Dileptons with a coarse-grained transport approach

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May 13, 2015

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Outline

1 Electromagnetic probes (theory perspective)
   - QCD and accidental symmetries
   - The QCD-phase diagram
   - motivation for electromagnetic probes
   - Electromagnetic radiation from hot/dense matter
   - the (essential) hadronic sources of em. probes
   - hadronic many-body theory

2 Bulk-medium evolution with transport and coarse graining
   - coarse-graining in UrQMD
   - Dimuons (SPS/NA60)
   - Dielectrons (SIS/HADES)

3 Conclusions and Outlook
Electromagnetic probes
theory perspective
QCD and (“accidental”) symmetries

- fundamental theory of strong interactions: QCD

\[ \mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_{\mu \nu}^a F_{\mu \nu}^a + \bar{\psi} (i \slashed{D} - \hat{M}) \psi \]

- particle content:
  - \( \psi \): Quarks, including flavor- and color degrees of freedom, \( \hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) \) = current quark masses
  - \( A_\mu^a \): gluons, gauge bosons of SU(3)_{color}

- symmetries
  - fundamental building block: local SU(3)_{color} symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry \( \Rightarrow \) connection between QCD and effective hadronic models
Phenomenology and Chiral symmetry

- in **vacuum**: Spontaneous breaking of chiral symmetry
- ⇒ mass splitting of chiral partners

**qq-excitations of the QCD vacuum**

- $\pi$ (140)
- $\rho$ (770) + cont.
- $\omega$ (782)
- $f_0$ (400-1200)
- $a_1$ (1260)
- $f_1$ (1285)
- $f_1$ (1420)
- $\phi$ (1020)

**Energy (MeV)**

**P-S, V-A splitting in the physical vacuum**

$-\text{Im} \frac{\Pi_{V,A}}{\pi s}$ [dim.−less]

- $V [\tau \rightarrow 2n\pi \nu_\tau]$
- $A [\tau \rightarrow (2n+1)\pi \nu_\tau]$
- $\rho$ (770) + cont.
- $a_1$ (1260) + cont.
The QCD-phase diagram

- **Hot and dense matter**: Quarks and gluons close together.
- Highly energetic collisions ⇒ “deconfinement”.
- Quarks and gluons relevant dof ⇒ quark-gluon plasma.
- Still strongly interacting ⇒ fast thermalization!

![Phase Diagram](image)
The QCD-phase diagram

- at high temperature/density: restoration of chiral symmetry
- lattice QCD: $T_c^\chi \simeq T_c^{\text{deconf}}$

- mechanism of chiral restoration?
- two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \bar{\psi} \psi \rangle$
  - "melting resonances": broadening of spectra through medium effects
- More theoretical question: realization of chiral symmetry in nature?
Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^\pm$: no strong interactions
- reflect whole “history” of collision:
  - from pre-equilibrium phase
  - from thermalized medium
  - QGP and hot hadron gas
  - from VM decays after thermal freezeout

![Diagram of dileptons in heavy-ion collisions]

**Fig. by A. Drees**
Electromagnetic probes from thermal source

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function: \( J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f \)
- McLerran-Toimela formula \(^{[MT85, GK91]}\)

\[
q_0 \frac{dN_\gamma}{d^4 x d^3 \vec{q}} = -\frac{\alpha_{em}}{2\pi^2} g^{\mu\nu} \text{Im} \left. \Pi^{(\text{ret})}_{\mu\nu}(q, u) \right|_{q_0 = |\vec{q}|} f_B(q \cdot u)
\]

\[
\frac{dN_{e^+e^-}}{d^4 x d^4 q} = -g^{\mu\nu} \frac{\alpha^2}{3q^2\pi^3} \text{Im} \left. \Pi^{(\text{ret})}_{\mu\nu}(q, u) \right|_{q^2 = M_{e^+e^-}^2} f_B(q \cdot u)
\]

- Lorentz covariant (dependent on four-velocity of fluid cell, \( u \))
- \( q \cdot u = E_{cm} \): Doppler blue shift of \( q_T \) spectra!
- to lowest order in \( \alpha \): \( 4\pi\alpha \Pi_{\mu\nu} \approx \Sigma^{(\gamma)}_{\mu\nu} \)
- vector-meson dominance model:

\[
\Sigma_{\mu\nu} = G_\rho
\]

- \( \ell^+\ell^- \)-inv.-mass spectra
  \( \Rightarrow \) in-med. spectral functions of vector mesons (\( \rho, \omega, \phi \))!
Radiation from thermal QGP: $q\bar{q}$ annihilation

- **General:** McLerran-Toimela formula

\[
\frac{dN_{l^+l^-}^{(MT)}}{d^4xd^4q} = -\frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} g_{\mu\nu} \text{Im} \sum_i \Pi_{\text{em},i}^{\mu\nu}(M,\vec{q}) f_B(q \cdot u)
\]

- $i$ enumerates partonic/hadronic sources of em. currents
- In-medium em. current-current correlation function

\[
\Pi_{\text{em},i}^{\mu\nu} = i \int d^4x \exp(iq\cdot x) \Theta(x^0) \langle [j_{\text{em},i}^\mu(x), j_{\text{em},i}^\nu(0)] \rangle
\]

- In QGP phase: $q\bar{q}$ annihilation
- Hard-thermal-loop improved em. current-current correlator

\[
-i\Pi_{\text{em},\text{QGP}} = \gamma^* \quad \bar{q} \quad \gamma^*
\]
Radiation from thermal sources: $\rho$ decays

- model assumption: vector-meson dominance

\[
\frac{dN^{(\text{MT})}_{\rho\rightarrow\ell^+\ell^-}}{d^4x d^4q} = \frac{M}{q^0} \frac{\Gamma_{\rho\rightarrow\ell^+\ell^-}(M)}{d^3\vec{x} d^4q} \\
\quad = -\frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} \frac{m^4_{\rho}}{g^2_{\rho}} g_{\mu\nu} \text{Im} D^{\mu\nu}_{\rho}(M, \vec{q}) f_B \left( \frac{q \cdot u - 2\mu_\pi(t)}{T(t)} \right)
\]

- special case of McLerran-Toimela (MT) formula
- $M^2 = q^2$: invariant mass, $M$, of dilepton pair
- $L(M^2) = (1 + 2m^2_{l}/M^2)\sqrt{1 - 4m^2_{l}/M^2}$: dilepton phase-space factor
- $D^{\mu\nu}_{\rho}(M, \vec{q})$: (four-transverse part of) in-medium $\rho$ propagator at given $T(t)$, $\mu_{\text{meson/baryon}}(t)$
- analogous for $\omega$ and $\phi$
**Hadronic many-body theory**

- **hadronic many-body theory (HMBT) for vector mesons**
  
  [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, …]

- **ππ interactions and baryonic excitations**

- effective hadronic models, implementing symmetries

- parameters fixed from phenomenology
  
  (photon absorption at nucleons and nuclei, \( \pi N \to \rho N \))

- evaluated at **finite temperature and density**

- self-energies \( \Rightarrow \) **mass shift and broadening in the medium**

**Baryons important, even at low net baryon density \( n_B - n_{\bar{B}} \)**

**reason:** \( n_B + n_{\bar{B}} \) relevant (CP inv. of strong interactions)
Meson contributions

\[ \text{Re } \Sigma_\rho / m_\rho \text{ [MeV]} \]

\[ \text{Im } \Sigma_\rho / m_\rho \text{ [MeV]} \]

\[ T=150\text{MeV} \]
\[ q=0.3\text{GeV} \]

\[ \sum \]

[GR99]
In-medium spectral functions and baryon effects

- **baryon effects** important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small $M$

---

[RW99]
Radiation from thermal sources: multi-$\pi$ processes

- use vector/axial-vector correlators from $\tau$-decay data
- Dey-Eletsky-Ioffe mixing: $\hat{\epsilon} = 1/2\epsilon(T, \mu_\pi)/\epsilon(T_c, 0)$

$$\Pi_V = (1 - \hat{\epsilon}) z^4_{\pi} \Pi_{V, 4\pi}^{\text{vac}} + \frac{\hat{\epsilon}}{2} z^3_{\pi} \Pi_{A, 3\pi}^{\text{vac}} + \frac{\hat{\epsilon}}{2} (z^4_{\pi} + z^5_{\pi}) \Pi_{A, 5\pi}^{\text{vac}}$$

- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$
  (already contained in $\rho$ spectral function)

Data: [R. Barate et al (ALEPH Collaboration) 98]
Non-thermal sources

- Drell-Yan: \( q + \bar{q} \rightarrow \ell^+ \ell^- \) in early hard collisions
  \[
  \frac{dN^{AA}_{DY}}{dM dy} \bigg|_{b=0} = \frac{3}{4\pi R_0^2} A^{4/3} \frac{d\sigma^{NN}_{DY}}{dM dy}
  \]
  \[
  \frac{d\sigma^{NN}_{DY}}{dM dy} = K \frac{8\pi \alpha}{9sM} \sum_{q=u,d,s} e_q^2 [q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)]
  \]

- parton distribution functions: GRV94LO
- higher-order effects
  - \( K \) factor
  - non-zero pair \( q_T \): for IMR and HMR fitted by Gaussian spectrum (NA50 procedure)
  - extrapolation to LMR: constrained by photon point \( M \rightarrow 0 \)
- \( \rho \) decays after thermal freeze-out: Cooper-Frye formula
  \[
  \frac{dN^{(fo)}_{\rho \rightarrow \ell^+ \ell^-}}{d^3 \vec{x} d^4q} = \frac{\Gamma_{\ell^+ \ell^-}^{tot}}{\Gamma_{\rho}^{tot}} \frac{dN_i}{d^3 \vec{x} d^4q} = \frac{q_0}{M} \frac{1}{\Gamma_{\rho}^{tot}} \left[ \frac{dN^{(MT)}_{\rho \rightarrow \ell^+ \ell^-}}{d^4x d^4q} \right]_{t=t_{fo}}
  \]
in-medium **hadron gas** matches with QGP
similar results also for $\gamma$ rates
“quark-hadron duality”?
Bulk-medium evolution
established transport models for **bulk evolution**
- e.g., UrQMD, GiBUU, BAMPS, (p)HSD,...
- solve Boltzmann equation for hadrons and/or partons

**dilemma:** need medium-modified dilepton/photon emission rates

usually available only in **equilibrium QFT calculations**

ways out:
- use (ideal) hydrodynamics ⇒ local thermal equilibrium
  ⇒ use equilibrium rates
- use transport-hydro hybrid model: treat early stage with transport, then **coarse grain** ⇒ switch to hydro
  ⇒ switch back to transport (Cooper-Frye “particlization”)

here: **UrQMD transport** for entire bulk evolution
⇒ use **coarse graining** in space-time cells ⇒ extract $T, \mu_B, \mu_\pi, \ldots$
⇒ use equilibrium rates locally
problem with medium modifications of spectral functions/interactions

only available in equilibrium many-body QFT models

use “in-medium cross sections” naively: double counting?!?

way out: map transport to local-equilibrium fluid

use ensemble of UrQMD runs with an equation of state

fit temperature, chemical potentials, flow-velocity field from anisotropic energy-momentum tensor \[ T_{\mu\nu} = (\epsilon + P_\perp) u^{\mu} u^{\nu} - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^{\mu} V^{\nu} \]

thermal rates from partonic/hadronic QFT become applicable

here: extrapolated lattice QGP and Rapp-Wambach hadronic many-body theory

caveat: consistency between EoS, matter content of QFT model/UrQMD!
Coarse-grained UrQMD (CGUrQMD)

- $T_c = 170$ MeV; $T > T_c \Rightarrow$ lattice EoS; $T < T_c \Rightarrow$ HRG EoS
Coarse-grained UrQMD (CGUrQMD)

- pressure anisotropy (In-In collisions (NA60) at SIS)

In+In @ 158 AGeV
<\text{d}N_{\text{ch}}/\text{d}\eta>=120
Central cell (x=y=z=0)

$$
\begin{align*}
\text{In+In} & \quad \text{at} \quad 158 \text{ AGeV} \\
<\text{d}N_{\text{ch}}/\text{d}\eta> & = 120 \\
\text{Central cell (x=y=z=0)}
\end{align*}
$$

Time t [fm]
0 2 4 6 8 10 12 14
-3 10
-2 10
-1 10
1 10
2 10

\text{P}_{||} \quad \text{P}_{\perp} (\text{GeV/fm}^3)

Anisotropy parameter x
Relaxation function r(x)
Coarse-grained UrQMD (CGUrQMD)

- energy/baryon density $\Rightarrow T, \mu_B$ (for In+In @ SPS; NA60)
- central “fluid” cell!

![Graphs showing energy density and baryon density over time](image)

In+In @ 158 AGeV
$<dN_{ch}/d\eta>=120$
Central cell (x=y=z=0)

(a) **Energy density** $\varepsilon/\varepsilon_0$
(b) **Lattice EoS**

T and $\mu_B$

Hadron Gas EoS

In + In @ 158 AGeV
$<dN_{ch}/d\eta>=120$
Central cell (x=y=z=0)

T

$\mu_B$

$\mu_\pi$

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- energy ($\epsilon$) and baryon ($\rho$) density profiles (for In+In@SPS; NA60)

Transverse density profiles
In+In @ 158 AGeV

- $t = 1$ fm:
  - $\epsilon/\epsilon_0$
  - $\rho/\rho_0$
- $t = 3$ fm:
  - $\epsilon/\epsilon_0 \times 5$
  - $\rho/\rho_0 \times 5$
- $t = 5$ fm:
  - $\epsilon/\epsilon_0 \times 8$
  - $\rho/\rho_0 \times 8$

Longitudinal density profiles
In+In @ 158 AGeV

- $t = 1$ fm:
  - $\epsilon/\epsilon_0$
  - $\rho/\rho_0$
- $t = 3$ fm:
  - $\epsilon/\epsilon_0 \times 5$
  - $\rho/\rho_0 \times 5$
- $t = 5$ fm:
  - $\epsilon/\epsilon_0 \times 8$
  - $\rho/\rho_0 \times 8$
Dimuons (SPS/NA60)
dimuon spectra from $\text{In} + \text{In}(158\text{ AGeV}) \to \mu^+\mu^-$ (NA60)

min-bias data ($dN_{\text{ch}}/dy = 120$)
- dimuon spectra from \( \text{In} + \text{In}(158 \text{ AGeV}) \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data \( (dN_{\text{ch}}/dy = 120) \)
- higher IMR: provides **averaged true temperature** (no blueshifts in the invariant-mass spectra!)

![Graph showing dimuon spectra](image)
dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
min-bias data (dN_{ch}/dy = 120)
\( p_T < 0.2 \) GeV
- dimuon spectra from $\text{In} + \text{In}(158 \text{ AGeV}) \rightarrow \mu^+ \mu^-$ (NA60)
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.2 \text{ GeV} < p_T < 0.4 \text{ GeV}$

![Graph showing dimuon spectra with invariant mass and transverse momentum](image)
dimuon spectra from In + In(158 AGeV) → µ⁺µ⁻ (NA60)
min-bias data (dN_{ch}/dy = 120)
0.4 GeV < p_T < 0.6 GeV
dimuon spectra from In + In (158 AGeV) → μ⁺μ⁻ (NA60)
min-bias data (dN_{ch}/dy = 120)
0.6 GeV < p_T < 0.8 GeV
dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
min-bias data (dN_{ch}/dy = 120)
0.8 GeV < p_T < 1.0 GeV
dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
min-bias data (dN_{ch}/dy = 120)
1.0 GeV < p_T < 1.2 GeV
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158 \text{ AGeV}) \rightarrow \mu^+\mu^- $ (NA60)
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $1.2 \text{ GeV} < p_T < 1.4 \text{ GeV}$

![Graph showing dimuon spectra](a)

1.2 < $p_T$ < 1.4 GeV
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
- min-bias data (dN_{ch}/dy = 120)
- 1.4 GeV < p_T < 1.6 GeV
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
- min-bias data (dN_{ch}/dy = 120)
- 1.6 GeV < p_T < 1.8 GeV
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → µ⁺µ⁻ (NA60)
- min-bias data (dN_{ch}/dy = 120)
- 1.8 GeV < p_T < 2.0 GeV
dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
min-bias data (dN_{ch}/dy = 120)
2.0 GeV < p_T < 2.2 GeV
 dimuon spectra from In + In(158 AGeV) \rightarrow \mu^+ \mu^- (NA60)

min-bias data (dN_{ch}/dy = 120)

2.2 \text{ GeV} < p_T < 2.4 \text{ GeV}
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
- min-bias data (dN_{ch}/dy = 120)
dimuon spectra from In + In (158 AGeV) → \( \mu^+ \mu^- \) (NA60)

min-bias data (dN_{ch}/dy = 120)
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
- min-bias data (dN_{ch}/dy = 120)
dimuon spectra from In + In (158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60)

min-bias data (d$N_{ch}$/d$y$ = 120)
Dielectrons (SIS/HADES)
coarse-graining method works at low energies!

UrQMD-medium evolution + RW-QFT rates
dielectron spectra from $\text{Ar} + \text{KCl}(1.76 \text{ AGeV}) \rightarrow e^+e^-$ (SIS/HADES)

$m_t$ spectra

$M_{ee} < 0.13 \text{ GeV}$
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- $m_t$ spectra
- $0.13 \text{ GeV} < M_{ee} < 0.3 \text{ GeV}$
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- $m_t$ spectra
- $0.3 \text{ GeV} M_{ee} < 0.45 \text{ GeV}$

![Graph showing dielectron spectra](image-url)
CGUrQMD: Ar + KCl (1.76 AGeV) (SIS/HADES)

- Dielectron spectra from Ar + KCl (1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- \( m_t \) spectra
- 0.45 GeV < \( M_{ee} \) < 0.65 GeV
dielectron spectra from \( \text{Ar} + \text{KCl}(1.76 \text{ AGeV}) \rightarrow e^+e^- \) (SIS/HADES)

- \( m_t \) spectra
- \( M_{ee} > 0.65 \text{ GeV} \)
- dielectron spectra from Ar + KCl (1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- \( m_t \) spectra
- rapidity spectrum (\( M_{ee} < 0.13 \text{ GeV} \))
CGUrQMD: Au+Au (1.23 AGeV) (SIS/HADES)

caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV

correct filter urgently needed!

excellent agreement with preliminary HADES data
(data points not shown here on request of the HADES collaboration)
What to learn about the “bulk dynamics”?

- hadronic observables like $p_T$ spectra: “snapshot” of the stage after kinetic freezeout
- particle abundancies: chemical freezeout
- em. probes: emitted during the whole medium evolution
  life time of the medium ⇒ “four-volume of the fireball”
- use CGUrQMD to study system-size dependence
- study AA collisions for different $A$
- hard to quantify “life time” of the “thermal” medium in transport
- here: use time, for which the central cell has $T \geq 50$ MeV
\[
\frac{V_{AA}^{(4)}}{V_{CC}^{(4)}} \frac{A}{12}
\]

of cells larger than various \( T \)

- how to explain “scaling behavior”?
consider central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76$ AGeV

- $\Delta t \propto A^{1/3}$
- $A \propto V^{(3)}$ of nuclei $\Rightarrow A^{1/3} \propto d_{\text{nucl}}$
- fireball lifetime $\propto$ time of nuclei to traverse each other
Lifetime of the central cell

\[ \frac{\text{yield}_{AA}/A}{\text{yield}_{CC}/12} \]

\[ \text{yield}_{\text{had}} \propto A \propto V_{fo}^{(3)} \]
\[ \text{yield}_{\text{non-thermal } ee} \propto A \propto V_{fo}^{(3)} \]
⇒ hadronic decays after kinetic freeze-out

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Scaling behavior of thermal-dilepton yield

- thermal-dilepton yield roughly $\propto V_{\text{therm}}^{(4)} \propto A^{4/3} \propto A t_{\text{therm}} \propto N_{\pi^0}^{4/3}$
Possible signatures of QCD-phase structure?

- measurement of thermal-dilepton spectra/yields a la NA60
- scaling behavior at low energies studied with one HRG EoS
- beam-energy scan like at RHIC ⇒ deviations from naive scaling behavior?
- possible variations in fireball lifetime due to different phase transitions
- cross over at higher RHIC and LHC energies [RH14]
- deviations in regions of larger $\mu_B$?
- possible signature of 1st-order line?
- possible signature of critical point through “anomalies in fireball lifetime” due to critical slowing-down???
- NB: $\ell^+\ell^-$ also “thermometer” from invariant-mass slopes in IMR (needs a good handle on correlated $D\bar{D}$ decays a la NA60!)
Conclusions and Outlook

- **General ideas**
  - em. probes ⇔ in-medium em. current-correlation function
  - dual rates around $T_c$ (compatible with $\chi$ symmetry restoration)
  - medium modifications of $\rho$, $\omega$, $\phi$
  - importance of baryon-resonance interactions

- **Application to dileptons in HICs**
  - coarse-grained transport (here: CGUrQMD)
  - allows use of thermal-QFT spectral VM functions
  - applicable also at low collision energies
  - allows use of thermal-QFT models for dilepton rates
  - successful description at SIS, SPS energies
  - consistent description of $M$ and $m_T$ spectra!
  - effective slope of $M$ spectra in higher IMR ($1.5 \text{ GeV} < M < M_{J/\psi}$)
    provides $\langle T \rangle$

- **Outlook**
  - check at available RHIC data
  - beam-energy scan at RHIC and FAIR ⇒ signature of phase transition?
  - signature of cross-over vs. 1st order (or even critical endpoint)???

- for details see [BESH15, EHWB13, EHB13, EHWB15a, EHWB14, EHWB15b, HWEB15, WEH+ 14a, WEH+ 14b]


http://dx.doi.org/10.1088/1742-6596/503/1/012039


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