Can you Hear and See a Quark-Gluon Plasma ?

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The John Cramer Symposium

University of Washington

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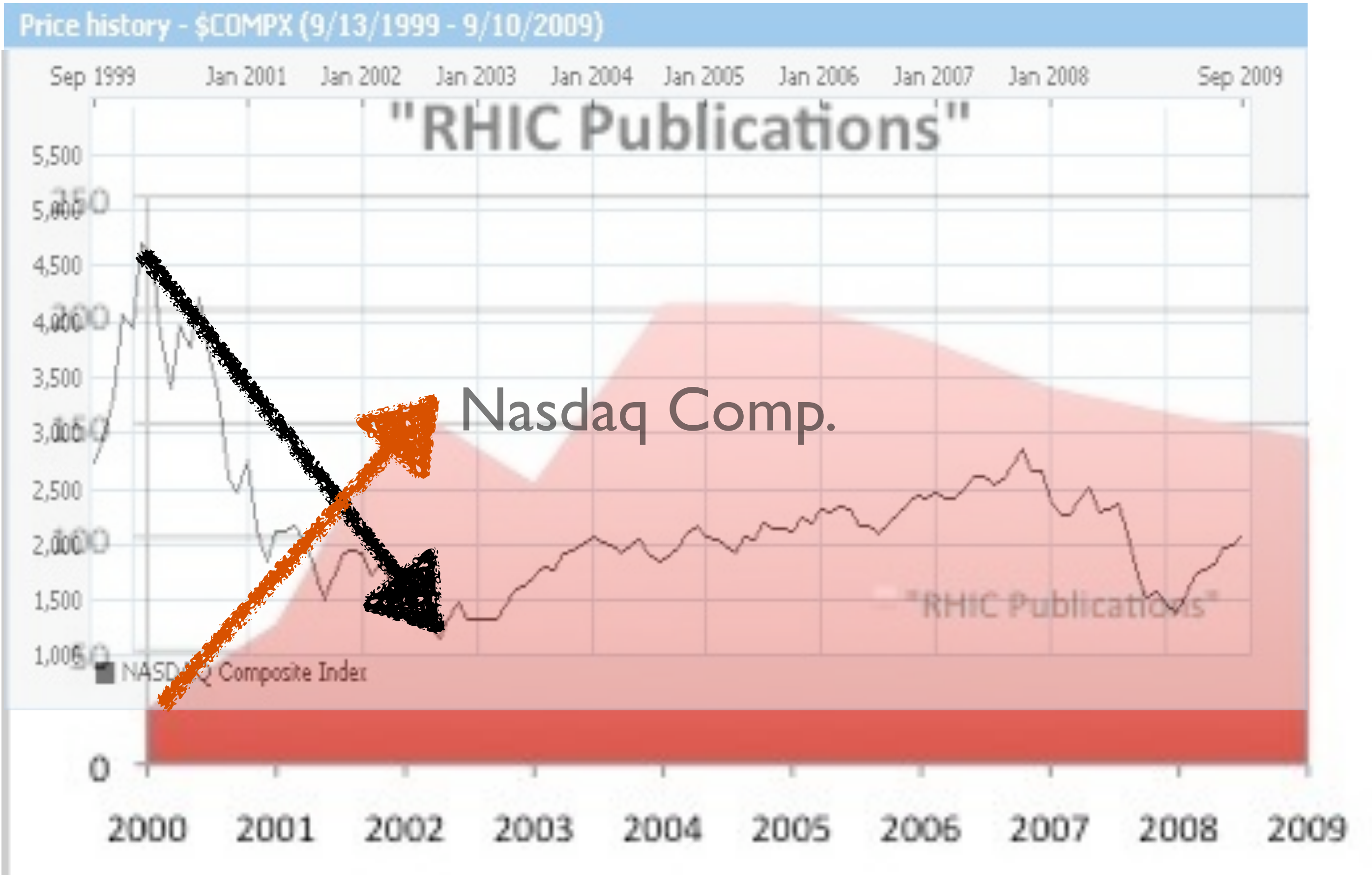
Why all scientists interested in the Quark-Gluon Plasma owe gratitude to John Cramer ...

...because he chose
to write
Einsteins Bridge
about the SSC,
not about RHIC !

RHIC has not destroyed our world

... or has it ?



The original QGP allegory

You can't hear it

Don't make bold claims about it

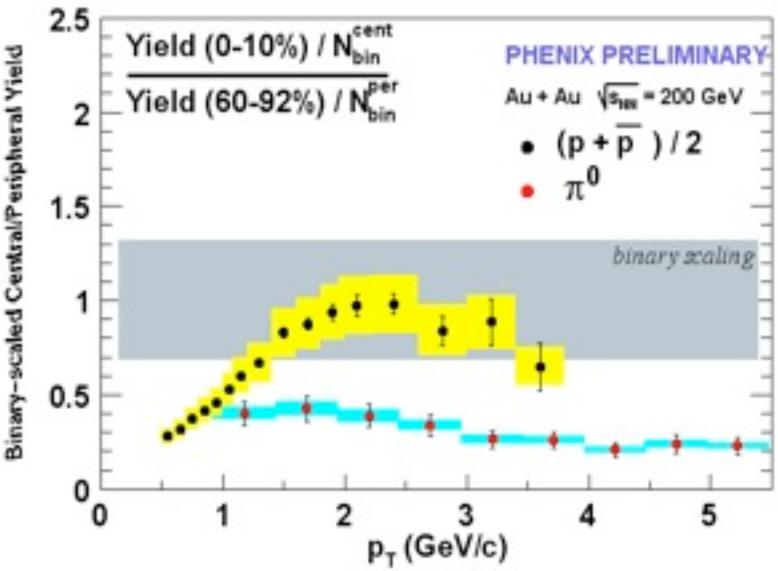
You can't see it

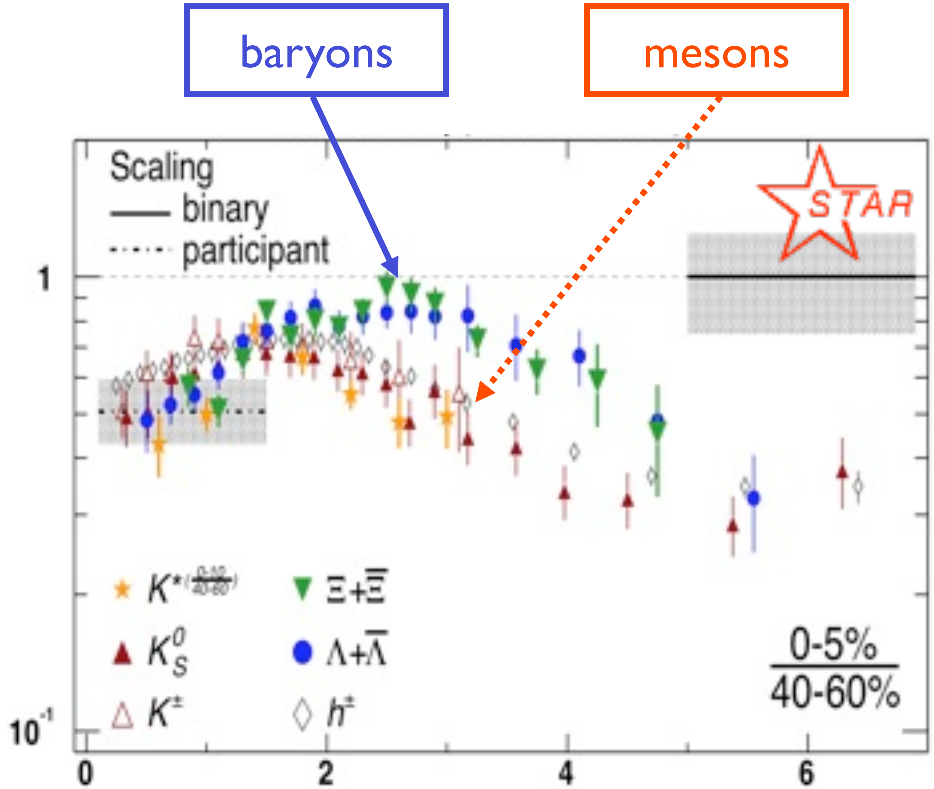
Part 1

“Seeing” the QGP

Suppression Pattern: Baryons vs. Mesons

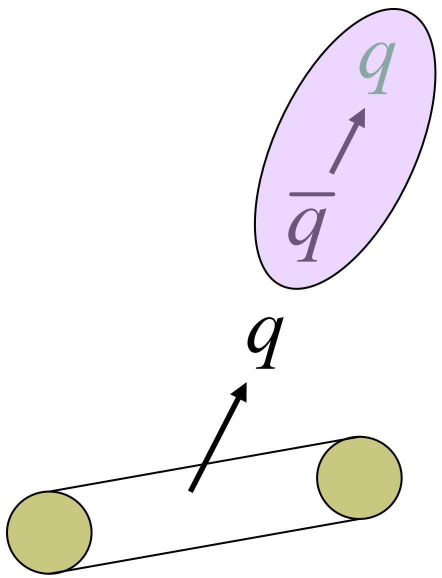
… the "**proton puzzle**" came as a complete surprise …





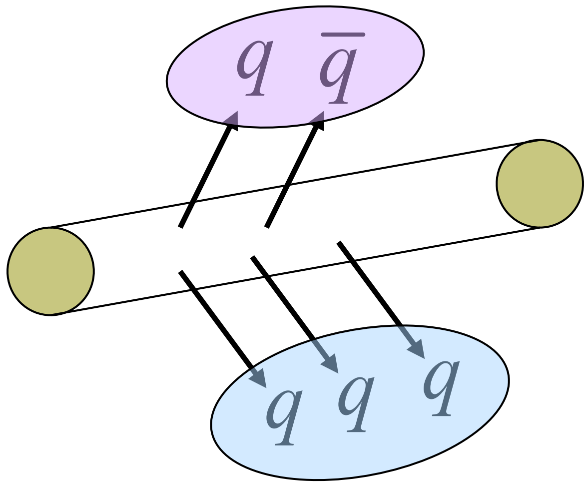
- What makes baryons different from mesons ?

Hadronization Mechanisms



Fragmentation

$$\frac{\text{Baryon}}{\text{Meson}} \ll 1$$

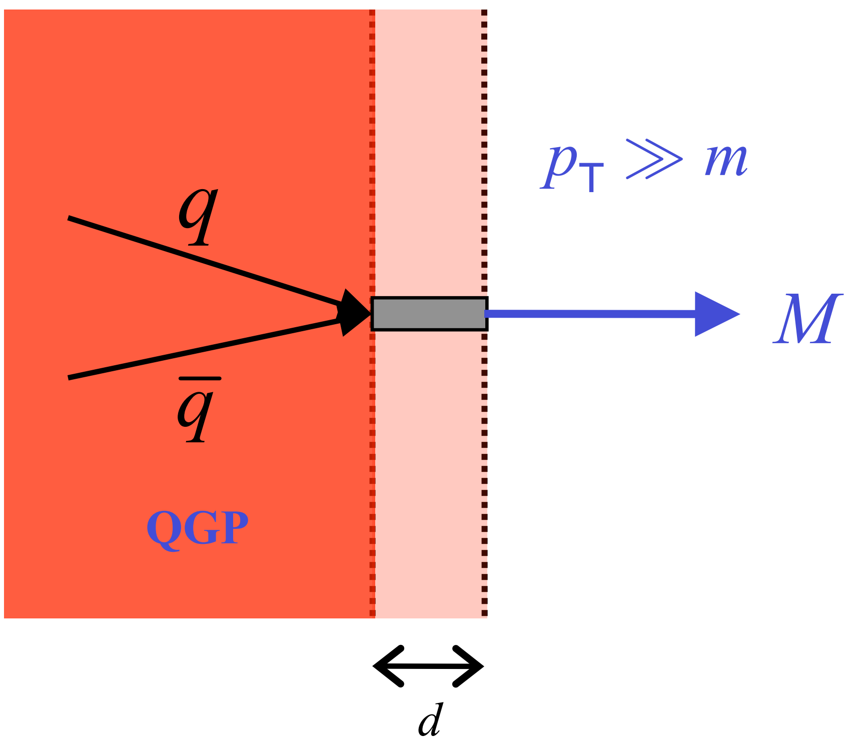


Recombination

$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

$$p_{\mathrm{M}} \approx 2p_{\mathrm{Q}} \qquad p_{\mathrm{B}} \approx 3p_{\mathrm{Q}}$$

Sudden recombination picture



Transition time from QGP into vacuum (in rest frame of produced hadron) is:

$$\tau_f = d/\gamma = d\,\frac{m}{p_T}$$

Allows to ignore complex dynamics in hadronization region; corrections $O(m/p_T)^2$

Not gradual coalescence from dilute system !!!

Relativistic formulation

Relativistic formulation using hadron light-cone frame ($P = P_{\|}$):

$$d^3k = \frac{k^0}{k_+} dk^+ d^2k_\perp \quad \text{with} \quad k^+ = \tfrac{1}{\sqrt{2}}\left(k^0 + k_{\|}\right) \quad \text{and} \quad k^+ = xP^+$$

$$E\frac{dN_{\mathrm{M}}}{d^3P} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha,\beta} \int dx\, w_\alpha(R, xP^+)\,\overline{w}_\beta(R,(1-x)P^+)\left|\overline{\phi}_{\mathrm{M}}(x)\right|^2$$

$$E\frac{dN_{\mathrm{B}}}{d^3p} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha,\beta,\gamma} \int dx dx'\, w_\alpha(R, xP^+)\, w_\beta(R, x'P^+)\, w_\gamma(R,(1-x-x')P^+)\left|\overline{\phi}_{\mathrm{B}}(x, x')\right|^2$$

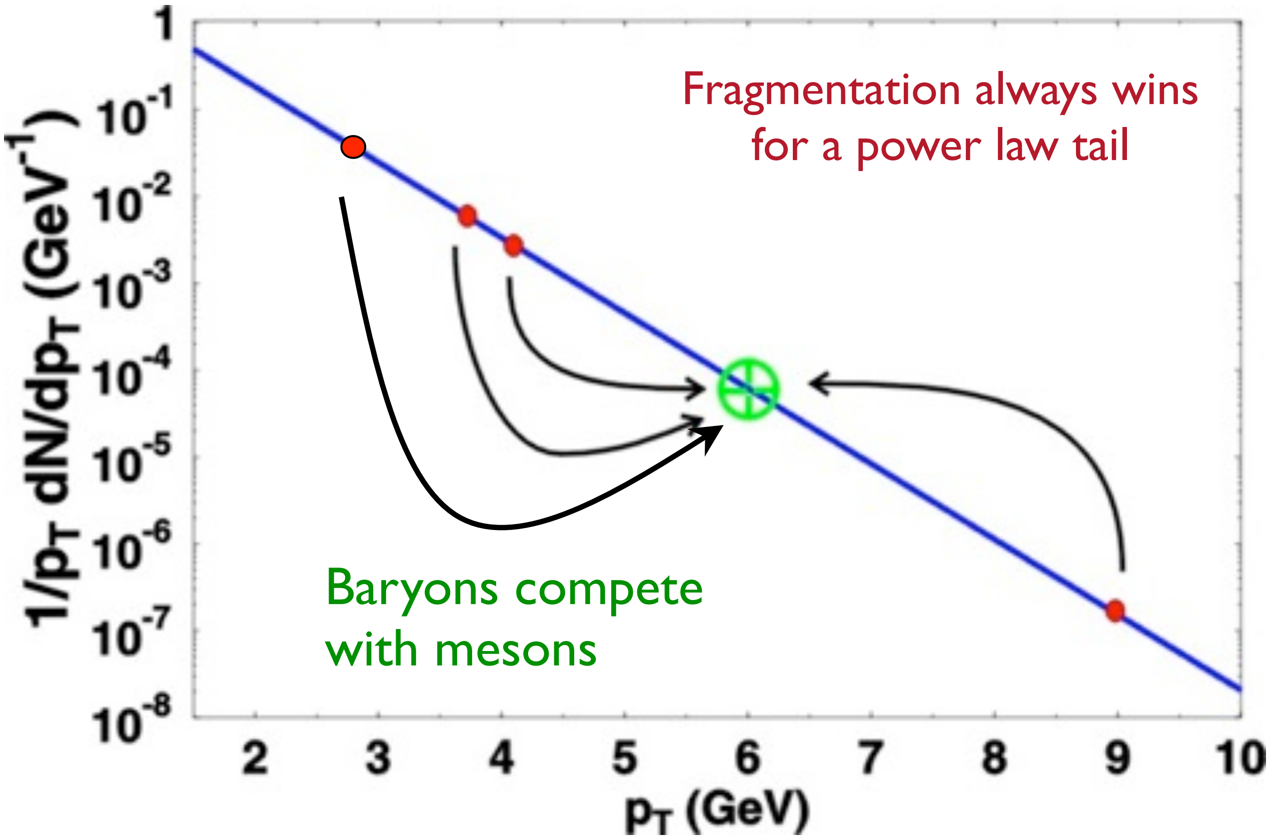
For a thermal distribution, $w(r,p) \sim \exp(-p\cdot \mathrm{v}/T)$

the hadron wavefunctions can be integrated out, eliminating the model dependence of predictions.

This is true even if higher Fock space states are included!

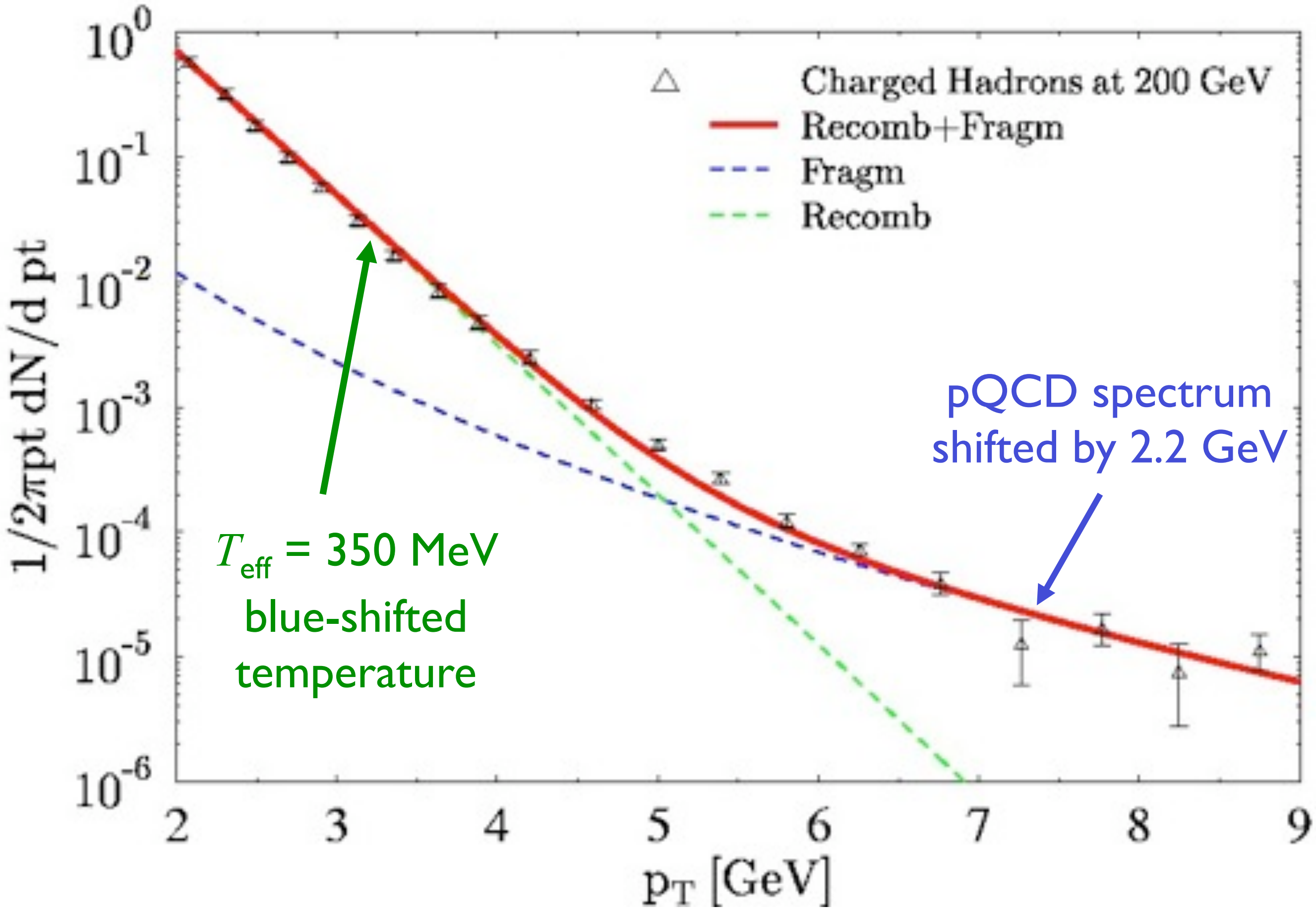
Recombination is favored …

… for a thermal source

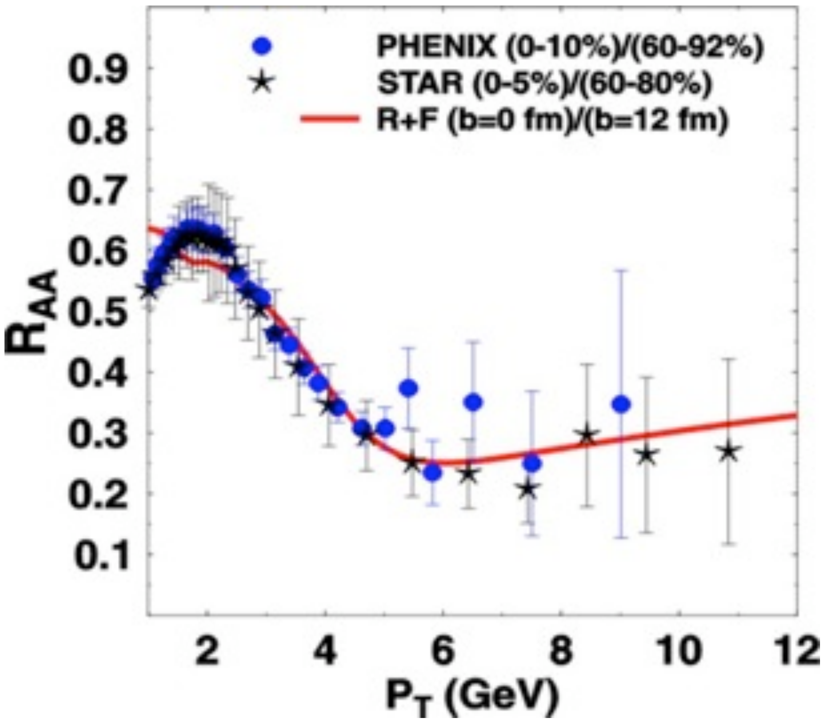


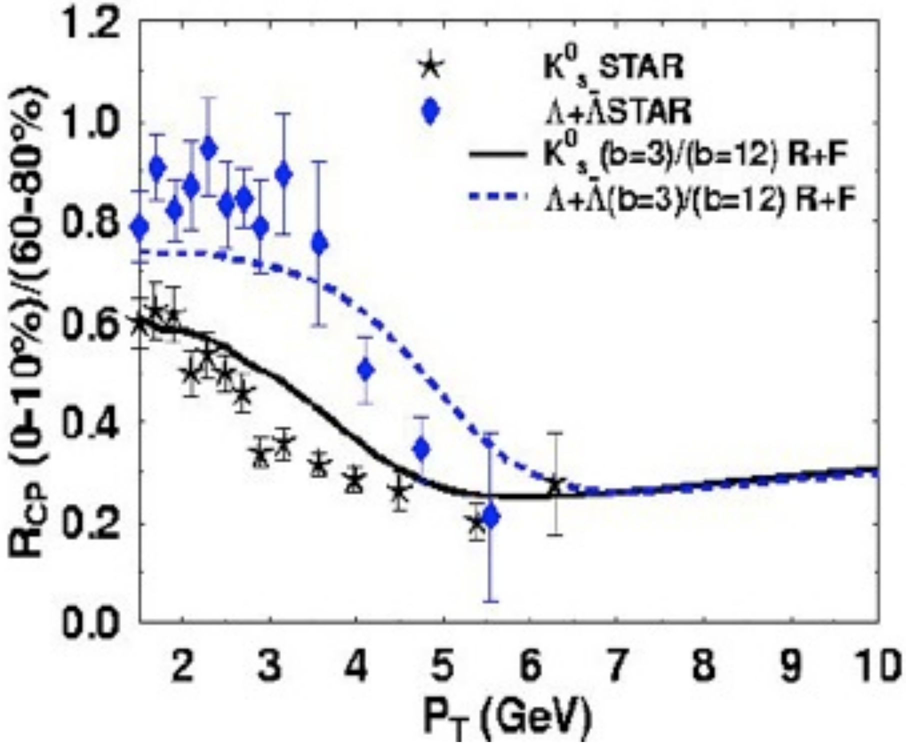
Model fit to RHIC hadron spectrum

R.J. Fries, BM, C. Nonaka, S.A. Bass, *PRL* 90, 202303 (2003)



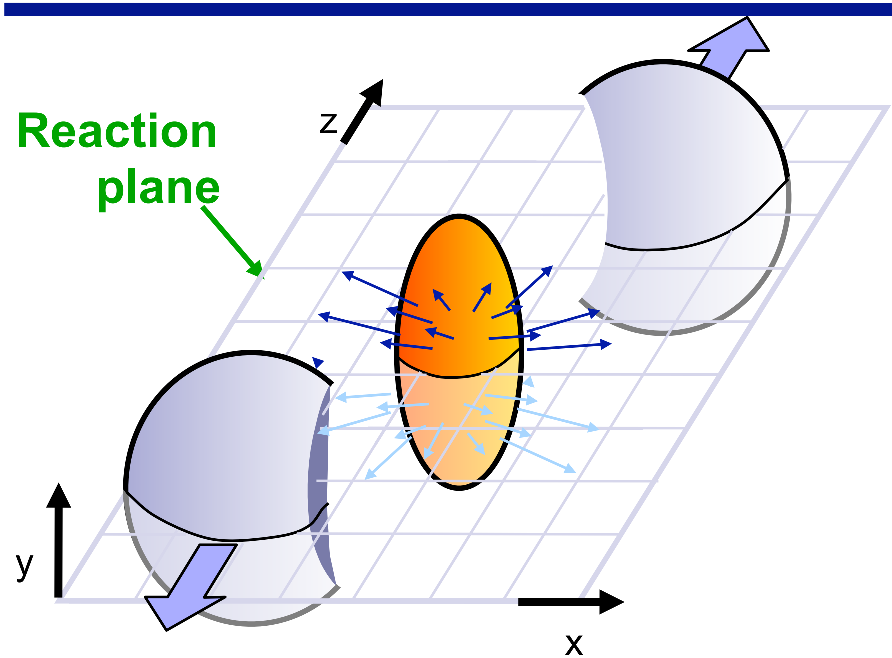
Confronting RHIC data





- R+F model describes different R_{AA} behavior of protons and pions
- Jet-quenching becomes universal in the fragmentation region

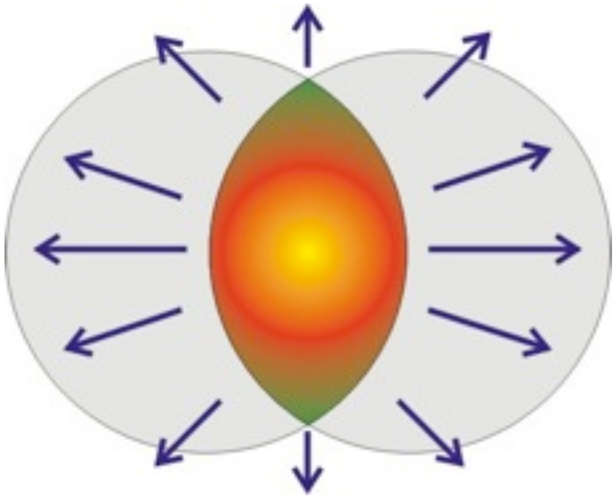
Collision Geometry: Elliptic Flow



- Bulk evolution described by relativistic fluid dynamics,
- assumes that the medium is in local thermal equilibrium,
- but no details of how equilibrium was reached.
- **Input:** $\varepsilon(x,\tau_i)$, $P(\varepsilon)$, $(\eta$, etc.).

Elliptic flow (v_2):

- Gradients of almond-shape surface will lead to preferential expansion in the reaction plane
- Anisotropy of emission is quantified by 2nd Fourier coefficient of angular distribution: v_2



- prediction of fluid dynamics

Quark Number Scaling of Elliptic Flow

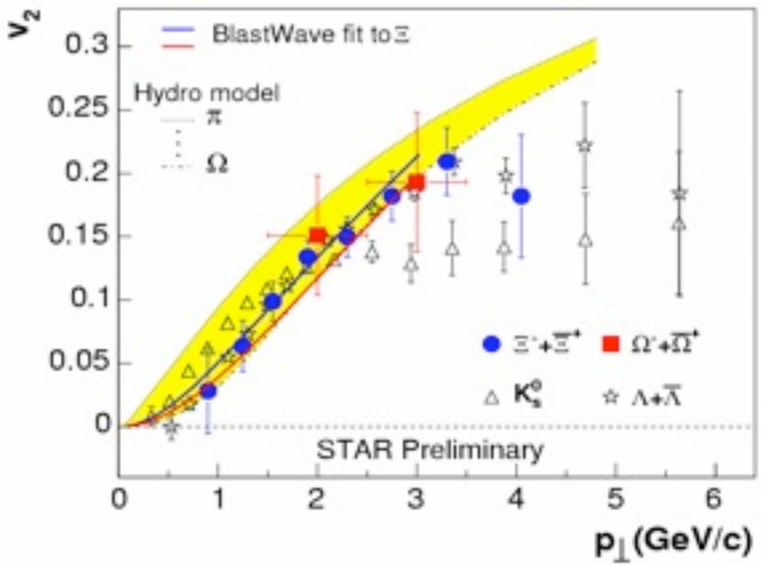
In the recombination regime, meson and baryon v_2 can be obtained from the parton v_2 (using x_i = 1/n):

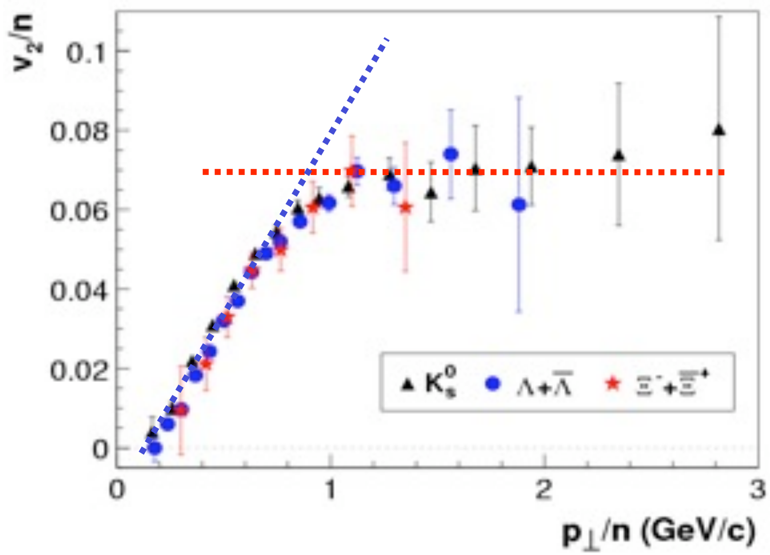
$$v_2^M(p_t) = \frac{2v_2^p\left(\frac{p_t}{2}\right)}{1+2\left(v_2^p\left(\frac{p_t}{2}\right)\right)^2} \quad \text{and} \quad v_2^B(p_t) = \frac{3v_2^p\left(\frac{p_t}{3}\right)+3\left(v_2^p\left(\frac{p_t}{3}\right)\right)^3}{1+6\left(v_2^p\left(\frac{p_t}{3}\right)\right)^2}$$

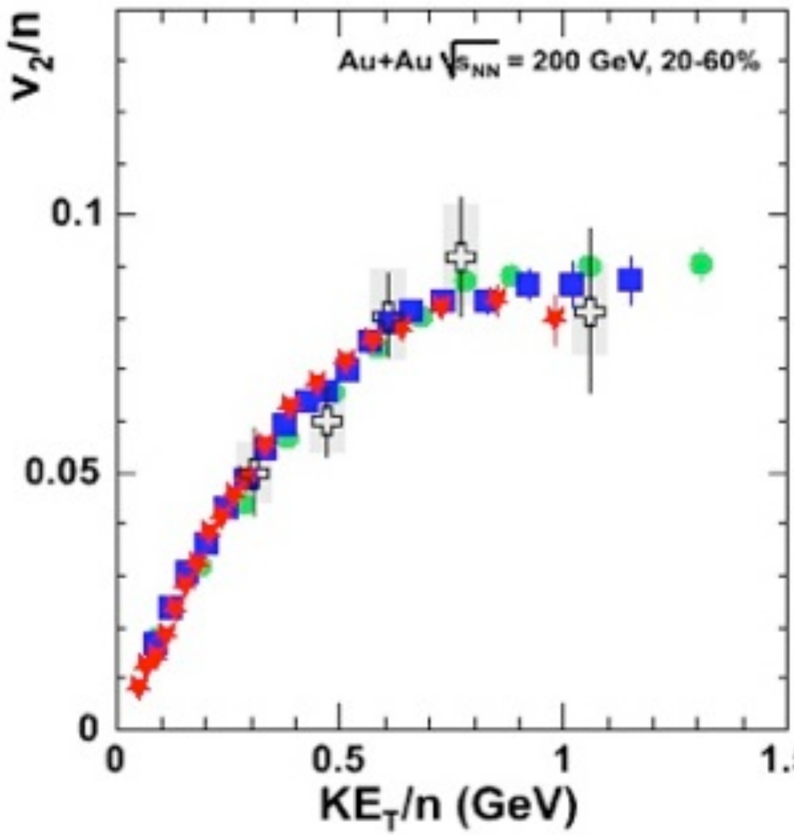
Neglecting quadratic and cubic terms, a simple scaling law holds:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

Hadron v_2 reflects quark flow !





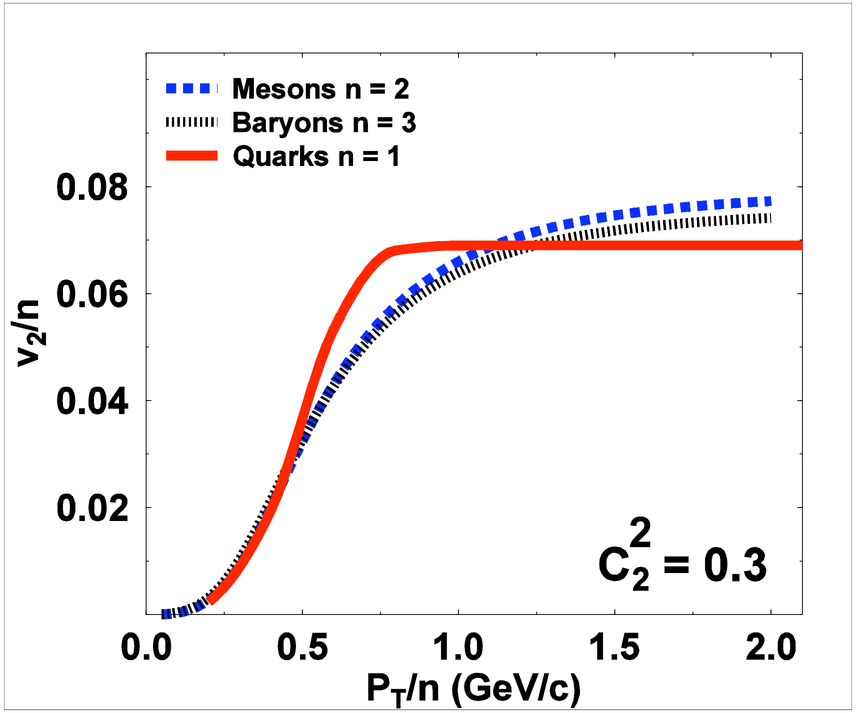


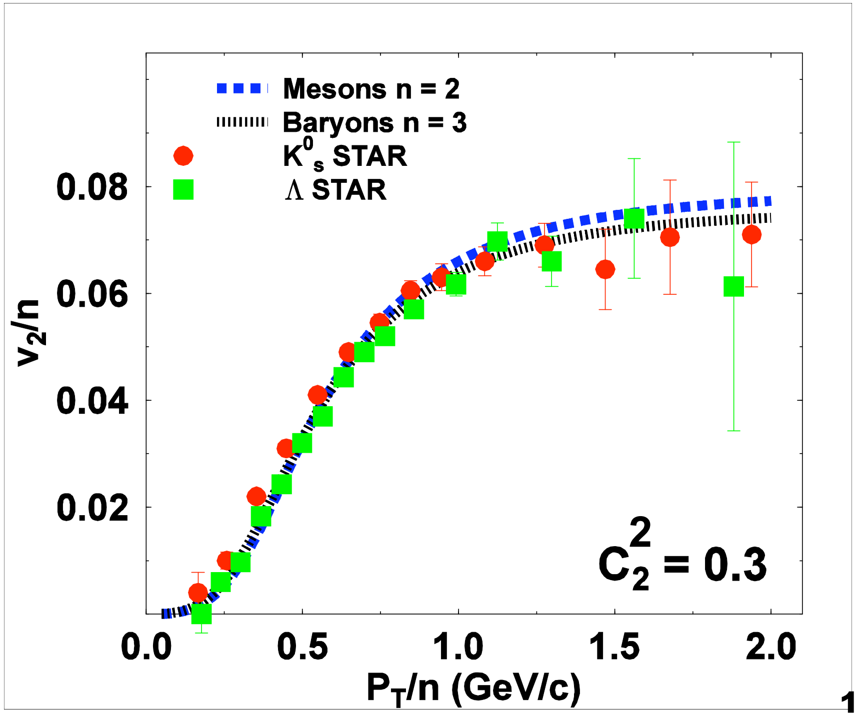
Higher Fock states don't ...

... spoil the analysis, they just modify the quark-hadron v_2 mapping

$$|M\rangle = C_1|q\bar{q}\rangle + C_2|q\bar{q}g\rangle$$
$$|B\rangle = C_1|qqq\rangle + C_2|qqqg\rangle$$

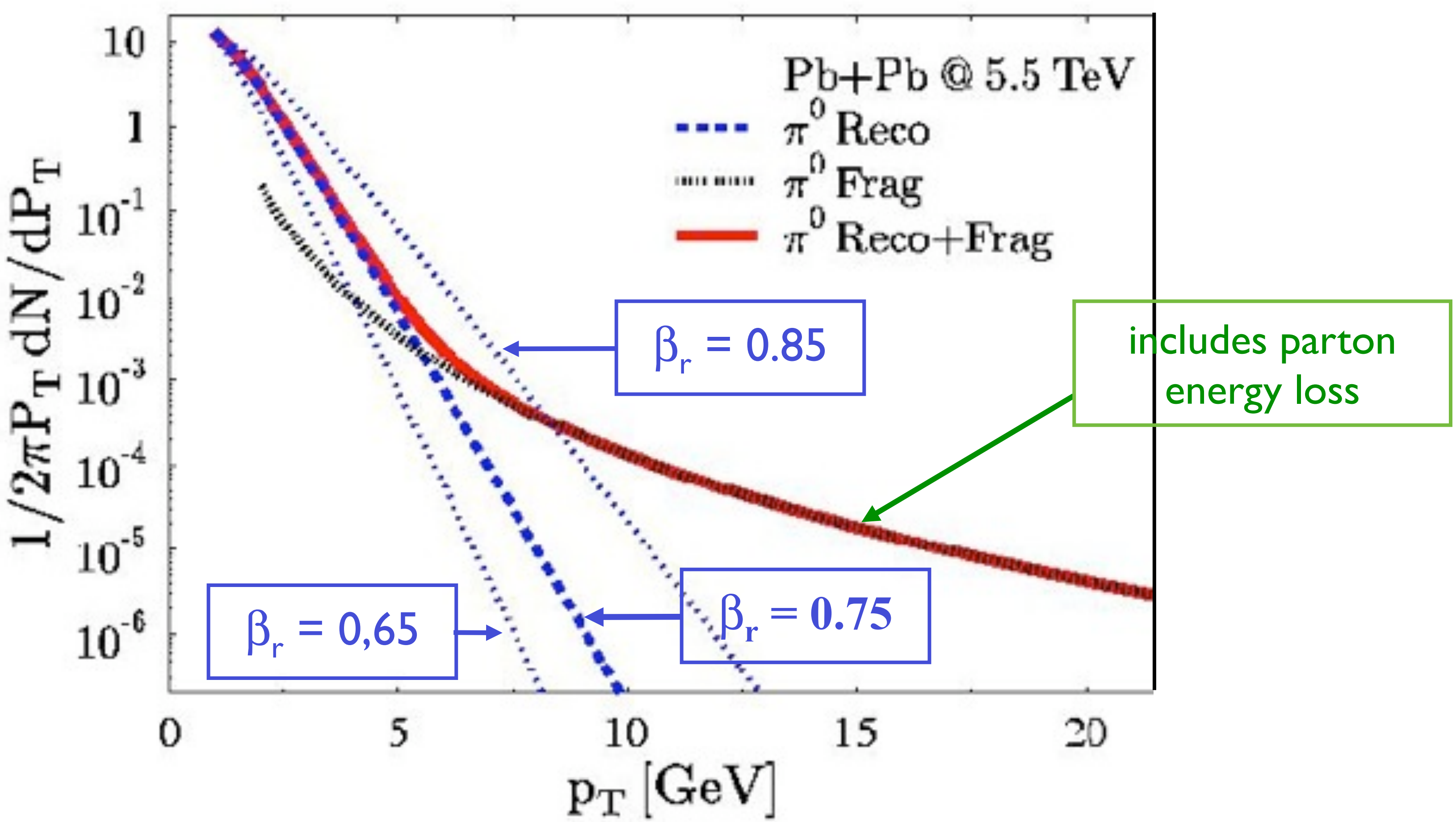
$$\phi_1^{(M)}(x_a, x_b) \sim x_a x_b$$
$$\phi_2^{(M)}(x_a, x_b, x_g) \sim x_a x_b x_g^2$$
$$\phi_1^{(B)}(x_a, x_b, x_c) \sim x_a x_b x_c$$
$$\phi_2^{(B)}(x_a, x_b, x_c, x_g) \sim x_a x_b x_c x_g^2$$





Hadron production at the LHC

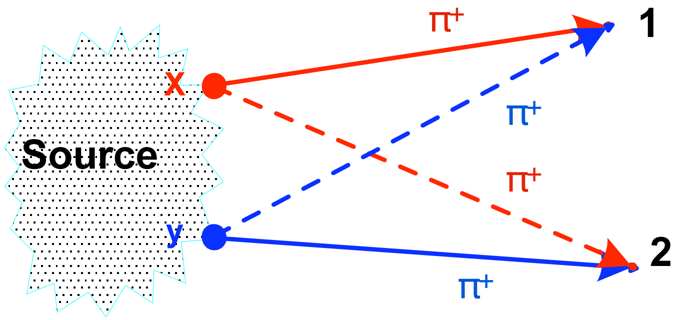
R.J. Fries & BM, *EJPC* 34, S279 (2004)



Part 2

Imaging the Fireball

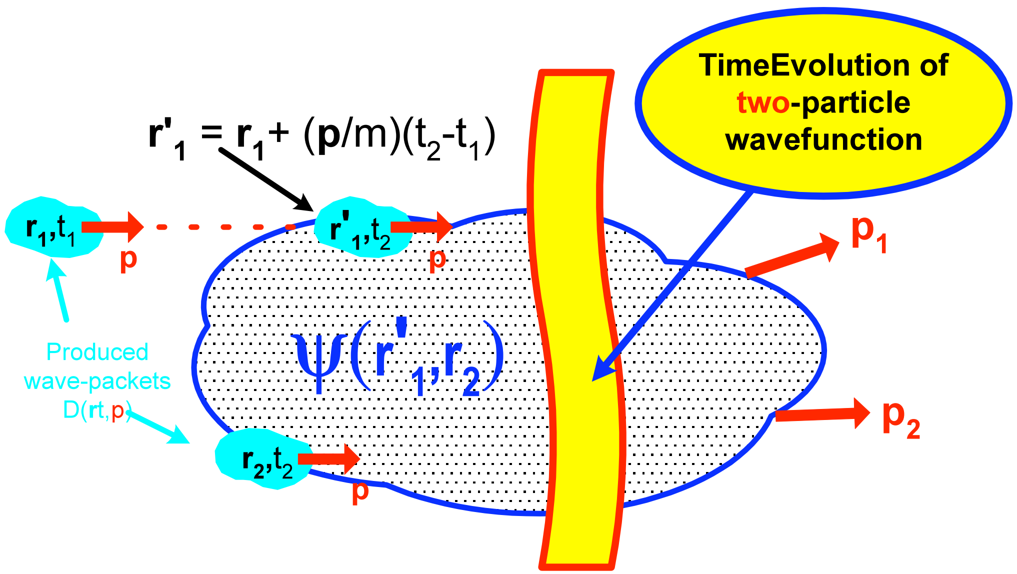
HBT density interferometry



$$A_{12} = \frac{1}{\sqrt{2}}[e^{ip_1\cdot(r_1-x)}e^{ip_2\cdot(r_2-y)} + e^{ip_1\cdot(r_1-y)}e^{ip_2\cdot(r_2-x)}]$$

so that

$$\mathcal{P}_{12} = \int d^4x\, d^4y\, |A_{12}|^2 \rho(x)\rho(y) = 1 + |\tilde{\rho}(q)|^2 \equiv C_2(q)$$



Two-particle wave function needs to account for the interactions among the two particles and between particles and the emitting medium, encoded in their *optical potential.*
(JG Cramer and GA Miller)

Formalism

Two-particle emission function:

$$S(x;p_1,p_2)=\int\frac{d^4y}{2(2\pi)^3}\left\langle J^*(x+\tfrac{1}{2}y)J(x-\tfrac{1}{2}y)\right\rangle \psi_{p_1}^{(-)}(x+\tfrac{1}{2}y)\psi_{p_2}^{(-)}(x-\tfrac{1}{2}y)$$

J = pion source

Exact outgoing scattering solution: $$\left(\frac{\partial^2}{\partial t^2}-\nabla^2+U_{\text{opt}}+m_\pi^2\right)\psi_p^{(-)}(x)=0$$

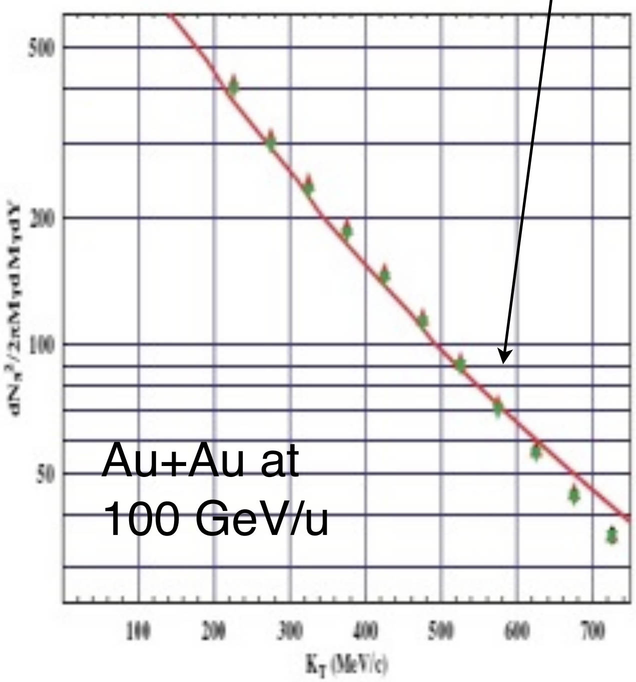
Two-particle correlation function:

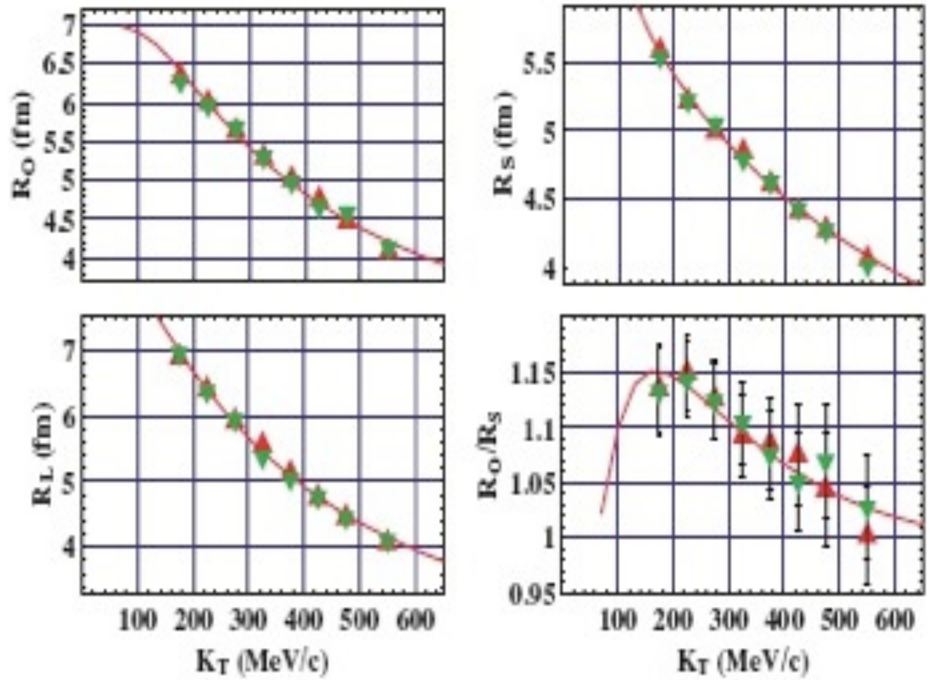
$$C(p_1,p_2)=1+\frac{\left|\int d^4x\,S(x;p_1,p_2)\right|^2}{\int d^4x\,S(x;p_1)\int d^4x\,S(x;p_2)}$$

Pion source fits

Pion spectrum

Pion source radii



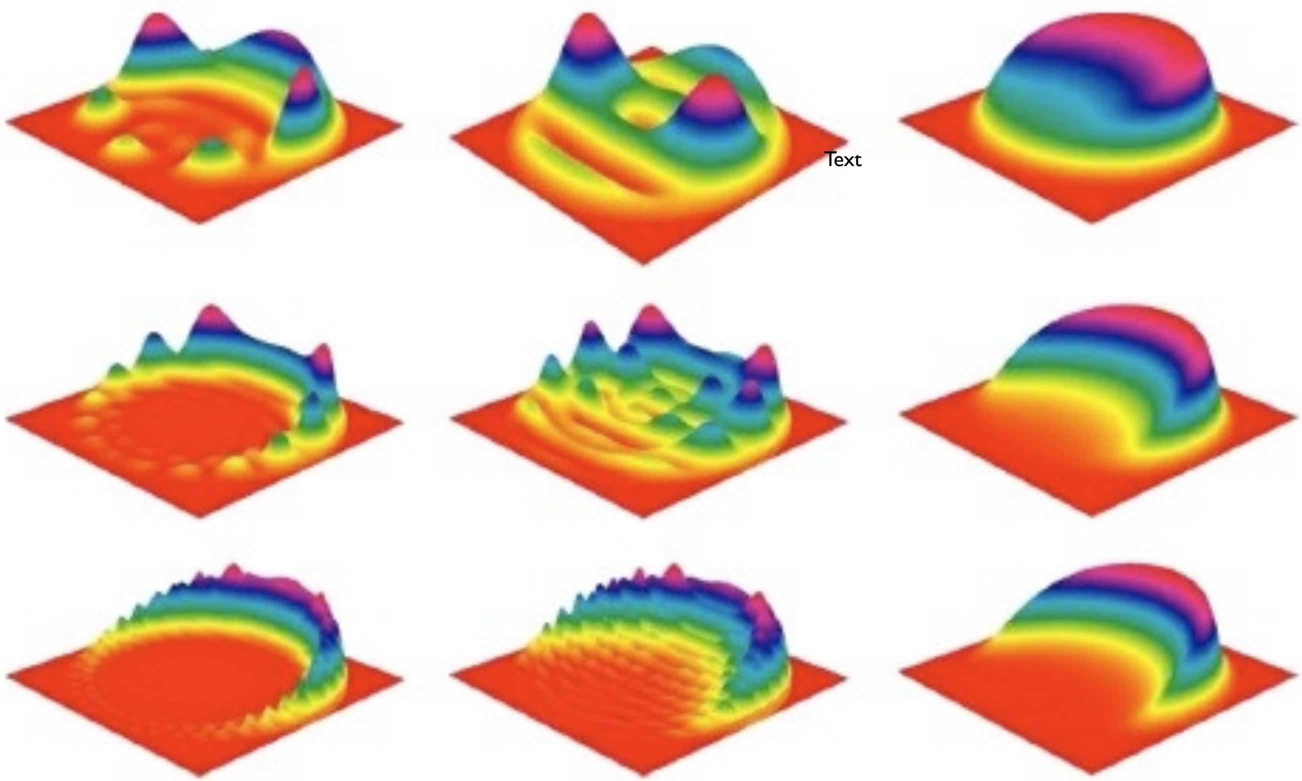


T (MeV)	η_f	$\Delta\tau$ (fm/c)	R_{WS} (fm)	a_{WS} (fm)	w_0 (fm^{-2})	w_2	τ_0 (fm/c)	$\Delta\eta$	ϵ	μ_π (MeV)
156.58	1.310 $\pm$0.025	2.0731 $\pm$0.07	11.867 $\pm$0.06	1.277 $\pm$0.015	0.0693 $\pm$0.046	$0.856+i0.116$ $\pm0.014\pm0.002$	9.04 $\pm$0.10	1.047 $\pm$0.032	0.000	139.57

“Polishing” the lens

GA Miller & JGC
JPG 34 (2007) 703

Full optical potential U	Re(U) = 0	Eikonal (U = 0)



K_T = 100 MeV/c

K_T = 250 MeV/c

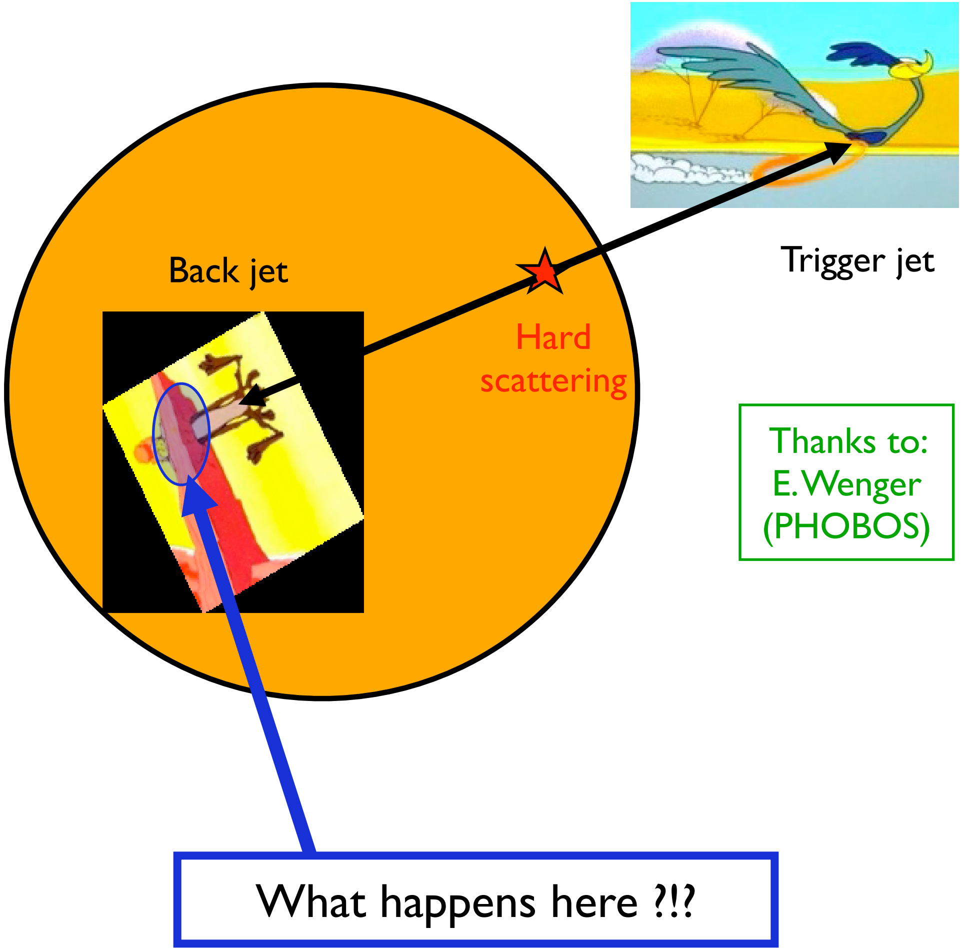
K_T = 600 MeV/c

Part 3

"Hearing" the QGP

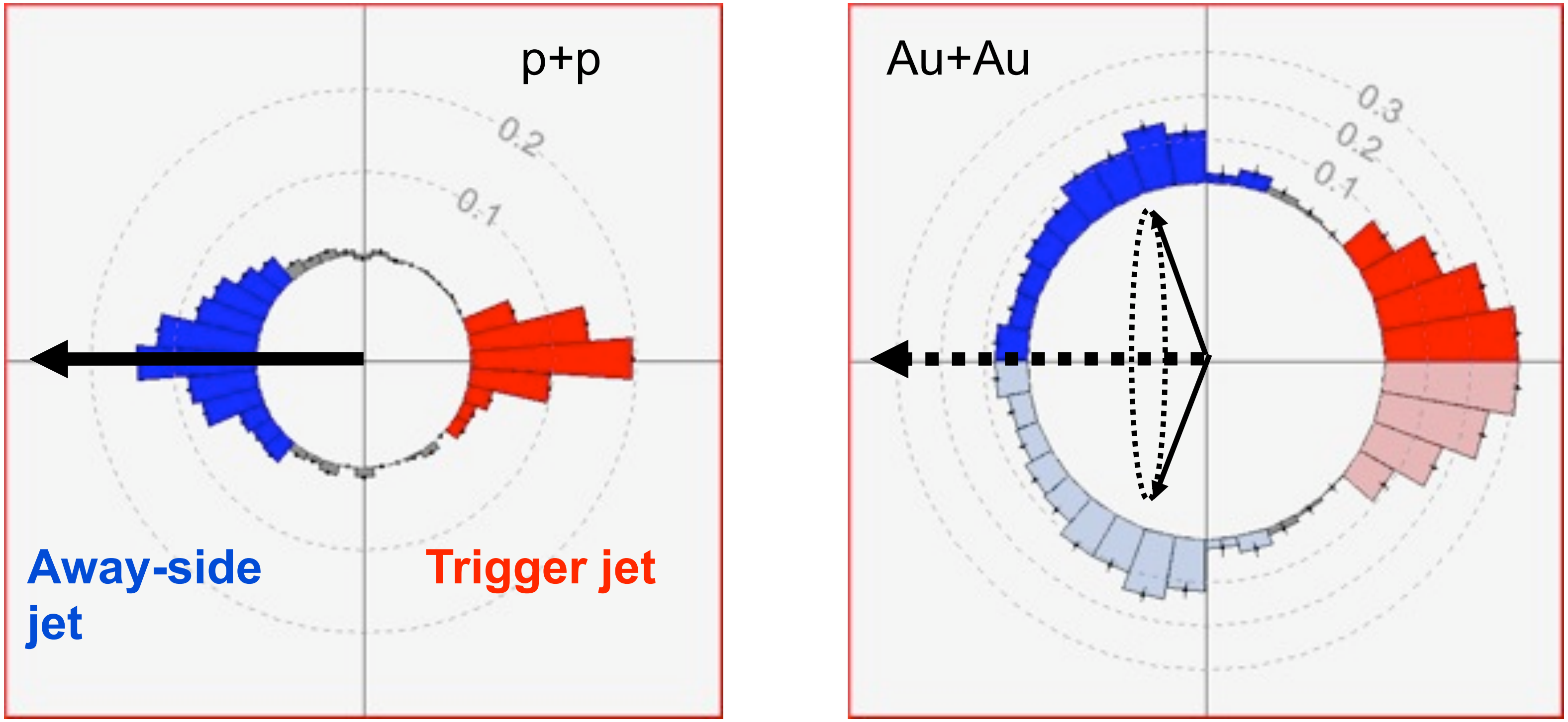
Jet-medium interactions

- How does a fast parton interact with the quark-gluon plasma ?
- What happens to the energy and momentum lost by a fast parton on its passage through the hot medium ?
- How does the energy and momentum perturbation of the medium propagate ?



Thanks to: E. Wenger (PHOBOS)

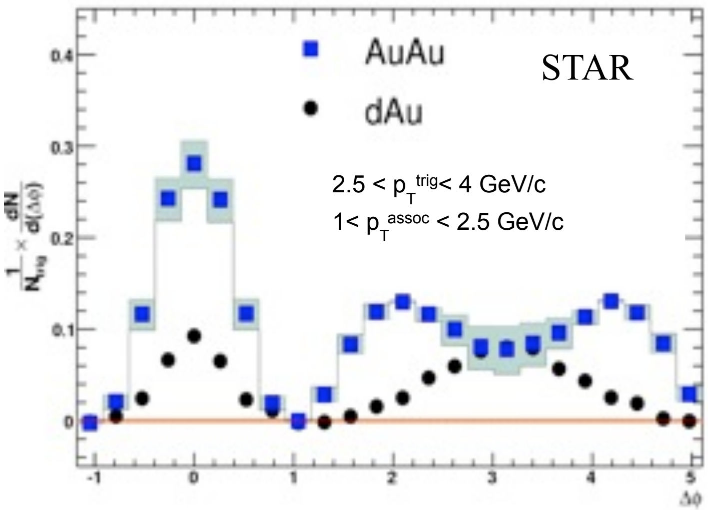
Where does the “lost” energy go ?



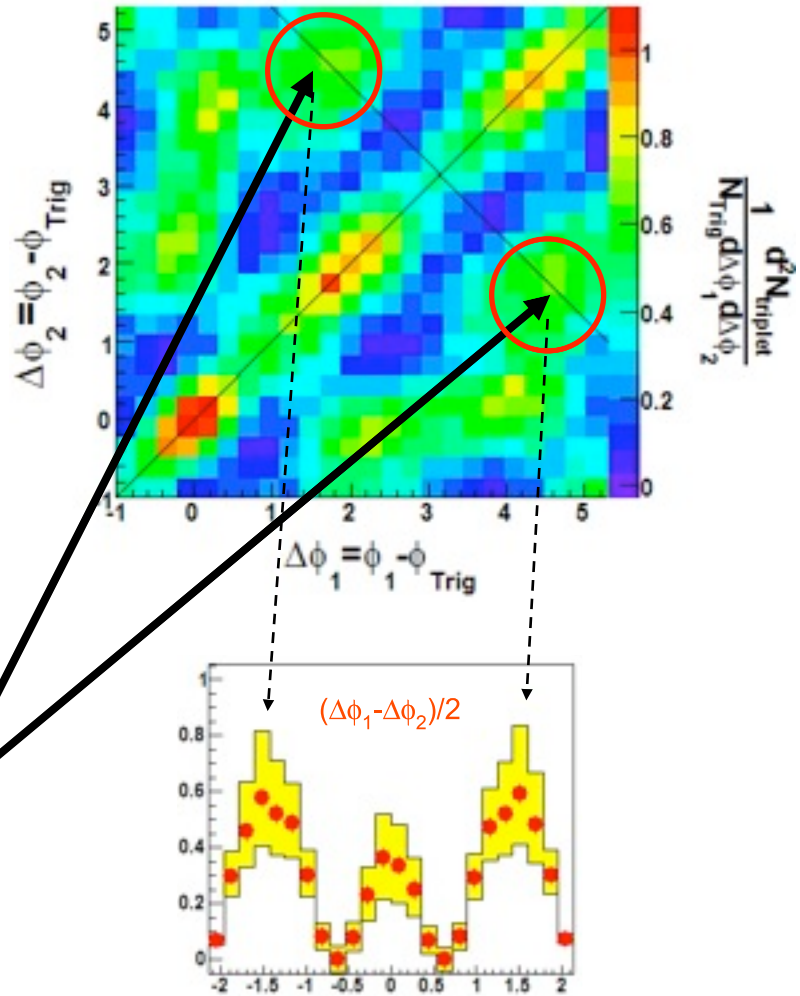
Lost energy of away-side jet is redistributed to angles away from 180° and low transverse momenta p_T < 2 GeV/c (Mach cone?).

STAR data

Away side shape modification



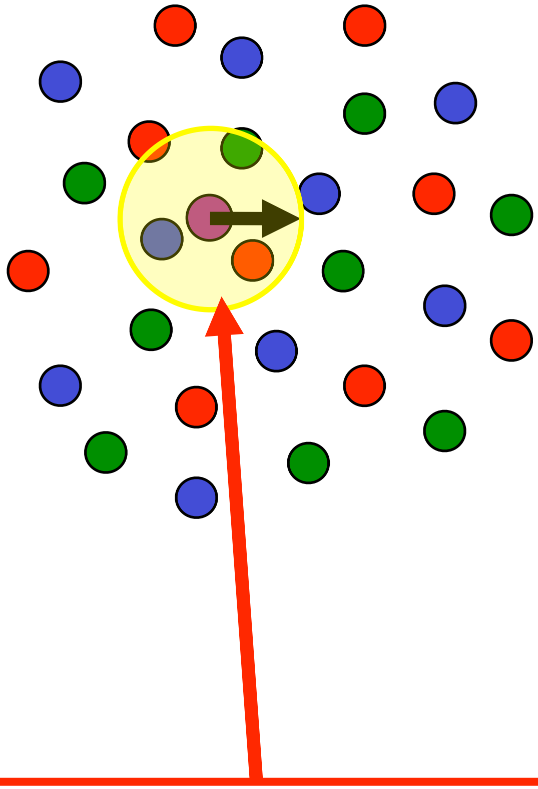
Central Au+Au 0-12% (STAR)



Technique: Measure 2- and 3- particle correlations on the away-side triggered by "high" p_T hadron in central collisions.

Cone-shaped emission shows up in 3-particle correlations as signal on both sides of the backward direction.

Parton-medium coupling



$$\left[\frac{p^\mu}{E}\frac{\partial}{\partial x^\mu} - \nabla_p \cdot D(x,p) \cdot \nabla_p\right] f_0(x,p) = C[f_0]$$

with

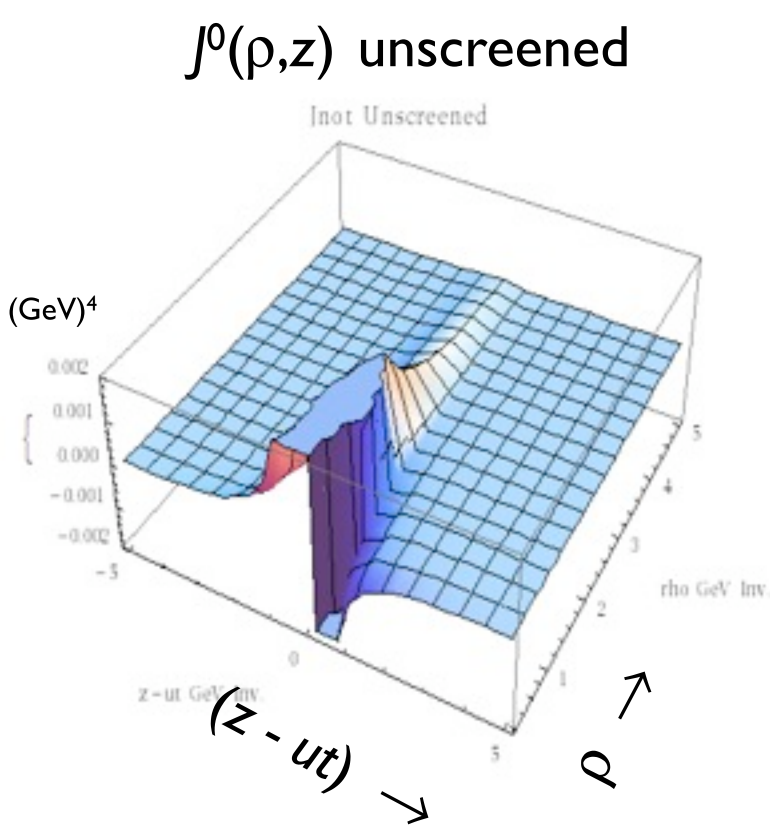
$$D_{ij}(x,p) = \int_{-\infty}^{t} dt' F_i(\vec{x},t) F_j(\vec{x} + \vec{v}(t'-t),t') \ .$$

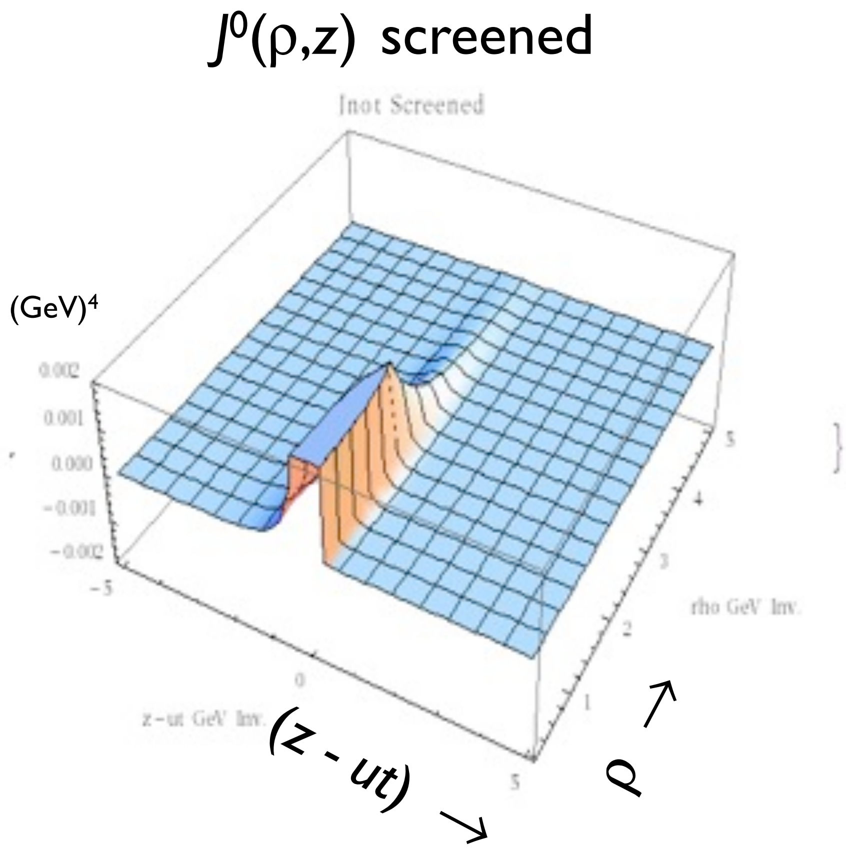
$$\frac{\partial}{\partial x^\mu} T^{\mu\nu} = J^\nu$$

Space-time distribution of collisional energy loss

with
$$\begin{cases} T^{\mu\nu} = (\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu} + T^{\mu\nu}_{\text{diss}} \\ J^\nu = \int d\mathbf{p}\, p^\nu\, \nabla_p \cdot D(x,p) \cdot \nabla_p\, f(x,p) \end{cases}$$

Energy density





Bryon Neufeld

$u = 0.99$

Linearized hydro

Linearize hydro eqs. for a weak source: $T^{00} \to \varepsilon_0 + \delta\varepsilon$, $T^{0i} \to g^i$.

$$\frac{\partial}{\partial t}\delta\varepsilon + \nabla\cdot\vec{g} = J^0 \qquad \frac{\partial}{\partial t}\vec{g} + c_s^2\nabla\delta\varepsilon + \frac{\eta}{\varepsilon_0 + p_0}\frac{4}{3}\nabla(\nabla\cdot\vec{g}) = \vec{J}$$

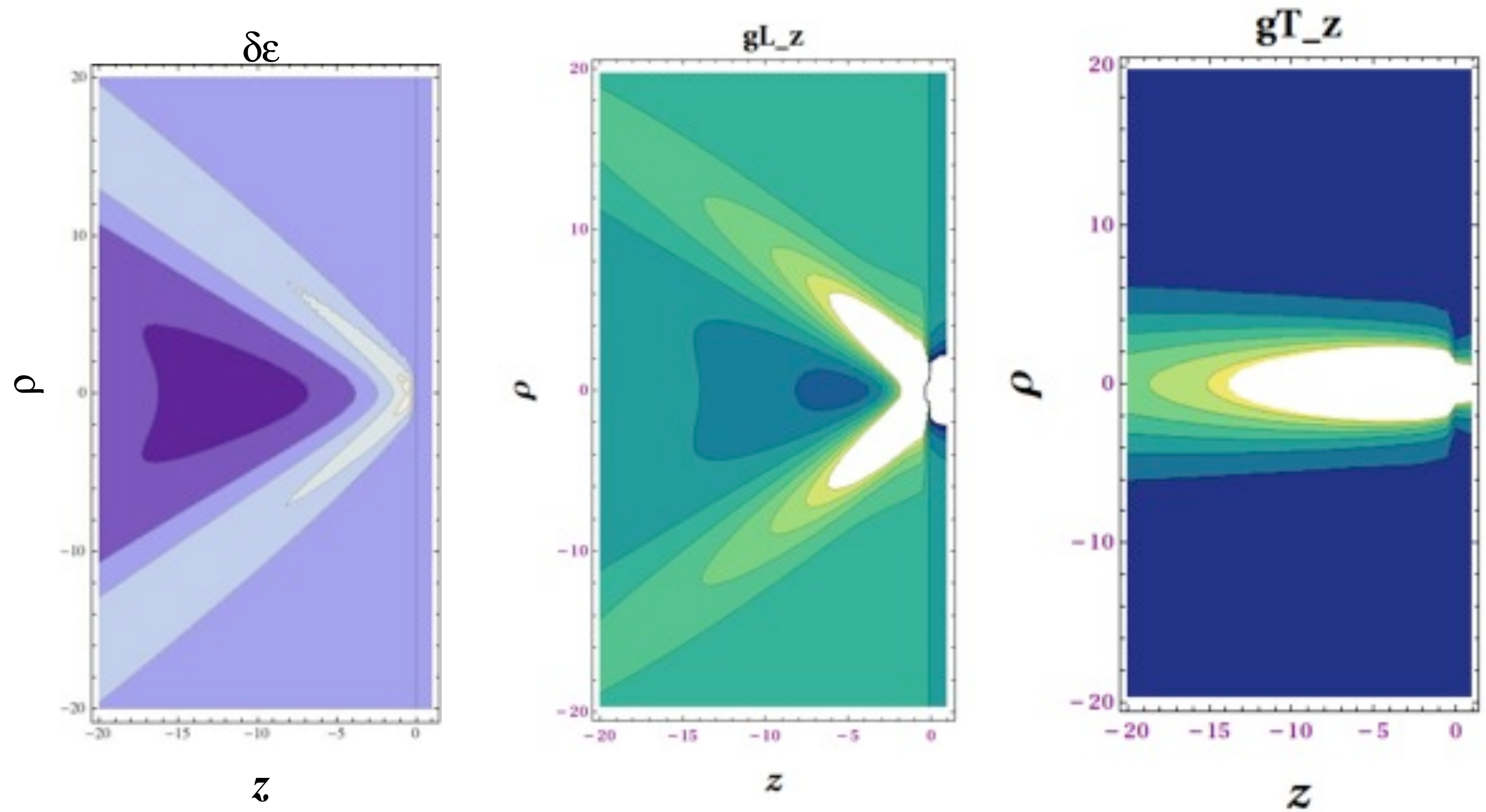
Solve in Fourier space for longitudinal sound:

$$\delta\varepsilon = i\frac{(\omega + i\Gamma_s k^2)J^0 + kJ_L}{\omega^2 - c_s^2 k^2 + i\Gamma_s\omega k^2} \qquad g_L = i\frac{c_s^2 k J^0 + \omega J_L}{\omega^2 - c_s^2 k^2 + i\Gamma_s\omega k^2}$$

… and dissipative transverse perturbation: $g_T = i\dfrac{J_T}{\omega + \frac{3}{4}i\Gamma_s k^2}$

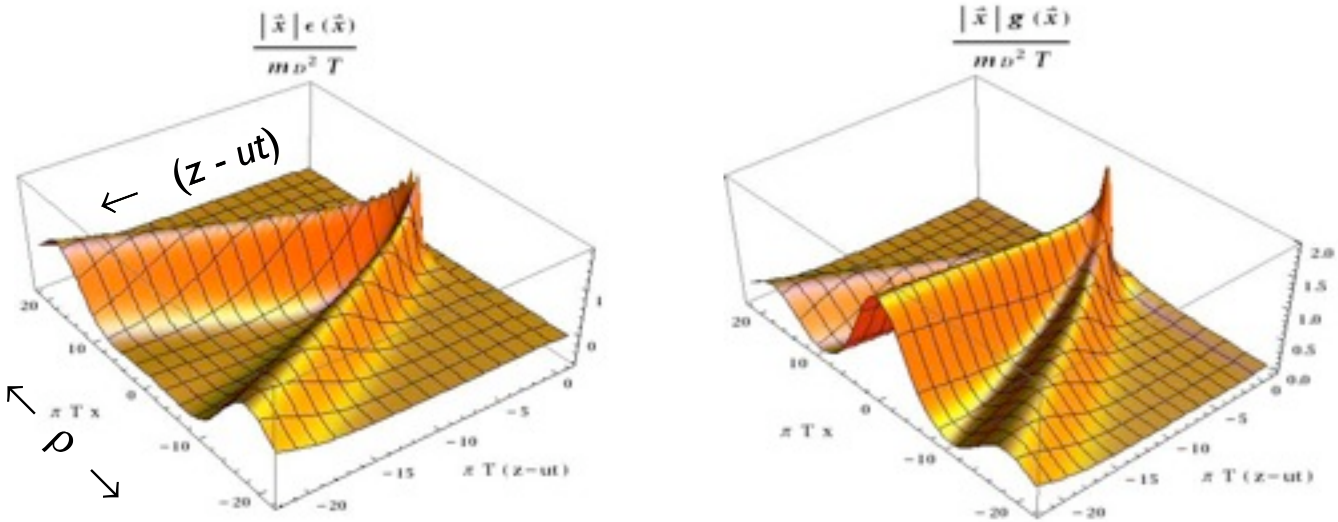
Use: $u = 0.99955c$, $c_s^2 = \dfrac{1}{3}$, $\Gamma_s = \dfrac{1}{3\pi T}$ for $T = 350$ MeV.

Contour plots



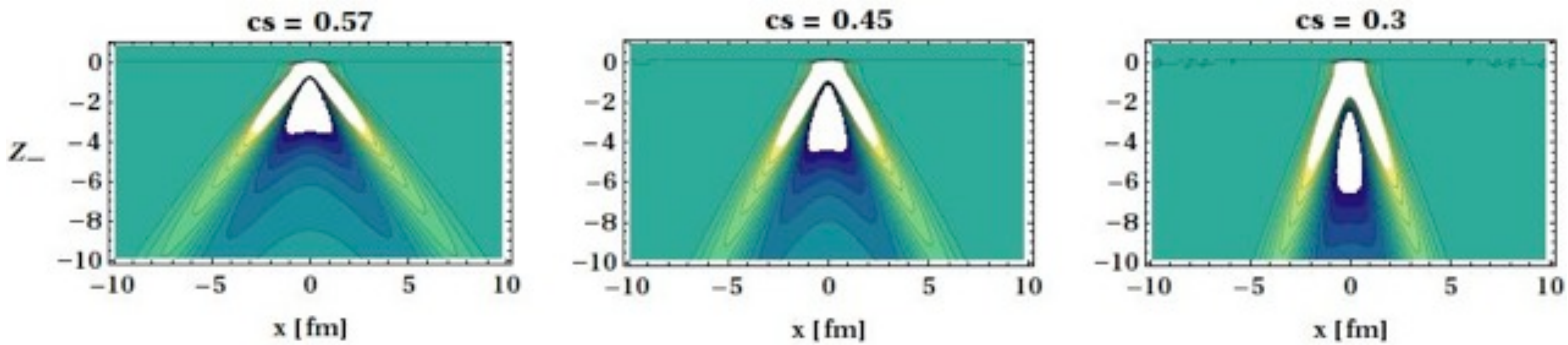
R.B. Neufeld, J. Ruppert, BM, *Phys. Rev.* C78, 041901(R) (2008)

Mach cone

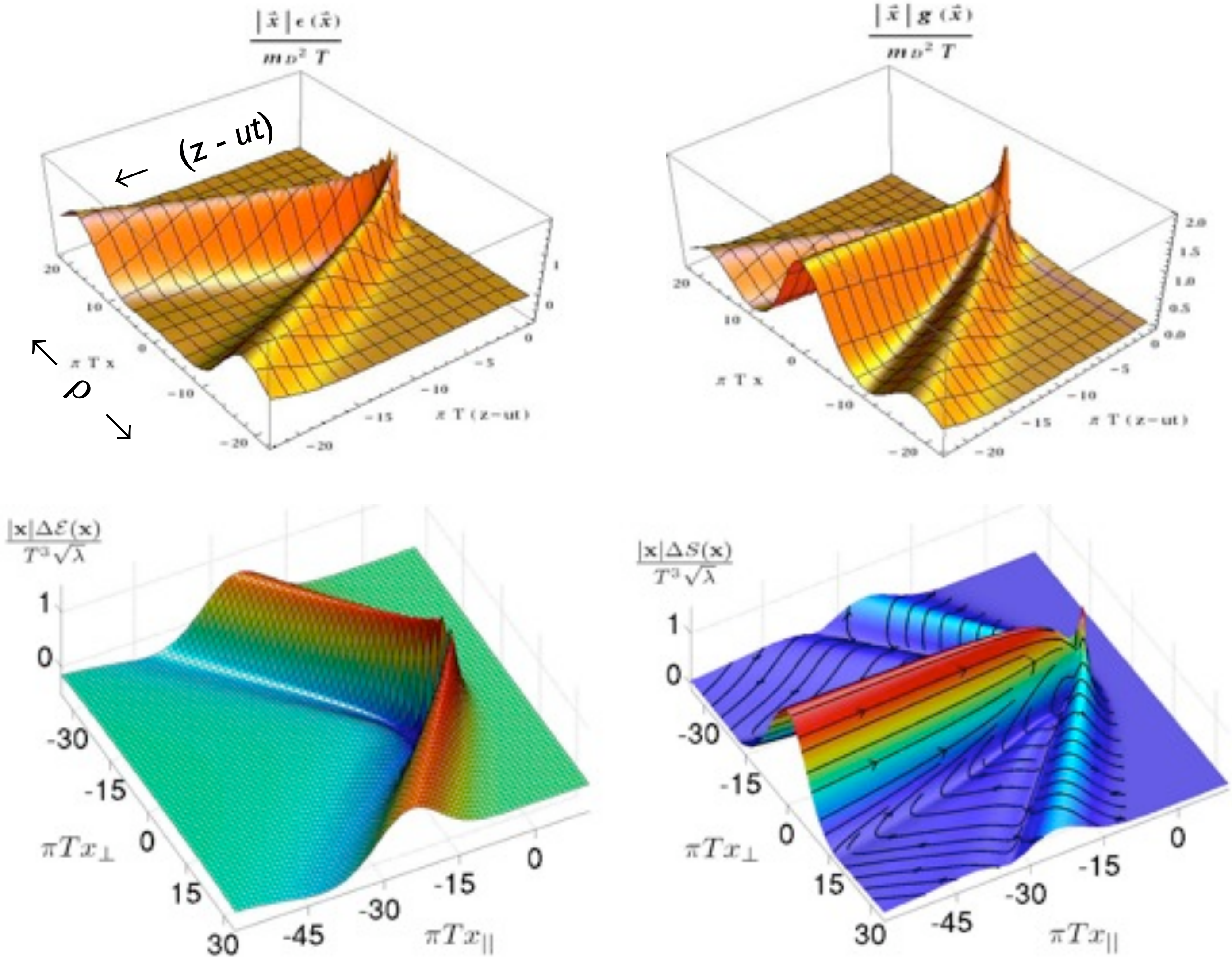


u = 0.99955 c

($\gamma \approx 30$)



pQCD vs. *N*=4 SYM



u = 0.99955 c

Neufeld et al.
arXiv:0802.2254

Chesler & Yaffe
arXiv:0712.0050

u = 0.75 c

The ultimate "crescendo"

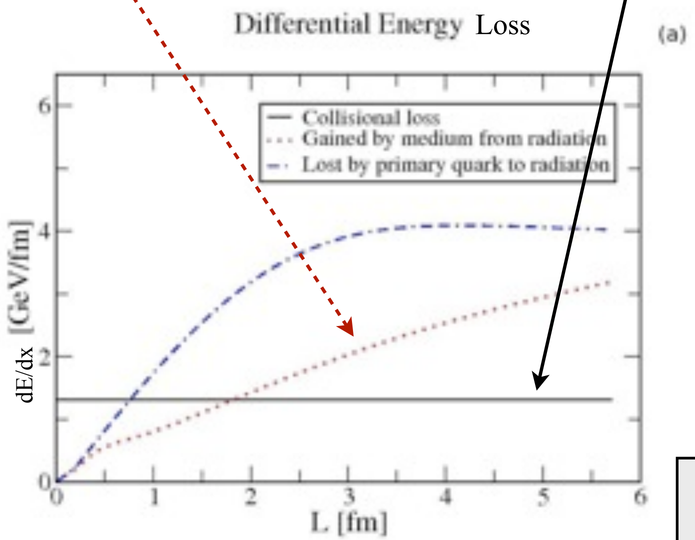
Radiative energy loss > collisional energy loss, but only collisions deposit energy into the plasma. However, radiated gluons contribute to the sound source:

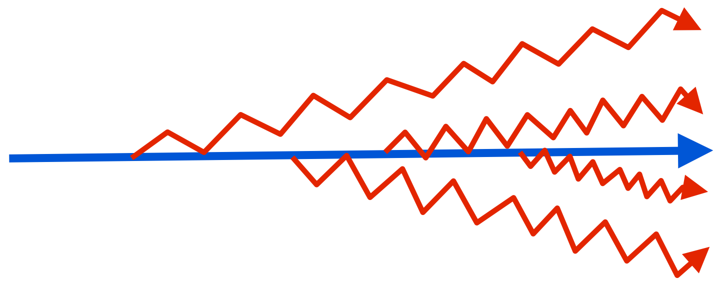
The "soloist" becomes a chamber "orchestra" !

R.B. Neufeld & BM, PRL 103, 042301

Energy deposit by quark is constant

Energy deposit by gluons grows with *L*

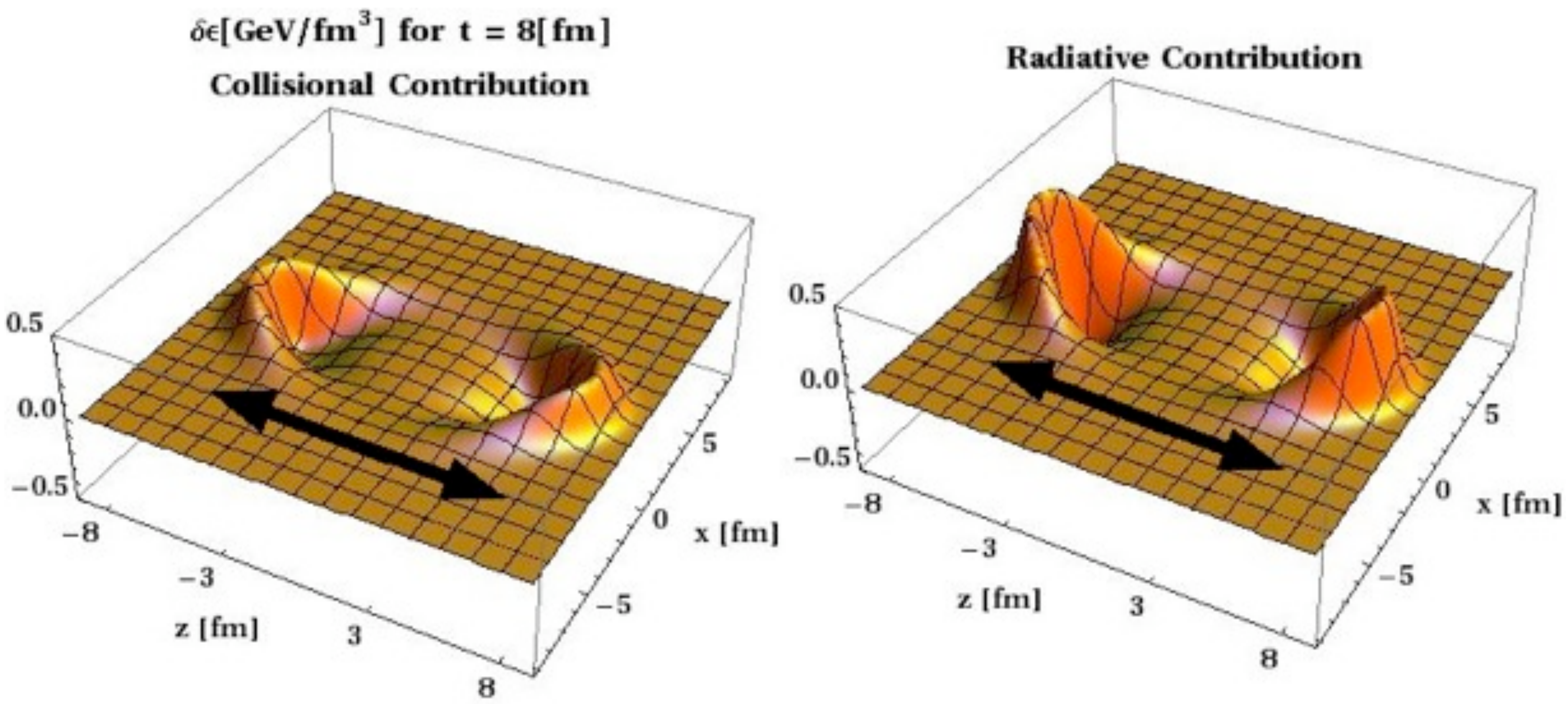




$$\frac{\partial}{\partial x} f(\omega,x) - \frac{\partial}{\partial \omega}\left[\varepsilon(\omega) f(\omega,x)\right] = \frac{dI(\omega,x)}{d\omega\, dx}$$

The "crescendo" could explain why experiments show sound velocity c_s = 0.3 corresponding to T_c .

Back-to-back partons



Linearized hydro simulation of radiation-enhanced Mach cone (R.B. Neufeld)

Time to wrap up!

- The QGP can be “seen” through the formation of hadrons via recombination of collectively flowing quarks.
- “Slow” hadron quantum correlations reveal an image of the emitting source, which is sensitive to the hadron interactions with the medium.
- Energetic partons (jet progenitors) produce a sonic Mach cone in the QGP, which grows with time and peaks at T_c.
- Thus - can we hear and see the quark-gluon plasma?

Yes, we can !