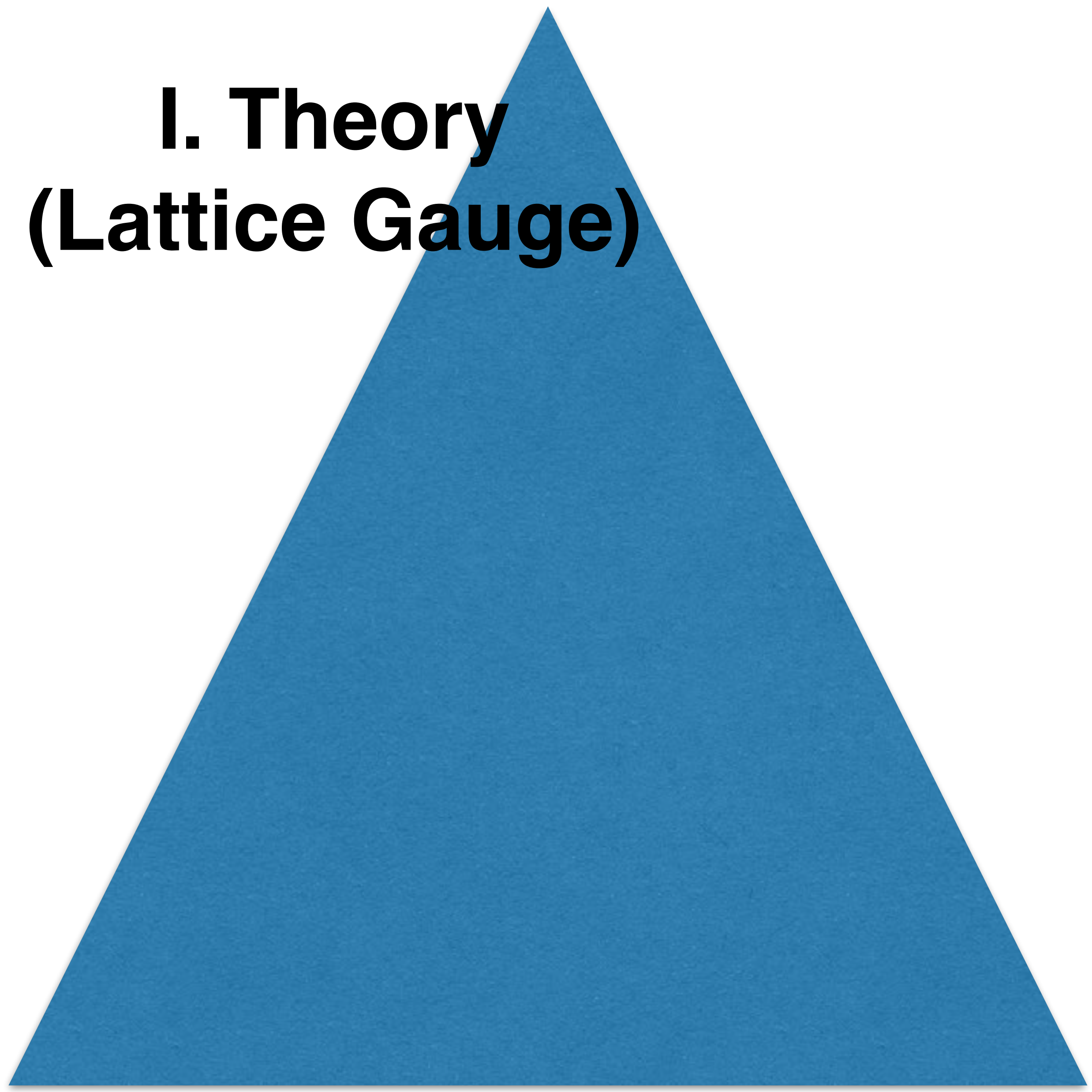
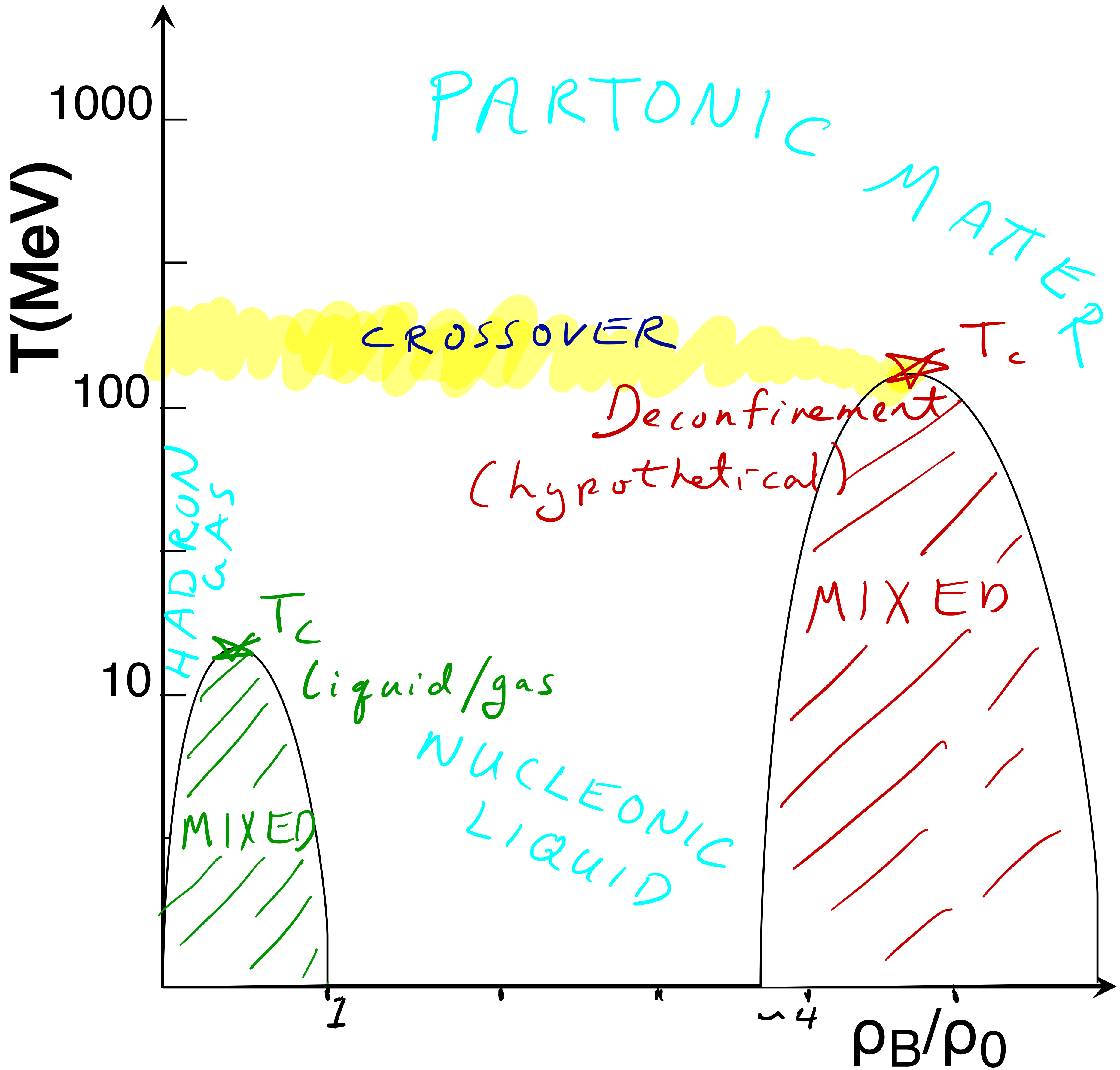
Relativistic Heavy Ion Collisions



PHASES OF QCD



Theory Basics

As you heat the vacuum…

- **Density depends only on T**

$$\rho_{\text{hadrons}} = \sum_{\alpha}(2S_{\alpha}+1)\int \frac{d^3p}{(2\pi\hbar)^3}\,\frac{e^{-E_p/T}}{1\mp e^{-E_p/T}}$$

hadrons=π,K,p…

- **When T≳165 MeV, ρ≳1/V_{hadron} and quarks are confused**
- **For T>>165 MeV,**

$$\rho_{\text{partons}} = \sum_{a}(2S_{a}+1)\int \frac{d^3p}{(2\pi\hbar)^3}\,\frac{e^{-E_p/T}}{1\mp e^{-E_p/T}}$$

partons=u,d,s,gluons (56 deg.s of freedom)

Theory Basics

For $T \gtrsim 165$ MeV,

- **Create QGP (Quark Gluon Plasma)**
- **Restore Chiral Symmetry**
  - **Symmetry related to ~massless quarks**
  - **Dissolve quark-antiquark condensate**

Lattice Gauge Theory

Integrate over field configurations —> Partition function

$$Z(\beta = 1/T) = \sum_i \langle i | e^{-\beta H} | i \rangle$$

$$= \sum_{i_1 \cdots i_N} \langle i_1 | e^{-\delta\beta H} | i_2 \rangle \langle i_2 | e^{-\delta\beta H} \cdots | i_N \rangle \langle i_N | e^{-\delta\beta H} | i_1 \rangle, \quad \delta\beta = \beta / N$$

Change basis to "fields"

$$|\phi\rangle = \exp\left\{ i\phi a - \phi^* a^\dagger) \right\} |0\rangle, \;\; \phi = p + iq$$

$$\sum_i |i\rangle\langle i| \to \int dp\, dq\, |\phi\rangle\langle\phi|$$

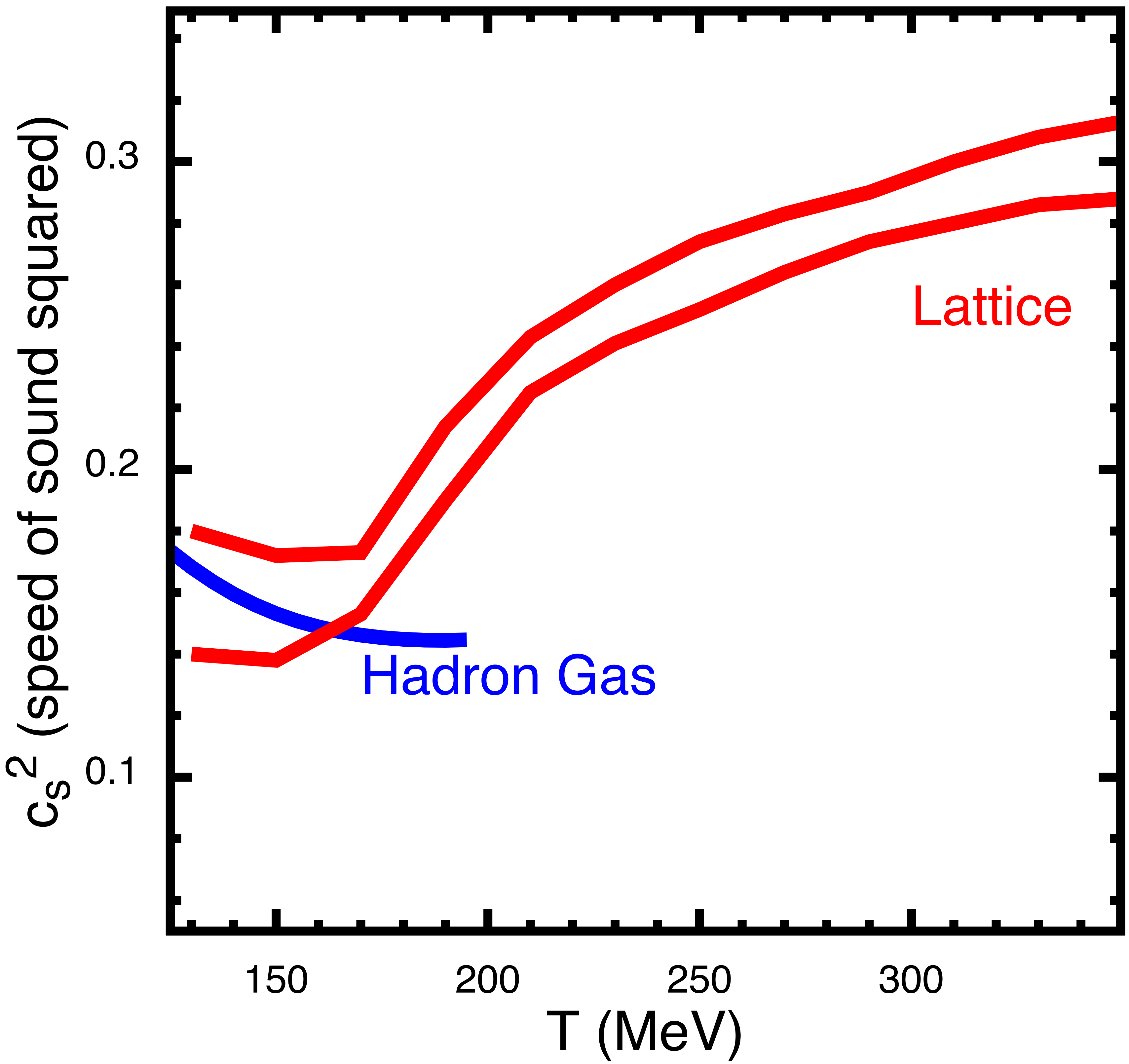
$$\langle \phi(t) | \phi(t+\delta t) \rangle = \exp\left\{ (ip\dot{q} - iq\dot{p})\delta t / 2 \right\}, \sim\sim \langle \phi(t) | e^{-iH\delta t} | \phi(t+\delta t) \rangle = \exp\left\{ iL(p,q)\delta t \right\}$$

Problem reduced to high-dimensional integral

$$Z(\beta) = \prod_{i_1 i_2 \cdots i_N} \int dp_1 dq_1 dp_2 dq_2 \cdots dp_N dq_N \exp\left\{ i \int_0^{i\beta} d\tau \;\; L(p(\tau), q(\tau)) \right\}$$

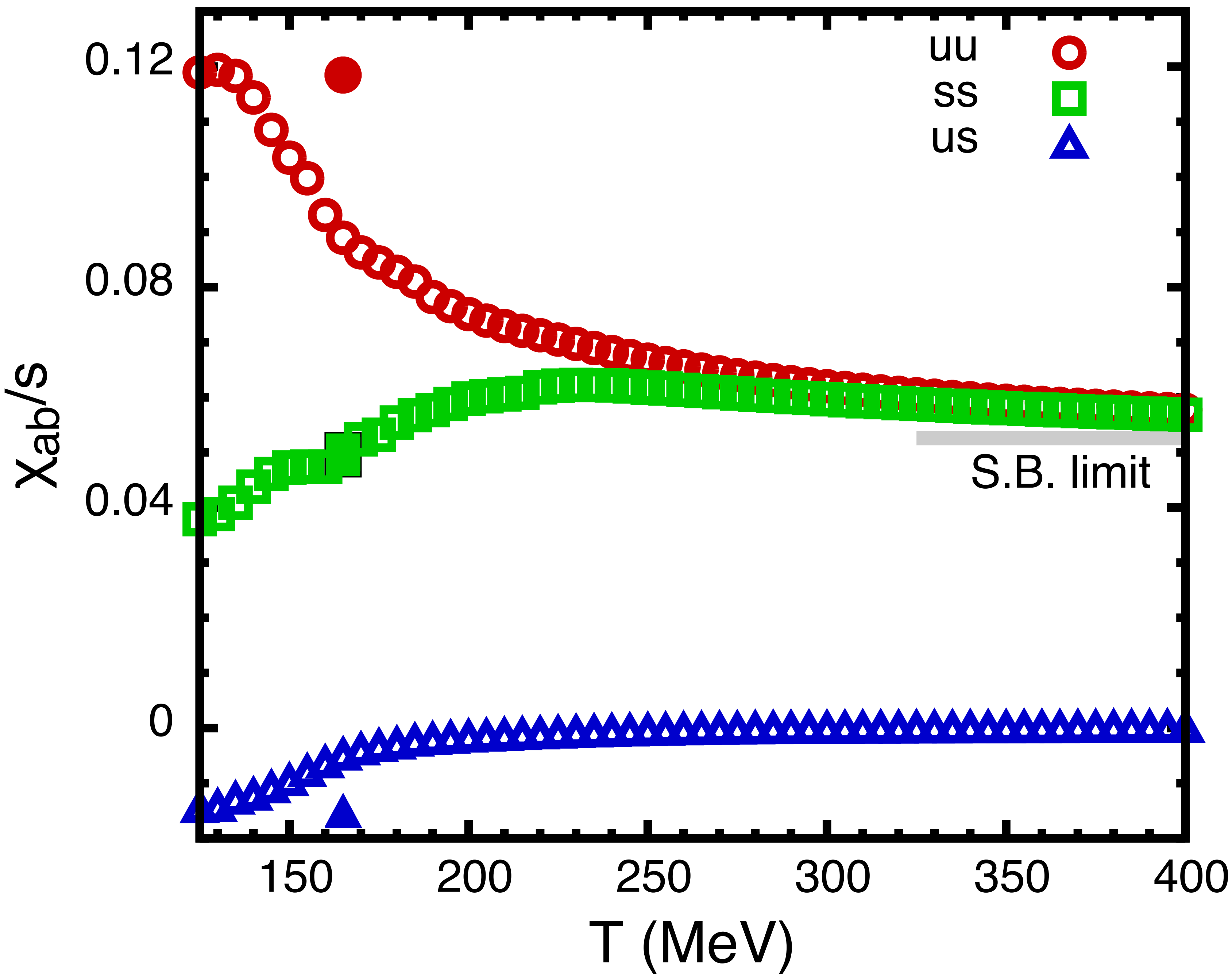
Three Lattice Results

1. Equation of State



Three Lattice Results

2. Charge Fluctuations

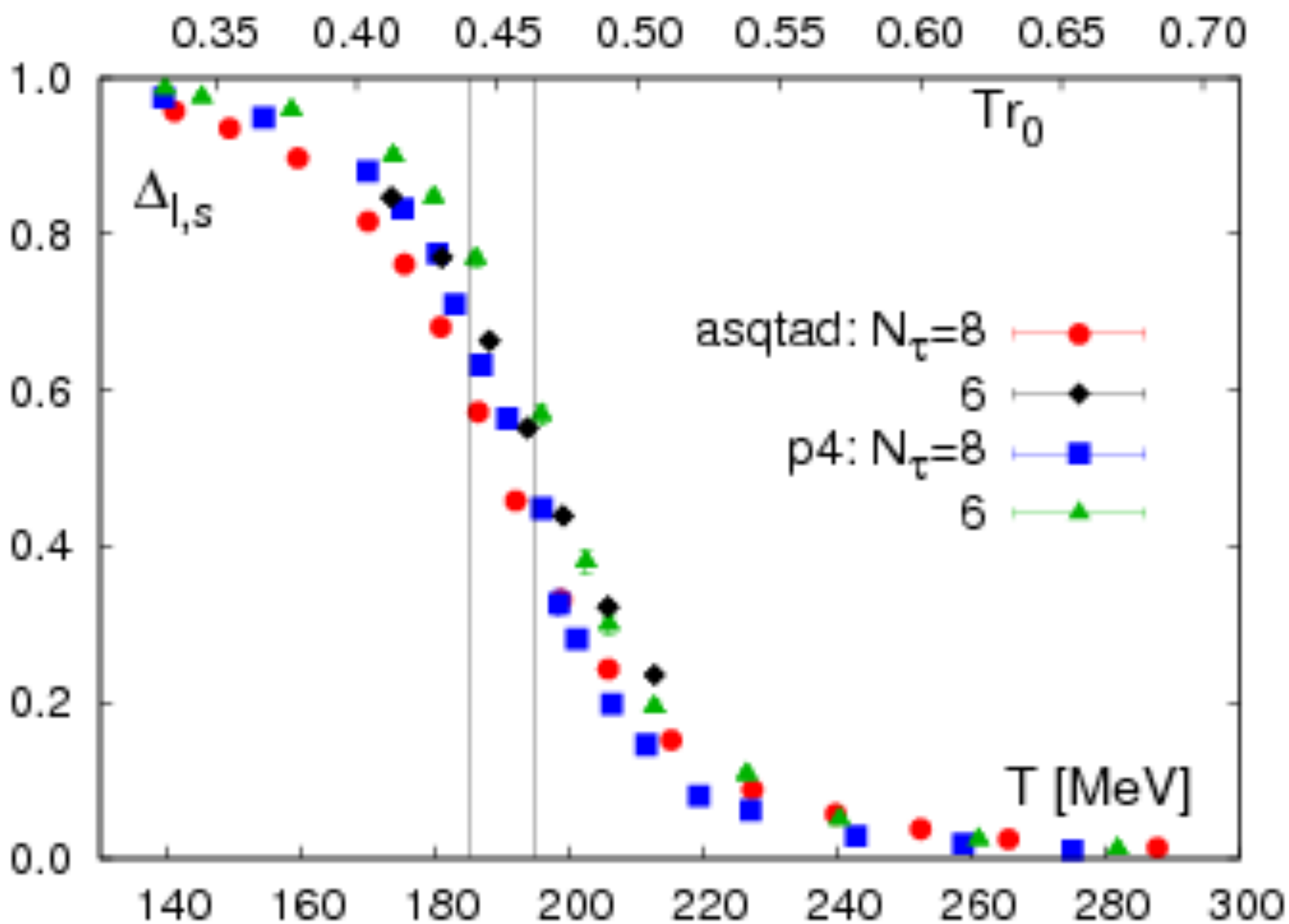


$$\chi_{ab} = \frac{\langle Q_a Q_b \rangle}{V}$$

$$\chi_{ab}(T \to \infty) = \delta_{ab}(n_a + n_{\bar{a}})$$

Three Lattice Results

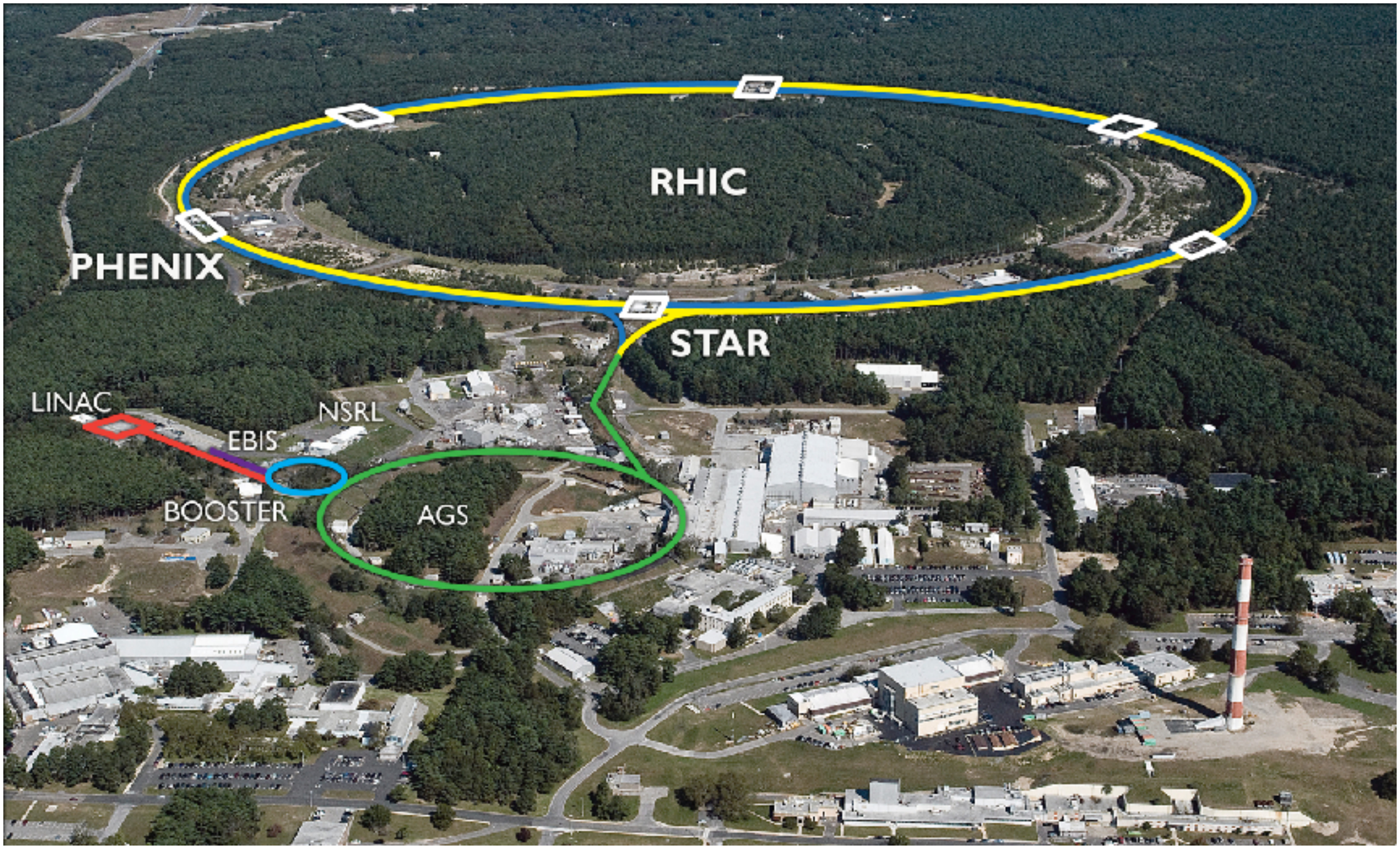
3. Melt the q-qbar condensate, aka ⟨σ⟩ condensate, aka restore chiral symmetry



Condensate couples to quarks and gives them mass

Facilities (RHIC)

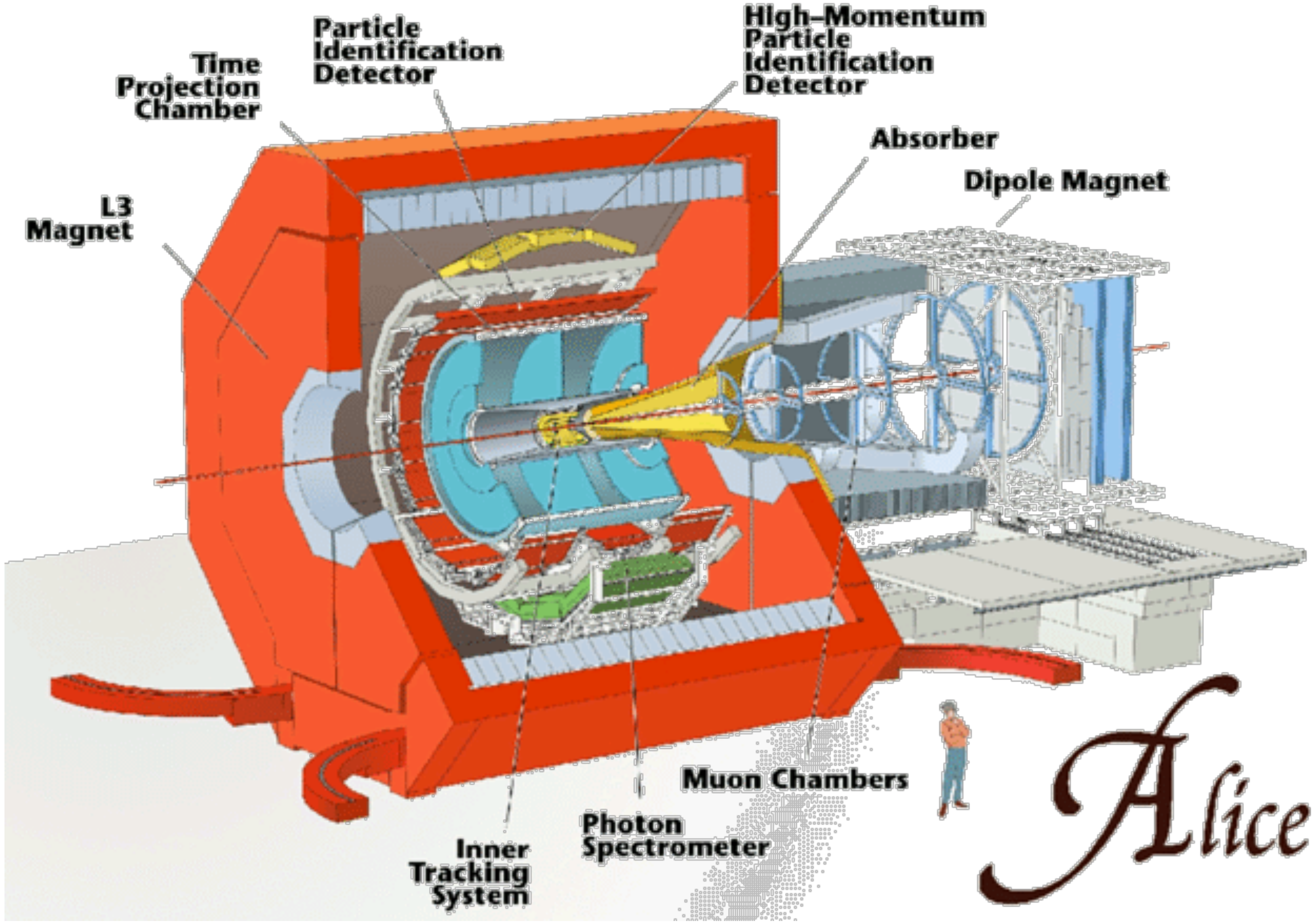
100 GeV Au + 100 GeV , can vary beams and energy



Collaborations: STAR, PHENIX

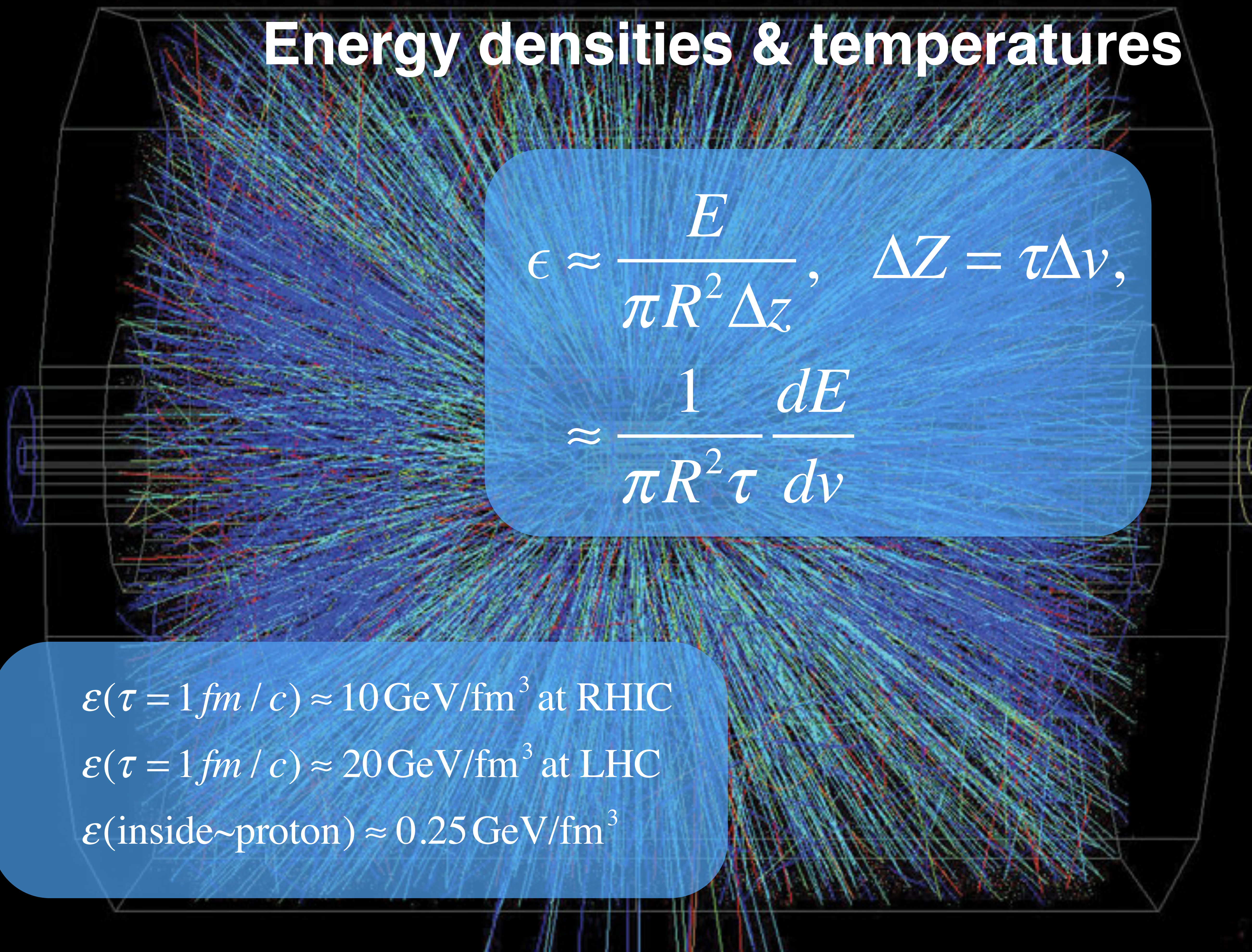
Facilities (LHC)

6.5*A* TeV Pb +6.5*A* TeV Pb



Collaborations: ALICE, ATLAS CMS

Energy densities & temperatures



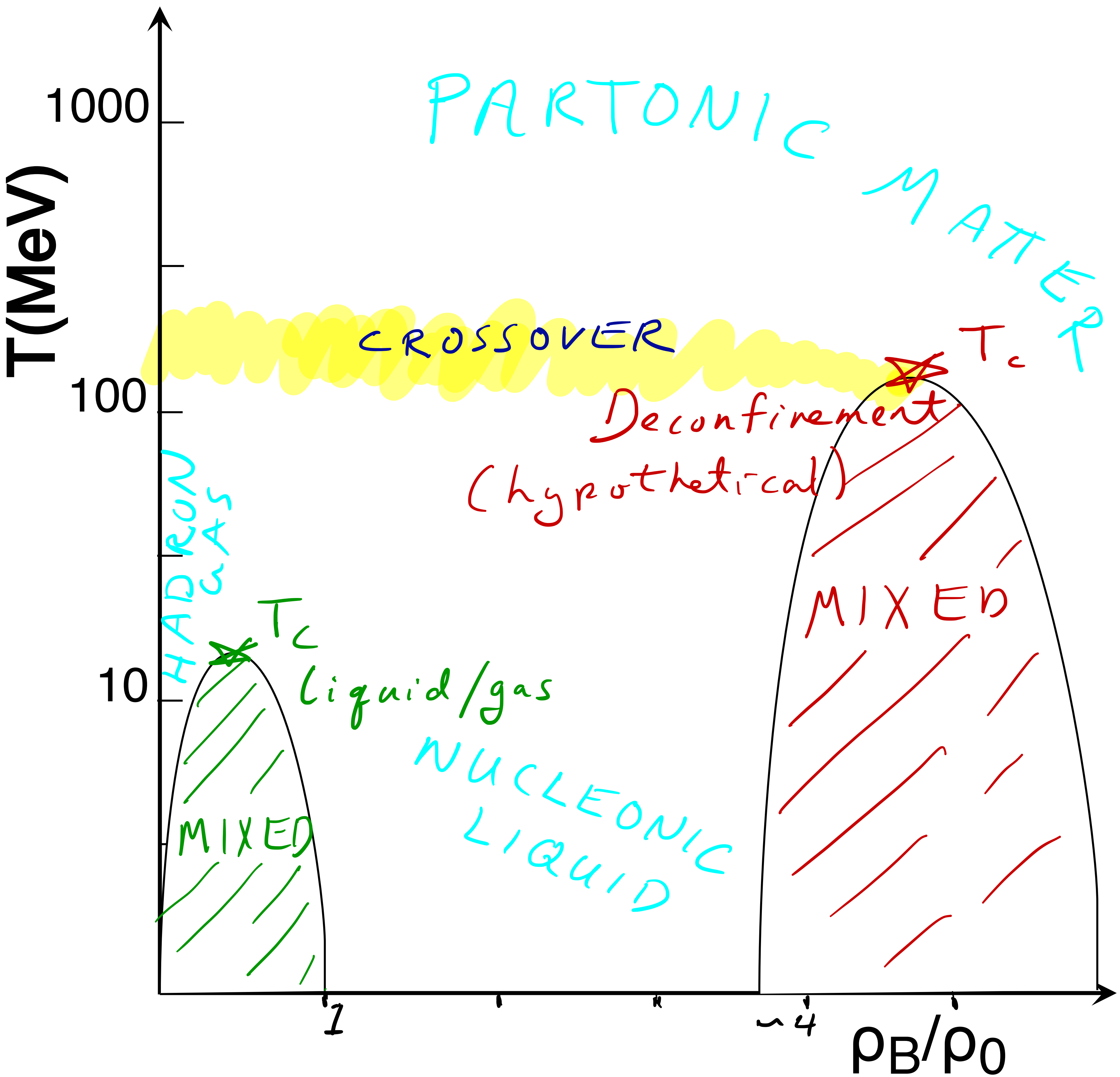
$$\epsilon \approx \frac{E}{\pi R^2 \Delta z}, \quad \Delta Z = \tau \Delta v,$$

$$\approx \frac{1}{\pi R^2 \tau} \frac{dE}{dv}$$

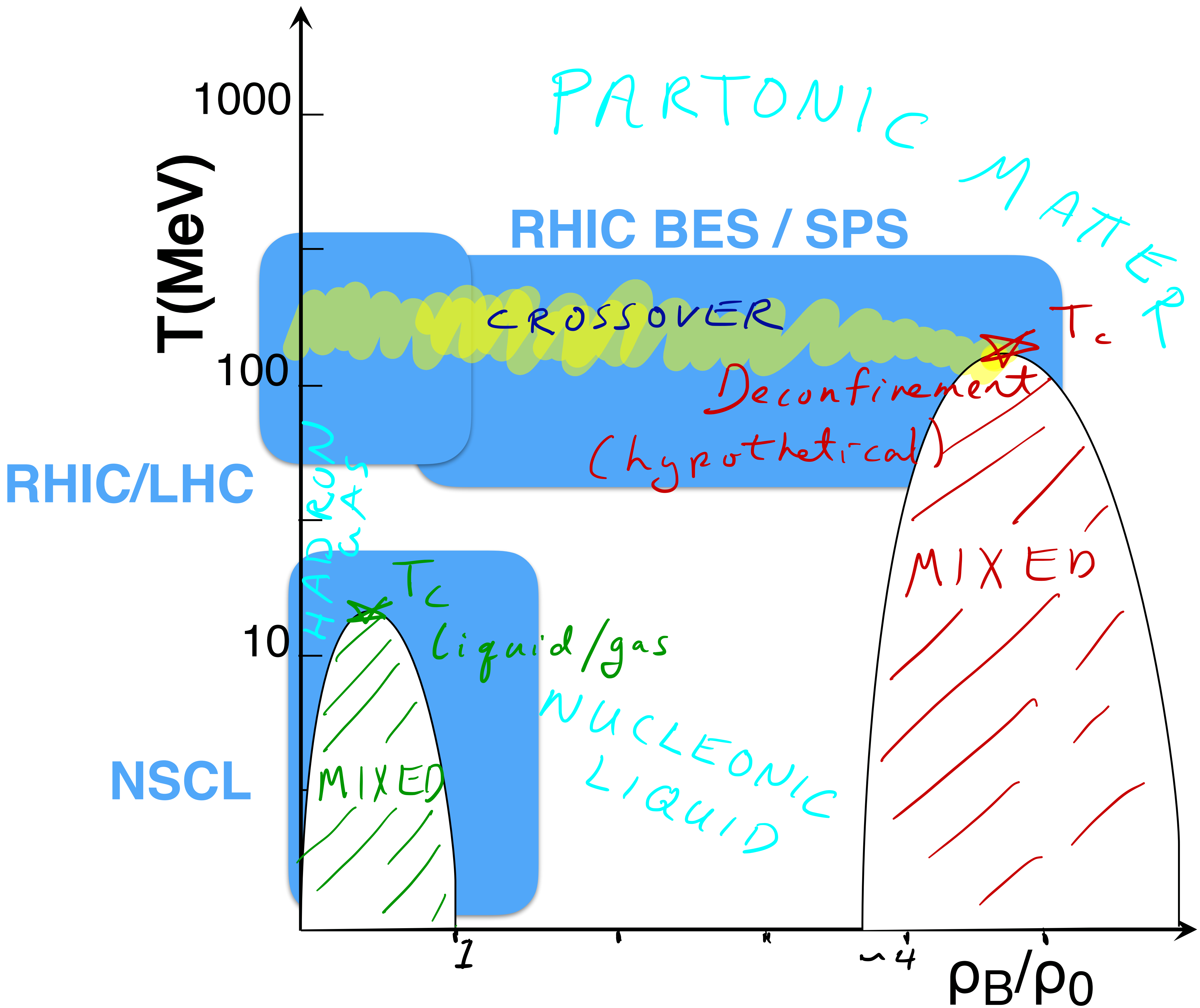
$\varepsilon(\tau = 1\,fm/c) \approx 10\,\mathrm{GeV/fm^3}$ at RHIC

$\varepsilon(\tau = 1\,fm/c) \approx 20\,\mathrm{GeV/fm^3}$ at LHC

$\varepsilon(\mathrm{inside{\sim}proton}) \approx 0.25\,\mathrm{GeV/fm^3}$



T(MeV)
1000
100
10
PARTONIC MATTER
CROSSOVER
Tc
Deconfinement
(hypothetical)
HADRON GAS
Tc
Liquid/gas
MIXED
NUCLEONIC LIQUID
MIXED
1
~4
ρB/ρ0



T(MeV)
1000
100
10
ρB/ρ0
1
~4
RHIC BES / SPS
RHIC/LHC
NSCL
PARTONIC MATTER
CROSSOVER
Tc
Deconfinement
(hypothetical)
MIXED
HADRON GAS
Tc
liquid/gas
NUCLEONIC LIQUID
MIXED

Observables

- **Spectra**
  driven by radial flow and final temperature
- **Elliptic Flow**
  $v_n \equiv \langle \cos n\phi \rangle$
- **Femtoscopic correlations**
  measure spatial extent of final *f(p,r,t)*
- **Jets**
  strongly damped by QGP
- **rare probes**
  charmonium states should be dissolved
- **numerous other correlations**
  related to chemistry or phase transition
- **direct photons and dileptons**
  known as penetrating probes
- **tens of PB of data are stored yearly**

MODELS

- **Pre-Equilibrium ($0<\tau<1$ fm/c)**
  mixture of gluonic fields and partons
  not decisively understood

- **Hydrodynamics ($T>160$ MeV)**
  relativistic, viscous
  most strongly affects results

- **Hadronic cascade ($T<160$)**
  microscopic evolution of *f(p,r,t)* for each species
  hydro can't handle 100 species flowing differently

- **Jets, rare probes, bulk correlations & EM probes**
  calculations overlaid on hydro evolution

- **Femtoscopic correlations**
  calculated from final *f(p,r,t)*

Comparing to Experiment

- **Spectra**
  sensitive to eq. of state, initial ε

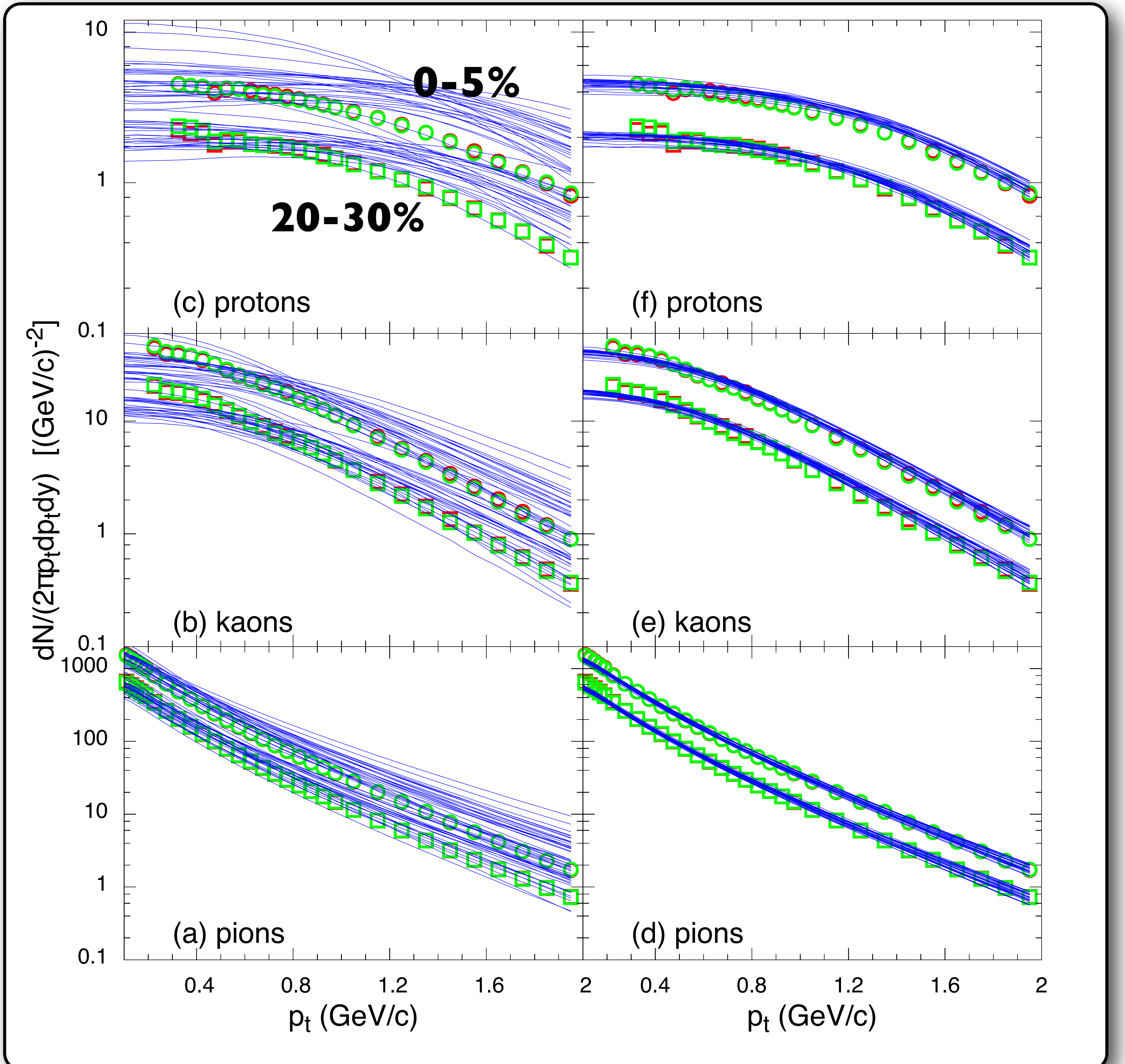
- **Elliptic flow**
  strongly affected by viscosity

- **Femtoscopy**
  sensitive to eq. of state

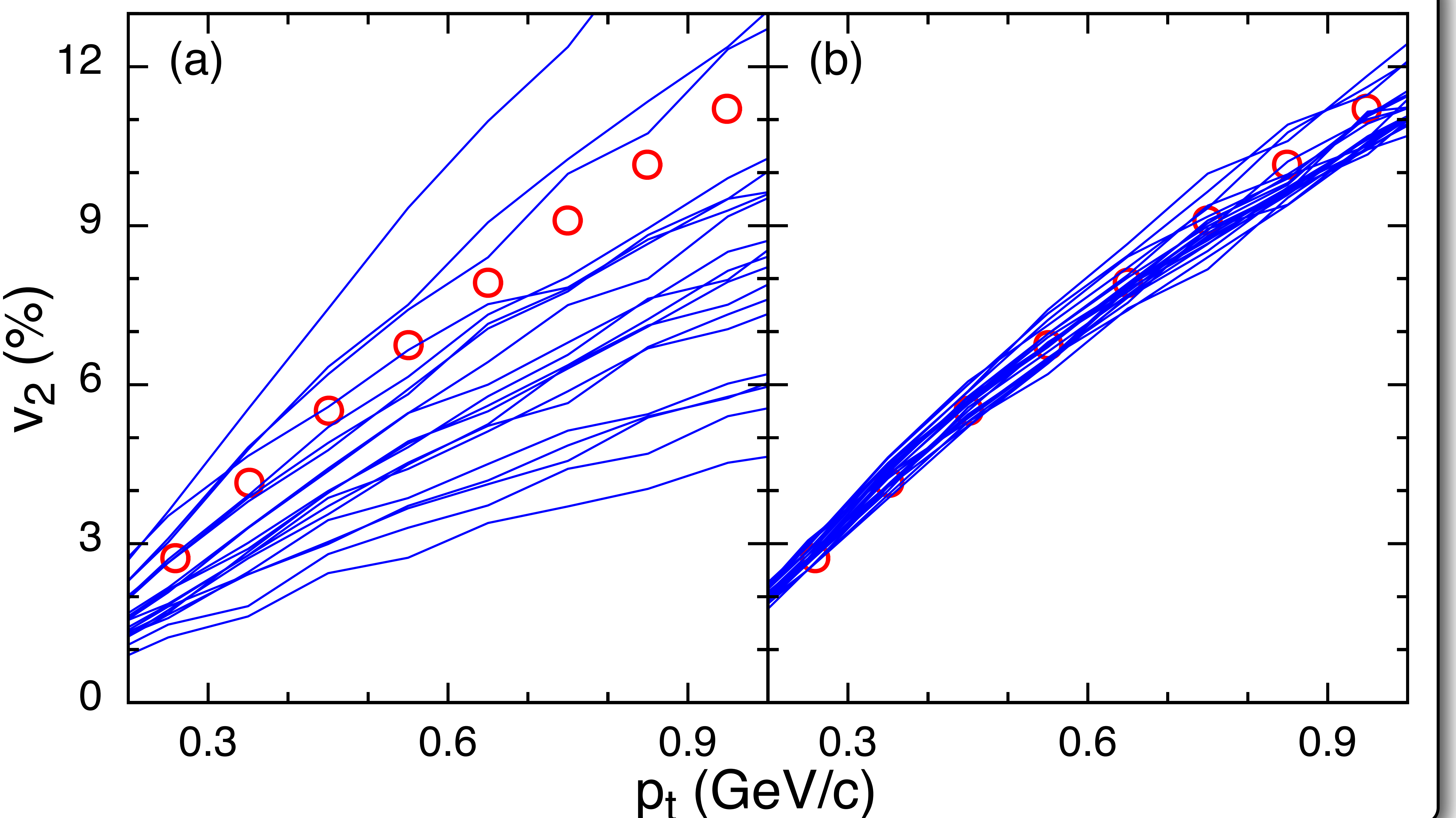
- **Jets, rare probes, EM probes**
  related physics

- **Correlations**
  sensitive to chemistry, phase structure

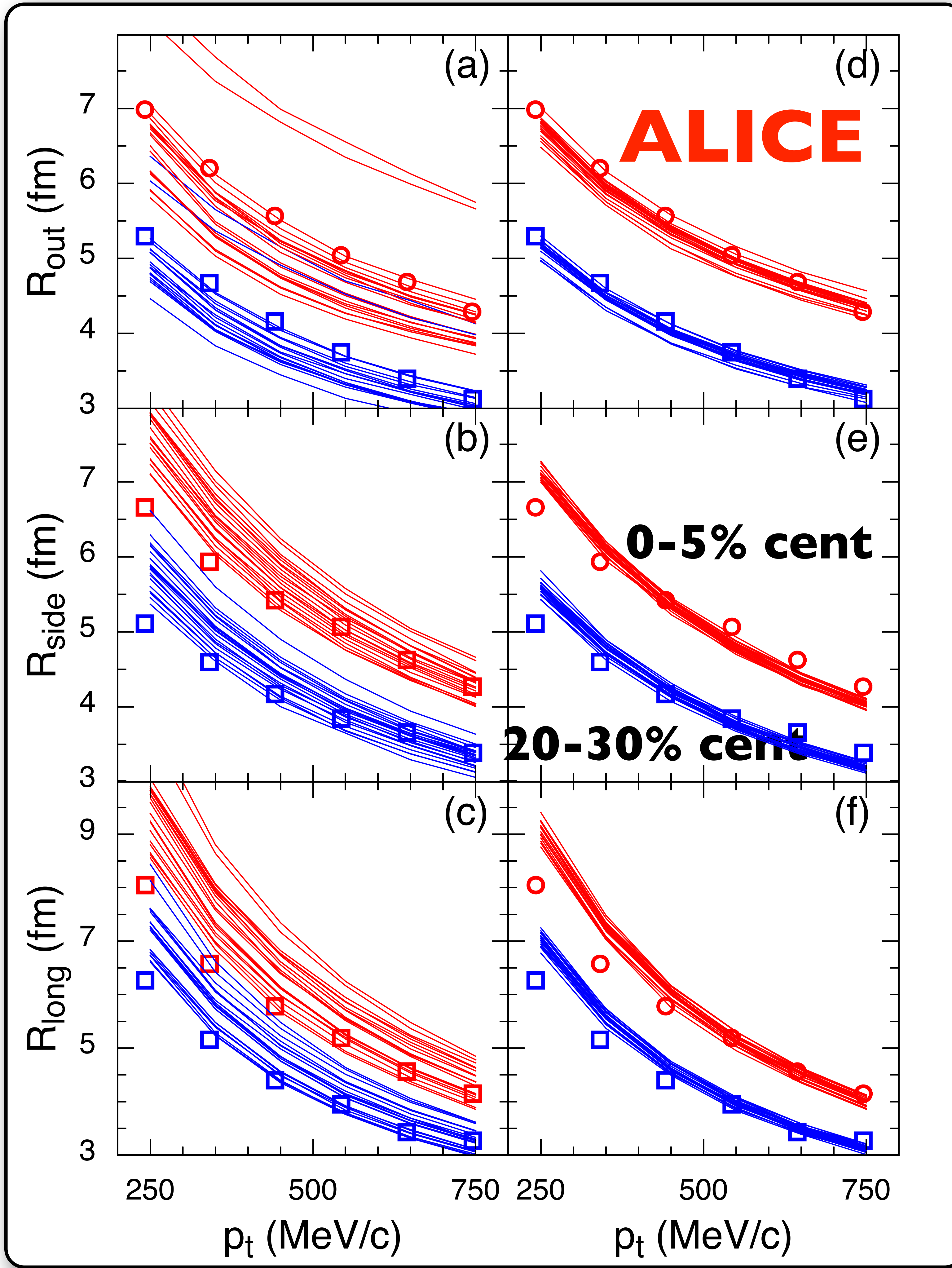
Spectra


0-5%
20-30%
(c) protons
(f) protons
(b) kaons
(e) kaons
(a) pions
(d) pions
dN/(2πp$_t$dp$_t$dy) [(GeV/c)$^{-2}$]
p$_t$ (GeV/c)
p$_t$ (GeV/c)
10
1
0.1
10
1
0.1
1000
100
10
1
0.1
0.4
0.8
1.2
1.6
2
0.4
0.8
1.2
1.6
2

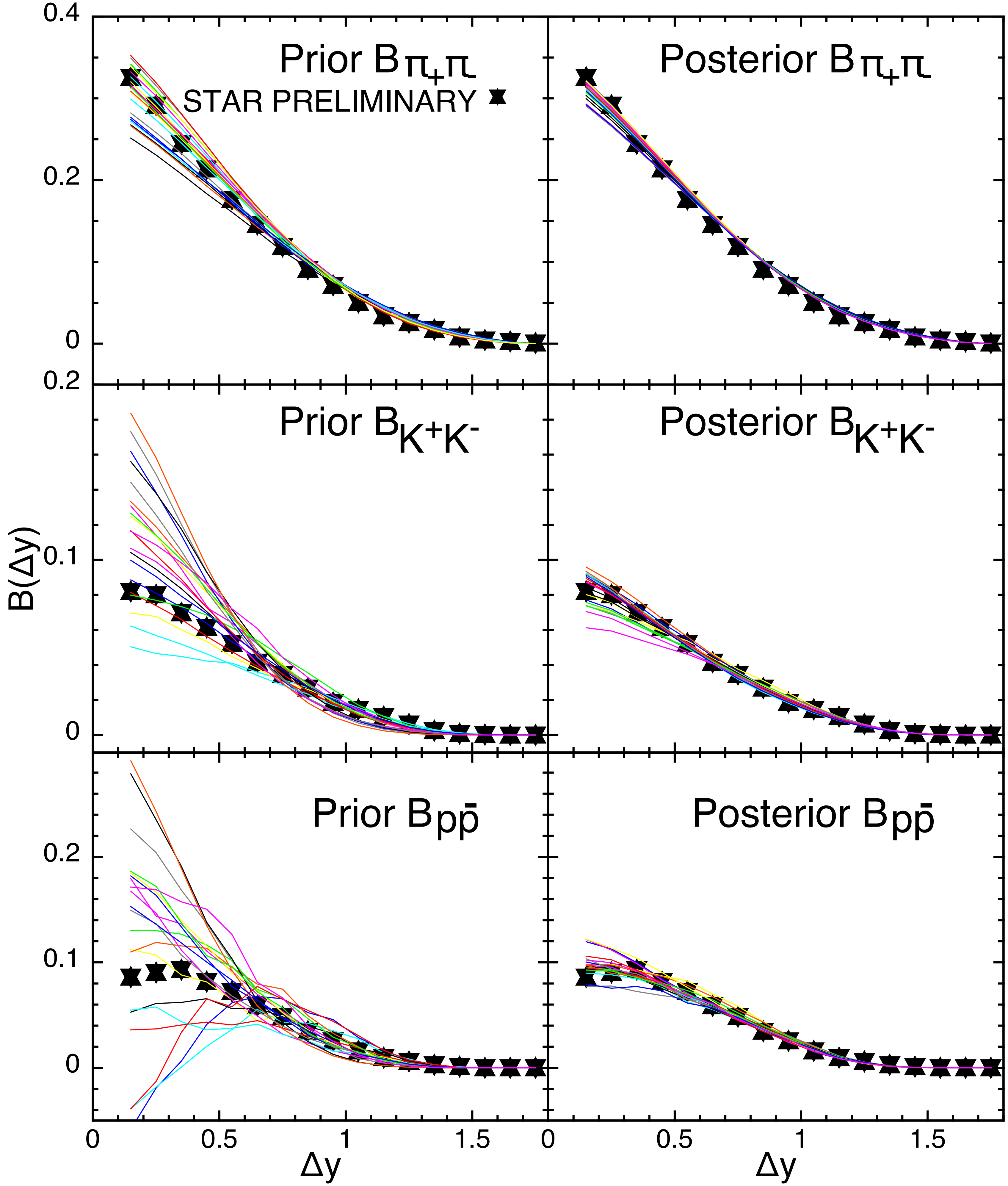
V_2 (elliptic flow)



Femtoscopic Radii



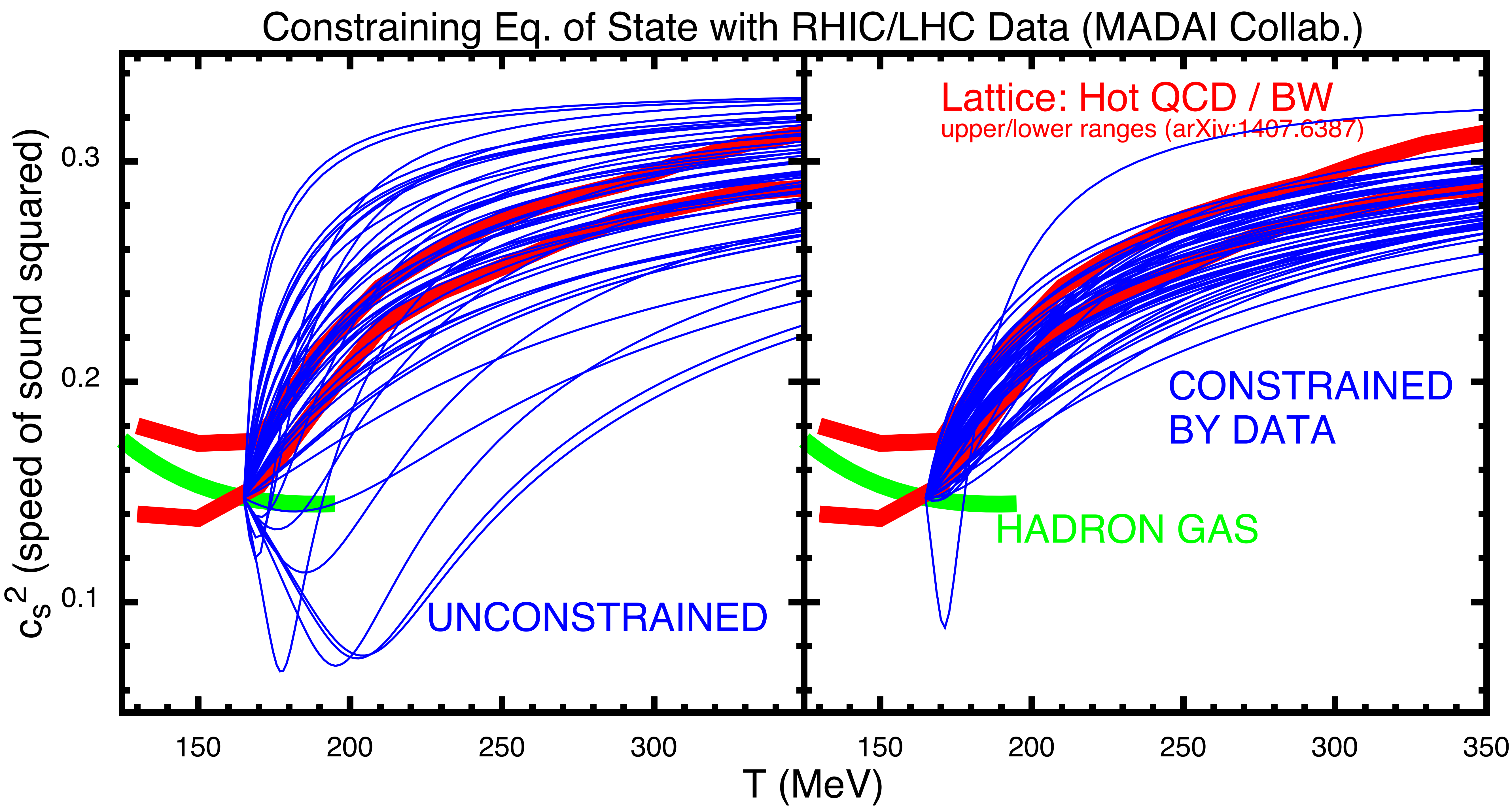
Charge Correlations



$\pi^+\pi^-$

K^+K^-

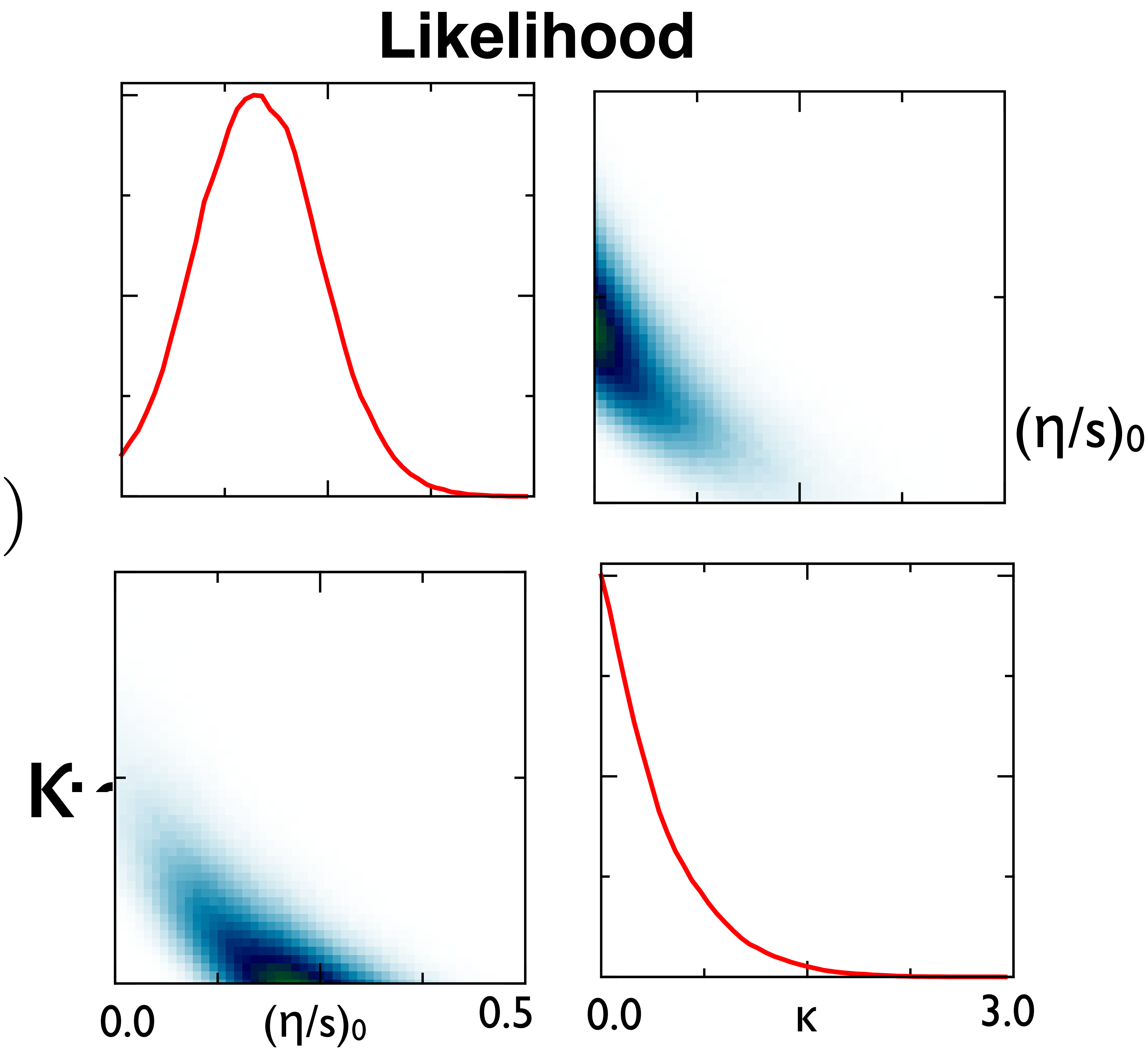
$p\overline{p}$



Constraining Eq. of State with RHIC/LHC Data (MADAI Collab.)
Lattice: Hot QCD / BW
upper/lower ranges (arXiv:1407.6387)
CONSTRAINED
BY DATA
HADRON GAS
UNCONSTRAINED
c_s^2 (speed of sound squared)
0.3
0.2
0.1
150
200
250
300
350
T (MeV)

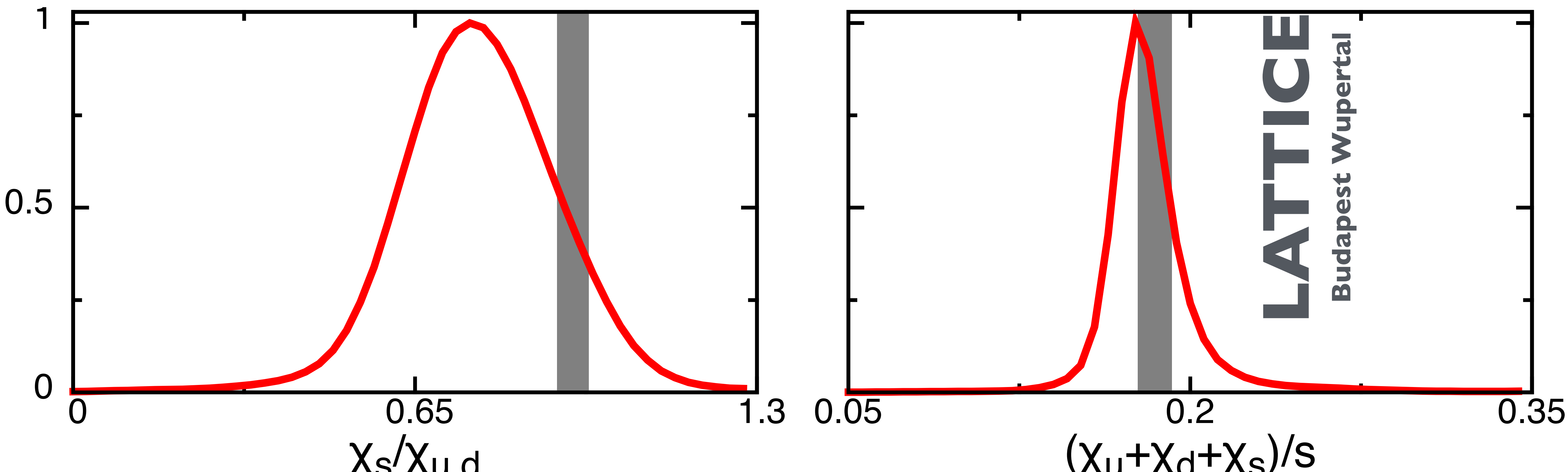
Viscosity from spectra, femtoscopy, elliptic flow at RHIC & LHC

$$\eta/s = (\eta/s)_0 + \kappa \ln(T/165)$$



Charge fluctuations from charge correlation measurements

Likelihood from Data Comparison



Summary

Strong Evidence for:

- SE tensor(**pressure**) near **equilibration**
- **chemically equilibrated** QGP
- extremely good **liquid** with low viscosity
- strong jet damping ➔ **strongly interacting** liquid

Missing:

- Experimental evidence of **chiral symmetry restoration**
- **Baryon Density** dependence of Eq. of State,
  QCD critical point