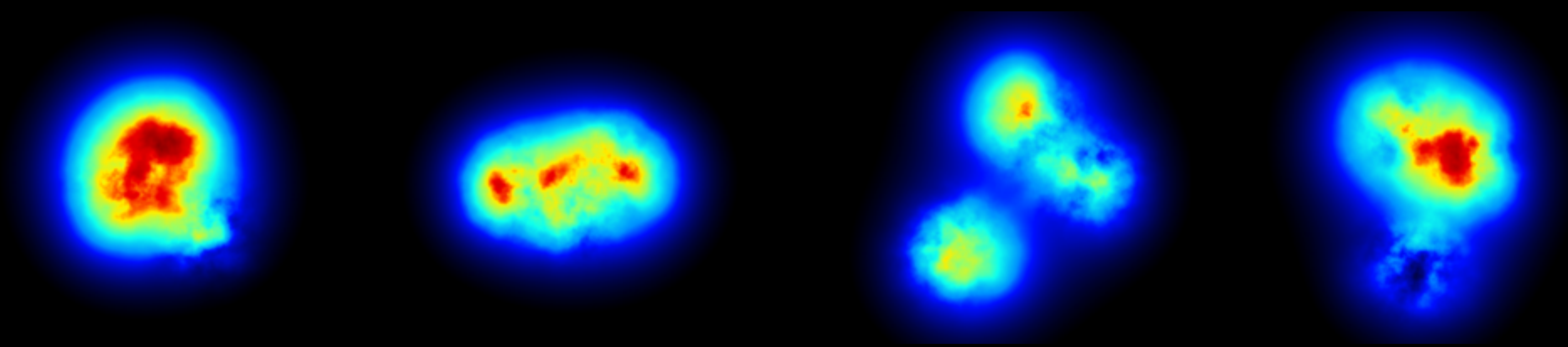
RELATIVISTIC HYDRODYNAMICS: GOING SMALL AND GOING FORWARD

Björn Schenke
Brookhaven National Laboratory



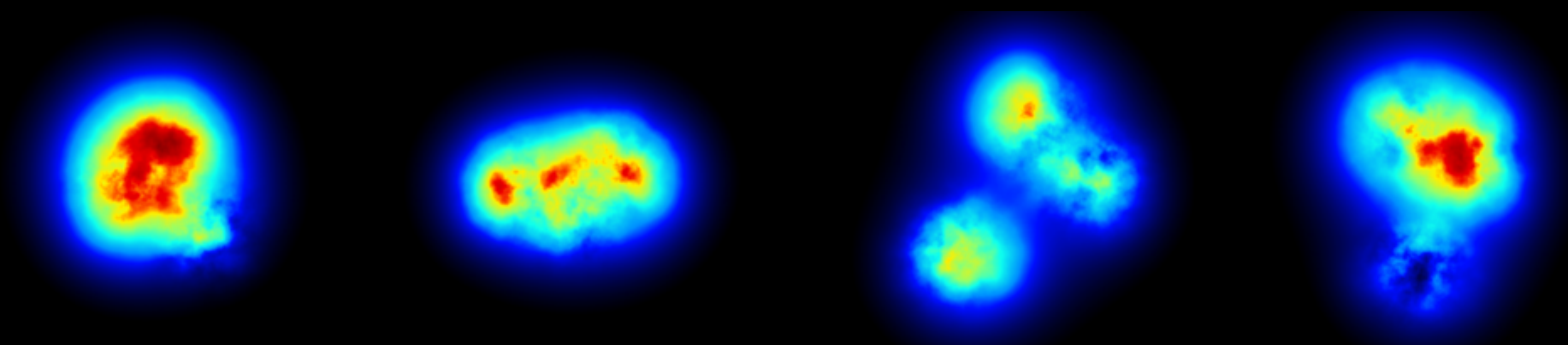
October 10, 2016
Relativistic Hydrodynamics: Theory and Modern Applications
Mainz Institute for Theoretical Physics
Johannes Gutenberg University

U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

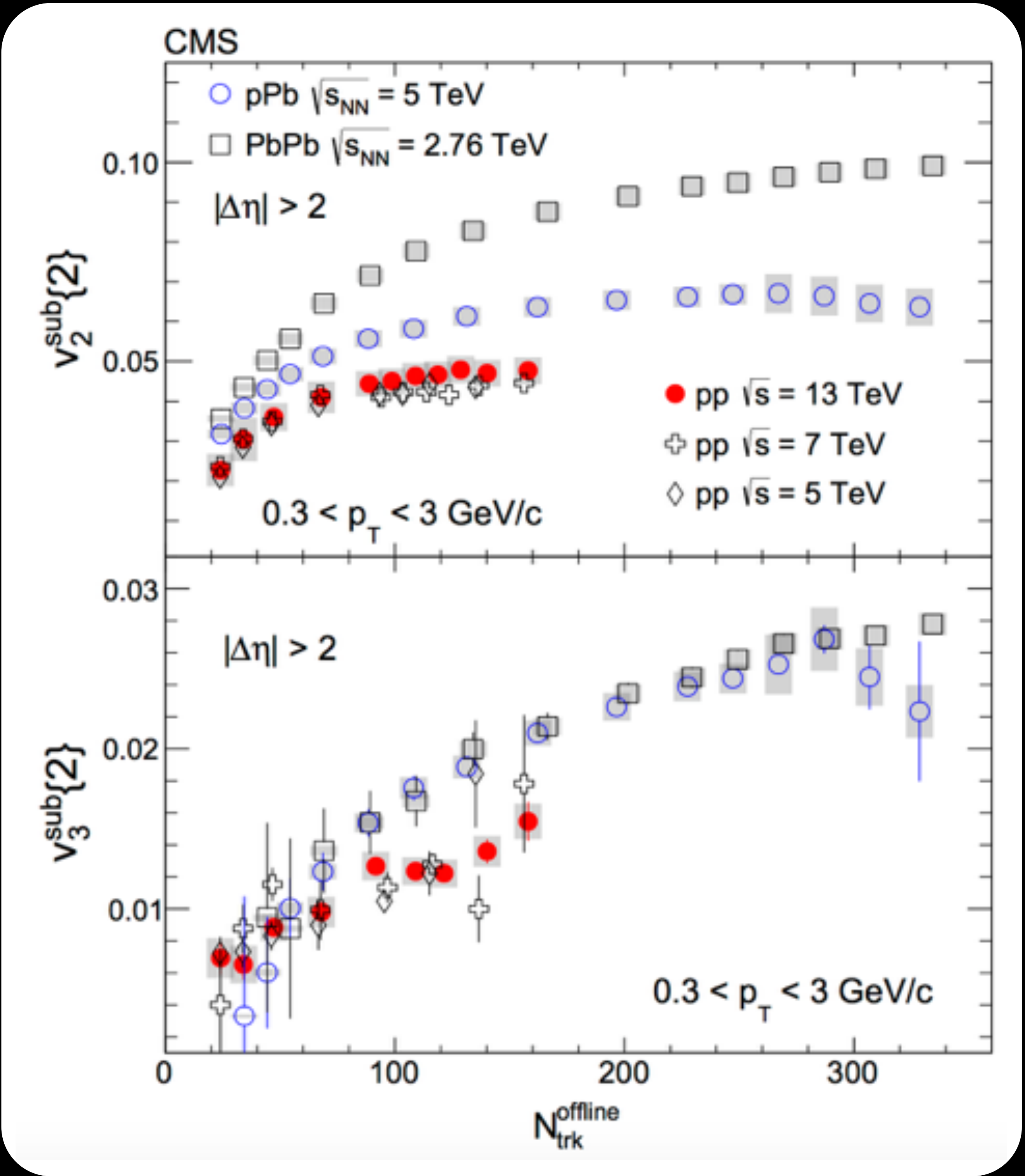
RELATIVISTIC HYDRODYNAMICS: **GOING SMALL** AND GOING FORWARD

Björn Schenke
Brookhaven National Laboratory



October 10, 2016
Relativistic Hydrodynamics: Theory and Modern Applications
Mainz Institute for Theoretical Physics
Johannes Gutenberg University

v_n IN p+p, p+Pb, Pb+Pb COLLISIONS



CMS COLLABORATION, ARXIV:1606.06198

SEE ALSO:

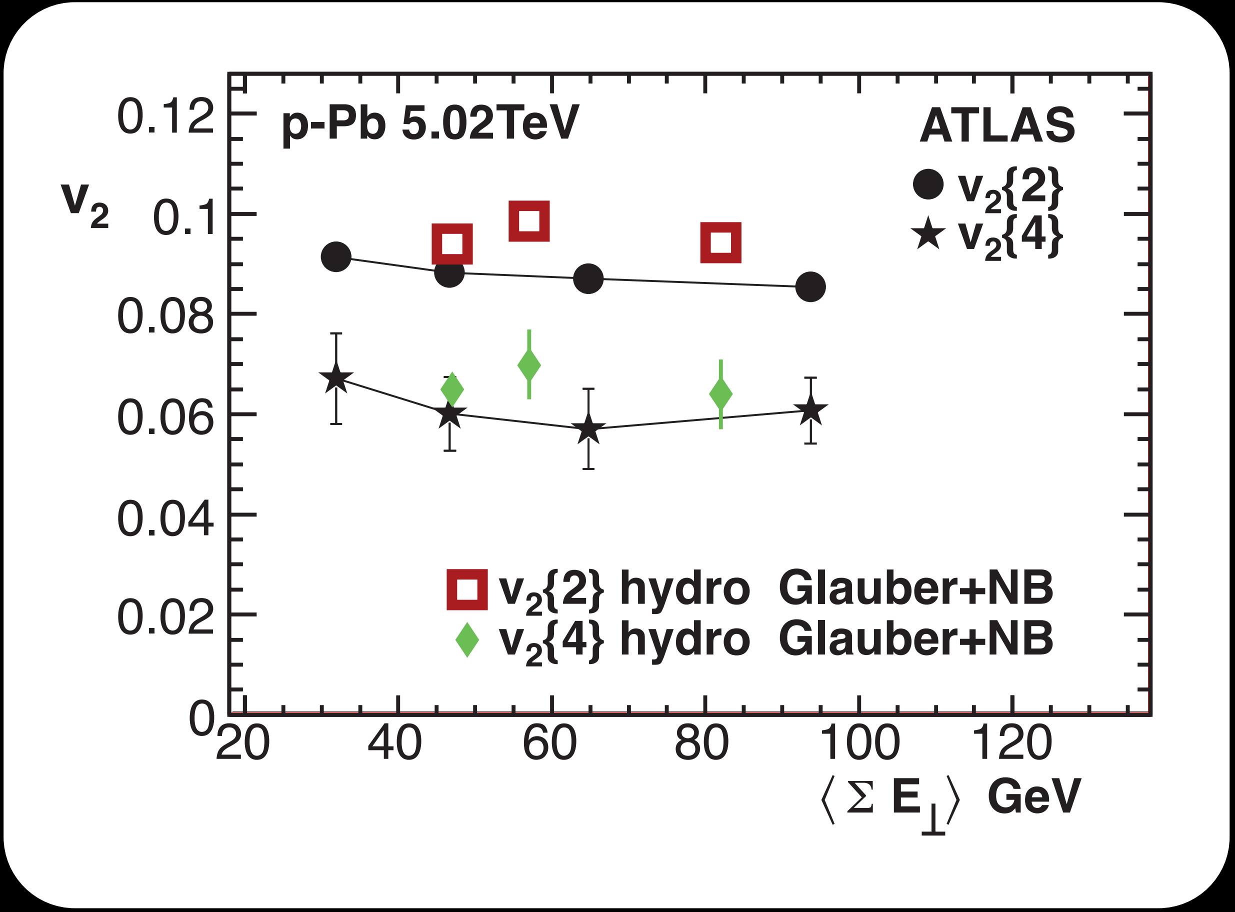
ALICE COLLABORATION
PHYS. LETT. B719 (2013) 29-41; PHYS. REV. C 90, 054901

ATLAS COLLABORATION
PHYS. REV. LETT. 110, 182302 (2013); PHYS. REV. C 90.044906 (2014)

CMS COLLABORATION
PHYS.REV.LETT. 115, 012301 (2015)

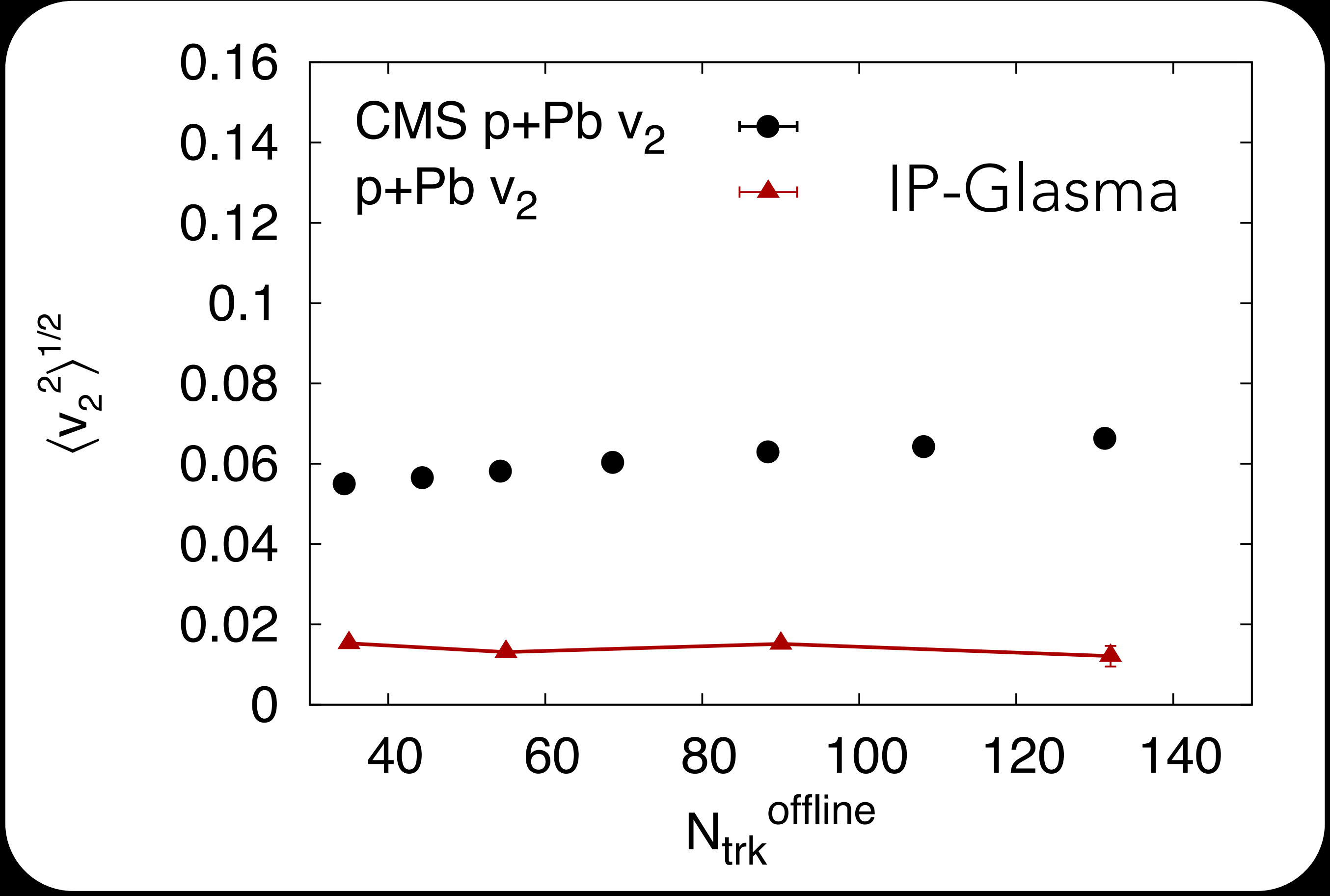
STRONG FINAL STATE EFFECTS IN SMALL SYSTEMS? EVEN HYDRODYNAMICS?

MC-Glauber initial state + hydro works



BOZEK, BRONIOWSKI
PRC88 (2013) 014903

Calculation I showed before does not work in p+Pb



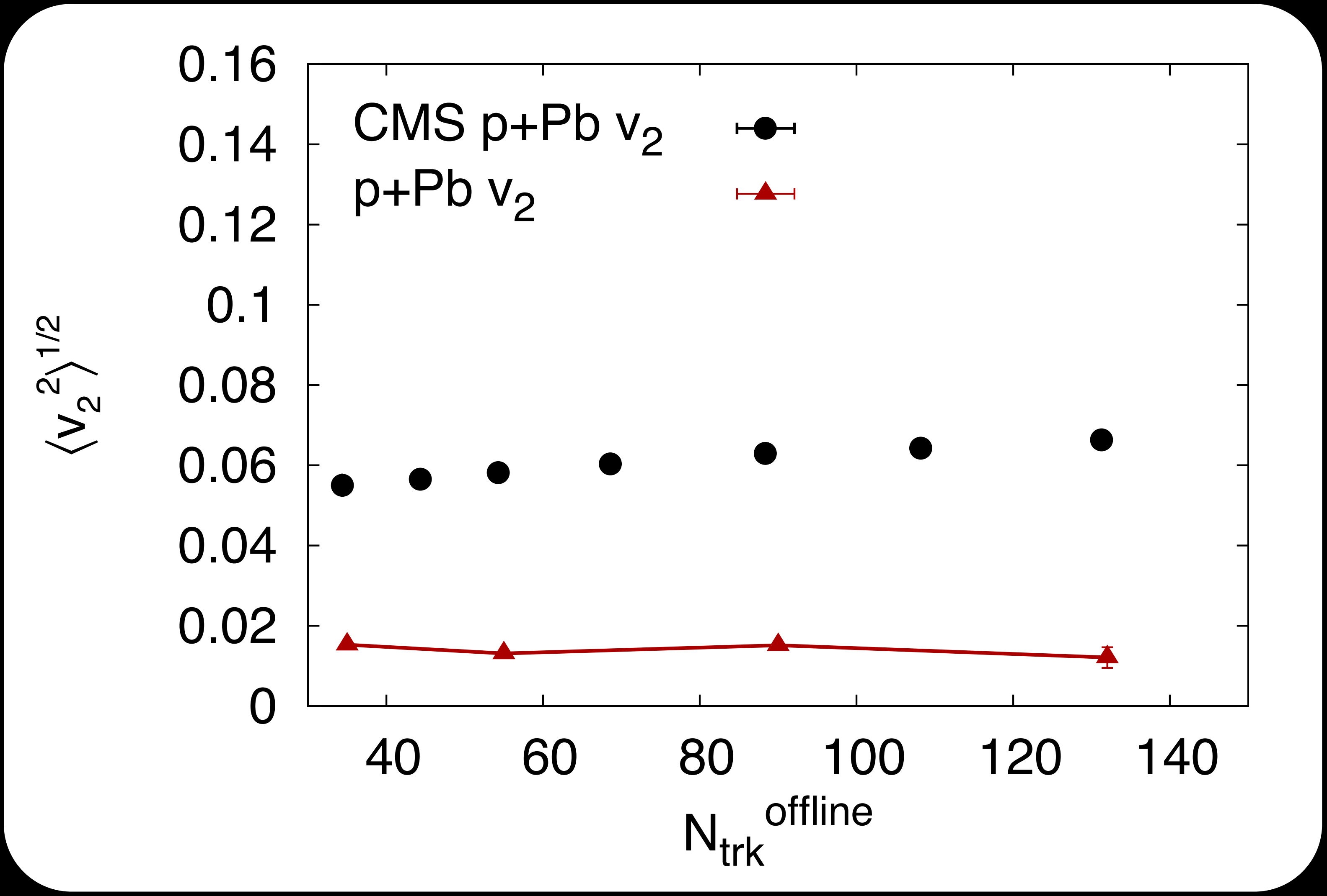
SCHENKE, VENUGOPALAN
PRL113 (2014) 102301

OTHER CALCULATIONS: KOZLOV, LUZUM, DENICOL, JEON, GALE; WERNER, GUIOT, KARPENKO, PIEROG; ROMATSCHKE; SHEN, PAQUET, DENICOL, JEON, GALE ...

STRONG FINAL STATE EFFECTS IN SMALL SYSTEMS? EVEN HYDRODYNAMICS?

B. SCHENKE, R. VENUGOPALAN, PRL113 (2014) 102301

SAME MODEL THAT WORKS WELL IN Pb+Pb FAILS IN p+Pb



DAN COLEN WILE E COYOTE, 2010

SHAPE OF THE SYSTEM FOLLOWS SHAPE OF THE PROTON

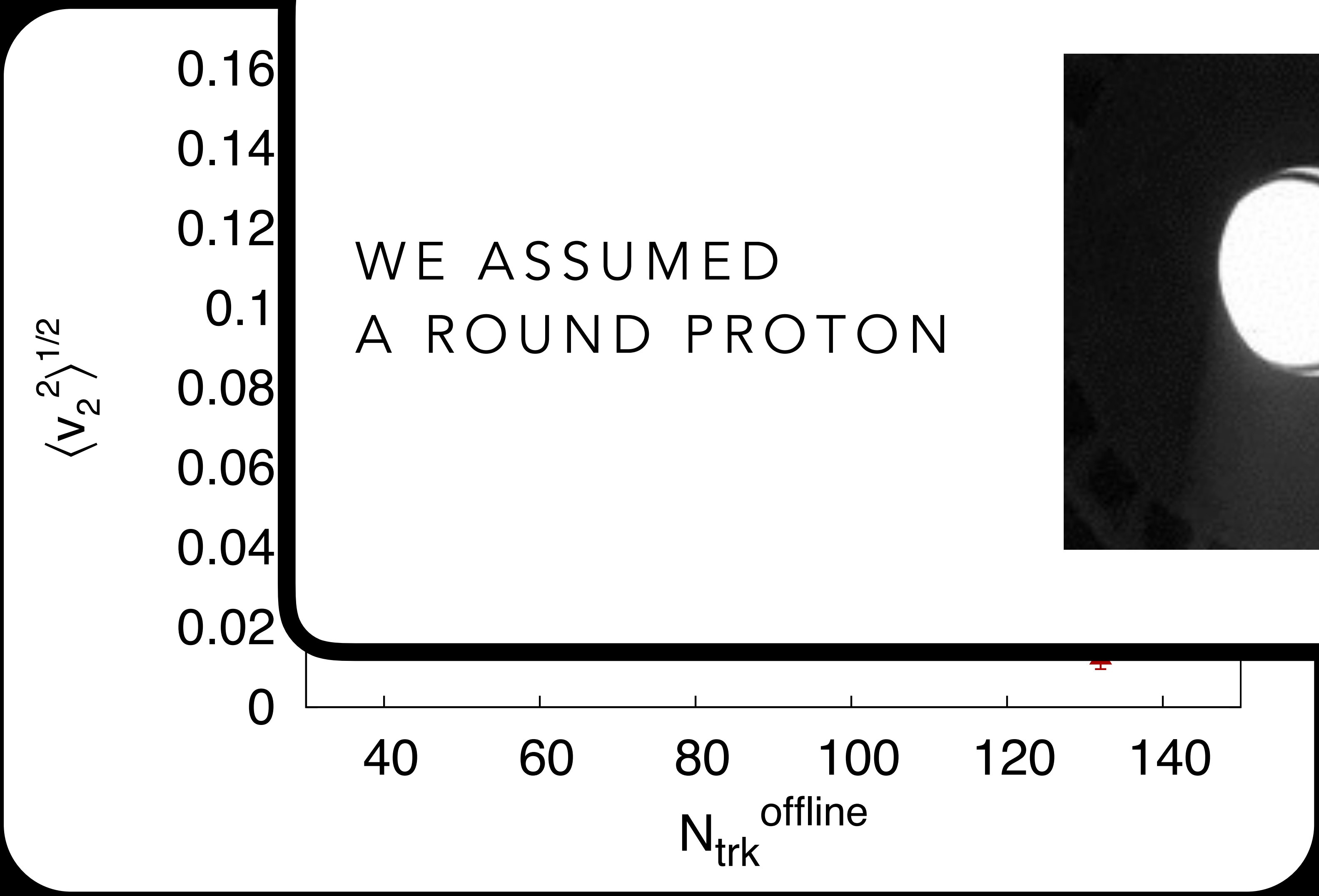
PROTON: WILE E COYOTE

LEAD: WALL

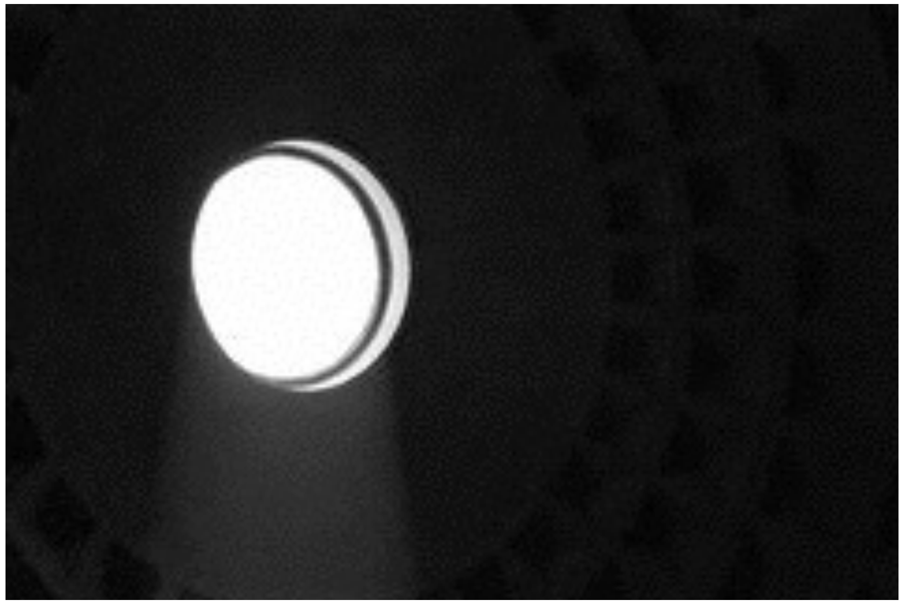
STRONG FINAL STATE EFFECTS IN SMALL SYSTEMS? EVEN HYDRODYNAMICS?

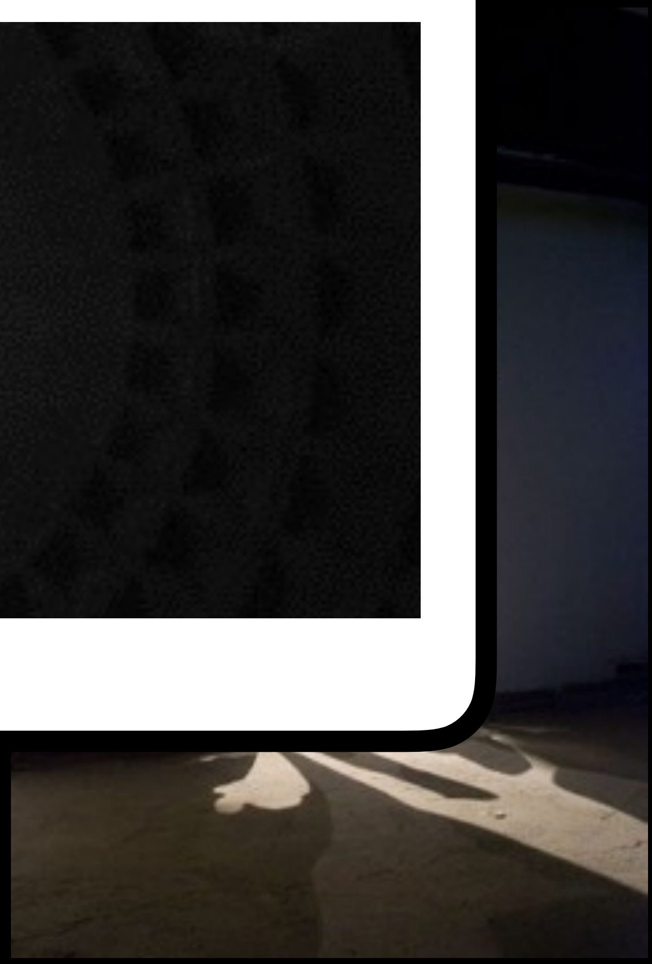
B. SCHENKE, R. VENUGOPALAN, PRL113 (2014) 102301

SAME MODEL THAT WORKS WELL IN Pb+Pb FAILS IN p+Pb



WE ASSUMED
A ROUND PROTON

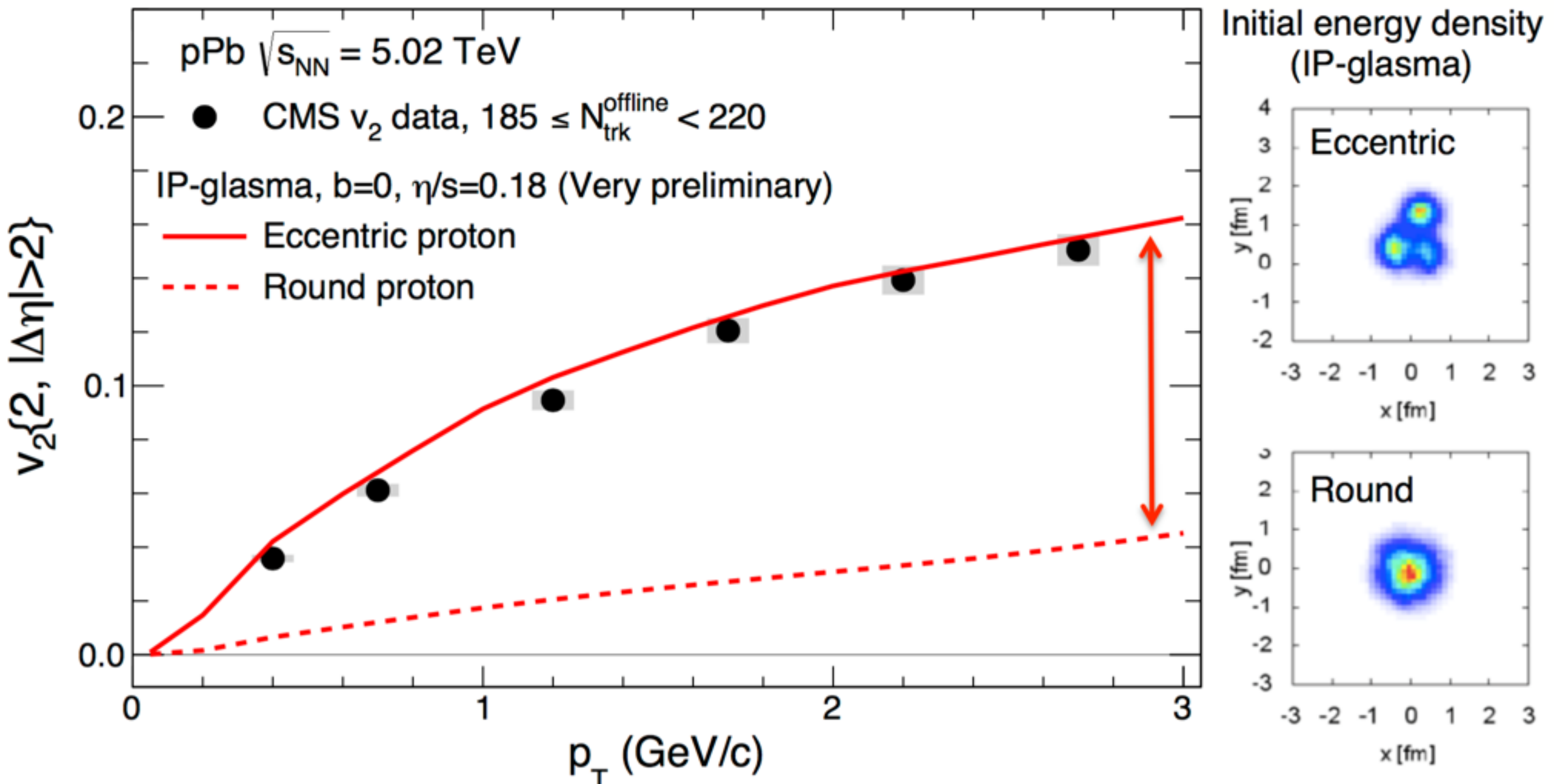




DAN COLEN WILE E COYOTE, 2010

SHAPE OF THE SYSTEM FOLLOWS SHAPE OF THE PROTON
PROTON: WILE E COYOTE
LEAD: WALL

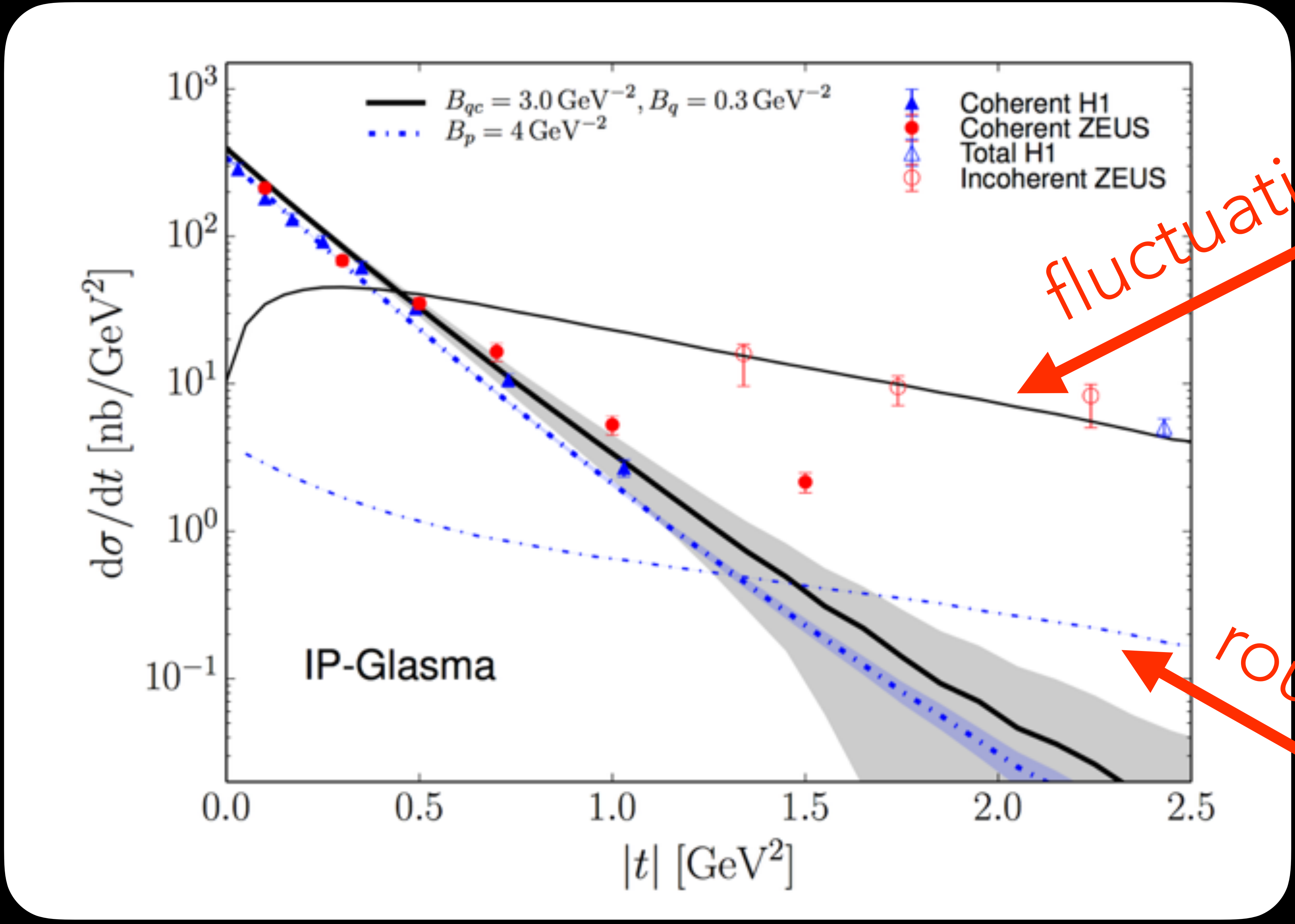
WITH FLUCTUATING PROTON IP-GLASMA RESULT CHANGES DRAMATICALLY

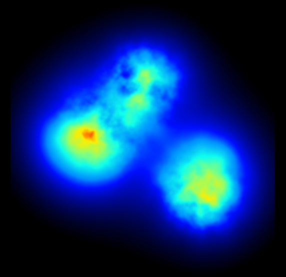


MORE EVIDENCE FOR PROTON SHAPE FLUCTUATIONS

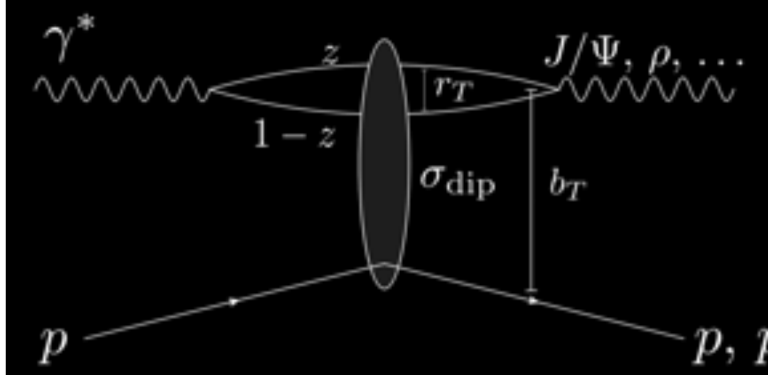
H. MÄNTYSAARI, B. SCHENKE, PHYS. REV. LETT. 117, 052301 (2016)

Exclusive diffractive J/Ψ production

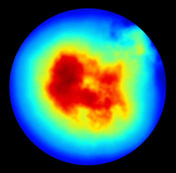




fluctuating proton

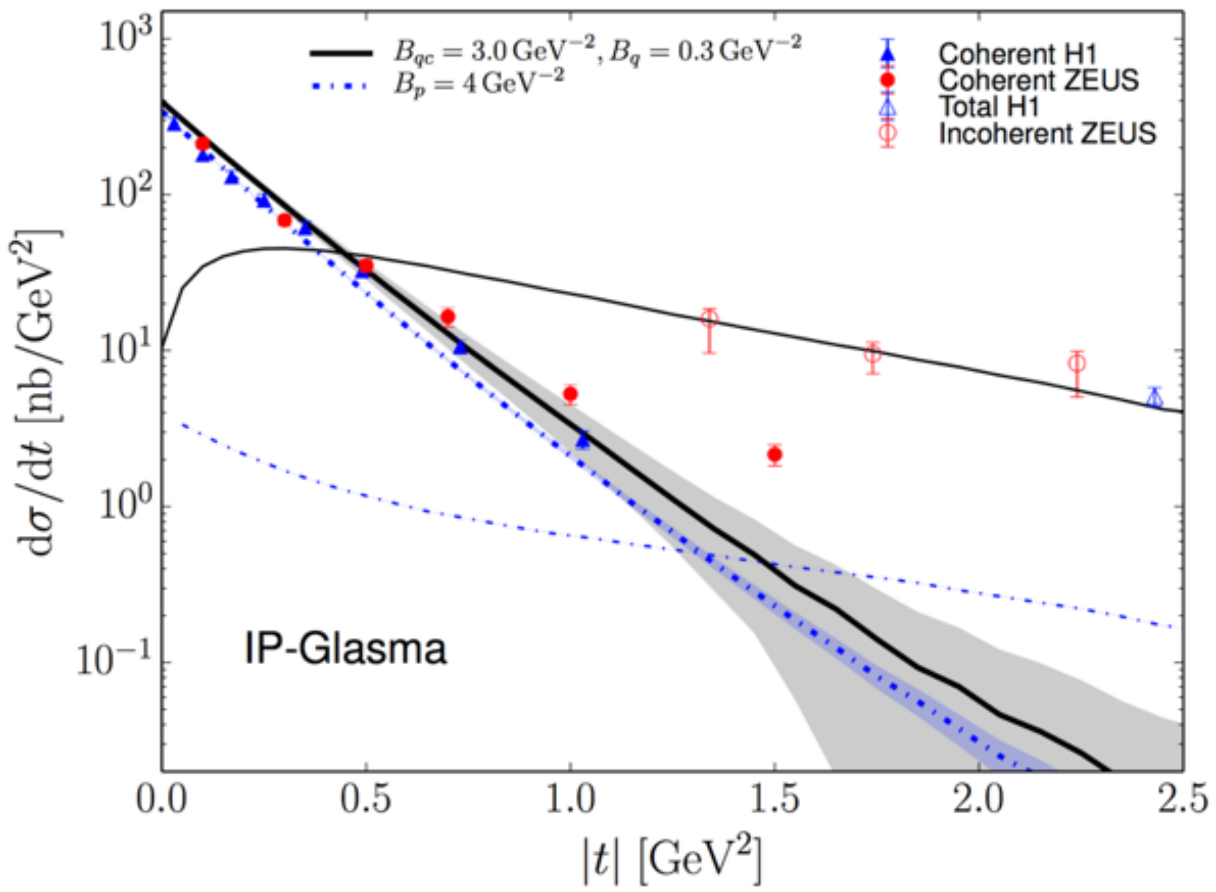


round proton

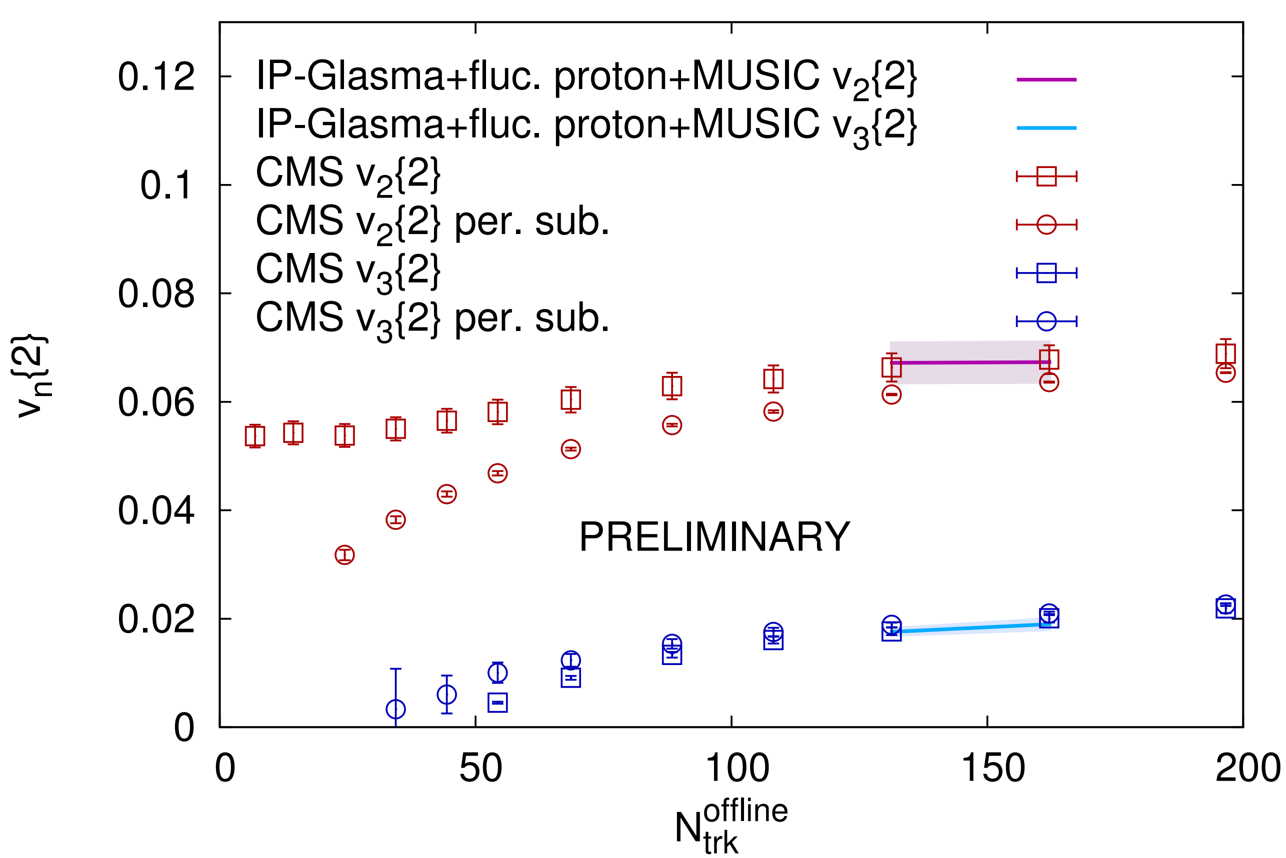


STRATEGY: CONSTRAIN PROTON FLUCTUATIONS WITH J/Ψ PRODUCTION AND PREDICT FLOW IN p+Pb COLLISIONS

H. MÄNTYSAARI, P. TRIBEDY, B. SCHENKE, IN PREPARATION



Use constrained proton to predict v_2 in p+Pb collisions

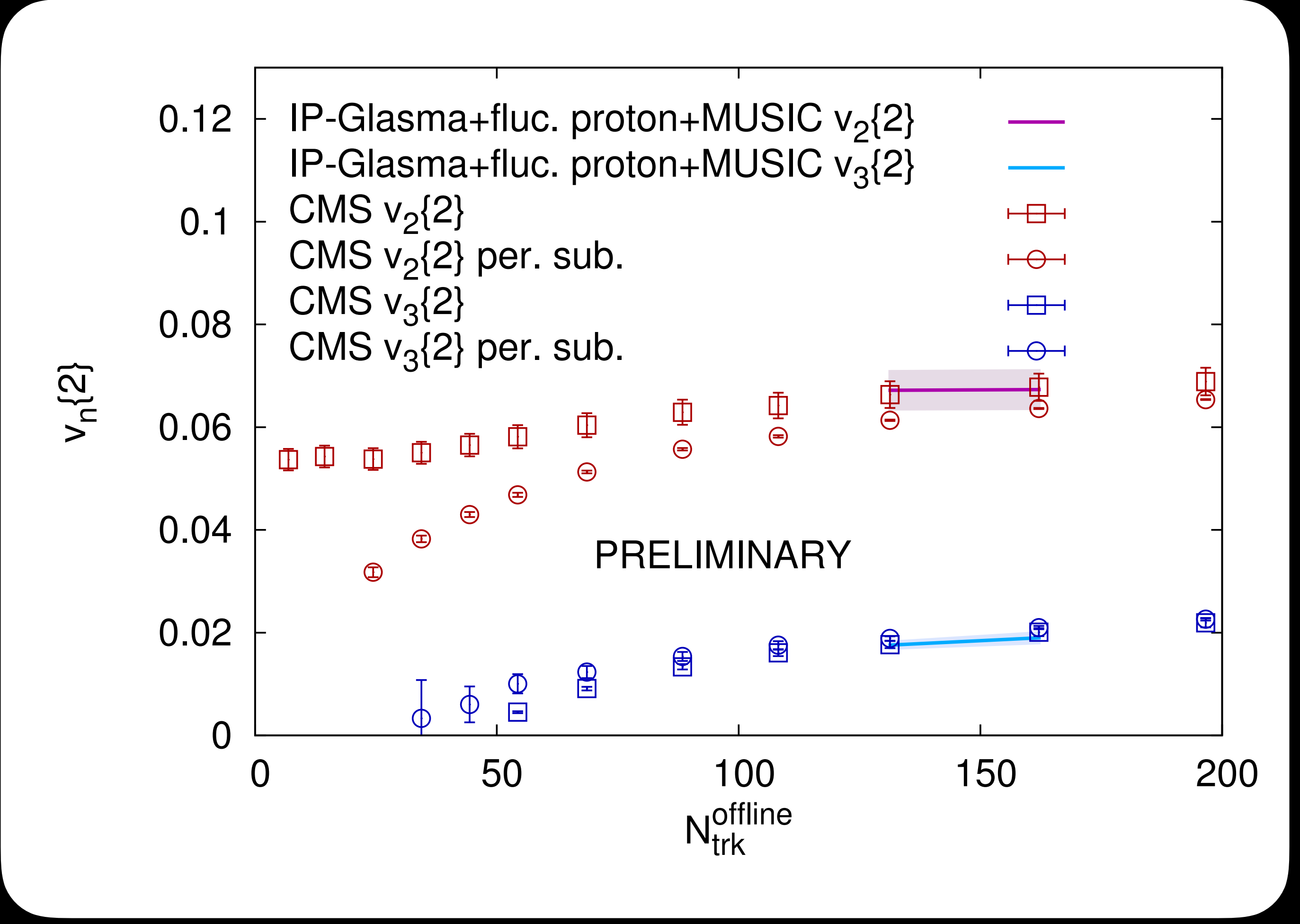


Temperature dependent η/s constrained in A+A collisions

G. DENICOL, A. MONNAI, B. SCHENKE
PHYS.REV.LETT. 116 (2016) NO.21, 212301

BUT: RESULTS ARE VERY SENSITIVE TO ALL THE DETAILS!

which is the subject of this talk



used τ_0=1 fm here, no initial $\pi^{\mu\nu}$

SIGNIFICANCE OF INITIAL STATE IN SMALL SYSTEMS

Lifetime in small systems is shorter than in typical A+A event

Details of the initial state matter more:

- Initial/switching time
- Initial flow
- Initial viscous stress tensor
- Possibly the details of matching

Will analyze various effects in one typical p+A event using the IP-Glasma initial state model and MUSIC hydrodynamics

Björn Schenke, BNL

VISCOUS STRESS IN THE INITIAL STATE

We have always neglected the initial $\pi^{\mu\nu}$ from the IP-Glasma

But of course it is there - In p+A it is likely very big

Further there is a u^{η}, flow in the rapidity direction, that also needs to be included

Finally one can define bulk stress as $\Pi = \frac{\varepsilon}{3} - P$ using *P* from the EoS in hydrodynamics to match to all components of the CYM $T^{\mu\nu}$

This last part has a small effect.

$\pi^{\mu\nu}$ FROM THE IP-GLASMA

Determine ε and u^μ from

$$\varepsilon u^\nu = u_\mu T^{\mu\nu}$$

then, using $P=\varepsilon/3$
(it would be, had we reached isotropy in the CYM system):

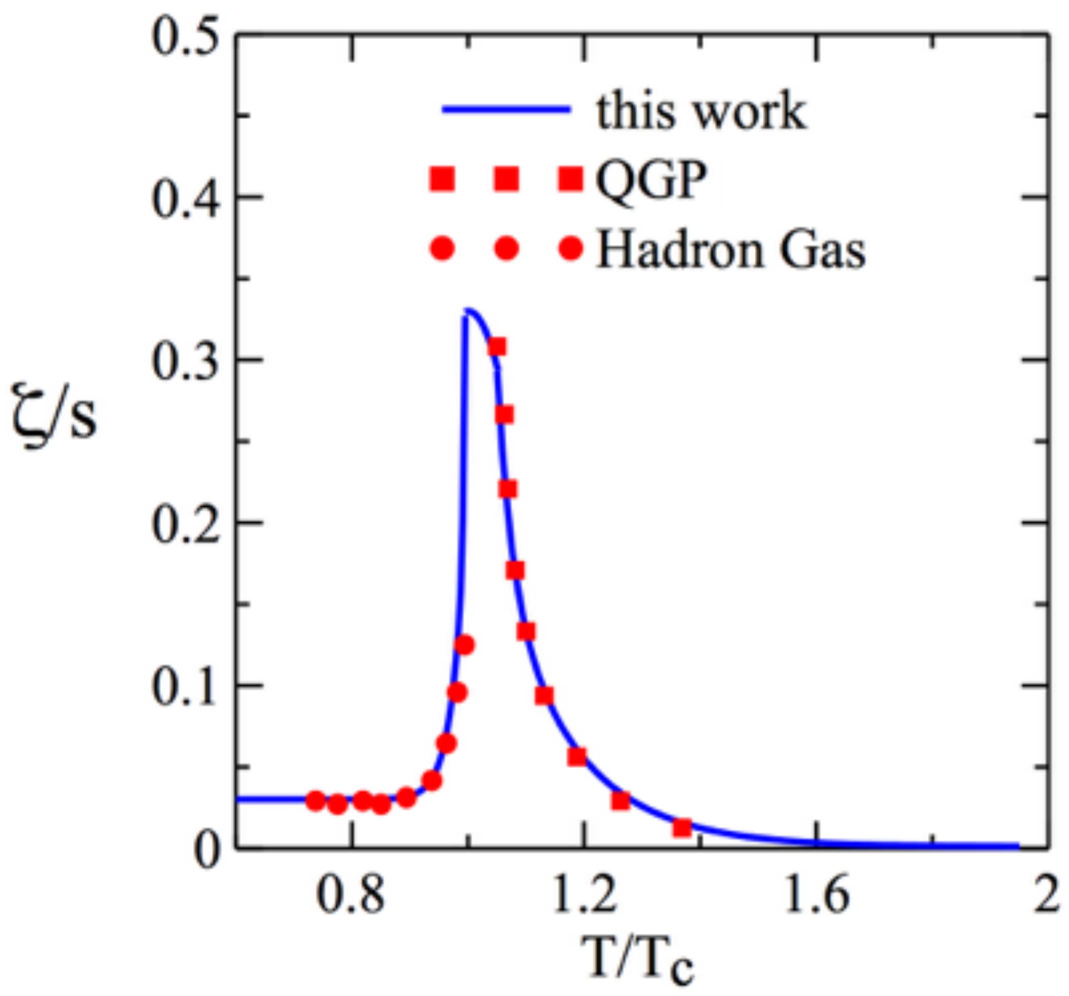
$$\pi^{\mu\nu} = T^{\mu\nu}_{\mathrm{CYM}} - \frac{4}{3}\varepsilon u^\mu u^\nu + \frac{\varepsilon}{3} g^{\mu\nu}$$

This is potentially quite large

Will analyze this in a p+A event. Going to the extreme…

SHEAR AND BULK VISCOSITIES

In the examples we will use
$\eta/s = 0.1$ and a T dependent ζ/s



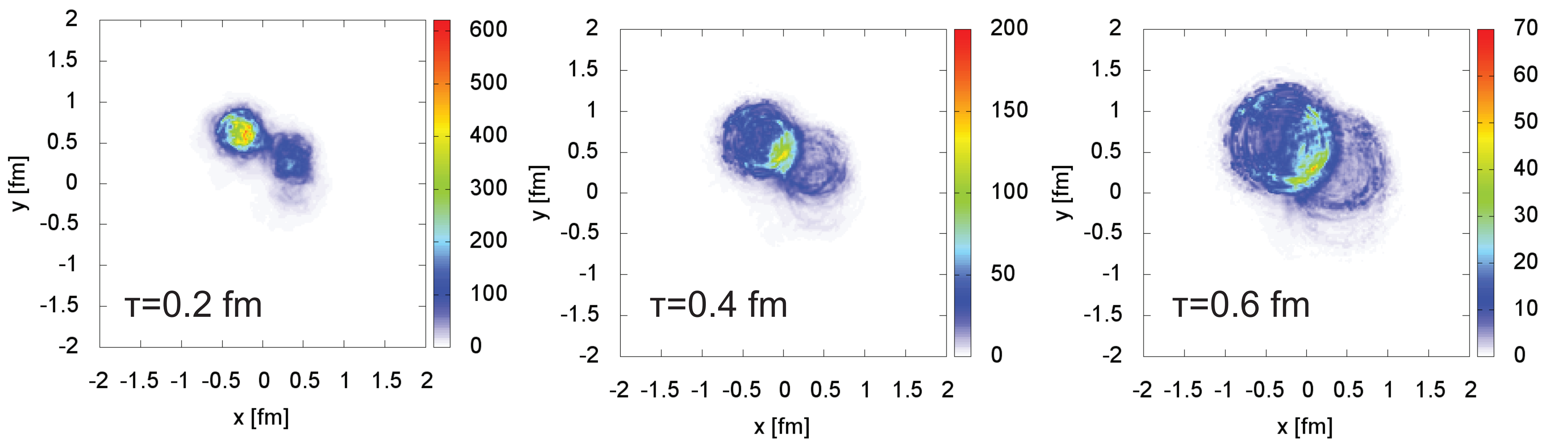
S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol,
B. Schenke, S. Jeon, C. Gale
Phys.Rev.Lett. 115 (2015) 13, 132301

G. S. Denicol, U. W. Heinz, M. Martinez,
J. Noronha and M. Strickland,
Phys. Rev. D 90, 125026 (2014);
Phys. Rev. Lett. 113, 202301 (2014)

QGP: F. Karsch, D. Kharzeev and K. Tuchin,
Phys. Lett. B 663, 217 (2008)
Hadron Gas:
J. Noronha-Hostler, J. Noronha and C. Greiner,
Phys. Rev. Lett. 103, 172302 (2009)

INITIAL DISTRIBUTIONS

Energy densities [GeV/fm^3]

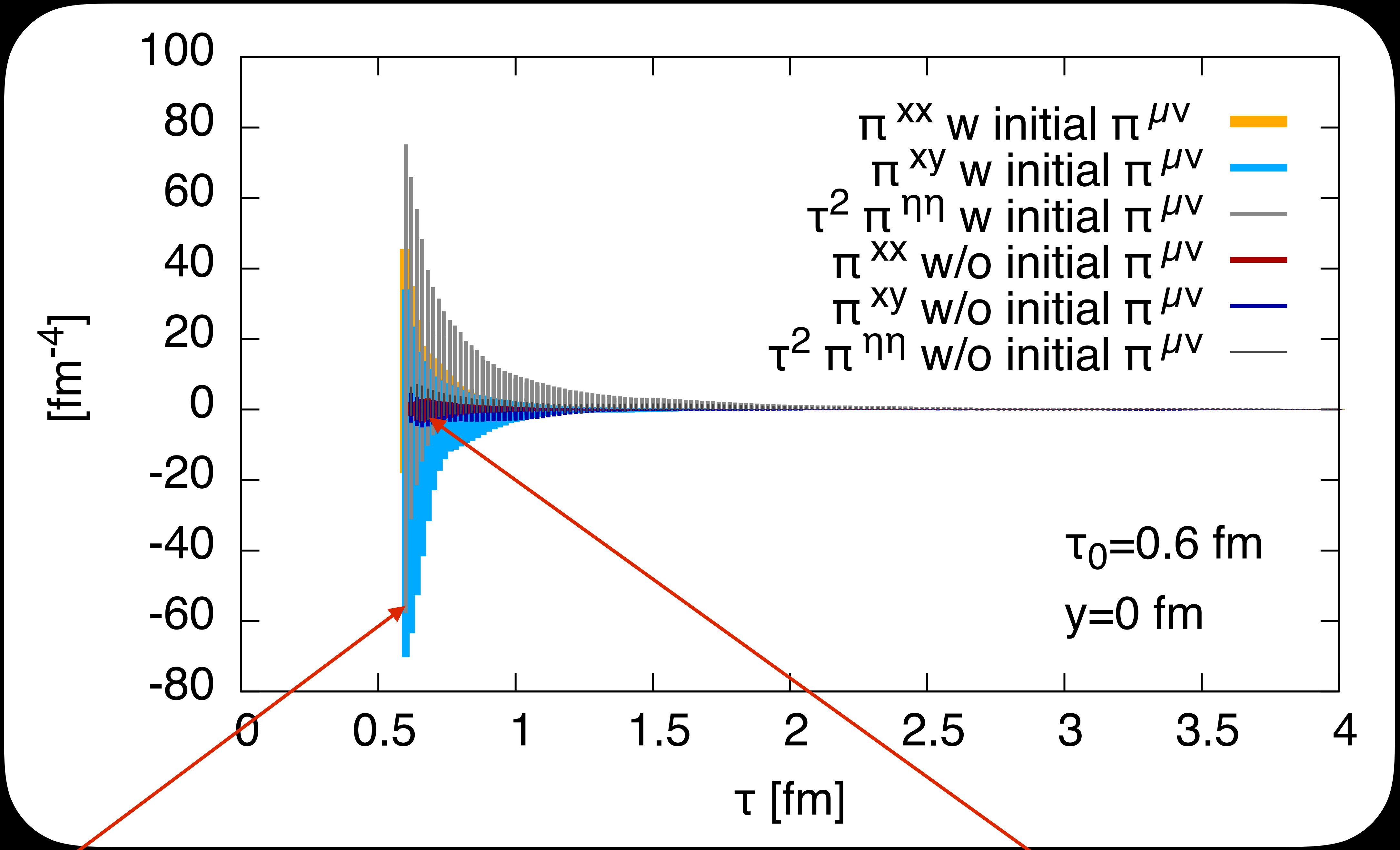


CYM evolution

(~free streaming)

EVOLUTION OF $\pi^{\mu\nu}$

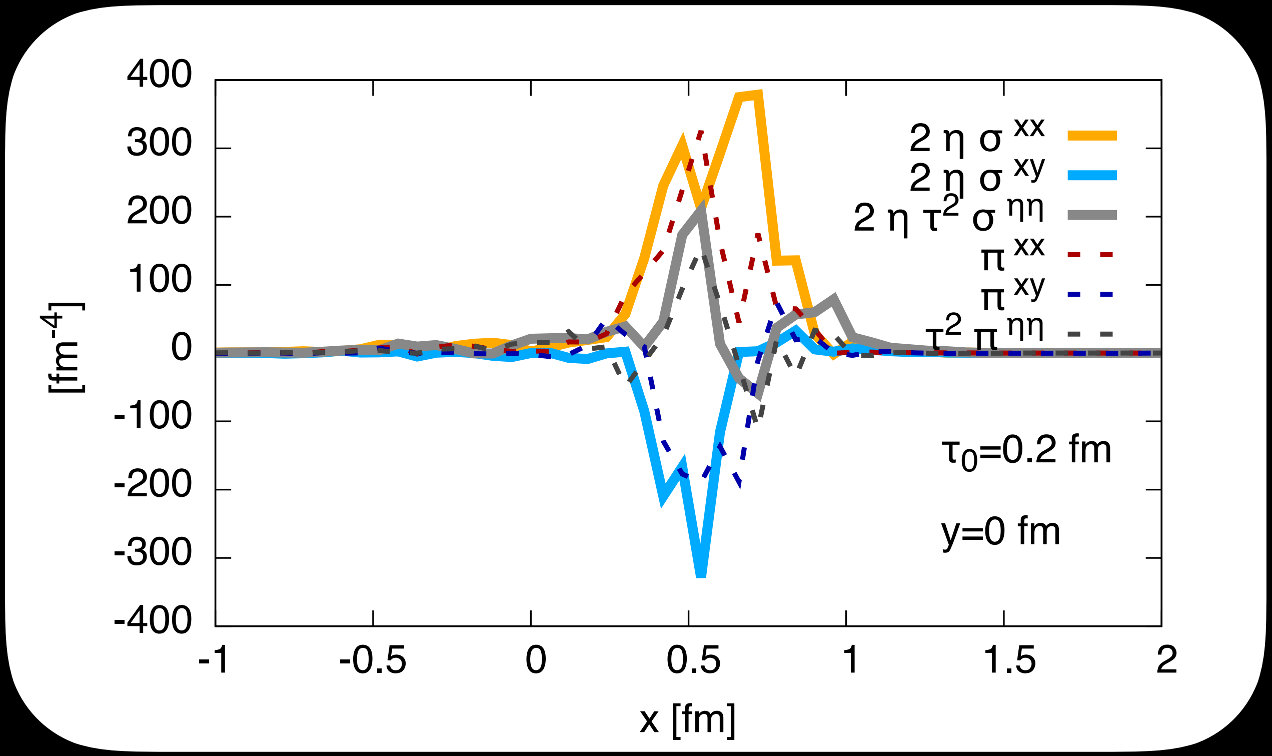
$\eta/s = 0.1$ and T dependent ζ/s



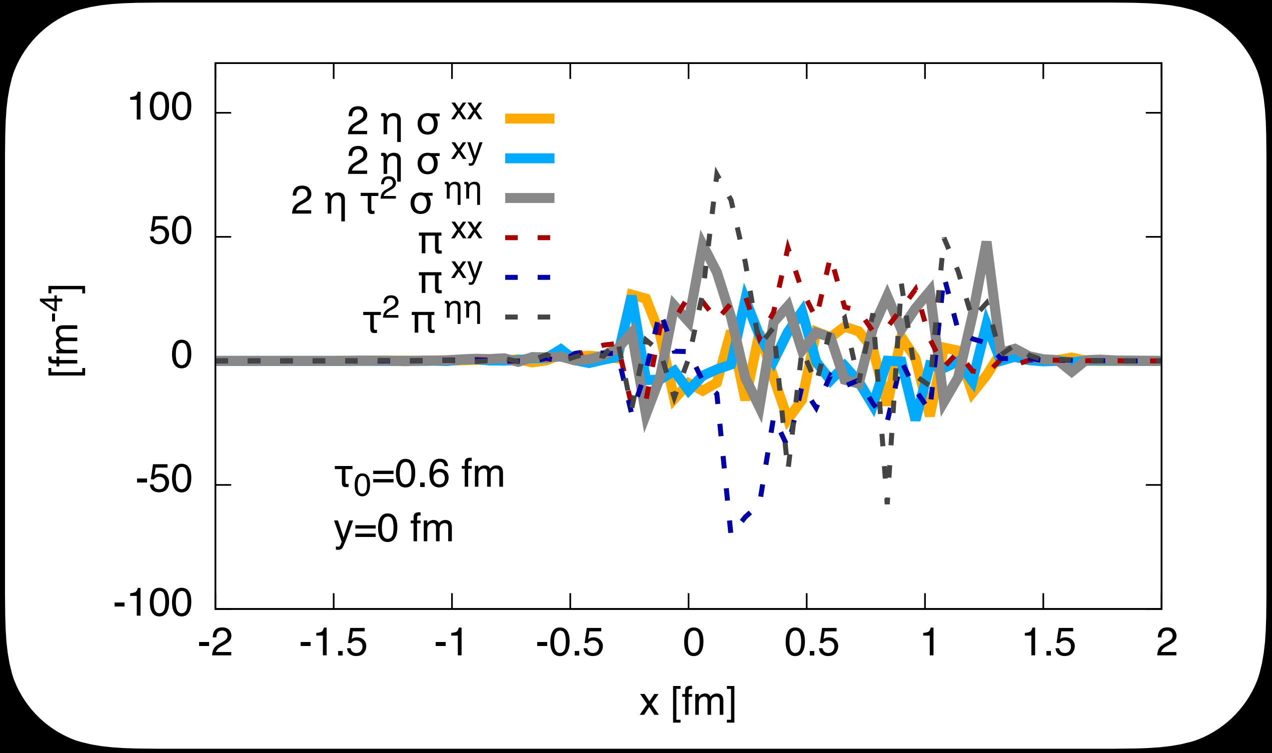
with initial $\pi^{\mu\nu}$

without initial $\pi^{\mu\nu}$

INITIAL IP-GLASMA $\pi^{\mu\nu}$ COMPARED TO INITIAL NAVIER-STOKES VALUE

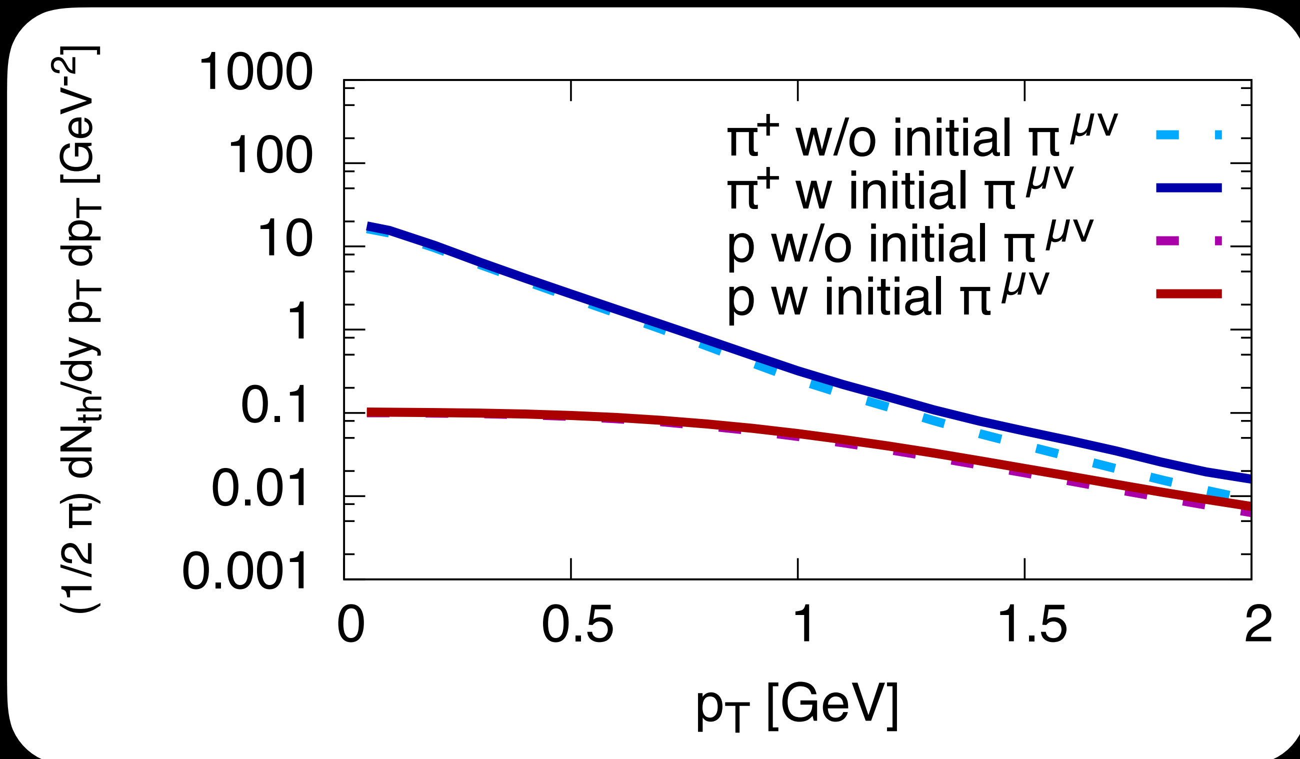


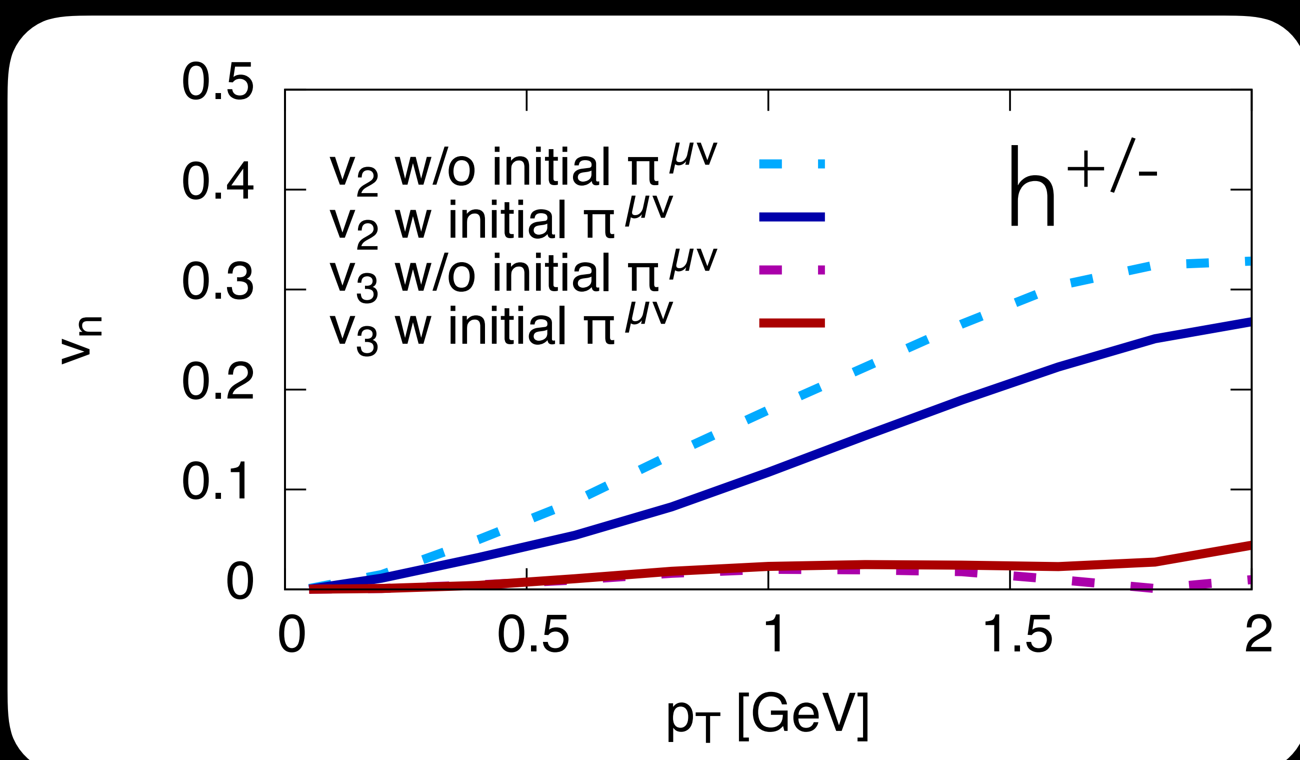
$$\sigma^{\mu\nu} = \nabla^{(\mu}u^{\nu)} - \frac{1}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha$$



Similar magnitude for $\eta/s = 0.1$

EFFECT OF INITIAL $\pi^{\mu\nu}$





Testing in just one event:

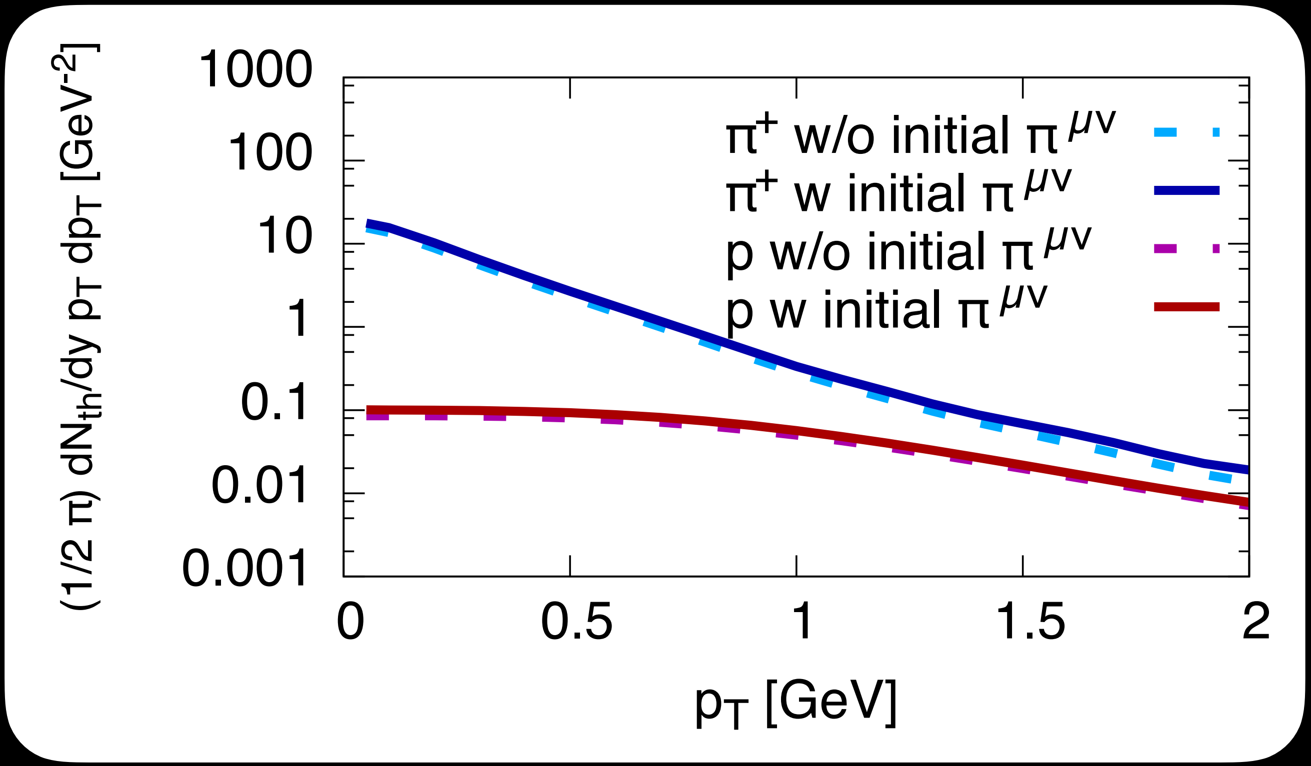
- more entropy production
- different viscous effects

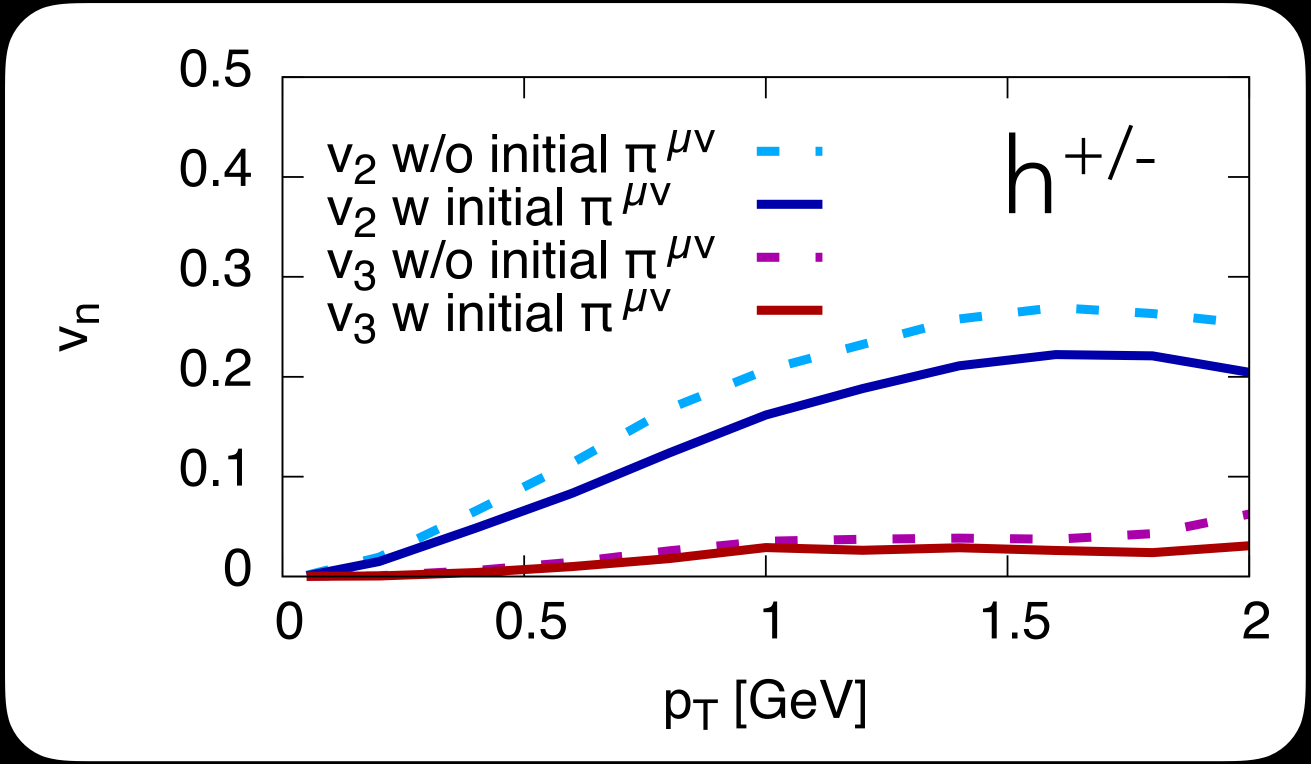
- initial $\pi^{\mu\nu}$ reduces v_2

$$\tau_\pi = 3\frac{\eta}{\varepsilon + P}$$

τ_0=0.6 fm

EFFECT OF INITIAL $\pi^{\mu\nu}$





Testing in just one event:

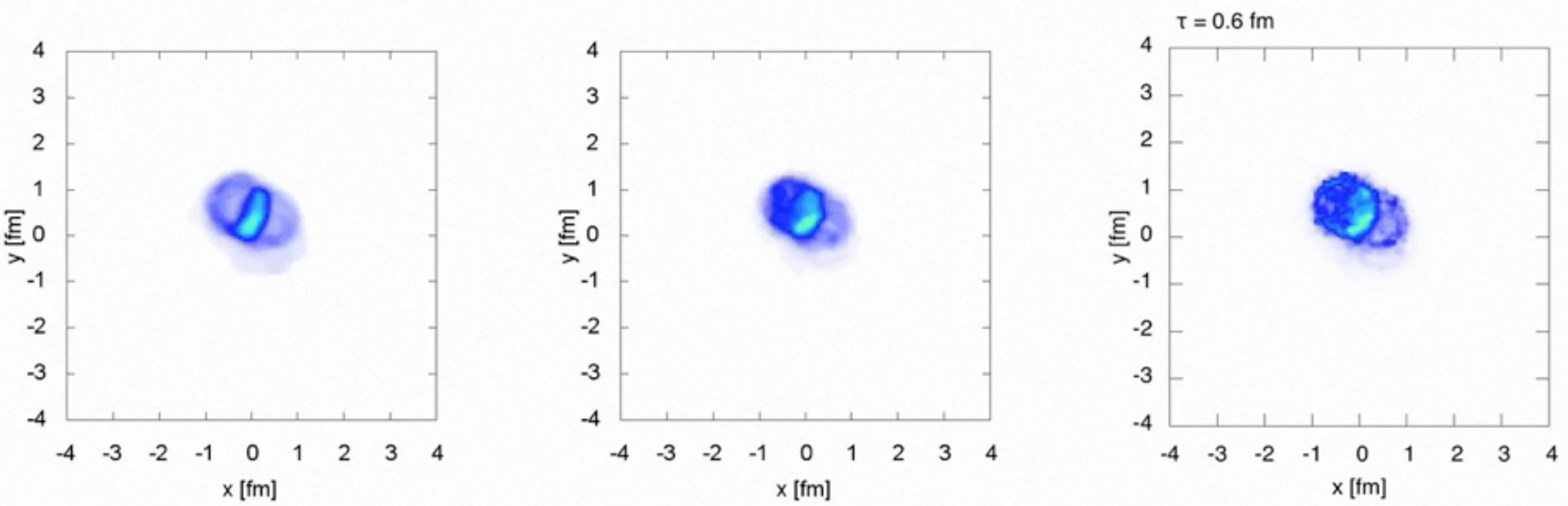
- more entropy production
- different viscous effects

- initial $\pi^{\mu\nu}$ reduces v_2

$$\tau_\pi = 3\frac{\eta}{\varepsilon + P}$$

τ_0=0.4 fm

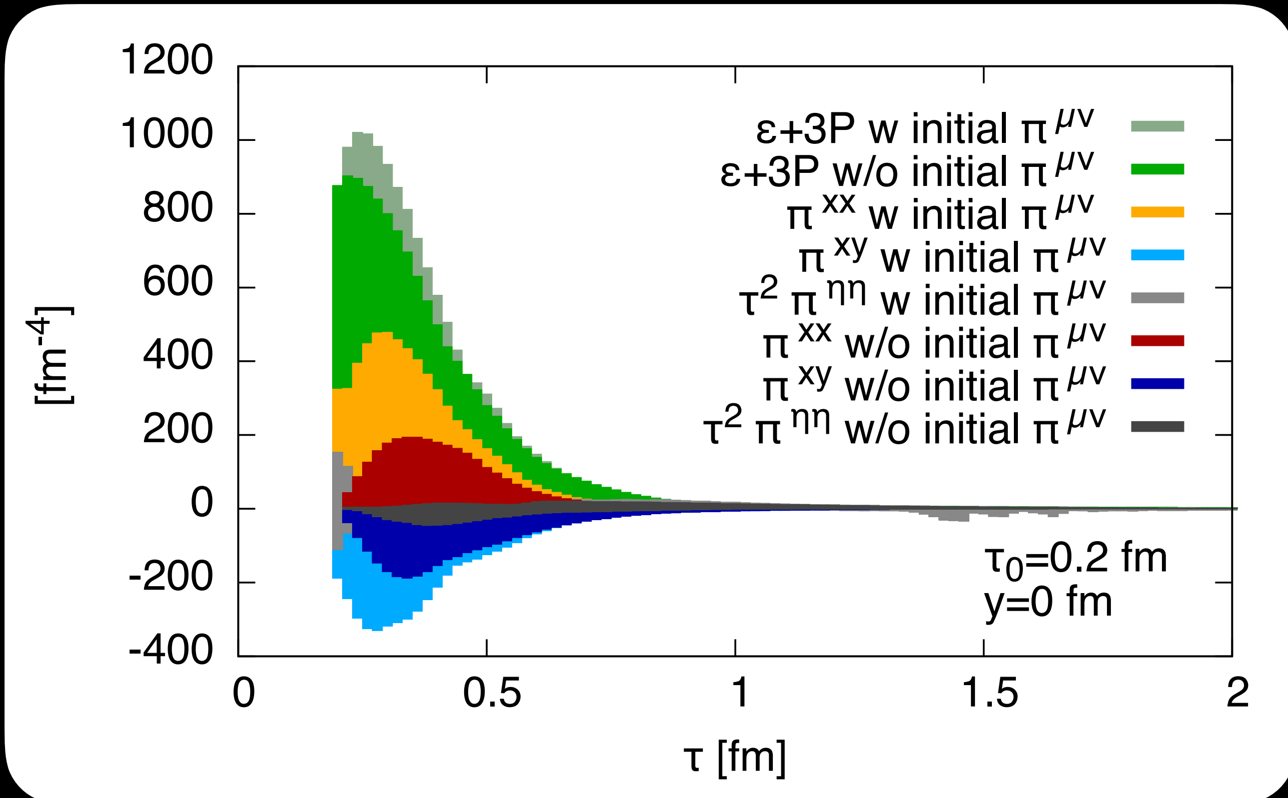
EFFECT OF SWITCHING TIME

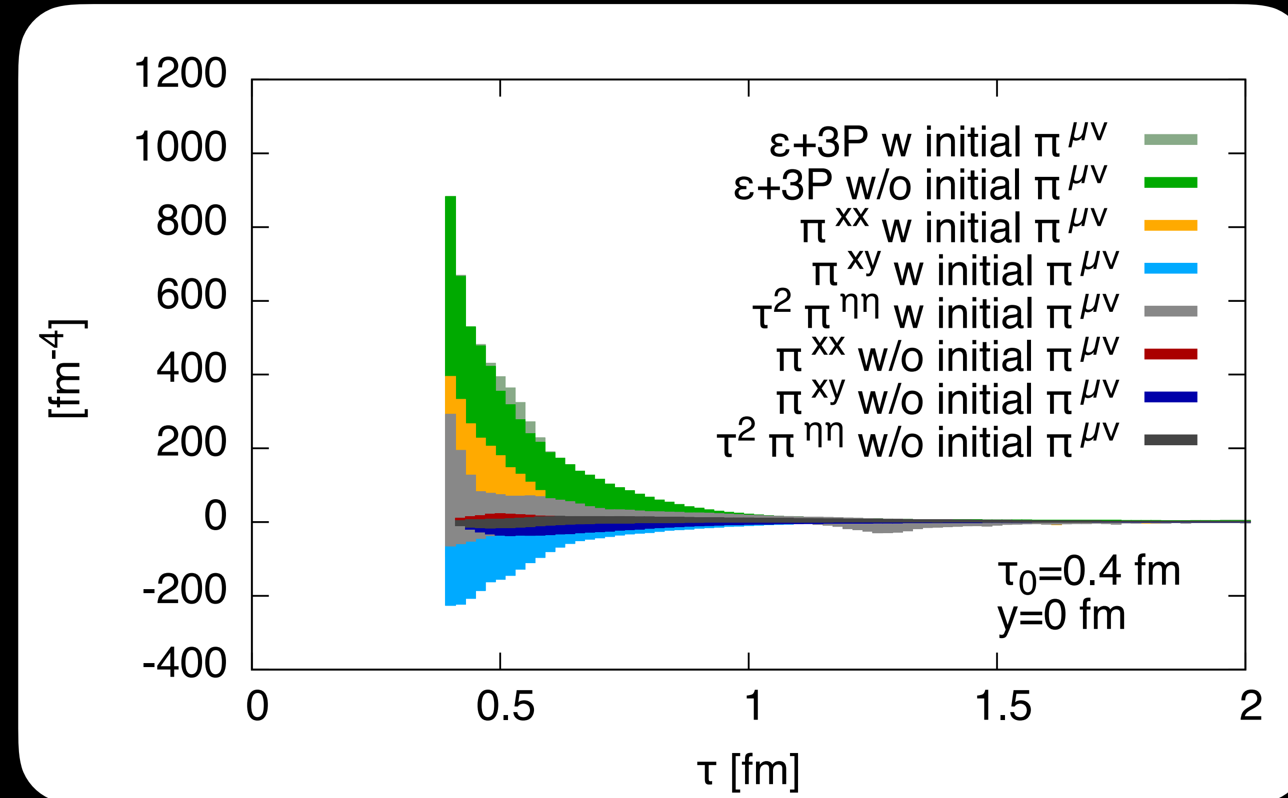


τ_0=0.2 fm τ_0=0.4 fm τ_0=0.6 fm

Björn Schenke, BNL

EVOLUTION OF $\pi^{\mu\nu}$

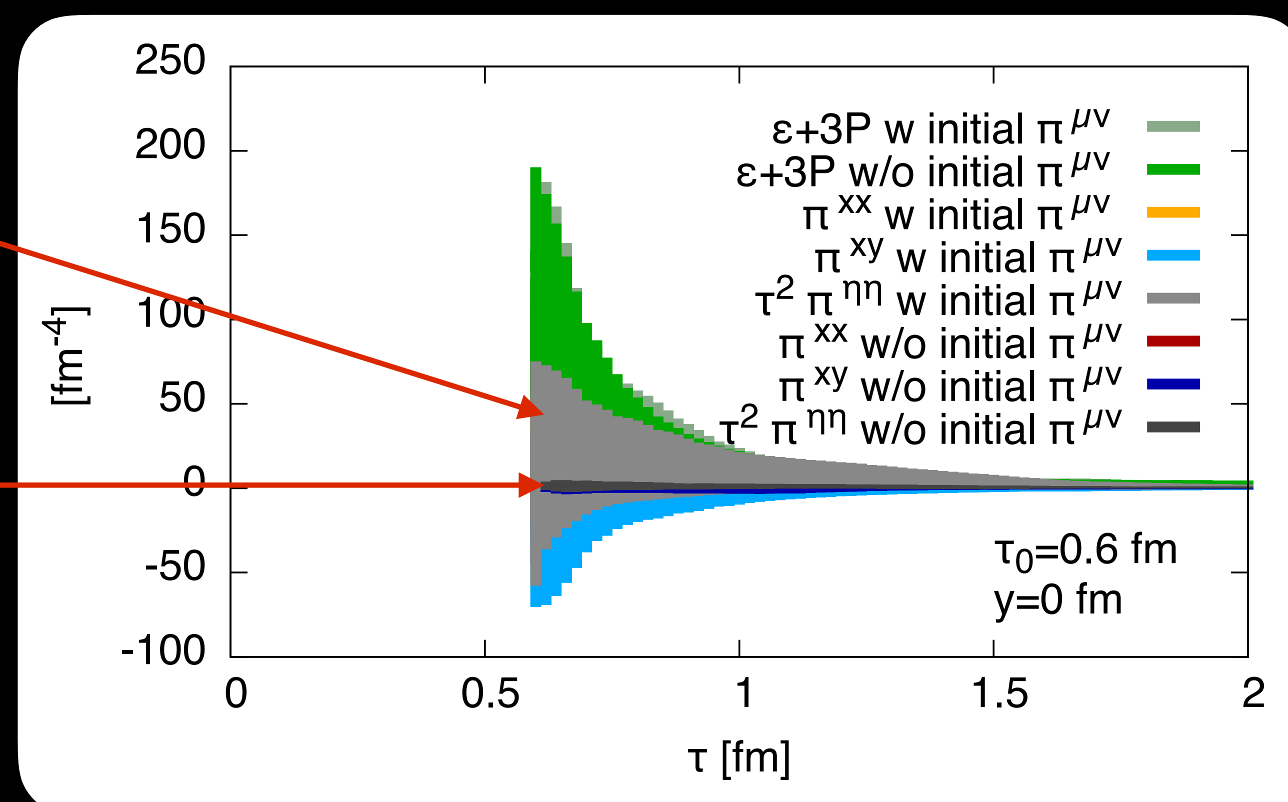




$$\tau_\pi = 5\frac{\eta}{\varepsilon + P}$$

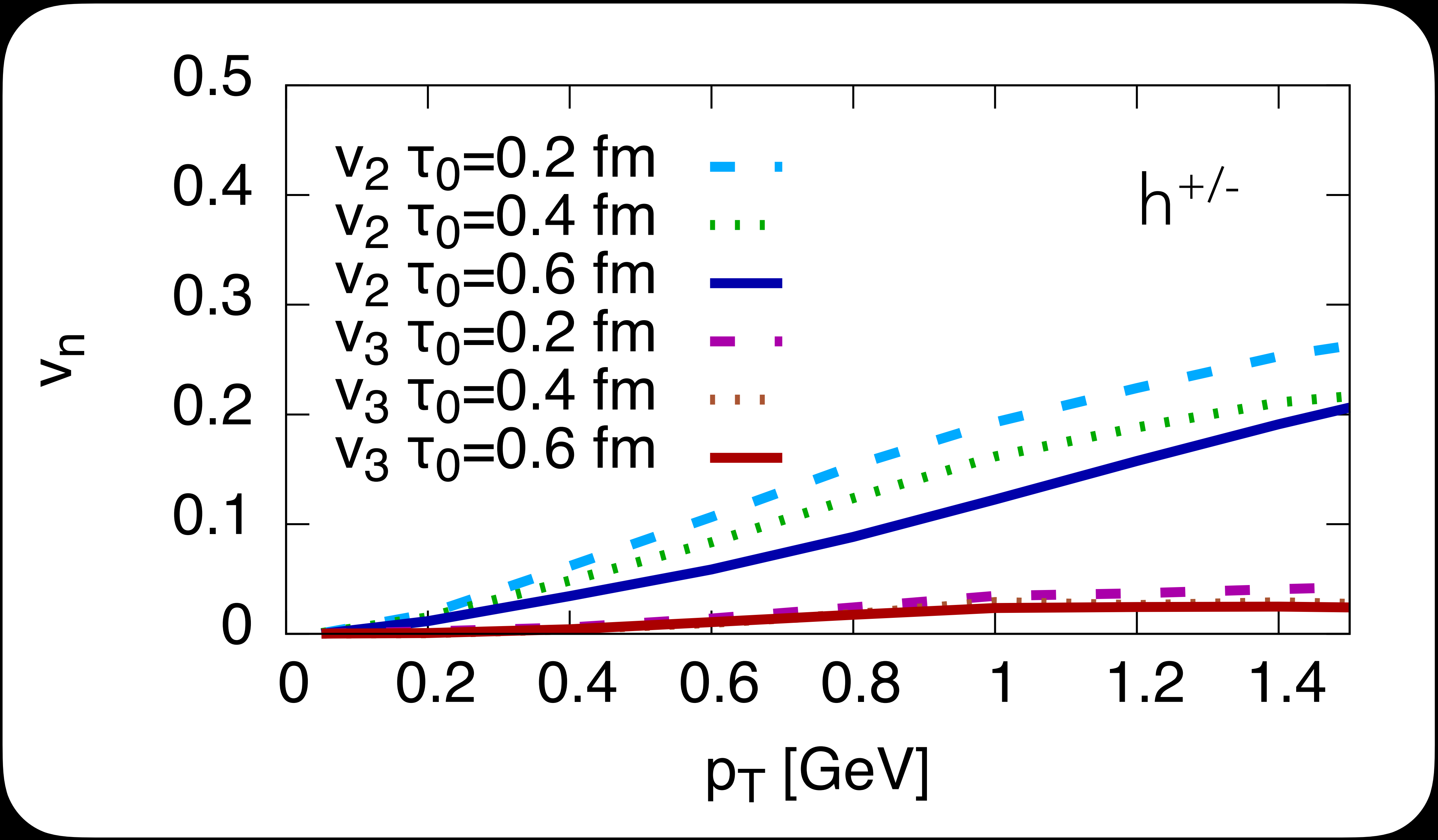
with initial $\pi^{\mu\nu}$

without initial $\pi^{\mu\nu}$



T dependent **η**/s and **ζ**/s

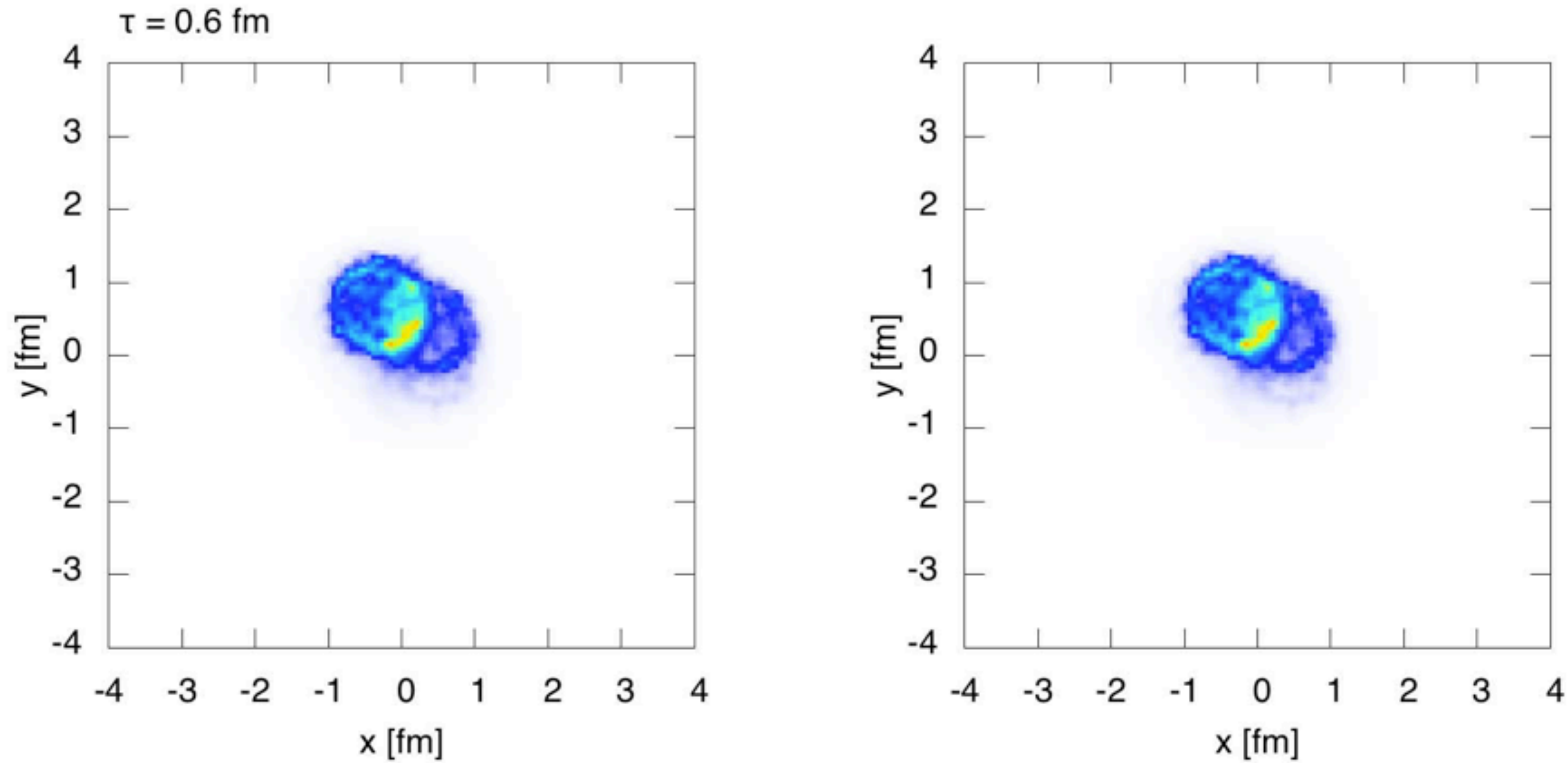
EFFECT OF SWITCHING TIME



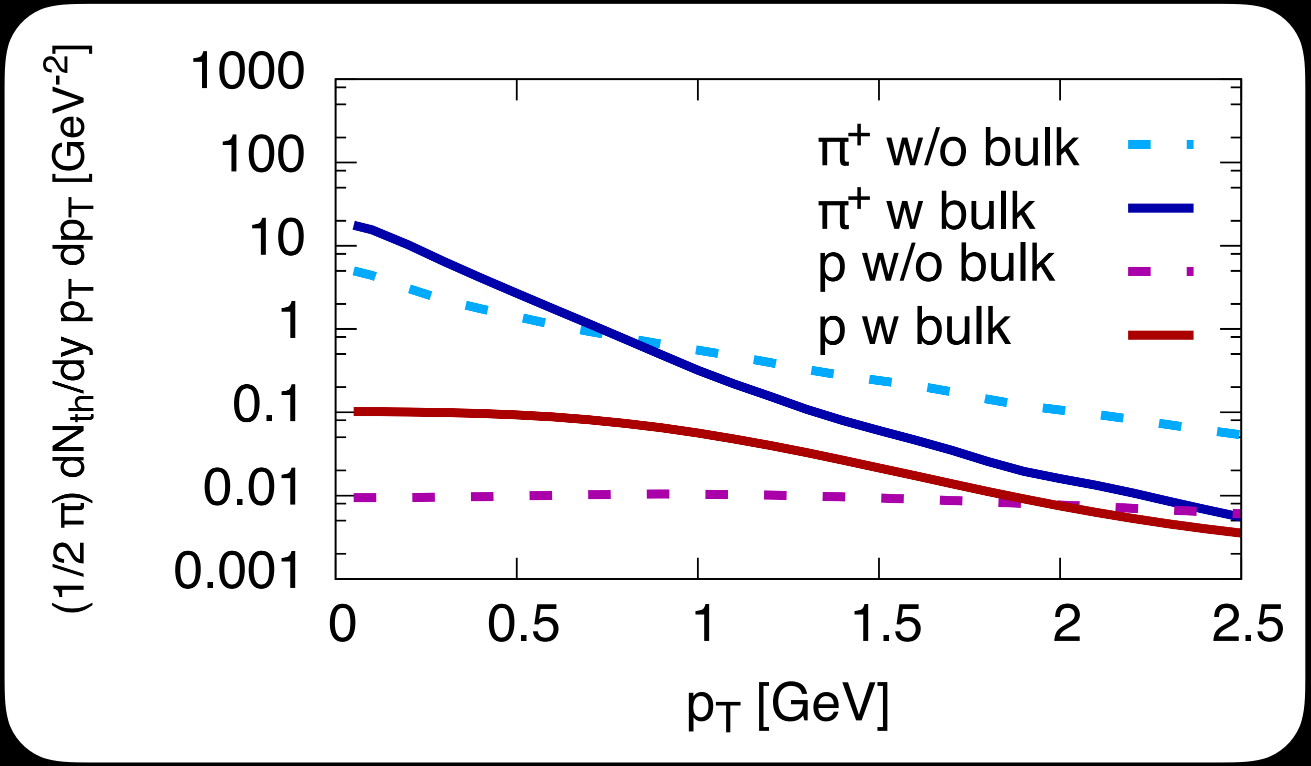
more hydro → larger v_n

Björn Schenke, BNL

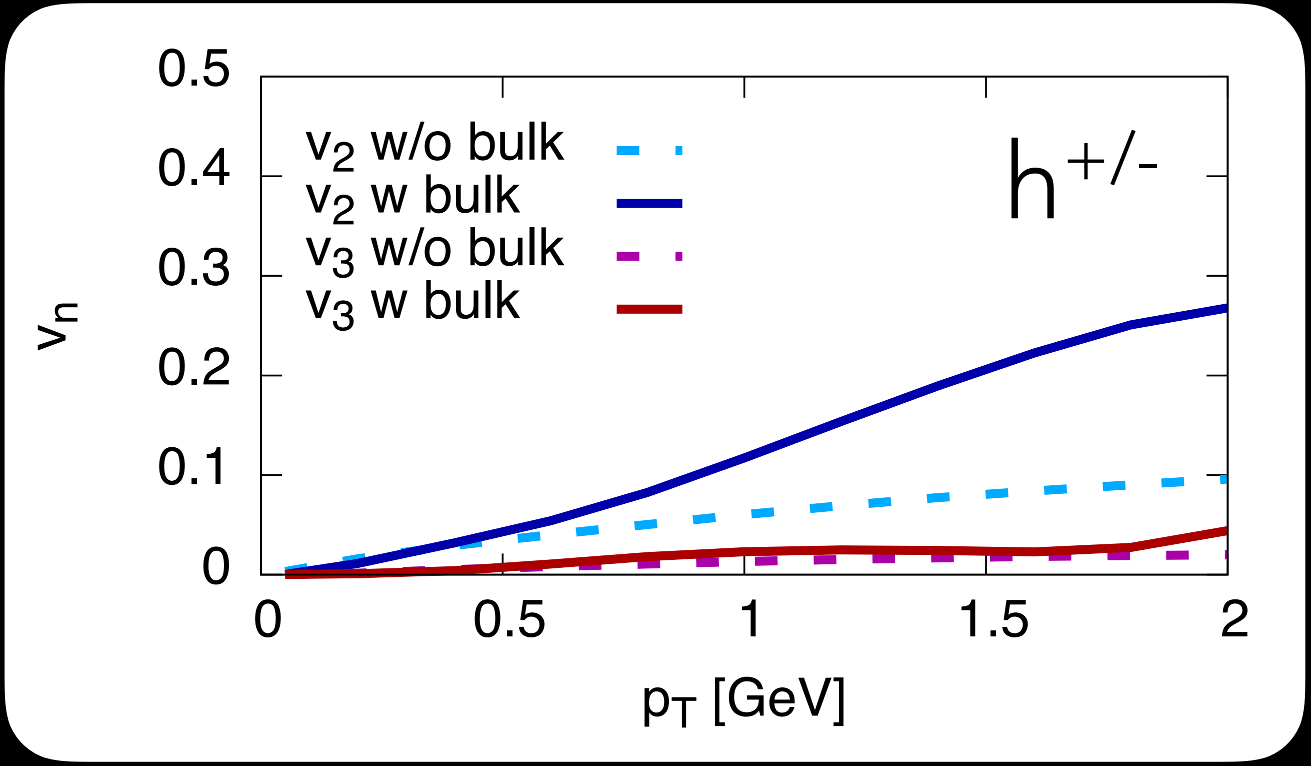
EFFECT OF BULK VISCOSITY



EFFECT OF BULK VISCOSITY

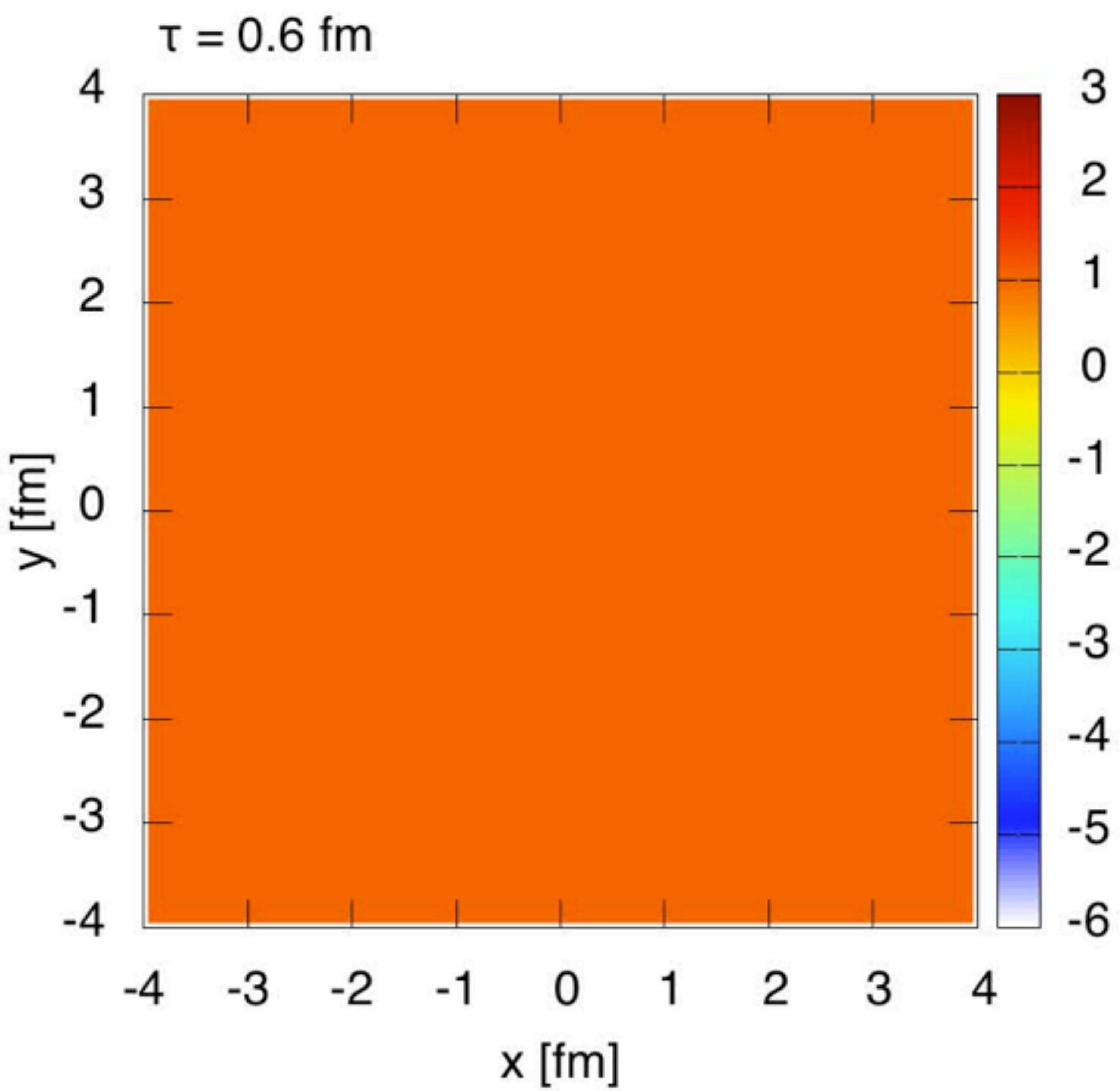


Spectra become significantly steeper (decreased radial flow)

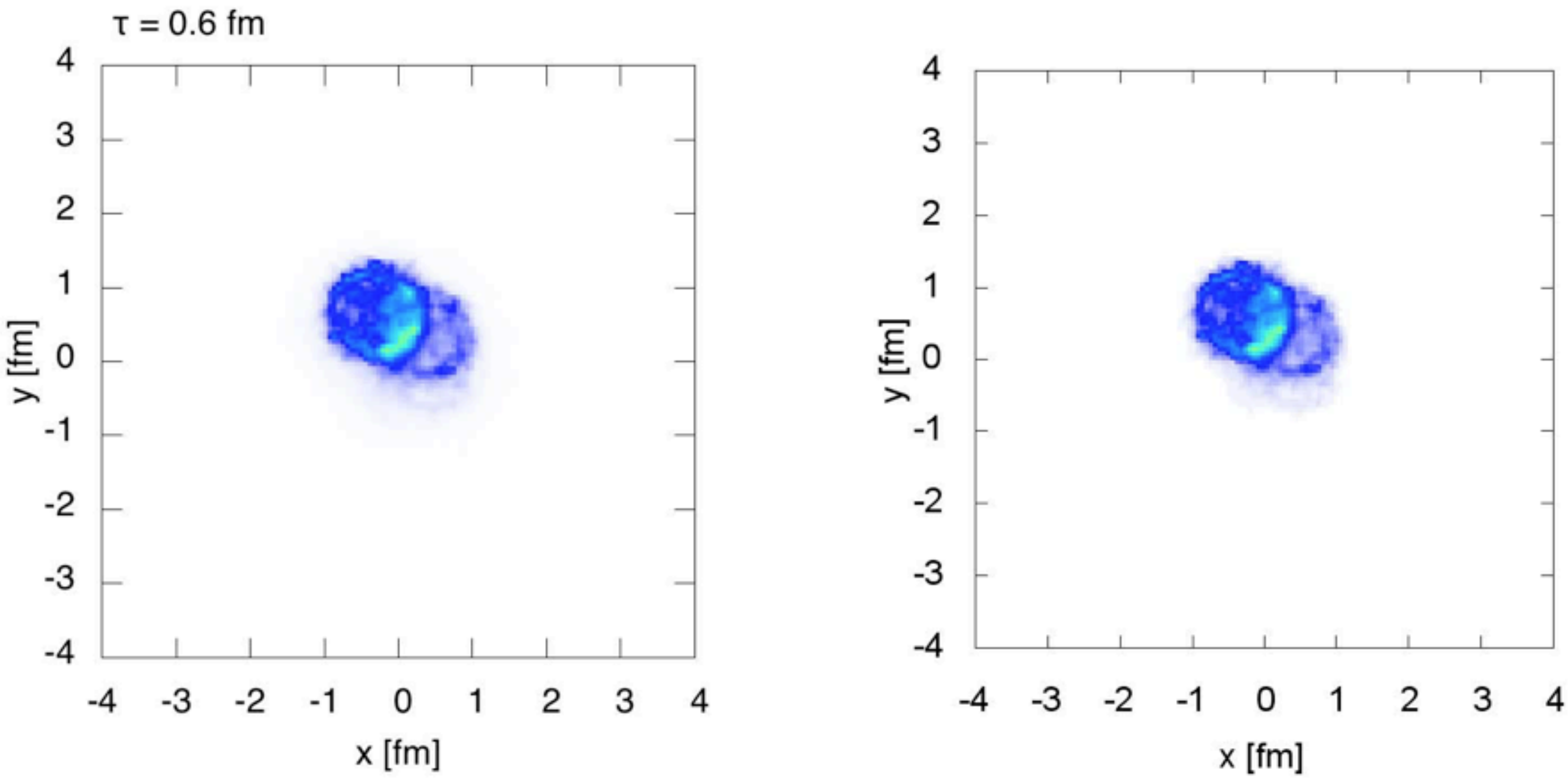


v_n are increased likely mainly due to the steeper spectra

EFFECTIVE PRESSURE 1-Π/P

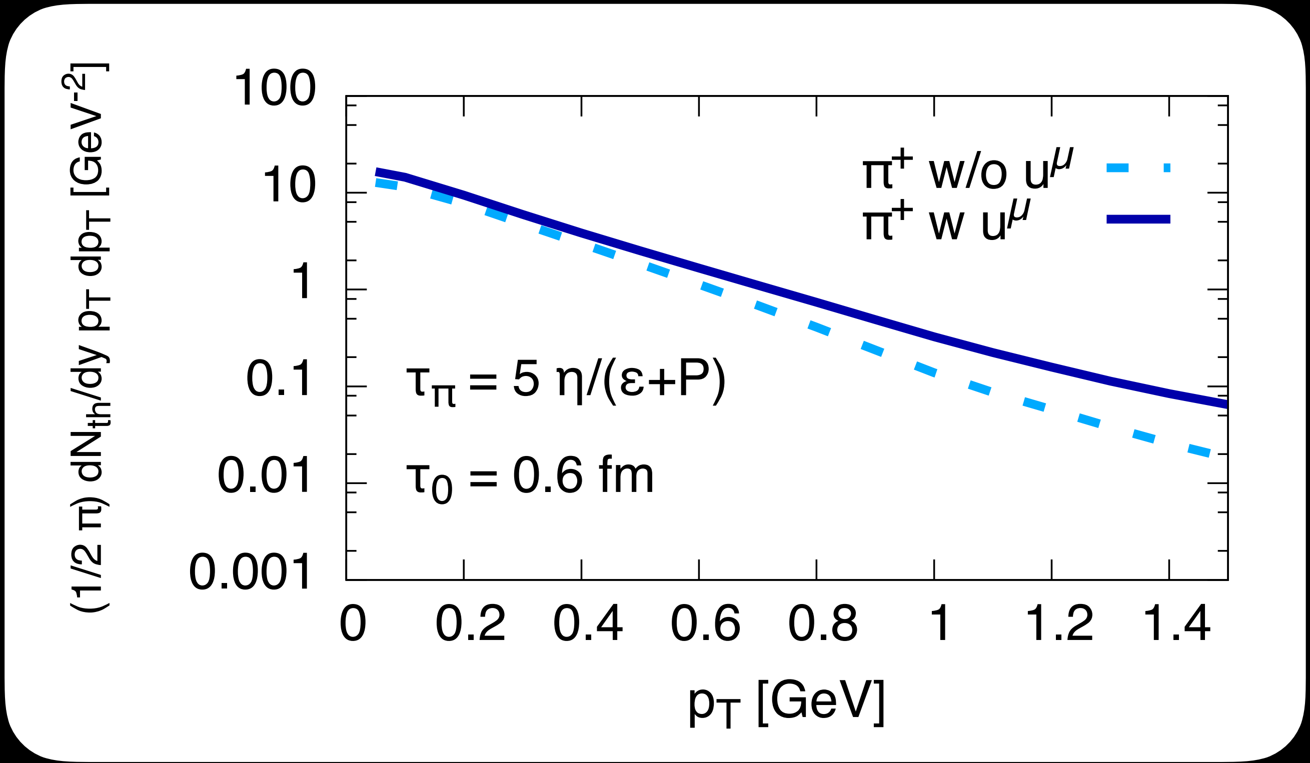


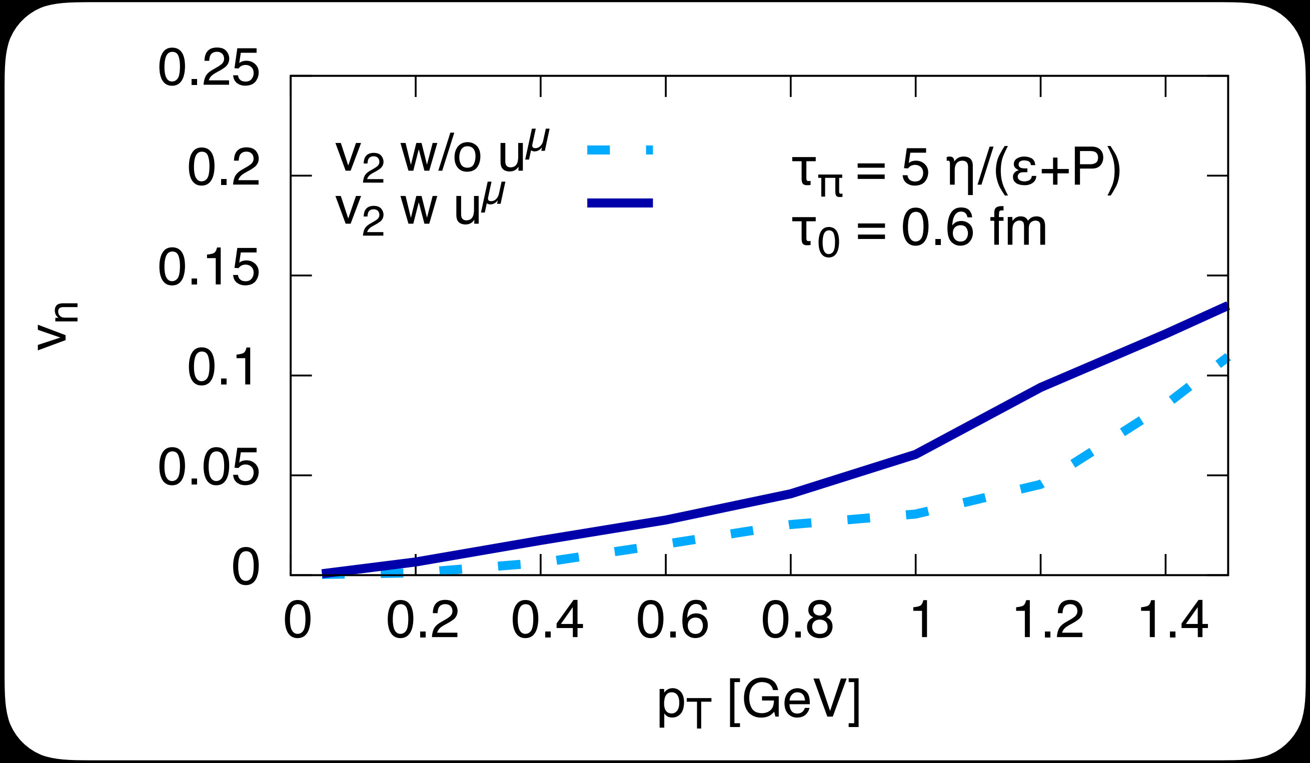
EFFECT OF INITIAL u^μ



w/o initial flow   w initial flow

EFFECT OF INITIAL u^μ (with initial $\pi^{\mu\nu}$)





Harder spectra

τ_0=0.6 fm: $\sqrt{\langle u^{x2}\rangle} = 0.47$

$\sqrt{\langle u^{y2}\rangle} = 0.53$

$\sqrt{\langle (\tau u^\eta)^2\rangle} = 0.14$

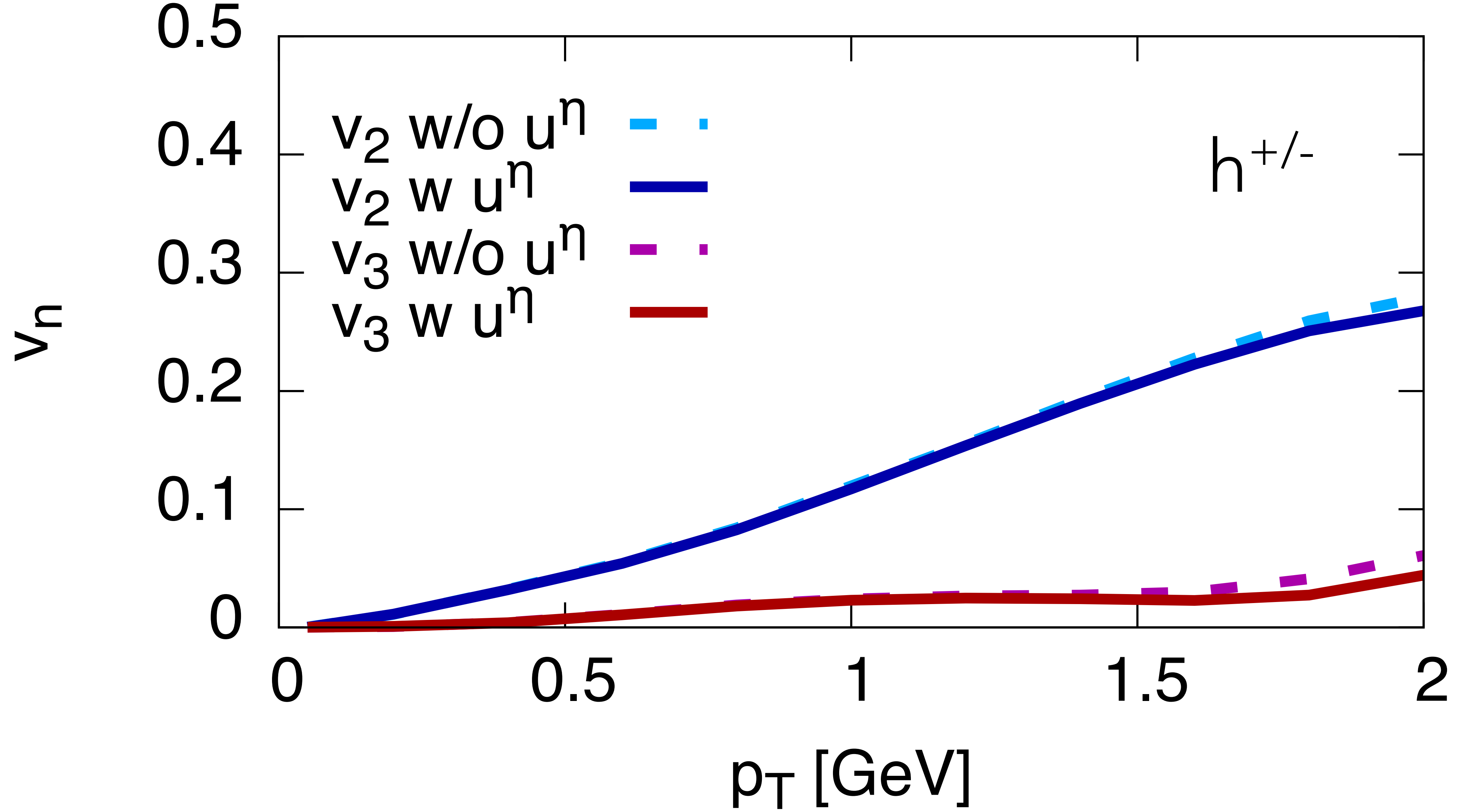
τ_0=0.2 fm: $\sqrt{\langle u^{x2}\rangle} = 0.38$

$\sqrt{\langle u^{y2}\rangle} = 0.41$

$\sqrt{\langle (\tau u^\eta)^2\rangle} = 0.53$

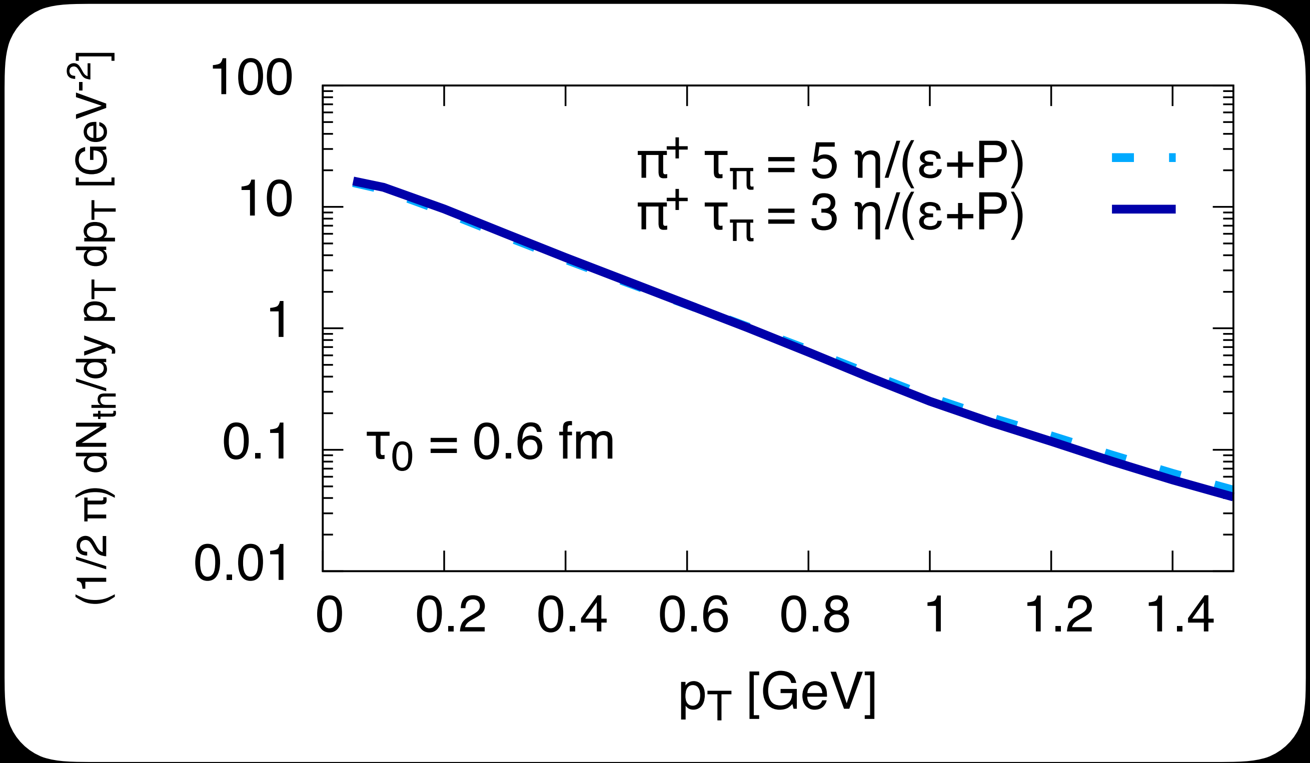
Less v_2

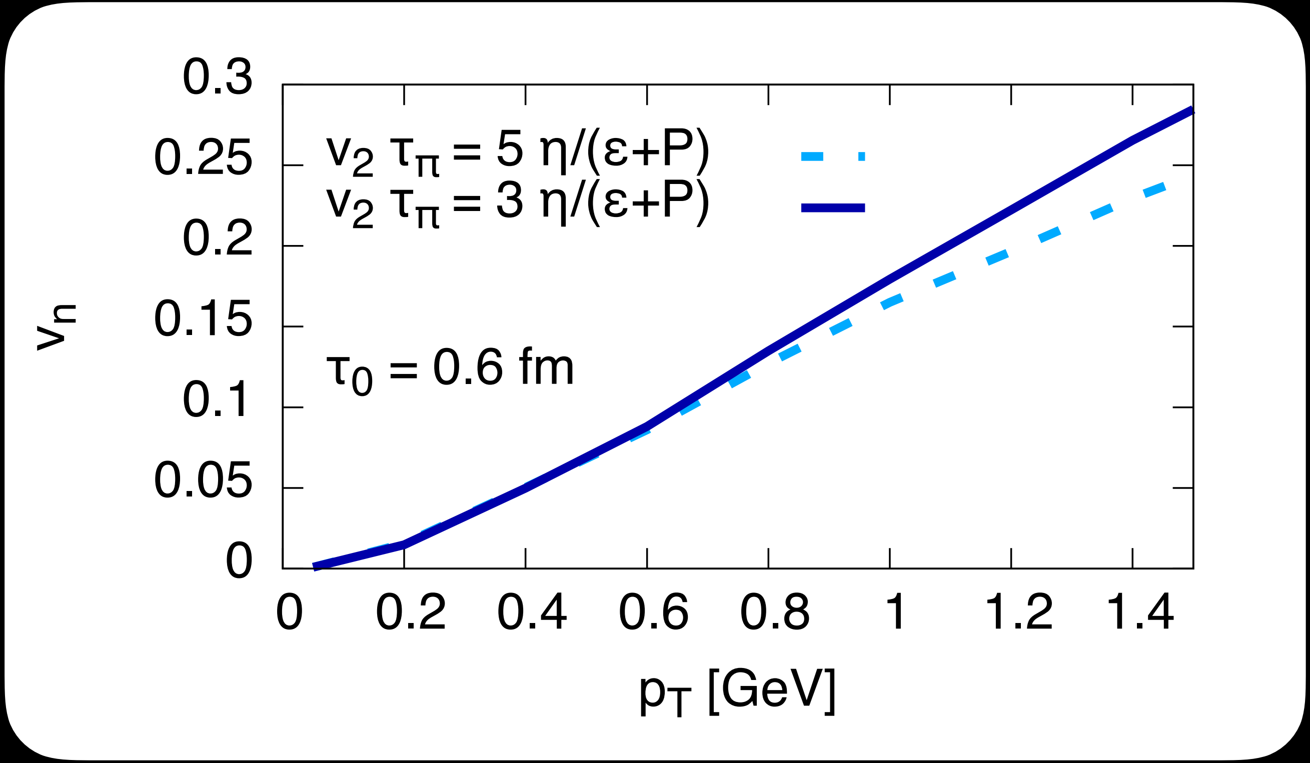
EFFECT OF INITIAL u^η



small effect: with u^η a little more suppression of v_n as one would expect

EFFECT OF RELAXATION TIME

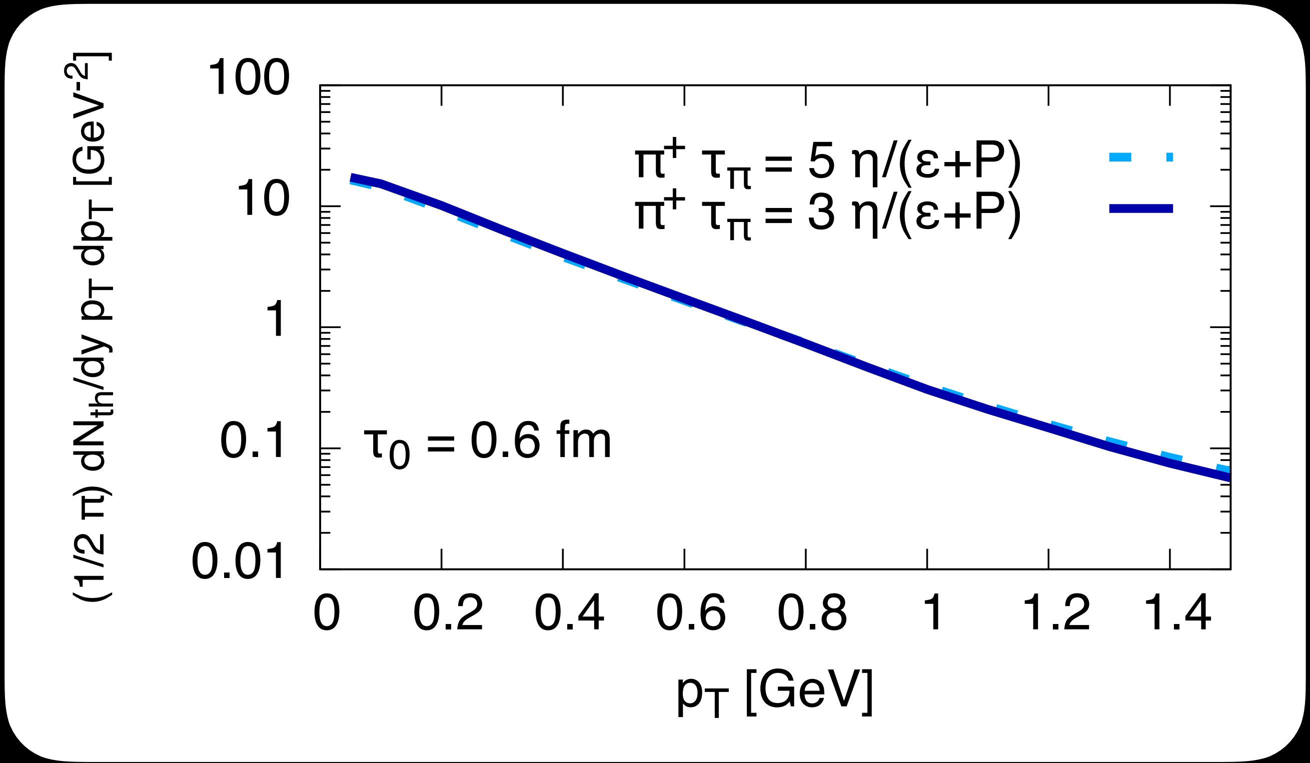




Weak effect when not including initial $\pi^{\mu\nu}$

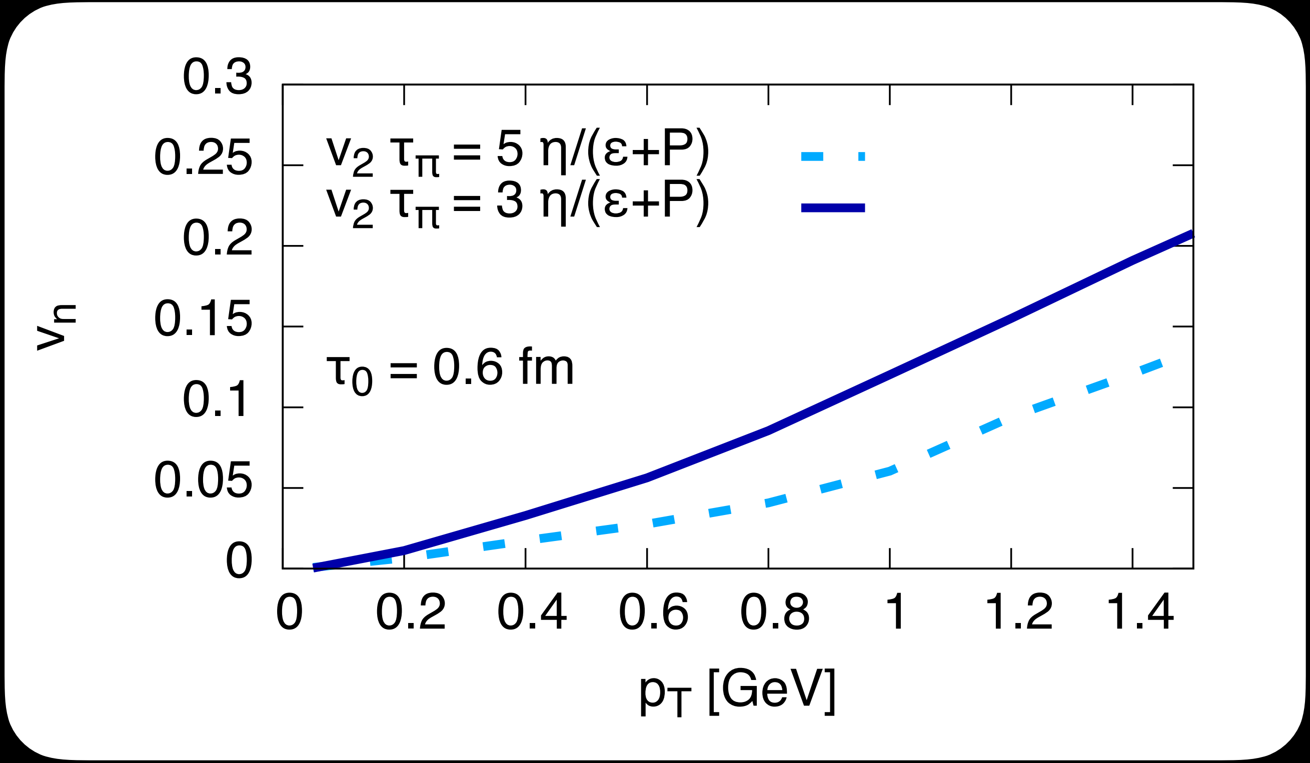
w/o initial $\pi^{\mu\nu}$

EFFECT OF RELAXATION TIME



With initial $\pi^{\mu\nu}$ surprisingly large effect on v_2

probably a δf effect



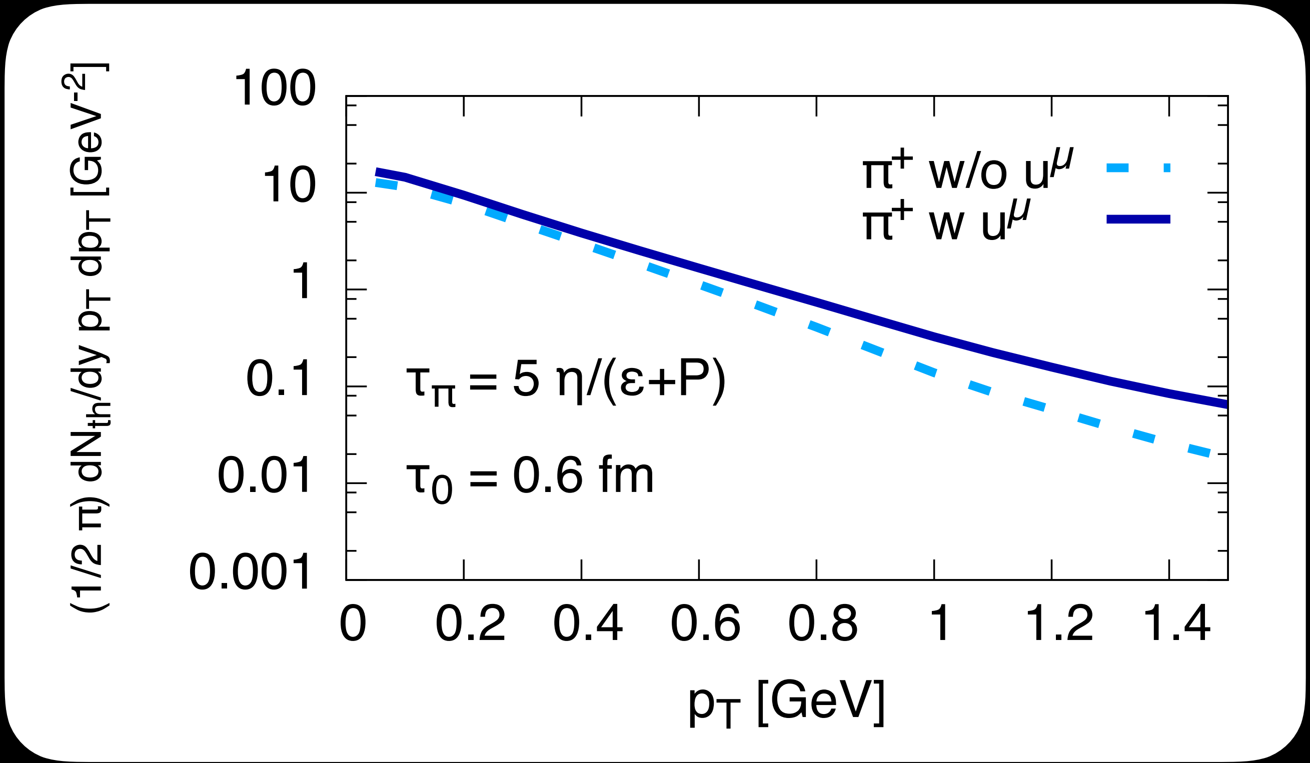
with initial $\pi^{\mu\nu}$

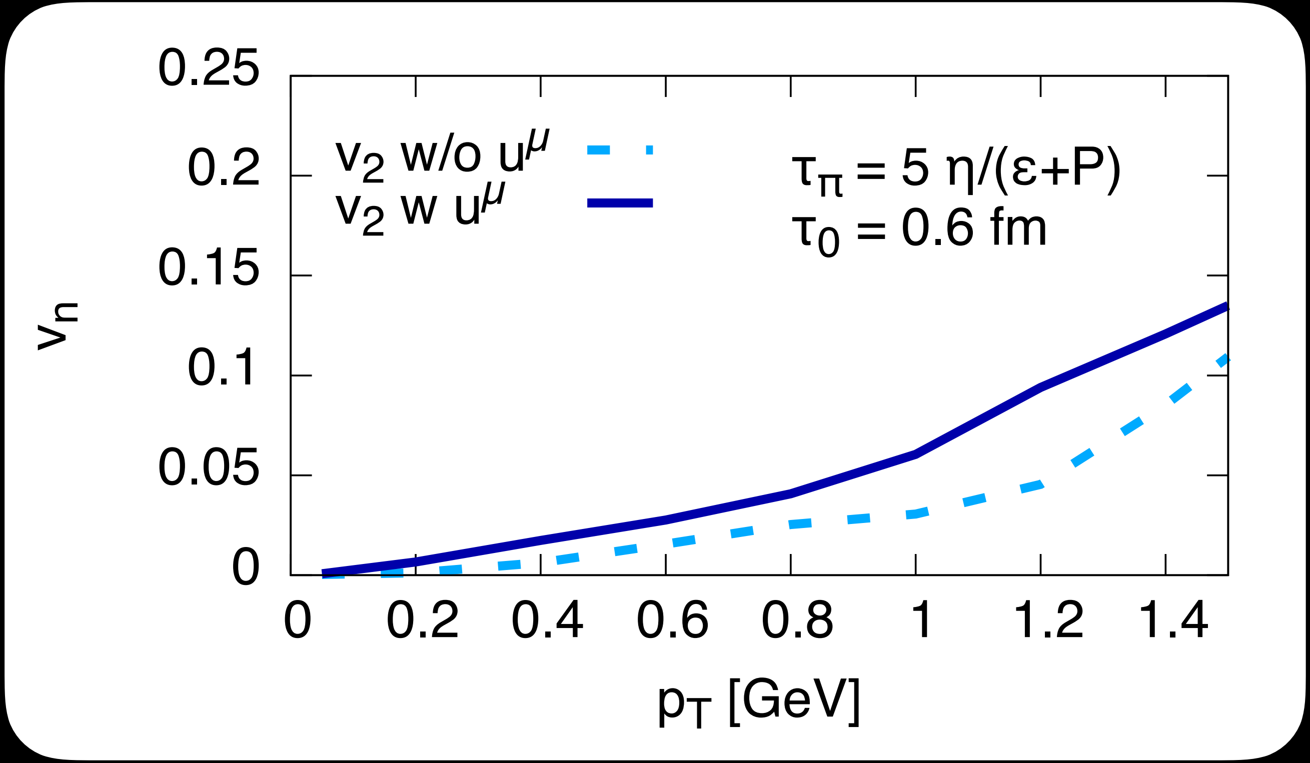
SUMMARY

- Correlations observed in the low momentum region (p_T<1.5 GeV) of small systems could be dominated by strong final state effects
- Fluctuating protons and IP-Glasma initial state result in anisotropic flows in the right ballpark
- But the details of the initial state and the hydrodynamic medium do matter
- Next will be larger scale simulations in the most realistic scenario (with initial $\pi^{\mu\nu}$ and flow, for different switching times and hydro parameters)

BACKUP

EFFECT OF INITIAL u^μ (with initial $\pi^{\mu\nu}$)





Harder spectra

τ_0=0.6 fm:

$$\sqrt{\langle v^{T2} \rangle} = 0.52$$

$$\sqrt{\langle (\tau v^{\eta})^2 \rangle} = 0.11$$

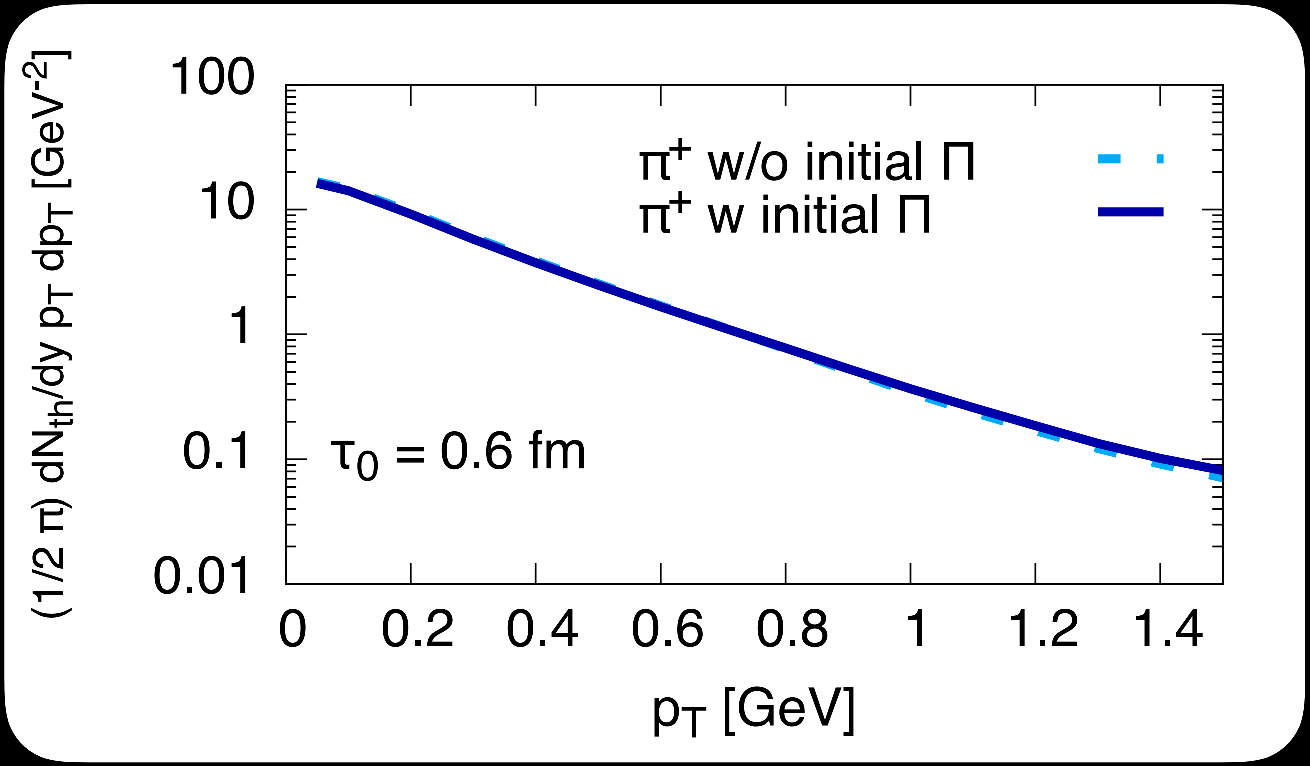
τ_0=0.2 fm:

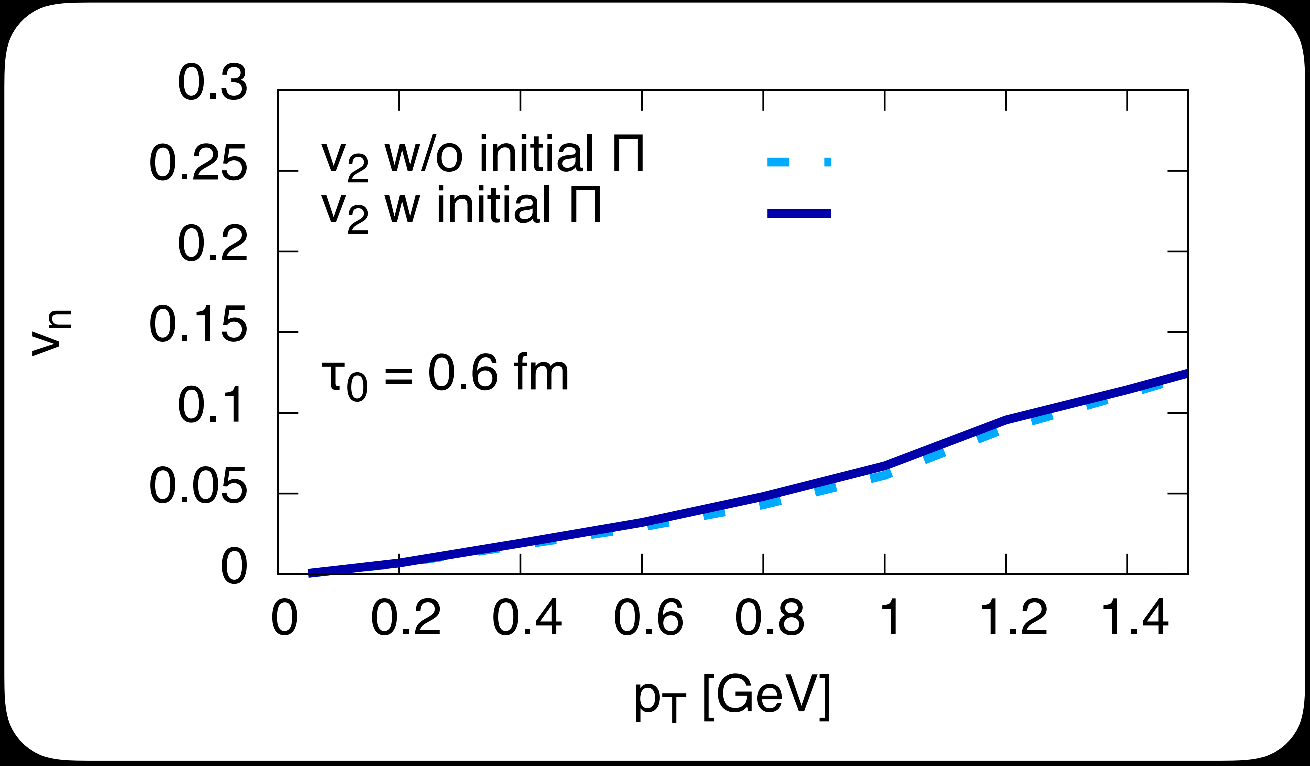
$$\sqrt{\langle v^{T2} \rangle} = 0.46$$

$$\sqrt{\langle (\tau v^{\eta})^2 \rangle} = 0.46$$

Less v_2

EFFECT OF INITIAL Π





HOW TO CONSTRAIN PROTON SHAPE FLUCTUATIONS?

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, PRL IN PRINT

ADDITIONAL DEGREE OF FREEDOM:
PROTON SHAPE FLUCTUATIONS

NEED ADDITIONAL PIECE OF DATA AS CONSTRAINT
IN THE SPIRIT OF THE ORIGINAL IP-GLASMA MODEL

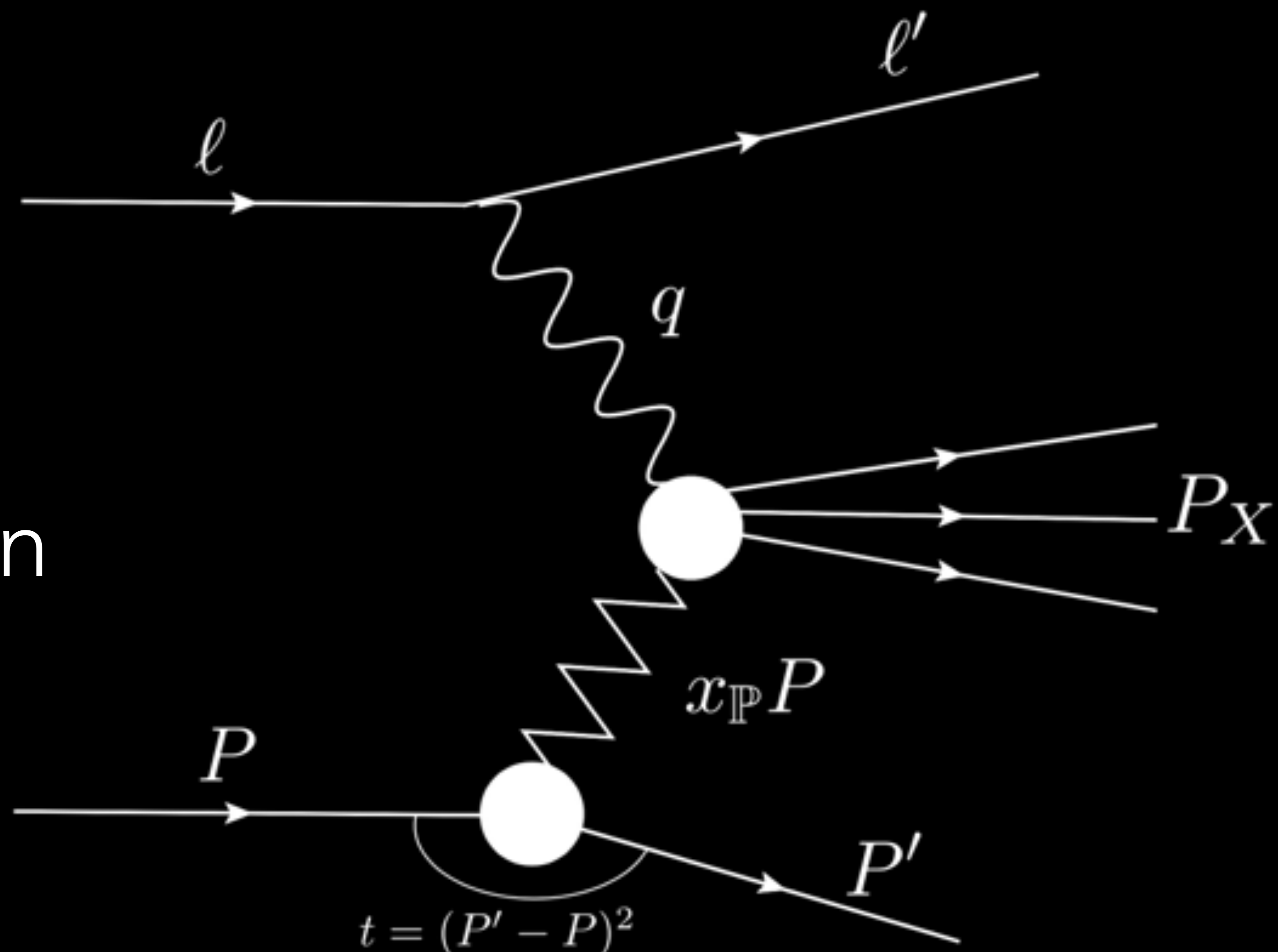
THIS DATA IS INCOHERENT EXCLUSIVE DIFFRACTIVE VECTOR MESON PRODUCTION AT E.G. HERA

DIFFRACTIVE J/Ψ PRODUCTION

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, PRL IN PRINT; ARXIV:1607.01711

No exchange of color charge

Large rapidity gap



Coherent diffraction:

Proton remains intact

Sensitive to average gluon distribution in the proton

Incoherent diffraction:

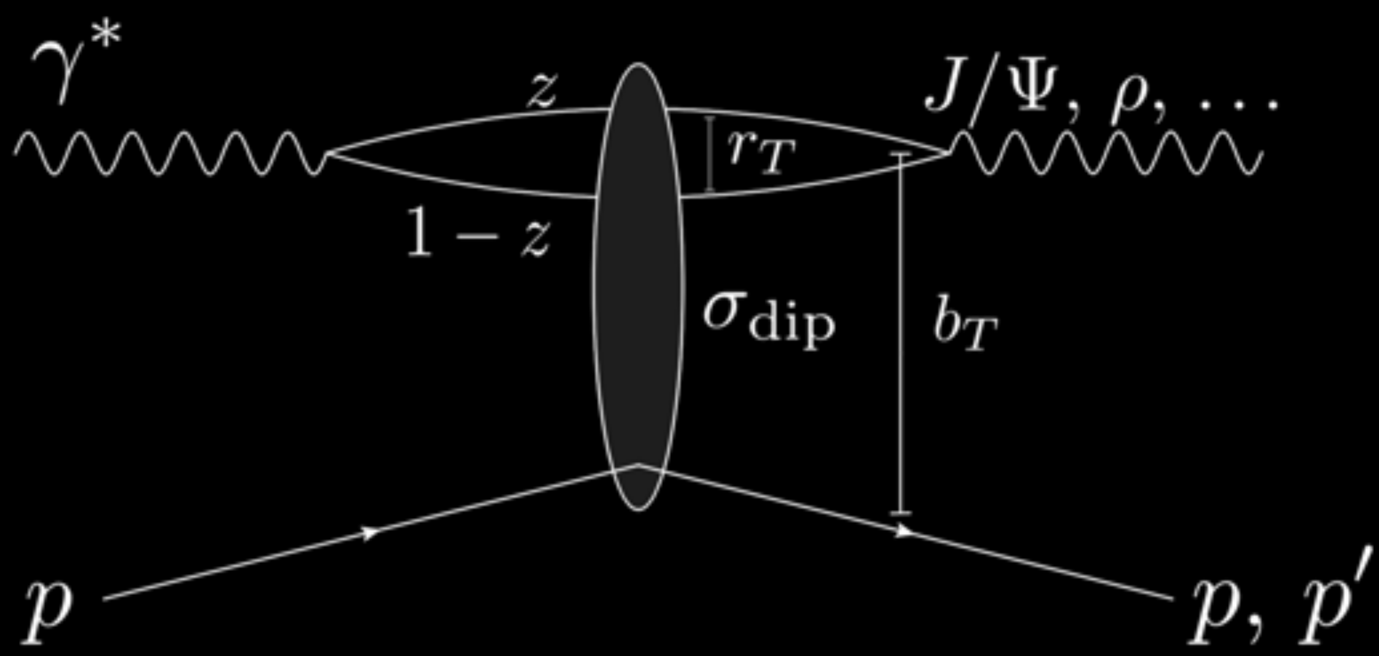
Proton breaks up

Sensitive to shape fluctuations

CGC FRAMEWORK J/Ψ PRODUCTION

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, PRL IN PRINT; ARXIV:1607.01711

Diffractive eigenstates are color dipoles at fixed r_T and b_T



SEE
M. L. GOOD AND W. D. WALKER
PHYS. REV. 120 (1960) 1857.

Scattering amplitude

$$\mathcal{A} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^* \Psi^V(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

$$\sigma_{\rm dip}(x, r, \Delta) = 2 \int \mathrm{d}^2 b e^{ib\cdot\Delta} N(r, x, b)$$

AVERAGING OVER THE TARGET

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, PRL IN PRINT; ARXIV:1607.01711

COHERENT DIFFRACTION:
TARGET STAYS INTACT

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Vp}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle \mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\rangle\right|^2$$

INCOHERENT DIFFRACTION:
TARGET BREAKS UP

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Vp^*}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle\left|\mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\right|^2\right\rangle - \left|\langle \mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\rangle\right|^2\right)$$

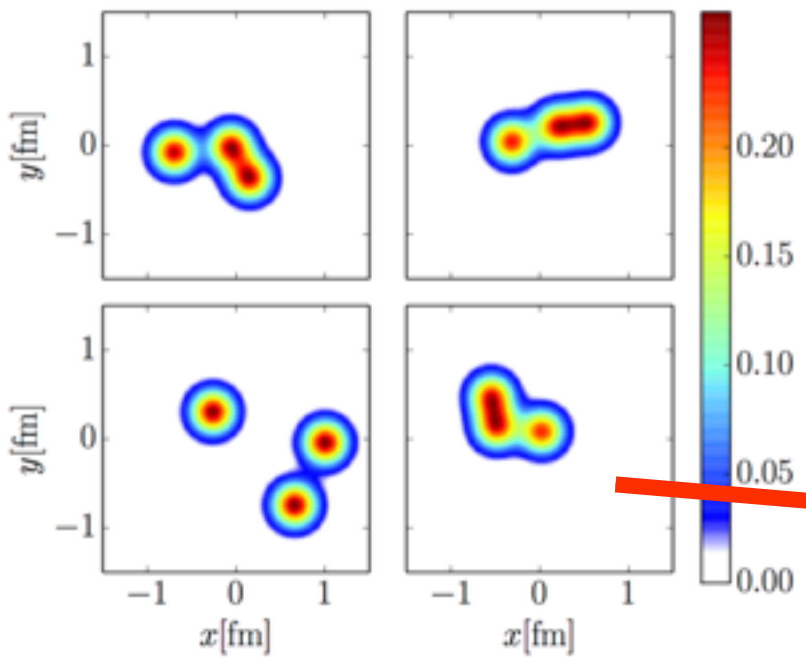
SENSITIVE TO FLUCTUATIONS!

SEE
H. I. MIETTINEN
AND J. PUMPLIN
PHYS. REV. D18 (1978) 1696

Y. V. KOVCHEGOV
AND L. D. MCLERRAN
PHYS. REV. D60 (1999) 054025

A. KOVNER AND
U. A. WIEDEMANN
PHYS. REV. D64 (2001) 114002

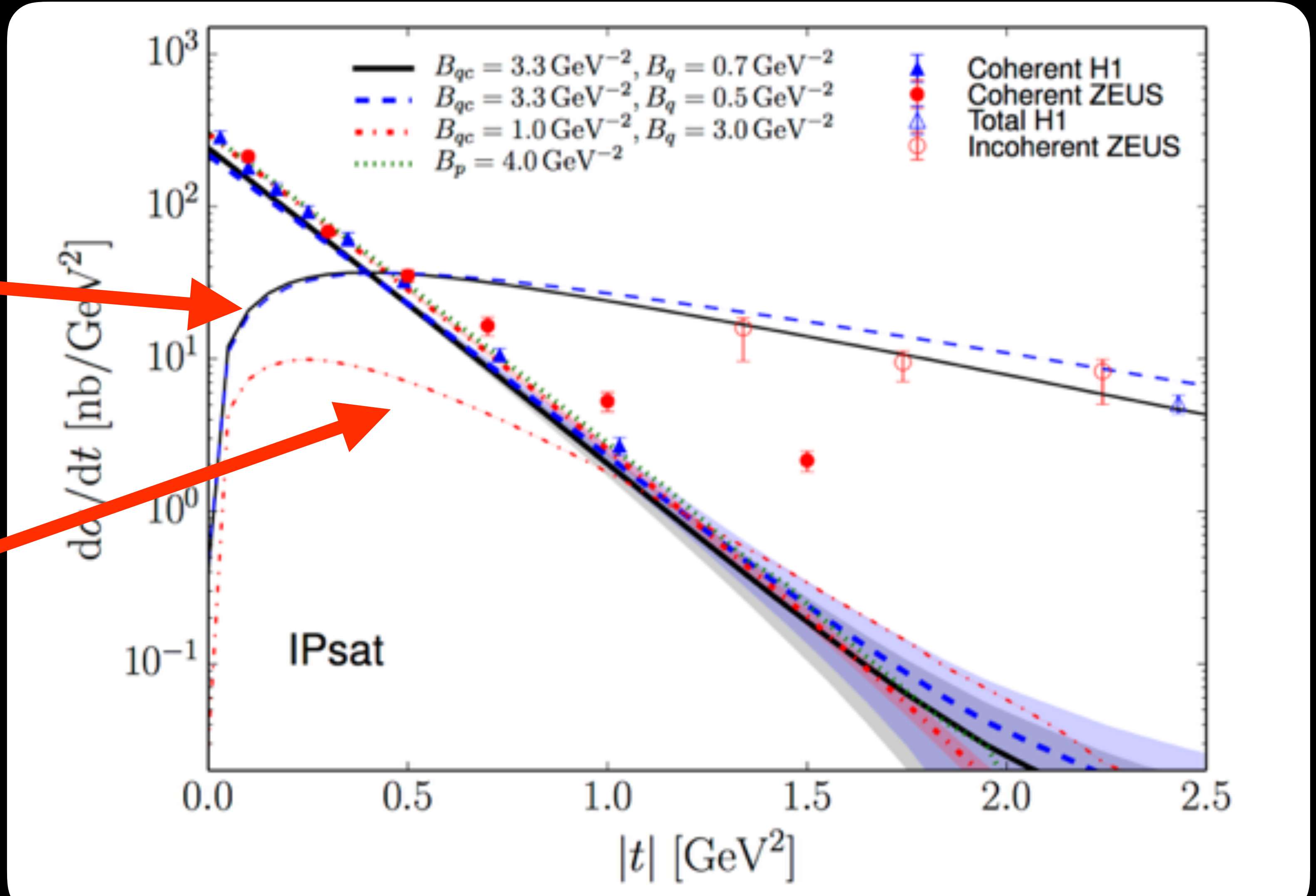
GEOMETRIC FLUCTUATIONS



(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$

(b) $B_{qc} = 1.0\ \mathrm{GeV}^{-2}, B_q = 3.0\ \mathrm{GeV}^{-2}$

H. MÄNTYSAARI, B. SCHENKE
ARXIV:1603.04349, PRL IN PRINT; ARXIV:1607.01711

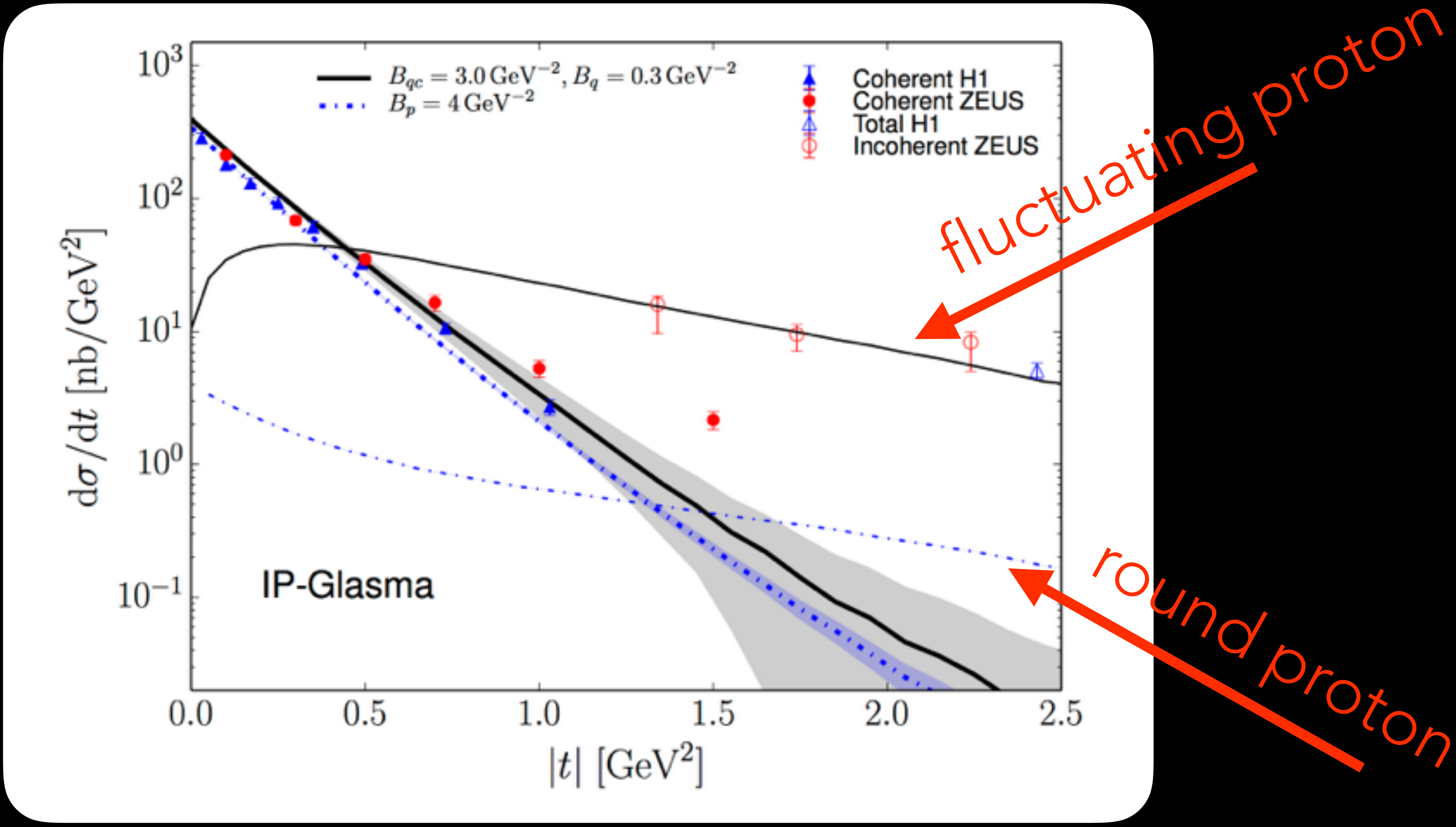


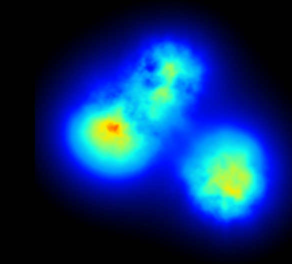
H1 COLLABORATION, EUR. PHYS. J. C46 (2006) 585,
PHYS. LETT. B568 (2003) 205
ZEUS COLLABORATION, EUR. PHYS. J. C24 (2002) 345
EUR. PHYS. J. C26 (2003) 389

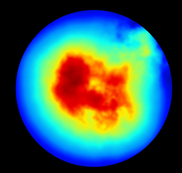
ADDING COLOR CHARGE FLUCTUATIONS

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, PRL IN PRINT; ARXIV:1607.

IPSat → IP-Glasma





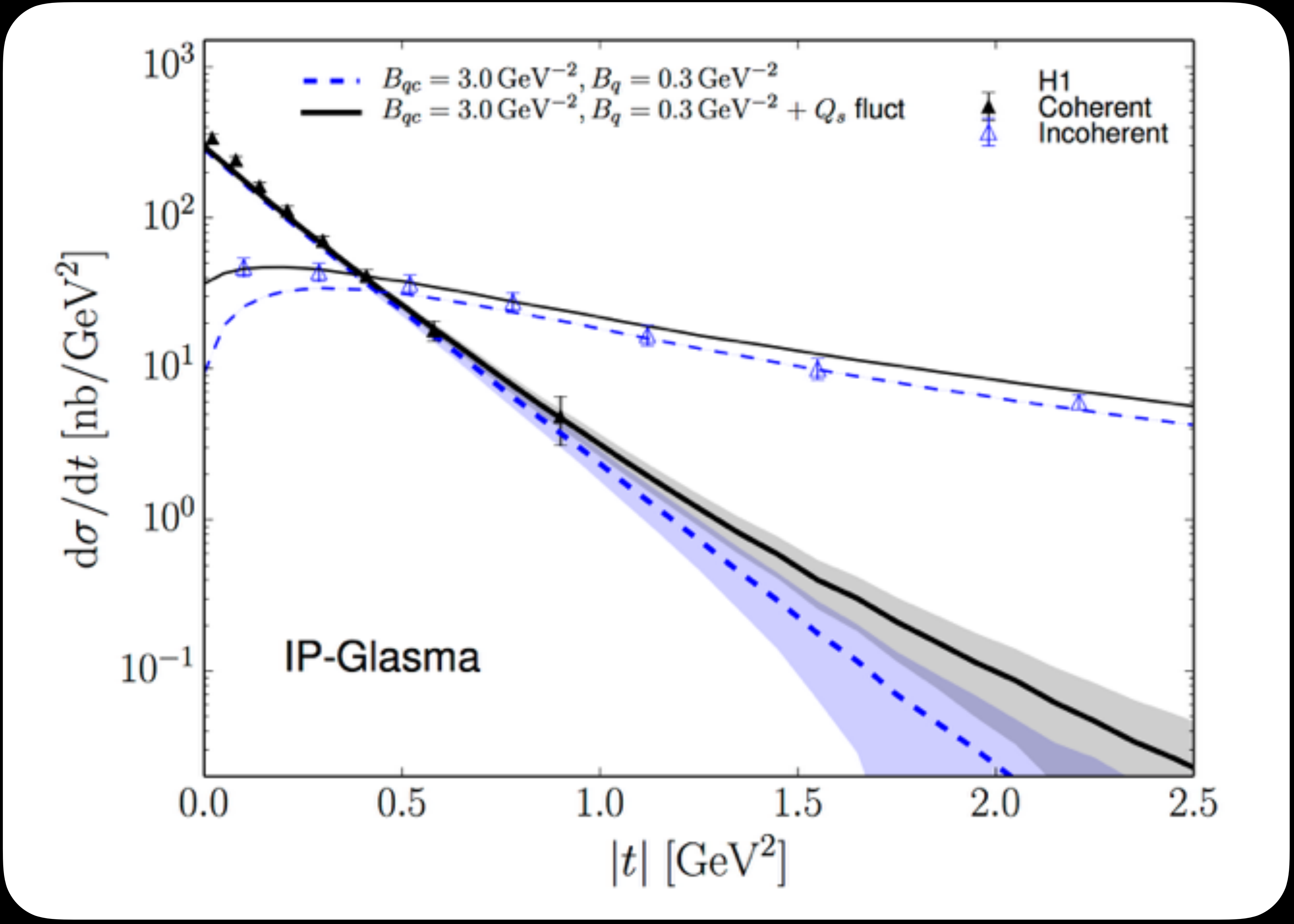


H1 COLLABORATION, EUR. PHYS. J. C46 (2006) 585, PHYS. LETT. B568 (2003) 205
ZEUS COLLABORATION, EUR. PHYS. J. C24 (2002) 345, EUR. PHYS. J. C26 (2003) 389

ADDING Q_S FLUCTUATIONS

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, PRL IN PRINT; ARXIV:1607.01711

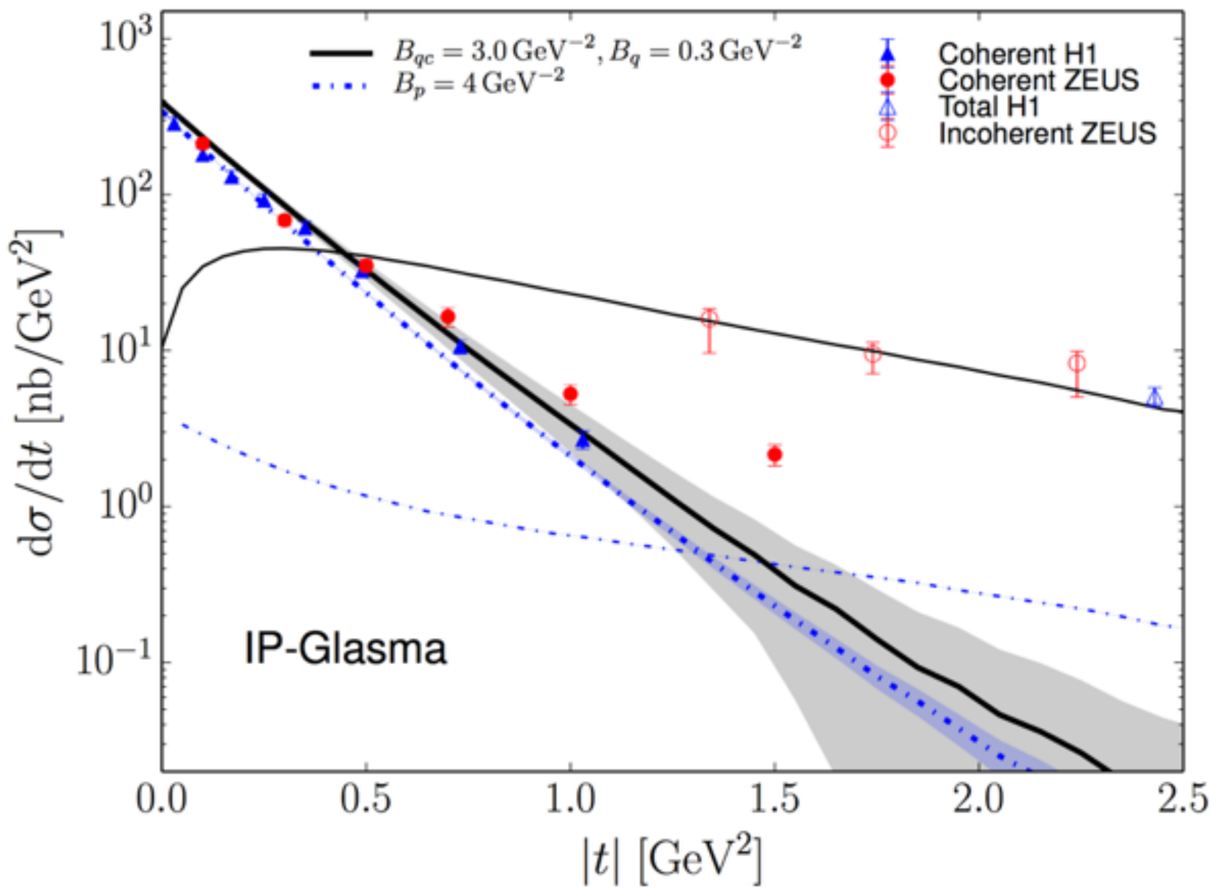
IPSat → IP-Glasma and add Q_S fluctuations



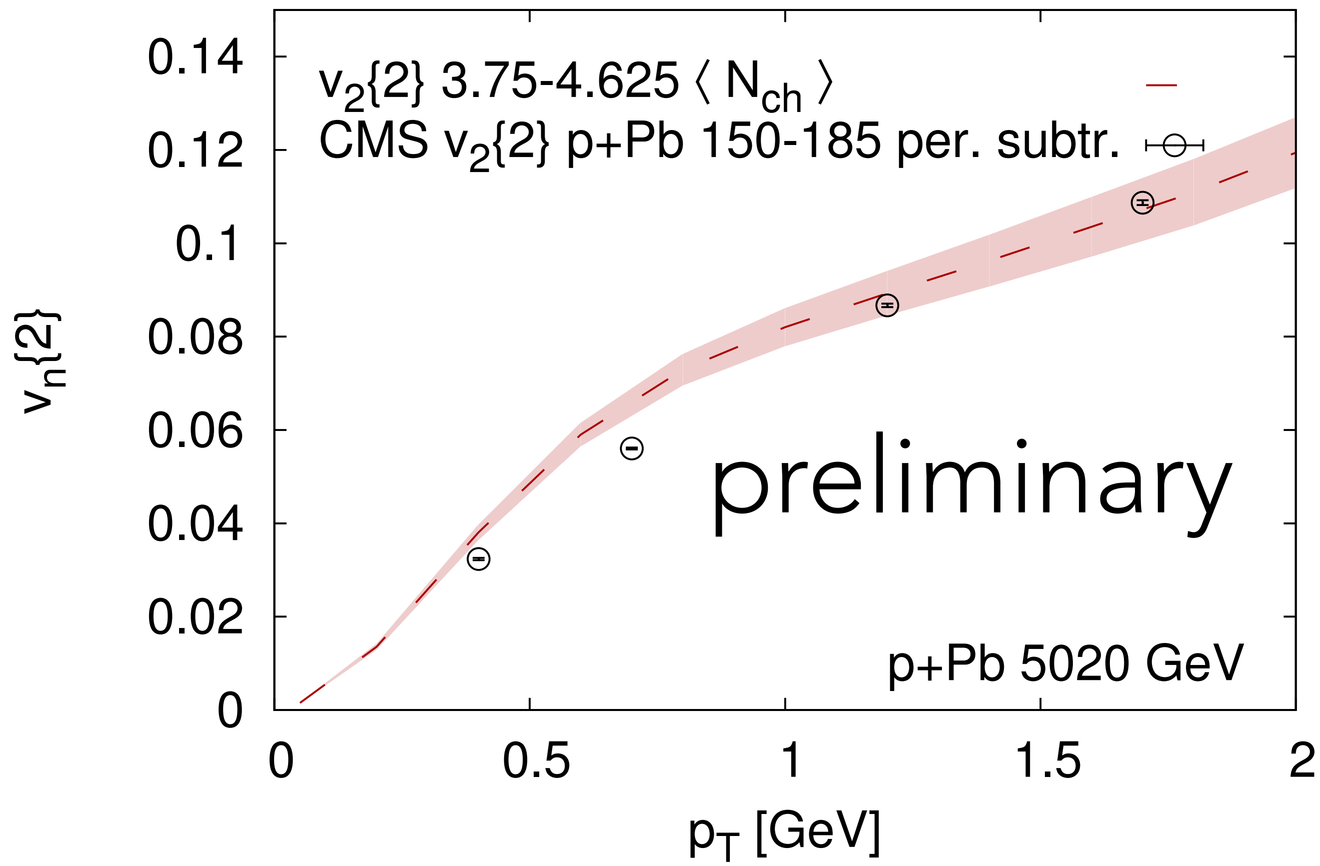
EXPERIMENTAL DATA: H1 COLLABORATION, JHEP 1005 (2010) 032

STRATEGY: CONSTRAIN PROTON FLUCTUATIONS WITH J/Ψ PRODUCTION AND PREDICT FLOW IN p+Pb COLLISIONS

H. MÄNTYSAARI, P. TRIBEDY, B. SCHENKE, IN PREPARATION



Use constrained proton to predict v_2 in p+Pb collisions



Temperature dependent η/s constrained in A+A collisions

G. DENICOL, A. MONNAI, B. SCHENKE
PHYS.REV.LETT. 116 (2016) NO.21, 212301

TEMPERATURE DEPENDENT SHEAR VISCOSITY FROM RAPIDITY DEPENDENT FLOW

Björn Schenke, BNL

LONGITUDINAL STRUCTURE

A. MONNAI, B. SCHENKE, PHYS. LETT. B752, 317-321 (2015)

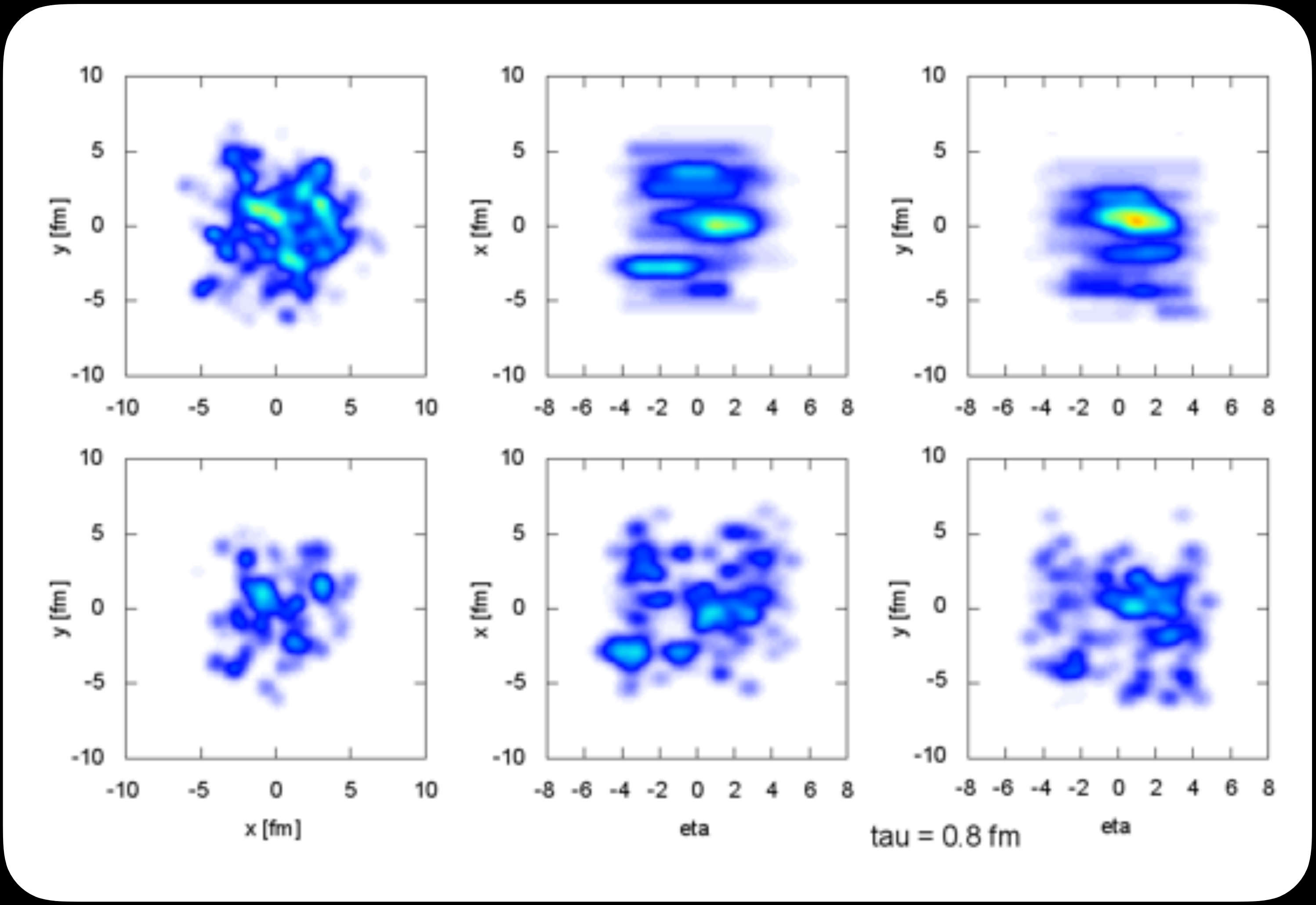
- INCLUDE 3D FLUCTUATING INITIAL STATE
- STUDY v_n AS FUNCTION OF RAPIDITY
- CAN CONSTRAIN RAPIDITY DEPENDENCE OF η/s
- WILL NEED THIS FOR SIMULATIONS OF BES@RHIC

LONGITUDINAL DISTRIBUTION: IMPLEMENT AN MC VERSION OF THE **LEXUS** MODEL

RAPIDITY DISTRIBUTIONS IN HEAVY ION COLLISIONS FOLLOW VIA LINEAR EXTRAPOLATION FROM P+P COLLISIONS

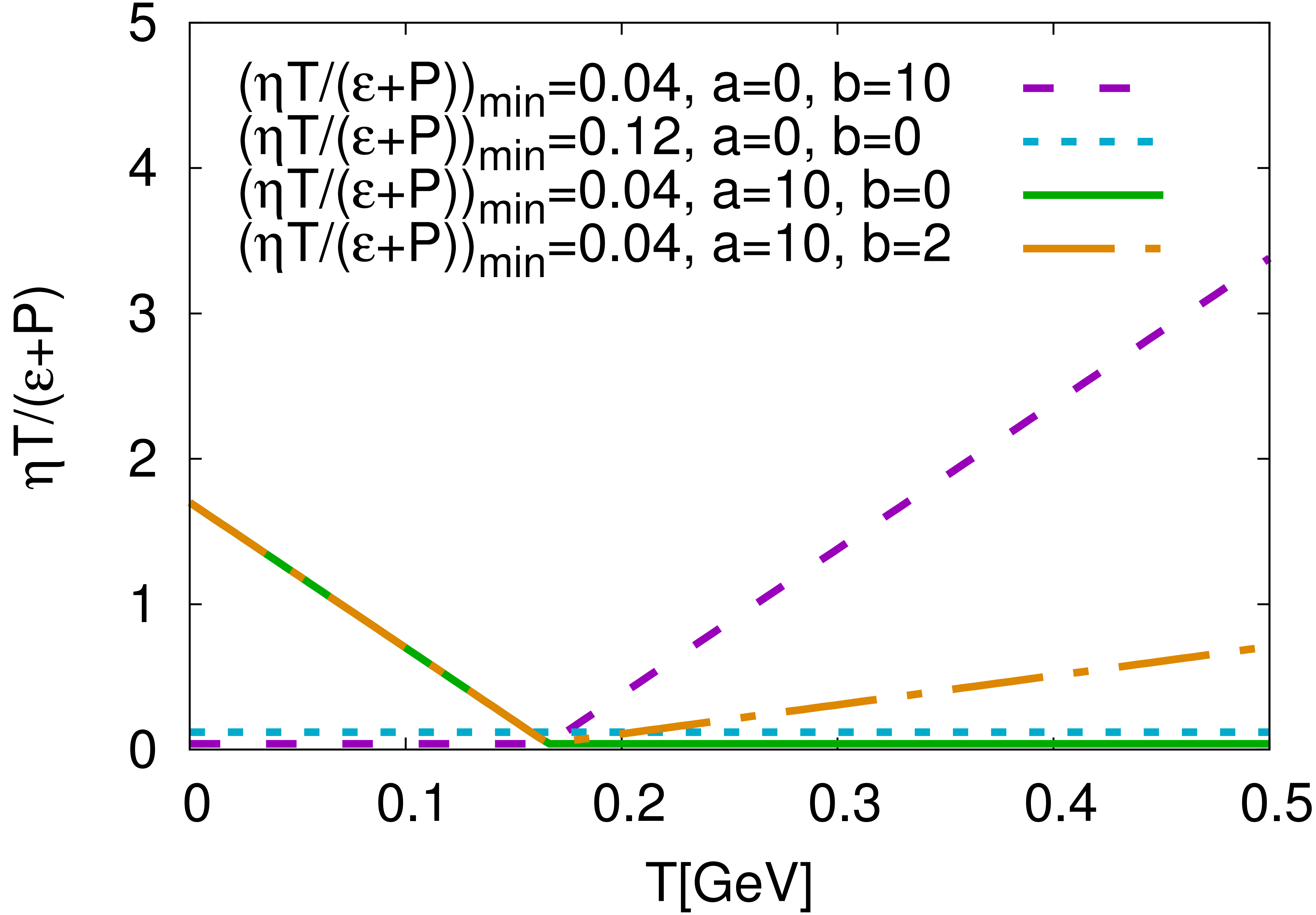
S. JEON AND J. KAPUSTA, PRC56, 468 (1997)

ENERGY DENSITY (UPPER)
BARYON DENSITY (LOWER)



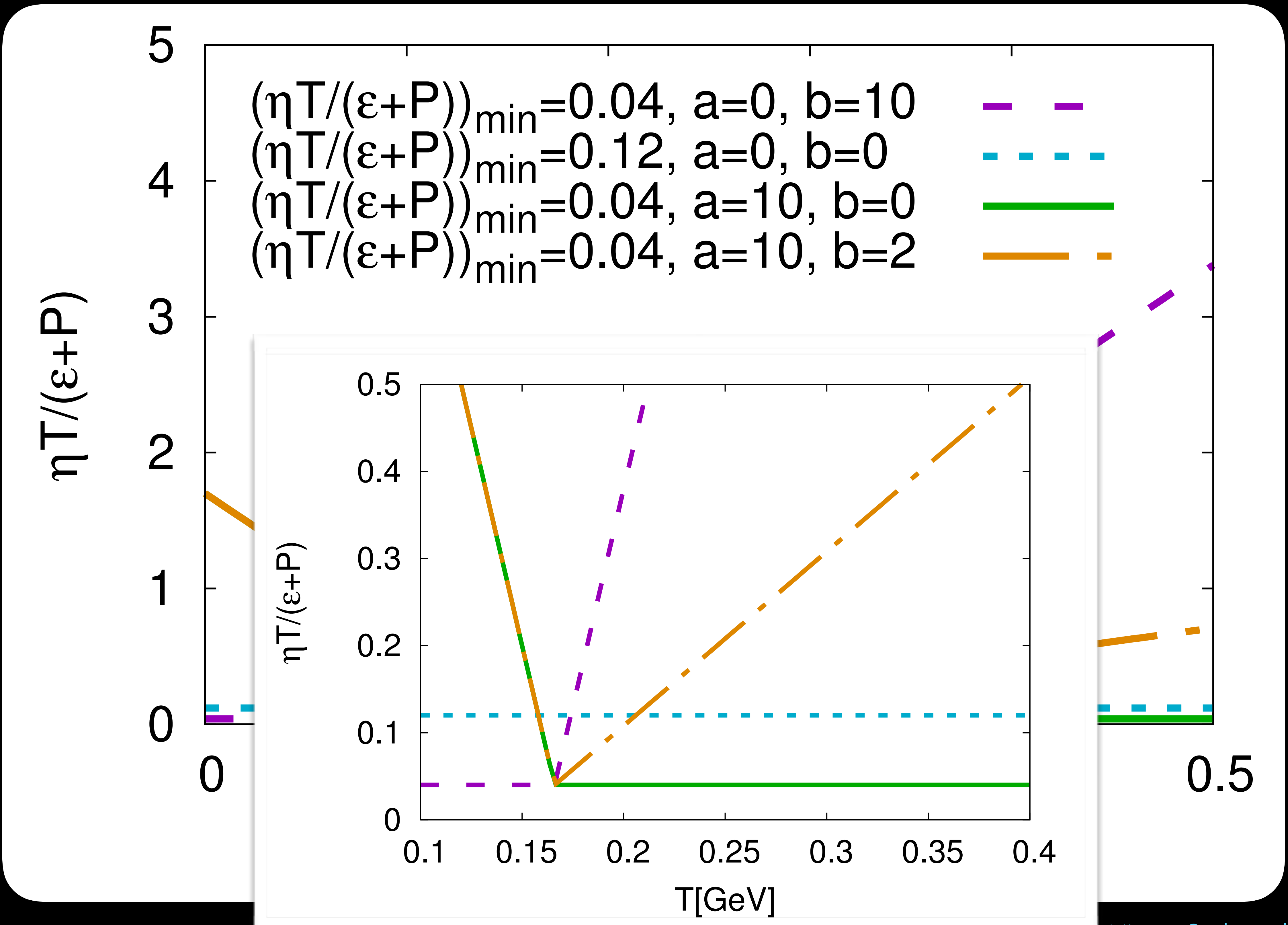
CONSTRAINING η/s vs. TEMPERATURE

G. DENICOL, A. MONNAI, B. SCHENKE, PHYS. REV. LETT. 116, 212301 (2016)



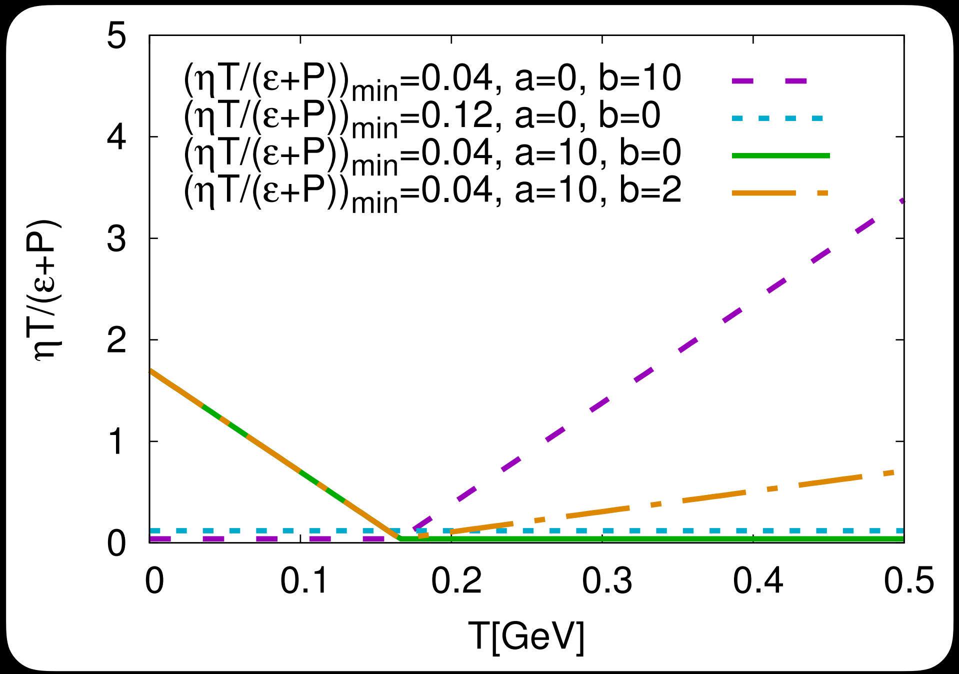
CONSTRAINING η/s vs. TEMPERATURE

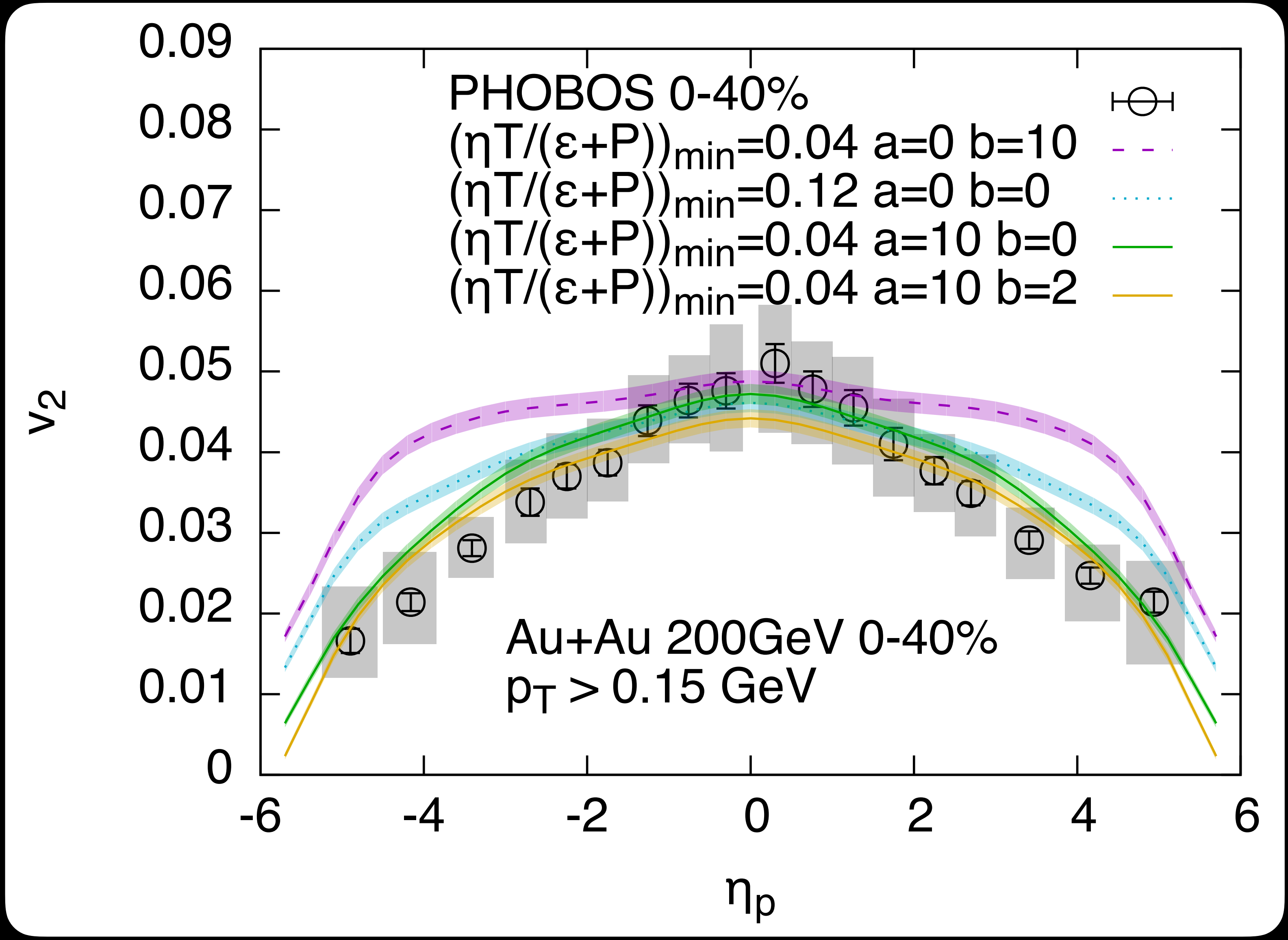
G. DENICOL, A. MONNAI, B. SCHENKE, PHYS. REV. LETT. 116, 212301 (2016)



CONSTRAINING η/s vs. TEMPERATURE

G. DENICOL, A. MONNAI, B. SCHENKE, PHYS. REV. LETT. 116, 212301 (2016)





EXP DATA: PHOBOS COLL., B.B. BACK,ET AL., PHYS.REV. LETT. 94 (2005) 122303

CONCLUSIONS:

η/s IS NOT CONSTANT   HADRONIC η/s IS LARGE   QGP η/s CANNOT RISE QUICKLY

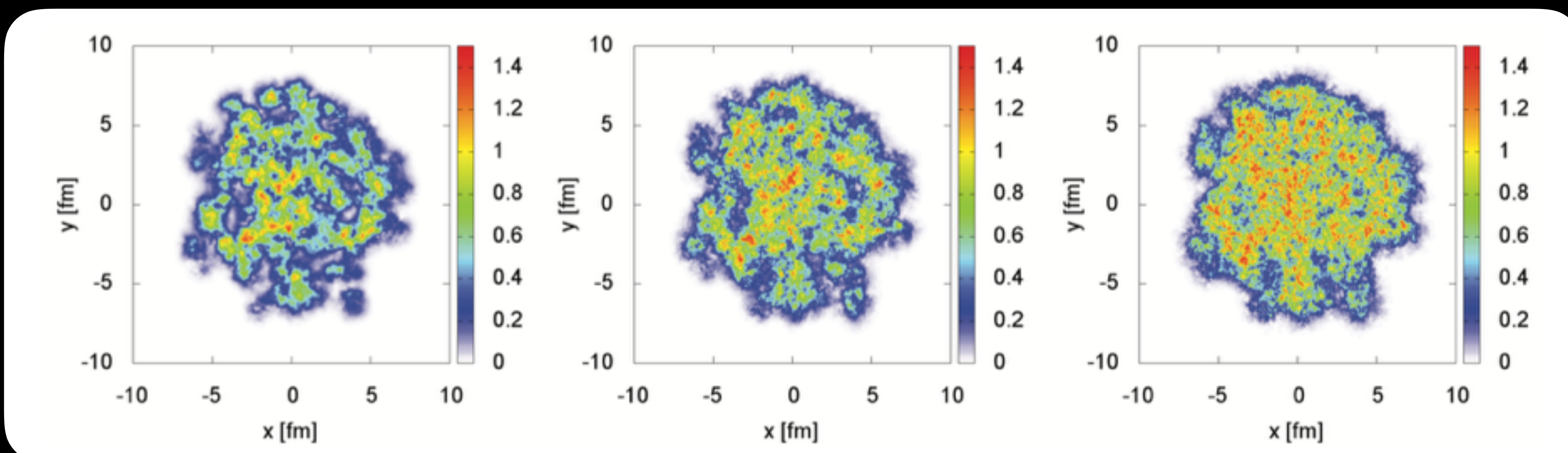
3D GLASMA INITIAL STATE

B. SCHENKE, S. SCHLICHTING, ARXIV:1605.07158, SUBMITTED TO PRC

EXISTING 3D INITIAL STATE MODELS ARE VERY SIMPLISTIC

NOW DO A FIRST PRINCIPLES 3D CALCULATION USING CLASSICAL YANG-MILLS + QCD JIMWLK EVOLUTION

GLUON FIELDS IN A NUCLEUS AT DIFFERENT *x*:

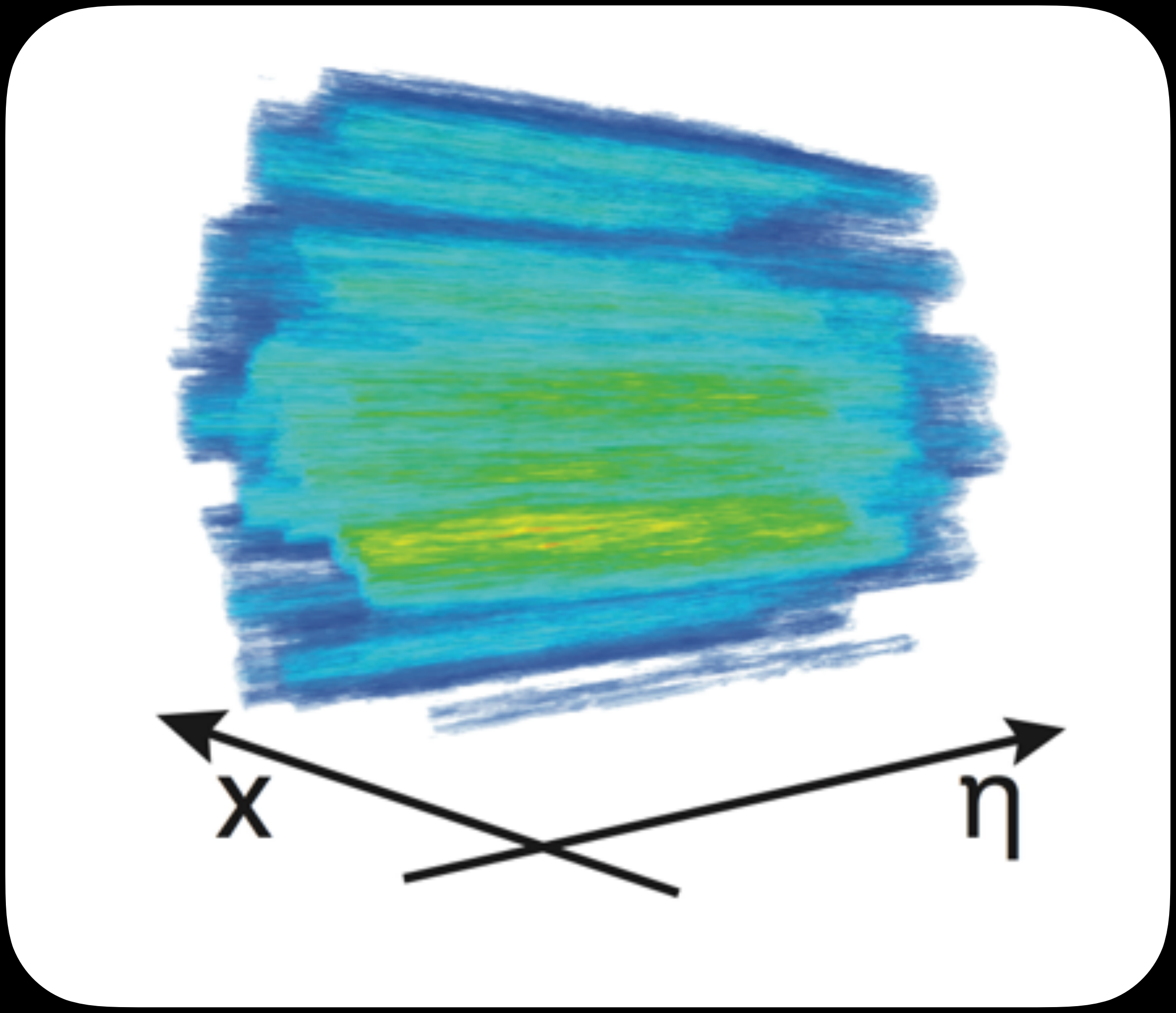


$Y = -2.4$ ($x \approx 2\times10^{-3}$) $Y = 0$ ($x \approx 2\times10^{-4}$) $Y = 2.4$ ($x \approx 1.6\times10^{-5}$)

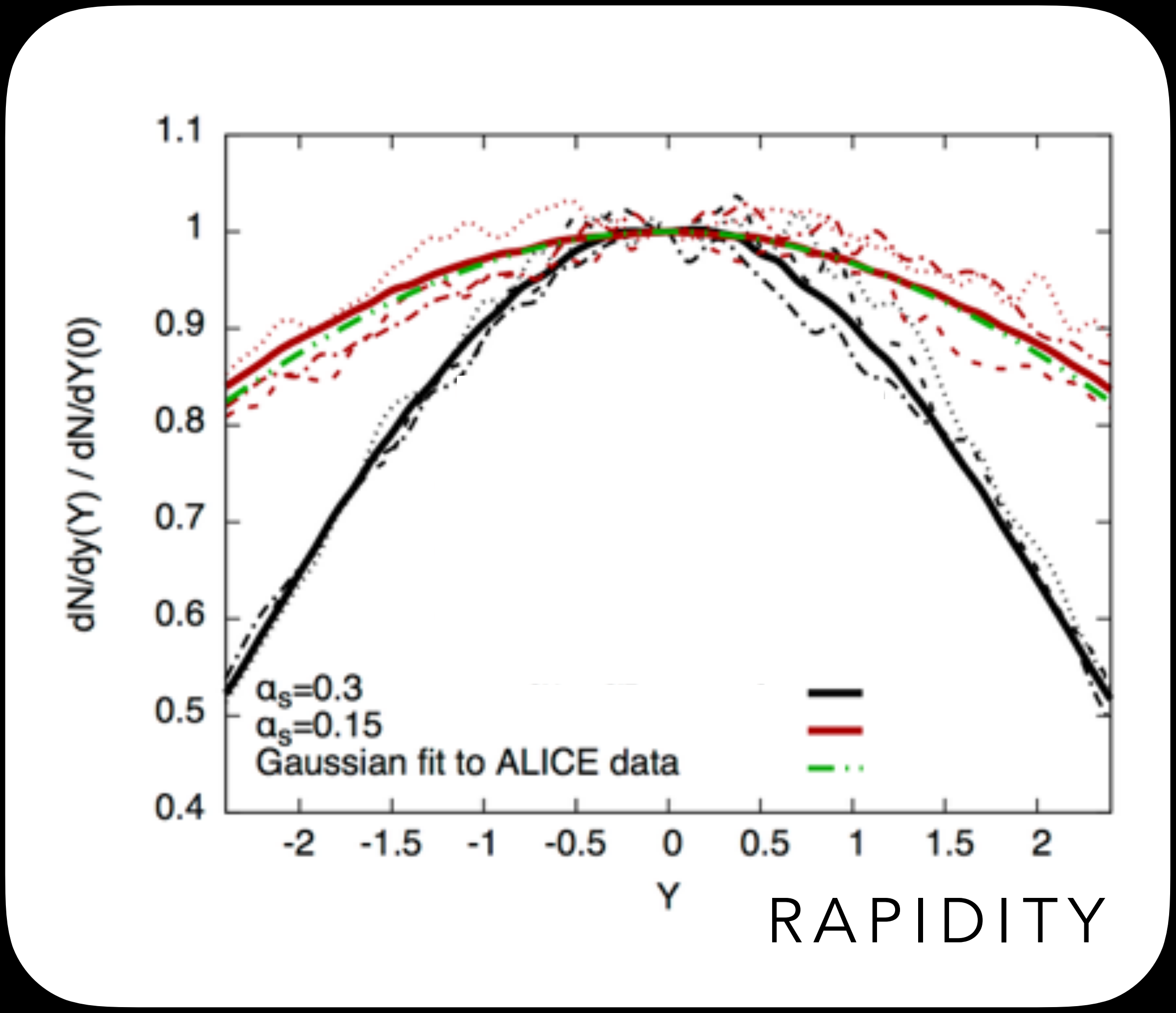
3D GLASMA INITIAL STATE

B. SCHENKE, S. SCHLICHTING, ARXIV:1605.07158, SUBMITTED TO PRC

- COLLIDE TWO JIMWLK EVOLVED NUCLEI



ENERGY DENSITY



GLUON MULTIPLICITY