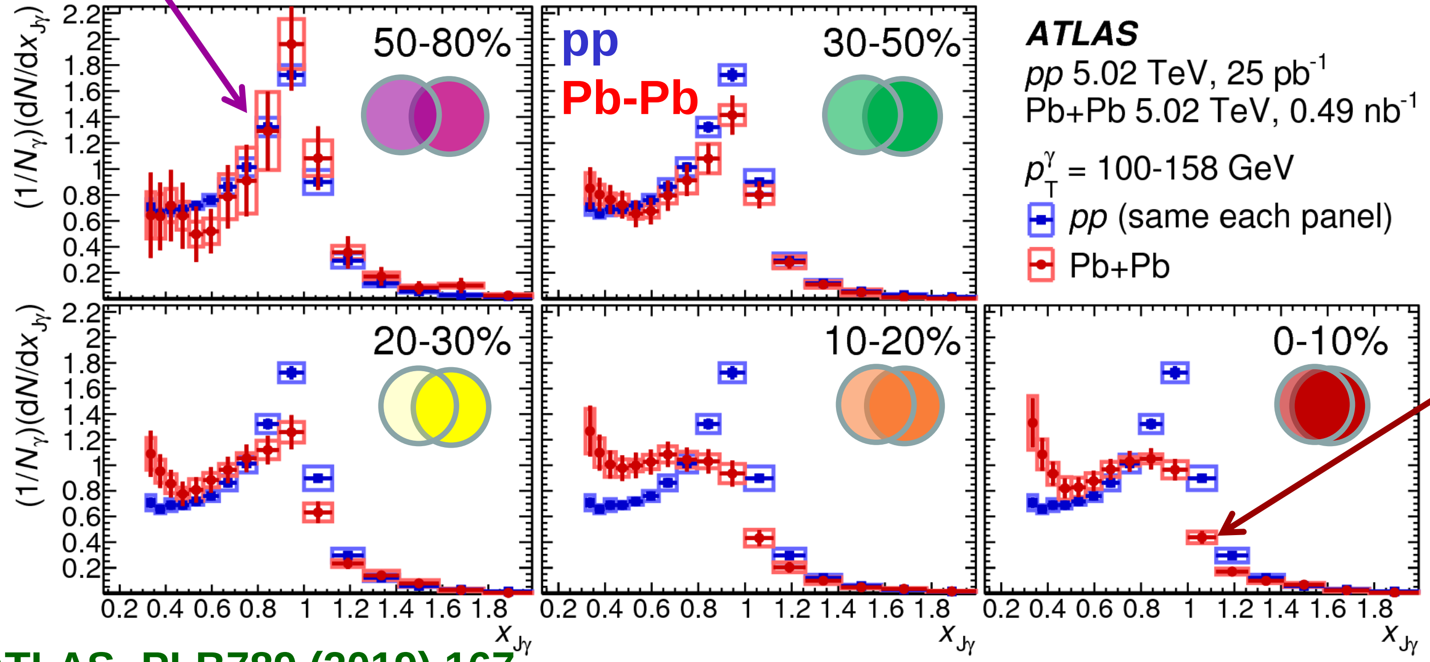
- Photon-jet p_T balance:
  - ⇨ Photon does not interact with medium
  - ⇨ Access to p_T of hard-scattered parton before it loses energy in the medium



Quenched jet

$$x_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$$

Peripheral Pb-Pb:
- $x_{J\gamma}$ consistent with pp



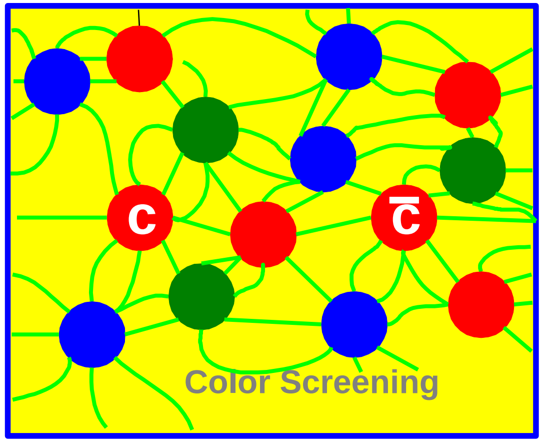
Central Pb-Pb:
- Strong modification
- No peak at $x_{J\gamma}$~1
- Due to parton in-medium energy loss

📖 **ATLAS, PLB789 (2019) 167**

Quarkonium: in-medium dissociation

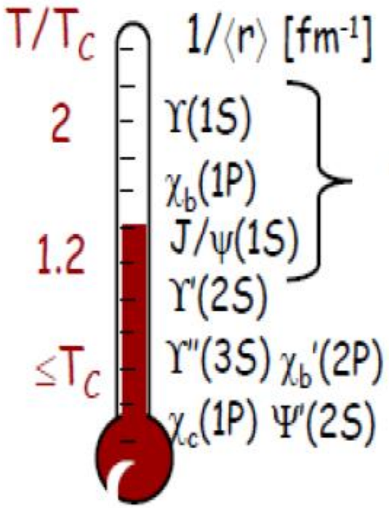
- In the QGP, quarkonium states with radius larger than Debye screening length are expected to **melt** due to colour screening of the $q\bar{q}$ potential.
  - ⇨ Quarkonium production **suppressed** in A-A collisions due to colour screening in the QGP

📖 **Matsui, Satz, PLB178 (1986) 416**

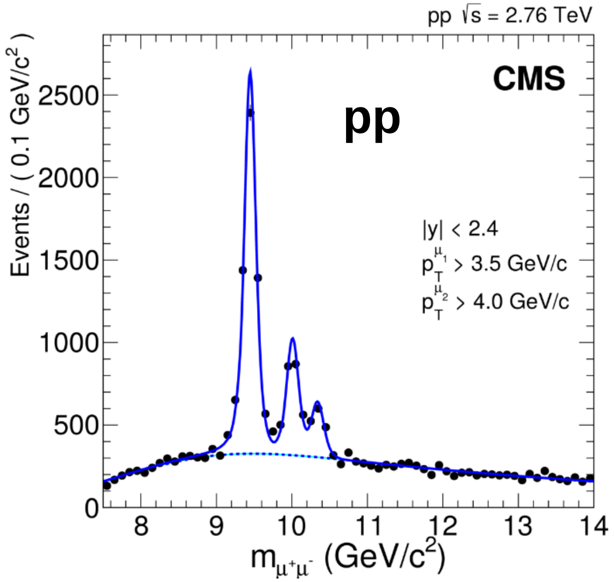


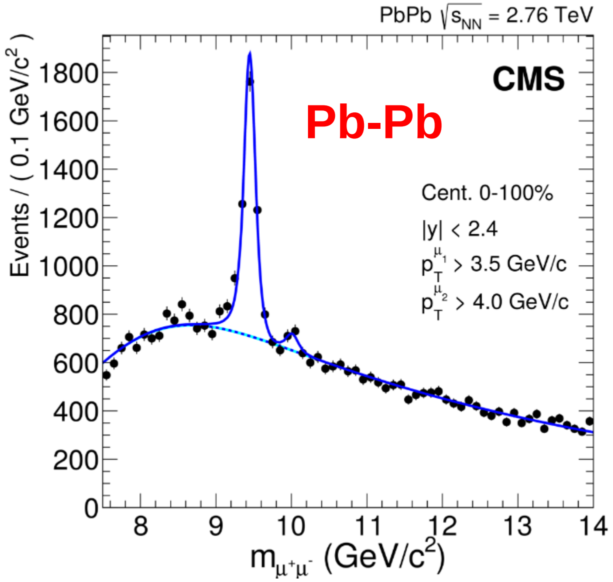
- Different quarkonium states melt at different temperatures, depending on their binding energy
  - ⇨ **Sequential suppression pattern**
- Melting sequence of quarkonia as a **QGP thermometer**
  - ⇨ Relevant for the interpretation of experimental results: **feed-down** from higher quarkonium states and (for charmonia) from B decays

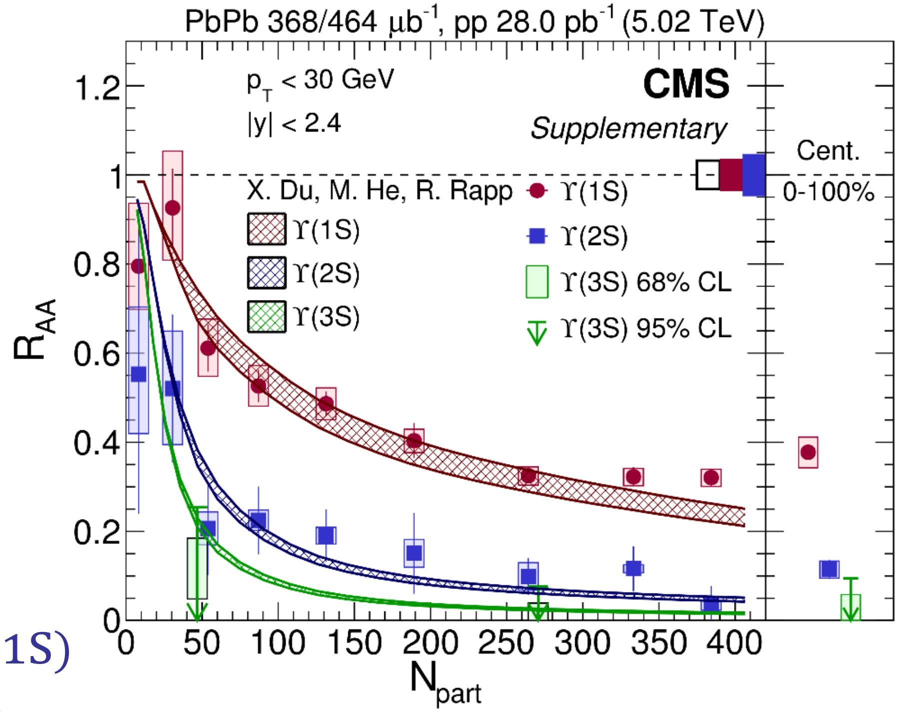
📖 **Digal et al., PRD64 (2001) 094015**



Bottomonium: thermometer?







- Sequential suppression pattern: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
  - ⇨ Ordered by binding energy, as expected from sequential melting in QGP
- Described by transport models with quarkonium in-medium dissociation

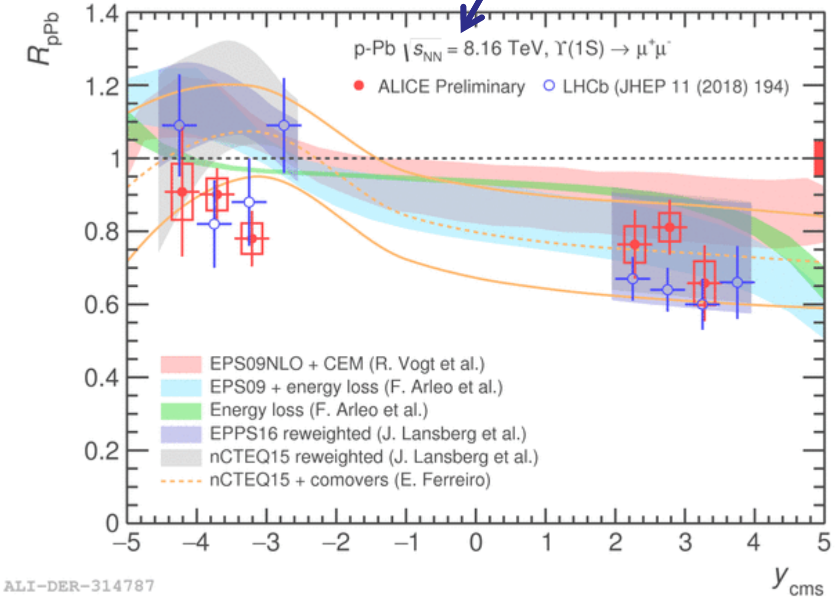
$$R_{AA}^{\Upsilon(1S)} = 0.376 \pm 0.013 \pm 0.035$$
$$R_{AA}^{\Upsilon(2S)} = 0.117 \pm 0.022 \pm 0.019$$
$$R_{AA}^{\Upsilon(3S)} < 0.096 \text{ at } 95\% \text{ CL}$$

📖 **Krouppa et al, NPA 967 (2017) 604**
📖 **Du et al., PRC96 (2017) 054901**

📖 **CMS, PLB790 (2019) 270**

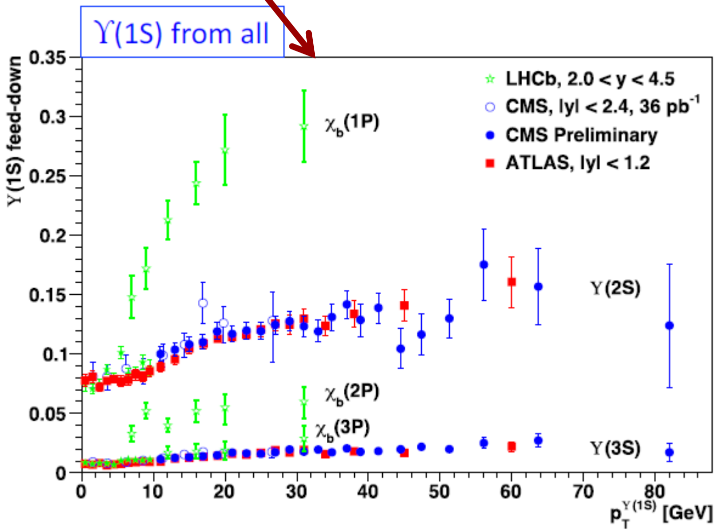
Bottomonium: thermometer?

- Suppression of directly produced $\Upsilon(1S)$?
  - ⇨ Need to assess **feeddown from higher states** and **cold nuclear matter** effects

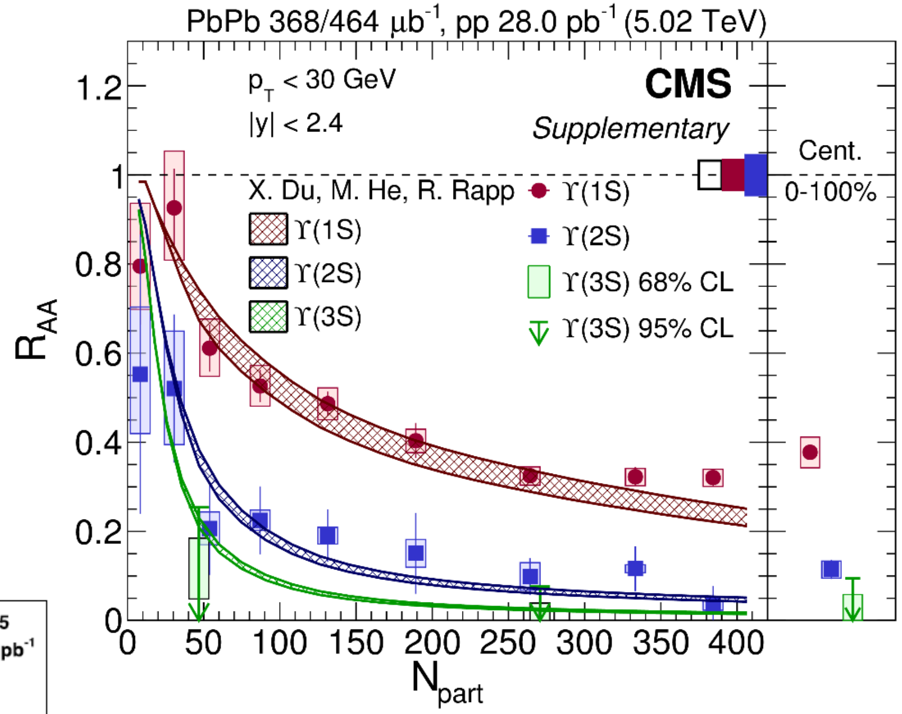


📖 LHCb, JHEP 11 (2018) 194

📖 ALICE, ALICE-PUBLIC-2018-008



📖 H. Wohri, Quarkonium Working Group 2014



$$R_{AA}^{\Upsilon(1S)} = 0.376 \pm 0.013 \pm 0.035$$

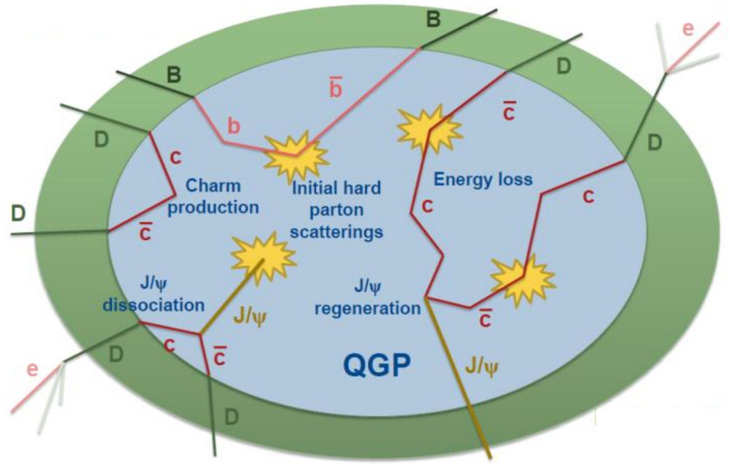
$$R_{AA}^{\Upsilon(2S)} = 0.117 \pm 0.022 \pm 0.019$$

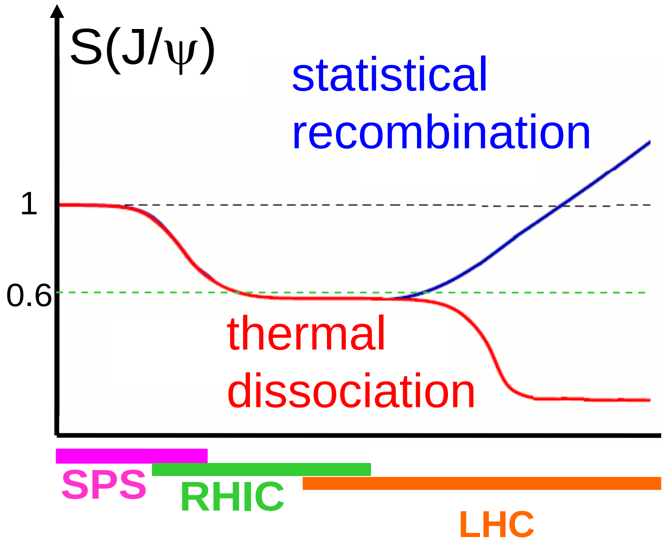
$$R_{AA}^{\Upsilon(3S)} < 0.096 \text{ at } 95\% \text{ CL}$$

📖 CMS, PLB790 (2019) 270

Charmonium production via recombination

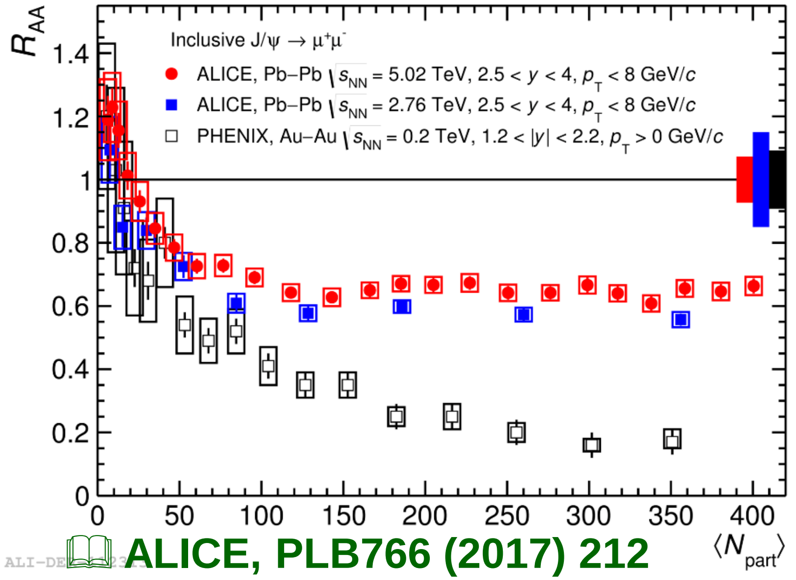
- Charmonium production in A-A collisions expected to occur also via **$c\bar{c}$ recombination** in the QGP or at the phase boundary
  - ⇨ J/ψ from recombination mainly produced with **low momentum**
  - ⇨ Recombination expected to be less relevant for bottomonium
- Charm production cross section increases with increasing $\sqrt{s}$
  - ⇨ Recombination increases with $\sqrt{s}$
  - ⇨ Quarkonium production **enhanced** in A-A collisions at higher $\sqrt{s_{NN}}$





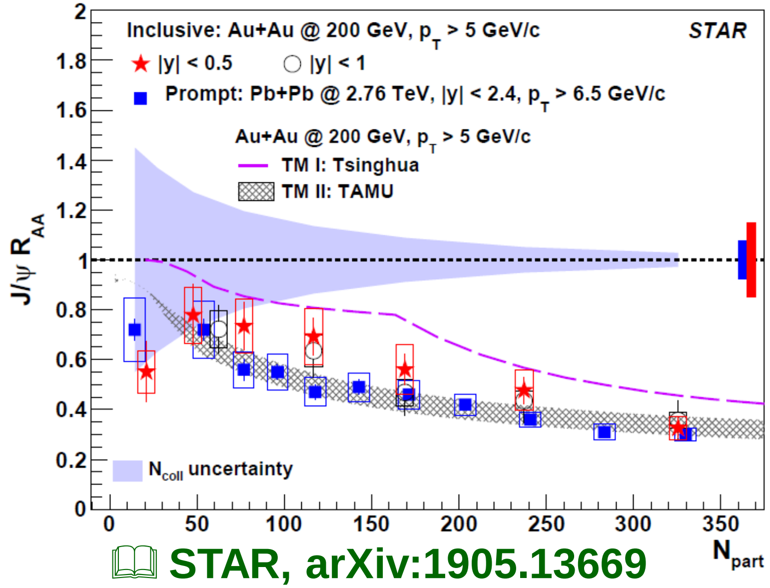
📖 **Braun-Munzinger, Stachel, PLB 490 (2000) 196**
📖 **Thews et al., PRC 63 (2001) 054905**

J/ψ R_{AA} at different $\sqrt{s_{NN}}$



📖 ALICE, PLB766 (2017) 212

📖 PHENIX, PRC84 (2011) 05912



📖 STAR, arXiv:1905.13669

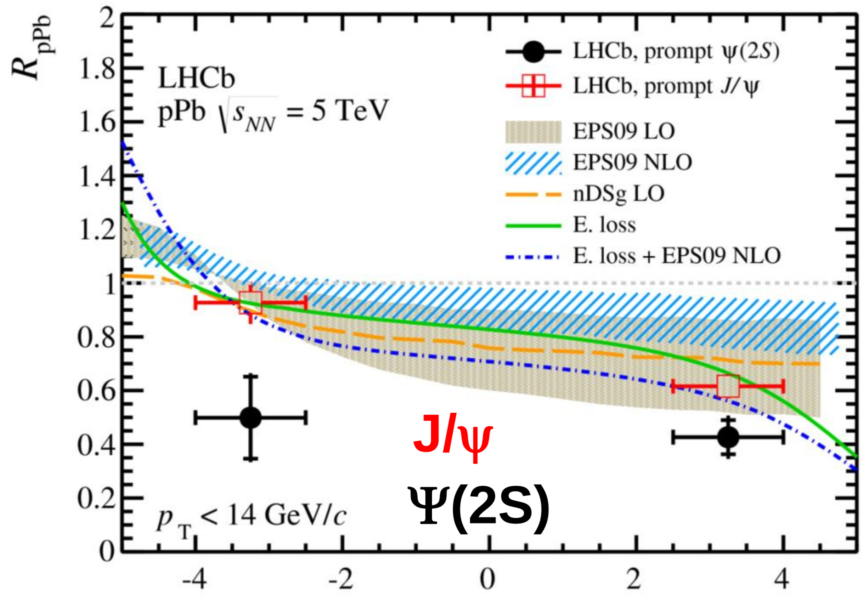
📖 CMS, EPJ C77 (2017) 252

- 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

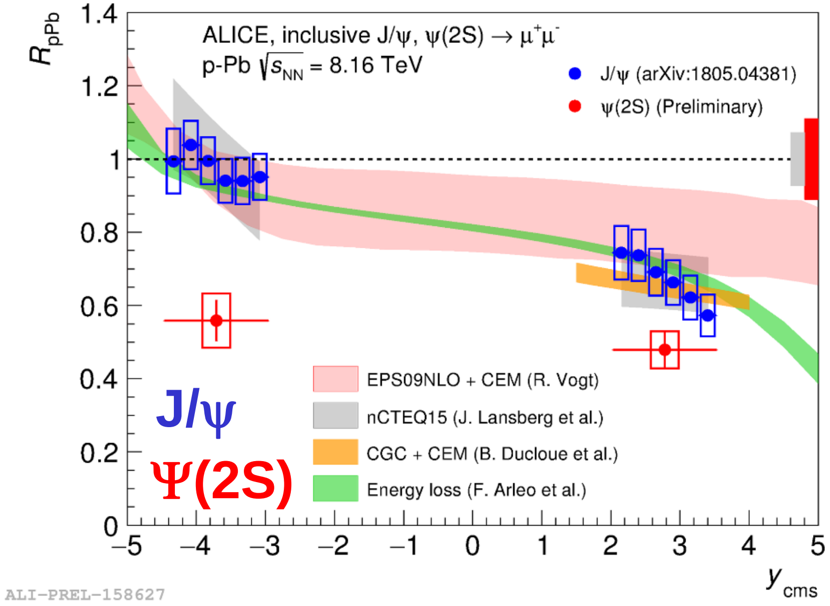
- High p_T
  - ⇨ **Hint for more suppression at LHC** ($\sqrt{s}$=**2.76** TeV) than at RHIC ($\sqrt{s}$=**200** GeV)
  - ⇨ Higher temperature reached at higher $\sqrt{s}$ → larger dissociation rate

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

Charmonium in p-Pb collisions



📖 LHCb, JHEP 1603 (2016) 133



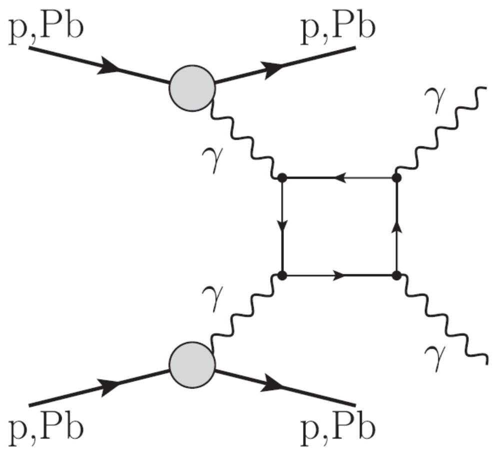
- J/ψ R_{pPb} described reasonably well by CNM effects
- Ψ(2S) production suppressed relative to J/ψ at both backward and forward rapidity
  - ⇨ Shadowing and energy loss, expected to be the same for J/ψ and Ψ(2S), cannot describe the different suppression
- Indication for **additional final-state effects**
  - ⇨ Interactions with co-moving hadrons? Dissociation in QGP droplet?

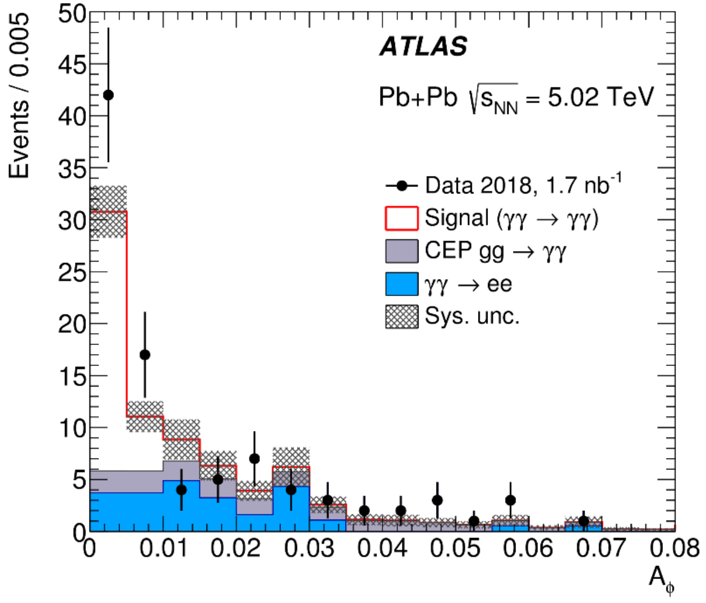
Summary and prospects

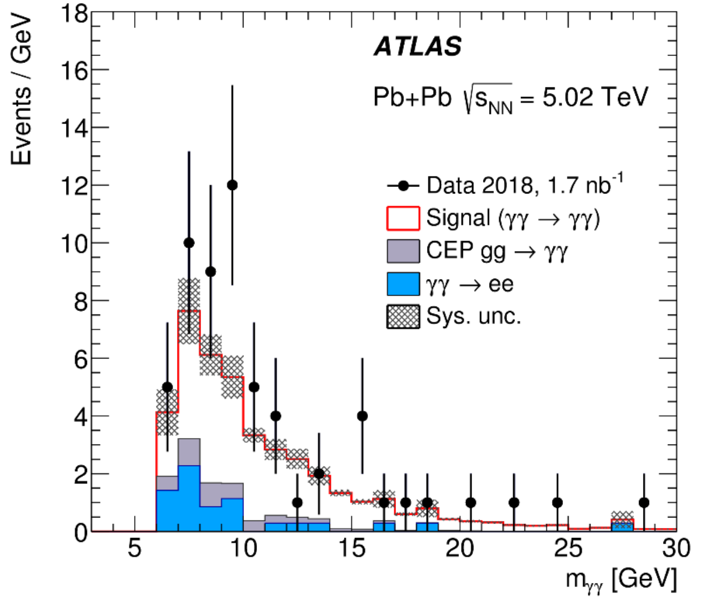
- Important step forwards in the understanding of QCD at extreme conditions of high temperature and energy density
  - ⇨ Wealth of results from RHIC and LHC experiments in the last years
  - ⇨ Tremendous progress also on the theoretical side towards an "**heavy-ion standard model**"
- Discovery of heavy-ion like phenomena in pp and p-Pb collisions
  - ⇨ Change of paradigm for small collision systems: more that "just reference data"
    - ✓ ***What is the smallest system in which heavy-ion "standard model" remains valid?***
    - ✓ ***Can the standard tools for pp physics remain standard?***
- More will come in the next years from:
  - ⇨ LHCb fixed target program
  - ⇨ LHC Run-3 and Run-4 with upgraded detectors and higher Pb-Pb integrated luminosities
    - ✓ ***New precision era for ultra-relativistic heavy-ion collisions***
    - ✓ ***Characterise the QGP properties with unprecedented precision***
  - ⇨ sPHENIX experiment at RHIC
  - ⇨ Low-energy frontier to investigate the high μ_B region: RHIC Beam Energy Scan phase II, SPS, NICA, FAIR

… and more: light-by-light scattering

- Ultraperipheral collisions with impact parameter b > 2R
  - ⇨ Hadronic interactions suppressed, electromagnetic interactions dominate
- Boosted protons / nuclei are source of photons of small virtuality
  - ⇨ Described using equivalent photon approximation
- One of the processes: light-by-light scattering
  - ⇨ First direct observation in Pb-Pb collisions at the LHC
  - ⇨ Potential sensitivity to production of pseudoscalar axion-like particles





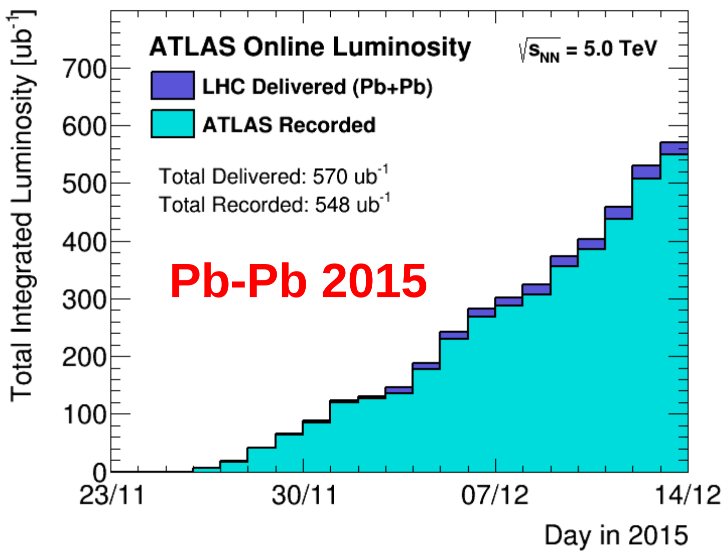


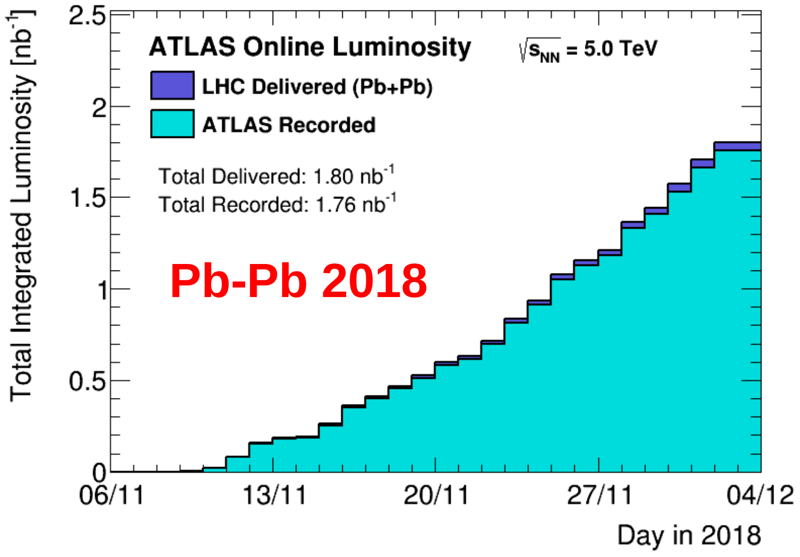
📖 **ATLAS, Nature Physics 13 (2017) 85**
📖 **ATLAS, PRL 123 (2019) 052001**
📖 **CMS, arXiv:1810.04602**

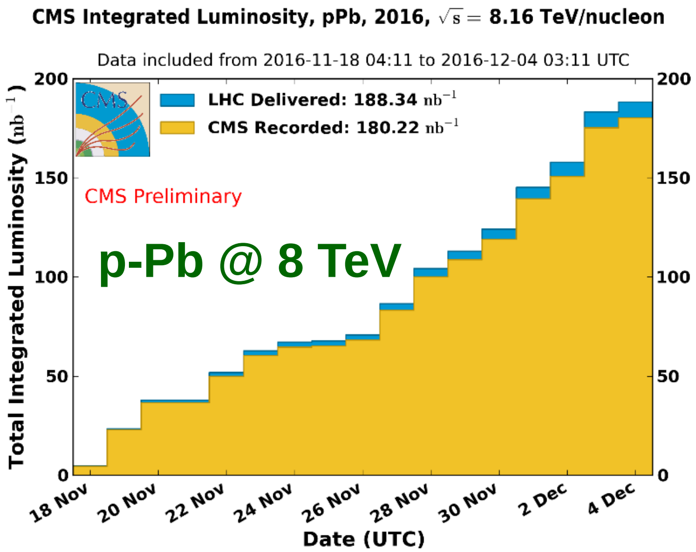
Backup

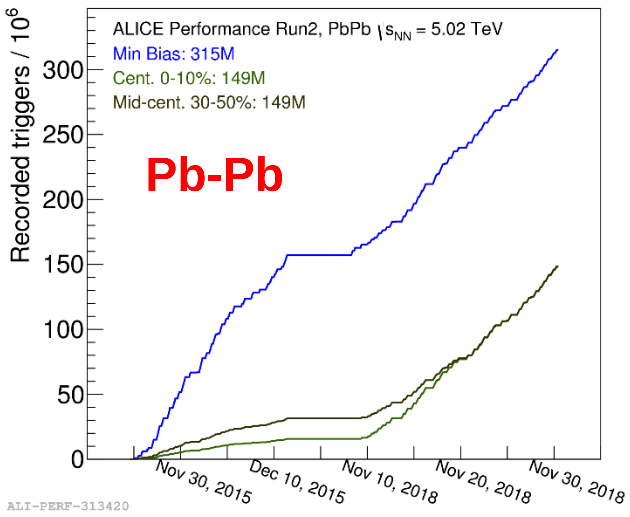
LHC: run-2 samples for heavy-ion physics

- Pb-Pb, $\sqrt{s_{NN}}$=5 TeV
  - ⇨Two runs: 2015 and 2018
  - ⇨Delivered $\int Ldt$ ~2.3 nb^{-1}
- Xe-Xe pilot run in 2017
- p-Pb in 2016
  - ⇨Two $\sqrt{s_{NN}}$: 5 and 8 TeV
  - ⇨p-Pb and Pb-p
- pp reference runs at $\sqrt{s}$=5 TeV



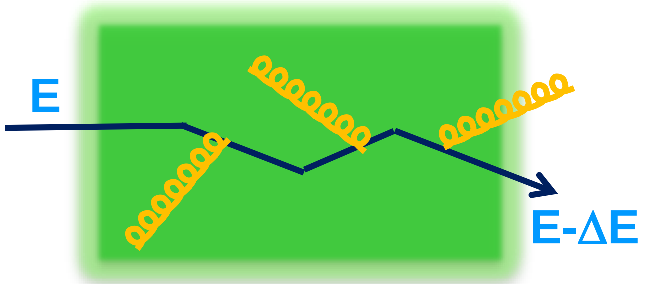






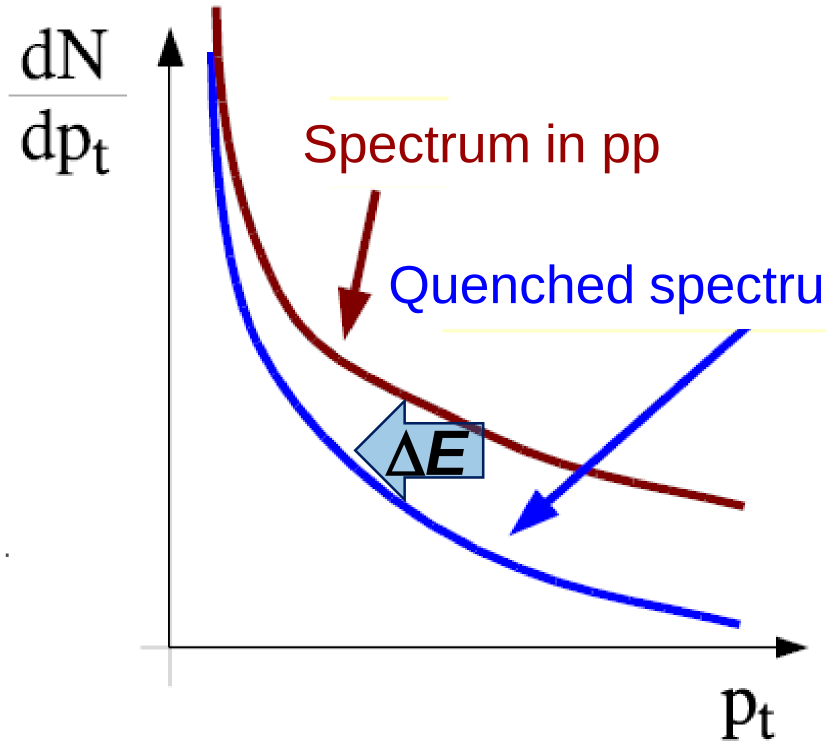
Hard partons in the QGP

- The hard-scattered parton interacts with the medium constituents -> **energy loss**
  - ⇨Elastic collisions (-> collisional energy loss)
  - ⇨Gluon radiation



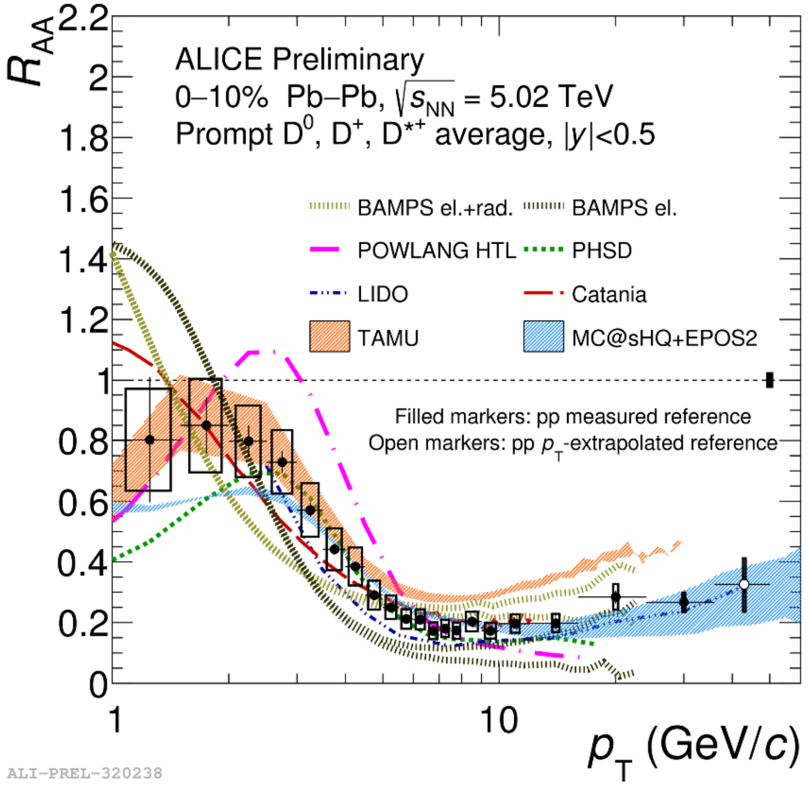
- Energy loss depends on:
  - ⇨Medium density
  - ⇨Path-length in the medium
  - ⇨Parton species (gluon vs. quark) and mass

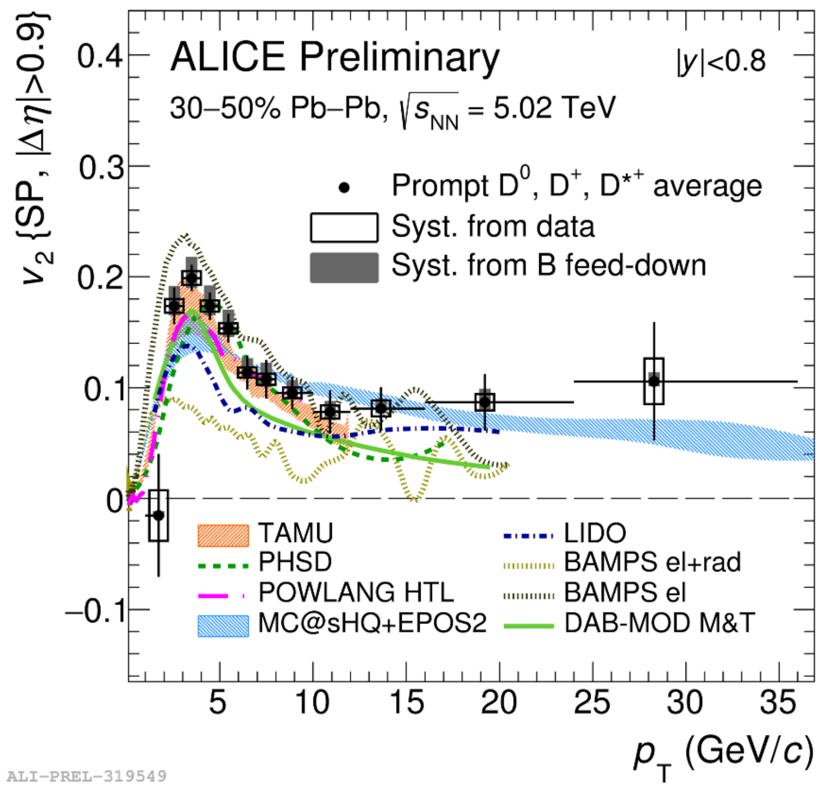
- Modification of the particle (and jet) momentum distributions
  - ⇨Suppression of yield at high p_T (**jet quenching**) relative to pp collisions where no medium is present



Charm R_{AA} and v_2 phenomenology

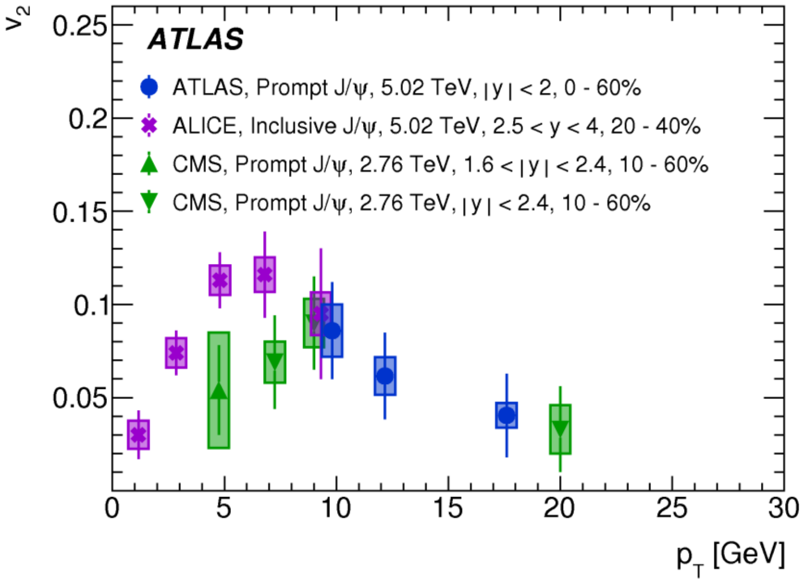
- Simultaneous comparison of R_{AA} and v_2 to models can constrain QGP properties and the description of charm-quark interaction and diffusion in the medium
  - ⇨ Interplay of CNM effects, collisional and radiative energy loss, hadronisation via coalescence and fragmentation and realistic underlying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



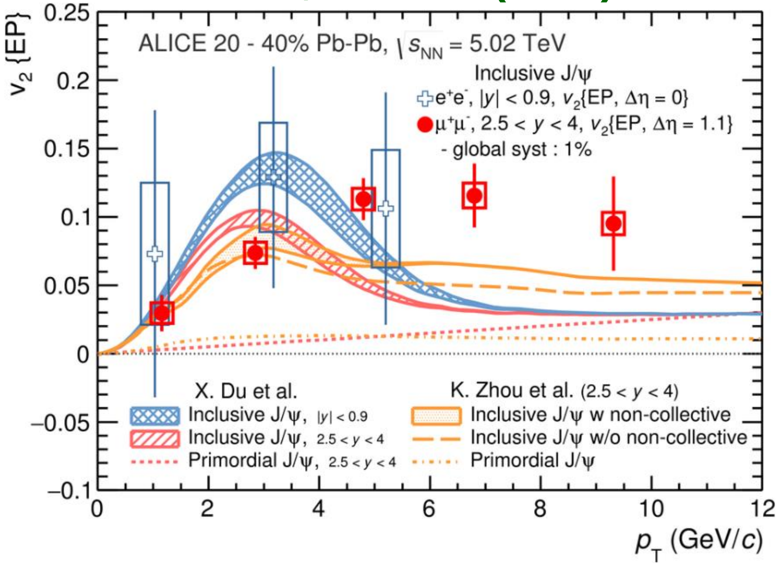


J/ψ v_2 in Pb-Pb and p-Pb

📖 ATLAS, EPJC78 (2018) 784



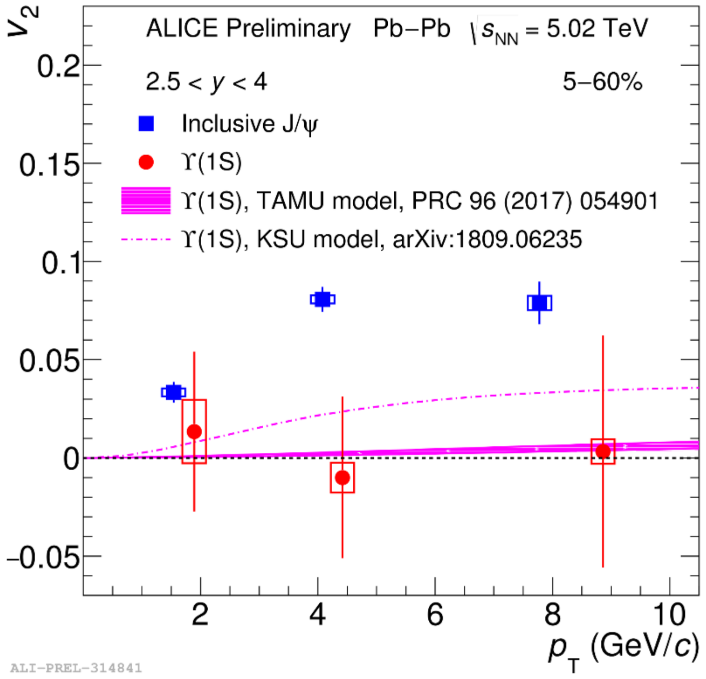
📖 ALICE, PRL119 (2017) 242301



- 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

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 bb 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**