„Collective Flow signals the QGP" H. Stoecker FIAS

LQCD: First Order Quark-Hadron Phase Transition @ high baryon density MU_B > 400 MeV

2. Thermalization &Thermometers: Hadron Yields

3. The Barometer: Proton Flow

4. Discovery of 1. Order Q-H P.T.

Collapse of proton flow @ SpS -> FAIR

5. Flow and Jets…

- Thermalization?
- Yields and flow from nonequilibrium hadron transport theory

IQMD,UrQMD, HSD

Bleicher, Bass, Bratkovskaya…

Delta transport in n+pi+delta system: IQMD

$$\frac{\partial f_\Delta}{\partial t} + \vec{v}\cdot\frac{\partial f_\Delta}{\partial r} - \nabla_r U_\Delta \cdot \frac{\partial f_\Delta}{\partial p} = I_{\Delta\Delta\to\Delta\Delta} + I_{\Delta N\to\Delta N} + I_{\Delta\pi\to\Delta\pi} + I_{\Delta N\to\Delta\Delta} + I_{\Delta N\to NN} + I_{\Delta\Delta\to NN} + I_{\Delta\Delta\to\Delta N} + I_{\Delta\to N\pi}$$

$$= \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{\Delta\Delta}c^2\cdot\mu_{\Delta\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$

$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_\Delta(p_2')(1-f_\Delta(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}\Delta(p_1)f_\Delta(p_2)(1-f_\Delta(p_1'))(1-f_\Delta(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{\Delta N}c^2\cdot\mu_{\Delta N}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$

$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_N(p_2')(1-f_\Delta(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}\Delta(p_1)f_N(p_2)(1-f_\Delta(p_1'))(1-f_N(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{\Delta\pi}c^2\cdot\mu_{\Delta\pi}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$

$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_\pi(p_2')(1-f_\Delta(p_1))(1+f_\pi(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}f_\Delta(p_1)f_\pi(p_2)(1-f_\Delta(p_1'))(1+f_\pi(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{\Delta N}c^2\cdot\mu_{\Delta\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$

$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_\Delta(p_2')(1-f_\Delta(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}\Delta(p_1)f_N(p_2)(1-f_\Delta(p_1'))(1-f_\Delta(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{\Delta N}c^2\cdot\mu_{NN}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$

$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_N(p_2')(1-f_\Delta(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}\Delta(p_1)f_N(p_2)(1-f_N(p_1'))(1-f_N(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{\Delta\Delta}c^2\cdot\mu_{NN}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$

$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_N(p_2')(1-f_\Delta(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}\Delta(p_1)f_\Delta(p_2)(1-f_N(p_1'))(1-f_N(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{\Delta\Delta}c^2\cdot\mu_{\Delta N}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$

$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_N(p_2')(1-f_\Delta(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}\Delta(p_1)f_\Delta(p_2)(1-f_\Delta(p_1'))(1-f_N(p_2'))\right]$$

$$+ \int\frac{d^3p_N}{(2\pi\hbar)^3}\int\frac{d^3p_\pi}{(2\pi\hbar)^3}|\langle p_N p_\pi|T|p_\Delta\rangle|^2\cdot(2\pi\hbar)^3\delta^3(p_\Delta-p_N-p_\pi)\delta(\varepsilon_\Delta-\varepsilon_N-\varepsilon_\pi)\cdot$$

$$[f_N(p_N)f_\pi(p_\pi))(1-f_\Delta(p_\Delta)) - f_\Delta(p_\Delta)(1-f_N(p_N))(1+f_\pi(p_\pi))]$$

Control of thermo- and hydro models necessary!!!

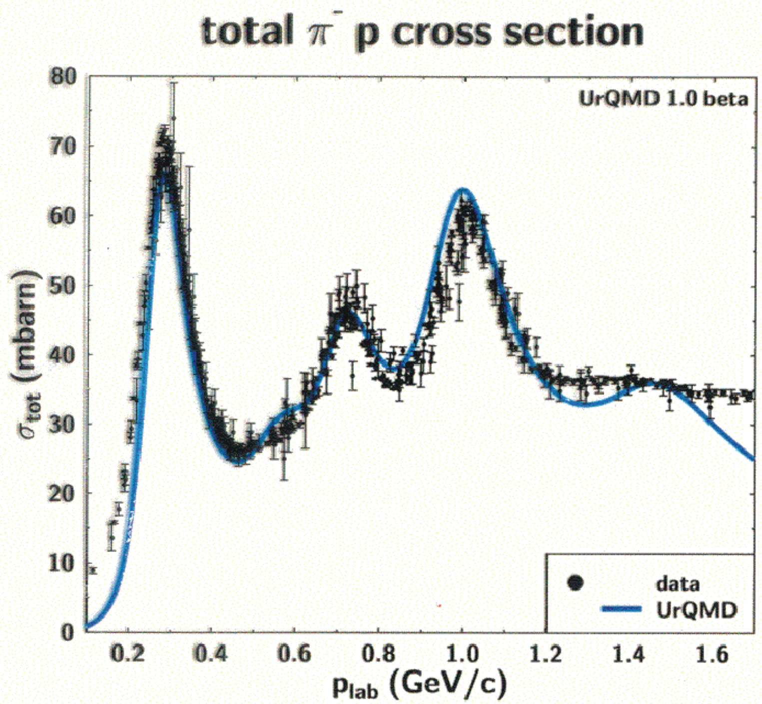
Two Robust Hadron Based nonequil. Transport Models HSD vs UrQMD

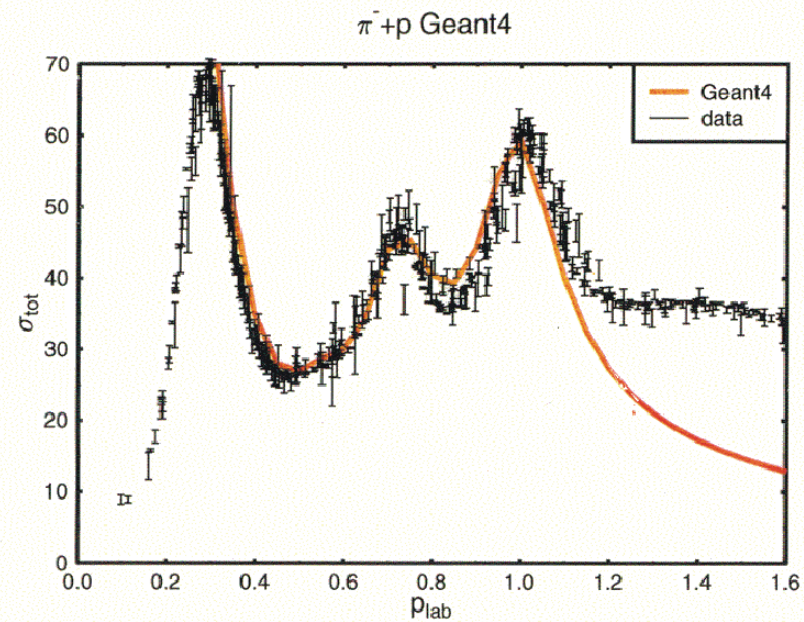
allows to estimate systematic uncertainties

UrQMD	HSD
• molecular dynamics with Gaussian particle distributions	parallel ensemble dynamics of point-like test-particles
• cascade mode	self-energies for hadrons $U_h(\rho, \vec{p})$
• all baryonic resonances up to 2.25 GeV, all mesonic resonances up to 1.9 GeV	baryon octet, decuplet states and N*(1440), N*(1535), 0^- and 1^- meson octets + non-resonant $\pi\pi$ production
• realization of string (LUND) model	
'Frankfurt' string code	FRITIOF-7.02 (LUND string code)
fragmentation function $f(x, m_T)$: different for leading hadrons and for produced particles	similar for all particles
• formation time (in hadron rest frame) $\tau_F = f(M,p) \simeq 1 - 2$ fm/c	$\tau_F \simeq 0.8$ fm/c
	• energy density cut for hadronization $\epsilon \lesssim 1$ GeV/fm^3
	• HSD - recent developments: – off-shell dynamics with spectral functions – multi-meson fusion channels

• Proton pi- Cross Sections UrQMD vs. Geant4

Weber

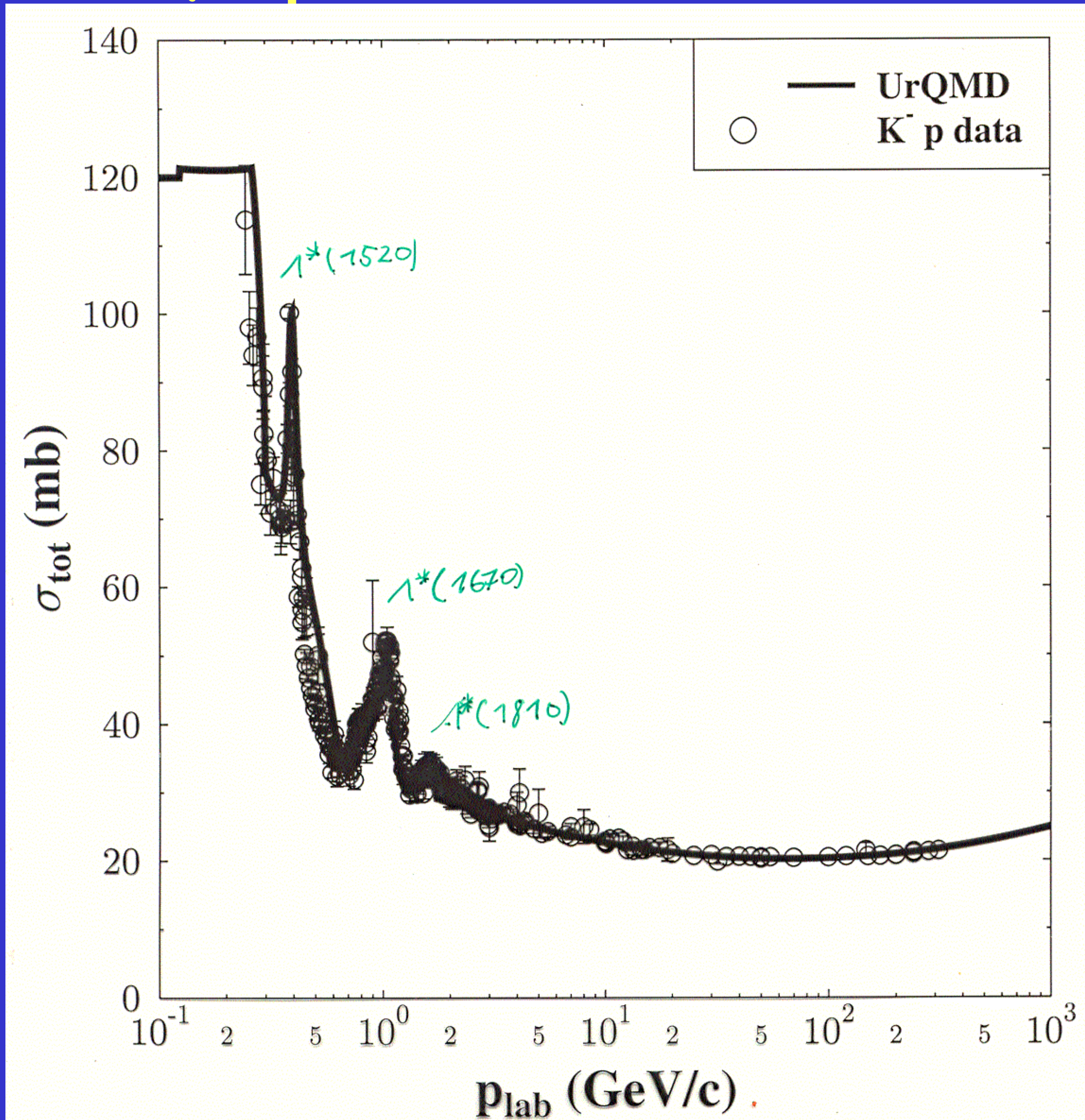




→ calculate cross section according to:

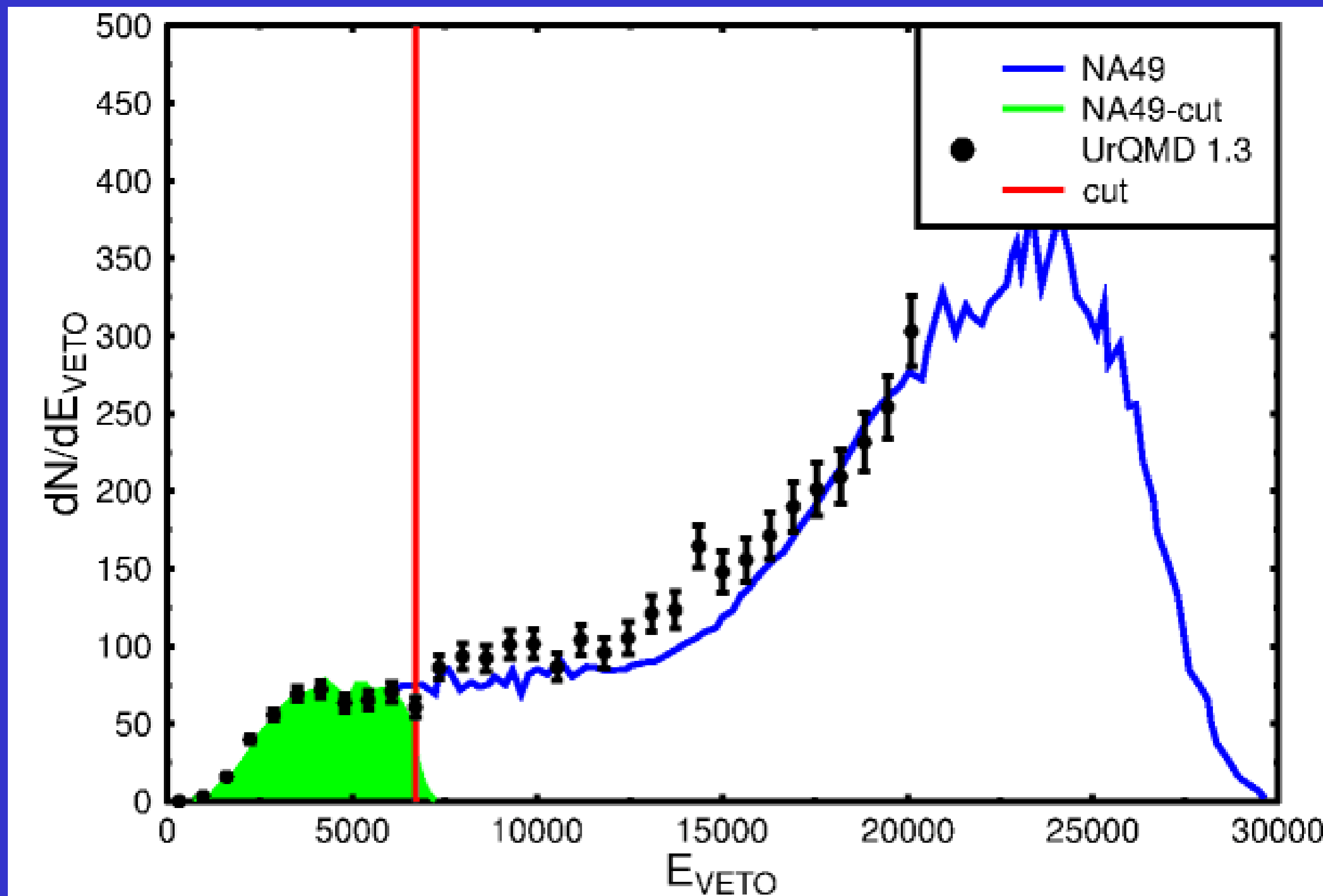
$$\sigma_{tot}^{MB} = \sum_{R=\Delta,N^*} \frac{2I_R + 1}{(2I_B + 1)(2I_M + 1)} \frac{\pi}{p_{CMS}^2} \frac{\Gamma_{R\to MB}\Gamma_{tot}}{(M_R - \sqrt{s})^2 + \frac{\Gamma_{tot}^2}{4}}$$

• K^- p Cross Section



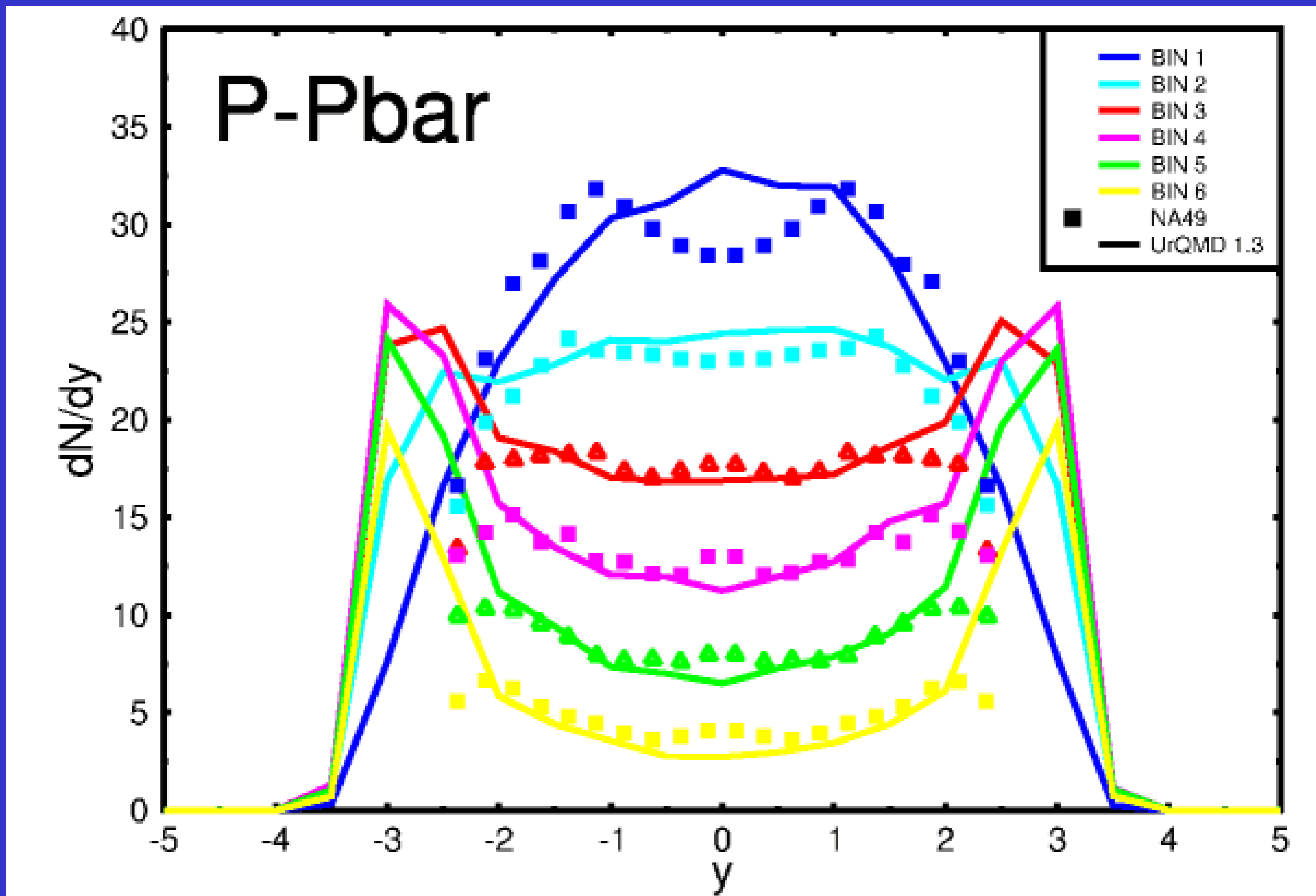
Weber

NA49 Centrality Cut
Pb+Pb 40AGeV



Weber

•Protons vs. Centrality Pb+Pb 158AGeV Thermalization? 4Pi Thermal?



Weber

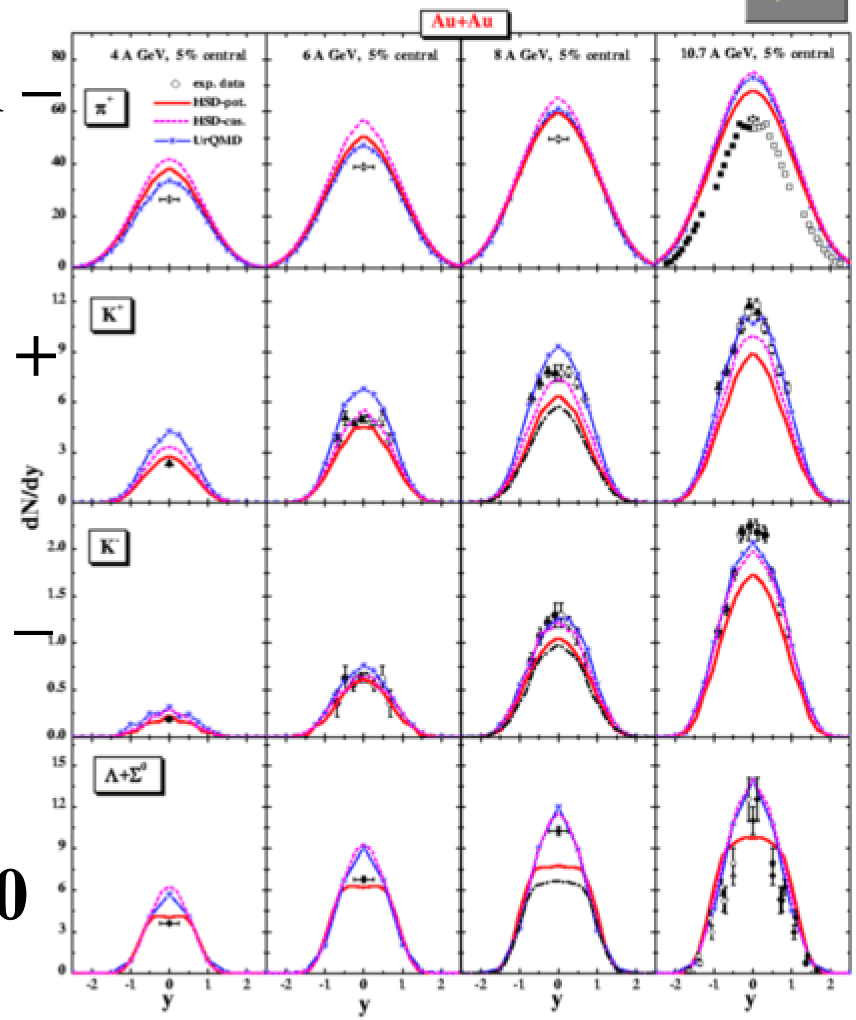
•AGS: Rapidity distributions Au+Au central 4, 6, 8, 11 AGeV

Pi –

K +

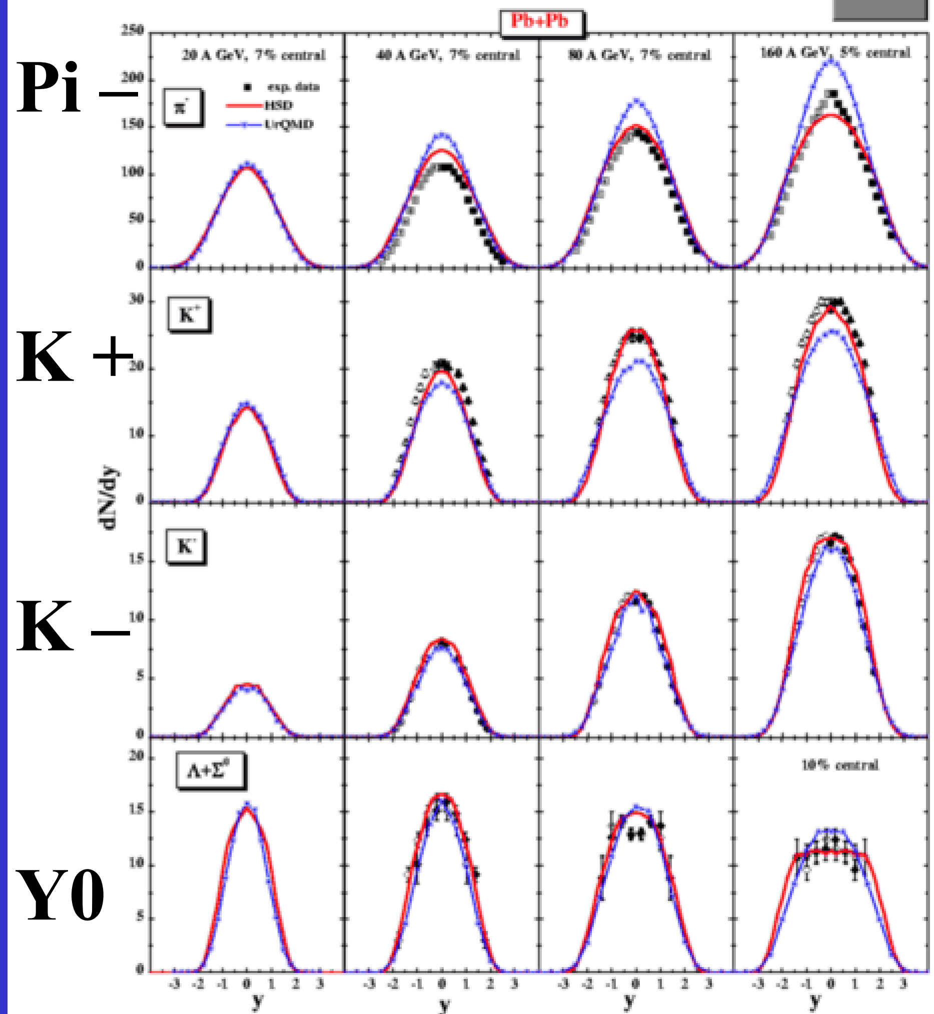
K –

Y0

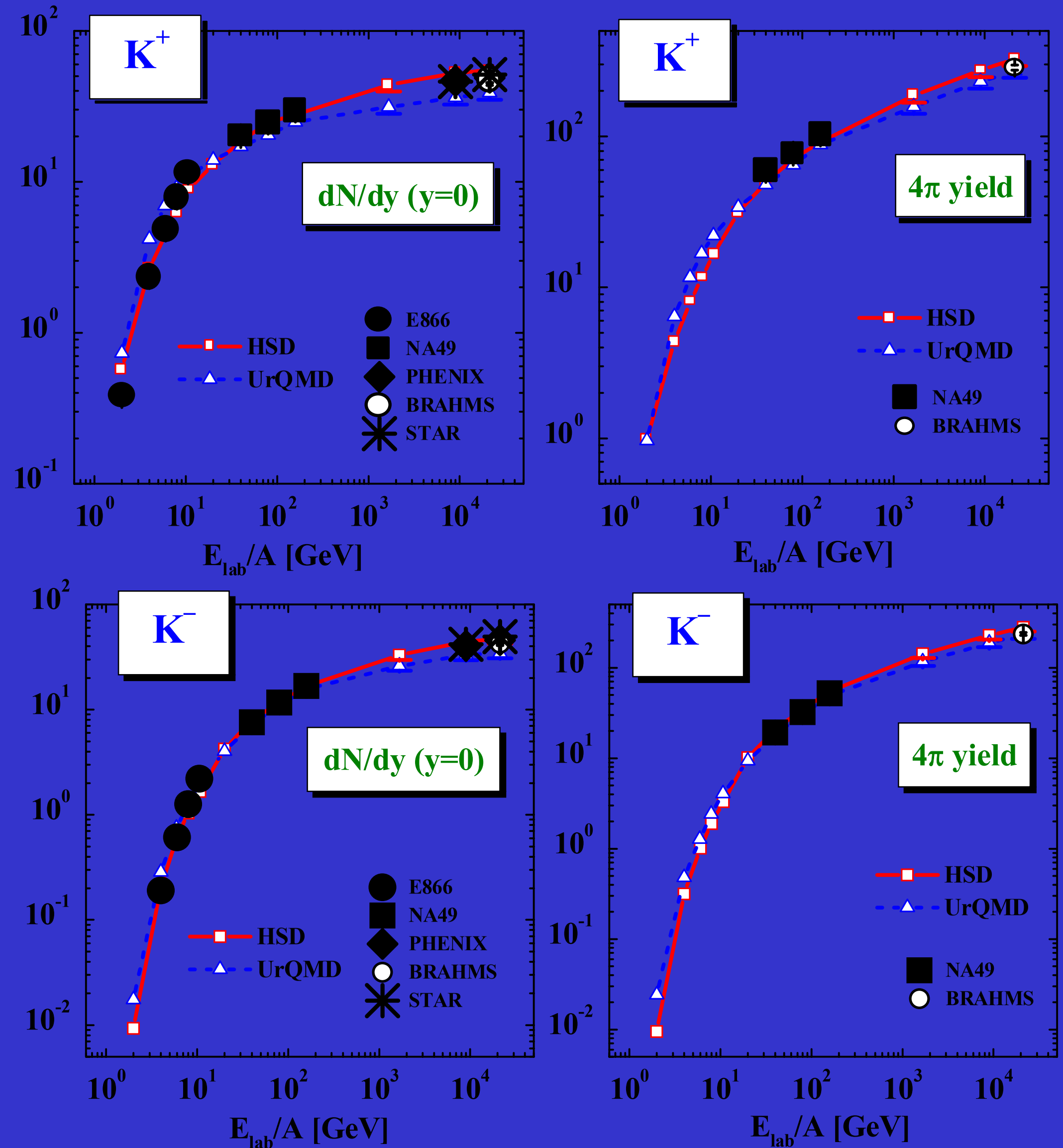


•SPS: Rapidity distributions Pb+Pb central

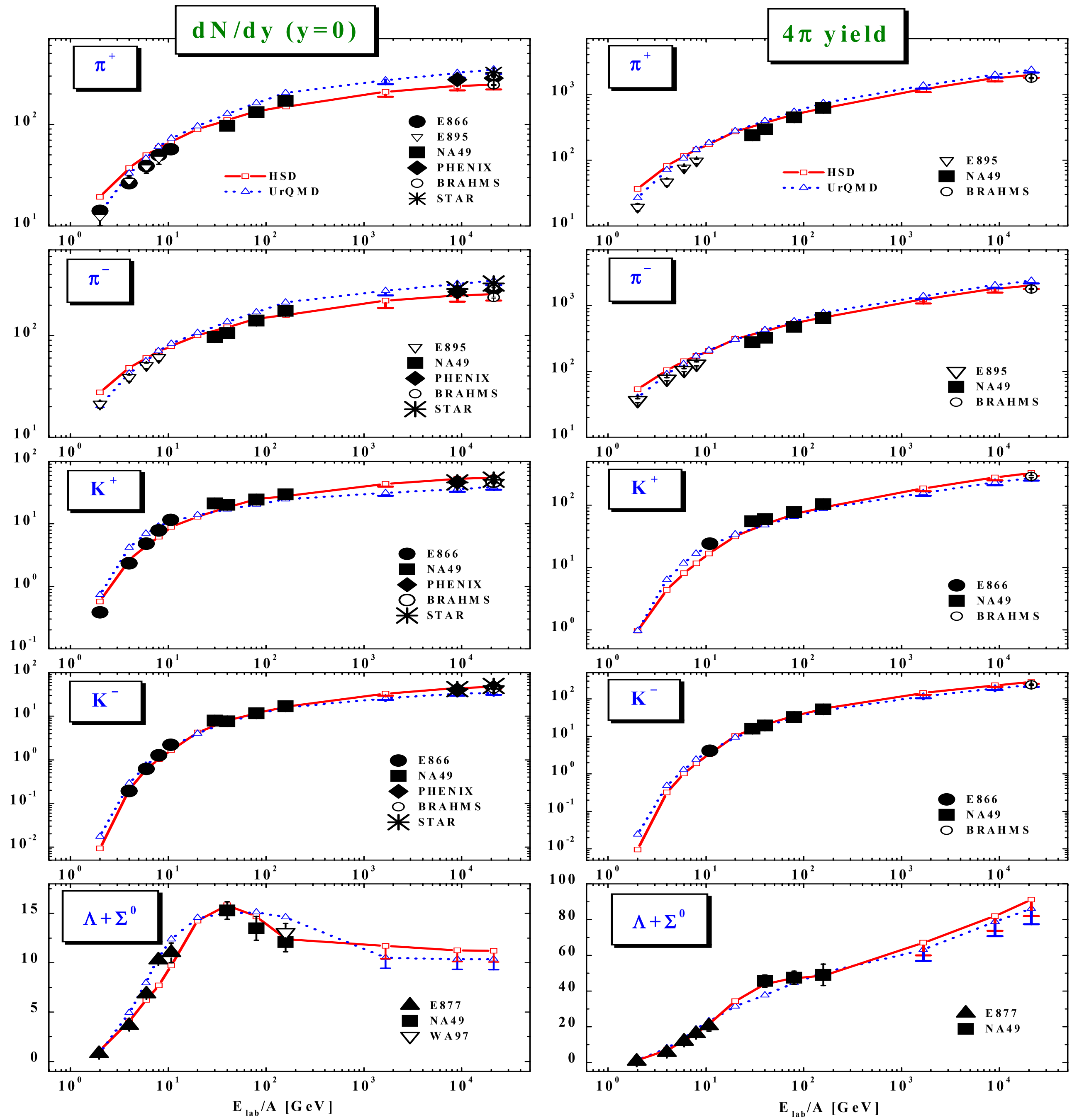
20 40 80 160 AGeV



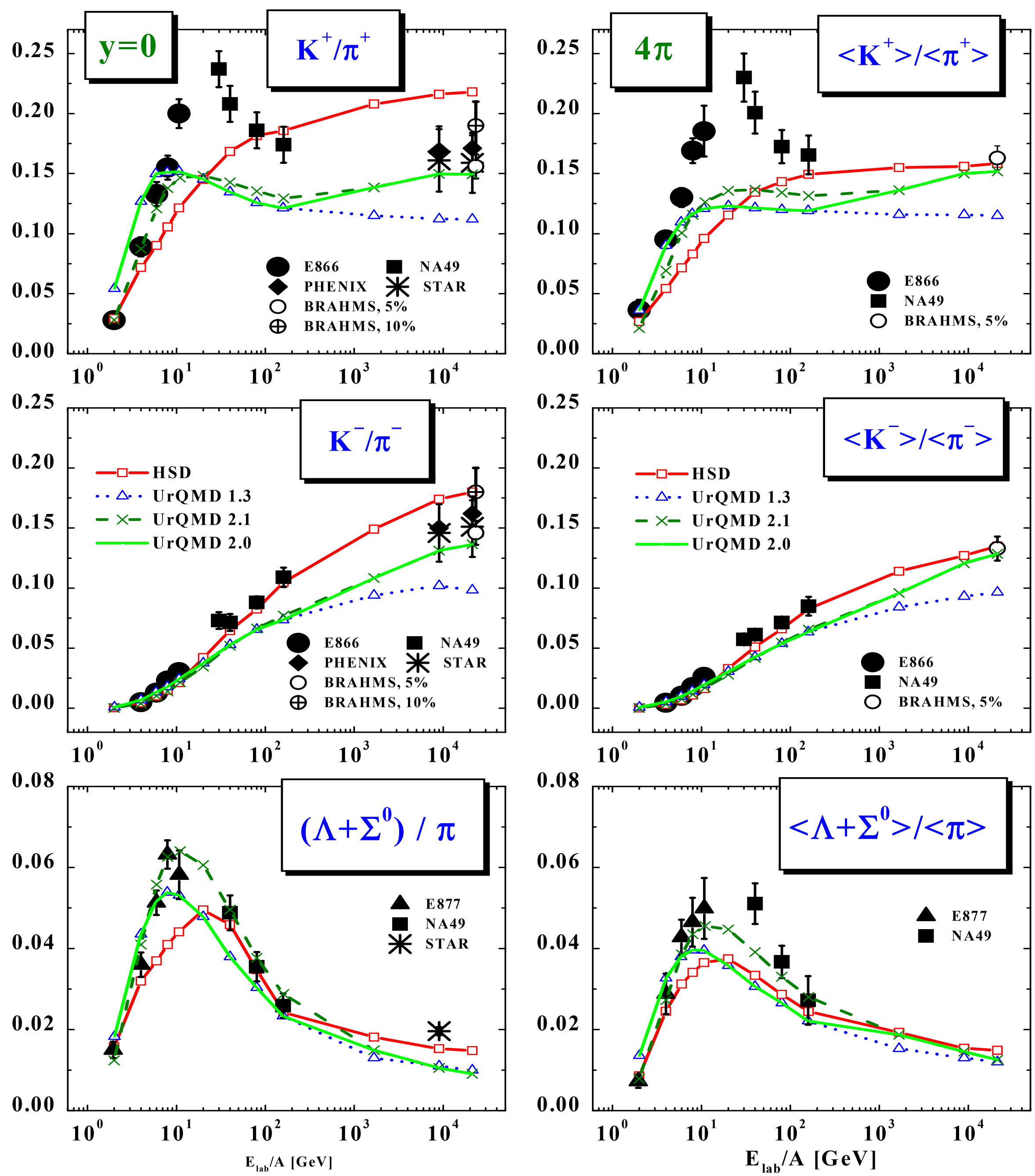
·Excitation function of $K^{\pm}$ yields



- Good description of K^+ and K^- yields by HSD and UrQMD

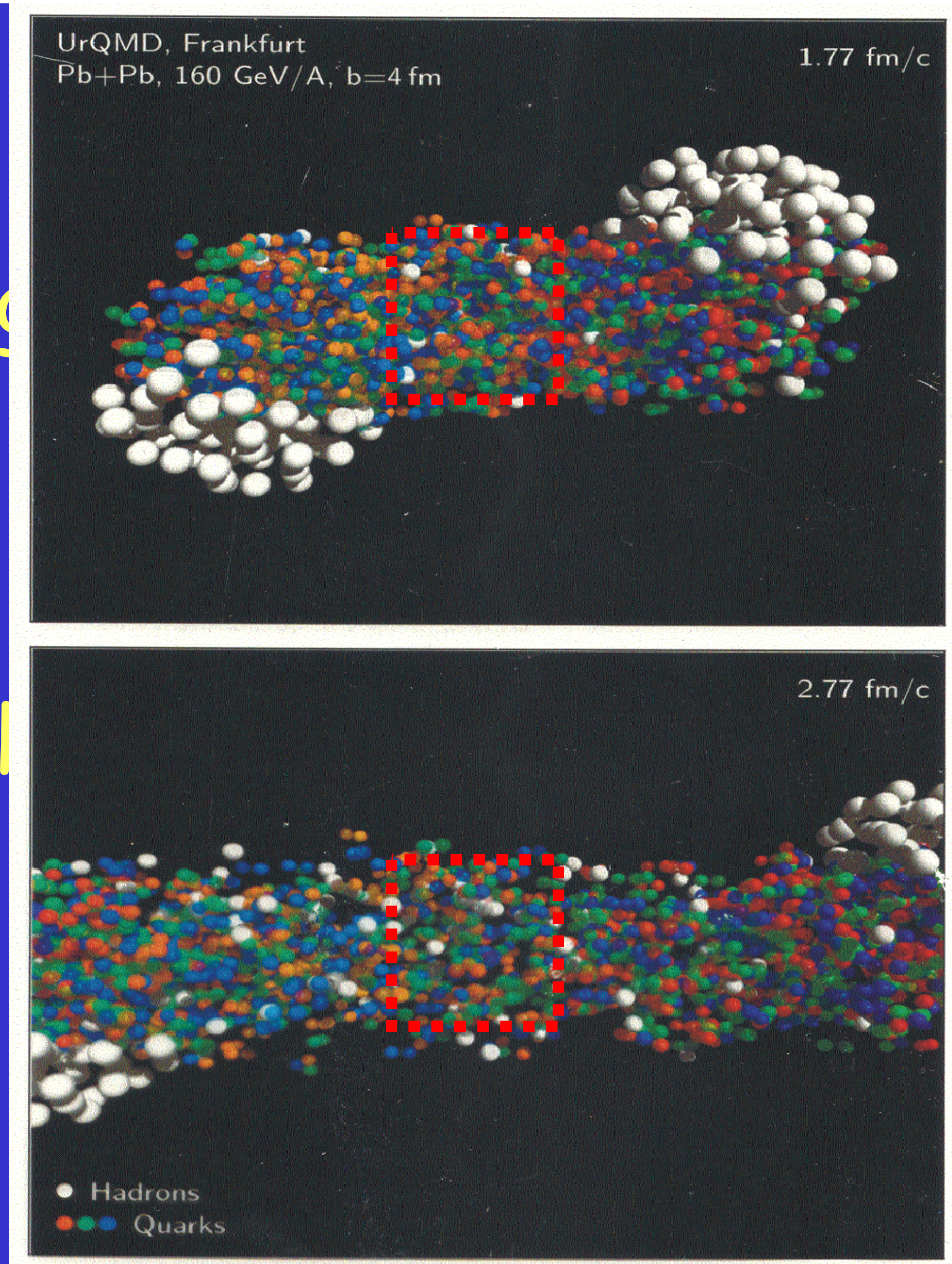


- Yields from transport theorie- no thermal equilibrium assumed


y=0
K⁺/π⁺
E866
PHENIX
BRAHMS, 5%
BRAHMS, 10%
NA49
STAR
4π
<K⁺>/<π⁺>
E866
NA49
BRAHMS, 5%
K⁻/π⁻
HSD
UrQMD 1.3
UrQMD 2.1
UrQMD 2.0
<K⁻>/<π⁻>
(Λ+Σ⁰) / π
E877
NA49
STAR
<Λ+Σ⁰>/<π>
E877
NA49
E_lab/A [GeV]
E_lab/A [GeV]

- **Nonequilibrium Microscopic models yield ok yields – is thermalization achieved?**

- Simulating thermo-dynamics in central cel



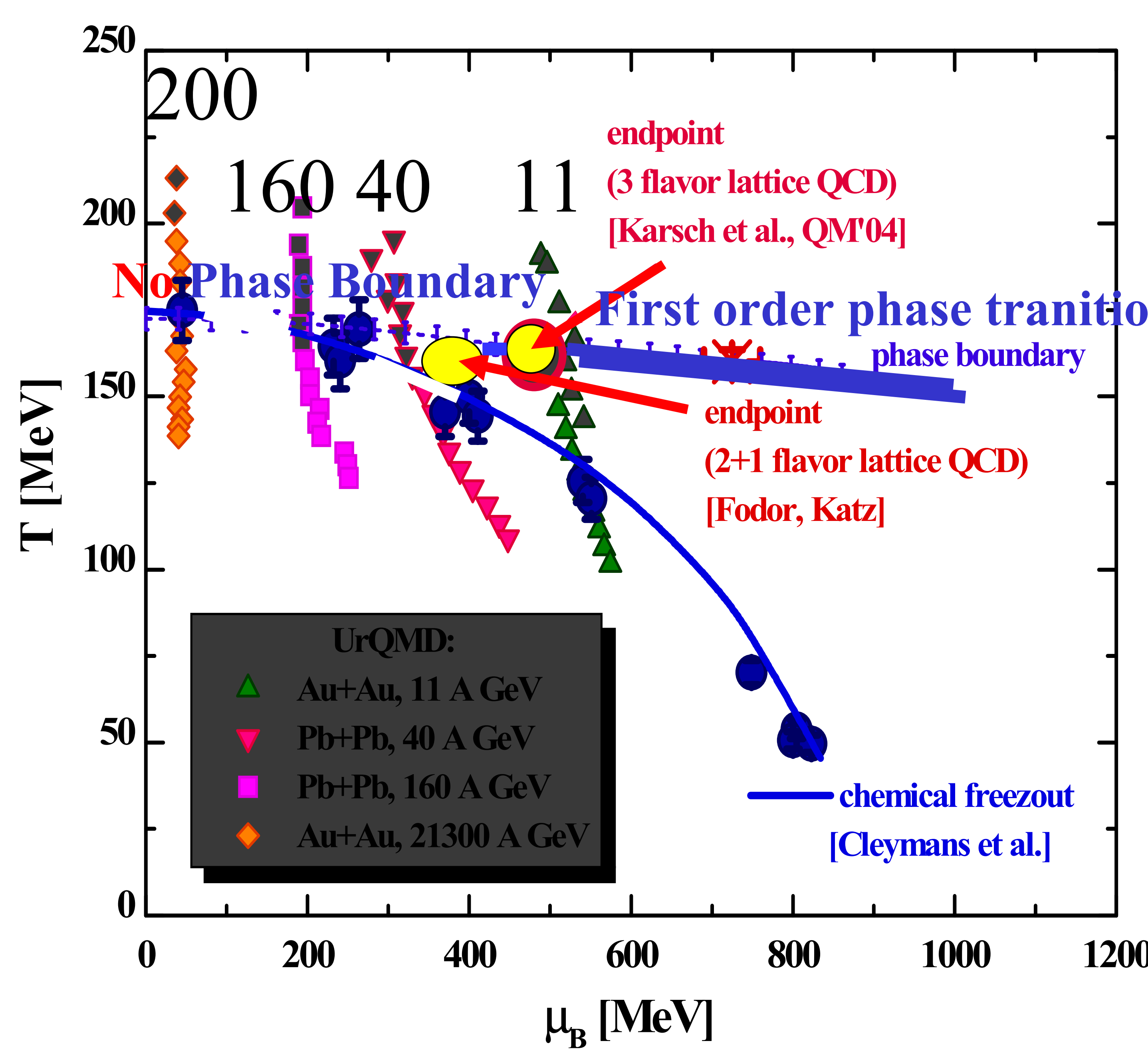
Weber, Bravina

- Time evolution in T-Mu_B Plane

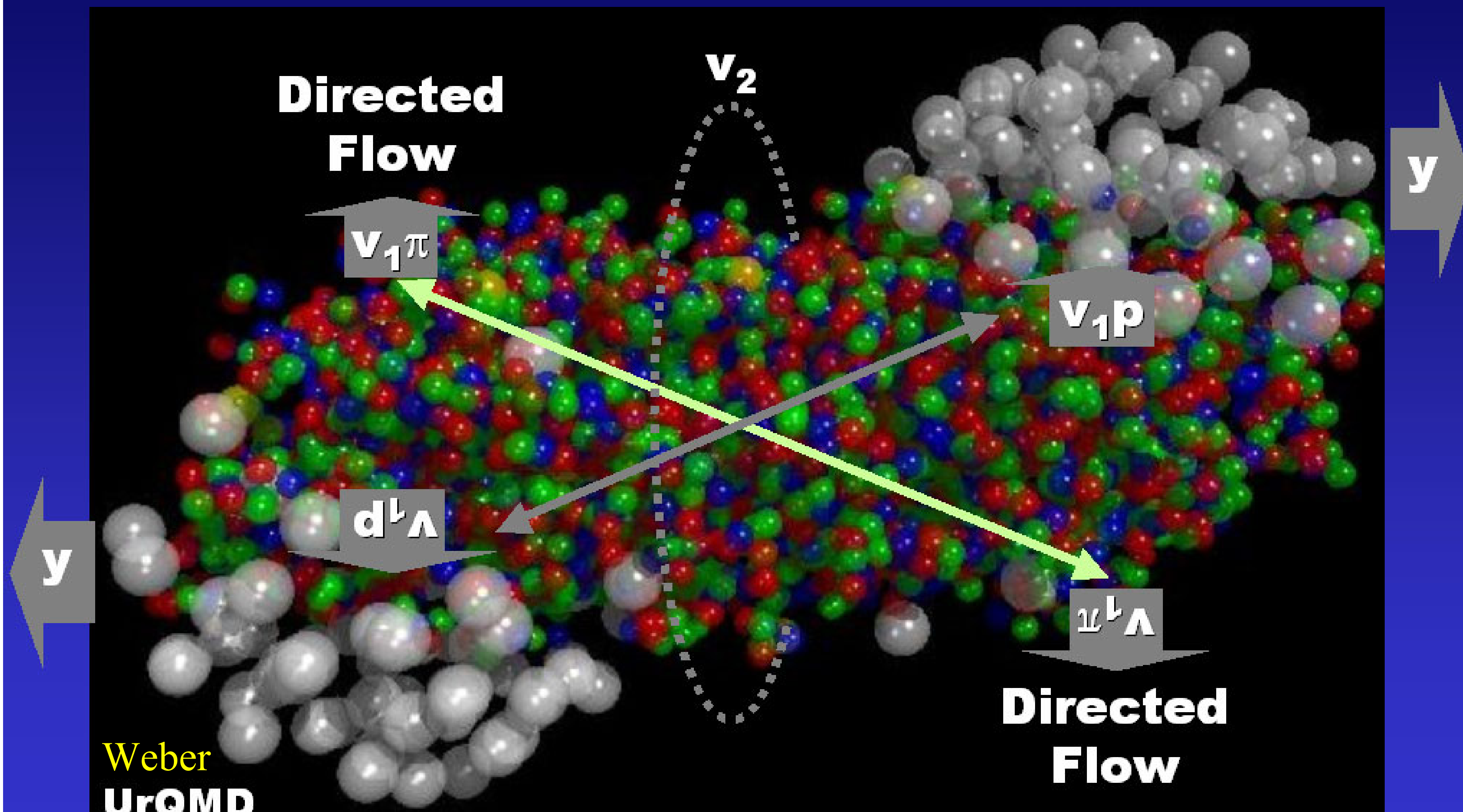
UrQMD Bravina

–

looks like thermal after 5 fm/c!



Directed and Elliptic Flow

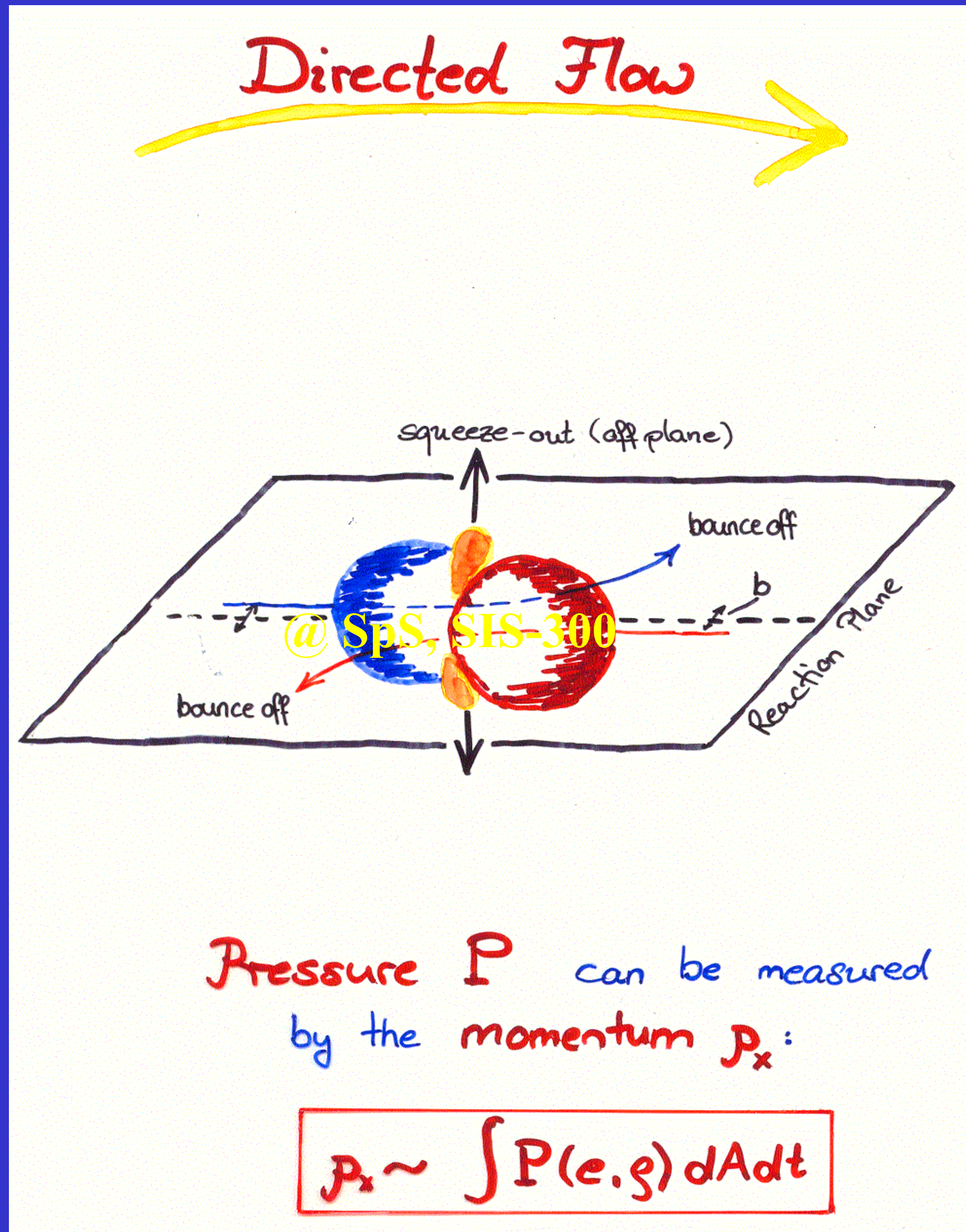


Proton Flow as Barometer:

Bounce-Off = v1

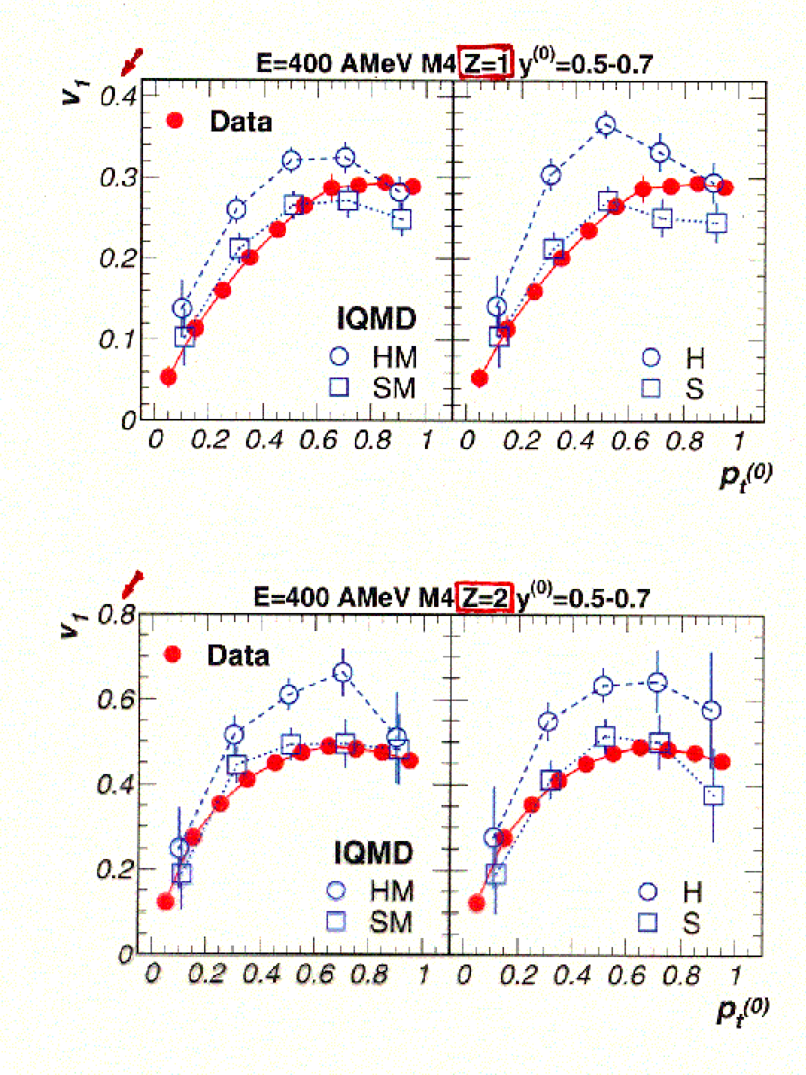
SqueezeOut = v2

It is in the protons. Period.



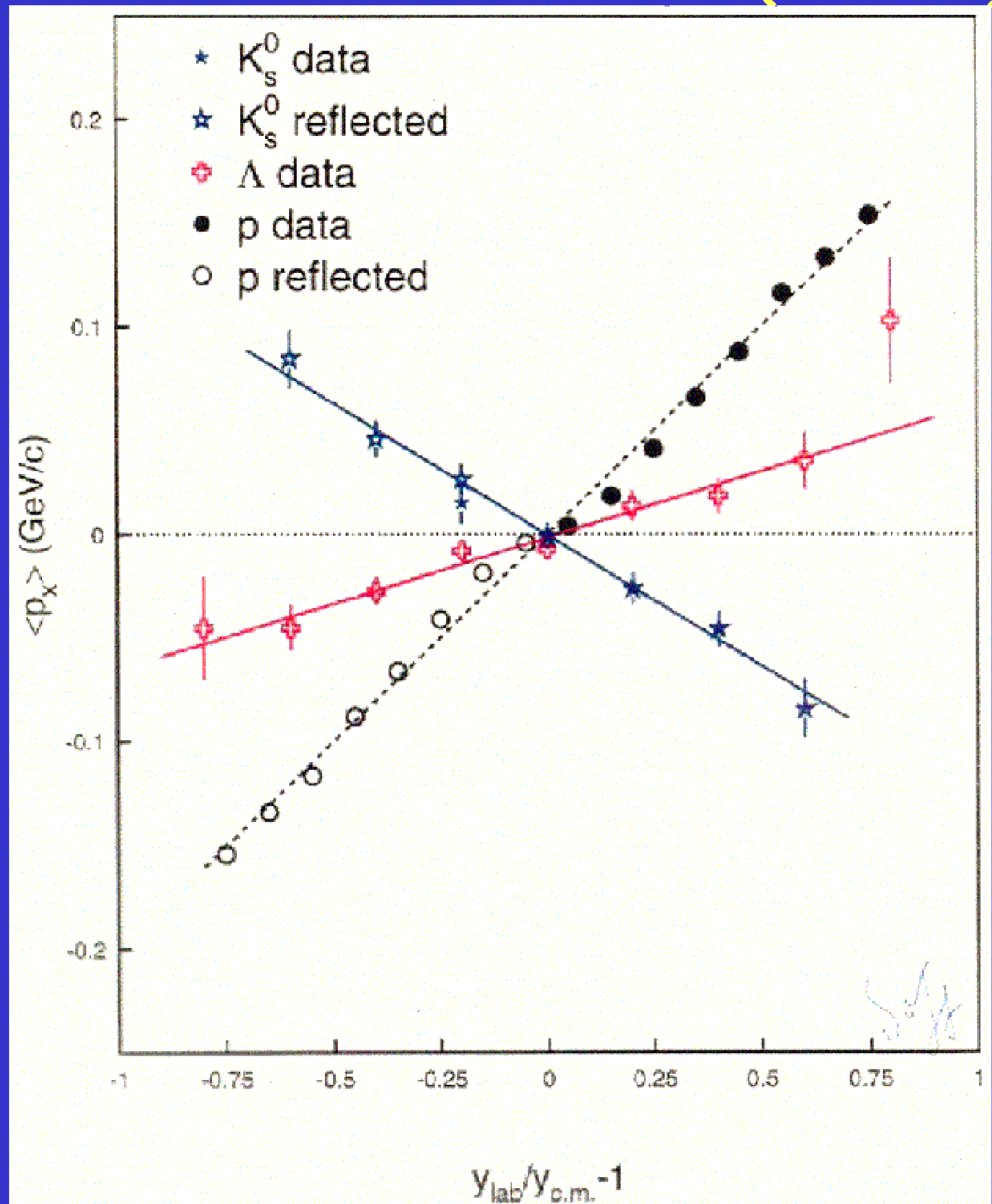
•Yes! Triple Differential Flow is a barometer! Model Comparison FOPI – IQMD (A. Andronic)

It is in the protons.
Period.



→ IQMD reproduces the particle dependence (but not in detail)

•6 GeV Sideward Flow (b<7fm)



E895
Pions
antiflow-
all baryons
flow!
R. Lacey

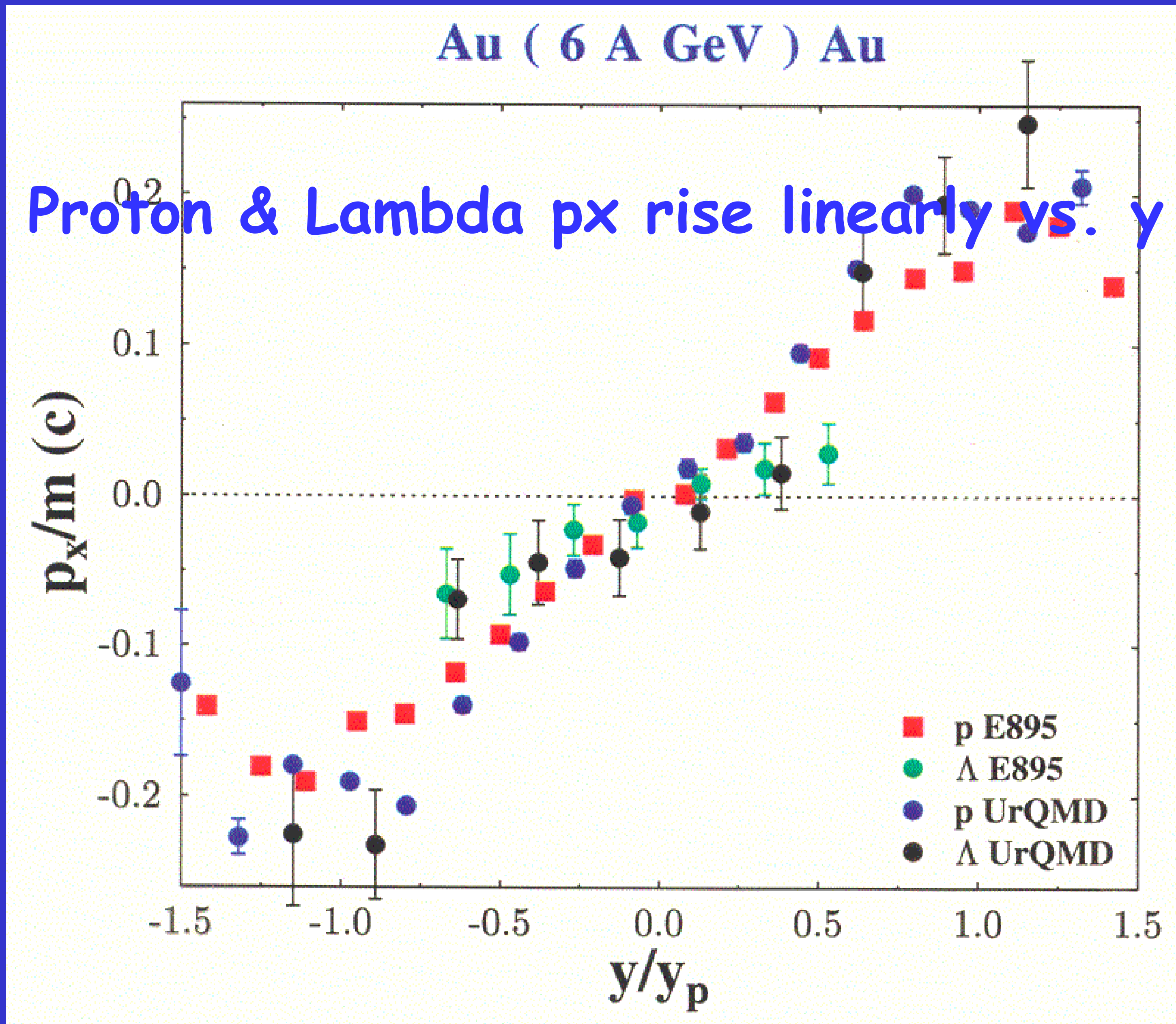
- **Directed proton Flow**
  v1 = px / pt

- **Proton Flow – straight forward in hydrodynamics...**

Cross check by microscopic hadron models: multicomponent transport theory

- **UrQMD, HSD...**

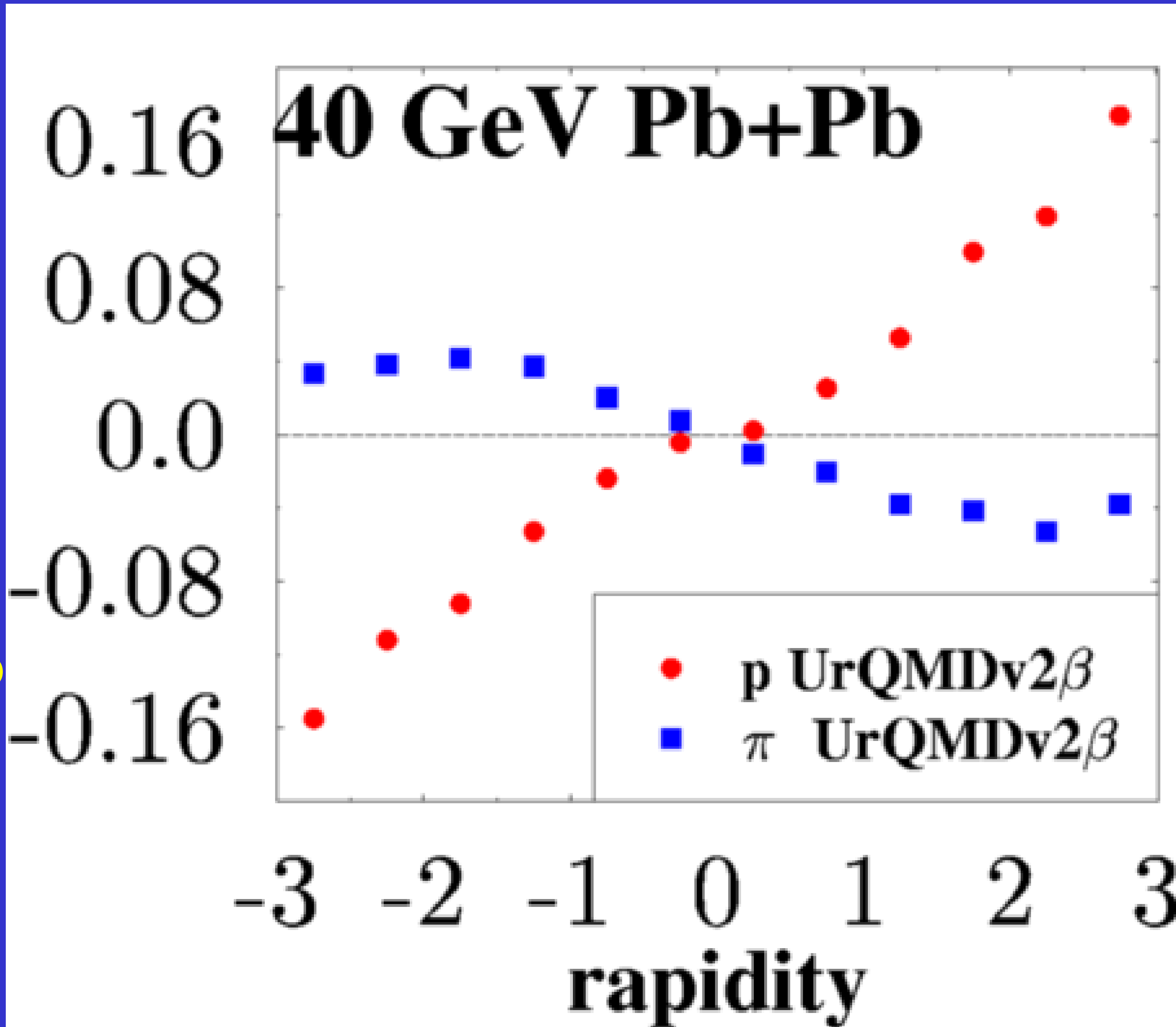
Proton & Lambda px rise linearly vs. y



Soff, Urqmd

- Bass: UrQMD Predicts Pion v1 Drops Linearly with Y: Absorptio

What do Data Say?



• Multi-Fluid-Hydrodynamics

→ for each fluid: $j^{\mu}_{(i)}$, $T^{\mu\nu}_{(i)}$

→ every fluid for itself is in thermal equilibrium (but not necessarily with the others)

→ only the sum of all fluxes is conserved!

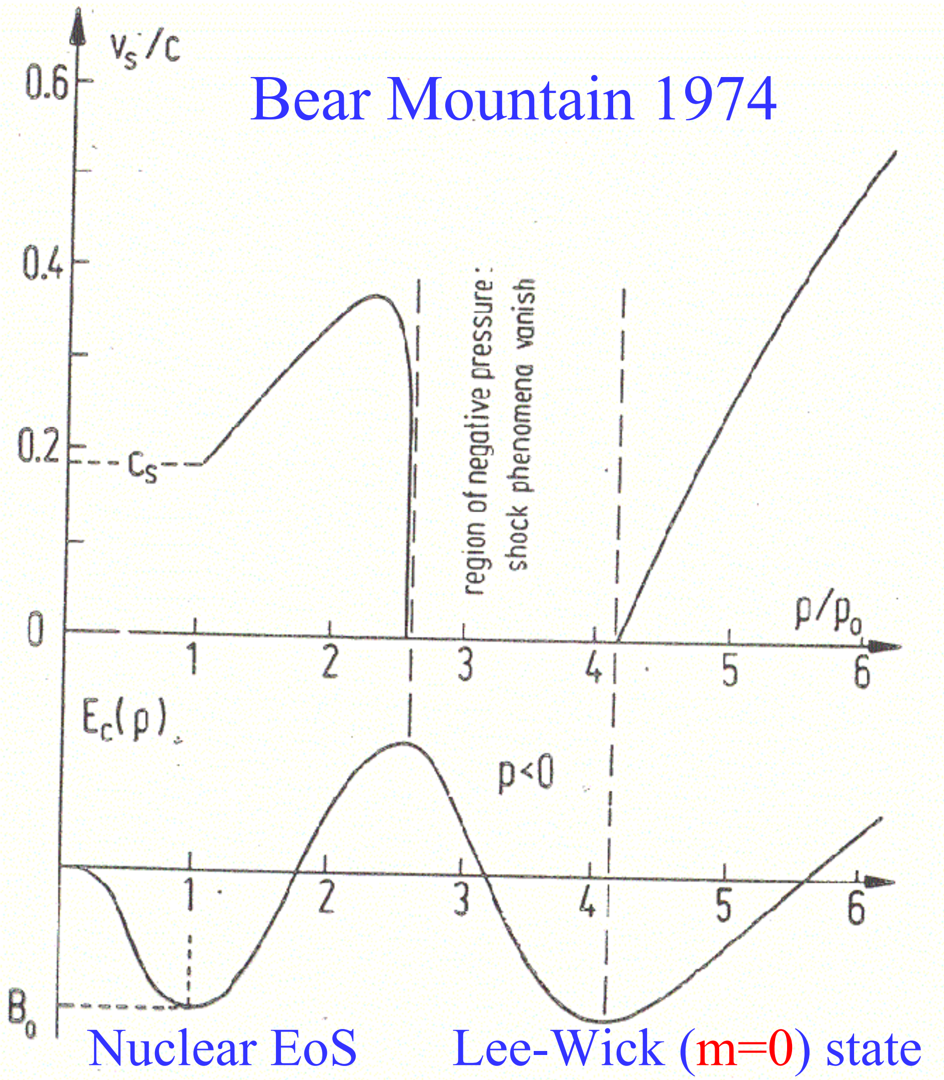
$$\partial_{\mu} j^{\mu} = \sum_i \partial_{\mu} j^{\mu}_{(i)} = \sum_i S_{(i)} = 0$$

$$\partial_{\nu} T^{\mu\nu} = \sum_i \partial_{\nu} T^{\mu\nu}_{(i)} = \sum_i F^{\nu}_{(i)} = 0$$

→ **3-Fluid-Model**

1. Projektile
2. Target
3. Fireball (Produced Particles)

Collapse of Baryon Flow signals 1. Order Phase Transition
HST, Hofmann, Scheid, Greiner 1974/76

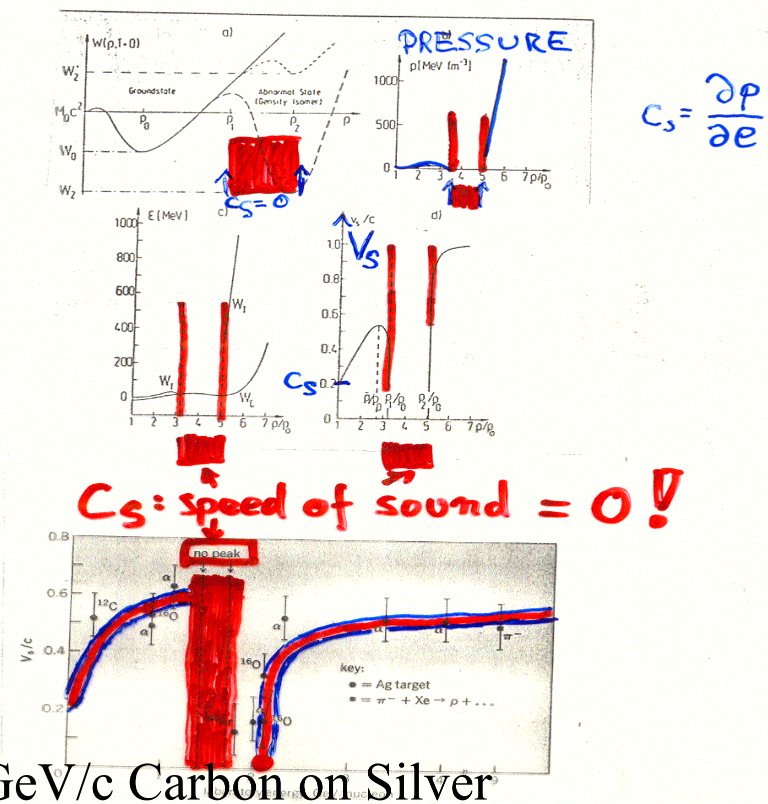


VOLUME 36, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JANUARY 1976

Possibility of Detecting Density Isomers in High-Density Nuclear Mach Shock Waves*

Jürgen Hofmann, Horst Stöcker, Ulrich Heinz, Werner Scheid, and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt am Main, Frankfurt am Main, Germany
(Received 29 September 1975)

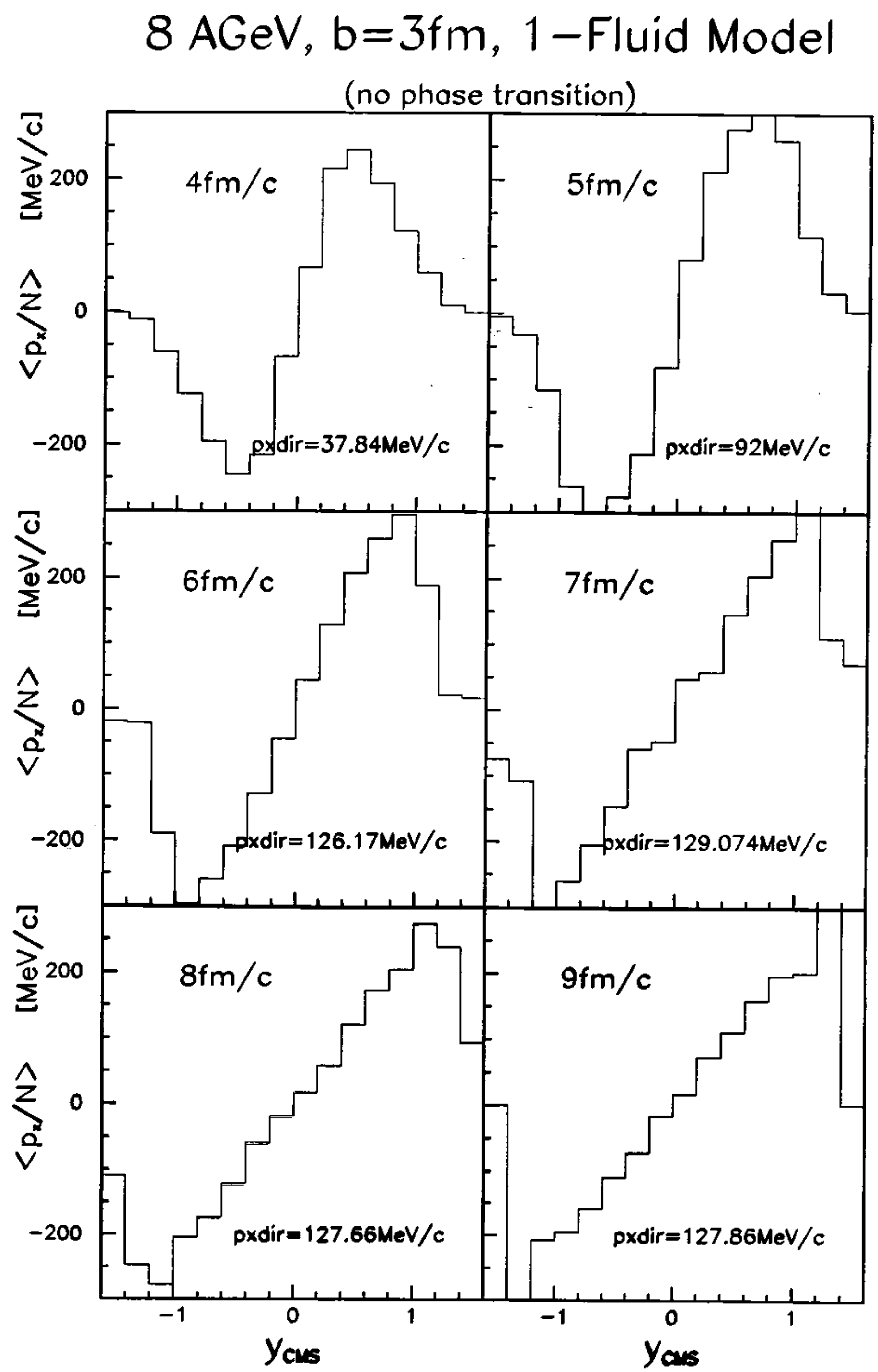
Up to now no experimentally feasible method for detecting abnormal nuclear states has been known. We propose to observe them in high-energy heavy-ion collisions through the disappearance of, or irregularities in, high-density nuclear Mach shock phenomena.



- Hydro:w/o P.T.

proton v1=px/pt rise linearly

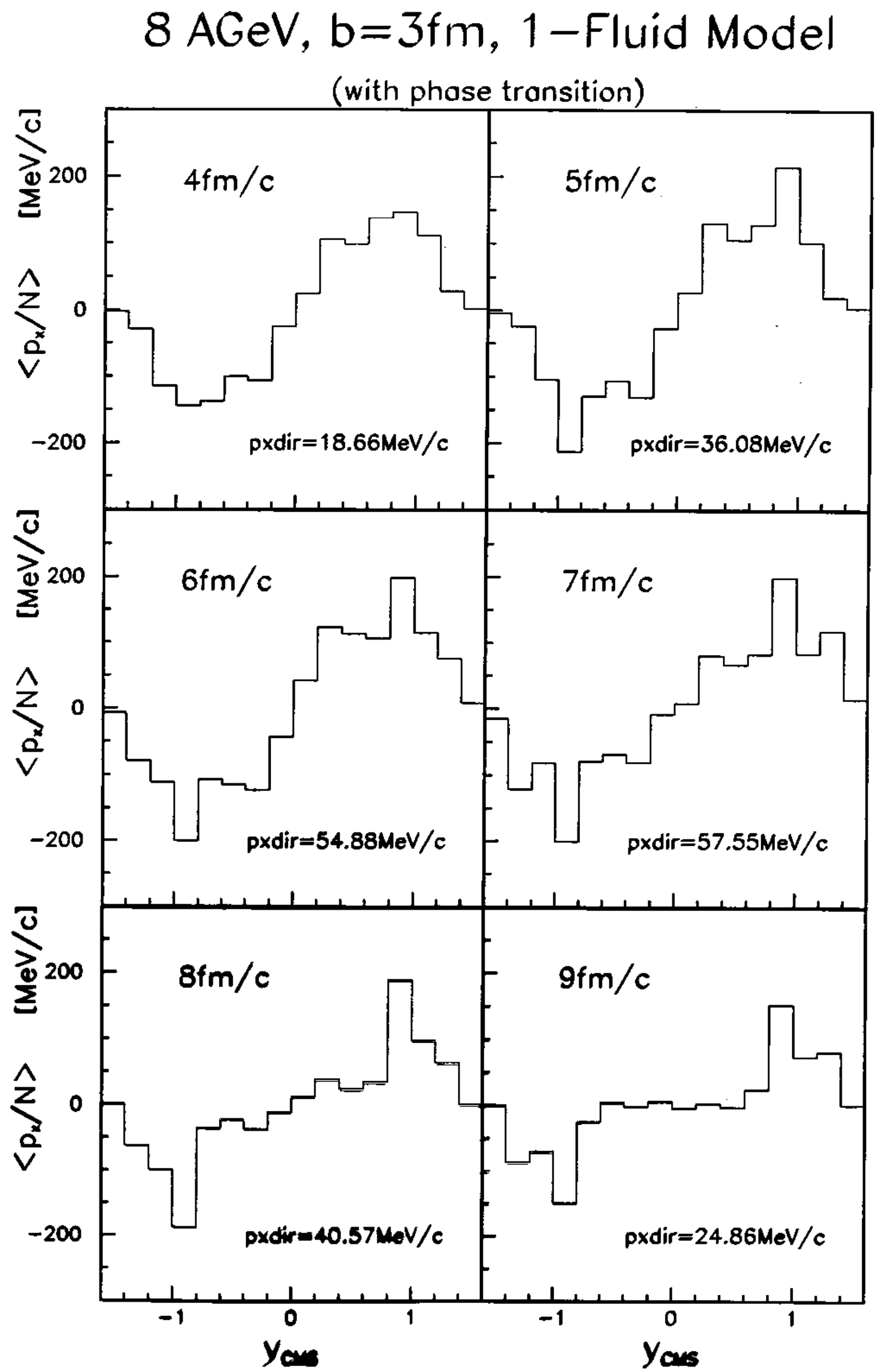
Brachmann, Paech, Dumitru



- BUT: Hydro w. 1.Order Phase Transition:

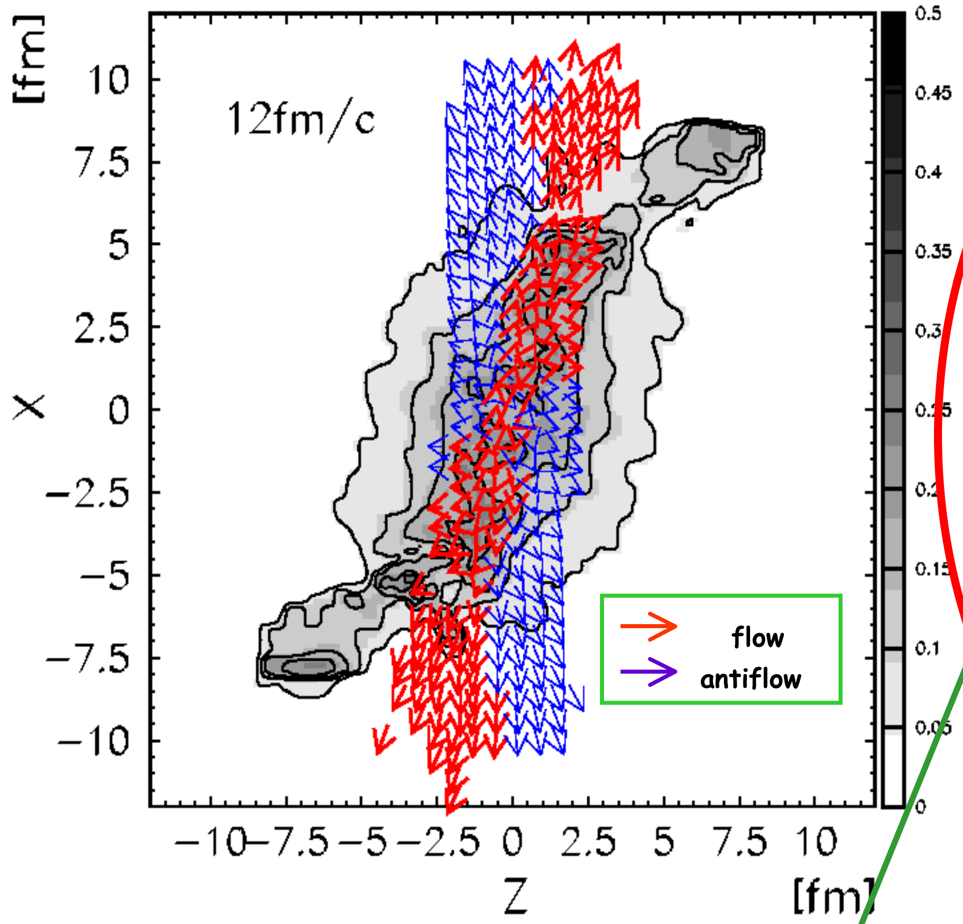
Collapse of proton flow!!!

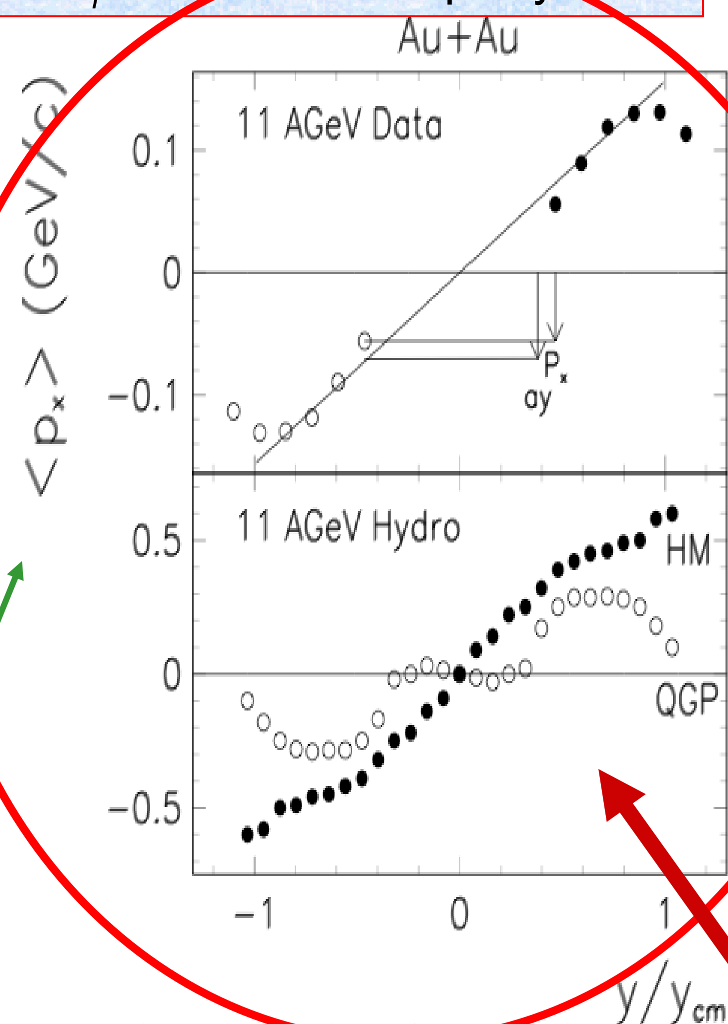
Paech, Brachmann Dumitru



Proton Directed flow (v_1) and phase transition

Anti-flow/3rd flow component, with QGP $\Rightarrow$ v_1 flat at middle rapidity.



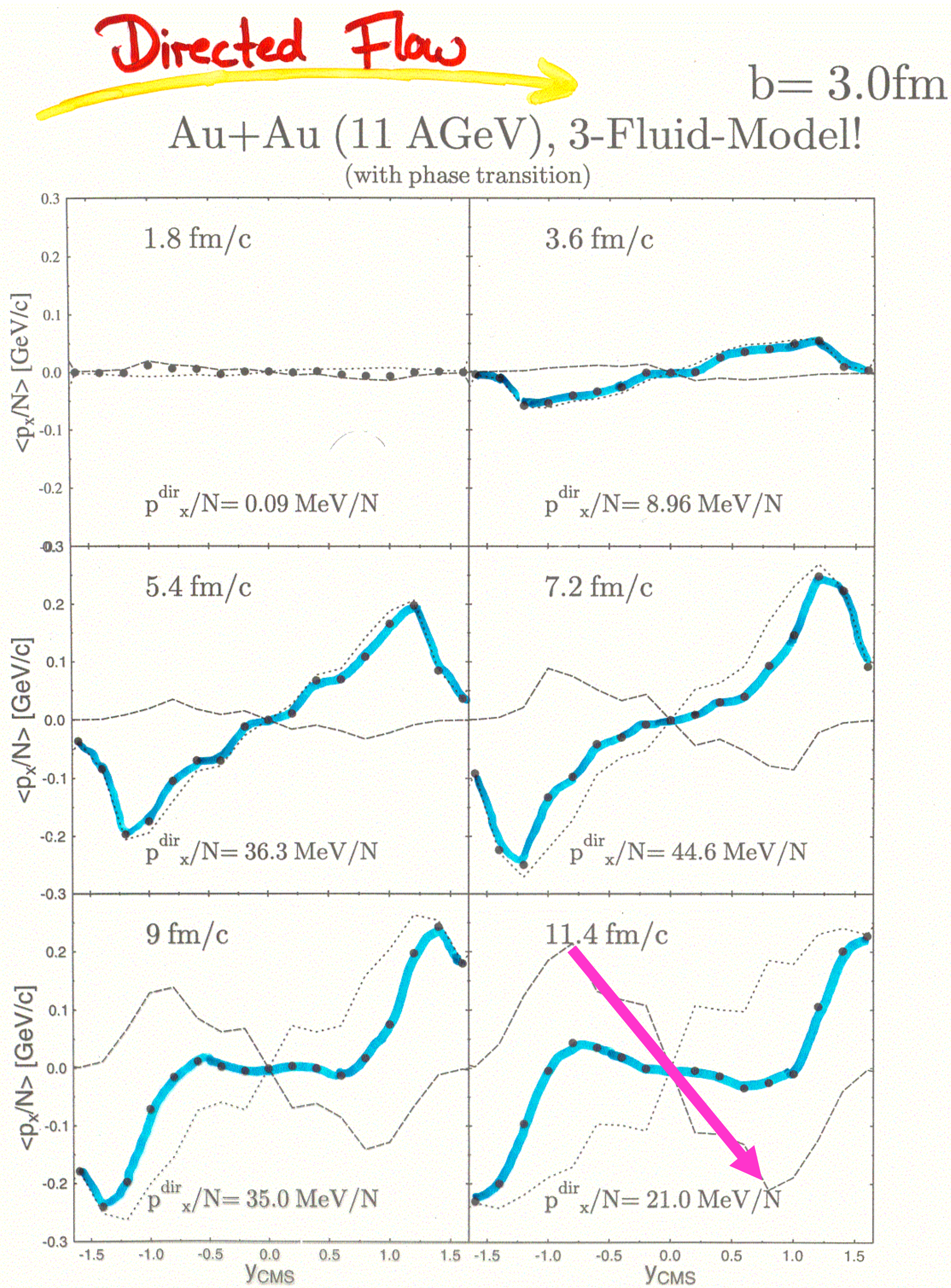


Brachmann, Soff, Dumitru, Stocker, Maruhn, Greiner Bravina, Rischke , PRC 61 (2000) 024909.
L.P. Csernai, D. Roehrich PLB 458, 454 (1999) M.Bleicher and H.Stocker, PLB 526,309(2002)

Hydro [Csernai, HIPAGS'93]

- **Anti-Flow of protons at 11 AGeV**

in hydro as a result of 1. order phasetransition

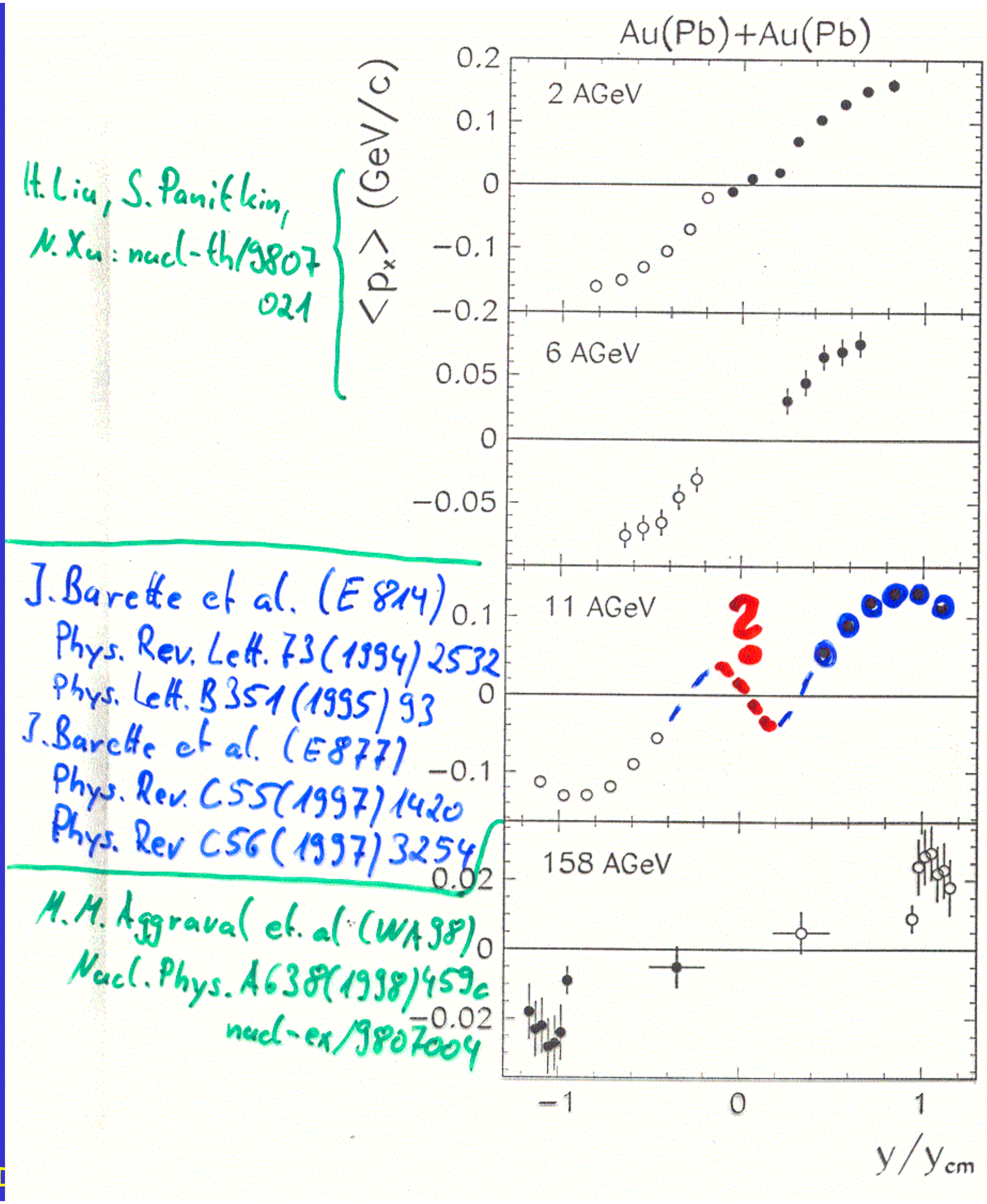


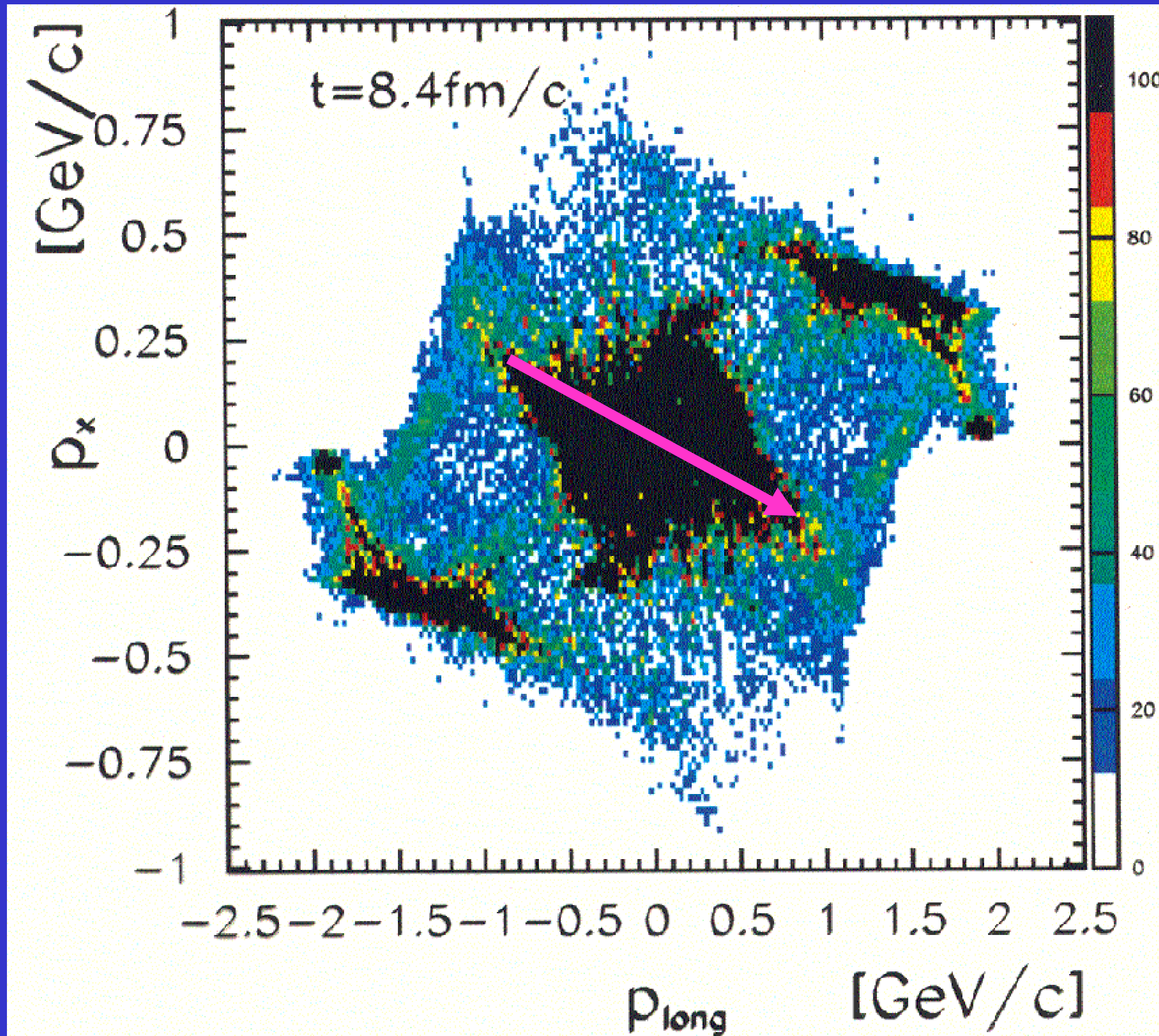
It is in the protons. Period.

•px

Excita-
tion fct.

AGS
Csernai &
Roehrich



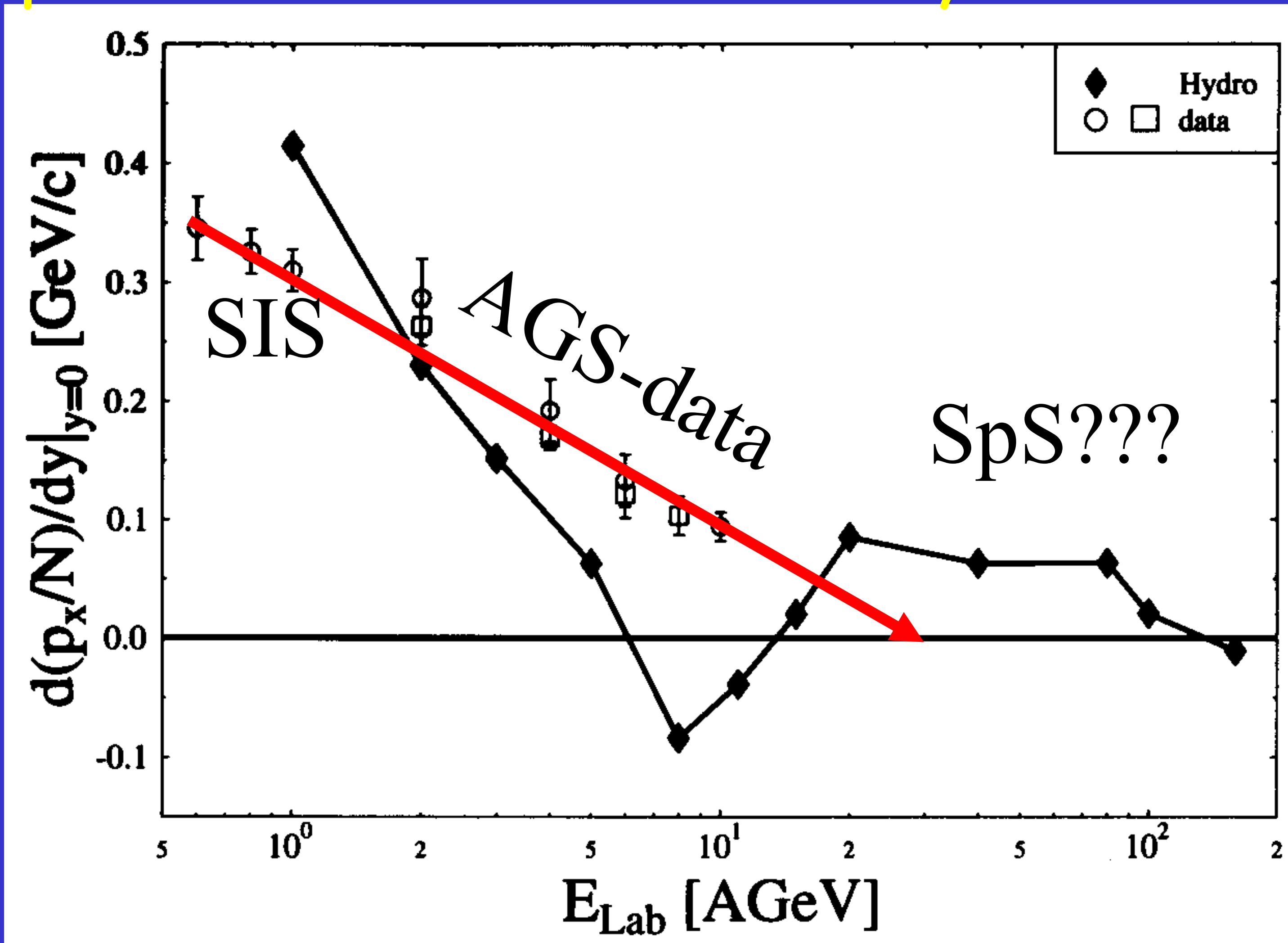


- **Au+Au, 8GeV, b=3fm, Triple differential Cross section**

- v1-Excitation Function: 3D-Hydro: Anti-Flow @AGS !!!

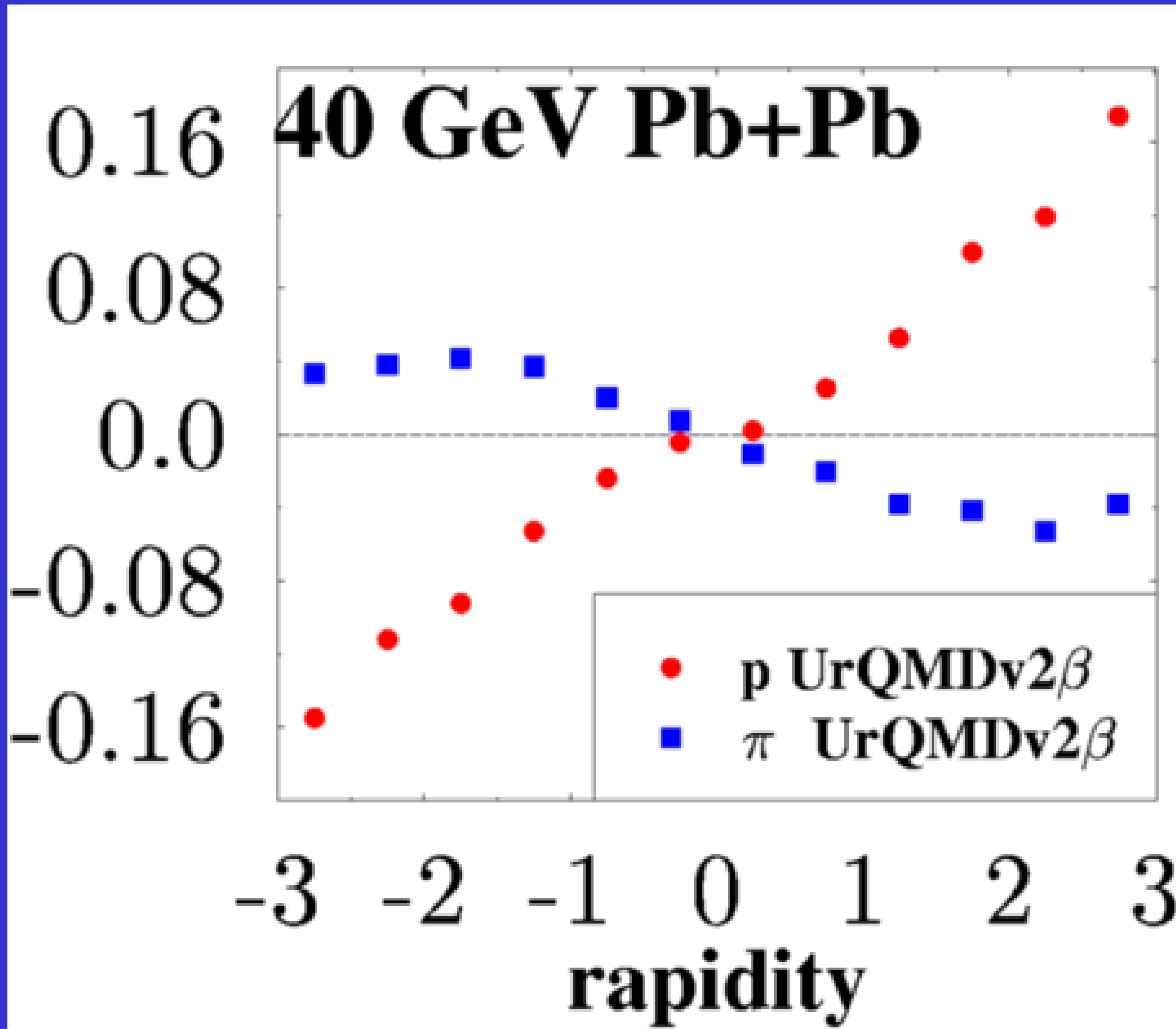
Extrapolated Data: NO! Anti-Flow only @ 30 AGeV ???

Paech, Dumitru

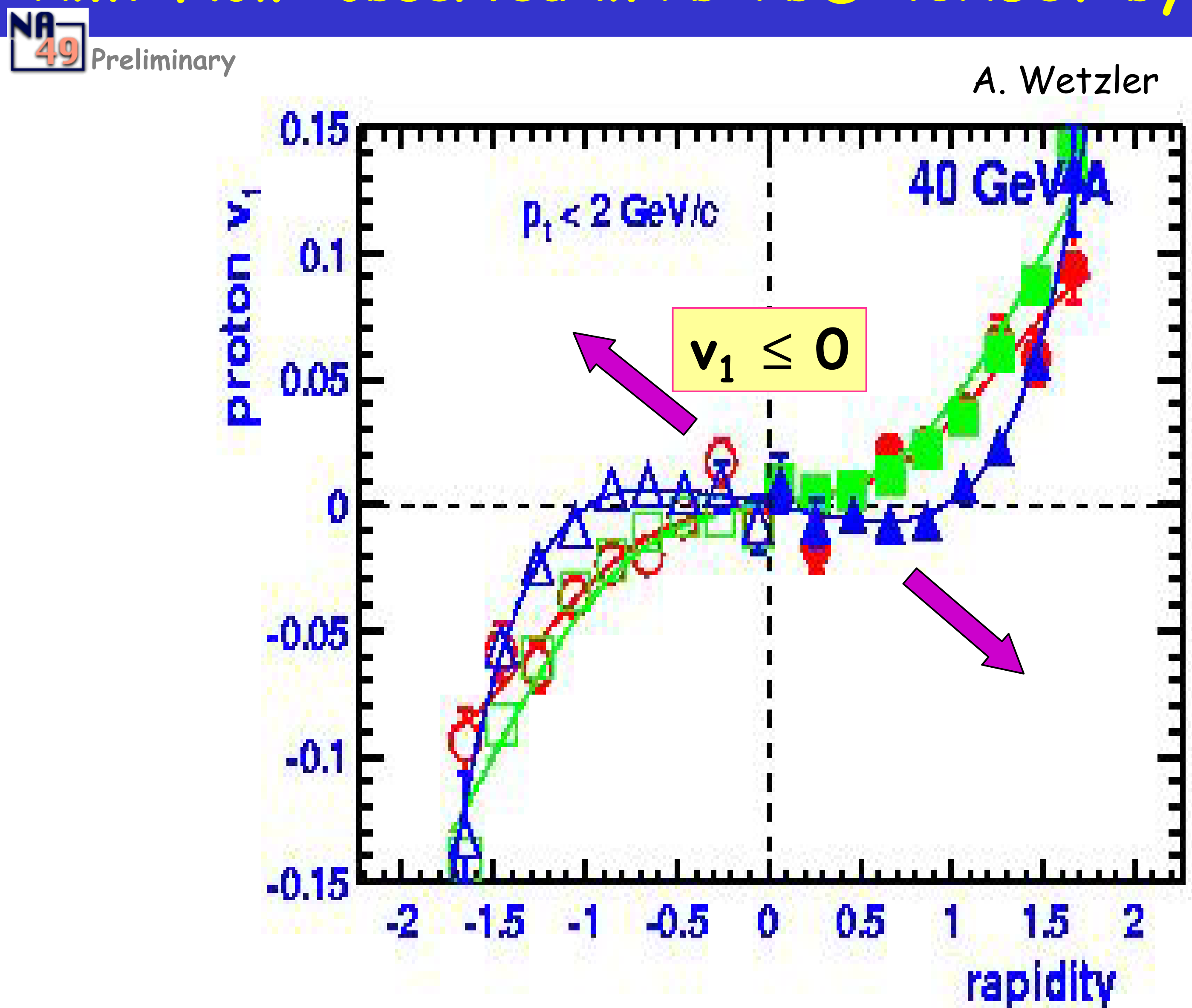


- Soff: UrQMD Predicts Proton v1 Rises Linearly with Y & E -

What do Data Say?



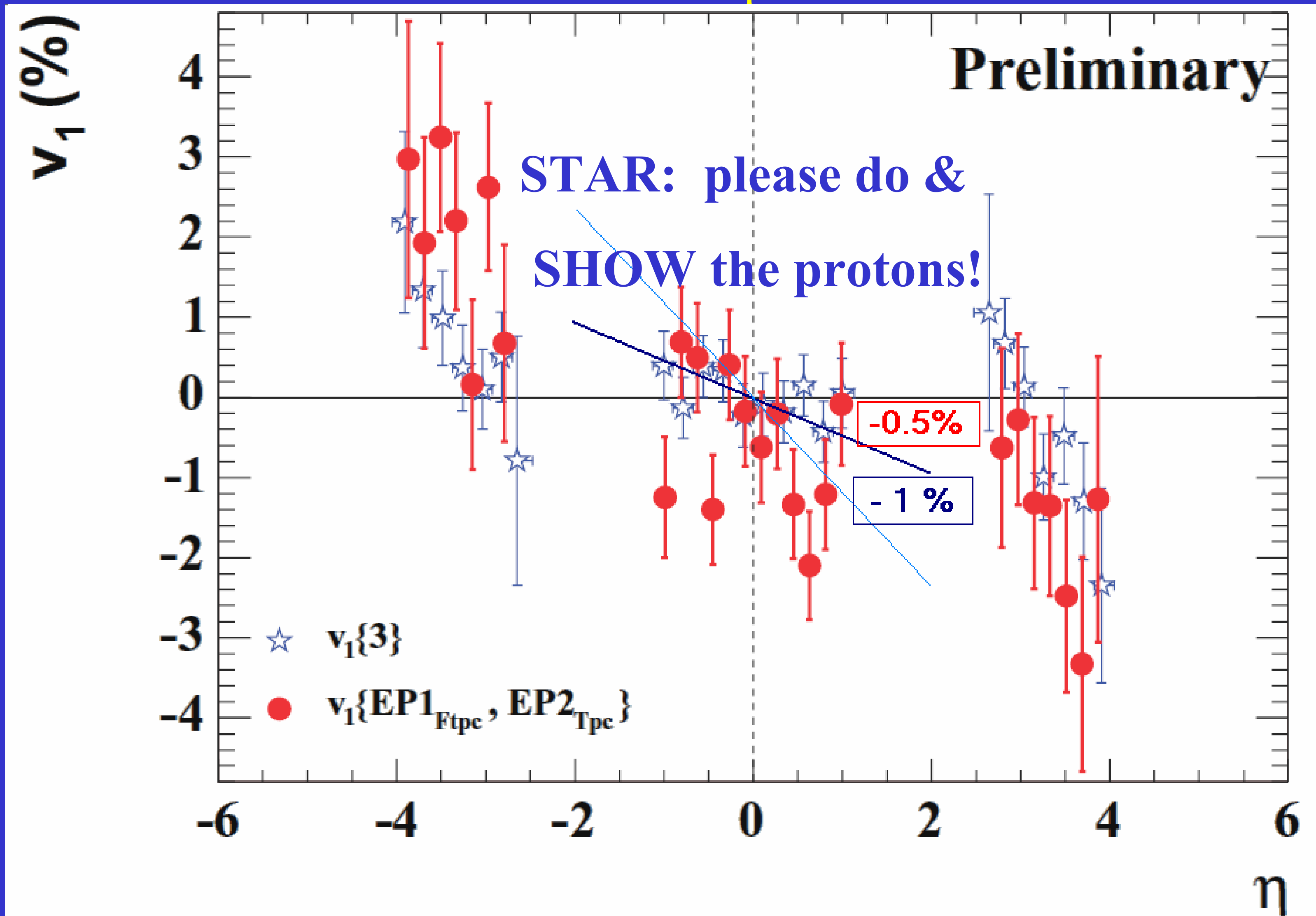
Proton "Anti-Flow" observed in Pb+Pb@ 40AGeV by NA49:



"Anti-Flow" discovered! -> 1. Order Phase Transition!

It is in the protons.
Period.

Pion v1 STAR, M.D. Oldenburg , QM'04 & nucl-exp/0403007 v2



SqueezeOut & Elliptic Flow: v_2 of Protons

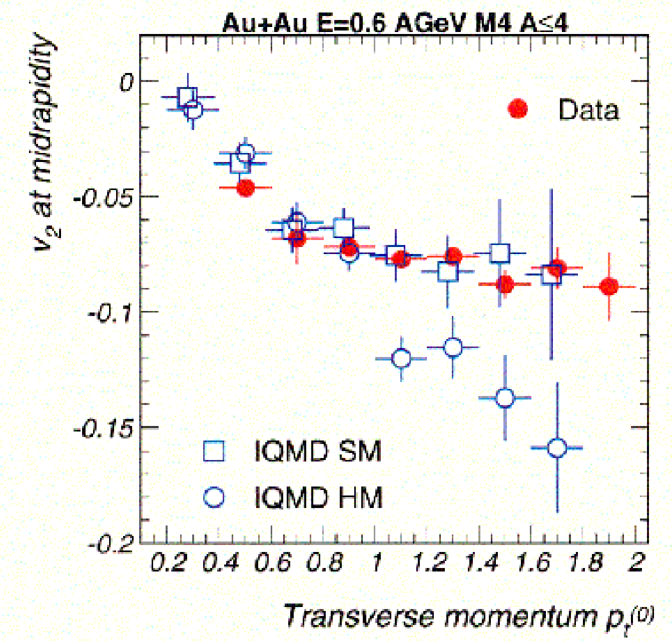
- $$v2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

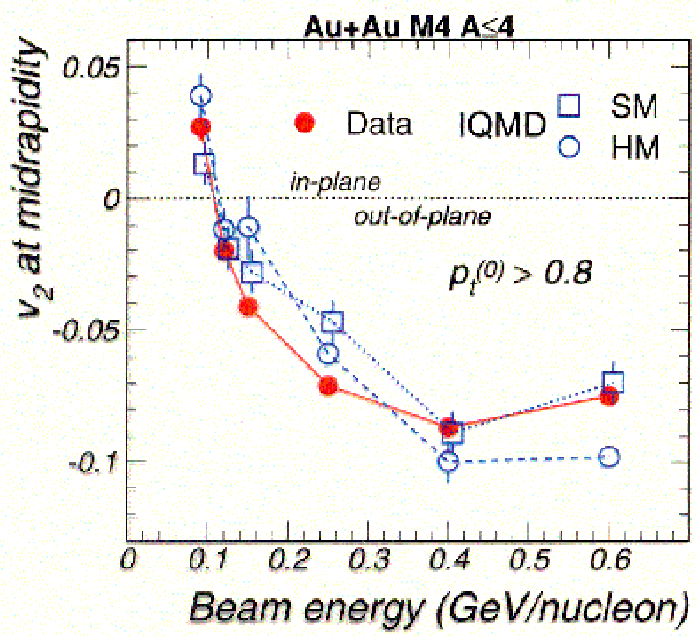
- Proton Elliptic Flow

v2 is a barometer!

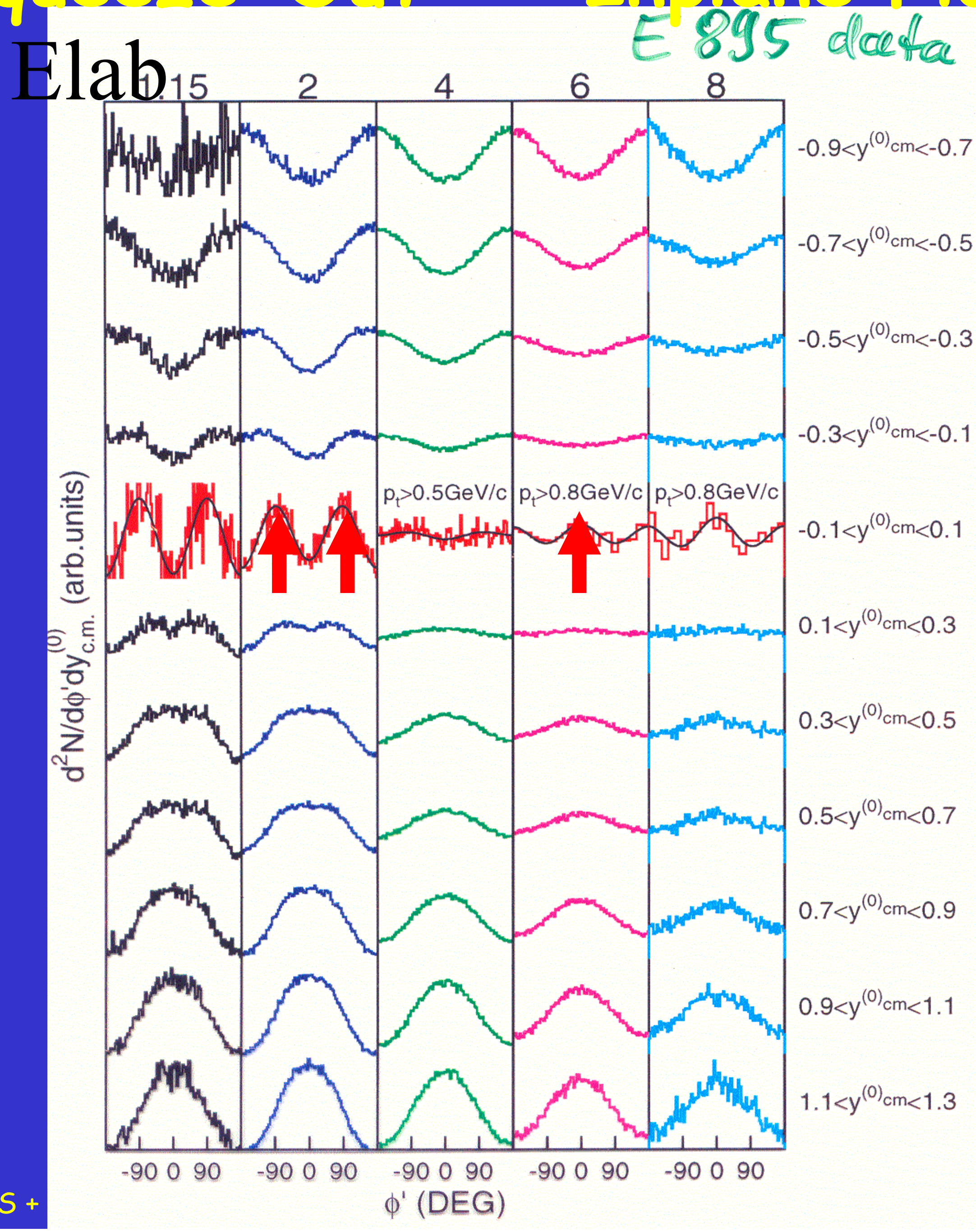
FOPI-data vs. IQMD: sensitivity to EOS !

Negative v2 at SIS & AGS: Squeeze Out!





Squeeze-Out -> Inplane Flow @ AGS

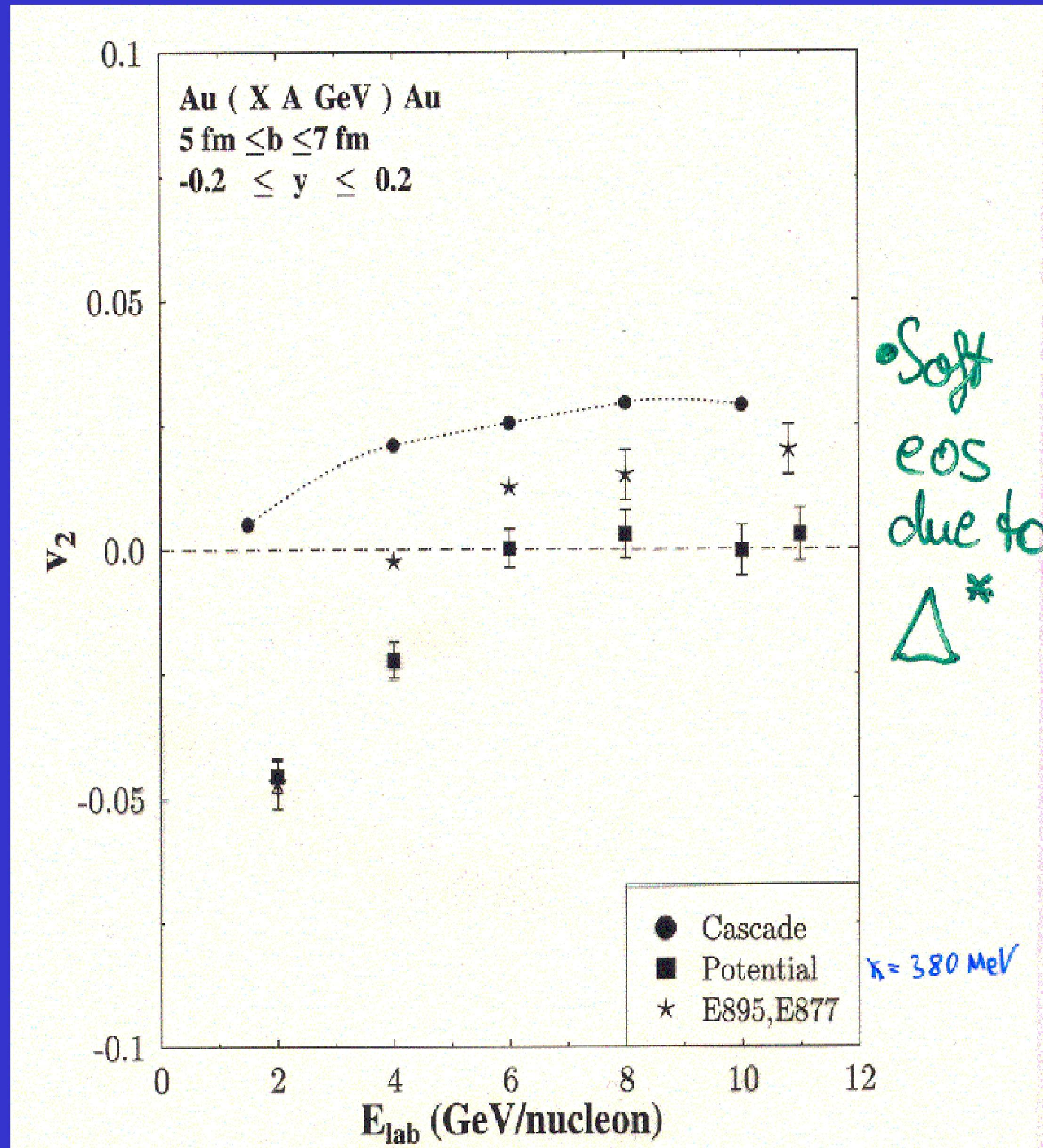


Excitation function of elliptic flow @ AGS

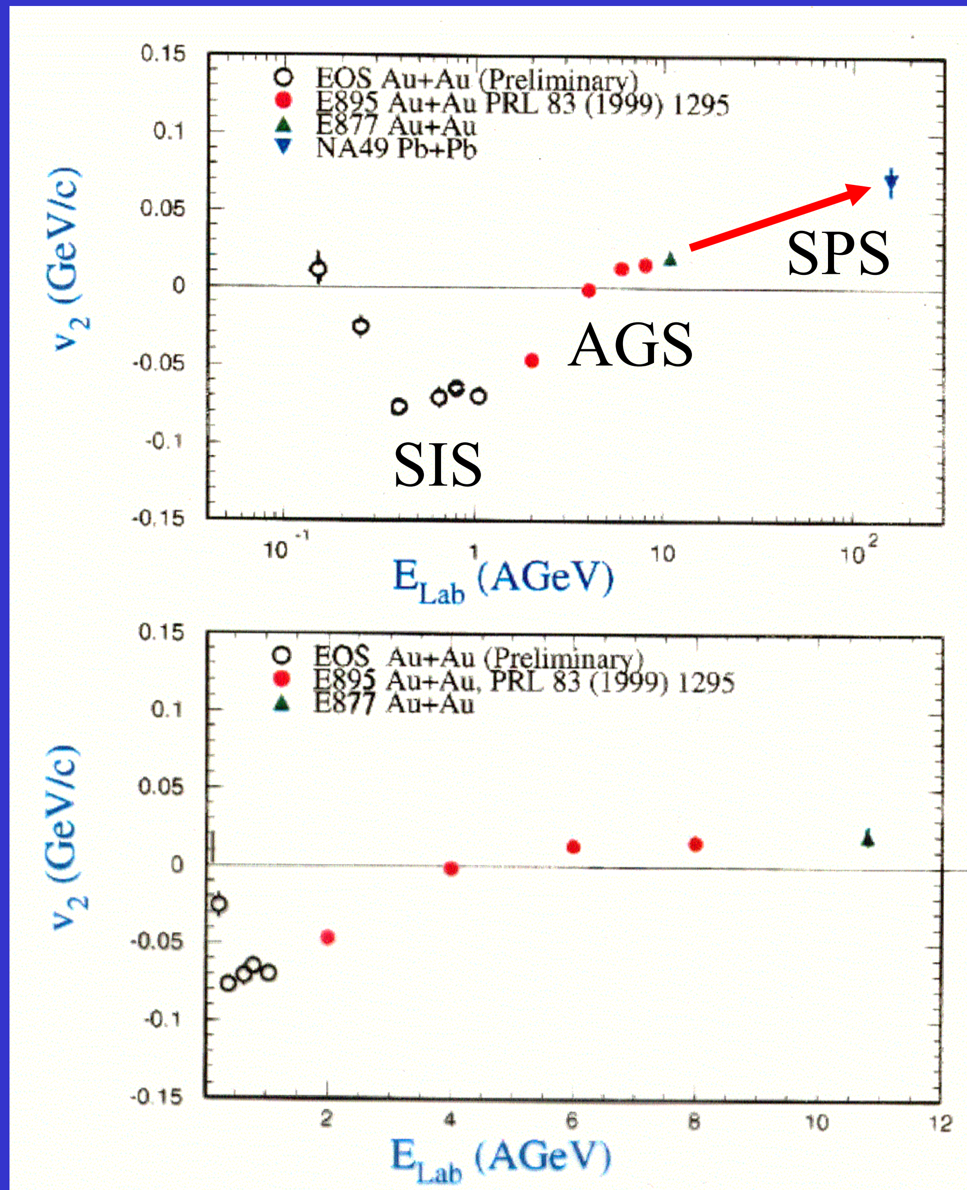
- $v_2 = < \cos(2\varphi) > =$
- $(p_x^2 - p_y^2)/(p_x^2 + p_y^2)$

- **v2 changes sign at 6 AGeV, then:**

smooth increase predicted by hadronic models UrQMD!   S. Soff

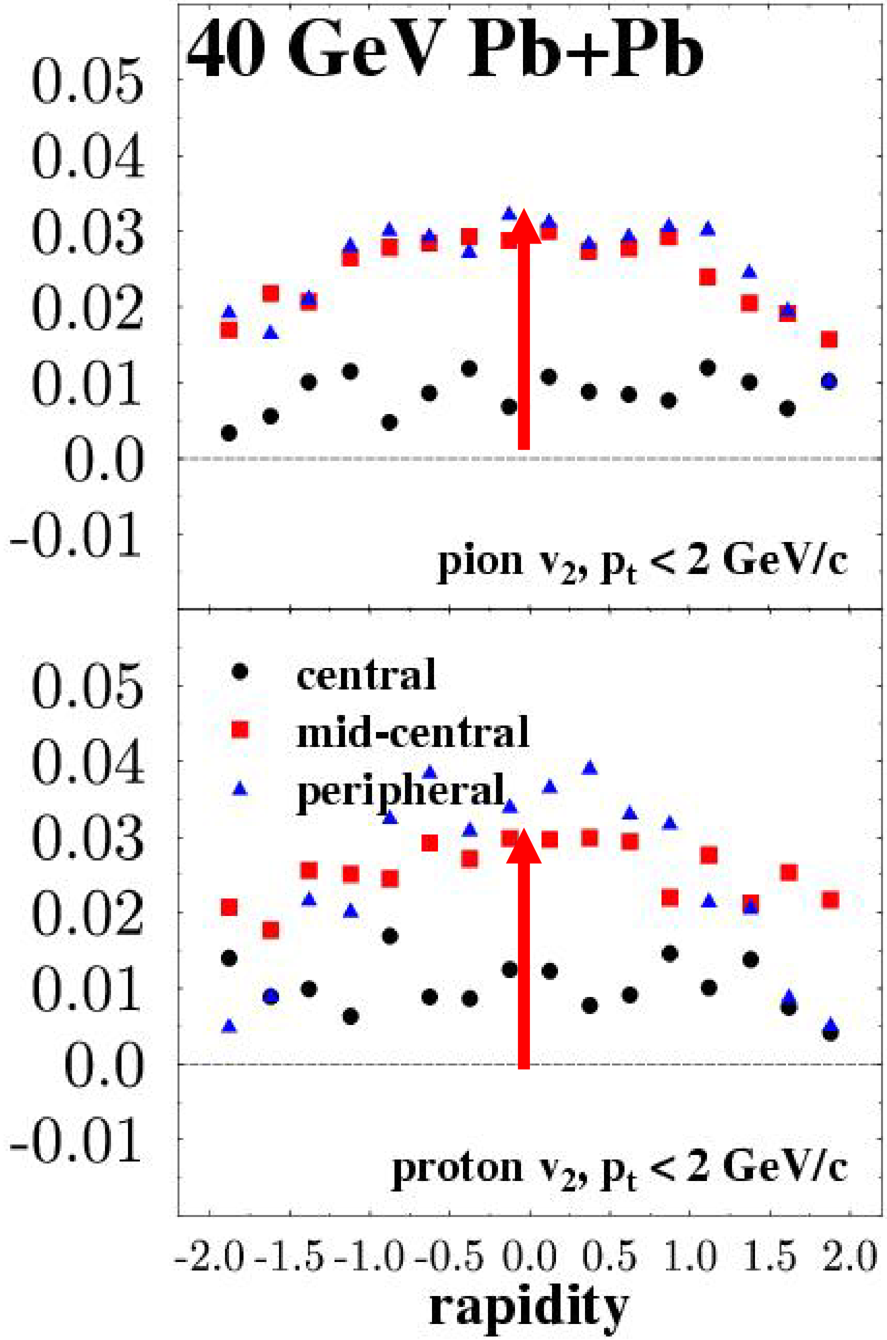


- v2(Elab): Elliptic flow excitation function



UrQMD:

Expect
Smooth
Increase
of v2 > 0
above
6 AGeV



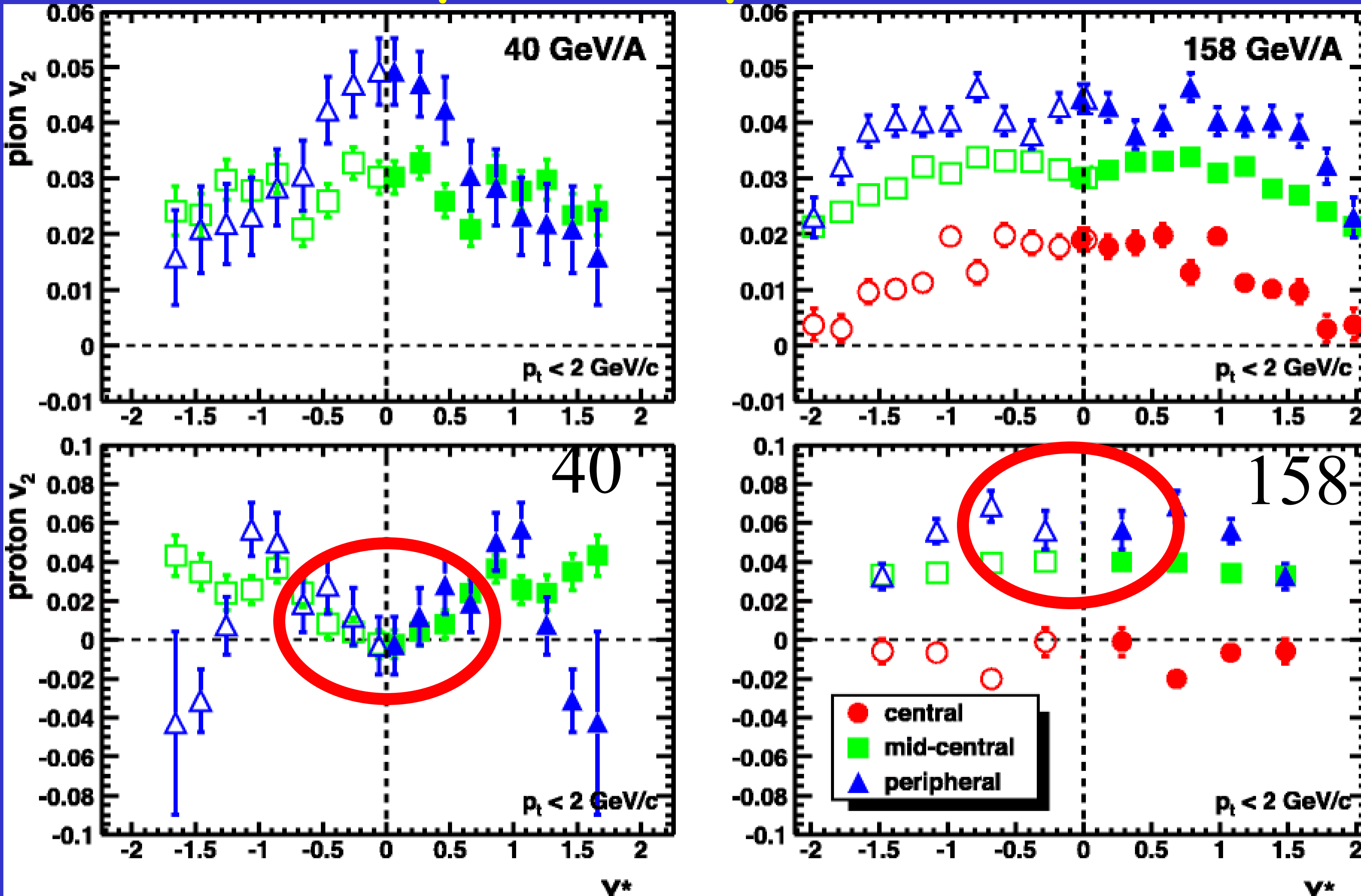
PIONS

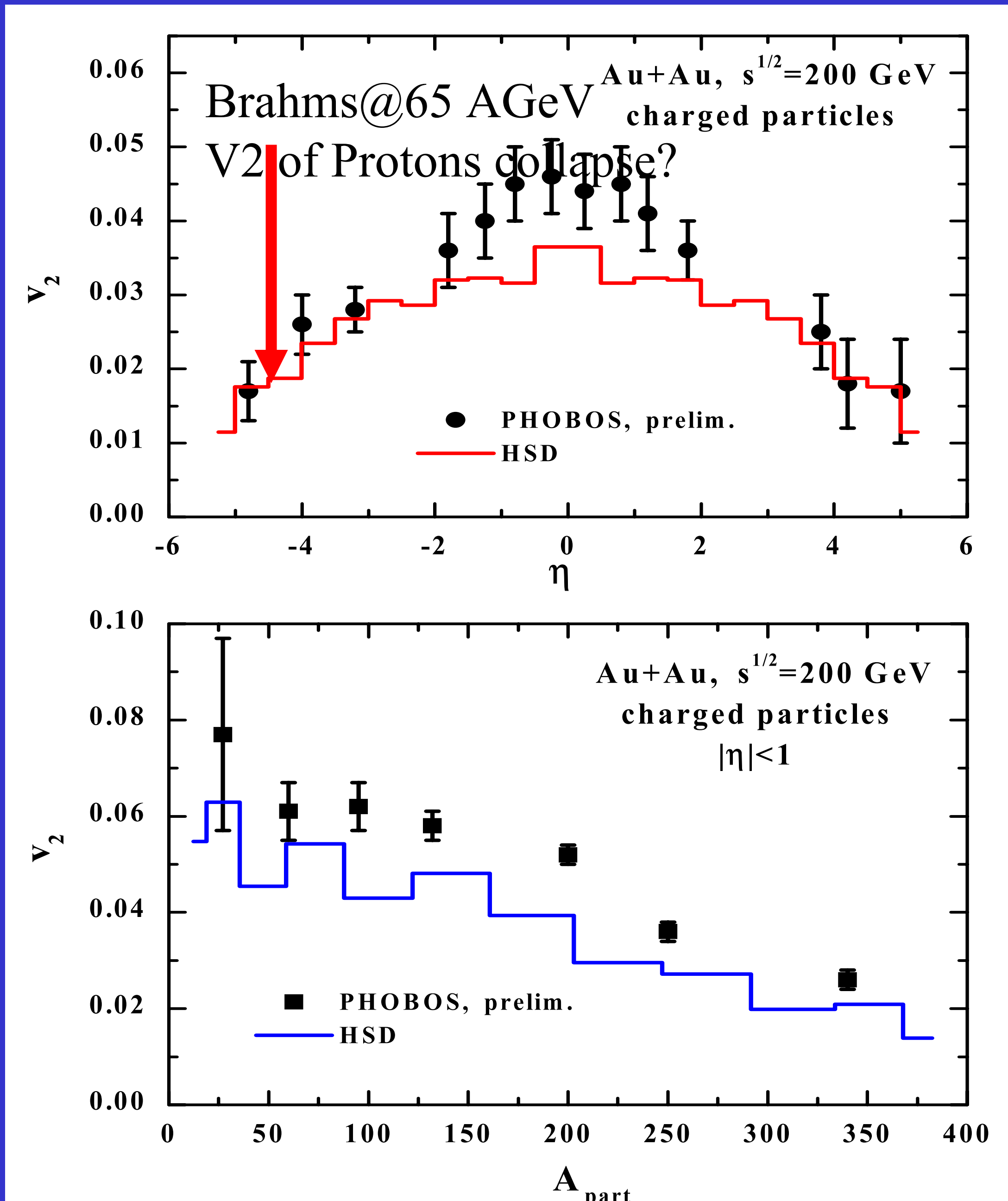
V2:40AGeV UrQMD

Protons

S. Soff

•NA49: Collapse of V2(protons) at 40 AGeV





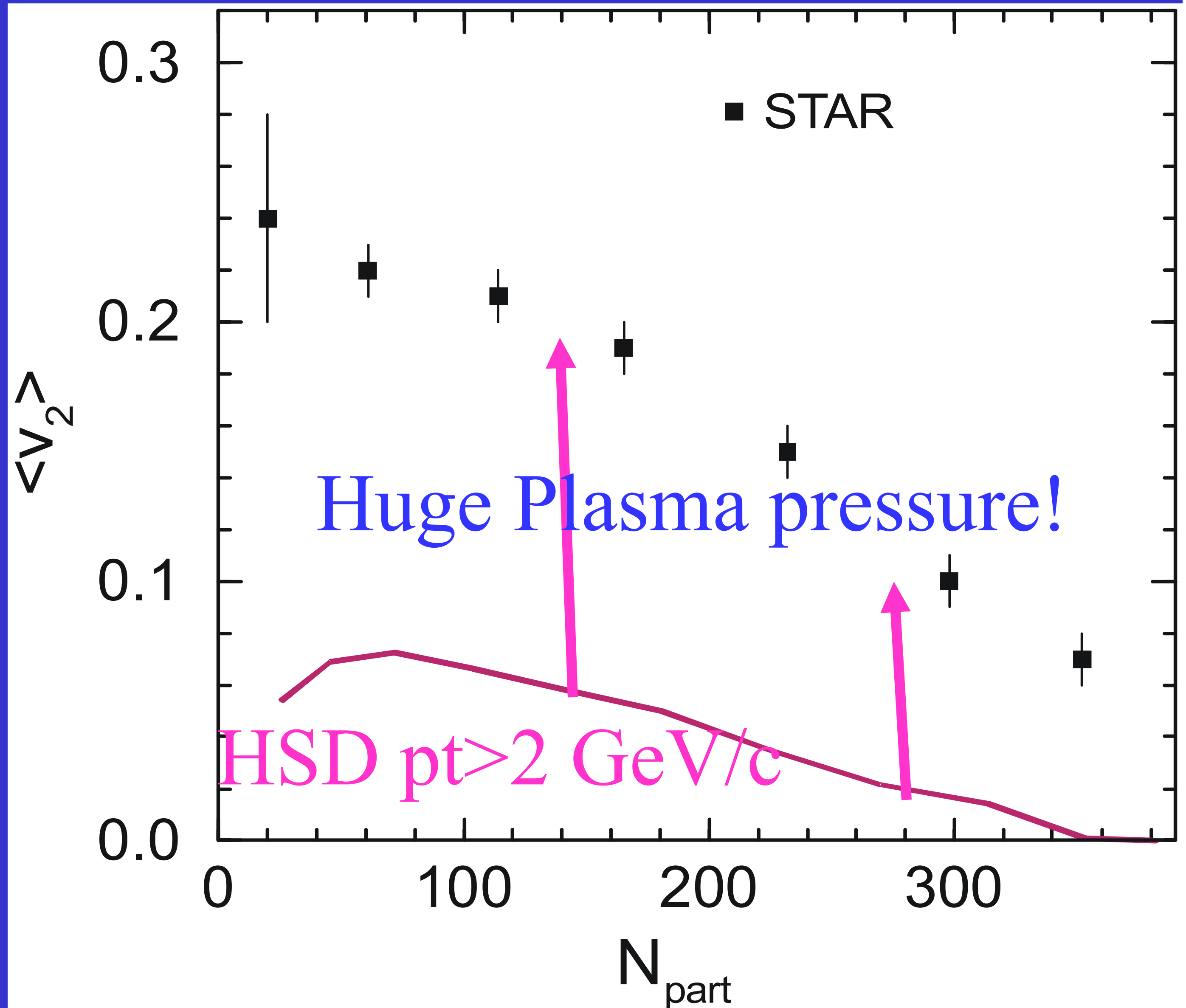
- v2 of all charged particles at RHIC Phobos- data

It is in the protons.

Bratkovskaya, H.ST,Cassing, HSD, tau=0.8 fm/c

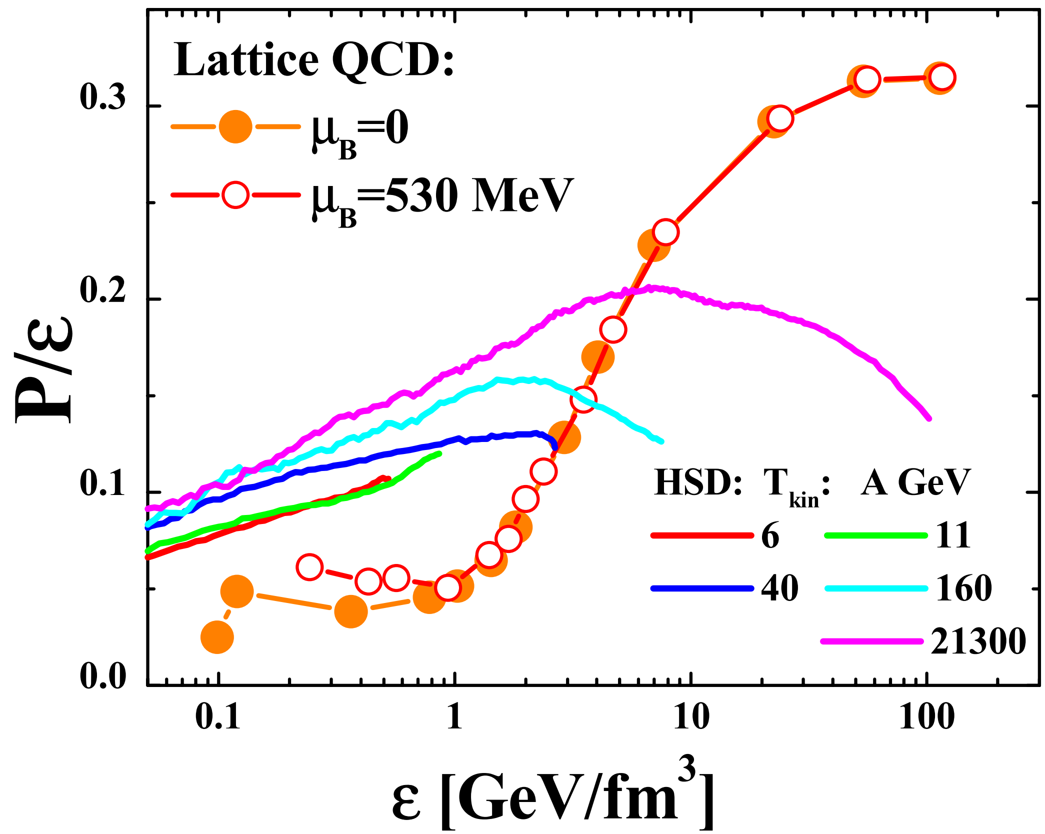
- $\langle v2 \rangle$ of high pt particles:

Factors 3-5 from plasma pressure!



Cassing, Gallmeister, C. Greiner, HSD

•Pressure: LQCD & hadron-string model (HSD)



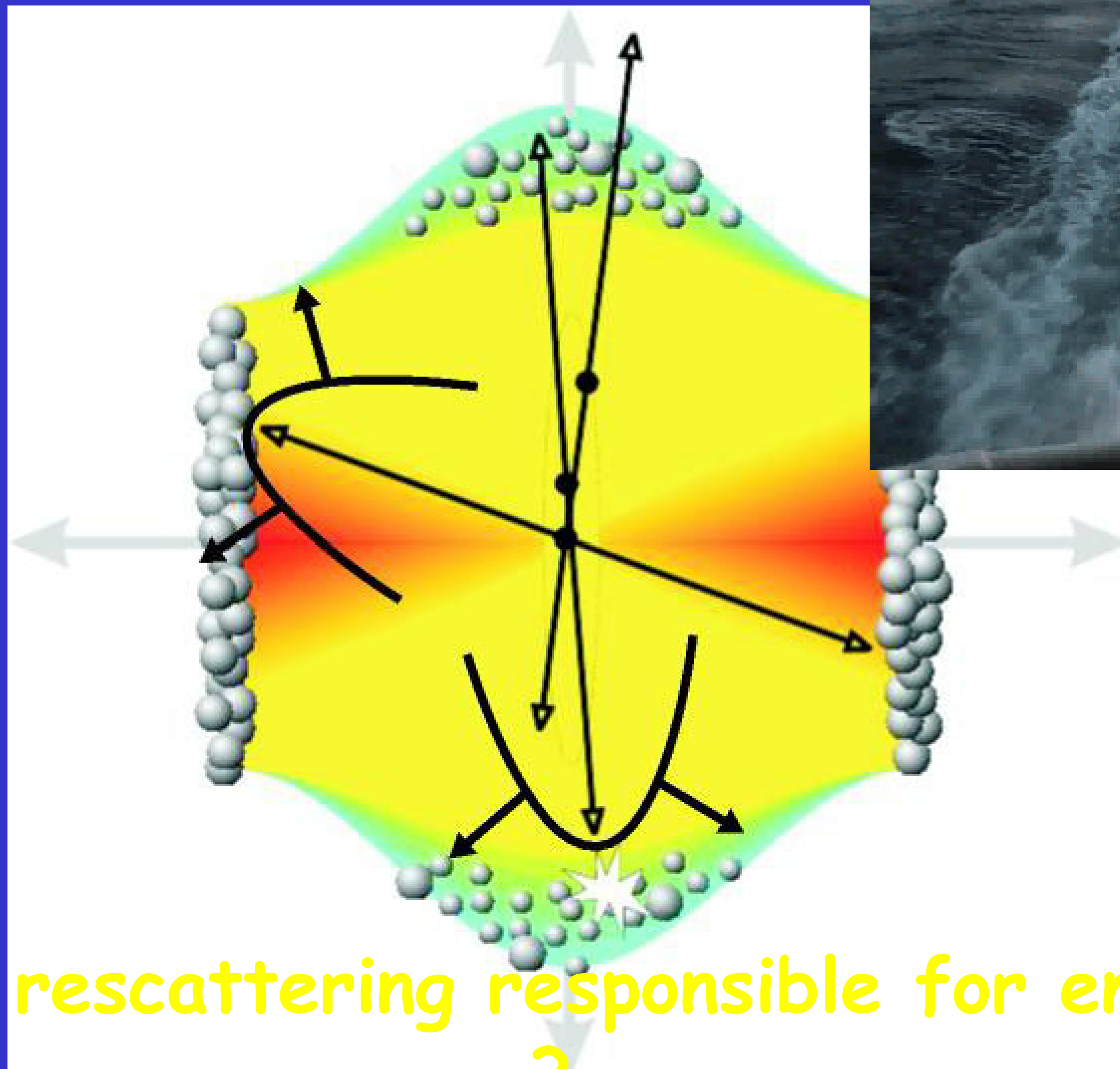
Note: ONLY qualitative comparison, since LQCD results correspond to the equilibrium situation, whereas HSD results correspond to the non-equilibrium /or approximate equilibrium situation

Here HSD pressure $P=3P_{xx}$
- valid only in equilibrium !

- The hadron-string picture does not generate enough initial pressure!

• Jets interact in the plasma, causing wakes and bow waves c_s/v_jet=cos (alfa) rel. to jet-axis

Cs=0.2 in N.M.
Cs=057 m=0



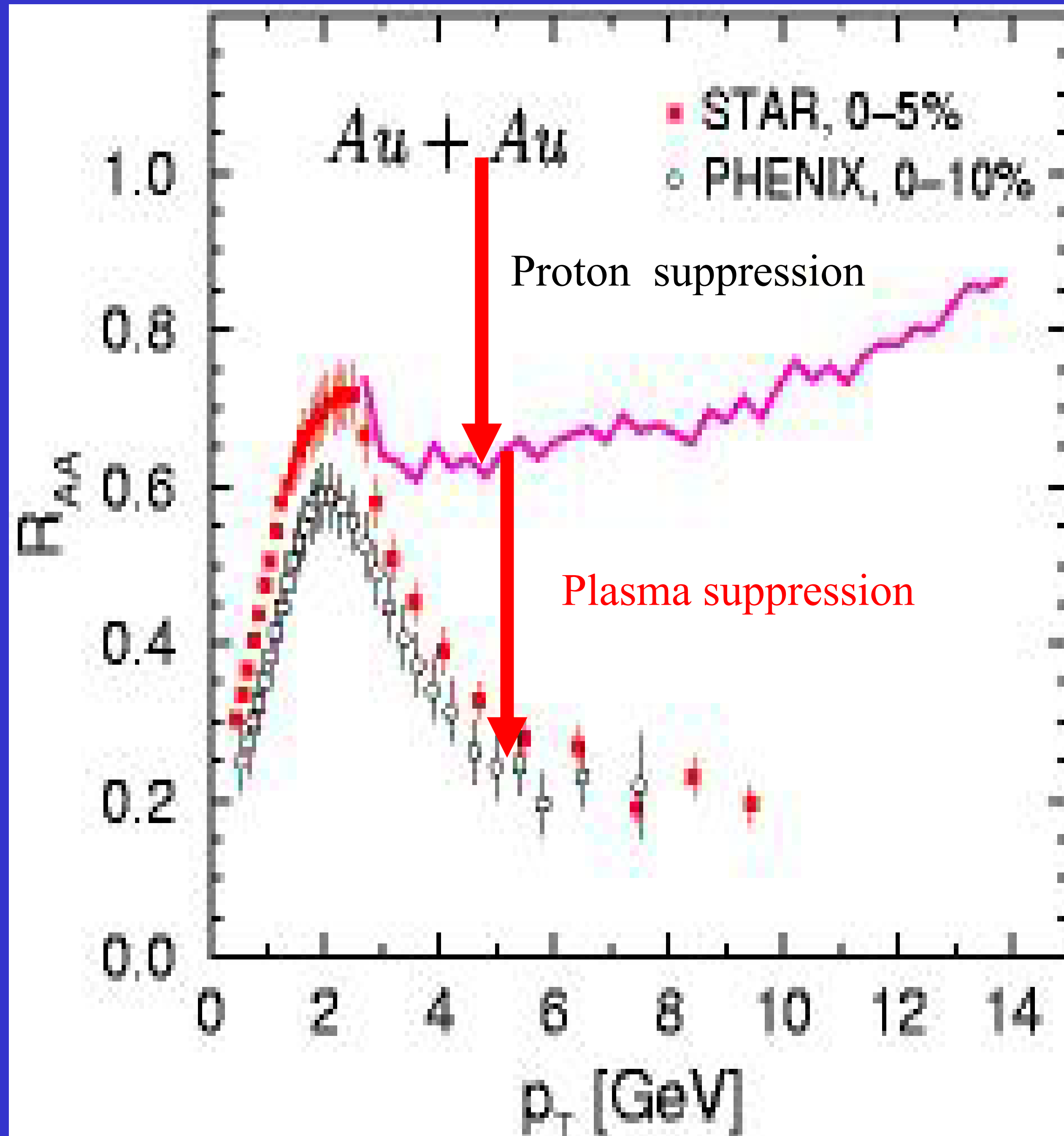
• Hadronic rescattering responsible for energy loss ?

Casssing
Gallmeister
C.Greiner

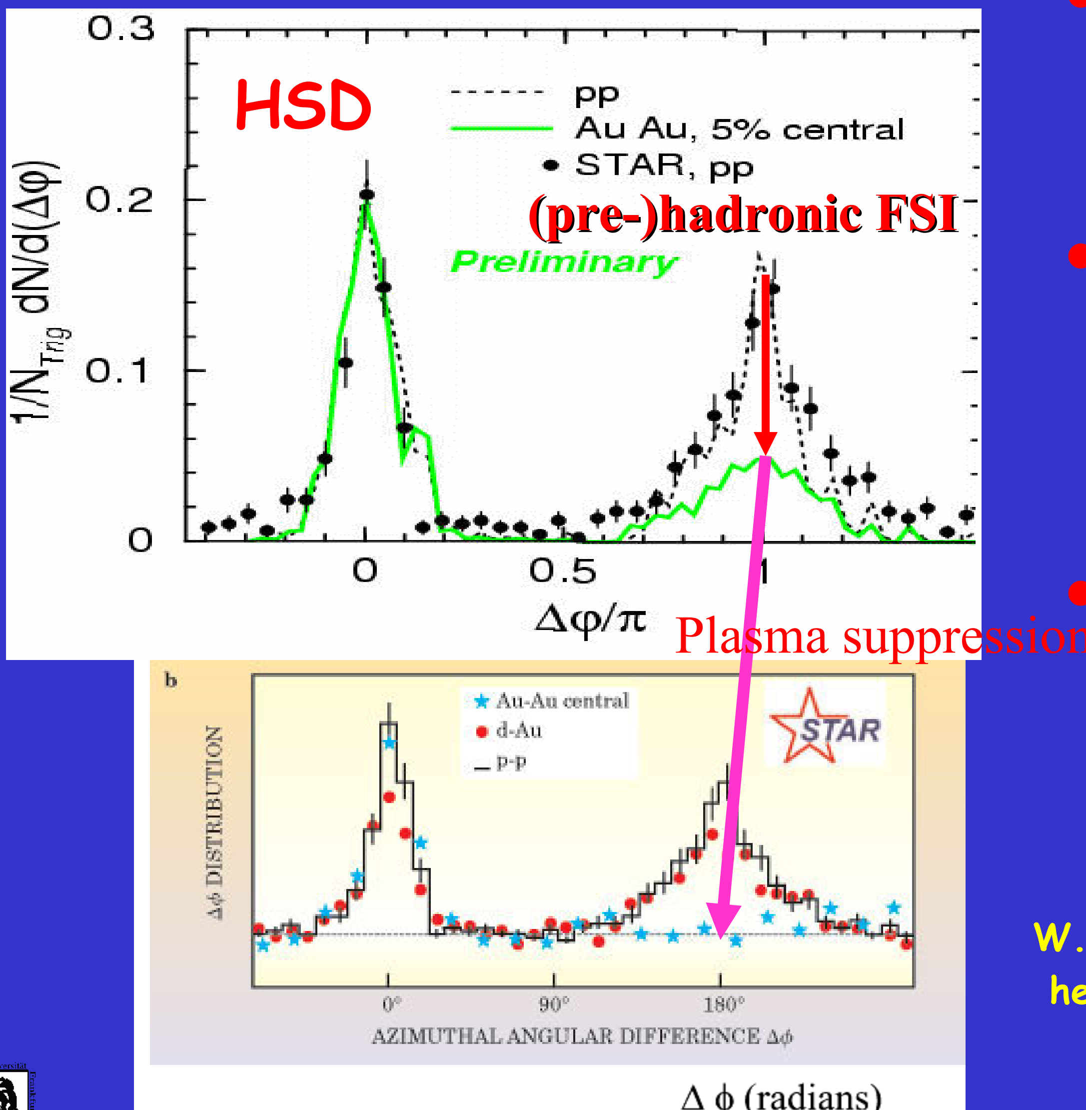
HSD: expansion of small color transparency configuration

too little quenching!

QGP needed!



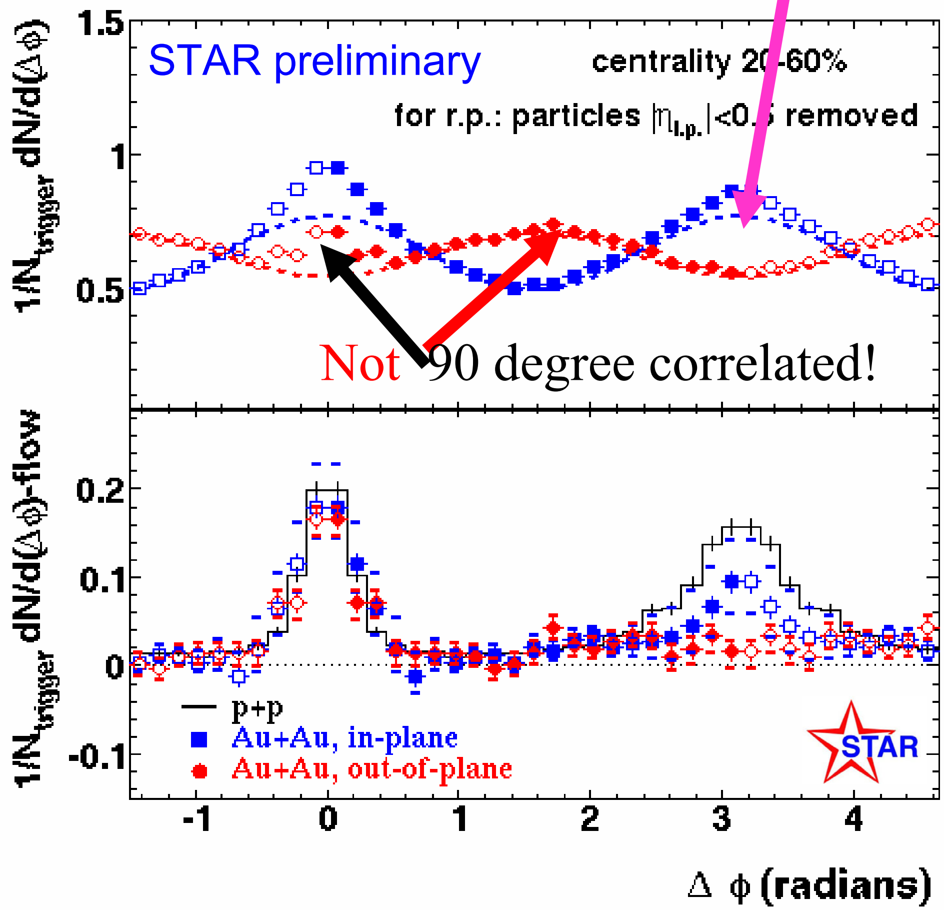
How much of Jet quenching is due to (pre-)hadronic FSI?

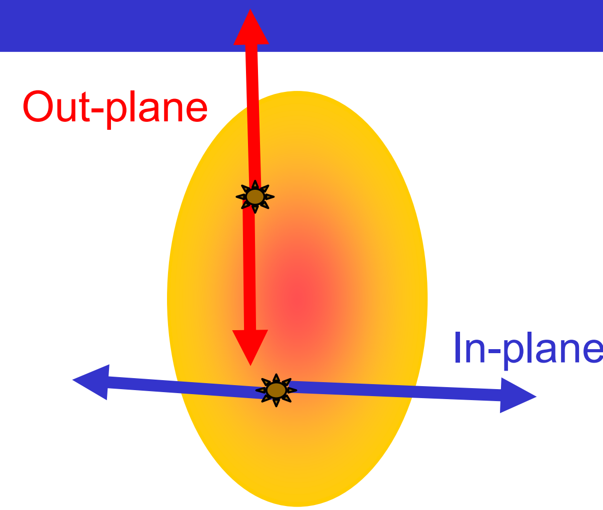


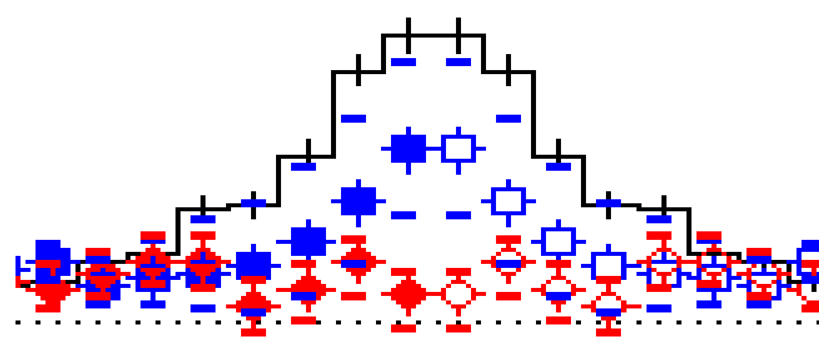
- p-p jet angular correlations o.k.
- near-side jet angular correlation ok for central Au+Au
- Way Too little suppression of far-side HSD-jet by hadrons !

W. Cassing, K. Gallmeister and C. Greiner, hep-ph/0403208, QM'04 Proceedings

•High-p_T correlations: in-plane vs. out-of-plane
Do jets fake large "v2" values by wake-riding?







Is the v2 in protons?

K. Filimonov, DNP03 K.Schweda, QM04

- **Thermodynamics in the T-mu plane**
- **1. order phase transition at high mu_B:**
- **v1 & v2 at SIS-AGS-SPS: Collapse of Proton Flow**
- **Signals 1. order phase transition**

- **observe 1. order transition by collapse of proton flow at y=3 @ RHIC 65 AGeV!**
- **Strong collective flow at RHIC signals QGP at mu=0**

- **How much jet quenching due to Hadron FSI?**
- **Do jets fake large v2 values observed?**
- **Use jet-induced Mach-cones to**
- **measure c_s of plasma!**

• Thank You!!!

Elena Bratkovskaya,	GSI& ITP J.W. Goethe- Univ.
Marcus Bleicher,	Adrian Dumitru,
Carsten Greiner,	A. Muronga,
Kerstin Paech,	Manuel Reiter,
Stefan Scherer,	Sven Soff,
Henning Weber,	Z. Xu
Gebhardt Zeeb	Detlef Zschiesche

Wolfgang Cassing, A. Gallmeister, J. Liebig- Universität
Steffen Bass, Duke University
B. Tavares, L. Portugal, C. Aguiar, T. Kodama, UFRJ, Rio