Open questions and experimental prospects: Hot and dense QCD & QCD connections (hadronic, nuclear and astrophysics)

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on behalf of the Strong Interactions WG

European Strategy
for Particle Physics

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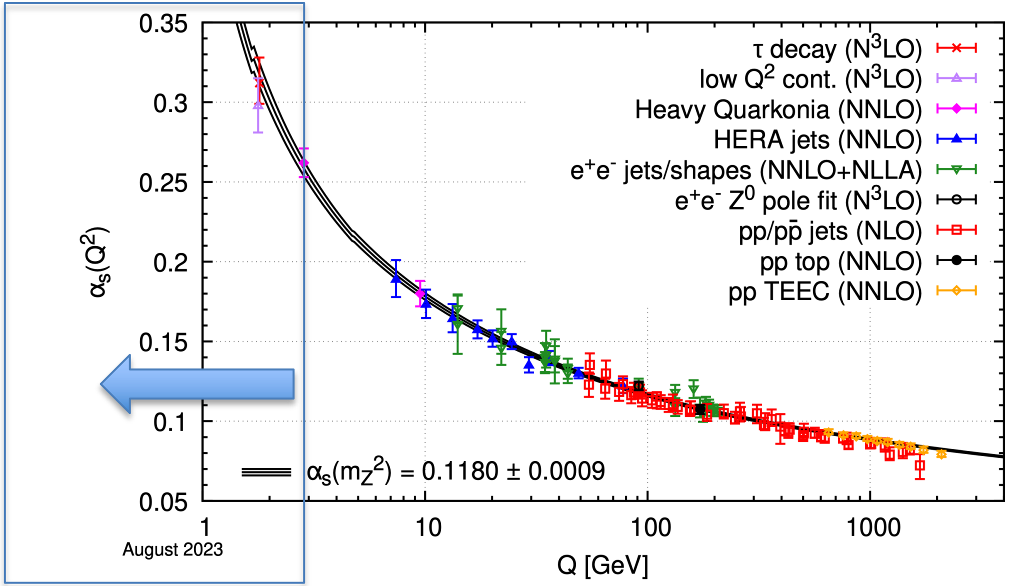
The rich landscape of non-perturbative QCD

Low momentum-exchange regime, Q<<10 GeV

→ strong coupling $\alpha_s(Q^2)$ becomes large

→ non-perturbative QCD



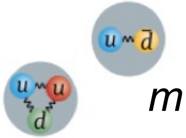
The rich landscape of non-perturbative QCD

Low momentum-exchange regime, Q<<10 GeV
→ strong coupling $\alpha_s(Q^2)$ becomes large
→ non-perturbative QCD

→ Many low-Q interactions: High Temperature
Hot and dense QCD many-body system

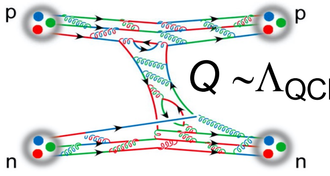
$T \sim \Lambda_{QCD}$

→ Scale of hadronization and hadron mass
Hadron formation, hadron mass, hadron structure and exotica

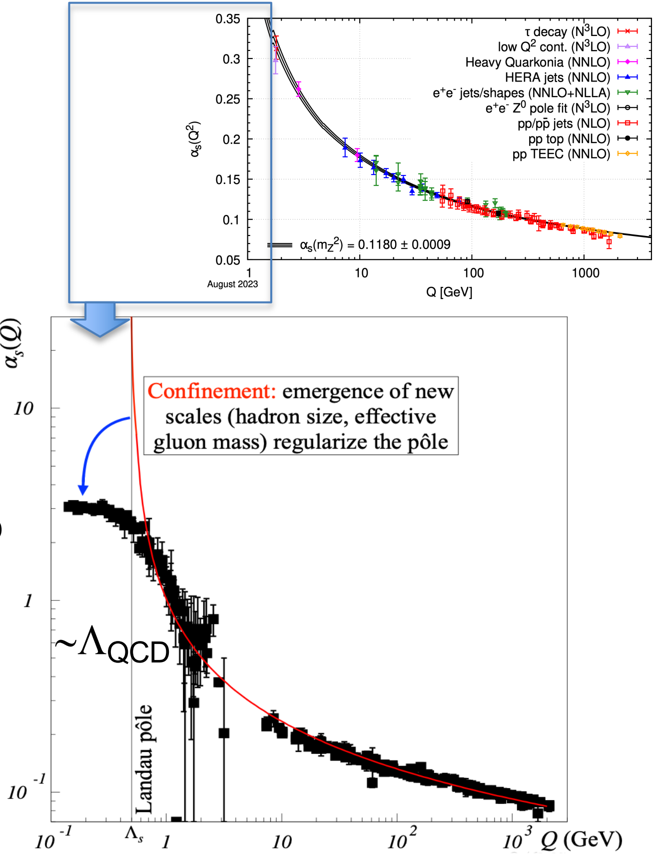


$m \sim \Lambda_{QCD}$

→ Scale of hadron size and interactions
Processes in neutron stars, formation of light anti-nuclei in cosmic rays



$Q \sim \Lambda_{QCD}$



Deur, arXiv:2502.06535

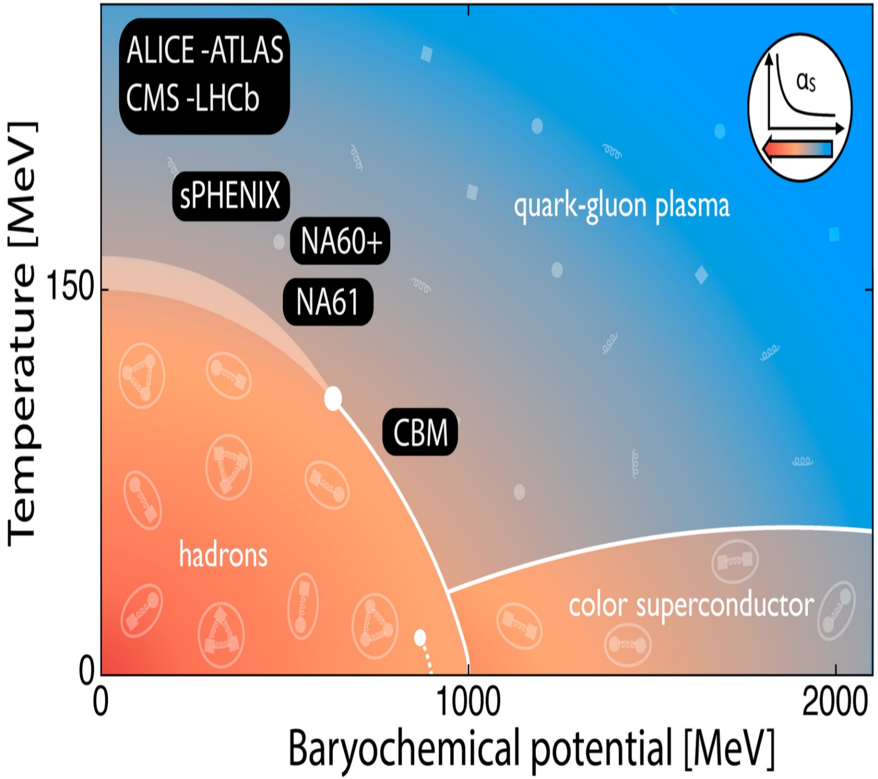
Facility, Experiments	Colliding systems, c.m.s. energy	Timeline	Precision QCD	Partonic dynamics in protons and nucleons	Hot and dense QCD	QCD connections (hadronic, nuclear, astrophysics)
HL-LHC: ALICE 3, ATLAS & CMS pII, LHCb U2, LHCspin	pp 14 TeV AA 5.5 TeV pA 8.8 TeV	> 2035 (ALICE 3, LHCb U2)	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, m_W	(n)PDF, TMD, small x, intrinsic charm	Precision charm, beauty, hard and e.m. probes, μ_B=0; time evolution	Hadr. int., (hyper/charm)nuclei, Exotica, Cosmic antinuclei, Neutron Star EoS
HL-LHC: FPF	LHC collisions, neutrino-nucleon	> 2031		(n)PDF, small x, intrinsic charm		Cosmic rays (ν, modeling primary interaction)
SPS: NA60+, NA61	pA, AA, 5-17 GeV	> 2030 (NA60+)		nPDF, medium/large x	Charm, dileptons, critical point?, μ_B=200-450MeV	Cosmic antinuclei, ν
FAIR SIS-100: CBM	pA, AA, 2.5-5 GeV	> 2028			Hadrons, dilept., critical point?, μ_B =500-700MeV	(Hyper)nuclei
SPS: AMBER pII	μ, π, K, p(250 GeV)-N	> 2030				K, π properties, spectroscopy, Cosmic antinuclei
MUonE	μ(160 GeV)-e	> 2030	g-2 (hadronic)			
HIE-ISOLDE upgrades	Radioactive ion beams	> 2029				Nucl. phys. Inputs NS EoS
KEK: Belle II upg.	ee 10 GeV	> 2035	$\alpha_s(m_\tau^2)$			Exotica (c,b)
STCF	ee 2-7 GeV	> 2033	$\alpha_s(m_\tau^2)$			Exotica (c)
EIC	ep, eA 28-140 GeV	> 2036	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	(n)PDF, TMD, GPD, medium/large x		Exotica (c,b)
LHeC	ep, eA 1.2 TeV	> 2043	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	(n)PDF, TMD, GPD, small to large x		Exotica (c,b)
FCC	ee 90-365 GeV pp 85 TeV AA 33.5 TeV pA 53.4 TeV	> 2047 > 2074	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, Γ_t, m_W	(n)PDF, TMD, small to large x	New probes of time evolution, early times, μ_B=0	Cosmic rays (modeling primary interaction)

ESPP Inputs:
hot and dense QCD
& QCD connections

>30 Input Documents map to these two areas of Strong Interactions

(mostly) The realm of Hadron Machines

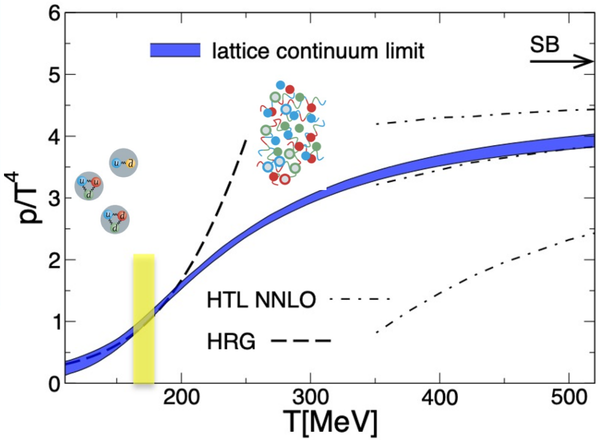
Phase diagram of strongly-interacting (QCD) matter



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*

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

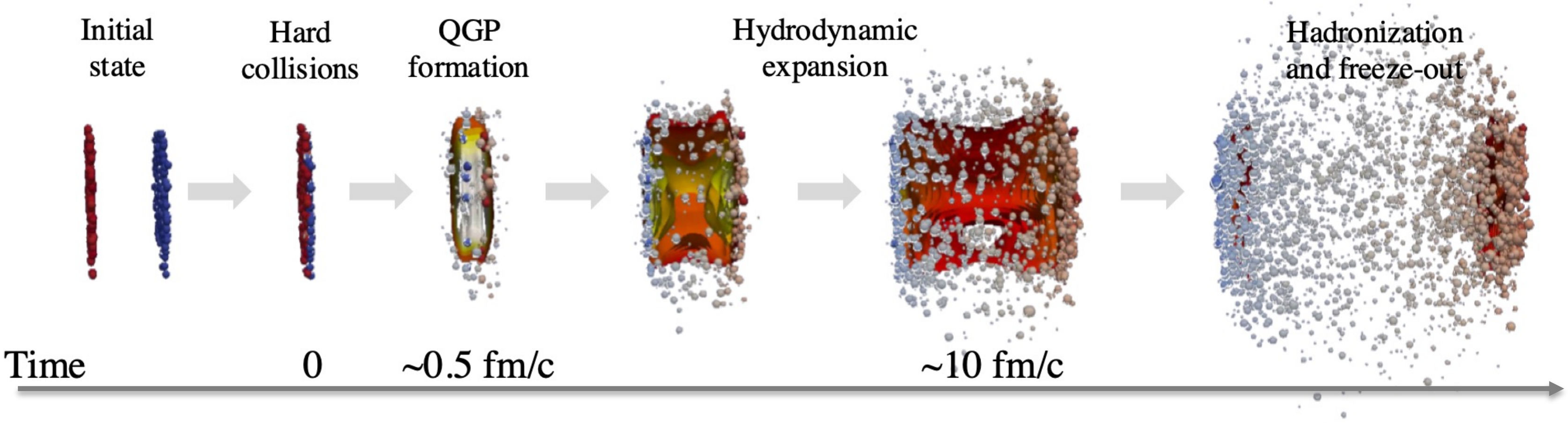


$p / T^4 \sim n_{dof}$ changes rapidly at T_c ~155 MeV

→ ε_c **= 0.6 GeV/fm³**
~ 10 $\varepsilon_{nucleus}$

Heavy-ion collisions and the QGP

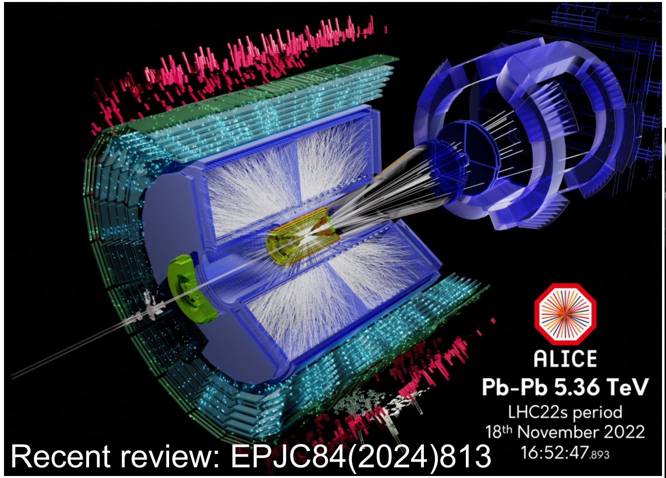
- Explore the deconfined phase of QCD matter → quark-gluon plasma
- **LHC Pb-Pb → large energy density** (initial ε > 10 GeV/fm^3) & **large volume** (~ 5000 fm^3)

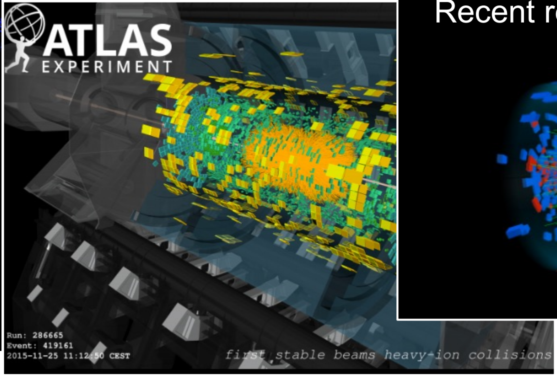


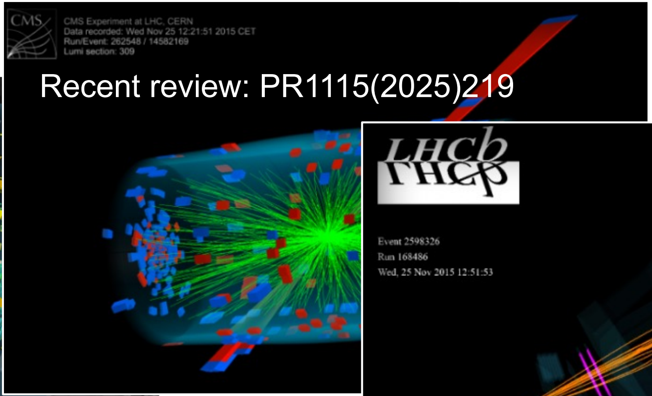
Visualization by J.E. Bernhard, arXiv:1804.06469

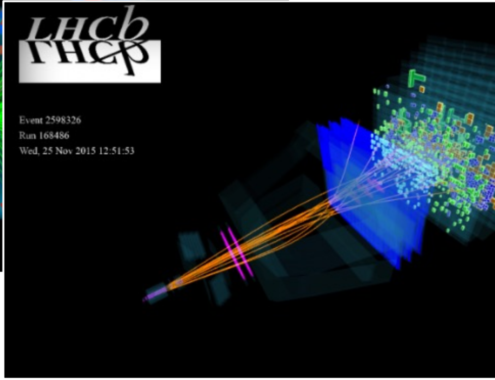
Quark-gluon plasma study at the LHC

Runs 1-3: Pb-Pb $\sqrt{s_{NN}}$ =2.76-5.36 TeV, L_{int} ~7 nb^{-1}







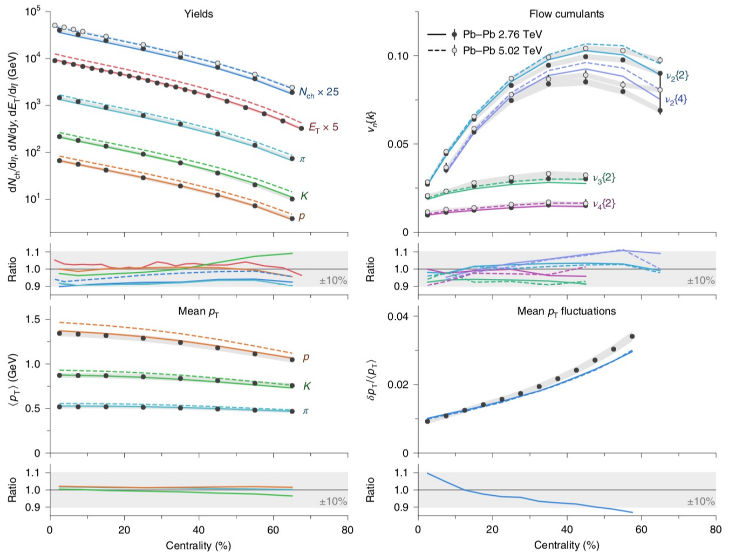


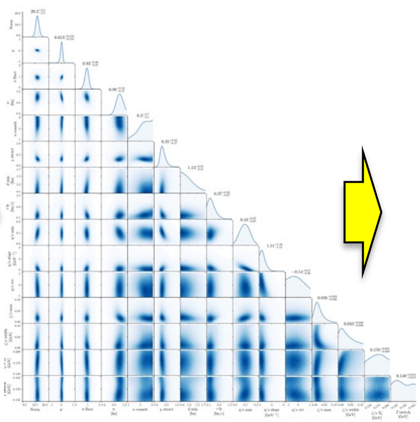
QGP features in a nutshell:

- ✓ Energy density > 10 GeV/fm^3
- ✓ Colour charge deconfined
- ✓ Strong energy loss for hard partons
- ✓ Expands hydro-dynamically like a very-low viscosity liquid
- ✓ Hadronises in thermal equilibrium
- ✓ Large (anti)baryon production
- ✓ Smooth evolution of collectivity down to pA and pp collisions (discovery at LHC! QGP?)

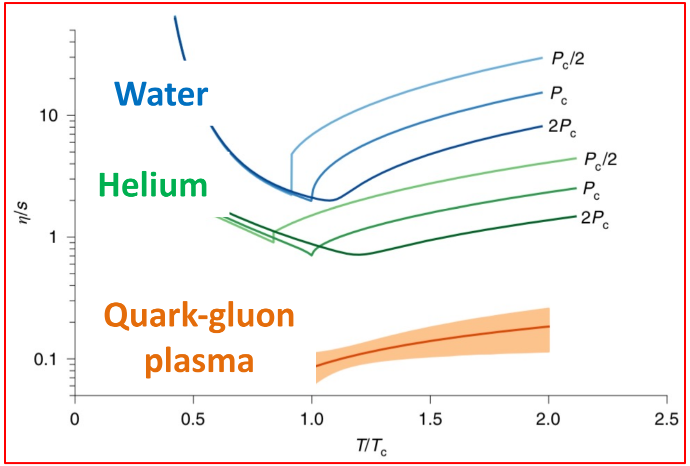
Example: from data to QGP fluid-dynamic properties

- Theory groups use **high-precision** LHC data to estimate the **properties of the QGP fluid** with a Bayesian procedure. Example: S. Bass et al, Nature Phys. 15(2019)1113





QGP shear viscosity vs. temperature



→ QGP viscosity with ~20% precision

→ QGP x10 less viscous than any other form of matter

Current summary of quark-gluon plasma properties (LHC)

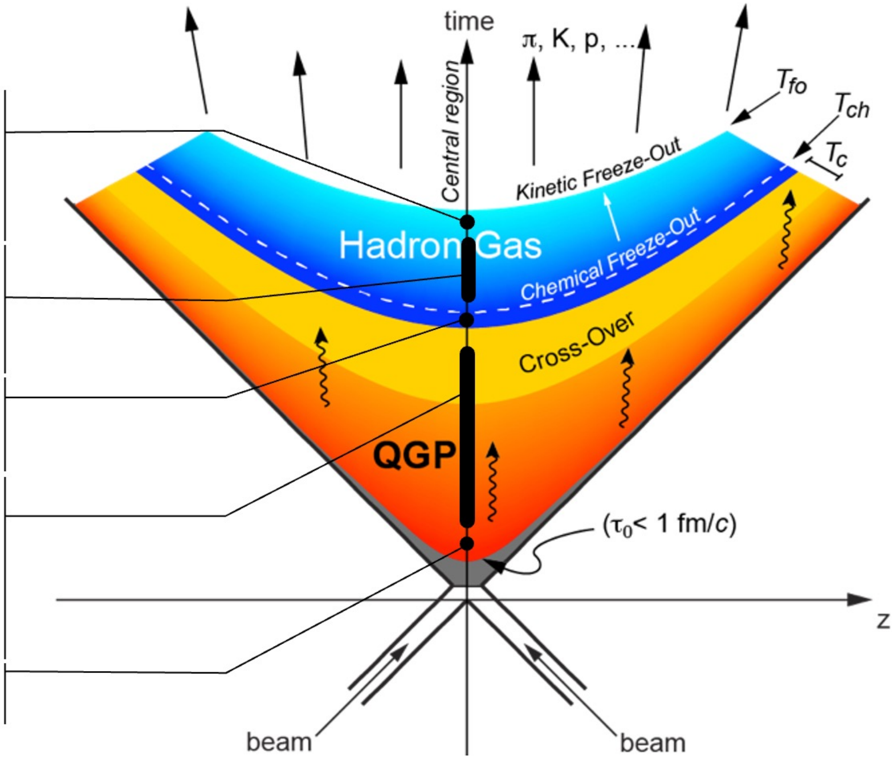
$\tau_{dec.} \approx 10$ fm/c
$V_{dec.} \approx 5000$ fm^3
$\varepsilon(\tau_{dec.}) \approx 0.4$ GeV/fm^3

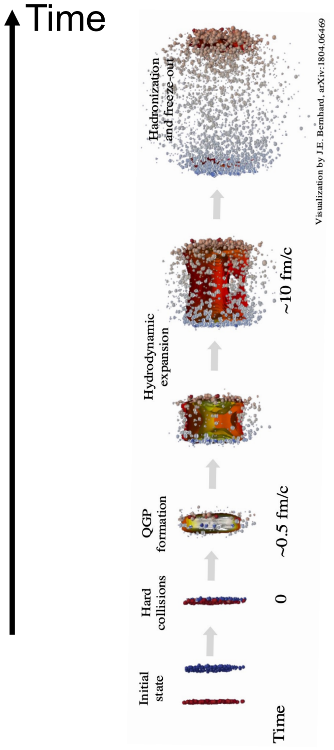
$T_{kin.} \approx 100 - 150$ MeV
$v_{T,kin.} \approx 0.65\ c$
$\tau_{hadr.} \approx 1 -$ few fm/c

$T_{chem.} = 156 \pm 2$ MeV
$\mu_B = 0.71 \pm 0.45$ MeV

η/s at $T_c \approx 0.06 - 0.12$
$2\pi T D_s$ at $T_c \approx 1.5 - 4.5$
$T_{photon} = 304 \pm 41$ MeV
$\hat{q}/T^3$ at $T_c \approx 2 - 11$

$\varepsilon(1$ fm/$c) \approx 14$ GeV/fm^3



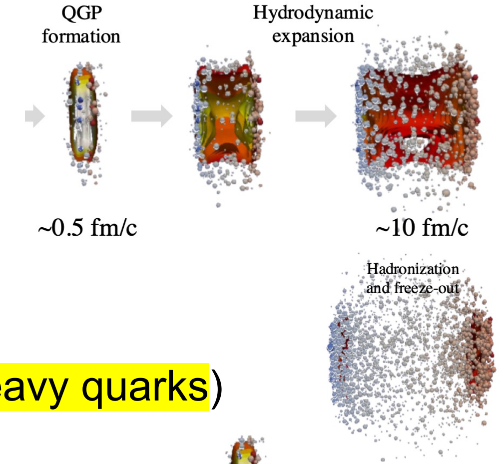


Audurier (LHCb), Cole (ATLAS), Dainese (ALICE), Lee (CMS), https://doi.org/10.1142/9789811280184_0005

Main open questions in hot and dense QCD

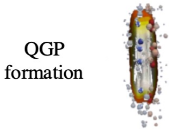
with broad impact on QCD and particle physics at large!

- **Temporal evolution of QCD many-body system**
  - < 1 fm/c — Onset of hydrodynamic regime (multi-parton → "liquid")
  - QGP temperature and density vs time
  - 1-10 fm/c — Microscopic mechanisms of quark interactions in QGP
  - Approach to thermal equilibration (heavy quarks)



- **Mechanisms of hadron formation** in dense QCD environment
  - General question in QCD; QGP = ideal testbed (deconfined heavy quarks)

- Mechanism of **chiral symmetry restoration** in the QGP
  - Generates 99% of atomic mass ($m_{u,d}/m_p$ ~ 1%)



- **Emergence of collectivity in QCD: smaller collision systems** down to pp

- **Critical endpoint in QCD phase diagram?**

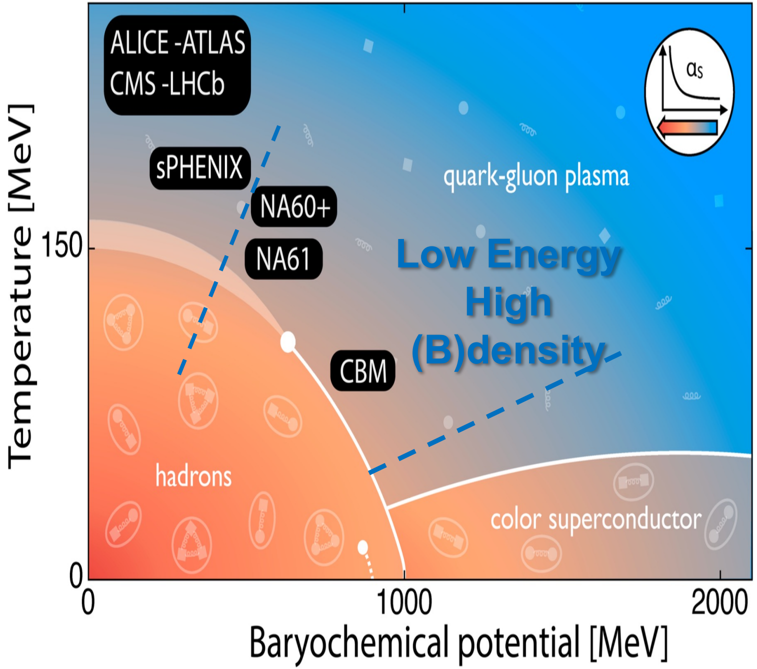
European Strategy for Particle Physics

Future research directions with heavy ions

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

◆ Caloric curve of QCD matter (temp. vs. c.m.s. energy)

◆ Search for the Critical Endpoint



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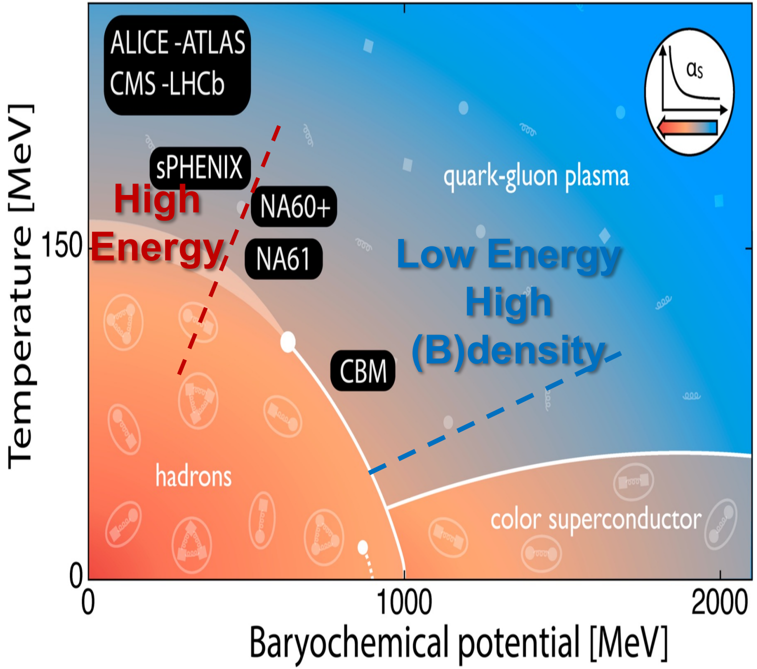
High energy collisions (HL-LHC ~ 5.5 TeV):

- 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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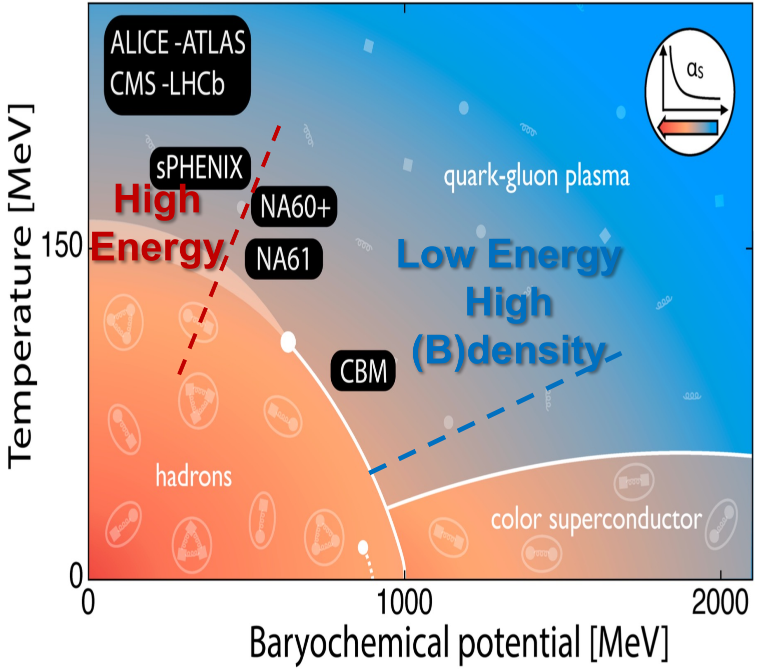
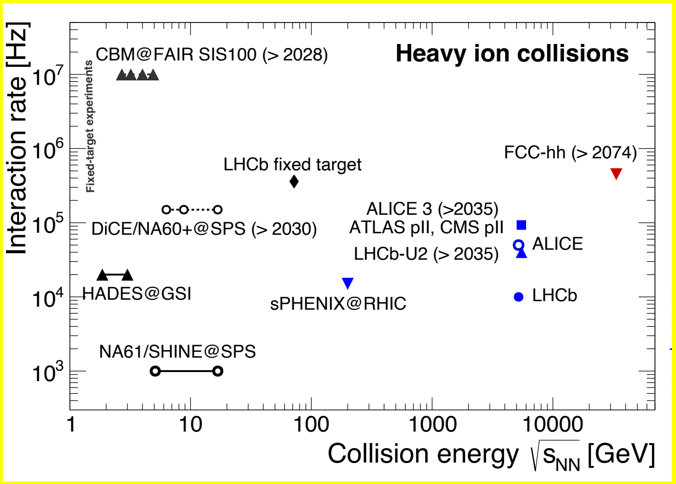
Further future (FCC-hh ~ 35 TeV):
- New rare probes and time-scales of the QGP accessible
    - Thermal charm, boosted top decays, …



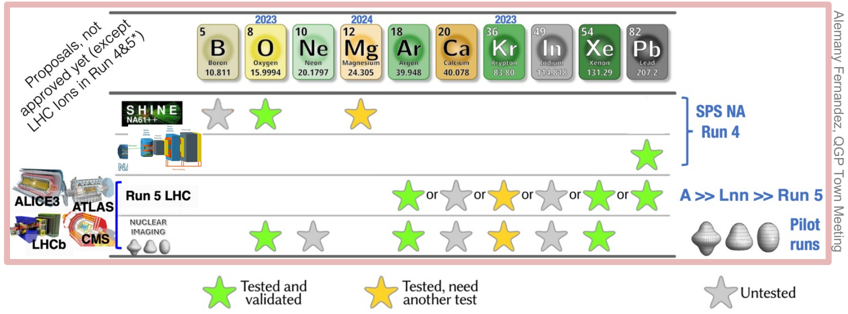
Full physics exploitation of facilities with ion beams

- HL-LHC
  - Full exploitation (2020 ESPPU) requires:
  - Detector upgrades with frontier sensors, to extend physics reach
  - Maximisation of integrated luminosity for large ions
  - Possibility of short runs with light ions for specific goals (onset of QGP effects and of thermalisation, nuclear shapes & neutron skin)
- SPS/FAIR
  - With state-of-the-art detectors
  - Unprecedented high-rate fixed-target collisions
  - Energy and nuclei variations
- FCC-hh
  - Large energy and luminosity increase
  - Keep possibility to accelerate ions

→ maximise FCC science case and community



Galatyuk, NPA 982 (2019), update June 2025



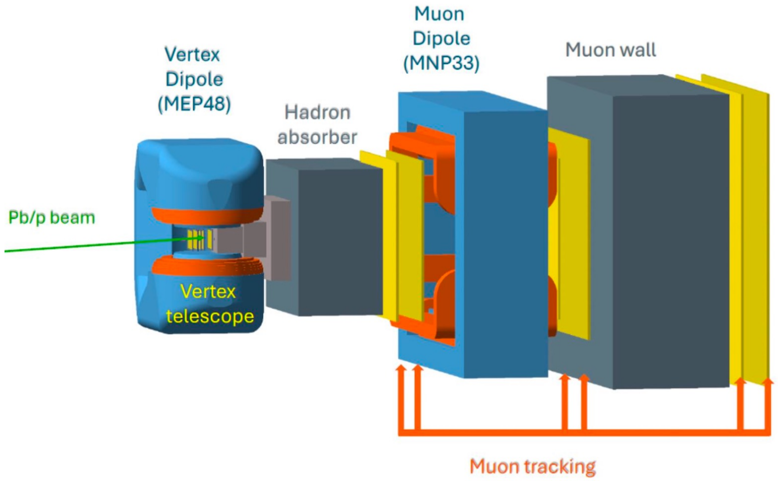
Alemany Fernandez, QGP Town Meeting

Id131:NA60+ Id171:NA61
Id106:NuPECC Id7:HITownM Id235:PBC

European Strategy for Particle Physics

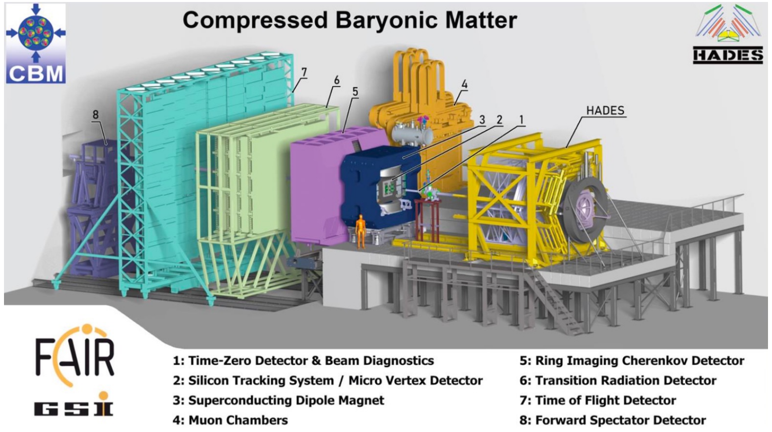
CERN SPS: new NA60+ experiment and NA61 upgrade
FAIR SIS-100: new machine and CBM experiment

- NA60+/DiCE: dimuon spectrometer following a silicon pixel tracker (ALICE ITS3 MAPS)
- Letter of Intent positively reviewed by SPSC in 2023; Proposal submitted in spring 2025
- Data taking ~ 2029-2036; scan of beam energy 20-150 GeV/nucleon



- NA61/Shine: large-acceptance hadron detector, upgraded with silicon pixel tracker (ALICE ITS2 MAPS)
- Data taking < 2033; light-ion collision systems
- Proposed upgrade (TPC→Silicon) for high-rate Pb-Pb

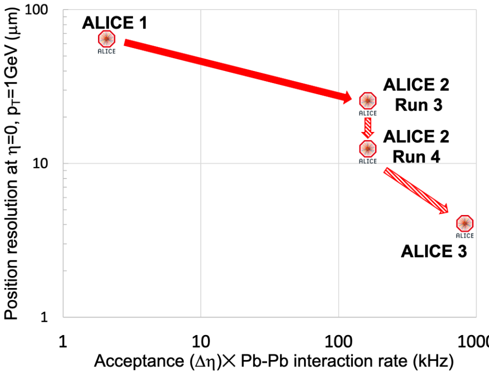
- New accelerator SIS-100 at FAIR – Data taking ~ 2029
  - SIS-300 would bridge to SPS coverage in the 2040s
- CBM/HADES: silicon tracking; hadron, μ and e ID

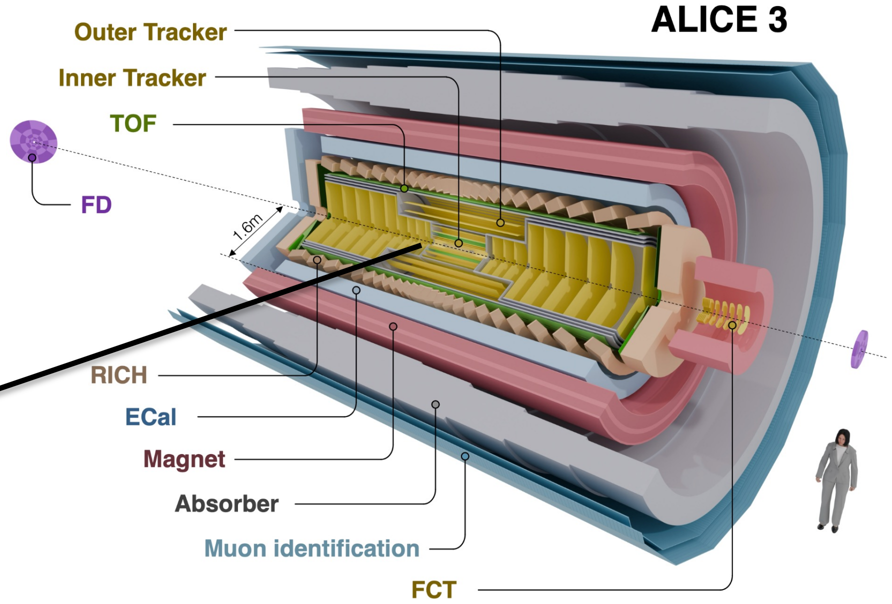


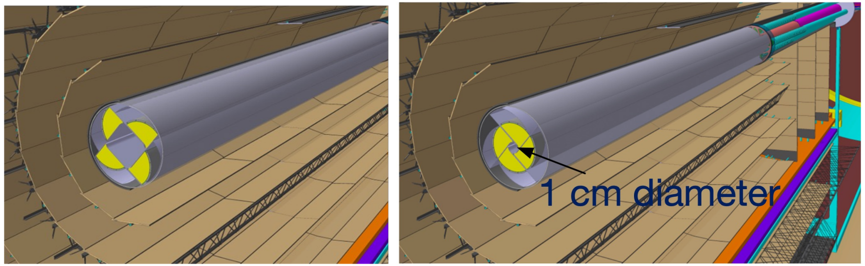
Id68:ALICE
Id106:NuPECC Id7:HITownM

ALICE 3: next-generation heavy-ion detector

→ Tracking precision × 4: 4 μm at p_T = 1 GeV/*c*, “ultimate” Si-MAPS tracker
→ Acceptance × 4.5: |η| < 4, p_T > 50 MeV, with particle ID (Si-TOF, SiPM-RICH, Mu)
→ Interaction rate × 5 (pp × 25)

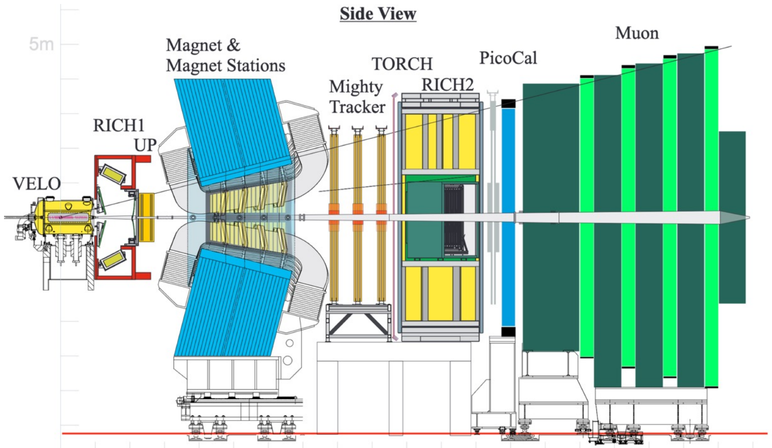






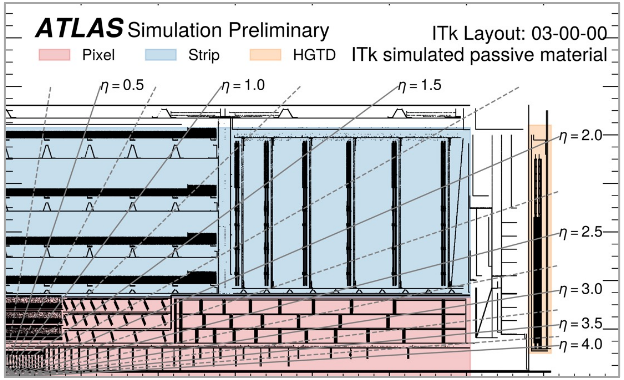
Letter of Intent: CERN-LHCC-2022-009
Scoping Document: CERN-LHCC-2025-002

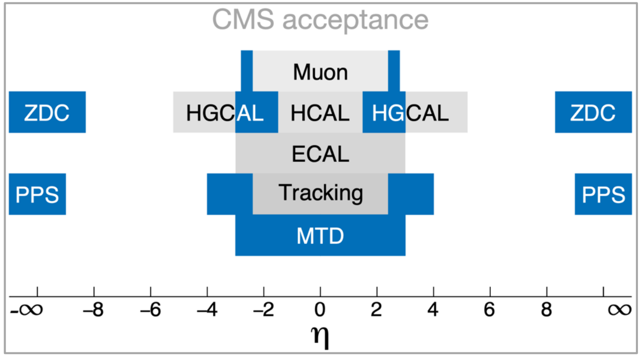
General purpose detectors: LHCb Upgrade 2 and ATLAS+CMS phase II



- → Extend capability 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

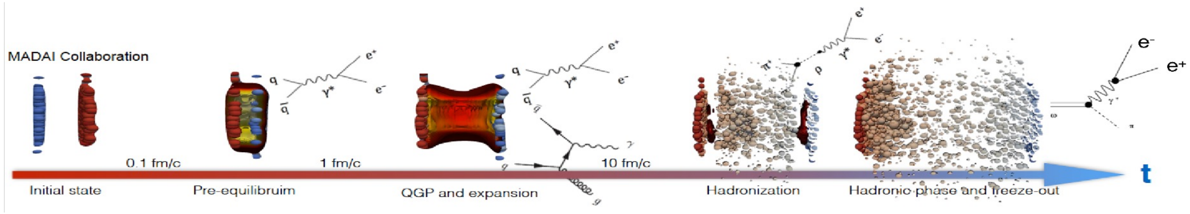


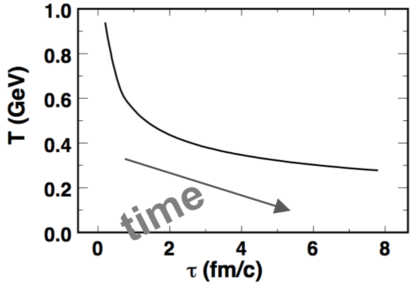


- → Runs 4+5
- → Extend tracking to $|\eta|$ = 4
- → Increased DAQ bandwidth and new hadron ID (CMS)

Id68:ALICE Id131:NA60+
Id7:HITownM

Thermal radiation: QGP temp. vs energy and vs time





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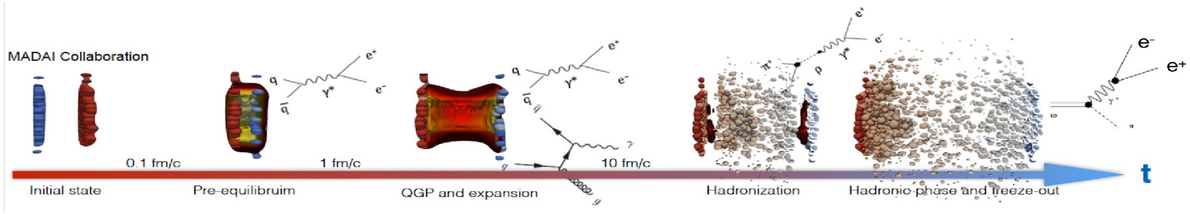

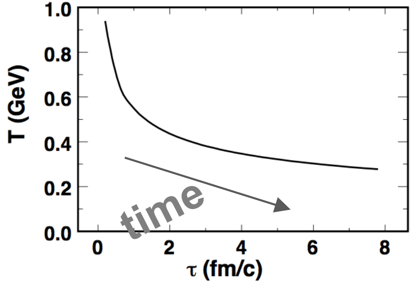

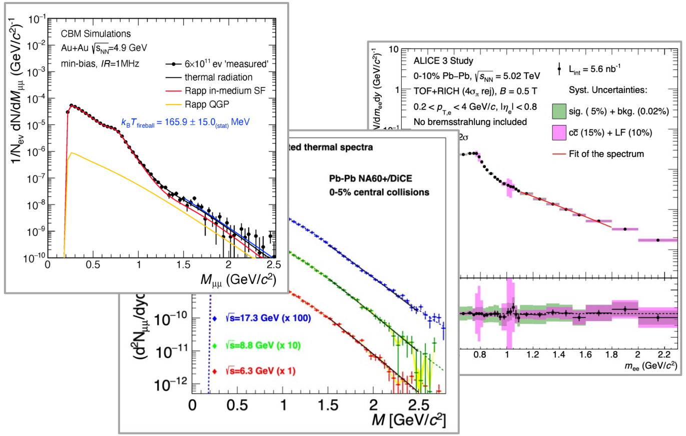

ALICE 3, CBM, NA60+: high-precision (<5%) temperature

Id68:ALICE Id131:NA60+
Id7:HITownM

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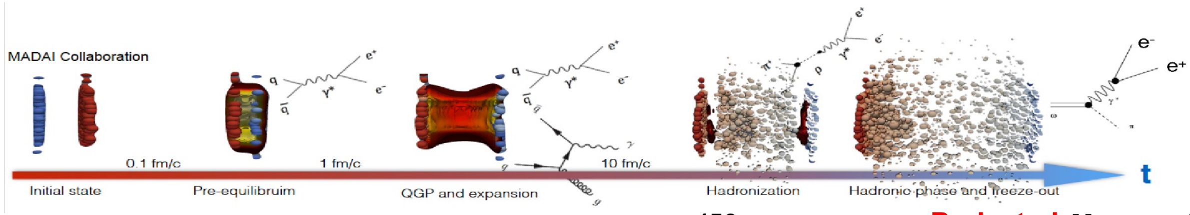
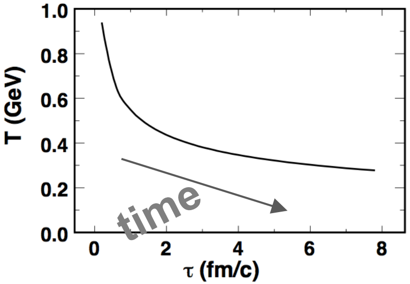
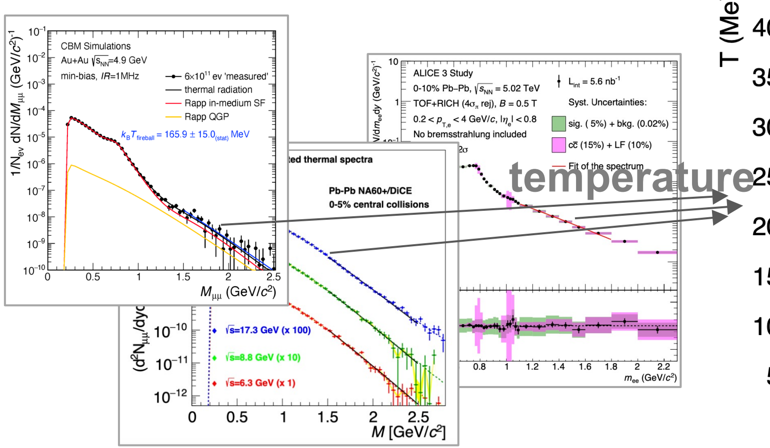
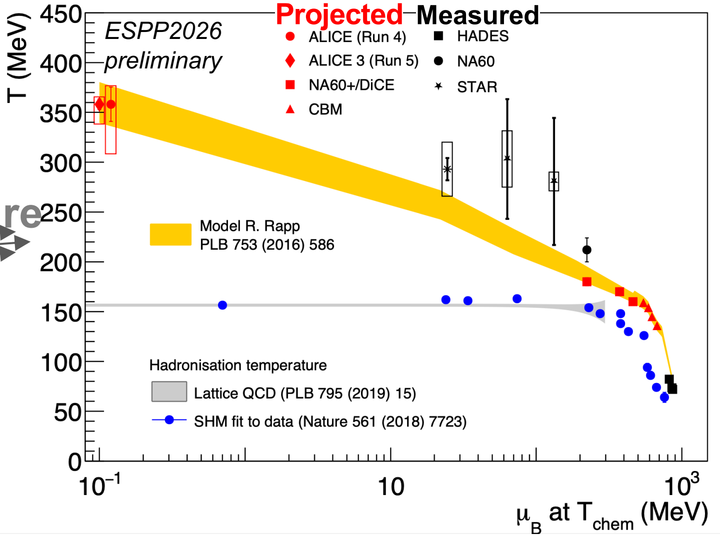
Thermal radiation: QGP temp. vs energy and vs time





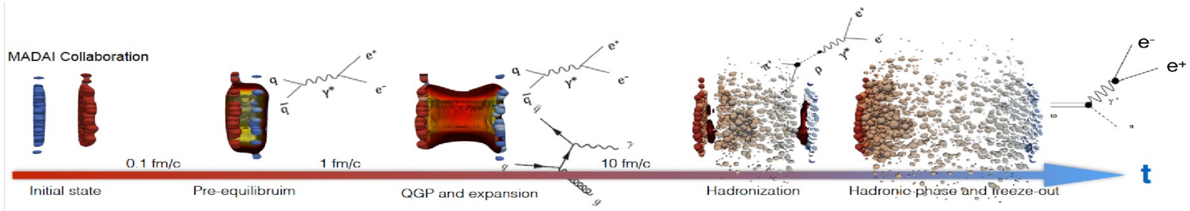


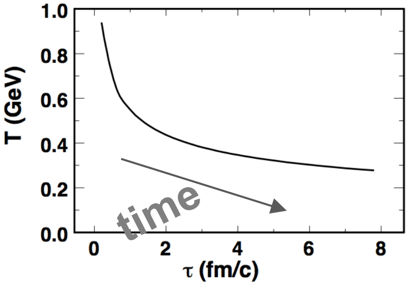


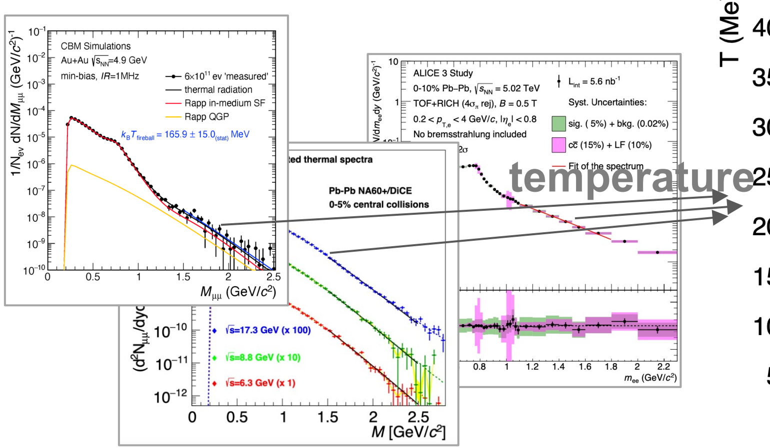
ALICE 3, CBM, NA60+: high-precision (<5%) temperature → mapping across phase diagram

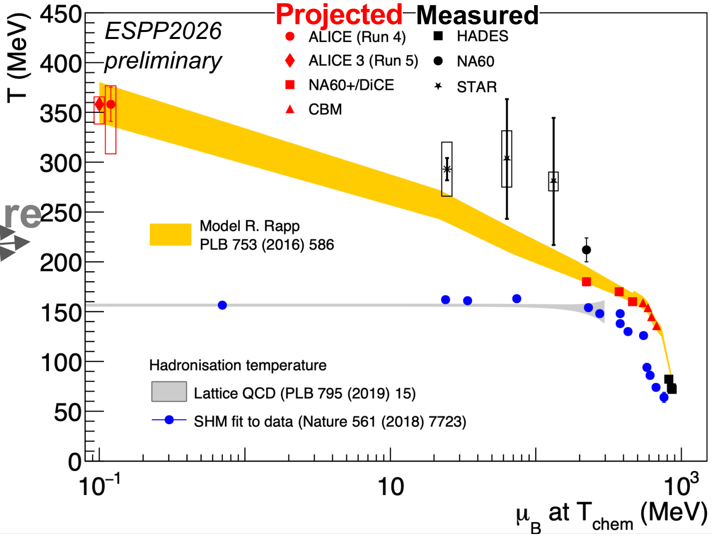
Id68:ALICE Id131:NA60+
Id7:HITownM

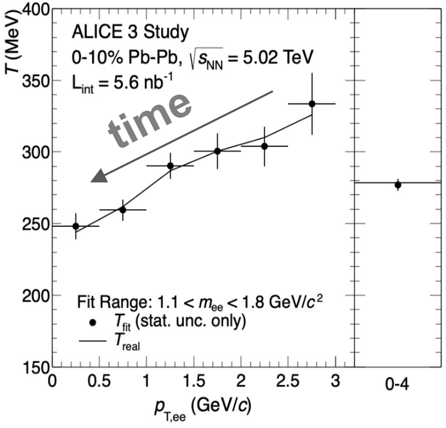
Thermal radiation: QGP temp. vs energy and vs time





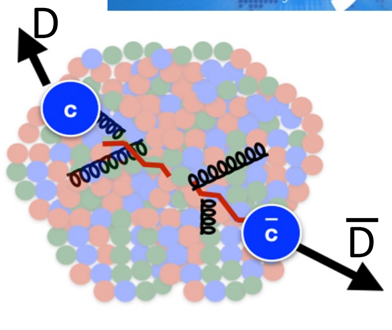




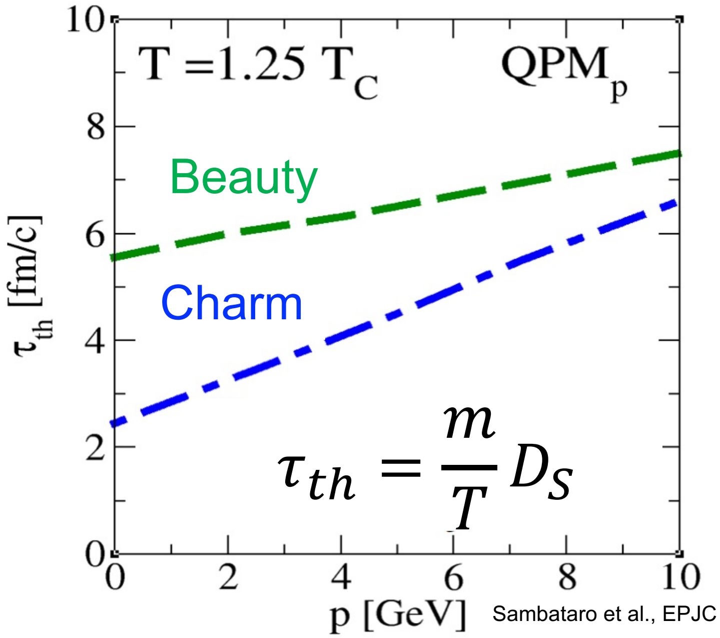


ALICE 3, CBM, NA60+: high-precision (<5%) temperature → mapping across phase diagram
ALICE 3: first access to time evolution of the temperature with thermal dileptons vs p_T

Heavy-quark thermalisation in QCD matter



- Charm and beauty: perfect probes of interactions and of transport coefficients
  - Interaction strength and effect decreases with mass
  - Thermalisation time τ_{charm} ~ 1/3 τ_{beauty}, and ~ QGP lifetime O(10) fm/c



Sambataro et al., EPJC 84 (2024) 9, 881

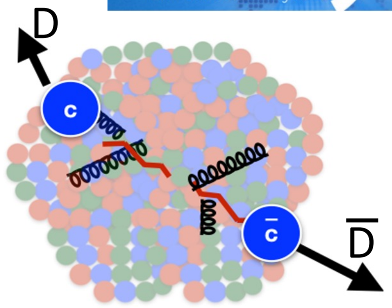
Heavy-quark diffusion coefficient D_s: a characterising property of the QGP

Id68:ALICE

Id7:HITownM

European Strategy for Particle Physics

Heavy-quark thermalisation in QCD matter



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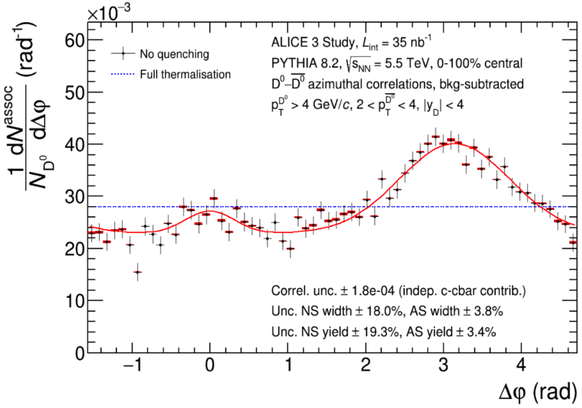
  - Thermalisation time τ_{charm} ~ 1/3 τ_{beauty}, and ~ QGP lifetime O(10) fm/c
- HL-LHC: precise study of degree of thermalisation with low-p_T charm and with beauty

Charm-anticharm azimuthal correlations (Δφ)



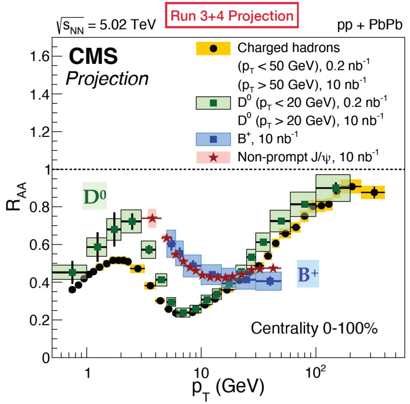
→ "Rutherford experiment" for QGP

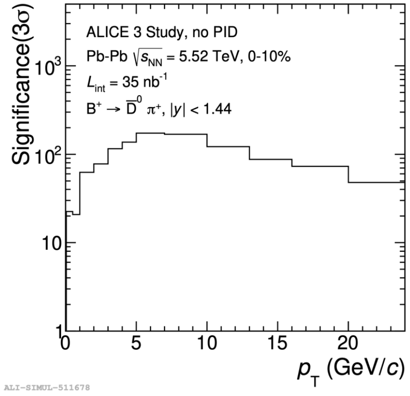
→ Direct constraints on charm equilibration

B meson production over wide p_T range

CMS: 5-100 GeV/c

ALICE 3: 0-30 GeV/c

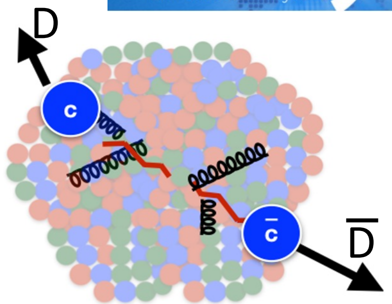




→ b quark interactions and (approach to) equilibration

[Id131:NA60+](#)
[Id68:ALICE](#)

Heavy-quark thermalisation in QCD matter



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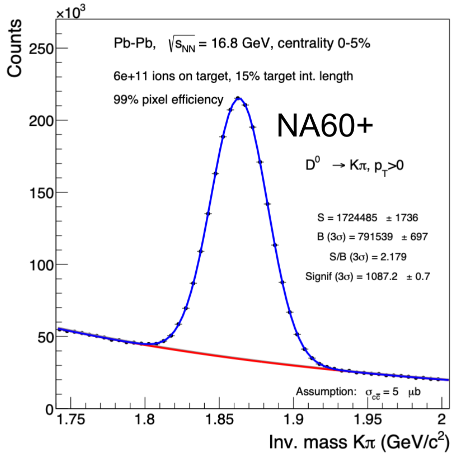
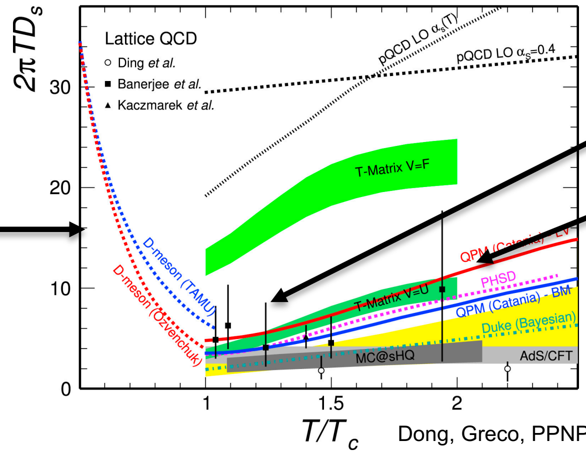
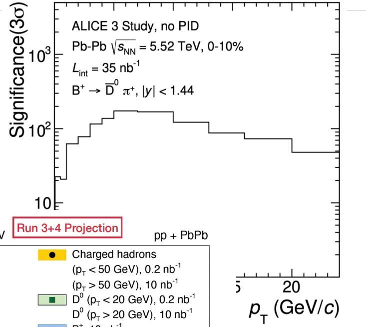
- HL-LHC: precise study of degree of thermalisation with low-p_T charm and with beauty
- SPS: charm hadron diffusion in hadronic phase ($T < T_c$)

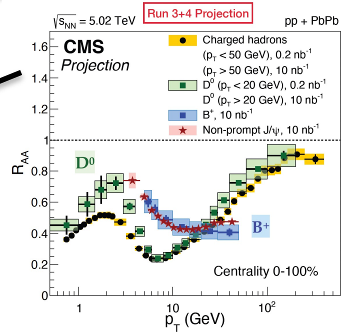


Heavy-quark diffusion coefficient D_s ~ τ / m

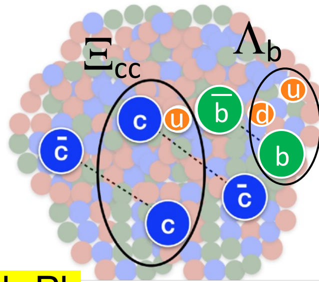


Dong, Greco, PPNP104(2019)97

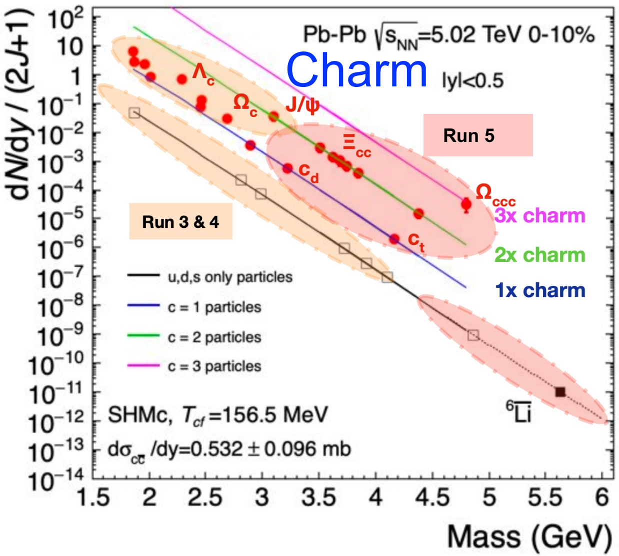


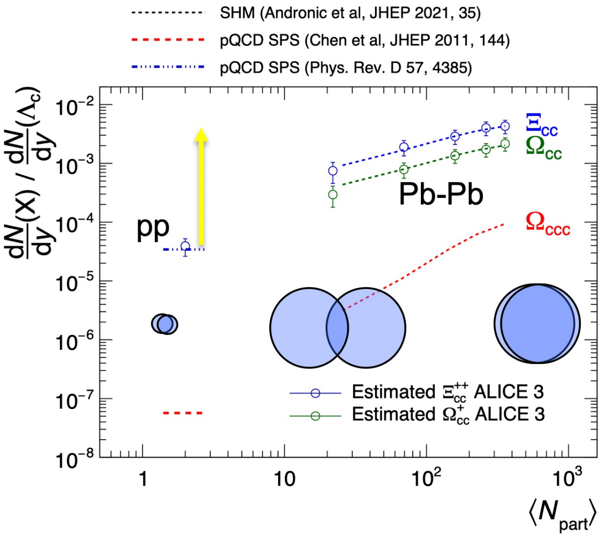


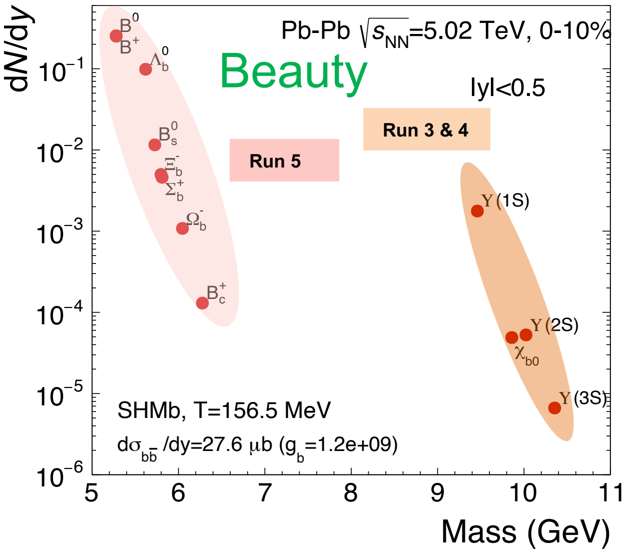
(Multi-)heavy-flavour hadron formation from QGP



- Sensitive to degree of thermal equilibration of heavy quarks
  - Mass-dependence with c and b quarks
- Multi-charm baryons
  - Require recombination of multiple charm quarks
  - Full thermalisation scenario: yield ~ g_c^n → x100 (cc) -1000 (ccc) enhancement in Pb-Pb



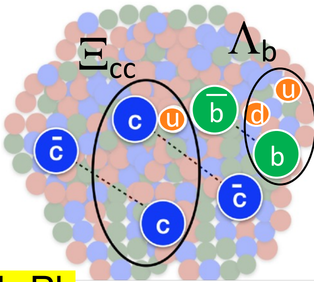




Andronic et al., https://arxiv.org/abs/2209.14562

Id68:ALICE
Id82:LHCb

(Multi-)heavy-flavour hadron formation from QGP



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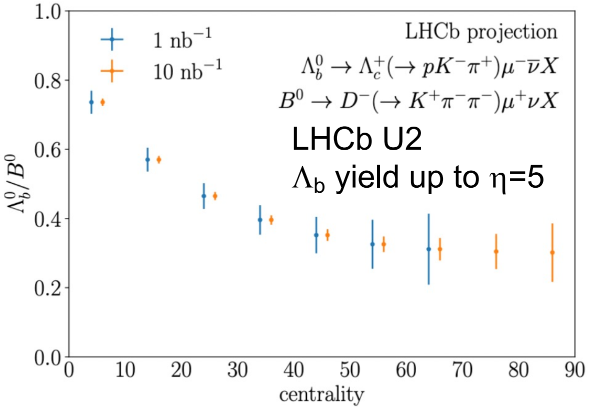
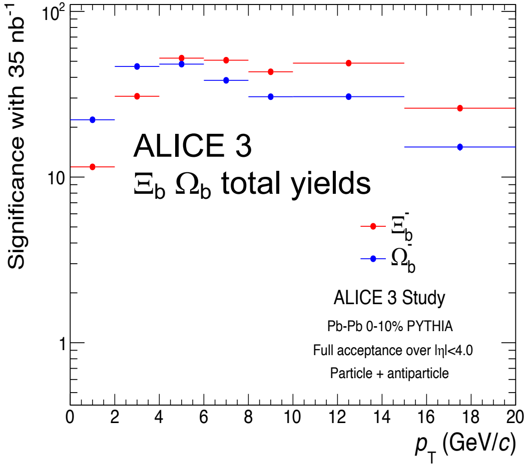
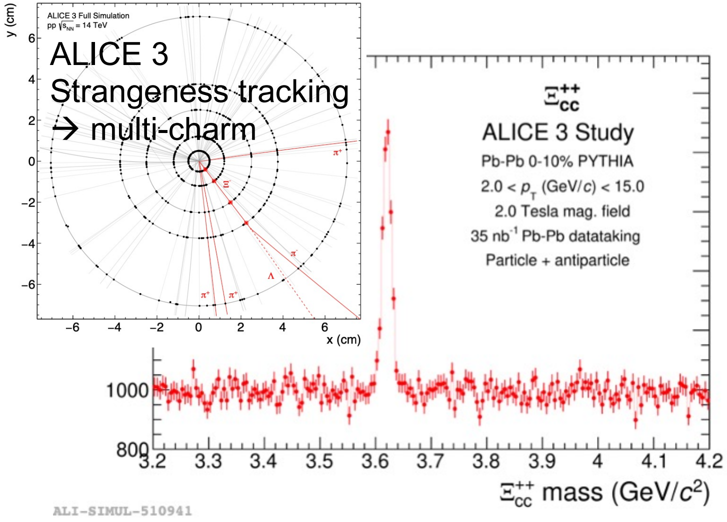






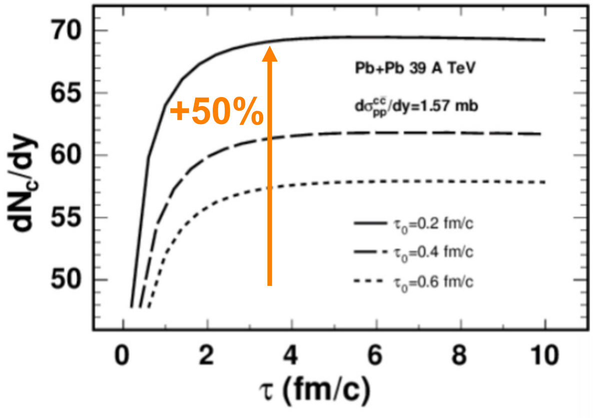
Id209:FCC-QCD
Id7:HITownM

European Strategy for Particle Physics

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

- FCC-hh HI performance: Pb-Pb $\sqrt{s_{NN}}$ ~ 35 TeV **~ 7 x LHC $\sqrt{s_{NN}}$**
- >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**

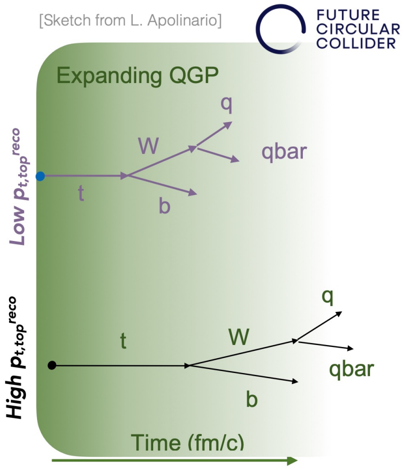
Thermal charm-anticharm from QGP gluons → initial temperature

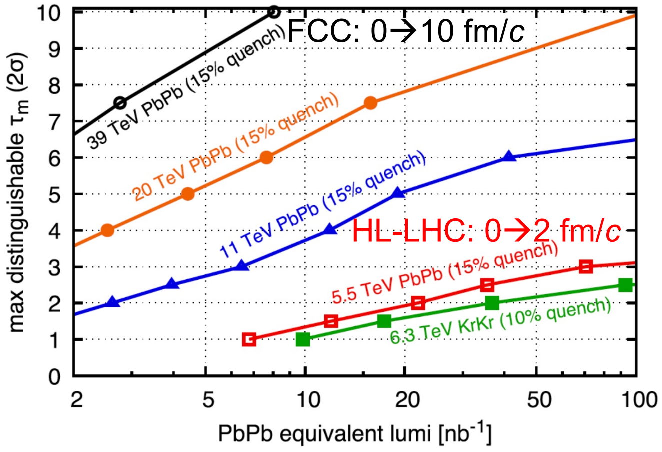


Ko, Liu, JPG43 (2016) 12, 125108
Zhou et al., PLB758 (2016) 434

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

[Sketch from L. Apolinario]

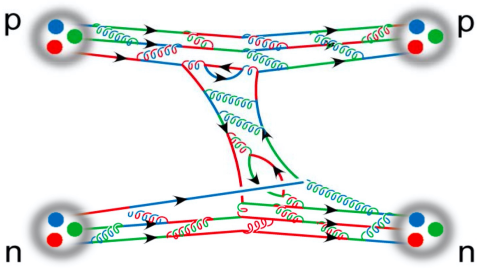


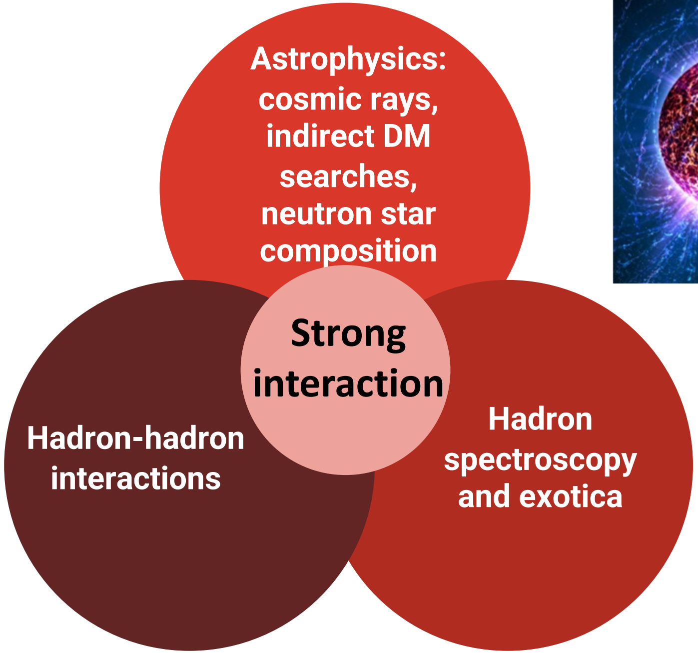


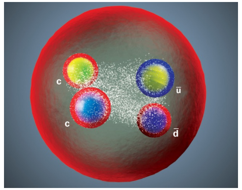
Apolinario et al., PRL120 (2018) 23, 232301

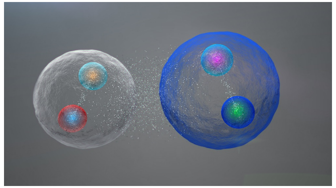
QCD connections
with hadronic, nuclear, astro(particle) physics

Very broad area → Focus on aspects with strongest benefit from large-accelerator experiments







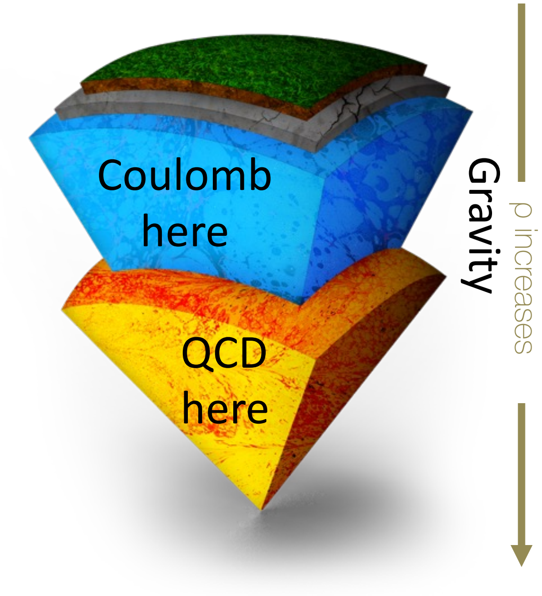


Nature of Neutron Star matter and their equation of state

Dimensions:
R ~ 10 – 15 km
M ~ 1.2 – 2.2 $M_\odot$

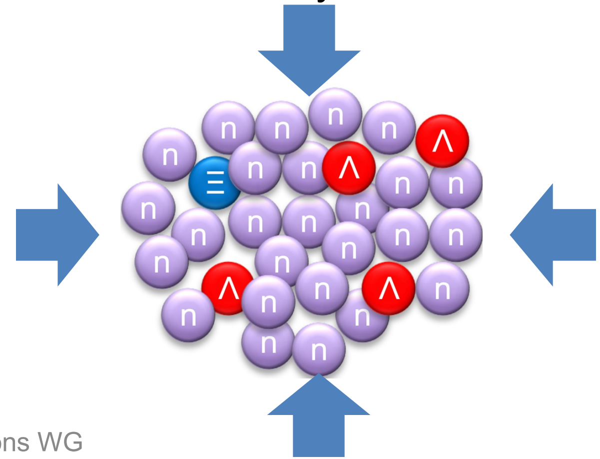
Outer crust:
Ions, electron gas, neutrons

Inner core:
Neutrons?
Protons?
Hyperons (Y)?
Kaon condensate?
Quark matter?

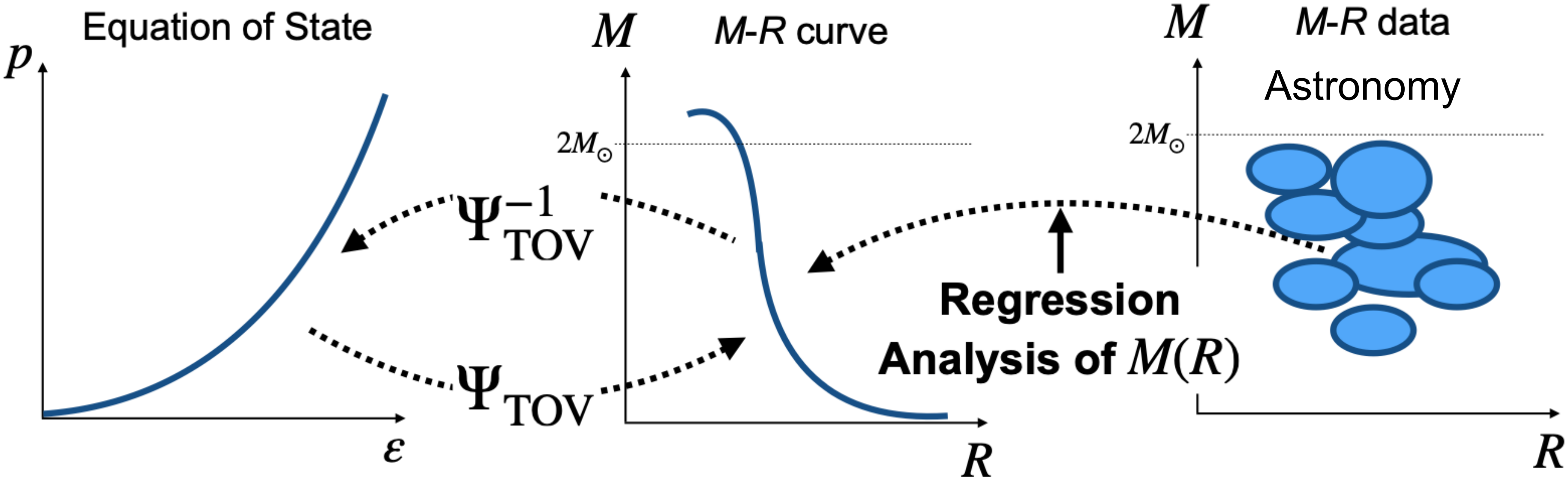


Neutron stars: very dense, compact objects

- How does the **equation of state** of neutron star look like?
  - What are the constituents to consider?
  - How do they interact?



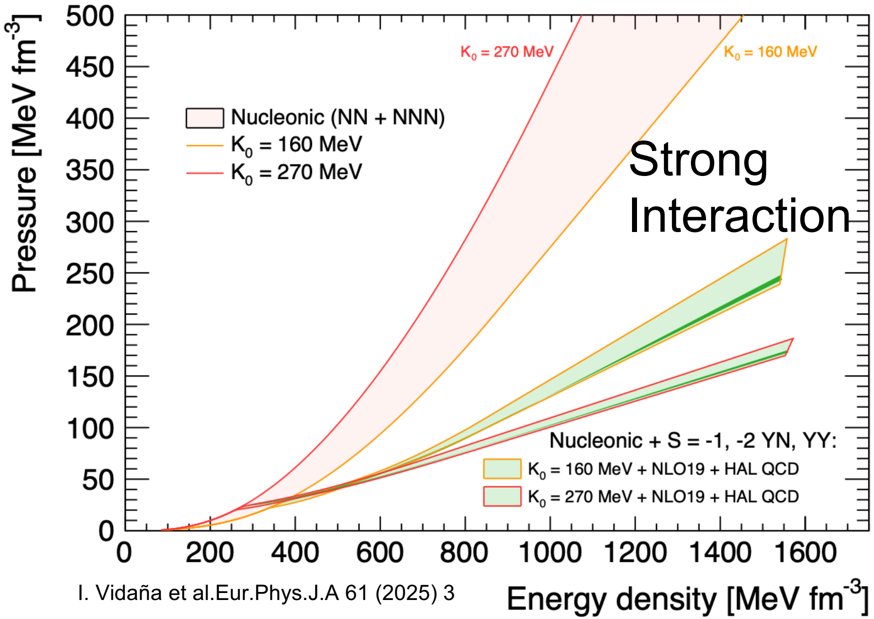
Nature of Neutron Star matter and their equation of state



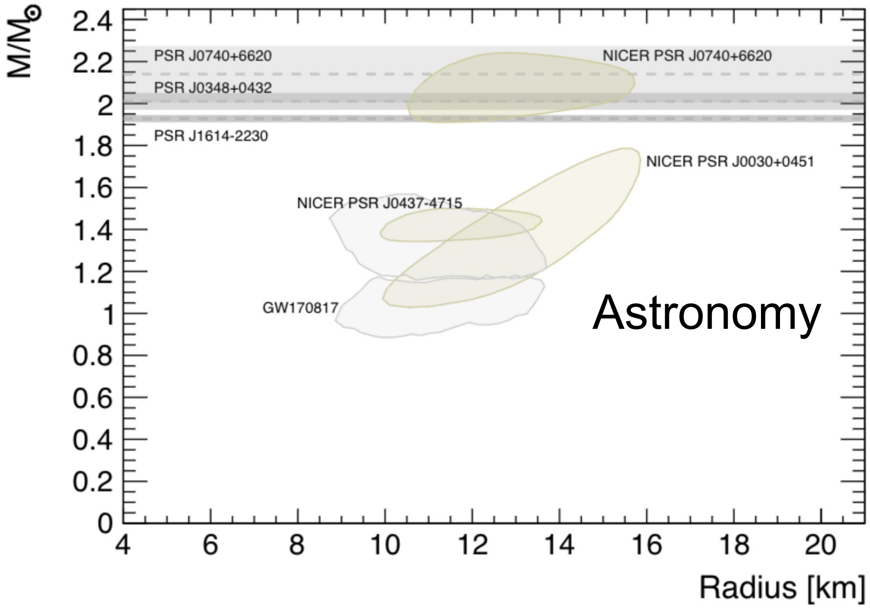
Pressure vs. energy density of NS matter

Mass vs. Radius of NS

Nature of Neutron Star matter and their equation of state



I. Vidaña et al.Eur.Phys.J.A 61 (2025) 3

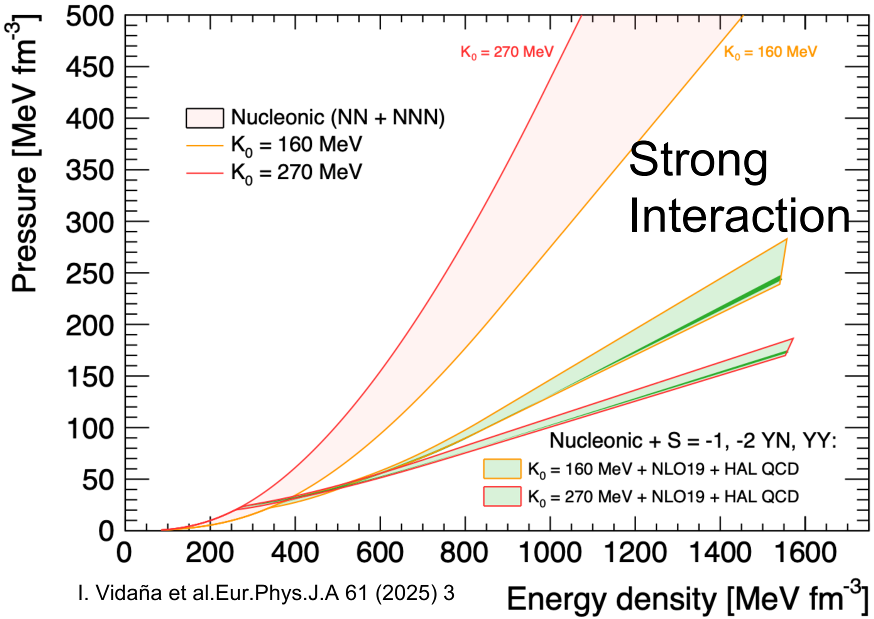


Pressure vs. energy density of NS matter

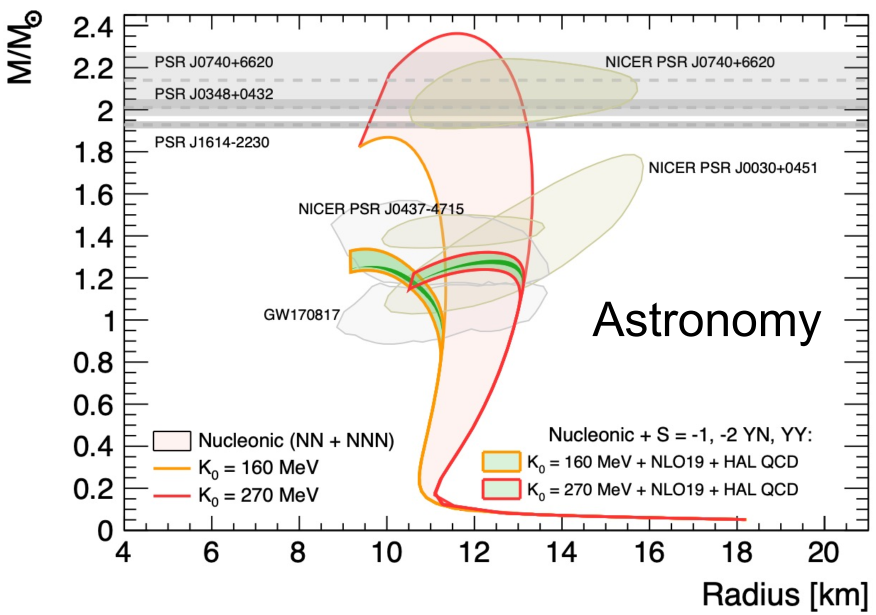
- Strength of 2-body and 3-body hadronic interactions
- Nuclear incompressibility K_0 and other properties

Mass vs. Radius of NS

Nature of Neutron Star matter and their equation of state



I. Vidaña et al.Eur.Phys.J.A 61 (2025) 3



Pressure vs. energy density of NS matter
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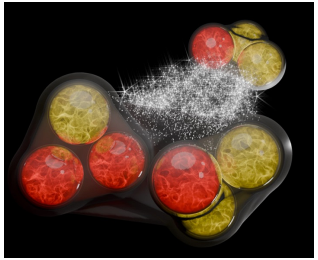
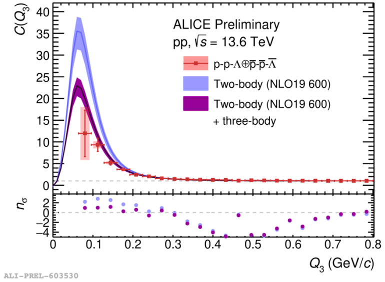
Mass vs. Radius of NS
→ Precise laboratory measurements needed for sharp comparison with astrophysical data

NS: required inputs from strong interaction measurements





Femtoscopy at HL-LHC:

High-precision data on YN, YY and YNN (Ξ,Σ)

- Ongoing in ALICE
- ALICE 3 (large acceptance and pp lumi increase)
- Complementarity with JPARC-HI (Japan), FAIR

Pressure vs. energy density of NS matter

- Strength of 2-body and 3-body hadronic interactions
- Nuclear incompressibility K_0 and other properties

ISOLDE:

Nuclear properties away from stability valley

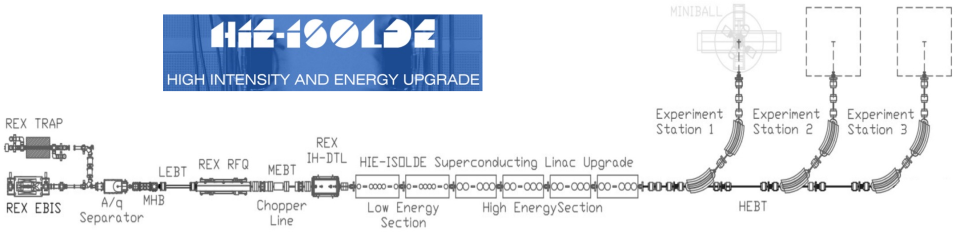
- HIE-ISOLDE upgrade: higher energy (10 MeV/n) and intensity (LINAC4) → larger production of exotic nuclei

High-precision mass and radii of n-rich nuclei

Neutron-skin thickness

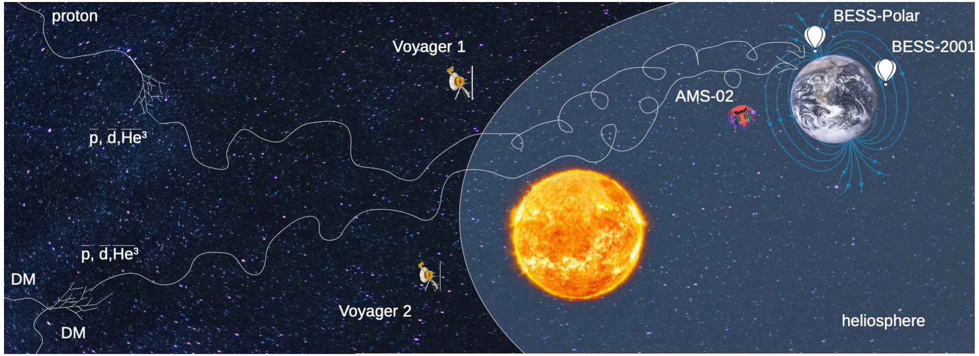
Input for r-/s-processes (SN expl., stellar nucleosynthesis)

- Complementarity with FAIR, SPIRAL2-Ganil, ...



Id89:CosmicRays

Indirect Dark Matter searches (anti-nuclei) in cosmic rays

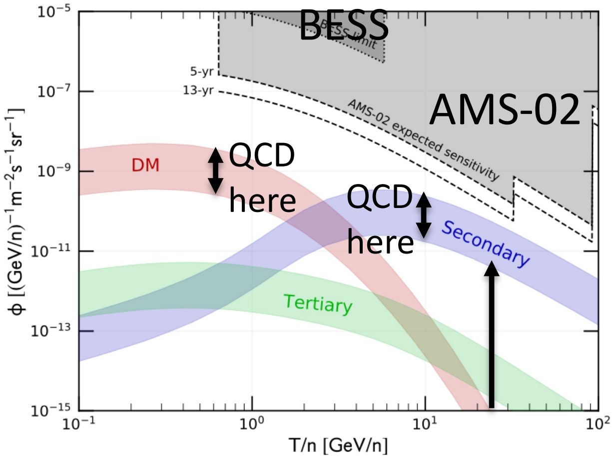


Searches of anti-nuclei from DM decays, e.g. $\chi_0\chi_0 \rightarrow \bar{p}, \bar{d}, \overline{^3He}$+X (AMS-02, GAPS, BESS), need "strong interaction" inputs from hadron collider and fixed-target experiments:

- Ordinary anti-nuclei hadroproduction by cosmics is a major background
- Anti-nuclei absorption in Space poorly constrained

Example: $\overline{^3He}$ flux

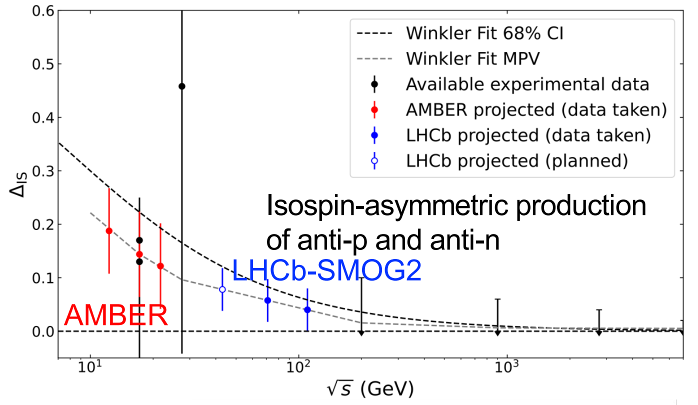
Donato et al., PRD97(2018)10

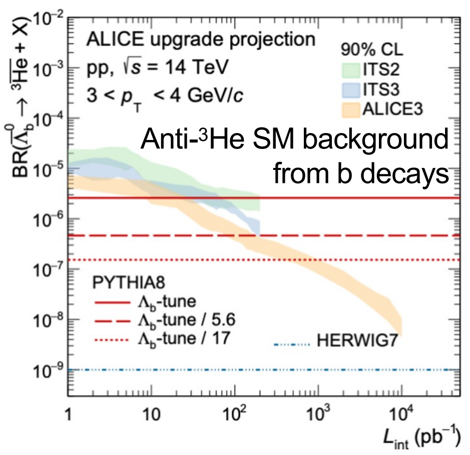


Id82:LHCb Id68:ALICE Id171:NA61
Id235:PBC Id89:CosmicRays

Indirect Dark Matter searches (anti-nuclei) in cosmic rays

Goal	Measurement	Experiments
Constraining cosmic anti-nuclei production	Anti-nuclei production in p+p, p+He, p+d $\sqrt{s}$ ~ 5-100 GeV	LHCb (fixed targ.), AMBER, NA61/Shine
	Anti-nuclei production mechanism (coalescence, source dependence)	ALICE 3, LHCb, NA61/Shine
Cosmic anti-nuclei absorption	Anti-nucei annihilation cross sections	ALICE, ALICE 3
Support DM search $\chi\chi \rightarrow \overline{\Lambda}_b + X \rightarrow {}^3\overline{He} + X$	$BR(\overline{\Lambda}_b \rightarrow {}^3\overline{He}+X)$	ALICE 3, LHCb

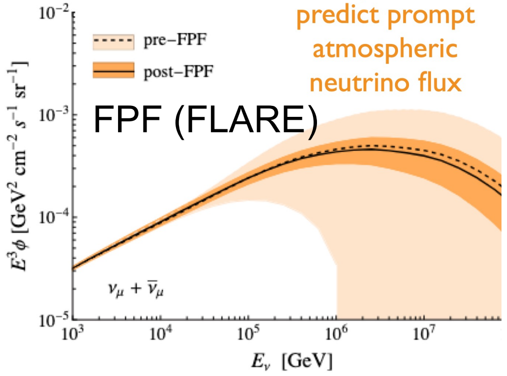


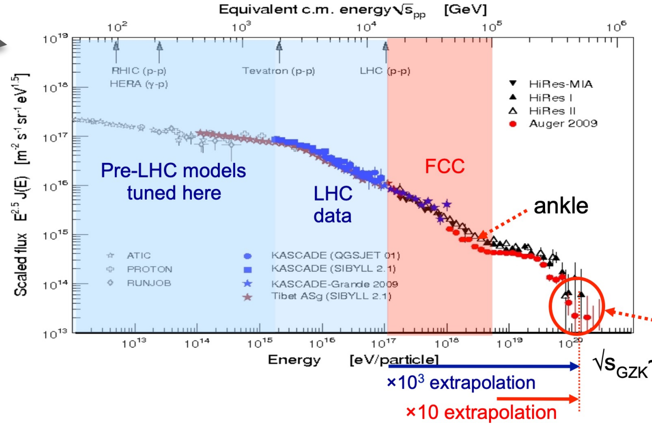


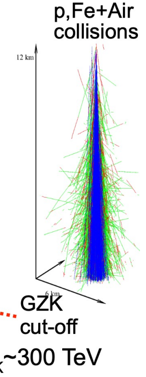
QCD connections with astrophysics: benchmarks

Ultra-High Energy Cosmic Rays (UHECR): primary neutrino flux and primary interaction modelling

Goal	Measurement	Experiments
Understanding primary neutrino flux in CRs	ν energy spectra and ν-N cross-section	FASER, then FPF (FLARE)
	Atmospheric-ν background fluxes	FPF, NA61/Shine
Muon puzzle and modeling (U)HECRs	Hadron production in pp, pA, AA collisions	HL-LHC (all exp), FPF, FCC-hh

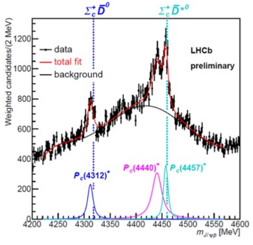


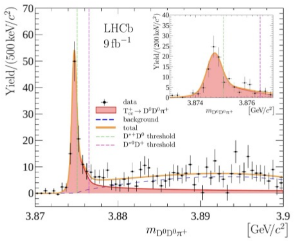


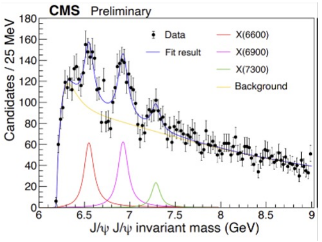


Exotic hadrons: future goals

- Large number of exotic hadrons discovered in e^+e^- and pp collisions

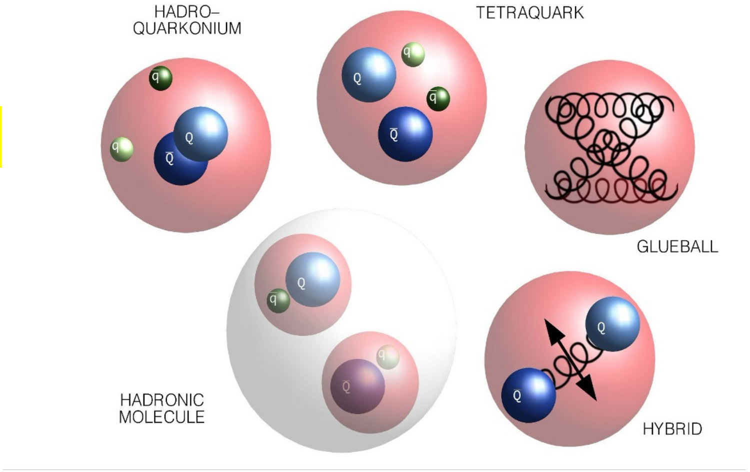






...

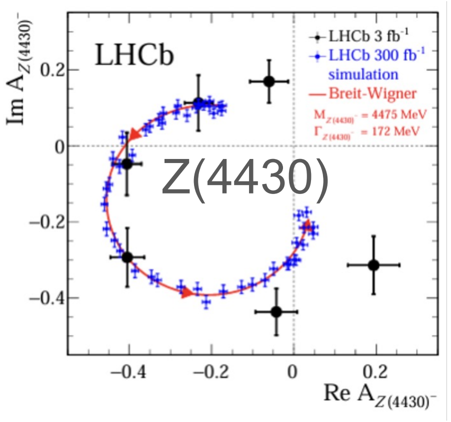
- Main open questions:
  - Nature of exotic hadrons? Constituents?
  - Do hybrids/glueballs exist?
  - Why do many exotic hadrons lack flavour/isospin partners?



Exotic hadrons: experimental opportunities

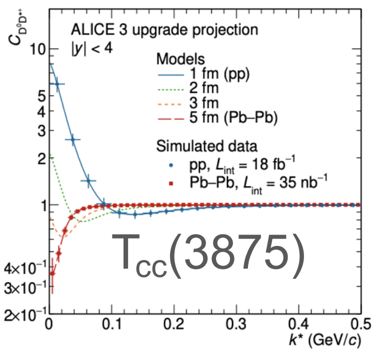
LHCb U2: ultimate precision for states spectroscopy and spectral function analysis

- Including T_{bc} and T_{bb}, which are expected to have large enough binding energies such that only weak decays are possible

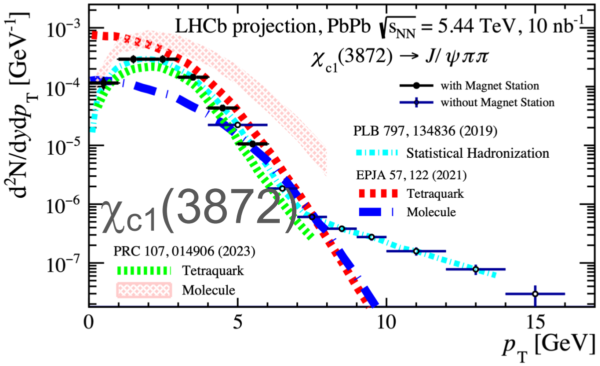


ee, ep: extensive programs at Belle II, STCF, EIC, LHeC, FCC-ee, LCF

ALICE 3: use femtoscopy to search for exotic hadrons as D-D bound states (e.g. χ_{c1}, T_{cc})

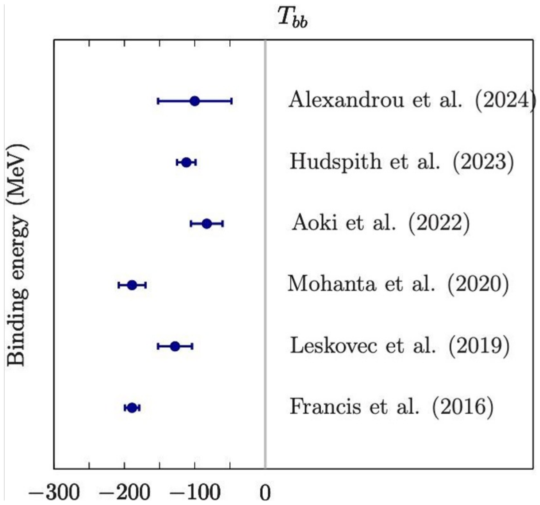


ALICE 3, CMS, LHCb: use coalesce mechanism in HI collisions to constrain inner structure



Exotic hadrons: lattice QCD approach

- Lattice QCD provides crucial information on exotic hadrons
  - predictive (quantifiable uncertainties) → guide experimental searches
  - complementary to exp. : e.g. tune the quark masses, probe internal structure
- Example: T_{bb} from lattice → strongly bound tetraquark



Future resource requirements:
→ Increasing need of computing resources
→ Access to CPU and storage (PBs)
→ Access to HPC centres
→ Training/synergy with computer science

Conclusions

- Very rich physics programme ahead in non-perturbative QCD:
  - High-temperature QCD → genuine many-body QCD system (elementary → macro)
  - Hadron nature (exotica) and interactions → fundamental questions and mandatory studies for astro(particle)physics

large Community interest: >30 Input Documents

- HL-LHC: unique machine for these areas of QCD
  → Accomplishing the 'Full exploitation' recommended in 2020 requires…
  → New detectors with frontier sensor technologies and maximising heavy-ion luminosity
- SPS, FAIR: high rates, versatility, and "LHC-driven" sensor technologies
  → Complement LHC (high baryon-density, hadron phys.), possibly extending to post-LHC era
- FPF, HIE-ISOLDE: perfect example of far-reaching QCD and of scientific synergy
- FCC-hh: novel studies in high-*T* QCD and closer to UHECR conditions

Thanks for your attention!

Thanks for the community inputs and the discussion in the parallel session

Thanks to the WG members for these areas:
R. Arnaldi, A. Gérardin, V. Mantovani Sarti,
M. Pappagallo, R. Snellings, U. Wiedemann

Hot and dense QCD benchmarks: QGP temperature

Experiment	When	Strengths / Uniqueness	Measurement	Physics insight
ALICE 3 @ HL-LHC	**> 2035**	Unique pointing resolution of few um (remove HF backgrounds); low material budget	Invariant mass spectrum of **thermal dielectrons**, differential in mass, pT, azimuthal angle	**Temperature of QGP with accuracy of 1-2%** (no backgrounds), compared to 10% ALICE 2. **Temperature as a function of time during QGP evolution.**
CBM @ SIS100	**> 2028**	Fill a region where no data are so far available, complement with existing measurements. With SIS100, cover sqrt(sNN) range where hadronic phase dominates	**Dimuon and dielectron** invariant mass spectra (1.5 < M < 2.5 GeV). Measurements will be obtained in an energy scan (3 < $\sqrt{s_{NN}}$ < 5 GeV)	Study phase transition, **searching for a flattening of T vs sqrt(s) < 5 GeV, signature of a first-order phase transition**. Experimental precision on T of a few MeV
NA60+/DiCE @ SPS	**> 2029**	Fill a region where no data are so far available, complement with existing measurements. Cover sqrt(sNN) range where QGP onset is expected	**Caloric curve** with T extracted from the dimuon invariant mass spectra (1.5 < M < 2.5 GeV). Measurements will be obtained in an energy scan (6 < $\sqrt{s_{NN}}$ < 17 GeV)	Study phase transition, **searching for a flattening of T vs sqrt(s) < 17 GeV, signature of a first-order phase transition**. Experimental precision on T of a few MeV (1-2%)
FCC-hh	**>2060**	x6-7 larger sqrt(sNN) and ~ x10 larger L_int	**Quarkonium** yields	**Sensitivity to initial QGP temperature using Y(1,2,3s) melting and regeneration patterns** - Y(1s) melting only at FCC?
			Total charm hadron yields and yield increase wrt pp scaling with Ncoll	**Thermal charm** production from gg->c-cbar in QGP when temperature ~1 GeV **-> novel way to access initial QGP temperature**

Hot and dense QCD benchmarks: heavy flavour HL-LHC

Experiment	When	Strengths / Uniqueness	Measurement	Physics insight
ALICE 3 @ HL-LHC	**> 2035**	Unique pointing resolution of few um Large acceptance in pT and eta, with particle ID	Precise measurement of **beauty meson and baryon** spectra and flow at pT>0	**Degree of thermalization in QGP of heavy quarks with different masses** (beauty vs charm)
			Multi-charm baryons (Xi_cc, Omega_cc)	Pure recombination hadrons: x100 enhancement in Pb-Pb **Kinetic equilibration of deconfined charm quarks**
			Rare charmonia: chi_c1,2, X(3872)	**Suppression pattern for p-wave charmonia**; Low-pT mid-y X -> **Structure (molecular vs compact tetraquark)**
LHCb U2 @ HL-LHC	**> 2035**	Forward eta acceptance 2-5, with PID	Precise measurement of **beauty meson and baryon** spectra and flow at pT>0, fwd y	**Degree of thermalization in QGP of heavy quarks with different masses** (beauty vs charm) - fwd-y only, more limited sensitivity
			Rare charmonia: X(3872)	Low-pT fwd-y X -> **Structure (molecular vs compact tetraquark)**
ATLAS/CMS II @ HL-LHC	**>2030**	Large eta acceptance, partly with PID (CMS), high pT and jet performance	**Beauty and charm hadrons** at medium-high pT	**Energy loss and hadronization of b and c quarks**
			t-tbar events in Pb-Pb: exploratory measurements	**Jet quenching** effect on (t->)W->qqbar; **explore time-dependence** with pT_top dependence
FCC-hh	**>2060**	x6-7 larger sqrt(sNN) and ~ x10 larger L_int	**t-tbar** events in Pb-Pb: full exploitation of new obs.	**Access to time-dependence of jet quenching and QGP opacity** with pT_top dependence to up ~ 1 TeV/c

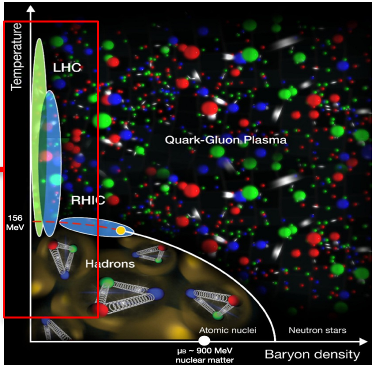
Hot and dense QCD benchmarks: heavy flavour SPS

Experiment	When	Strengths / Uniqueness	Measurement	Physics insight
NA61/SHINE @ SPS	**> 2029**	Large acceptance and hadron ID at SPS, vertex detector, but limited interaction rate	**D-Dbar azimuthal correlations** SPS energy (but no experimental projections)	Study azimuthal correlations in Pb-Pb (in principle, there is no combinatorial background of uncorrelated c-cbar pairs)
NA60+/DiCE @ SPS	**> 2029**	Measurements performed at high muB, in an energy range, below top SPS energies, never explored so far	**Quarkonium** measurements (in the dimuon channel) performed via a beam energy scan between $6 < \sqrt{s_{NN}} < 17$ GeV	**Onset of quarkonium suppression and possibility to correlate it with the temperature of the system** measured via thermal dimuons, to identify the threshold temperature for the melting of the charmonium states
		At colliders, intrinsic charm effects should appear only at very forward rapidities, while at fixed-target, their contributions dominate at mid-rapidity, in a more accessible range	**Intrinsic charm** via J/Psi in p-Pb	Investigate the **intrinsic charm component of the nucleon wavefunction**, which should lead to an enhancement in the J/Psi production in p-Pb close to mid-rapidity
		Very few open charm studies at SPS energies (indirect measurement by NA60, upper limit by NA49 and first D0 measurement by NA61/SHINE)	**Baryon and meson open charm** states: integrated and differential cross sections, azimuthal distributions	Impact of a shorter-lived medium on charm →**charm-quark thermalization** and searches on features connected with **collective behaviour** **Charm hadronization mechanisms at high muB** investigated via the relative abundances of the different charm-hadron species

Phase transition in lattice QCD

Pressure density of ideal gases:

$$p = \frac{\varepsilon}{3} = n_{dof} \frac{\pi^2 T^4}{90} \Rightarrow \frac{\varepsilon}{T^4} \; vs. \; T \quad \propto n_{dof} = n_b + \frac{7}{8} n_f$$

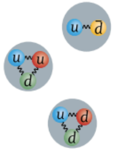


- Lattice QCD applicable at low μ_B
- $p / T^4 \sim n_{dof}$ changes rapidly around T_c
- ***Critical temperature T_c ~155 MeV (~10^{12} K)***

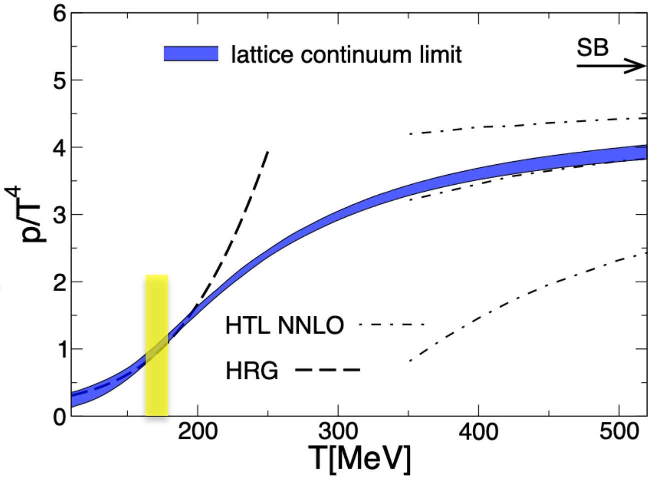
  → ε_c = 0.6 GeV/fm³

Below T_c: gas of pions $n_{dof} = 3$

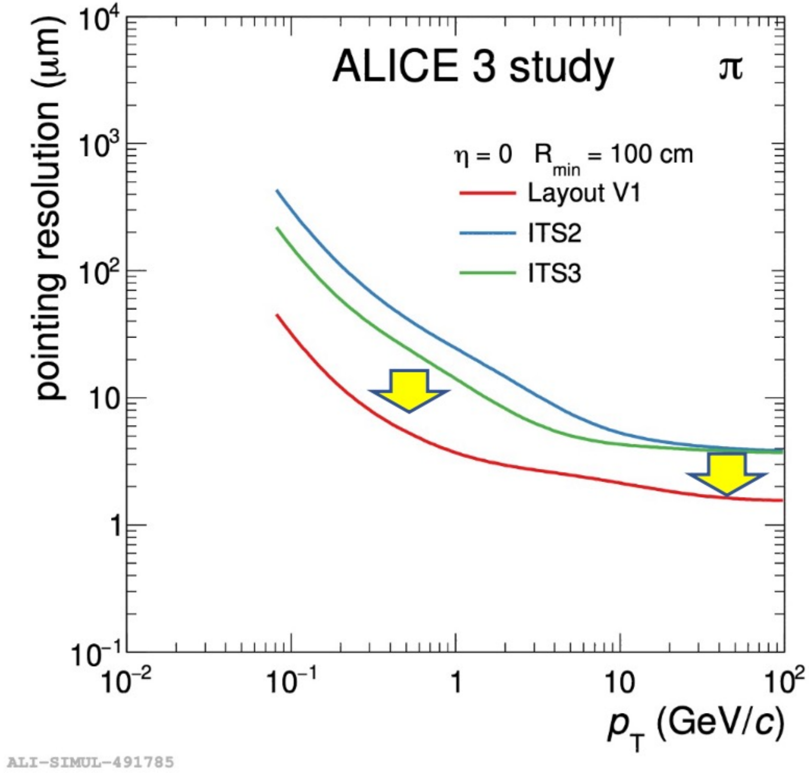
Above T_c: gas of g, u, d and anti-quarks $n_{dof} = 37$

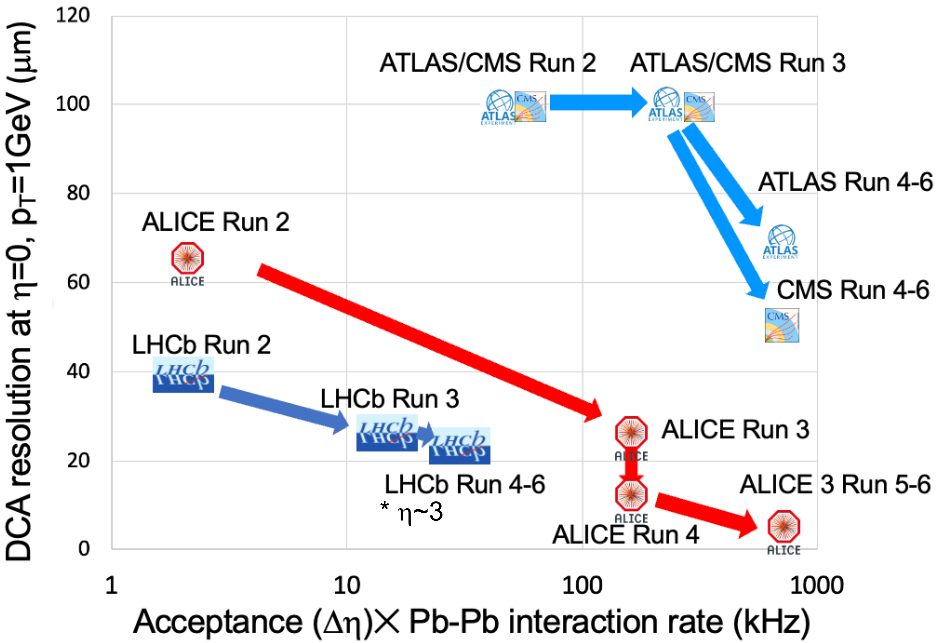


[PRD 90 094503 (2014)]



Tracking precision vs acceptance

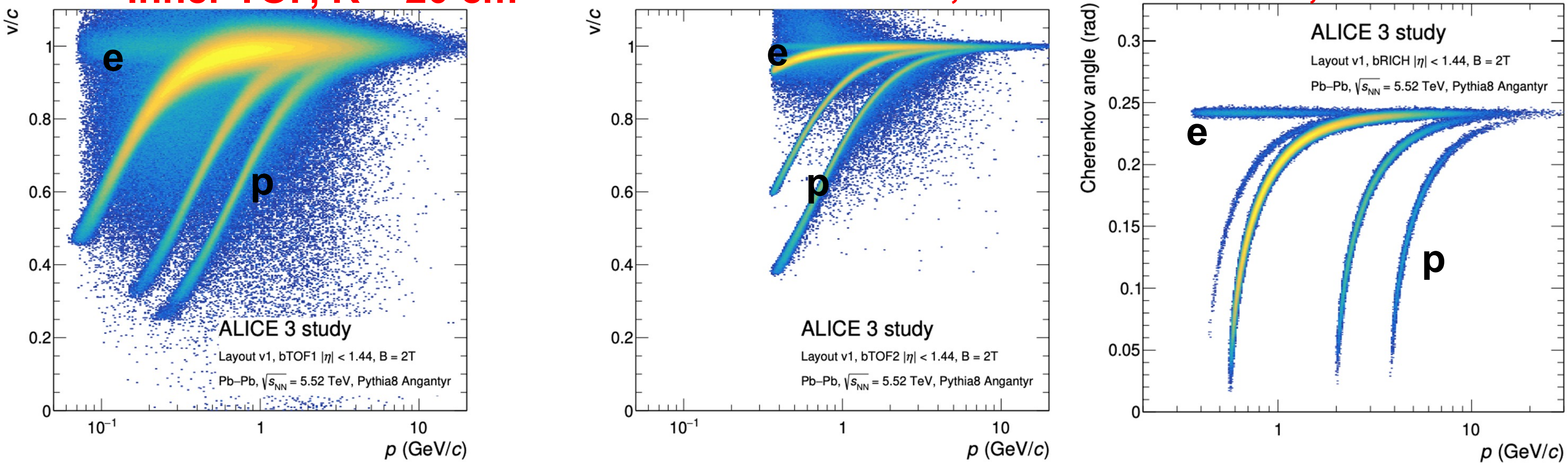




ALICE 3 Particle Identification

e, π, K, p separation with TOF + RICH detectors, with specifications σ_t = 20 ps, σ_θ = 1.5 mrad

Inner TOF, R = 20 cm | **Outer TOF, R = 85 cm** | **RICH, R = 90 cm**

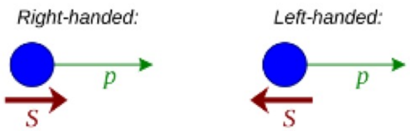


+ endcap TOF and RICH

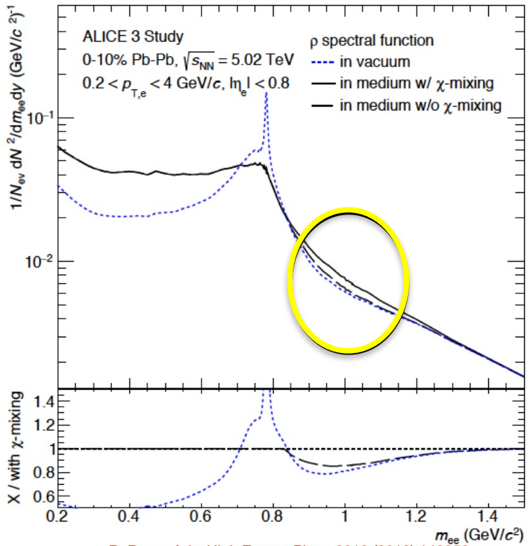
QGP phase transition: chiral symmetry restoration

- 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)

- 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



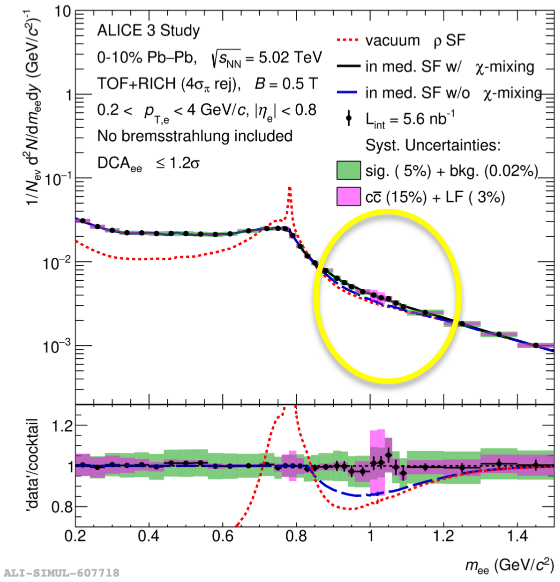
Chirality = helicity for massless particles

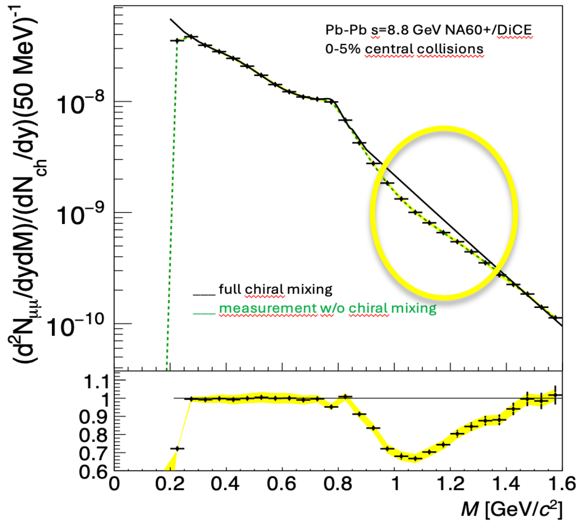


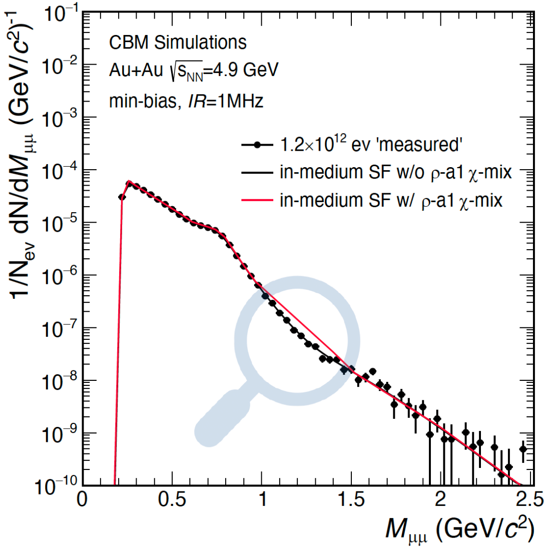
R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103
R. Rapp private communication

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

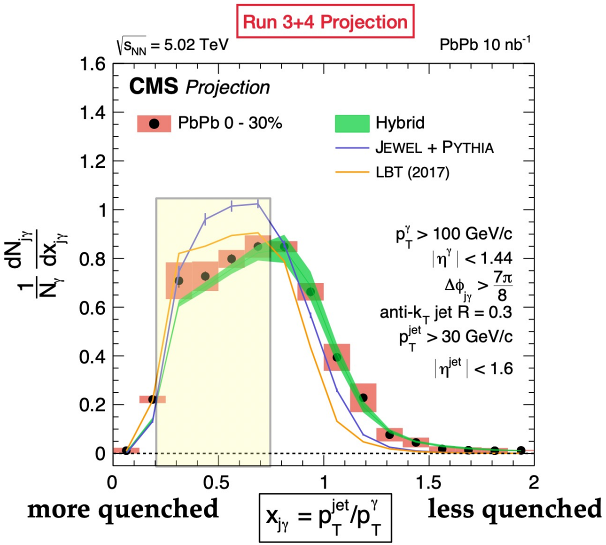


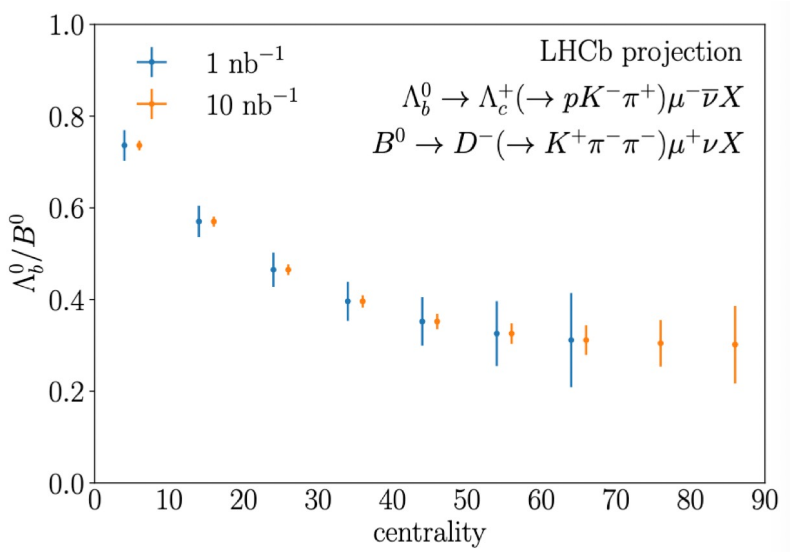




Plans of ATLAS, CMS, LHCb for HIs in Runs 4-5

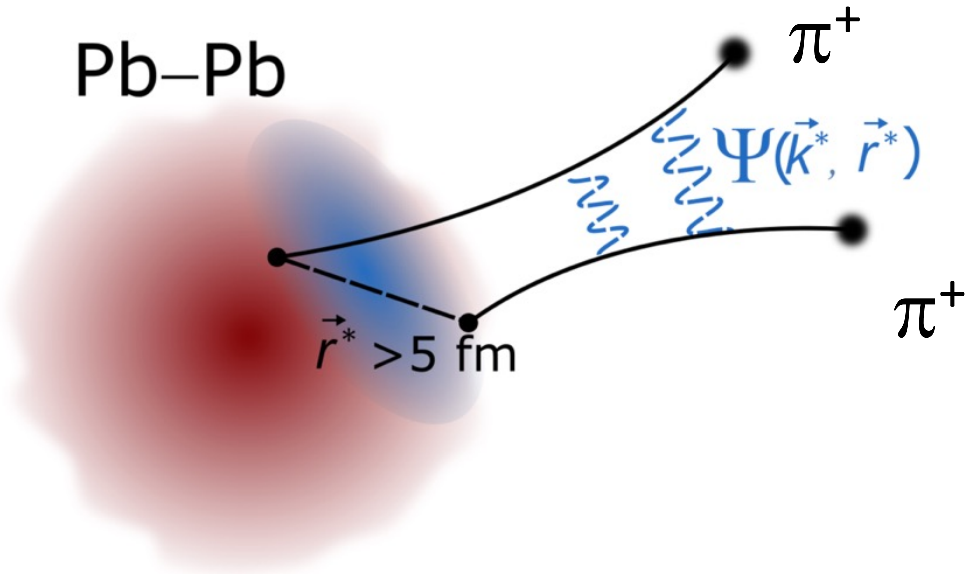
- Upgrades of ATLAS, CMS, LHCb will improve their performance and physics reach also in heavy-ion collisions
  - ATLAS and CMS complement ALICE with a strong high-p_T and jet programme
  - LHCb complements with heavy-flavour at forward rapidity and fixed target (SMOG)



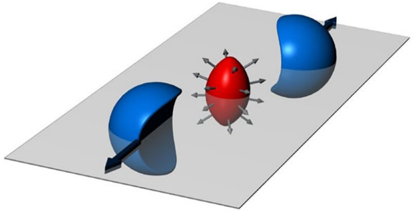


‘Global’ properties of the collisions: system volume from Hambury Brown Twiss interferometry

- Quantum effect: enhancement of correlation function for identical bosons, e.g. pairs of pions
- From Heisenberg’s uncertainty principle:
  - $\Delta p \cdot \Delta x \sim r^* \cdot k^* \sim \hbar$
  - → extract source size from momentum correlation function

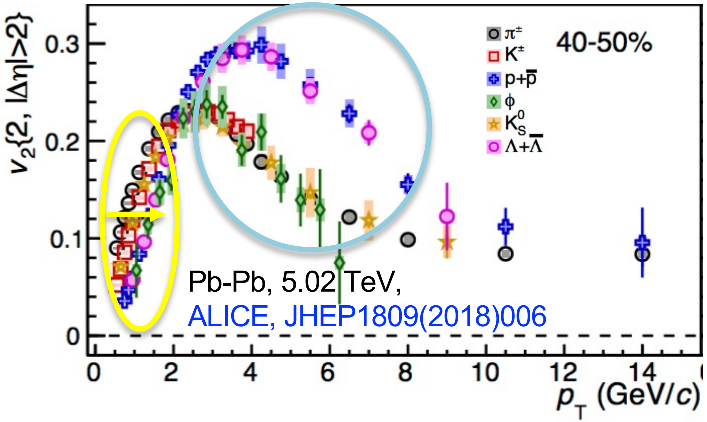


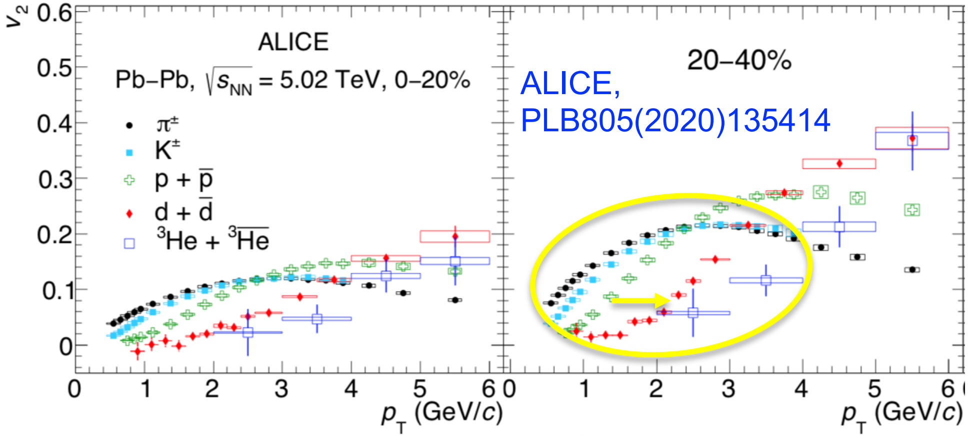
Elliptic flow by hadron species



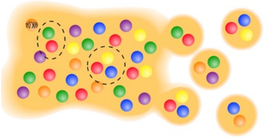
- Non-central collisions: flow maps the geometrical elliptical shape into an azimuthal modulation in momentum distributions

$$\frac{dN}{Nd\phi} = 1 + 2v_2 \cos\left(2(\phi - \Psi_{RP})\right) + \ldots \quad \textit{higher harmonics } (v_3, v_4, \ldots)$$



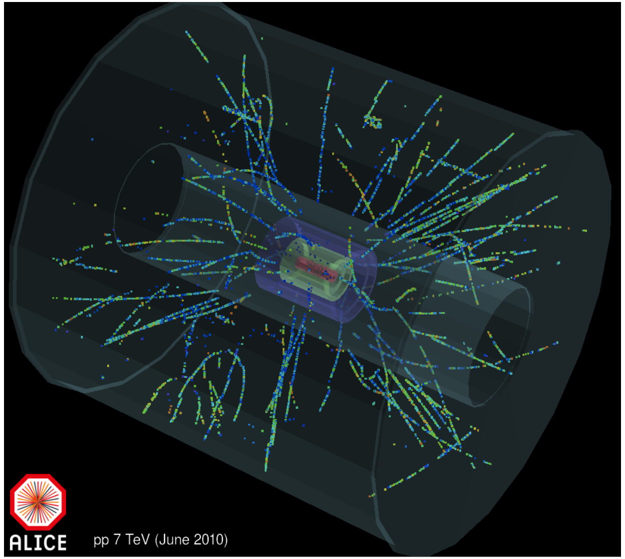


- Mass ordering at low p_T → **hydrodynamic flow, very small viscosity**
- Even A=2 and A=3 light nuclei pushed by the flow
- Baryon vs. meson grouping at higher p_T
  → **quark-level flow + recombination?**

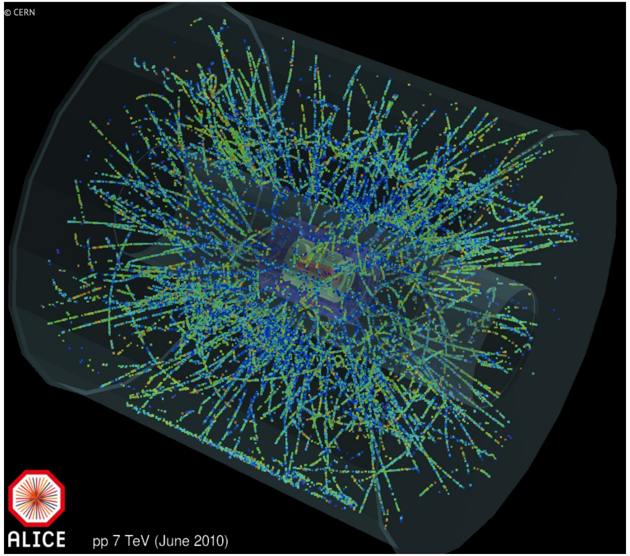


A big surprise at the LHC: ‘heavy-ion physics’ in pp collisions?

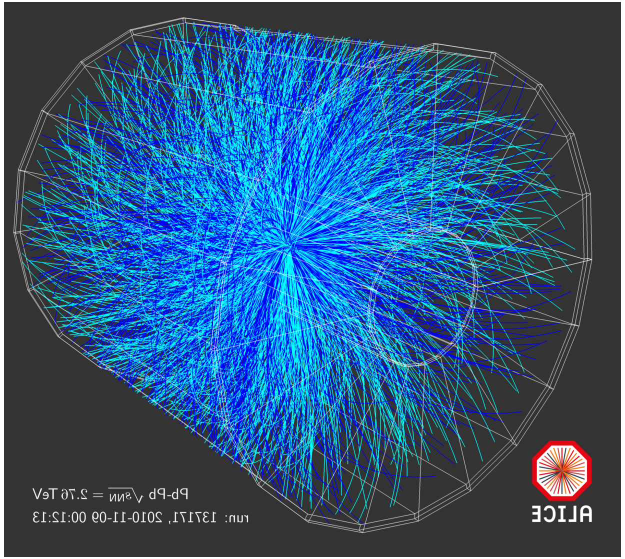
“Typical” pp collision



High-multiplicity pp collision



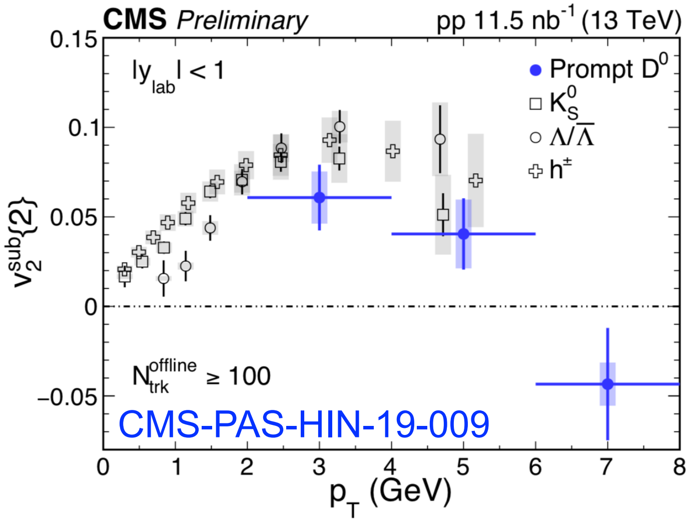
Pb-Pb collision

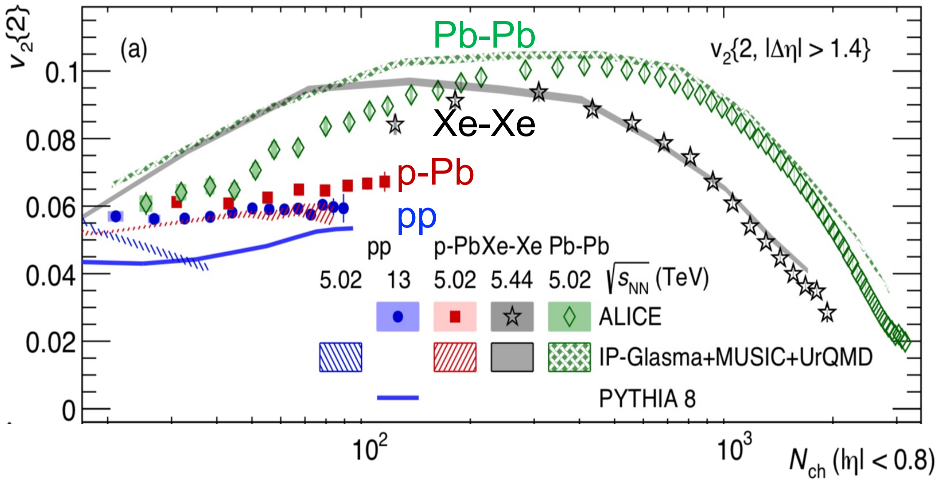


What is the smallest system (number of particles) for QGP formation?

From heavy-ions to p-nucleus and pp: flow-like effects

- Observation of collective effects in pp and p-Pb collisions: one of the few *unexpected* findings of the LHC





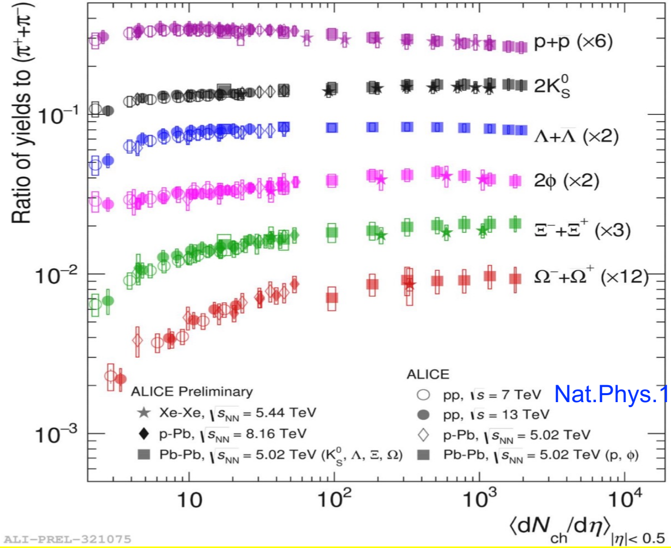
ALICE, PRL123(2019)142301

Mass ordering of elliptic flow

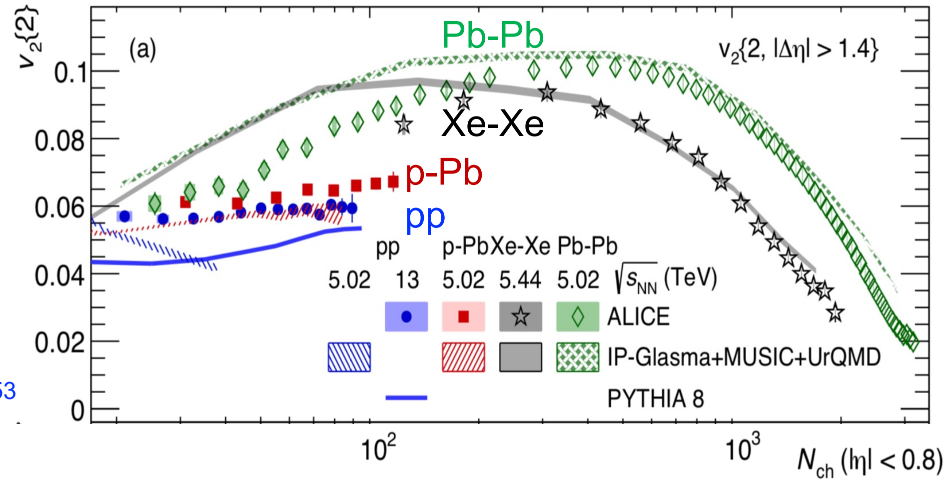
Similar flow in pp, p-Pb, Xe-Xe, Pb-Pb at the same multiplicity

From heavy-ions to p-nucleus and pp: flow-like effects & ‘hadrochemistry’

- Observation of collective effects in pp and p-Pb collisions: one of the few *unexpected* findings of the LHC



Nat.Phys.13(2017)353



ALICE, PRL123(2019)142301

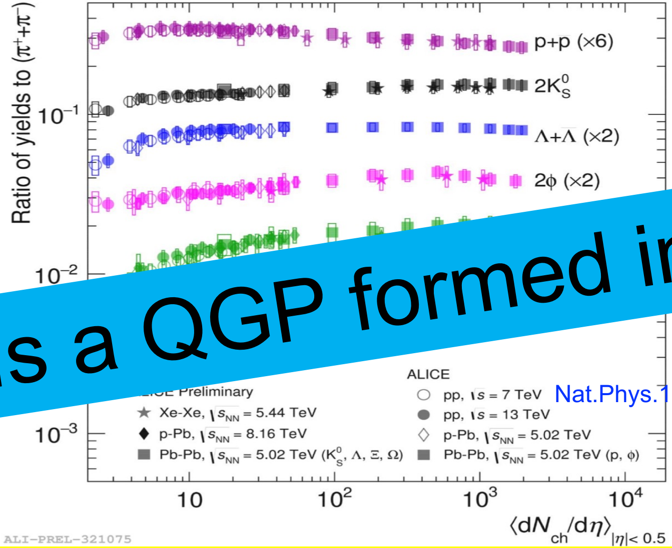
Continuous increase of strangeness yields with multiplicity in pp, p-Pb, Xe-Xe, Pb-Pb

Similar flow in pp, p-Pb, Xe-Xe, Pb-Pb at the same multiplicity

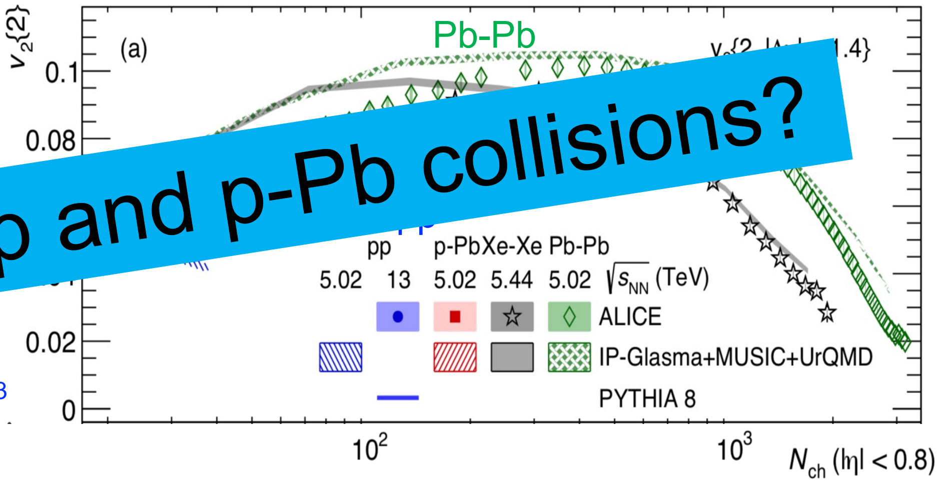
From heavy-ions to p-nucleus and pp: flow-like effects & ‘hadrochemistry’

- Observation of collective effects in pp and p-Pb collisions: one of the few *unexpected* findings of the LHC

Is a QGP formed in pp and p-Pb collisions?



Nat.Phys.13(2017)353



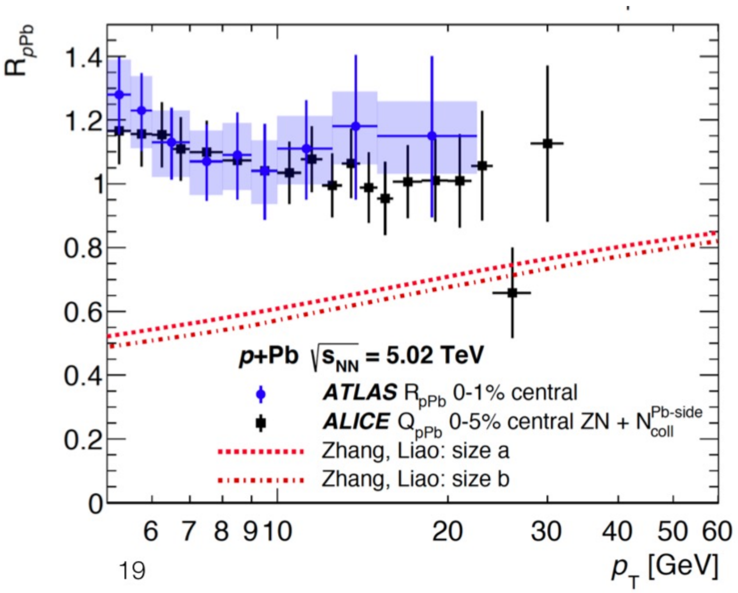
ALICE, PRL123(2019)142301

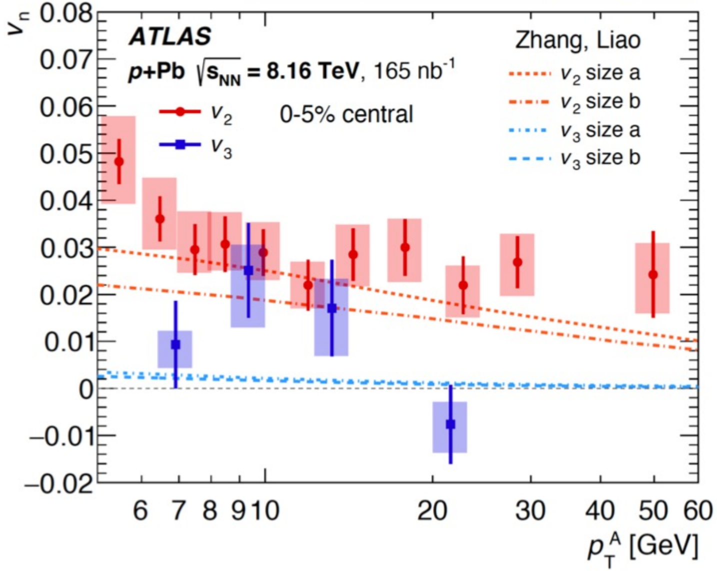
Continuous increase of strangeness yields with multiplicity in pp, p-Pb, Xe-Xe, Pb-Pb

Similar flow in pp, p-Pb, Xe-Xe, Pb-Pb at the same multiplicity

From heavy-ions to p-nucleus and pp: flow-like effects & 'hadrochemistry' & energy loss?

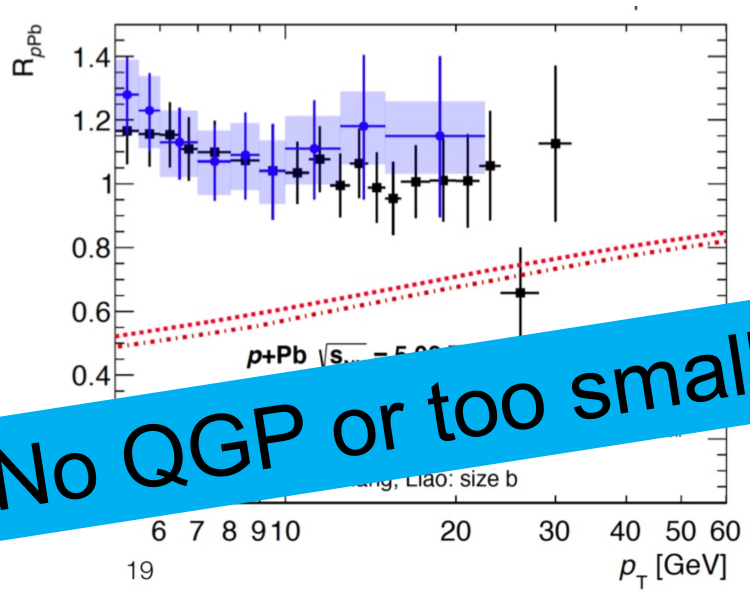
Eur. Phys. J. C 80 (2020) 73





- p-Pb nuclear modification factor ~1 → no suppression of yields
- But persistence of azimuthal asymmetry (v_2) to high p_T suggestive of final state interactions

From heavy-ions to p-nucleus and pp: flow-like effects & 'hadrochemistry' & energy loss?



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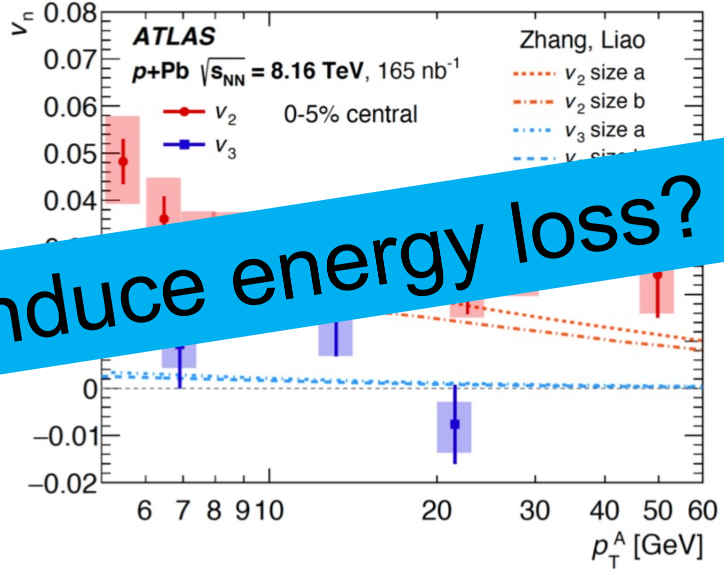

No QGP or too small to induce energy loss?

- p-Pb nuclear modification factor ~1 → no suppression of yields
- But persistence of azimuthal asymmetry (v_2) to high p_T suggestive of final state interactions