Phenomenology of Heavy-Ion Collisions

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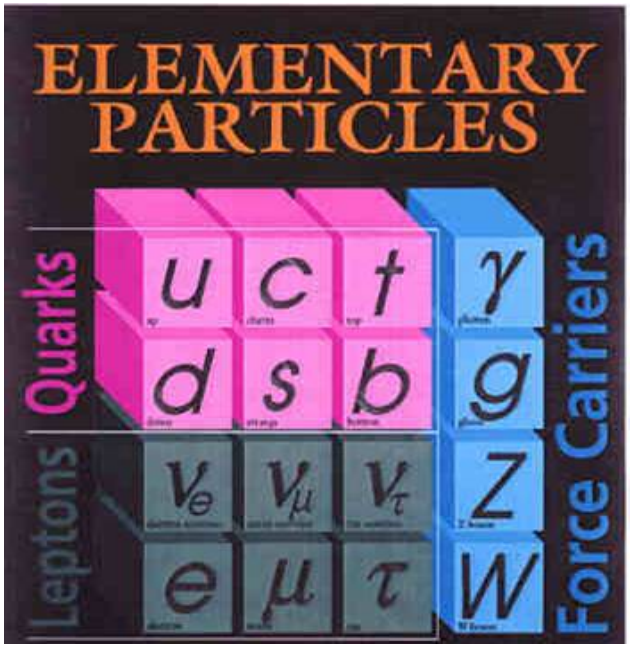
Outline

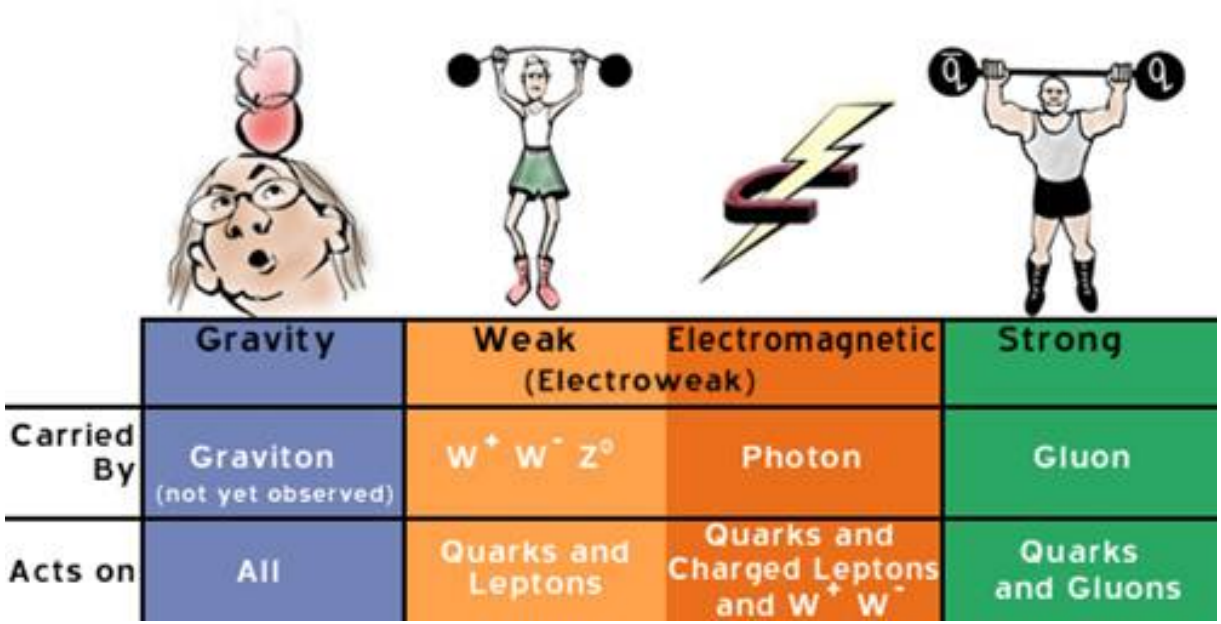
Plan of the lectures

- Introduction: Phenomenology of ultrarelativistic heavy-ion collisions
- Classical transport theory
  - relativistic phase-space distributions
  - the Boltzmann equation
  - entropy and H theorem
  - equilibrium distributions and hydrodynamics of the perfect fluid
  - the Boltzmann-Uehling-Uhlenbeck equation and quantum statistics
  - strategies of solving the transport equations
- Foundations on relativistic many-body quantum-field theory
  - Schwinger-Keldysh real-time formulation
  - gradient expansion
  - outlook on "off-shell transport"
- web site: http://fias.uni-frankfurt.de/~hees/
- lecture notes: http://fias.uni-frankfurt.de/~hees/publ/roorkee.pdf
- this presentation: http://fias.uni-frankfurt.de/~hees/publ/roorkee-intro.pdf

Elementary Particles and Fundamental Interactions

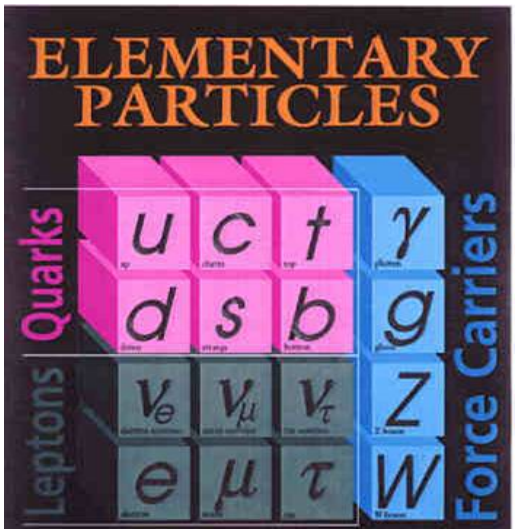
- Fundamental forces or interactions
- Described with high accuracy by Standard Model of Elementary Particles





+ Higgs boson (discovered 2012 at LHC!)

Matter particles vs. Force Carriers



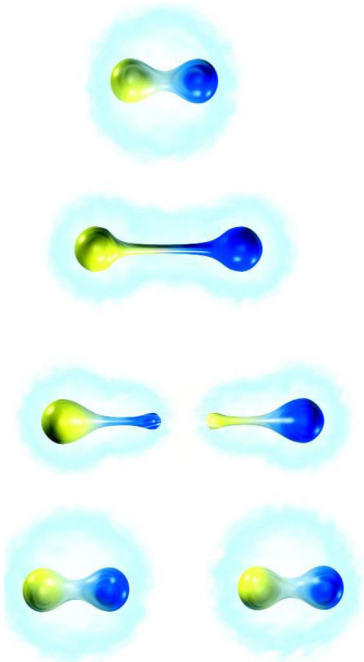
- Elementary particles:
  quarks and leptons
  spin $s = 1/2$ (fermions)
- Elementary force carriers
  gluons, photons (γ), $W^{\pm}$, Z
  spin $s = 1$ (bosons)
- Higgs boson
  spin $s = 0$

- gluons, photons (γ), $W^{\pm}$, Z: gauge bosons of gauge group
  $SU(3)_c \times SU(2)_w \times U_Y(1)$
- gauge group spontaneously broken to $SU(3)_c \times U_{em}$
- Higgs mechanism $\Rightarrow$ W+Z massive, masses of quarks and leptons

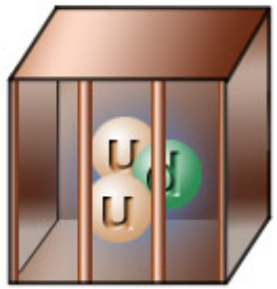
Quantum Chromo Dynamics

- free quarks or gluons never seen!

I want free quarks!
$\Rightarrow$ break up a meson



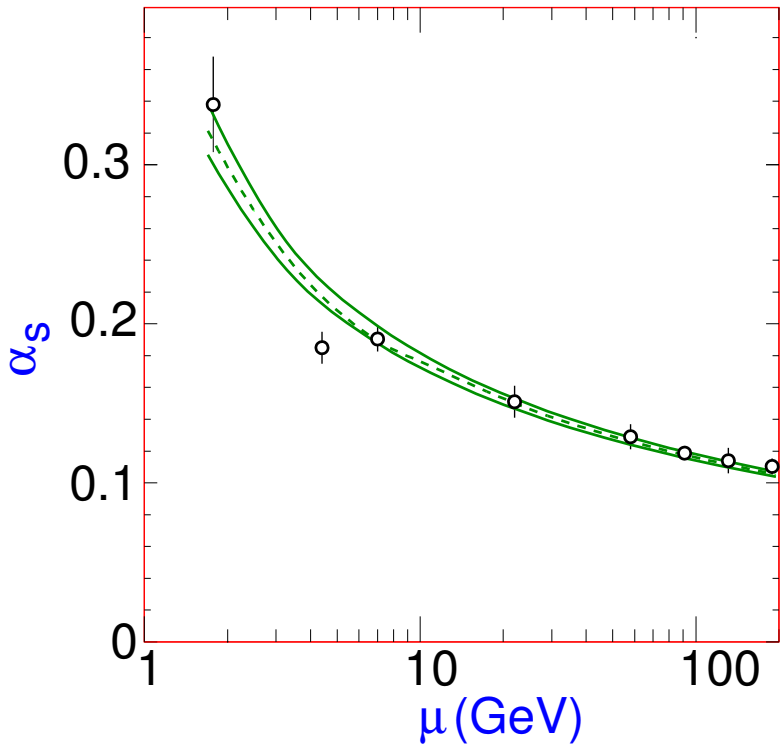
cannot break the meson, but produce more hadrons!



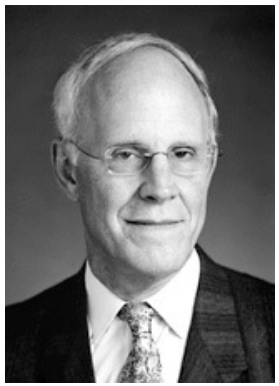
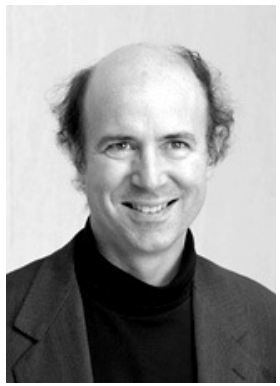
- quarks confined in hadrons
- 1973: Gross and Wilczek, Politzer
- build theory based on color symmetry!
- force becomes stronger for longer distances
- reason: force carriers themselves have color

Quantum Chromo Dynamics

- from color symmetry of quarks (color charge conserved)
- force carriers: gluons (spin 1)
- matter particles: quarks (spin 1/2)
- QCD based on non-abelian gauge group SU(3)
- gluons self-interacting (fundamental three- and four-gluon vertex)
- force becomes weaker at small distances/high energy (asymptotic freedom)



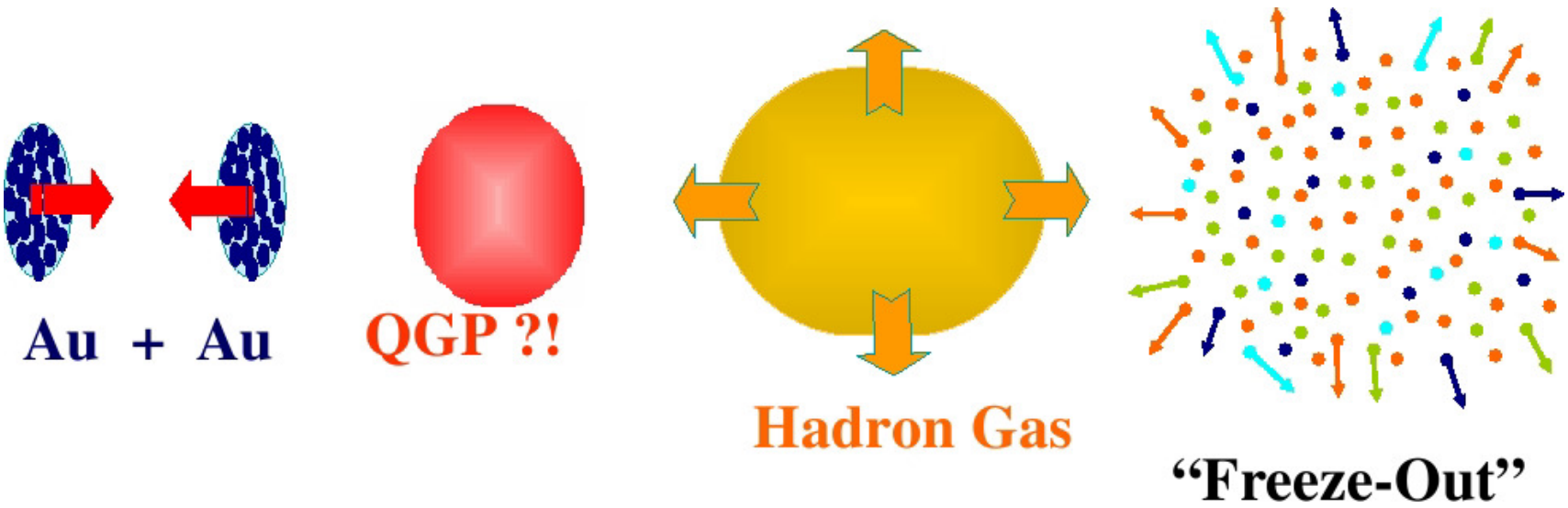
Nobel prize in physics 2004:


Gross, Wilczek, Politzer

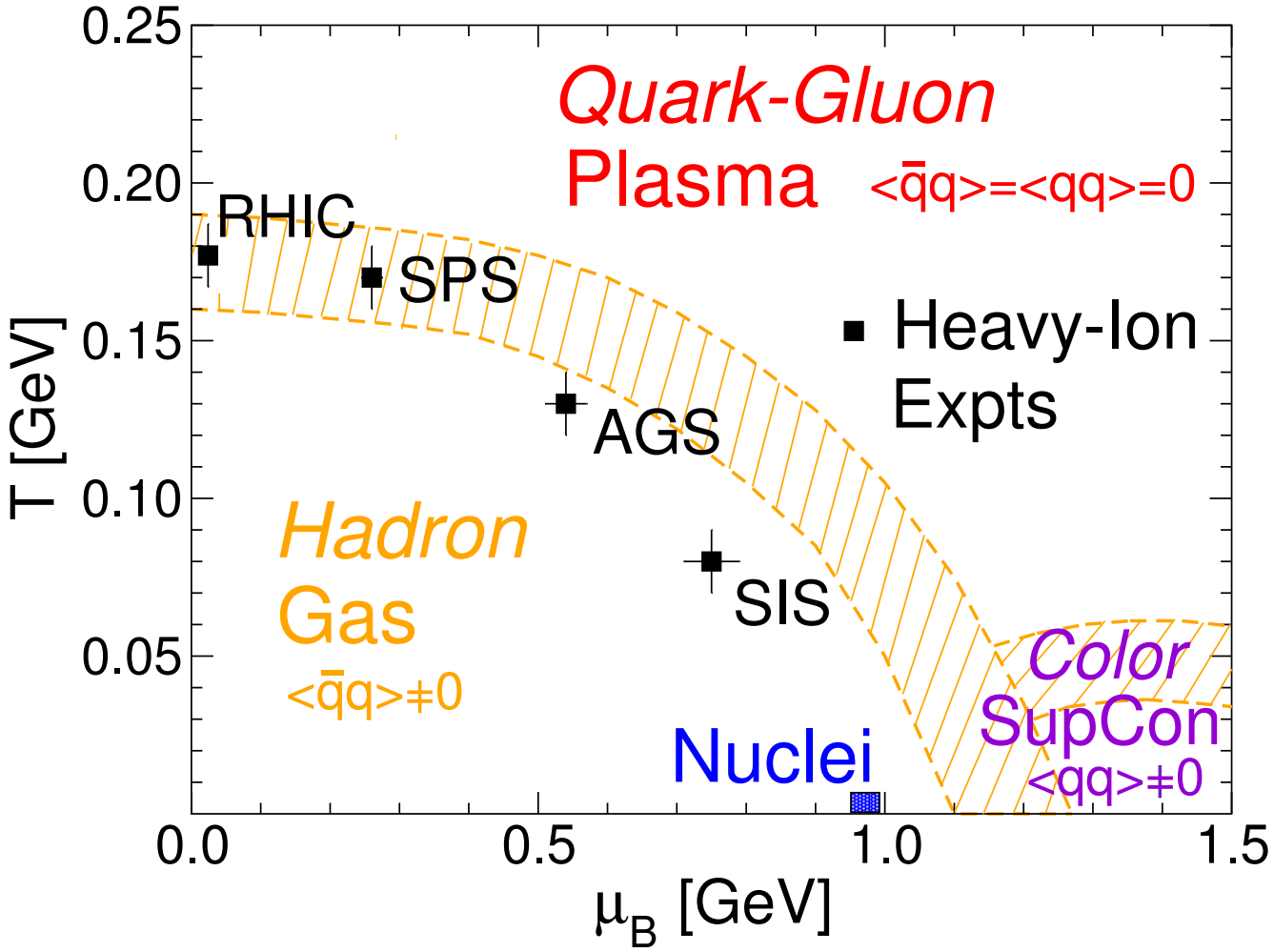
Heavy-ion collisions

- collisions of relativistic (heavy) nuclei
- many collisions of partons inside nucleons
- creation of many particles $\Rightarrow$ hot and dense fireball
- formation of (thermalized) QGP?
- how to learn about properties of QGP?

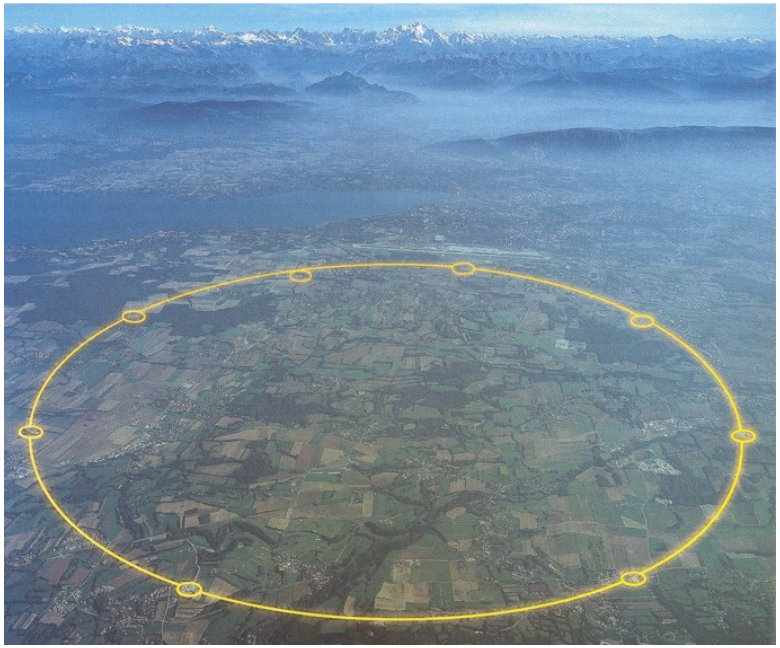


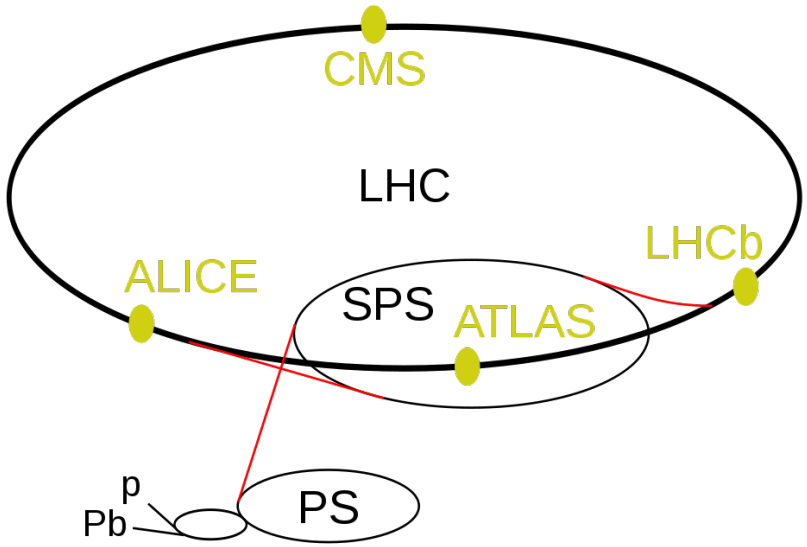
Phase diagram of strongly interacting matter

- hot and dense matter: quarks and gluons at high temperature
- high-energy collisions of quarks and gluons ⇒ "Deconfinement"
- quarks and gluons relevant degrees of freedom ⇒ Quark-Gluon-Plasma
- interactions still strong: fast thermalization!



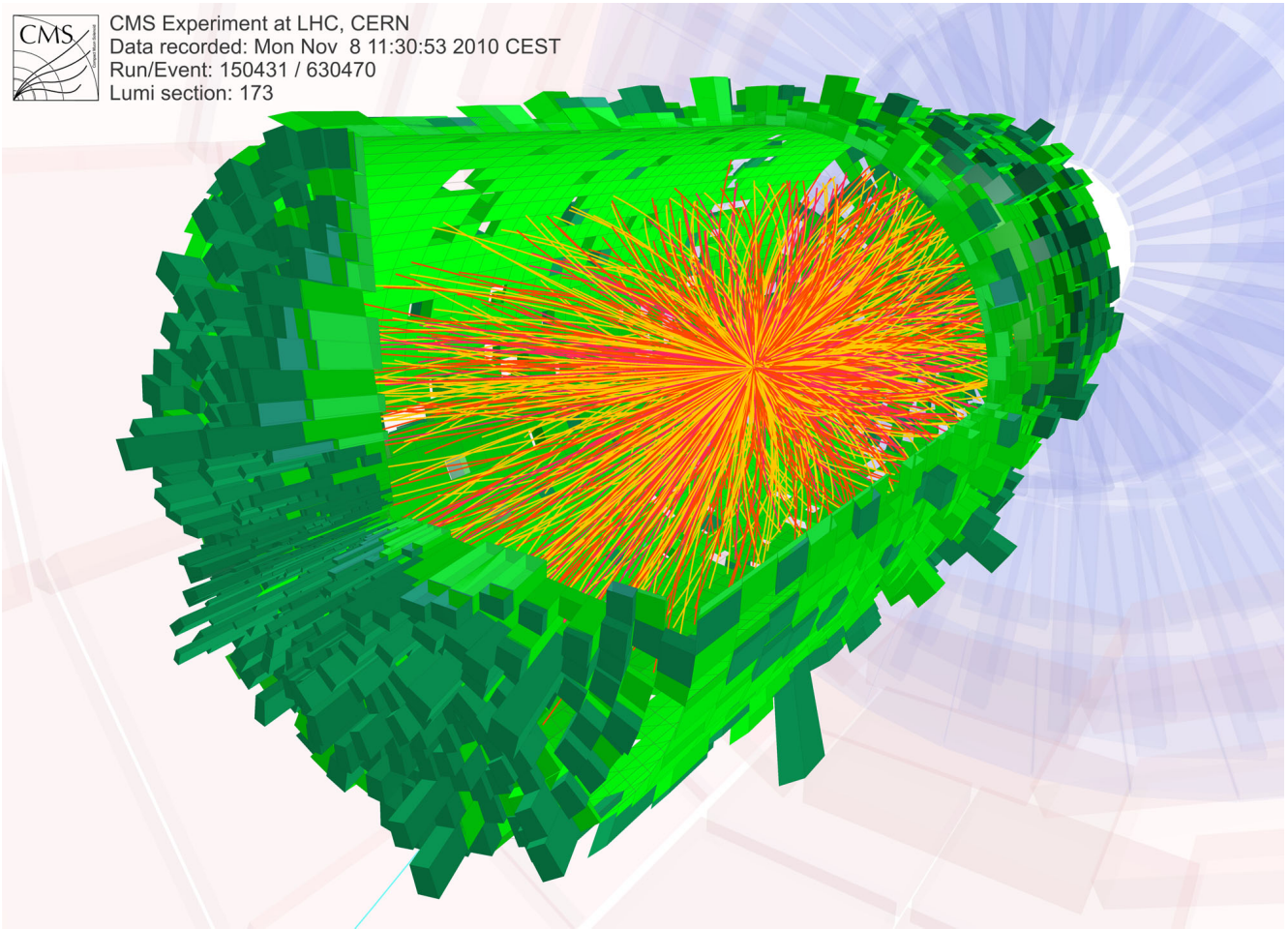
Large Hadron Collider





- accelerates protons to $\sqrt{s} = 7$ TeV
- accelerates lead nuclei to $\sqrt{s} = 2.76\ A$TeV
- detectors
  - ATLAS: A Toroidal LHC Apparatus
  - CMS: Compact Muon Solenoid
  - LHCb: LHC-beauty
  - ALICE: A Large Ion Collider Experiment

Large Hadron Collider



- problem: fireball (QGP?) exists only for a time of ~ 10 fm/c
- quarks and gluons unobservable $\Rightarrow$
  measure hadrons, leptons, and photons
- observables for QGP?

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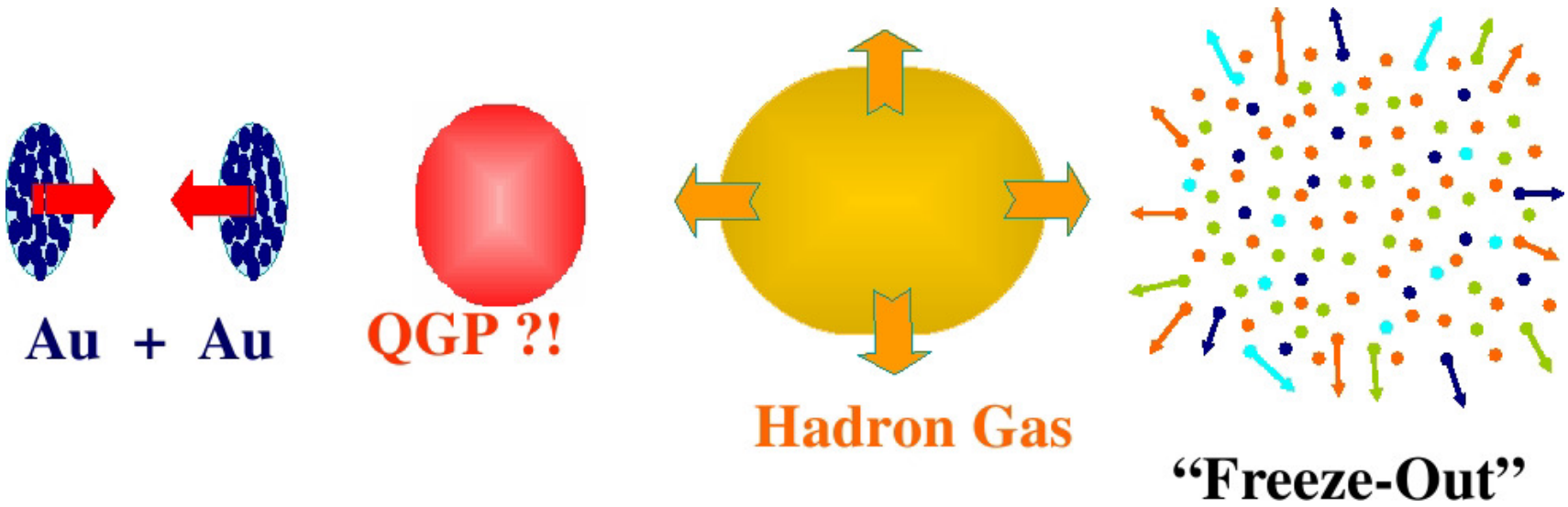
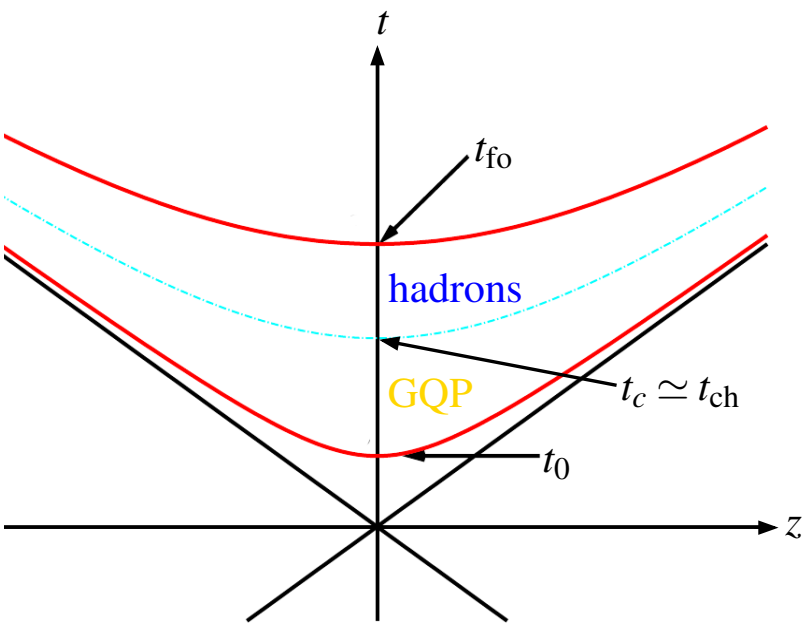
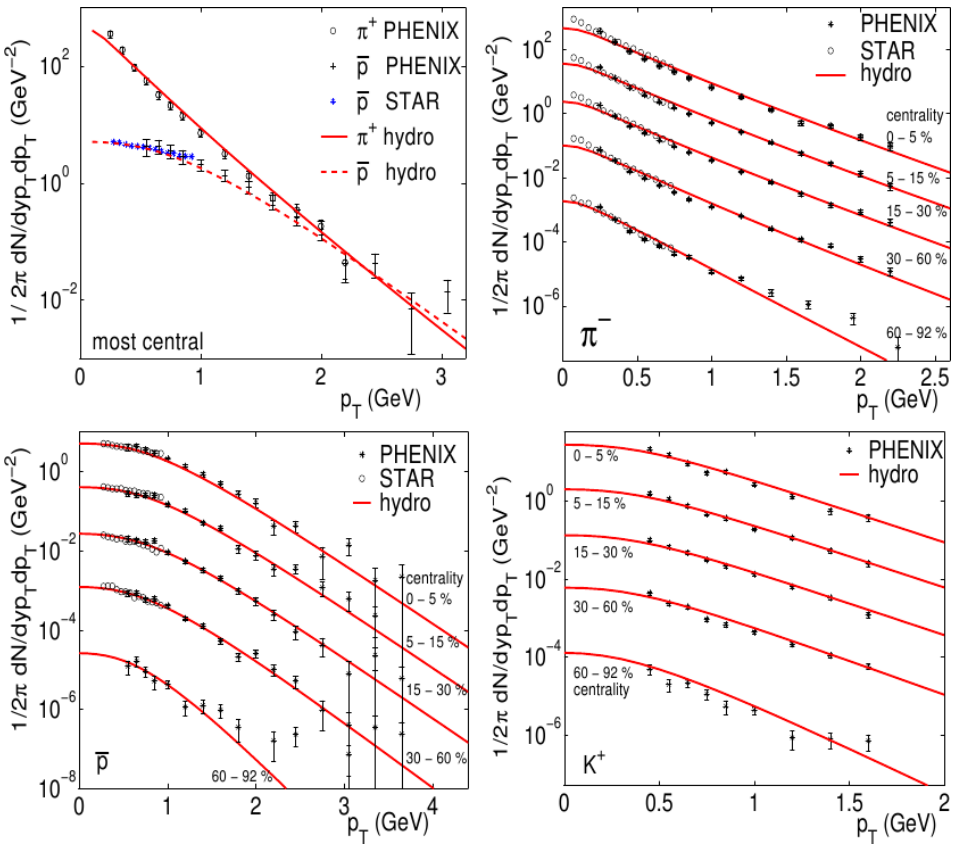


Hydrodynamical radial flow of the bulk

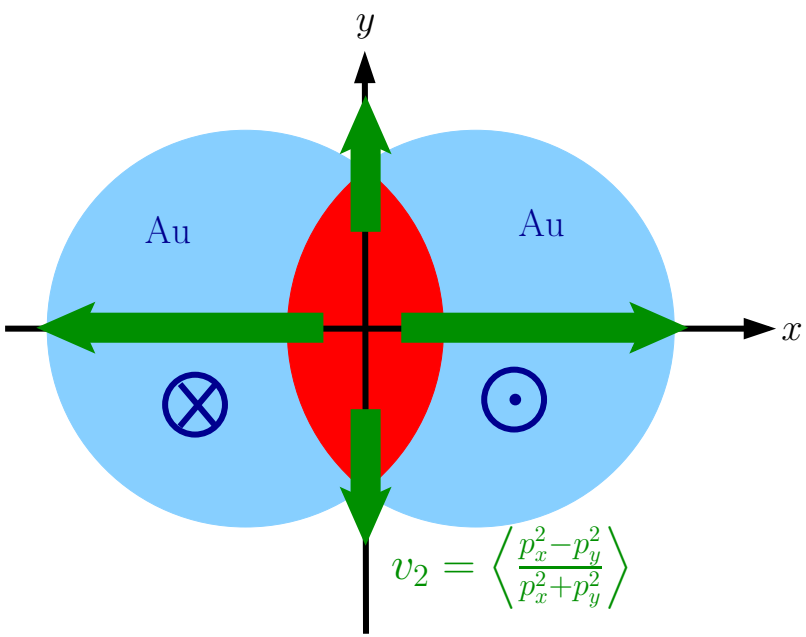
- ideal fluid in local thermal equilibrium
- hydrodynamical model for ultra-relativistic heavy-ion collisions
  - after short formation time ($t_0 \lesssim 1$ fm/c)
  - QGP in local thermal equilibrium $\rightarrow$ hadronization at $T_c \simeq 160 - 190$ MeV
  - chemical freeze-out: (inelastic collisions cease) $T_{\rm ch} \simeq 160 - 175$ MeV
  - thermal freeze-out: (also elastic scatterings cease)

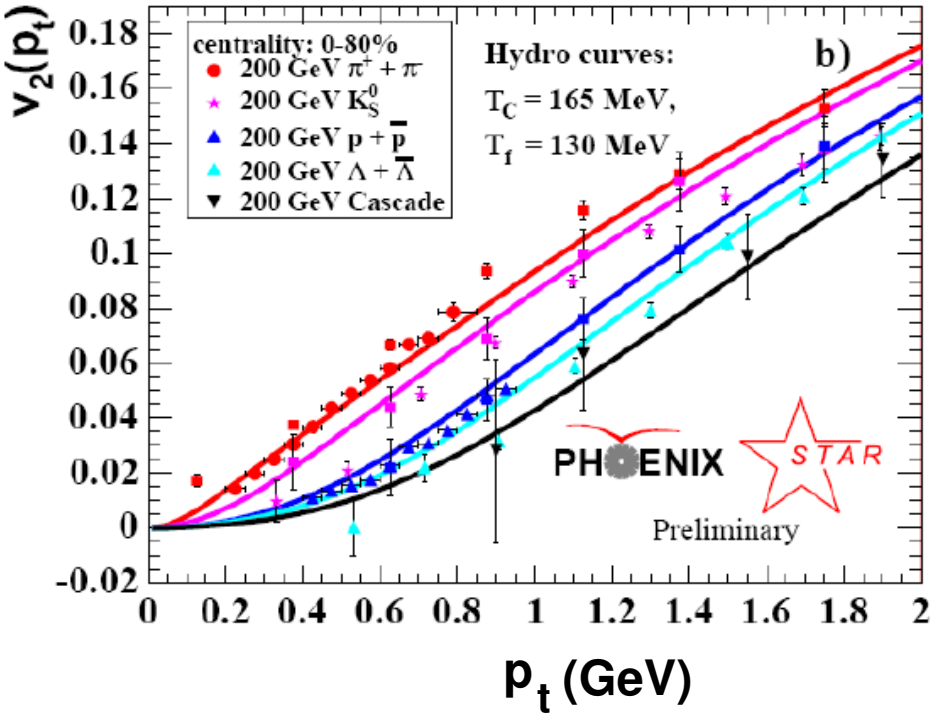




Hydrodynamical behavior

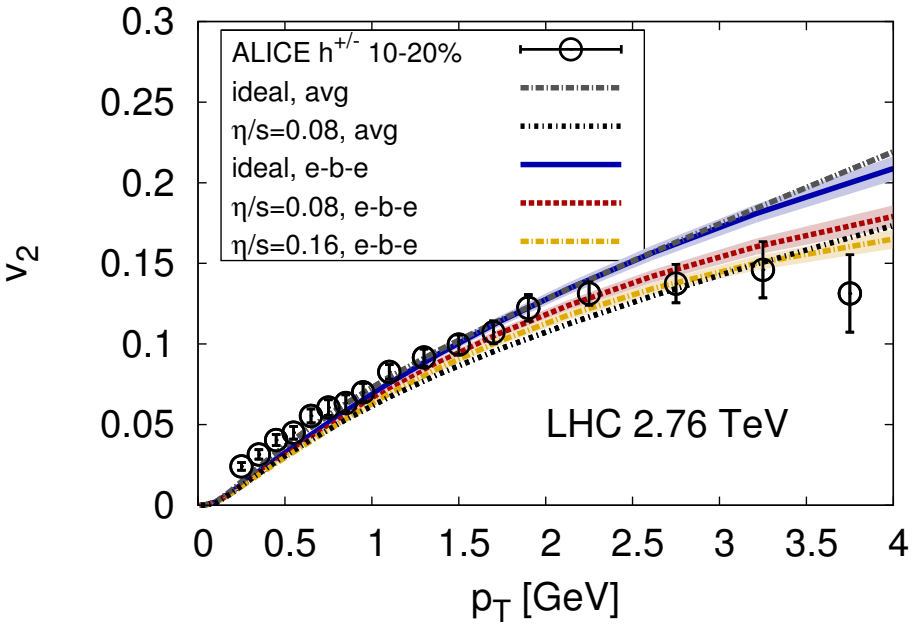
- low-p_T particle spectra compatible with ideal-fluid (Hydrodynamik) $\Rightarrow$ small shear-viscosity over entropy-density ratio, $\eta/s \simeq 1/(4\pi)$
- Medium in local thermal equilibrium (after short formation time $\lesssim 1$ fm/c)

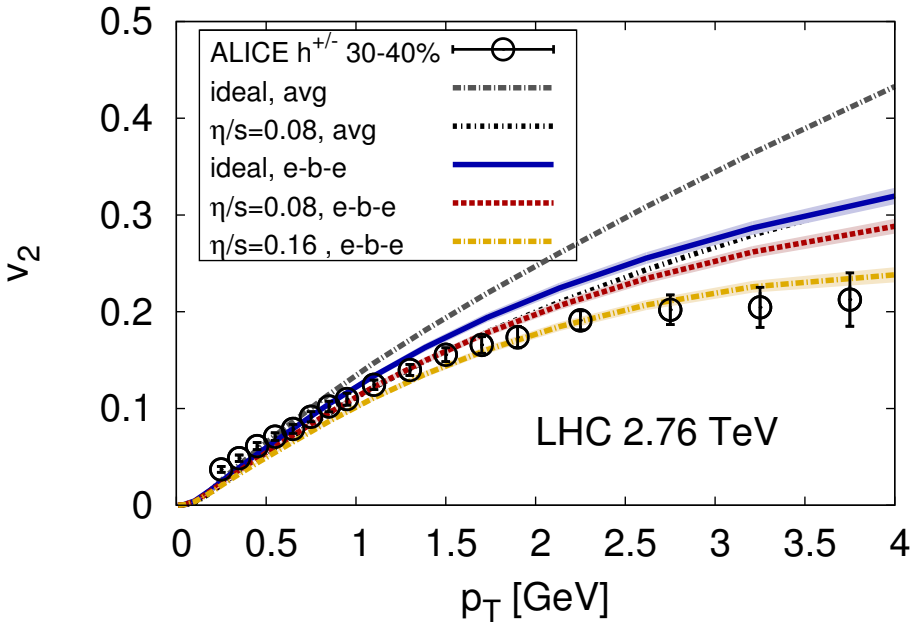




Hydrodynamical behavior

- successful description with relativistic ideal and viscous hydrodynamics





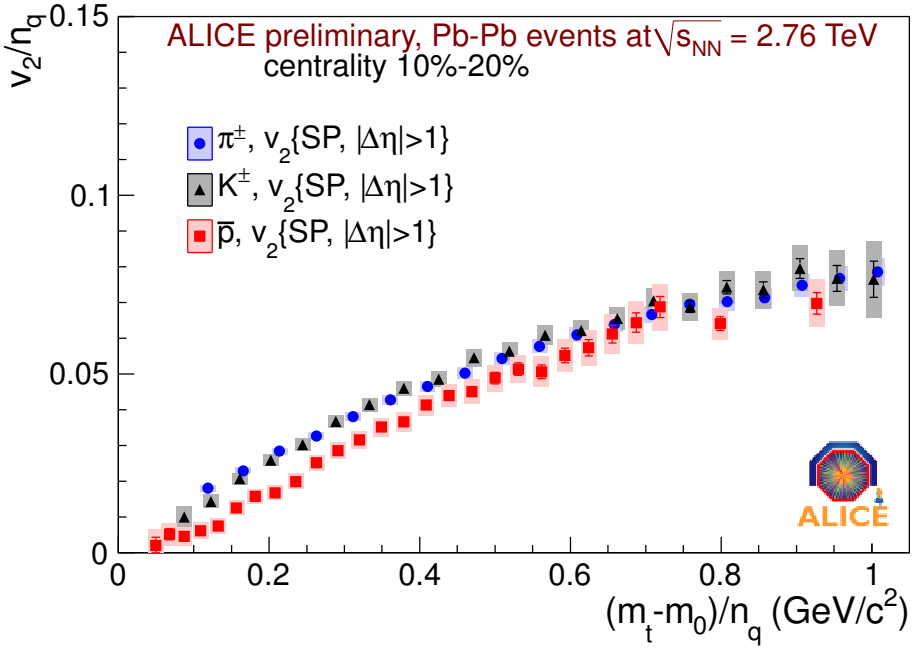
[Bjoern Schenke, Sangyong Jeon, Charles Gale, Phys. Lett.B **702**, 59 (2011)]

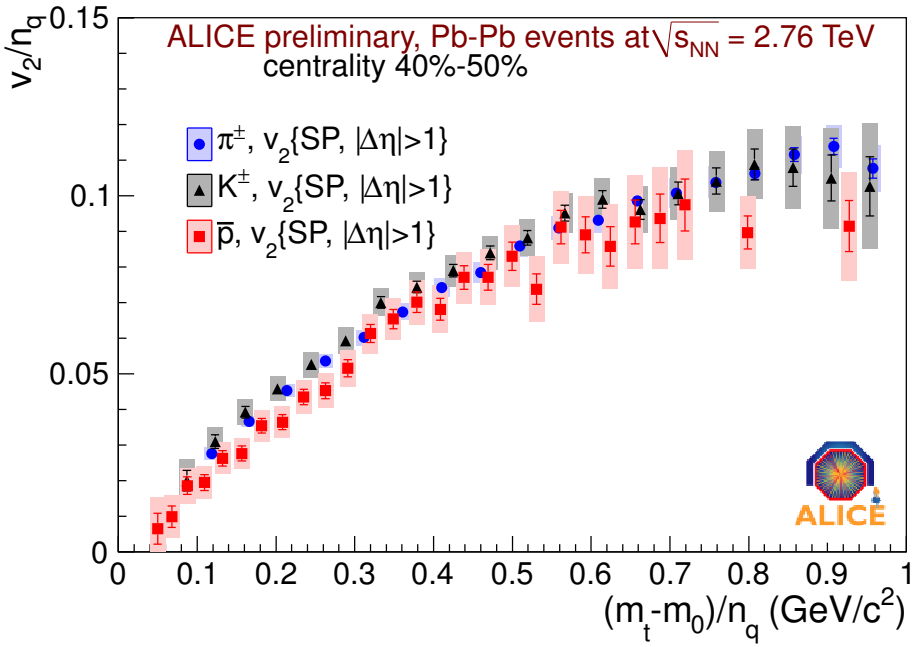
Constituent-quark-number scaling of v_2

- Elliptic flow scales with number of constituent quarks

$$v_2^{(\mathrm{had})}(p_T^{(\mathrm{had})}) = n_q v_2^{(q)}(p_T^{(\mathrm{had})}/n_q)$$

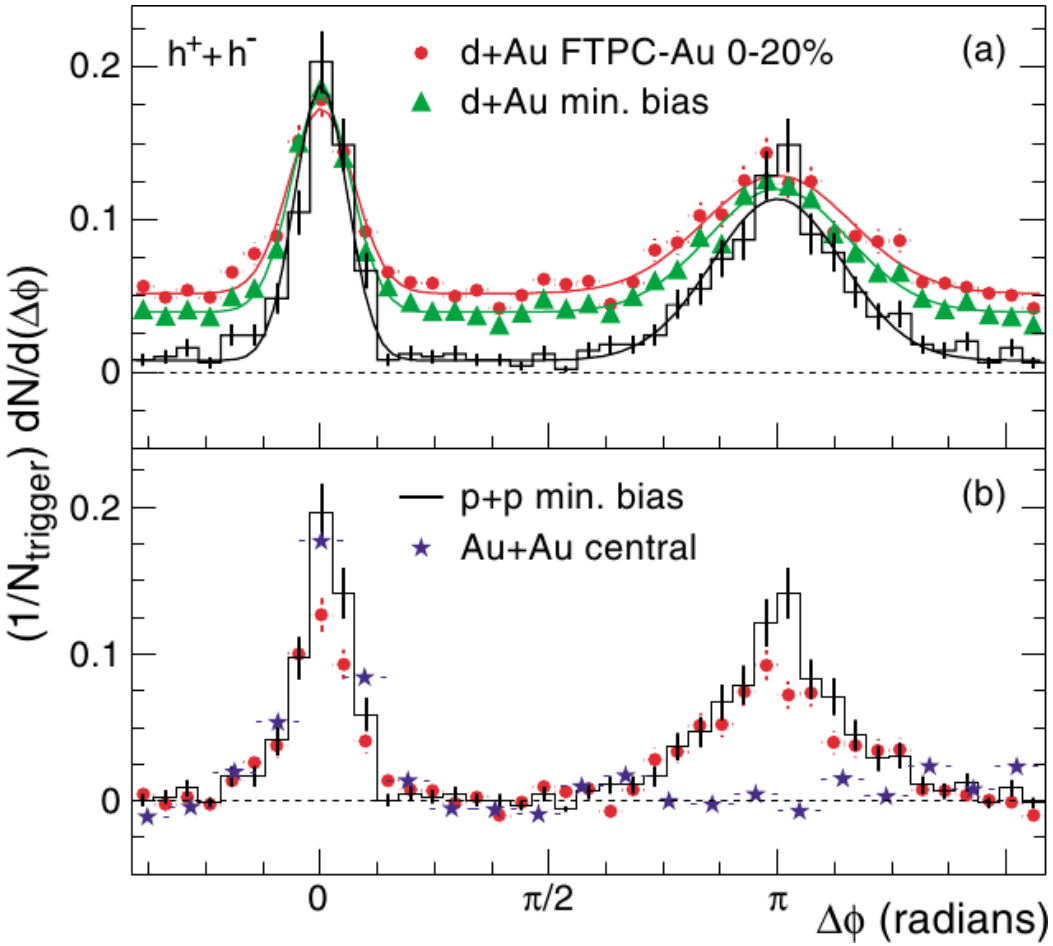
- recombination Quarks in the medium at T_c
- meson and baryon $v_2 = \simeq$ sum of quark v_2's

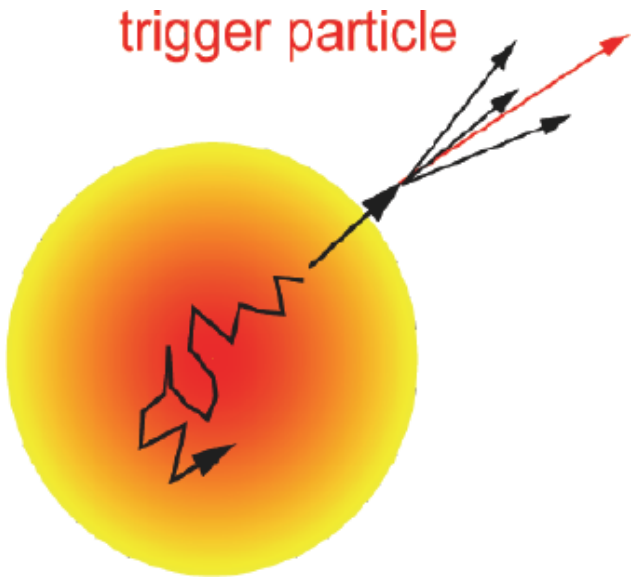




[M.Krzewicki (ALICE Collaboration) arXiv:1107.0080v1 [nucl-ex]]

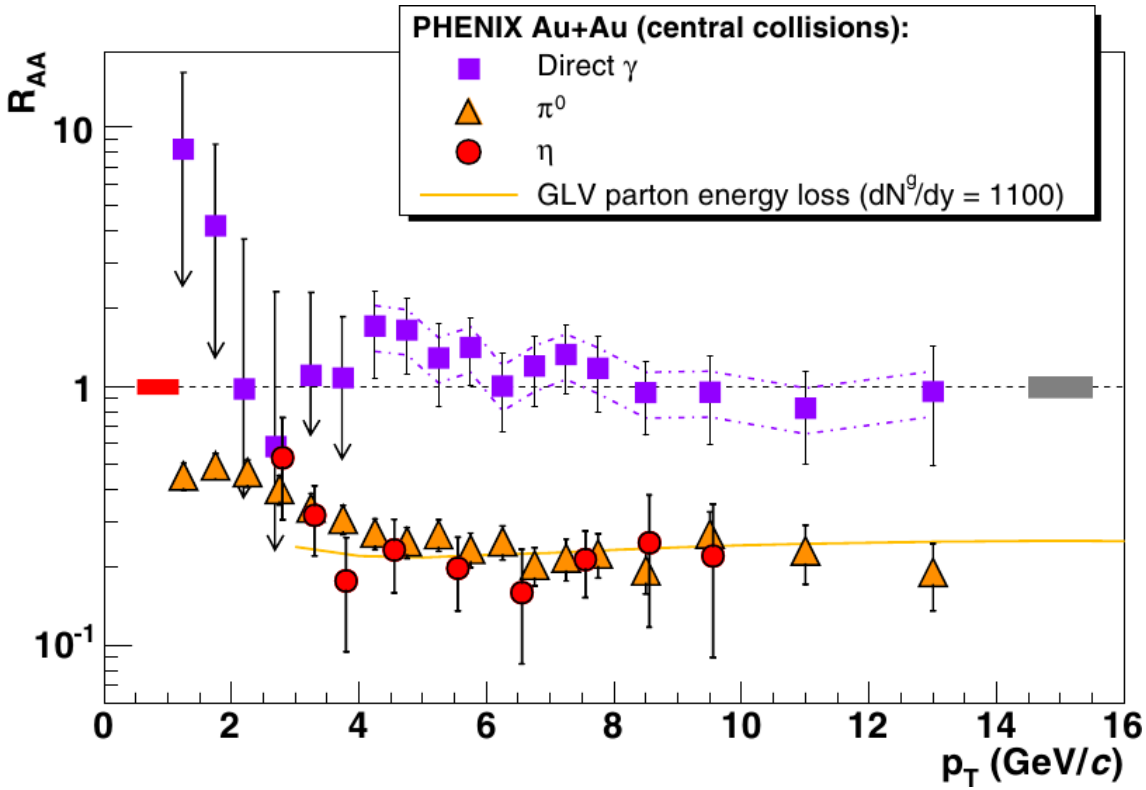
Jet quenching





- jets going through medium suppressed
- not seen in d+Au"=St"o"sen auf $\Rightarrow$ medium effect!
- suppression: medium of high density $\Rightarrow \rho > \rho_{\text{krit}}$

Jet quenching



- comparison to pp collisions: $R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_t}{N_{\mathrm{coll}}\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_t}$
- $R_{AA} < 1$ for large p_t: jets absorved by medium
- photons (γ) nearly unsuppressed: medium transparent for photons
- γ only electromagnetically interacting!

Jet quenching

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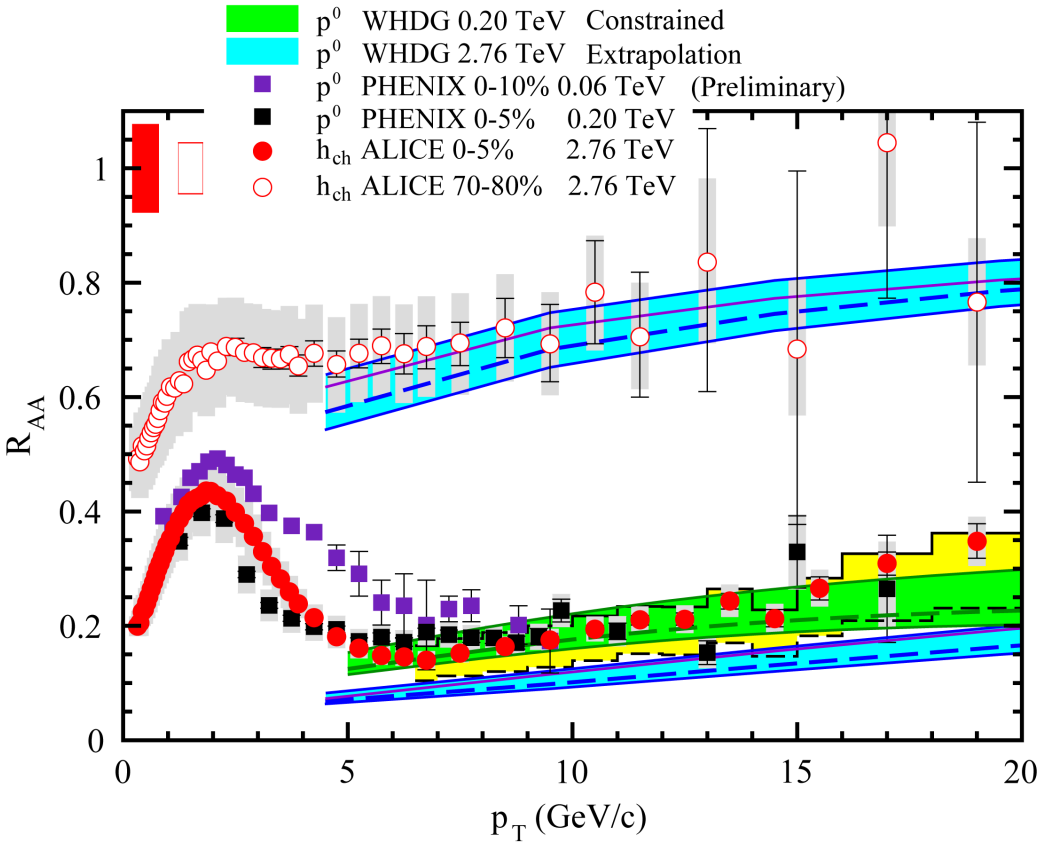

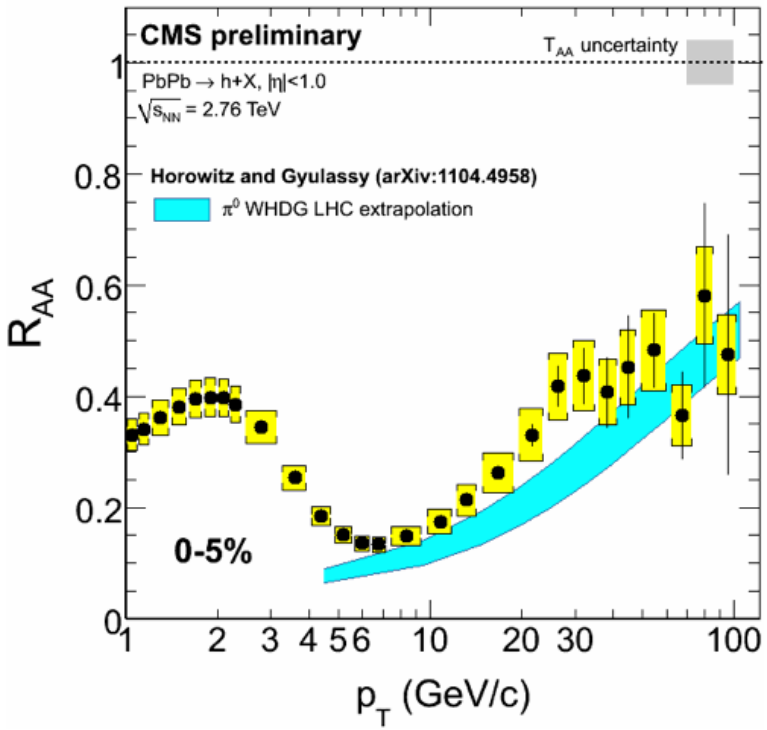

[W. A. Horowitz, M. Gyulassy, arXiv:1107.2136v1 [hep-ph]]

- energy loss: elastic scattering and radiation of gluons in QGP
- density of medium $> \rho_{\rm crit}$!

Motivation for transport theory

- collective behavior of matter from underlying microscopic models
- QCD, effective hadronic models
- fundamental level $\Rightarrow$ quantum (field) theory
- relevant observables of matter:
  bulk quantities like density, temperature, fluid flow fields
- "coarse graining" of microscopic observables
- transport equations $\Rightarrow$ single-particle phase-space distribution
- macroscopic transport coefficients (viscosity, heat conductivity, electric conductivity,...) $\Leftrightarrow$ microscopic dynamics
- for heavy-ion collisions
  - relativistic sytem $\Rightarrow$ aim at relatistically covariant description!
  - admits systematic derivation of relativistic (viscous) hydro
  - allows description of non-equilibrium phenomena
  - e.g., freeze-out dynamics, quark recombination to hadrons, heavy-quark diffusion in QGP, jets in QGP
- basics understandable from classical-particle picture! $\Rightarrow$ these lectures!