Jet fragmentation via shower parton recombination

Che-Ming Ko
Texas A&M University

- Jet fragmentation
- Jet shower partons
- Shower parton recombination
- Medium effects

In collaboration with Kyongchol Han and Rainer Fries

Supported by U.S. National Science Foundation, Department of Energy, and The Welch Foundation

DOE Topical Collaboration on Quantitative Jet and Electromagnetic Tomography (JET) of Extreme Phases of Matter in Heavy-ion Collisions

May 1, 2010 – April 30, 2015

Miklos Gyulassy (Columbia University)

Steffen Bass and Berndt Mueller (Duke University)

Volker Koch, Xin-Nian Wang and Feng Yuan (Lawrence Berkeley National Laboratory)

Ramona Vogt (Lawrence Livermore National Laboratory)

Ivan Vitev (Los Alamos National Laboratory)

Charles Gale and Sangyong Jeon (McGill University)

Ulrich Heinz and Abhijit Majumder (Ohio State University)

Denes Molnar (Purdue University)

Rainer Fries and Che-Ming Ko (Texas A & M University)

Co-Spokespersons: Ulrich Heinz (Ohio State University) and Xin-Nian Wang (LBNL)

Scientific goals

- Extend the calculation of medium induced gluon bremsstrahlung beyond collinear and soft approximation and explore matching schemes connecting collinear and hard gluon radiation, thereby reducing a major theoretical uncertainty in jet tomographic studies.

- Develop a general framework and numerical implementations of different approaches to jet modification in a medium, incorporating elastic and radiative energy loss, flavor conversion, quark mass dependence (heavy quarks) and exact four-momentum conservation.

- Consider hadronization via quark recombination and possible effects of rescattering between hadrons from jet fragmentation and the bulk medium, including the heavy flavor mesons.

- Calculate direct γ production within NLO pQCD, including effects of parton energy loss, induced γ bremsstrahlung and γ conversion, thermal emission from QGP and hadronic phases.

- Calculate jet and high-p_T hadron spectra, multi-hadron and γ-hadron correlations, and jet shape within NLO pQCD and their medium modification in high-energy heavy-ion collisions.

- Develop and utilize viscous hydrodynamics and parton and hadron cascade models for a complete description of all stages of the expanding medium; explore applying jet tomography to constrain initial conditions for accurate extraction of shear viscosity within viscous hydrodynamics; study collective excitations induced by jet-medium interaction.

- Develop Monte Carlo simulation codes in the form of Open Source Codes and Algorithmic Routines (OSCAR) based on the theoretical and numerical efforts within the JET Collaboration and make them available to the entire heavy-ion community.

- Carry out systematic and quantitative phenomenological studies of experimental data on jet and electromagnetic tomography to extract properties of the sQGP, such as jet transport parameter, shear viscosity, initial temperature and screening mass of the medium.

Jet fragmentation

$$\frac{dN}{d^2\mathbf{p}_{\rm had}} = \sum\nolimits_{\rm jet} \int dz \frac{dN}{d^2\mathbf{p}_{\rm jet}} \frac{D_{\rm had/jet}(z,Q^2)}{z^2}$$

$z = \frac{p_{\rm had}}{p_{\rm jet}}$: fraction of jet momentum carried by formed hadron

$Q = \frac{p_{\rm had}}{2z}$: momentum scale for hadronization

- Independent fragmentation: KKP, BKK, AKK, …..
- String fragmentation: PYTHIA
- Cluster fragmentation: HERWIG
- Quark Recombination: Hwa and Yang

Recombination of shower partons Hwa and Yang, PRC 70, 024904 (2004)

$$zD_M(z) = \int_0^z \frac{dz_1}{z} \int_0^z \frac{dz_2}{z} F_{q\bar{q}}(z_1, z_2) R_M(z_1, z_2, z)$$

Factorization of quark and antiquark distribution functions

$$F_{q\bar{q}}(z_1, z_2) = S_q(z_1) S_{\bar{q}}(z_2)$$

Collinear approximation for recombination function (valon model)

$$R_\pi(z_1, z_2, z) = \frac{z_1 z_2}{z^2} \delta\left(\frac{z_1}{z} + \frac{z_2}{z} - 1\right)$$

$$R_K(z_1, z_2, z_3) = 12 \left(\frac{z_1}{z}\right)^2 \left(\frac{z_2}{z}\right)^3 \delta\left(\frac{z_1}{z} + \frac{z_2}{z} - 1\right)$$

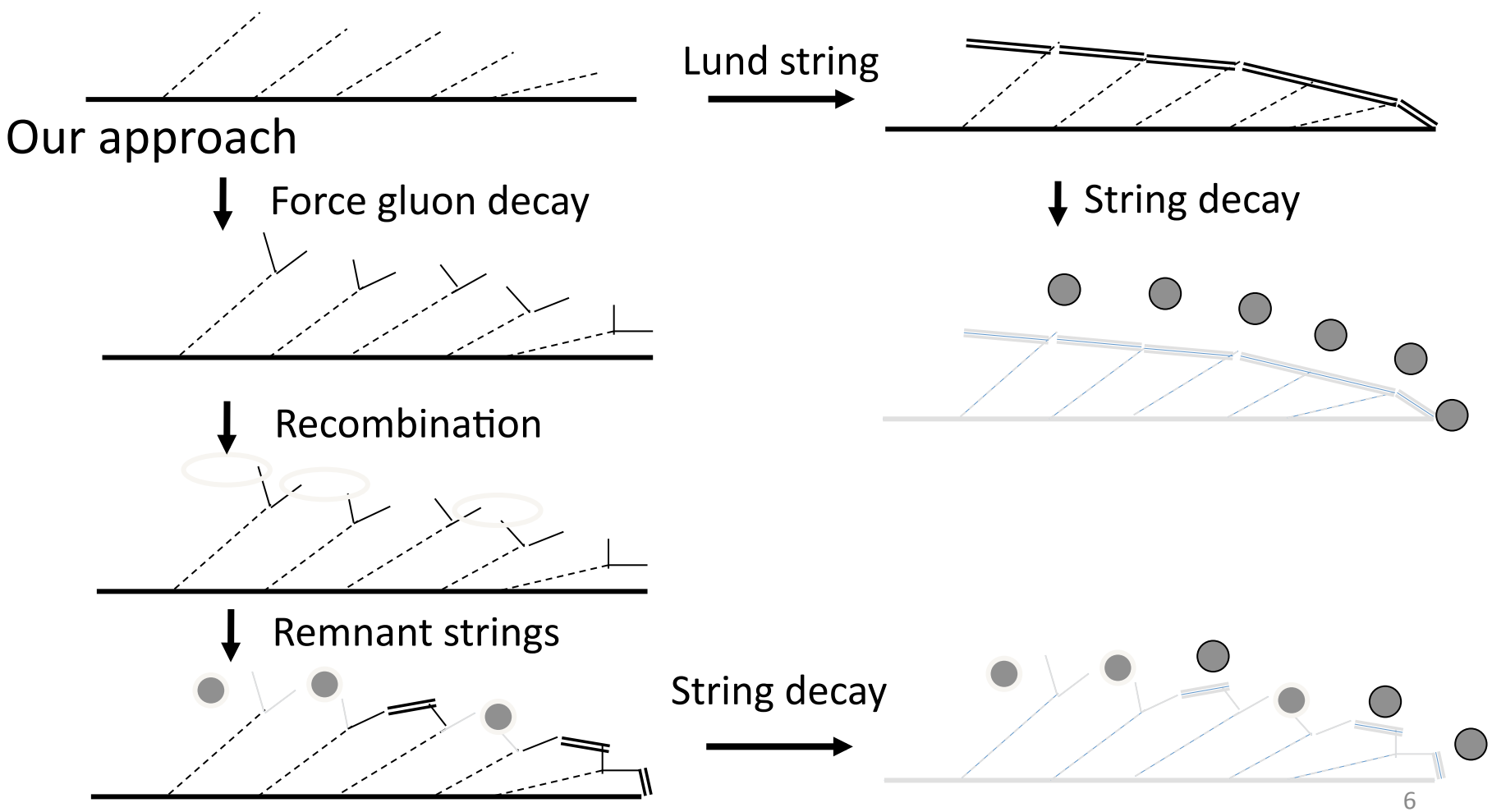
Fit shower light and strange quark distribution functions to empirical fragmentation functions and predict baryon fragmentation functions

$$zD_p(z) = \int_0^z \frac{dz_1}{z} \int_0^z \frac{dz_2}{z} \int_0^z \frac{dz_3}{z} S_u(z_1) S_u(z_2) S_d(z_3) R_p(z_1, z_2, z_3, z)$$

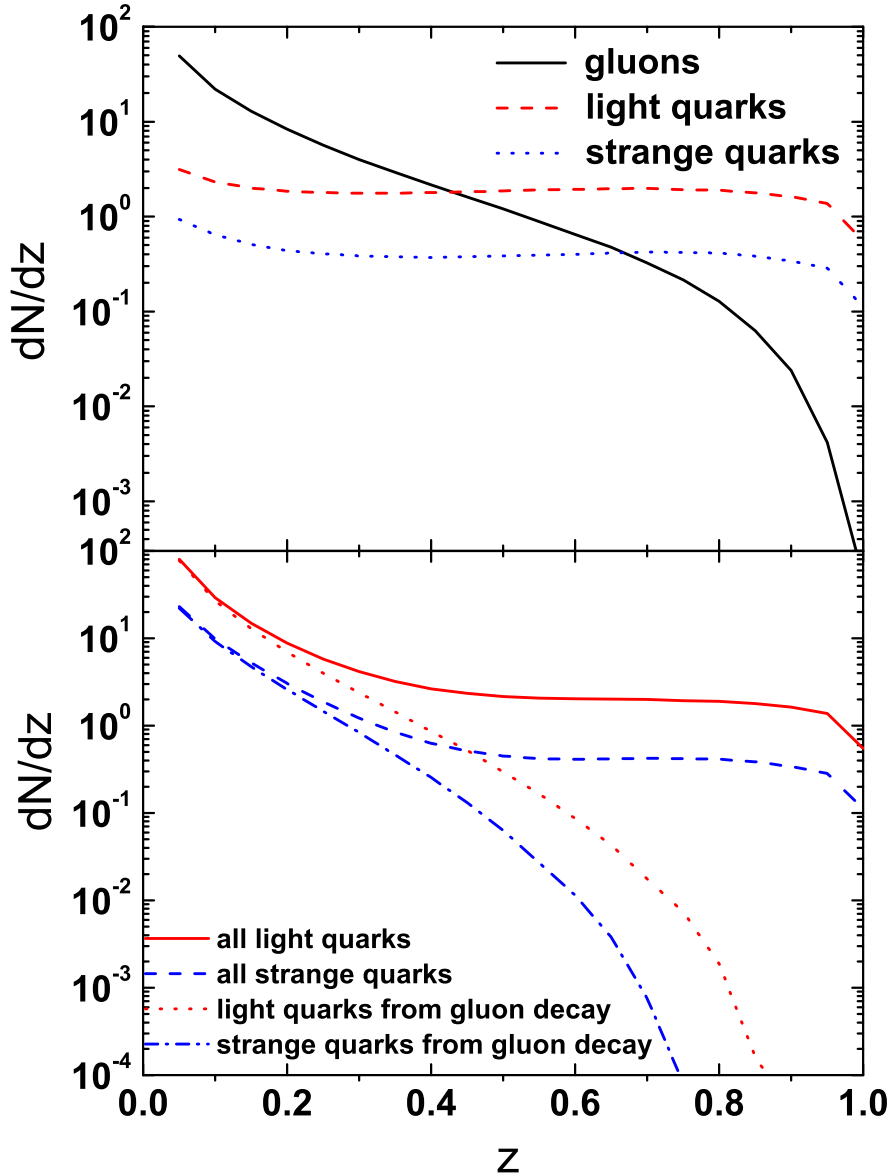
Shower parton recombination and remnant partond decays

Extract PYTHIA parton showers evolved to a scale Q_0

Standard PYTHIA Lund string fragmentation



Shower partons from PYTHIA



- Obtained from PYTHIA for e^++e^- collisions at √s=200 GeV based on DGLAP evolution, which is stopped when gluon virtuality drops below $Q_0 \approx 1$ GeV
- Shower gluons converted to quark and antiquark pair with relative probabilities to different flavors according to their branching ratios
- Space-time information of shower partons obtained by taking lifetime of virtual partons inversely proportional to their virtualities

Quark recombination model for mesons

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

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

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

Meson Wigner function: $\quad f_s(\mathbf{y},\mathbf{k}) = 8 g_M \exp\left(-\frac{\mathbf{y}^2}{\sigma_M^2} - \sigma_M^2 \mathbf{k}^2\right)$

$$\mathbf{y} = \frac{\mathbf{x}_1' - \mathbf{x}_2'}{\sqrt{2}}, \quad \mathbf{k} = \frac{\sqrt{2}}{m_1+m_2}(m_2\mathbf{p}_1' - m_1\mathbf{p}_2')$$

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

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

Quark recombination model for baryons

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

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

Baryon Wigner function

$$f_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) = 64 g_B \exp\left(-\frac{\mathbf{y}_1^2+\mathbf{y}_2^2}{\sigma_B^2} - \sigma_B^2(\mathbf{k}_1^2+\mathbf{k}_2^2)\right)$$

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

Primed coordinates and momenta refer to baryon rest frame after earlier produced ones are propagated to the time of 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

Width parameters σ_M and σ_B are fitted to hadron charge radii

$$r_M = \langle Q_1(\mathbf{x}_1 - \mathbf{X})^2 + Q_2(\mathbf{x}_2 - \mathbf{X})^2 \rangle^{1/2} = \sqrt{3}\frac{(Q_1 m_2^2 + Q_2 m_1^2)^{1/2}}{m_1 + m_2}\sigma_M$$

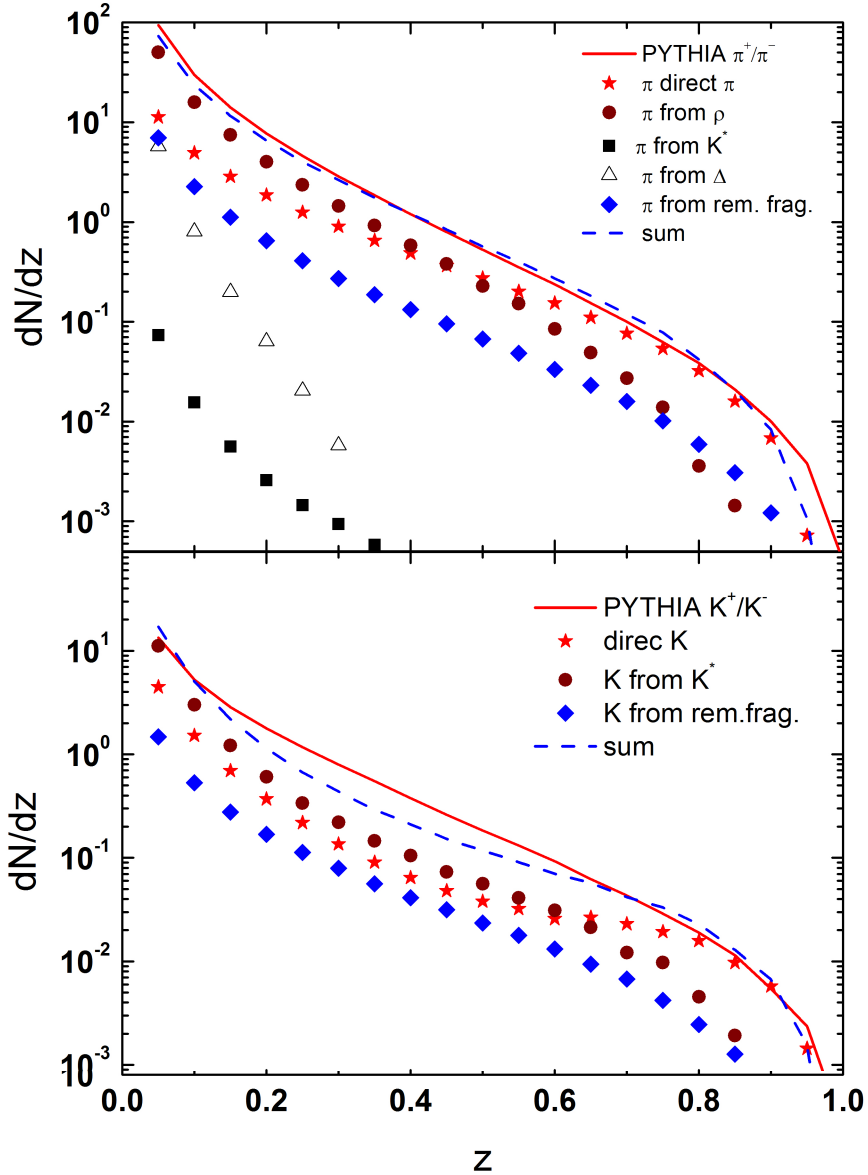
$$r_B = \langle Q_1(\mathbf{x}_1 - \mathbf{X})^2 + Q_2(\mathbf{x}_2 - \mathbf{X})^2 + Q_3(\mathbf{x}_3 - \mathbf{X})^2 \rangle^{1/2} = \sigma_B$$

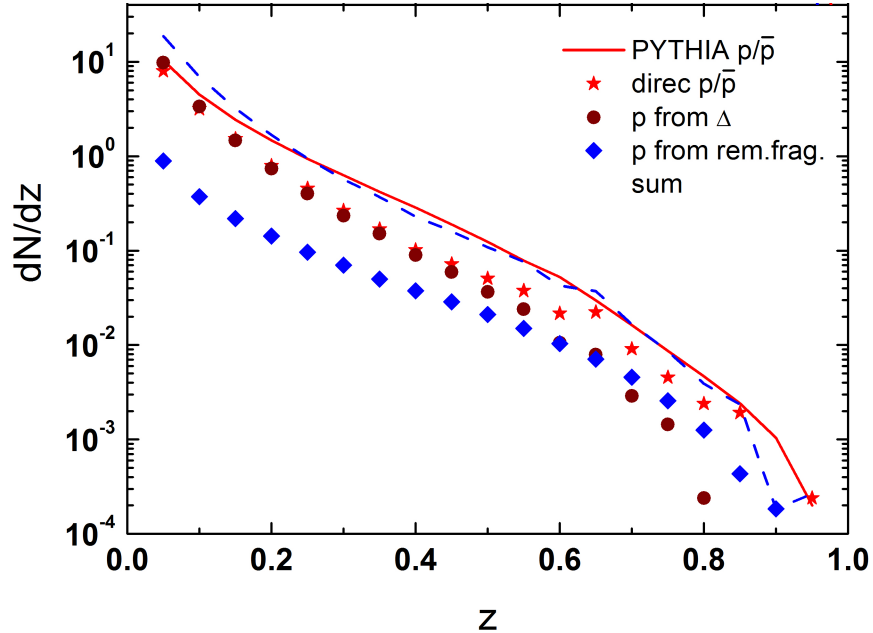
with center of mass coordinate $\mathbf{X} = (\mathbf{x}_1 + \mathbf{x}_2)/2$ for mesons and $\mathbf{X} = (\mathbf{x}_1 + \mathbf{x}_2 + \mathbf{x}_3)/3$ for baryons

Using r_π=0.67 fm, r_K=0.56 fm, r_p=0.88 fm from particle data book and taking $m_u = m_d$=0.3 GeV, m_s=0.45 GeV gives

σ_π=1.34 fm, σ_K=0.75 fm, σ_p=0.88 fm

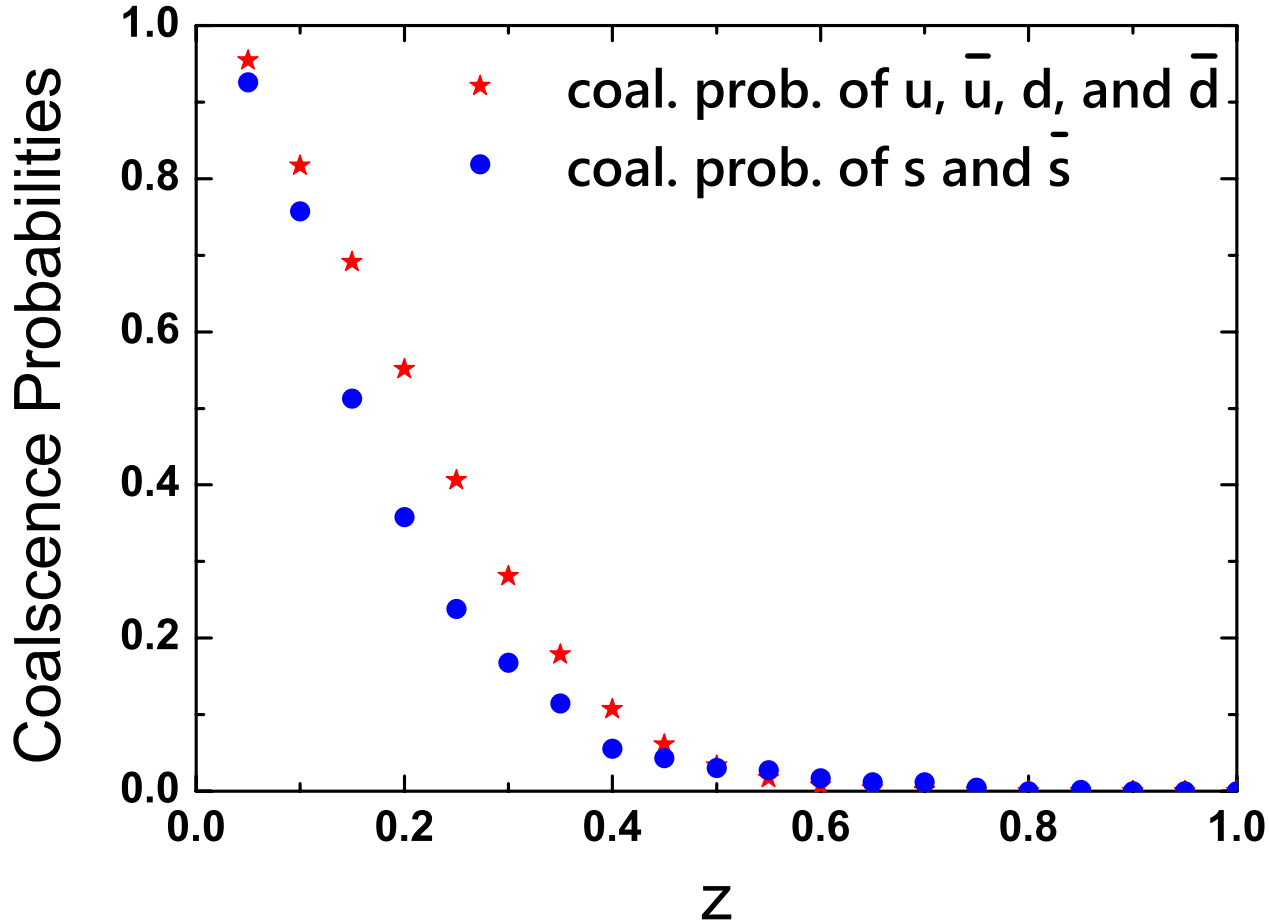
Charged pion, kaon and proton spectra





- Charged pions and protons well described
- Charged kaons slightly underestimated
- String fragmentation of remnant partons not important

Remnant partons and short string fragmentation

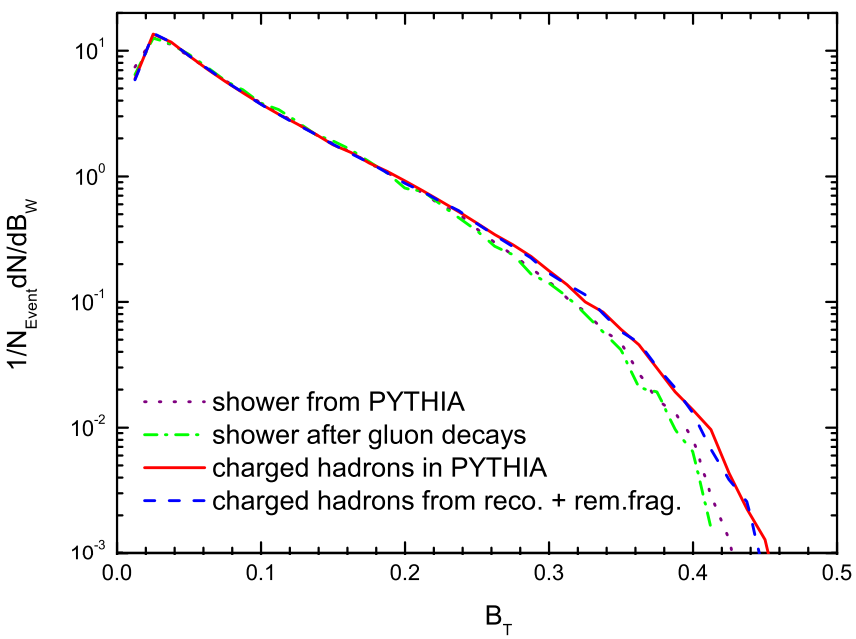


- Coalescence probabilities are close to one for small momentum fraction but decrease quickly with increasing momentum fraction.
- Remnant partons are ordered as quark-antiquark pairs, which form short strings and are converted hadrons by string fragmentation.

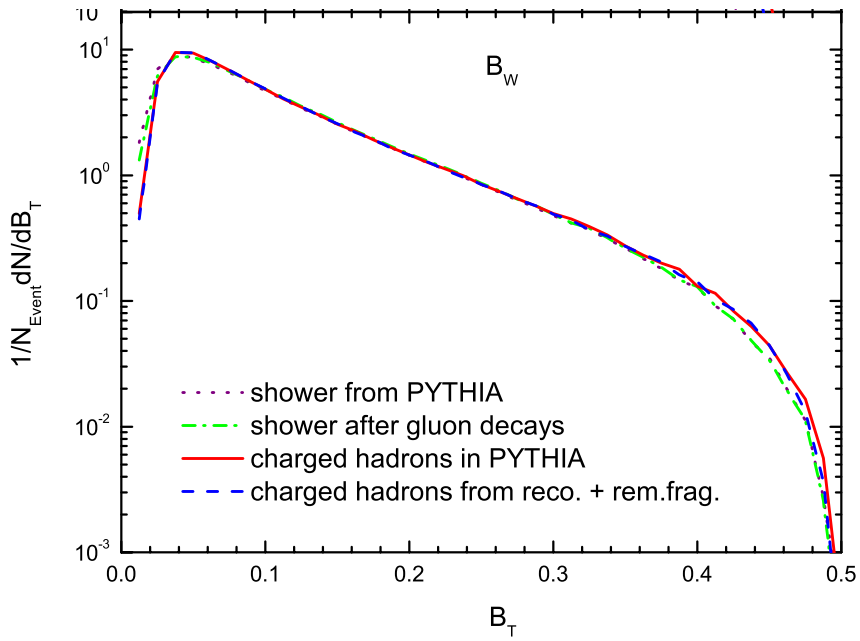
Jet broadening

$$B_\pm = \sum_{i \in H_\pm} |\mathbf{p}_i \times \mathbf{n}_T| / (2 \sum_j |\mathbf{p}_j|)$$

Thrust axis n_T is the jet axis which maximizes $T \equiv \max\left(\frac{\sum_i \mathbf{p}_i \cdot \mathbf{n}_T}{\sum_i |\mathbf{p}_i|}\right)$



wide jet broadening B_W=max(B_+,B)



Total jet broadening B_T=B_++B_-

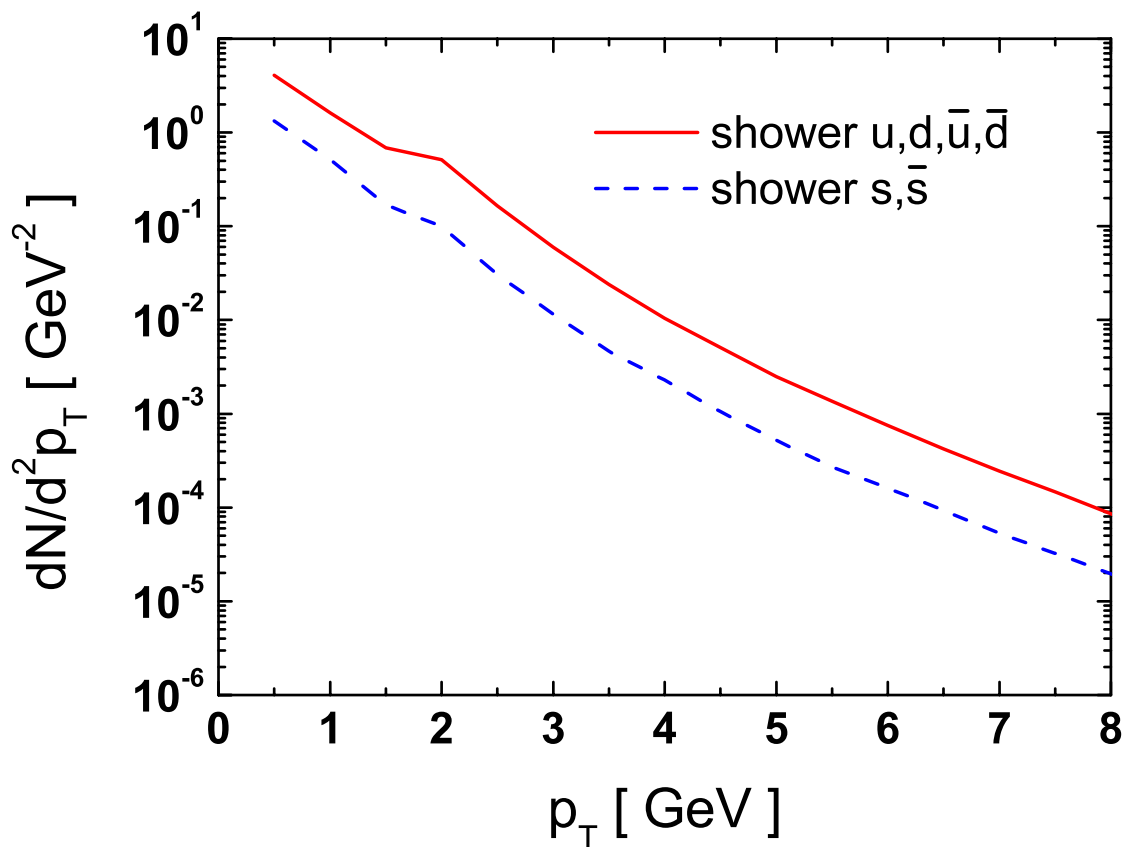
- Similar jet broadening from PYTHIA and coalescence model
- Similar hadron and shower parton jet broadening

Shower parton recombination in heavy ion collisions

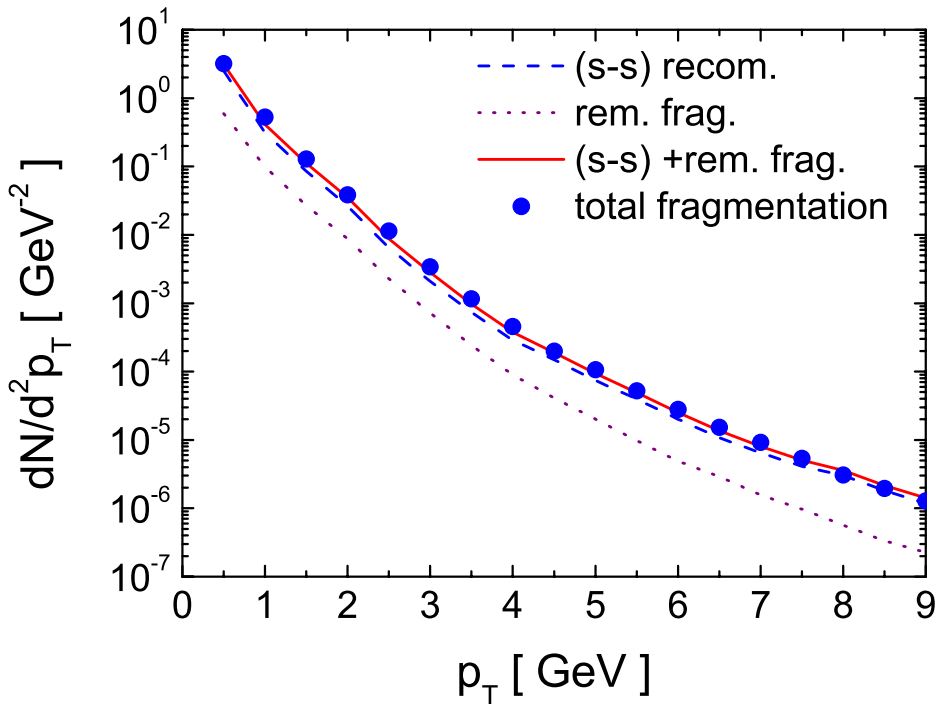
Quenched jets in Au+Au @ 200GeV

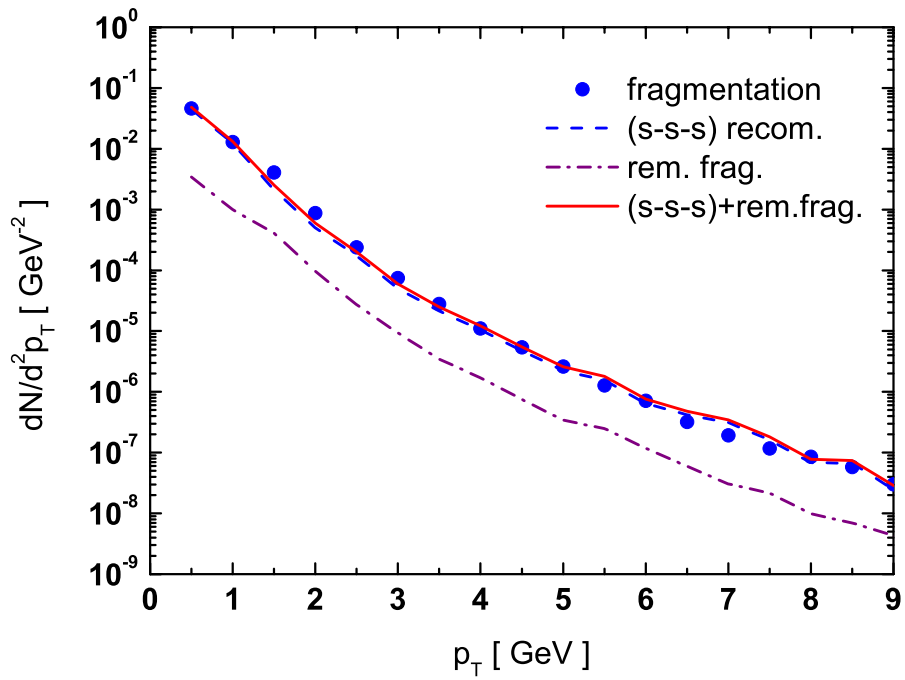
$$\frac{dN_{\rm jet}}{d^2\mathbf{p}_T} = A\left(\frac{B}{B+p_T}\right)^n$$

	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 parton recombination vs jet fragmentation





- Recombination of shower partons reproduces jet fragmentation in PYTHIA

Medium effects on shower parton recombination

Thermal partons modeled by an expanding fireball

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

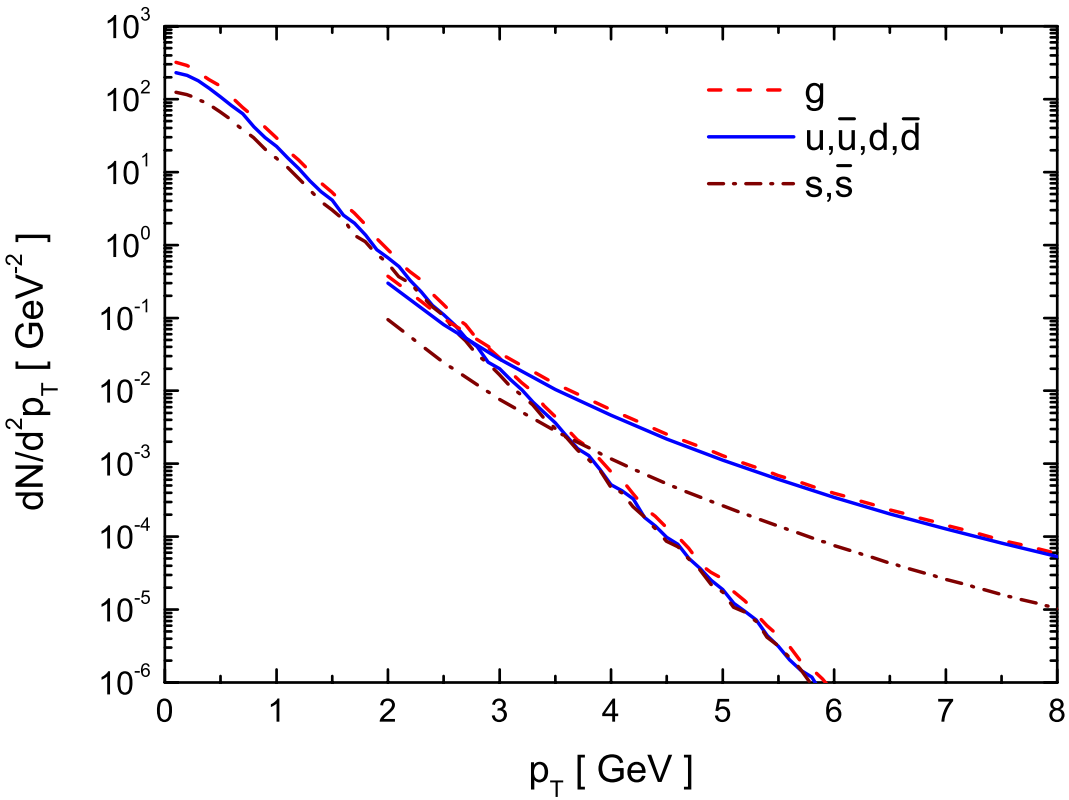
Isotropic in transverse plane and boost invariant longitudinally

RHIC: Au+Au @ 200 GeV

LHC: Pb+Pb @ 2.76 TeV

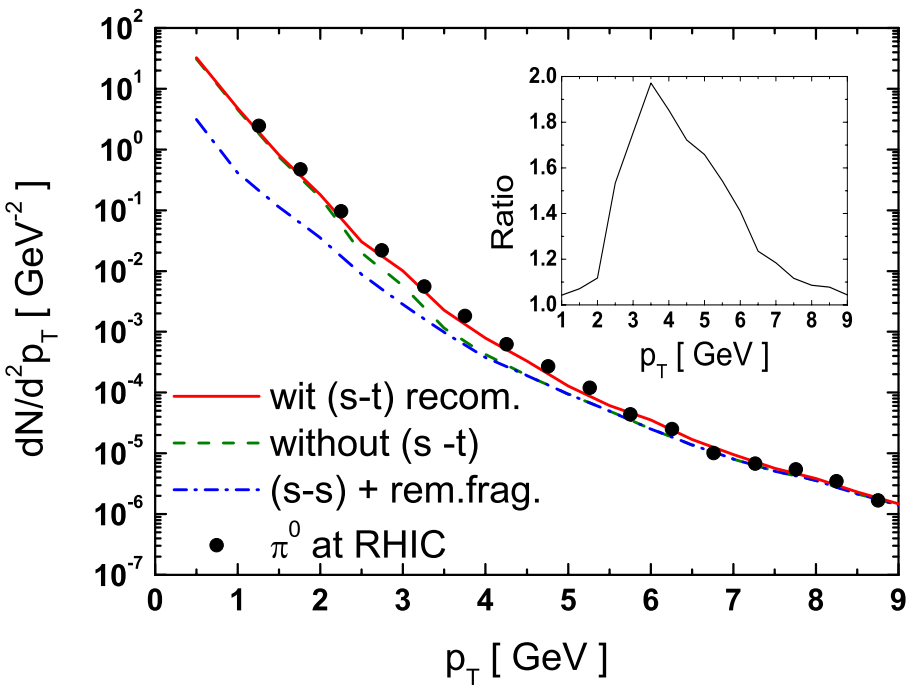
	RHIC	LHC
$R_\perp$ (fm)	8.3	12
τ (fm/c)	4	6
β (c)	0.5	0.65
μ_B (MeV)	10	0
T (MeV)	170	170

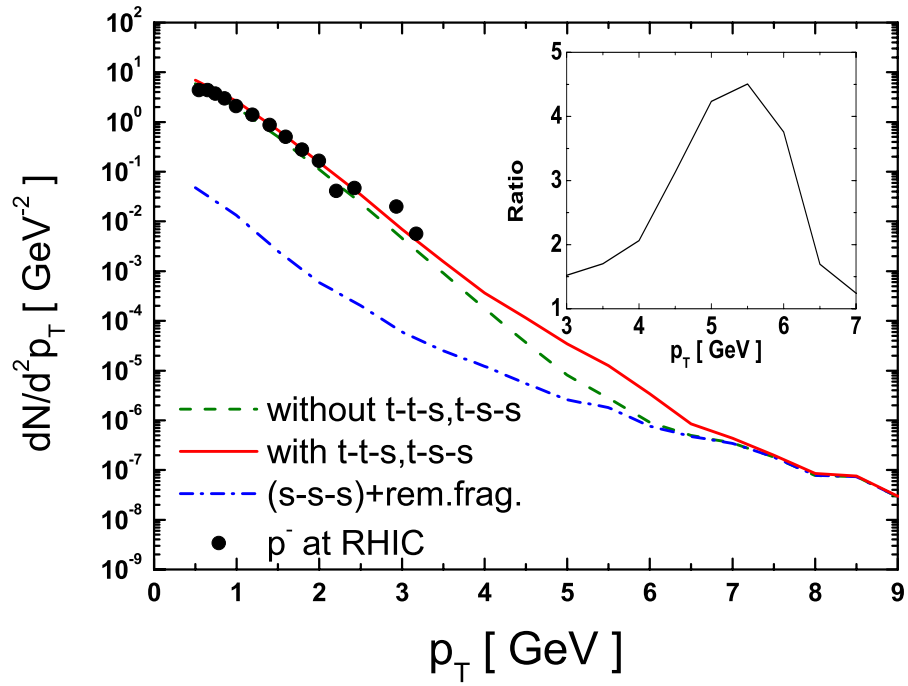
Shower and thermal partons at RHIC



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

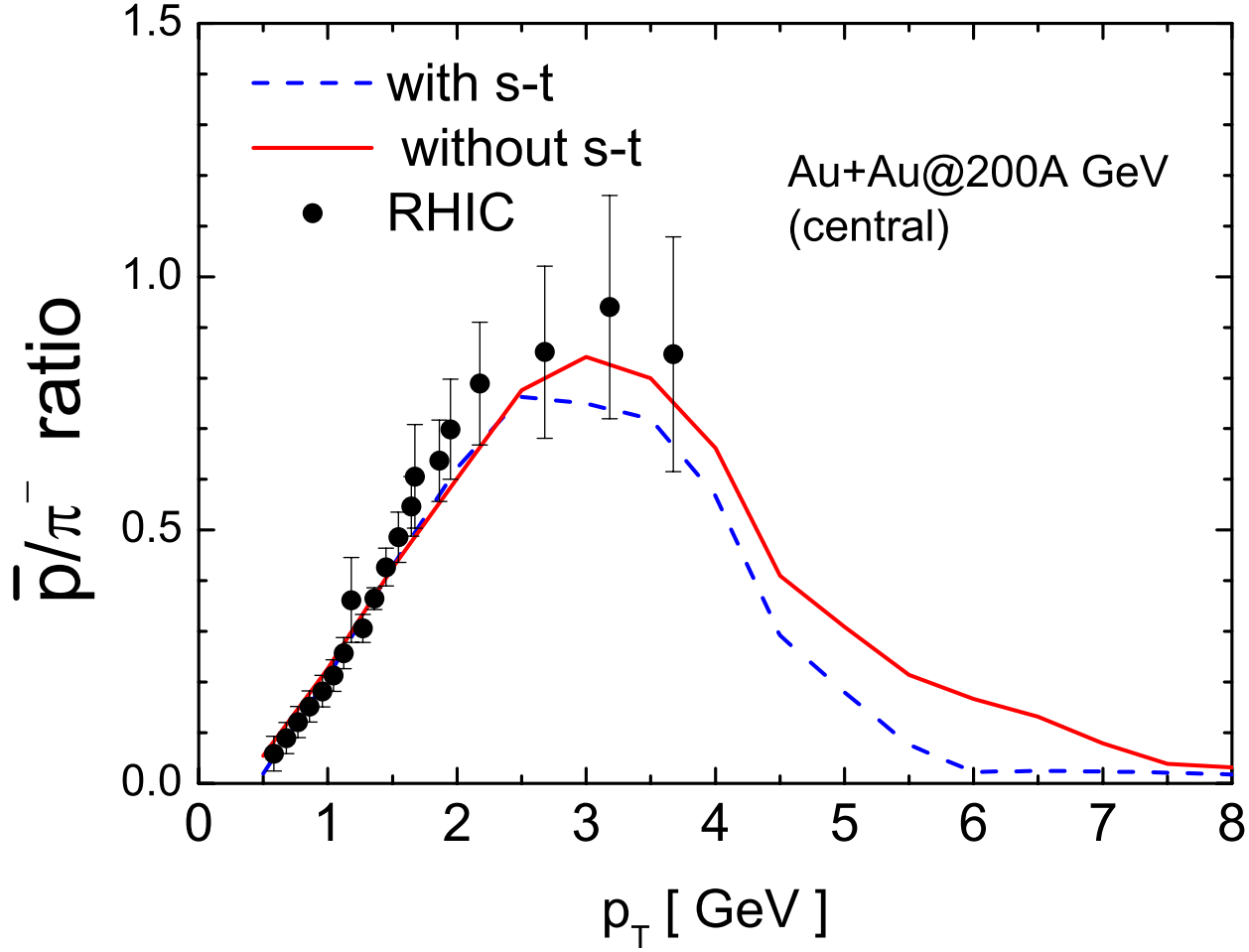
Pion and antiproton spectra at RHIC





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

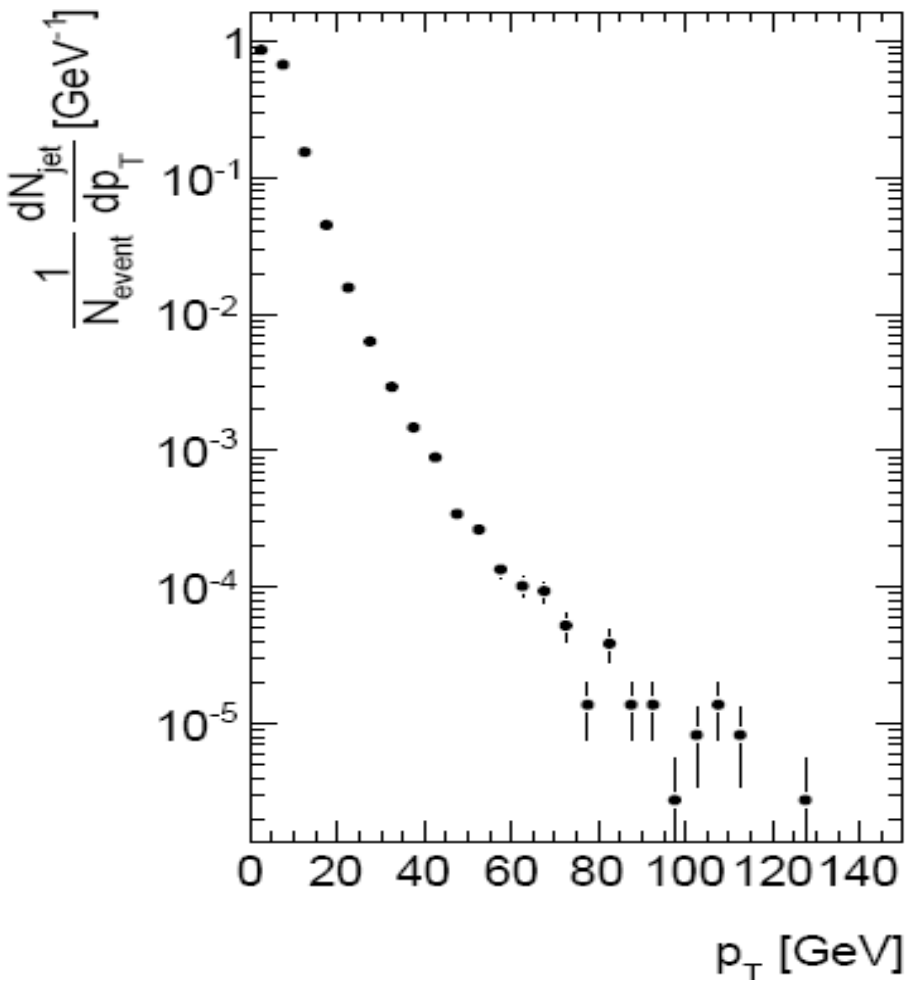
Antiproton /pion ratio at RHIC



- Similar to that of PRC 68, 034904 (2003) based on jet-thermal coalescence

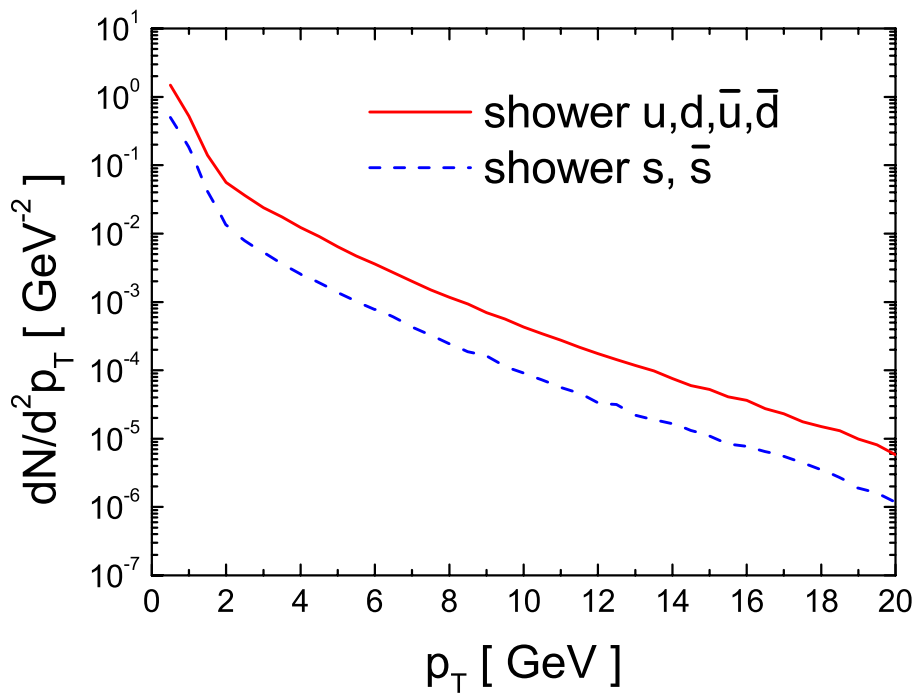
Shower partons from jets in Pb+Pb @ 2.76 TeV

A. Angerami, arXiv:1208.5043

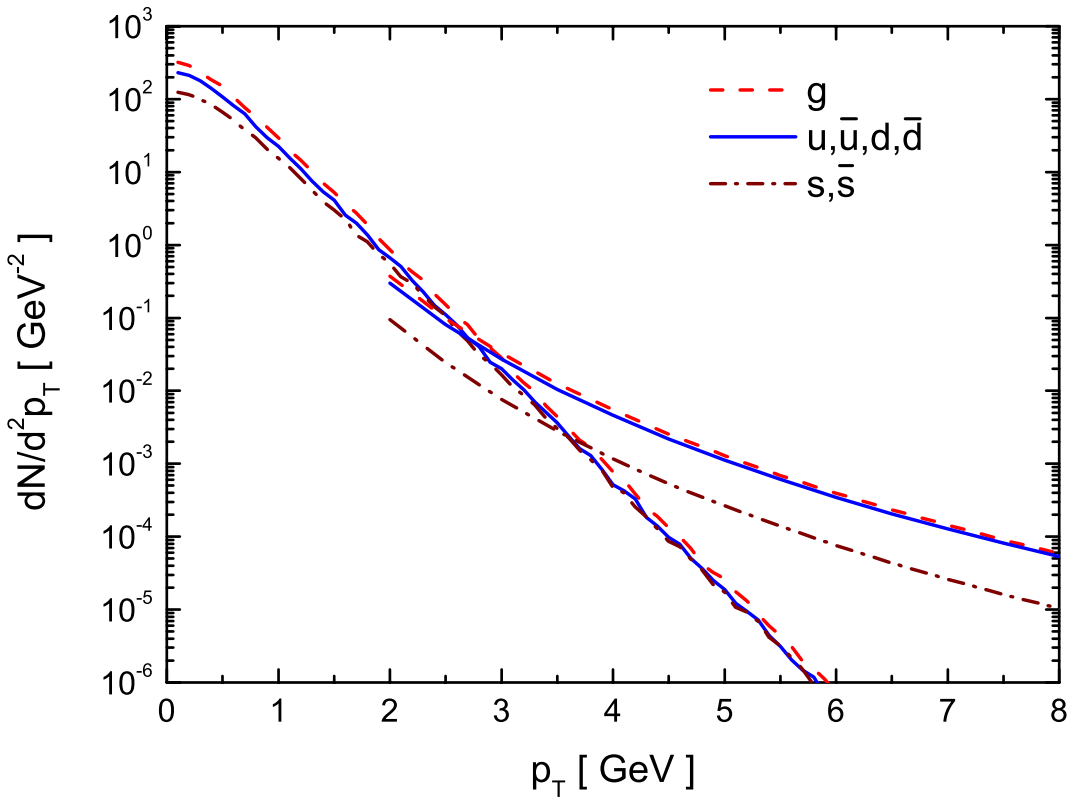


HIJING plus energy loss

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

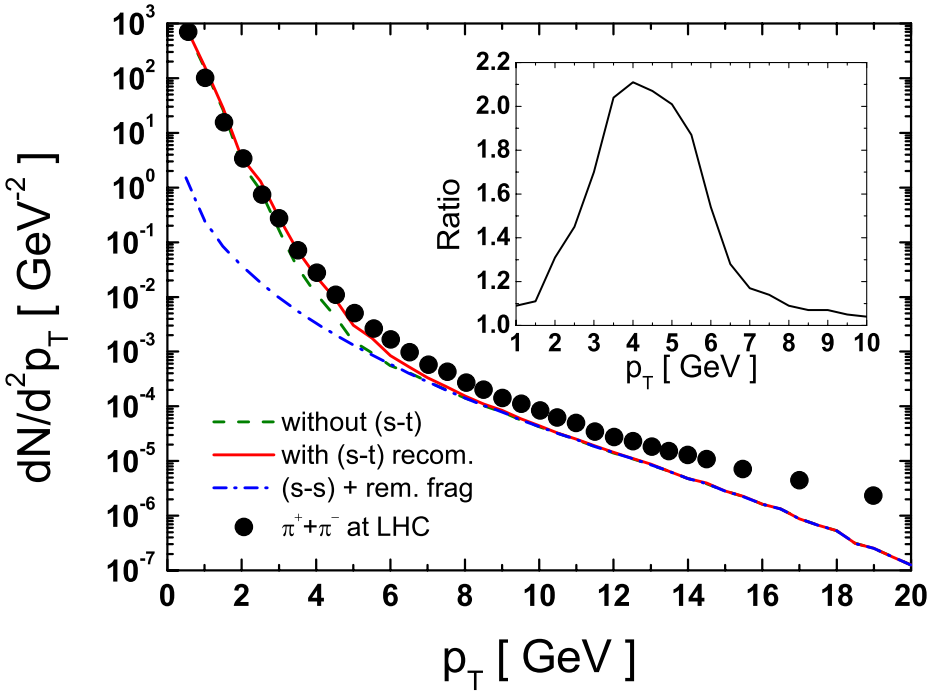


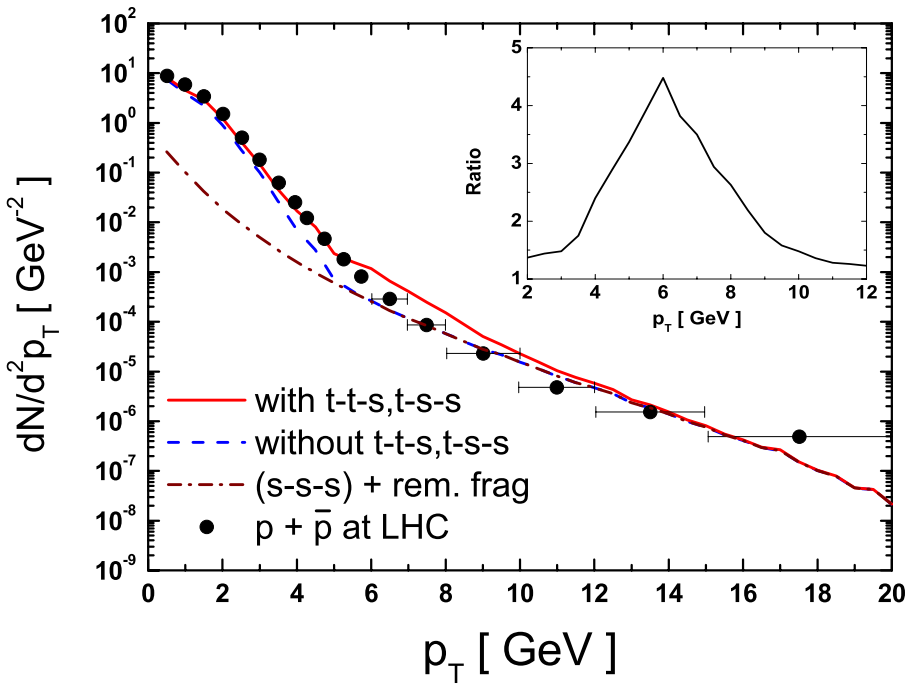
Shower and thermal partons at LHC



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

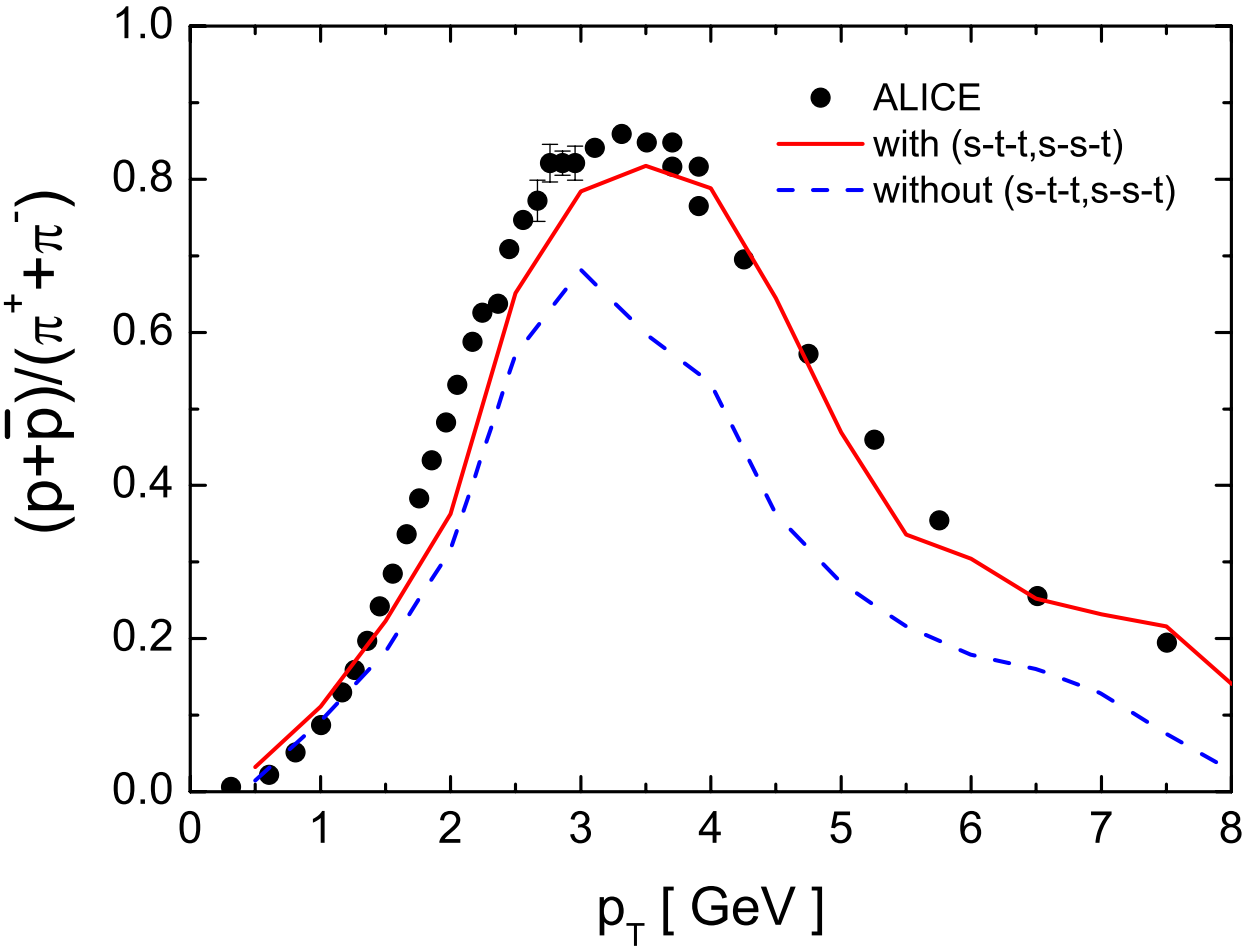
Pion and antiproton spectra at LHC





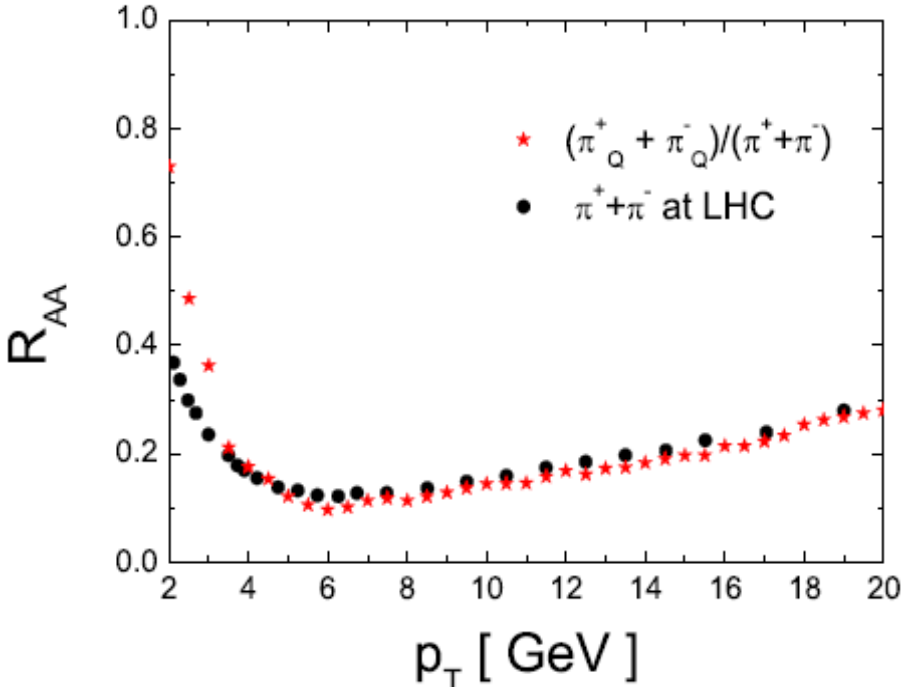
- Enhanced production of pions (~2) and protons (~4) at intermediate transverse momentum due to coalescence of shower partons with thermal partons.

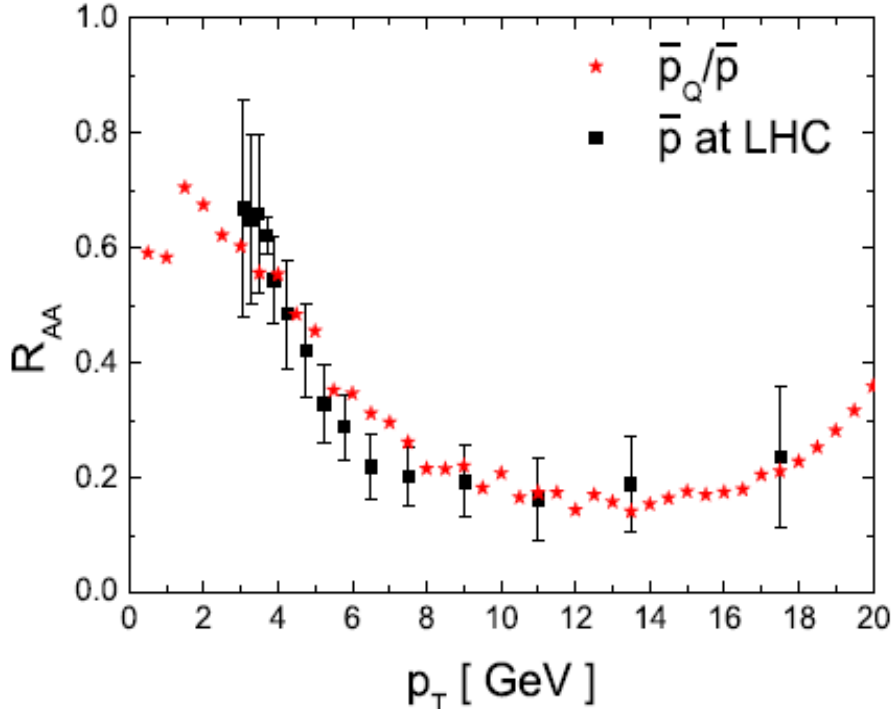
Proton/pion ratio at LHC



- Shower-thermal recombination helps explain the observed large proton/pion ratio at intermediate transverse momentum

R_{AA} for charged pions and anti-protons





- Reproduce reasonably data from Pb+Pb @ 2.76 TeV

Summary

- 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.

  - Reproduce measured pion and proton spectra at RHIC and LHC.

  - Enhanced p/π ratio at intermediate momentum as observed in experiments.