The Standard Model for QGP Evolution: experimental status and future

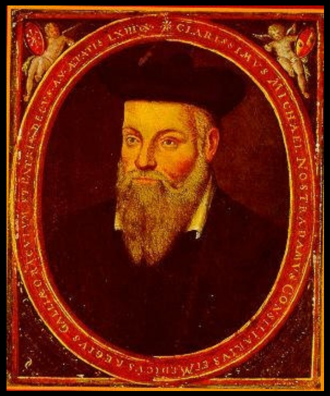
Raimond Snellings

Universiteit Utrecht

NIKHEF

Outline

- Brief history of the field
- Current status and main open questions
- Important future measurements



disclaimer: personal view and limited set of observables

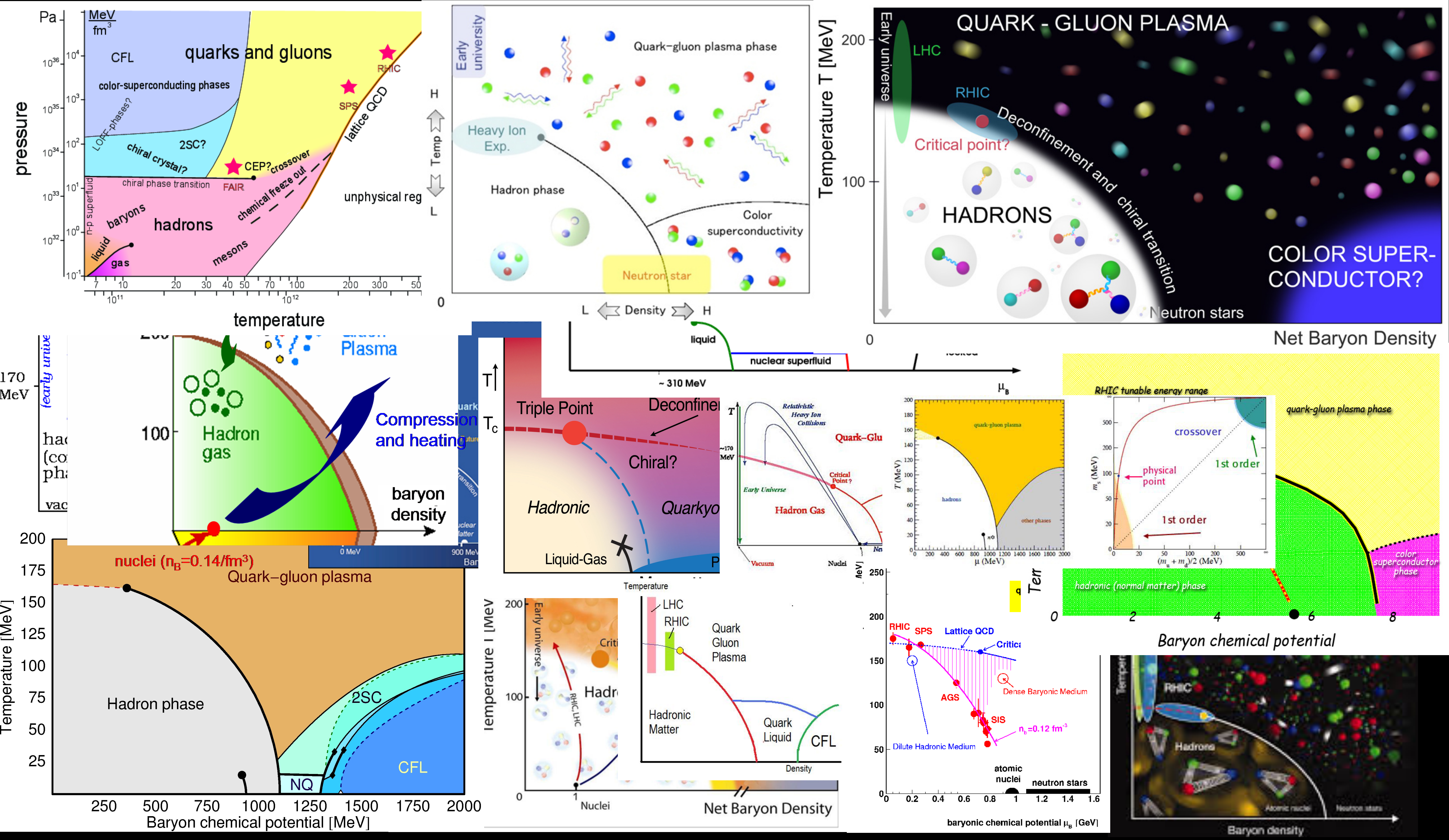
Brief History

- 1970: QCD, asymptotic freedom, shock flow, *Bevalac, Dubna*
  - first characterisation of the collision; fireball model, coalescence, …
- 1980: Quark Gluon Plasma, Bevalac, *AGS, SPS*
  - collective flow, HBT, thermal model, ….
- 1990: AGS, SPS
  - J/Ψ suppression, strangeness enhancement, …
- 2000: SPS, *RHIC*, the perfect liquid (*paradigm change*)
  - large collective flow, high-p_t suppression, …
- 2010: SPS, RHIC, *LHC*
  - higher harmonics, jet suppression, open heavy flavor, quarkonia, …

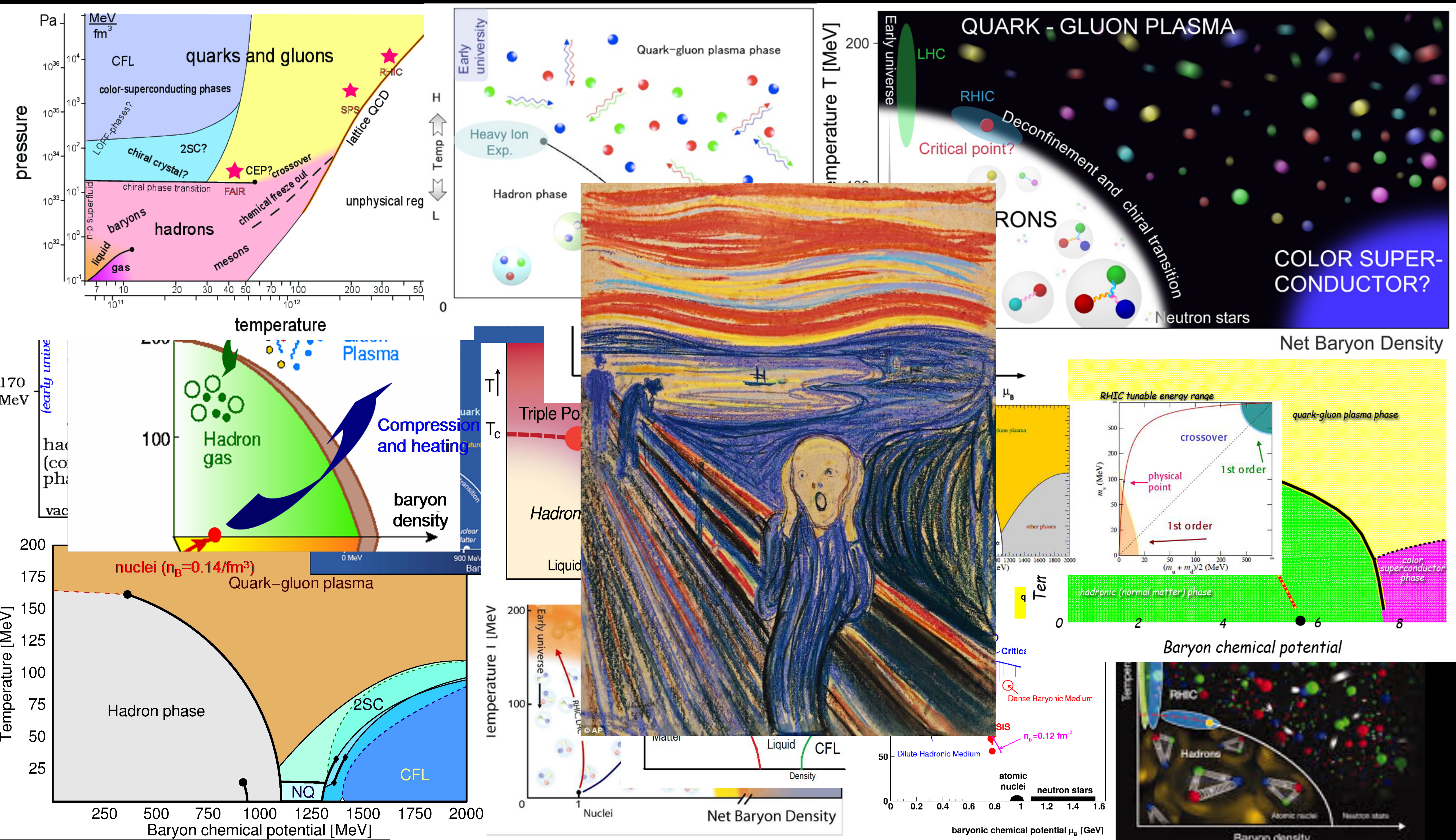
Leading to a standard model for the QGP evolution!

Due to 40 years of experimental and theoretical effort for different size systems and energies!

QCD Phase Diagram

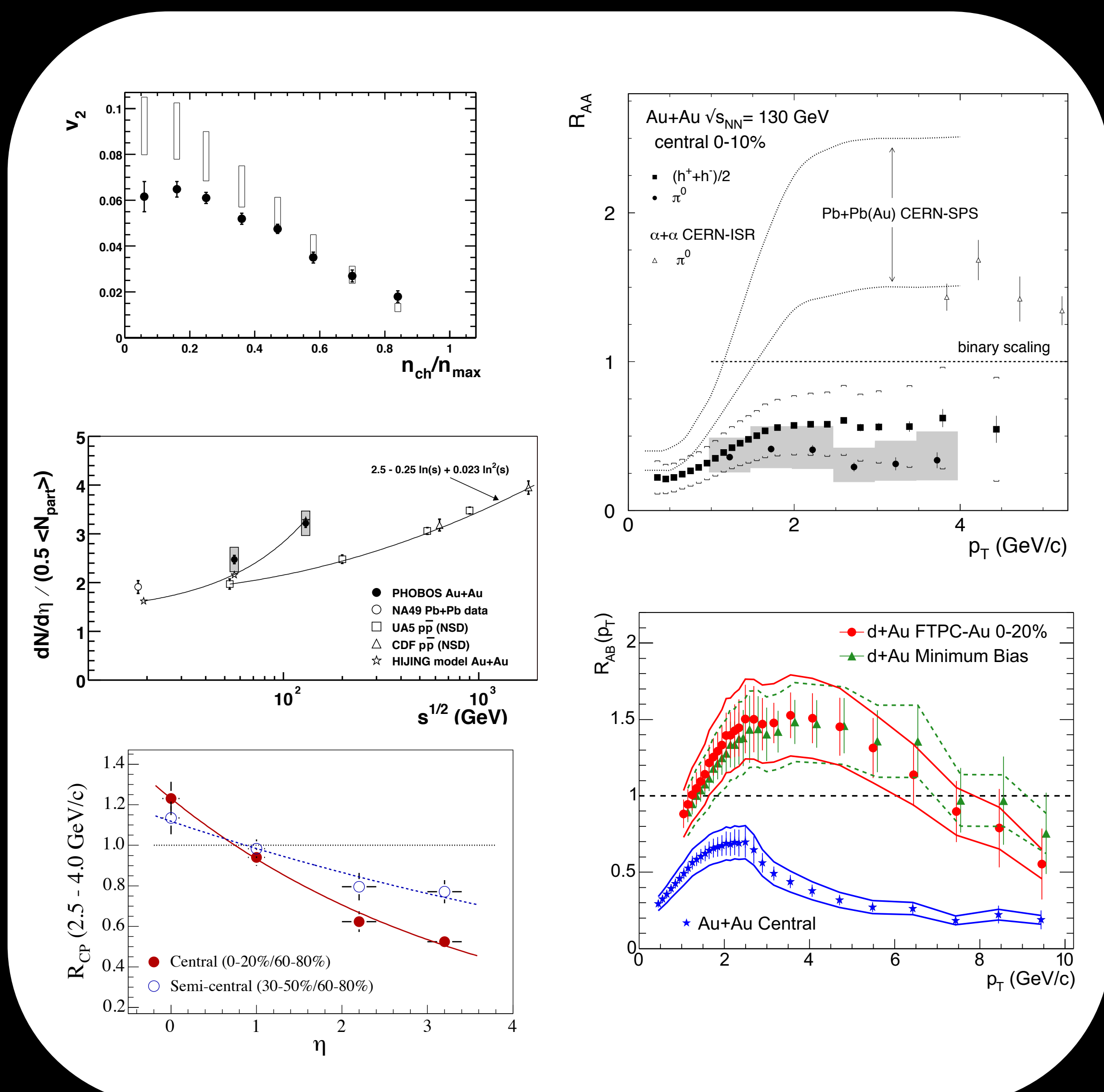


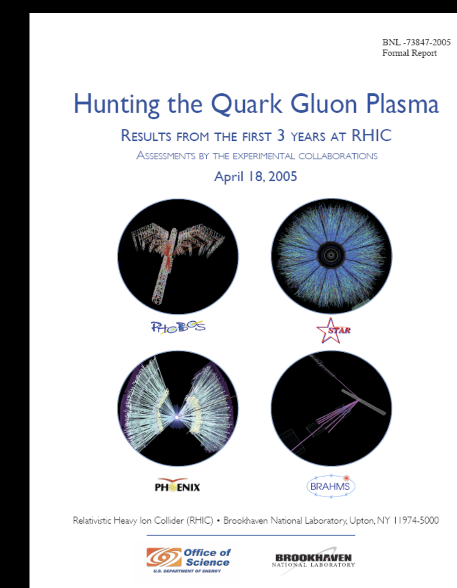
QCD Phase Diagram



2002 Long Range Plan

- *and very possibly, new and unexpected phenomena in the realm of nuclear matter at the highest densities*





2005
A dense almost perfect liquid

2007 Long Range Plan

- *The major discoveries in the first five years of RHIC must be followed by a broad, quantitative study of the fundamental properties of the quark-gluon-plasma*

- The almost Perfect Liquid (2005)
  - discovered experimentally: elliptic flow, high-p_t suppression
  - macroscopic description: viscous relativistic hydrodynamics
  - we are still lacking understanding from first principle QCD: quasiparticles, fields,…?
    - required even for an effective theory

Analogy: Superconductivity
experimentally discovered 1911:
Heike Kamerlingh Onnes
macroscopic theory 1950:
Ginzburg-Landau
microscopic theory 1957:
Bardeen, Cooper and Schrieffer

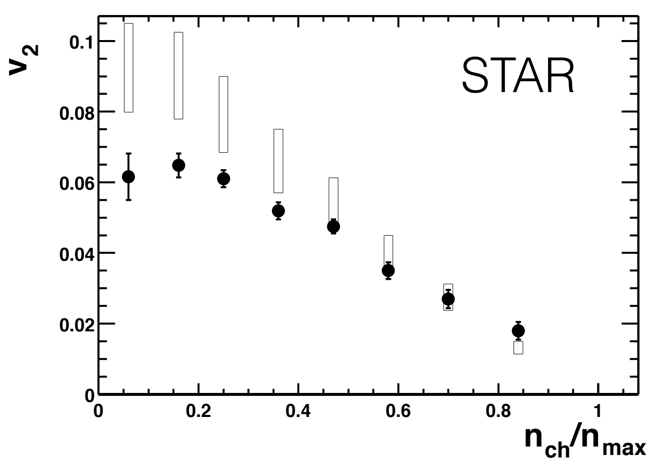
recent excitement/controversie of finding collective effects in pA (dA) is a clear practical example of how important this is

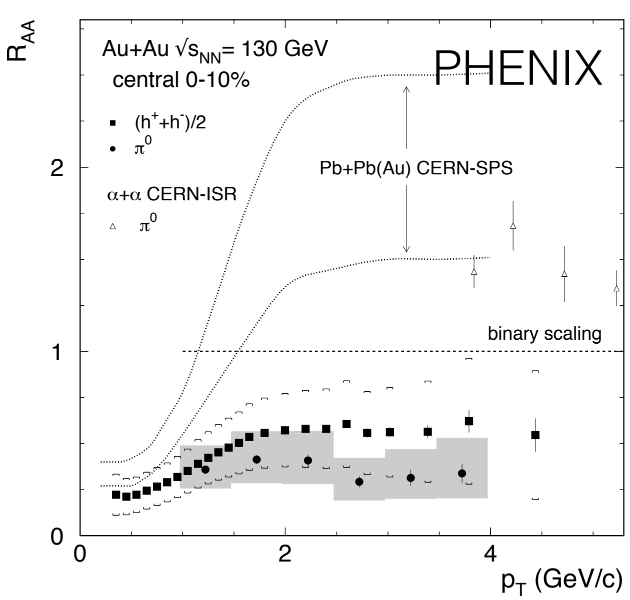
Experimental Progress

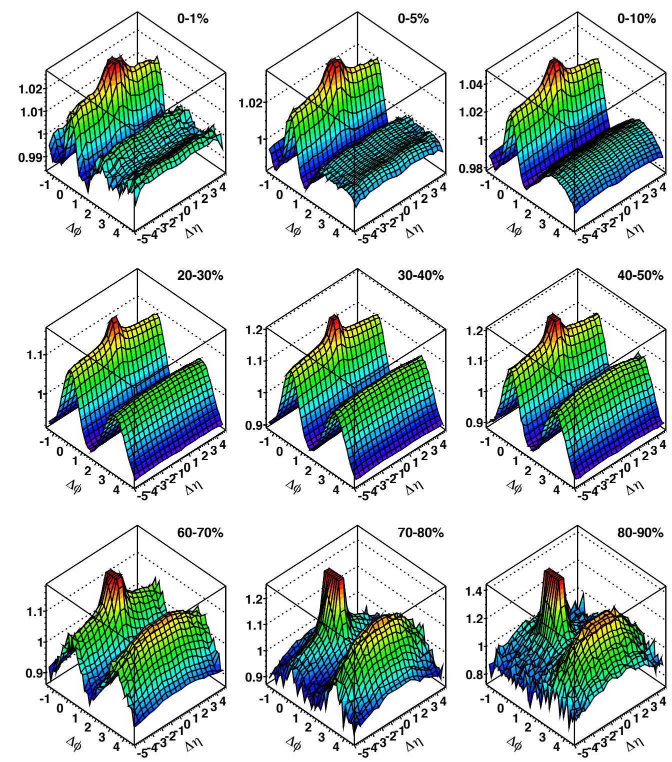
just a few examples

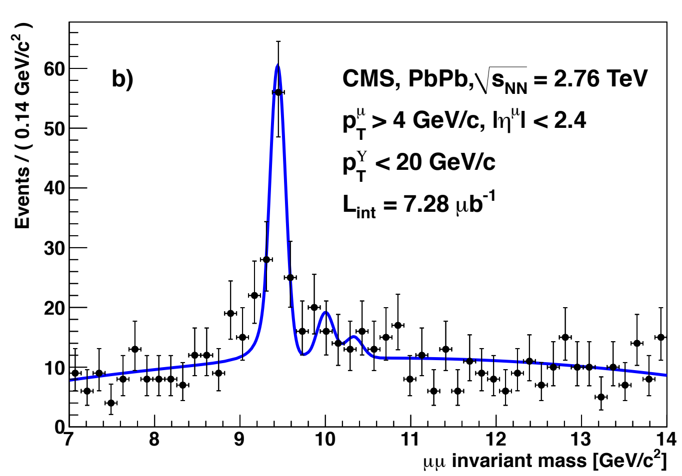
2001

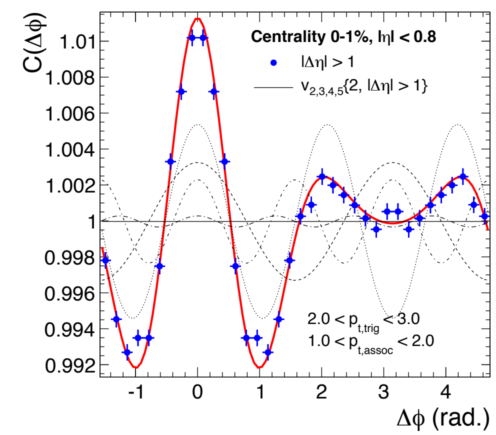
2011

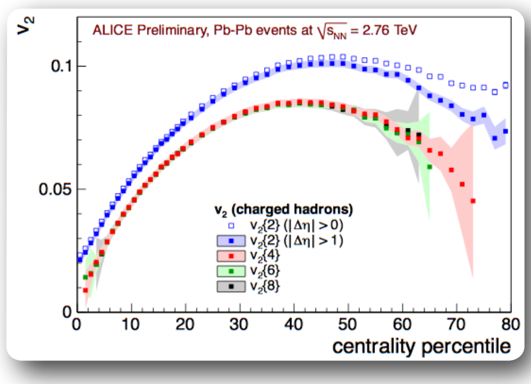


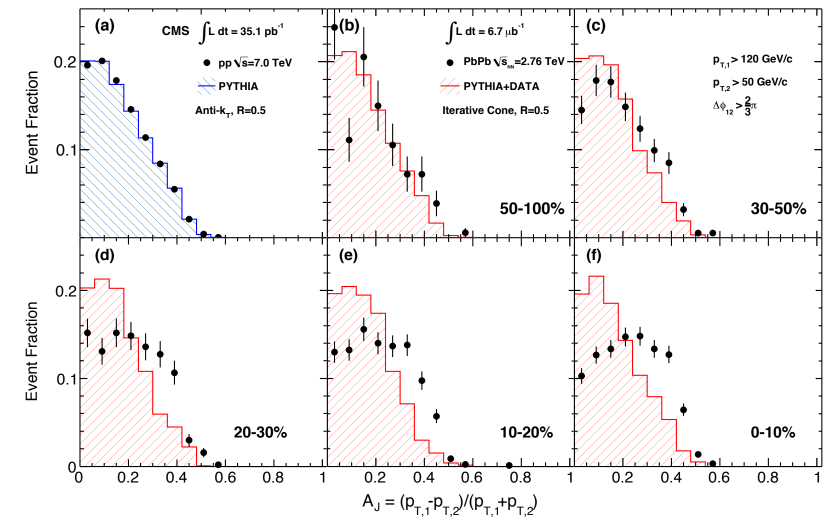


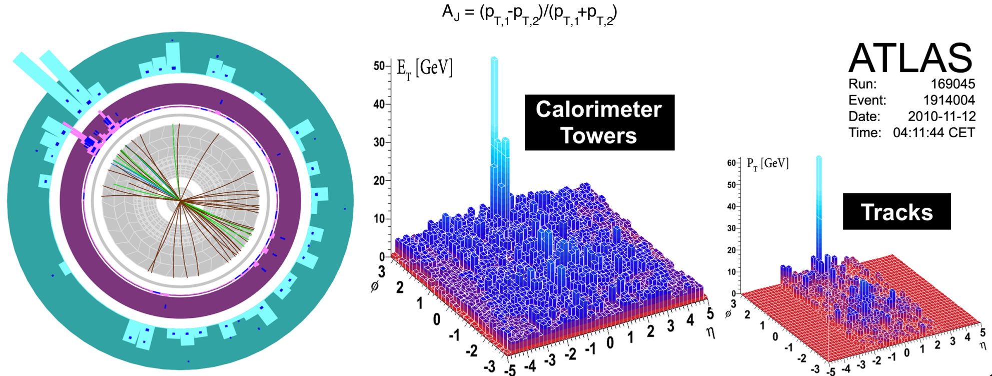








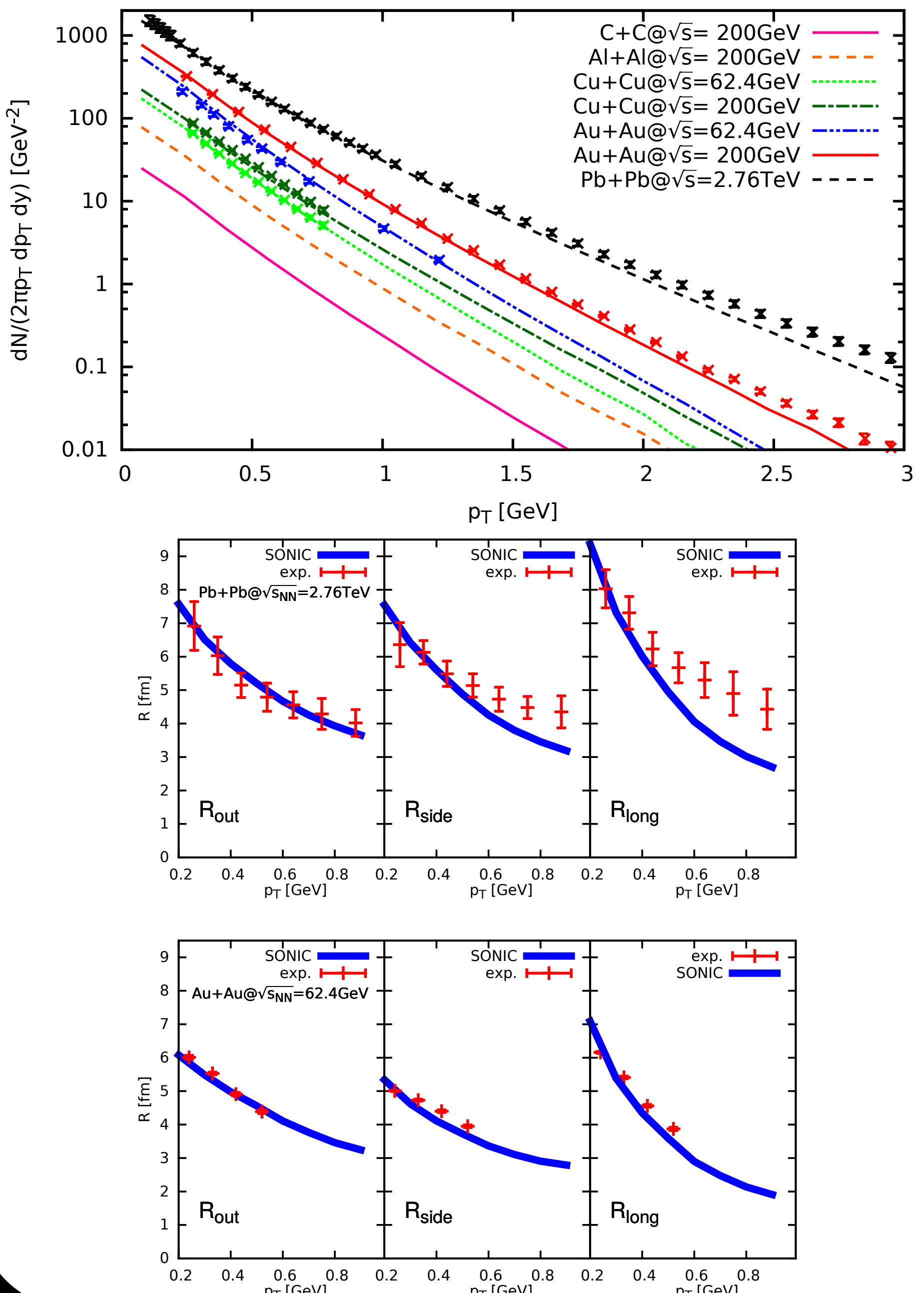


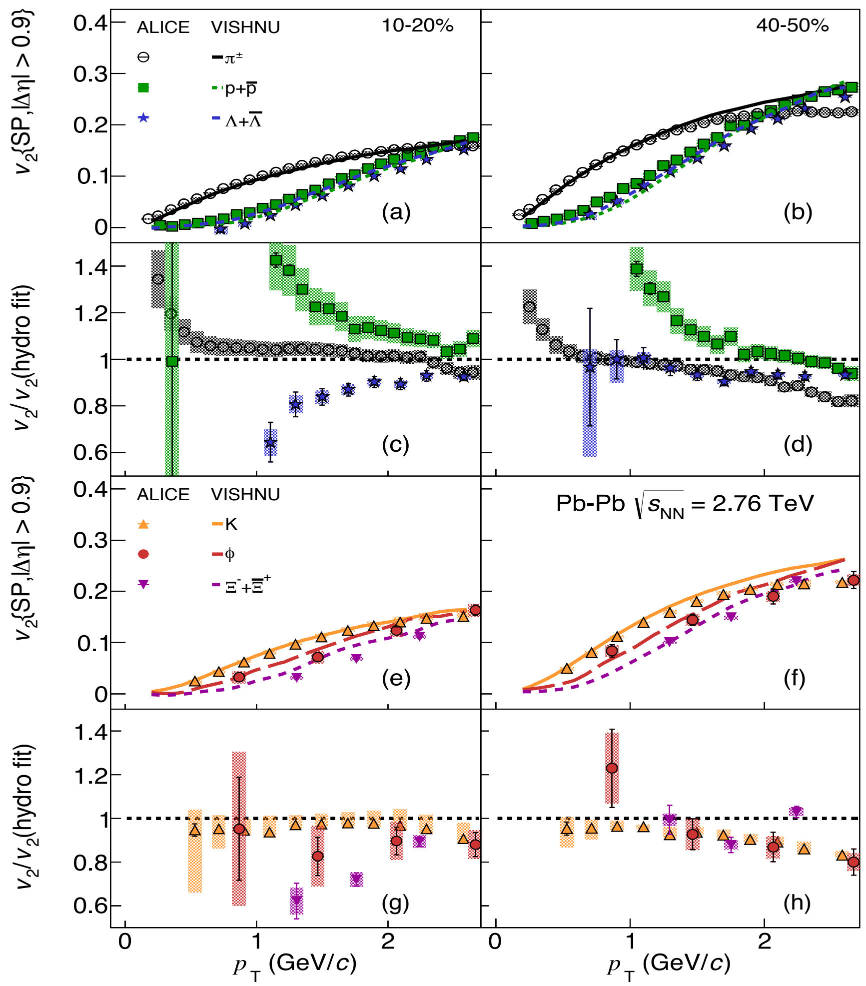


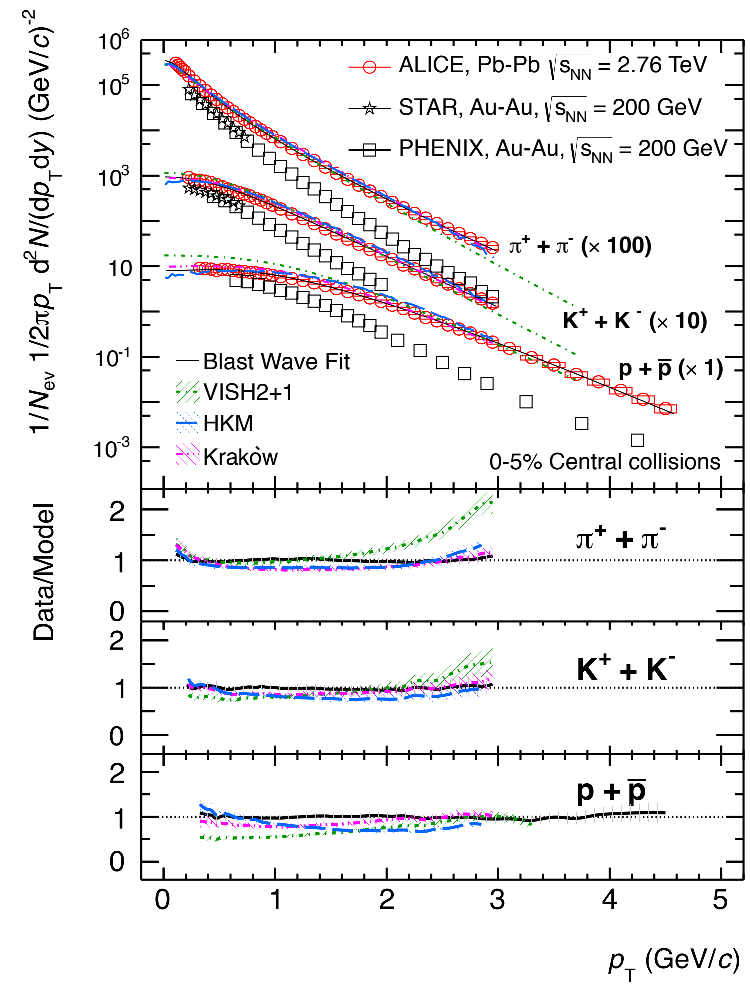
Impact Publications

- the experimental RHIC program is very productive in producing papers and the papers are highly cited
  - whitepapers (1500-2000), many individual key papers 500-1000, average papers ~100
- the same is true at the LHC, the heavy-ion papers are cited as well and even while compared to particle physics and the Higgs discovery 4 heavy-ion papers in the top 10, 9 in top 30 of LHC physics papers

The Standard Model for QGP Evolution

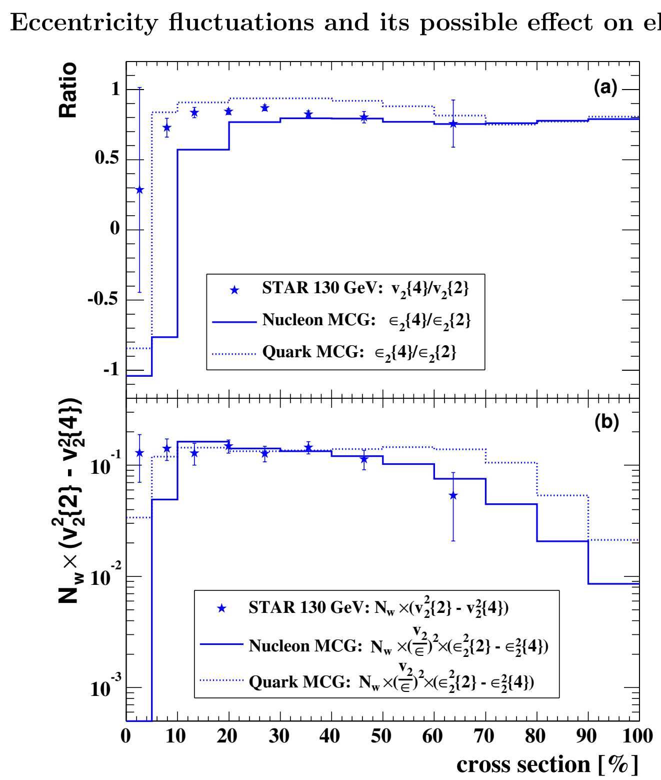




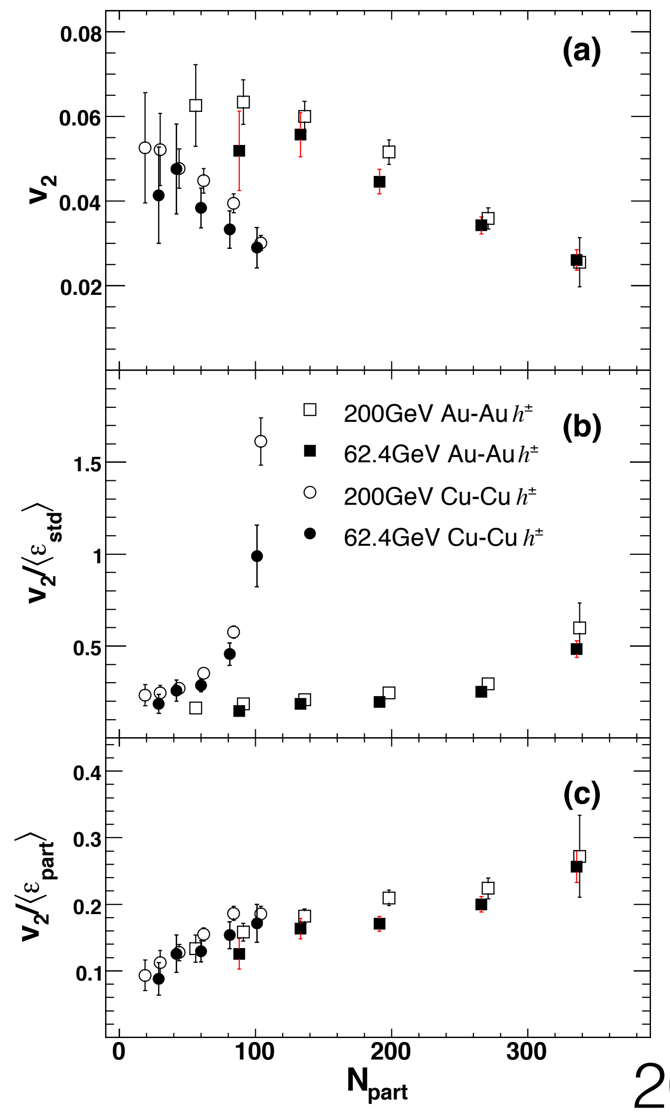


- working description over large range of energies
- with at the same time also some clear deviations! how important are those?

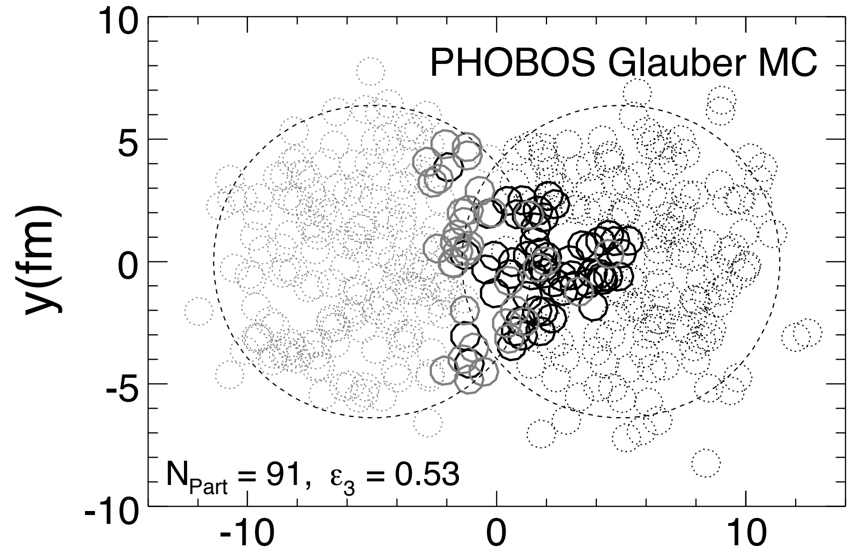
The Standard Model for QGP Evolution (fluctuations)



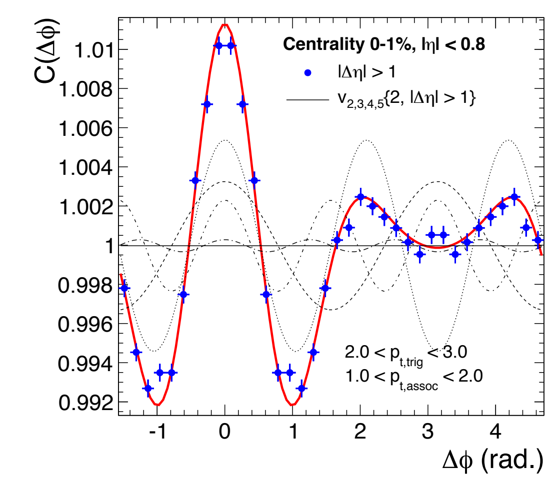
2003



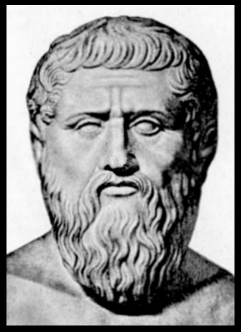
2006



2010

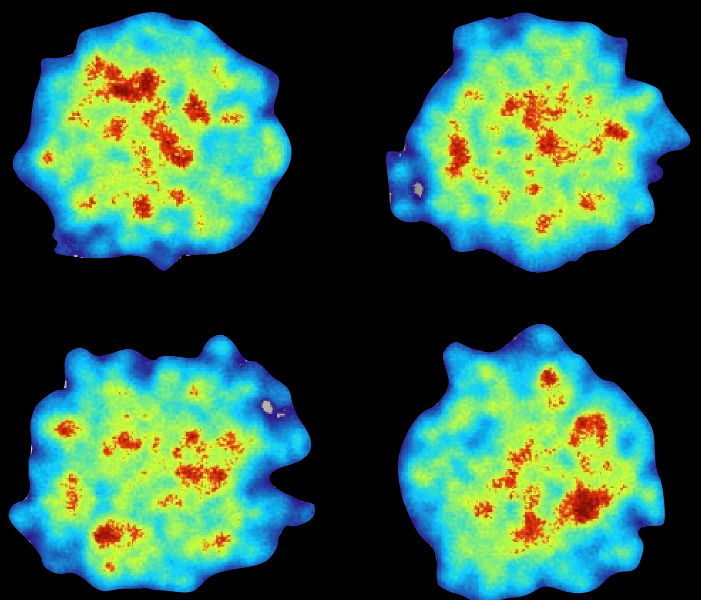


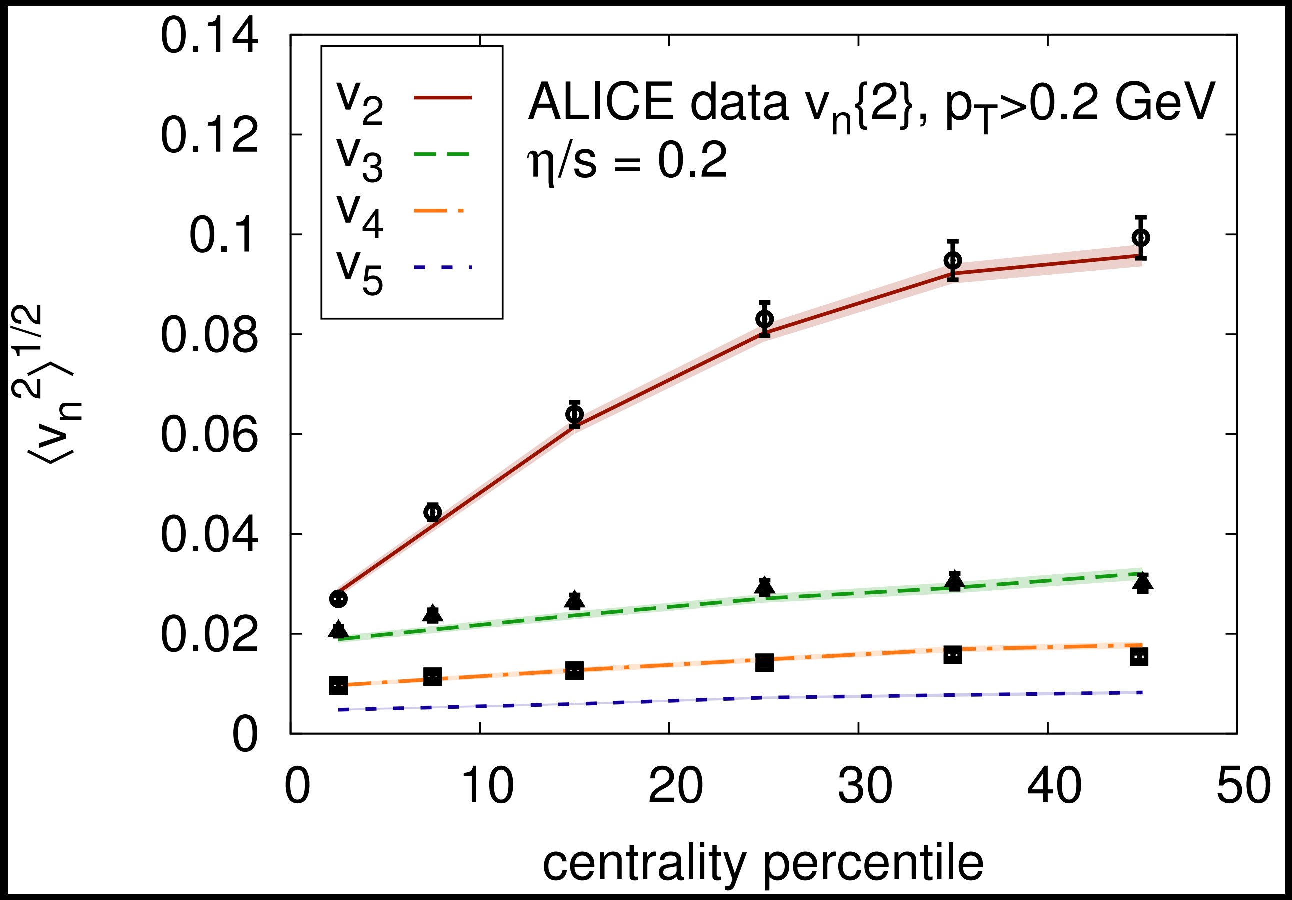
2011

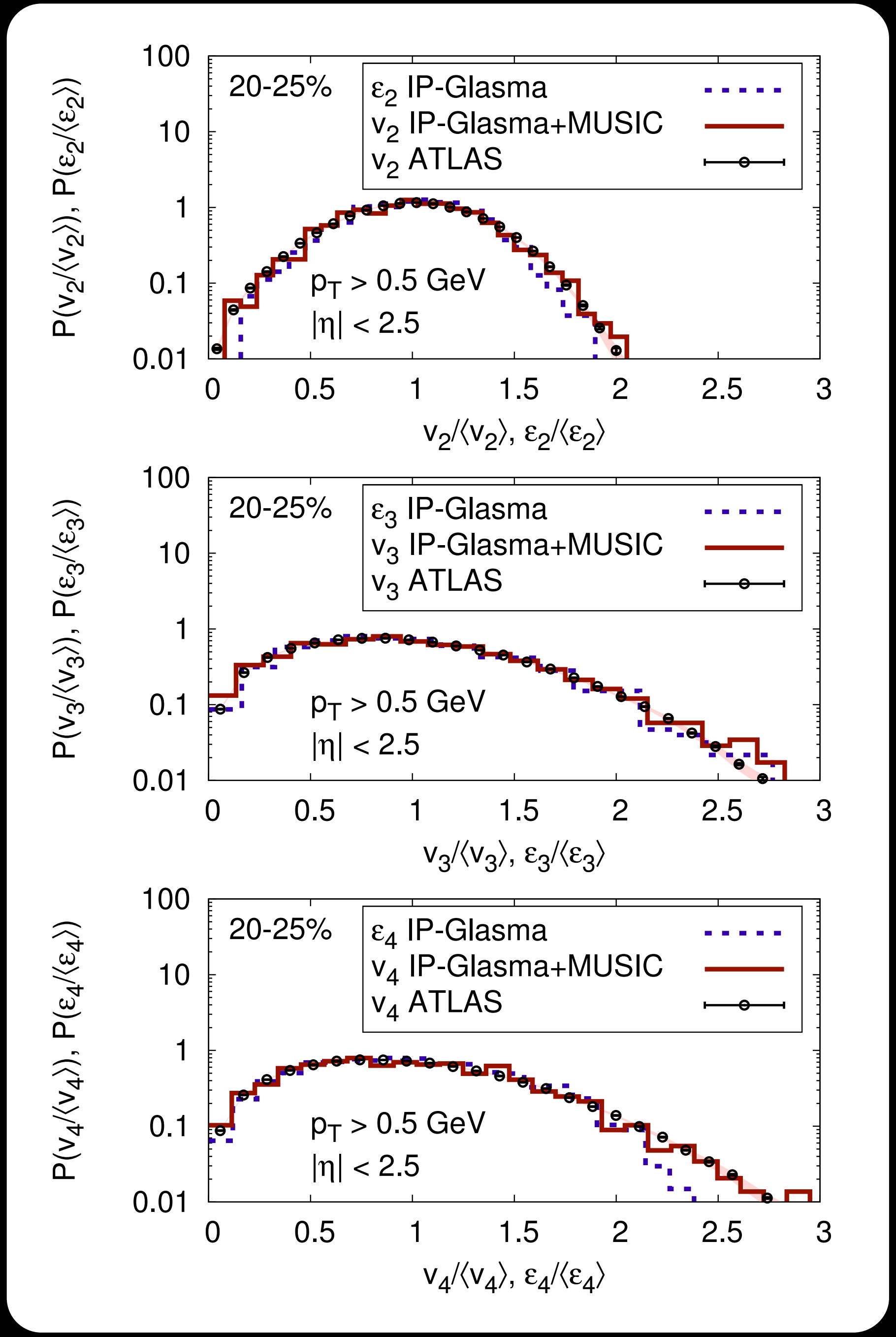


Small deviations from expectations sometimes lead to important tools. Took a decade!

The Standard Model for QGP Evolution (fluctuations)







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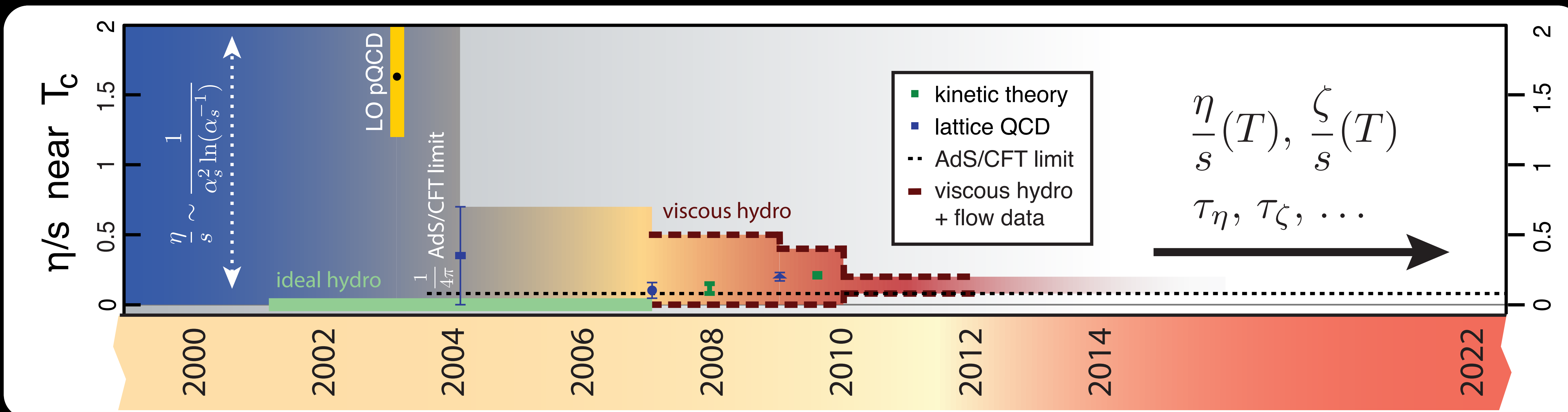
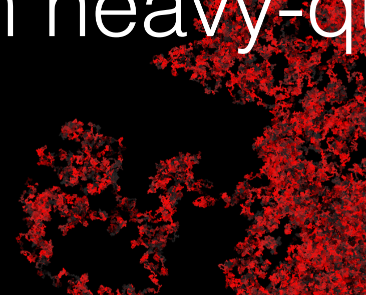
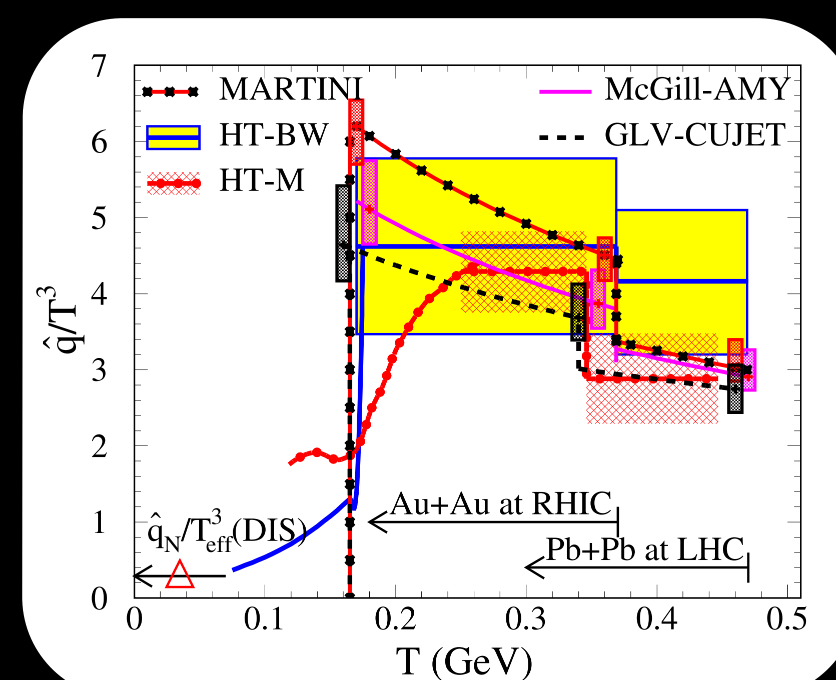


- constraints from parton energy loss?
- constraints from heavy-quark diffusion?





What have we learned?

- The matter is almost opaque for partons traversing it
- The QGP at these temperatures (from direct photon measurements) behaves like an almost perfect liquid (from anisotropic flow)
- At (highest) RHIC and LHC energies all observations are consistent with the creation of a strongly interacting QGP in heavy-ion collisions

- We have a working description with a standard model of heavy-ion collisions
  - initial state fluctuations of the (sub) nucleonic degrees of freedom
  - rapid applicability of relativistic viscous hydrodynamics with lattice EoS for bulk of the system evolution
  - late stage described by hadronic transport

What have we learned?
-> *open questions*

- What are the initial spatial densities (we have a good match with theory but how unique is this?), how much pre-equilibrium flow?
    - pre-equilibrium flow; follows from general arguments but also from AdS/CFT, CGC, …, required to explain e.g. HBT
- How big is the bulk viscosity and how precise can we constrain the specific shear viscosity as function of temperature?
- How well do we understand the transition from the high density QGP stage to the hot hadronic stage?
- Which systems can still be described in terms of bulk (hydro)dynamics?
- What are the relevant degrees of freedom from low to high-p_t ?
    - what is happening at intermediate p_t?
- The lattice QCD EoS is used as input; how well can we constrain it?
- Can we get the standard model of the QGP precise enough for discoveries of new phenomena (CME,…)?

- *experimental constrains from excitation functions (testing temperature dependence of the system) with precision measurements at the highest energies (RHIC and LHC) and variation of system size (and new tools like e.g. event-shape engineering!)*

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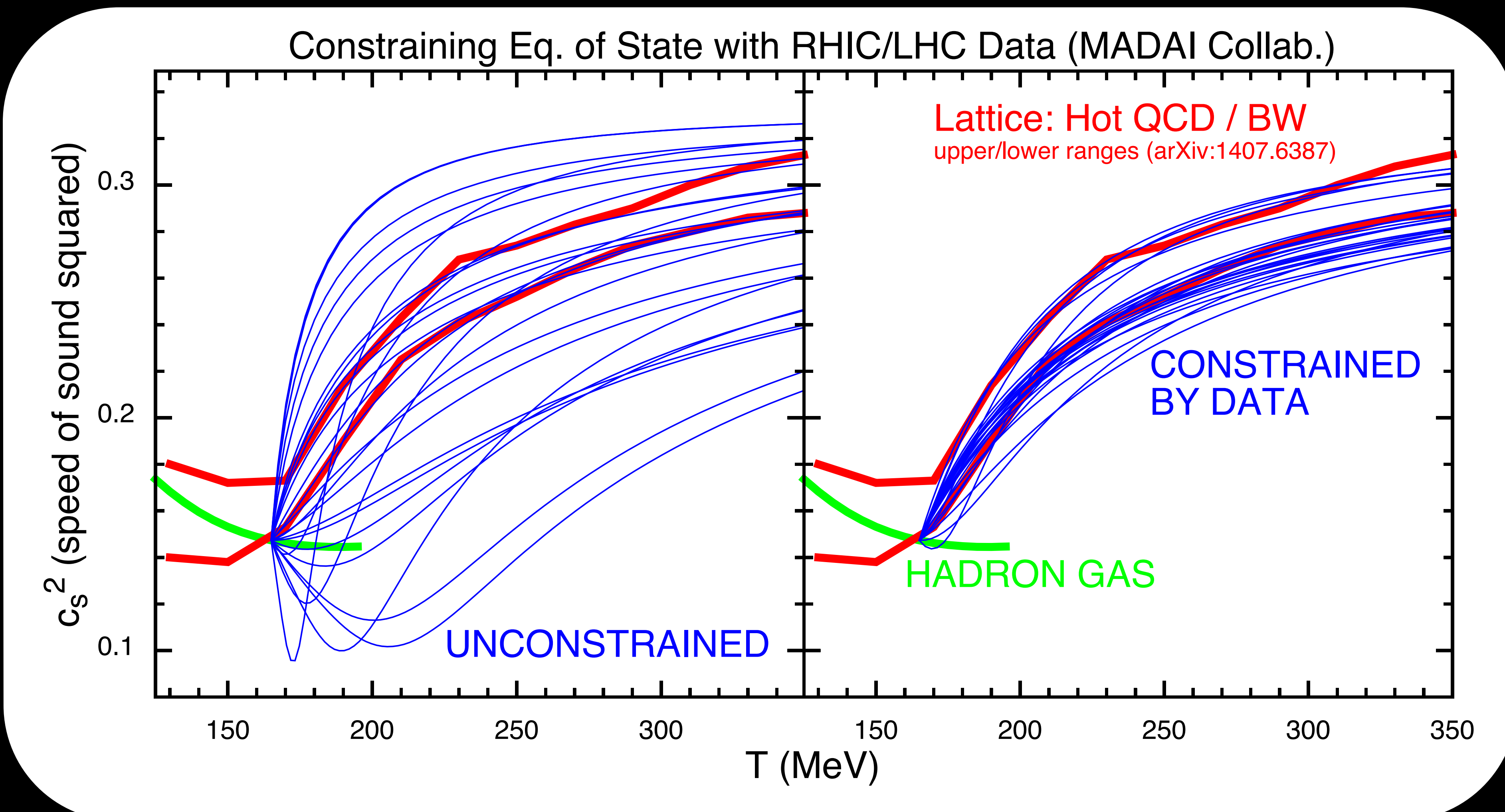
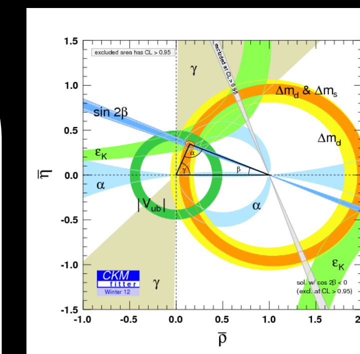
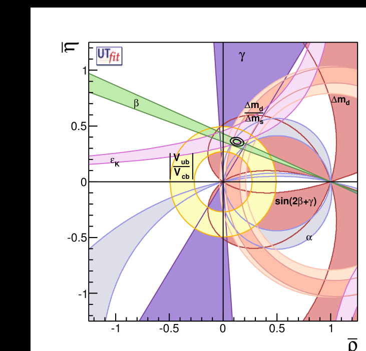
Equation of State

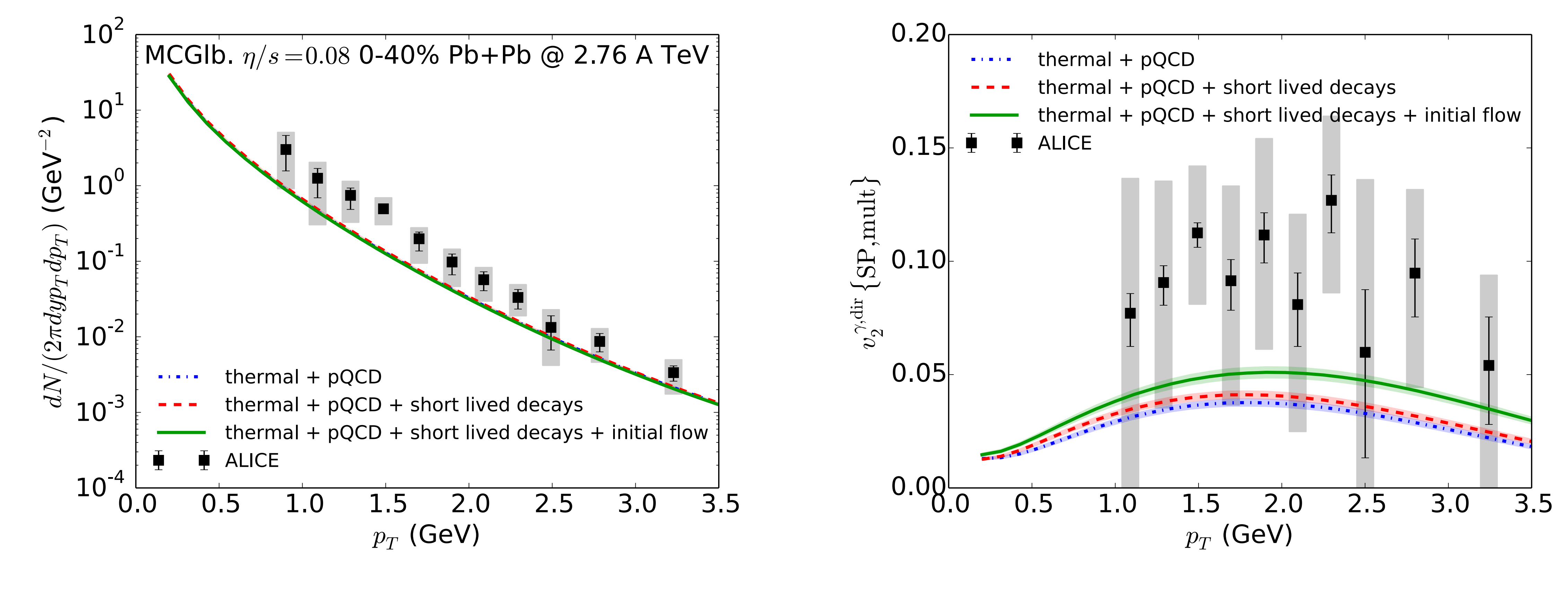






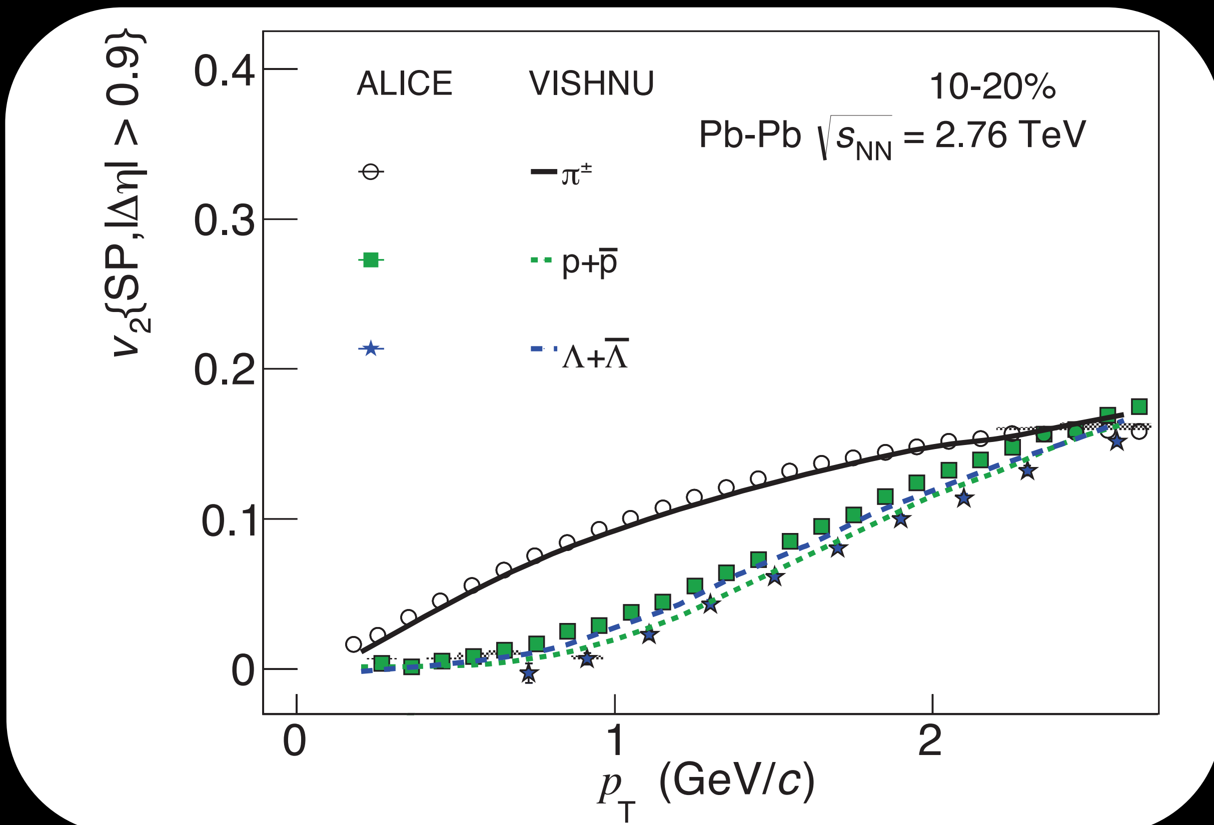
Constraints from RHIC and LHC data
We start to answer the question how well we can constrain the EoS
We need more developments like this

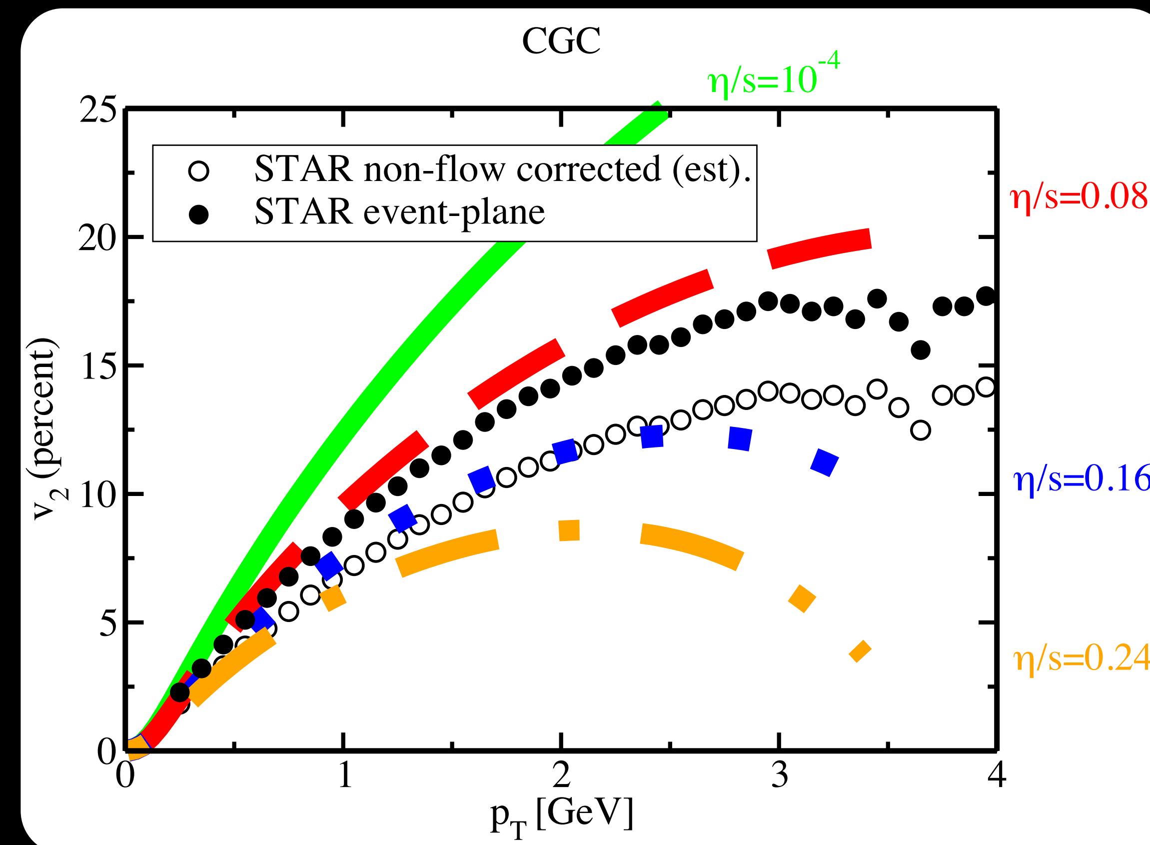
Working description?



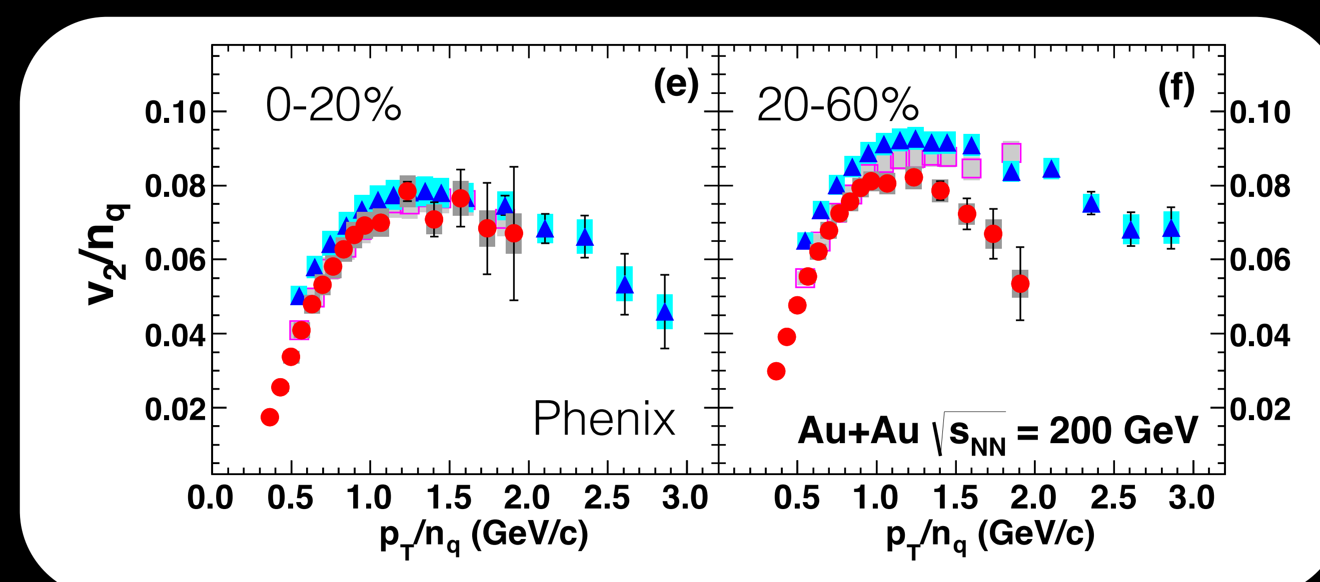
- repairing both yield and v_2 is a challenge
- A standard model for QGP evolution should describe this, both at RHIC and at the LHC!

Do we understand the transition from the QGP to a hot hadron gas?

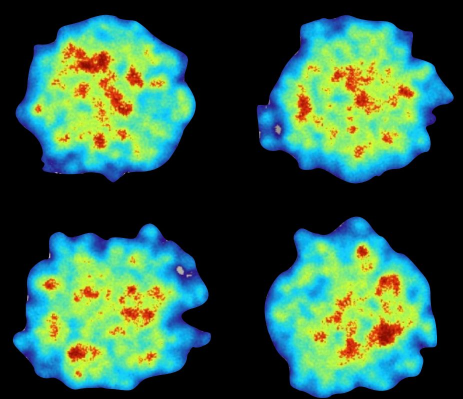


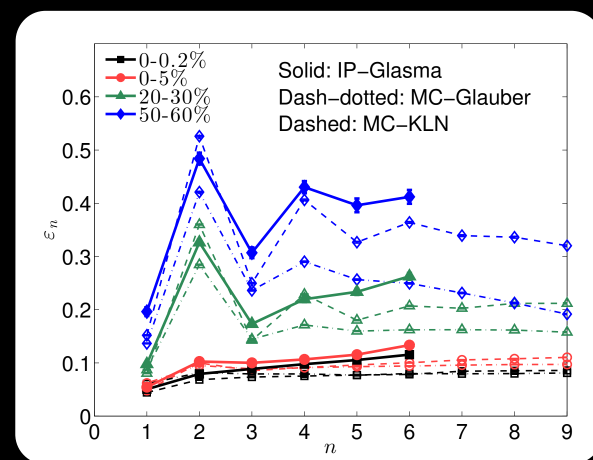


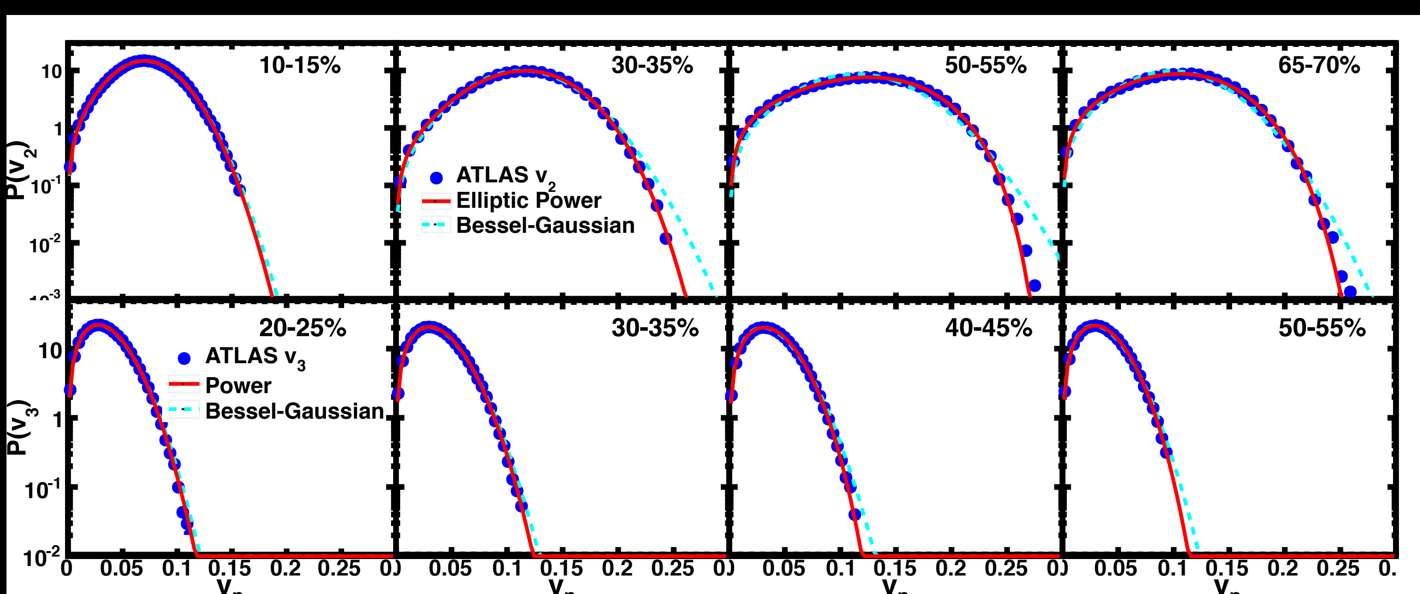
- hadronic stage description of $v_2(m,p_t)$?
- particle production?
- intermediate p_t; δf?
  - centrality dependence $v_2(p_t)$, v_n?

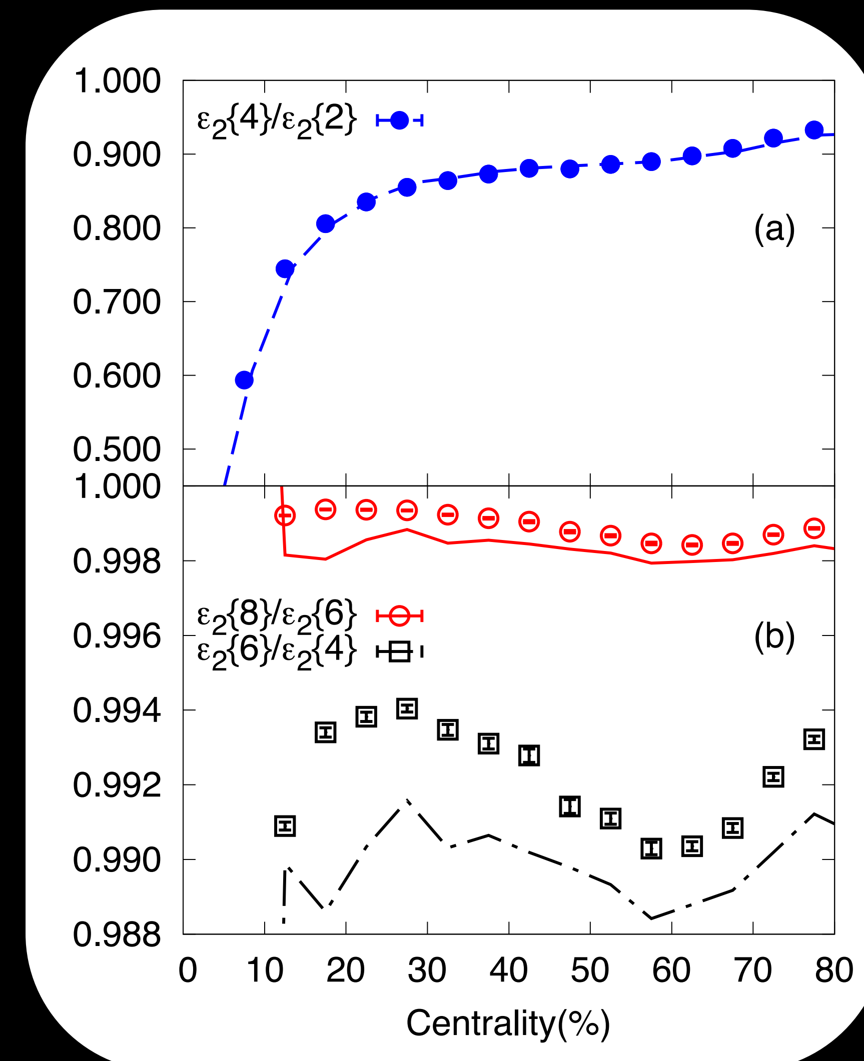


Initial Spatial Density Distributions



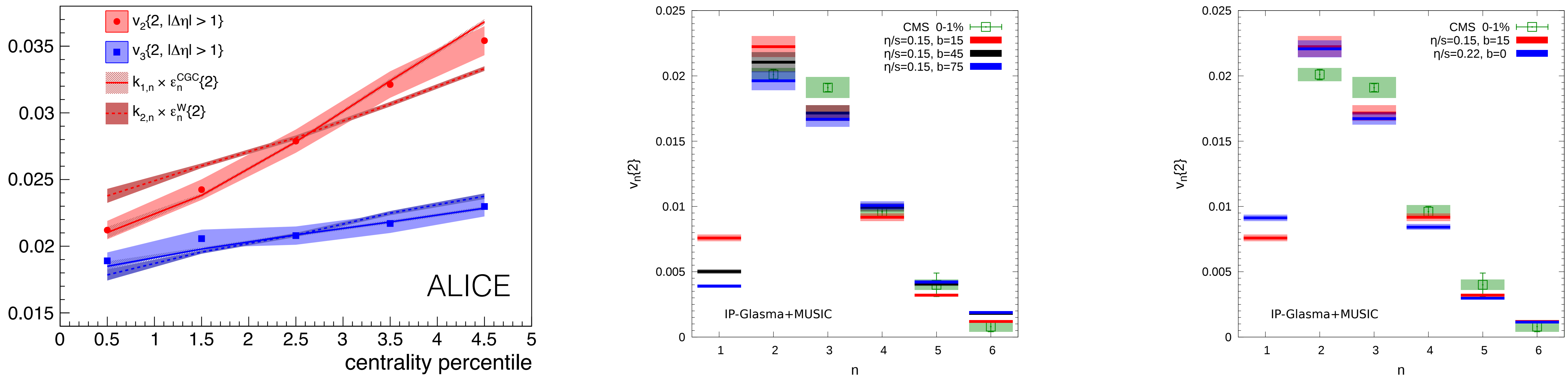






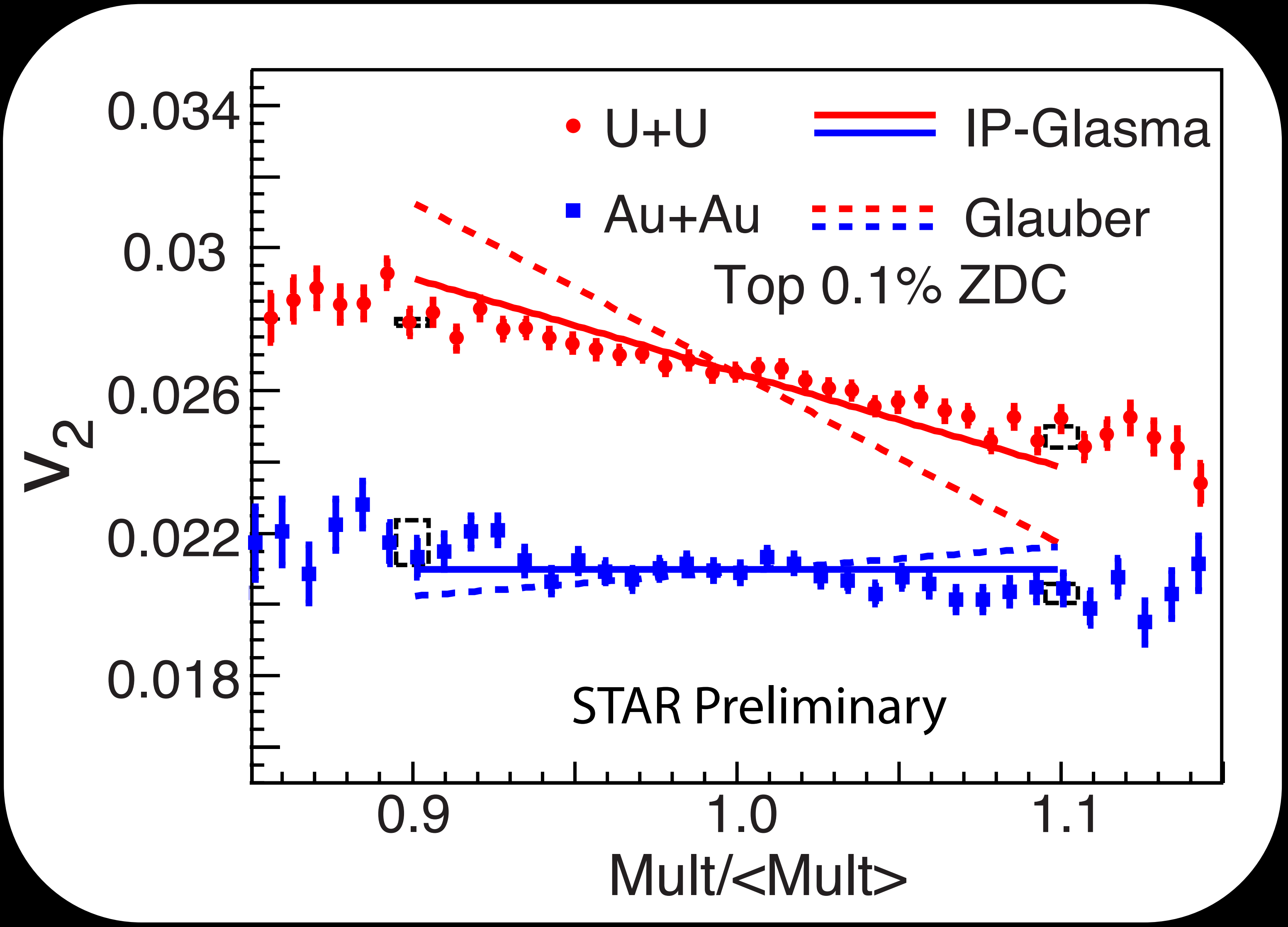
To determine if the match is truly unique or can be obtained in more models, with some modifications, we need to understand the sensitivity to the underlying distribution

Bulk Viscosity?



- The effects of bulk and shear viscosity are in most descriptions not separately tested
- constraining bulk viscosity is an important next step
- (ultra) central collisions is an unexpected place where anisotropic flow is a sensitive probe which might help constraining even the bulk viscosity

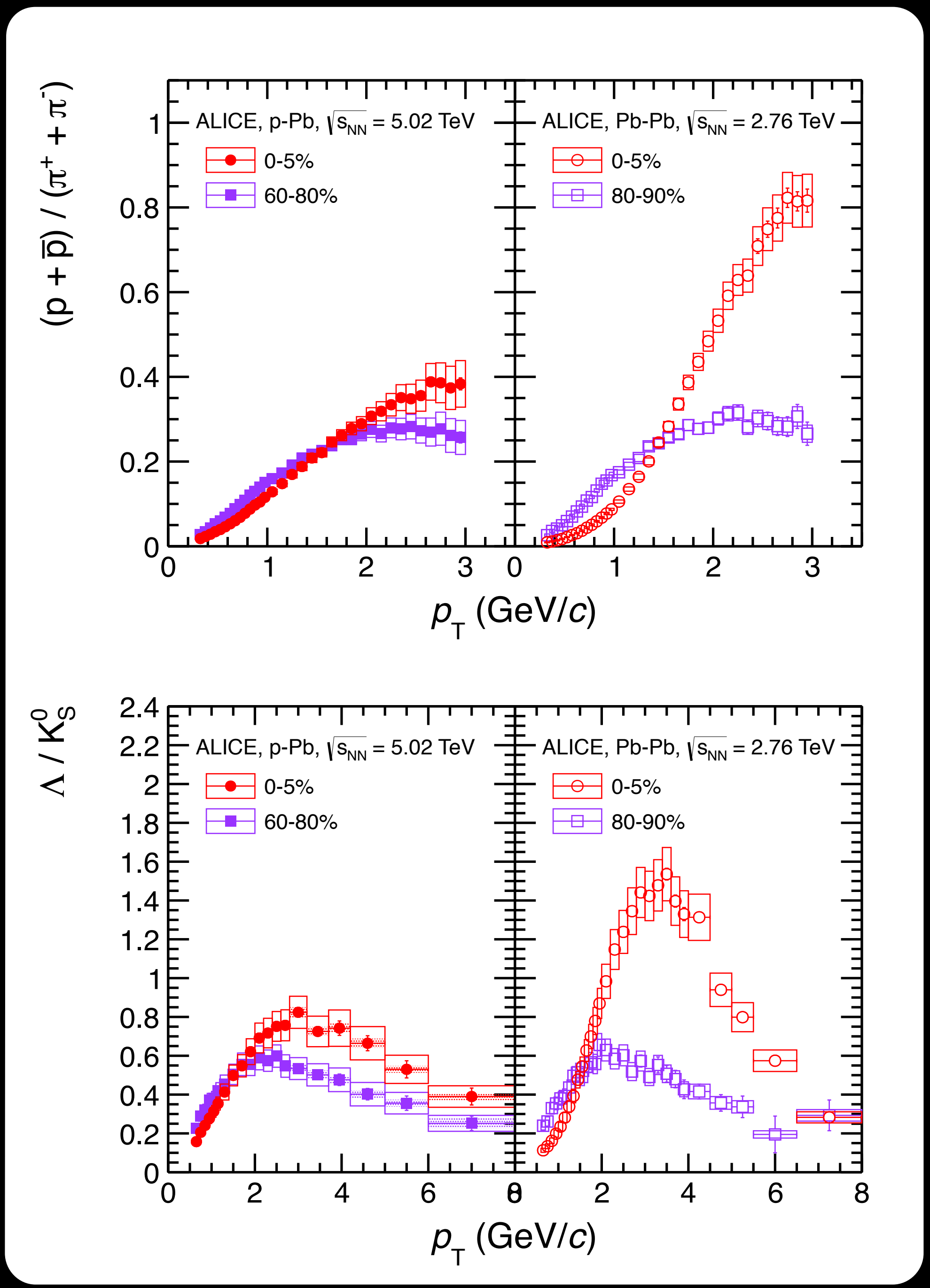
Other Collision Systems: U+U

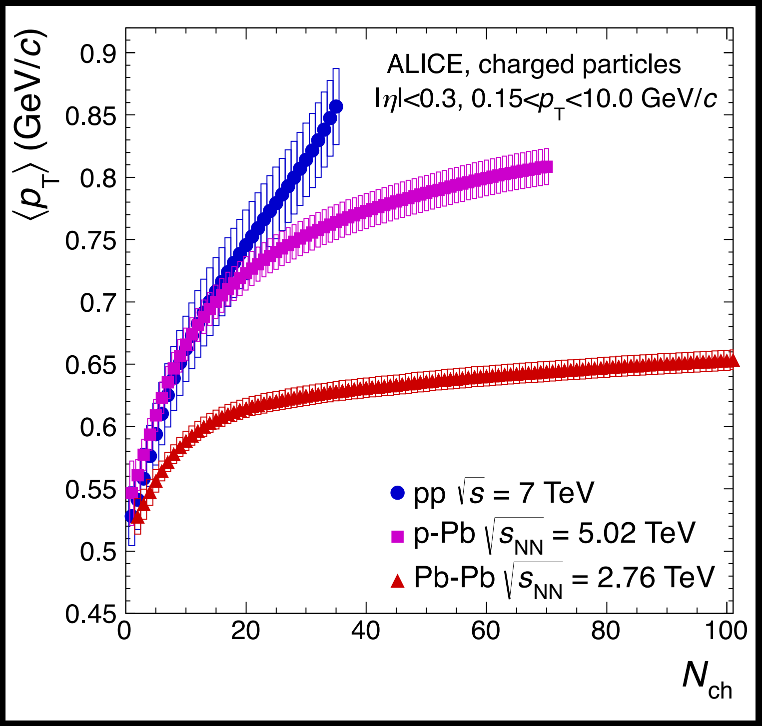


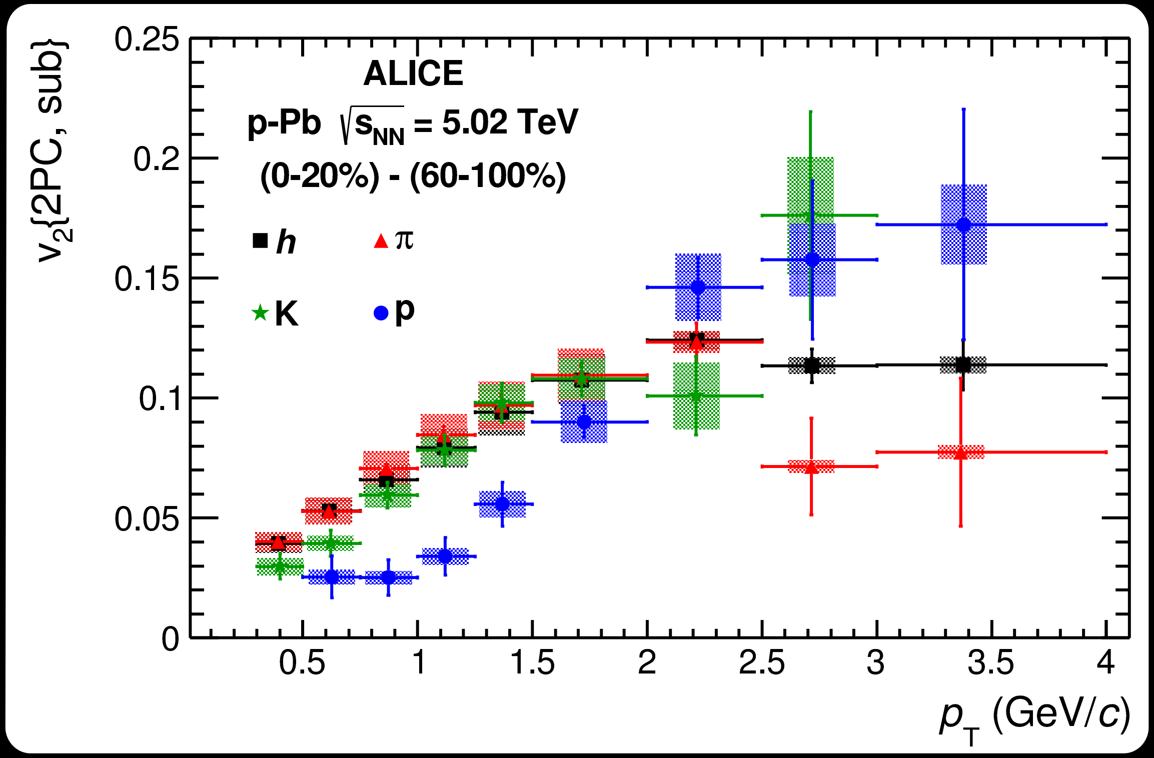
- with a special system like U+U one get get large variations of the initial eccentricities while keeping impact parameter fixed!
- sensitivity to initial spatial density distribution
- looking forward to results from ^{3}He+Au

Other collision systems: pA

- The ridges
- similarities between pA and AA large!

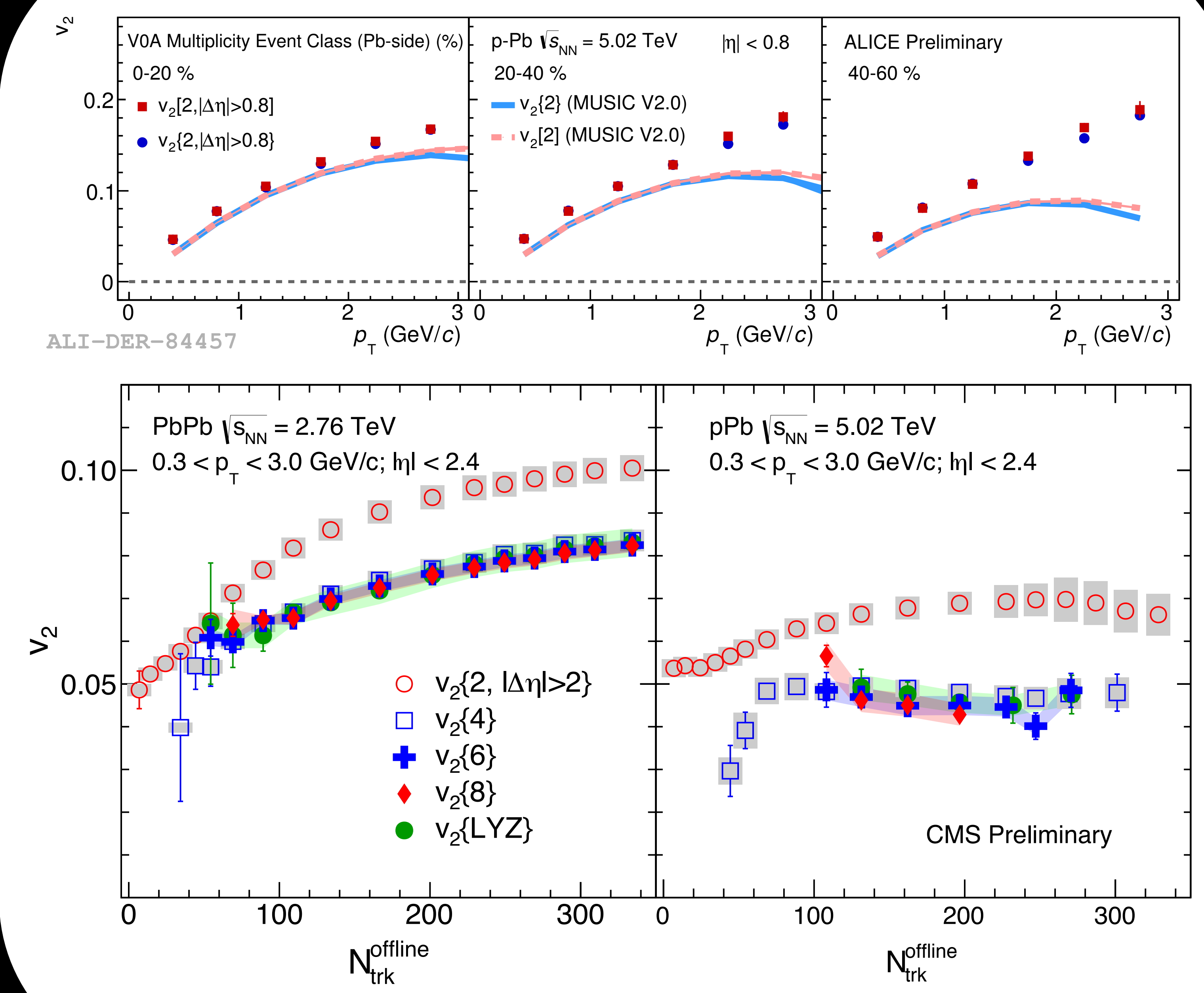






Other collision systems: pA

- factorization
- multi-particle cumulants
- clear evidence of collective behaviour
  - not necessarily hydrodynamic behaviour!
- experimentally measured multiplicity and connection to geometry not very clear
- do we understand were hydro should break down?



Future RHIC Program

low energy e
cooling upgrade

sPHENIX
STAR forward upgrade

transition to eRHIC

2017 — **2020** — **2023**

2015-2016
runs:
200 GeV
pp, pAu, dAu,
AuAu

goals:
initial state fluctuations
heavy flavour flow
color screening quarkonia
constraining η/s
saturation
energy loss in CNM
nPDF

2018-2019
runs:
5-20 GeV
AuAu BES2

goals:
critical point
onset deconfinement

2021-2022
runs:
200 GeV
pp, p(d)A, AuAu

goals:
jet, dijets, γ-jet,
b-tagged jets
parton transport and energy loss
color screening quarkonia
saturation
energy loss in CNM
nPDF

Key future measurements to improve the heavy-ion standard model, understand the perfect liquid from QCD and discover the critical point

Future LHC Program

upgrade to full energy	increase in luminosity	high luminosity LHC
10 x more data	10x	100 x more data
LS1 2014	LS2 7/2018-2019	LS3 2023-2025

2015-2018
runs:
5.5 TeV
PbPb (2015), PbPb (2016), pPb (2017)

2020-2022
runs:
5.5 TeV
pA, PbPb

2025-2027
runs:
5.5 TeV
pA, PbPb, ArAr

goals:
jet, dijets, γ-jet, Z-jet
differentially versus centrality, flow plane, pid
multi-particle correlations, v_n correlations
parton transport and energy loss
color screening quarkonia
low-mass di-leptons, ρ-spectral function, thermal photons
saturation, low-x
collectivity in pA

goals:
jet, dijets, γ-jet, Z-jet, W-jet
differentially versus centrality, flow plane, pid
parton transport and energy loss
color screening quarkonia
low-mass di-leptons, ρ-spectral function, thermal photons
saturation, low-x
t-tbar in heavy-ions

Key future measurements to improve the heavy-ion standard model and understand the perfect liquid from QCD

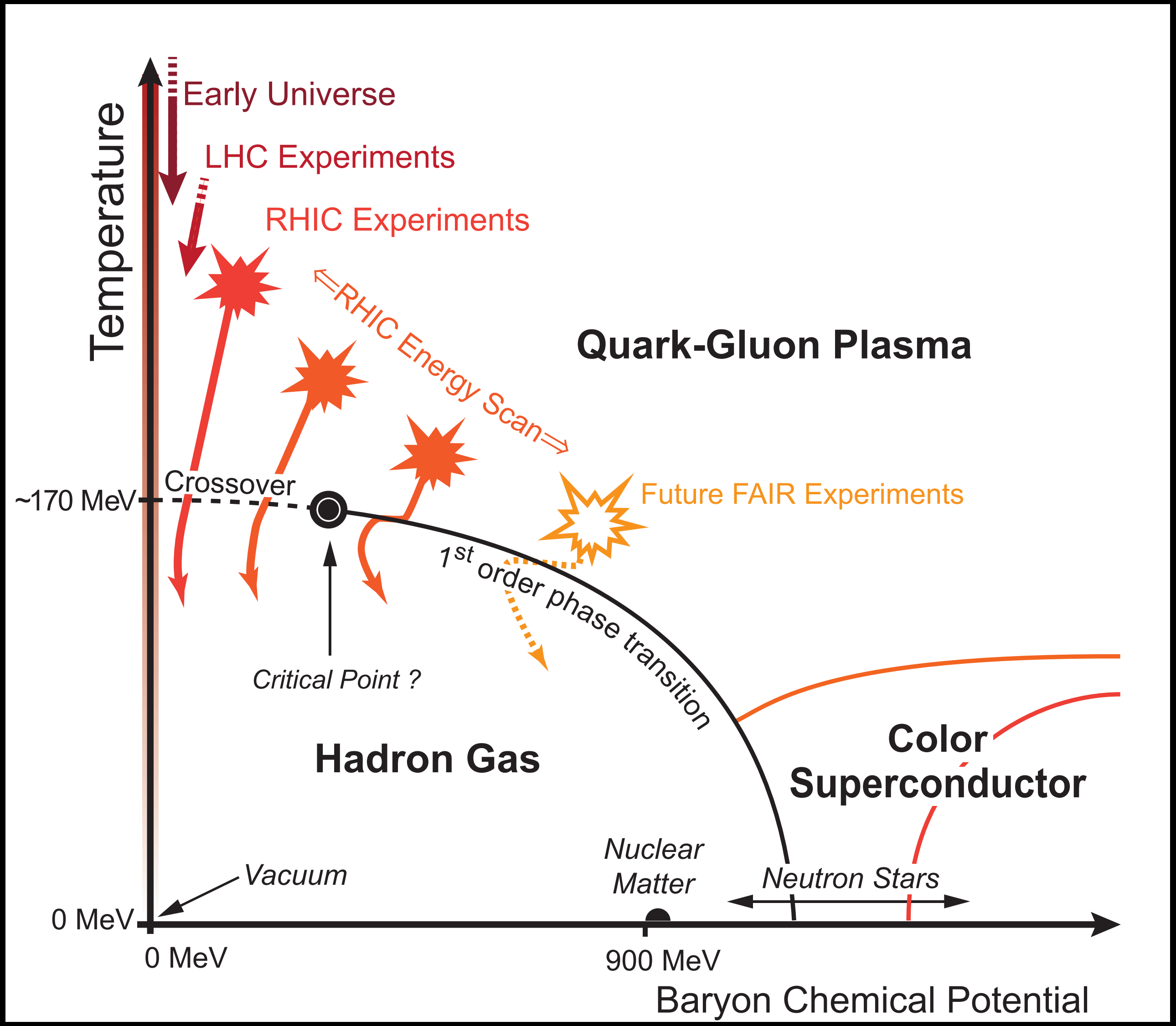
Why both RHIC and the LHC, and what will they deliver?

- Both RHIC and the LHC are unique facilities
- The properties of the QGP at small μ_B and parts of the QCD phase diagram are already understood much better due to RHIC and the LHC
  - At small μ_B a ***precise standard model for the QGP evolution is emerging***
- Currently the field is ***poised to make an important breakthrough*** in the understanding of how the ideal fluid bulk behaviour emerges from QCD degrees of freedom
  - For this we need to complete the heavy-ion “standard model”, which goes hand in hand with ***precision*** bulk observables and hard probes, which ***become available with the new/upgraded detectors and facilities delivering collisions for different systems and energies***
- We need both precision data and range in T and μ_B
  - Imagine how the J/Ψ story would look like with only measurements at the SPS
- The energy scan which is an important ingredient for completing the heavy-ion “standard model” and provides a unique opportunity to discover one of the main landmarks in the QCD phase diagram; ***the critical point***

QCD Phase Diagram

The beam energy scan is important in the construction of a precise model of the evolution of the QGP and hadronic phase. With such a precise model, the opportunity to discover one of the main landmarks of the QCD phase diagram is maximised

Highest RHIC and LHC energies allow us to obtain a precise model of the QGP evolution (also contributions from hadronic phase)
and with precision hard probes we might have the possibility to explain how a perfect liquid emerges around T_C from QCD degrees of freedom.
A precise model would provide an important bases for discoveries such as CME and other unexpected phenomena



Outlook/Conclusions

- In the last 40 years enormous progress has been made in the field
    - a paradigm change in the last 10 years
- The *next decade is crucial*, could be a perfect storm (RHIC, LHC, machine and detector upgrades and a strong theoretical commitment)
- *very possibly, new and unexpected phenomena in the realm of nuclear matter at the highest densities will be discovered*