Quark-Gluon Plasma: experimental overview -- selected topics --

A. Rossi, INFN Padova

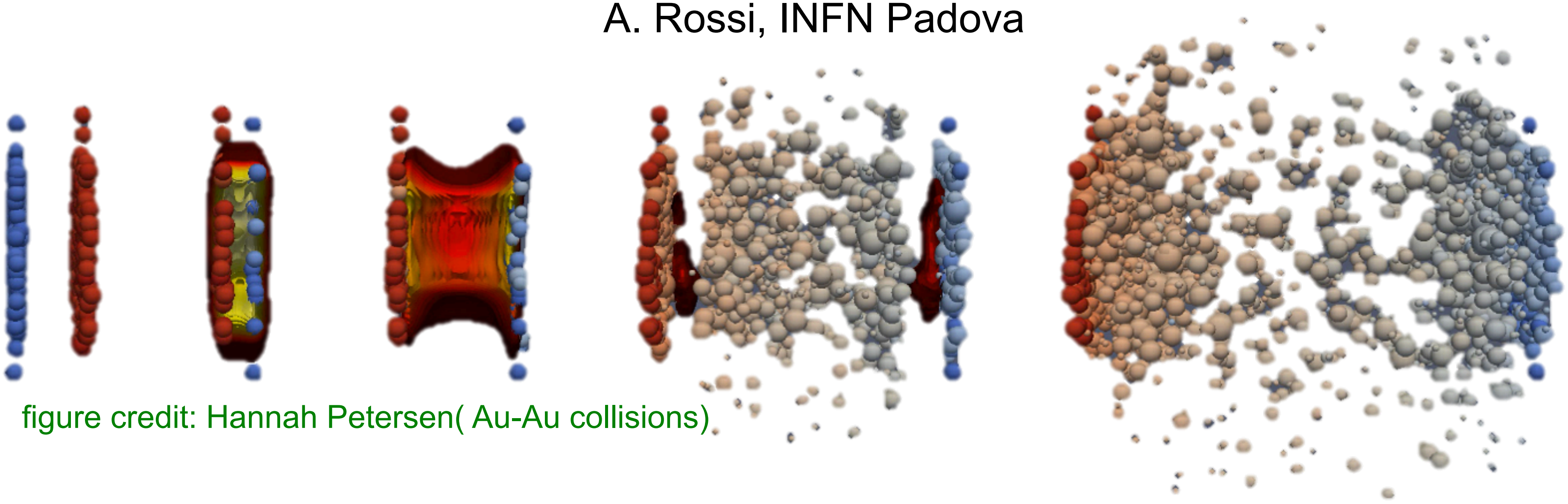


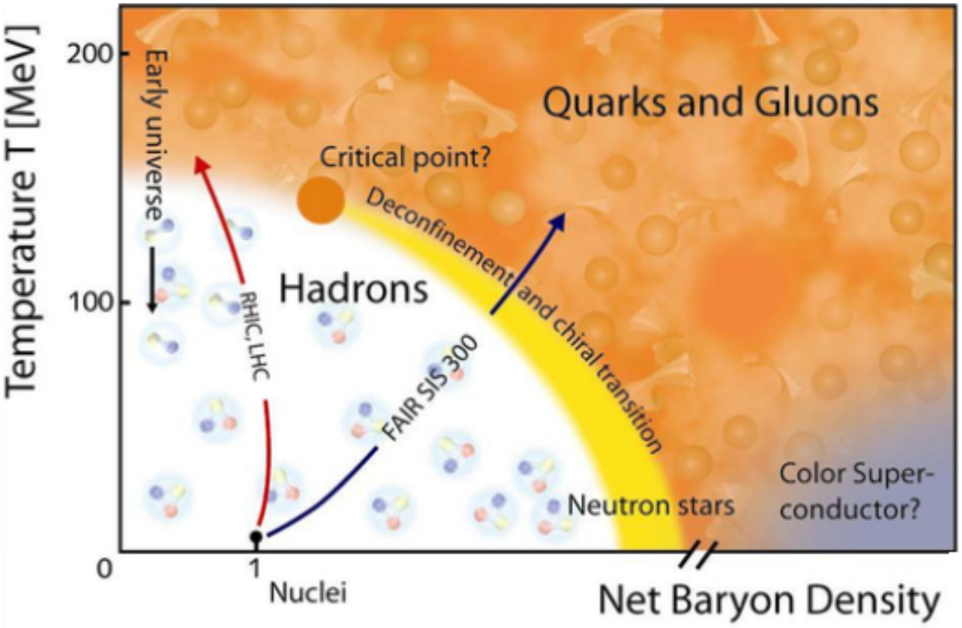
figure credit: Hannah Petersen(Au-Au collisions)

Hadron Physics and Non Perturbative QCD 2017 - Pollenzo (CN)

22-24 May 2017

A. Beraudo this morning

Phase diagram of strongly-interacting (QCD) matter



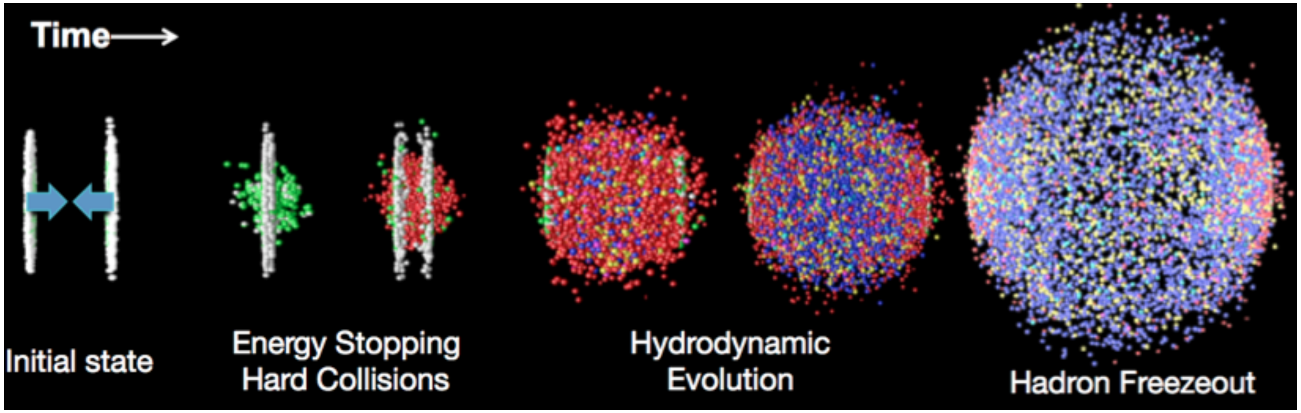
At high energy density ε (high temperature and/or high density) hadronic matter undergoes a phase transition to the *Quark-Gluon Plasma (QGP): a state in which colour confinement is removed*

Phase transition: confined state → deconfined state

Lattice QCD calculations:
Critical temperature at 0 baryon density~ 155 MeV
Critical energy density ε_c ~ 1 GeV/fm^3 ~ 6-7 $\varepsilon_{nucleus}$

QGP in laboratory: nucleus-nucleus collisions

- Can we form the QGP in laboratory? Need to compress/heat matter to very high energy densities.



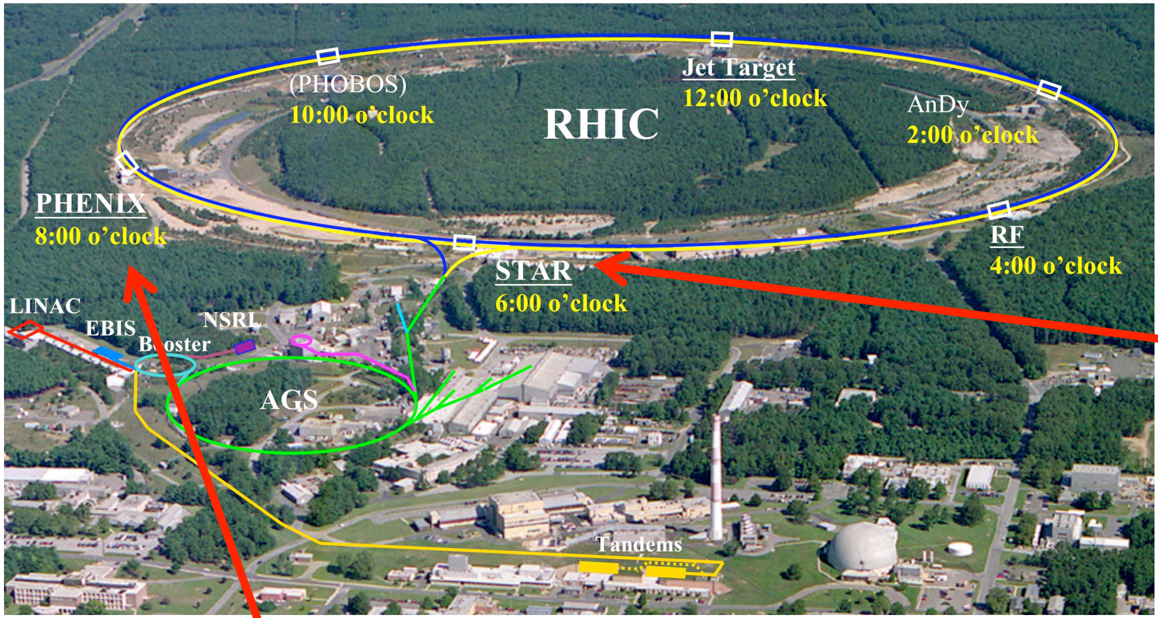
- By colliding two heavy nuclei at ultra-relativistic energies we recreate, for a short time span (about 10^{-23} s, or a few fm/c) the conditions for deconfinement
- As the system expands and cools down it undergoes a phase transition from QGP to hadron again, like at the beginning of the life of the Universe: we end up with confined matter again
- **Chemical freeze out**: time at which inelastic interactions cease →abundances of particle species (π,K,p,.. yields, not resonance) are fixed
- Kinetic freeze out: all interactions cease → free streaming of particles to detector

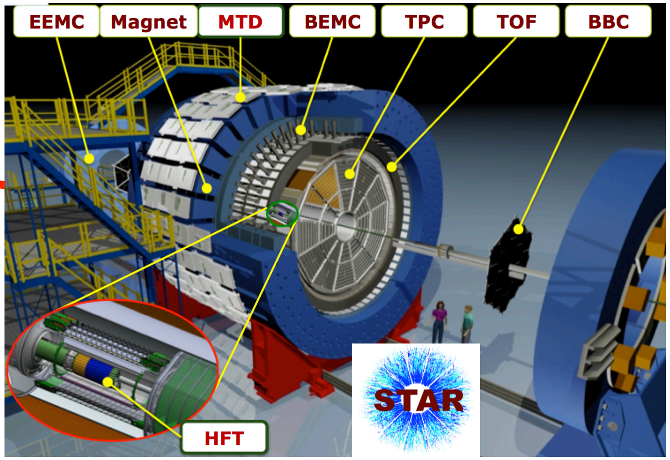
Ultra-relativistic heavy-ion accelerators

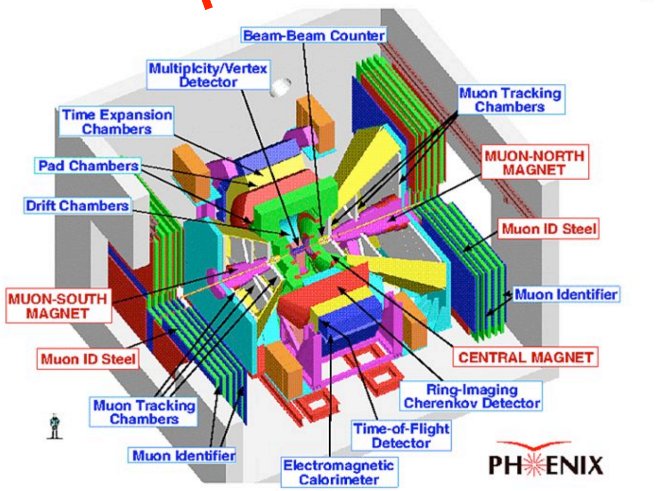
-- only main collision systems are indicated --

- **BNL-AGS**, early ’90s, Au-Au up to $\sqrt{s_{NN}} = 5\ \mathrm{GeV}$
- **CERN-SPS**, from 1994, Pb-Pb up to $\sqrt{s_{NN}} = 17\ \mathrm{GeV}$
- **BNL-RHIC**, from 2000, Au-Au $\sqrt{s_{NN}} = 8 - 200\ \mathrm{GeV}$
- **CERN-LHC**, from 2010, Pb-Pb $\sqrt{s_{NN}} = 2.76 - 5.5\ \mathrm{TeV}$

Heavy-ion experiments at RHIC

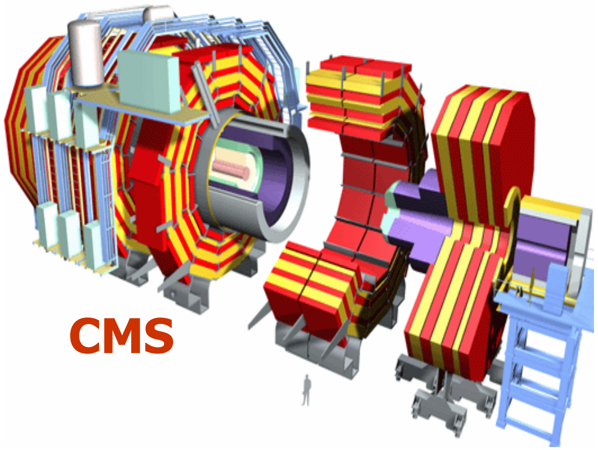


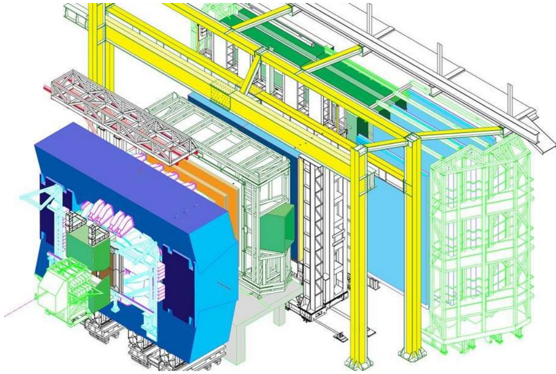


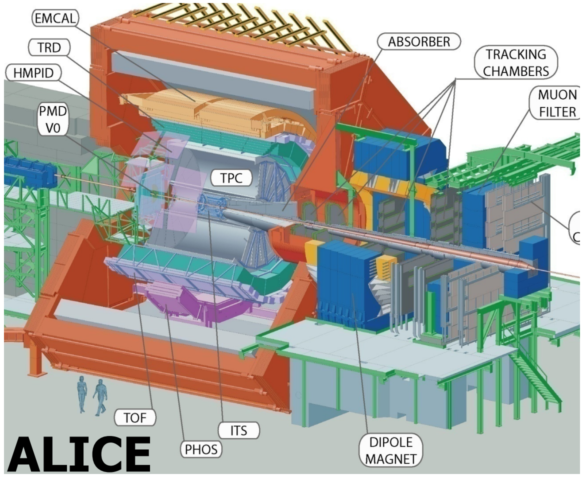


+ (completed) PHOBOS, BRAHMS

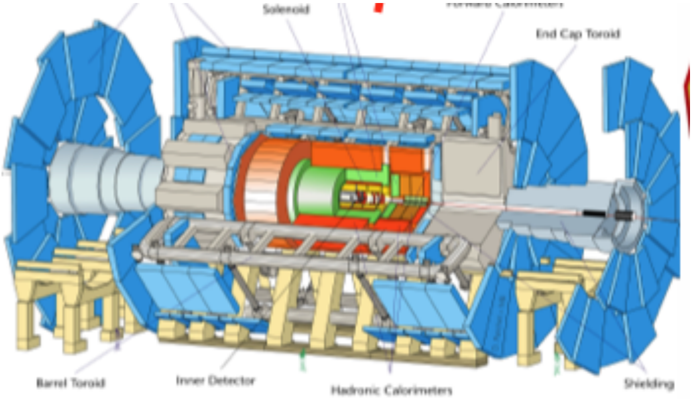
Heavy-ion experiments at the LHC


CMS


LHCb



ALICE



ATLAS

Few introductory concepts: centrality, R_{AA}

Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a "geometrical" factor (from Glauber model) to account for the larger number of nucleon-nucleon collisions

Pb-Pb

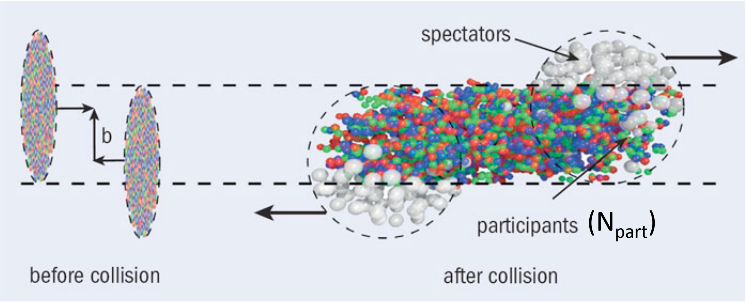
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

Binary nucleon-nucleon collisions, encodes collision geometry

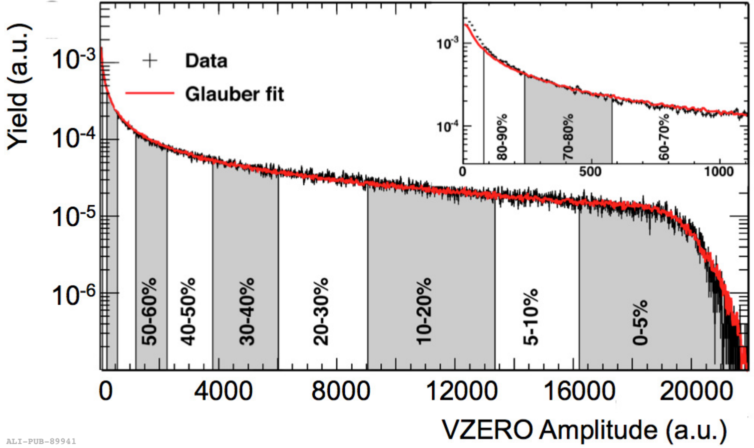
pp

If R_{AA}=1 → no nuclear effects

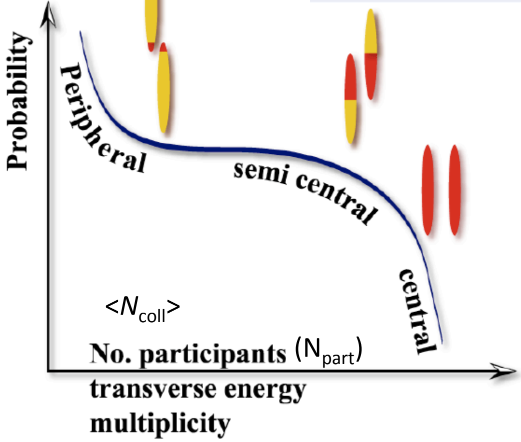
If R_{AA}≠1 → nuclear effects



$\langle N_{part} \rangle$,$\langle N_{coll} \rangle$ from Glauber model



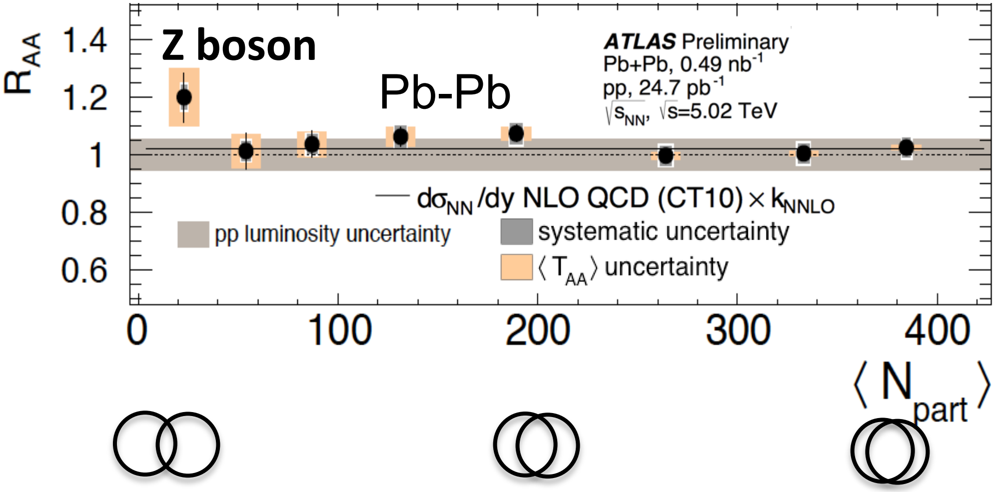
~ particle multiplicity/deposited energy



Geometry of heavy ion collisions

How can we be sure that we have the collision geometry under control? → Smaller/simpler collision systems (QGP not formed / not big impact on hard-probes production)

Probes not sensitive to medium formation
→ electroweak signals (γ,W, Z bosons)



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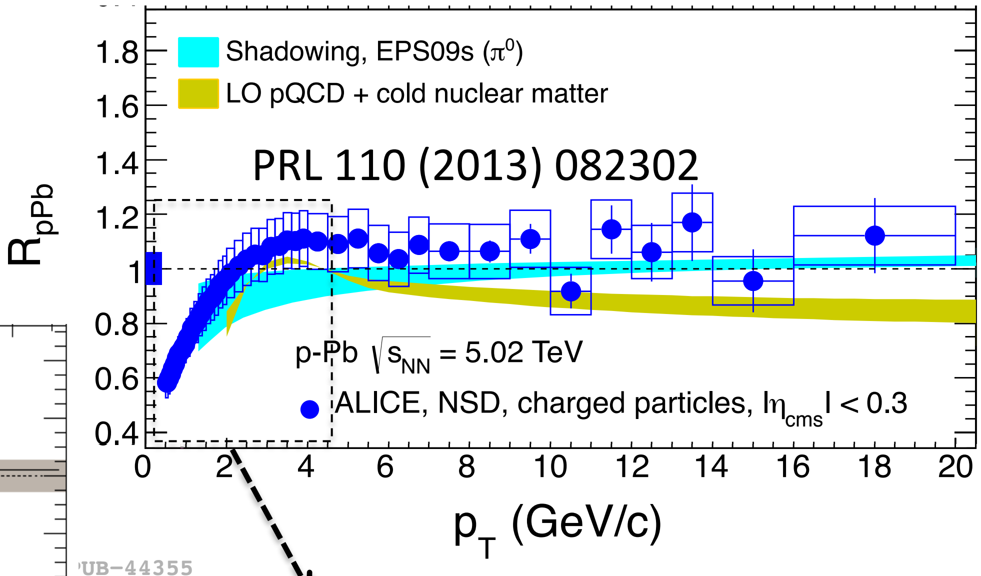


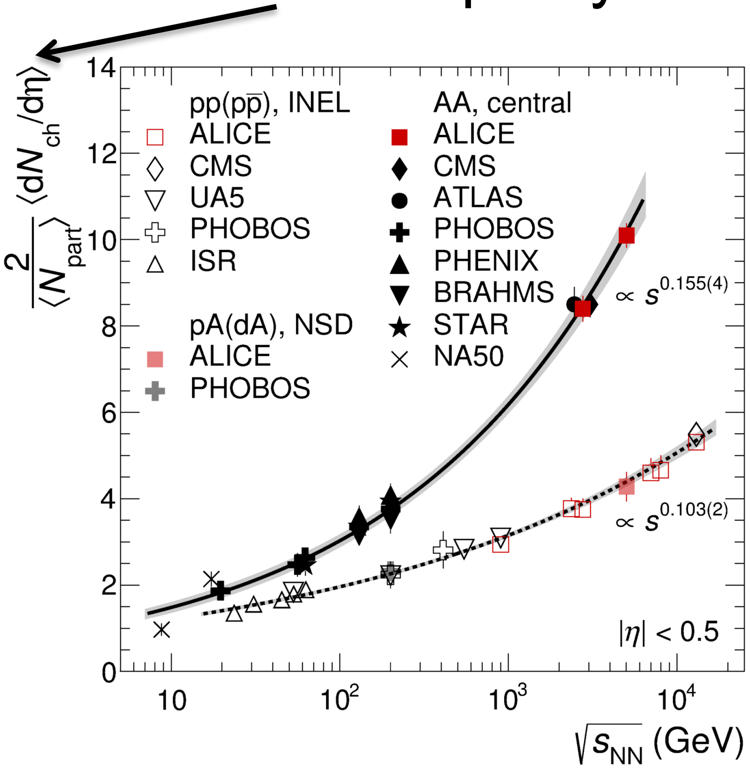
PRL 110 (2013) 082302

Caveats: initial state/ cold-nuclear matter effects at low p_T

Medium global properties

Energy density

- Particle multiplicity at mid-rapidity → transverse energy density



[Phys. Rev. Lett. 116 (2016) 222302]

Bjorken formula:

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

S = transverse dimension of nucleus

τ_0 = "formation time"~1 fm/c

	SPS	RHIC	LHC
$\left.\frac{dE_T}{dy}\right\|_{y=o}$ (GeV) *	400	800	2000
ε (GeV/fm^3) *	2.5	5	12

*Indicative numbers

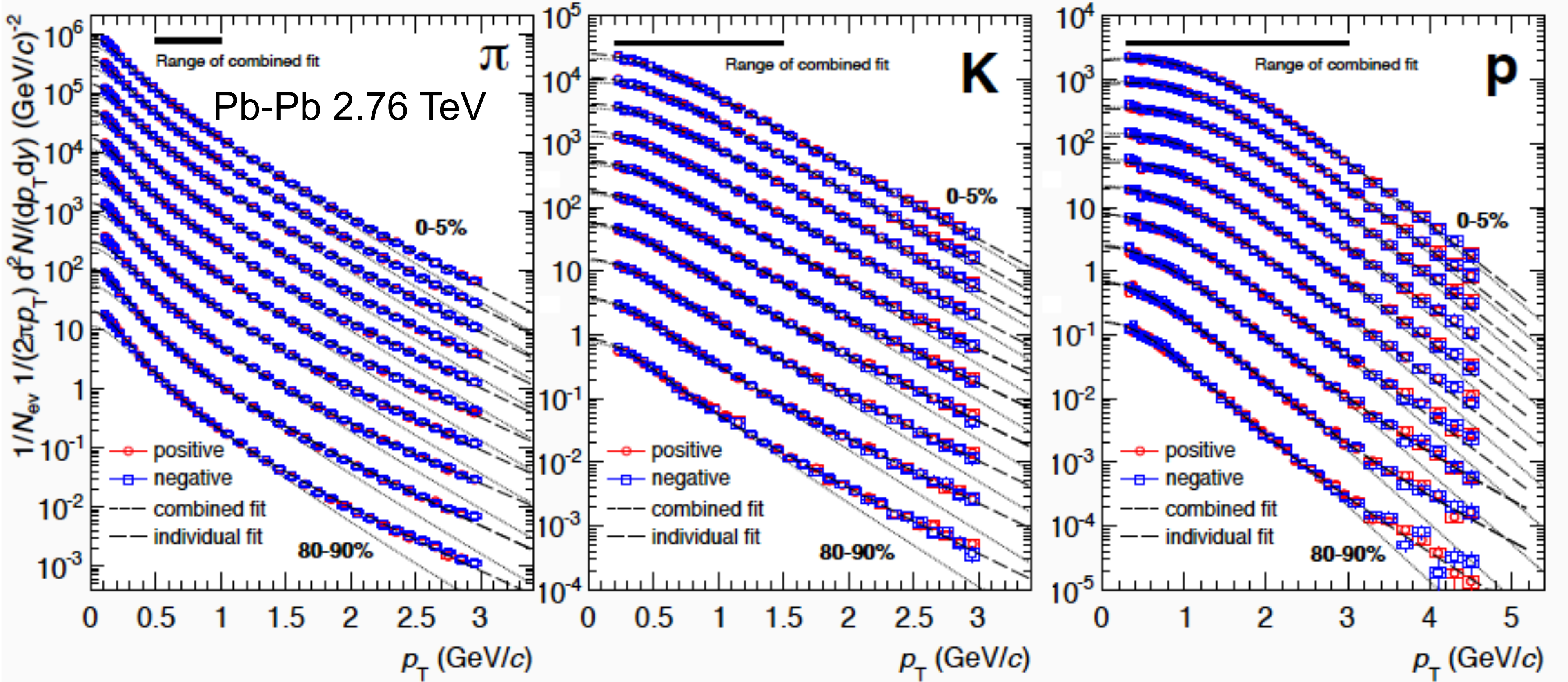
More than enough for deconfinement!

$\varepsilon_c \sim 0.6$ GeV/fm^3

see also R. Preghenella's talk

Kinetic freeze-out temperature

Phys. Rev. C 88, 044910 (2013)



Combined fit to several particle spectra → system properties at kinetic freeze-out

"Blast-wave" model: thermalized volume elements expanding in a common velocity field (→ convolution of thermal velocity with expansion velocity)

- Goodness of the global fit → hydro-dynamical description holds

see also R. Preghenella's talk

Kinetic freeze-out temperature

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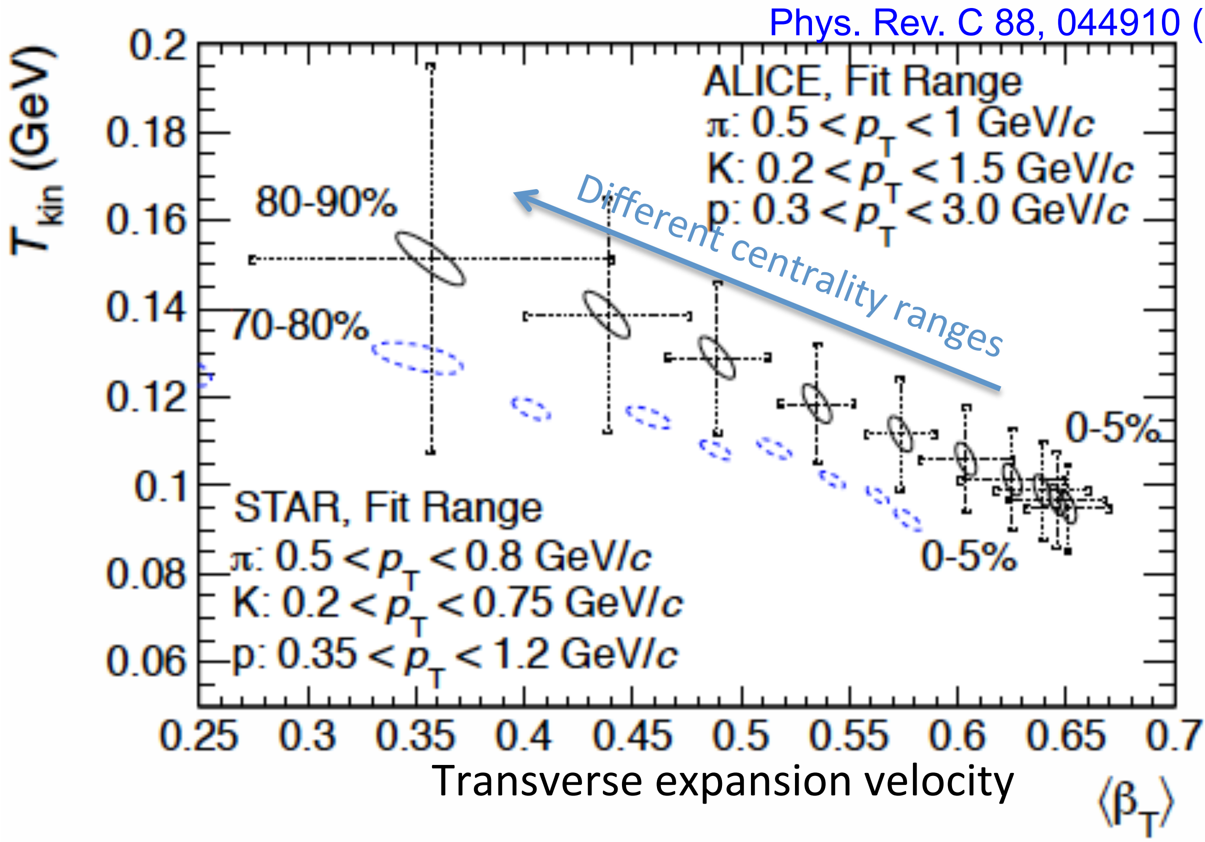


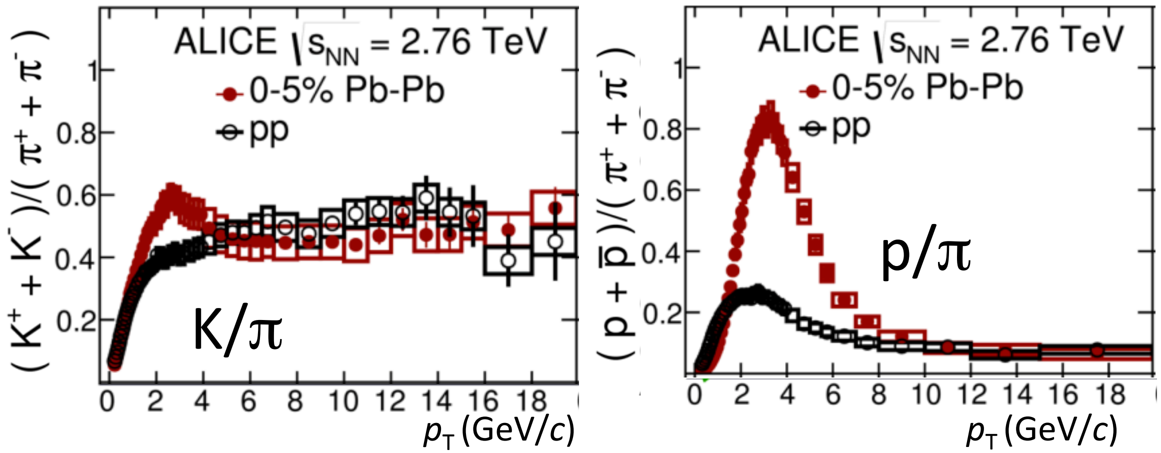
Combined fit to several particle spectra → system properties at kinetic freeze-out
"Blast-wave" model: thermalized volume elements expanding in a common velocity field (→ convolution of thermal velocity with expansion velocity)

- Goodness of the global fit → hydro-dynamical description holds
- In central collisions at LHC: T_{kin}**~ 90 MeV, transverse expansion velocity ~0.65 *c***

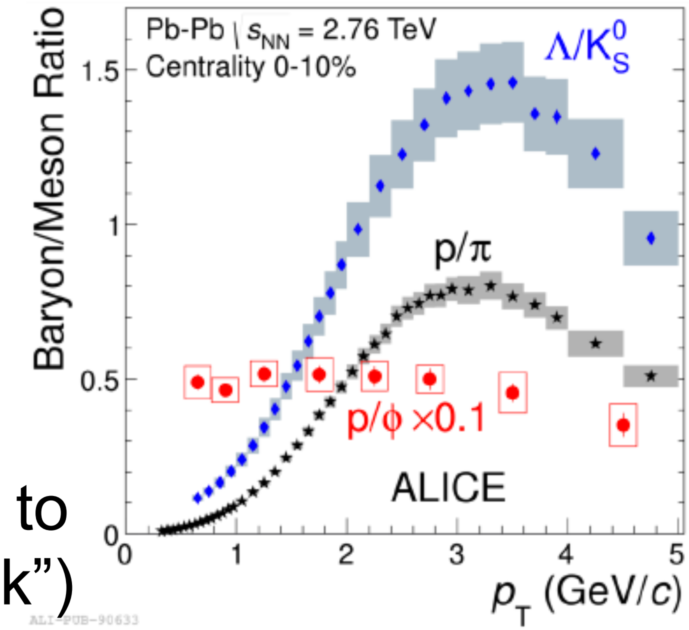
see also R. Preghenella's talk

Particle ratios

Phys. Rev. C 93, 034913 (2016)



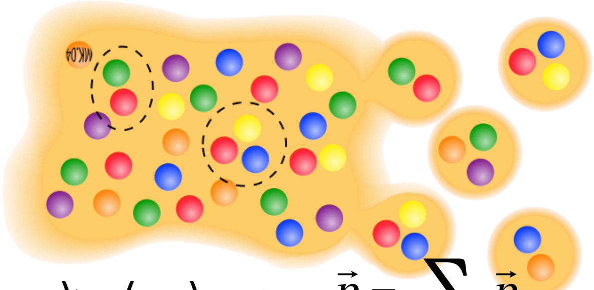
Phys. Rev. C 91 024609 (2015)



Strong modification of p/π vs. pt from pp to central Pb-Pb collisions ("radial flow peak")

Indication of collective behaviour

- Pressure gradients leads to radial flow
- Same "velocity" boost gives larger momentum to heavier particles
- Alternative/concurrent explanation: hadronisation via quark coalescence → higher momentum for baryons (3 quarks) than mesons (2 quarks): challenged by φ/p ratio

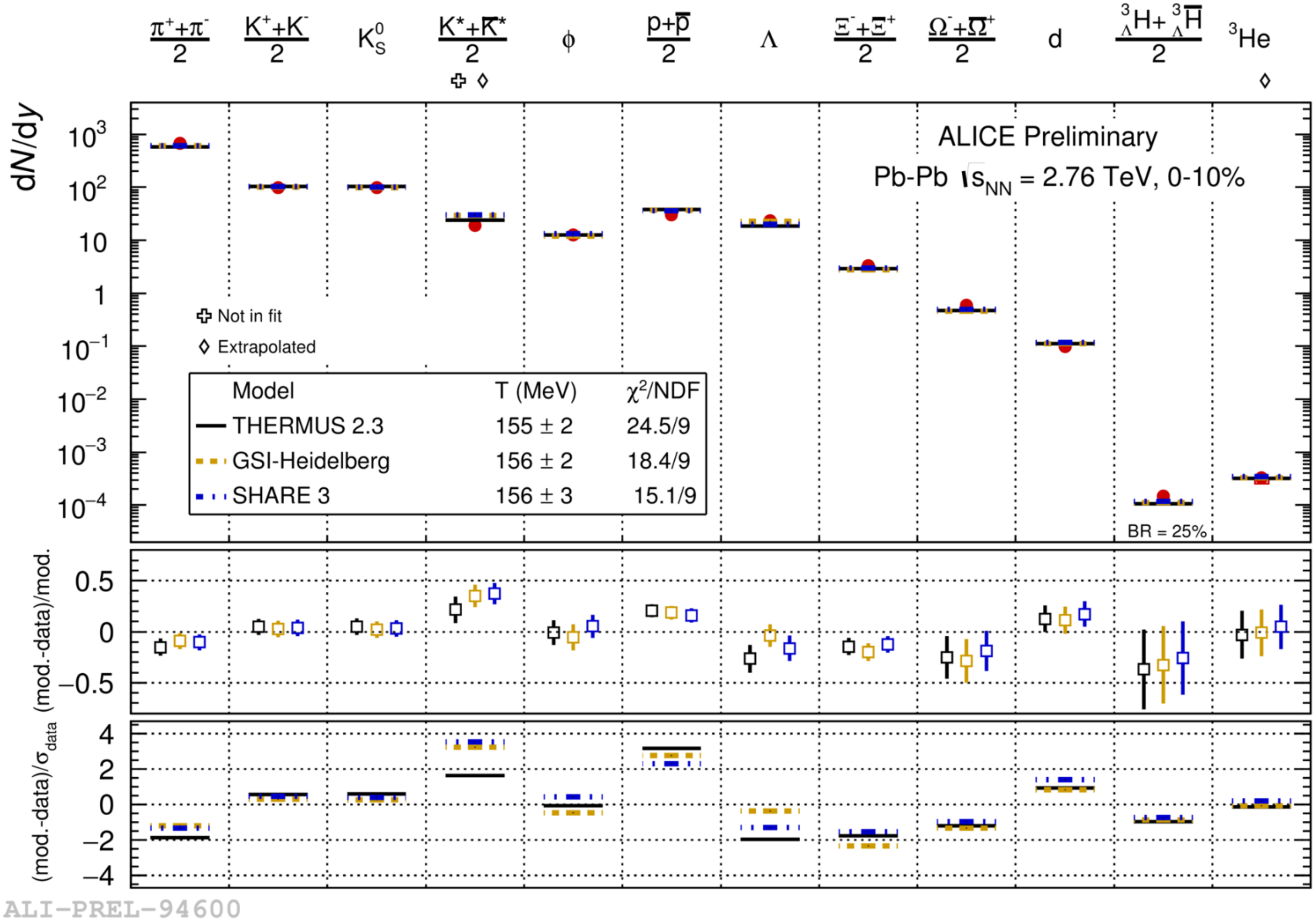


$p(qqq) > p(qq) \longleftarrow \vec{p} = \sum_{\text{quarks}} \vec{p}_i$

see also R. Preghenella's talk

Thermal model and chemical freeze-out temperature

Chemical freeze-out temperature estimated from **relative particle abundances**
Model assuming statistical hadronization: particle abundances determined by their mass and quantum numbers (spin) at by system properties (T_{ch},u_B,..)



Hadron yields described assuming chemical equilibrium and T_{ch}~156 MeV → close to lattice QCD

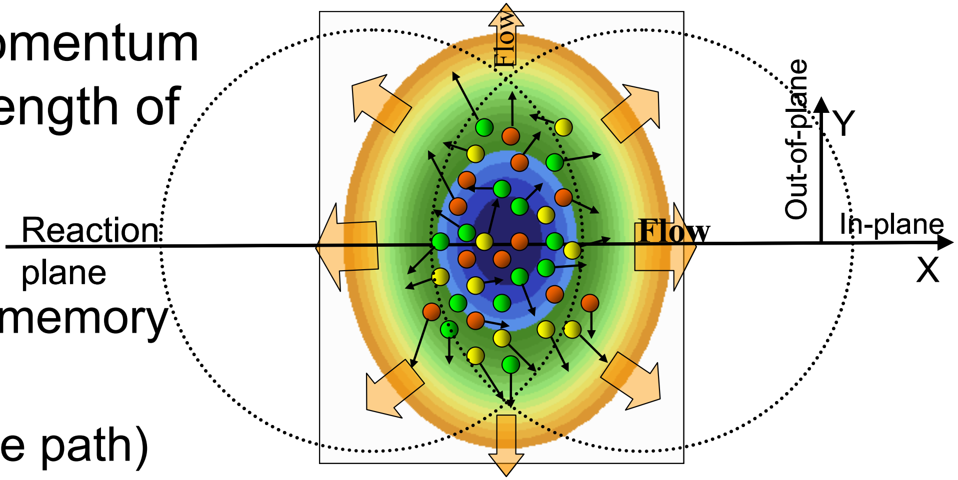
Some tension for protons and K*

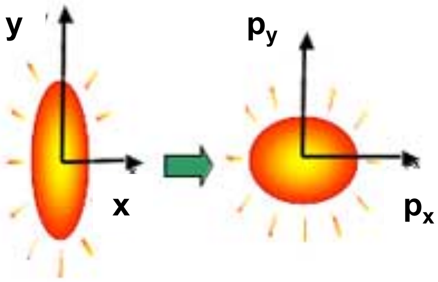
Anisotropic (Elliptic) flow

- 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 (← low viscosity)
  - larger density gradient → larger pressure gradient → larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)





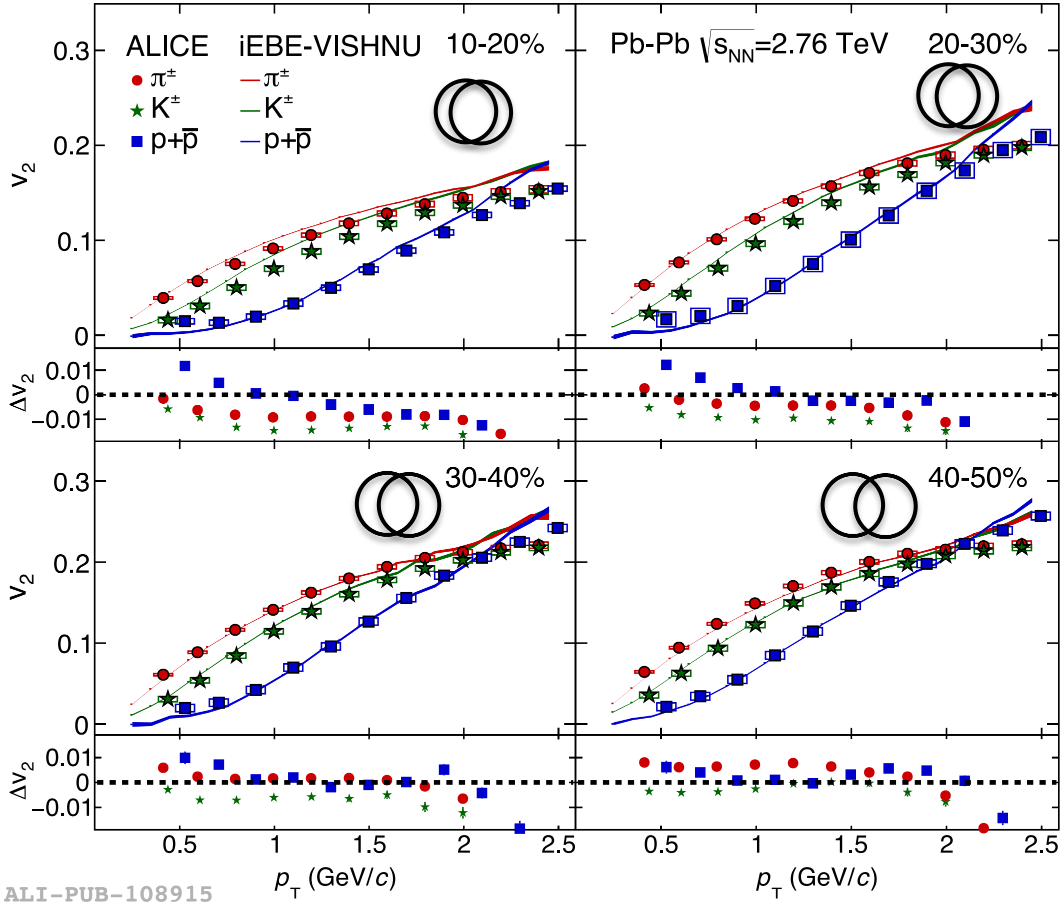
Effects addressed by measuring the azimuthal distribution of the particles

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

v_2= Elliptic flow

Anisotropic (Elliptic) flow

Points= data curves=model



Elliptic flow (v_2) significantly>0

- Evidence of system collective motion
- "Early signal": develops in partonic phase
- Well described by hydrodinimical models
- Expected trends vs. particle mass

→ **Thermalized partonic system**

→ (via more detailed comparisons with models) **Data suggest very low viscosity (← small mean free path)**

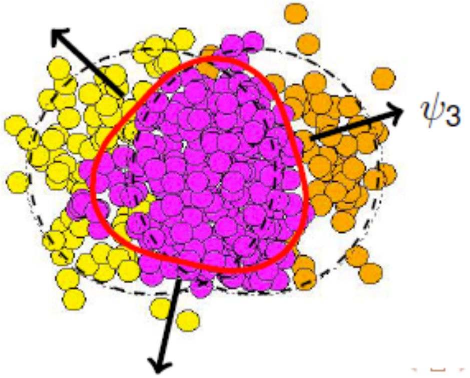
System behaves as ~perfect liquid (the RHIC "paradigm")

JHEP 1609 (2016) 164

Constraining further viscosity: higher harmonics

Initial geometry is not an ideal almond shape

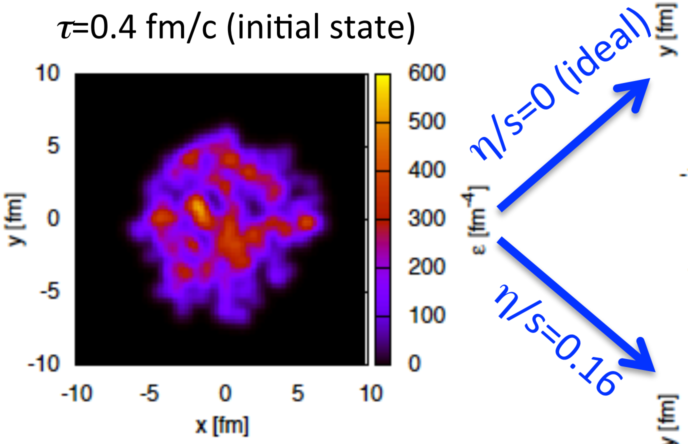
- Fluctuations of initial energy/pressure distributions lead to "irregular" shapes (→ need more harmonics to describe them) that fluctuate event-by-event

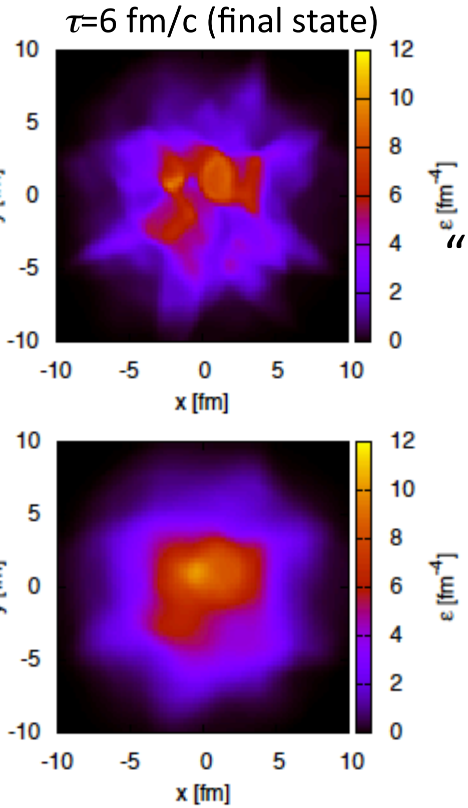


Simulation of energy density evolution

(ideal and viscous hydro)

Schenke, Jeon, Gale, PRL 106:042301,2011



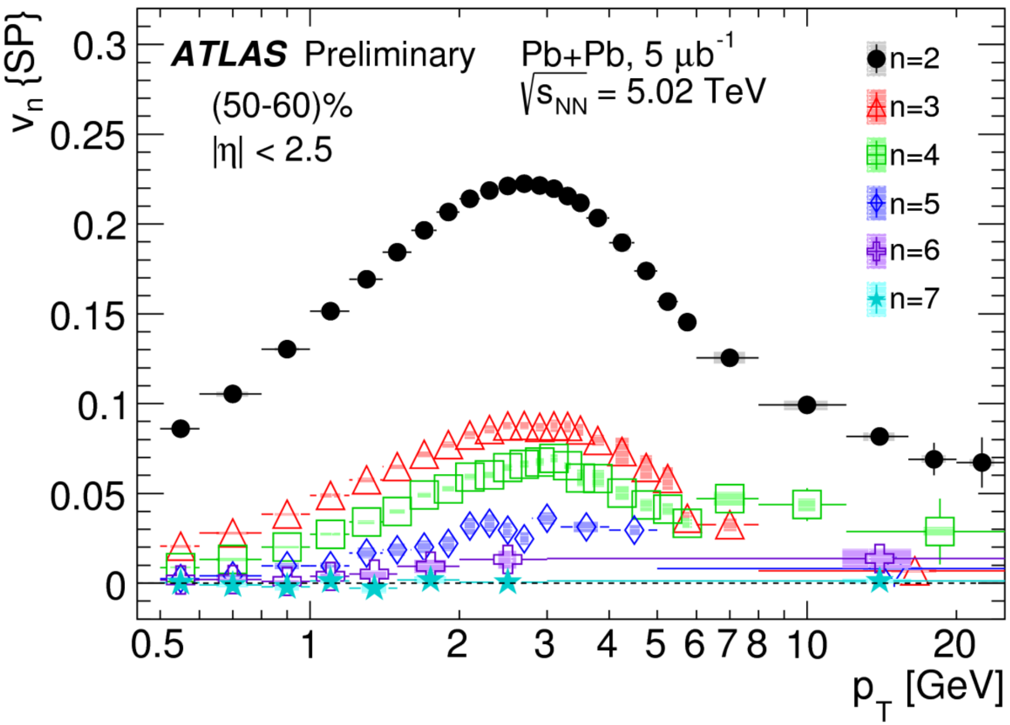


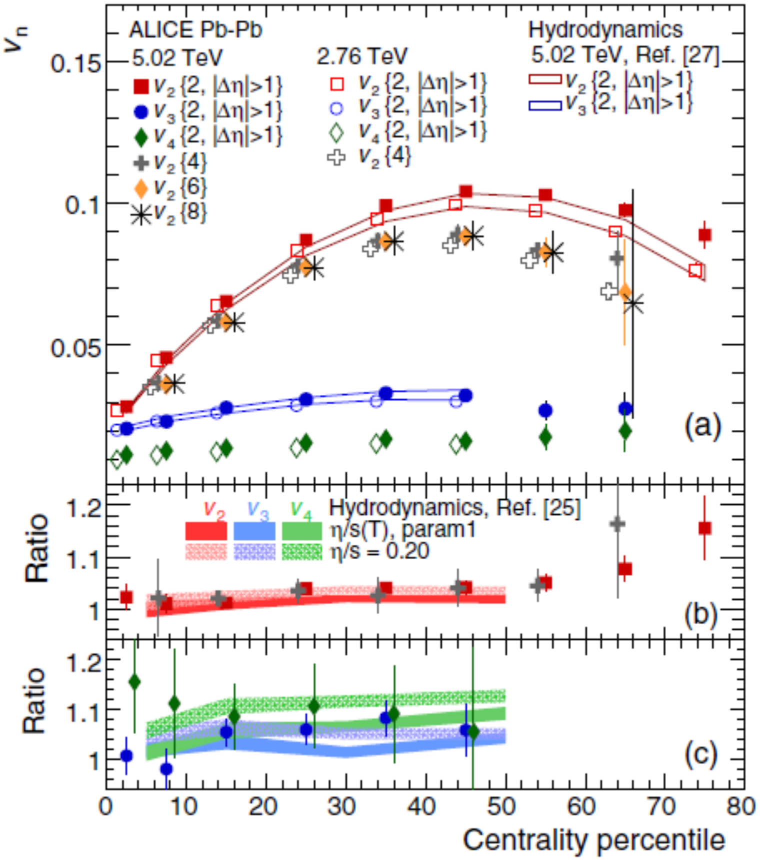
Fluctuations of initial state are damped by viscosity

Viscosity determines the "conversion efficiency" of the initial shape into final momentum azimuthal distribution

Higher harmonics add sensitivity to the value of shear viscosity

Constraining further viscosity: higher harmonics





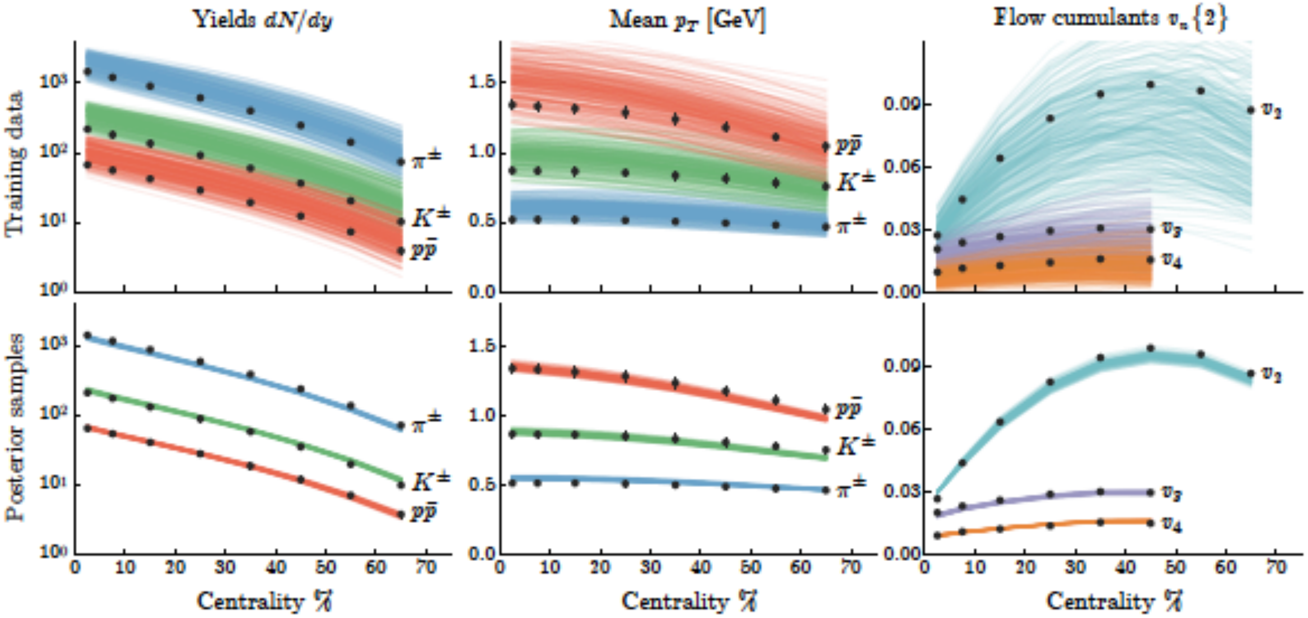
Higher-harmonic coefficients significantly non-zero
→ discriminate and constraint models

Constraining further viscosity: example with a model

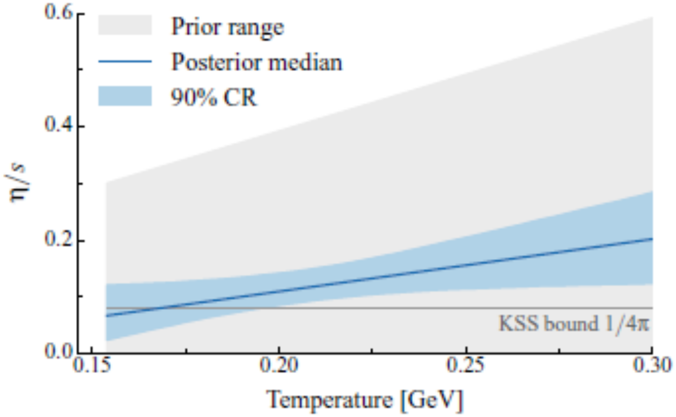
J. E. Bernhard et al. Phys. Rev. C 94, 024907 (2016)

9 parameters: 3 initial state, 4 for QGP response, 2 model parameters

Particle yields, <p_T>, flow coefficients used to calibrate the model parameters to reproduce data



Bayes method used to extract probability distribution for the true values of the parameters



Main results: viscosity vs. temperature

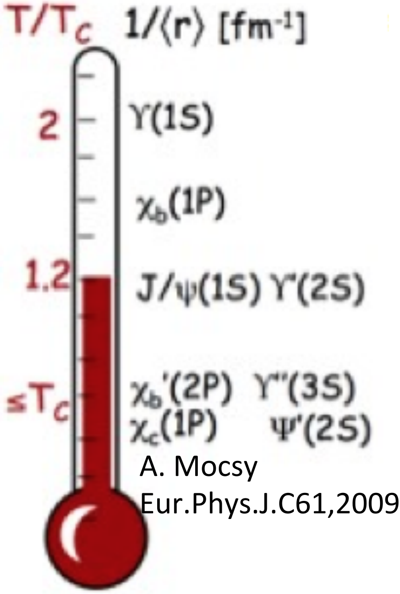
QGP viscosity very low
(lower than any atomic matter)

High-energy probes → microscopic processes (local interactions) in the medium

More in R. Arnaldi's talk

Quarkonium suppression & regeneration

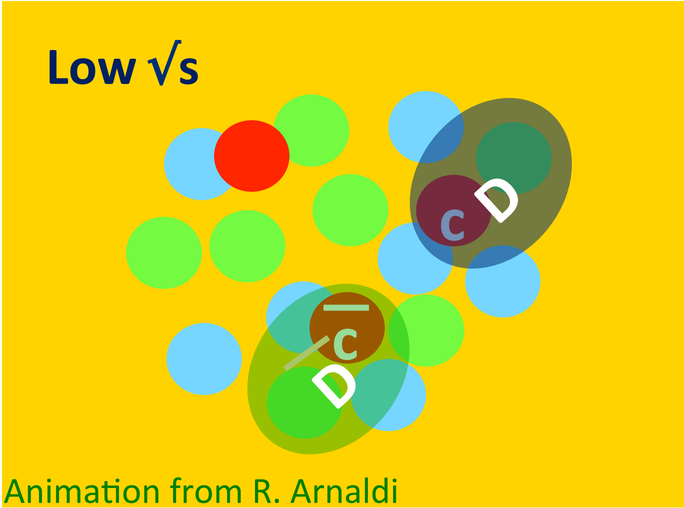
Hot QGP→ quarkonia suppression due to Debye-like screening of QCD $Q\bar{Q}$ potential ("melting" of bound $Q\bar{Q}$ states)
→ **"historical" signature of deconfinement**
(T. Matsui and H. Satz, PLB 178 (1986) 416)



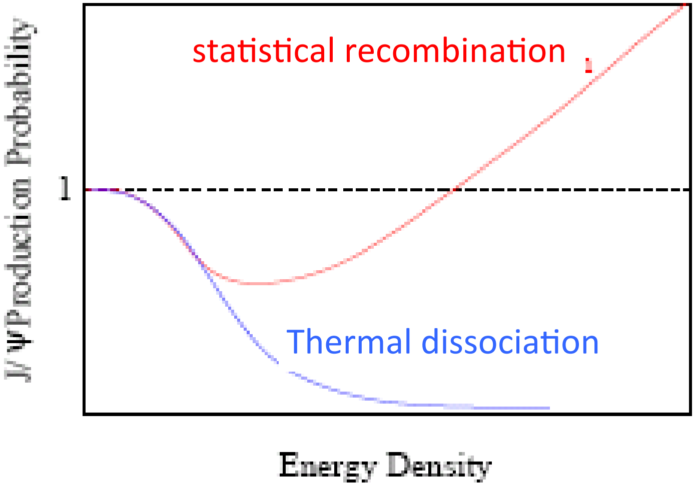
A. Mocsy
Eur.Phys.J.C61,2009

→ **Sequential suppression of quarkonium states**, stronger for less bounded states (S. Digal, P. Petreczky, H. Satz, PRD 64 (2001) 0940150)

Surprisingly similar J/ψ suppression at RHIC and SPS energies
→ Could quarkonia states be **(re)generated via recombination (coalescence) of deconfined quarks**?(P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196)



Animation from R. Arnaldi



LHC vs. RHIC

Larger energy density
→**stronger suppression**
Higher $c\bar{c}$ multiplicity
→**larger recombination**

Quarkonium suppression & regeneration

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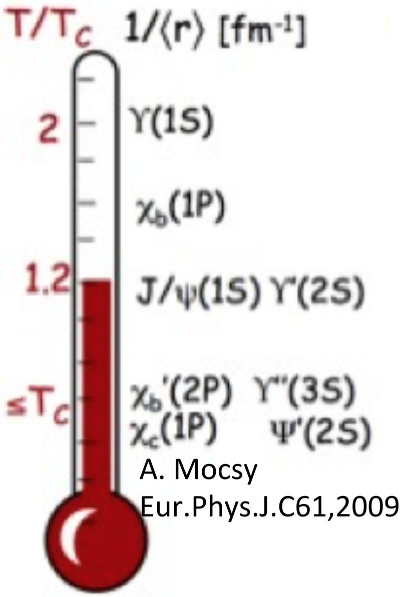

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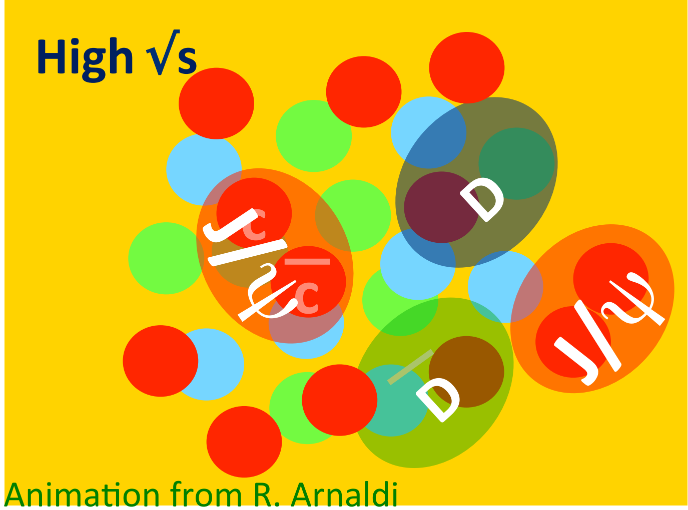

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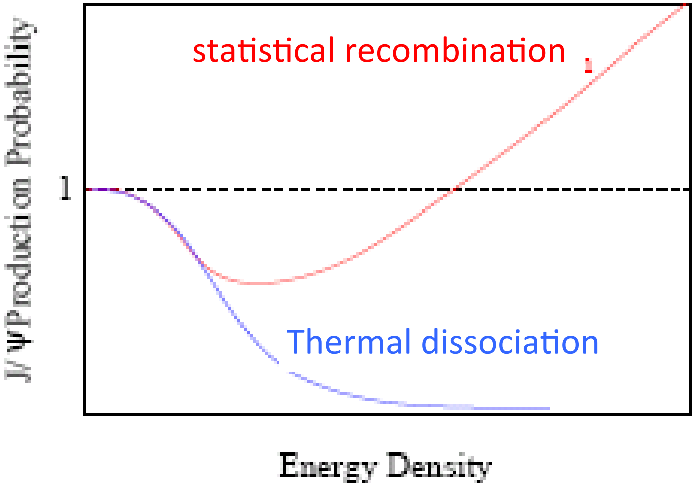

LHC vs. RHIC

Larger energy density
→stronger suppression
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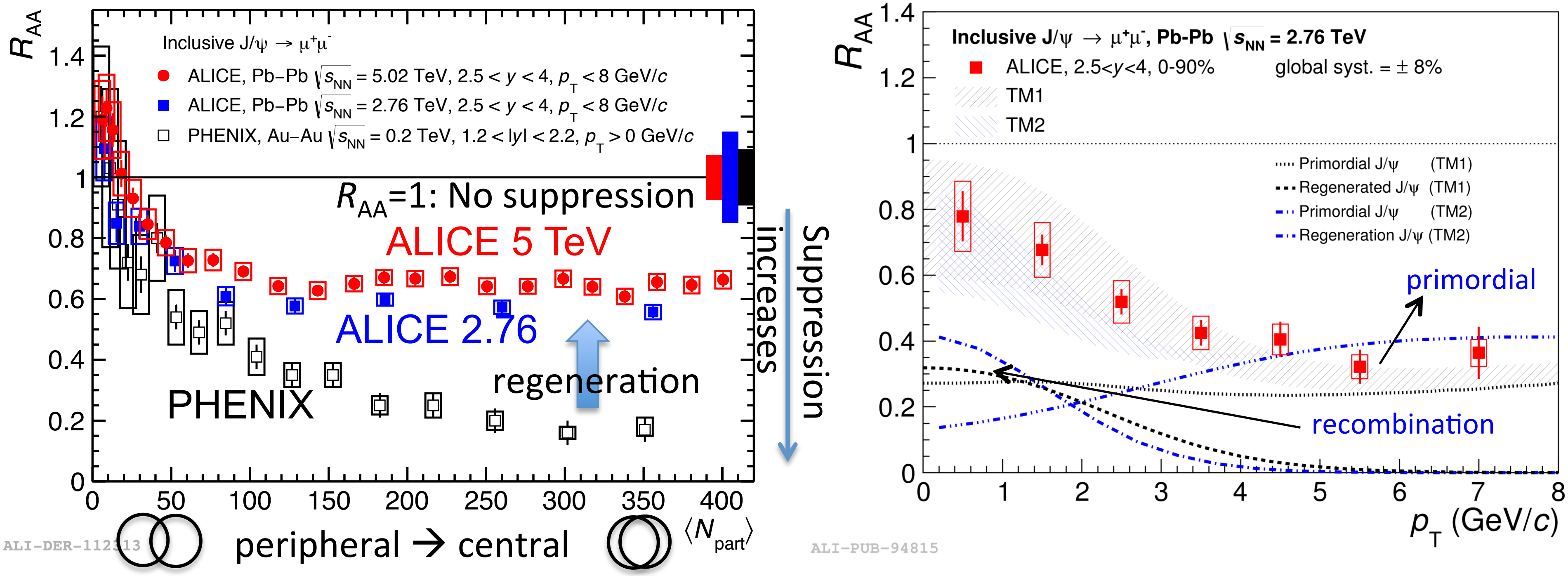
→larger recombination

J/ψ suppression: LHC vs. RHIC

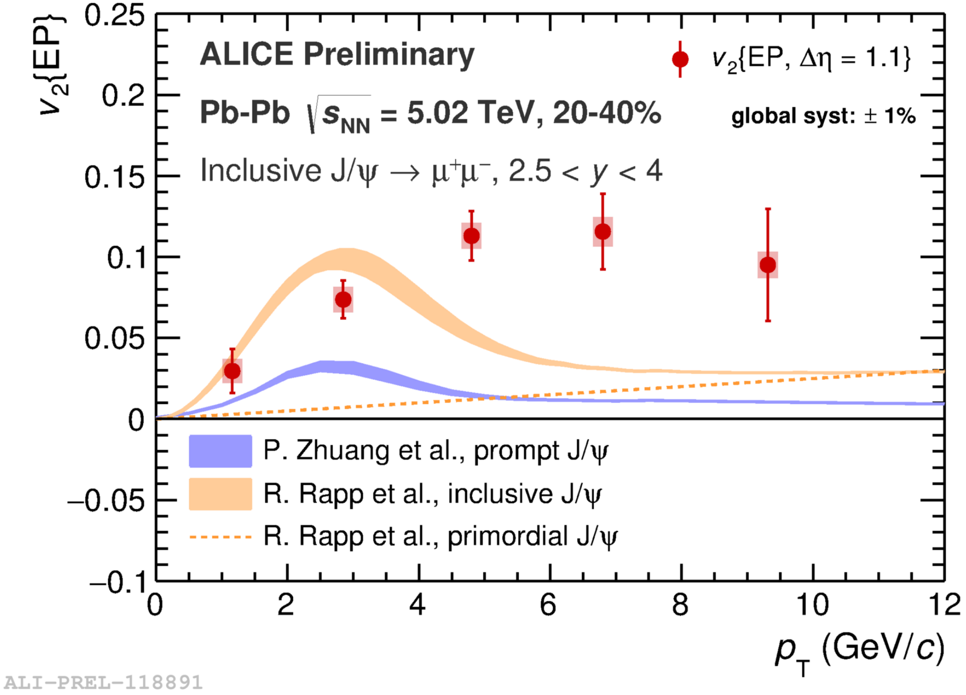
More in R. Arnaldi's talk

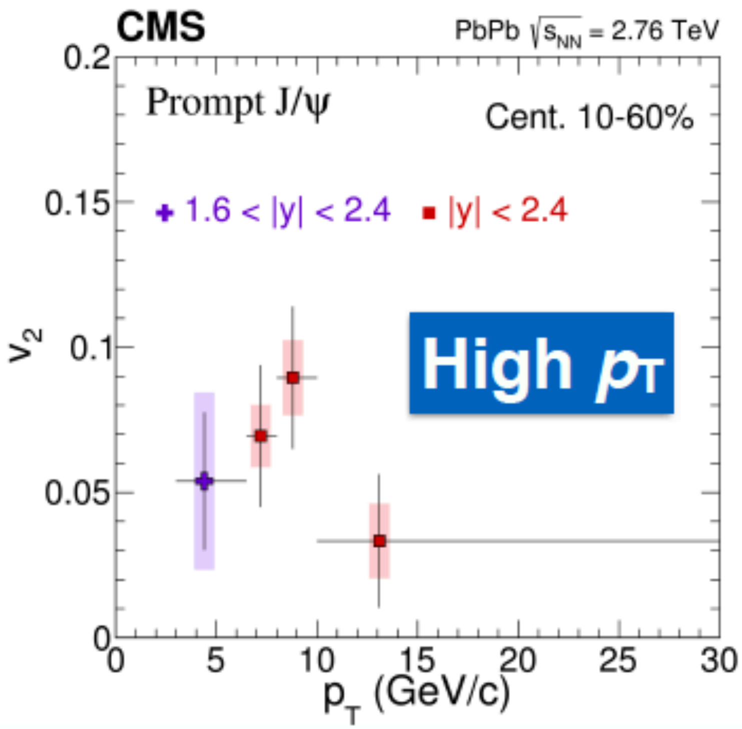


- J/ψ suppression stronger in central events than peripheral
- Smaller suppression at LHC than RHIC
- Analysis vs. transverse momentum: suppression stronger at higher momentum. In agreement with models expecting about 50% contribution of J/ψ from recombination at low p_T.

"Twice a signature of QGP"

J/ψ elliptic flow

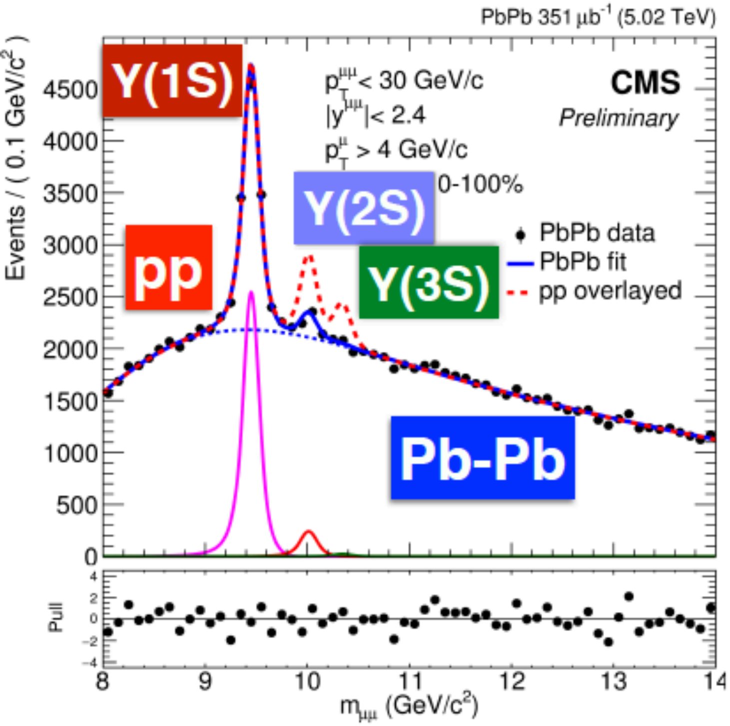


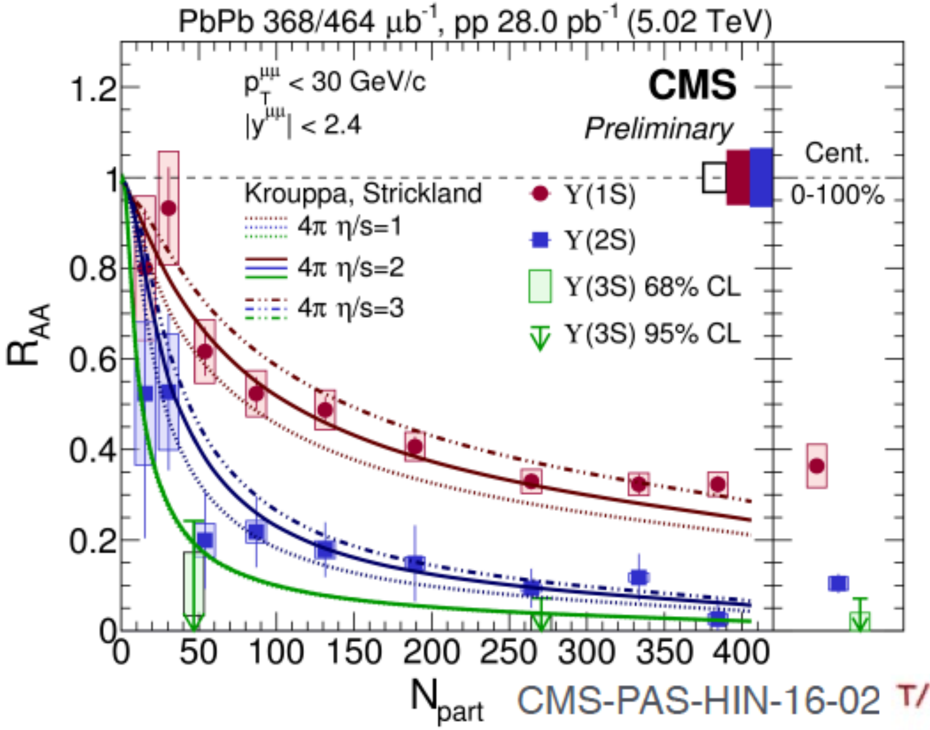


EPJC 77 (2017) 252

Positive J/ψ elliptic flow
Expected for J/ψ from recombination
Remains high at high pt → not expected from models

Bottomonium suppression





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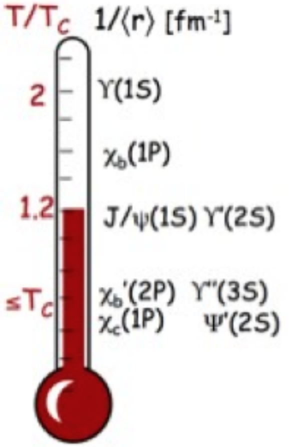


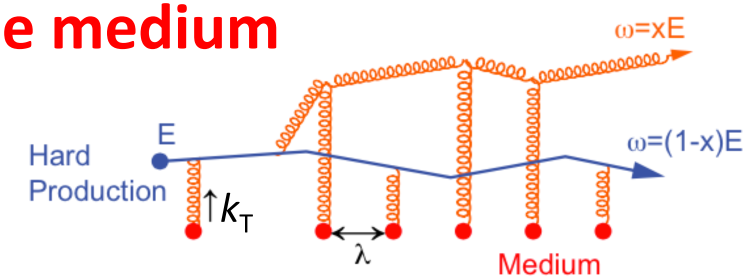
- Y(1s) ($E_{binding}$~1100 MeV), Y(2s) and Y(3s) (Eb~200 MeV) have different sensitivity to the medium
- Strong suppression of Y(2s,3s) with respect to Y(1s) increasing with centrality

→Trend expected from “sequential suppression”

QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

⇨ **"Calibrated probes" of the medium**



Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes

~ Study QCD "Bethe-Block" curve for partons in the QGP

⇩

Connection of "local" interactions with global medium properties
→ Microscopic description of the medium

e.g. in BDMPS-Z formalism*

$$\langle \Delta E \rangle^{\text{rad}} \propto \alpha_s C_R \hat{q} L^2$$

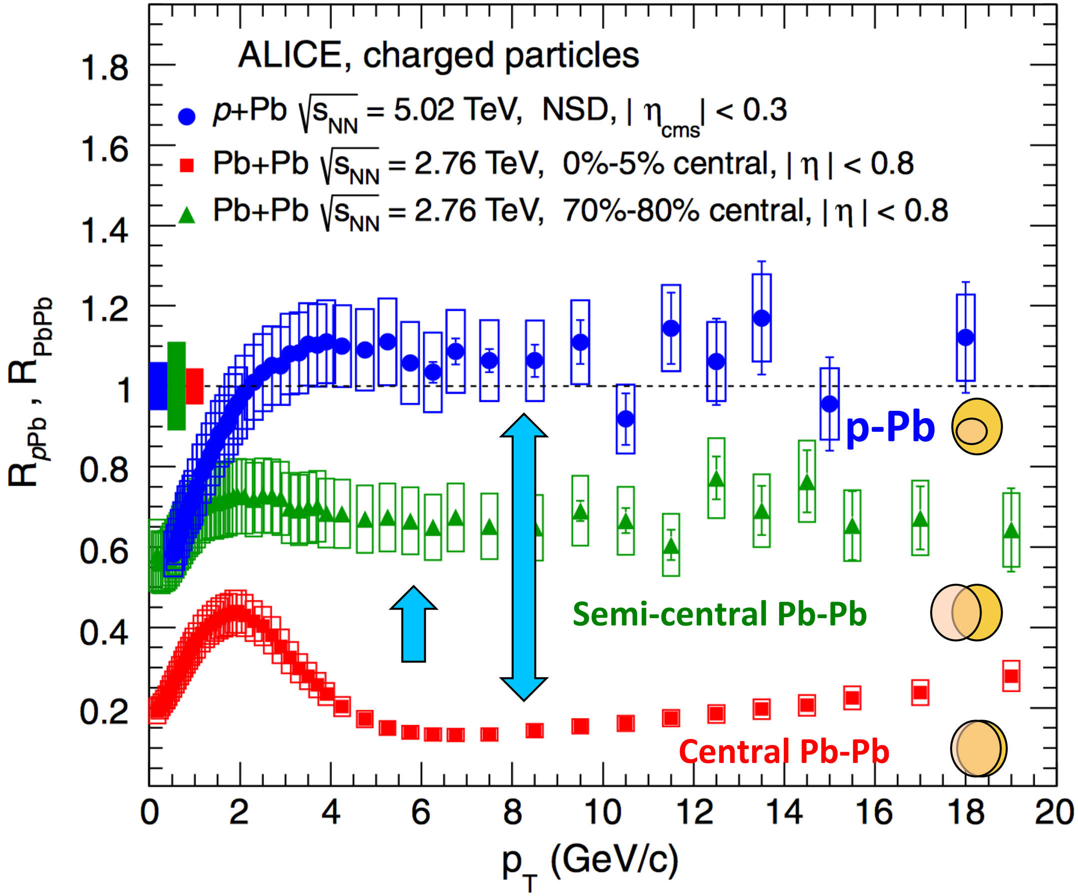
$$\hat{q} = \frac{\langle k_{\mathrm{T}}^2 \rangle}{\lambda} = \langle k_{\mathrm{T}}^2 \rangle \rho \sigma$$

Transport coefficient(s)

*Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 29
Zakharov, JTEPL 63 (1996) 952.

QGP tomography with high-energy partons

ALICE, PRL 110 (2013) 082302



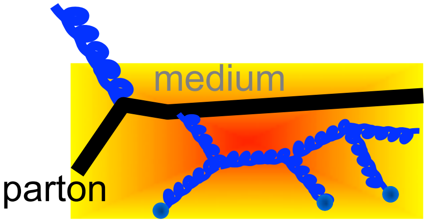
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

Strong suppression of intermediate/ high p_T particles in central Pb-Pb collisions

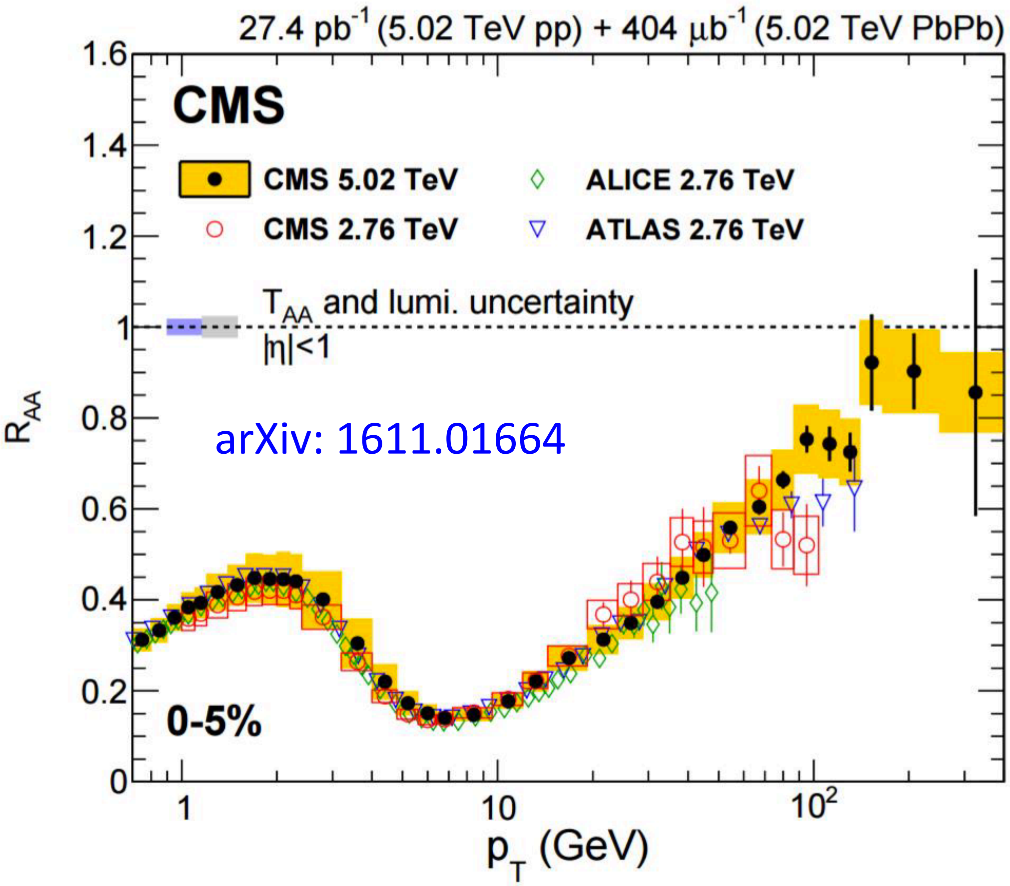
Absent in p-Pb collisions (no QGP expected)

→ final-state effect

→ Evidence of in-medium partonic energy loss



QGP tomography with high-energy partons



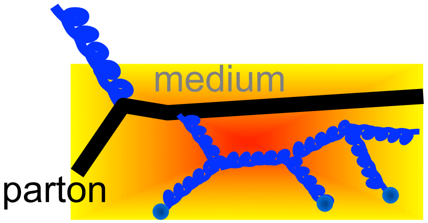
Suppression up to very high p_T

Strong suppression of intermediate/ high p_T particles in central Pb-Pb collisions

Absent in p-Pb collisions (no QGP expected)

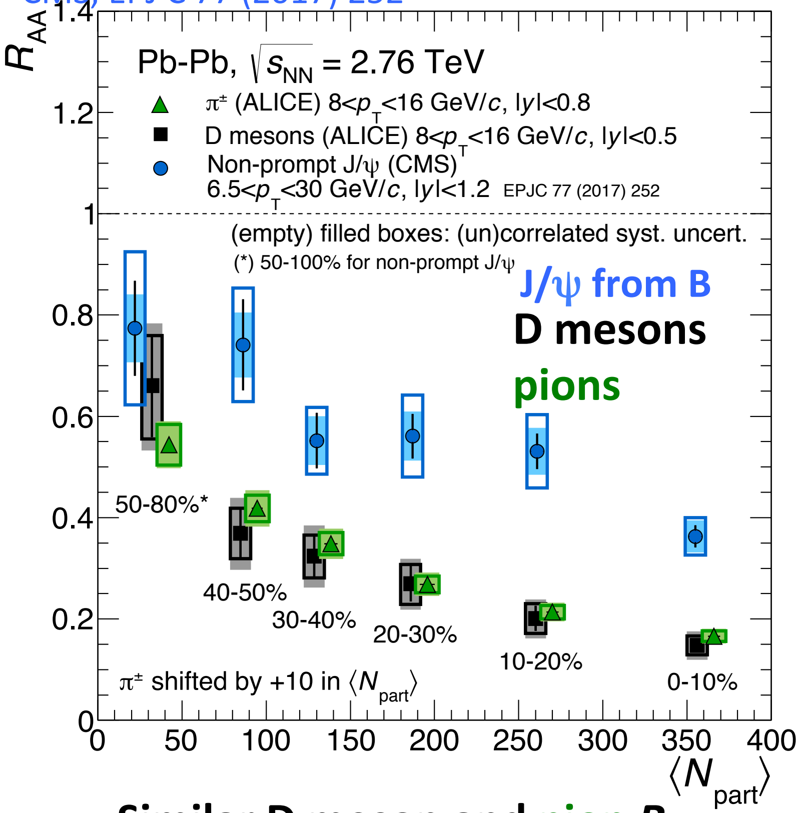
→ final-state effect

→ Evidence of in-medium partonic energy loss



Open charm and beauty

ALICE, JHEP 1511 (2015) 205
CMS, EPJ C 77 (2017) 252



Similar D meson and pion R_{AA}

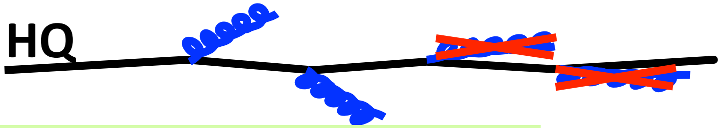
Expected from small charm-quark mass + differences between charm and gluon/LF spectra slope and fragmentation

R_{AA} (J/ψ from B) > R_{AA}(D) in central collisions

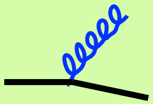
Indication of R_{AA} (B) > R_{AA}(D)

The different suppression and the centrality dependence as expected from **models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b$)**

Expected from dead cone effect:



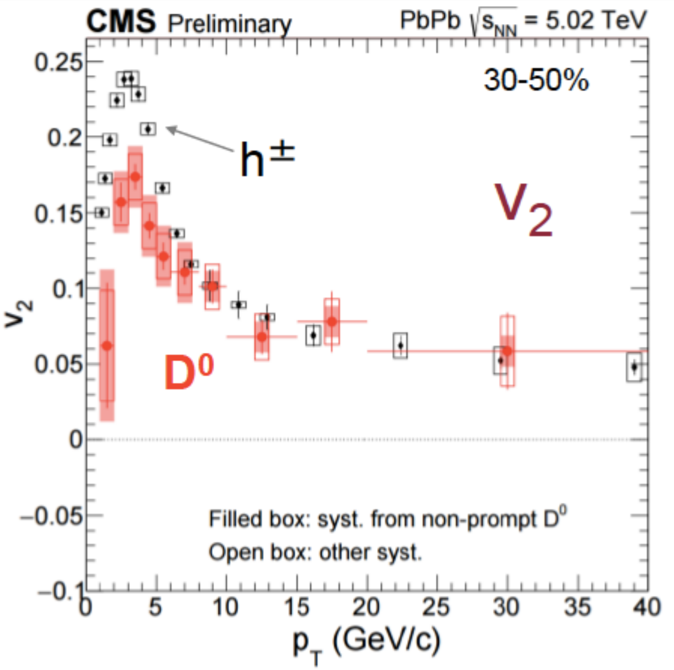
Gluonsstrahlung probability

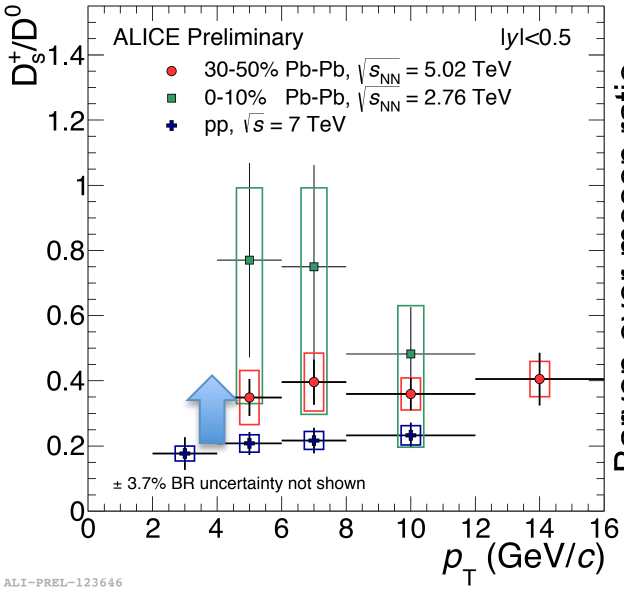


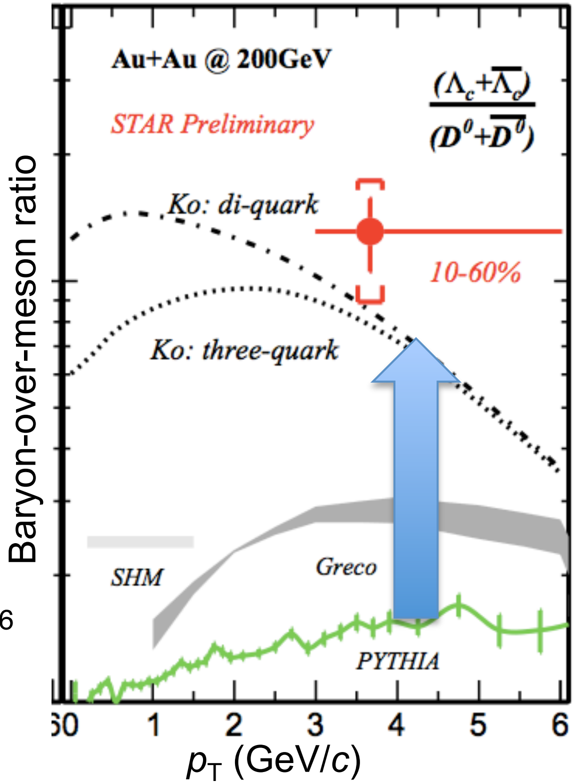
$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Open charm and beauty





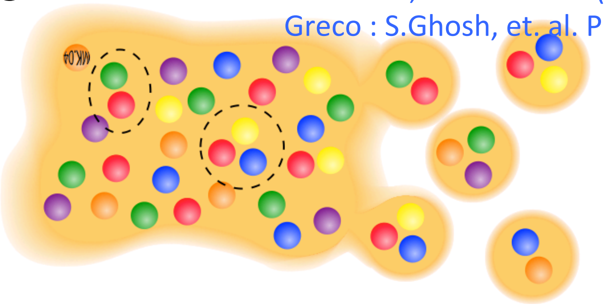


Ko : Y. Oh, et.al. PRC 79 (2009) 044905;
Greco : S.Ghosh, et. al. PRD 90 (2014) 054018

Charm flows

Modification of particle species abundances

→hadronisation via coalescence?

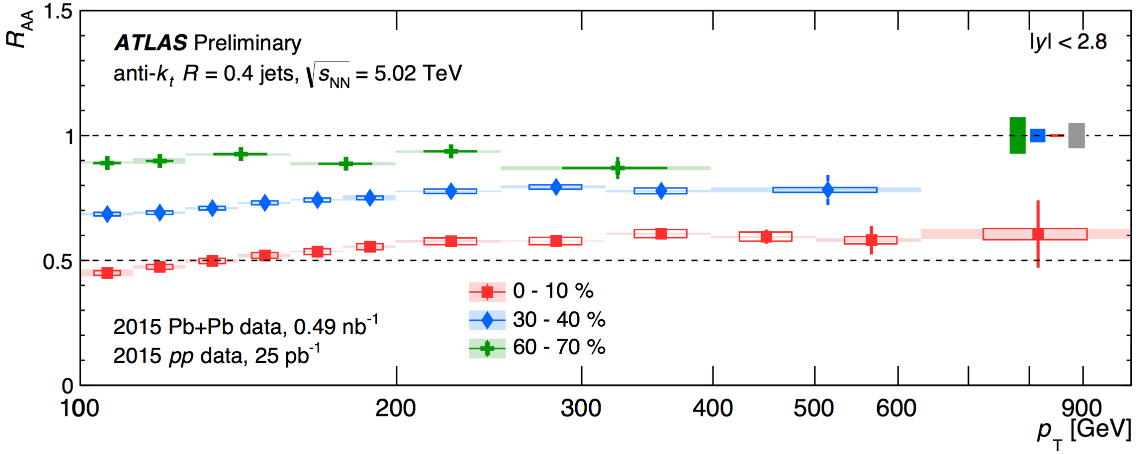


- → Charm participates to system collective motion
- → Possible thermalisation?

Jet quenching

Jets are "extended" objects → provide complementary information to single particle observables

- Address spatial distribution and kinetic properties of radiated energy
  - **Out-of-cone radiation → jet suppression**

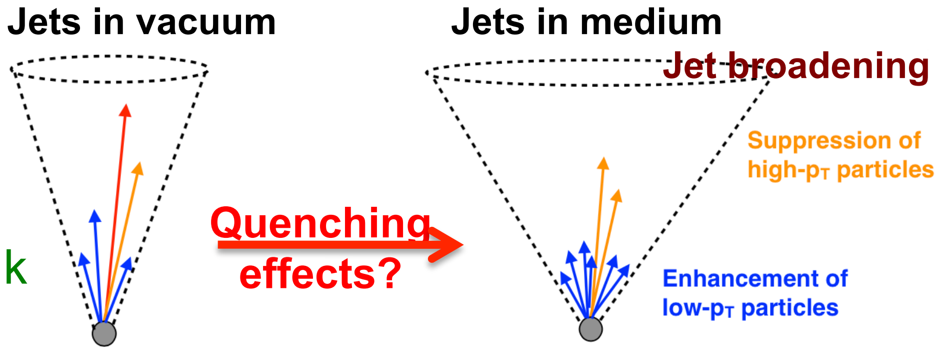


Jet suppression up to ~1 TeV!

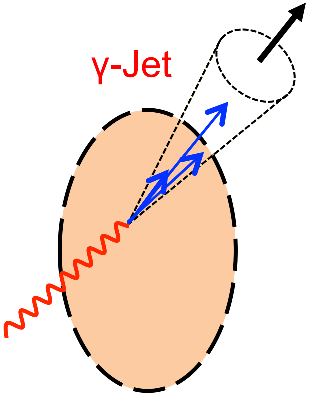
Is the jet internal structure modified?

- Kinetic properties
- Spatial distribution of jet constituents
- Particle specie composition

Many studies performed → E. Bruna's talk



Jet quenching with γ-jet



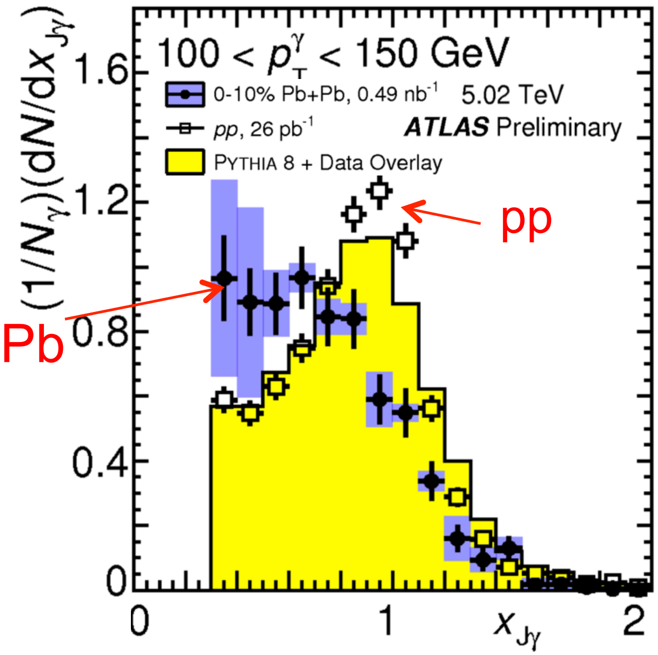
γ provides calibration of jet energy before quenching

- medium effects via $\mathbf{x_{J\gamma} = p_{T,jet}/p_{T,\gamma}}$ and Δϕ decorrelation

Central 0-10% PbPb compare to pp

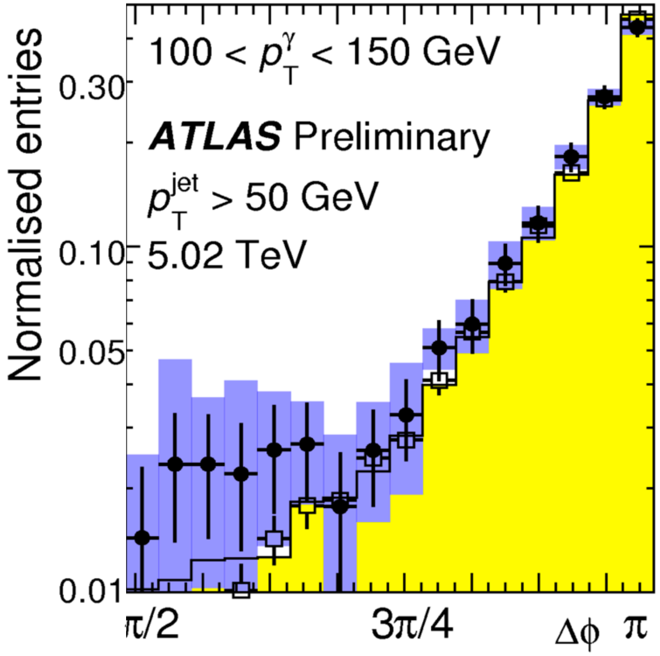
- $\langle x_{J\gamma} \rangle$ shifted towards lower value
  - ➔ Strong energy loss for associated jet.
- Δϕ distribution consistent with pp data
  - ➔ Little modification of the jet direction.

CONF-2016-110



pp

Central PbPb

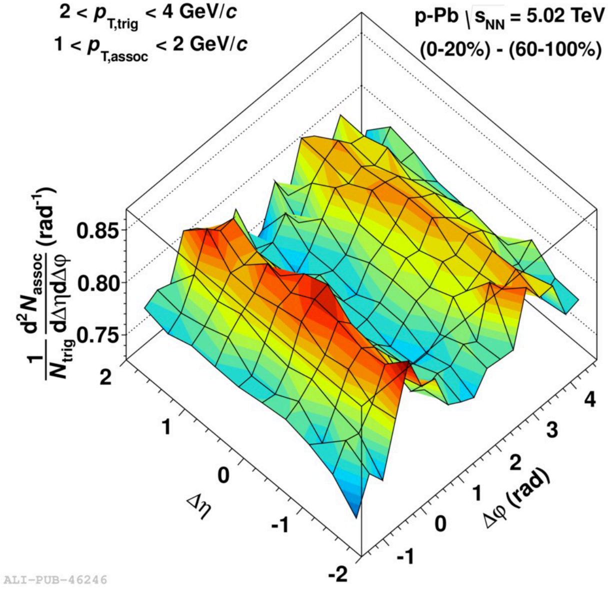


QGP in small systems?

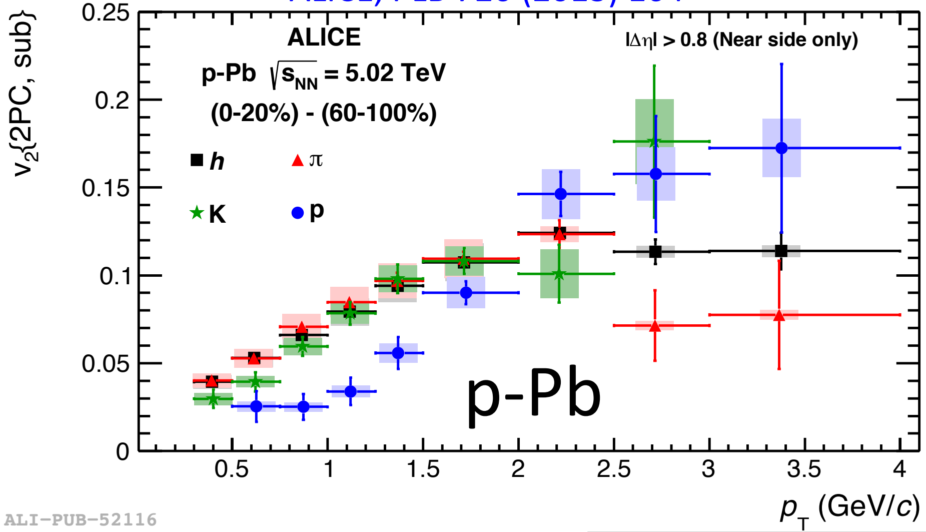
More in P. Bartalini's talk

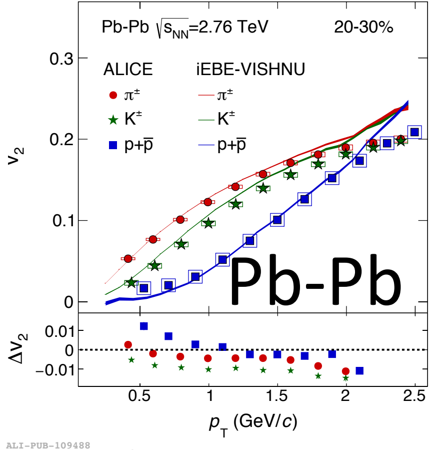
Long range correlations and flow in p-Pb

ALICE, PLB 719 (2013) 29



ALICE, PLB 726 (2013) 164





arxiv:1606.06057

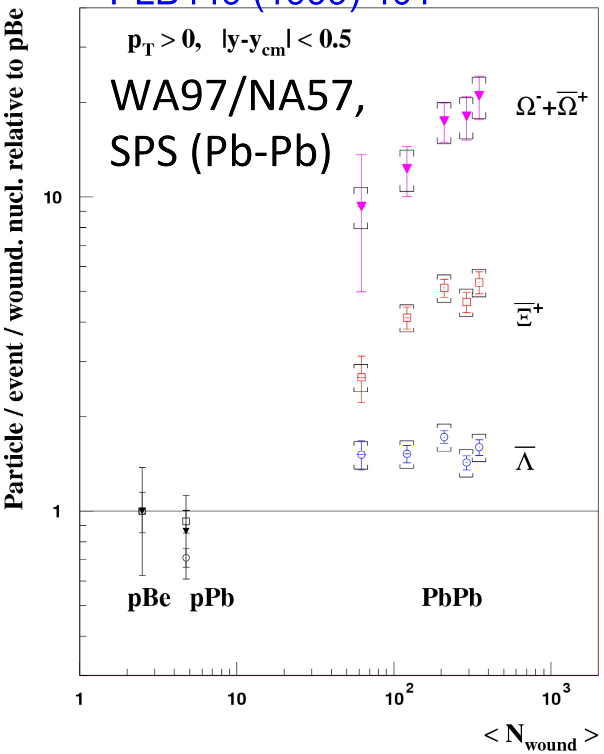
Large v_2 (elliptic flow) values!

Mass ordering and "crossing" similar to Pb-Pb, where data are reproduced by hydrodynimical models

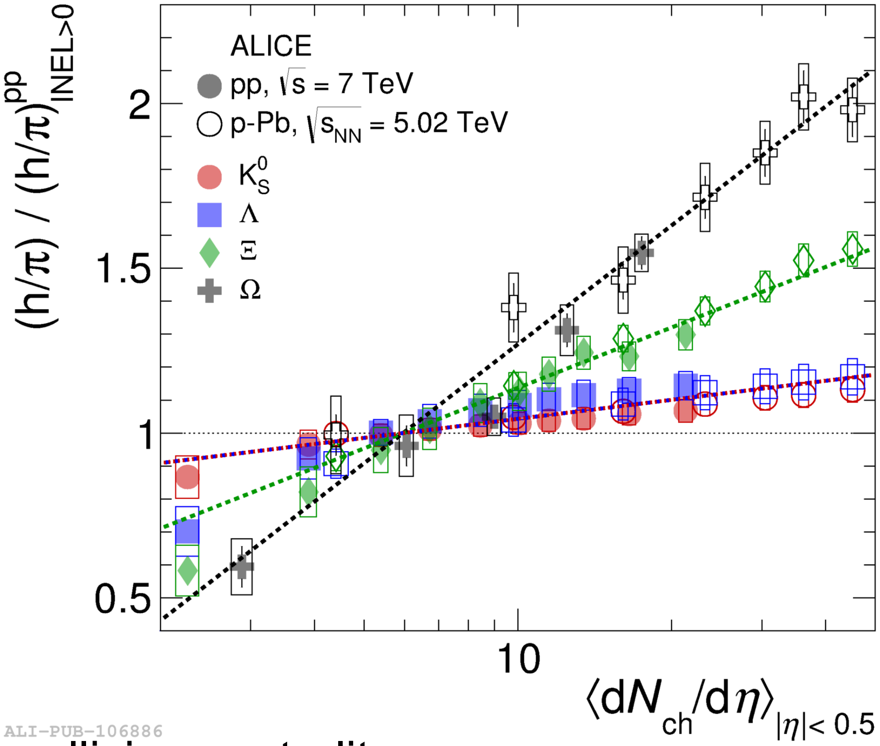
More in P. Bartalini’s talk

Strangeness enhancement

PLB449 (1999) 401



Nature Physics (2017) doi:10.1038/nphys4111



- Increase of strange particle yield with collision centrality
- Stronger effect for particles with larger strangeness content
- Historical QGP “smoking gun” (Rafelski, Müller, PRL48(1982)1066), associated with chiral symmetry restoration and removal of canonical suppression

Now observed also in pp collisions at high multiplicity

→ New research direction

Summary

… only a snapshot of the main results presented, see also talks by R. Arnaldy, P. Bartalini, E. Bruna, R. Preghenella, S. Bufalino

After 30 years of studies QGP formation in heavy-ion collisions quite established

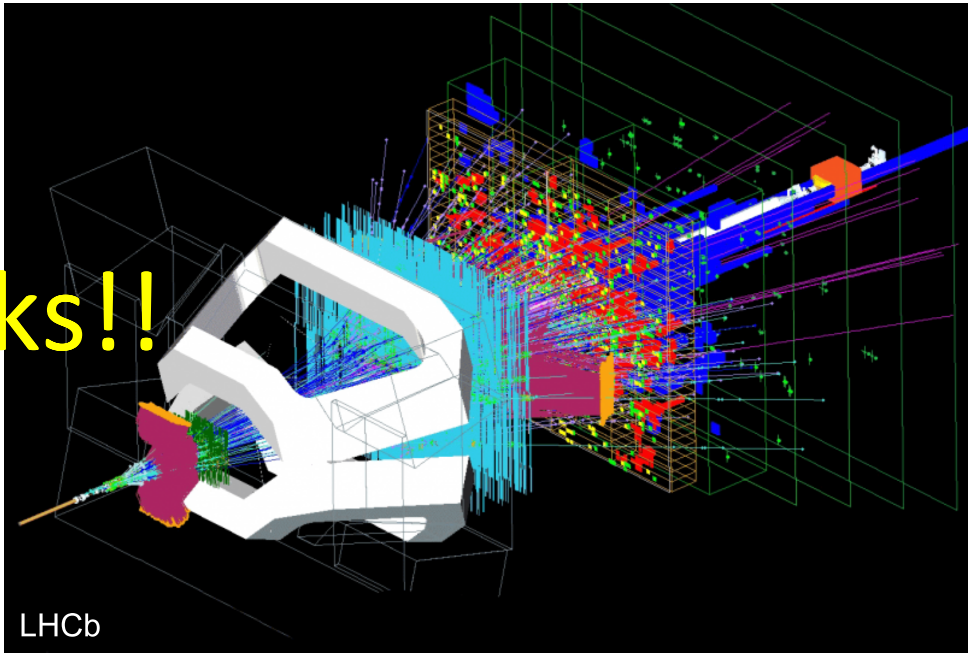
The experimental goal is now to measure precisely its properties and achieve a comprehensive microscopic description of the medium
- Event-by-event studies and fluctuations
- Push precision for particle chemistry (baryon/mesons, resonances,…)
- Hard-probes: still much room for improving precision and for more differential measurements → still a lot to learn!

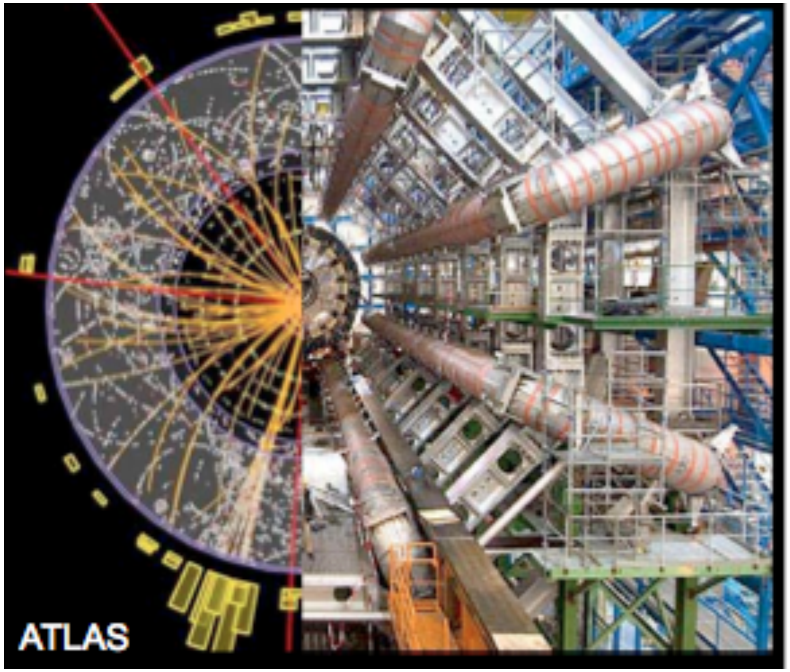
Recent years: indication of collective QGP-like effects in small collision systems with particle multiplicity a possible “collant”/common scale
→ Really QGP in pp/p-A collisions?
→ Possibility to study onset of these phenomena?
→ New research direction

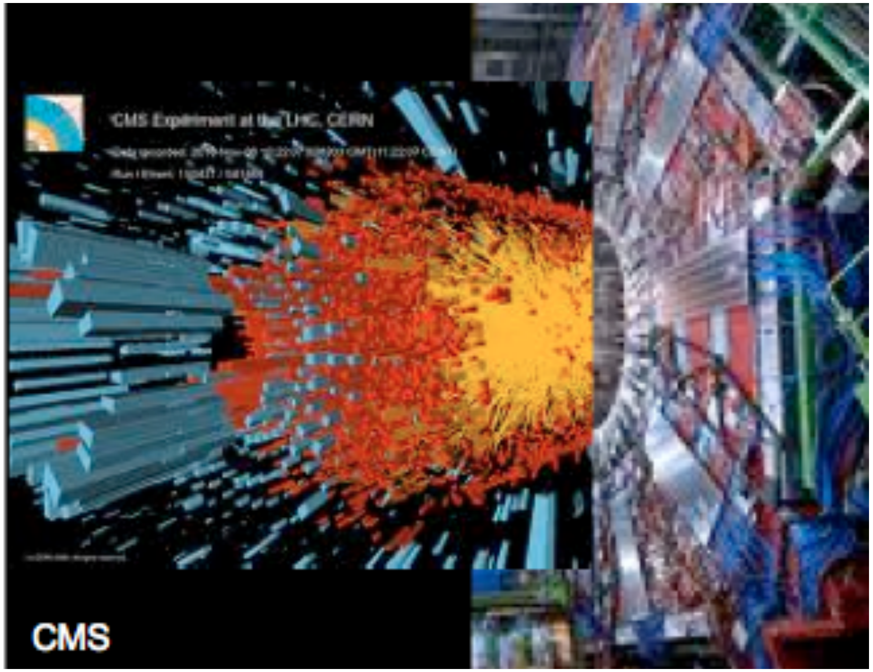
A lot of work for ongoing and future/upgraded experiments!

Thanks!!


ALICE


LHCb


ATLAS

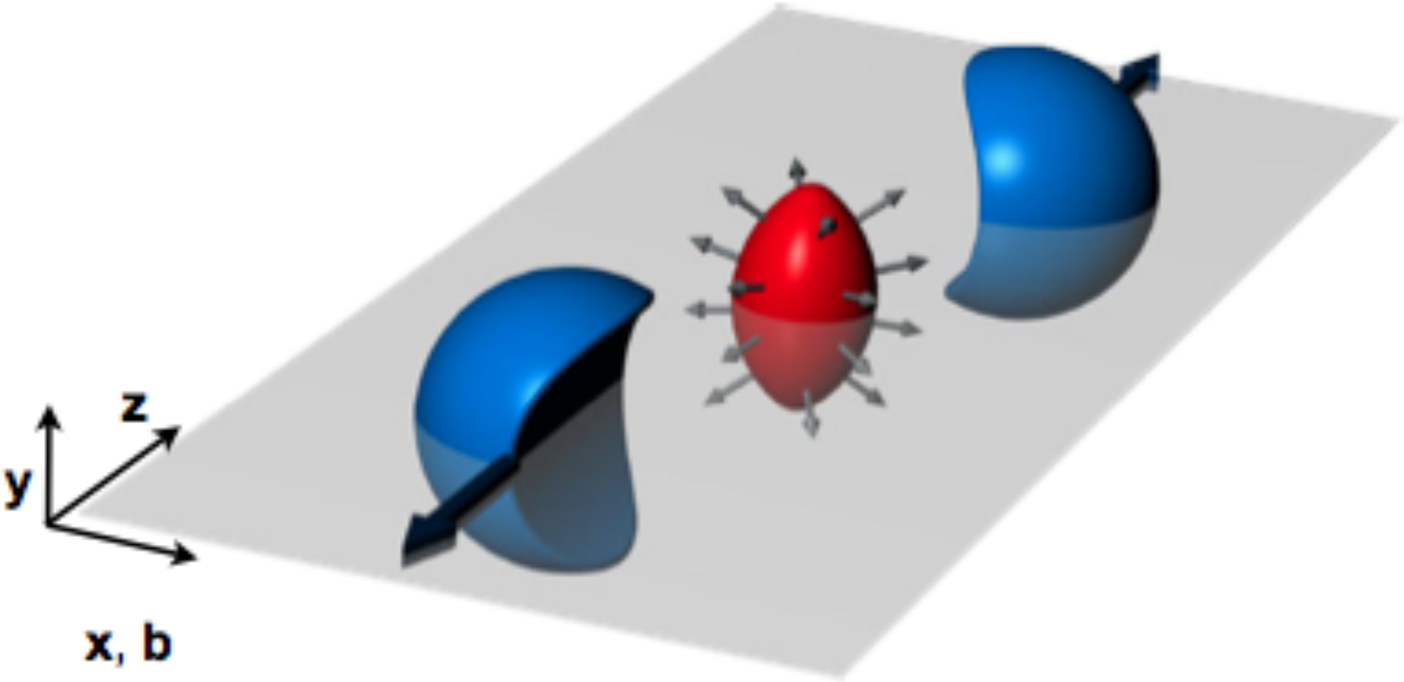


CMS

Extra

Anisotropic (Elliptic) Flow

- Non-central collisions are azimuthally asymmetric

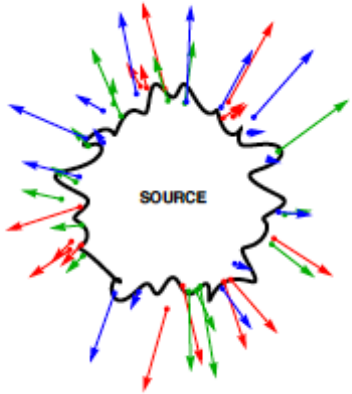


System size: HBT interferometry

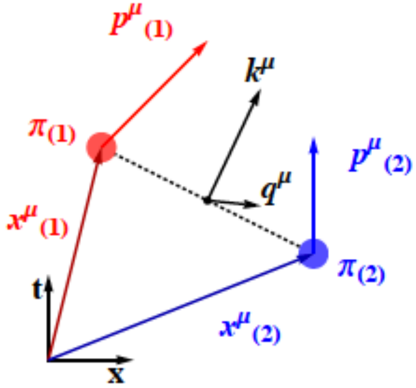
Hanbury-Brown and Twiss

“Bose-Einstein” enhancement in the momentum correlation of identical bosons emitted close in phase ⟶ Probe “homogeneity emission region” and decoupling time

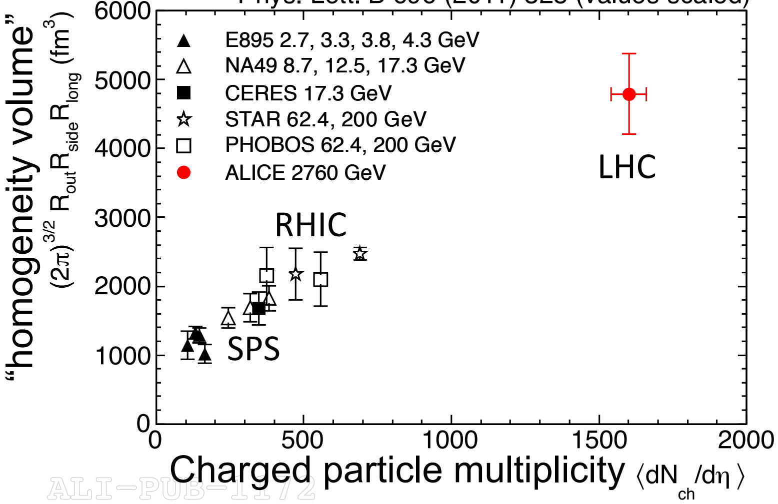
source emitting particles



two identical pions, $\pi^+\pi^+$, $\pi^-\pi^-$

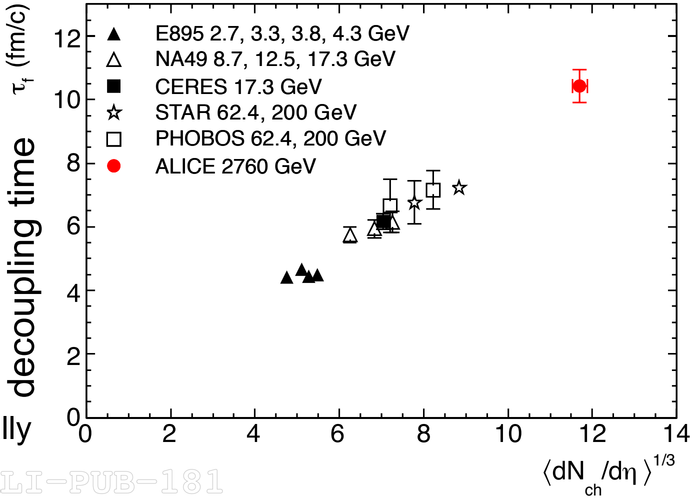


Phys. Lett. B 696 (2011) 328 (values scaled)



R_{out}~R_{side}~6 fm
R_{long}~8 fm

As expected, larger-size and longer living system produced at the LHC



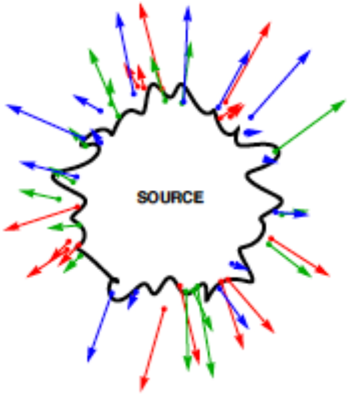
From R_{long}, assuming longitudinally expanding emission source

System size: HBT interferometry

Hanbury-Brown and Twiss

“Bose-Einstein” enhancement in the momentum correlation of identical bosons emitted close in phase ⟶ Probe “homogeneity emission region” and decoupling time

source emitting particles



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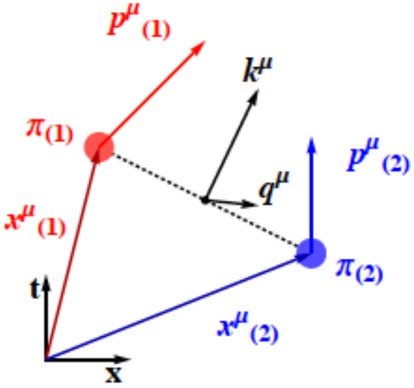
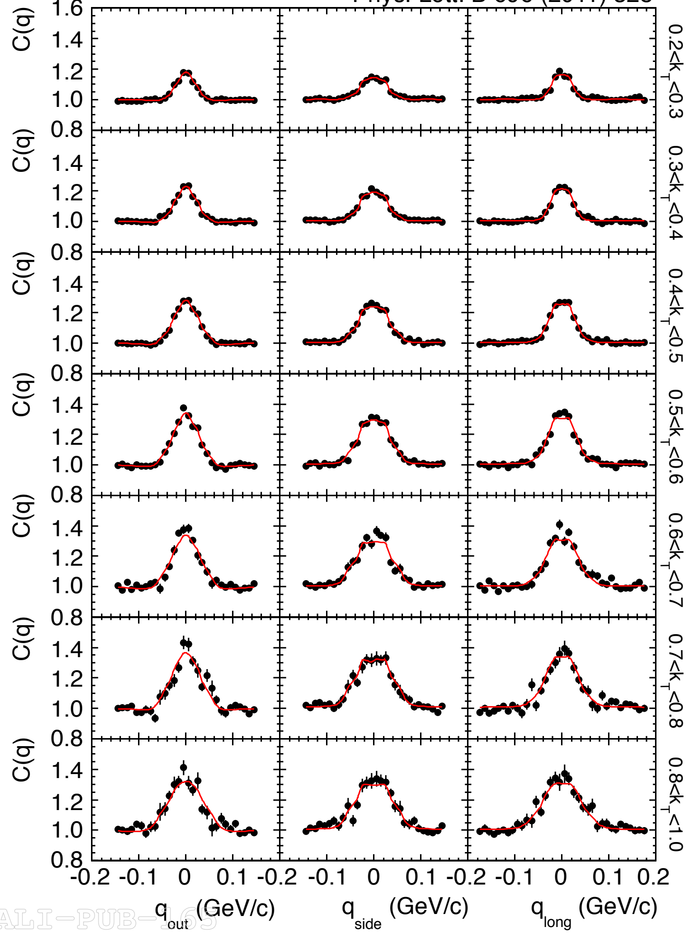


Phys. Lett. B 696 (2011) 328



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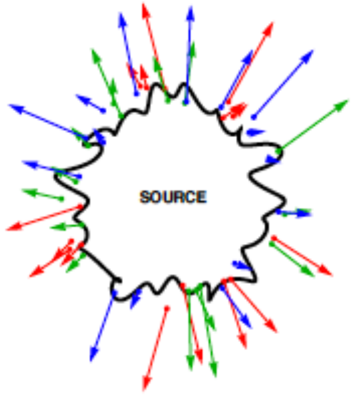

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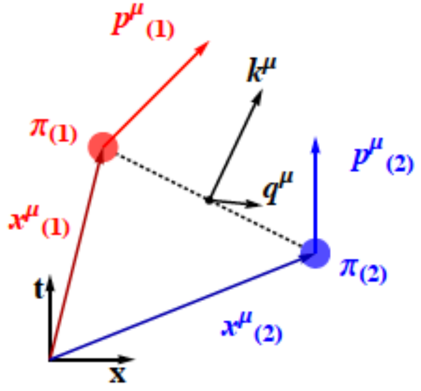
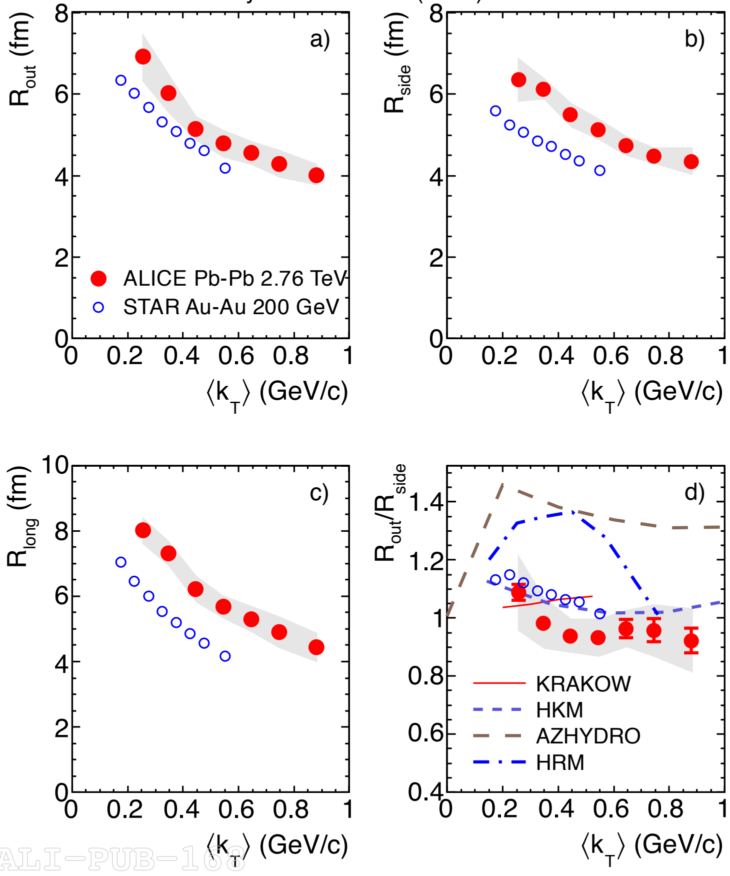
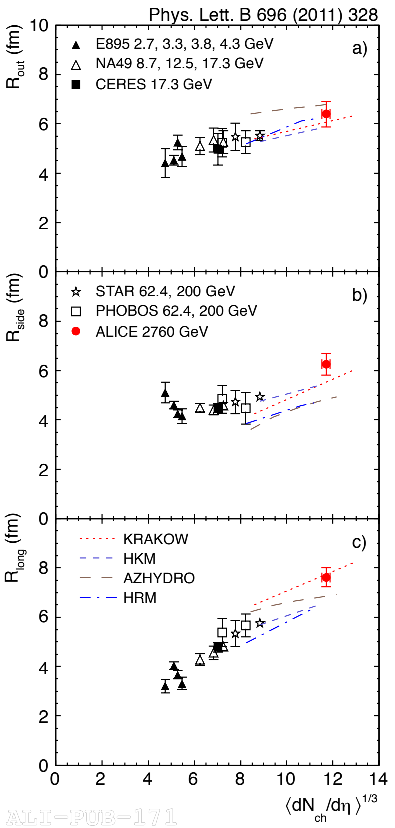


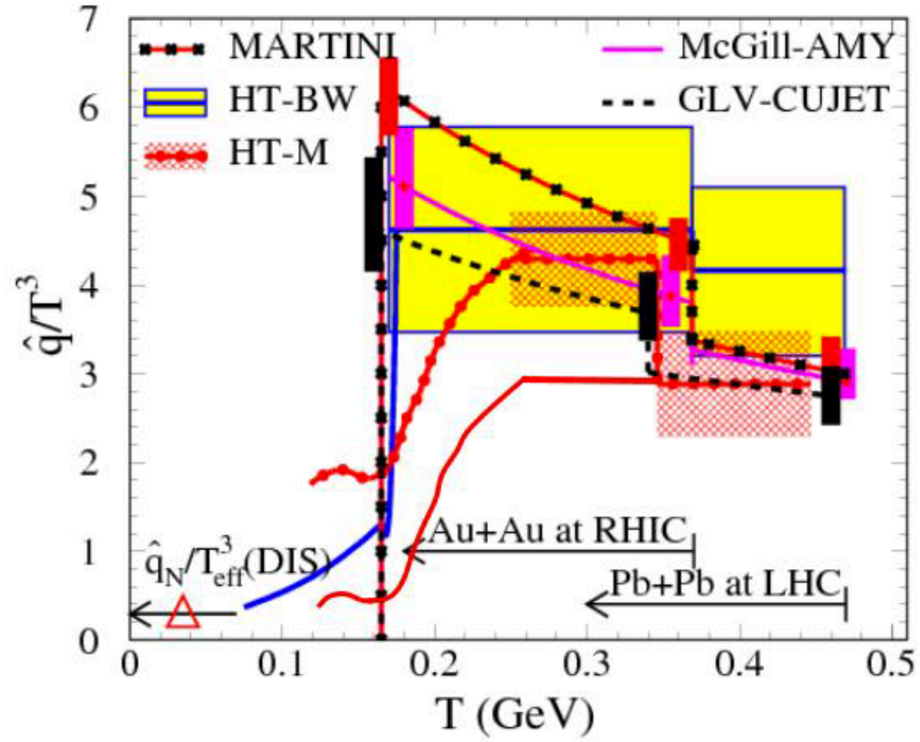
Phys. Lett. B 696 (2011) 328





Started to extract information from data

From analysis of inclusive charged particle spectra at RHIC and LHC and considering many models

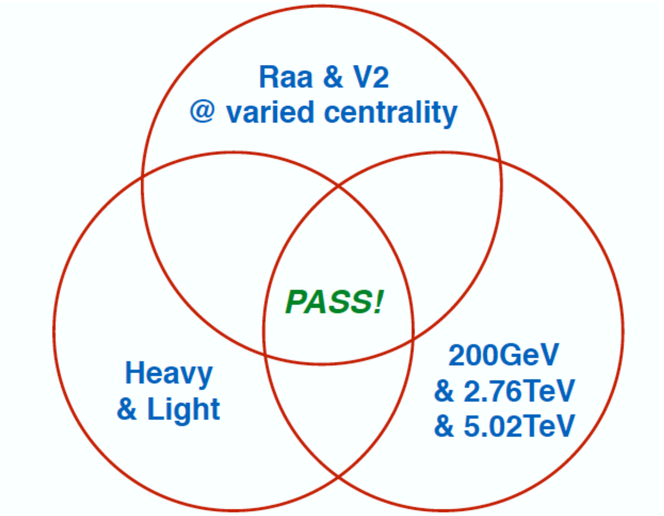


Nucl.Phys. A931 (2014) 404-409

$$\hat{q} = 1.2 \pm 0.3\ \mathrm{GeV}^2/\mathrm{fm}\ (\text{central Au-Au}\ \sqrt{s_{\rm NN}}=200\ \text{GeV})$$

$$\hat{q} = 1.9 \pm 0.7\ \mathrm{GeV}^2/\mathrm{fm}\ (\text{central Pb-Pb}\ \sqrt{s_{\rm NN}}=2.76\ \text{TeV})$$

Only a starting point!



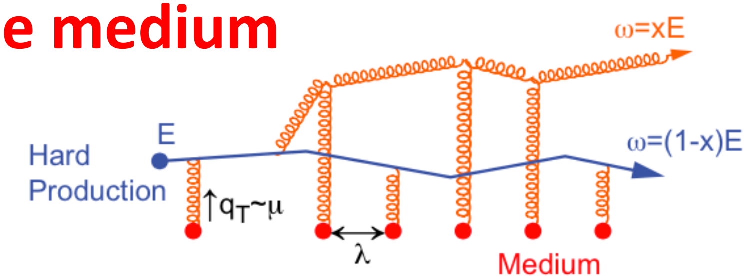
from J. Liao, QM2017

QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

at all p_T for charm and beauty
(large masses >> Λ_{QCD})

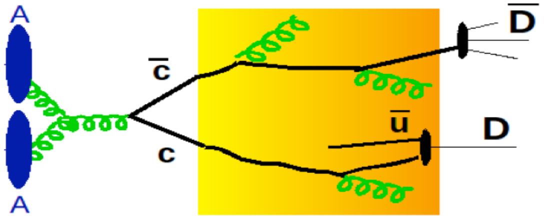
⇒ **"Calibrated probes" of the medium**



Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes
  - path length and medium density
  - **color charge** (Casimir factor)
  - **quark mass** (e.g. from dead-cone effect)

$$\left.\right\}\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



- medium **modification to HF hadron formation**
  - hadronization via quark coalescence

- participation in collective motion → flow

Quarkonium in the QGP

More in R. Arnaldi's talk

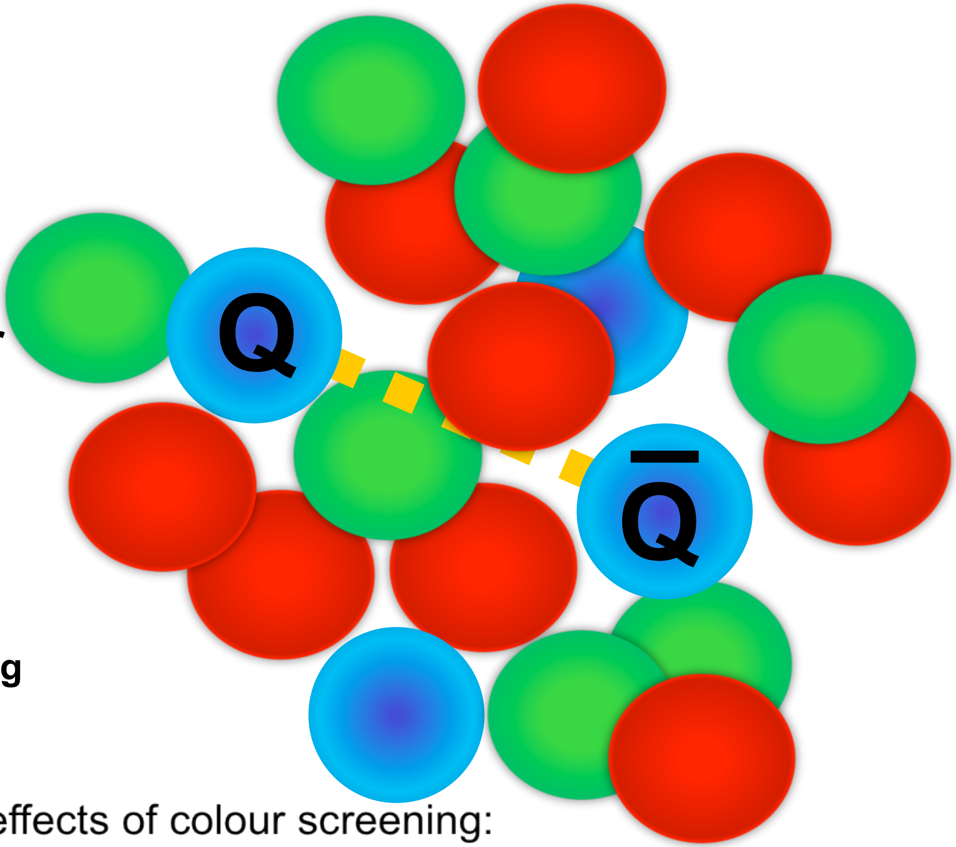
Recall: quant-antiquark QCD potential

$$V(r) = -\frac{\alpha}{r} + kr$$

The QGP consists of deconfined colour charges → screening effect

$$V(r) = -\frac{\alpha}{r} e^{-r/\boxed{\lambda_D}}$$

λ_D: screening radius

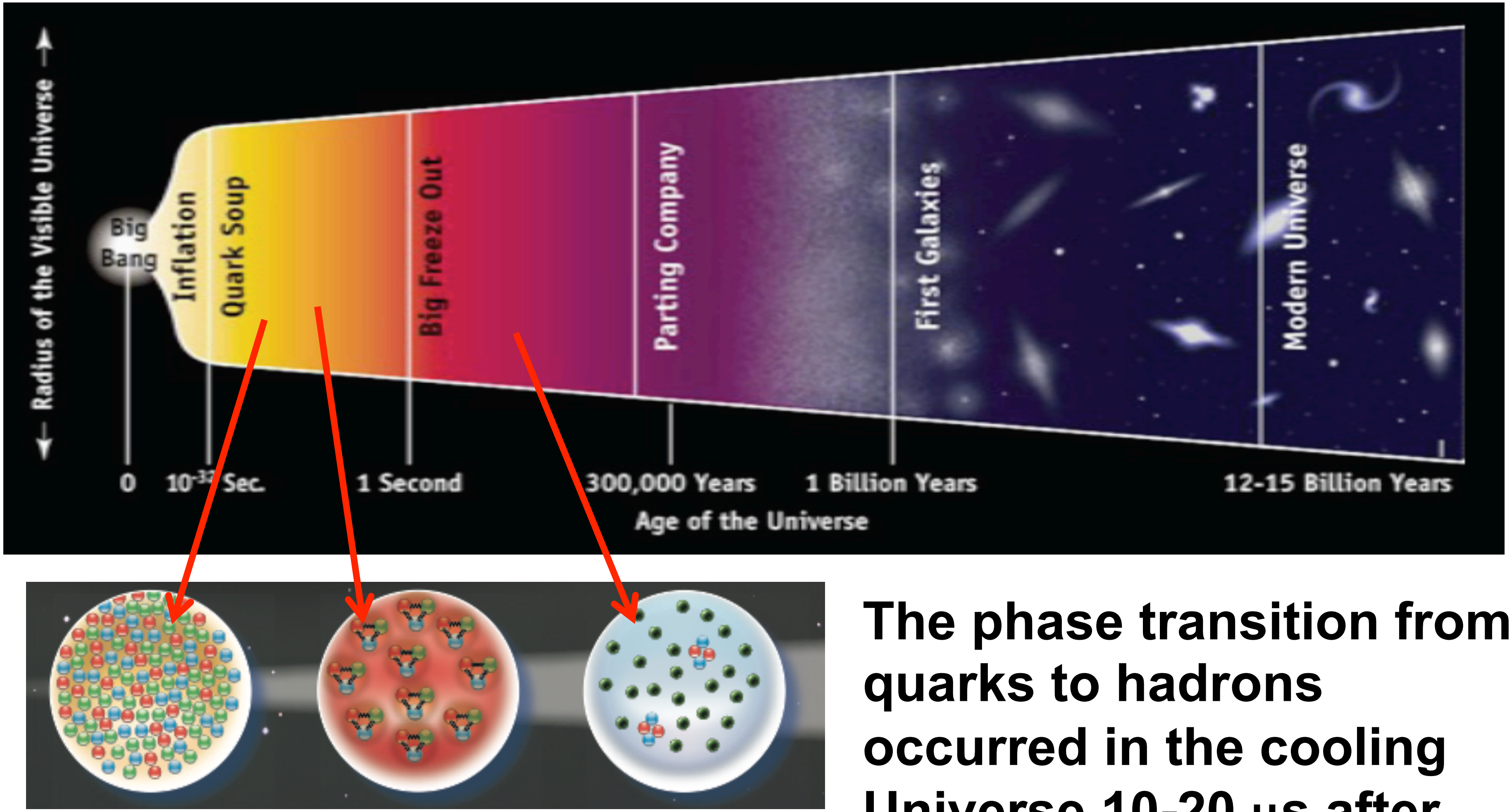


➡ the binding of a $q\bar{q}$ pair is subject to the effects of colour screening:

- the "confinement" contribution disappears
- the coulombian term of the potential is screened by the high color density

Matsui, Satz, PLB178 (1986) 416

Quark-Gluon Plasma (QGP): the first “matter” in the primordial Universe



quark-gluon plasma

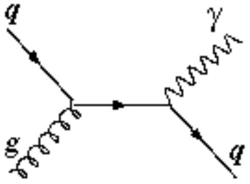
formation of protons/neutrons

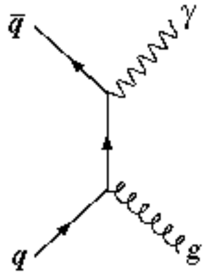
formation of atomic nuclei

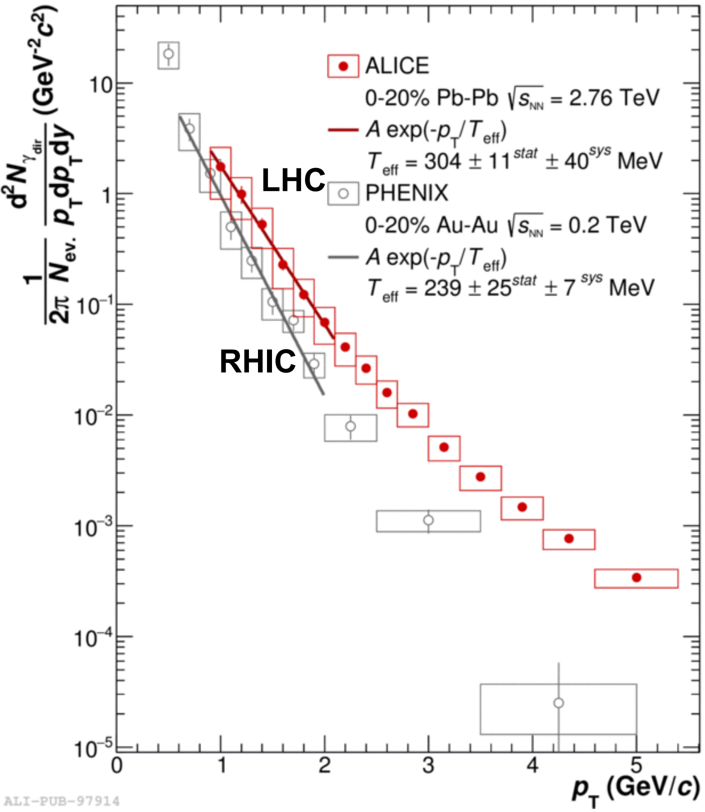
The phase transition from quarks to hadrons occurred in the cooling Universe 10-20 μs after the Big Bang

Temperature from Photon spectrum

- Photons in heavy-ion collisions
  - Photons from QCD hard scattering: power law spectrum – dominant at high p_T
  - Thermal photons, emitted by the hot system (analogy with black body radiation): exponential spectrum – dominant at low p_T
    - From inverse slope:



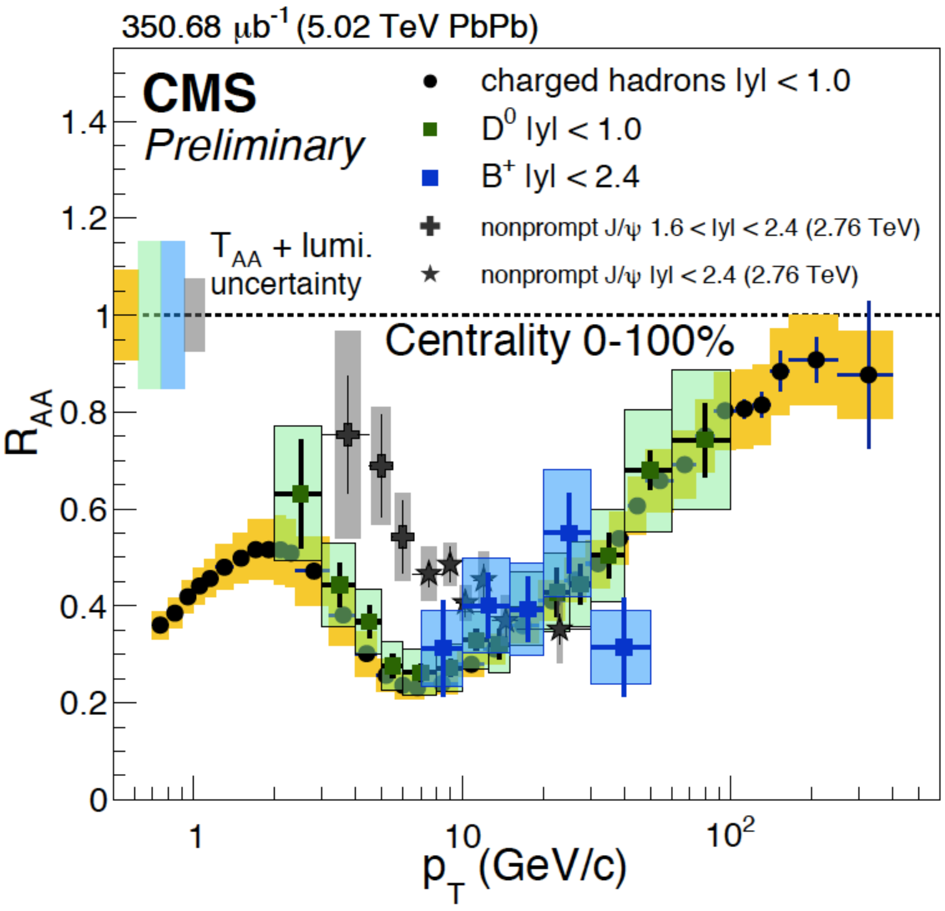




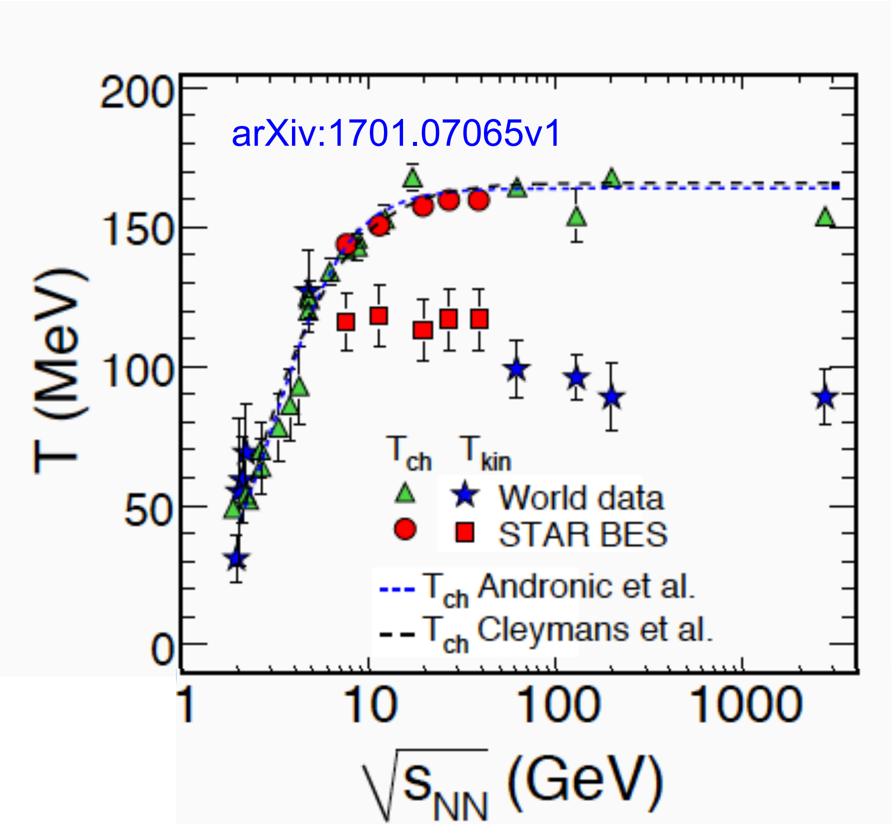
T_{eff} = 304 ± 41 MeV
~ 2 T_c (T_c~160 MeV)
~ 1.25 x T_{eff}(RHIC)

ALICE, Phys.Lett. B754 (2016) 235

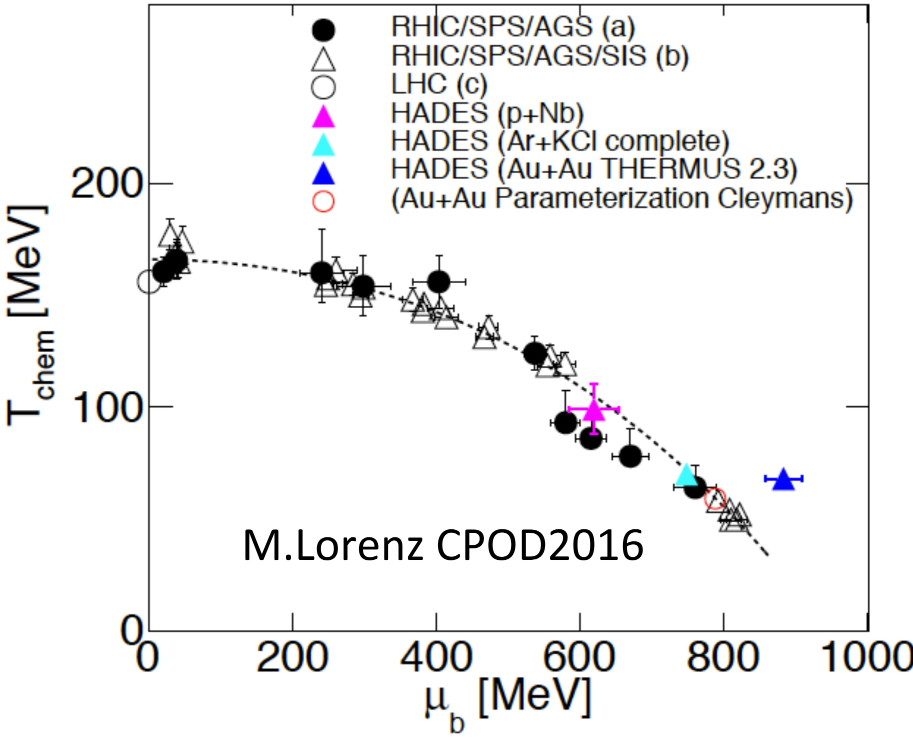
Beauty nuclear modification factor



Beam-energy scan at RHIC



arXiv:1701.07065v1

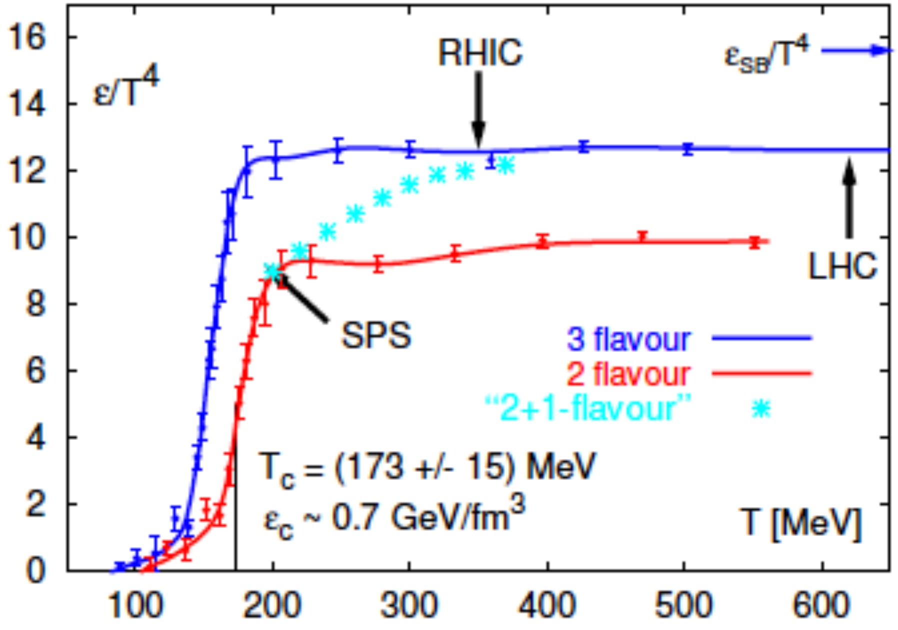


M.Lorenz CPOD2016

Lattice QCD: Phase Transition

Lattice QCD is neither a calculation not a simulation: “realization” of QCD over a discretized space. It allows to compute thermodynamical properties of a system even in a non-perturbative regime of QCD

$$\frac{\varepsilon}{T^4} \quad vs. \quad T \longrightarrow$$ Proportional to number of degrees of freedom (ndof) (S. Boltzmann’s law)



- Zero baryon density, 2(u, d) or 3 (u, d, s) quark flavours
- **ε changes rapidly around T_c**
- **→ signal change in number of degrees of freedom**

- Most recent calculations:

  $T_c \sim 155$ MeV :

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

F. Karsch. Lattice QCD at High Temperature and Density. Lecture Notes of Physics, vol. 583, 2002. arXiv:hep-lat/0106019.

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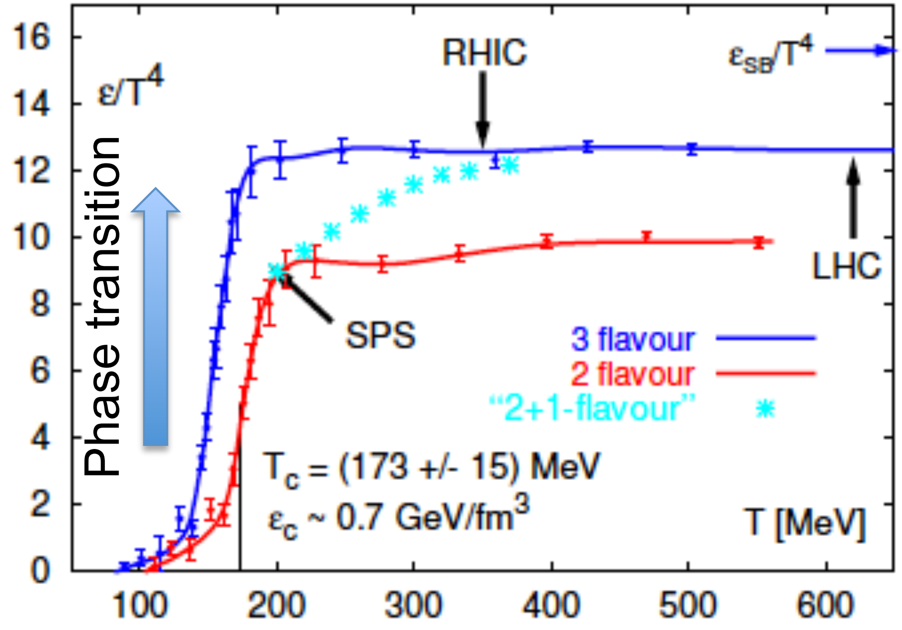


$$n_{dof} = n_b + \frac{7}{8} n_f$$

Below T_c: gas of pions

$$n_b = 3(\text{isospin});\ n_f = 0 \quad \Rightarrow n_{dof} = 3$$

Above T_c: gas of g, u, d, (s) and anti-quarks

$$n_b = 8(\text{colors}) \times 2(\text{polar.})$$

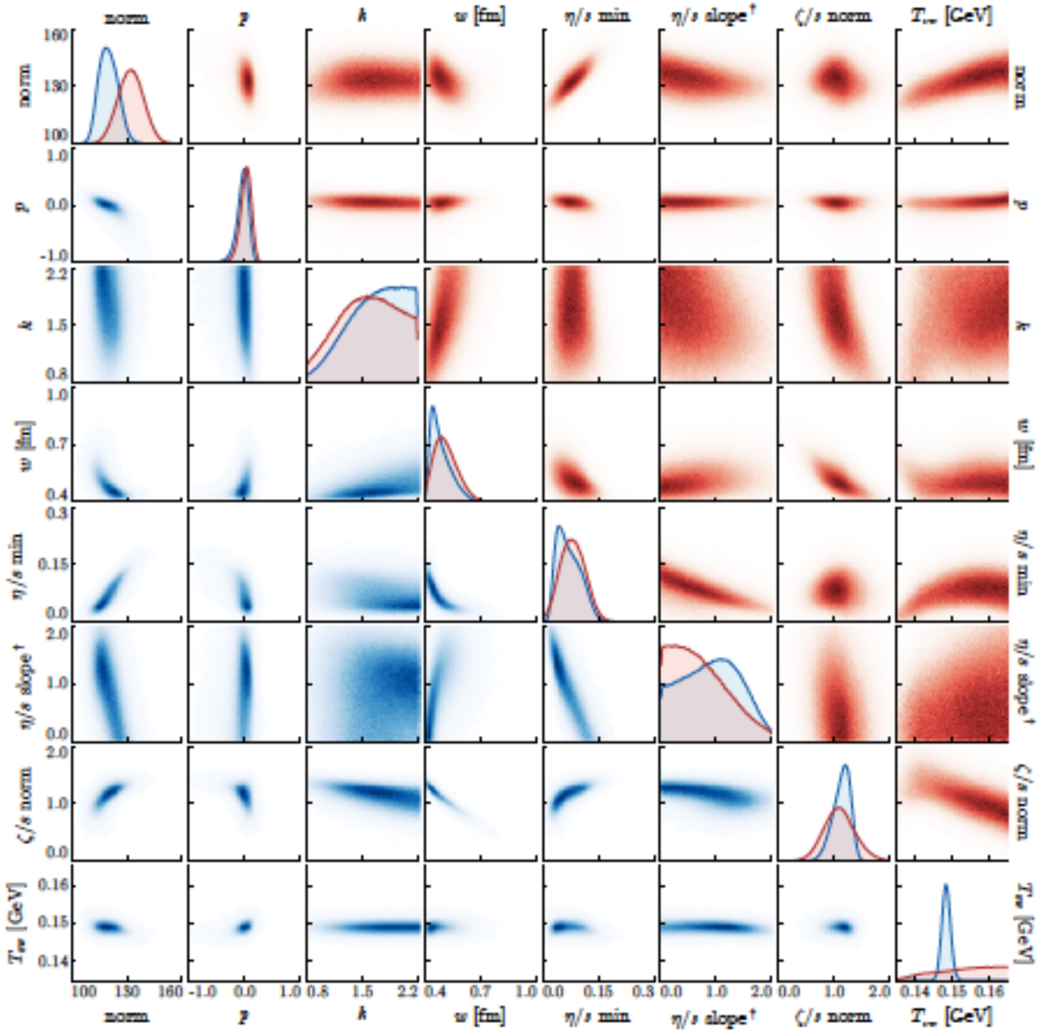
$$n_f = 3(\text{colors}) \times 2(\text{polar.}) \times 2(\text{flav.}) \times 2(\text{charg.})$$

$$\Rightarrow n_{dof} = 37(47.5)$$

F. Karsch. Lattice QCD at High Temperature and Density. Lecture Notes of Physics, vol. 583, 2002. arXiv:hep-lat/0106019.

Constraining further viscosity: example with a model

J. E. Bernhard et al. Phys. Rev. C 94, 024907 (2016)

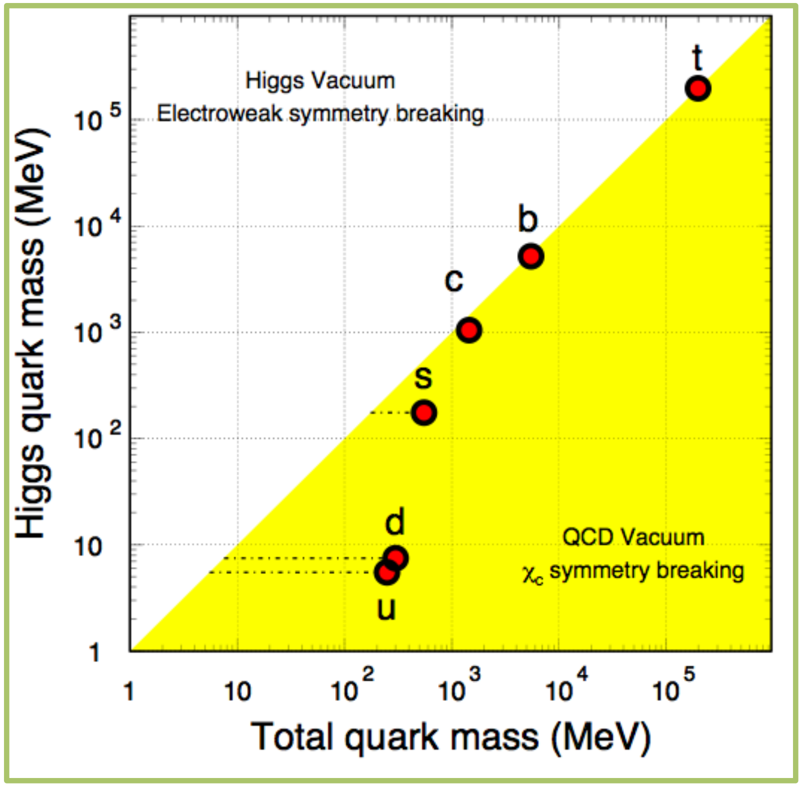


Restoration of bare quark masses

- Confined quarks acquire an additional mass (~ 350 MeV) dynamically, through the confining effect of strong interactions

- Deconfinement is expected to be accompanied by a restoration of the masses to the “bare” values they have in the Lagrangian
  - m(u,d): ~ 350 MeV → a few MeV
  - m(s): ~ 500 MeV → ~ 150 MeV

- (This effect is usually referred to as “Partial Restoration of Chiral Symmetry”. Chiral Symmetry: fermions and antifermions have opposite helicity. The symmetry is exact only for massless particles, therefore its restoration here is only partial)



X.Zhu et al., PLB 647 (2007) 366