

Raa and High p_T azimuthal anisotropy

(in light of recent $p+A$ and $D+A$ (un)Control)

Mkiz Gyulassy, alias Barbara Betz



High p_T nuclear modification of jets in and out of reaction plane at RHIC and LHC
B.Betz, MG, in preparation

Examining a reduced jet-medium coupling in Pb+Pb collisions at the LHC,
B.Betz, MG PRC86 (2012)

Fourier Harmonics of High- p_T Particles Probing the Fluctuating Initial Condition Geometries in Heavy-Ion Collisions, B.Betz, MG, G.Torrieri, PRC84 (2011)

Part 1: Jet Quenching prior to 2012

Part 2: D+Au and p+Pb Shock Waves QM12 and RBRC13

Part 3: Azimuthal Tomography (ignoring part 2)

High- p_T Tomography of $d + Au$ and $Au + Au$ at SPS, RHIC, and LHC

Ivan Vitev^{1,2} and Miklos Gyulassy¹

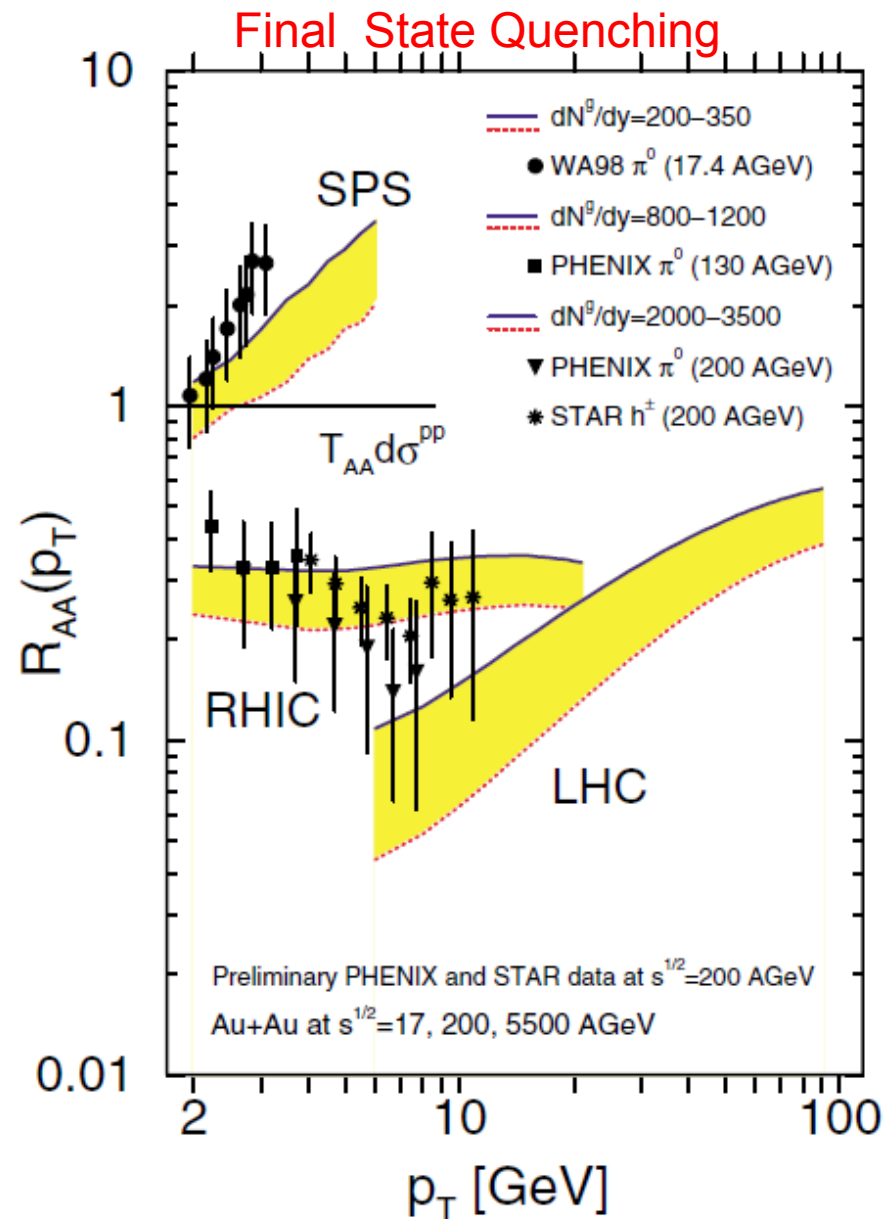
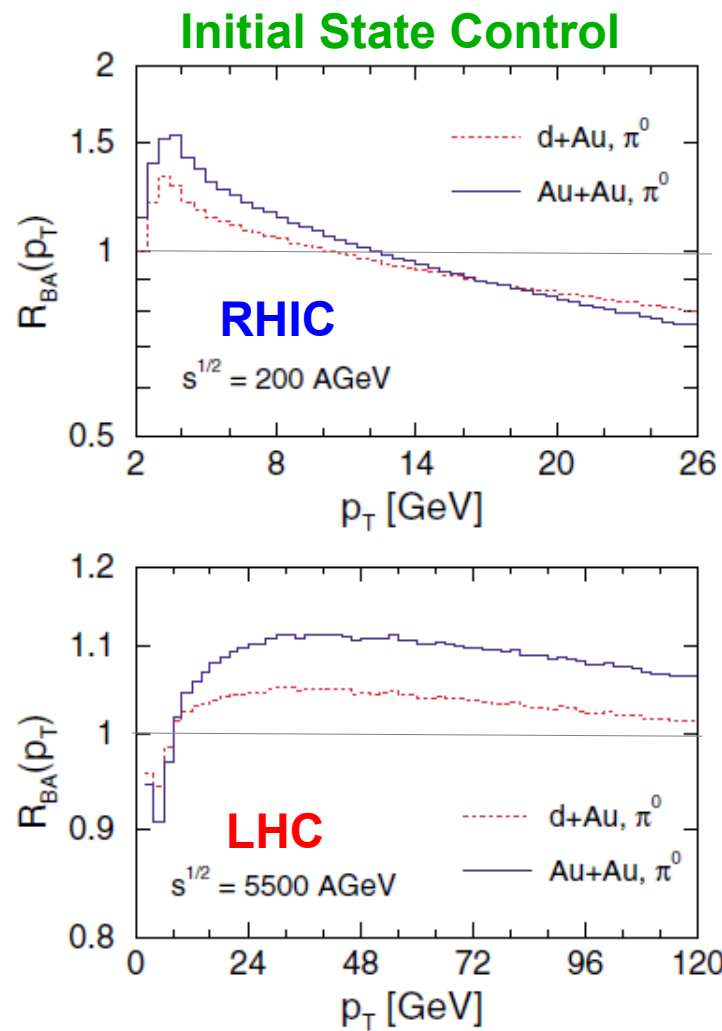


FIG. 2 (color online). The nuclear modification $R_{BA}(p_T)$ due to Cronin effect and shadowing (but not energy loss) for π^0 in $d + Au$ ($B = d, A = Au$) and central $Au + Au$ ($B = A = Au$)

M reactions at $\sqrt{s_{NN}} = 17, 200, \text{ and } 5500$ GeV.

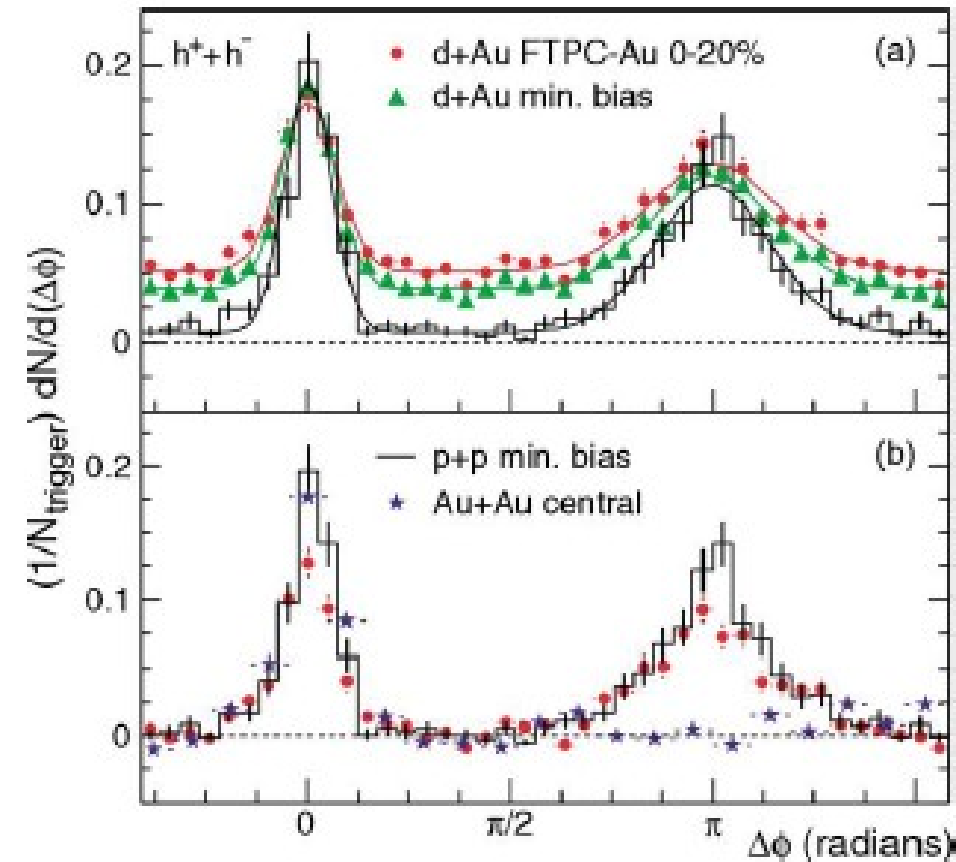


In the beginning...

Gabor David RBRC13

STAR, PRL 91 (2003) 072304

PHENIX, PRL 91 (2003) 072303

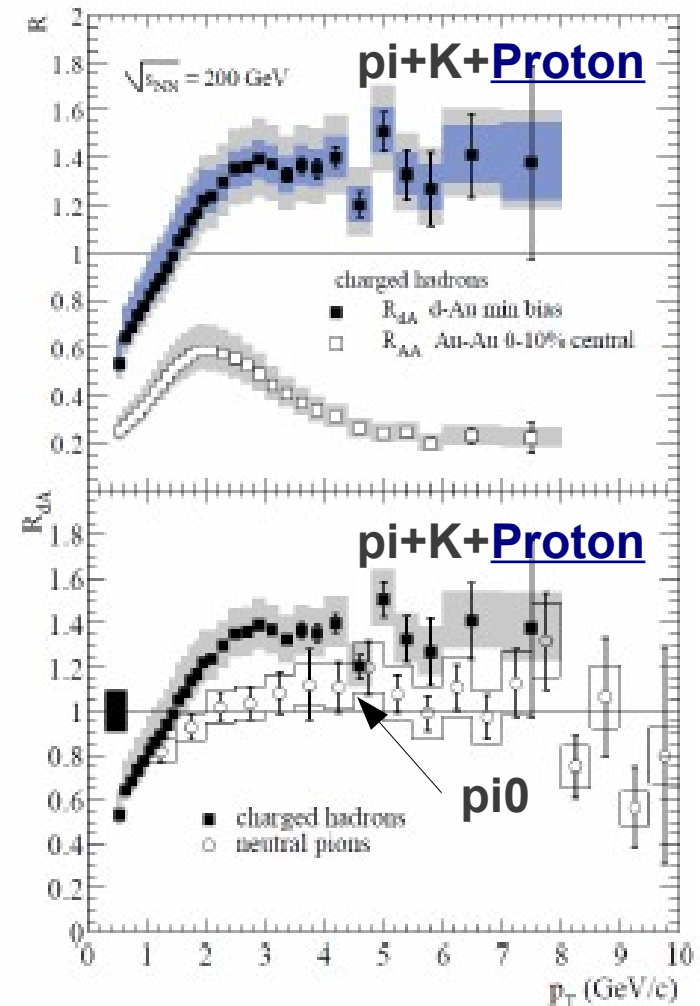


STAR: back-to-back jets reappear in d+Au

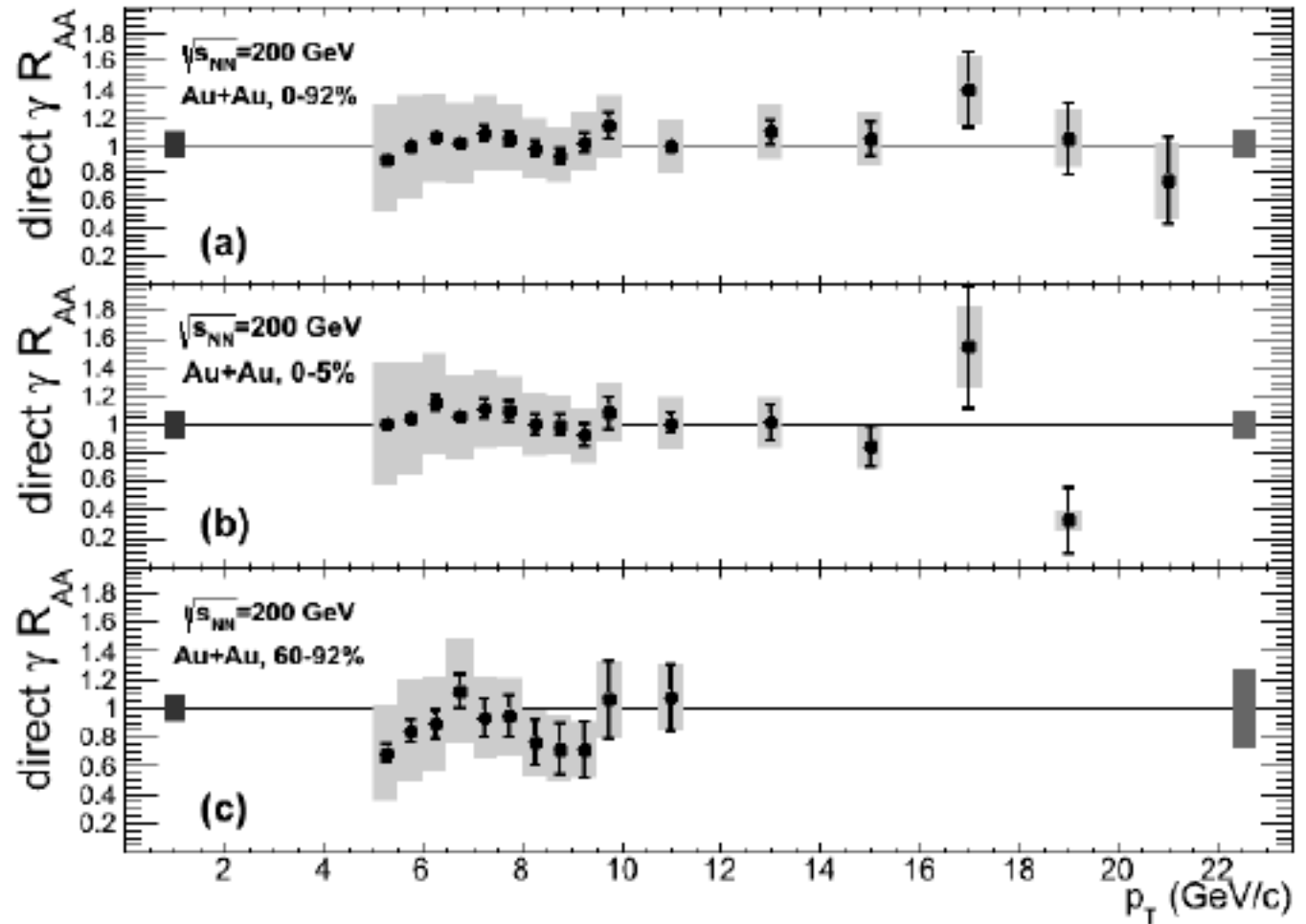
PHENIX: large suppression in Au+Au,

no suppression in d+Au

→ **final state effect (as of 2003)**



Null-Control D+Au \rightarrow Direct Photon N_{coll} scaling works!



PHENIX, PRL 109, 152302 (2012)

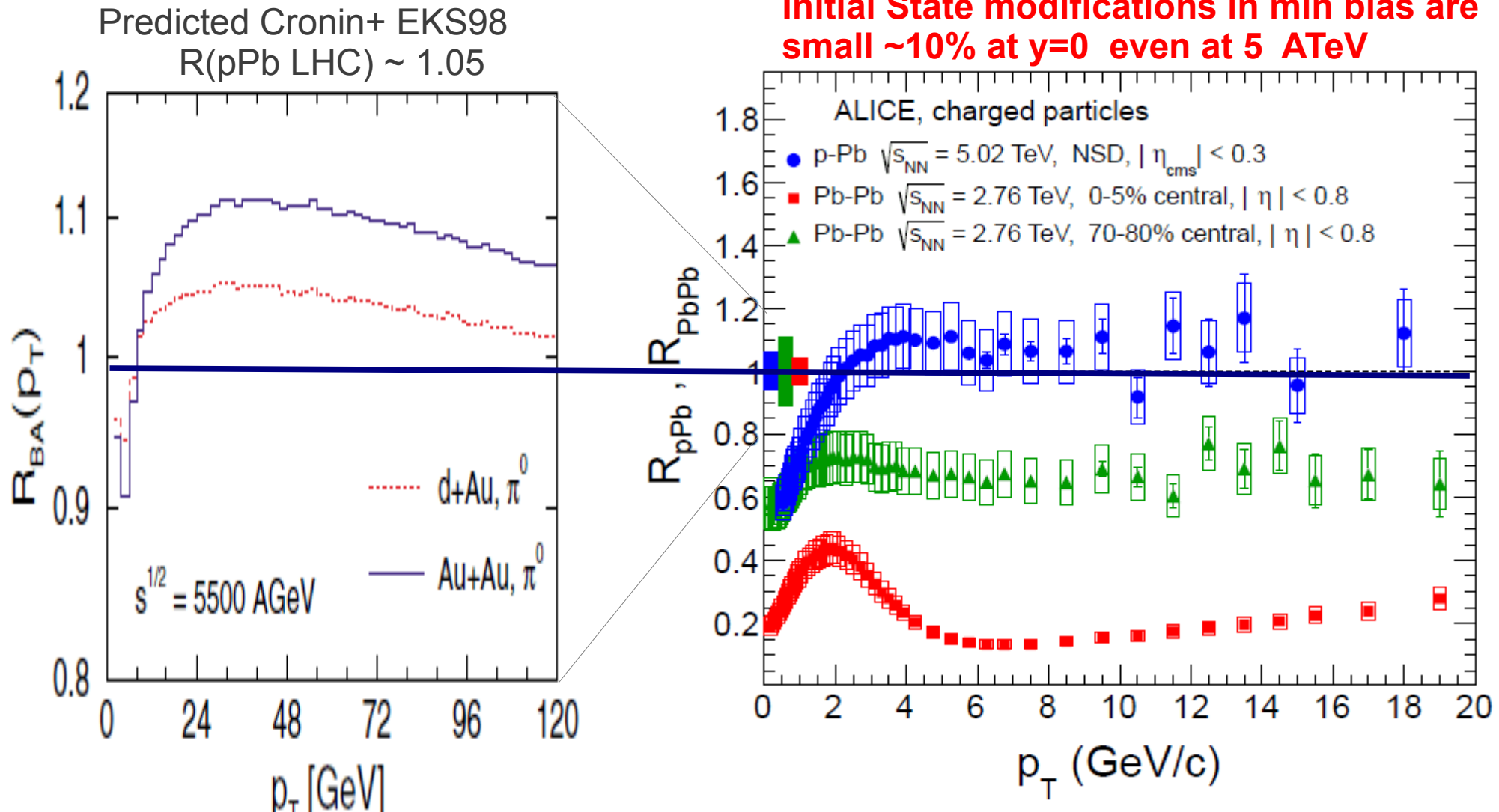
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RBRC jet quenching workshop, April 15-17, 2013 – G. David, BNL

High- p_T Tomography of $d + Au$ and $Au + Au$ at SPS, RHIC, and LHC

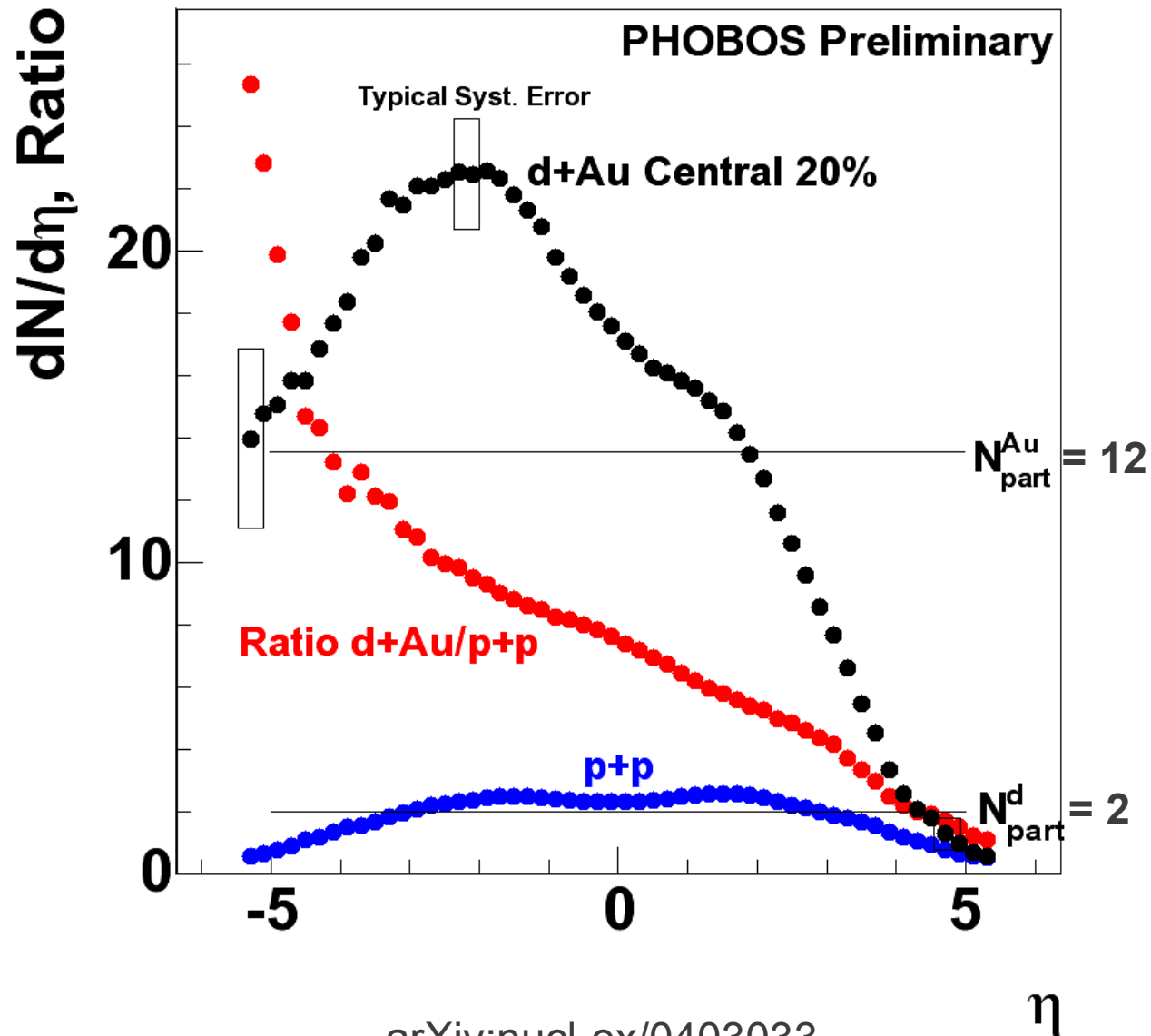
Ivan Vitev^{1,2} and Miklos Gyulassy¹

ALICE 2012 pPb 1210.4520v1
Initial State modifications in min bias are
small $\sim 10\%$ at $y=0$ even at 5 ATeV



We can safely calculate $R_{PbPb}(y=0, p_T > 4, \text{LHC})$ *neglecting* initial state interactions

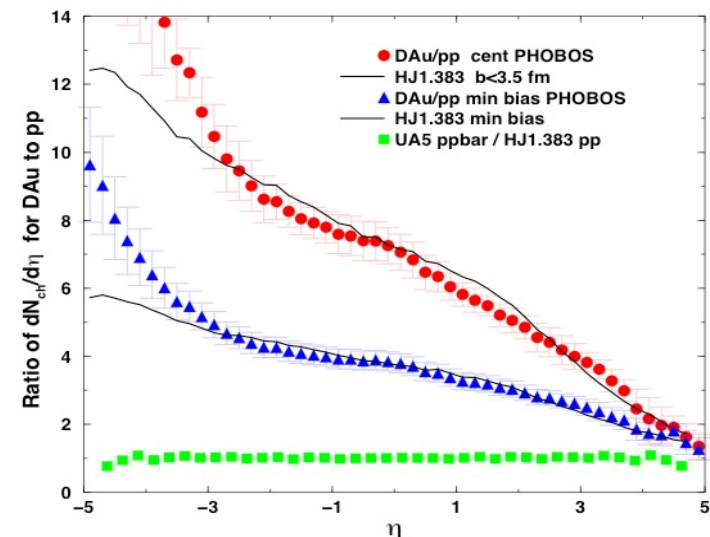
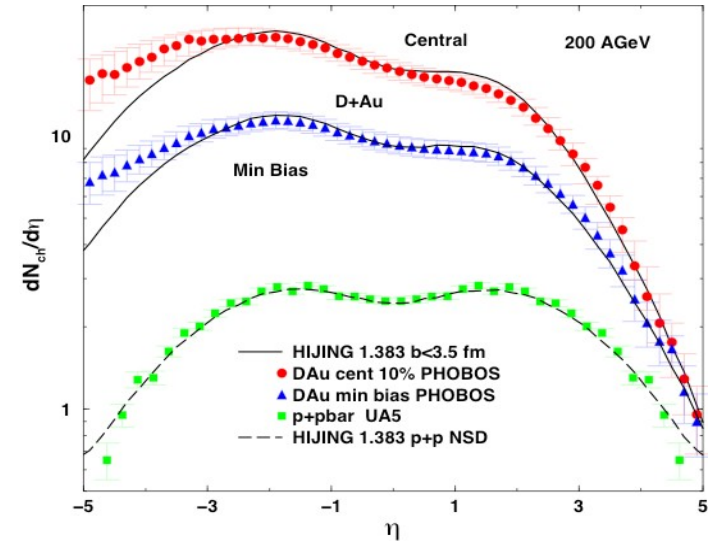
N_{part} scaling for asymmetric collisions:



arXiv:nucl-ex/0403033

Busza p+A/p+p dNdy Triangle well described at RHIC via HIJING

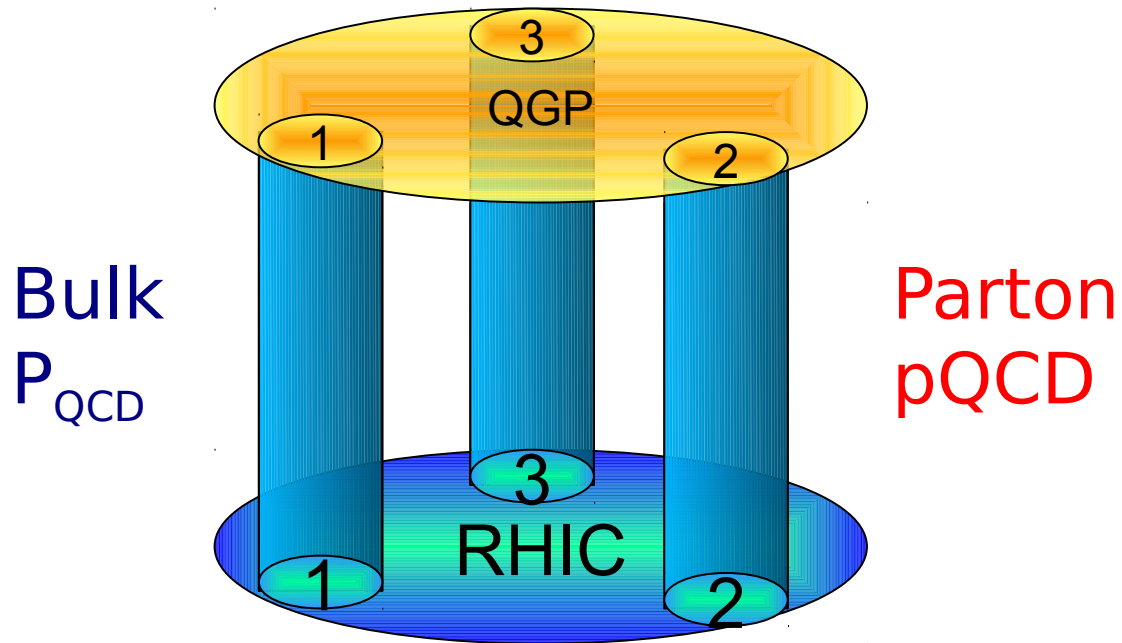
- Lund model ***beam jet*** flux tubes (as encoded in HIJING) account well for RHIC data and reproduced the basic BGK77 triangle form of the ratio p+A/p+p, as well as the **absolute** magnitudes dNch/deta
- Except in target frag region $y < -3$ where FSI enhance nch yields



In 2003 Three Lines of Data Seemed to Converged to QGP at RHIC

Null Control

Three Legs
Stable even
if unequal



1. Bulk P_{QCD} Collective Elliptic Flow v_2 ✓
2. Parton $p\text{QCD}$ Jet Quenching RAA ✓
3. $p+p$ Calibration and $d+A$ Null Control ✓ ✓

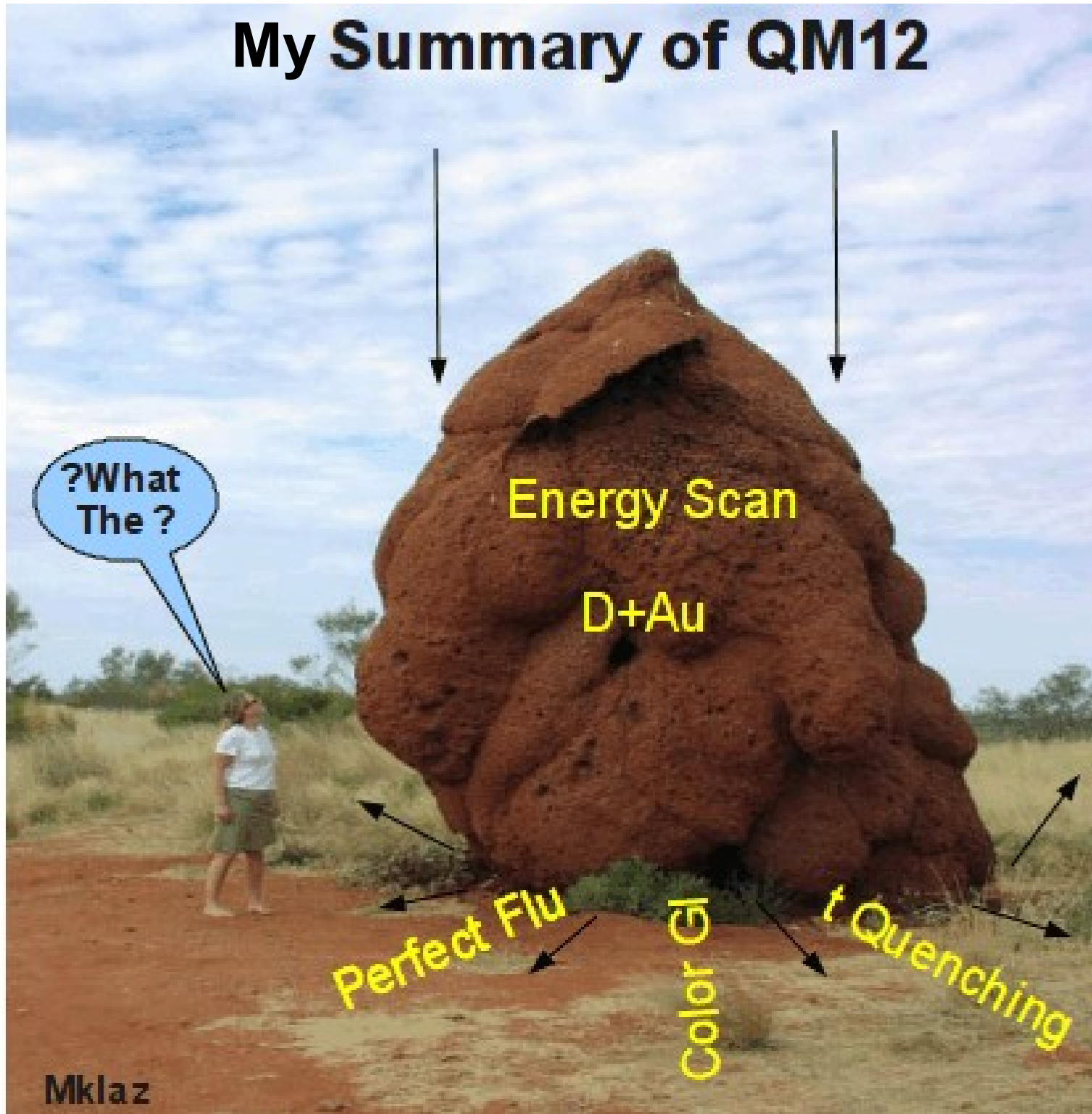
$$\mathbf{QGP} = \mathbf{P}_{\text{QCD}} + \mathbf{pQCD} + \mathbf{dA} = \mathbf{v}_2 + (\mathbf{R}_{\text{AA}} + \mathbf{I}_{\text{AA}}) + \mathbf{R}_{\text{dA}}$$

Part 1: Jet Quenching prior to 2012

Part 2: D+Au and p+Pb Shock Waves QM12 and RBRC13

Part 3: Azimuthal Tomography (ignoring part 2)

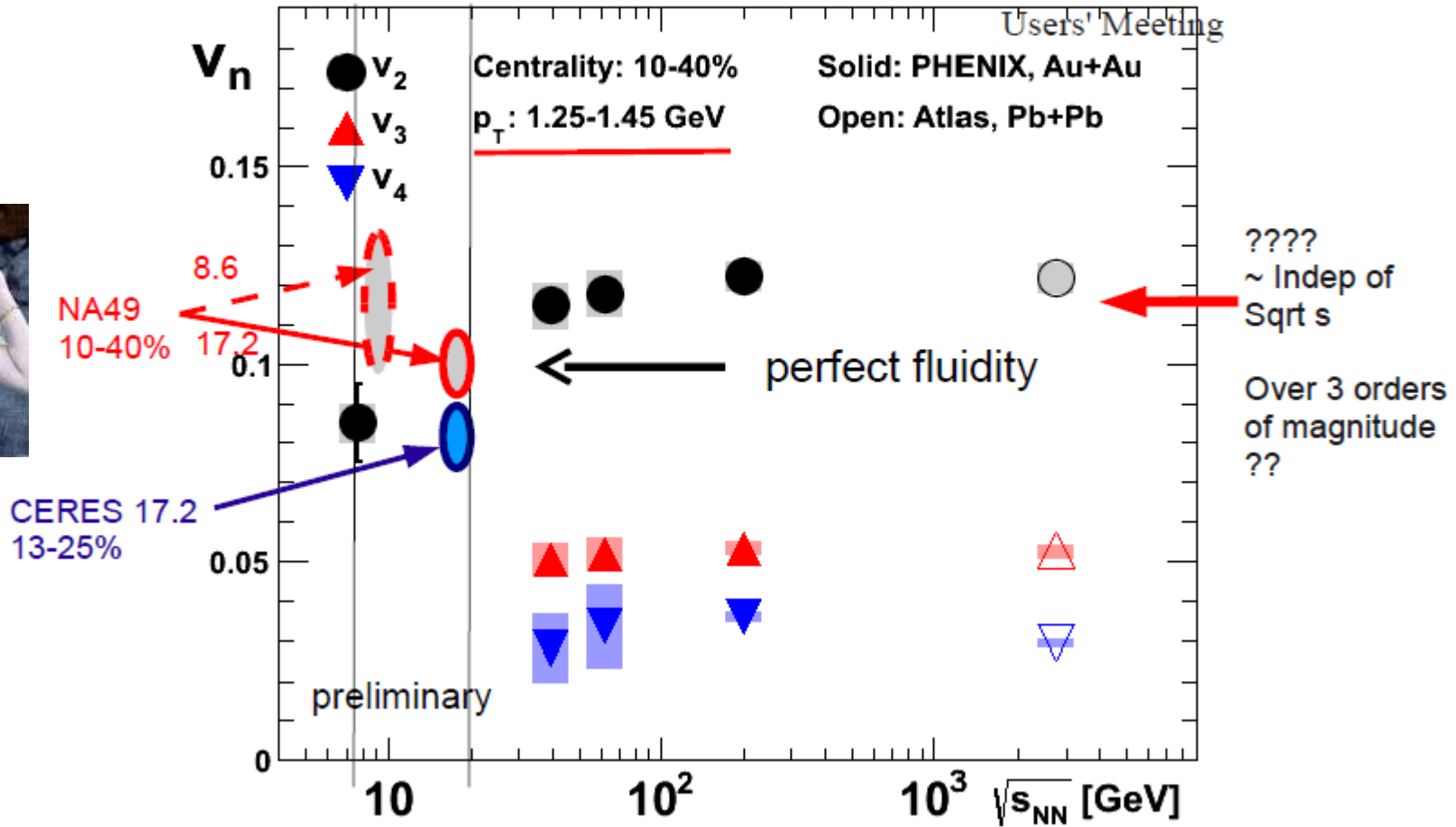
My Summary of QM12



Mklaz

In
 ↓
 QM12 PHENIX story: (same as STAR BES story)
 Ecm dependence of $v_n\{\Psi_n\}$ for charged hadrons

R.Pack, 2012 RHIC & AGS Annual



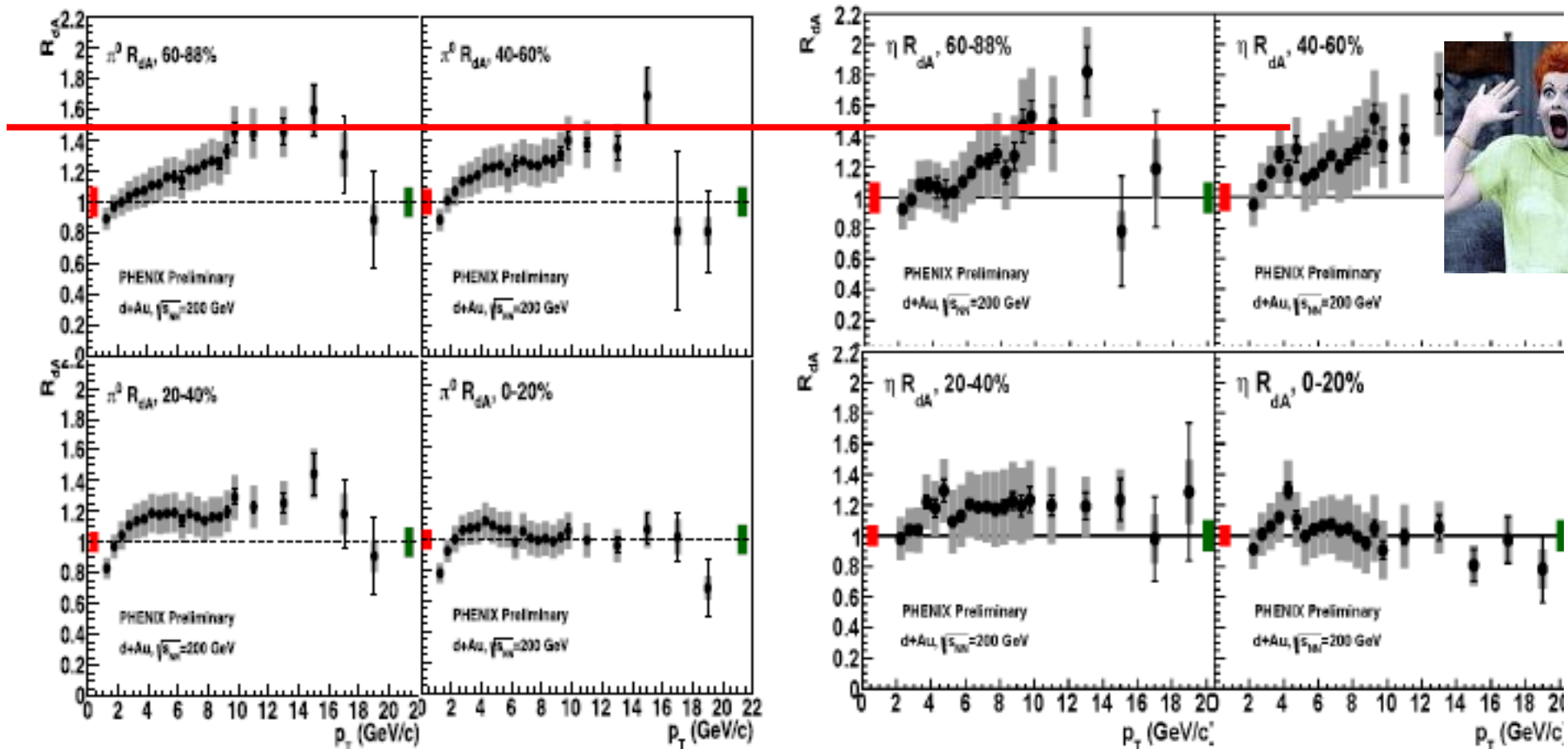
The (Bevalac, AGS, SPS, RHIC 200) Perfect Fluid QGP Core + Lousy HRG Corona Was Crushed: $v_n(p_T)$ shows no sign of LOUSY HRG Corona down to AGS!!!

more
↓
Now some results to lose sleep over



PHENIX preliminary, QM'12

2008 (high) statistics d+Au data, nuclear modification factors vs centrality



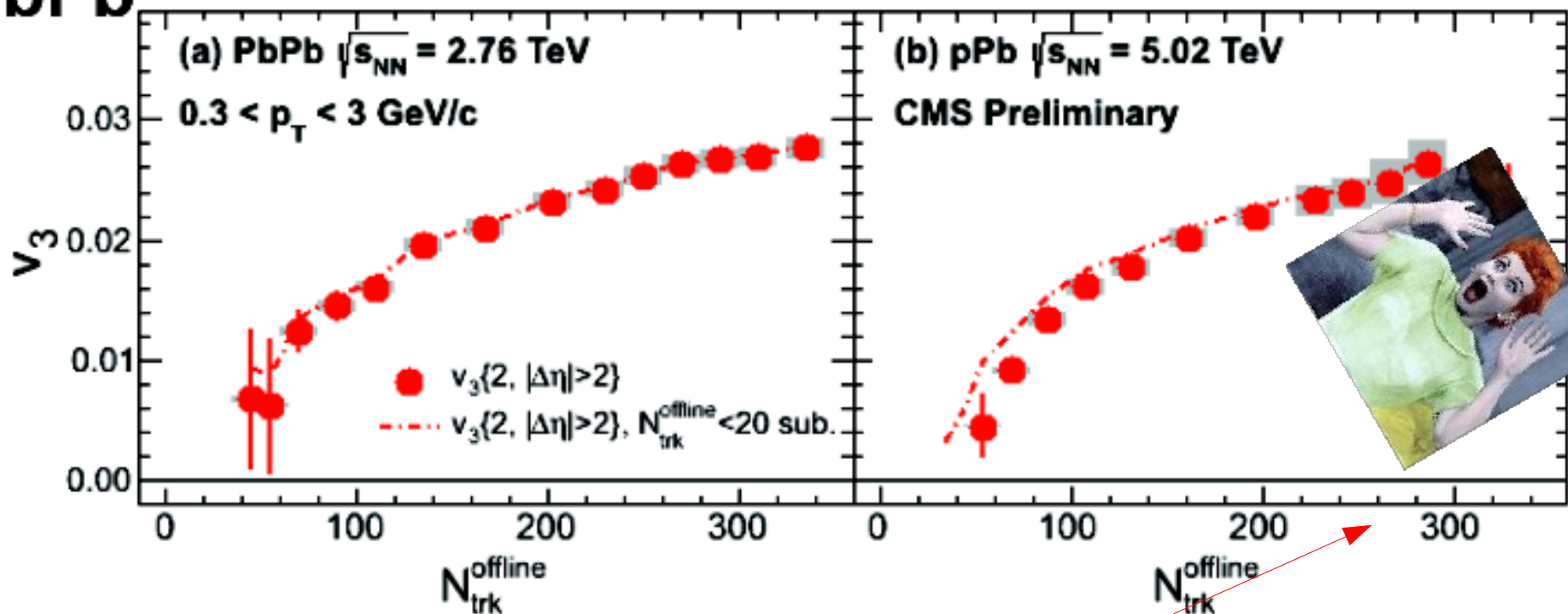
Is it possible that π_0 , η production at high p_T in peripherals is enhanced???

v_3 in pPb and PbPb

RBRC13 CMS SHOCK waves from super central pPb @ LHC

PbPb

pPb

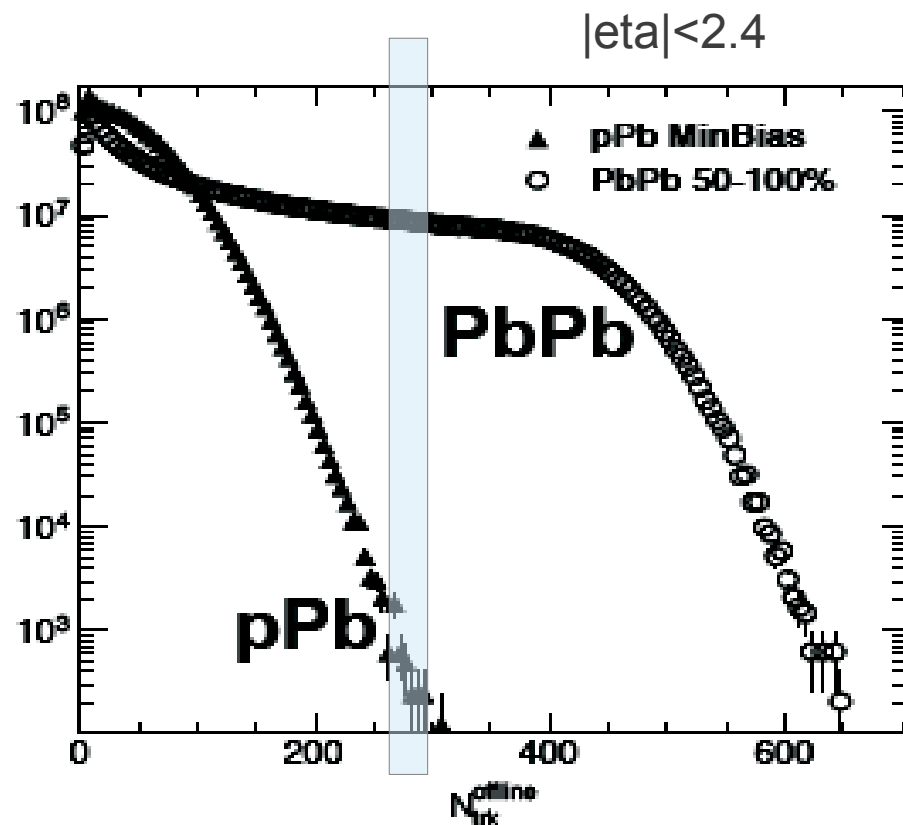
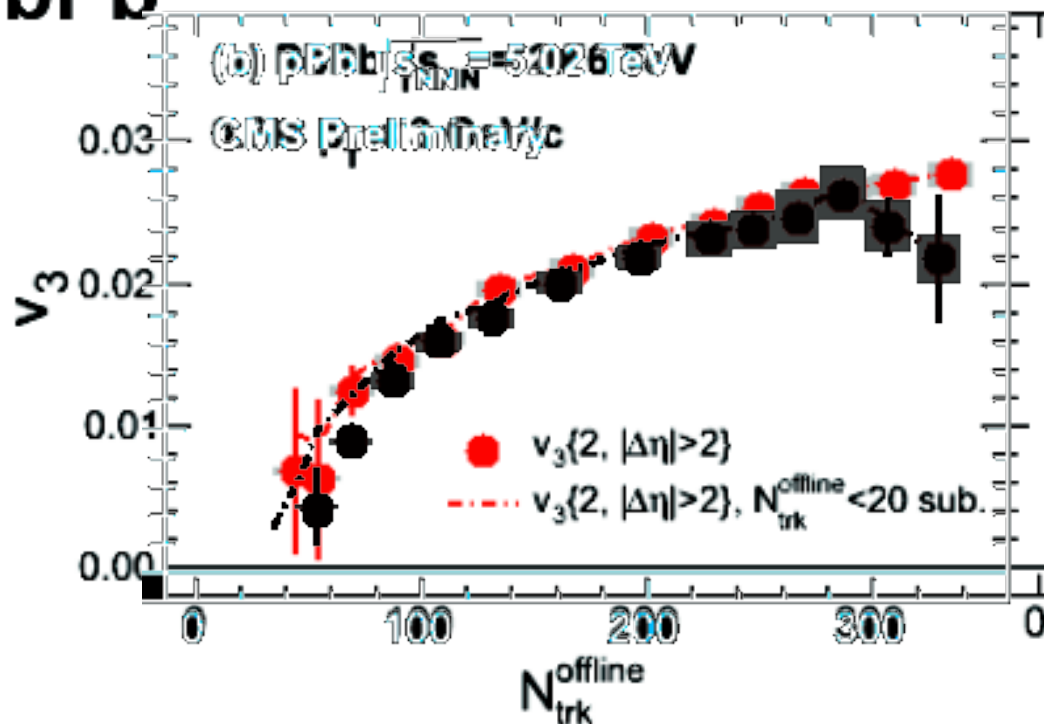


v_3 shows similar shape in pPb and PbPb; magnitude comparable

very rare events
1/ 1,000,000

v_3 in pPb and PbPb

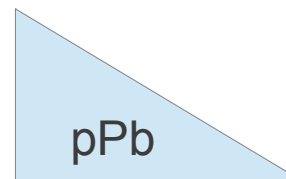
PbPb



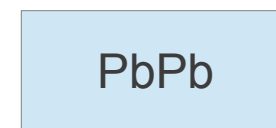
v_3 shows ~~similar~~ shape in pPb and PbPb; magnitude ~~comparable~~
same same

Data seem to falsify “Apples = Oranges” theorem

But $dN/d\eta$ shapes could differ a lot
 (Or it could be multi jetty)



vs



Recall old BGK p+A “Rapidity Triangle”

- Multiple independent wee parton dx/x collisions produce ~uniform in rapidity color charges between valence p and valence wounded A.
- Color neutralizes via pair production between wee and valence partons
- Leaving a stack in 10% of
- $A^{1/3} \sim 10$ Target beam jets
- For rare $N_{tr} \sim 300$ maybe 30 Pb nucleons line up
- There is 1 Projectile beam jet
-
- Y Slope $\delta = N_{tr} / \log(s)$
- RHIC $\delta \sim 2 \times$ LHC δ

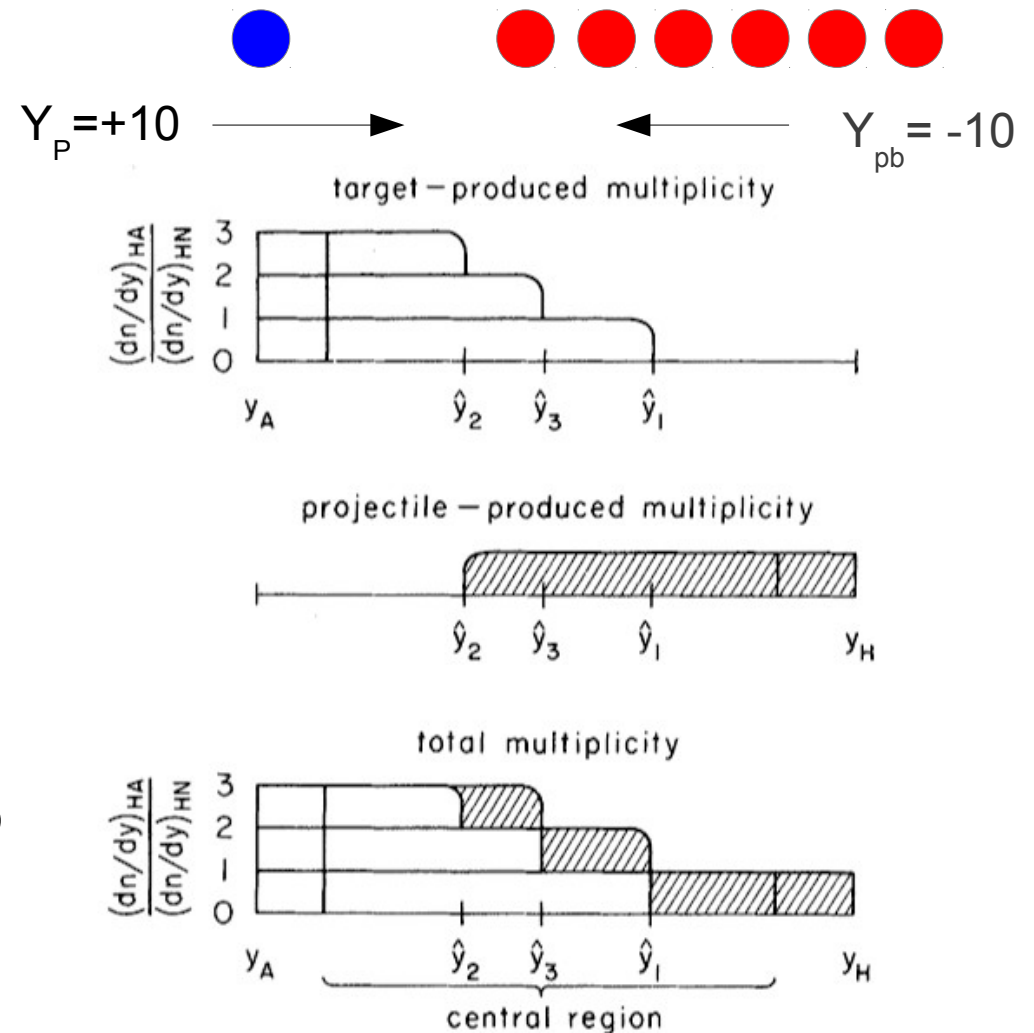


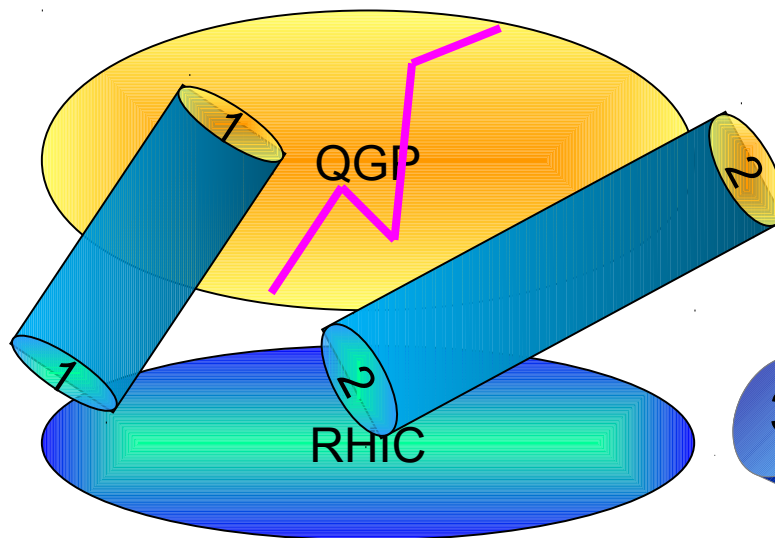
Figure from Brodsky, Gunion, Kuhn 1977

Can sQGP survive the RBRC 2013 D+Au and p+Pb tsunami?

BES , D+Au and p+Pb uncalibrated our v2 Barometer of sQGP
D+Au (and ? soon p+Pb) uncalibrated our RAA opacity meter

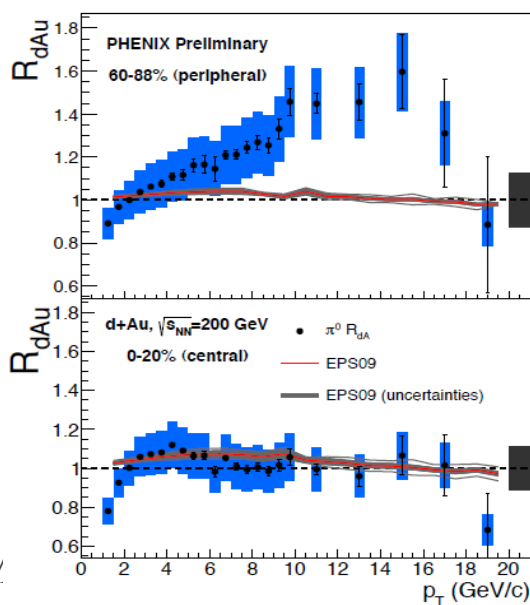
One or No
Legged
Tables are
Unstable!

D+Au
Broke
 P_{QCD}
Flow?

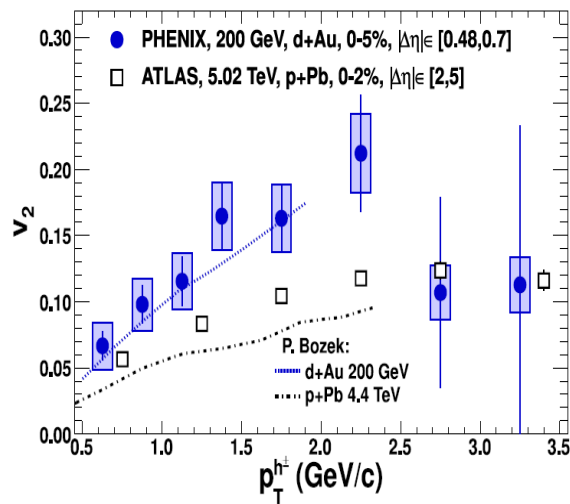


D+Au Broke
pQCD
Quenching?

$R(DAu) \neq 1$??



$v_2(DAu) = v_2(AuAu)$??



Have we lost our
pA Control ?



Maybe $v_2(\text{DAu}, 5\%) = v_2(\text{AuAu}, 30\%)$ is just coincidence bad luck ??

Maybe QM12 BES is also just coincidence ?

$v_2(\text{AuAu}, 7 \text{ AGeV}) \sim v_2(\text{AuAu}, 200 \text{ AGeV}) \sim v_2(\text{PbPb}, 2800 \text{ AGeV})$??

Should we ignore the “peripheral” $R_{\text{DAu}}(15 \text{ GeV}) \sim 1.5$ anomaly
and rely instead only on Null Control direct gammas

$R_{\text{DA}}(\text{gamma}) \sim R_{\text{AuAu}}(\text{gamma}) \sim 1$

We need global data on dN/dy , dET/dy , and $dN/dydp_T$
at both RHIC and LHC on rare $p + A$ processes

Entropy has been produced (Clausius is happy) but
we need to step back and reassess which of our (many)
Geometric and dynamical assumptions may
fail in very rare pA and DA processes.

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Part 3:

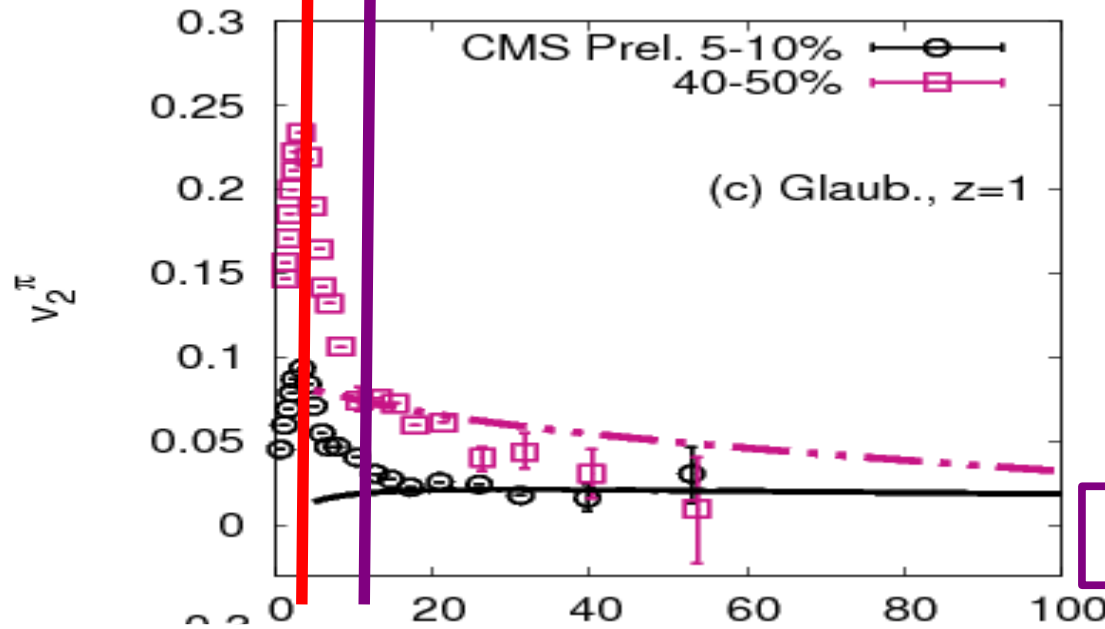
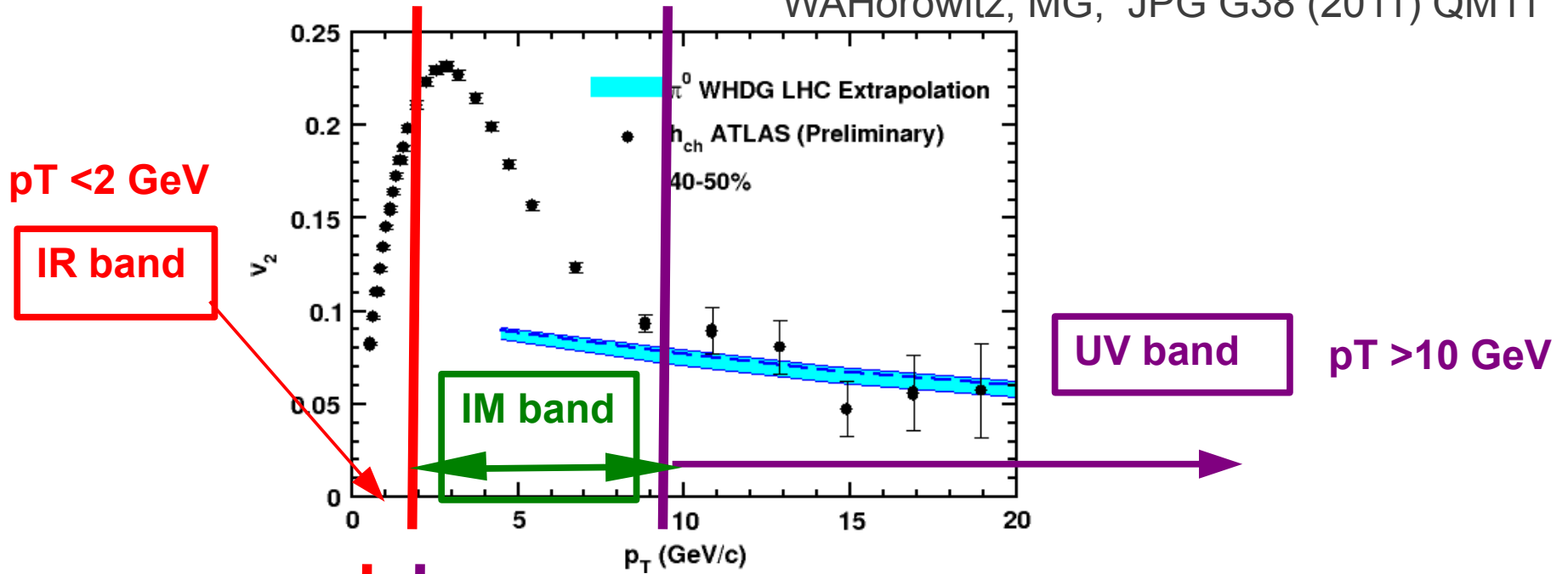
The High p_T azimuthal asymmetry $v_2(p_T, E_{cm})$

In the IM $2 < p_T < 10$ and the deep UV $p_T > 10$

Puzzling Status update

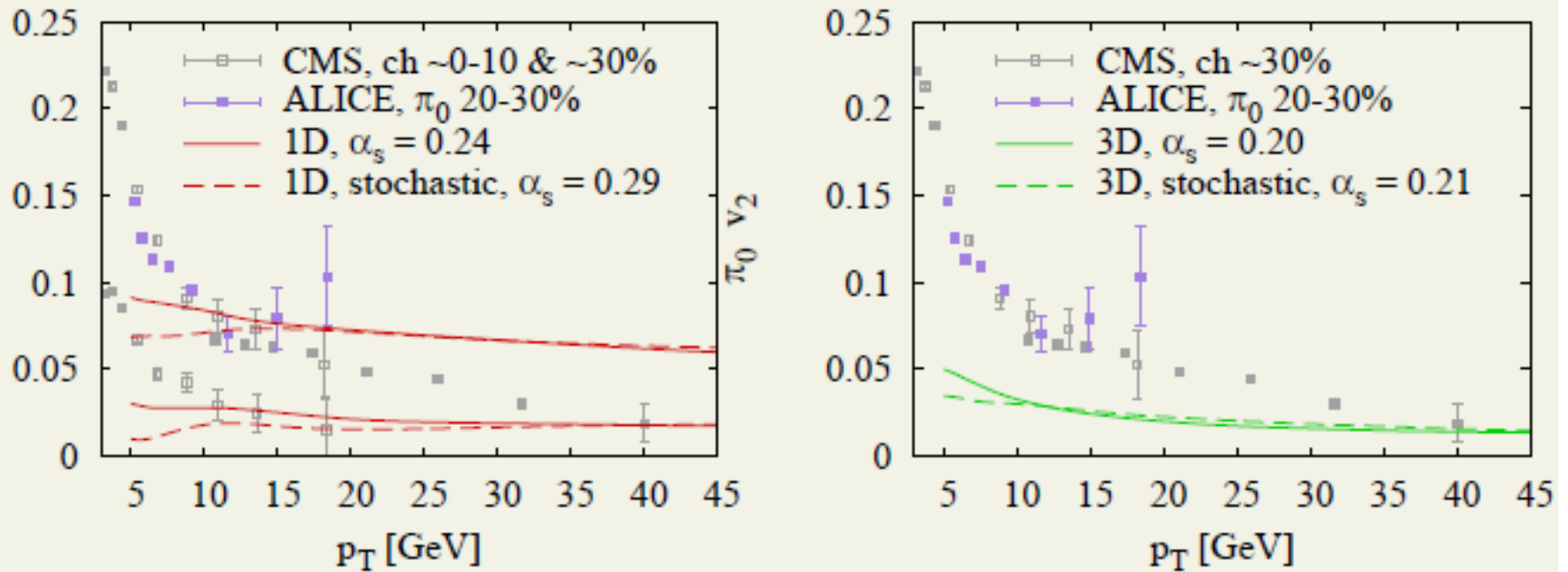
The **Deep UV Band** $p_T > 10$ GeV seemed to agree with pQCD tomography @LHC
 Unlike the **intermediate IM Band** $2 < p_T < 10$ interpolating between **IR** and **UV** bands

WAHorowitz, MG, JPG G38 (2011) QM11



Latest CMS 2012
 v_2 data probe
 very deep into UV ~ 60 GeV !

high- p_T pion v_2 , LHC (α_s scaled to RAA at $p_T = 6$ GeV)



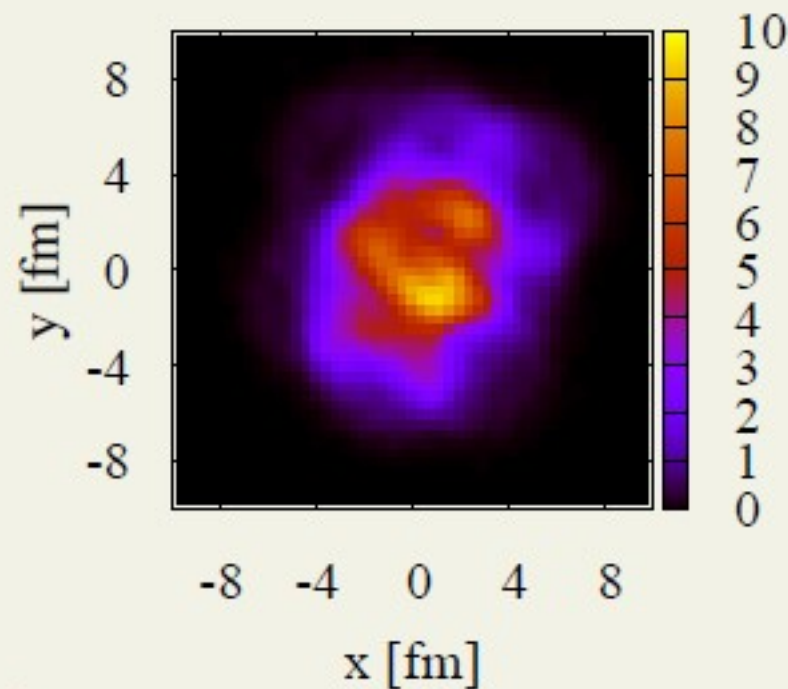
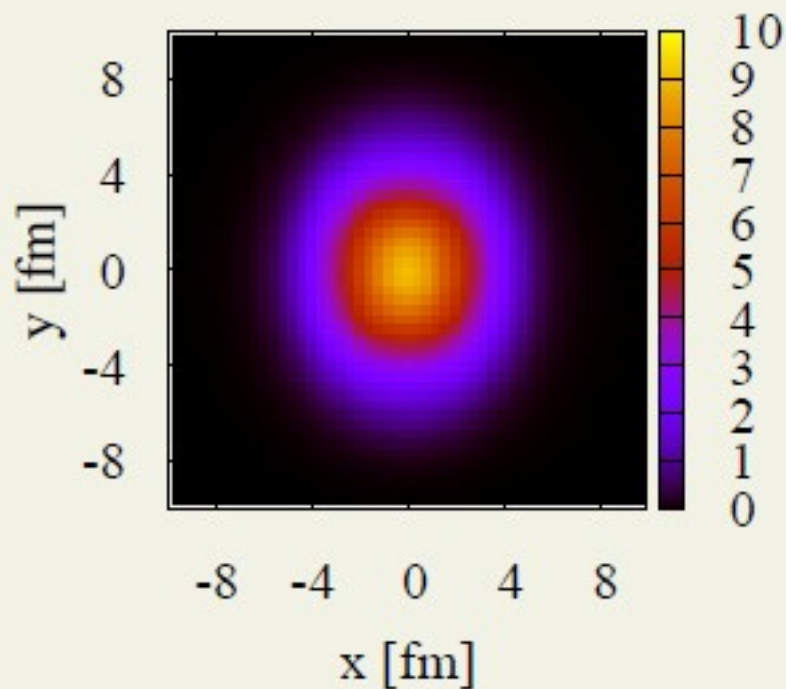
They concluded that transverse expansion reduced pQCD $v_2(p_T)$ by factor ~ 2 below data

average Au+Au, b=8 fm

single MC Glauber

$\tau dN/d^2x_T$ [fm]

$\tau dN/d^2x_T$ [fm]



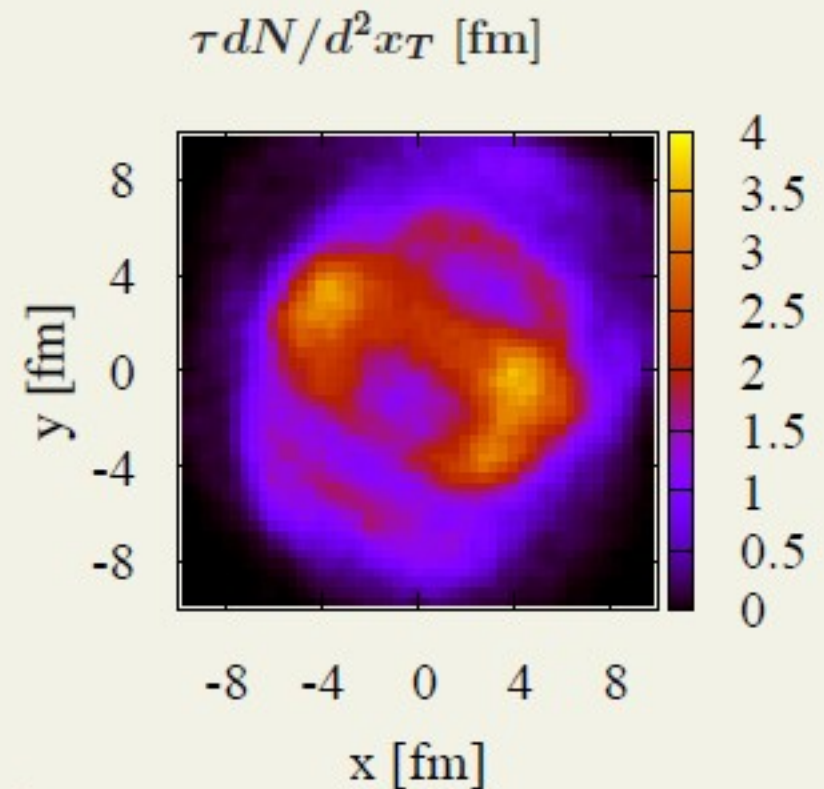
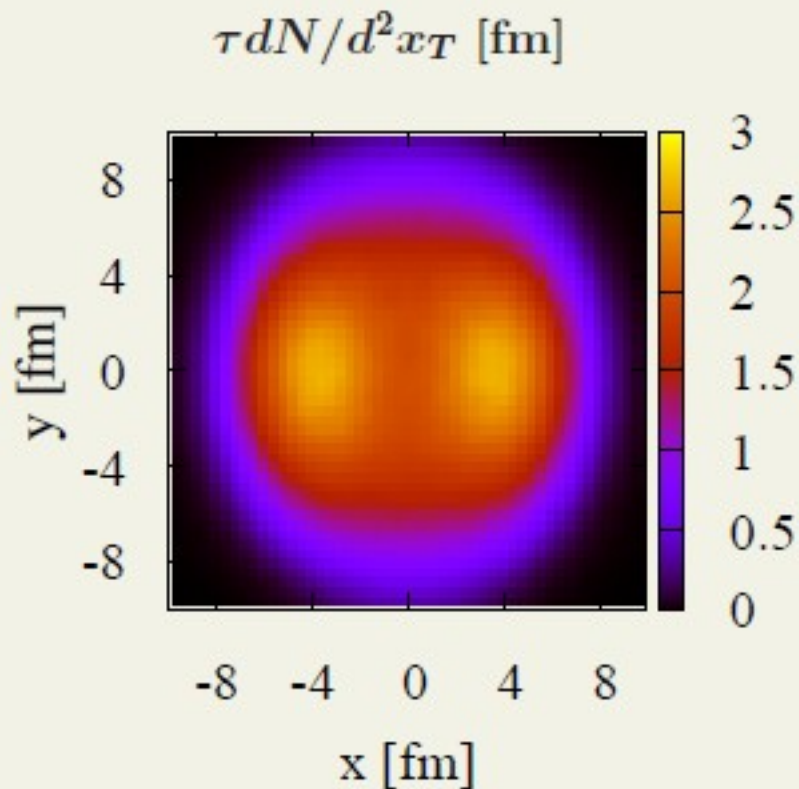
$\tau = 3.6$ fm

Similar to the Ed's 1999 "Nutcracker" scenario bulk hydro like evolution

With rapid decrease of eccentricity to negative values for $t > R$

average Au+Au, $b=8$ fm

single MC Glauber



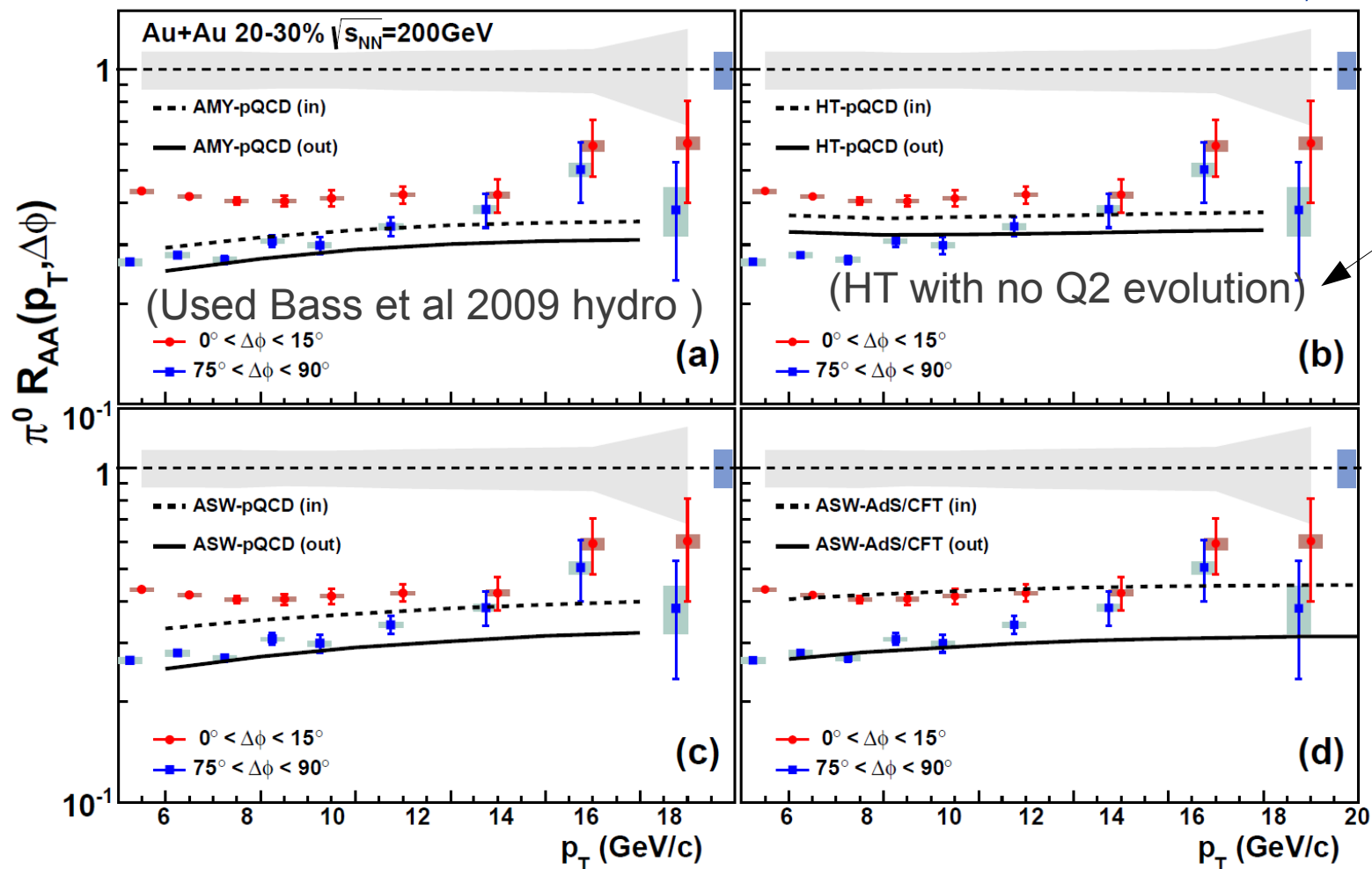
$\tau = 6.6$ fm

$$R_{AA}^{in} = R_{AA}(1 + 2v_2)$$

vs

$$R_{AA}^{out} = R_{AA}(1 - 2v_2)$$

A. Adare et al., arXiv:1208.2254



See A. Majumder RBRC13 update

$E^0 L^2$
En loss

→ PHENIX Concluded: Only Schematic ASW-AdS/CFT can fit both $R_{AA}^{in/out}$ for a 3d expanding medium. PQCD based dedx underestimate

→

Provide information about **both R_{AA} and v_2**

abc Model of Jet Energy Loss and RAA

For pQCD
 $a \sim 1/3$, $b \sim 1$

$$\frac{dP}{d\tau} = -\kappa P^a \tau^b T^{2-a+b}(x(\tau), \tau)$$

$$P_0(P_f) = \left[P_f^{1-a} + K \int_{\tau_0}^{\tau_f} \tau^z T^c[\vec{x}_\perp(\tau), \tau] d\tau \right]^{\frac{1}{1-a}}$$

For Holographic
 Falling Strings
 (Chesler Yaffe)

$$L_{\text{stop}} \sim E^{1/3}$$

$\Rightarrow a = 1/3$, $b = 1$
OR $a = 0$, $b = 2$

For Holographic
 String Drag
 (Gubser, Herzog)

$$a = 1 \quad . \quad b = 0$$

$$R_{AA}(p_f; s, A) = \frac{\partial p_0}{\partial p_f} \frac{d\sigma(p_0(p_f))/dp}{d\sigma(p_f)/dp}$$

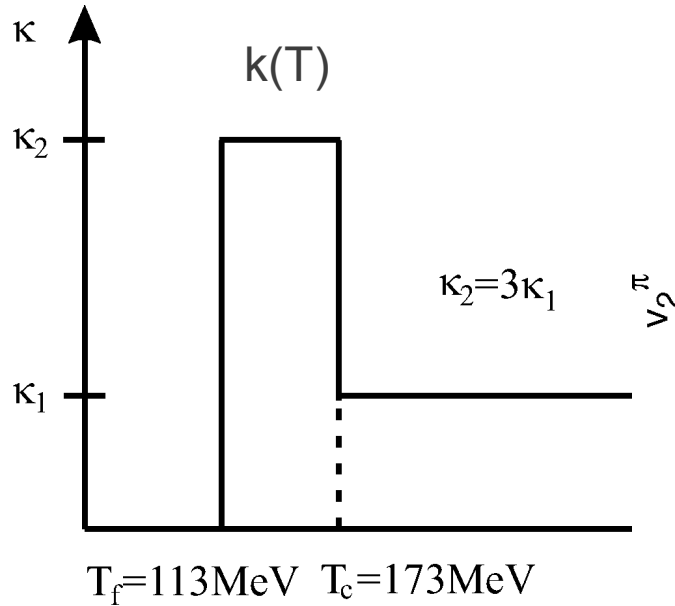
Spectral index
 From pQCD

$$\text{For Bj Brick} \approx \left(1 + \kappa' \frac{(dN/dy)^{(2-a+b)/3}}{(Lp_f)^{1-a}} \right)^{\frac{a-n(p_f)}{1-a}}$$

Fix κ' by fit to one RHIC R(pf=10 GeV , dNdy=1000) reference point.

„Magnetic Monopole“ scenario of Liao, Shuryak

B. Betz et al., in preparation

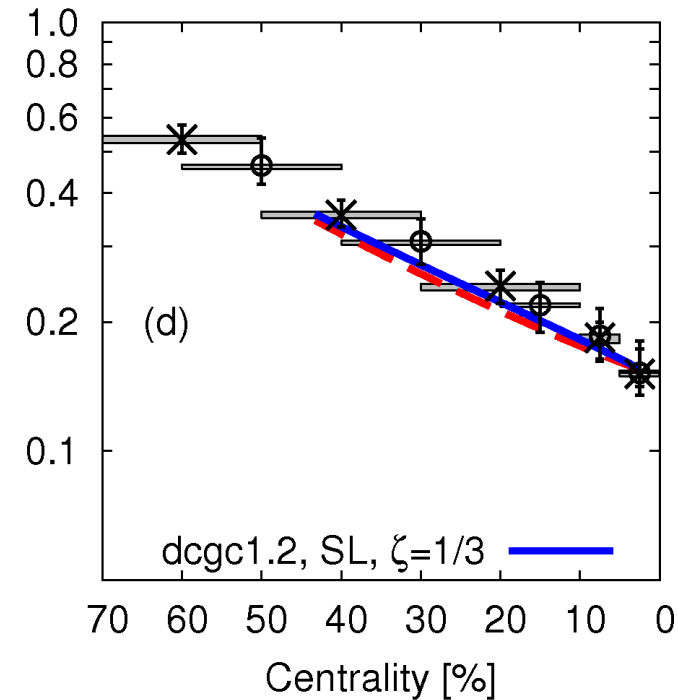
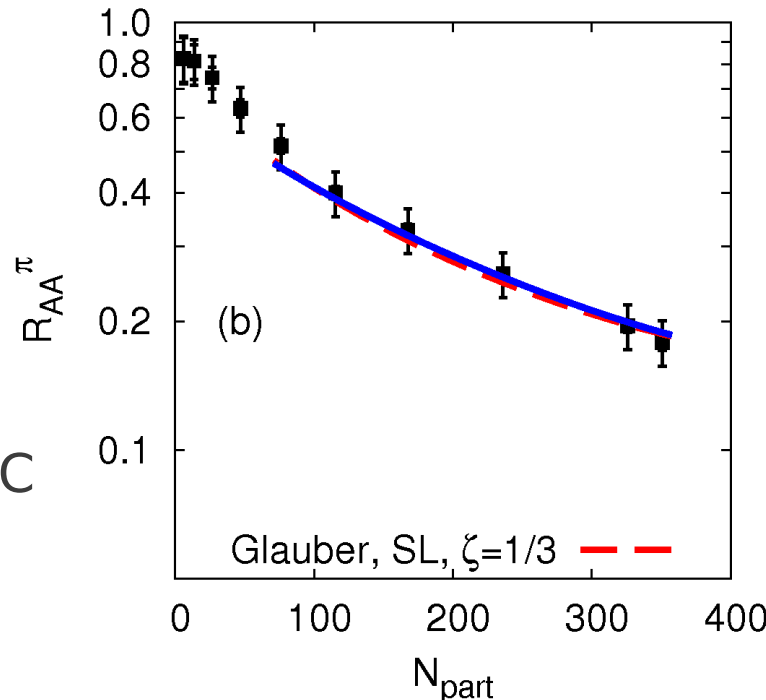
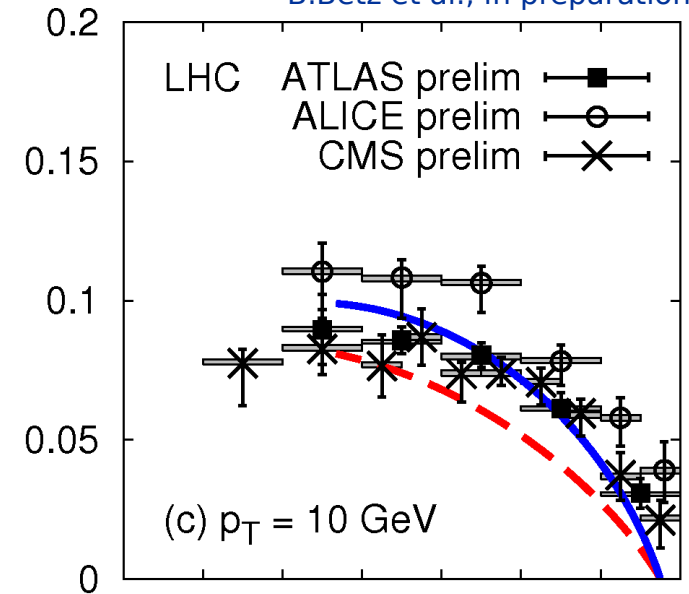
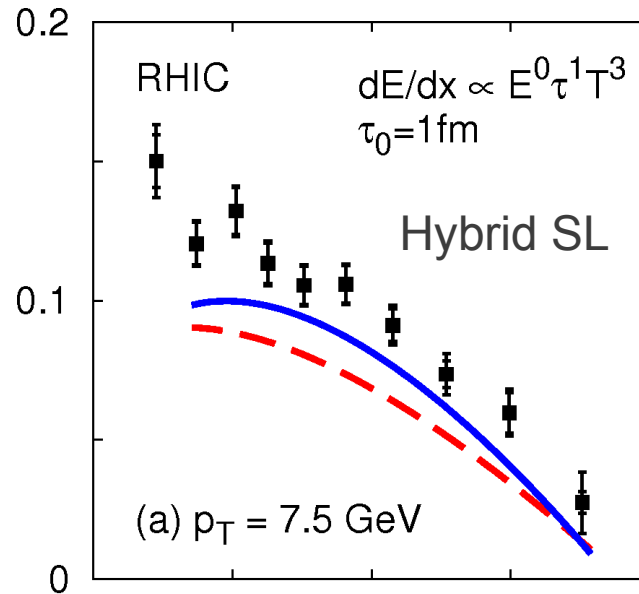


J. Liao et al., PRL **102** (2009) 202302

$$\zeta = \kappa_1 / \kappa_2$$

→ Apply **same**
 $\kappa(T)$ at RHIC and LHC

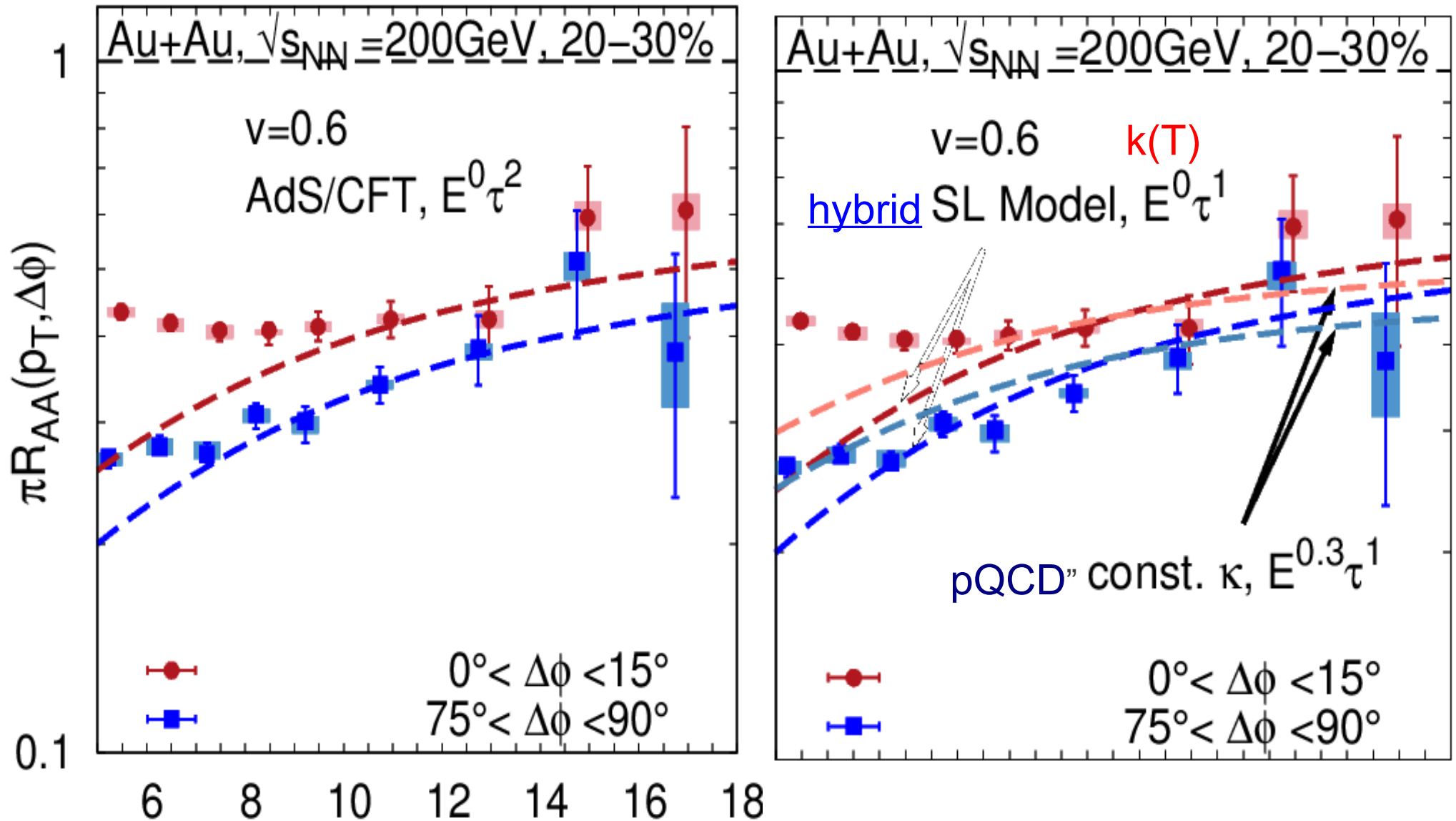
Original SL, RAA was independent of p_T



(a=0,b=2,c=4) is like Renk's "AdS" model

B.Betz.MG 2013

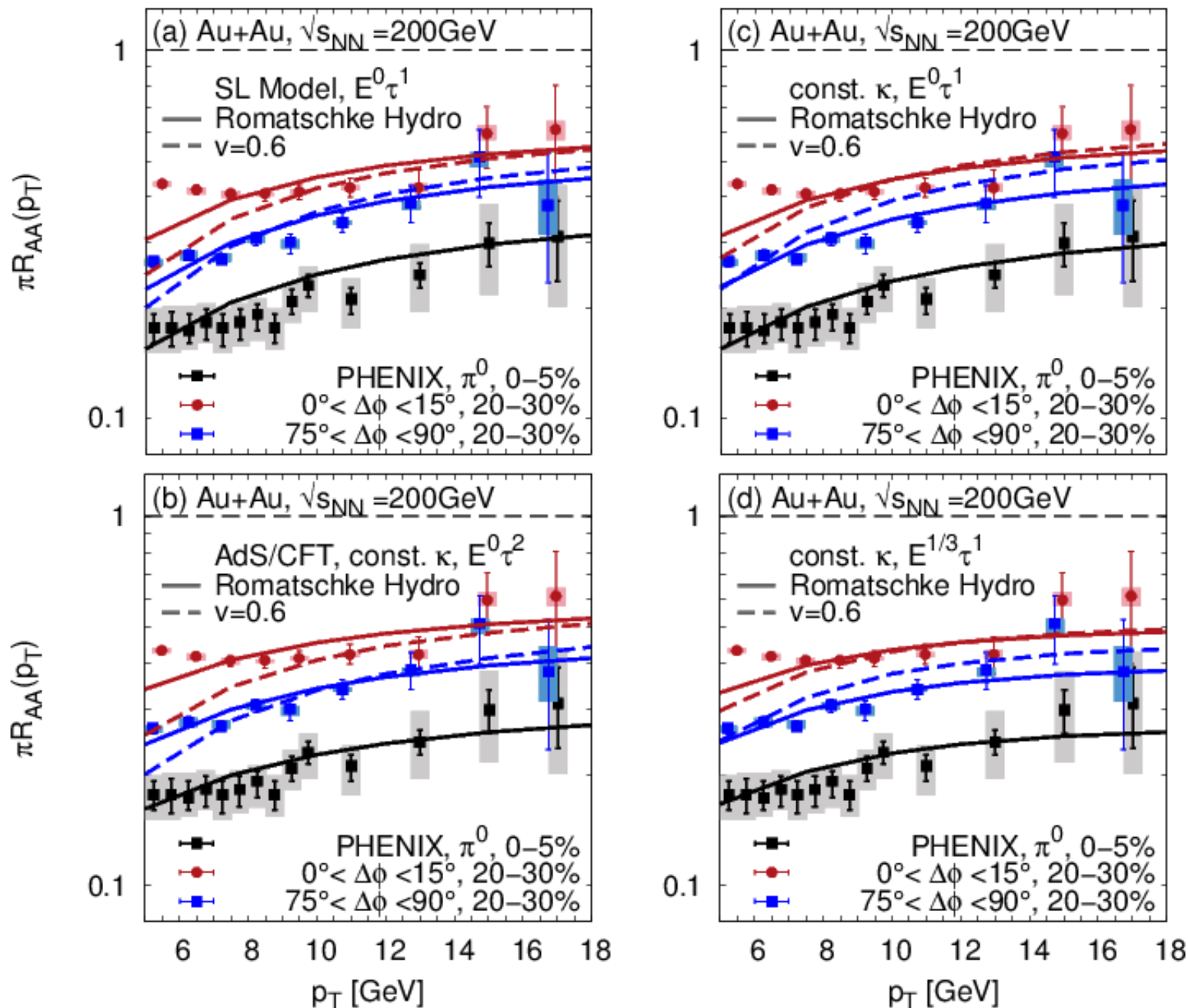
(a=0,b=1,c=3) is like Liao's "SL" mag.mono. model



Including transverse flow UV $p_T > 10 \text{ GeV}$, pQCD or "AdS" are adequate within errors
 None of the models pQCD, SL, or AdS reproduce in and out in IM $p_T < 10$ range

(B.Betz, MG, to be published)

Compare 4 dEdx models using Romatschke hydro or Bj+ radial flow $v=0.6$ bulk models



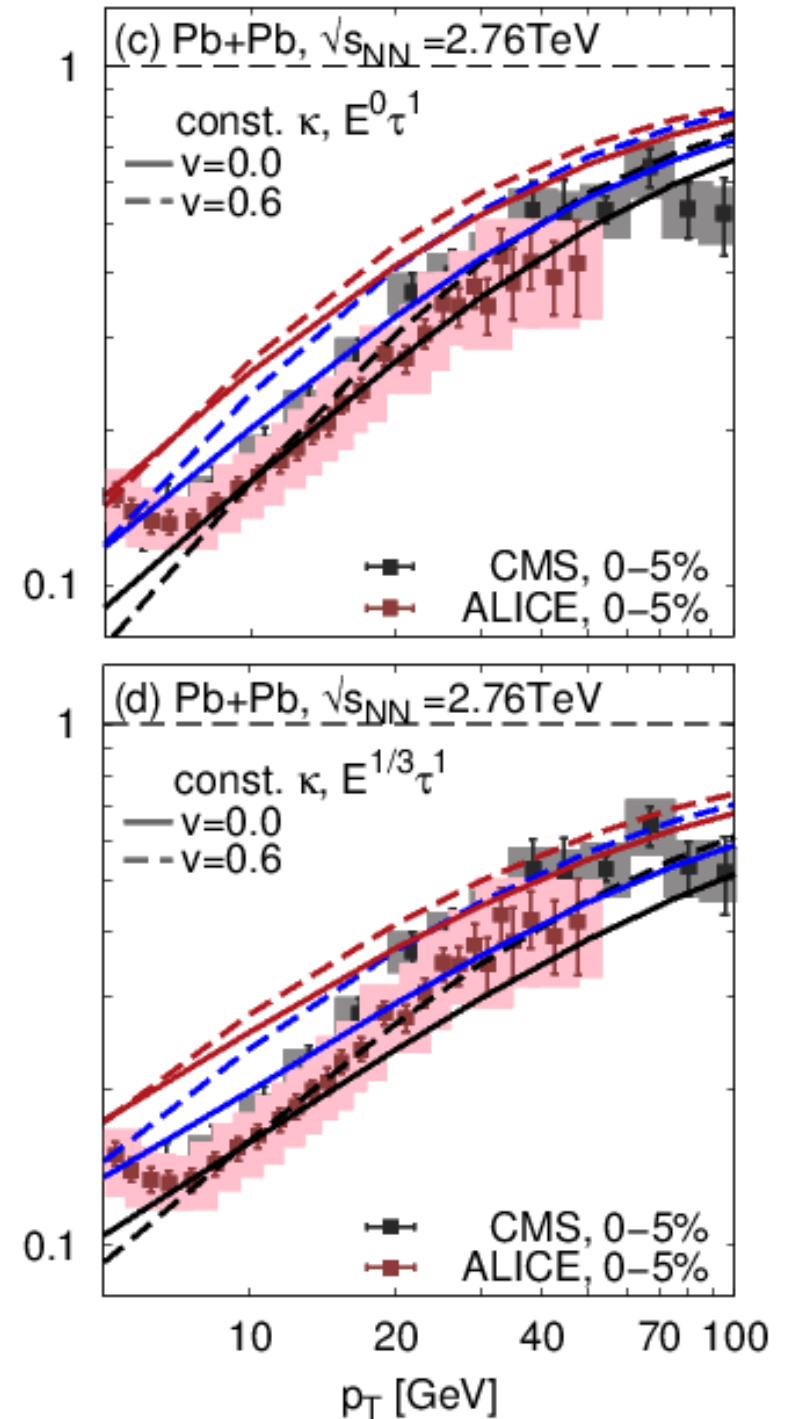
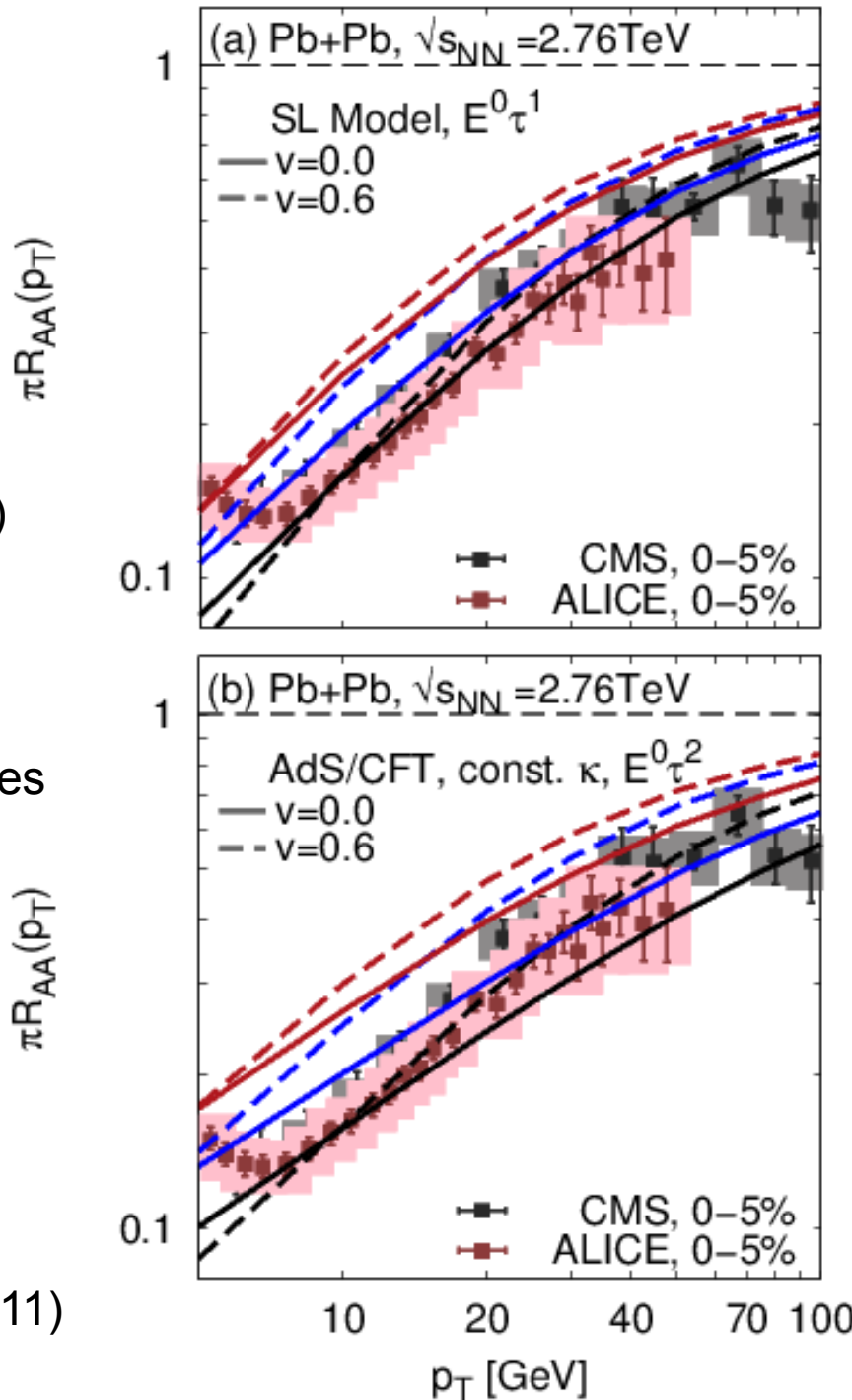
None of 8 scenarios appears preferred within current errors at RHIC
 B.Betz, MG (13)

8 Scenarios
Extrapolated
to
LHC

Sensitivity
To dE/dx (abc)
and $\kappa(T)$
is weaker
than at RHIC
because
spectral shapes
are harder

Large
Sensitivity of
RAA in/out
To bulk flow
Evolution

(as per Renk 11)



Final remarks :

- 1) Azimuthal tomography is sensitive to details of the bulk flow $T(x,t)$ and $u(x,t)$ field evolutions that is complementary to low p_T v_n systematics. This is the good news.
- 2) However sensitivity is weak more precise RAAin/out(p_T) needed to resolve current array of (pQCD, SL, and AdS dEdx models) times the array bulk flow models (Bass, Heinz, Romat, MPC)
- 3) Different jet asymmetry using Romat hydro and Bass hydro flow fields needs to be clarified.
- 4) Meanwhile, the new QM12 and RBRC13 p+A and D+A data on bulk v_n and anomalous jet modification “discoveries” severely challenge our entire framework of A+A analysis.

Our homework now is to try to regain the lost Null-Controls !

The p-A/p+p “Rapidity Triangle”- BGK Model

- Multiple independent wee parton dx/x collisions produce uniform in rapidity color charges between valence p and and valence wounded A.
- Color neutralizes via pair production between wee and valence partons
-
- Leaving a stack of
- $\sim A^{1/3}$ Target **beam** jets
-
- and 1 Projectile **beam** jet
- $\nu_A(b) \approx \sigma_{in} T_A(b)$
- Y Slope $\delta = O(A^{1/3}/\log(s))$
- RHIC $\delta \sim 0.45$, LHC $\sim \delta 0.28$

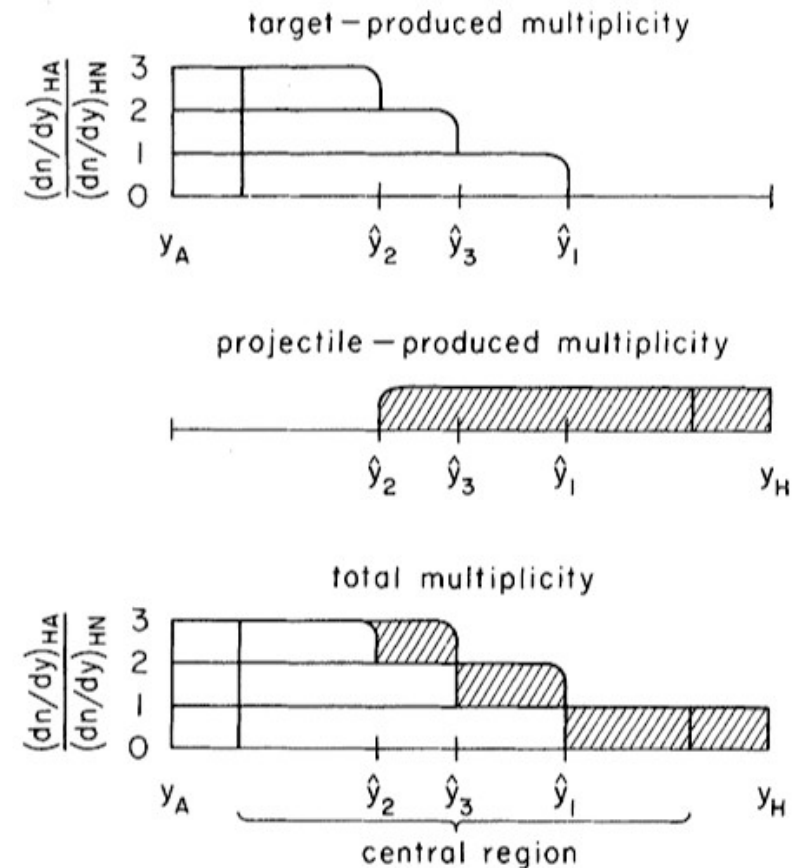
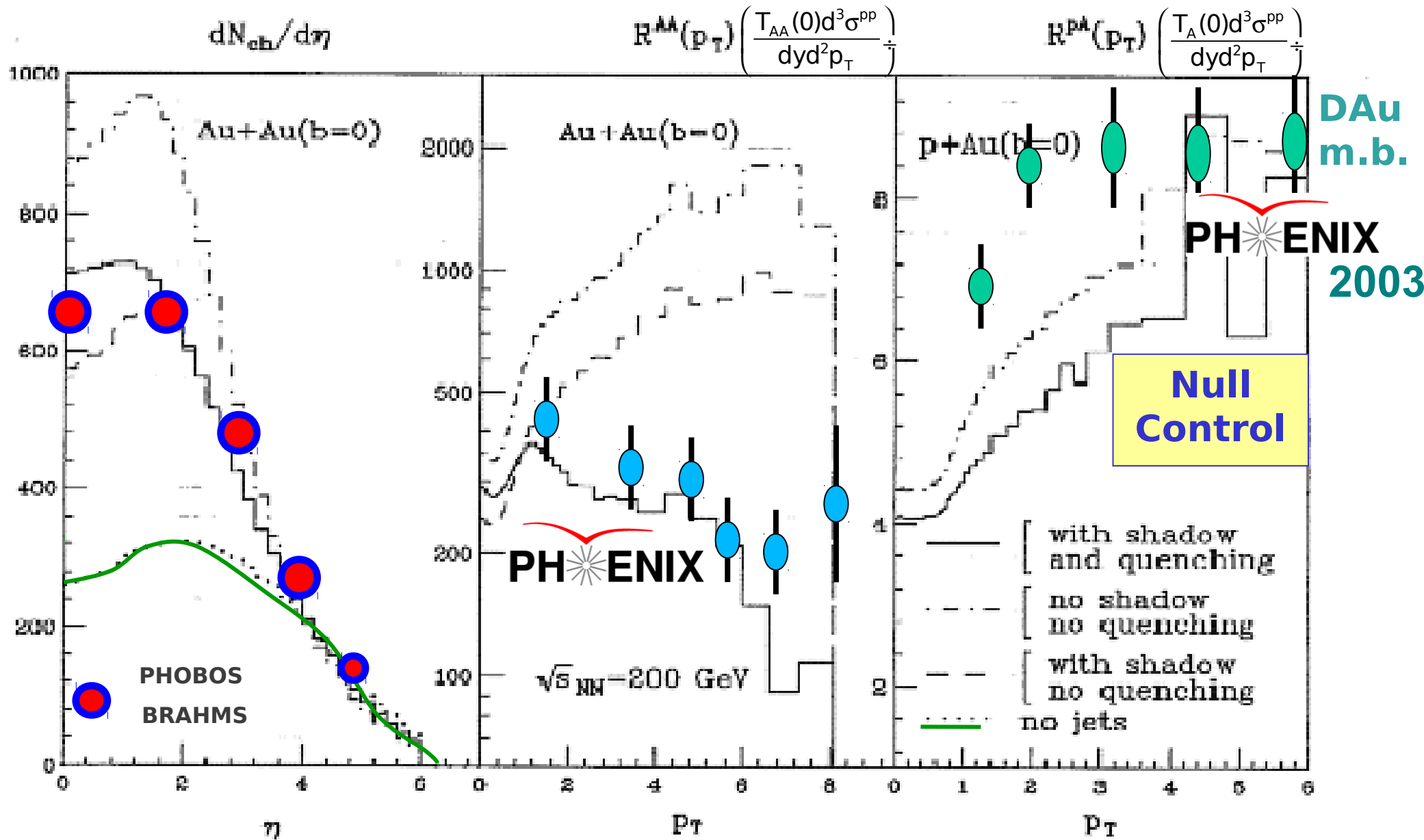


Figure from Brodsky, Gunion, Kuhn 1977

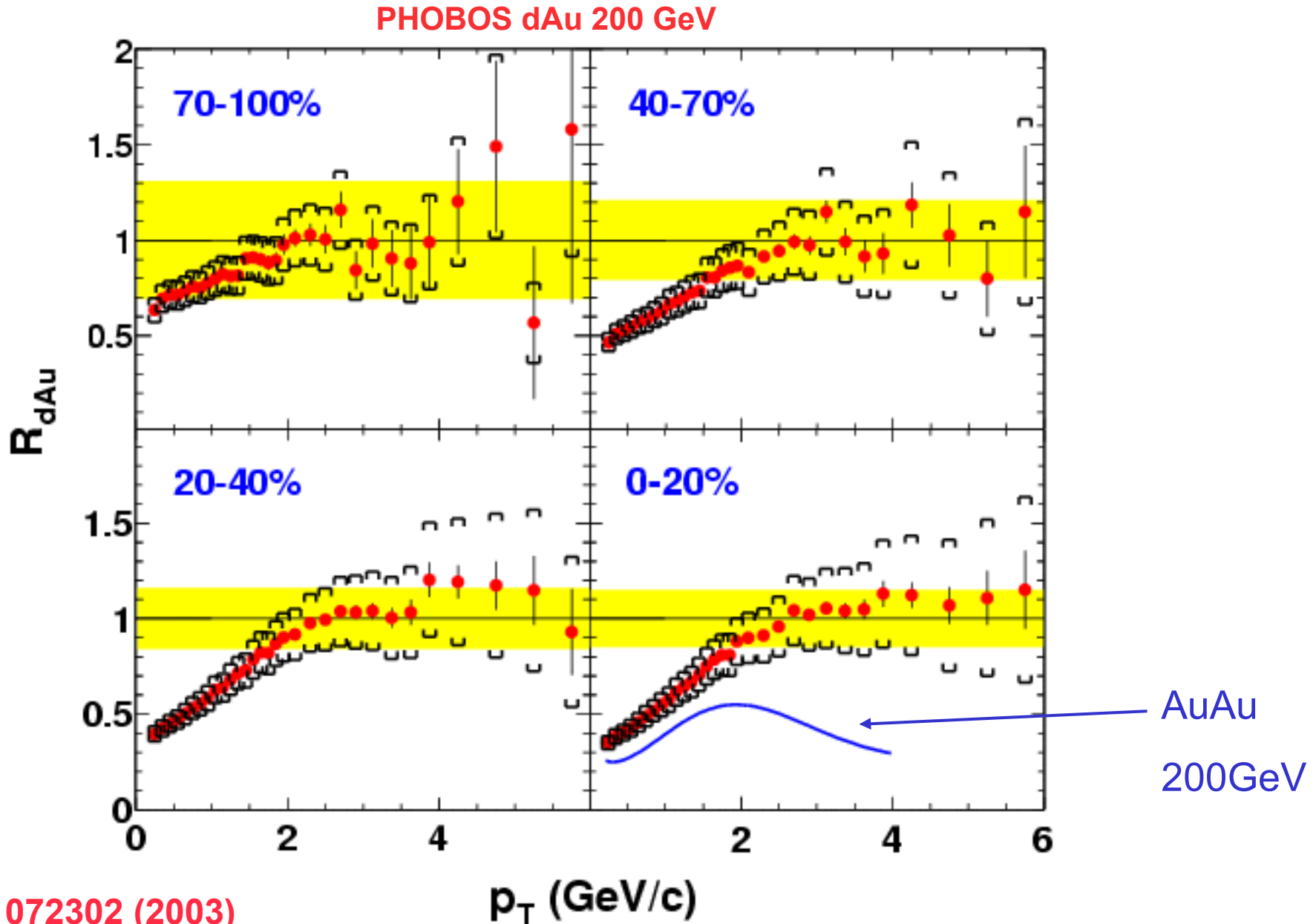


Null Control with p+A @ RHIC was critical to prove that $R_{AA} \sim 0.2$ Was due to final state jet quenching (not to initial state shadow)

Evidence from the suppression of high- p_T particles:

[in central AA but not in D+A]

W.Busza, RBRC 4/15/2004



PRL 91, 072302 (2003)

M Gyulassy F