Future physics programme and facilities for relativistic heavy-ion collisions

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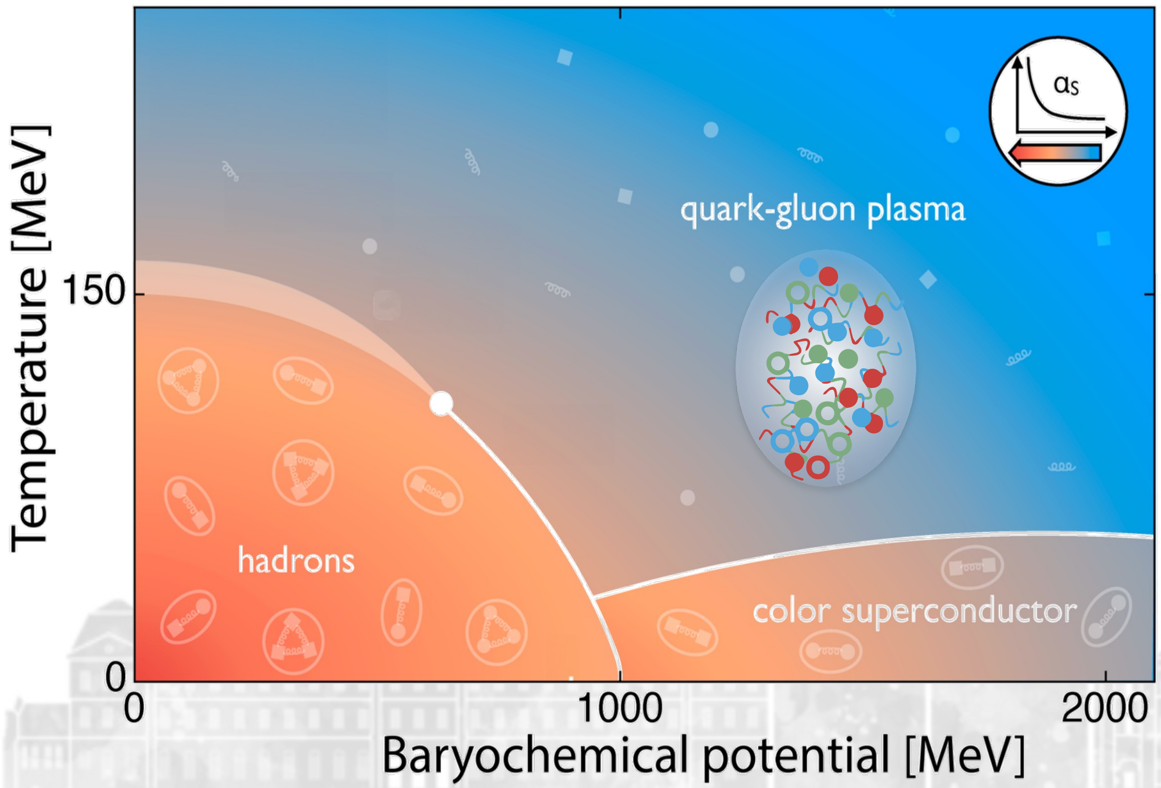
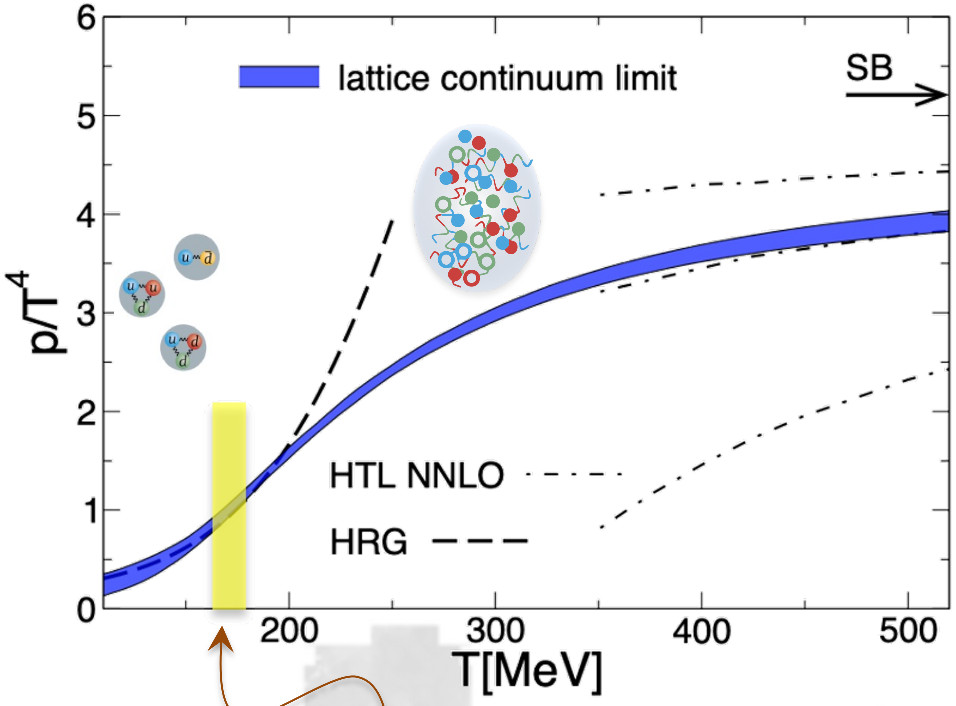
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN
MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

The phase diagram of QCD matter

At **high temperature**, hadronic matter undergoes a **phase transition to the quark-gluon plasma (QGP)**
- colour confinement is removed
- quark and gluon degrees of freedom (vs hadronic)



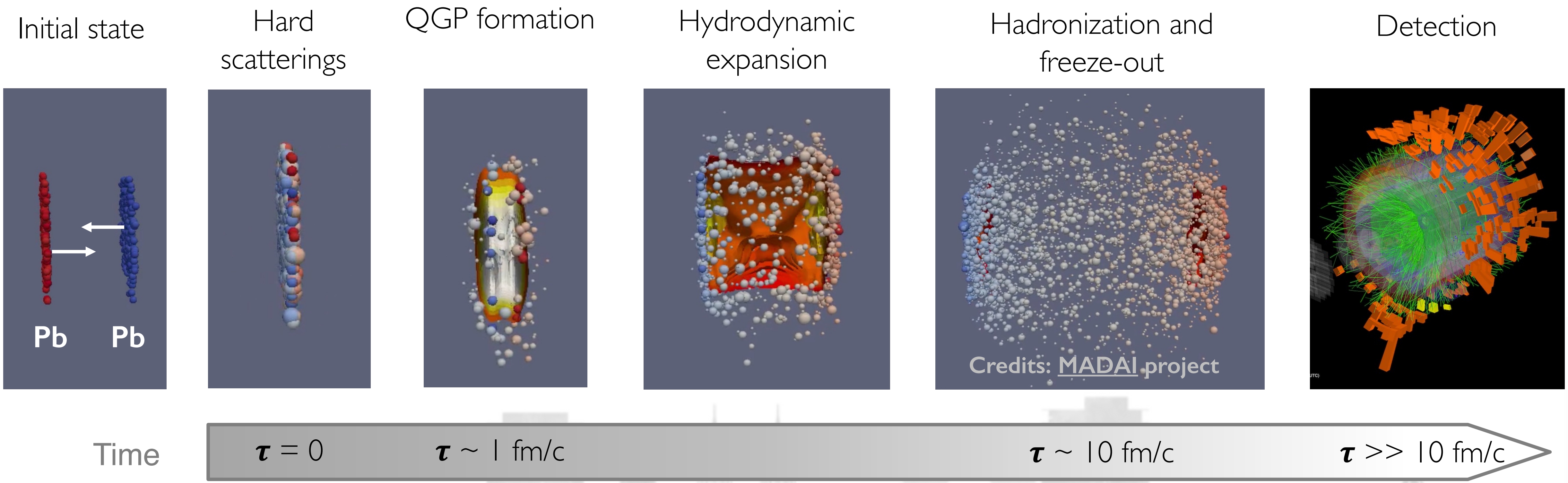
Bazavov et al. **[PRD 90 094503 (2014)]**



p / T^4 (~ n_{dof}): **changes rapidly** at T_c ~155 MeV

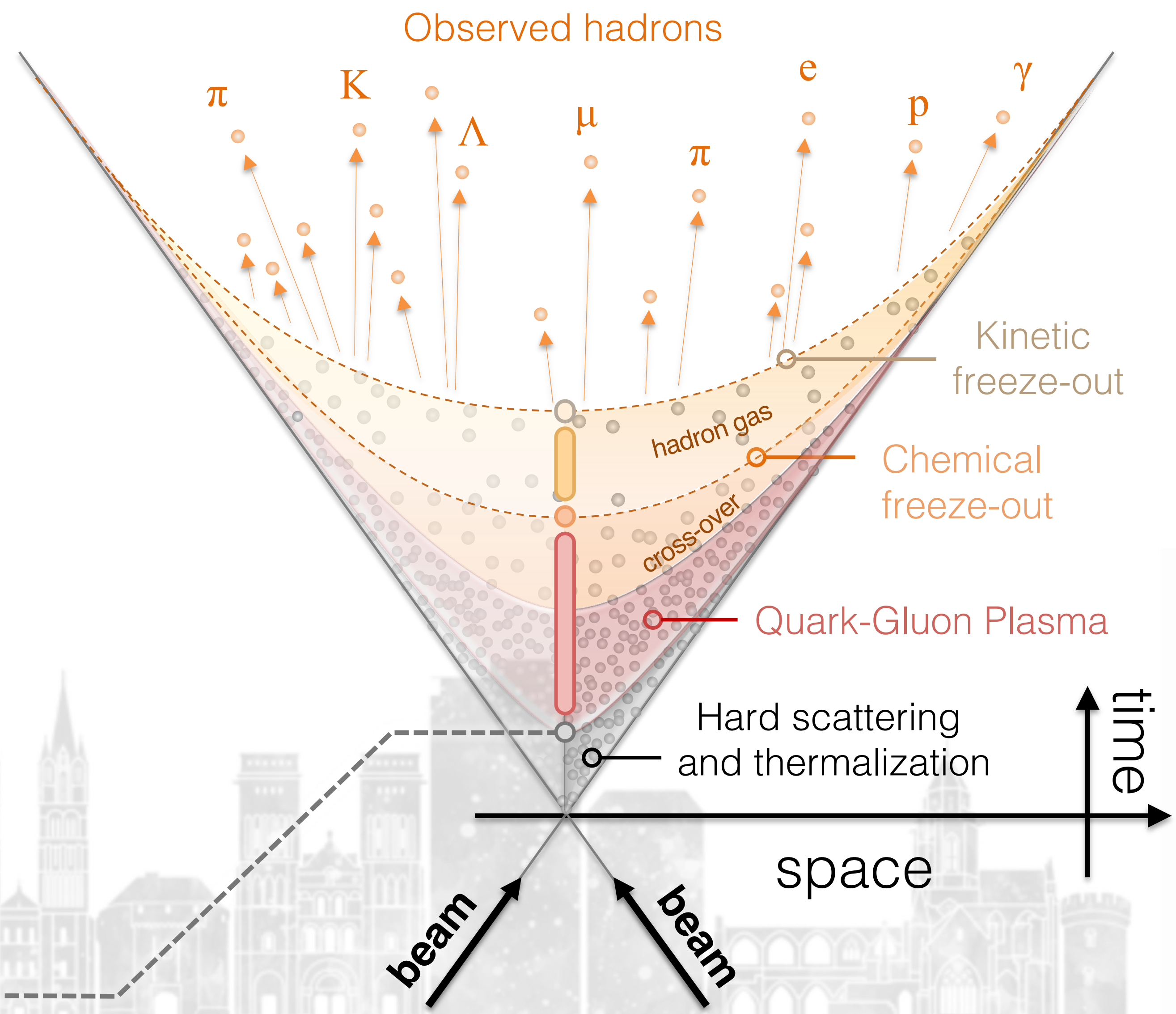
Corresponds to a density of:
$\rightarrow\ \varepsilon_c = 0.6\ \text{GeV/fm}^3 \rightarrow \sim 10 \times \varepsilon_{\text{nucleus}}$

Heavy-ion collisions and the quark-gluon plasma



- **Heavy ion collisions**: crucial to **measure the properties of deconfined QCD matter** in the laboratory

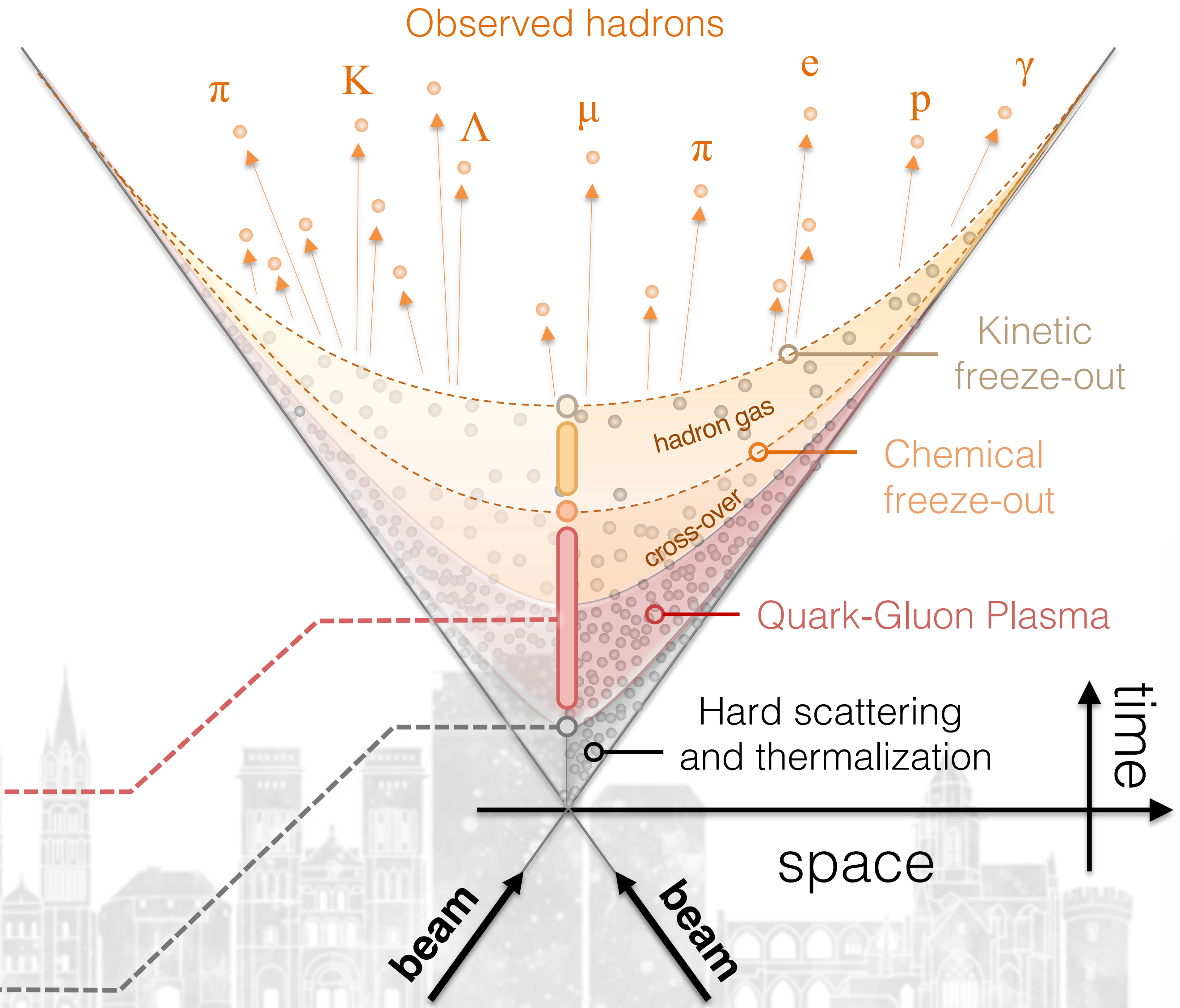
State-of-the-art of QGP knowledge at the LHC



Energy density ε at 1 fm/c	14 GeV/fm^3

Check out Kara Matioli's talk Monday 12:00

State-of-the-art of QGP knowledge at the LHC



Momentum transf. per unit length $\hat{q}/T^3$	2-11
Diffusion coefficient $2\pi TD_s$ at T_c	1.5-4.5
Shear viscosity to entropy η/s at T_c	0.06-0.12
Effective temperature (direct photons)	304±41 MeV
Energy density ε at 1 fm/c	14 GeV/fm^3

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State-of-the-art of QGP knowledge at the LHC

Chemical freeze-out temperature T_{ch}	156±2 MeV
Net baryon density μ_B	0.71±0.45 MeV
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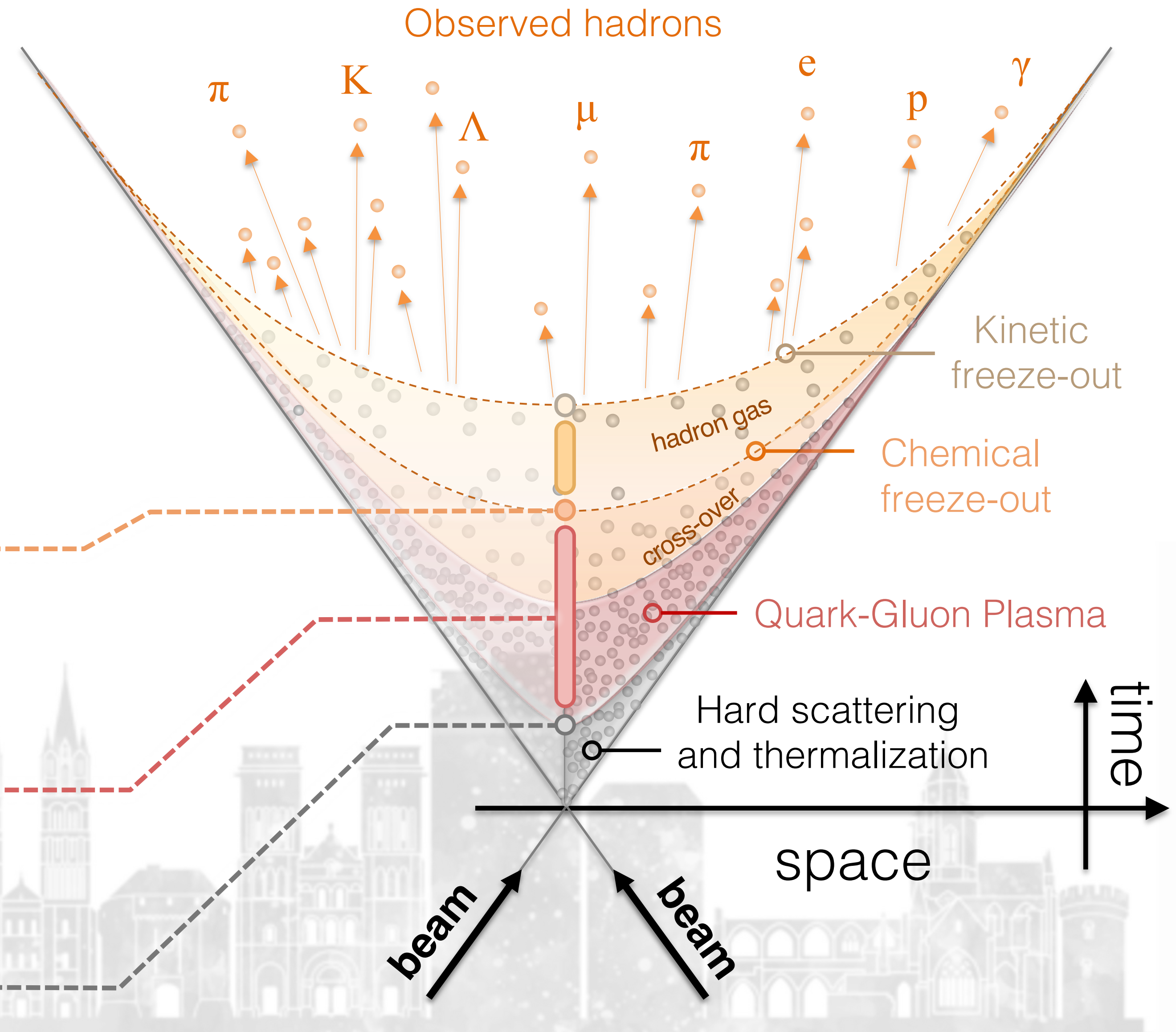

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State-of-the-art of QGP knowledge at the LHC

Kinetic freeze-out temperature T_{kin}	100-150 MeV
Transverse velocity at freezeout $v_{T,kin}$	≅ 0.65c
Duration of hadronic phase τ_{had}	≅ 1-few fm/c
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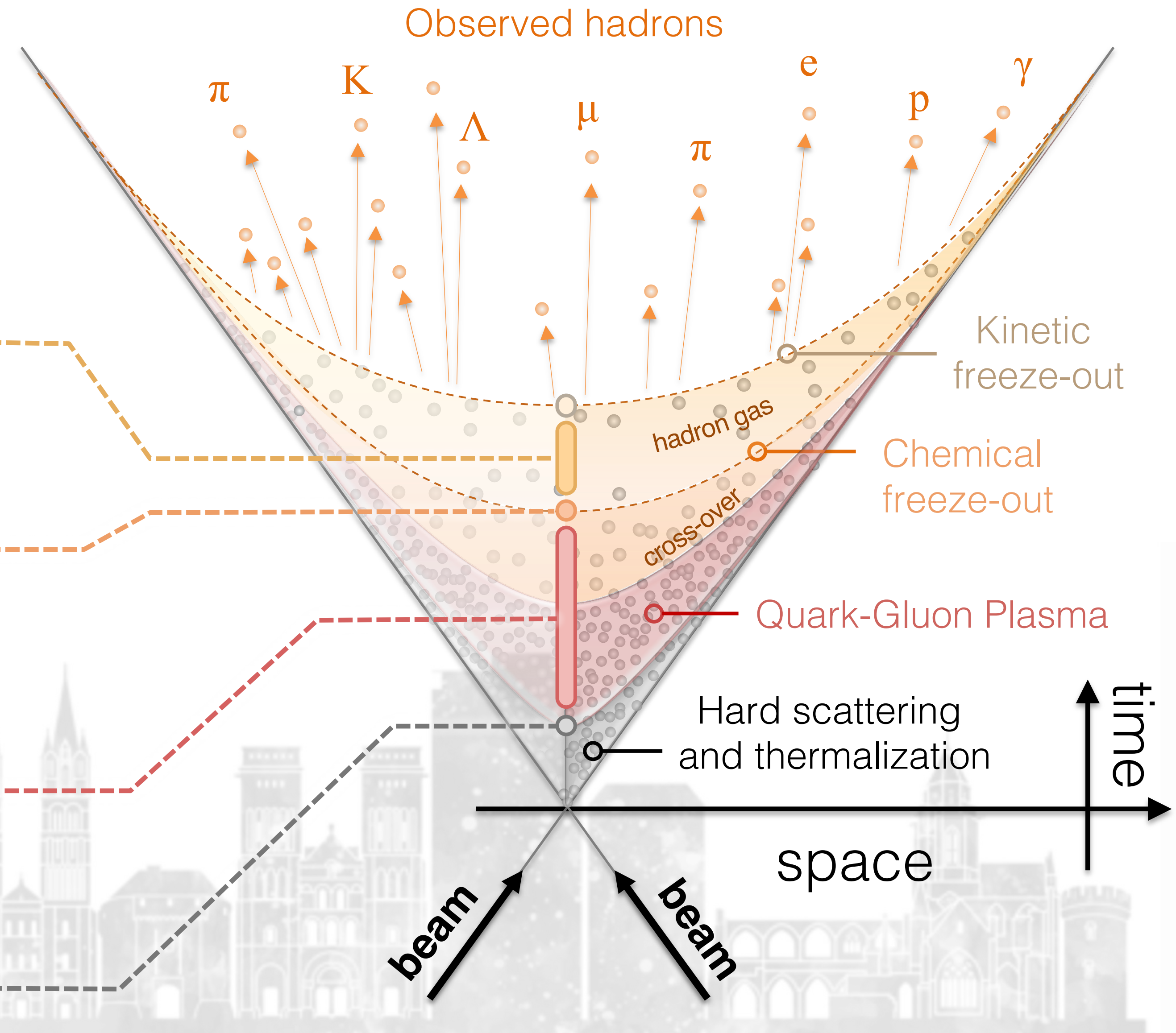

Check out Kara Matioli's talk Monday 12:00

State-of-the-art of QGP knowledge at the LHC

Volume at decoupling V_{dec}	~5000 fm^3
Decoupling time τ_{dec}	~10 fm/c
Energy density at decoupling $\varepsilon(\tau_{dec})$	0.4 GeV/fm^3
Kinetic freeze-out temperature T_{kin}	100-150 MeV
Transverse velocity at freezeout $v_{\mathrm{T,kin}}$	≅ 0.65c
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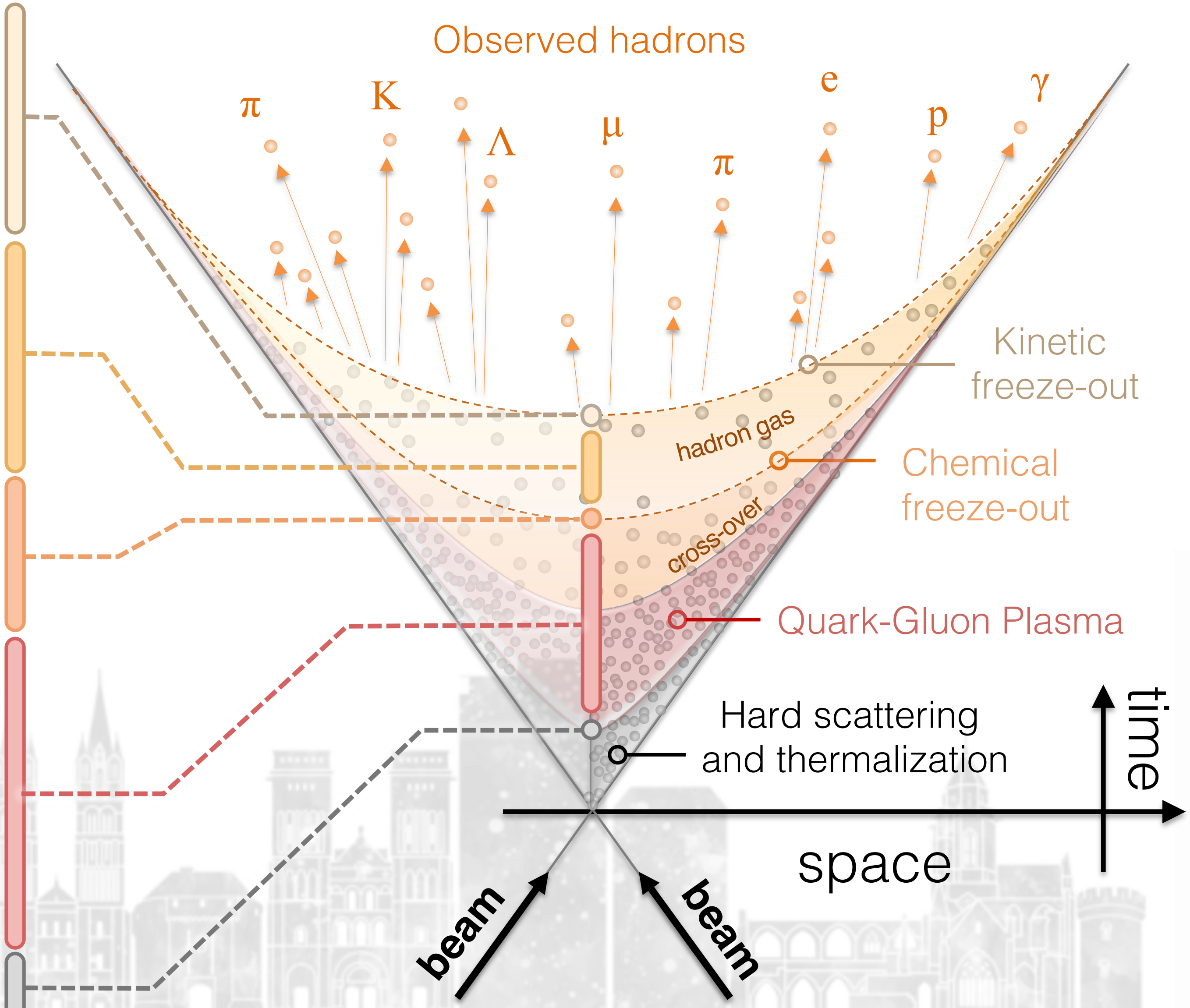

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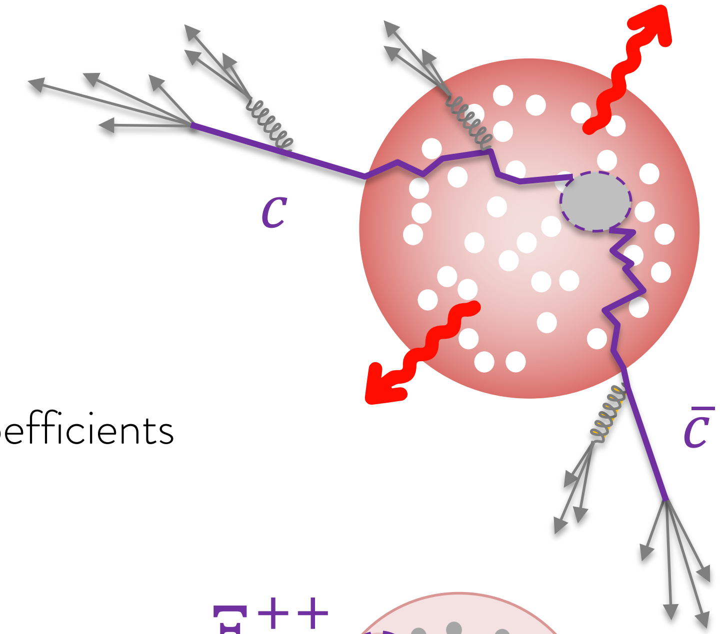
Open questions in heavy-ion physics



- **<u>Evolution</u> of a QCD many-body system**
  - How does the QGP **temperature** and density evolve with time?
  - Evolution conected to kinematic equilibration: hydrodynamic description, transport coefficients
  - How do **heavy flavour** quarks propagate in the medium?
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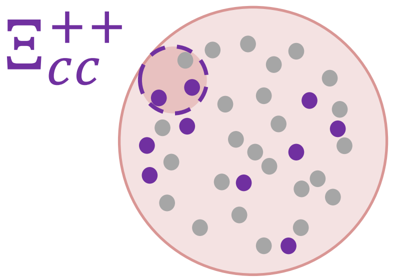


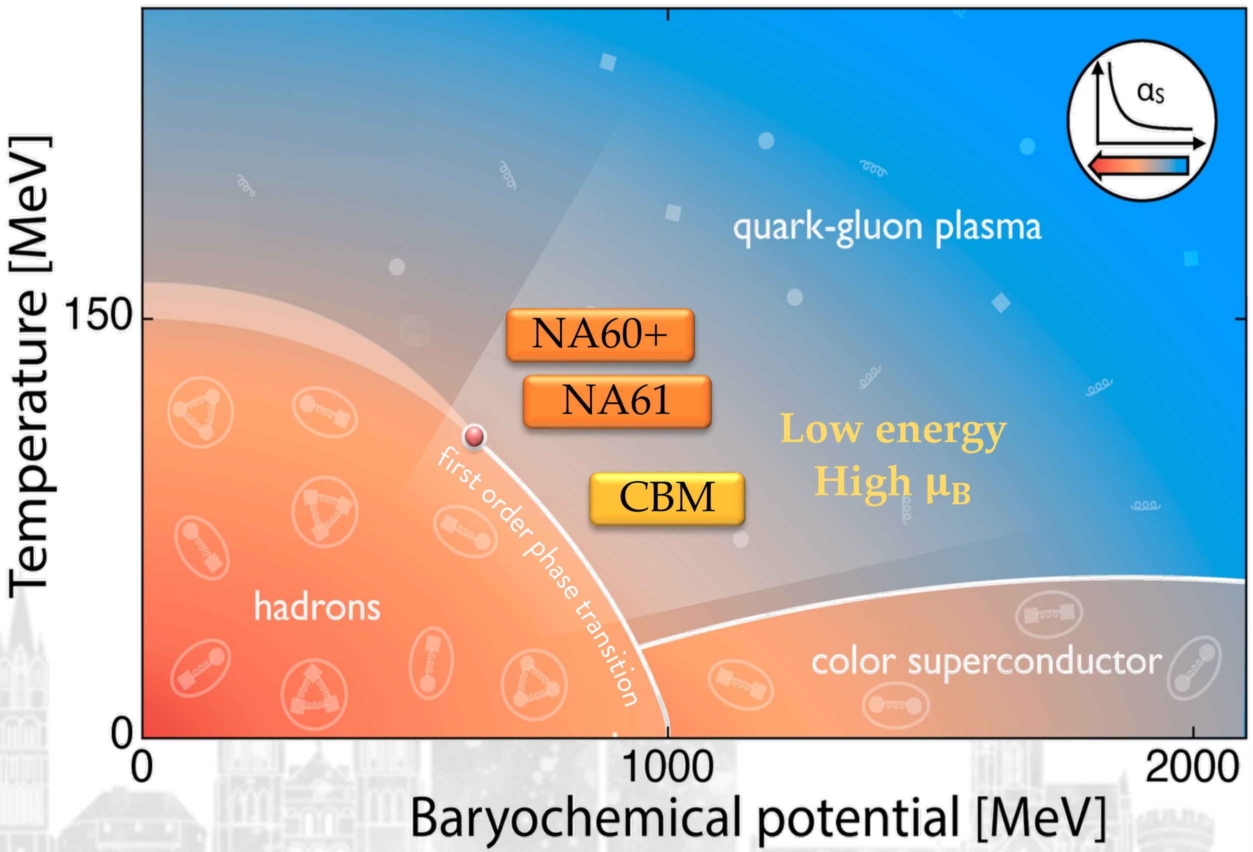
- **How are hadrons <u>formed</u>** in a dense environment?
  - Hadronization and relationship to statistical principles: realm of thermal models
  - How are **heavy quarks** distributed in hadronization?
  - Open heavy flavour quarks: charm fugacity, hidden flavour: quarkonium melting/regeneration

- **How do dense QCD effects and collectivity emerge** in small systems down to pp?
- **Under which conditions** in the QCD phase diagram does one obtain a first-order phase transition?

The phase space of future directions in heavy ion physics

Low energy: SPS ~ 5-17 GeV, FAIR ~ 2-5 GeV

- Temperature of QCD matter (temp. vs. energy)
- Search for the Critical Endpoint (●)



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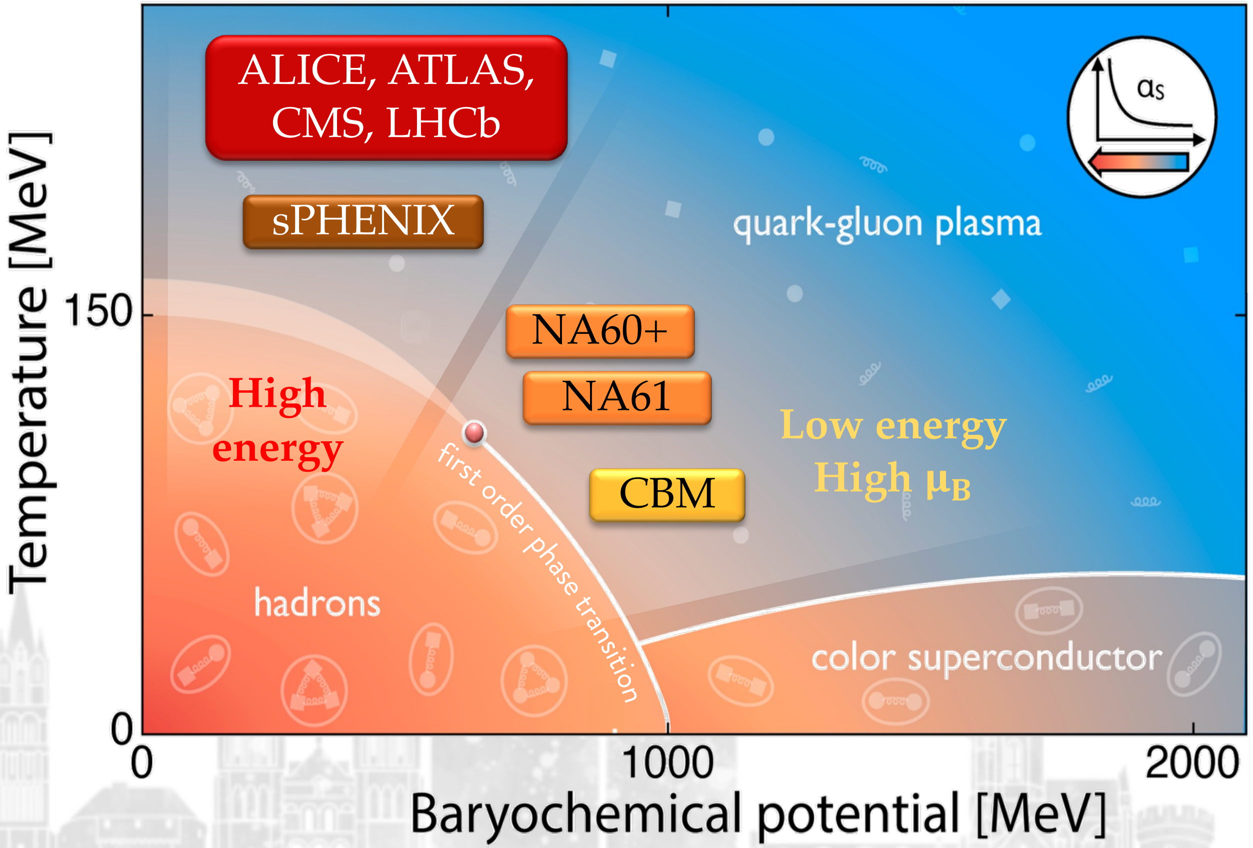
High energy collisions: HL-LHC ~ 5.5 TeV

- Time-evolution of a many-body QCD system: linking elementary QCD interaction to equilibration at macroscopic level
- Systematic exploration of QGP properties - precision!



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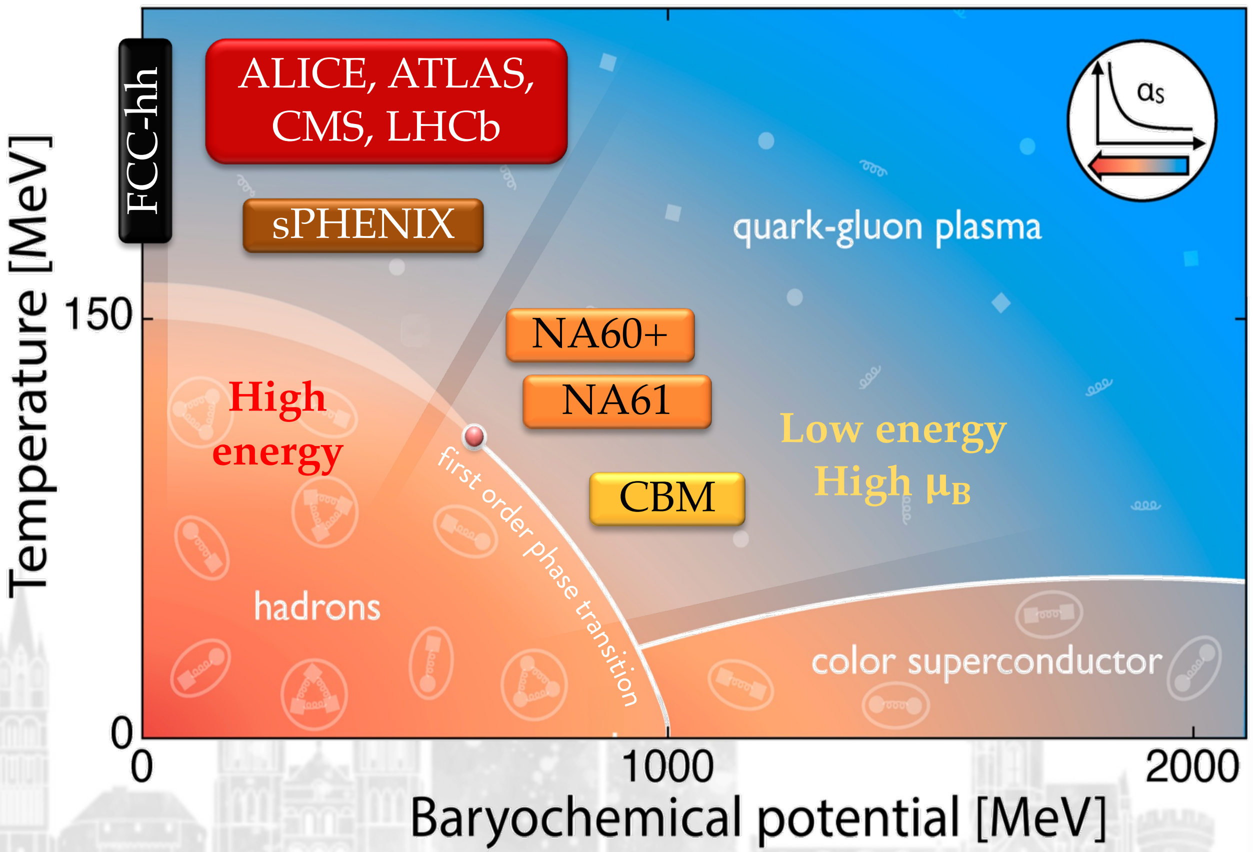
Far future: FCC-hh ~ 35 TeV

- New rare probes and time-scales of the QGP accessible
- Thermal charm, boosted top decays, …



Heavy ions at lower energies / high μ_B:

NA60+ and NA61 at SPS and CBM at FAIR SIS-100

NA60+/DiCE: dimuon spectrometer following a silicon pixel tracker (ALICE ITS3 MAPS)

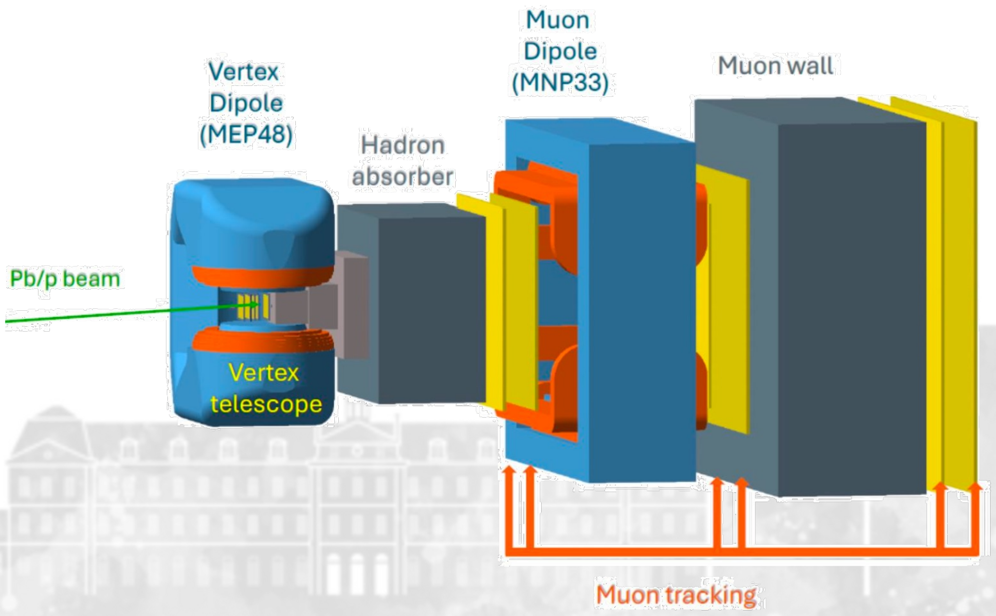
- Thermal dimuons; HF/strangeness, critical point search
- Letter of Intent positively reviewed by SPSC in 2023
- Proposal submitted in spring 2025
- Data taking ~2029-2036
- beam energy scan 20-150 GeV/nucleon

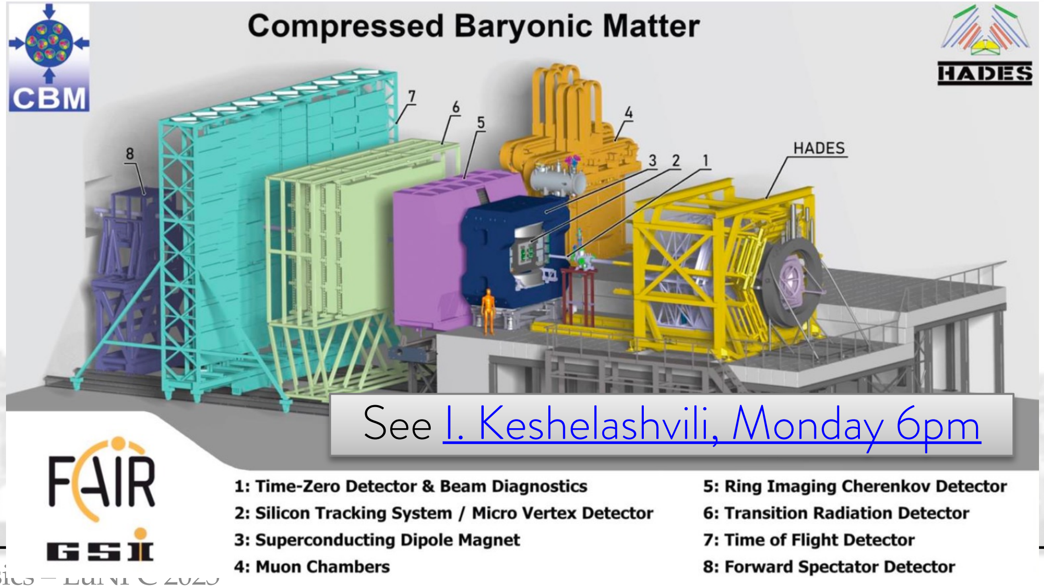
NA61/Shine: large-acceptance hadron detector, upgraded with silicon pixel tracker (ALICE ITS2 MAPS)

- Onset of deconfinement and critical point search
- Data taking < 2033; light-ion collision systems
- Proposed upgrade (TPC → Silicon) for high-rate Pb-Pb

CBM/HADES: silicon tracking; hadron, m and e ID

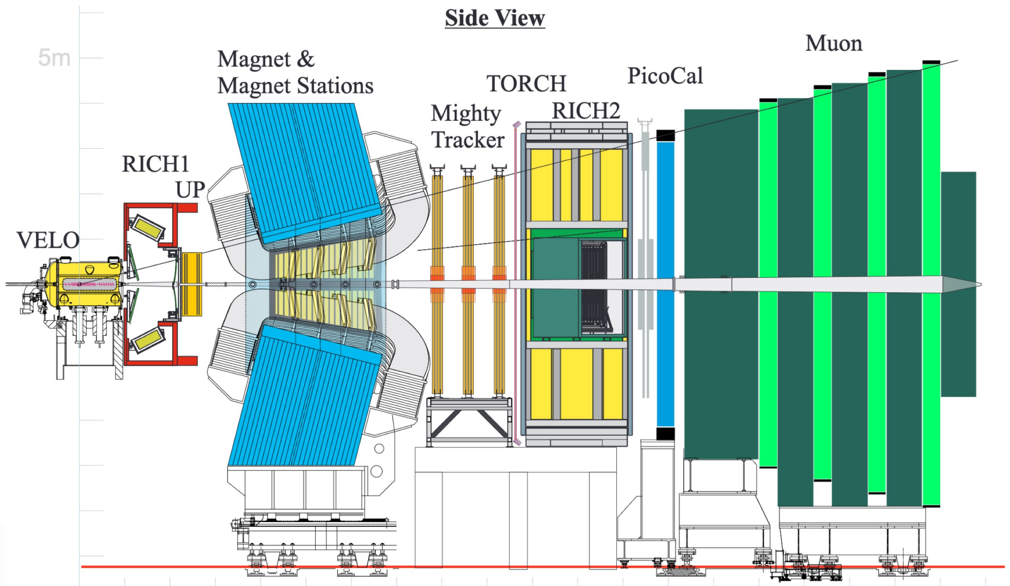
- QGP characterization (including T) and critical point search
- At new accelerator SIS-100 at FAIR – Data taking ~ 2029

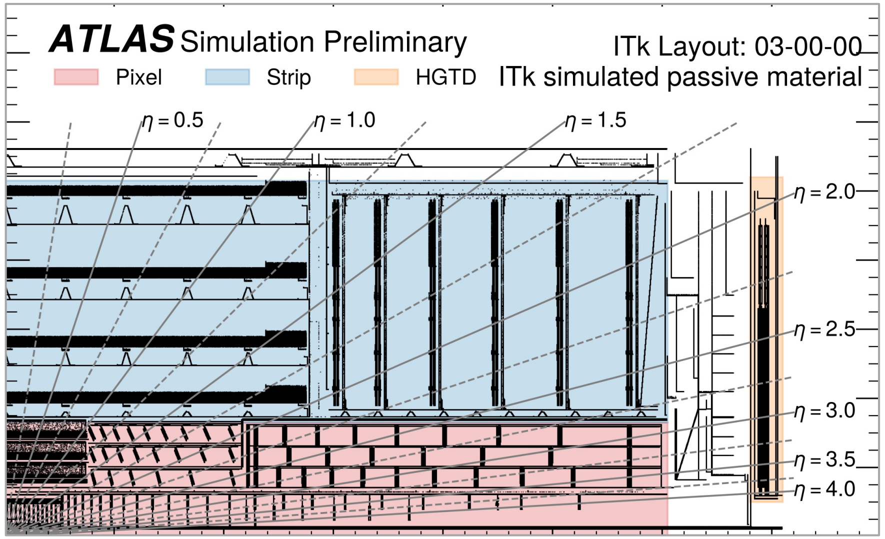




See I. Keshelashvili, Monday 6pm

High energies and full exploitation of the LHC:
LHCb upgrade 2 and ATLAS / CMS phase II





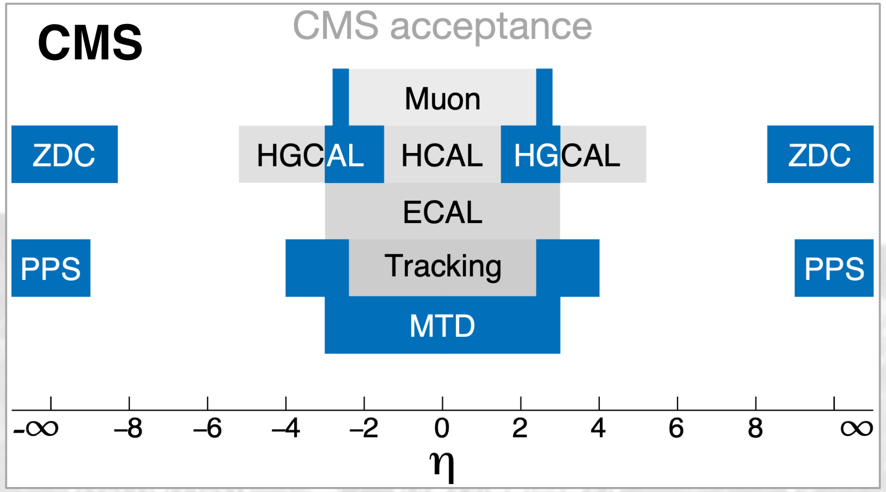
LHCb upgrade 2

extend tracking capabilities to central Pb-Pb

Acceptance up to η = 5

fixed-target $\sqrt{s_{NN}} = 70$ GeV with SMOG2

Framework TDR: CERN-LHCC-2021-012
Scoping Document: CERN-LHCC-2024-010



ATLAS, CMS phase II

Upgrade for runs 4+5

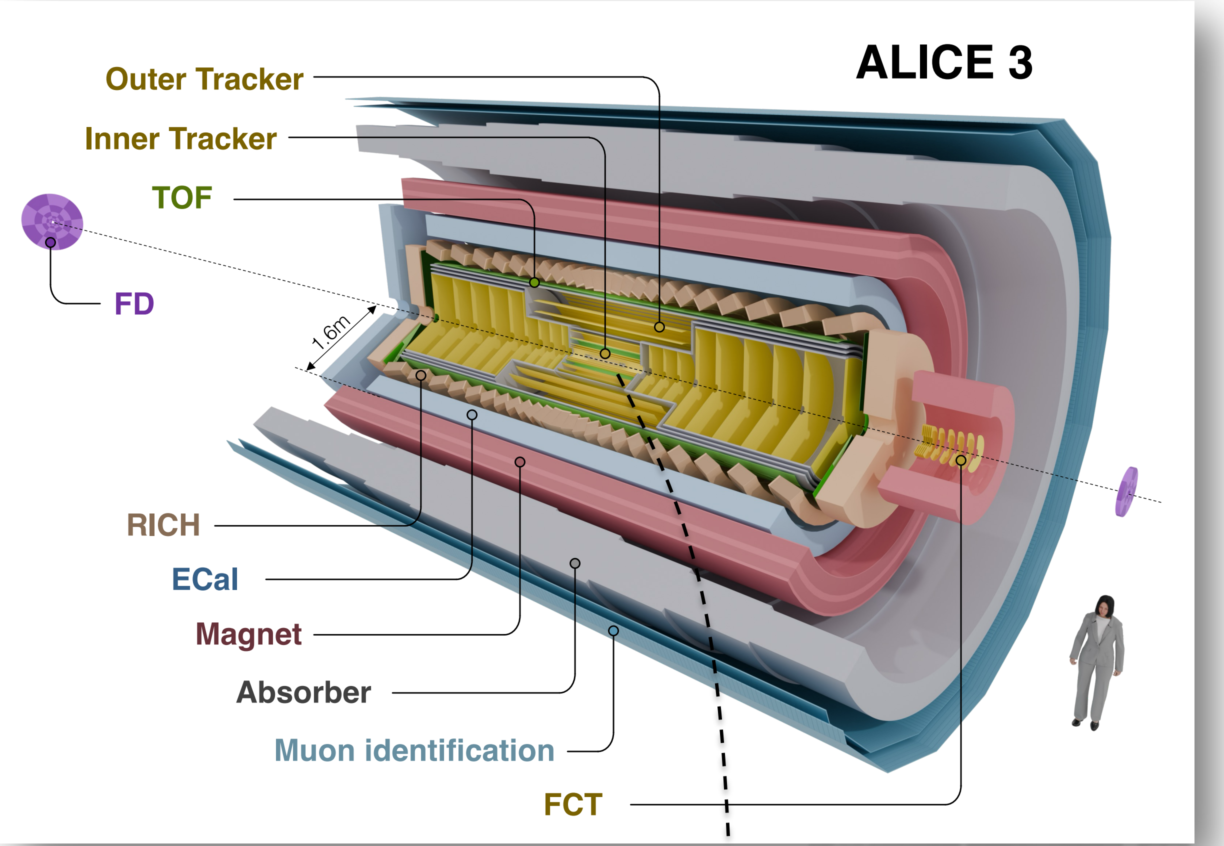
Extend tracking to $|\eta|$ = 4

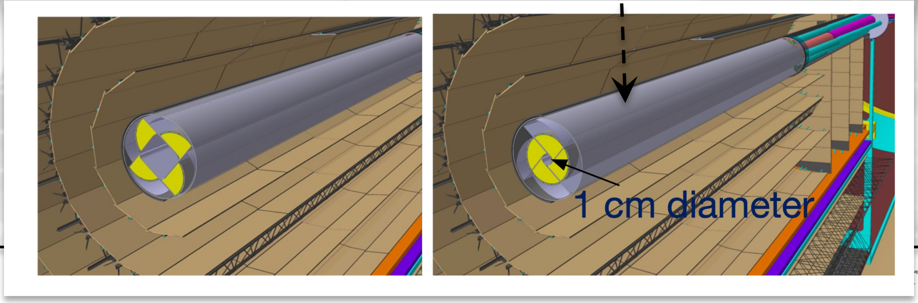
Increased DAQ bandwidth and new h ID (CMS MTD)

More on SMOG(2): G. Ricart, Tuesday 3:15pm

High energies and full exploitation of the LHC:

The ALICE 3 experiment





- **All-silicon, large-acceptance, very light tracker**
  - High rate: 5x bigger luminosity, exploit LHC
  - Momentum precision of $\sigma_p/p \sim 1\%$
- **State-of-the-art particle identification**
  - Silicon-based TOF and RICH
  - Muon identification
- **Unprecedentedly high vertexing precision**
  - First layer at 5 mm from interaction point
  - Impact parameter resolution:
    - ~10 μm at p_T ~200 MeV/c
    - ~3 μm at p_T >1 GeV/c

- Major physics goals:
  - **Heavy-flavour quark thermalization**
  - **Thermal emission of the Quark-gluon plasma**

See D. Colella, Monday 5pm

Letter of Intent: CERN-LHCC-2022-009
Scoping Document: CERN-LHCC-2025-002

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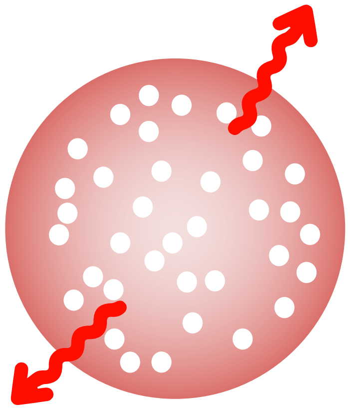

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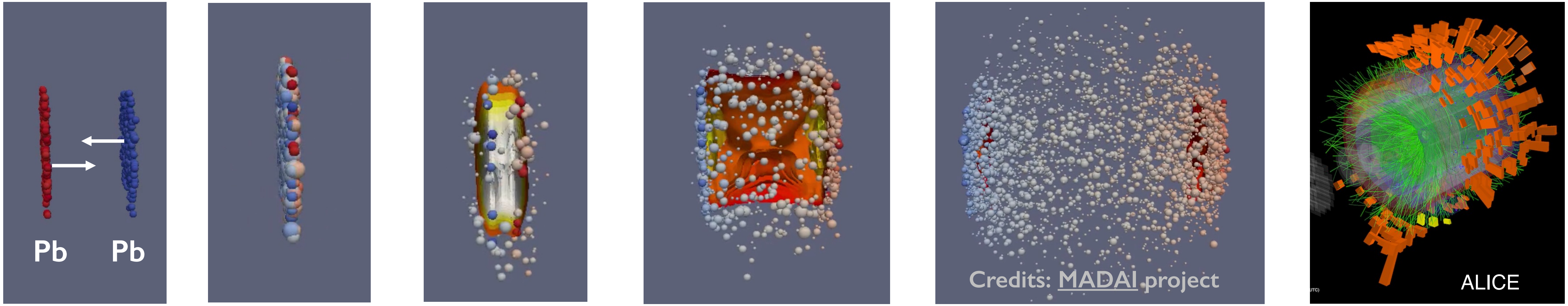
The temperature of the QGP

Initial state | Hard scatterings | QGP formation | Hydrodynamic expansion | Hadronization and freeze-out | Detection



Time: $\tau = 0$ → $\tau \sim 1$ fm/c → $\tau \sim 10$ fm/c → $\tau > 10$ pm/c

Temperature: T ~ 200-800 MeV [1] | T ~ 155-100 MeV [4]

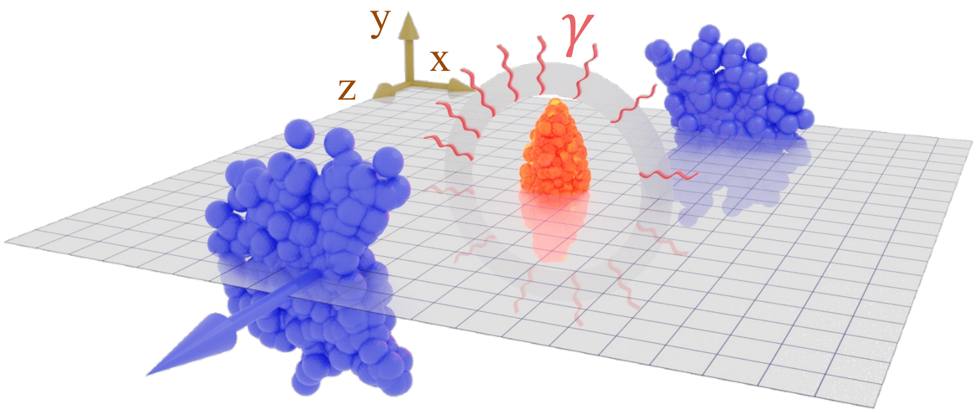
$T_{c,\,lQCD} \sim$ 155-159 MeV [2,3]

[1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
[2] A. Bazavov et al., Phys. Lett. B 795 (2019)
[3] Borsaniy et al. PRL 125 (2020) 5, 052001
[4] A. Andronic et al., Nature 561 (2018) 7723, 321-330

304±41 MeV ≅ **5.5 million Kelvin**
[Highest (effective) temperature ever]
100000x hotter than the center of the sun

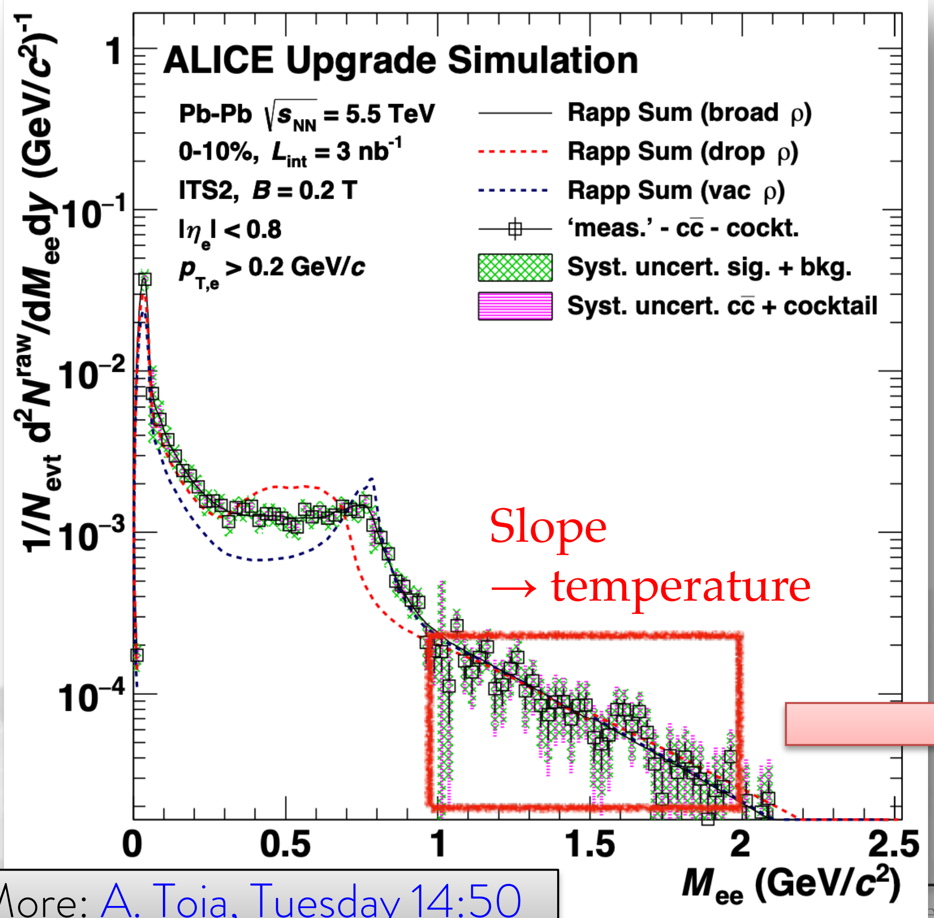
How can pre-hadronization temperatures be measured?

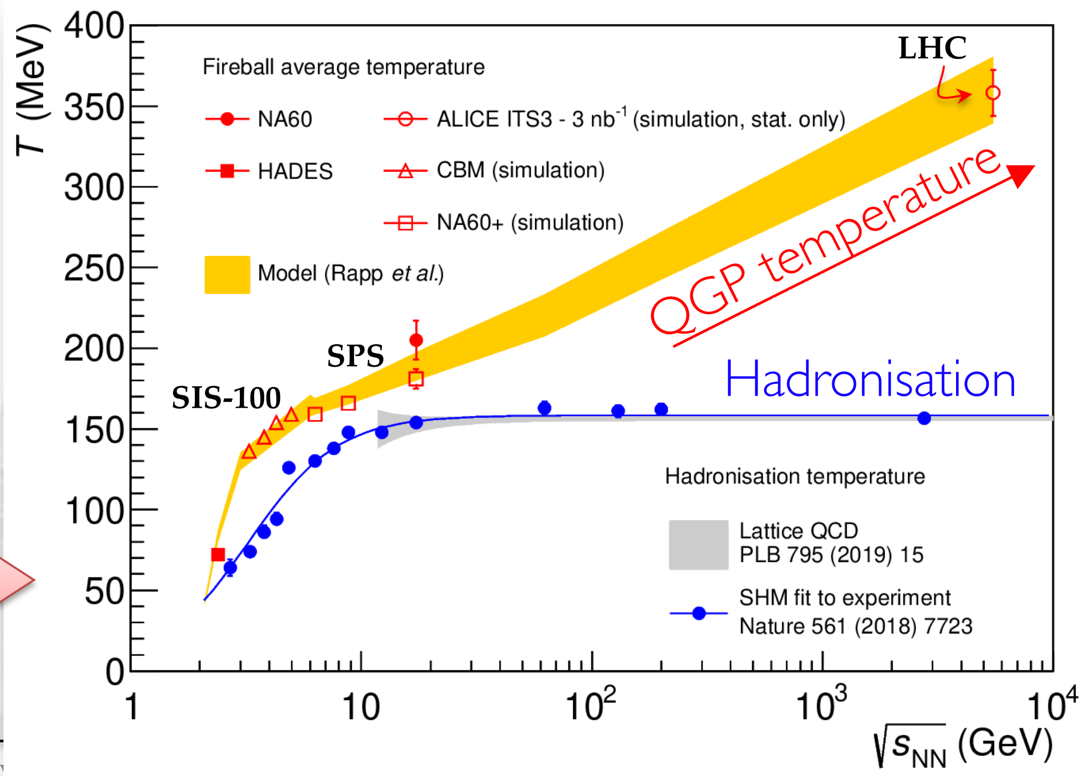
Measuring thermal emissions of the QGP



- Measurements thus far: direct photons, blue shifted
- Opportunity: **dielectron invariant mass spectra**
  - Direct access to (invariant) temperature!
  - But very challenging: HF background
- SIS-100, SPS, LHC Runs 3+4:
  - time-averaged QGP temperature, ~5% precision

[CERN-LPCC-2018-07]



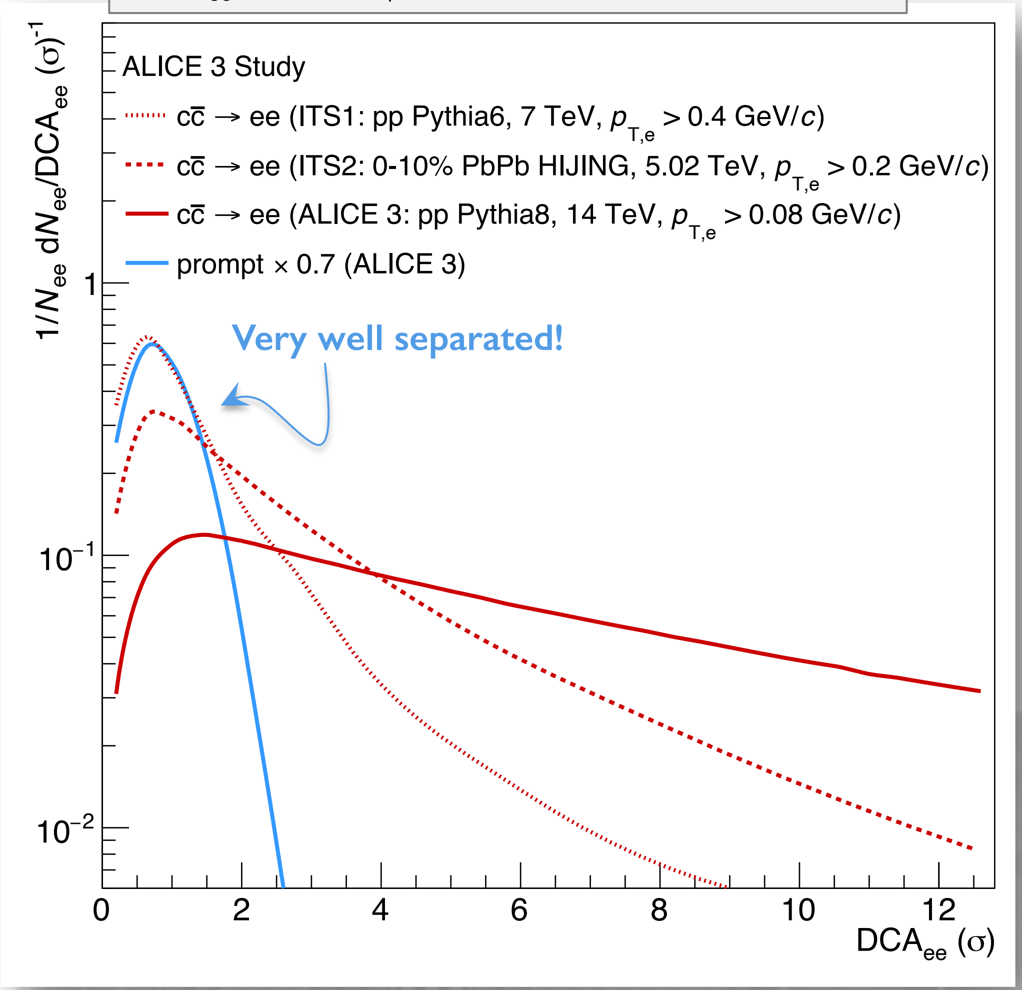


T. Galatyuk, https://github.com/tgalatyuk/QCD_caloric_curve

More: A. Toia, Tuesday 14:50

Dileptons as a QGP thermometer with ALICE 3

DCA$_{ee}$: Sum of squares of normalized DCAs to PV



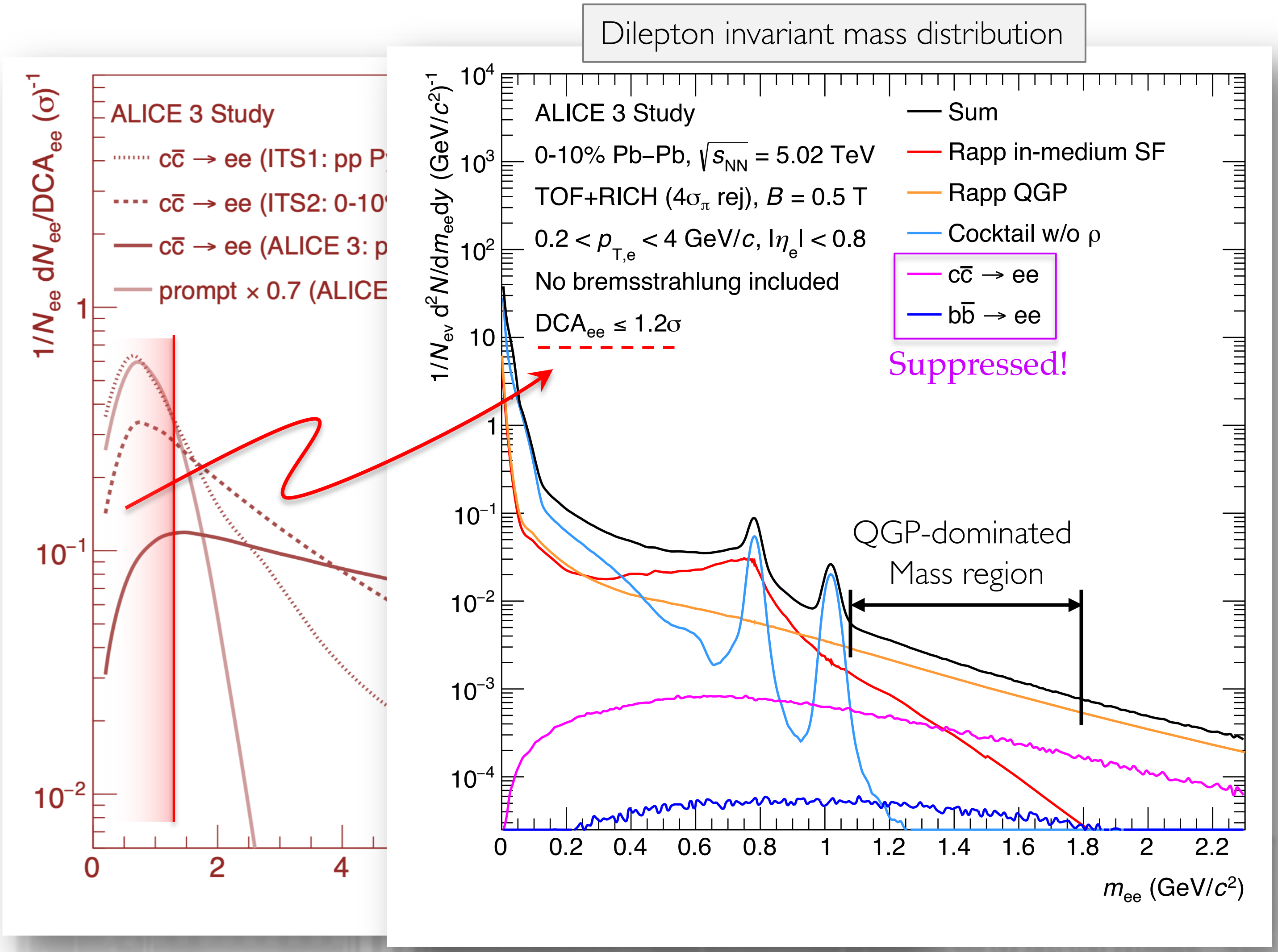
→ **Specificity of ALICE 3 for dileptons:**

High-precision tracking
- 1st layer at R = 5mm

Electron Identification
- Time-of-flight (TOF) via silicon
- Ring-imaging Cherenkov (RICH)
- Electromagnetic Calorimeter

Unprecedented HF rejection and wide-p_T range e ID
- DCA$_{ee}$: separation of e^+e^- pairs and HF daughters
  - ALICE 3: extreme performance!
  - Sets the stage: the ultimate dielectron experiment

Dileptons as a QGP thermometer with ALICE 3



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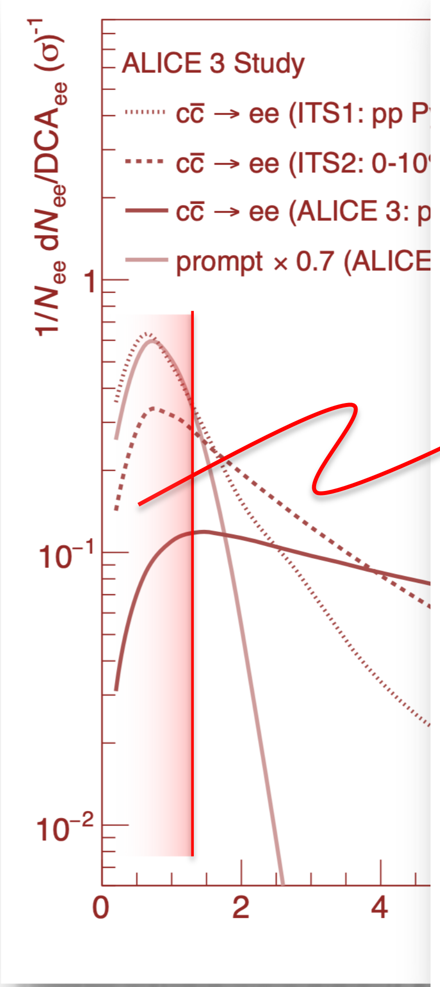
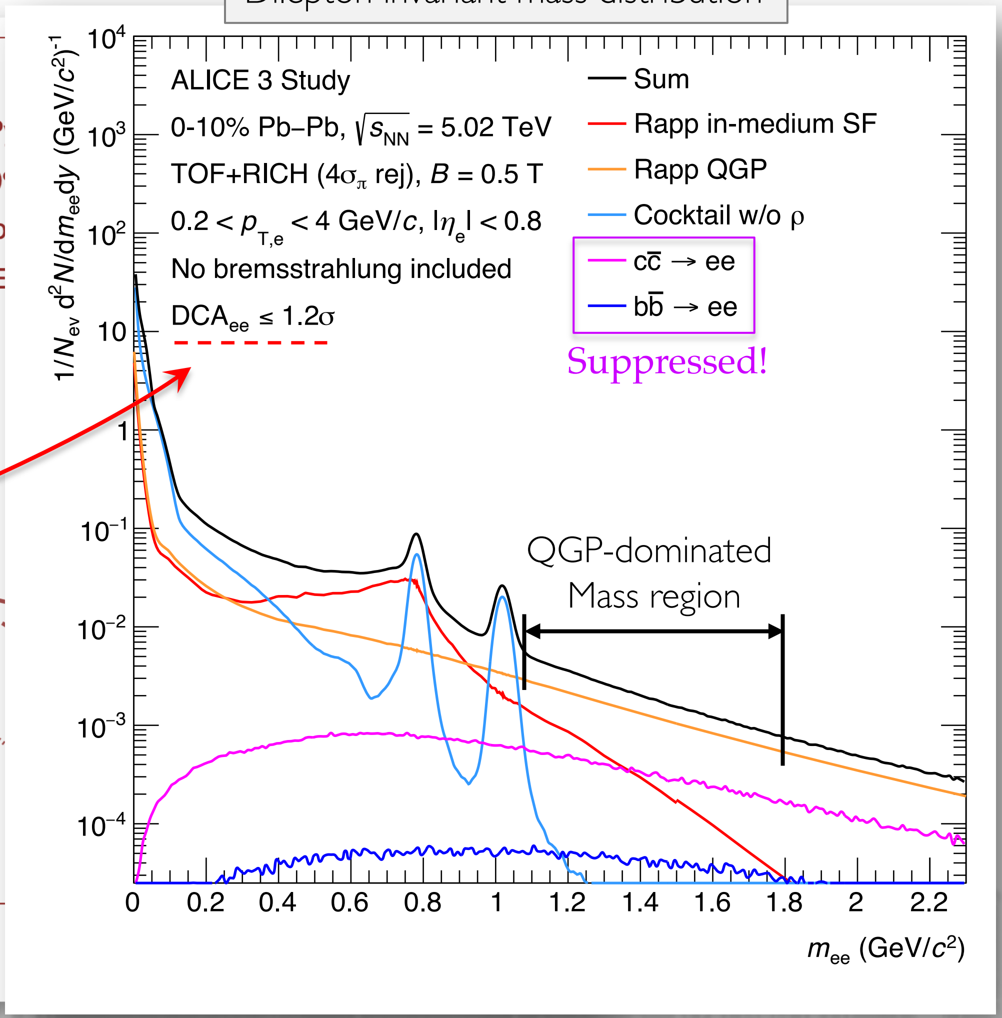
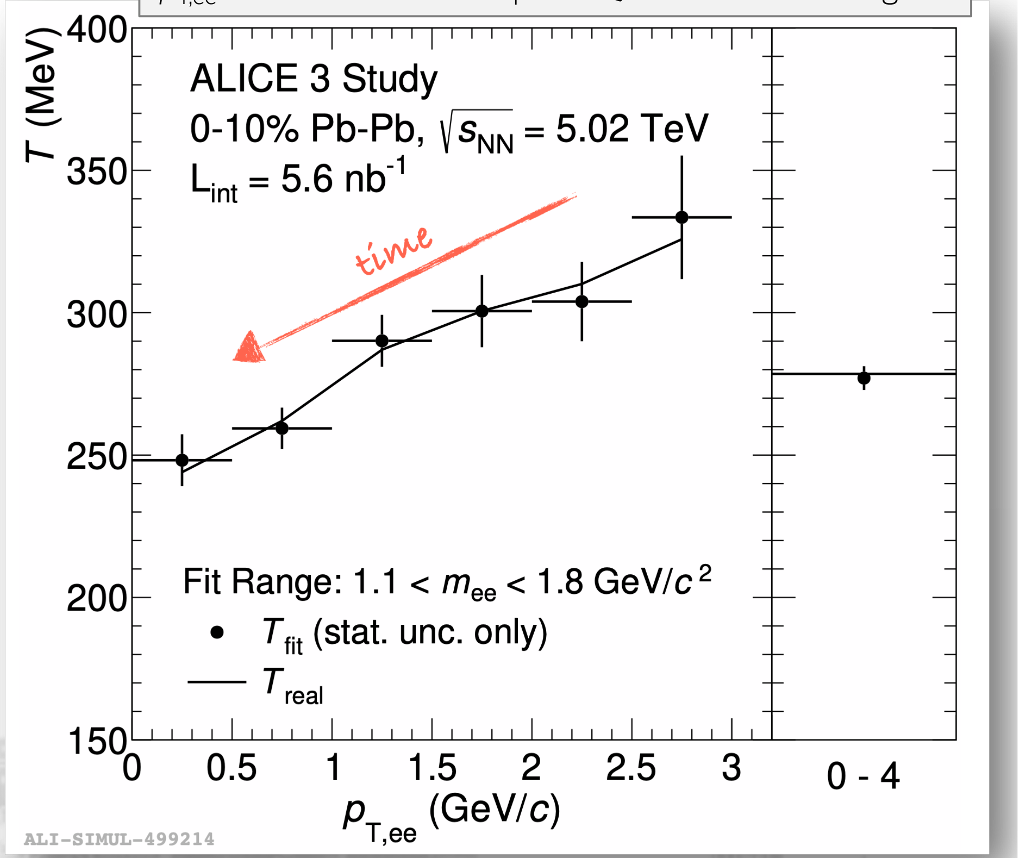


Dilepton invariant mass distribution



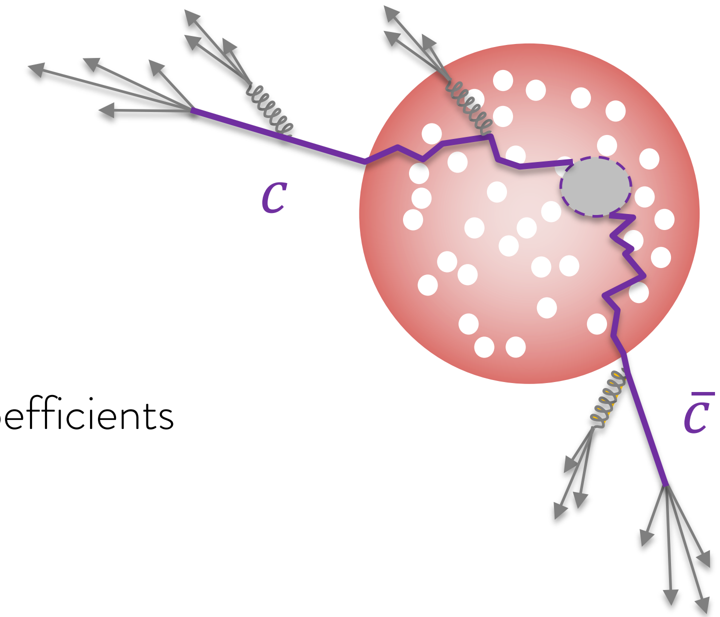
$p_{T,ee}$-differential mass slope in QGP-dominated region



Differential analysis in $p_{T,ee}$:

- Unique opportunity to probe system evolution!

Open questions in heavy-ion physics



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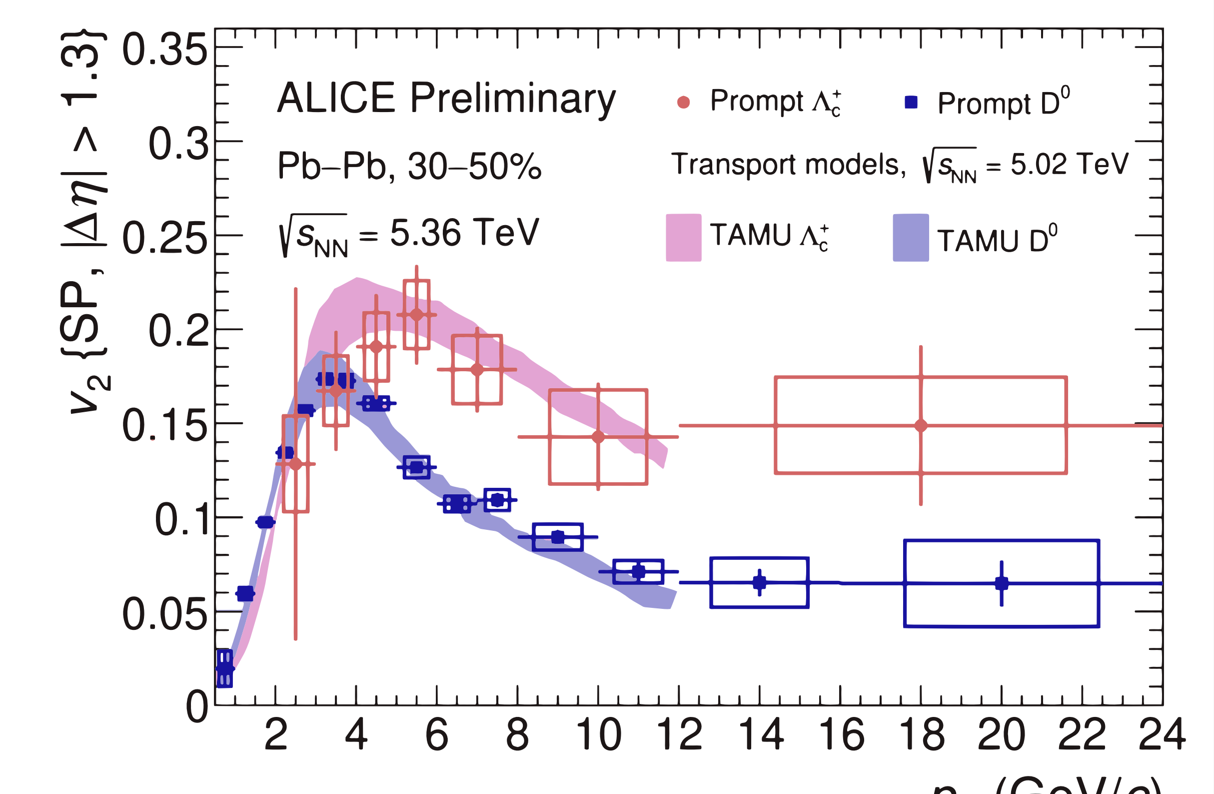
Measuring charm collectivity: current status

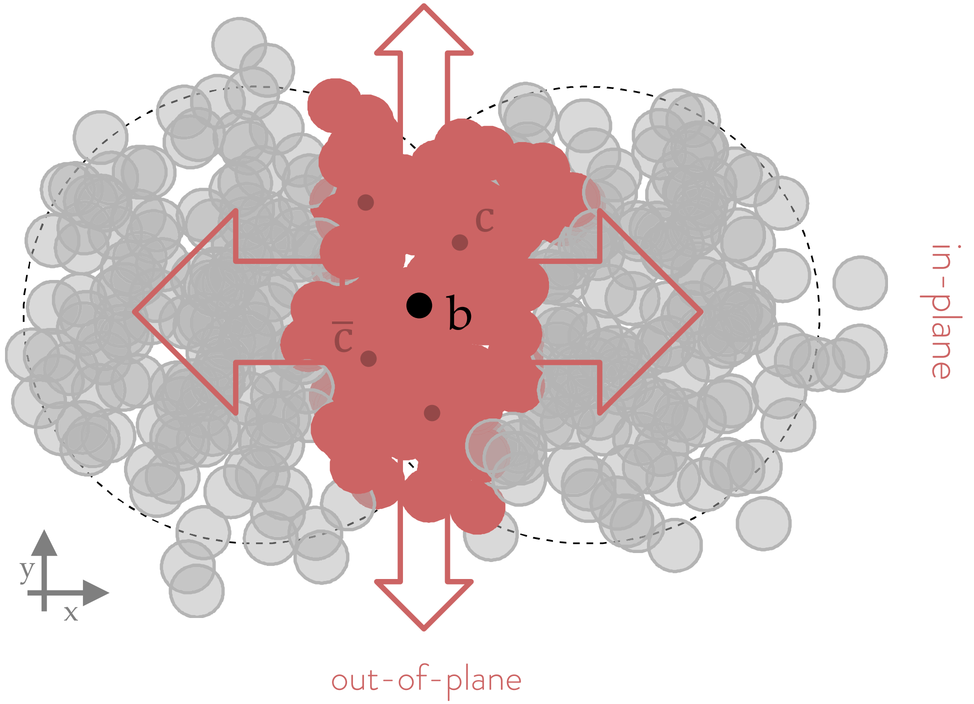
Nearly all particle species participate in collective flow

- quantified via a Fourier decomposition:

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{\infty} v_n(cos[n(\varphi - \Psi_n)])\right)$$



Leading term: v_2, "elliptic flow"



- D^0 and Λ_c^+ v_2 measured in Run 3 by ALICE
  - Fundamental to Run 3+4 physics programme, viable with large samples and upgraded precision
  - Described by **quark coalescence** mechanism
- **Does this extend to beauty hadrons?**
  - So far measured with limited precision / indirectly

More on collectivity N. Valle, 2pm, Gl. Nijs, 2:25pm, B. Kardan 3:35pm (Monday)

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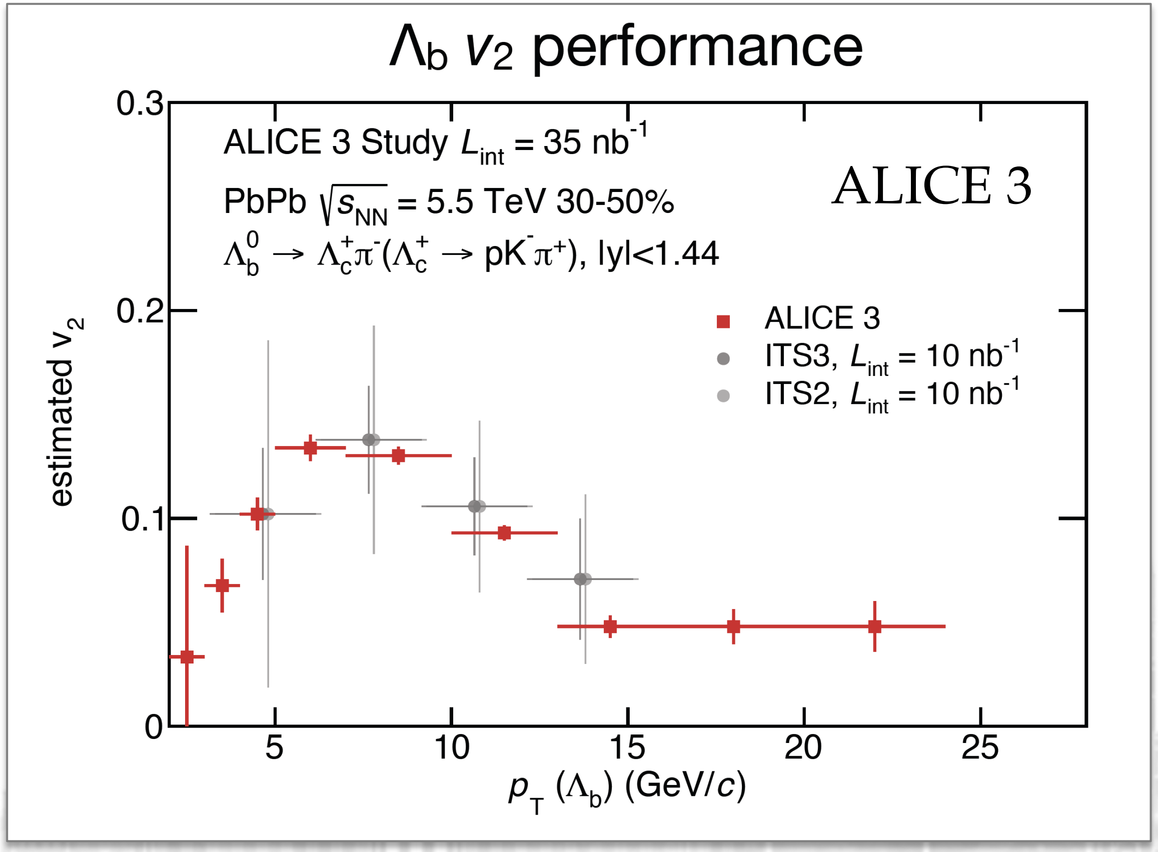

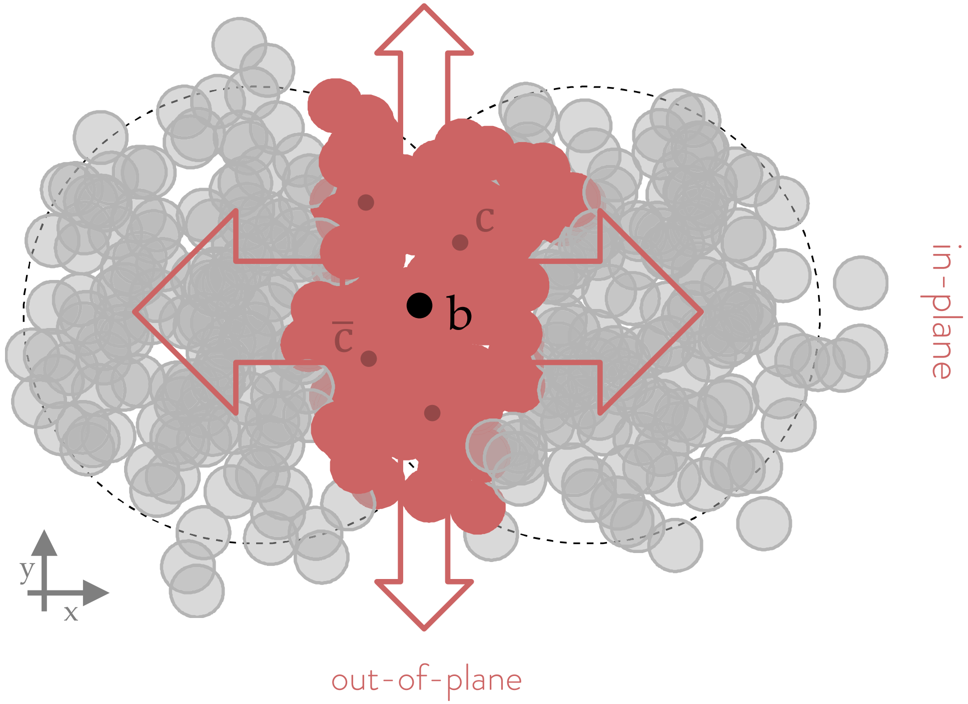

- B^+ and Λ_b^0 elliptic flow…
  - …measurement with large uncertainties in Run 4
  - …**precise measurement in Run 5 with ALICE 3** down to zero low p_T due to improvement in pointing precision
- N.B.: value in figure is **estimate with full kinematic equilibration** (blast wave / simplified hydro model)
  → unclear if this will be the case → crucial measurement!

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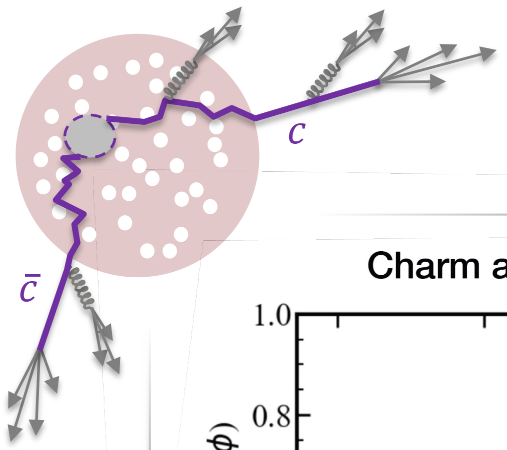
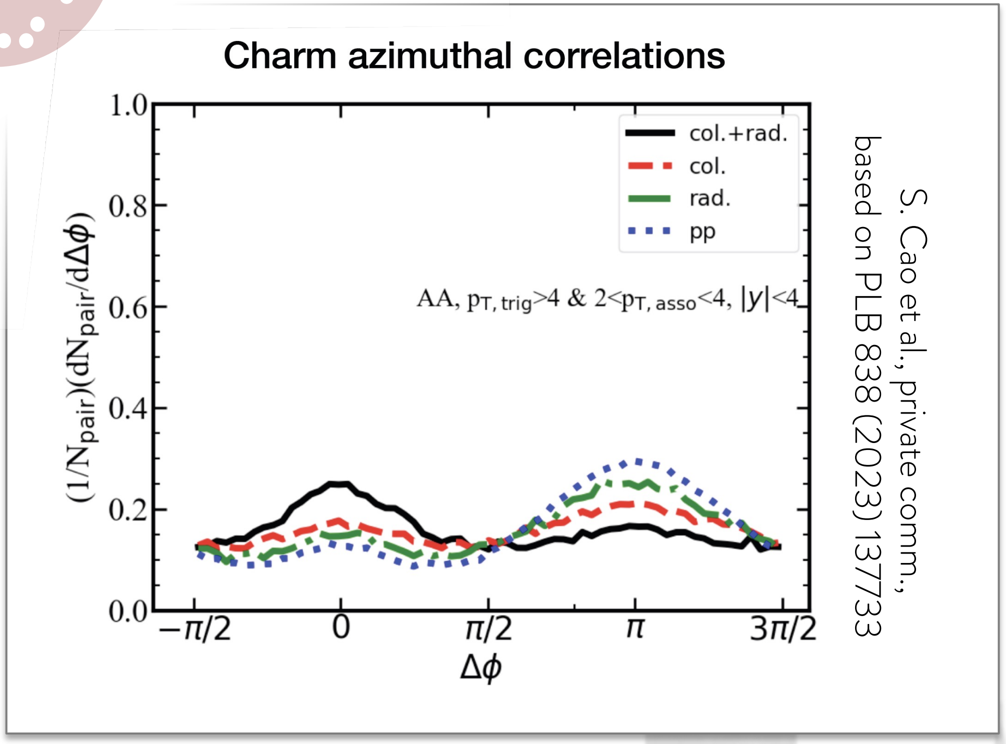
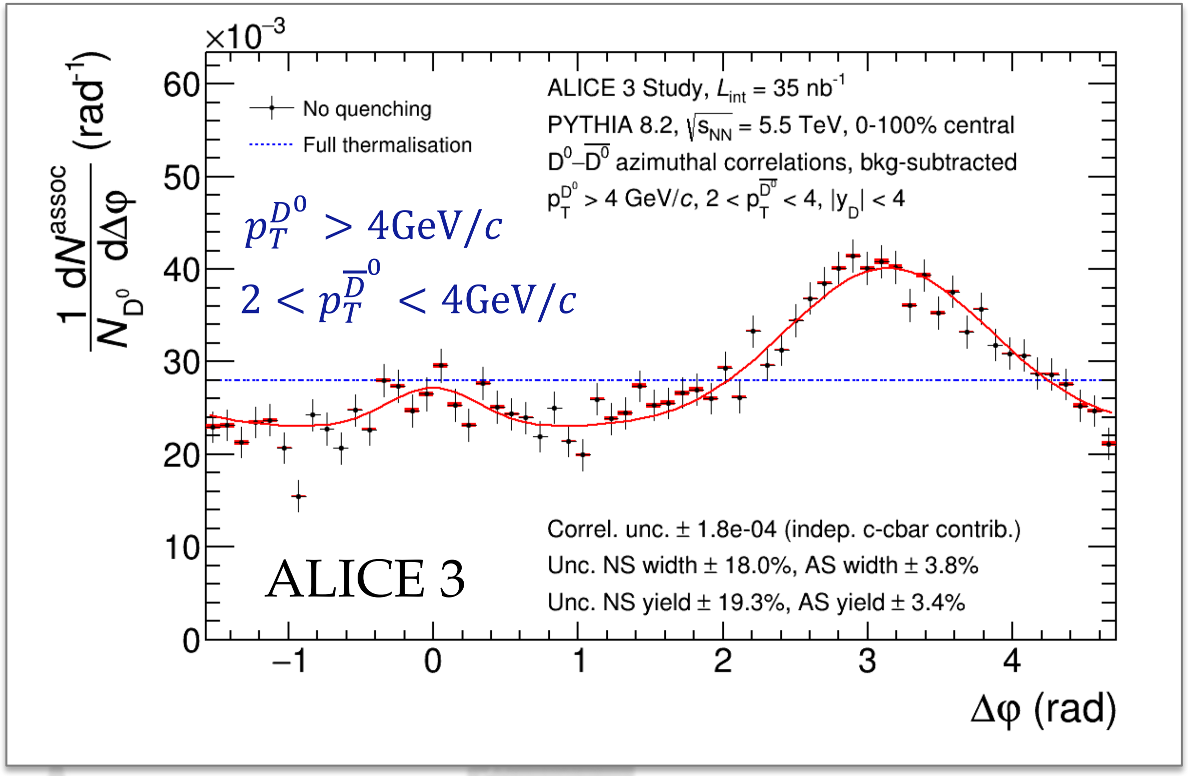
Zooming in on HF propagation in the medium



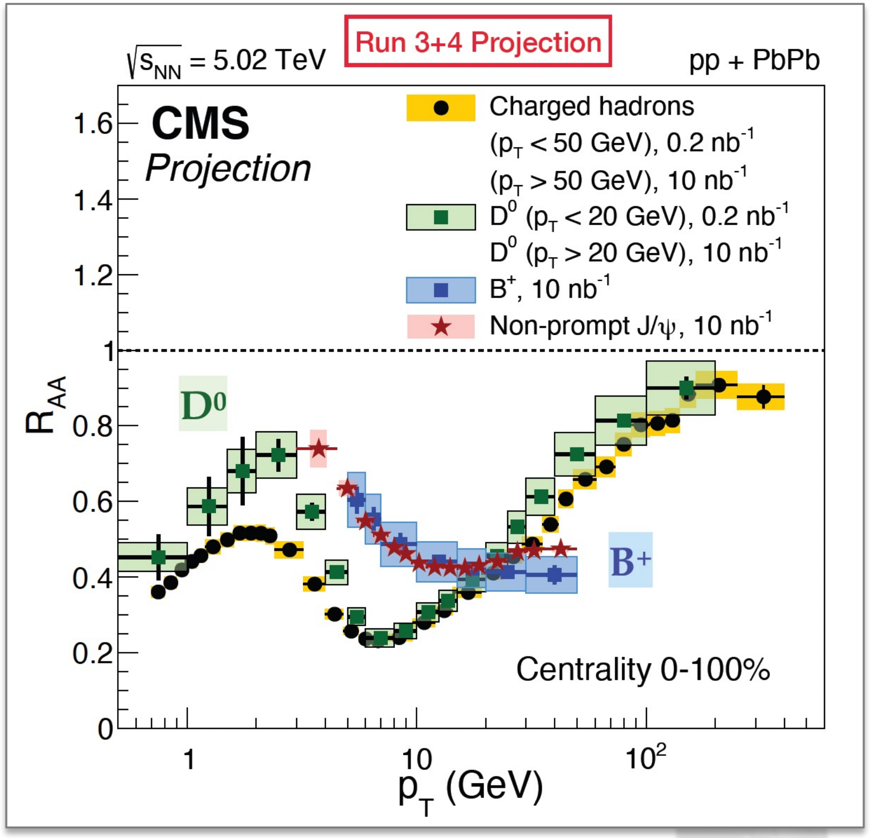




- ALICE 3: extreme pointing precision and low material budget ideal for pushing to low p_T
- Expect unprecedentedly precise $D\overline{D}$ study to be possible down to $p_T > 2.0$ GeV/c
  - Direct access to **diffusion** of produced $c\bar{c}$
  - Study **collisional versus radiative energy loss**: signal strongest at lowest momenta accessible with ALICE 3

More on diffusion (coefficients) of charm: J. Wang, Tuesday 2pm

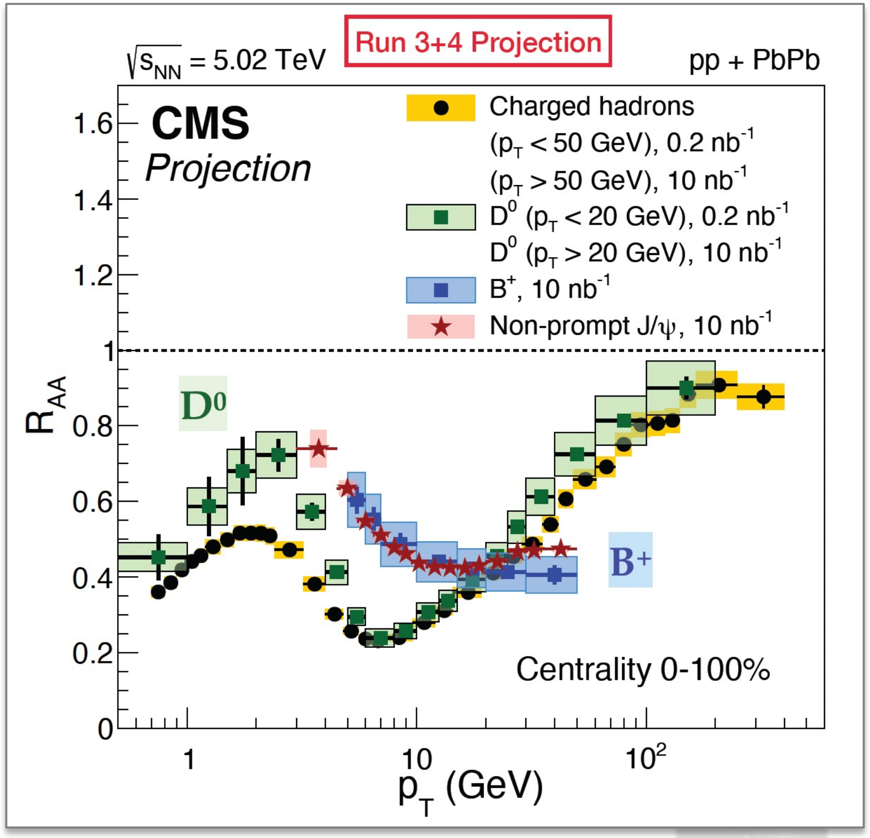
Large momentum interactions with the medium: R_{AA}



CMS at the HL-LHC

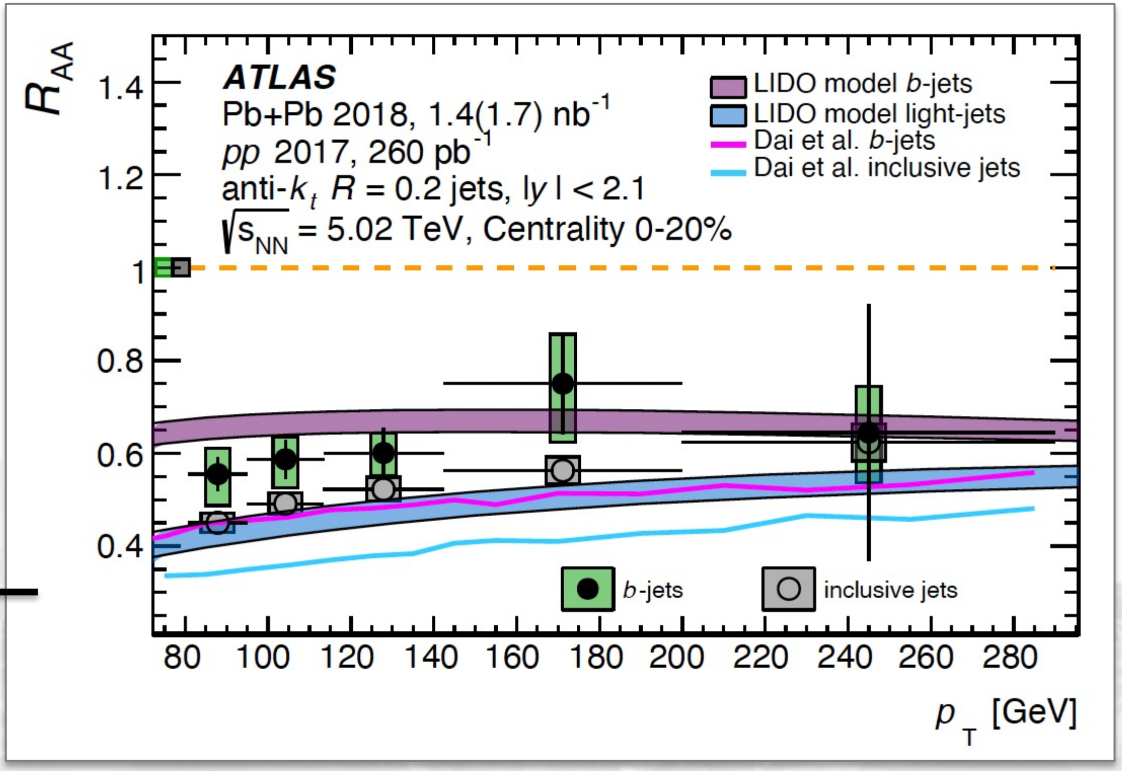
- Nuclear modification: 1 if no suppression, < 1 if particles lose energy
- **Mass-dependent, medium-induced energy loss** due to dead cone effect expected: e-loss hierarchy is [u,d,s] > [c] > [b]
- Target: precise charm and beauty modification factors
- And beyond: B_c (double-HF) → sensitive to coalescence

Large momentum interactions with the medium: R_{AA}

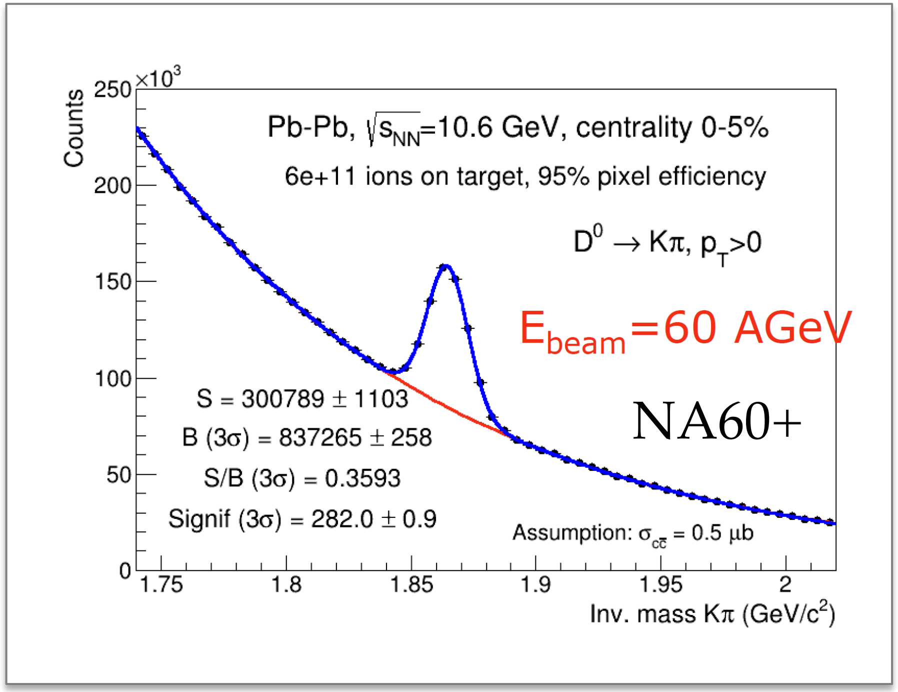


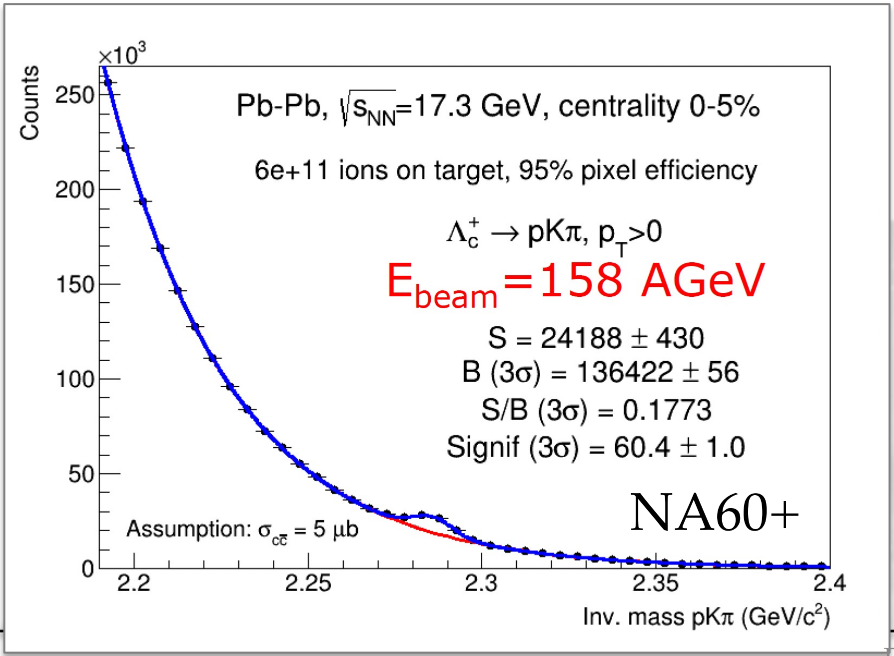
CMS at the HL-LHC

- Nuclear modification: 1 if no suppression, < 1 if particles lose energy
- **Mass-dependent, medium-induced energy loss** due to dead cone effect expected: e-loss hierarchy is [u,d,s] > [c] > [b]
- Target: precise charm and beauty modification factors
- And beyond: B_c (double-HF) → sensitive to coalescence



- ATLAS: combinatorial background prohibits vertex-based beauty tagging for R_{AA} calculation
  – Currently done with muon-tagged b jets only
- **All-new silicon tracker ITk: first layer at 3.4cm**
  – **Vertex-based b tagging to be pursued**



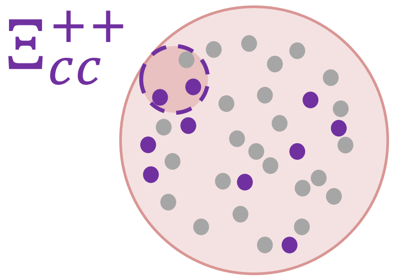


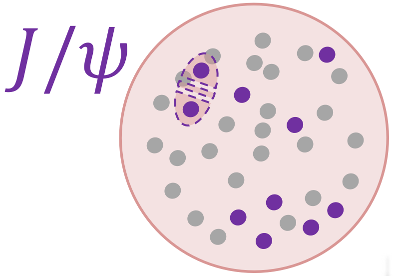
Charm transport studies at high μ_B

- **NA60+:** high rate (150 kHz), great open HF performance
  - Charm R_{AA} and v_2: diffusion coefficient D_S at $T < T_C$
  - Interactions predominantly in hadronic phase
  - $c\bar{c}$ correlations may be accessible as well
- **NA61/SHINE**: high rate (>10 kHz) operation
  - Feasibility studies ongoing to perform $c\bar{c}$ ($D\bar{D}$) correlations
  - Top SPS energies: less than one $c\bar{c}$ pair per event, no uncorrelated background → very different than LHC

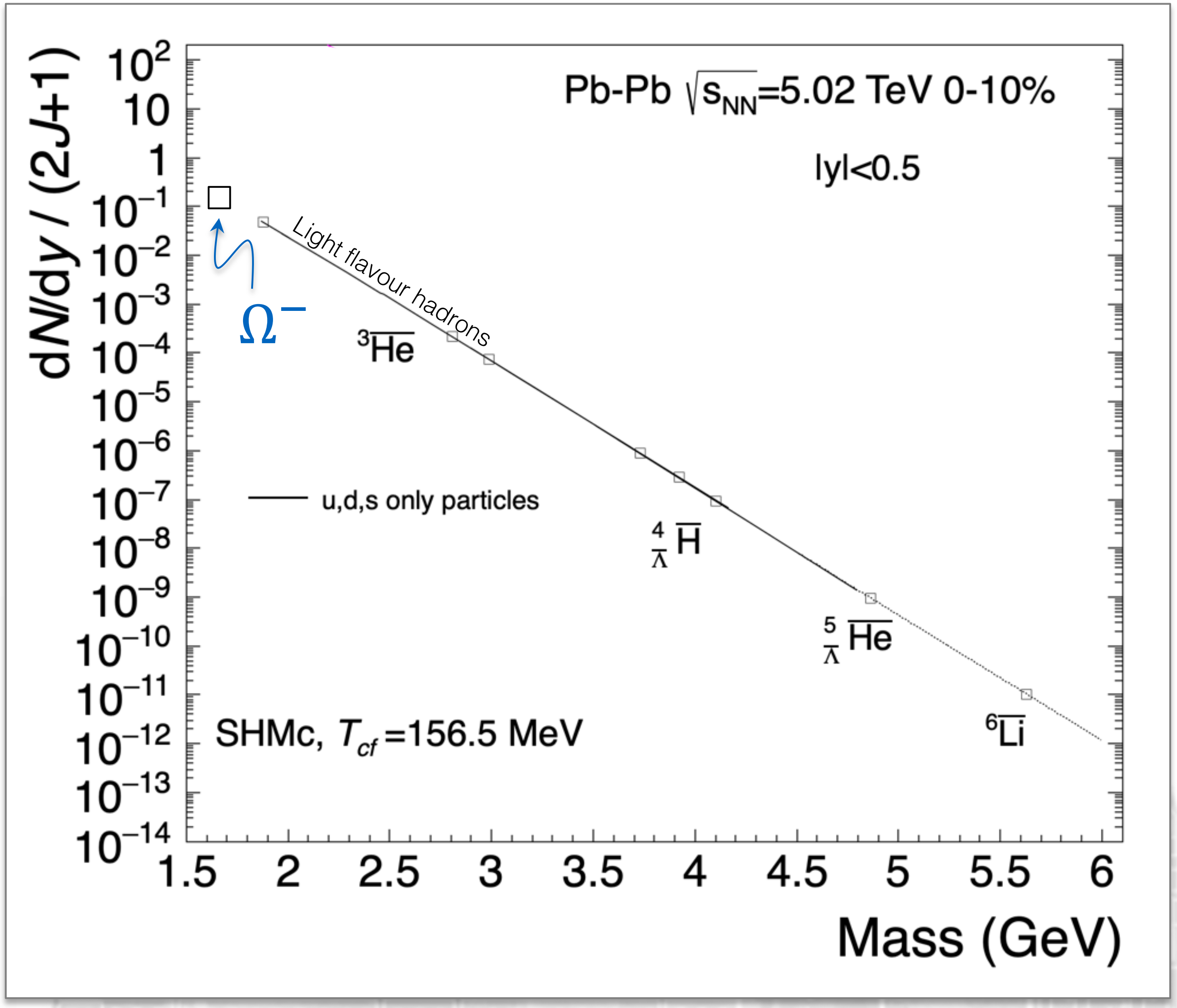
Open questions in heavy-ion physics

- **Evolution of a QCD many-body system**
  - How does the QGP **temperature** and density evolve with time?
  - Evolution conected to kinematic equilibration: hydrodynamic description, transport coefficients
  - How do **heavy flavour** quarks propagate in the medium?
  - Can we pinpoint microscopic interaction dynamics of **heavy quarks**?



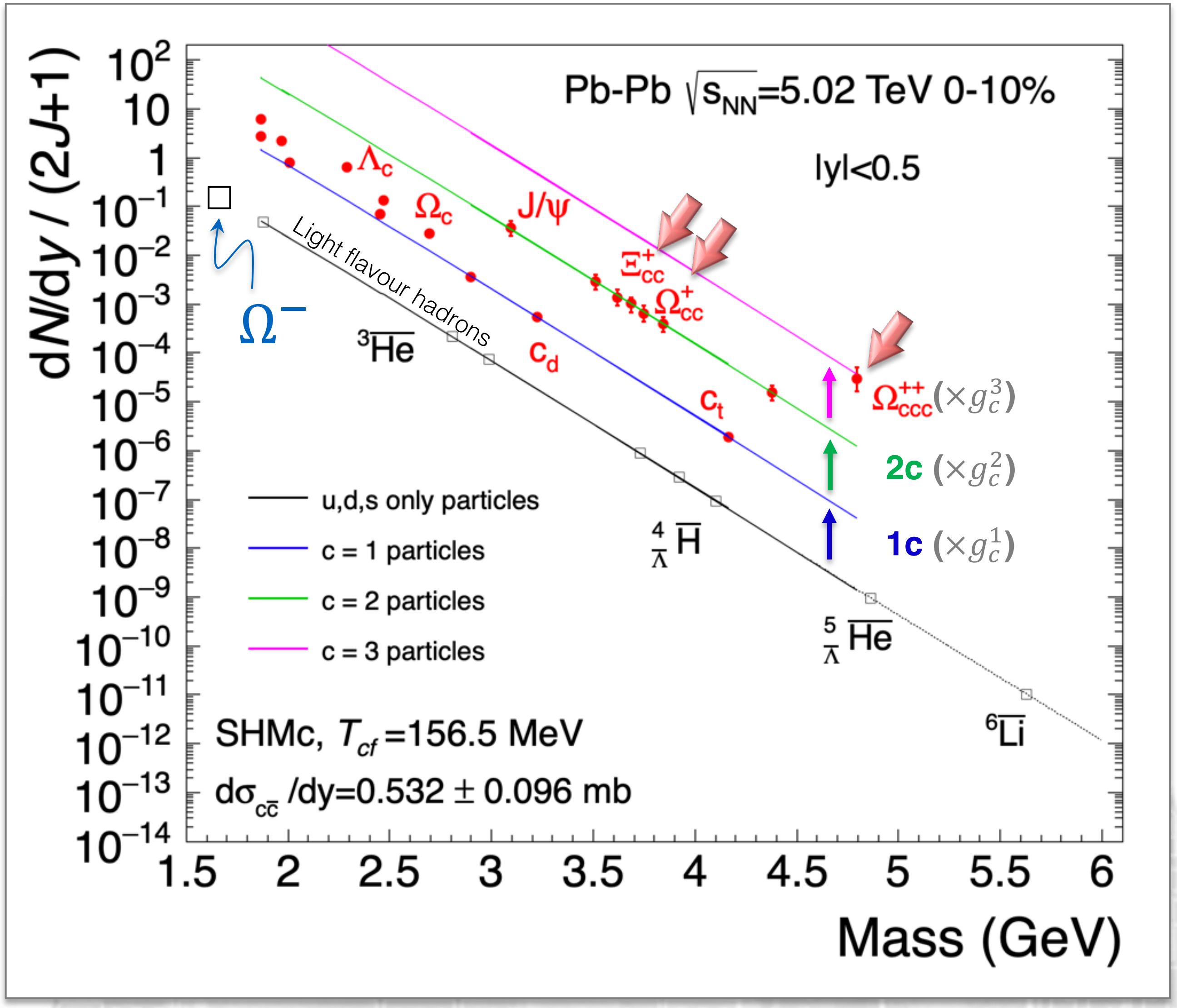


- **How are hadrons formed** in a dense environment?
  - Hadronization and relationship to statistical principles: realm of thermal models
  - How are **heavy quarks** distributed in hadronization?
  - Open heavy flavour quarks: charm fugacity, hidden flavour: quarkonium melting/regeneration
- **How do dense QCD effects and collectivity emerge** in small systems down to pp?
- **Under which conditions** in the QCD phase diagram does one obtain a first-order phase transition?



Charm hadron yield thermalization

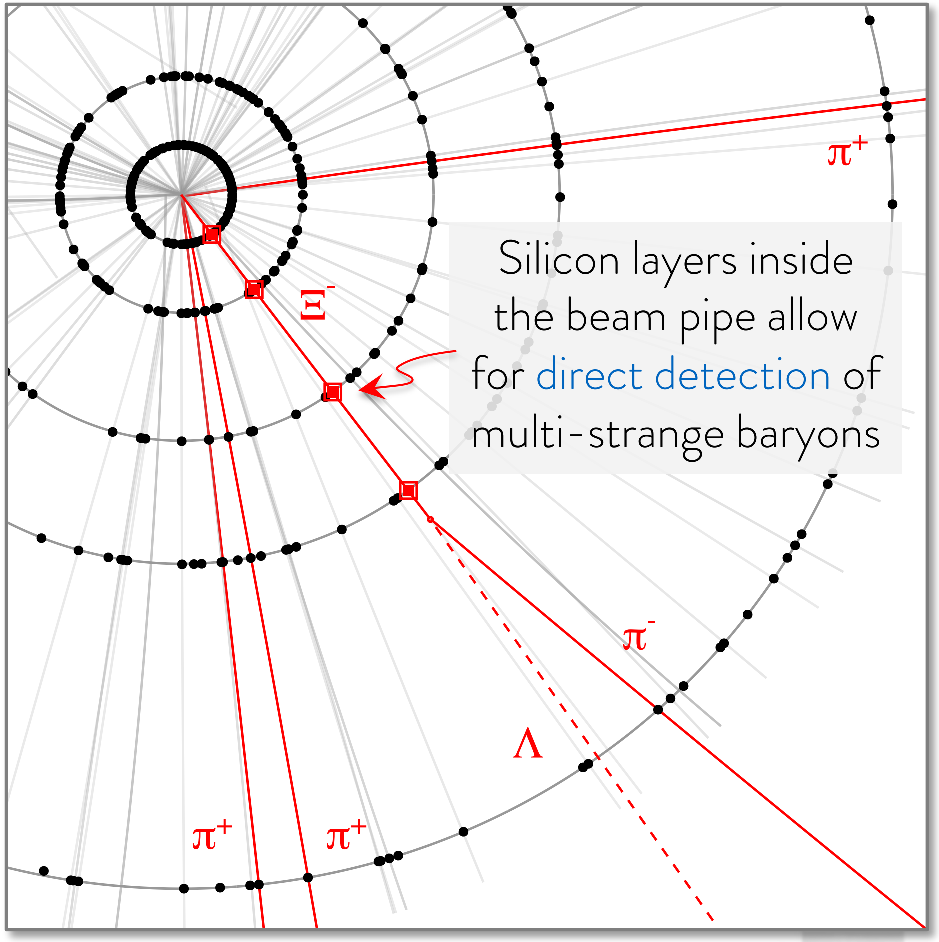
- **u, d, s-hadrons**: mass exponential hierarchy, dominated by quarks created at phase boundary (e.g. Ω^-)
    - Realm of **classical strangeness studies**



Charm hadron yield thermalization

- **u, d, s-hadrons**: mass exponential hierarchy, dominated by quarks created at phase boundary (e.g. Ω^-)
  - Realm of **classical strangeness studies**
- Charm: still an exponential with mass (thermalised yields) but **exponential displaced by charm fugacity g_c^n** [1,2]
  - SHMc: g_c provides information about mechanisms
  - Due to large, fixed N_{charm}: game changer
  - **Strongest for multi-charm**: extreme sensitivity
- Very large centrality dependence of production rates
  - **Complete charm thermalization not a given**

Multi-charm baryons with ALICE 3

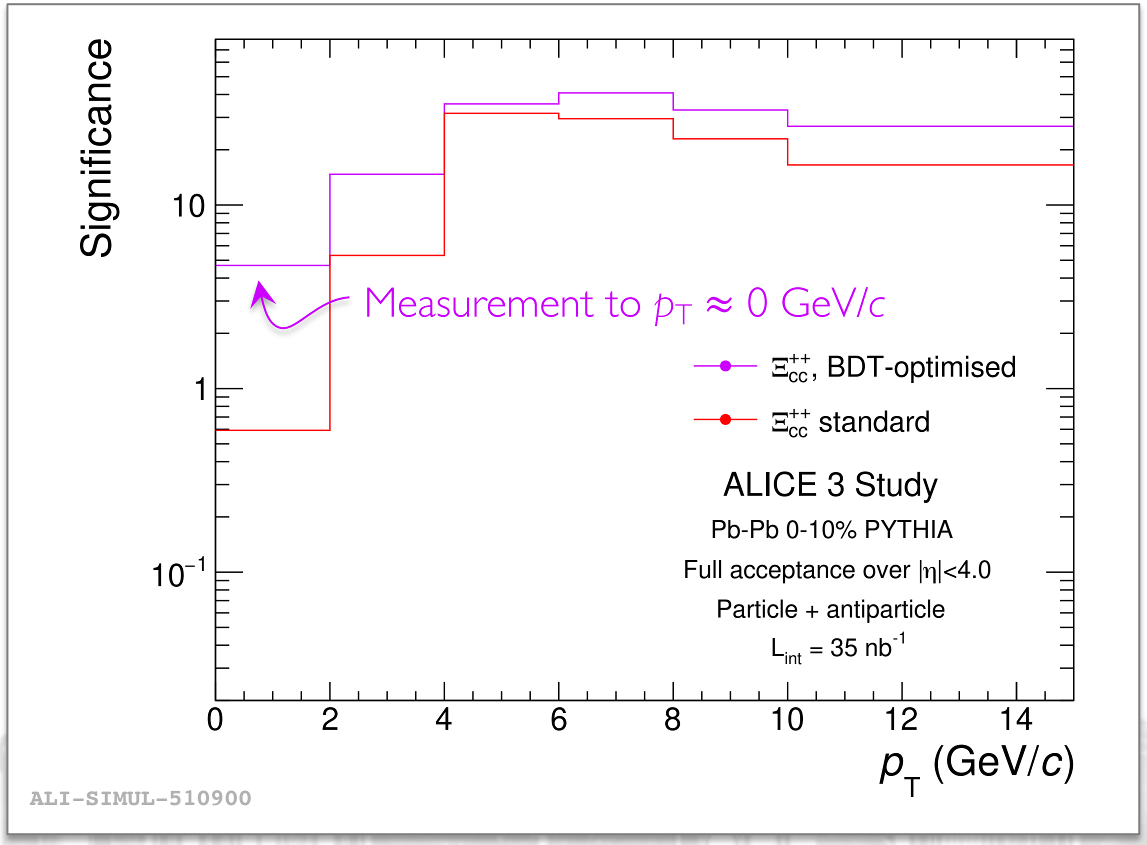


$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+$ (cτ ~77 μm)

$\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$

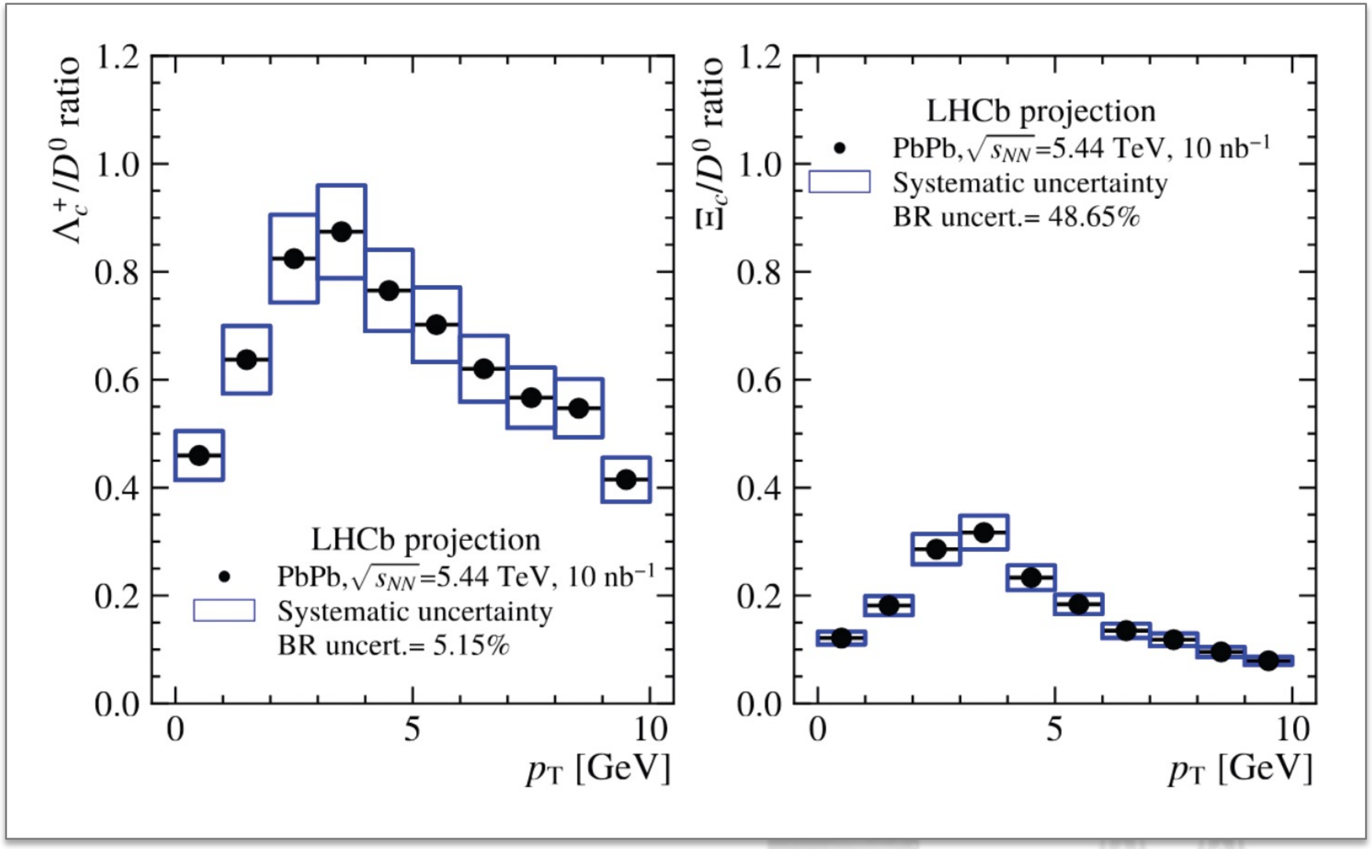
Relies on **extremely challenging multi-prong decay analyses**

- State-of-the-art vertexing, tracking and particle identification



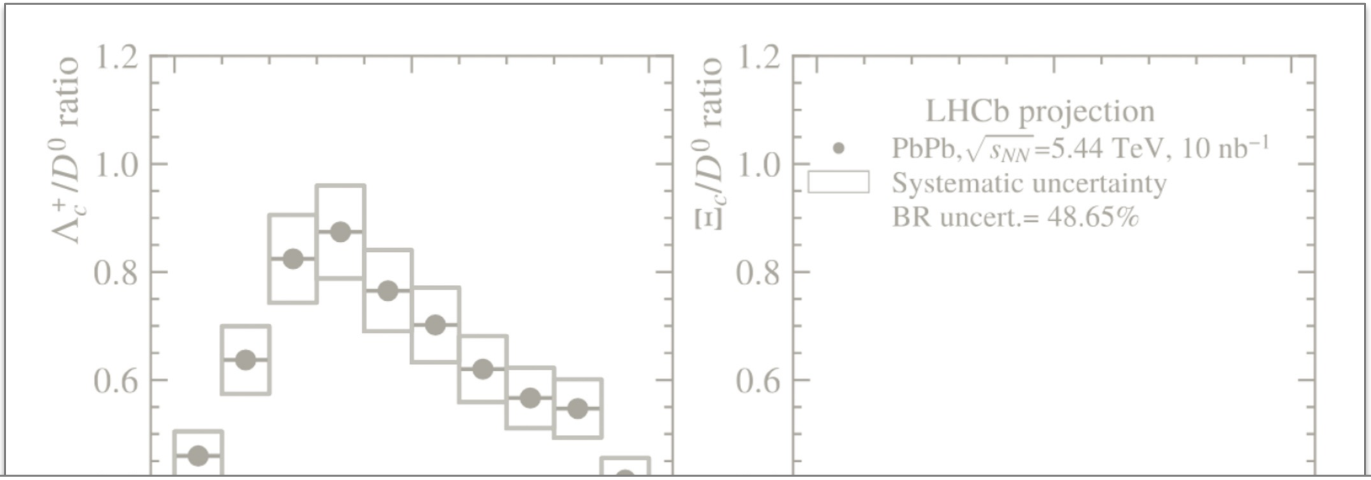
- Standard analysis down to $p_T > 2.0$ GeV/c
- With machine learning techniques: measurement down to zero momentum may be feasible

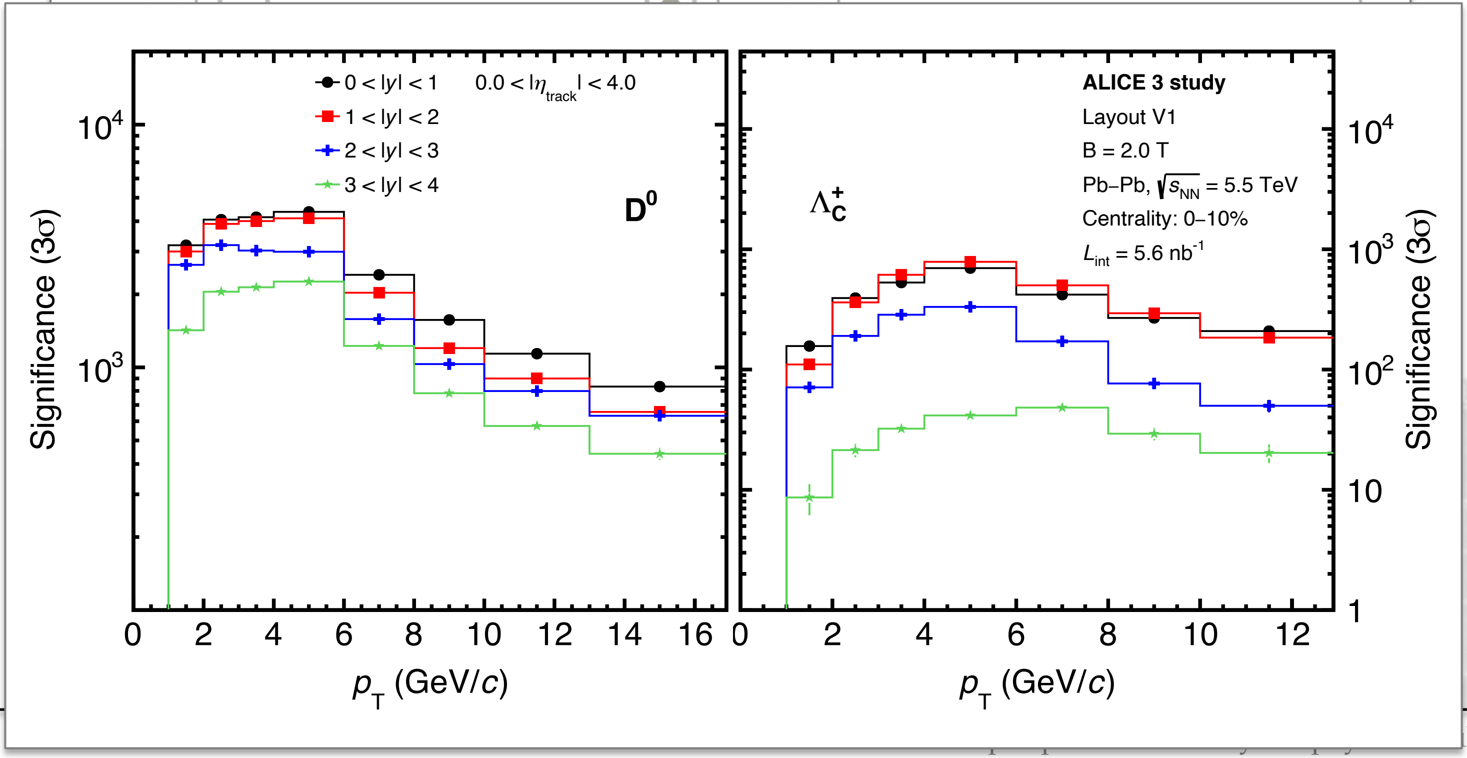
Towards a complete picture of charm chemistry vs rapidity



- **LHCb**: probe charmed hadrons at forward rapidity down to low momentum
- Access both yields and spectrum shapes
  - Kinematics probed as well
- Necessary to answer: **in what way does thermalization depend on rapidity?**
  - Competing effects: coalescence in medium and fragmentation in vacuum

Towards a complete picture of charm chemistry vs rapidity





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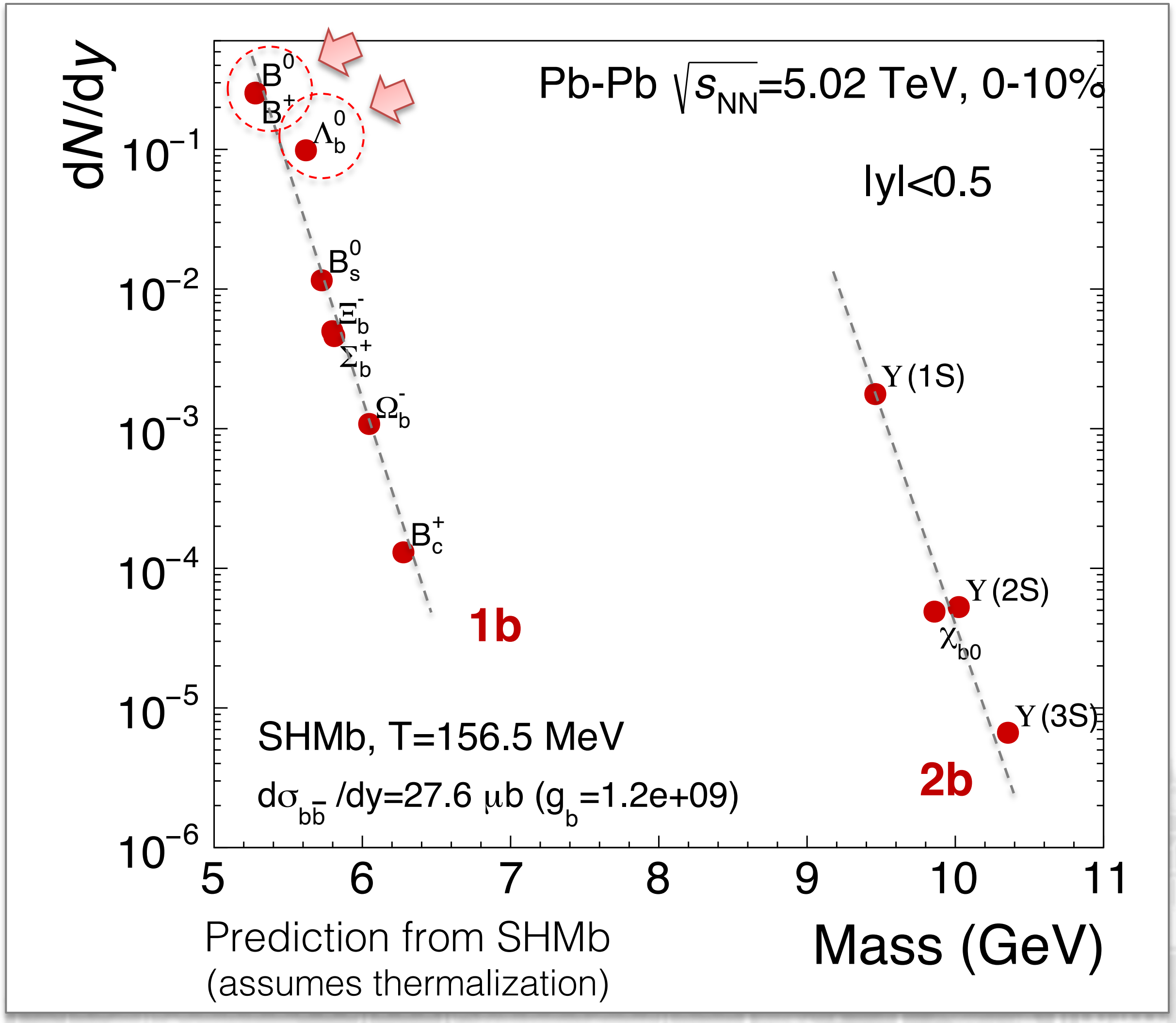
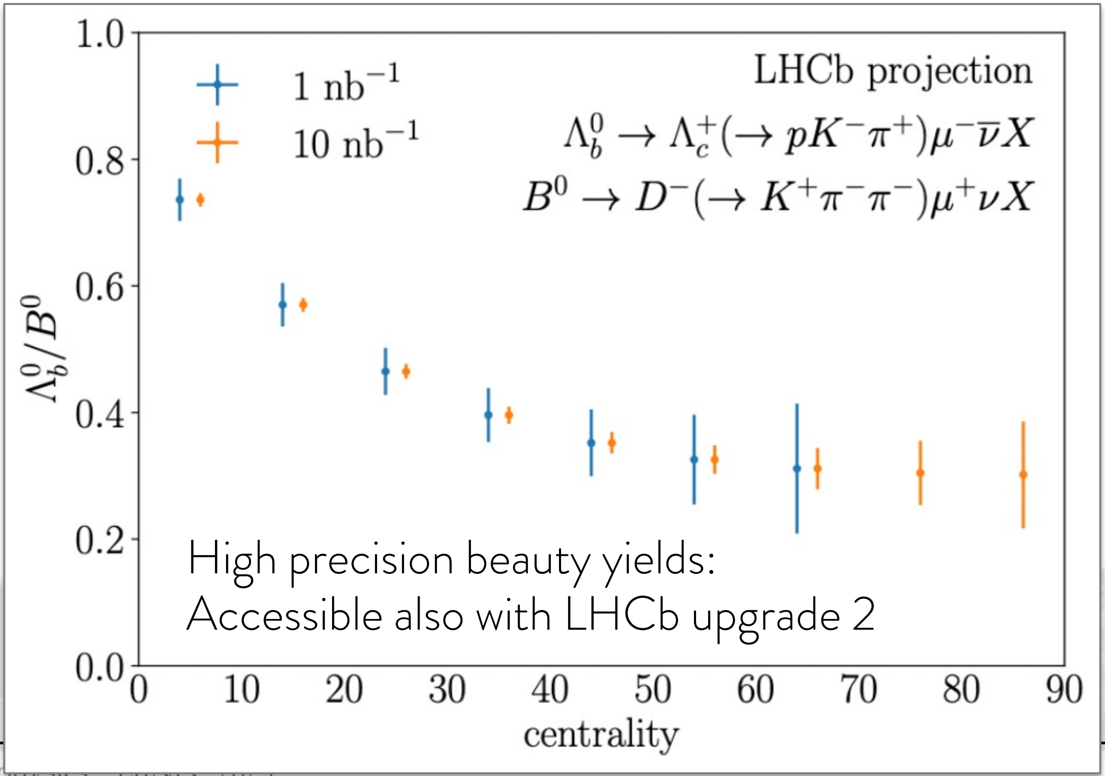
- **ALICE 3**: wide rapidity acceptance and extreme vertexing allows for direct rapidity dependence measurement

Beauty hadron yield thermalization



SHMb reference: https://arxiv.org/abs/2209.14562

- **b-hadrons**: thermalization of yields would mean following displaced exponentials vs mass, **but thermalization slower**
- Thermalization most likely partial → **key insight into onset!**
- Requires systematic measurements of b-hadron yields down to low momentum: B^+, B^0, Λ_c^+



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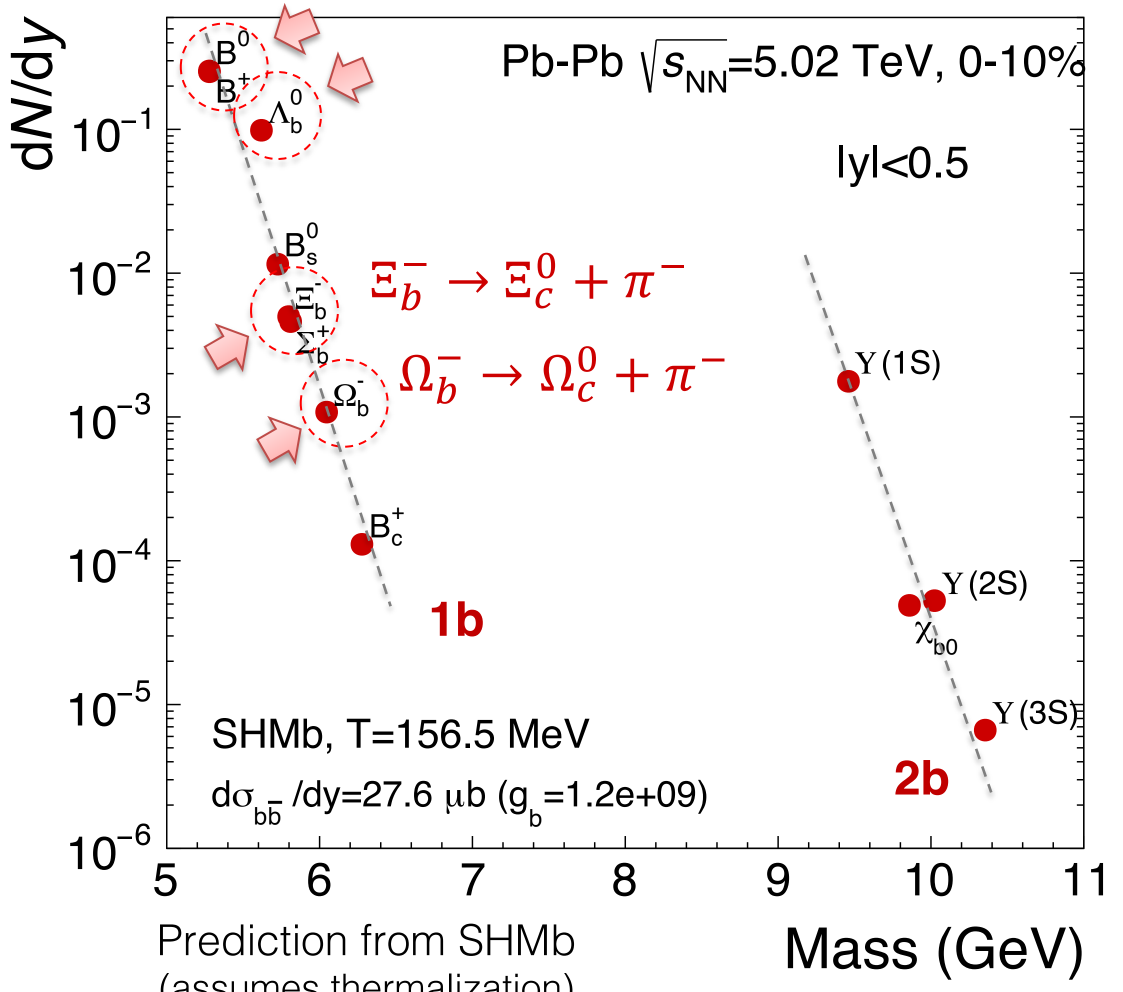

Prediction from SHMb
(assumes thermalization)

SHMb reference: https://arxiv.org/abs/2209.14562

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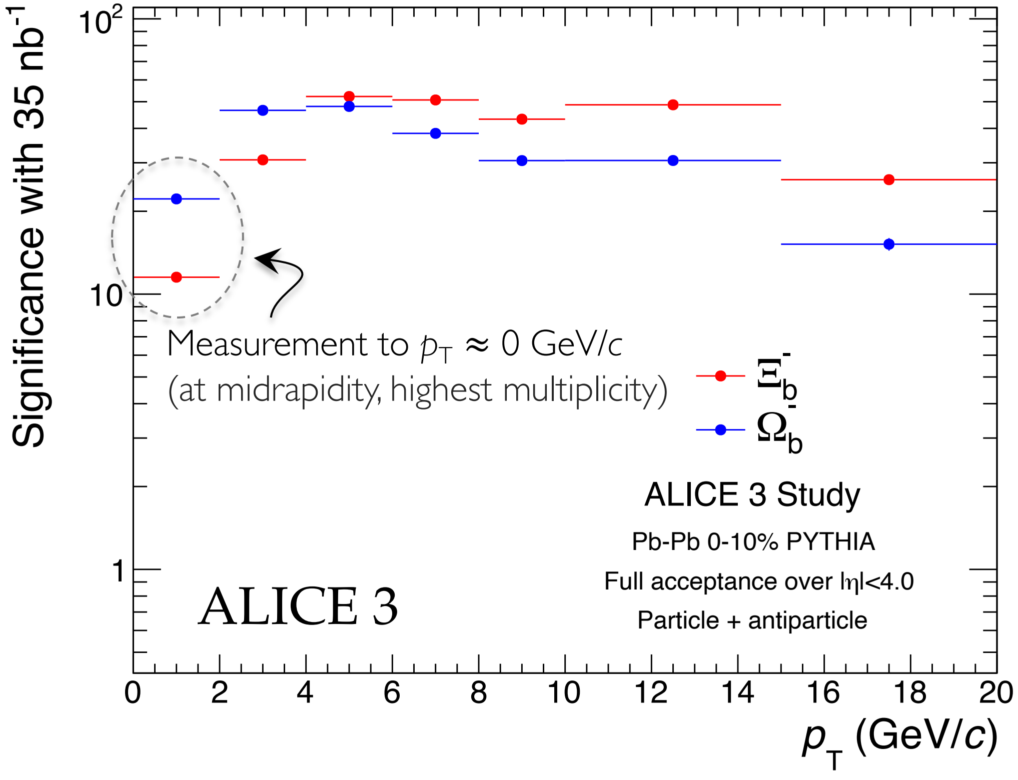
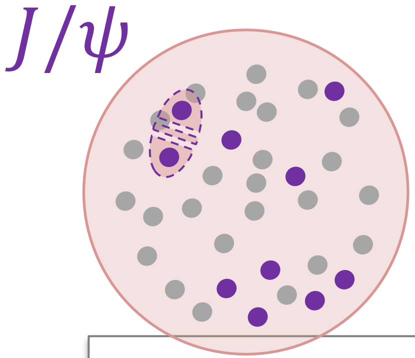
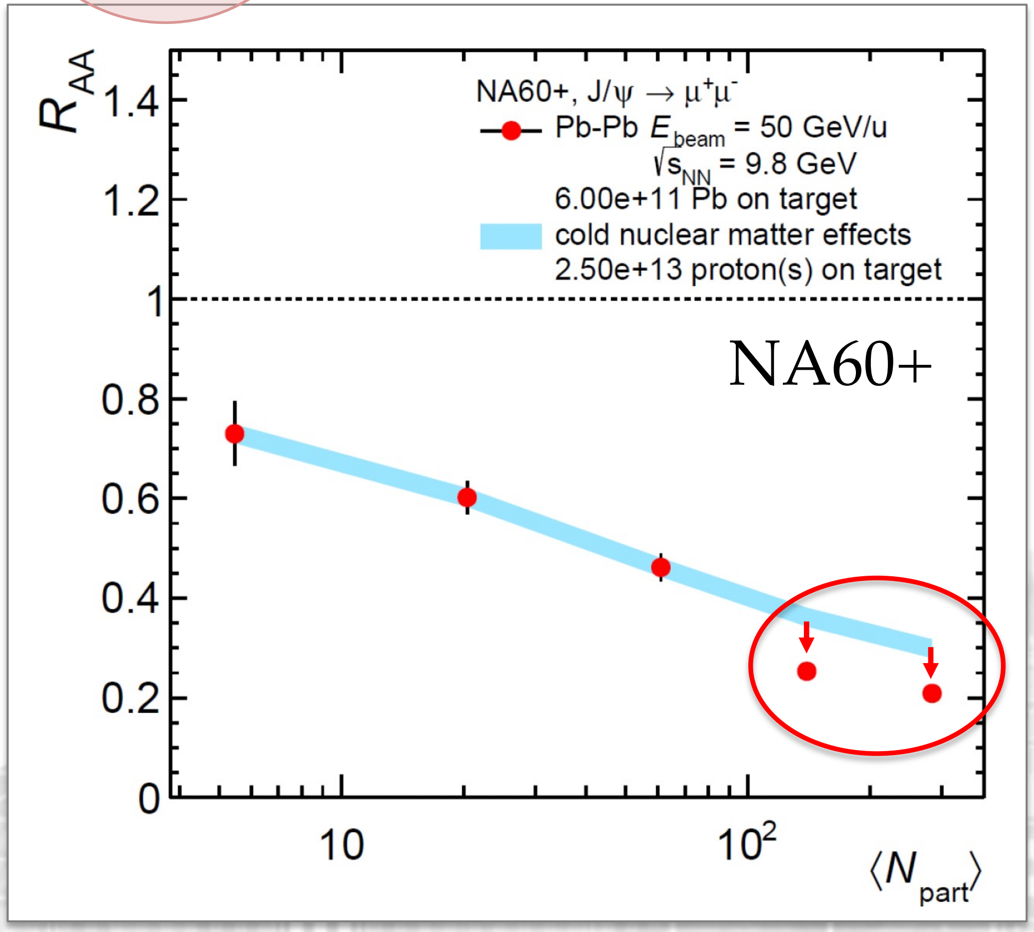




Measuring the onset of quarkonium suppression

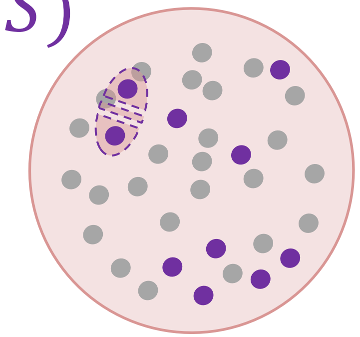


- On top of typical suppression of R_{AA}: **quarkonium melting due to colour screening**
- At which energies / QGP temperatures does this phenomenon occur?

Direct answer with **NA60+:**

- **quarkonium suppression** can be studied versus $\sqrt{s}$
- **associated QGP temperature** measured with dimuons

$\Upsilon(1S)$



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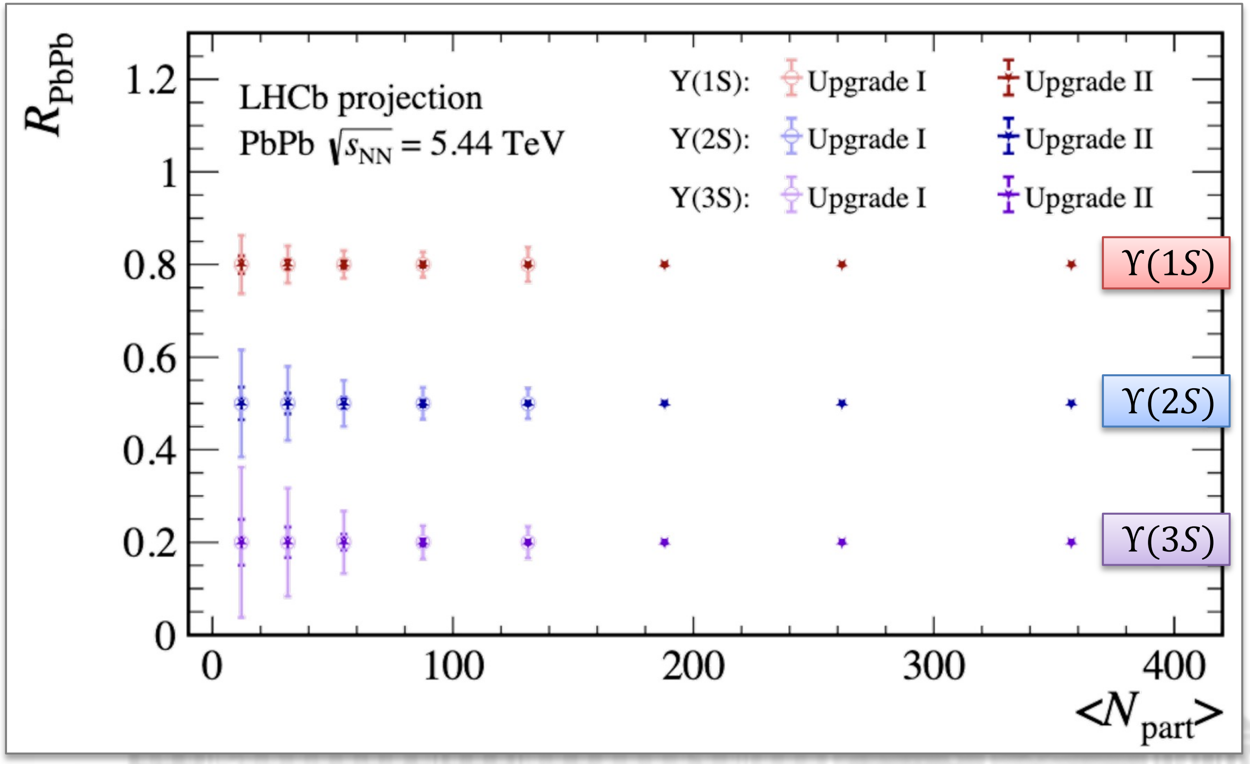

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At **HL-LHC(b):**

- Precision measurement of **sequential Υ melting**
- To be pursued in addition: χ_c and χ_b

More on *current* quarkonia measurements:
S Trogolo, Tuesday 2:25pm ; R. Cerri, Tuesday 4:15pm

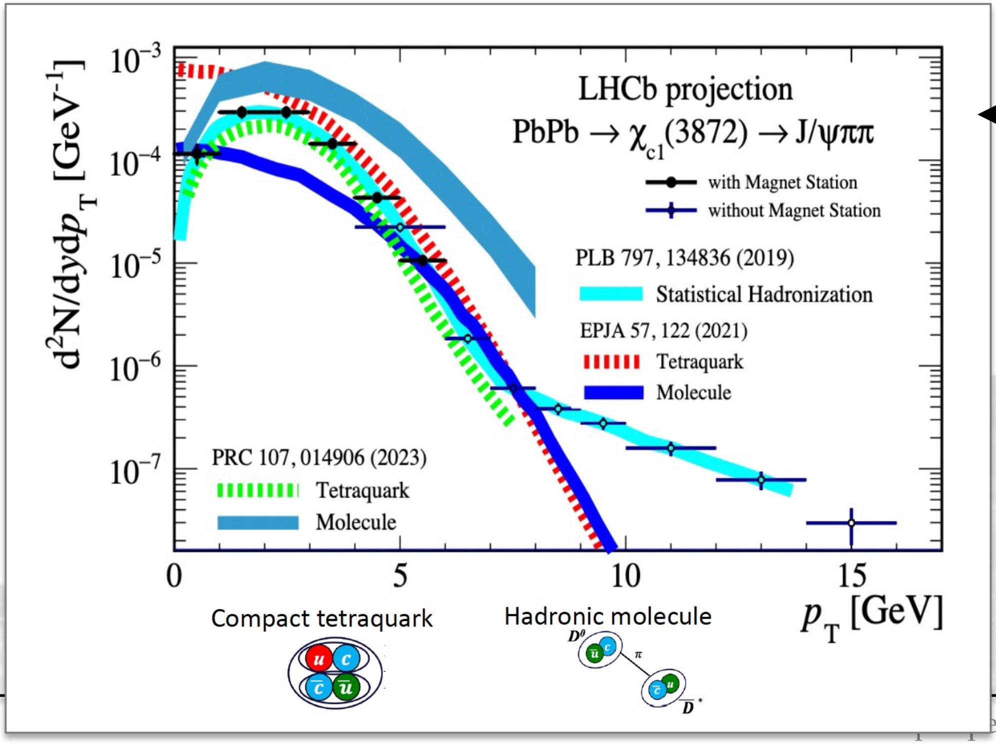
Heavy-ion collisions as a QCD laboratory: an example

Opportunities for physics of exotic states of QCD

Many exotic states found in hadronic collisions…

… But fundamental questions still remain:

- Do hybrids/glueballs exist?
- Why do many exotic hadrons lack flavour/isospin partners?
- Nature of exotic hadrons: e.g. tetraquark / molecule?



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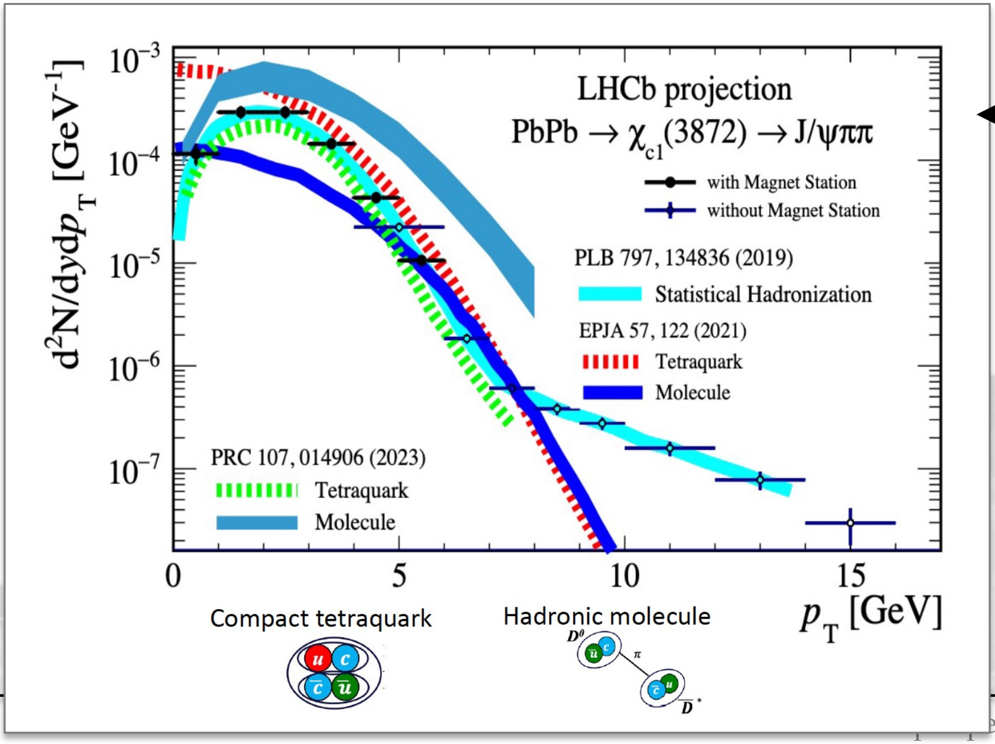
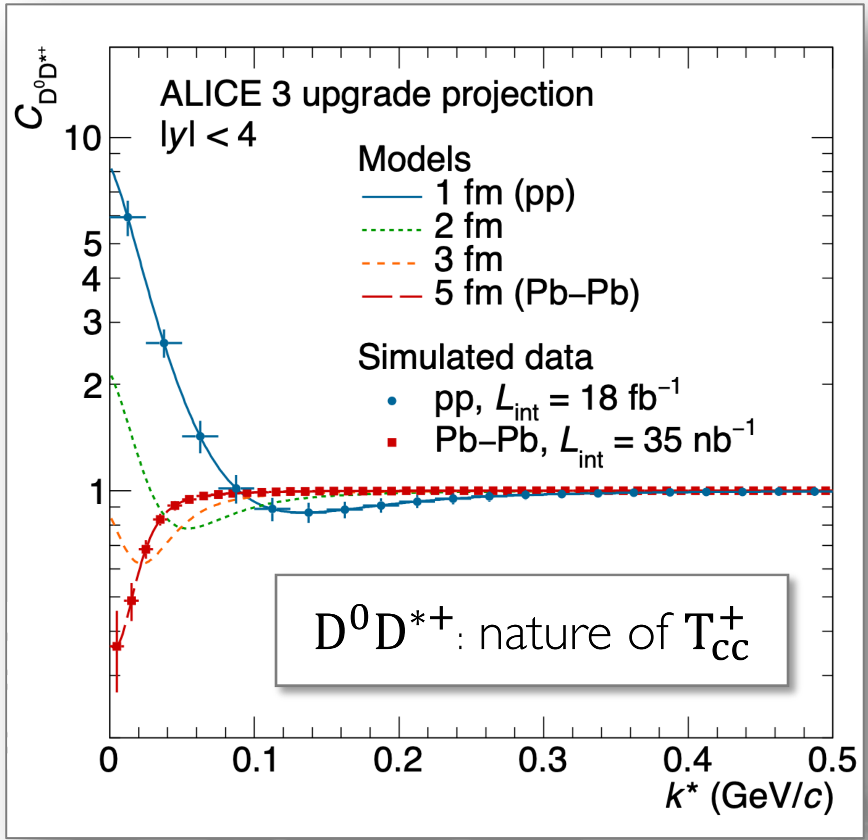




- **ALICE 3** well positioned for low momentum measurement of exotica
- **Momentum correlations with ALICE 3**: direct study
  - Nature of the T_{cc}^+ via correlation of D^0D^{*+}

More about femtoscopy: V. Sarti, Monday 12:30

Heavy-ion physics in the years to come: outlook

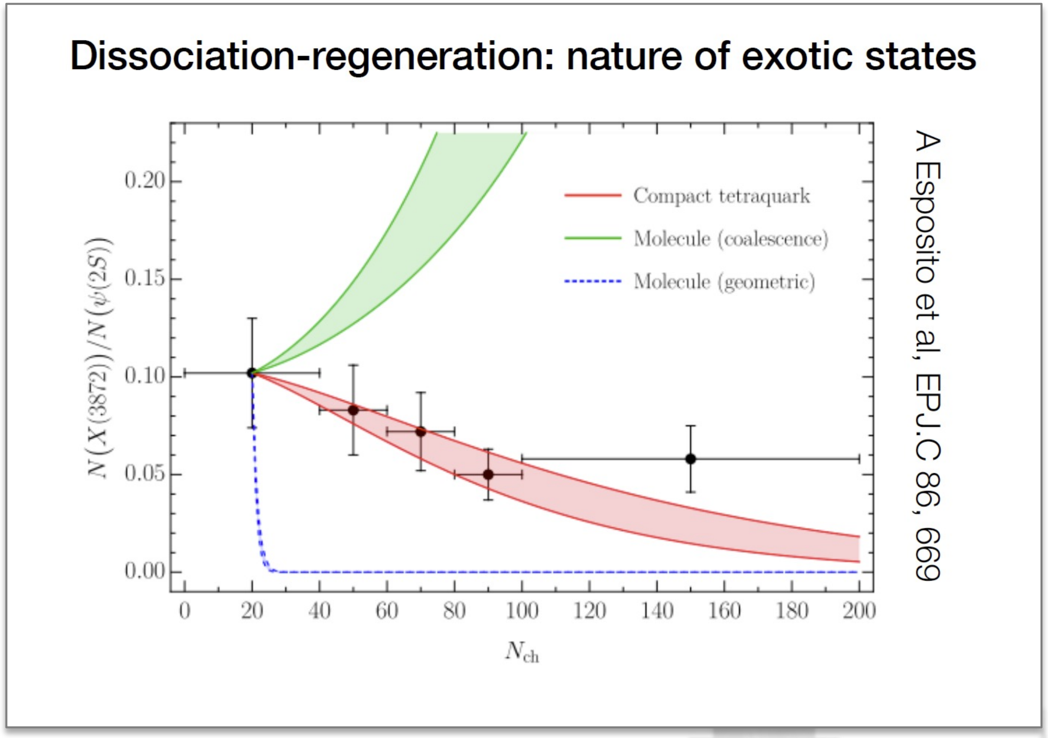
- Building a path towards a precise understanding of a many-body QCD system
  - **Quark-gluon plasma temperature and cooldown** → thermal emission via dilepton mass spectra
  - **Heavy quarks** as high-precision **probes of microscopic processes and dynamics** → transport, approach to equilibrium
- Heavy-ion collisions: very effective as as **general-purpose laboratory for QCD**
  - Study of exotica (nature of T_{CC}, ...), hadronic interactions via femtoscopy and beyond
- **HL-LHC**: fully exploiting a unique machine
  - New detectors with **frontier sensor technologies** and **maximising heavy-ion luminosity**
- **SPS, FAIR**: high rates, versatility, and state-of-the-art sensor technologies
  - Complement LHC (high baryon-density, hadron phys.), possibly extending to post-LHC era
- **FCC-hh**: possibility to inject ions would lead to exploration of new regime

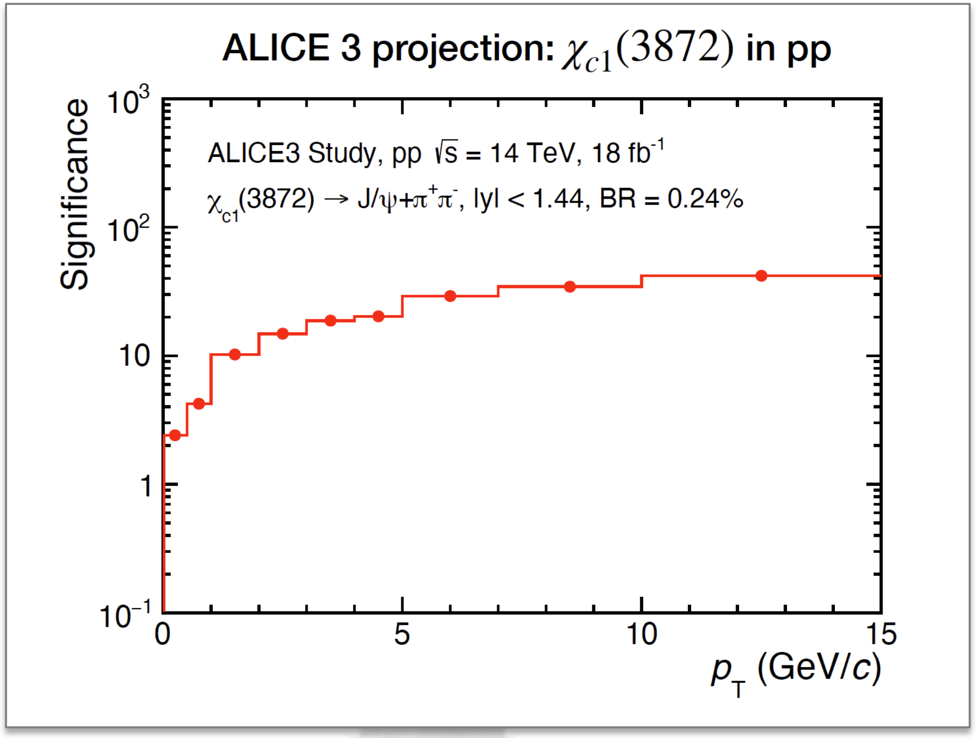
Acknowledgement / further reading:
ESPPU Open Symposium in Venice (June 2025)

Thank you!

Backup

Nature of exotic states: tetraquark vs molecular





- Is the $\chi_{c1}(3872)$ a compact tetraquark or a molecule?
  - Even further: coalescence formation?
- Requires low-momentum measurement (yields)
- Ratio to $\psi(2S)$ sensitive to structure

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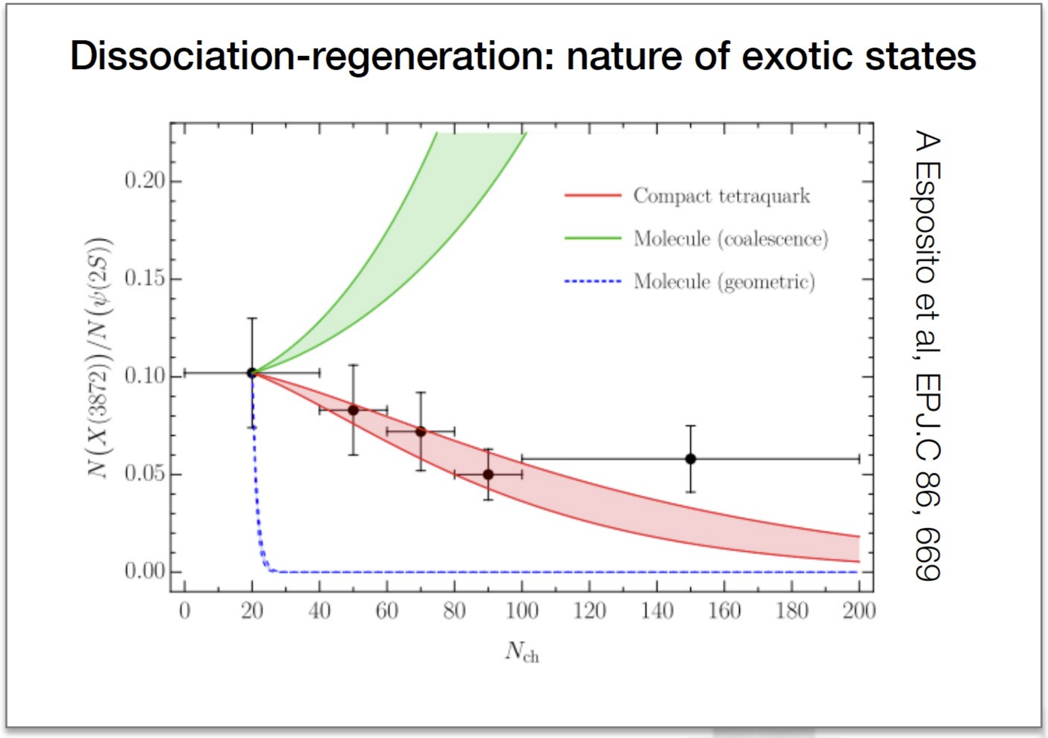
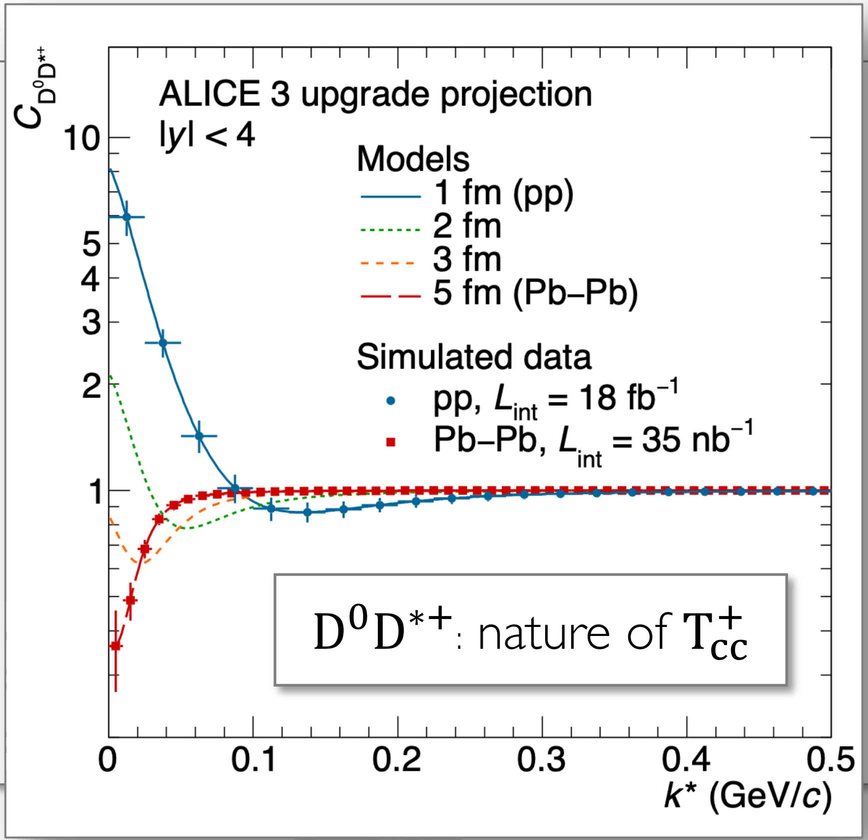
Nature of exotic states: tetraquark vs molecular





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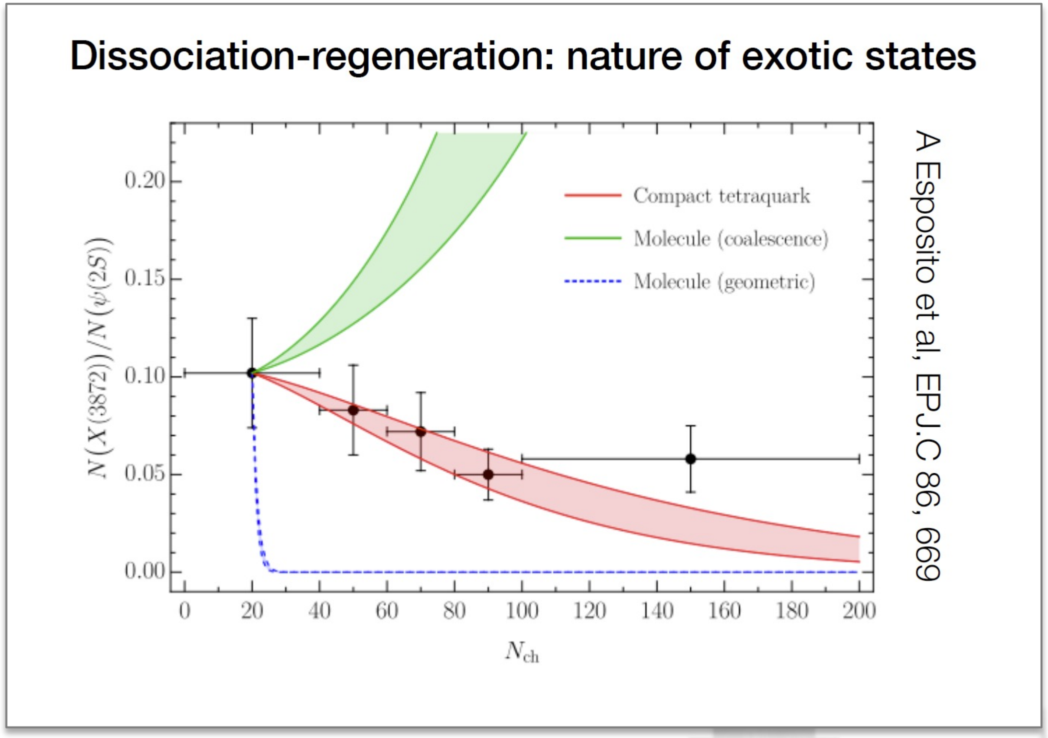

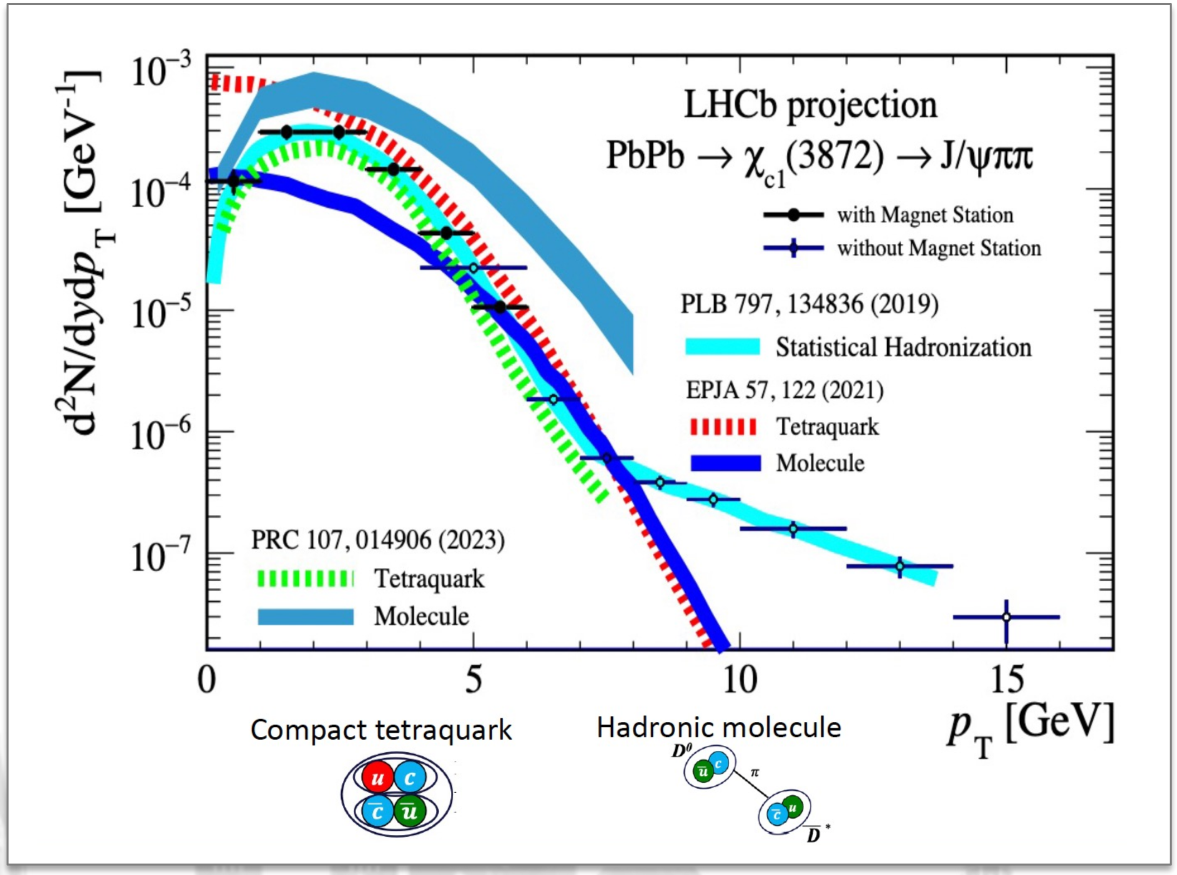

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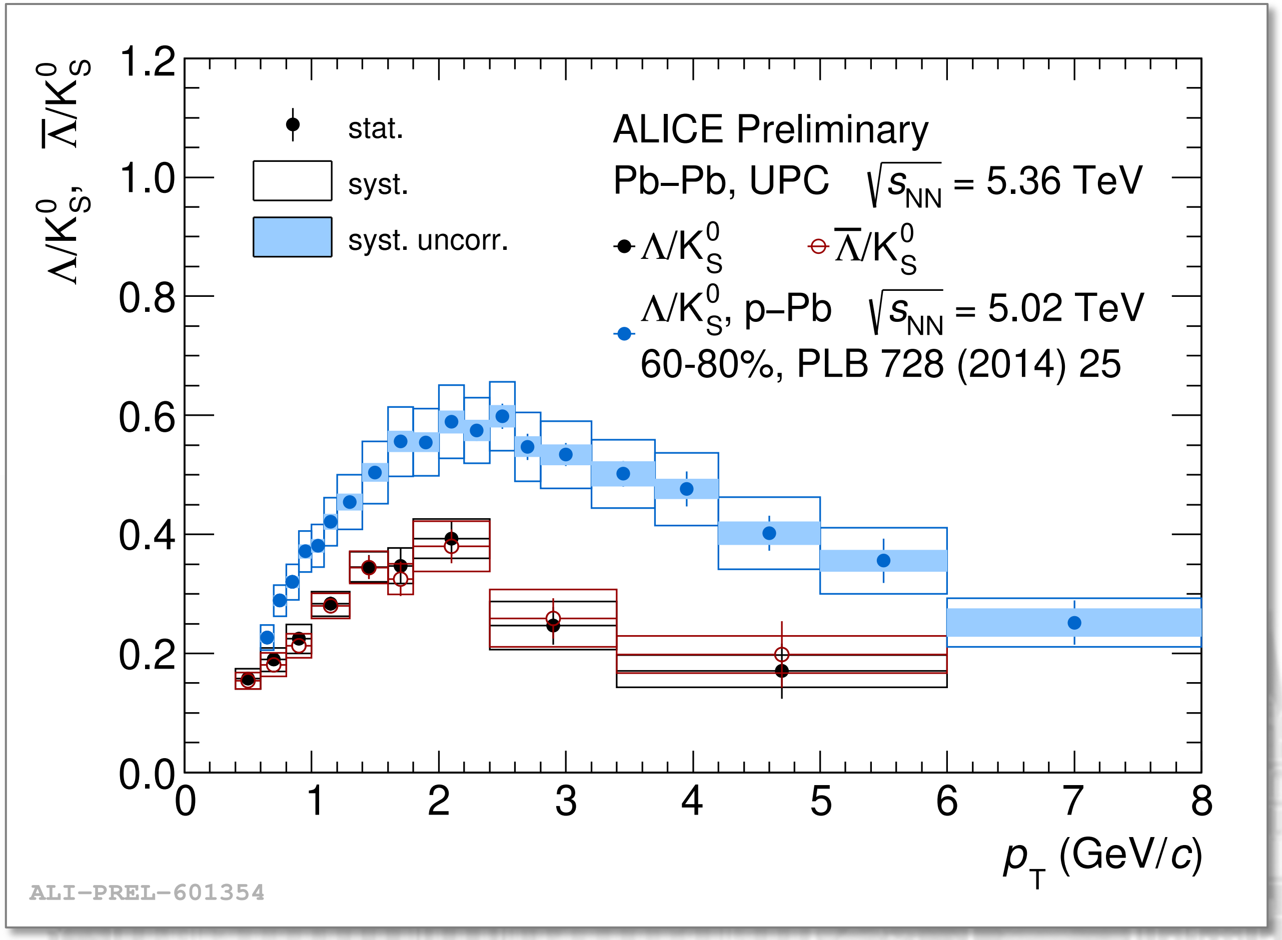
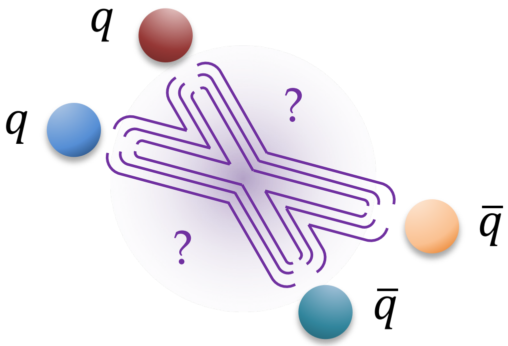
- **LHCb:** expect measurement of exotica down to low p_T
  - Very sensitive to tetraquark/molecular nature

Down to the (more) elementary:
Exploring γ-Pb collisions





In which conditions do QGP-related phenomena emerge?

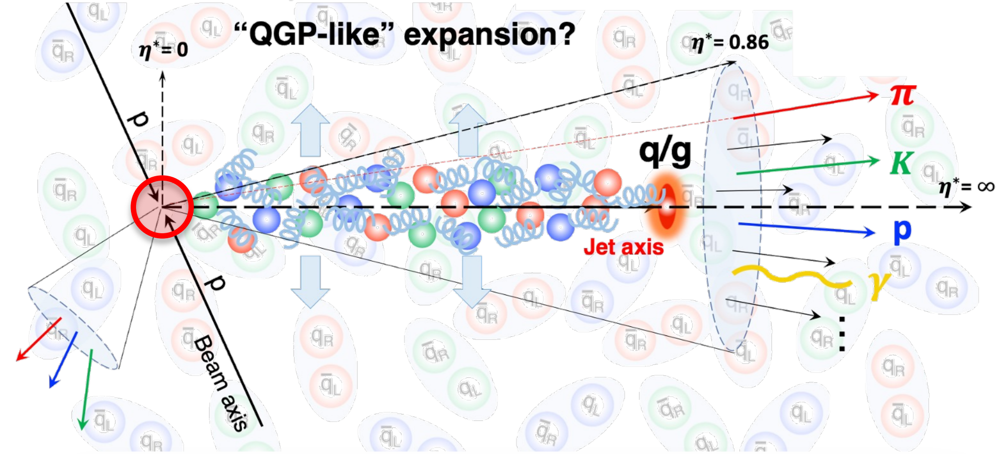
- Two phenomena observed in pp already:
  - **Strangeness enhancement**
  - **Baryon/meson grouping** of v_2, spectra modification

Photonuclear collisions present a unique opportunity to answer this question!

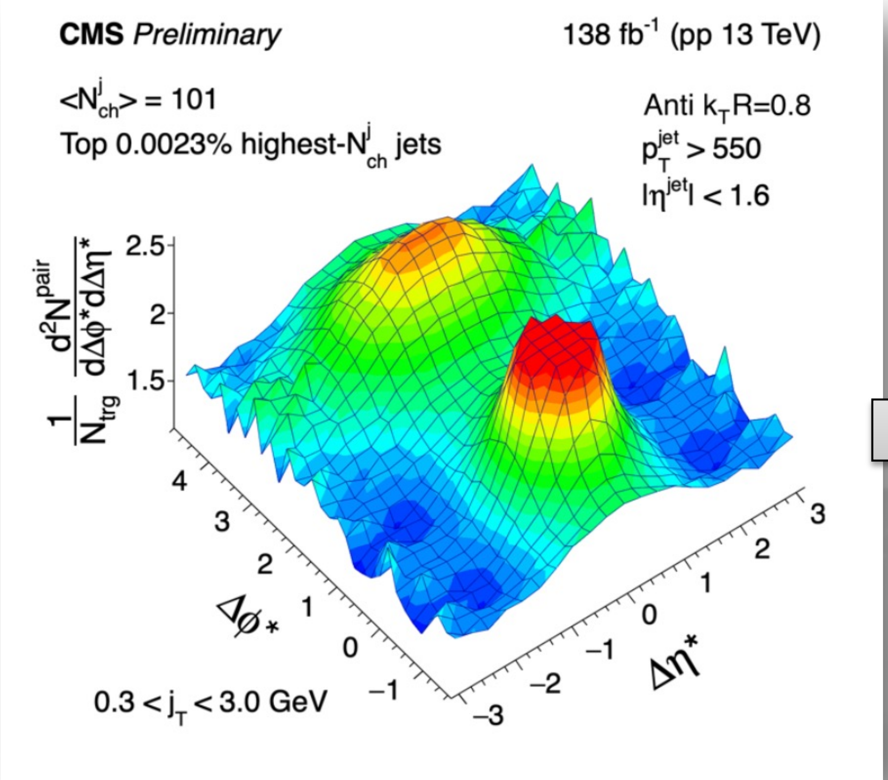
Λ/K^0_S ratio in γ-Pb approximately **2x below p-Pb 60-80%**

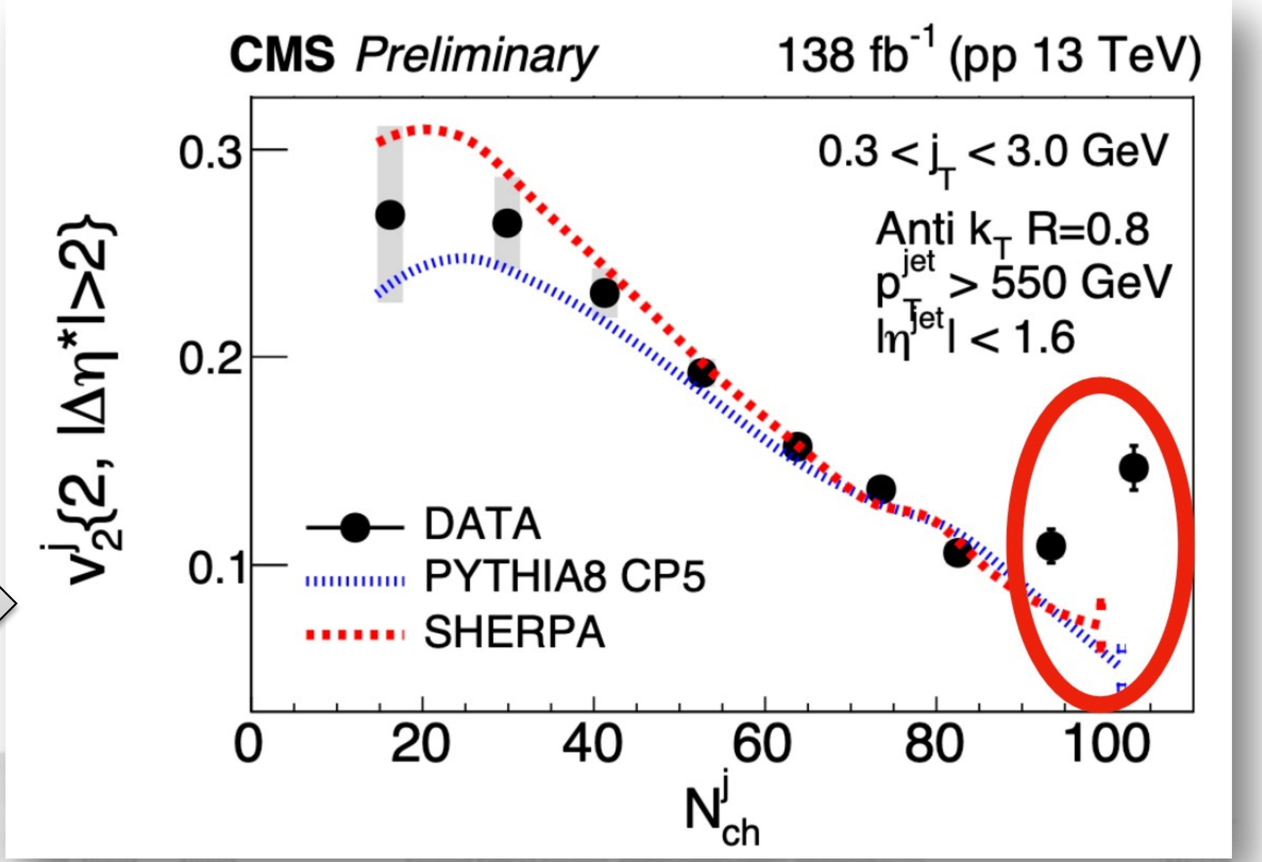
- Multiplicity dependence to be studied

→ will we see similar behaviour as in other systems?



Flow in individual jets?



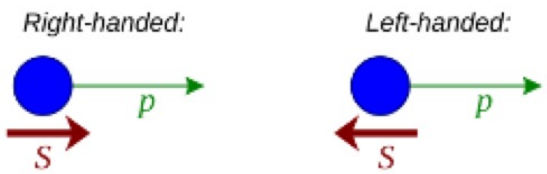


- Elliptic flow with respect to jet axis anomalously high for high N^{j}_{ch}
- Possibly a sign of collectivity in jets?

✓ Flow correlations
✓ Hard/soft interplay

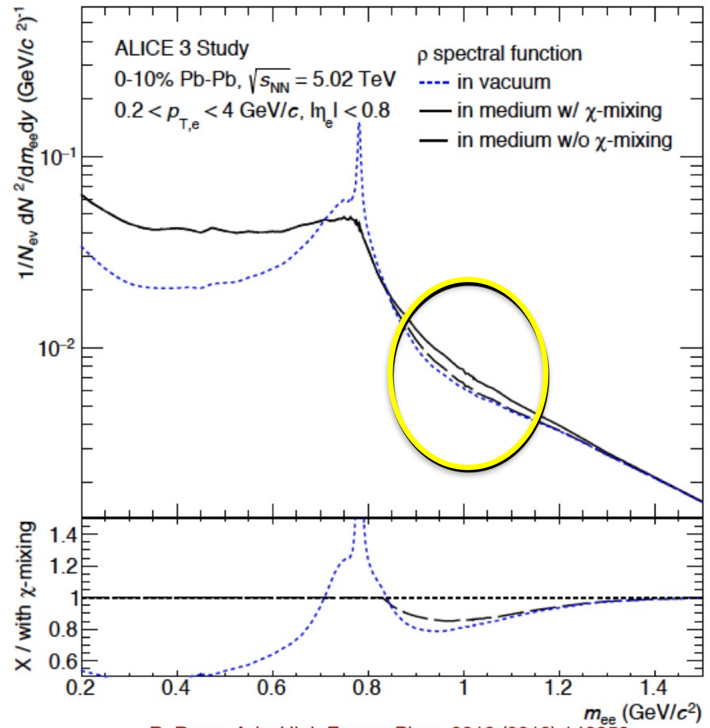
QGP phase transition: chiral symmetry restoration

- In the massless limit, QCD Lagrangian is symmetric under chiral transformations between left- and right-handed states
- Chiral symmetry breaking, with the associated formation of quark-antiquark condensates, generates most (~99%) of the mass of the baryons, while the contribution of the mass generated by the Higgs field is almost negligible (bare u/d quark mass)



Chirality = helicity for massless particles

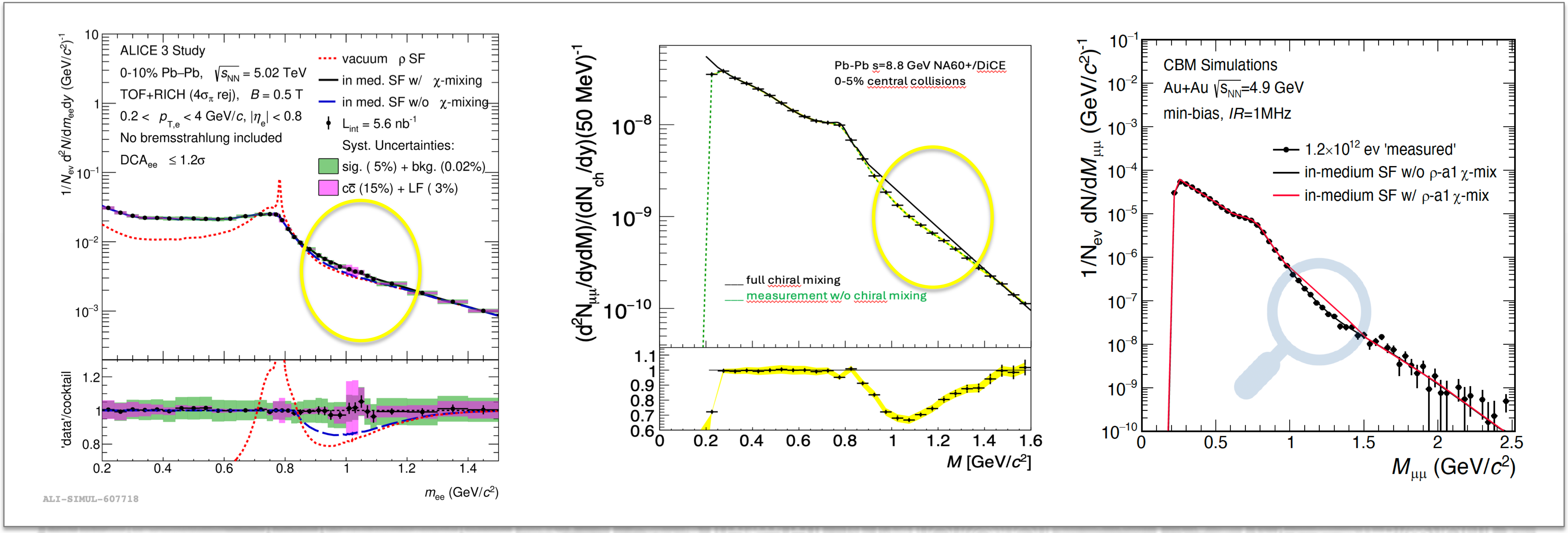
- In QCD vacuum (T=0), symmetry is broken and chiral partners have different mass, e.g. $\rho_0 - a_1$ mesons
- QGP: chiral symmetry (partially) restored
  - $\rho_0 - a_1$ masses get closer
  - Can be observed in $\rho^0 \rightarrow l^+l^-$ mass spectrum



R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103
R. Rapp private communication

QGP phase transition: chiral symmetry restoration

- Di-lepton measurements in ALICE 3, NA60+, CBM will enable direct experimental access to chiral symmetry restoration in the QGP



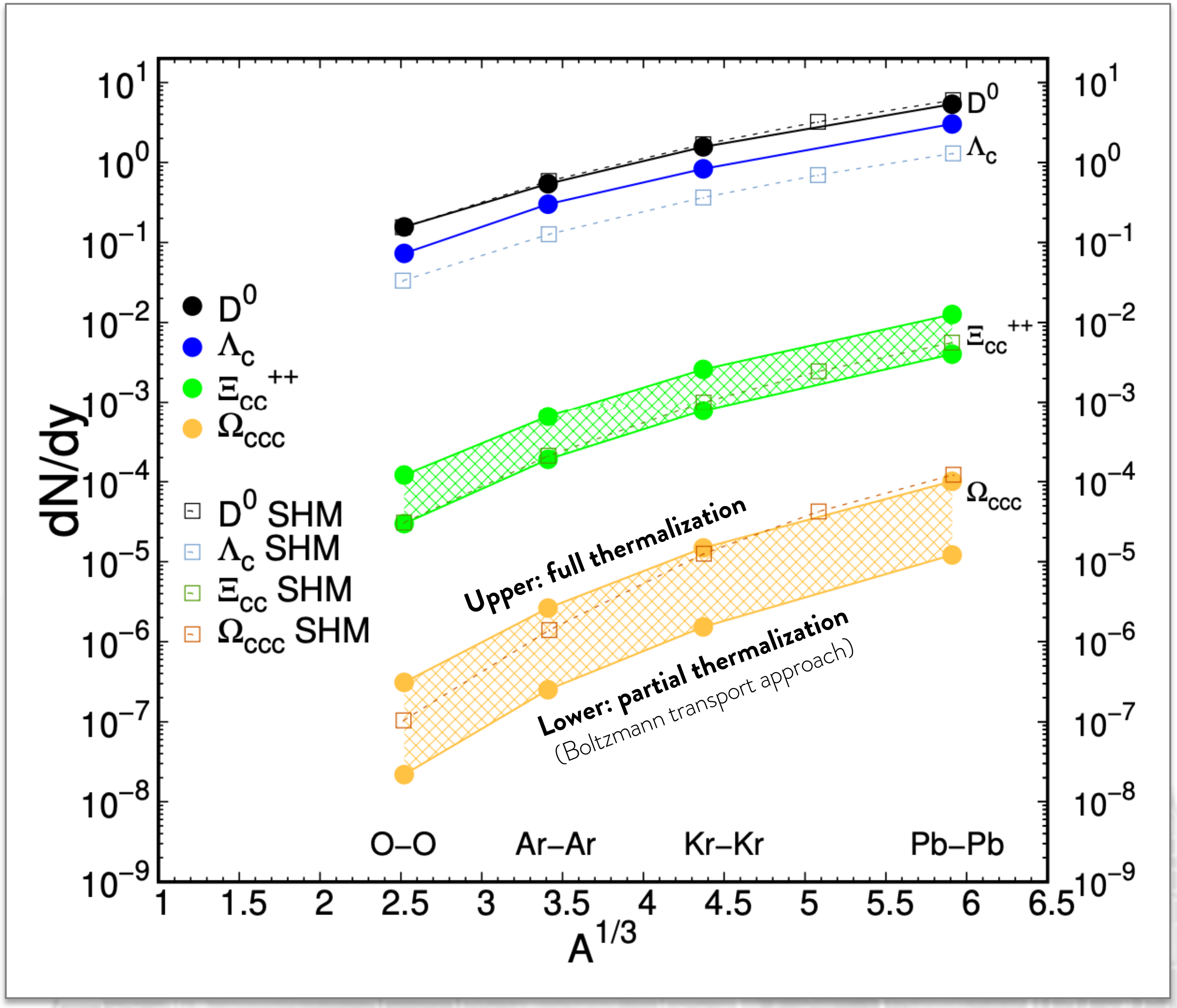


Figure from Eur.Phys.J.C (2024) 84:228

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  - Due to large, fixed $N_{charm:}$ game changer
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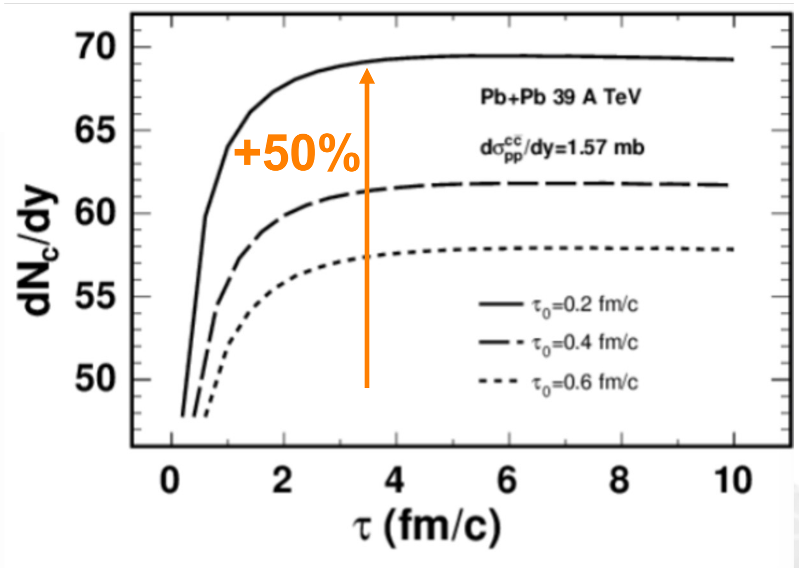
- Very large centrality dependence of production rates
  - **Complete charm thermalization not a given**

Ultimate high energy and lumi – FCC-hh

Heavy ions at FCC-hh: novel probes of the QGP

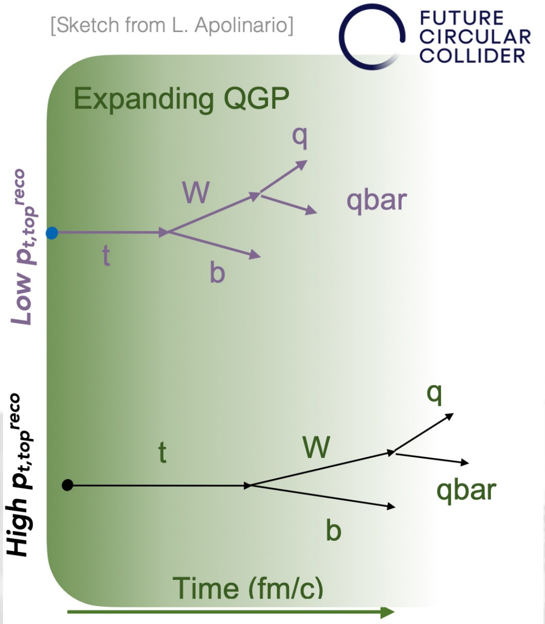
- FCC-hh HI performance: Pb-Pb at ~ 35 TeV **~ 7 x LHC energies**
- >100 nb^{-1}/month in "ultimate" luminosity scenario: **~ 20-30 x LHC L_{int}**
- QGP from LHC to FCC: **volume x2, energy density x3, initial temperature ~1 GeV**

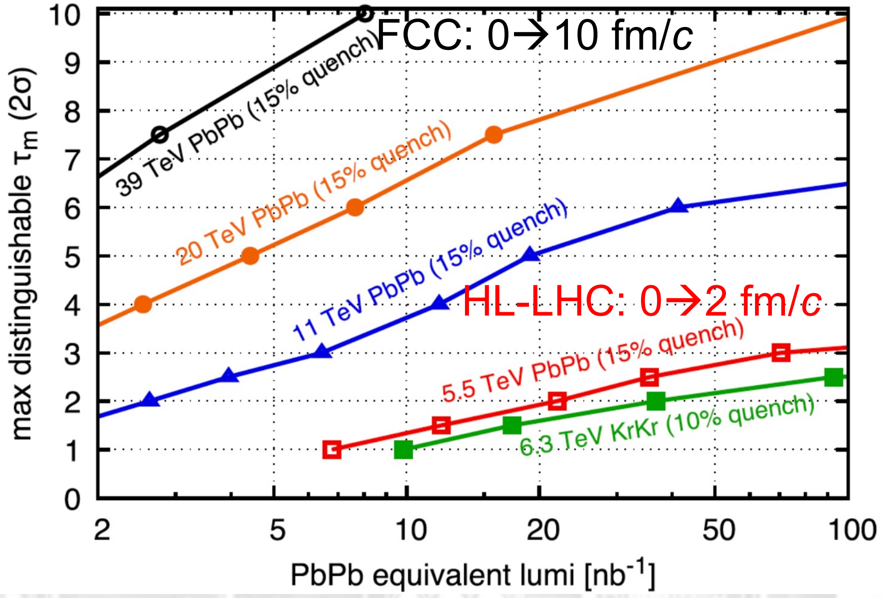
Thermal charm-anticharm from QGP gluons → initial temperature



Ko, Liu, JPG43 (2016) 12, 125108
Zhou et al., PLB758 (2016) 434

Boosted top decay chain → QGP density vs. time (yoctosecond chronometer)





Apolinario et al., PRL120 (2018) 23, 232301