Heavy Ions: Experiments

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ALICE ATLAS CMS LHCb

Marseille, July 11th 2025

Heavy Ions: Experiments

a personal perspective, not the full picture

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Heavy-ion collisions and QCD

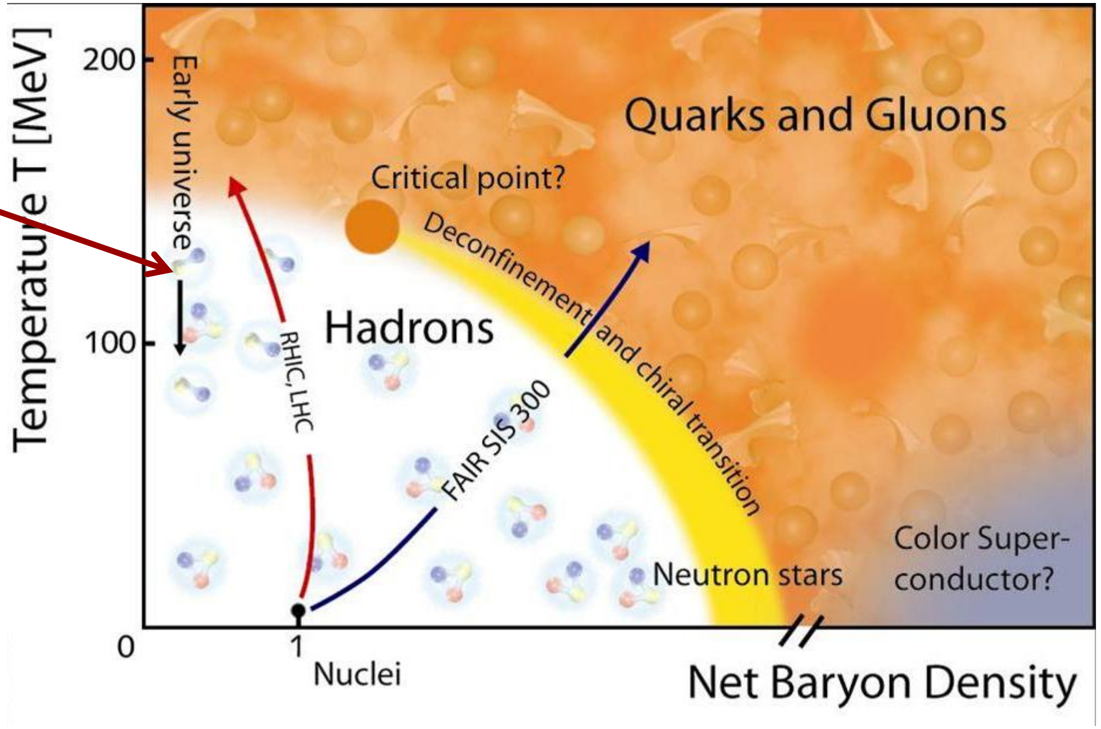
- Goal: study the properties of strongly-interacting matter at extreme conditions of temperature and energy density
  - ⇨ Explore the rich **phase diagram of QCD** matter
  - ⇨ Transition to a state where quarks and gluons are **deconfined** (**Quark Gluon Plasma**, QGP) and **chiral symmetry** is **restored**
  - ⇨ Heavy-ion collisions at different energies allow us to explore different regions of QCD phase diagram

Vanishing net-baryon density region

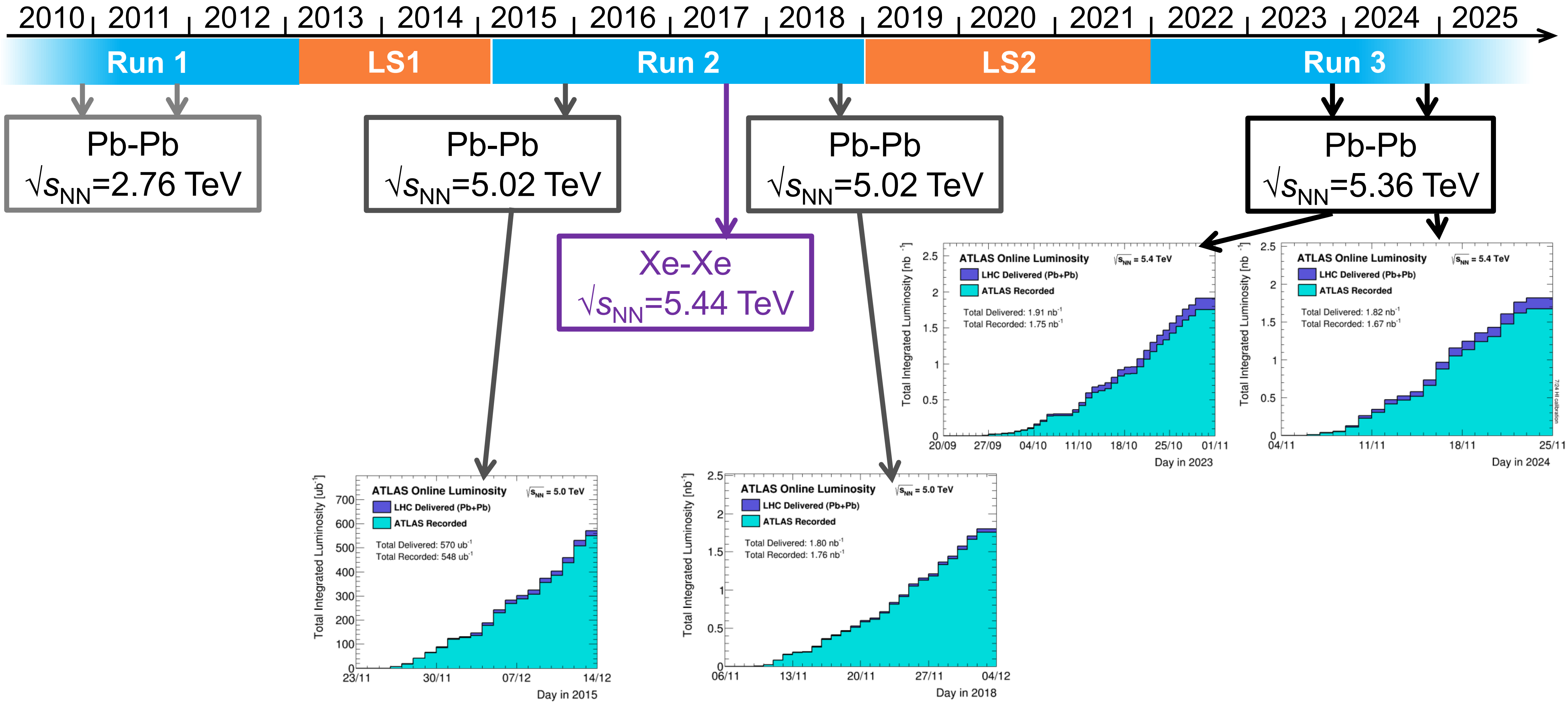
- Lattice QCD: cross-over from hadrons to QGP at T_C**≈155-160 MeV** $\rightarrow \varepsilon_C \approx 0.5$ GeV/fm^3
- **Early universe**: QGP-hadron transition at $t \sim 10^{-6}$ s after the Big Bang

Explored at LHC, RHIC top energy

- All four big LHC experiments have a heavy ion program
- sPHENIX experiment taking data at RHIC

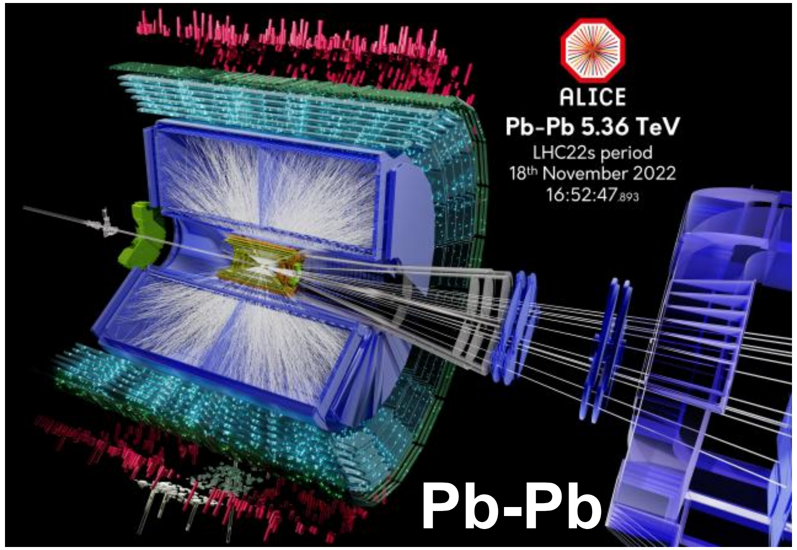


Heavy-ion collisions at the LHC

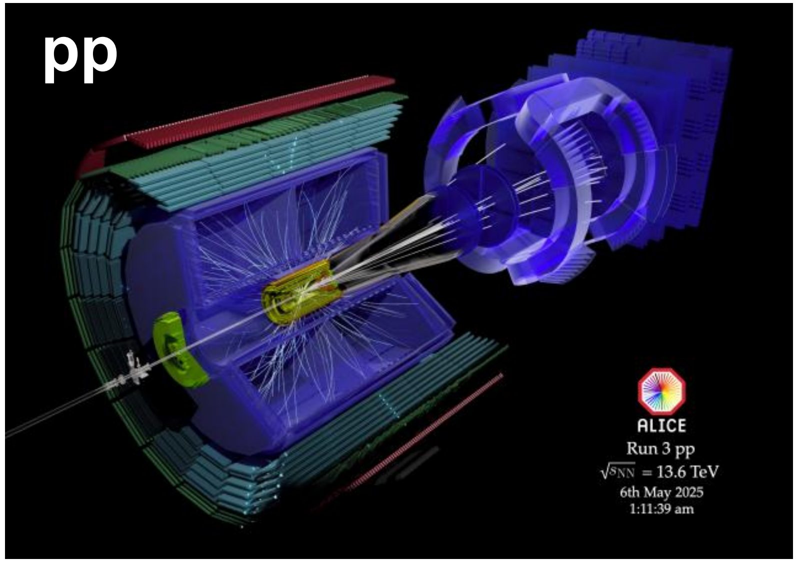


Colliding systems

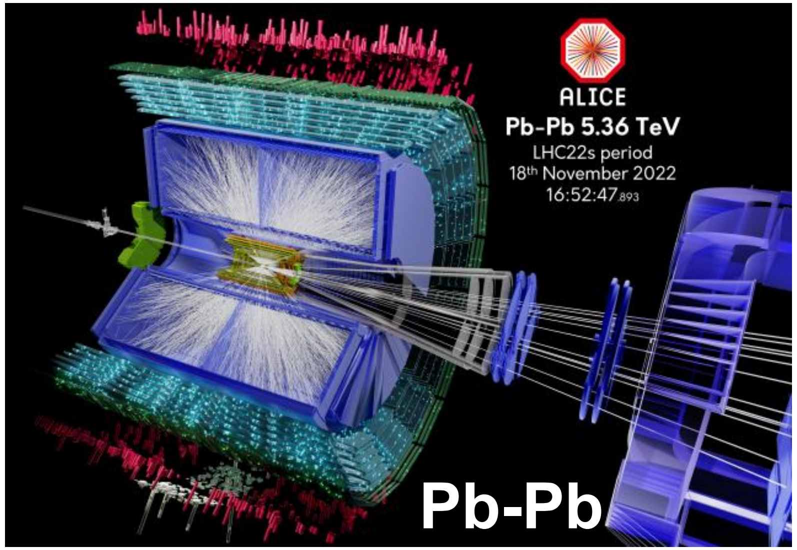
- Heavy-ion (**A-A**) collisions:
  - ⇨ Produce extremely hot and dense QCD matter
  - ⇨ Access the regime of QCD phase transition and **study QGP properties**



- And reference systems:
  - ⇨ Proton-nucleus (**p-A**) collisions
    - ✓ ***Initially aimed at studying "cold nuclear matter" effects and disentangle them from QGP effects***
  - ⇨ Proton-proton (**pp**) collisions
    - ✓ ***Initially aimed at providing the necessary reference for A-A collisions***



Colliding systems



- Heavy-ion (**A-A**) collisions:
  - ⇨ Produce extremely hot and dense QCD matter
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- And reference systems:
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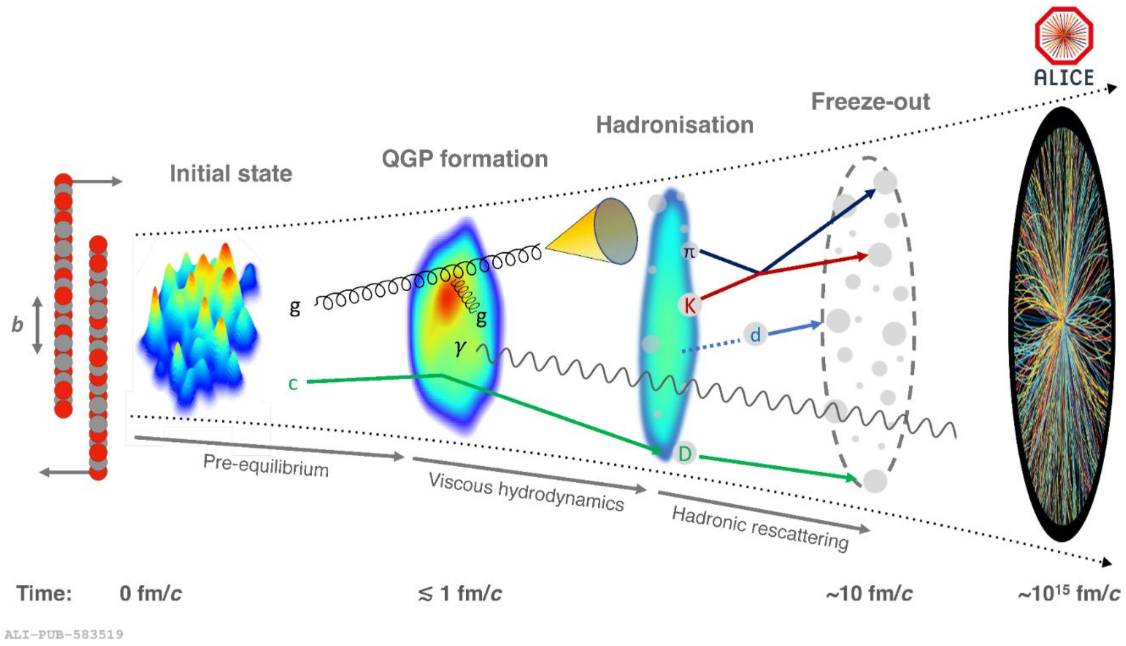
  - ⇨ Proton-proton (**pp**) collisions
    - ✓ ***Initially aimed at providing the necessary reference for A-A collisions***

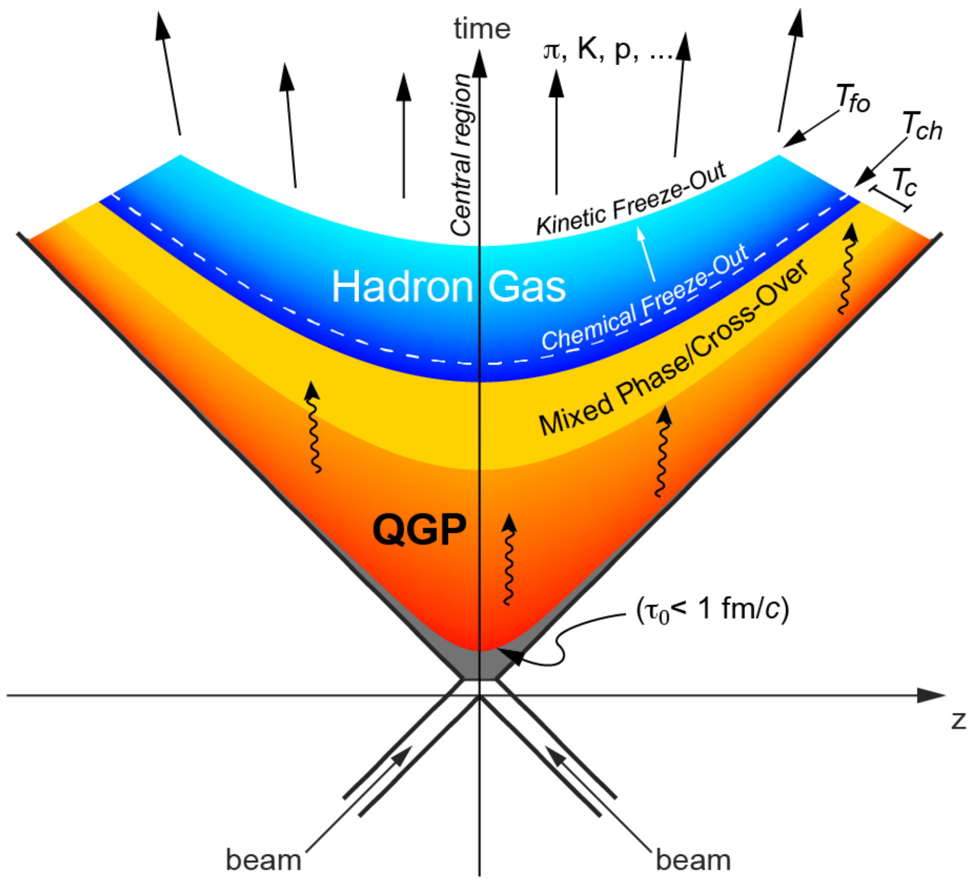
- Not just reference systems:
  - ⇨ *Discovery at the LHC*: high-multiplicity pp and p-A collisions show "features" resembling those observed in A-A collisions and understood as due to the collective expansion of the QGP
  - ⇨ Paradigm shift: chasing the **small-size limit of the QGP**

Space-time evolution of A-A collisions



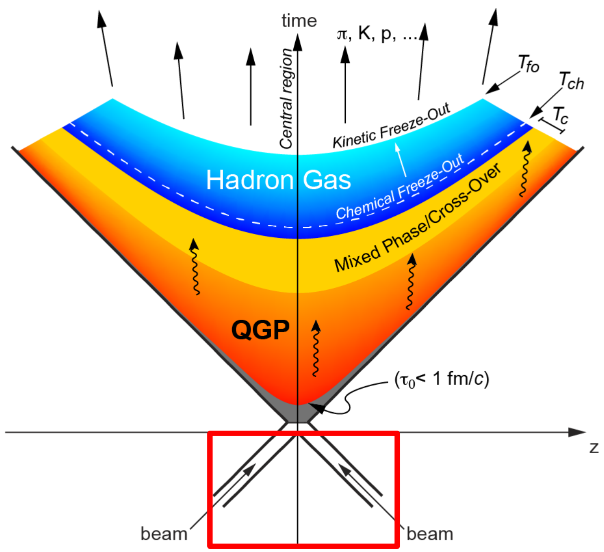
- Heavy-ion collisions lead to large energy deposition in the collision region
- Formation of a **"strongly coupled" QGP**
  - ⇨ **Expands** (and **cools down**) under strong pressure gradients according to viscous hydrodynamics
- Transition to hadrons when the temperature drops below the (pseudo)critical value
- Hadron gas phase after QGP hadronization until decoupling / freeze-out
- System lifetime ~ a few fm/*c*
  - ⇨ Long with respect to elementary collisions in high-energy particle physics → space-time picture

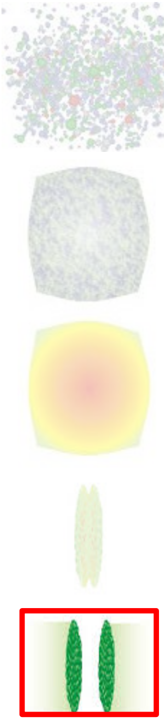
Get insight into QGP properties



- How to investigate the QGP which stays "beyond the horizon" of the freeze-out?
- Three classes of observables (multi-messengers from the QGP):
  - **Soft particles**: Hadrons with small momentum, decoupling from the equilibrated system at the kinetic freeze-out
  - **Electromagnetic probes**: Photons and dileptons produced in the hot phase and not influenced by later stages
  - **Hard probes**: Energetic and/or massive particles / jets produced in hard-scattering processes in the early stages of collision and traversing the QGP

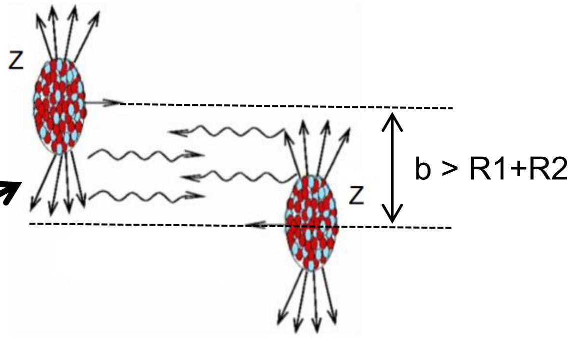
Before diving in the QGP: initial state

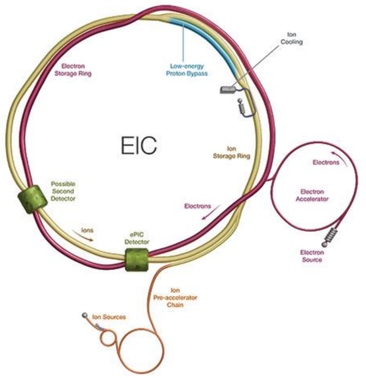




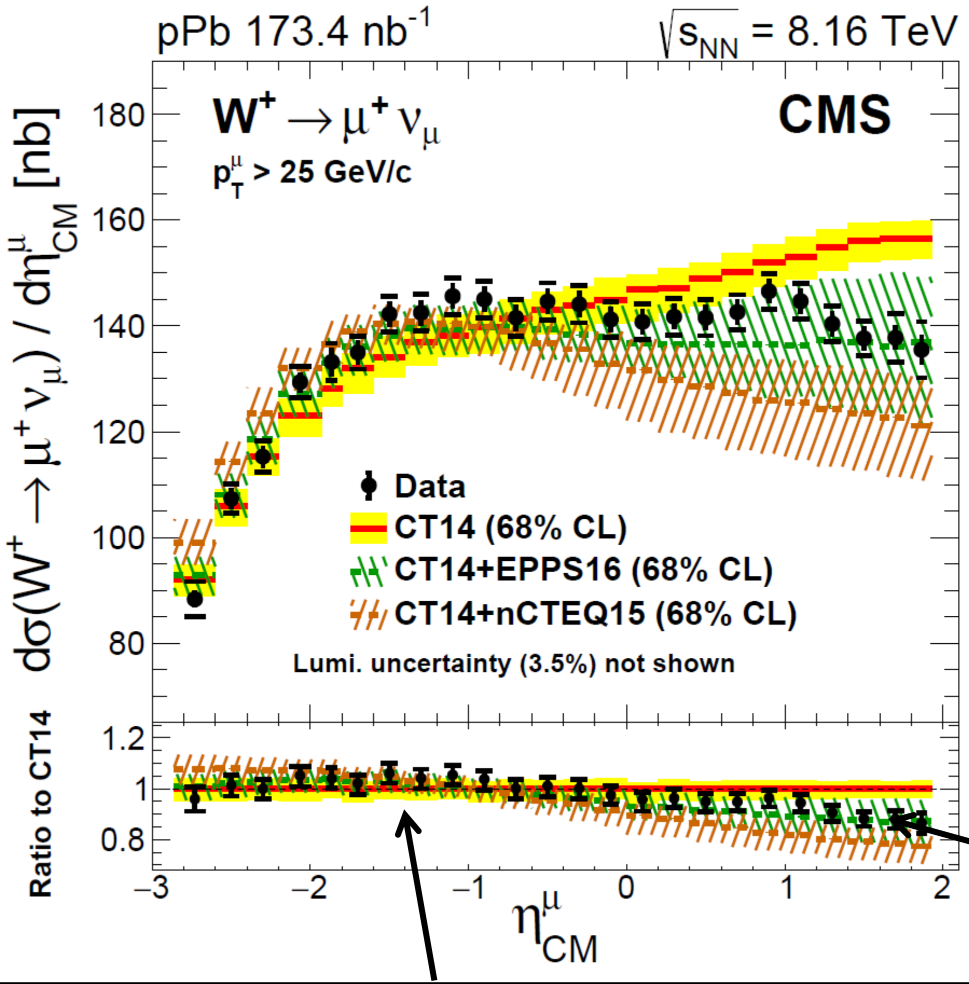
- What is the structure of the colliding objects?
  - ⇨ Spatial distribution of incoming nucleons inside nuclei
  - ⇨ Momentum distribution of partons inside nucleons
  - ⇨ Modification of the **PDFs in bound nucleons** (nPDF)
  - ⇨ Gluon saturation at small Bjorken-*x*

- Insight into initial state via:
  - ⇨ **p-A** collisions
  - ⇨ **Ultra-peripheral** A-A collisions
    - ✓ ***The impact parameter of the two colliding nuclei is greater than the sum of the two nuclear radii***
    - ✓ ***The strong electromagnetic fields surrounding the nuclei give rise to γA interactions***
  - ⇨ Future measurements in e-A interactions at the **electron-ion collider**





Initial state: W bosons in p-Pb collisions



- ElectroWeak bosons
  - ⇨ Produced on short timescales + lifetime ~ 0.1 fm/c
  - ⇨ Decay into energetic leptons
    - ✓ ***Do not interact strongly with other particles produced in the collision***
  - ⇨ Encode information about the early stages
- Measured cross sections in p-Pb collisions described by predictions using nPDFs better than with those using the free proton PDFs
  - ⇨ Results incorporated into global fits to extract the parton densities in heavy nuclei

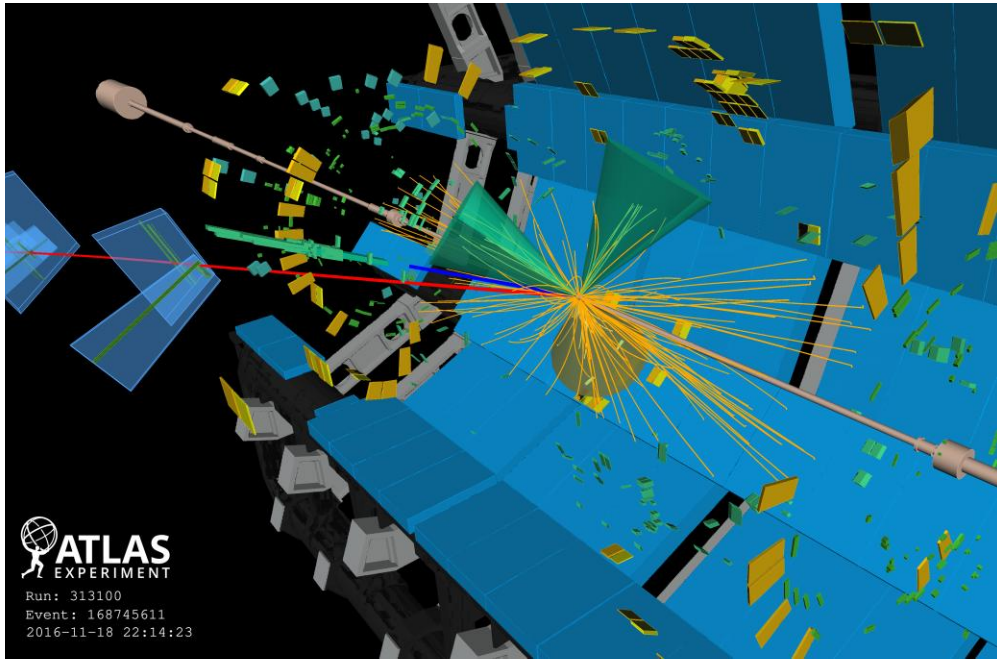
📖 **CMS, Phys.Rept. 1115 (2025) 219**

Negative rapidity (Pb-going):
Higher-*x* partons in Pb nucleus → antishadowing

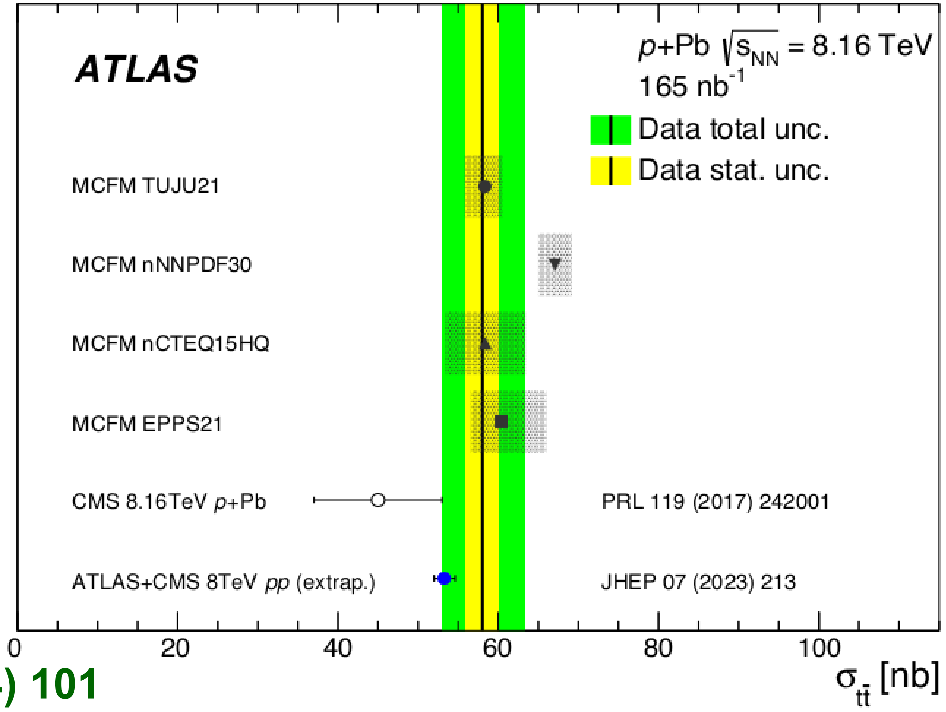
Positive rapidity (p-going):
Low-*x* partons in Pb nucleus → shadowing

Initial state: $t\bar{t}$ in p-Pb collisions

- Top quark production measured from W+b decay → sensitive probe of gluon nPDFs
  - ⇨ Cover antishadowing and EMC regions at large Bjorken-x ($3\times10^{-3} < x < 0.5$)
    - ✓ ***Complementary to EW bosons***
- Measured cross sections described by NNLO calculations with different nPDF sets
  - ⇨ Largest discrepancy for nNNPDF30, which does not include Run 2 LHC data in the tuning
- Data can further constrain nPDFs in the high Bjorken-x region



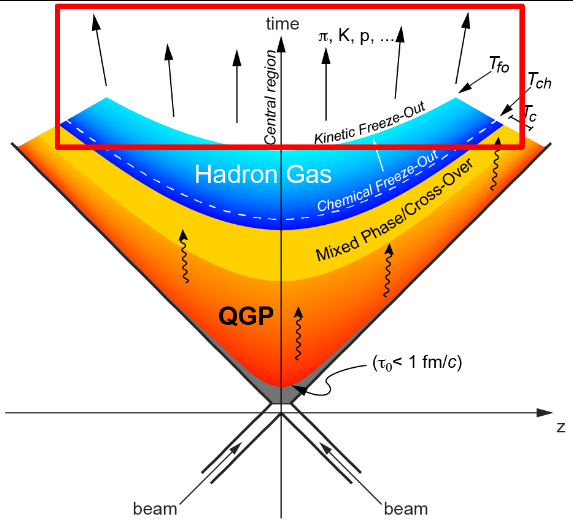
M. Tamlihat
T04 Mon 9.25

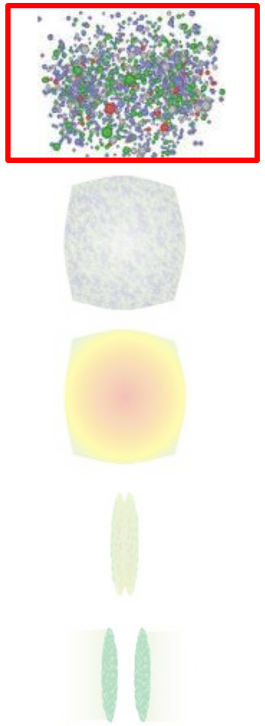


📖 **ATLAS, JHEP 11 (2024) 101**

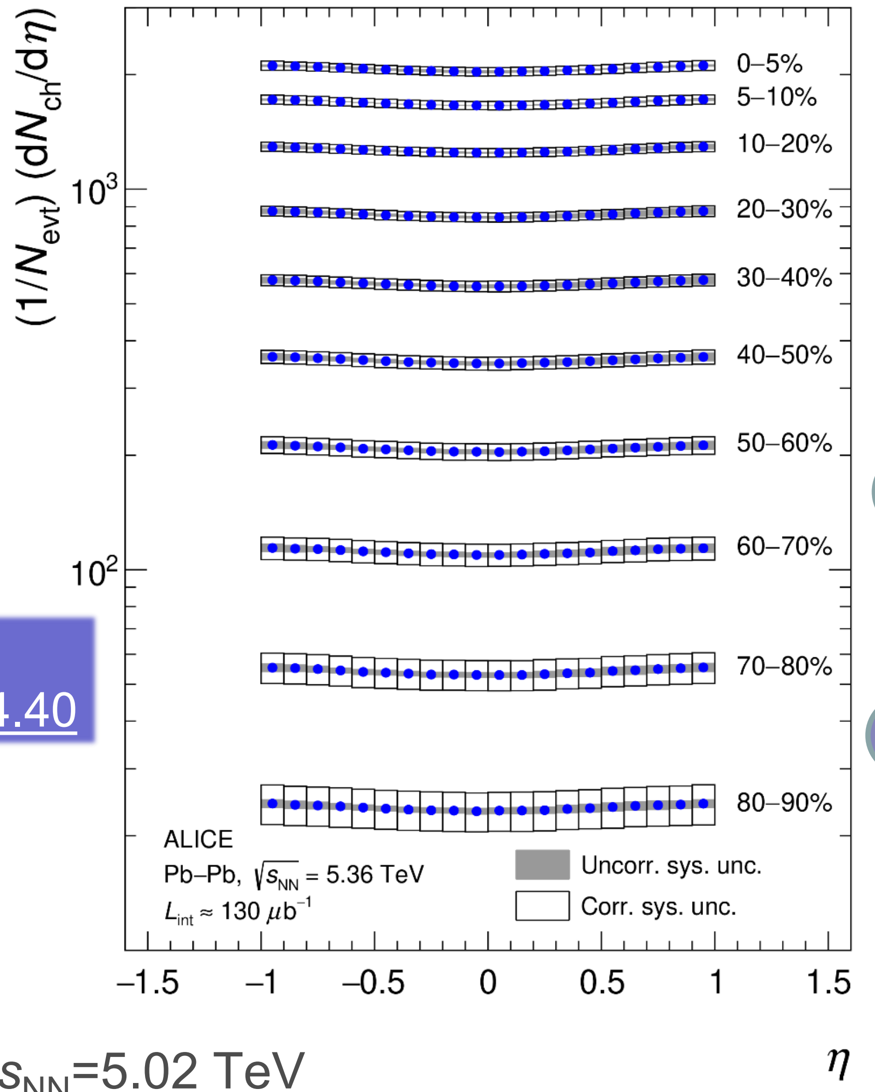
Final state: the "bulk" of soft particles

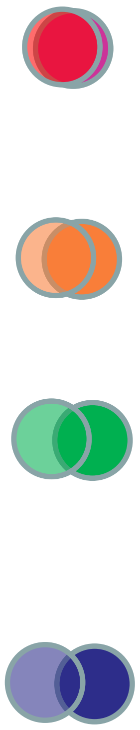
~**20000** particles produced in central Pb-Pb collisions @ LHC





A. Modak
T04 Mon 14.40

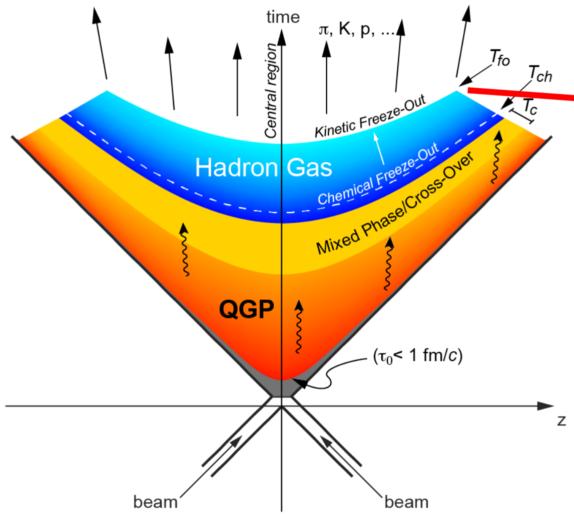


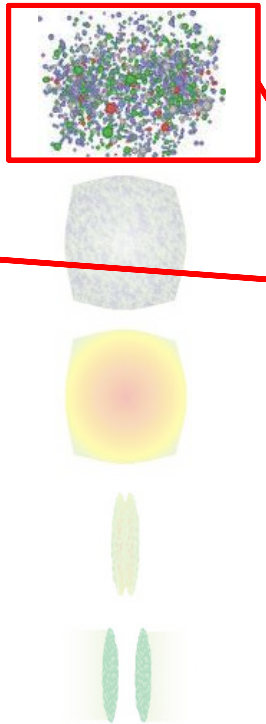


- Multiplicity of produced particles
  - ⇨ $dN_{ch}/d\eta$ ~ 2000 in central collisions at $\sqrt{s_{NN}}$=5.36 TeV
  - ⇨ Decreases from central to peripheral collisions
- Large energy density in the created "fireball":
  - ⇨ ε > **10 GeV/fm³** at τ=1 fm/c in central Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

ALICE, arXiv:2504.02505

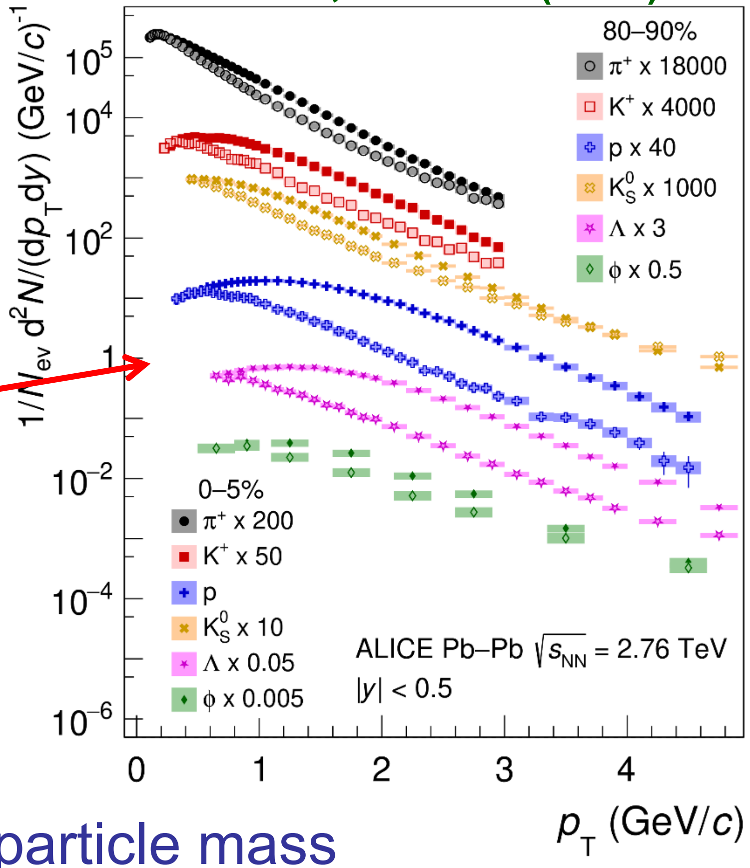
The flowing “bulk” of soft particles





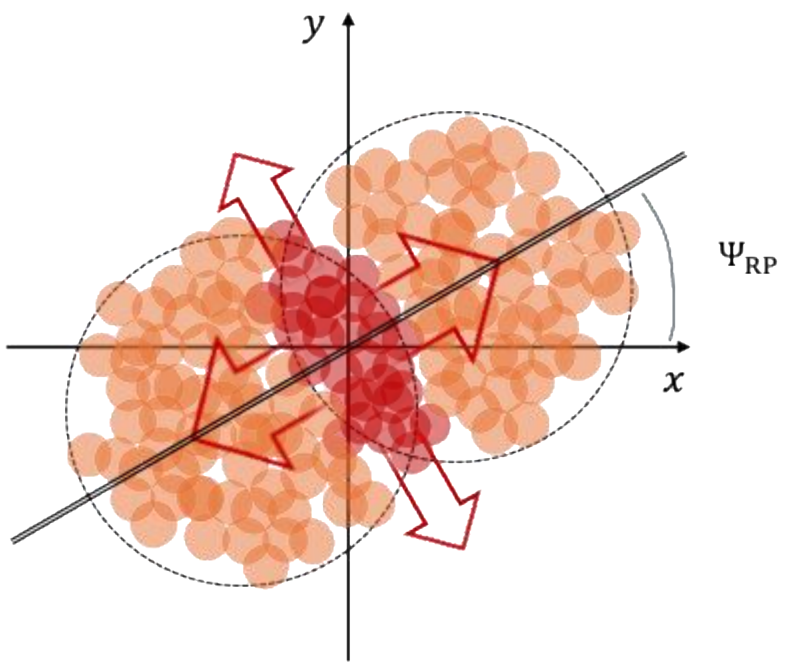
Particle momentum spectra frozen at the **kinetic freeze-out**

ALICE, EPJC 84 (2024) 813



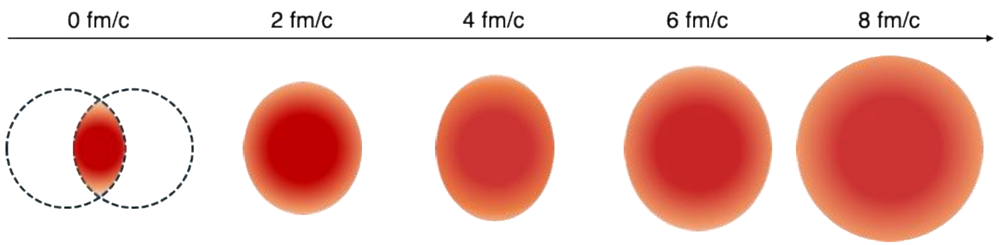
- Hardening of spectral shapes with increasing centrality and particle mass
  - ⇨ Effect of random **thermal motion** + **collective expansion** with common **radial flow** velocity
- Described by hydrodynamic expansion of the medium
  - ⇨ Radial flow velocity β_T~0.5-0.6c at freeze-out temperature T_{fo}~100 MeV

Anisotropic transverse flow



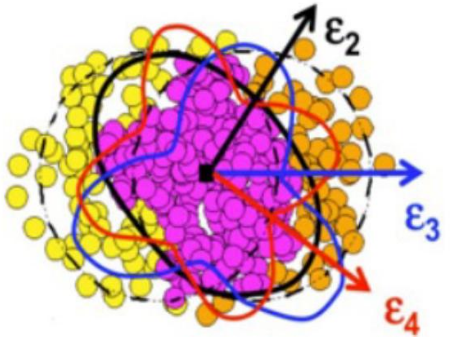
- Initial geometrical anisotropy in non-central collisions
  - ⇨ Impact parameter selects preferred direction in the transverse plane
- Hydrodynamical evolution converts the initial geometrical anisotropy into an observable final-state particle momentum anisotropy
  - ⇨ Characterized by anisotropic flow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

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

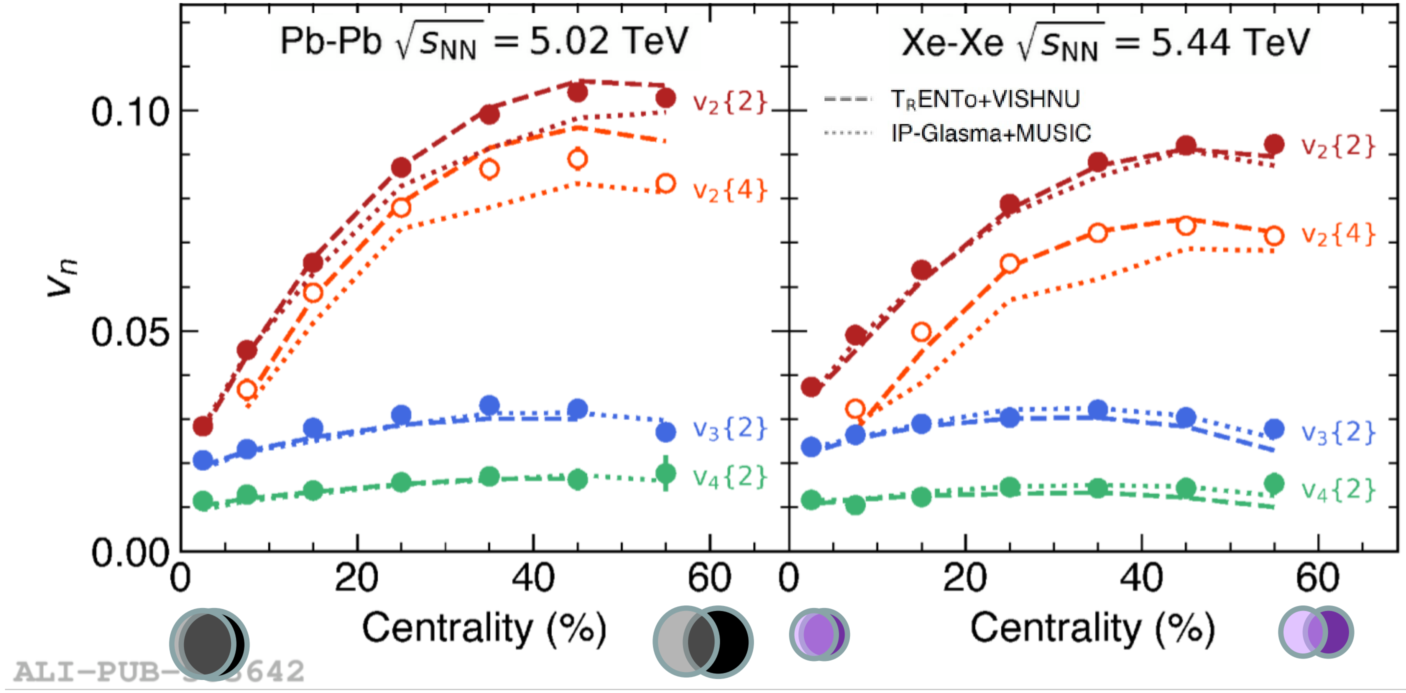


- Fourier coefficient v_2 = **elliptic flow**
  - ⇨ Dominant effect from initial geometry (v_2 > other harmonics) in non-central collisions
  - ⇨ Sensitive to the equation of state of the system in the early stages of the medium

Anisotropic flow: higher order harmonics



- **Fluctuations** and **lumpiness** of initial geometry (participant nucleons) and initial energy density profile give rise to non-zero values of **higher harmonics** (v_3, v_4, …), if they are not damped
  - ⇨ Connection between initial-state fluctuations and final-state particle v_n sensitive to "slow modes" in the hydrodynamics, which depend on the transport coefficients of the QGP (like shear and bulk **viscosity**)

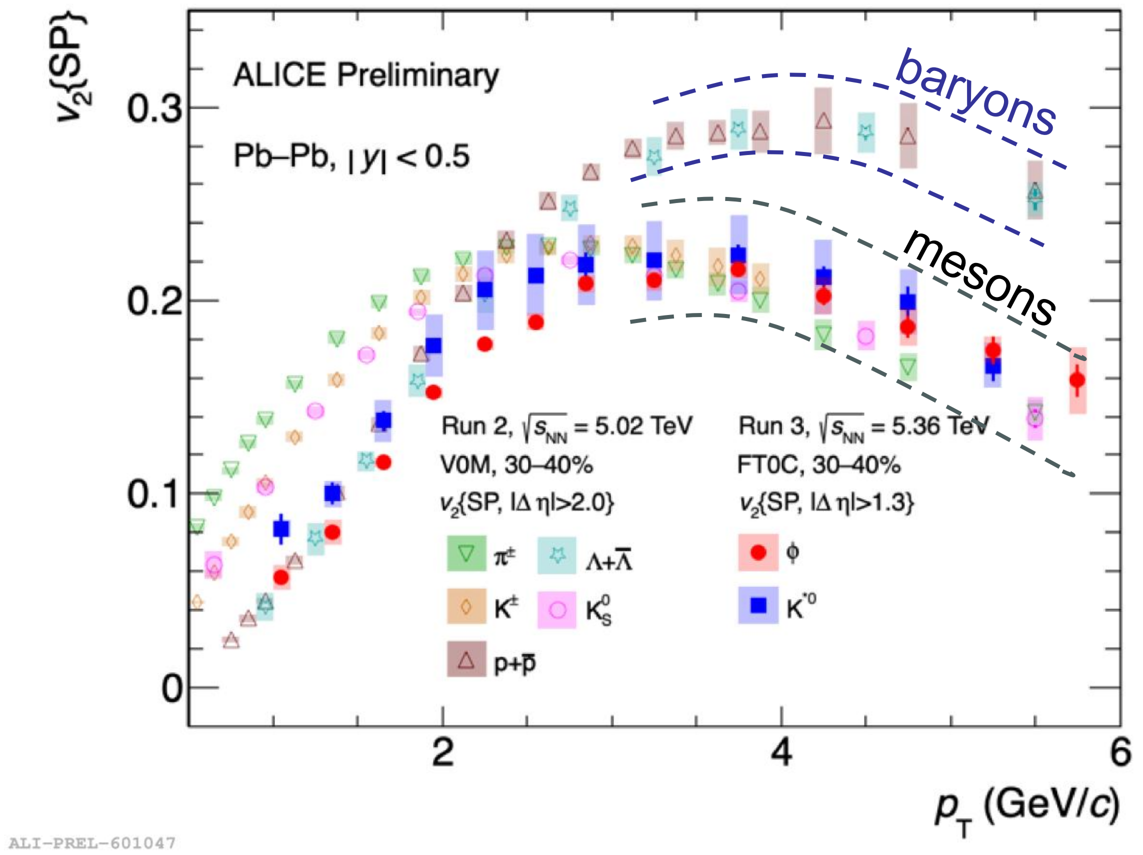


📖 ALICE, EPJC 84 (2024) 813

- 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**

Open question: how does a strongly coupled liquid emerge from QCD which is asymptotically free at short distances?

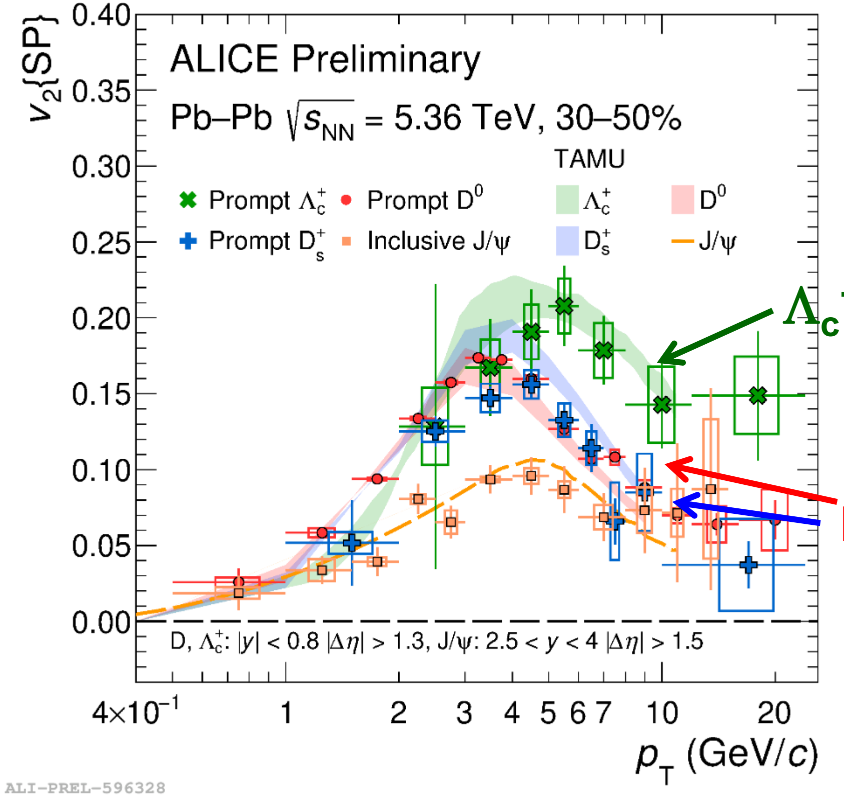
Elliptic flow of light-flavour hadrons



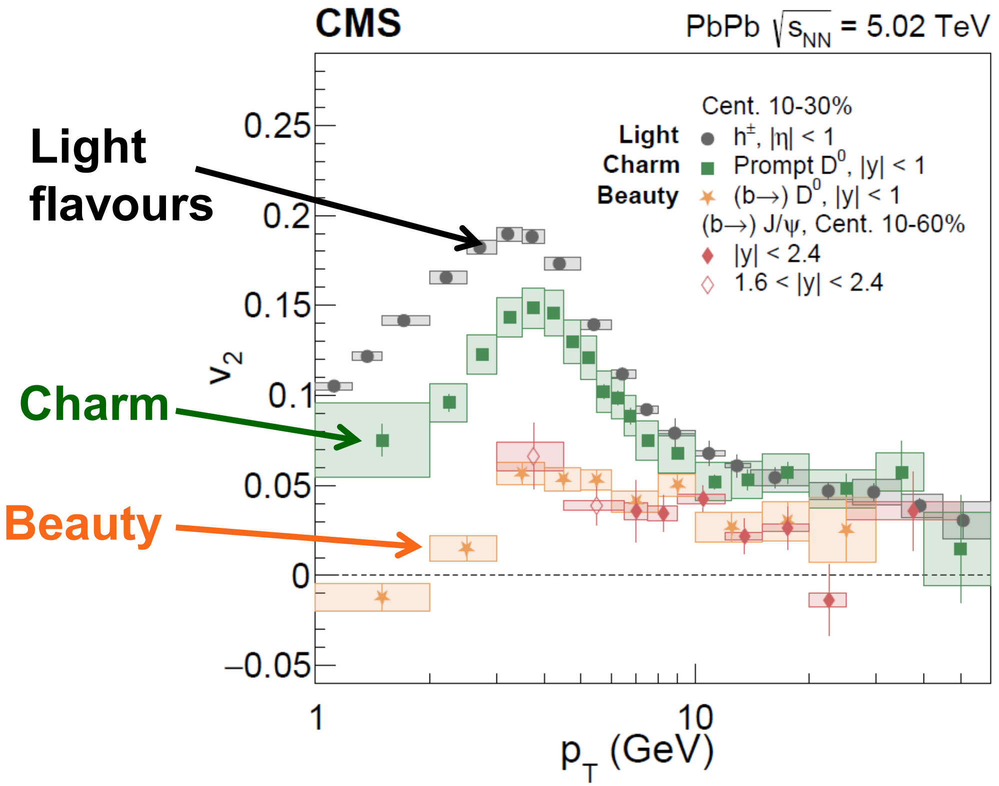
- Mass ordering of v_2 **at low p_T**
  - ⇨ Originating from interplay between radial flow and anisotropic expansion of the fireball
  - ⇨ Mass ordering develops not only during the partonic evolution of the medium but also in the late hadronic re-scattering phase
  - ⇨ Described by hydrodynamic models
- Baryon/meson grouping at **intermediate p_T**
  - ⇨ Anisotropic flow is driven by quark content rather than by mass in this momentum range
  - ⇨ Pattern expected in the case of hadron formation via quark recombination at the QGP hadronization
  - ⇨ Evidence of **partonic collectivity**

Elliptic flow of heavy-flavour hadrons

- Charm hadrons
  - ⇨ Large v_2 + first evidence of charm baryon/meson splitting
  - ⇨ Indication that low/mid-p_T **charm quarks (partially) thermalize in the QGP**



M. Di Costanzo
T04 Wed 17.00

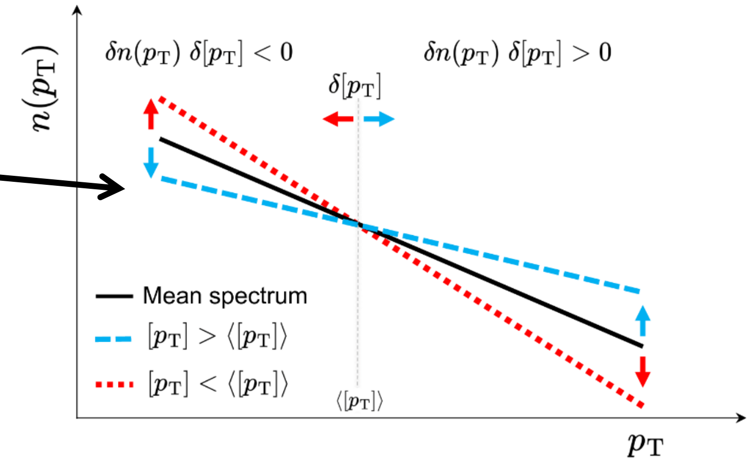


CMS, Phys.Rept. 1115 (2025) 219

- Beauty hadrons (via non-prompt D and J/ψ)
  - ⇨ Smaller v_2 as compared to charm hadrons
  - ⇨ Stronger degree of equilibration for charm than for beauty quarks
    - ✓ ***Due to longer thermalization time of the heavier beauty quarks***

Back to radial flow

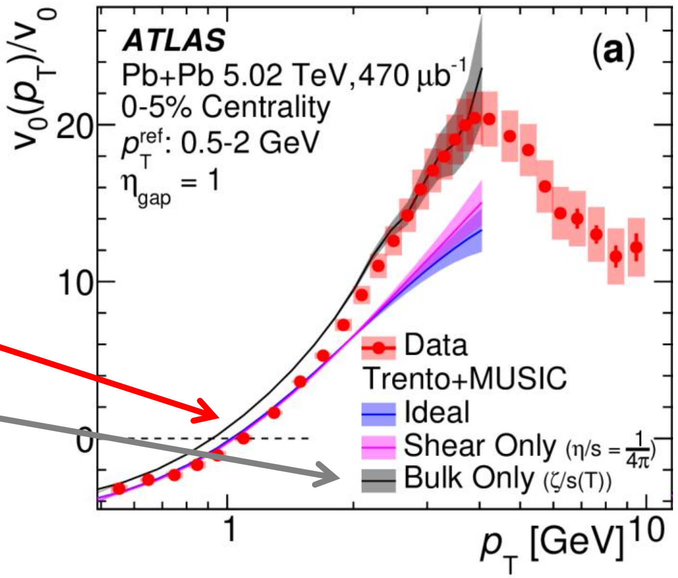
- New observable: $v_0(p_T)$ from event-by-event fluctuations of the p_T spectrum
  - ➯ Correlation between particle spectra, $n(p_T)$, and mean p_T of particles in the event, $[p_T]$
    - ✓ ***Events with larger (smaller) radial flow feature a flatter (steeper) spectrum $n(p_T)$ and a higher (lower) $[p_T]$***



$$v_0(p_T) = \frac{\langle \delta n(p_T)\delta[p_T]\rangle}{\langle n(p_T)\rangle \sigma_{[p_T]}} = \frac{\langle \delta n(p_T)\delta[p_T]\rangle}{\langle n(p_T)\rangle \sqrt{\langle(\delta[p_T])^2\rangle}}$$

$$v_0 = \frac{\sigma_{[p_T]}}{\langle[p_T]\rangle} = \frac{\sqrt{\langle(\delta[p_T])^2\rangle}}{\langle[p_T]\rangle}$$

- Features in $v_0(p_T)/v_0$
  - ➯ Change sign at $p_T \sim 1$ GeV/c ~ $[p_T]$
  - ➯ Sensitive to bulk viscosity

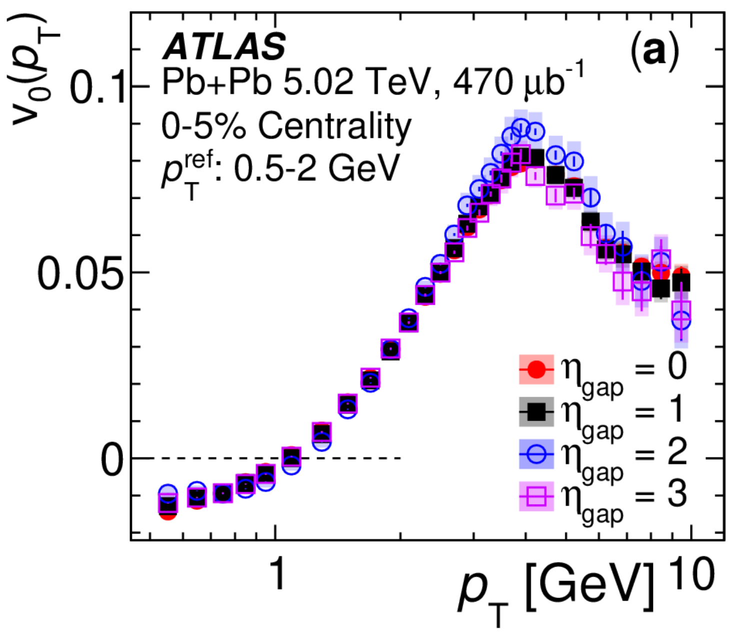


📖 **Schenke et al., PRC 102 (2020) 034905**
📖 **Parida et al., PLB 857 (2024) 138985**
📖 **ATLAS, arXiv:2503.24125**

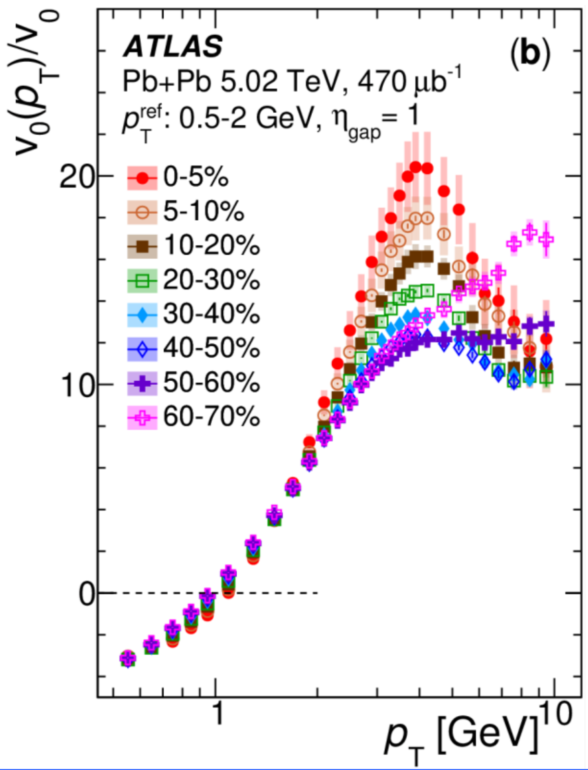
Back to radial flow

- New observable: $v_0(p_T)$ from event-by-event fluctuations of the p_T spectrum
  - ⇨ Radial flow shows **collective features**

📖 ATLAS, arXiv:2503.24125

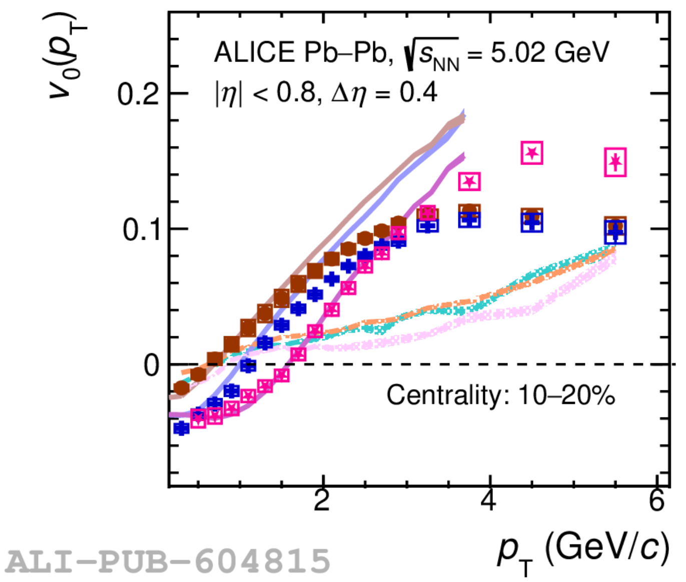


- Correlation is long-range in η



- $v_0(p_T)$ shape at low p_T independent of centrality → governed by hydro

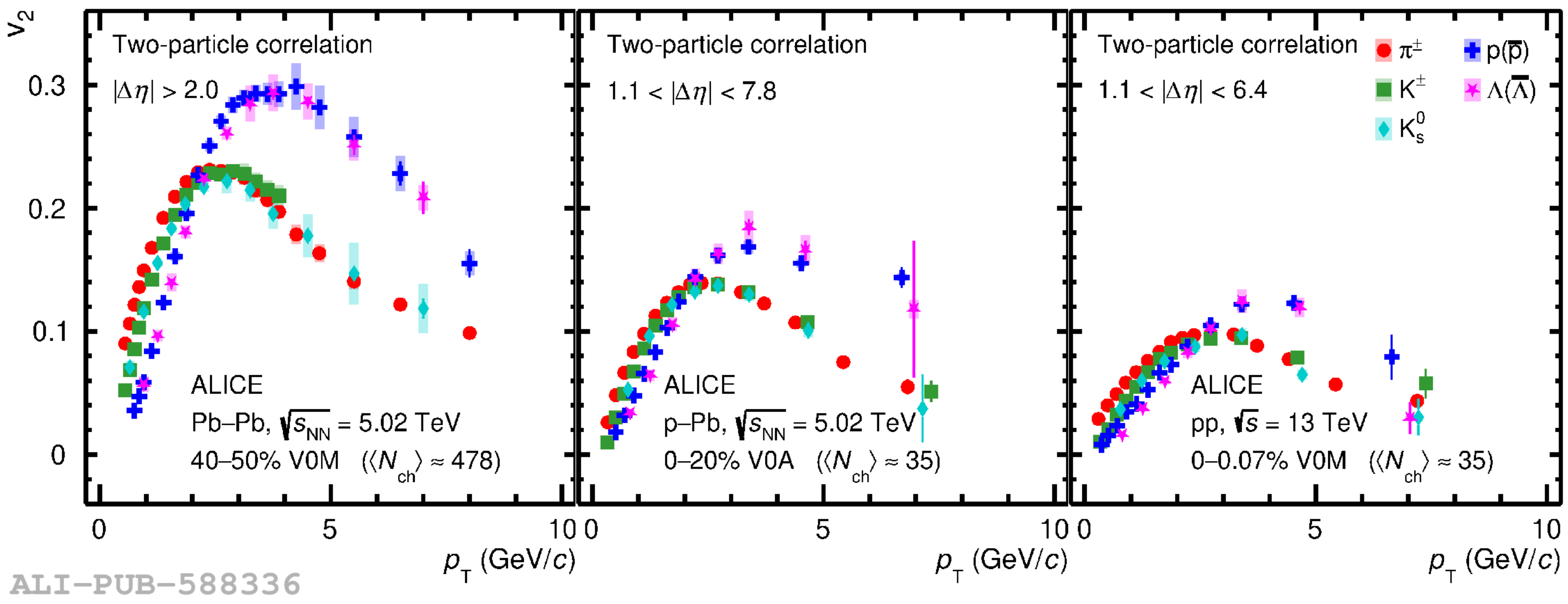
📖 ALICE, arXiv:2504.04796



- Mass ordering for π, K, p at low p_T
- v_0(p) > v_0(π, K) for p_T >3 GeV/c
  → reminiscent of baryon/meson grouping in anisotropic flow

Collectivity in small collision systems

- Long-range angular correlations observed in high-multiplicity pp and p-Pb collisions
  - ⇨ Similar features as those observed in Pb-Pb and interpreted as due to collective flow
  - ⇨ Clear **mass ordering** of the v_2 coefficients at low p_T
    - ✓ ***Significant evidence of radial flow in small collision systems***
  - ⇨ Distinctive **grouping of anisotropic flow for baryons and mesons** at intermediate p_T
    - ✓ ***Anisotropic flow development at the parton level***



The system created in high-multiplicity pp and p-Pb collisions includes a stage with **collectively flowing partons**

📖 **ALICE, arXiv:2411.09323**

Collectivity in smaller collision systems

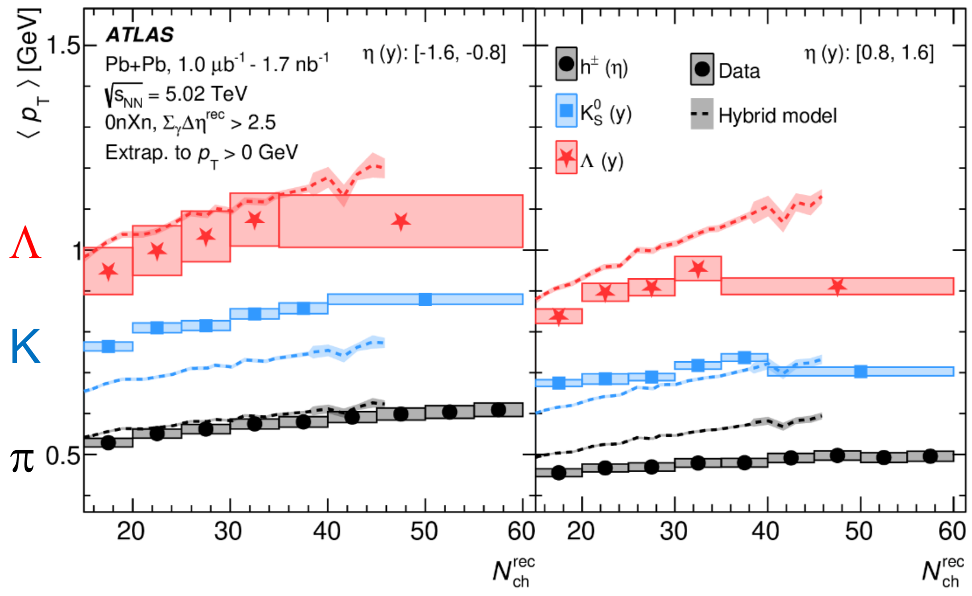
- Photo-nuclear events show similar features as p-Pb collisions for observables sensitive to anisotropic and radial flow (+ baryon-to-meson ratios, strangeness enhancement)
  - ⇨ E.g.: distinct mass ordering in $\langle p_{\mathrm{T}} \rangle$ + larger $\langle p_{\mathrm{T}} \rangle$ in Pb-going direction in γ-Pb events
  - ⇨ Hybrid model (assuming QGP formation and hydrodynamic expansion) captures qualitatively some features of the data
  - ⇨ Supports the vector meson dominance picture: γ fluctuates into a vector meson → a subset of events are, e.g., ρ-A collisions

R. Schotter
T05 Wed 9.50

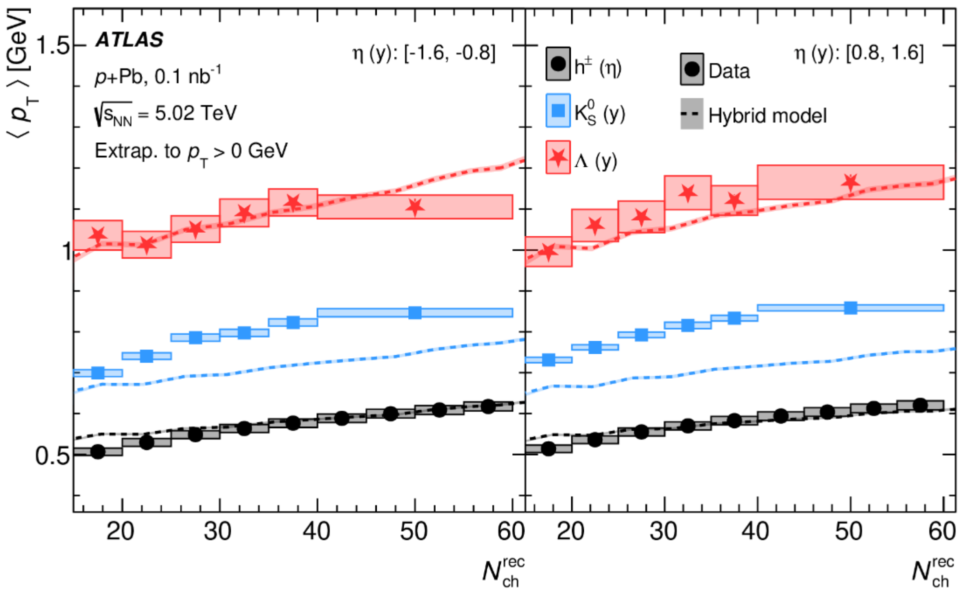
S. Ragoni
T04 Tue 8.50

ATLAS, PRC 111 (2025) 064908

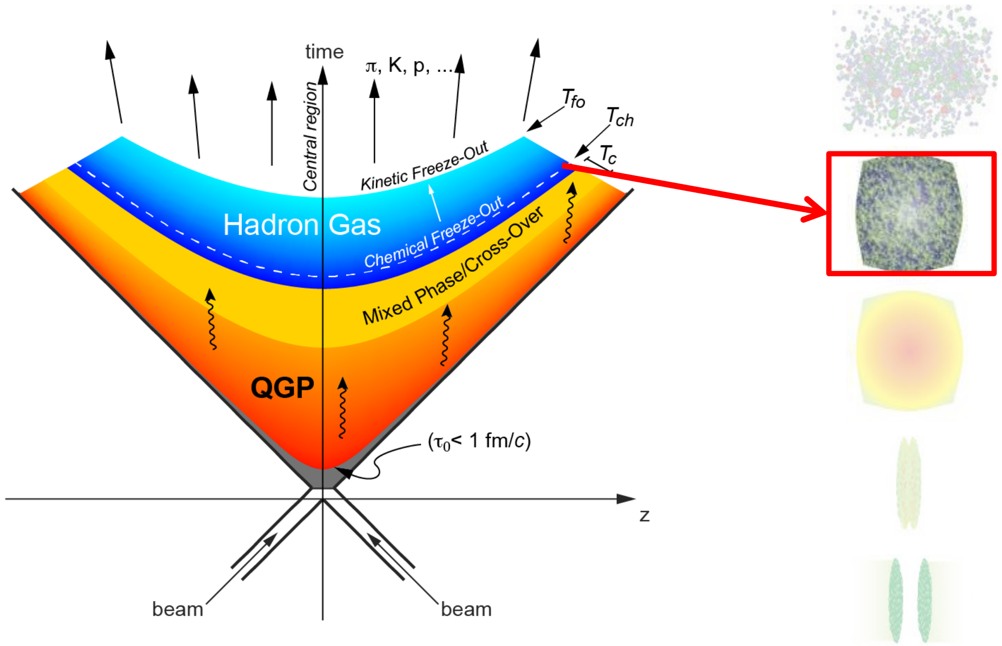
γ-Pb

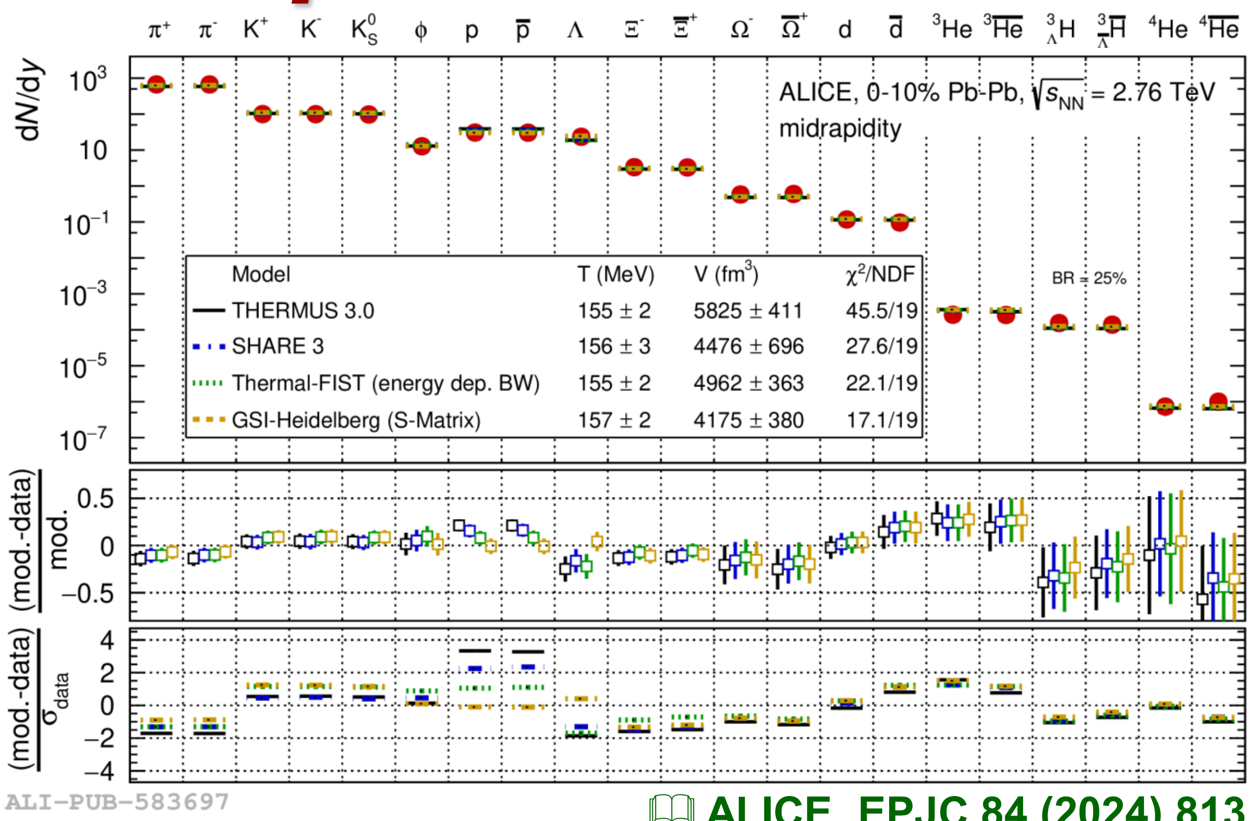


p-Pb



"Chemical" composition

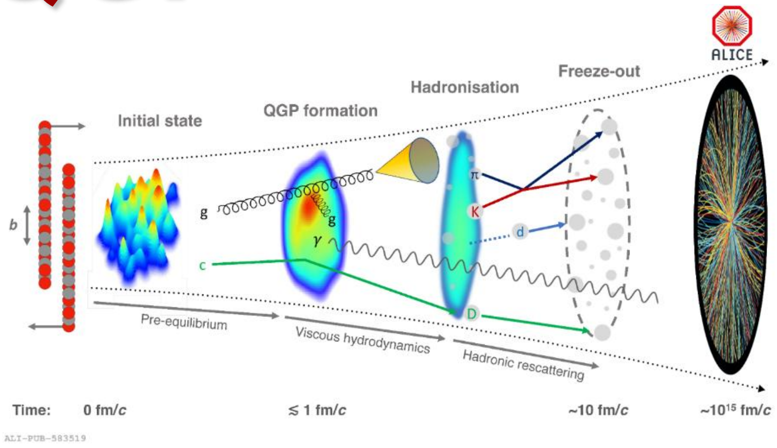




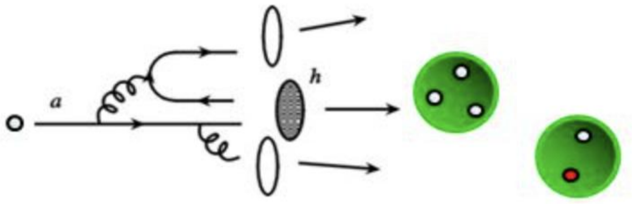
📖 **ALICE, EPJC 84 (2024) 813**

- 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
  - ⇨ Hadron abundances follow **equilibrium populations** → thermal origin of particle production
  - ⇨ Hadron abundances depend on hadron masses (and spins), chemical potentials, and temperature
  - ⇨ Estimate **temperature** at the **chemical freeze-out:** T_{chem}=155 MeV

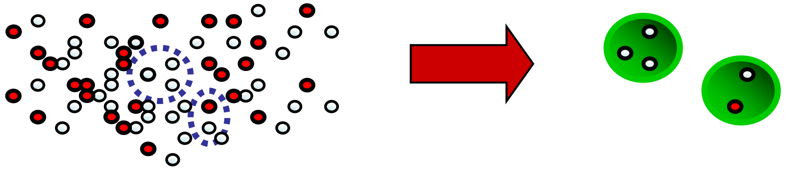
Hadronization of the QGP



- Hadronization of the QGP at the (pseudo)critical temperature
  - ⇨ Transition from a deconfined medium composed of quarks, antiquarks and gluons to color-neutral hadronic matter
  - ⇨ Hadronic phase space populated following “maximal entropy”
- How does the hadronization occur at microscopic level?
- Non-perturbative process, requires phenomenological models
  - ⇨ Parton **fragmentation** (“vacuum-like” dynamics)
    - ✓ ***Creation of $q\bar{q}$ and/or diquark pairs in the hadronization process***
    - ✓ ***One parton fragments into many hadrons, each of them taking a fraction z of the parton momentum***
    - ✓ ***Modelled via fragmentation functions or string fragmentation (PYTHIA)***



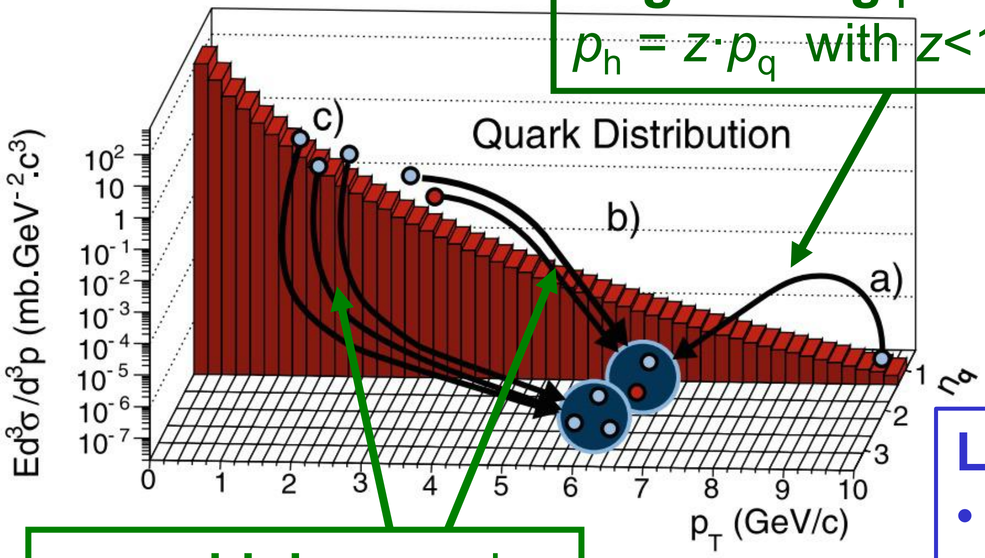
  - ⇨ Quark **recombination**/coalescence
    - ✓ ***Phase space at the QGP hadronization filled with (thermalized) partons***
    - ✓ ***No need to create $q\bar{q}$ pairs via splitting / string breaking***
    - ✓ ***Partons that are “close” to each other in phase space (position and momentum) can recombine into hadrons***



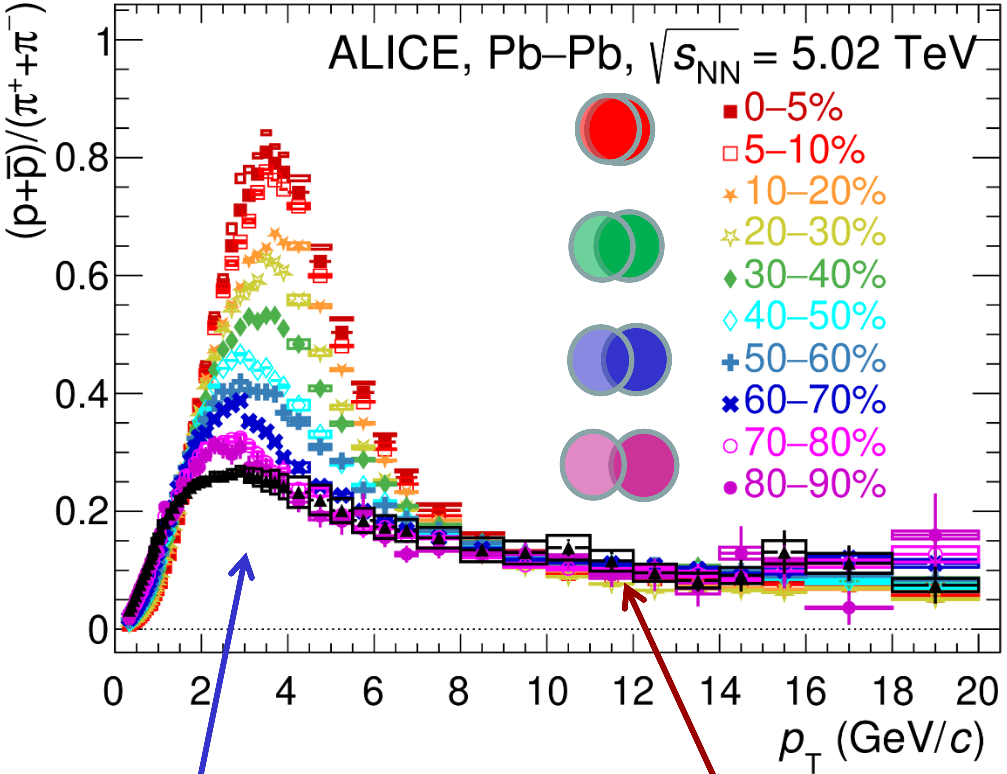
Hadronization of the QGP

- Baryon/meson ratios
  - ⇨ Expected to be enhanced at intermediate p_T by hadronization via recombination

fragmenting parton: $p_h = z \cdot p_q$ with $z<1$



recombining quarks:
$p_{meson} = p_{q1}+p_{q2}$
$p_{baryon} = p_{q1}+p_{q2}+p_{q3}$



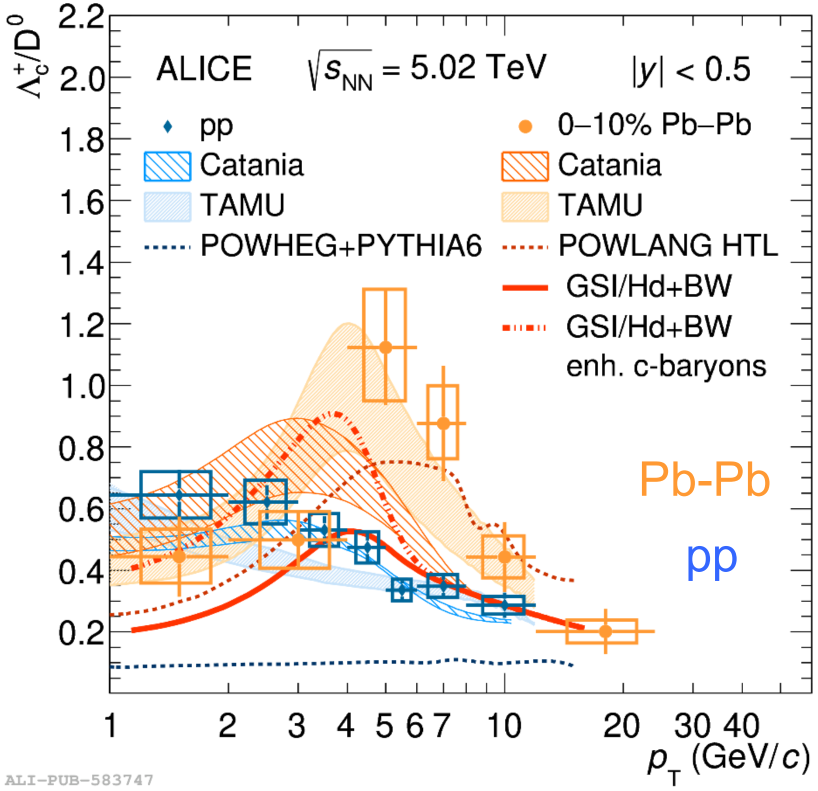
ALICE, EPJC 84 (2024) 813

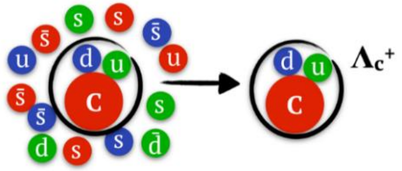
Low/mid p_T (<8 GeV/c) :
- Ratios p/π (Λ/K^0_s) enhanced in **Pb–Pb** compared to **pp**
- Interplay of **radial flow** and **recombination**

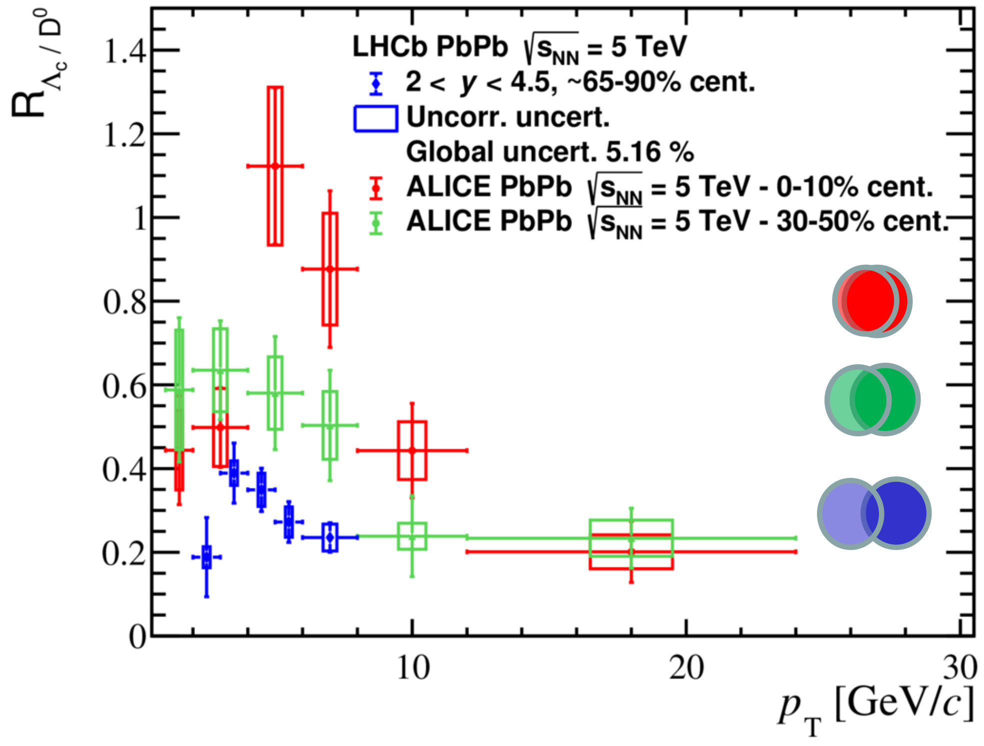
High-p_T (>10 GeV/c) :
- Ratios in Pb-Pb compatible with those in pp
- Hadronization via independent **fragmentation**

Hadronization of heavy flavours

ALICE, EPJC 84 (2024) 813





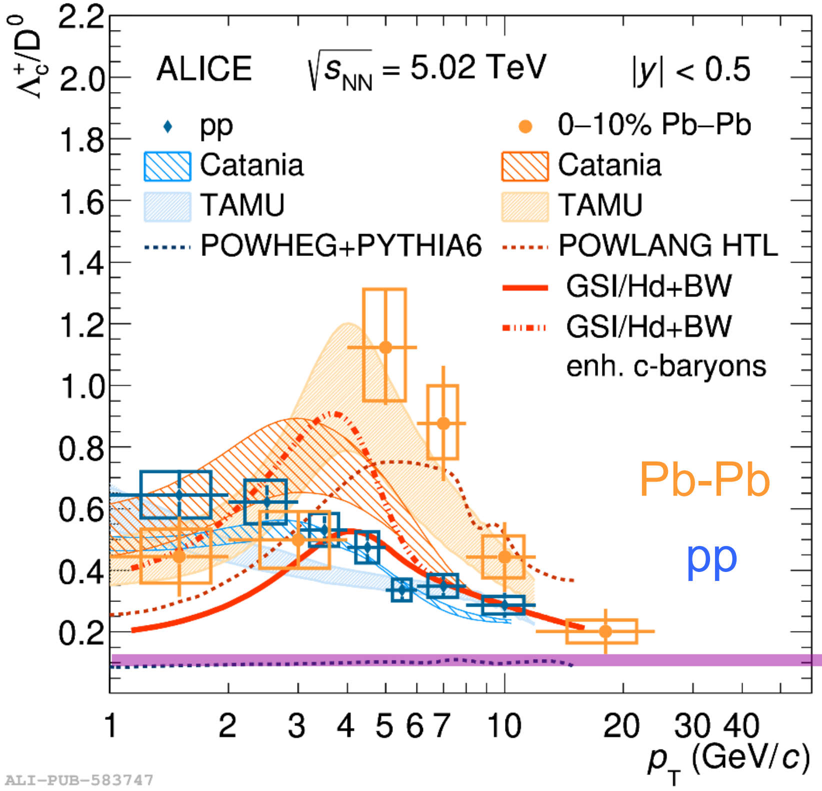


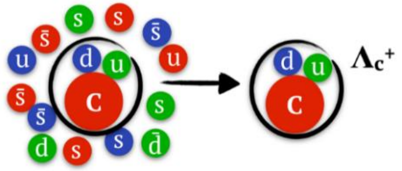
LHCb, JHEP 06 (2023) 132

- Λ_c/D^0 ratios at intermediate p_T (<10 GeV/c) enhanced in Pb-Pb compared to pp
  - ⇨ Enhancement increases from peripheral to central collisions
  - ⇨ Described by models including hadronization via recombination with light quarks from the bulk

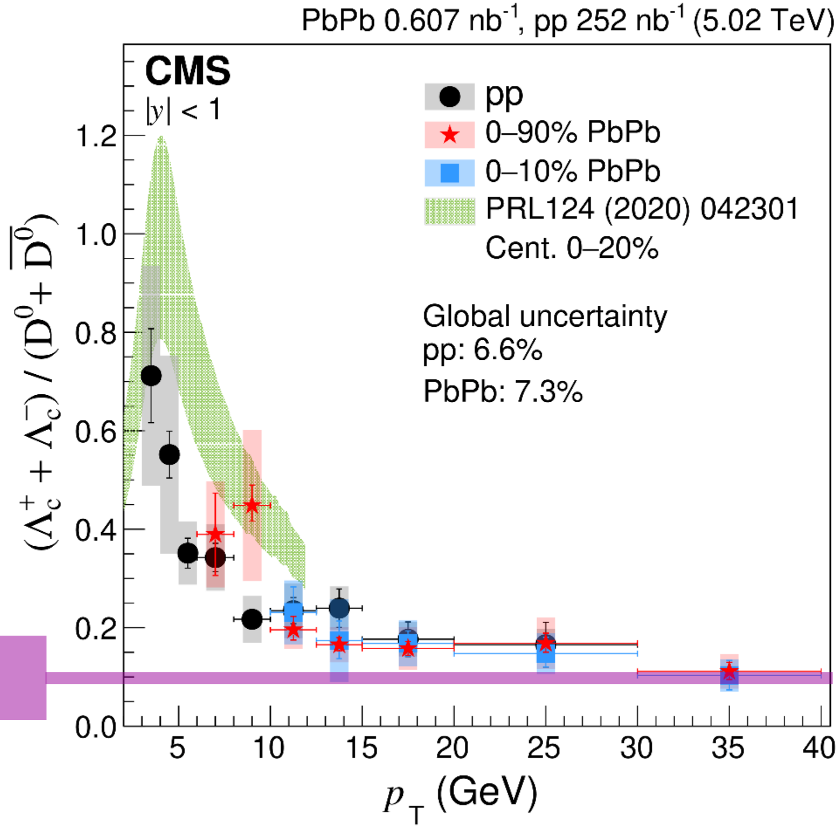
Hadronization of heavy flavours

ALICE, EPJC 84 (2024) 813





e⁺e⁻@LEP



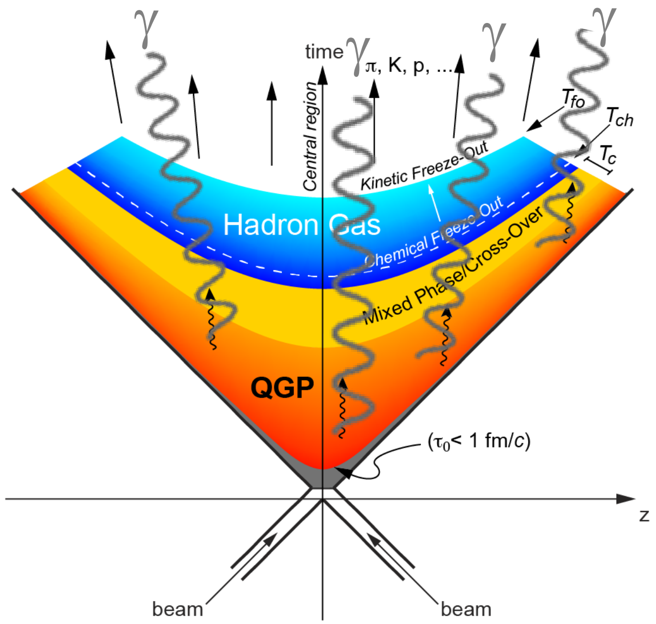
CMS, Phys.Rept. 1115 (2025) 219

- Λ_c/D^0 ratio in pp collisions at the LHC substantially higher than in e^+e^- collisions
  - ⇨ Indicates a **breakdown of the universality** of charm quark **fragmentation functions**
  - ⇨ Captured in theoretical models with different approaches:
    - ✓ ***Color reconnections beyond-leading-color in PYTHIA8***
    - ✓ ***Small QGP droplet + hadronization via recombination / statistical hadronization***

M. Karwoska
T05 Tue 18.10

J. Aichelin
T05 Wed 8.50

Electromagnetic probes

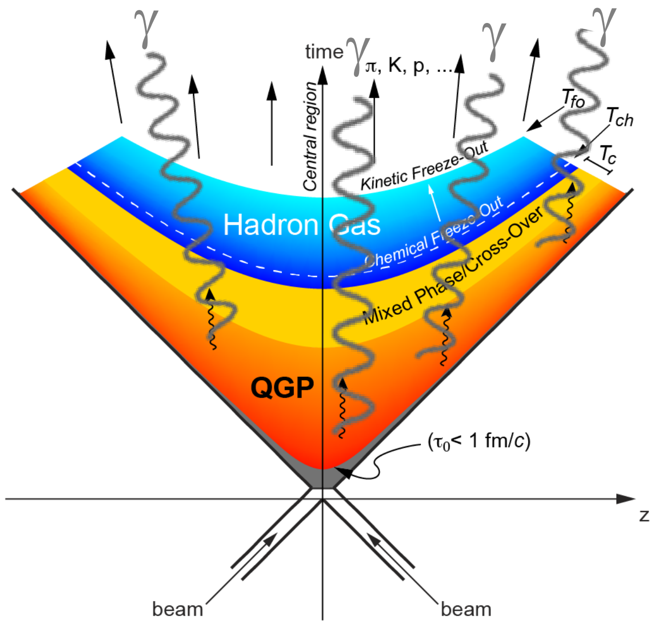


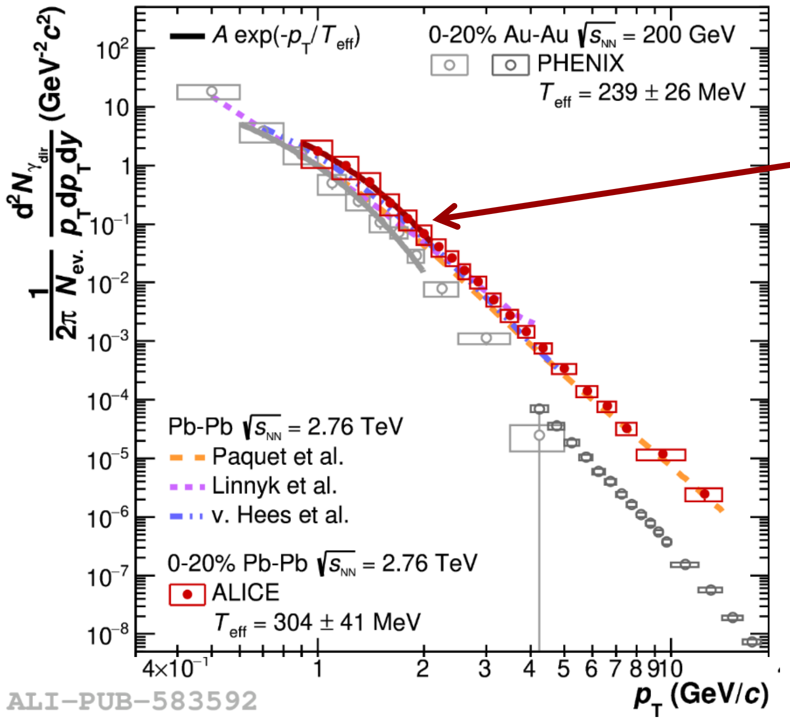
- Electromagnetic radiation emitted throughout the system evolution by a variety of sources in the form of:
  - ⇨ Real “direct” photons
    - ✓ ***Direct photons = do not originate from parton fragmentation nor hadronic decays***
  - ⇨ Virtual photons, measurable via their internal conversion into e^+e^- or $\mu^+\mu^-$ pairs
    - ✓ ***Dilepton measurements at the LHC not yet sensitive to possible thermal signals***

E. Ege
T04 Tue 9.50

- Photons and dileptons escape the fireball unaffected, delivering information on the QGP conditions

Electromagnetic probes





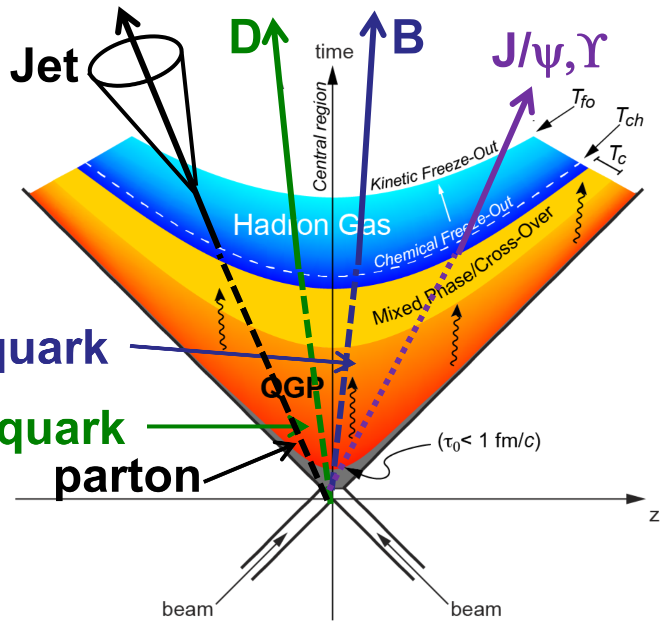
Exponential fit

$$\frac{d^2N_{\gamma\mathrm{dir}}}{p_T dp_T dy} \propto e^{-\frac{p_T}{T_{\mathrm{eff}}}}$$

ALICE, EPJC 84 (2024) 813

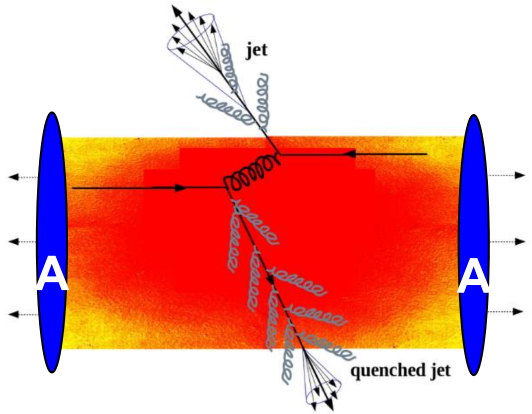
- Estimate an effective temperature of the fireball T_{eff} via exponential fit to **direct photon** p_T spectrum at low p_T
  - ⇨ Low-p_T region (<3 GeV/*c*) dominated by **thermal photons** emitted by the QGP during its evolution
  - ⇨ T_{eff} ~ 304 MeV in central collisions at the LHC → larger than the (pseudo)critical temperature
- Relating T_{eff} to the initial temperature of the fireball is challenging
  - ⇨ Requires models that incorporate the QGP evolution and account for the radial expansion of the medium, which causes a blue-shift of the emitted photons

Hard probes of the QGP medium

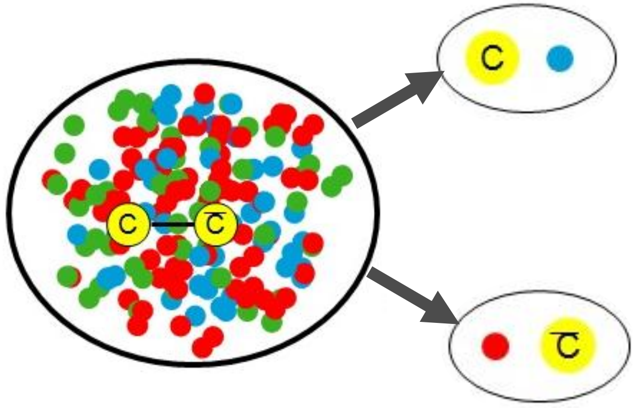


- Produced at the **very early stages** of the collision in partonic scattering processes with large momentum transfer
  - ⇨ Produced out-of-equilibrium
- Traverse the hot and dense medium interacting with its constituents
  - ⇨ **Unique probes** of the properties of the QGP

Jet quenching:
the hard-scattered parton loses energy while crossing the QGP + modification of parton shower and jet properties



Quarkonium dissociation in the QGP

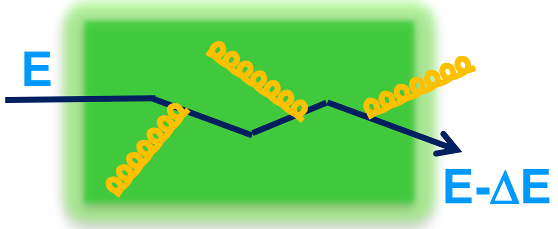


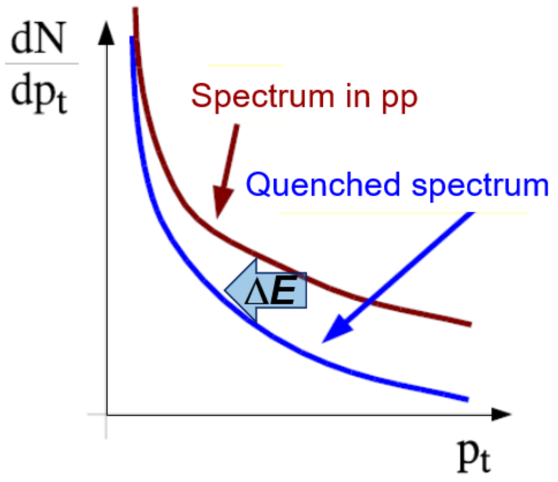
Nuclear modification factor

- Hard processes in nuclear collisions
  - ⇨ Production scales with the number of nucleon-nucleon collisions, N_{coll}
- Nuclear modification factor

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

  - ⇨ If **no nuclear effects** are present: $\boldsymbol{R_{AA} = 1}$
- Interactions in the QGP cause **energy loss** leading to suppression of yield (R_{AA}<1) at high p_T





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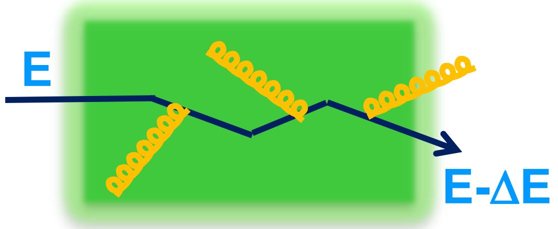
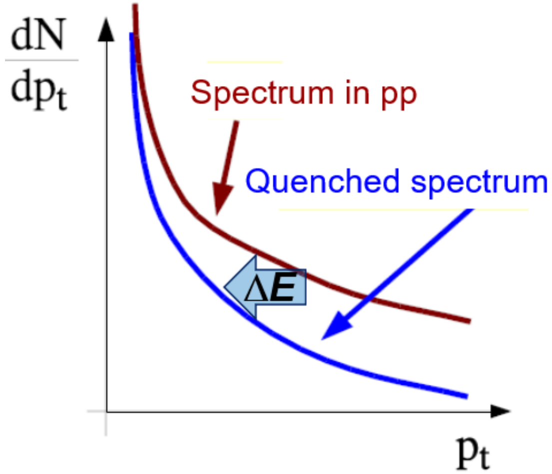
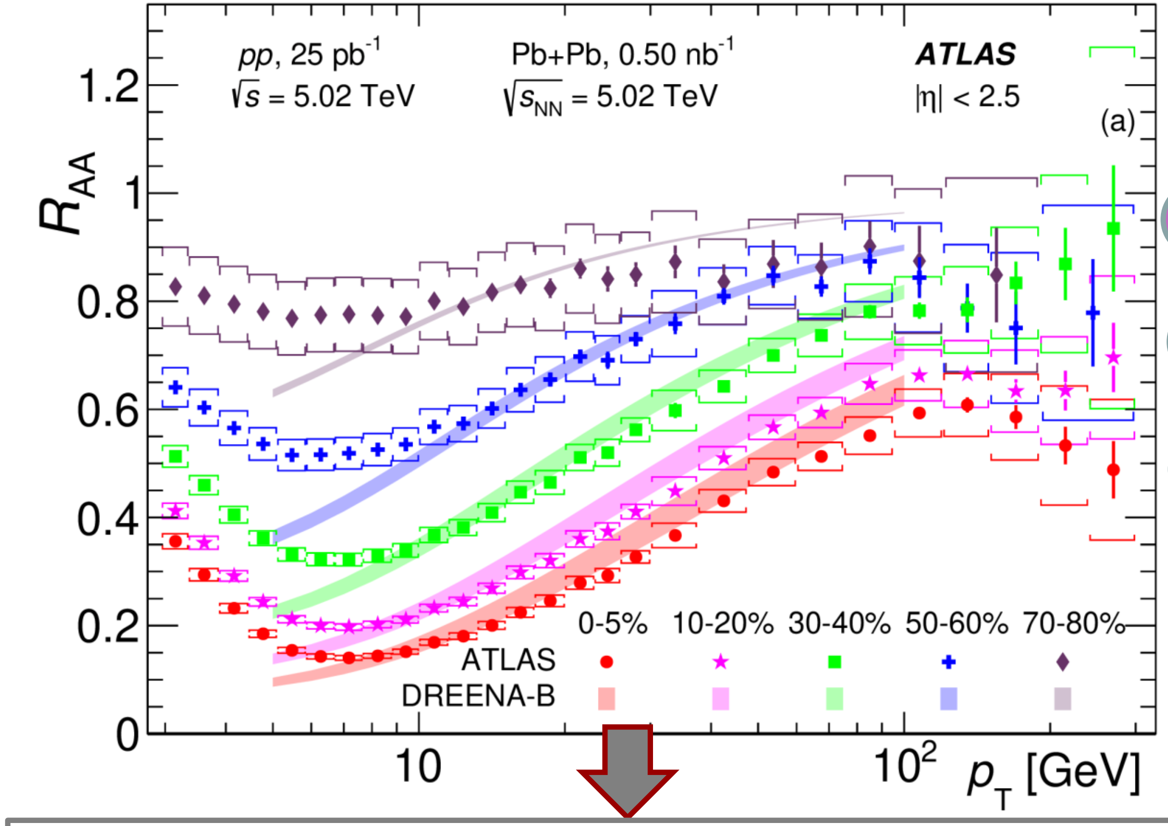
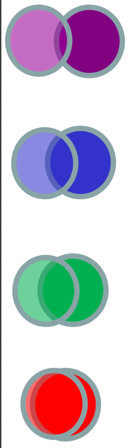




📖 ATLAS, JHEP 07 (2023) 074

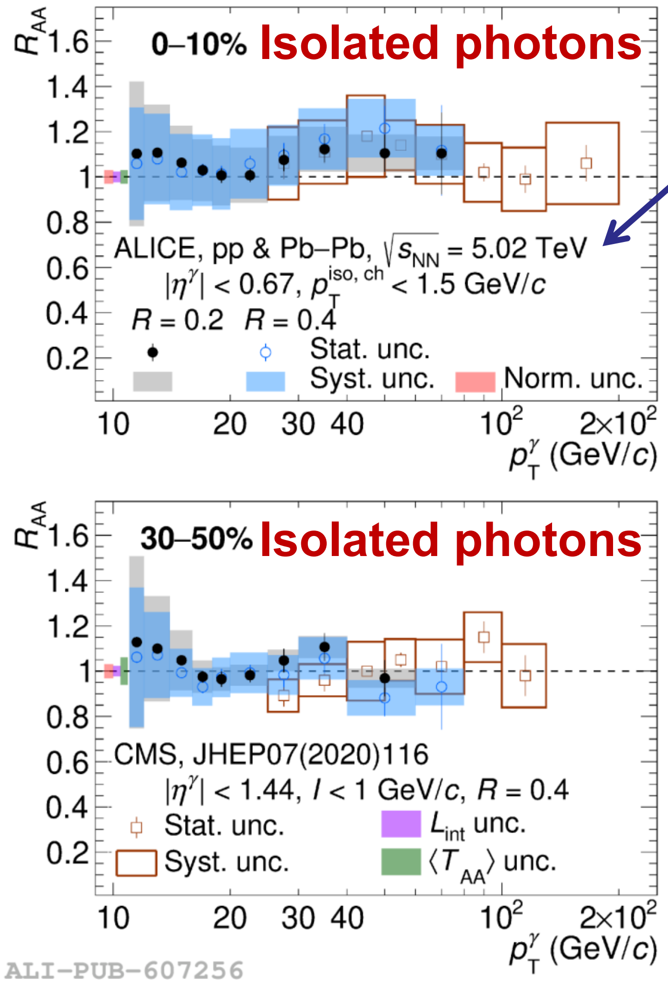




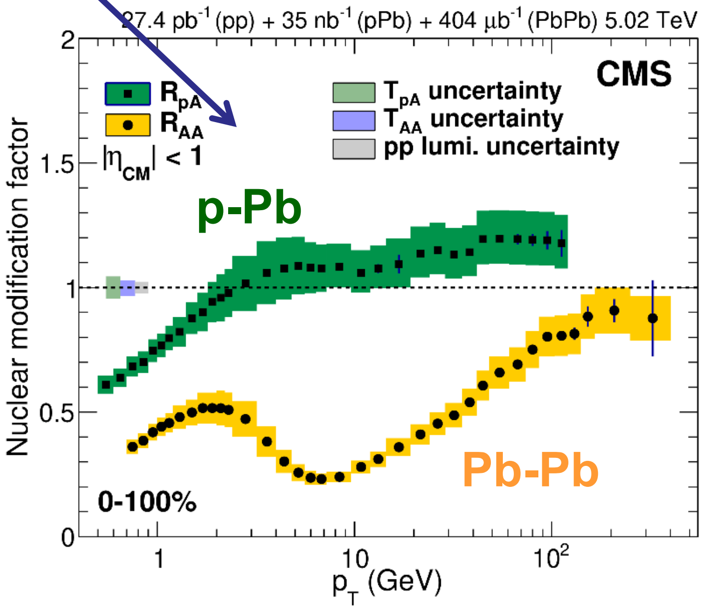
- Measured charged-hadron R_{AA}:
  - ⇨ Strong suppression, minimum R_{AA} at p_T ~ 7 GeV/c
  - ⇨ Larger suppression in central collisions
  - ⇨ Described by models with energy loss in the QGP

Control experiments

ALICE, EPJC 85 (2025) 553



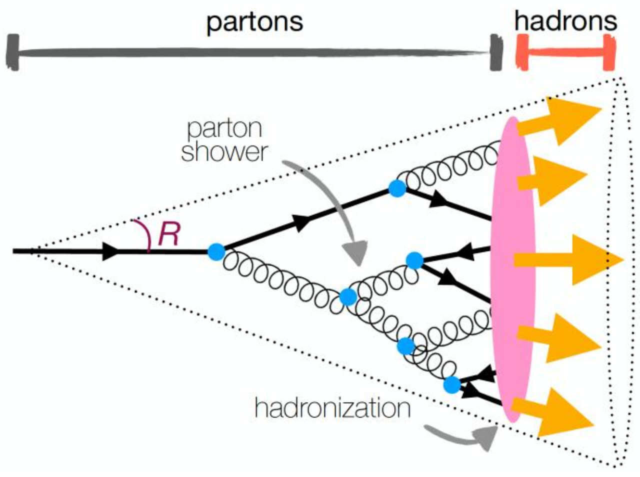
- Medium-blind probes (γ, Z^0, W)
  - ⇨ Production of particles w/o color charge not modified by the QGP
  - ⇨ Test binary scaling
  - ⇨ R_{AA} of **isolated (prompt) photons** compatible with 1
- Charged hadrons in p-Pb minimum-bias collisions
  - ⇨ Large-size QGP phase not expected
  - ⇨ Test cold-nuclear matter effects
  - ⇨ R_{pPb}~1 for p_T > 3 GeV/c

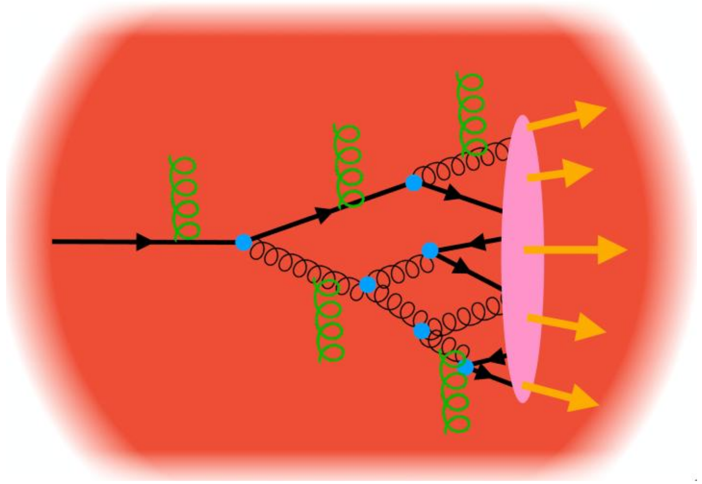


CMS, Phys.Rept. 1115 (2025) 219

→ suppression of high-p_T hadrons is due to energy loss of colored partons in the QGP

Probing the QGP with jets



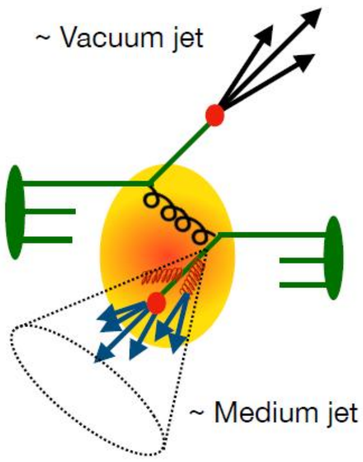


- Jets: “in-vacuum” fragmentation
  - ⇨ Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of energetic partons

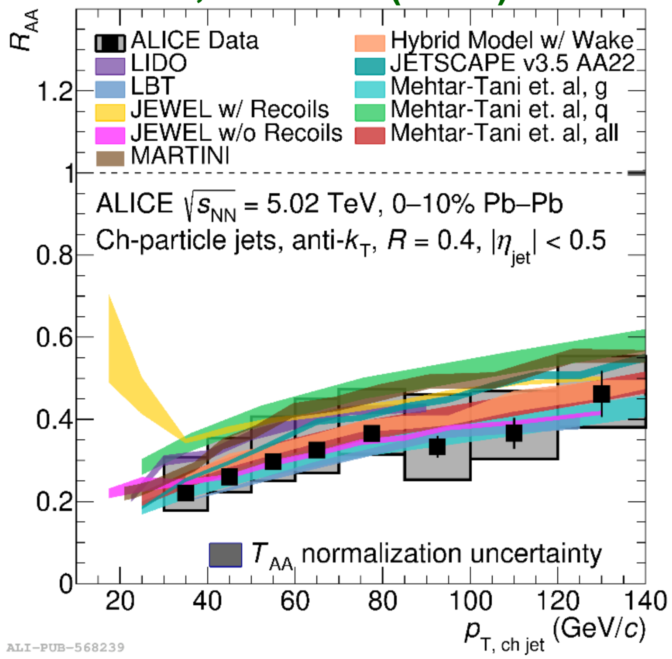
- Jets in A-A collisions
  - ⇨ Parton showers propagate through the QGP: interactions with medium constituents
  - ⇨ **Jet quenching** → QGP alters the energy and structure of jets passing through it
  - ⇨ **Medium response** → motions induced by the jet energy deposited in the QGP

→ probe the QGP at short-distance scales

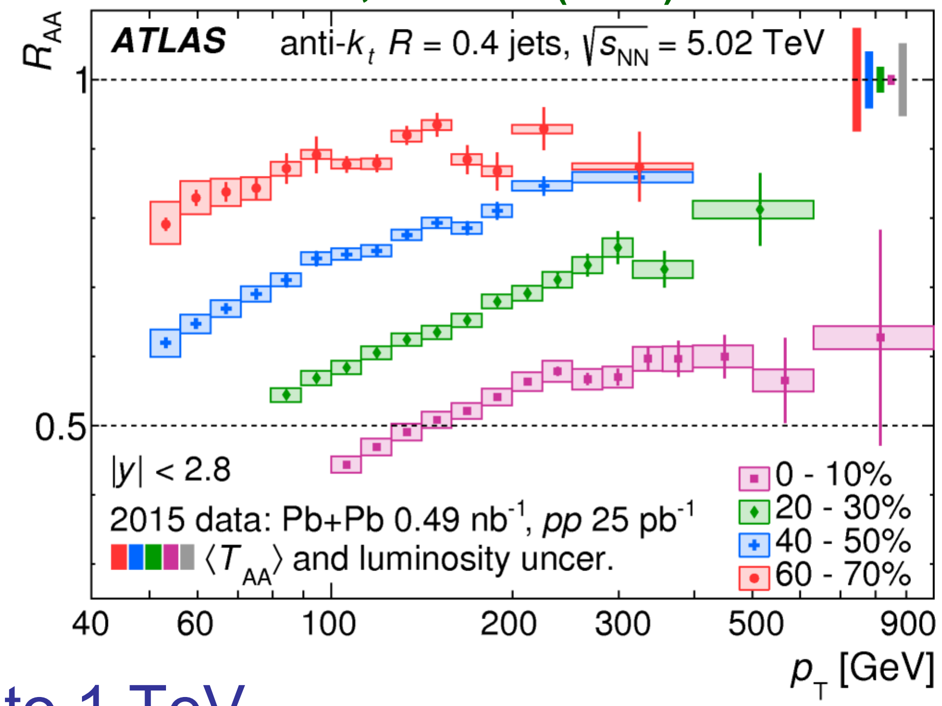
Jet R_{AA}



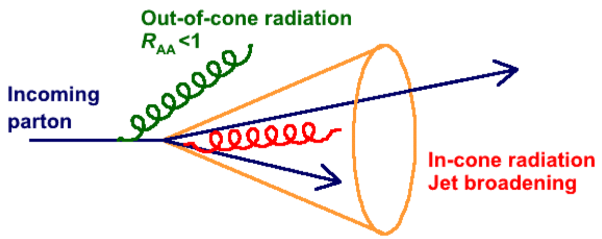
📖 ALICE, PLB849 (2024) 138412



📖 ATLAS, PLB790 (2019) 108



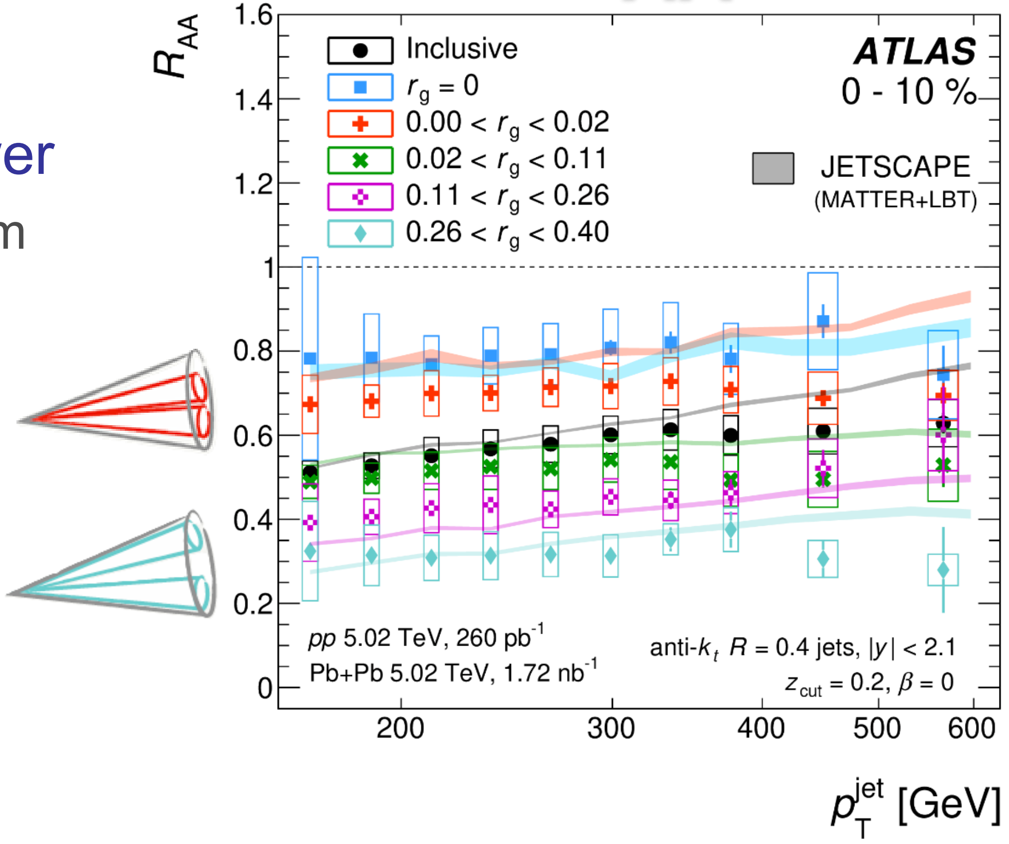
- Jet yield at the LHC suppressed from 30 GeV to 1 TeV
  - ⇨ Hard-scattered quarks and gluons evolve as parton showers that propagate through the hot and dense medium
  - ⇨ Part of energy of parton shower transferred outside the jet cone through interactions with QGP (→ soft radiation at large angles)



- Suppression decreases from central to peripheral collisions

Substructure dependent jet R_{AA}

- R_{AA} vs. angular separation (r_g) of the sub-jets defined by the hardest splitting in the parton shower
  - ⇨ Hard splitting tagged with soft-drop grooming algorithm
  - ⇨ Jets with r_g**=0** failed the soft-drop requirement and considered as single-prong jets
- Jet quenching depends on structure of parton shower
  - ⇨ **Wide jets** are more suppressed than **narrow jets**

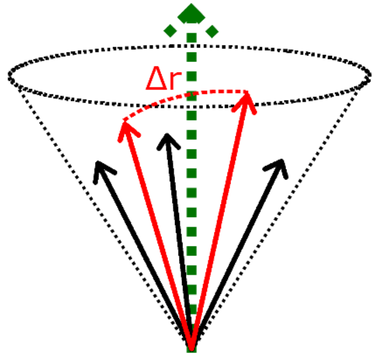


ATLAS, PRC107 (2023) 054909

- r_g-dependent suppression explained in models as arising from coherence effects → wider jets are "more resolved" by the medium
  - ⇨ Large r_g : jet constituents resolved by the medium → radiation as multiple color charges
  - ⇨ Small r_g : jet constituents unresolved → sub-jets radiate coherently as a single-color charge

Energy-energy correlators

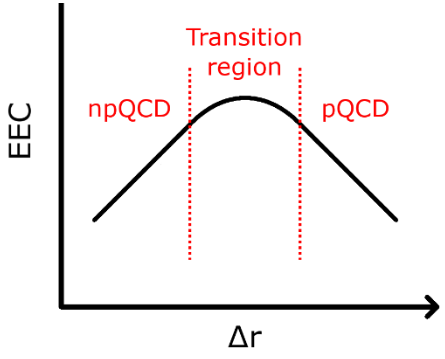
- EEC = weighted distribution of angular separation Δr of all possible particle pairs within a jet cone

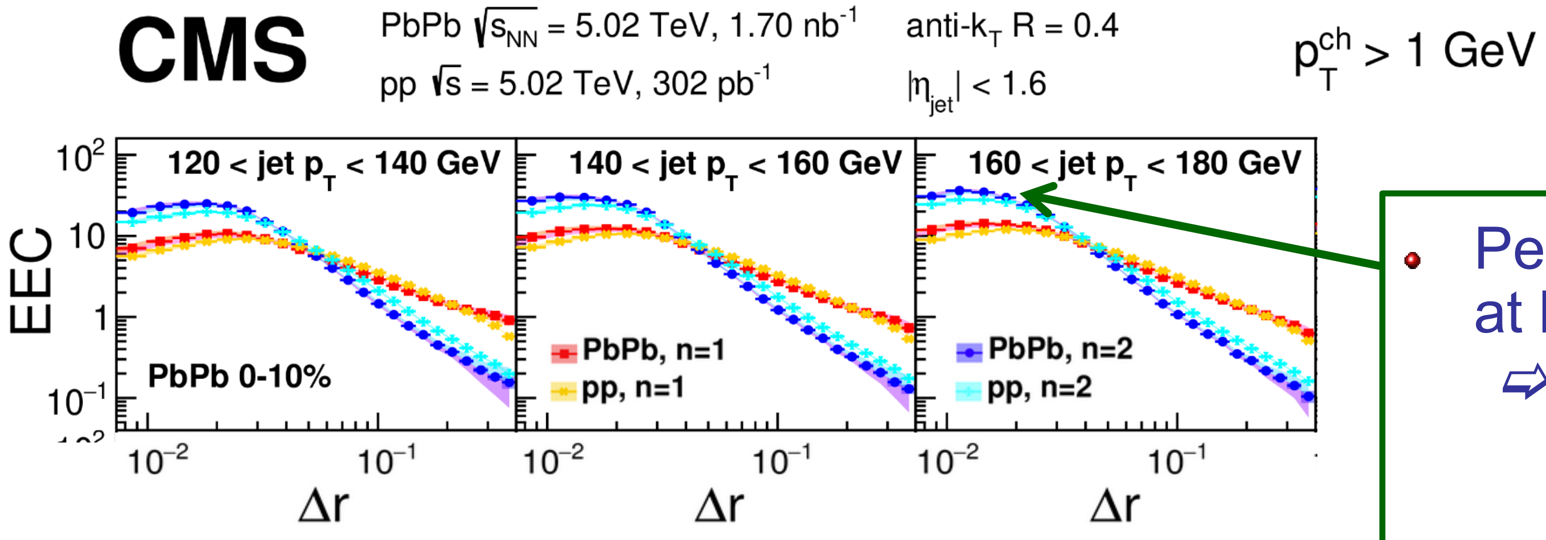


$$\mathrm{EEC}(\Delta r) = \frac{1}{W_{\mathrm{pairs}}} \frac{1}{\delta r} \sum_{\mathrm{jets} \in [p_{\mathrm{T},1}, p_{\mathrm{T},2}]} \sum_{\mathrm{pairs} \in [\Delta r_a, \Delta r_b]} \left(p_{\mathrm{T},i}\, p_{\mathrm{T},j} \right)^n$$

⇨ time scales in jet evolution imprinted in different angular scales of the EEC

✓ ***Early times correspond to large angles; late times to small angles***





- Peak in the transition region shifted at lower Δr in Pb-Pb w.r.t. pp

  ⇨ Sign of jet quenching

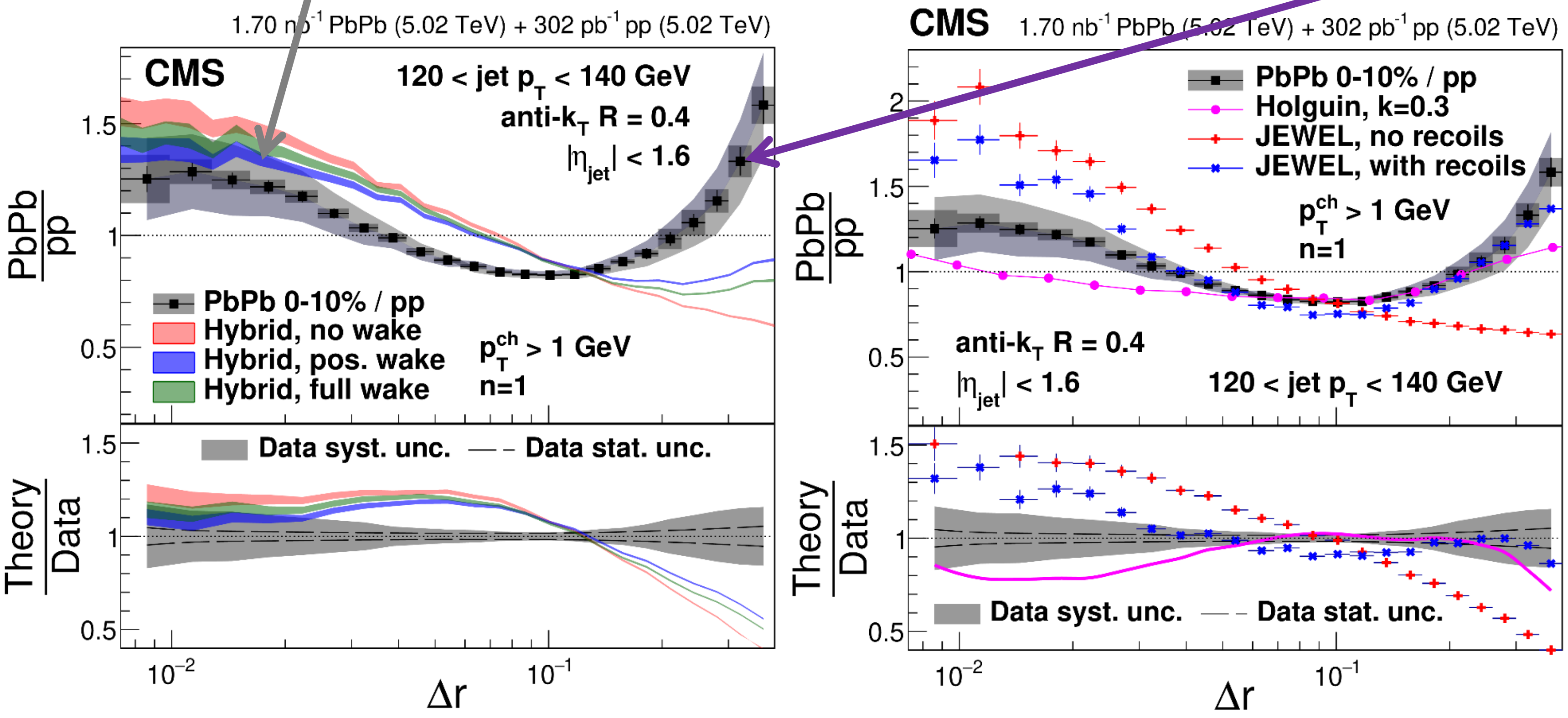
  ✓ ***Jets in given p_T interval in Pb-Pb started with higher initial energy/virtuality***

  ✓ ***Longer shower duration to reach hadronization***

📖 **CMS, arXiv:2503.19993**

EEC ratios: Pb-Pb/pp

- Enhancement at small Δr
  - ⇨ Due to shift in the peak position as consequence of jet quenching

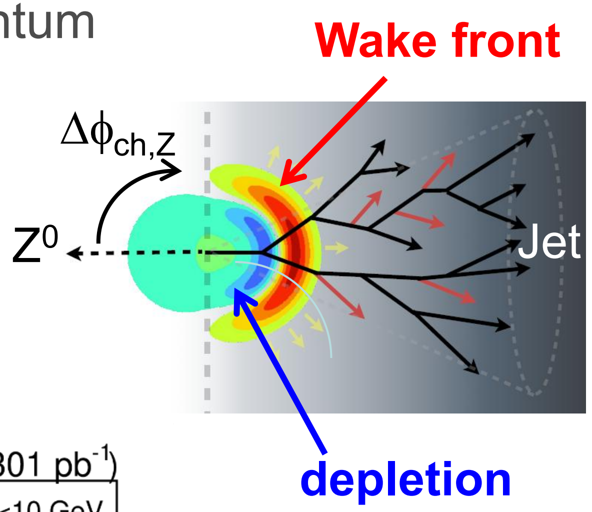


📖 CMS, arXiv:2503.19993

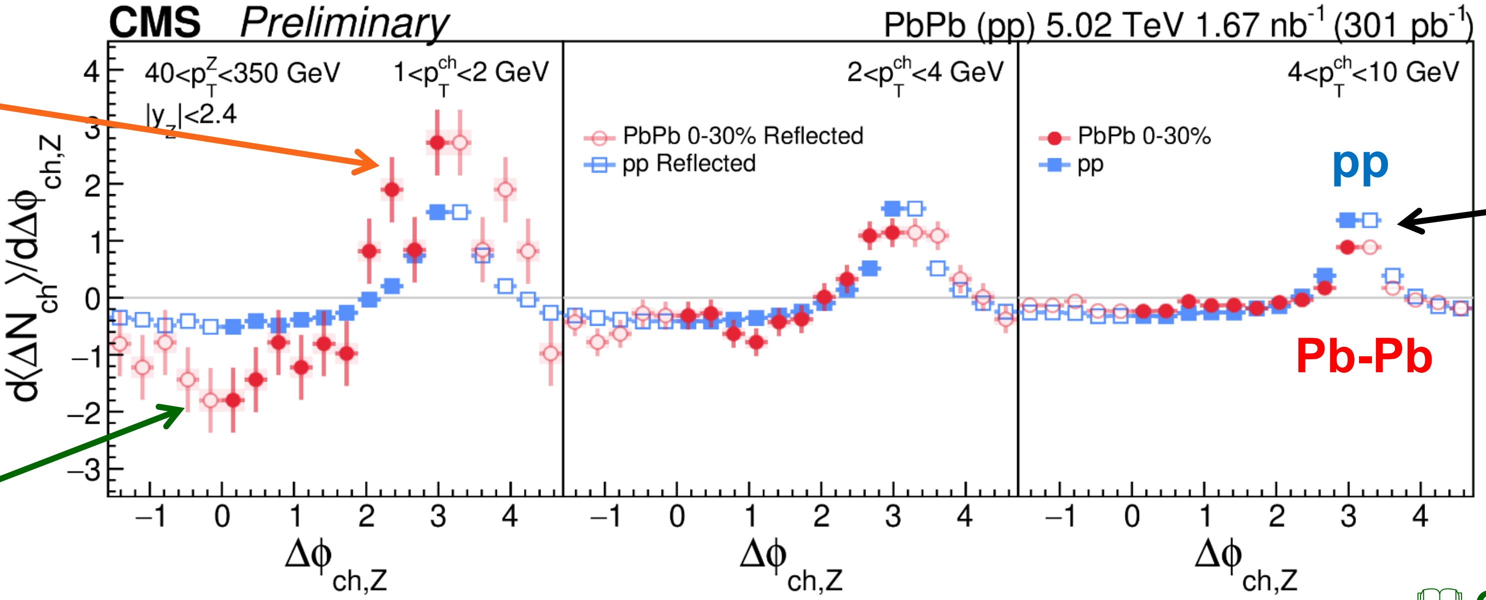
- Enhancement at large Δr
  - ⇨ Sensitive to medium-induced modifications
  - ⇨ Mainly due to soft particles at the periphery of jet cone
- Qualitatively captured by models including
  - ⇨ Medium response to jets
    - ✓ ***Jet wake / recoils***
  - ⇨ Color coherence effects
    - ✓ ***Only gluons emitted above a critical angle can independently emit more gluons***

Medium response via Z^0+jet events

- Z^0 bosons and jets from the same hard scattering
  - ⇨ Z^0 do not interact strongly in QGP → access to hard-scattered parton momentum
- Explore medium response by measuring yield of Z^0-tagged charged hadrons vs. azimuthal angle relative to Z^0 ($\Delta\phi_{ch,Z}$)
  - ⇨ **Modified** in central **Pb-Pb** as compared to **pp** collisions
  - ⇨ Data better described by models that include medium recoil effects
  - ⇨ First evidence of medium response effects caused by a hard probe



Low p_T: excess at $\Delta\phi_{ch,Z}=\pi$ (jet side) due to medium-induced radiation + momentum broadening



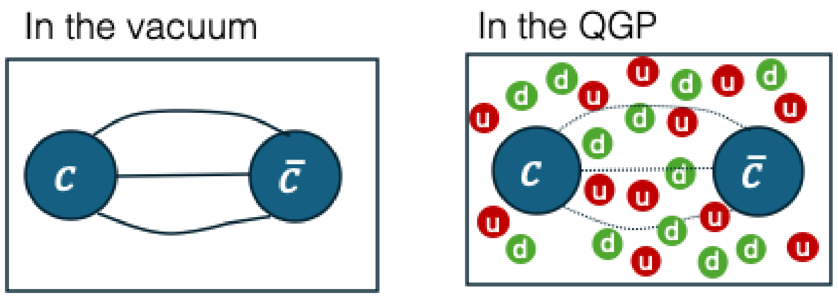
Low p_T: dip at $\Delta\phi_{ch,Z}=0$ (Z^0 side) → indicate negative medium wake or medium holes

Reduction of jet peak at high p_T due to jet quenching

📖 CMS, PAS HIN-23-006

Quarkonium: in-medium dissociation

- Dissociation of quarkonia in the QGP
  - ⇨ High density of free color charges in the QGP leads to a screening of the QCD force that binds the quarkonium states
  - ⇨ Quarkonium production **suppressed** in A-A collisions



📖 **Matsui, Satz, PLB178 (1986) 416**

- Sequential pattern expected from the rich spectroscopic structure of quarkonia
  - ⇨ Different quarkonium states dissociate in the QGP at different temperatures, depending on their binding energy
    - ✓ ***The more strongly bound the state is, the hotter must be the medium to dissociate it***
  - ⇨ **Sequential suppression** as a **QGP thermometer**

	J/ψ	χ_c	$\psi(2S)$
Mass (GeV)	3.10	3.53	3.68
E_B (GeV)	0.64	0.20	0.05

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass (GeV)	9.46	10.02	10.36
E_B (GeV)	1.10	0.54	0.20

Quarkonium: in-medium dissociation

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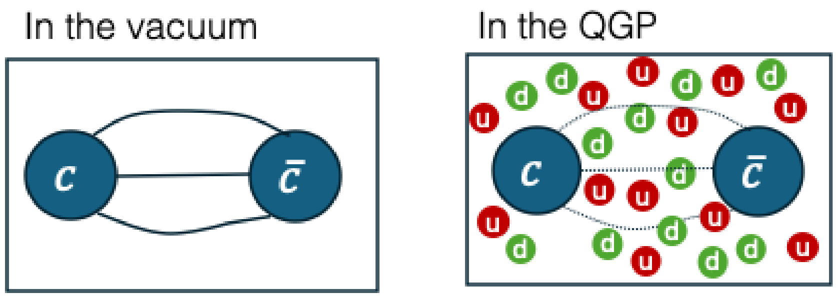
    - ✓ ***The more strongly bound the state is, the hotter must be the medium to dissociate it***
  - ⇨ **Sequential suppression** as a **QGP thermometer**
- Several effects lead to a more complex situation:
  - ⇨ **Cold nuclear matter (CNM) effects** affecting quarkonia
    - ✓ ***Nuclear PDFs, coherent energy loss in CNM***
  - ⇨ Break-up by comoving hadrons in the hadronic phase
  - ⇨ **Feed-down** from higher quarkonium states
  - ⇨ Production via **recombination** of uncorrelated quark pairs originated from different hard scattering processes



📖 **Matsui, Satz, PLB178 (1986) 416**

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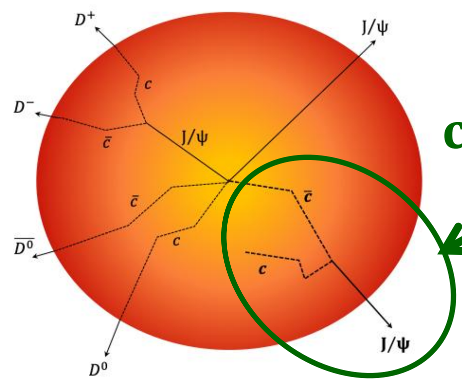
Low-p_T charmonium: recombination

- If QGP is formed, charmonium production can occur also via $c\bar{c}$ **recombination** during the QGP expansion or at the phase boundary
  - ⇨ Charmonia from recombination mainly produced with **low momentum**
  - ⇨ Recombination expected to be **negligible for bottomonium** (b quarks are rare)

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

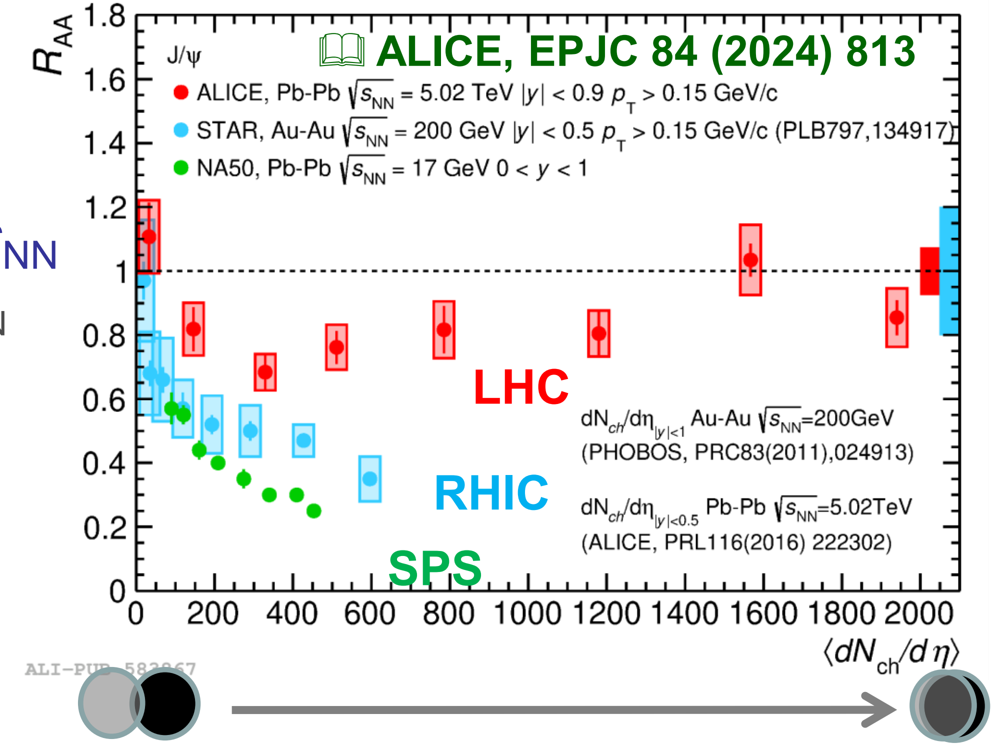
- Tested by measuring J/ψ yield in A-A collisions vs. $\sqrt{s_{NN}}$
  - ⇨ Charm quark production cross section increases with $\sqrt{s_{NN}}$
  - ⇨ Probability of $c\bar{c}$ recombination increases with $\sqrt{s_{NN}}$
- J/ψ yield enhanced in A-A collisions at higher $\sqrt{s_{NN}}$
  - ⇨ Strong **evidence of J/ψ formation via $c\bar{c}$ recombination**

→ implies the presence of a deconfined phase



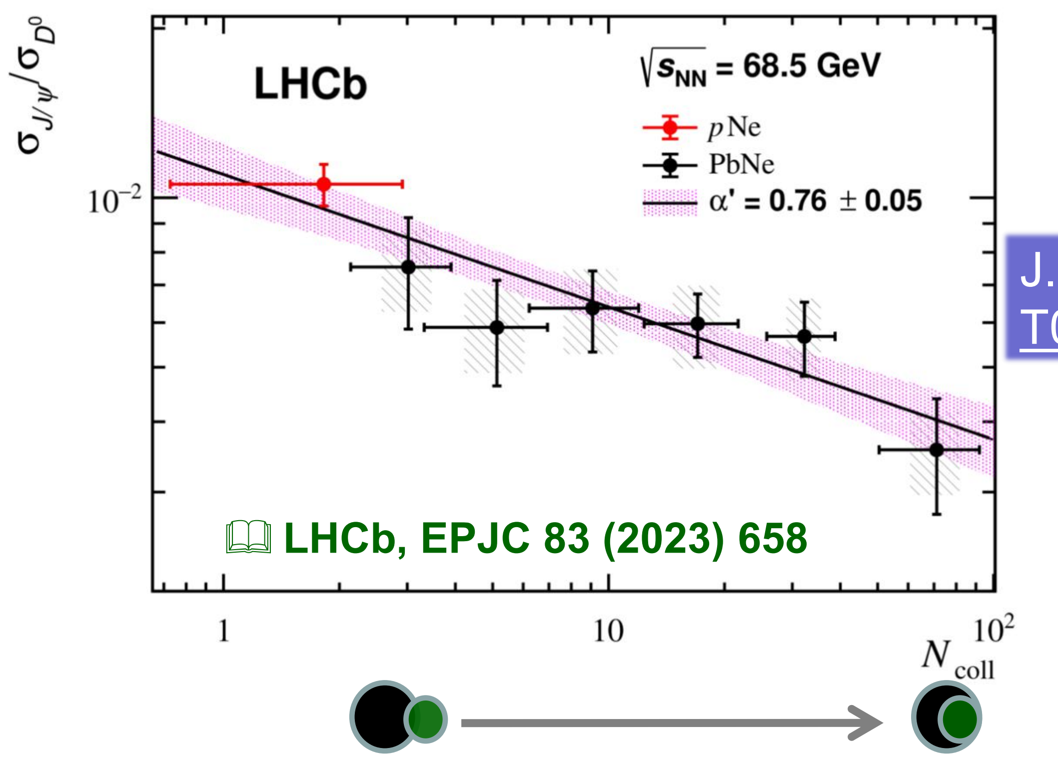
$c\bar{c}$ recombination

L. Micheletti
T04 Wed 16.40

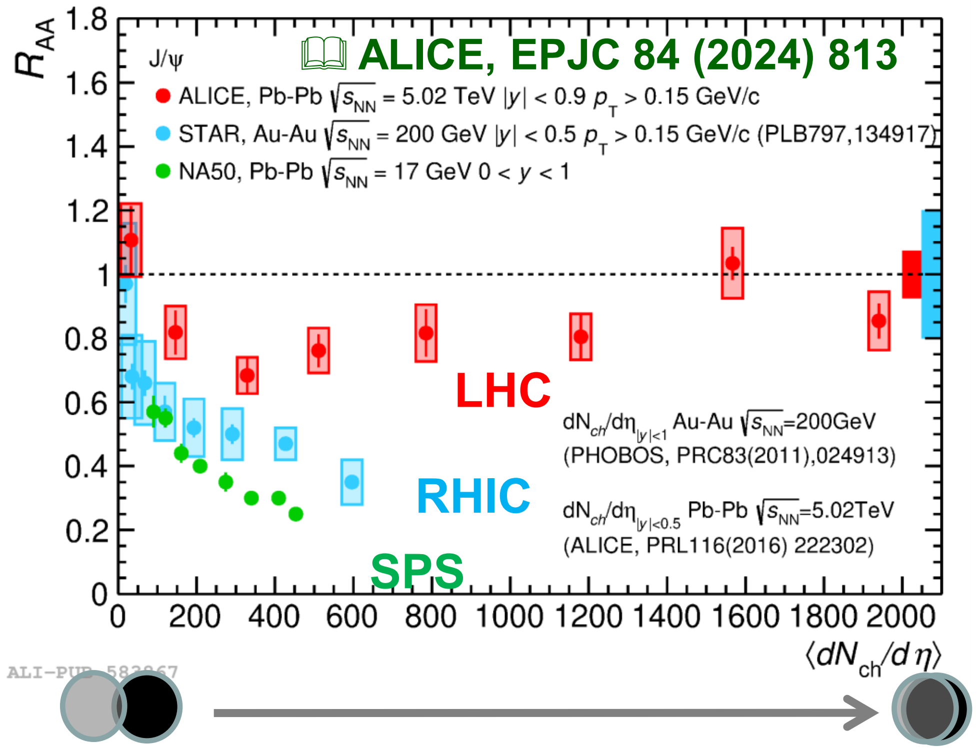


Enriching the J/ψ picture with SMOG@LHCb

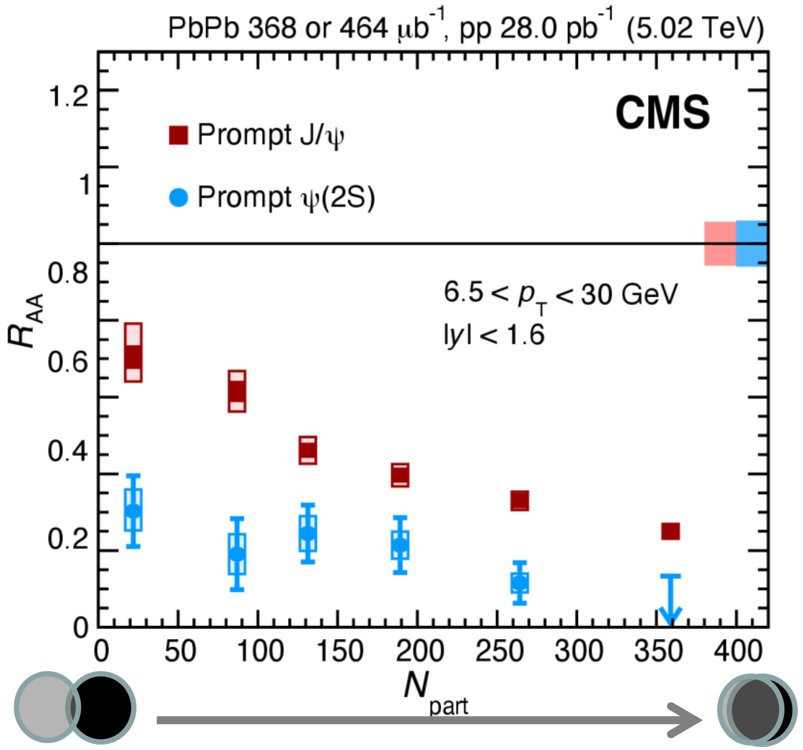
- J/ψ / D^0 ratio in p-Ne and Pb-Ne using fixed-target configuration (SMOG) of LHCb
  - ⇨ $\sqrt{s_{NN}}$ = 68.5 GeV, in between SPS and RHIC
  - ⇨ J/ψ yield suppressed relative to D^0 → J/ψ affected by additional nuclear effects compared to D^0
  - ⇨ Continuous trend from p-Ne to central Pb-Ne collisions within current uncertainties

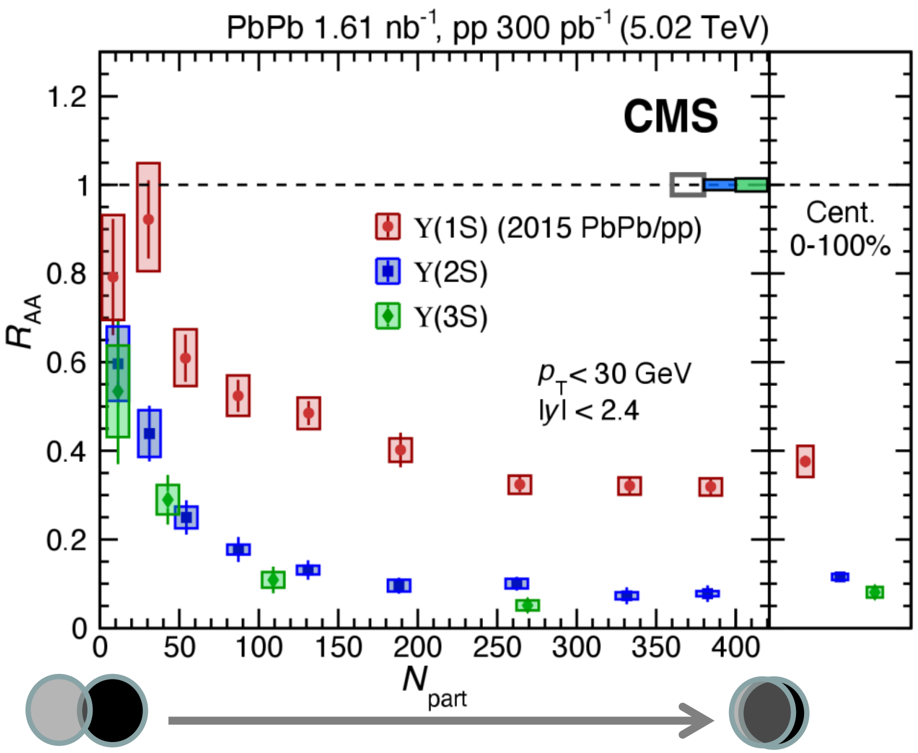


J. Auhtier
T04 Wed 16.00



Bottomonium and high-p_T charmonium





📖 **CMS, Phys.Rept. 1115 (2025) 219**

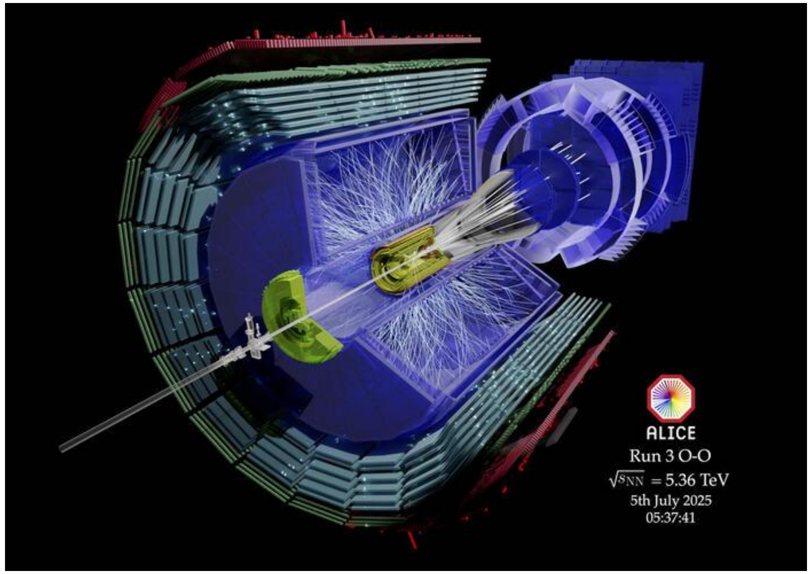
- High-p_T charmonia: $R_{AA}^{\psi(2S)} < R_{AA}^{J/\psi}$. Bottomonia: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
  - ⇨ The more fragile states are the most suppressed
- Strong **indication of sequential suppression effects**, ordered by binding energy
  - ⇨ For a conclusive interpretation of quarkonia as a QGP thermometer, one needs to account for the feed-down from decays of excited S- and P-wave quarkonium states

LHC: what's next?

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037

Run 3 | LS3 | Run 4 | LS4 | Run 5

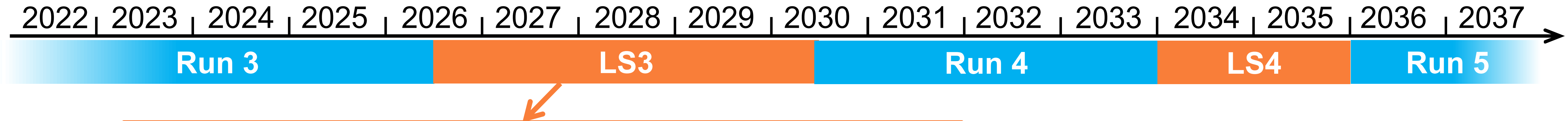
July 2025
O-O, Ne-Ne, p-O data taking



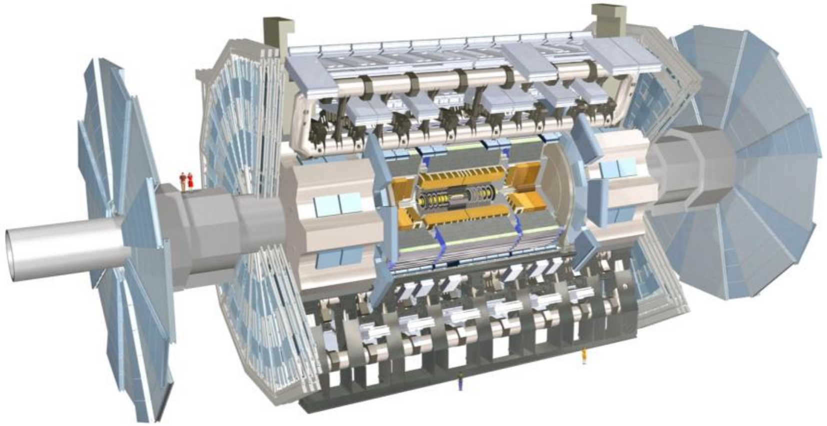
Chasing the small size-limit of QGP

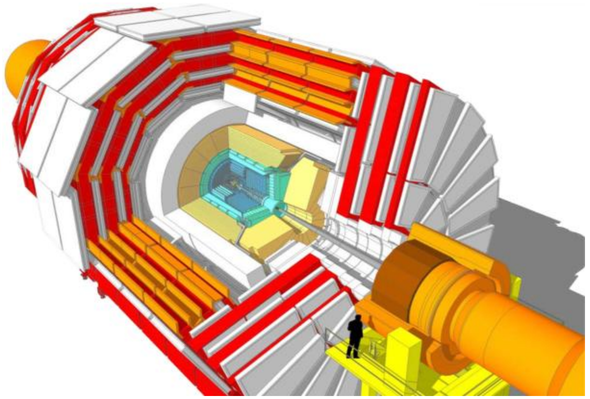
- Collective-like effects present in high multiplicity pp and p-Pb collisions
- But: No jet quenching observed in p-Pb (d-Au) at high multiplicity
- Open questions
  - ⇨ How plasma-like properties emerge in QCD?
  - ⇨ What is the smallest droplet of QGP?

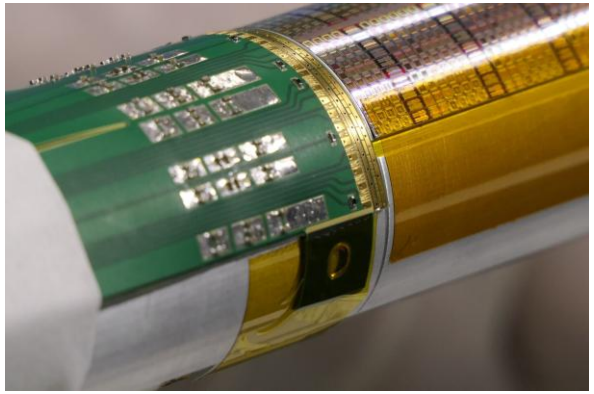
LHC: what's next?



- ATLAS and CMS Phase II upgrades
  - New trackers: tracking in heavy-ion collisions up to $\eta = 4$
  - PID / timing layers
  - New ZDCs
- ALICE
  - FOCAL (forward calorimeter)
  - ITS3 (truly cylindrical inner tracking layers)





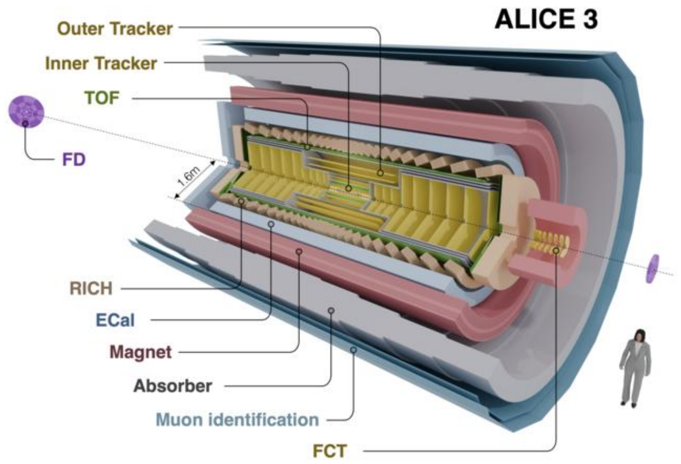


LHC: what's next?

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037

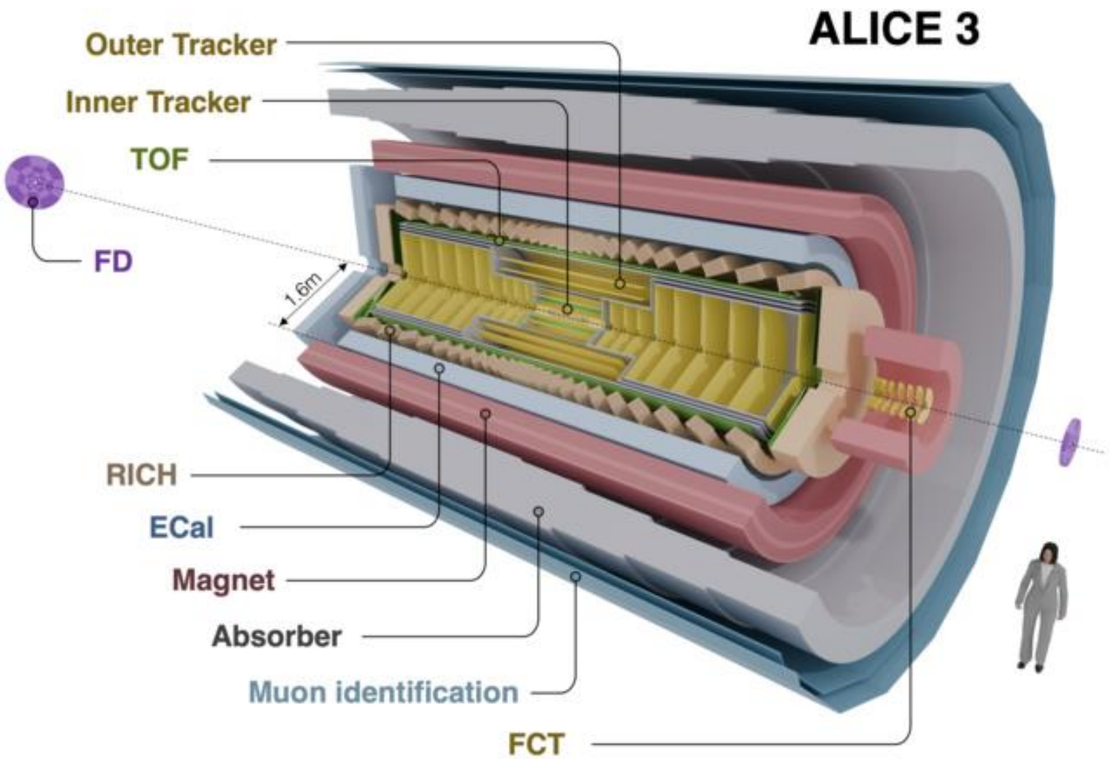
Run 3 | LS3 | Run 4 | LS4 | Run 5

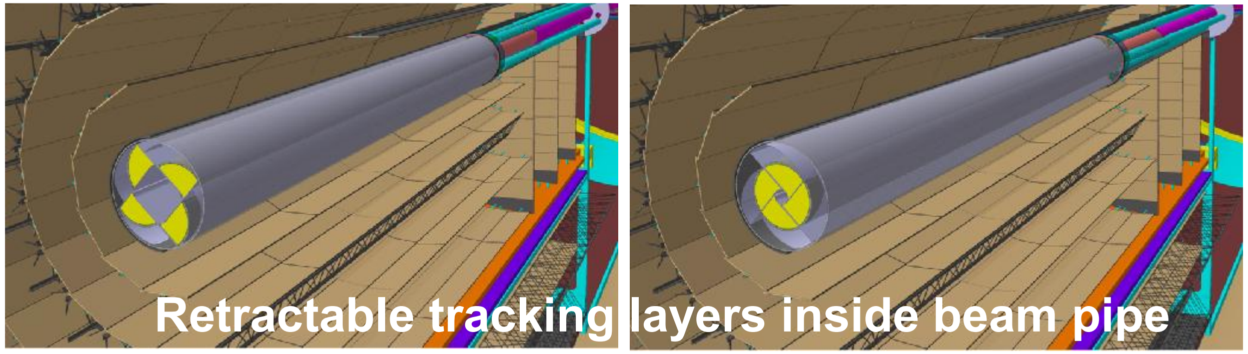
- ALICE3
  - ⇨ Brand new detector
  - ⇨ Excellent pointing resolution
  - ⇨ Large η coverage
- LHCb upgrade II
  - ⇨ Full centrality range in Pb-Pb



ALICE 3

- Innovative detector concept
  - ⇨ Compact and lightweight all-pixel silicon tracker
  - ⇨ Retractable vertex detector
  - ⇨ Extensive particle identification TOF, RICH, MID
  - ⇨ Large acceptance $|\eta|<4$
  - ⇨ Superconducting solenoid magnet B = 2 T
  - ⇨ Continuous readout and online processing

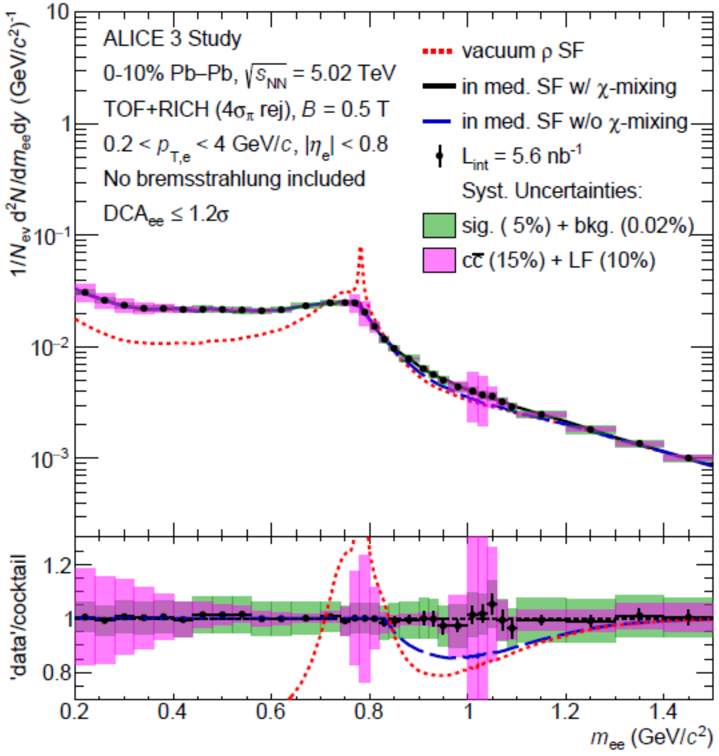



Retractable tracking layers inside beam pipe

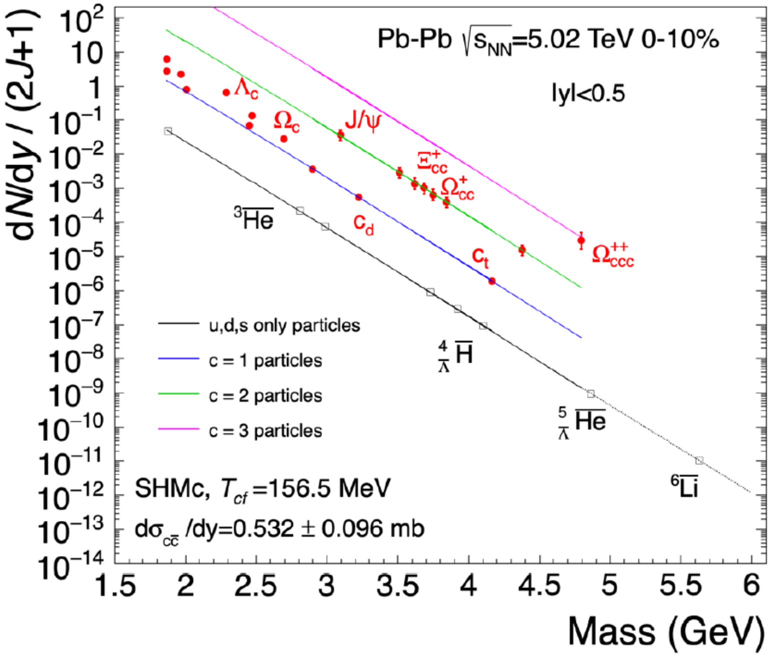
A. Maire
T11 Mon 15.42

ALICE 3: new physics opportunities

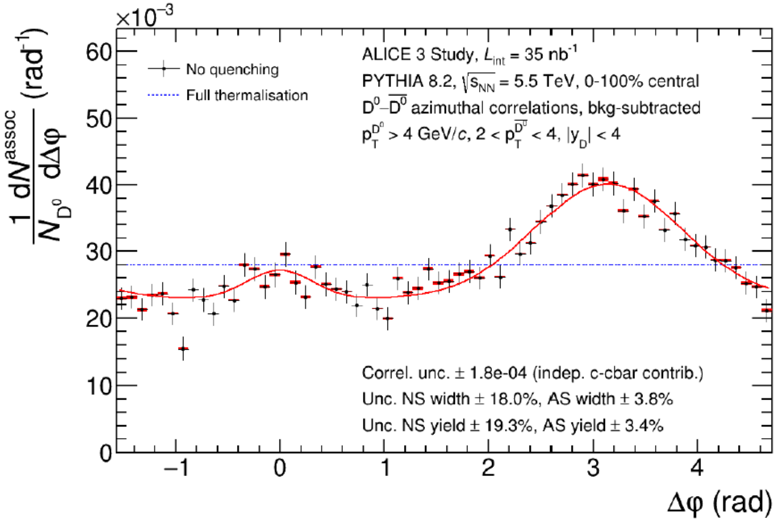
- Low-mass dileptons
  - ⇨ Access ρ/a_1 mixing to study chiral symmetry restoration
  - ⇨ Sensitive to QGP temperature



- Multi-charmed baryons
  - ⇨ Ultimate probe of charm deconfinement and thermalization



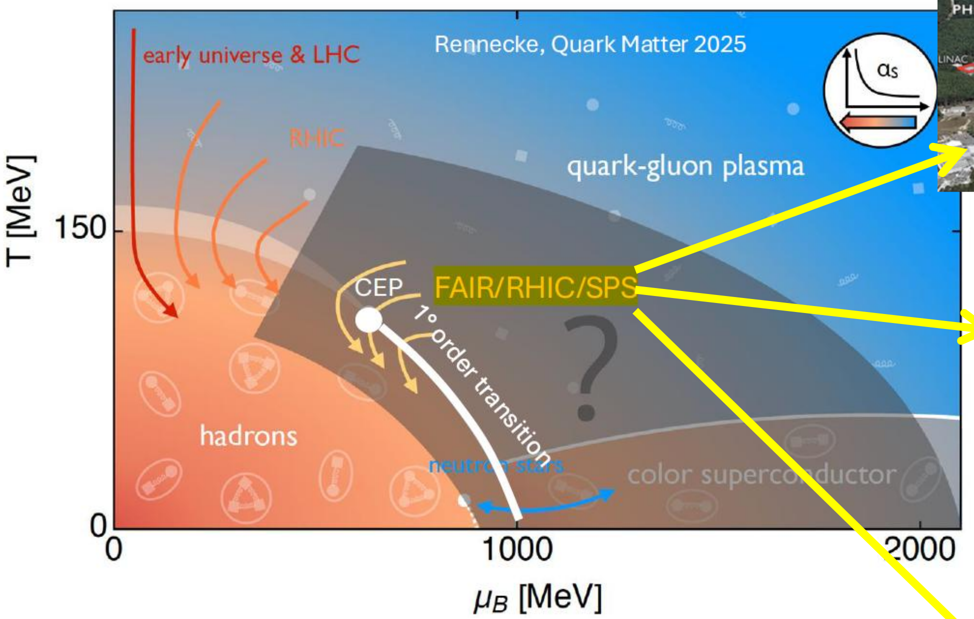
- $D - \bar{D}$ correlations
  - ⇨ Measure momentum broadening in QGP

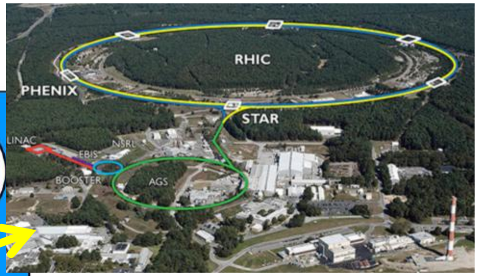


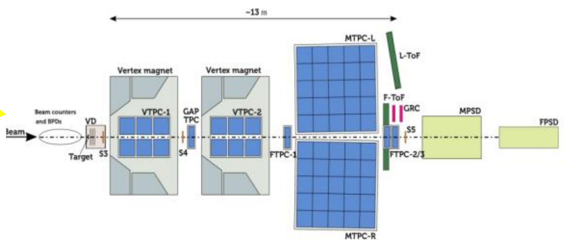
📖 **ALICE3 LoI, arXiv:2211.02491**

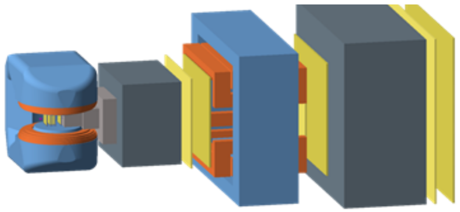
… and much more

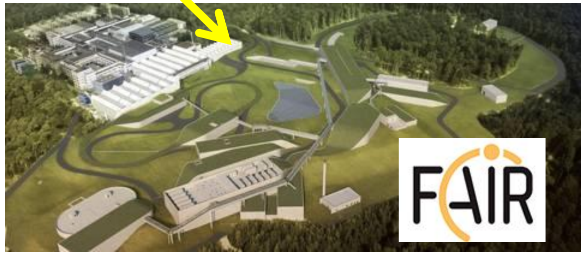
Heavy-ion collisions at low $\sqrt{s_{NN}}$ bridge between early Universe and Neutron Stars











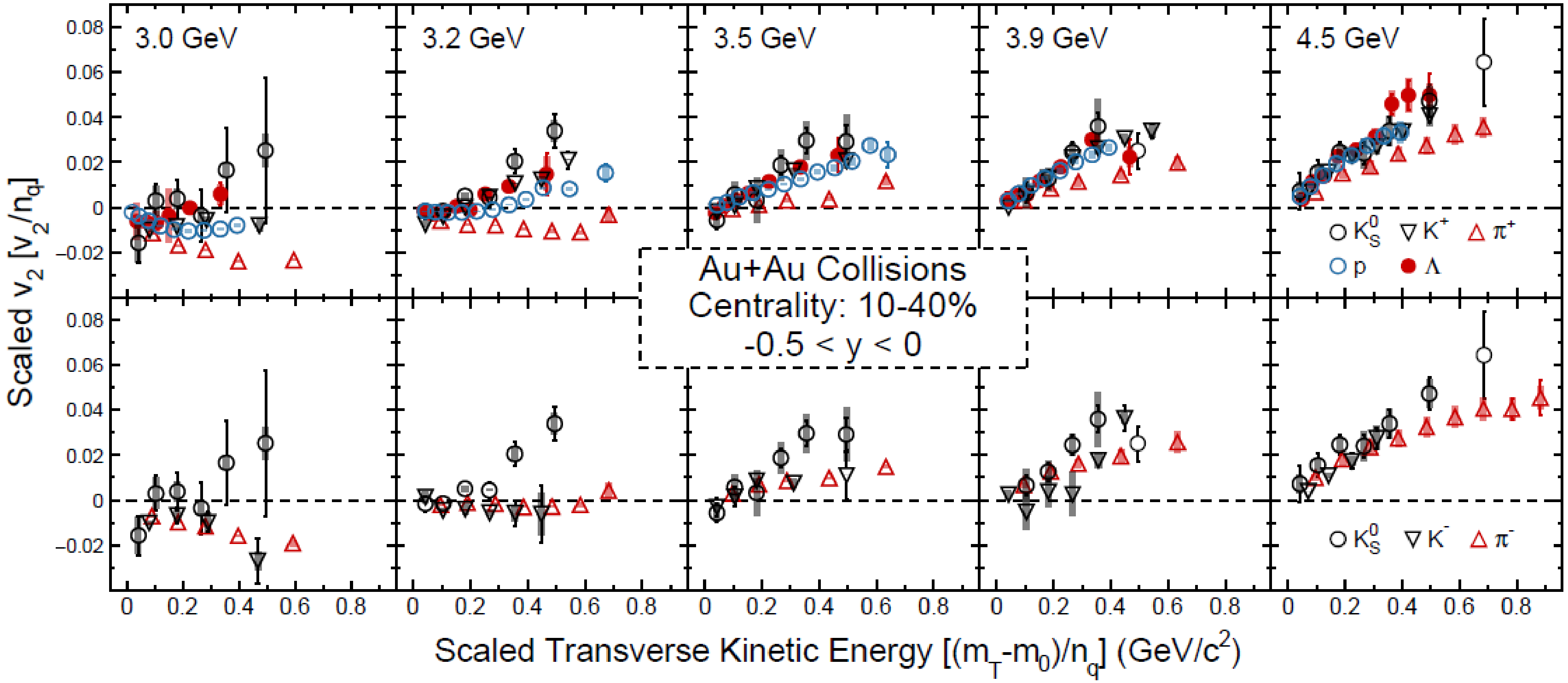
- **RHIC** Beam Energy scan
  - ⇨ Covers $\sqrt{s_{NN}}$ = 3-200 GeV
  - ⇨ Hadronic (soft) obsrvables
- NA61/SHINE @ **SPS**
  - ⇨ Hadronic observables

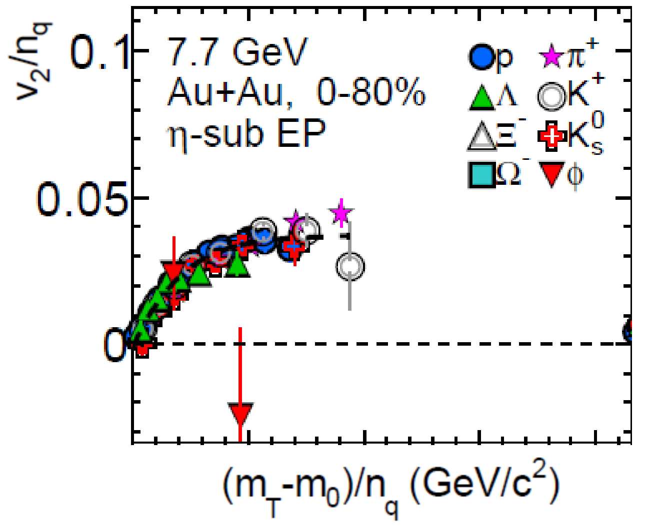
G. Stefanek
T04 Wed 8.30

- New proposed experiment @ **SPS**: NA60+/DiCE
  - ⇨ Hard and electromagnetic probes
- Future CBM experiment @ **FAIR**
  - ⇨ $\sqrt{s_{NN}}$ = 2-7 GeV, high luminosity

Onset of partonic collectivity at low √s

- Scaling of v_2 with number of constituent quarks (NCQ) expected to reflect the effective degrees of freedom of the medium
- Results from beam energy scan at RHIC:
  - ⇨ NCQ scaling completely broken for $\sqrt{s_{NN}} \leq 3.2$ GeV
  - ⇨ Gradual onset of NCQ scaling at higher energies
  - ⇨ Dominance of partonic interactions for $\sqrt{s_{NN}} > 4.5$ GeV → emergence of partonic collectivity

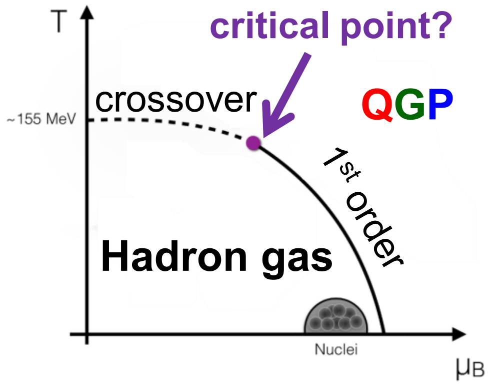


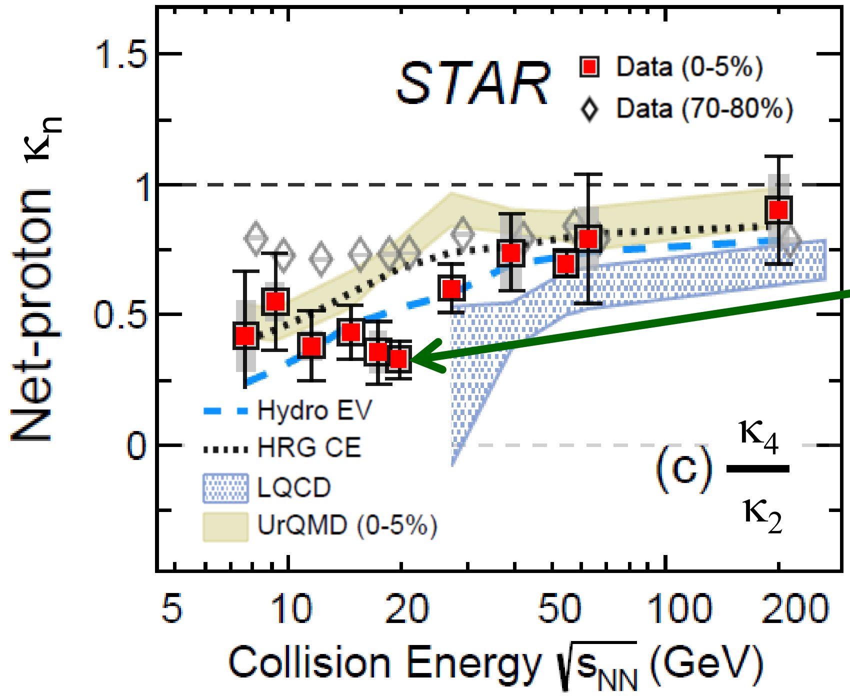


📖 **STAR, arXiv:2504.02531,**
📖 **STAR, PRC 88 (2013) 014902**

Search for the Critical Point

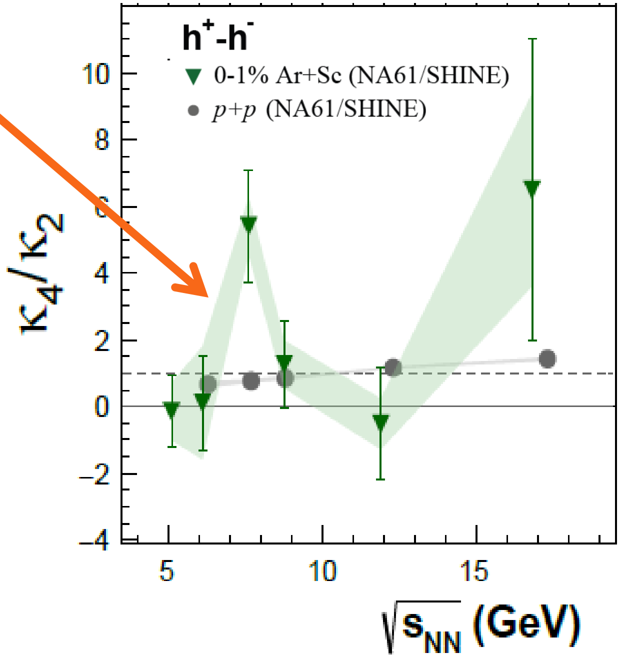
- Event-by-event fluctuations of net-proton (net-charge) number *N*
  - ⇨ Sensitive to correlation length of the system that diverges at the critical point
  - ⇨ Quantified via cumulants $\kappa_1 = \langle N \rangle$, $\kappa_2 = \langle \delta N^2 \rangle$, $\kappa_3 = \langle \delta N^3 \rangle$, $\kappa_4 = \langle \delta N^4 \rangle - 3\kappa_2^2$, with $\delta N = N - \langle N \rangle$
  - ⇨ Search for **non-monotonic dependence on $\sqrt{s_{NN}}$**





The minimum in net-proton κ_4/κ_2 vs. $\sqrt{s_{NN}}$ seen at RHIC is a characteristic feature of the proposed signature of the critical point

No clear critical point signal in net-charge cumulants from NA61/SHINE @ SPS



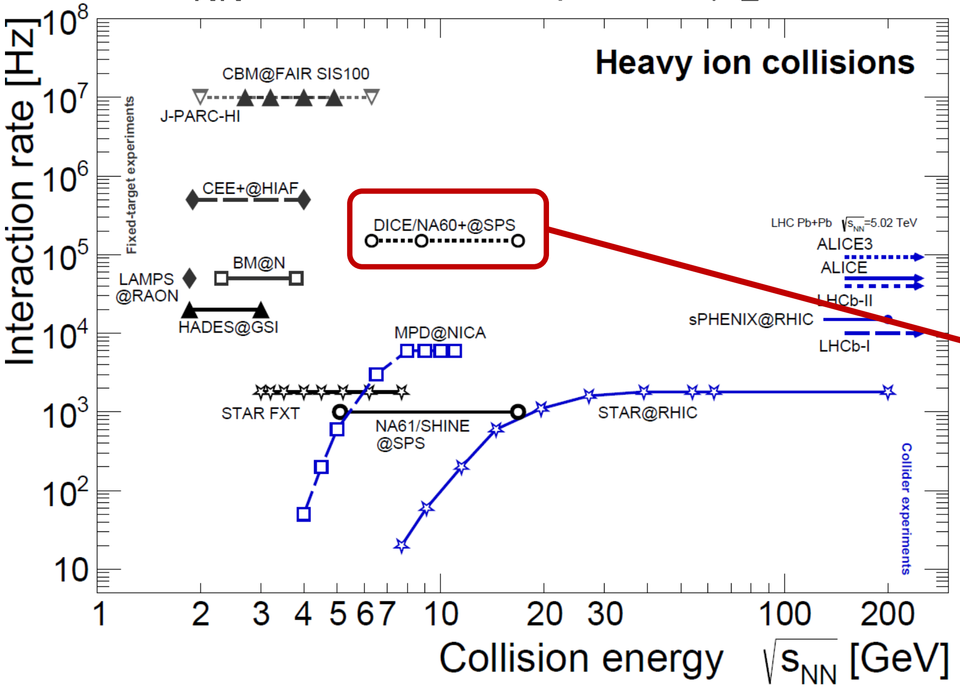
The jury is still out

📖 STAR, arXiv:2504.00817

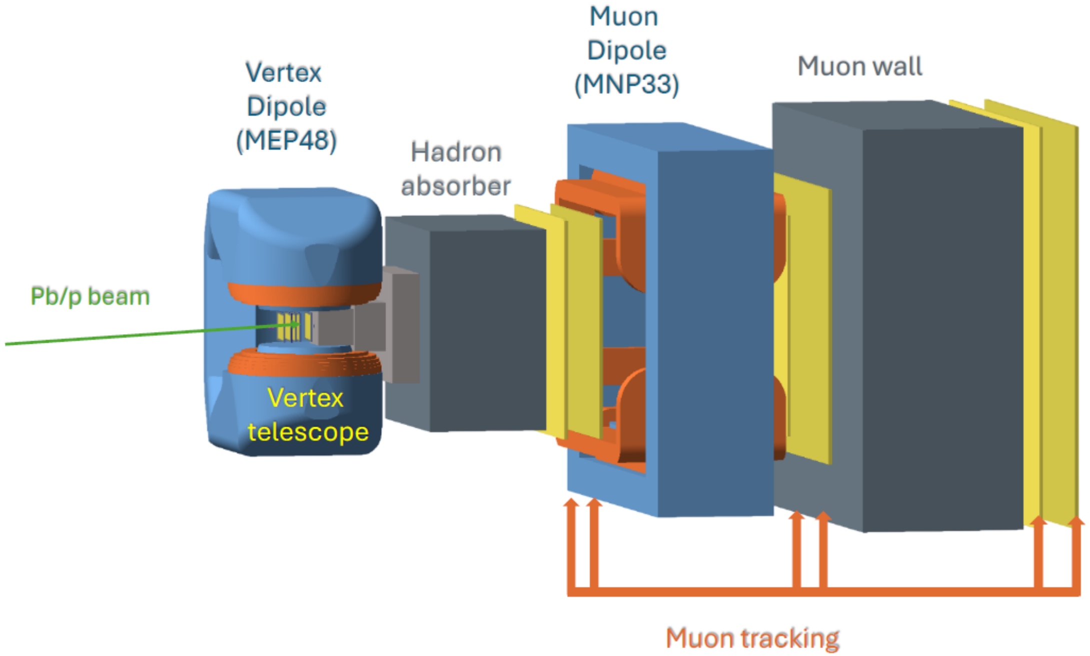
📖 NA61, arXiv:2503.22484

Future heavy-ions @ SPS: NA60+/DiCE

- New proposed experiment at SPS: **NA60+/DiCE**
  - ➪ Study **hard and electromagnetic probes** of the QGP with a beam energy scan in the range $\sqrt{s_{NN}}$ = 6-17 GeV (200 < μ_B < 450 MeV)



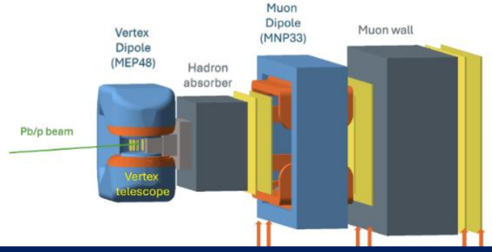
📖 Galatyuk, NPA 982 (2019), update May2025



- Study rare probes thanks to large integrated luminosity
- Complementarity with experiments accessing:
  - ➪ Different (hadronic) observables in the same energy range (RHIC BES, NA61/SHINE)
  - ➪ Similar observables in a lower energy range (CBM at FAIR)

Future heavy-ions @ SPS: NA60+/DiCE

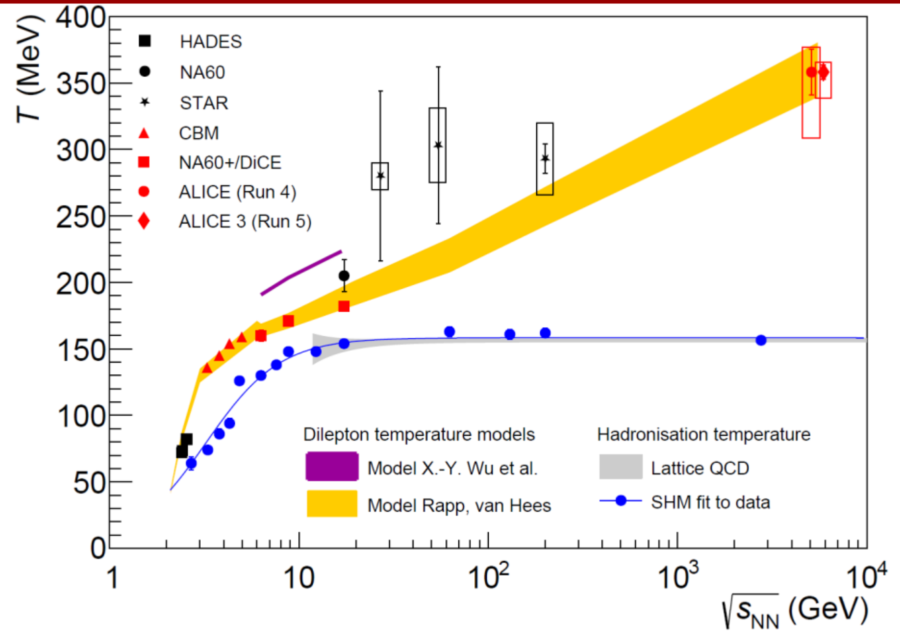
- Physics program based on three main pillars

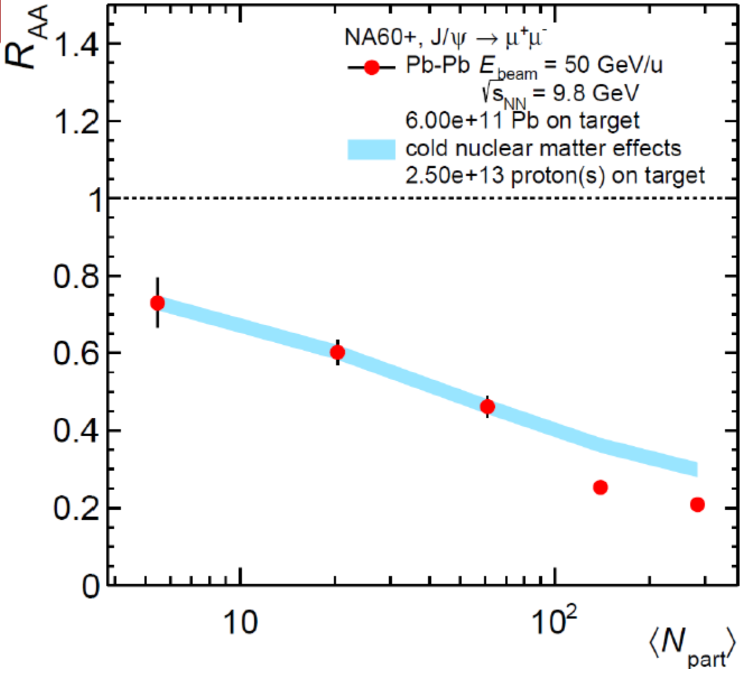


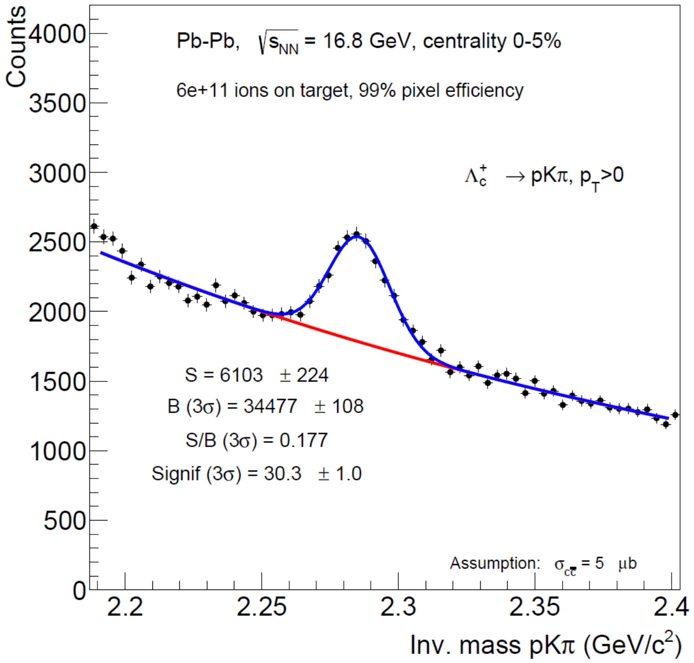
Low- and mid-mass dimuons:
- QGP thermal radiation, caloric curve
- Chiral symmetry via ρ/a_1 mixing

Charmonium → $\mu^+\mu^-$:
- Onset of deconfinement

Open charm hadrons:
- Transport properties
- Heavy quark thermalization







📖 **NA60+/DiCE proposal, CERN-SPSC-2025-023**

Conclusions and prospects

- Important progresses in the understanding of QCD at extreme conditions of high temperature and energy density
  - ⇨Wealth of results from LHC and RHIC experiments in the last years
- Open questions being actively investigated on the experimental and theoretical sides
  - ⇨More will come in the next years
- **Multi-messengers** from the QGP will be studied with **multiple experiments** at **different energies** in **different facilities**
  - ⇨Rich physics program at the **LHC** in Run 3, 4 and 5:
    - ✓ ***Major upgrades of ATLAS and CMS in Long Shutdown 3***
    - ✓ ***ALICE3 and upgraded LHCb after Long Shutdown 4***
  - ⇨NA60+/DiCE for a beam energy scan at the **SPS**
  - ⇨CBM at **FAIR** to study the very-high-μ_B region
  - ⇨**EIC** to provide important information about the initial state

Thank you for the attention!

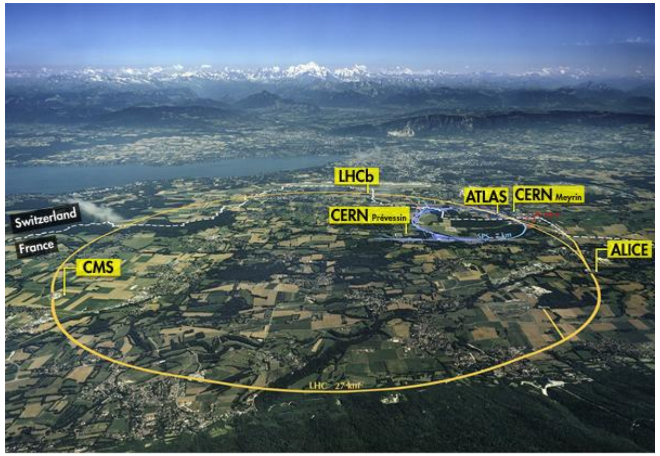
Backup

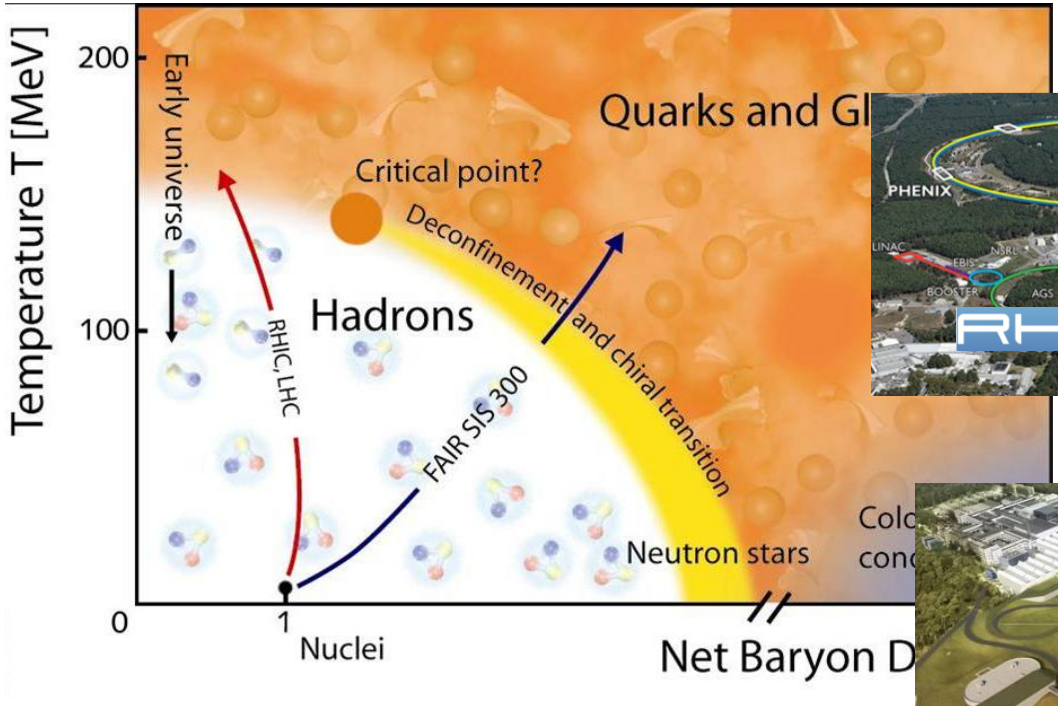
Exploring the QCD phase diagram

- Experimentally, heavy-ion collisions at different energies allow us to explore different regions of the QCD phase diagram

High energy frontier: LHC, RHIC top energy

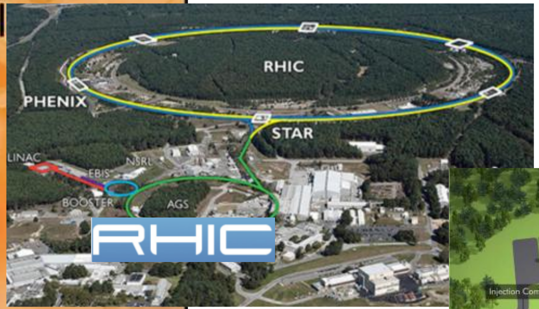
- All the four main LHC experiments have a heavy ion program
- sPHENIX experiment taking data at RHIC



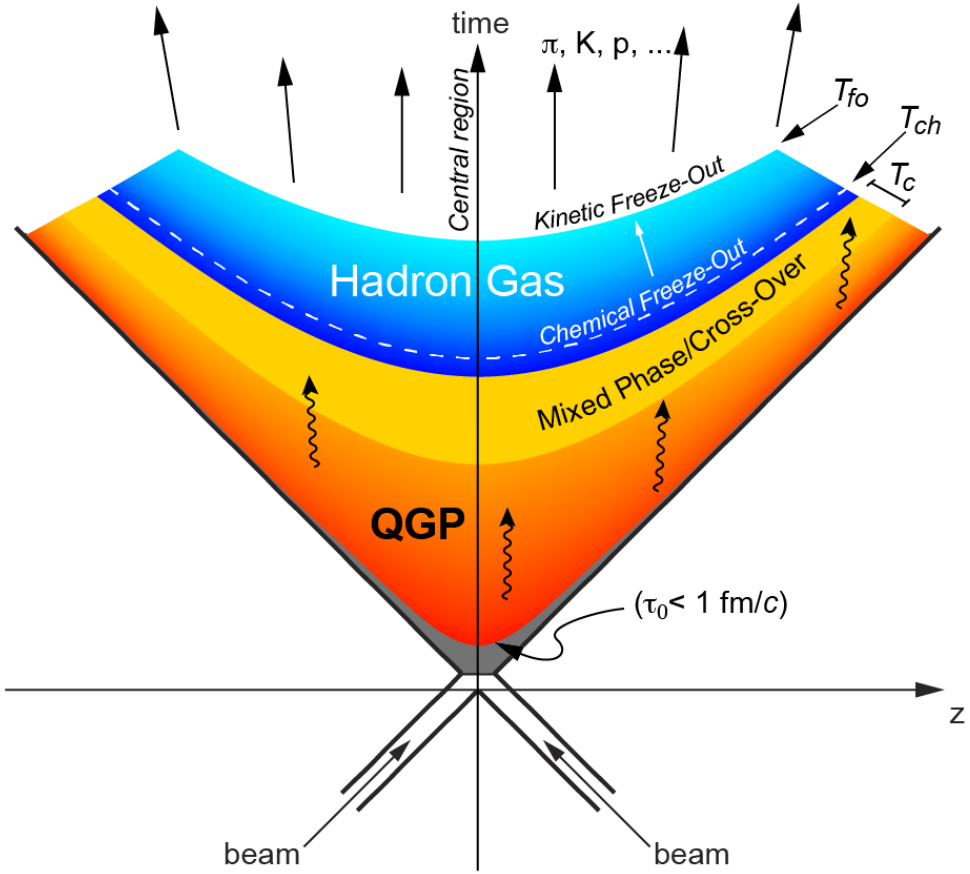


Low energy frontier:

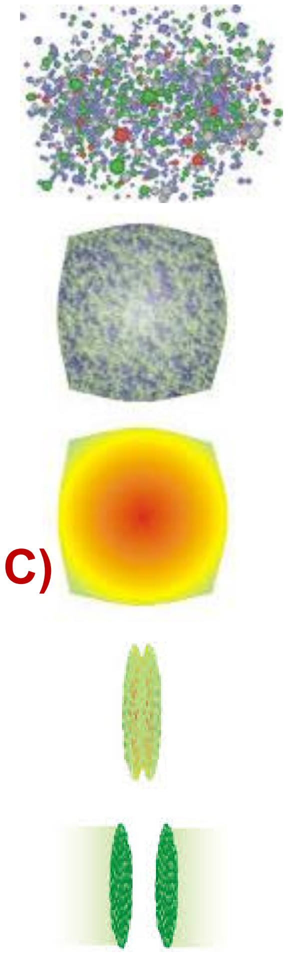
- RHIC and SPS beam energy scan
- Future facilities: FAIR, NICA



Space-time evolution of A-A collisions



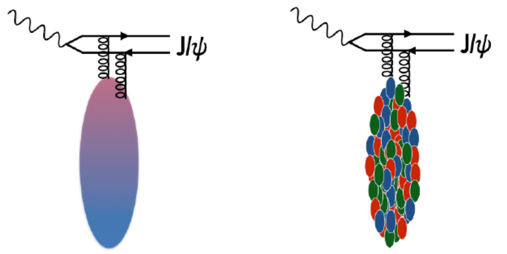
Time		Temperature
Kinetic freeze-out	t~10 fm/c	T~100 MeV
Chemical freeze-out Hadronization		T~160 MeV
QGP hydrodynamic evolution		T>300 MeV (Pb-Pb@LHC)
Pre-equilibrium	t~1 fm/c	
Collision	t=0 fm/c	



UPC: incoherent J/ψ production

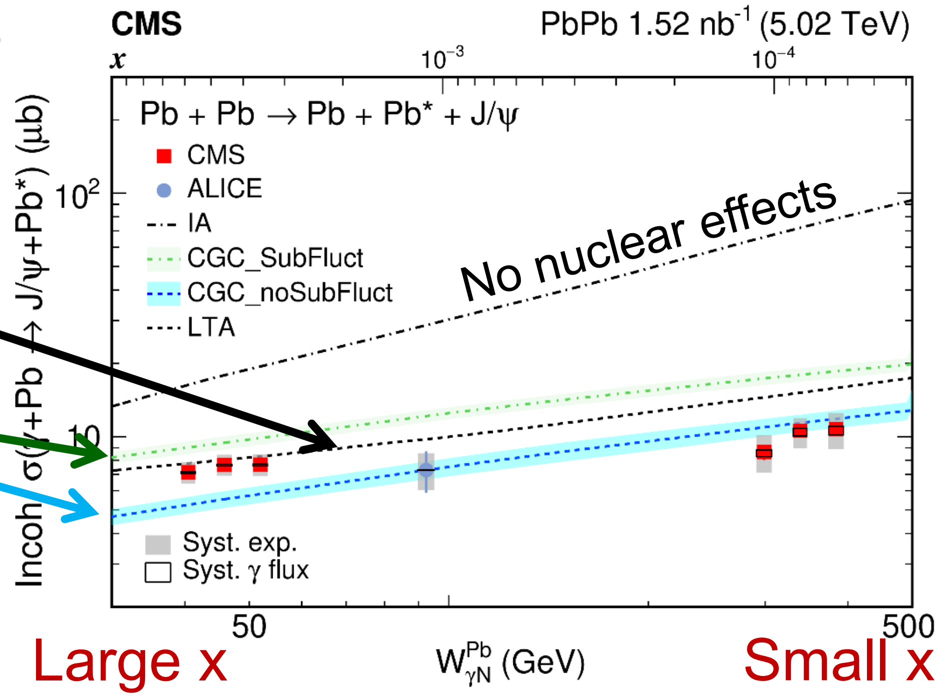
- Coherent photoproduction: the photon couples to the entire nucleus
- Incoherent photoproduction: the photon couples to individual nucleons
  - ⇨ Sensitive to localized, fluctuating gluonic hotspots
  - ⇨ Often accompanied by nuclear breakup
- Test shadowing / saturation models
  - ⇨ Nuclear shadowing and gluon saturation can influence coherent and incoherent photoproduction in distinct ways
- Study vs. photon-nucleon center-of-mass energy $W_{\gamma N}^{Pb}$

📖 **CMS, arXiv:2503.08903**



Weak nuclear shadowing

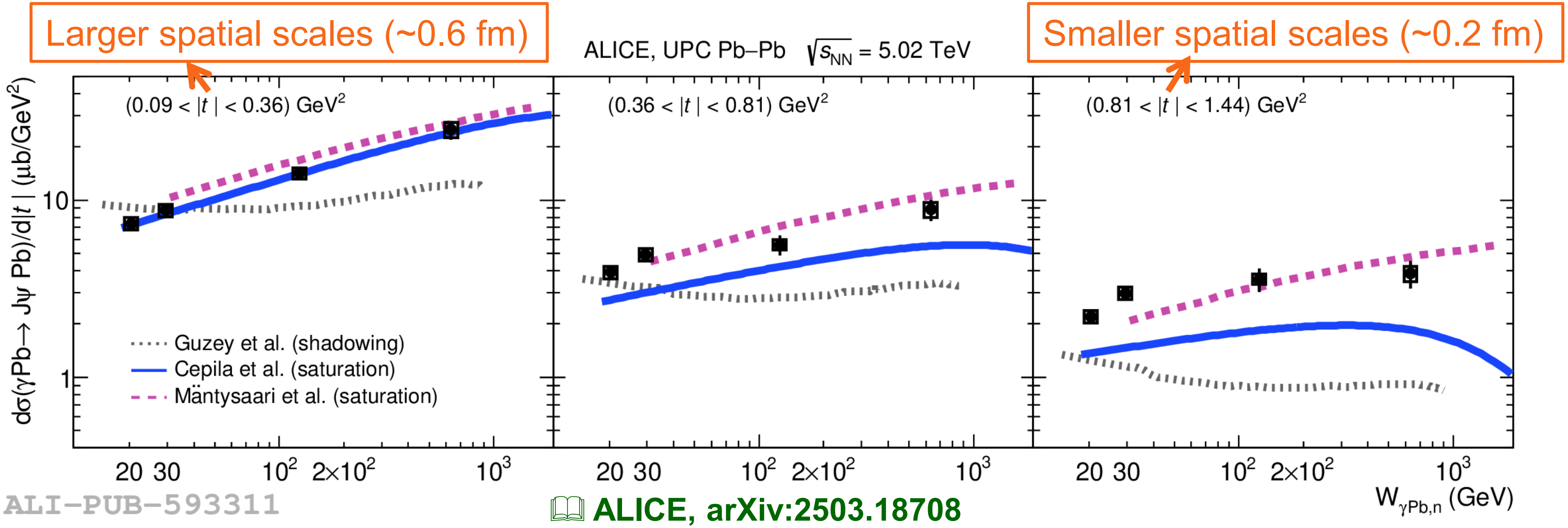
Color Glass Condensate
(effective theory of high-gluon density QCD)
with and without nucleon substructure fluctuations



→ challenge models of shadowing and saturation

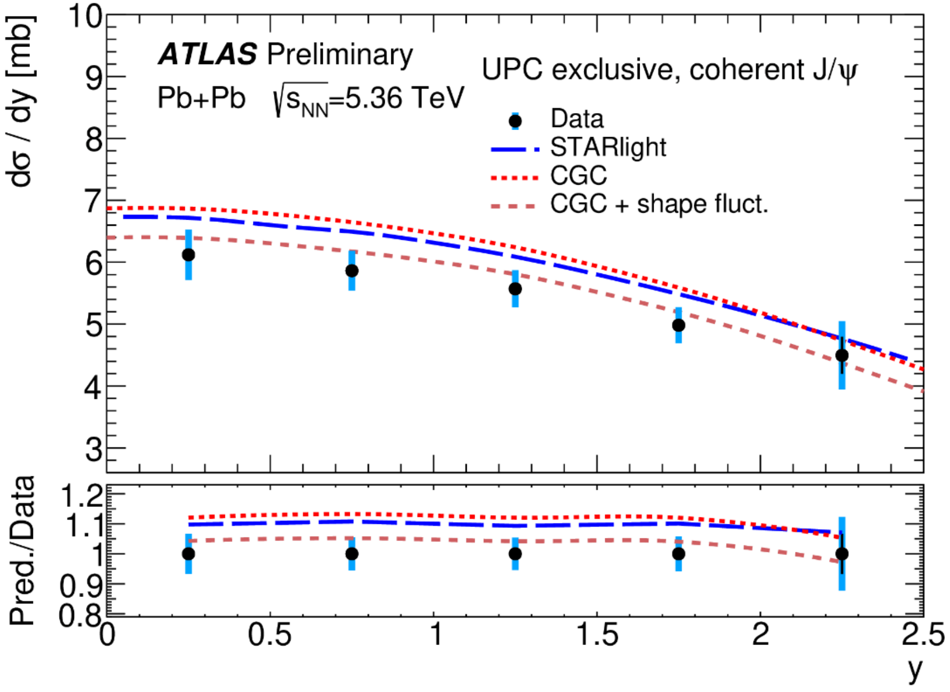
UPC: incoherent J/ψ production

- Energy dependence of incoherent J/ψ photonuclear production in bins of Mandelstam *t*
  - ⇨ From measurements as a function of y and p_{T} → extract $W^2_{\gamma\mathrm{Pb}} = M_{\mathrm{J}/\psi}\sqrt{s_{\mathrm{NN}}}e^{\pm y}$ and $|t| = p^2_{\mathrm{T}}$
  - ⇨ Different ranges in Mandelstam-*t* sensitive to the dynamics of the gluon field at different spatial size scales
- Rate of growth of cross section with increasing energy suppressed at large |*t*|
  - ⇨ Data favour saturation-based models over shadowing models

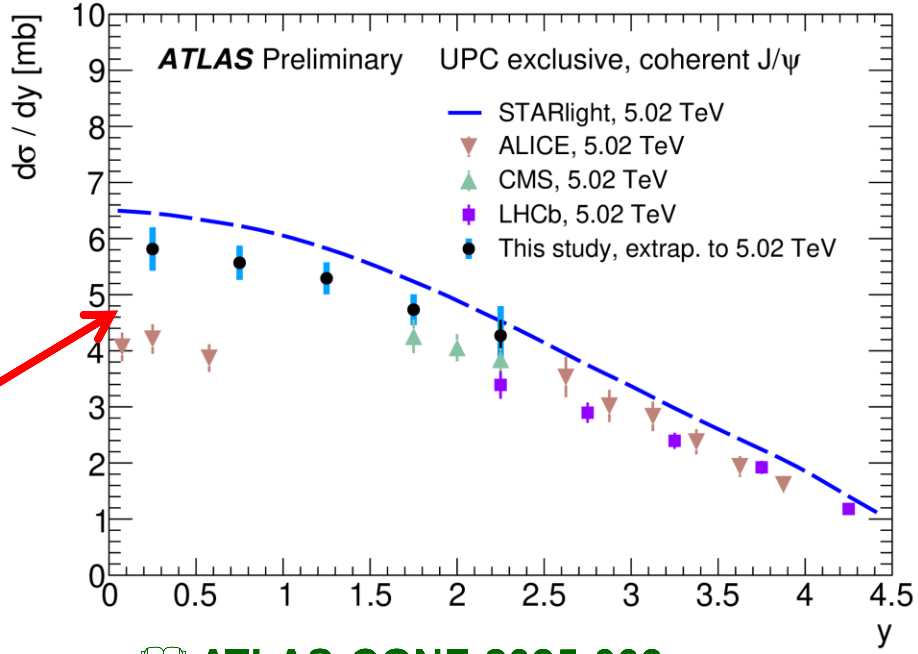


📖 **ALICE, arXiv:2503.18708**

UPC: coherent exclusive J/ψ production



- Sensitive to nuclear gluon dynamics at low Bjorken-x
  - ⇨ Test shadowing / saturation models
  - ⇨ Best description of the data by the color glass condensate (CGC) approach including the effect of nucleon shape fluctuations



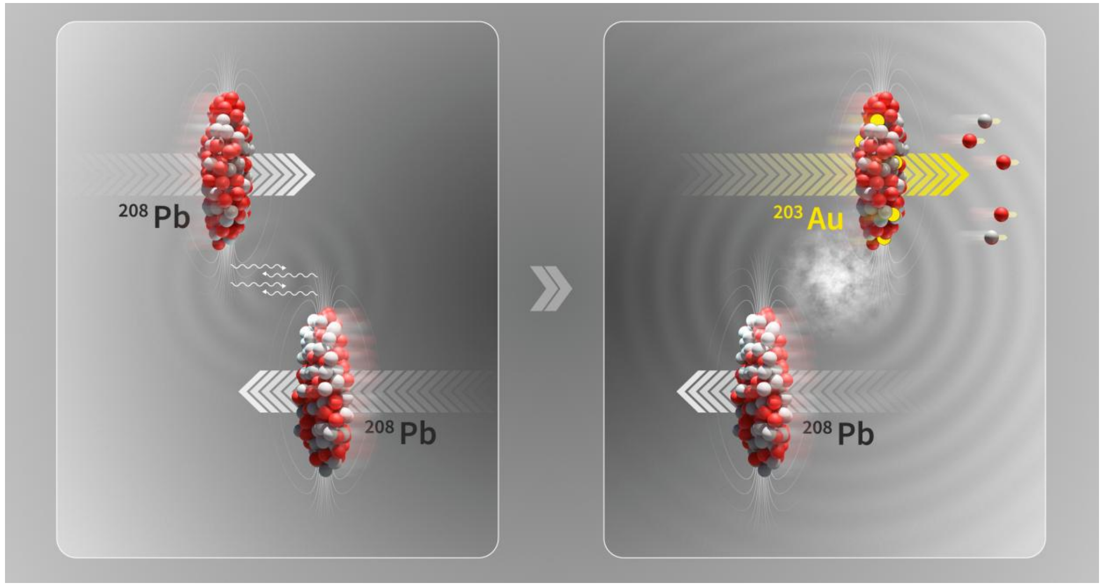
Tension between ALICE and ATLAS results:

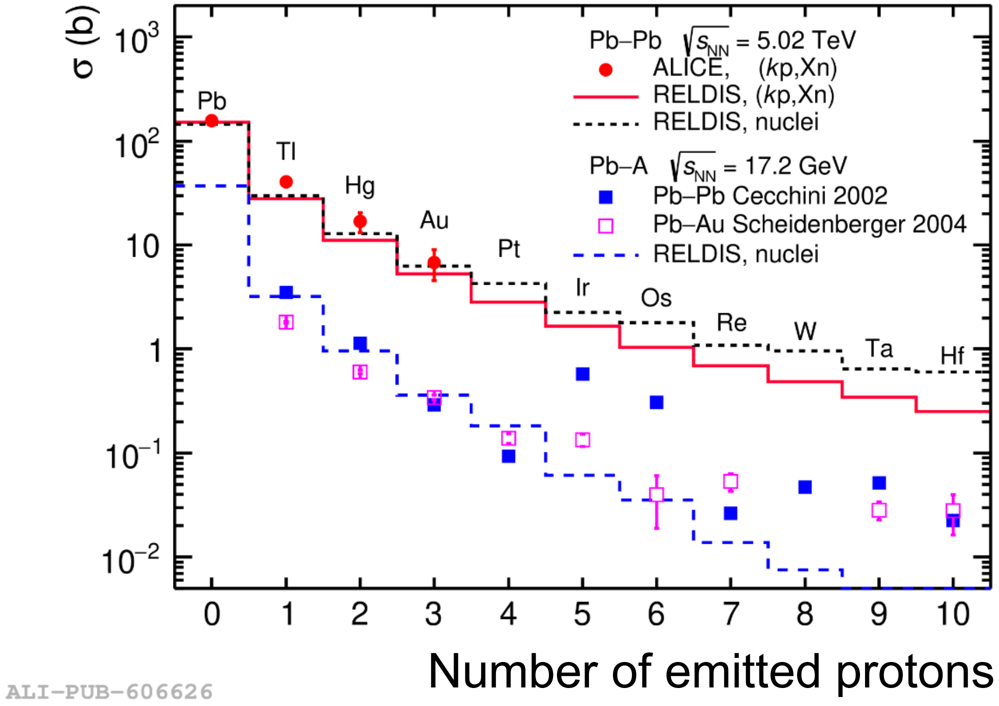
- Due to production of additional particle pairs accompanying the J/ψ and violating the exclusivity requirements?

ATLAS-CONF-2025-003

Parenthesis: alchemy at the LHC

- Electromagnetic dissociation processes in ultraperipheral collisions
  - ➩ Dominant de-excitation via neutron emission
  - ➩ When high-energy photons are absorbed by the Pb nucleus, also some protons are emitted
  - ➩ Detected in Zero Degree Calorimeters
- The emission of 3 protons corresponds to the production of Au nuclei
  - ➩ About 9×10^{10} nuclei (~ 2.9×10^{-11} g) of Au produced in Run-2 at the LHC
- Lead transmuted into gold by light

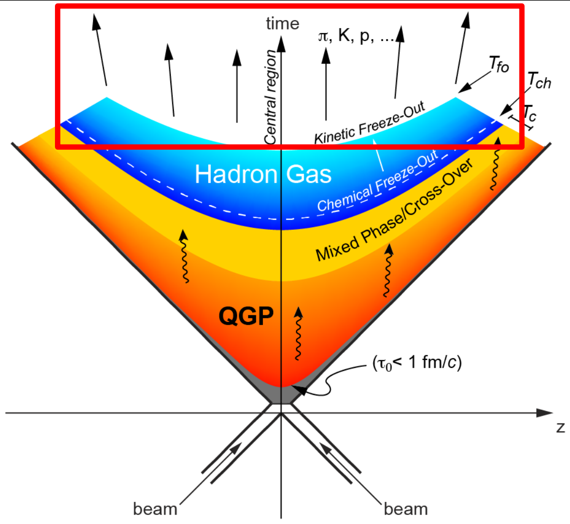


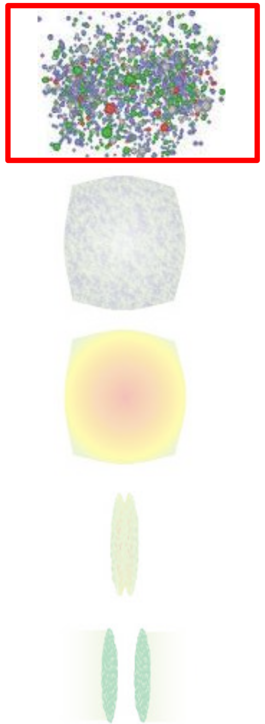


ALICE, PRC111 (2025) 054906

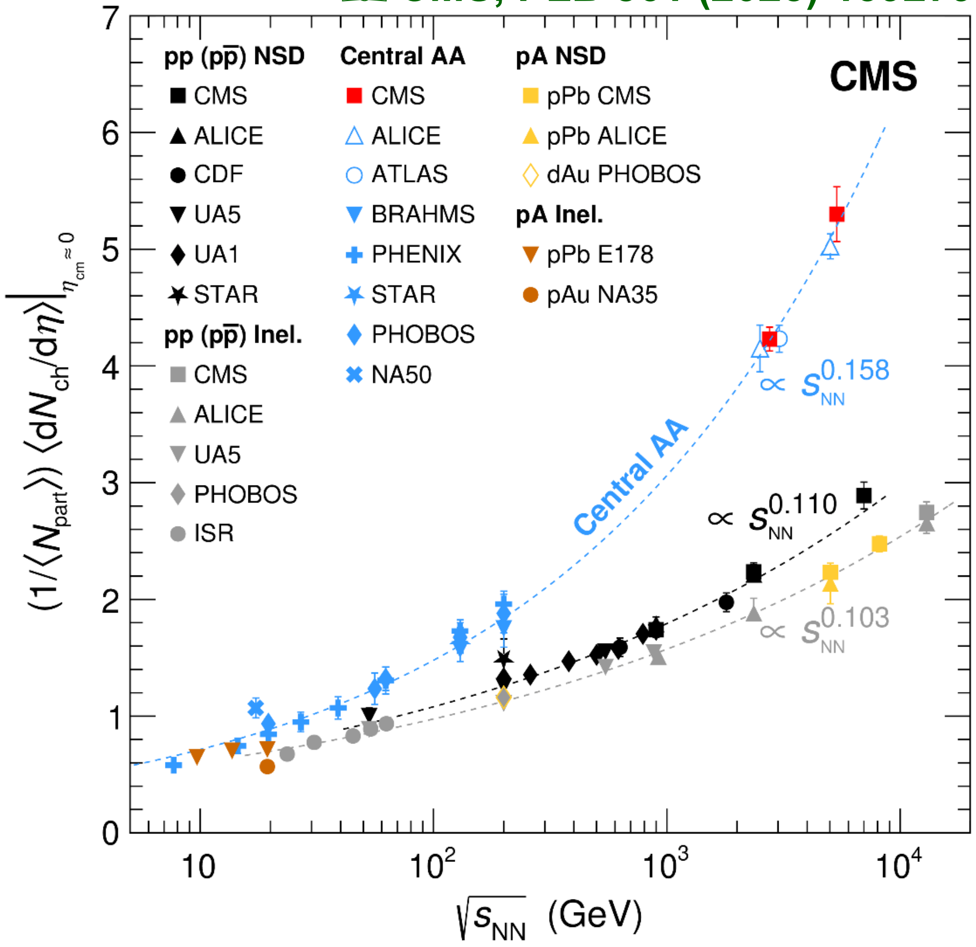
Final state: the "bulk" of soft particles

~20000 particles produced in central Pb-Pb collisions @ LHC





📖 CMS, PLB 861 (2025) 139279



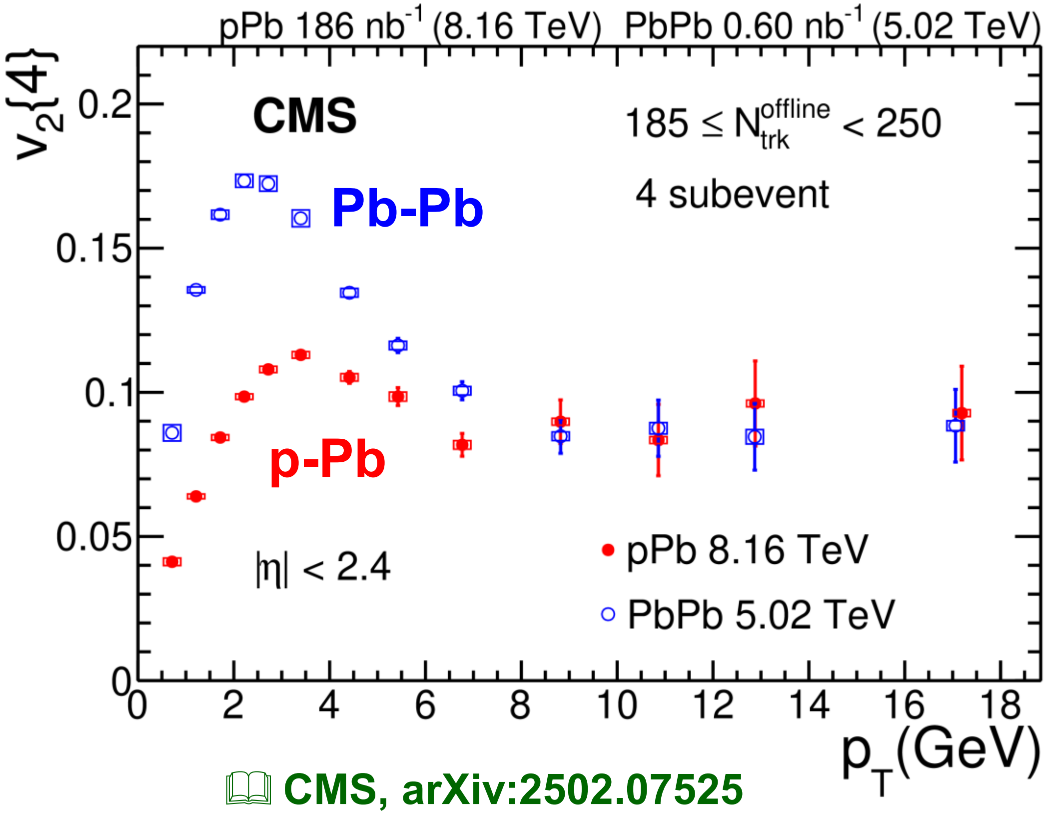
- Multiplicity of produced particles depends on:
  - ➩ Collision geometry
  - ➩ Collision energy: power law dependence on $\sqrt{s_{NN}}$
- Large energy density in the created "fireball":
  - ➩ $\varepsilon >$ **10 GeV/fm³** at τ=1 fm/c in central Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

📖 **ALICE, EPJC 84 (2024) 813**

Collectivity in small collision systems

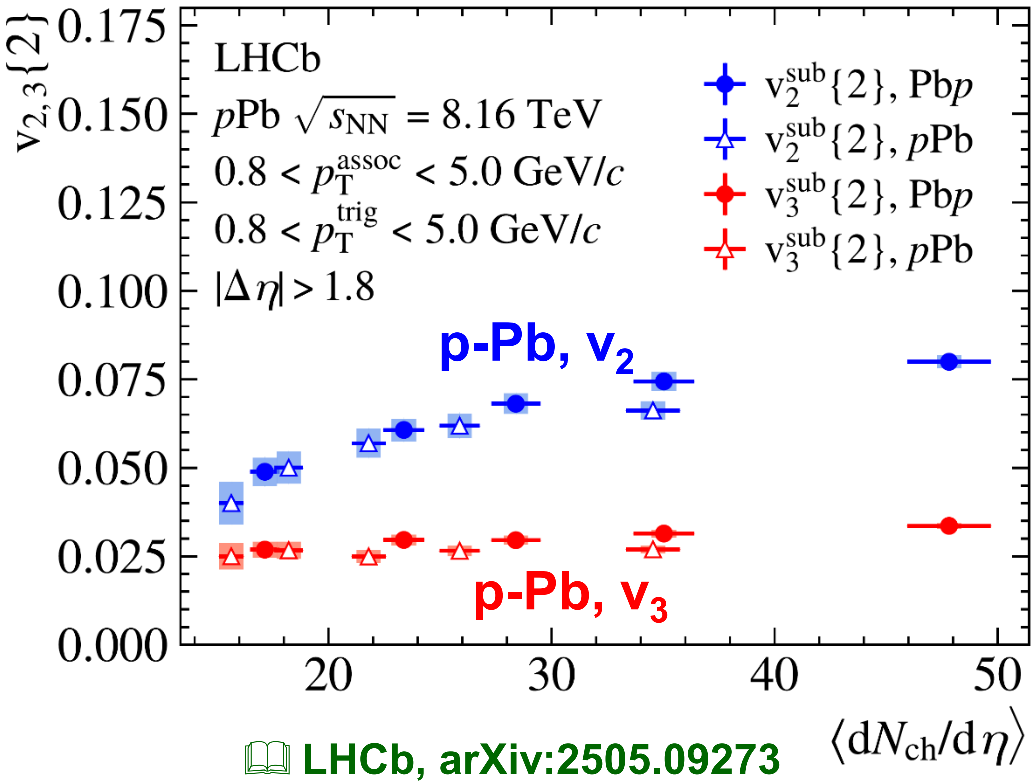
- Long-range angular correlations observed in high-multiplicity pp and p-Pb collisions
  - ⇨ Similar features as those observed in Pb-Pb and interpreted as due to collective flow

midrapidity



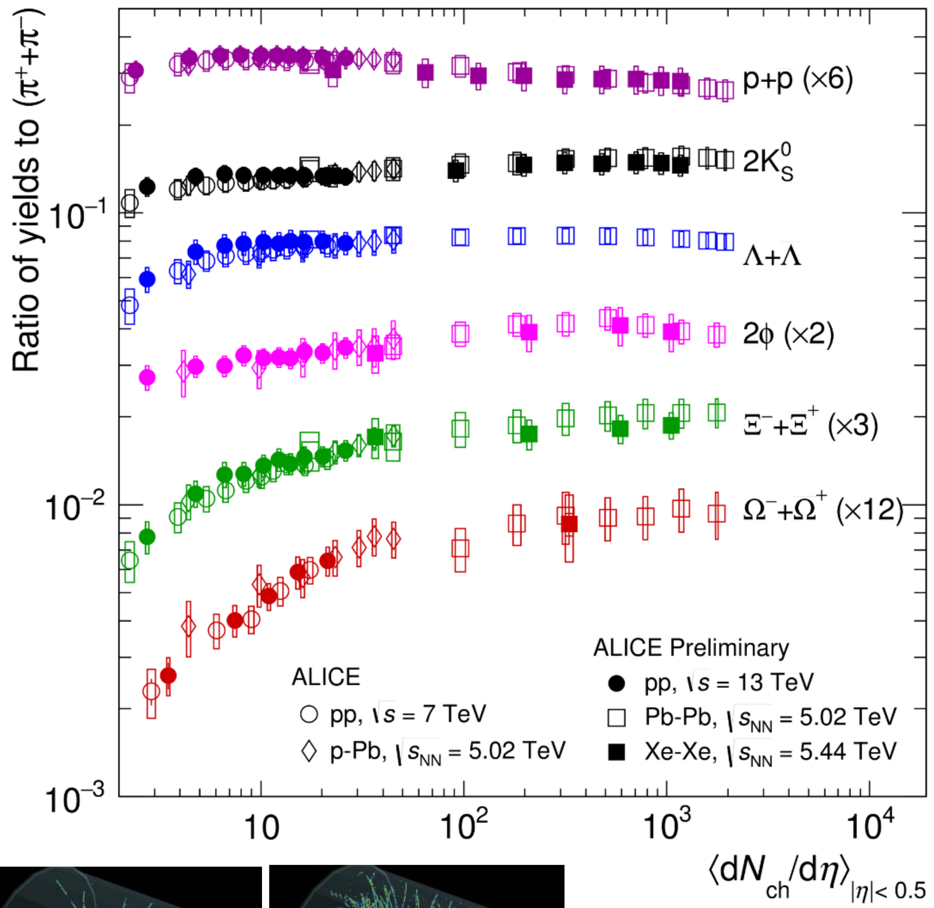
📖 CMS, arXiv:2502.07525

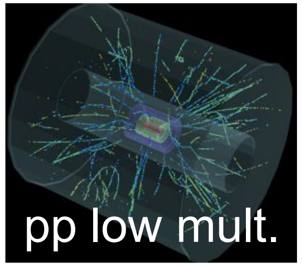
forward rapidity

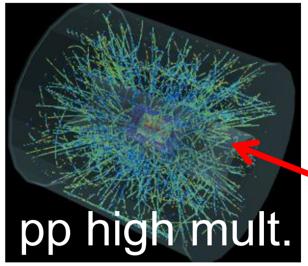


📖 LHCb, arXiv:2505.09273

Strangeness production vs. multiplicity







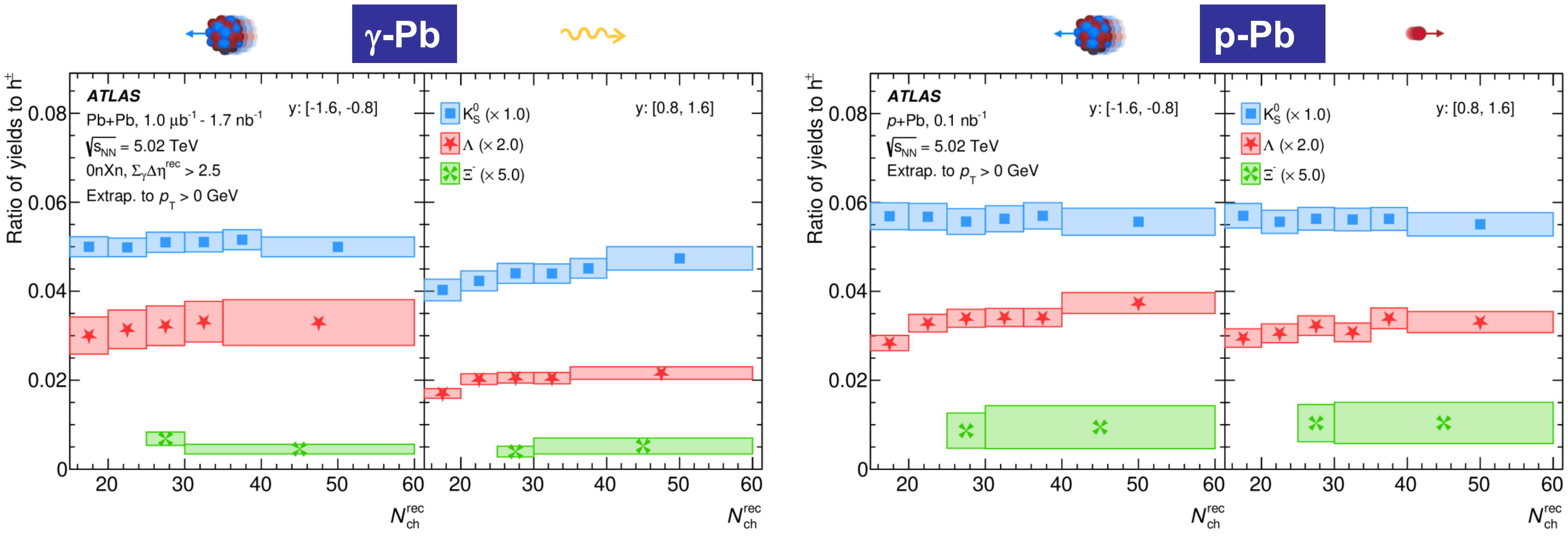
Similar multiplicity as in peripheral Pb-Pb

- 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**

Strangeness production in UPC

- Yields of hadrons, K^0_s, Λ and Ξ^- in same multiplicity classes in p-Pb and photonuclear events in Pb-Pb collisions (γ-Pb)
  - ⇨ Similar strange / hadron rations for p-Pb and in the Pb-going side of γ-Pb events
  - ⇨ Lower ratios on γ-going side

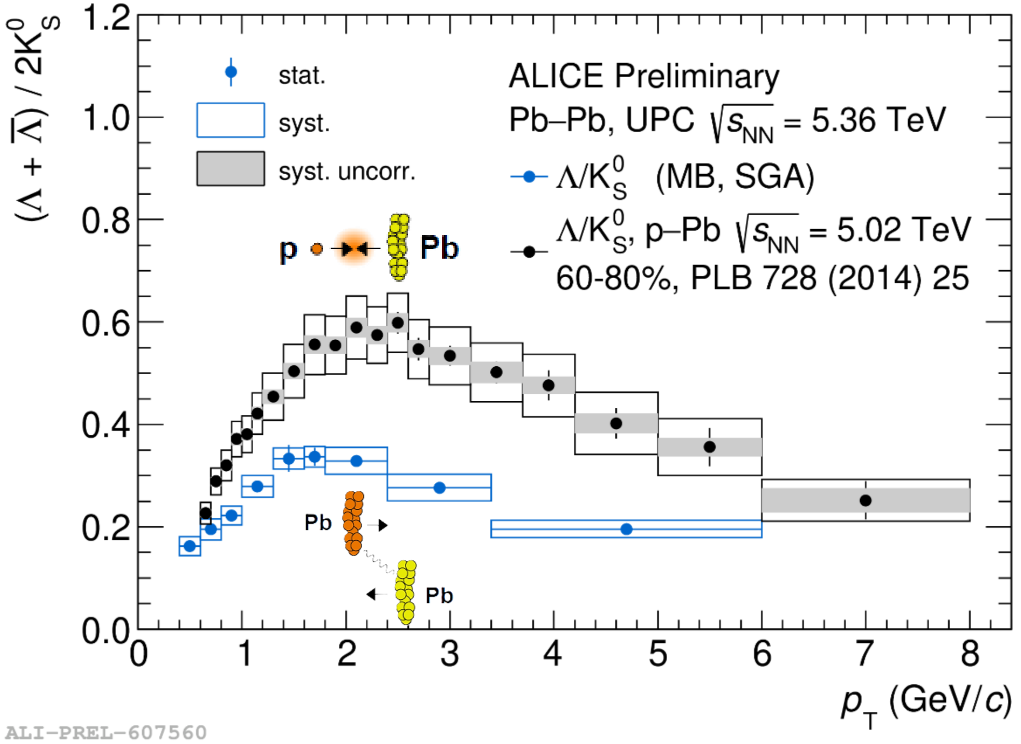


📖 **ATLAS, PRC 111 (2025) 064908**

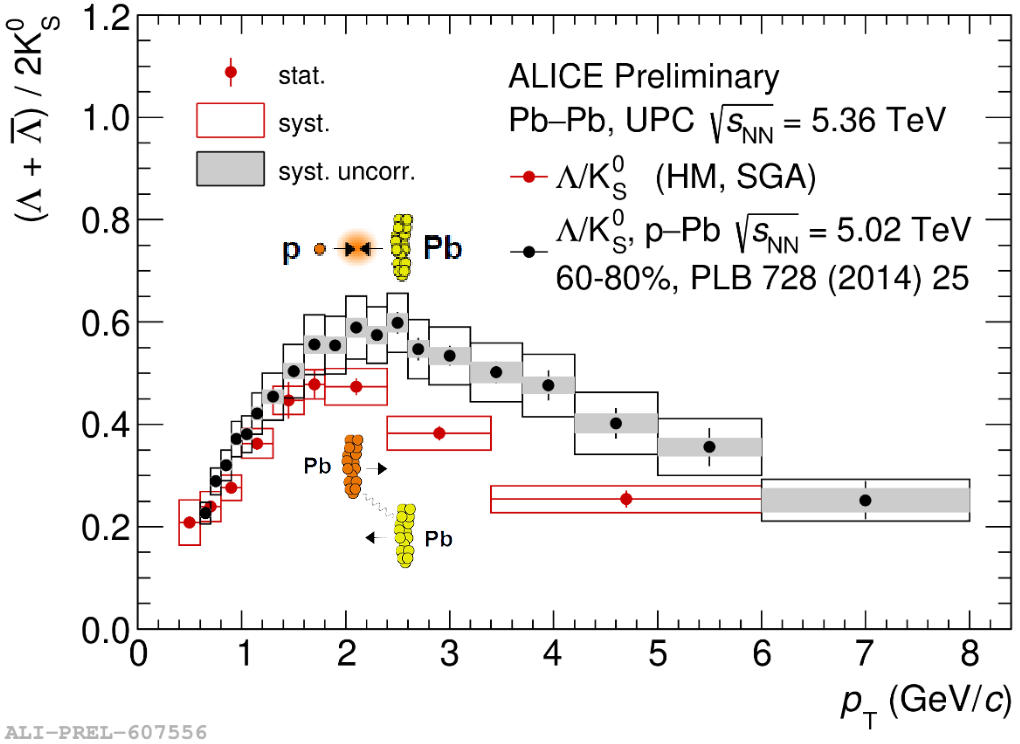
Strangeness production in UPC

- Enhancement of Λ/K^0_s ratio in photo-nuclear collisions at intermediate p_T reminiscent of that measured in p-Pb collisions
  - ⇨ In high-multiplicity photo-nuclear events, the Λ/K^0_s ratio approaches the values measured in low-multiplicity p-Pb

γ-Pb Minimum Bias

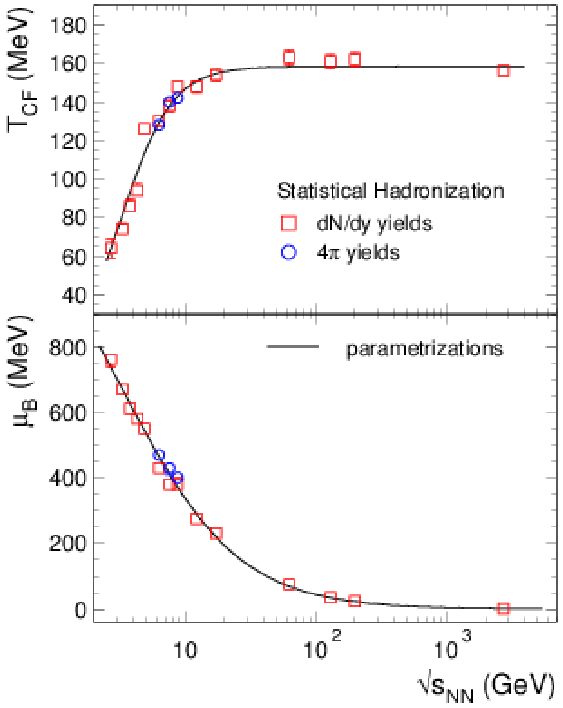


γ-Pb High multiplicity

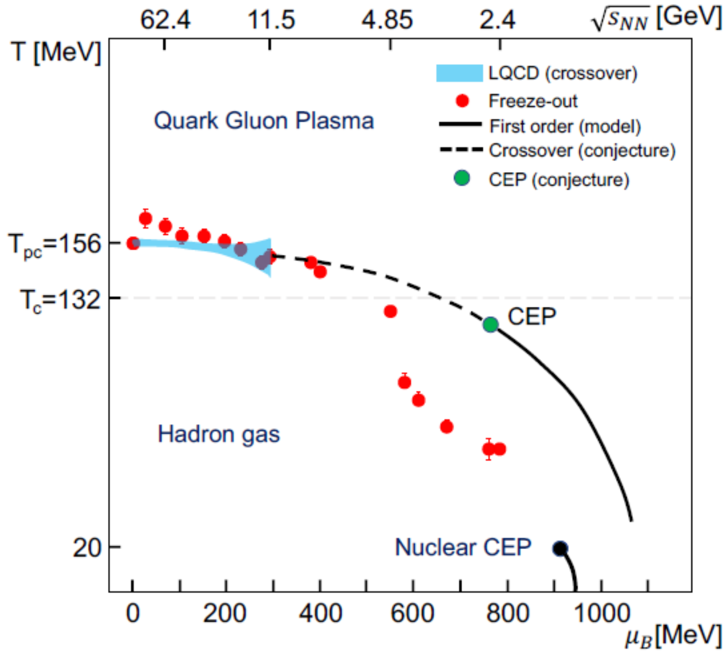


Mapping the phase diagram

- Statistical hadronization analysis of hadron yields at different collision energies
  - ⇨ **Chemical freeze-out temperature** T_{ch} increases with $\sqrt{s_{NN}}$ at low energies and saturates at T_{ch}~156 MeV at top SPS energy
- At high $\sqrt{s_{NN}}$: T_{ch} very **close to the pseudo-critical** temperature from lattice QCD
  - ⇨ Inelastic interactions between hadrons cease within a narrow temperature interval after QGP hadronization



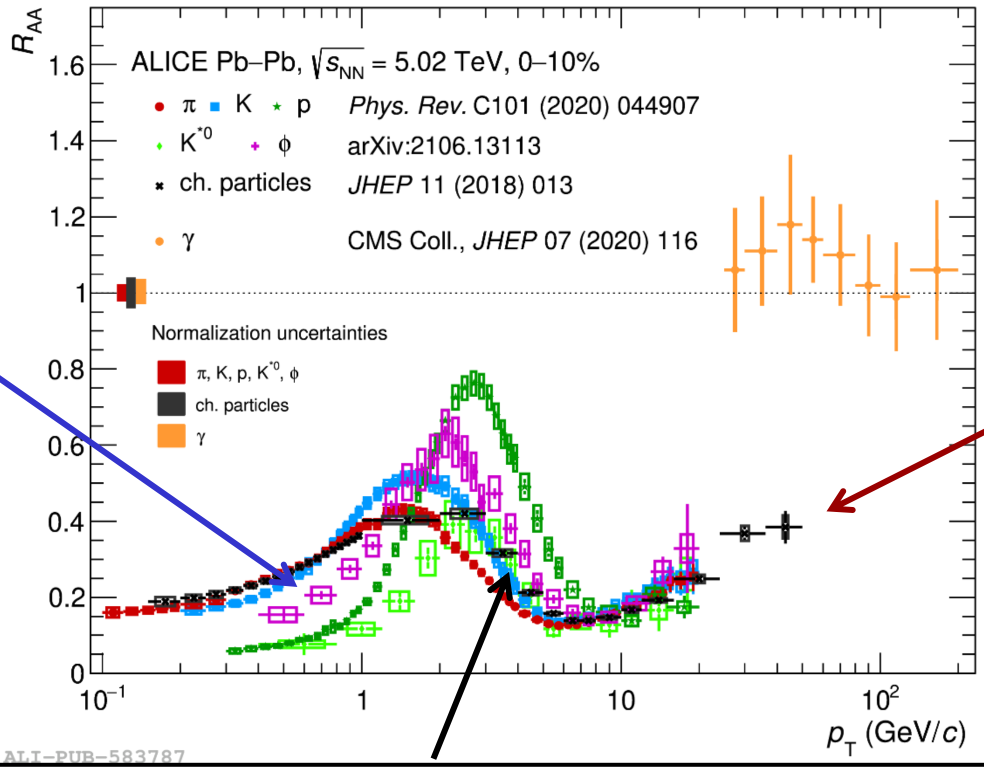
Use the (T_{ch},μ_B) pairs from statistical-hadronization analysis at each $\sqrt{s_{NN}}$ to map a diagram of the chemical freeze-out conditions



📖 **P. Braun-Munzinger et al. arXiv:2506.04733**

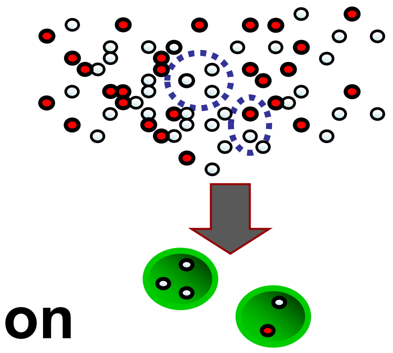
Single particle R_{AA}: family portrait

Low-p_T (<~2 GeV/c) :
- Soft/thermal regime
- Production not scaling with N_{coll}
- Hydrodynamic expansion driven by pressure gradients
- Radial flow peak, mass dependence



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

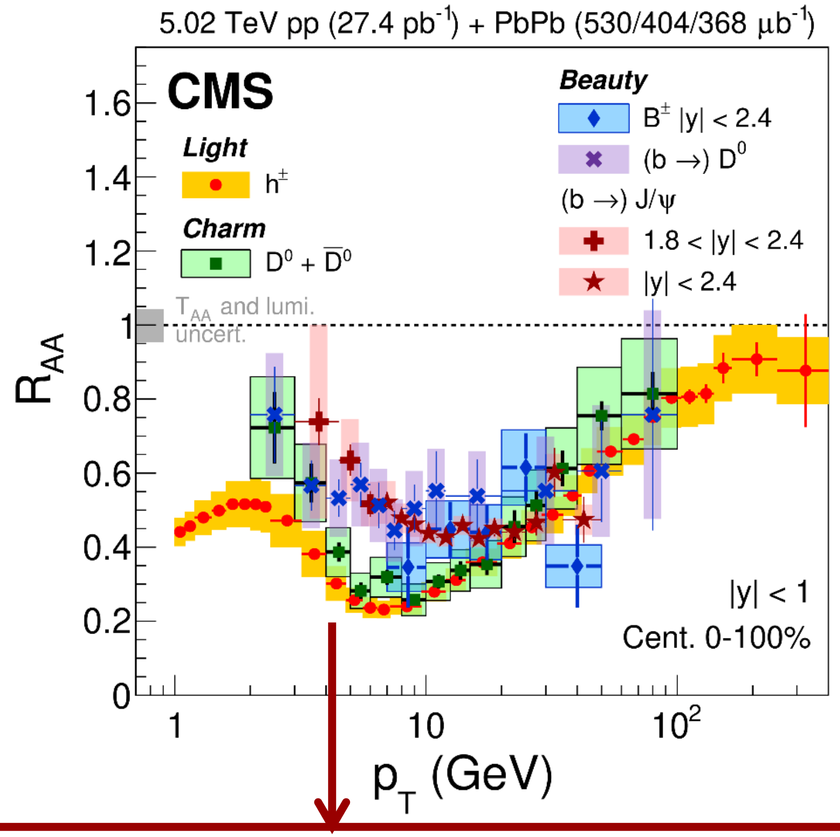
Intermediate-p_T (ca. 3<p_T<8 GeV/c) :
- Kinetic regime (not described by hydro)
- Different R_{AA} for different hadron species
  - Inconsistent with hard partons + energy loss + universal fragmentation
- Features described with in-medium **hadronization via quark recombination**

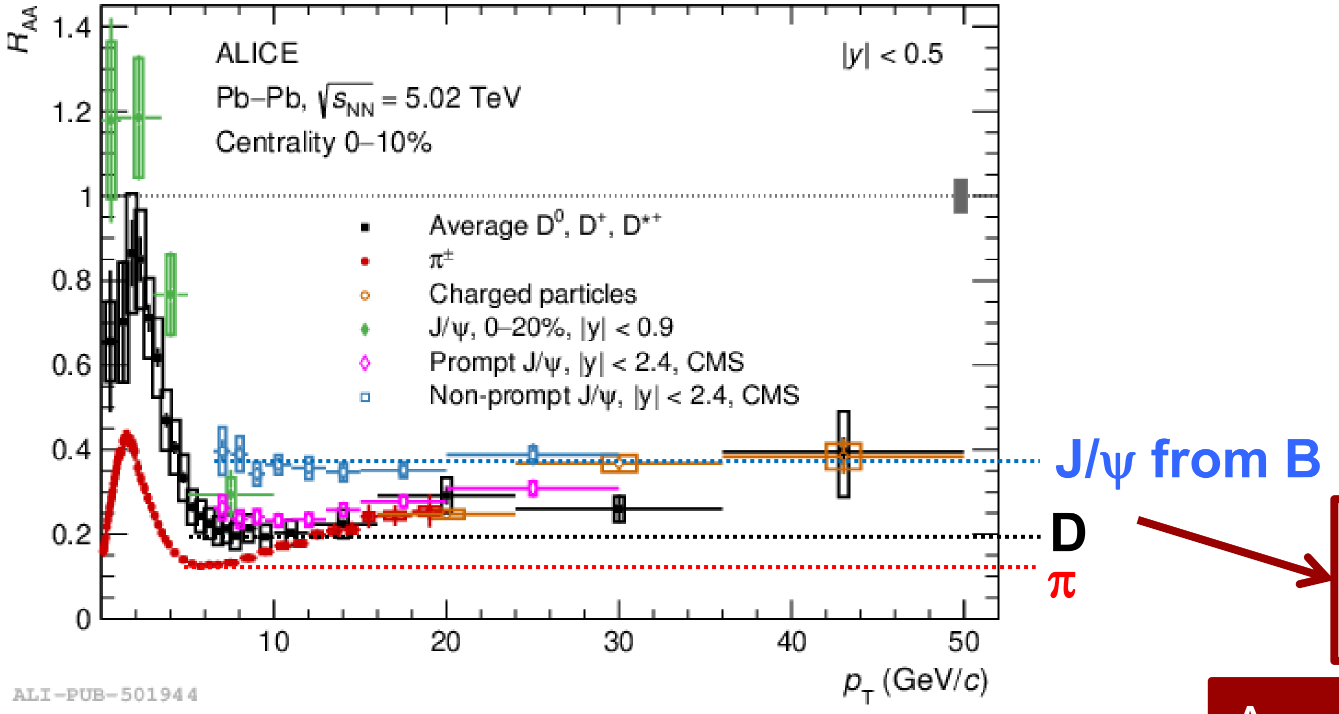


Charm vs. beauty vs. light flavours

- In-medium energy loss ΔE depends on properties of the parton (**colour charge, mass**) traversing the QGP
  - ⇨ Expected hierarchy: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Test by comparing R_{AA} of light, charm and beauty hadrons

CMS, Phys.Rept. 1115 (2025) 219





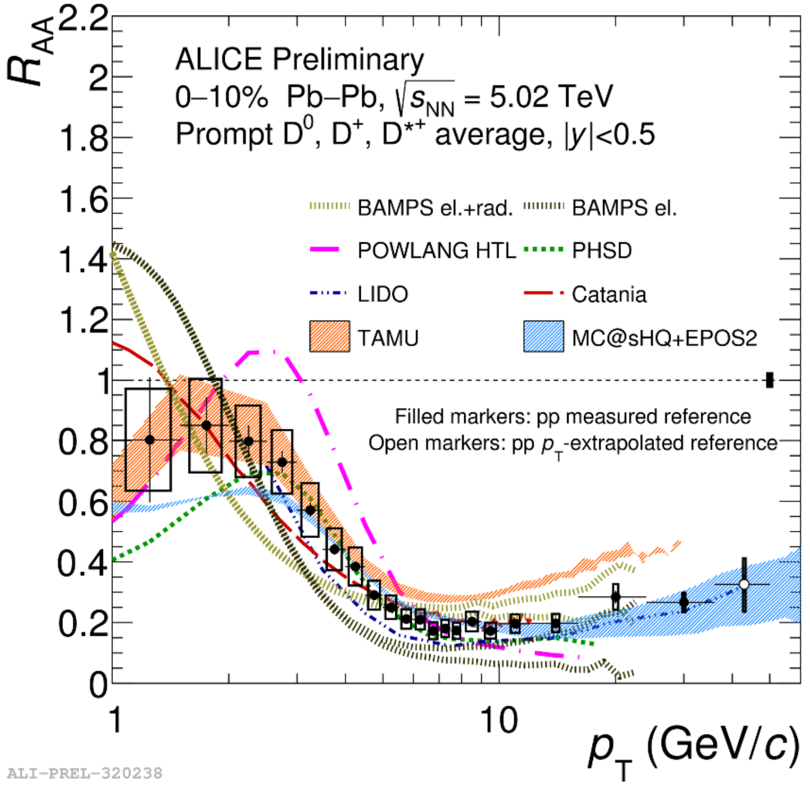
ALICE, JHEP01 (2022) 174

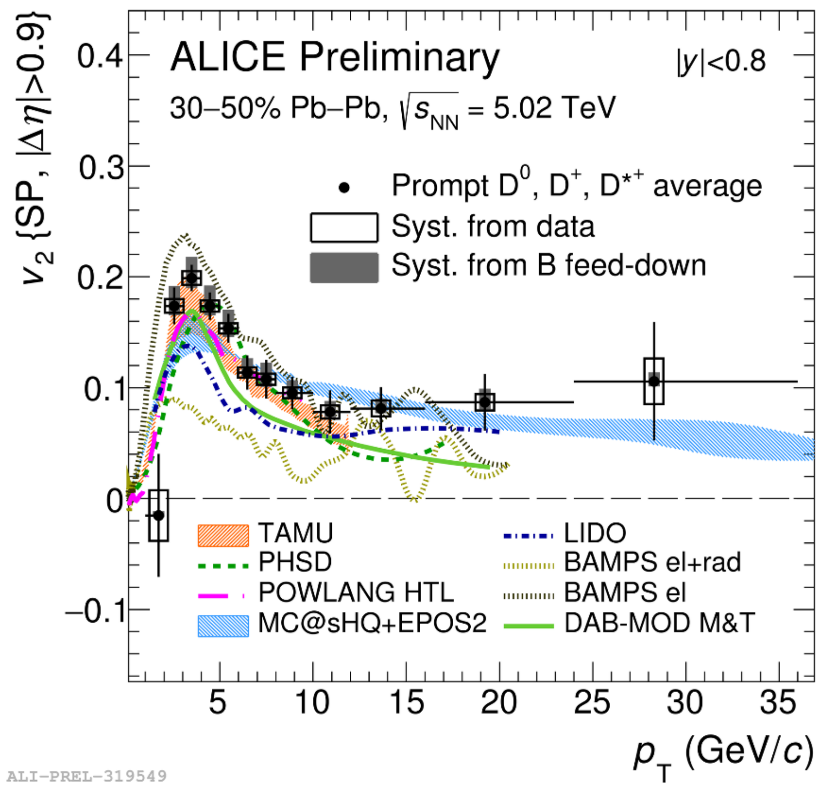
R_{AA}(charm) > R_{AA}(light) for p_T<8 GeV/c
R_{AA}(beauty) > R_{AA}(charm) for p_T<20 GeV/c

As expected from parton in-medium energy loss

Charm R_{AA} and v_2 phenomenology

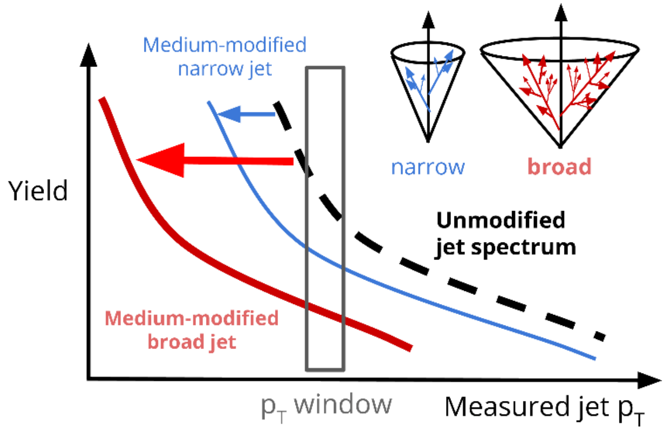
- Simultaneous comparison of R_{AA} and v_2 to models can constrain QGP properties and the description of charm-quark interaction and diffusion in the medium
  - ⇨Interplay of CNM effects, collisional and radiative energy loss, hadronisation via coalescence and fragmentation and realistic underlying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



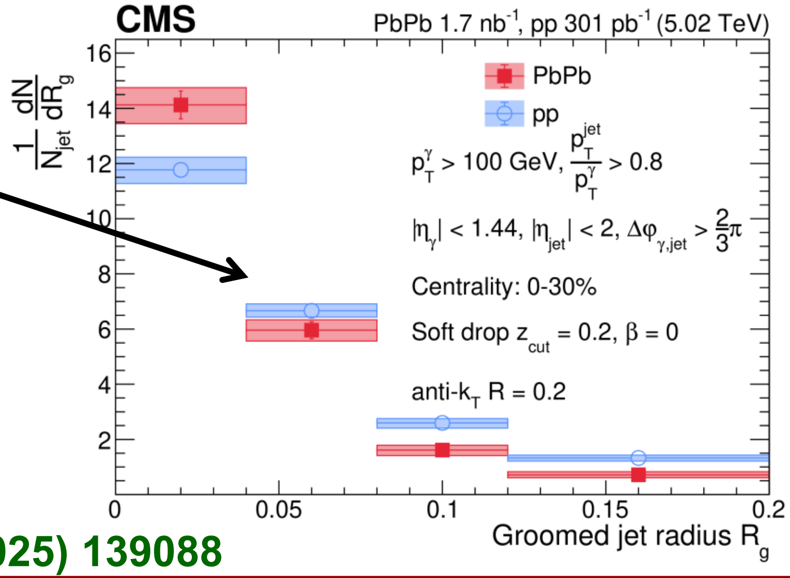


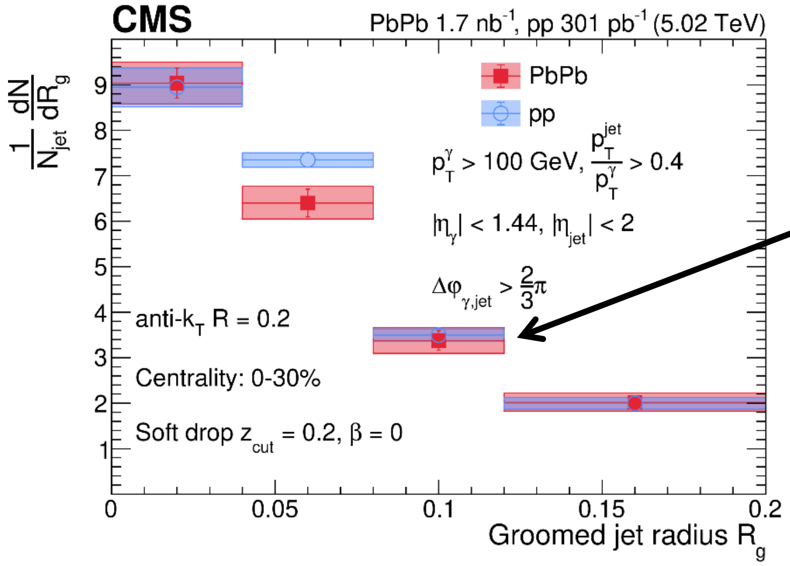
Jet substructure in γ-jet events

- Jet substructure: narrower jets in Pb-Pb than in pp for inclusive jets with same p_T
  - ⇨ Interpretation in terms of broadening of parton shower require to assess potential selection biases
    - ✓ ***A given jet p_T interval is preferentially populated by jets that are less quenched***
- Measurements of groomed jet radius R_g in γ-jet events
  - ⇨ Photon provides access to p_T of the parton that initiated the recoiling jet
  - ⇨ Show that selection biases play an important role



Jets with $p_T^{jet}/p_T^{\gamma} > 0.8$ (less quenched jets): narrower in Pb-Pb than in pp collisions



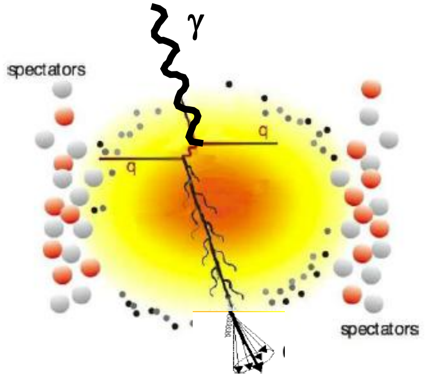


Jets with $p_T^{jet}/p_T^{\gamma} > 0.4$ (more inclusive jet selection): no significant narrowing relative to the pp reference

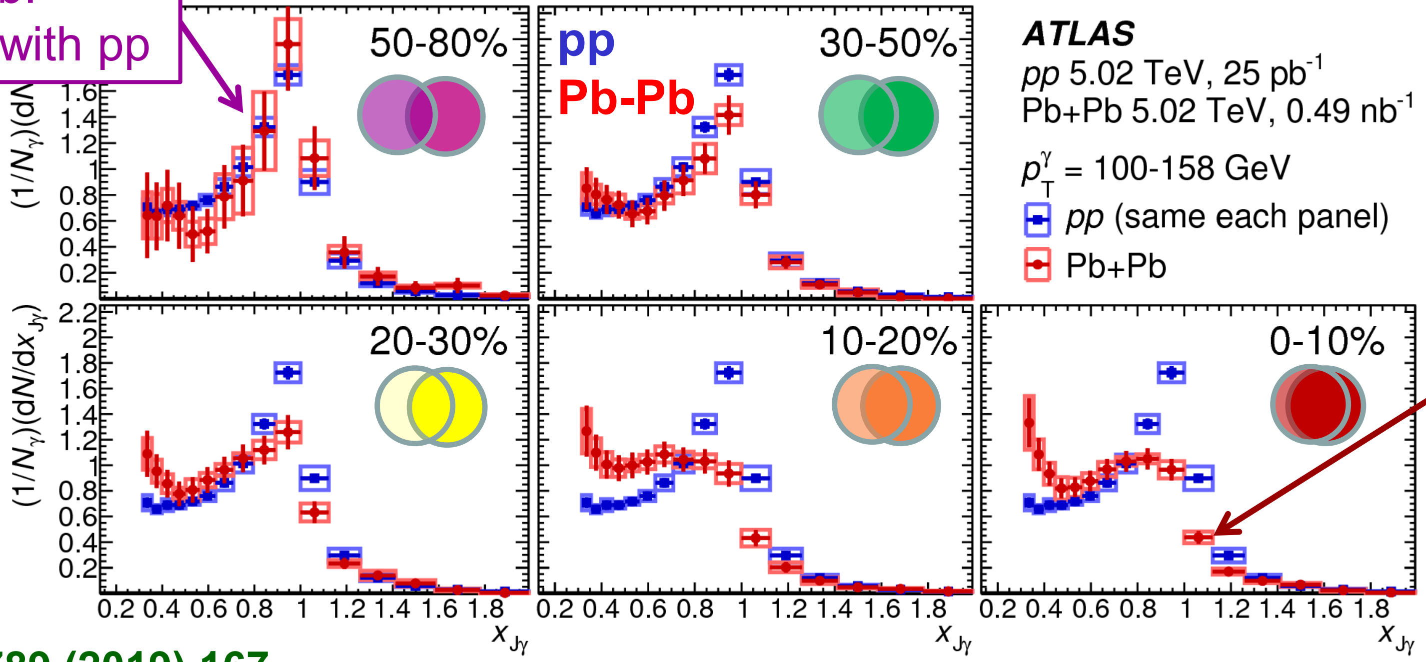
📖 **CMS, PLB 861 (2025) 139088**

Photon-jet correlations

- Photon-jet p_T balance:
  - ⇨ Photon does not interact strongly in the QGP
  - ⇨ Access to p_T of hard-scattered parton before it loses energy in the medium
- Momentum balance quantified by $x_{J\gamma}$: $x_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$



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

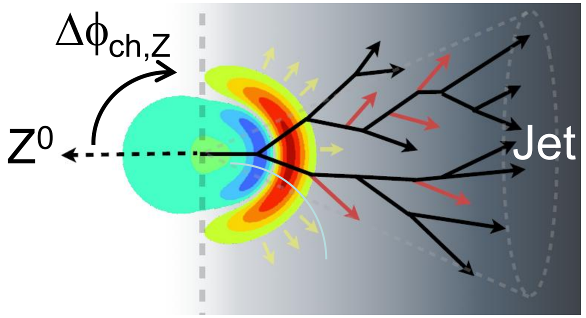


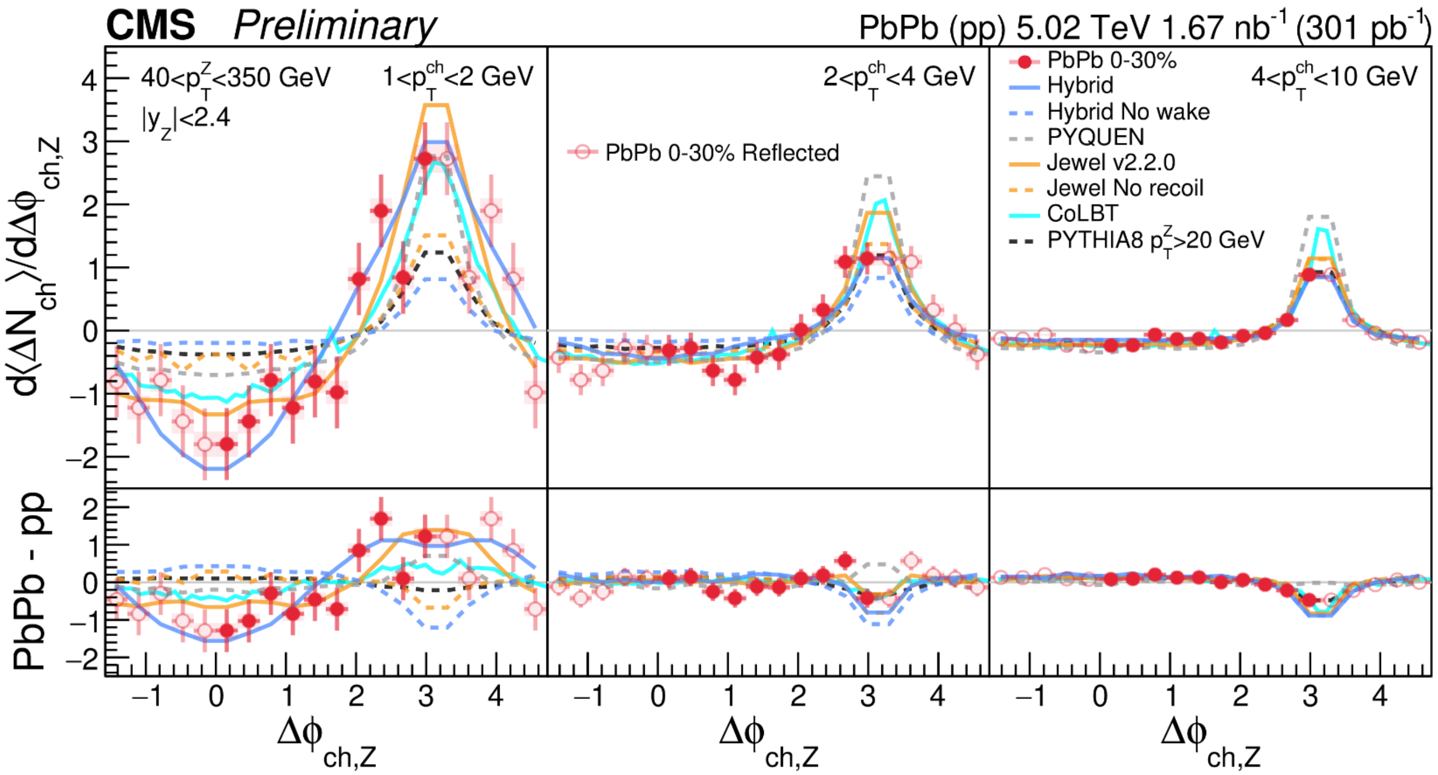
Central Pb-Pb:
- Strong modification
- No peak at $x_{J\gamma}$~1
- Due to parton in-medium energy loss

📖 **ATLAS, PLB789 (2019) 167**

Medium response via Z^0+jet events

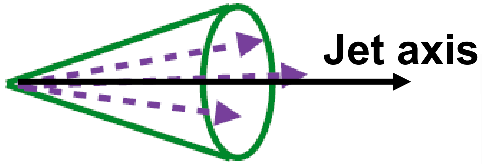
- Explore medium response by measuring yield of Z^0-tagged charged hadrons vs. azimuthal angle relative to Z^0 ($\Delta\phi_{ch,Z}$)
  - ➪ Modified in central Pb-Pb as compared to pp collisions
  - ➪ Data better described by models that include medium recoil effects
  - ➪ First evidence of medium response effects caused by a hard probe





CMS, PAS HIN-23-006

Fragmentation functions

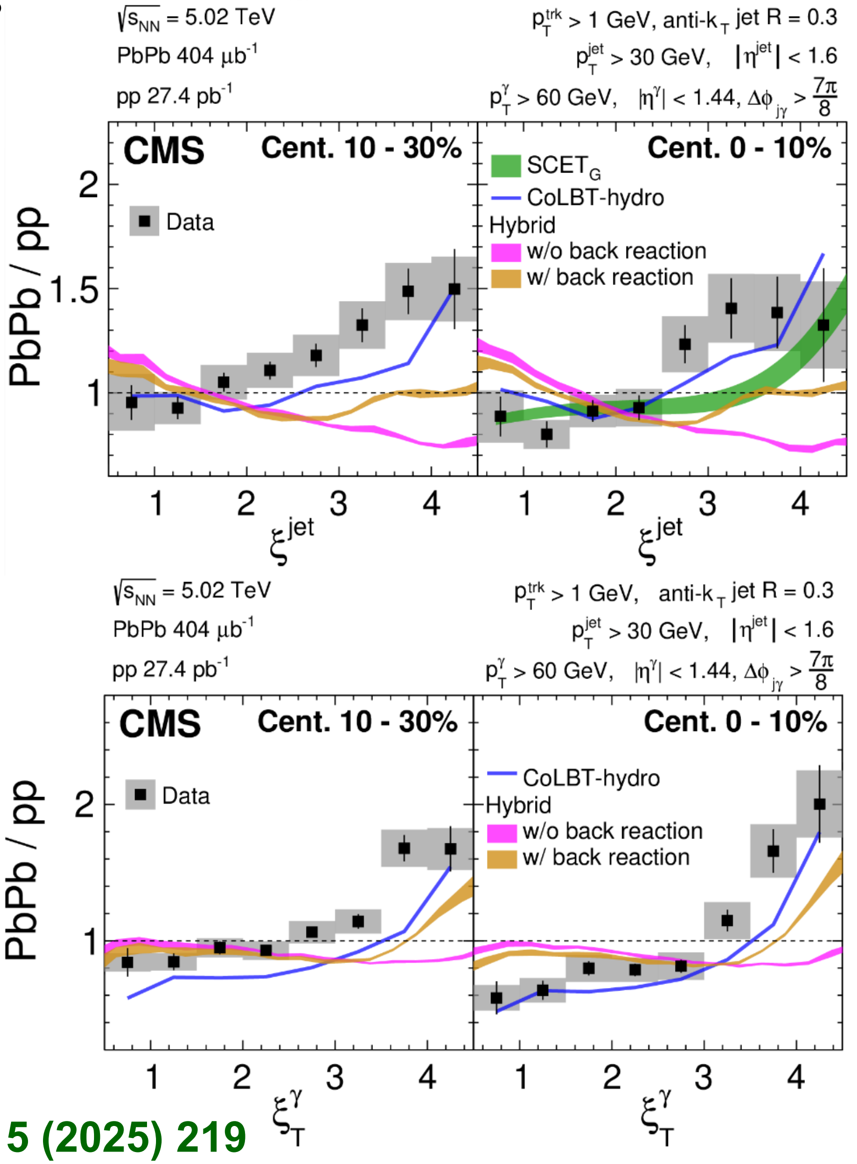


$$z = \frac{p_{||}^{\text{track}}}{p^{\text{jet}}}$$

↓

$$\xi^{\text{jet}} = \ln\frac{1}{z} = \ln\frac{|\vec{p}^{\,\text{jet}}|^2}{\vec{p}^{\,\text{track}}\cdot\vec{p}^{\,\text{jet}}}$$

$$\xi_T^{\gamma} = \ln\frac{-|\vec{p}_T^{\,\gamma}|^2}{p_T^{\text{track}}\cdot\vec{p}_T^{\,\gamma}}$$

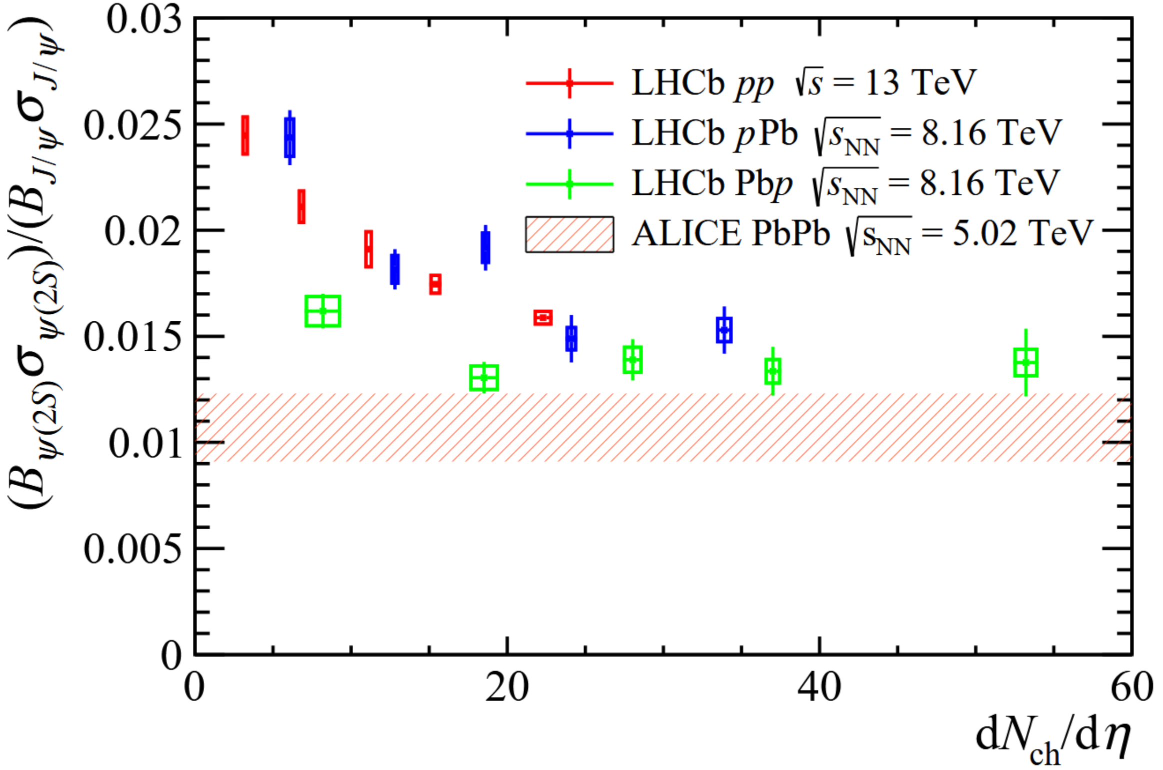


- Distributions of particle momenta within the jet modified in Pb-Pb collisions with respect to pp
  - ⇨ Jet fragmentation affected by jet quenching
- Fragmentation functions of jets associated with isolated photons
  - ⇨ Allows for tagging the properties of the initial parton before quenching occurs
- Enhancement of soft particles (large ξ)
  - ⇨ Energy lost transmitted to low-momentum particles within and around the jet
- Suppression of particles at high and intermediate p_T (small ξ)
- Data qualitatively described by models
  - ⇨ Medium response needed in the hybrid model

📖 CMS, Phys.Rept. 1115 (2025) 219

Charmonia in p-Pb collisions

📖 LHCb, arXiv:2506.08624



- Ratio of Ψ(2S) / J/ψ yield vs. multiplicity
  - ⇨ For p-Pb configuration (charmonia measured in the p-going direction)
    - ✓ ***Decreasing ratio with increasing multiplicity***
    - ✓ ***Trend compatible with measurements in pp collisions, described by models with dissociation by comoving hadrons***
  - ⇨ For Pb-p configuration (charmonia measured in the Pb-going direction)
    - ✓ ***No significant dependence on multiplicity***
    - ✓ ***Stronger Ψ(2S) suppression with flatter behaviour, compatible with ALICE Pb-Pb results***

→ Additional suppression mechanisms in the Pb-going direction beyond comover effects?