Understanding RHIC Collisions

Modified QCD fragmentation *vs* quark coalescence from a thermalized flowing medium

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Agenda

- Parton fragmentation in spectra and correlations
  - Spectrum hard components and pQCD
  - Minijet correlations and pQCD
- Paradigm challenges for spectrum analysis
  - Jet quenching and R_{AA}
  - Anomalous p/π ratio
  - Radial flow
- Paradigm challenges for correlation analysis
  - p_t-integral elliptic flow
  - p_t-differential elliptic flow

Parton Fragmentation in Spectra

pQCD-calculated <u>fragment distributions</u> **– FD**

vs

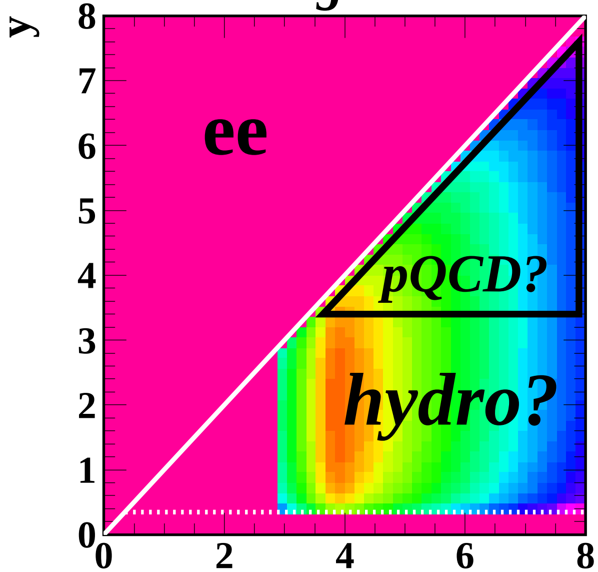
measured spectrum <u>hard components</u> **– H_{xx}**

$$\mathbf{y = \ln\{(E + p)/m_\pi\}}$$

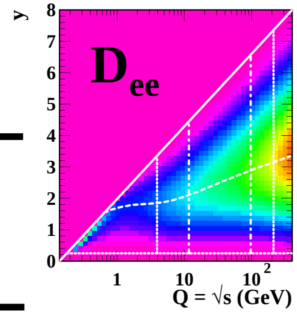
$$\mathbf{y_t = \ln\{(m_t + p_t)/m_\pi\}}$$

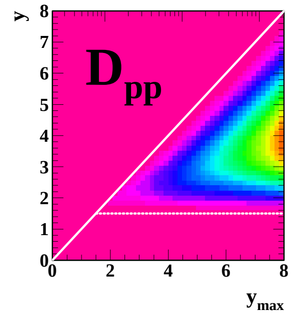
pQCD Folding Integral → FDs

integrand

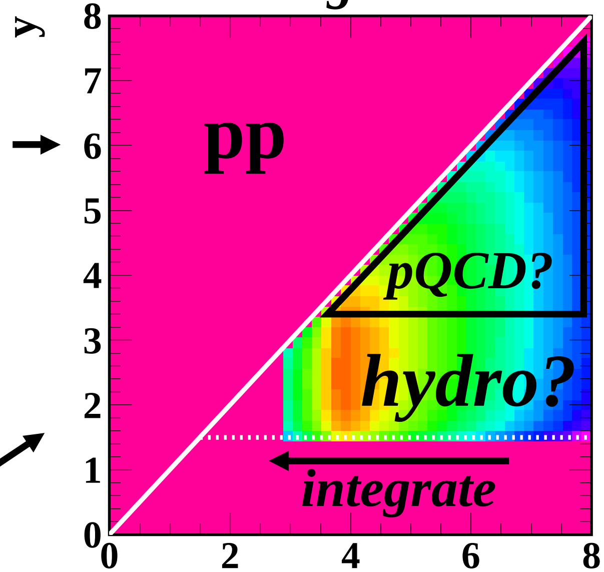


measured FF ensembles



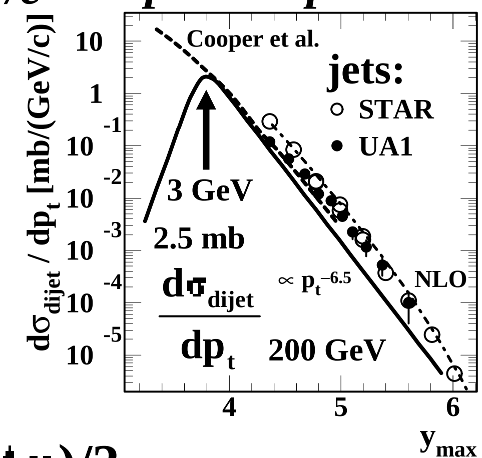


integrand



2 GeV/c

parton spectrum

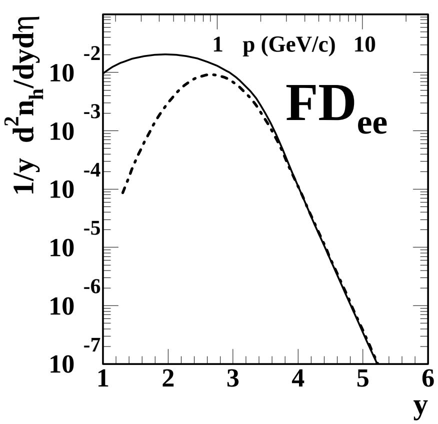


$\ln(2E_{jet}/m_\pi) = y_{max}$

y_{max}

PRC 80, 044901 (2009)

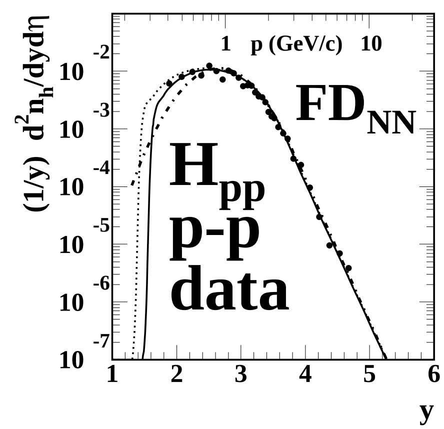
problem



$$\frac{d^2n_h}{dy\,d\eta} \approx \frac{\varepsilon_j(\Delta\eta)/2}{\sigma_{NSD}\Delta\eta_{4\pi}} \int_0^\infty dy_{max} D_{xx}(y, y_{max}) \frac{d\sigma_{dijet}}{dy_{max}}$$

FD *FF*

integrand



***fragment distributions* (FDs) ↔**
***spectrum hard components* (H_{xx})**

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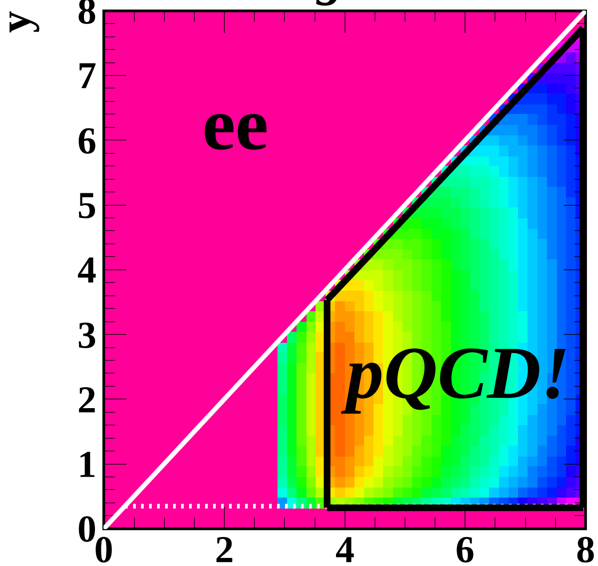
pQCD Folding Integral → FDs

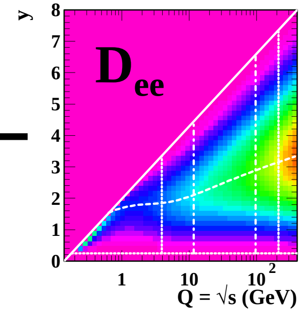
integrand

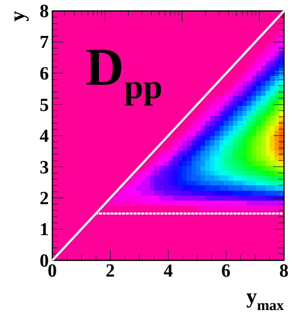


$\ln(2E_{jet}/m_\pi) = y_{max}$

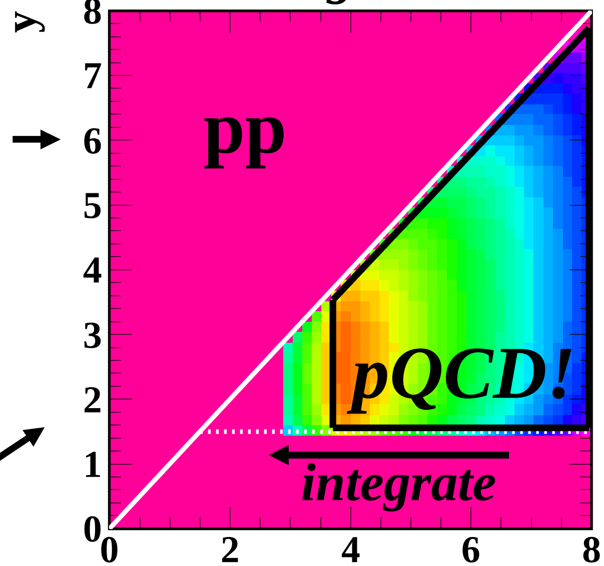
PRC 80, 044901 (2009)

measured FF ensembles



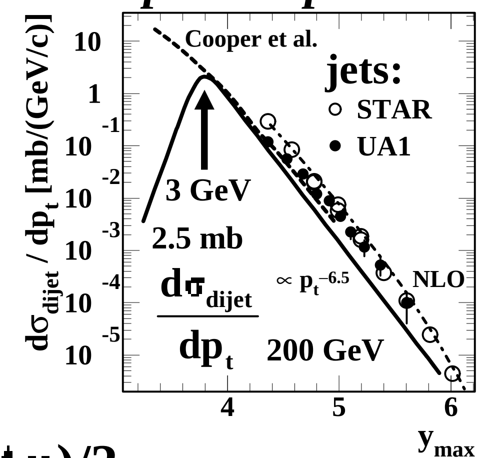


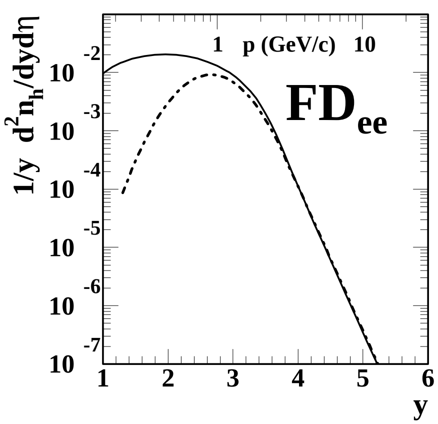
integrand



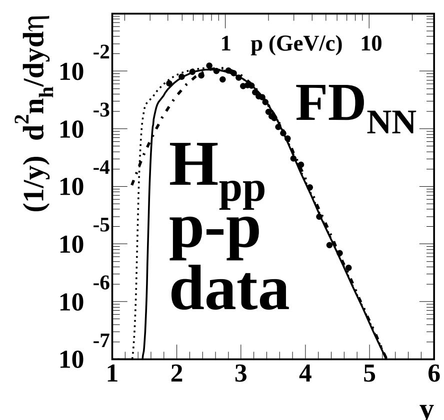
y_{max}

parton spectrum





$$\underbrace{\frac{d^2 n_h}{dy\,d\eta}}_{\text{FD}} \approx \frac{\epsilon_j(\Delta\eta)/2}{\sigma_{NSD}\Delta\eta_{4\pi}} \int_0^\infty \underbrace{dy_{max} \underbrace{D_{xx}(y, y_{max})}_{FF} \frac{d\sigma_{dijet}}{dy_{max}}}_{\text{integrand}}$$



***fragment distributions* (FDs) ↔**

***spectrum hard components* (H_{xx})**

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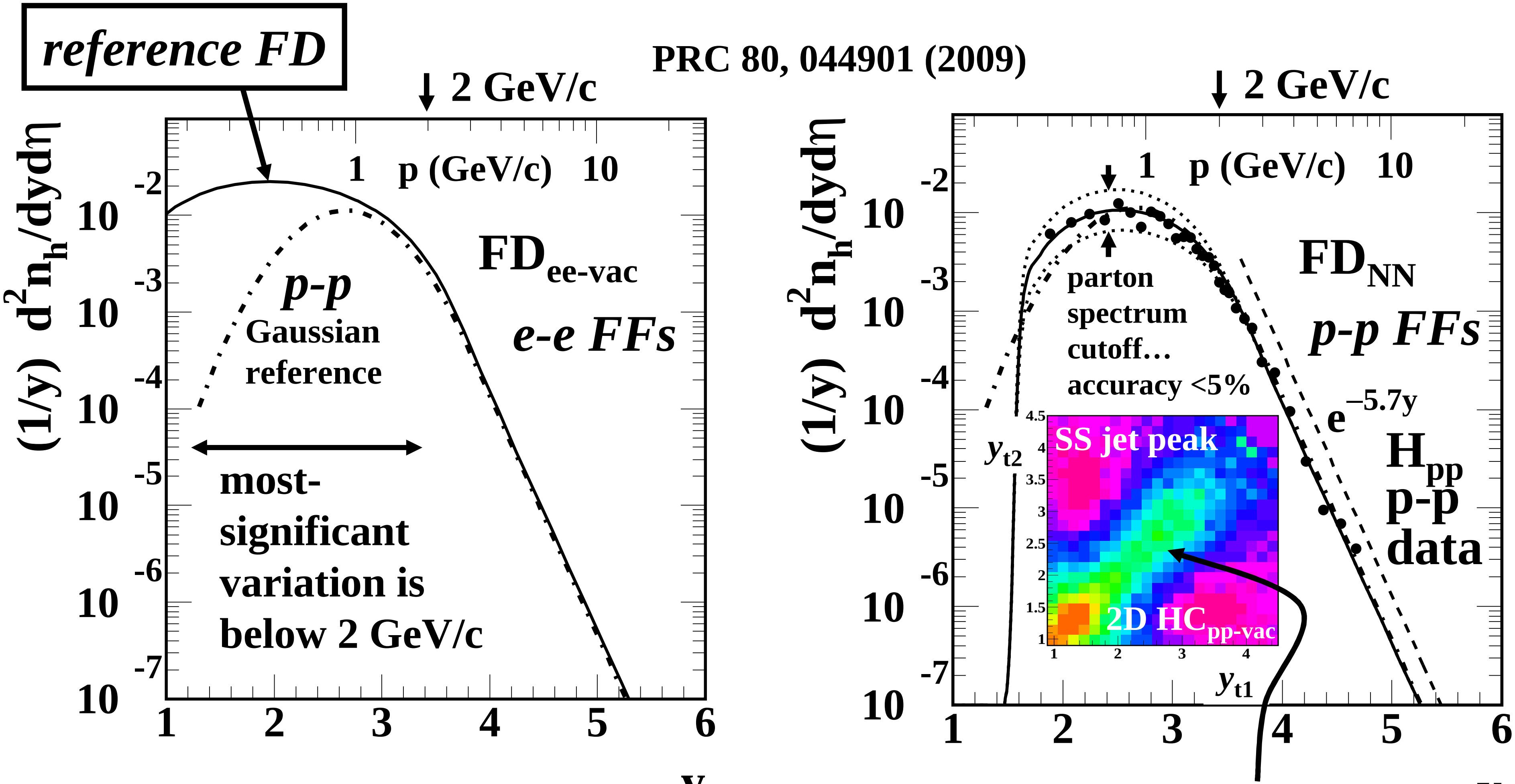
Fragment Distributions – FDs



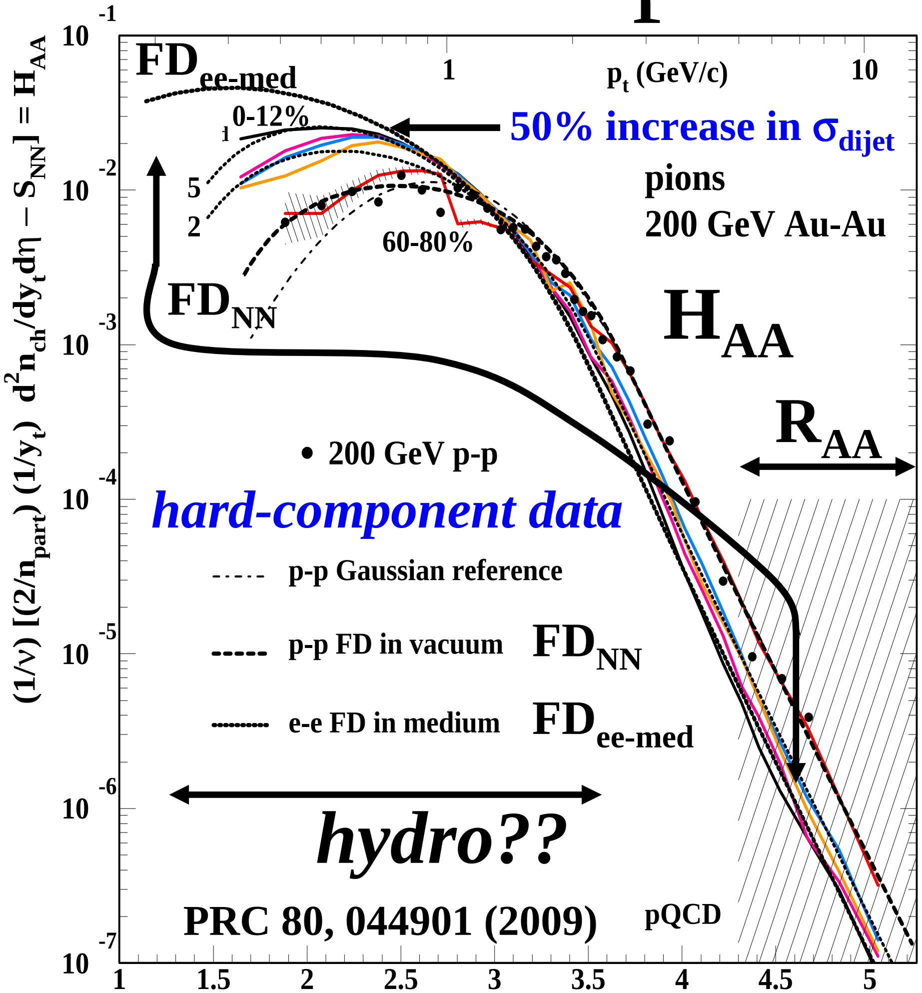
3 GeV parton spectrum cutoff

p-p intrajet correlations

PoS CFRNC2006 004 (2006)

$FD_{ee\text{-}vac}$ – reference for H_{AA} evolution

Hard Component Evolution – H_{xx}

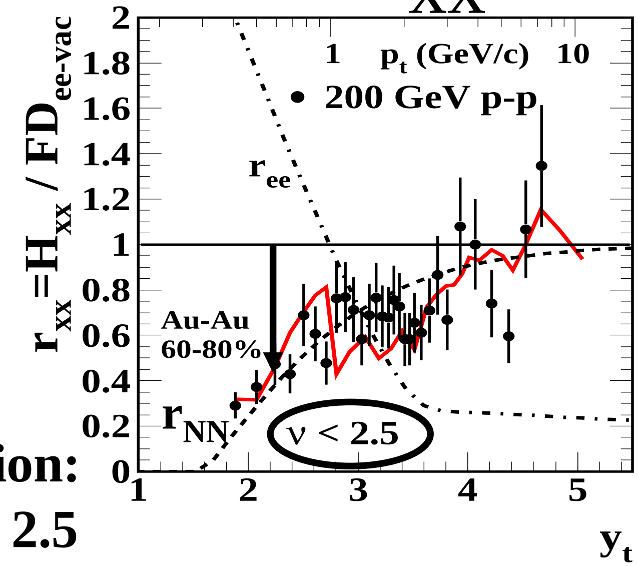


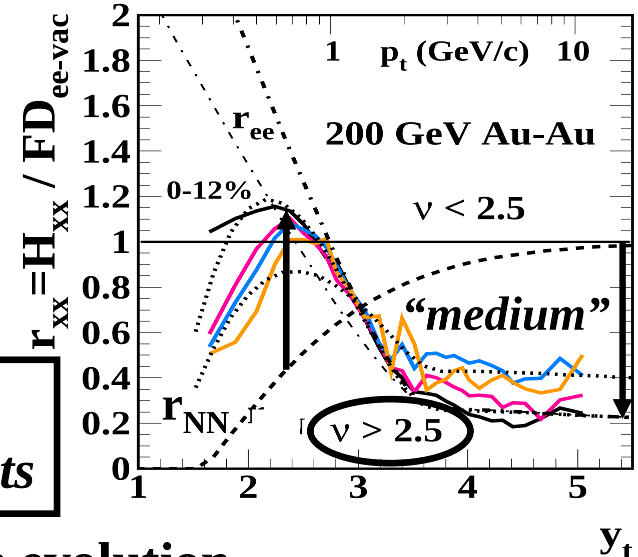
$$r_{ee} = \frac{FD_{ee\text{-}med}}{FD_{ee\text{-}vac}}$$

$$r_{NN} = \frac{FD_{NN}}{FD_{ee\text{-}vac}}$$

sharp transition: centrality $\nu \sim 2.5$

$$\nu = \frac{2n_{bin}}{n_{part}}$$





all partons survive as jets

$$\frac{2}{n_{part}}\frac{1}{y_t}\frac{dn_{ch}}{dy_t} = S_{NN}(y_t) + \nu H_{AA}(y_t, b)$$

↔ **fragmentation evolution**

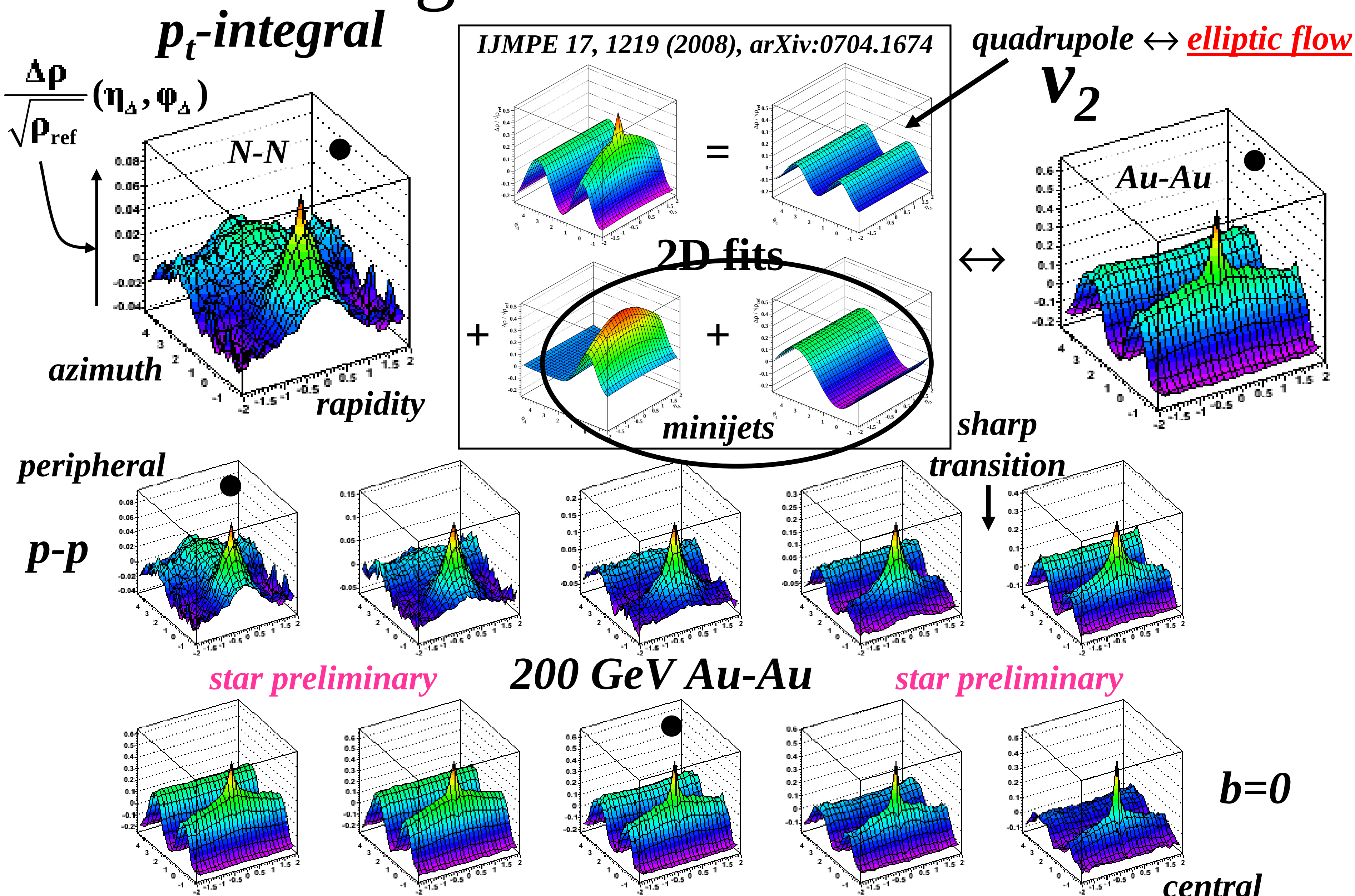
pQCD describes A-A spectrum hard-component evolution

Parton Fragmentation in Correlations

Minijet phenomenology

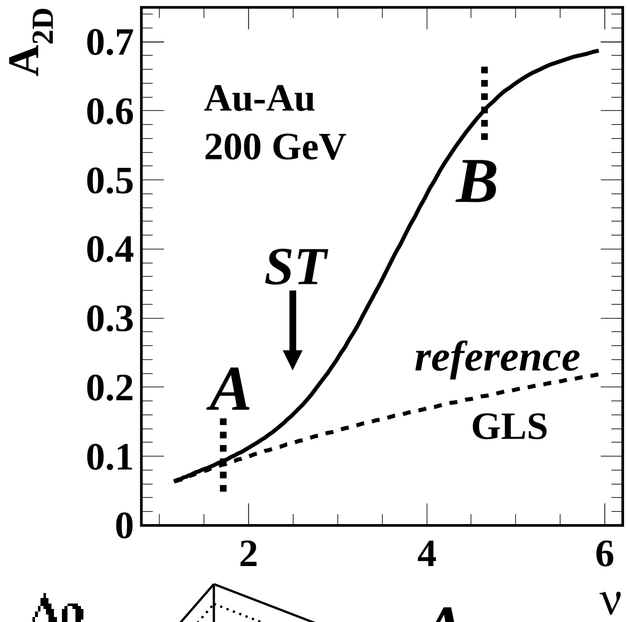
Minijets and hadron production

2D Angular Autocorrelations



JPhysG 35, 104090 (2008)

Jet Angular Correlations – 200 GeV Au-Au



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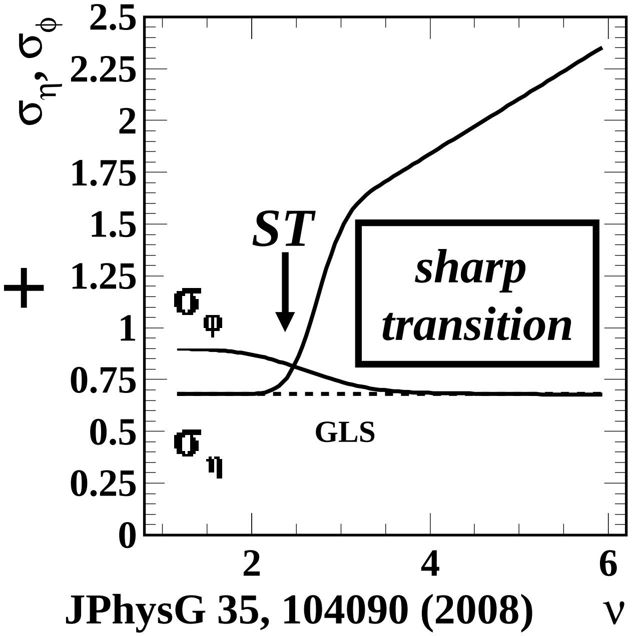

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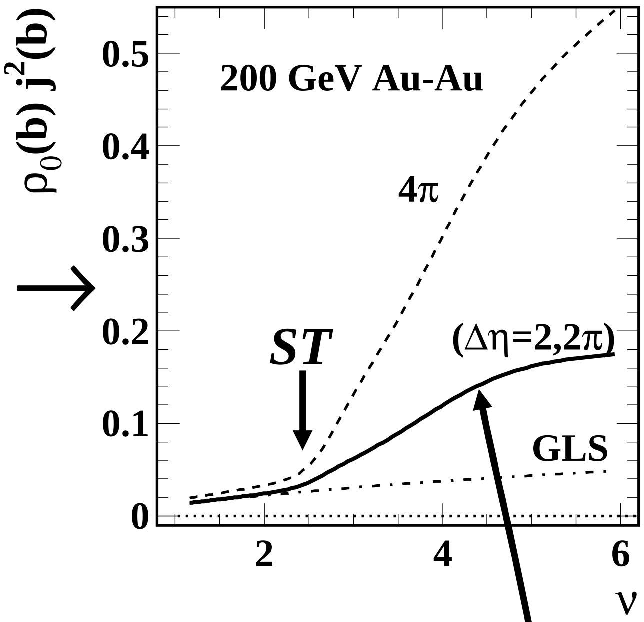
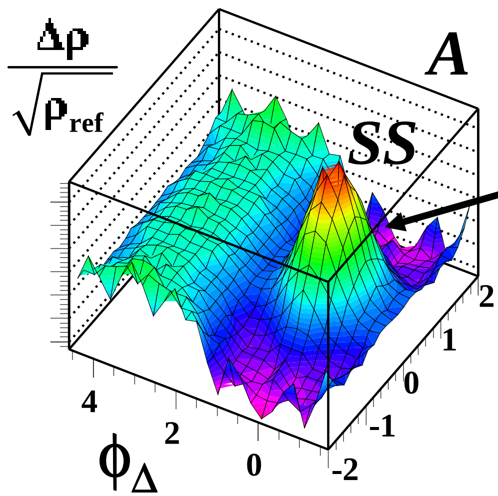
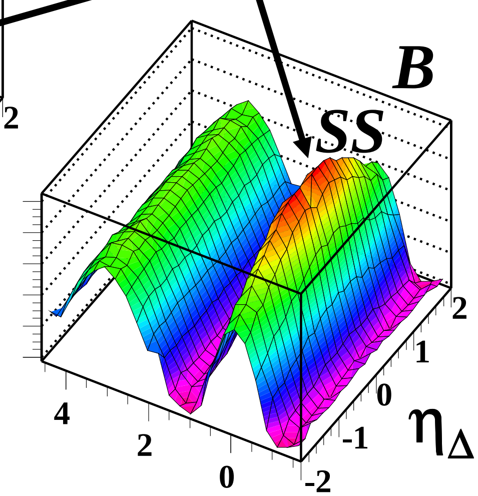


JPhysG 35, 104090 (2008)



$$\rho_0(b) j^2(\eta_\Delta, \phi_\Delta, b) = A_{2D}\ \exp\{-\phi_\Delta^2/2\sigma_\phi^2\}\ \exp\{-\eta_\Delta^2/2\sigma_\eta^2\}$$

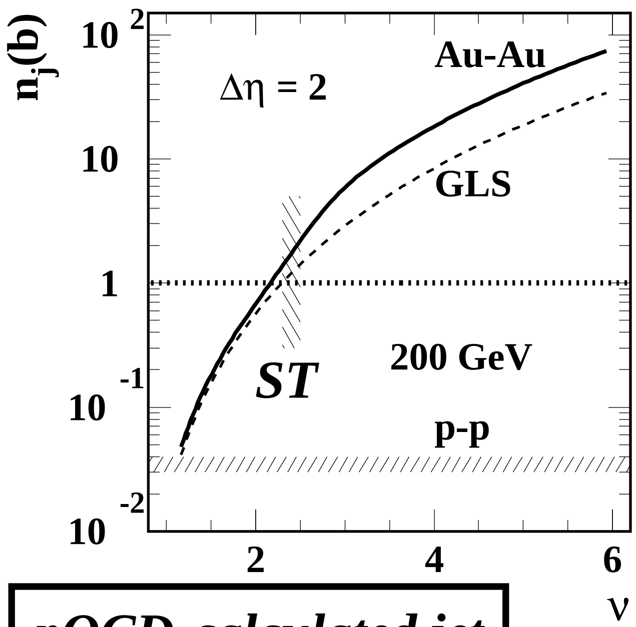


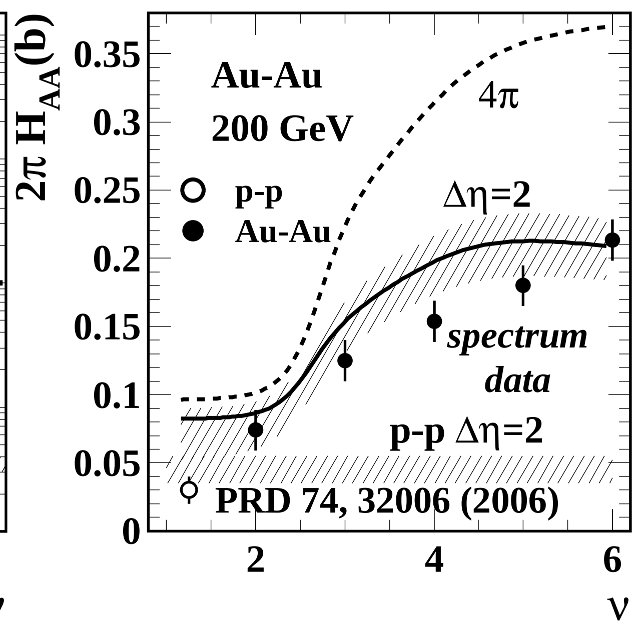
same-side jet peak:
all jet fragment pairs

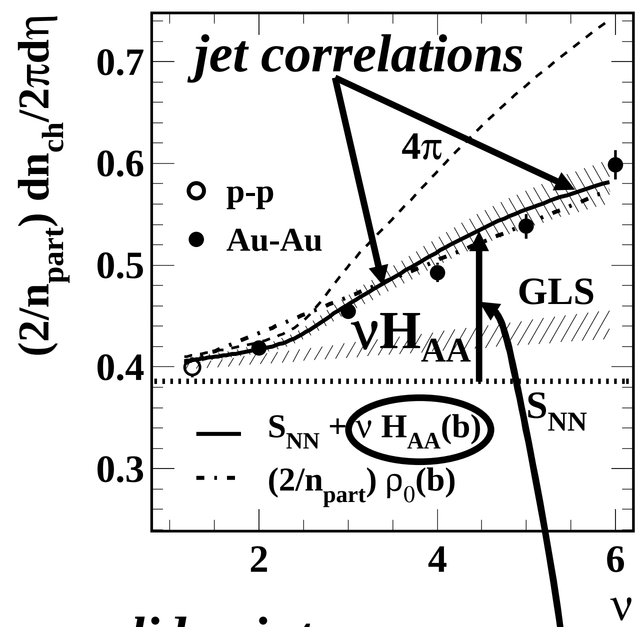
no "ridge"
no "Mach cones"

<u>angle-averaged</u>
pair ratio within angular acceptance

Final-state Hadrons from Jets







pQCD-calculated jet number in A-A

$$\frac{dn_h}{d\eta} \equiv 2\pi H_{AA} = f(b) \times n_{ch,j}(b)$$

solid points:

JPhysG 34, 799 (2007) ***spectra***

jet fragment yield

total single-particle density

$$f(b) = (1/n_{bin})\, n_j(b)/\Delta\eta$$

$$\nu H_{AA}(b) = \frac{2}{n_{part}} \rho_0(b) \sqrt{n_j(b) \times j^2(b)}$$

hard-component yield from jets

$$n_{ch,j}(b) = n_{ch}(b) \sqrt{j^2(b)/n_j(b)}$$

1/3 of all hadrons in 200 GeV central Au-Au collisions are contained within <u>resolved jets</u>

arXiv:1008.4759

Paradigm Tests and Spectrum Structure

Jet quenching / R_{AA}

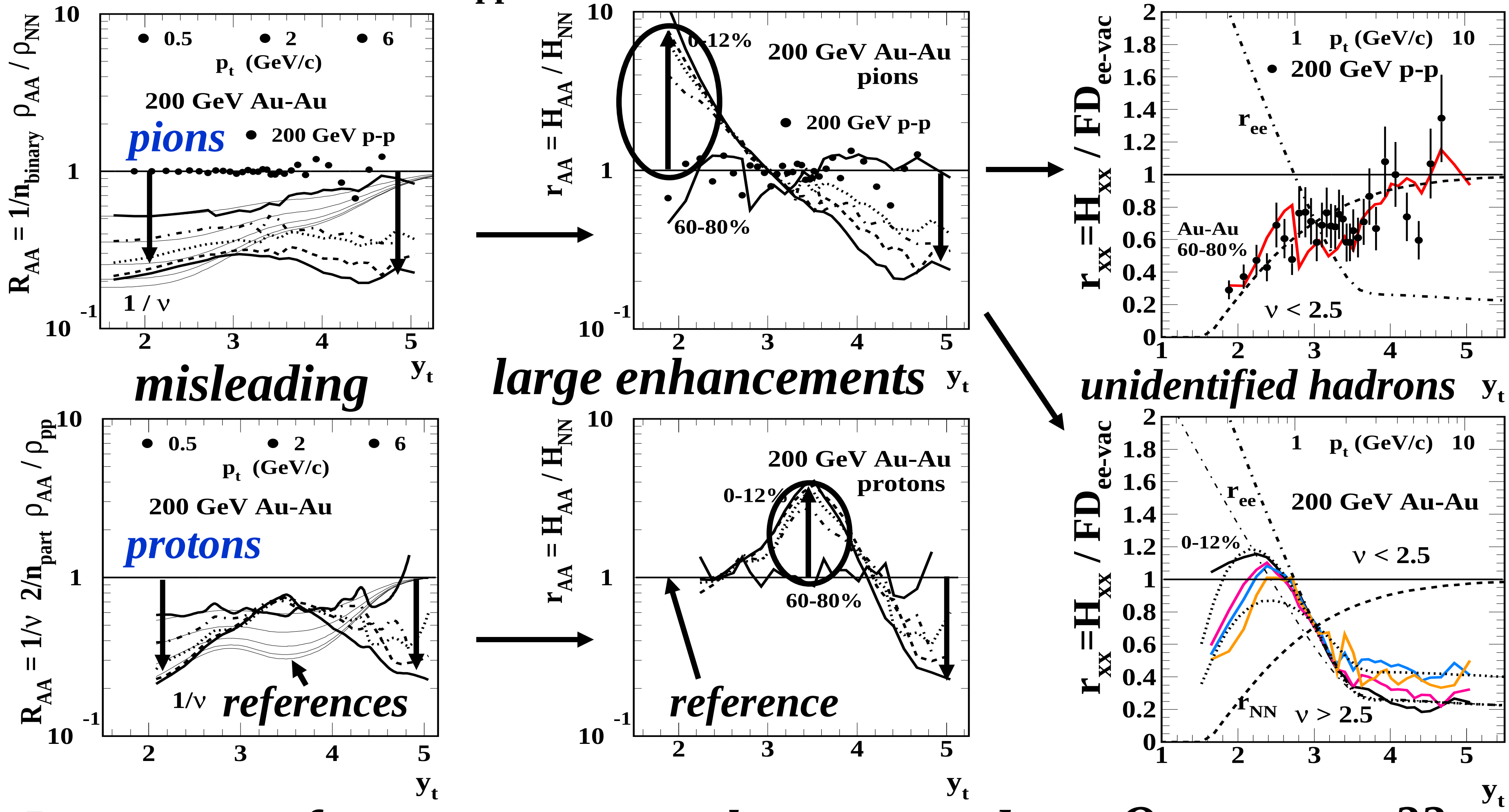
p/π ratio

Radial flow

fragmentation vs recombination vs hydrodynamics

Jet quenching / R_{AA} $(2/n_{part})\,\rho_{AA} = S_{NN}(y_t) + \nu H_{AA}(y_t, b)$

$R_{AA}=(1/n_{bin})\,\rho_{AA} / \rho_{pp}$ $\quad$ $r_{AA}=H_{AA} / H_{NN}$ $\quad$ $r_{xx}=H_{xx} / FD_{ee\text{-}vac}$

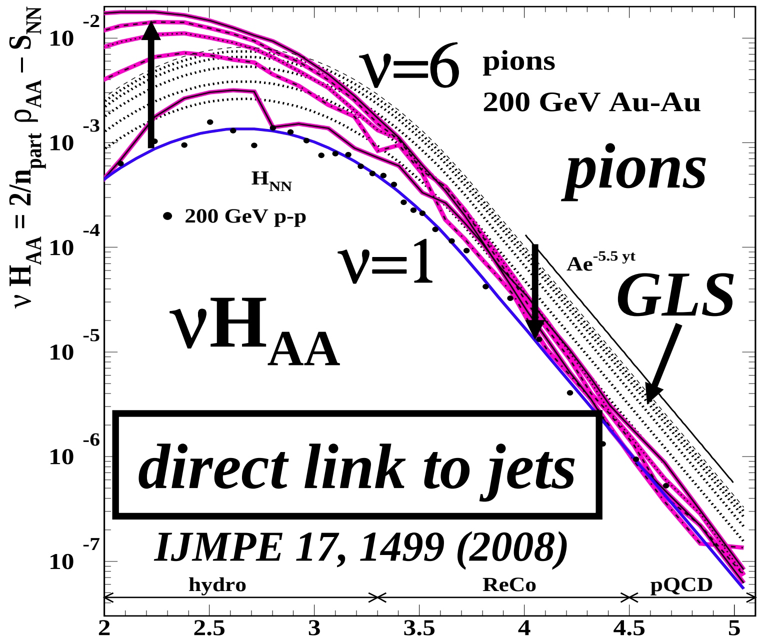


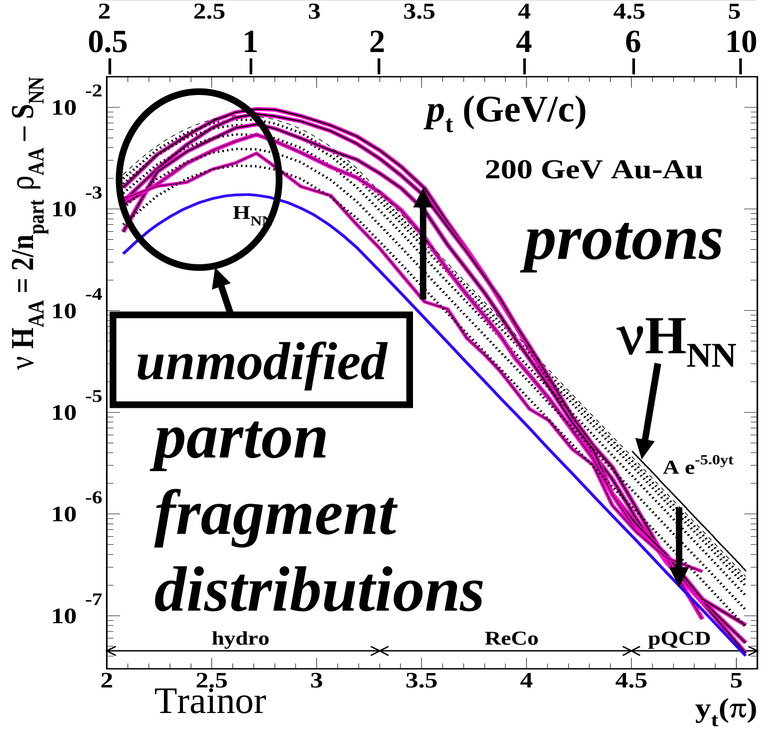
R_{AA}: parton fragments apparently suppressed

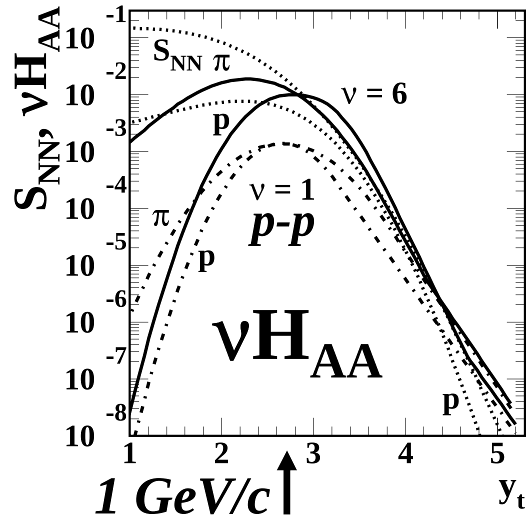
large fragmentation <u>increase</u> in central collisions

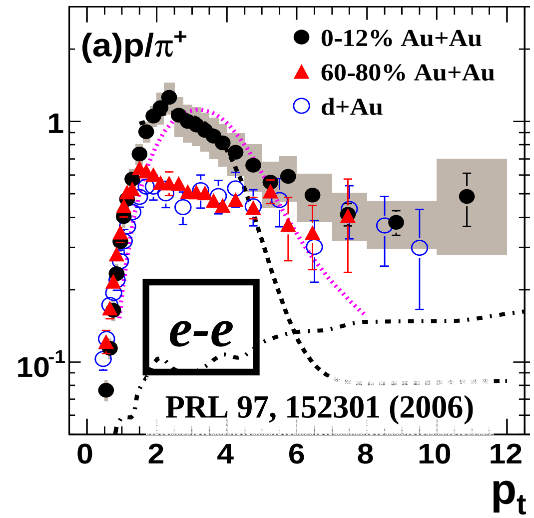
p/π Ratio

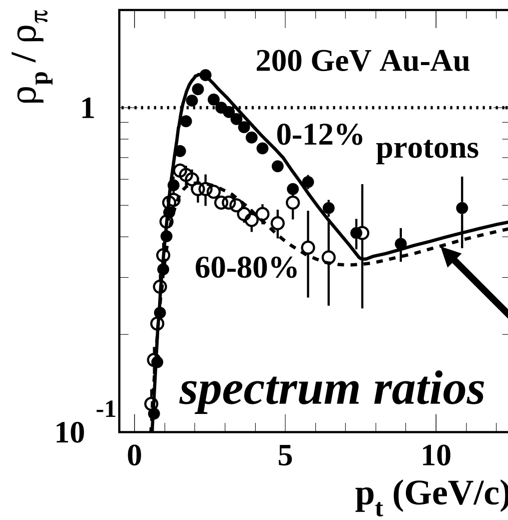
spectrum hard components

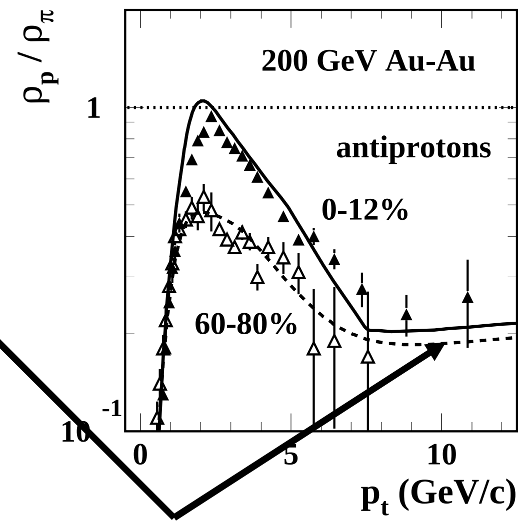












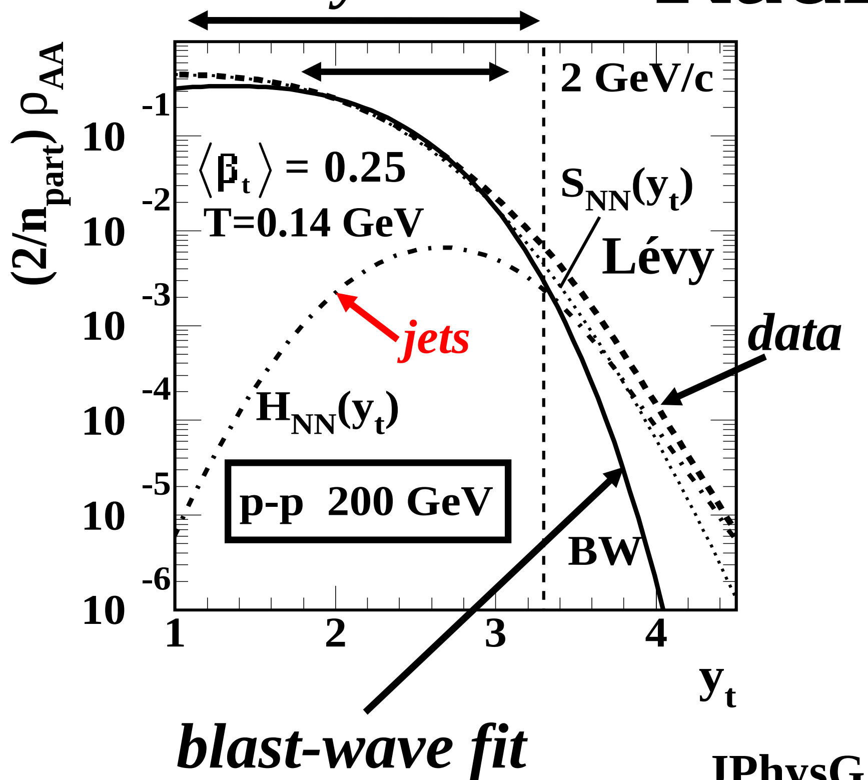
two-component description

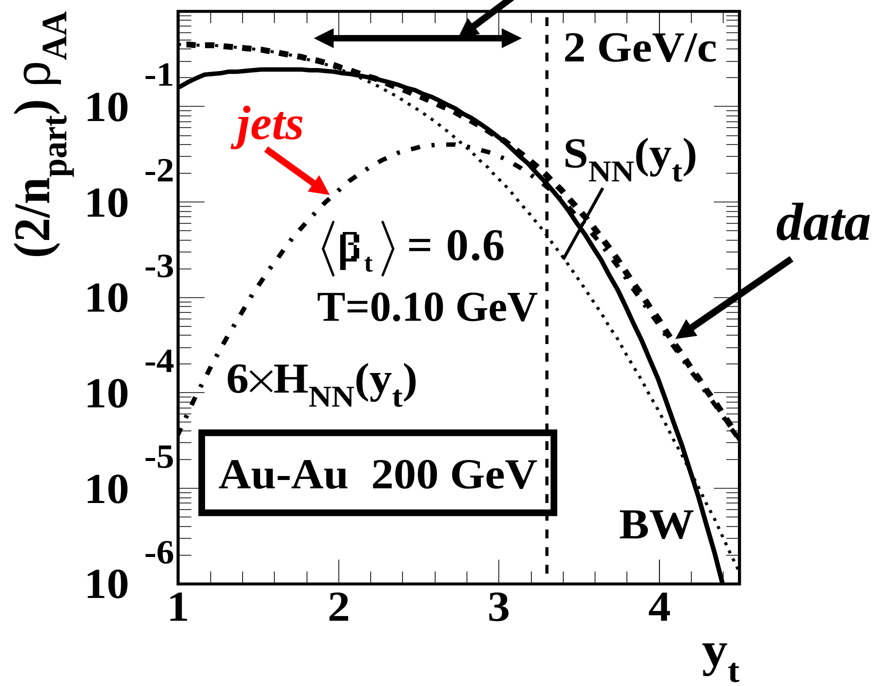
B/M anomaly is a consequence of modified fragmentation

Radial Flow

hydro?

fit interval

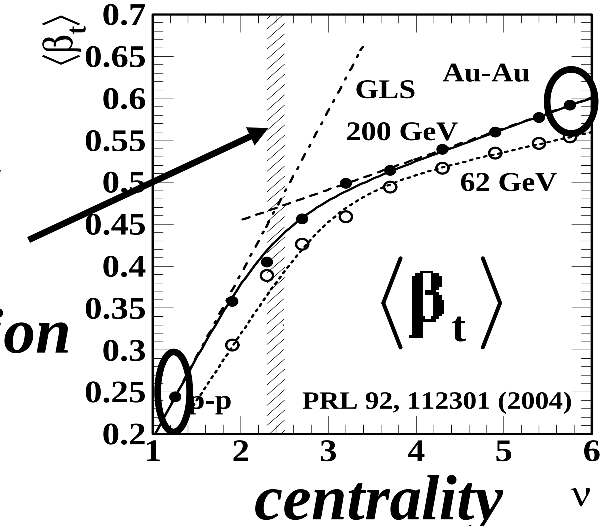




JPhysG 37, 085004 (2010)

blast-wave fits accommodate parton fragment distributions

minijet sharp transition



"radial flow" is a jet manifestation

Paradigm Tests and Correlation Structure

Azimuth quadrupole correlations: "Elliptic Flow"

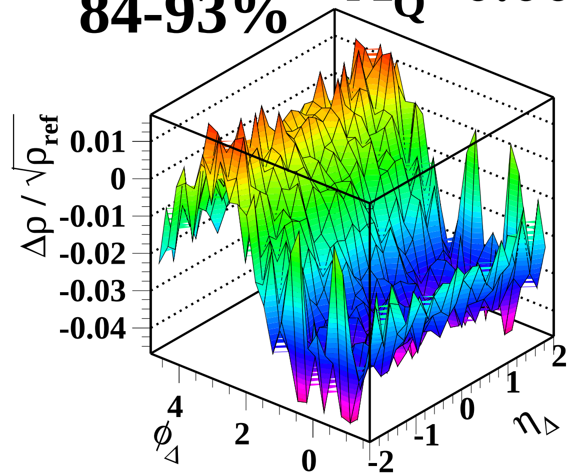
p_t integral

p_t differential

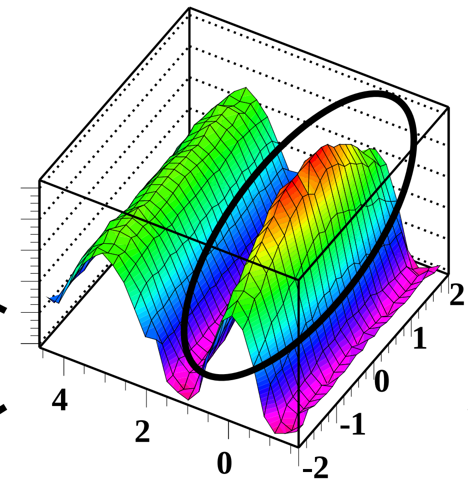
$v_2\{2D\}$ η_Δ-independent Structure

N-N ~ p-p ***quadrupole***

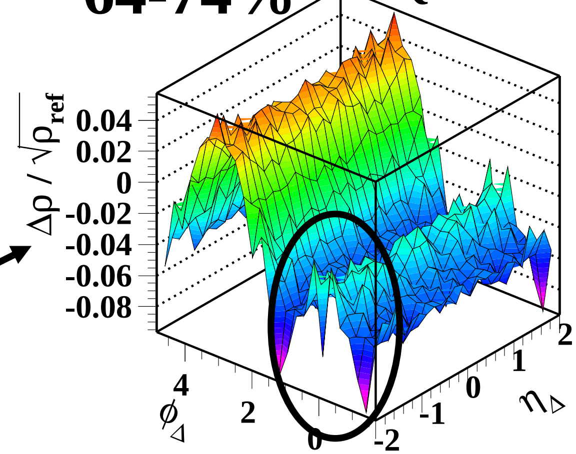
84-93% **A_Q=0.002**



200 GeV Au-Au



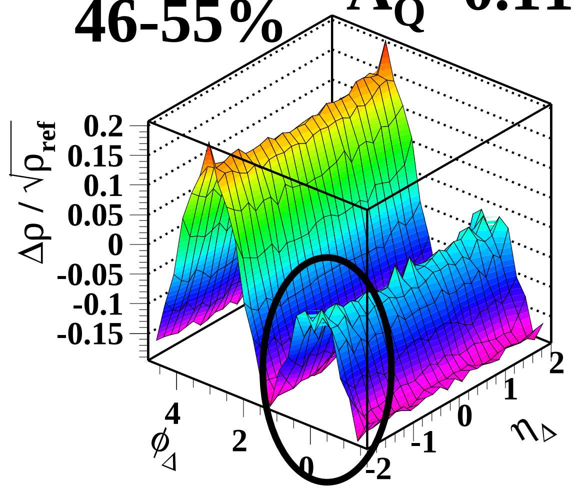
64-74% **A_Q=0.026**



remove fitted SS 2D jet peak

***v_2*{2D}**

46-55% **A_Q=0.117**

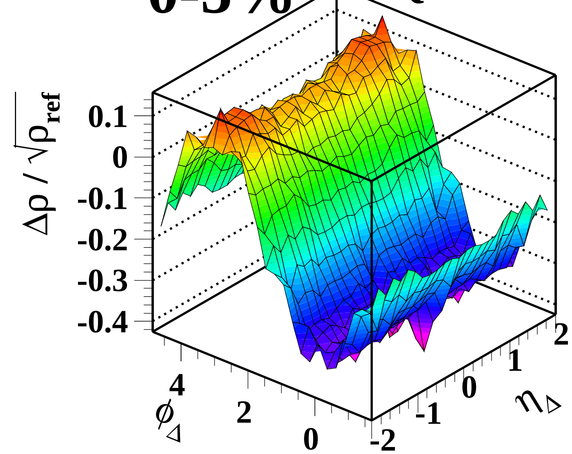


dipole *vs* quadrupole

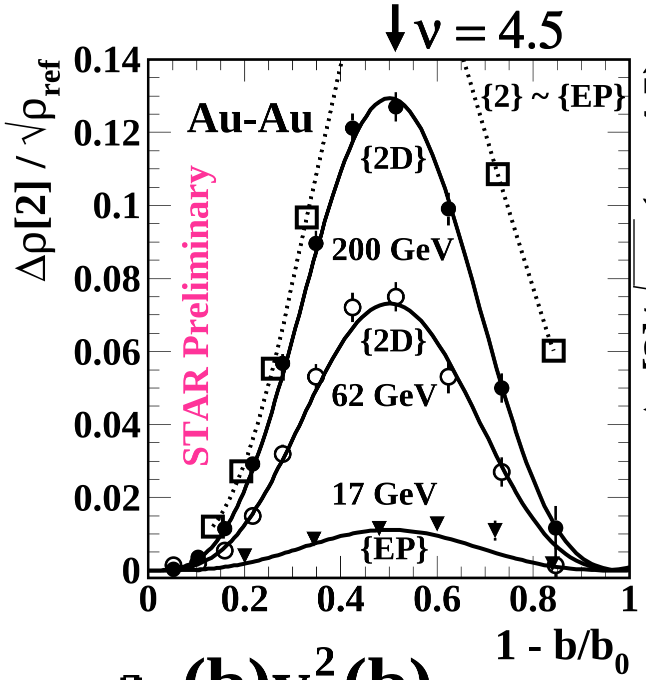
two <u>orthogonal</u> components

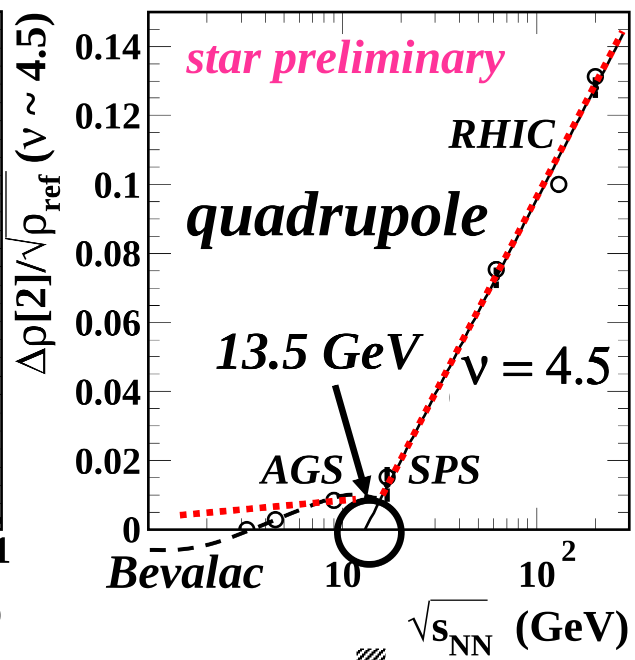
separated without ambiguity

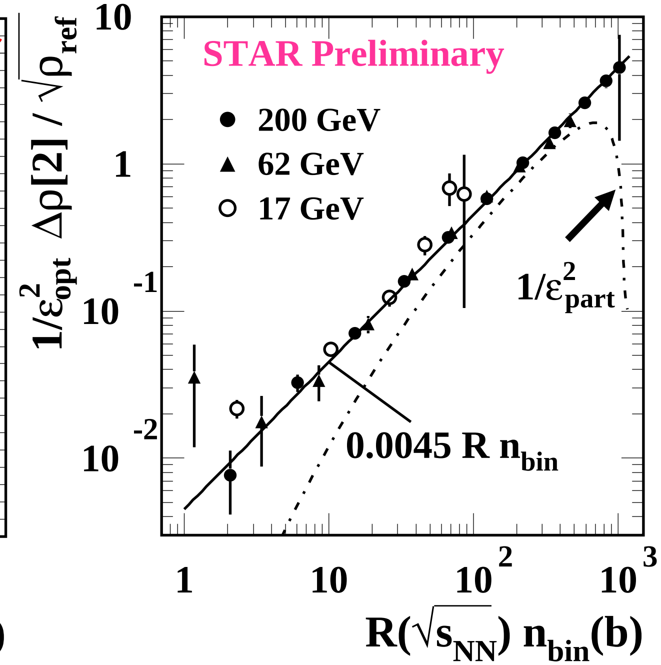
0-5% **A_Q=0.008**



Systematics of p_t-integral $v_2\{2D\}(b)$







$\rho_0(b) v_2^2(b)$

optical eccentricity

nucleon MD → ▨ → *low-x glue*

Eur Phys J C 62, 175 (2009); arXiv:0907.2686

compare with jets: $\rho_0(b) j_2^2(b)$

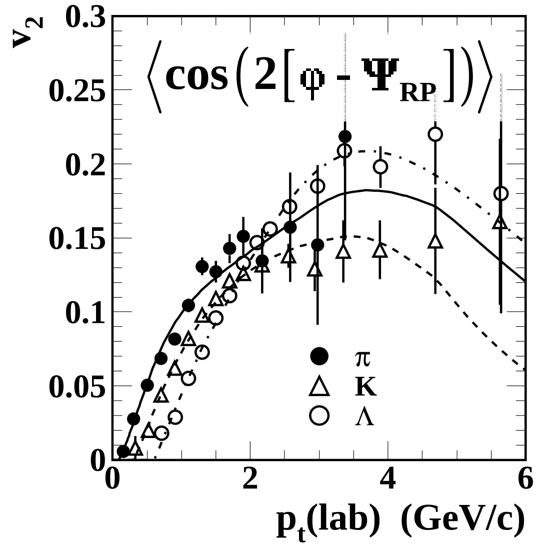
$\rho_0(b)$ single-particle density

$$\frac{\Delta\rho[2]}{\sqrt{\rho_{ref}}} = 0.0045\, R\left(\sqrt{s_{NN}}\right) \varepsilon_{opt}^2(b)\, n_{bin}(b)$$

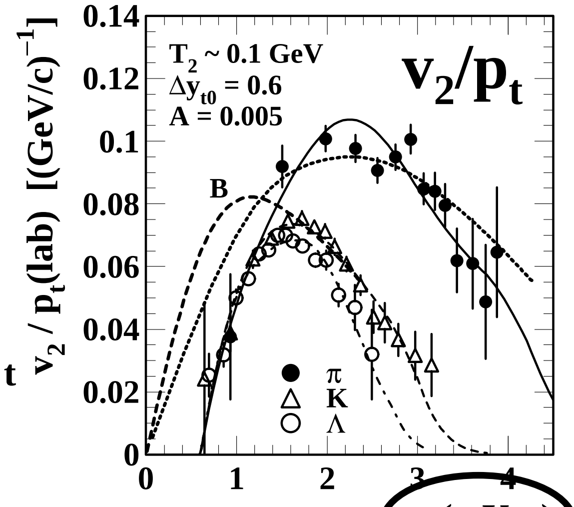
bold solid curves

centrality and energy dependence factorize

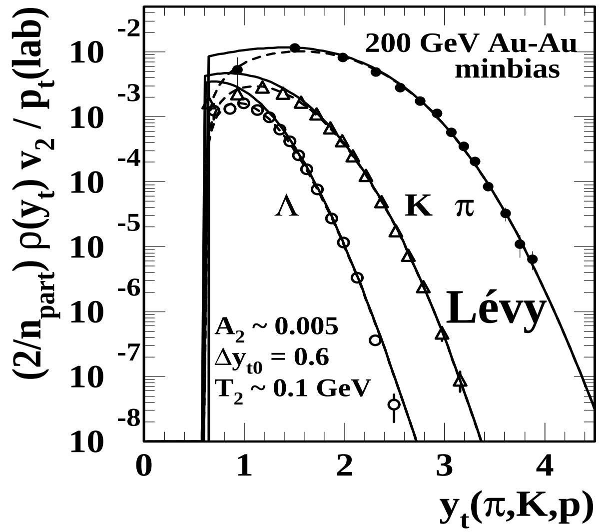
Published Minimum-bias $v_2(p_t)$



$\div \vec{p}_t$



$\times \vec{\rho}_0$

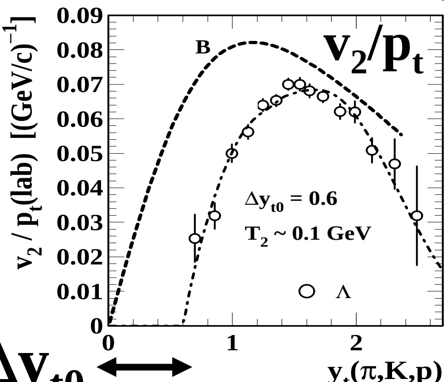


PRC 66, 034904 (2002)
PRL 92, 052302 (2004)

B: viscous hydro

quadrupole spectra

PRC 78, 064908 (2008)

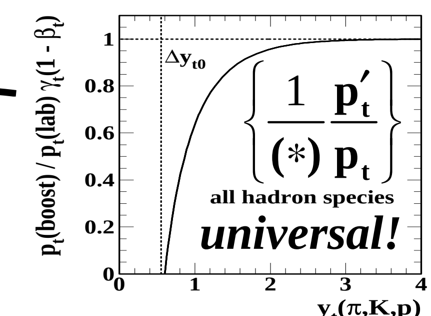


what is source boost distribution B(Δy_{t0})?

very simple systematics

narrow boost distribution… what centrality dependence?

boost Δy_{t0}



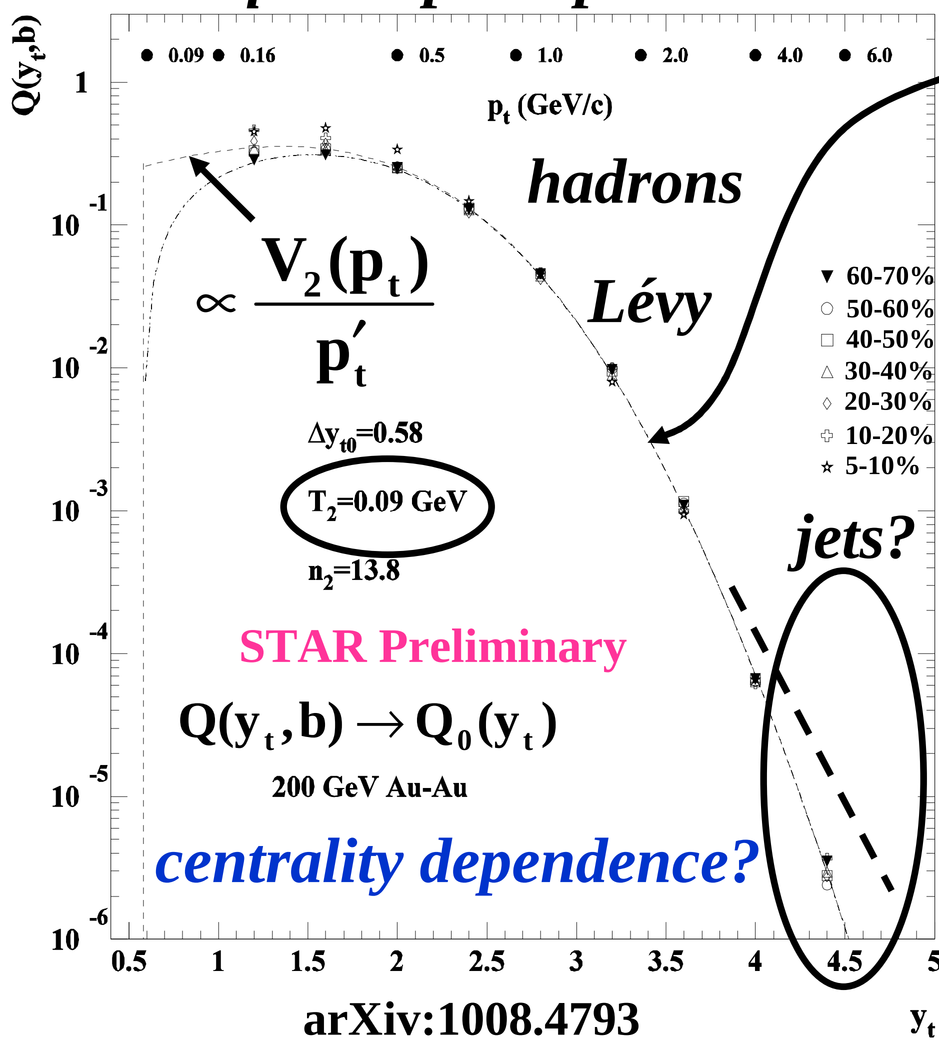
$$\frac{v_2(p_t)}{p_t} = \frac{(*)}{\rho_0(y_t, b)} \int d\Delta y_{t0} B(\Delta y_{t0}) \left\{ \frac{1}{(*)} \frac{p_t'}{p_t} \right\} \frac{1}{p_t'} V_2(y_t, \Delta y_{t0}, b)$$

PRC 78, 064908 (2008)

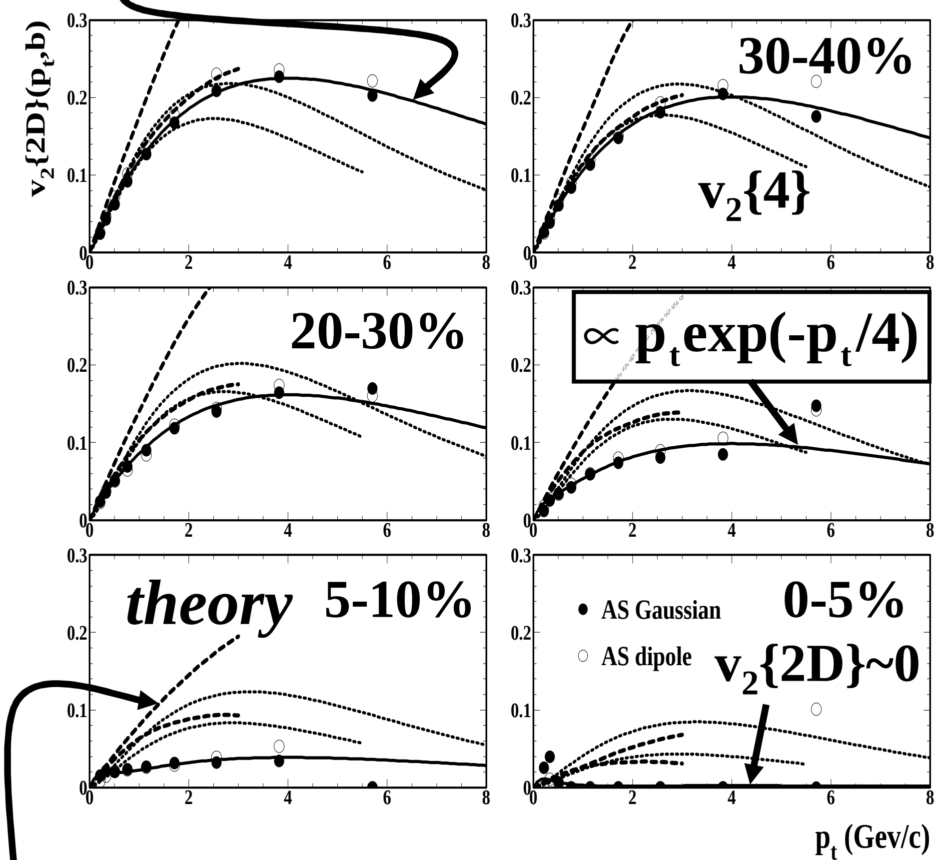
quadrupole spectrum

Systematics of differential $v_2\{2D\}(p_t,b)$

quadrupole spectrum



parametrized $v_2\{2D\}(p_t)$



arXiv:1008.4793

cold spectrum, no jet contribution

<u>boost independent of centrality</u>

no relation to jet sharp transition!

hydro theory: PRC 78, 034915 (2008)

Summary

- **Hydro-motivated analysis suppresses fragmentation**
- **Most parton fragments appear below 2 GeV/c**
- **New fragmentation features are described by pQCD**
- **Jet correlations transform to absolute fragment yields**
- **1/3 of hadrons in central Au-Au lie within resolved jets**
- **“Sharp transition” in spectrum and jet properties**
- **2D quadrupole analysis leads to full v_2 factorization**
- **No apparent coupling between jets and quadrupole**

perturbative QCD describes RHIC collision evolution

evidence for hydrodynamic flows is questionable