Recombination Models

Hadronization of a dense parton system

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Plenary Talk at QM 2004
Oakland CA --- January 15, 2004

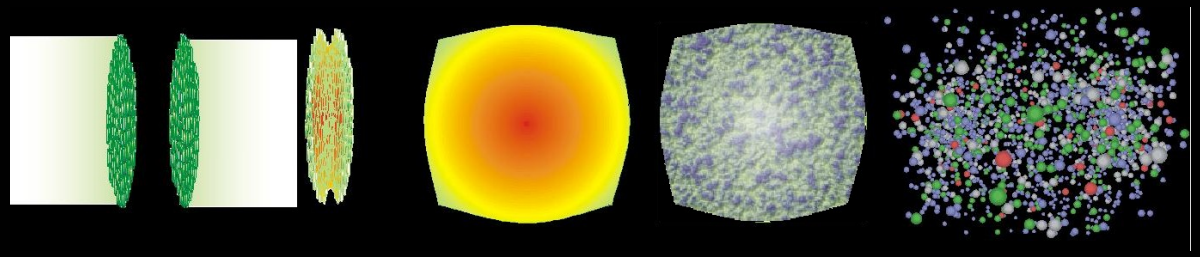
Outline

- Hadronization and fragmentation
- The ReCo (recombination/coalescence) idea
- The leading particle effect
- What can ReCo do for RHIC?
- Azimuthal anisotropy v_2
- ReCo implementations
- Myths and facts
- Conclusions

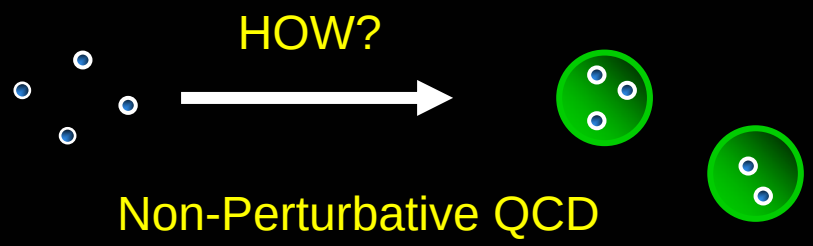
Thanks to my collaborators: B. Müller, S. A. Bass, C. Nonaka

Hadronization

- We produce "free" partons in high energy collisions like $e^+ + e^-$, e+p, p+p, A+A.



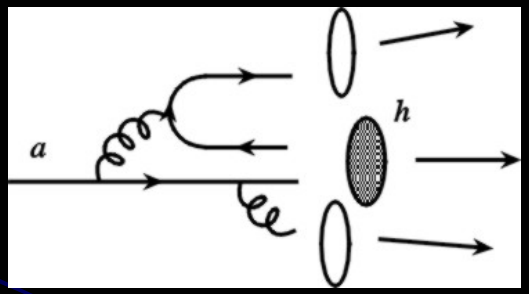
- Partons in the final state have to be converted into hadrons.



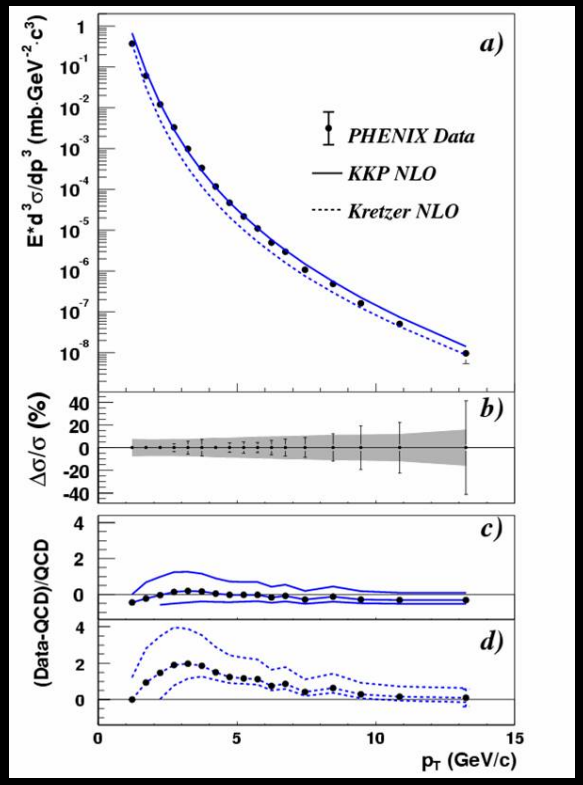
- Can we learn about the parton phase from a theory of hadronization?

Fragmentation

- There is a theory at large P_T: pQCD factorization.
- Long- and short-distance contributions separated for single parton fragmentation.



$$\sigma_{\mathrm{h}} = \sigma_{\mathrm{p}} \otimes D_{\mathrm{p}\to\mathrm{h}}$$

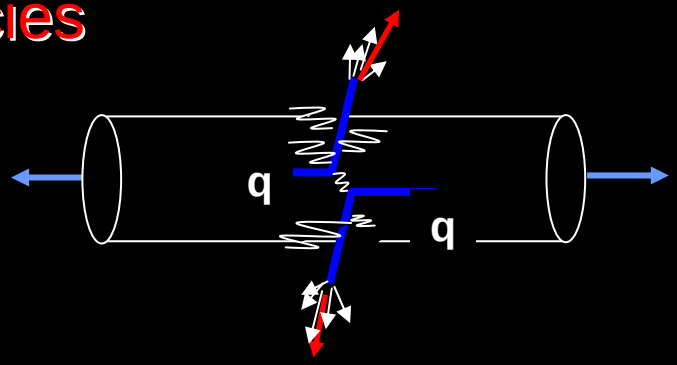


- Fragmentation functions D are not calculated; determined from e^+e^- data.
- Works well for pion production in p+p at RHIC.

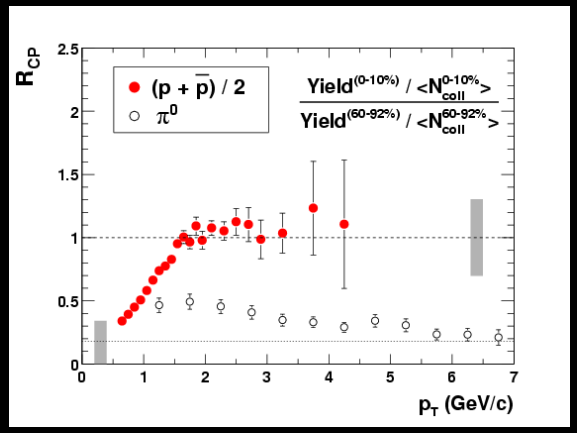
Limitations of Fragmentation

Fragmentation is not working:

- in central heavy ion collisions at RHIC. Fragmentation + energy loss seem to work above 6 GeV/c. But below:
  ↳ Baryon enhancement, dependence of R_{AA} on hadron species



FF modified in the medium by parton energy loss (Wang, Guo; Gyulassy, Levai, Vitev; ...)

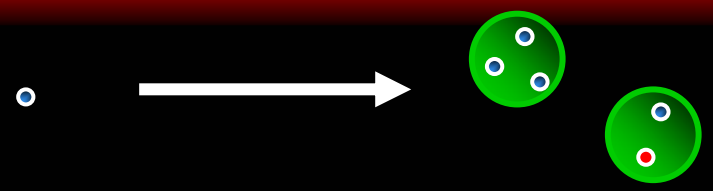


R_{CP} from PHENIX

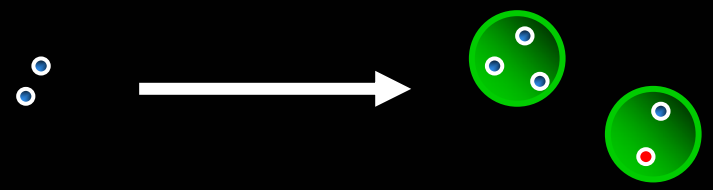
- in the low P_T/forward region ↳ Leading particle effect

👎 when the single parton picture breaks down.

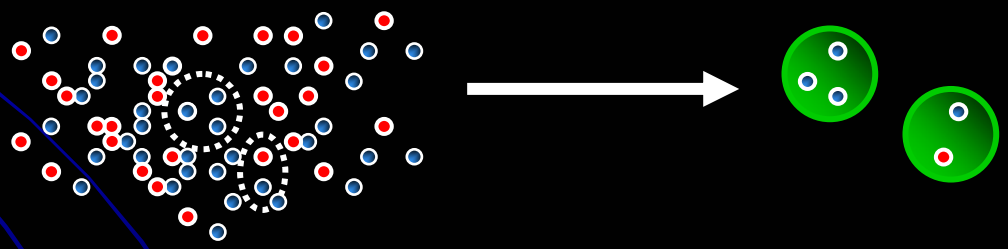
From Fragmentation to Recombination



- With more partons around: multiple parton fragmentation (higher twist)



- If phase space is filled with partons, recombine/coalesce them into hadrons.



- Use just the lowest Fock state, i.e. valence quarks:

$qqq \to B \quad q\bar{q} \to M$

The Leading Particle Effect

- K.P. Das & R.C. Hwa: Phys. Lett. B68, 459 (1977):
  Quark-Antiquark Recombination in the Fragmentation Region

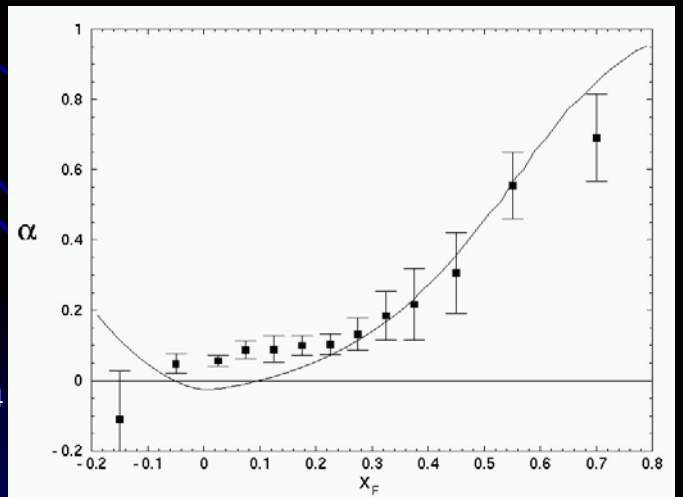
$$d\sigma_{\mathrm{M}}(x) = \int \frac{dx_1 dx_2}{x_1 x_2} F(x_1, x_2) R_{\mathrm{M}}(x_1, x_2, x)$$

Recombination of beam partons in forward direction.

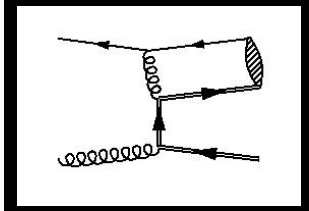
- Braaten, Jia, Mehen: Phys. Rev. Lett. 89, 122002 (2002)

$$\alpha(x) = \frac{d\sigma_{D^-}(x) - d\sigma_{D^+}(x)}{d\sigma_{D^-}(x) + d\sigma_{D^+}(x)}$$

Asymmetry of D mesons in forward direction, α=0 from LO fragmentation.

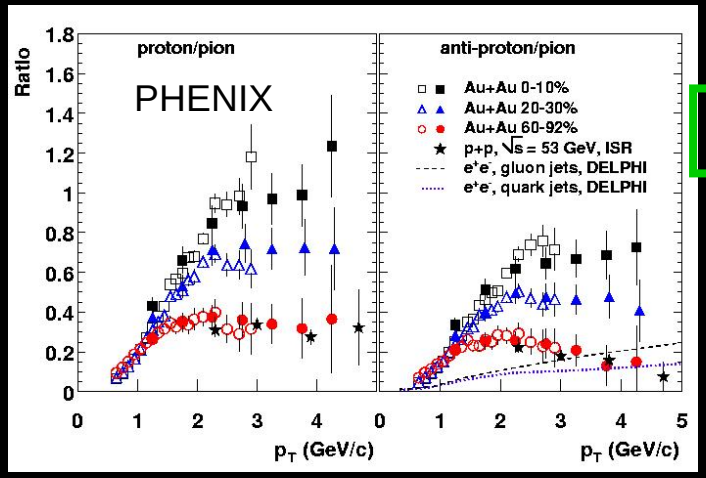


E791 π^- beam: hard $c\bar{c}$ production; recombine $\bar{c}$ with d valence quark from π^- > reco of c with $\bar{d}$

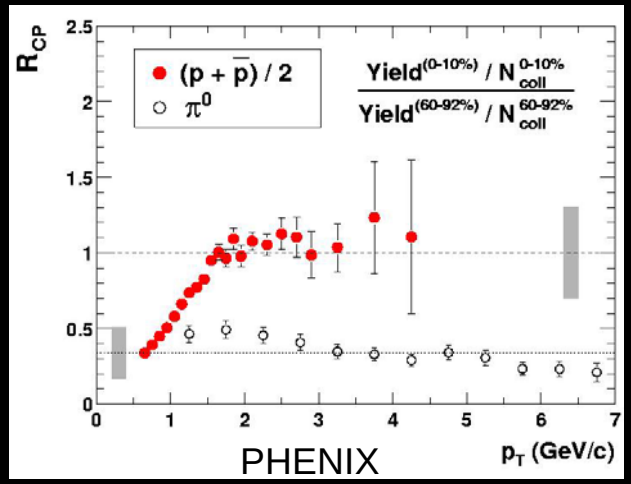


RHIC puzzles

- Anomalous baryon enhancement.



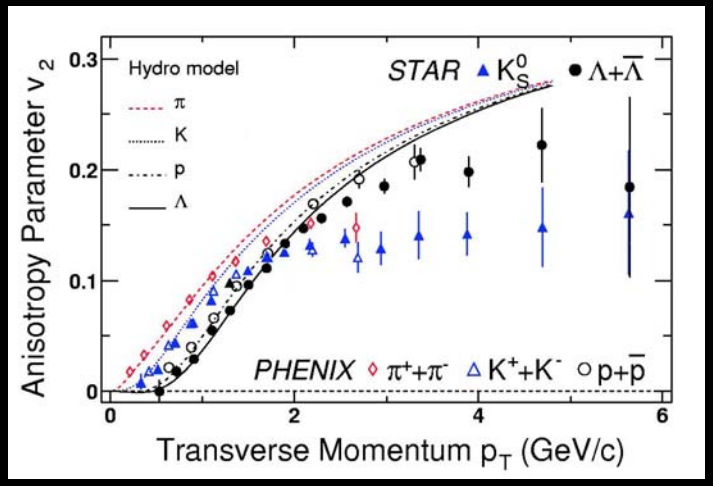
p/π~1



- Difference in baryon and meson v_2.

R_{CP}~1 for protons

Saturation of v_2 at different P_T and on different levels.



Recombination for a dense parton system

- ReCo of hadrons: convolution of Wigner functions

$$\frac{dN_M}{d^3P} = \sum_{a,b} \int \frac{d^3R}{(2\pi)^3} \int \frac{d^3q d^3r}{(2\pi)^3} W_{ab}\left(R - \frac{r}{2}, \frac{P}{2} - q; R + \frac{r}{2}, \frac{P}{2} + q\right) \Phi_M(r,q)$$

- Where does ReCo win?

$W_{ab}(1;2) = w_a(1) w_b(2)$

Exponential: $w \sim A e^{-p_T/T}$

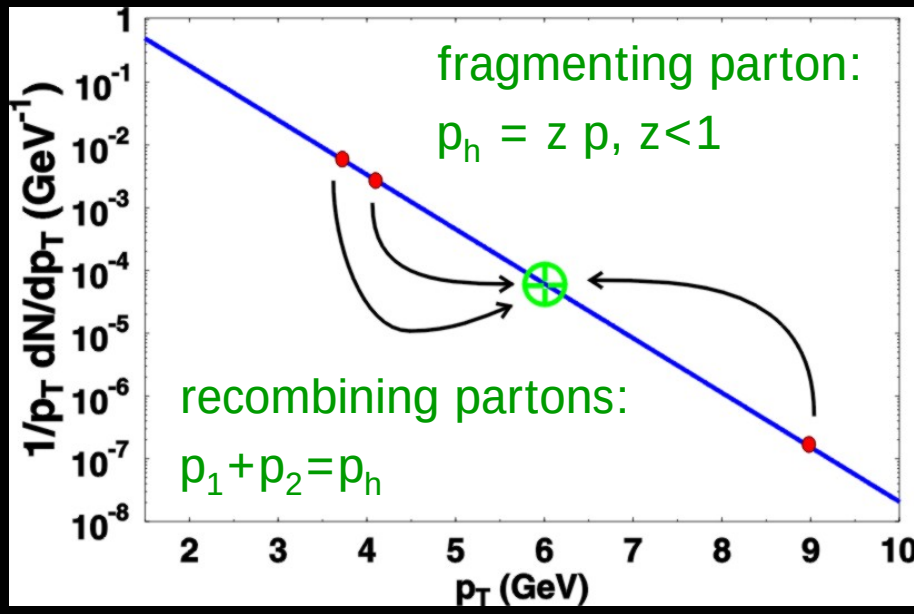
$$N_{\text{frag}} = w \otimes D \sim A e^{-P_T/\langle z \rangle T} \langle D \rangle$$

$$N_{\text{reco}} = w \otimes \Phi \otimes w \sim A^2 e^{-P_T/T}$$

Power law: $w \sim p_T^{-\alpha}$

$$N_{\text{frag}} \sim P_T^{-\alpha}$$

$$N_{\text{reco}} \sim P_T^{-2\alpha}$$



Azimuthal anisotropy v_2

- Anisotropy v_2:

$$\frac{d^2N}{p_t\,dp_t\,d\phi_p} = \frac{1}{2\pi}\left[\frac{dN}{p_t dp_t}\right]\left(1+2v_2\cos\left(2\phi_p\right)\right)$$

- Voloshin, Lin & Ko, Molnar, Nonaka: v_2 from ReCo

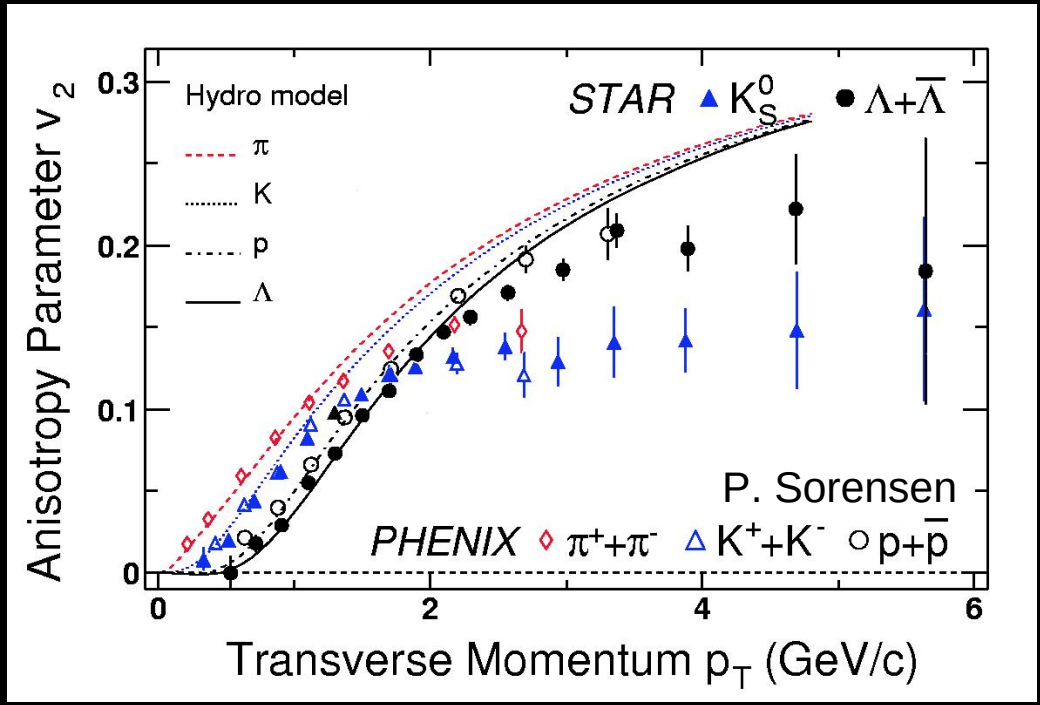
$$v_2^M\left(p_t\right) = \frac{2v_2^p\left(\frac{p_t}{2}\right)}{1+2\left(v_2^p\left(\frac{p_t}{2}\right)\right)^2} \quad \text{and} \quad v_2^B\left(p_t\right) = \frac{3v_2^p\left(\frac{p_t}{3}\right)+3\left(v_2^p\left(\frac{p_t}{3}\right)\right)^3}{1+6\left(v_2^p\left(\frac{p_t}{3}\right)\right)^2}$$

- v_2 scaling law:

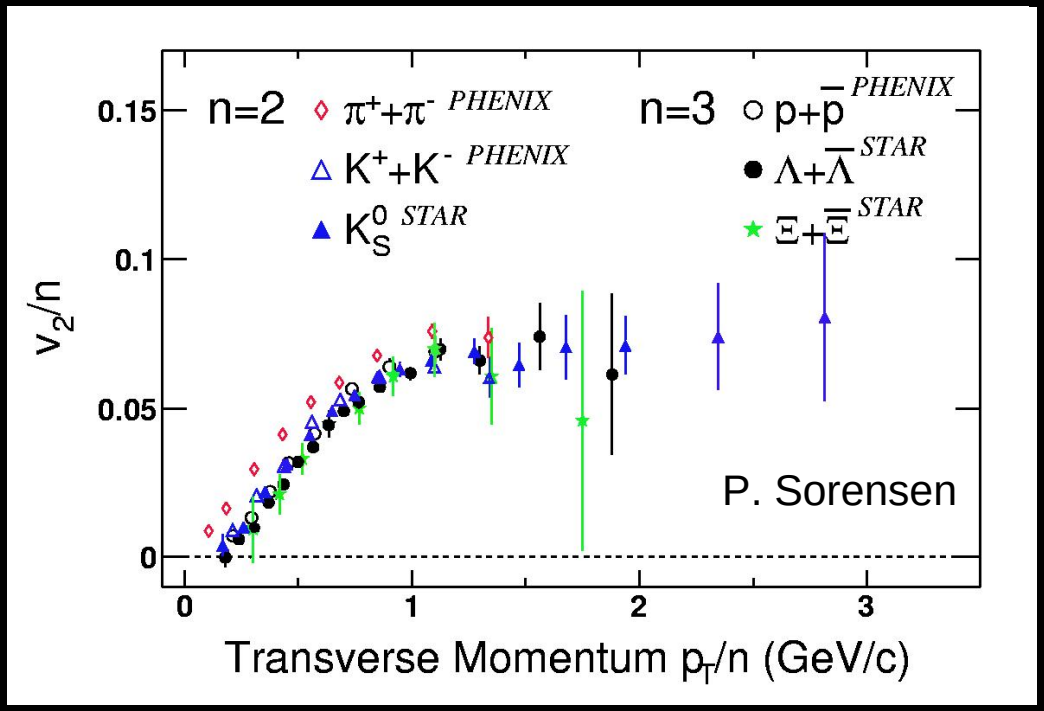
$$v_2^M\left(p_t\right) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B\left(p_t\right) = 3v_2^p\left(\frac{p_t}{3}\right)$$

- v_4, v_6 from ReCo: Chen, Ko, Lin

v_2 Scaling

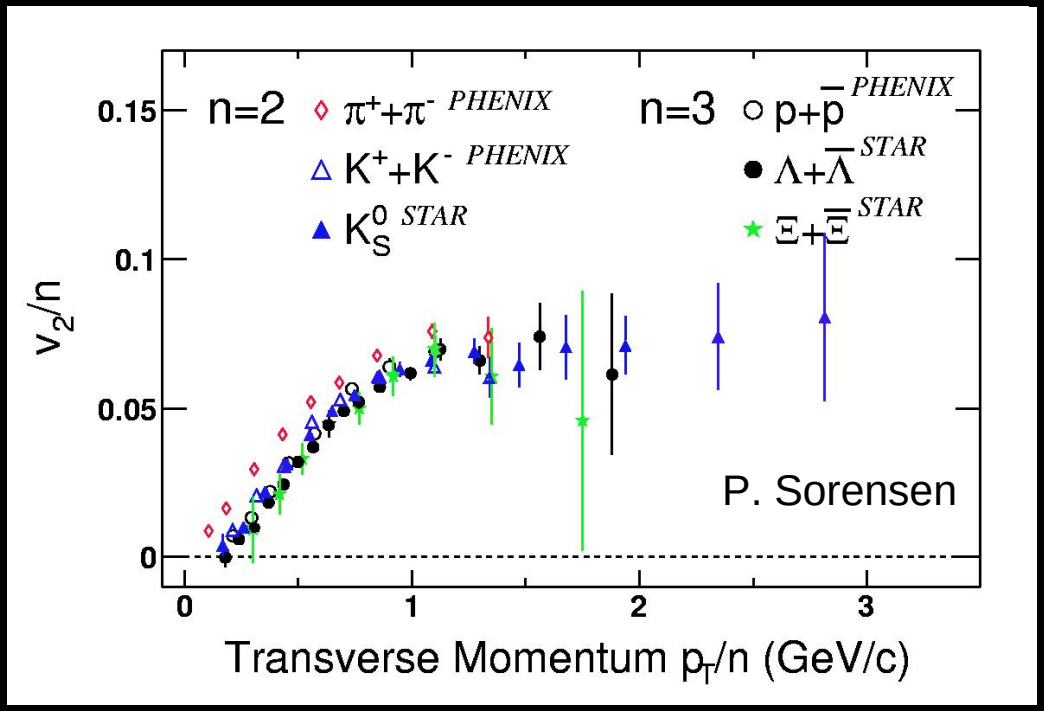

Hydro model
π
K
p
Λ
STAR
K^0_S
$\Lambda+\bar{\Lambda}$
P. Sorensen
PHENIX
$\pi^+ + \pi^-$
$K^+ + K^-$
$p+\bar{p}$
Anisotropy Parameter v_2
Transverse Momentum p_T (GeV/c)
0
0.1
0.2
0.3
0
2
4
6

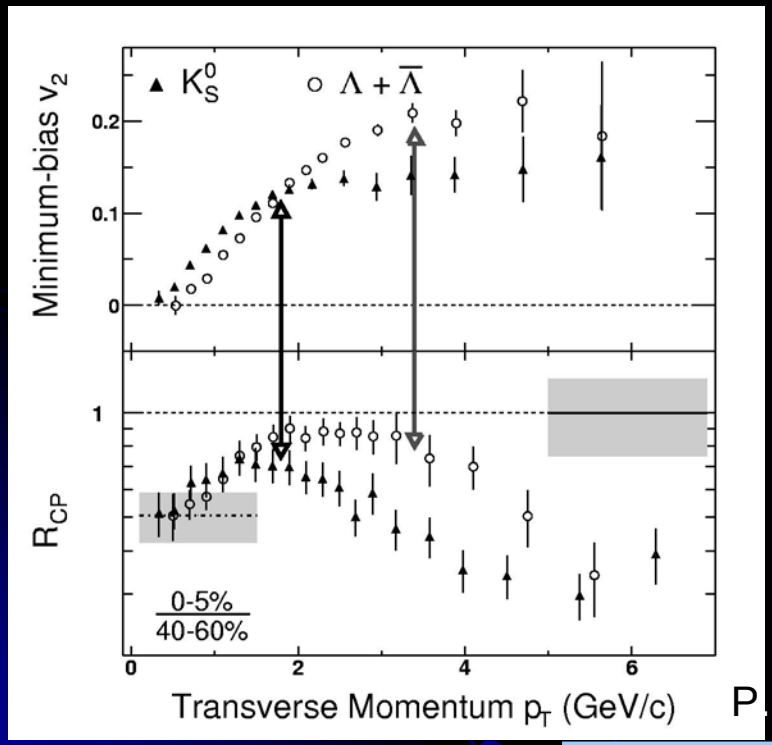
v_2 Scaling



Perfect scaling for all measured hadrons, some deviation for pions (from ρ decays)

v_2 Scaling





P. Sorensen

Perfect scaling for all measured hadrons, some deviation for pions (from ρ decays)

Baryons are pushed further in P_T

ReCo Challenges

Current formalism not suitable at very low P_T:

- Particle number scaling.
- Hadronic rescattering?
- Energy conservation, particles off the mass shell ($2\to2$, $3\to2$ instead of $2\to1$, $3\to1$ processes)
- Decreasing entropy?

↳ include resonances, $\rho\to\pi\pi$ etc.

Correlations in the hadron spectrum.

Duke ReCo

Duke/Minnesota/Kyoto (Fries, Müller,Nonaka,Bass,Asakawa)

- Recombine thermal ensemble of massive quarks (constituent quarks) at the phase transition.

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

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

$$w_a(\sigma, p) = g_a e^{-p\cdot v(\sigma)/T}\, e^{-\eta^2/2\Delta^2}\, f(\rho,\phi)$$

Hadr. hypersurface Σ
T=175 MeV
Radial flow v=0.55c

- Add pQCD calc. using fragmentation and energy loss.
- No soft-hard ReCo; resonances studied, but no ρ.
- Many different hadron species; b dependence.

Texas ReCo / Ohio ReCo

Texas A&M/Budapest (Greco, Ko, Levai, Chen)

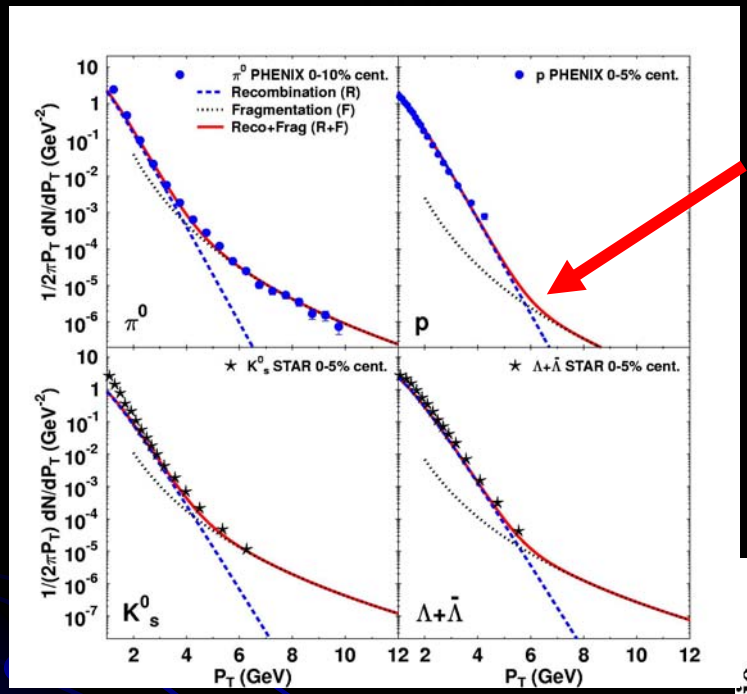
- Monte Carlo implementation (using also spatial overlap)
- Soft (thermal/AMPT) and hard (minijet) partons
- Soft-hard coalescence is allowed.
- Effects of resonances studied ↳ ρ significantly increases the low P_T yield of pions; solution to the entropy problem?
- Resonances don't destroy the v_2 scaling law.

Ohio State (Lin, Molnar)

- ReCo as a solution to the opacity puzzle; input MPC.

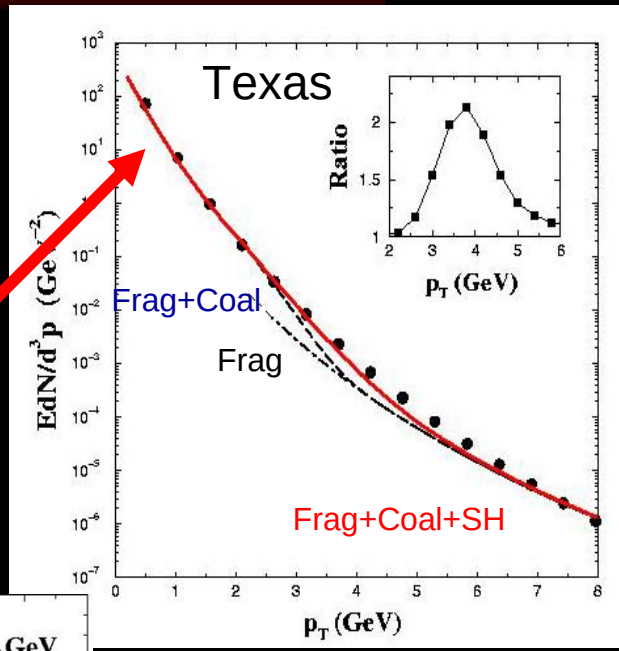
↳ Denesh Molnar's talk

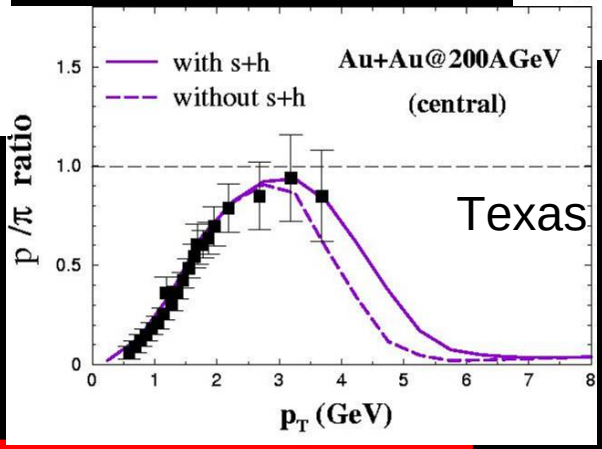
Results for RHIC

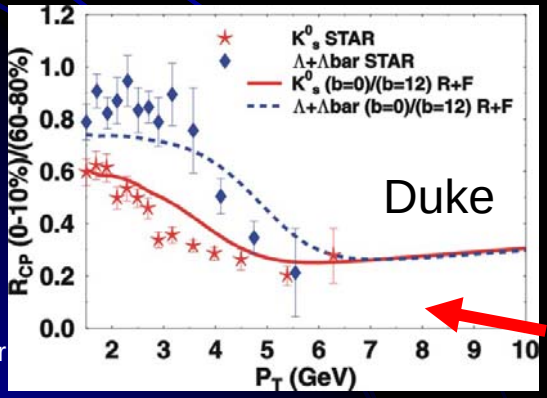


ReCo dominates up to 4..6 GeV/c; fragmentation and energy loss takes over above.

ρ→ππ

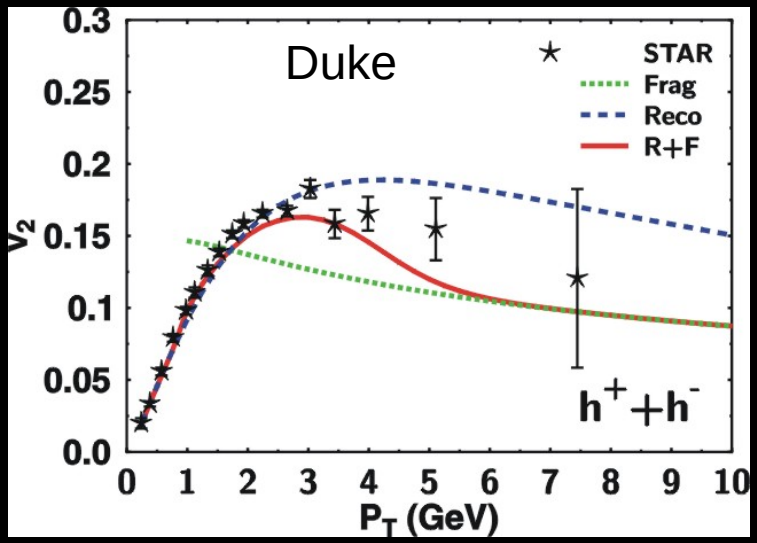






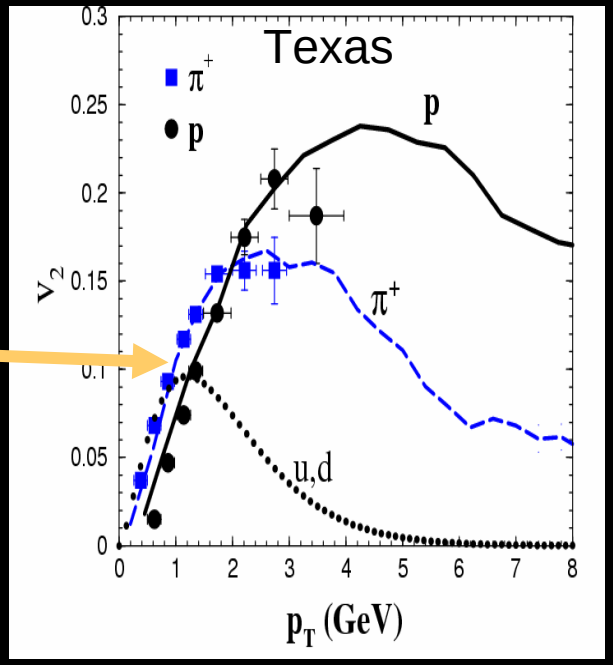
Good description of the *different* hadron species

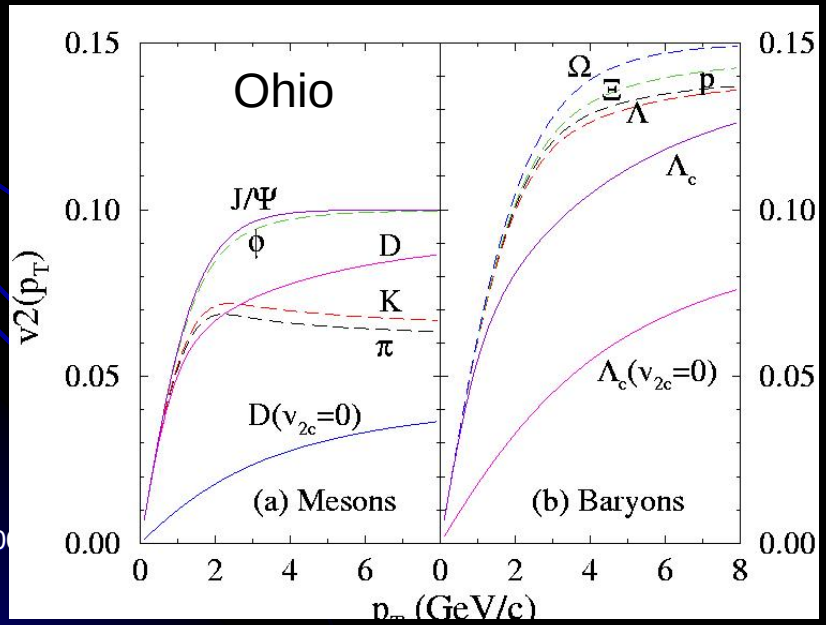
Elliptic flow results



When does v_2 from pQCD take over?

$\rho \rightarrow \pi\pi$





Experimental result:
$v_2(s) = v_2(u,d)$
What about charm?

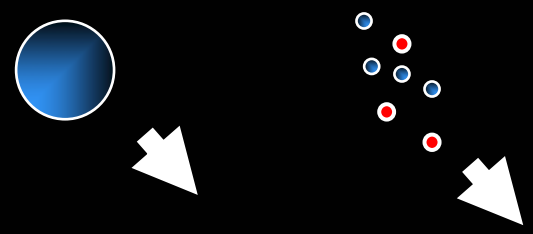
Chiho Nonaka's poster

Back to Fragmentation

Oregon (Hwa, Yang):

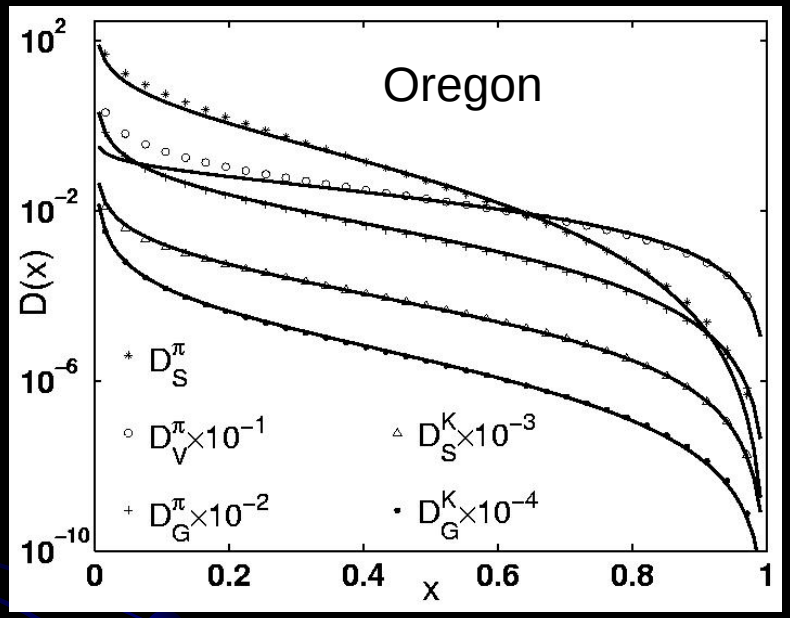
- Fragmentation function is a black box.
- Early attempts to calculate FF with ReCo:

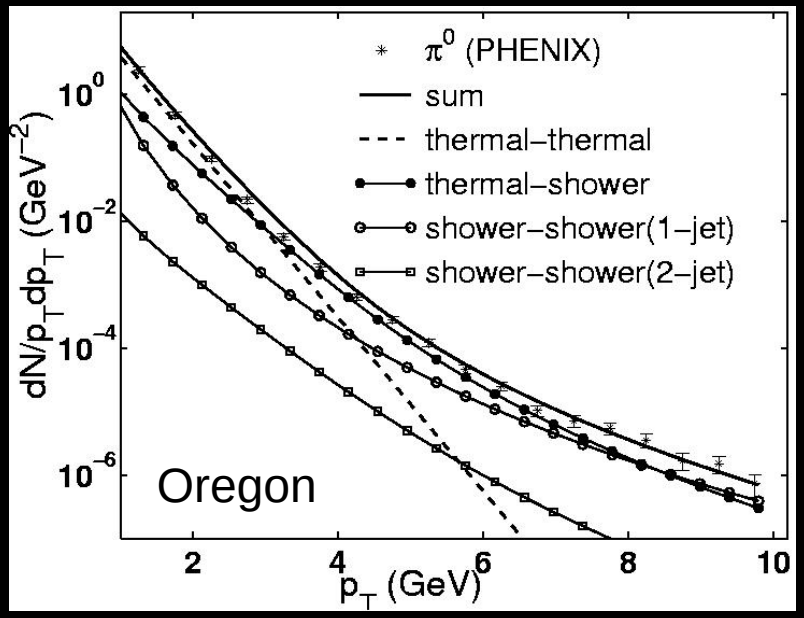
  Migneron, Jones, Lassila: PRD 26, 2235 (1982)
- Let jet partons shower and recombine. (Convert gluons to quark antiquark pairs)



- Thermal-Thermal, Thermal-Shower, Shower-Shower ReCo for a meson.

Results on fragmentation





Shower distributions from π, K FF; check proton FF.

Oregon: shower-thermal is very important at RHIC.

- Rudy Hwa's talk

Myths about ReCo

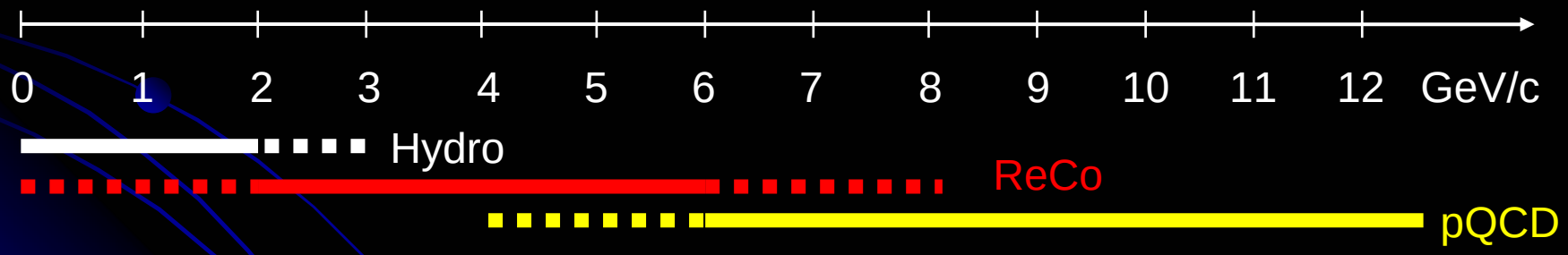
- ReCo makes pQCD & jet quenching obsolete.

>> pQCD has to dominate for $P_T \to \infty$.

>> Without large jet quenching, ReCo might be invisible.

- ReCo contradicts hydrodynamics (v_2 scaling).

>> v_2 mass splitting at low P_T is perfectly explained by hydro, no scaling there.



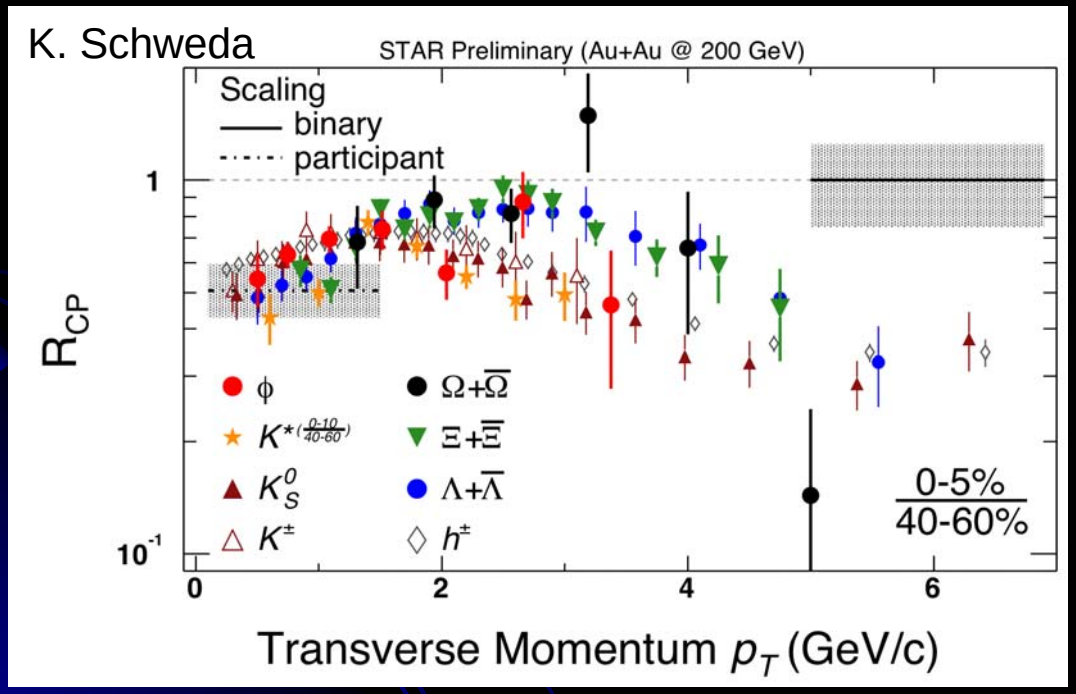
- ReCo is free of particle correlations.

>> Wrong. Hadron correlations reflect parton correlations.

Facts about ReCo

Mass vs valence quark number

- Pure hydro + pQCD descriptions associate anomalous hadron behavior at intermediate P_T with mass effects (Hirano, Nara)



STAR: ϕ and K* behave like mesons, despite of the large mass: ReCo prediction!

Correlations I

2-meson production:

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

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

Partons with pairwise correlations

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

Using narrow width appr.

$$C_0 = C(0)$$

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

$$C_{MM}(P_1,P_2) = \frac{dN_{MM}/d^3P_1 d^2P_2}{(dN_M/d^3P_1)(dN_M/d^3P_2)} \approx \frac{N_4}{N_2^2}\left[1+4C\left(\frac{1}{2}P_1-\frac{1}{2}P_2\right)\right]$$

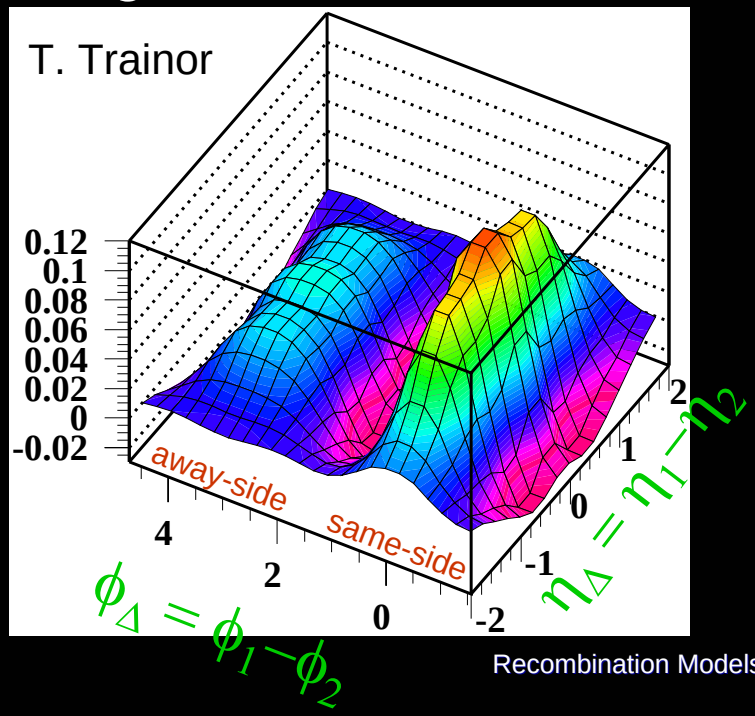
$$C_{BB}(P_1,P_2) \approx \frac{N_6}{N_3^2}\left[1+9C\left(\frac{1}{3}P_1-\frac{1}{3}P_2\right)\right]$$

$$C_{BM}(P_1,P_2) \approx \frac{N_5}{N_3 N_2}\left[1+6C\left(\frac{1}{3}P_1-\frac{1}{2}P_2\right)\right]$$

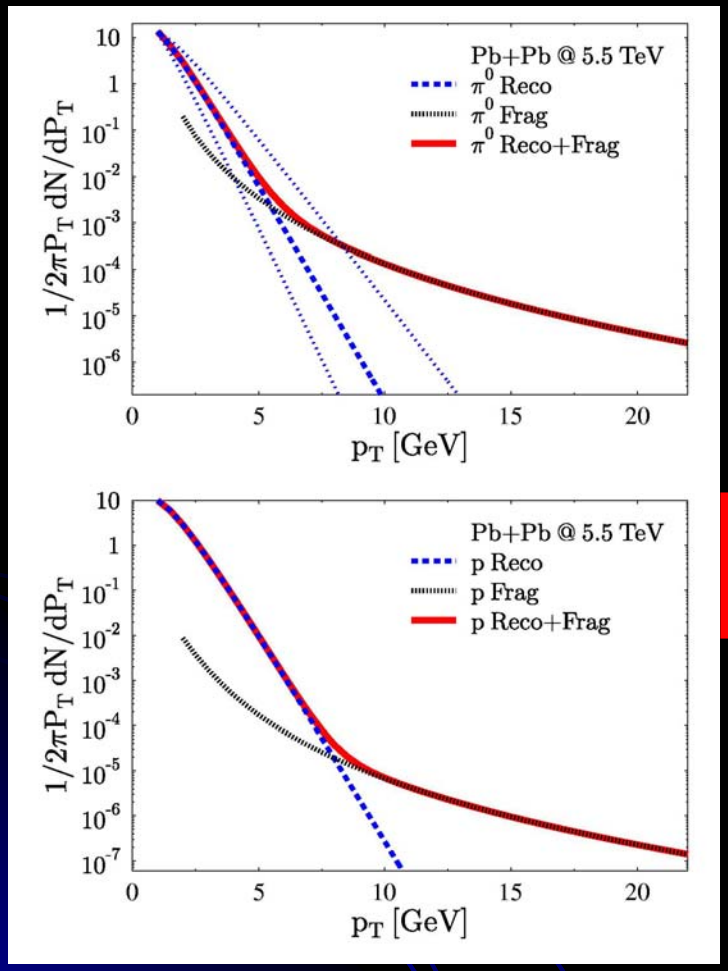
Correlations II

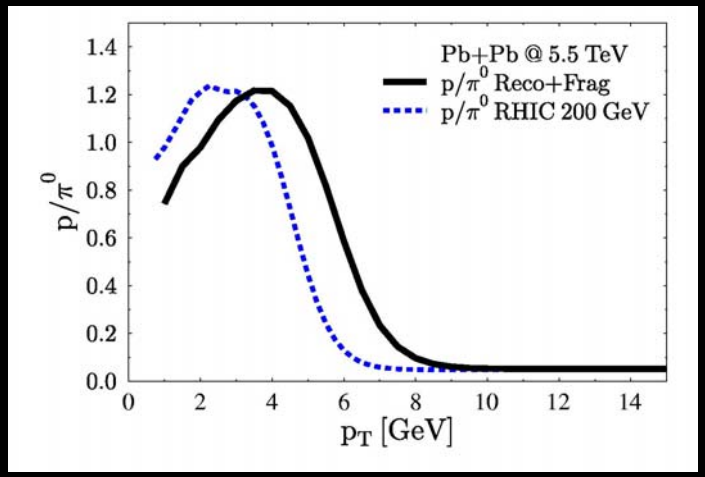
- Parton correlations trivially translate into hadron correlations.
- Modelling of correlations on the parton side: baryon/meson difference; quark/antiquark difference.
- Soft-hard/thermal-shower ReCo gives such correlations.
- Parton correlations even in the "thermal" regime?

STAR: 2-point velocity correlations



A Glance at LHC





More hard partons,
but stronger energy loss.

Thermal phase will be pushed out further!

Fries, Müller: Proc. for LHC 2003; CERN Yellow Rep. "Hard probes..."

Conclusions

- Hadronization of a dense phase space of partons can be described by ReCo.
- ReCo is the dominant hadronization mechanism for central Au+Au collisions at RHIC for $P_T < 4...6$ GeV/c.
- ReCo naturally explains differences between hadron species; baryon enhancement, v_2 scaling, R_{AA}/R_{CP}...
- All observed hadron species seem to obey the ReCo systematics (π^0, $\pi^\pm$, K^0, $K^\pm$, ϕ, p, Λ, Ξ, Ω, d etc.)
- Different implementations agree on basic concepts; dense parton phase with collective properties.

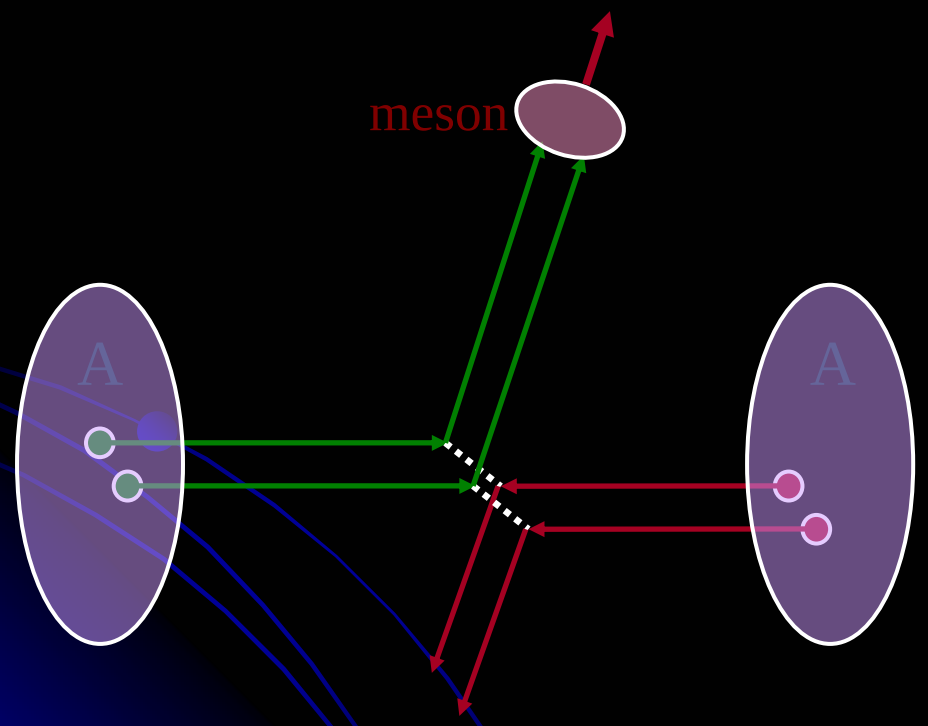
- The future: explore the soft-hard region, role of resonances, v_2 scaling violations, charm, 2-particle correlations ....

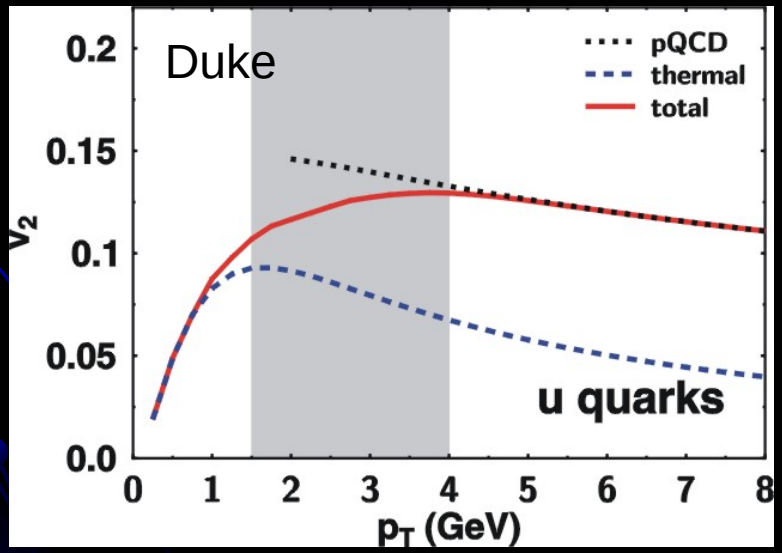
The End

Backup

ReCo & Hard Scattering

- T. Ochiai, Prog. Theor. Phys. 75 (1986) 1184



Is the parton phase accessible?

- How well defined are results for the parton phase?
- Results for the parton spectrum can have different interpretations (e.g. minijet vs shower)
- Consensus: (thermalized) dense parton phase with collective flow.
- Elliptic flow seems to be an unambiguous property of the parton phase: