TALLER DE ALTAS ENERGÍAS 2011
Spanish Graduate School on High Energy Physics 2011
University of the Basque Country, Bilbao
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Heavy-Ion Collisions (I)

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Contents:

1. QCD: asymptotic freedom, confinement and chiral symmetry.

2. QCD at finite temperature: perturbative and lattice techniques.

3. Dynamics of heavy-ion reactions: initial state (Glauber theory), equilibration, hydrodynamics, transport models, freeze-out.

4. Particle production.

5. Fundamentals of QGP signatures: soft, hard and EM probes.

6. Hadrochemistry: different temperatures.

7. Quarkonium production and suppression.

See Ynduráin, The theory of quark and gluon interactions, Springer; Wong, Introduction to HEHIC, World Scientific; Quark-Gluon Plasma 1 to 4, World Scientific; students talks at QM2011, http://indico.cern.ch/conferenceTimeTable.py?confId=30248#20110522.

QCD (I):

Elementary fields: Quarks Gluons

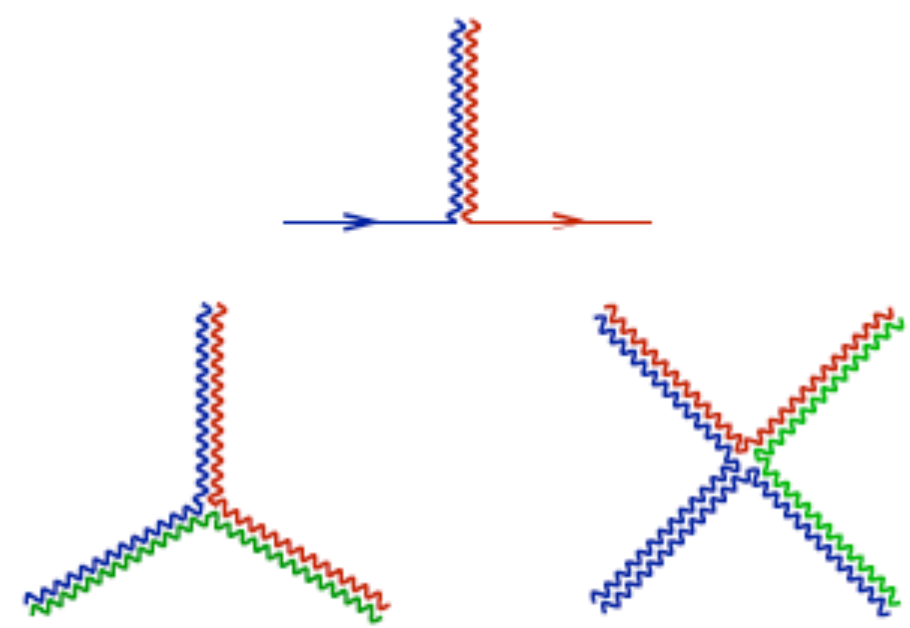
$$(q_\alpha)^a_f \begin{cases} \text{color} & a = 1,\ldots,3 \\ \text{spin} & \alpha = 1,2 \\ \text{flavor} & f = u,d,s,c,b,t \end{cases} \qquad A^a_\mu \begin{cases} \text{color} & a = 1,\ldots,8 \\ \text{spin} & \epsilon^\pm_\mu \end{cases}$$

Dynamics: Generalized Maxwell (Yang-Mills) + Dirac theory

$$\boxed{\mathcal{L} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}}$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

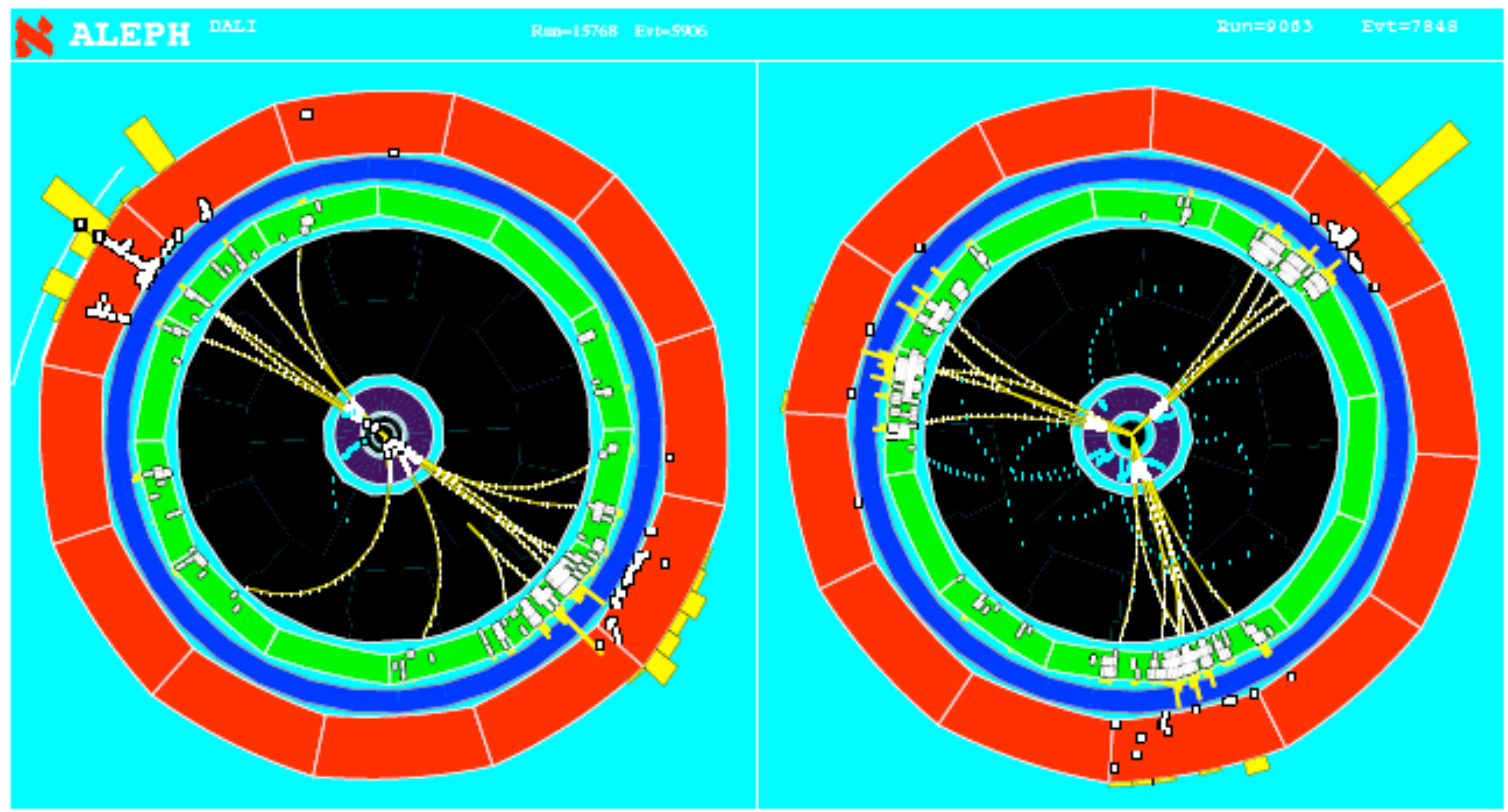
$$i\not{D} q = \gamma^\mu \left(i\partial_\mu + g A^a_\mu t^a \right) q$$



QCD (II):

- QCD is the theory of strong interactions: it describes the interactions between hadrons and nuclei.

- The Lagrangian, though, is written in terms of non-asymptotic states: partons i.e. quarks and gluons.



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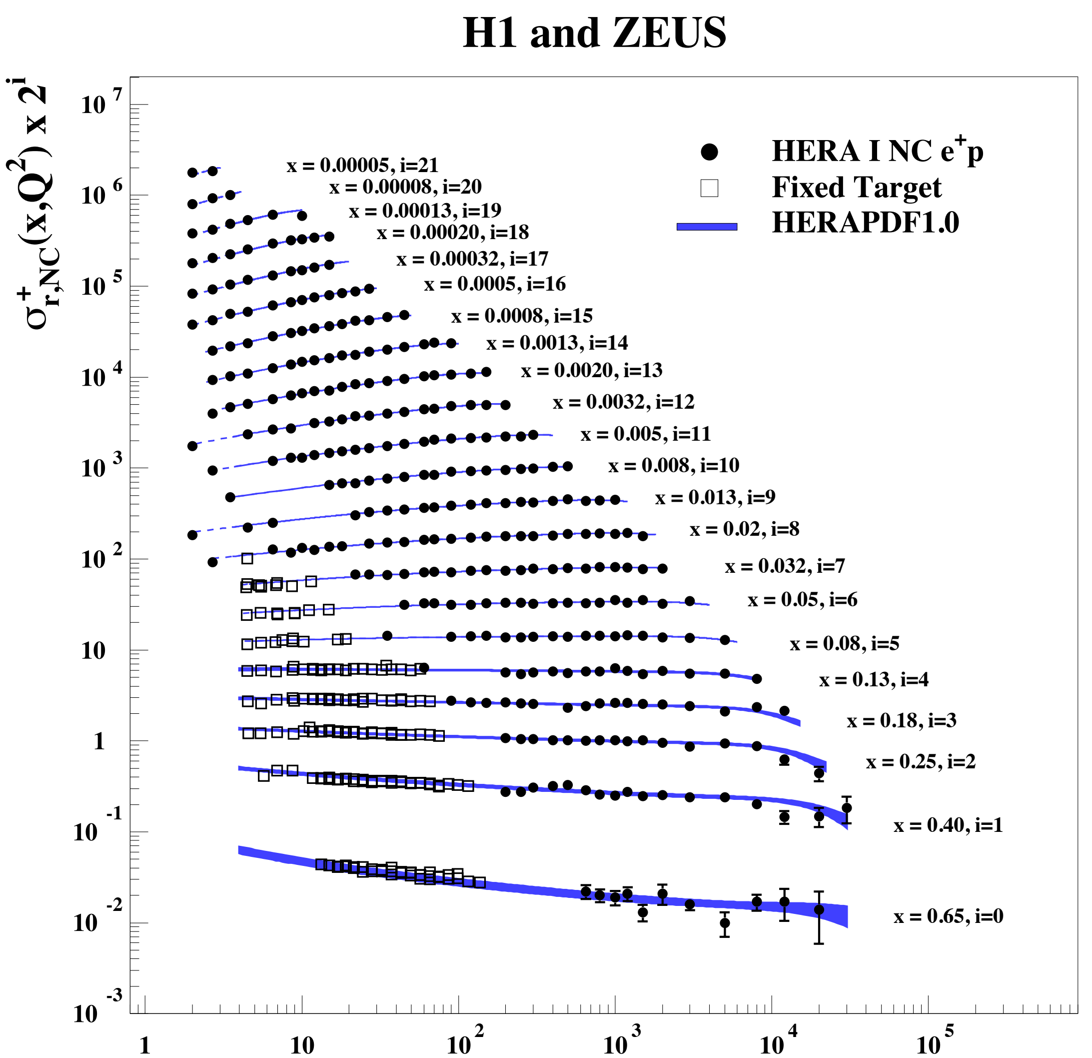
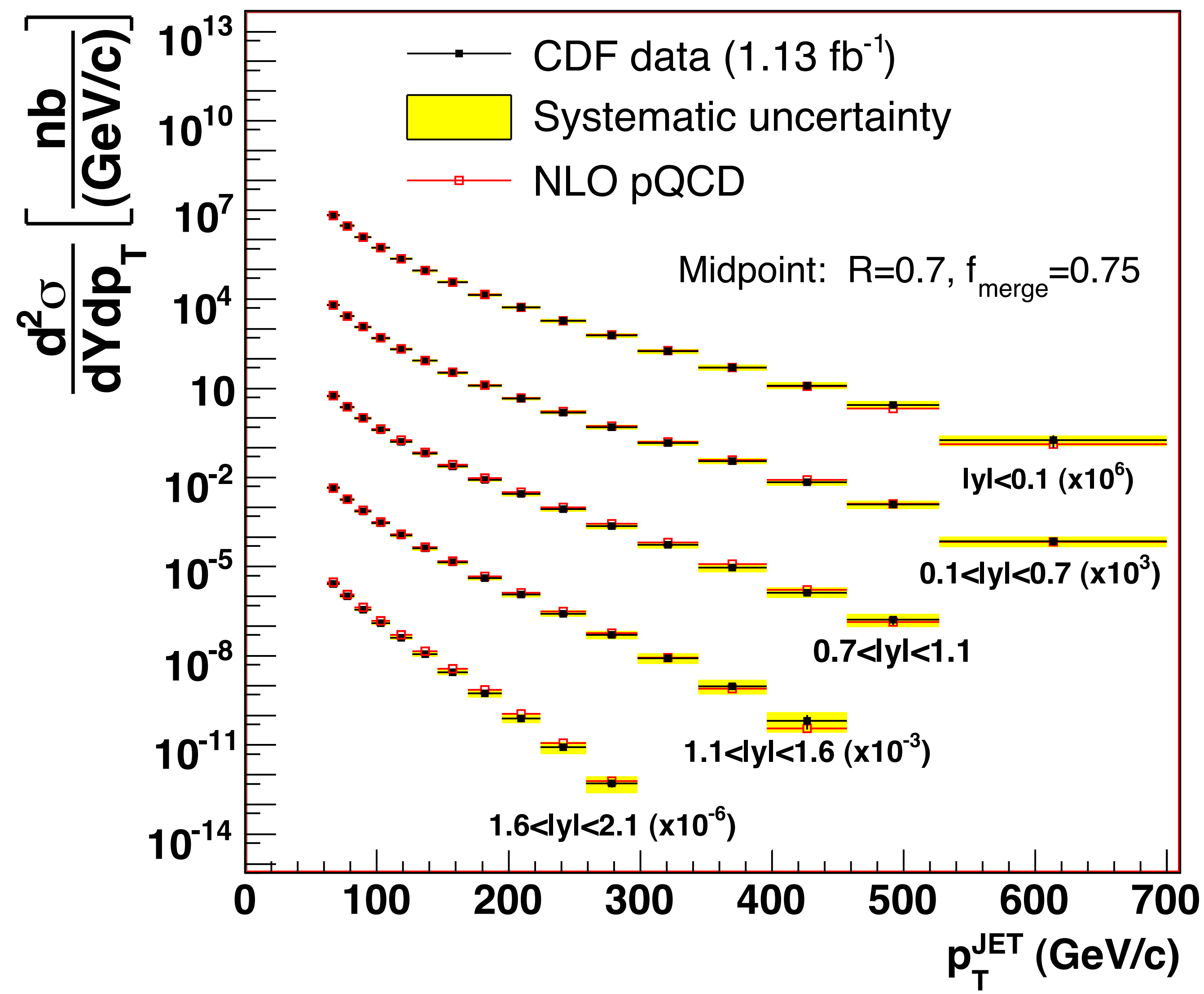


H1+ZEUS, '10

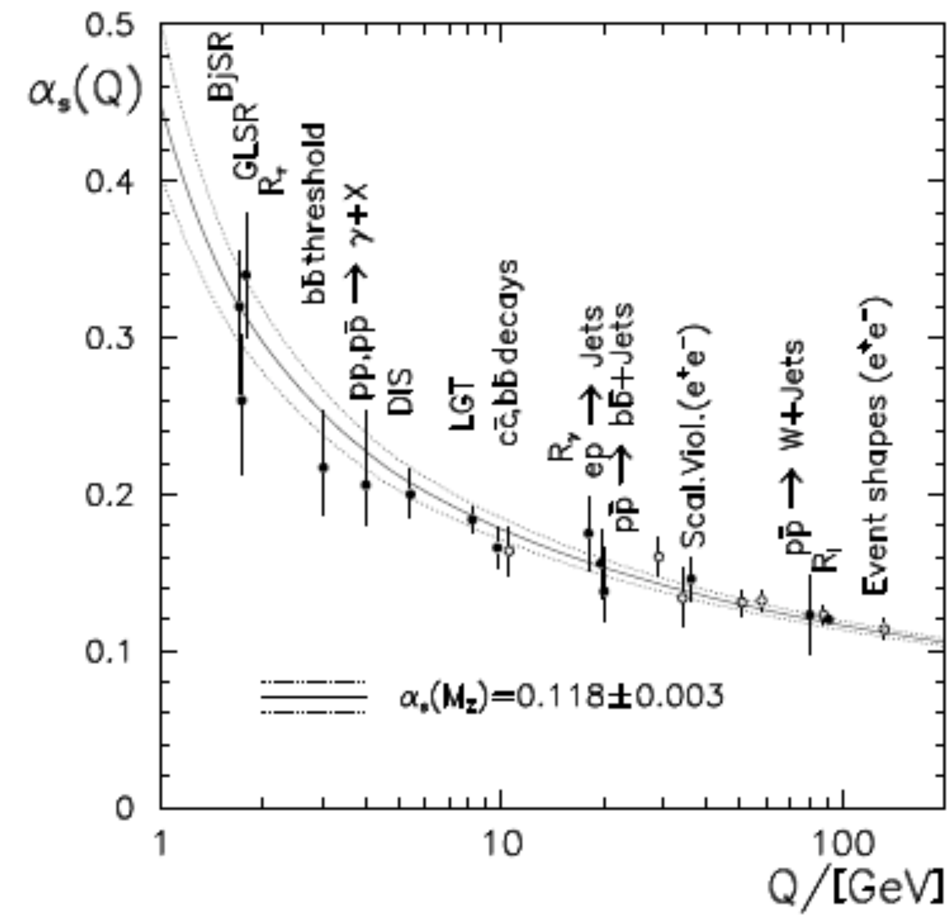


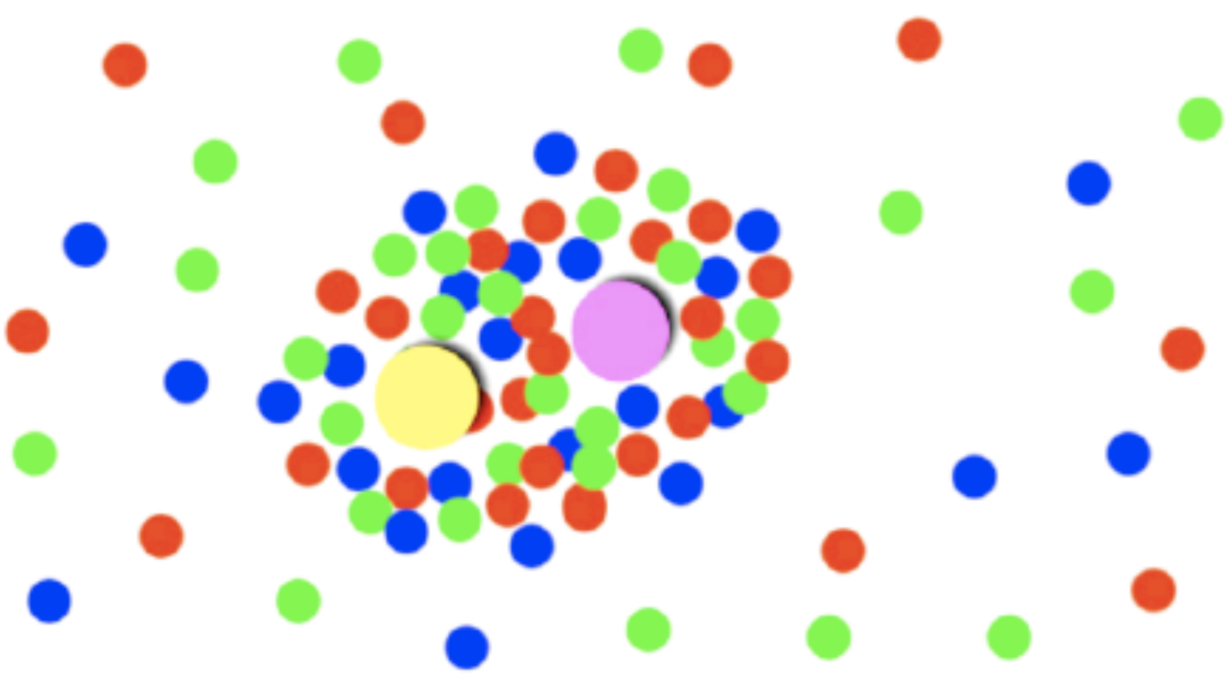
QCD (III):

- The strength of the interaction is smaller at smaller distances: asymptotic freedom.

$\alpha_s = g^2/(4\pi)$

$$\beta(g) = \frac{\partial g}{\partial \log(\mu)} = \frac{g^3}{(4\pi)^2}\left\{\left[\frac{1}{3} - 4\right]N_c + \frac{2}{3}N_f\right\} < 0$$





- Partons carry color SU(3) which is not visible (singlets): confinement.

QCD (IV):

- The qqbar potential contains a linear term: string, which breaks when $V(r_{crit})=m_q+m_{qbar}$.

$$V(r) = -\frac{A(r)}{r} + Kr$$

- Mass of light mesons and baryons has mainly a dynamical origin.

$$m_N = 890\,\mathrm{MeV} + 45\,\mathrm{MeV}$$

$$(\mathrm{QCD},\ 95\%) + (\mathrm{Higgs},\ 5\%)$$

	mass (GeV)	$\sum q_m$ (GeV)
p	$\sim$1	$2m_u + m_d \sim$0.03
π	$\sim$0.13	$m_u + m_d \sim$ 0.02

- The Lagrangian, for 2 massless quarks, is $SU(2)_L$ X $SU(2)_R$ invariant: chiral symmetry.

$$\langle \bar\psi_L^f \psi_R^g + \bar\psi_L^f \psi_R^g \rangle \simeq -(230\,\mathrm{MeV})^3\ \delta^{fg}$$

- This symmetry is not observed: SSB, Goldstone bosons (pions), <qqbar>≠0 ⇒ dynamical mass.

$$m_Q = 300\,\mathrm{MeV} \gg m_q$$

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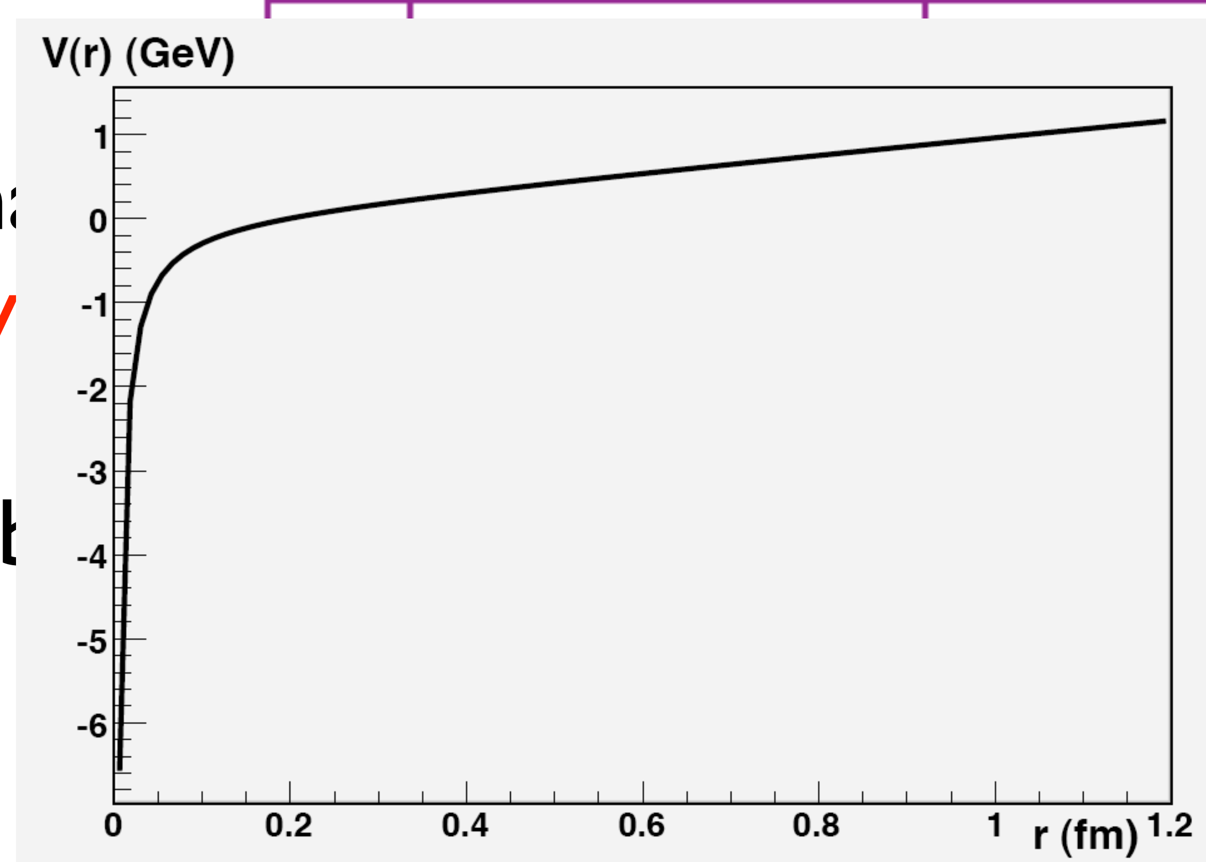

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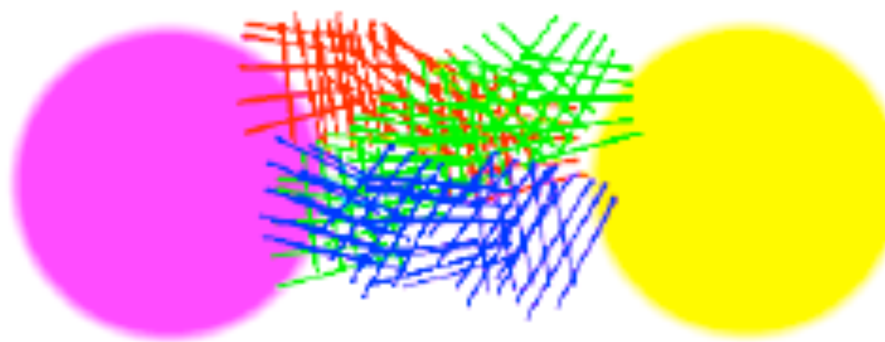

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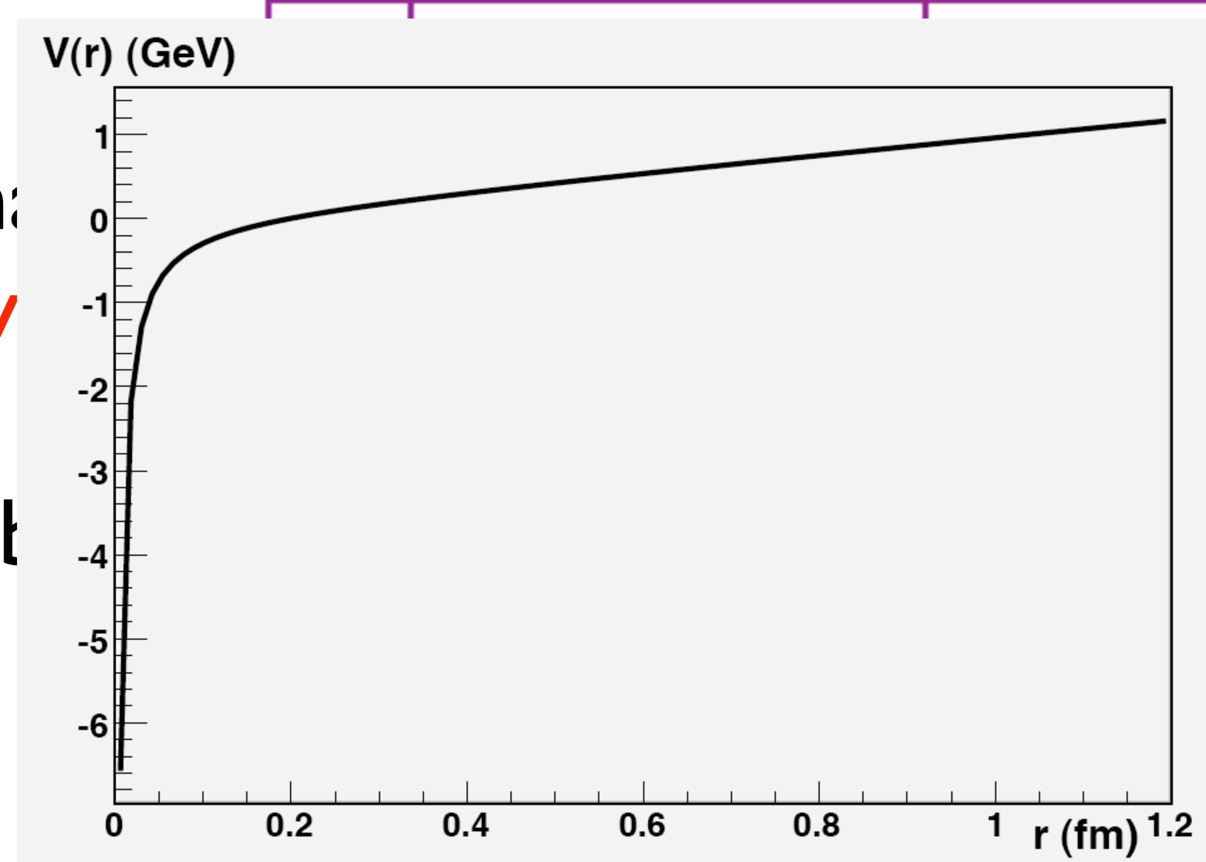

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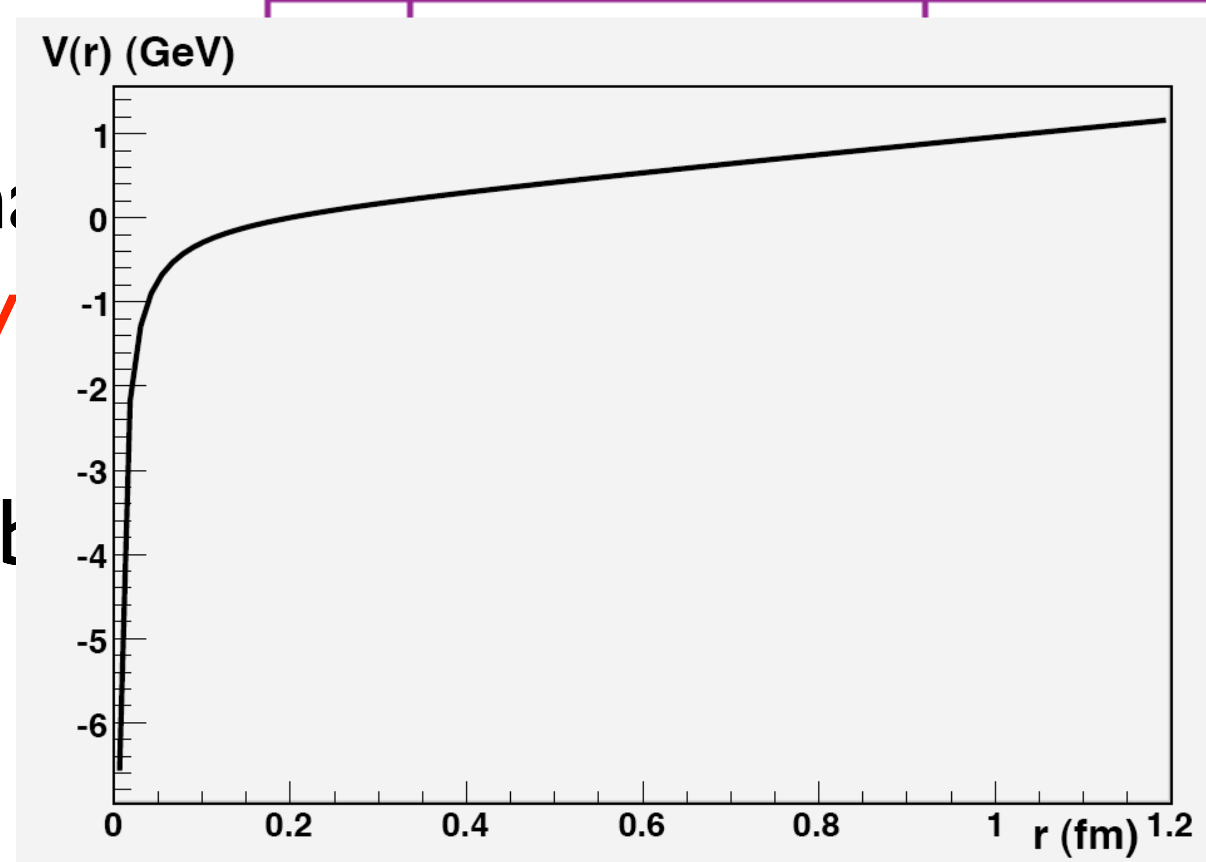

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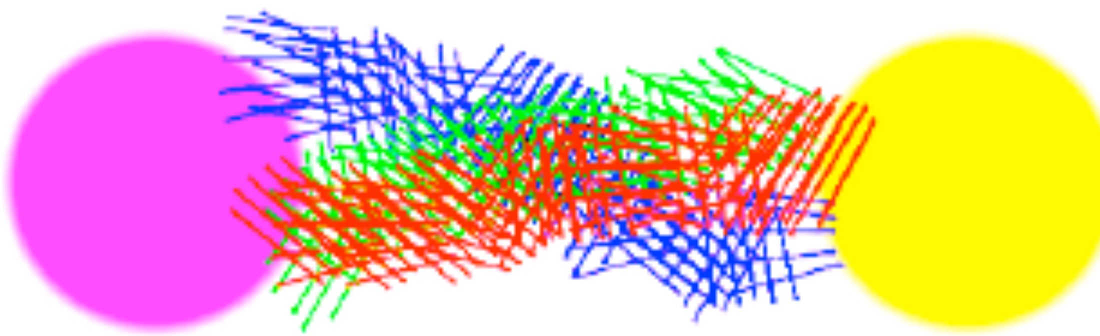

dynamical origin.

$m_N = 890\,\text{MeV} +$

$(\text{QCD},\,95\%) + (\text{Higgs},\,5\%)$

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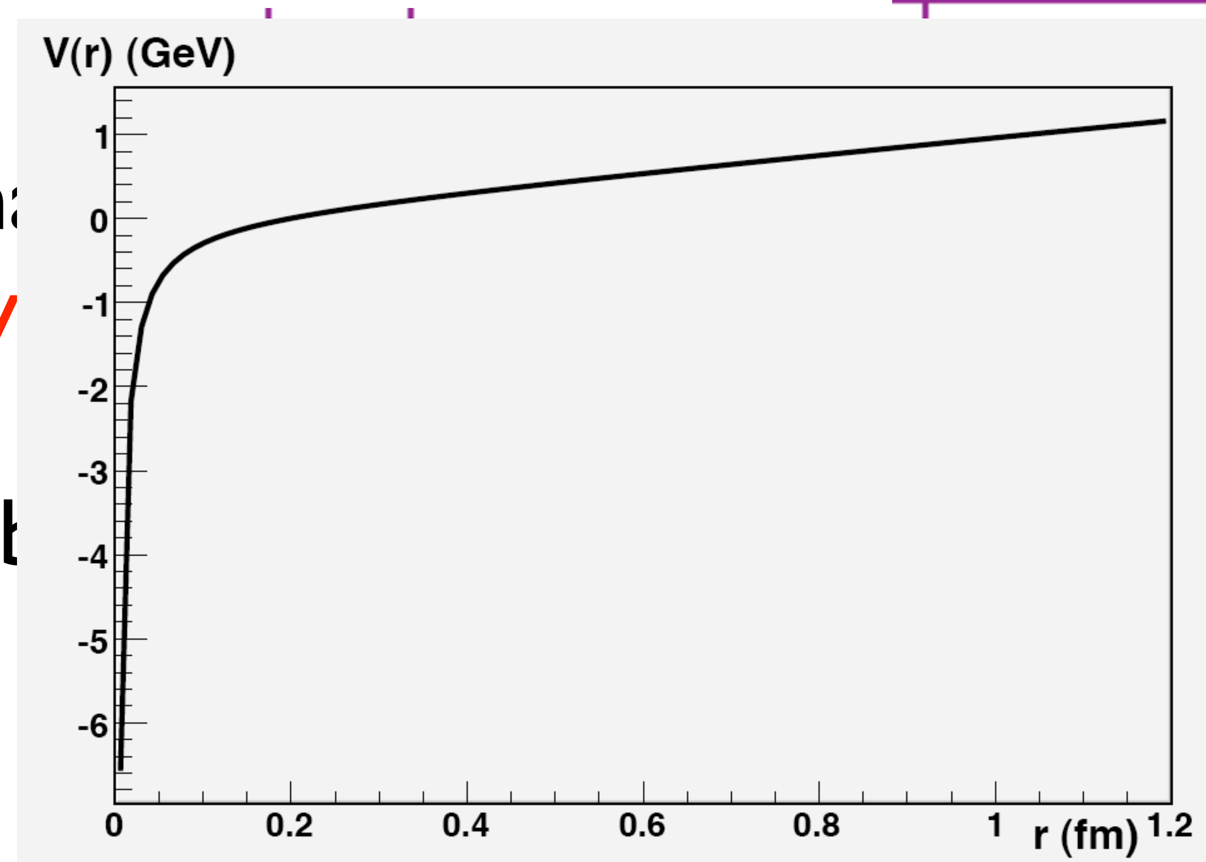

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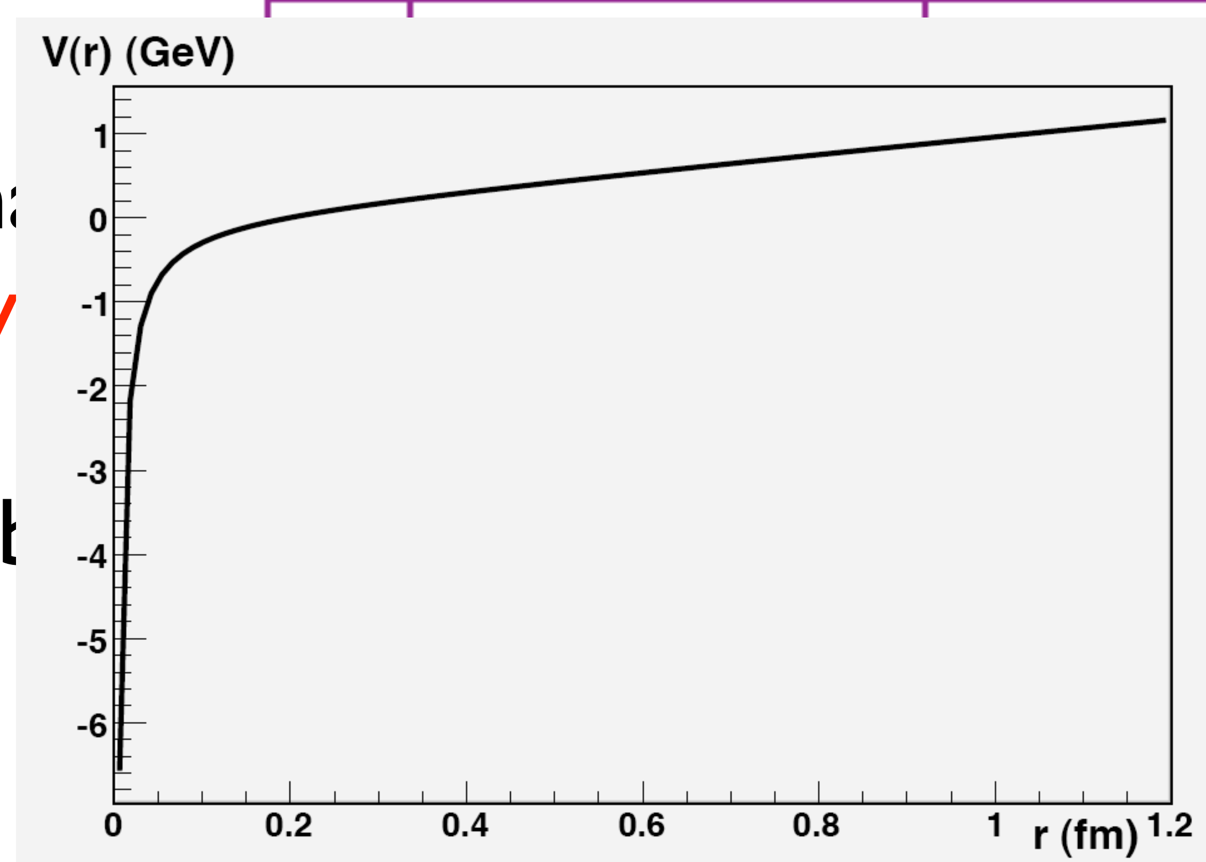

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origi

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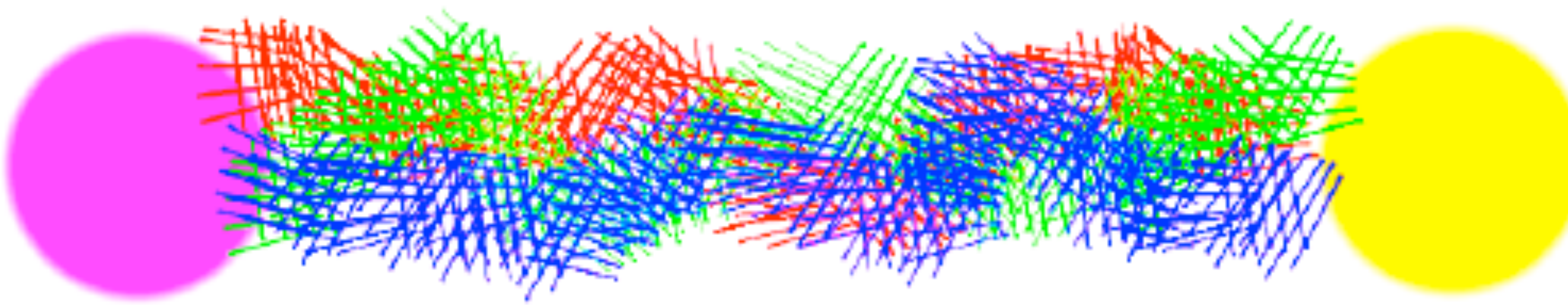

V)

0.03

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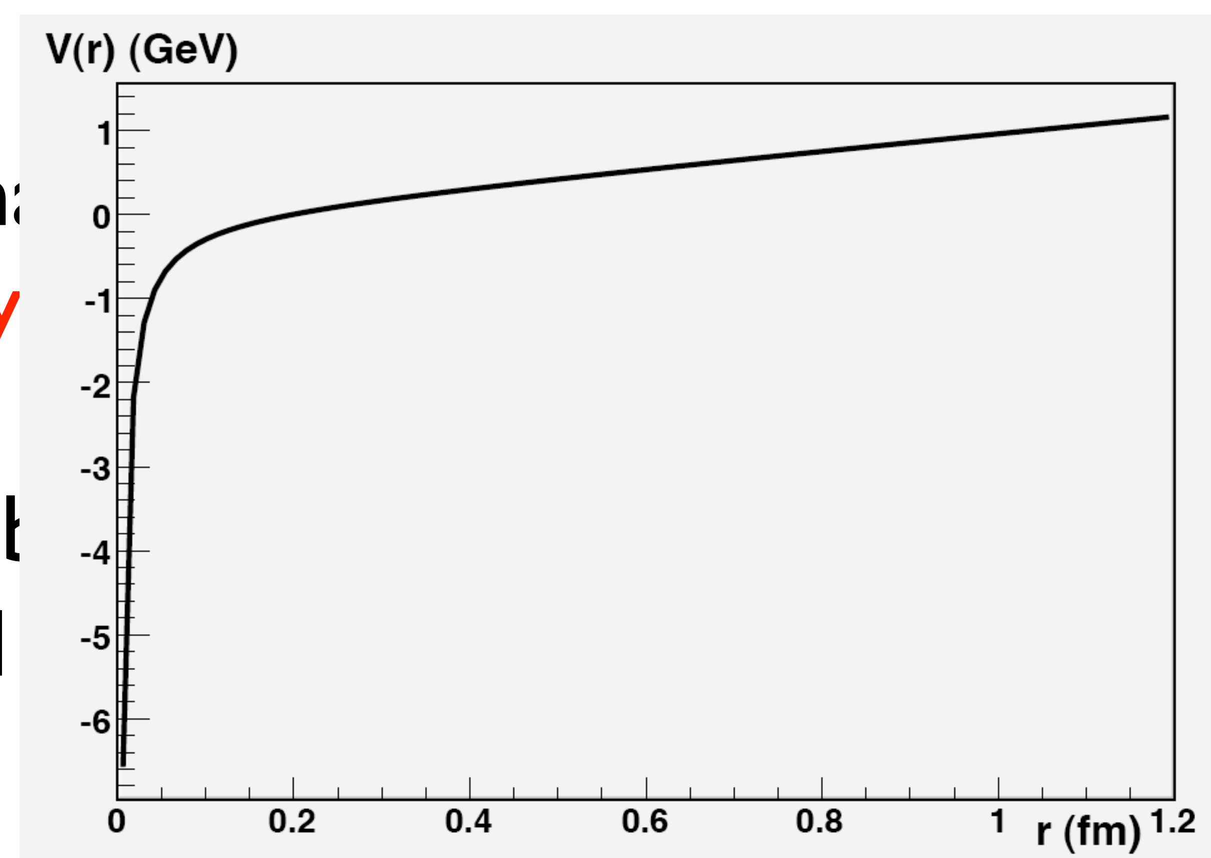
(QCD, 95%) + (Higgs, 5%)



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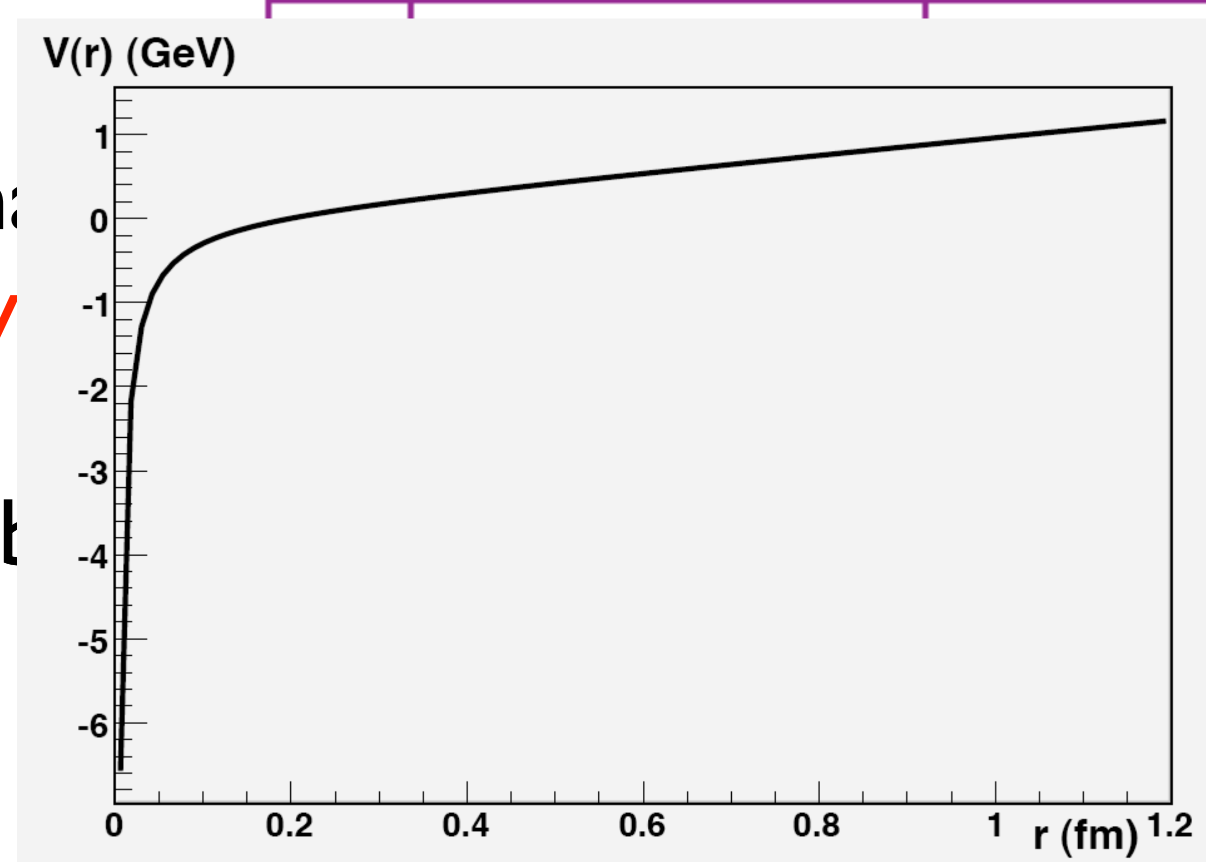

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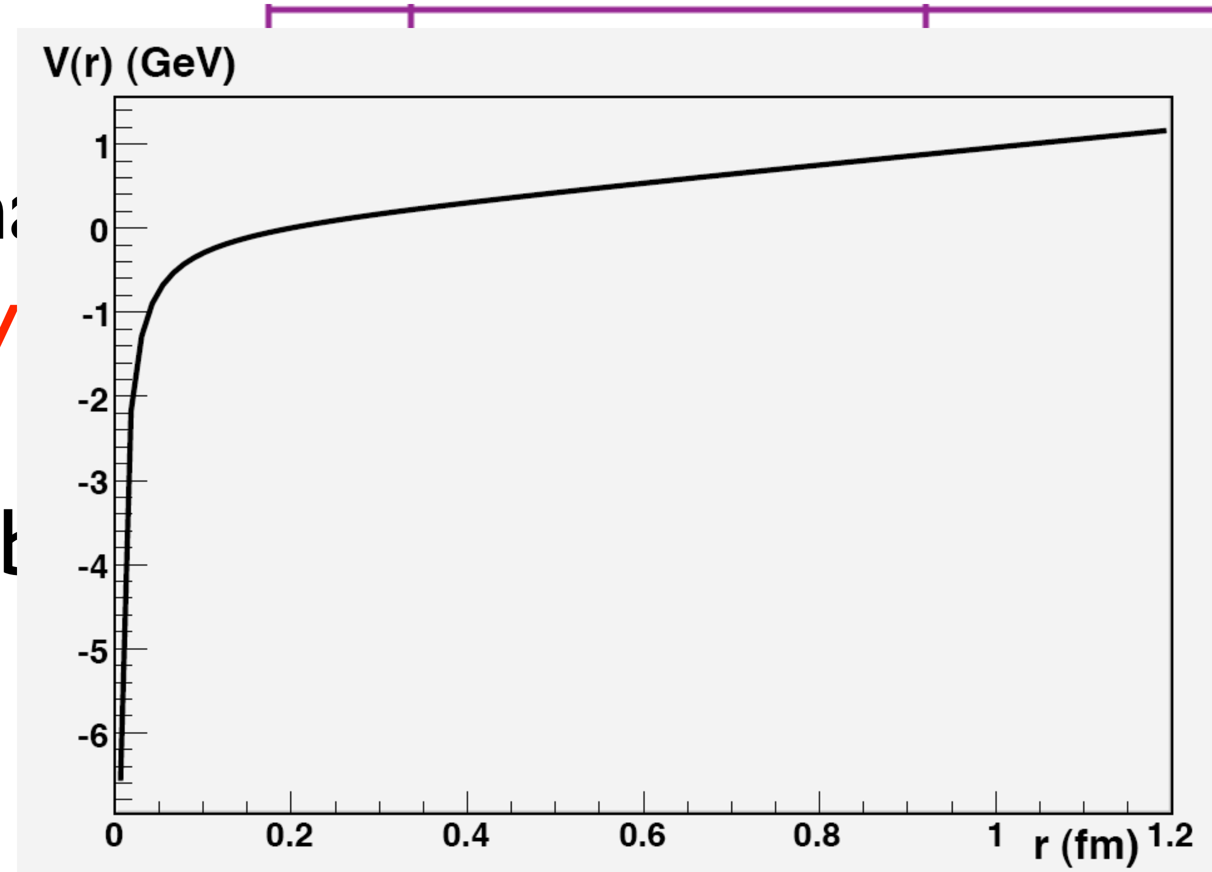

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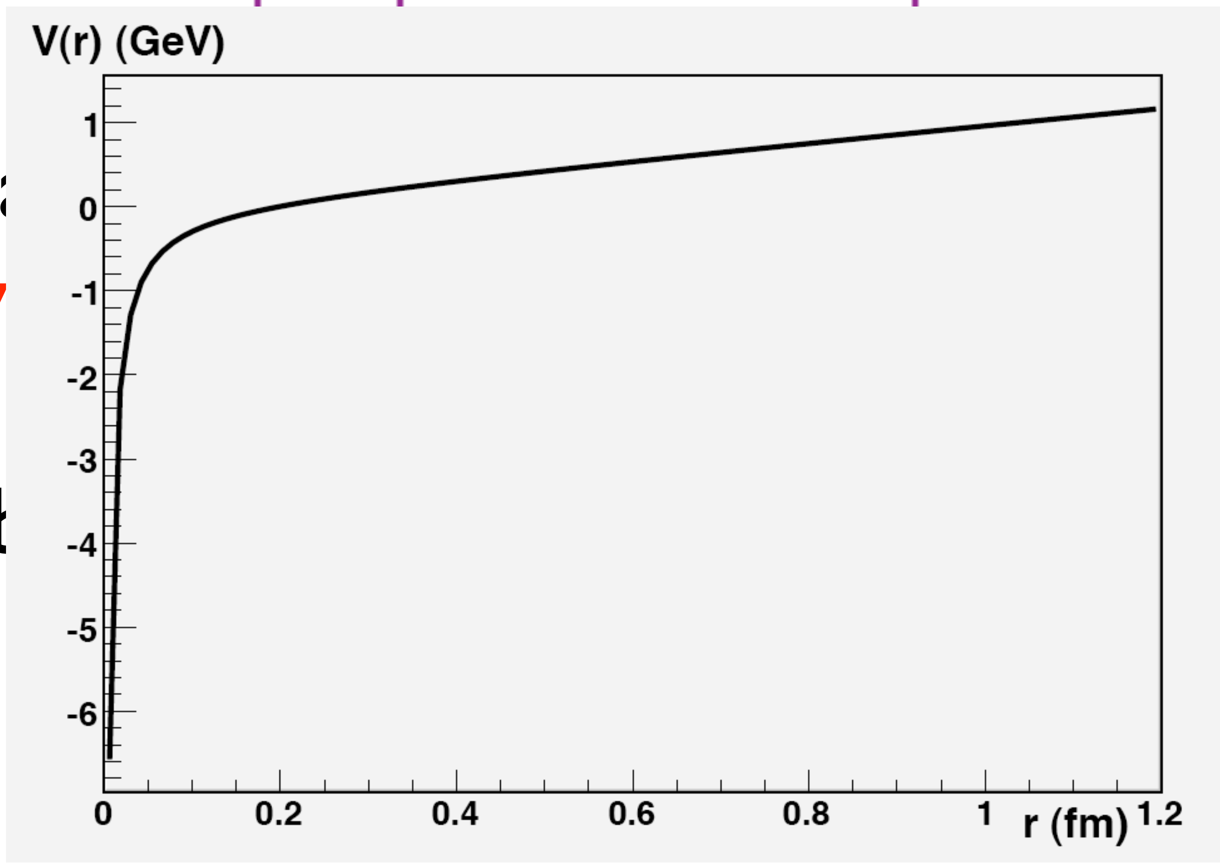

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QCD (IV):

S. Durr et al., arXiv:1011.2403, 2711 [hep-lat]

	RI(4 GeV)	RGI	$\overline{\text{MS}}$(2 GeV)
m_s	96.4(1.1)(1.5)	127.3(1.5)(1.9)	95.5(1.1)(1.5)
m_{ud}	3.503(48)(49)	4.624(63)(64)	3.469(47)(48)
m_u	2.17(04)(10)	2.86(05)(13)	2.15(03)(10)
m_d	4.84(07)(12)	6.39(09)(15)	4.79(07)(12)

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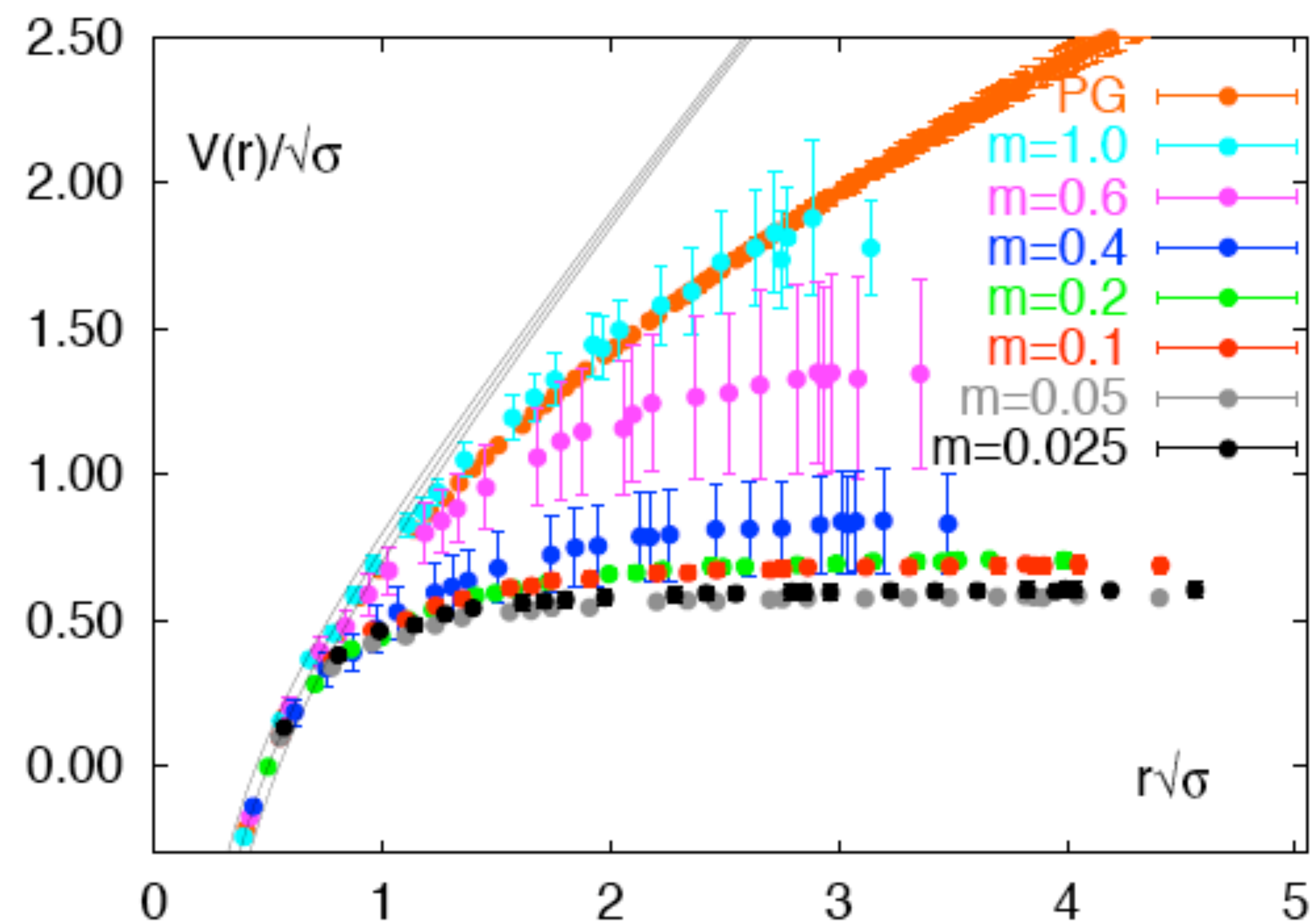
$$(\text{QCD}, 95\%) + (\text{Higgs}, 5\%)$$



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QCD (V):

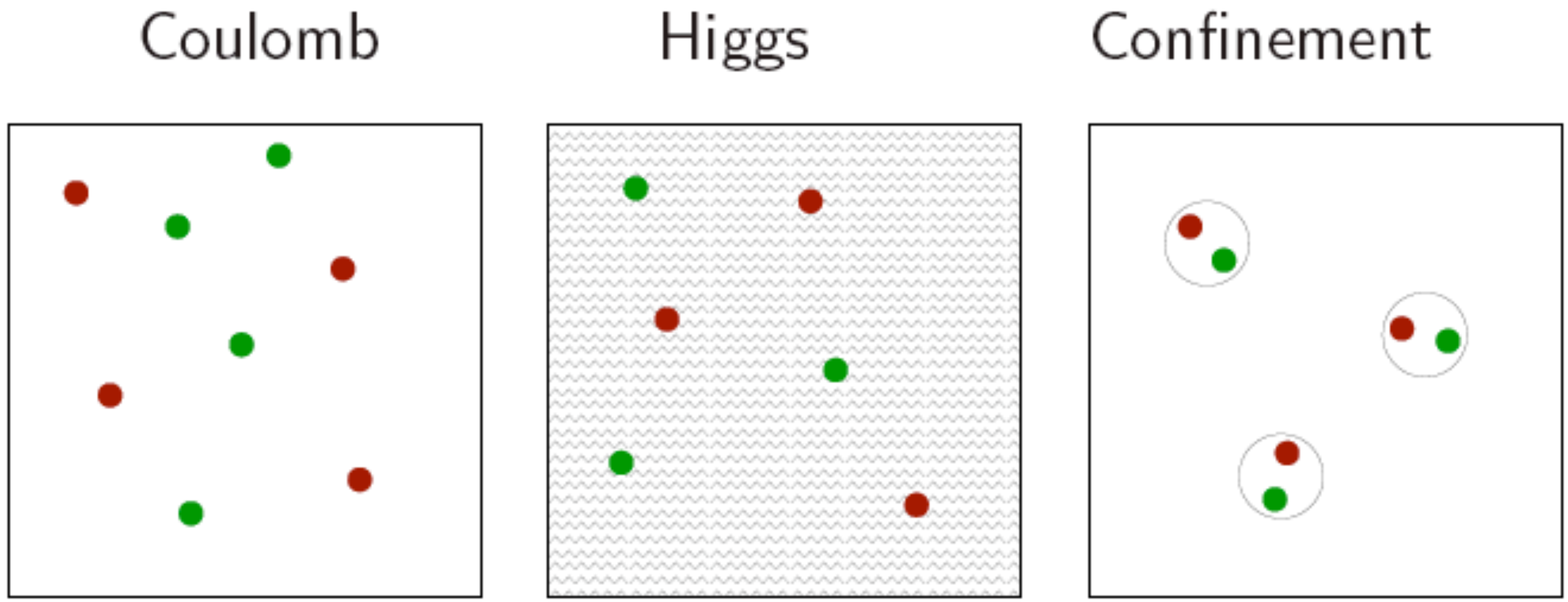
- This is what happens at normal conditions of T(=0) and ρ(~0.17 nucleons/fm^3).

- Is it there a regime where these symmetries are restored?: Quark-Gluon Plasma.

- Asymptotic freedom: smaller distances or higher momenta → increase density or temperature.

- **Where?**: ☛ in the Universe ~10^{-5} s after the Big-Bang;
  ☛ in the core of neutron stars;
  ☛ in ultra-relativistic heavy ion collisions.

QCD (VI):



$$V(r) \sim -\frac{e^2}{r} \qquad V(r) \sim -\frac{e^{-mr}}{r} \qquad V(r) \sim kr$$

QCD: High T phase — High μ phase — Low T, μ phase

QCD (VI):

URHIC: interdisciplinary field where QFT is applied to collective phenomena, transition between microscopic description and macroscopic language. Understanding confinement and chiral symmetry breaking is the ultimate goal.

Accelerator	Collisions
SPS	pp to PbPb at E_{cm}=17-30 AGeV
RHIC	pp to AuAu at E_{cm}=20-200 AGeV
LHC	pp to PbPb at E_{cm}=2.76-14 ATeV

$V(r) \sim -$ ... $V(r) \sim kr$

QCD: High T ph... ...w T, μ phase

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Finite-T QFT:

- In the grand-canonical ensemble, the thermodynamical properties of a system in thermodynamical equilibrium are given by (see Karsch, Lecture Notes in Physics '02):

$$Z(T,V,\mu_i) = \mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}$$

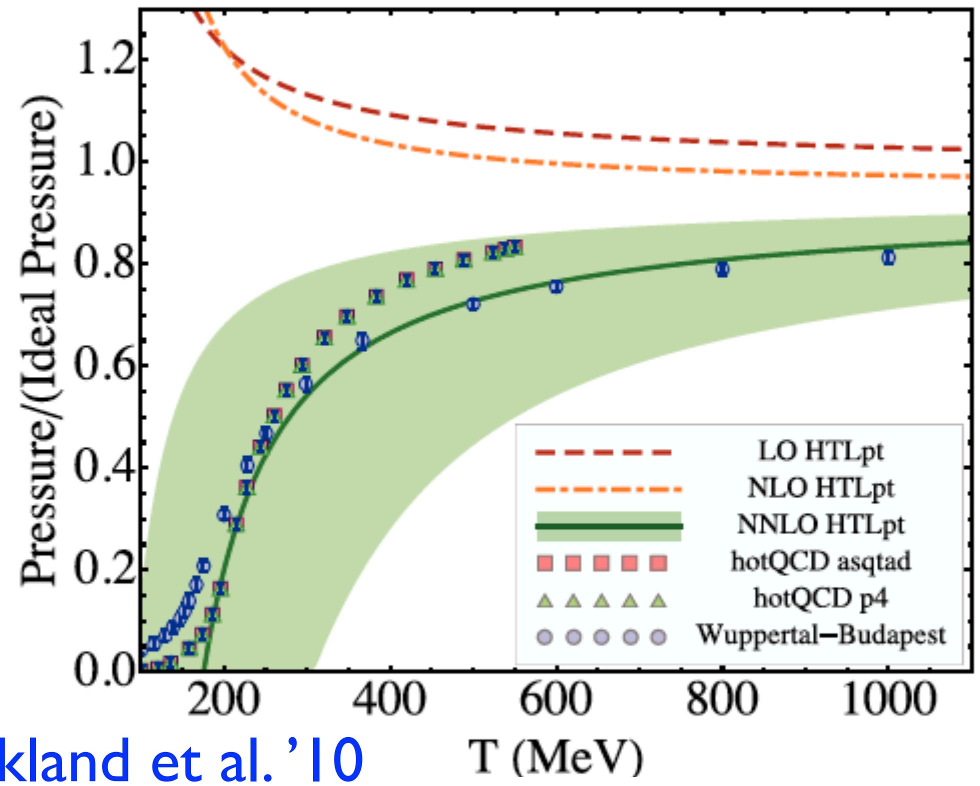
$$P = T\frac{\partial \ln Z}{\partial V}\,, \quad S = \frac{\partial (T\ln Z)}{\partial T}\,, \quad N_i = T\frac{\partial \ln Z}{\partial \mu_i} \qquad \langle \mathcal{O}\rangle = \frac{\mathrm{Tr}\mathcal{O}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}{\mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}$$

- With a rotation to Euclidean space -it→1/T and imposing (anti)periodic boundary conditions for (fermions) bosons,

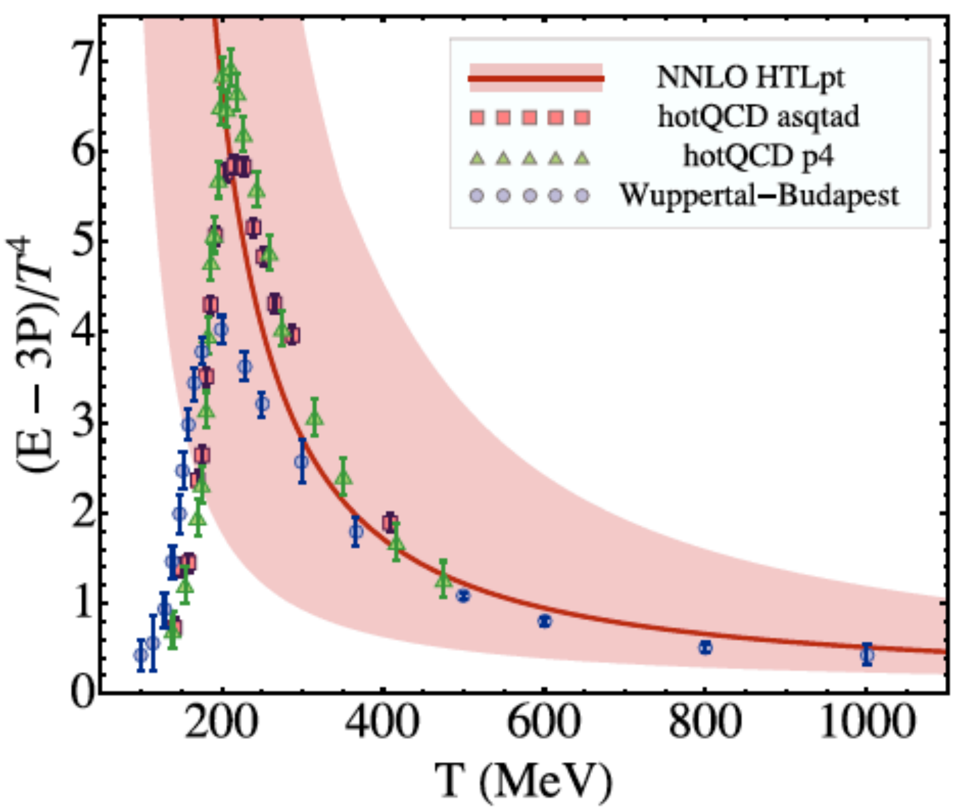
$$Z(T,V,\mu) = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A^\mu \exp\{-\int_0^{1/T} dx_0 \int_V d^3x(\mathcal{L}_E - \mu\mathcal{N})\}$$

- The partition function may be computed perturbatively, or by discretization and Monte Carlo methods: lattice QCD.

pQCD at finite T:



Strickland et al. '10



- Very slow convergence until T>>T_c; problems close to T_c. At LO:

$$\mu^2 = 4\pi\alpha_s T^2$$

$$\rho_g = \frac{16}{\pi^2}\zeta(3)T^3$$

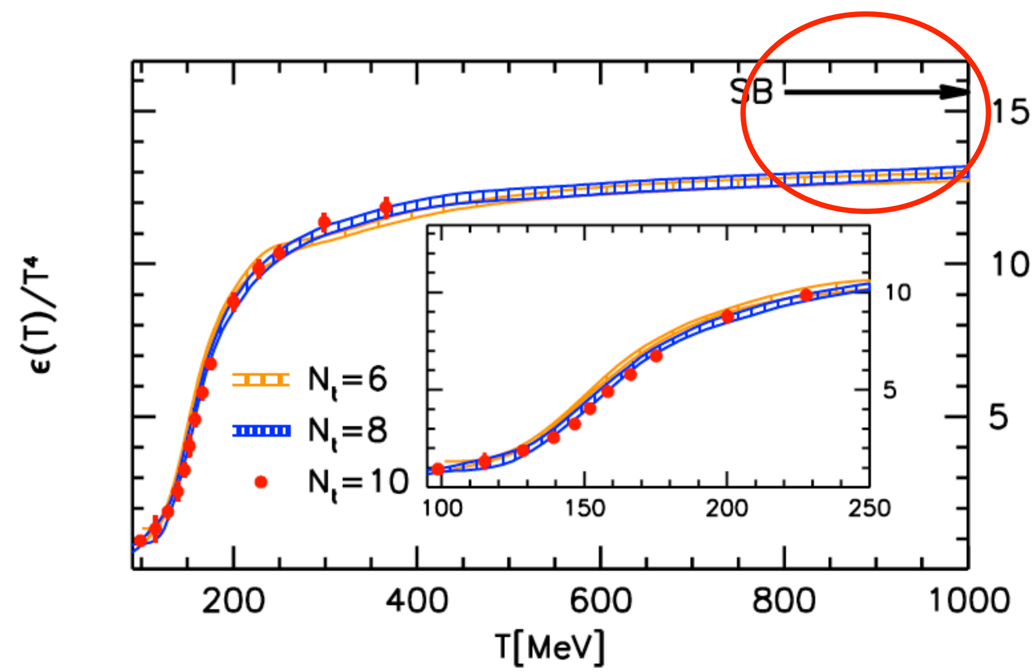
$$\sigma_T^{gg} \simeq \frac{N_c}{C_F}\frac{2\pi\alpha_s^2}{\mu^2}\ln(1/\alpha_s)$$

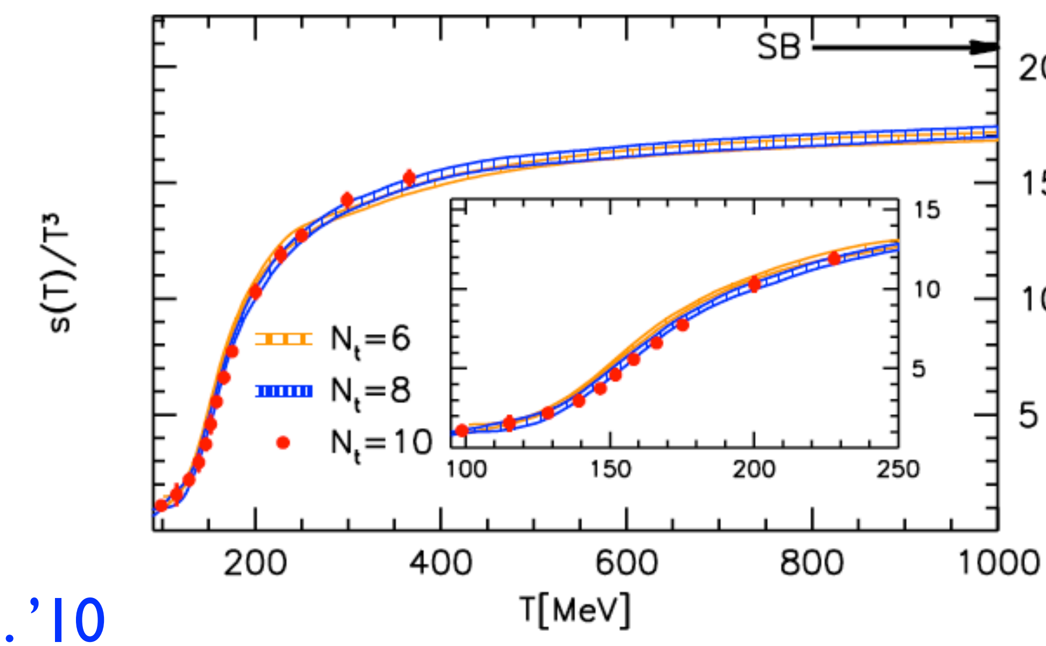
$$1/\lambda_g = \rho_g\sigma_T^{gg} \simeq \frac{18}{\pi^2}\zeta(3)\alpha_s T$$

- Thermal masses for q and g, m∝gT.

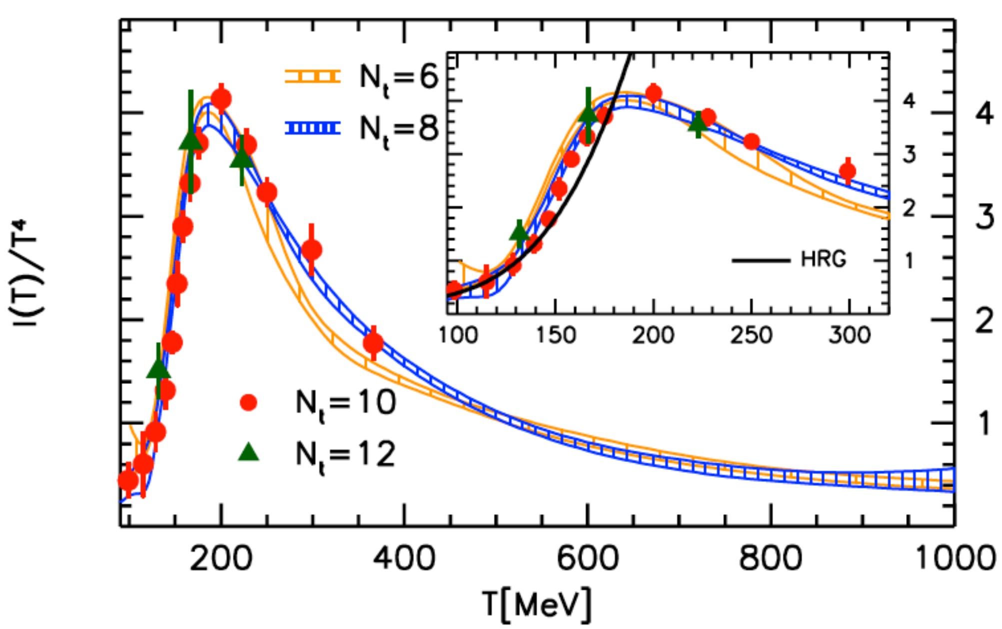
Lattice QCD (I):

$$\epsilon_{\rm HG} = \frac{\pi^2}{30}\, 3\, T^4 \simeq T^4 \qquad \epsilon_{\rm QGP} = \frac{\pi^2}{30}\left[2\times 8 + \frac{7}{8}\times 2(3)\times 2\times 2\times 3\right] T^4 = \frac{\pi^2}{30}\left[16 + 21(31.5)\right] T^4$$

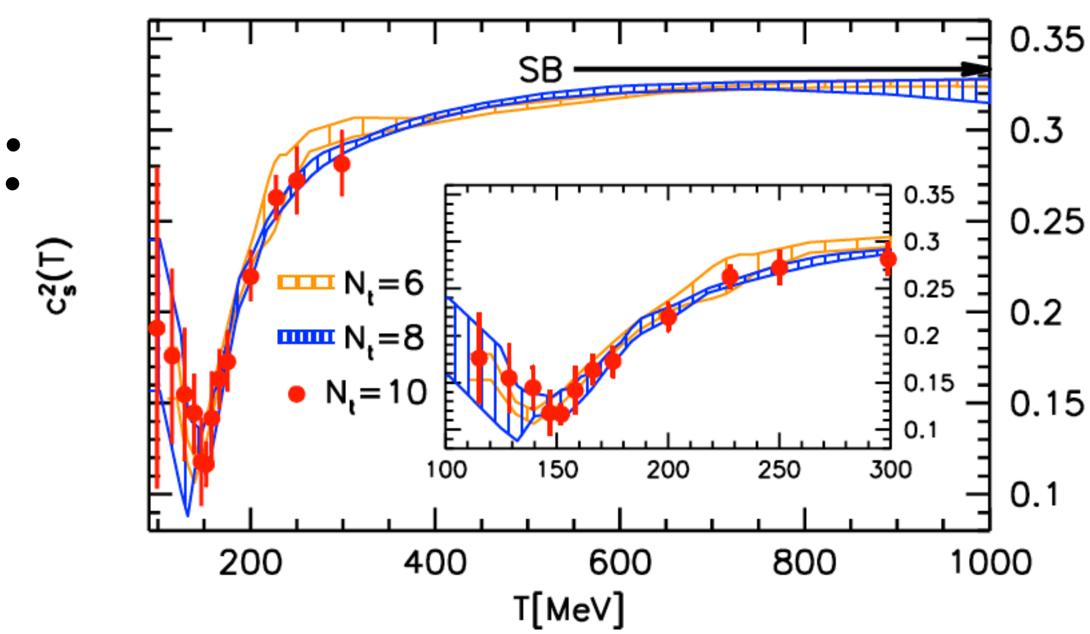




Borsanyi et al. '10



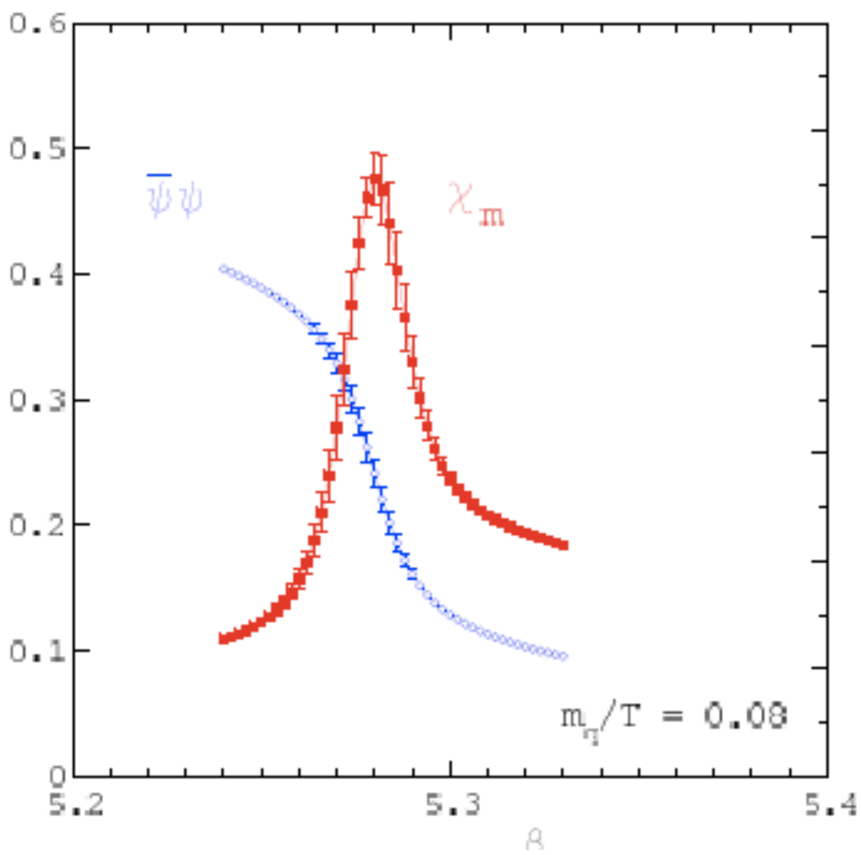
Ideal gas:
$\varepsilon=3P$,
$c_s^2=1/3$.

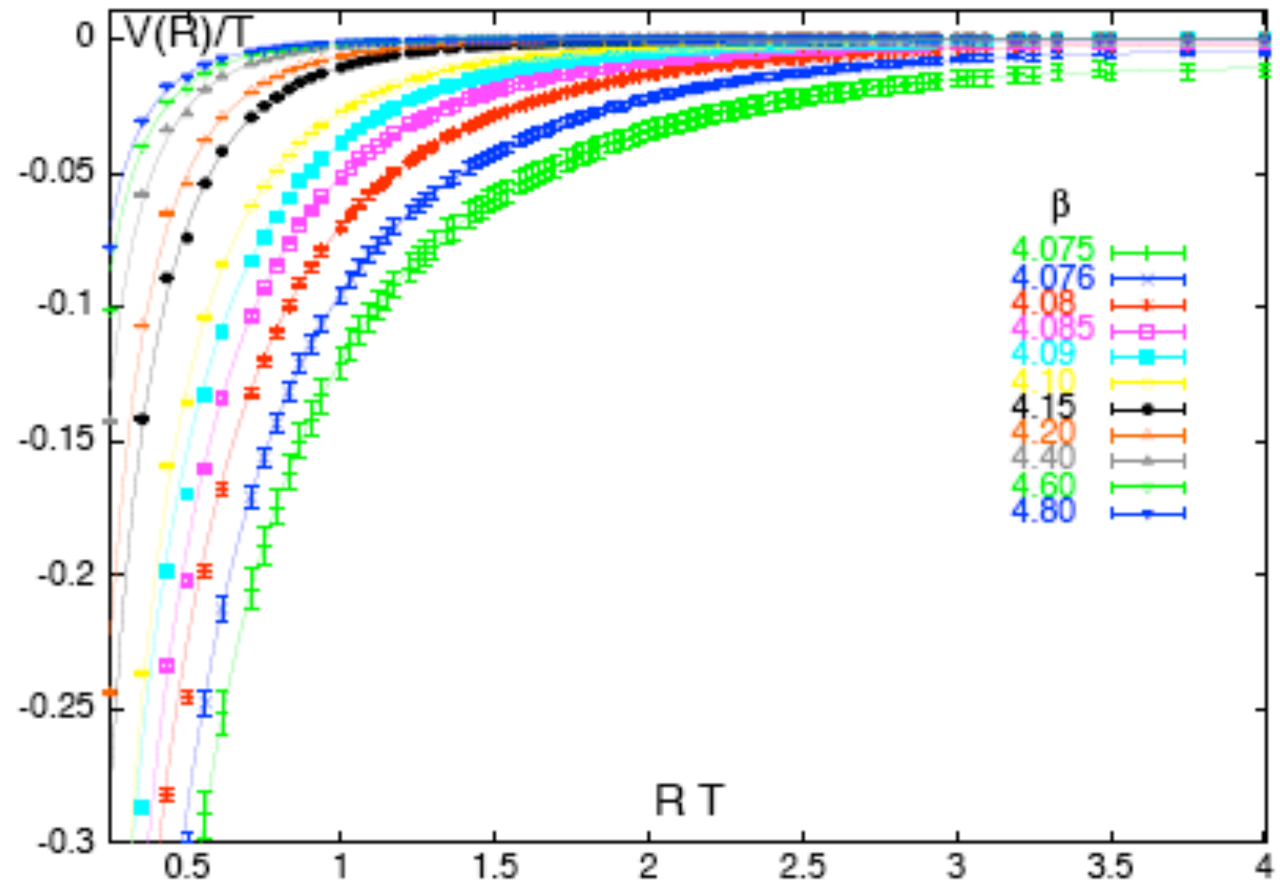


Until very recently, simulations for $\mu=0$.

Lattice QCD (II):

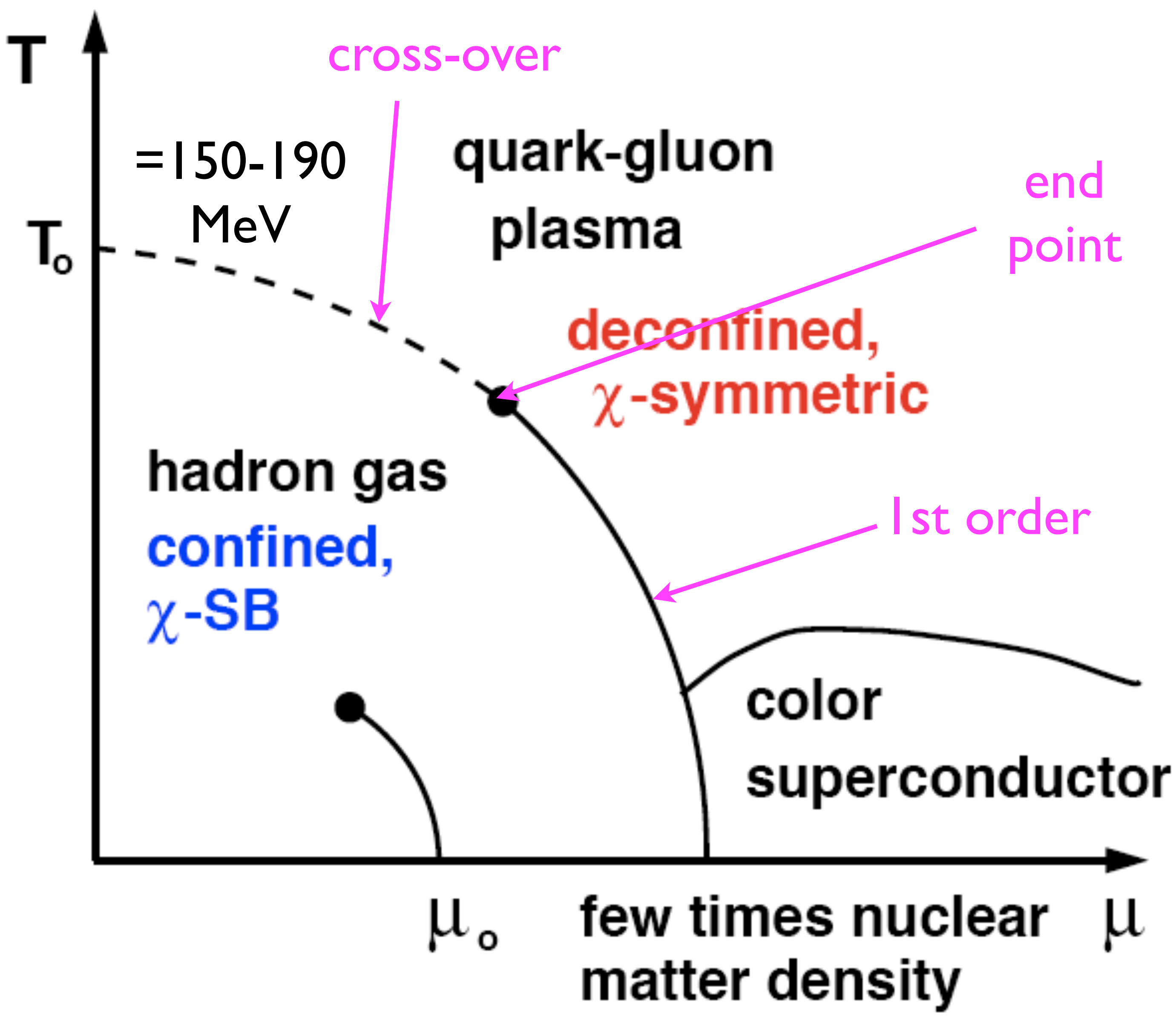
$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \xrightarrow[T\to\infty]{} \langle 0|\bar{q}_L q_R|0\rangle = 0$$





Temperatures for deconfinement and χSB approximately equal, T_c=150-190 MeV.

Phase diagram:



Plasma Effects

Debye screening

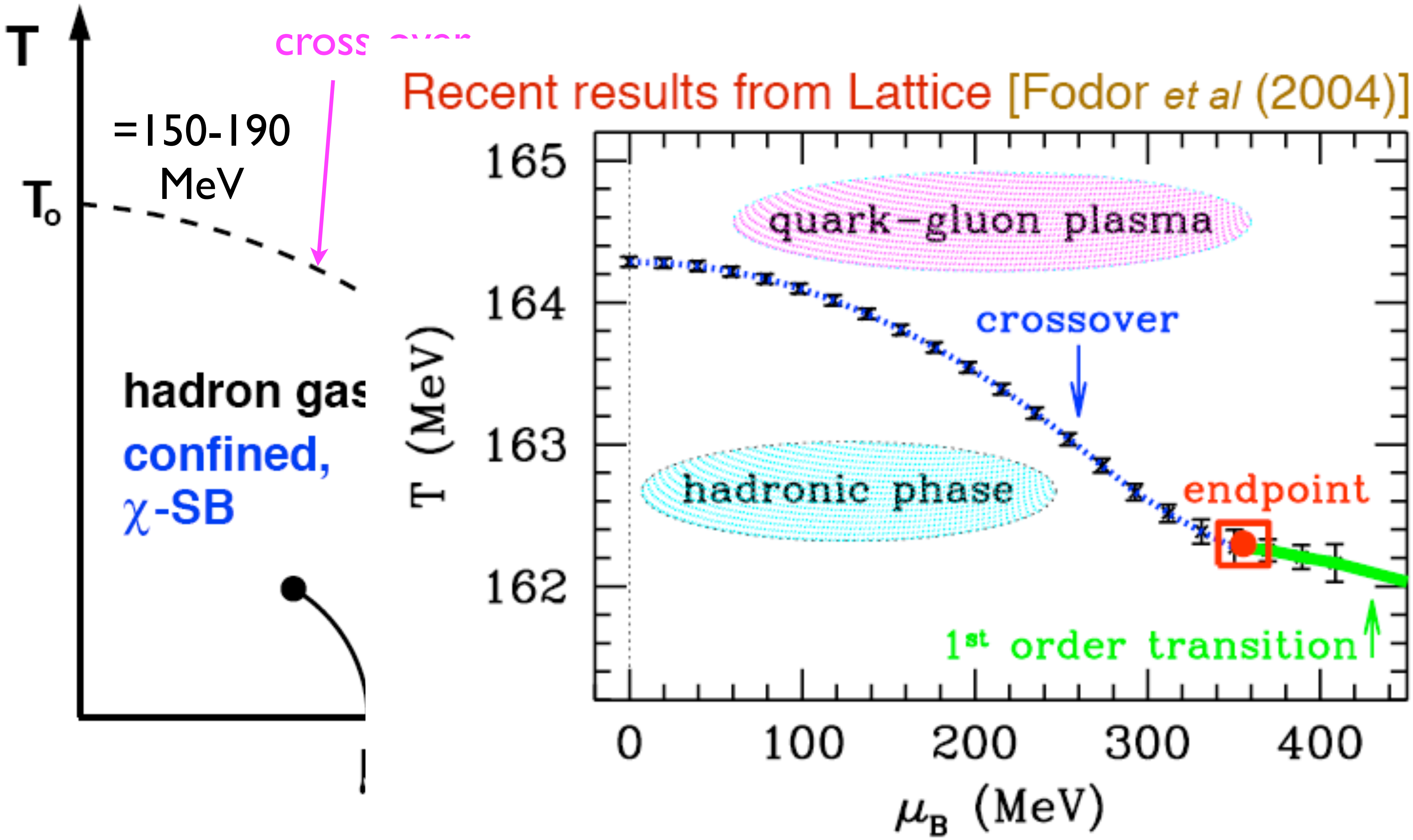
$$V(r) = -\frac{e}{r} e^{-m_D r}$$

$$m_D^2 = \frac{4\pi e^2 n}{kT}$$

Plasma oscillations

$$\omega_{pl} = \frac{4\pi e^2 n}{m}$$

Phase diagram:



Effects

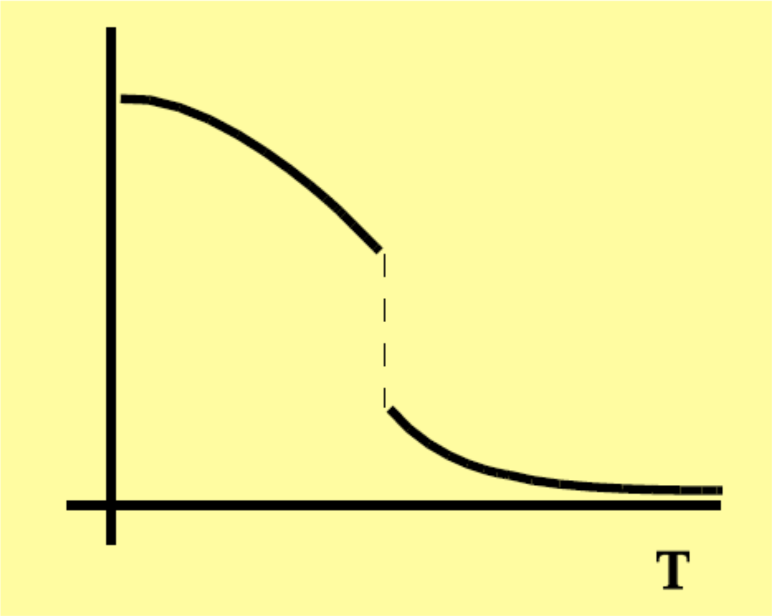
$$(r) = -\frac{e}{r}e^{-m_D r}$$

$$m_D^2 = \frac{4\pi e^2 n}{kT}$$

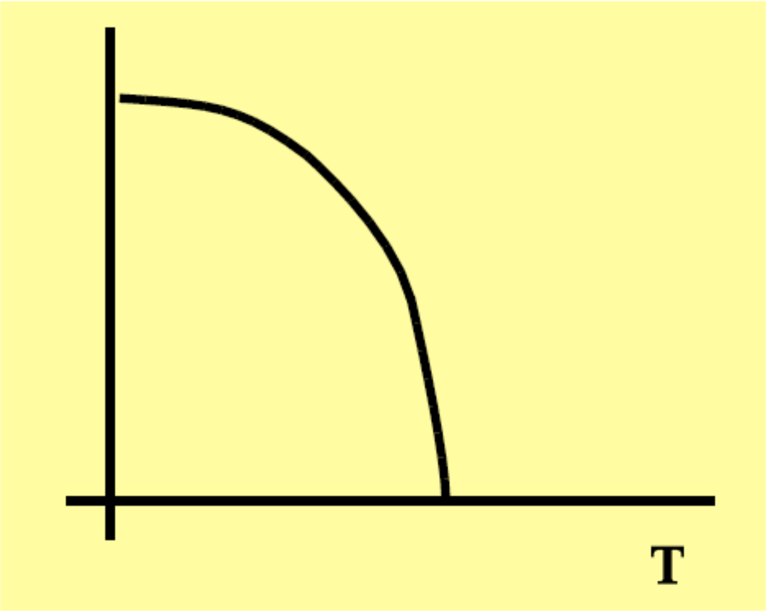
s

$$\frac{\pi e^2 n}{m}$$

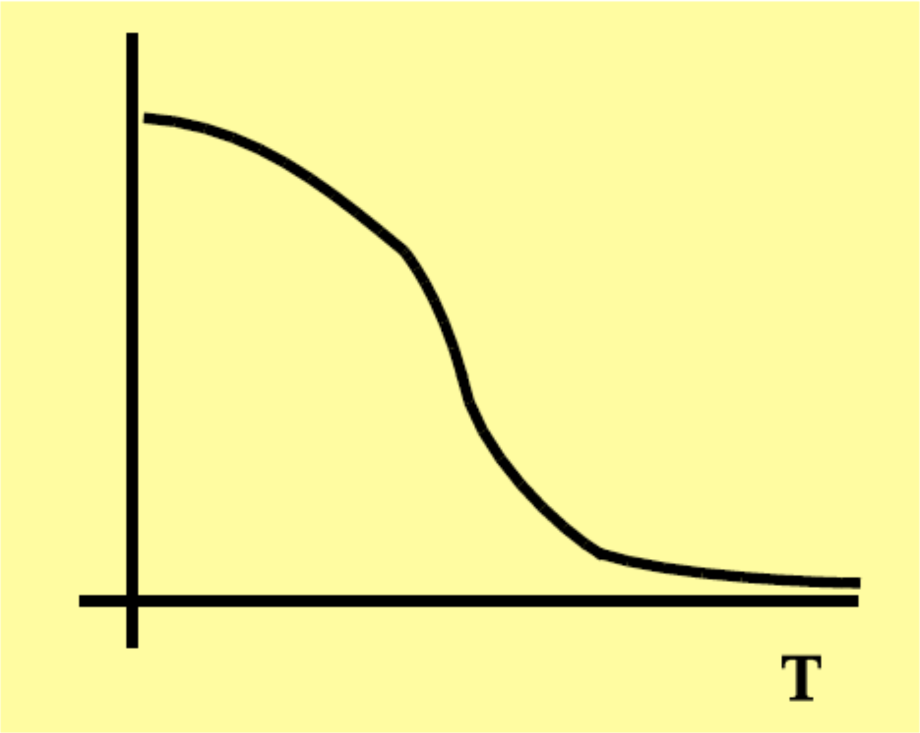
Order of the transition:



First order: discontinuity in the order parameter.

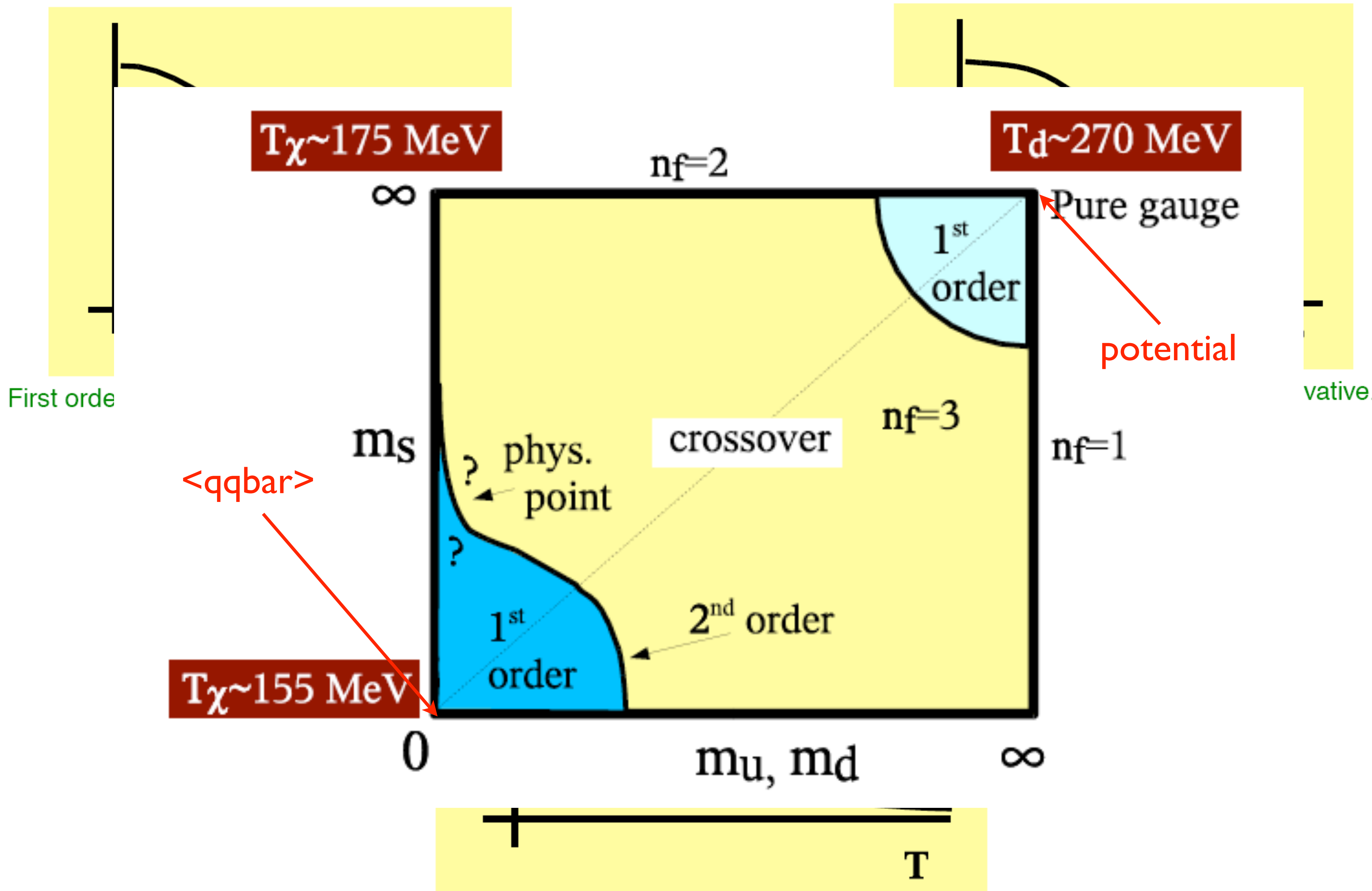


Second order: discontinuity in the derivative.



Crossover: Continuous function.

Order of the transition:



Crossover: Continuous function.

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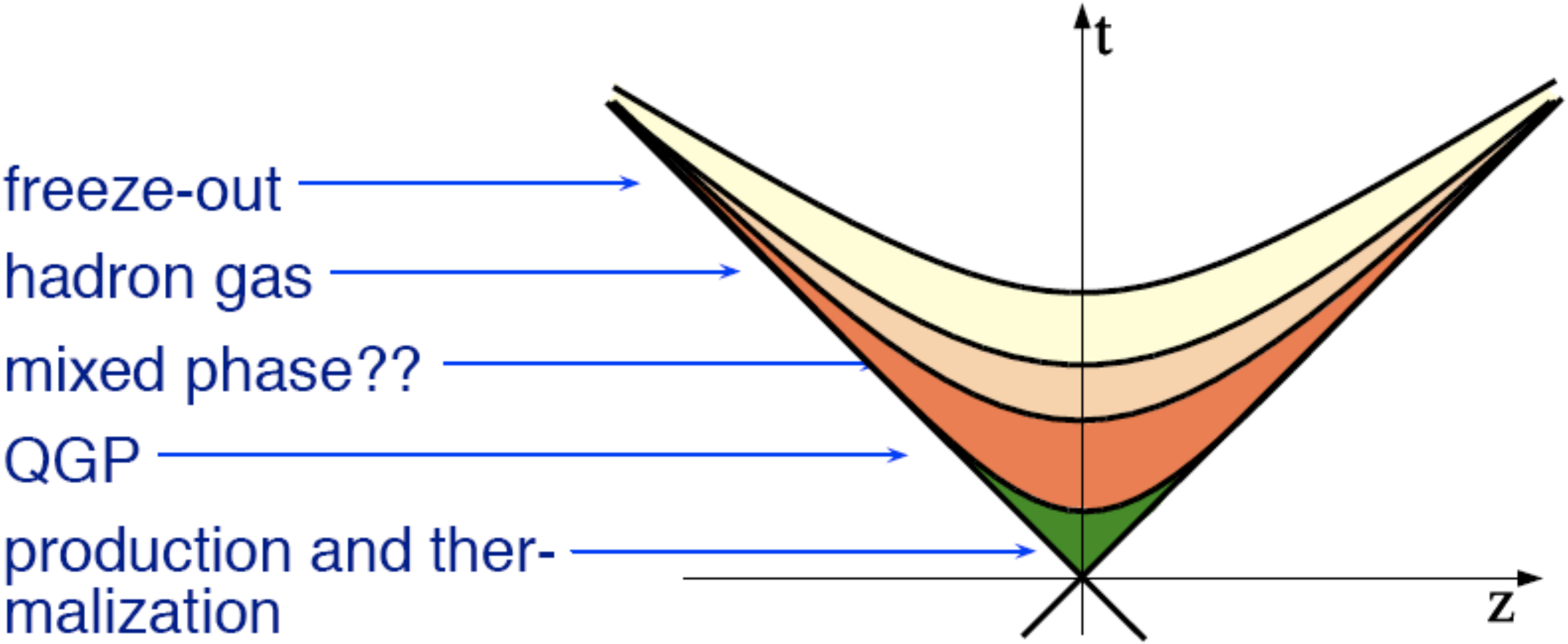
Stages of a HIC:



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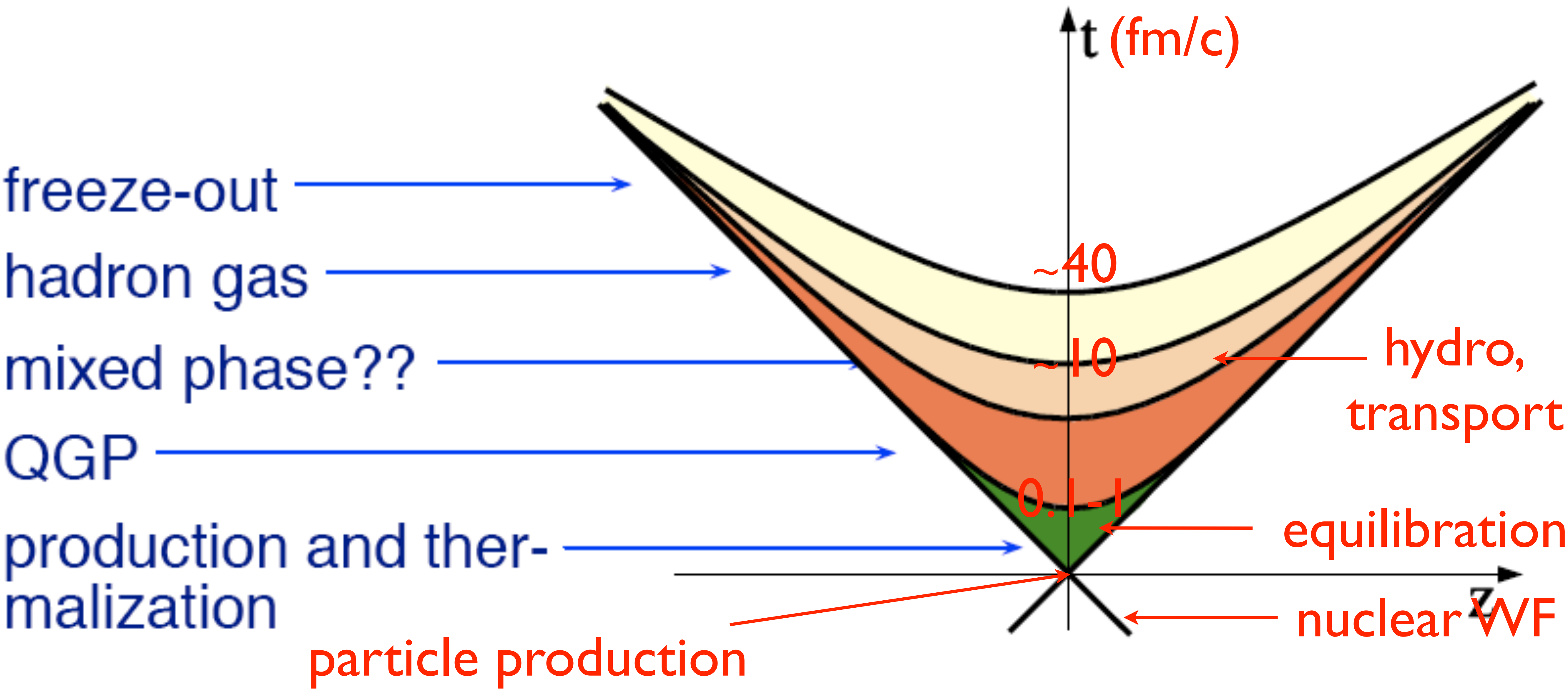
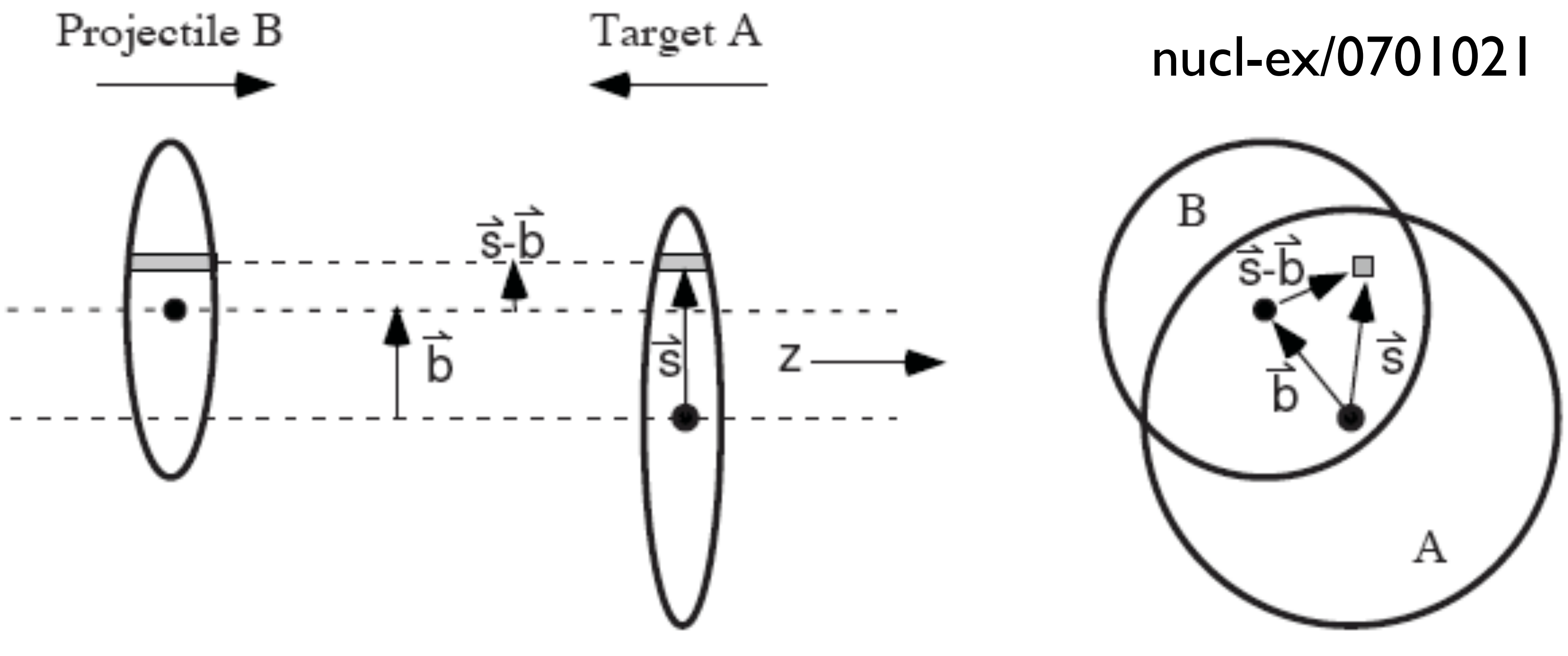


Glauber model (I):

- The Glauber model provides the number of nucleons involved in the collision and how many times they collide one each other.
- It results in a probabilistic interpretation but is a QFT result, based on the factorization of the nuclear scattering amplitudes.



a) Side View b) Beam-line View

$$T_A(\vec{s}) = \int_{-\infty}^{+\infty} dz\, \rho_A(\vec{s}, z)$$

$$T_{AB}(\vec{b}) = \int d\vec{s}\, T_A(\vec{s}) T_B(\vec{b} - \vec{s})$$

$$\int d\vec{b}\, T_{A(B)}(\vec{b}) = 1$$

$$\sigma_{in}^{pA(AB)}(b) = 1 - \left[1 - \sigma T_{A(B)}(b)\right]^{A(B)}$$

$$= \sum_{n=1}^{A(B)} C_n^{A(B)} \left[\sigma T_{A(B)}(b)\right]^n \left[1 - \sigma T_{A(B)}(b)\right]^{A(B)-n}$$

Glauber model (II):

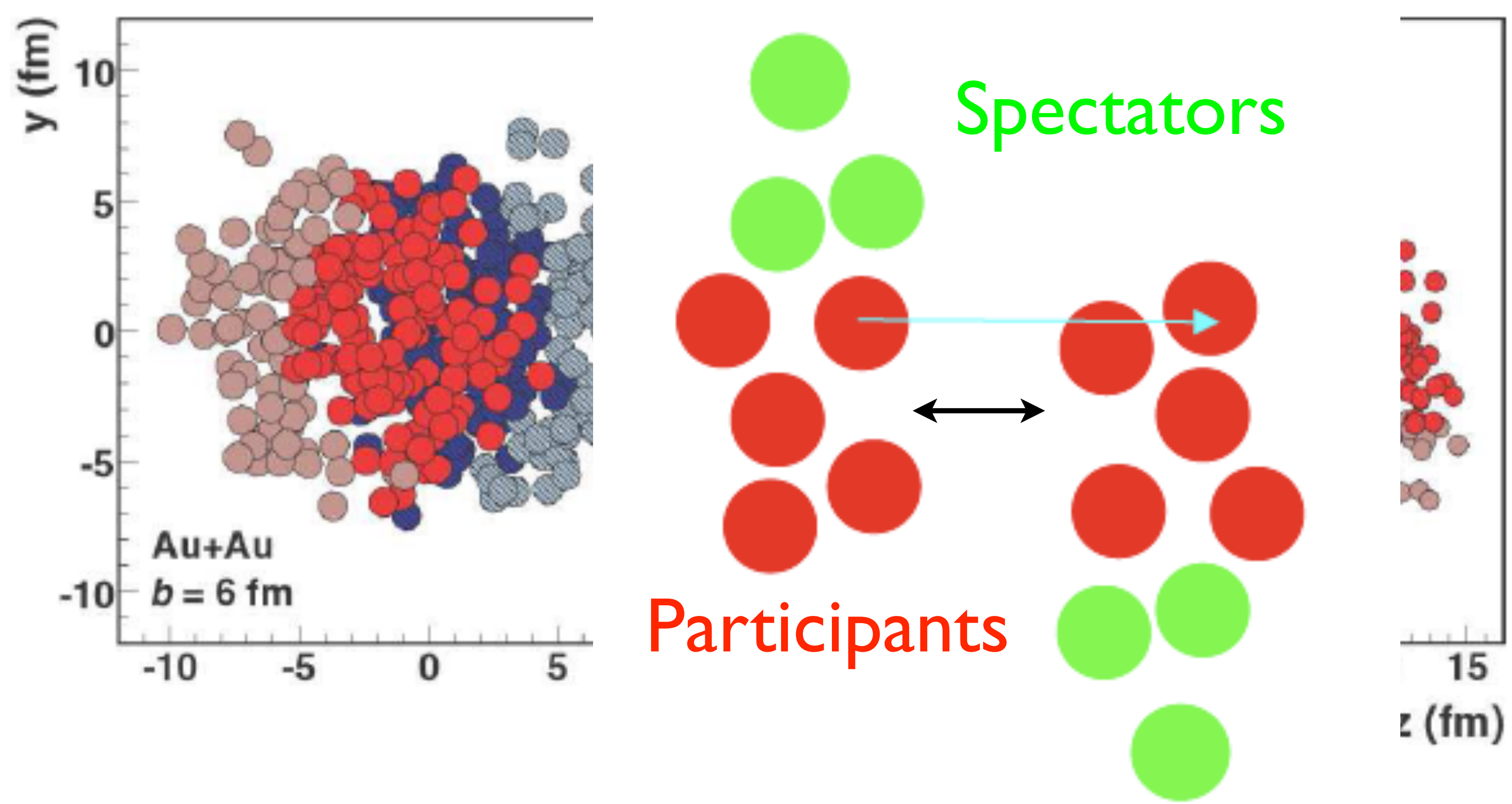
- The number of binary NN collisions and of participants **(P3)**:

$$\langle N_{coll}(b)\rangle \sigma_{in}^{pA(AB)}(b) = A(B)\sigma T_{A(B)}(b), \quad \langle N_{coll}\rangle = \frac{A(B)\sigma}{\sigma_{in}^{pA(AB)}} \propto \frac{A(B)}{A^{2/3}(+B^{2/3})}$$

$$P(n,m,\vec{b},\vec{s}) = \frac{1}{\sigma} C_n^A \left[\sigma T_A(s)\right]^n \left[1-\sigma T_A(s)\right]^{A-n} C_m^B \left[\sigma T_B(\vec{b}-\vec{s})\right]^n \left[1-\sigma T_B(\vec{b}-\vec{s})\right]^{B-m}$$

$$\langle N_A(\vec{b},\vec{s})\rangle = \sum_{n=1}^{A} n \sum_{m=1}^{B} P(n,m,\vec{b},\vec{s}) = A T_A(s)\sigma_{in}^{pB}(\vec{b}-\vec{s}), \quad \langle N_A\rangle \propto \frac{AB^{2/3}}{A^{2/3}+B^{2/3}}$$

- In practice one goes beyond simplified (optical) expressions for AB and does MC.



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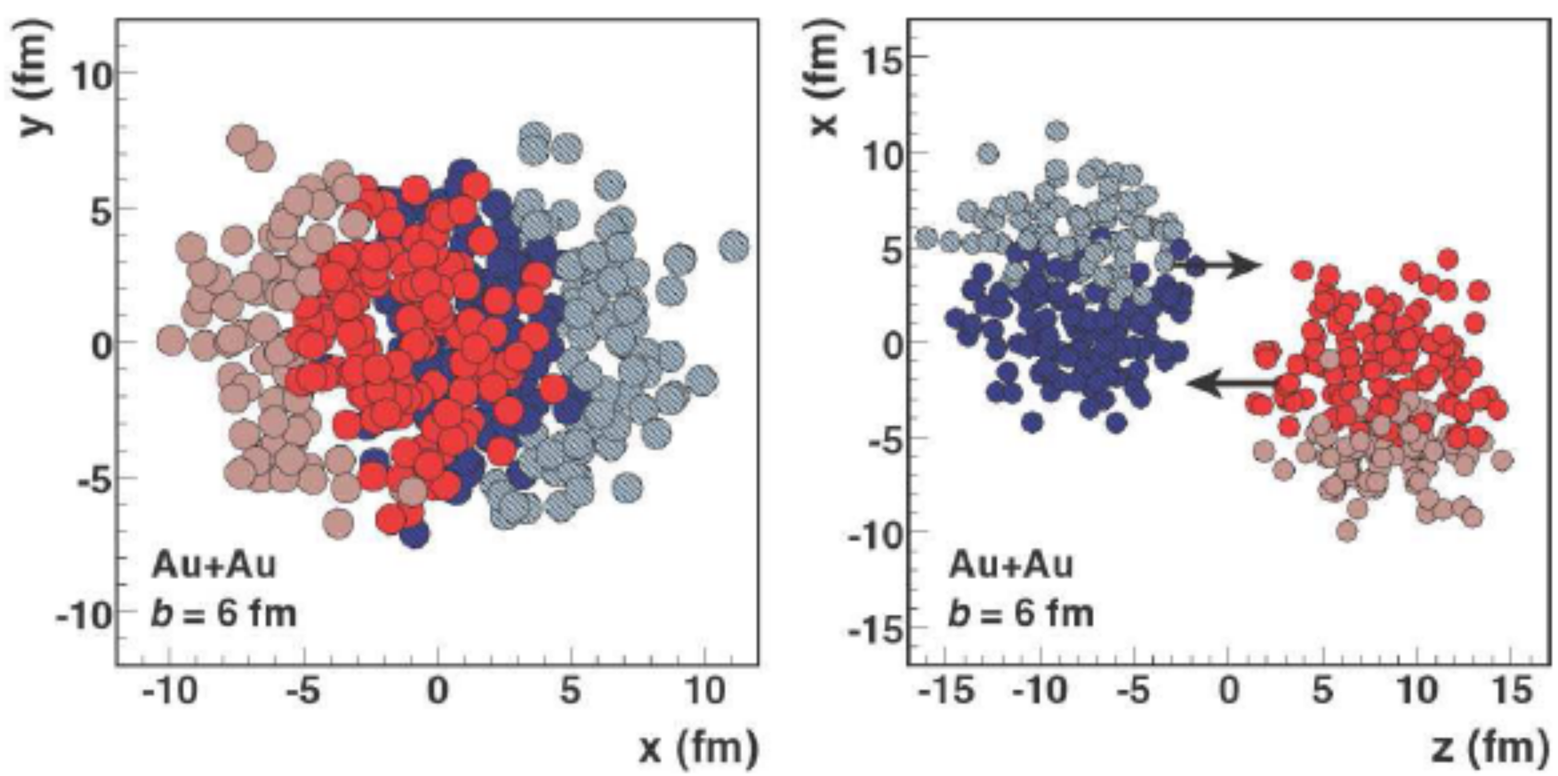


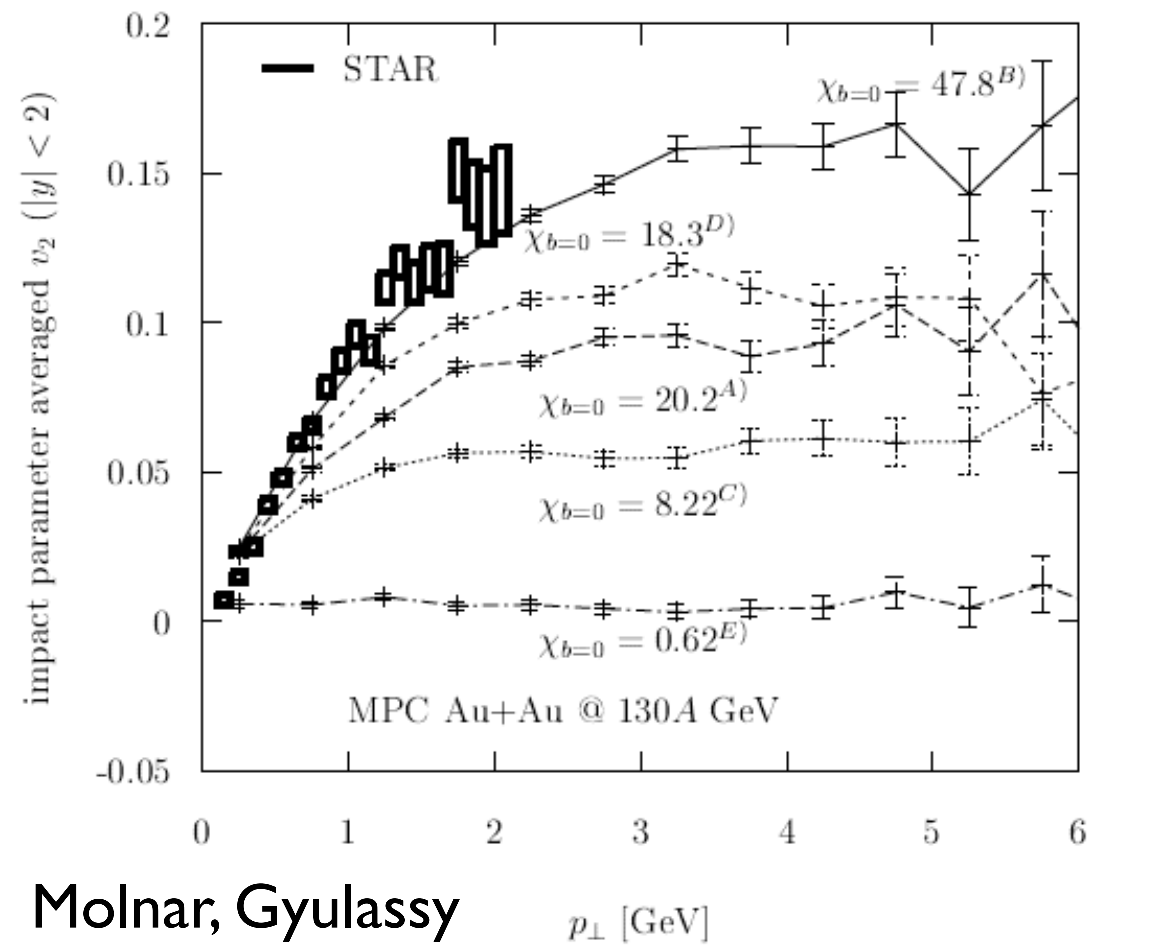
Equilibration:

- Data on collective flow are well reproduced by ideal hydro if it is initialized very early, $\tau_0 < 1$ fm/c.

- (Ideal) hydro requires $\lambda=(\rho\sigma)^{-1} << R$: large opacities for the particles, equilibrium/isotropization.

- Parton transport is only able to reproduce collective flow if opacities are very large, non-perturbative.

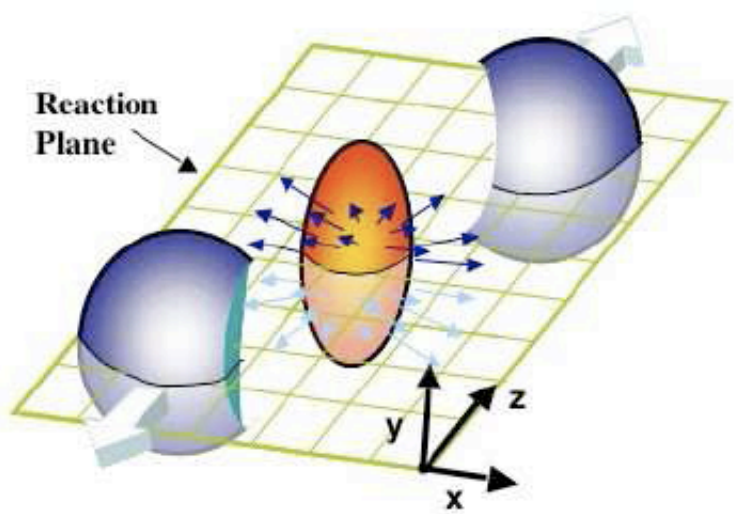
- If the system is initially anisotropic, instabilities appear that accelerate isotropization.

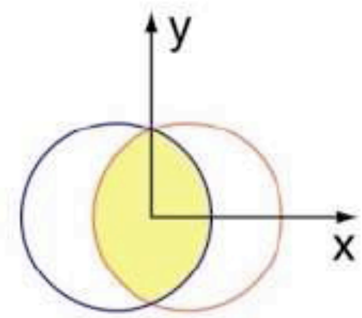


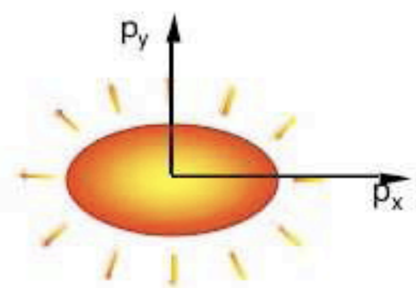
Molnar, Gyulassy

- Alternatively, non-perturbative mechanisms may be at work: strong coupling.

Hydrodynamics (I):





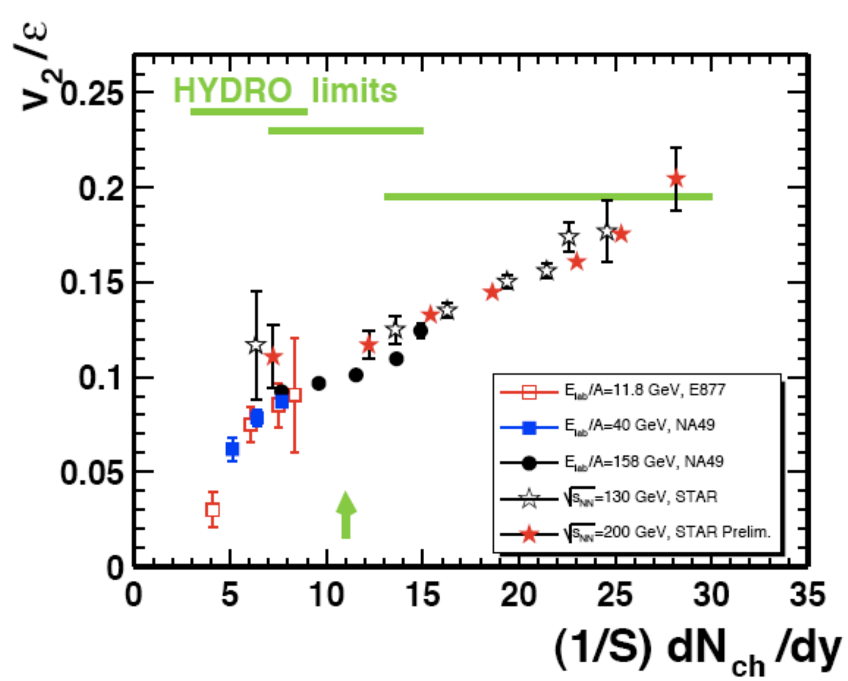


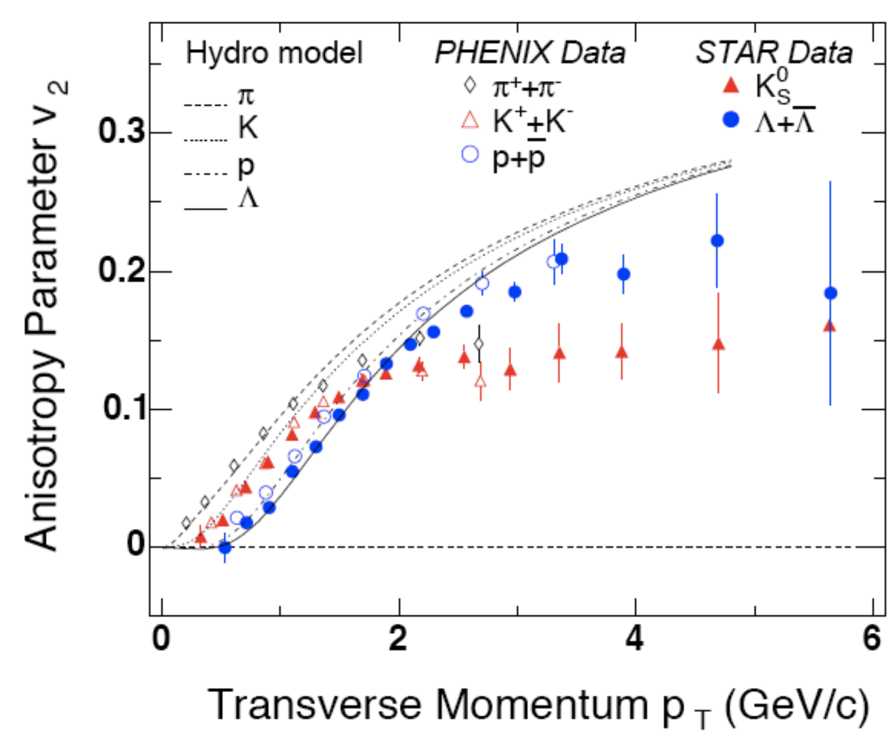
$$\frac{dN_k}{dy dp_T^2 d\phi} = \frac{dN_k}{dy dp_T^2}\frac{1}{2\pi}\left[1 + 2v_1 \cos(\phi - \phi_R) + 2v_2 \cos 2(\phi - \phi_R) + \ldots\right]$$

$$v_2 = \langle \cos 2(\phi - \phi_R) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

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

- v_2, also called elliptic flow, is usually interpreted in terms of a final momentum anisotropy dictated by an initial space anisotropy.





Hydrodynamics (II):

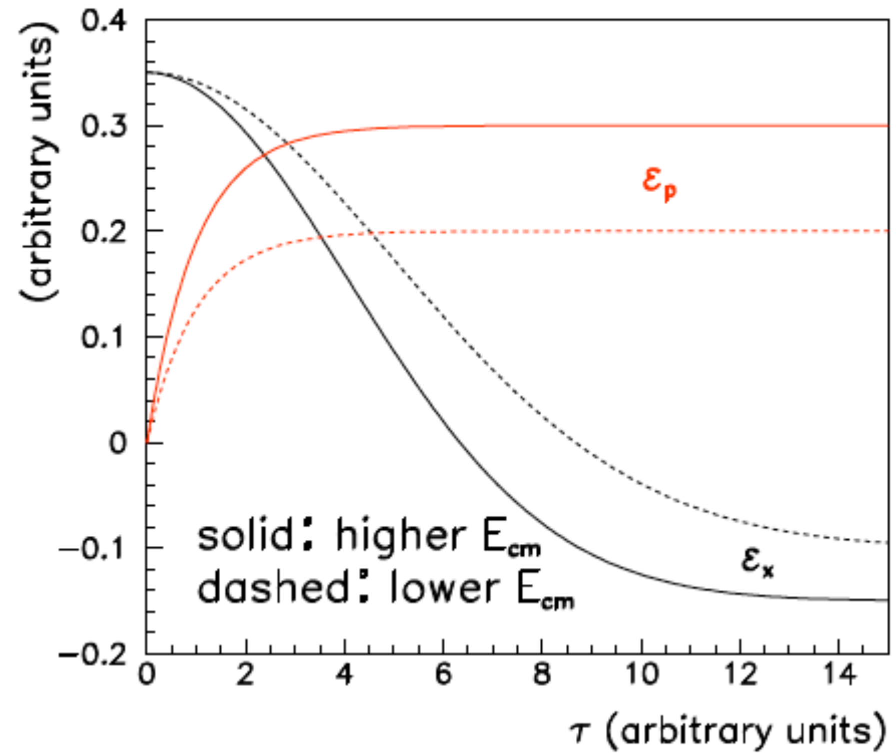
• Ideal hydro: EOS (5+M variables, 4+M equations), initial conditions and hadronization prescription:

$$u^\mu = \gamma\,(1, v_x, v_y, v_z)$$

$$T^{\mu\nu}_{(0)}(x) = \Big(e(x) + p(x)\Big) u^\mu(x) u^\nu(x) - p(x)\, g^{\mu\nu}$$

$$\partial_\mu\, T^{\mu\nu}_{(0)}(x) = 0\,, \qquad (\nu = 0, \ldots, 3)$$

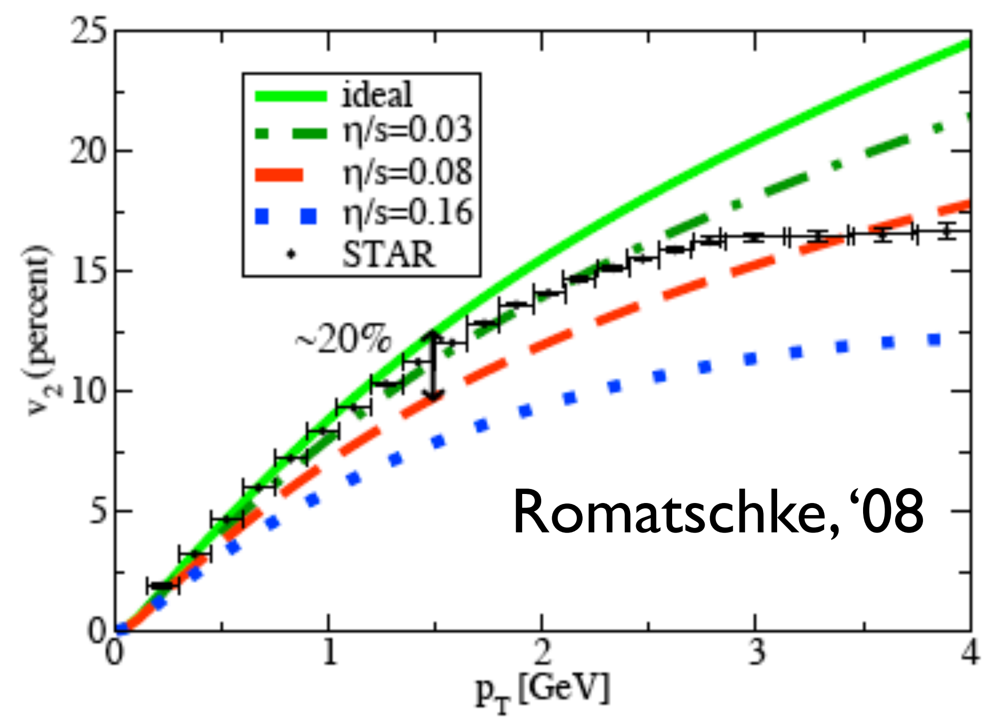
$$\partial_\mu j_i^\mu(x) = 0, \qquad i = 1, \ldots, M$$



• Non-ideal hydro: dissipative (viscous) corrections.

$$T^{\mu\nu} = T^{\mu\nu}_{(0)} + \Pi^{\mu\nu}$$

• $\Pi^{\mu\nu}$ introduces bulk viscosity plus gradients of u: 1st order (shear viscosity), 2nd order (5 constants for a CFT),...



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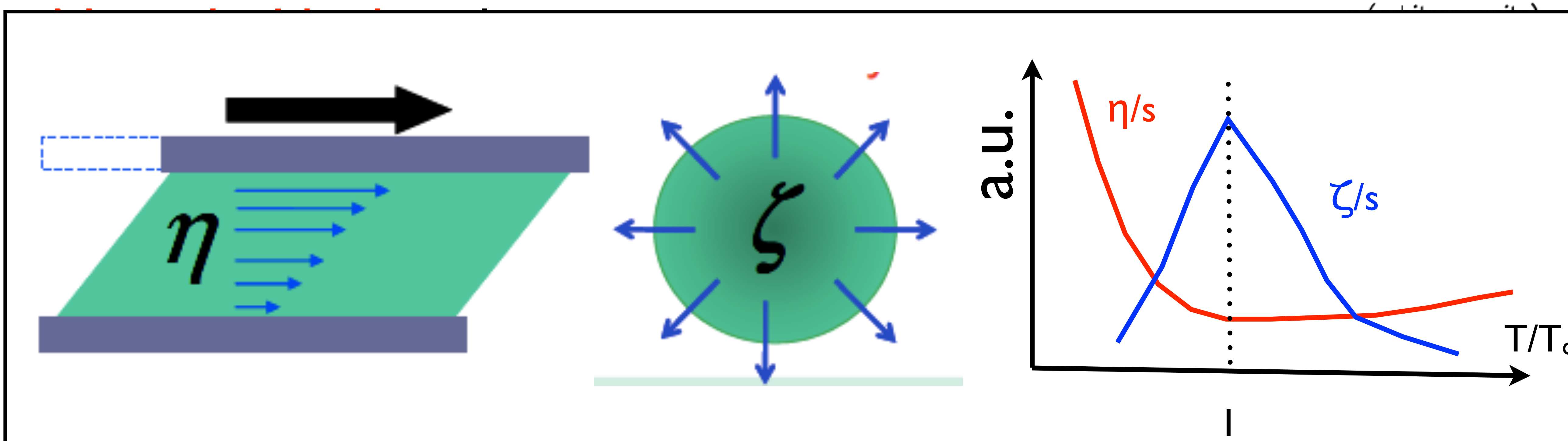
$T^{\mu\nu}_{(0)}(x) = \Big(e$

$\partial_\mu\, T^{\mu\nu}_{(0)}(x) =$

$\partial_\mu j^\mu_i(x) = 0,$

- Ideal (0th order): relativistic Euler equation.
- 1st order: relativistic Navier-Stokes.
- 2nd order: Müller-Israel-Stewart.
- η/s=1/(4π) and ζ=0 in CFT.
- η/s=0.1-1 in pure glue lattice QCD.
- ζ has a peak around T_c in QCD.



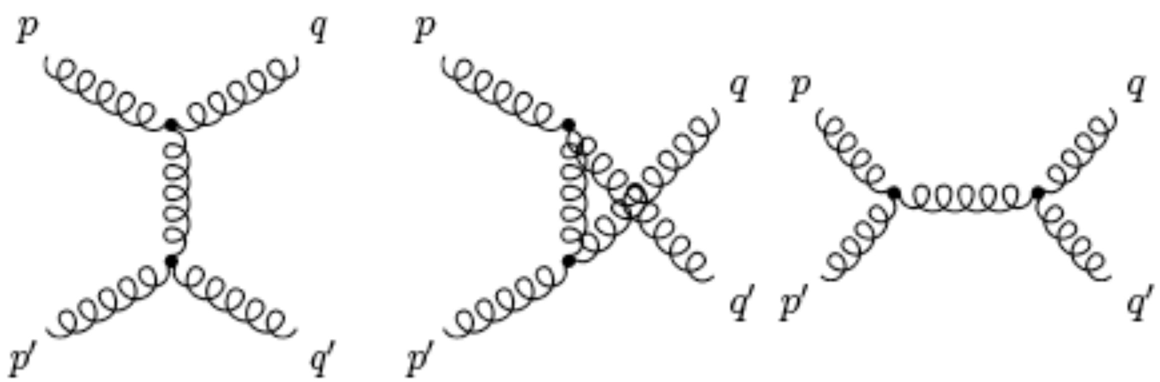
constants for a CFT),...

Transport models:

• Ideal hydro is the extreme version of transport for very large opacities. If thermalization/isotropization is not achieved, small deviations can be dealt with through viscous corrections, but large deviations require transport: relativistic Boltzmann equation.

$$f(\vec{p}, t, \vec{x}) \propto \frac{dN}{d^3p\, d^3x} \qquad p^\mu \partial_\mu f = -\mathcal{C}[f]$$

Collision term $C[f_p] = C_{gain} - C_{loss}$



• Parton transport now includes 2↔2 and 2↔3 reactions (BAMPS):

accelerates isotropization.

• Hadron transport includes many reactions/species (AMPT, UrQMD).

Freeze-out:

- The results from hydro (or a parton cascade) have to be projected onto hadrons.

- For hydro: decoupling using the Cooper-Fry formula for an isothermal freeze-out surface Σ (T_{dec}) $\Rightarrow$ $\lambda=0\rightarrow\infty$ instantaneously.

$$E\frac{dN}{d^3p} = \int_\Sigma f(x,p,t)p\cdot d\sigma(x) \xrightarrow{\text{viscous}} f(p^\mu, x^\mu) = f_{\rm eq}\left(\frac{p^\mu u_\mu}{T}\right)\left[1+\frac{1}{2a_{42}}p^\alpha p^\beta \pi_{\alpha\beta}\right]$$

$$= \frac{d}{(2\pi)^3}\int_\Sigma \frac{p\cdot d\sigma(x)}{\exp\left[(p\cdot u(x)-\mu(x))/T(x)\right]\pm 1}$$

- Other prescriptions exist (e.g. isochronous).

- You can use hydro for the hadron phase.

- Or you can also link to a hadron cascade: done for parton cascades (AMPT, UrQMD).

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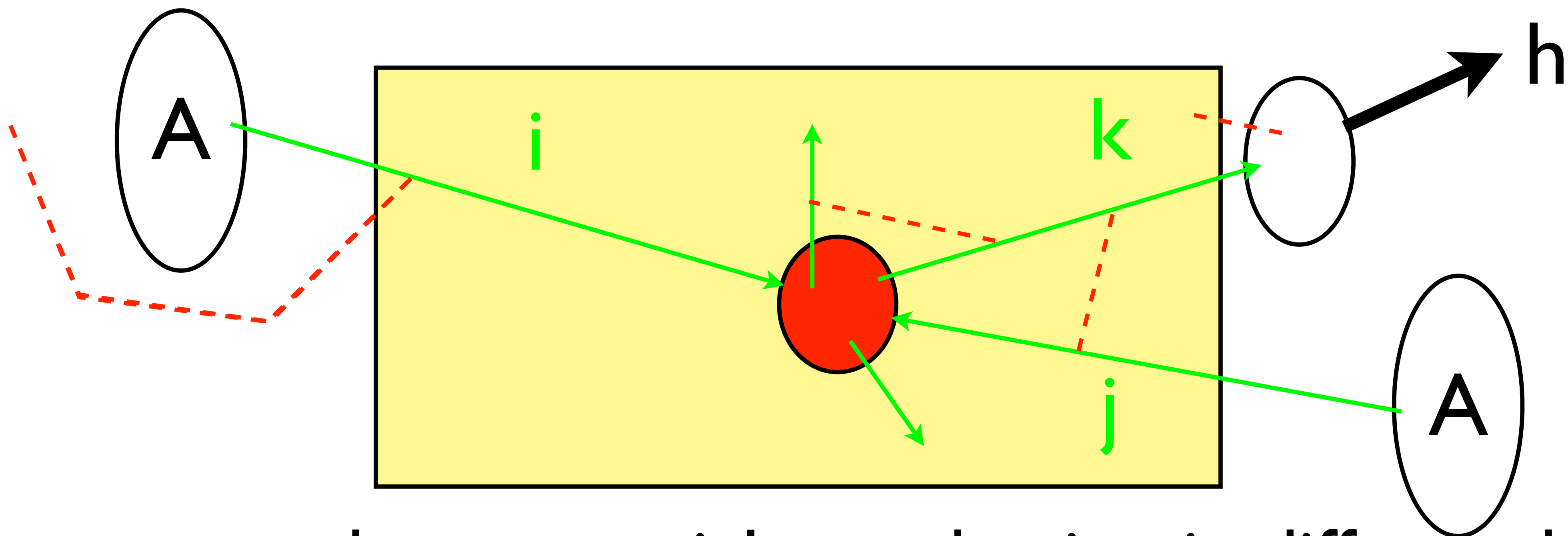
Different scales:



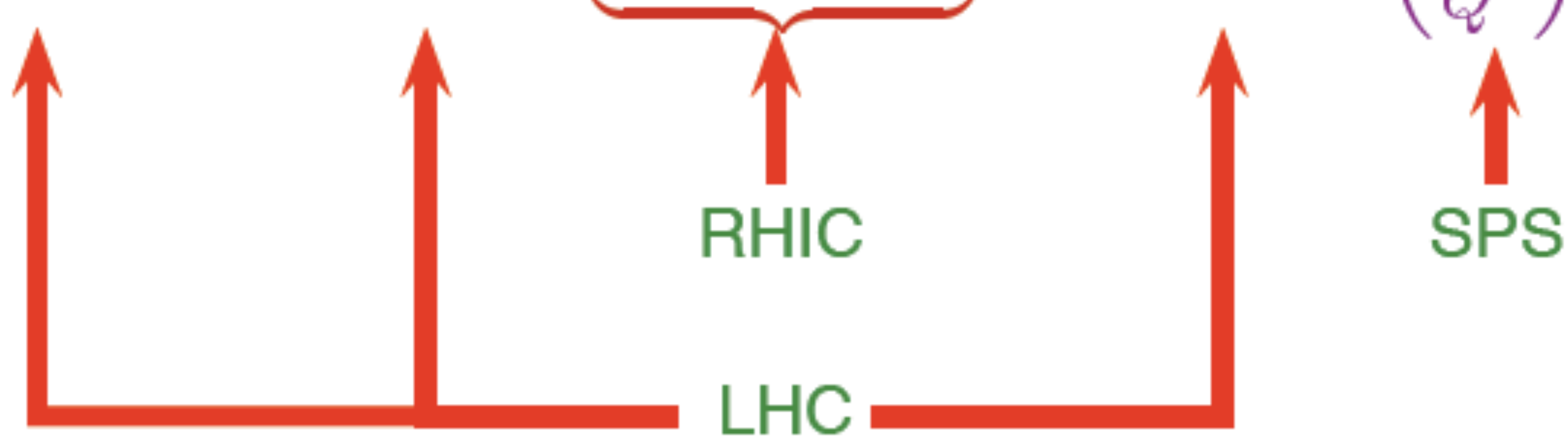
• Different approaches to particle production in different kinematical regions, comparing the typical soft parton momenta (Λ_{QCD}, T) with the momenta of the observable (Q) and the total energy $\sqrt{s}=E_{cm}$.

• The ideal case relies on factorization theorems: universal pieces associated with initial hadrons and final observables, and others hadron-independent (and computable in pQCD). Initial (with the other constituents of the initial hadrons) and final (with other produced hadrons/observables/medium) state interactions break it.

Hard scales: collinear

- Collinear factorization used in the region $E_{cm} \sim Q \gg \Lambda_{QCD}, T$.

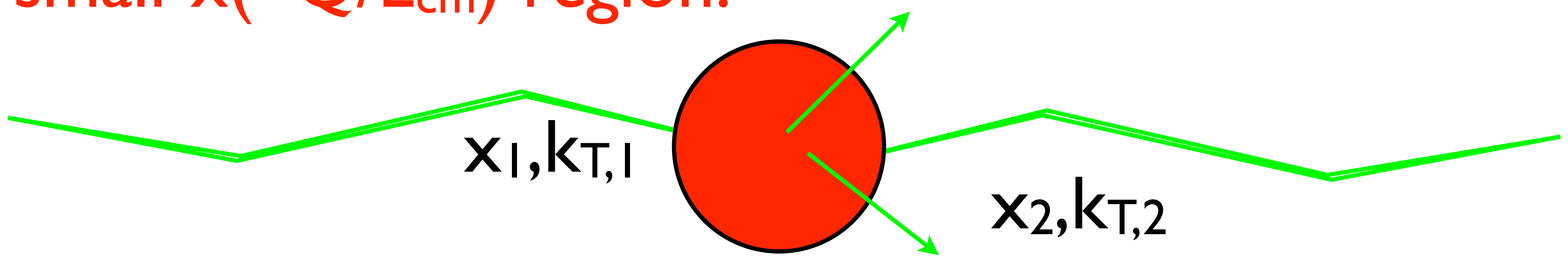
$$\sigma^{pp\to h} = f_p(x_1,Q^2) \otimes f_p(x_2,Q^2) \otimes \underbrace{\sigma(x_1,x_2,Q^2)} \otimes D(z,Q^2) + \left(\frac{1}{Q^2}\right)^n$$



- Parton densities (pdf's) and fragmentation functions unknown but its evolution given by DGLAP in the dilute (e.g. pp) case.
- Power corrections are process-dependent and enhanced by nuclear size.
- No proof of DGLAP in the dense (AB) case: looks plausible for pdf's, fragmentation functions?
- Ex.: jets (collinear and IR safe), high-mass DY, highly energetic hadrons/γ, EW bosons.

Semihard scales: k_T

- k_T factorization used in the region $E_{cm} >> Q >> \Lambda_{QCD}, T$. Note that this is the small-x($\sim Q/E_{cm}$) region.



$$\sigma^{pp\to g} = \phi_A(x_1, k_{T,1}) \otimes \phi_B(x_2, k_{T,2}) \otimes \hat{\sigma}(x_1, k_{T,1}, x_2, k_{T,2}, \mu)$$

- Unintegrated parton densities (updf's) unknown but its evolution given by BFKL in the dilute (e.g. pp) case; fragmentation functions?
- All power corrections included.
- Colliding partons no longer collinear: intrinsic k_T.
- Ex.: particle production in the region of a few GeV.
- It works for gluon production in pp (BFKL) and pA (BK evolution), not for quark production or in AB → more involved.

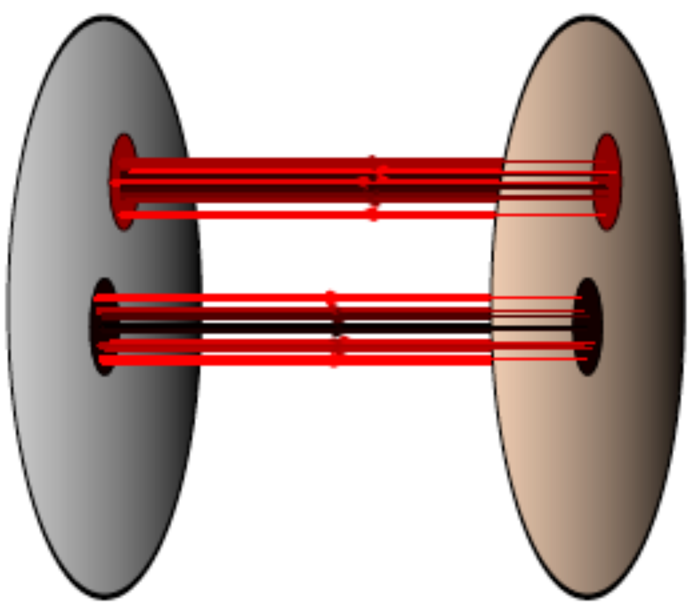
Soft scales: models

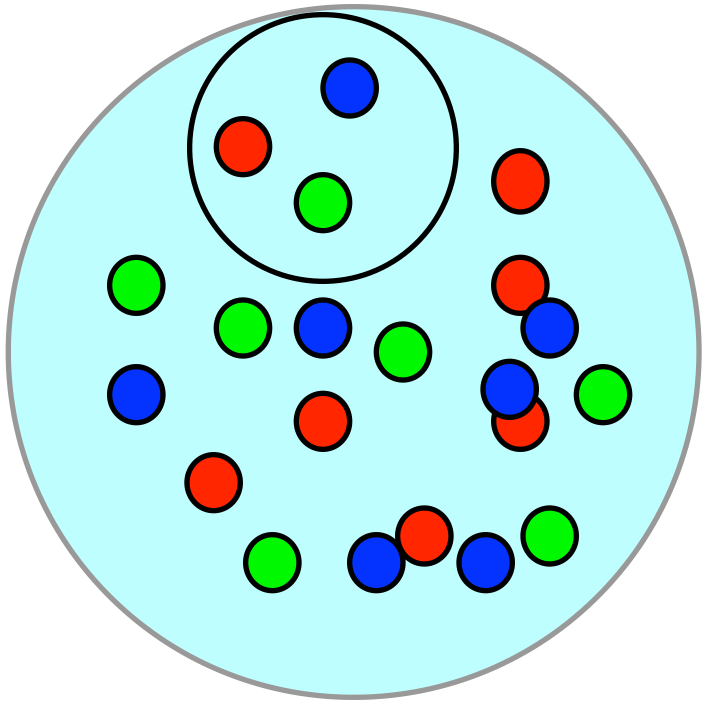
- Models used in the region $E_{cm} >> Q \sim \Lambda_{QCD}, T$: confinement at work.
- Alternatives (the most popular ones):

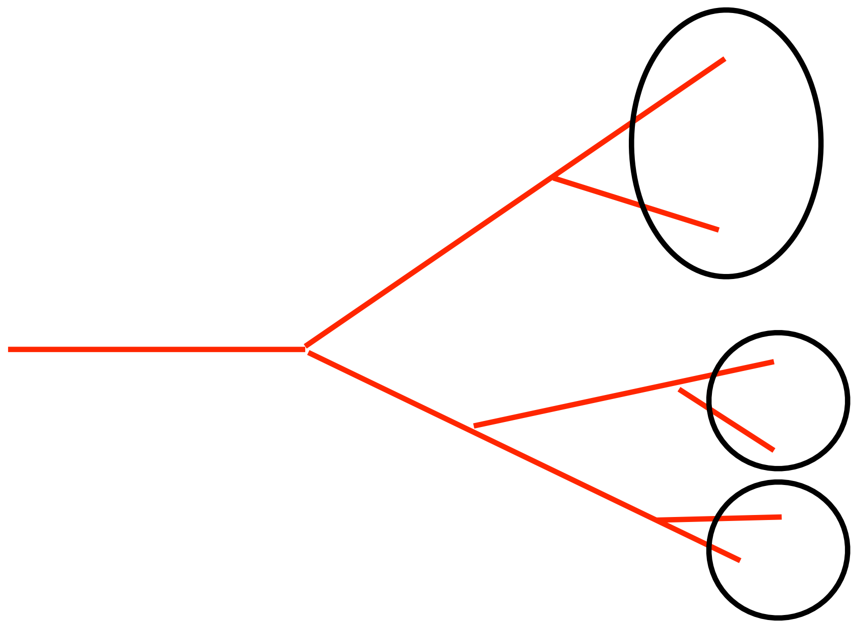
  * String models (Lund, DPM): particle production through string (color flux tubes) formation and breaking.

  * Cluster formation: color neutralization by formation of colorful partons (HERWIG, statistical models, recombination in HI).

  * Local Parton-Hadron Duality (LPHD): a parton evolved to a low scale ($\sim \Lambda_{QCD}$) gives κ hadrons, κ energy-independent.







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Probes of the medium:

Signatures which would allow to identify the medium created in URHIC with a phase of matter built of quasi-free partons:

1) Signatures from the medium itself (**soft**, momenta ~ T):

☛ Thermalization/collective behavior: elliptic flow, thermal photon/dilepton emission, statistical hadronization.

☛ Chiral-symmetry restoration: strangeness enhancement, broadening of resonances (ρ).

☛ Phase transition: fluctuations and correlations.

2) Probes whose comparison measured/expected (in perturbative QCD - $Q \gg \Lambda_{QCD}, T$; **hard**) characterizes the medium:

☛ Suppression of QQbar bound states: quarkonium linear potential becomes Debye screened.

☛ Suppression of high energy particles: jet quenching.

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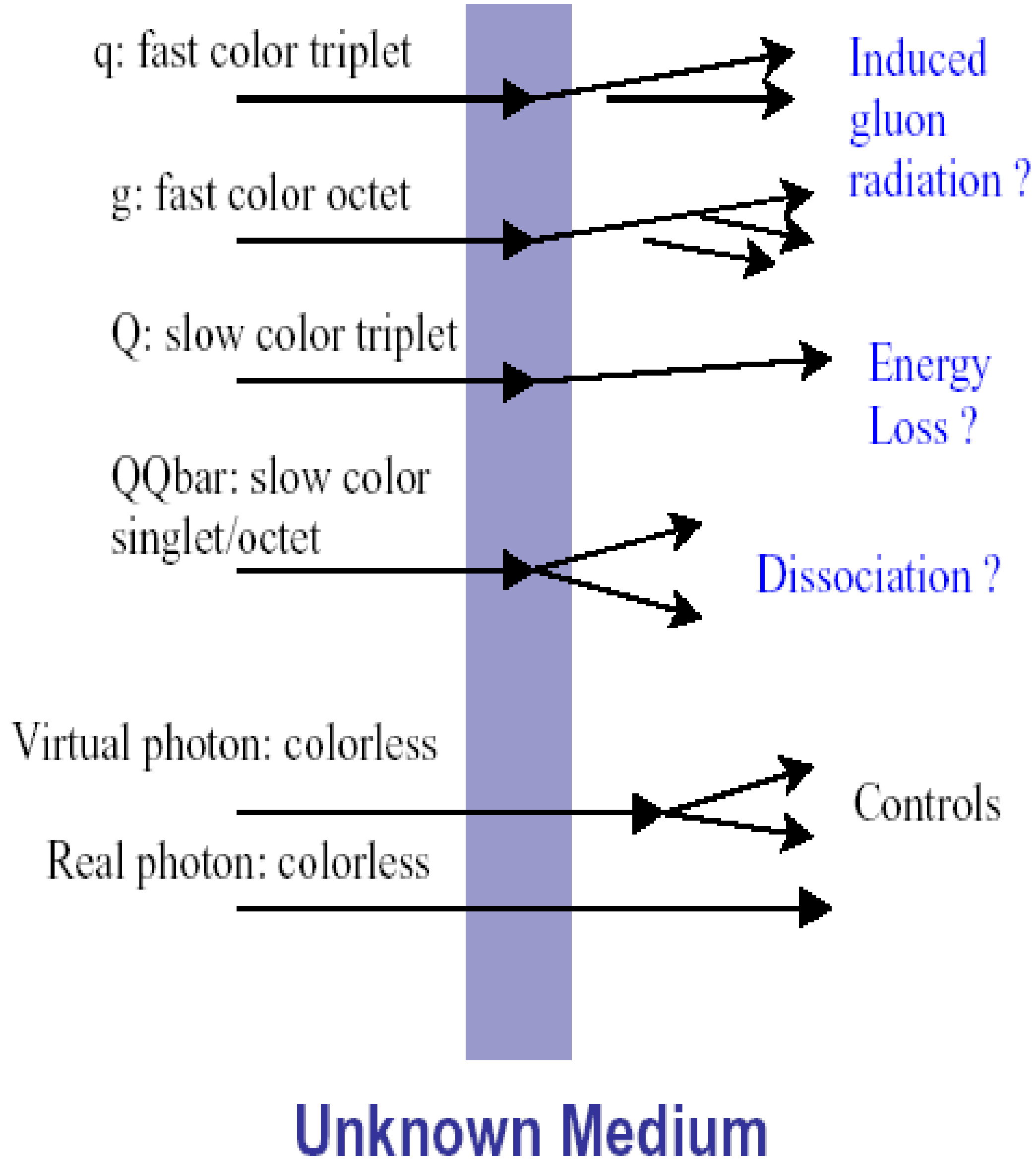

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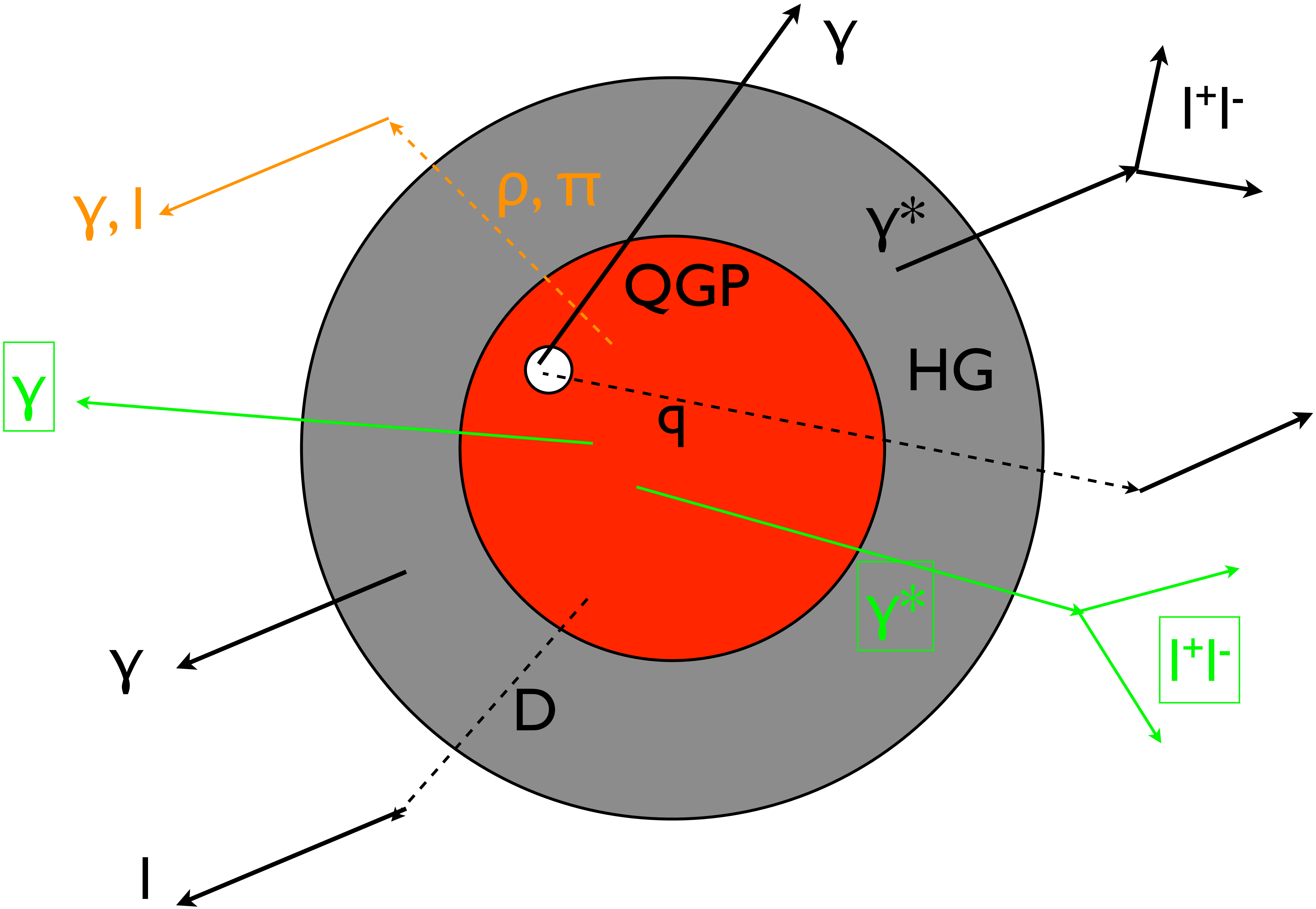
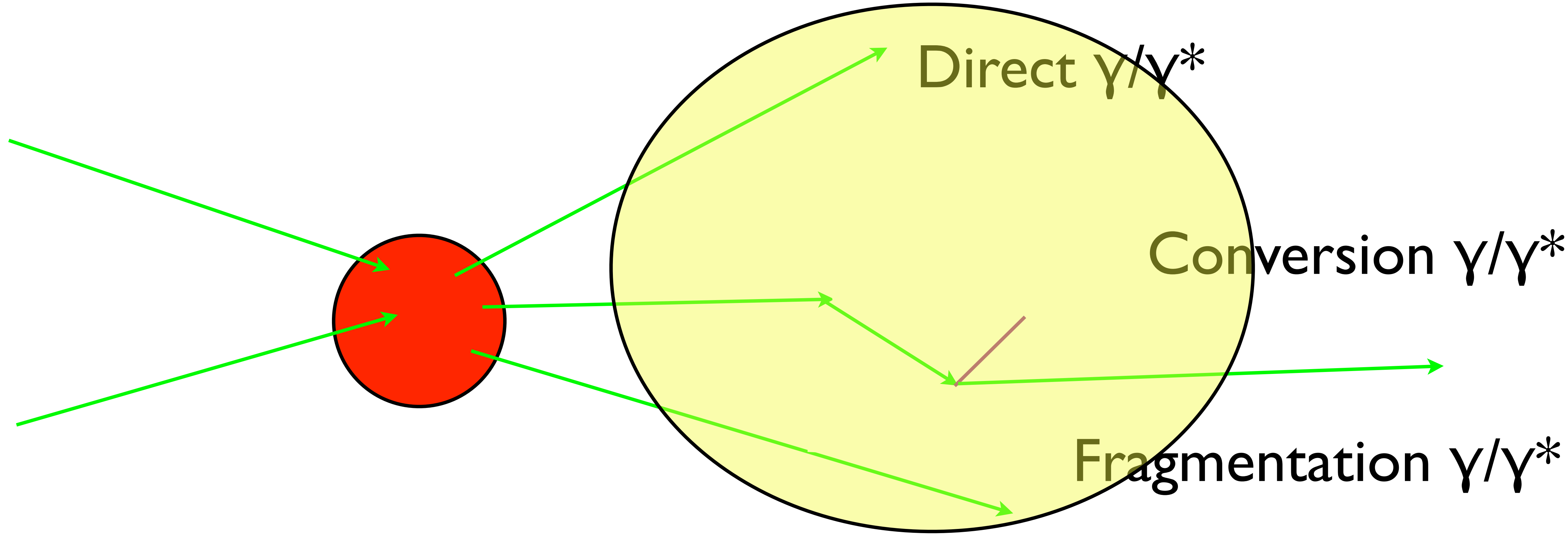
Photons and dileptons (I):



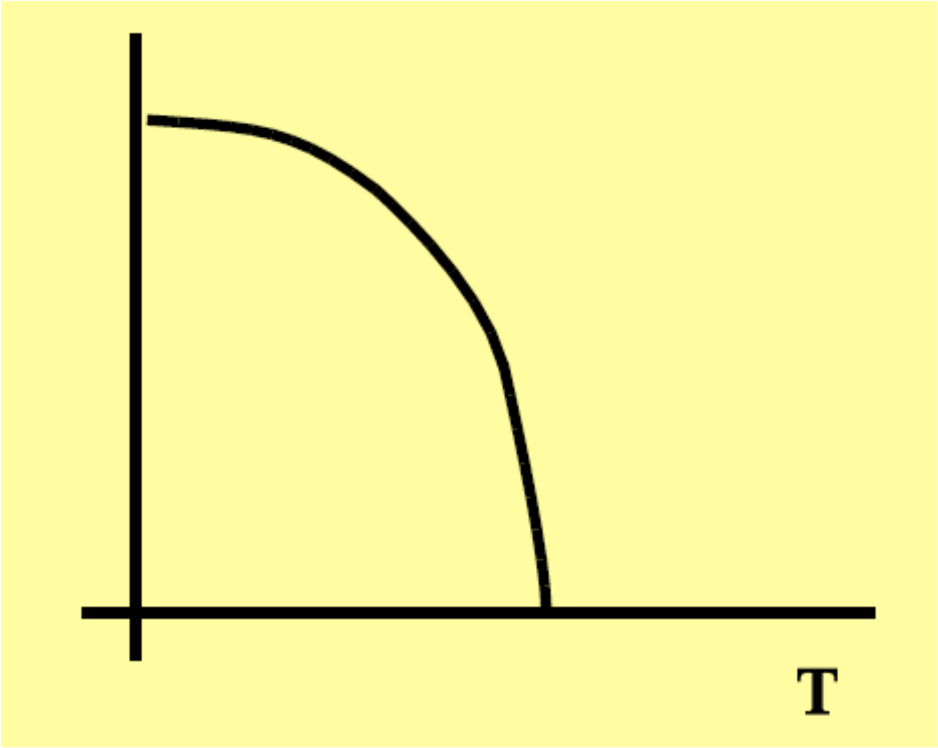
Photons and dileptons (II):

- Photons and dileptons (EM probes) may be produced by decays and by direct sources:
    - * Thermal (black-body) radiation, direct proof of T.
    - * From the hard parton scattering: benchmark.
    - * From fragmentation of partons: affected by medium.
    - * From jet conversions: determined by the medium.

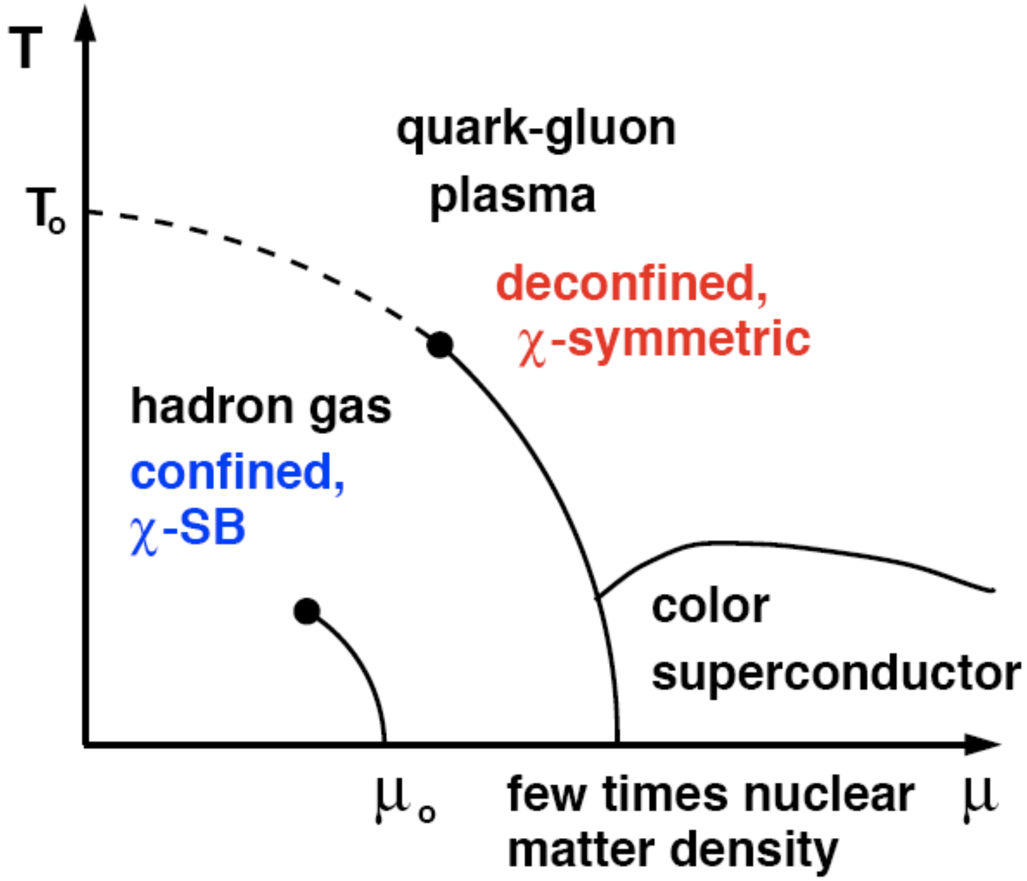


- All these mechanisms have to be implemented within a realistic medium model: density and evolution.

Fluctuations/correlations:



Second order: discontinuity in the derivative.

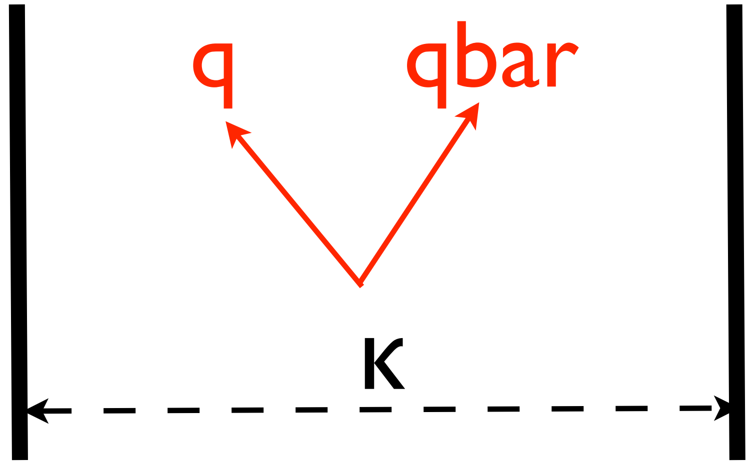


- In a 2nd order phase transition, the correlation length diverges at T_c: long range correlations and fluctuations.
- Around the tri-critical point, systems which go around it turn to show large fluctuations.
- Fluctuations in baryon number, in charge,...; correlations in p_T, in rapidity,..., have been proposed.

Strangeness/masses:

- Strangeness (heavy flavor) production is suppressed by:
  * The larger constituent quark mass (m_s~450 MeV, $m_{u,d}$~300 MeV), 1:1:0.25.

$$\frac{\Delta N}{\Delta t \Delta x \Delta y \Delta z \, d^2 p_T} = \frac{\kappa}{(2\pi)^3} \exp\left(-\frac{\pi(m^2+p_T^2)}{\kappa}\right)$$



  * The larger hadron mass e.g. K(600) versus π(140), in the hadronic gas reactions.

- Deconfinement implies pair production at parton level; χSB implies a reduction of constituent masses ⇒ strangeness

enhancement and resonance mass reduction/broadening (ρ). Broadening may be collisional, though.

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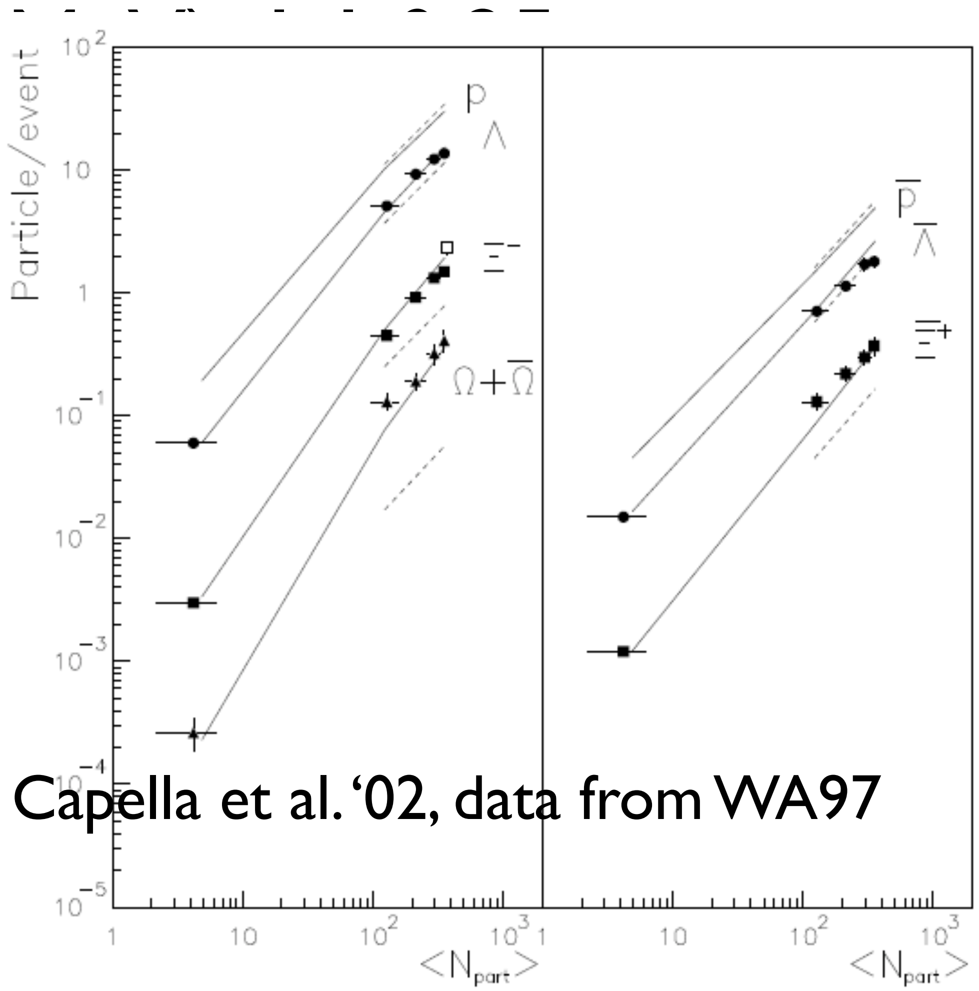
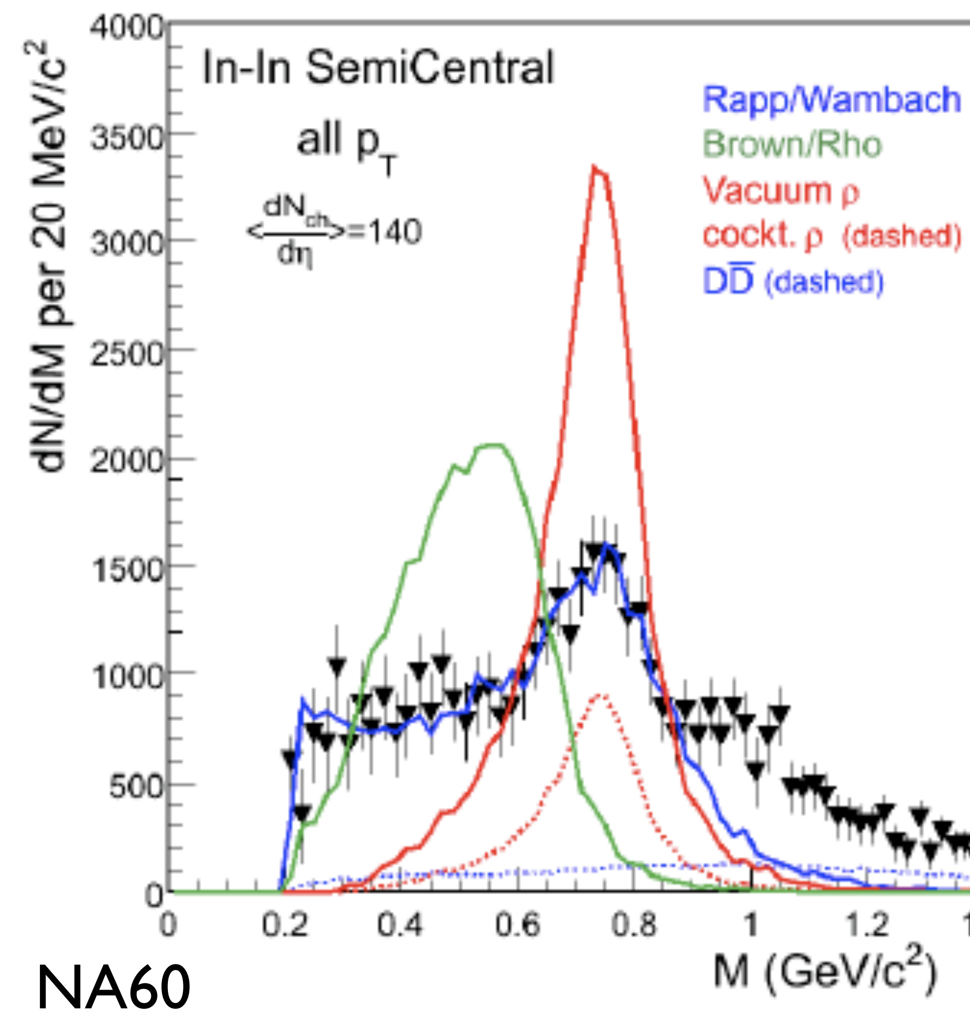
$\overline{\Delta t/}$ ... $^2 + p_T^2)$ / κ)

e.g. K(6



Capella et al. '02, data from WA97



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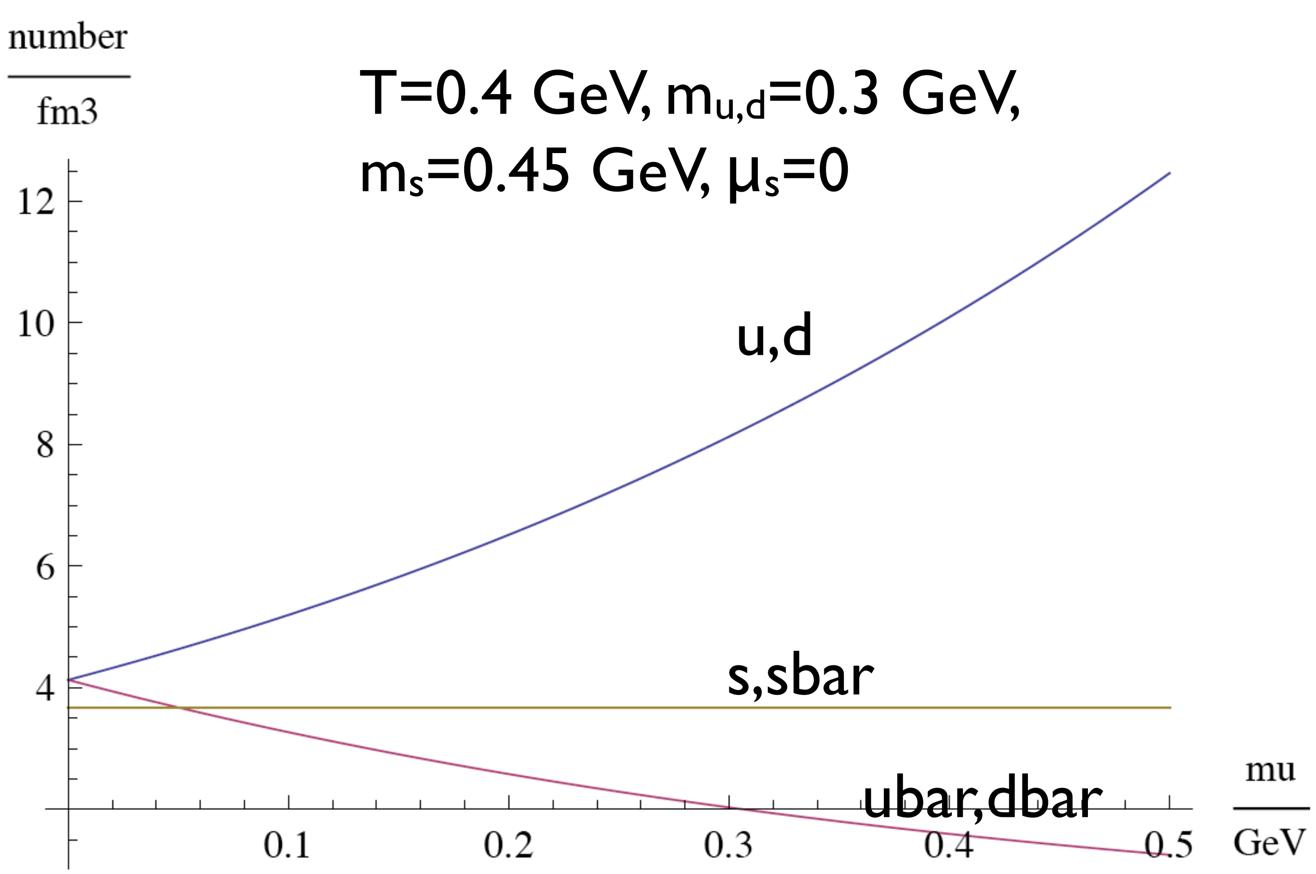
The statistical model (I):

$$n_i(T) = \frac{1}{(2\pi)^3}\int_0^\infty \frac{4\pi p^2 dp}{e^{\sqrt{p^2+m_i^2}/T}-1}$$

$$n_{q(\bar{q})}(T,\mu_q) = \frac{N_c N_s}{(2\pi)^3}\int_0^\infty \frac{4\pi p^2 dp}{e^{(\sqrt{p^2+m_q^2}\mp\mu_q)/T}+1}$$



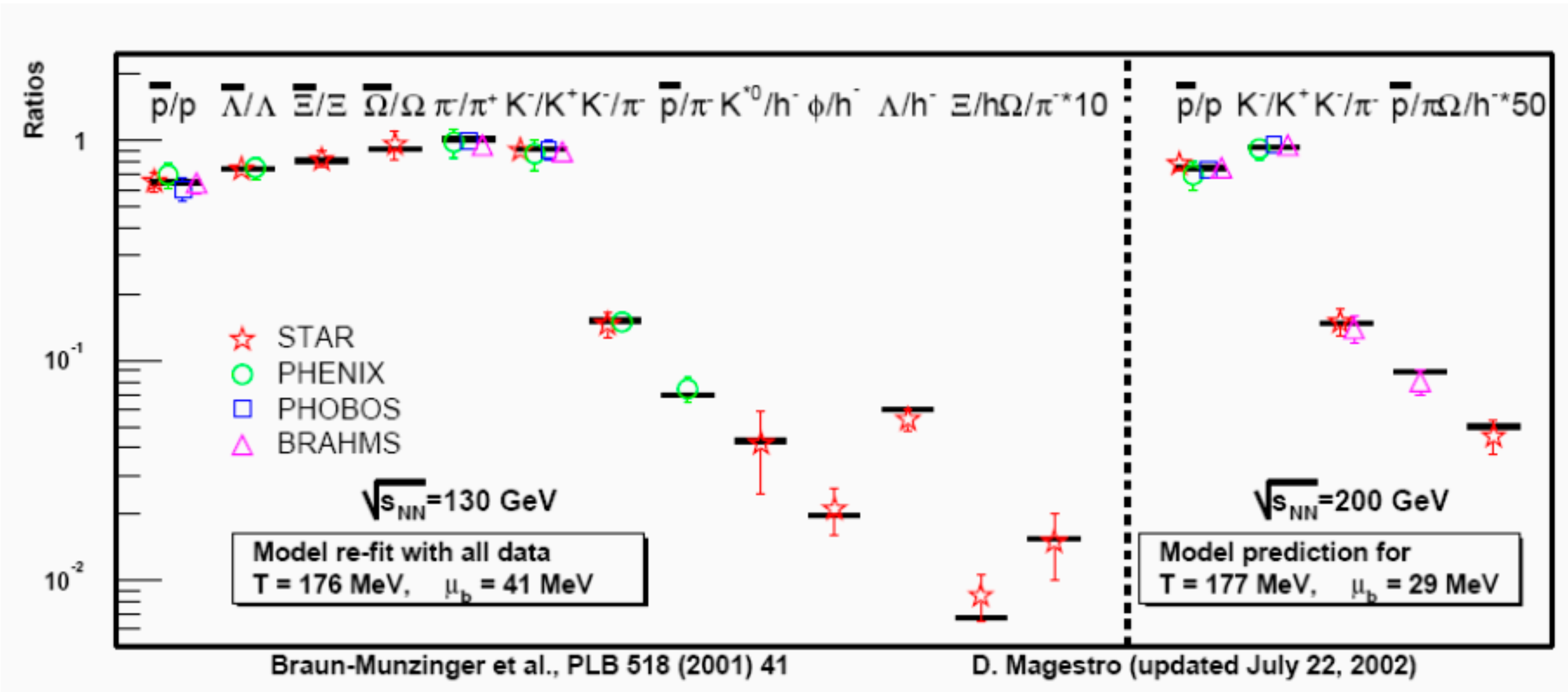
- Within the grand-canonical ensemble, equilibrium hadron/parton densities can be computed: T, μ, V.
- K/π ratio ~0.4>> values for pA: suppression factor γ_s to include chemical non-equilibrium effects.

- Within the statistical model, strangeness enhancement points to chemical equilibrium.
- At parton level it can be used as input for clustering.

The statistical model (II):

• The statistical model gives an good description of particle ratios in AB, with $T \sim T_c$ (and $\gamma_s \sim 1$ at RHIC): hint of partonic equilibrium.

• It also works (though not so well) in e^+e^- and pp(bar): statistical nature of hadronization (cluster models do work).



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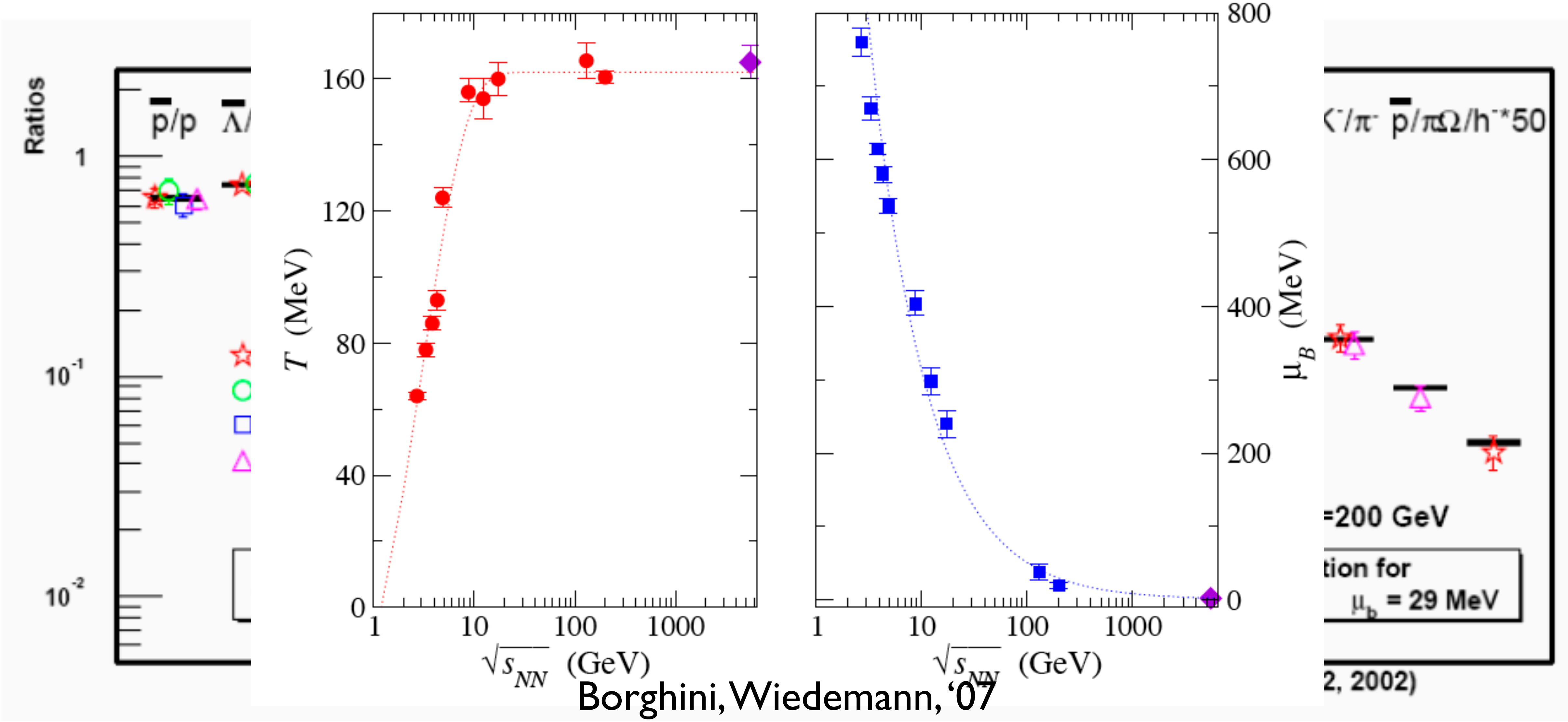


Reactions, temperatures:

• At a partonic level, the strangeness enhancement reactions which lead to chemical equilibrium are qqbar→ssbar and gg→ssbar.

• In the evolution of the created matter, there are two freeze-out temperatures:

* That at which inelastic reactions, a+b→X, X≠a+b, stop: chemical freeze-out.
* That at which elastic reactions, a+b→a+b, stop: kinetic freeze-out.

• In the plasma, conversions may change the hadrochemistry at large p_T: fast q or g + s(bar) from the plasma → fast s(bar) + X ⇒ information about the medium at large p_T.

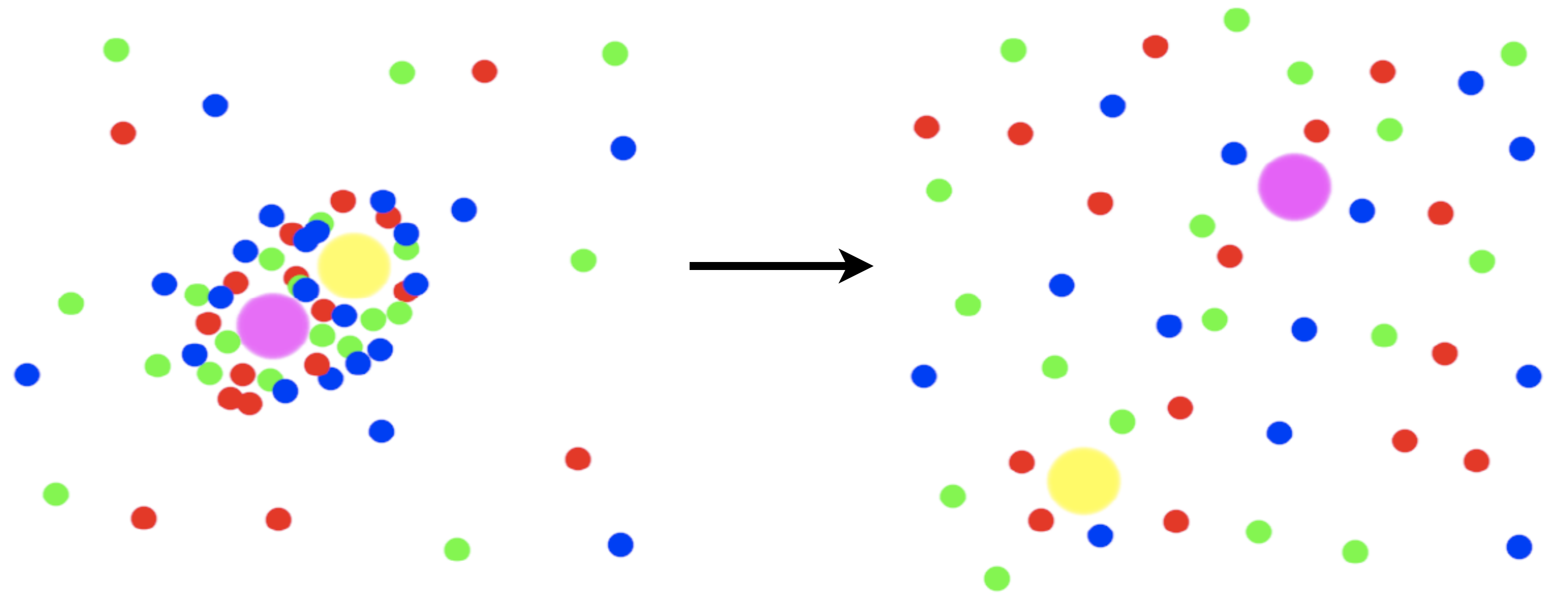
Contents:

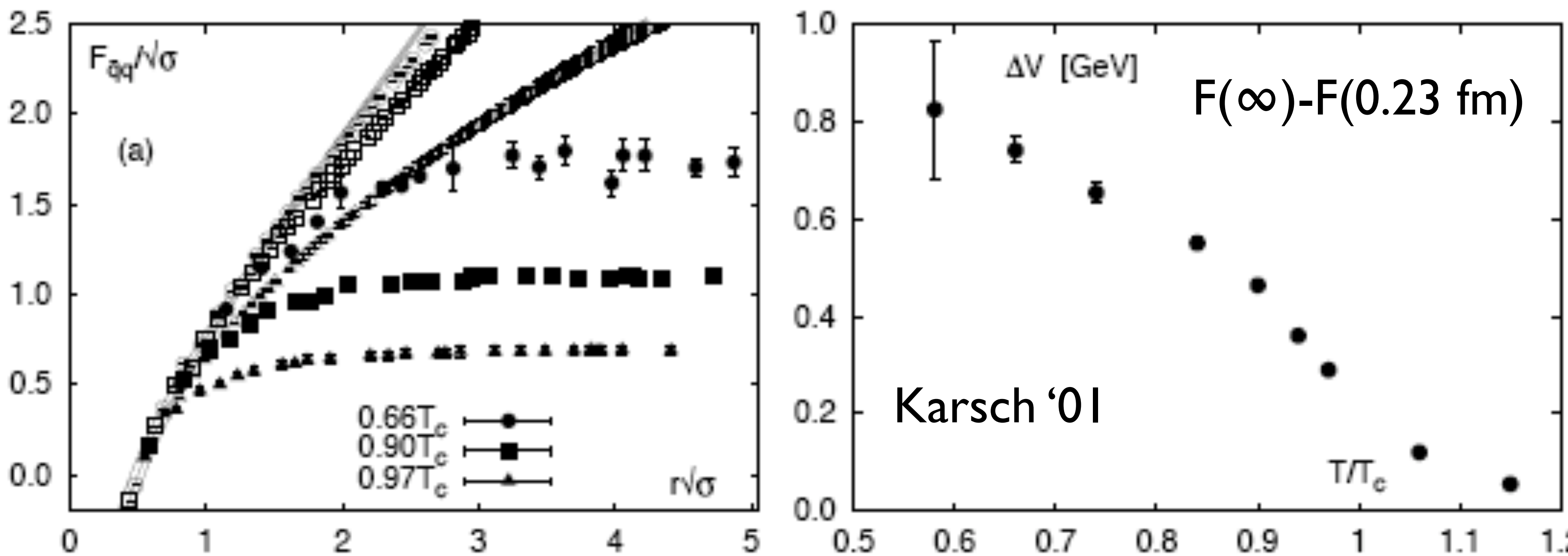
1. QCD: asymptotic freedom, confinement and chiral symmetry.
2. QCD at finite temperature: perturbative and lattice techniques.
3. Dynamics of heavy-ion reactions: initial state (Glauber theory), equilibration, hydrodynamics, transport models, freeze-out.
4. Particle production.
5. Fundamentals of QGP signatures: soft, hard and EM probes.
6. Hadrochemistry: different temperatures.
7. Quarkonium production and suppression.
(See e.g. Kluberg and Satz, arXiv:0901.3831 [hep-ph] and refs. therein).

Quarkonium

- From Matsui and Satz's proposal ('86), the suppression of QQbar bound states plays a central role in the discussion of QGP formation.

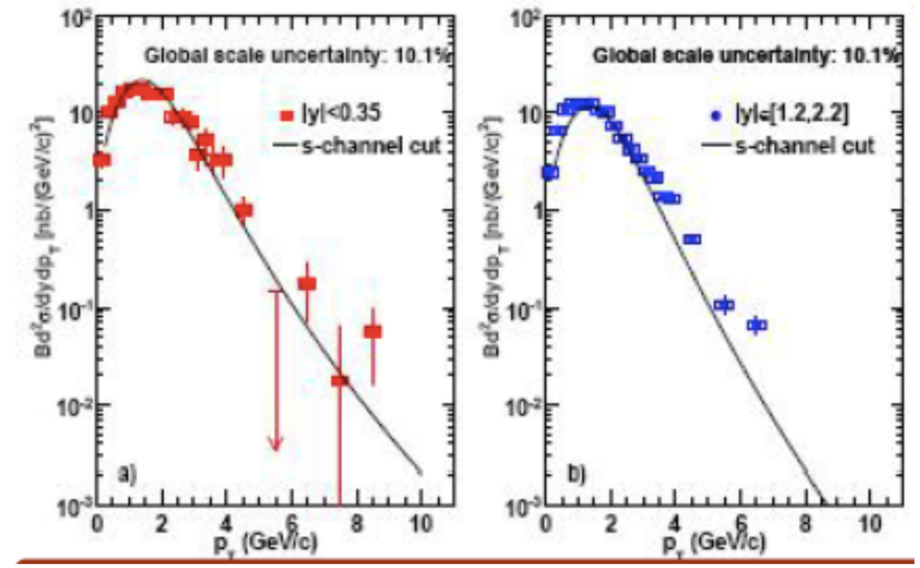
- Debye screening due to the free color charge in the plasma modifies the linear part of the QQbar potential.

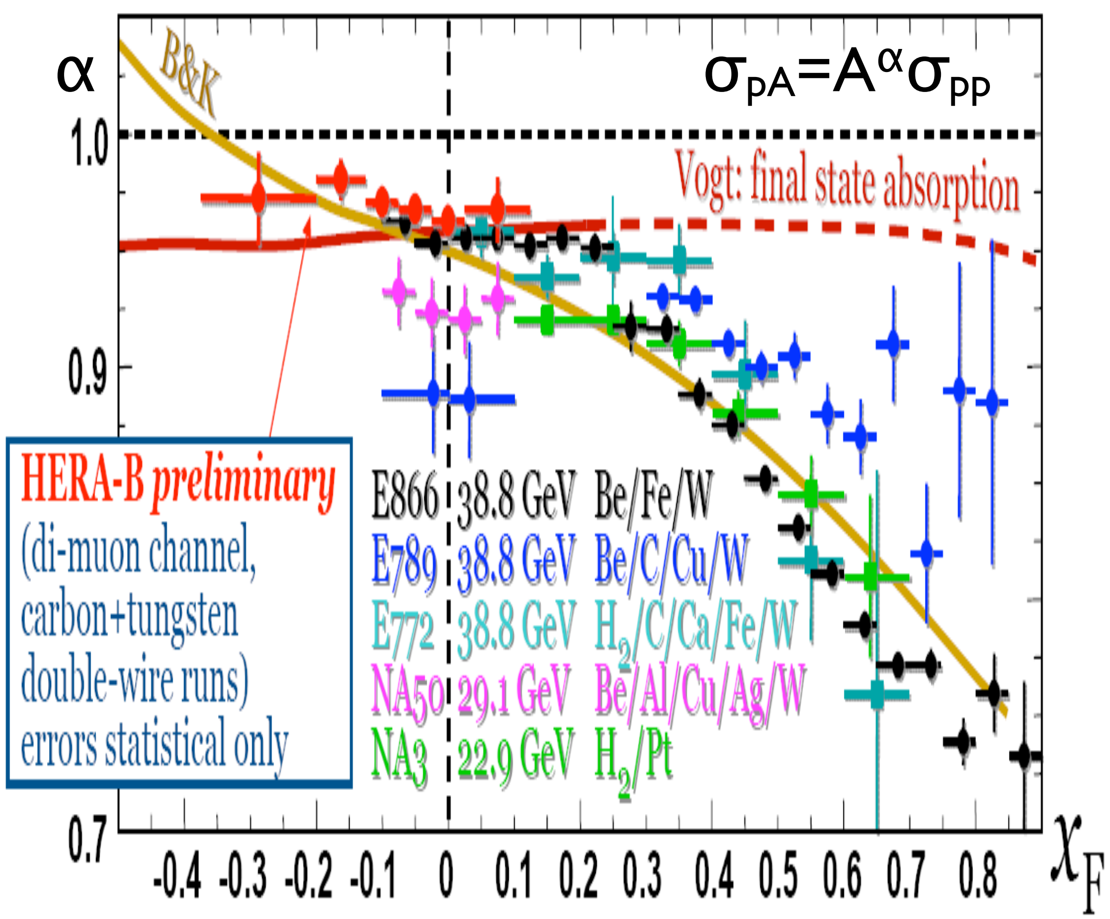


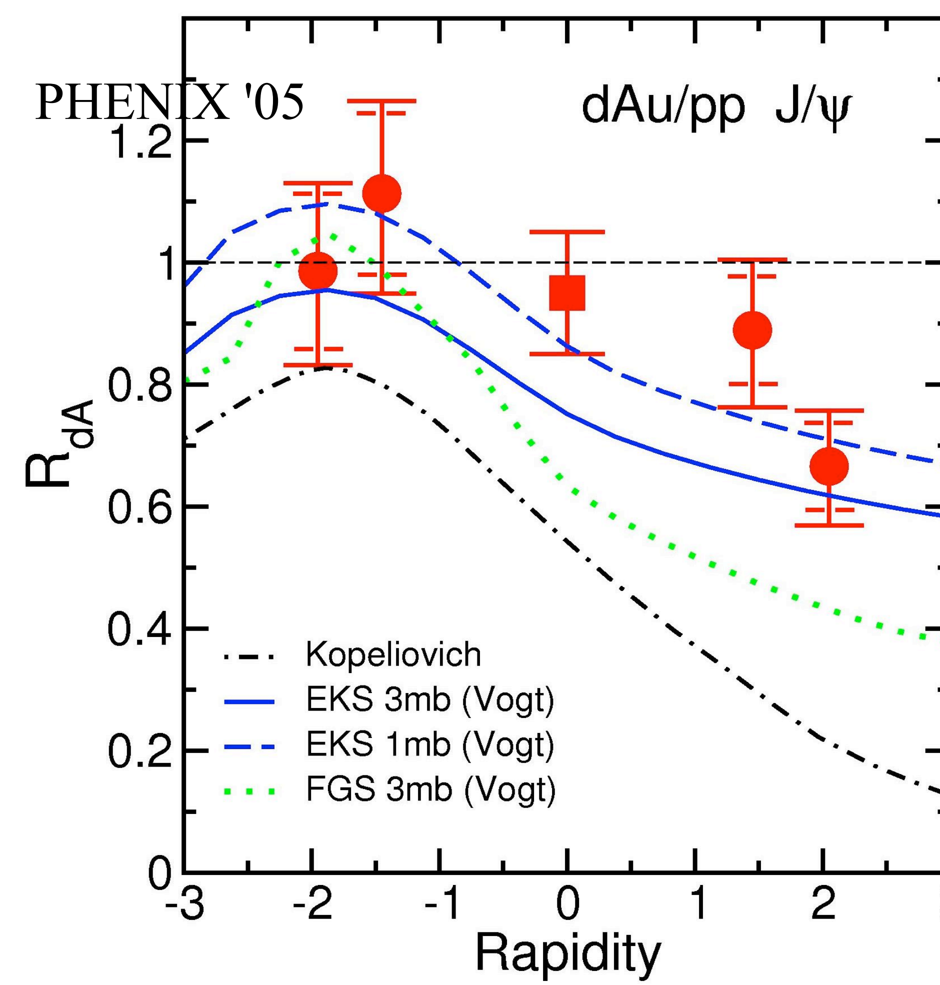


Quarkonium: the baseline

- e^+e^-: 60-80 % of J/psi produced with more charm (Belle, BaBar): higher orders in NRQCD?, additional mechanisms.
- pp(bar): polarization puzzle goes on: NRQCD?
- pA: smaller absorption at RHIC than at SPS, negative x_F (HERA-B).







Quarkonium: the baseline

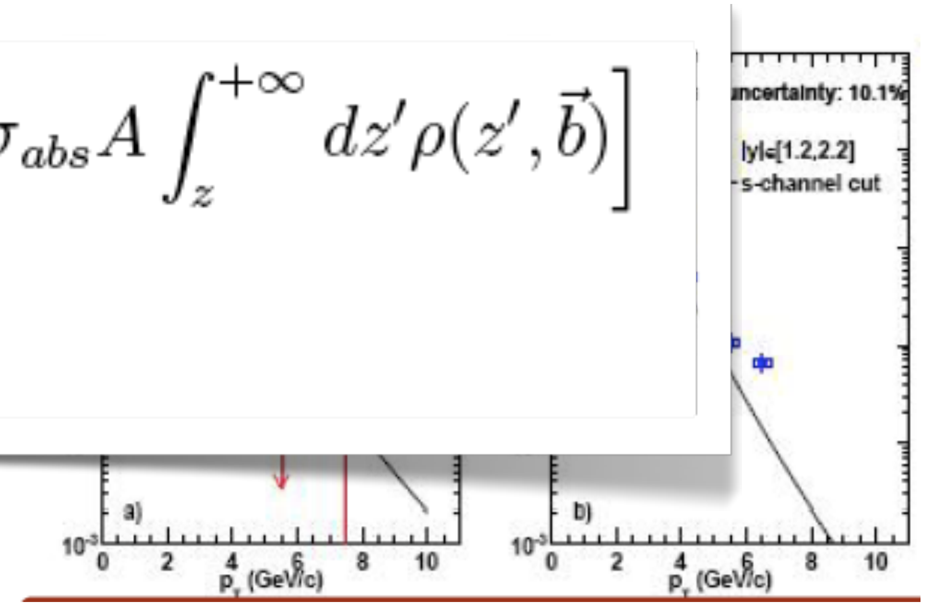
• e^+e^-: 60-80 % of J/psi produced with more charm (Belle, BaBar): higher orders in NRQCD?

additic

• pp(b

NRQC

$$
\begin{aligned}
\sigma_{pA}^{\Psi} &= \sigma_{pN}^{\Psi}\, A \int d^2b \int_{-\infty}^{+\infty} dz\, \rho(z,\vec{b})\, \exp\left[-\sigma_{abs} A \int_{z}^{+\infty} dz' \rho(z',\vec{b})\right] \\
&= \frac{\sigma_{pN}^{\Psi}}{\sigma_{abs}} \int d^2b \left[1 - e^{-\sigma_{abs} A T_A(b)}\right];
\end{aligned}
$$



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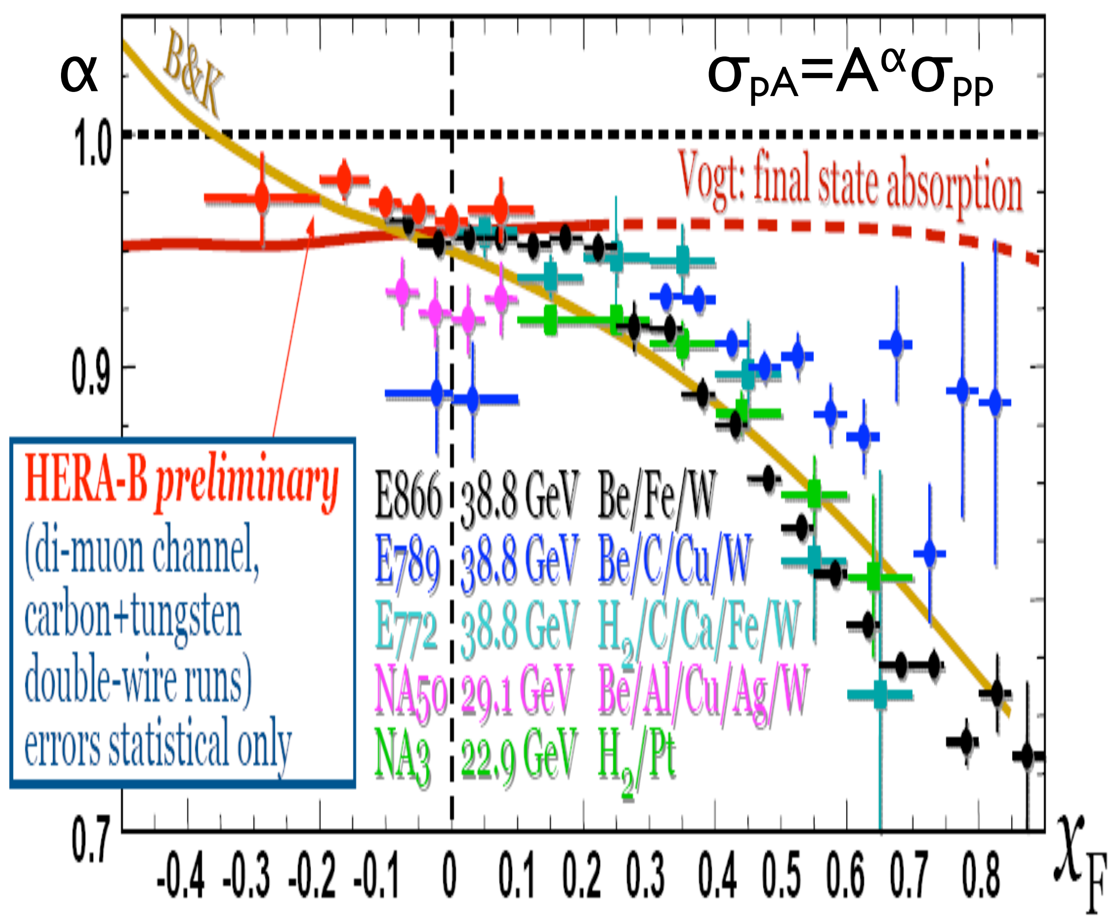
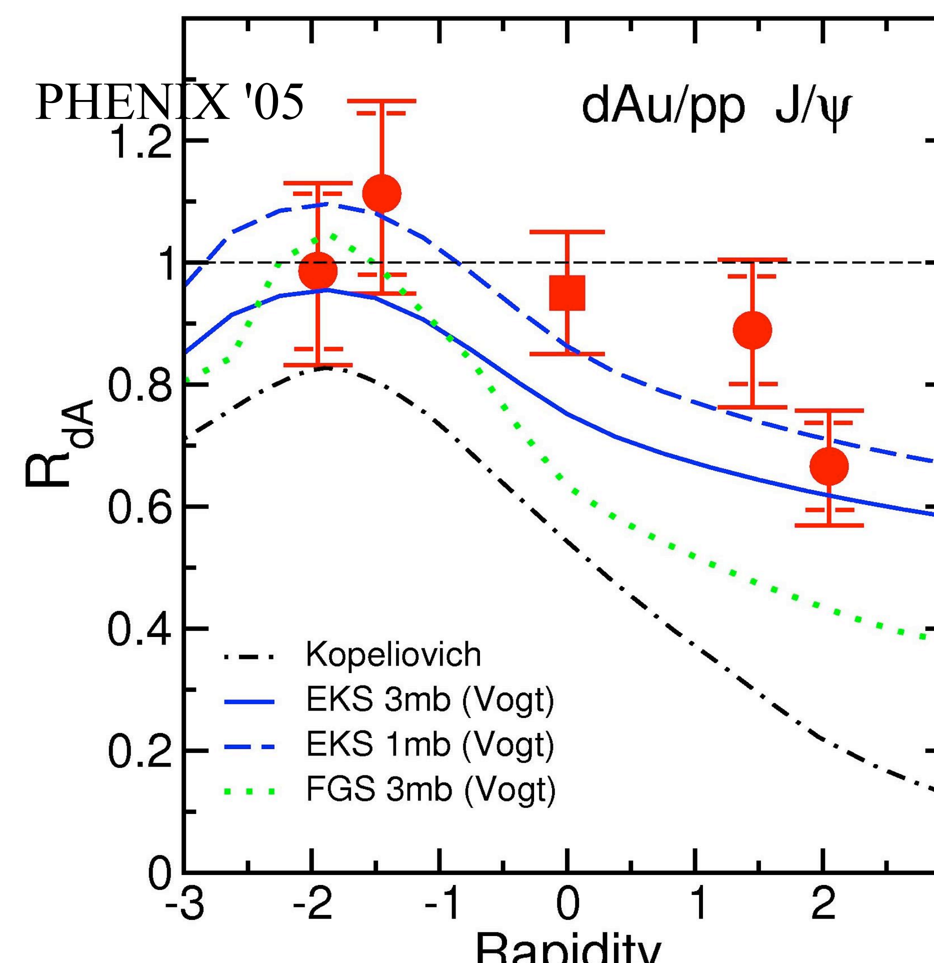


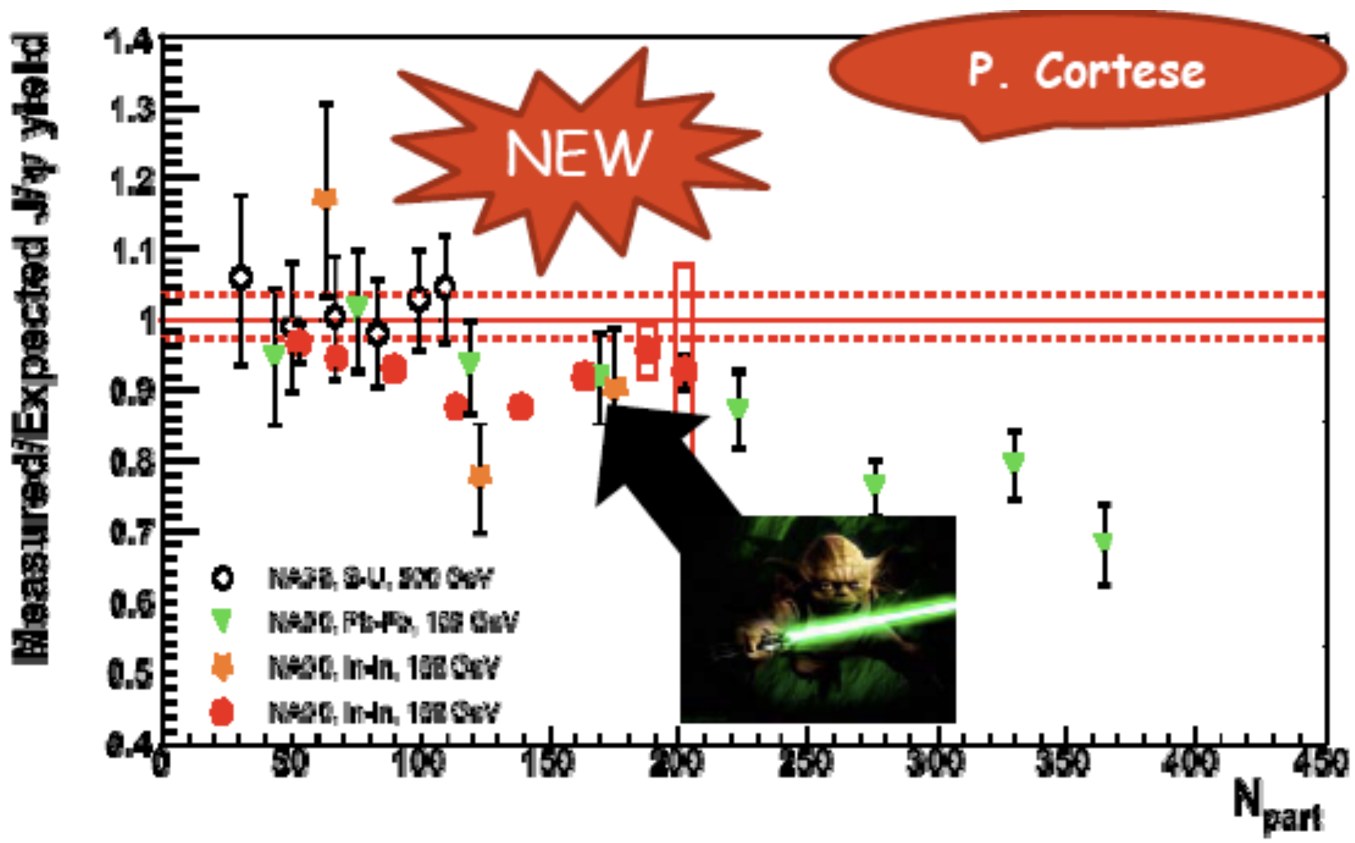


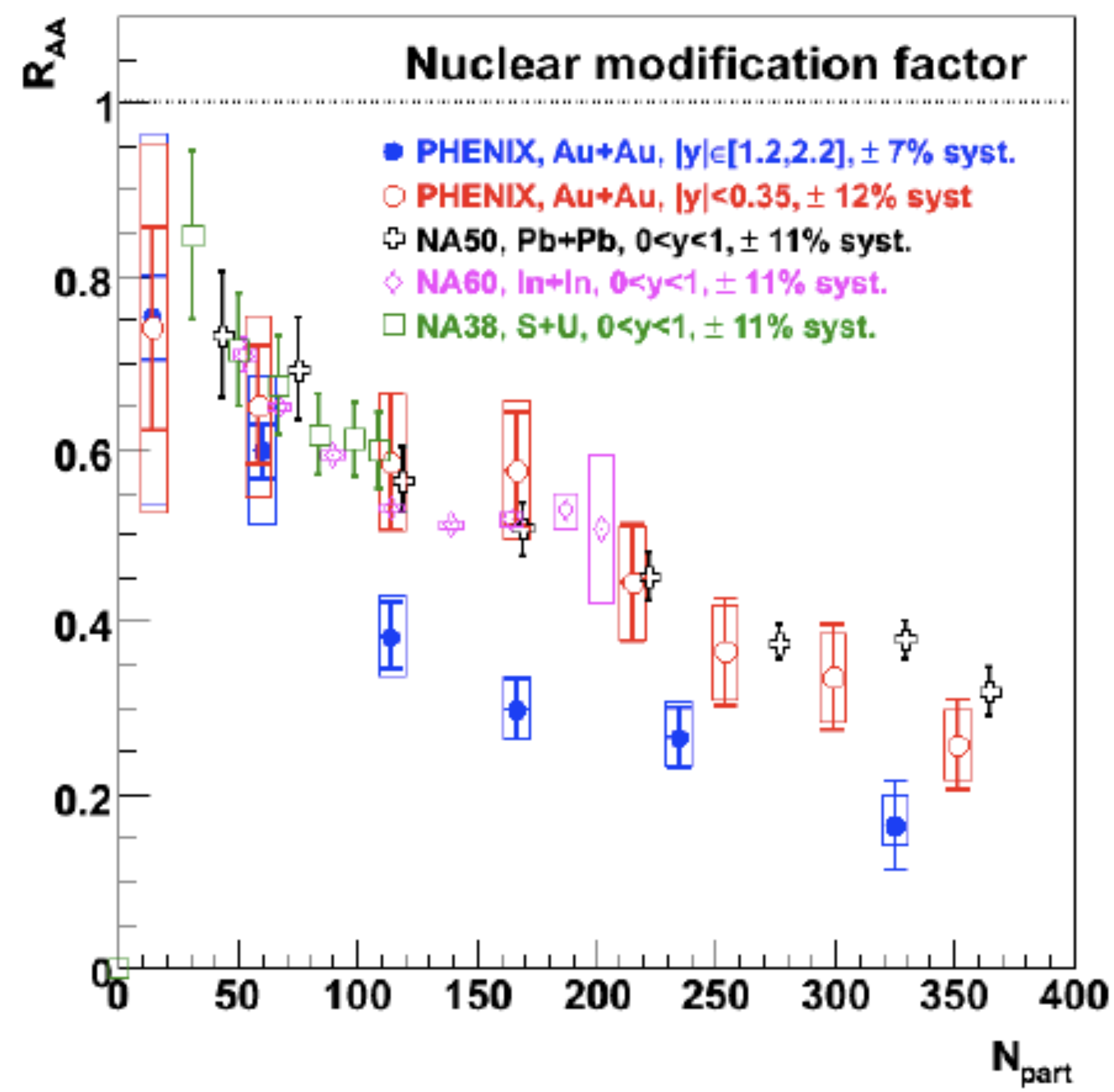
Quarkonium: HI data

- SPS data show anomalous suppression.

- Data show 'scaling' versus the number of participants.

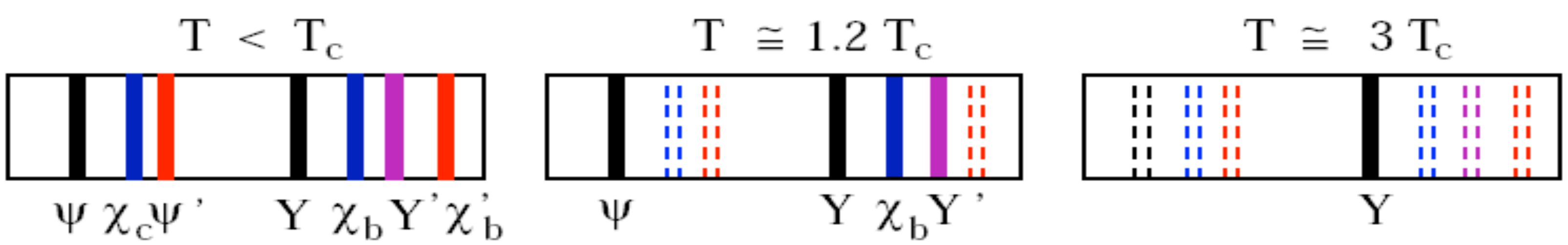
- At RHIC, larger suppression at forward rapidities, opposite to expected from a density effect.





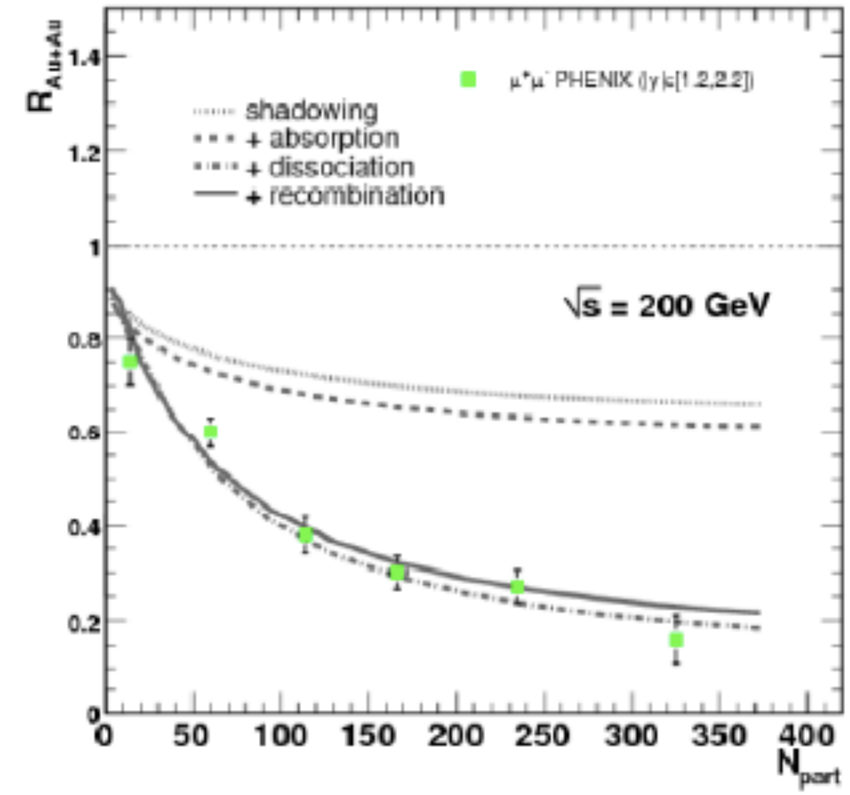
Quarkonium: theoretical interpretation

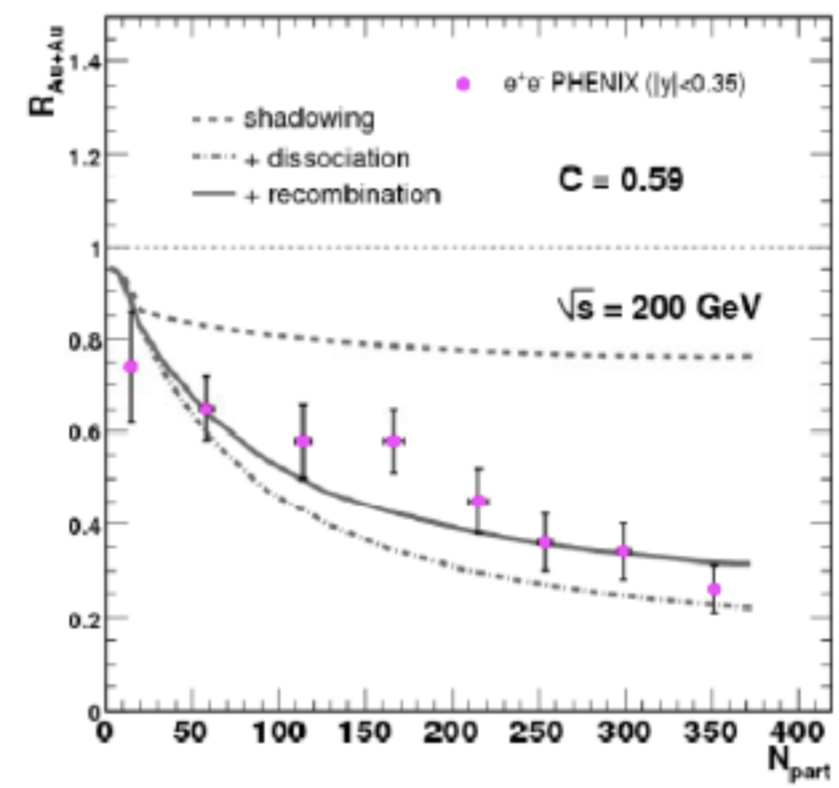
- Lattice suggests a sequential picture of quarkonia melting (potential models?).



- Other explanations rely on dissociation + recombination of Q's and Qbar's in a deconfined medium, eventually combined with shadowing.

- Initial state effects may also explain the larger suppression at higher rapidities.

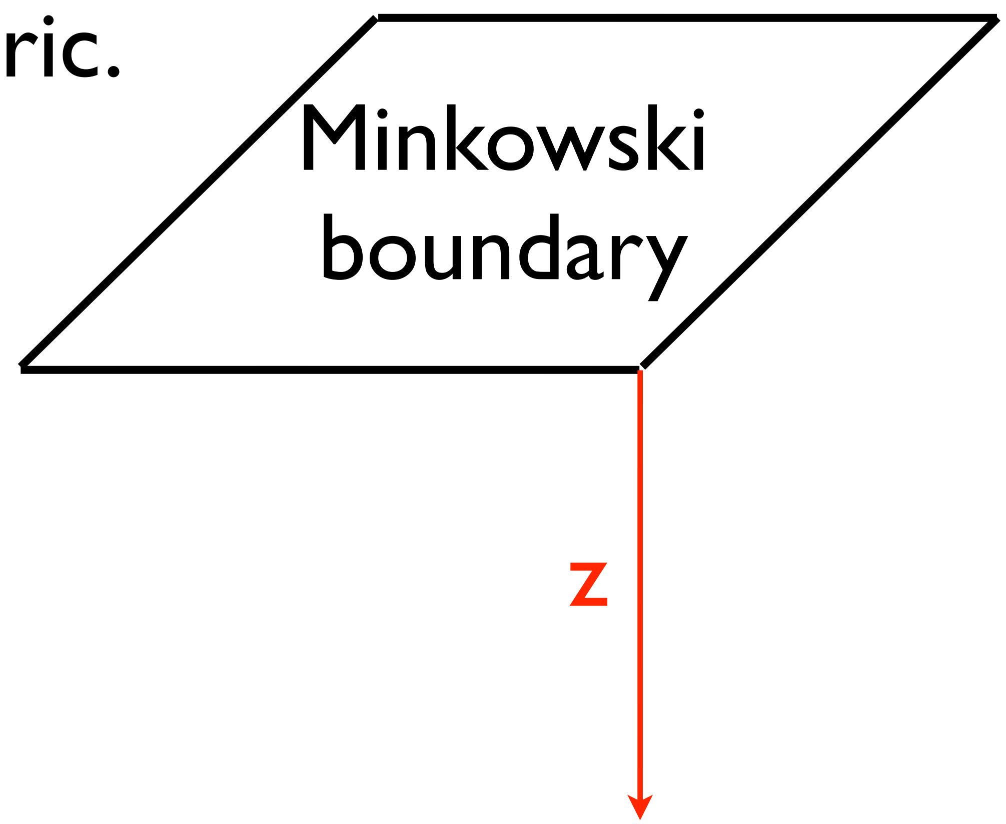




Backup:

Strong coupling calculations (I):

- Strong coupling is suggested by:
  → The quasi-ideal fluid behavior ($\lambda=(\rho\sigma)^{-1}<<R$).
  → The early isotropization/thermalization, difficult to explain in pQCD (Romatschke et al ’04, Xu et al ‘05).
  → The strong quenching of high-energy particles.
- AdS/CFT correspondence: dynamics of N=4 SUSY QCD for $N_c,\lambda=g^2N_c\rightarrow\infty$ can be computed using classical gravity in $AdS_5\times S^5$.
  → Temperature through black-hole metric.
  → No confinement, no asymptotic freedom, no quarks,...

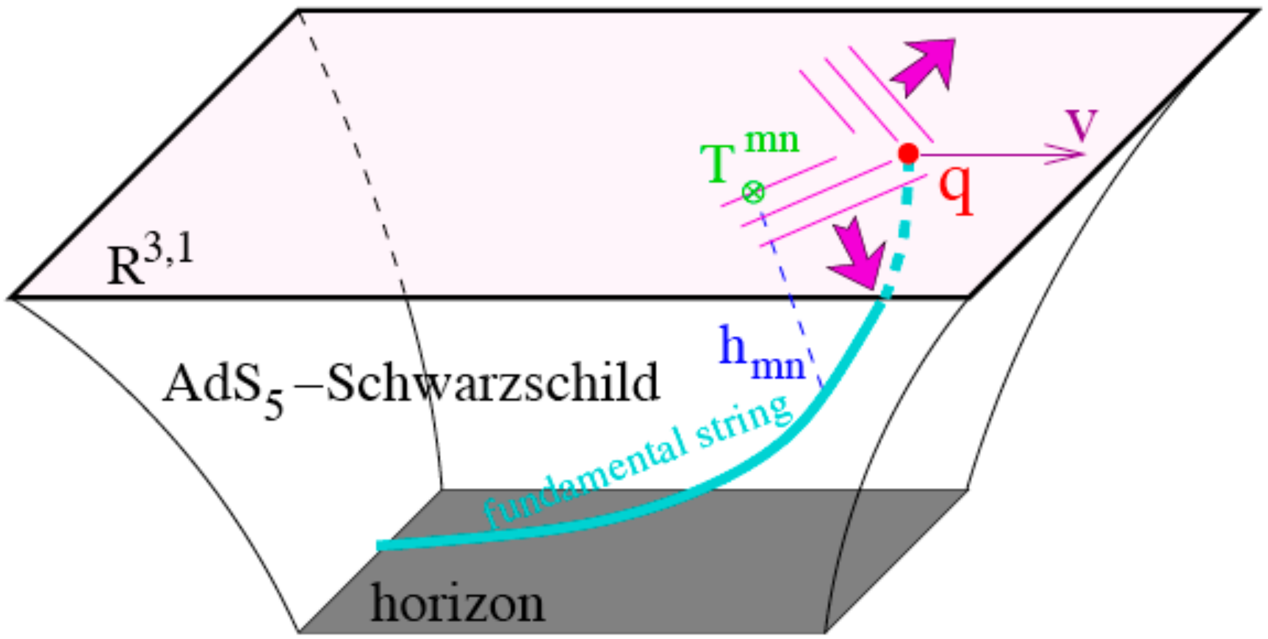


$$\mathcal{Z}_{\text{string}}\left[\Phi_i(z,x^\mu)\Big|_{z=0}=\varphi_i(x^\mu)\right]=\left\langle \exp\left(\int d^4x\,\varphi_i\mathcal{O}_i\right)\right\rangle_{\text{SYM}}$$

O_i is the SYM operator associated with the supergravity field Φ_i.

Strong coupling calculations (II):

- AdS/CFT has been applied to several aspects of HIC (see the review by Casalderrey et al. '10 and Janik's lectures):
  - → The energy loss of fast and slow partons.
  - → The energy deposition and medium disturbance created by the energetic particle.



  - → The early isotropization/thermalization problem.
  - → The hydrodynamical behavior.

$$\tilde{g}_{\mu\nu}(x,z) = \tilde{g}^{(0)}_{\mu\nu}(x) + z^2\,\tilde{g}^{(2)}_{\mu\nu}(x) + z^4\,\tilde{g}^{(4)}_{\mu\nu}(x) + \ldots \qquad \langle T_{\mu\nu}\rangle = \frac{N_c^2}{2\,\pi^2}\,\tilde{g}^{(4)}_{\mu\nu}(x)$$

  - → The initial conditions for a HIC.