Hadronization in Heavy Ion Collisions: Recombination and Fragmentation

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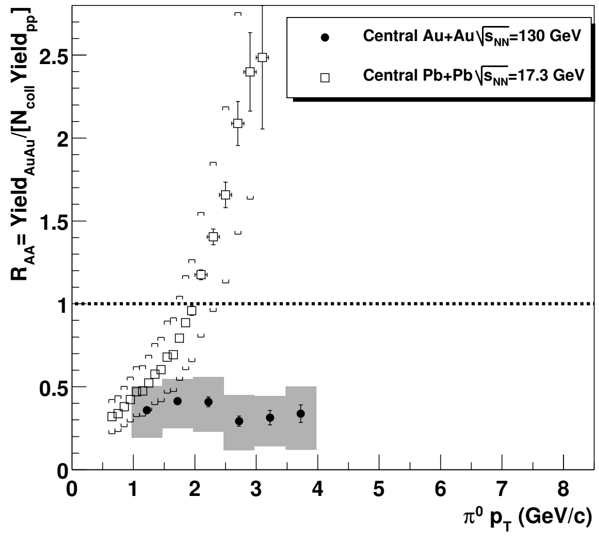
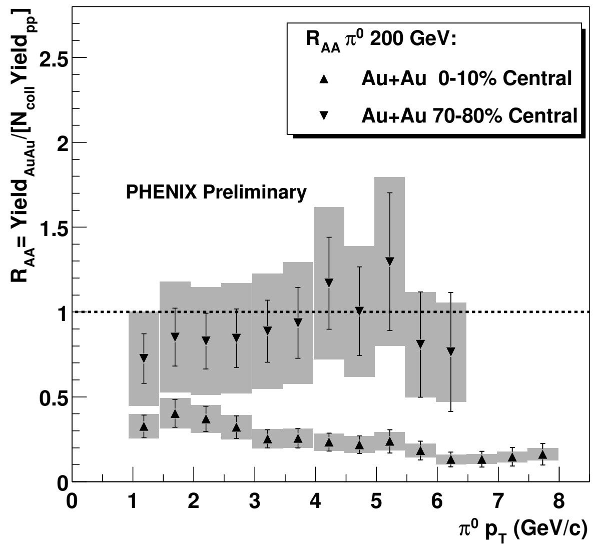
Hadrons at RHIC: pions

- A new domain of heavy ion collisions: Where are the pions?



R_{AA} for π^0 from SPS to RHIC ($\sqrt{S}$=130 GeV) as seen by PHENIX. (nucl-ex/0210021)

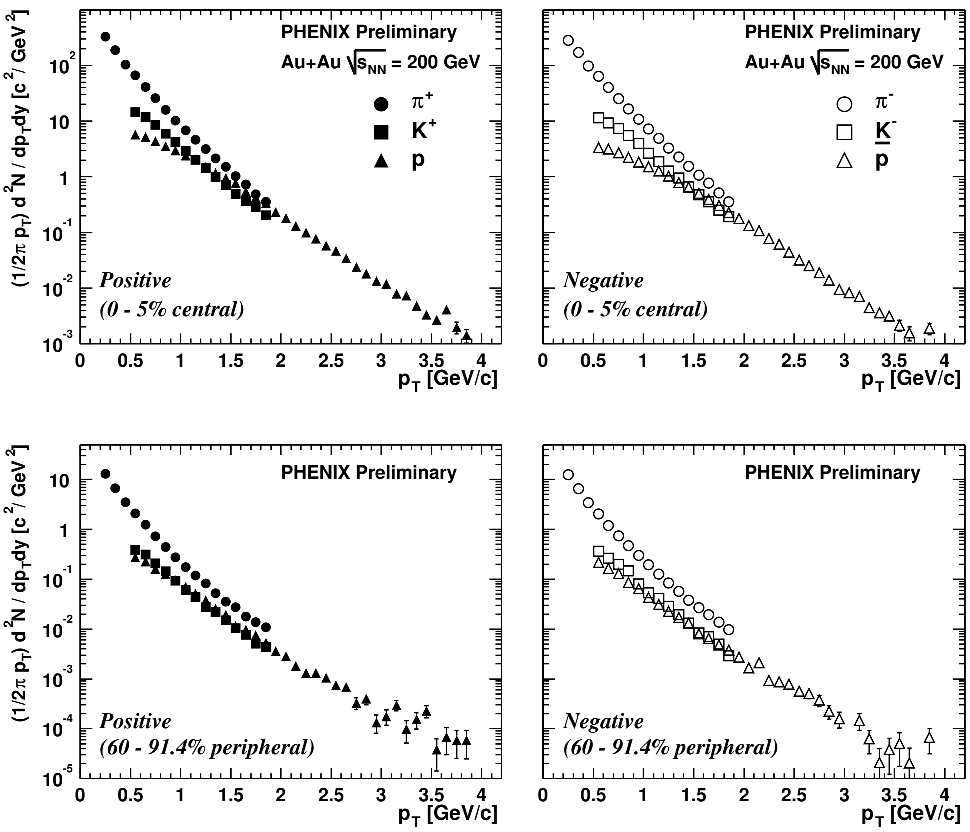


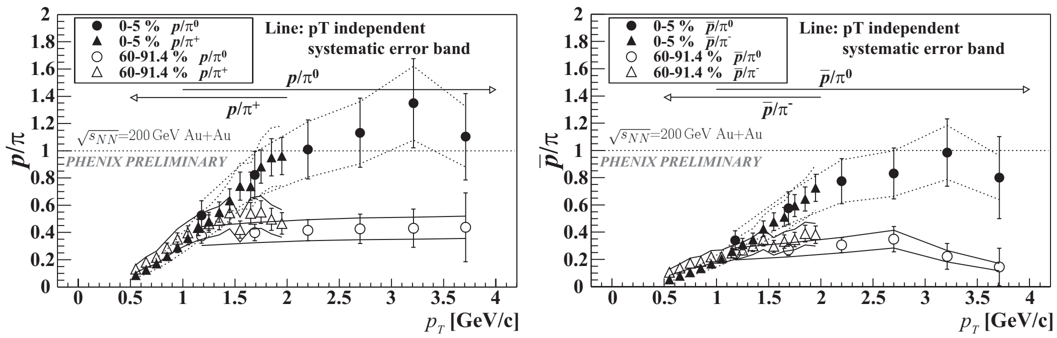
R_{AA} for π^0 in Au+Au ($\sqrt{S}$=200 GeV) from central to peripheral as seen by PHENIX. (nucl-ex/0210021)

- $\Rightarrow$ Jet quenching. Energy loss of fast partons traveling through a plasma seems to be confirmed.

Hadrons at RHIC: protons

- Why are there so many protons?



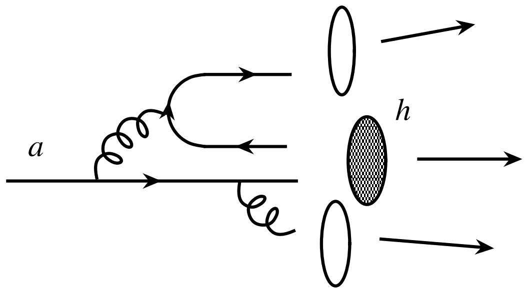


Charged hadrons in central and peripheral Au+Au ($\sqrt{S}$=200 GeV) as seen by PHENIX. (nucl-ex/0209027)

- The proton puzzle!

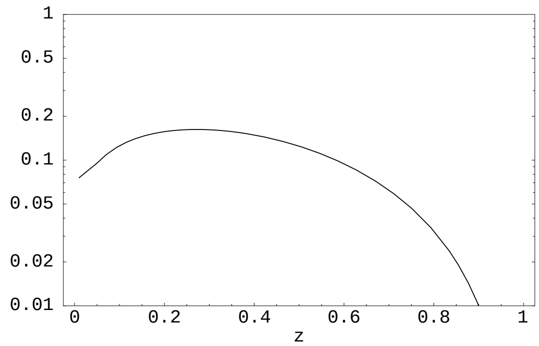
The proton puzzle: Why is it interesting at all?

- Our picture of hadronization (in terms of pQCD) is fragmentation



Fast parton in the vacuum with a color string: $a \to h + X$

$$E\frac{dN_h}{d^3P} = \int \frac{dz}{z^2}\frac{E}{z}\frac{dN_a}{d^3(P/z)} D_{a\to h}(z)$$



Ratio of KKP fragmentation functions of protons and pions from u quarks $D_{u\to p}(z)/D_{u\to\pi}(z)$, Nucl. Phys. **B** 582, 514 (2000).

- From fragmentation: $p \ll \pi$
- Mass penalty for protons at low P_T
- Since fragmentation starts with a single fast parton: energy loss should affect pions and protons in the same way!

From fragmentation to recombination

- Partons are created, $\surd$
- are propagating and interacting, $\surd$
- are finally hadronizing.

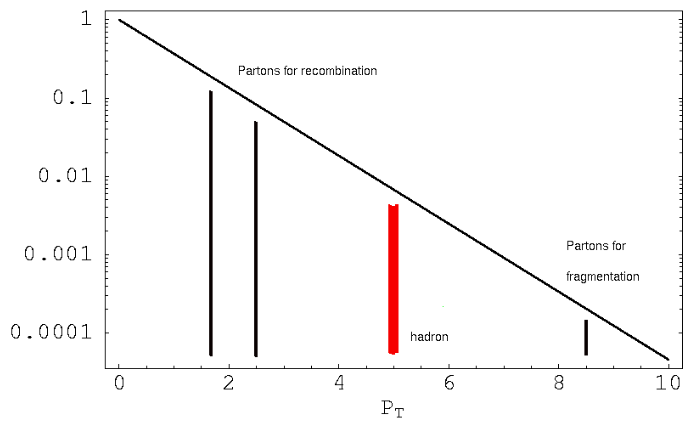
$\surd$ they do not distinguish between protons and pions.

- Apparently something is not correct in our understanding of hadronization, even at intermediate P_T.

- Fragmentation is not very effective! Why? Fragmentation has to create a lot of gluons and $q\bar{q}$ pairs and finally a hadron out of the vacuum. This requires energy! $E_h = zE_a$, $z < 1$, ineffective for steeply falling spectra.

- But there are already a lot of partons populating phase space in heavy ion collisons.

- Combine the partons that are already there. Cheaper!

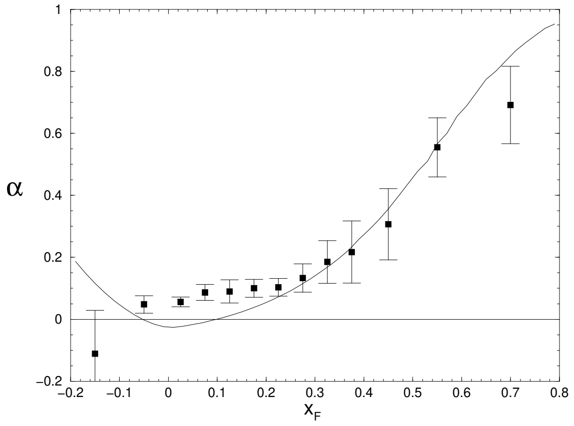


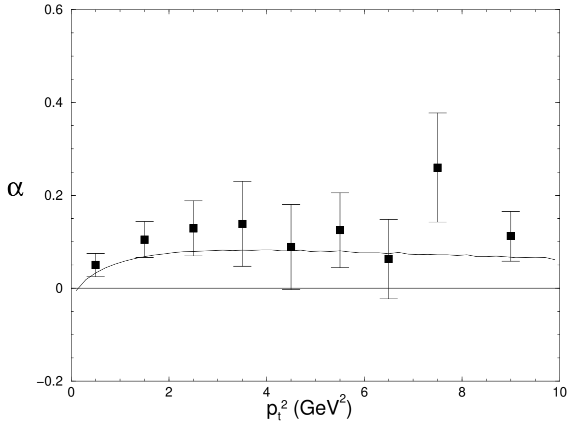
- Recombination will shift features of the parton spectrum to higher P_T in the hadron spectrum.

Recombination: a quick example

- Fermilab E791: 500 GeV π^- beam on C/Pt targets; measurement of the D^+/D^- asymmetry.

$$\alpha[D] = \frac{d\sigma[D^-] - d\sigma[D^+]}{d\sigma[D^-] + d\sigma[D^+]}$$





E. Braaten, Y. Jia and Th. Mehen, Phys. Rev. Lett. 89, 122002 (2002).

In beam direction, hadronization of a charmed quark into a meson with the same valence quark as the beam pion is favored: $(\bar{u}d) \to (\bar{c}d)$, "leading particle effect".

$d\sigma[D] = d\sigma[\bar{q}g \to (c\bar{q})^n + \bar{c}]\rho[(c\bar{q})^n \to D]$

$(\ldots)^n$: relative momentum of order Λ_{QCD}.

A non-relativistic model (I)

Start with quarks and antiquarks in a volume V.

$$\text{quarks:} \qquad \langle x \mid q, \mathbf{p}_1\mathbf{p}_2\rangle = V^{-1} e^{i(\mathbf{p}_1\mathbf{x}_1+\mathbf{p}_2\mathbf{x}_2)}$$

$$\text{pions:} \qquad \langle x \mid \pi, \mathbf{P}\rangle = V^{-1/2} e^{i\mathbf{P}\mathbf{R}}\,\Phi_\pi(\mathbf{y})$$

$\mathbf{R} = (\mathbf{x}_1 + \mathbf{x}_2)/2$, $\mathbf{y} = (\mathbf{x}_1 - \mathbf{x}_2)/2$

$$\langle q, \mathbf{p}_1\mathbf{p}_2 \,|\pi, \mathbf{P}\rangle = \frac{(2\pi)^3}{V^{3/2}} \delta^3(\mathbf{P} - \mathbf{p}_1 - \mathbf{p}_2)\hat{\Phi}_\pi(r).$$

$\mathbf{q} = \mathbf{p}_1 + \mathbf{p}_2$, $\mathbf{r} = (\mathbf{p}_1 - \mathbf{p}_2)/2$, conjugate to $\mathbf{R}$ and $\mathbf{y}$, $r = |\mathbf{r}|$.

Total number of pions:

$$N_\pi = \sum_{a,b} V^3 \int \frac{d^3q}{(2\pi)^3}\frac{d^3r}{(2\pi)^3}\frac{d^3P}{(2\pi)^3}\, w_a(\mathbf{p}_1)w_b(\mathbf{p}_2)\; |\langle q, \mathbf{p}_1\mathbf{p}_1 \,|\pi, \mathbf{P}\rangle|^2$$

Quark distributions: $N_a = V \int \frac{d^3p}{(2\pi)^3} w_a(p)$

Non-relativistic wave function: $\hat{\Phi}_\pi(r) = \mathcal{N}_\pi e^{-r^2/2\Lambda_\pi^2}$

Summation over quantum numbers: assume color singlet with the correct helicity structure (exclude soft mechanisms for helicity flips and color migration)
$\sum_{a,b} \to C_\pi$: degeneracy factor.

A non-relativistic model (II)

$$\frac{dN_\pi}{d^3P} = C_\pi \frac{V}{(2\pi)^3} \int \frac{d^3r}{(2\pi)^3}\, w\Big(\frac{\mathbf{P}}{2}+\mathbf{r}\Big) w\Big(\frac{\mathbf{P}}{2}-\mathbf{r}\Big) |\hat{\Phi}_\pi(r)|^2$$

For $P \gg r \approx \Lambda_\pi \approx \Lambda_{\rm QCD}$ expand:

$$w\Big(\frac{\mathbf{P}}{2}+\mathbf{r}\Big) w\Big(\frac{\mathbf{P}}{2}-\mathbf{r}\Big)$$
$$= w\Big(\frac{\mathbf{P}}{2}\Big)^2 + \sum_{ij} r_i r_j \left[w\Big(\frac{\mathbf{P}}{2}\Big)\partial_i\partial_j w\Big(\frac{\mathbf{P}}{2}\Big) - \partial_i w\Big(\frac{\mathbf{P}}{2}\Big)\partial_j w\Big(\frac{\mathbf{P}}{2}\Big)\right] + \mathcal{O}(r^3)$$

$$\frac{dN_\pi}{d^3P} = C_\pi \frac{V}{(2\pi)^3}\left[w^2(\mathbf{P}/2) + \frac{\Lambda_\pi^2}{2}\left[w(\mathbf{P}/2)\triangle w(\mathbf{P}/2) - \left(\nabla w(\mathbf{P}/2)\right)^2\right]\right]$$

- The first term is model independent!

Take e.g. thermal parton distribution $w_a(p) = e^{-E/T}$:

$$\frac{dN_\pi}{d^3P} = C_\pi \frac{V}{(2\pi)^3} e^{-E/T}\left[1 - \frac{2\Lambda_\pi^2}{ET}\right]$$

A non-relativistic model (III)

- For nucleons:

$$\frac{dN_N}{d^3P} = C_N \frac{V}{(2\pi)^3} \int \frac{d^3r}{(2\pi)^3} \frac{d^3s}{(2\pi)^3} w\left(\frac{\mathbf{P}}{3}+\frac{\mathbf{r}}{2}+\mathbf{s}\right) w\left(\frac{\mathbf{P}}{3}+\frac{\mathbf{r}}{2}-\mathbf{s}\right) w\left(\frac{\mathbf{P}}{3}-\mathbf{r}\right) |\hat{\Psi}_N(r,s)|^2$$

Wave function: $\hat{\Psi}_N(r,s) = \mathcal{N}_N e^{-r^2/2\Lambda_r^2} e^{-s^2/2\Lambda_s^2}$

$$\frac{dN_N}{d^3P} = C_N \frac{V}{(2\pi)^3} \left[w(\mathbf{P}/3)^3 + \left(\frac{1}{2}\Lambda_z^2 + \frac{3}{8}\Lambda_y^2\right) \left[w(\mathbf{P}/3)^2 \triangle w(\mathbf{P}/3) - w(\mathbf{P}/3)\left(\nabla w(\mathbf{P}/3)\right)^2 \right] \right]$$

- Leading term in $\Lambda_{\mathrm{QCD}}/P_T$ gives a very simple result for thermal distributions:

$$w(P/2)^2 \longleftrightarrow w(P/3)^3$$

$$\Longrightarrow \frac{dN_p}{dN_{\pi^+}} \approx \frac{C_p}{C_{\pi^+}} = \frac{5}{3}$$

A realistic scenario

- Choose a hypersurface Σ where hadronization takes place.
$d\sigma^\mu = u^\mu(r) d\sigma$ with $d\sigma$: measure on Σ,
$u^\mu(r)$: the future oriented unit vector orthogonal to Σ in $r \in \Sigma$.

- Invariant phase space element: $$\int \frac{d^3P}{(2\pi)^3\, E}\, P_\mu d\sigma^\mu$$

- Number of mesons in the parton system given by the density matrix $\hat\rho$:

$$N_M = \int \frac{d^3P}{(2\pi)^3\, E} \langle M; P|\, \hat\rho\, |M; P\rangle$$

Two-parton Wigner function

$$\langle r_1 - r_1'/2, r_2 - r_2'/2 \mid \hat\rho | r_1 + r_1'/2, r_2 + r_2'/2\rangle$$
$$= \int \frac{d^4p_1}{(2\pi)^4} \frac{d^4p_2}{(2\pi)^4}\, e^{ip_1\cdot r_1'} e^{ip_2\cdot r_2'}\, W(r_1, r_2; p_1, p_2)$$

assume factorization into single particle Wigner functions $w_a(r_1; p_1) w_b(r_2; p_2)$

- Description in local light cone coordinates (hadron defining the + axis)

$$E\frac{dN_M}{d^3P} = \int_\Sigma d\sigma \frac{P\cdot u(r)}{(2\pi)^3} \sum_{a,b} \int_0^1 dz\, |\psi^M_{ab}(z)|^2 w_a(r; zP^+)\, \bar w_b(r; (1-z)P^+)$$

$$E\frac{dN_B}{d^3P} = \int_\Sigma d\sigma \frac{P\cdot u(r)}{(2\pi)^3} \frac{1}{3!} \sum_{a,b,c} \int_0^1 dz_1 \int_0^{1-z_1} dz_2\, |\psi^B_{abc}(z_1, z_2)|^2$$
$$w_a(r; z_1P^+)\, w_b(r; z_2P^+)\, w_c(r; (1-z_1-z_2)P^+)$$

Recombination from a thermal phase

Assume $w_a(r;p) = \exp[-(p \cdot u - \mu)/T]$, $\mu = \mu_B/3$:

$$w_a(r; zP^+)\, \bar{w}_b(r; (1-z)P^+) = \exp(-P \cdot u/T)$$

$$w_a(r; z_1 P^+)\, w_b(r; z_2 P^+)\, w_c(r; (1-z_1-z_2)P^+) = \exp(-(P \cdot u - \mu_B)/T)$$

- This is independent of the dynamical model for recombination!

- The proton/pion ratio will always be constant and essentially be given by degeneracies:

$$\Longrightarrow \quad \frac{dN_p}{dN_{\pi^+}} = e^{\mu_B/T} \frac{C_p}{C_{\pi^+}} = \frac{5}{3} e^{\mu_B/T}$$

- Analogously:

$$\frac{dN_\Lambda}{dN_{K_s^0}} = \frac{C_\Lambda}{C_{K_s^0}} = \frac{4}{3} \qquad \frac{dN_{\bar{p}}}{dN_p} = \frac{C_{\bar{p}}}{C_p} = e^{-2\mu_B/T}$$

- These are upper limits in the sense that secondary decays will enhance mesons.

Recombination vs fragmentation

- Competition between different processes:

$$E\frac{dN_h^{\text{frag}}}{d^3P} = \int \frac{d\sigma \cdot P}{(2\pi)^3}\, w(P/z) \otimes D_{a\to h}(z)$$

$$E\frac{dN_M^{\text{rec}}}{d^3P} = C_M \int \frac{d\sigma \cdot P}{(2\pi)^3}\, w^2(r, P/2)$$

$$E\frac{dN_B^{\text{rec}}}{d^3P} = C_B \int \frac{d\sigma \cdot P}{(2\pi)^3}\, w^3(r, P/3)$$

- Recombination on an exponential spectrum:

$$\frac{dN_\pi^{\text{frag}}}{dN_\pi^{\text{rec}}} \sim \frac{D(\langle z\rangle)}{C_M} e^{-P_T(1/\langle z\rangle - 1)} < 1$$

Recombination is more effective on a thermal spectrum!

- Recombination on a power law spectrum $w_a = A_a(1 + p_T/B)^{-\alpha}$:

$$\frac{dN_\pi^{\text{frag}}}{dN_\pi^{\text{rec}}} \propto P_T^\alpha$$

Fragmentation will win at high P_T.

Quantitative predictions: input

- Use a hypersurface with $\tau_{\rm f} = \sqrt{t^2 - z^2} = $ const. Fix $\tau = 5$ fm$/c$.

- Thermal parton spectrum, longitudinally expanding:

$$w_a^{\rm th}(\eta; y, p_T) = A_{\rm th}\, e^{-p_T \cosh(\eta - y)/T}\, e^{-y^2/2\Delta^2}$$

with rapidity width $\Delta = 2$ and blue-shifted temperature $T = 350$ MeV, [equiv. $T_{\rm phys} = 175$ MeV, $\beta_r = 0.6$].

- Full equilibration for partons? $A_{\rm th} \approx 0.03$, equiv. $A_{\rm th} \approx 1/3$ with respect to $T_{\rm phys}$. Interpretation depends on τ and the transverse size $A_\perp$ of the system!

- Perturbative parton spectrum LO pQCD, with energy loss $\Delta p_T = -\sqrt{\lambda p_T}$, $\lambda = 1$ GeV.

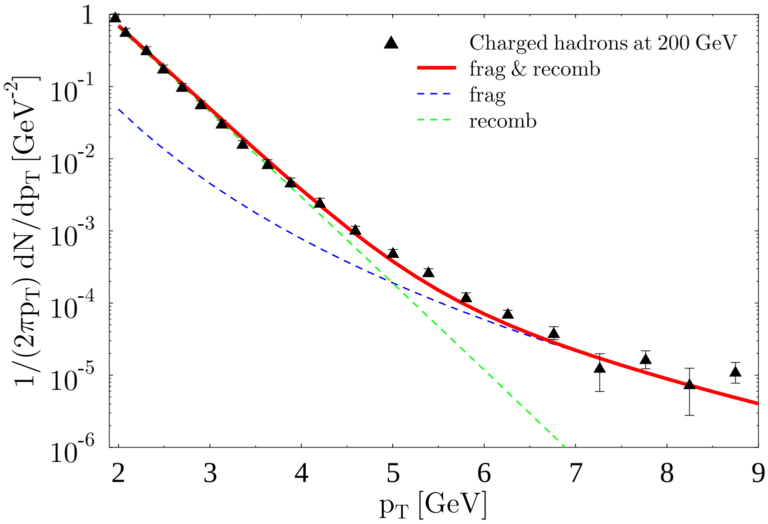
$$w_a^{\rm pert}(p_T) = A_a \left(1 + \frac{p_T - \Delta p_T}{B}\right)^{-\alpha}$$

- Include recombination from the thermal part, fragmentation from the perturbative part (KKP fragmentation functions).

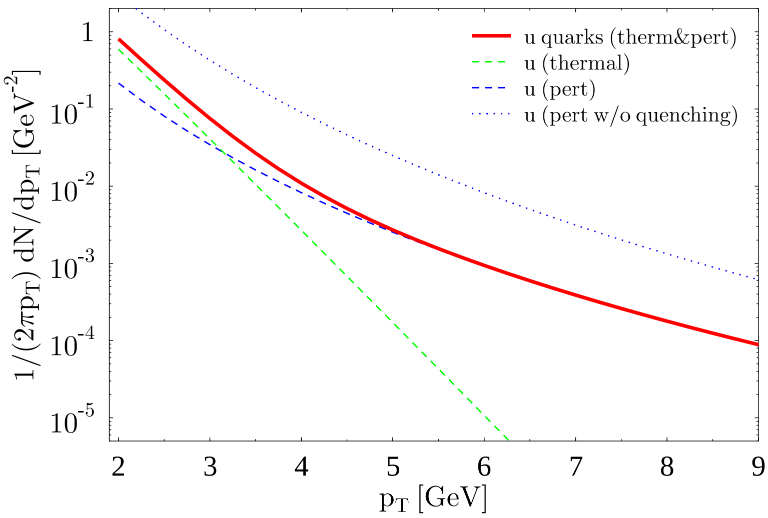
- Fit parameters to the charged hadron spectrum of PHENIX, nucl-ex/0209029, counting π, p, $\bar{p}$, K. No suppression for strange quarks included.

Charged hadron and parton spectrum

- Charged hadron spectrum in central Au+Au collisions at $\sqrt{S} = 200$ GeV. (PHENIX, nucl-ex/0209029):
Transition thermal/recombination $\leftrightarrow$ perturbative/fragmentation at $5 \ldots 6$ GeV.

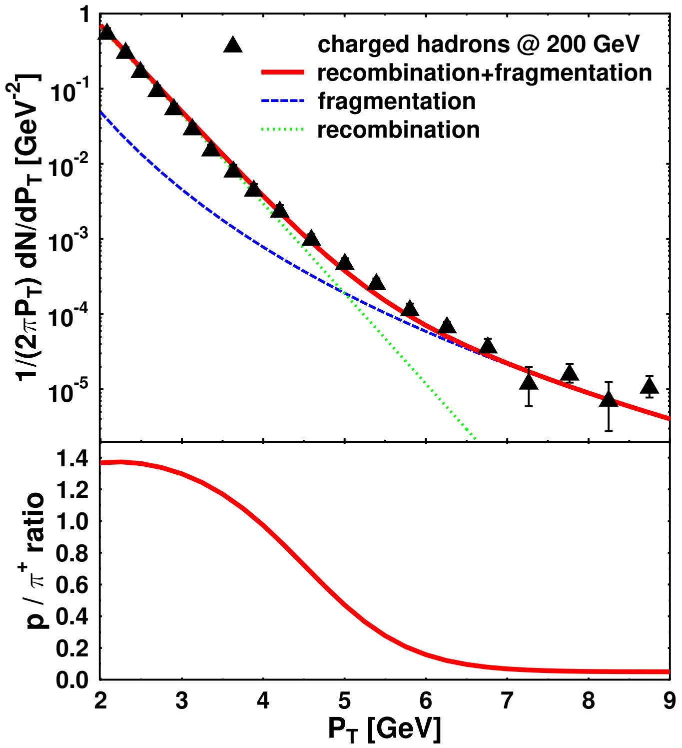


- Spectrum of u quarks: Transition at $\sim 3.5 \ldots 4$ GeV, consistent with the parton cascade model.



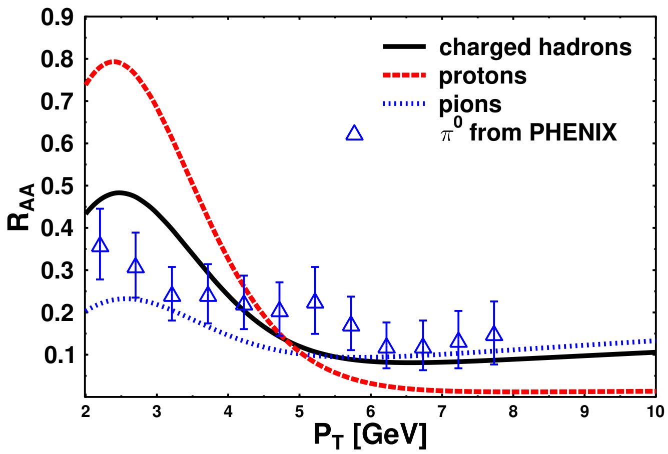
Proton-pion ratio and R_{AA}

- Charged hadron spectrum (upper panel) and p/π^+ ratio (lower panel)
- p/π^+ ratio of order 5/3, sharp transition between 4 and 6 GeV predicted, saturation at the value expected from pQCD.
- The transition may be too steep, since we omitted mixed contributions. New mechanisms may come into the game at the transition region!
- Similar behaviour for the Λ/K ratio!



- $R_{AA} = dN_{AuAu}/N_{\mathrm{coll}} dN_{pp}$ for charged hadrons, pions and protons.

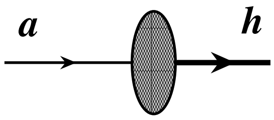
π^0 data: PHENIX, nucl-ex/0210021.
- Uncertainty from the $p+p$ part of the calculation, in particular for protons!
- Recombination reduces the nuclear suppression by jet quenching.



Hadronization: the full picture

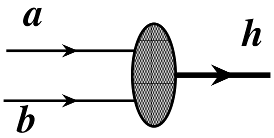
- Very high P_T ($\gg 10$ GeV)

Fragmentation of 'lonely" partons, described by leading twist fragmentation functions.



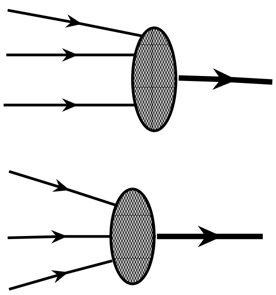
- High P_T (~ 5 GeV)

Multiparton fragmentation, described by higher twist fragmentation functions, becomes important.



- Intermediate P_T ($\sim 2 \ldots 5$ GeV)

Hadronization dominated by 'exclusive" fragmentation, effectively described by the recombination of partons.



- Small P_T (< 2 GeV)

Bulk production of hadrons, recombination (?).

Summary

- We have discussed a new mechanism of hadronization: recombination of quarks.
- Recombination competes with fragmentation. Recombination is more effective with thermalized parton spectra. Fragmentation eventually wins at large P_T.
- Recombination shifts properties of parton spectra to higher transverse momentum, fragmentation shifts them to lower momentum.
- $\Rightarrow$ Region of soft physics seems to be extended to ~ 5 GeV. Nuclear suppression by jet quenching significantly reduced in this regime.
- Ratio $p/\pi^+ \approx 1.5$, constant for intermediate P_T, drops steeply after 4 GeV.
- Recombination can make predictions for $P_T \gg M_h$. No predictive power in the low P_T region, where the bulk of hadrons is produced.
- More theoretical control for heavy quarks: charm production?
- To do: d+Au, better v_2, Λ/K ratio.