Detecting quarkyonic matter via EM probes?

Based on ongoing work with Sascha Vogel
PRL107:152301,2011 , arXiv:1204.3272 with Stefano Lottini
Also , 1006.2471 (PRC),with with Igor Mishustin ,1105.0188 (JHEP) with Piero Nicolini

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Synopsis

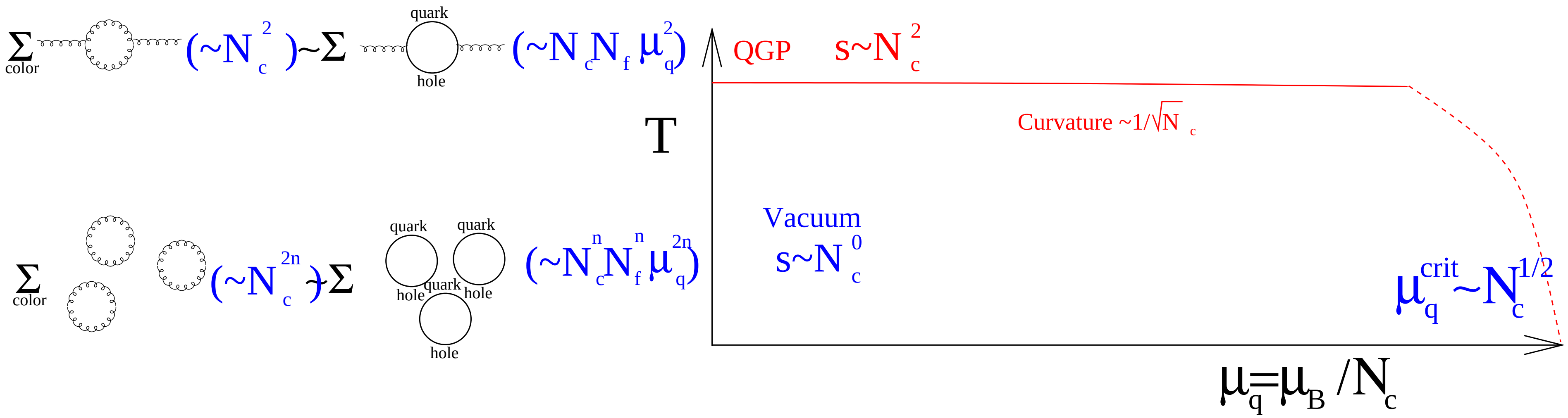
What is quarkyonic matter. Definition from Nucl. Phys. A **796**, 83 (2007), by McLerran and Pisarski:
Coexistance of pQCD with confinement/baryonic degrees of freedom !
NOT confinement-chiral symmetry separation, chirally inhomogeneus phases etc!

Does it exist? An attempt at an estimate from percolation theory

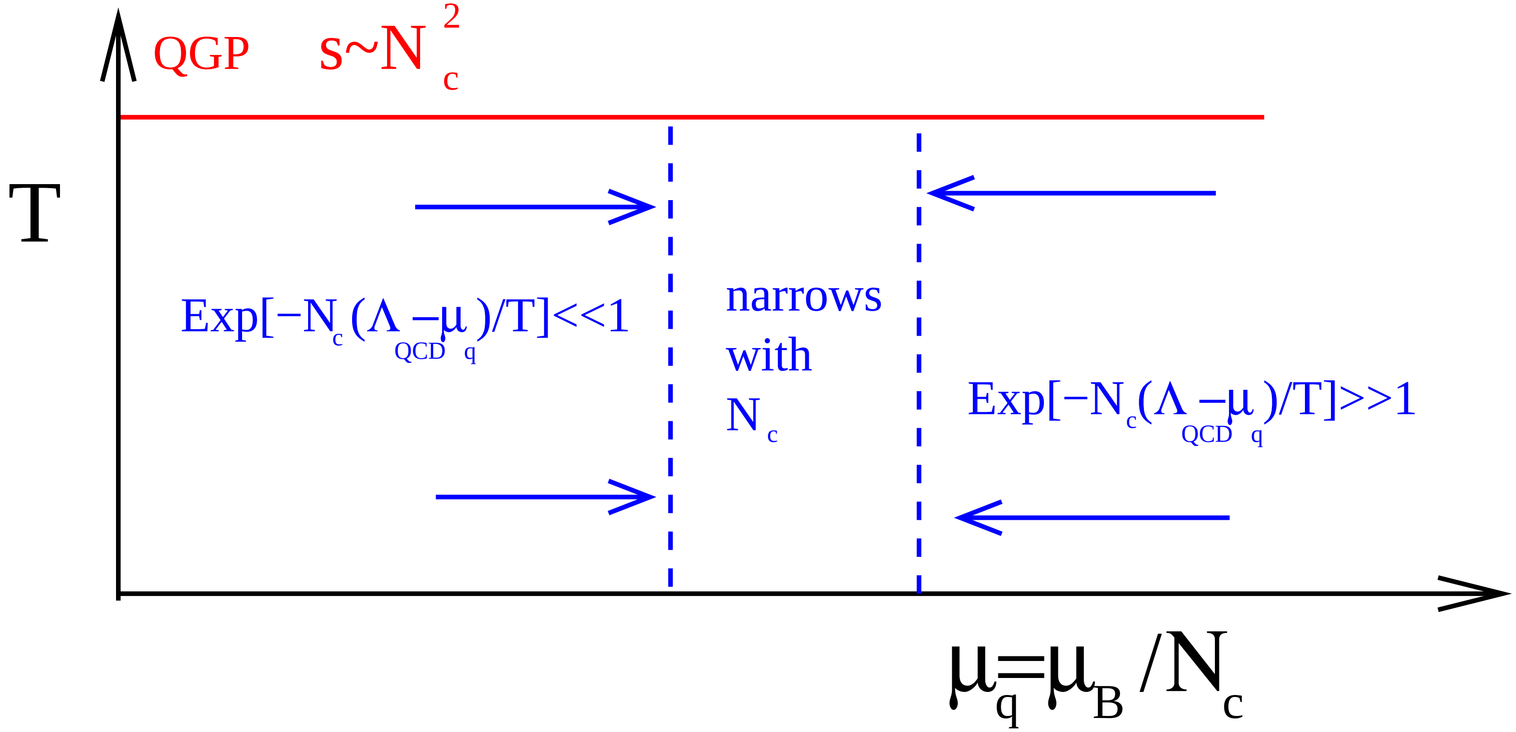
Towards a pheonomenolgy of quarkyonic matter via electromagnetic signals

No conclusions as yet.

Lets get some insights in the large N_c limit... $(N_c \simeq 3 \gg 1, N_c^{-1} \ll 1)$

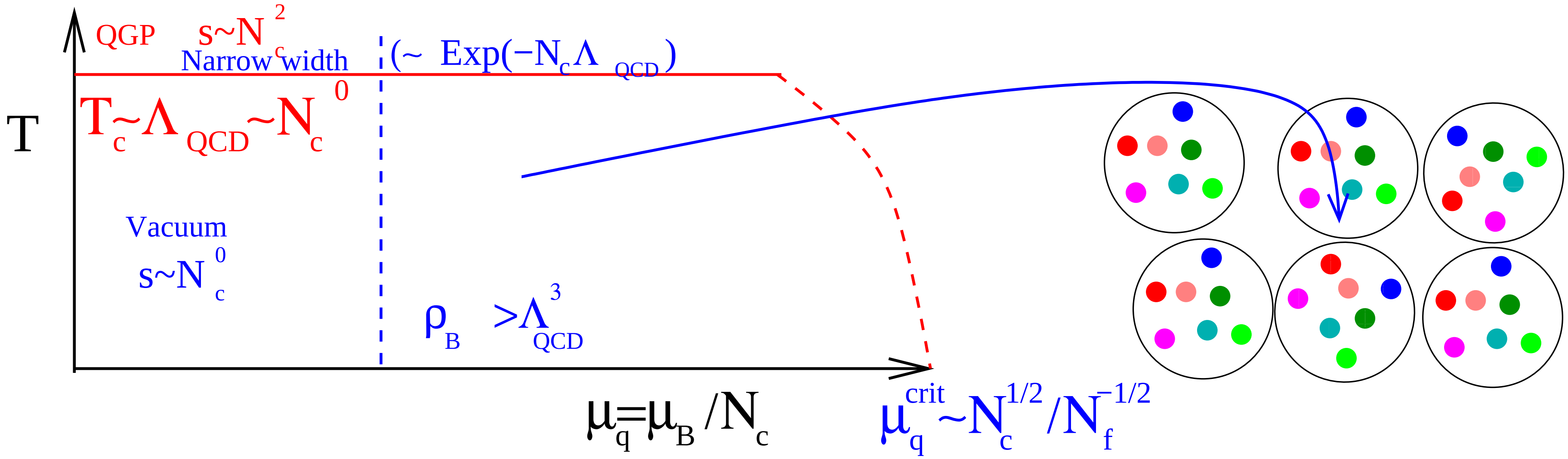


Deconfinement line flattens, since for deconfinement $\mu_Q \sim N_c^{1/2} N_f^{-1/2} m_B$ (also No critical point , $N_c \gg N_f$ means confined phase has Z_N global symmetry, Deconfinement always a phase transition!)



line separating "vacuum" from "dense nuclear matter" narrows

McLerran+Pisarski, arXiv:0706.2191: line defines new "quarkyonic" phase!



Inter-quark distance in this phase $\sim N_c^{-1/3} \to 0$, asymptotic freedom in configuration space!
Confined but quasi-free quarks below fermi surface and $P \sim N_c$ (quark-hole?)

A totally new phase (FAIR,RHIC@low$\sqrt{s}$,Neutron stats,...) alternative to critical point, inaccessible to EFT! But...

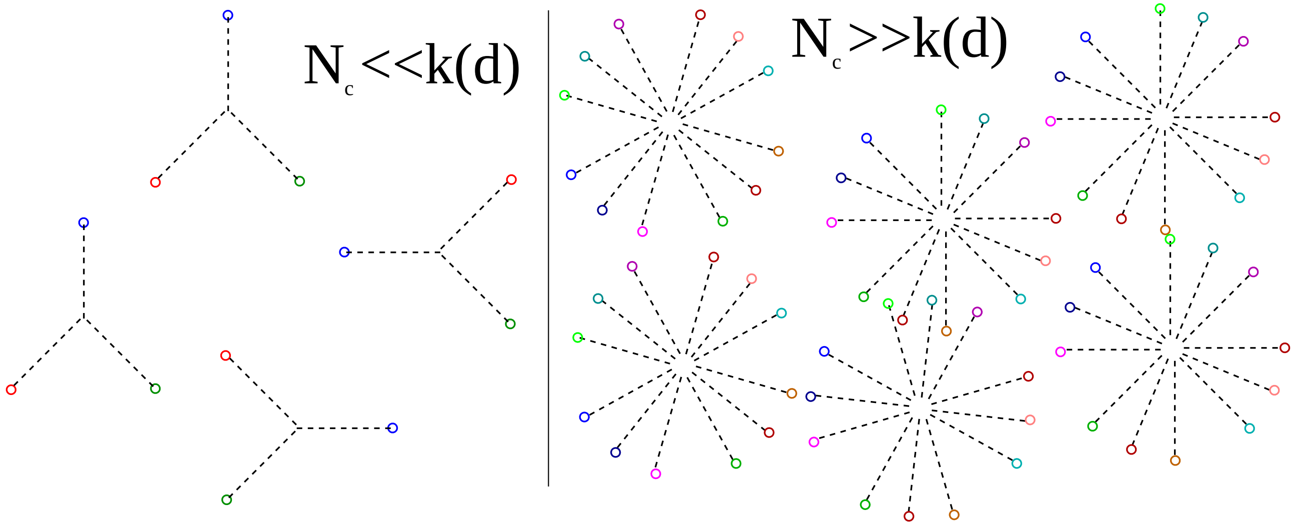
How close are we to the $N_c \to \infty$ limit?

In vacuum many qualitative ($\sim \mathcal{O}(30\%)$) agreements (Skyrme,planar diagrams, OZI rule,...). In-medium remarkable ($\sim \mathcal{O}(1000\%)$) failures

Quantity	$N_c \to \infty$	QCD
$E_{Nucleus}^{binding}$	$N_c \Lambda_{QCD}$	$\ll \Lambda_{QCD}, m_\pi$
$\Delta E_{spin-flip}$	$\sim \Lambda_{QCD}/N_c$	$\sim \Lambda_{QCD}$
Ground state	Crystal	Liquid

Phase transitions in N_c between $N_c = 3$ and $N_c = \infty$?
(Or is "quarkyonic matter" simply nuclear matter at large N_c?)

A conjecture: "in-medium" N_c "not large" wrt number of neigbhors



G.Torrieri,S.Lottini Phys.Rev.Lett. 107 (2011) 152301

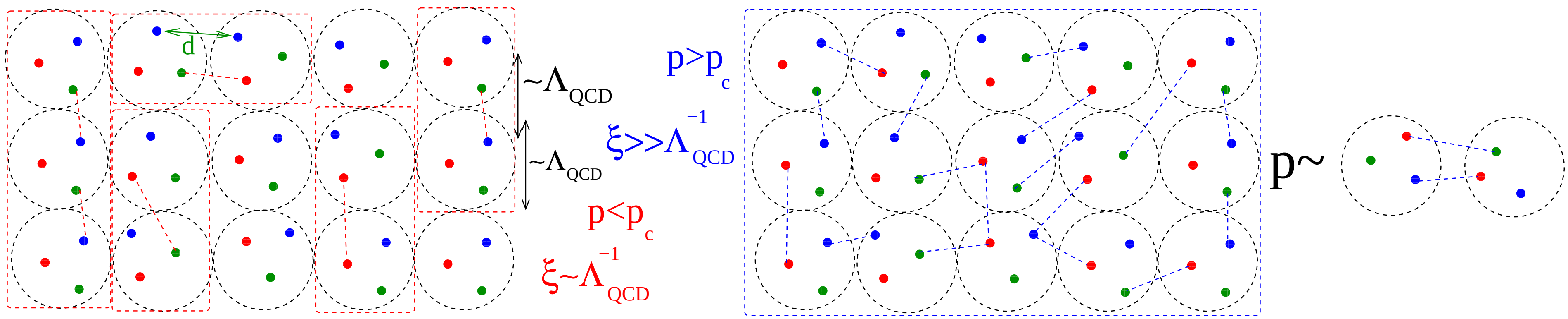
G.Torrieri,I.Mishustin Phys.Rev. C82 (2010) 055202

Pauli-blocking of color wavefunctions in dense system ($\sim N_c/(N_f N_N)$)

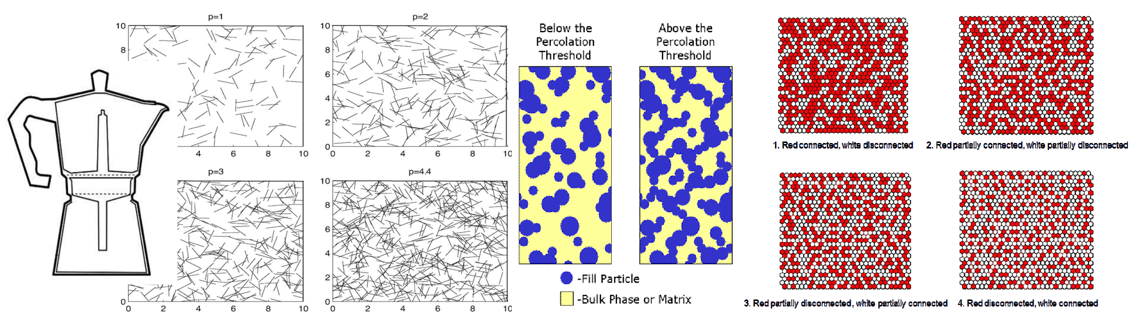
Percolation of any "perturbative" interactions ($\sim N_c/N_N$)

Any "quarkyonic" phase-line will curve in $N_c - \rho_B$

N_c scaling and Percolation at $\mu_Q = \Lambda_{QCD}$



With N_c colors, ways two baryons can interact with one another grows fast with N_c . Correlation length diverges at percolation, existence of transition independent of microscopic details (percolation behavior universal!)



An ansatz with confinement and correct N_c scaling

$$p = 1-\left(q_{(1),ij}\right)^{(N_c)^\alpha} \quad , \quad q_{(1),ij} = \int f_A(x_i)\mathrm{d}x_i \int f_B(x_j)\mathrm{d}x_j \left(1 - F(|x_i - x_j|)\right)$$

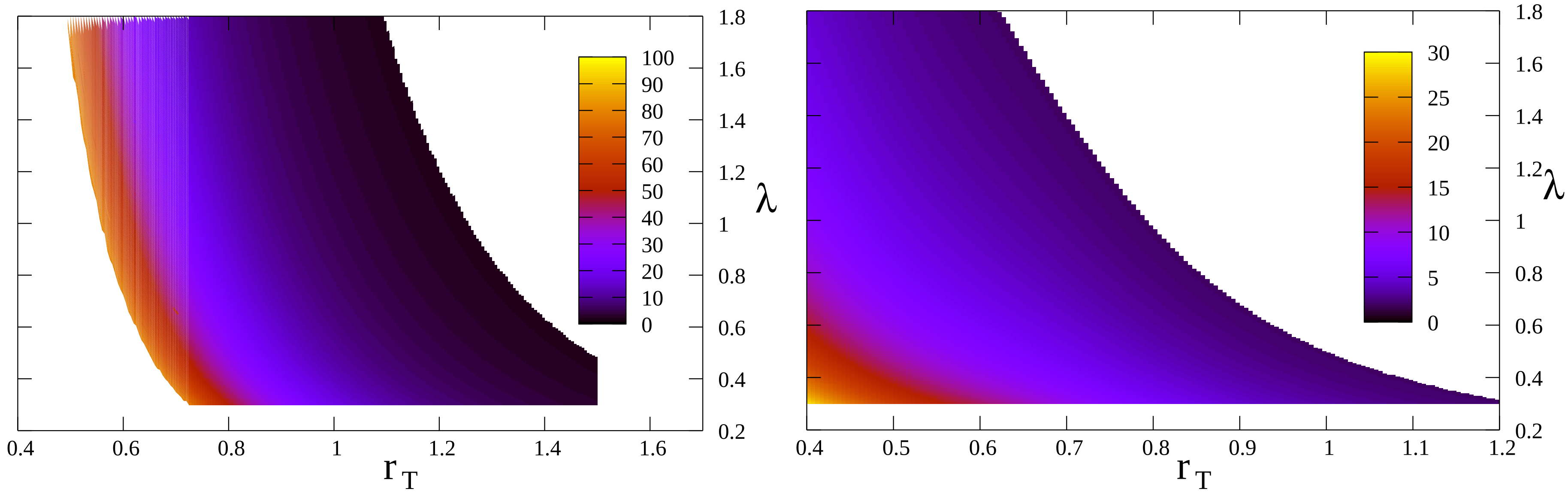
(Mathematically very similar to Glauber model) We assume a range of probability amplitudes for the exchange $i \leftrightarrow j$ with rapid fall-off at distances Λ_{QCD}^{-1}) (confinement) and right N_c scaling ($\sim \lambda/N_c$)

$$F(y) = \frac{\lambda}{N_c}\mathcal{N}\begin{cases} \theta(1-\frac{y}{r_T}) \\ \exp\left(-\frac{3}{4}\frac{y^2}{r_T^2}\right) \\ \frac{2r_T^2}{\pi y^2}\sin^2\left(\frac{y}{r_T}\right) \end{cases}$$

(Generic phenomenological propagators including confinement, eg Gribov-Zwanziger)

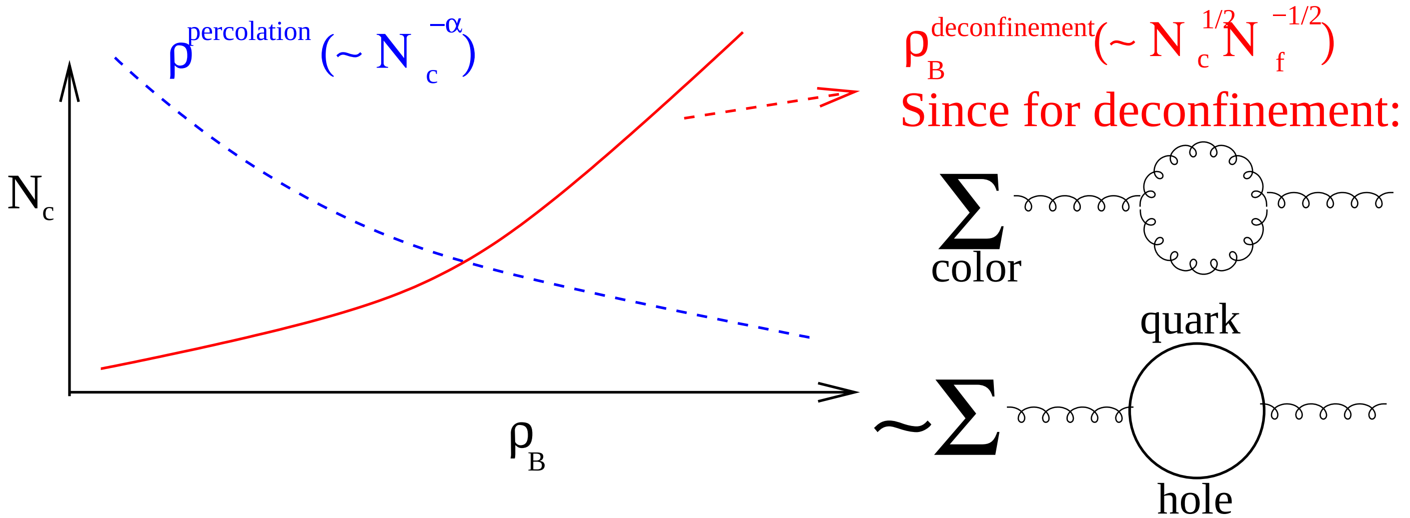
A percolation transition in N_c was found .

Keeping density fixed, Critical N_c for Θ-function $P_{i \leftrightarrow j}$ in position and momentum



"typical" Parameters of order unity give a critical number of colors for percolation well above 3. These are lower limits, since we assume hexagonal lattice (Skyrme cubic and disordered p_c higher).

But lets vary μ_Q:Percolation and deconfinement



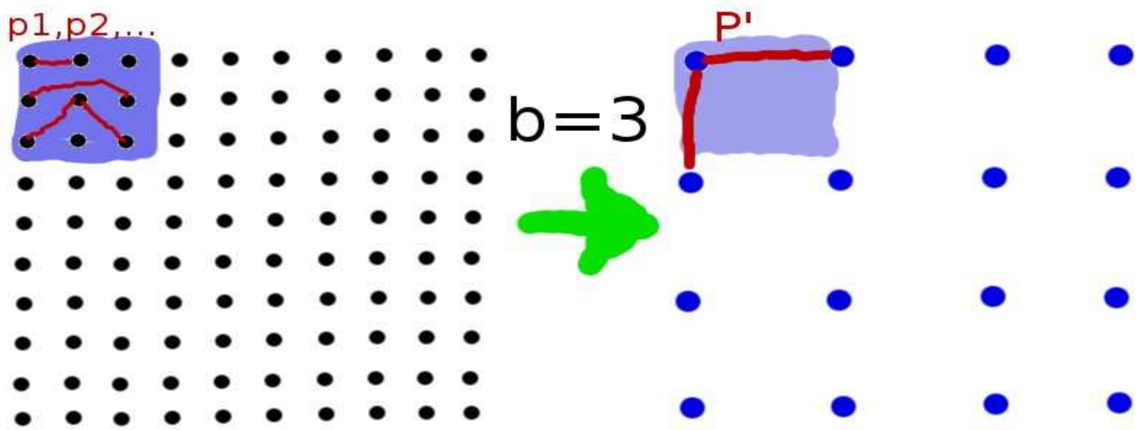
Percolation: $\rho - N_c$ anti correlated.

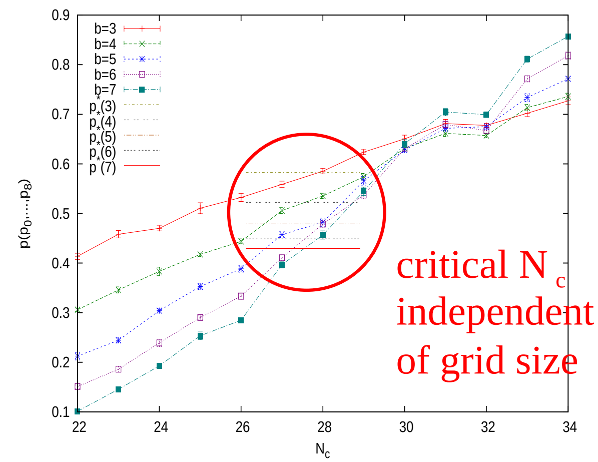
Deconfinement: $\rho - N_c$ correlated $\mu_B^{dec} \sim N_c^{1/2} N_f^{-1/2} m_B \sim N_c^{3/2} N_f^{-1/2} \mu_q$

$N_c \leq N_c^{crit}$ Deconfinement happens below percolation, ie percolation transition does not exist separately from deconfinement

$N_c \geq N_c^{crit}$ Percolation, deconfinement separate (Quarkyonic phase?)

What is this critical N_c? Percolation in a “glass”: Conceptually similar, technically more involved





Gimel,Nicolai,Durand, J Phys A Math Gen 32 L515 (1999)

$$p^* \left(b, \Theta(x_T, \lambda, N_c)\right) = \Pi_{physical}\left(\Theta(x_T, \lambda, N_c)\right) + \beta b^{-y} \quad , \quad y = 0.81$$

Quarkyonic phase might exist at $\Lambda_{QCD} \leq \mu_Q \leq N_c N_f^{-1} \Lambda_{QCD}$

In PRL we neglected Density-N_c curvature and fixed density to $\mu_B \sim \Lambda_{QCD}$

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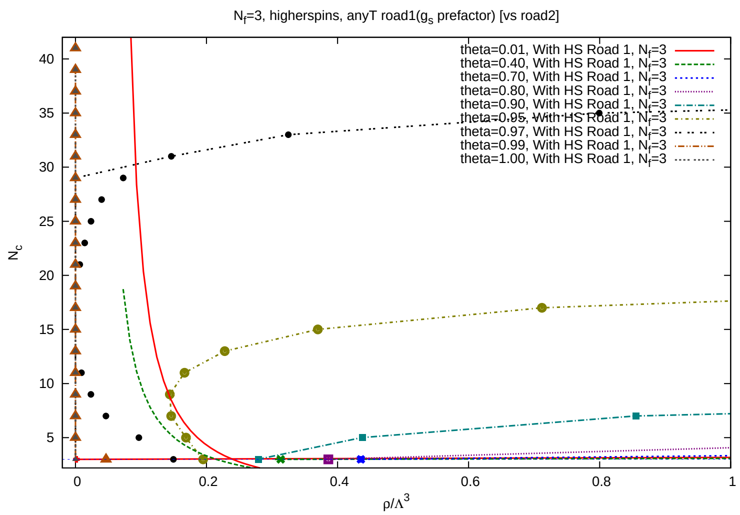
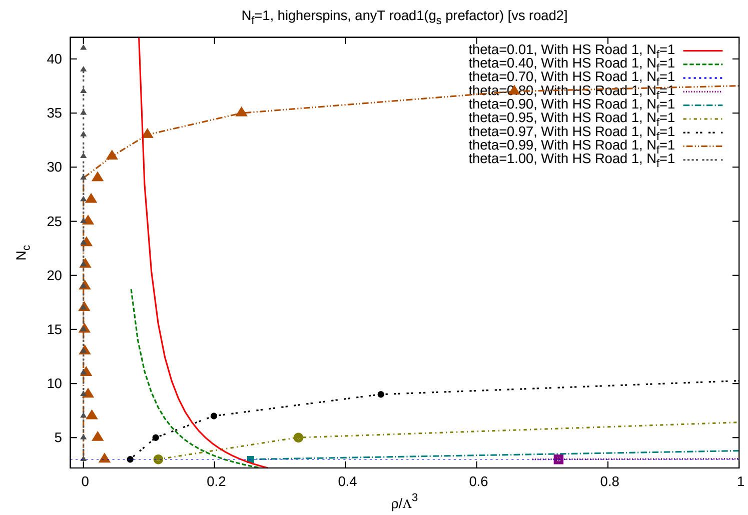


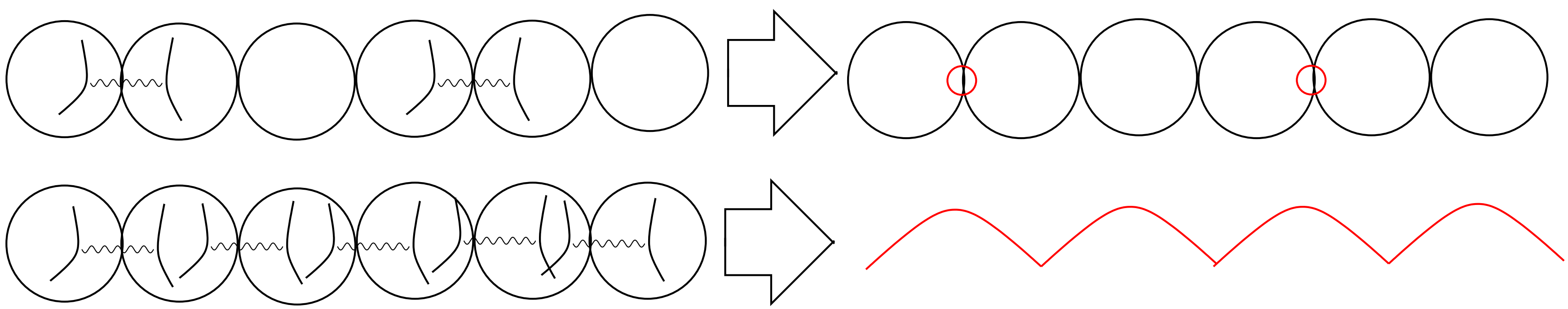


A sliver of $n - \rho - N_c = 3$ space which is percolating but confined seems to be there, but... Width depends a lot on whether $N_f = 2$ or $N_f = 3$. "Systematic error too big . Need phenomenology (an experimental signature for quarkyonic matter)!

Observing such a percolating phase: What does it look like?

Baryons are heavy and immobile "background"

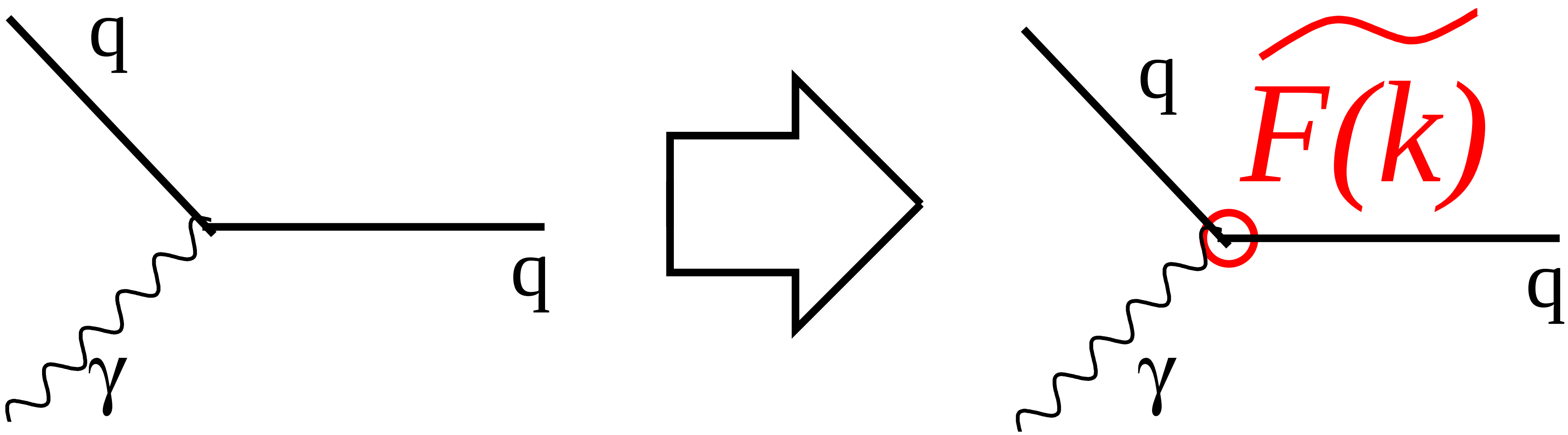
Quarks are delocalized, since $\rho_{baryon}^{-1/3} \leq R_{baryon}$ but color confined Color-Flavor-Spin separation could ensure "free" quarks while localizing color



EoS similar to QGP. transport coefficients "non-trivial" (2-scale system)
An immediate physical analogy: conductor in QED, with baryons playing the role of atoms, percolation analogous to conductor-insulator transition

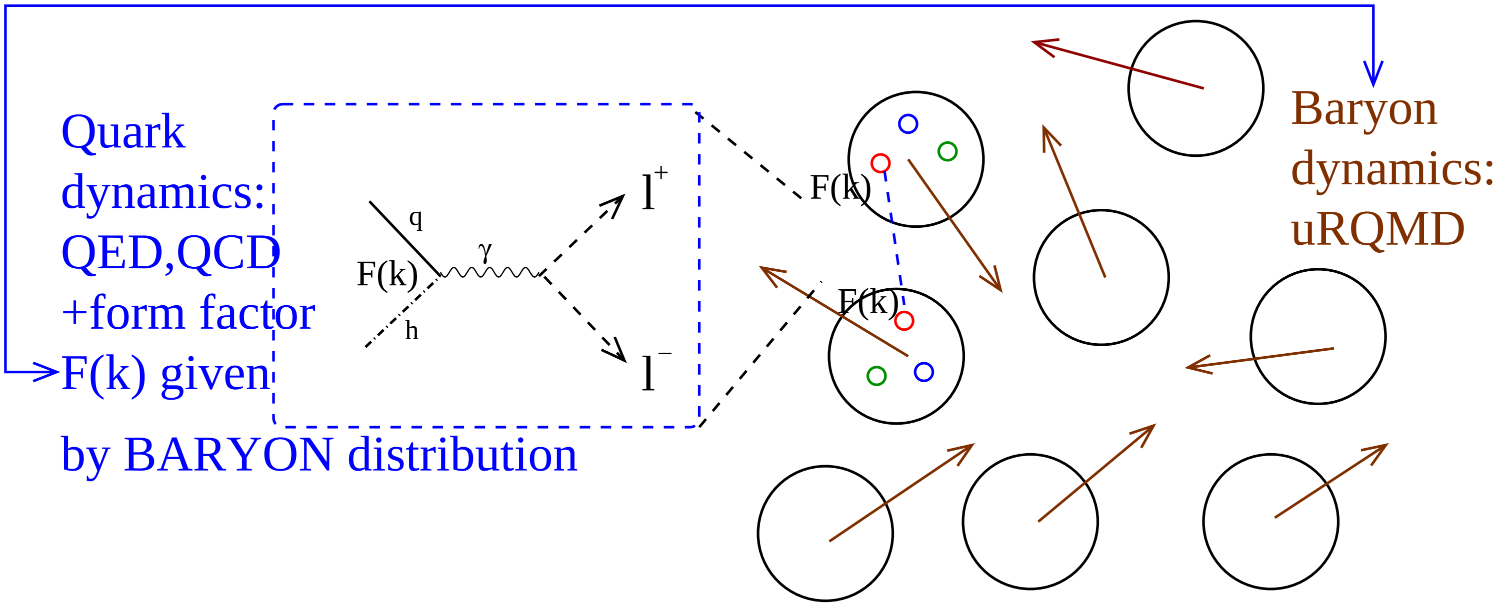
pQCD but not quite: the role of baryons

Unlike pQCD, quarkyonic matter's "vacuum" is a classical dense baryon state. Treating baryons as mean fields will give a momentum-dependent form factor to all pQCD processes



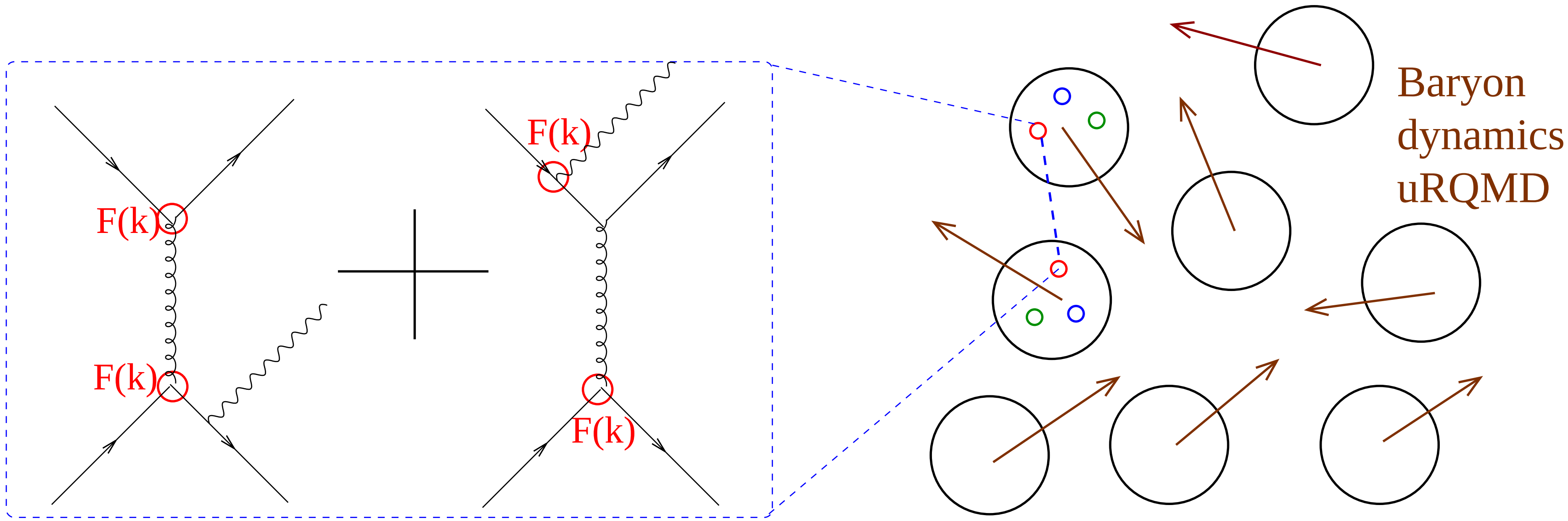
$F(k)$ gives the F.T. of the baryonic gluon content. For the equation of state, it should just be a $\mathcal{O}(1)$ normalization factor, but for scattering processes it is a qualitative difference from naive QCD.

Modeling quarkyonic matter for FAIR/NICA/RHIC@low$\sqrt{s}$



$$\Gamma \sim \left| \overbrace{\Psi(k_1)\Psi^*(k_2)}^{\hat{H}^{mf}_{baryons}|\psi>=E_k|\psi>} \quad \underbrace{\mathcal{M}(k_{1,2,out})}_{pQCD} \right|^2 , \Psi(k) \sim \underbrace{e^{\left[-\frac{k^2}{\Lambda^2_{QCD}}\right]} \left(\sum_i^{baryons} \overbrace{\exp\left[i\vec{k}_i.\vec{x_{0i}}\right]}^{\vec{x_0}\leftarrow uRQMD} \right)^2}_{FT\quad baryon\quad mean\quad field}$$

Experimental implications: direct photon via quarkyonic Brehmsstrahlung

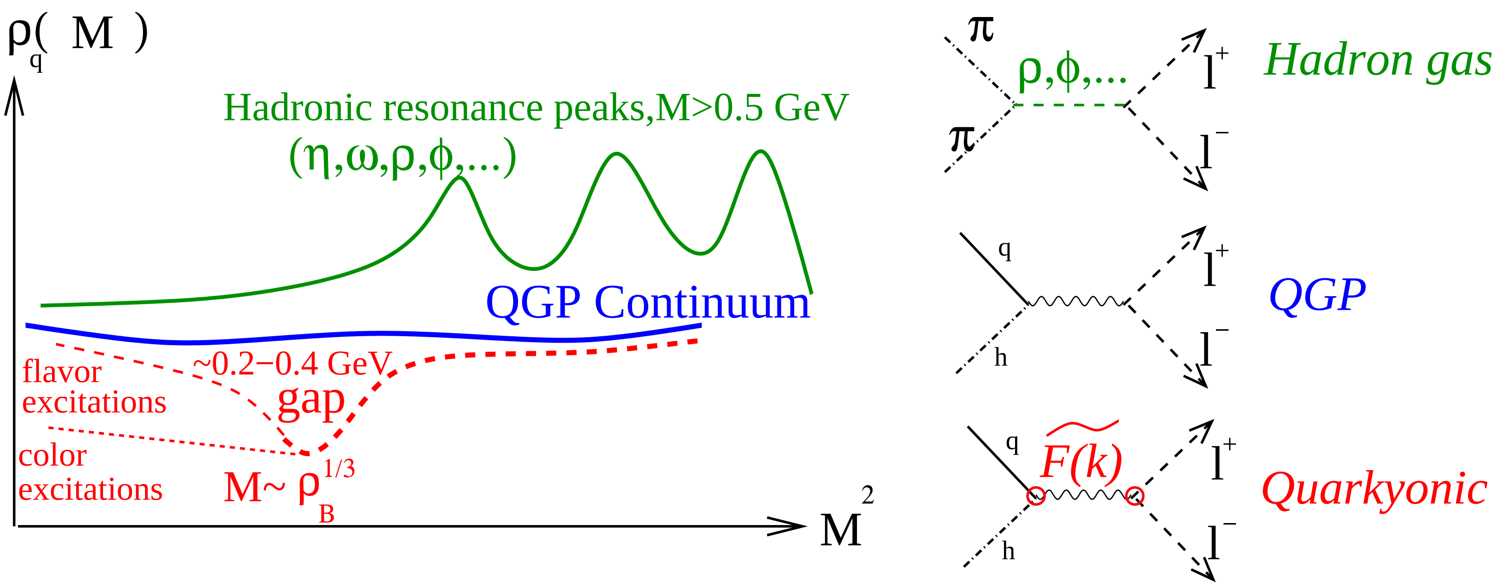


Calculation in progress: structures reflecting baryon radius,baryon flow expected

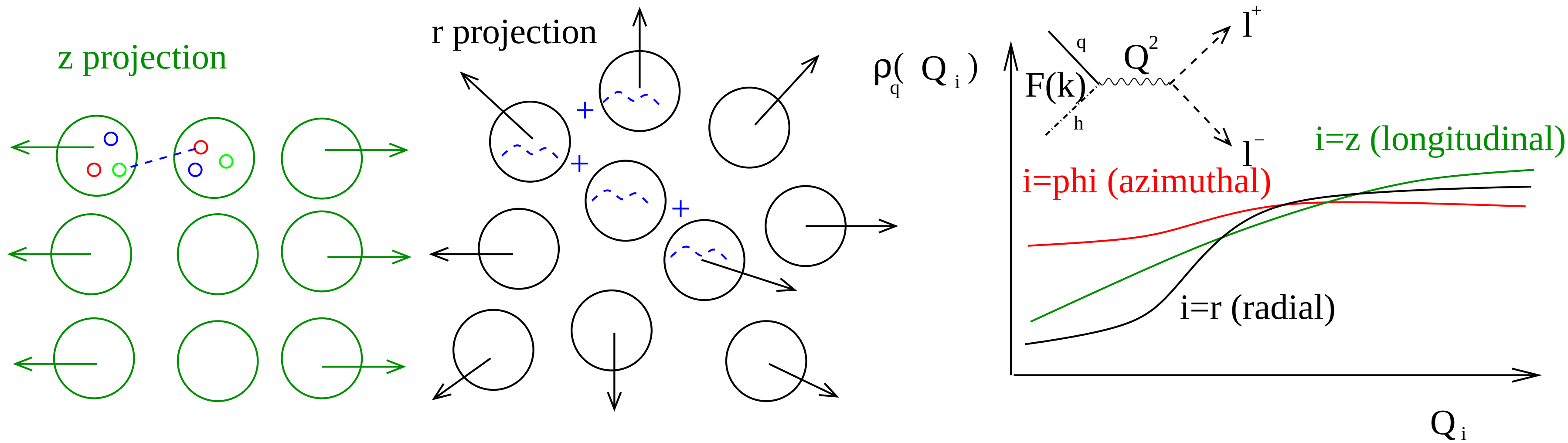
Experimental implications: dilepton production via quark-hole annihillation

Holes essential, so Initial state not enough, need

$$\ln Z_{quarks} \simeq \ln \left[\left(1 + \exp \left[\frac{E_n - \mu_q}{T} \right] \right) \right], \left(\gamma_\mu \partial^\mu + m + V_{baryons}^{mf} \right) \psi = E_n \psi$$



If baryons uniformly distributed, we have a qualitative signature: Analogue of energy gap in conductors due to Bloch-invariance of the quark wavefunction but alas, at high density baryons might be highly irregular!



Event by event fireball structure not regular, but Collective structures exist in events flow profile (radial, longitudinal flow) and baryons have repulsive potential, soo structures in 3D dilepton spectral function $Q_{z,r,\phi}$ bound to exist!

Conclusions

- Large N_c expansion and asymptotic freedom imply quark degrees of freedom could appear even at confinement!
- On the other hand, not at all clear $N_c = 3 \simeq N_c \to \infty$
  Phase transition between the two likely to certain
- Percolation a natural model for quarkyonic matter, analogy with conductor in QED
- It is not clear whether percolating but confined phase possible at $N_c = 3$
- Phenomenology of quarkyonic matter needed. Electromagnetic probes best candidates