Fragmentation via shower parton recombination

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- ☐ Quarkonia production (Taesoo Song)

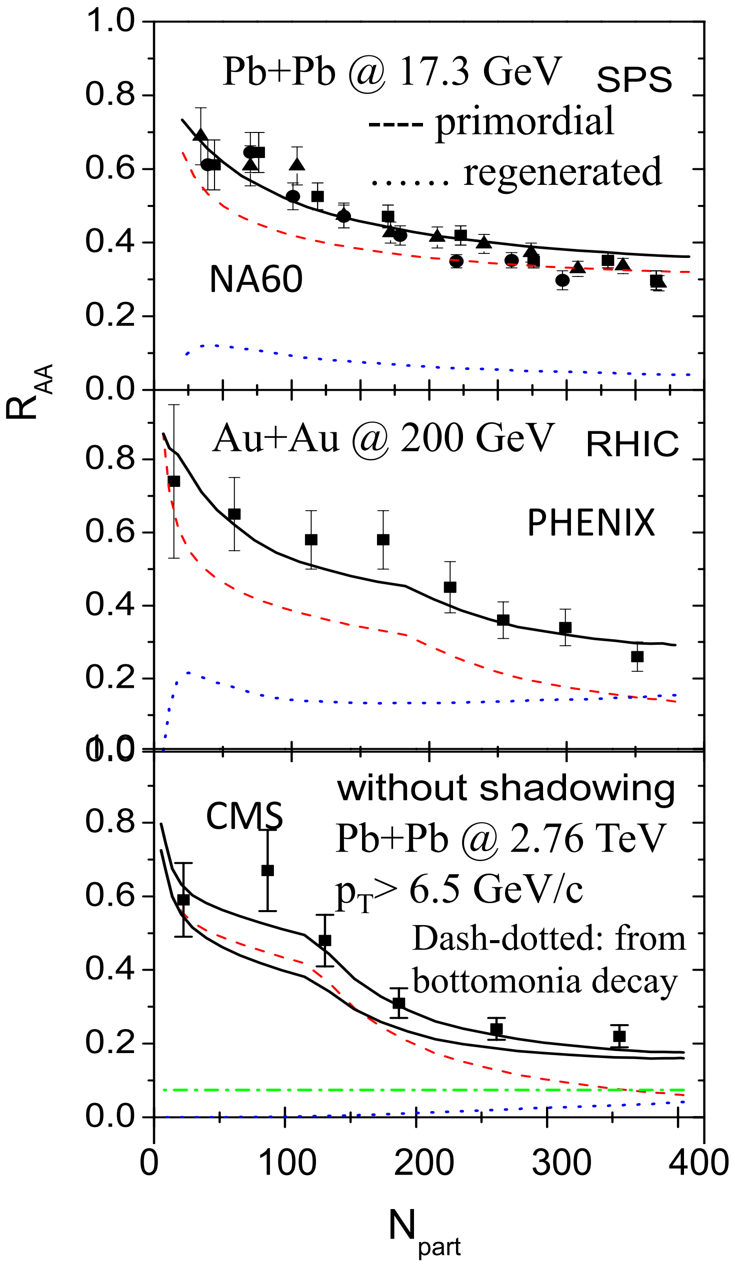
- ☐ Jet fragmentation
- ☐ Jet shower partons
- ☐ Shower parton recombination in vacuum
- ☐ Shower parton recombination in medium

In collaboration with Kyongchol Han and Rainer Fries as apart of JET

Supported by Department of Energy and the Welch Foundation

Nuclear modification factor for J/ψ

Song, Han & Ko, PRC 84, 034907 (2011)

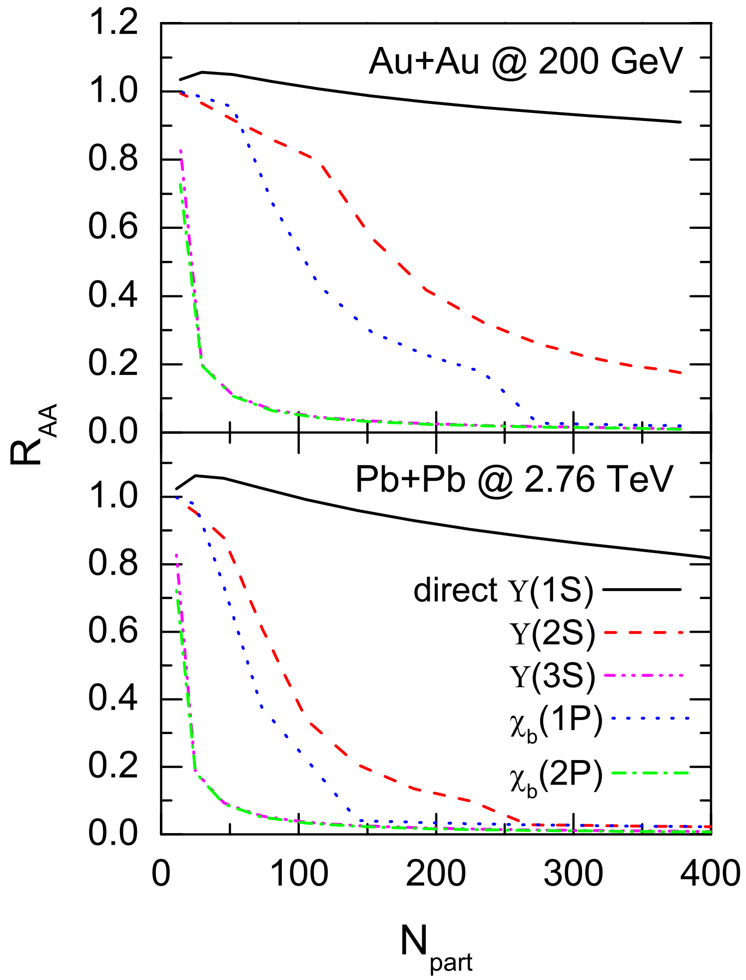


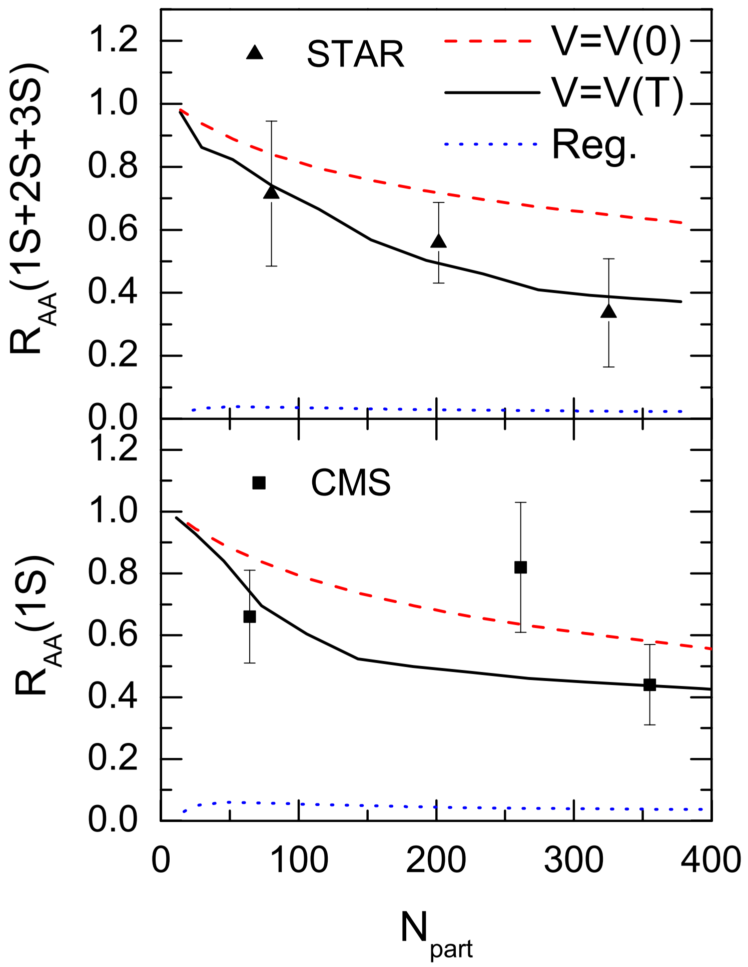
- Potential: Screened Cornel potential
- Dissociation: NLO perturbative QCD with massive thermal partons
- Dynamics: 2+1 ideal hydro
- Relaxation effect
- Formation time as parameter

- Most J/ψ are survivors from initially produced.
- Kink in R_{AA} is due to the onset of initial temperature above the J/ψ dissociation temperature in QGP.
- Inclusion of shadowing reduces slightly R_{AA}. Upper and lower solid lines for LHC are for nuclear absorption cross section of 0 and 2.8 mb.

Nuclear modification factor for ϒ(1S)

Song, Han & Ko, PRC 85, 014902 (2012)

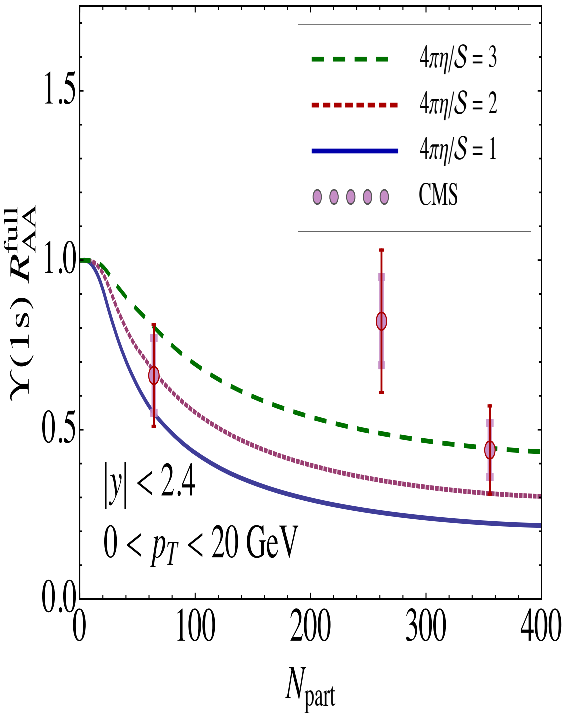




- Regeneration contribution is negligible
- Primordial excited bottomonia are largely dissociated
- Medium effects on bottomonia reduce R_{AA} of ϒ(1S)

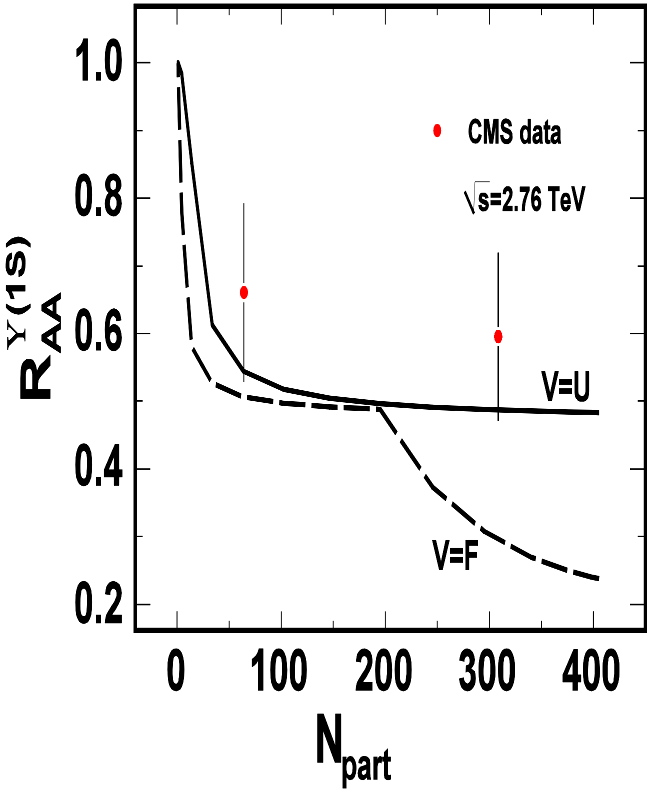
Y(1S) nuclear modification factor at LHC from theoretical models

1) Strickland, PRL 107, 132301 (2011)



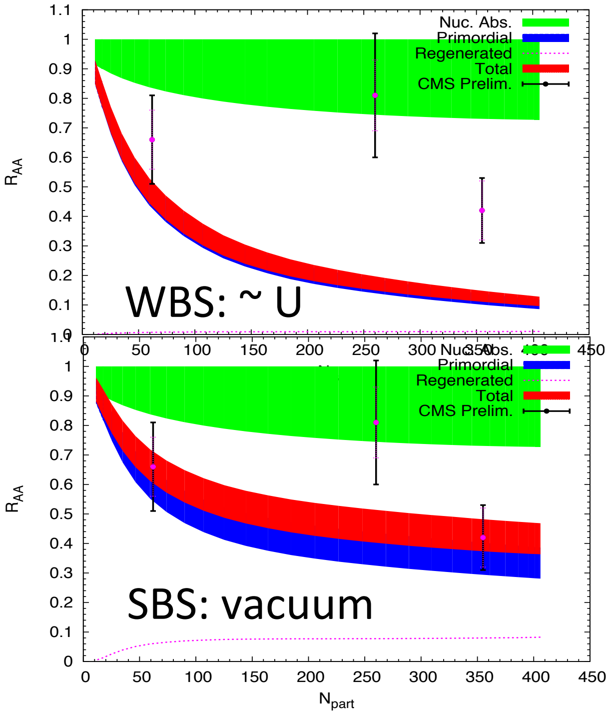
- Potential: in-medium Cornell
- Disso.: LO pQCD
- Dynamics: anisotropic hydro

2) Zhuang et al.,



- Potential: U or F
- Disso.: vacuum LO gluo-disso.
- Dynamics: ideal hydro

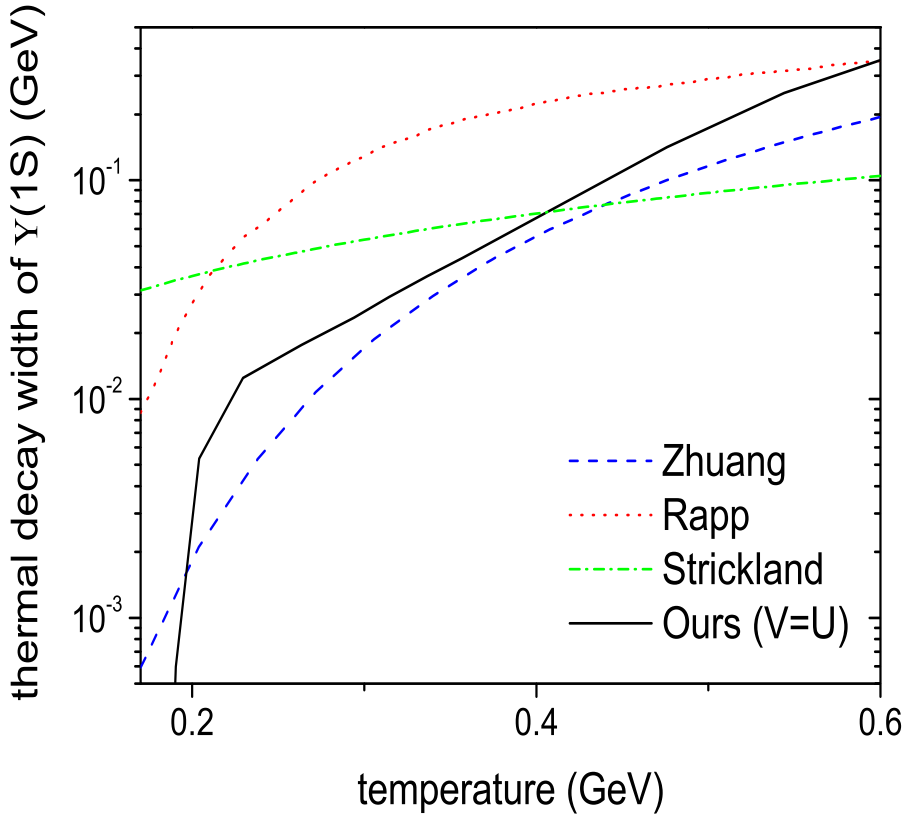
3) Emerick, Zhao & Rapp, EPJA 48, 72 (2012)



- Potential: ~ U or vacuum
- Diss.: quasi-elastic
- Dynamics: fireball

4) Brezinzki & Wolschin, PLB 707, 534 (12): schematic estimate using in-medium LO gluo-dissociation

Thermal decay width of Y(1S) in different models

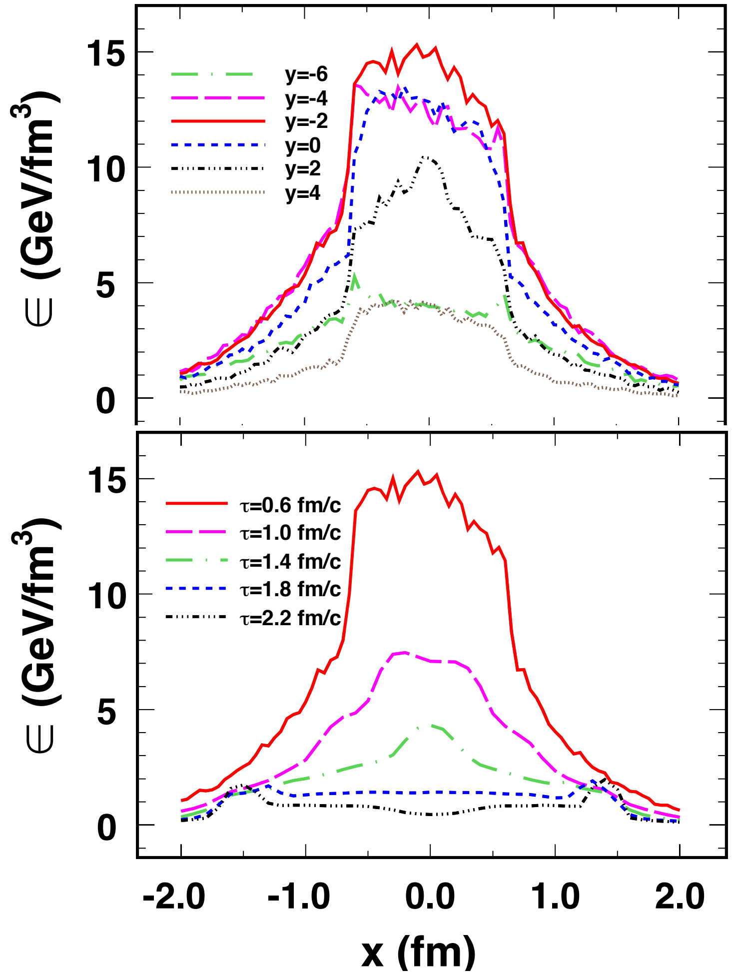


- Thermal decay width
  - Rapp: quasielastic scattering
  - Zhuang: OPE by Peskin
  - Strickland: LO pQCD
  - Song: NLO pQCD with massive thermal partons

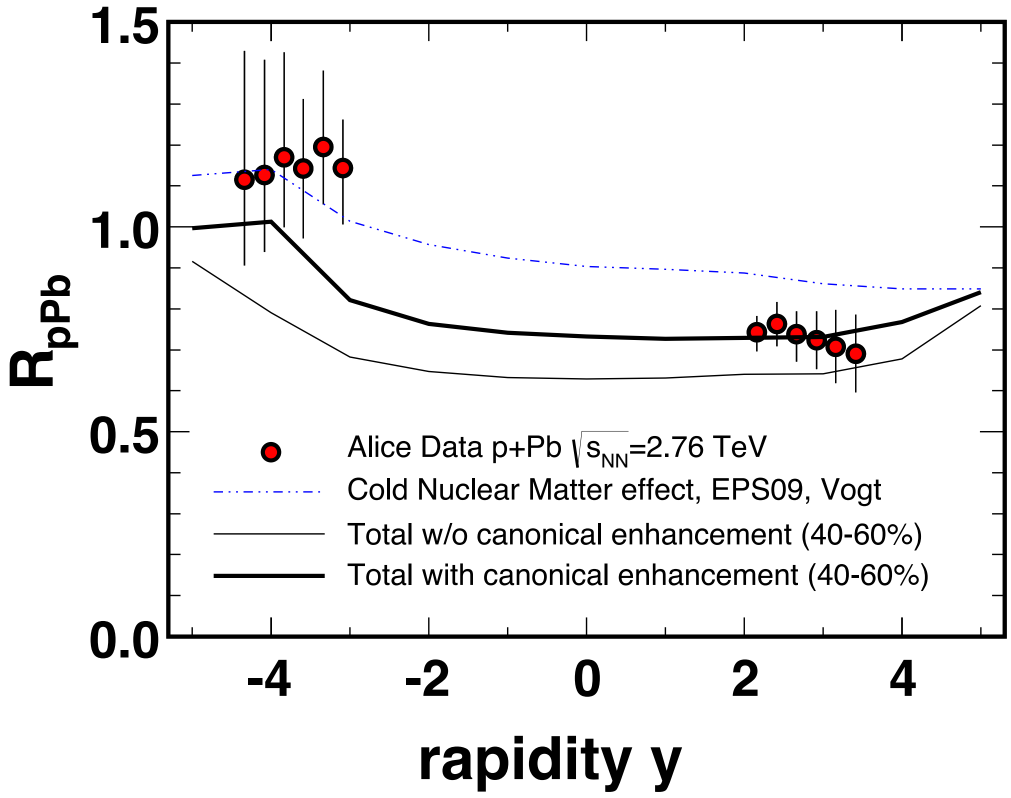
- Very different models are used for calculating thermal decay widths are used.

J/ψ production in p+Pb @ 5.02 TeV

Liu, Song & Ko, PLB 728, 437 (2013)



- Most central 10% collisions from AMPT



- Including hot medium effects better describes data.
- Canonical enhancement

$$N_c^{\rm dir} \quad = \quad \gamma N_D^{\rm th} + (1+1/N_c^{\rm dir})\gamma^2 N_{J/\psi}^{\rm th}$$

Summary on quarkonia production

- J/ψ survives up to 1.7 T_c and Y(1S) survives up to 4 T_c.
- Most observed J/ψ and Y(1S) are from primordially produced; contribution from regeneration is small at present HIC.
- Various models with different assumptions can describe experimental data.
- Elliptic flow of regenerated J/ψ is large, while that of directly produced ones is essentially zero. Studying v_2 of J/ψ is useful for distinguishing the mechanism for J/ψ production in HIC.
- Initial fluctuations affect R_{AA} of bottomonia in peripheral collisions and at low p_T.
- Hot medium effects describe better J/ψ data from p+Pb collisions.

Jet fragmentation

$$\frac{dN}{d^2\mathbf{p}_{\mathrm{had}}} = \sum_{\mathrm{jet}} \int dz \frac{dN}{d^2\mathbf{p}_{\mathrm{jet}}} \frac{D_{\mathrm{had/jet}}(z,Q^2)}{z^2}, \qquad z = \frac{p_{\mathrm{had}}}{p_{\mathrm{jet}}}$$

Q: Momentum scale for hadronization (~ 1 GeV)

- Lund String fragmentation: PYTHIA

$$D = z^{-1}(1-z)^a \exp\left[-\frac{b(m^2+p_T^2)}{z}\right], \qquad \kappa \sim [b(2+a)]^{-1}$$

- Independent fragmentation : KKP, BKK, AKK, ….

  Fragmentation function is obtained empirically from hadron yields in e^++e^- and p+p collisions

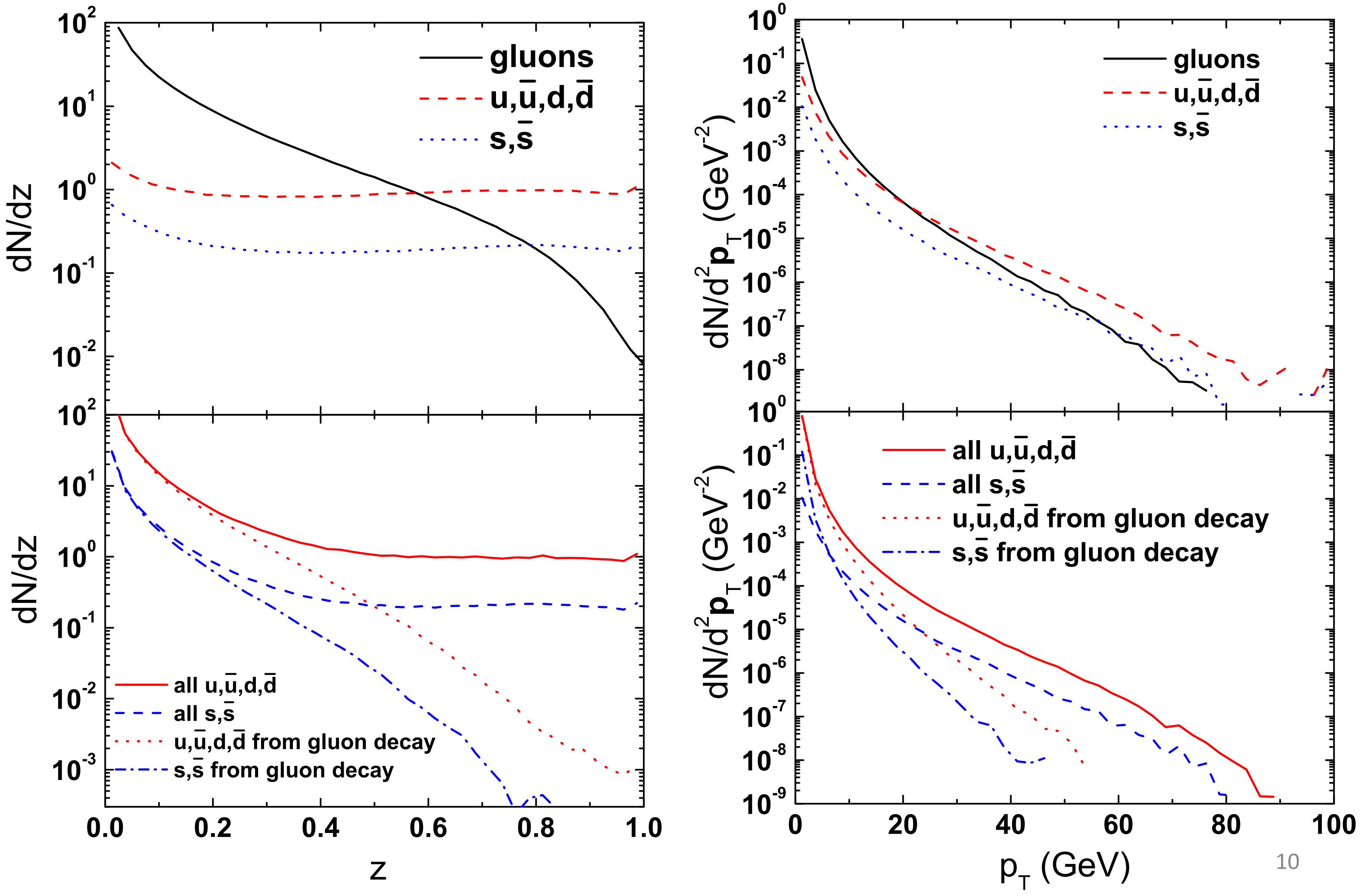
- Cluster fragmentation: HERWIG
- Quark Recombination: Das and Hwa, PLB 68, 459 (1977);
  Hwa and Yang, PRC 67, 034902 (2003): Shower light and strange quark distribution functions from fitting to empirical fragmentation functions.

Jet fragmentation via shower parton recombination

Han, Fries & Ko, PRC 93, 045207 (2016)

- Using PYTHIA to obtain momenta of shower partons from jets produced in e^++e^- collisions.
- Spatial information of shower partons are determined by taking their lifetimes to be inverse of their virtualities and propagating accordingly.
- Final gluons with low virtualities are decayed to quark-antiquak pairs.
- Using quantum Wigner calculation to coalesce shower partons to hadrons in an event by event basis up to hadron excited states with n = 8 harmonic oscillator wave functions.
- Remnant shower partons not used in coalescence are formed into short strings and converted to hadrons by string fragmentation.
- Results reasonably reproduce those from PYTHIA via fragmentation of the entire string.

Longitudinal and transverse momentum spectra of shower partons from $e^+ + e^-$ @ 200 GeV



Quark recombination model for mesons

Greco, Ko & Levai, PRC 68, 034904 (2003)

$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2)$$
$$\times \bar{W}_M(\mathbf{y},\mathbf{k})\delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2)$$

F$_q$(**x**,**p**): quark distribution function $N_{q,\bar{q}} = \int d^3\mathbf{x} d^3\mathbf{p} f_{q,\bar{q}}(\mathbf{x},\mathbf{p})$

Wave-packet convoluted meson Wigner function:

$$\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!}e^{-v}, \quad v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2\sigma_M^2\right)$$
$$\mathbf{y} = \frac{\mathbf{x}_1' - \mathbf{x}_2'}{\sqrt{2}}, \quad \mathbf{k} = \frac{\sqrt{2}}{m_1 + m_2}(m_2\mathbf{p}_1' - m_1\mathbf{p}_2')$$

Primed coordinates and momenta refer to meson rest frame after earlier produced quark is propagated to the time of the later produced.

g$_M$: statistical factor for spin ½ colored quark and antiquark to form a colorless meson; $g_\pi = g_K = 1/36$, $g_\rho = g_{K*} = 1/12$

In quantum Wigner approach, wave functions of particles 1 and 2 are Gaussian wave packets

$$\begin{aligned}\phi_i(x_i'-x_i) &= \frac{1}{(\pi\delta^2)^{1/4}}\exp\left[-\frac{(x_i'-x_i)^2}{2\delta^2}\right]\exp(ik_ix_i') \\ W(x_i',k_i') &= 2e^{-(x_i'-x_i)^2/\delta^2}e^{-\delta^2(k_i'-k_i)^2}\end{aligned}$$

Using harmonic oscillator wave functions for the wave function of formed particle 3

$$\begin{aligned}\Phi_n(x) &= \left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\frac{1}{\sqrt{2^n n!}}H_n(\xi)e^{-\xi^2/2} \\ \xi &= \sqrt{\frac{m\omega}{\hbar}}x, \qquad H_n(\xi) : \text{Hermite polynomials} \\ W_n(\mathbf{x},\mathbf{k}) &= \int d^3\mathbf{y}\phi_n^*\left(\mathbf{x}-\frac{\mathbf{y}}{2}\right)\phi_n\left(\mathbf{x}+\frac{\mathbf{y}}{2}\right)e^{-i\mathbf{k}\cdot\mathbf{y}}\end{aligned}$$

leads to recurrence relations for the overlap integrals of Wigner functions

$$\overline{W}_n(\mathbf{y},\mathbf{k}) = \int\frac{d^3\mathbf{x}_1'd^3\mathbf{k}_1'}{(2\pi)^3}\frac{d^3\mathbf{x}_2'd^3\mathbf{k}_2'}{(2\pi)^3}W_1(\mathbf{x}_1',\mathbf{k}_1')W_2(\mathbf{x}_2',\mathbf{k}_2')W_n(\mathbf{y}',\mathbf{k}')$$

$$\begin{aligned}
\overline{W}_{n+5} &= -\frac{1}{\Lambda_5}(\Lambda_4\overline{W}_{n+4} + \Lambda_3\overline{W}_{n+3} + \Lambda_2\overline{W}_{n+2} + \Lambda_1\overline{W}_{n+1} + \Lambda_0\overline{W}_n) \\
\Lambda_0 &= -[(1+\alpha)^2 + n](1-\alpha)^2, \\
\Lambda_1 &= [\alpha(1-\alpha) + 2(x/\sigma)^2 + 2\alpha^2(k\sigma)^2 + n + 1](1-\alpha)^2 x \\
\Lambda_2 &= [(1-\alpha)(\alpha^2 + 4\alpha + 1) - 2(x/\sigma)^2(3\alpha + 1) - 2\alpha(k\sigma)^2(-\alpha^2 + 3\alpha + 2) \\
&\quad -2(n+2)(1+\alpha)^2(1-\alpha)](1-\alpha), \\
\Lambda_3 &= [\alpha(1-\alpha)^2 + 2(x/\sigma)^2(3\alpha^2 - 2\alpha - 1) + 2\alpha(k\sigma)^2(\alpha^3 - 3\alpha^2 + 9\alpha - 7) \\
&\quad -2(n+3)(1+\alpha)^2(1-\alpha)^2], \\
\Lambda_4 &= [2(x/\sigma)^2 + 2\alpha^2(k\sigma)^2 - (n+4)(1-\alpha)^2](1+\alpha)^2, \\
\Lambda_5 &= -(n+5)(1+\alpha)^2, \qquad \alpha = 2\delta^2/\sigma^2, \quad \sigma = \sqrt{\frac{\hbar}{m\omega}}
\end{aligned}$$

In the special case of α=1

$$\begin{aligned}
\overline{W}_{n+1} &= \frac{v}{n+1}\overline{W}_n, \qquad v = \frac{1}{2}\left(\frac{x^2}{\sigma^2} + k^2\sigma^2\right) \\
\overline{W}_0 &= \exp(-v), \qquad \overline{W}_n = \frac{v^n}{n!}e^{-v}
\end{aligned}$$

Quark recombination model for baryons

Greco, Ko & Levai, PRL 90, 202302 (2003)

$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3)$$
$$\times \bar{W}_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2)\delta^{(3)}(\mathbf{P}_B-\mathbf{p}_1-\mathbf{p}_2-\mathbf{p}_3)$$

Wave-packet convoluted baryon Wigner function

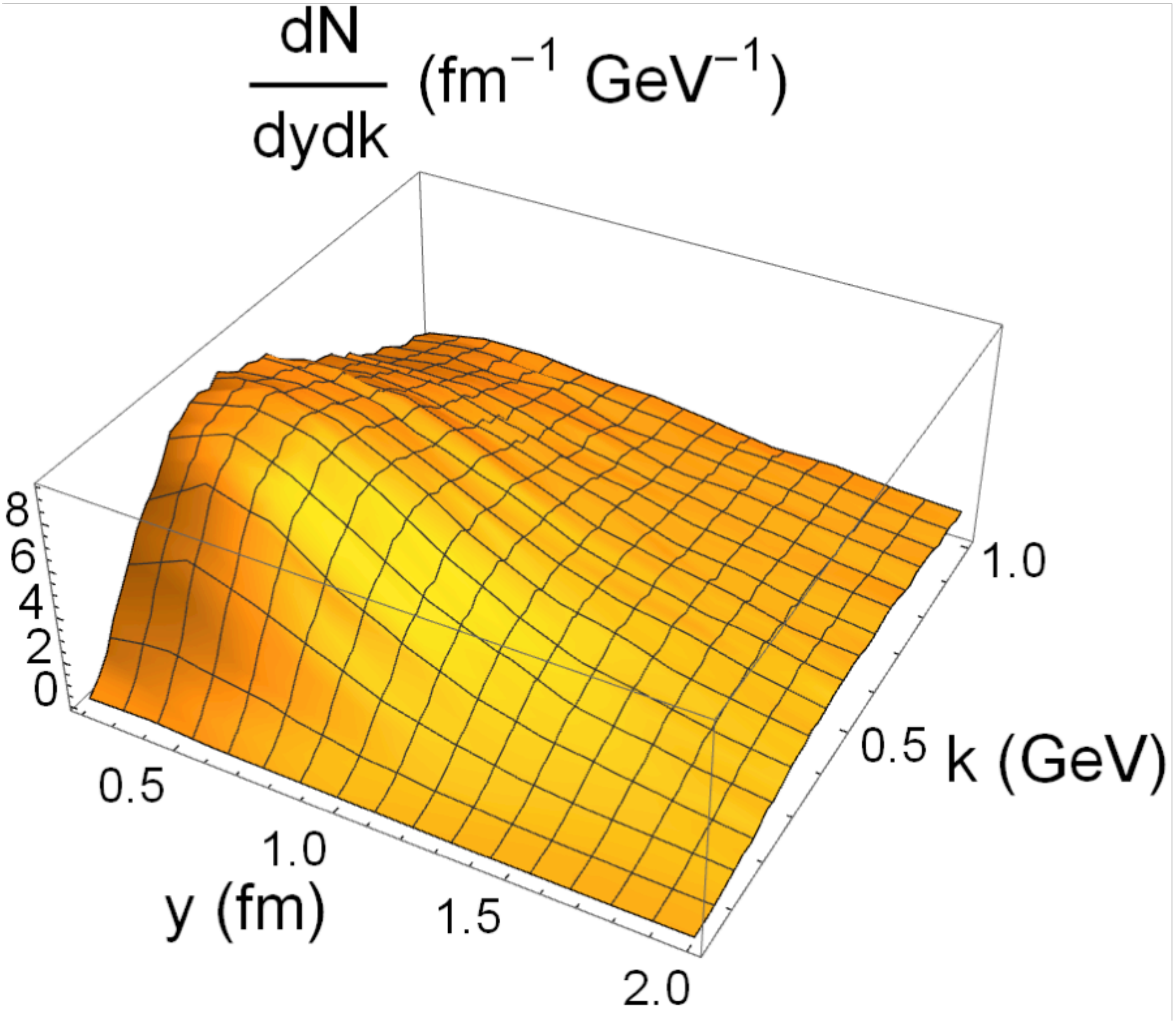
$$\overline{W}_{B,n_1,n_2}(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) = \frac{v_1^{n_1}}{n_1!}e^{-v_1}\cdot\frac{v_2^{n_2}}{n_2!}e^{-v_2},\ \ v_i = \frac{1}{2}\left(\frac{\mathbf{y}_i^2}{\sigma_{Bi}^2} + \mathbf{k}_i^2\sigma_{B_i^2}\right),\ \ i = 1,2.$$

$$\mathbf{y}_1 = \frac{\mathbf{x}_1'-\mathbf{x}_2'}{\sqrt{2}},\quad \mathbf{y}_2 = \frac{\mathbf{x}_1'+\mathbf{x}_2'-2\mathbf{x}_3'}{\sqrt{6}},\quad \mathbf{k}_1 = \frac{\mathbf{p}_1'-\mathbf{p}_2'}{\sqrt{2}},\quad \mathbf{k}_2 = \frac{\mathbf{p}_1'+\mathbf{p}_2'-2\mathbf{p}_3'}{\sqrt{6}}$$

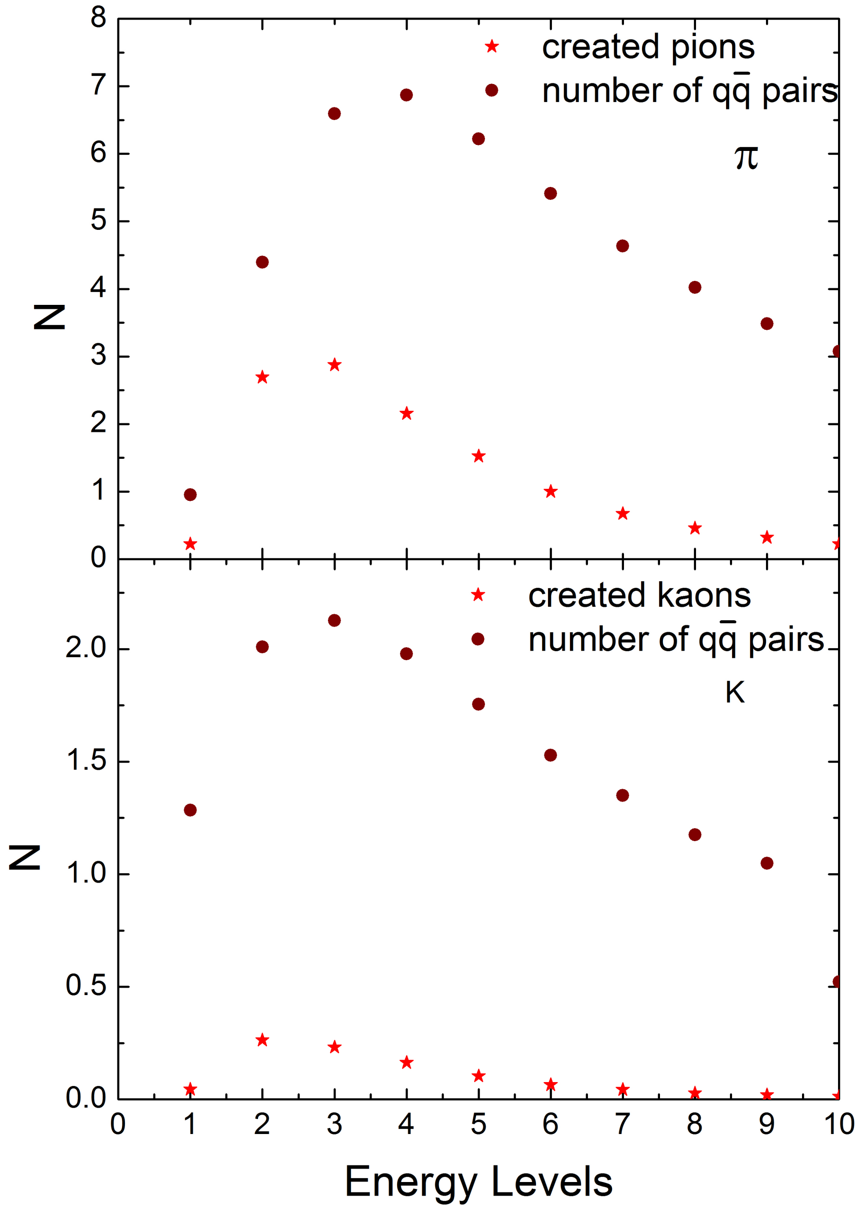
Primed coordinates and momenta refer to baryon rest frame after earlier produced quarks are propagated to the time of the latest produced one.

g_B: statistical factor for 3 spin ½ colored quarks or antiquarks to form a colorless baryon or antibaryon; g_N=1/108, g_Δ=1/54

Relative spatial and momentum distributions of shower parton pairs

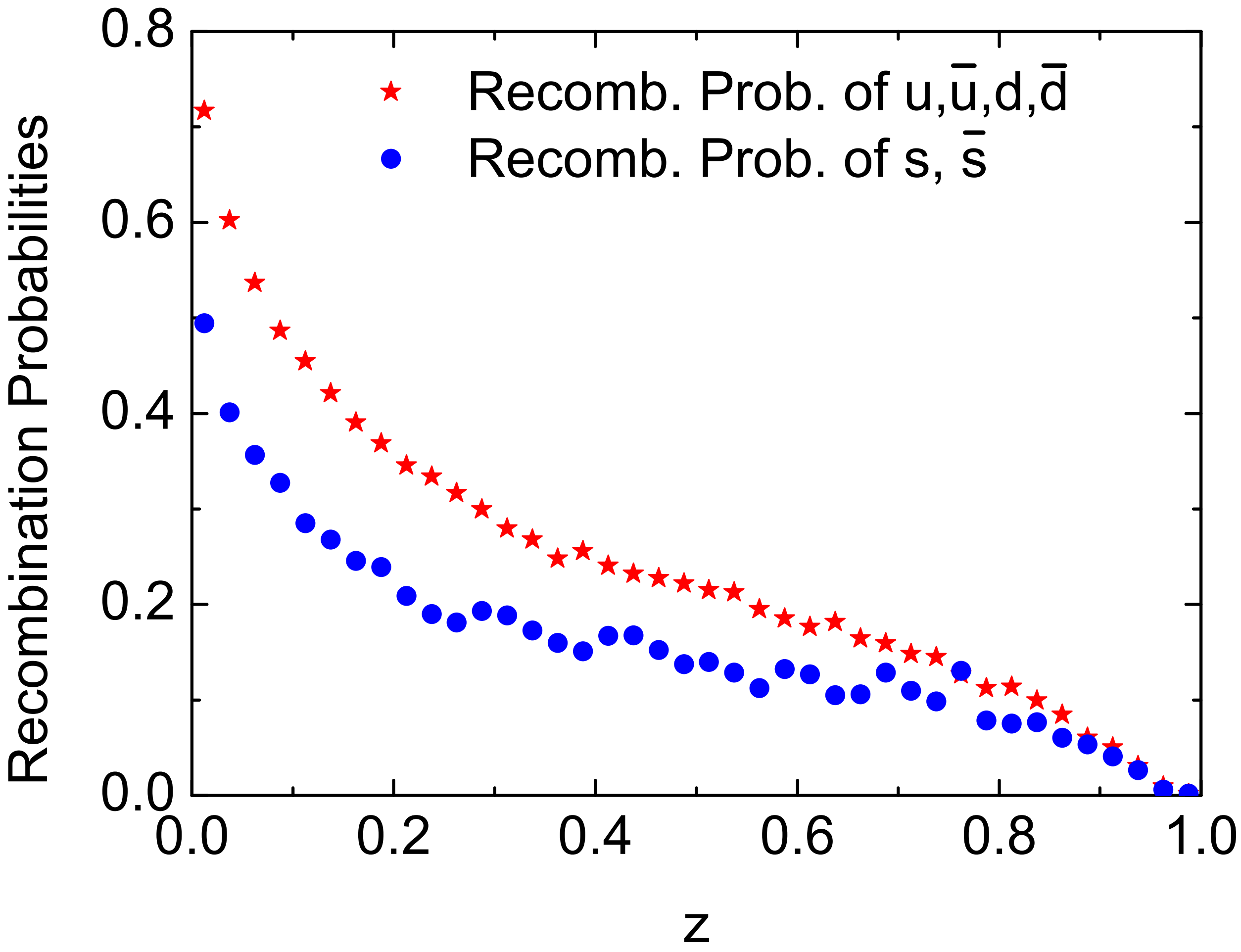


Mesonic state distribution of quark-antiquark pairs



- Quark-antiquark pair relative momentum peaks at values corresponding to that of third (n=4) mesonic excited states
- Pions are mostly produced from decays of first (n=2) and second (n=3) mesonic excited states
- Kaons are mostly produced from excited states of strange mesons

Remnant partons and short string fragmentation



- Coalescence probabilities are close to one for small momentum fraction but decrease quickly with increasing momentum fraction.
- Remnant partons are ordered as quark-antiquark pairs, which form short strings and are converted to hadrons by string fragmentation.

Decay of excited states

- Pion

  - n = 1: Rho meson decay to two pions
  - n ≥ 2: Excited mesons decay to k pions with relative probability

$$M_k(M) = C \left[\frac{1}{6\pi^2} \left(\frac{M}{m_\pi} \right)^3 \right]^n \frac{(4k-4)!(2k-1)!}{(2k-1)!^2 (3k-4)!}$$

- Kaon

  - n = 1: K^* decay to kaon and pion
  - n ≥ 2: Excited strange mesons decay to kaon and pions

- Nucleon

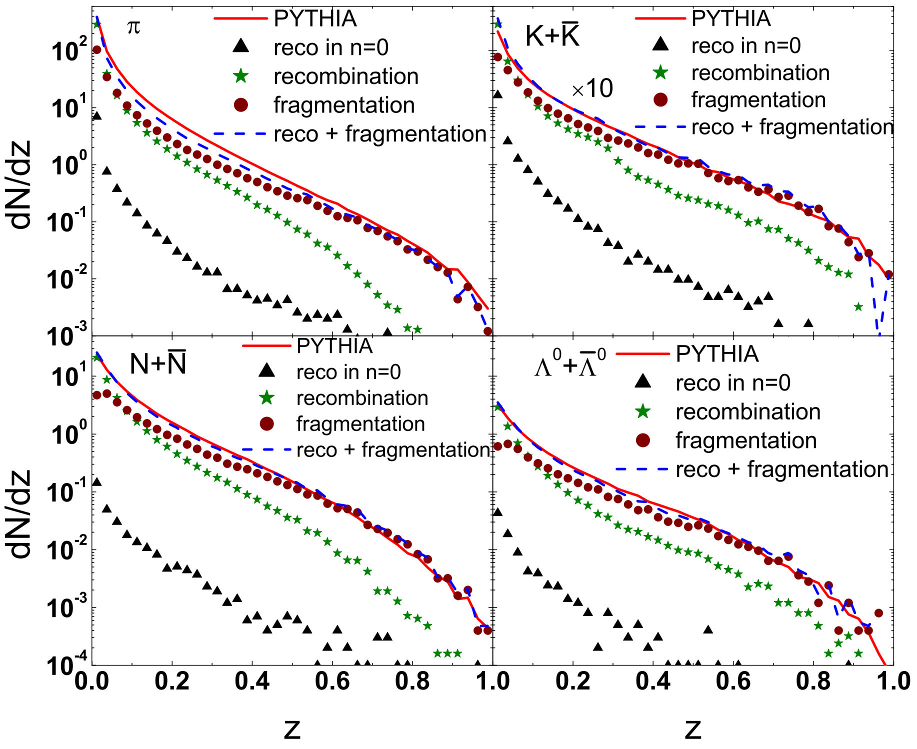
  - n = m = 1: Delta decay to nucleon and pion
  - n+m>2: Excited baryons decay to nucleon and pions

- Lambda

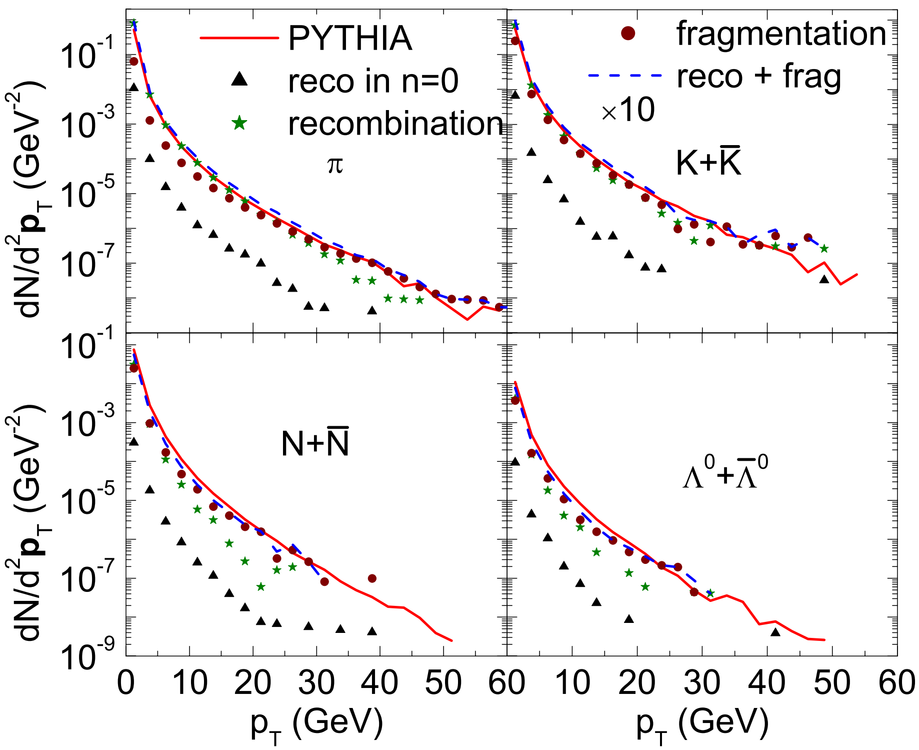
  - n = m = 1: Decay to Lambda and pion
  - n+m>2: Decay to Lambda and pions

Longitudinal and transverse momentum spectra for E_{jet} = 100 GeV

Longitudinal momentum fraction



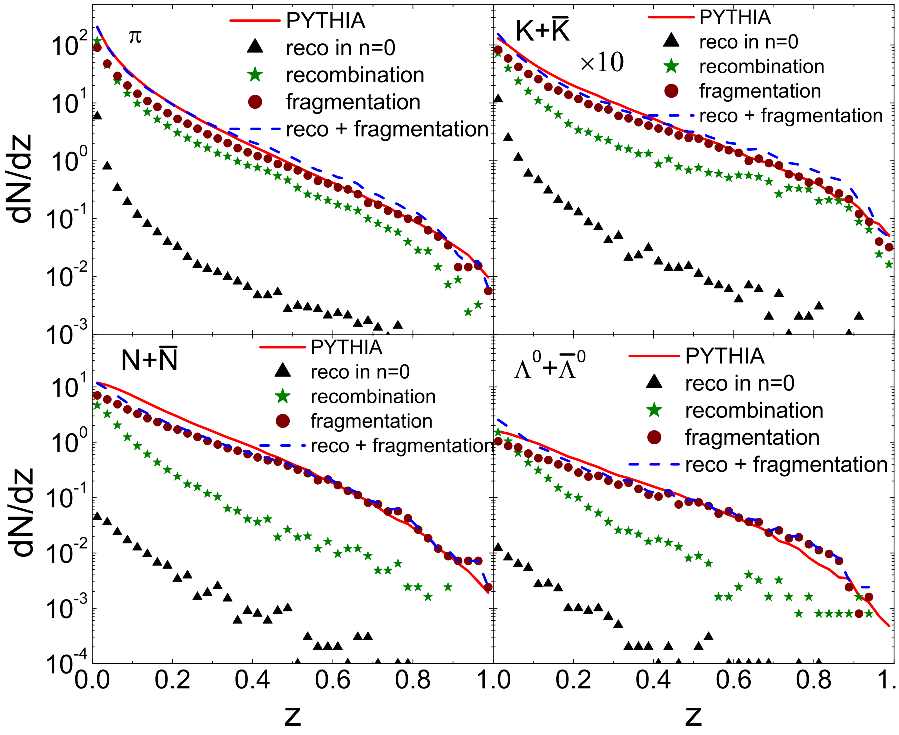
Transverse momentum



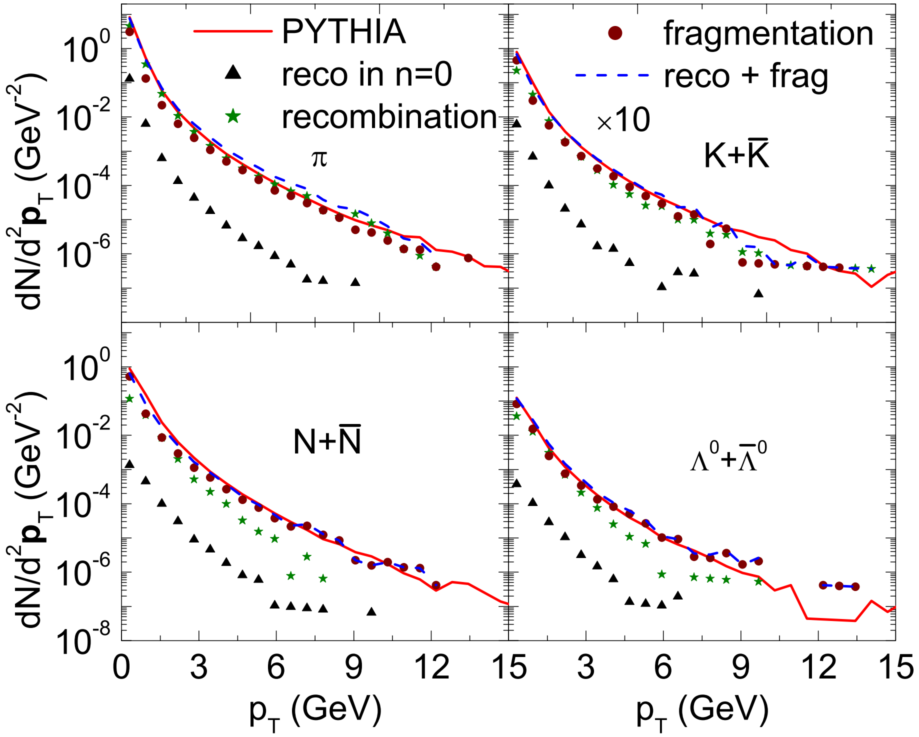
- Recombination contribution is dominated by excited states.
- Contribution from remnant short strings dominates at large z and p_T.

Longitudinal and transverse momentum spectra for E_{jet} = 25 GeV

Longitudinal momentum fraction



Transverse momentum



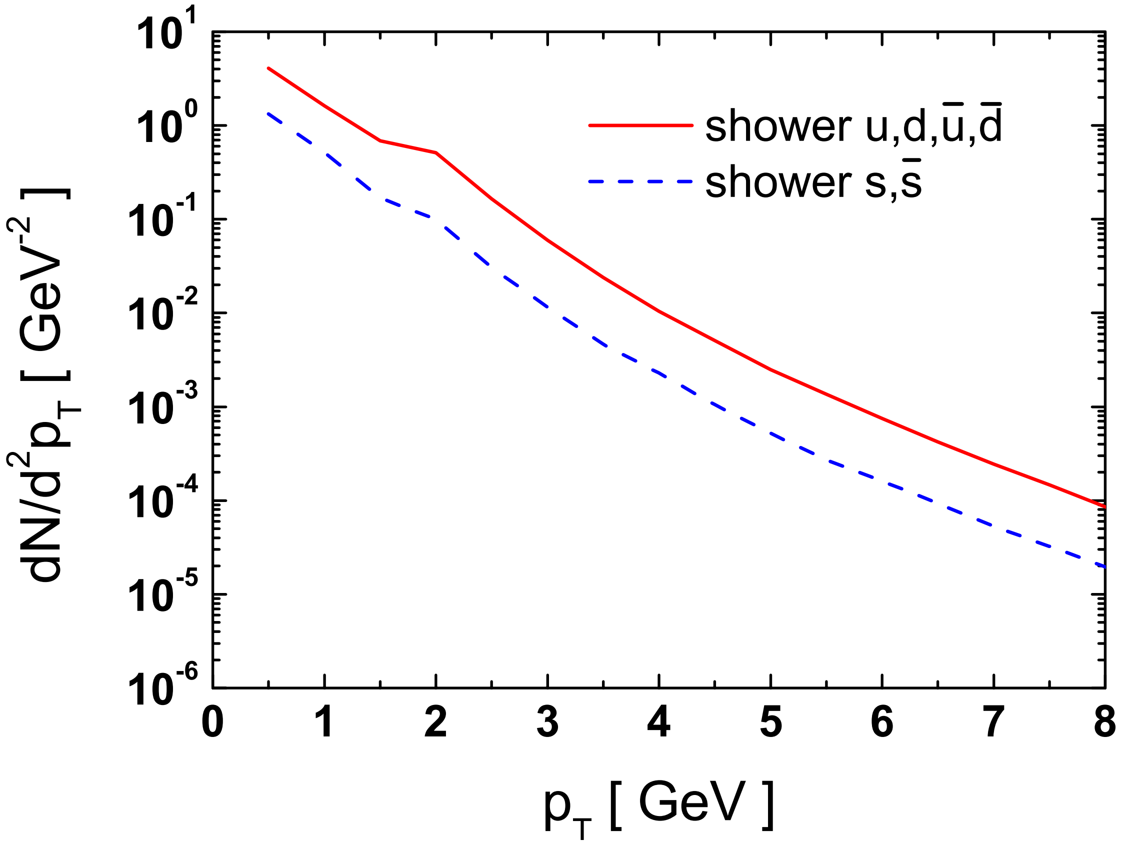
- Recombination contribution is dominated by excited states.
- Contribution from remnant short strings dominates at large z and p_T.

Shower parton from queched jets in Au+Au @ 200 GeV

Quenched jets in Au+Au @ 200GeV

$$\frac{dN_{\rm jet}}{d^2\mathbf{p}_T} = A\Big(\frac{B}{B+p_T}\Big)^n$$

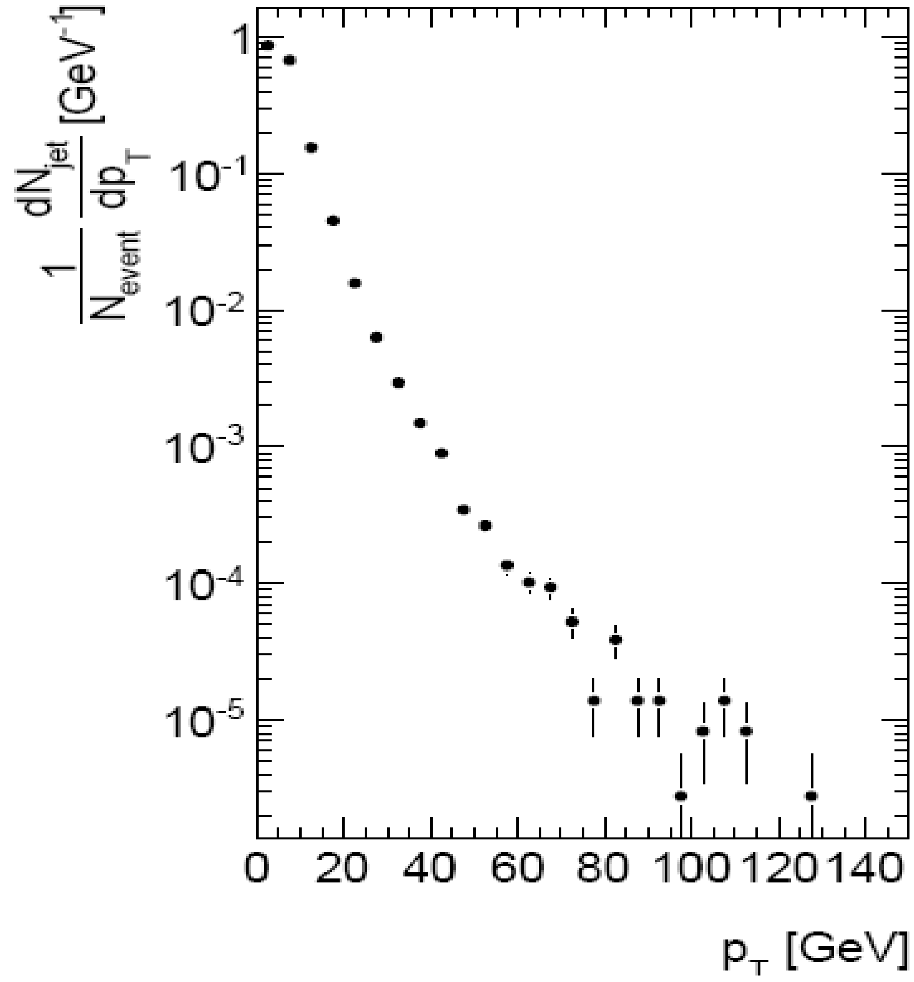
	A[1/GeV^2]	B[GeV]	n
g	3.2×10^4	0.5	7.1
u,d	9.8×10^3	0.5	6.8
$\bar{u}, \bar{d}$	1.9×10^4	0.5	7.5
s,$\bar{s}$	6.5×10^3	0.5	7.4



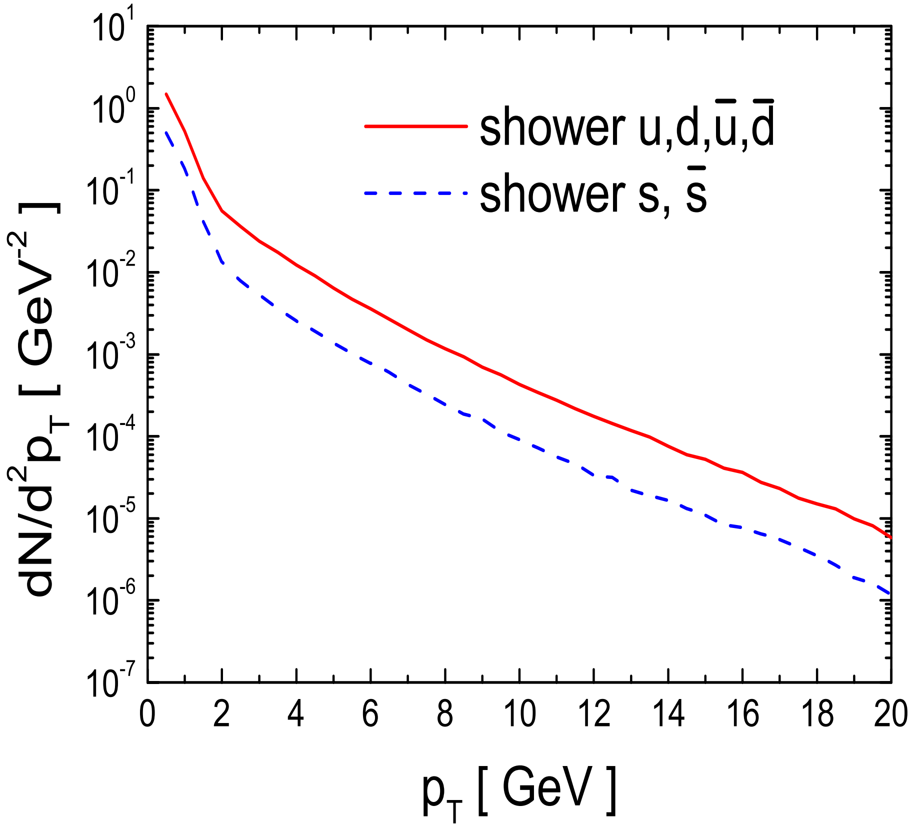
Shower partons from jets in Pb+Pb @ 2.76 TeV

A. Angerami, arXiv:1208.5043

HIJING plus energy loss



$$\Delta E = C \int d\tau \tau^{\beta} \rho(\mathbf{r} + \tau \mathbf{e})$$



Thermal partons from an expanding QGP

Thermal partons modeled by an expanding fireball

$$\frac{dN_{q,\bar{q}}}{d^2\mathbf{r}_T d^2\mathbf{p}_T} = \frac{g_{q,\bar{q}}\tau m_T}{(2\pi)^3} \exp\Big(-\frac{\gamma_T(m_T - \mathbf{p}_T\cdot\mathbf{v}_T) \mp \mu_b}{T}\Big)$$

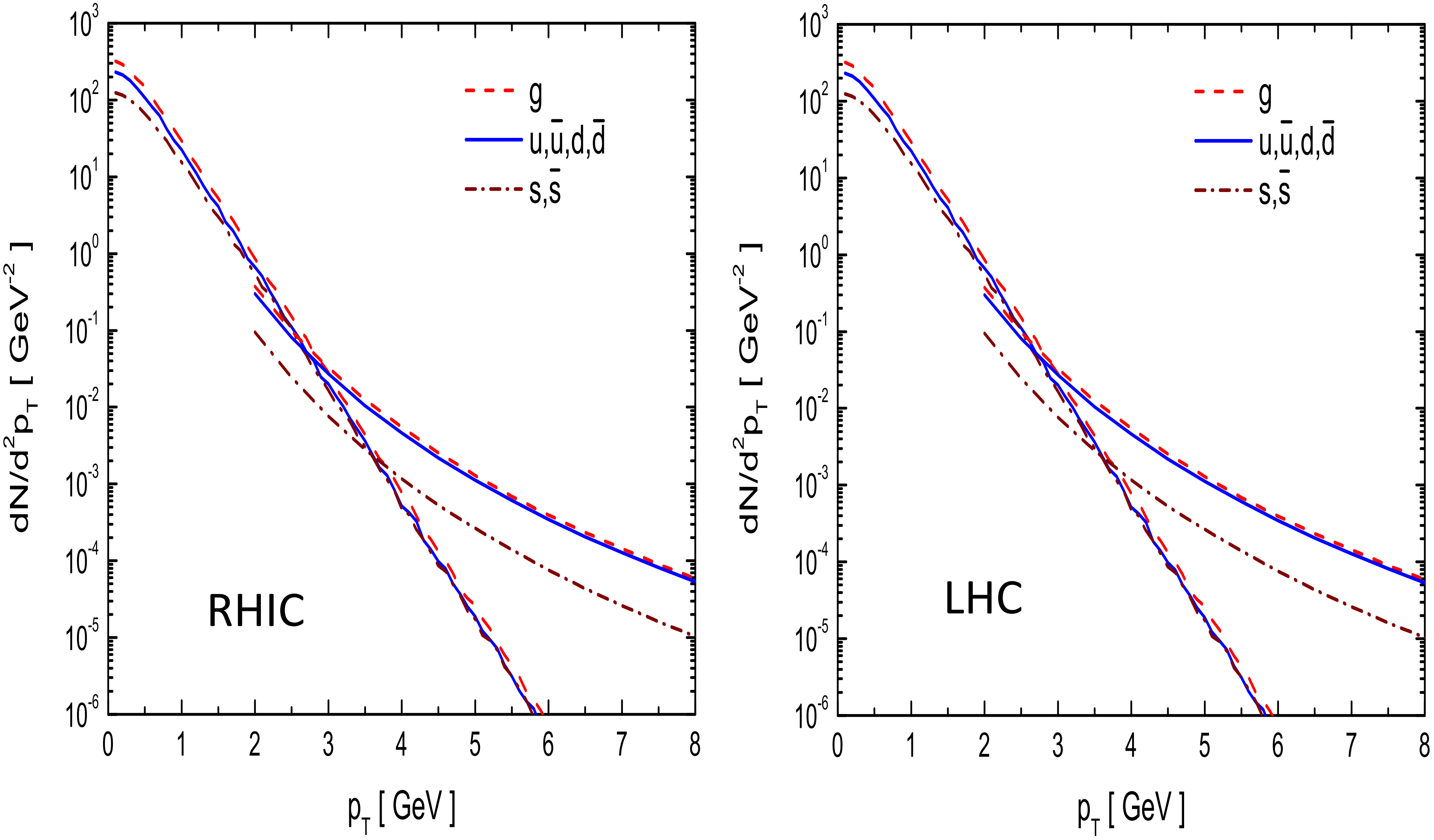
Isotropic in transverse plane and boost invariant longitudinally

RHIC: Au+Au @ 200 GeV

LHC: Pb+Pb @ 2.76 TeV

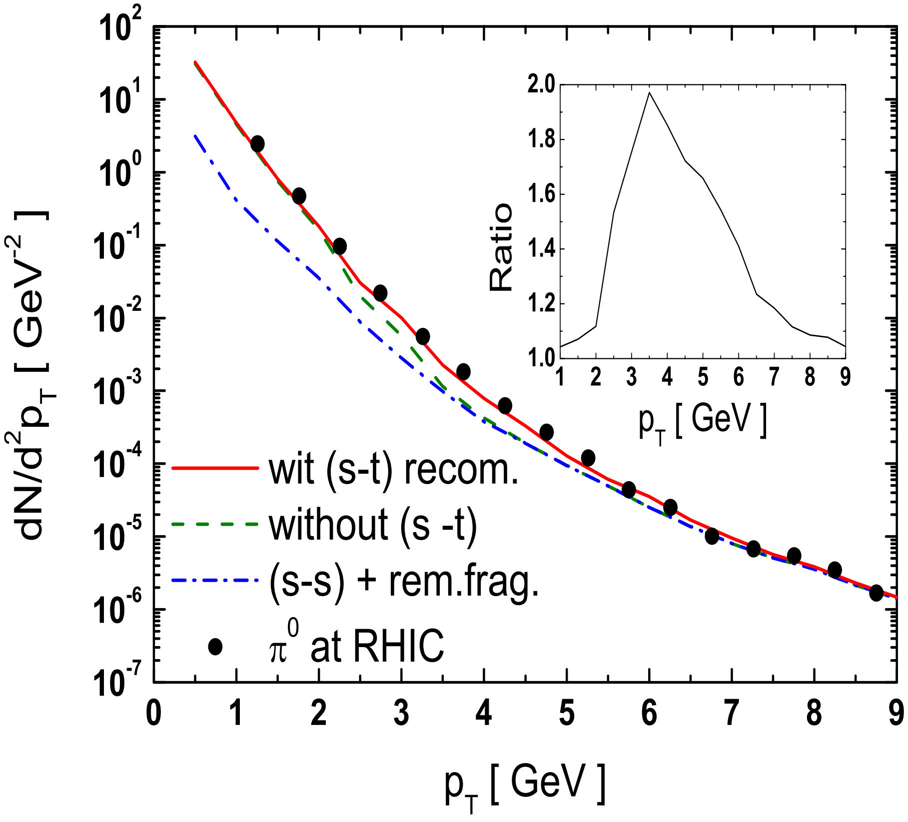
	RHIC	LHC
$R_\perp$ (fm)	8.3	12
τ (fm/c)	4	6
β (c)	0.5	0.65
μ_B (MeV)	10	0
T (MeV)	170	170

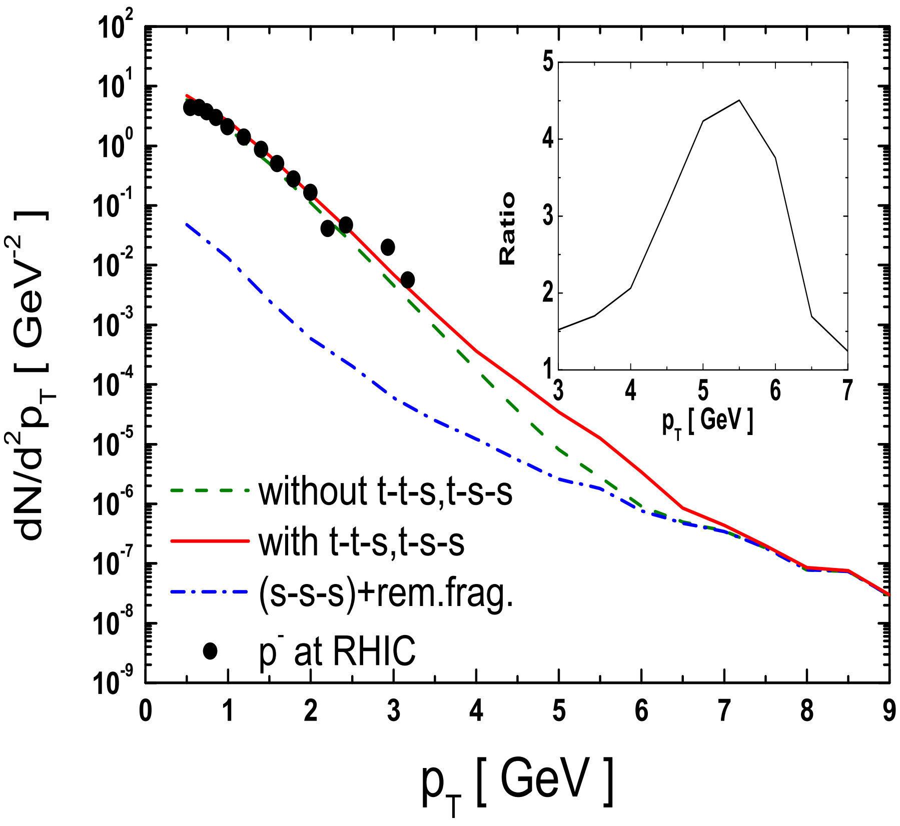
Shower and thermal partons in HIC



- Thermal partons below and shower partons above 2.5-3 GeV

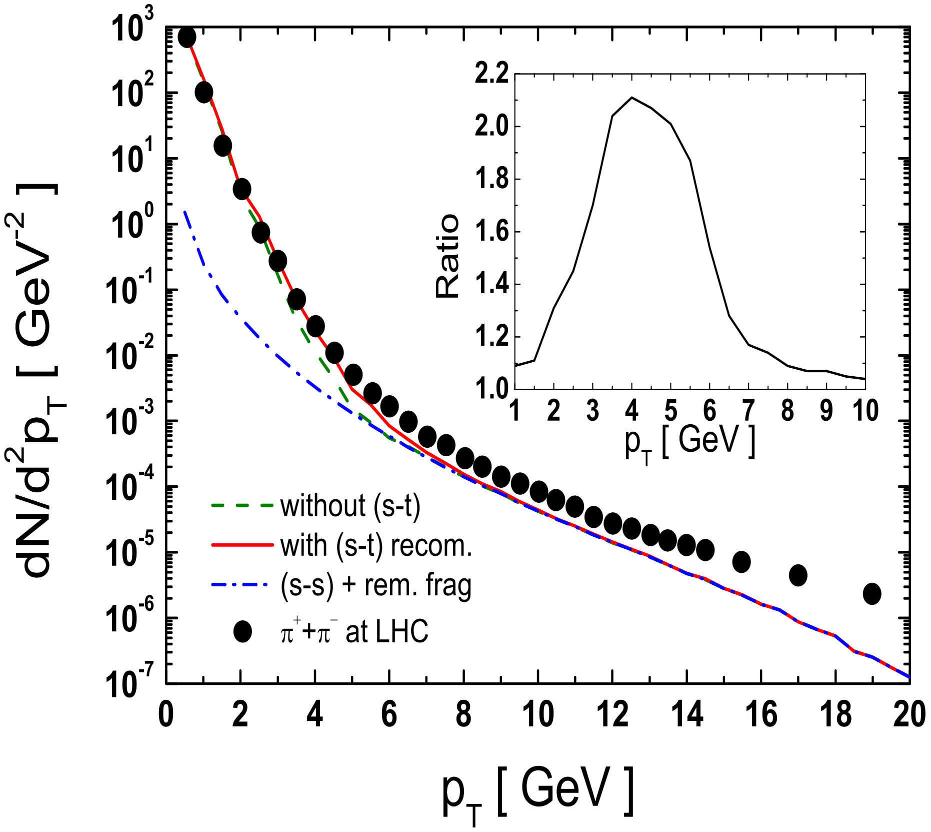
Pion and antiproton spectra at RHIC

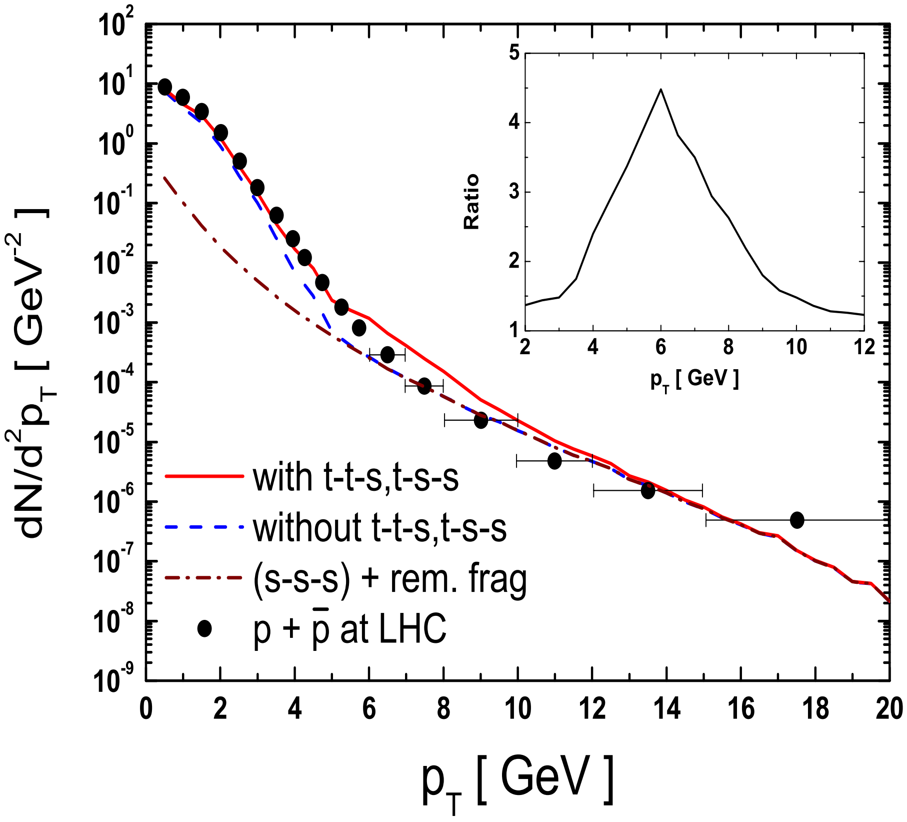




- Enhanced production of pions (~2) and antiprotons (~4) at intermediate transverse momentum due to coalescence of shower partons with thermal partons.

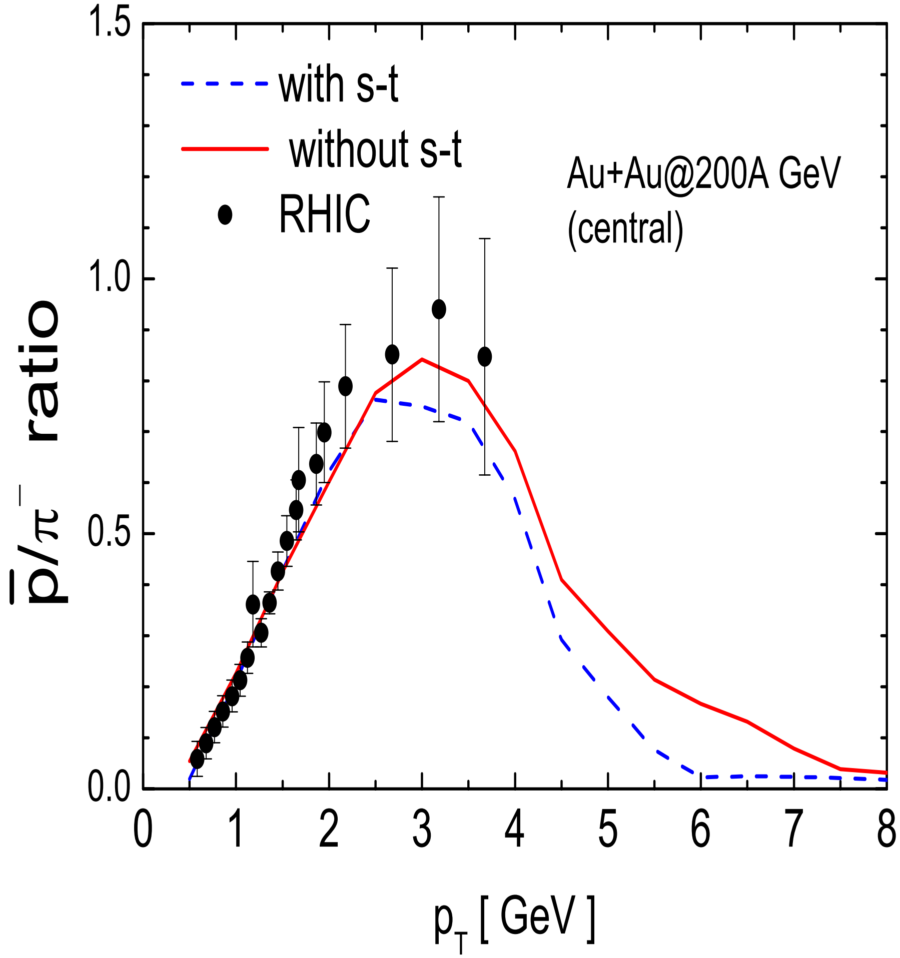
Pion and antiproton spectra at LHC

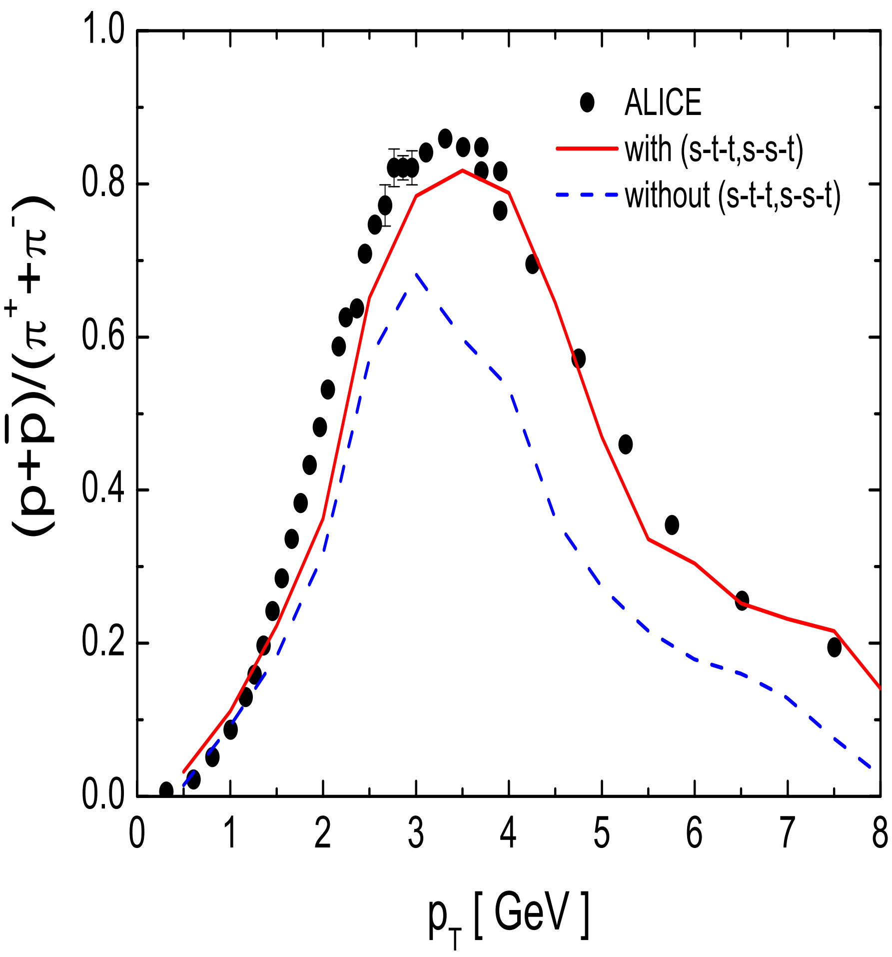




- Enhanced production of pions (~2) and protons (~4) at intermediate transverse momentum due to coalescence of shower partons with thermal partons.

Proton/pion ratio at RHIC and LHC





- Shower-thermal recombination helps explain the observed large proton/pion ratio at intermediate transverse momentum.
- Similar to that in PRC 68, 034904 (2003) based on jet-thermal coalescence for RHIC.

Summary on shower parton recombination

- In vacuum: Fragmentation of jets can be reproduced by the sum of shower parton coalescence or recombination and the fragmentation of remnant jets.
- In medium: Including also recombination of shower partons with thermal partons in QGP enhances the production of intermediate-momentum pions and protons at both RHIC and LHC.
- Shower-shower and shower-thermal recombination s are being implemented in realistic Monte-Carlo jet quenching codes to study medium modification of jet fragmentation in heavy ion collisions.
- Possible mprovements in shower parton recombination

  - Include all physical hadrons in particle data book, which correspond to excited states up to about n=5.
  - Cluster fragmentation for recombining quarks of large invariant masses.
  - Clusters of exceedingly large invariant masses form short string and hadronize via string fragmentation.