About International Conference on New Frontiers in Physics 2013

https://indico.cern.ch/conferenceDisplay.py?confId=198153

from 28 August 2013 to 5 September 2013 Kolymbari, Crete, Greece

A High Energy Particle Physics:

Searches for new particles and new phenomena at the LHC and other colliders (Higgs boson, SUSY, top quarks, extra dimensions, flavour physics, precision electroweak measurements and other), neutrino experiments, and related theoretical topics.

B Heavy Ion Collisions and Critical Phenomena :

Establishing the properties of QCD matter at extreme conditions and the QCD phase diagram with Heavy Ion Collisions and related theoretical topics. Branching out to neighboring disciplines, including Superconductivity and Critical Phenomena, Neutron Stars, Quark Stars, Exotics.

C Quantum Physics and Quantum Entanglement :

Quantum Physics, Quantum Optics, Quantum Entanglement, Foundations of Quantum Mechanics, Entanglement and our Universe: Black Holes and Cosmology, Quantum Non-Locality.

D Cosmology, Astrophysics, Gravity, Mathematical Physics :

Cosmic Microwave Background, Dark Energy, Modified Gravity, direct and indirect searches for Dark Matter, Astroparticle Physics, Quantum Gravity, String Theory, Non Commutative Geometry, Holography, Black Holes.

From the talk of Peter Braun-Munzinger:

Relativistic nuclear collisions: main goals, recent achievements, and future opportunities

Outline:

- The general context: QCD and extreme matter
- Fundamental questions
- The hot fireball and the QCD phase boundary
- The 'high baryon density' regime – are there new phases?
- Strongly coupled systems, flow and parton energy loss
- Heavy quarks, quarkonia, and deconfinement
- Outlook and strategical issues

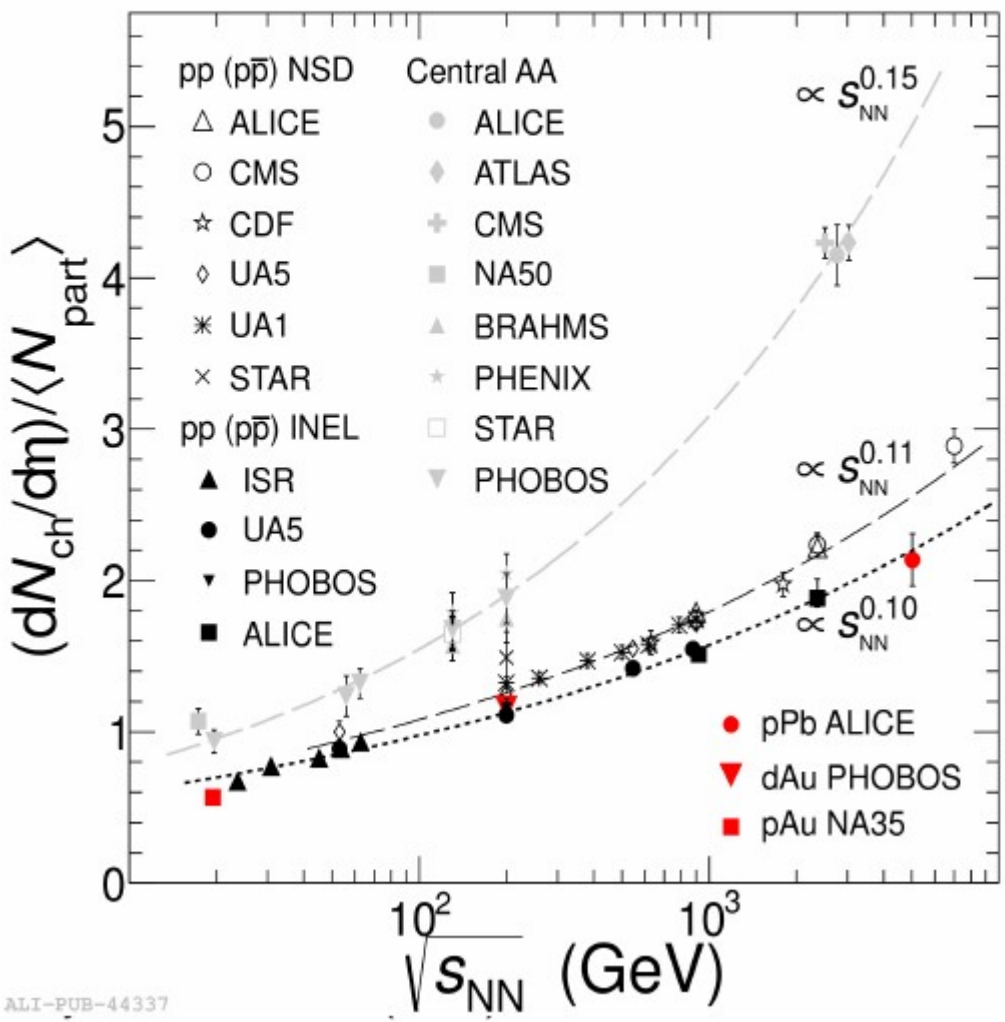
pbm, ICNFP, Kolymbari, Crete, Greece, Aug. 29, 2013

The 'condensed matter' phases of QCD – F. Wilczek, 2000
fundamental questions about extreme matter

- what are the properties of deconfined matter at extreme temperatures and densities, is chiral symmetry restored?
- can the transition temperature to the QGP be measured?
- what are its macroscopic transport parameters and equation of state?
- what is the nature of microscopic excitations and quasi-particles?
- is the QGP a strongly coupled liquid? how is its structure related to other strongly coupled systems?

Relativistic nuclear collisions:
a tool to study bulk properties of non-abelian matter in the laboratory

Charged particle multiplicity in pp, pPb and central PbPb collisions

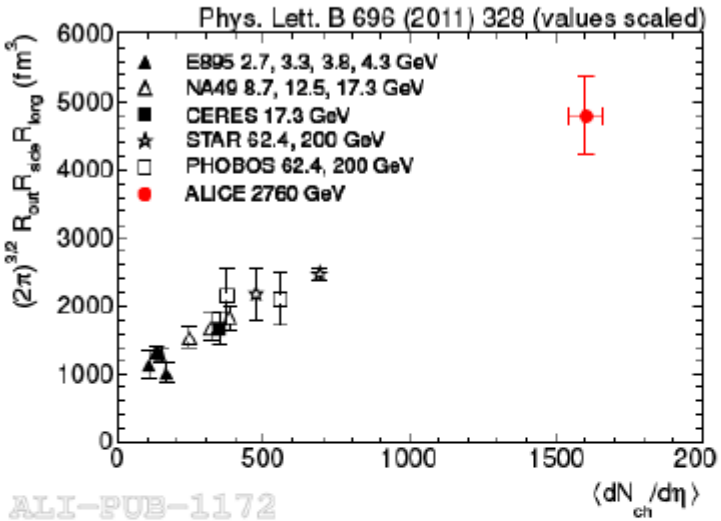


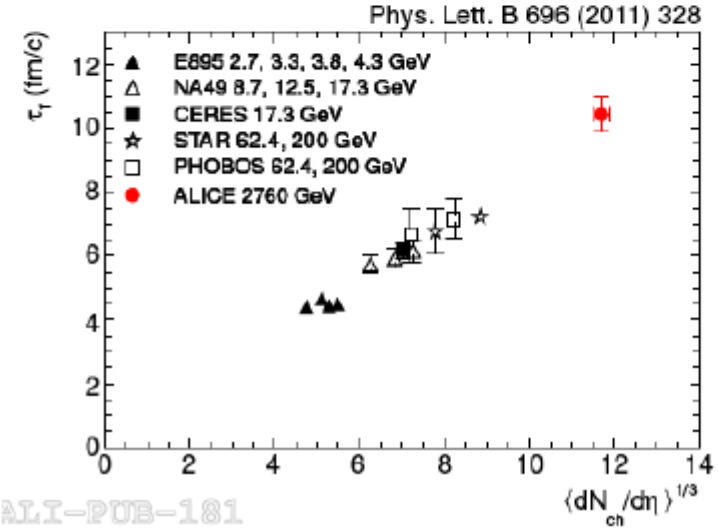
increase with beam energy significantly steeper than in pp

Fireball at LHC energy has much larger size and lives longer

volume and lifetime from HBT analysis

fireball volume at freeze-out is about 5 x large than volume of a Pb nucleus





Equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: a test of equilibration of quark matter near the phase boundary

- No (strangeness) equilibration in hadronic phase

- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis

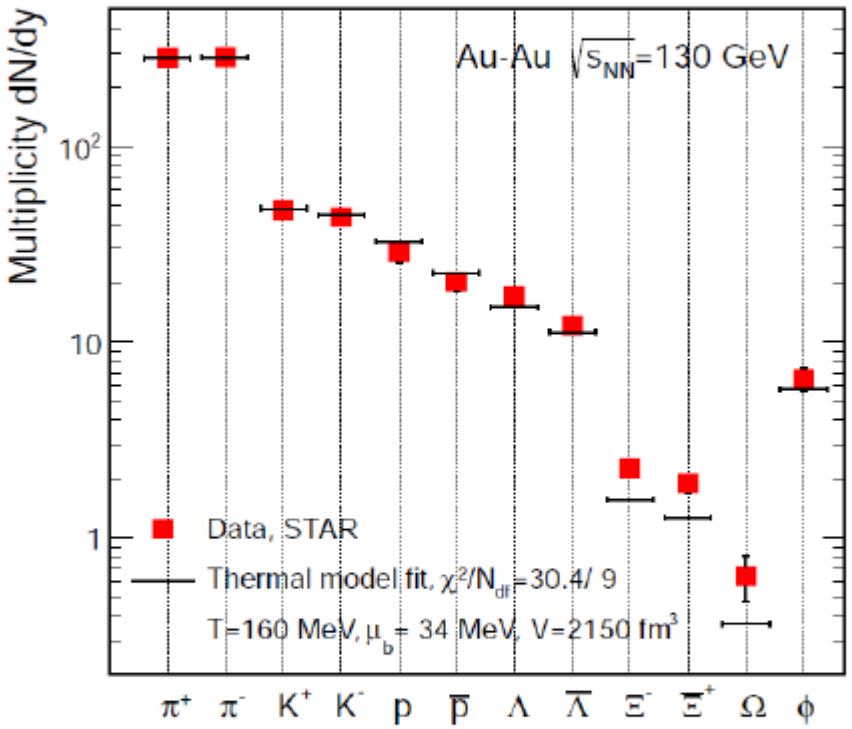
pbm, Stachel, Wetterich,
Phys.Lett. B596 (2004) 61-69

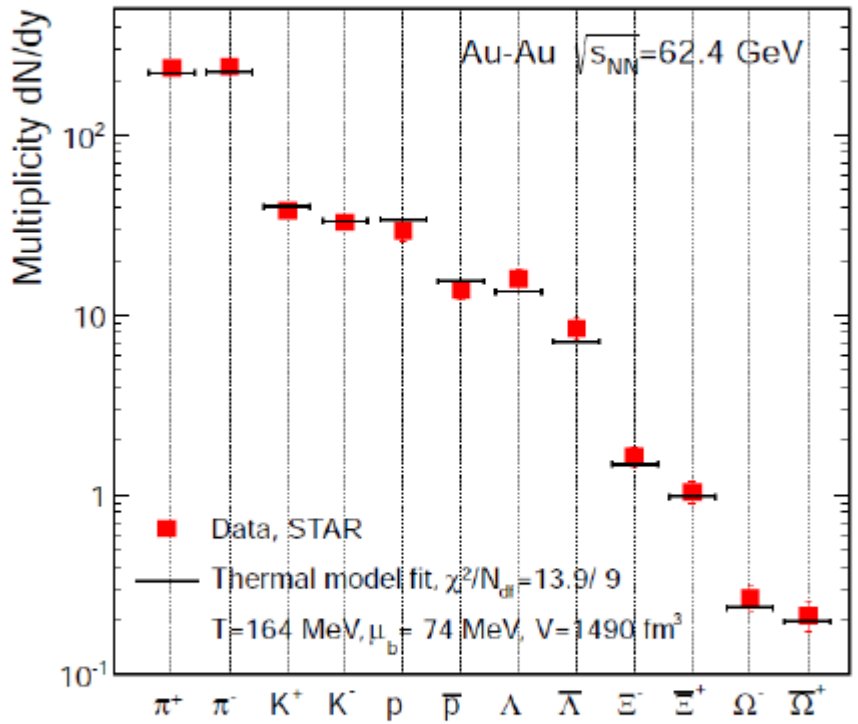
- This implies little energy dependence above RHIC energy

- Analysis of hadron production → determination of T_c

Is this picture also supported by LHC data?

Example: RHIC lower energies, STAR data alone





good fits, T = 160 – 164 MeV

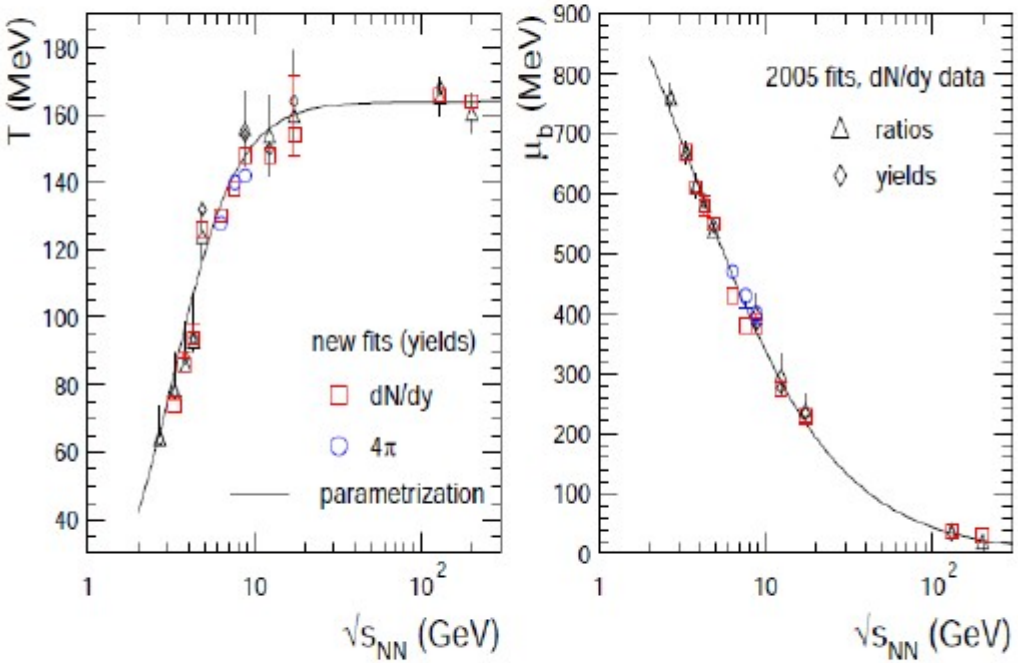
Parameterization of all freeze-out points before LHC data

note: establishment of limiting temperature

T_{lim} = 160 +/- 4 MeV

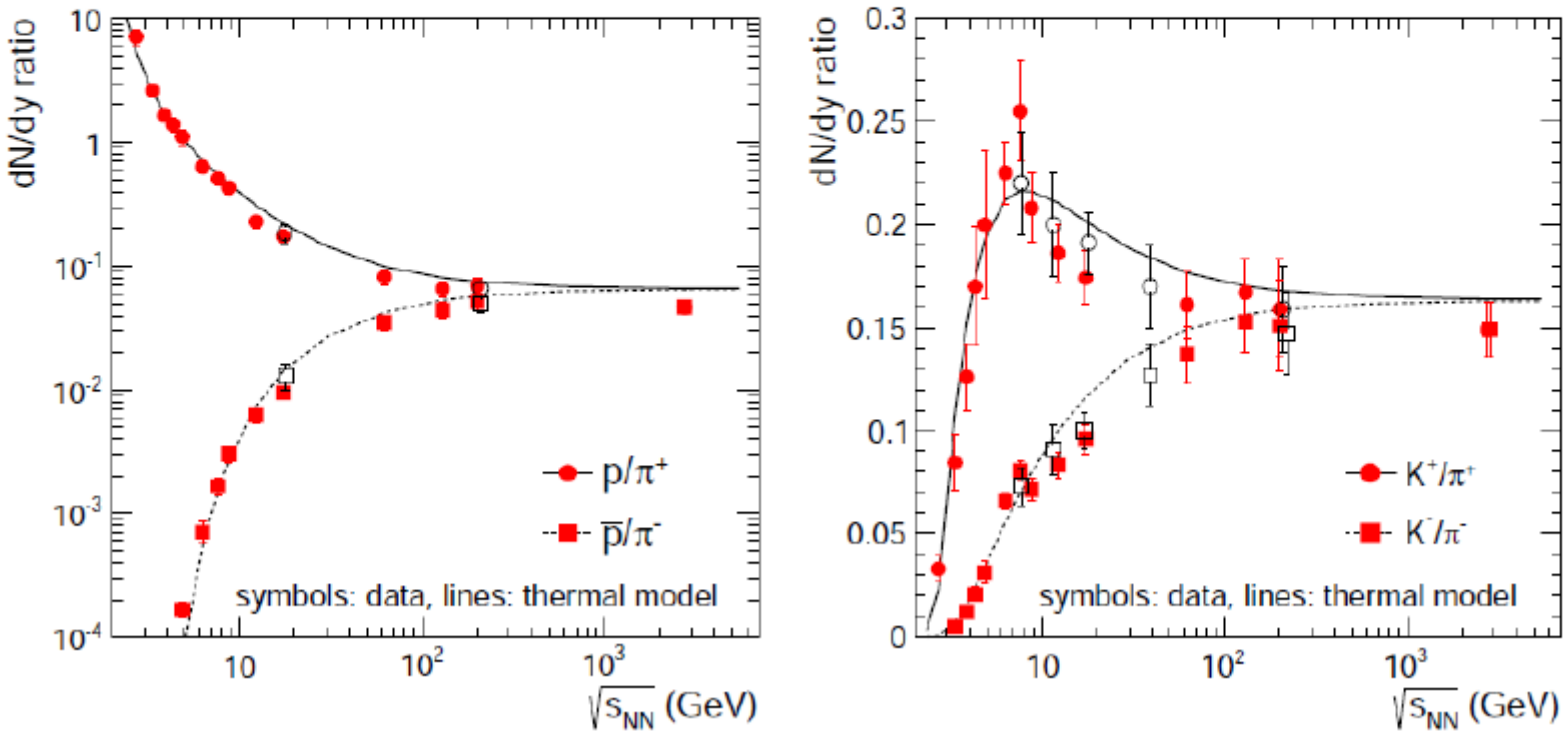
get T and μ_B for all energies

for LHC predictions we picked T = 164 MeV

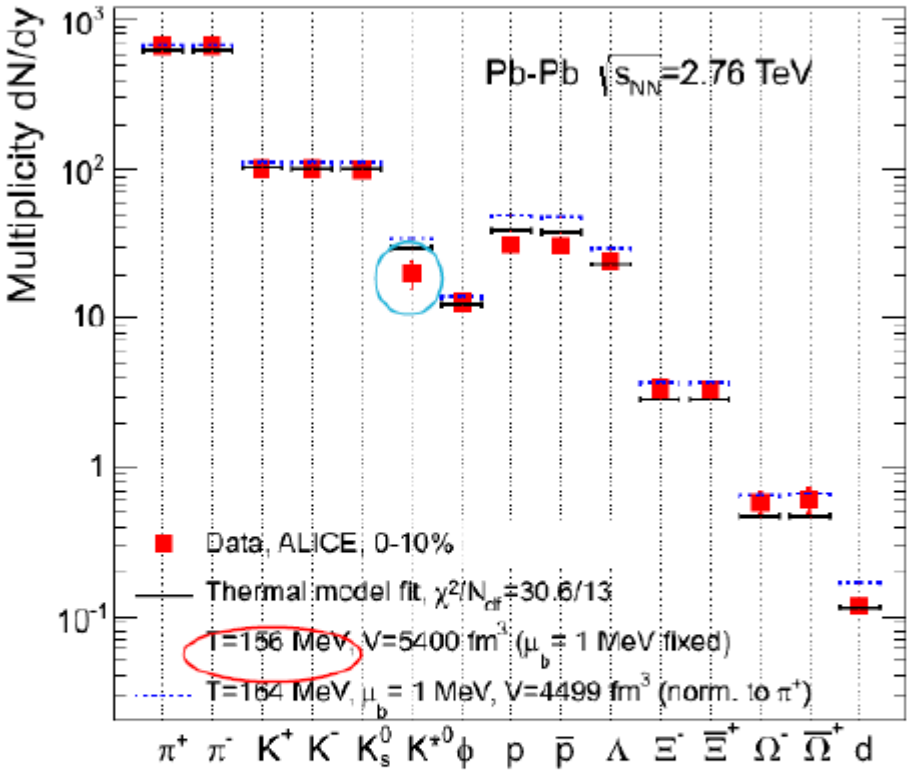


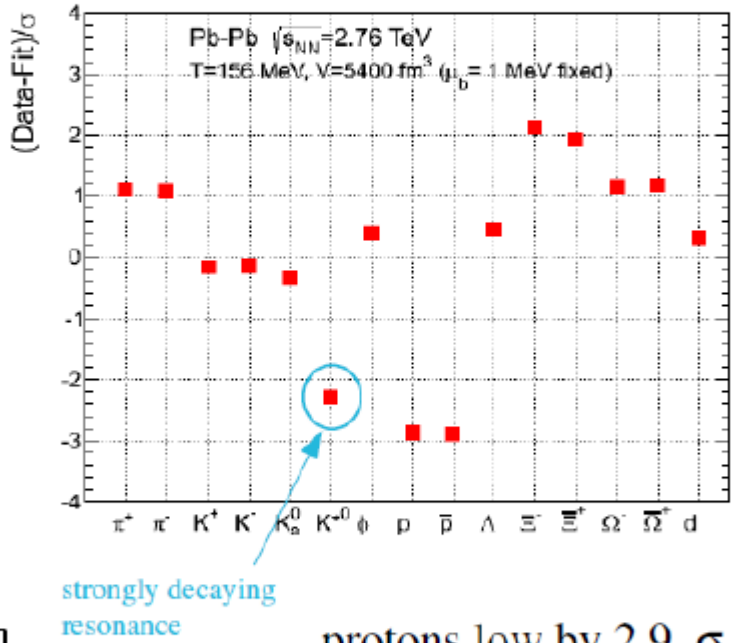
A. Andronic, pbm, J. Stachel, Nucl. Phys. A772 (2006) 167
nucl-th/0511071

overall systematics, including ALICE data, on proton/pion and kaon/pion ratios



New fit of Alice data including hyperons and light nuclei





protons low by 2.9 σ

as compared to 2012: more and final data

T went from 152 to 156 MeV

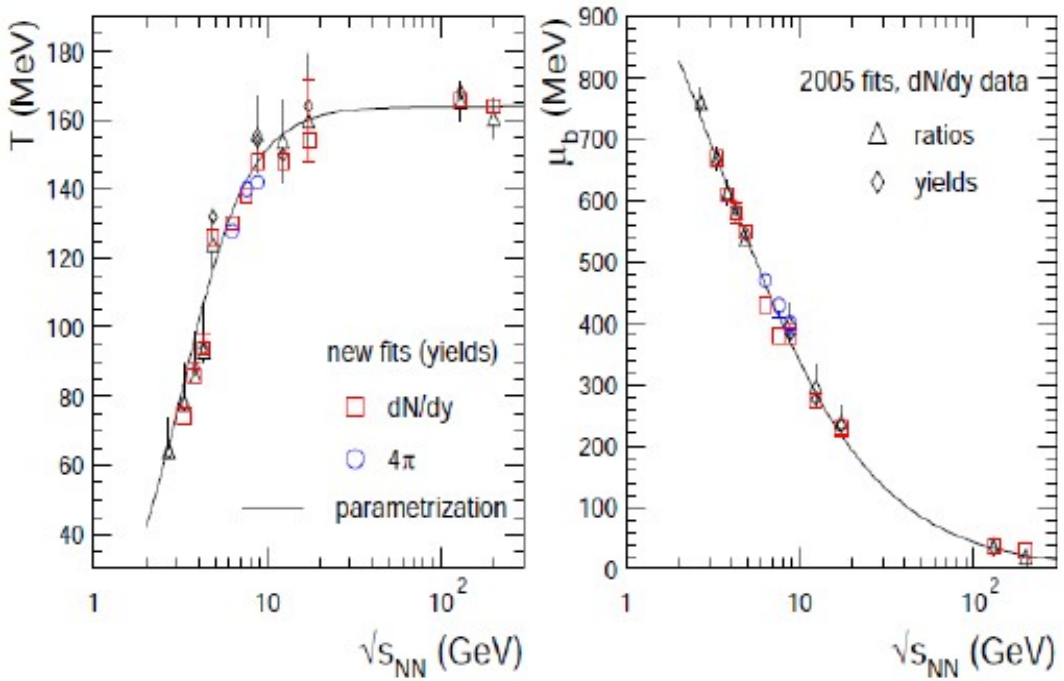
red. χ^2 went from 4 to 2.35

hot off the press

T = 156 MeV produces quite a good fit to all data!

summary

- energy dependence of (u,d,s) hadron production well understood
- limiting temperature reflects phase boundary
- critical temperature close to 160 MeV
- remaining baryon discrepancy: an issue of active debate
  annihilation? non-equilibrium hadronization? light nuclei will tell!



Universality of QCD Hadronization

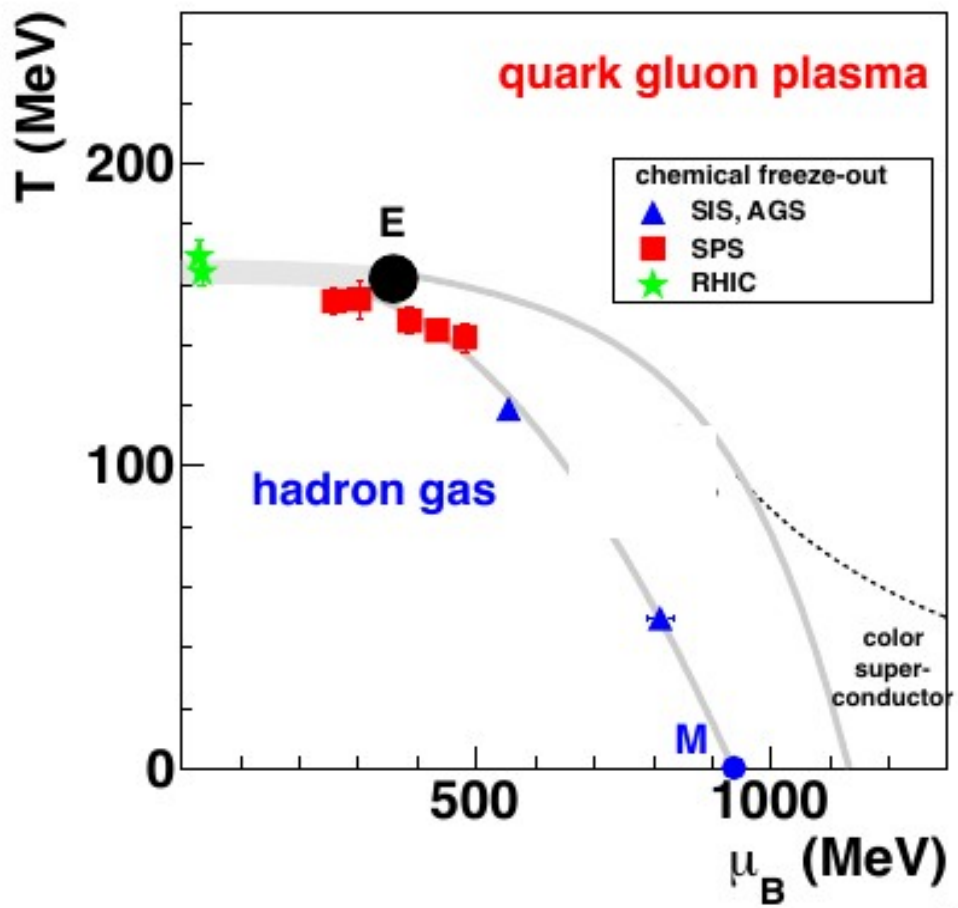
Reinhard Stock

Sketch of the QCD Phase Diagram

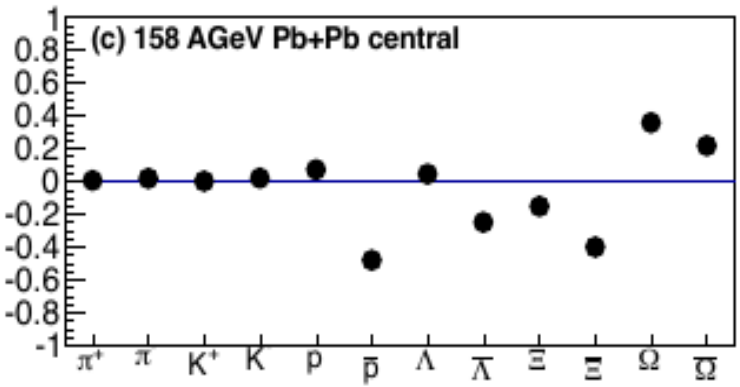
Assumption in the stat. model analysis:

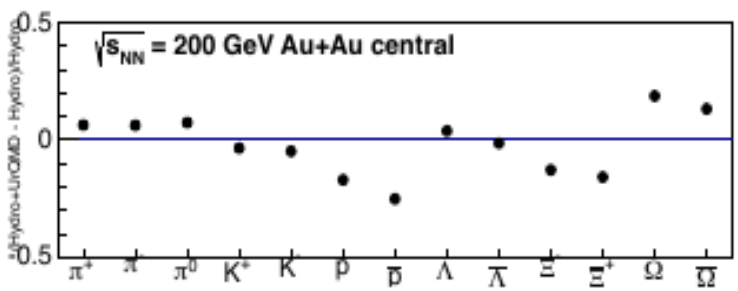
Hadron abundances freeze out directly at QCD hadronization and thus survive the hadronic expansion stage

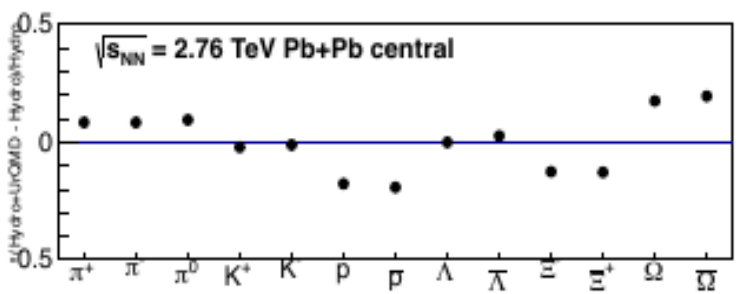
TRUE?



UrQMD Study of Hadronic Expansion Effects on Hadron Yields







- Employ the recent hybrid version of UrQMD:
  - Hydrodynamic (3+1) phase until energy density < 1 GeV/fm3, plus hadronic emission à la Cooper-Frye.
  - Attach UrQMD hadronic expansion as an "afterburner" stage.

- Compare hadronic yields directly after Cooper-Frye with those after the "afterburner" stage.

SERIOUS ANNIHILATION EFFECTS in baryon and antibaryon sector!

Regeneration also active.

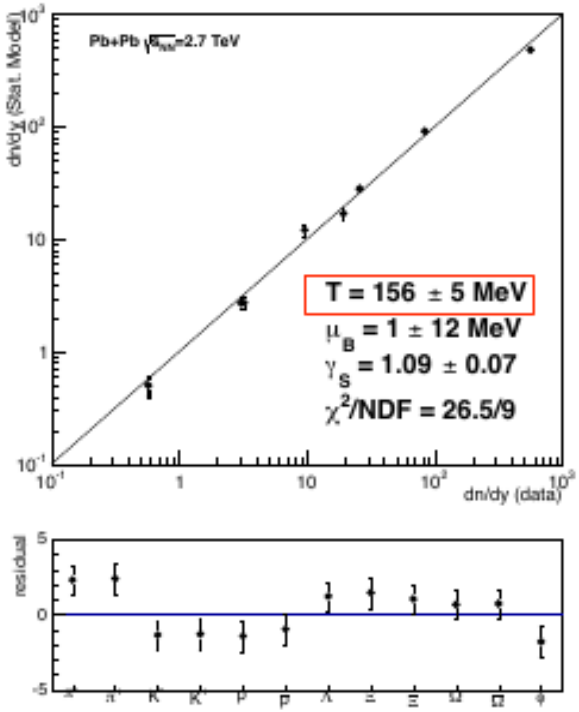
- Effect depends on energy

Survival factors from UrQMD

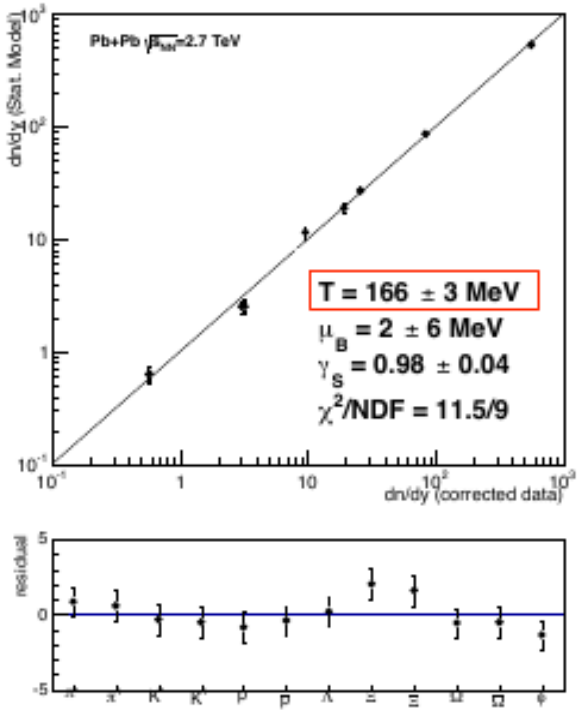
LHC at 2.76 TeV, Central Pb+Pb

F.Becattini et al., arXiv:1212.2431 **(accepted by PRL)**

Standard SM fit



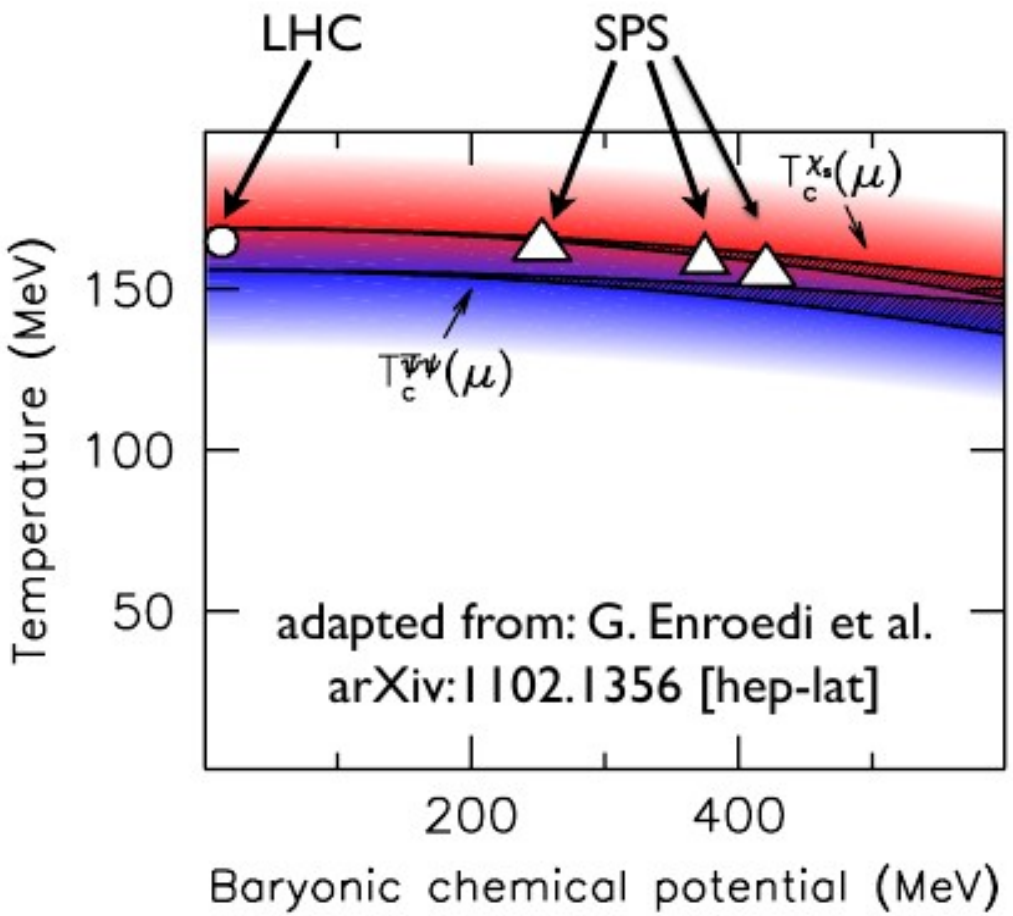
Apply correction factors



T as in e^+e^- Annihilation

Data: ALICE collaboration, preliminary Quark Matter 2012

Freeze-out revisited:
The Phase Diagram



F.Becattini et al., arXiv:1212.2431 **(accepted by PRL)**

16.8.13

Hadrosynthesis and Quark Confinement

Helmut Satz

Universität Bielefeld, Germany

basic observation in all high energy multihadron production

thermal production pattern

Fermi, Landau, Pomeranchuk, Hagedorn

- species abundances $\sim$ ideal resonance gas at T_H
- universal $T_H \simeq 150 - 200$ MeV for all (large) $\sqrt{s}$

caveats

- strangeness suppression in elementary collisions
- strangeness suppression weakened/removed in nuclear collisions

1. Thermal Hadron Production

what is "thermal"?

- equal *a priori* probabilities for all states in accord with given overall average energy $\Rightarrow$ temperature T;

- partition function of ideal resonance gas

$$\ln Z(T) = V \sum_i \frac{d_i}{(2\pi)^3} \phi(m_i, T)$$

Boltzmann factor $\phi(m_i, T) = 4\pi m_i^2 T K_2(m_i/T) \sim \epsilon^{-m_i/T}$;

- relative abundances $\dfrac{N_i}{N_j} = \dfrac{d_i \phi(m_i, T)}{d_j \phi(m_j, T)} \sim \epsilon^{-(m_i - m_j)/T}$

predicted in terms of temperature T

Abundances

e^+e^-, LEP Data [Becattini 1996]

Fit relative abundances to ideal resonance gas of all hadronic resonances, with $M \leq 1.7$ GeV, two parameters T and γ_s

$T = 169.9 \pm 2.6$ MeV

$\gamma_s = 0.691 \pm 0.053$

$\chi^2/\text{dof} = 17.2/12$

estimate systematic error by varying resonance gas scheme, contributing resonances

e^+e^- $\sqrt{s} = 91.2$ GeV				
species	measured			fit
π^+	8.53	$\pm$	0.40	8.72
π^0	9.18	$\pm$	0.82	9.83
K^+	1.18	$\pm$	0.052	1.06
K^0	1.015	$\pm$	0.022	1.01
η	0.934	$\pm$	0.13	0.908
ρ^0	1.21	$\pm$	0.22	1.16
K^{*+}	0.357	$\pm$	0.027	0.349
K^{*0}	0.372	$\pm$	0.027	0.343
η'	0.13	$\pm$	0.05	0.1070
p	0.488	$\pm$	0.059	0.484
ϕ	0.10	$\pm$	0.0090	0.167
Λ	0.185	$\pm$	0.0085	0.152
Ξ^-	0.0122	$\pm$	0.00079	0.011
Ξ^{*0}	0.0033	$\pm$	0.00047	0.00391
Ω	0.0014	$\pm$	0.00046	0.000782

$$T = 170 \pm 10 \text{ MeV}, \ \gamma_s \simeq 0.7 \pm 0.1$$

corresponding analyses for hadronic collisions

- pp at $\sqrt{s} = 19.4,\ 23.8,\ 26.0,\ 27.4$ GeV
- $p\bar{p}$ at $\sqrt{s} = 200,\ 500,\ 900$ GeV
- $\pi^+ p$ at $\sqrt{s} = 21.7$ GeV
- $K^+ p$ at $\sqrt{s} = 11.5,\ 21.7$ GeV

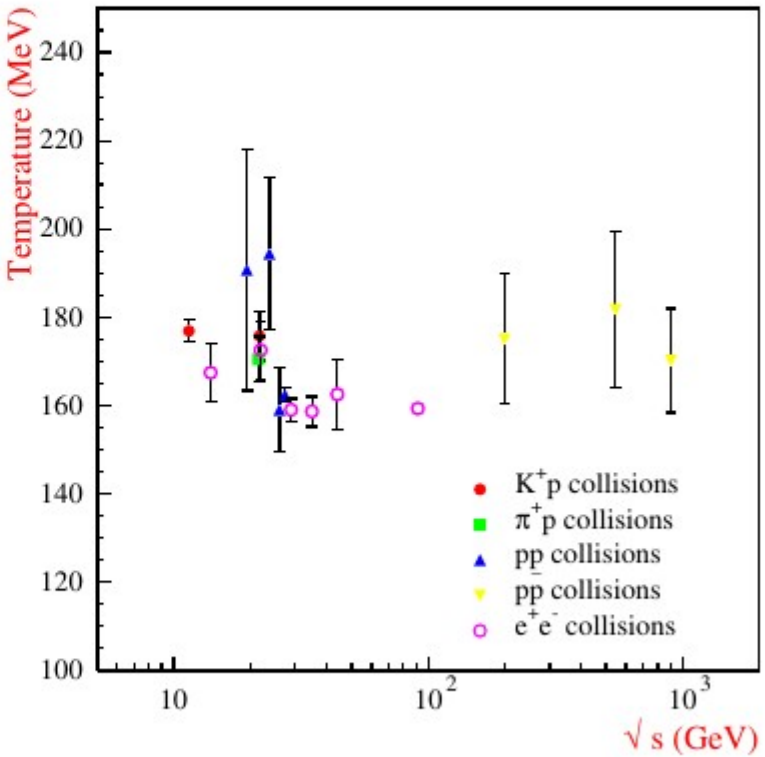
compilation Becattini 2006

Result:

$$T \simeq 170 \pm 20 \text{ MeV}$$

$$\gamma_s \simeq 0.7 \pm 0.2 \text{ MeV}$$

independent of
- collision energy
- collision configuration



Heavy ion collisions ⇒ baryon density

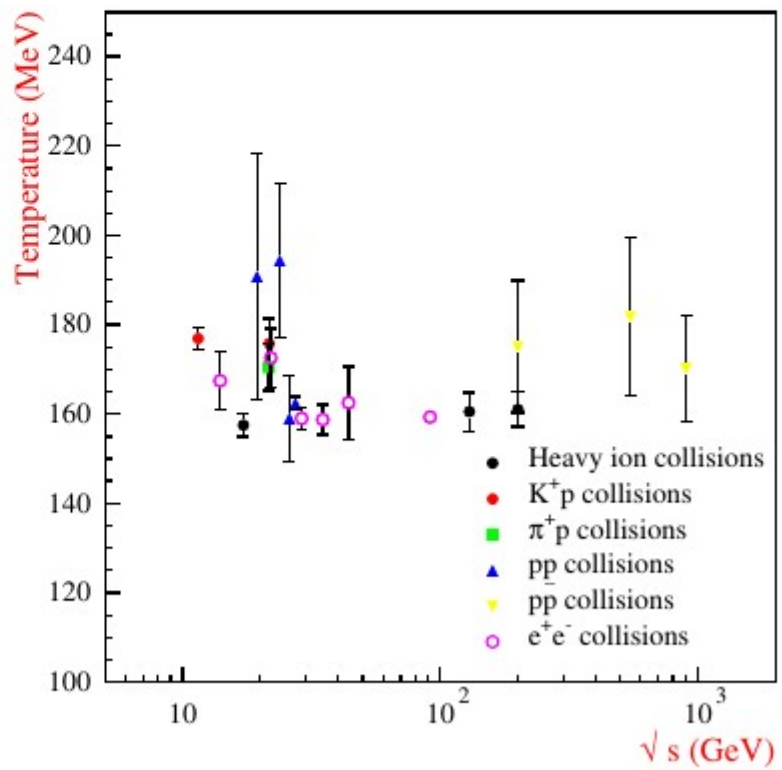
- resonance gas at T, μ_B; $\mu_B \Downarrow$ for $\sqrt{s} \Uparrow$
- consider species abundances in high energy heavy ion collisions (peak SPS, RHIC)

compilation Becattini 2006

Result:

<u>same hadronization temperature</u>
for high energy heavy ion and elementary collisions, collision energy independent

<u>increased strangeness</u>
$\gamma_s \longrightarrow 0.8 - 1.0$ for high energy heavy ion collisions



Conclude:

Hadron abundances in all high energy collisions (e^+e^- annihilation, hadron-hadron interactions and heavy ion collisions) are those of an ideal resonance gas at a universal temperature

$$T_H \simeq 170 \pm 20 \text{ MeV}.$$

Strangeness production in elementary collisions is uniformly **suppressed** by $\gamma_s \simeq 0.6 - 0.7$

suppression **weakened/removed** in heavy ion collisions

WHY?

- Why do elementary high energy collisions produce a thermal medium?

  For nucleus-nucleus collisions possibly multiple parton interactions $\longrightarrow$ kinetic thermalization; e^+e^-, $pp/p\bar{p}$ not

- Is there another non-kinetic thermalization mechanism, providing a common origin of thermal production in all high energy collisions?

- Why is strangeness production universally suppressed in elementary collisions?

- Why no strangeness suppression in nuclear collisions?

- Why do elementary high energy collisions produce a thermal medium?

  For nucleus-nucleus collisions possibly multiple parton interactions $\longrightarrow$ kinetic thermalization; e^+e^-, $pp/p\bar{p}$ not

- Is there another non-kinetic thermalization mechanism, providing a common origin of thermal production in all high energy collisions?

- Why is strangeness production universally suppressed in elementary collisions?

- Why no strangeness suppression in nuclear collisions?

Conjecture:

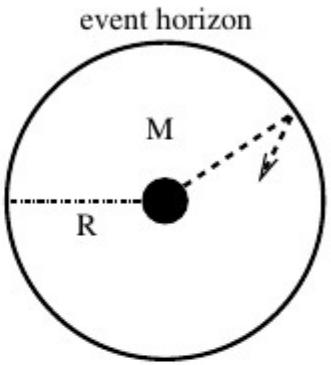
physical vacuum $\sim$ event horizon for colored constituents
thermal hadron production $\sim$ Hawking-Unruh radiation of QCD

[Paolo Castorina, Dmitri Kharzeev, HS 2007]

2. Black Holes and Event Horizons

- black hole

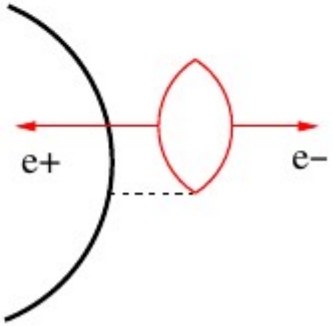
  neutron star after gravitational collaps
  large mass M and compact size
  gravitation so strong that matter &
  light are confined $\Rightarrow$ event horizon R
  no communication with outside, but...

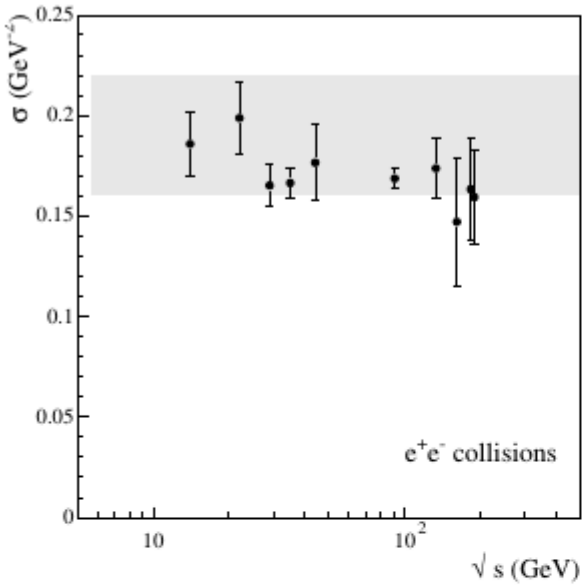


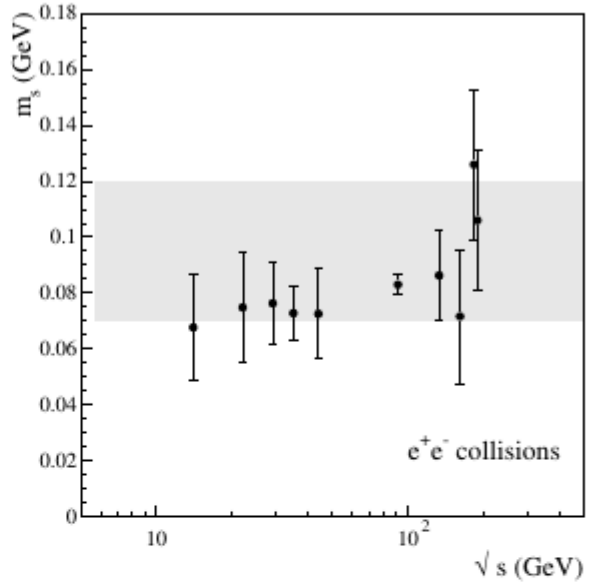
- Hawking radiation

[Hawking 1975]

  quantum effect $\sim$ uncertainty principle
  vacuum fluctuation e^+e^- outside event
  horizon, with $\Delta E \Delta t \sim 1$
  if in Δt, e^+ falls into black hole,
  then e^- can escape; equivalent:
  e^- tunnels through event horizon







Conclude

thermal hadron production in e^+e^- annihilation, includ'g strangeness suppression, is reproduced parameter-free as

Hawking-Unruh radiation of QCD

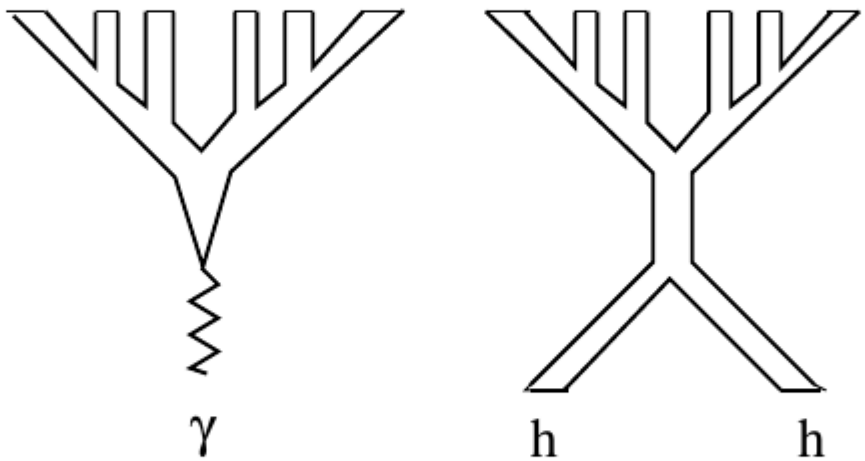
$\Rightarrow$ $pp/p\bar{p}$ (straight-forward); heavy ions (interesting)

6. Summary

- The physical vacuum is an event horizon for coloured quarks and gluons; thermal hadrons are Hawking-Unruh radiation produced by quark tunnelling through event horizon.
- The corresponding hadronization temperature T_H is determined by quark acceleration and deceleration in the colour field at the (quantum) horizon.
- Strangeness suppression arises through modified Unruh temperature for strange quark mass. In nuclear collisions, it is effectively removed by averaging.
- Given string tension σ and strange quark mass m_s, the resulting scenario provides a parameter-free description of thermal hadron production in all high energy interactions.

generalize:

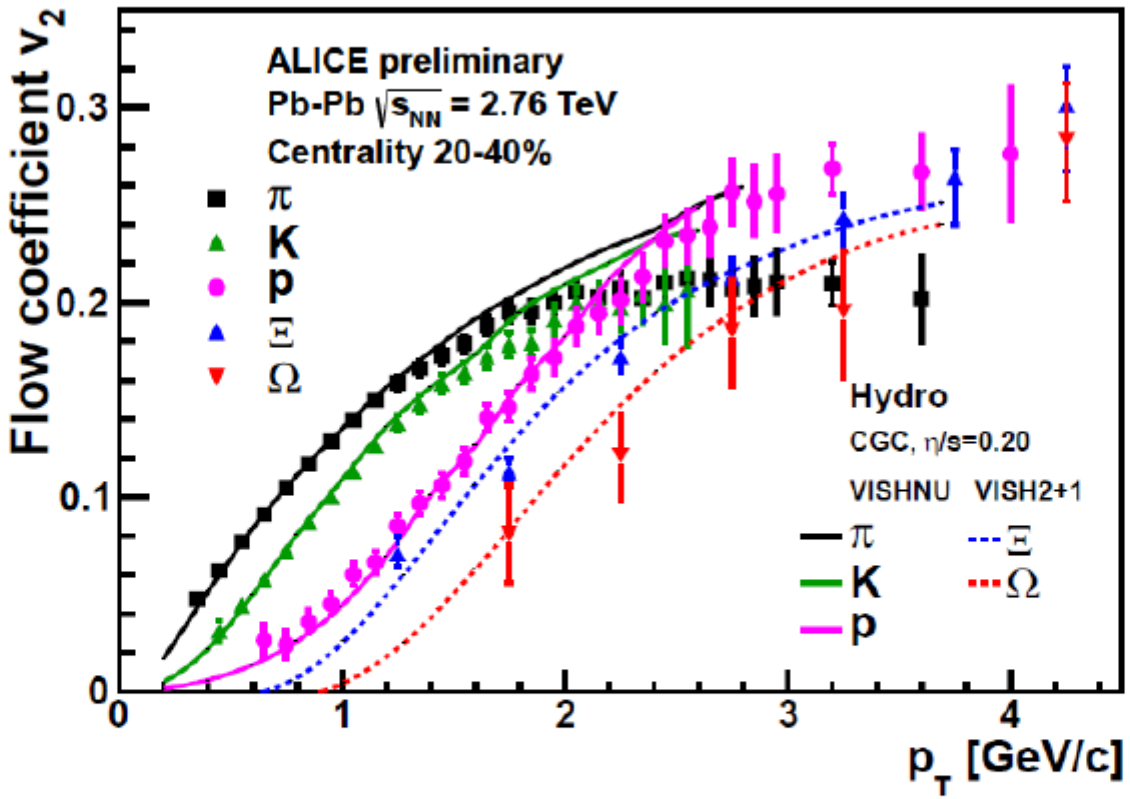
e^+e^- annihilation	hadron-hadron collision
"black hole" creation	"black hole" fusion



both → self-similar cascades

Heavy ion collisions: interference between emitted hadrons

Elliptic Flow in PbPb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

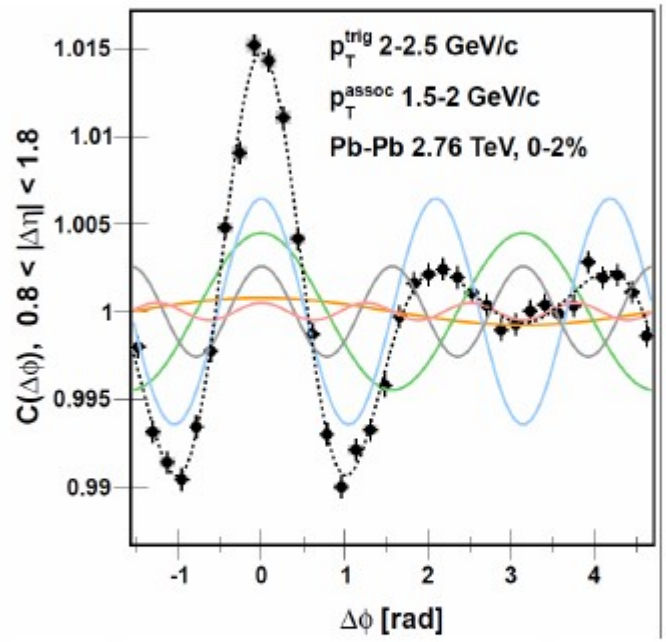


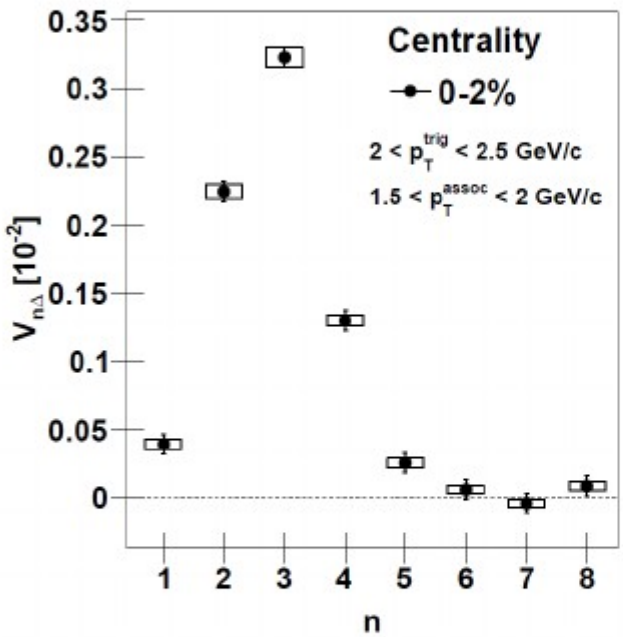
rapidly rising v_2 with p_t and mass ordering are typical features of hydrodyn. expansion

nearly ideal (non-dissipative) hydrodynamics reproduces data, system fairly strongly coupled

The 2-particle correlation function – higher moments

ALICE, PRL 107 (2011) 032301





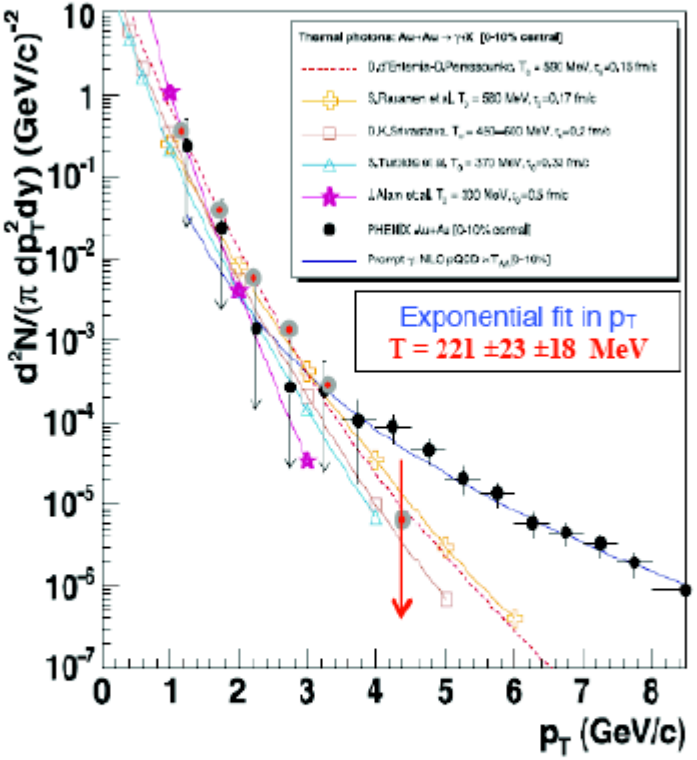
measurement of the first 8 harmonic coefficients

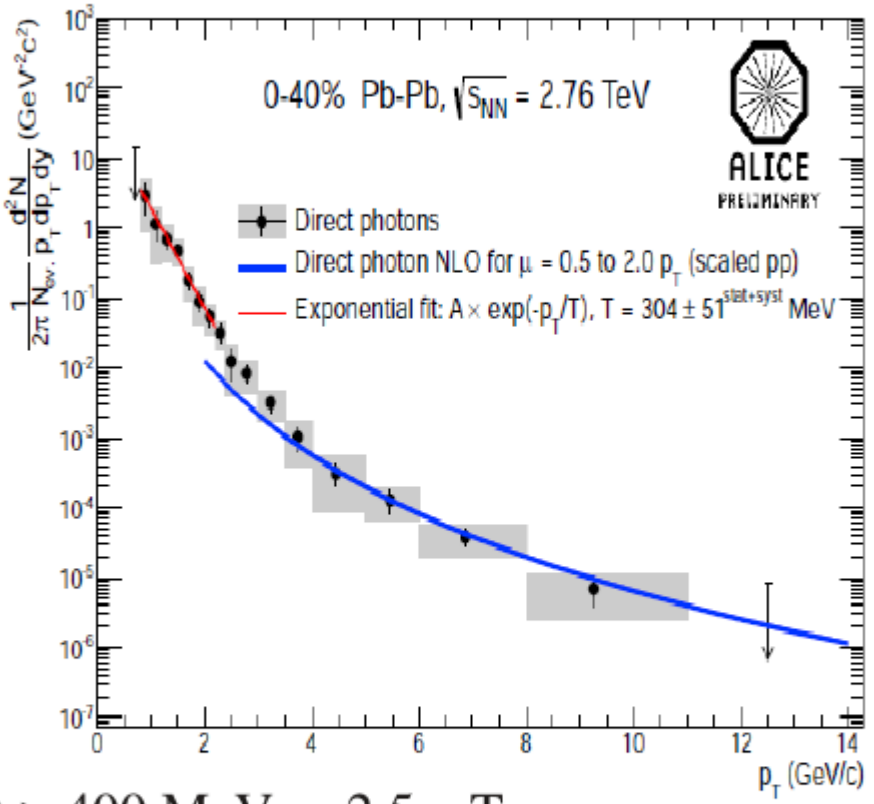
v_1-v_5 significantly larger than 0, maximum at v_3

current understanding: higher harmonics (3,4,5,...) are due to initial inhomogeneities caused by granularity of binary parton-parton collisions

Analogy with early universe power spectrum of CMB

PHENIX and ALICE results





at LHC T_ini(fireball) > 400 MeV = 2.5 x T_c

average T = 304 +/- 51 MeV temperature

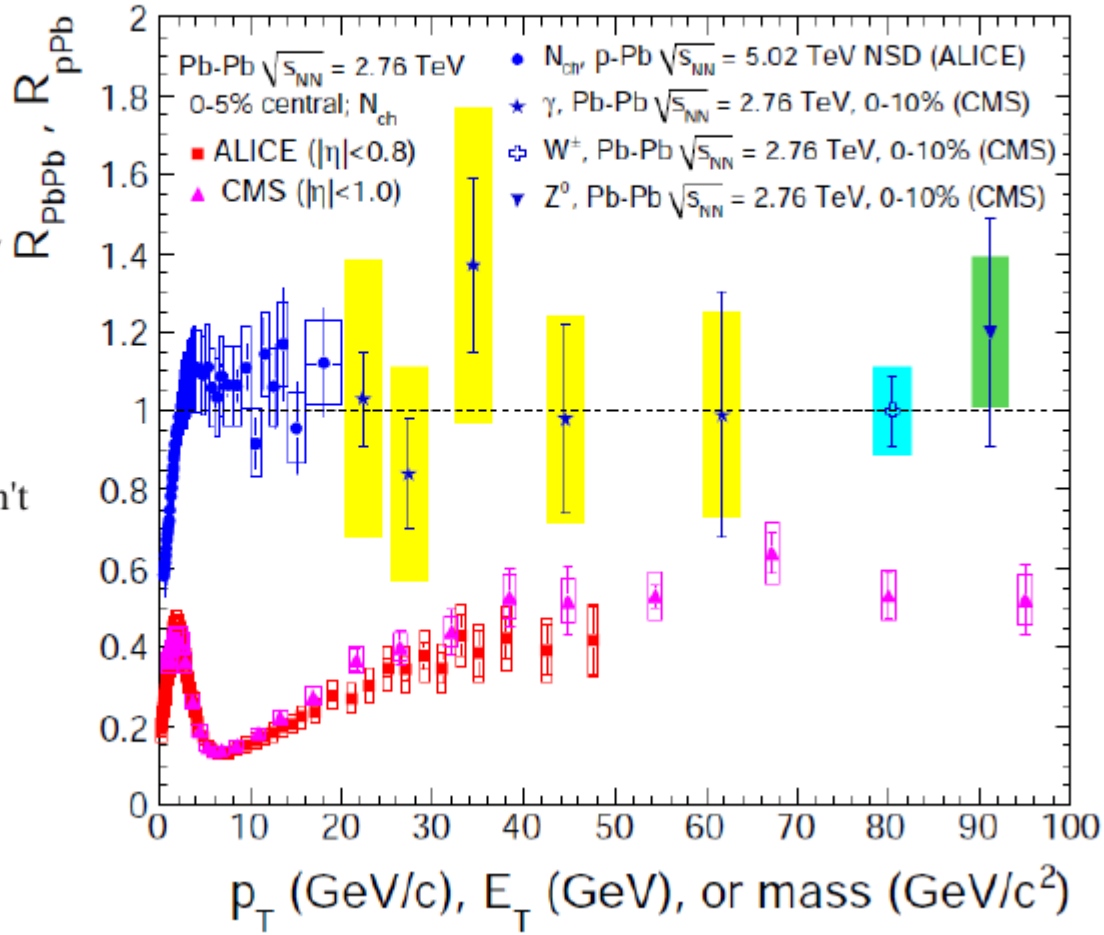
highest ever measured

currently not understood large photon elliptic flow calls interpretation into question!

Nuclear Modification Factor

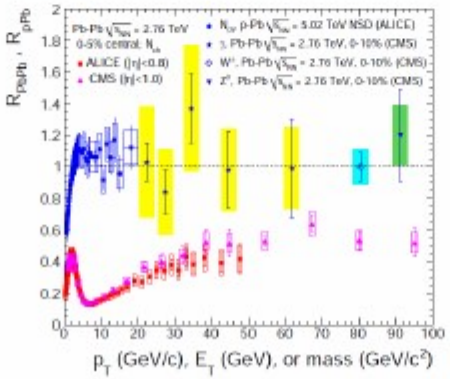
R_AA << 1 for strongly interacting probes, even for large transverse momenta,

electro-weak probes don't see the dense medium

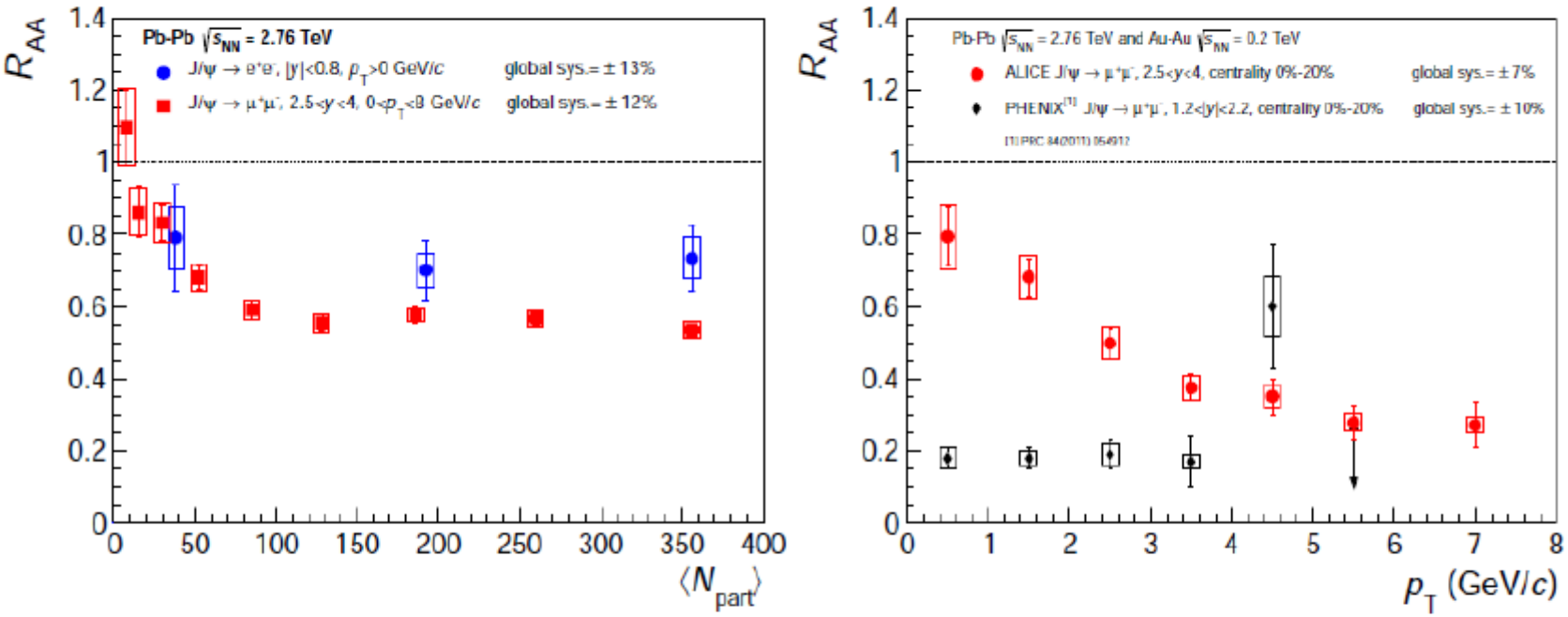


summary, high p_t and jet phenomena

- hadron production in Pb—Pb at high p_t is strongly suppressed compared to collision scaling from pp, even up to 100 GeV
- jets are quenched up to 300 GeV
- pQCD is not reached at asymptotically high p_t values (?)
- the fireball is dense enough to affect high p_t partons but not as dense as presumed in AdS/CFT scenarios



main ALICE results on J/psi production in Pb—Pb collisions

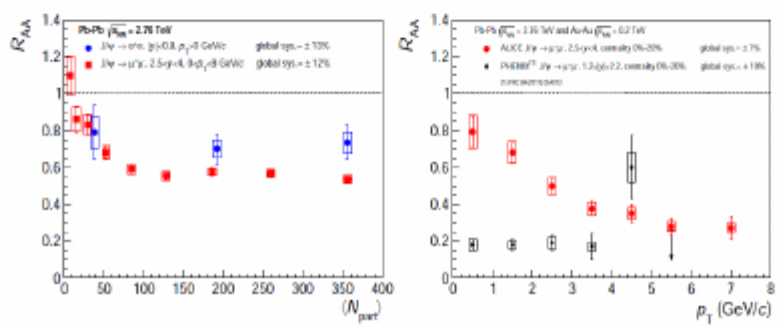


Despite increased energy density at LHC energy, R_AA increases at low transverse momenta when going from RHIC to LHC energy →

complete color screening and deconfinement for charm quarks

summary – quarkonium production

- spectacular difference between results from RHIC and LHC
- J/psi production is consistent with complete Debye screening and (re-)generation at the QCD phase boundary
- charm quarks are thermalized and deconfined
- Y production: also suppressed but unclear relation to color screening are b quarks and/or Y thermalized?



From the talk :

The fluid dynamic paradigm of relativistic heavy ion collisions

Urs Achim Wiedemann
CERN PH-TH

From elementary interactions to collective phenomena

For any QFT of elementary particles and their interactions, we can ask:

How do macroscopic properties of matter emerge from fundamental interactions?

⇨ QCD much richer than QED:
- non-abelian theory
- degrees of freedom change with Q^2

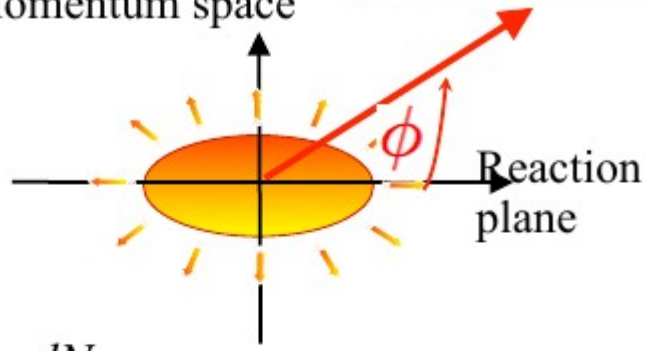
⇨ Equilibrium QCD at high temperature $T >> T_{crit}$ particularly interesting
- in experimental reach in heavy ion collisions $\varepsilon_{crit} \approx (3-5)\varepsilon_{nuclear\,matter}$
- many properties of hot QCD calculable from L_{QCD}
  (transition to QGP, chiral symmetry restoration, viscosities, conductivities, relaxation times, susceptibilities, QED emission rates…)

⇨ But: matter in heavy ion collisions expands quickly $\tau_{lifetime} \approx O(10\,fm)$
- global equilibrium state not realized
- local equilibration may be expected $\tau_{lifetime} >> \tau_{QCD\,rates}$

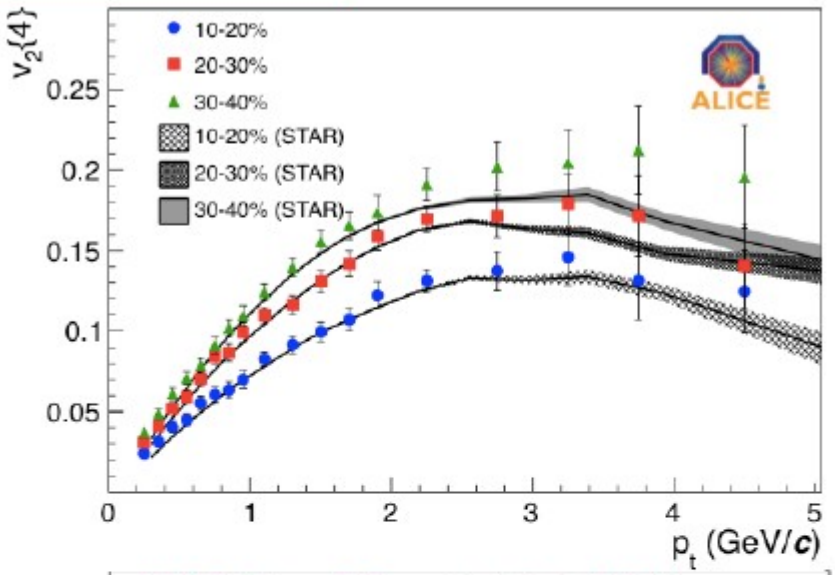
➡ Establishing fluid dynamic behavior is prerequisite for testing equilibrium QCD in heavy ion collisions.

v_2 @ RHIC and LHC

- Momentum space



$$\frac{dN}{d\phi\, p_T dp_T} \propto \left[1 + 2\, v_2\left(p_T\right)\cos\left(2\phi\right)\right]$$



- Signal $v_2 \approx 0.2$ implies 2-1 asymmetry of particles production w.r.t. reaction plane.

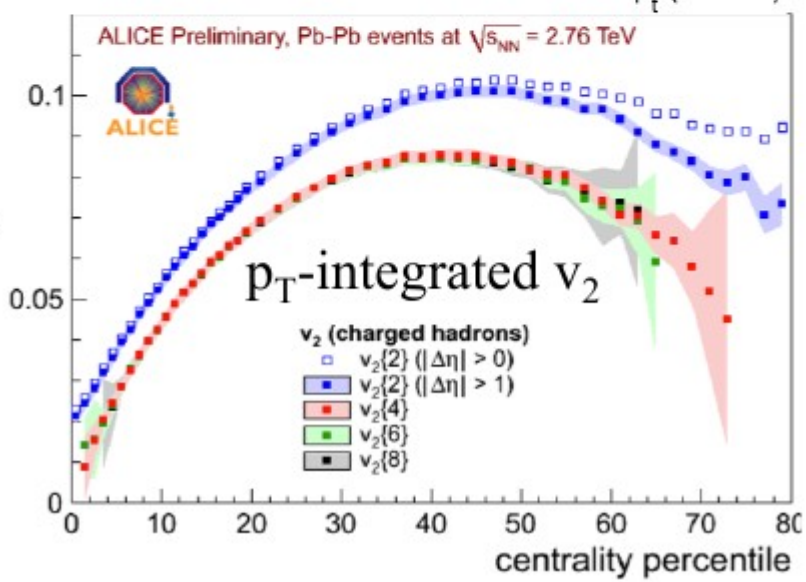
- 'Non-flow' effect for 2nd order cumulants

$$N \sim 100 - 1000 \Rightarrow 1/\sqrt{N} \sim 0.1 \sim O(v_2)\ ??$$

2nd order cumulants do not characterize solely collectivity.

$$1/N^{3/4} \sim\leq 0.03 \ll v_2$$

Strong Collectivity !



Spatial eccentricities drive flow

- Initial transverse energy (or entropy) densities expected to vary event-by-event

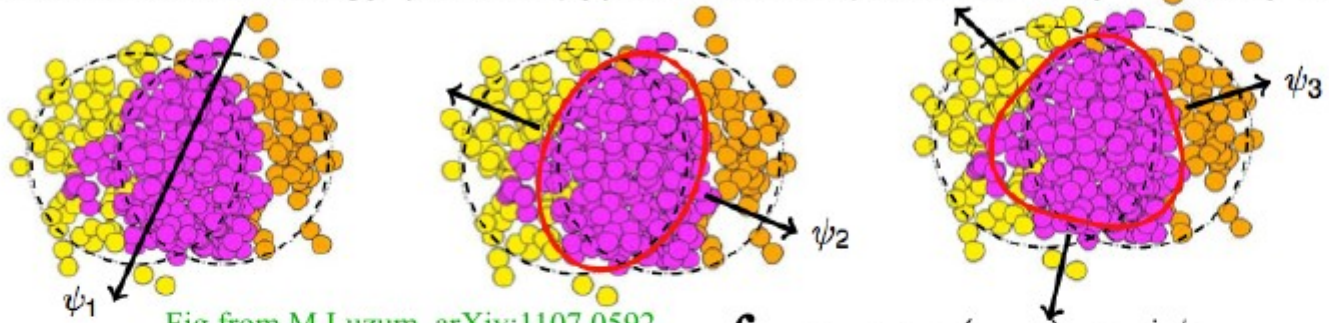


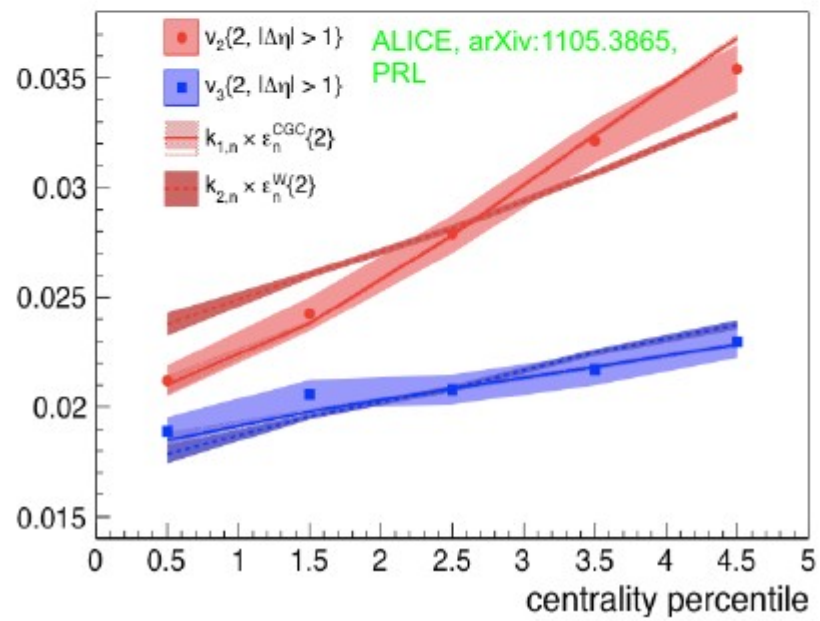
Fig from M.Luzum, arXiv:1107.0592

- Characterize their shape via **spatial eccentricities**

$$\varepsilon_{m,n} e^{in\phi_{m,n}} \equiv \frac{\int r\,dr\,d\phi\,\rho(r,\phi)\,r^m e^{in\phi}}{\int r\,dr\,d\phi\,\rho(r,\phi)\,r^m}, \quad \varepsilon_n \equiv \varepsilon_{n,n}$$

- Experiments establish **approximately linear response** between **momentum flow** and **spatial eccentricities**

$$v_n \exp[in\psi_n] \approx k\,\varepsilon_n \exp[in\phi_n]$$

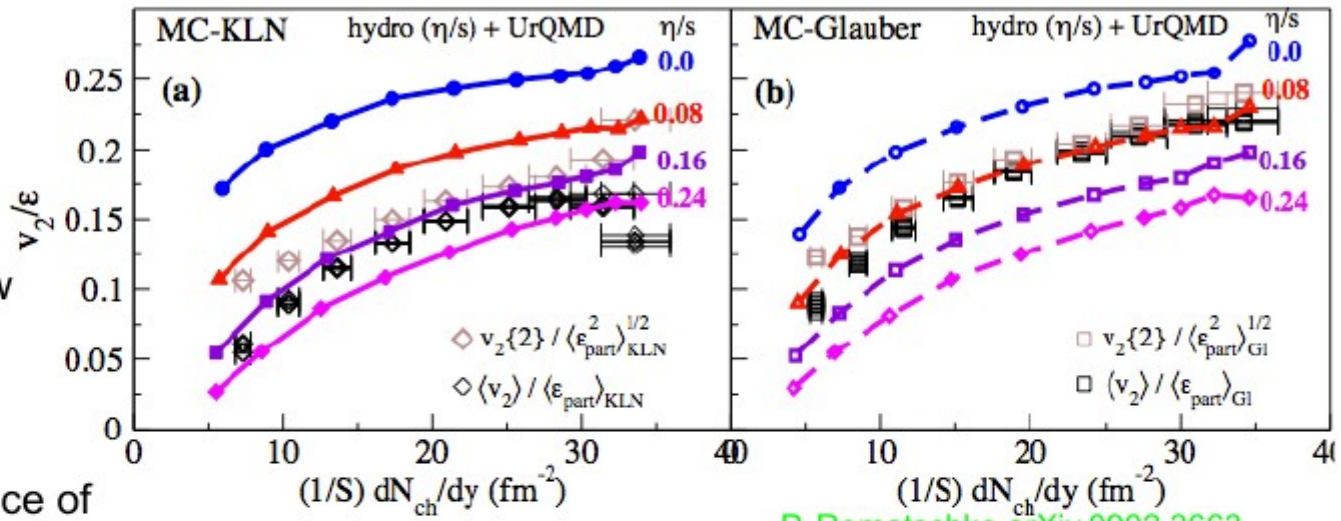


For tests, see e.g.
F. Gardim et al, arXiv:1111.6538

Fluid dynamics prior to LHC - results

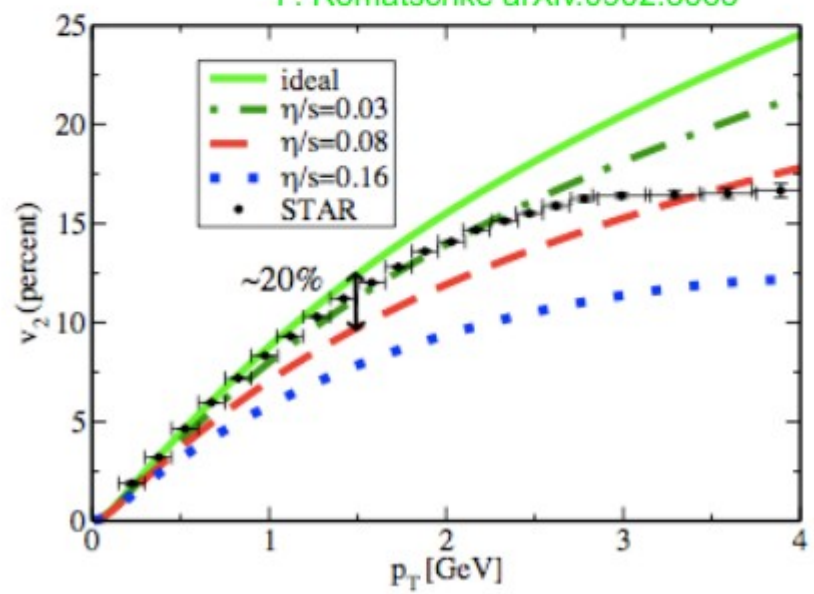
Fluid dynamics accounts for:

- Centrality dependence of elliptic flow



P. Romatschke arXiv.0902.3663

- pt-dependence of elliptic flow
- **Mass dependence** of elliptic flow (all particle species emerge from common flow field)
- Single inclusive transverse momentum spectra at pt (< 3 GeV)



In terms of fluid with QCD equation of state and minimal shear viscosity

$$\frac{\eta}{s} << 1$$

Phenomenological implication

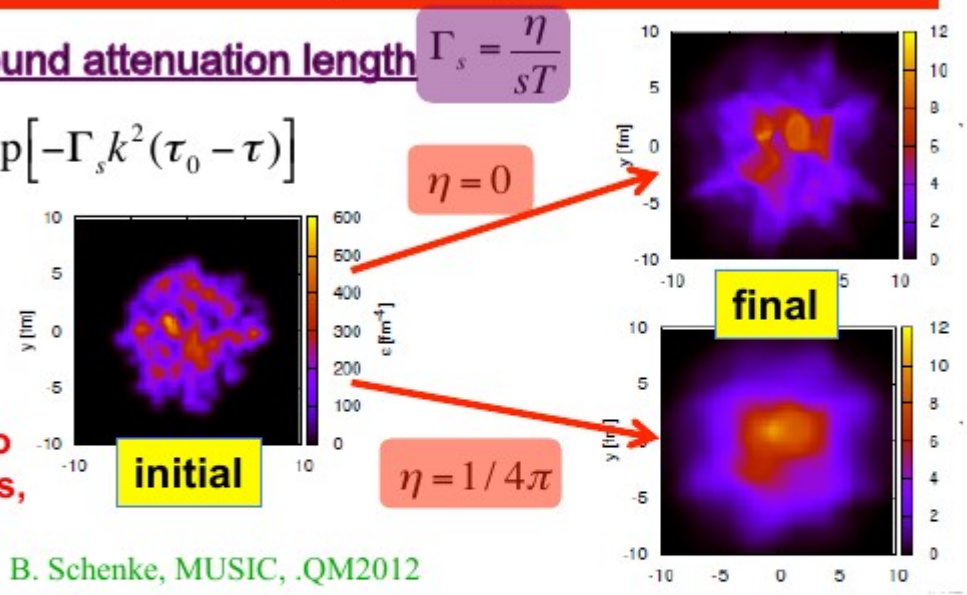
Minimal dissipation ⇔ Maximal Transparency to Fluctuations

- Linear fluctuations governed by **sound attenuation length** $\Gamma_s = \frac{\eta}{sT}$

$$\delta v(\tau,k) = \delta v(\tau_0,k)\left(\frac{\tau_0}{\tau}\right)^{*} \exp\left[-\Gamma_s k^2(\tau_0-\tau)\right]$$

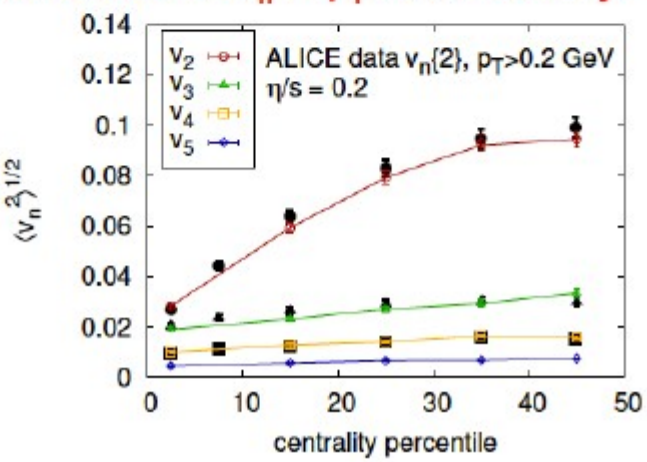
Fluctuations decay on time scale,

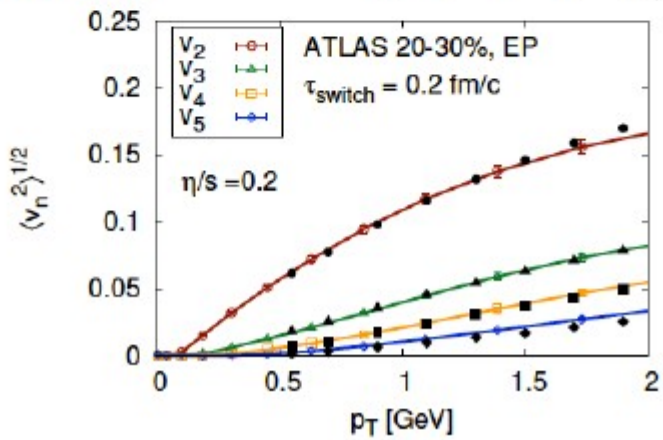
$$\tau_{1/e}(k) = \frac{1}{\Gamma_s k^2}$$



- **Viscous fluid dynamics with close to minimal shear viscosity, realistic eos, and suitable initial conditions accounts for v_n in p_T and centrality.**

B. Schenke, MUSIC, .QM2012





Fluid dynamical modeling of heavy ion collisions Washington (2012)

Compilation by J.-Y. Ollitrault: Plenary

Many independent model studies, one general conclusion:

Viscous fluid dynamics with

- **Minimal eta/s**
- **realistic eos**
- **suitable initial conditions**

accounts for v_n in p_T, and centrality.

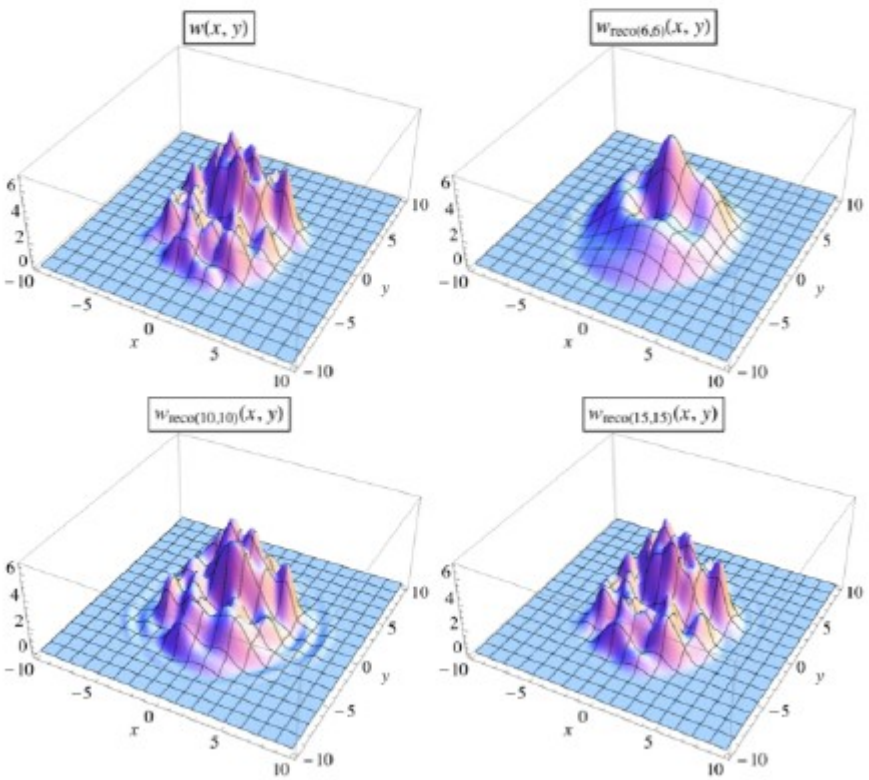
Author/Presenter	QM2012	arXiv	initial fluctuations	3+1d	viscous	afterburner
Huichao Song	1D	1207.2396			✓	✓
Teaney/Yan	1A	1206.1905			✓	
Chun Shen	1A	1202.6620			✓	
Sangyong Jeon	2A		✓	✓	✓	✓
Matt Luzum	2A				✓	
Piotr Bozek	2C	1204.3580	✓	✓	✓	
Björn Schenke	3A	1109.6289	✓	✓	✓	
Dusling/Schaefer	3A	1109.5181			✓	
Chiho Nonaka	3A	1204.4795	✓	✓	✓	
Ryblewski/Florkowski	3D	1204.2624		✓		
Longgang Pang	4D	1205.5019	✓	✓		
Hannah Petersen	VA	1201.1881	✓	✓		✓
Fernando Gardim	6D	1111.6538	✓	✓		
Zhi Qiu	29	1208.1200	✓		✓	
Gardim/Grassi	52	1203.2882	✓	✓		
Katya Retinskaya	57	1203.0931			✓	
Hirano/Murase	255	1204.5814	✓	✓		✓
Holopainen/Huovinen	284	1207.7331	✓			
Asis Chaudhuri		1112.1166	✓		✓	
Iurii Karpenko		1204.5351		✓		✓
Yu-Liang Yan		1110.6704		✓		✓
Josh Vredevoogd		1202.1509		✓	✓	
Ron Soltz		1208.0897			✓	✓
Rafael Derradi de Souza		1110.5698	✓	✓		

3.
'Flow'
New Frontiers/new challenges

More differential studies of the role of fluctuations

- Characterizing initial conditions in terms of orthonormal basis of fluctuating modes with radial (l) and azimuthal (m) wave number

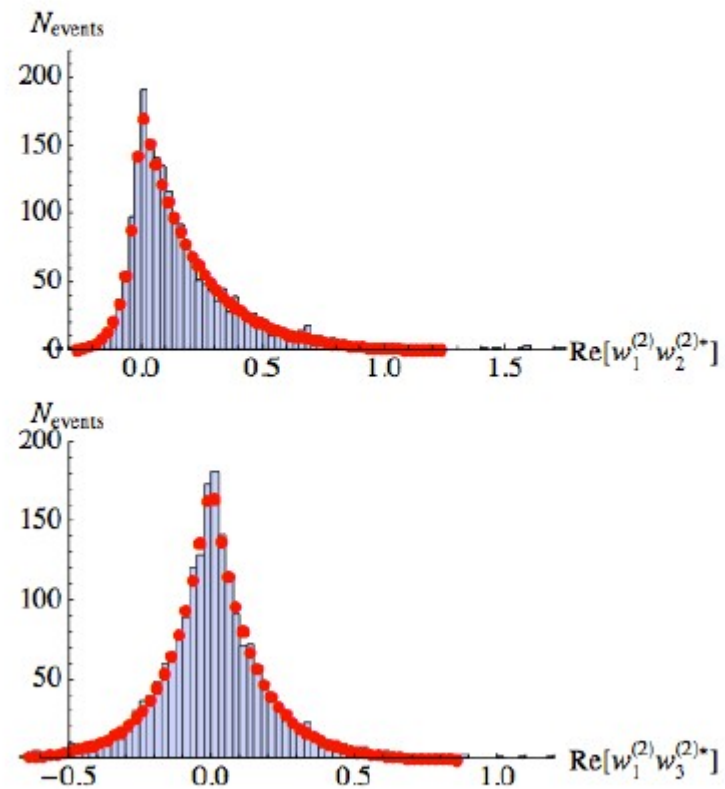
$$w^{(m)}(r) \approx \sum_{l=1}^{N_l} w_l^{(m)} \, J_m\left(k_l^{(m)} r\right)$$



- Characterizing probability distributions

$$P\left[\{w_l^{(m)}\}\right]$$

of event classes



⇒ S. Flörchinger parallel Friday

3.4 Anomalous hydrodynamics

- In QFTs with quantum anomalies, 2nd law of thermodynamics implies that currents flow along magnetic fields and along vorticity
  (see also Vilenkin's work in 1980s,
  explicitly realized in QFTs with gravity dual, see Erdmenger et al.)

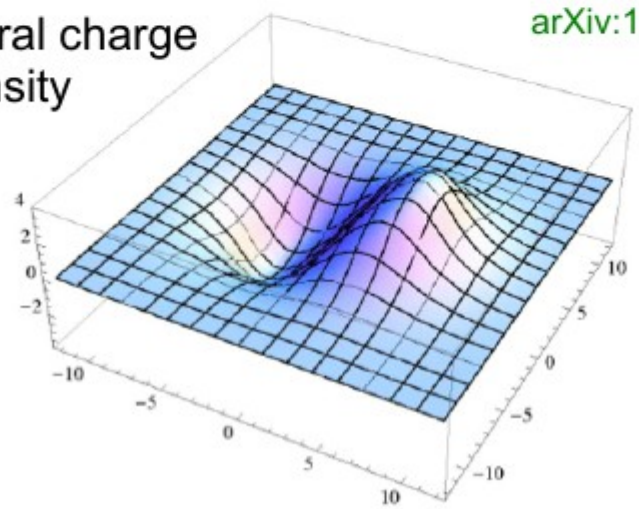
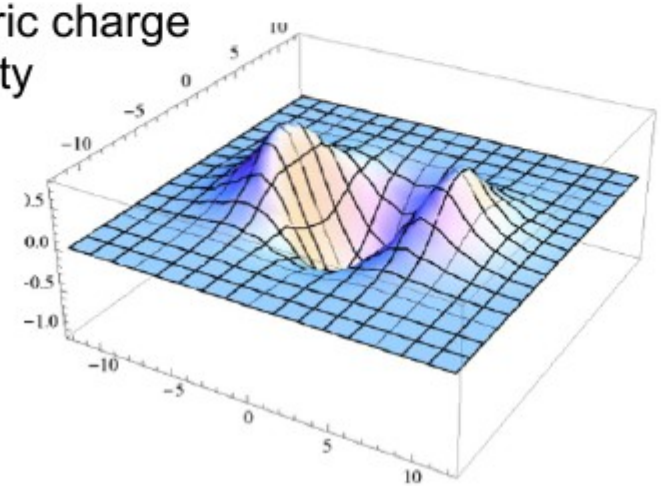
Son&Surowka,
PRL 103 (2009) 191601

- In QCD, this implies $J_V^\mu \propto C\,\mu_A\,B^\mu$

  $J_A^\mu \propto C\,\mu_V\,B^\mu$
- Heavy ion collisions have strong but transient magnetic field, $eB \sim O(m_\pi^2)$ and finite vector potential.
  This realizes the condition for an axial current, that will generate and axial chemical potential, that will separate electric charge along B-field
- <u>Can we see this chiral magnetic wave in heavy ion collisions?</u>

Y. Burnier, D. Kharzeev, ..
arXiv:1103.1307

Chiral charge density



Electric charge density