QGP Viscosity & Elliptic Flow for Multi-strange Hadrons

Huichao Song

Peking University

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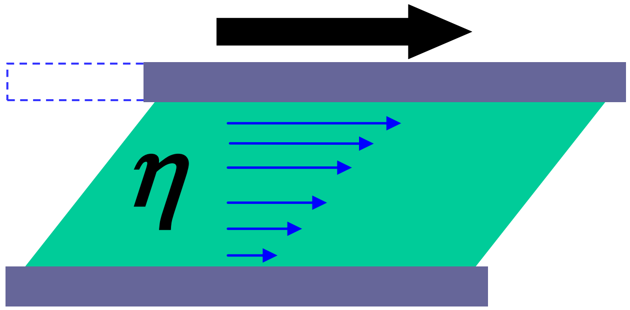
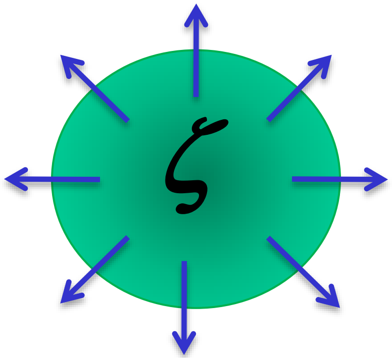
Shear viscosity:



Bulk viscosity:



viscous hydrodynamics

$$\partial_\mu T^{\mu\nu}(x)=0 \qquad T^{\mu\nu}=(e+p+\Pi)u^\mu u^\nu-(p+\Pi)g^{\mu\nu}+\pi^{\mu\nu}$$

$$\tau_\pi \Delta^{\alpha\mu}\Delta^{\beta\nu}\dot{\pi}_{\alpha\beta}+\pi^{\mu\nu}=2\eta\sigma^{\mu\nu}-\frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\lambda\left(\frac{\tau_\pi}{\eta T}u^\lambda\right)$$

$$\tau_\Pi\dot{\Pi}+\Pi=-\zeta(\partial\cdot u)-\frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

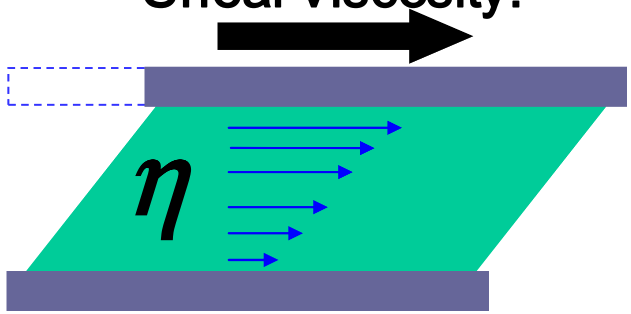
Input: “EOS”

$$\varepsilon=\varepsilon(p)$$

Assume **zero net baryon density & heat conductivity** at RHIC and LHC

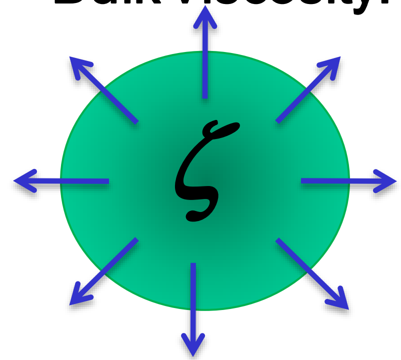
Generic features of shear & bulk viscosities

Shear viscosity:

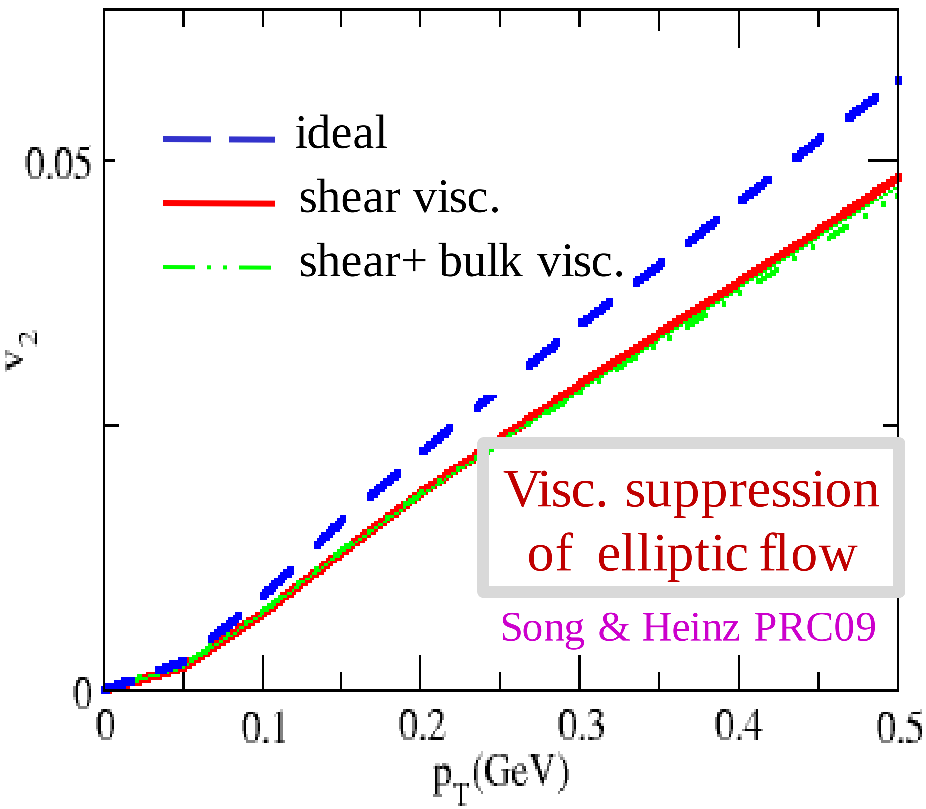


acts against the buildup of **flow anisotropy**

Bulk viscosity:



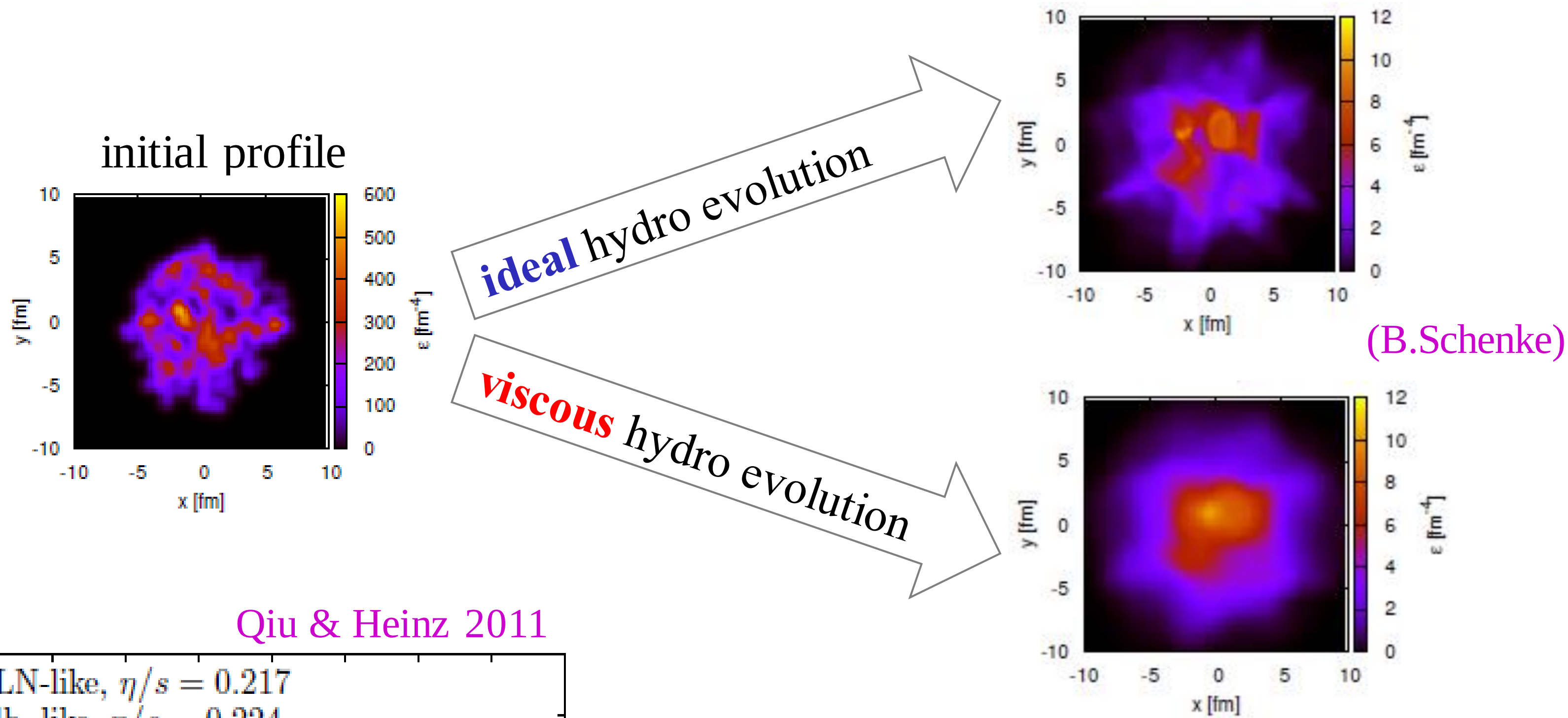
acts against the buildup of **radial flow**

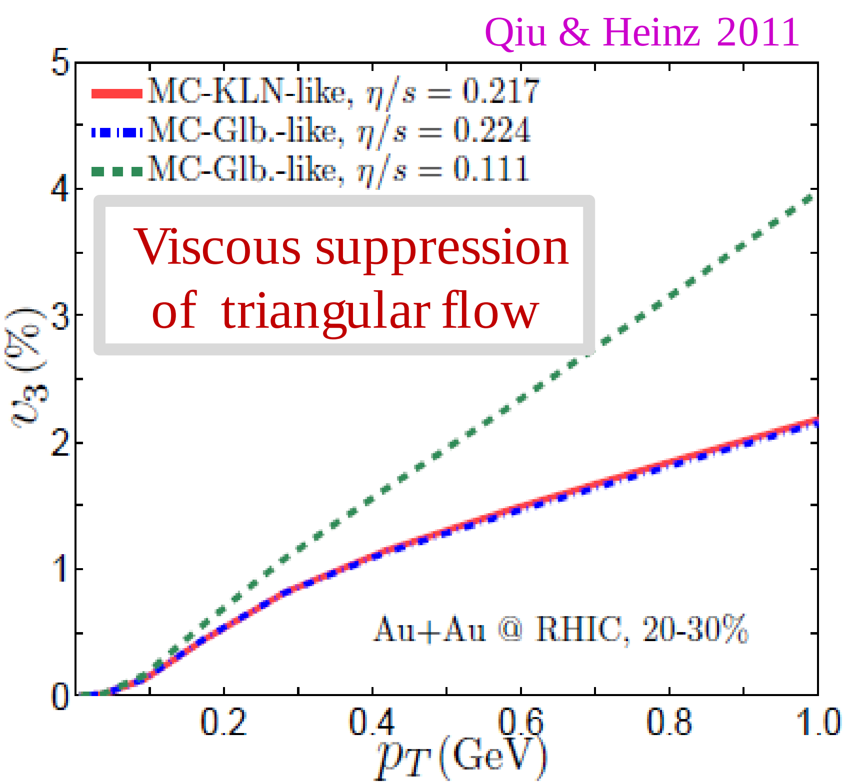


The shear viscosity leads to a significant suppression of v_2 (Romatsche & Romatsche PRL07; song & Heinz PLB08, PRC08; Dusling & Teaney PRC 08; Molnar & Huovinen JPG 08 … …)

Bulk viscous effects are much smaller than shear ones due to the critical slowing down near phase transition (Song & Heinz PRC09)

One can extract the QGP shear viscosity from exp data without large contaminations from bulk viscosity





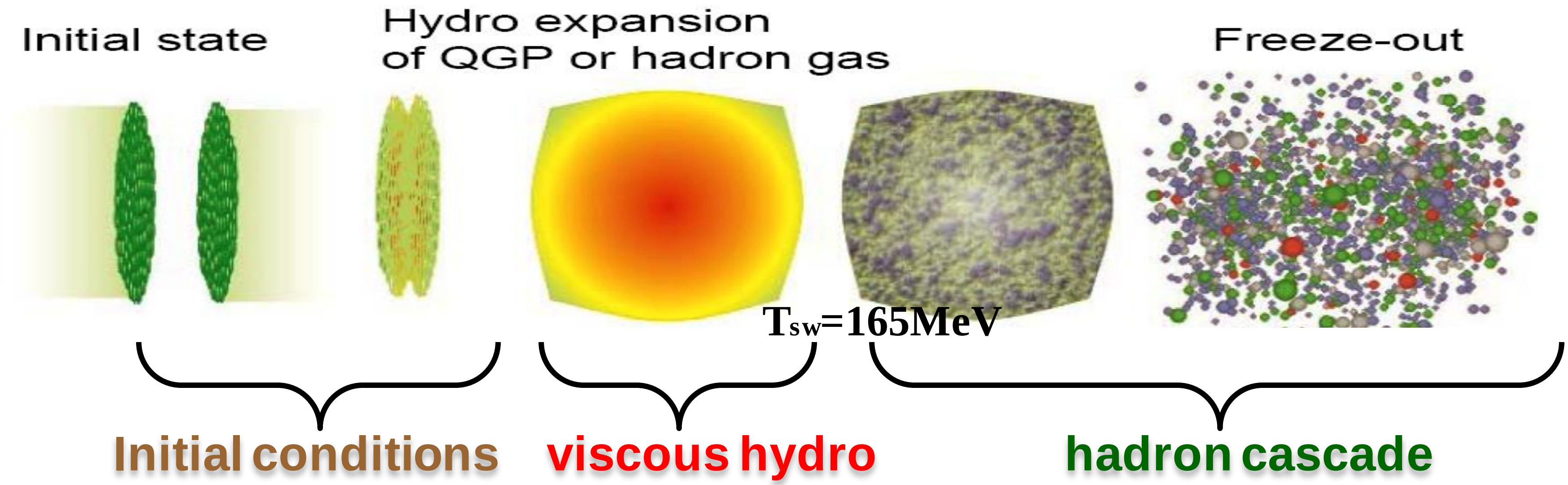
The shear viscosity tends to smear out the inhomogeneous structures, leading to a suppression of V_3 (Schenke, Jeon & Gale PRL2011, PRC2012; Qiu & Heinz PRC2011 … …)

QGP viscosity at RHIC and the LHC

-results from the VISHNU hybrid model

VISHNU hybrid approach

H. Song, S. Bass, U. Heinz, PRC2011



VISHNU:

-chemical composition of HRG } Hadron Cascade
-transport properties of HRG

-EoS: (s95p-PCE) (Huovinen & Petreczky10)

-switching temperature: T_{sw}=165MeV

-initial conditions

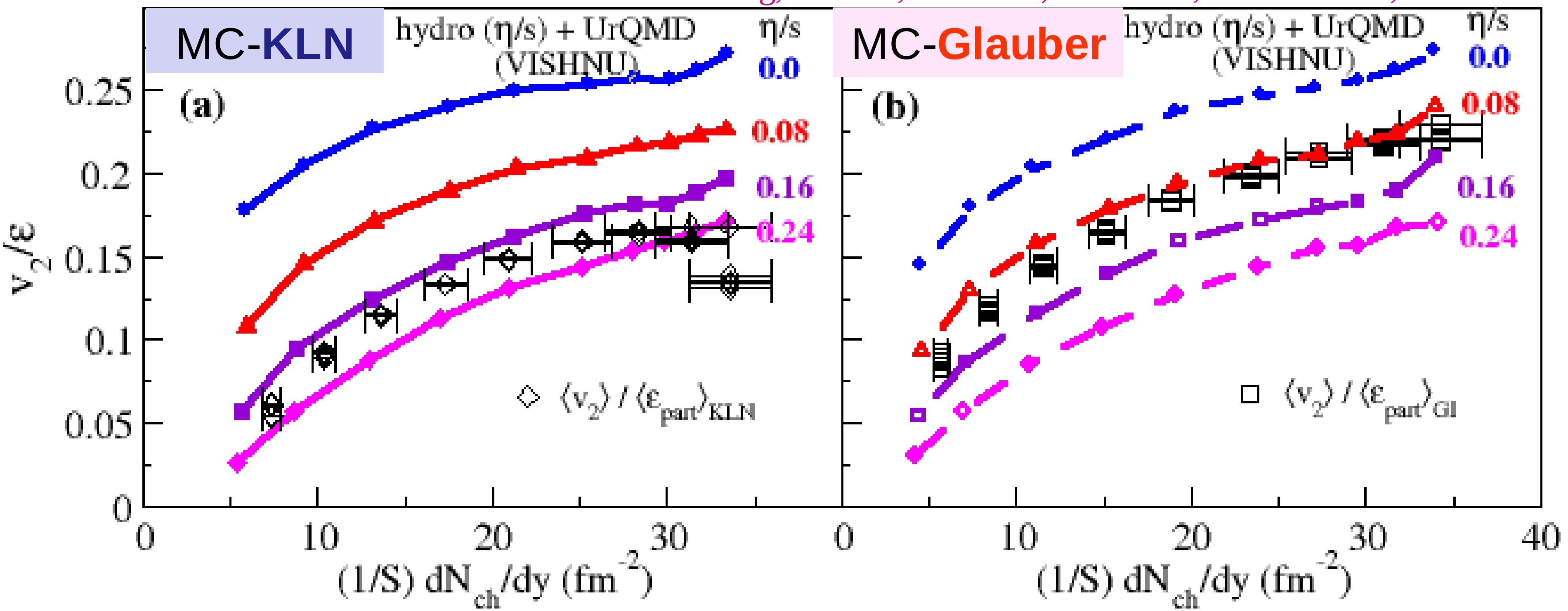
Other related developments

-3+1 d viscous hydro+ hadron cascade: Ryu et al., arXiv1210.4588 .

-2+1 d vs 3+1 viscous hydro: Shen, Schenke & Heinz on going work; Vredevoogd &Pratt, PRC85,044908(2012)

v_2 and QGP viscosity at RHIC

H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen, PRL2011



$$1\times(1/4\pi) \le (\eta/s)_{QGP} \le 2.5\times(1/4\pi)$$

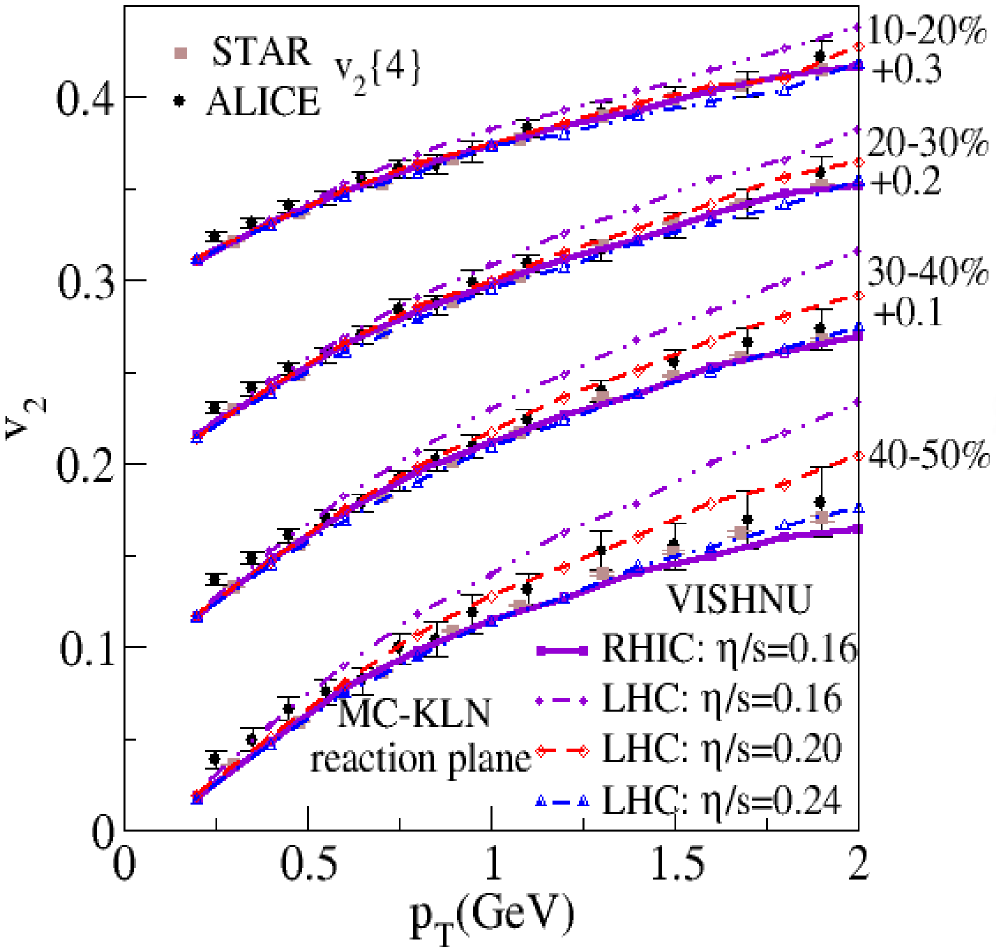
The analysis uses:

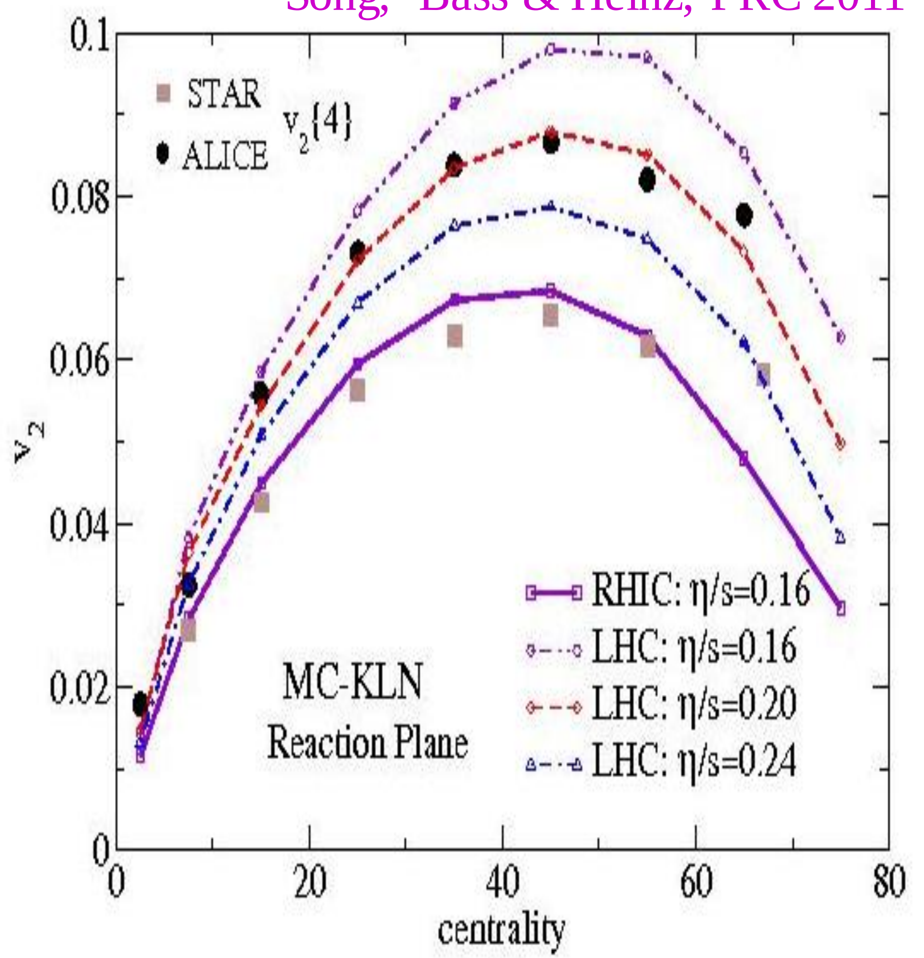
-integrated v_2 for all charged hadrons: In contrast to $v_2(p_T)$, it is less sensitive to bulk viscosity, δf corrections, radial flow & chemical composition of HRG

-corrected exp. v_2 data that remove non-flow & fluc. effects

V_2 and QGP viscosity at the LHC

Song, Bass & Heinz, PRC 2011





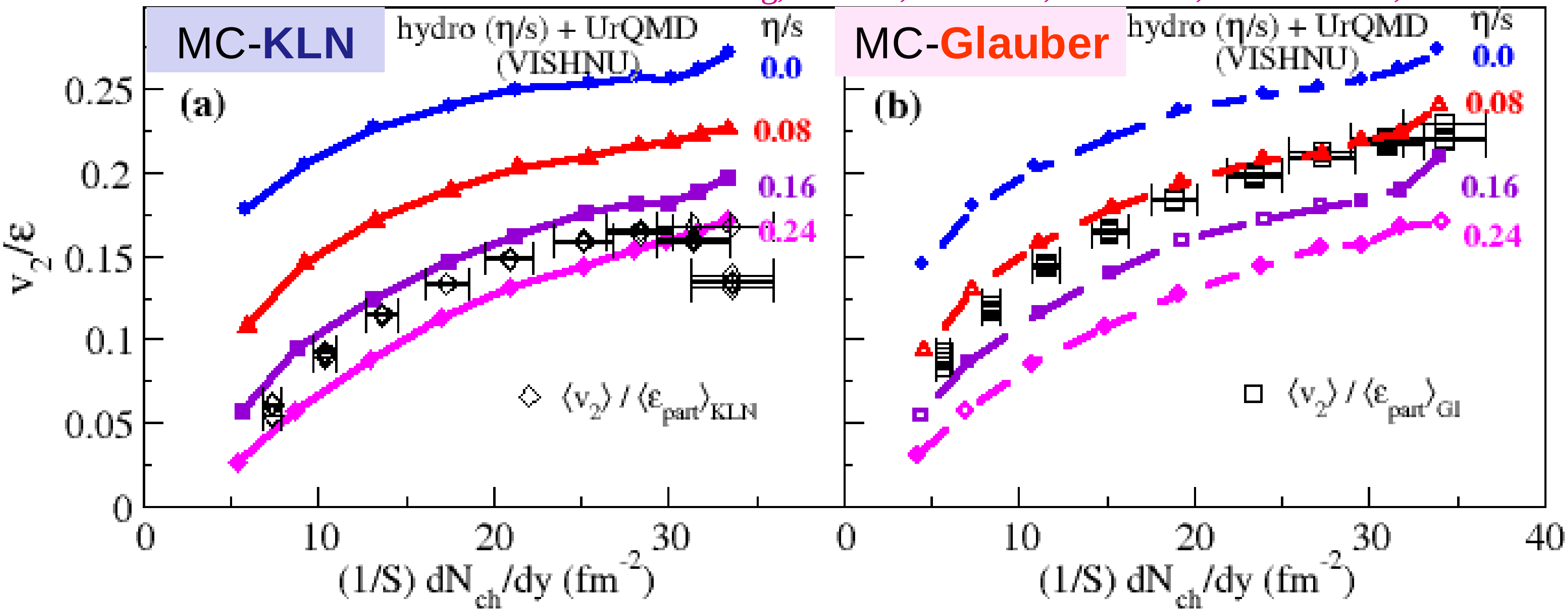
The average QGP viscosity is roughly the same at RHIC and LHC

Please also refer to C. Gale, et al., ArXiv: 1209.5330 [nucl-th]

Initial state fluctuations, final state correlations & the QGP viscosity

Uncertainties from Initial Conditions

H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen, PRL2011



$$1\times(1/4\pi) \le (\eta/s)_{QGP} \le 2.5\times(1/4\pi)$$

Main uncertainties come from initial conditions

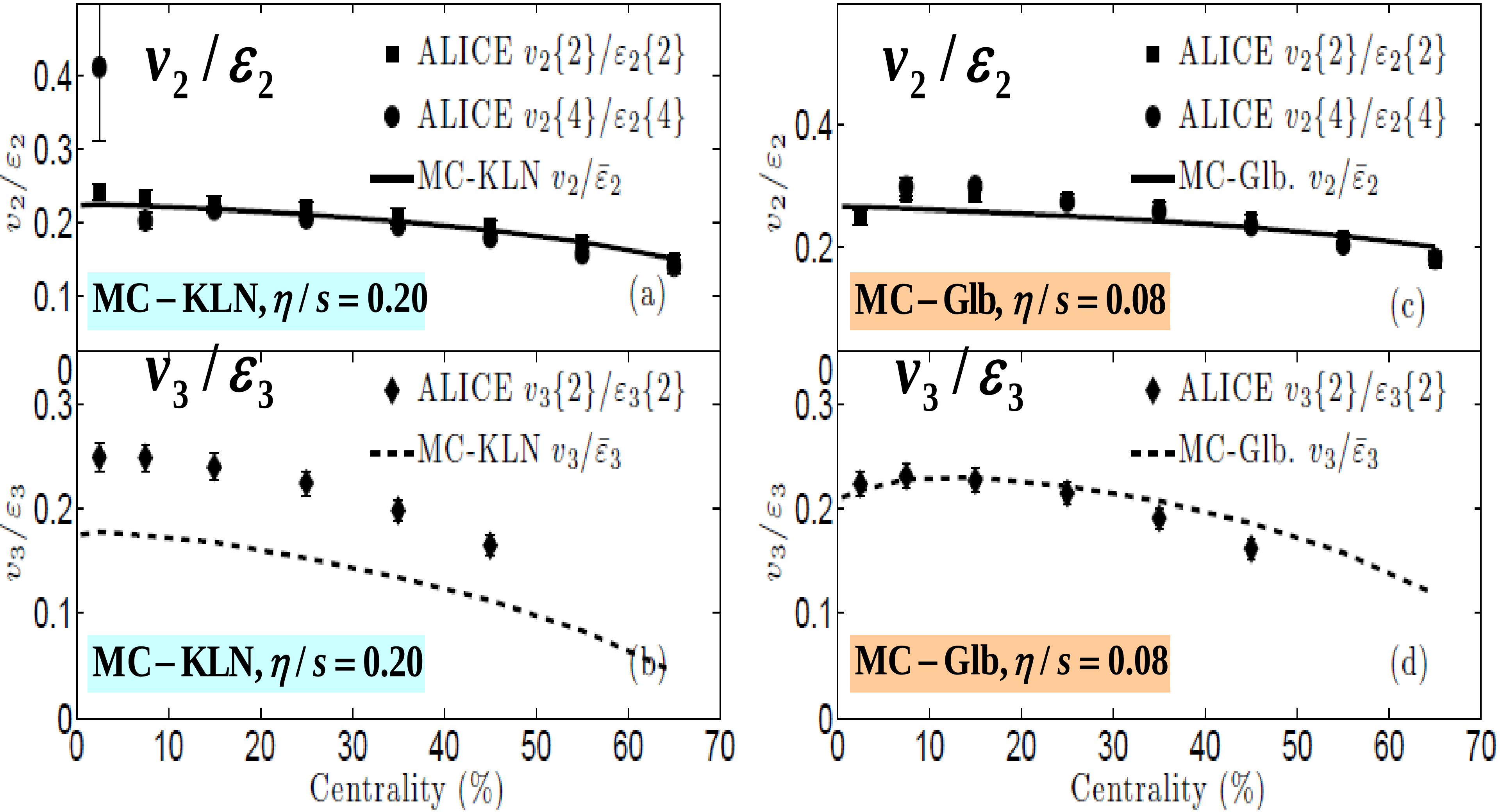
MC-KLN, larger ε_2 ⟶ HIGHER value of QGP viscosity

MC-Glauber, smaller ε_2 ⟶ LOWER value of QGP viscosity

MC-KLN & MC-Glauber initializations & V_3

Pure viscous hydro simulations :

Qiu, Shen & Heinz 2011



V_3 prefer lower value of QGP viscosity

MC-Glauber & MC-KLN initializations are based on **fluctuation of nucleon positions**

Theoretical Development on Initialization Models:

-color charge fluctuations (IP-Glasma, correlated fluctuations)
-multiplicity fluctuations for local gluon numbers
-transverse /longitudinal flow fluctuations
- UrQMD , AMPT, EPOS/NUSES
… … … …

Related flow Data:

-elliptic flow
-triangular flow & higher order flow harmonics
-higher-order event plane correlations
-Event by event v_n distributions
-V_n in ultra-central collisions
… ...

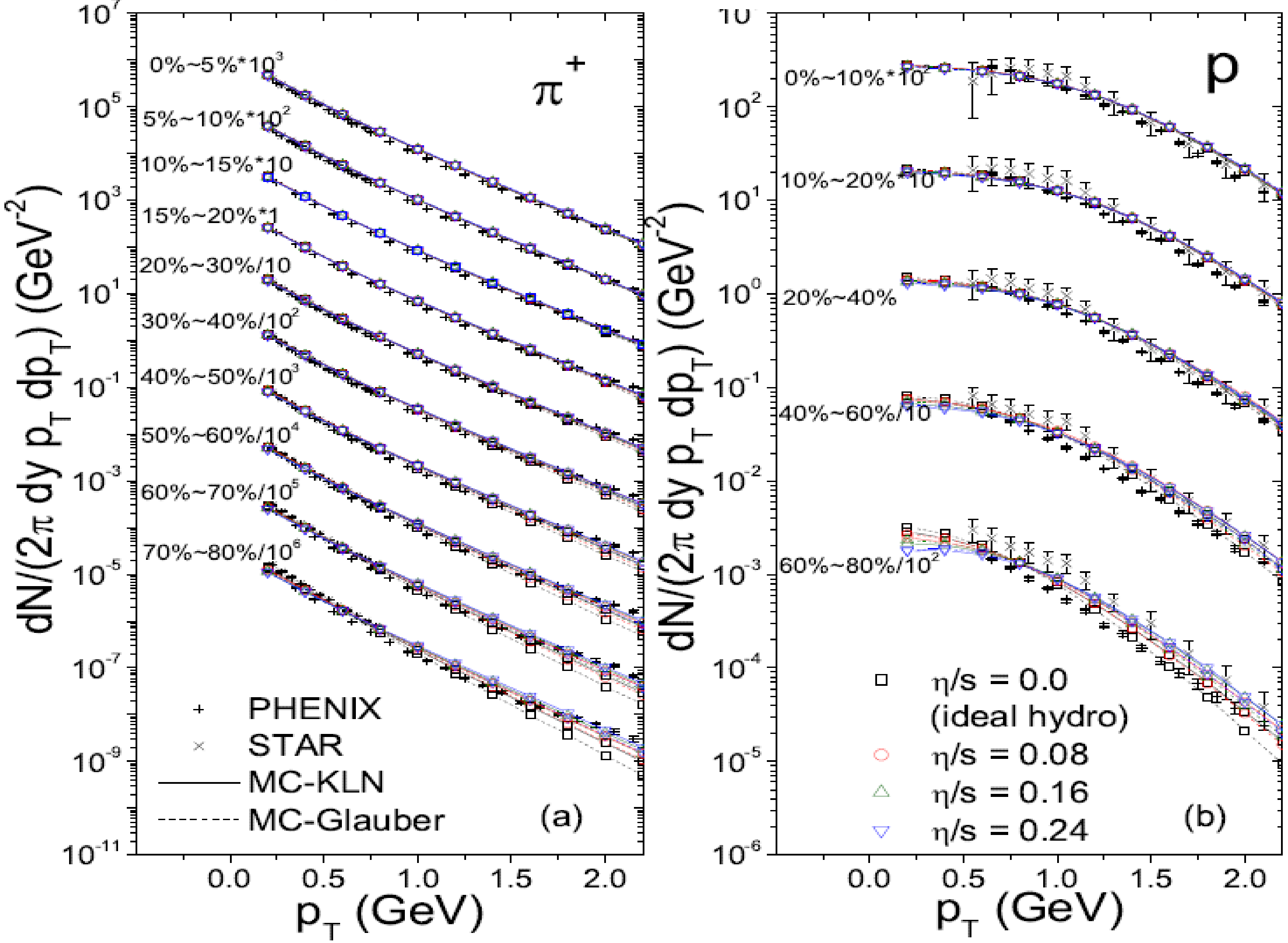
A further study of flow data in different aspects, using e-b-e VISHNU will constrain initialization models, tightening the limit on $(\eta/s)_{QGP}$

--Please also refer the work from B. Schenke and OSU group for recent developments

Multiplicity, Spectra and elliptic flow for identified hadrons

RHIC: spectra for identified hadrons

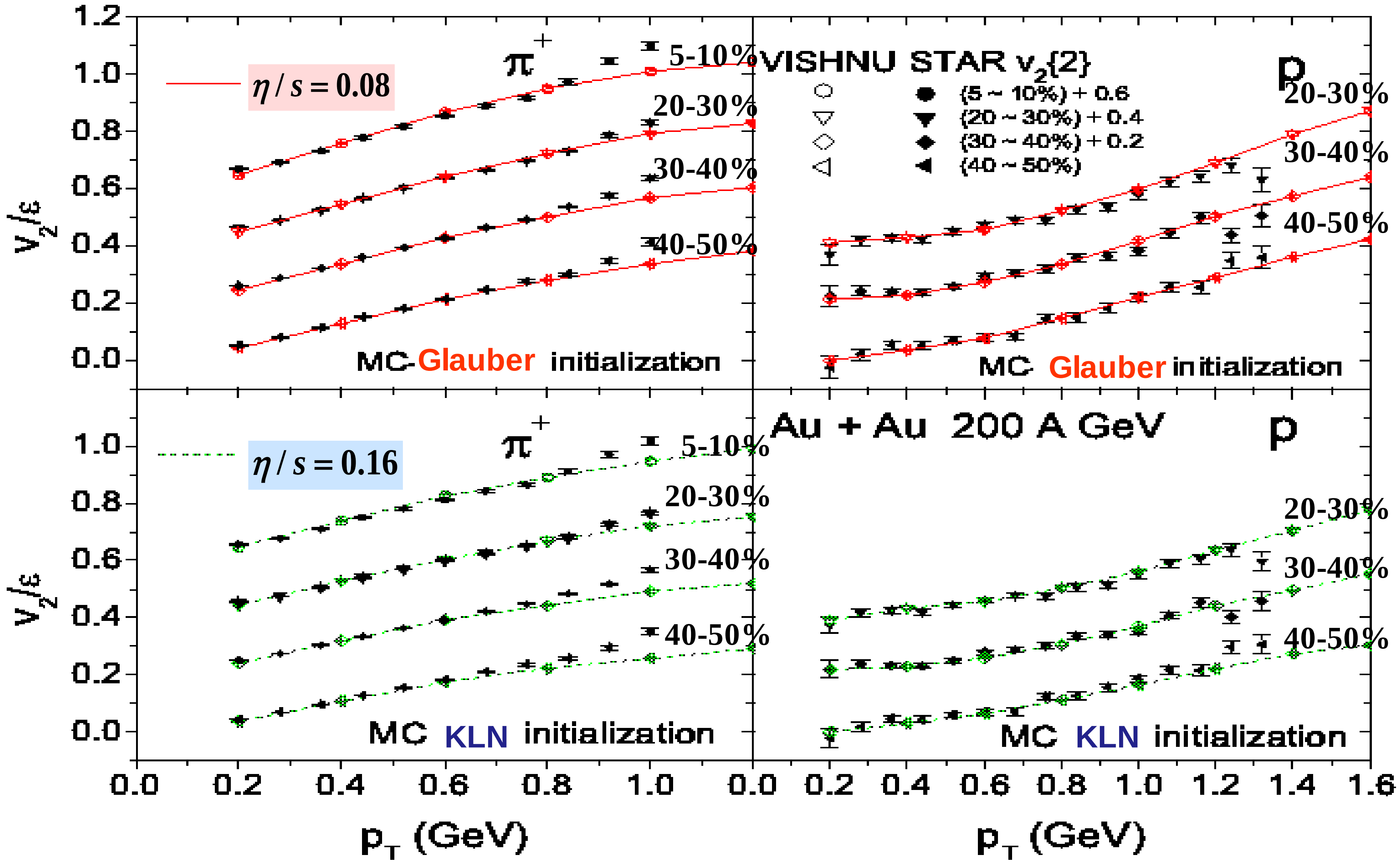
H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen,PRC2011



-a nice fit for both pion and proton spectra, insensitive to QGP viscosity

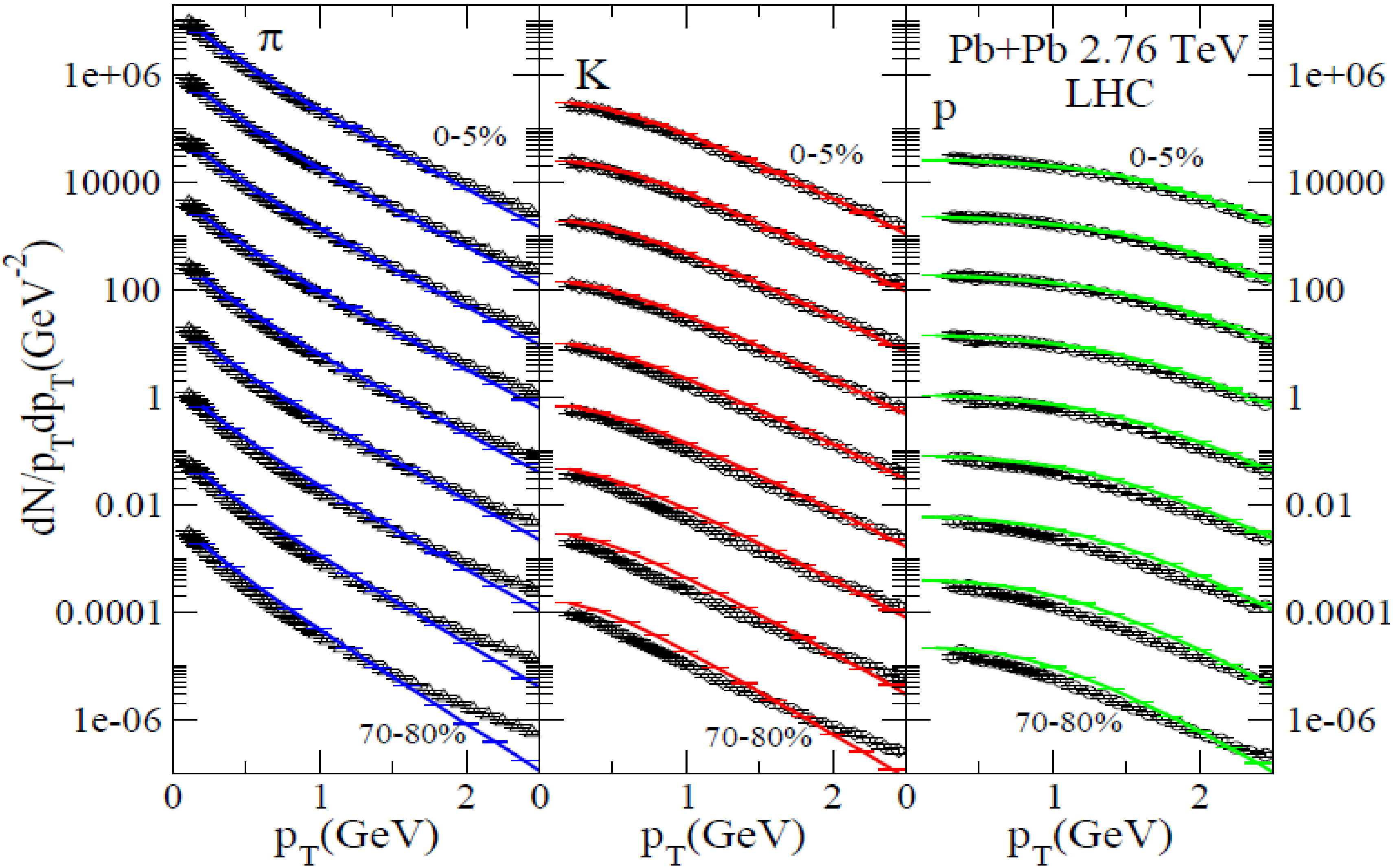
RHIC: $v_2(p_T)$ for identified hadrons

H.Song, S. Bass, U. Heinz, T. Hirano, and C. Shen, PRC2011



LHC: spectra for identified hadrons

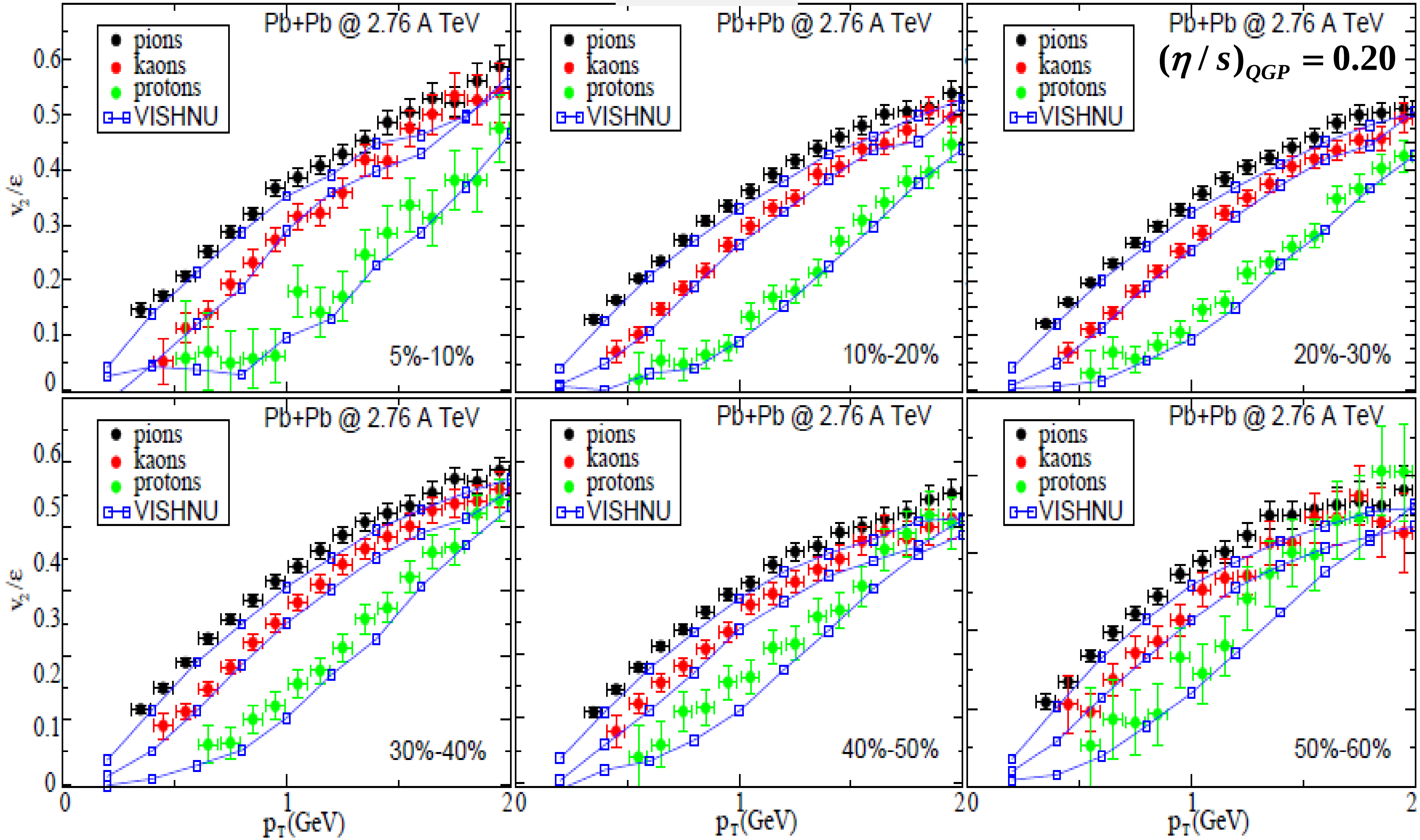
H. Song, S. Bass, U. Heinz, in preparations



-a nice fit for pions, kaons and proton spectra

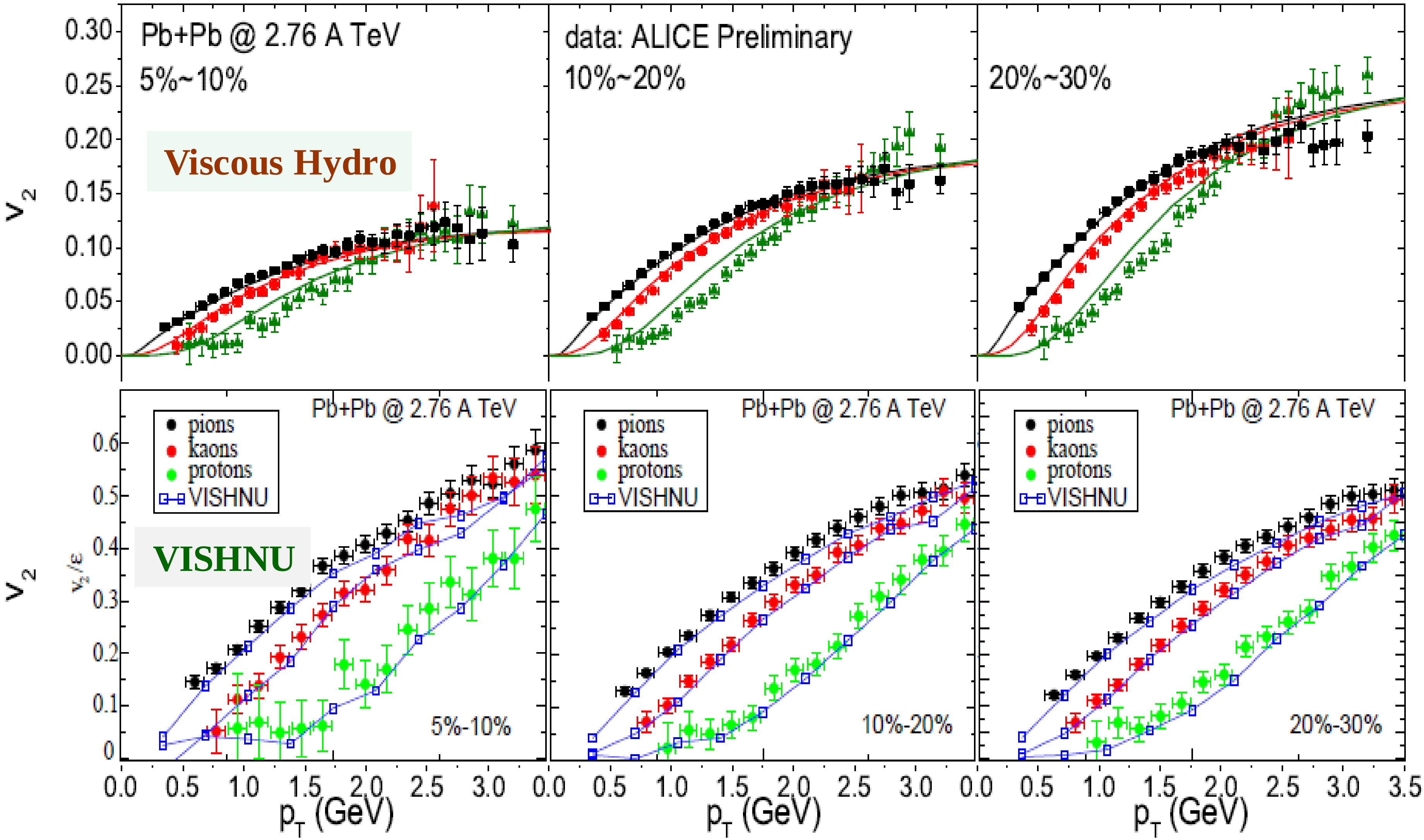
LHC: $v_2(p_T)$ for identified hadrons

VISHNU



A very nice fit of $V_2(P_T)$ for all centrality bins at LHC from VISHNU hybrid model

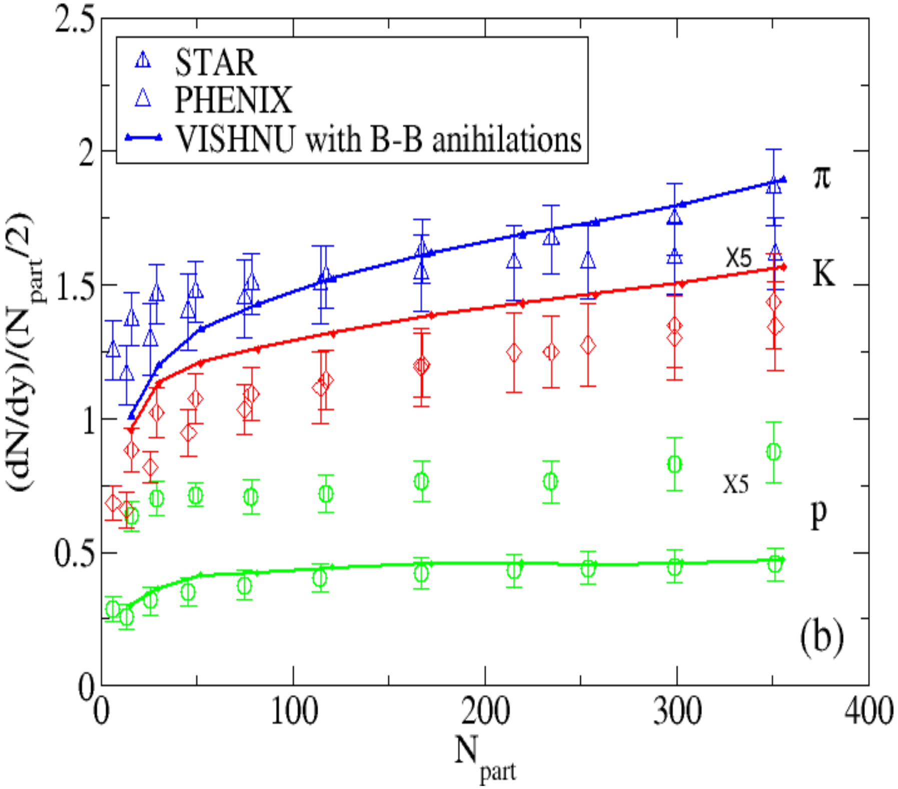
LHC: $v_2(p_T)$ for identified hadrons



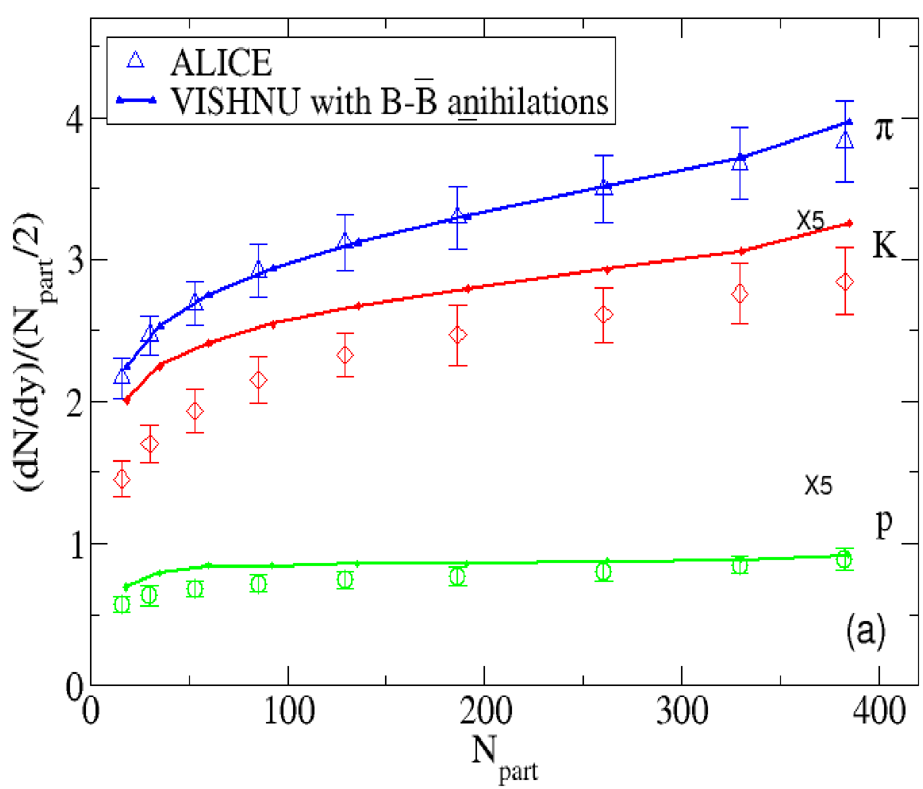
A comparison between viscous hydrodynamics and VISHNU

dN/dy for identified hadrons (RHIC & LHC)

RHIC : 200 A GeV Au+Au

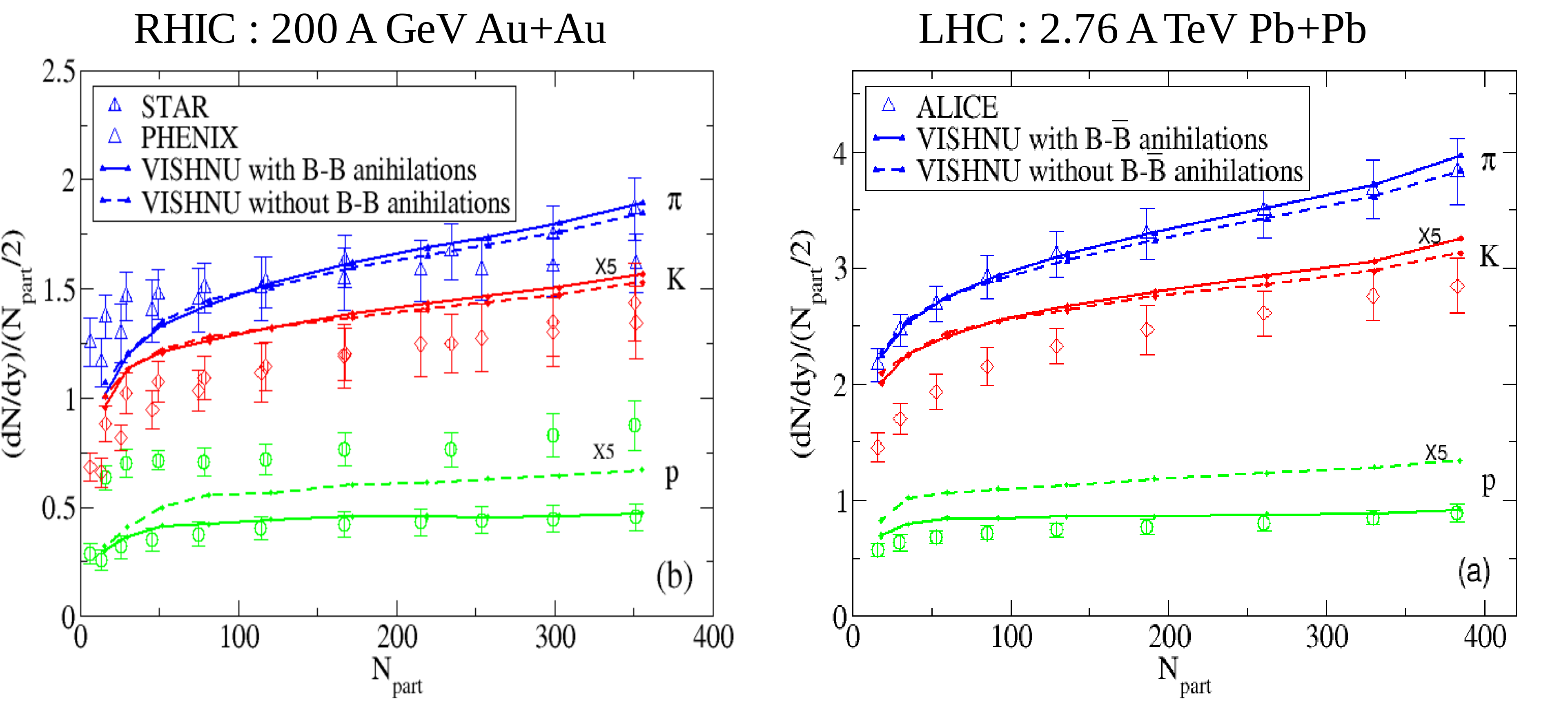


LHC : 2.76 A TeV Pb+Pb



-VISHNU nicely describes the multiplicity for pions, kaons & protons

dN/dy for identified hadrons (RHIC & LHC)

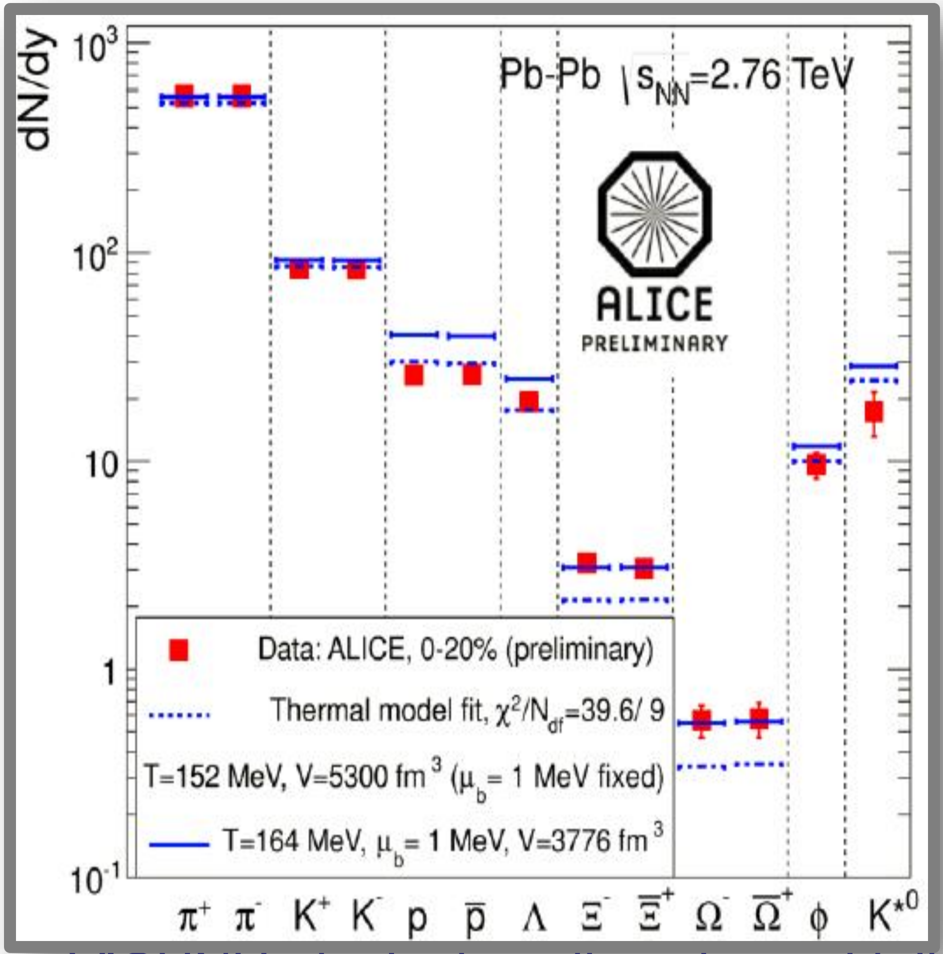


-VISHNU nicely describes the multiplicity for pions, kaons & protons

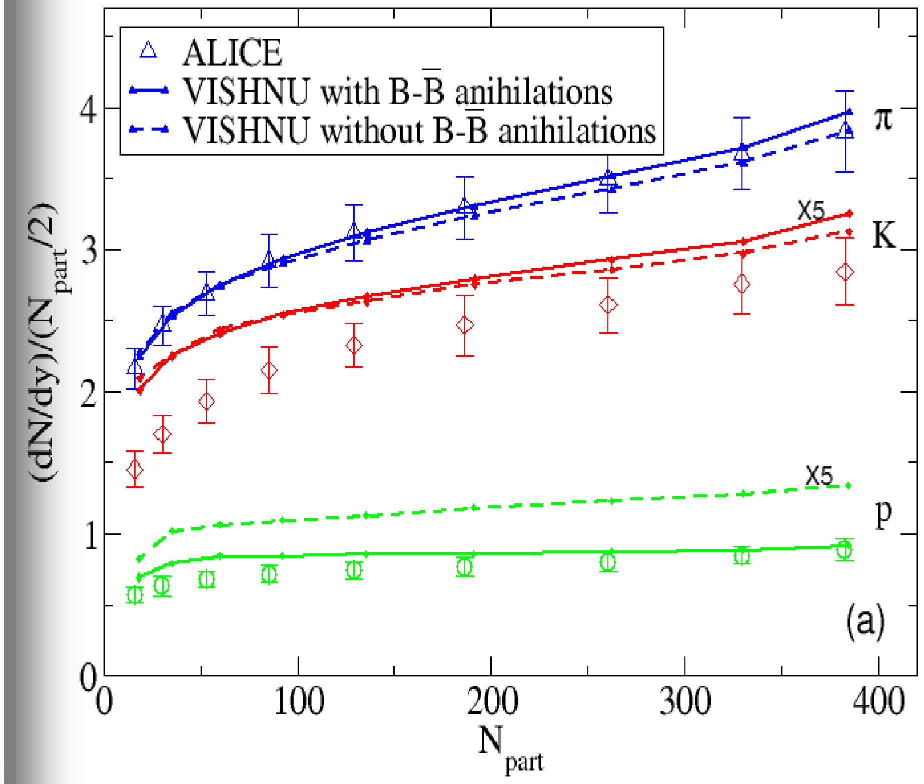
-B-Bbar annihilations plays an important role for a nice fit of the proton data

VISHNU : T_{ch}= 165MeV

dN/dy for identified hadrons (RHIC & LHC)



LHC : 2.76 A TeV Pb+Pb



-VISHNU nicely describes the multiplicity for pions, kaons & protons

-B-Bbar annihilations plays an important role for a nice fit of the proton data

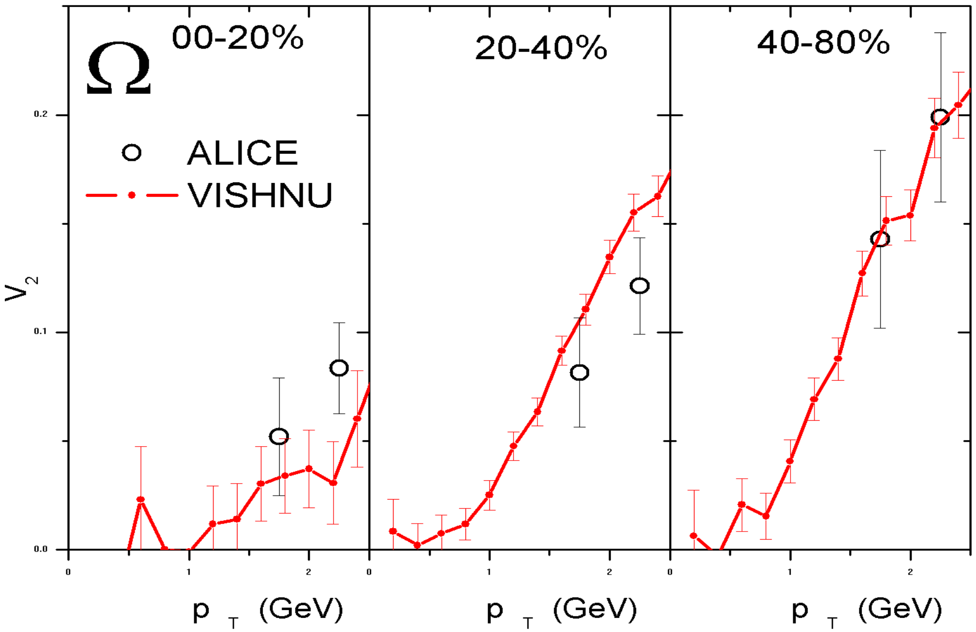
Statistical Model : T_{ch}~ 150 MeV ?

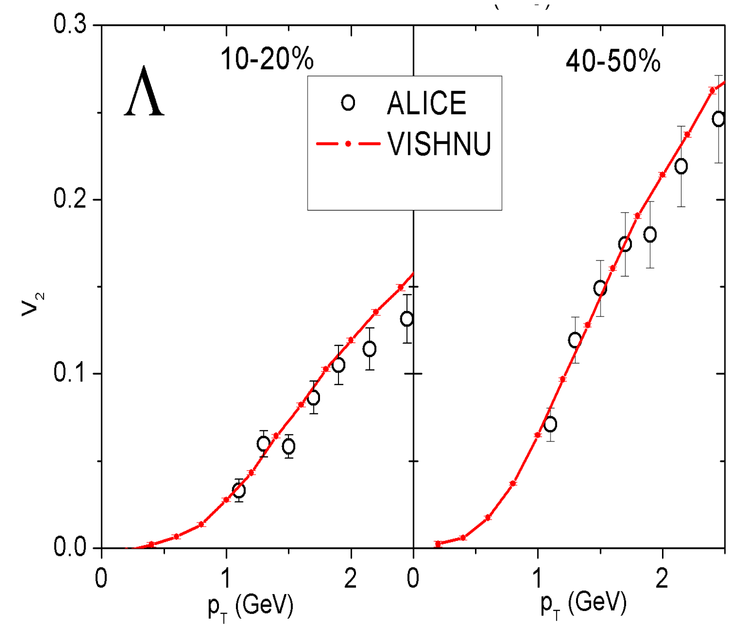
(no B-Bbar annihilations!)

VISHNU : T_{ch}= 165MeV

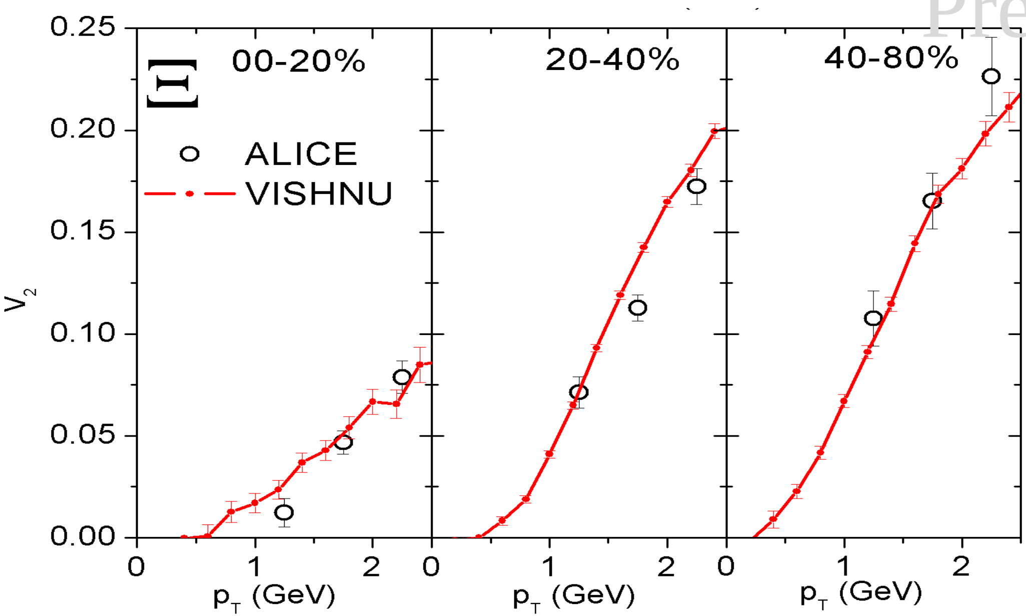
Elliptic flow for multi-strange hadrons

v_2 for multi-strange hadrons (LHC)





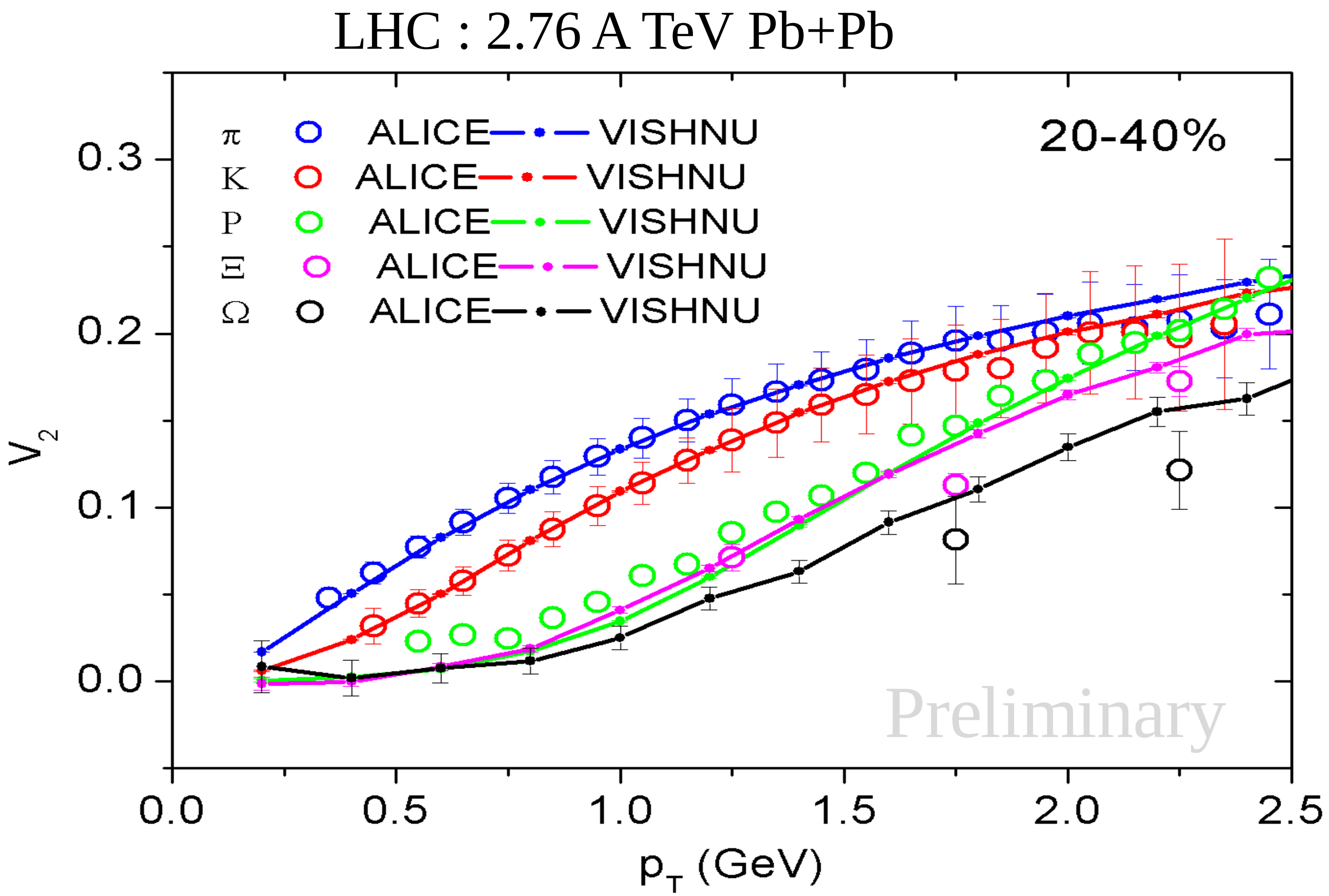
Preliminary



2.76 A TeV Pb +Pb collisions

-a nice description for the elliptic flow for Lambda, Xi and Omega up to 2.5 GeV !

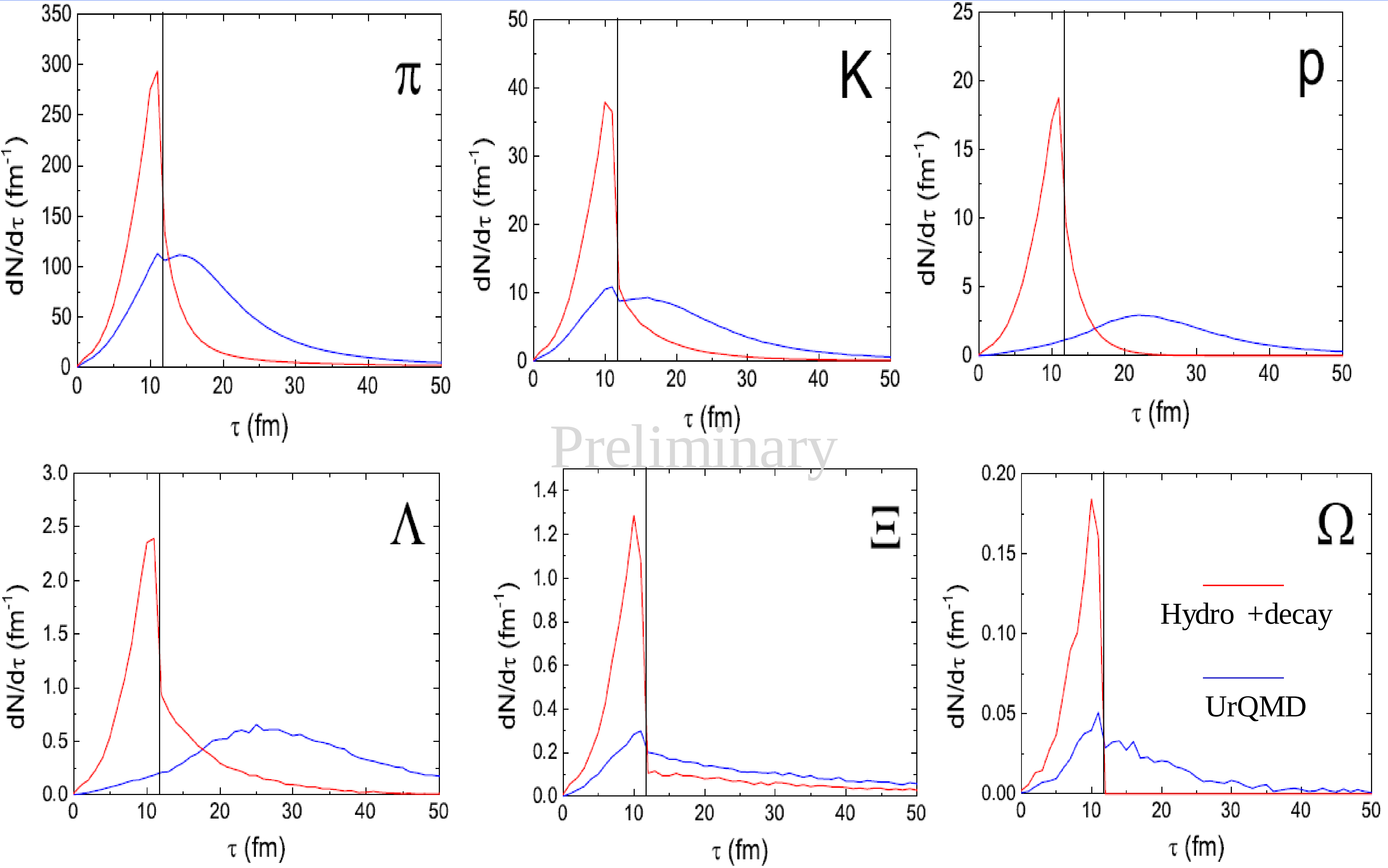
Mass ordering of elliptic flow (LHC)



-Roughly reproduce the mass-ordering!

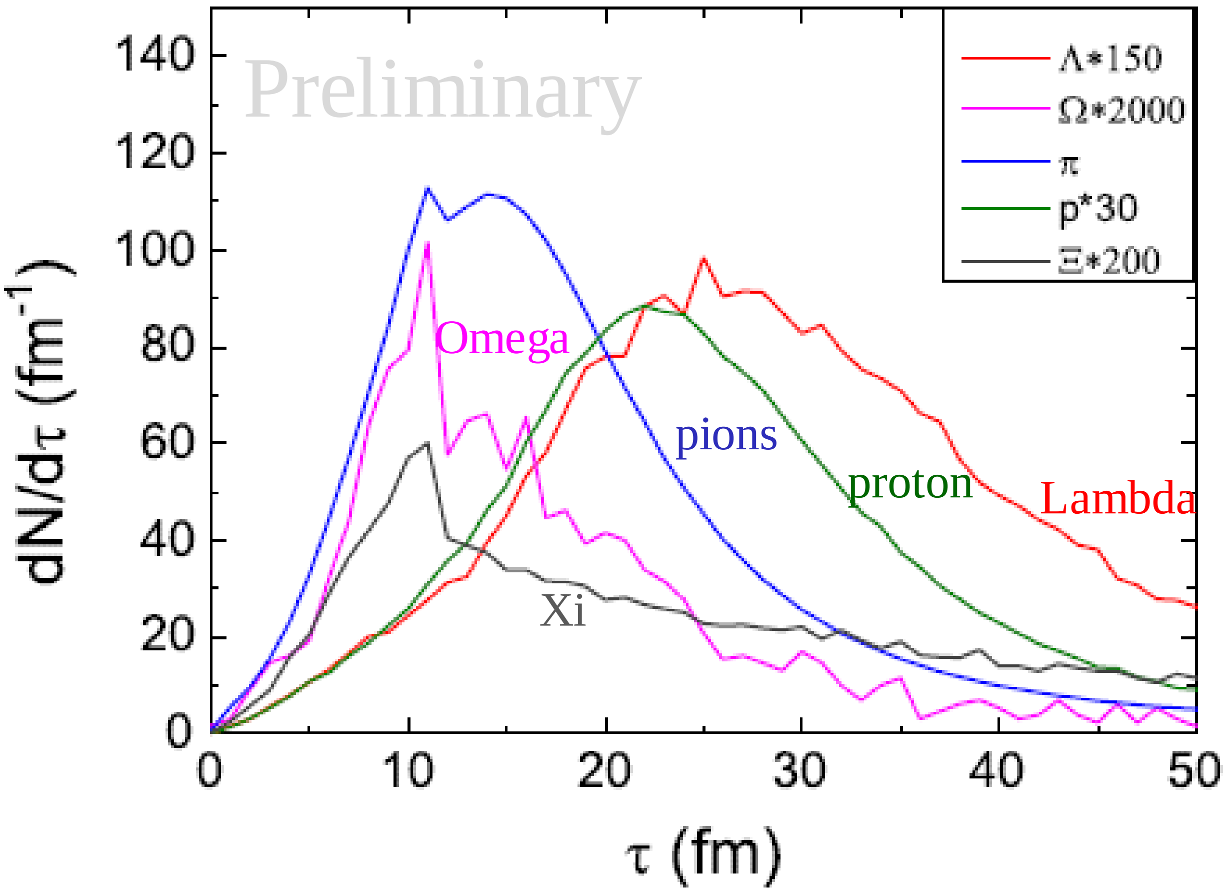
Do these multi-strange hadrons decouple from the system near T_c ?

UrQMD/decay freeze-out time distributions



-These multi-strange hadrons are NOTthat weakly coupled with the medium!

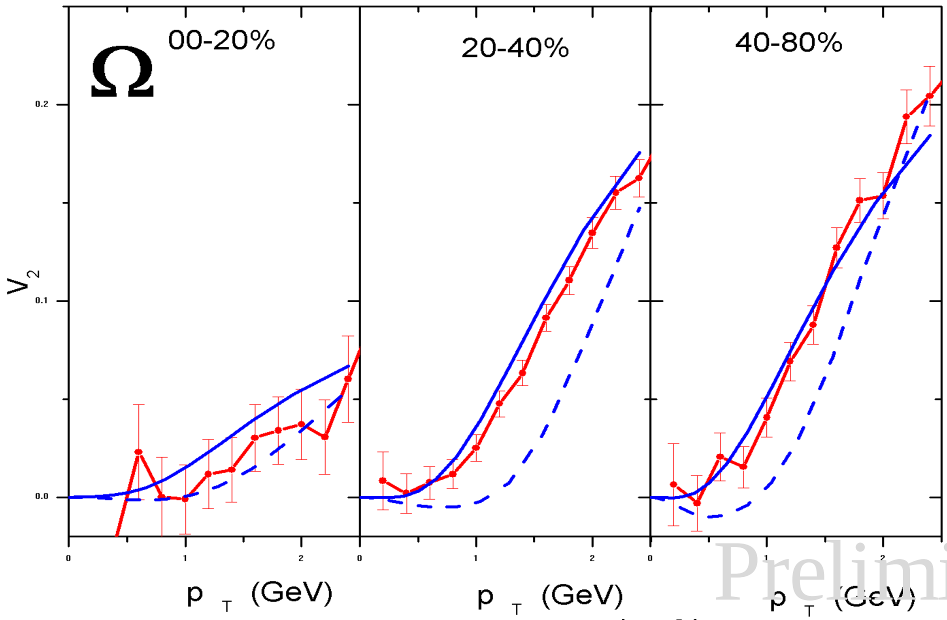
UrQMD freezeout time distributions

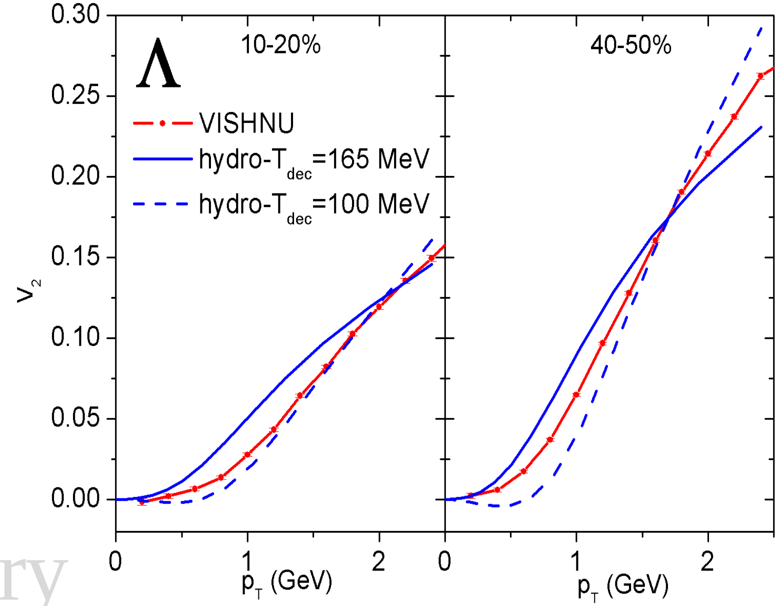


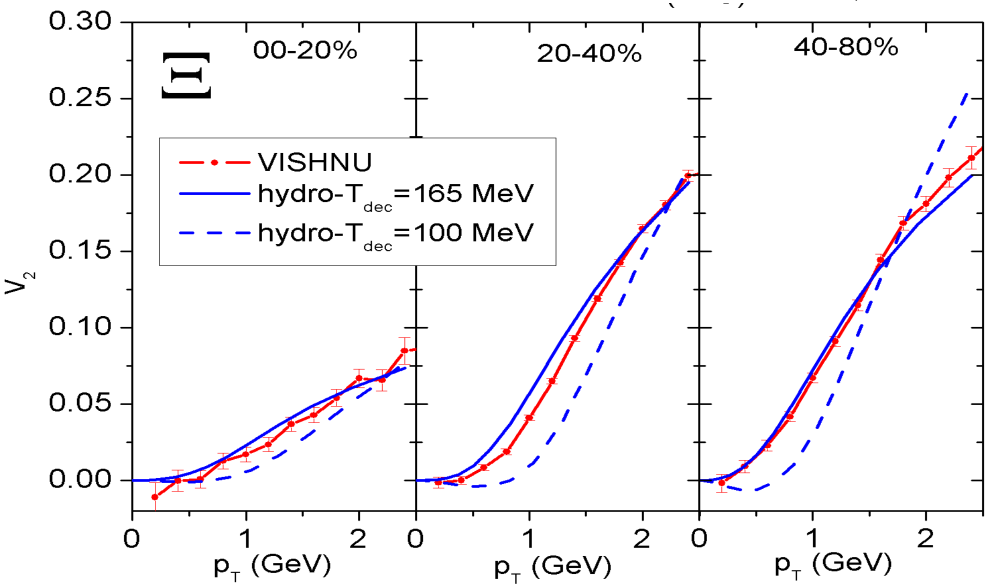
-Lamba freeze-out even later than pion and protons !

-earlier freeze-out for Xi and Omega!

VISHNU vs Hydro with T_{dec} =165 & 100 MeV







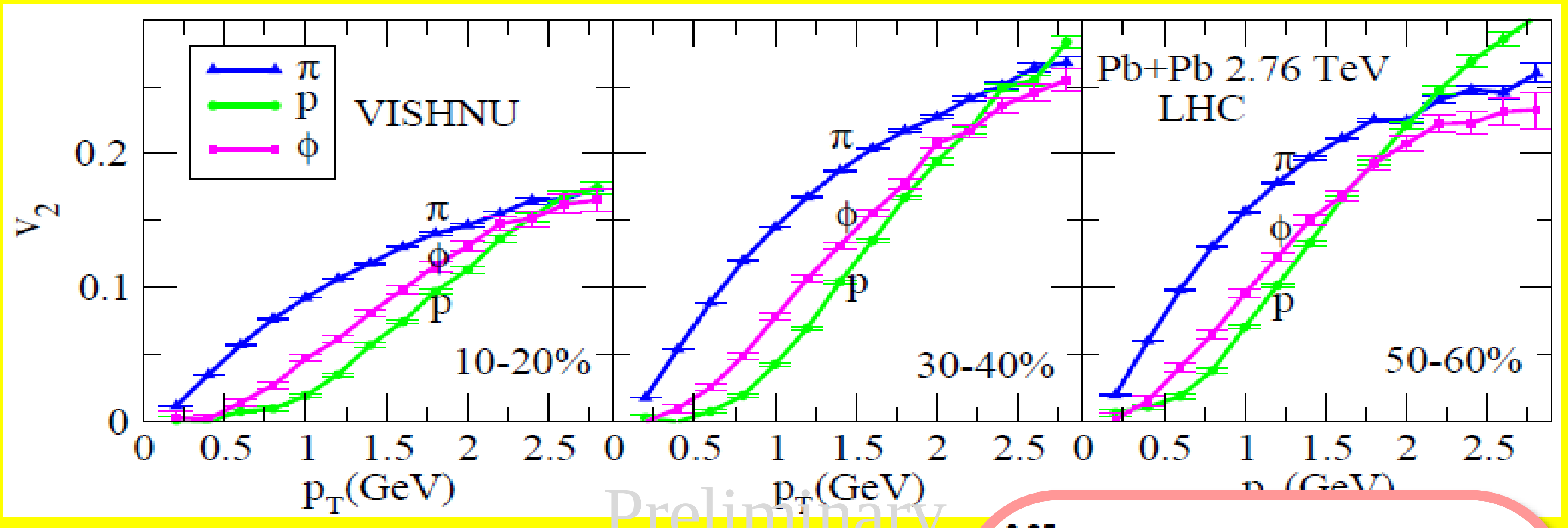
-freeze-out temperature for Lambda is much below T_c!

-freeze-out temperatures for Omega and xi are closer to T_c!

-need more studies for firm conclusions

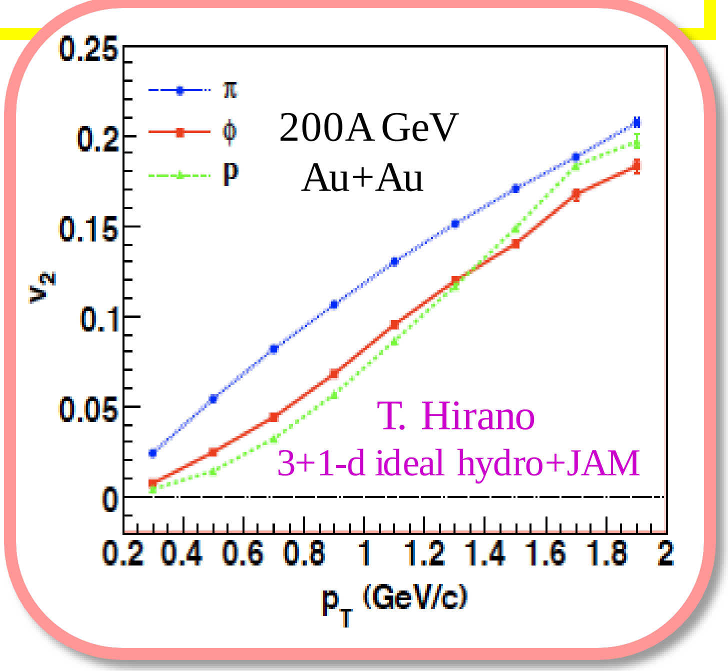
phi-meson

Elliptic flow for phi at the LHC

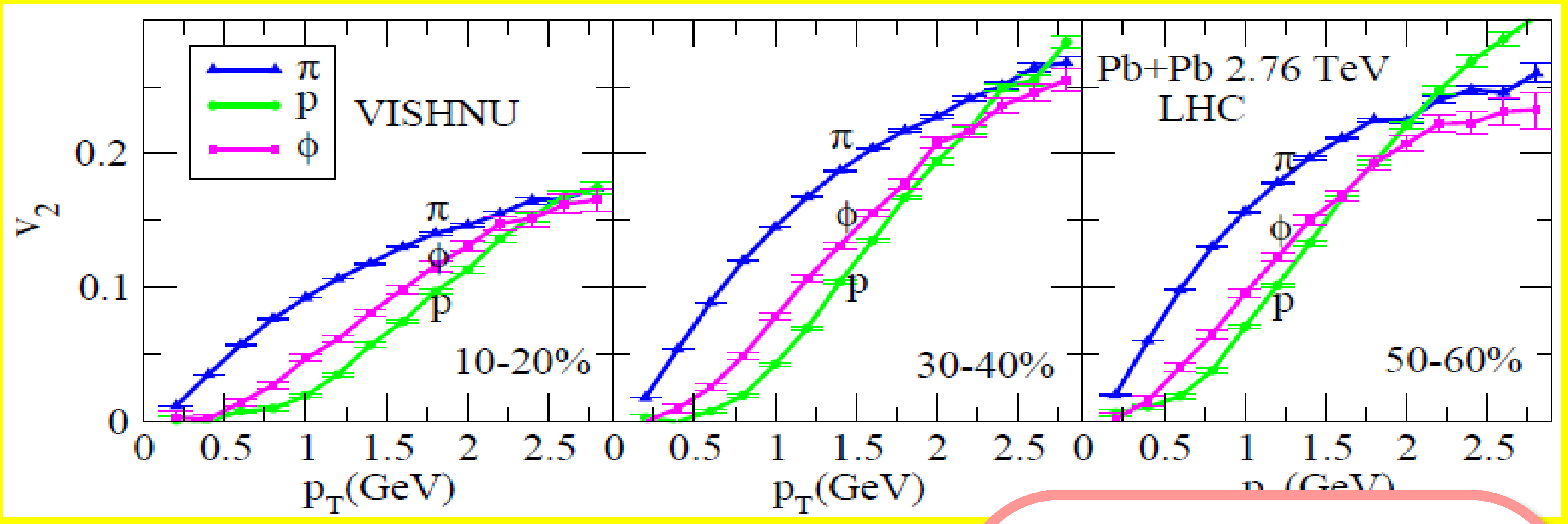


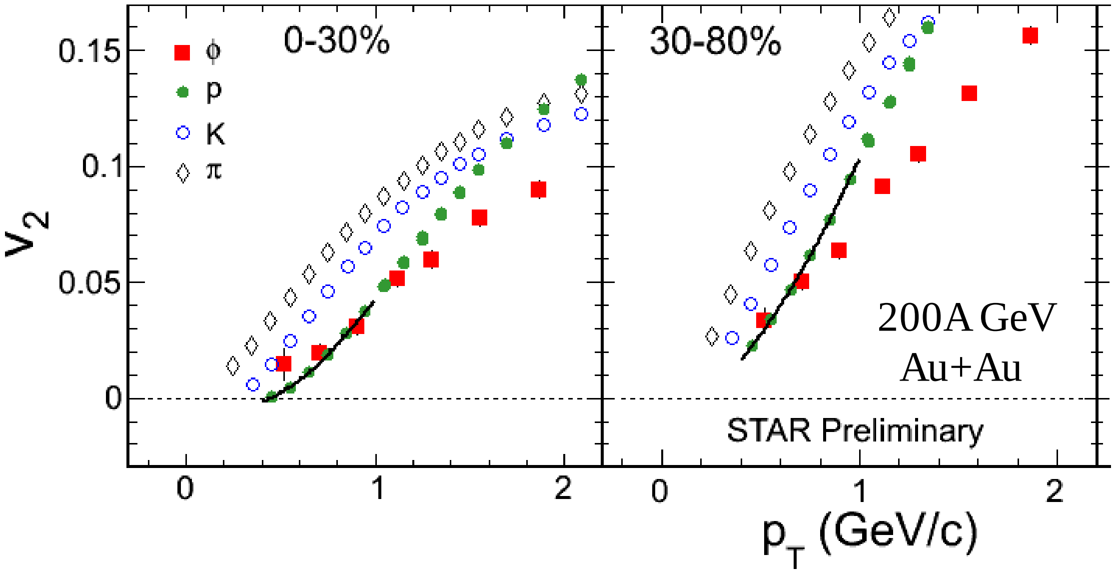
-Hadron cascade: small cross sections for phi

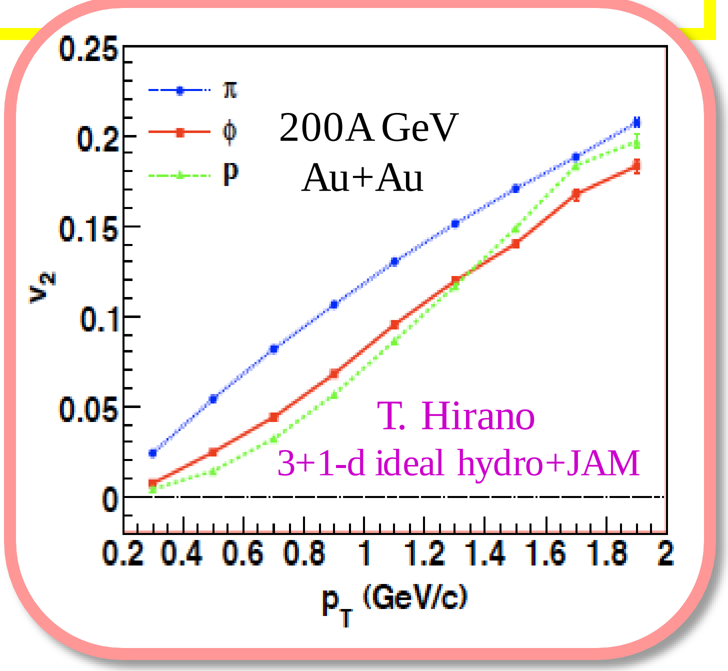
-mass ordering between phi and proton are independent of collision energies, centralities & theoretical details



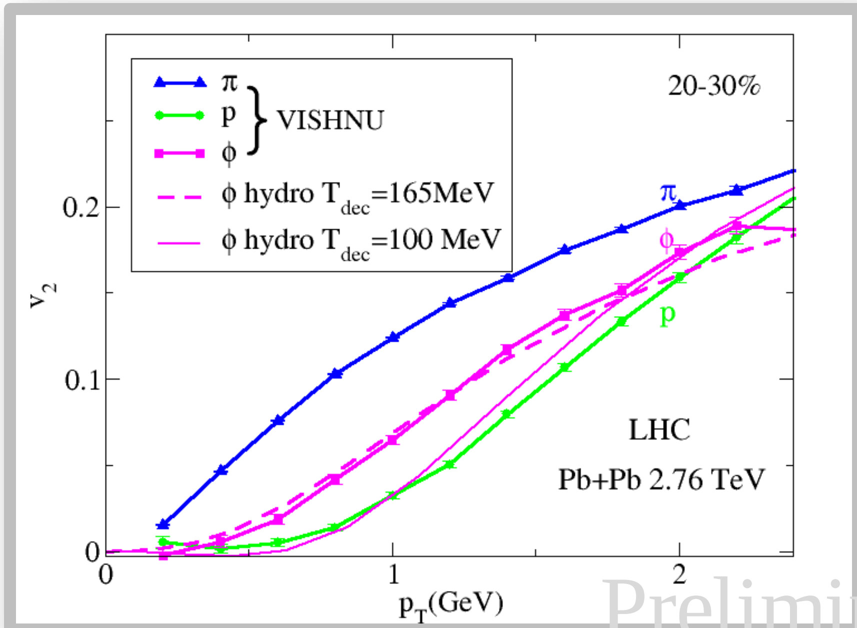
Elliptic flow for phi at the LHC







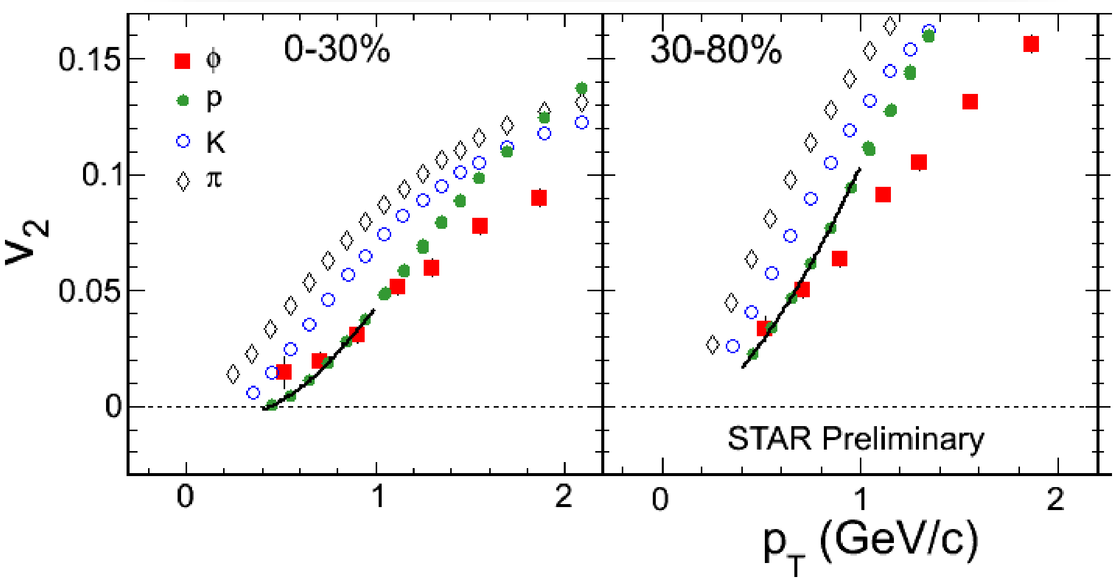
phi V2 in strong & weakly coupling limit



-hydro + T_{dec} =165 MeV
weakly coupling limit

-hydro + T_{dec} =100 MeV
strong coupling limit

VISHNU:
small cross sections for phi



Neither the strongly nor the weakly coupling limit nor the cases in between (VISHNU) could explain the mass-ordering between proton & phi shown in experiment

phi-meson puzzle !

Summary

QGP viscosity at RHIC and the LHC

Extraction η/s from elliptic flow data using VISHNU indicates:

$$1\times(1/4\pi) \le \eta/s \le 2.5\times(1/4\pi)$$ (MC-Glauber; MC-KLN)

Approximately similar averaged QGP viscosity at RHIC and LHC energies

Recent developments on initialization models:

color charge fluctuations; multiplicity fluctuations; initial flow fluctuations … …

to implement e-b-e VISHNU to further study: **triangular flow & higher order flow harmonics, higher-order event plane correlations e-b-e v_n … ...**

will help us to constrain initialization models, tightening the limit on $(\eta/s)_{QGP}$

Spectra & V_2 for identified hadrons (& multi-strange hadrons)

- A nice description of the p_T spectra and v_2 for pions, kaons and protons

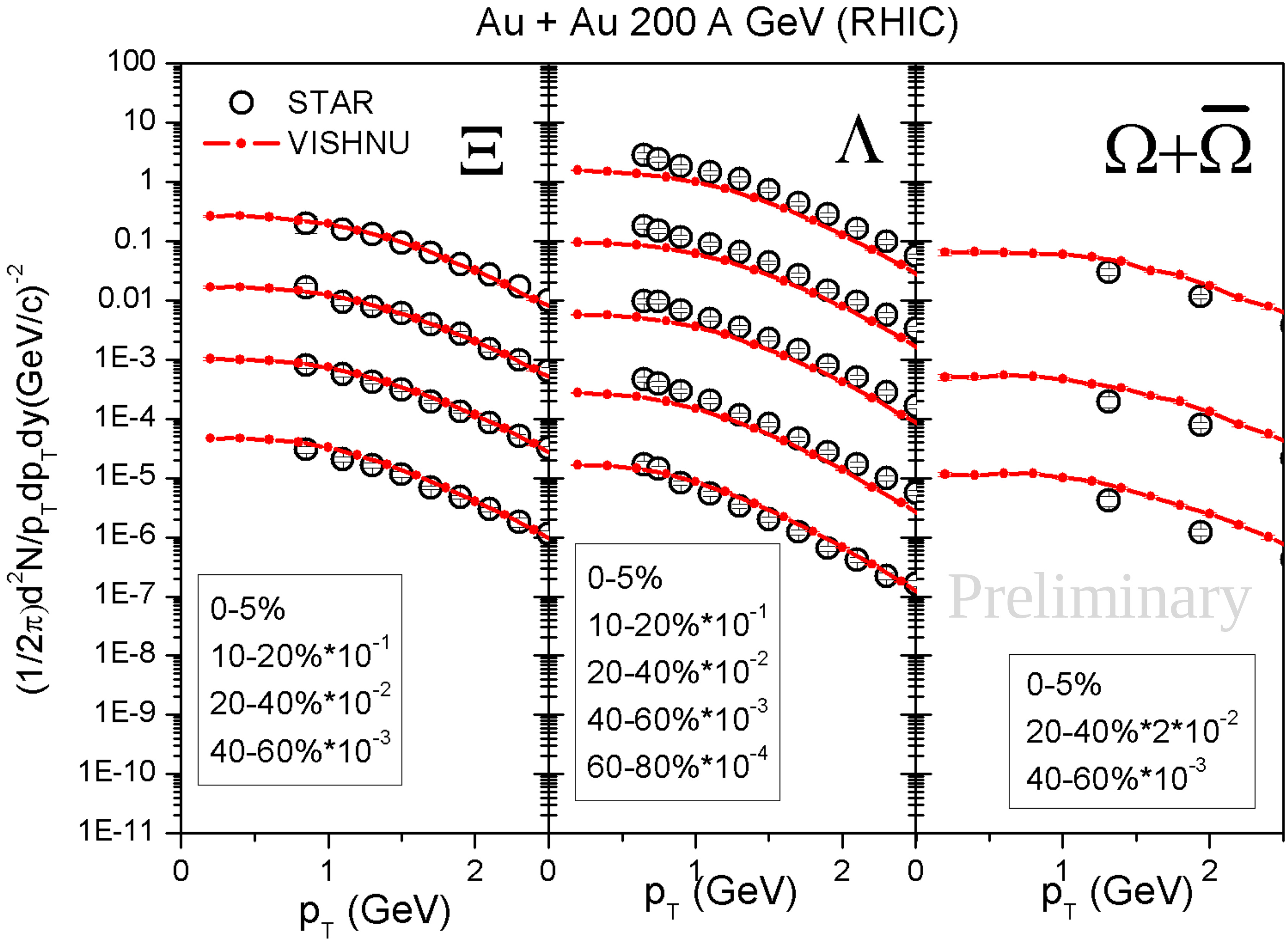
- VISHNU with B-Bbar annihilations prefer T_{ch}=165 MeV

-A nice description for v_2 (p_T) for multi-strangeness at the LHC for various of centrality.

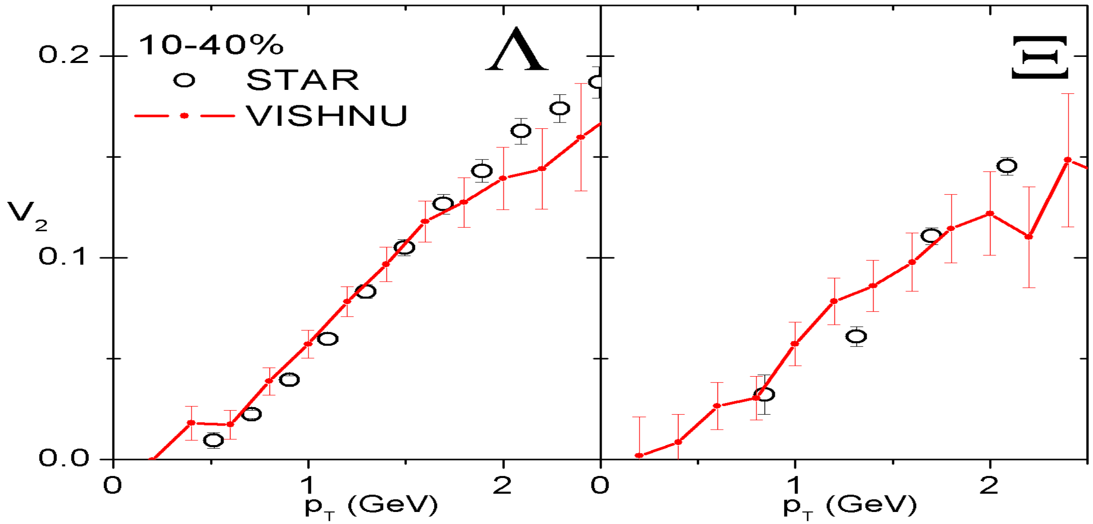
- Fails to describe the phi-v_2(RHIC) within the strongly, weakly coupling limit or VISHNU

Thank you

Spectra for multi-strange hadrons (RHIC)



v_2 for multi-strange hadrons (RHIC)

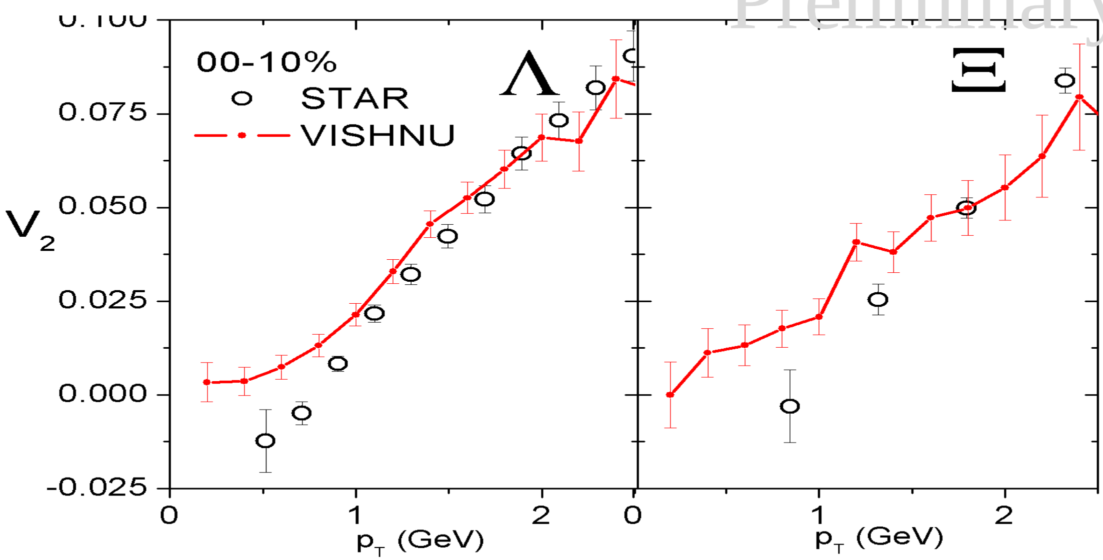


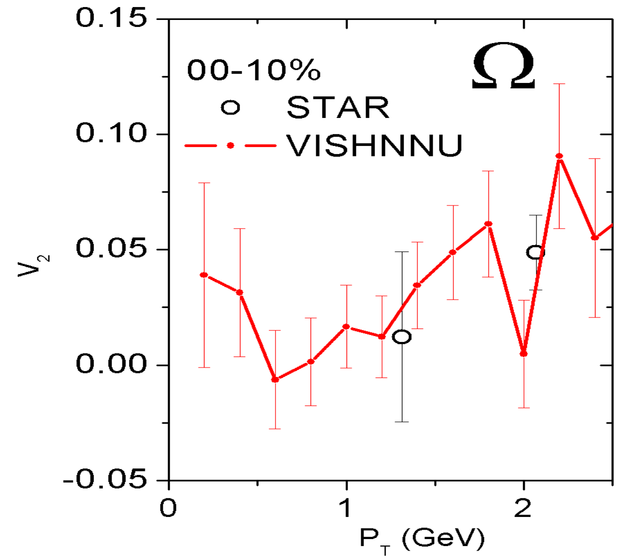
-10-40% :nice description of the experimental data

-High statistic runs are needed in the near future !

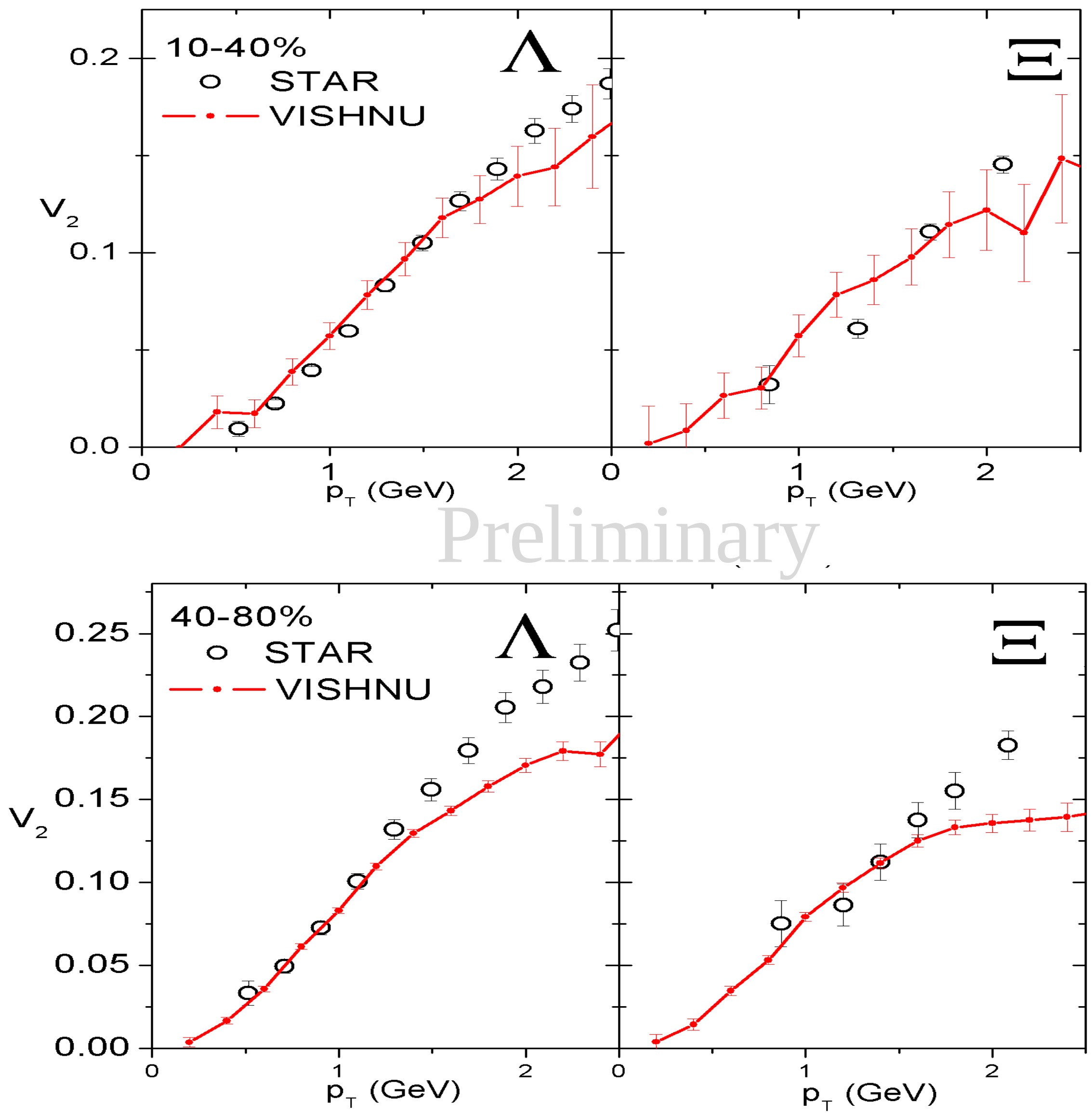
-0-10% : non-flow & fluctuation effects

Preliminary





v_2 for multi-strange hadrons (RHIC)

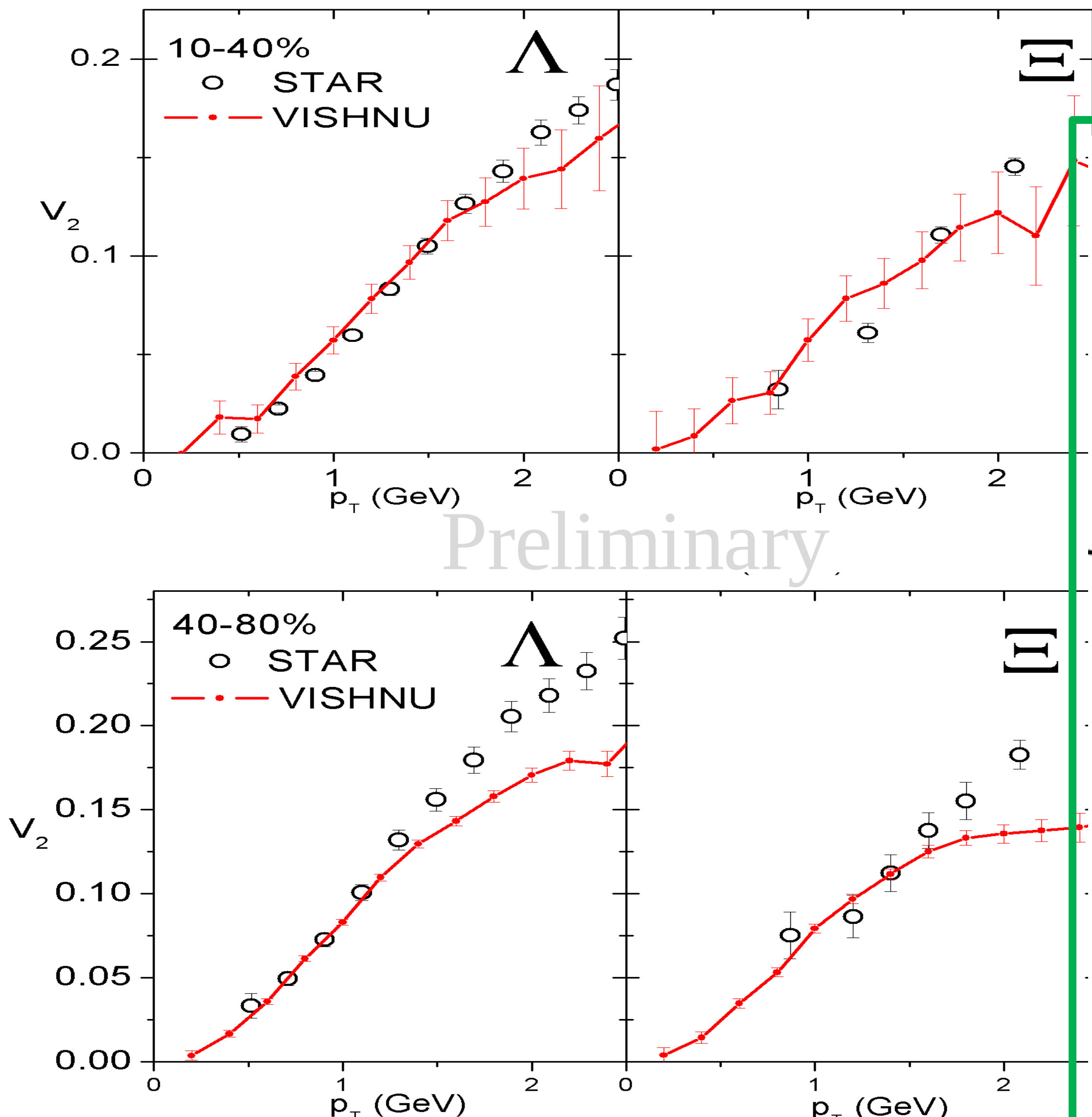


-10-40% :nice description of the experimental data

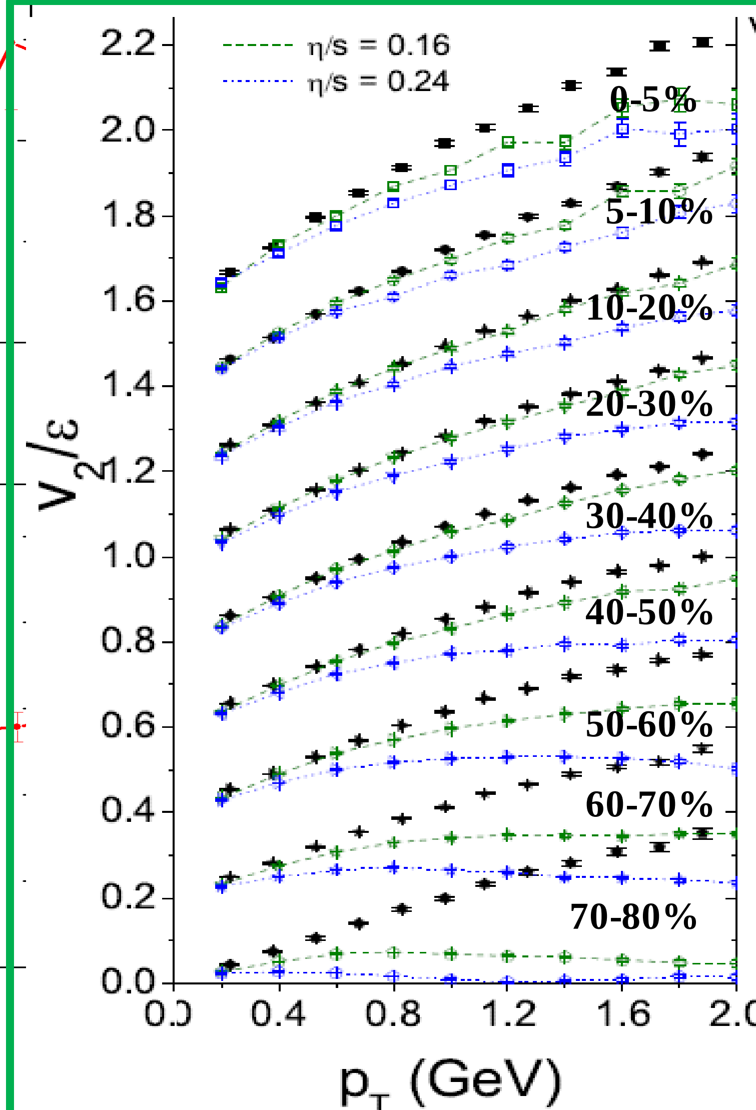
-High statistic runs are needed in the near future !

-40-80%: non-flow & fluctuation effects

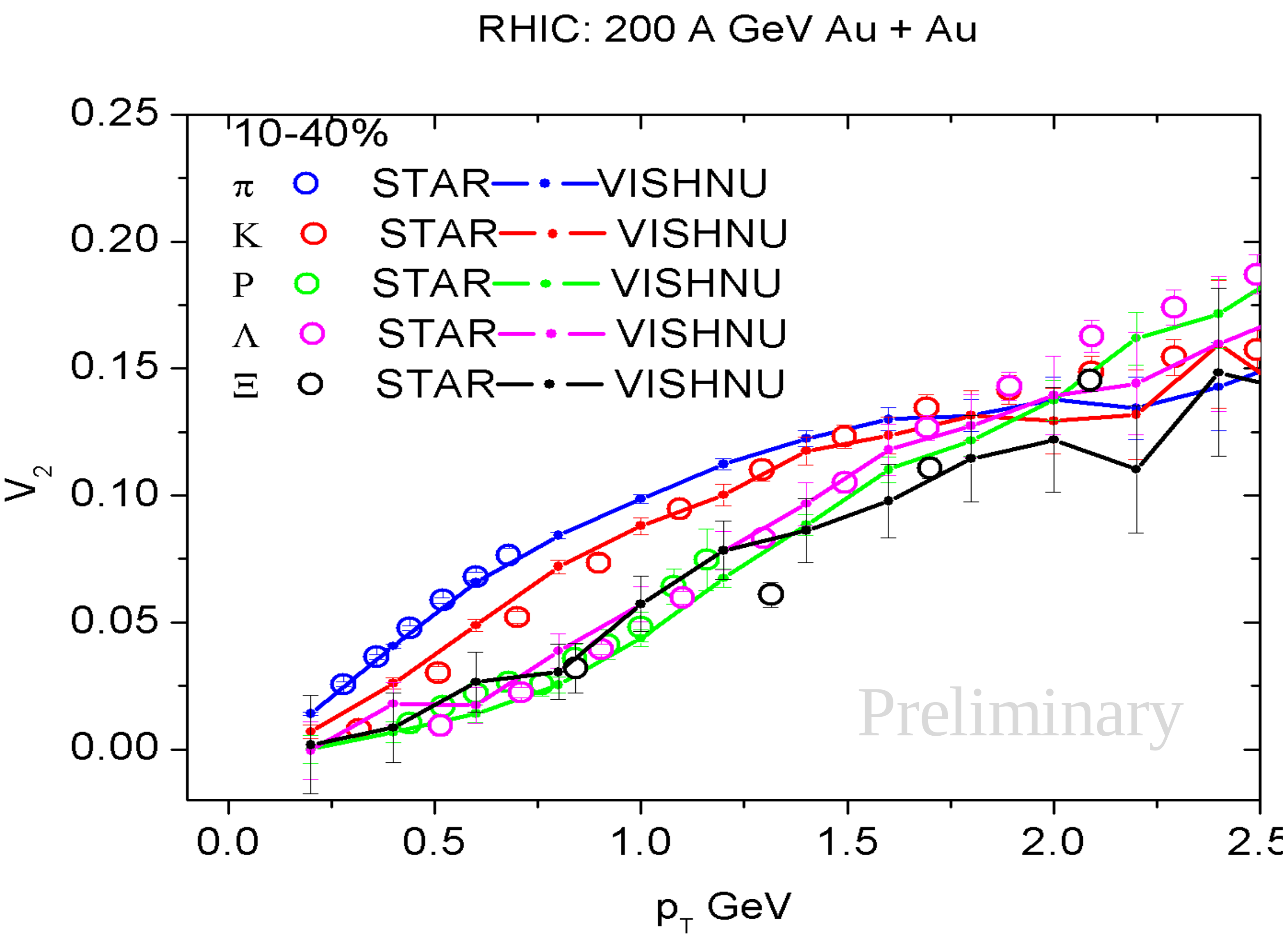
v2 for multi-strange hadrons (RHIC)



v2 {EP} for all charged Hadorns
Non –flow & fluctuations



Mass ordering of elliptic flow (RHIC)

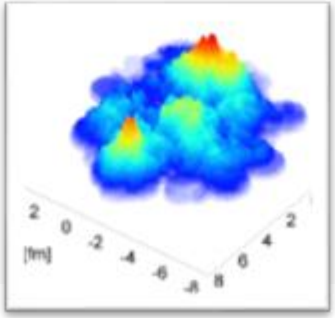


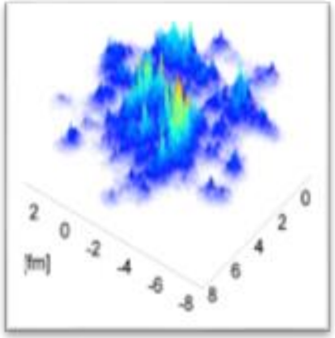
-High statistic runs are needed in the near future !

Initialization Models

-fluctuations of nucleon positions:

MC-Glauber: } T. Hirano & Y. Nara, Phys. Rev. C 79 064904 (2009)
MC-KLN: } **(used in the VISHNU hybrid model)**





-fluctuations of color charges (in the framework of CGC):

IP-Glasma: B. Schenke et al., arXiv:1202.6646; 1206.6805 [nucl-th]
C. Gale, et al., arXiv: 1210.5144, 1209.5330 [nucl-th].

Correlated Fluctuation: B. Muller & A. Schafer, arXiv:1111.3347 [hep-ph]
S. Moreland, Z. Qiu and U. Heinz, arXiv:1210.5508

-fluctuations of local gluon numbers (in the famework of MC-KLN):

Multiplicity fluctuations: A. Dumitru and Y. Nara, Phys. Rev. C 85, (2012) 034907
A. Dumitru, arXiv:1210.7864 [hep-ph].

Pre-equilibrium dynamics

Free Streaming limit: G. Qin, et. al., Phys. Rev. C82 064903 (2010); OSU, on-going work
Hydro limit: OSU group, on-going work

Pre-equilibrium dynamics smoothes out fluctuations, reducing $\varepsilon_2, \varepsilon_3$, but building radial flow

-early flow & fluctuations from dynamical models:

URQMD initialization: H.Petersen & M. Bleicher, Phys. Rev. C81, 044906,2010

AMPT initialization: L. Pang, Q.Wang & X.N.Wang, arXiv:1205.5019 [nucl-th]
L. Pang, Q.Wang & X.N.Wang, arXiv: 1211.1579[nucl-th]

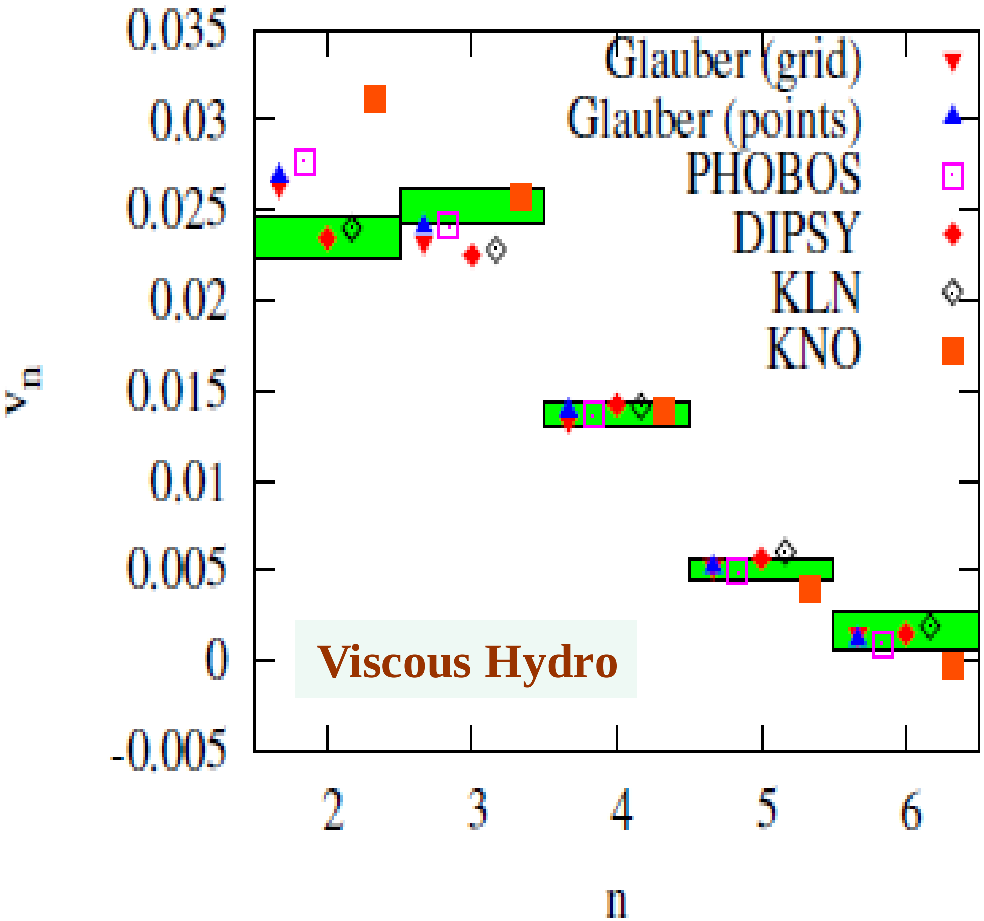
EPOS/NEXUS initialization: K. Werner et al., Phys. Rev. C83:044915,2011;
H. J. Drescher et, al., Phys.Rev. C65 , 054902 (2002).

IP-Glasma: B. Schenke, et.al, arXiv:1202.6646; 1206.6805 [nucl-th]
C. Gale, et al., arXiv:1210.5144, 1209.5330 [nucl-th].

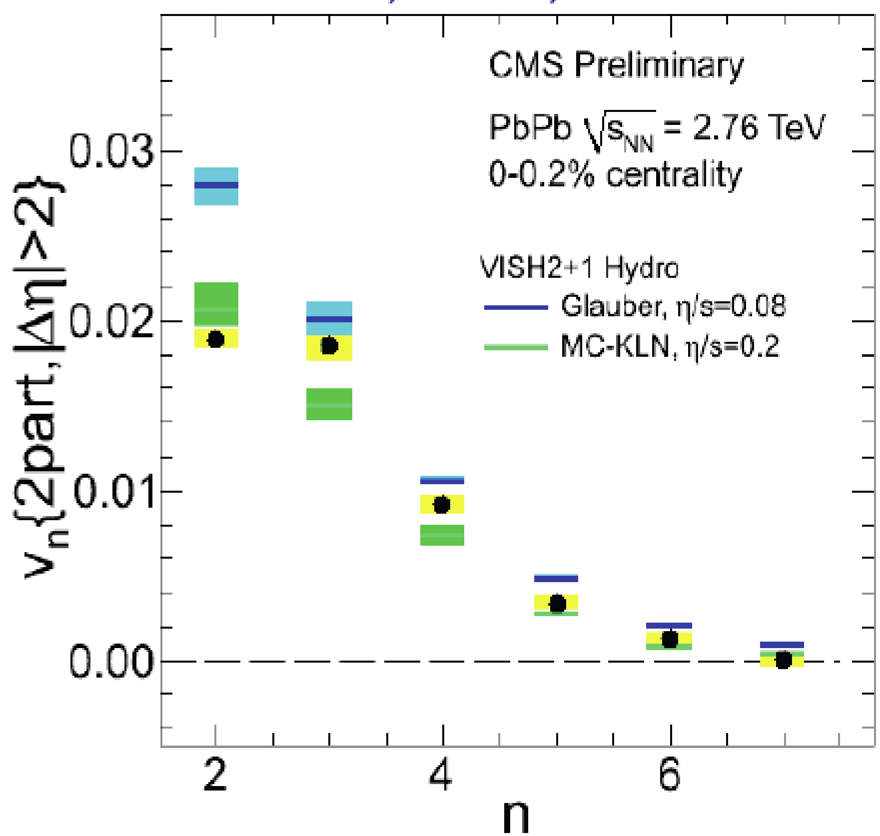
Except IP-Glamsa, most pre-equilibrium dynamics was studied within the ideal hydro framework. Their quantitative influences on $(\eta/s)_{QGP}$ are still unknown.

Extracting η/s from V_n in ultra-central collisions

Luzum & Ollitrault, arXiv: 1210.8422



C. Shen, Z. Qiu, and U. Heinz.

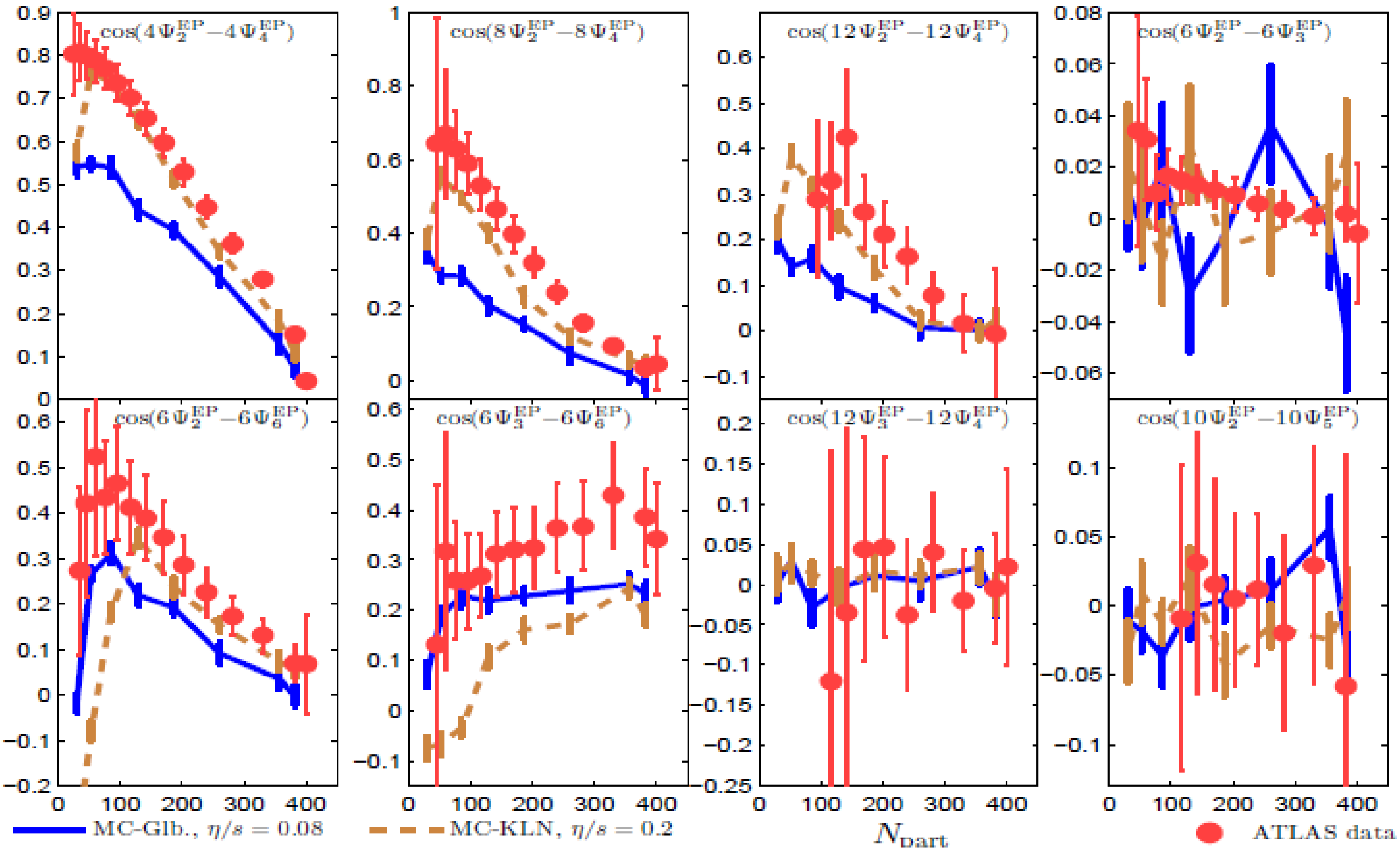


-In most central collisions, fluctuation effects are dominant (Geometry effects are suppressed)

-can not simultaneously fit V_2 and V_3 with single η/s (MC-Glauber & MC-KLN)

Higher Order Event Plane Correlations

Qiu & Heinz, arXiv:1208.1200[nucl-th]



EXP. data:[ATLAS Collaboration],
CERN preprint ATLAS-CONF-2012-049

Pure e-b-e viscous hydro simulations :

qualitatively reproduce the measured event plane correlations

V_n & E-b-E V_n distributions

C. Gale et al., arXiv:1209.4330[nucl-th]