Systematics of Complete Fragment Distributions from Nuclear Collisions

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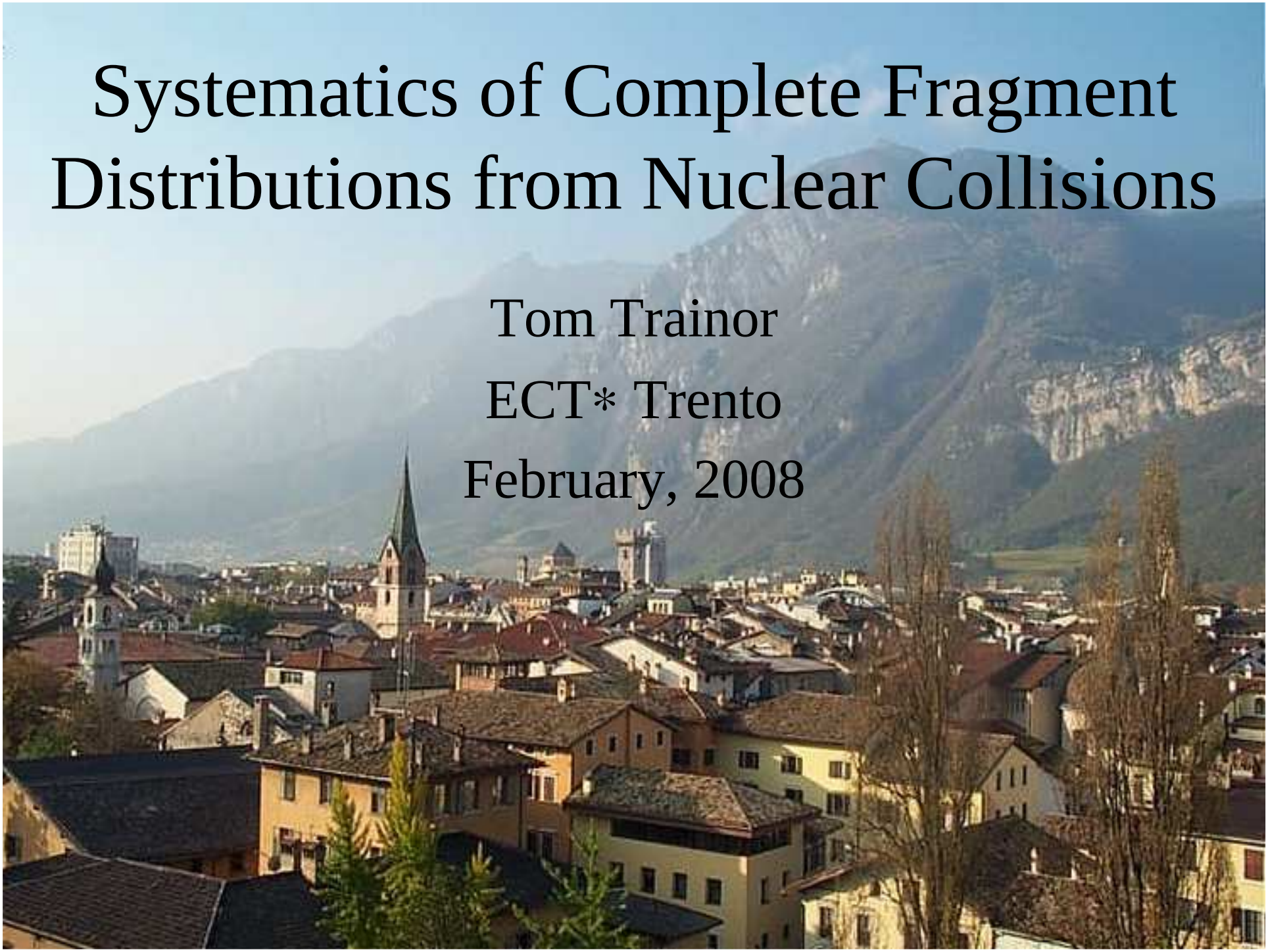
ECT* Trento

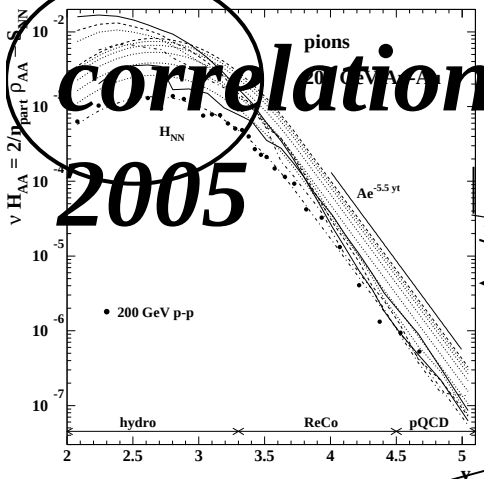
February, 2008

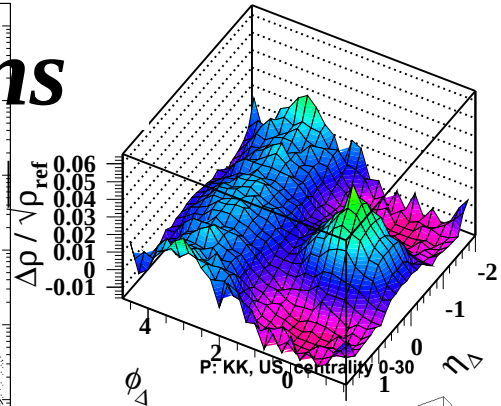


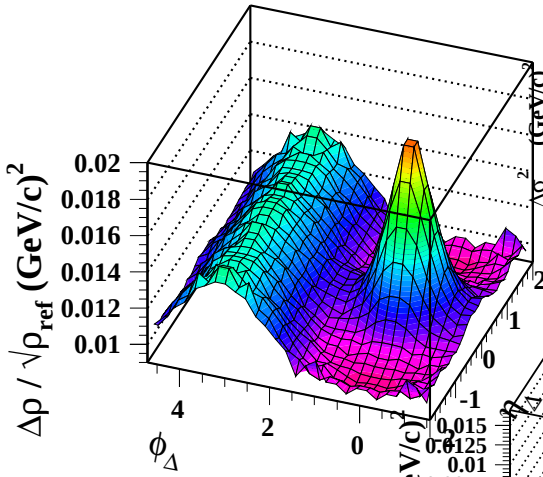
spectrum correspondence

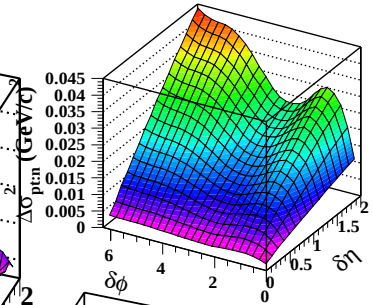
New Physics at RHIC: Minijets

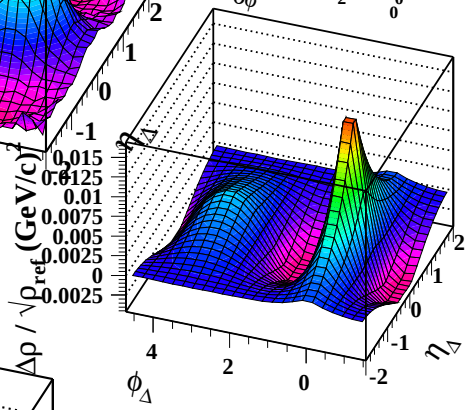
correlations 2005

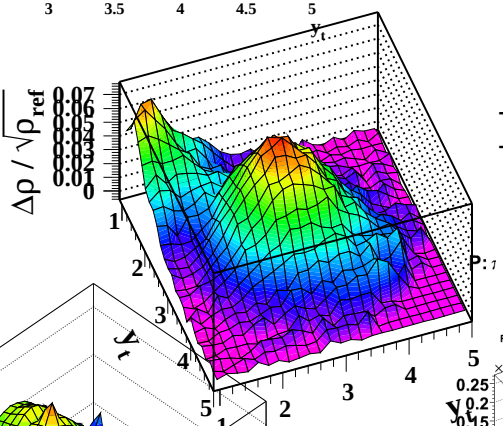


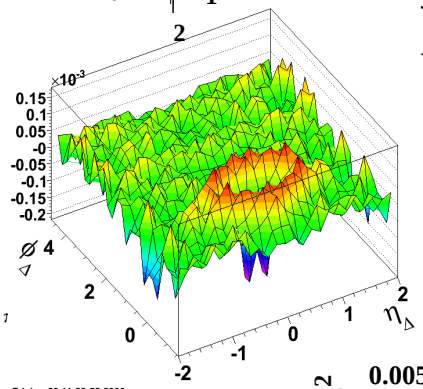


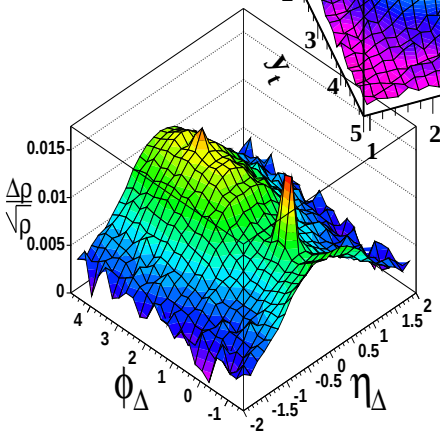


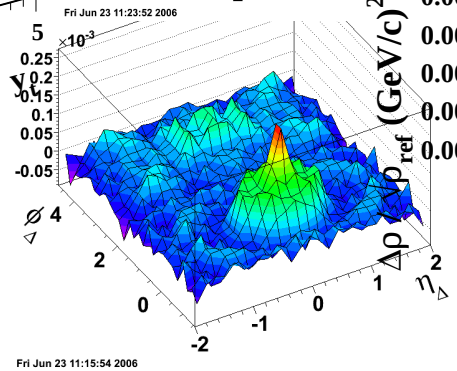


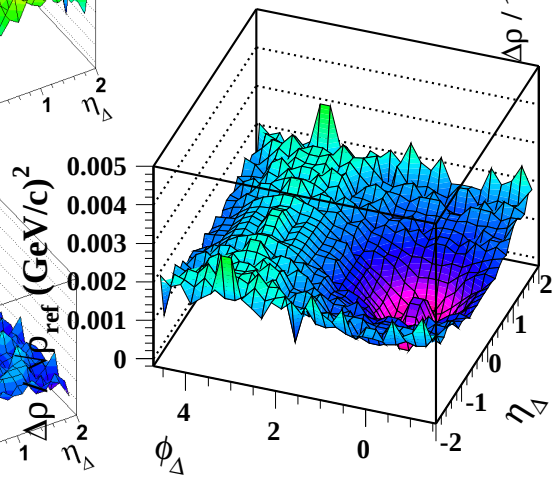


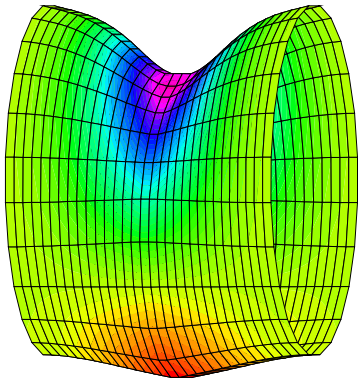












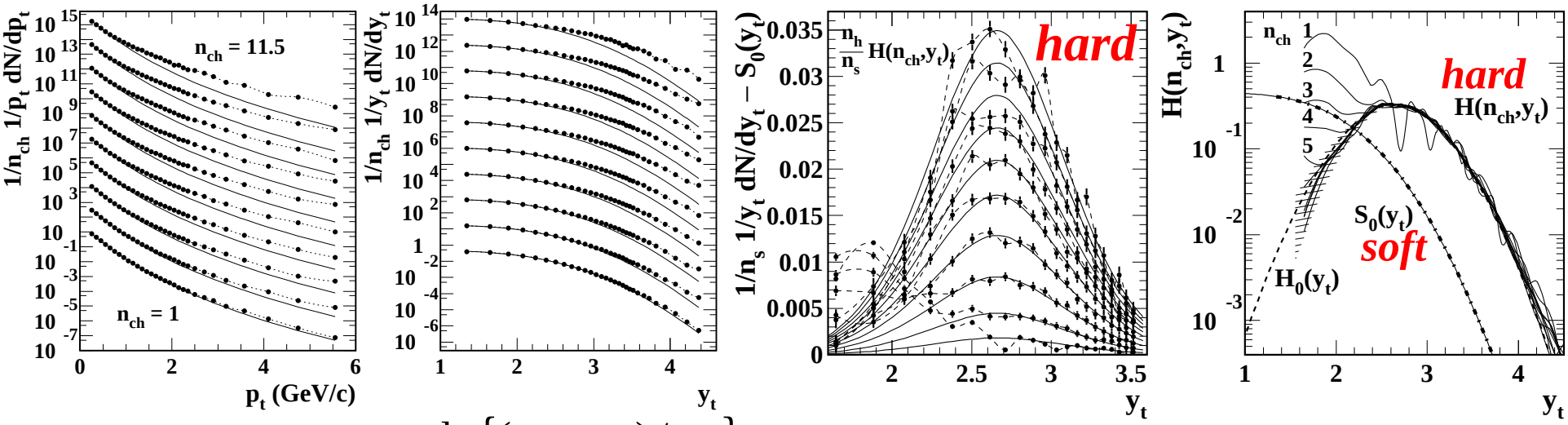
these are the dominant structures in RHIC collisions

Agenda I: Two-component Spectra

- ***p-p two-component spectra***
- ***Au-Au*** p_t ***and*** y_t ***spectra***
- R_{AA}, H_{AA} ***and*** r_{AA}
- ***Proton-to-pion ratio***
- ***Parton energy loss***

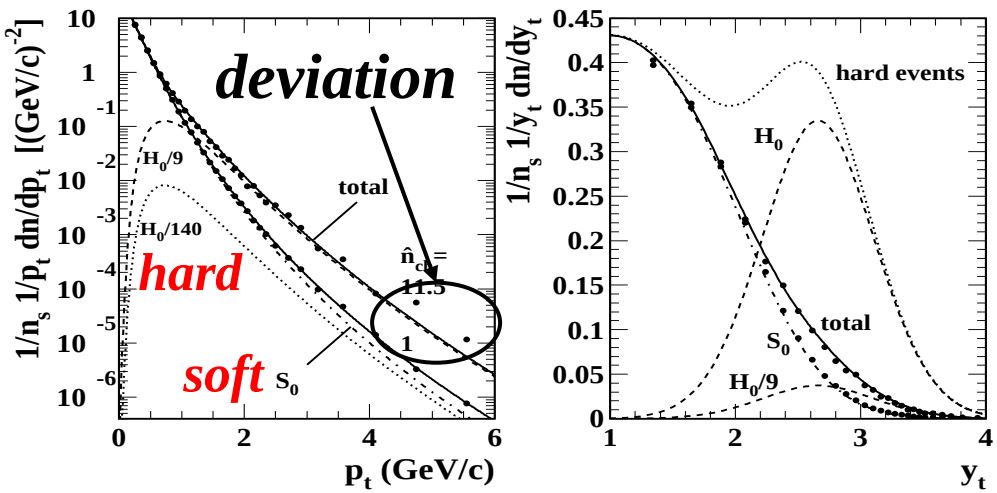
What role does fragmentation play?
Is hydro apparent in spectra?

Two-component p-p Collisions



$$y_t \equiv \ln\{(m_t + p_t)/m_0\}$$

hard + soft model: accurate decomposition of longitudinal and transverse fragmentation

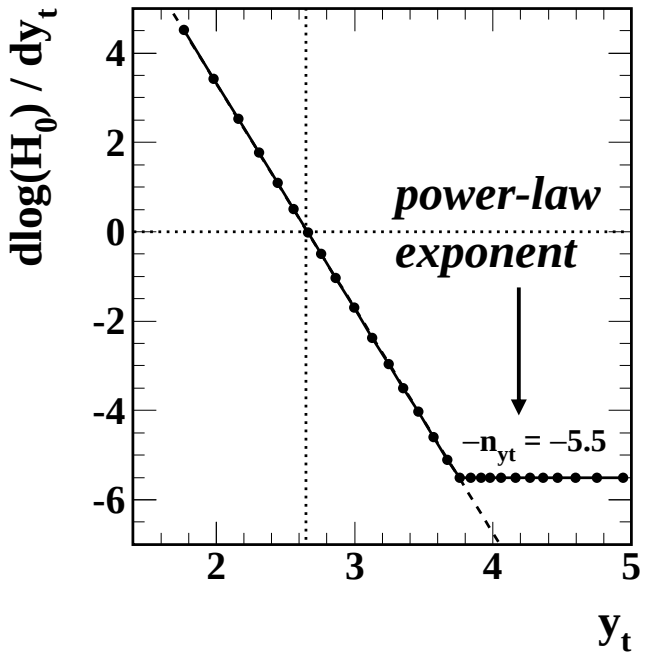


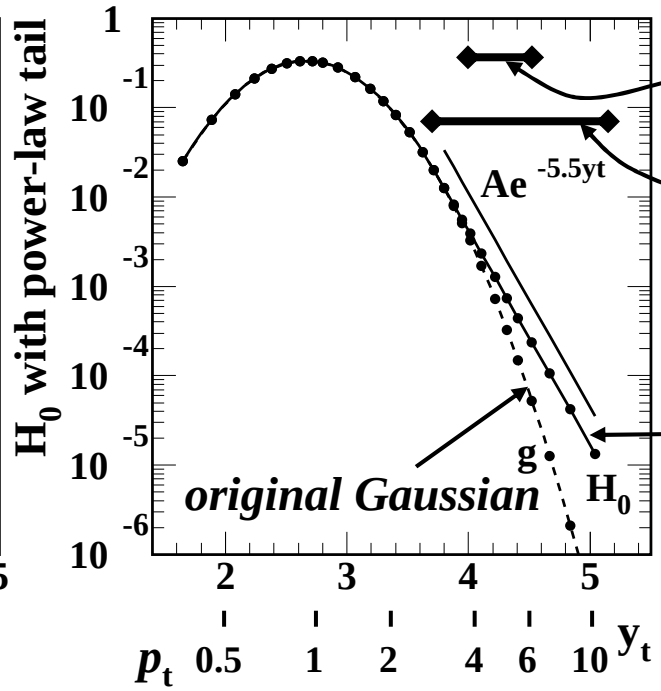
what implications for Au-Au spectra?

Phys. Rev. D 74, 032006 (2006)

also, Phys. Rev. D 74, 034012 (2006)

QCD Power Law and Hard Component





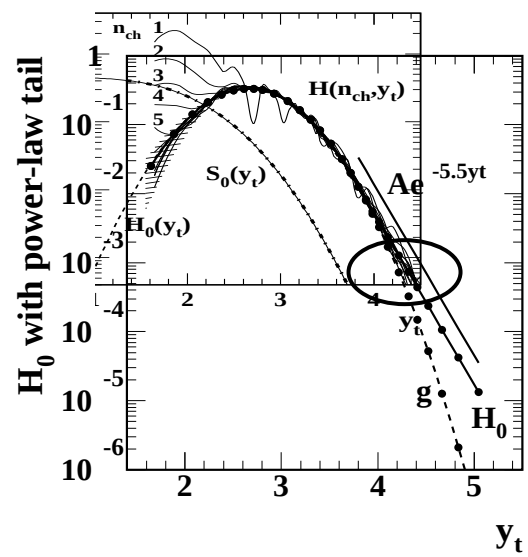
initial RHIC triggered jet correlation analysis

NLO FD comparisons

new exponential tail: real QCD power law

hard component with exponential tail generated by running integration

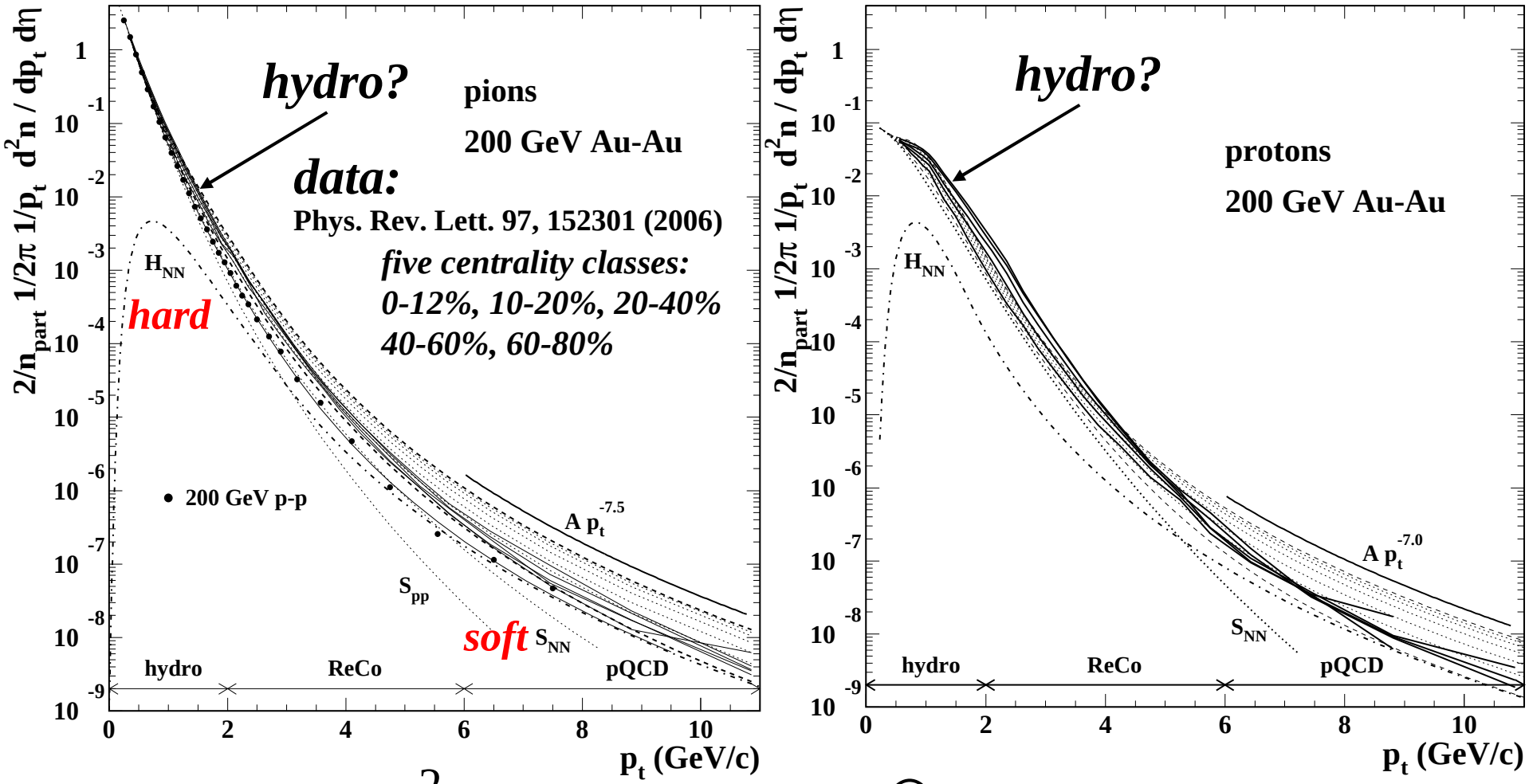
$$\frac{\overline{n}_s}{n_s}\rho_{pp}(x_t;n_{ch}) = S_{pp}(x_t) + \frac{n_{ch}}{\overline{n}_{ch}} H_{pp}(x_t) \quad \textbf{p-p}$$



now, apply to Au-Au collisions

compare with p-p data

200 GeV Au-Au PID p_t Spectra



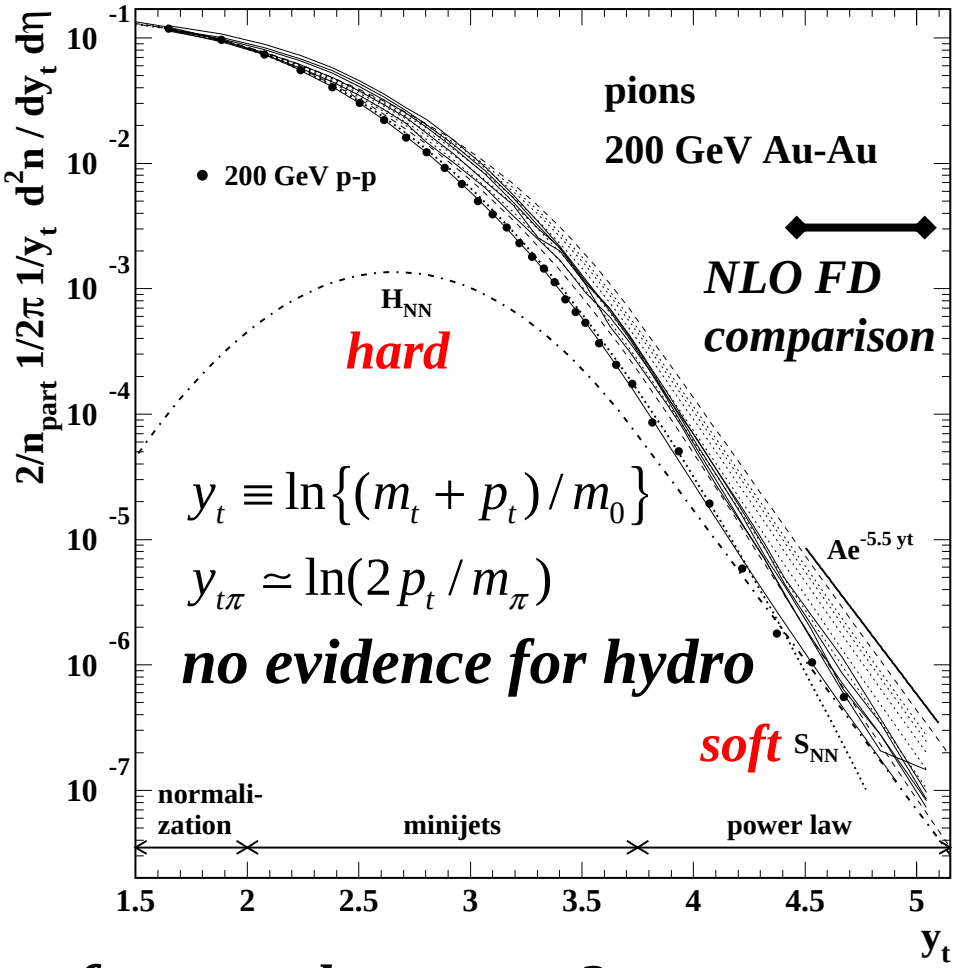
two-component reference

$$\frac{2}{n_{part}}\rho_{AA}(x_t;\nu) = S_{NN}(x_t) + \nu H_{NN}(x_t)$$

A-A ***dotted curves in all plots***

centrality: $\nu = 2n_{bin} / n_{part}$

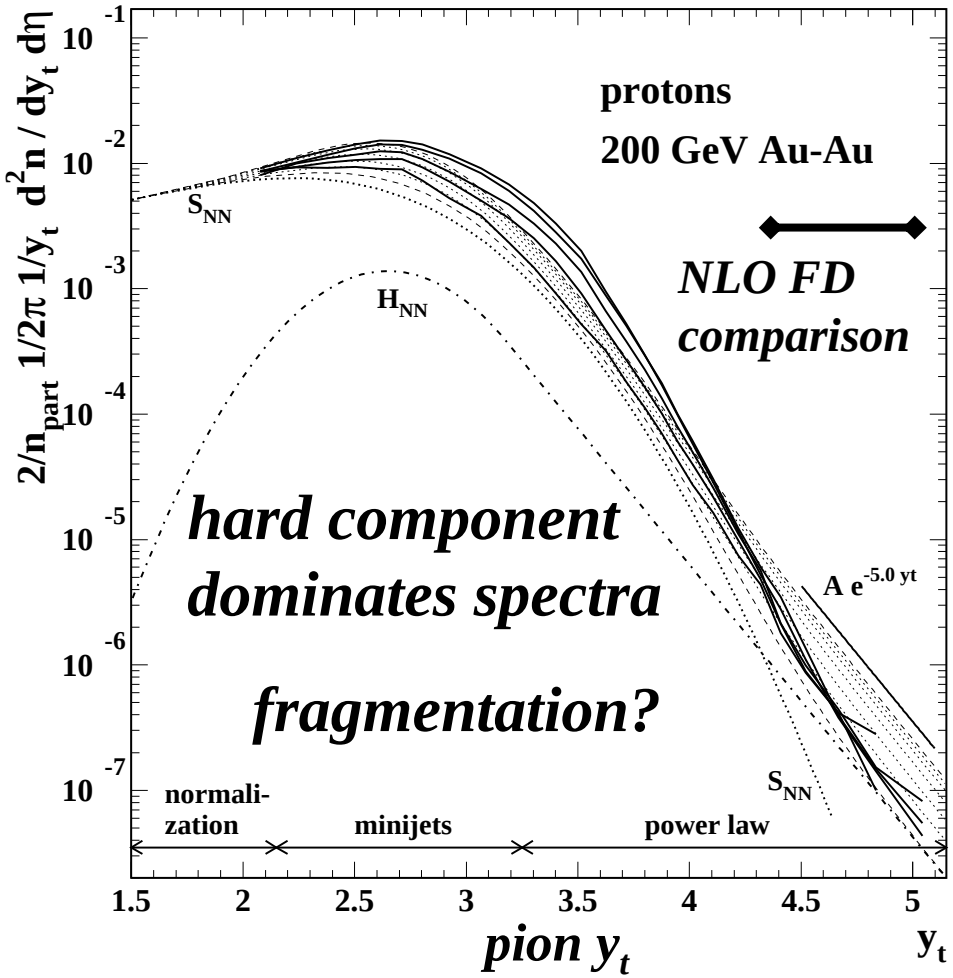
200 GeV Au-Au PID y_t Spectra



$$y_t \equiv \ln\{(m_t + p_t)/m_0\}$$

$$y_{t\pi} \simeq \ln(2p_t/m_\pi)$$

no evidence for hydro



hard component dominates spectra

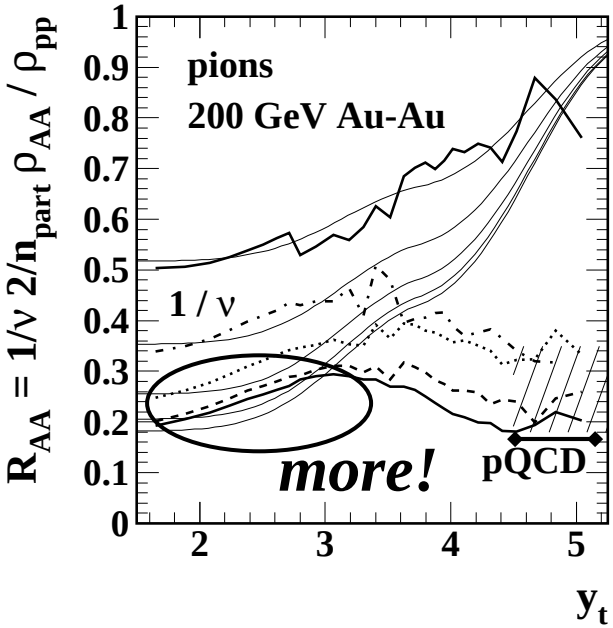
fragmentation?

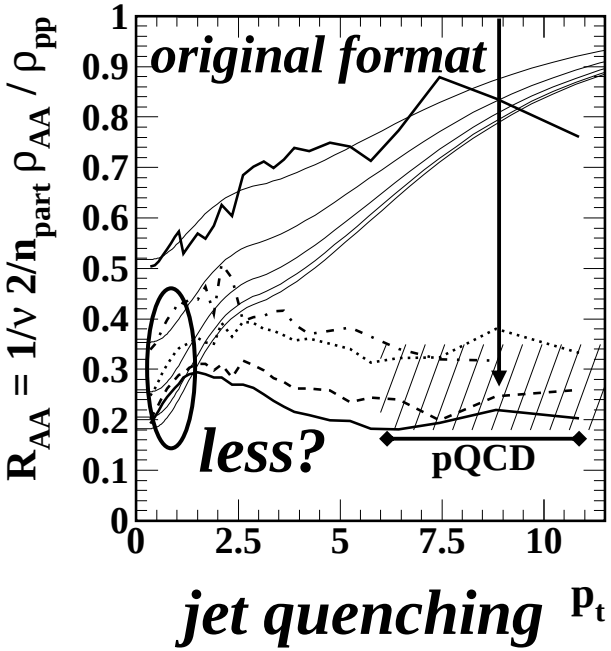
reference elements: $\frac{2}{n_{part}}\rho_{AA}(x_t;\nu) = S_{NN}(x_t) + \nu H_{NN}(x_t)$

Lévy distribution on m_t

Gaussian with tail on y_t

R_{AA}





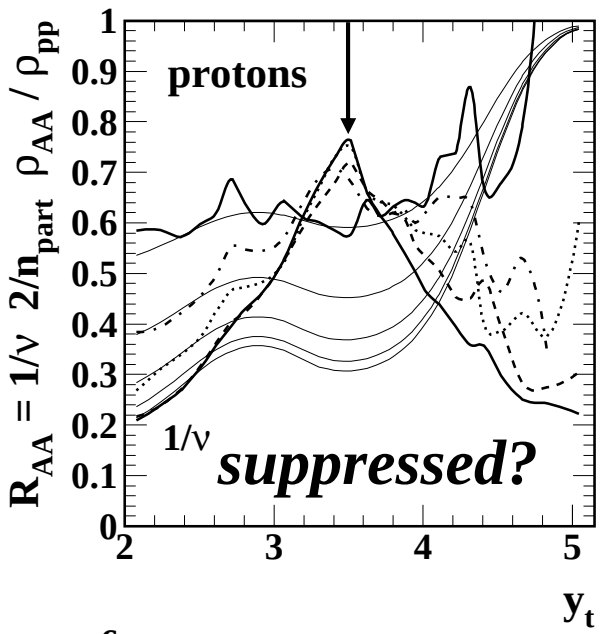
jet quenching

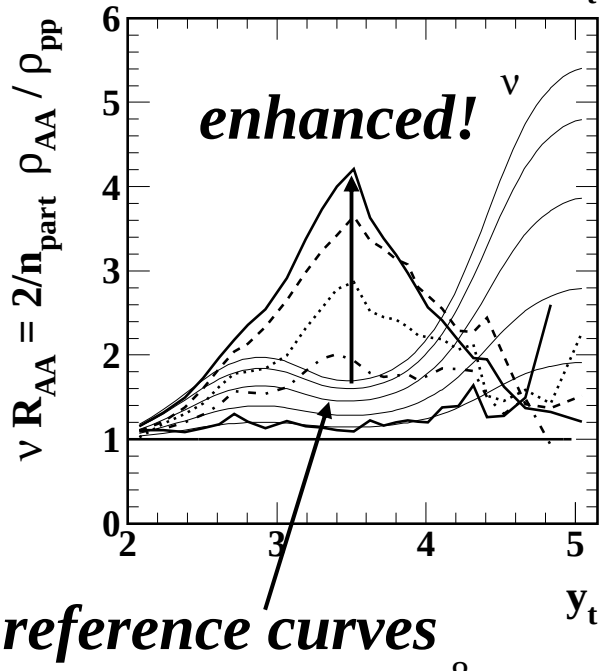
soft and hard components are mixed

unity is adopted as an incorrect reference

suppression and enhancement are ambiguous

$$\frac{1}{\nu}\cdot\frac{S_{NN}(y_t)+\nu H_{AA}(y_t;\nu)}{S_{pp}(y_t)+H_{pp}(y_t)}$$



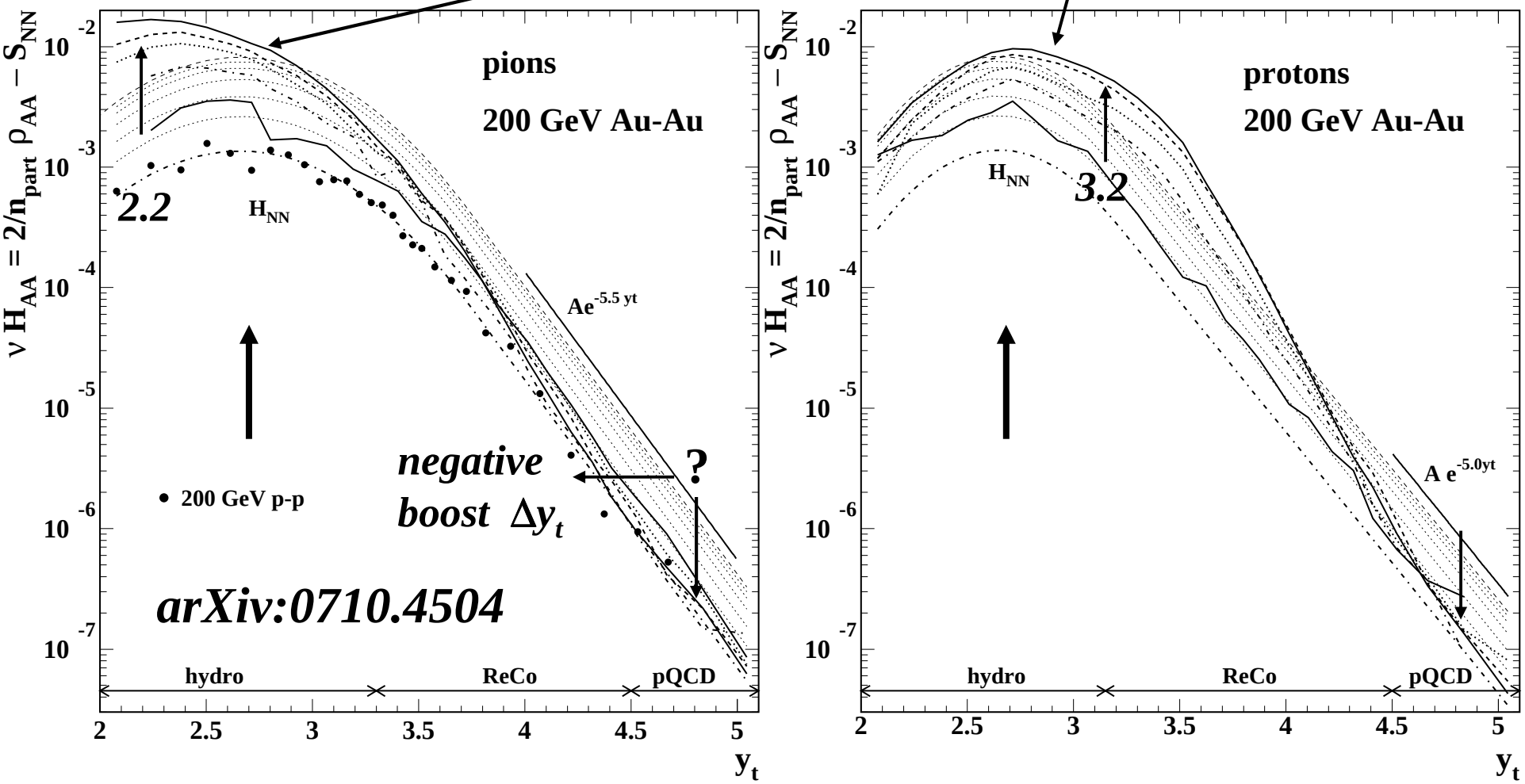


reference curves

H_{AA}

minijets

and protons



the elephant in the living room

data hard components n_{part} ***FD: fragment*** **distribution**

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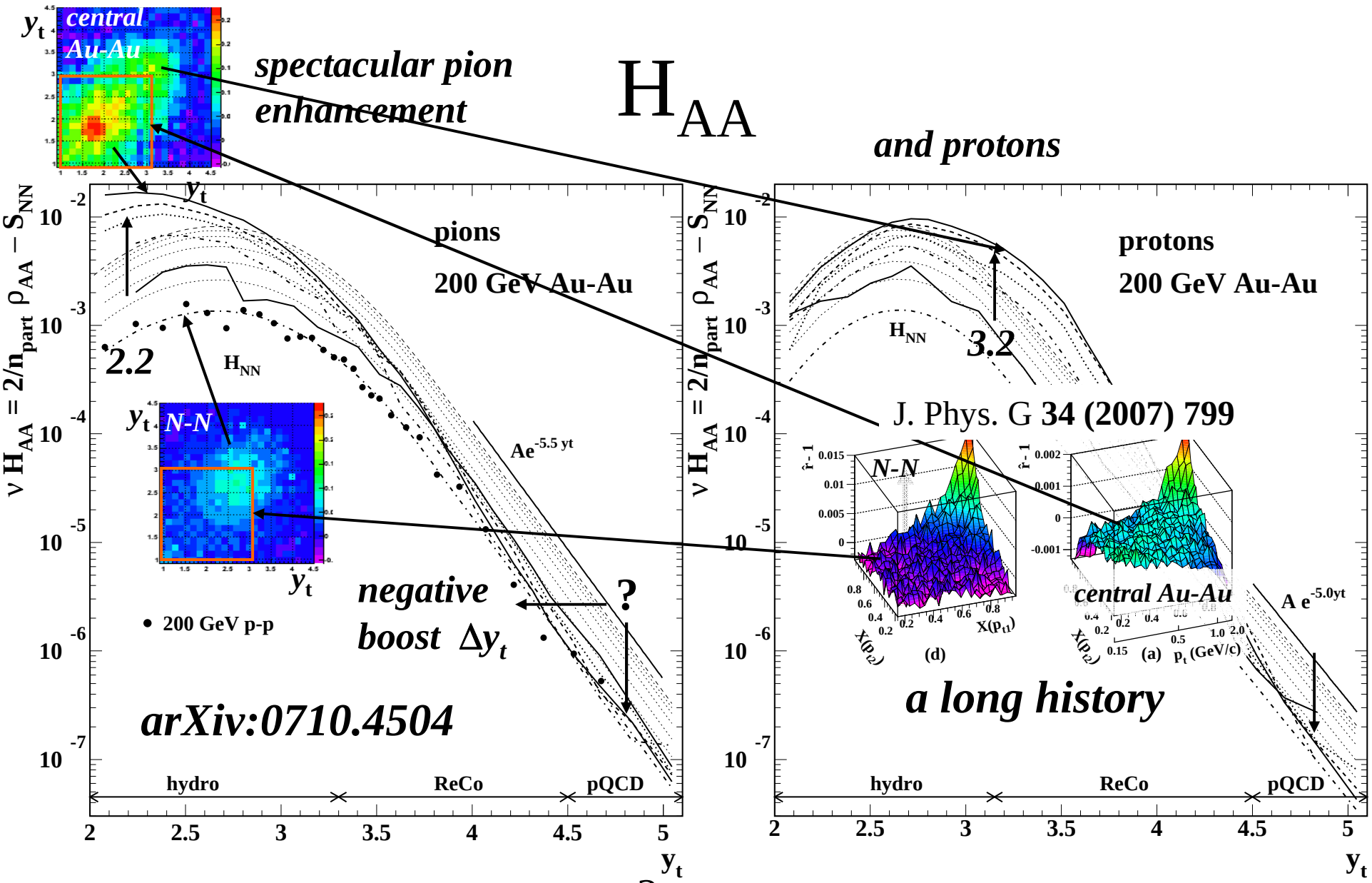


$$\nu H_{AA}(y_t;\nu) = \frac{2}{n_{part}}\rho_{AA}(y_t;\nu) - S_{NN}(y_t)$$

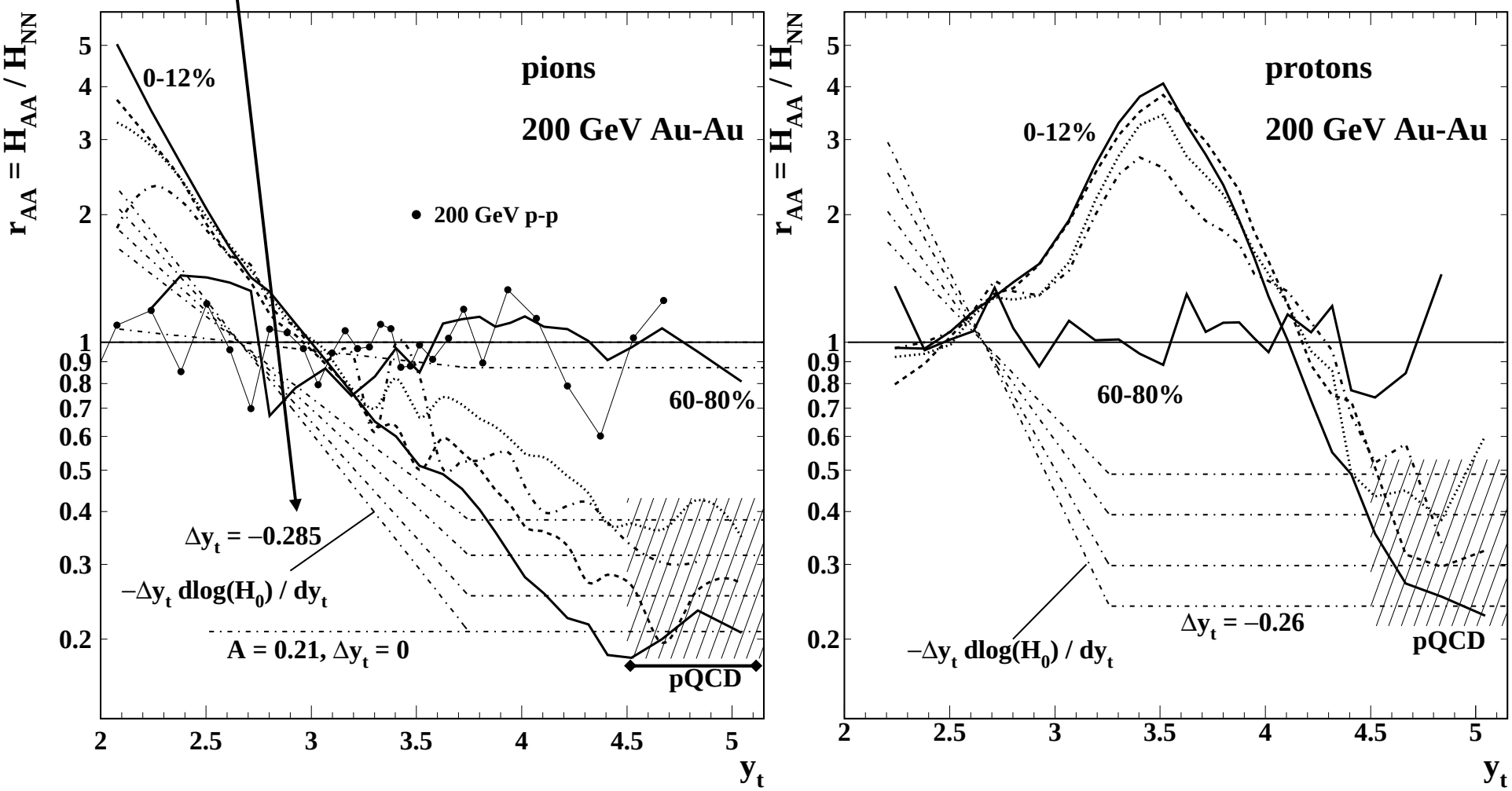
data hard components

Trainor

***FD: fragment* distribution**

energy-loss model: negative boost of FD

$$R_{AA} \rightarrow r_{AA} = H_{AA}/H_{NN}$$



$$r_{AA}(y_t;\nu) = H_{AA}(y_t;\nu) / H_{NN}(y_t)$$

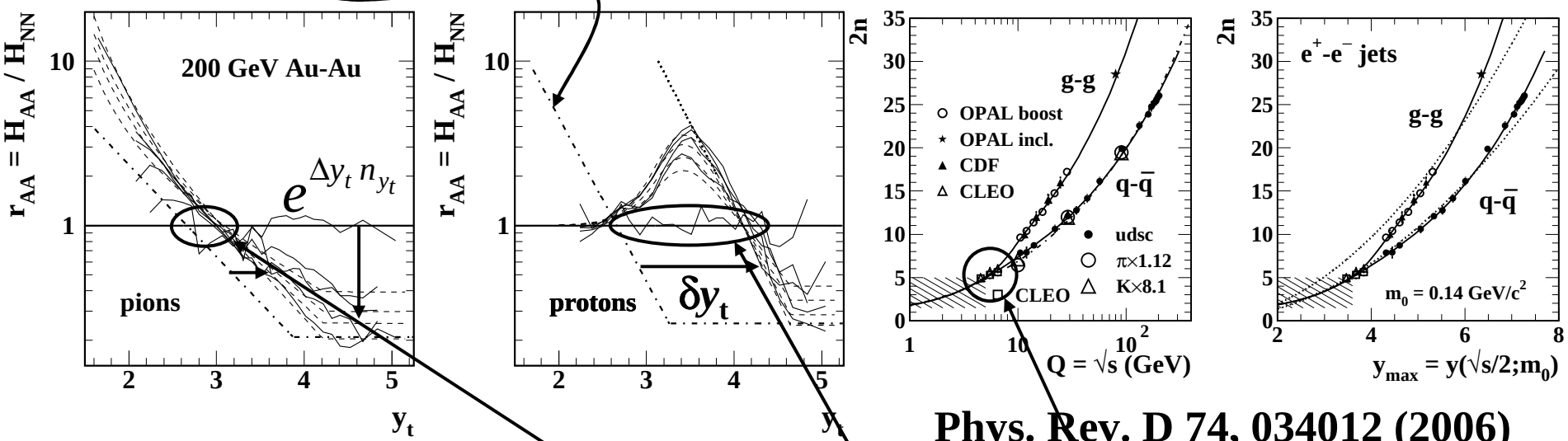
hard-component ratios

includes all deviations from the reference

Δy_t and Parton Energy Loss

naïve model

$$-\Delta y_t \; d\log[H_{NN}(y_t)]/dy_t$$



Phys. Rev. D 74, 034012 (2006)

evidence for color screening in e^+-e^- collisions

modeling r_{AA}

if 'energy loss' is a negative boost

$$H_{AA}(y_t;\nu) \approx A H_{NN}(y_t + \Delta y_t[\nu])$$

then by Taylor expansion

$$\log[r_{AA}(y_t;\nu)] \approx$$

anomalous

$$-\Delta y_t(\nu) \; d\log[H_{NN}(y_t - \delta y_t)]/dy_t$$

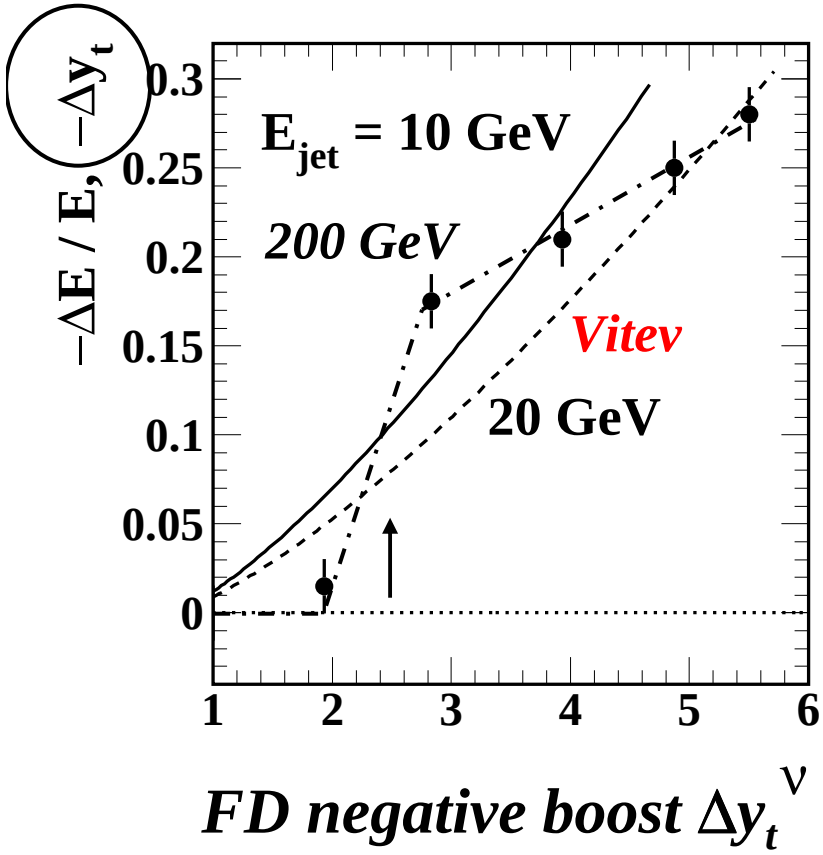
displacements may indicate color screening of partons

dashed model curves fully describe data

arXiv:0710.4504

Parton Energy Loss

from spectra

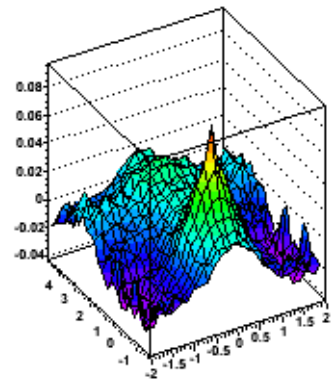


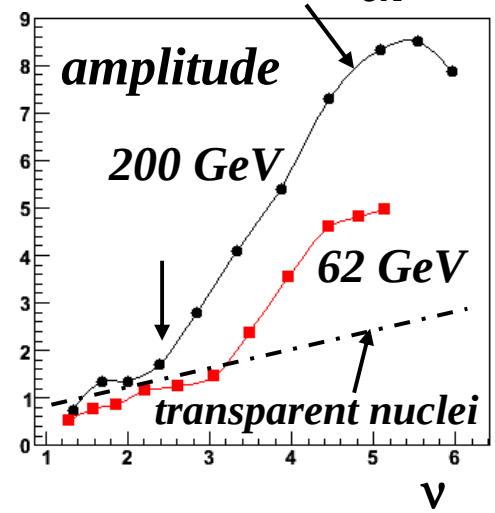
FD negative boost Δy_t

relative energy loss vs negative boost

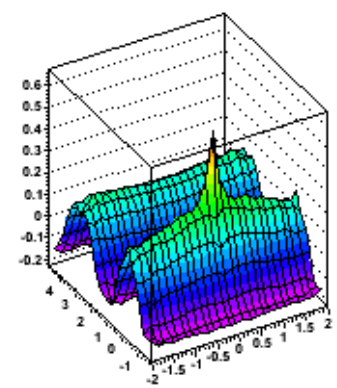
theory ΔE/E (curves) from I. Vitev

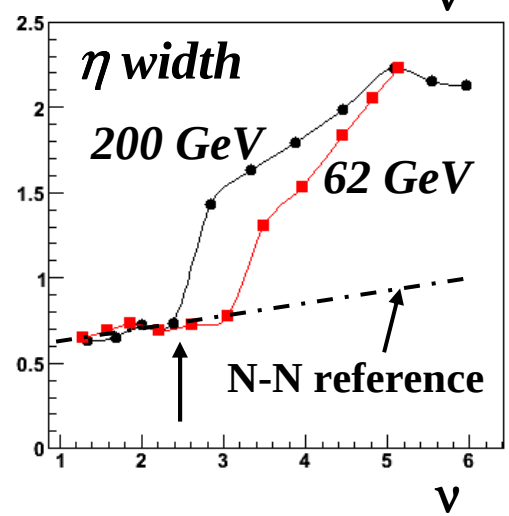
3x increase in minijet n_{ch}





minijet same-side peak properties



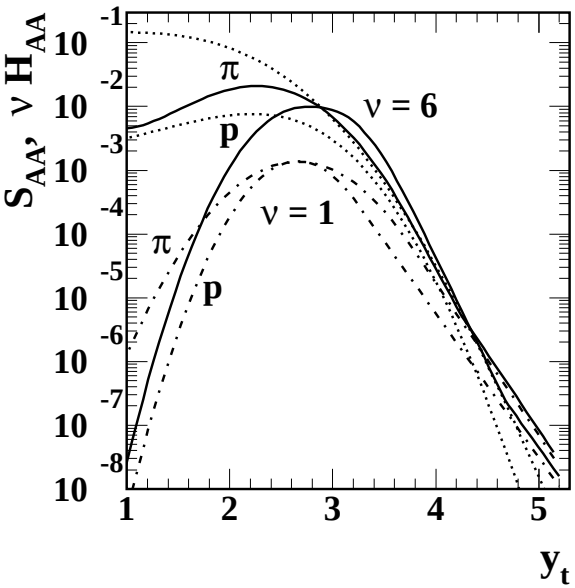


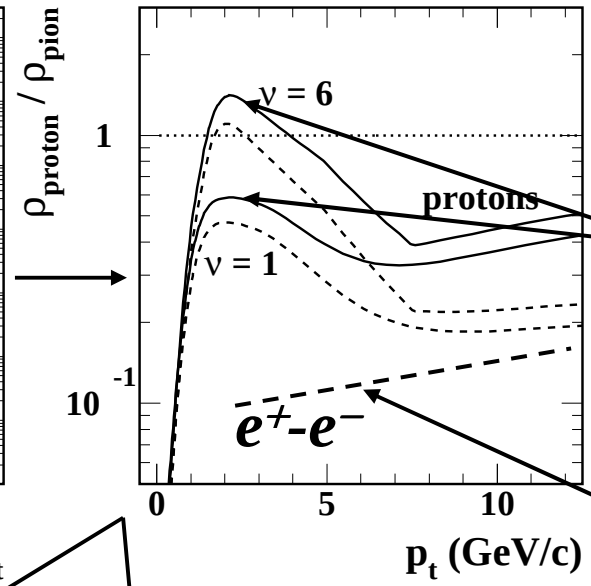
$\nu = 2.5 \Rightarrow n_{part}/2 = 19,\ n_{bin} = 46,\ b = 11\,\text{fm}$

step-like structures, related to a medium?

The Proton *vs* Pion Problem

model summary



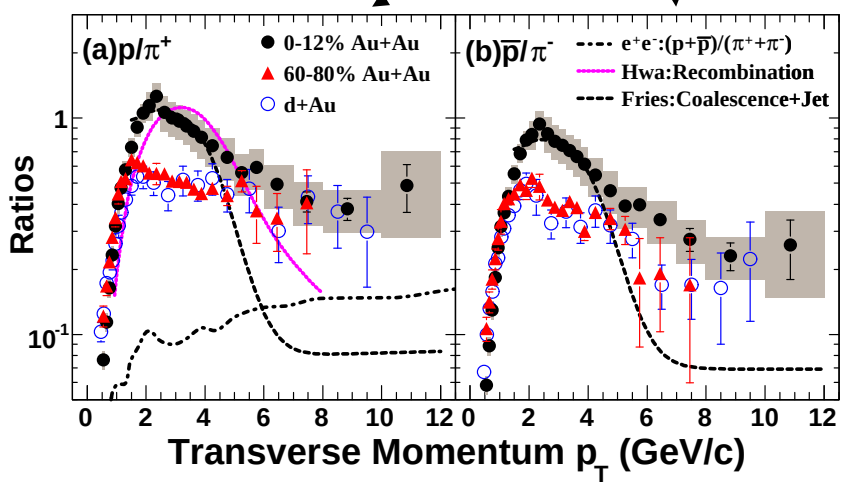


the Au-Au 'anomaly' is only a factor 2×

ReCo, or parton energy loss?

spectrum ratio not comparable to fragmentation* function *ratios

good agreement



$$\frac{\rho_{proton}}{\rho_{pion}} = \frac{S_{NNp}(y_t) + \nu H_{AAp}(y_t;\nu)}{S_{NN\pi}(y_t) + \nu H_{AA\pi}(y_t;\nu)}$$

ratio mixes soft and hard components

$$H_{AAp}(y_t;\nu) / H_{AA\pi}(y_t;\nu)$$

is more intepretable

Trainor **Phys. Rev. Lett. 97, 152301 (2006)**

Spectrum Summary

- ***The hard component describes FDs in elementary collisions***
- ***Two-component model works well in Au-Au as well as p-p***
- ***R_{AA} strongly distorts the hard component $\rightarrow$ misleading picture***
- ***Hard-component ratio r_{AA} properly describes fragments***
- ***A simple E-loss model emerges $\rightarrow$ color screening?***
- ***Sharp transition in Δy_t coincides with minijet systematics***
- ***p/π ratio – apparently fragmentation, not recombination***
- ***Interpretation of integral spectrum measures is questionable***
- ***No evidence for radial flow***

Au-Au collisions are highly structured, not thermalized

QCD medium presence and properties are subtle

Agenda II: Azimuth Correlations

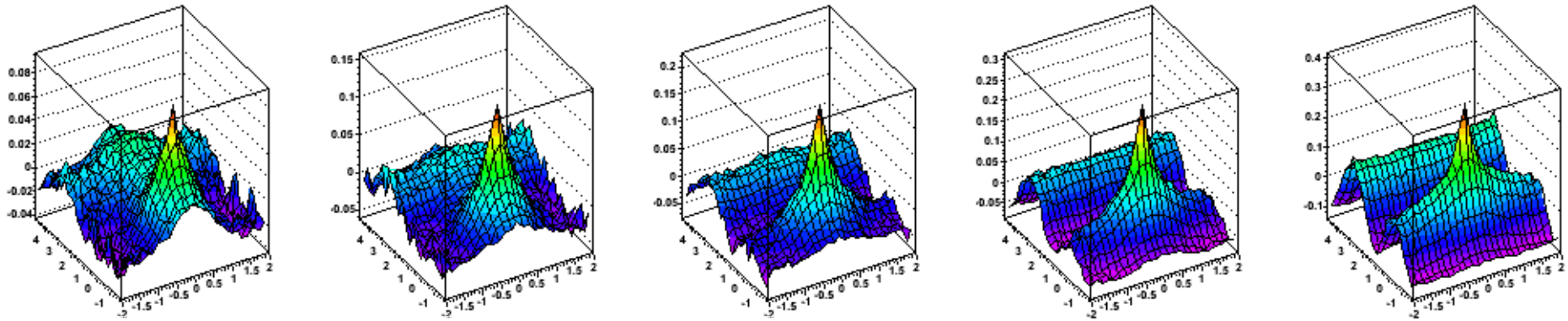
- ***Autocorrelations and power spectra***
- ***2D autocorrelations and model functions***
- ***Quadrupole centrality and energy trends***
- ***Optical or participant eccentricity?***
- ***Universal azimuth quadrupole trends***
- ***What is the quadrupole?***

Is "elliptic flow" a hydro phenomenon?

200 GeV Au-Au Data

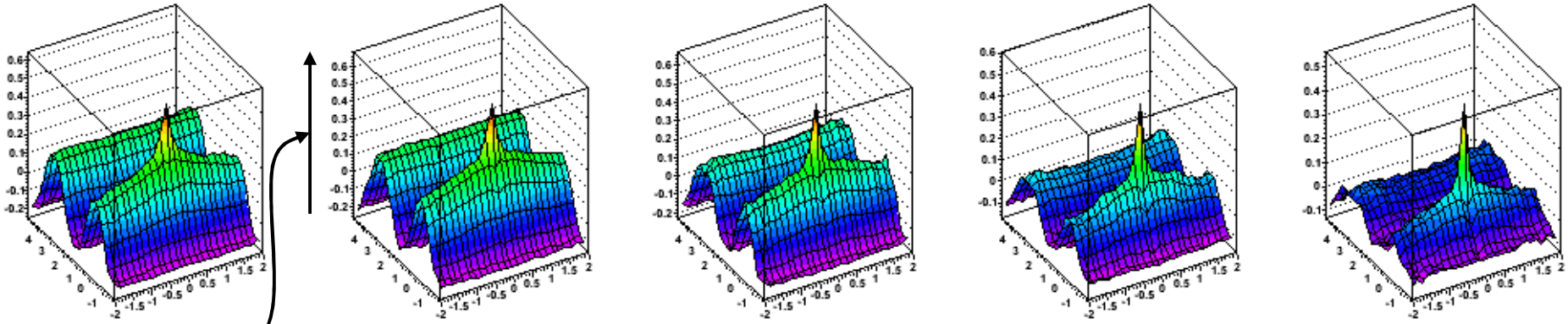
most peripheral

CI=LS+US Angular Autocorrelations



Michael Daugherity (U. Texas - Austin) data histograms

star preliminary



most central

$$\frac{\Delta\rho_A}{\sqrt{\rho_{ref}}}(\eta_\Delta, \phi_\Delta)$$

2D angular autocorrelations

Autocorrelations and Power Spectra

$$\rho(\phi) = \sum_{i=1}^{n} \delta(\phi - \phi_i) = \frac{Q_0}{2\pi} + 2\sum_{m=1}^{\infty} \frac{\vec{Q}_m}{2\pi} \cdot \vec{u}(m\phi) \qquad \vec{Q}_m = \sum_{i=1}^{n} \vec{u}(m\phi_i)$$

FT → ***EP flow analysis*** ***RT*** →

$$\rho_A(\phi_\Delta) \equiv \frac{1}{2\pi} \int_{-\pi}^{\pi} d\phi \; \rho(\phi)\rho(\phi + \phi_\Delta) = \frac{Q_0^2}{[2\pi]^2} + 2\sum_{m=1}^{\infty} \frac{Q_m^2}{[2\pi]^2} \cos(m\phi_\Delta)$$

FT →

arXiv:0704.1674

power spectrum: $Q_m^2 = n + \sum_{i \neq j=1}^{n.n-1} \vec{u}(m\phi_i) \cdot \vec{u}(m\phi_j)$

Wiener-Khintchine theorem ***RT*** →

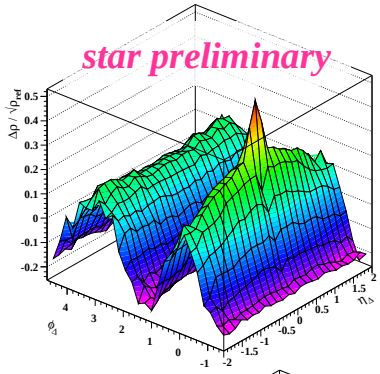
signal: $V_m^2 = n(n-1)v_m^2 \rightarrow \mathbf{v_2\{2\}}$

azimuth autocorrelation:

$$\rho_A(\phi_\Delta) = \underbrace{\frac{n}{2\pi}\delta(\phi_\Delta) + \frac{V_0^2}{[2\pi]^2}}_{\rho_{ref}\ \textbf{2D random walk}} + \underbrace{2\sum_{m=1}^{\infty} \frac{V_m^2}{[2\pi]^2} \cos(m\phi_\Delta)}_{\textbf{correlations}}$$

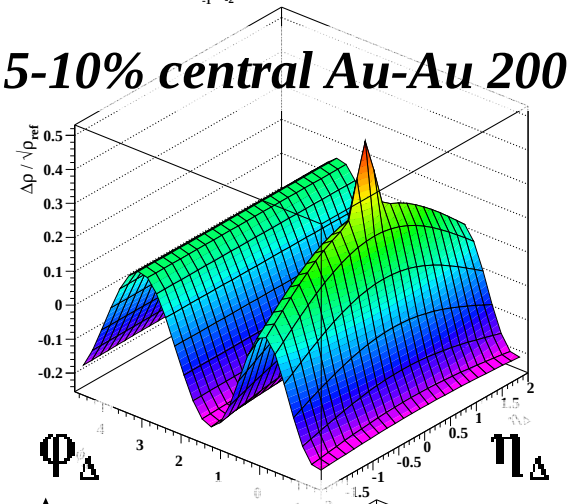
arXiv:0704.1674

Modeling 2D Autocorrelations



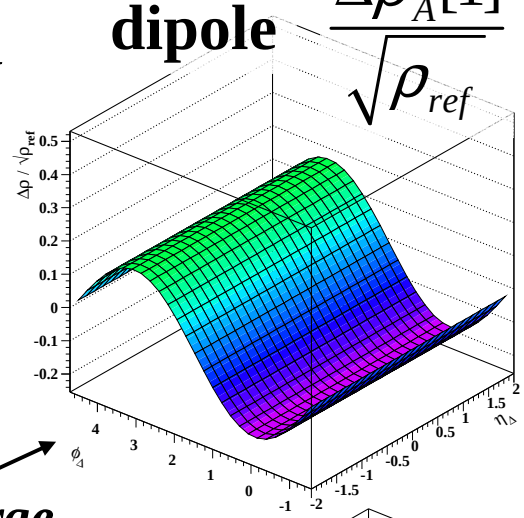
David Kettler model fits

5-10% central Au-Au 200 GeV



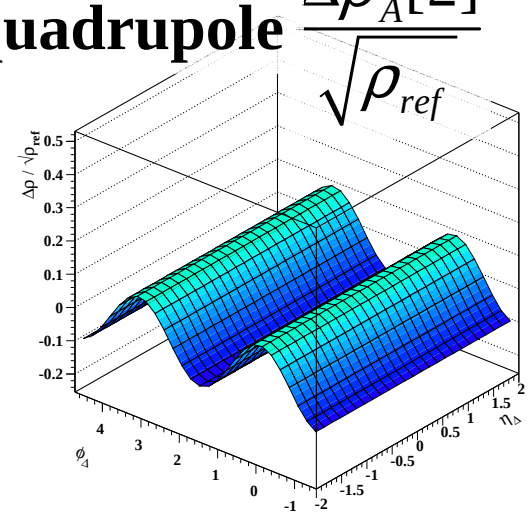
=

dipole $\dfrac{\Delta\rho_A[1]}{\sqrt{\rho_{ref}}}$



+

quadrupole $\dfrac{\Delta\rho_A[2]}{\sqrt{\rho_{ref}}}$

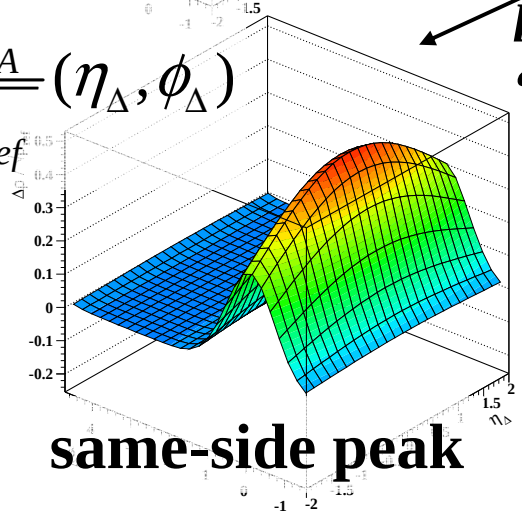


large "nonflow"

small "flow"

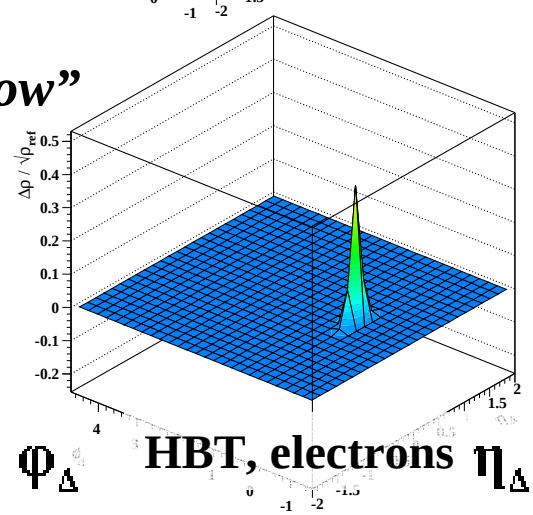
$$\frac{\Delta\rho_A}{\sqrt{\rho_{ref}}}(\eta_\Delta, \phi_\Delta)$$

+



same-side peak

+

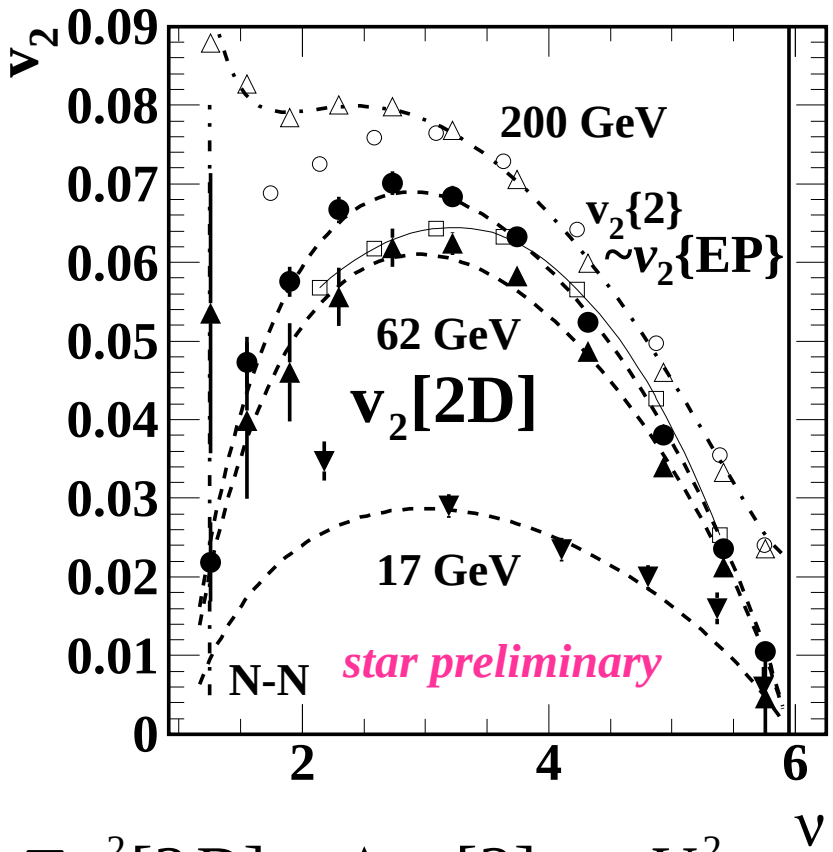


HBT, electrons

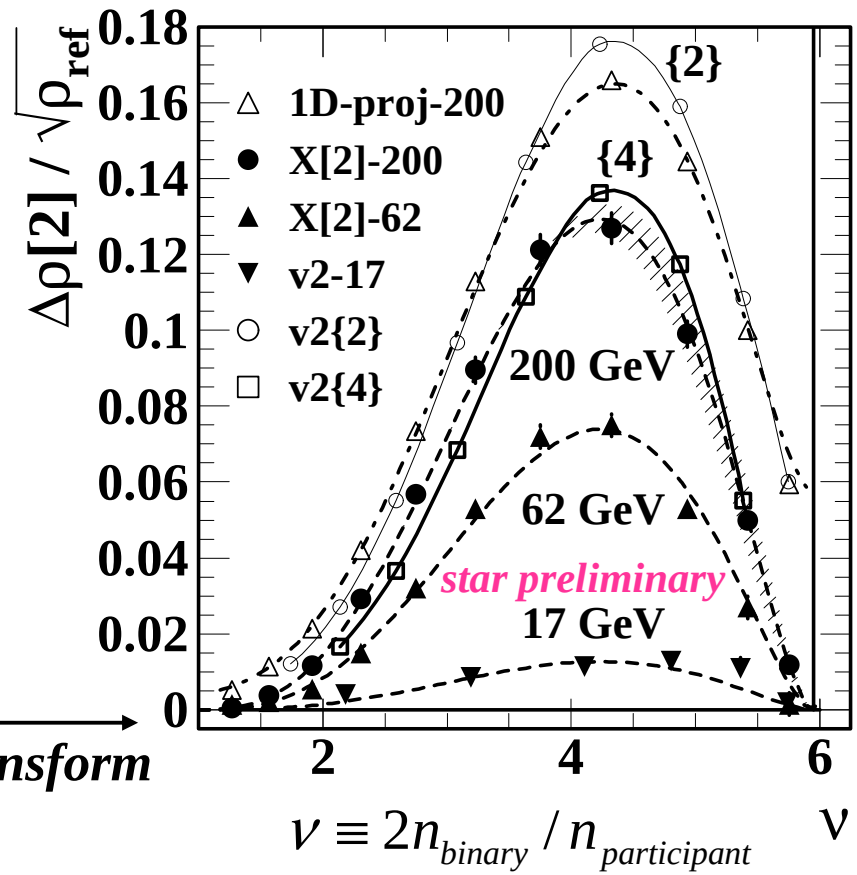
$$\Delta\rho_A \equiv \rho_A - \rho_{ref}$$

no *physical* model

Quadrupole Centrality Systematics



transform



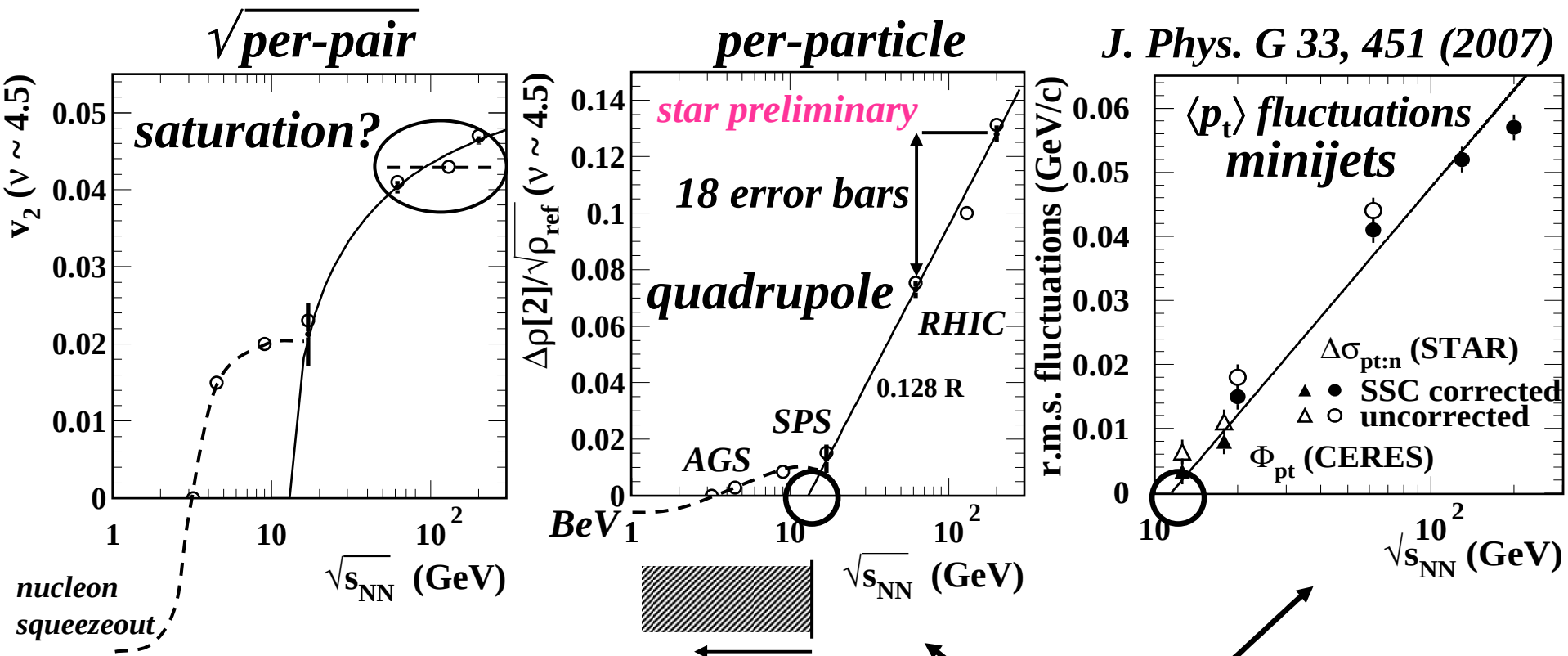
$$\frac{\bar{n}\, v_2^2[2D]}{2\pi} \equiv \frac{\Delta\rho_A[2]}{\sqrt{\rho_{ref}}} = \frac{V_2^2}{\bar{n}/2\pi}$$

2D autocorrelation model fits

David Kettler

***dashed curves** have common shape –*
amplitudes are $\propto \log(\sqrt{s_{NN}}/13\ \mathrm{GeV})$

Quadrupole Energy Systematics



$$v_2\{2D\} \equiv \sqrt{\frac{2\pi}{\bar{n}} \cdot \frac{\Delta\rho[2]}{\sqrt{\rho_{ref}}}}$$

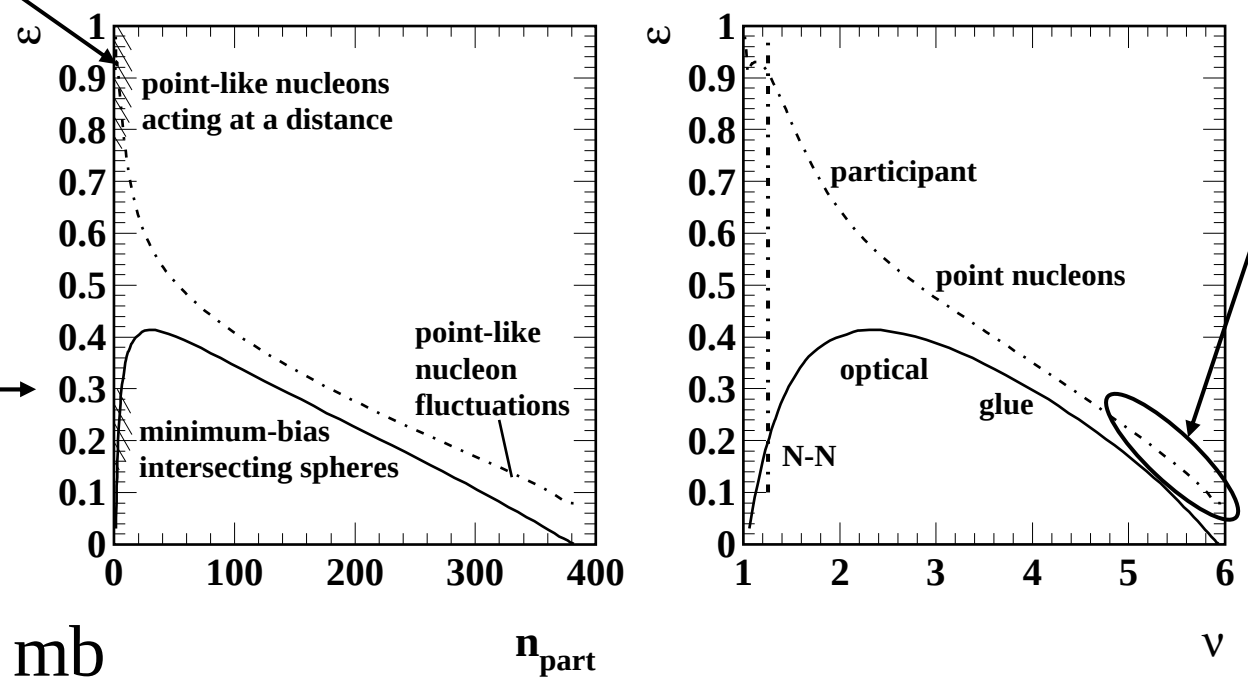
suggests a common underlying mechanism: QCD

A-A Eccentricity

point-like objects acting at a distance

point-like nucleon structure

N-N minbias: interacting spheres



$$\sigma_{NN} = 42 \text{ mb}$$

optical Glauber parameterization

$$\varepsilon_{opt}(n_{\text{bin}}) = \frac{1}{5.68}\log_{10}\left(\frac{3n_{\text{bin}}}{2}\right)^{0.96} \cdot \log_{10}\left(\frac{1136}{n_{\text{bin}}}\right)^{0.81}$$

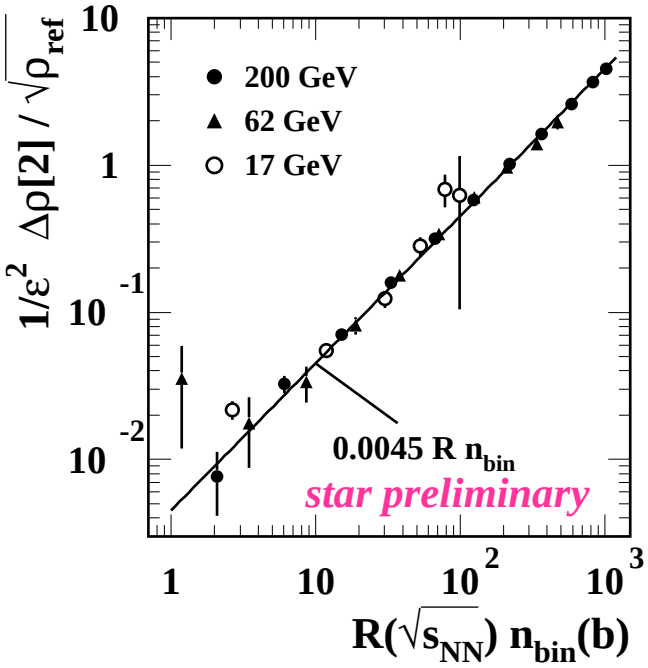
arXiv:0708.0792

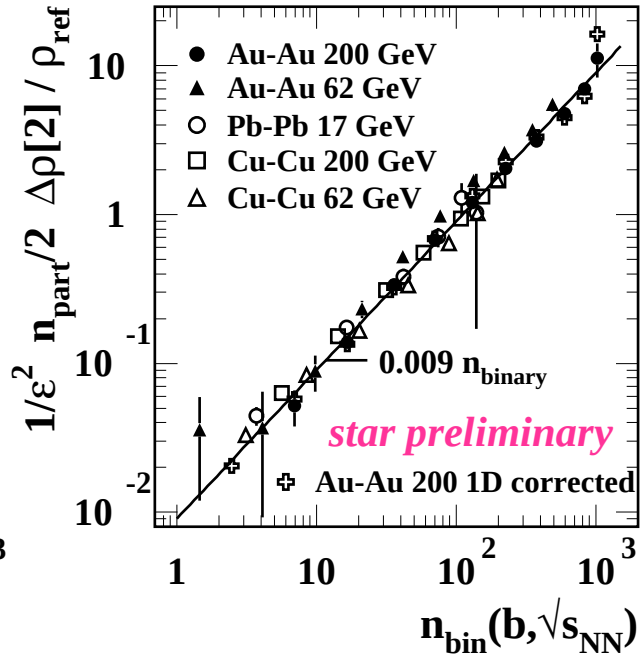
David Kettler simulation

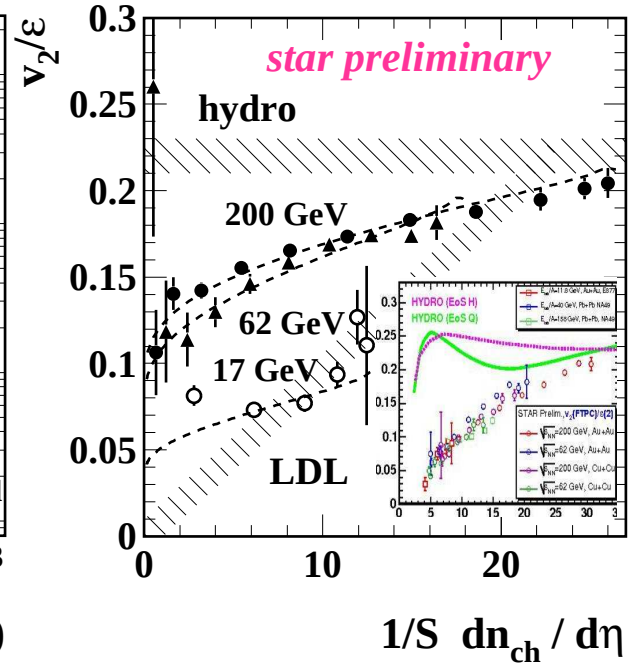
beta distribution

we use the <u>optical</u> Glauber eccentricity

Universal Centrality and Energy Trends







universal trend for all A-A systems down to 13 GeV

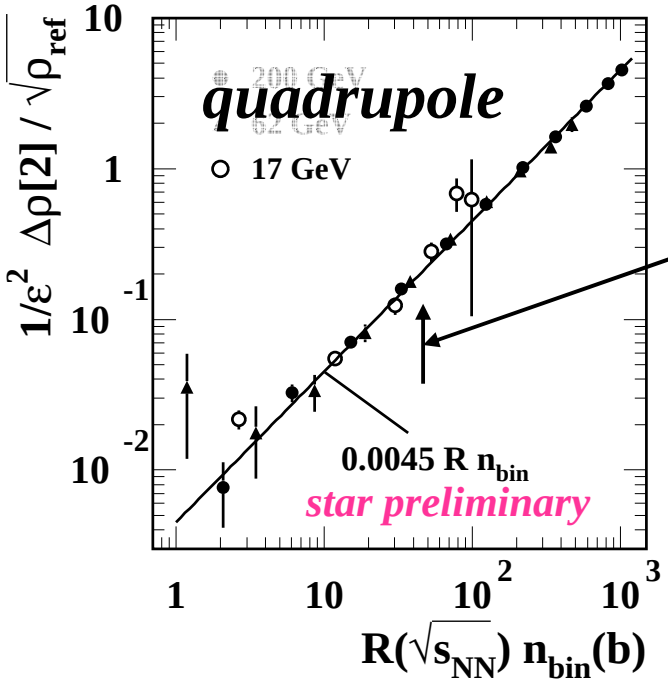
is this hydro format relevant to data?

$$R\left(\sqrt{s_{NN}}\right) = \frac{\log\left(\sqrt{s_{NN}}/13\right)}{\log(200/13)}$$

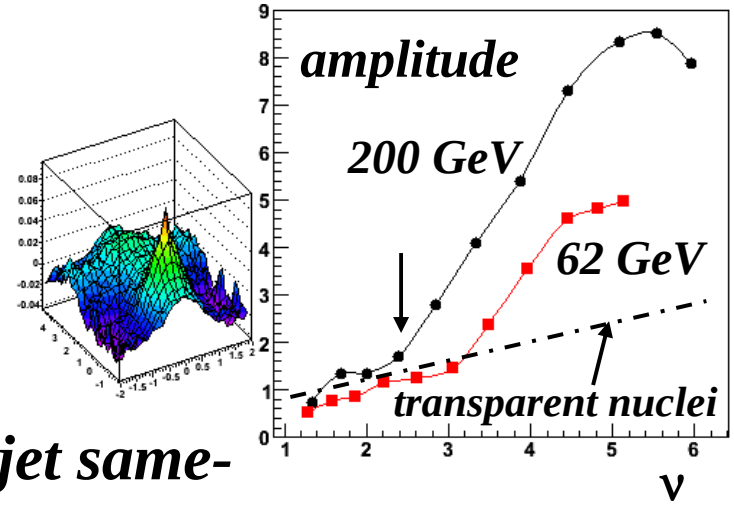
$$\boxed{\frac{\Delta\rho[2]}{\sqrt{\rho_{ref}}} = 0.0045\, R\left(\sqrt{s_{NN}}\right) \varepsilon_{opt}^{2}(n_{bin})\, n_{bin}}$$

no medium properties, EoS, viscosity

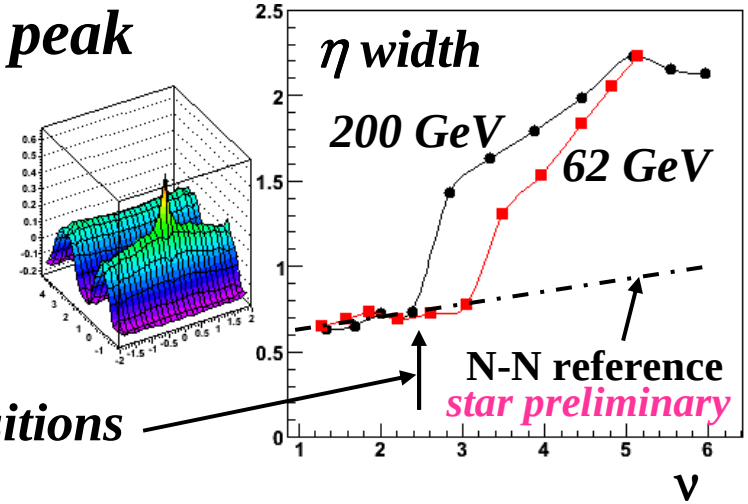
Does “elliptic flow” Relate to the Medium?



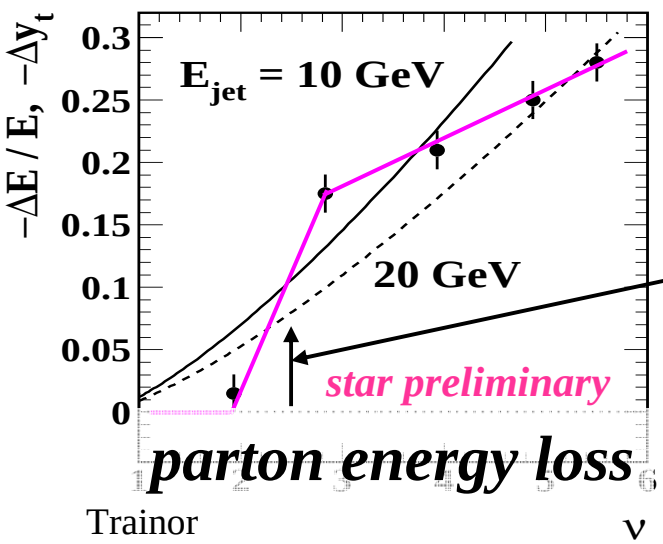
no transition
no medium?



minijet same-side peak



medium?
sharp transitions

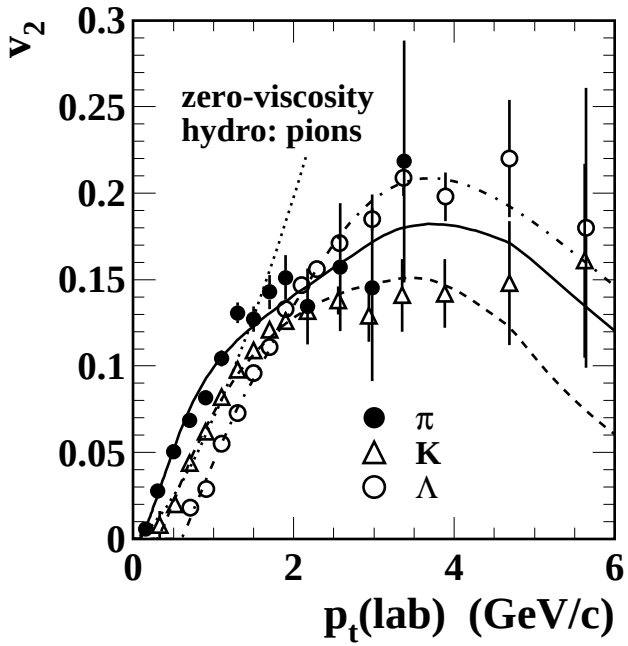


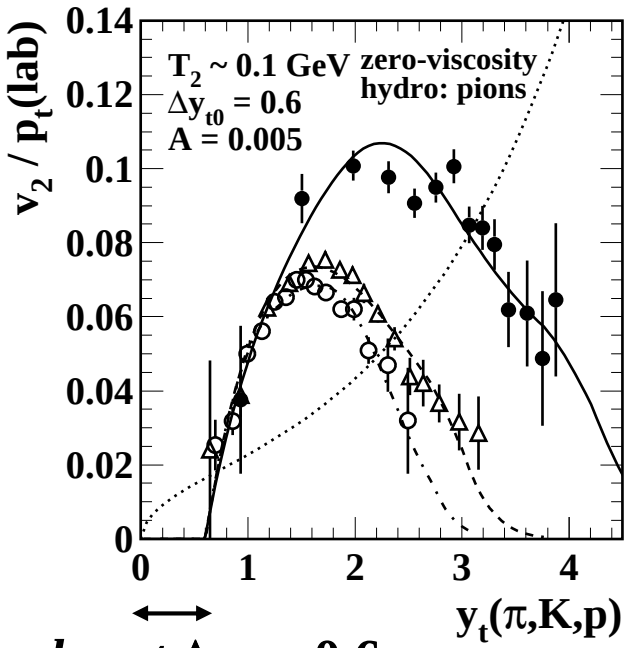
parton energy loss

$$\nu = 2.5 \Rightarrow n_{part}/2 = 19,\ \ n_{bin} = 46,\ \ b = 11\,\text{fm}$$

200 GeV parameters

What is $v_2(p_t)$?





common boost $\Delta y_{t0} \sim 0.6$

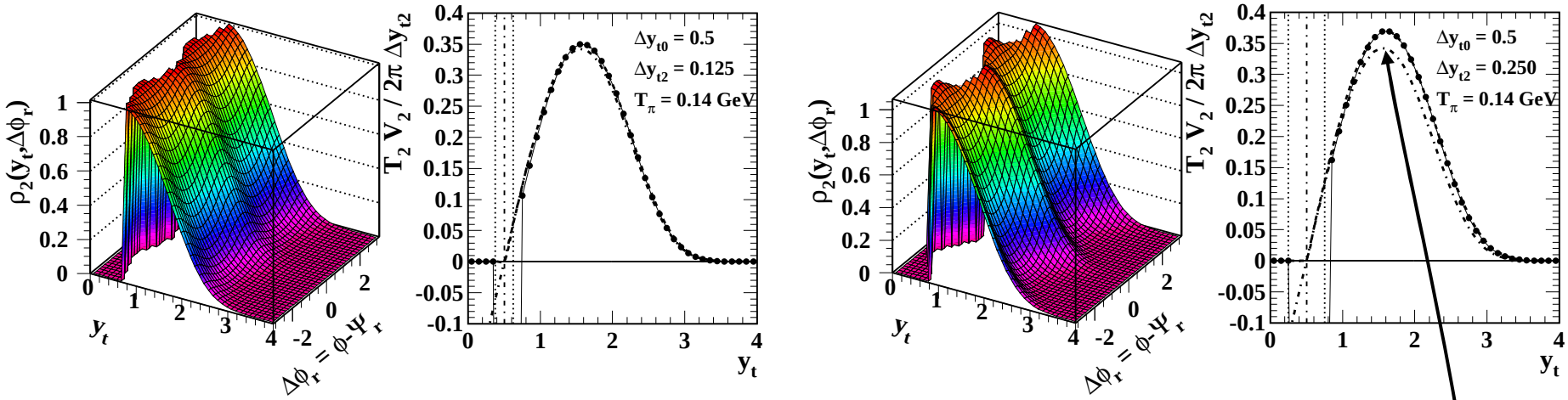
p_t-integrated $\frac{\bar{n}\, v_2}{2\pi} \equiv V_2 \rightarrow \rho_0(y_t) v_2(p_t) = V_2\,(y_t; \Delta y_{t0}, \Delta y_{t2})$

$$V_2\,(y_t; \Delta y_{t0}, \Delta y_{t2}) = \int_{-\pi}^{\pi} d\phi\, \rho_2(y_t, \Delta y_t[\phi]) \cos(2\Delta\phi_r)$$

$v_2(p_t)$ is the ratio of two spectra

V_2 and the Boost Model

quadrupole 2D density

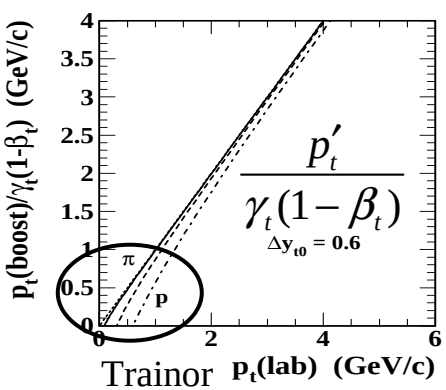


boost model $\Delta y_t(\phi) = \Delta y_{t0} + \Delta y_{t2}\cos(2\Delta\phi_r)$

$$\frac{V_2\,(y_t;\Delta y_{t0},\Delta y_{t2})}{2\pi} = \frac{1}{2\pi}\int_{-\pi}^{\pi} d\phi\,\rho_2(y_t;\Delta y_t[\phi])\cos(2\Delta\phi_r)$$

$$\simeq \frac{p_t'}{2T_2}\,\Delta y_{t2}\,\rho_2(y_t;\Delta y_{t0},T_2)$$

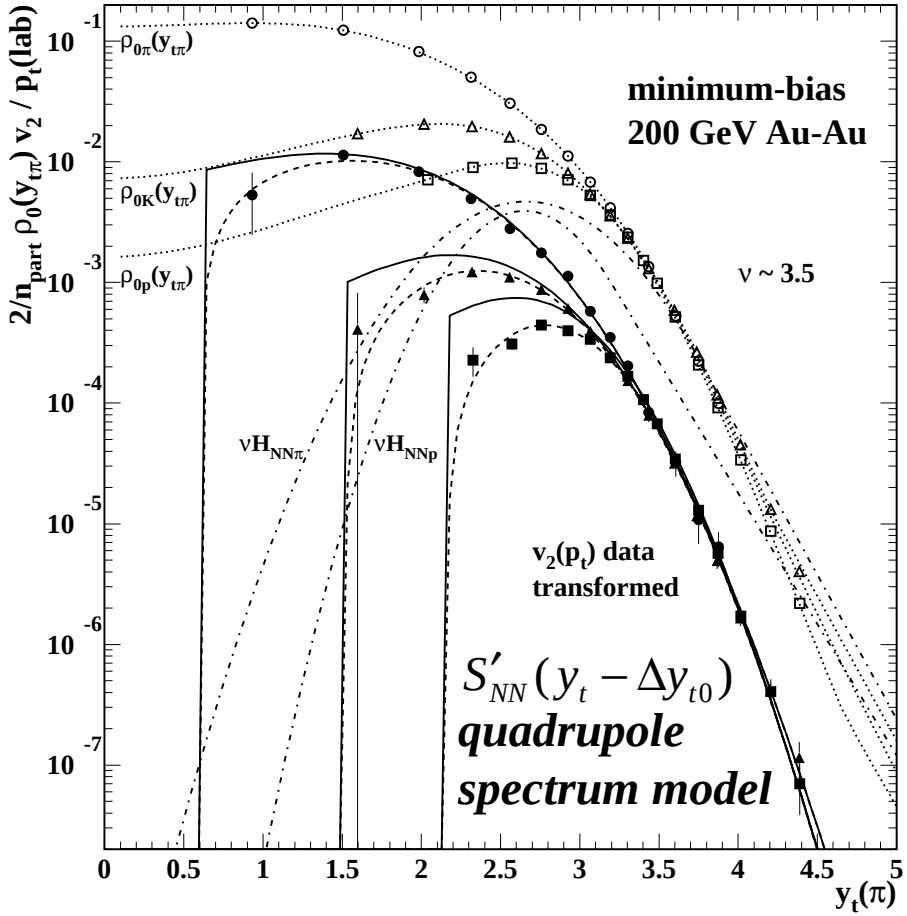
quadrupole y_t spectrum

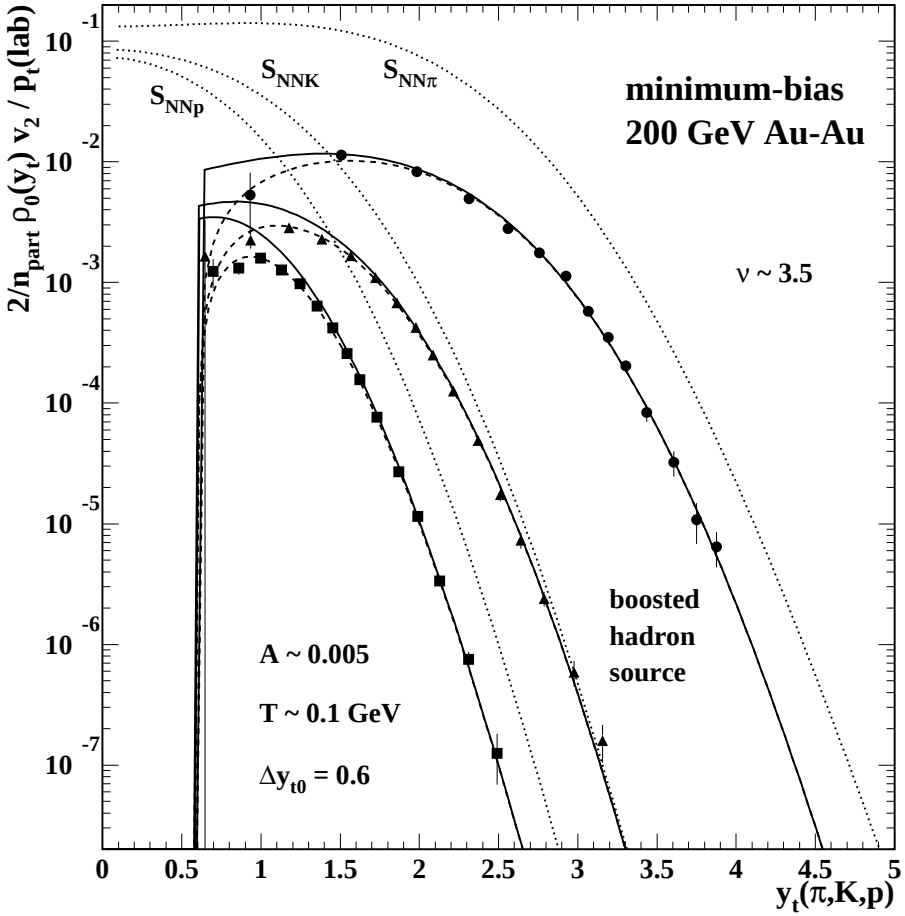


Trainor

$p_t' = p_t$ in the boost frame

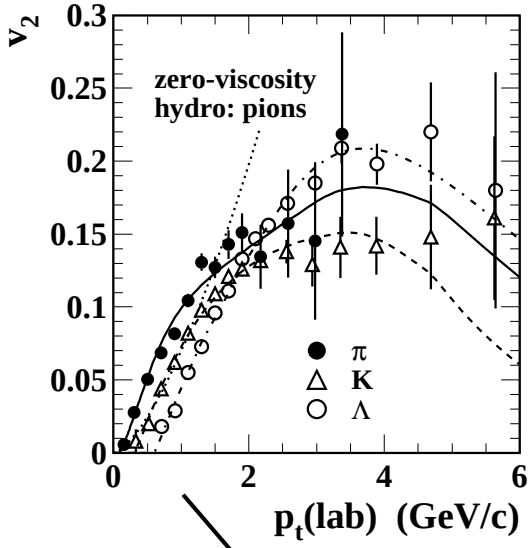
The Quadrupole Spectrum

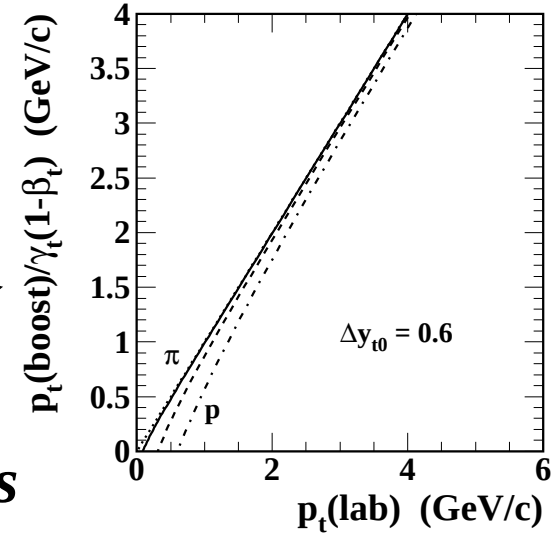




$$\underbrace{\frac{2}{n_{part}}\frac{\rho_0(y_t)v_2(p_t)}{p_t}}_{\textbf{measured data}} \simeq \underbrace{\left\{\frac{p'_t}{p_t\,\gamma_t(1-\beta_t)}\right\}\left\{\frac{\gamma_t(1-\beta_t)}{2T_2}\right\}}_{\textbf{known quantities}} \Delta y_{t2}\underbrace{\frac{2}{n_{part}}\rho_2(y_t;\Delta y_{t0},T_2)}_{\textbf{quadrupole spectrum}}$$

v_2 Deconstructed



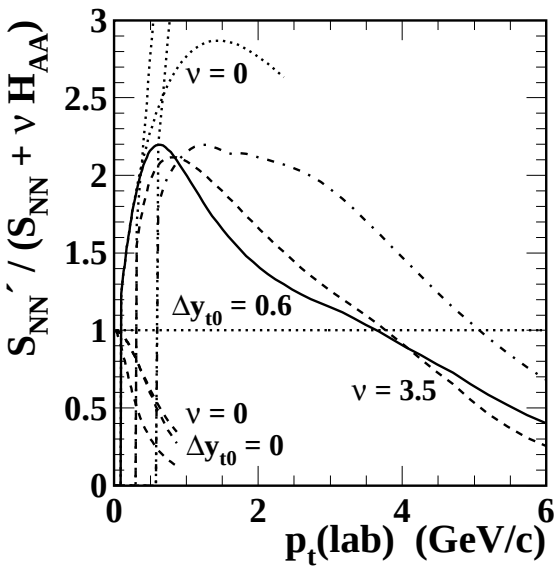


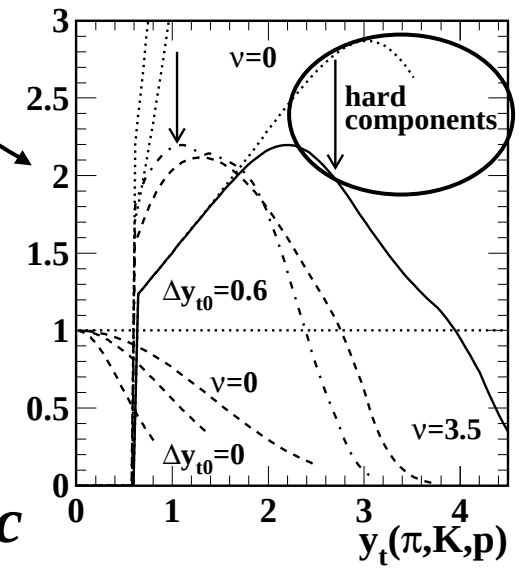
boost kinematics

$$v_2(p_t) \simeq \left\{ \frac{p_t'}{\gamma_t(1-\beta_t)} \right\} \left\{ \frac{\gamma_t(1-\beta_t)}{2T_2} \right\} \Delta y_{t2} \frac{\rho_2(y_t;\Delta y_{t0},T_2)}{\rho_0(y_t)}$$

spectrum ratios

$$\frac{S'_{NN}(y_t - \Delta y_{t0})}{\rho_0(y_t) = S_{NN} + \nu H_{AA}}$$

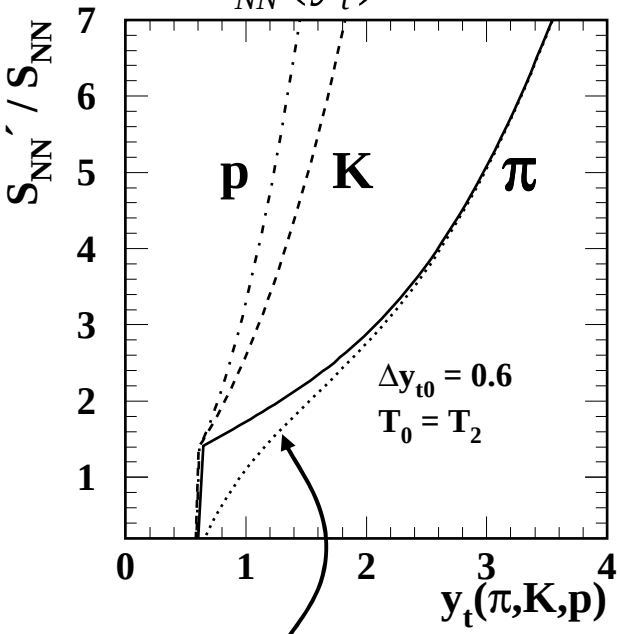


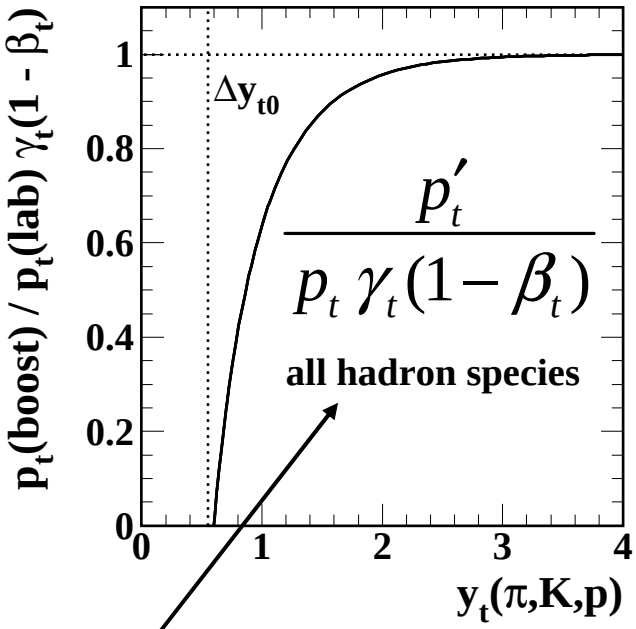


parton fragmentation (minijets) dominates $v_2(p_t)$ above 0.5 GeV/c

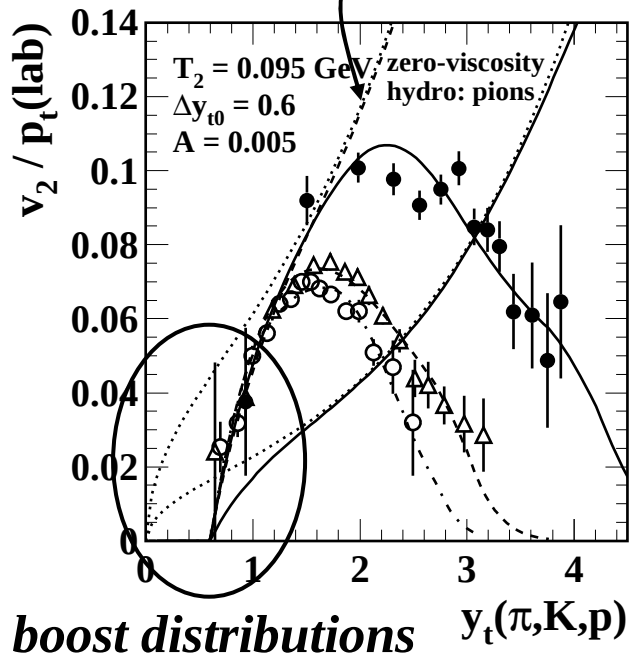
v_2 *vs* Hydro Theory

$$\frac{S'_{NN}(y_t - \Delta y_{t0}; T_2)}{S_{NN}(y_t)}$$





~ 3× hydro



boost distributions

$$\frac{v_2(p_t)}{p_t} \simeq \left\{\frac{p_t'}{p_t\,\gamma_t(1-\beta_t)}\right\}\left\{\frac{\gamma_t(1-\beta_t)}{2T_2}\right\}\Delta y_{t2}\,\frac{\rho_2(y_t;\Delta y_{t0},T_2)}{\rho_0(y_t)}$$

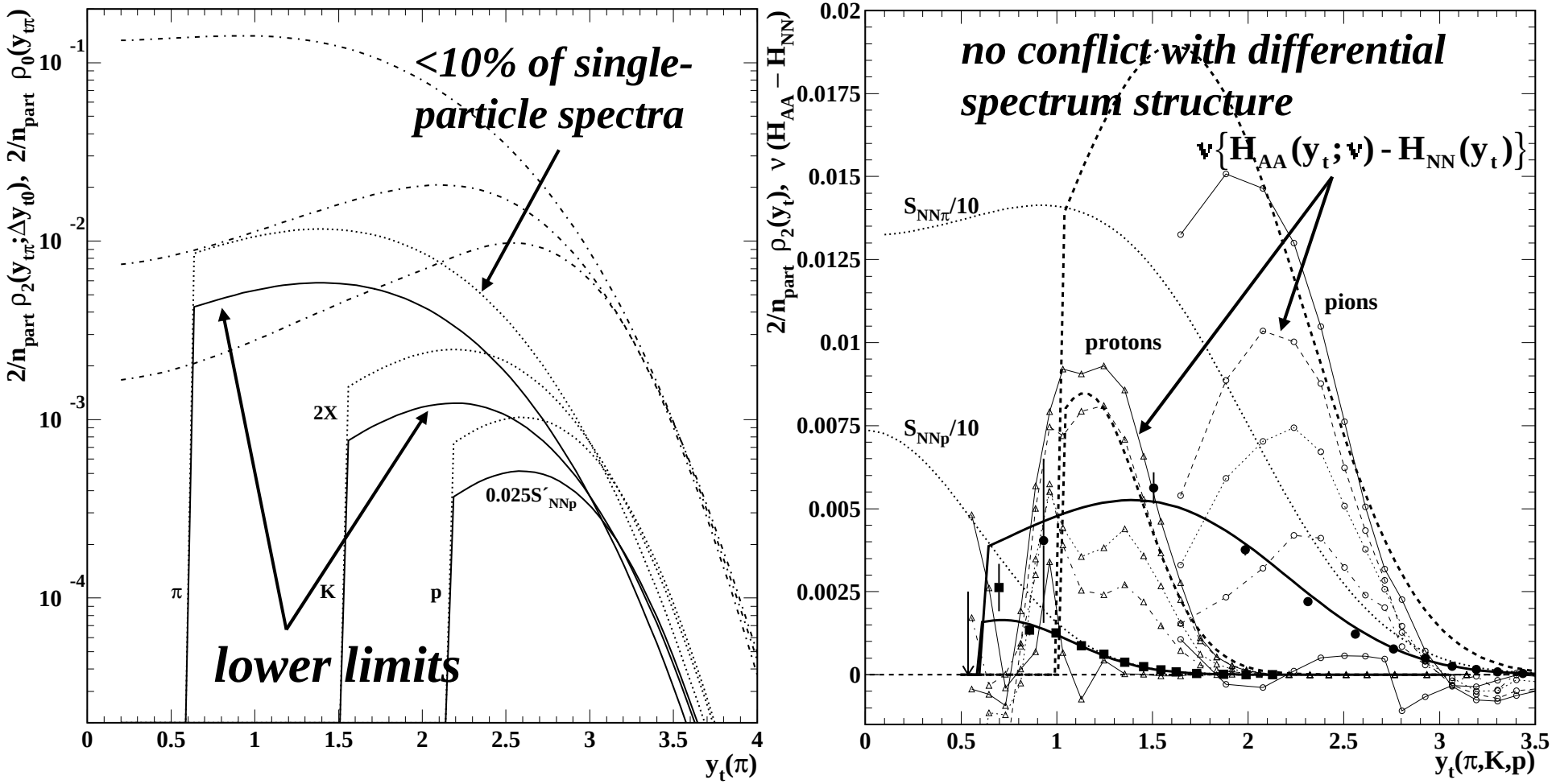
$$\propto \left\{\frac{p_t'}{p_t\,\gamma_t(1-\beta_t)}\right\}\frac{S'_{NN}(y_t - \Delta y_{t0}; T_2)}{S_{NN}(y_t)}$$ hydro model

no hard component

hydro is inconsistent with quadrupole data

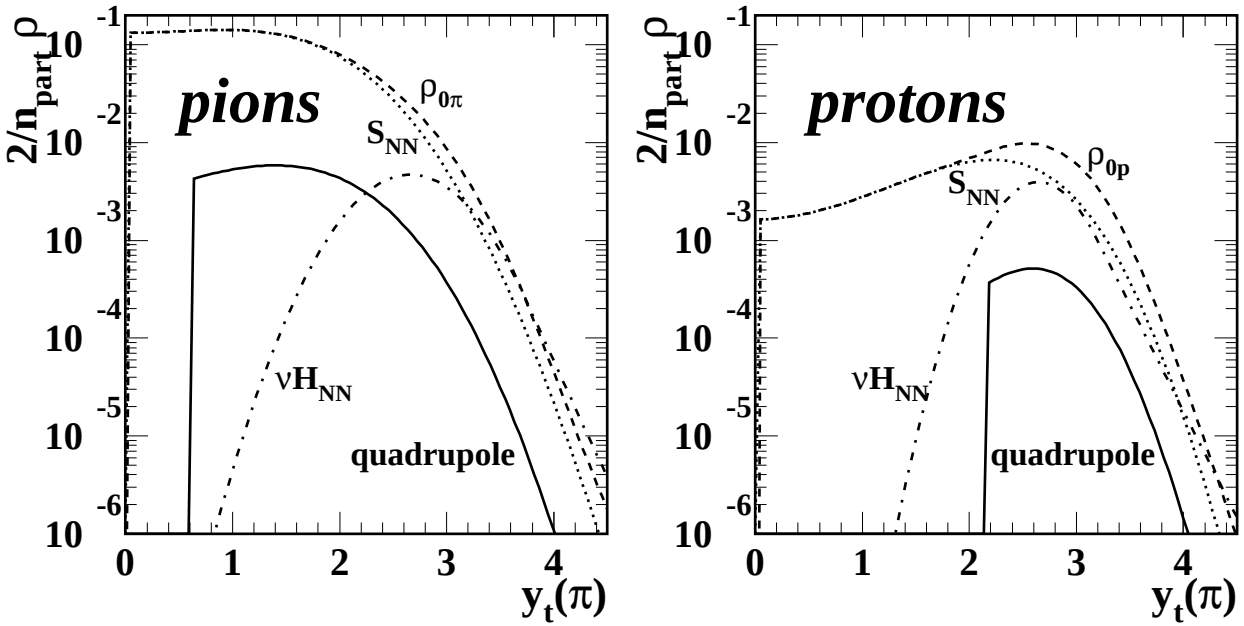
Quadrupole Absolute Yield?

requirements for upper limit



comparisons with features of single-particle spectra imply that the quadrupole is < 5% of total hadrons

What is the Quadrupole?



- ***Small fraction of all hadrons* (< 5%)**
- ***Much smaller slope parameter* (T_2 ~ 0.7 T_0)**
- ***Unique boost distribution (not Hubble expansion)***
- ***Chemical abundances match N-N soft component***
- ***No coupling to EoS, minijets or medium effects***

Azimuth Quadrupole Summary

- ***Conventional flow analysis mixes "flow" and "nonflow"***
- ***2D angular autocorrelations separate the two structures***
- ***The isolated quadrupole component is linear on*** $\mathbf{log(\sqrt{s_{NN}})}$
- ***The optical eccentricity appears to better model small-x glue***
- ***The quadrupole consists of hadrons from a boosted source***
- ***Quadrupole systematics determined only by*** $\mathbf{log(\sqrt{s_{NN}})}$ ***and*** $\mathbf{n_{bin}}$
- ***Quadrupole seems unrelated to the medium (sharp transitions)***
- ***Quadrupole seems inconsistent with hydro (boost distribution)***

The quadrupole may be a gluonic radiation field fragmenting to hadrons

Universal Features of Nuclear Collisions

Participant nucleon fragmentation
(*soft component*)

Parton fragmentation to minijets
(*hard component*)

QCD *field-field* interactions and fragmentation to hadrons?
(*quadrupole component*)

What is unique to A-A collisions?