Quark-Gluon Plasma

An Overview

Ewha Women’s University

Seoul, April 21, 2005

Thank you for the invitation to Korea

Berndt Müller
Duke University

Hadronic Probes of Quark Deconfinement

Hadrons encode essential properties of the partonic phase of dense, hot matter created in RHI reactions.

Special thanks to…

- ***M. Asakawa***
- ***S.A. Bass***
- ***R.J. Fries***
- ***C. Nonaka***
- ***J. Ruppert***

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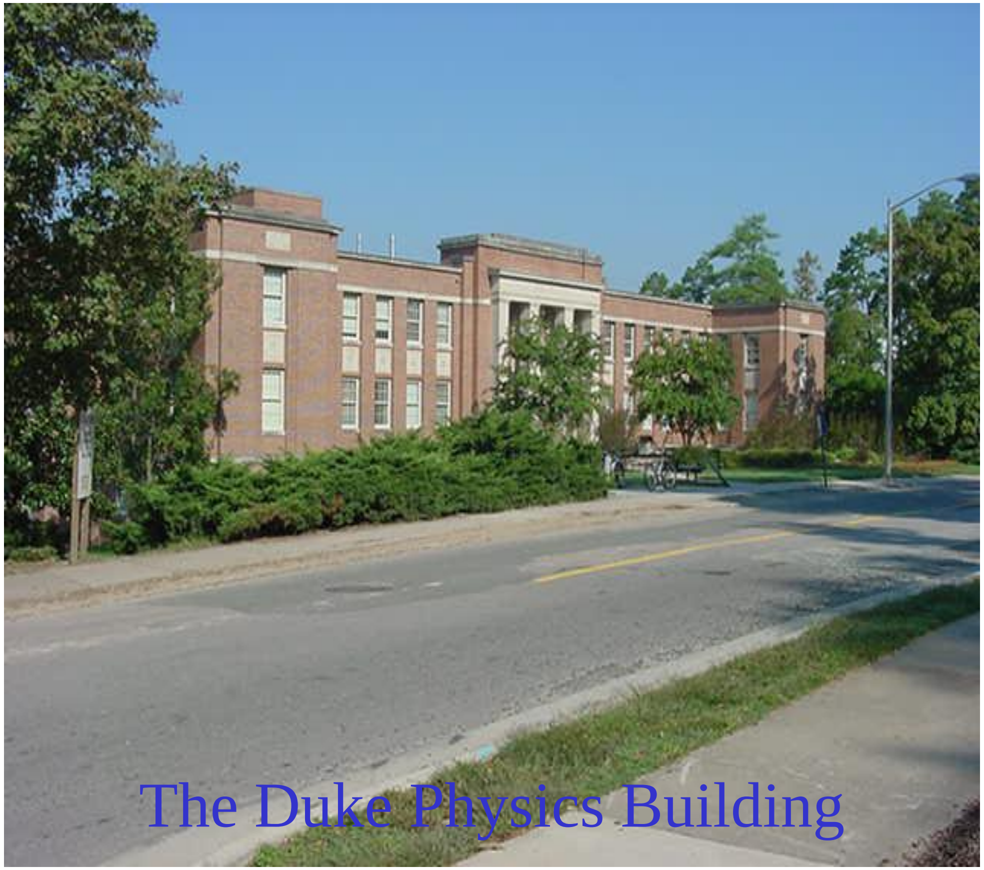
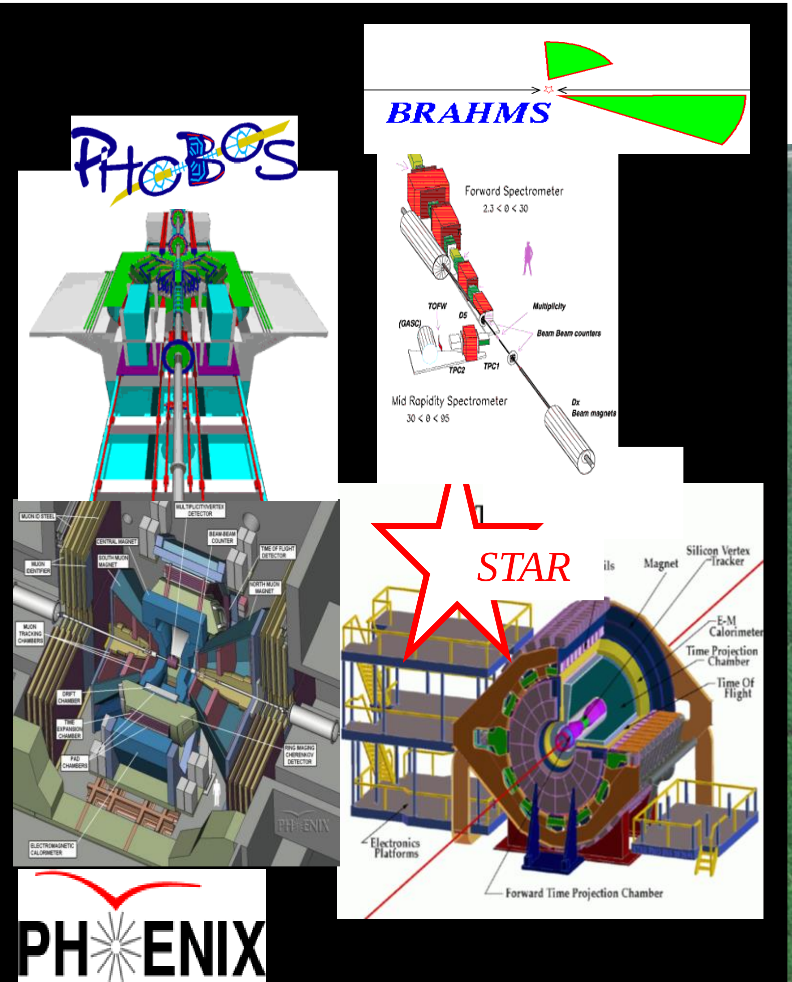

The Duke Physics Building

… and to the brave RHIC experimental collaborations!

The Road to the Quark-Gluon Plasma…

…Is Circular and 2.4 Miles Long – Insights from 4 years of RHIC Experiments

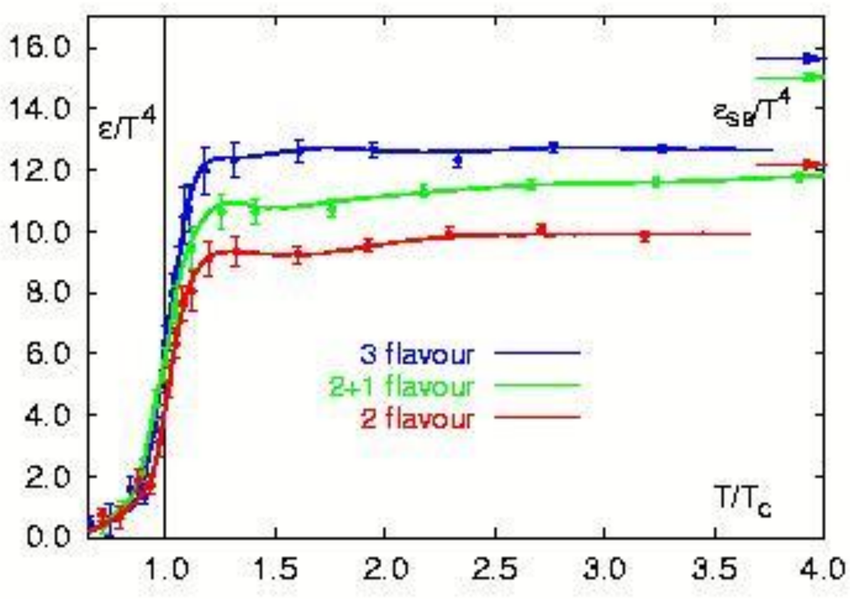


RHIC Scientists Serve Up “Perfect” Liquid

- **New state of matter more remarkable than predicted -- raising many new questions**
- *April 18, 2005*
- TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom “smasher” located at the U.S. Department of Energy’s Brookhaven National Laboratory -- say they’ve created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC’s heavy ion collisions appears to be more like a liquid.

Simplicity is Beautiful

The equation of state of strongly interacting matter according to lattice QCD



- Before the QGP concept, matter at high energy density was a *mess*!
- The QGP predicted that hot matter becomes *simple* (not necessarily weakly interacting).
- Characteristic features: deconfinement and chiral symmetry restoration.

What would it take…?

Question (from an un-named friend):

What would it take to convince you that a quark-gluon plasma has been produced at RHIC?

My answer – If we could show that:

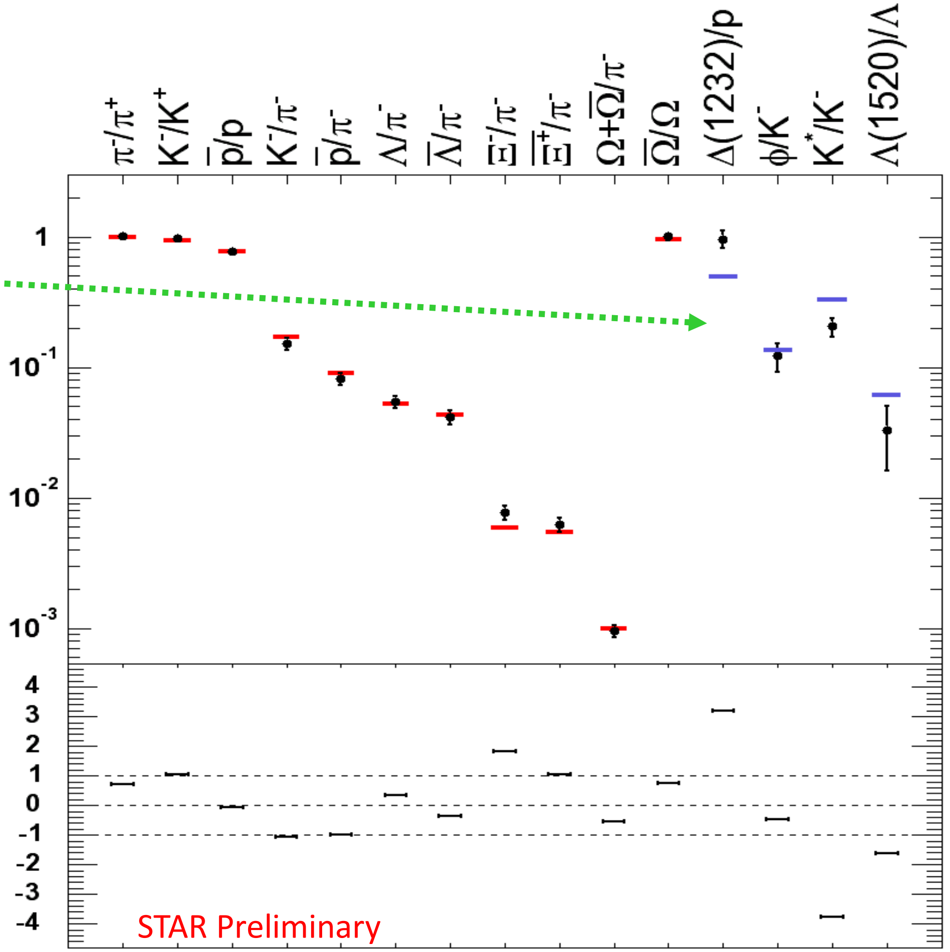
- ***Hadrons are emitted in universal equilibrium abundances;***
- ***Hadrons are produced by recombination of quarks from a thermal, dense phase;***
- ***Hadrons show clear evidence of collective flow (v_0 and v_2);***
- ***Flow pattern is not universal for hadrons, but universal for the constituent quarks.***

Equilibrium fits work…

- Chemical equilibrium fits work, *except* where they should not (resonances with large rescattering).

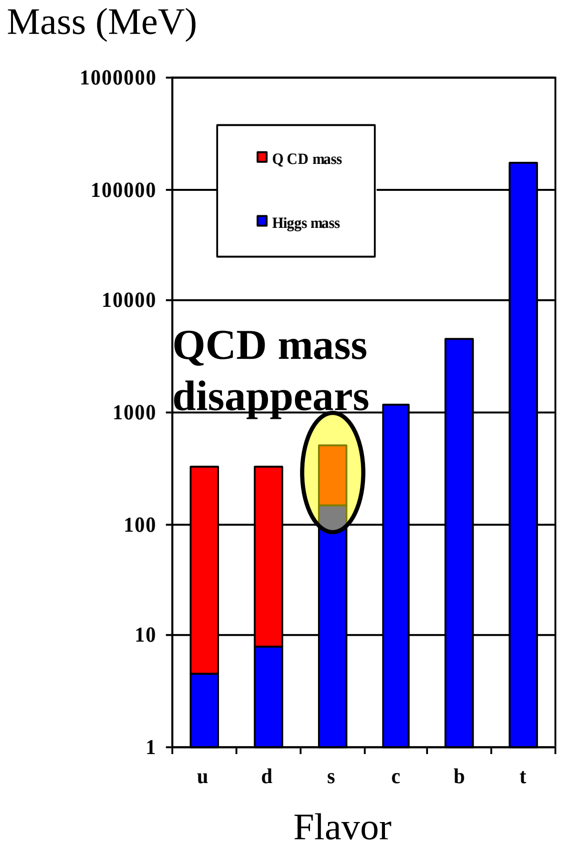
RHIC Au+Au @ 200 GeV

  - T_{ch} = 160 ± 10 MeV
  - μ_B = 24 ± 5 MeV

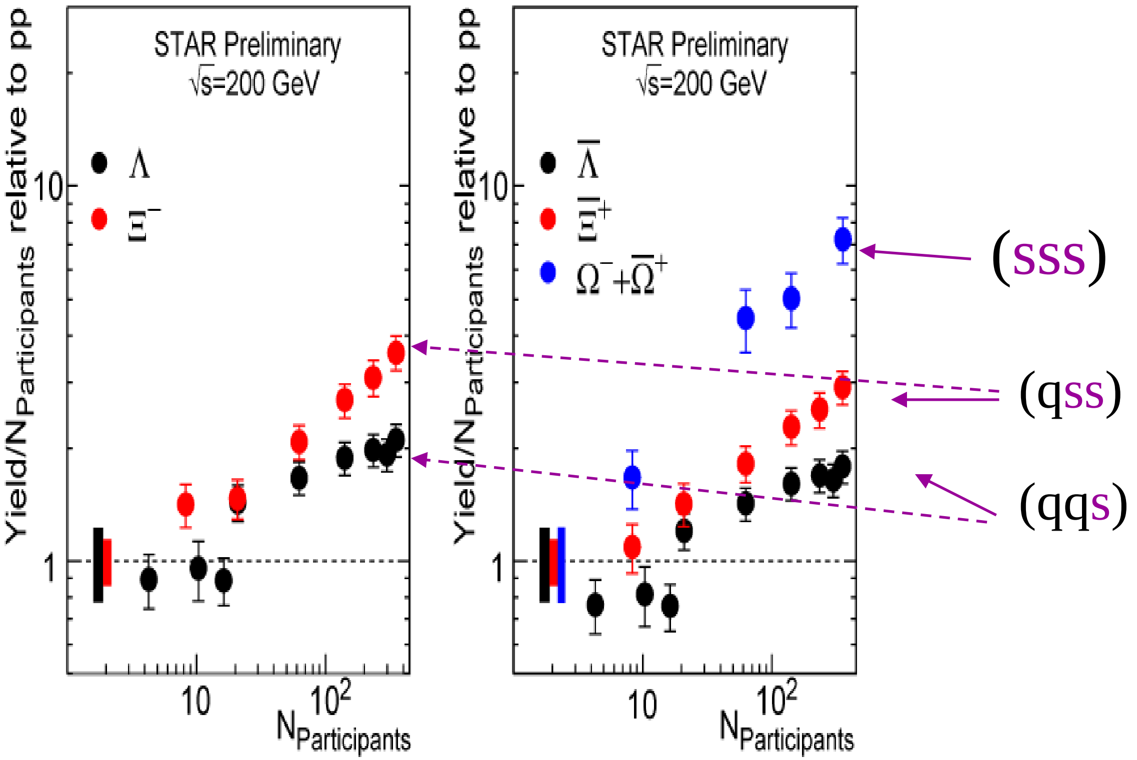


Strangeness in Au+Au at RHIC

The strangeness "enhancement" is less than at SPS energy, as expected from chemical equilibrium paradigm!



QCD mass disappears



(sss)

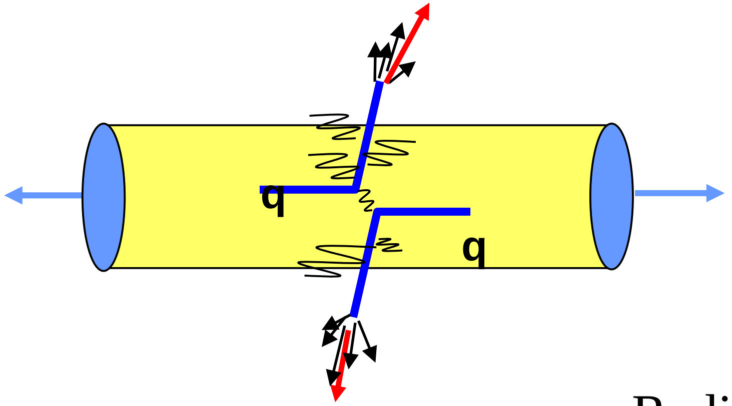
(qss)

(qqs)

Conclusions (1)

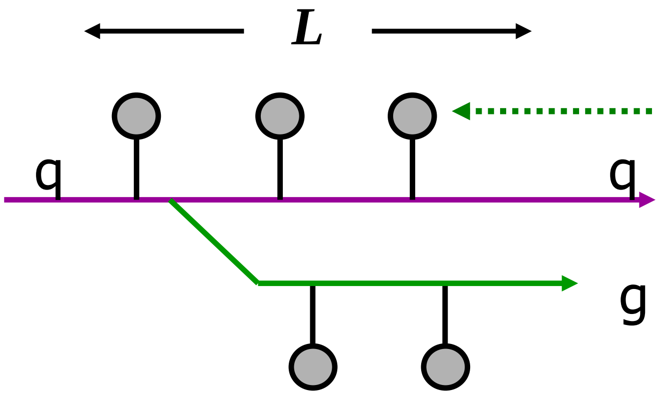
- Clear evidence for a *universal* hadronization temperature $T_{\mathrm{ch}} \equiv T_{\mathrm{c}}$ is seen in RHIC data;
- Already visible at SPS, but only RHIC data make the evidence compelling (T_{ch} does not increase);
- Strangeness equilibration is critical discriminator between phase space dominance (pp, e^+e^-) and equilibration (AA) - only achieved at RHIC.

"Jet Quenching" = Energy Loss



High-energy parton loses energy by rescattering in dense, hot medium.

Radiative energy loss: $dE/dx \propto \rho L \langle k_T{}^2 \rangle$



Scattering centers = color charges

Can be described as medium effect on parton fragmentation:

$$D_{p\to h}(z,Q^2) \to \tilde{D}_{p\to h}(z,Q^2) \approx D_{p\to h}\left(\frac{z}{1-\Delta E/E}, Q^2\right)$$

Energy loss in QCD

Density of scattering centers

Scattering "power" of QCD medium:

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho \left\langle k_T^2 \right\rangle$$

Property of medium (range of color force)

With expansion:

$$\hat{q}L^2 \Rightarrow \left(\hat{q}L^2\right)_{\mathrm{eff}} = \frac{2\hat{q}_0}{\rho(r)} \int \tau d\tau \rho(r_\tau, \tau)$$

For power law parton spectrum (□$p_T^{-\nu}$) effective momentum shift for fast partons:

$$\Delta p_T \approx -\alpha_s \sqrt{\pi \hat{q} L^2 p_T / \nu}$$

Analytical model: Surface emission

Quenching factor: $$\frac{d\tilde{N}}{d^2 p_{\mathrm{T}}} = Q(p_{\mathrm{T}})\frac{dN}{d^2 p_{\mathrm{T}}}$$

$(Q \rightarrow R_{AA})$

partons

hadrons

$$Q(p_T) \approx \frac{2(p_0 + p_T)}{\pi R \eta \rho (\nu - 1) p_T^{1/2}}$$

Volume / ***R*** = surface

$\rho \leq$ final dN/dy / volume

η = QCD energy loss parameter:

$$\eta \equiv \pi \alpha_s^2 \hat{q} / \rho = \tfrac{3}{2} C_2 (\pi \alpha_s^2)^2 \ln\left(q_{\max}^2 / \mu_{\mathrm{D}}^2\right)$$

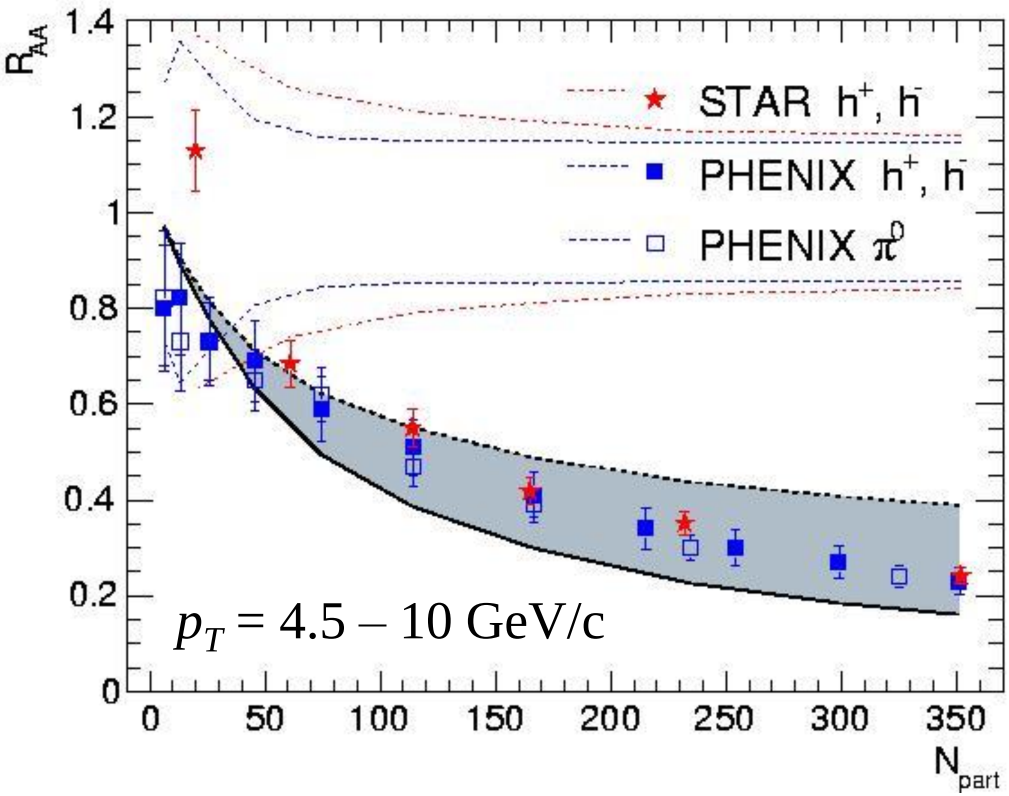
$\eta \approx 0.5 \ln(\ldots)$ for gluons; $\eta \approx 0.25 \ln(\ldots)$ for quarks

Energy loss at RHIC

- Data can be fitted with a large loss parameter for central collisions:

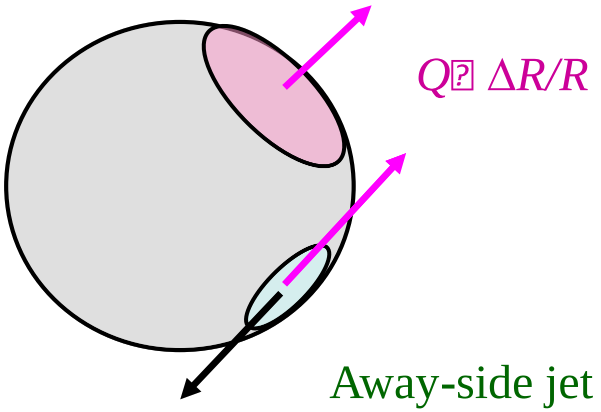
$$\langle \hat{q} \rangle \approx 5 - 10\ \mathrm{GeV}^2/\mathrm{fm}$$

(Dainese, Loizides, Paic,
hep-ph/0406201)

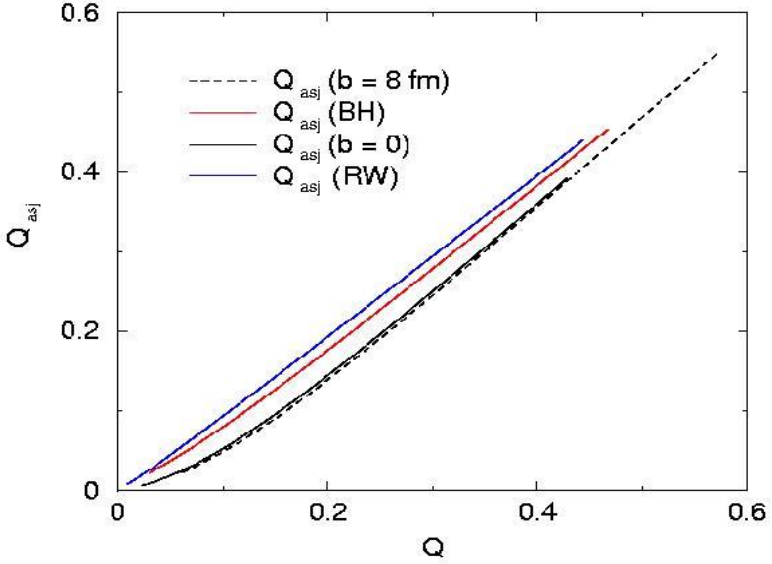


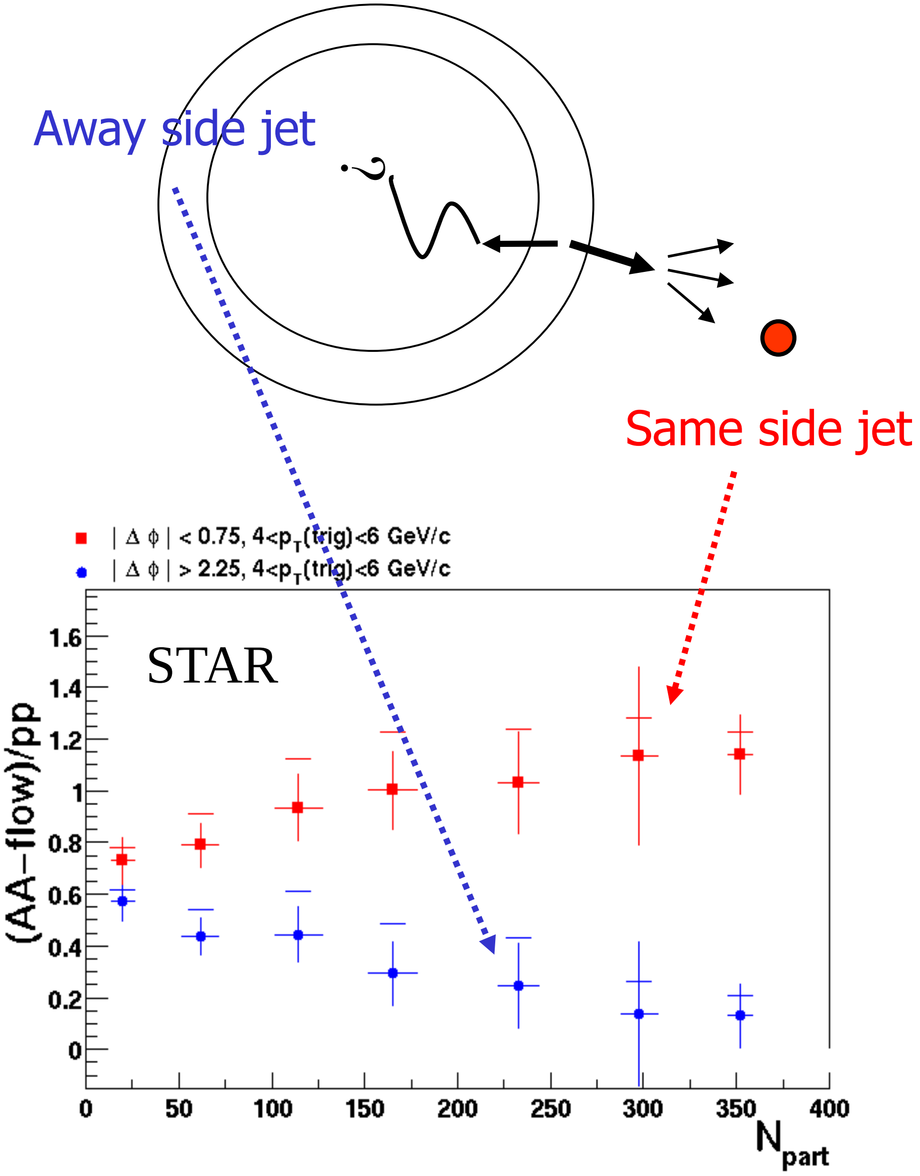
Is this compatible with perturbative energy loss?

Correlations

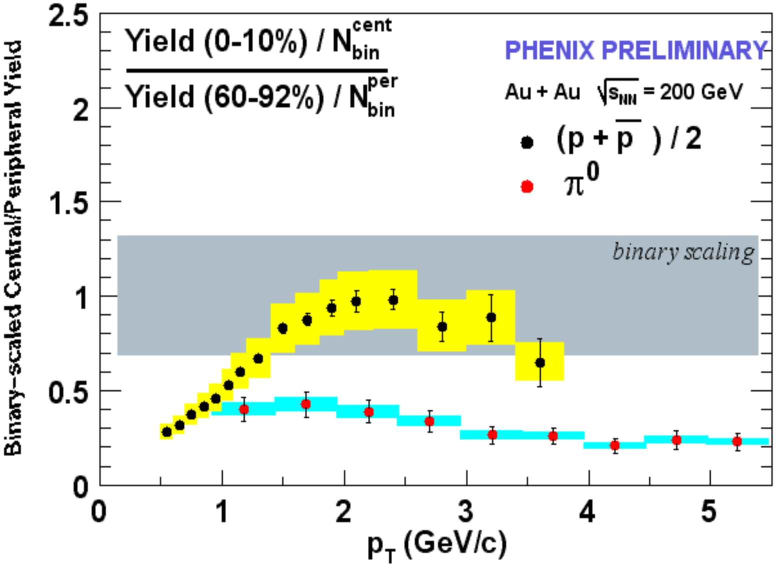


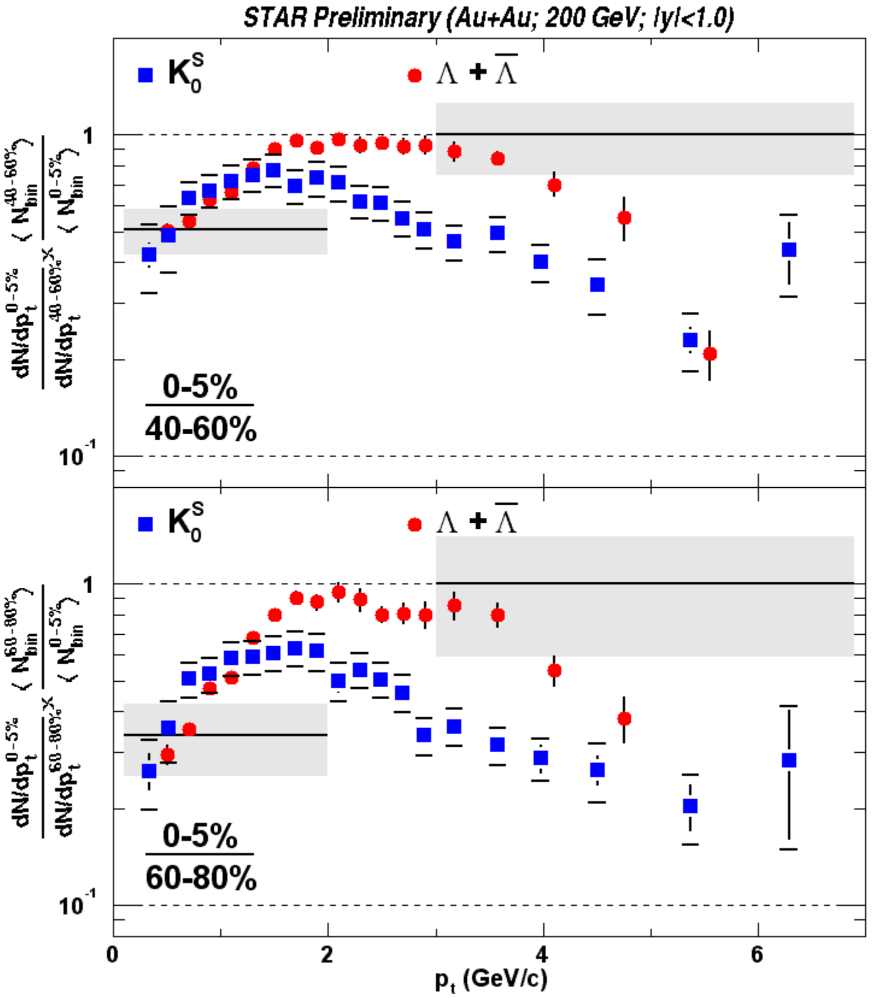
$$Q' \propto (\Delta R / R)^2 = Q \times Q_{\mathrm{asj}}$$





Suppression Patterns: Baryons vs. Mesons

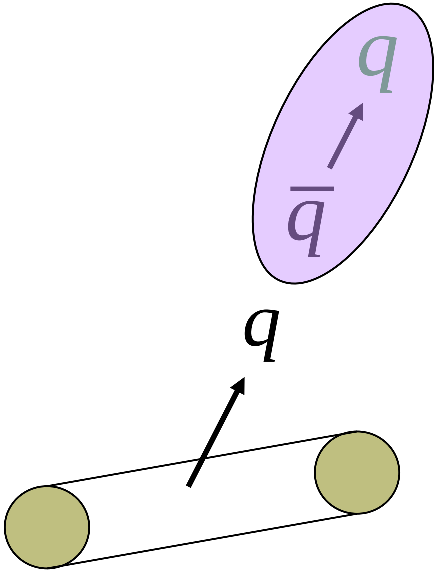




- What makes baryons different from mesons ?

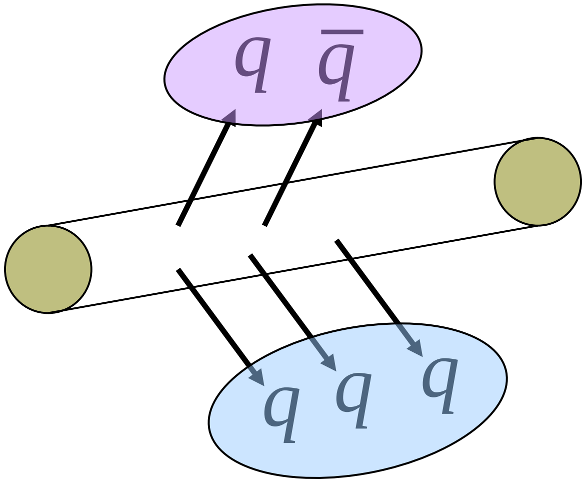
Hadronization Mechanisms

Recombination was predicted in the 1980’s – but a surprise after all



Fragmentation

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



Recombination

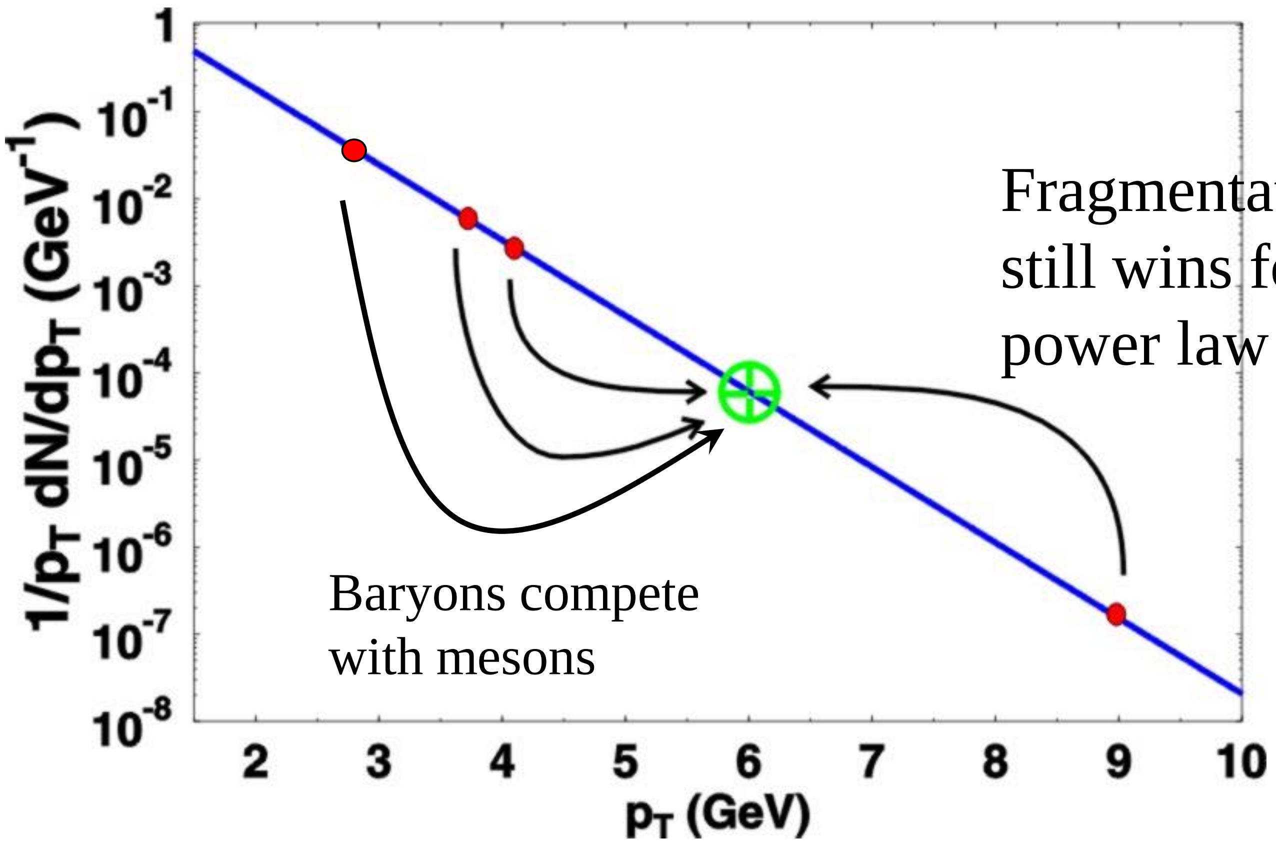
$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

Not:
Coalescence from dilute medium

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

Recombination “wins” …

… always for a thermal source



Fragmentation still wins for a power law tail

Baryons compete with mesons

Recombination of Thermal Quarks

Relativistic formulation using hadron light-cone frame:

$w_\alpha(r,p) =$ Quark distribution function at “freeze-out”

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

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

For a thermal distribution, $w(r,p) \square \exp(-p\cdot u/T)$

the hadron wavefunctions can be integrated out, eliminating the model dependence of predictions. This is true even if higher Fock space states are included!

Beyond the lowest Fock state

$$\left|M;Q^2\right\rangle=\int_0^1 dx_a\,dx_b\,\delta(x_a+x_b-1)\,\phi_1(x_a,x_b;Q^2)\left|q(x_a)\bar{q}(x_b)\right\rangle$$

$$+\int_0^1 dx_a\,dx_b\,dx_c\,\delta(x_a+x_b+x_c-1)\,\phi_2(x_a,x_b,x_c;Q^2)\left|q(x_a)\bar{q}(x_b)g(x_c)\right\rangle+\ \cdots$$

$$W_{q\bar{q}}=\int_0^1 dx_a\,dx_b\,\delta(x_a+x_b-1)\left|\phi_1(x_a,x_b)\right|^2\left\langle q(x_a)\bar{q}(x_b)\right|\rho\left|q(x_a)\bar{q}(x_b)\right\rangle$$

$$=\int_0^1 dx_a\,dx_b\,\delta(x_a+x_b-1)\left|\phi_1(x_a,x_b)\right|^2 w_q(x_a)w_{\bar{q}}(x_a)=e^{-P/T}\int_0^1 dx_a\left|\phi_1(x_a,1-x_a)\right|^2$$

$$\Uparrow$$

$$\boxed{e^{-x_aP/T}e^{-x_bP/T}=e^{-(x_a+x_b)P/T}}$$

For thermal medium

$$W_{q\bar{q}g}=\int_0^1 dx_a\,dx_b\,dx_c\,\delta(x_a+x_b+x_c-1)\left|\phi_2(x_a,x_b,x_c)\right|^2 w_q(x_a)w_{\bar{q}}(x_a)w_g(x_c)\ \Leftarrow$$

$$=e^{-P/T}\int_0^1 dx_a\,dx_b\left|\phi_2(x_a,x_b,1-x_a-x_b)\right|^2$$

$$\boxed{e^{-x_aP/T}e^{-x_bP/T}e^{-x_cP/T}=e^{-(x_a+x_b+x_c)P/T}}$$

$$\boxed{W_M=W_{q\bar{q}}+W_{q\bar{q}g}+\cdots=e^{-P/T}\left[\int_0^1 dx_a\left|\phi_1(x_a,1-x_b)\right|^2+\int_0^1 dx_a\,dx_b\left|\phi_2(x_a,x_b,1-x_a-x_b)\right|^2+\cdots\right]=e^{-P/T}}$$

Recombination vs. Fragmentation

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

Fragmentation:
$$E\frac{dN_{\mathrm{h}}}{d^3P}=\int d\sigma\,\frac{P\cdot u}{(2\pi)^3}\int_0^1\frac{dz}{z^3}\sum_\alpha w_\alpha(r,\tfrac{1}{z}P)D_{\alpha\to\mathrm{h}}(z)$$

Recombination…
$$w_\alpha(r,xP^+)\bar{w}_\beta(r,(1-x)P^+)=\exp\left(-P\cdot u/T\right)$$ Meson

$$w_\alpha(r,xP^+)w_\beta(r,x'P^+)w_\gamma(r,(1-x-x')P^+)=\exp\left(-P\cdot u/T\right)$$ Baryon

…always wins over fragmentation for an exponential spectrum ($z<1$):

$$\exp(-P\cdot u/T) \quad > \quad \exp(-P\cdot u/zT)$$

… but loses at large p_T, where the spectrum is a power law ~ $(p_T)^{-b}$

Recombination & Statistical Model

In statistical model, hadron distributions at freeze-out are given by:

$$E\frac{d^3N_i}{d^3P} = \int_\sigma f_i\left(P\cdot u\right) P^\lambda d\sigma_\lambda \quad \text{with}$$

$$f_i\left(P\cdot u\right) = \frac{g_i}{\left(2\pi\right)^3}\left(\exp\left[\left(P\cdot u - \mu_B B_i - \mu_s S_i - \mu_I I_i\right)/T \pm 1\right]\right)^{-1}$$

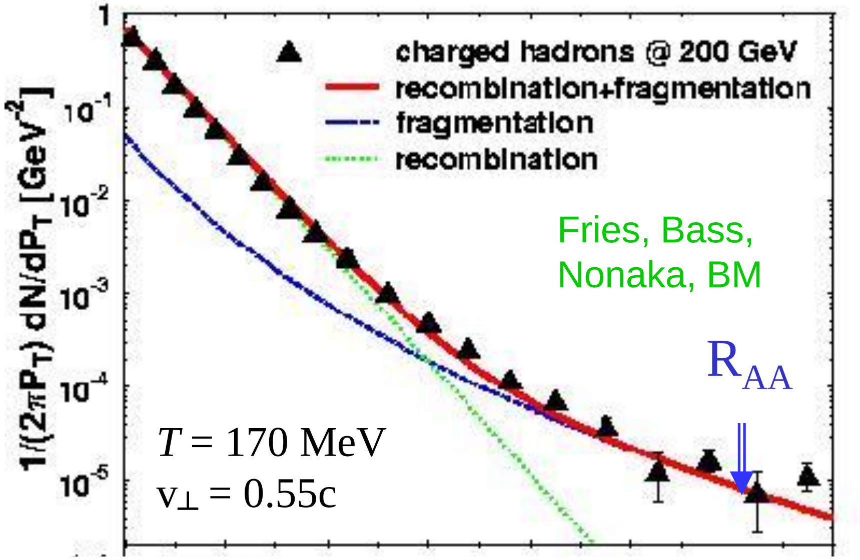
For p_t →∞, hadron ratios are identical to those in recombination!

(only determined by hadron degeneracy factors & chem. pot.)

- recombination provides a microscopic basis for the apparent chemical equilibration among hadrons at (moderately) large p_t

But: The elliptic flow velocity is approximately additive in valence quark number, showing partonic, rather than hadronic origin of the elliptic flow.

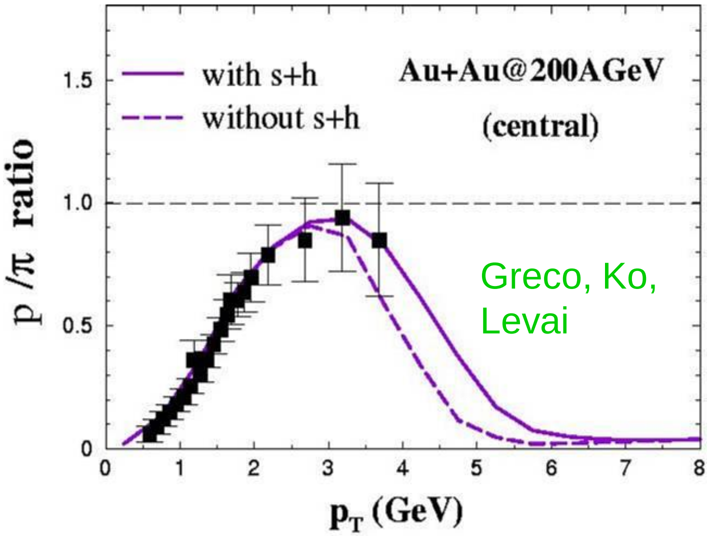
Recombination vs. Fragmentation



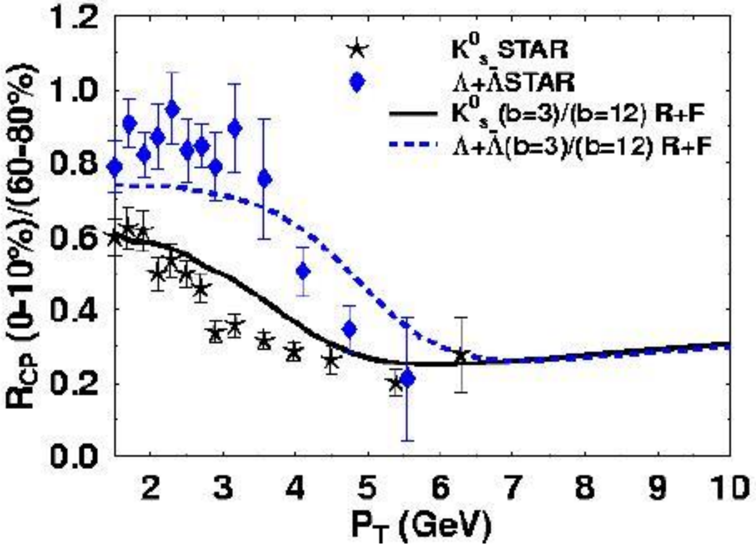
Fries, Bass, Nonaka, BM

R_{AA}

T = 170 MeV
$v_\perp$ = 0.55c



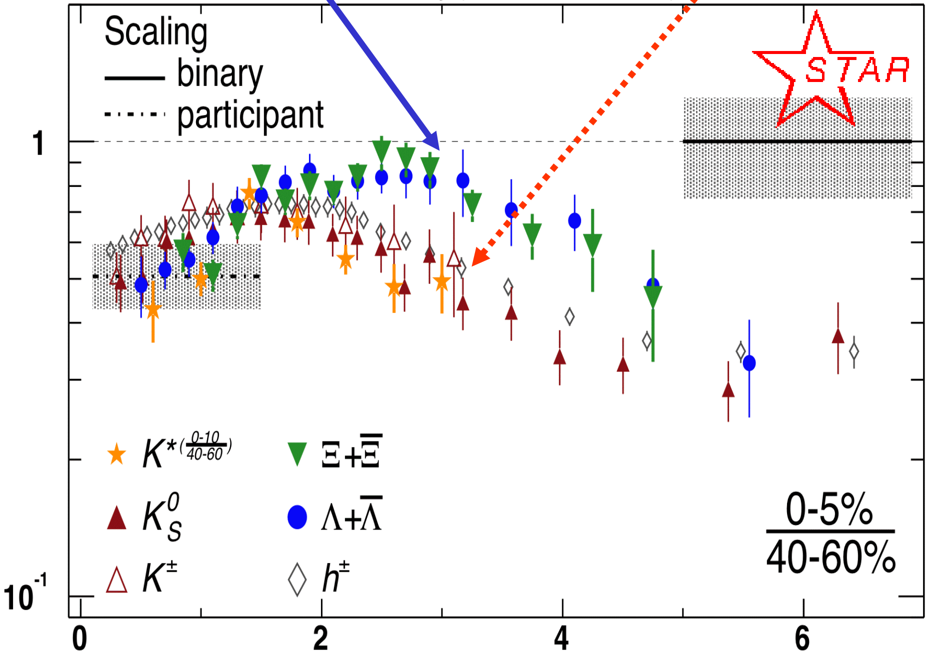
Greco, Ko, Levai

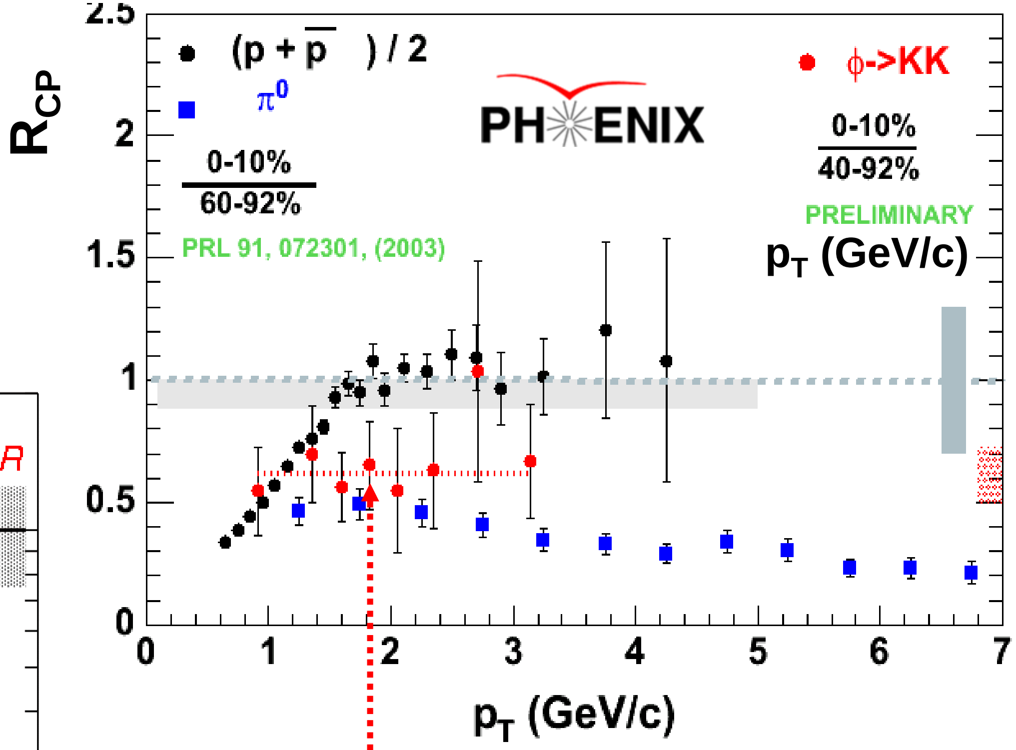


Suppression: Baryons vs. mesons

baryons

mesons





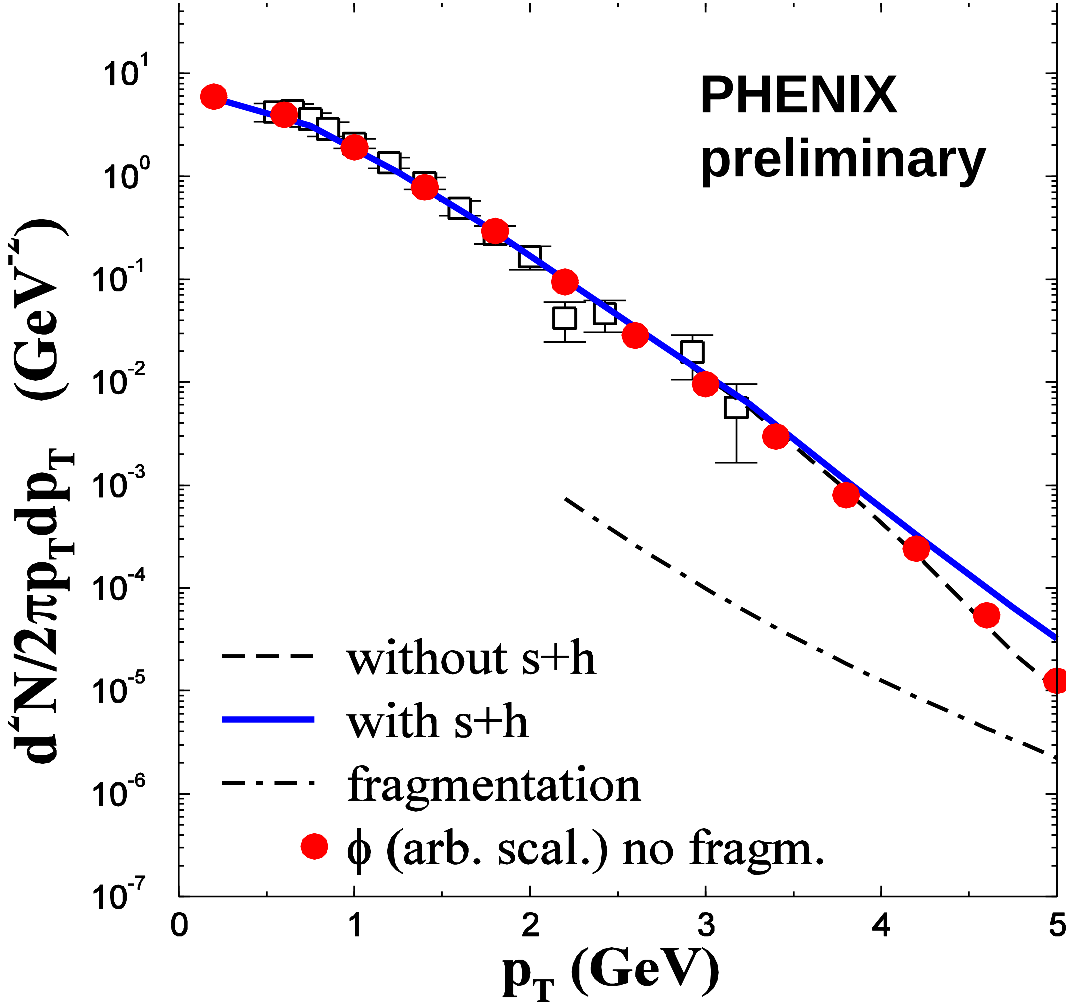
ϕ behaves like meson ?

(also η-meson)

Conclusions (2)

- Evidence for dominance of hadronization by quark recombination from a thermal, deconfined phase comes from:
  - Large baryon/meson ratios at moderately large p_T;
  - Compatibility of measured abundances with statistical model predictions at rather large p_T;
  - Collective radial flow still visible at large p_T.
- Φ-meson is an excellent test case (if not from $KK \to \Phi$).

PHENIX adds the ϕ meson…



Parton Number Scaling of Elliptic Flow

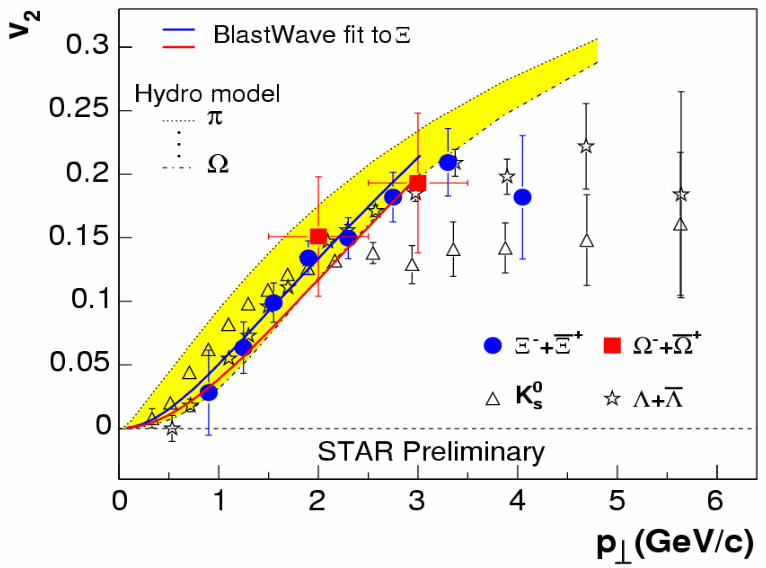
In the recombination regime, meson and baryon v_2 can be obtained from the parton v_2 :

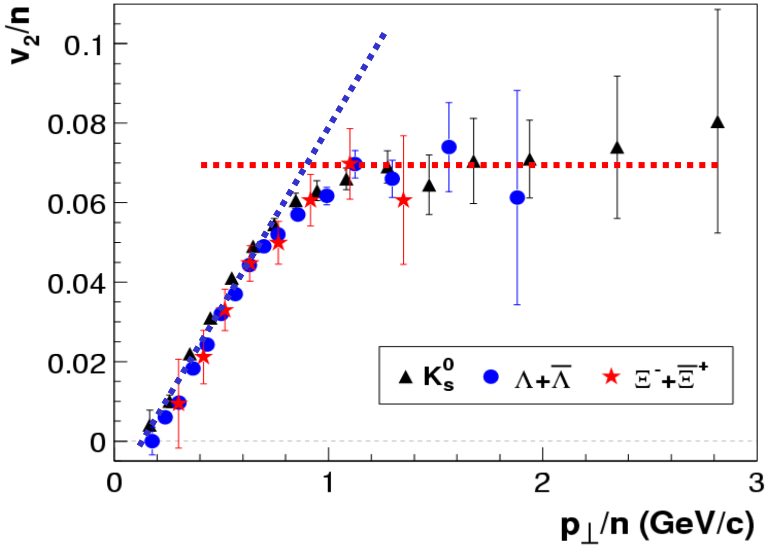
$$\mathrm{v}_2^M(p_t) = \frac{2\mathrm{v}_2^p\left(\frac{p_t}{2}\right)}{1+2\left(\mathrm{v}_2^p\left(\frac{p_t}{2}\right)\right)^2} \quad \text{and} \quad \mathrm{v}_2^B(p_t) = \frac{3\mathrm{v}_2^p\left(\frac{p_t}{3}\right)+3\left(\mathrm{v}_2^p\left(\frac{p_t}{3}\right)\right)^3}{1+6\left(\mathrm{v}_2^p\left(\frac{p_t}{3}\right)\right)^2}$$

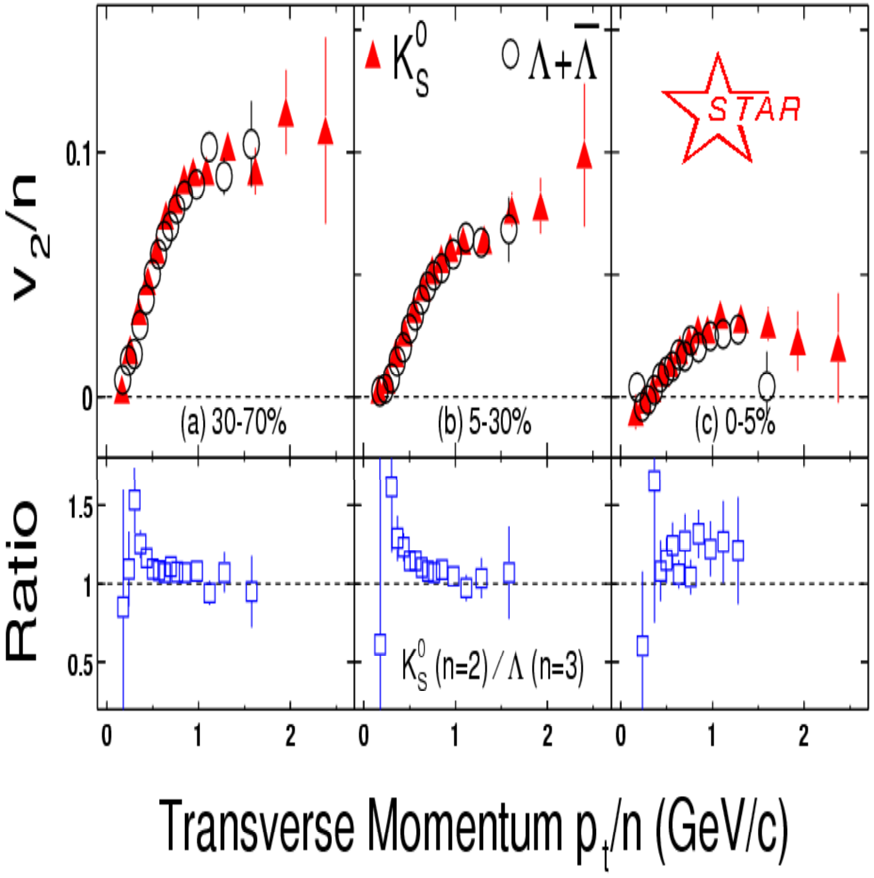
Neglecting quadratic and cubic terms, a simple scaling law holds:

$$\mathrm{v}_2^M(p_t) = 2\mathrm{v}_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad \mathrm{v}_2^B(p_t) = 3\mathrm{v}_2^p\left(\frac{p_t}{3}\right)$$

Hadron v_2 reflects quark flow !







Higher Fock states don’t spoil the fun

$$\phi_1^{(M)}(x_a, x_b) \square\ x_a x_b$$

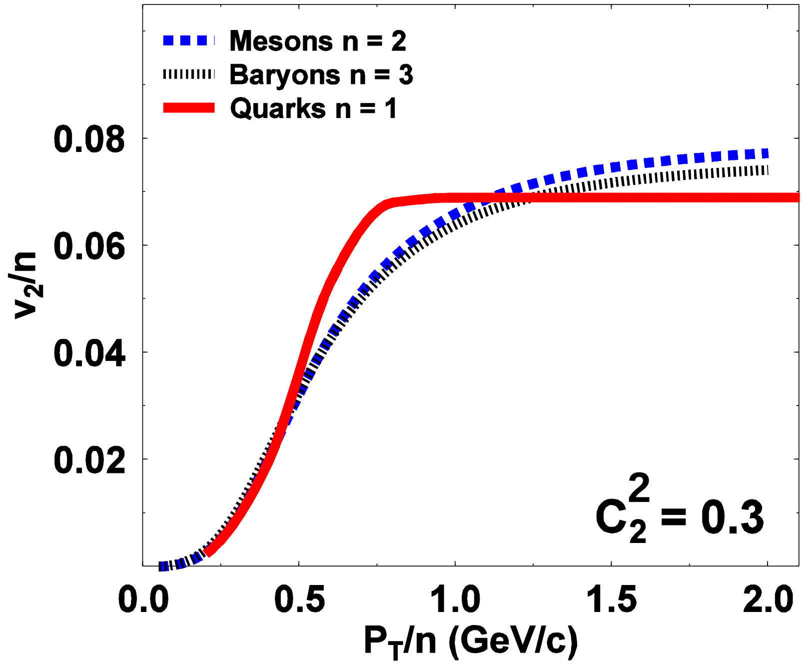
$$\phi_2^{(M)}(x_a, x_b, x_g) \square\ x_a x_b x_g^2$$

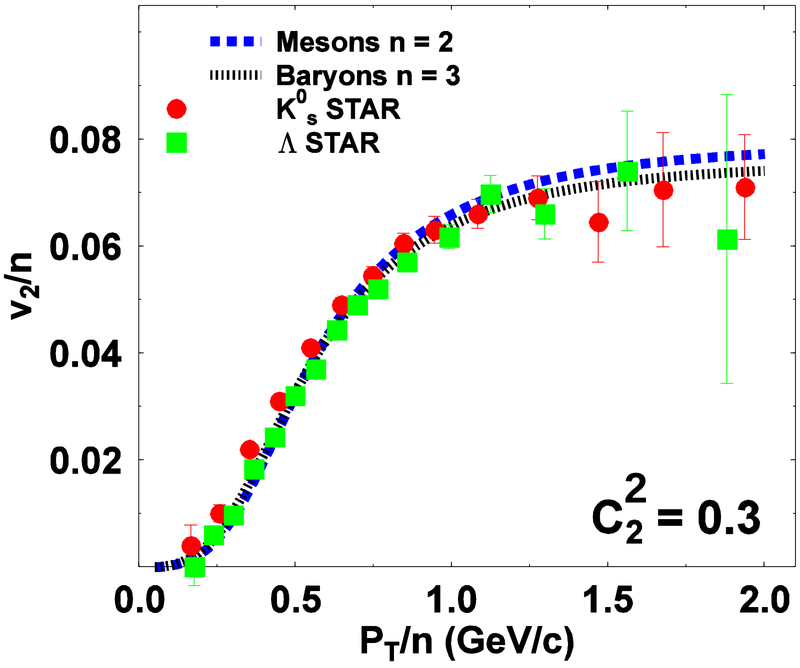
$$\phi_1^{(B)}(x_a, x_b, x_c) \square\ x_a x_b x_c$$

$$\phi_2^{(B)}(x_a, x_b, x_c, x_g) \square\ x_a x_b x_c x_g^2$$

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

$$|B\rangle = C_1 |qqq\rangle + C_2 |qqqg\rangle$$

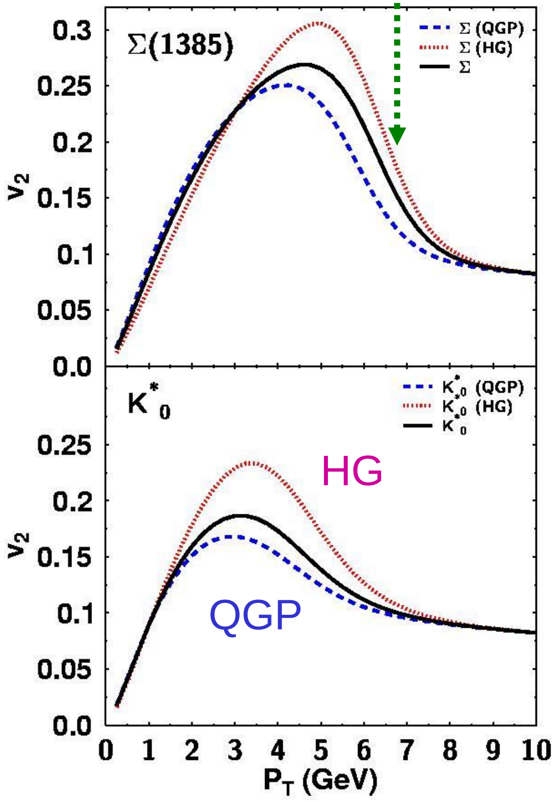




Conclusions (3)

- Recombination model works nicely for v_2:
  - $v_2(p_T)$ curves for different hadrons collapse to *universal* curve for constituent quarks;
  - Saturation value of v_2 for large p_T is *universal* for quarks and agrees with expectations from anisotropic energy loss;
  - Vector mesons (Φ, K^*) permit test for influence of mass versus constituent number (but note the *effects of hadronic rescattering on resonances*!)

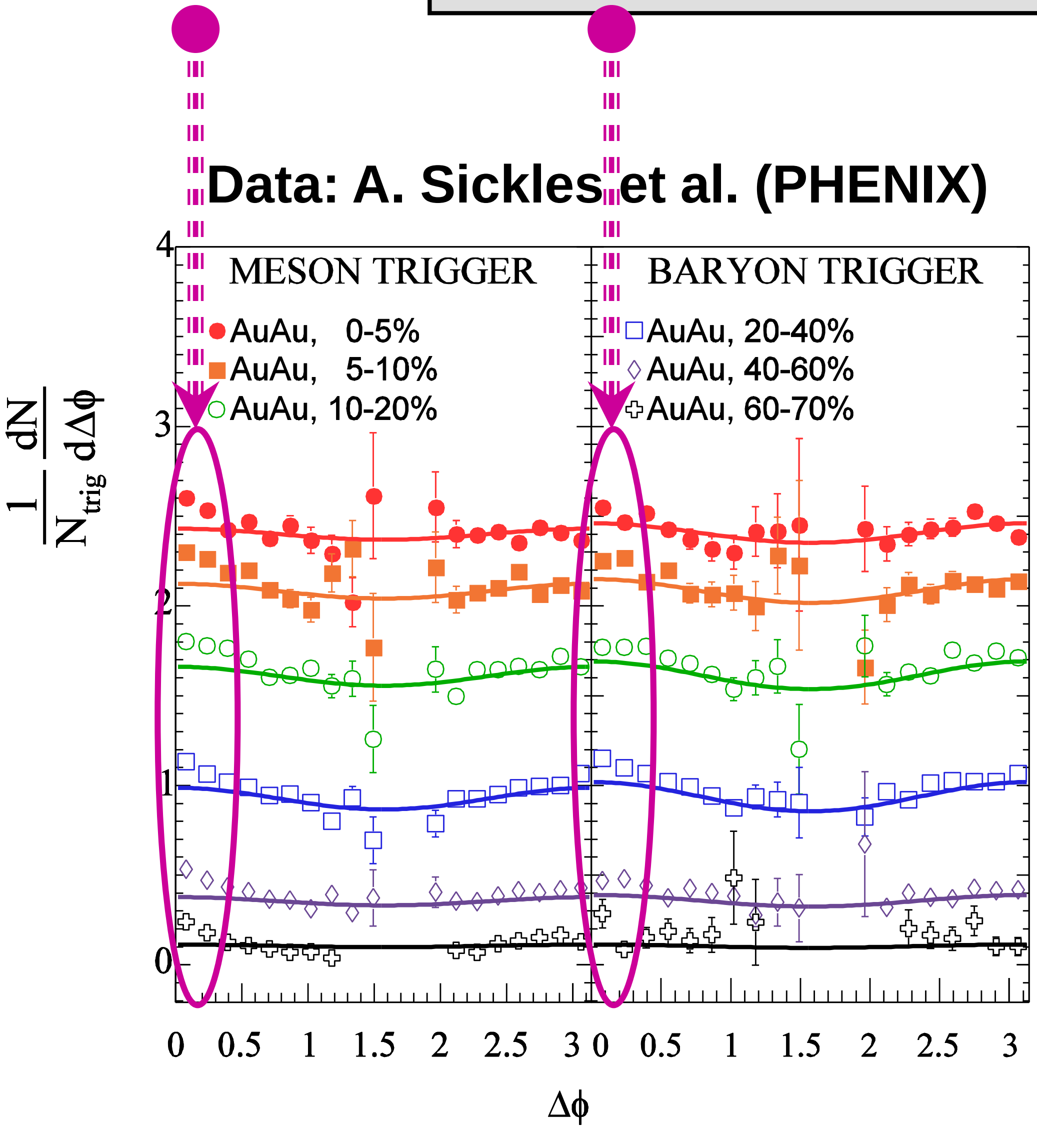
Strong drop of v_2 predicted for all baryons.



Enough of the Successes…

Give us some Challenges!

Dihadron correlations


Data: A. Sickles et al. (PHENIX)

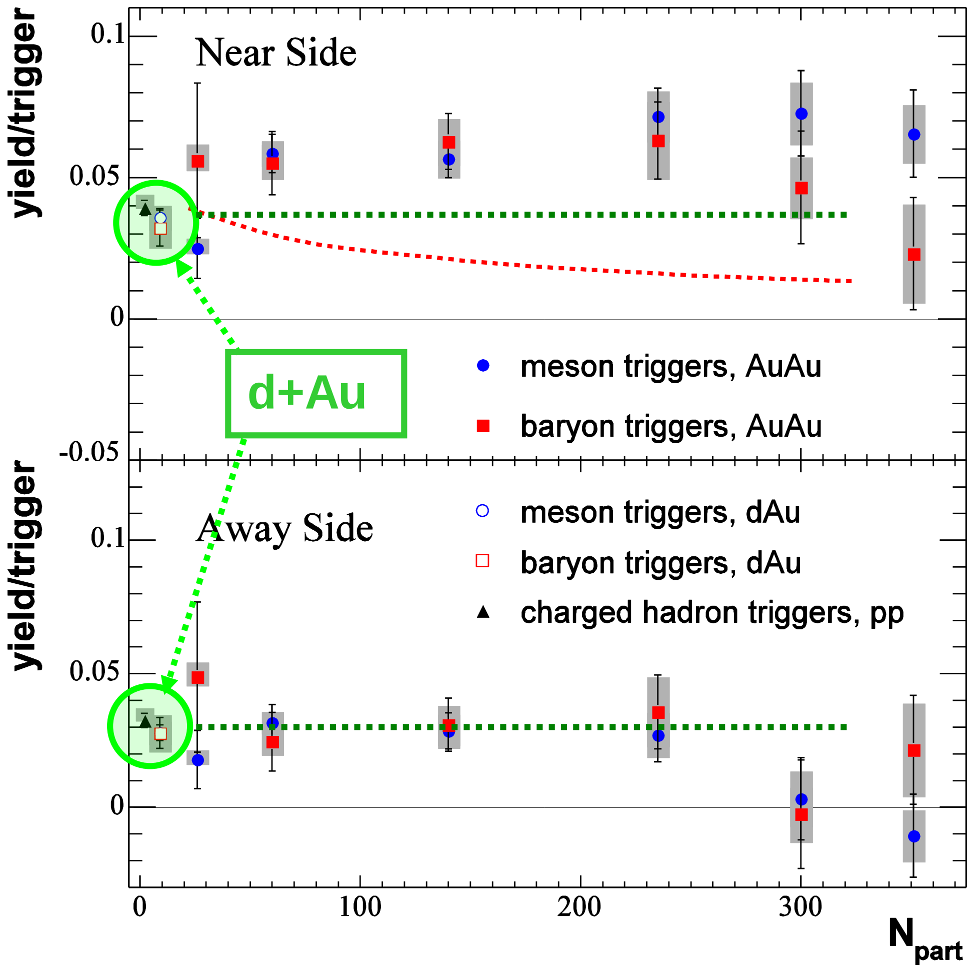
Hadrons created by reco from a thermal mediums should not be correlated.

But jet-like correlations between hadrons persist in the momentum range (p_T ⍰ 4 GeV/c) where recombination is thought to dominate!

(STAR + PHENIX data)

Hadron-hadron correlations

A. Sickles et al. (PHENIX)



Near-side dihadron correlations are larger than in d+Au !!!

Far-side correlations disappear for central collisions.

Sources of correlations

- Standard fragmentation
- Fragmentation followed by recombination with medium particles
- Recombination from (incompletely) thermalized, correlated medium

- But how to explain the baryon excess?
- "Soft-hard" recombination (Hwa & Yang). Requires microscopic fragmentation picture
- Requires assumptions about two-body correlations (Fries et al.)

How serious is this?

- Original recombination model is based on the assumption of a one-body quark density. Two-hadron correlations are determined by *quark correlations*, which are not included in pure thermal model.

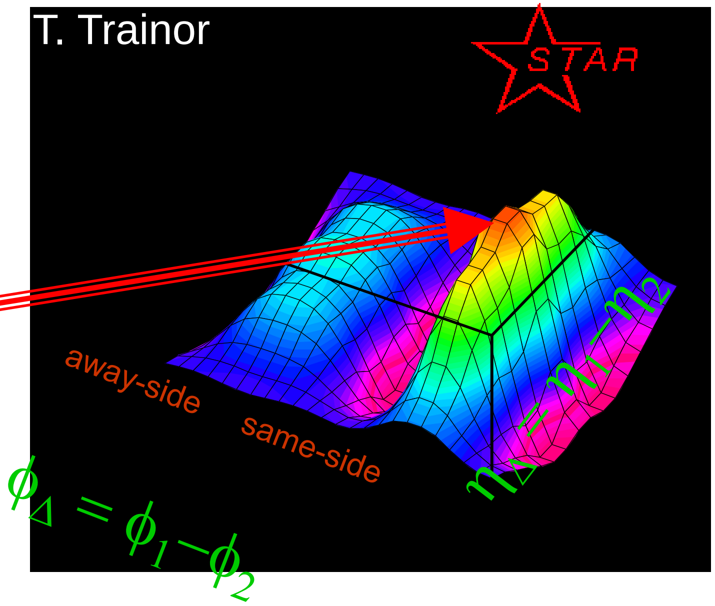
- Two- and multi-quark correlations are a natural result of jet quenching by energy loss of fast partons.

- Incorporation of quark correlations is straightforward, but introduces new parameters: $C(p_1, p_2)$.

Diparton correlations

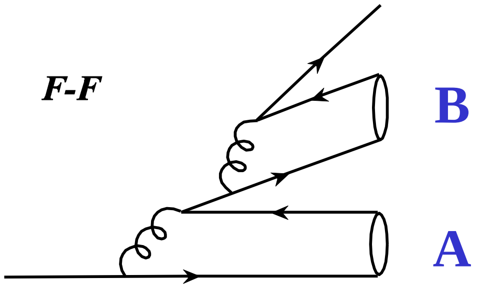
A plausible explanation?

- **Parton correlations naturally translate into hadron correlations.**
- **Parton correlations exist even in the "thermal" regime, created as the result of stopping of energetic partons.**

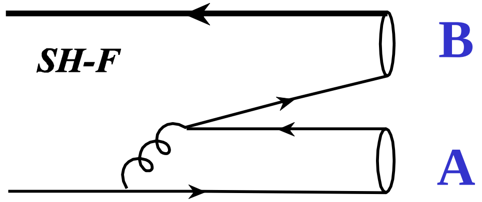


Two-point velocity correlations among 1-2 GeV/c hadrons

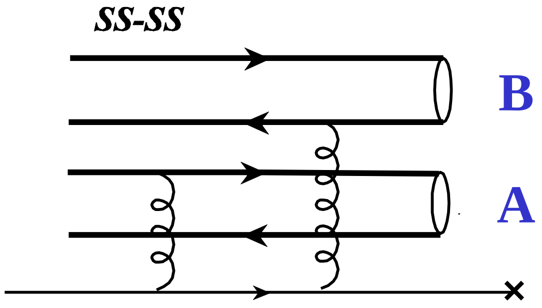
Dihadron mechanisms



$$\color{red}{FF} \quad \square \int \frac{dz_A}{z_A(1-z_A)} g_a\left(\frac{P_A}{z_A}+\Delta E\right) \times D(z_A) D\left(\frac{z_A P_B}{(1-z_A)P_A}\right)$$



$$\color{red}{SH-F} \quad \square\, g_a\left(P_A+\tfrac{1}{2}P_B+\Delta E\right) \times D\left(\frac{P_A}{P_A+\frac{1}{2}P_B}\right)\exp\left(-\frac{P_B}{2T_{\text{eff}}}\right)$$



$$\color{red}{SS-SS} \quad \square\, \exp\left(-\frac{P_A+P_B}{T_{\text{eff}}}\right)$$

Correlations - formalism

Di-meson production:

$$\frac{dN_{MM}}{d^3P_1 d^3P_2} = \frac{V^2}{(2\pi)^6}\int d^3q_1 d^3q_2 \left|\phi(q_1)\right|^2 \left|\phi(q_2)\right|^2 W_4\left(\frac{1}{2}P_1+q_1, \frac{1}{2}P_1-q_1, \frac{1}{2}P_2+q_2, \frac{1}{2}P_2+q_2\right)$$

$$W_n(p_1,\ldots,p_n) = \prod_n w(p_i)\left(1+\sum_{i<j} C_{qq}\left(p_i, p_j\right)\right)$$

Partons with pairwise correlations

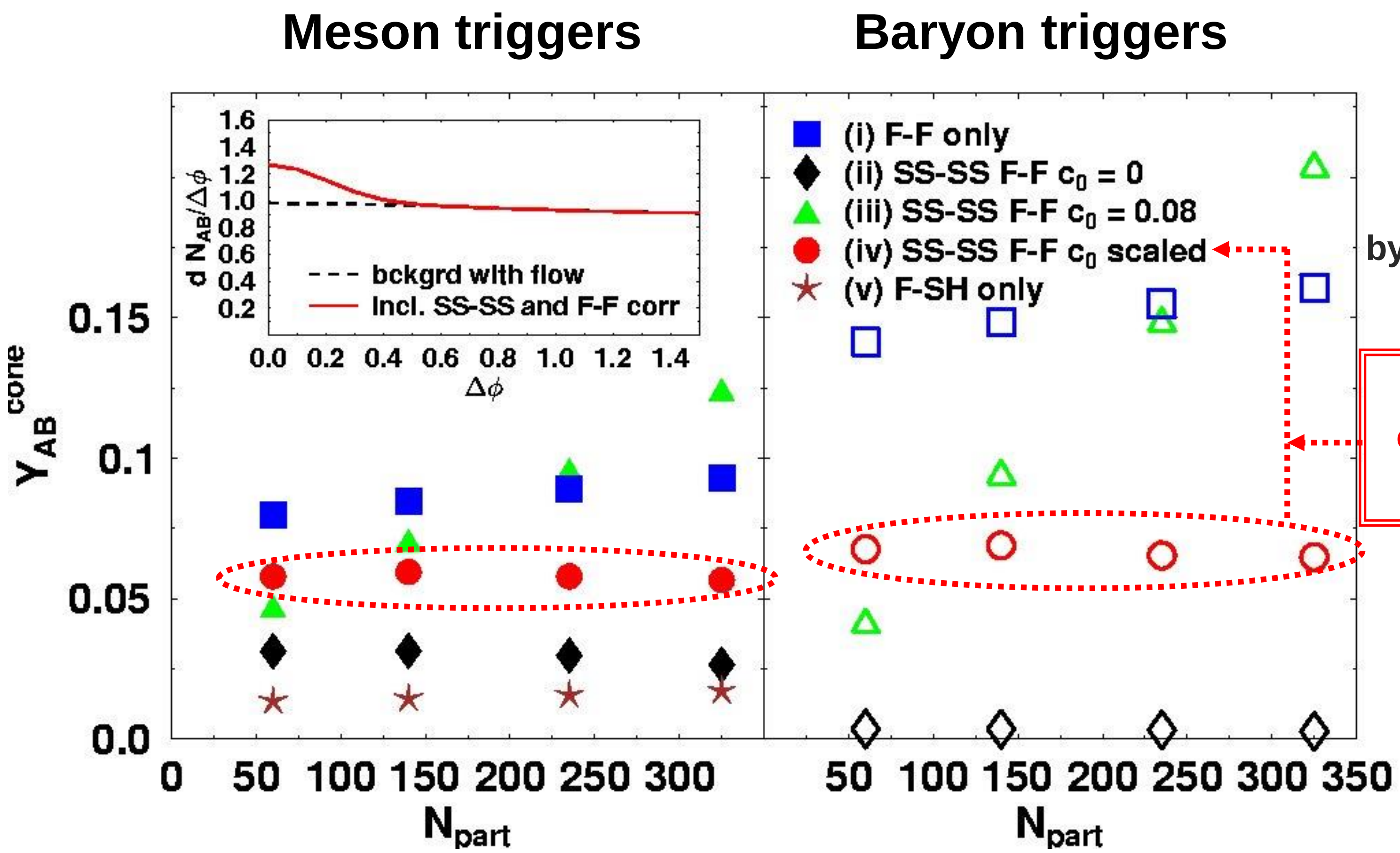
$$\Rightarrow \frac{dN_{MM}}{d^3P_1 d^3P_2} = \frac{V^2}{(2\pi)^6} w^2\left(\frac{1}{2}P_1\right) w^2\left(\frac{1}{2}P_2\right)\left[1+2C_0+4C_{qq}\left(\frac{1}{2}P_1, \frac{1}{2}P_2\right)\right]$$

Meson-meson, baryon-baryon, baryon-meson correlations

$$C_{BB} = 9C_{qq}, \quad C_{MB} = 6C_{qq}, \quad C_{MM} = 4C_{qq}$$

First results of model studies are encouraging ⟶

Dihadron correlations - results

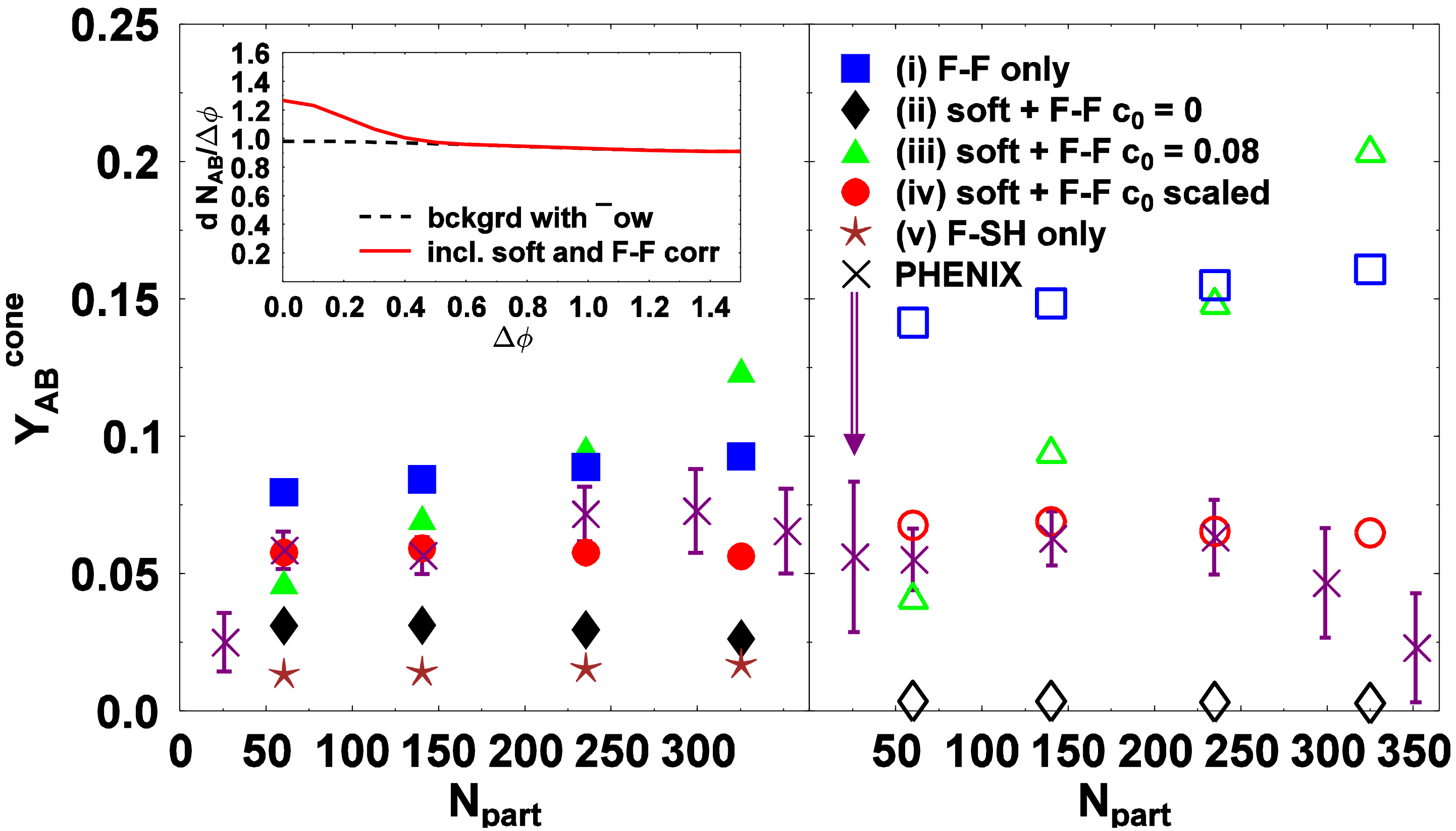


by $100/N_{part}$

Fixed correlation volume

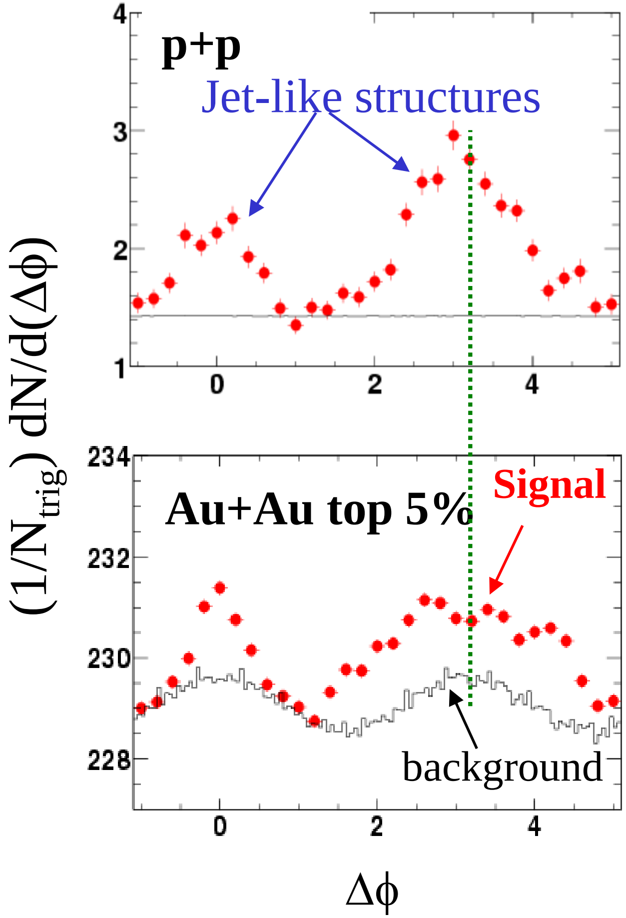
Comparison with Data

R.J. Fries, S.A. Bass & BM, PRL 94, 122301

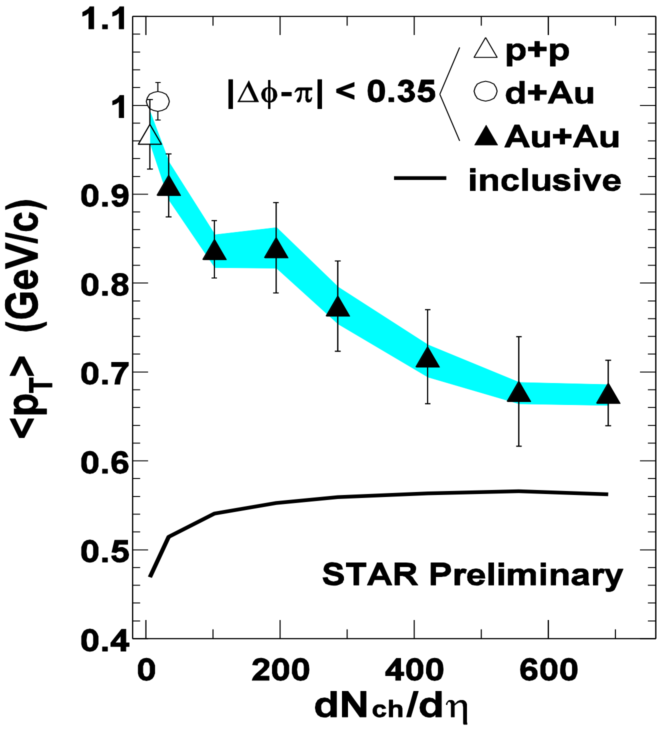


Associated hadrons

Preliminary



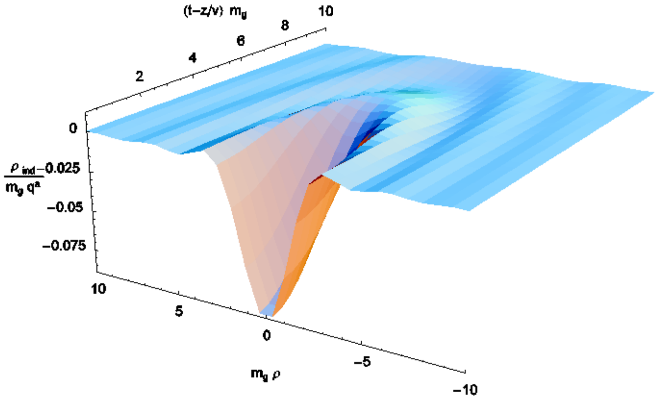
$4 < p_T^{trig} < 6$ GeV/c , $0.15 < p_T^{assoc} < 4$ GeV/c

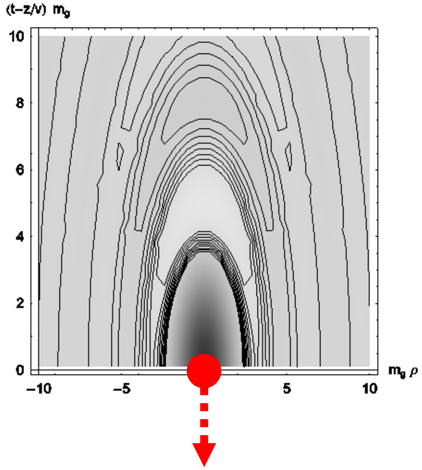


Explore the interaction of an hard parton with the dense medium

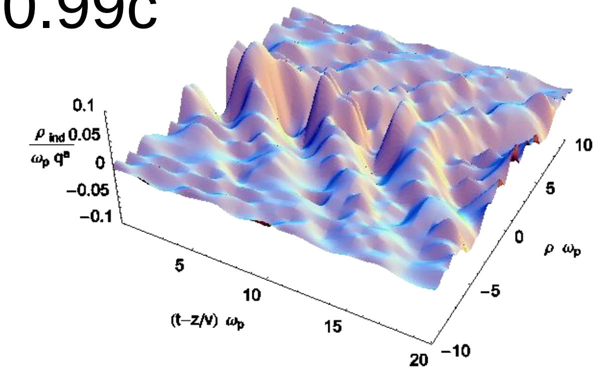
“Waking” the sQGP

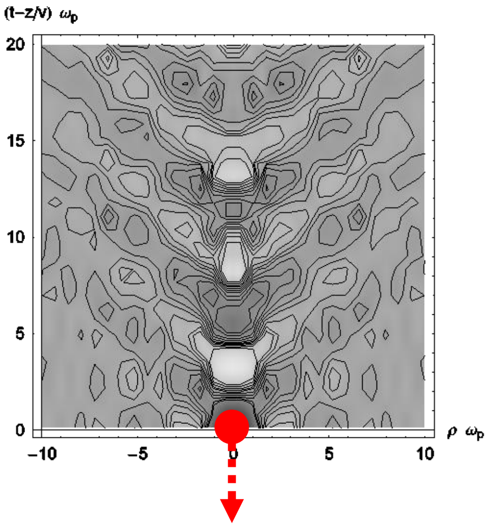
v=0.55c





v=0.99c





Conclusions – at last!

Evidence for the formation of a deconfined phase of QCD matter at RHIC:

- ✓ *Hadrons are emitted in* ***universal*** *equilibrium abundances;*
- ✓ *Most hadrons are produced by* ***recombination of quarks****;*
- ✓ *Hadrons show evidence of* ***collective flow*** (v_0 *and* v_2);
- ✓ *Flow pattern* (v_2) *is not universal for hadrons, but* ***universal for the constituent quarks****.*

The “s”QGP

- **The QGP observed at RHIC is strongly interacting**
  - **Not surprising: $\alpha_s(1.5T_c) \approx 0.5$**
  - **Elliptic flow requires very fast equilibration and nearly ideal fluid properties ($\eta/s <$ few times/4π)**
  - **Strong energy loss of leading partons**

- **So – Have we already discovered the QGP ?**
  - **Many theorists (including the speaker!) believe the evidence is compelling**
  - **But: the experimental collaborations are not ready to claim success (see RHIC white papers!)**
  - **Results from Runs-4&5 will be the judge (QM2005!).**