THE PHOTON ANISOTROPY PUZZLE AND COLLISIONS OF DEFORMED NUCLEI: EFFECTS OF THE GLASMA

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

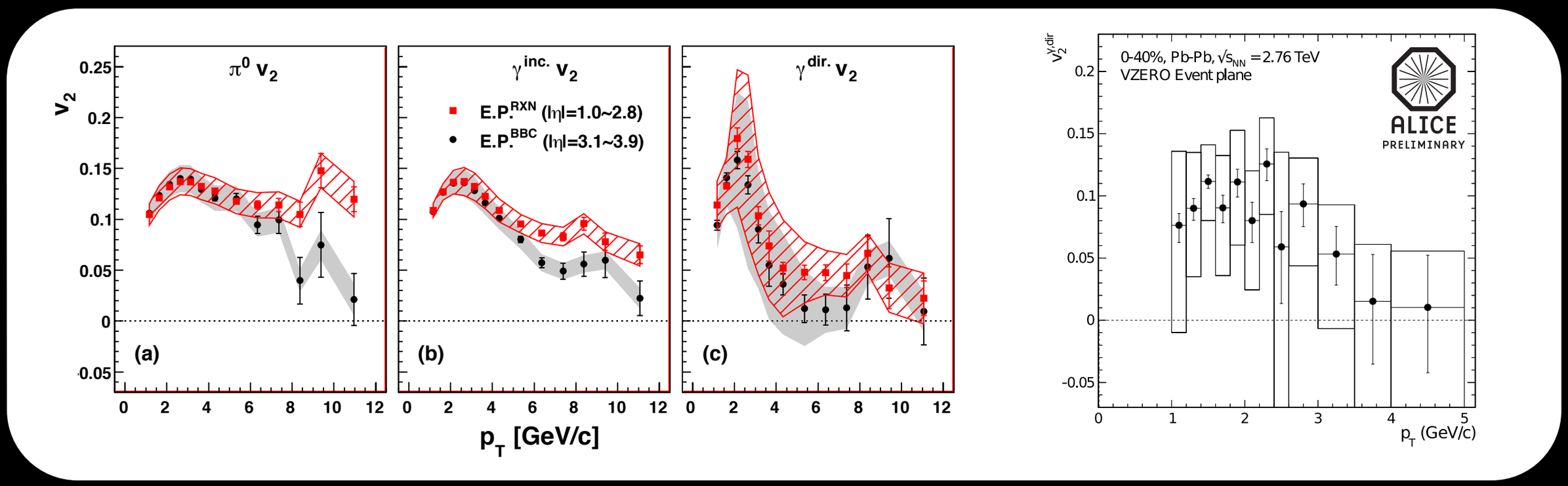
RHIC & AGS ANNUAL
USERS' MEETING 2014
JUNE 17 2014

BROOKHAVEN
NATIONAL LABORATORY

PHOTON AZIMUTHAL ANISOTROPY

Puzzle: Direct photon elliptic anisotropy is as large as that for pions (at RHIC & LHC)

QM2014: Also large photon v_3

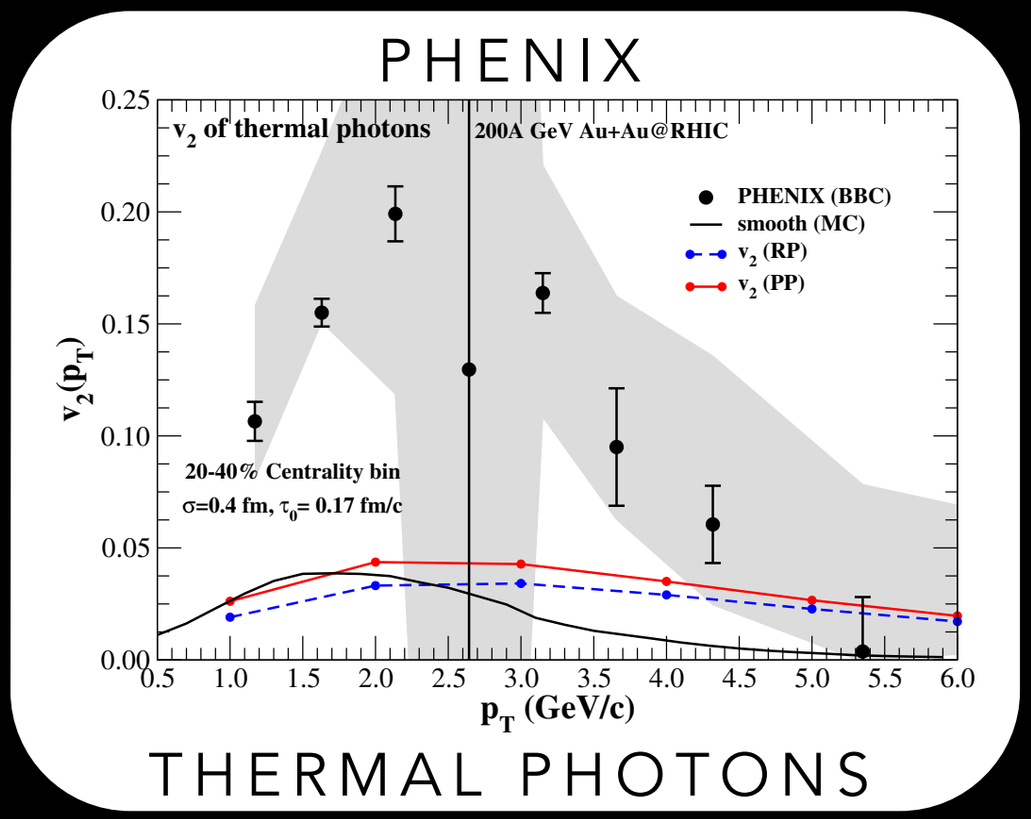


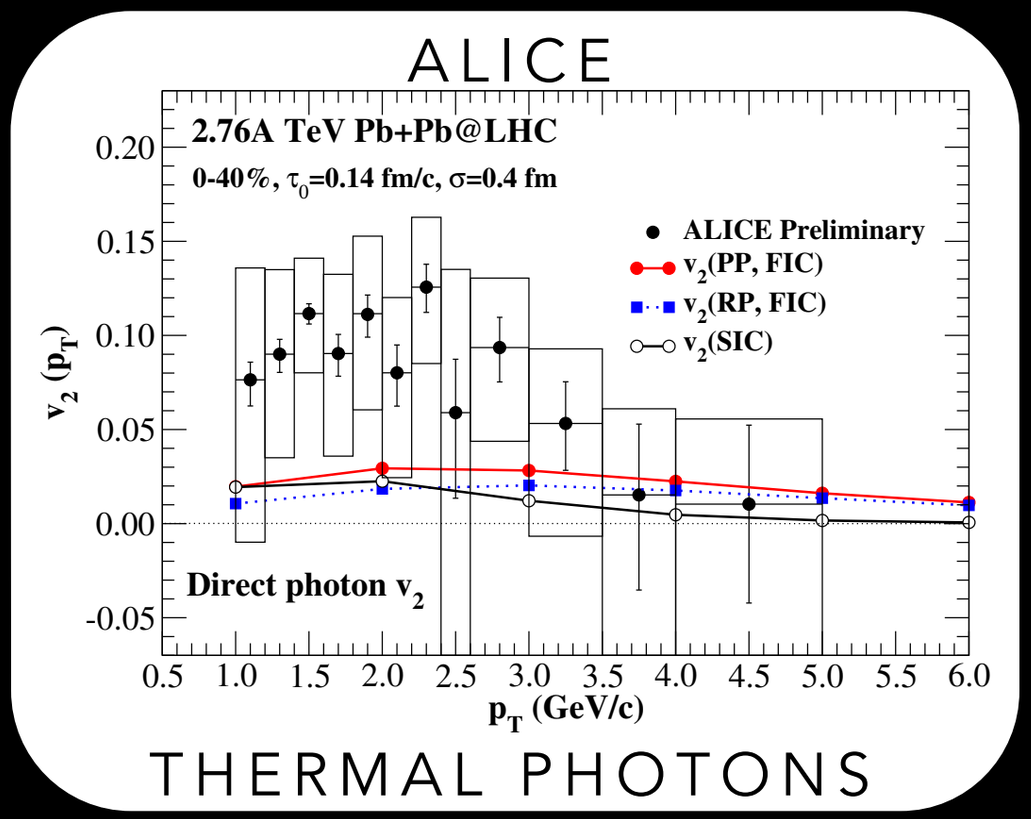
PHENIX, PHYS. REV. LETT. 109, 122302 (2012) ALICE, J.PHYS.CONF.SER. 446 (2013) 012028

Calculations have a problem describing this

PHOTON AZIMUTHAL ANISOTROPY

Problem: Photons are produced mostly early in the collision when flow is not yet built up





CHATTERJEE, HOLOPAINEN, HELENIUS, RENK, ESKOLA, PHYS.REV. C88 (2013) 034901

ALSO:

FIREBALL MODEL: VAN HEES, GALE, RAPP, PHYS.REV. C84 (2011) 054906
HYDRO: DION, PAQUET, SCHENKE, YOUNG, JEON, GALE, PHYS.REV. C84 (2011) 064901
PHSD: LINNYK, KONCHAKOVSKI, CASSING, BRATKOVSKAYA, PHYS.REV. C88 (2013) 034904
HYDRO: SHEN, HEINZ, PAQUET, KOZLOV, GALE, ARXIV:1308.2111, ARXIV:1403.7558

LATEST IP-GLASMA+MUSIC RESULTS

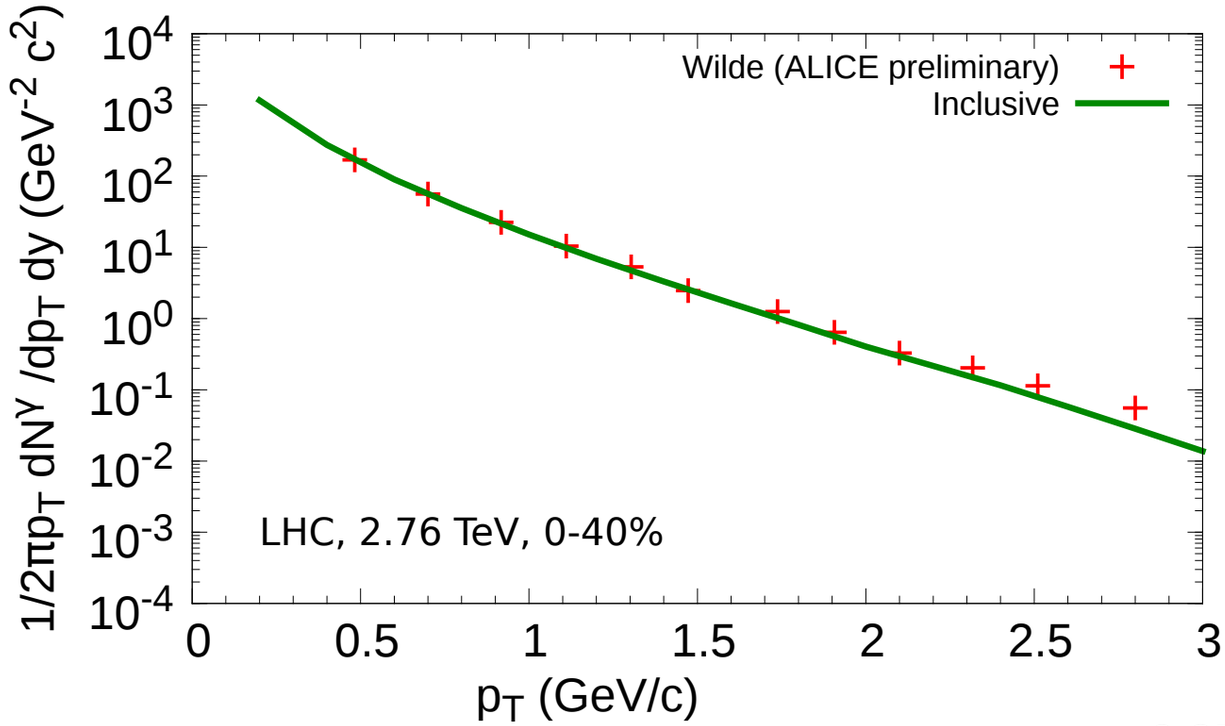
PAQUET, SHEN, VUJANOVIC, DENICOL, SCHENKE, LUZUM, HEINZ, JEON, GALE

Combine the following photon sources:

- prompt: NLO pQCD with nPDF, N_{coll} scaled
- thermal: fluid dynamics + QGP-, meson gas-, baryonic thermal photon rates
- hadronic decays: $\pi^0 \to \gamma\gamma, \eta \to \gamma\gamma, \omega \to \pi^0\gamma, \ldots$
- jet-medium interaction and pre-equilibrium production not yet included
- pre-equilibrium flow is built up in IP-Glasma

LATEST IP-GLASMA+MUSIC RESULTS

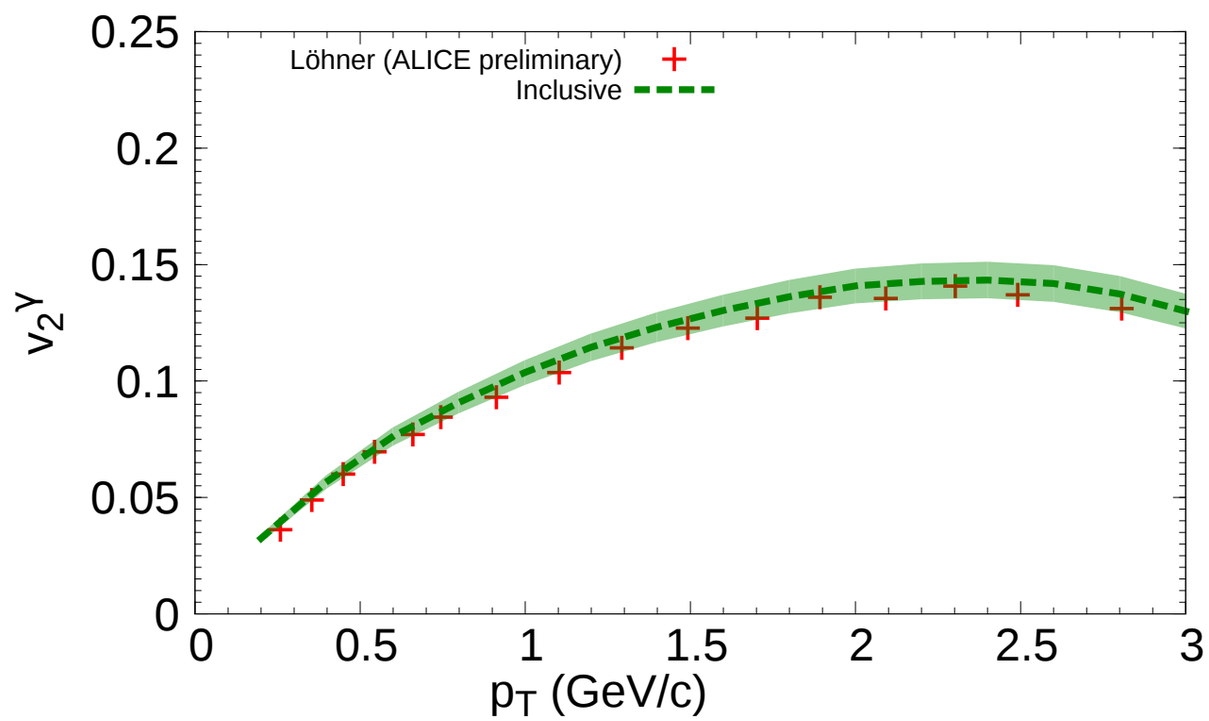
PAQUET, SHEN, VUJANOVIC, DENICOL, SCHENKE, LUZUM, HEINZ, JEON, GALE



Inclusive photons

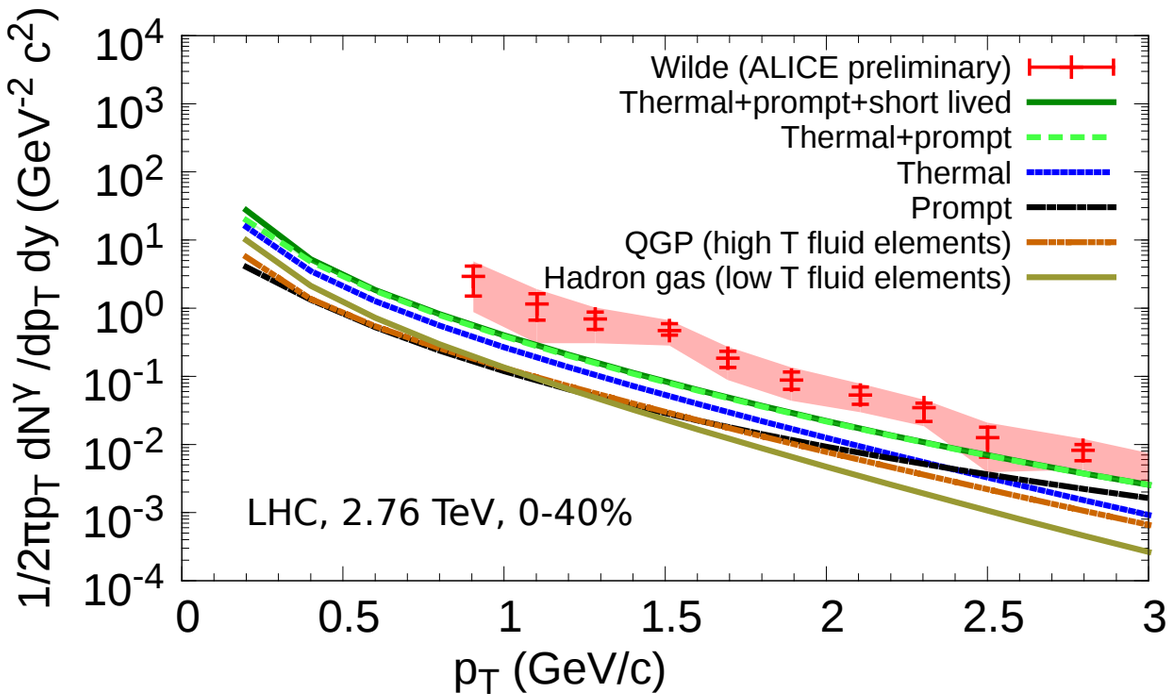
D. LOHNER [ALICE]
PHD THESIS, U. OF HEIDELBERG (2013)

M. WILDE [ALICE]
NUCL. PHYS. A 904-905 (2013) 573C



LATEST IP-GLASMA+MUSIC RESULTS

PAQUET, SHEN, VUJANOVIC, DENICOL, SCHENKE, LUZUM, HEINZ, JEON, GALE



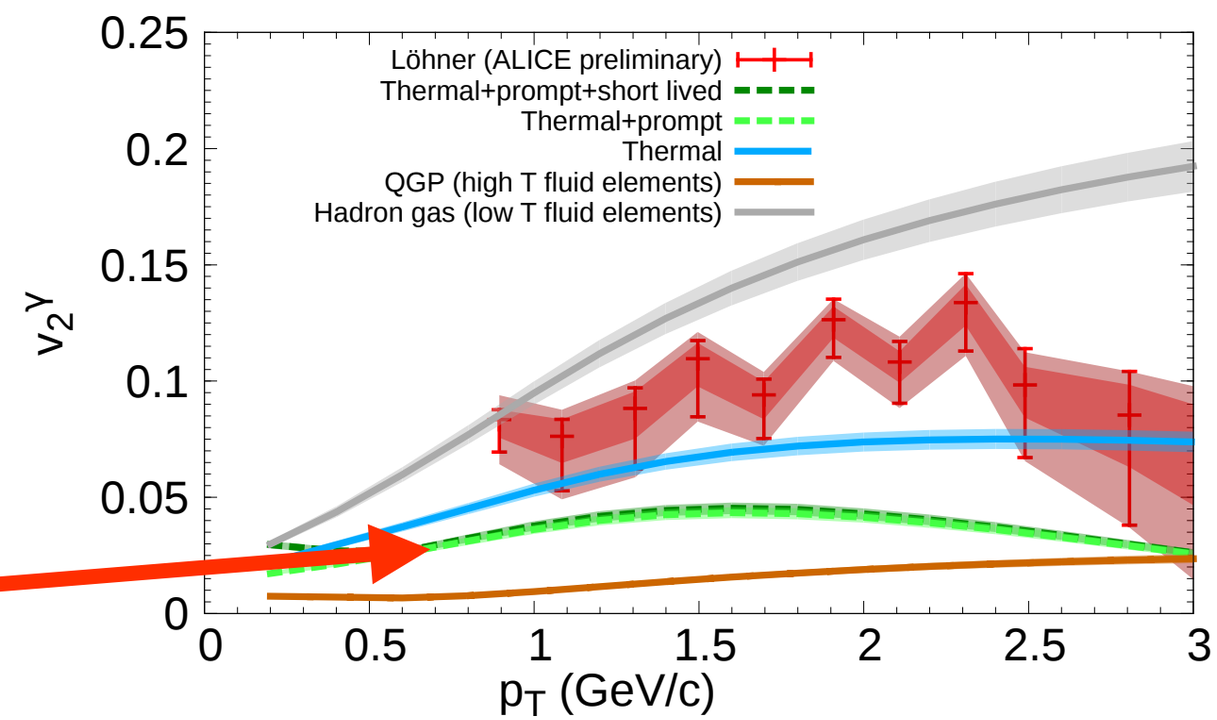
Direct photons

D. LOHNER [ALICE]
PHD THESIS, U. OF HEIDELBERG (2013)

M. WILDE [ALICE]
NUCL. PHYS. A 904-905 (2013) 573C

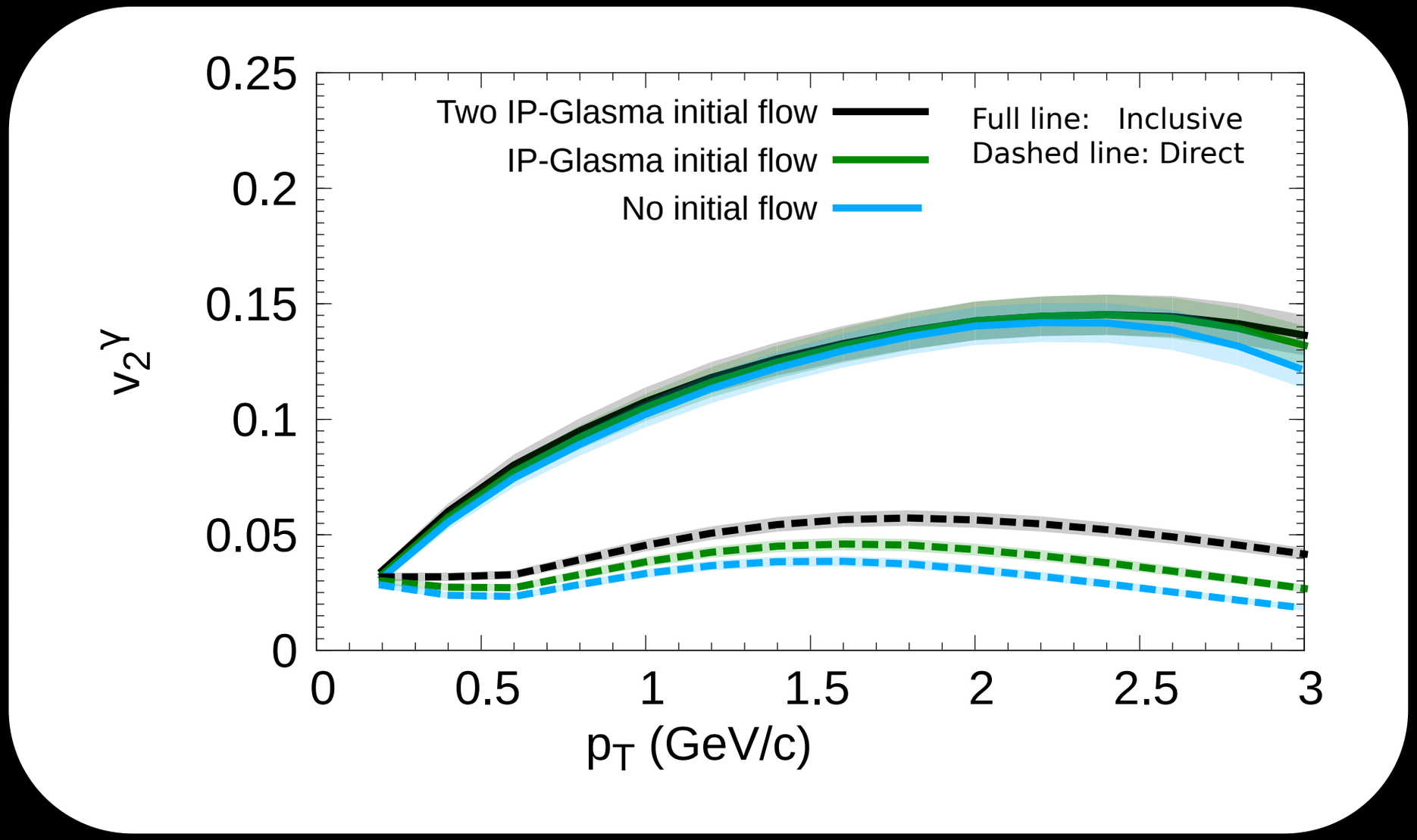
Calculated spectra underestimate data

Full result for v_2 too low



EFFECT OF PRE-EQUILIBRIUM FLOW

PAQUET, SHEN, VUJANOVIC, DENICOL, SCHENKE, LUZUM, HEINZ, JEON, GALE



Small effect (switching to hydro at $\tau_0 = 0.4\,\mathrm{fm}/c$)

PHOTON AZIMUTHAL ANISOTROPY

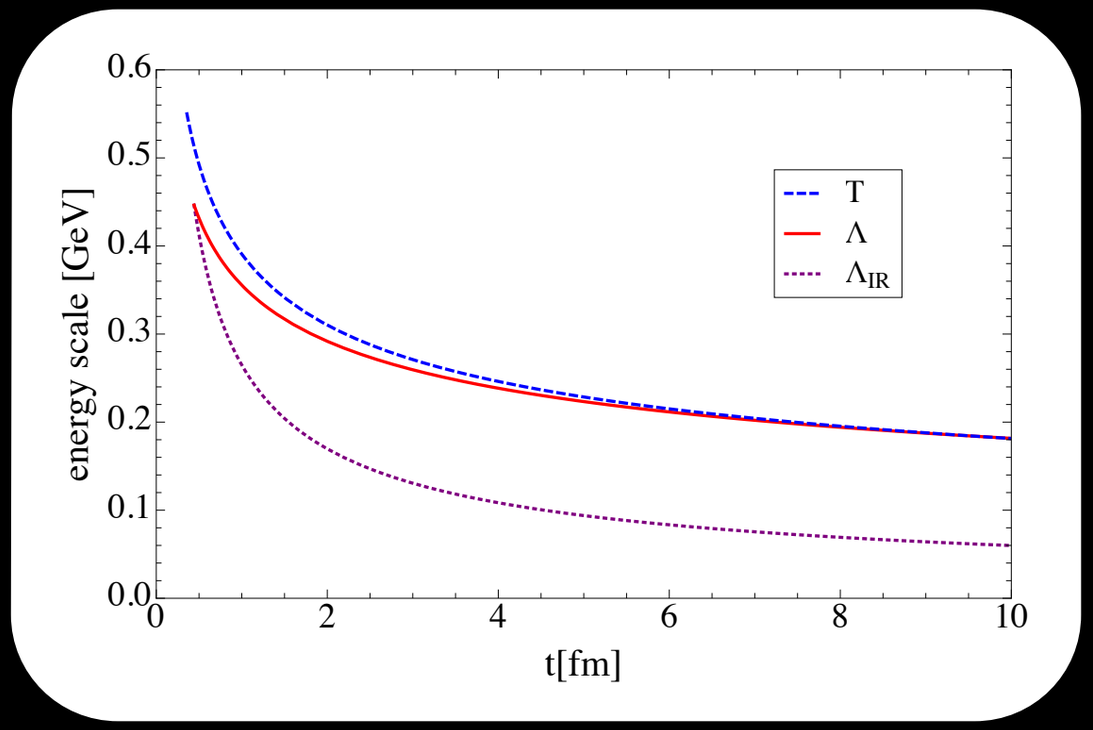
What can help?

- Strong Magnetic field and conformal anomaly
  BASAR, KHARZEEV, SKOKOV, PHYS.REV.LETT. 109 (2012) 202303
  BASAR, KHARZEEV, SHURYAK, ARXIV:1402.2286
- Photon enhancement around T_C
  VAN HEES, HE, RAPP, ARXIV:1404.2846
- Generally a suppression of the photon yield from early times or a delay of photon emission
  LIU, LIU, PHYS.REV. C89 (2014) 034906
  SEMI-QGP: LIN @QM2014
- Glasma evolution ⟶ this talk
  MCLERRAN, SCHENKE, ARXIV:1403.7462, TO APPEAR IN NUCL.PHYS.A

SIMPLE GLASMA DYNAMICS

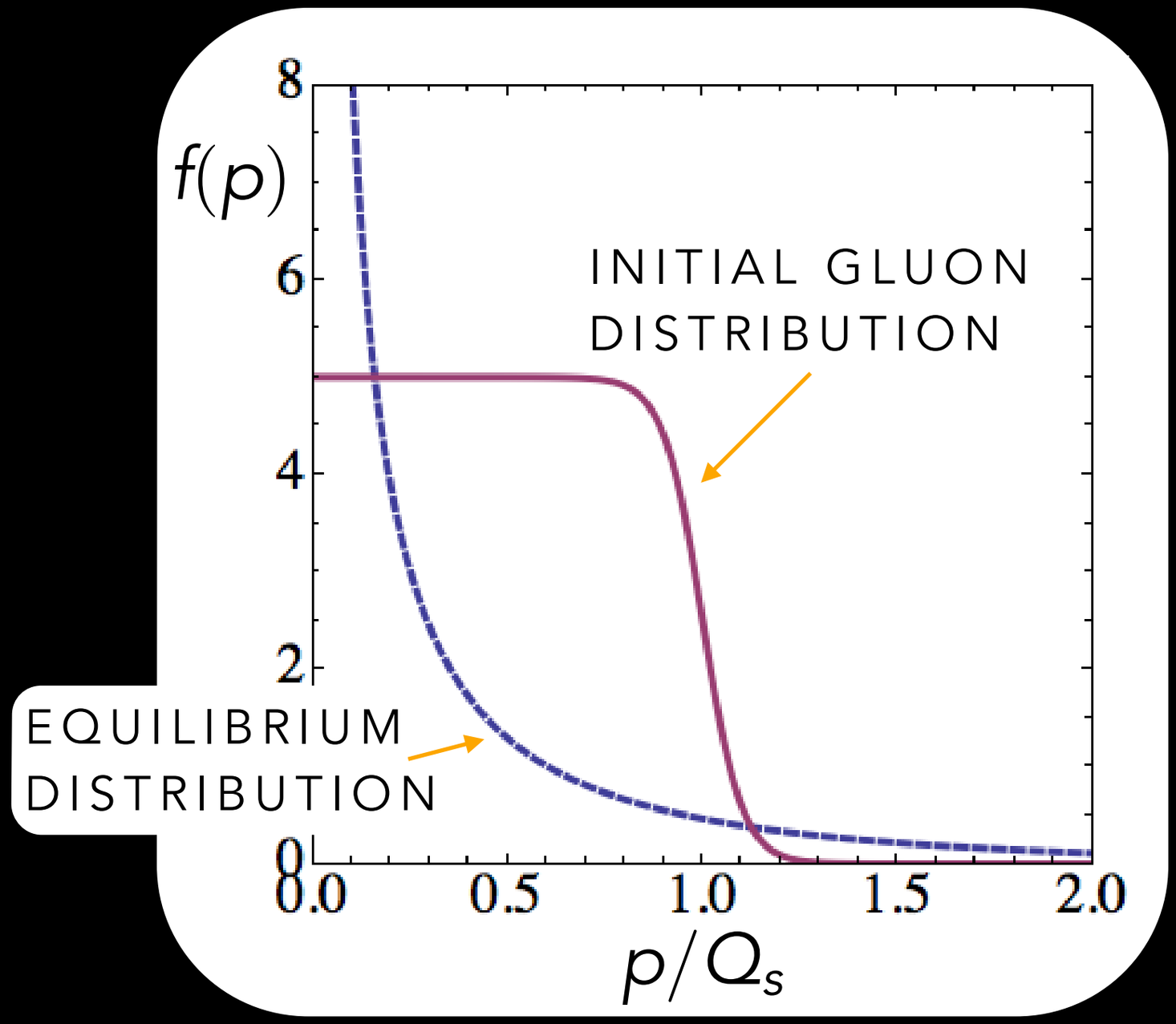
BLAIZOT, GELIS, LIAO, MCLERRAN, VENUGOPALAN, NUCL.PHYS. A873 (2012) 68-80

- Initially: High gluon density and one scale $Q_s = \Lambda_{\mathrm{IR}} = \Lambda$
- Elastic scattering is enhanced by large occupation numbers
- Separation of scales must happen towards thermalization $\Lambda_{\mathrm{IR}} \to \alpha_s \Lambda$



OVER-OCCUPATION

BLAIZOT, GELIS, LIAO, MCLERRAN, VENUGOPALAN, NUCL.PHYS. A873 (2012) 68-80



MODEL FOR GLASMA EVOLUTION

$$f_g(E) = \frac{\kappa \Lambda_{IR}}{N_c \alpha_s \Lambda} \frac{1}{e^{E/\Lambda} - 1}$$

over-occupied gluon distribution becomes thermal when

$$\Lambda_{IR} = \frac{N_c \alpha_s}{\kappa} \Lambda$$

κ is a constant related to $N_{\mathrm{gluon}}/N_{\mathrm{quarks}}$

$$f_q(E) = \frac{1}{e^{E/\Lambda} + 1}$$

quark distribution

Energy densities:

$$\varepsilon_g = \frac{\pi^2}{30} 2(N_c^2 - 1) \frac{\kappa}{N_c \alpha_s} \Lambda_{IR} \Lambda^3$$

$$\varepsilon_q = \frac{\pi^2}{30} 4 N_c N_f \frac{7}{8} \Lambda^4$$

MODEL FOR GLASMA EVOLUTION

Identify time with collision time in transport equations

BLAIZOT, GELIS, LIAO, MCLERRAN, VENUGOPALAN, NUCL.PHYS. A873 (2012) 68-80

$$t \sim \Lambda/\Lambda_{IR}^2$$

Energy density scales as

$\varepsilon \sim 1/t^{1+\delta}$ for simplicity (could also use 3D hydro)

$\delta = 1/3$ isotropic system

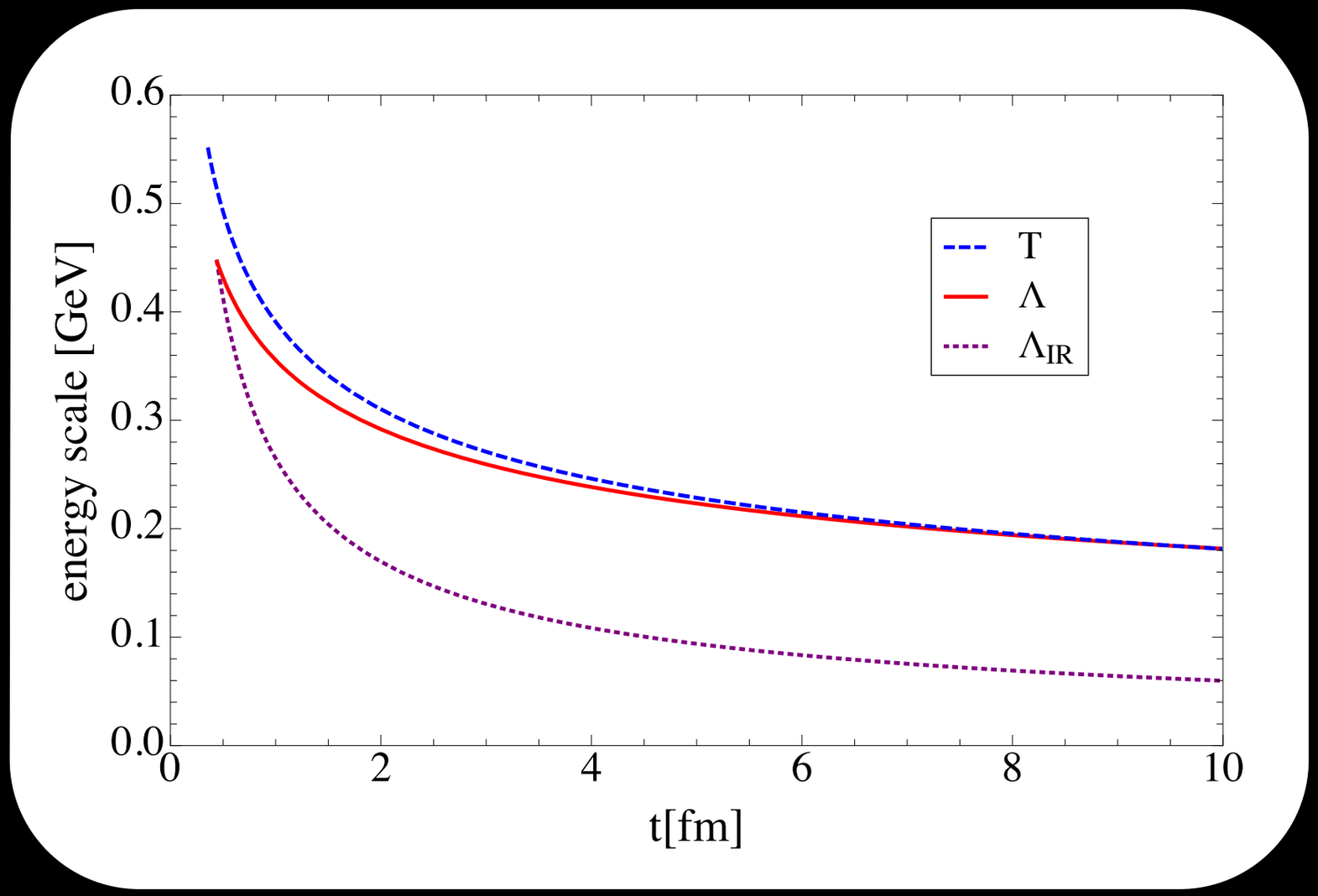
$\delta \neq 1/3$ pressure anisotropy

We can now solve for $\Lambda(t)$ and $\Lambda_{IR}(t)$

EVOLUTION OF ENERGY SCALES

MCLERRAN, SCHENKE, ARXIV:1403.7462, TO APPEAR IN NPA

$T_0 = 550\,\mathrm{MeV}, \alpha_s = 0.3, N_c = 3, \kappa = 3, \delta = 1/3$



Initial values are fixed by requiring energy conservation at time of "thermalization", when $\frac{\kappa \Lambda_{IR}}{\Lambda N_c \alpha_s} = 1 \quad (\Lambda_{\mathrm{IR}} \sim \alpha_s \Lambda)$

Here $t_{th} = 9.7\,\mathrm{fm}/c$

PHOTON PRODUCTION

MCLERRAN, SCHENKE, ARXIV:1403.7462, TO APPEAR IN NPA

UV-scale starts out lower and drops more slowly than T

This will shift photon production to later times

Production rates (Compton+annihilation):

J.I. KAPUSTA, P. LICHARD, D. SEIBERT, PHYS. REV. D 44 (1991) 2774

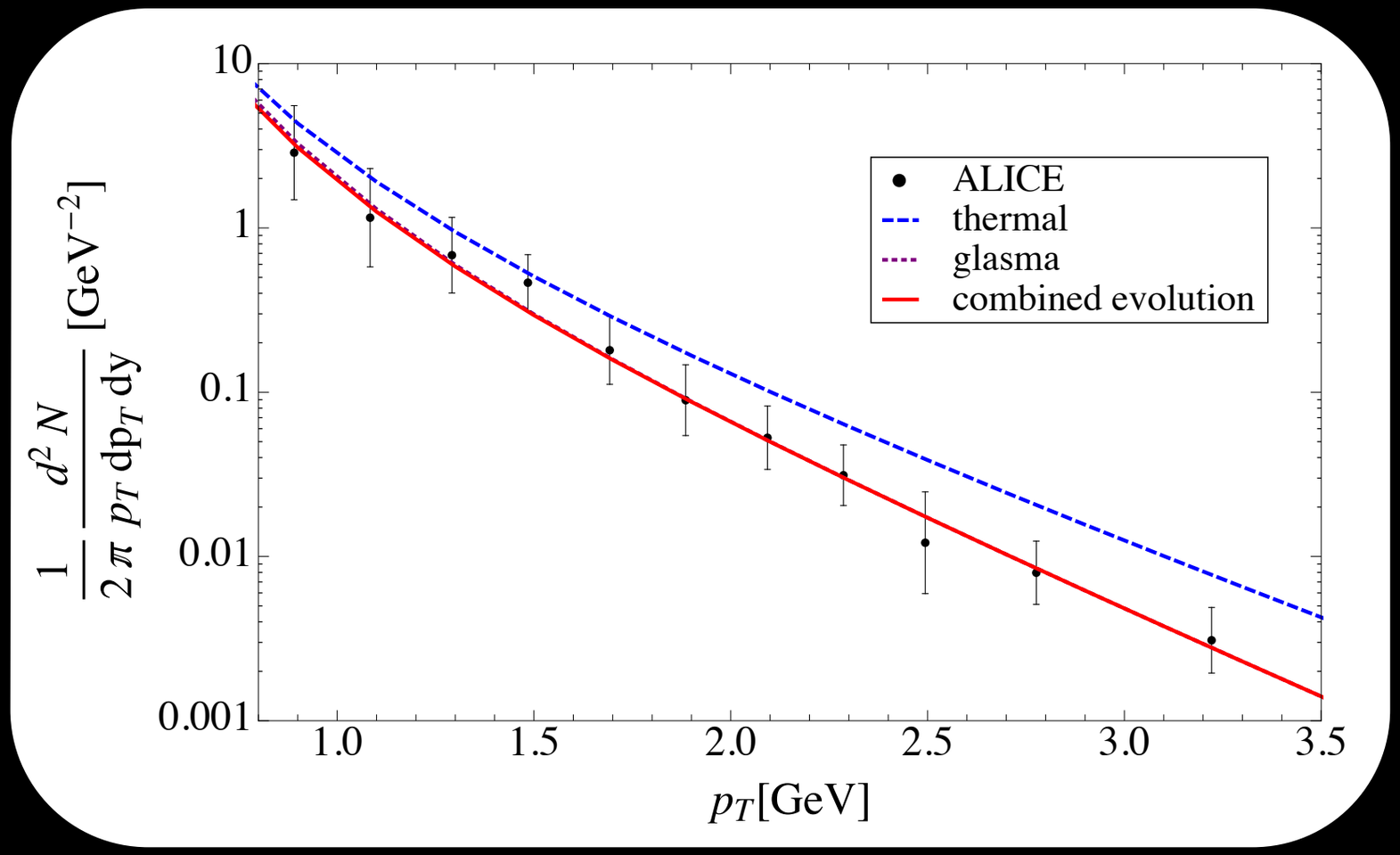
$$E\frac{dN_{\rm thermal}}{d^4x d^3p} = \frac{5}{9}\frac{\alpha_s\alpha}{2\pi^2}T^2 e^{-E/T}\ln\left(\frac{2.912E}{4\pi\alpha_s T}\right)$$

$$E\frac{dN_{\rm Glasma}}{d^4x d^3p} = \frac{5}{9}\frac{\alpha}{2\pi^2}\frac{\kappa}{N_c}\Lambda_{IR}\Lambda e^{-E/\Lambda}\ln\left(\frac{2.912EN_c}{4\pi\kappa\Lambda_{IR}}\right)$$

PHOTON PRODUCTION

MCLERRAN, SCHENKE, ARXIV:1403.7462, TO APPEAR IN NPA

Photon yields follow from time integration



K-factor of 7 (lots of sources are missing…)

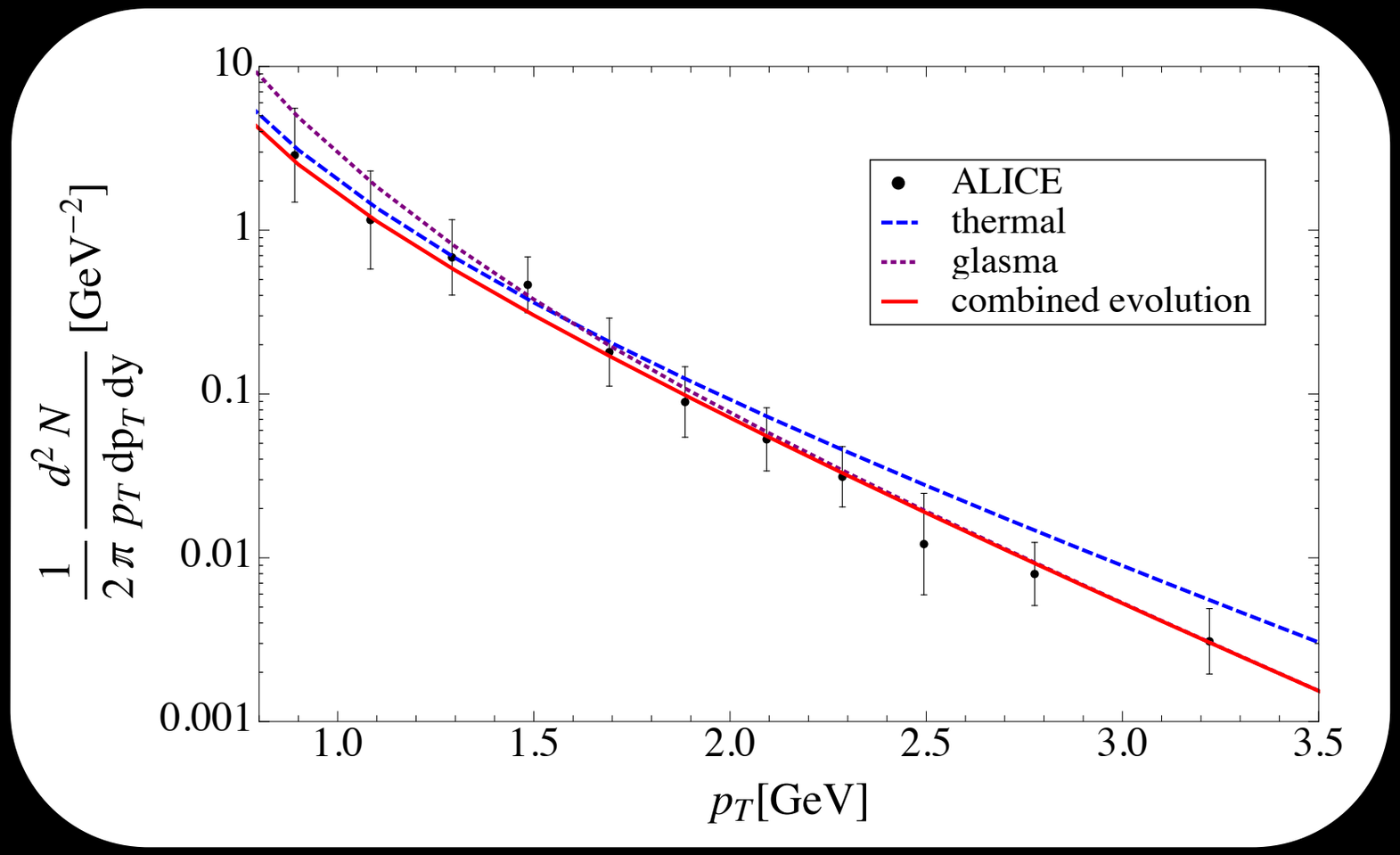
$\kappa = 3, \delta = 1/3$ ISOTROPIC

Glasma spectrum suppressed and steeper

PHOTON PRODUCTION

MCLERRAN, SCHENKE, ARXIV:1403.7462, TO APPEAR IN NPA

Photon yields follow from time integration



K-factor of 7 (lots of sources are missing…)

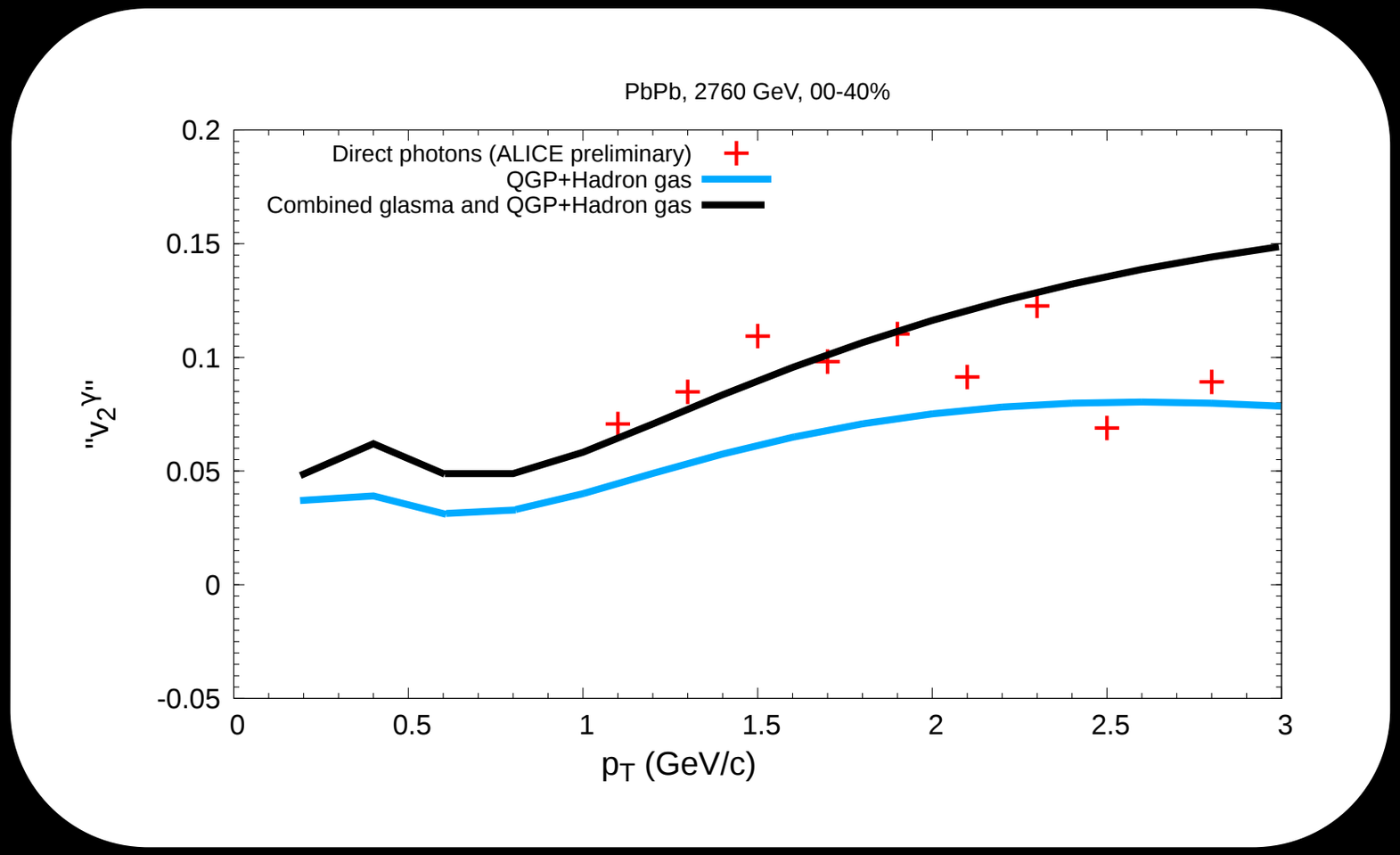
$\kappa = 3, \delta = 1/4$ ANISOTROPIC

Glasma spectrum suppressed and steeper

FIRST FULL HYDRO RESULTS

PAQUET, GALE, JEON, MCLERRAN, SCHENKE, WORK IN PROGRESS

MUSIC + Glasma rates vs. MUSIC + thermal rates

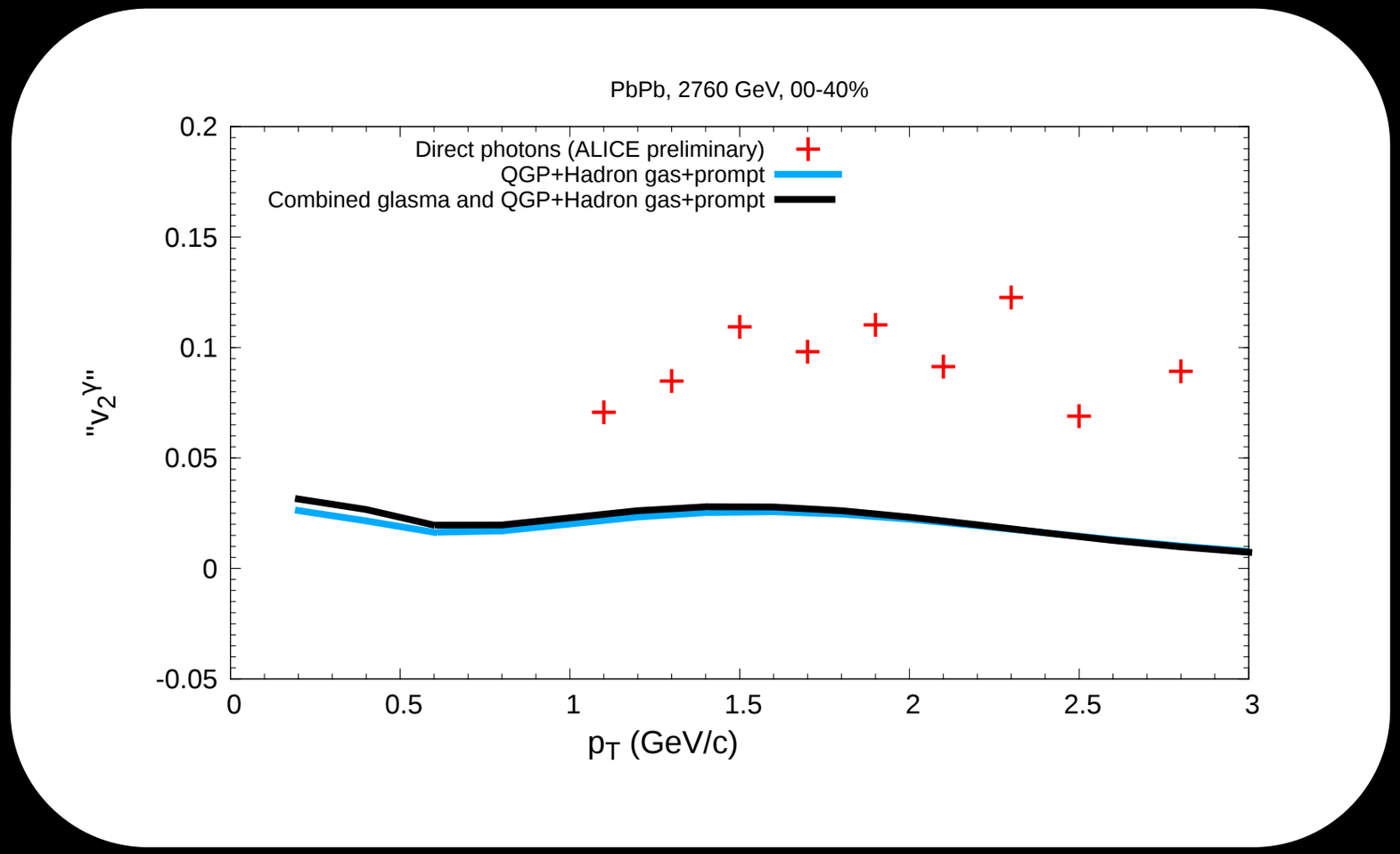


Mainly the suppression of the early time rates relative to the hadron gas production leads to the increase of photon elliptic anisotropy

FIRST FULL HYDRO RESULTS

PAQUET, GALE, JEON, MCLERRAN, SCHENKE, WORK IN PROGRESS

MUSIC + Glasma rates vs. MUSIC + thermal rates + prompt photons



Adding prompt photons reduces v_2 drastically…

DEFORMED NUCLEI

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232, TO APPEAR IN PRC

- U+U collisions can produce larger elliptic flow in central collisions, because of their deformation
- This can help to disentangle effects of strong magnetic fields and collective flow
- We show that it can also constrain the mechanism of particle production

DEFORMED NUCLEI

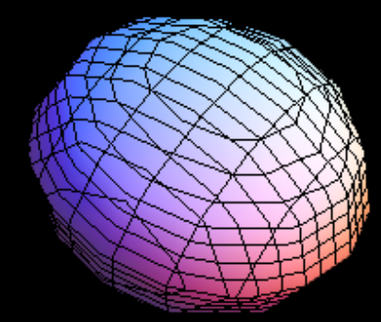
B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232, TO APPEAR IN PRC

Deformation is parametrized in the Woods-Saxon distribution as

$$\rho(r) = \frac{\rho_0}{1 + \exp([r - R']/a)}$$

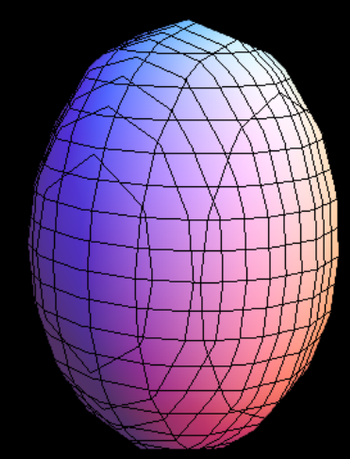
$$R' = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

with spherical harmonics Y_l^m



Au

dramatization

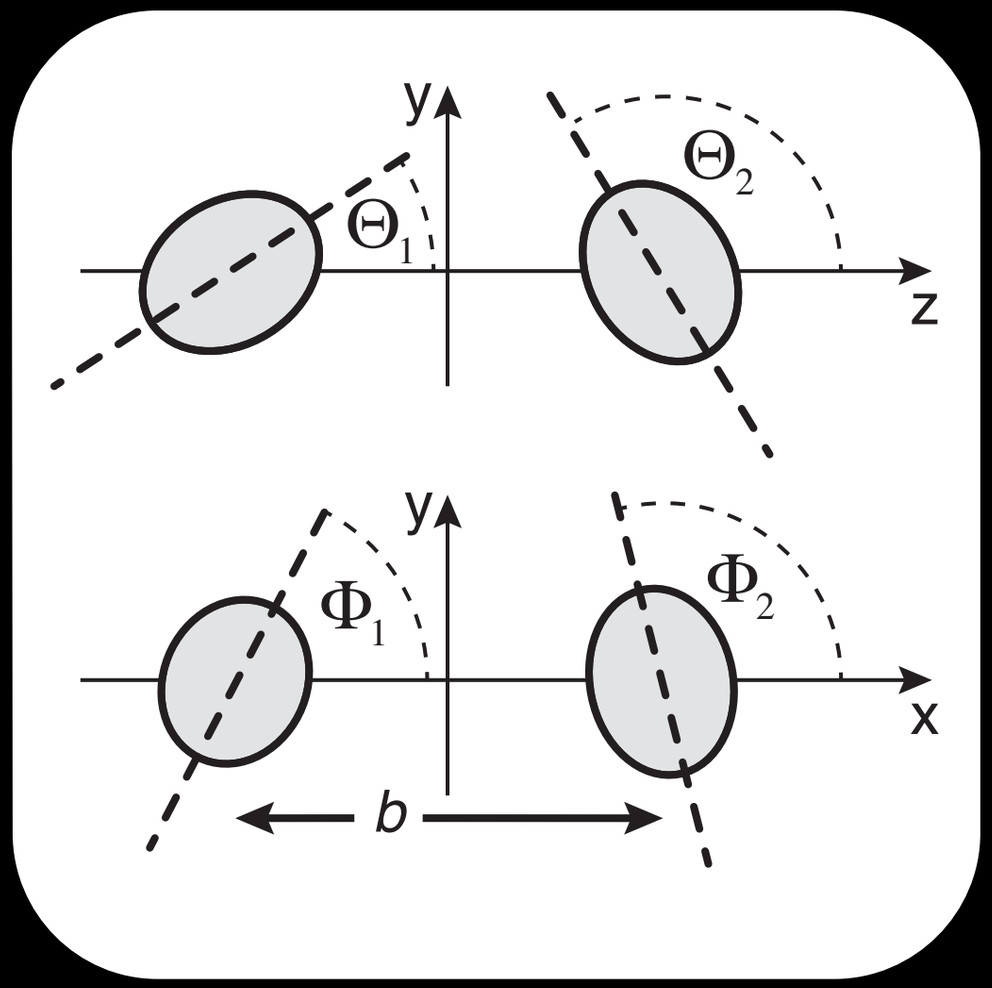


U

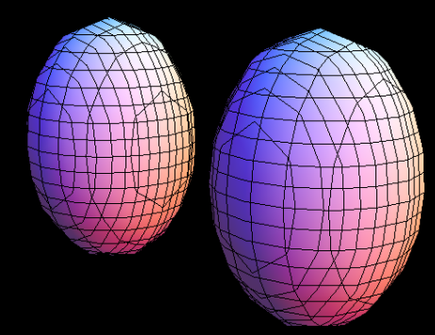
COLLISIONS OF DEFORMED NUCLEI

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232, TO APPEAR IN PRC

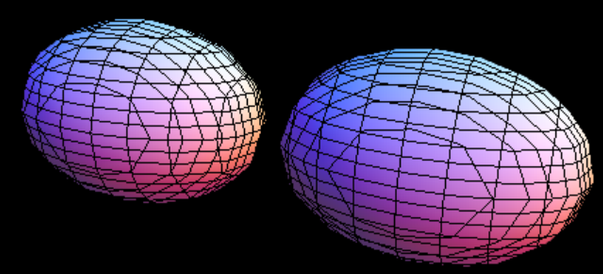
- Fluctuations in impact parameter and 4 angles



SPECIAL CASES:



U+U, SIDE-SIDE

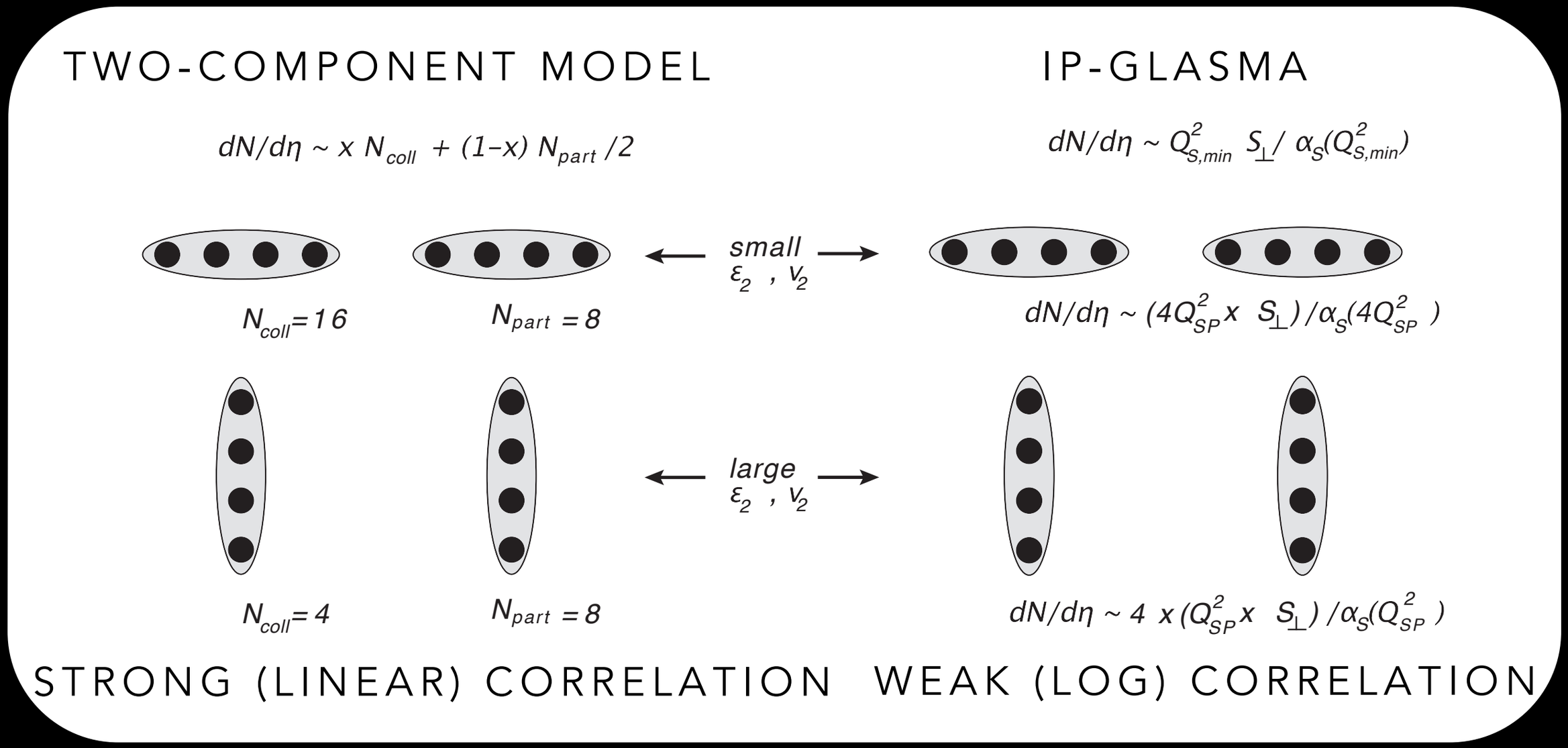


U+U, TIP-TIP

SHAPE-MULTIPLICITY CORRELATIONS

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232, TO APPEAR IN PRC

in ultra-central collisions. Example U+U:



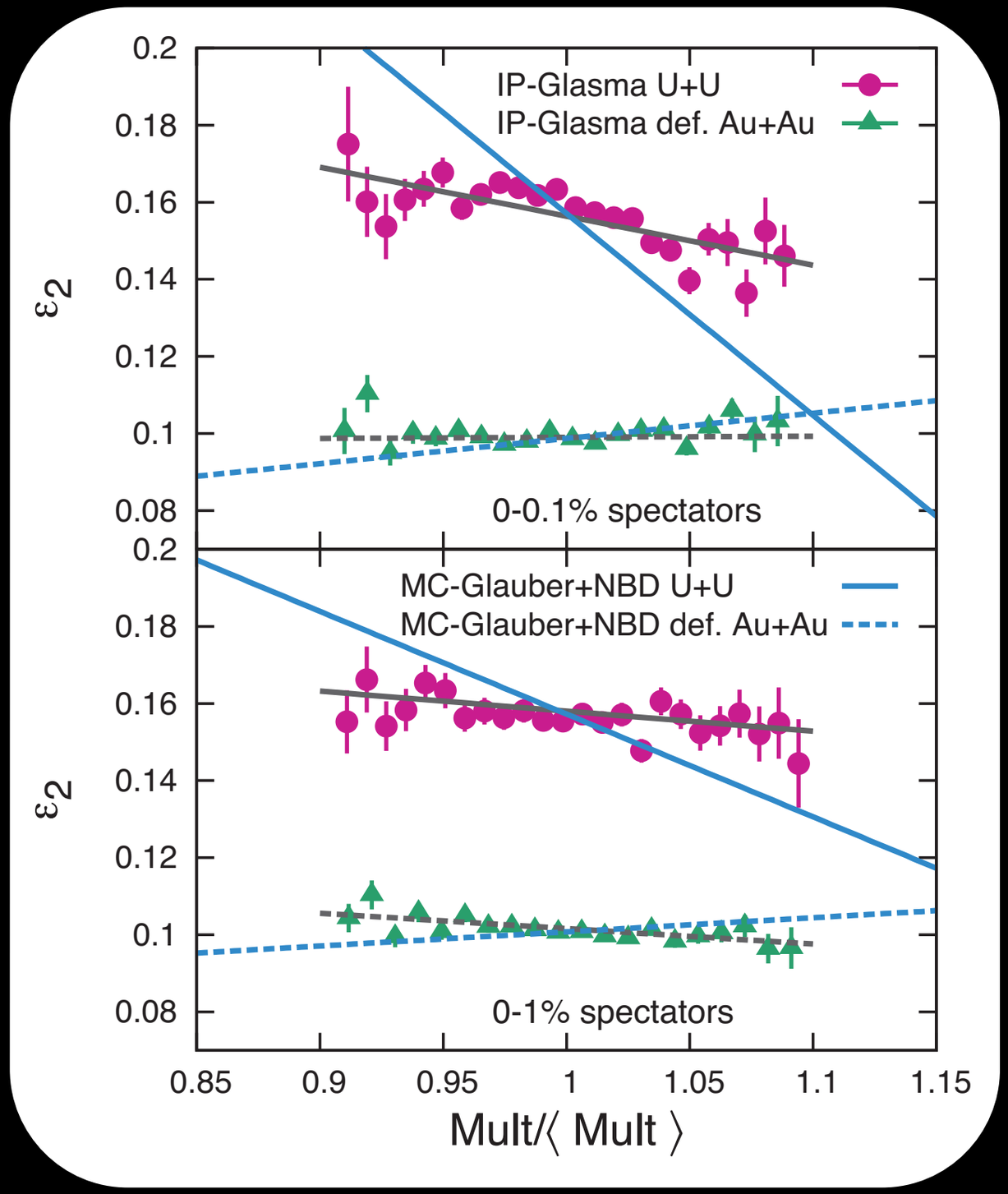
large $dN/d\eta \rightarrow$ small ε_2

small $dN/d\eta \rightarrow$ large ε_2

SHAPE-MULTIPLICITY CORRELATIONS

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232, TO APPEAR IN PRC

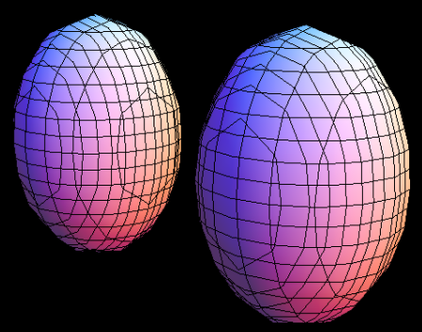
- Select ultra-central events based on neutrons in the ZDC
- Study correlation between ε_2 and multiplicity
- Correlation depends on model



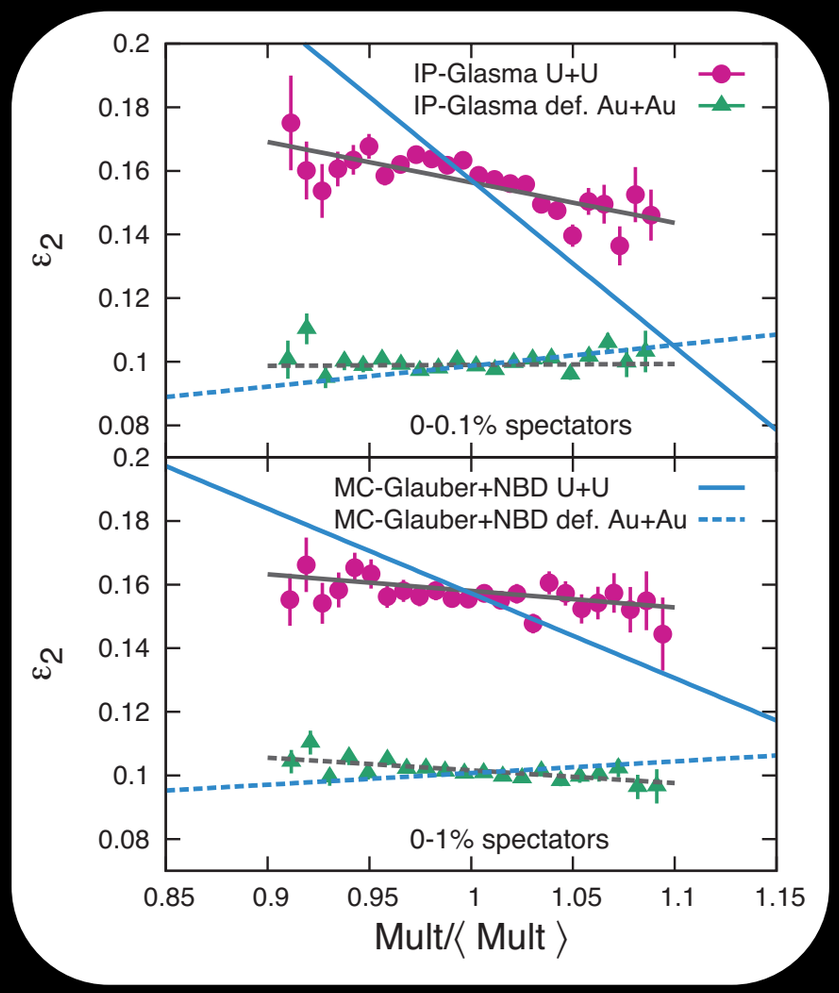
SHAPE-MULTIPLICITY CORRELATIONS

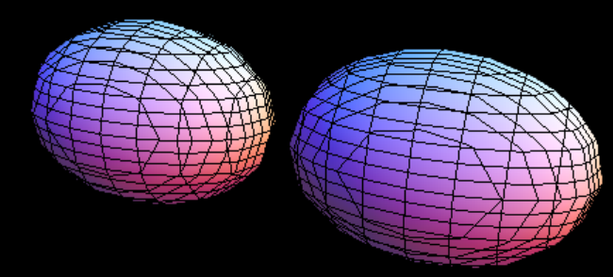
B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232

Uranium: prolate
Gold: oblate (?)

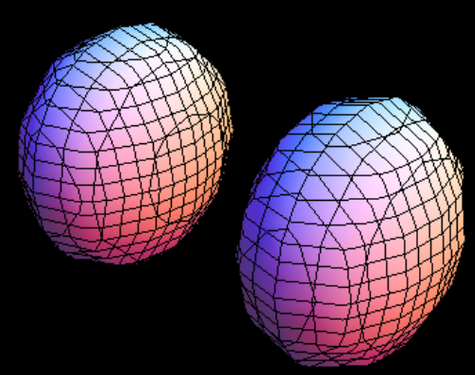


U+U, side-side

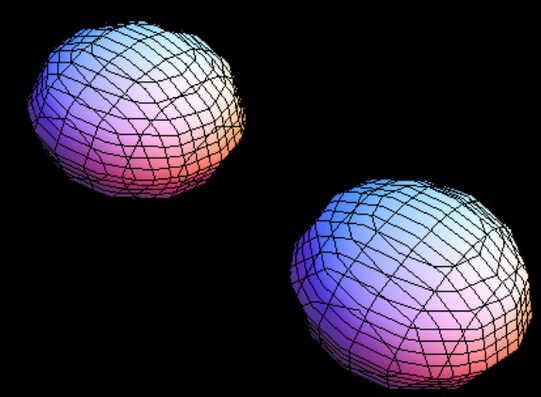




U+U, tip-tip



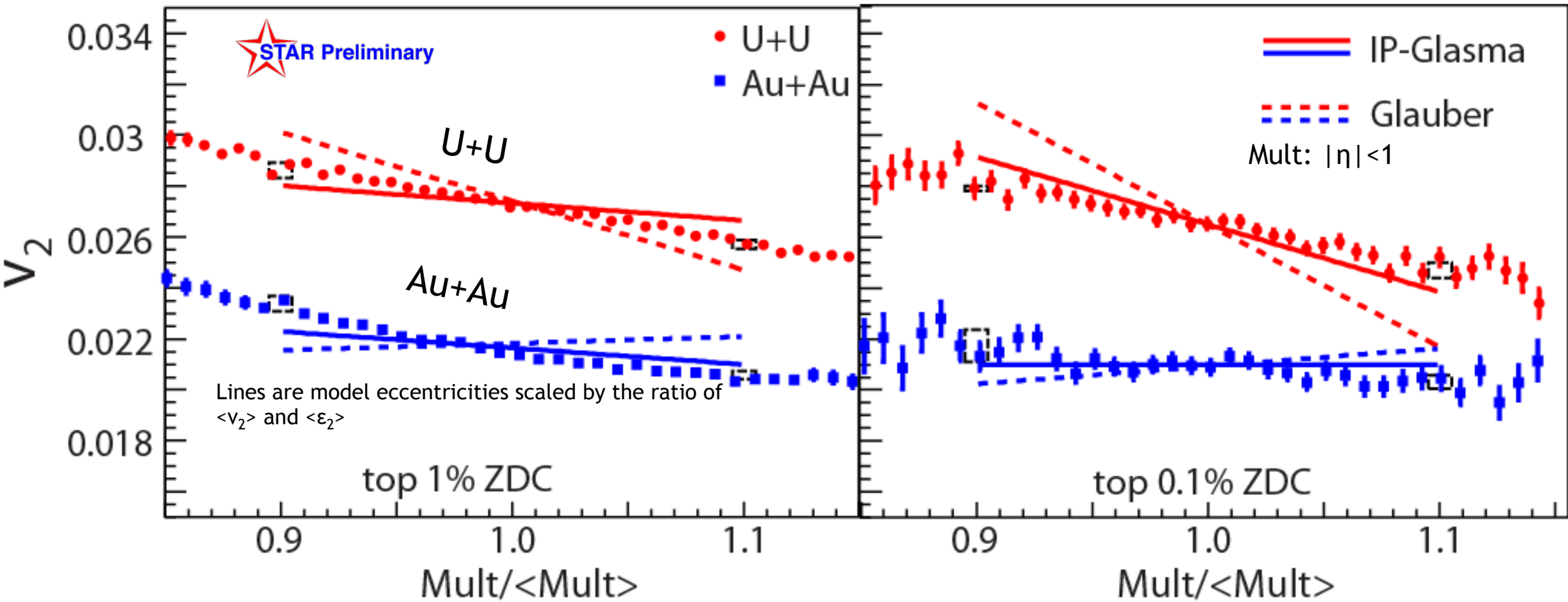
Au+Au, side-side



Au+Au, "tip-tip"

DEFORMED NUCLEI

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232, TO APPEAR IN PRC
EXPERIMENTAL DATA: STAR, HUI WANG AT QUARK MATTER 2014



SUMMARY

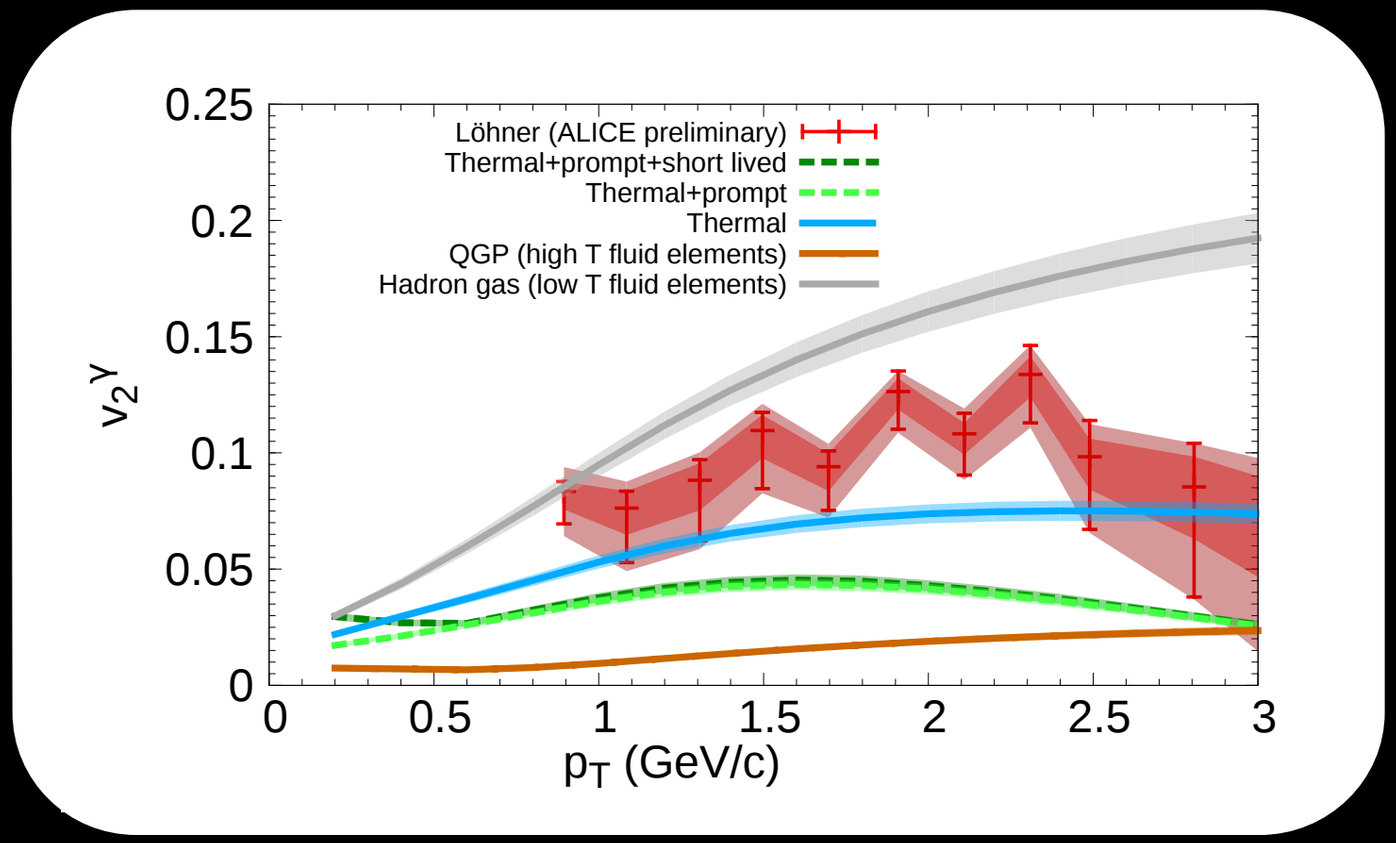
- Photon anisotropy remains a puzzle
- Mechanisms that reduce early photon emission help
- Glasma non-thermal evolution is one possibility
- Prompt photons are a big problem

- Deformed nuclei collisions can give insight into particle production mechanism, distinguish models
- IP-Glasma result of multiplicity-geometry correlation agrees better with preliminary STAR data than the two-component model

BACKUP

EXPERIMENTAL METHOD

D. LOHNER [ALICE], PHD THESIS, U. OF HEIDELBERG (2013)

Direct photon anisotropy

$$v_n^{\gamma,\mathrm{dir}} = \frac{R v_n^{\gamma,\mathrm{incl}} - v_n^{\gamma,\mathrm{cocktail}}}{R-1} \qquad \text{with } R = \frac{N^{\gamma,\mathrm{incl}}}{N^{\gamma,\mathrm{cocktail}}}$$