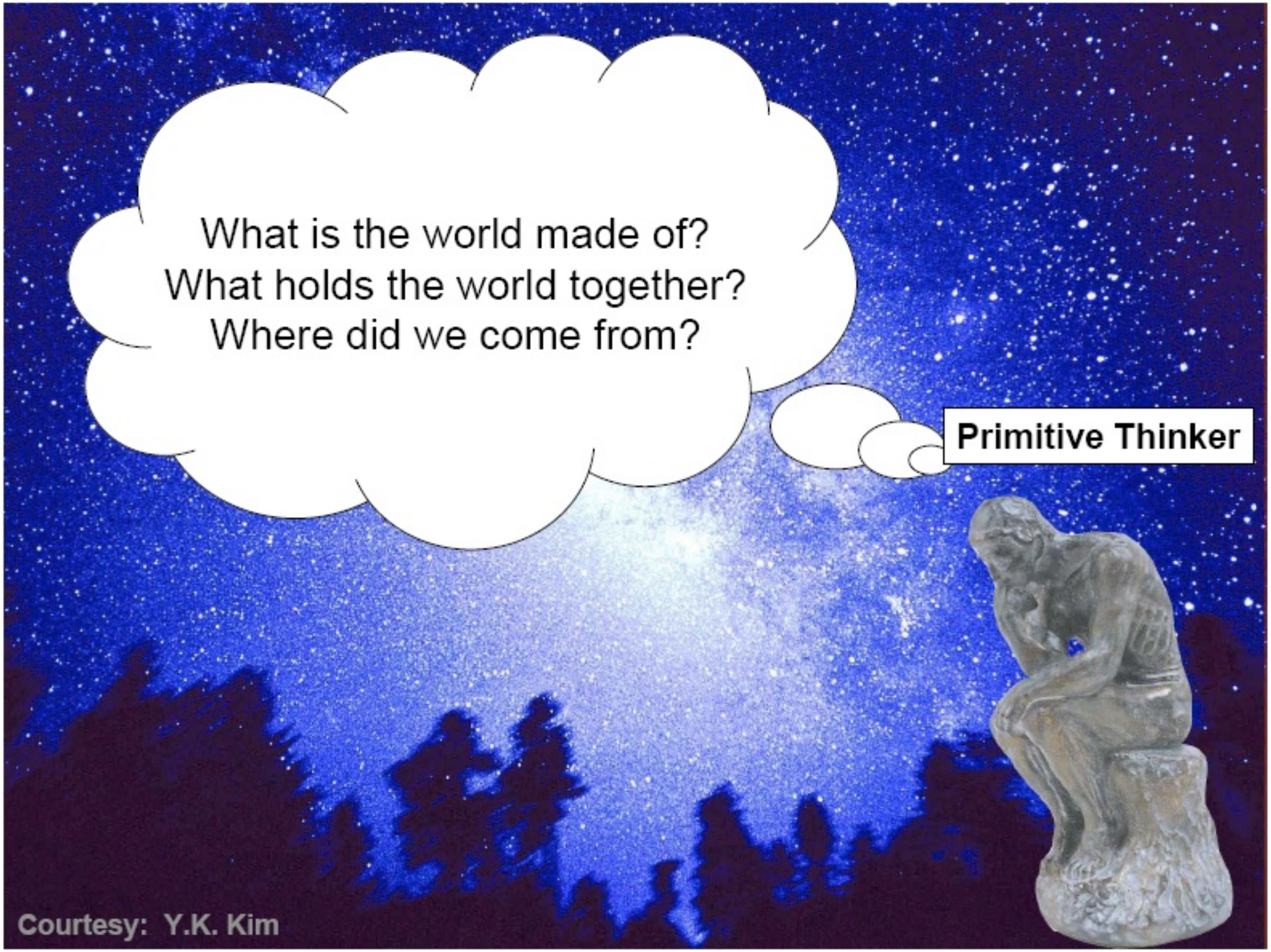
FYS3500
Relativistic Heavy Ion Collisions and Quark Gluon Plasma

By Larissa Bravina, FV225, tel 97549386
Larissa.bravina@fys.uio.no

- **Forces of Strong Interactions**
- **Quantum Chromodynamics**
- **Phase transitions from Deconefined Matter to Hadrons**
- **Signatures of Quark Gluon Plasma**
- **Discoveries and Opened Questions**

FOR READING:

- Yagi, Hatsuda, Miake, Quark-Gluon Plasma,Cambridge University Press, 2005 **Ch. 1, 14 (15,16) in** http://folk.uio.no/larissa/nuclphys/QGP_book/QGP_Yagi.pdf


What is the world made of?
What holds the world together?
Where did we come from?
Primitive Thinker
Courtesy: Y.K. Kim

Content

- *QCD, asymptotic freedom and quark – hadron phase transition*
- *Super-colliders – tools to study Big Bang in the laboratory?*
- *Lattice QCD – another tool to study partonic mater at extreme conditions*
- *Semi-phenomenological models for heavy ion collisions*
- *Modern interpretation of the experimental data*
- *Summary and perspectives*

2004 Nobel Prize in Physics for asymptotic freedom theory

- **David Gross**

- David Politzer

- Frank Wilczek

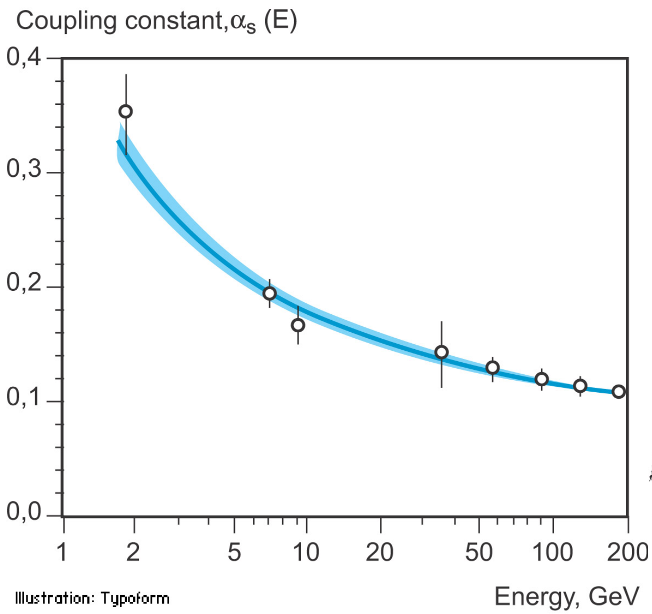


Illustration: Typoform

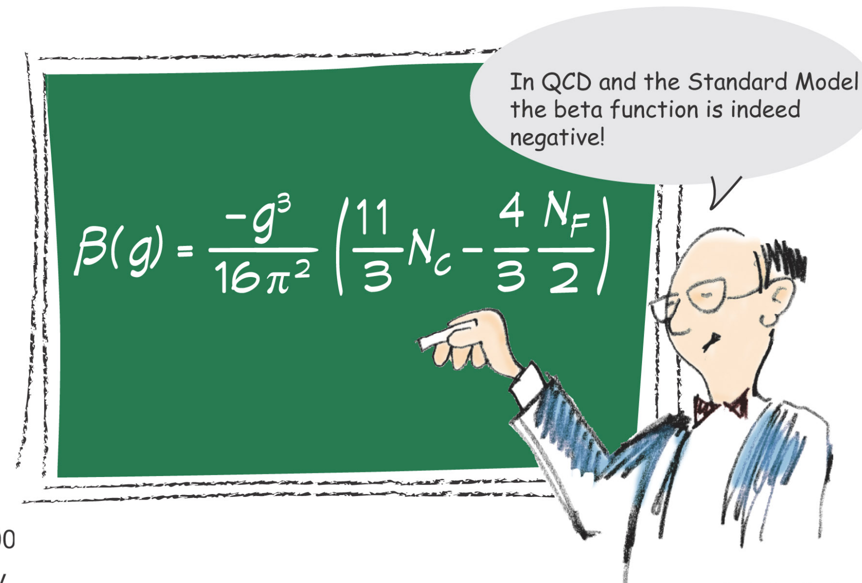


Illustration: Typoform

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer

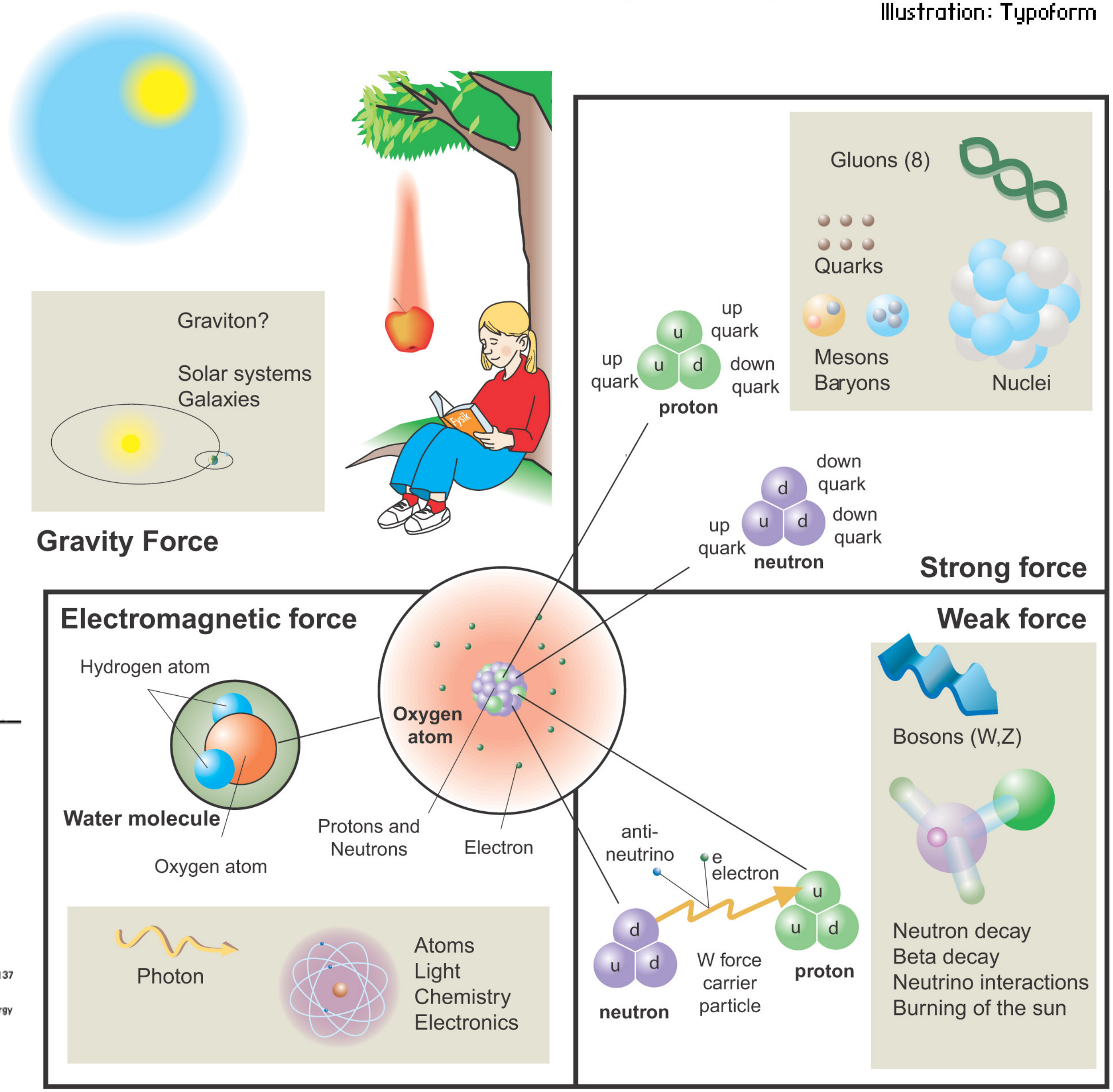
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138

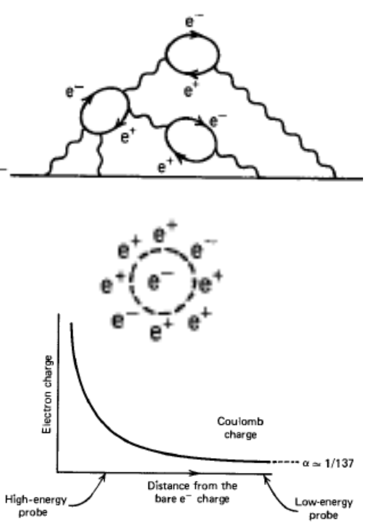
(Received 3 May 1973)

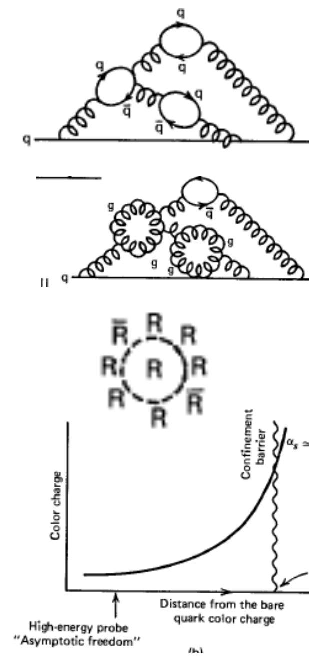
An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

Standard Model and the four forces of nature

Illustration: Typoform



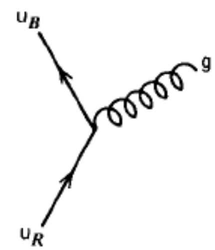
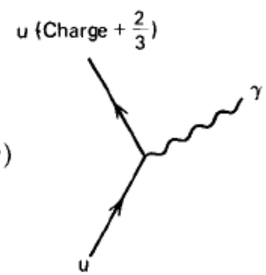
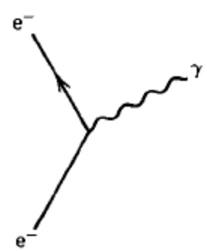
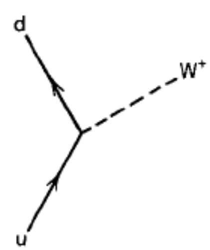
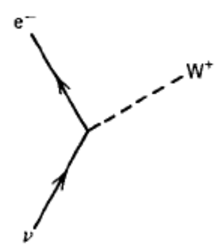


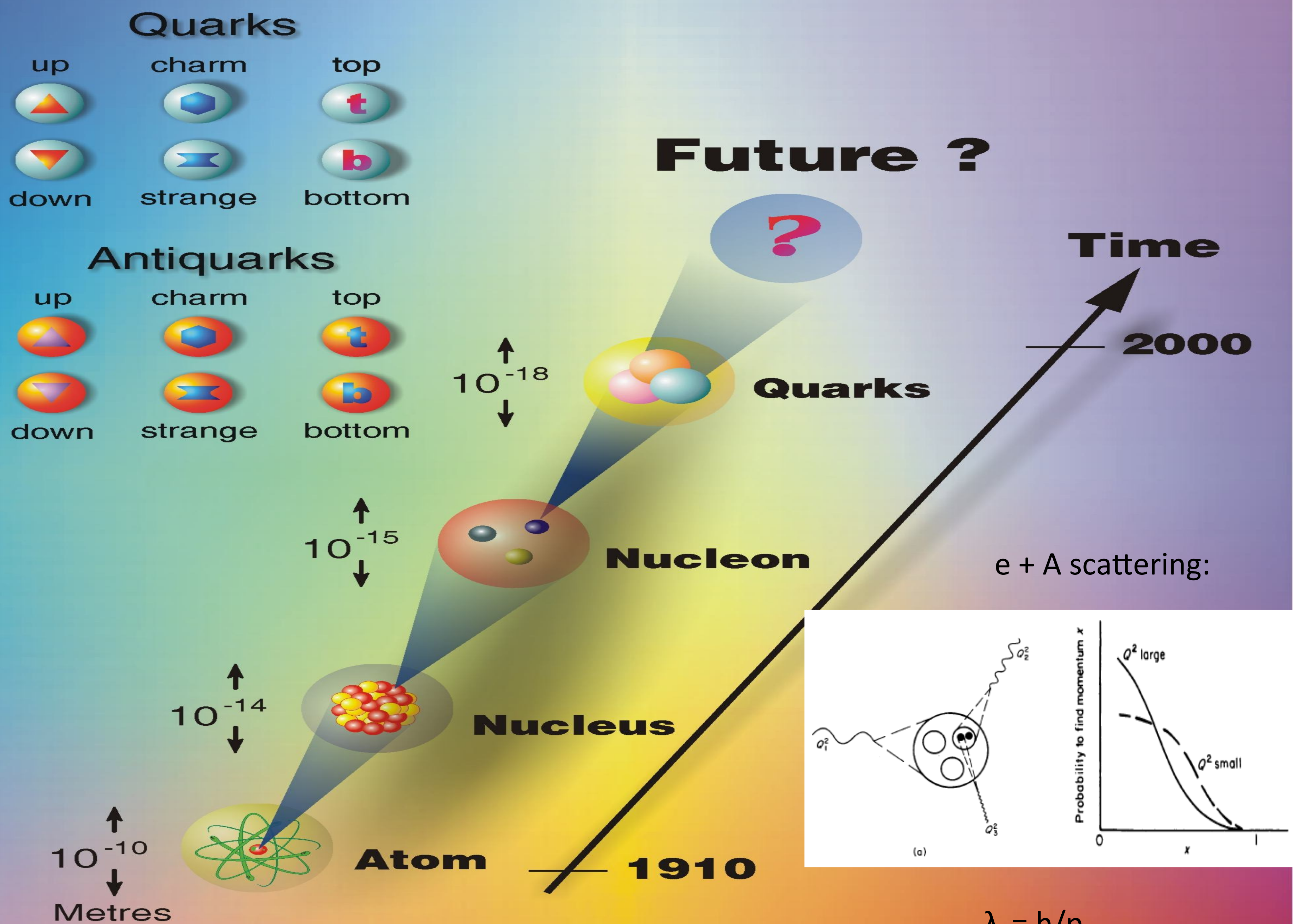


Typical Range of Interactions

Interaction	Range	Typical Lifetime (sec)	Typical Cross Section (mb)	Typical Coupling α_i
Strong	$1\ \mathrm{F} \simeq \frac{1}{m_\pi}$ Color confinement range[a]	10^{-23} e.g., $\Delta \to p\pi$	10 e.g., $\pi p \to \pi p$	1
Electromagnetic	∞	$10^{-20} \sim 10^{-16}$ e.g., $\pi^0 \to \gamma\gamma$ $\Sigma \to \Lambda\gamma$	10^{-3} e.g., $\gamma p \to p\pi^0$	10^{-2}
Weak	$\frac{1}{M_W}$ with $M_W \simeq 100 m_p$	10^{-12} or longer e.g., $\Sigma^- \to n\pi^-$ $\pi^- \to \mu^- \bar{\nu}$	10^{-11} e.g., $\nu p \to \nu p$ $\nu p \to \mu^- p \pi^+$	10^{-6}

Typical Diagrams of Interactions

Interaction	Charge	Quarks	Leptons
Strong	Color		–
Electromagnetic	Electric charge (e)		
Weak	Weak charge (g), giving u → d or $\nu \to e^-$ flavor-changing transitions		

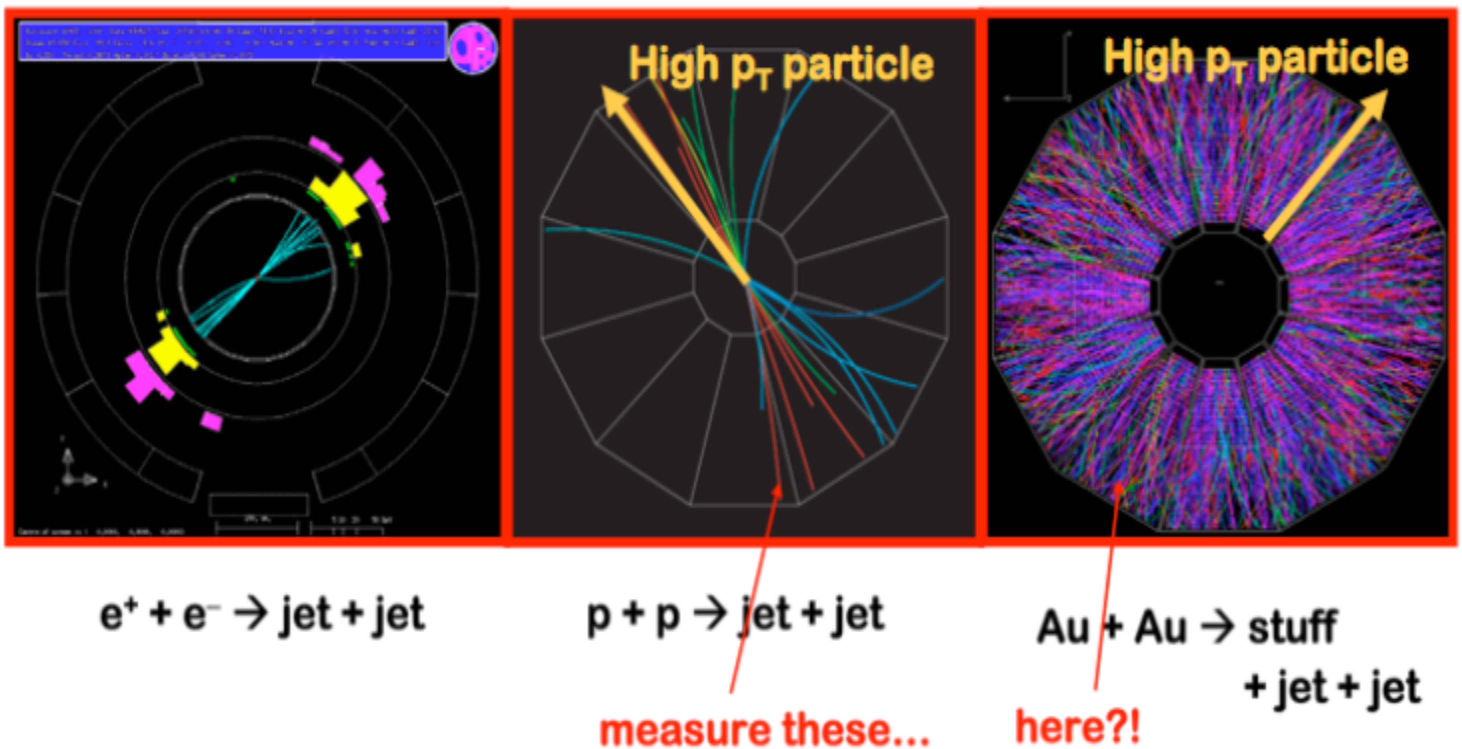


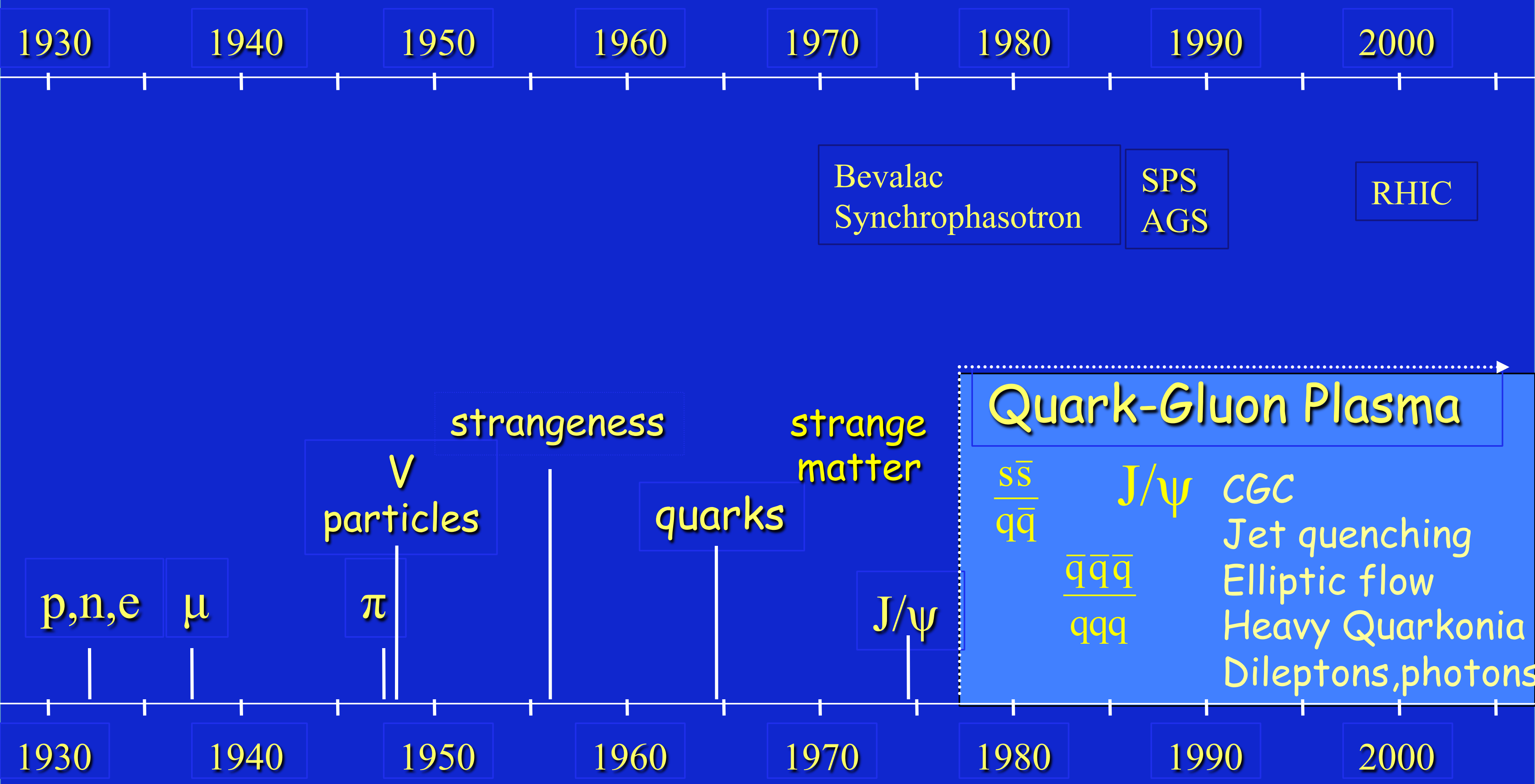
e + A scattering:

$\lambda_B = h/p$

High Energy Experiments classification

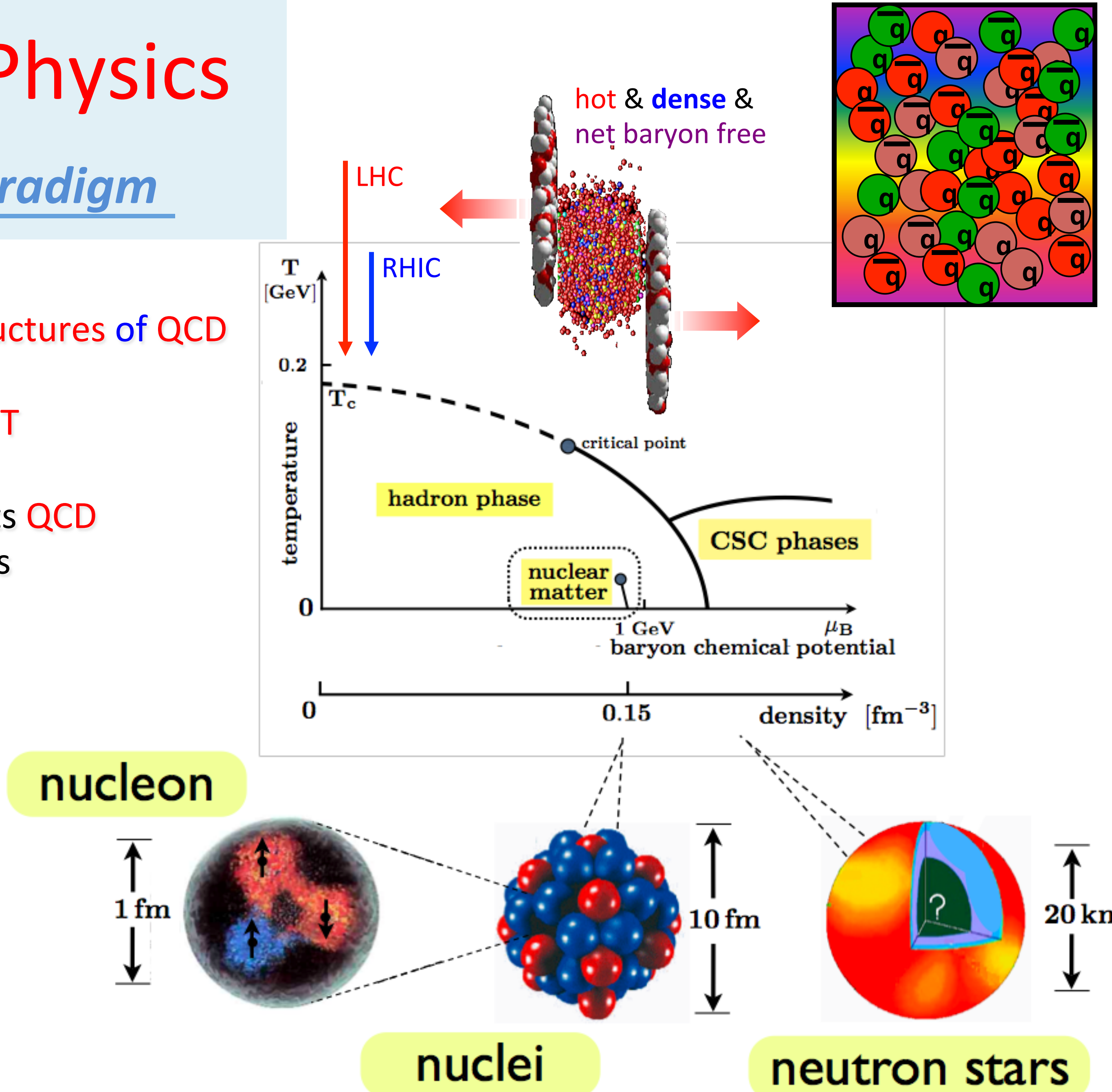
$e^+ + e^-$	most elementary/clean e.g. LEP luminosity issues, QED
$e^- + p,A$	Deep Inelastic Scattering (DIS), virtual γ^*+q, PDF, FF, e.g. HERA
$p + p,\bar{p}$	QCD, α_{QCD}, easier to get luminosity, "color transparency" or stopping, only a fraction of $\sqrt{s}$ available to the coll. dynamics.
$A+A,p$	HI, cold and hot, more efficient than $p+p$, less clean/more challenging, unique physics


High p_T particle
High p_T particle
e⁺ + e⁻ → jet + jet
p + p → jet + jet
Au + Au → stuff + jet + jet
measure these...
here?!


1930
1940
1950
1960
1970
1980
1990
2000
Bevalac
Synchrophasotron
SPS
AGS
RHIC
Quark-Gluon Plasma
$s\bar{s}$ / $q\bar{q}$
J/ψ
CGC
Jet quenching
Elliptic flow
Heavy Quarkonia
Dileptons,photons
$\bar{q}\bar{q}\bar{q}$ / qqq
strangeness
strange matter
V particles
quarks
p,n,e
μ
π
J/ψ

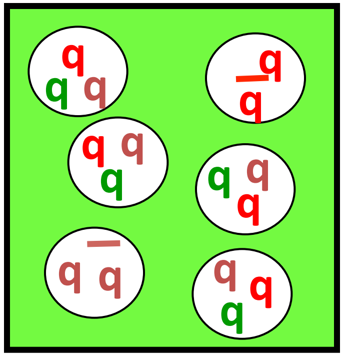
Heavy Ion Physics

1980-2004 old paradigm

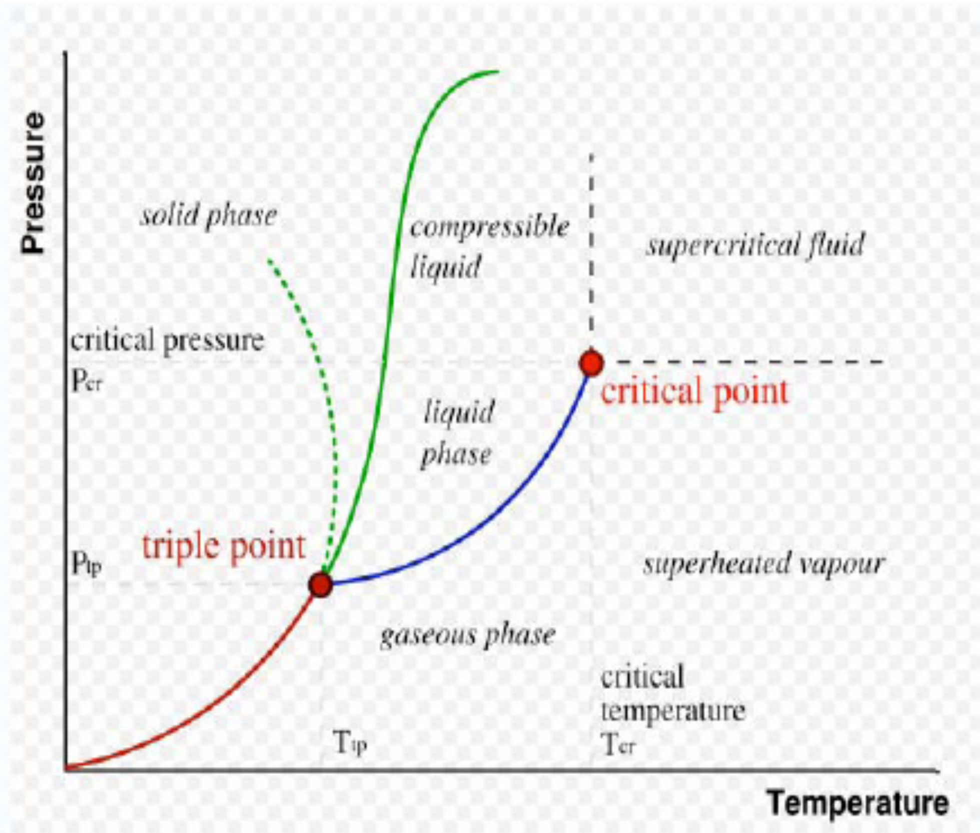


Exploring Phases and Structures of QCD phase diagram

- High temperature T
- High density ε
- Many-body aspects QCD
- Vacuum properties



Critical temperature CEP etc.

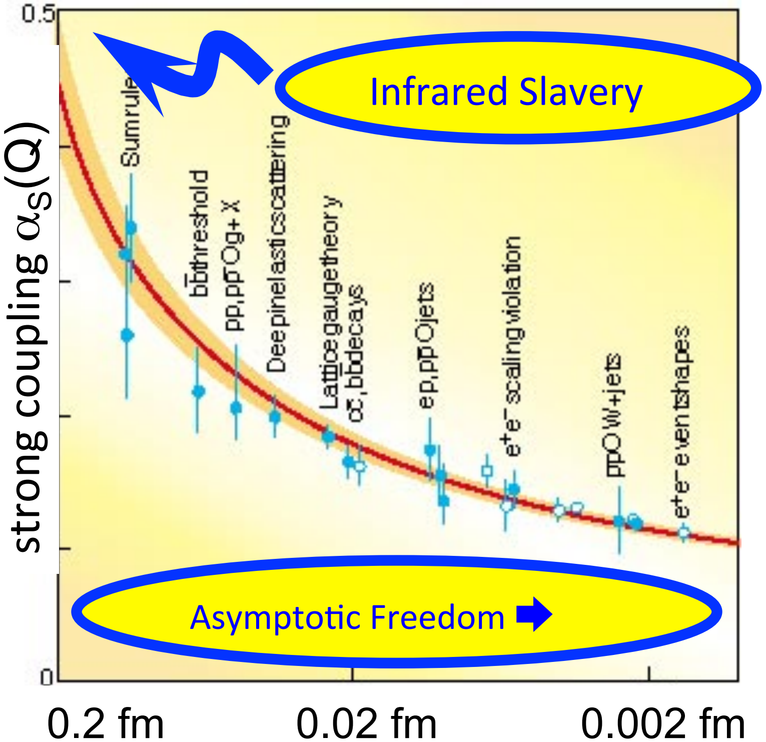


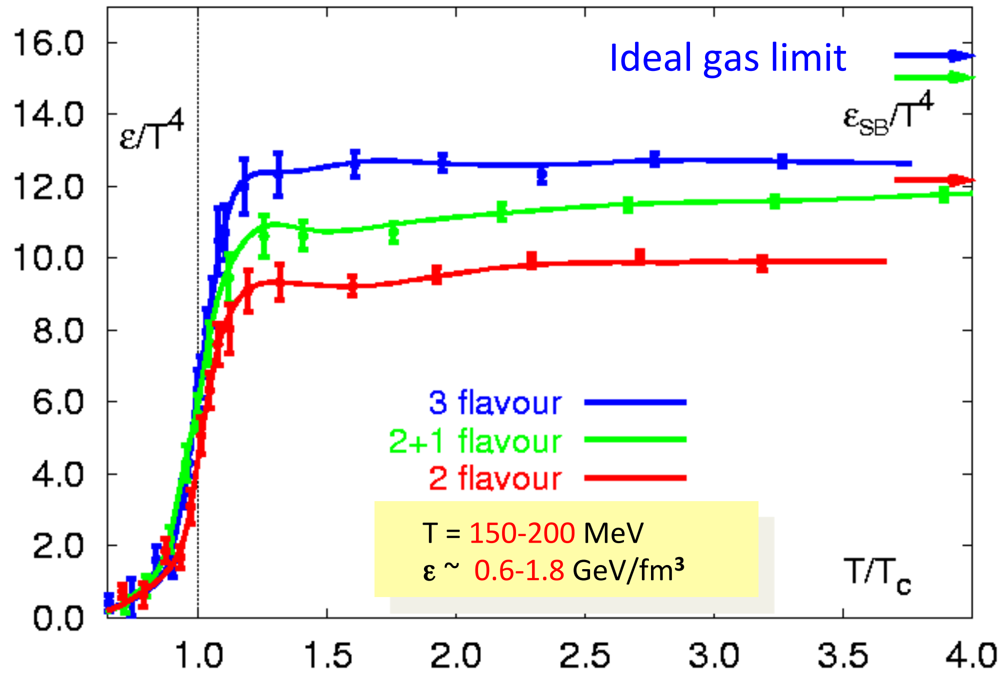
The **critical temperature**, T_c, of a material is the temperature above which distinct liquid and gas phases do not exist. As the critical temperature is approached, the properties of the gas and liquid phases become the same resulting in only one phase: the supercritical fluid. Above the critical temperature a liquid cannot be formed by an increase in pressure, but with enough pressure a solid may be formed. The **critical pressure** is the vapor pressure at the critical temperature. On the diagram showing the thermodynamic properties for a given substance, the point at critical temperature and critical pressure is called the critical point of the substance. The critical molar volume is the volume of one mole of material at the critical temperature and pressure.

For pure substances, there is an inflection point in the critical isotherm on a PV diagram. This means that at the critical point:

$$\left(\frac{\partial P}{\partial V}\right)_T = \left(\frac{\partial^2 P}{\partial V^2}\right)_T = 0$$

Phase transition in Heavy Ion collisions

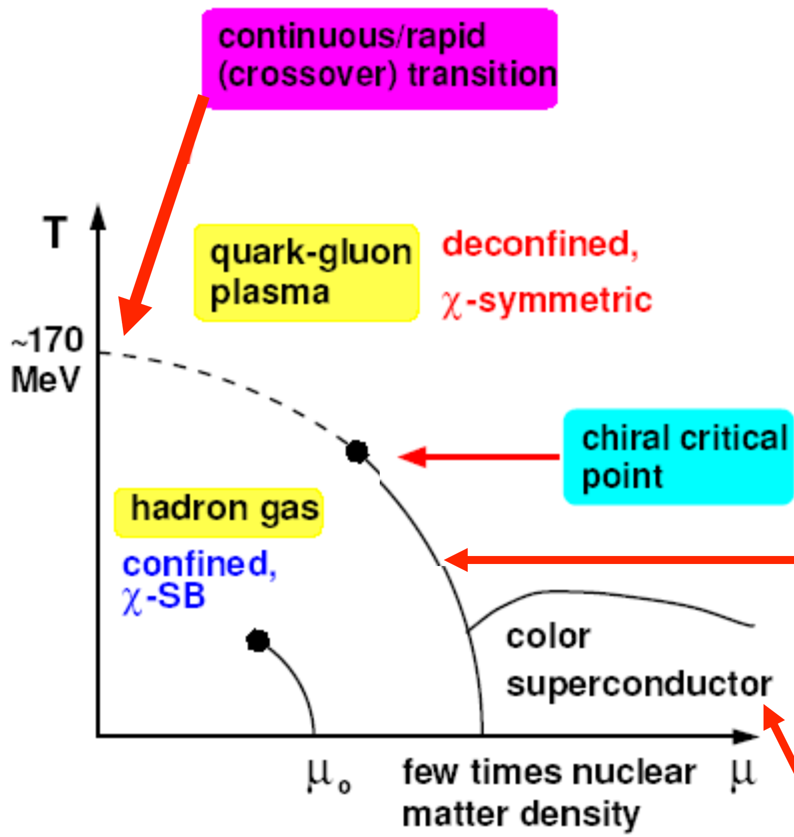




Lattice QCD, *Lect. Notes Phys* ***583****, 209 (2002)*

T.D.Lee (1974) Temporarily restored broken symmetries of the **physical vacuum**
Collins, Perry (1975) Asymptotic freedom in QCD → deconfined quarks/gluons matter
E.V. Shuryak (1978) Invented Quark Gluon Plasma → target of HI community

Critical behavior in hot and dense matter: QCD phase diagram



continuous transition for small chemical potential and small quark masses at

$T_c \simeq 170\ MeV$

$\epsilon_c \simeq 0.7\ GeV/fm^3$

2nd order phase transition; Ising universality class

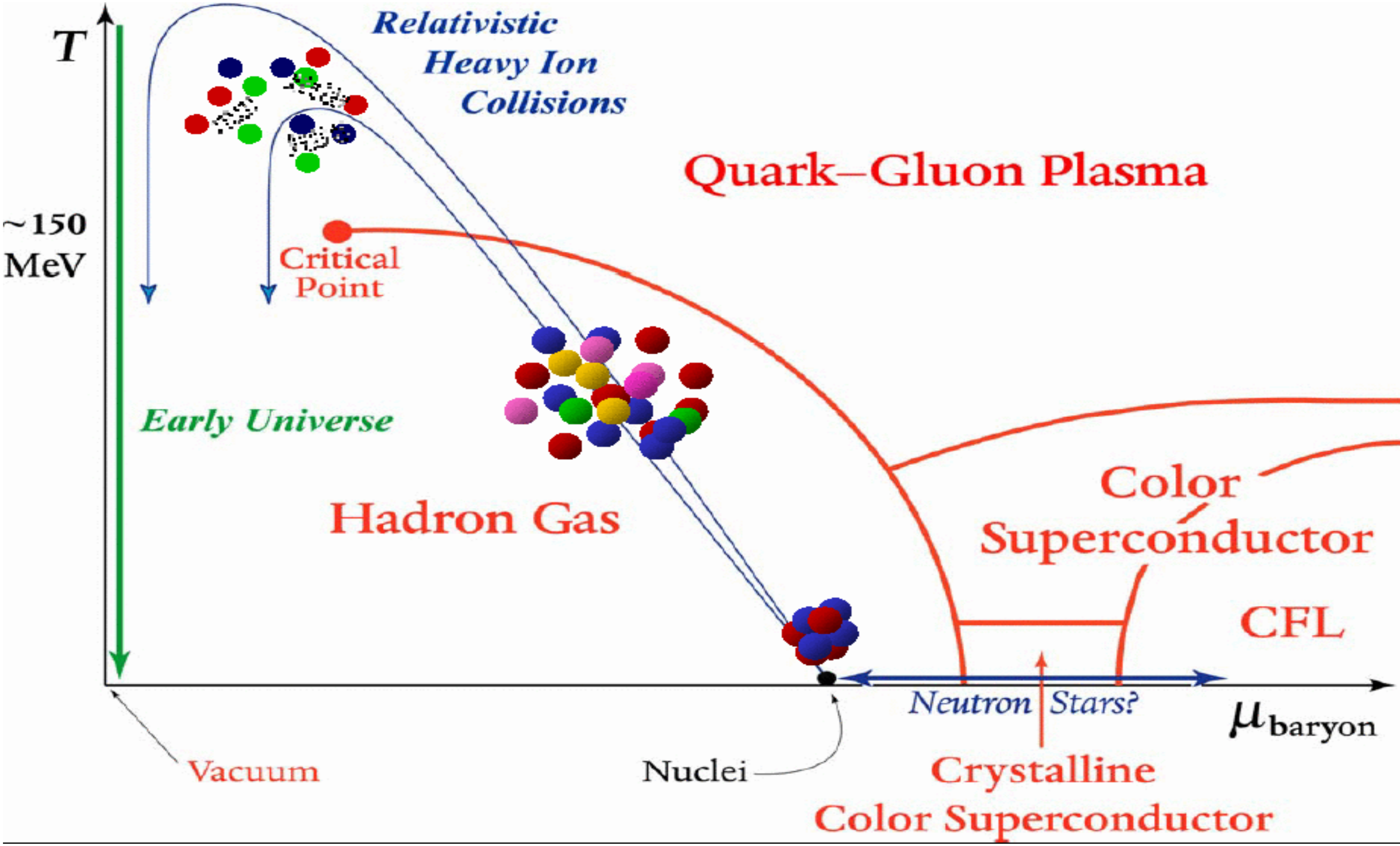
$T_c(\mu)$ under investigation

1st order phase transition ???

expected - however, so far no direct evidence from lattice QCD

attractive 1–gluon exchange => qq–condensates

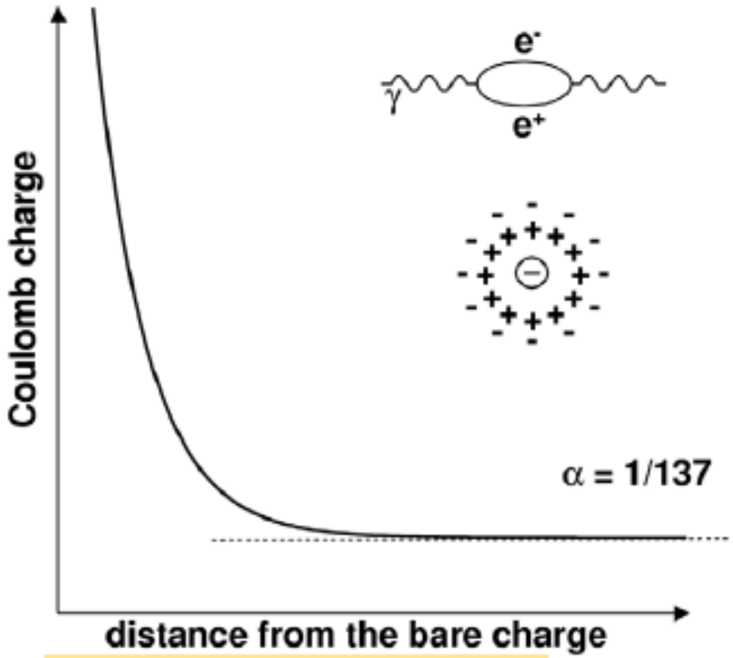
Present status of the Equation of State



Collider era – quantum field theory

Local gage invariance → two "identical" theories

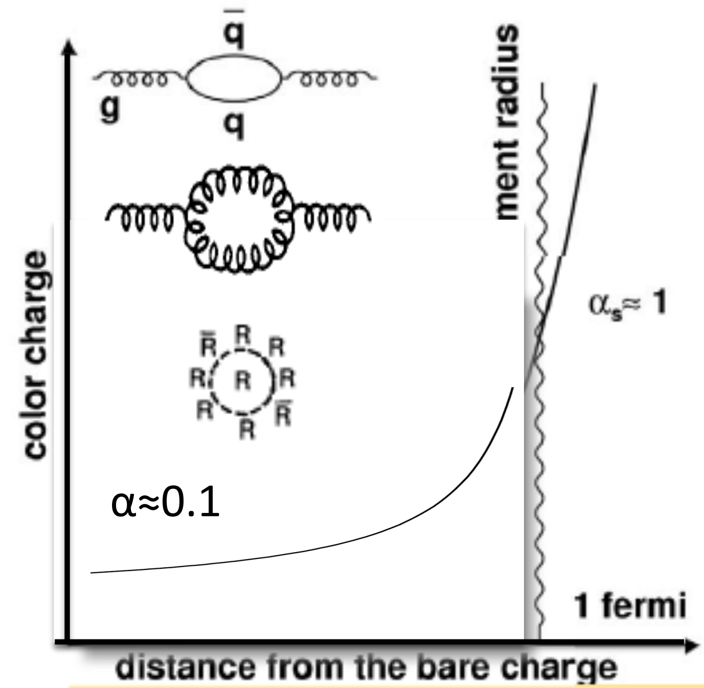
Electroweak interaction QED



$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log(\frac{Q^2}{\mu^2})}$$

Landau's zero charge problem
–vacuum rearrangement ?

Strong interaction QCD



$$\alpha_S(Q^2) = \frac{\alpha_S(\mu^2)}{1 + \frac{\alpha_S(\mu^2)}{12\pi}(33 - 2n_f)\log(\frac{Q^2}{\mu^2})}$$

Heavy ion coll. - QGP problem
–vacuum rearrangement ?

Quantum Chromodynamics (QCD)

- **Fields:**

$\psi_i^f(x)$ — Quark fields, Dirac fermions (like e^-)
Color triplet: $i = 1,2,3 = N_C$
Flavor: $f = u,d,s,c,b,t$

$A_{\mu,a}(x)$ — Gluon fields, spin-1 vector field (like γ)
Color octet: $a = 1,2,\ldots,8 = N_C^2-1$

- **Lagrangian density:**

$$L_{QCD}(\psi,A) = \sum_f \overline{\psi}_i^f \left[\left(i\partial_\mu - gA_{\mu,a}(t_a)_{ij} \right)\gamma^\mu - m_f \right] \psi_i^f$$
$$-\frac{1}{4}\left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c} \right]^2$$

+ gauge fixing + ghost terms

Color matrix: $[t_a, t_b] = iC_{abc}t_c$

- **Gauge invariance:**

$$\psi_i \to \psi'_j = U_{ji}(x)\psi_i$$

$$A_\mu \to A_\mu' = U(x)A_\mu U^{-1}(x) + \frac{i}{g}\left[\partial_\mu U(x)\right]U^{-1}(x)$$

where $A_\mu = A_{\mu,a}t_a$

Perturbative QCD

- Physical quantities can't depend on the renormalization scale - *μ*:

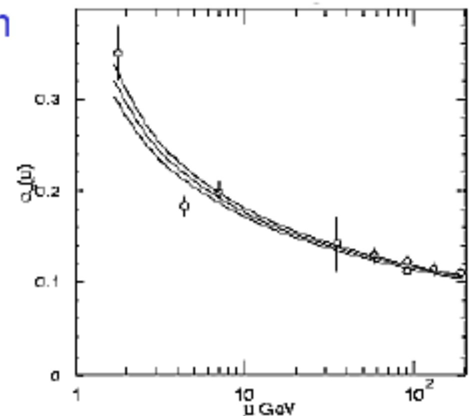
$$\mu^2 \frac{d}{d\mu^2}\sigma_{\text{phy}}\left(\frac{Q^2}{\mu^2}, g(\mu), \mu\right) = 0$$

$$\Longrightarrow \quad \sigma_{\text{phy}}(Q^2) = \sum_n \sigma^{(n)}(Q^2, \mu^2)\left(\frac{\alpha_s(\mu)}{2\pi}\right)^n$$

- Asymptotic freedom

$$\alpha_s(\mu) = \frac{g^2(\mu)}{4\pi}$$

$$\propto \frac{1}{\ell n(\mu^2 / \Lambda^2_{\text{QCD}})}$$



Can we choose μ^2 as large as we want?

No! $\quad \sigma^{(n)}(Q^2, \mu^2) \propto \ell n(Q^2 / \mu^2) + \ldots$

$$\Longrightarrow \quad \mu^2 \sim Q^2$$

Larger Q^2, larger effective μ^2, smaller $\alpha_s(\mu)$

⇨ Perturbative QCD works better for physical quantities with a large momentum exchange

Levels of the nuclear world

- Nuclei

  a large variety (Z=1-118, A=2-294), sizes: ~10^{-14} m

  nucleons are bound by about 1% of their mass ($m_p \approx m_n = 1.7 \times 10^{-27}$ kg)

- Hadrons

  baryons (p,n,...), mesons (π, K, …), sizes: 10^{-15} m

- Quarks

  6 flavours (light: u,d; “intermediate”: s; heavy: c,b; “super-heavy”: t)

  each in 3 “colours” (to build colourless hadrons: qqq, $\overline{qqq}$, $q\overline{q}$, …)

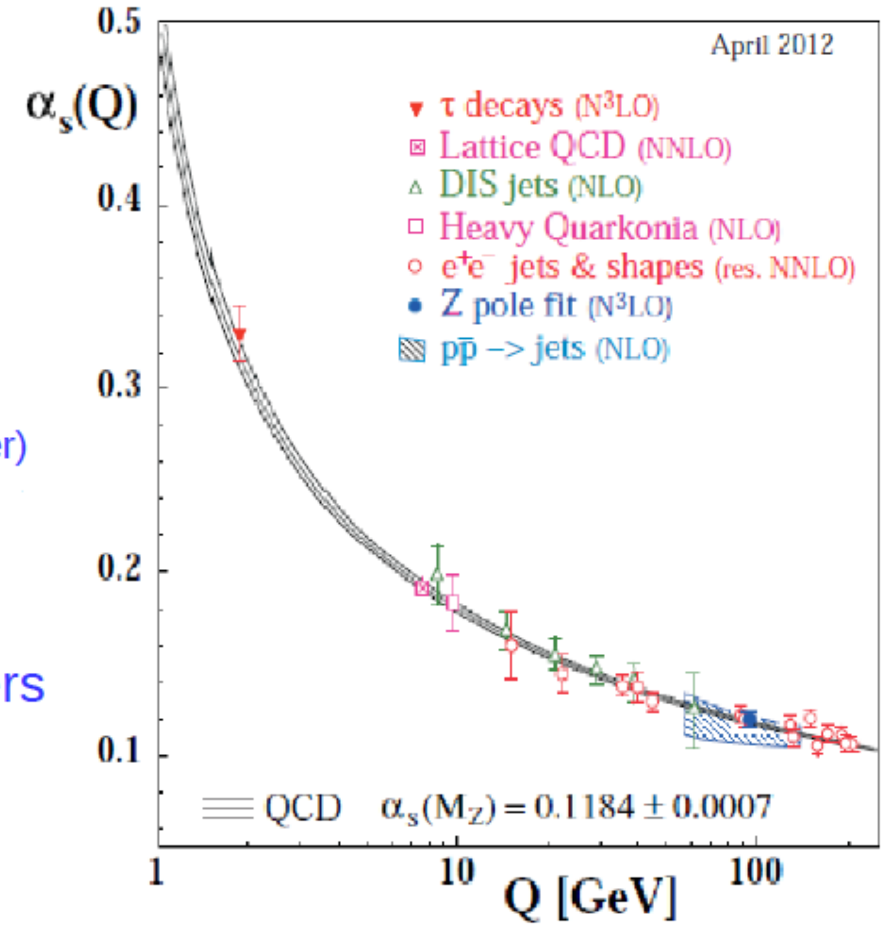
  sizes: point-like (<10^{-19} m)

- … all governed by the strong interaction
- Gravitation is negligible
- (electro)weak interactions act only indirectly (decays, final state interactions)

Quantum Chromo-Dynamics (QCD)

- 6 quarks, 3 colours (RGB) and 8 gluons (coloured!)
- ...difficult to calculate
  - No analytical solutions (except 1+1)
- **High *Q*:** asymptotic freedom

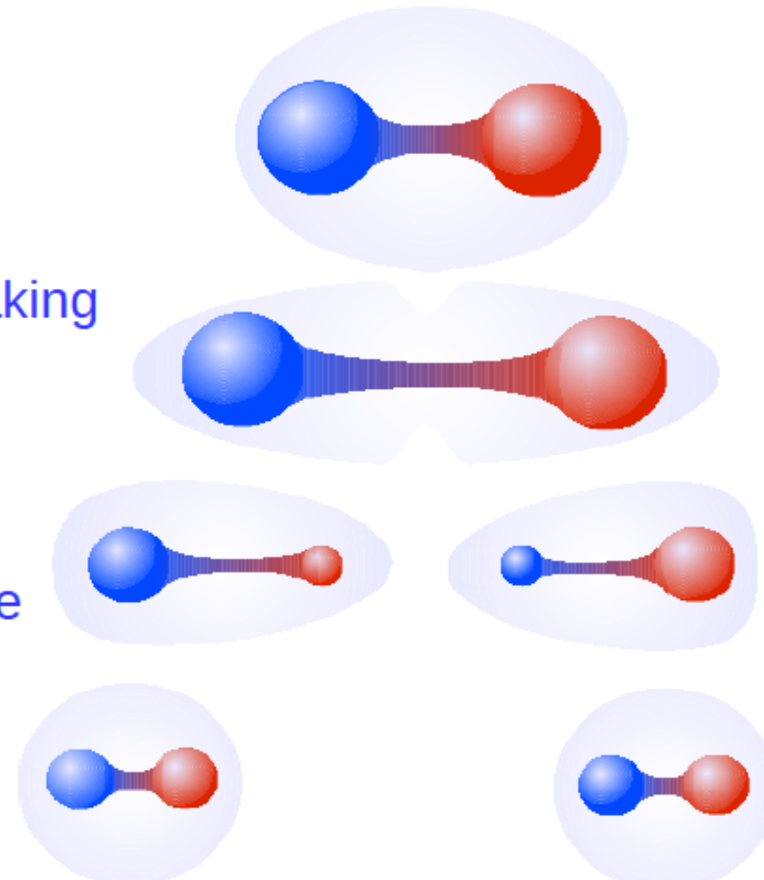
  Physics Nobel prize 2004 (Wilczek, Gross, Politzer)
- Typically solvable using perturbative theory
- Tested extensively at modern colliders

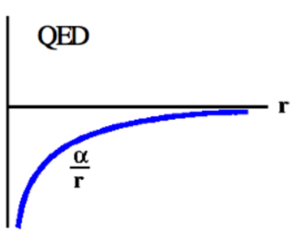


S.Bethke, arXiv:1210.0325

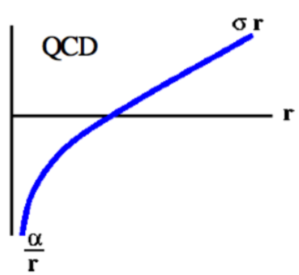
Quantum Chromo-Dynamics (QCD)

- 6 quarks, 3 colours (RGB)
  and 8 gluons (coloured!)
- ...difficult to calculate
  - No analytical solutions (except 1+1)
- **Low *Q*:** confinement / chiral symmetry breaking
  Physics Nobel Prize 2008 (Y.Nambu)
  - Non-perturbative, largely unknown
  - One of the millenium problems
  - Most of the visible matter in the Universe





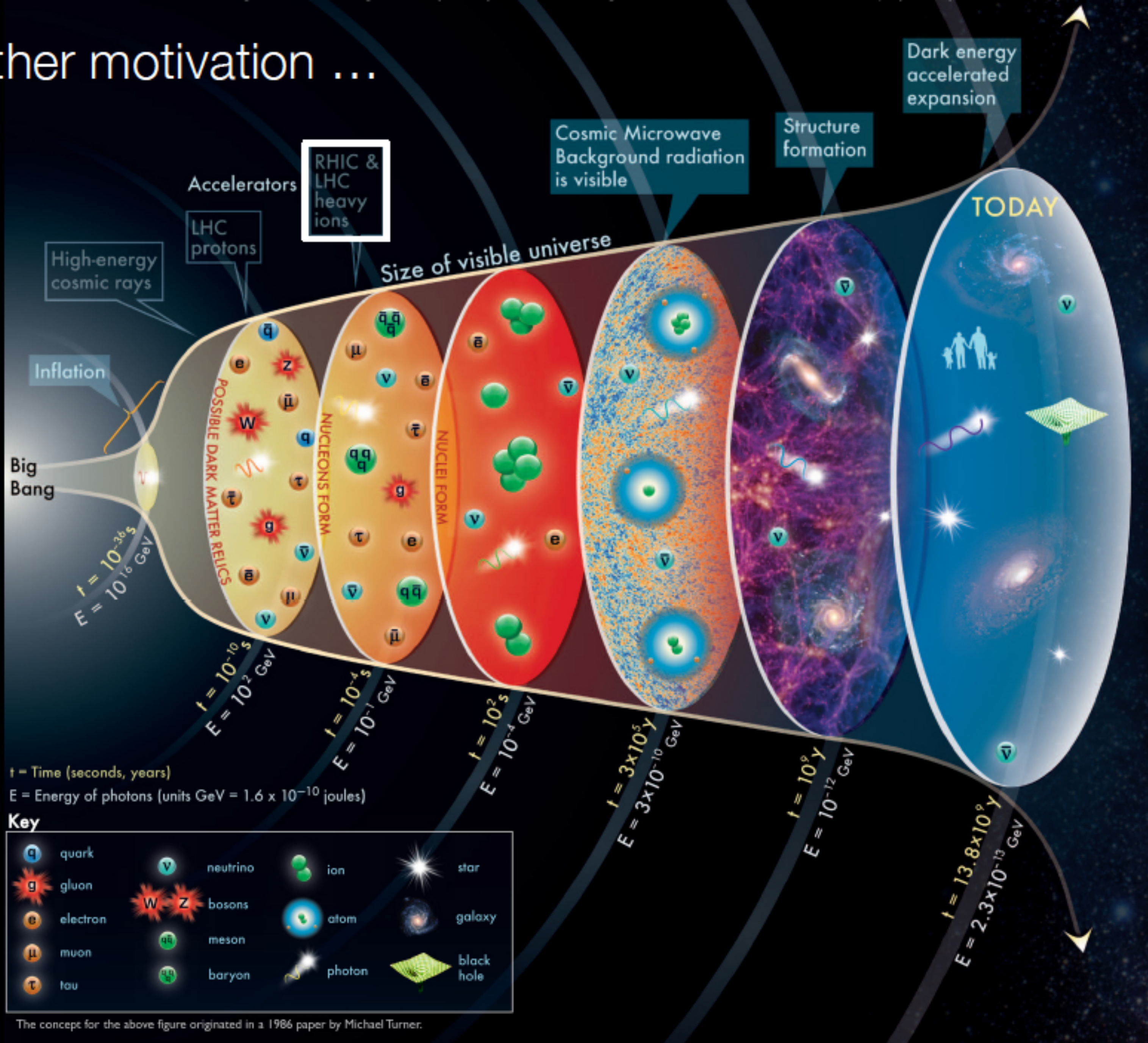
$$V(r) \propto \frac{\alpha}{r}$$



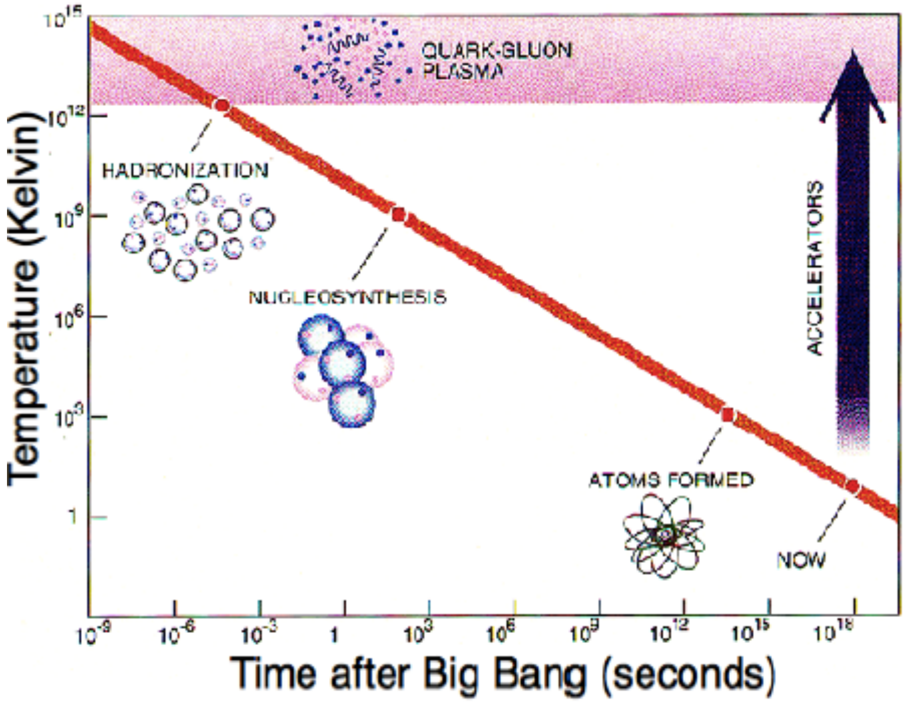
$$V(r) = -\frac{4\alpha_s(r)}{3r} + k\,r$$

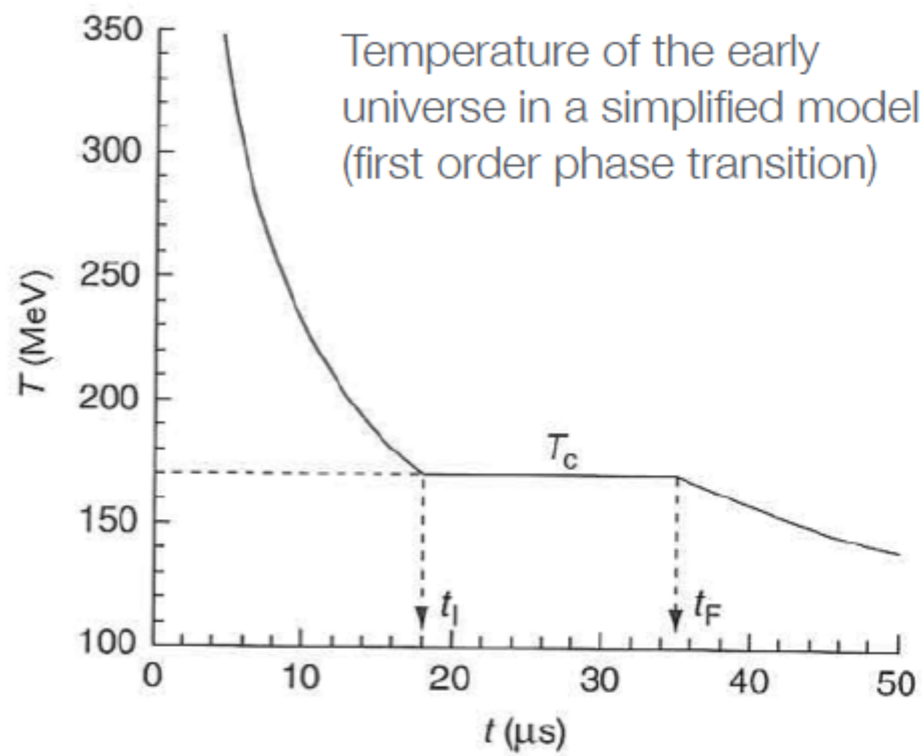
Linear term associated with confinement,
expected to disappear in the QGP

A further motivation …



QGP in the early universe

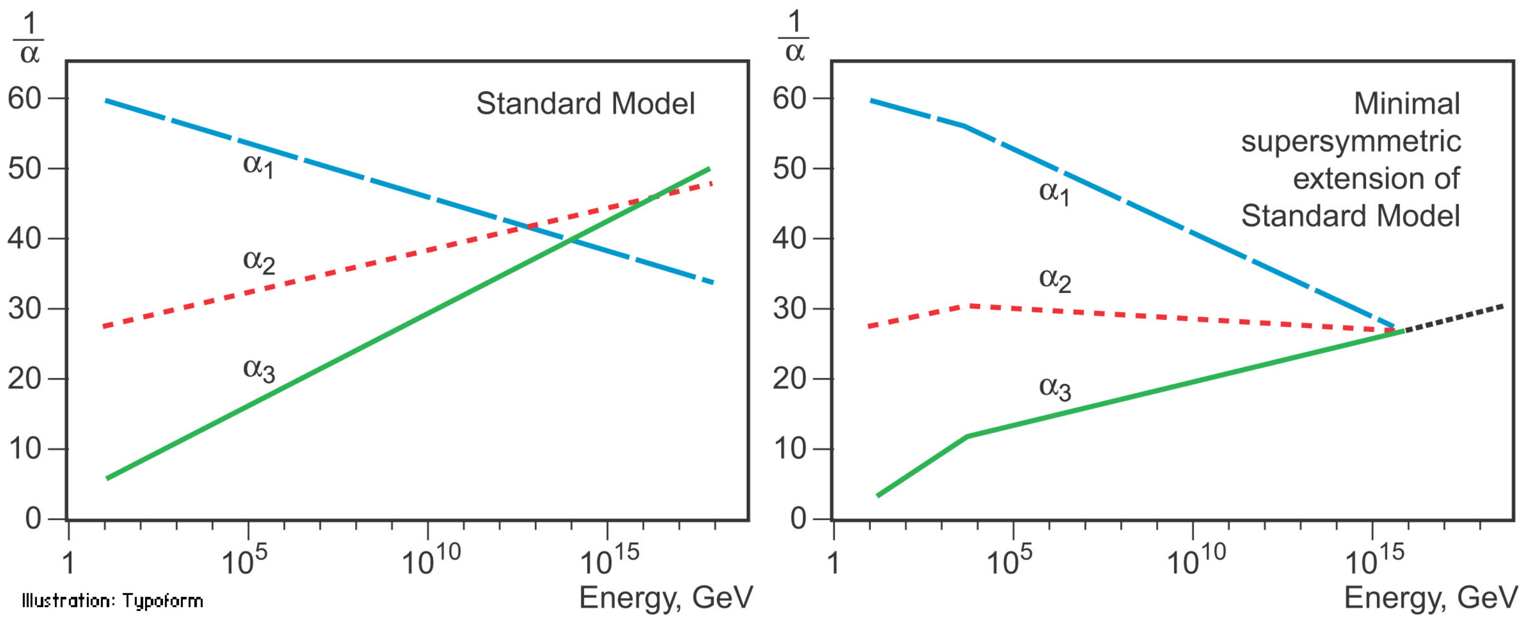




- Transition from the quark-gluon plasma to a gas of hadrons at a temperature of $T_c \approx 1.8 \times 10^{12}$ K
- 100 000 hotter than the core of the sun
- Early universe: QGP → hadron gas a few microseconds after the Big Bang

Can the forces of nature be unified ?

Can the forces of nature be unified?



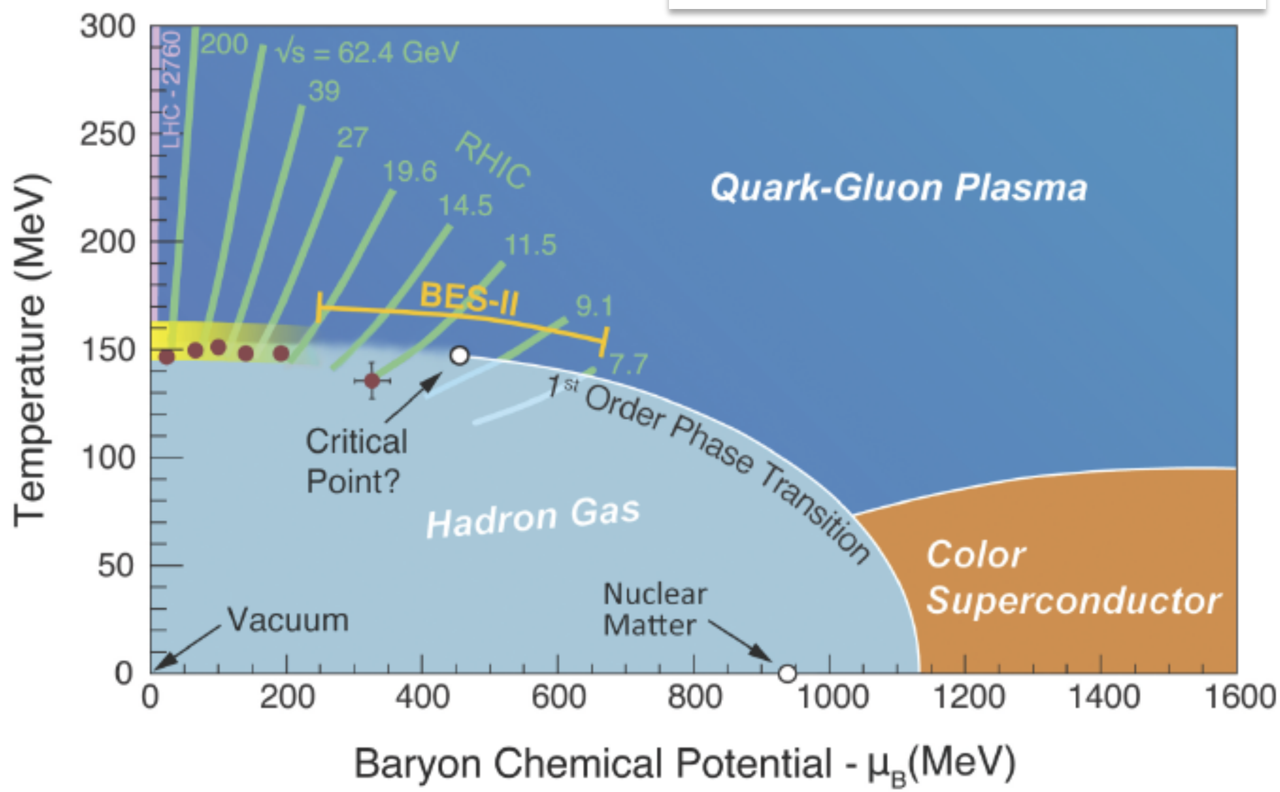
One possibility for Grand Unification is introduction of new set of supersymmetric particles

Relativistic heavy-ion collisions

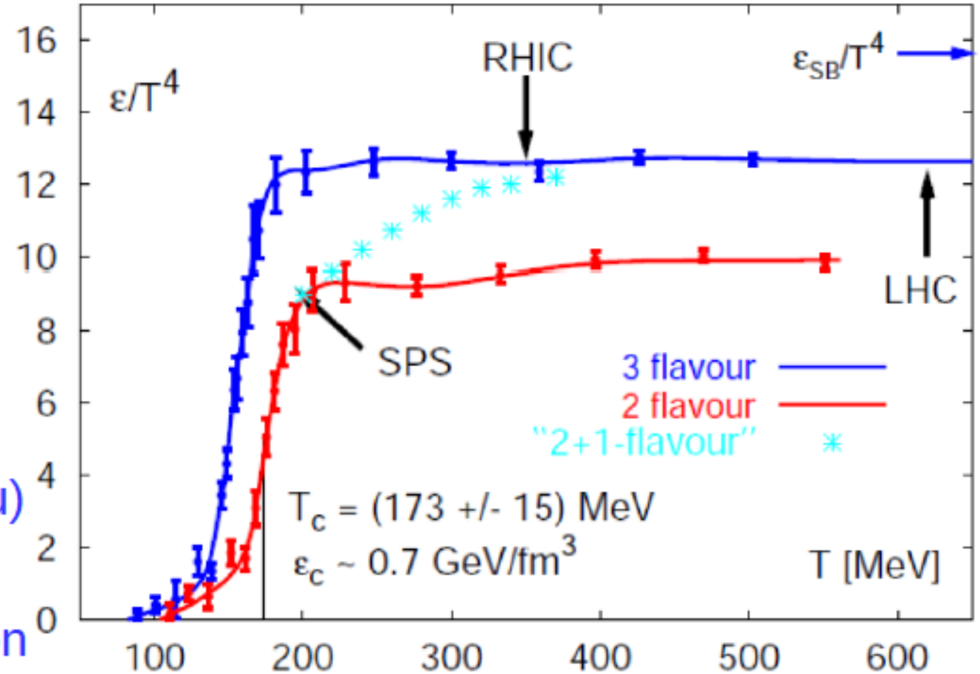
- Creates in lab conditions a chunk of **deconfined nuclear matter** with a lifetime long enough to allow the study of its properties

Relativistic heavy-ion collisions

- Relevance for:
  - QCD studies (low-Q, finite T and μ)
    Phase diagram of nuclear matter:
    - deconfinement phase transition



Relativistic heavy-ion collisions



F. Karsch, hep-lat/0106019

- Relevance for:
  - QCD studies (low-Q, finite T and μ)
    Phase diagram of nuclear matter:
    - deconfinement phase transition
    - Lattice QCD calculations conclude transition is cross-over type
      (Y.Aoki et al., Nature 443 (2006) 675)
    - "Critical" temperature: T_c≈155-160 MeV

(A.Bazavov et al., arXiv:1111.1710, S.Borsanyi et al., arXiv:1005.3508)

Problem: see http://folk.uio.no/larissa/nuclphys/Wong_book/Wong_Ch.9_q,g_and_QGP.pdf

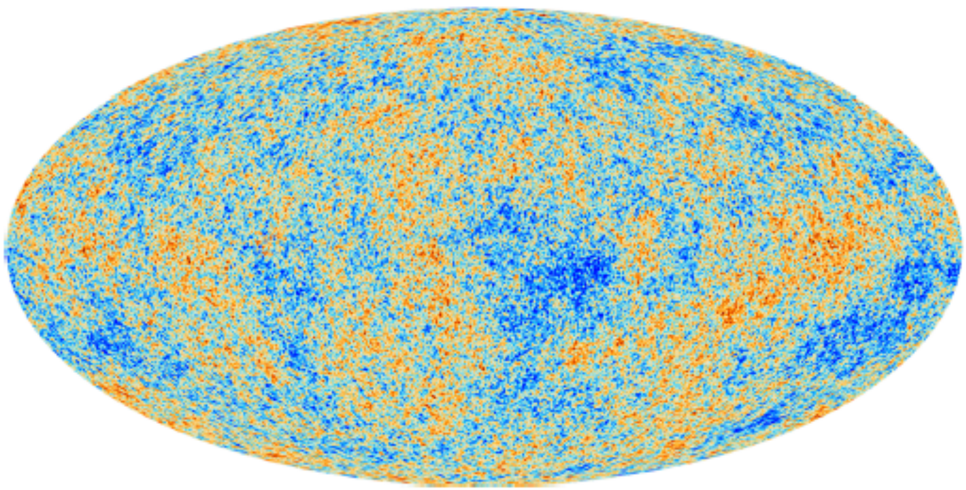
1) For the first order phase transition between pion gas and quark gluon equilibrated ideal gas (number of flavours is 2: u,d quarks only) find Critical temperature T_c for equal number of quarks and antiquarks

2) Find critical baryon chemical potential for quarks at zero temperature (in neutron stars)

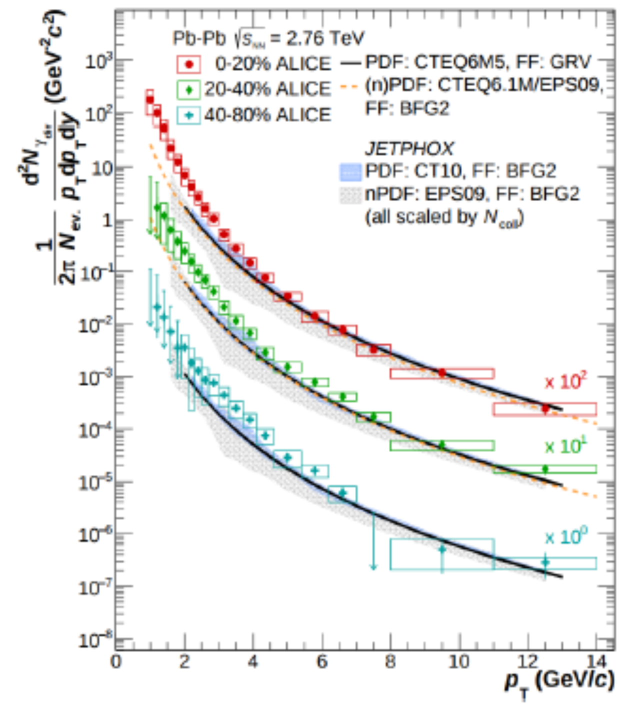
Relativistic heavy-ion collisions

- Creates in lab conditions a chunk of **deconfined nuclear matter** with a lifetime long enough to allow the study of its properties
- Relevance for:
  - QCD studies
  - Cosmology: access early Universe conditions (10^{-5} s)

Cosmic microwave background seen by Planck



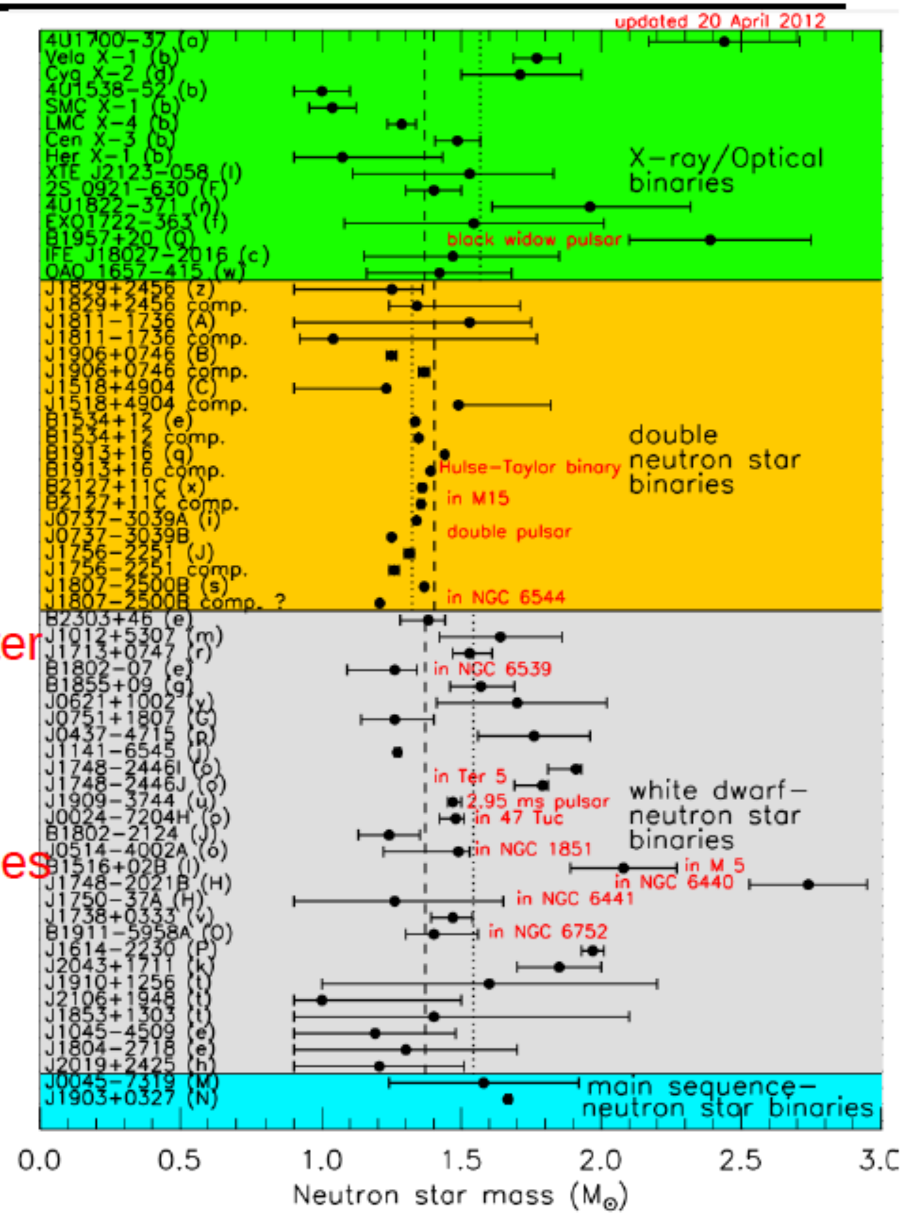
Direct photon production in Pb-Pb collisions at the LHC
T ~ 300 MeV



ALICE Collaboration, PLB754 (2016) 235

Relativistic heavy-ion collisions

- Relevance for:
  - QCD studies
  - Cosmology
  - Astrophysics: neutron stars mass controlled by the equation of state (EoS) of nuclear matter
  - “Canonical” mass: 1.4 M_{sun}
  - How can the outliers exist ?
    - Stiffer EoS at larger nuclear densities



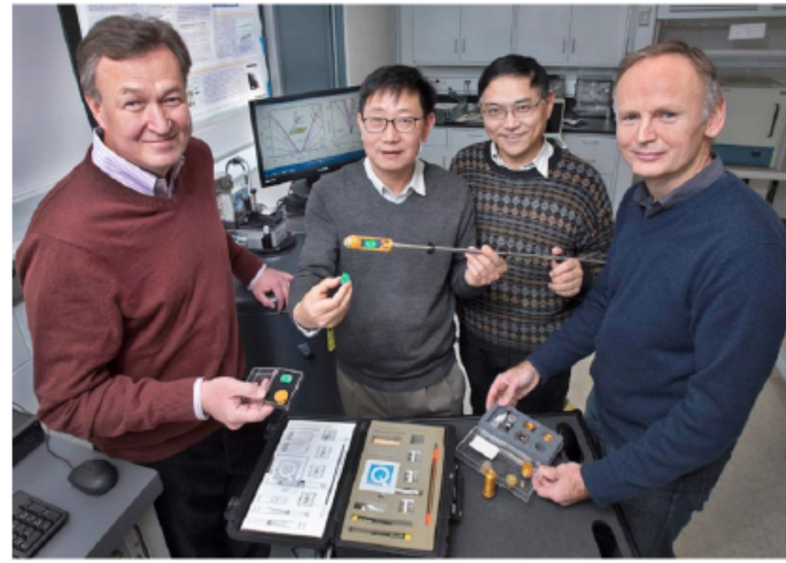
J.M.Lattimer, arXiv:1305.3510

Relativistic heavy-ion collisions

Chiral Magnetic Effect Generates Quantum Current

Separating left- and right-handed particles in a semi-metallic material produces anomalously high conductivity

February 8, 2016



Nuclear theorist Dmitri Kharzeev of Stony Brook University and Brookhaven Lab with Brookhaven Lab materials scientists Qiang Li, Genda Gu, and Tonica Valla in a lab where the team measured the unusual high conductivity of zirconium pentatelluride. + ENLARGE

- Relevance for:
  - QCD studies
  - Cosmology
  - Astrophysics
  - Solid state physics:

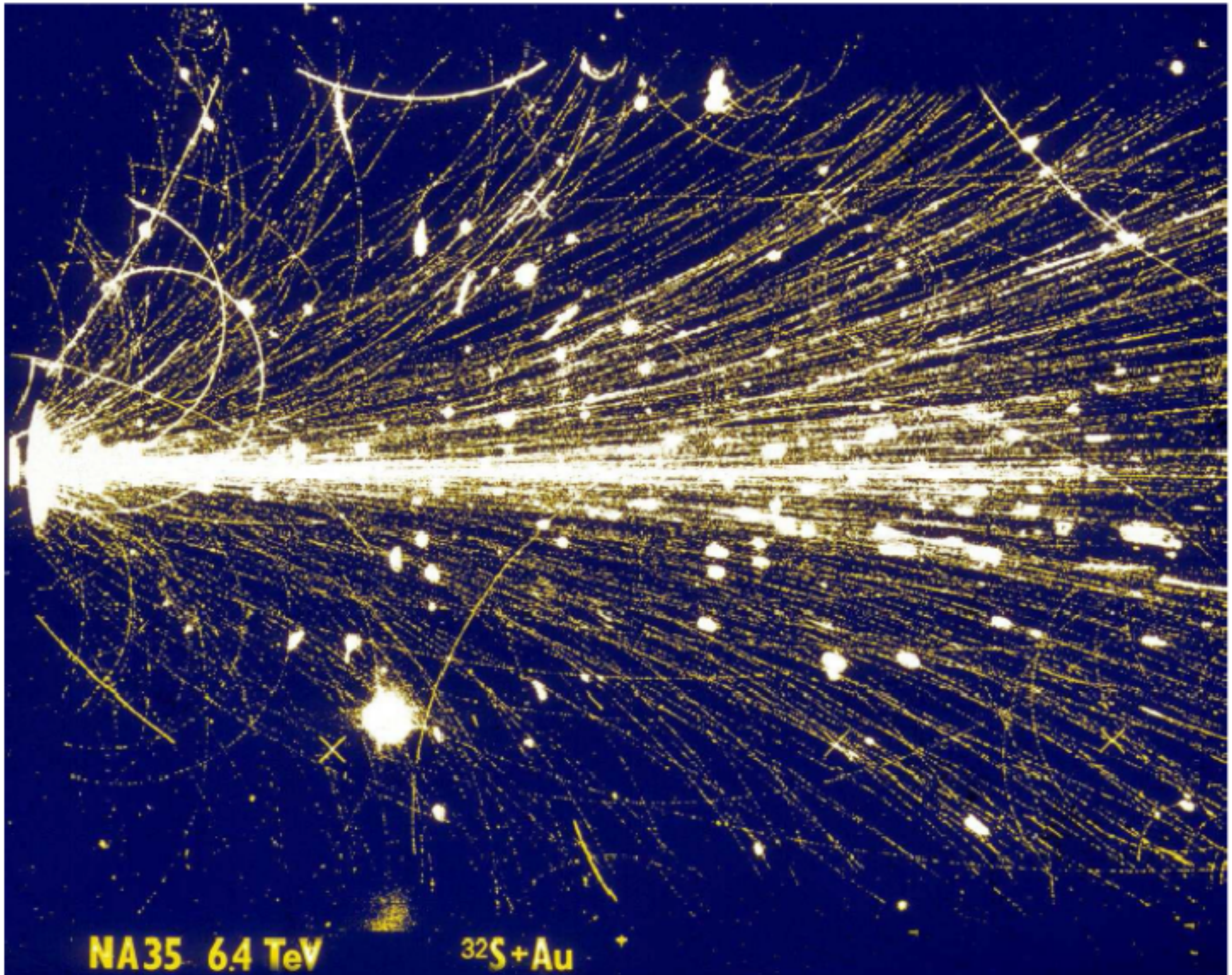
    Chiral magnetic effect first studied in HIC, now discovered in condensed matter experiments
    - Potential applications in quantum computing, “quantum electricity generators”, high temperature superconductivity

Q.Li, D.Kharzeev et al., Nature Physics Letters 2016

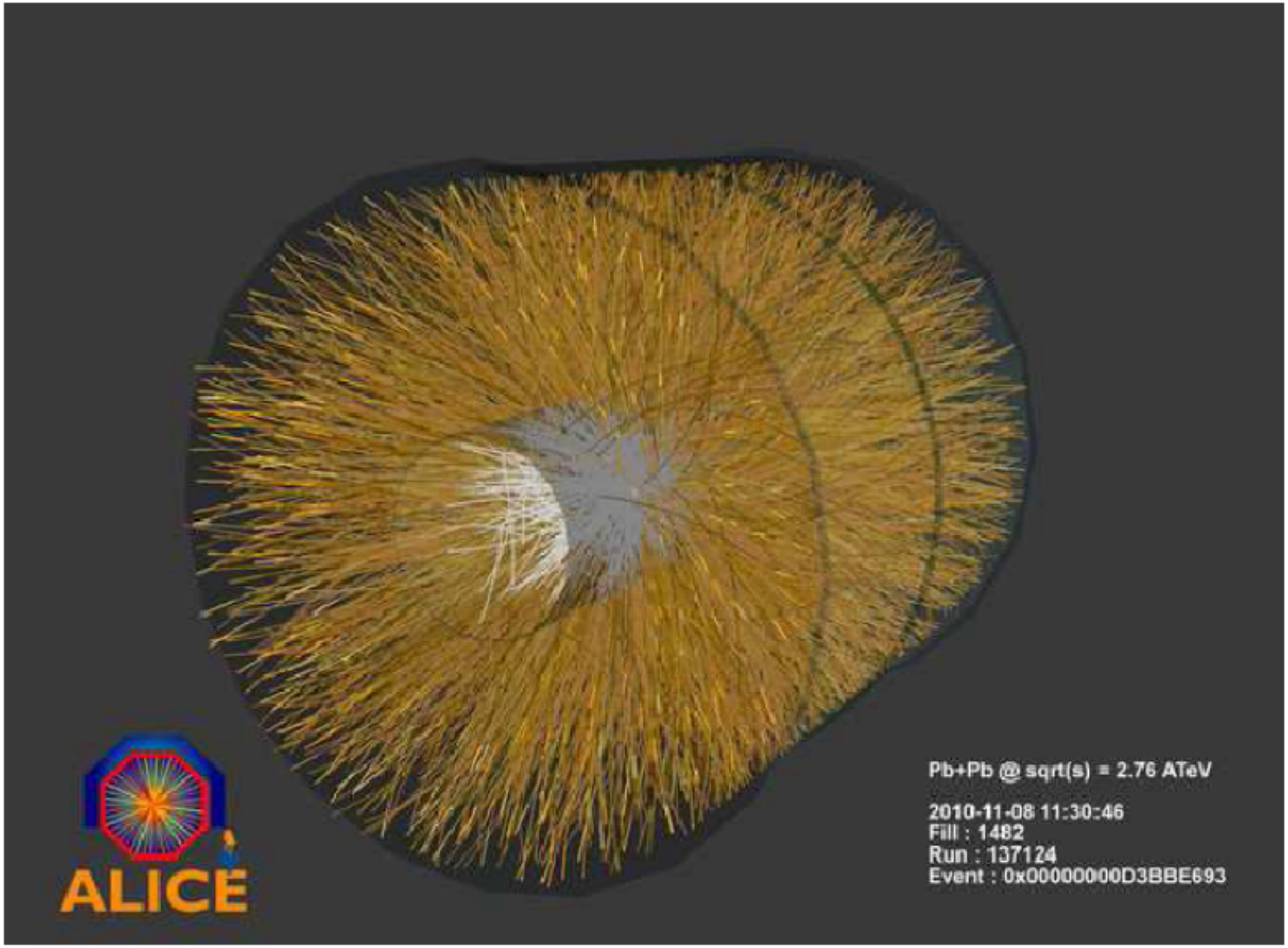
Heavy ion accelerators

- Past:
  - Bevalac @ LBL, Berkeley (1954): $\sqrt{s_{NN}}$=2.4 GeV
  - Synchrophasotron @ JINR, Dubna (1957): $\sqrt{s_{NN}}$=4GeV
  - AGS @ BNL, Brookhaven (1960): $\sqrt{s_{NN}}$=4.8 GeV
  - SPS @ CERN, Geneva (1976): $\sqrt{s_{NN}}$=17.3 GeV
- Present:
  - SIS @ GSI, Darmstadt: $\sqrt{s_{NN}}$=2.5 GeV
  - SPS @ CERN, Geneva: $\sqrt{s_{NN}}$=17.3 GeV
  - RHIC @ BNL, Brookhaven: $\sqrt{s_{NN}}$=200 GeV
  - LHC @ CERN, Geneva: $\sqrt{s_{NN}}$=2760, 5020 GeV
- Future:
  - FAIR @ GSI, Darmstadt (~2020): $\sqrt{s_{NN}}$=5 GeV
  - NICA @ JINR, Dubna (~2020): $\sqrt{s_{NN}}$=5 GeV
  - FCC @ CERN (?): $\sqrt{s_{NN}}$ ~ 40 TeV

An early picture of a heavy-ion collision (CERN)



A Pb-Pb collision measured by ALICE



- A 3D picture (with 500 million voxels) of a central collision (about 3000 primary tracks)

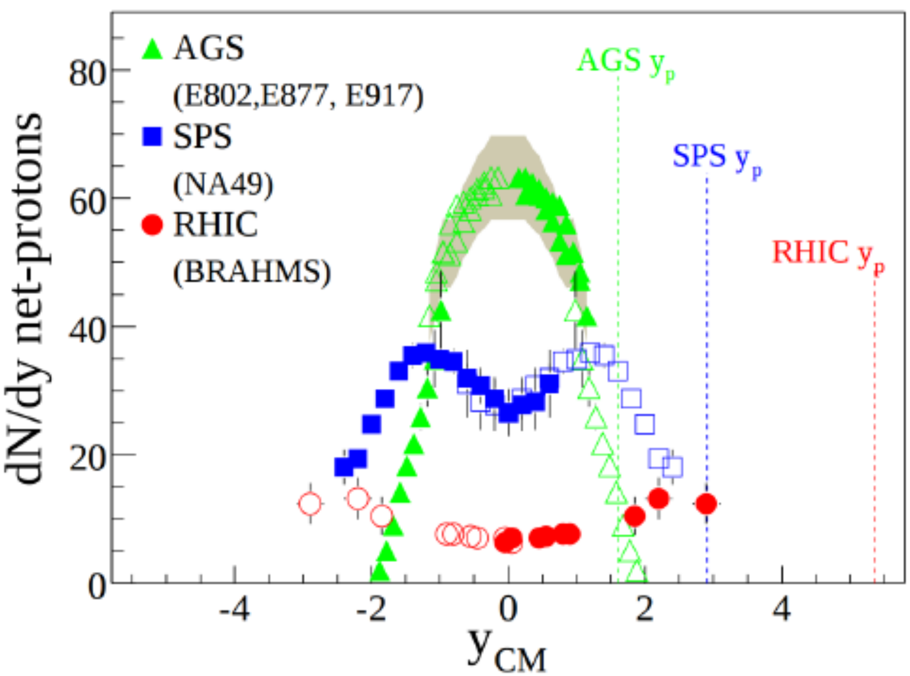
Physics results

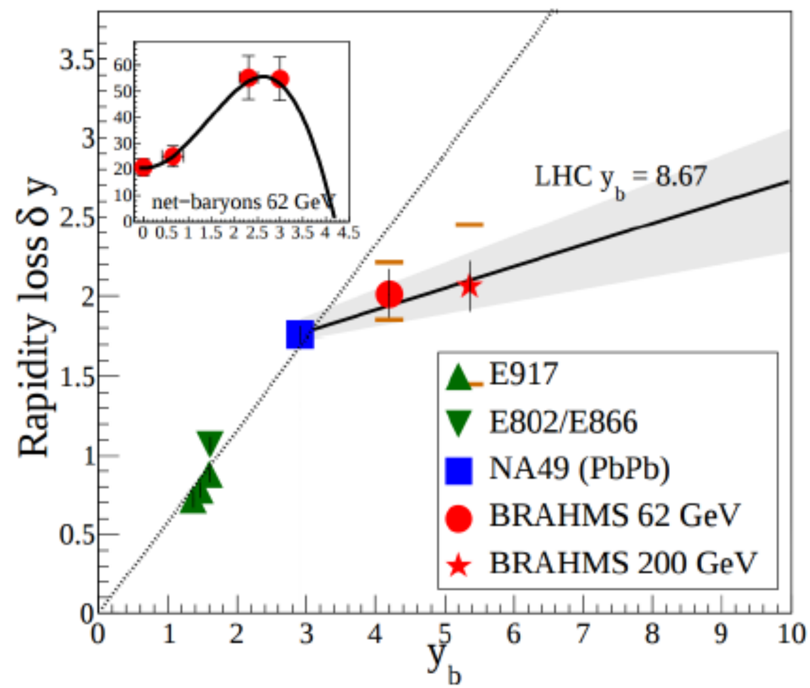
Collision energy ($\sqrt{s_{NN}}$)

- For relativistic heavy ion collisions, tipically $\sqrt{s_{NN}}$>1 GeV
  - Bevalac, JINR-Dubna, AGS, SIS-GSI: few GeV
  - SPS: ~20 GeV
  - RHIC: 200 GeV
  - LHC: 5 TeV
- Defines the allowed processes and the phase space

Collision energy ($\sqrt{s_{NN}}$)

- *Nota bene:* Not all energy is spent in the collision !
  - BRAHMS: ~70% of beam energy available for excitations

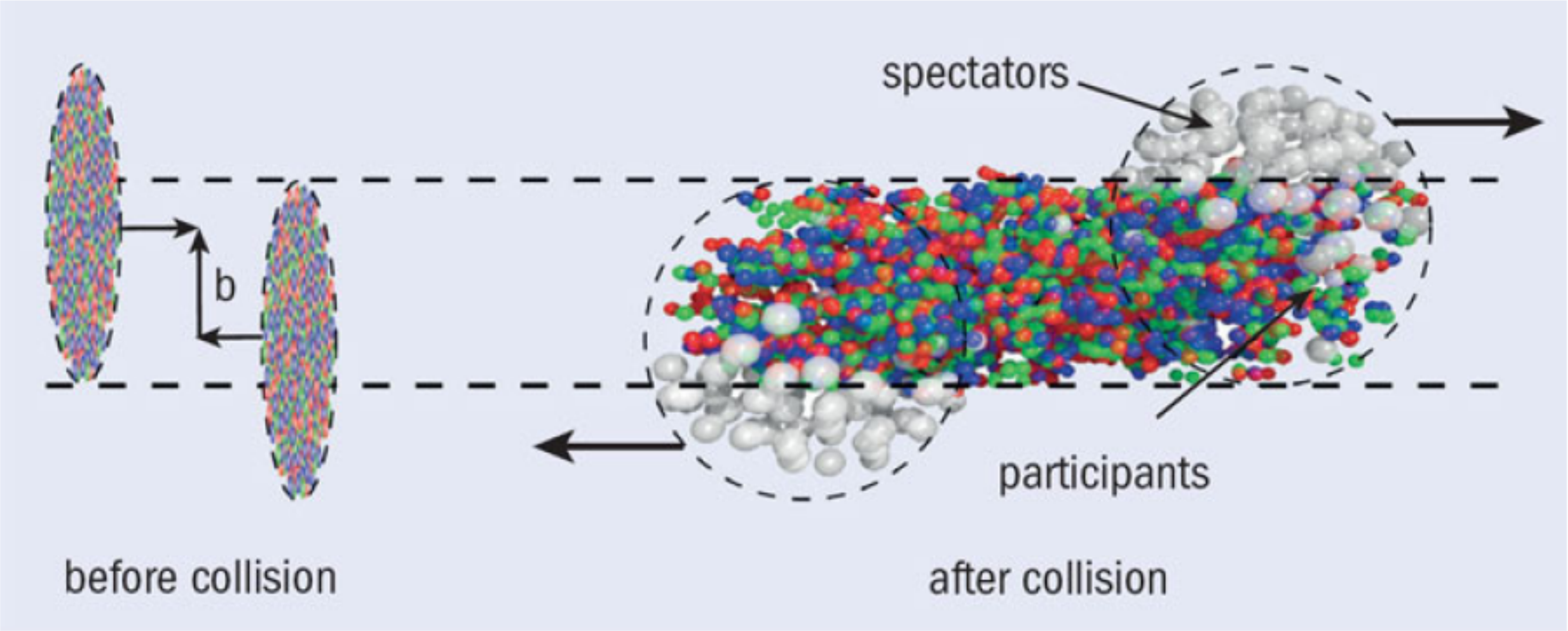




BRAHMS Collaboration, PRL93 (2004) 102301
BRAHMS Collaboration, PLB677 (2009) 267

Net-baryon density (ρ_p-ρ_{pbar}) : From baryon stopping to transparency at high energies!

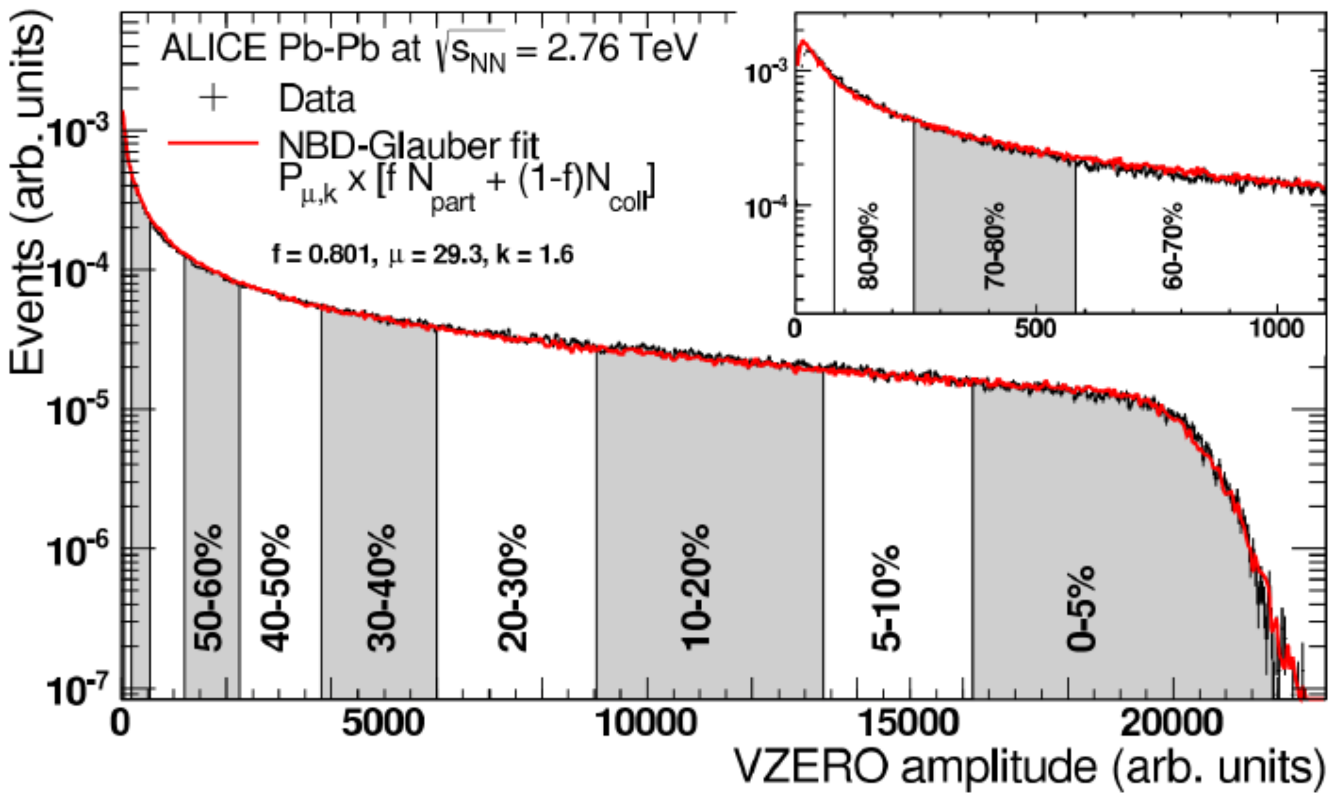
Collision centrality



- Impact parameter *b*, not measurable directly
- Assumption: strong correlation between *b* and event produced multiplicity
- Centrality tipically measured in percentage of the geometric cross-section
  - e.g. 0-10% → most central 10% collisions
- Number of participant pairs (npart)
- Number of binary collisions (ncoll)

Collision centrality

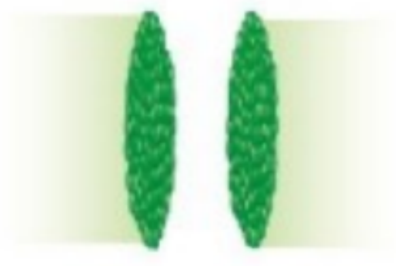
ALICE Collaboration, PRC88 (2013) 4, 044909



- Centrality determination in ALICE, using the charged particle measurement at forward rapidity (VZERO)
- Multiplicity distribution fitted well by an optical Glauber model which allows the determination of <npart> and <ncoll> for each centrality interval

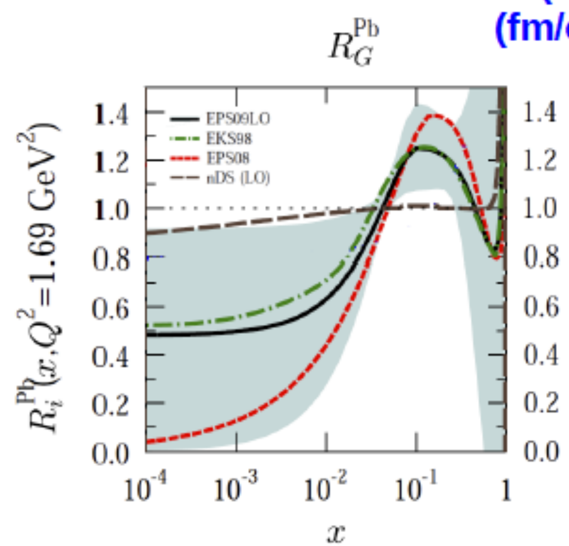
Stages of a high-energy nucleus-nucleus collision

Initial state

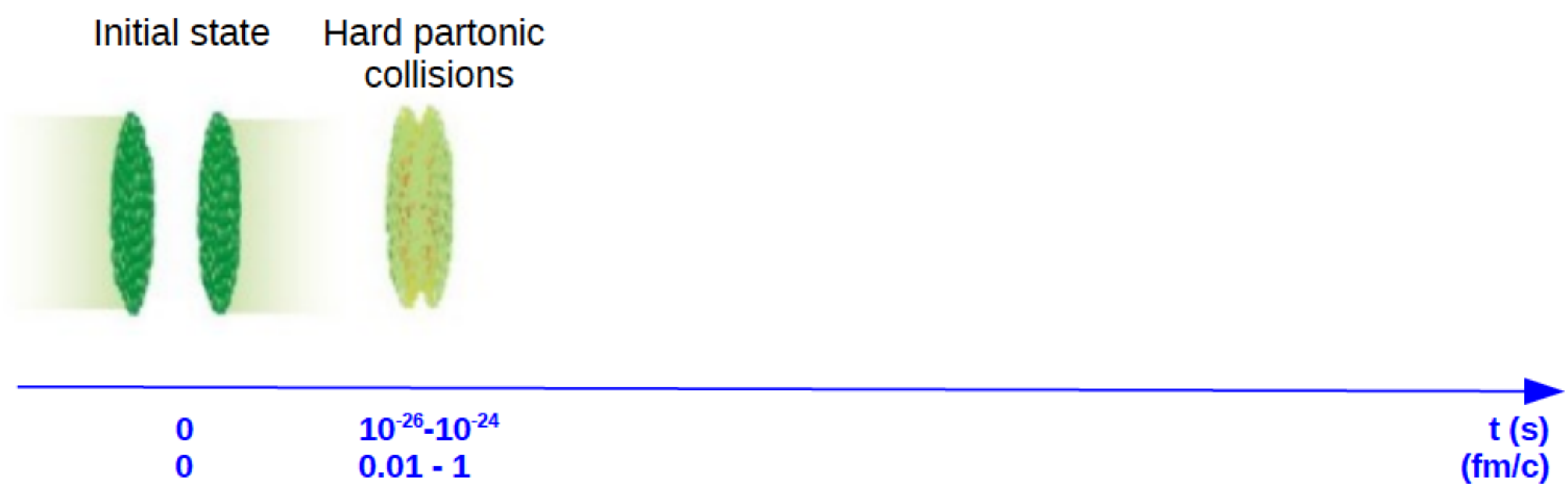


0 t (s)
0 (fm/c)

- Highly Lorentz contracted nuclei
- Initial state extremely important, interesting in itself
  - Gluon shadowing (modification of the gluon PDF in nuclei)
  - Crucial for disentangling the so called "cold nuclear matter"(CNM) effects from genuine hot medium effects

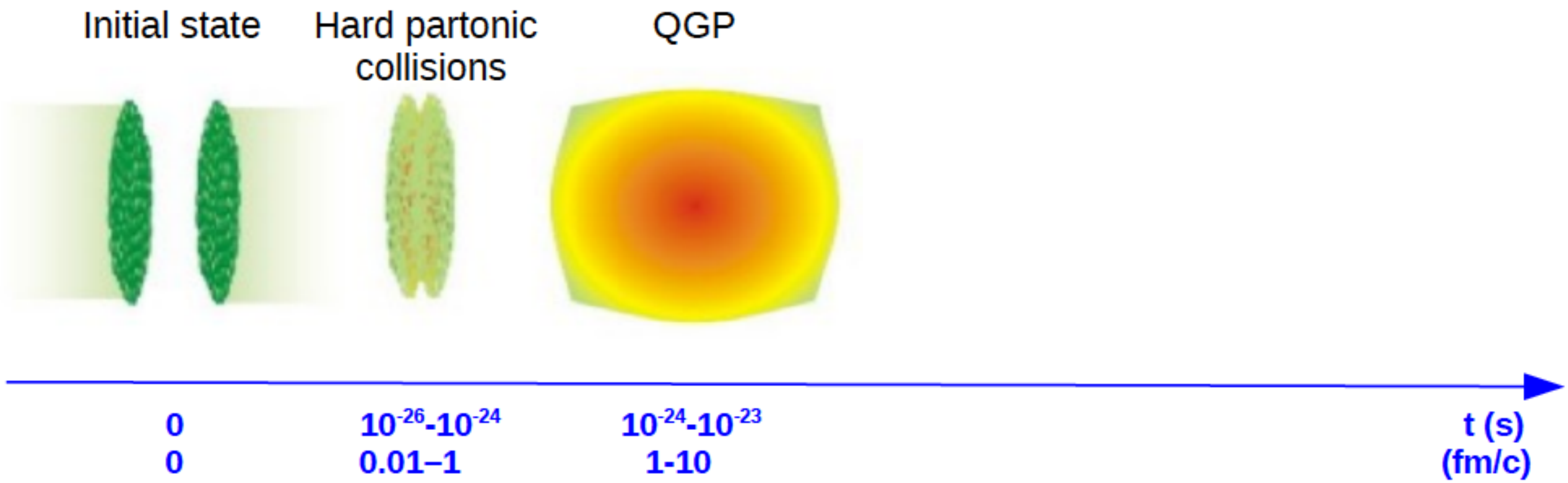


Stages of a high-energy nucleus-nucleus collision



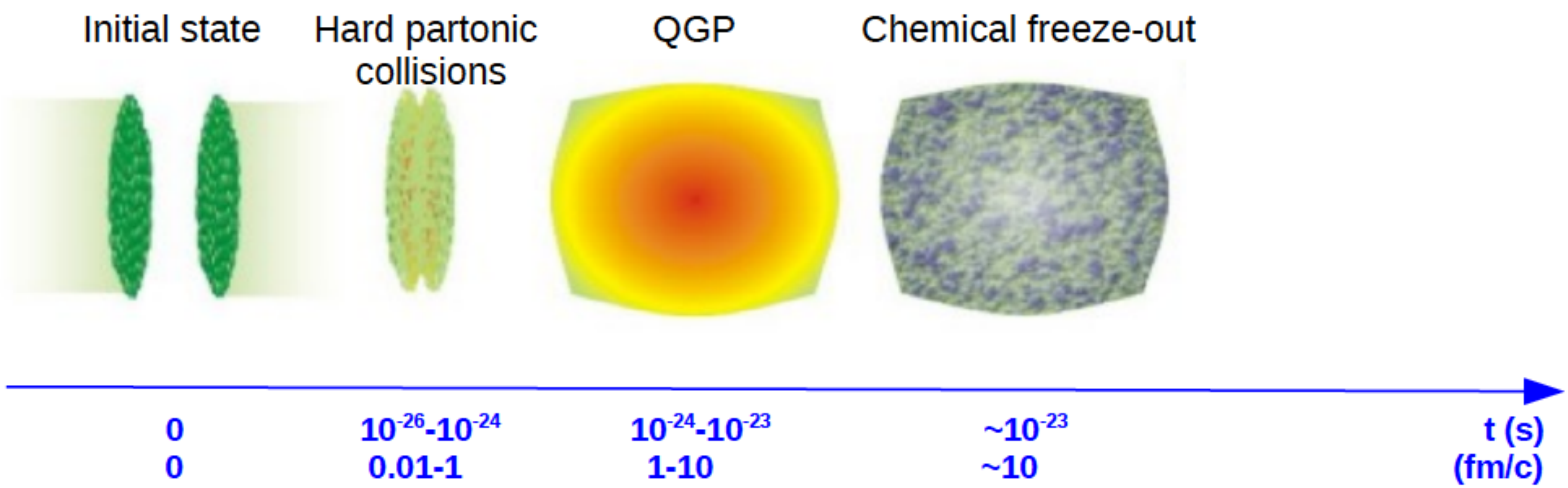
- Initial hard collisions take place
- Most of the entropy is created now → gluons and quark pairs
- Equilibrium (thermalization) takes place rapidly

Stages of a high-energy nucleus-nucleus collision



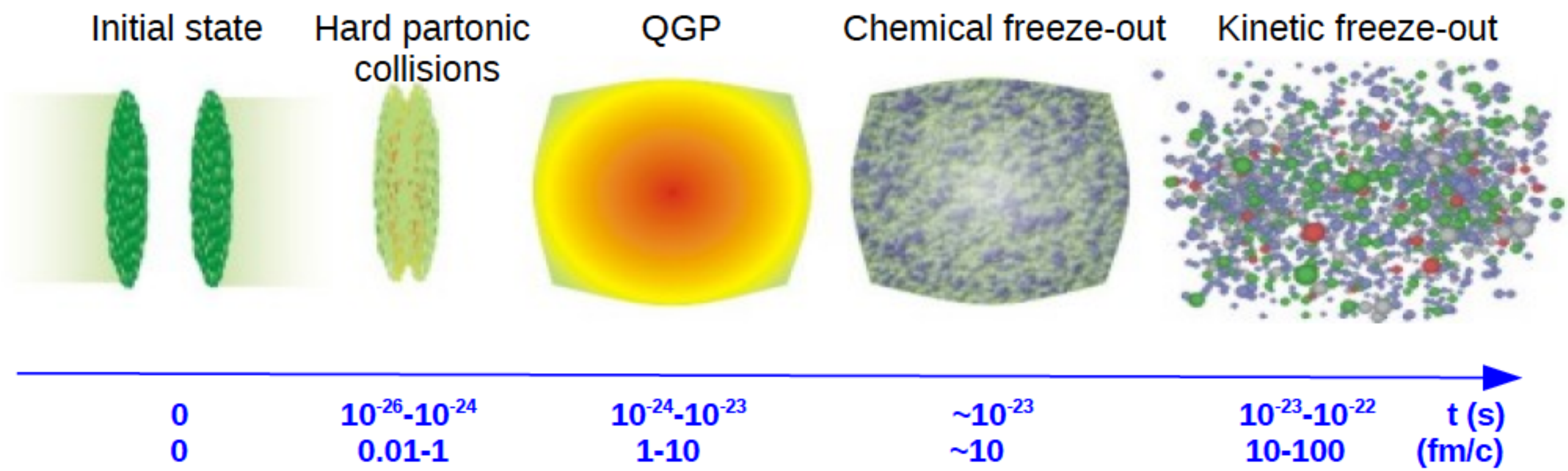
- Deconfined Quark-Gluon Plasma phase
- System expands and cools hydrodynamically

Stages of a high-energy nucleus-nucleus collision



- Hadronization: quarks and gluons form hadrons
- Non-perturbative process
- Chemical freeze-out: inelastic collisions cease; yields of various particle species are frozen

Stages of a high-energy nucleus-nucleus collision

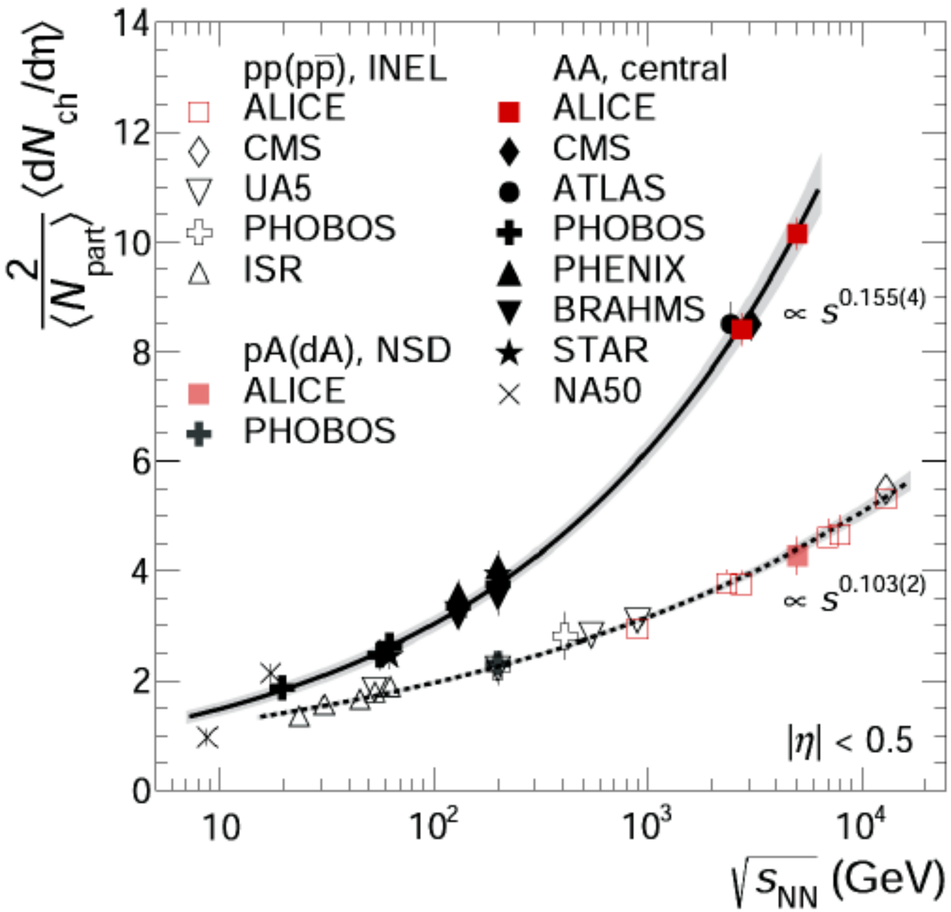


- Kinetic freeze-out:
  - Elastic collisions cease
  - Kinetic distributions are frozen

- We measure only at the latest stages but we want to understand the hard partonic and the QGP stages... extremely challenging!

Particle production

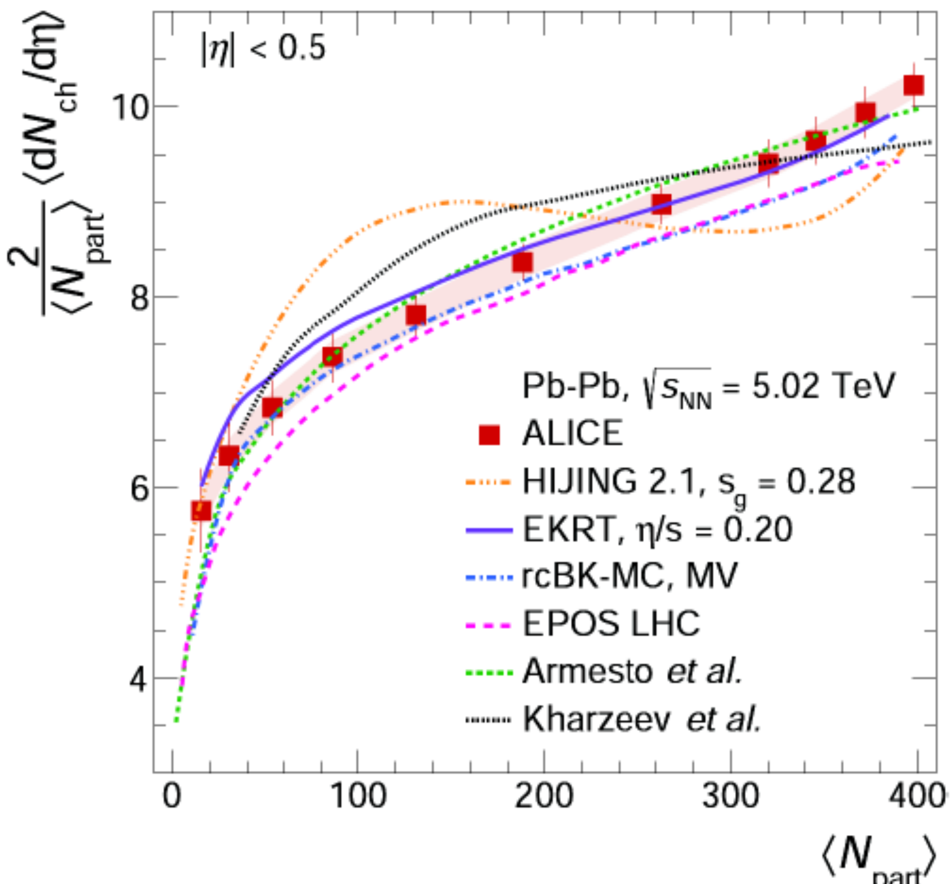
ALICE Collaboration, PRL116 (2016) 222302



- Yield per participant pair is larger in nuclear collisions than in proton-proton collisions:
  - larger entropy production
- The difference between nuclear and pp collisions also grows rapidly with energy

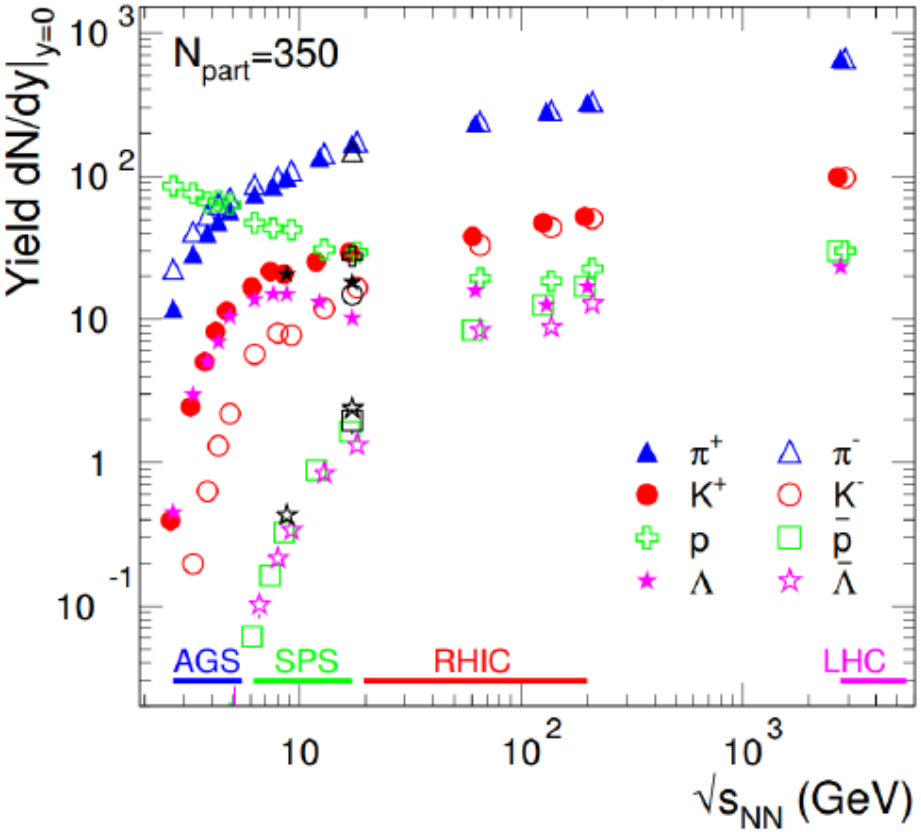
Particle production

ALICE Collaboration, PRL116 (2016) 222302



- Yield per participant pair is larger in nuclear collisions than in proton-proton collisions:
  - large entropy production
- The difference between nuclear and pp collisions also grows rapidly with energy
- Yield per participant pair also grows towards more central collisions
- These results allow to quantify the initial energy density and set constraints on initial state models

Identified hadron yields



Strangeness enhancement

- Lots of particles, most newly created from the excited gluon fields ($E=mc^2$)
- Large variety of species:

  $\pi^{\pm}(u\bar{d},d\bar{u})$, m=140 MeV

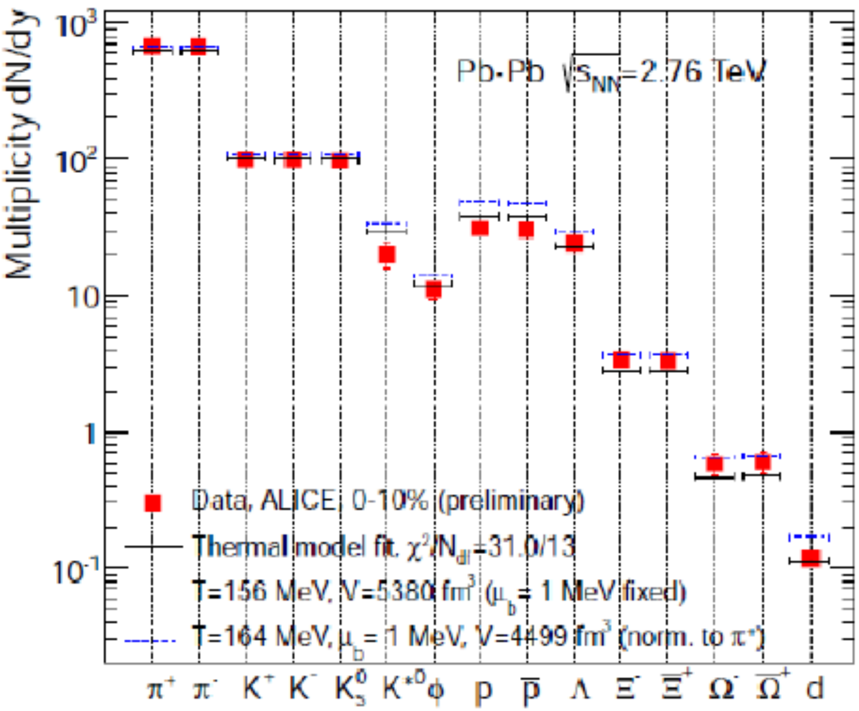
  $K^{\pm}(u\bar{s},s\bar{u})$, m=494 MeV

  p(uud), m=938 MeV

  Λ(uds), m=1116 MeV

  also: Ξ(dss), Ω(sss), …
- Abundancies follow mass hierarchy, except at low energies where remnants from the incoming nuclei are significant
- What do we learn?

Chemical freeze-out



- Thermal fits of hadron abundancies:

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T]\pm 1}$$

- Quantum numbers conservation

  $\mu = \mu_B B + \mu_{I3} I_3 + \mu_S S + \mu_C C$

- Hadron yields N_i can be obtained using only 3 parameters: (T_{chem}, μ_B, V)

- The hadron abundancies are in agreement with a thermally equilibrated system

  T_{chem}=155-165 MeV

  μ_B~0

Statistical thermal model

Grand Canonical Ensemble

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$$

$$n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \, dp}{\exp((E_i - \mu_i)/T) \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

Fit at each energy provides values for

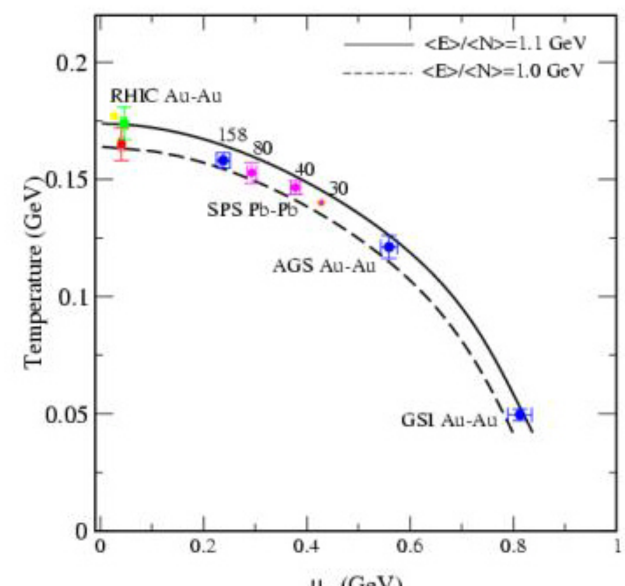
for every conserved quantum number there is a chemical potential μ

but can use conservation laws to constrain:

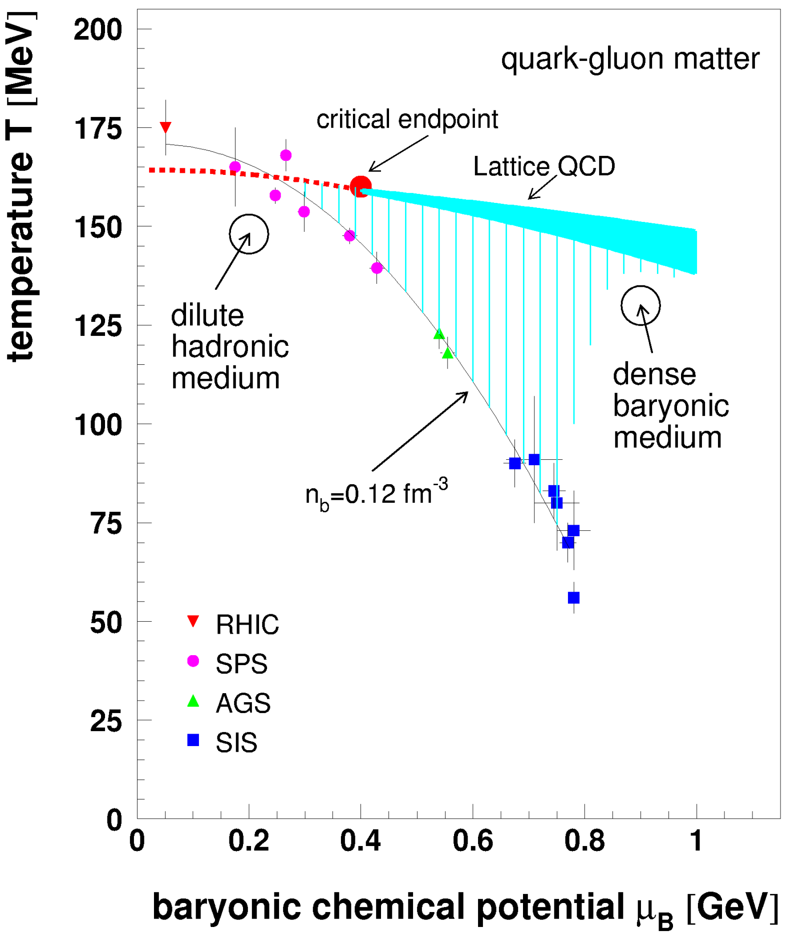
- Baryon number: $V \sum_i n_i B_i = Z + N \quad \rightarrow V$
- Strangeness: $V \sum_i n_i S_i = 0 \quad \rightarrow \mu_S$
- Charge: $V \sum_i n_i I_i^3 = \frac{Z - N}{2} \quad \rightarrow \mu_{I_3}$

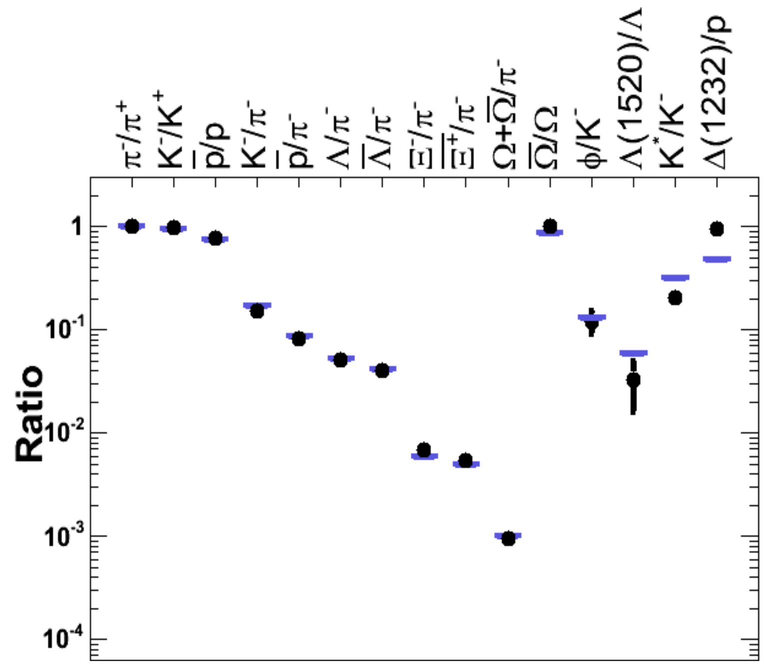
This leaves only μ_b and T as free parameter when 4π consi

for rapidity slice fix volume e.g. by dN_{ch}/dy



Exploring Freeze-out





Chemical freezeout describes many hadrons

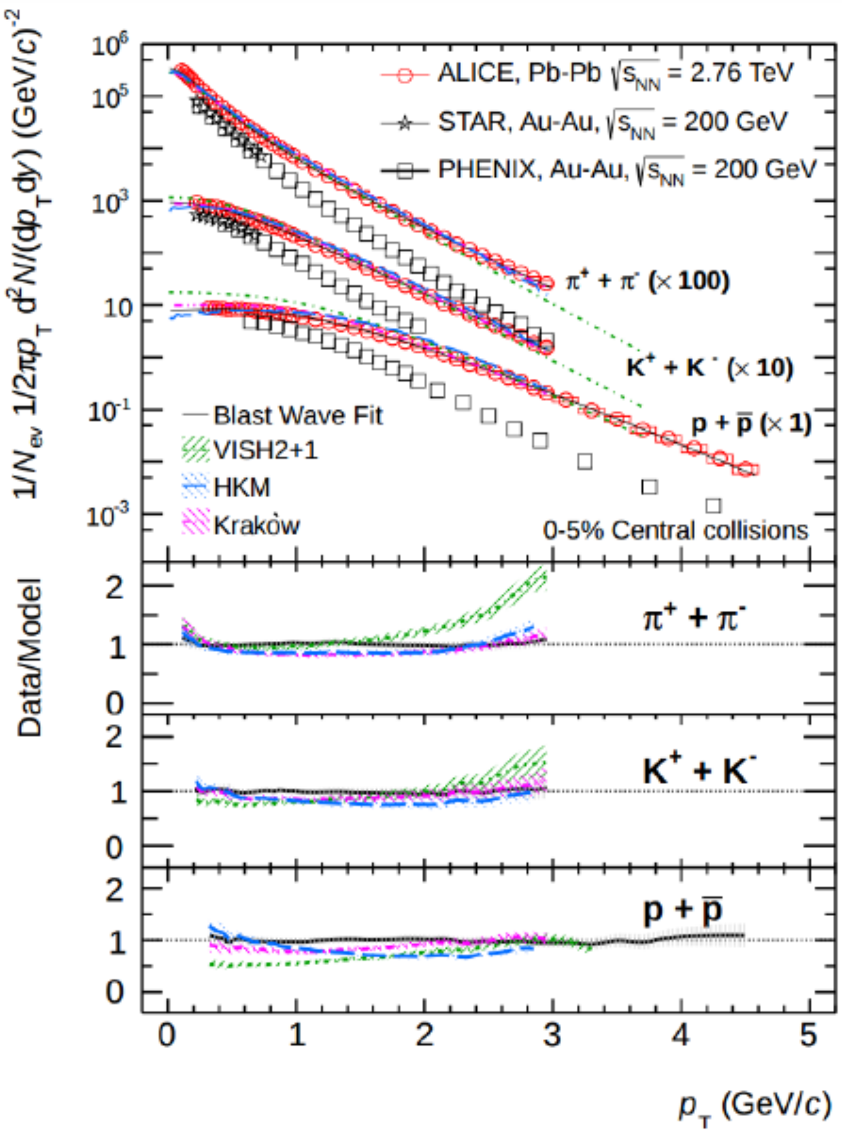
Many new strange ones soon on the market (van Buren, Witt, Estienne)

But possible discrepancies on the horizon (Markert)!

Becattini, Florkowski, PBM, Keranen, Manninen, Tawfik, Redlich…

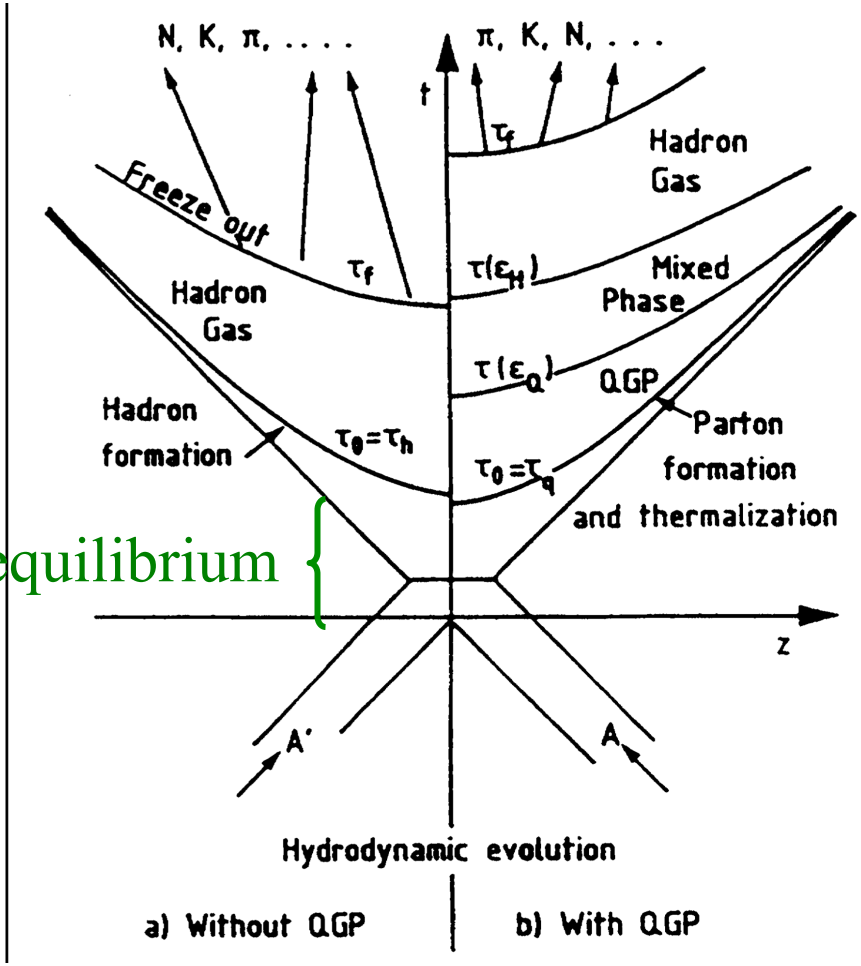
Transverse momentum spectra

ALICE, PRL 109 (2012) 252301



- Provides information on the fireball properties at the thermal freeze-out
- Hardness of the spectra depends on the collision energy, centrality and particle specie
- The mass dependence of the spectra “hardness” indicates collective motion / flow
- Hydrodynamical models reproduce the data → the fireball expands hydrodynamically nearly as a perfect fluid (very low viscosity)

Are the conditions at SPS/RHIC met to form a QGP?

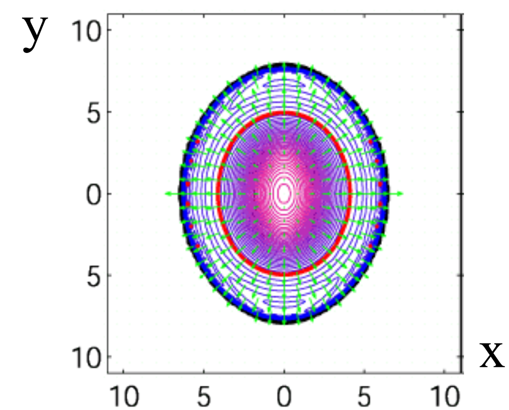


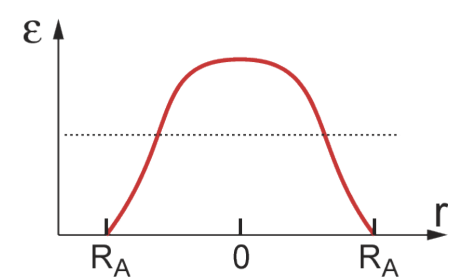
pre-equilibrium

QCD on Lattice (2-flavor):
Phase transition at
$T_C \approx 173 \pm 8$ MeV, $\varepsilon_C \approx (6 \pm 2)\ T^4$

hence $\varepsilon_C \approx 0.70 \pm 0.27$ GeV/fm^3

Remember: cold nuclear matter
$\varepsilon_{cold} \approx u\ /\ {}^4/_3\pi r_0^3 \approx 0.13$ GeV/fm^3

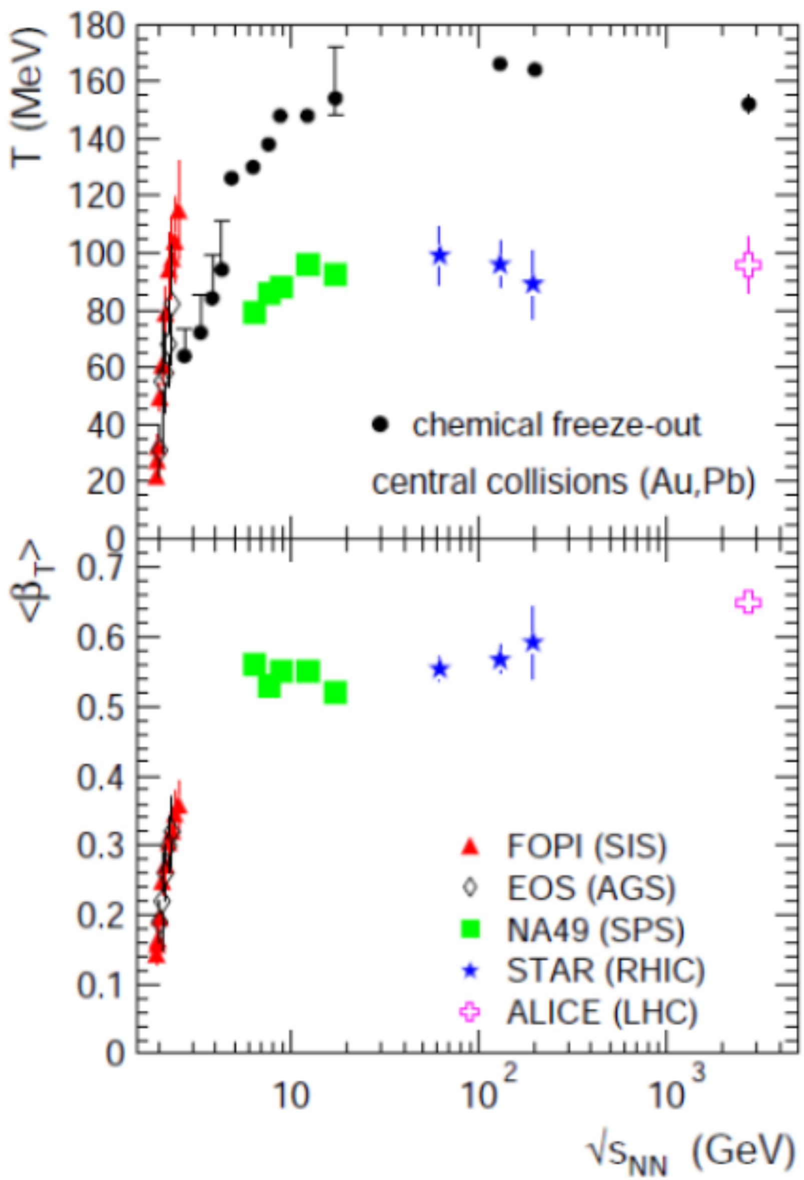




At a minimum we need to create ε_C in order to create a QGP.
Note: this is a necessary but not sufficient condition
Tevatron (Fermilab) ε(√s = 1.8 TeV pp) >> ε(Au+Au RHIC)
Thermal Equilibrium ⇒ many constitutents ⇒ Size matters !!!

The kinetic freeze-out

A.Andronic, arXiv: 1210.8126



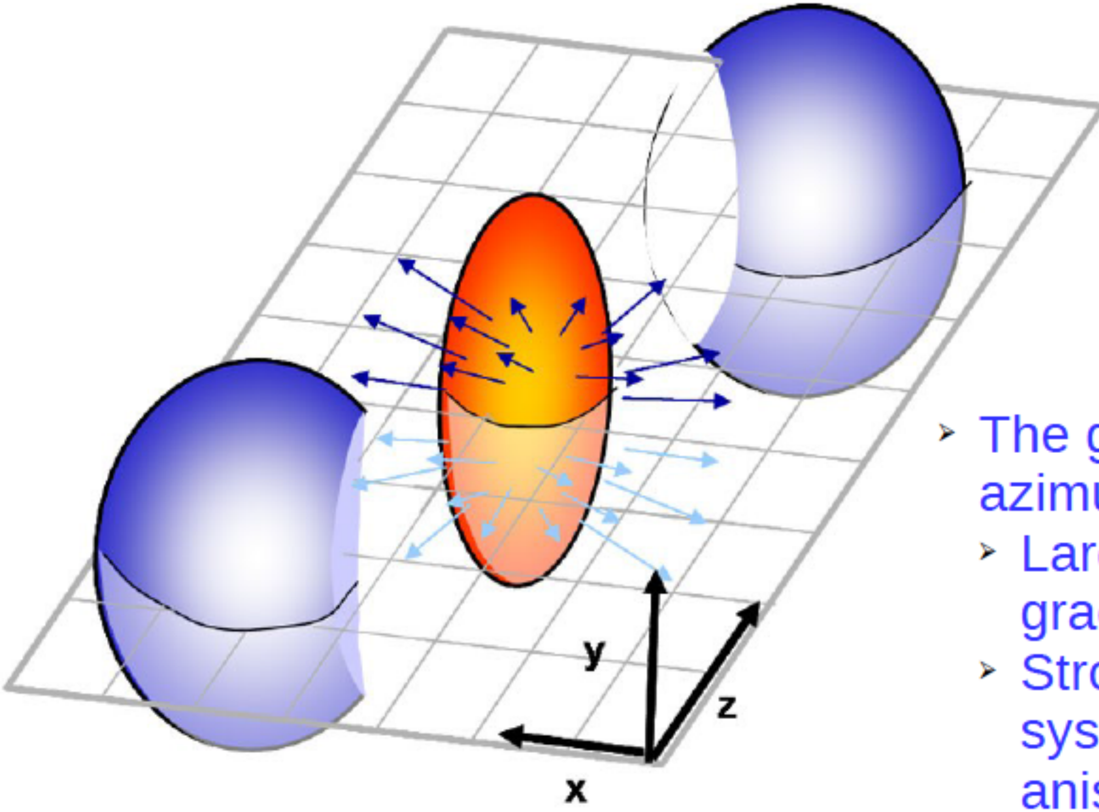
- Hydro-like "Blast-wave" fits allow to extract parameters like :

  T_{kine} = kinetic freeze-out temperature

  $<\beta>$ = collective average velocity

- Light quark hadrons "flow" with a collective velocity of 2/3 *c* additional to their own individual movement

Anisotropic flow



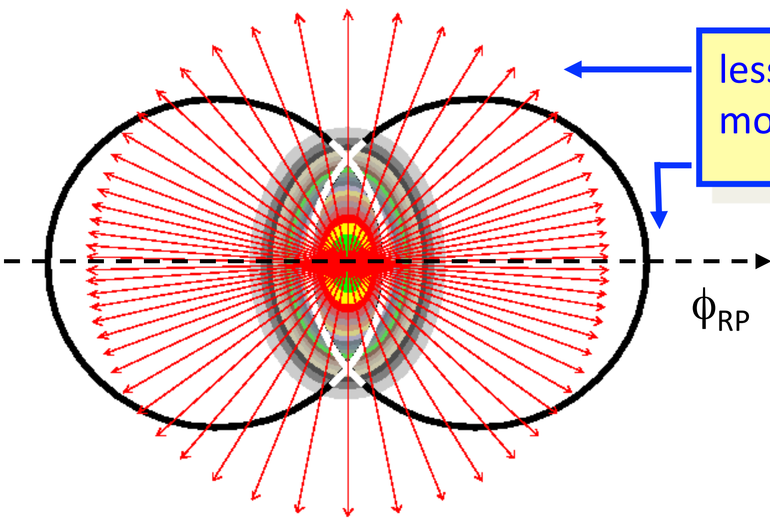
- The geometry of the collision is azimuthally non-uniform
  - Large initial energy density gradients
  - Strong multiple rescatterings in the system transform the geometrical anisotropy into a momentum anisotropy

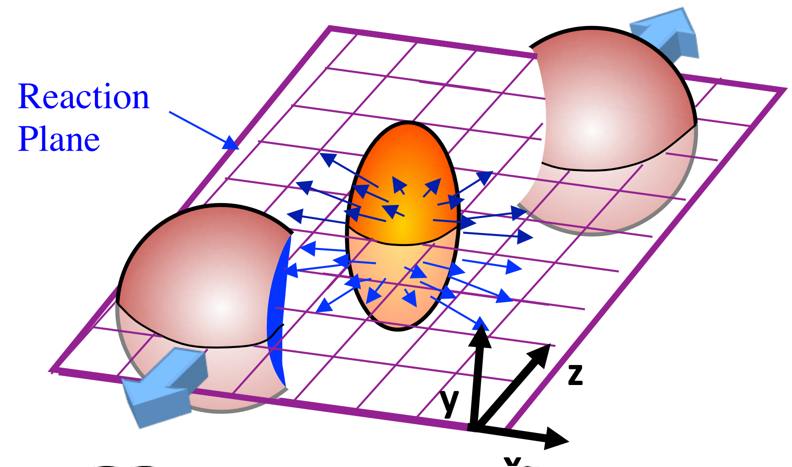
$$\frac{dN}{d\varphi} \simeq [1 + 2 v_1 \cos(\varphi - \Psi) + 2 v_2 \cos 2(\varphi - \Psi) + 2 v_3 \cos 3(\varphi - \Psi) + \ldots]$$

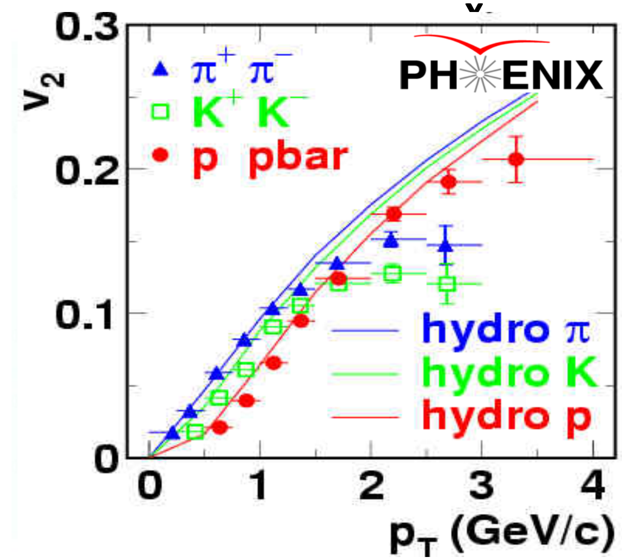
(Lorentz) invariant cross section: $Ed^3N/dp^3 = d^3N/(dy\ pTdpT\ d\varphi)$, depends on rapidity $y=0.5 \ln((E+pz)/(E-pz))$, transverse momentum $pT=\sqrt{px^2+py^2}$ and angle φ between px and pT of the produced particle. dN/dφ is expanded into Fourier series. First term (=1) is radial flow, second term $v_1=\langle\cos(\varphi-\Psi)\rangle$, is directed flow, third term $v_2= \langle\cos 2(\varphi-\Psi)\rangle$ -elliptic flow, $v_3= \langle\cos 3(\varphi-\Psi)\rangle$ - triangular flow

Nuclear Geometry and Hydrodynamic

multiple scattering → larger pressure gradient in plane → less yield out more in plane







Spatial asymmetry
eccentricity

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Mom. Asymmetry
elliptic flow

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

$$\frac{d^3N}{p_T dp_T dy d\varphi} \propto [1 + 2v_2(p_T)\cos 2(\varphi - \phi_{RP}) + \ldots]$$

What are the relevent DOF's in "Flow" ?

"Fine structure" of v2(pT) for different mass particles.

In Ideal "hydro" picture:

$$\partial_\nu T^{\mu\nu} = 0 \quad \rightarrow \quad \text{Work-energy theorem}$$

$$\rightarrow \int_{vol} \nabla P dV = \Delta E_K =$$

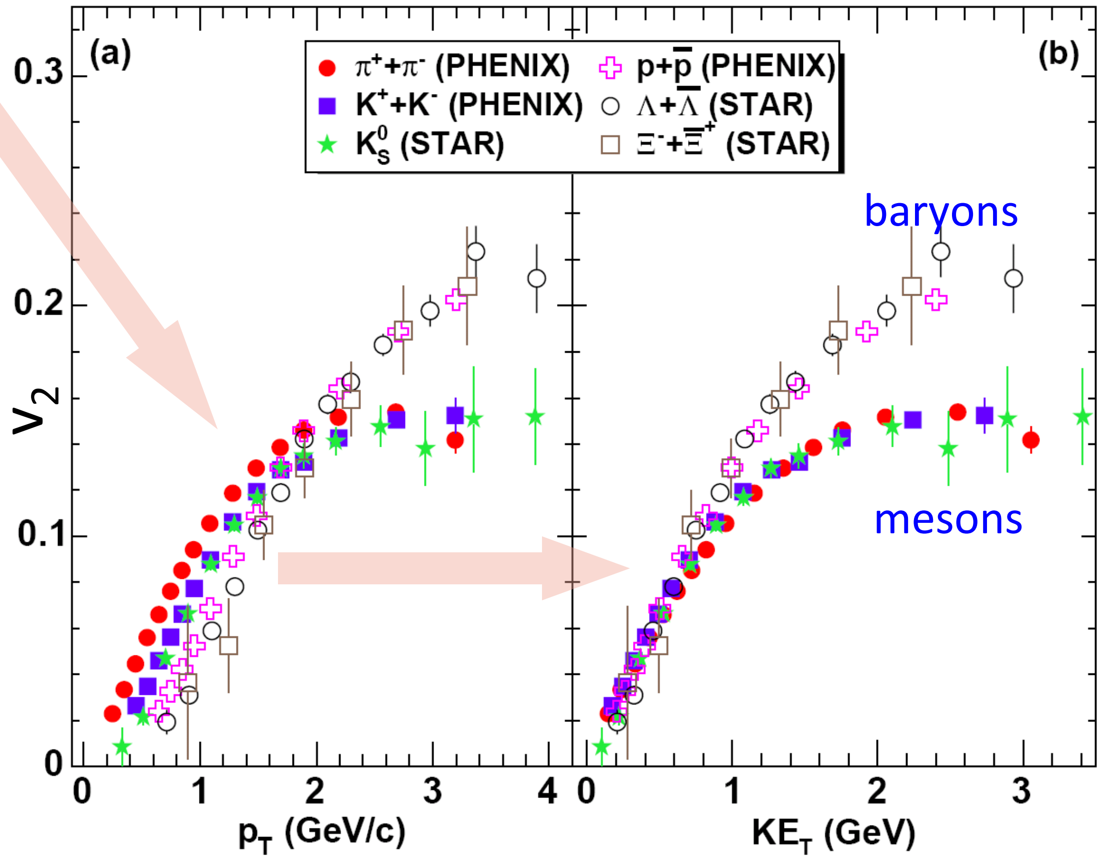
$$= m_T - m_0 \equiv \Delta KE_T$$

$v_2(p_T) \rightarrow v_2(KE_T)$

$v2(KE_T)$ universal for baryons

$v2(KE_T)$ universal for mesons

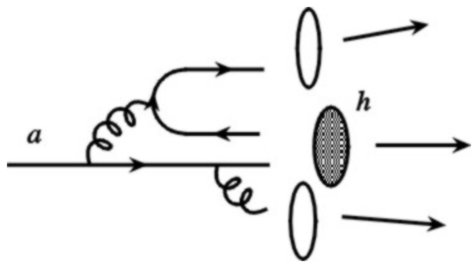
Phys. Rev. Lett., 2007, 98, 162301

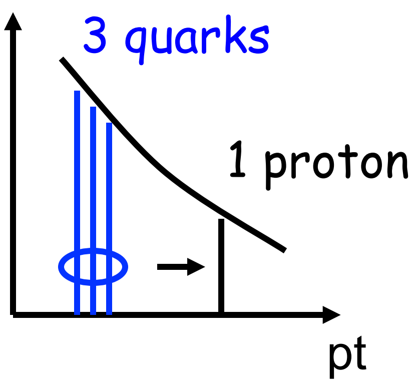


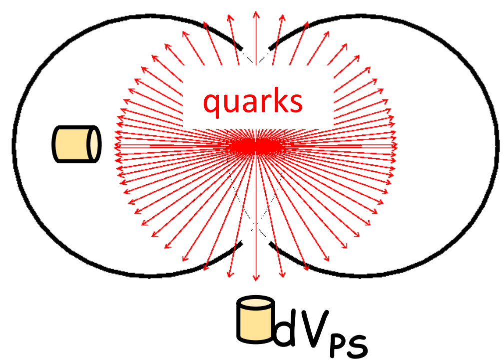
Do we have an even more universal scaling?

QG medium fragmentation-quark recombination

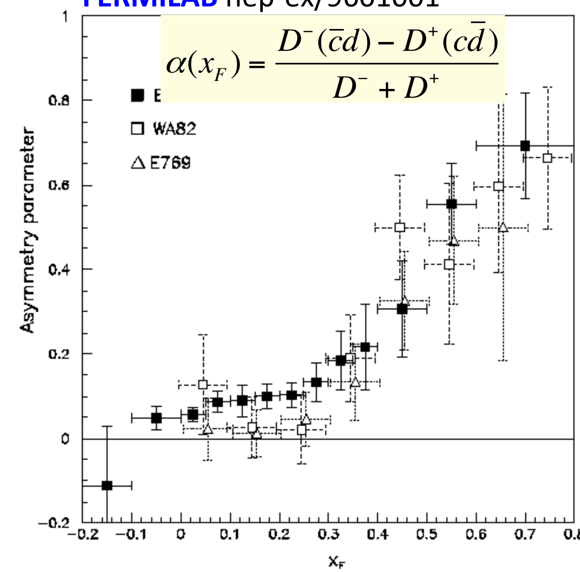
Why is the universal $v_2(KE_T)$ different for meson and baryons?
Exited quark-gluon medium → huge phase-space densities → constituent Quark Recombination / Coalescence







Phys. Lett.,1996,B371,157-162
FERMILAB hep-ex/9601001



Phys.Rev.Lett.91:092301,2003

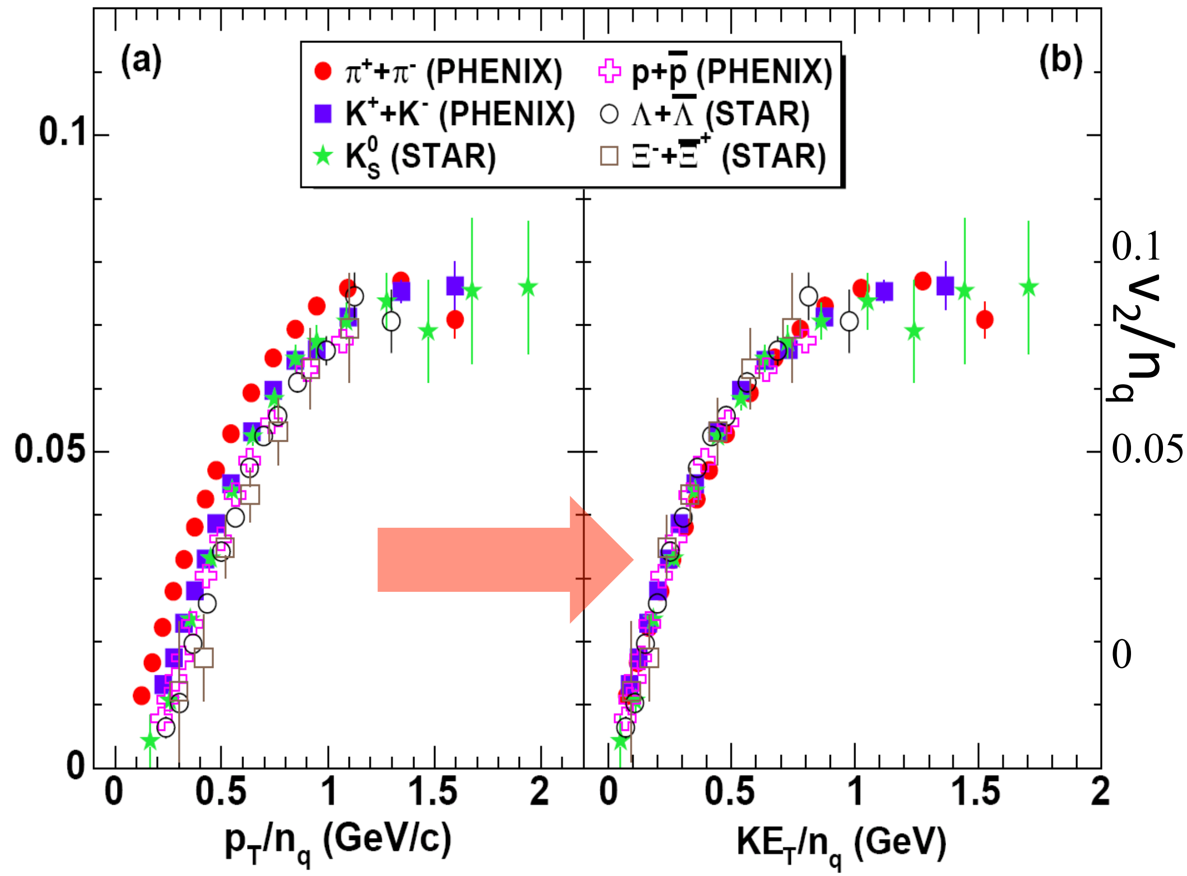
$$v_2^{meson}(p_T) \approx 2 \cdot v_2^{quark}\left(\frac{p_{T,quark}}{2}\right) \qquad v_2^{baryon}(p_T) \approx 3 \cdot v_3^{quark}\left(\frac{p_{T,quark}}{3}\right)$$

The "Flow" Knows Quarks

Assumption:

all bulk particles are coming from recombination of flowing partons

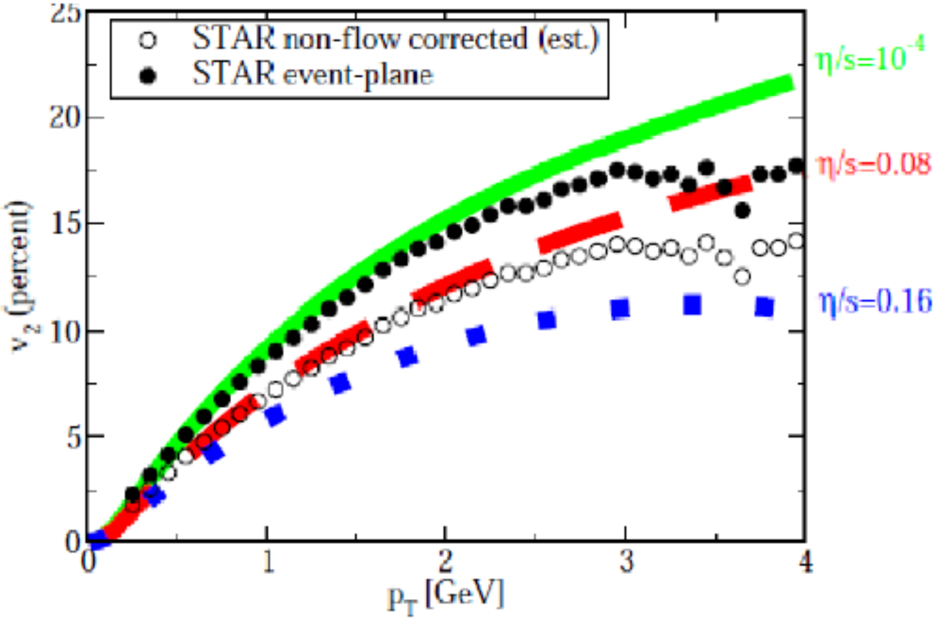
$$v_2(p_T) \rightarrow n_q \cdot v_2\left(\frac{KE_T}{n_q}\right)$$



Discovery of universal scaling:

- flow parameters scaled by quark content n_q resolves meson-baryon separation of final state hadrons. Works for strange and even charm quarks.
- strongly suggests the early thermalization and **quark degree of freedom**.

Elliptic flow in high energy HIC



Luzum & Romatschke, arXiv:0804.4015

- Why is elliptic flow important?
- Quantifies the medium response to the initial state geometry, which is sensitive to:
  - Initial state properties
  - QGP properties like equation of state, transport coefficients, viscosity
  - hadronization
- Shear viscosity much smaller than for any known substance
- Lower bound conjectured from AdS/CFT: $\eta/s = 1/4\pi \approx 0.08$

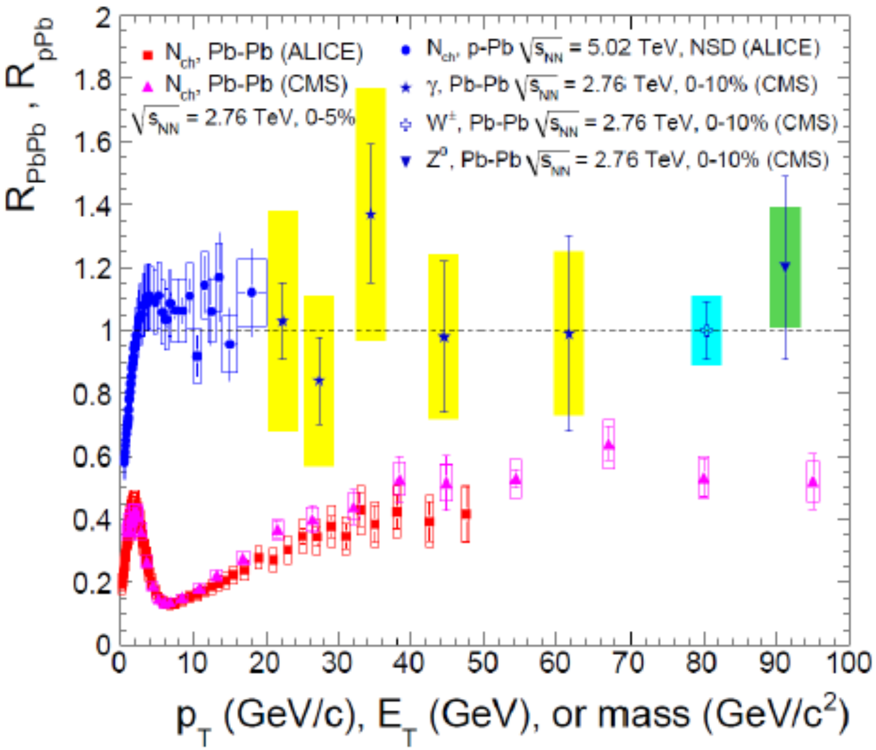
Kovtun, Son, Starinets hep-th/0405231

Hard probes

High-p_T suppression

p-Pb, ALICE PRL110(2013)082302
Pb-Pb, ALICE, Phys.Lett.B720 (2013)52
Pb-Pb, CMS, EPJC (2012) 72

γ, CMS, PLB 710 (2012) 256
W±, CMS, PLB715 (2012) 66
Z⁰, CMS, PRL106 (2011) 212301



$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

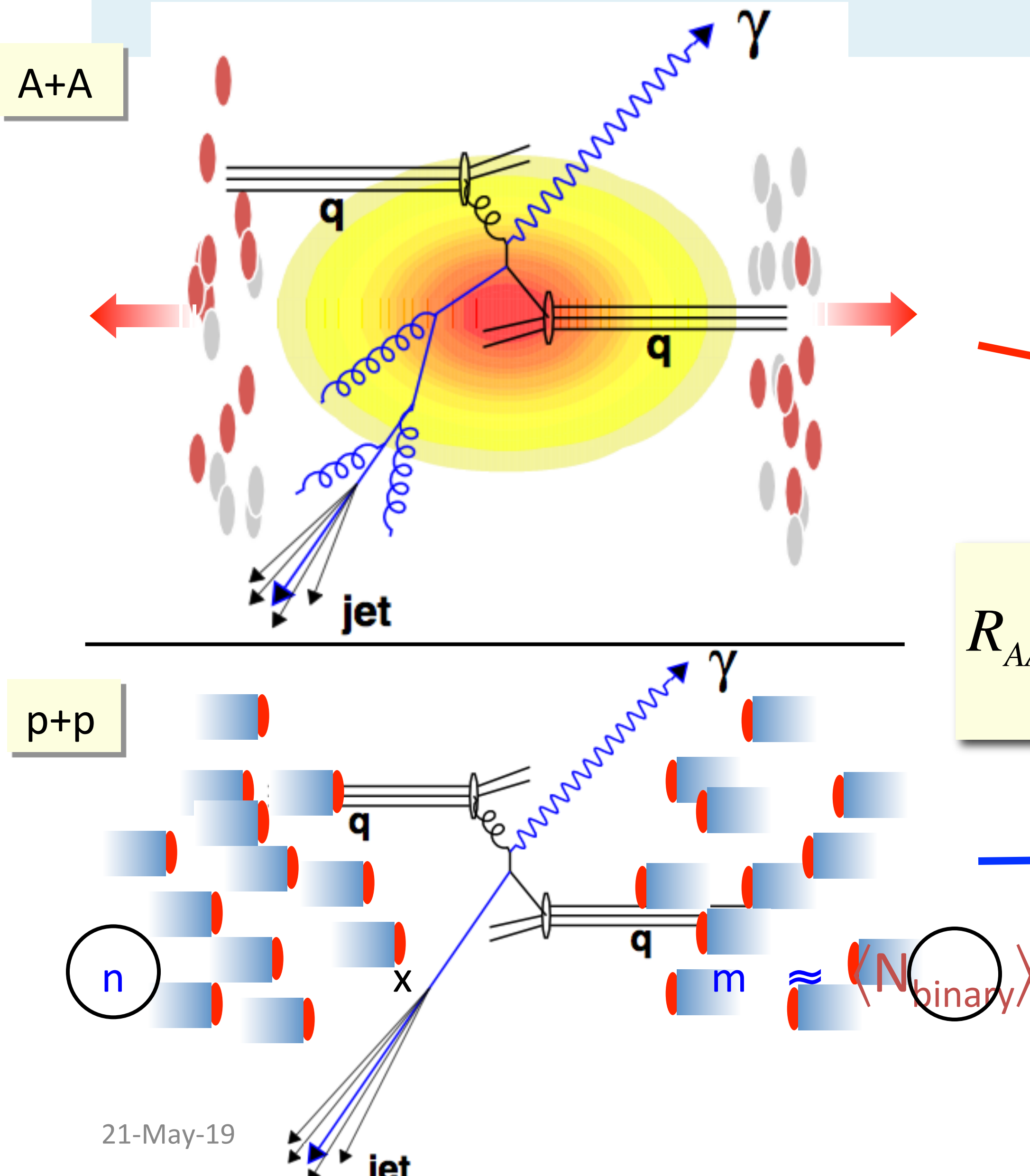
Superposition of NN collisions → $R_{AA}=1$

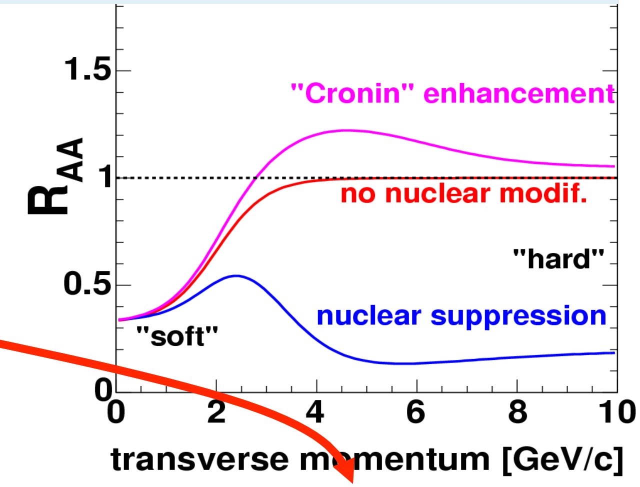
Suppression → $R_{AA}<1$

Enhancement → $R_{AA}>1$

- High-p_T hadrons strongly suppressed in central heavy-ion collisions
- Suppression persists even at 100 GeV/c
- No hadron high-p_T suppression in p-Pb collisions
- Photons and electroweak bosons production is compatible with binary collision scaling

HI collision - Nuclear Modification Factor R_{AA}

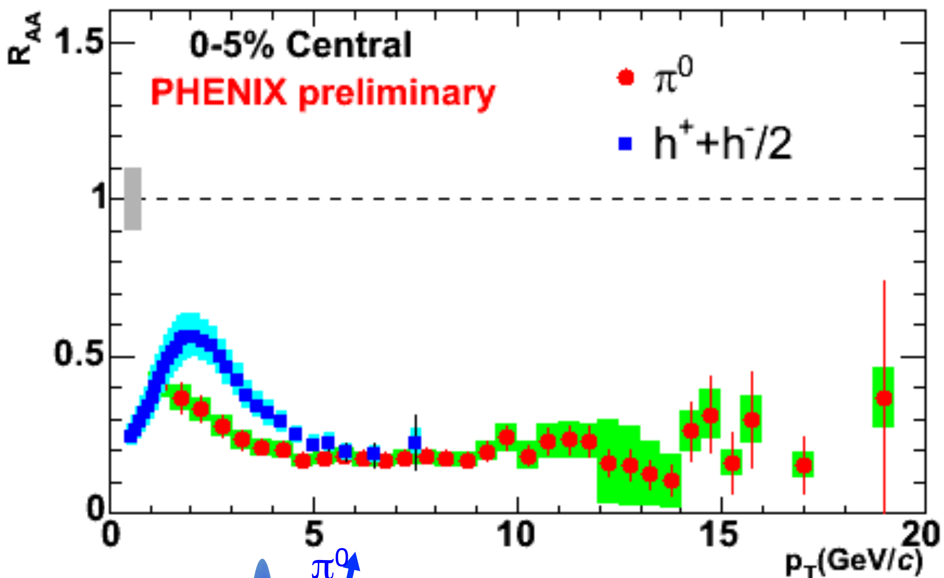


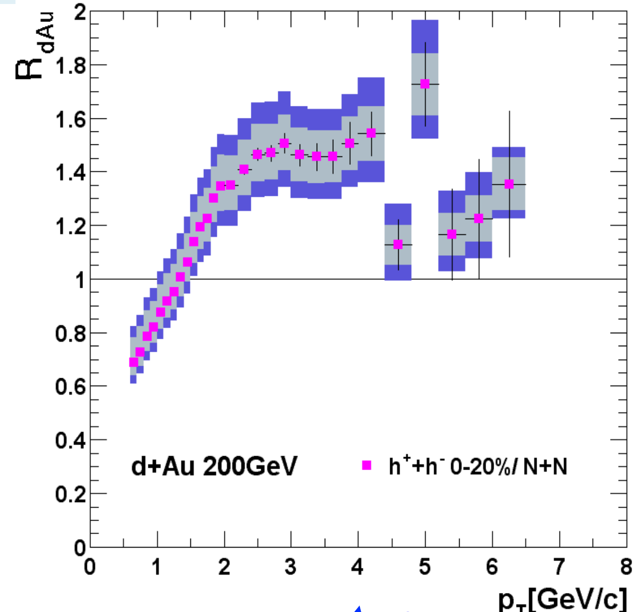


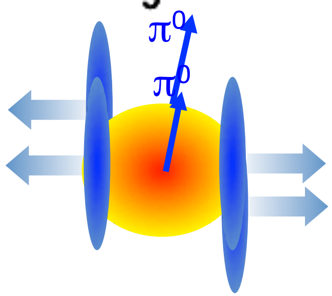
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary} \rangle d^2N^{pp}/dp_T d\eta}$$

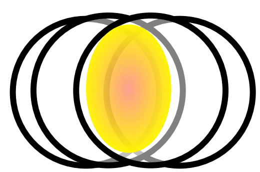
varies with impact parameter ***b***

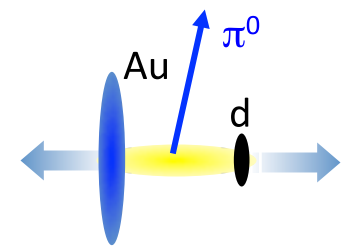
RHIC $\sqrt{s}$ = 200 π^o and h^++h^- data









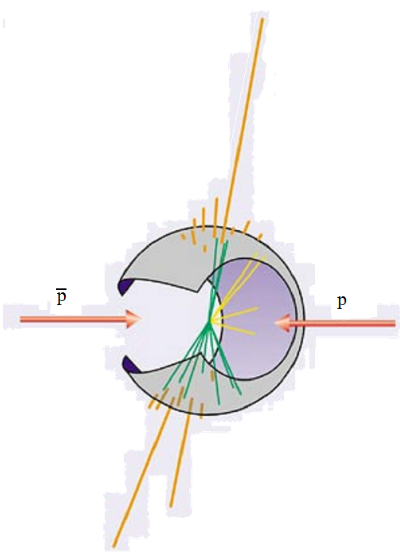


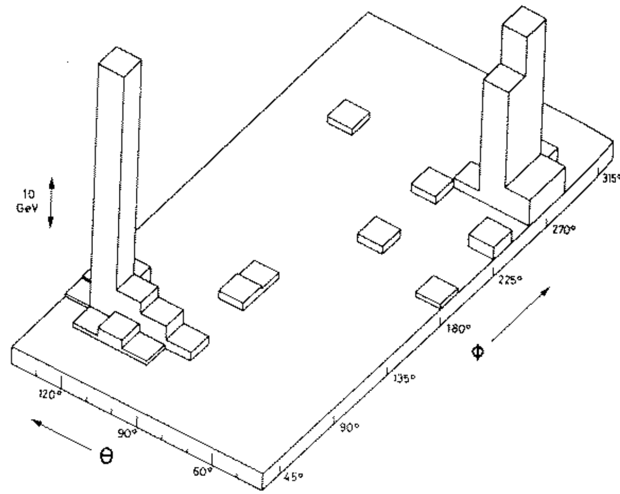
- Strong suppression (x5) in central Au+Au coll.
- No suppression in peripheral Au+Au coll.
- No suppression (Cronin enhancement) in control d+Au exp.

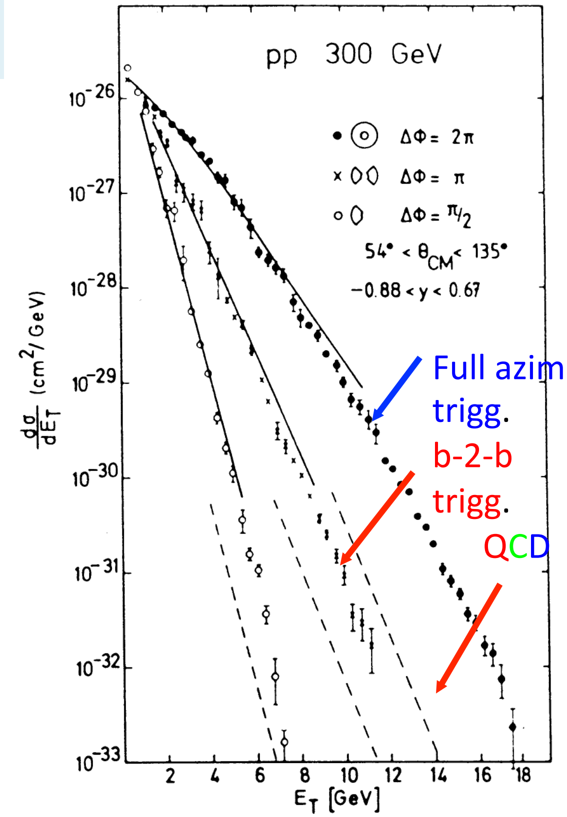
Convincing evidence for the **final state partonic** interaction - emergence of **sQGP**

QCD and Jets

- At the famous Snowmass conf. (July 1982) almost nobody believed that jets seen in e+e collisions exist also in p+p. NA5 data - no jet structure.
- The International HEP conference in Paris, three weeks later, changed everything.



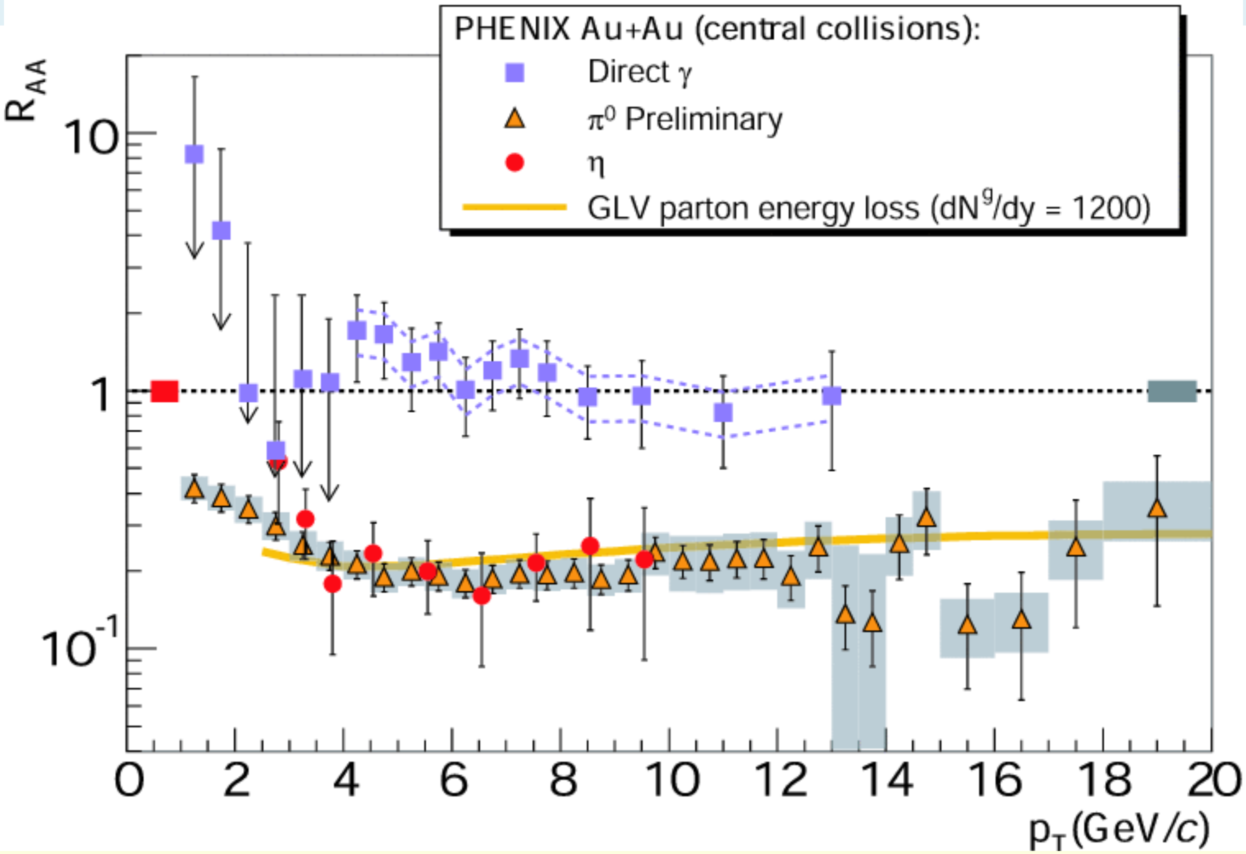




C. DeMarzo et al NA5, PLB112(1982)173

This one event from UA2 in 1982 changed everybody's opinion.

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV



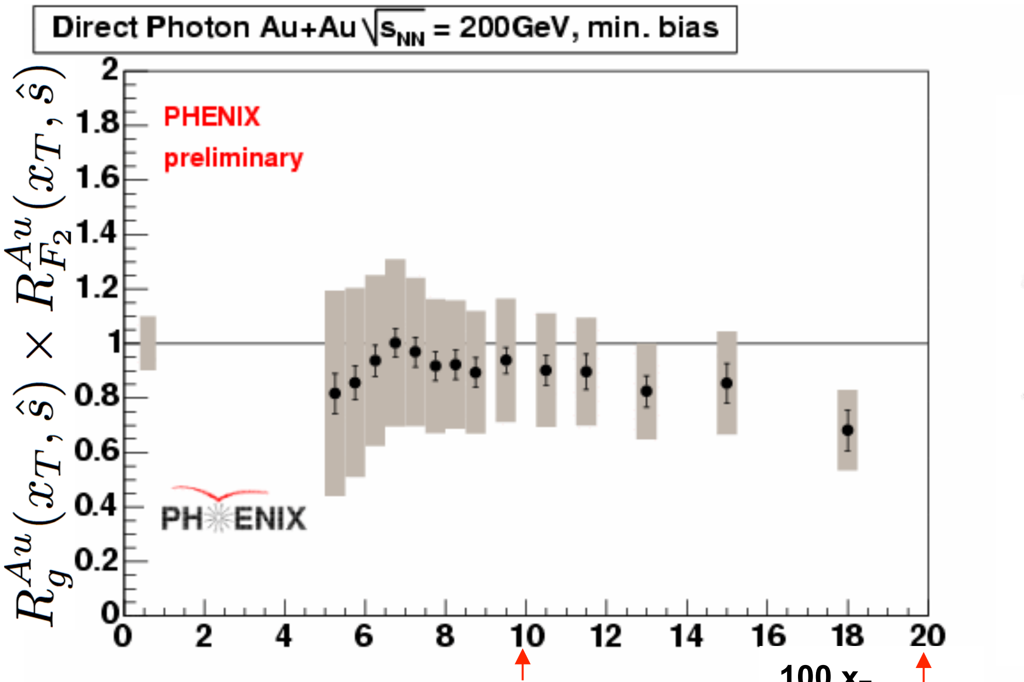
Direct γ are not suppressed. π^0 and η suppressed even at high p_T
Implies a **strong medium effect** (energy loss) since γ not affected.
Suppression is flat at high $p_{T.}$

For Au+Au min bias direct γ R_{AA} is simple

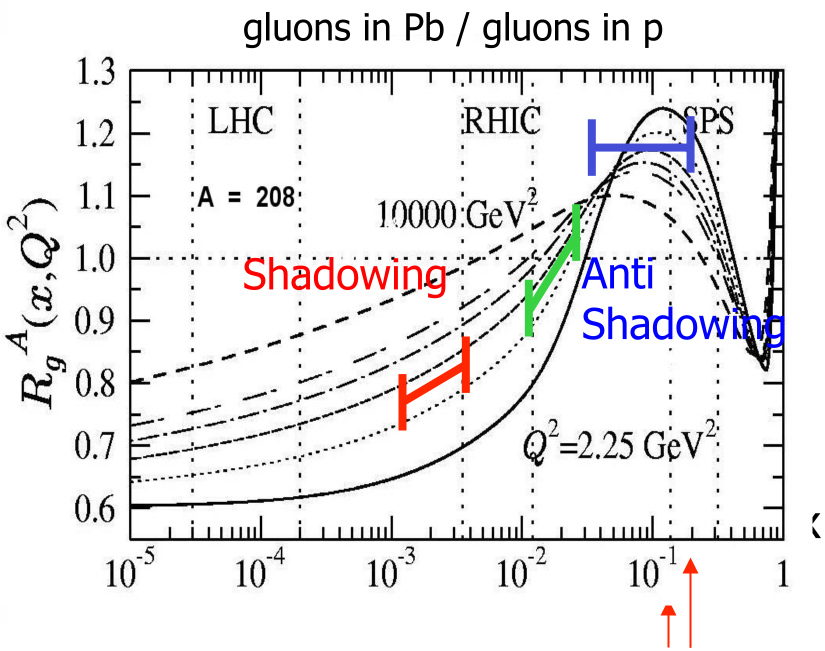
Au+Au minimum bias at mid-rapidity

Eskola,Kolhinen,Ruuskanen Nucl. Phys. B**535**(1998)351

$$R_{AA} = \frac{d^2\sigma_\gamma^{AA}/dp_T^2\, dy_\gamma}{AA\, d^2\sigma_\gamma^{pp}/dp_T^2\, dy_\gamma} \approx \left(\frac{F_{2A}(x_T)}{AF_{2p}(x_T)} \times \frac{g_A(x_T)}{Ag_p(x_T)}\right)$$

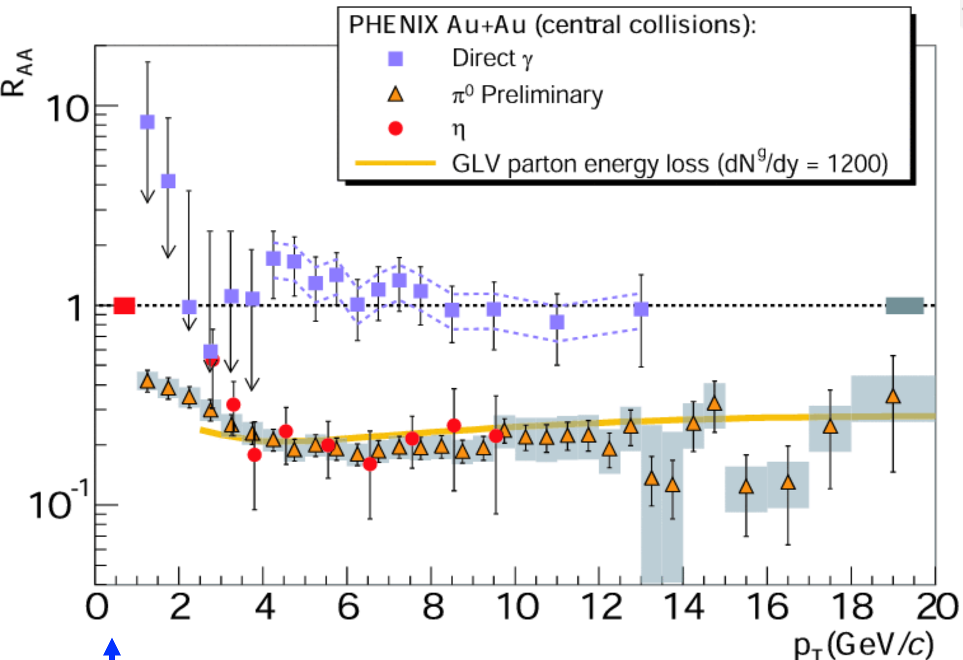


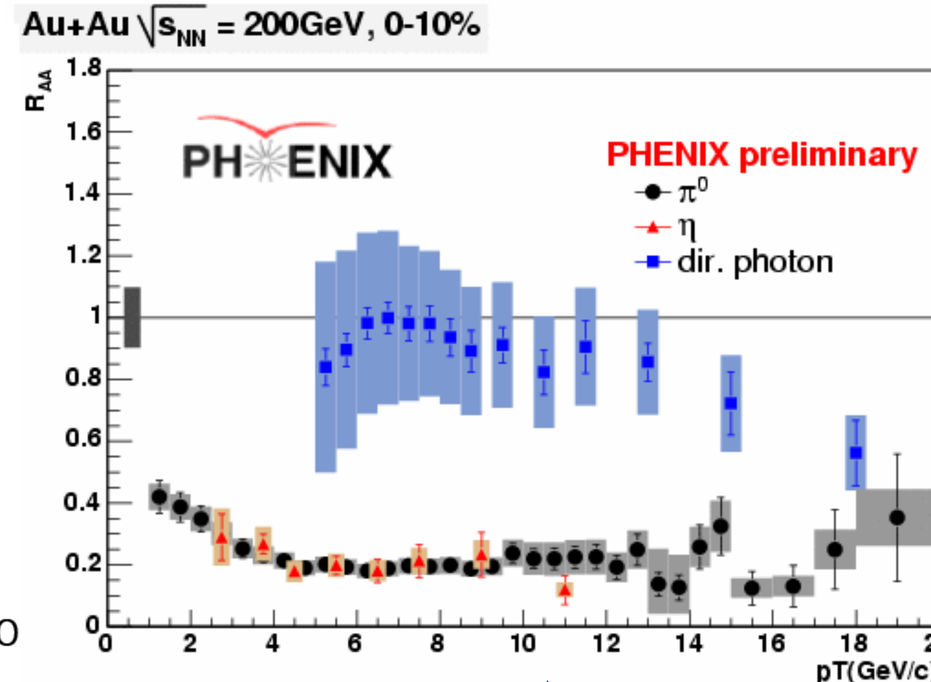
Eskola et al. NPA**696** (2001) 729



Do the structure function ratios actually drop by ~20% from x=0.1 to x=0.2?

The biggest result at QM2006?





p+p→γ+X reference

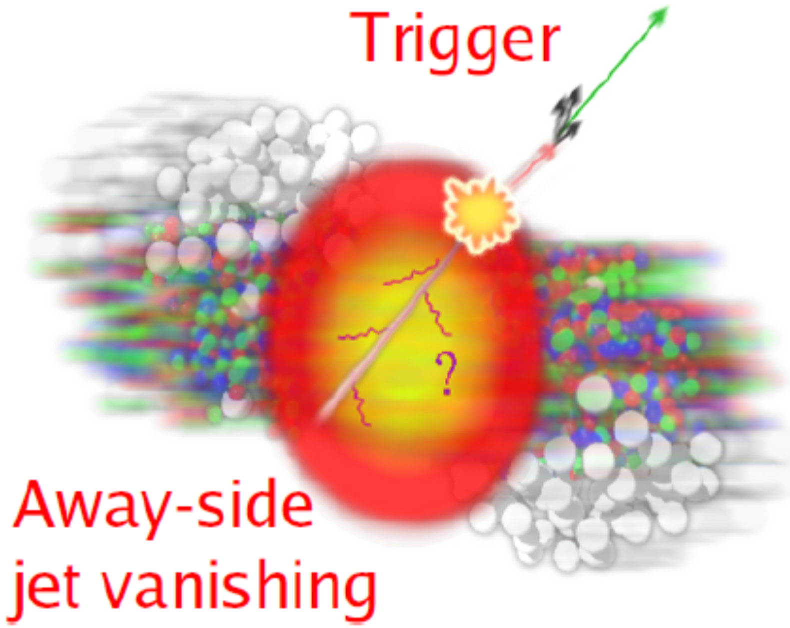
From FNAL, SPS, ISR extrapolation

our own measurement

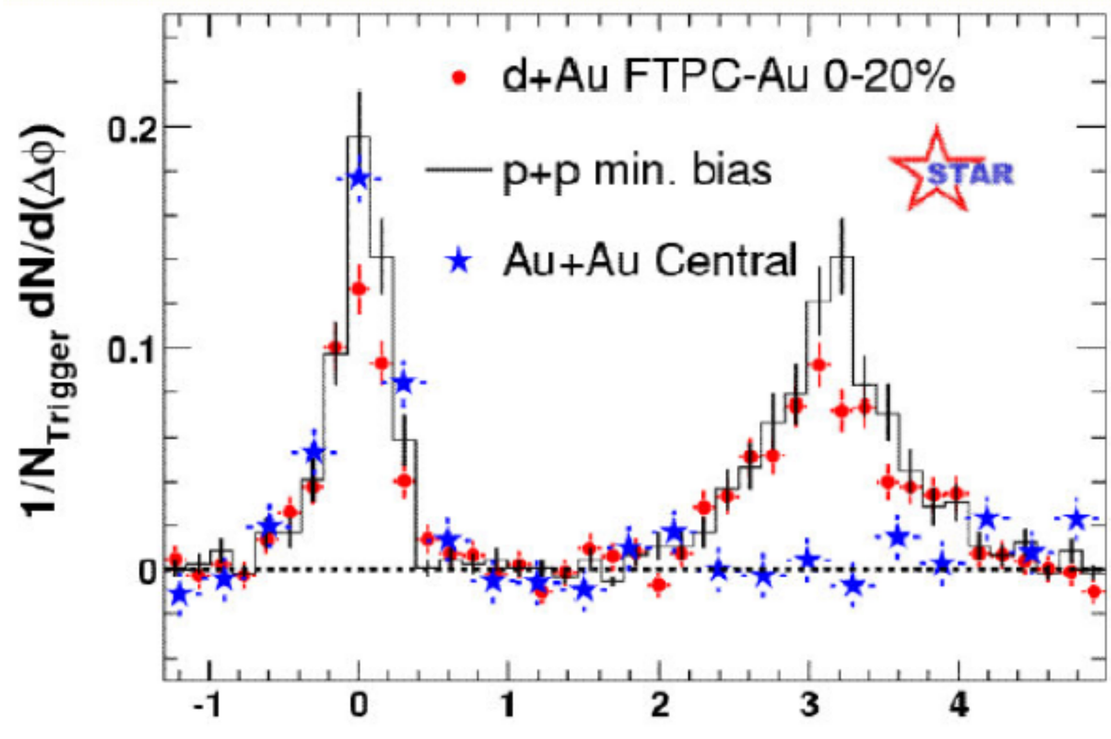
If $R^{\pi}_{AA} = R^{\gamma}_{AA}$ the whole concept of energy loss changes: perhaps no effect for pT>20 GeV.

New physics on the horizon?

Two-particle azimuthal correlations



Two-particle azimuthal correlations

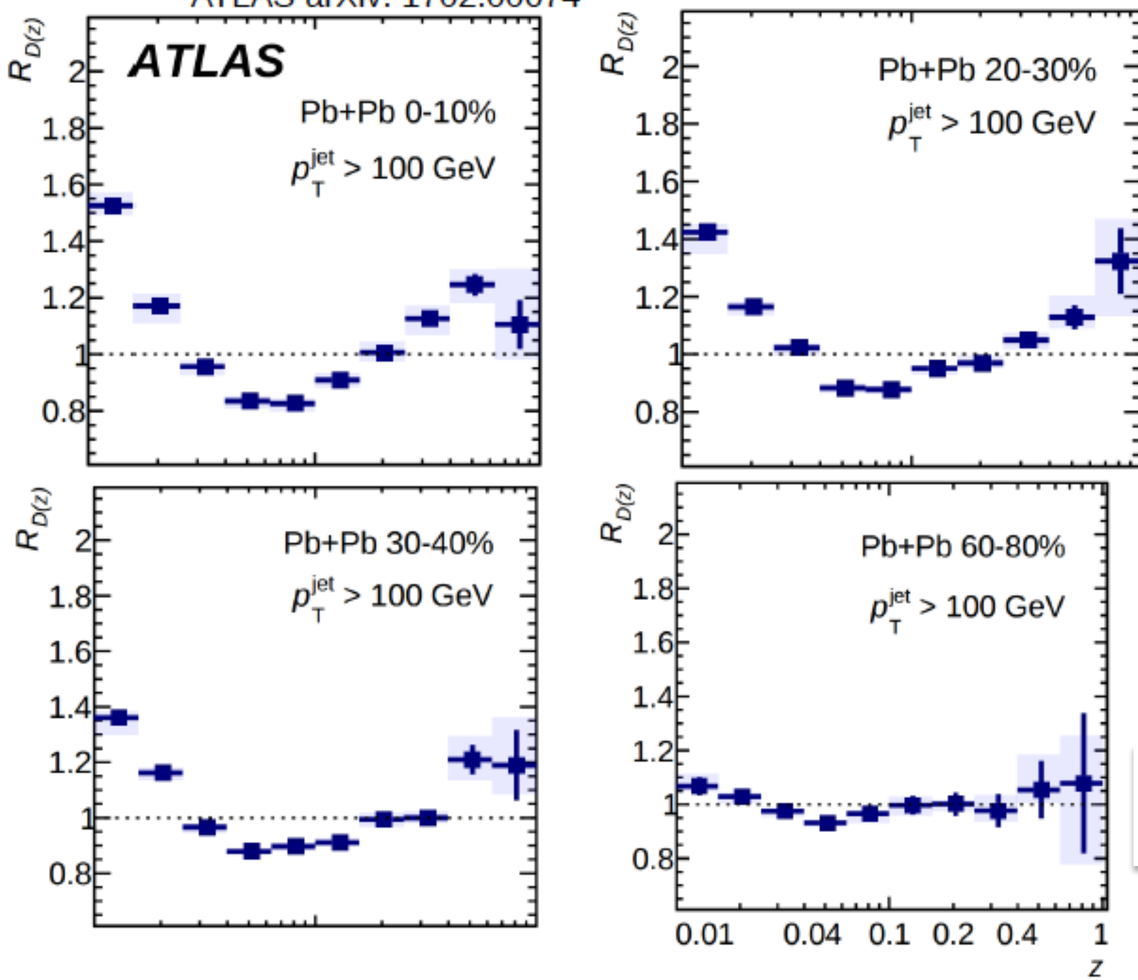


STAR, Phys Rev Lett 91, 072304

- Dissapearance of the associated particle is observed in nuclear collisions, while no effect is observed in pp and d-Au collisions.

Jets

ATLAS arXiv: 1702.00674



$z = p_T / p_T^{jet}$

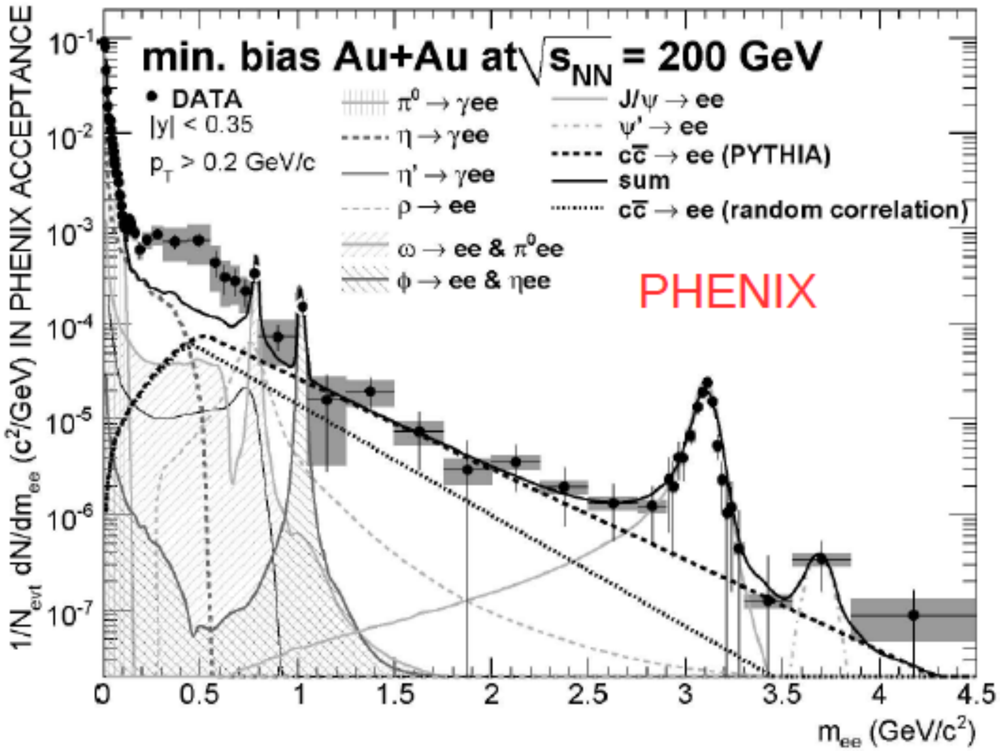
$R_{D(z)} = D(z)^{PbPb} / D(z)^{pp}$

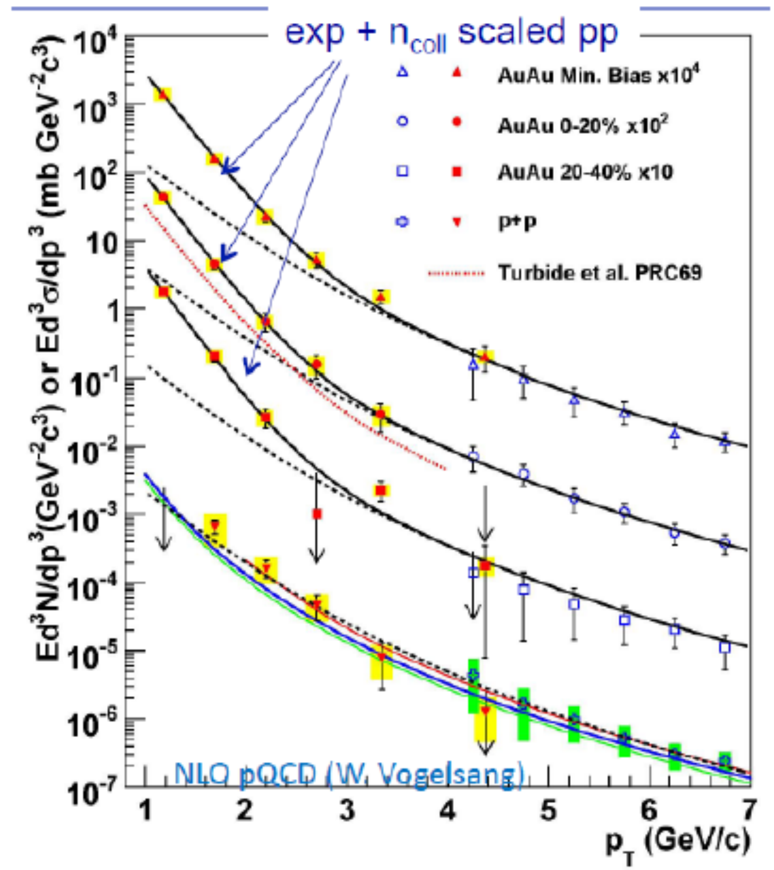
- Full jet reconstruction provides detailed insight into medium modification of the jet fragmentation

Electromagnetic probes

- Direct photons and low mass di-leptons
  - Clean information because of no re-interactions with the QCD medium
  - Emitted through the entire history of the collision
- Hard photons
  - from initial N+N collisions and jet fragmentation
- Soft photons
  - Hadronic sources
  - Thermal photons (both real and virtual) from $q\bar{q}$ annihilations and Compton scattering
- Chiral symmetry restoration
  - ρ-meson broadening and mass shift

EM probes: low mass dielectrons

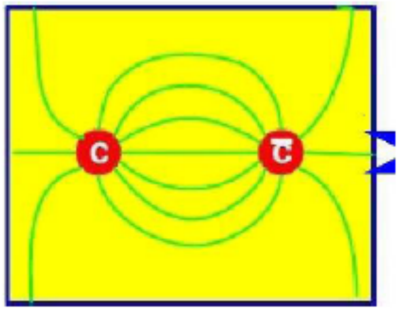




- Excess observed in the low mass dielectron spectrum in the region 0.3-0.7 GeV/c associated with thermal radion
- Strong direct photon excess at p_T<3 GeV/c

Heavy quarkonium and the QGP

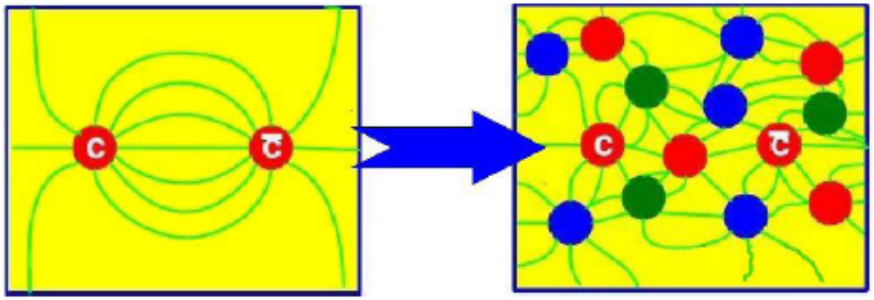
- What are heavy quarkonia ?
  - Bound states of heavy quark anti-quark pairs, e.g. ψ ($c\bar{c}$) and Υ ($b\bar{b}$) families
  - Relatively large binding energy, e.g. for J/ψ is ~600 MeV

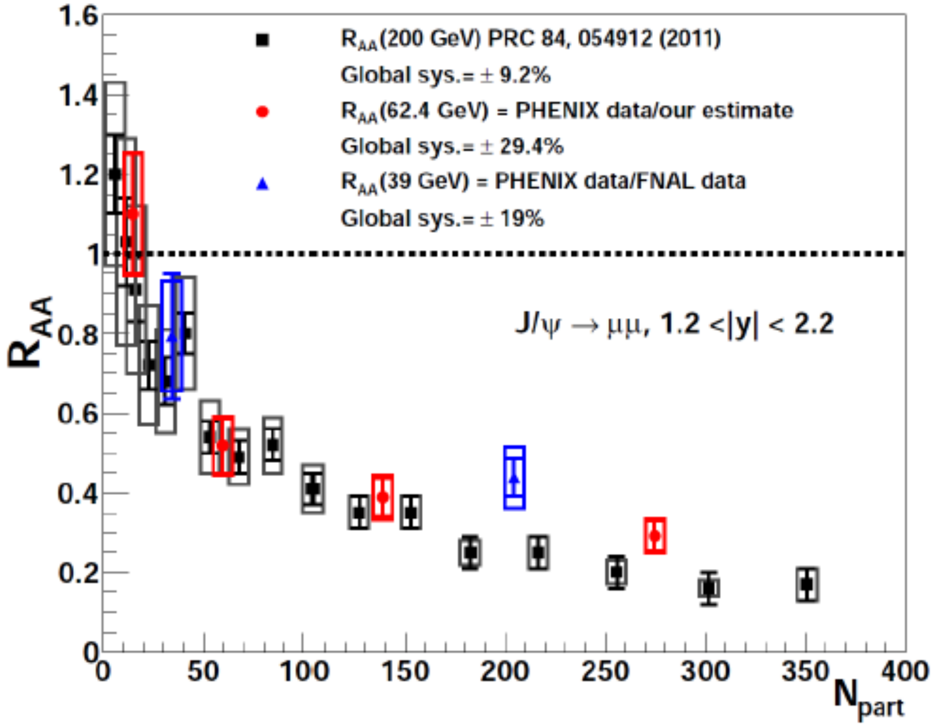


- Due to their large mass, heavy quarks can be produced only in initial hard partonic collisions and their number is conserved during the collision history
  - Ideal probe for QGP

Heavy quarkonium and the QGP

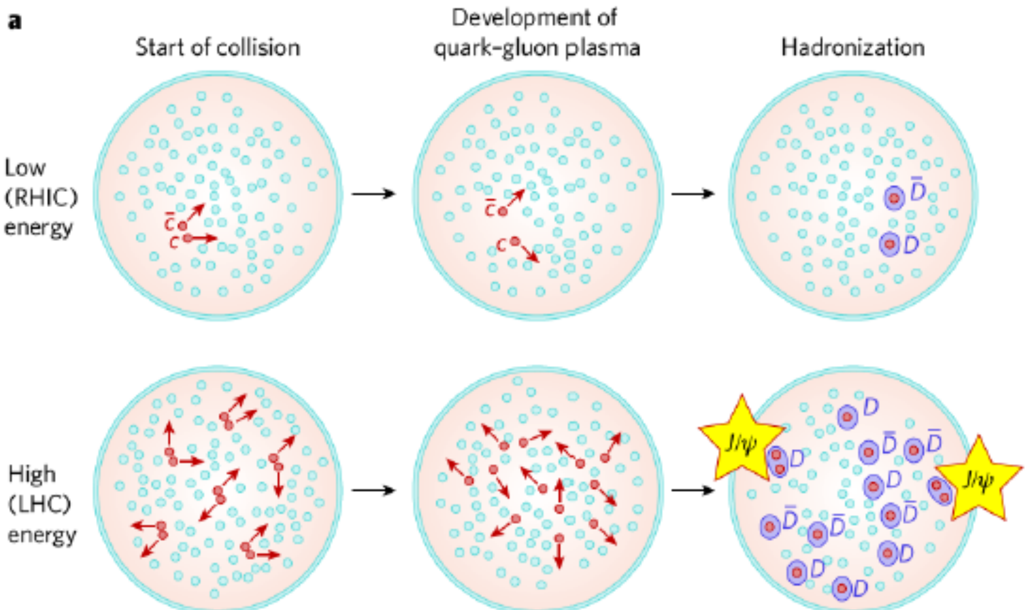
- The original idea (Matsui and Satz, PLB 178 (1986) 416):
  - In a deconfined medium with high density of color charges, the QCD analogue of the Debye screening can lead to heavy quarkonium suppression
  - No J/ψ if $\lambda_D < r_{J/\psi}$

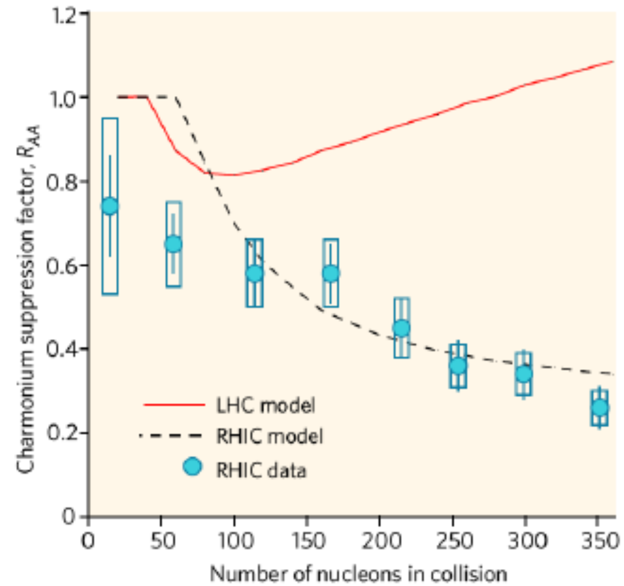




- Evidence of color screening?
- Not completely clear yet: we still need to take into account feed-down from higher mass states (e.g., χ_c, ψ(2S)) and CNM effects

Heavy quarkonium at the LHC (re-generation)





Nature 448 (2007) 302-309

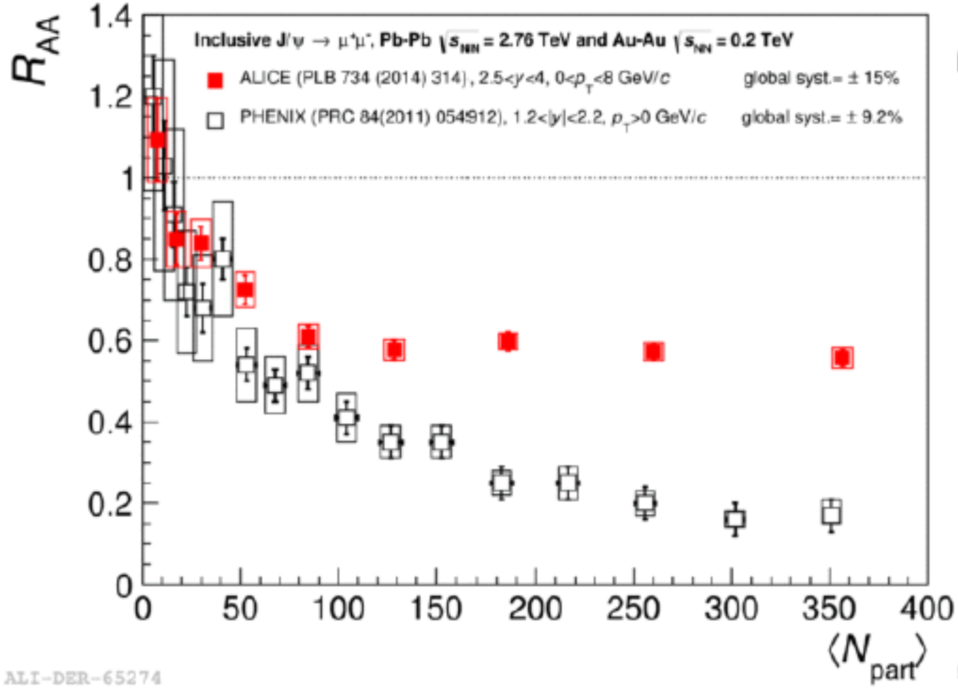
- At the LHC, there are many charm quark-pairs created in one single collision (~100)
- Possible to create charmonium states on a statistical basis → enhancement of charmonium states at LHC
  - Open charm and quarkonia abundancies calculated assuming statistical hadronization.

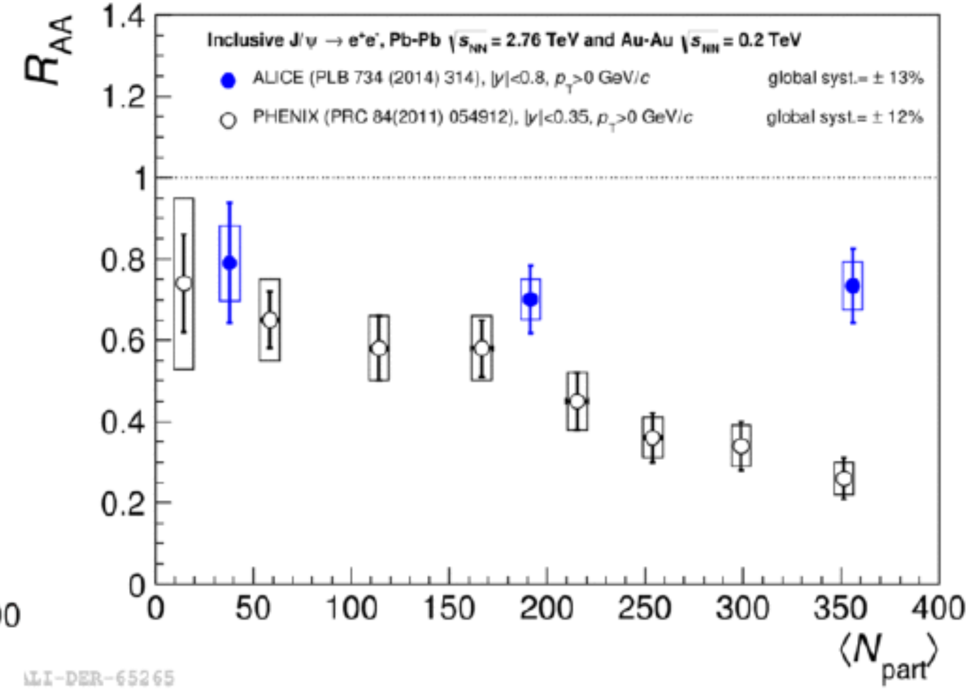
    Braun-Munzinger and Stachel, PLB 490 (2000) 196

    Thews et al., PRC 63 (2001) 054905

J/ψ at the LHC

Ionut Arsene, monday 22





- ALICE results show smaller suppression compared to lower energies (PHENIX) in central collisions
- Indication that regeneration plays an important role in the production of charmonium

Conclusions

- The aim of studying the high energy heavy ion collisions is to better understand QCD in conditions not possible in particle physics: confinement, phase diagram of nuclear matter, chiral symmetry restoration
- Conditions reachable are similar to the ones during the early Universe (few microseconds) and in the core of neutron stars
- This field incorporates knowledge from many other areas of physics:
  - Thermodynamics, hydrodynamics, string theory, ...
- … and technology
  - Detectors, Electronics, Scientific Computing
- and provides input for fields like:
  - cosmology, astrophysics, solid-state physics, etc.
- A relatively young and very challenging field of study with a rich phenomenology, the manifestation of many-body QCD

Signatures of Quark Gluon Plasma - Summary

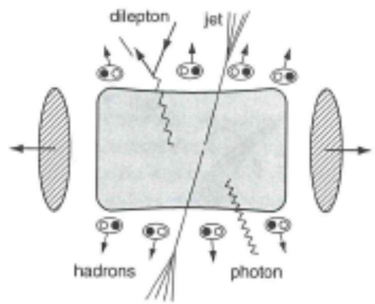


Fig. 1.10. Particles/radiations from the hot quark–hadron matter formed in a central collision between ultra-relativistic heavy nuclei.

dE_T/dy, to be measured in an electromagnetic calorimeter (**Chapter 17**) is closely connected to the energy density, ε.

In the following, (1)–(10) refer to Fig. 1.11.

(1) A second rise in the average transverse momentum of hadrons due to a jump in entropy density at the phase transition.
(2) Measurement of the size of the fireball by particle interferometry with identical hadrons (Hanbury-Brown and Twiss effect).
(3) Enhanced production of strangeness and charm from QGP.
(4) Enhanced production of anti-particles in QGP.
(5) An increase of an elliptic flow (v_2) of hadrons from early thermalization of an anisotropic initial configuration.
(6) Suppression of the event-by-event fluctuations of conserved charges.
(7) Suppression of high-p_T hadrons due to the energy loss of a parton in QGP.
(8) Modification of the properties of heavy mesons (J/ψ, ψ', Υ, Υ') due to the color Debye screening in QGP.
(9) Modifications of the mass and width of the light vector mesons due to chiral symmetry restoration.
(10) Enhancement of thermal photons and dileptons due to the emission from deconfined QCD plasma.

Obviously, the real situation is not as straightforward as that illustrated in Fig. 1.11 due to various backgrounds which tend to hide the possible signals. Also, there are theoretical indications that QGP is not a simple gas of free quarks and gluons, but rather is a strongly interacting system which may modify some of the basic ideas behind the signatures in Fig. 1.11. Nevertheless, as discussed in **Chapters 15** and **16**, the vast number of data from SPS and RHIC already provide quite promising clues which may help in pinning down the nature of QGP.

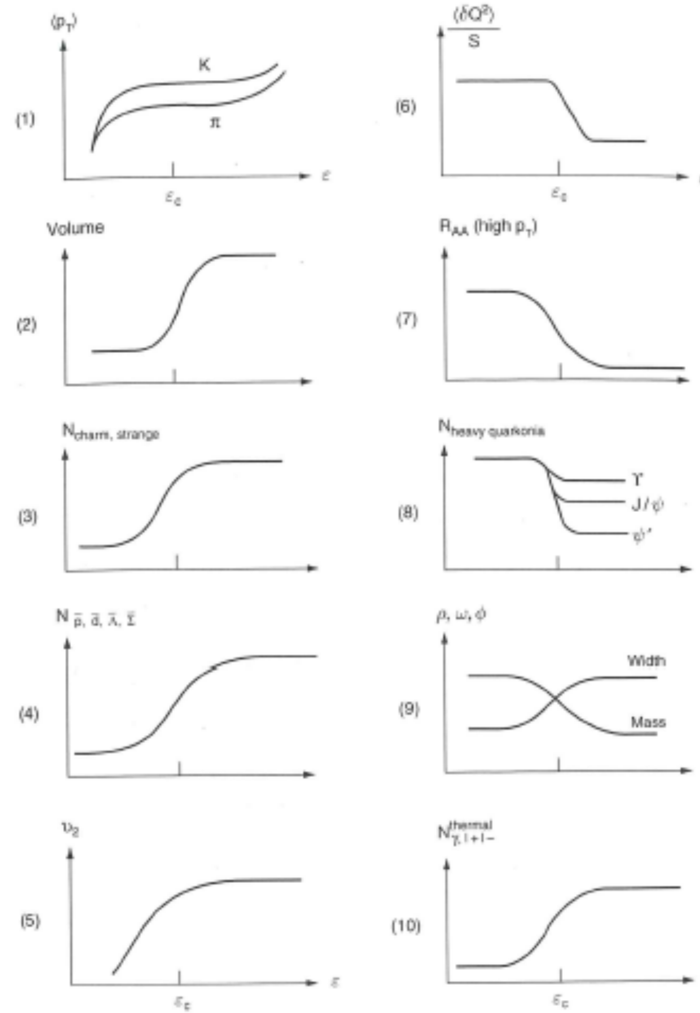


Fig. 1.11. Selected observables as a function of the central energy density ε in the relativistic heavy ion collisions. They are the possible signatures of QCD phase transitions; ε is related to the transverse energy per unit rapidity, dE_T/dy; ε_c is the critical energy above which the QGP is expected. This figure has been adapted from an original by S. Nagamiya. For an explanation of parts (1)–(10), please see the text.

Summary and outlook:

- *Experiments:* ***BRAHMS, PHENIX, PHOBOS, STAR*** ***(pp, dAu Au+Au collisions at 19.4, 62, 130 and 200 GeV)*** **:** "There is compelling experimental evidence that the matter created at RHIC differs from anything that has been seen before. Still there is no direct indication of QGP formation"
- ***Accelerator facilities will be upgraded by order of magnitude Super processors for Lattice QCD will be upgraded at least order of magnitude Microscopic and hydrodynamic models need urgently manpower for describing physics at LHC***

Potential of the Field