The broad away side of azimuthal correlations:

3 vs 2 final state particles in high energy nuclear collisions

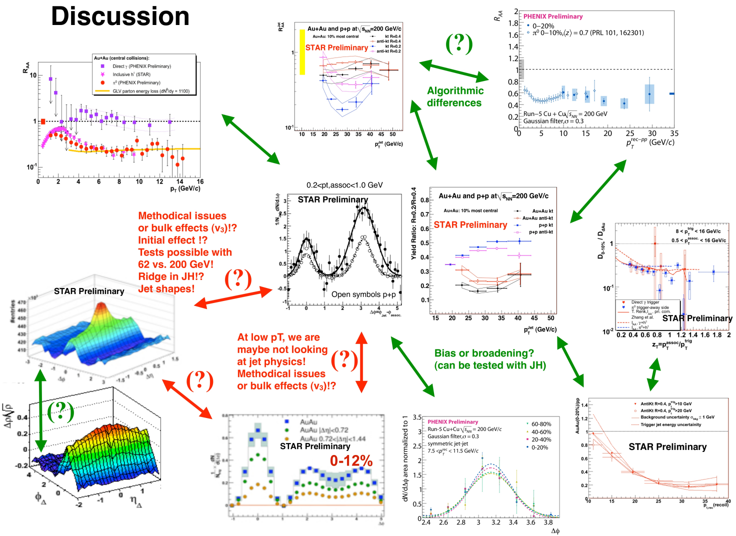
M.E. Tejeda-Yeomans

D. de Fisica, USON

High p_T physics at the LHC, 30/09/2010

As was discussed yesterday

Jörn Putschke (Yale University): JJ/Jh/hh correlations



Our proposal

Ayala, Jalilian-Marian, Magnin, Ortiz, Paic, Tejeda-Yeomans
Phys.Rev.Lett.104:042301,2010.
e-Print: arXiv:0911.4738 [nucl-th]

in a nutshell

medium induced energy loss effects on $2 \to \{2,\ 3\}$ xsecs

+ different geometry for the trajectories of 3 as opposed to 2 particles in the final state of A+A collision
+ scenario that enhances processes with 3 particles in the final state
+ one particle absorbed by the medium and the other one punches through

= on average, a **double hump structure**

Outline

QCD @ RHIC, LHC

A puzzle in angular correlations

Solving the puzzle

Final remarks

How to study the hot and dense medium?

- high p_T partons are produced through hard processes in the initial binary nucleon collisions: probe of the medium
- if partons hadronize with little interaction: # of produced high p_T hadrons should scale with # of binary collisions
- Experiment: # of produced high p_T hadrons is reduced significantly! e.g. up to 5 times in most central AuAu collisions

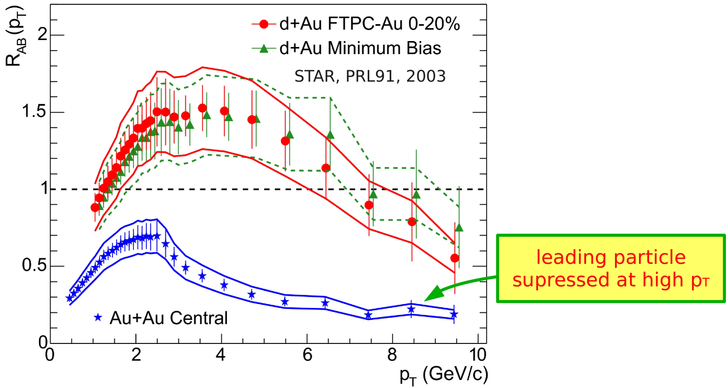
the medium is opaque for high p_T partons

[B. Back et al, PLB578, 2004; S.S. Adler et al. PRC69, 2004; J. Adams et al, PRL91, 2003]

Probing the medium with high p_T partons

the medium is opaque for high p_T partons

AB over binary and scaled with pp



How to study the hot and dense medium?

- Experiment: a *differential* study can be made by measuring azimuthal correlations between particle pairs at high p_T

The near-side correlation is similar for the pp and AuAu collisions, while the away-side correlation is not there for central AuAu events.

[C. Adler et al, PRL90 2003, J. Adams et al, NPA757 2005]

Near and away side correlation for pp and AuAu

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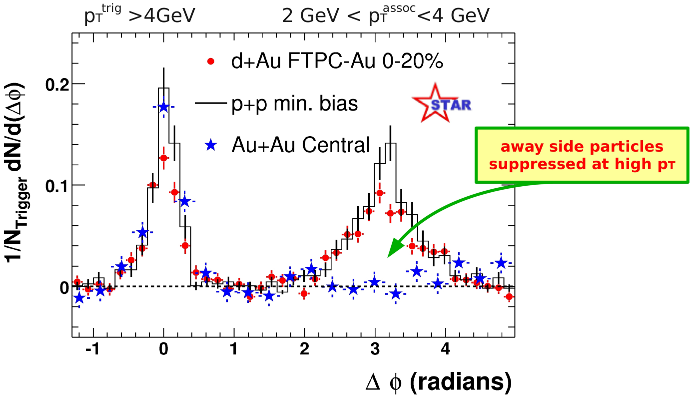

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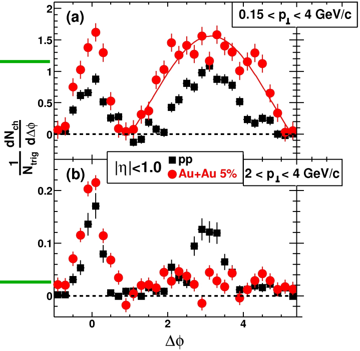
away side particles
enhanced at low p_T
and
suppressed at high p_T



Elliptic flow studies

- initial geometry of the collision region is anisotropic in the azimuthal direction
- after the initial binary collisions, the interacting system reaches local thermal equilibrium and preassure gradients arise
- preassure gradients are steeper in the b-direction
- elliptic flow arises: anisotropy in the momentum distribution of particles
- quantified by the second Fourier coefficient v_2 of the azimuthal particle distribution relative to the reaction plane

flow and near/away side studies

elliptic flow + two particle correlation studies

Among others, these observations indicate that an **opaque, strongly interacting partonic matter** is created in the high energy AuAu collisions at RHIC

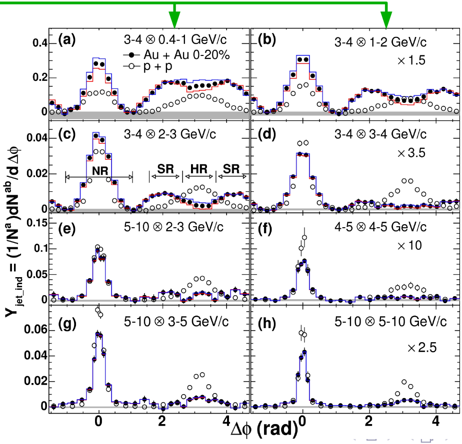
A puzzle in correlation studies

rich correlation structure in AuAu vs pp

the *ridge* and *broad away side*: excess yield of correlated particles at $\Delta\phi = 0^\circ$ and $\Delta\phi \approx 120^\circ$ extending out to $\Delta\eta > 2$

azimuthal correlations for large momentum difference, develop a “double hump” in the away side

PHENIX PRC78:014901,2008



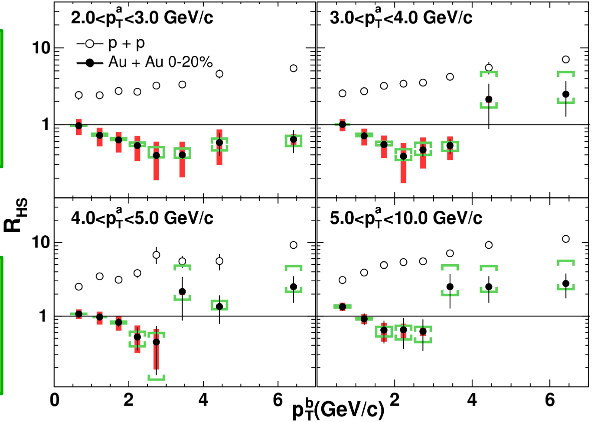
ratio head/shoulder

- pp: R_{HS} growing with p_T, narrower jet
- AuAu: jet fragmentation dominates at high p_T over medium effects

p_T < 4 GeV/c

pp: R_{HS} > 1 and grows with p_T

AuAu: R_{HS} < 1



p_T > 4 GeV/c

pp: R_{HS} > 1 and grows with p_T

AuAu: R_{HS} ≲1

Solving the puzzle

several theoretical models used to look for origins of such structures, among others

- Mach cone shock waves [J. Ruppert et al, APPS1:633, 2008]
- triangularity and triangular flow [B. Alver et al, PRC81:054905, 2010]

Solving the puzzle

Some recent comparisons/reviews

- none of the theoretical models are succesful to describe all the special characteristics of these structures

Nagle, NPA830 (2009)

- All of the theoretical models rely on the description of such structures as the manifestation of emergent behaviour due to the collective
(e.g. triangular flow: relies crucially on the existence of initial geometry fluctuations)
- no clear paradigm has emerged for the two-lobed wide away-jet structure

Critical examination of RHIC paradigms–mostly high pT.
Tannenbaum, e-Print: arXiv:1008.1536 [nucl-ex]

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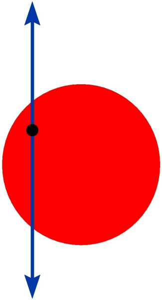

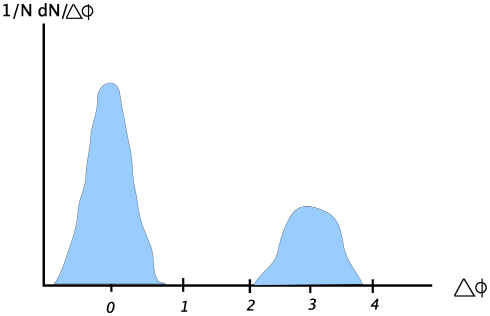

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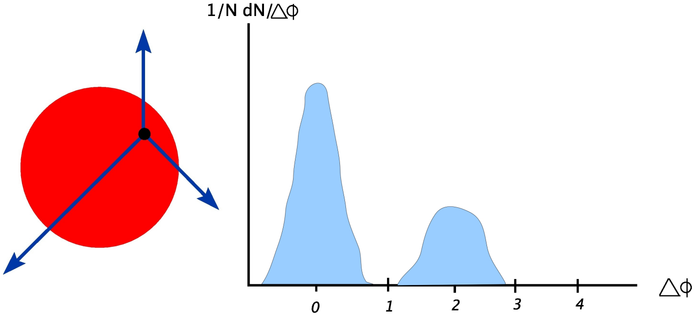

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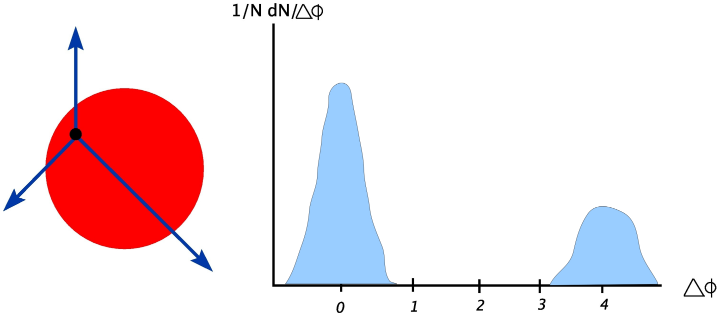

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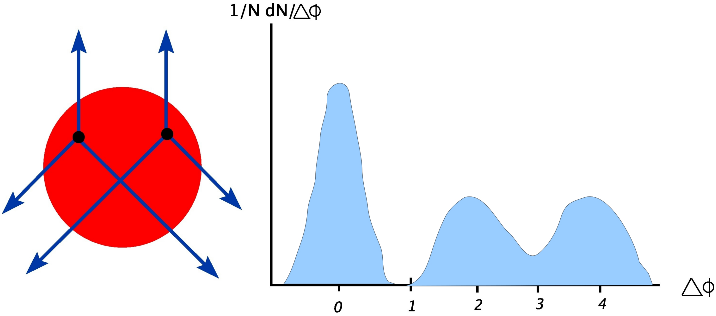


Full $2 \to \{2,\ 3\}$ differential xsecs

$$\frac{d\sigma^{pp\to h1\,h2\,X}}{d\,y_1 d\,y_2 d\,h_{1t} d\,h_{2t} d\,\phi_2} \propto \int dz_2 |\mathcal{M}^{2\to 2}|^2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) \times D^0_{h1/k}(z_1,\mu^2) D^0_{h2/m}(z_2,\mu^2)$$

$$\frac{d\sigma^{pp\to h1\,h2\,h3\,X}}{d\,y_1 d\,y_2 d\,y_3 d\,h_{1t} d\,h_{2t} d\,h_{3t} d\,\phi_2 d\,\phi_3} \propto \int dz_3 |\mathcal{M}^{2\to 3}|^2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) \times D^0_{h1/k}(z_1,\mu^2) D^0_{h2/m}(z_2,\mu^2) D^0_{h3/n}(z_3,\mu^2)$$

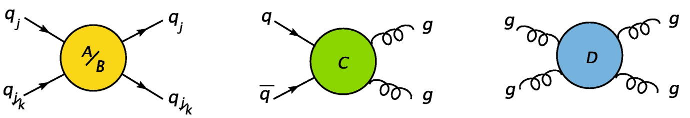
for both pp and AuAu collisions we need

$\mathcal{M}^{2\to 2}$, $\mathcal{M}^{2\to 3}$, $f_{i/p}$'s and $D_{h/k}$'s

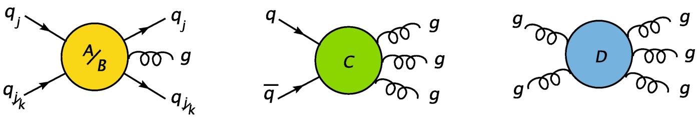
LO matrix elements

4 classes of diagrams + crossings at the parton level:
[e.g. Ellis and Sexton NPB 269 (1986)]

$\mathcal{M}^{2\to 2}$:



$\mathcal{M}^{2\to 3}$:



pdf's and (unmodified) pff's

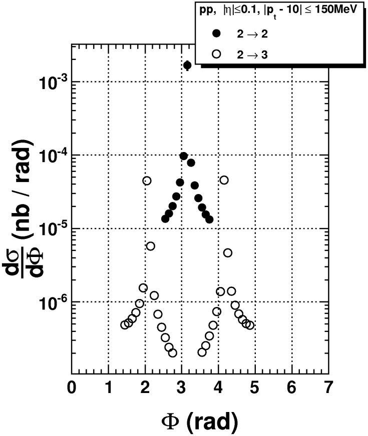
√ $f_{i/p}(x, \mu^2)$:
CTEQ6 parametrization
[Pumplin et al, JHEP07 (2002)]

√ $D^0_{h/k}(z, \mu^2)$:
KKP parametrization
[Kniehl et al, NPB582 (2000)]

+ LO DIPHOX [Binoth et al, EPJC24 (2002)]

$2 \to \{2,\ 3\}$ diff xsecs for pp collisions

for the away side hadrons
as a function of the azimuthal angle
focus on midrapidity region $(y_i = 0)$
all hadrons carry 10 GeV/c
$\Delta\phi = \pi$ or $\{2\pi/3, 4\pi/3\}$
at $\sqrt{S} = 200$ GeV



Use modified pff's in AuAu collisions

to get medium induced energy loss effects into $2 \to \{2,\ 3\}$ xsecs we use modified pff proposed by Zhang et al [PRL98 (2007)]:

$$D_{h/i}(z_i, \mu^2) = (1 - e^{-\langle \frac{L}{\lambda} \rangle}) \left[\frac{z_i'}{z_i} D^0_{h/i}(z_i', \mu^2) + \langle \frac{L}{\lambda} \rangle \frac{z_g'}{z_i} D^0_{h/g}(z_g', \mu^2) \right] + e^{-\langle \frac{L}{\lambda} \rangle} D^0_{h/i}(z_i, \mu^2)$$

$z_i' = \frac{h_t}{(b_{ti} - \Delta E_i)}$ rescaled momentum fraction of the leading parton with flavor i

$z_g' = \langle \frac{L}{\lambda} \rangle \frac{b_t}{\Delta E_i}$ rescaled momentum fraction of the radiated gluon

$\langle \frac{L}{\lambda} \rangle$ average number of scatterings

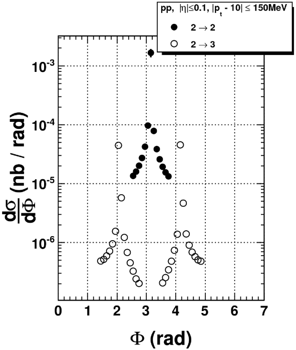
average radiative parton energy loss

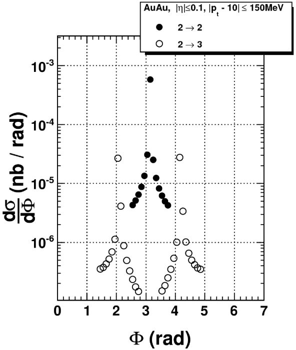
$\Delta E \propto \langle \frac{dE}{dL} \rangle_{1d} \int_{\tau_0}^{\infty} d\tau \Delta\tau \, \rho_g(\tau, \vec{r}_t + \vec{n}\tau)$

most central collisions: $\vec{b}_\perp = 0$

the xsections

2 → 2 and 2 → 3 angular distribution of the away side hadron(s)



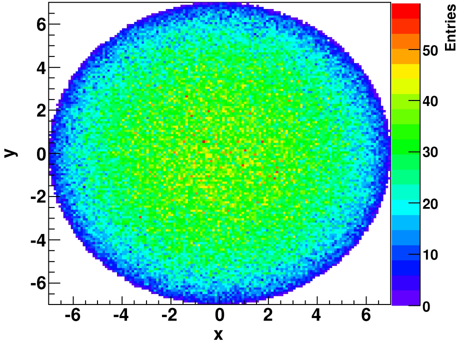


$$\frac{\text{AuAu}: \ \frac{2\to 3}{2\to 2}}{\text{pp}: \ \frac{2\to 3}{2\to 2}} \sim 2.26$$

the xsections

- the sole ingredient that distinguishes pp from AA calculation is the energy loss of partons that hadronize collinearly
- so this must be happening because of the different geometry for the trajectories of 3 as opposed to 2 particles in the final state
- let us test this idea: compute distribution of path lengths

the path



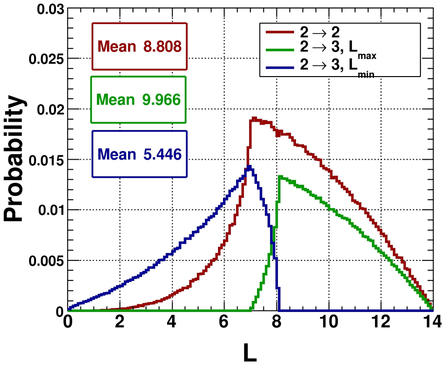
nuclear overlap area with a distribution of scattering centers denser in the middle and decreasing toward the edge

the path

distribution of away side partons' path lengths
for 2 ► 2 and 2 ► 3 processes

disregard shortest path length: trigger particle

compute the distribution of the other path lengths: away side particles



the path length

- $L^{2\to 3}_{\mathrm{min}} < L^{2\to 2} < L^{2\to 3}_{\mathrm{max}}$

the path length

- $L_{min}^{2\to3} < L^{2\to2} < L_{max}^{2\to3}$
- so, in the case of 3 particle final state, even if one of the non-leading particles gets absorbed by the medium (the one with the largest path length), the remaining particle has a large probability of punching through, compared to a 2 particle final state

the path length

- $L^{2\to3}_{min} < L^{2\to2} < L^{2\to3}_{max}$
- so, in the case of 3 particle final state, even if one of the non-leading particles gets absorbed by the medium (the one with the largest path length), the remaining particle has a large probability of punching through, compared to a 2 particle final state

we argue that...

in $2 \to 3$ processes, there is a large probability to have one of the two away side particles being absorbed and the other randomly getting out, producing on the average a double hump

In summary

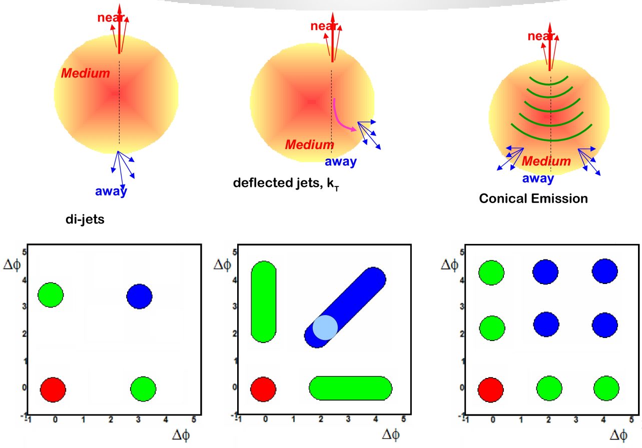
1. $2 \to 3$ processes are there and we should see them in current experiments
2. in fact their observation should be enhanced w.r.t. strongly suppressed $2 \to 2$
3. this effect may have bearing on the away side shape for different kinematical cuts in AuAu collisions
4. need 3 particle correlation measurements to distinguish between different scenarios that might be responsible for this shape in 2 particle correlation studies (see talk by Jason Glyndwr Ulery on Tuesday)

Work in progress!

EXTRAS

Jason Glyndwr Ulery (IKF)

$\Delta\phi$–$\Delta\phi$ 3-Particle Correlations



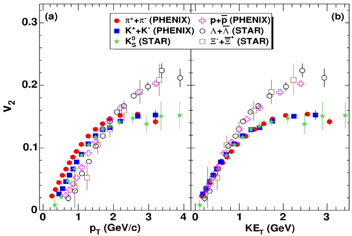
Elliptic flow from experiments

- elliptic flow in AuAu collisions at $\sqrt{s_{NN}} = 200$GeV indicate local thermal equilibrium established in $\tau < 2$fm/c (compare with $\tau \sim 0.1$fm/c which is the time it takes for Lorentz-contracted nuclei to pass each other in such collisions) [Kolb and Heinz, 2003]
- a more differential study: azimuthal anisotropy of final state particles for different particle species

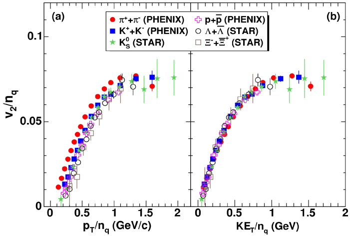
Elliptic flow from experiments

- the magnitude of elliptic flow scales with the number of constituent quarks which indicates that the thermalized system flow is best described with **partonic degrees of freedom**
  [PHENIX, A. Adare, et al Phys.Rev.Lett.98:162301,2007]

v_2 vs p_T and KE_T



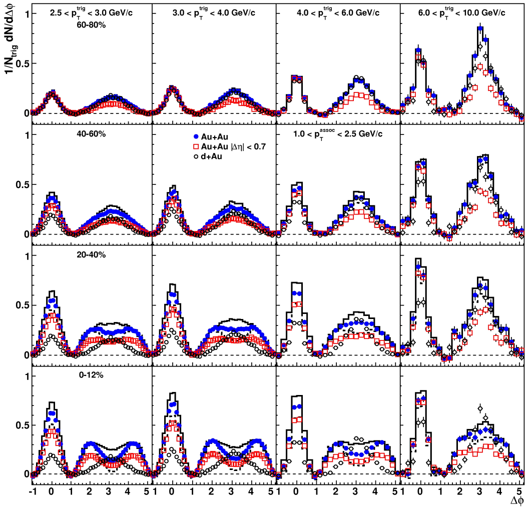
v_2 vs p_T/n_q and KE_T/n_q



Elliptic flow v_2 as a function of p_T and transverse kinetic energy KE_T for several identified species in 20-60% most central AuAu collisions at 200 GeV

A puzzle in correlation studies

STAR, Phys.Rev.C82:024912,2010. e-Print: arXiv:1004.2377 [nucl-ex]



Solving the puzzle

- several theoretical models used to look for origins of such structures, e.g.
  - momentum kick [C.-Y. Wong, PRC78:064905, 2008]
  - back splash from stopped parton [V. S. Pantuev, arXiv:0710.1882, 2007]
  - long range correlations [S. Gavin et al, PRC79:051902, 2009]
  - glasma flux tubes [A. Dumitru et al, NPA810:91, 2008]
  - Mach cone shock waves [J. Ruppert et al, APPS1:633, 2008]
  - transverse radial flow [C.A. Pruneau et al, NPA802:107, 2008]
  - parton recombination [R.C. Hwa, arXiv:0904.2159, 2009]
  - triangularity and triangular flow [B. Alver et al, PRC81:054905, 2010]

Use modified pff's in AuAu collisions

The average number of scatterings:

$$\langle \frac{L}{\lambda} \rangle = \int_{\tau_0}^{\infty} d\tau \frac{1}{\lambda_0 \, \rho_0} \, \rho_g(\tau, \vec{b}_\perp, \vec{r}_t + \vec{n}\tau).$$

The one dimensional energy loss $\langle \frac{dE}{dL} \rangle_{1d}$ is parameterized as

$$\langle \frac{dE}{dL} \rangle_{1d} = \epsilon_0 \Big[\frac{b_t}{\mu_0} - 1.6 \Big]^{1/2} \Big[7.5 + \frac{b_t}{\mu_0} \Big]^{-1}.$$

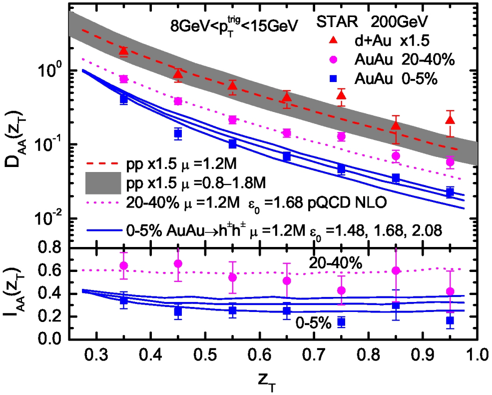
The gluon density of the medium ρ_g is related to the nuclear geometry of the produced medium and taken to be

$$\begin{aligned} \rho_g(\tau, \vec{b}_\perp, \vec{r}_t + \vec{n}\tau) &= \frac{\tau_0 \, \rho_0}{\tau} \frac{\pi R_A^2}{2A} \Big[t_A(\vec{r}_t + \vec{n}\tau) \\ &+ t_A(\vec{b}_\perp - \vec{r}_t - \vec{n}\tau) \Big], \end{aligned}$$

and t_A is the nuclear thickness function with a Woods-Saxon profile.

modified PFFs

Zhang et al [PRL98 (2007)



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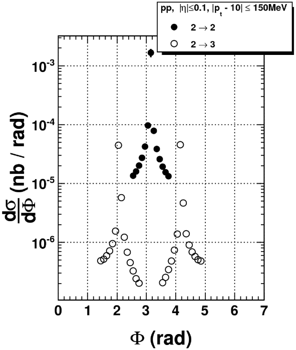

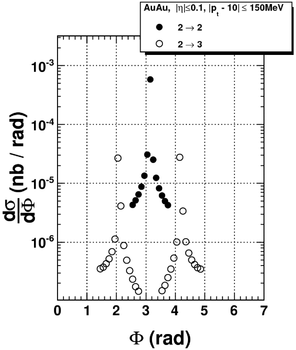

2 and 3 hadron production

mid-rapidity pp and AuAu collisions at 200 GeV

each of the three hadrons with hT = 10 GeV/c

fragmentation is collinear to the direction of the original parton

final hadrons are separated by an angle $\Delta\varphi = 2\pi/3$ radians