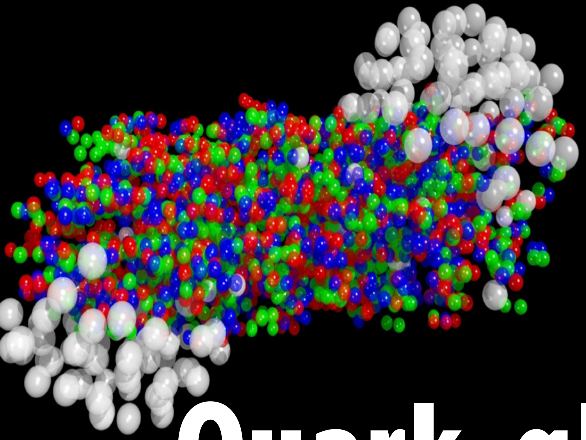

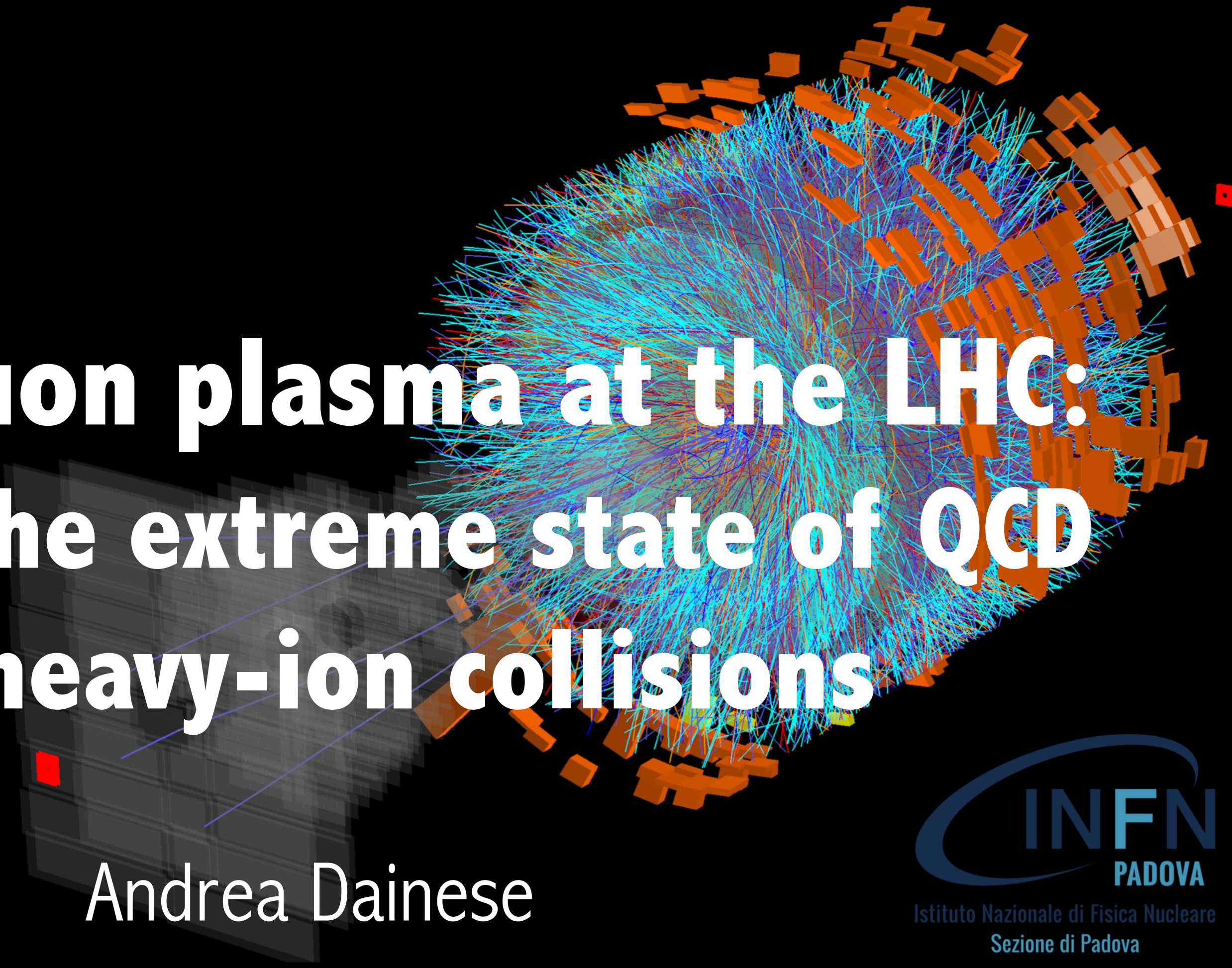

Quark-gluon plasma at the LHC: studying the extreme state of QCD with heavy-ion collisions

Andrea Dainese

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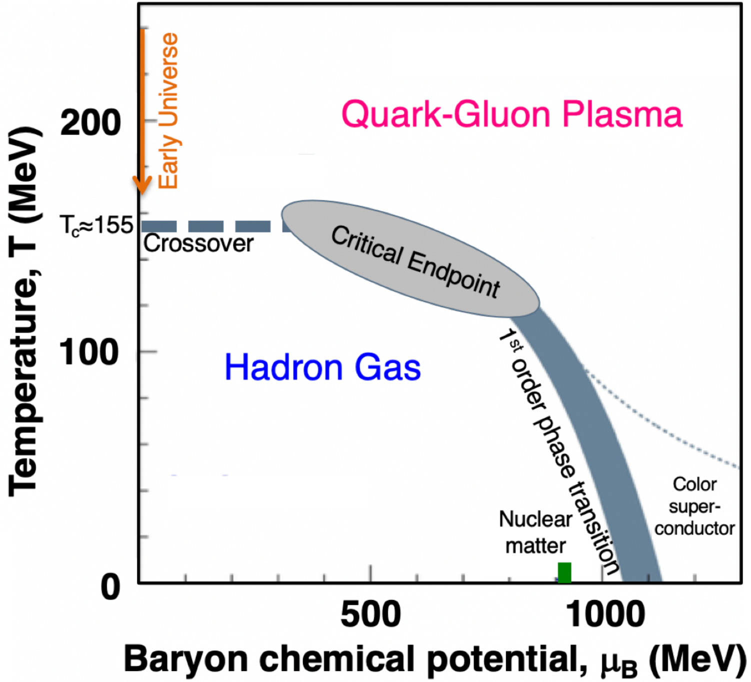
Sezione di Padova

Phase diagram of strongly-interacting (QCD) matter



At high energy density ε (high temperature and/or high density) hadronic matter undergoes a phase transition to the *Quark-Gluon Plasma (QGP)*

- *a state in which colour confinement is removed*
- *a high-density QCD medium of "free" quarks and gluons*

critical energy density $\varepsilon_c \sim 1$ GeV/fm^3 $\sim 10\ \varepsilon_{nucleus}$

Theoretical study of the phase diagram: lattice QCD

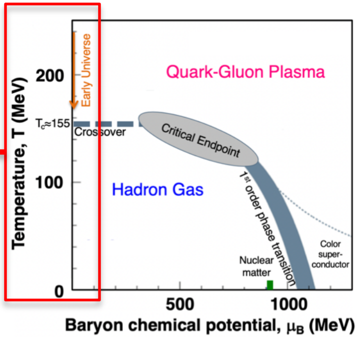
- Method for doing calculations in non-perturbative regime of QCD
- Discretization on a space-time lattice
- Ultraviolet (large momentum scale = small space-time scale) divergencies can be avoided

- Compute thermo-dynamical properties for a system of interacting quarks and gluons

Pressure density: $$p = \frac{\varepsilon}{3} = n_{dof} \frac{\pi^2 T^4}{90}$$ *for an ideal gas*

Phase transition in lattice QCD

$$\frac{\varepsilon}{T^4} \;\; vs. \;\; T \qquad \propto n_{dof} = n_b + \frac{7}{8} n_f$$

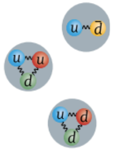


- Lattice QCD applicable at low μ_B
- $p / T^4 \sim \varepsilon / T^4$ changes rapidly around T_c
- ***Critical temperature T_c* ~155 MeV (~10^{12} K)**

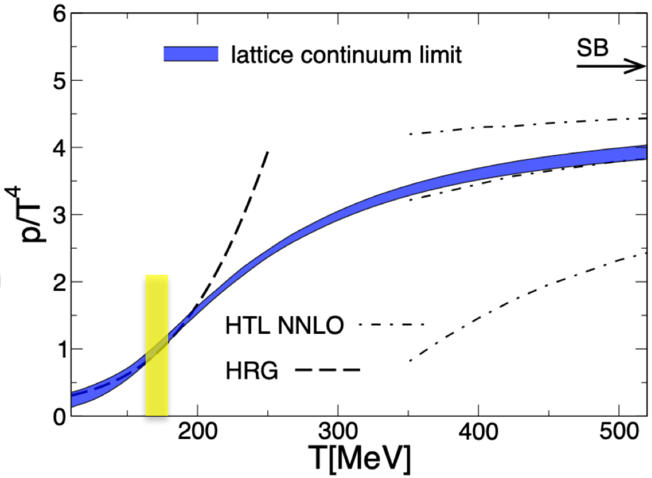
  $\rightarrow \varepsilon_c$ = 0.6 GeV/fm^3

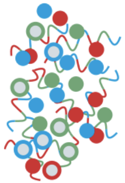
Below T_c: gas of pions $\quad n_{dof} = 3$

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

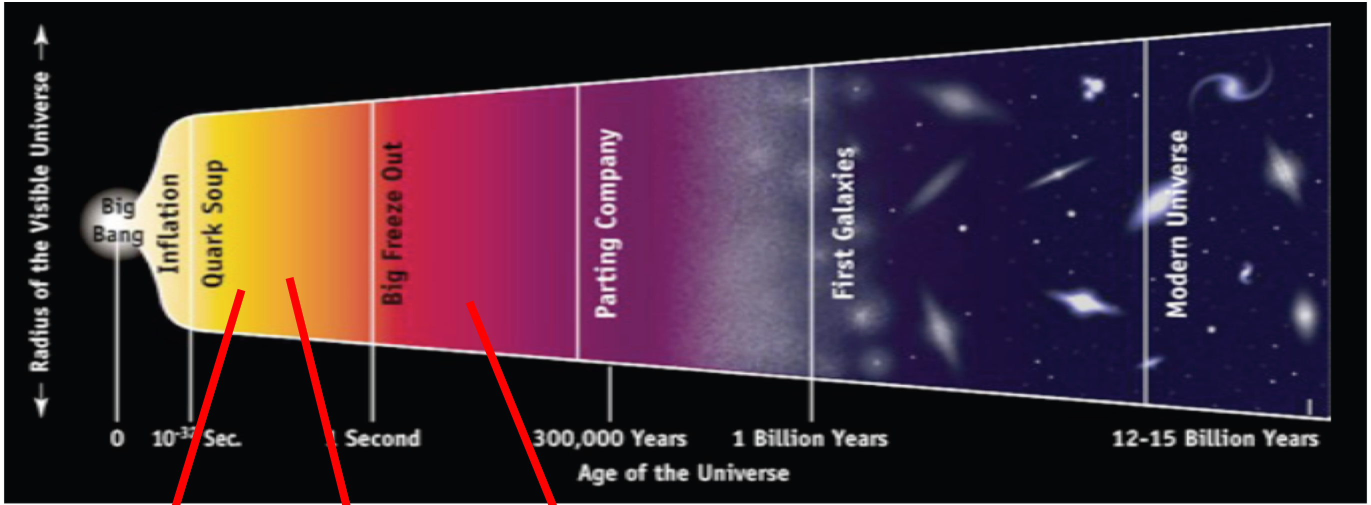


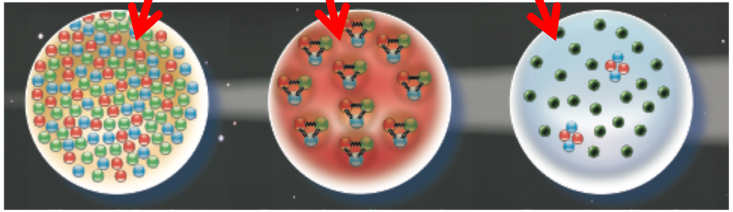
[PRD 90 094503 (2014)]





QGP: the first “matter” in the primordial Universe





quark-gluon plasma

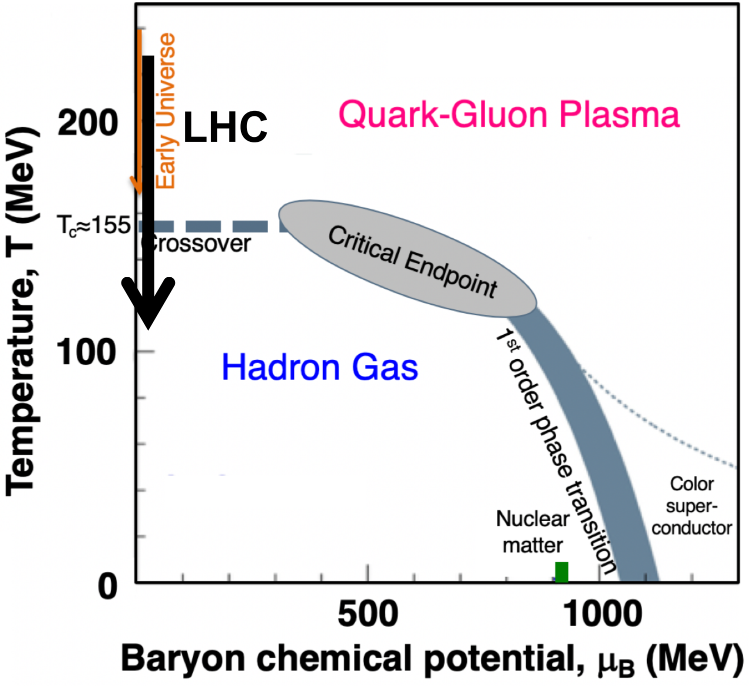
formation of protons/neutrons

formation of atomic nuclei

The phase transition from quarks to hadrons occured in the cooling Universe 10 μs after the Big Bang, at μ_B=0

Heavy-ion collisions and the QGP

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



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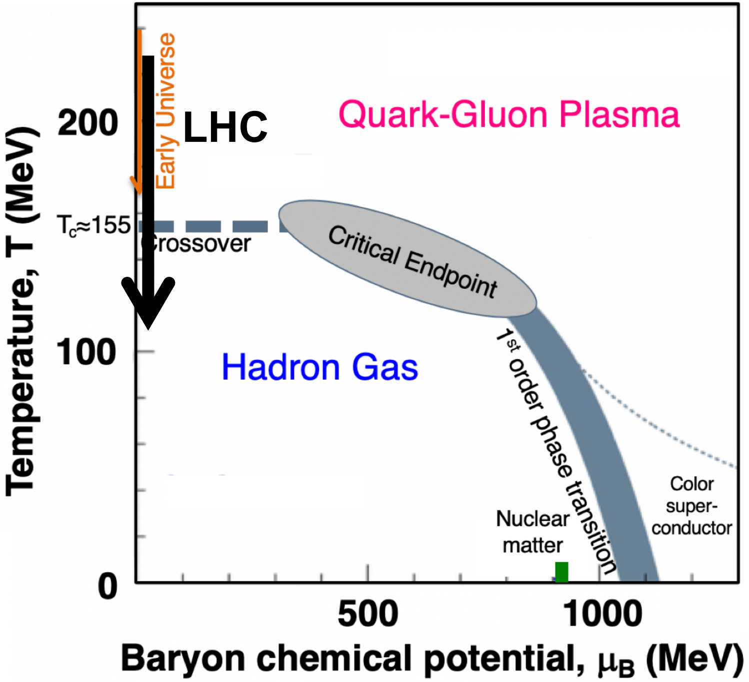

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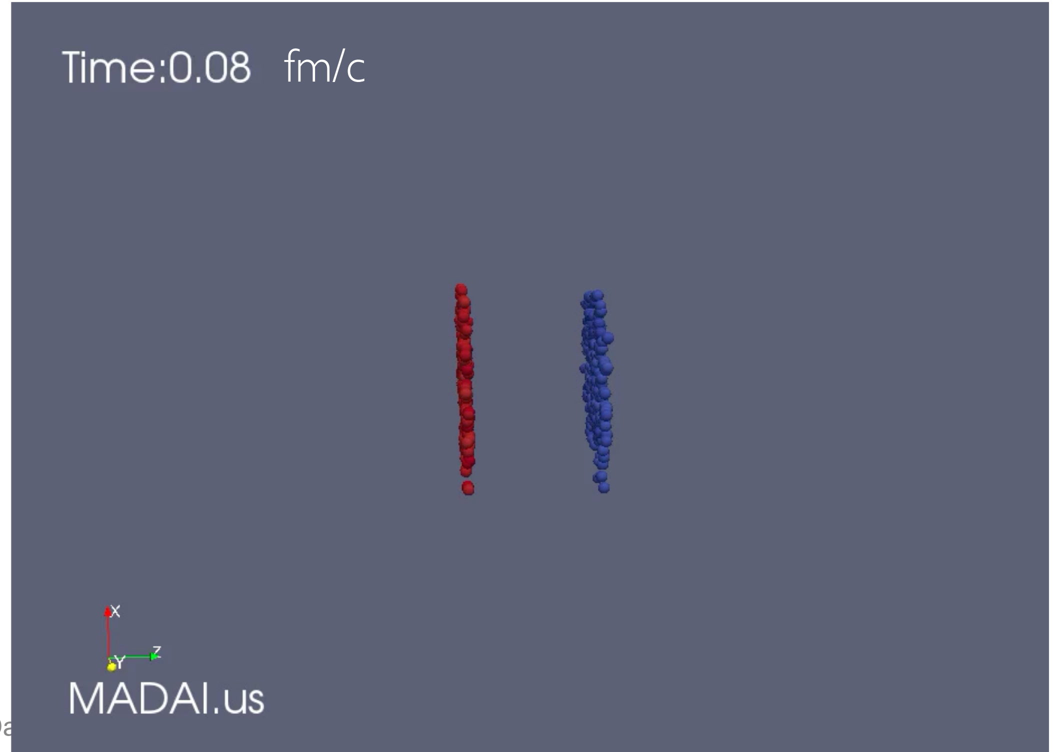
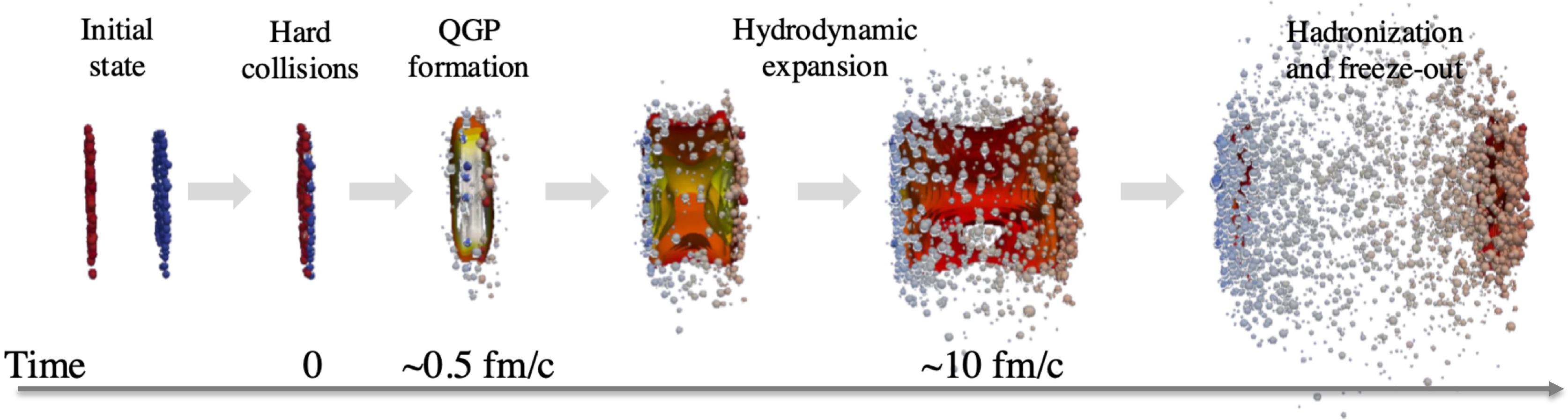


Heavy-ion collisions and the QGP

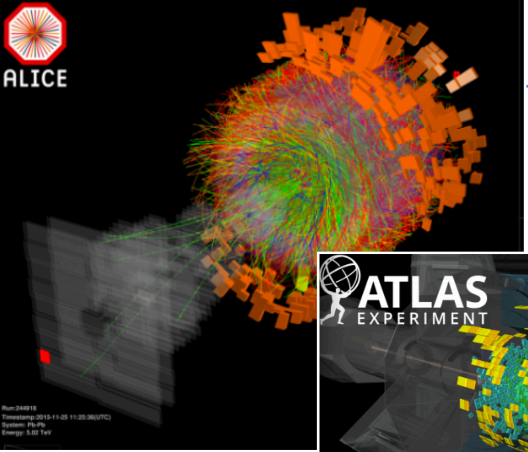
- Explore the deconfined phase of QCD matter → quark-gluon plasma (QGP)
- **LHC Pb-Pb → large energy density** (initial ε > 15 GeV/fm^3) & **large volume** (~ 5000 fm^3)

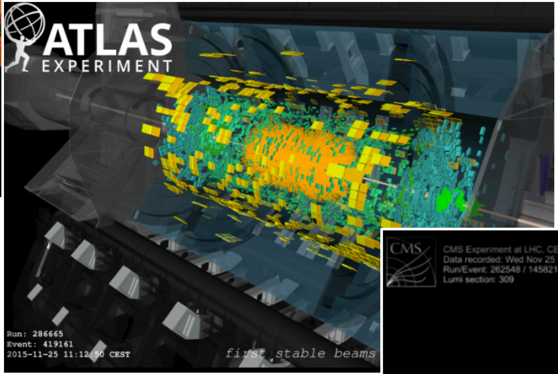


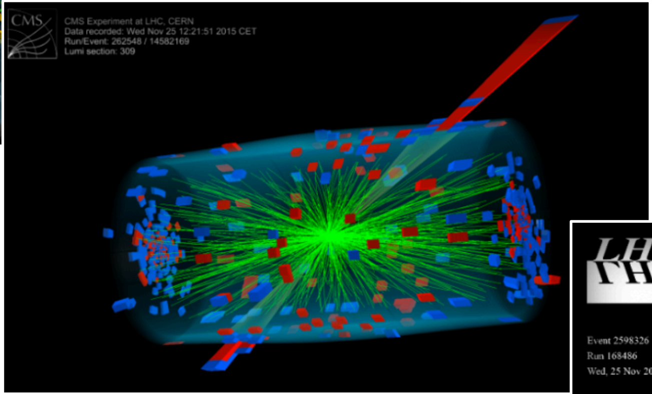
Visualization by J.E. Bernhard, arXiv:1804.06469

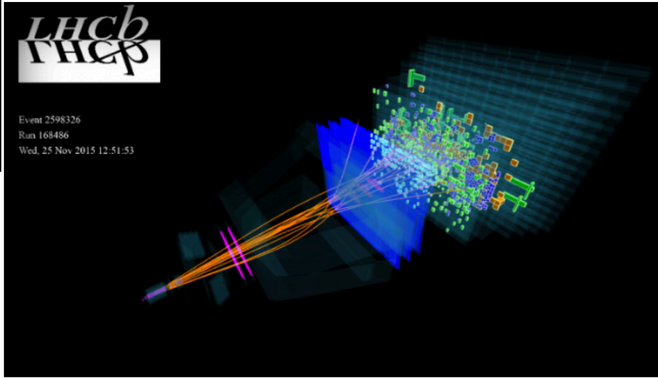
Ultrarelativistic heavy-ion accelerators

- **BNL-AGS**, early '90s, Au-Au up to $\sqrt{s_{NN}} = 5\ \mathrm{GeV}$
  - Below critical energy density
- **CERN-SPS**, since 1994, Pb-Pb up to $\sqrt{s_{NN}} = 17\ \mathrm{GeV}$
  - Estimated energy density ~ 1 × critical value ε_c
  - First signatures of the QGP observed
- **BNL-RHIC**, since 2000, Au-Au $\sqrt{s_{NN}} = 8-200\ \mathrm{GeV}$
  - Estimated energy density ~ 10 × critical value ε_c
  - Discovery of several properties of the QGP
- **CERN-LHC**, since 2010, Pb-Pb $\sqrt{s_{NN}} = 2.76-5.5\ \mathrm{TeV}$
  - Estimated energy density ~ 15-30 × critical value ε_c
  - (Ongoing) Precise characterization of the QGP, new probes available









Heavy-ion collisions at the LHC

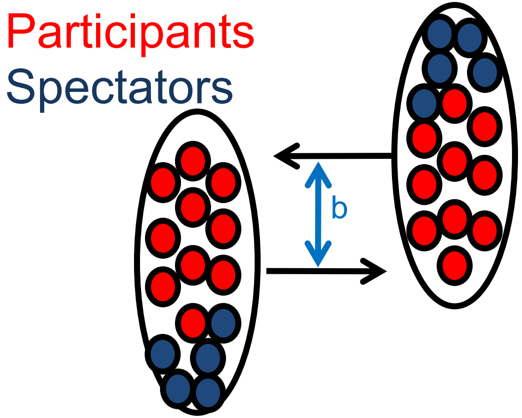
→ Characterise the QGP:

- Initial stage
- Global properties
- Colour deconfinement
- Parton interactions
- Viscosity and expansion dynamics

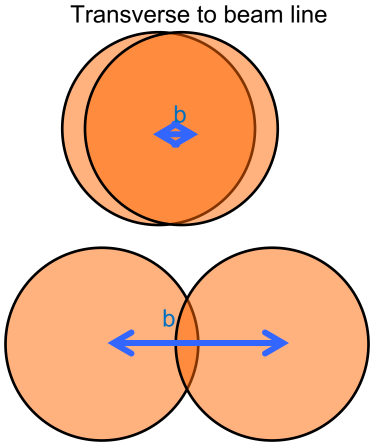
Runs 1-2: $\sqrt{s_{NN}}$ and delivered L_{int}

- Pb-Pb 2.76, 5.02 TeV, ~3 nb^{-1}
- Xe-Xe 5.44 TeV, ~3 μb^{-1}
- p-Pb 5.02, 8.16 TeV, ~200 nb^{-1}

Geometry of a nucleus-nucleus collision



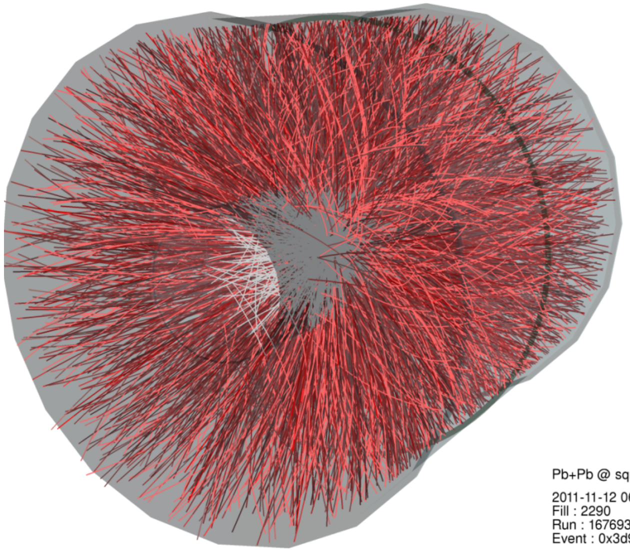
- central collisions
  - small impact parameter b
  - high number of participants
  - → high multiplicity
- peripheral collisions
  - large impact parameter b
  - low number of participants
  - → low multiplicity

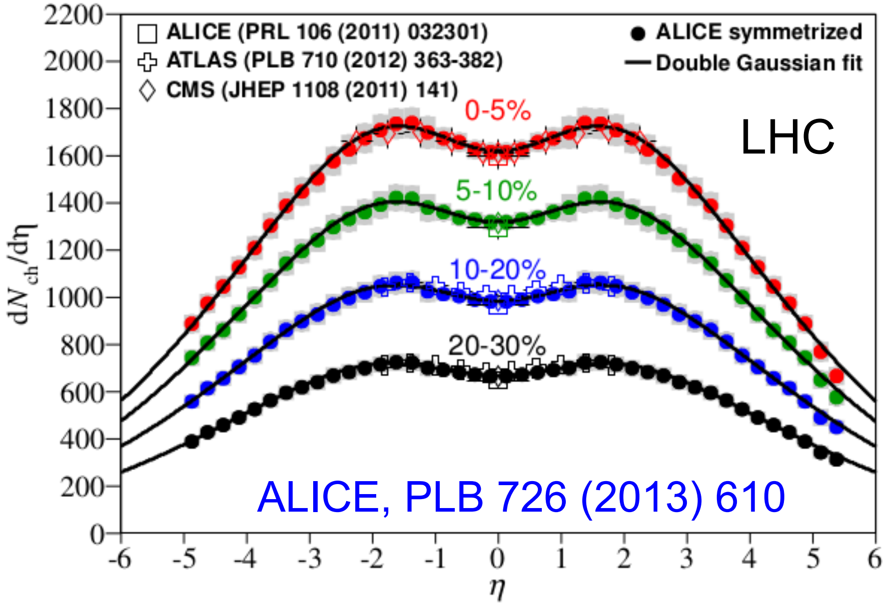


- System size strongly dependent on collision centrality
- Classify events in “centrality classes”
  - In terms of percentiles of total hadronic AA cross section
  - Measure multiplicity of particles in the acceptance of a given detector
  - Determine $\langle N_{participants} \rangle$ and $\langle N_{collisions} \rangle$ with a model of the collision geometry (Glauber model)

Glauber model: see e.g. M. Miller et al. Ann.Rev.Nucl.Part.Sci.57(2007)205

‘Global’ properties of the collisions: multiplicity





Central collisions at LHC: ~17,000 charged particles!

‘Global’ properties of the collisions: energy density

- Estimate of energy density reached in the collision:

$$\varepsilon = \frac{E}{V} = \frac{1}{Sc\tau_0} \left.\frac{dE_T}{dy}\right|_{y=0}$$

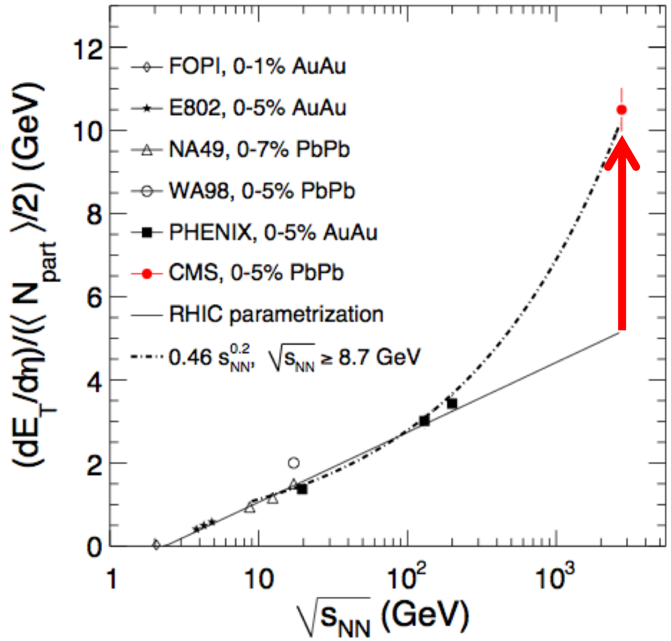
$$S = \text{transverse dimension of nucleus}$$
$$\tau_0 = \text{"formation time"} \sim 1\ \text{fm}/c$$

- Initial time τ_0 normally taken to be ~ 1 fm/c
  - i.e. equal to the “formation time”: the time it takes for the energy initially stored in the field to materialize into particles
- Transverse dimension:

$$S \approx 160\ \text{fm}^2 \qquad (R_A \approx 1.2 A^{1/3}\ \text{fm})$$

‘Global’ properties of the collisions: energy density

- Transverse energy x3 from RHIC to LHC:



CMS, PRL109 (2012) 152303

$$\left.\frac{dE_T}{dy}\right|_{y=o} \approx 2\ \text{TeV}$$

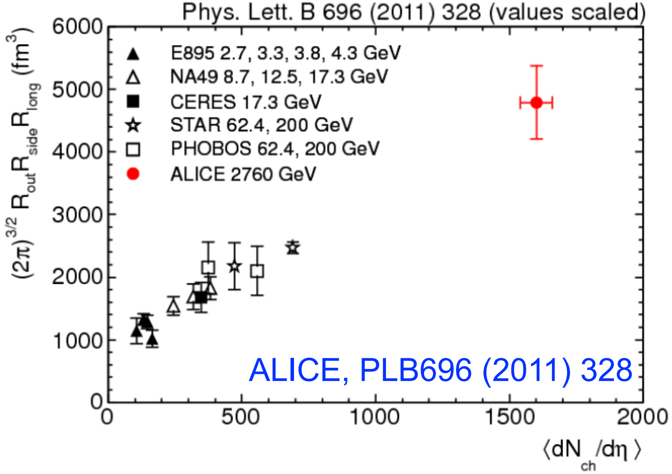
$$\varepsilon \sim (2000\,/\,160)\ \text{GeV/fm}^3 \approx 12\ \text{GeV/fm}^3$$

x20 larger than the critical energy density from lattice QCD

‘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:
  - $\Delta p \cdot \Delta x \sim \hbar$
  - → extract source size from momentum correlation function

- “Homogeneity” volume ~5000 fm^3 at LHC

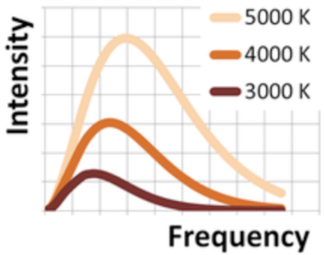


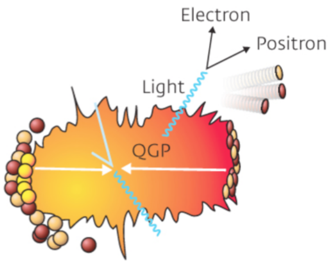
- compare to $V_{Pb\text{-}nucleus}$ ~ 1500 fm^3

→ strong (x3) expansion!

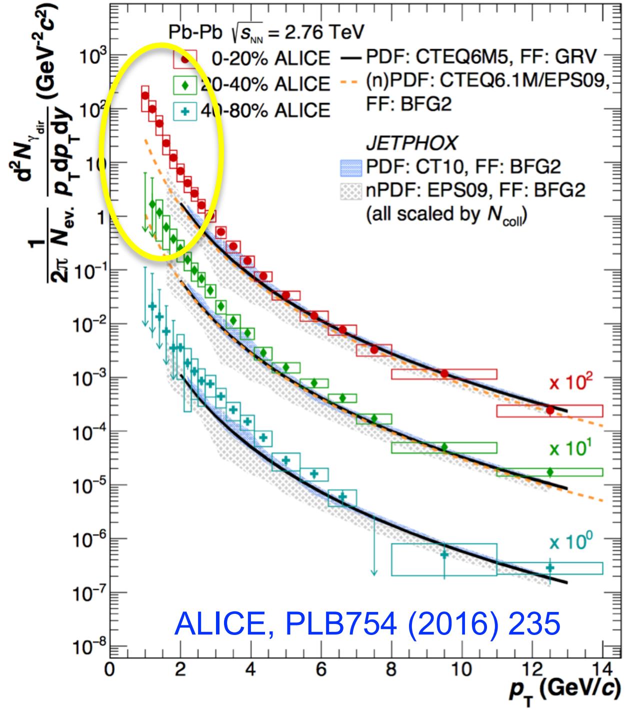
‘Global’ properties of the collisions: effective temperature from photon radiation

- QGP radiates real and virtual photons during all phases of its evolution
- Analogy to black body radiation



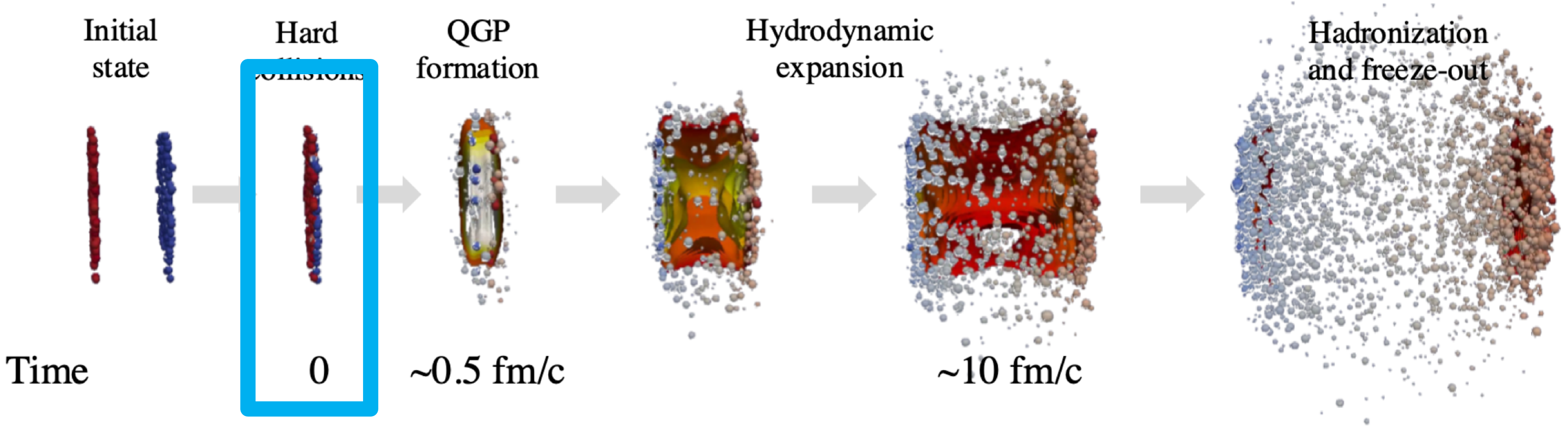


- Measured as exponential component of soft photons on top of photons from QCD processes
- T_{slope} = 304 ± 40 MeV (x2 larger than T_c)

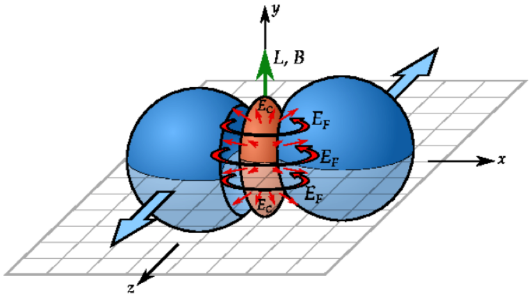


ALICE, PLB754 (2016) 235

Early phase: vorticity and magnetic field



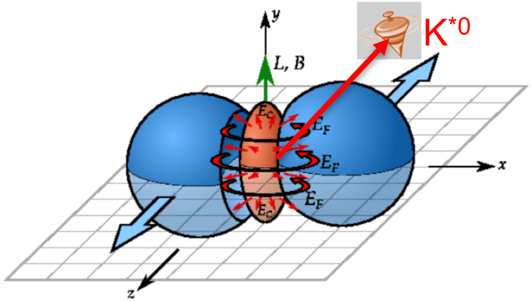
Visualization by J.E. Bernhard, arXiv:1804.06469



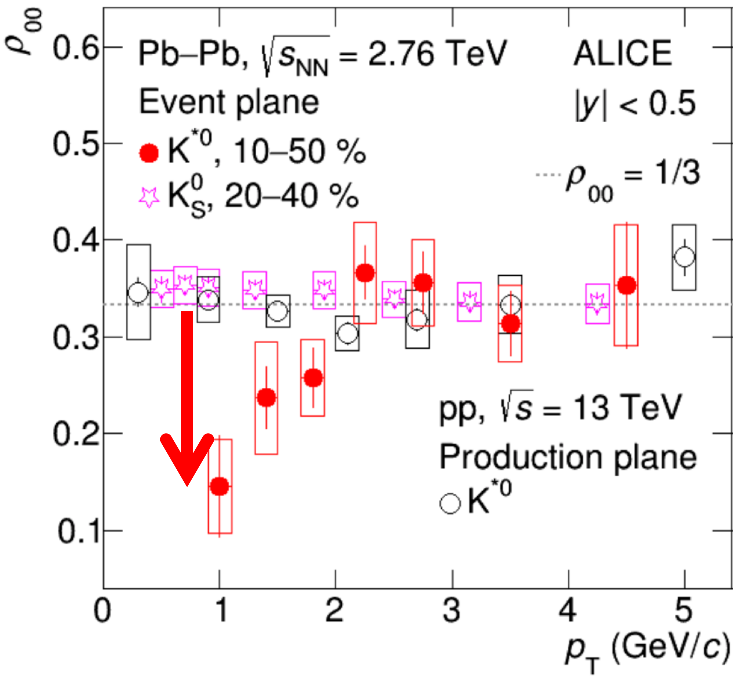
Non-central collisions:

- Large angular momentum L (~10^{21} revolutions per second)
- Large magnetic field B (~10^{14} Tesla)

Spin alignment of vector mesons in spinning QGP

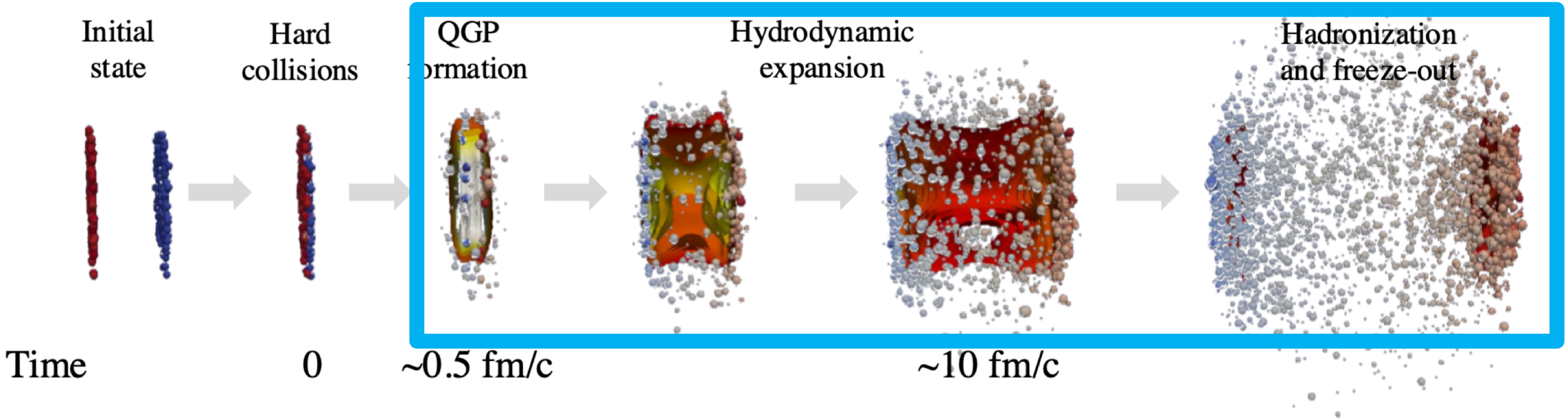


- Large angular momentum **L** in non-central collisions
- Spin-orbit interactions expected to polarise quarks
- If quarks recombine to produce vector mesons (spin=1), spin alignment could appear
- Measurement using $K^{*0} \rightarrow K\pi$ decays shows a 3σ effect at low momentum

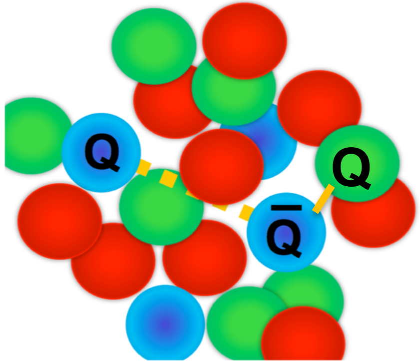


ALICE, PRL125 (2020) 012301

QCD deconfinement: melting and re-binding quarkonia



Visualization by J.E. Bernhard, arXiv:1804.06469



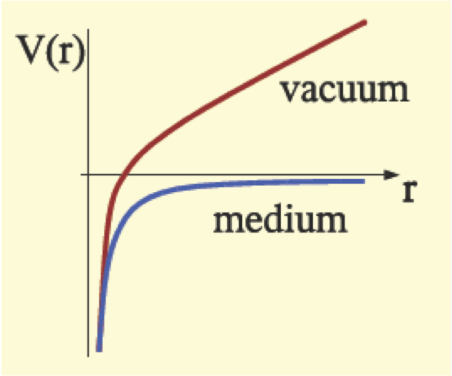
- Deconfinement → Colour screening → Quarkonium melting
- High charm density can lead to "additional" charmonium formation

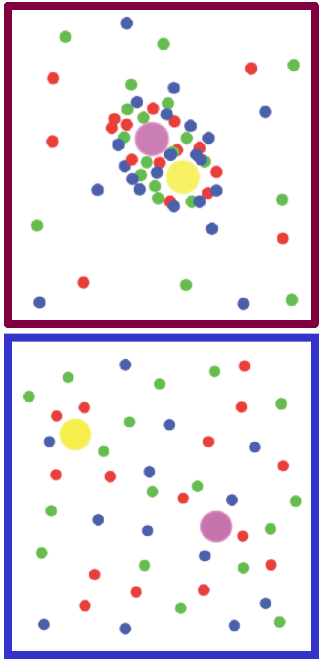
Quarkonium melting due to colour screening

- QGP signature proposed by Matsui and Satz, 1986

- In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening):

- Charmonium ($c\bar{c}$) and bottonium ($b\bar{b}$) states with r > λ_D will not bind; their production will be suppressed

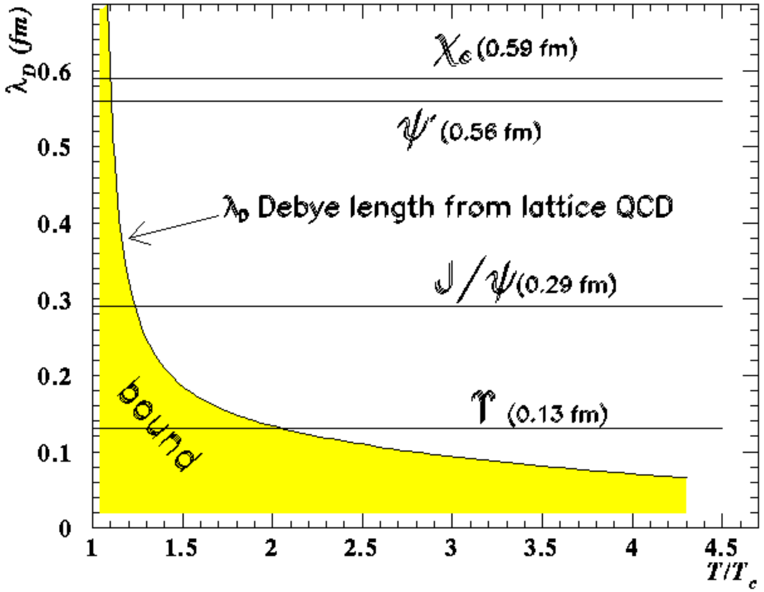




Matsui, Satz, PLB178 (1986) 416

Quarkonium melting due to colour screening

Debye screening length λ_D rapidly decreases when T > T_c (T/T_c > 1):



Digal,Petrecki,Satz PRD 64(2001) 0940150

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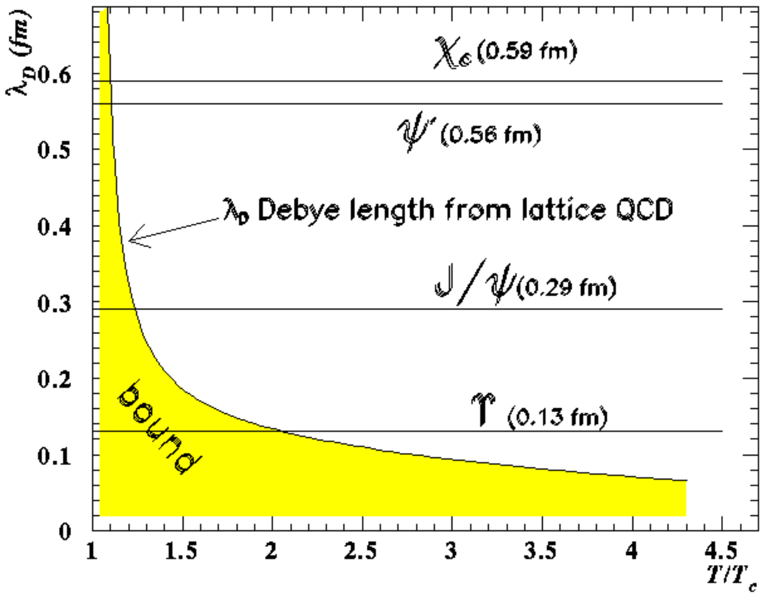

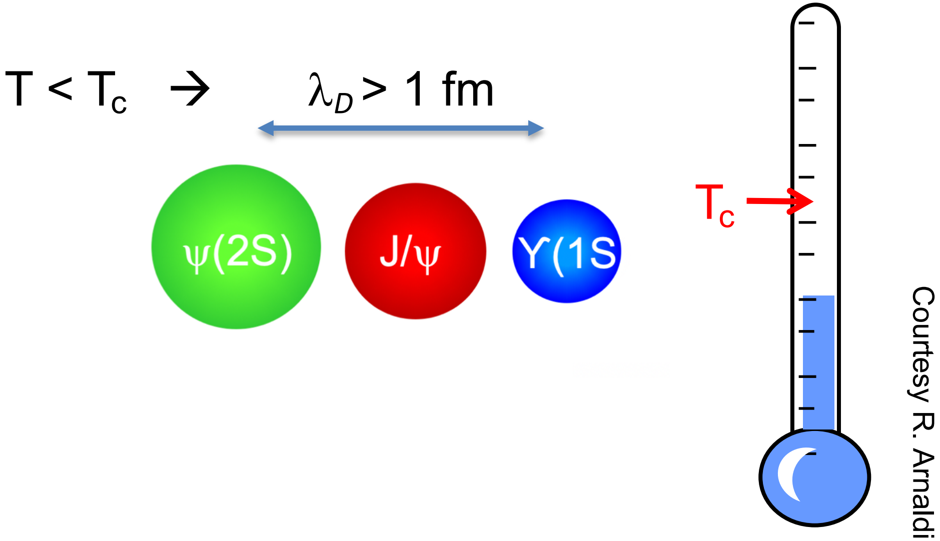

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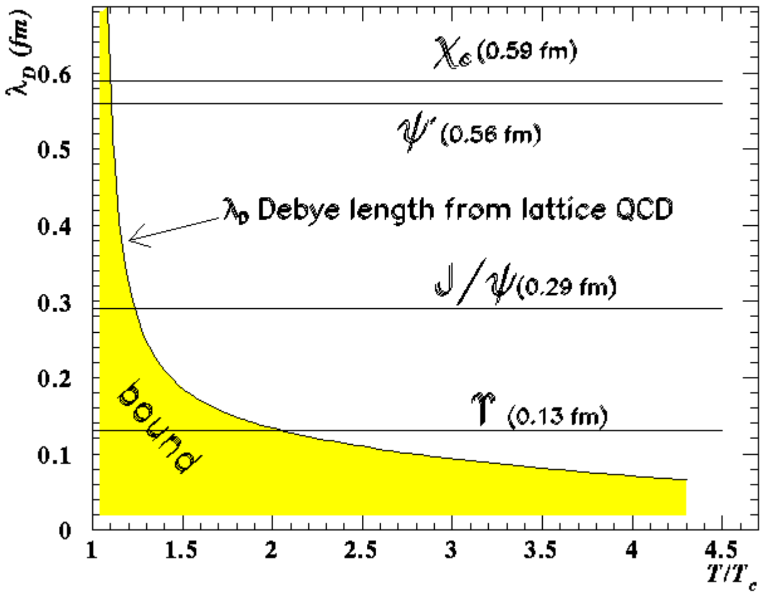

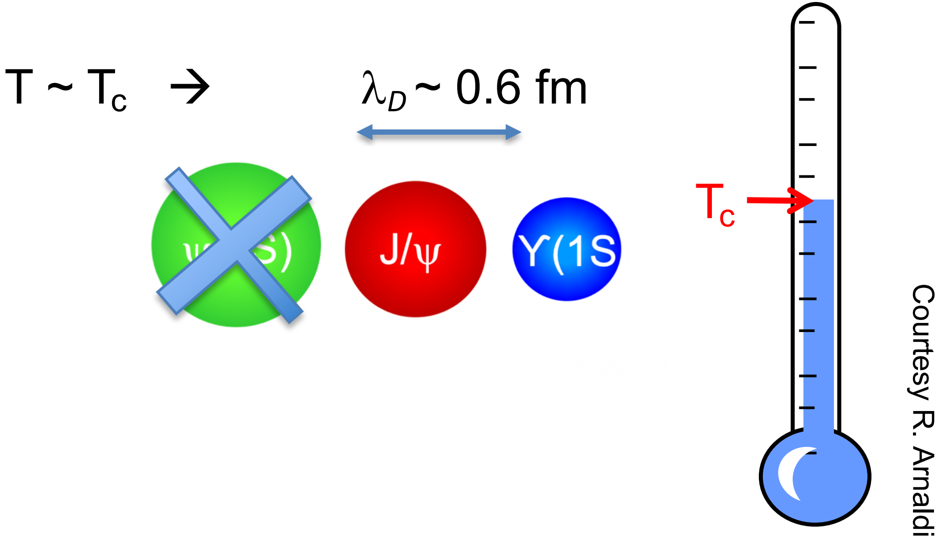

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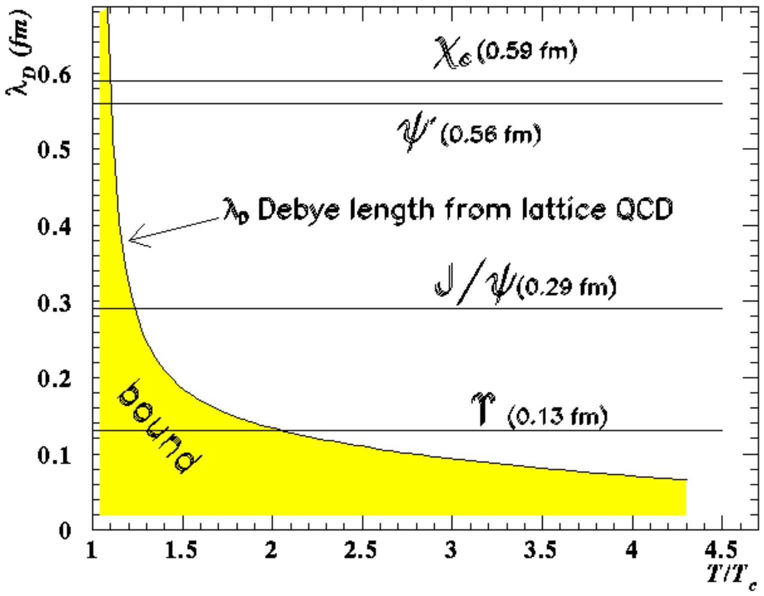
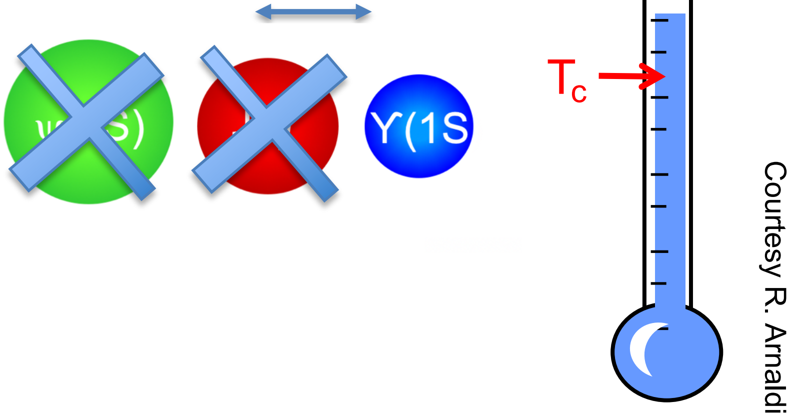


T ~ 2 T_c → λ_D ~ 0.15 fm



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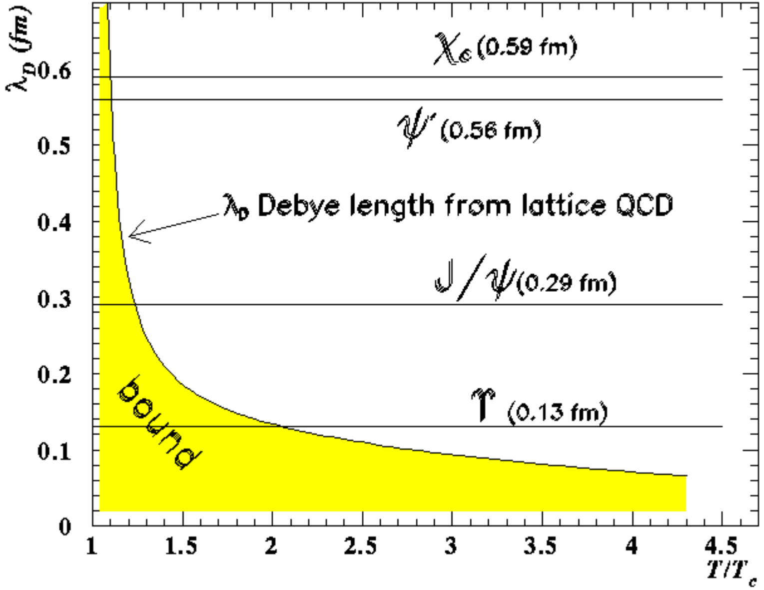
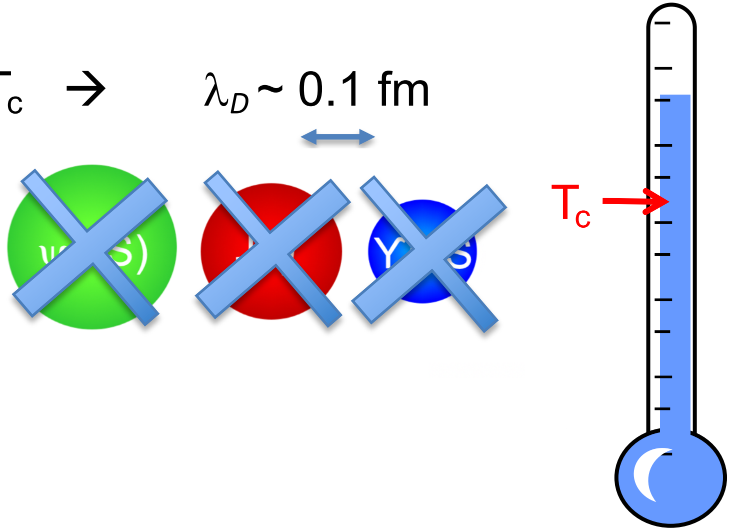


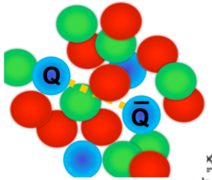
$T \sim 3\,T_c$ → $\lambda_D \sim 0.1$ fm



Courtesy R. Arnaldi

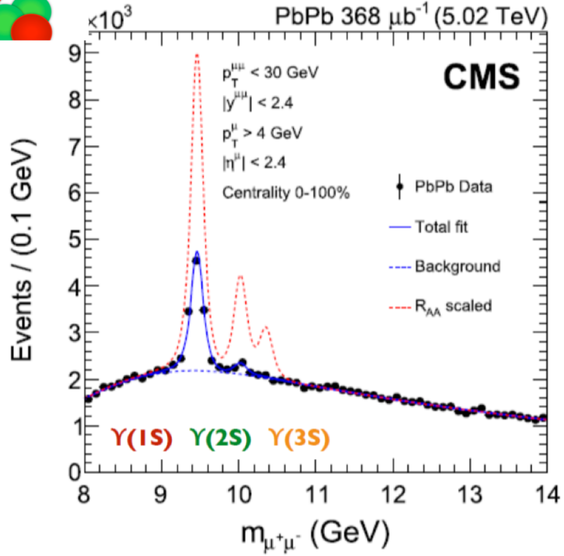
Digal,Petrecki,Satz PRD 64(2001) 0940150

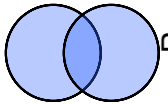
Bottonium sequential suppression: Y(1S), Y(2S), Y(3S)

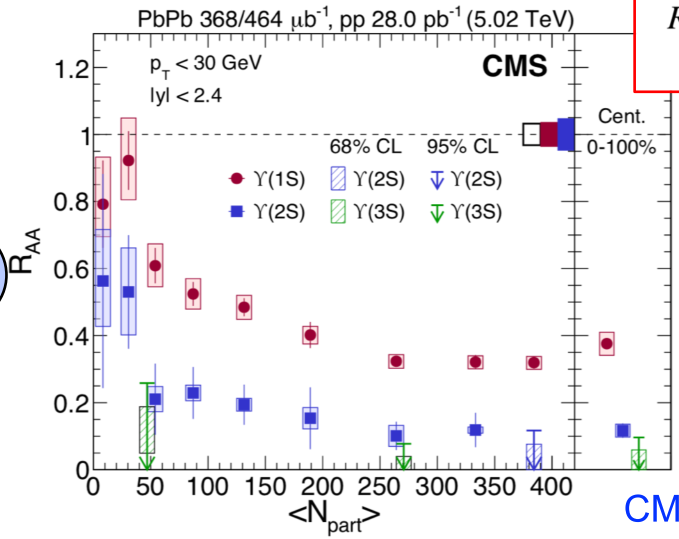


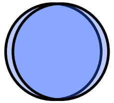
***Binding energy:* ~1.1 ~0.5 ~0.2 GeV**

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$









CMS, PLB790(2019)270

- Y(2S) 4x more suppressed than Y(1S); Y(3S) not observed in Pb-Pb
- Consistent with sequential suppression, ordered with binding energy, due to colour screening

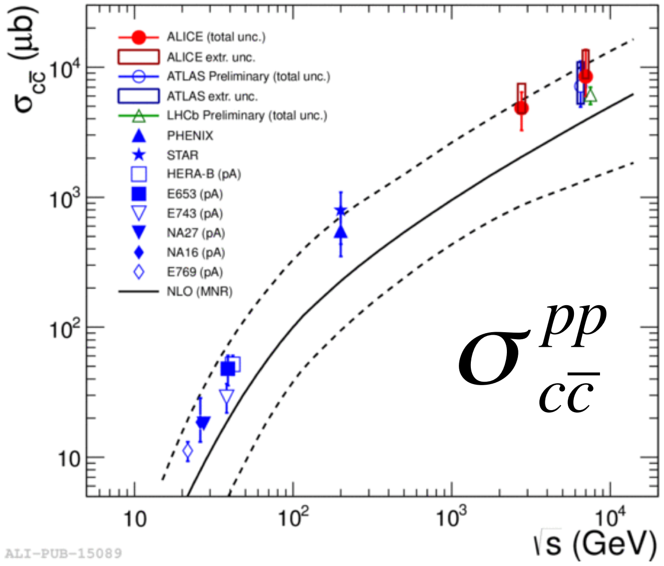
Charmonium regeneration at the LHC

- Uncorrelated c quarks from the medium could bind at system hadronization and form charmonium
- At LHC, about 100 $c\bar{c}$ pairs in central collisions:

$$N_{c\bar{c}} = \frac{\sigma^{pp}_{c\bar{c}}}{\sigma^{pp}_{inel}} \cdot N_{coll} \sim \frac{\sigma^{pp}_{c\bar{c}}}{65\text{ mb}} \cdot 1600$$

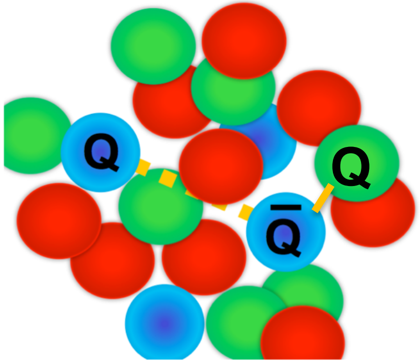
In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.1	~10	~100

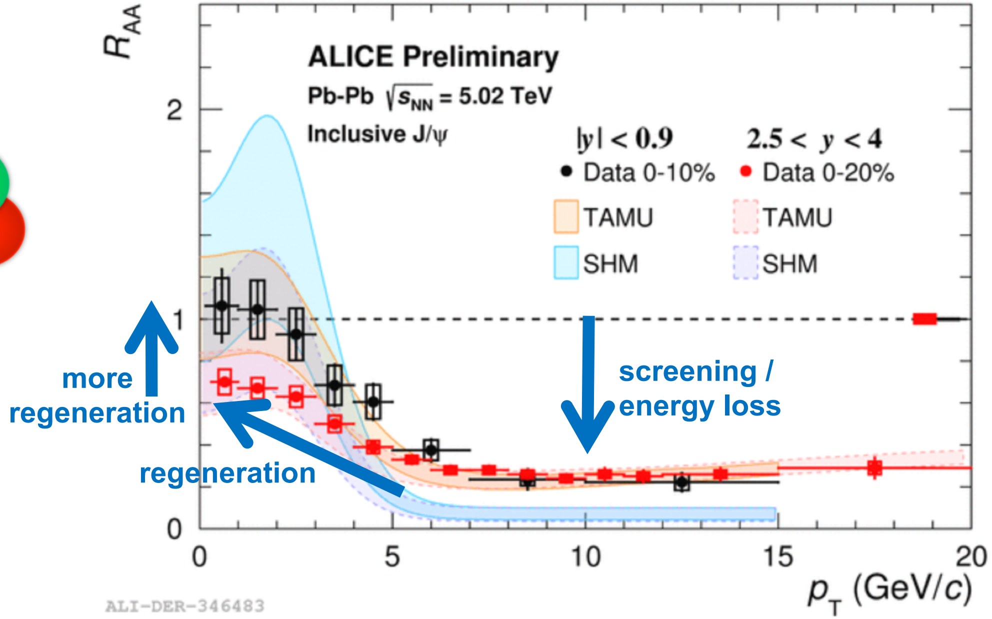
P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196
R. Thews et al, Phys.ReV.C63:054905(2001)



ALICE, JHEP1207 (2012) 191

J/ψ regeneration

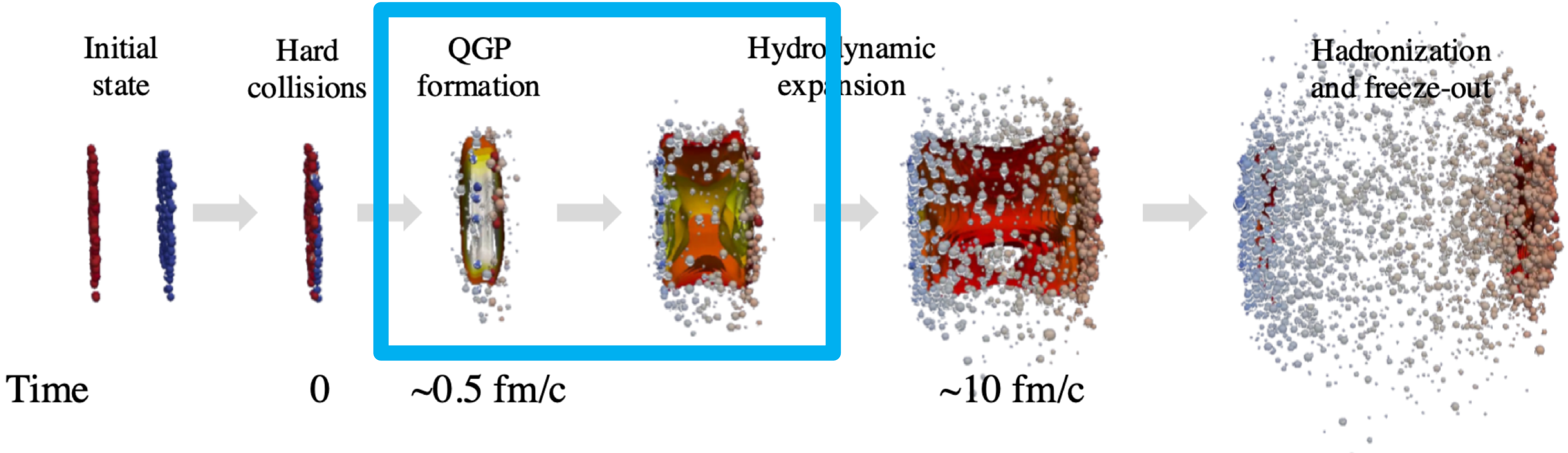




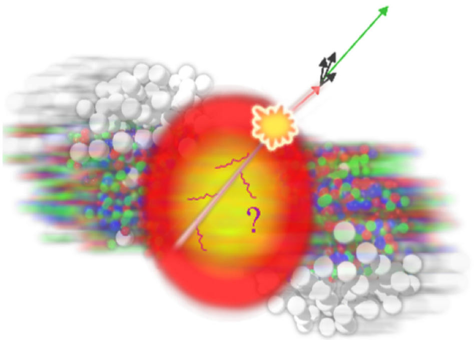
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

- J/ψ suppression reduced at low p_T
  - $c\bar{c}$ regeneration balancing the dissociation in the QGP
- At low p_T, modification decreases from **forward** to **central** rapidity
  - Reflects rapidity dependence of the $c\bar{c}$ cross section → regeneration probability

Jets and parton energy loss



Visualization by J.E. Bernhard, arXiv:1804.06469



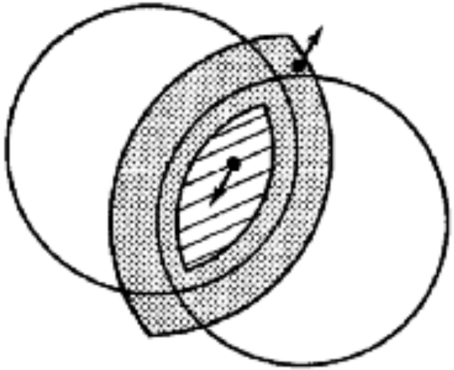
- Hard quarks and gluons strongly interact with QGP
- Jet energy loss and modification by induced gluon radiation

Parton energy loss: historics

- Partons travel ~4 fm in the high-density medium
- Bjorken (`82): energy loss due to elastic scattering

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma.

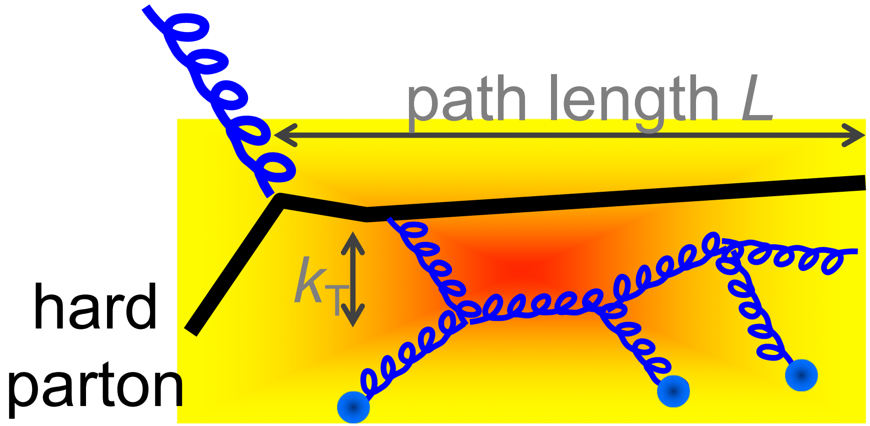
An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



J.D. Bjorken, FERMILAB-Pub-82/59-THY (1982).

Parton energy loss: QGP-induced gluon radiation

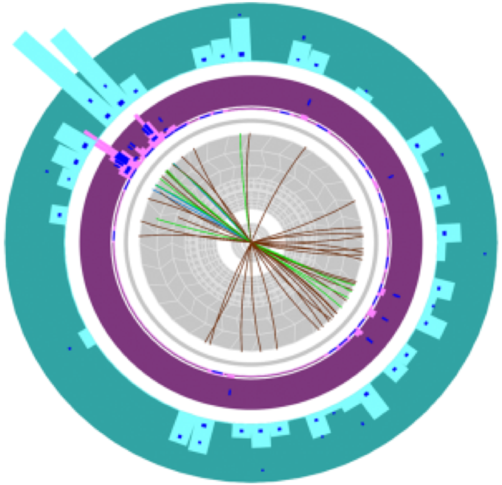
- Partons travel ~4 fm in the high colour-density medium
- Successive calculations (`92 →): a QCD mechanism dominates, medium-induced gluon radiation
- Coherent wave-function gluon acumulates k_T due to multiple inelastic scatterings in the medium → it decoheres and is radiated

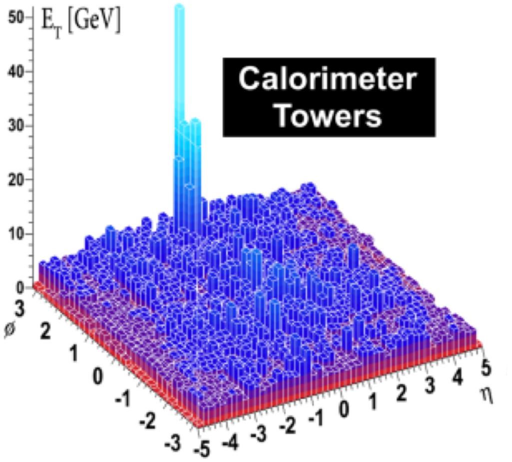


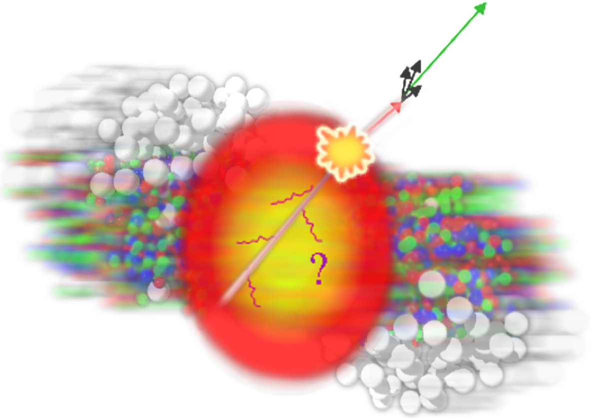
Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Peigne', Schiff, Levai, Vitev, Zhakarov, Salgado, Wiedemann, …

Observation of jet quenching at the LHC

- Full jet reconstruction: typically anti-k_T algorithm + sophisticated background subtraction techniques
- Jets and Di-jets with ~100 GeV energies
- Pb-Pb events with large di-jet imbalance observed





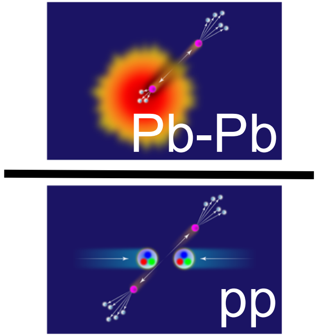


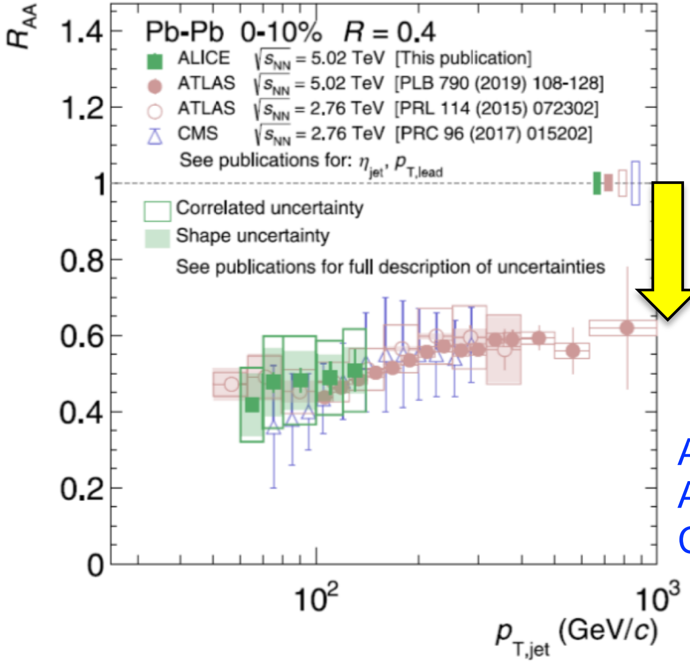
ATLAS, PRL105 (2010) 252303

→ Direct observation of jet quenching at single event level!

Quantifying jet quenching: inclusive yields

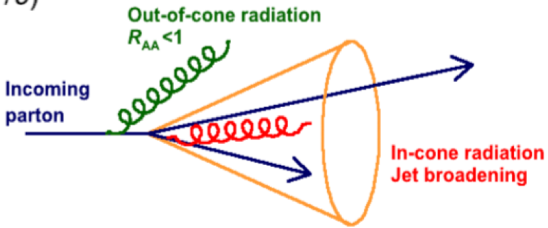
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$





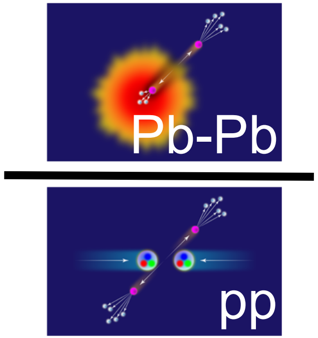
ALICE, PRC101(2020)034911
ATLAS, PLB790(2019)108
CMS, PRC96(2017)015202

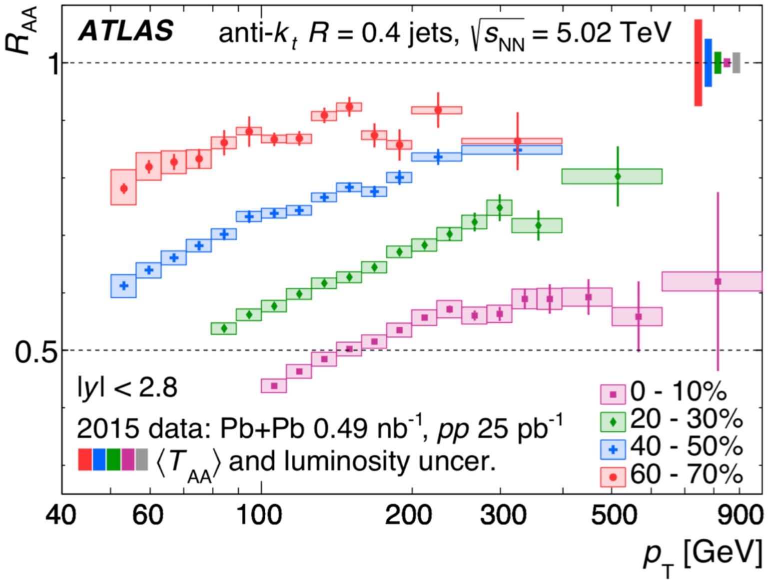
- Large **reduction** (x2-4) **of jet yields, from 50 GeV/c to 1 TeV/*c***
- Lost energy is not recovered within the jet “cone” → large angle QGP-induced gluon emission



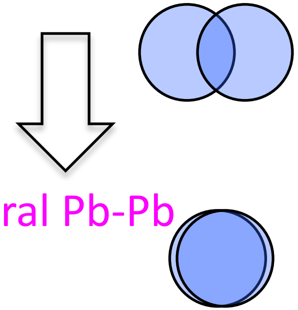
Quantifying jet quenching: inclusive yields

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$



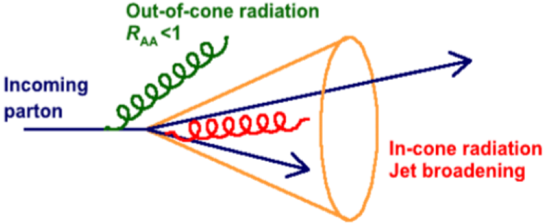


Peripheral Pb-Pb



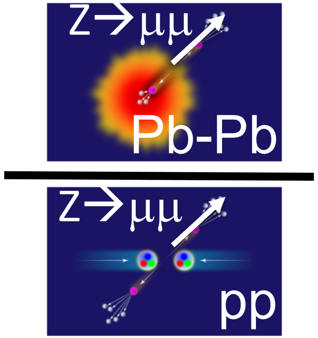
Central Pb-Pb

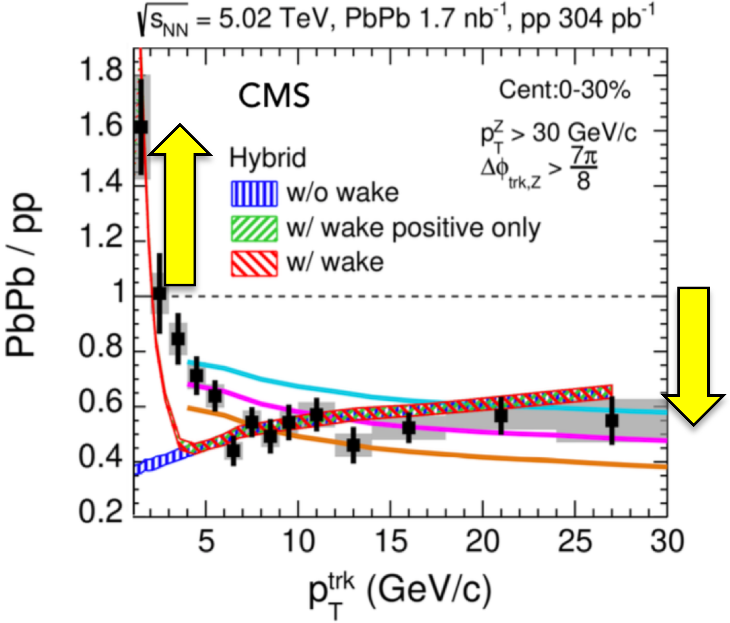
ATLAS, PLB790(2019)108



- Large **reduction** (x2-4) **of jet yields, from 50 GeV/c to 1 TeV/*c***
- Lost energy is not recovered within the jet "cone" → large angle QGP-induced gluon emission

Jet quenching: Z-jet recoil





CMS-PAS-HIN-19-006

- Z-jet correlations provide the scale of the initial jet (parton) energy (~Z energy)
- p_T distribution of recoil-jet tracks exhibits suppression at high p_T and increase at low p_T → energy loss

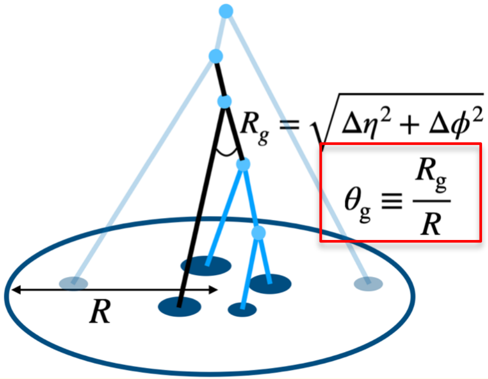
Jet quenching: substructure and jet collimation

Study medium-modified parton shower

e.g.: grooming: find first hard splitting

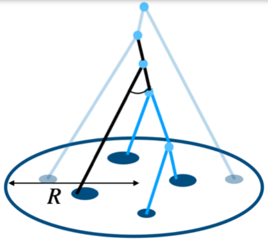
(Soft Drop)

$$z = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z > 0.2$$

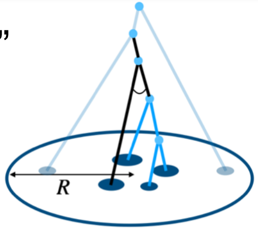


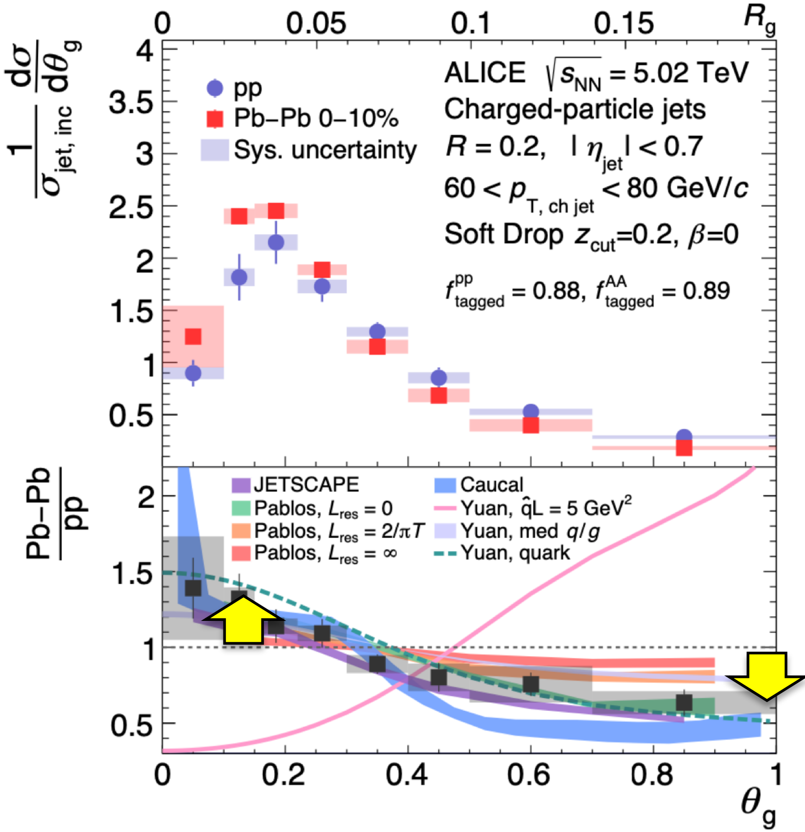
→ Jet core is more collimated in Pb-Pb than in pp

Cartoon: “pp”



“Pb-Pb”

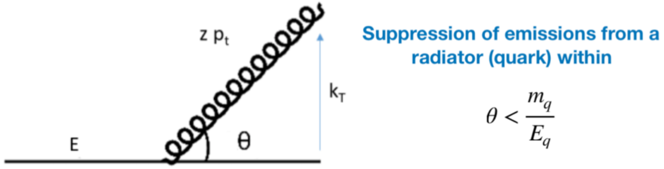




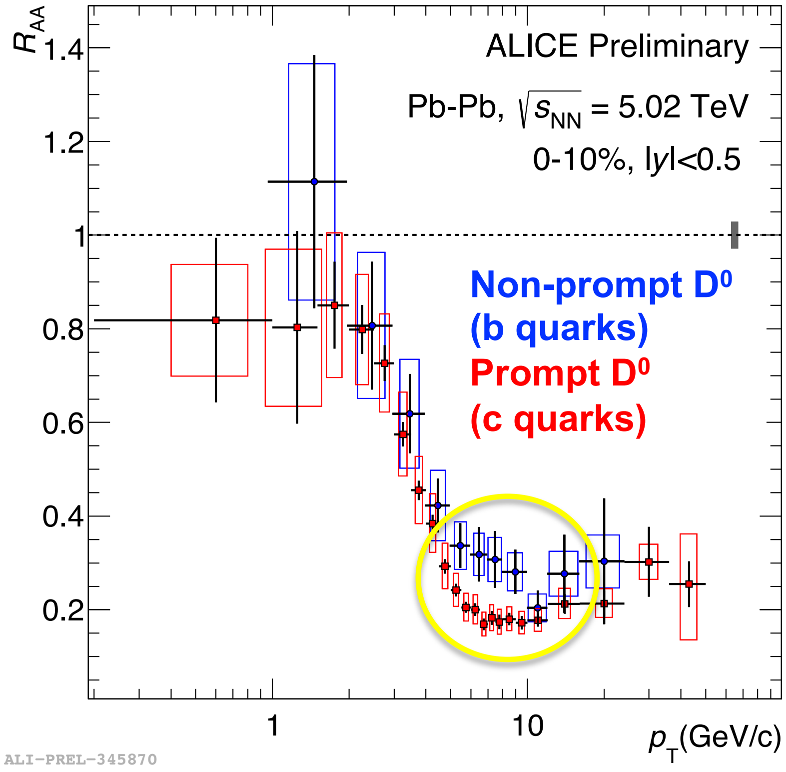
ALICE, arXiv:2107.12984

Quark-mass dependence of energy loss

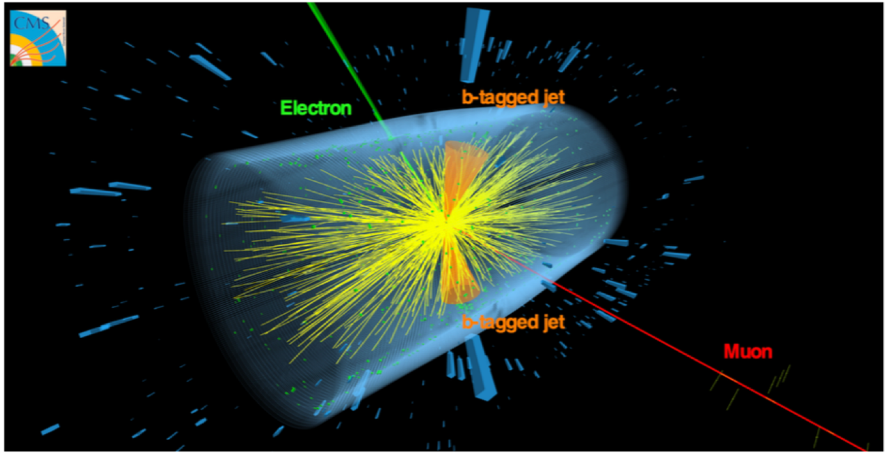
- Energy loss predicted to depend on QGP density, but also on quark mass
- "Dead cone" effect reduces small-angle gluon radiation for high-mass quarks

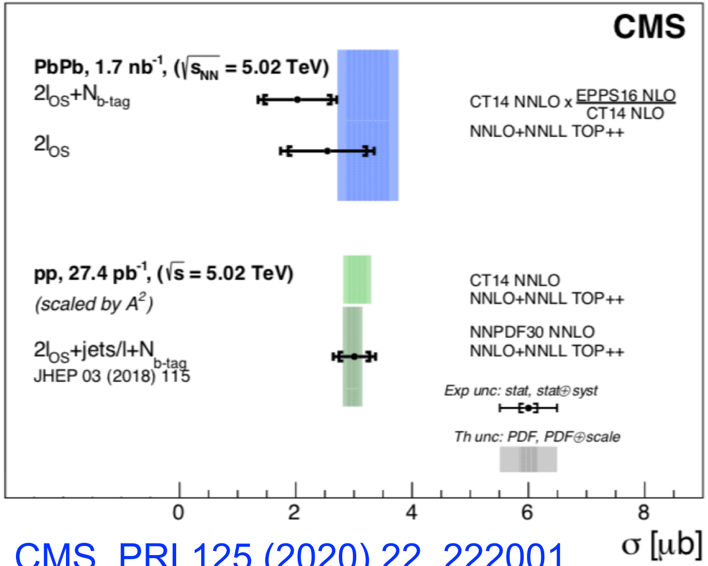


- Less suppression for (non-prompt) D mesons from B decays than prompt D mesons
  - Also note: first measurement of D meson production down to zero p_T in Pb-Pb



Going heavier: top quarks seen in Pb-Pb



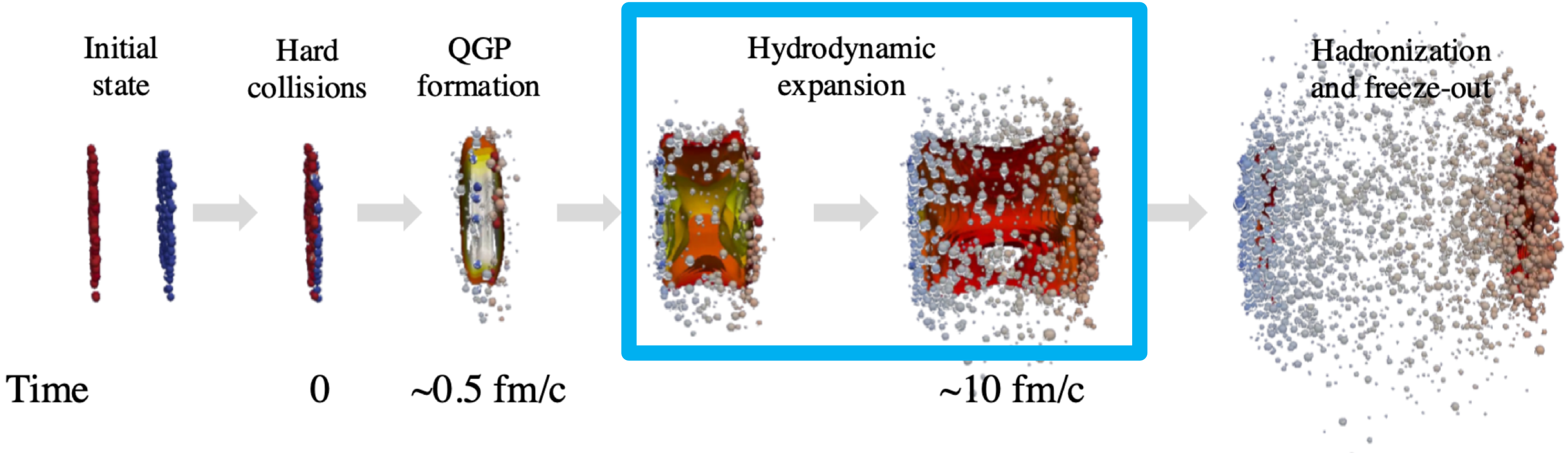


CMS, PRL125 (2020) 22, 222001

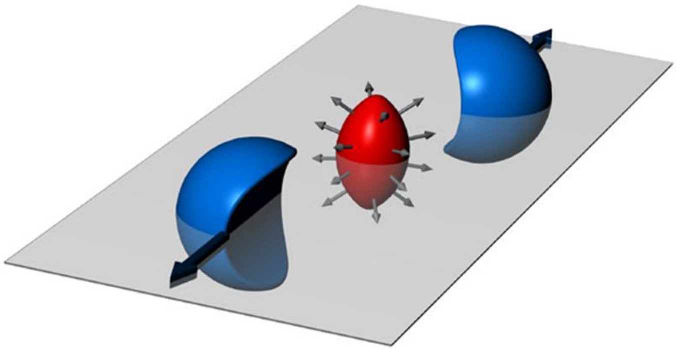
- First observation of top quarks in heavy-ion collisions
- Physics case with (much) larger luminosity: access time-dependence of jet quenching using time-delay from boosted top decay topologies t → W → jets

Apolinario et al, PRL120 (2018) 23, 232301

QGP expansion and flow

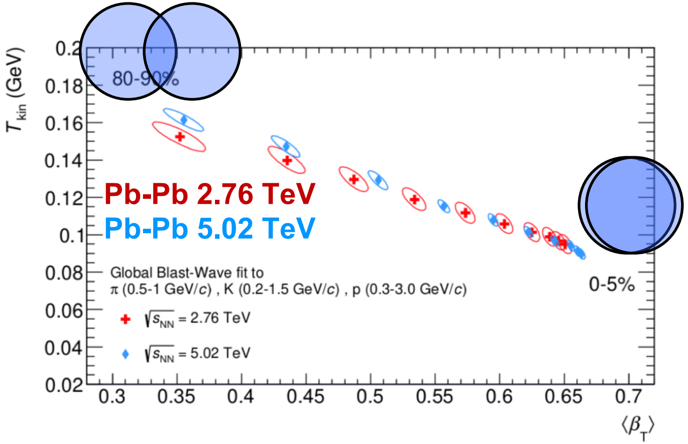


Visualization by J.E. Bernhard, arXiv:1804.06469

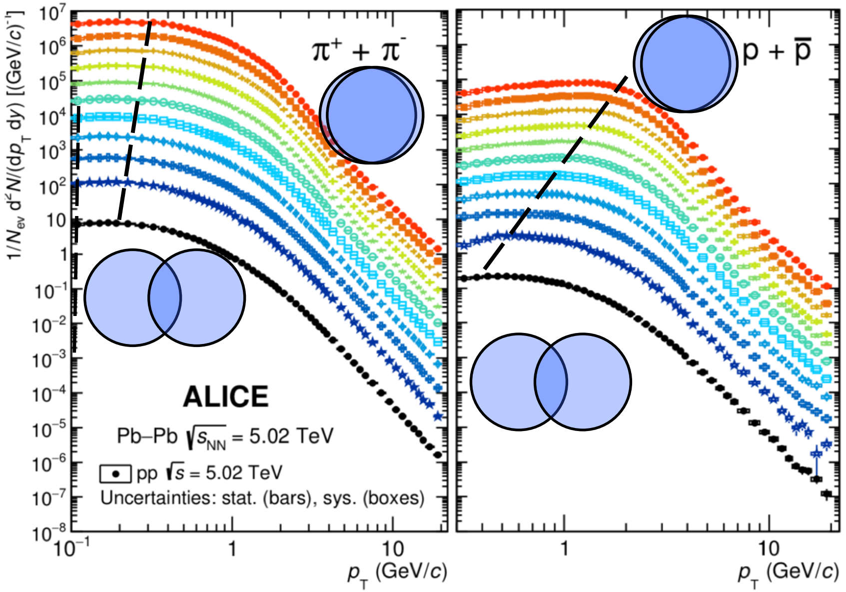


Identified particle spectra and radial flow

- p_T distributions for π, K, p in centrality classes
- Shift of peak of p_T distr. in central collisions, more pronounced for heavier hadrons → **flow**



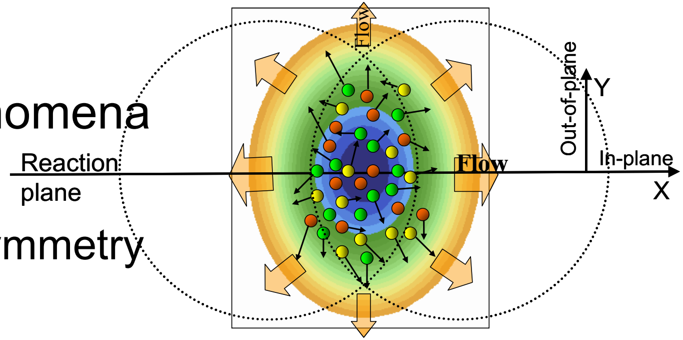
ALICE, PRC101 (2020) 044907

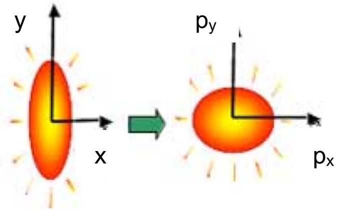


- Blast-wave fit to characterize radial flow
  - Hydrodynamic-inspired fit
  - Collective expansion with common flow velocity β_T imparts additional momentum to hadrons: $m_T \rightarrow m_T + m_0\, \gamma\beta_T$
- Largest ever $\beta_T \sim 0.67c$ in central Pb-Pb collisions at 5 TeV

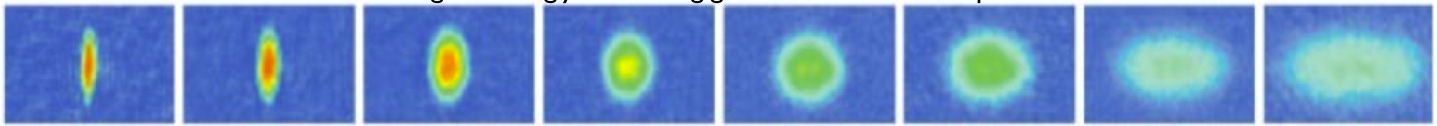
Anisotropic (elliptic) flow

- Non-central collisions are azimuthally asymmetric
- The transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena
- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- Small mean free path
  - larger density gradient → larger pressure gradient → larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)





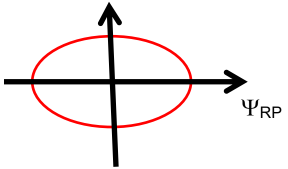
An atomic analogue: strongly-interacting gas of ultra-cold ^{6}Li "explodes" in vacuum

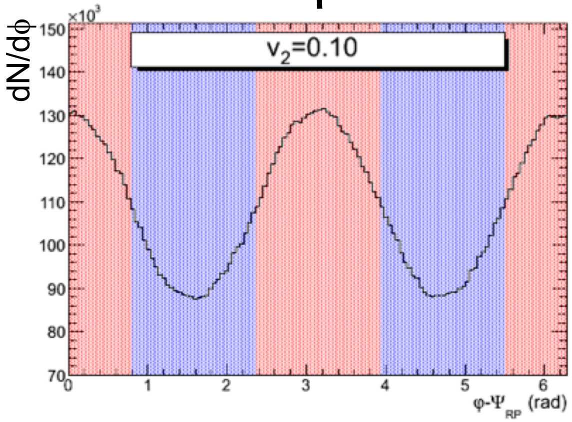


Anisotropic (elliptic) flow

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right)$$

$$v_2 = \langle \cos 2\phi \rangle \quad \text{"elliptic flow"}$$





Figures courtesy F.Prino

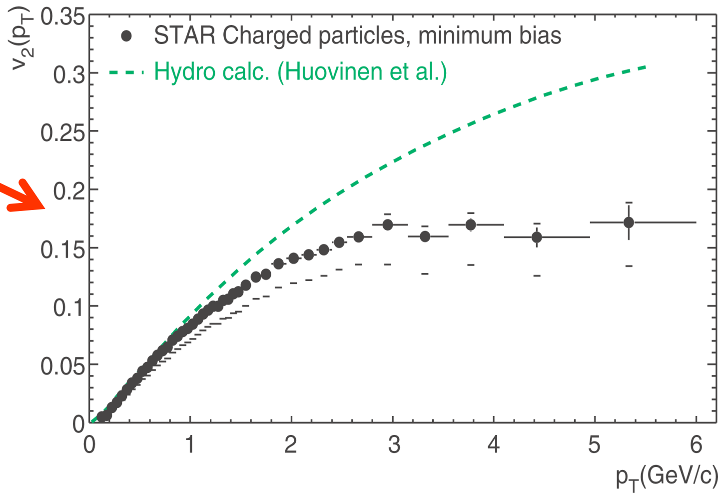
Azimuthal Anisotropy at RHIC

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right)$$

$$v_2 = \langle \cos 2\phi \rangle \quad \text{"elliptic flow"}$$

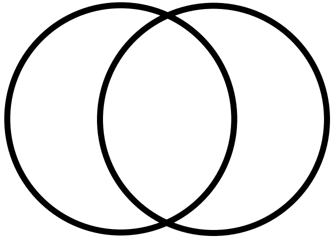
- Measurement at RHIC:
- Elliptic flow almost as large as expected at hydro limit!
- Very far from “ideal gas” picture of the QGP
- Looks like a “liquid”: frequent interactions and small mean free path

→ strongly-coupled QGP (sQGP)



Higher harmonics

- "Ideal" shape of nuclear overlap is elliptic
  - no odd harmonics expected (v_3, v_5, …)



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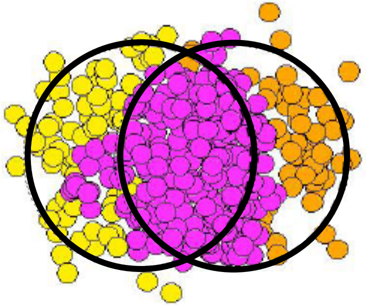
- but fluctuations in initial conditions:



Higher harmonics

- "Ideal" shape of nuclear overlap is elliptic
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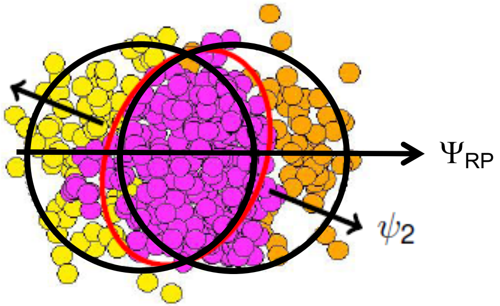
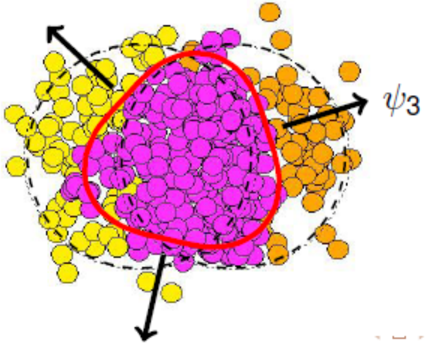
- but fluctuations in initial conditions:
  - participants plane $\psi_2 \neq$ reaction plane Ψ_{RP}



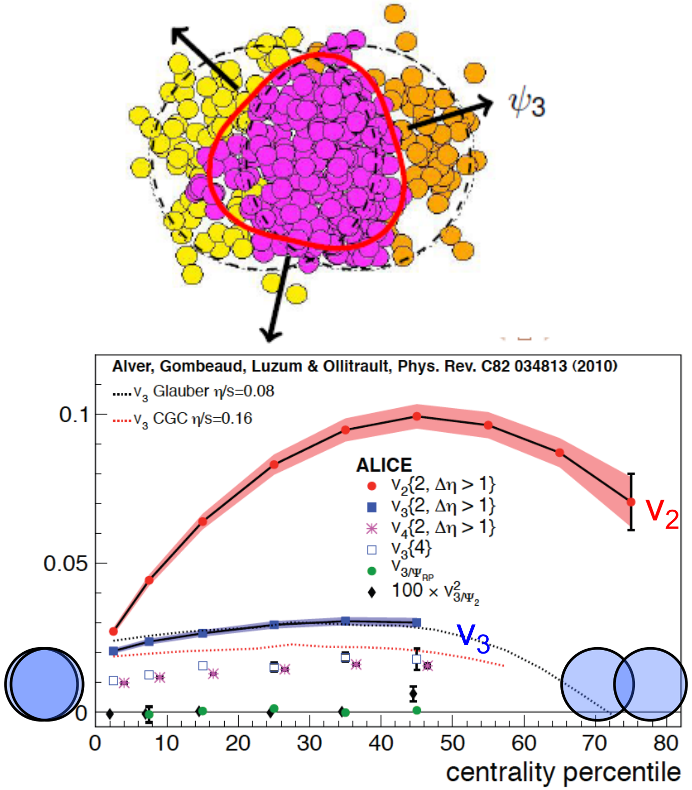
Higher harmonics

- “Ideal” shape of nuclear overlap is elliptic
  - no odd harmonics expected (v_3, v_5, …)
- but fluctuations in initial conditions:
  - participants plane $\psi_2 \neq$ reaction plane Ψ_{RP}
  - v_3 (“triangular”) harmonic appears
  - [B Alver & G Roland, PRC81 (2010) 054905]



Higher harmonics

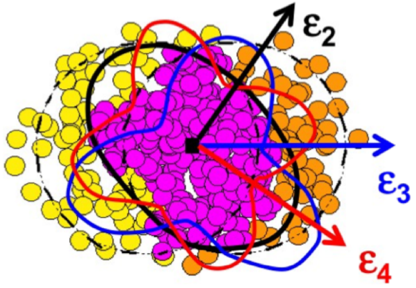
- and indeed, $v_3 > 0$!
- v_3 has weaker centrality dependence than v_2
- when calculated wrt participants plane, v_3 vanishes
  - as expected, if due to fluctuations…

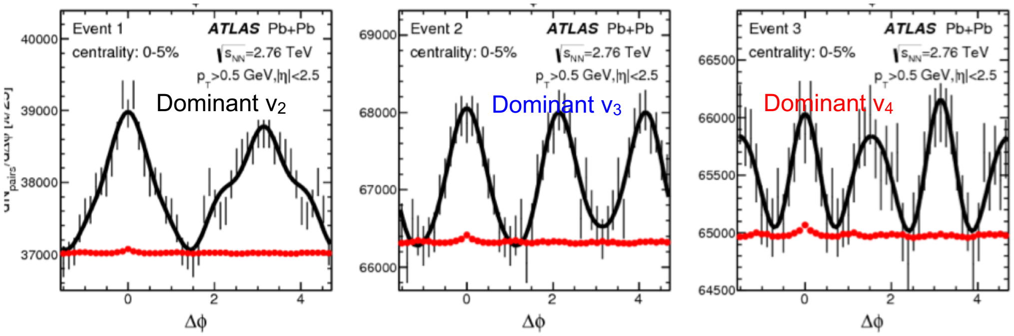


ALICE: PRL 107 (2011) 032301

Event-by-event shapes at the LHC

- And not only v_3 (triangular events), also v_4, v_5, …
- At LHC, multiplicity large enough to "see" event-by-event shapes

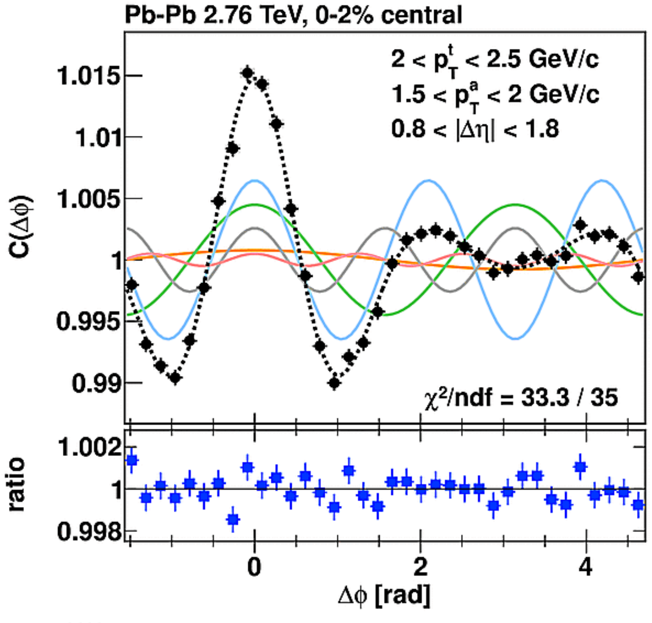




Harmonic decomposition of correlation distribution

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right)$$

- First five harmonics describe shape at 10^{-3} level
- Fourier analysis of new data suggests very natural alternative explanation in terms of hydrodynamic response to initial state fluctuations



ALICE, PLB708 (2012) 249

Initial conditions and viscosity of the QGP

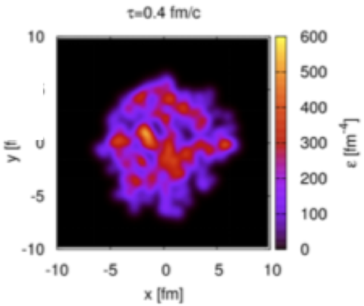
- Medium viscosity: one of its fundamental properties
- η/s: shear viscosity / entropy ratio

Initial conditions and viscosity of the QGP

- Medium viscosity: one of its fundamental properties
- η/s: shear viscosity / entropy ratio

Energy density profile in the transverse plane:

initial



S Jeon et al, QM 2012, B. Schenke, et al. PRL106, 042301 (2011)

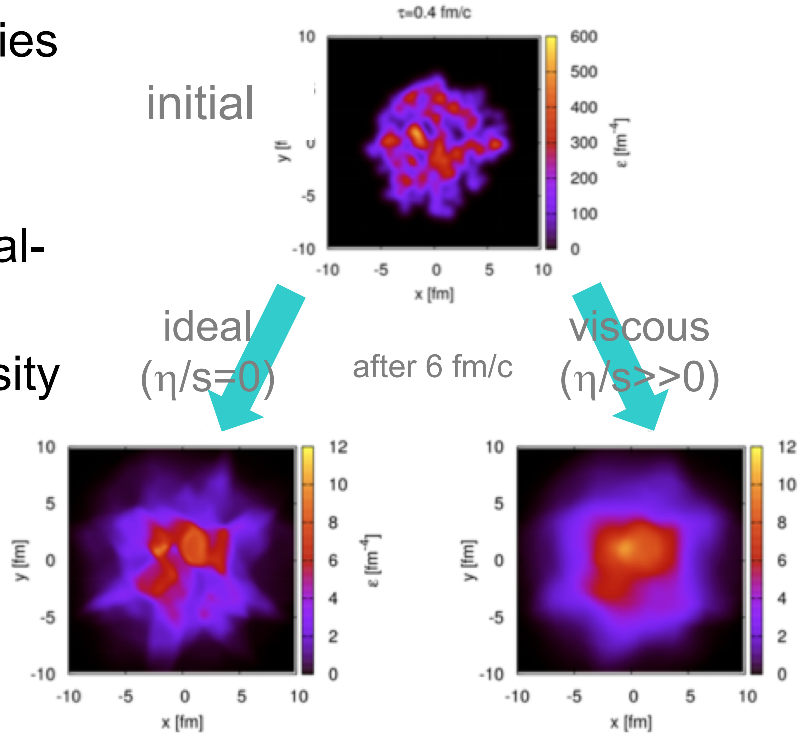
Initial conditions and viscosity of the QGP

- Medium viscosity: one of its fundamental properties
- η/s: shear viscosity / entropy ratio

- Large viscosity washes out the details of the initial-state

→ Final state fluctuations give information on viscosity

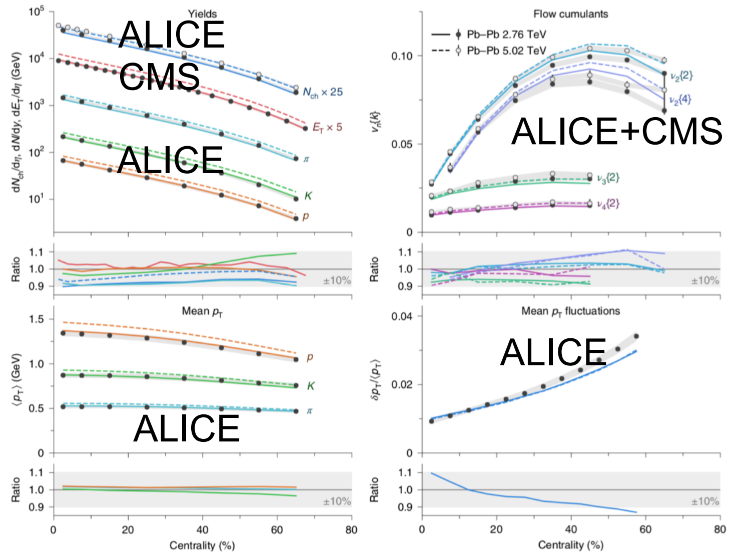
Energy density profile in the transverse plane:

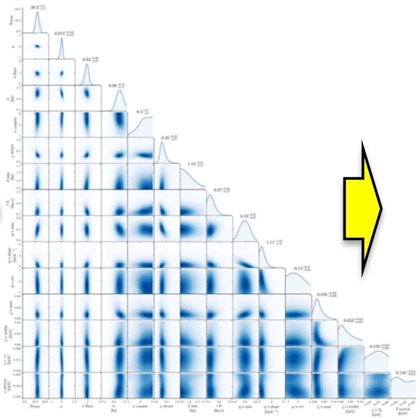


S Jeon et al, QM 2012, B. Schenke, et al. PRL106, 042301 (2011)

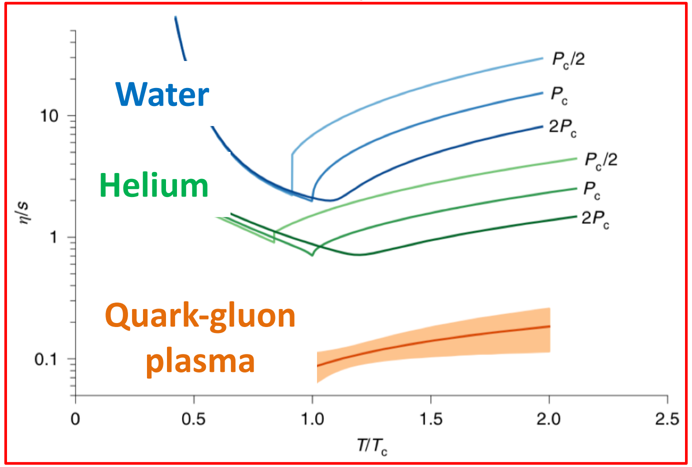
From LHC data to QGP fluid-dynamic properties

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





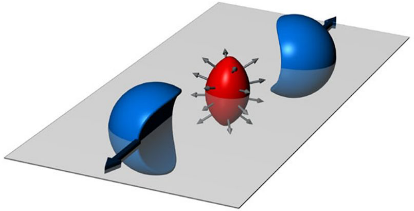
QGP shear viscosity vs. temperature



→ QGP viscosity with ~20% precision

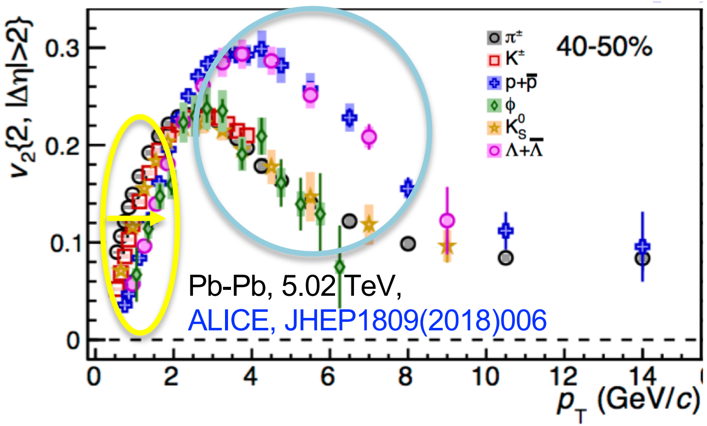
→ QGP x10 less viscous than any other form of matter

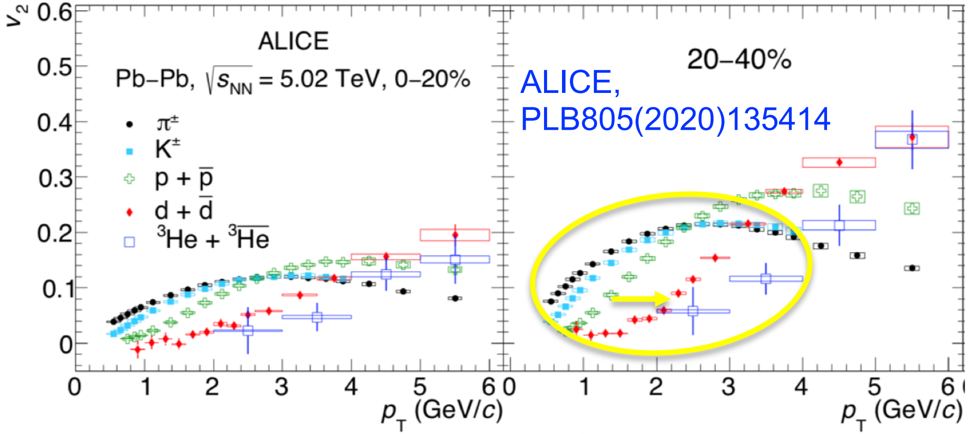
Elliptic flow by hadron species



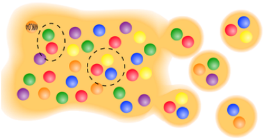
- Non-central collisions: flow maps the geometrical elliptical shape into an azimuthal modulation in momentum distributions

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

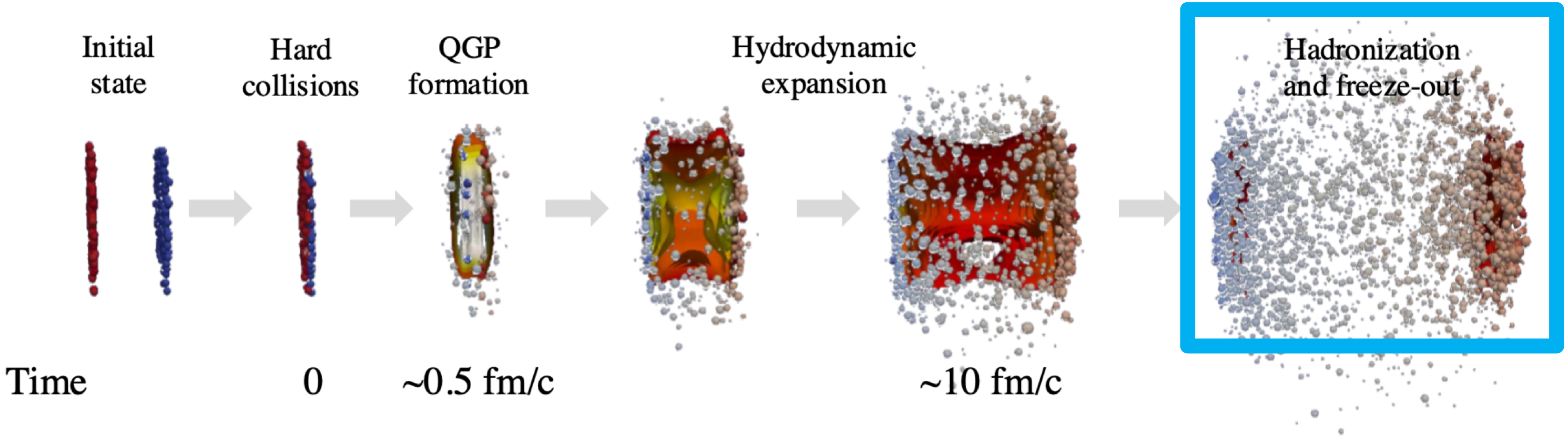




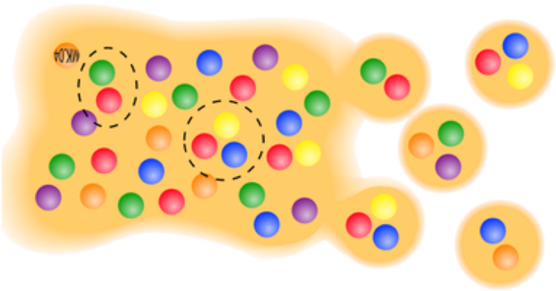
- Mass ordering at low p_T → **hydrodynamic flow, very small viscosity**
- Even A=2 and A=3 light nuclei pushed by the flow
- Baryon vs. meson grouping at higher p_T
  → **quark-level flow + recombination?**



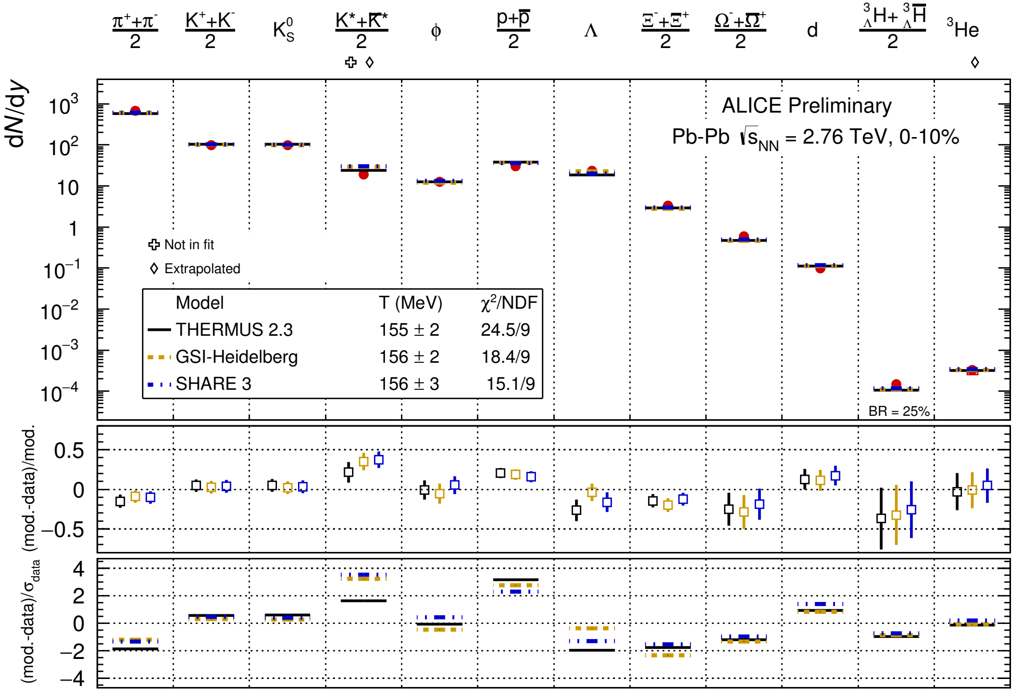
Hadronization of the QGP



Visualization by J.E. Bernhard, arXiv:1804.06469

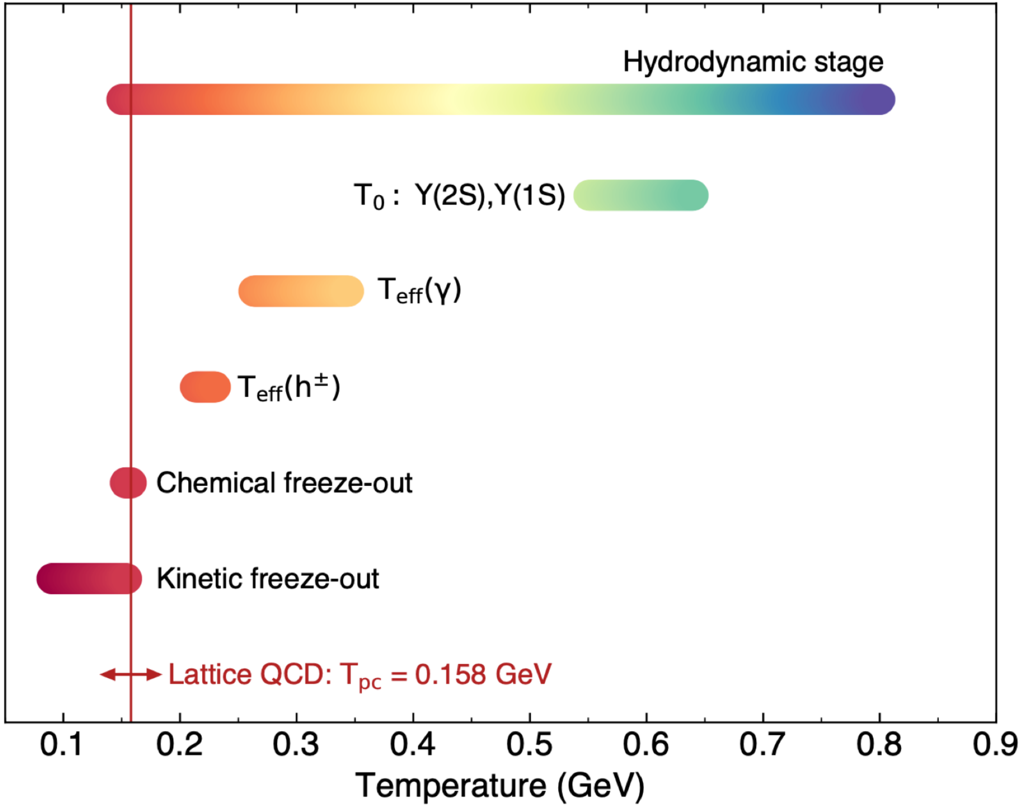


Statistical mechanics with quarks



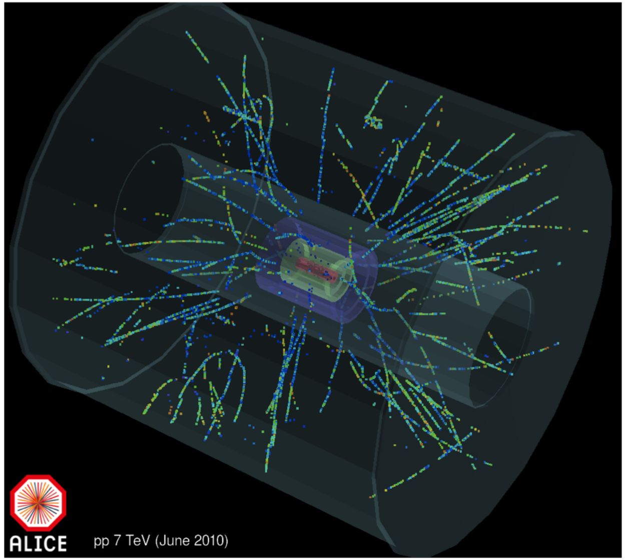
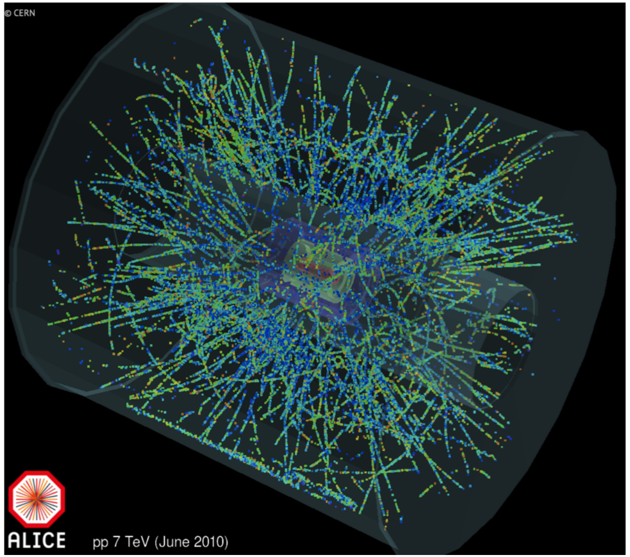
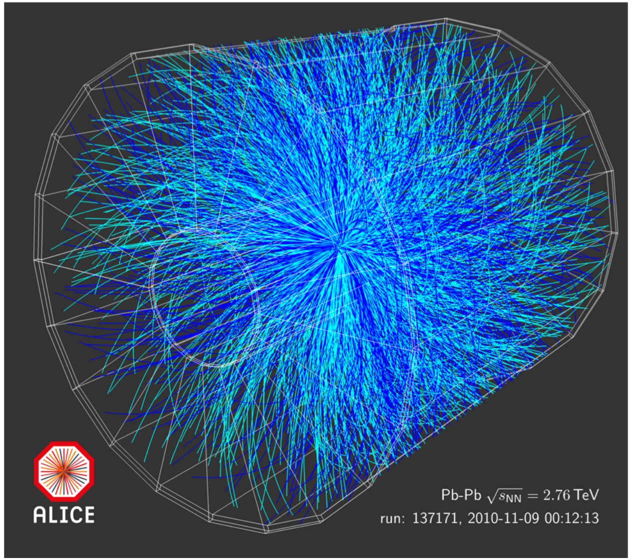
- Statistical Hadronization Model: thermally-equilibrated QGP → chemically-equilibrated hadron gas
  - Hadron yields only depend on hadron mass and a single temperature
- Hadron yields from π to ^{3}He described over **7 orders of magnitude** within 20% (except for K^{*0}) with a chemical freeze-out temperature of **T_{ch} ≈ 156 MeV**
  - Very close to lattice QCD phase transition temperature
- Hadrons produced in chemical equilibrium

Quark-gluon plasma thermometer



Courtesy A. Timmins (Houston/ALICE)

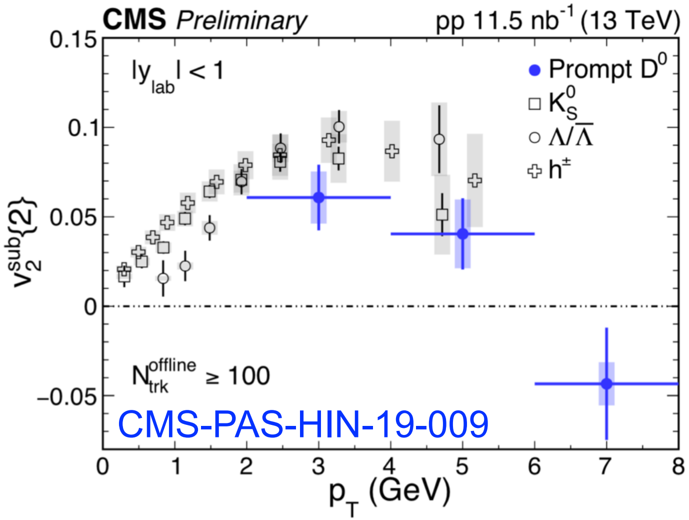
A big surprise at the LHC: ‘heavy-ion physics’ in pp collisions?

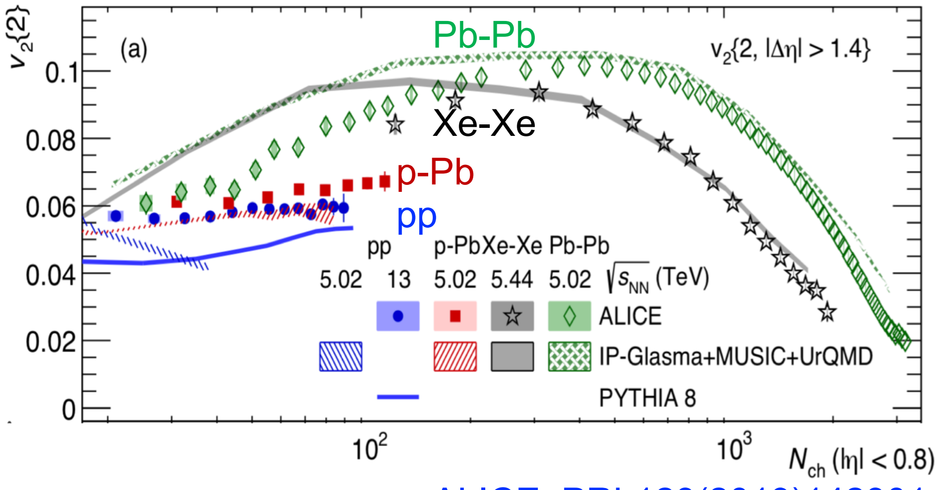
“Typical” pp collision	High-multiplicity pp collision	Pb-Pb collision
		

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





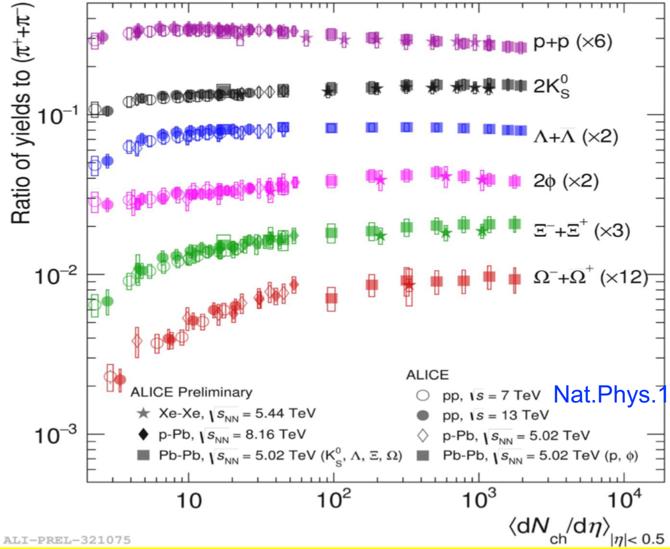
ALICE, PRL123(2019)142301

Mass ordering of elliptic flow

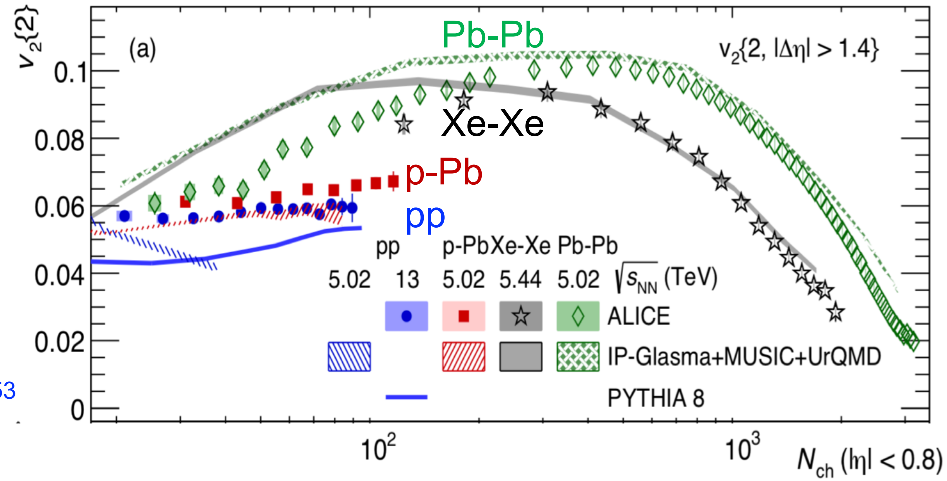
Similar flow in pp, p-Pb, Xe-Xe, Pb-Pb at the same multiplicity

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

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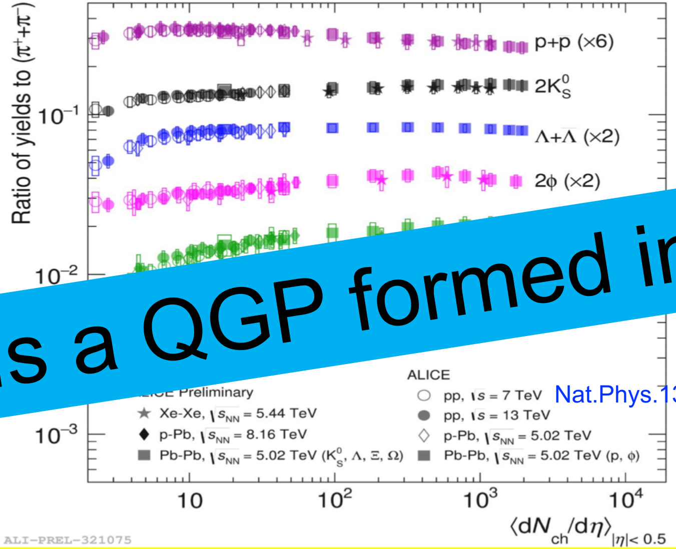
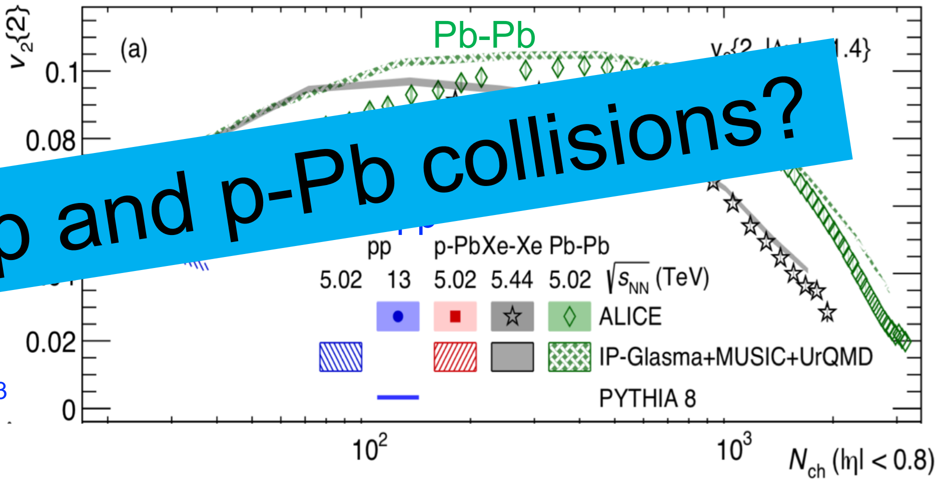


Nat.Phys.13(2017)353



ALICE, PRL123(2019)142301

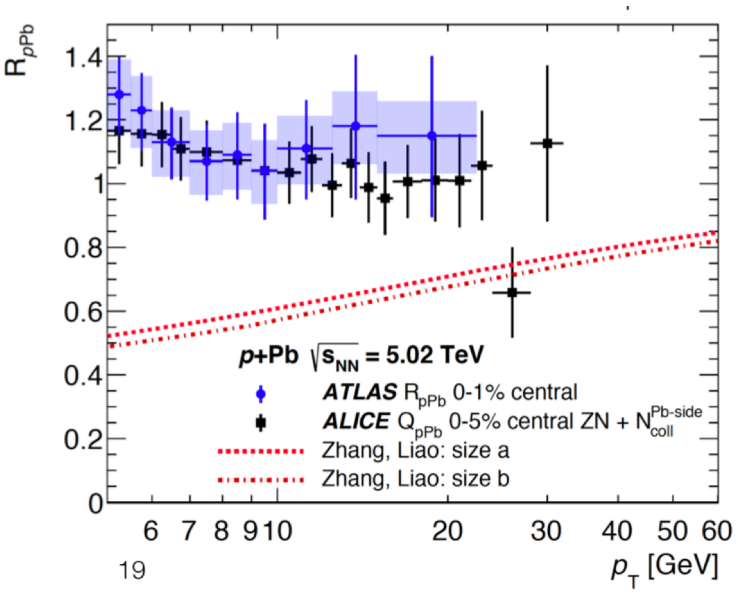
Is a QGP formed in pp and p-Pb collisions?

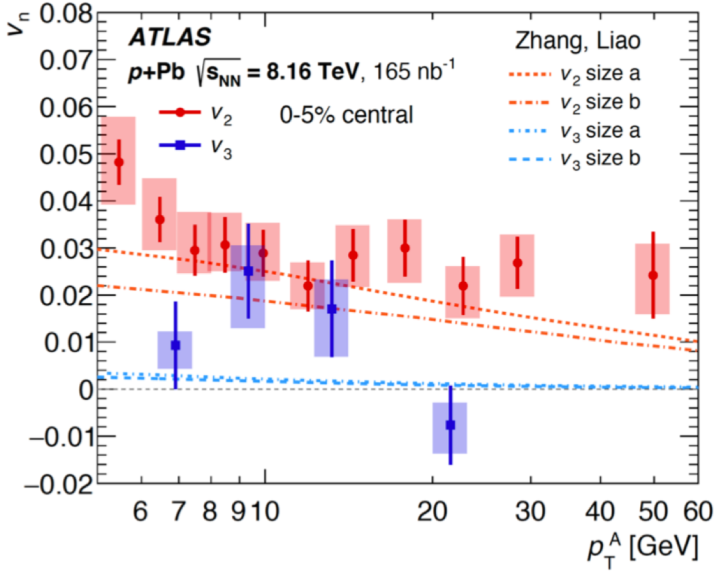
Continuous increase of strangeness yields with multiplicity in pp, p-Pb, Xe-Xe, Pb-Pb

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?

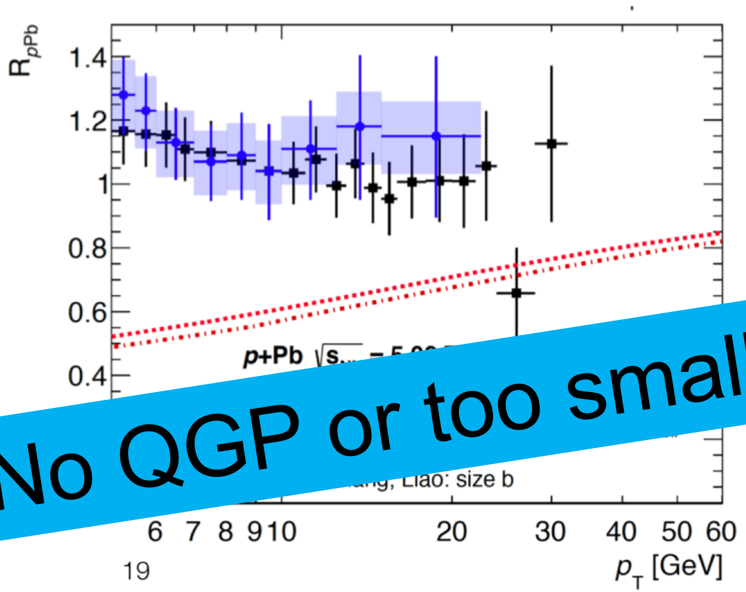
[Eur. Phys. J. C 80 (2020) 73]



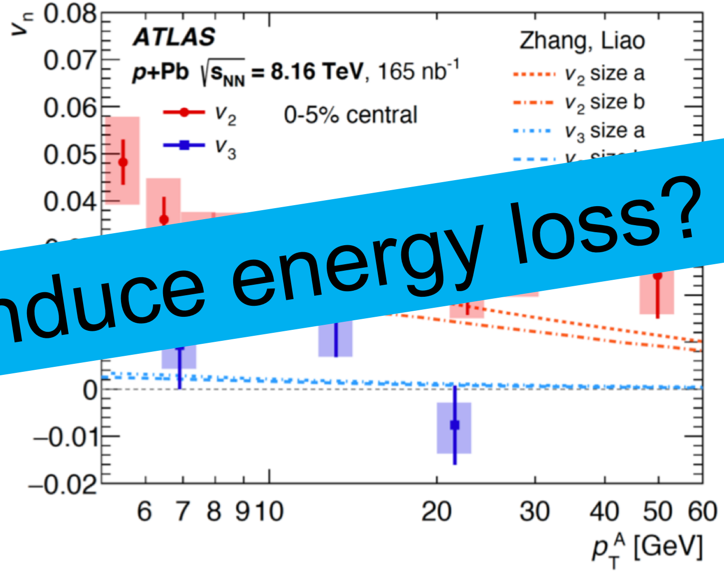


- p-Pb nuclear modification factor ~1 → no suppression of yields
- But persistence of azimuthal asymmetry (v_2) to high p_T suggestive of final state interactions

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



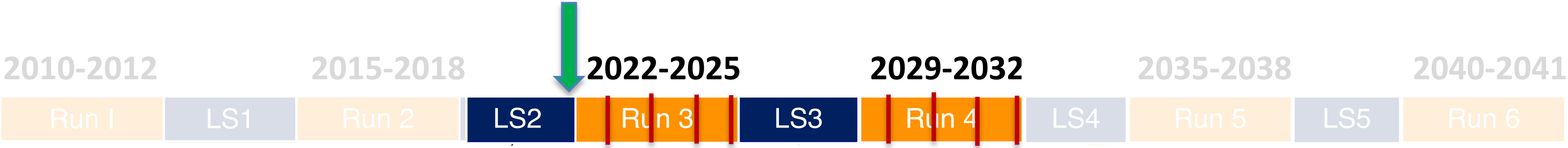
Eur. Phys. J. C 80 (2020) 73



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

Future LHC heavy-ion programme: Runs 3 and 4



- **Main priority: large Pb-Pb sample, 13 nb^{-1}**
  - **x10** L_{int} for "rare" triggers wrt Run 2
  - **x100** MB sample for upgraded ALICE
- Extension of "**small system**" **programme**
  - **Extended p-Pb** run: nPDFs, collectivity, hot system signals?
  - **pp 13.6 TeV** low pile-up with focus on **high multiplicity**
  - Short ^{16}**O**-^{16}**O** (and p-O) run in Run 3:
    - Jet quenching in "small" nucleus-nucleus system?

[Future opportunities for high-density QCD at LHC, arXiv:1812.06772]

2010-2012		2015-2018		2022-2025		2029-2032		2035-2038		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

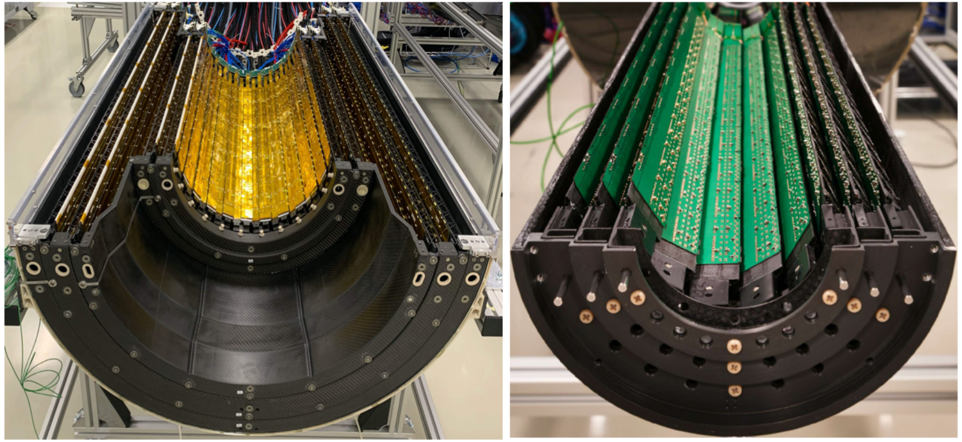
Experiment upgrades for Runs 3 and 4

ALICE upgrade for Run 3:

- x3 better tracking precision
- Continuous readout at 50 kHz

→ x100 Pb-Pb sample in Runs 3+4

ALICE monolithic pixels tracker: strong INFN contribution



ATLAS and **CMS** upgrades for Run 4:

- Extension of tracker acceptance
- Endcap calorimeters
- Precise timing detectors → t.o.f. PID

LHCb upgrade for Run 3:

- Tracker and readout upgrade should give access to Pb-Pb (non-central collisions)

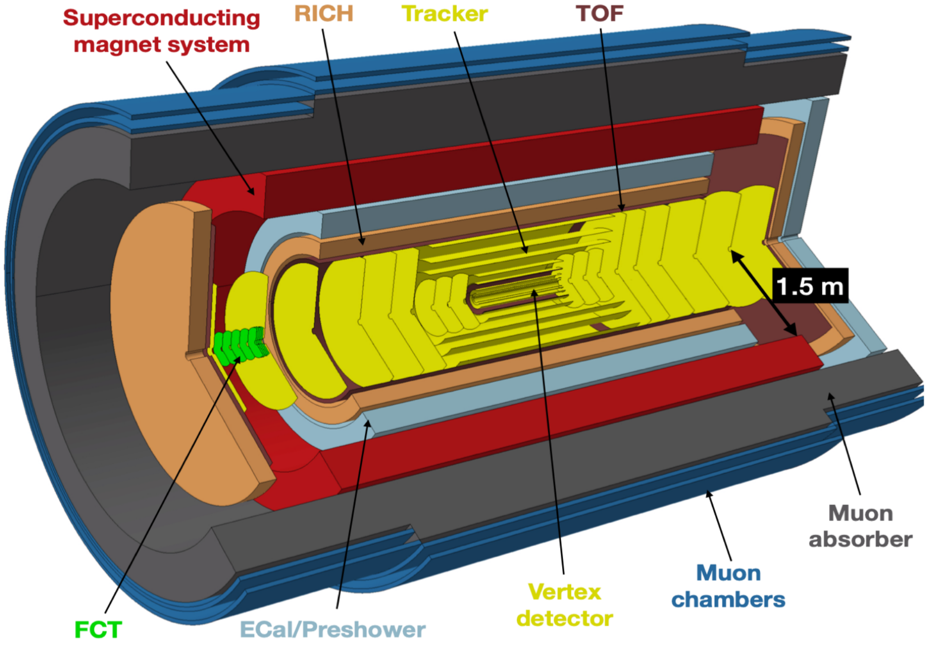
Further upgrade for Run 5 → Pb-Pb central collisions

2010-2012		2015-2018		2022-2025		2029-2032		2035-2038		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

ALICE 3: next-generation experiment

→ Tracking precision x3: 10 μm at p_T = 0.2 GeV/c
→ Acceptance x4.5: -4 < η < 4 (with particle ID)
→ A-A rate x5 (pp x25)

- Compact all-silicon tracker with high-resolution vertex detector
- Particle identification over large p_T and η acceptance
- Superconducting magnet systems
- Fast readout and GPU-based online processing



Letter of Intent being finalised

Conclusions

- First decade of LHC heavy-ion campaigns

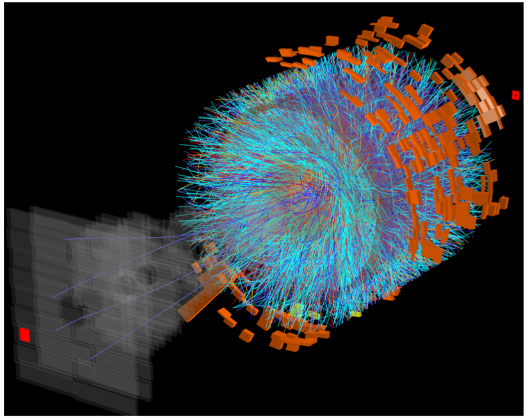
  → Detailed insight on the quark-gluon plasma properties:

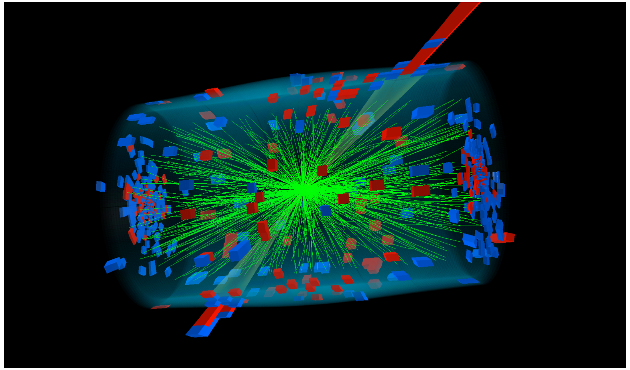
  - ✓ *Energy density > 10 GeV/fm^3*
  - ✓ *Colour charge deconfined*
  - ✓ *Strong energy loss for hard partons*
  - ✓ *Expands hydro-dynamically like a very-low viscosity liquid*
  - ✓ *Hadronizes as in thermal equilibrium*

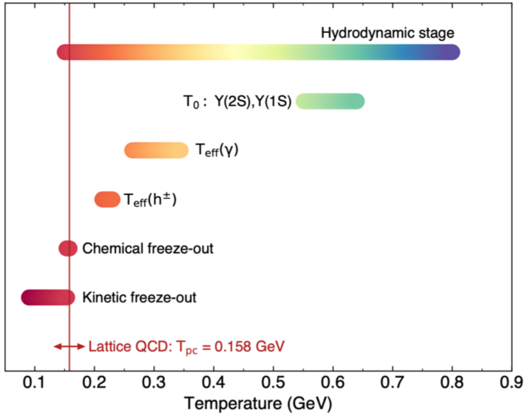
Conclusions

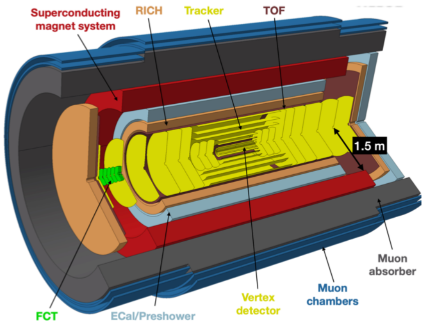
- First decade of LHC heavy-ion campaigns
  → Detailed insight on the quark-gluon plasma properties:
  - ✓ *Energy density > 10 GeV/fm^3*
  - ✓ *Colour charge deconfined*
  - ✓ *Strong energy loss for hard partons*
  - ✓ *Expands hydro-dynamically like a very-low viscosity liquid*
  - ✓ *Hadronizes as in thermal equilibrium*
- New research direction on emergence of collective effects from pp to heavy-ion
- Heading towards precision measurements in Runs 3-4
- Strong opportunities from extension to Runs 5-6 with frontier detector technologies

Grazie per l'attenzione!



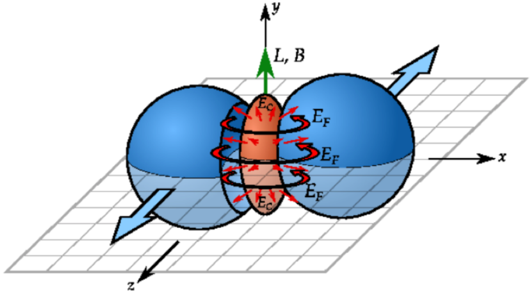






EXTRA SLIDES

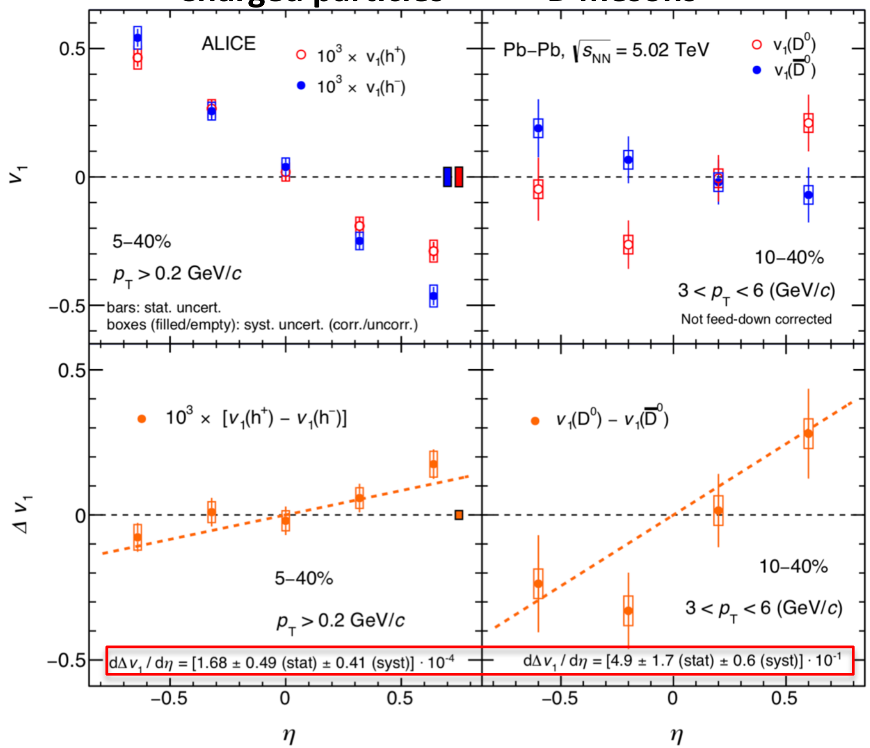
Probing the highest magnetic field with c quarks



- Magnetic field → charge-dependent particle emission anisotropies with respect to the collision plane
- Early-produced heavy quarks more sensitive
- **Effect for D mesons about three orders of magnitude larger than that of charged hadrons**

→ Significance ~2.5σ

→ High-precision studies in Runs 3-4

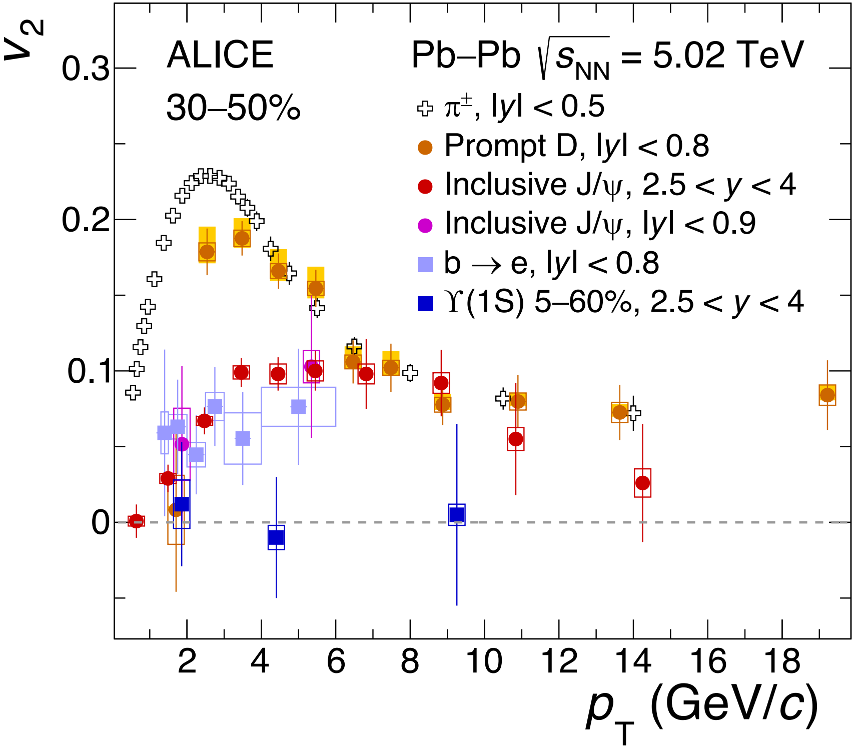


ALICE, PRL (2020) 125 022301

Going heavy: charm and beauty flow

- **D mesons and J/ψ exhibit large flow**
  - At intermediate p_T, **J/ψ < D < pions** → consistent with contribution of recombination
- Model description indicates c quark thermalisation time ~3-8 fm/*c* < QGP lifetime

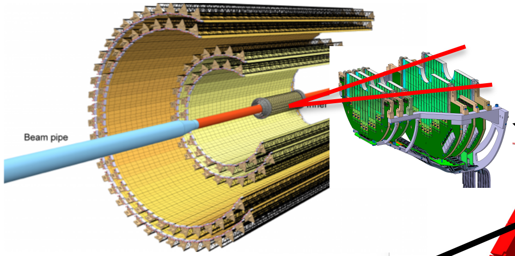
- **B mesons also flow**
  - Model description indicates smaller flow for b than for c
- **No indication of Υ(1S) flow**
  - Consistent with large Υ mass and small $b\bar{b}$ recombination



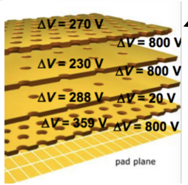
π: JHEP1809(2018)006
D: arXiv:2005.11131
J/ψ: JHEP10 (2020)141
b→e: arXiv:2005.11130
Y(1S): PRL123(2019)192301

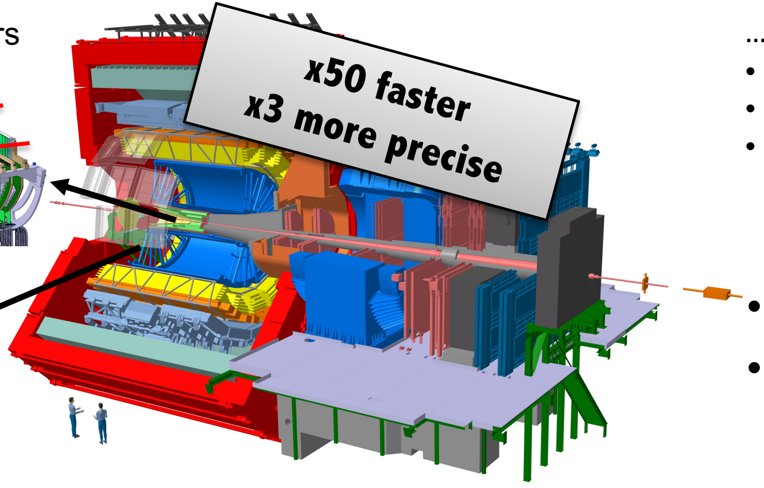
ALICE LS2 Upgrade and LS3 ideas

All-pixel central and fwd trackers



GEM-based TPC readout





... and more:

- Fast Interaction Trigger
- New Online-Offline system
- Readout upgrade of several detectors

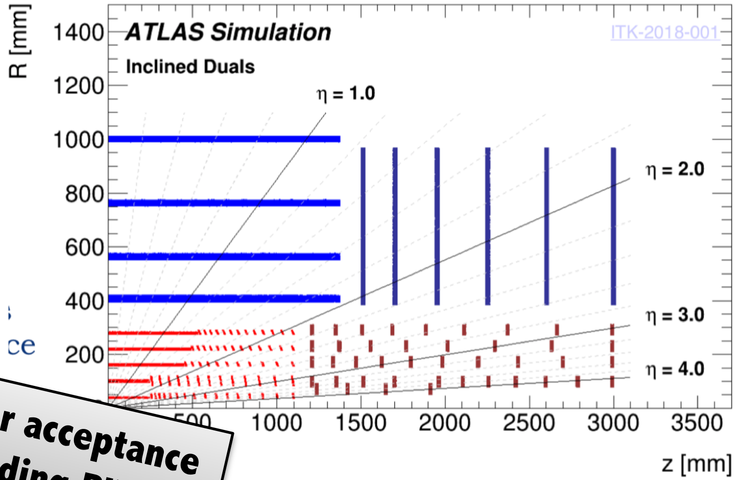
- x3 better tracking precision
- Continuous readout at 50 kHz

→ ~100B Pb-Pb in Runs 3+4

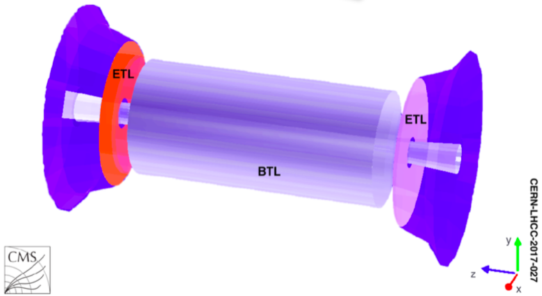
- Upgrade proposals for LS3 (2026):
  - Replace inner barrel with a truly-cylindrical ultralight one: x3 less material
  - FoCal with high-granularity readout for direct photons at $3.2 < \eta < 5.8$: probe gluon density down to $x \sim 5 \times 10^{-6}$
  - Exploring fixed-target programme with crystal collimated beam halo

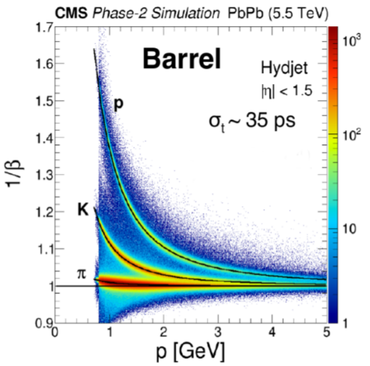
ATLAS and CMS LS3 Upgrades

- Run 3+4: goal 13 nb^{-1} Pb-Pb, focus on rare triggers
  - CMS, also large bandwidth for MB events: 6 kHz in Run 3, goal to increase for Run 4
- Major Phase-2 upgrades for HL-LHC
  - Extension of tracker acceptance from $|\eta|<2.5$ to $|\eta|<4$
  - Endcap calorimeters with higher granularity
  - Precise timing detectors for pile-up rejection → t.o.f. PID
    - ATLAS $2.5 < |\eta| < 5$
    - CMS $|\eta| < 4$



Larger acceptance
Adding PID

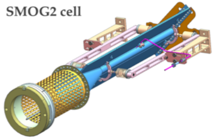


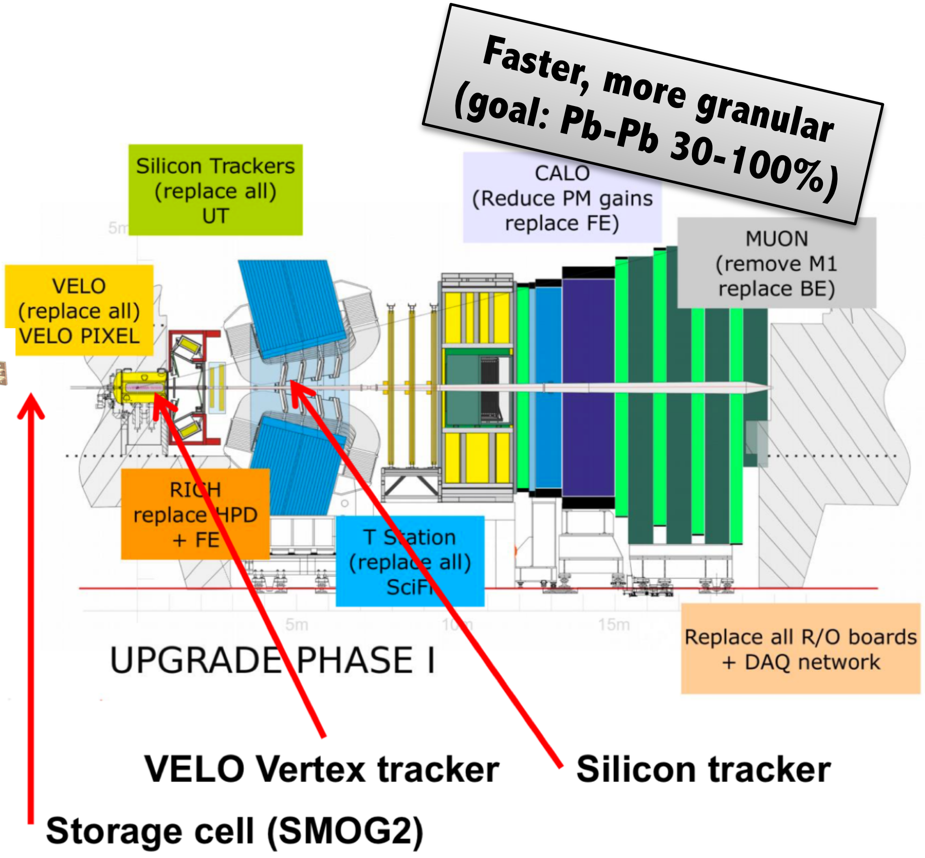


LHCb LS2 Upgrade

- Ongoing LS2 upgrade:
  - Tracker with higher granularity → **Pb-Pb 30-100%**
  - New **storage cell for fixed-target collisions** at up to x100 higher rates (p … Ne … Xe)

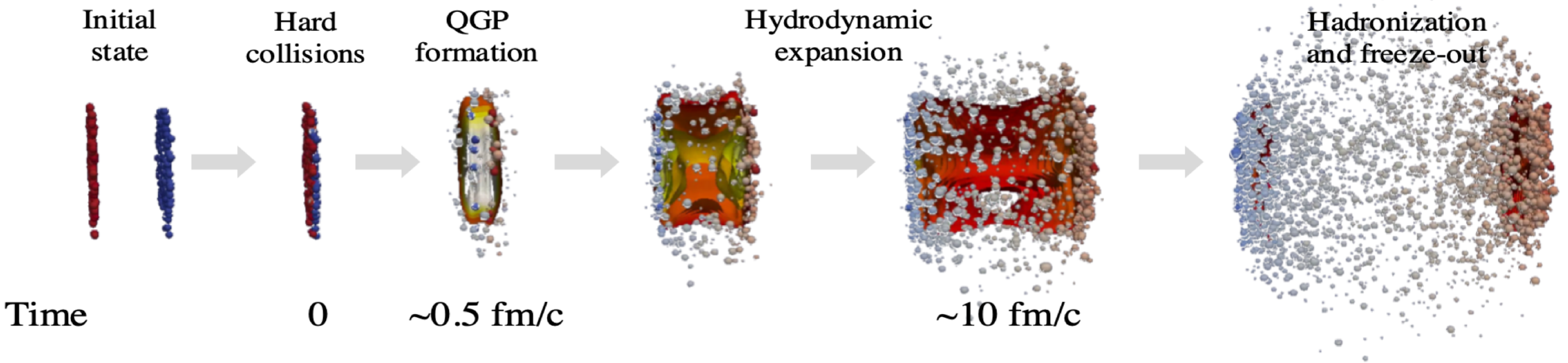
- Proposal for phase-2 upgrade for Run 5 (2031)
  - Increased readout rate and granularity → **central Pb-Pb**
  - Extended PID performance





QGP study with heavy-ion collisions

High-energy nucleus-nucleus → large ε & T ($>> \varepsilon_c$, T_c) over **large volume** (~ 10 fm^3)



Visualization by J.E. Bernhard, arXiv:1804.06469

The QGP as seen at the LHC:

- ✓ Energy density > 10 GeV/fm^3
- ✓ Colour charge deconfined
- ✓ Strong energy loss for hard partons
- ✓ Expands hydro-dynamically like a very-low viscosity liquid
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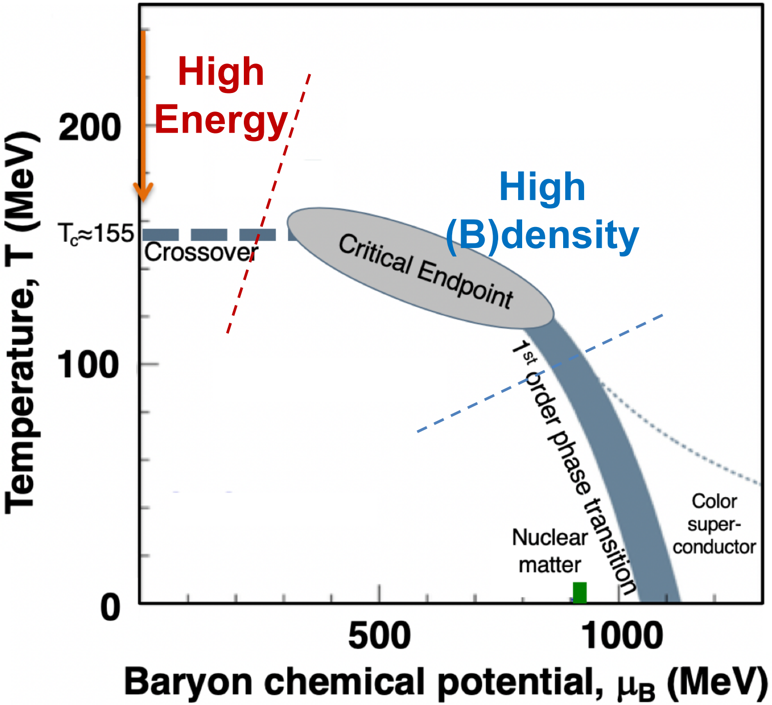
Future research directions in QGP physics

High (B)density collisions (SPS, RHIC-BES, NICA, FAIR, J-PARC):

- Search for the Critical Endpoint
- Observation of 1st order phase transition in QCD

High energy collisions (LHC, RHIC):

- Properties of QGP and their time-evolution
- Strong interaction in a deconfined system
- Observation of chiral symmetry restoration
- Emergence of QGP from QCD interactions



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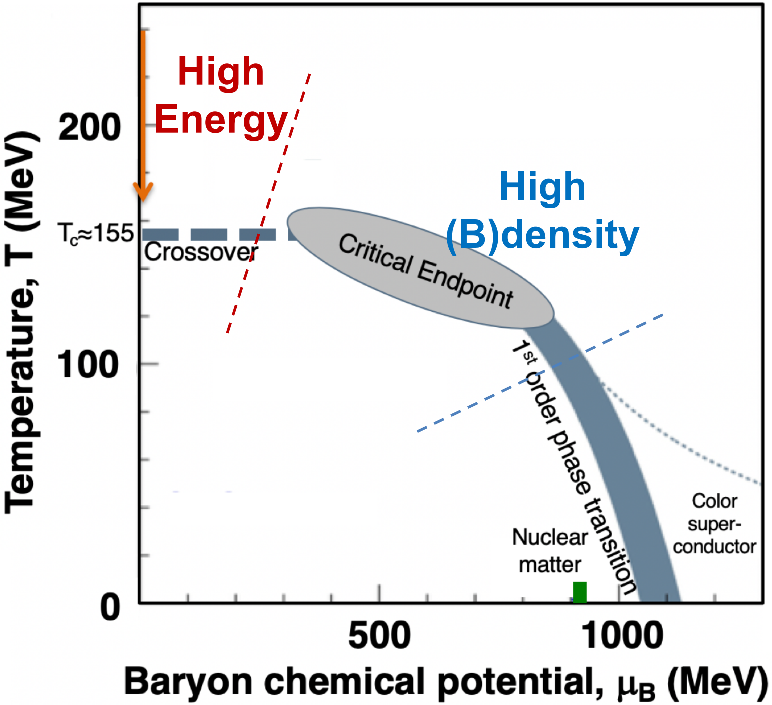
LHC ideally-suited to address these goals:

- ✓ $\mu_B=0 \rightarrow$ lattice QCD vs experiment
- ✓ Largest initial T and time evolution
- ✓ Large cross section for hard probes of the QGP



CERN Yellow Report on High-density QCD, arXiv:1812.06772, then endorsed by ESPPU2020