Dynamical Recombination model of QGP

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- Introduction – recombination model
- Dynamic recomination calculation :
  Hydrodynamic evolution of QGP +
  + Hadronization via recombination
  + Hadronic rescattering by URQMD
- Results
- Summary and Outlook

collaborators:
- S. Bass
- B. Müller
- C. Nonaka

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Recombination : long history

High Energy Physics Phenomenology:

- K.P. Das & R.C. Hwa, Phys. Lett. B68, 459 (1977)

  Quark-Antiquark Recombination in the Fragmentation Region

➢ description of leading particle effect

- T. Ochiai, Prog. Theo. Phys. 75, 1184 (1986)
- E. Braaten, Y. Jia & T. Mehen, Phys. Rev. Lett. 89, 122002 (2002)
- R. Rapp & E.V. Shuryak, Phys. Rev. D67, 074036 (2003)

Heavy-Ion Phenomenology:

- T. S. Biro, P. Levai & J. Zimanyi, Phys. Lett. B347, 6 (1995)

  ALCOR: a dynamical model for hadronization

➢ yields and ratios via counting of constituent quarks

- R.C. Hwa & C.B. Yang, Phys. Rev. C66, 025205 (2002)
- R. Fries, B. Mueller, C. Nonaka & S.A. Bass, Phys. Rev. Lett. 90
- R. Fries, B. Mueller, C. Nonaka & S.A. Bass, Phys. Rev. C68, 044902 (2003)
- V. Greco, C.M. Ko and P. Levai, Phys. Rev. Lett. 90 - AMPT

Anisotropic flow:

- S. Voloshin, QM2002, nucl-ex/020014
- Z.W. Lin & C.M. Ko, Phys. Rev. Lett 89, 202302 (2002)
- D. Molnar & S. Voloshin, nucl-th/0302014

Recombination+Fragmentation Model

R.J. Fries, C. Nonaka, B. Mueller & S.A. Bass, PRL 90 202303 (2003) ; PRC68, 044902 (2003)

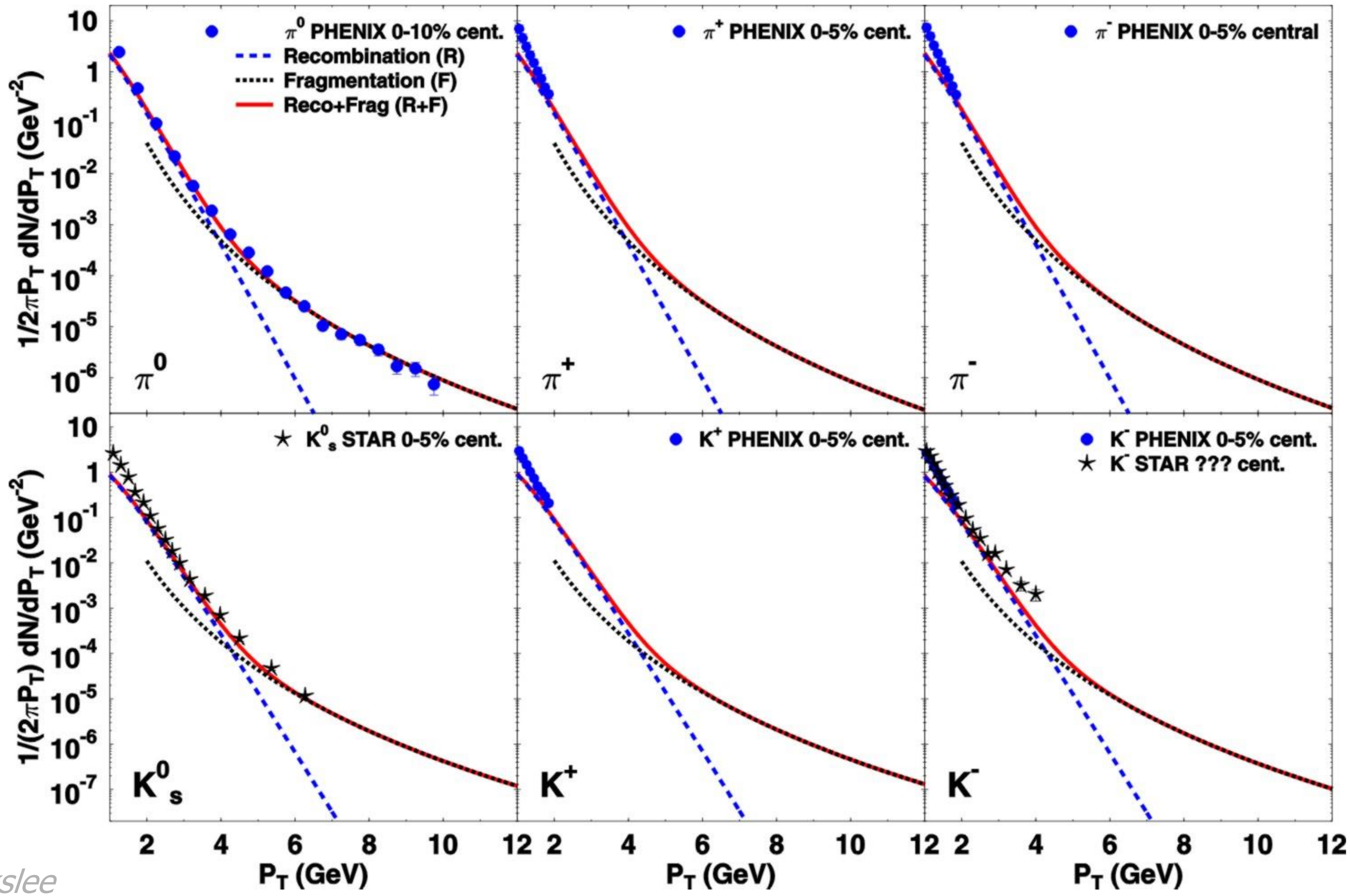
basic assumptions:

- at low p_t, the quarks and antiquark spectrum is thermal and they recombine into hadrons locally "at an instant":

$$q\bar{q} \rightarrow M \qquad qqq \rightarrow B$$

- at high p_t, the parton spectrum is given by a pQCD power law, partons suffer jet energy loss and hadrons are formed via fragmentation of quarks and gluons

Hadron Spectra I



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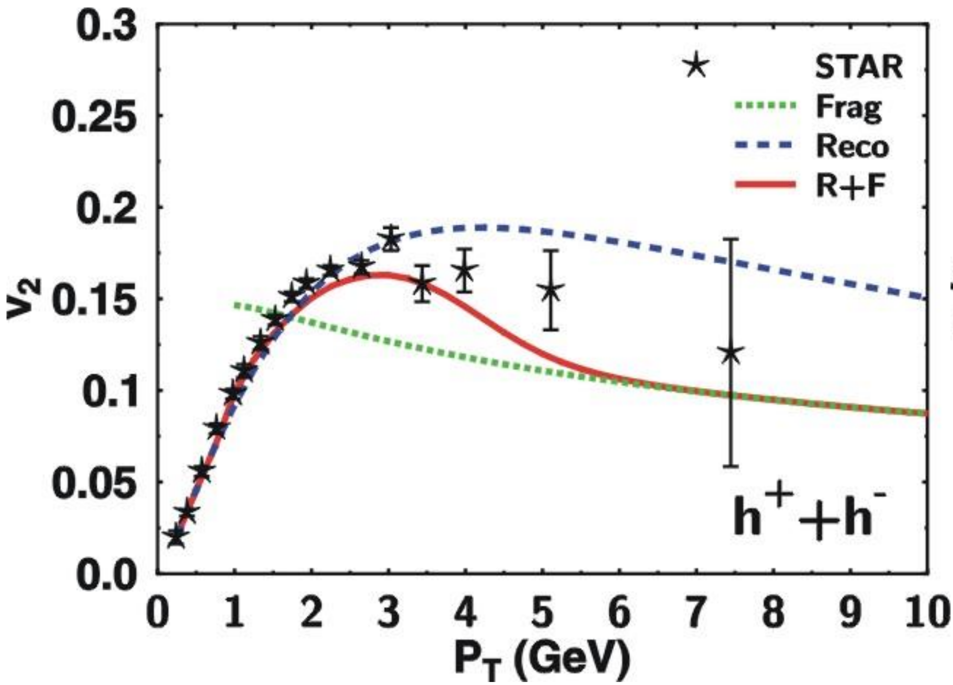
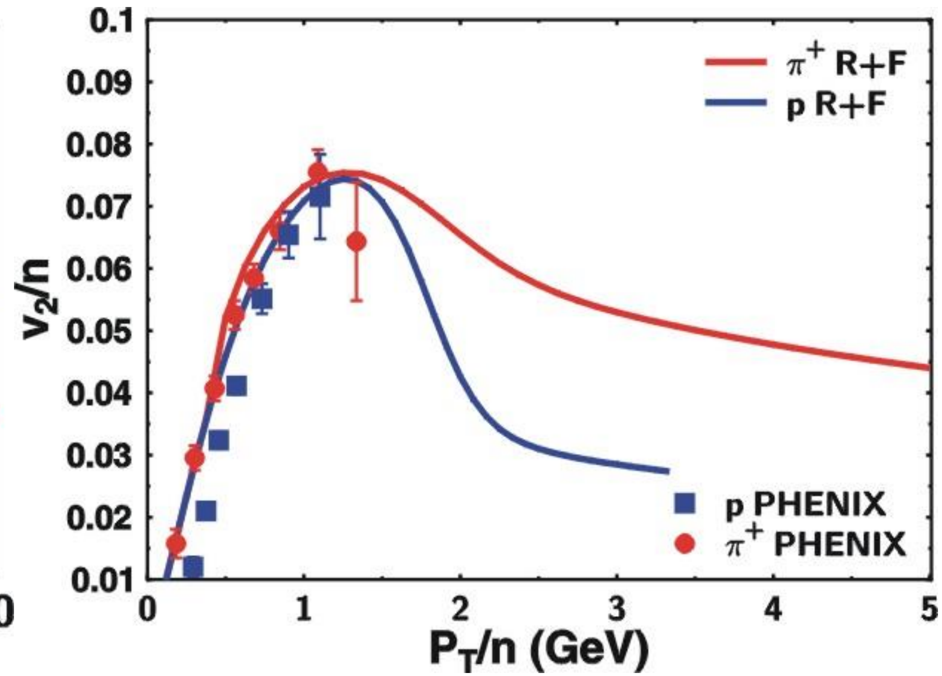
Elliptic Flow: Recombination vs. Fragmentation





- high p_t: v_2 for all hadrons merge, since v_2 from energy-loss is flavor blind

➢ charged hadron v_2 for high pt shows *universal & limiting* fragmentation v_2

➢ quark number scaling breaks down in the fragmentation domain

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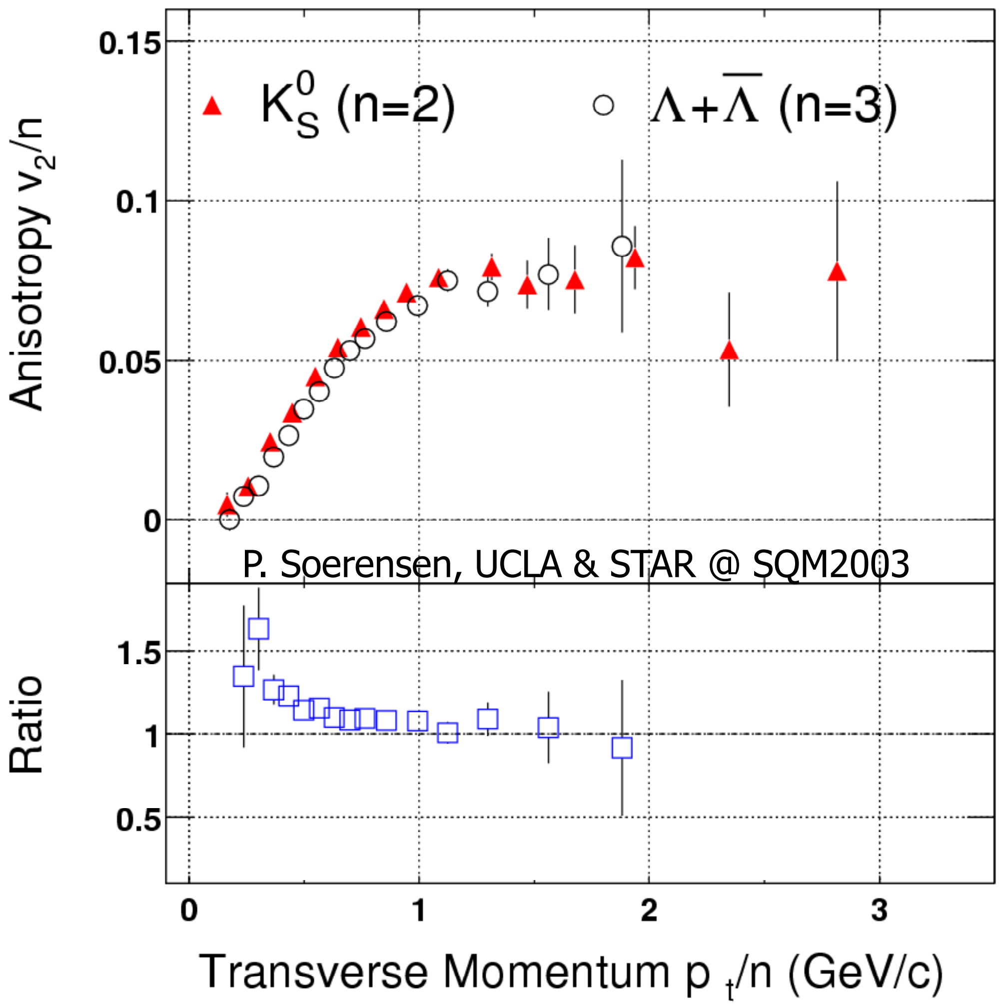
Parton Number Scaling of v_2



- in leading order of v_2, recombination predicts:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

- smoking gun for recombination
- measurement of partonic v_2 !

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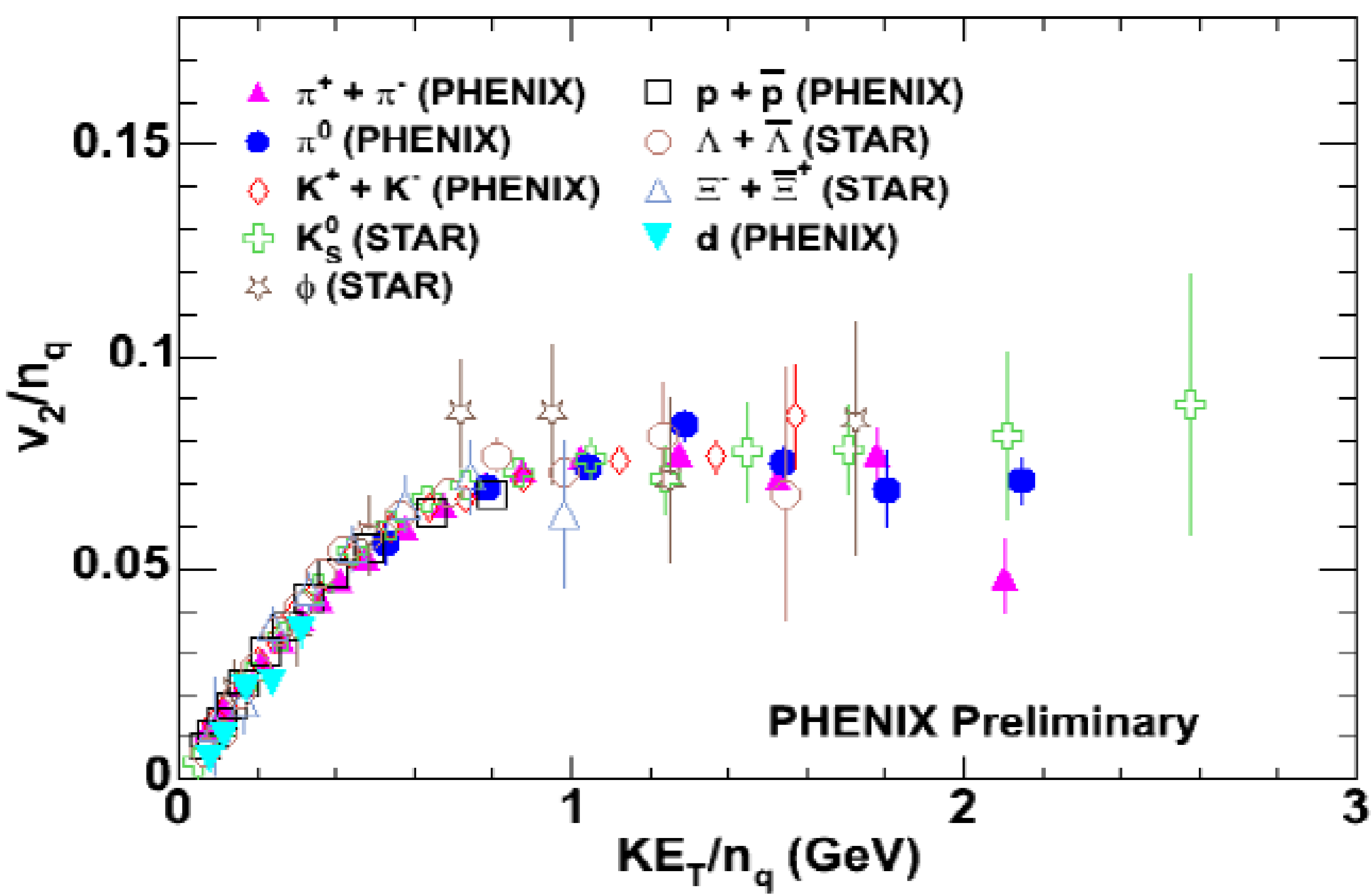
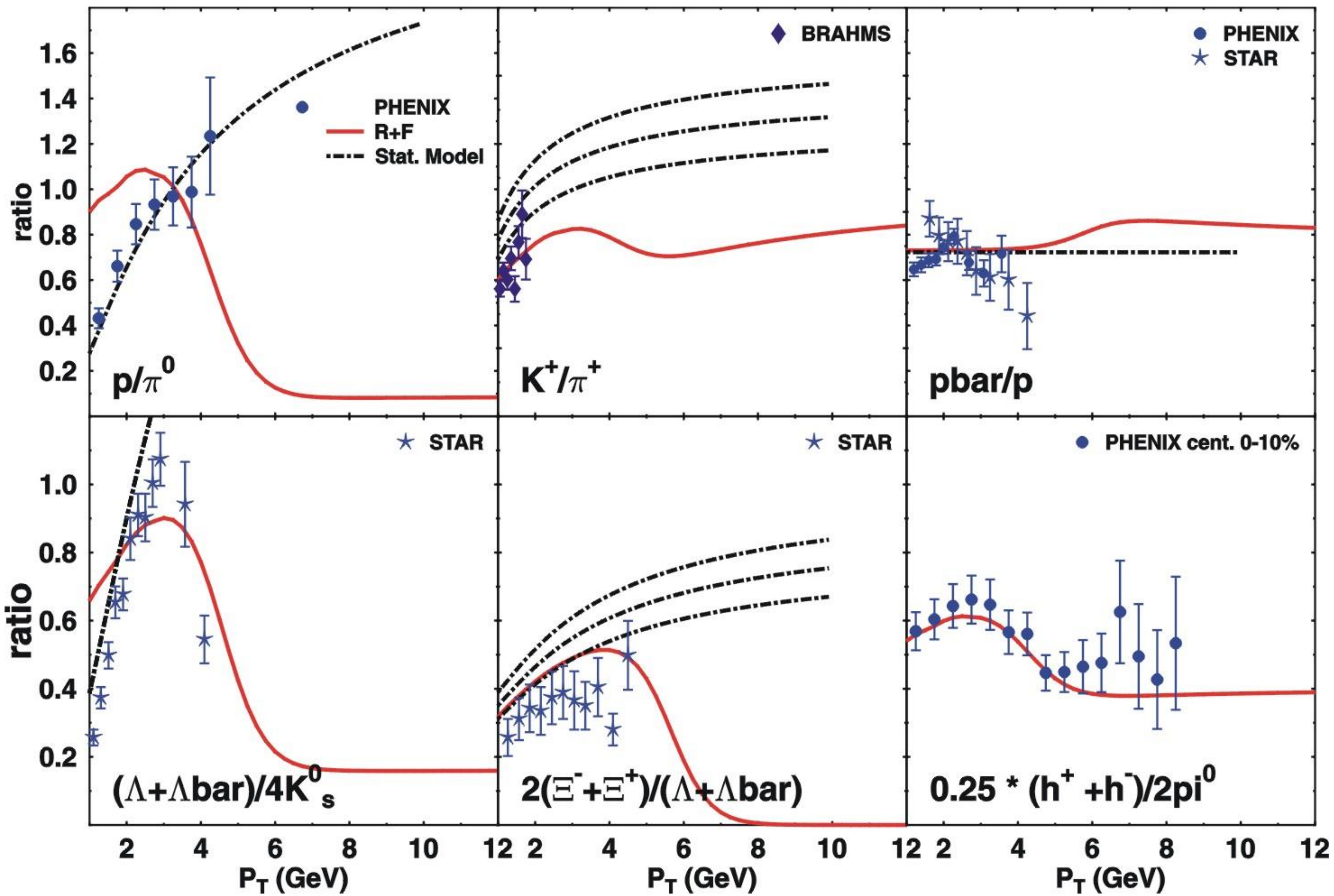
Parton Number Scaling of v_2



Hadron Ratios vs. p_t



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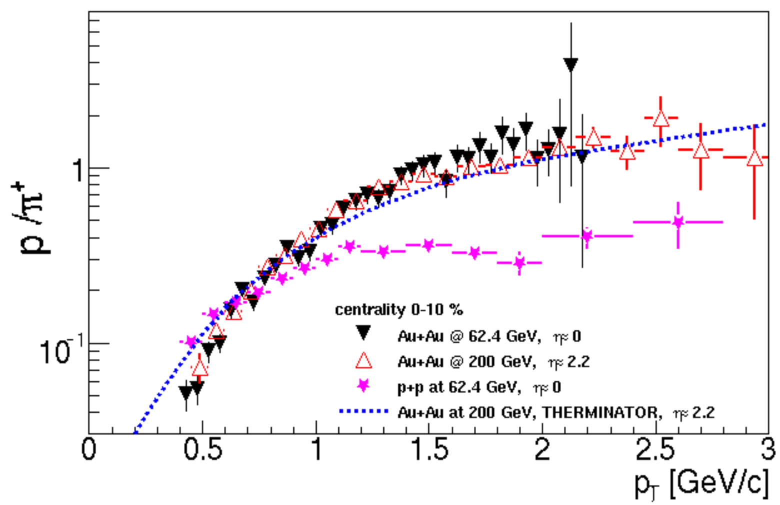
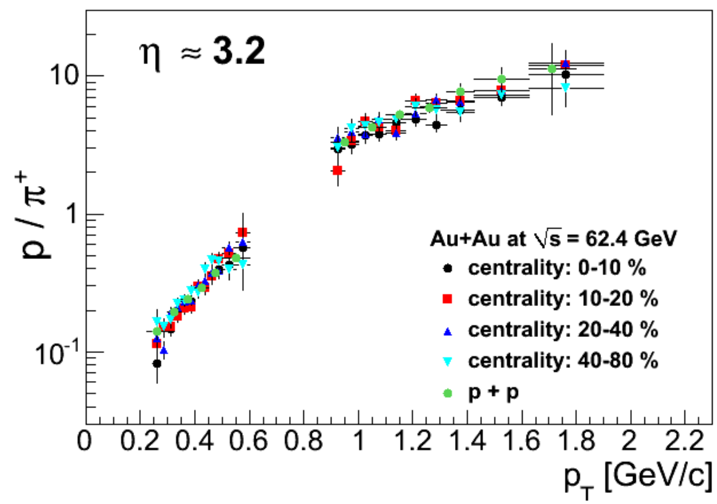
Energy systematics – 200 and 62

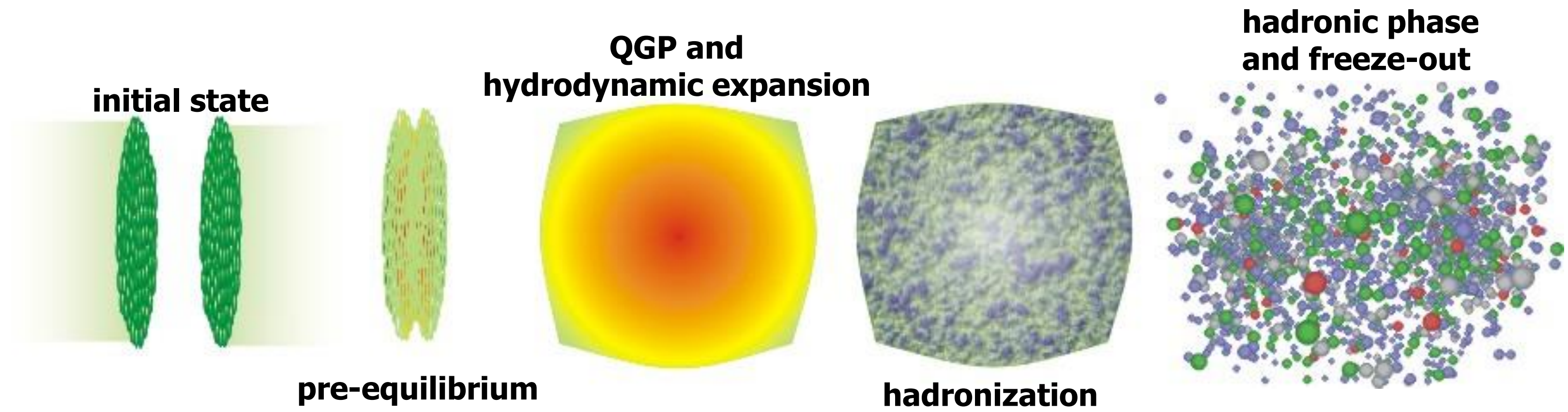
- Mid-rapidity 62 GeV similar to η~2.2 at 200 GeV with significant P/π ratios
- At y~0 and y~2.2 significant medium effects
- Close to beam rapidity (forward at 62 GeV) P/π exhibits no centrality dependence and is similar to pp indicating little influence from media (quark coalescence, hadronic re-scattering)





•Talk by Pawel Statzel, Friday

Exploring QCD Matter at RHIC and LHC



QGP

- hydrodynamic evolution - C. Nonaka
- reasonable for a perfect fluid

Hadronization via recombination

- recombination

Hadronic rescattering

- URQMD - S. Bass

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Recombination of thermal quarks I

$$E\frac{dN^{M}{}_{i}}{d^3P} = \frac{d_i}{(2\pi)^3}\int_{\Sigma} P^{\mu} d\sigma_{\mu} G^{M}{}_{ab}(k, P-k)$$

$$E\frac{dN^{B}{}_{\mathrm{i}}}{d^3p} = \frac{d_i}{(2\pi)^3}\int_{\Sigma} P^{\mu} d\sigma_{\mu} G^{B}{}_{abc}(k_1, k_2 P-k_1-k_2)$$

$$G^{M}{}_{ab} = \int d^3k\ \overline{w}_a(k)\left|\overline{\phi}_{\mathrm{M}}(k)\right|^2 \overline{w}_b(P-k)$$

$$G^{B}{}_{abc} = \int d^3k_1 d^3k_2 w_a(k_1) w_b(k_2) w_c(P-k_1-k_2)\left|\overline{\phi}_{\mathrm{B}}(k_1, k_2, P-k_1-k_2)\right|^2$$

- wave functions are best know in the light cone frame.
- for a thermal distribution: $w(r,k) \sim \exp(-\left(k\cdot u-\mu_q\right)/T)$

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Recombination of thermal quarks II

- hadronization hypersurface : mixed phase
- Energy conservation during the recombination

➢ For a cell at hadronization, $E_i \, \delta\alpha_\tau$ is the energy available for hadronization where $\alpha = V_Q / V_{tot}$ is the volume fraction of QGP phase.

$$\sum_i E_i^{cell} \Delta\alpha^i{}_\tau = \sum_j E_j{}^{had}$$

- In a hydrodynamic cell, i, hadronization rate in μ direction is proportional to $\Delta\alpha^i{}_\mu = \alpha^i{}_\mu - \alpha^{i+1}{}_\mu$

$$\int p^\mu d\sigma_\mu \rightarrow \sum_i \sum_\mu p^\mu d\sigma_\mu \Delta\alpha^i{}_\mu$$

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Recombination of thermal quarks III

- $G^M{}_{ab}(k_1, k_2)$ depends only on the quark masses and is independent of hadron mass.

- Since $m_q \neq m_s$, there are 4 cases for mesons and 8 cases for baryons.

$$q\bar{q} \to M1,\ q\bar{s} \to M2,\ s\bar{q} \to M3,\ s\bar{s} \to M4$$

$$qqq \to B1,\ qqs \to B2,\ qss \to B3,\ sss \to B4$$

$$\overline{qqq} \to B5,\ \overline{qqs} \to B6,\ \overline{qss} \to B7,\ \overline{sss} \to B8$$

➢ Inside a group, relative abundances are assumed to be

$$N_i / N_j = e^{(m_i - m_j)/T} C_i / C_j$$

(C_i : degeneracy factors)

e.g. $M1 = (\pi, \omega, \rho, \ldots)$

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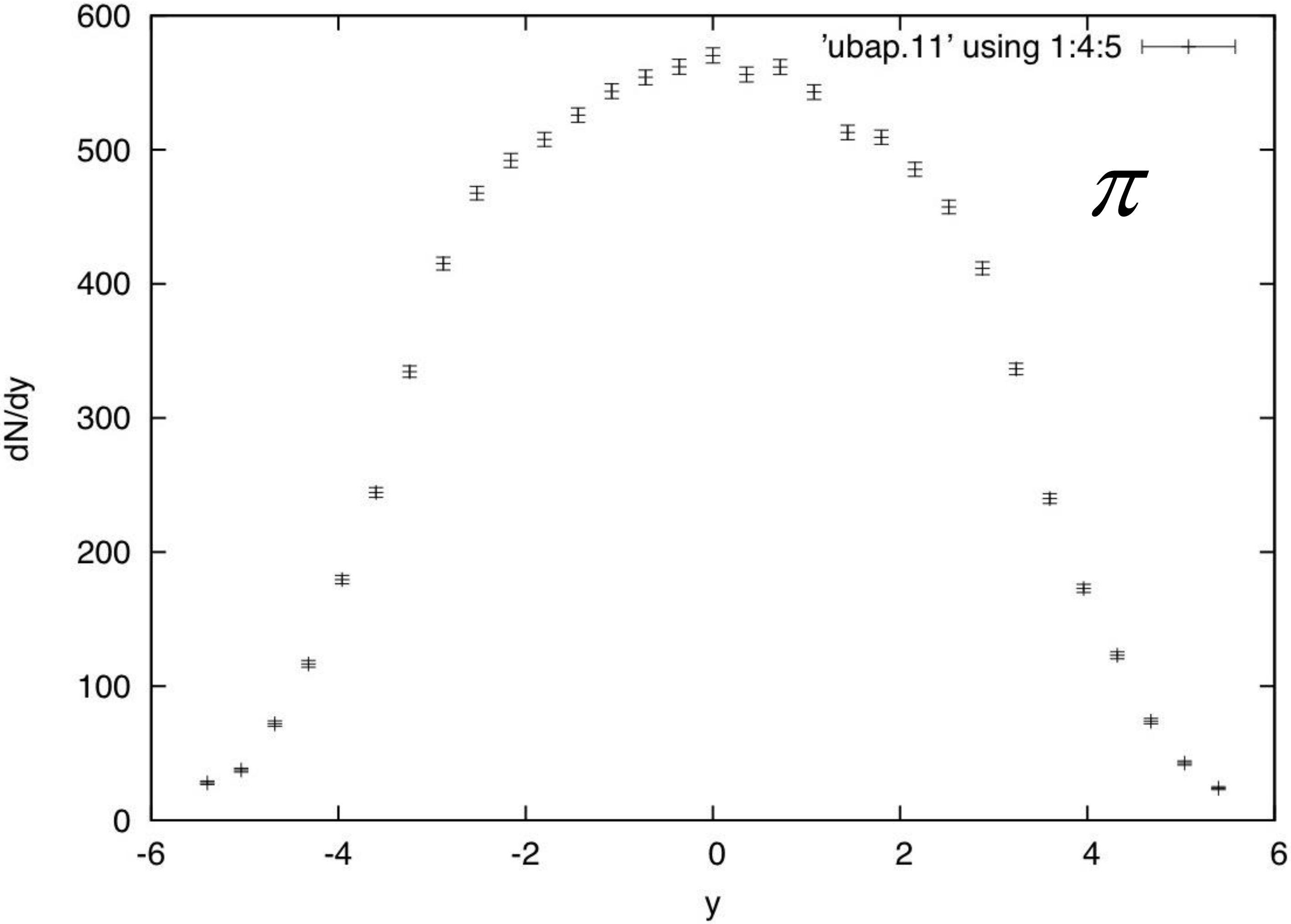
Recombination of thermal quarks IV

- After hadronization, hadronic rescattering is simulated by URQMD !

Results

- hadron spectra
- hadron ratios – coming soon
- R_{AA} – coming soon
- elliptic flow – coming soon
- Comparison with statistical model



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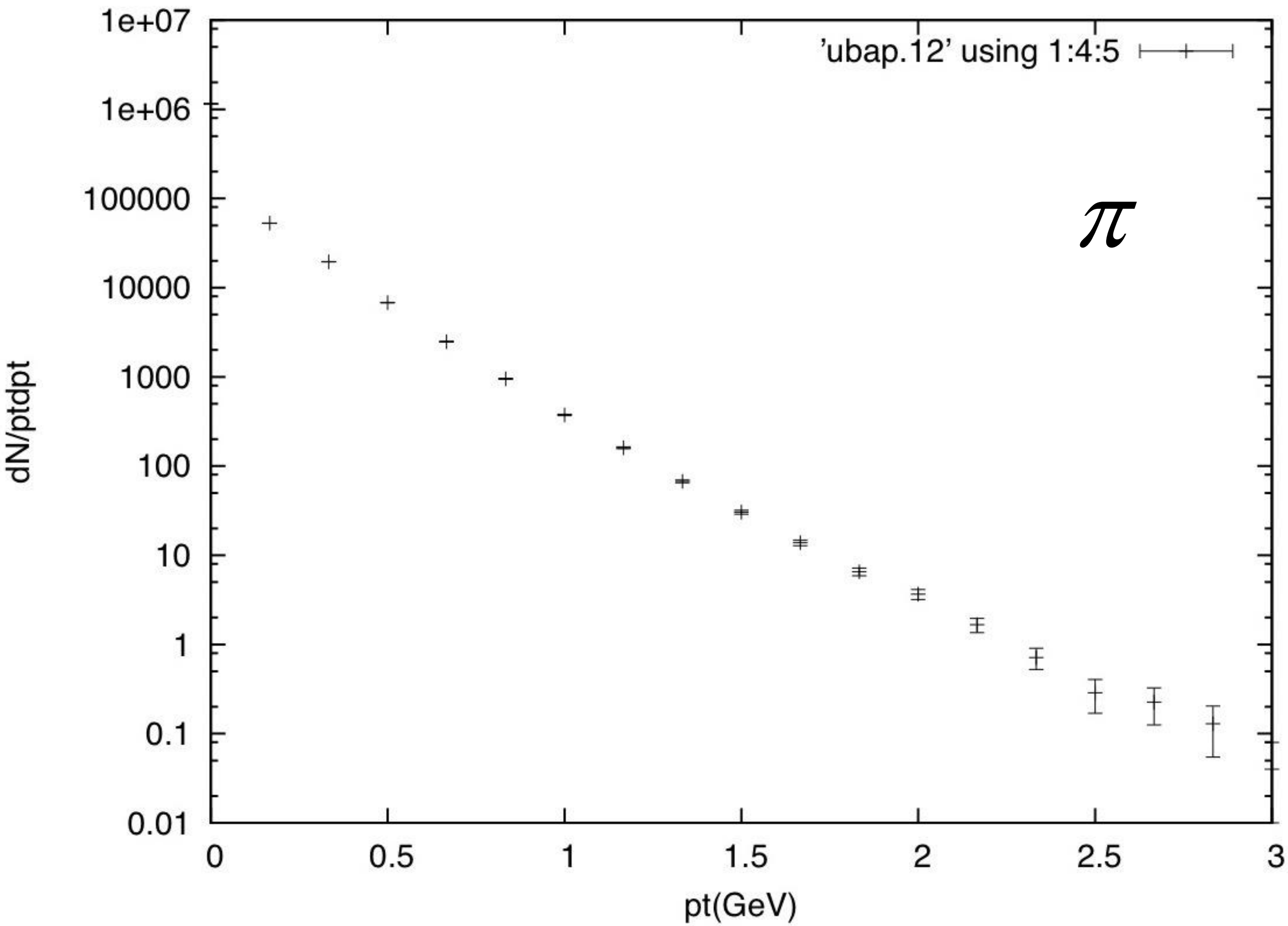
'ubap.12' using 1:4:5
π
dN/ptdpt
pt(GeV)
1e+07
1e+06
100000
10000
1000
100
10
1
0.1
0.01
0
0.5
1
1.5
2
2.5
3

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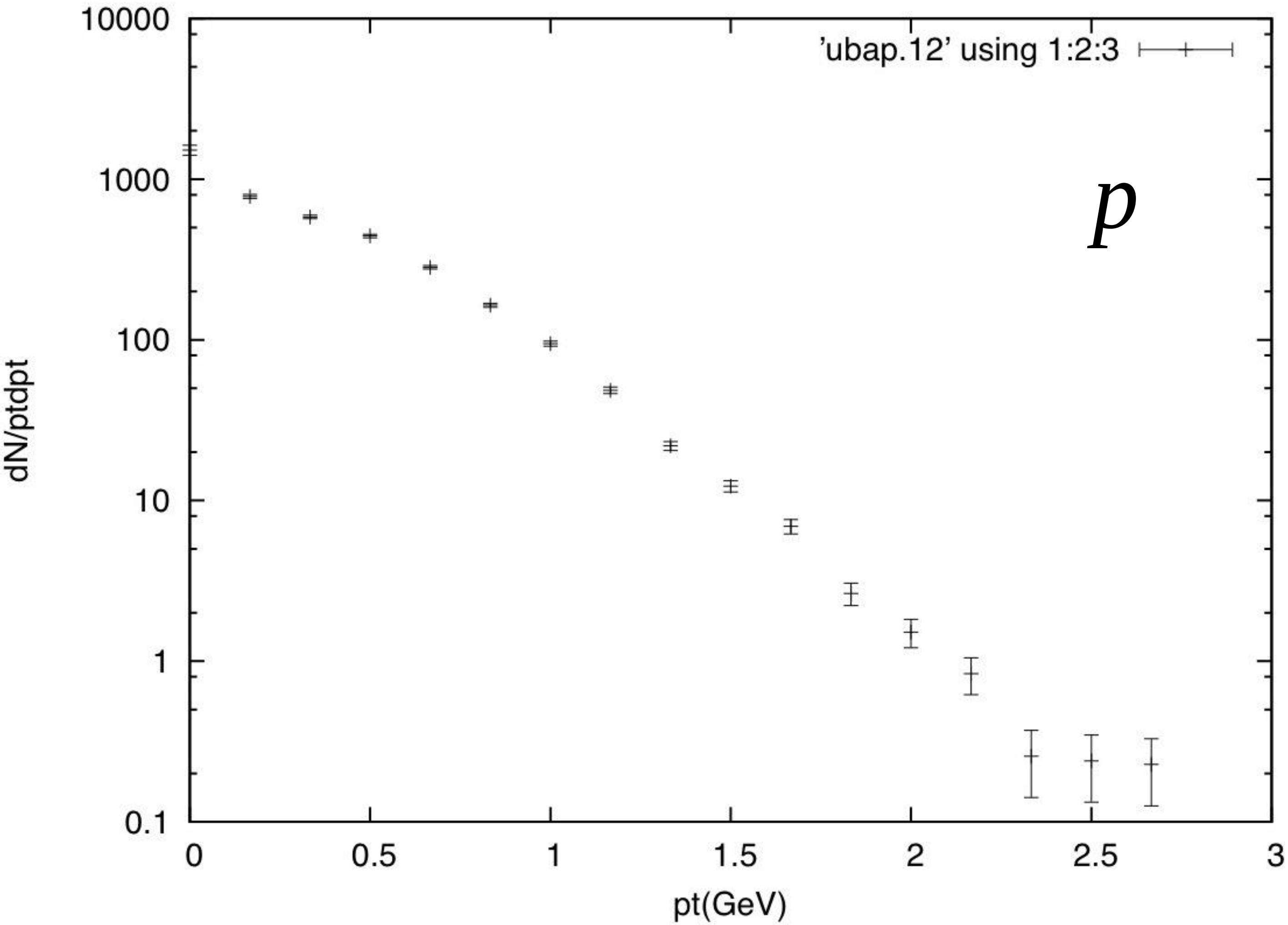

'ubap.12' using 1:2:3
p
10000
1000
100
10
1
0.1
0
0.5
1
1.5
2
2.5
3
dN/ptdpt
pt(GeV)

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Summary & Outlook

Hadronization of a QGP via Recombination:

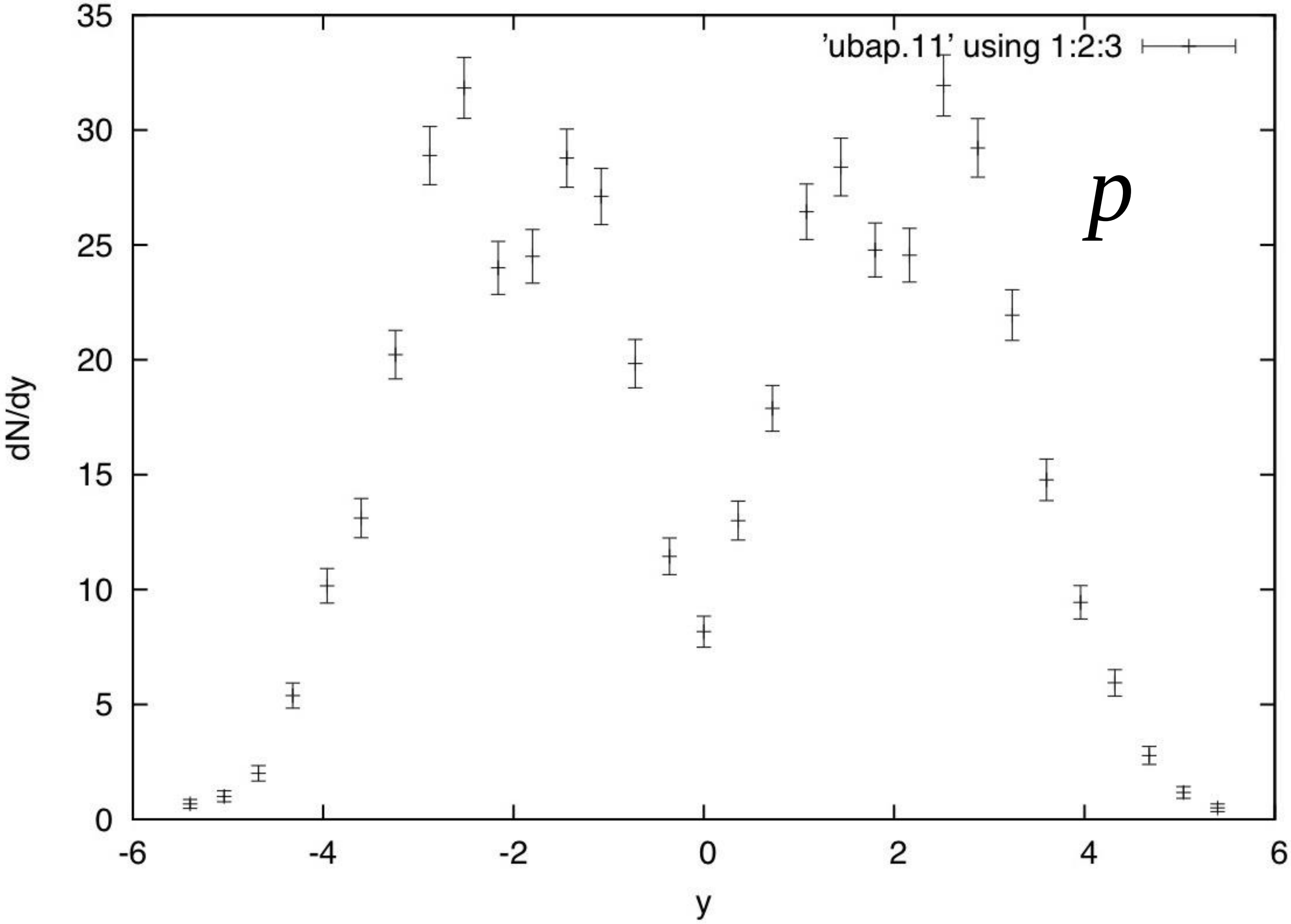
- Hydrodynamic evolution of a QGP until mixed phase
  - reasonable for a perfect fluid
- hadronization via quark recombination
  - quark number scaling of elliptic flow, …
- hadronic rescattering by URQMD
  - different chemical and thermal freeze-out

No problem of freeze-out prescription !!!

issues to be addressed in the future:

- results are coming soon.
- comparison with statistical hadronization
- combine with viscous hydrodynamics or parton cascade

The End



p

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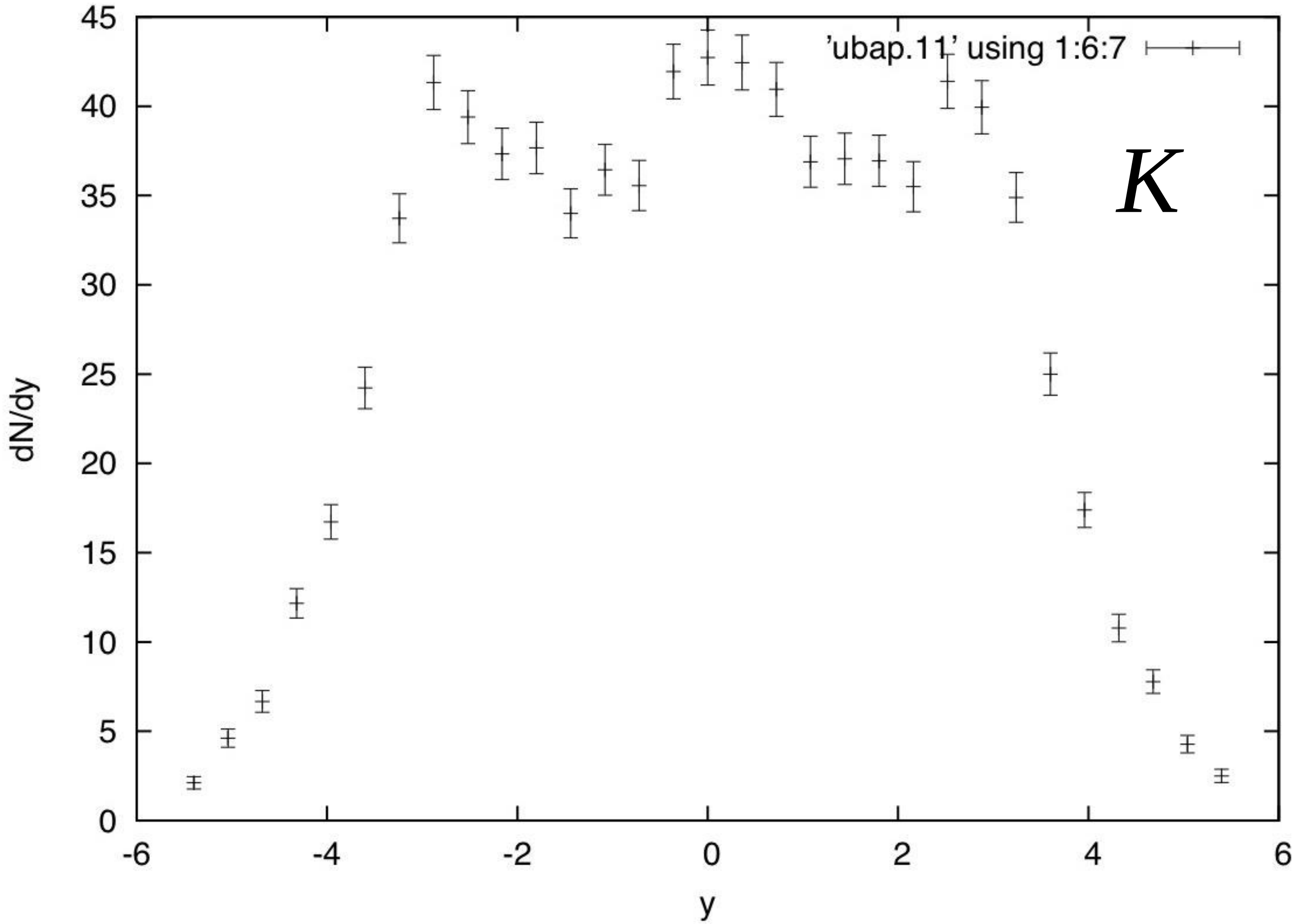

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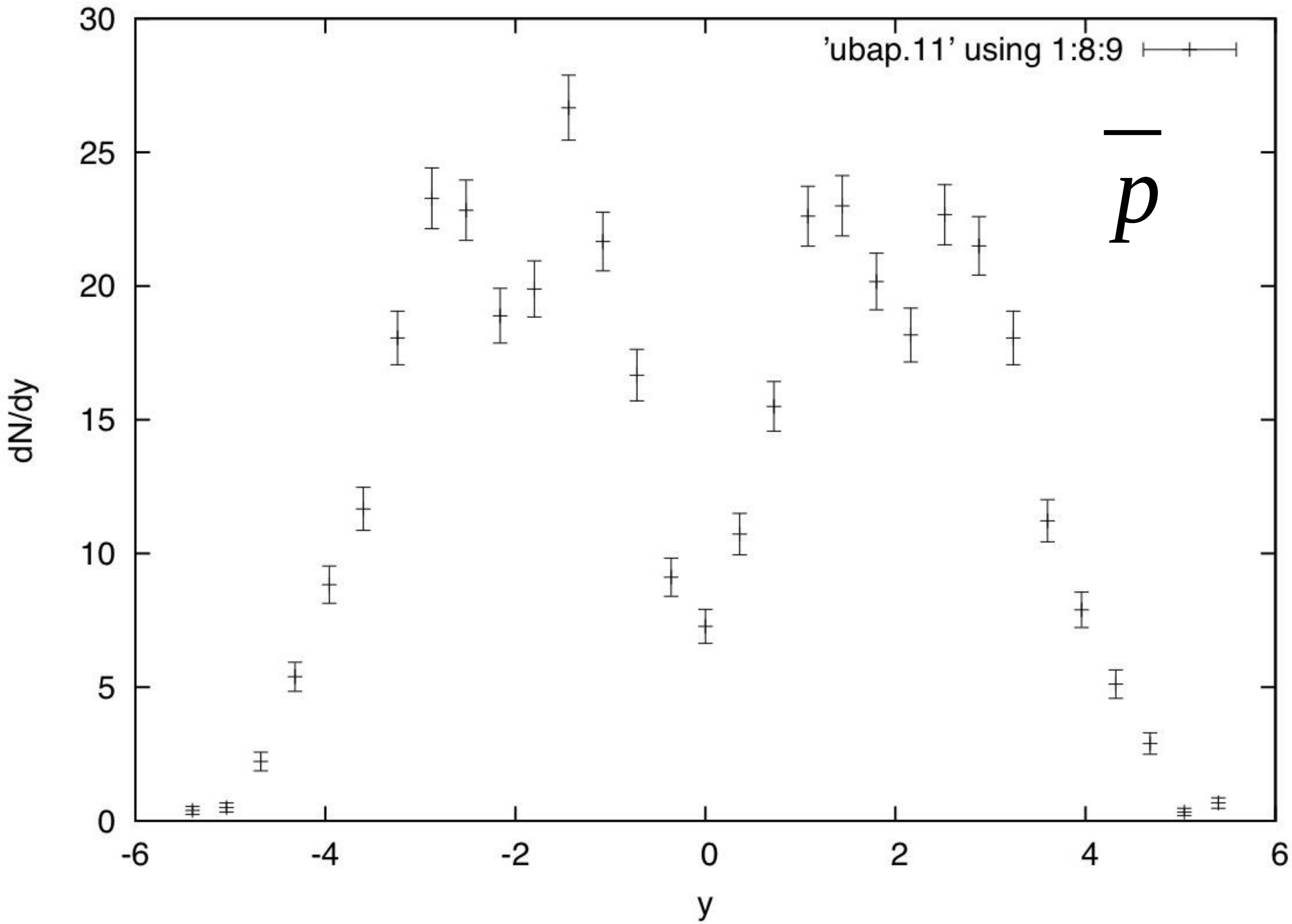

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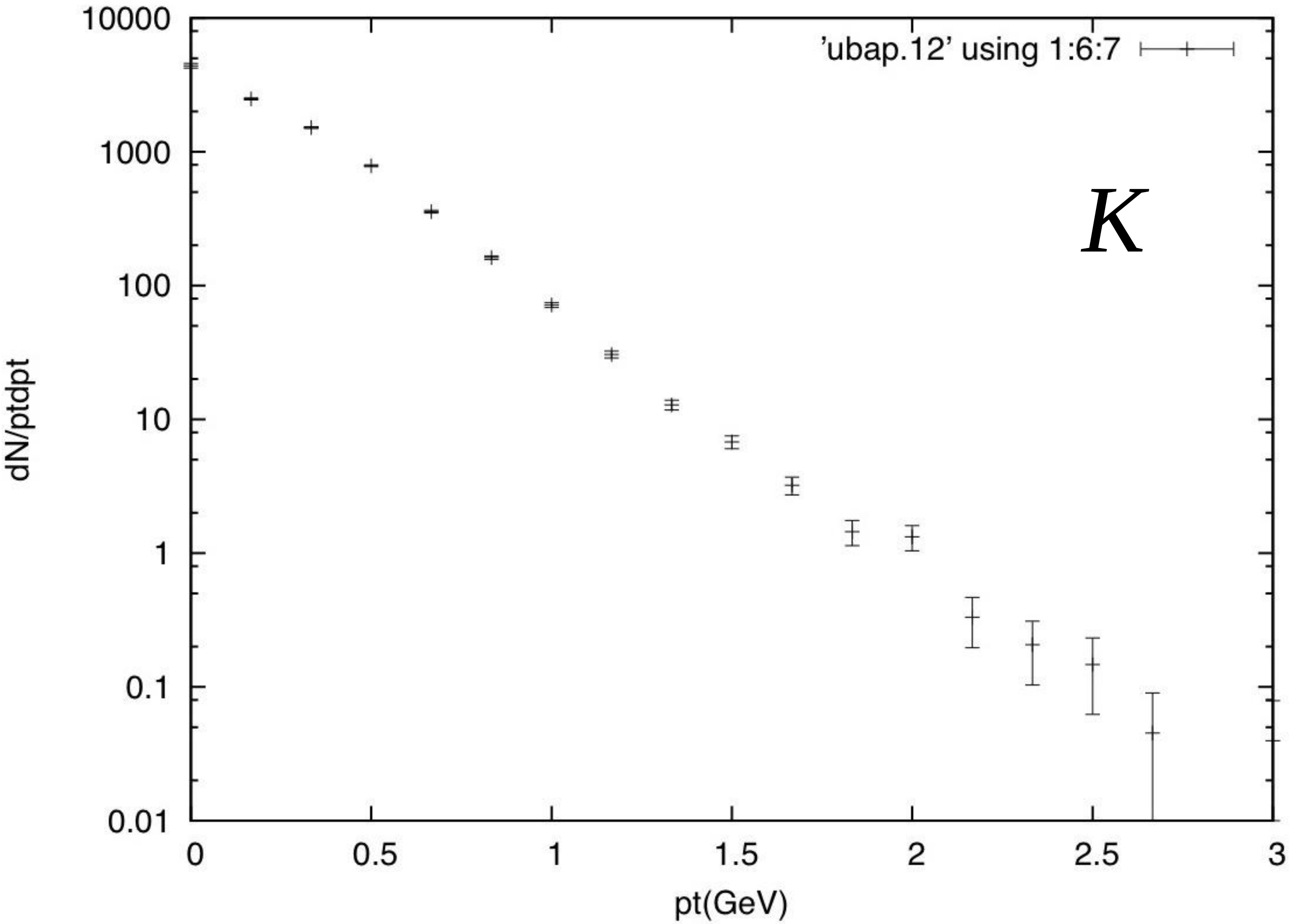

'ubap.12' using 1:6:7
K
dN/ptdpt
pt(GeV)
10000
1000
100
10
1
0.1
0.01
0
0.5
1
1.5
2
2.5
3

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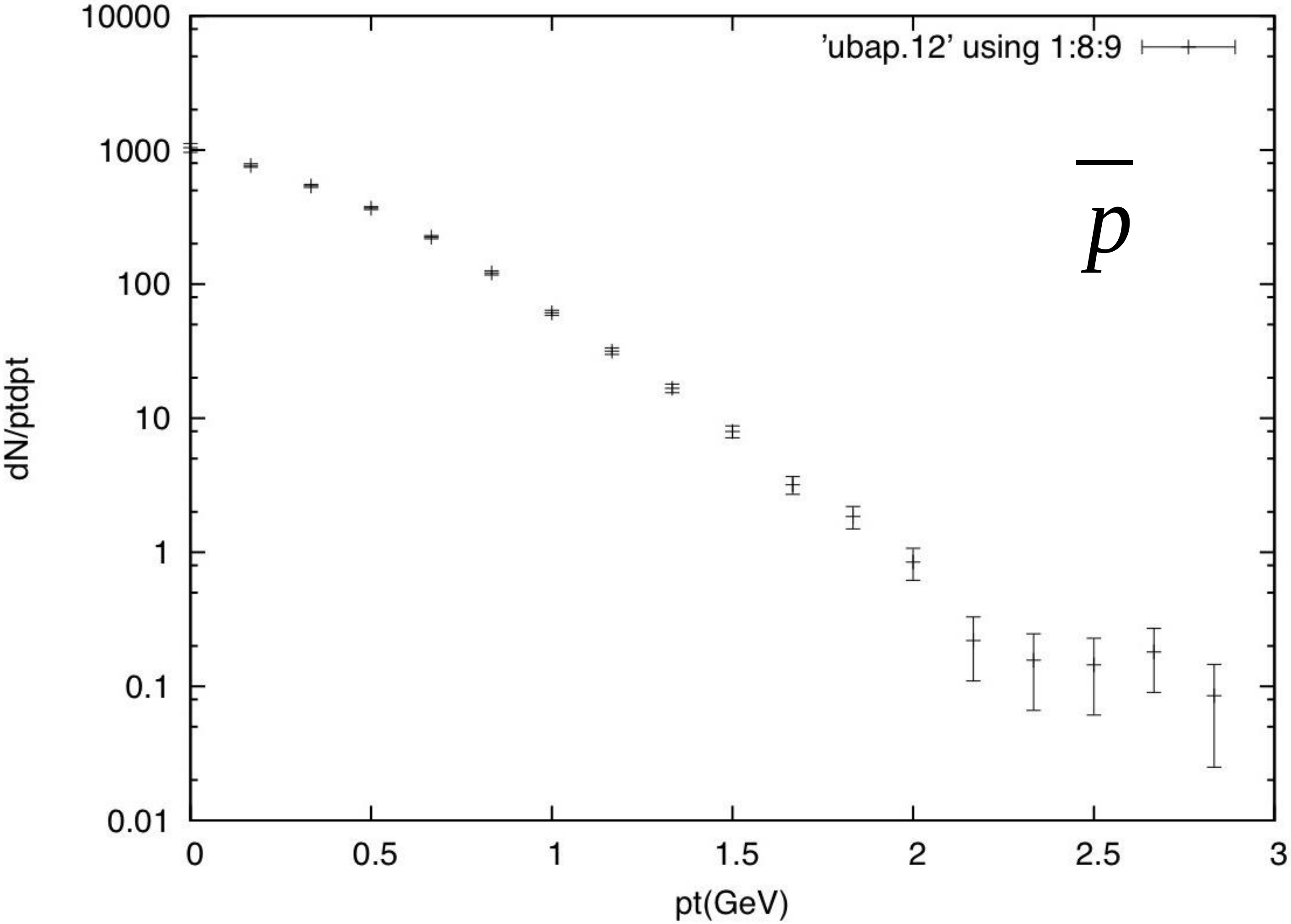

'ubap.12' using 1:8:9
$\bar{p}$
dN/ptdpt
pt(GeV)
10000
1000
100
10
1
0.1
0.01
0
0.5
1
1.5
2
2.5
3

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Statistical Model vs. Recombination

- in the Statistical Model, the hadron distribution at freeze-out is given by:

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

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

$$G^M{}_{ab}=\int d^3k\,\bar{w}_a(k)\left|\bar{\phi}_M(k)\right|^2\bar{w}_b(P-k)$$

$$G^B{}_{abc}=\int d^3k_1 d^3k_2 w_a(k_1)w_b(k_2)\,w_c(P-k_1-k_2)\left|\bar{\phi}_B(k_1,k_2,P-k_1-k_2)\right|^2$$

- If $E_h(P)=E_a(k)+E_b(P-k)$, recombination is identical to SM!

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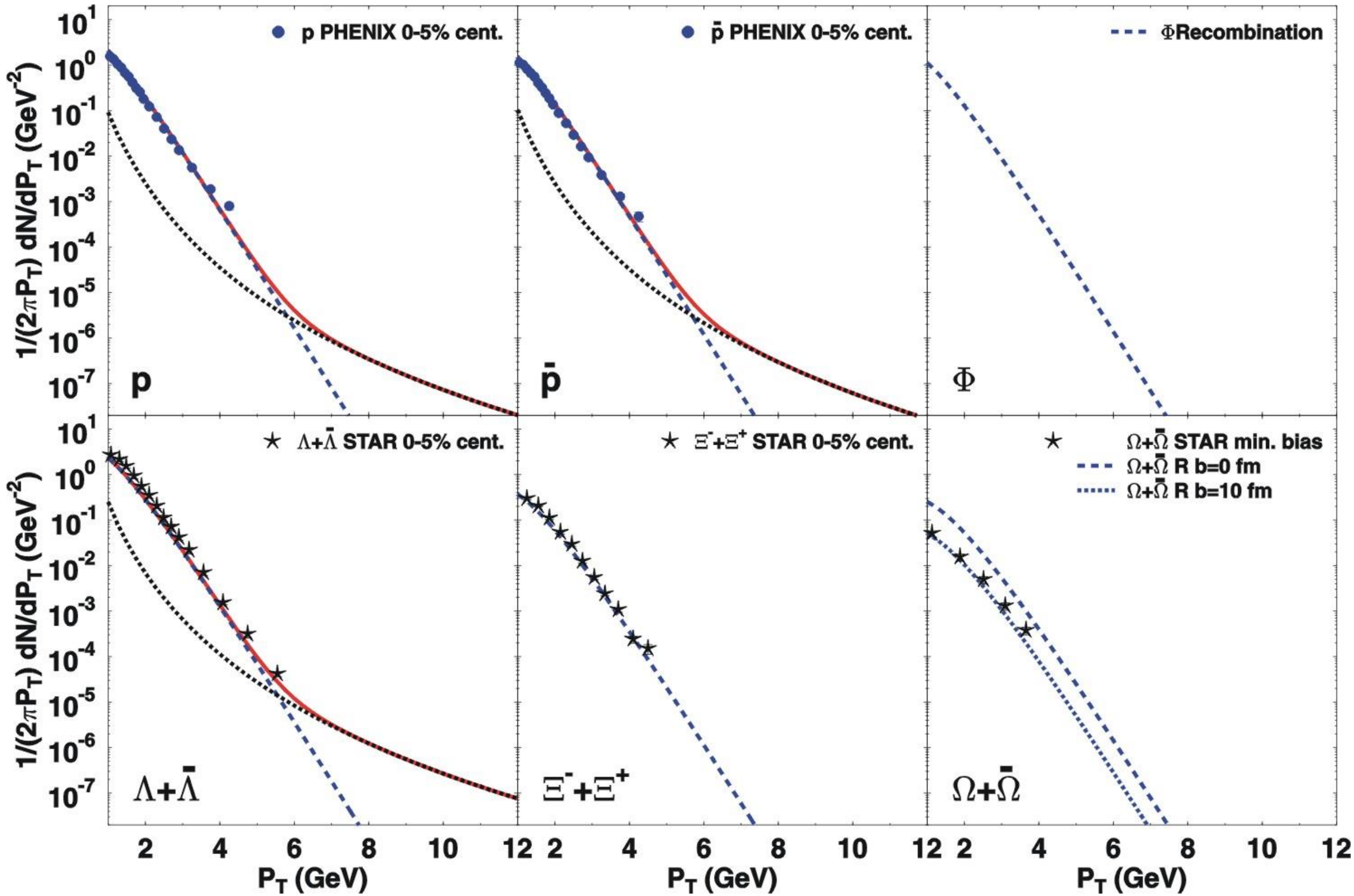
Hadron Spectra II



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Elliptic Flow: partons at low p_t

- azimuthal anisotropy of parton spectra is determined by elliptic flow:

$$\frac{d^2N}{p_t\, dp_t\, d\phi_p} = \frac{1}{2\pi}\left[\frac{dN}{p_t dp_t}\right]\left(1+2v_2\cos\left(2\phi_p\right)\right)$$ (Φ_p: azimuthal angle in p-space)

- with Blastwave parametrization for parton spectra:

$$v_2(p_t) = \left\langle \cos\left(2\phi_p\right)\right\rangle = \frac{\int_0^{2\pi} d\phi_s \cos\left(2\phi_s\right) I_2\left(\frac{p_t \sinh\left(\rho\left(\phi_s\right)\right)}{T}\right) K_1\left(\frac{m_t \cosh\left(\rho\left(\phi_s\right)\right)}{T}\right)}{\int_0^{2\pi} d\phi_s\, I_0\left(\frac{p_t \sinh\left(\rho\left(\phi_s\right)\right)}{T}\right) K_1\left(\frac{m_t \cosh\left(\rho\left(\phi_s\right)\right)}{T}\right)}$$

- azimuthal anisotropy is parameterized in coordinate space and is damped as a function of p_t:

$$\rho\left(\phi_s\right) = \frac{1}{2}\ln\left(\frac{1+\beta_t}{1-\beta_t}\right)\left(1+\alpha_p\left(p_t\right)\cos\left(2\phi_s\right)\right) \quad \text{and} \quad \alpha_p\left(p_t\right) = -\alpha_0 \frac{1}{1+\left(p_t/p_0\right)^2}$$

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Recombination: relativistic formalism

- choose a hypersurface Σ for hadronization
- use local light cone coordinates (hadron defining the + axis)
- $w_a(r,p)$: single particle Wigner function for quarks at hadronization
- Φ_M & Φ_B: light-cone wave-functions for the meson & baryon respectively
- x, x′ & (1-x): momentum fractions carried by the quarks
- integrating out transverse degrees of freedom yields:

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

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