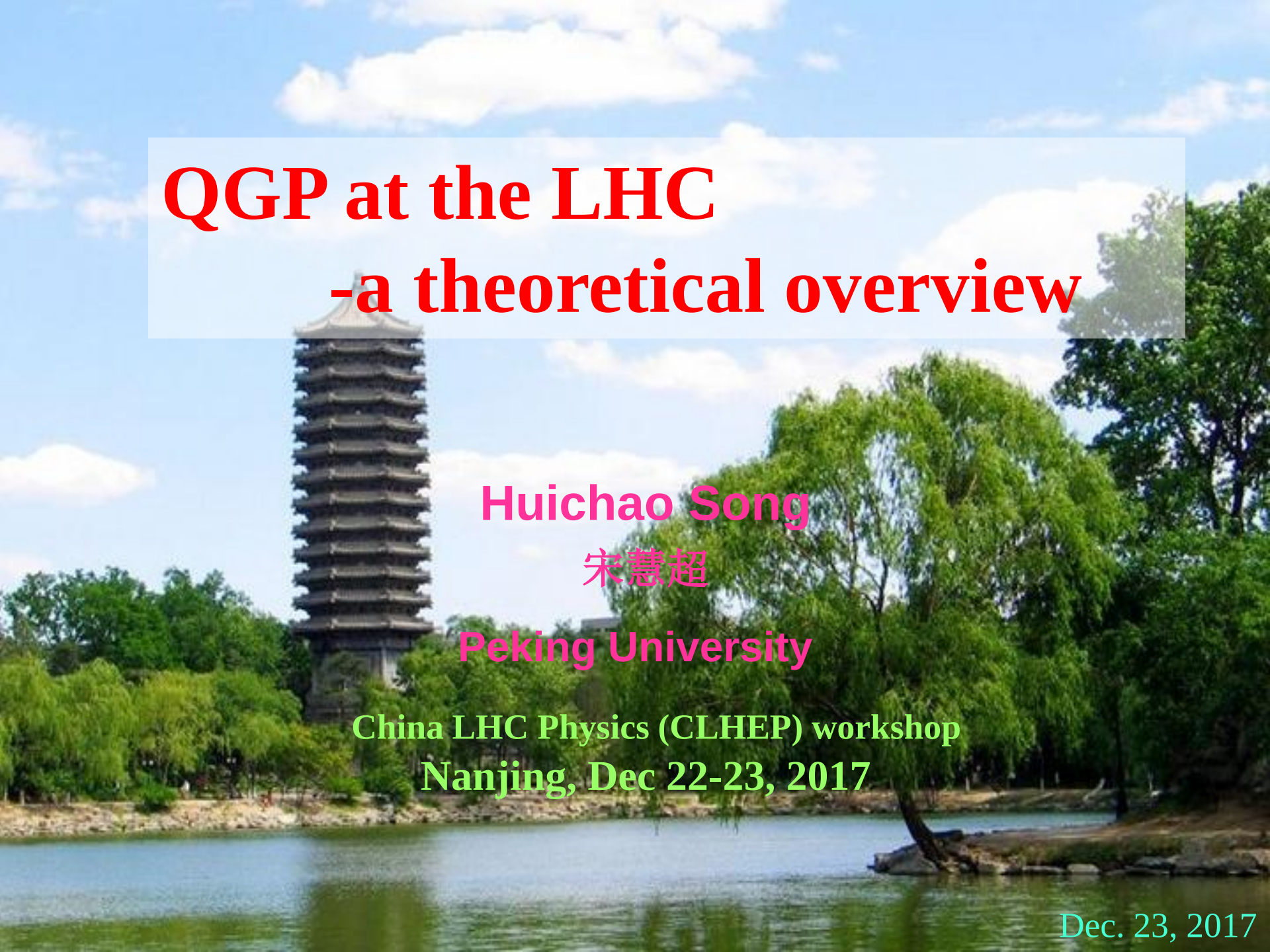


QGP at the LHC
-a theoretical overview

Huichao Song

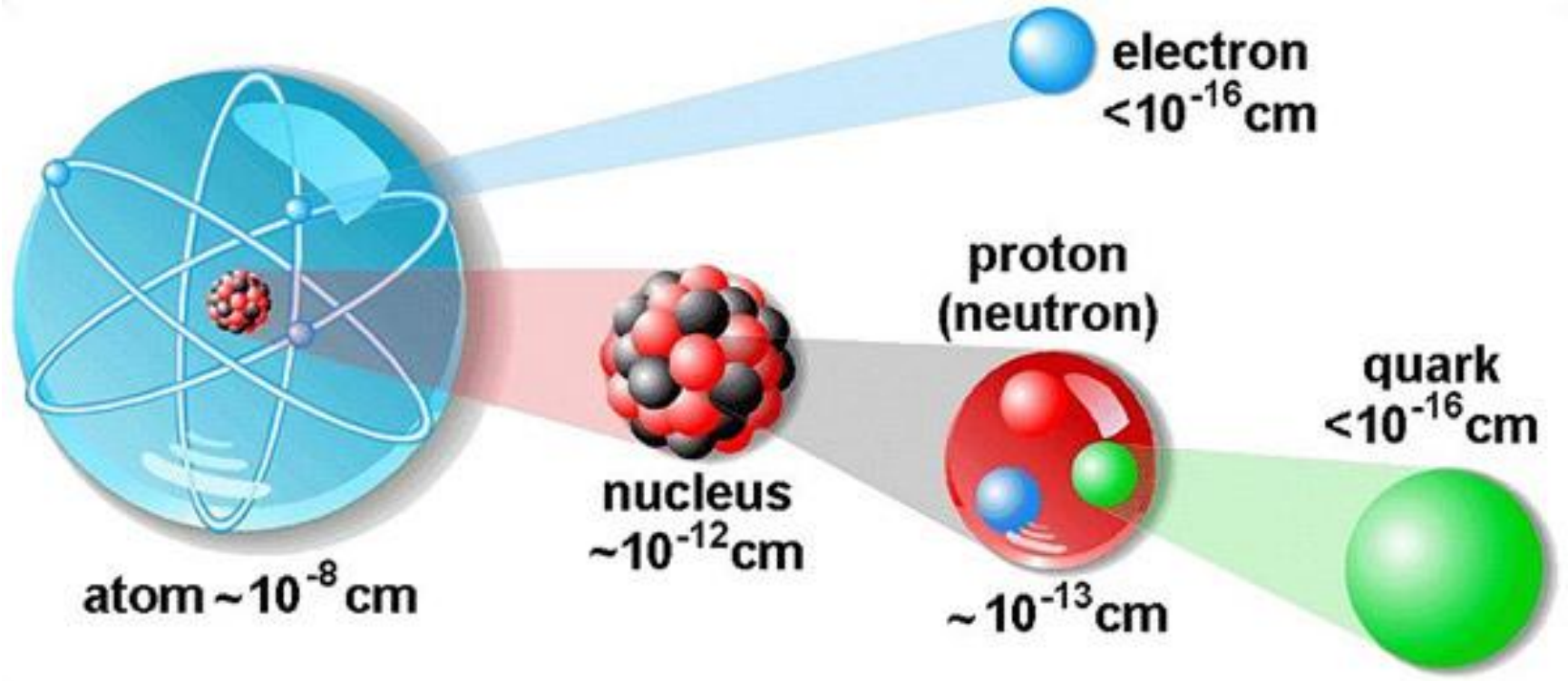
宋慧超

Peking University

China LHC Physics (CLHEP) workshop

Nanjing, Dec 22-23, 2017

Dec. 23, 2017

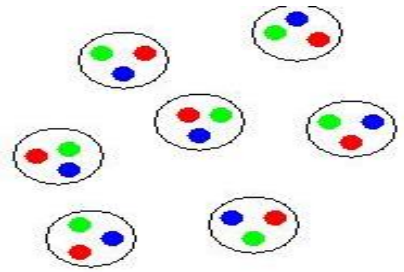


Quark and Gluons: confined in proton and neutrons through strong forces described by QCD

QGP (quark gluon plasma): deconfinement phase of QCD matter

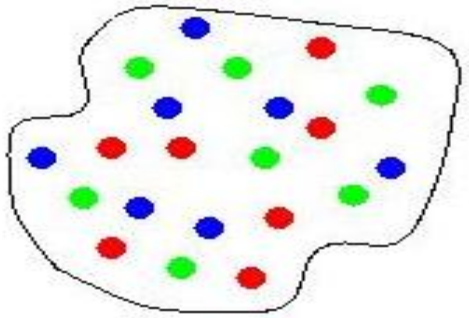
Nuclear Matter

Quark Gluon Plasma



Phase Transition

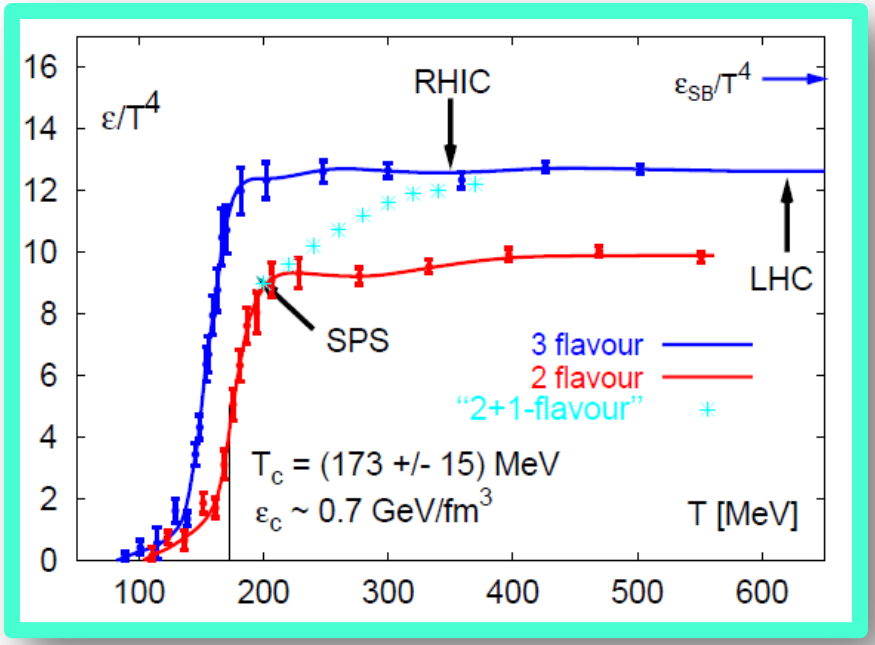
$T_c \sim 2X10^{12}$ K



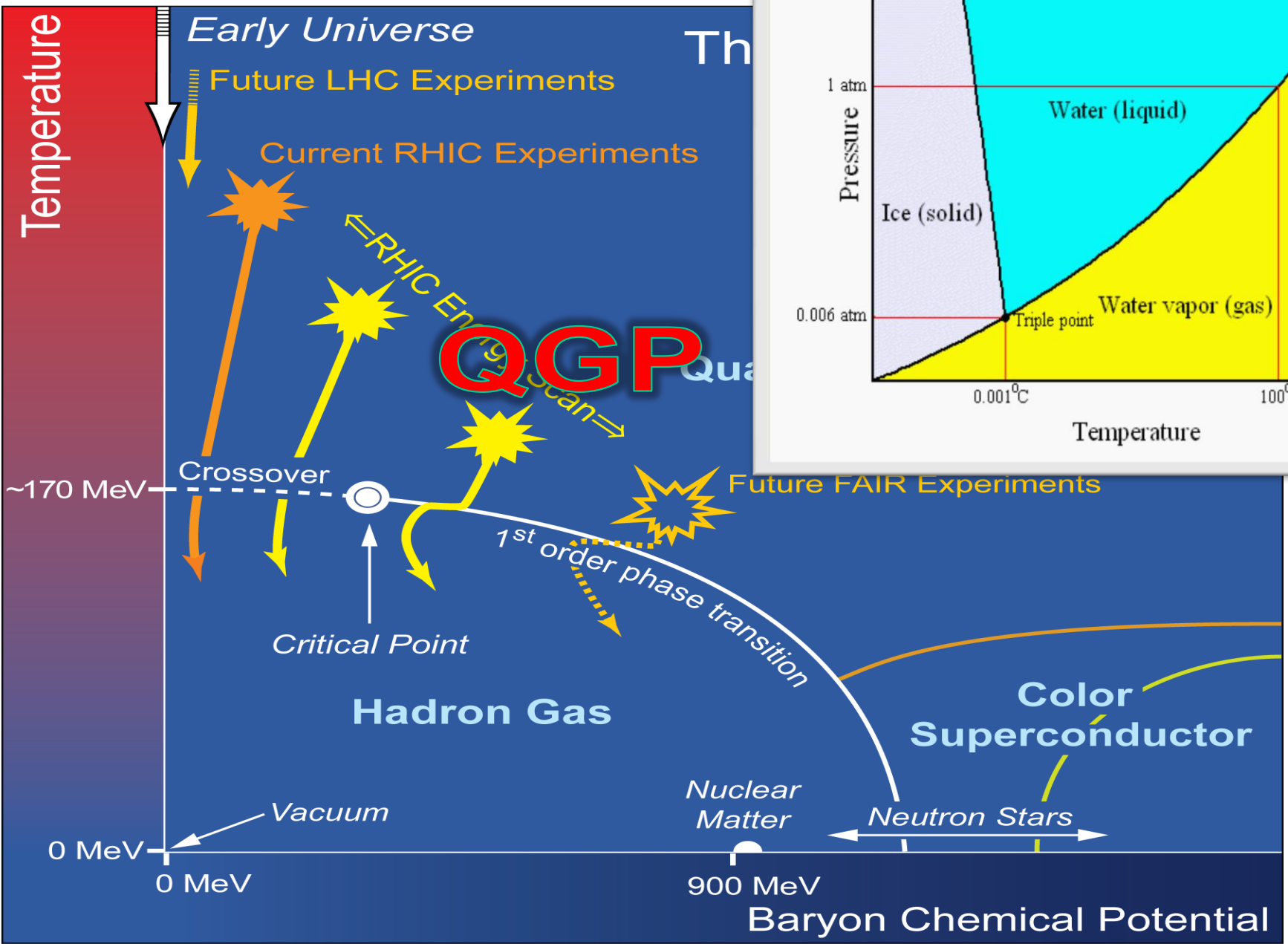
Confinement

Deconfinement

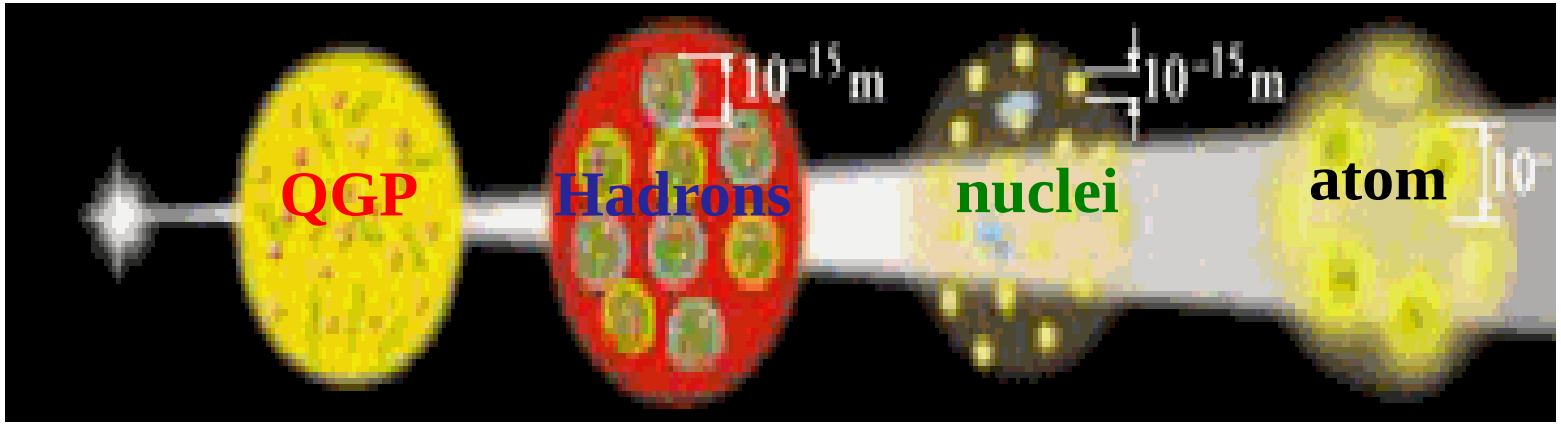
Lattice QCD simulations



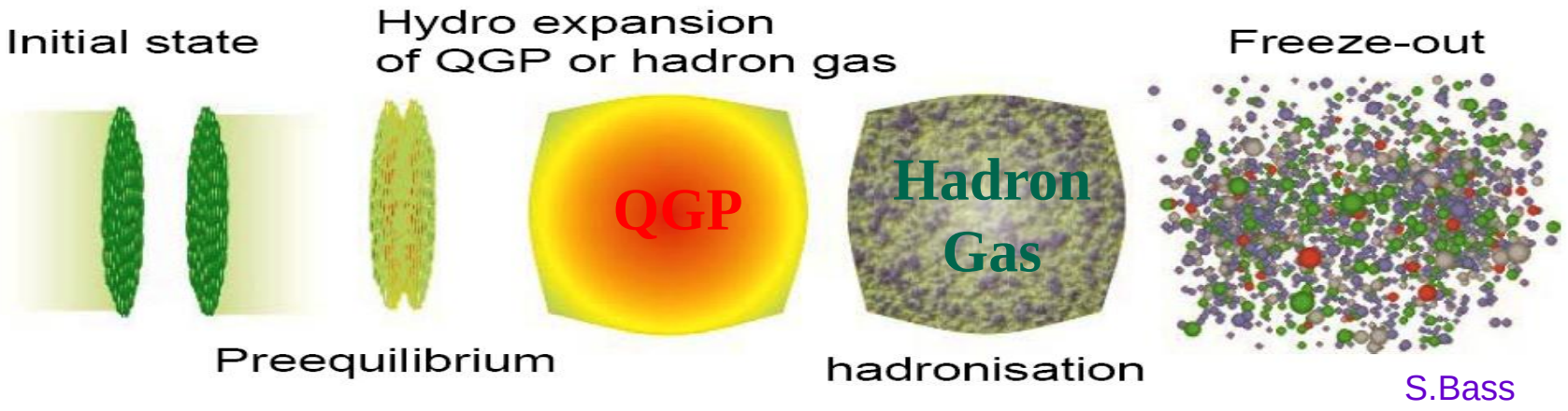
QCD Phase diagram



big bang: the very early history of the universe



little bang: the different stage for a relativistic heavy ion collisions

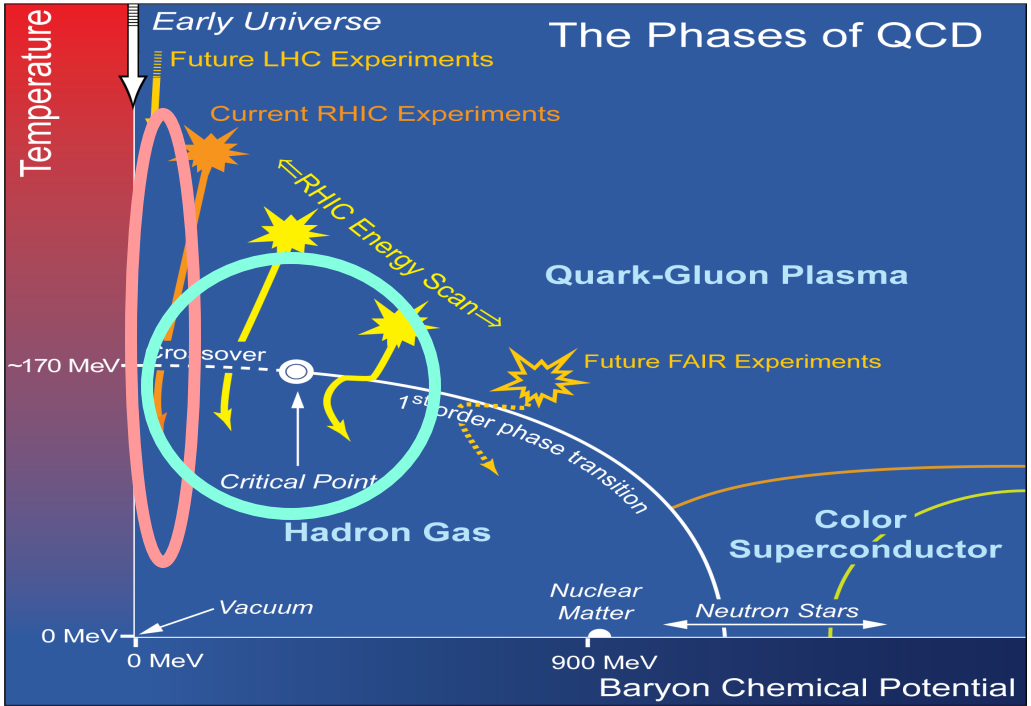


RHIC, BNL

LHC, CERN

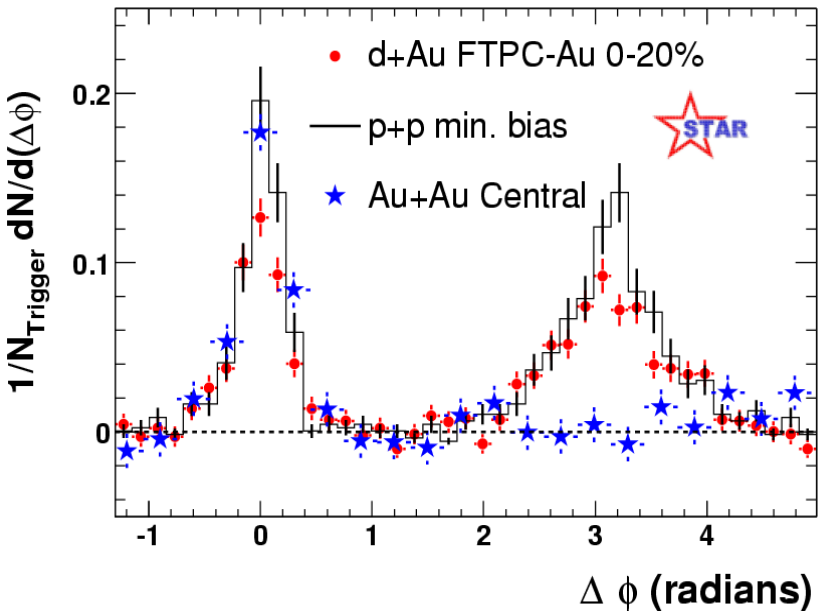
Current complementary Heavy Ion Program at RHIC and the LHC

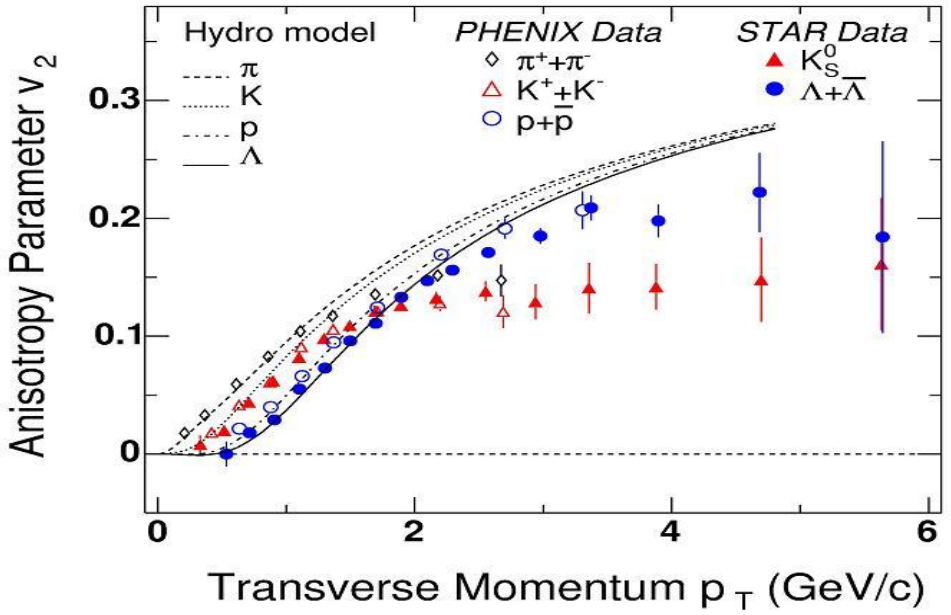
future heavy ion program
-FAIR
-NICA

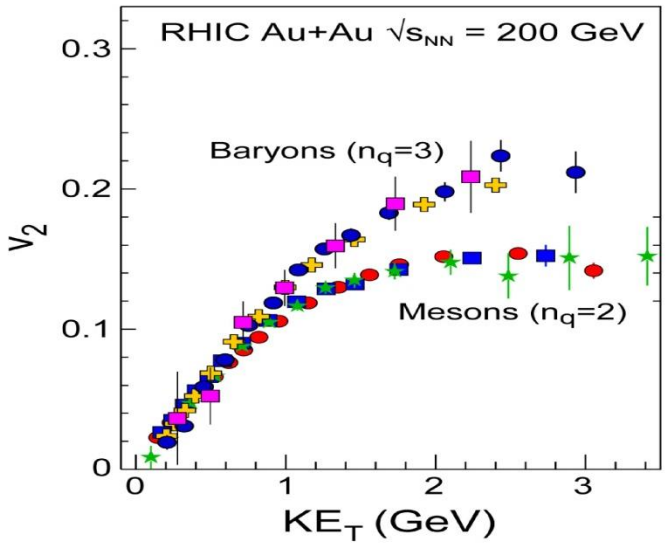


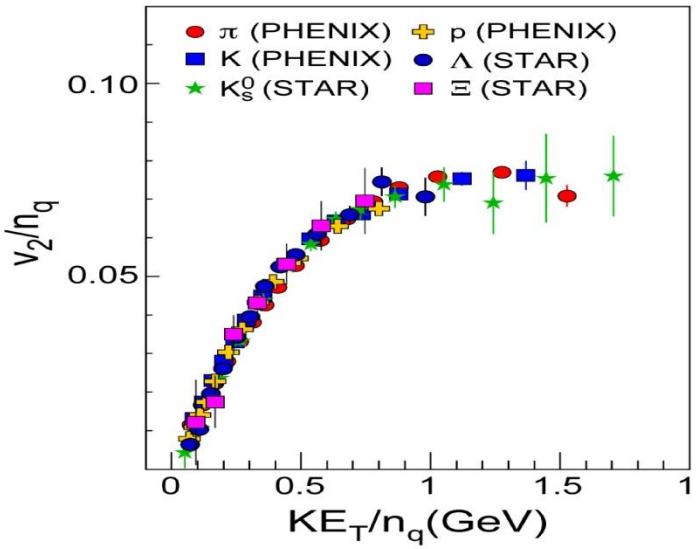
The QGP was discovered

RHIC (2000--









QGP-the most perfect fluid in the world

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LHC to Restart in 2009

Disappearing Superconductivity Reappears -- in 2-D

Electron Pairs Precede High-Temperature Superconductivity

World's biggest computing grid launched

First Beam for Large Hadron Collider

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RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

BNL News, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

Secretary of Energy Samuel Bodman

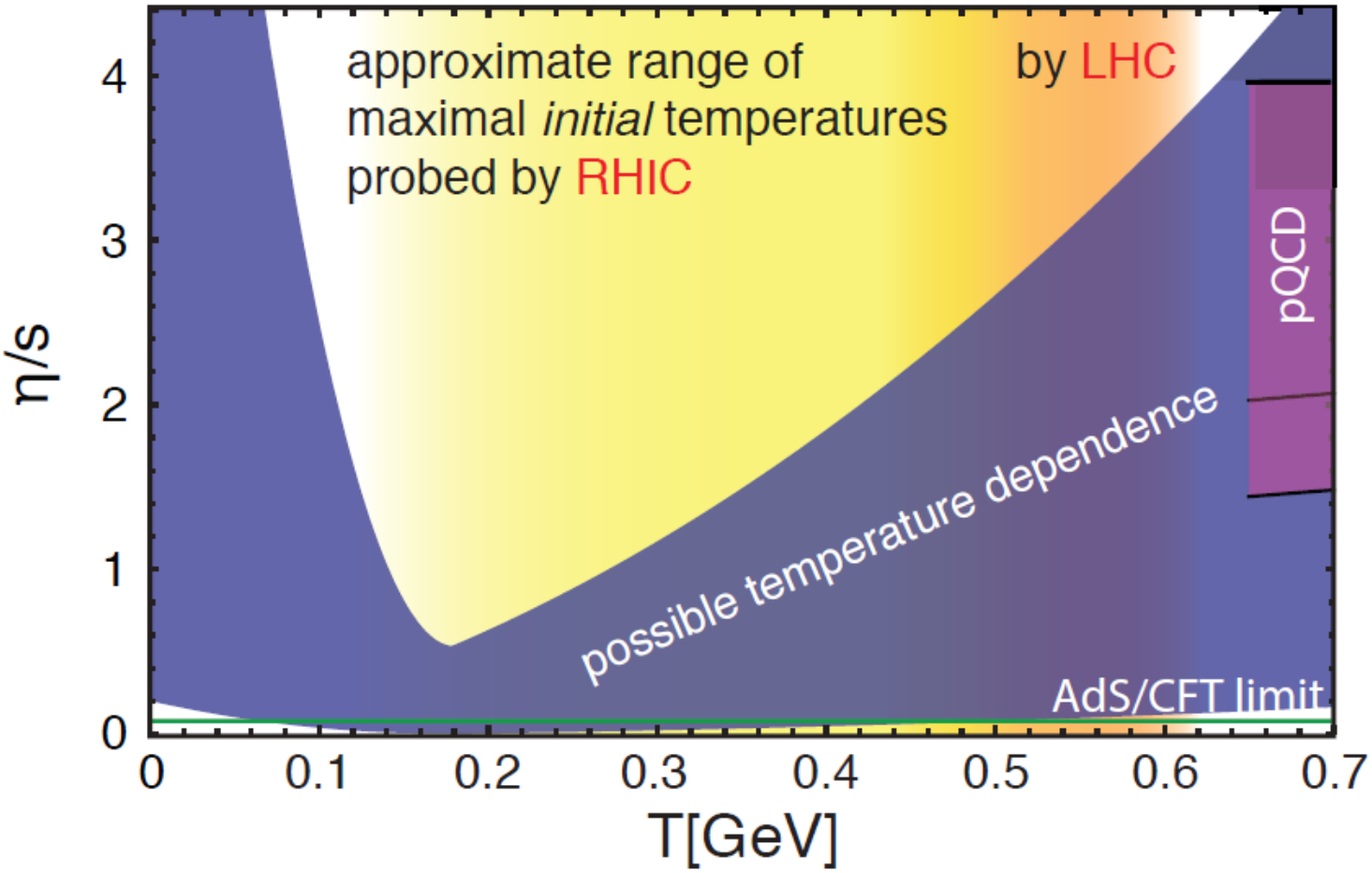
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain

Heavy Ion Program at the LHC

Heavy Ion Program from RHIC to the LHC (I)

Created QGP and its initial temperature



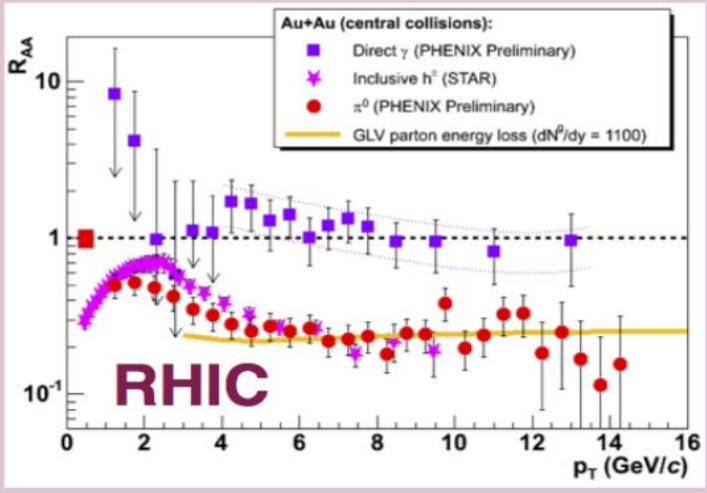
Bulk of the Matter: the QGP fireball is a locally thermalized system

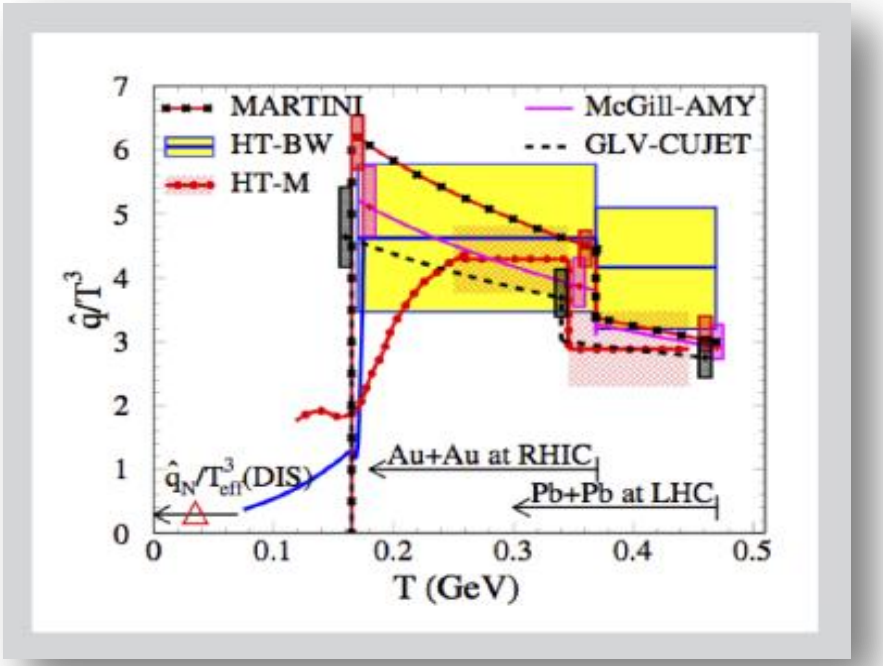
-the temperature range probe by LHC is larger than RHIC

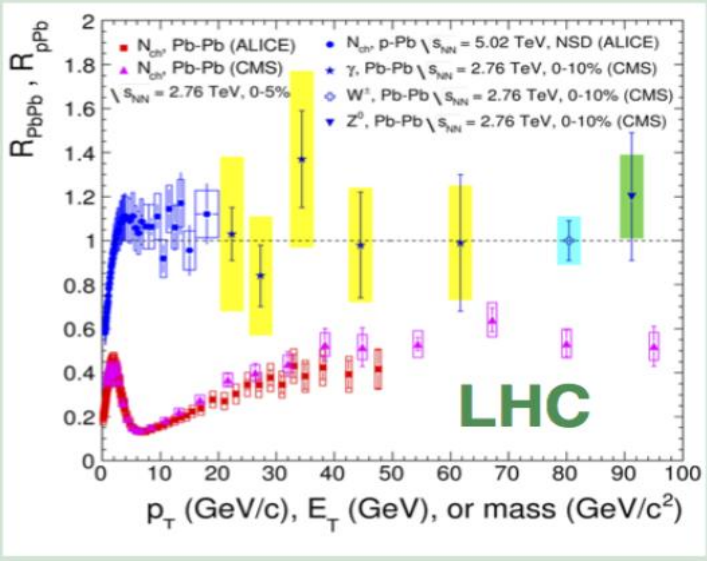
-study the temperature dependent QGP viscosity

Heavy Ion Program from RHIC to the LHC (II)

Jet physics & parton energy loss





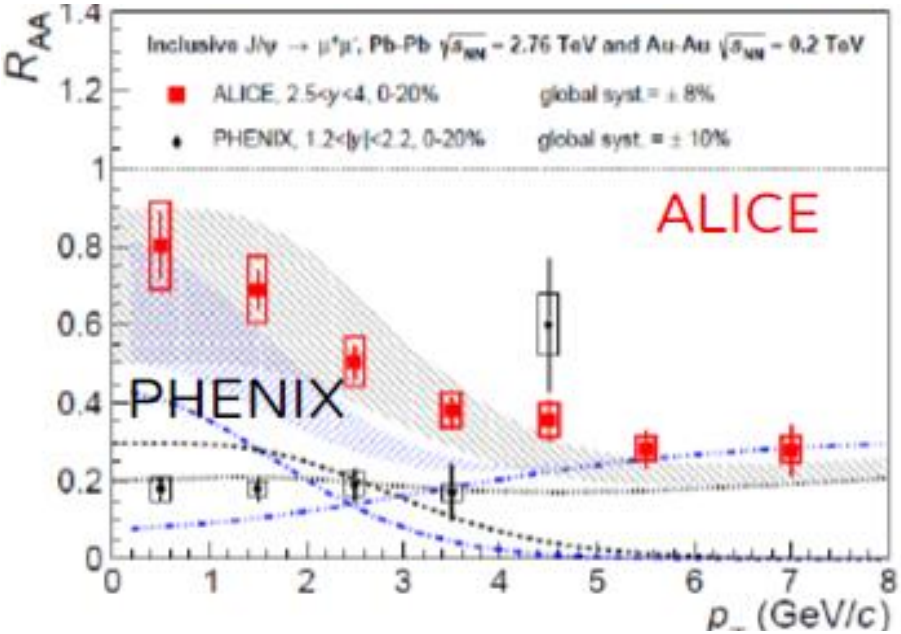


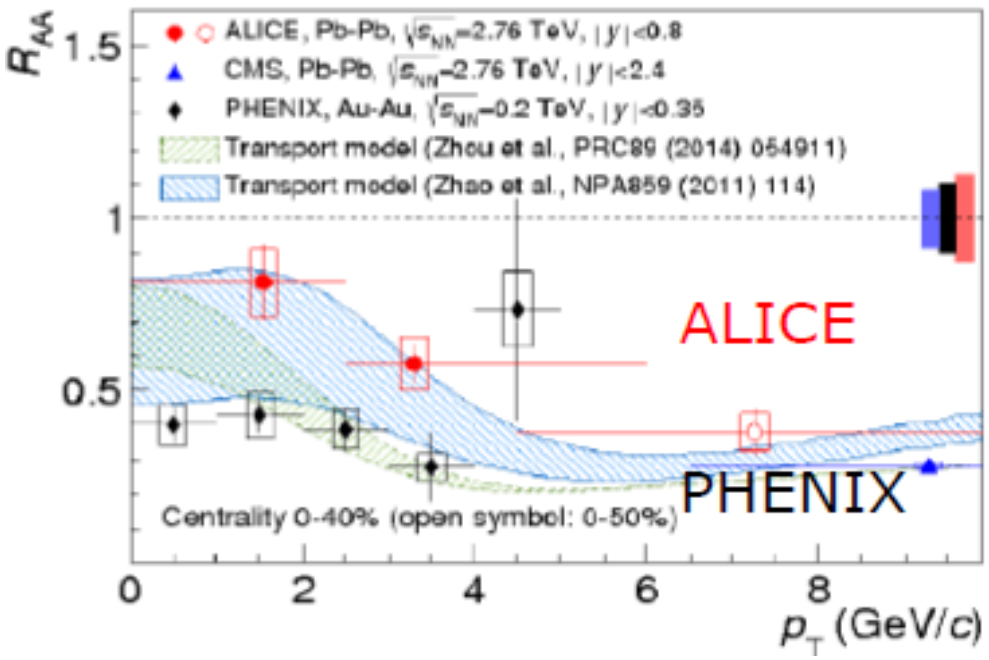
Jet physics: jet measured at the LHC increased to the energy up to several handred GeV

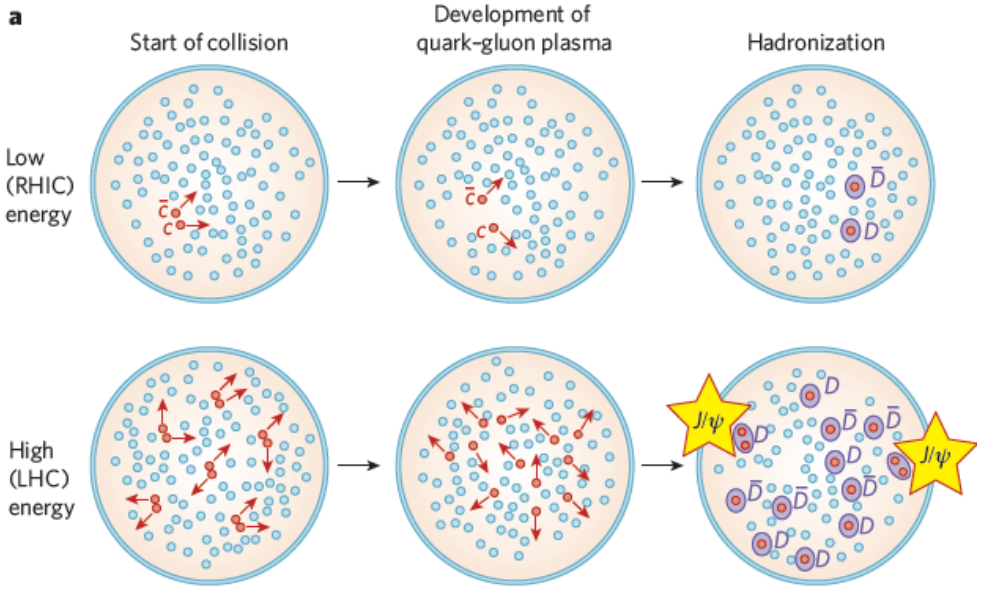
Parton energy loss: extract the temperature dependent transport coefficient q at RHIC and LHC regime (JET collaborations)

Heavy Ion Program from RHIC to the LHC (III)

J/Ψ suppression: evidence for recombinations







J/Ψ suppression:

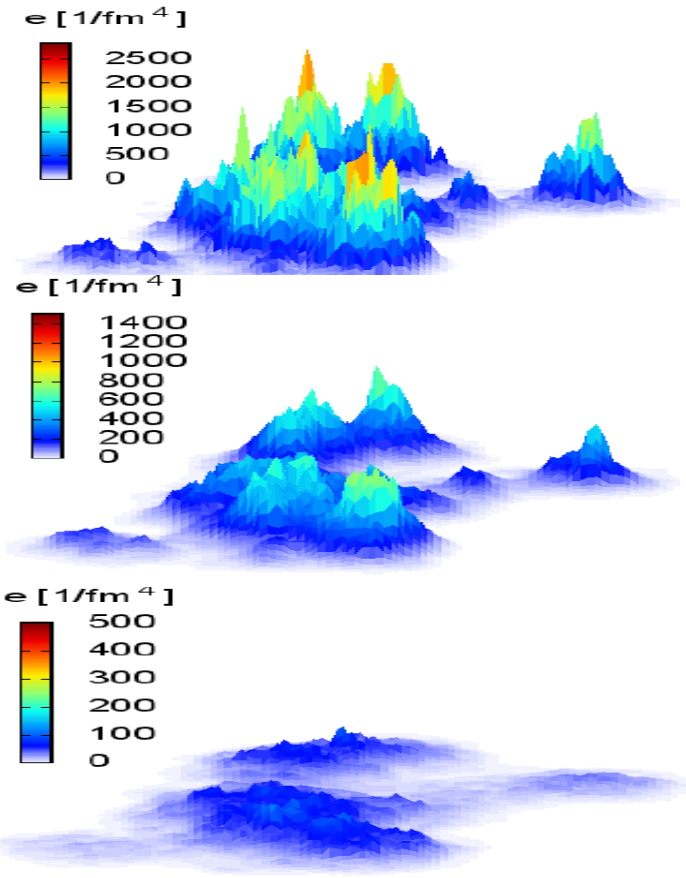
Show evidence of recombination at he LHC ; A fingerprint of a high-energy/ temperature QGP with more cċ pair produced

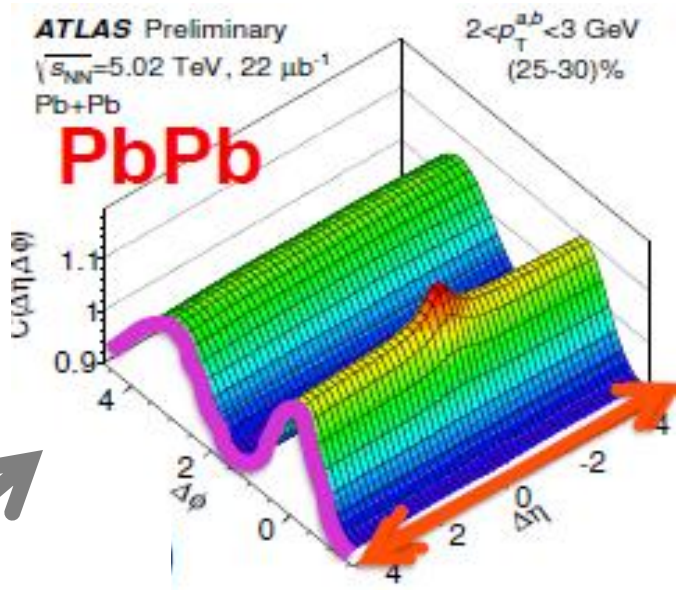
Nice agreement with the related model calculations

Heavy Ion Program at the LHC (IV)

Initial state fluctuations and final state correlations:

--a hot research topic since 2010



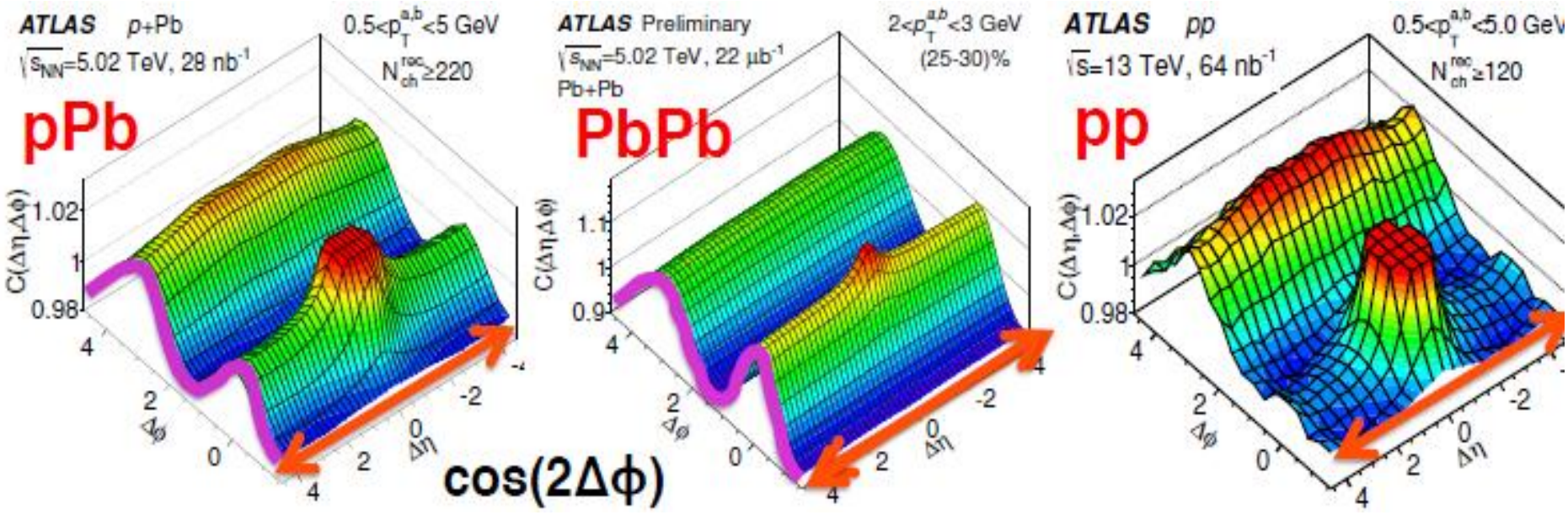


-Various flow obsevables have been extensively measured in Pb+Pb collisions at the LHC, which could provide strong constraint on initial conditions and QGP viscosity

Heavy Ion Program at the LHC (V)

Flow-like signals in small systems of high multipliciy p-p and p-Pb collisions:

--a hot research area since 2013



-Originally aim to pride reference data for Pb-Pb collisions

-Lots of unexpected flow-flike signals were obsered in p-Pb, and p-p collisions at the LHC

- indicating the development of collective flow at small systems

Heavy Ion Program at the LHC

Key Questions

-Is the QGP produced at LHC also a "Perfect" Liquid ?

-How does the initial state fluctuations translate into final state correlations

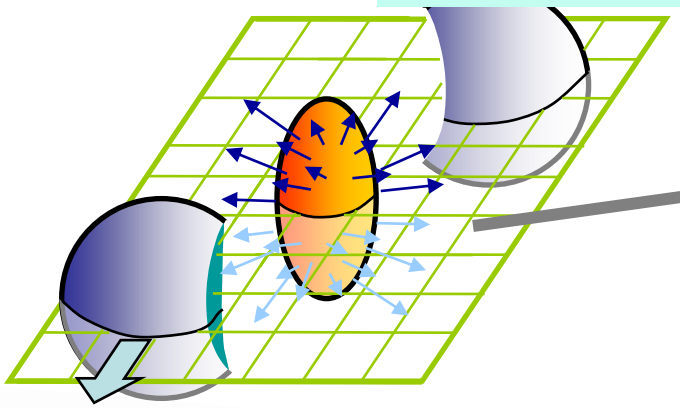
-How does the QGP thermalize ?

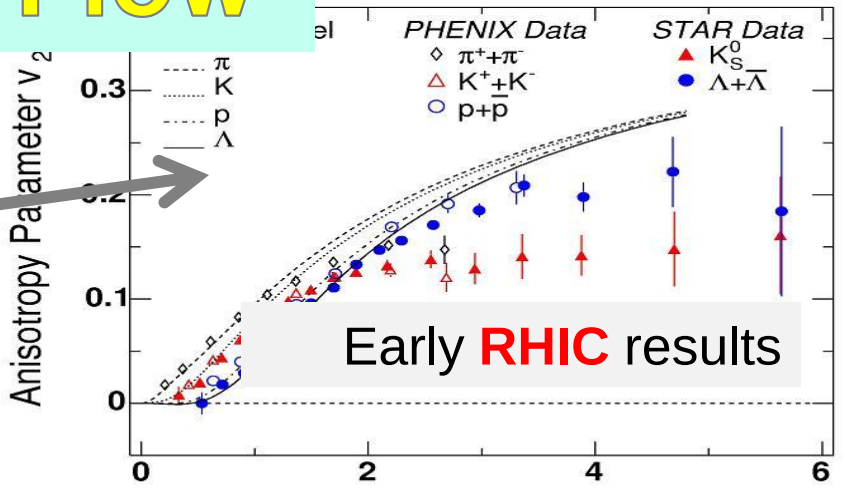
-Does the smalll p-Pb and p-p systems collectively expand?

-What are the solid flow signal? How about validity of the hydrodynamics in such small systems?

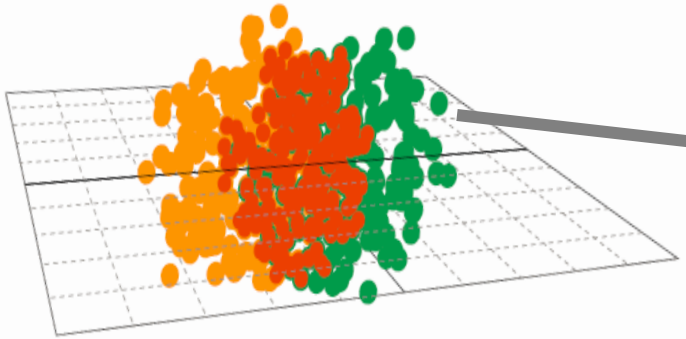
The Fluid Nature of QGP at the LHC

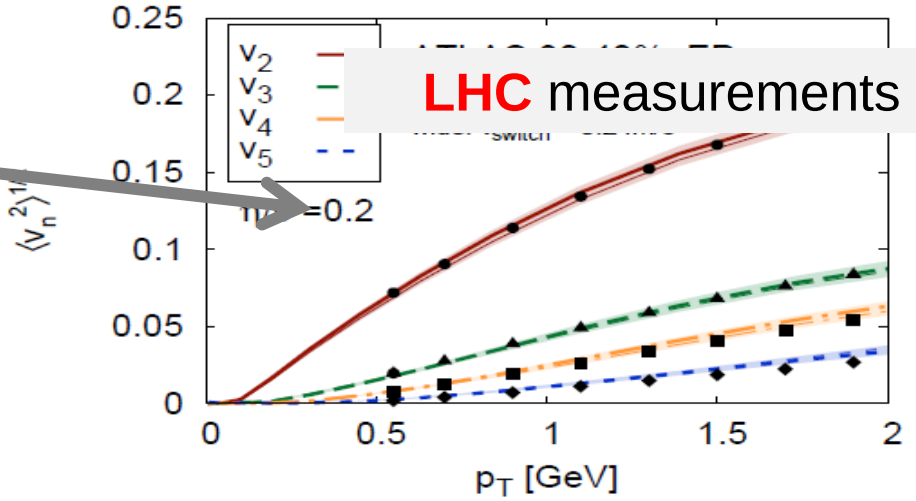
Collective Flow





Early **RHIC** results

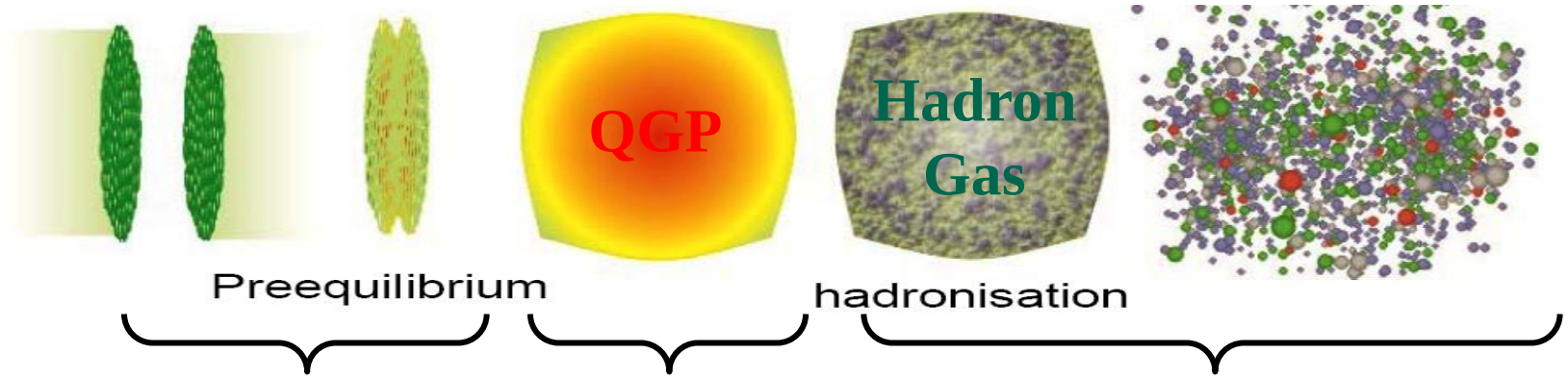




LHC measurements

$$E\frac{dN}{d^3p}=\frac{1}{2\pi}\frac{dN}{dyp_Tdp_T}[1+2v_1(p_T,b)\cos(\varphi)+2v_2(p_T,b)\cos(2\varphi)$$
$$+2v_3(p_T,b)\cos(3\varphi).....]$$

Hydrodynamics & Hybrid Model



Conservation laws:

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

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

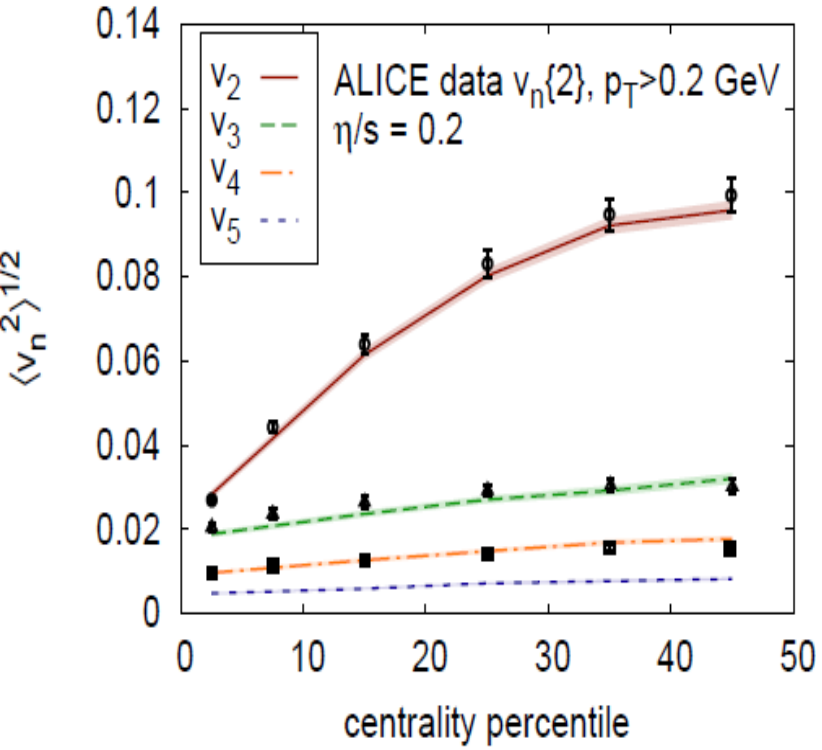
$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta(\partial\cdot u) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

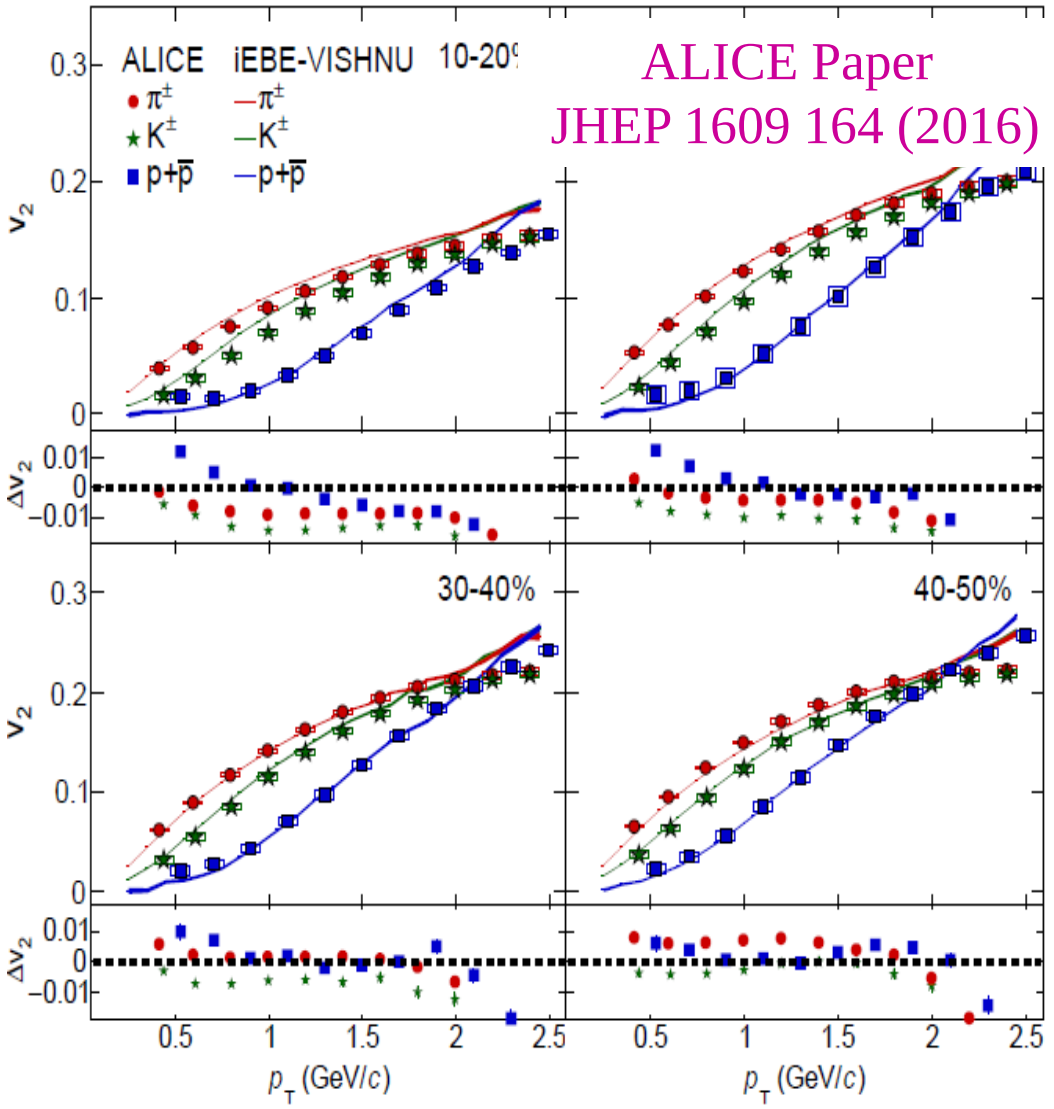
- Israel-Stewart eqns.

$$\partial_\mu S^\mu \geq 0$$

Input: "EOS" $\varepsilon = \varepsilon(p)$ initial and final conditions

The Success of Hydrodynamics





ALICE Paper
JHEP 1609 164 (2016)

-Hydro + IP-Glasma

Gale, et. Al, PRL2013

-iEBE-VISHNU + AMPT

Xu, Li, Song, PRC 2016

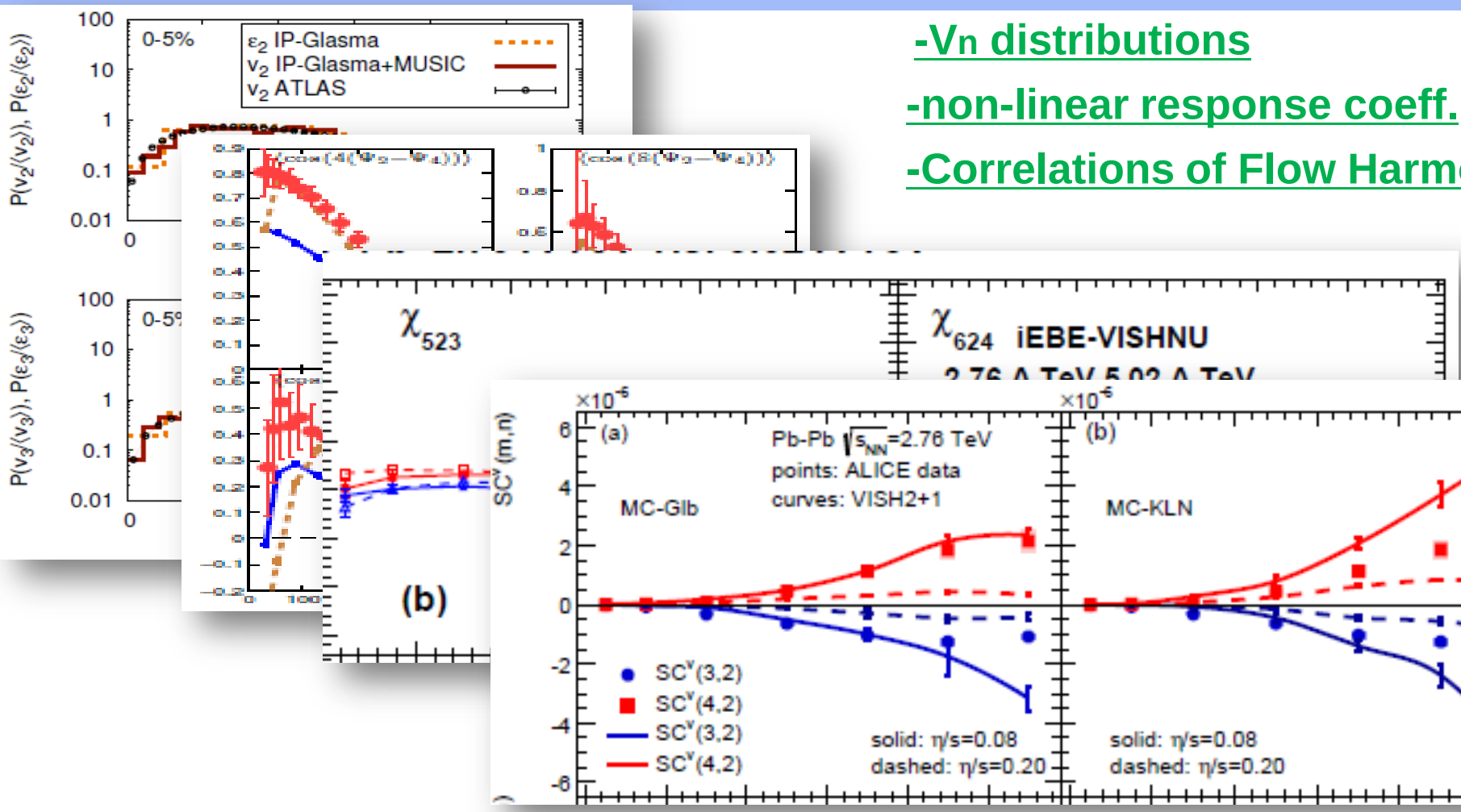
-nice descriptions of integrated and differential V_n of all charged and identified hadrons

Various flow observables at the LHC

-Vn distributions

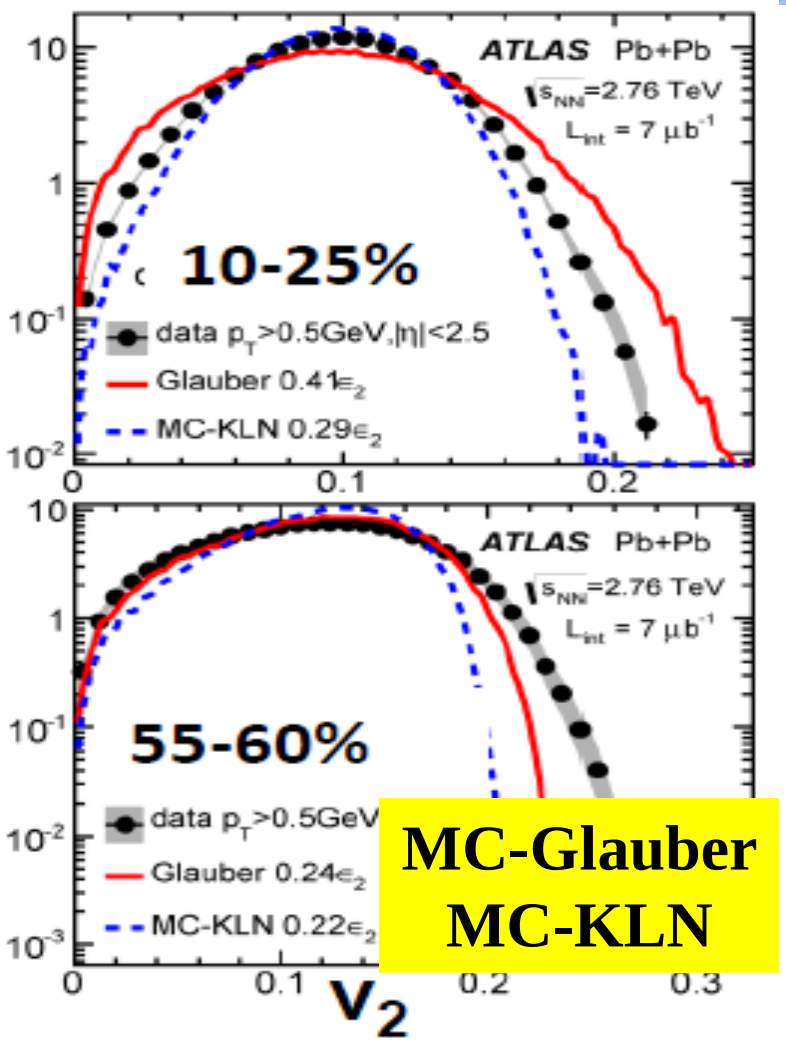
-non-linear response coeff.

-Correlations of Flow Harmonics



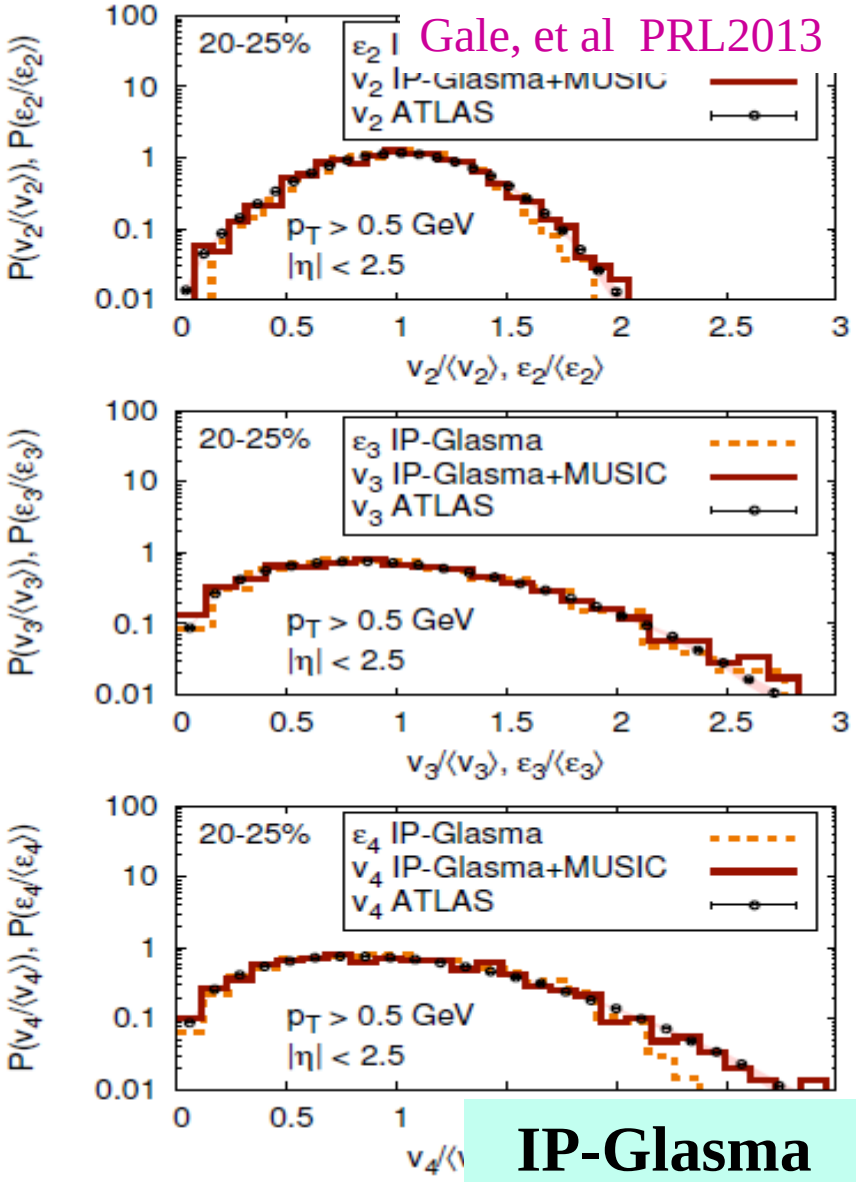
-Various flow data reflect the information of initial state fluctuations, some of them provide strong constraint for initial conditions

Other flow observables (I)



MC-Glauber
MC-KLN

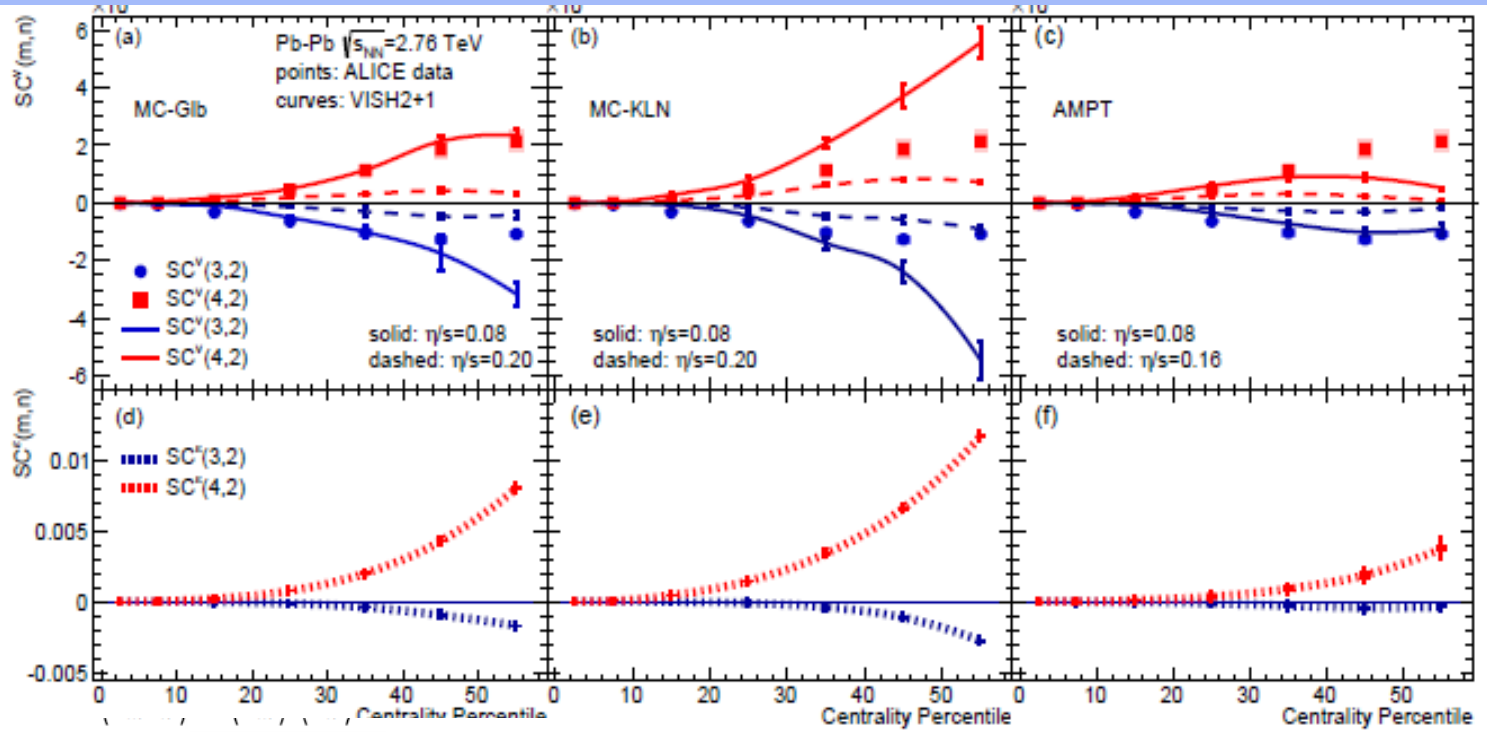
Gale, et al PRL2013

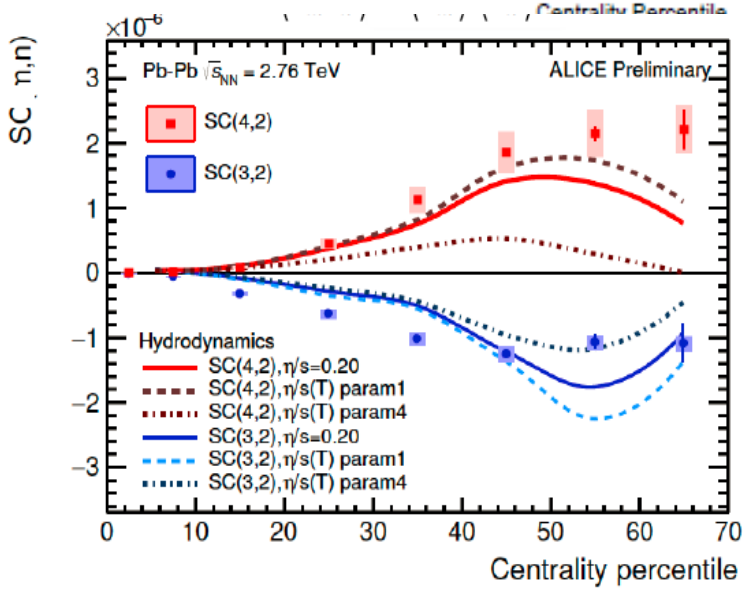


IP-Glasma

Vn distributions prefer the IP-Glasma initialization and ruled-out the MC-Glauber and MC-KLN initial conditions

Other flow observables (II)





Zhu, Xu, Zhou, Song, PRC 2016

-V_2 and V_4 are correlated

-V_2 and V_3 are anti-correlated

-provide strong constraint on $\eta/s(T)$

Extract QGP properties from bulk observ.

-massive data evaluation

Exp Observables

- particle yields
- spectra
- elliptic flow
- triangular flow & higher order flow harmonics
- event by event V_n distributions
- higher-order event plane correlations

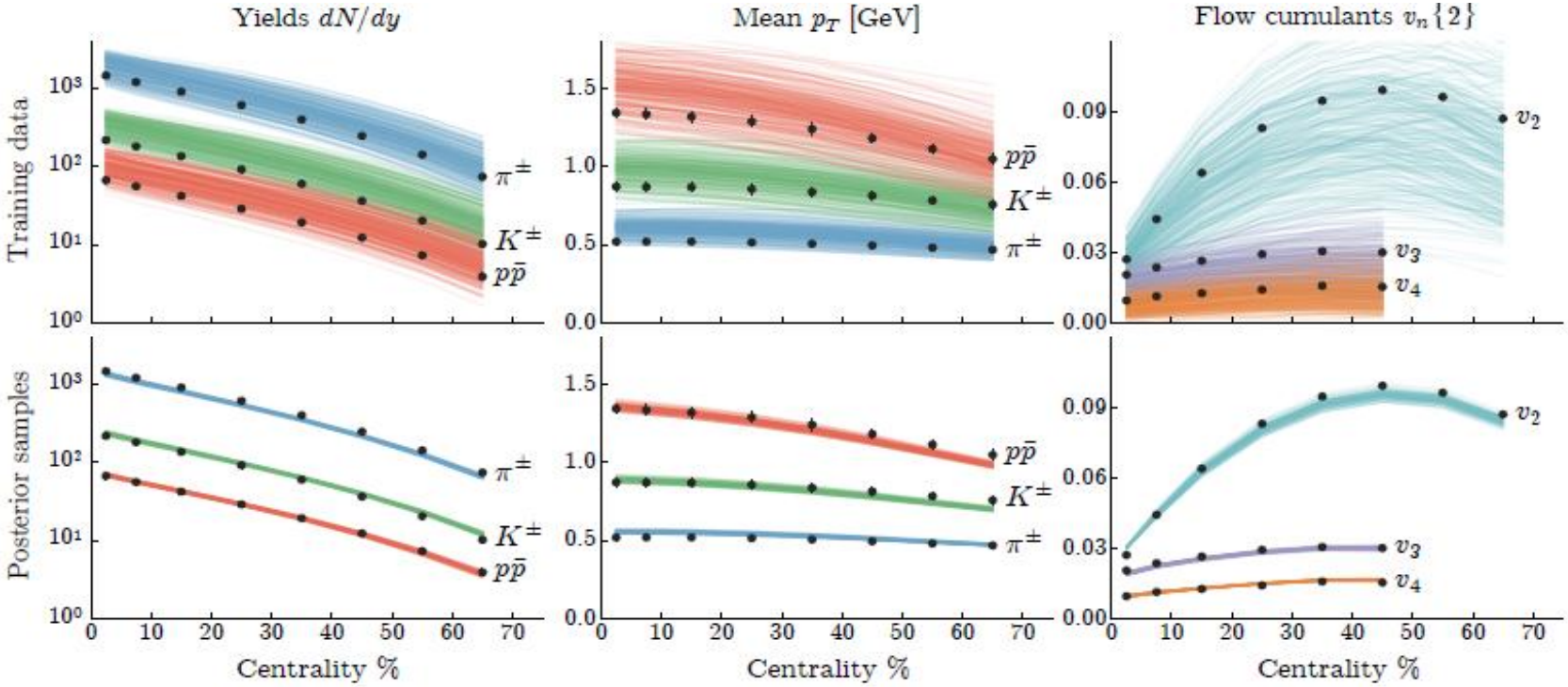
…… …… ……

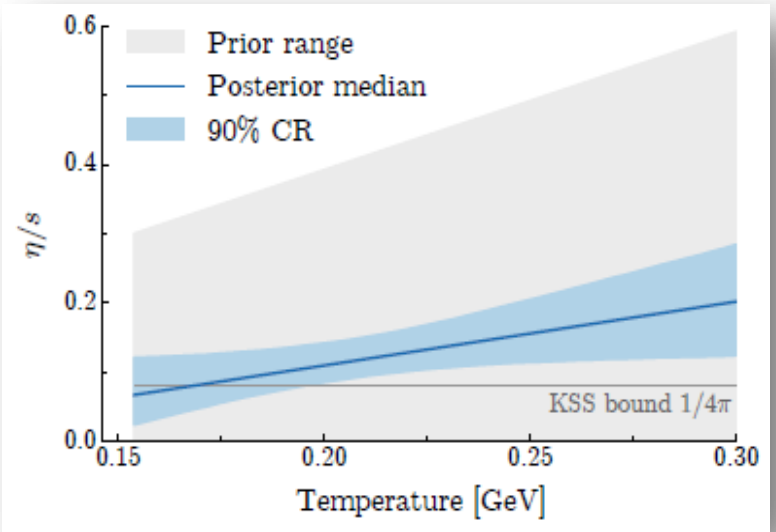
Hydro model & its Inputs:

- type of initial conditions
- initial flow
- starting time
- EoS
- shear viscosity
- bulk viscosity
- relaxation times
- freeze-out/switching cond.

…… …… ……

An quantitatively extract the QGP viscosity

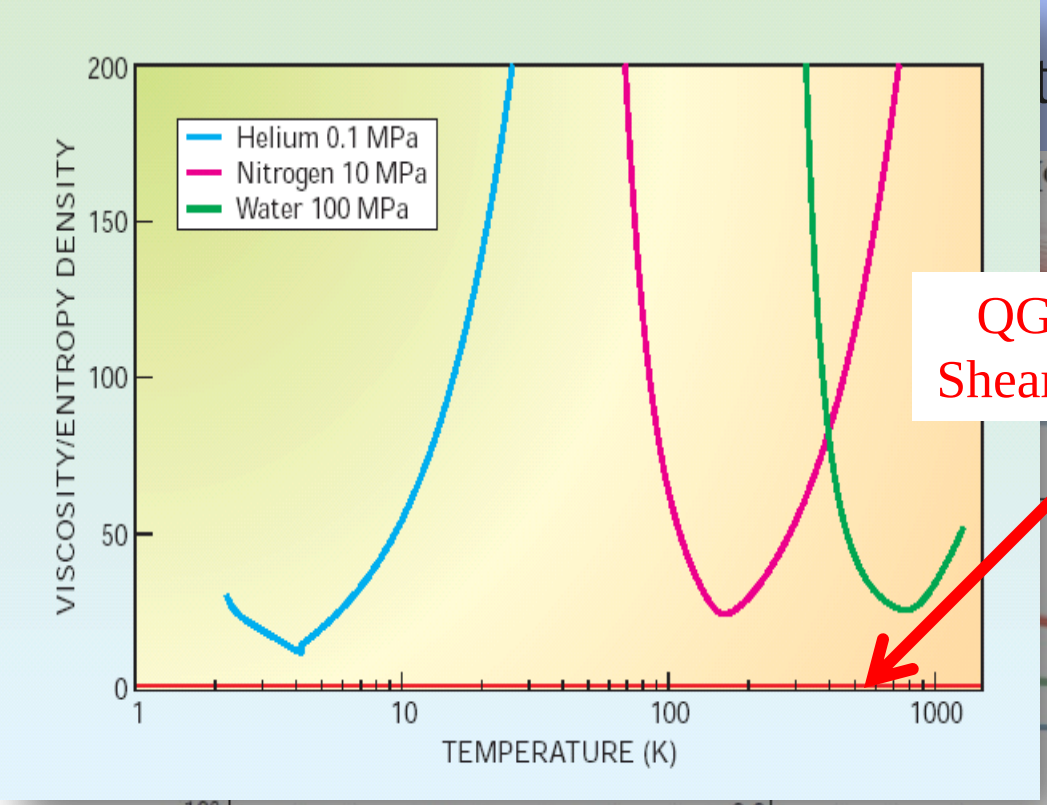




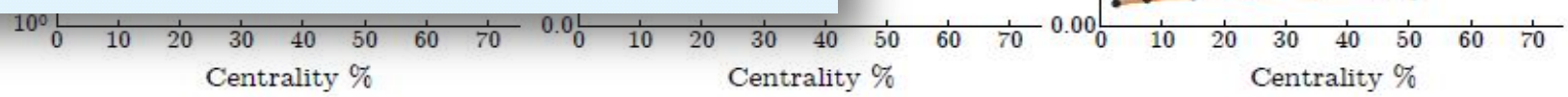
-An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

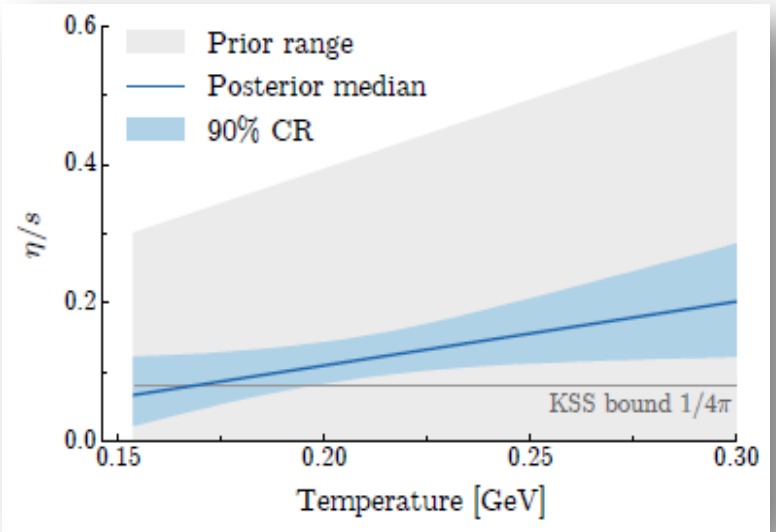
-η/s(T) is very close to the KSS bound of 1/4π

J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015



QGP specific
Shear viscosity





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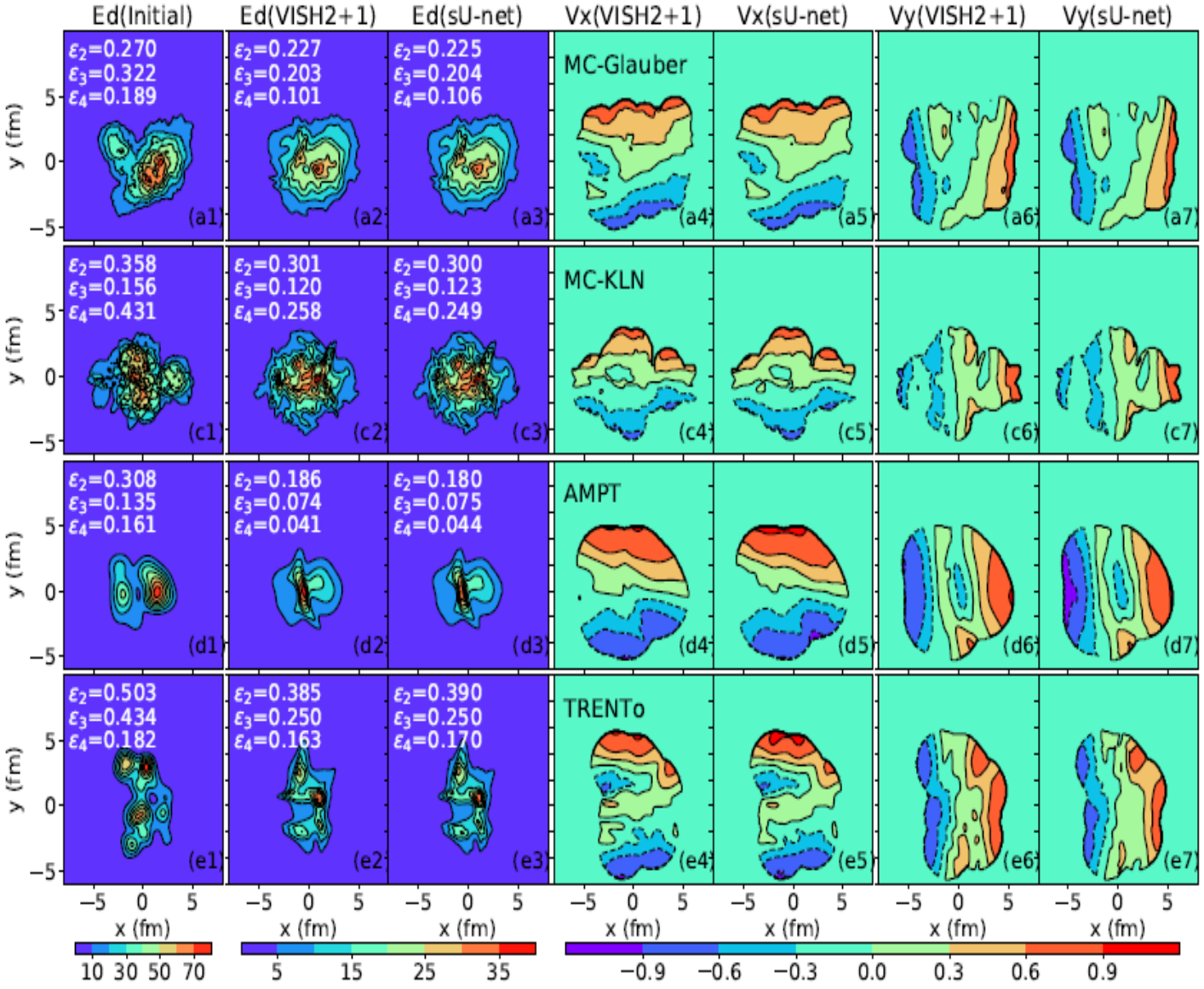
J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015

-Traditional hydro calculations are always time consuming

Application of deep learning to hydrodynamics

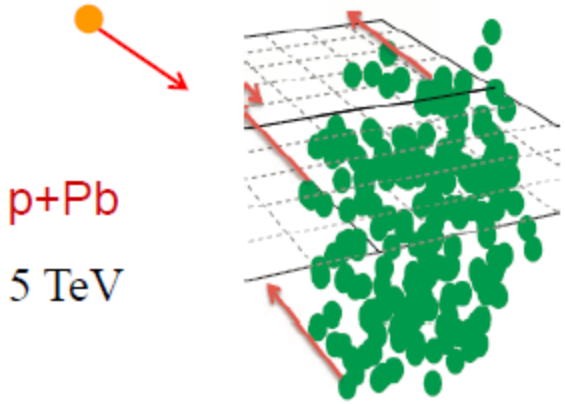


deep learning could capture the main feature of the non linear hydro evolution to largely accelerate the event by event simulations.

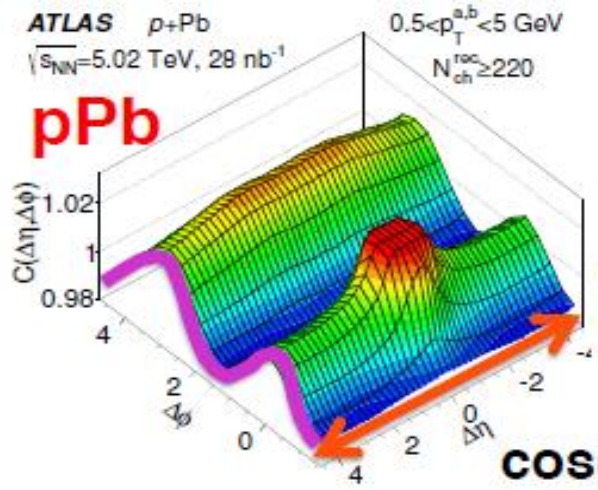
Huang, Xiao, Xiong
Wu, Mu, Song
in preparation

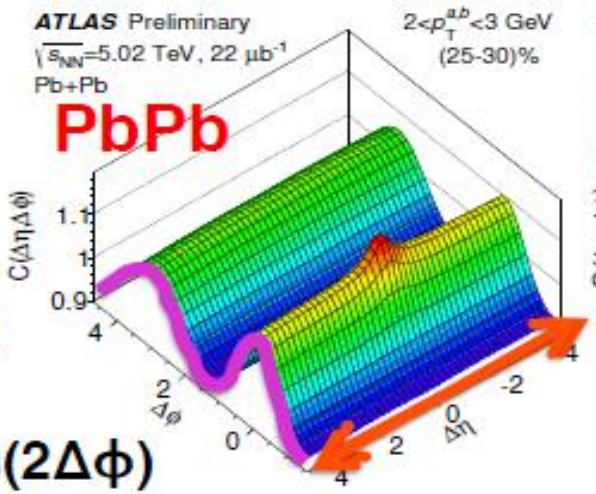
Small Systems at the LHC

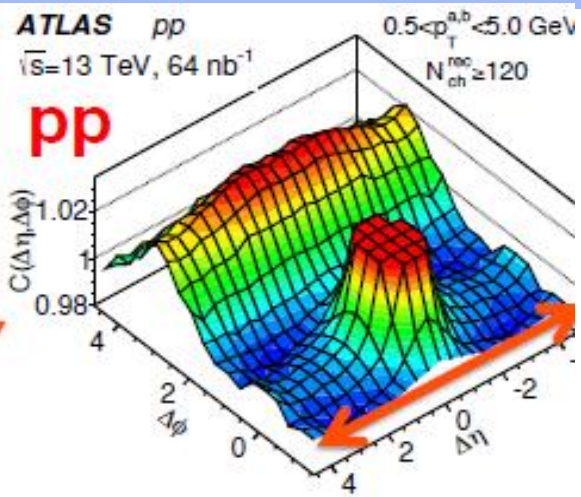
Flow like signals in p-Pb and p-p collissions



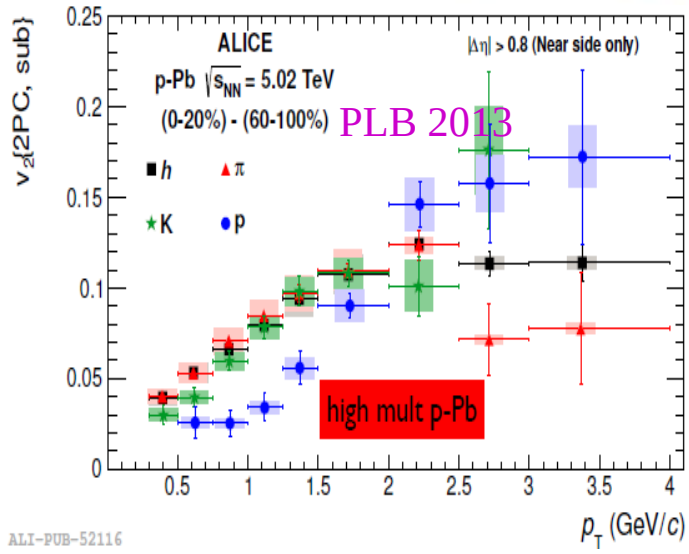
Flow like signals -- Experimental Observations

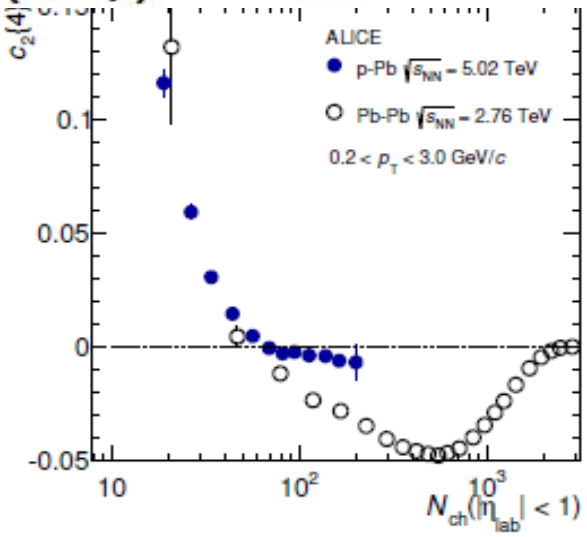


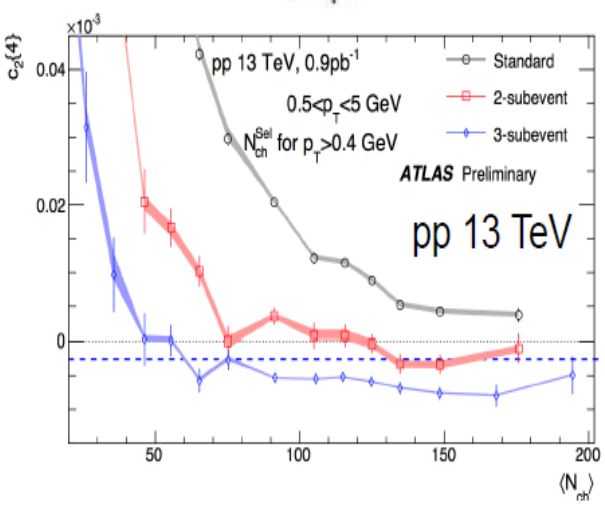




cos(2Δφ)







-Many flow-like signals have been observed in high multiplicity p-Pb collisions

-Similar flow-like observables, but with smaller magnitudes were also observed in p-p collisions

Flow like signals –theoretical interpolations

Initial state effects:

-K. Dusling and R. Venugopalan, PRL 2012, PRD2013, NPA 2014
-A. Dumitru and A. V. Giannini, NPA 2015, A. Dumitru and V. Skokov PRD2015
-B. Schenke, S. Schlichting, P. Tribedy, and R. Venugopalan, PRL2016

… … … …

Final state interactions:

-P. Bozek, W. Broniowski, G. Torrieri, PRL2013
-K. Werner, et. Al., PRL2014 G.-Y. Qin, B. Muller. PRC2014
-Y. Zhou, X. Zhu, P. Li, and H. Song, PRC2015
-P. Bozek, A. Bzdak, and G.-L. Ma, PLB2015
-H. Li, L. He, Z.-W. Lin, D. Molnar, F. Wang, and W. Xie,1604.07387.

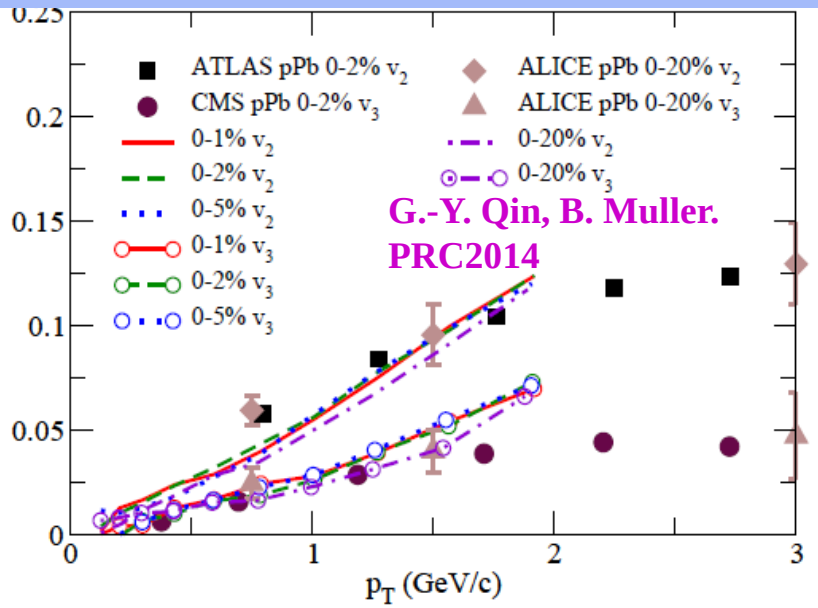
… … … …

Combinations of initial & Final state effects

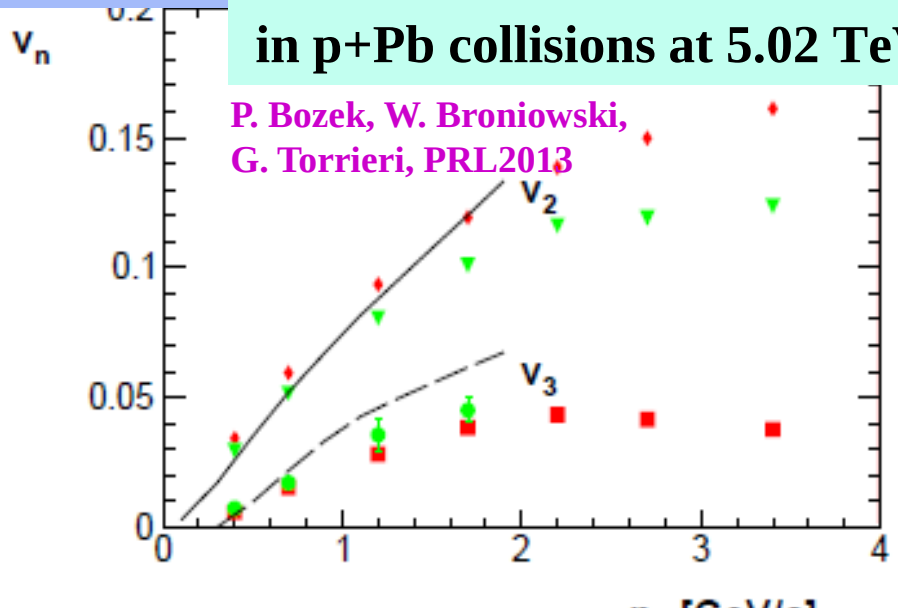
-H. M antysaari, B. Schenke, C. Shen, and P. Tribedy, PLB2017

Flow signal in p-Pb -- Hydrodynamics Simulations

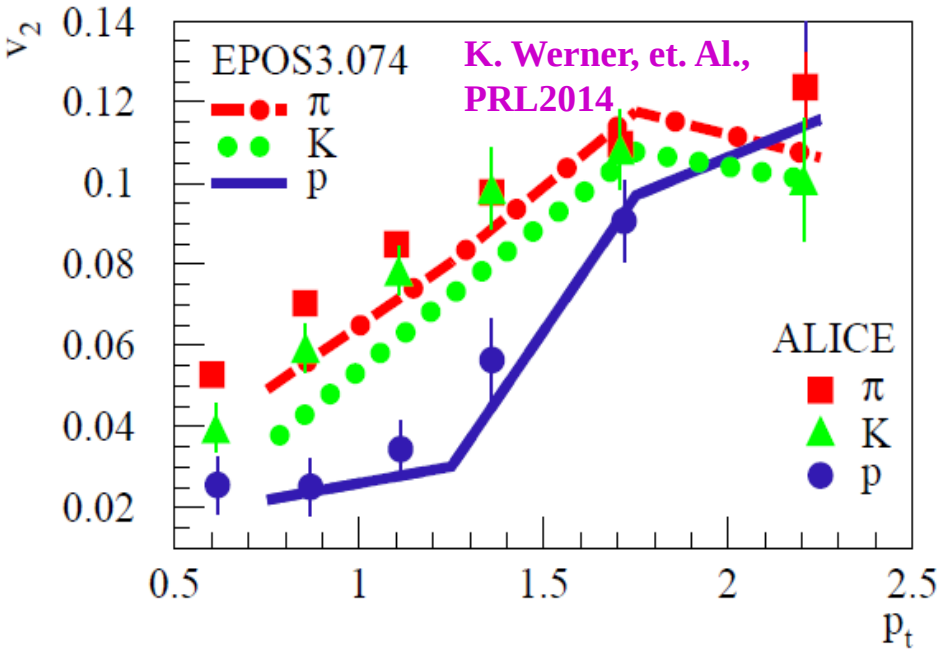
in p+Pb collisions at 5.02 TeV



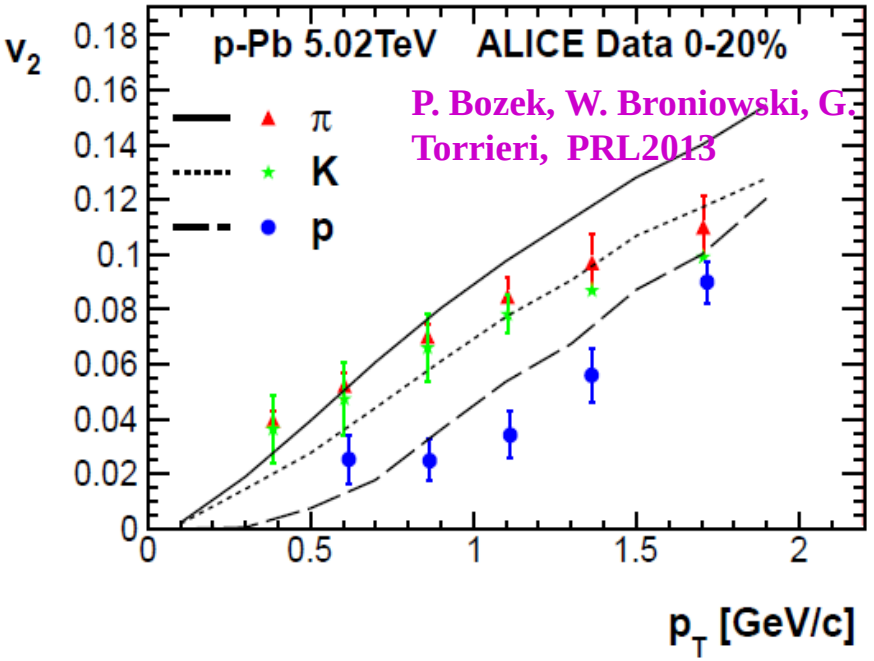
G.-Y. Qin, B. Muller. PRC2014



P. Bozek, W. Broniowski, G. Torrieri, PRL2013

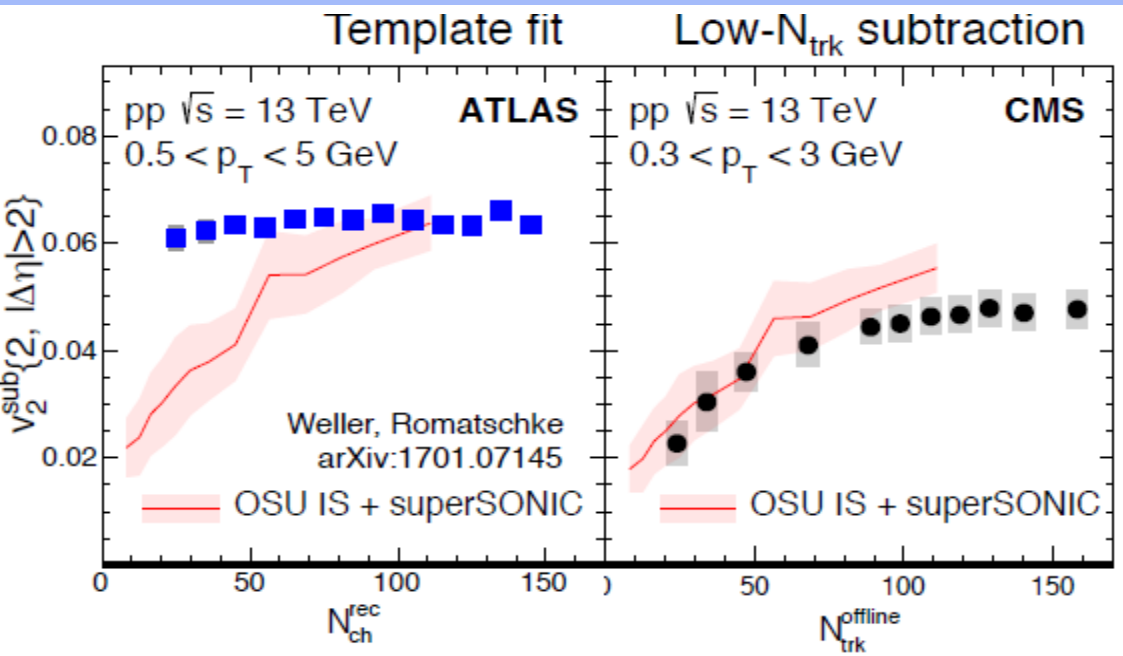


K. Werner, et. Al., PRL2014

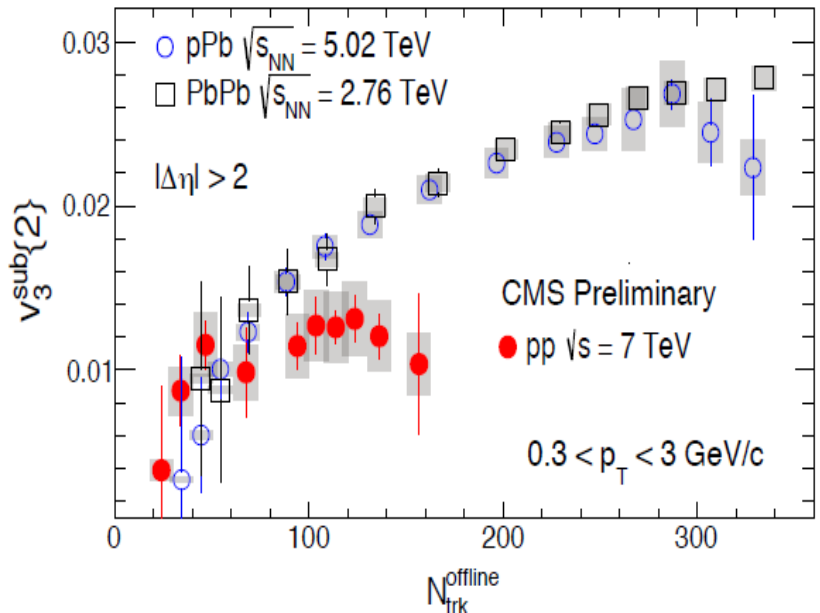


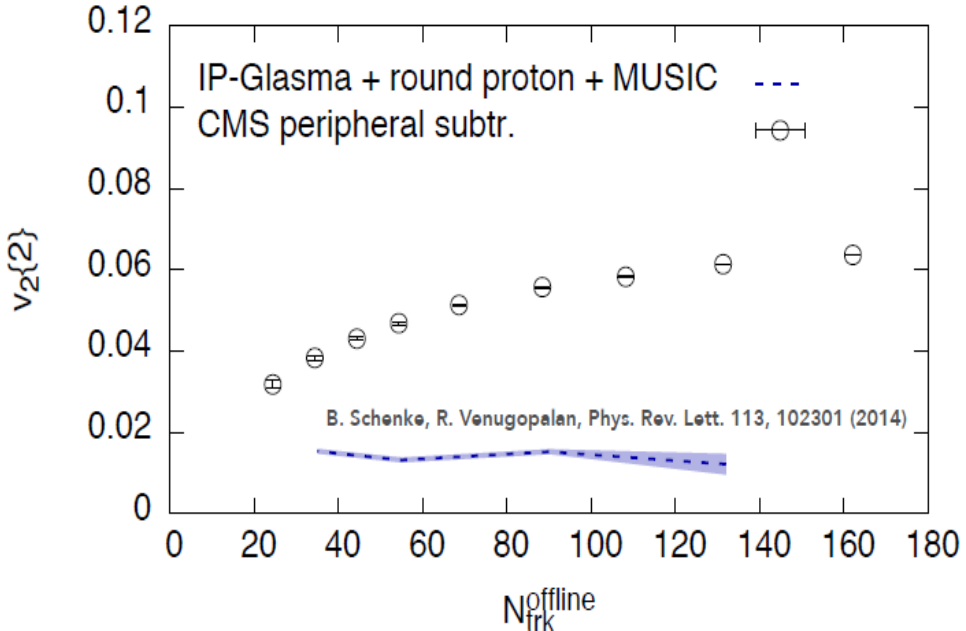
P. Bozek, W. Broniowski, G. Torrieri, PRL2013

Flow-like signal in p-p collisions

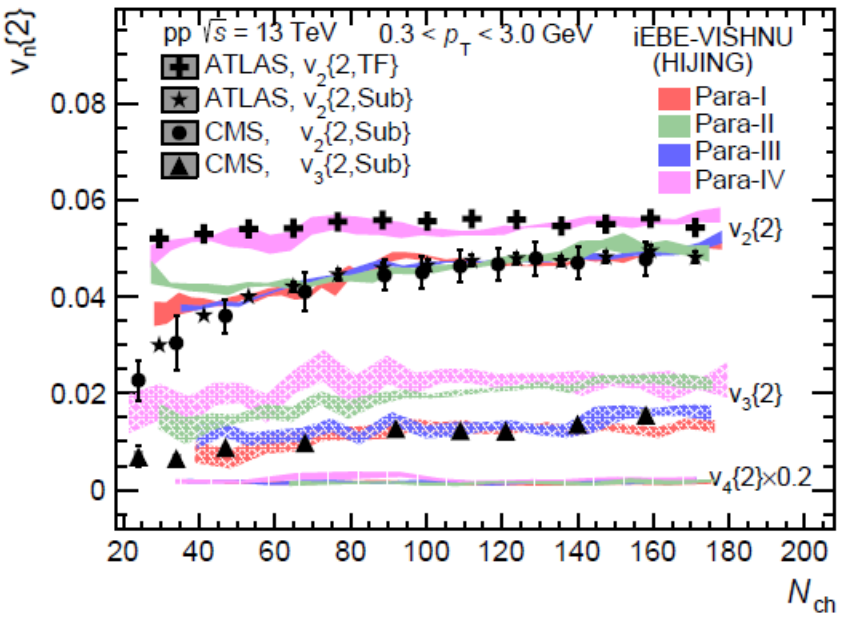


Indicates initial state fluctuations in p-p collisions





Hydrodynamic Collectivity in 13 TeV p+p (I)

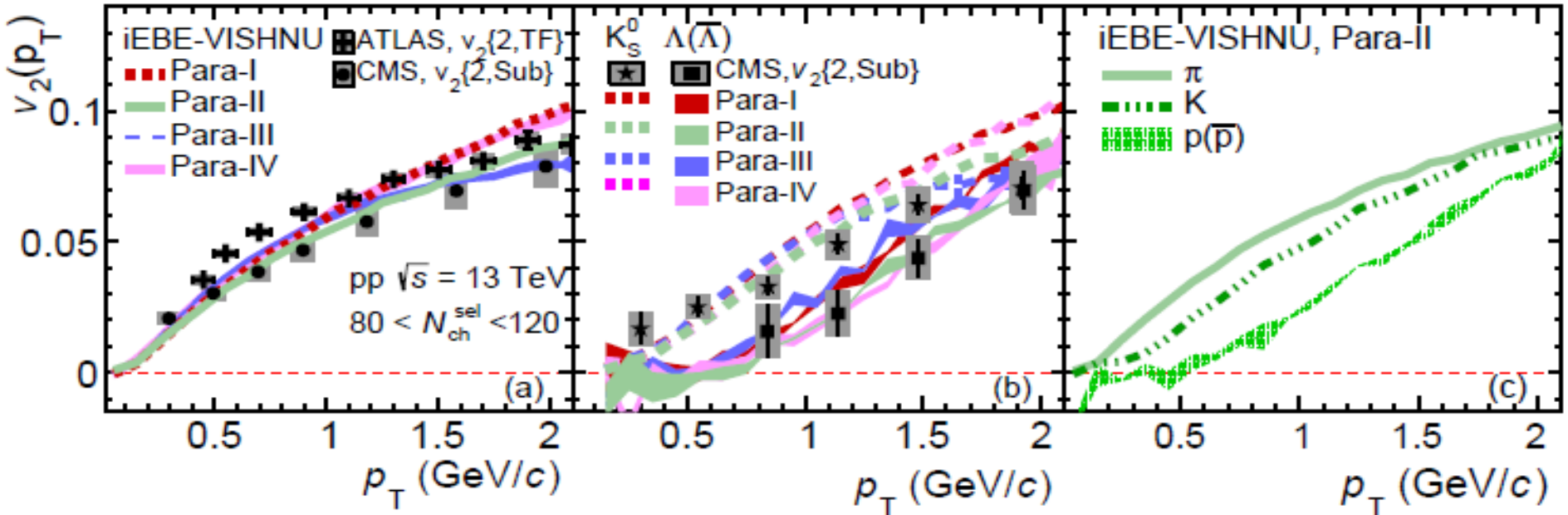


iEBE-VSIHNU+HIJING

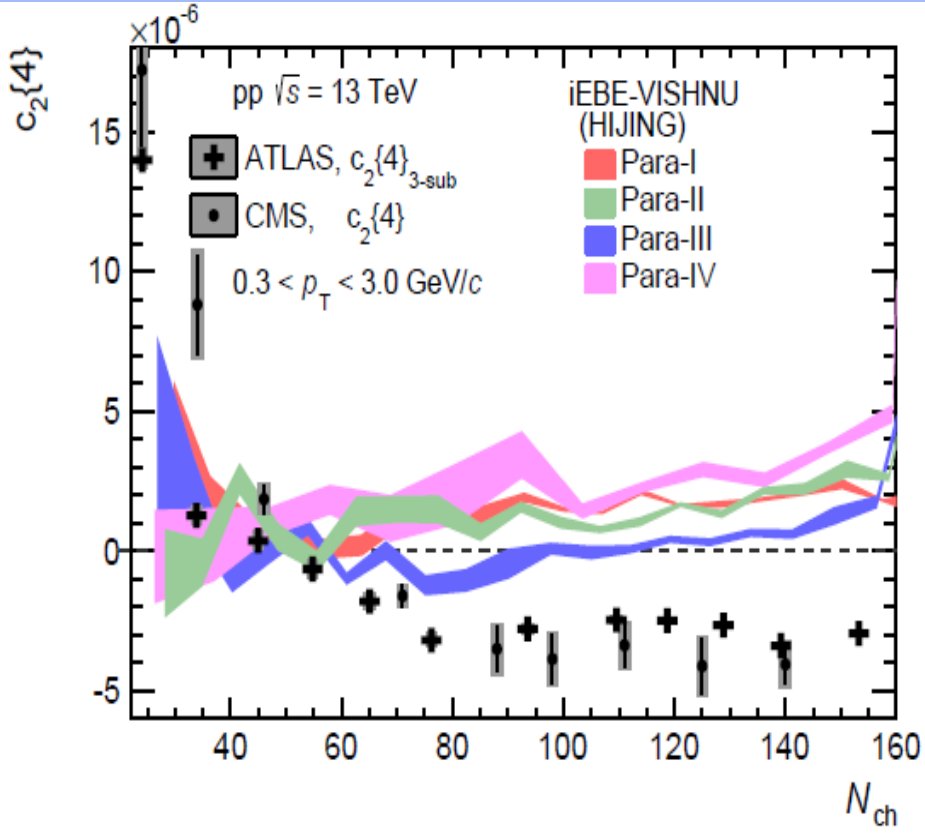
-Nice description of v2 and v3 with fine tuned parameters

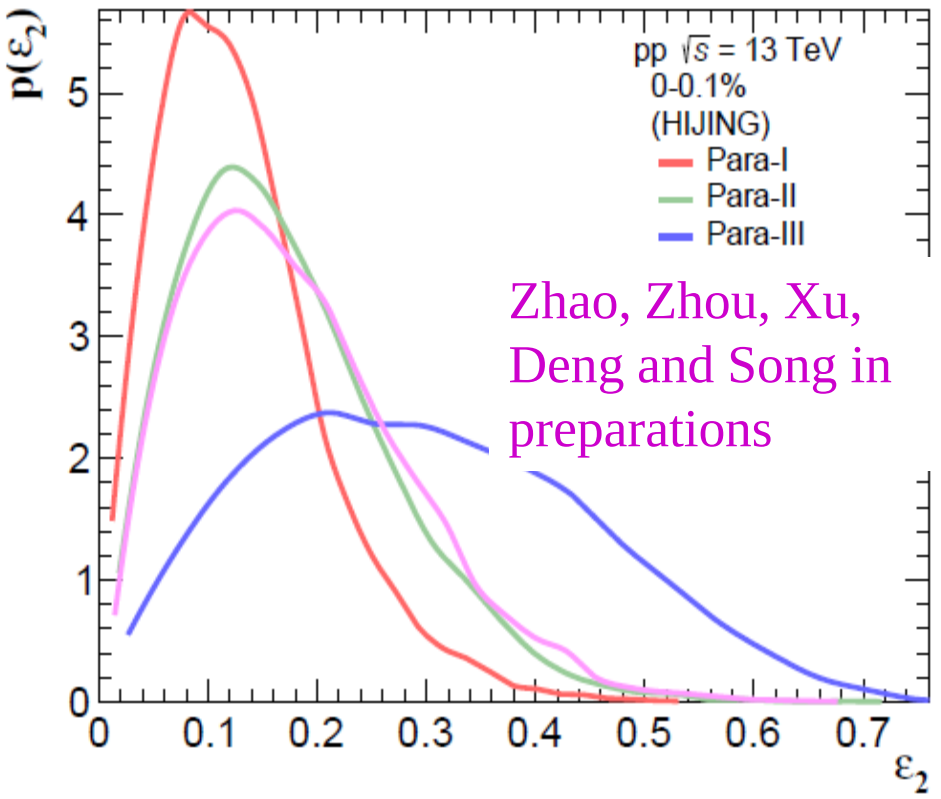
-Similar v2 mass orderings as in Pb+Pb & p-Pb collisions

Zhao, Zhou, Xu, Deng and Song in preparations



Hydrodynamic Collectivity in 13 TeV p+p (II)





Zhao, Zhou, Xu, Deng and Song in preparations

iEBE-VSIHNU+HIJING

-Positive 4-particle cumulant, and can not reproduced the data

-The fluctuations of the second order eccentricity increases with its mean value which leads to similar trend for flow fluctuations.

-Need better knowledge for the initial fluctuattions of p-p collisions .

Flow like signals – Experiment & theory

Initial state effects:

-K. Dusling and R. Venugopalan, PRL 2012

-A. Dumitru and A. V. Giannini, NPA 2015,

-B. Schenke, S. Schlichting, P. Tribedy, and

… … … …

Final state interactic

-P. Bozek, W. Broniows

-K. Werner, et. Al., PRI

-Y. Zhou, X. Zhu, P. Li,

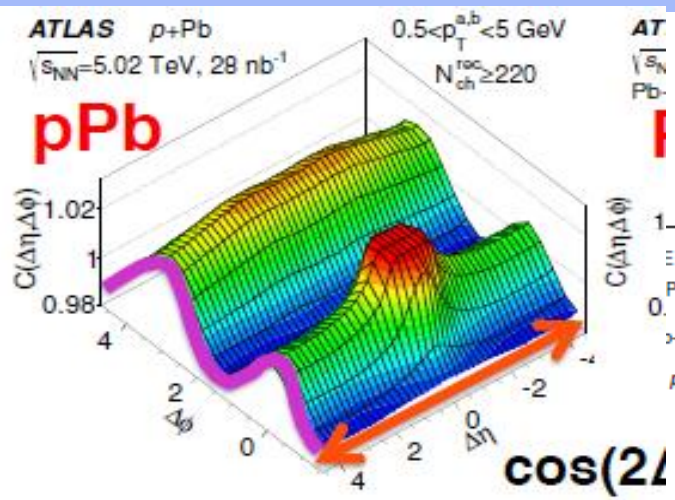
-P. Bozek, A. Bzdak, an

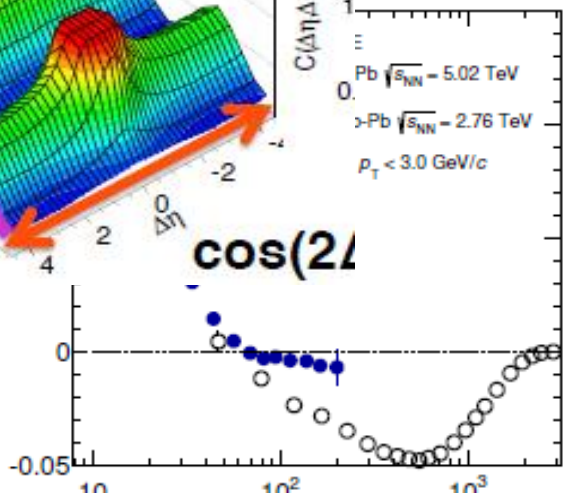
-H. Li, L. He, Z.-W. Lin

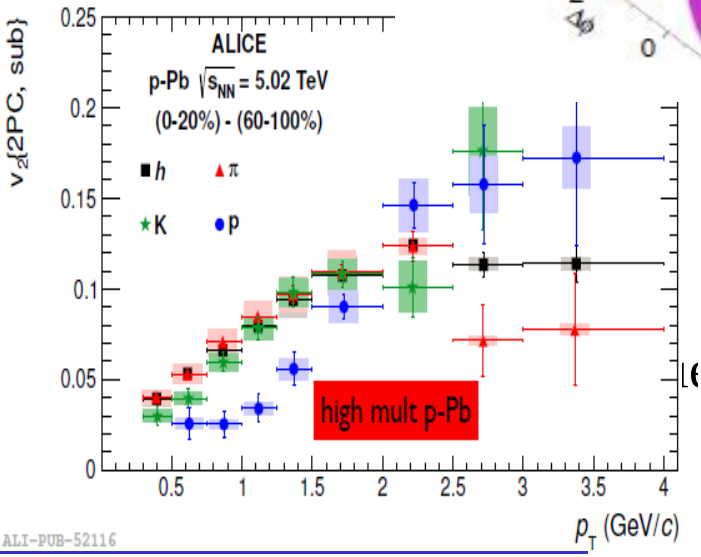
… … … …

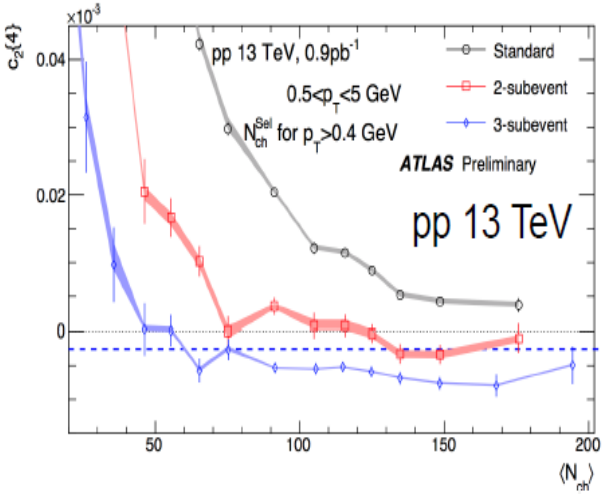
Combinations of ini

-H. M antysaari, B. Schenke, C. Shen, and P. Tribedy, PL









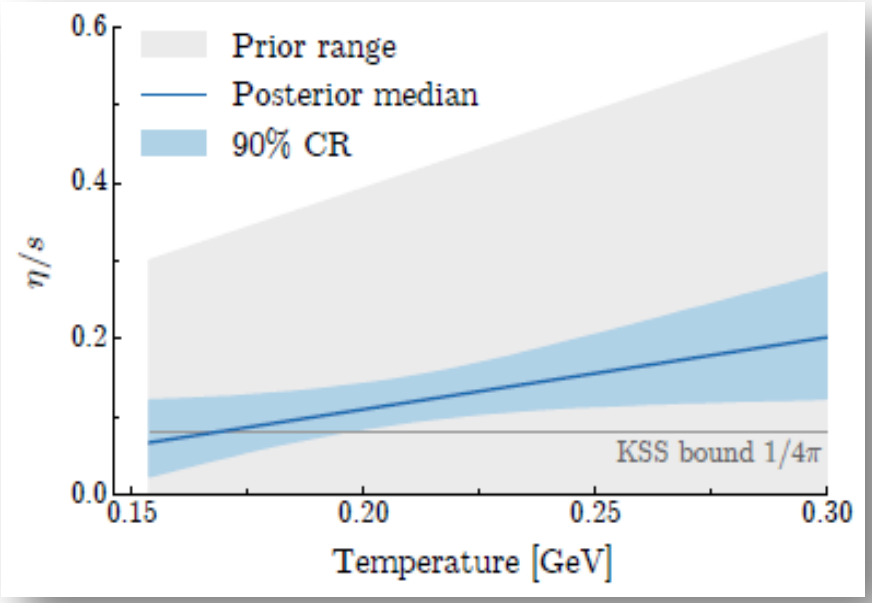
-What are the solid flow signals?

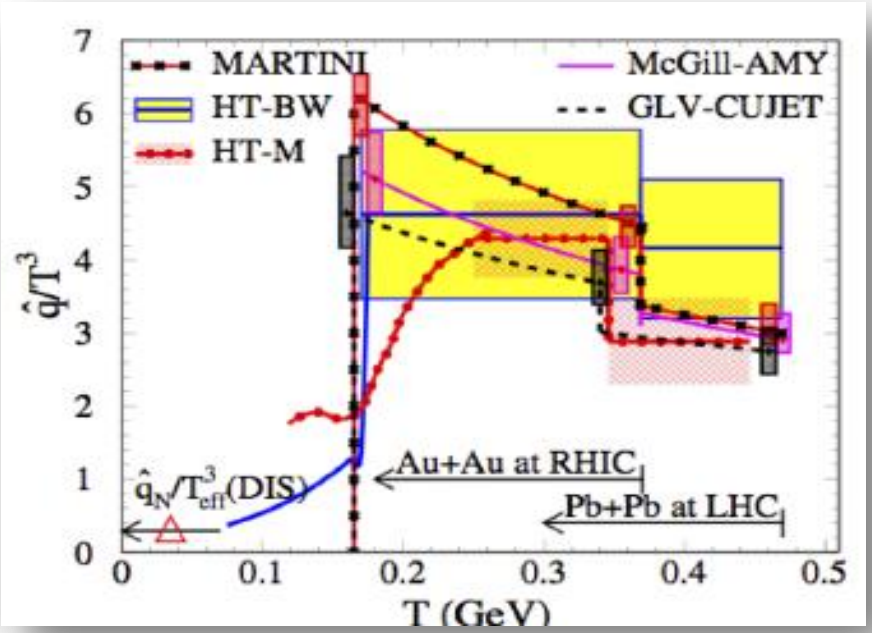
-Why hydrodynamics works in such small systems?

… … …

Summary

Pb+Pb collisions and the LHC





Flow –like signals in p-p and p+Pb collisions at the LHC

-Experimental measurements on 2 and 4 particle correlations indicates the development of collective flow

-theoretical studies: initial state effects, final state interactions

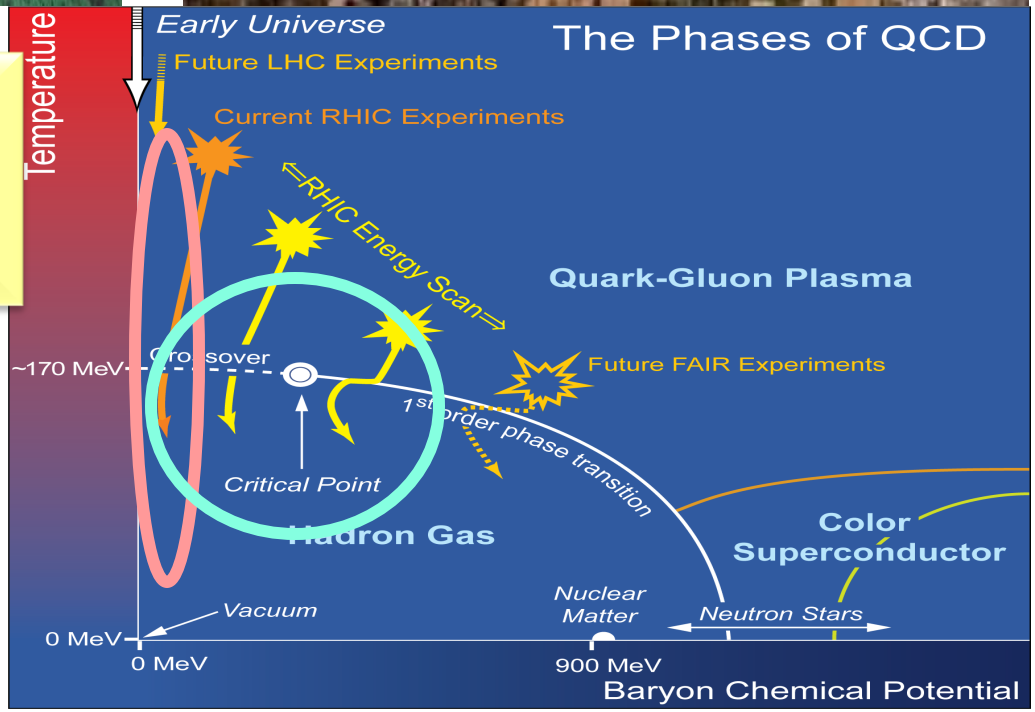
-More efforts from both experimental and theoretical side are needed

RHIC, BNL

LHC, CERN

RHIC and LHC Heavy Ion Program are COMPLEMENTARY

Many important physics have been discovered at RHIC, more will come out in the near future especially for the incoming RHIC BES program !



Thank You