Study of Hot QCD matter at RHIC and LHC

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Contents

- Temperature
- Energy loss
- Collective flow
- Critical point

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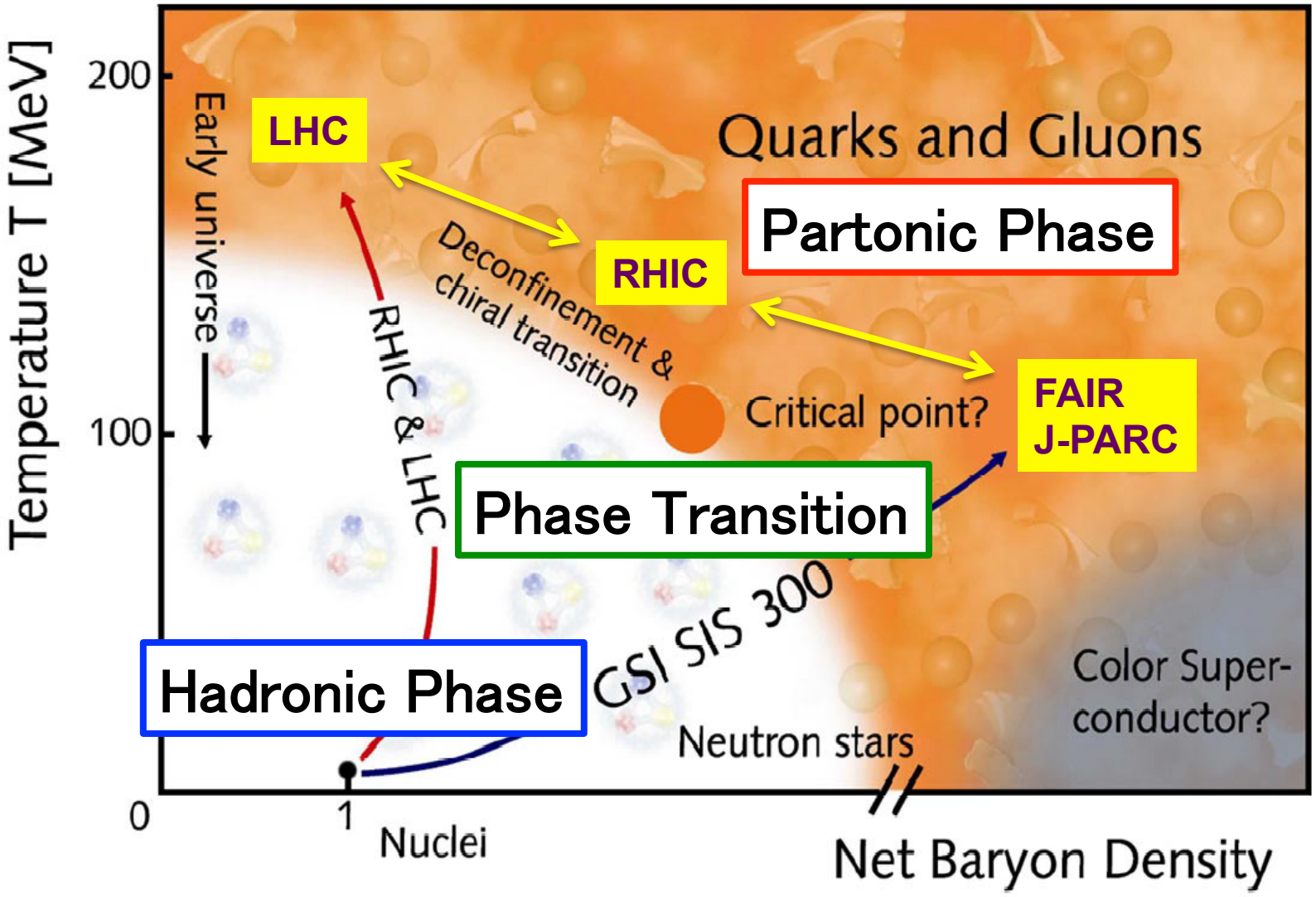
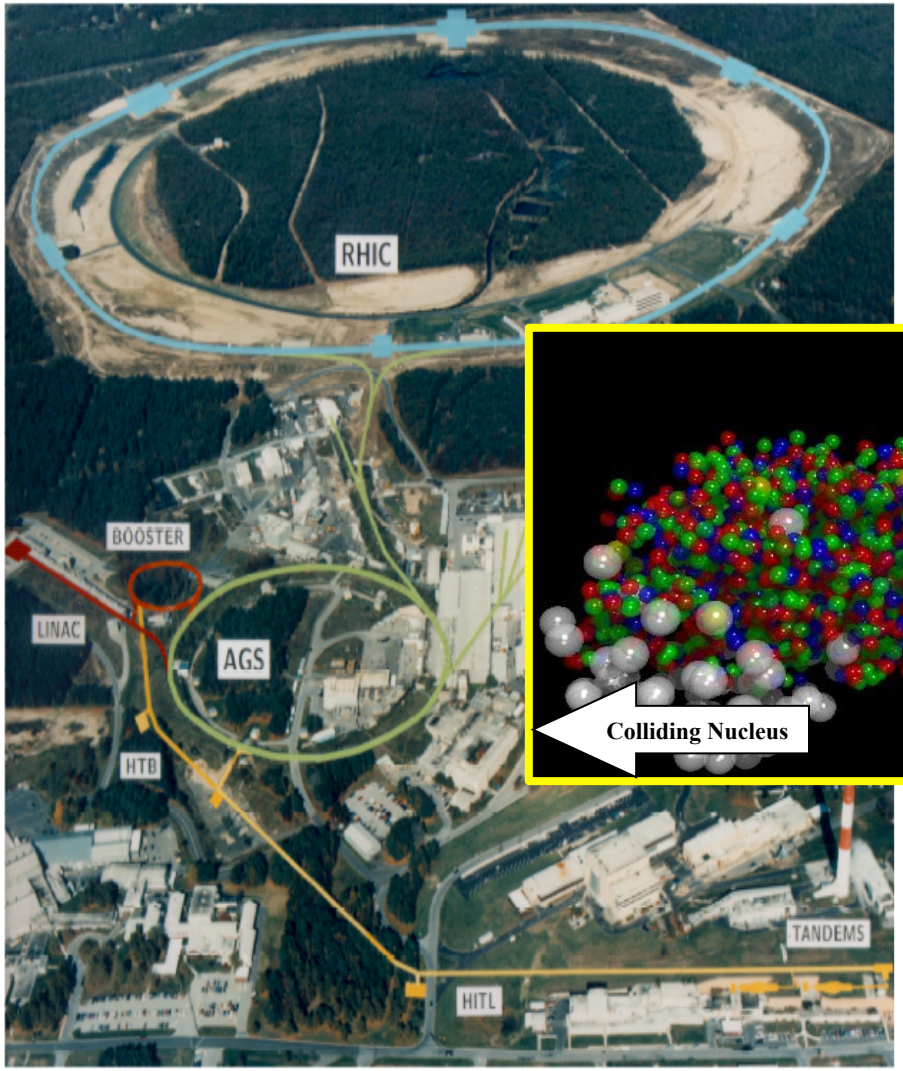
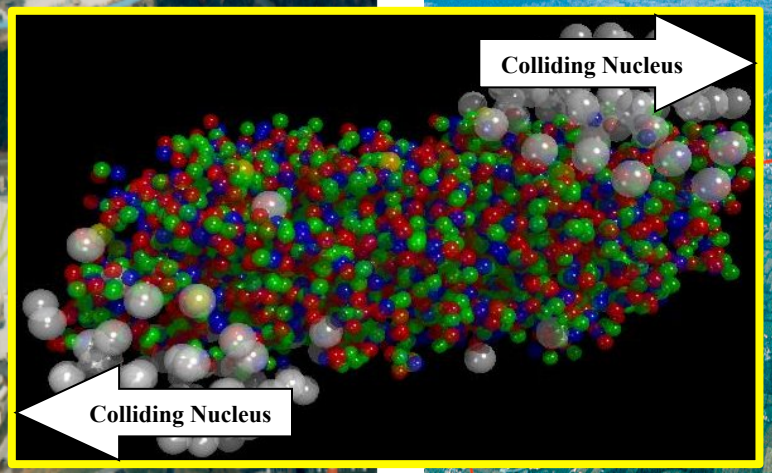
Hadronic Phase –> Partonic Phase

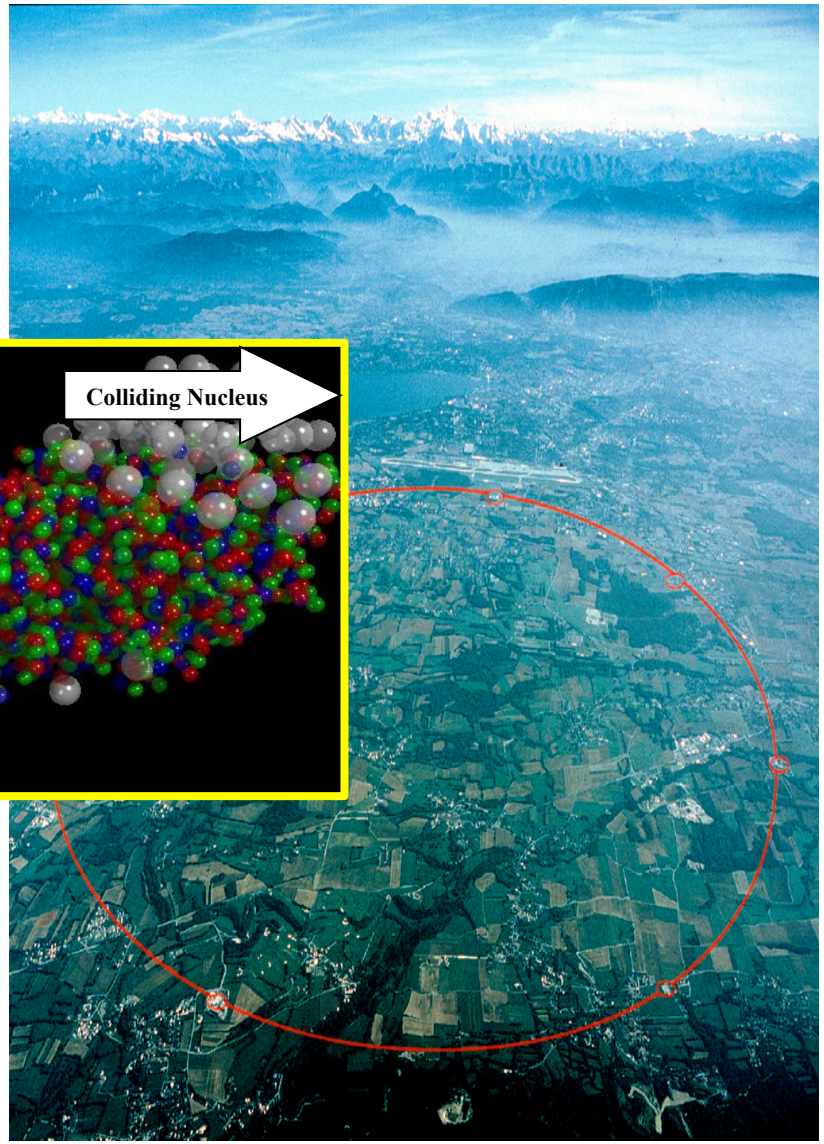


RHIC at BNL, sqrt(s_{NN}) = 10 – 200 GeV/c
(New York, USA)

LHC at CERN, sqrt(s_{NN}) = 0.5 – 5.5 TeV/c
(Geneva, Switzerland)

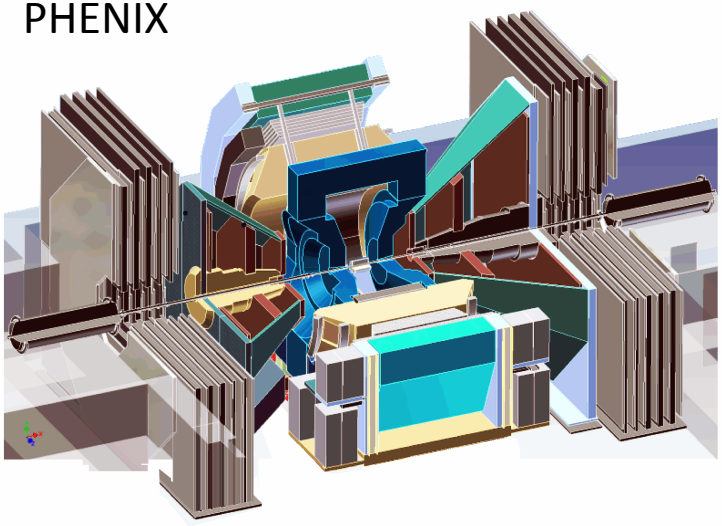






Experiments at RHIC and LHC

PHENIX



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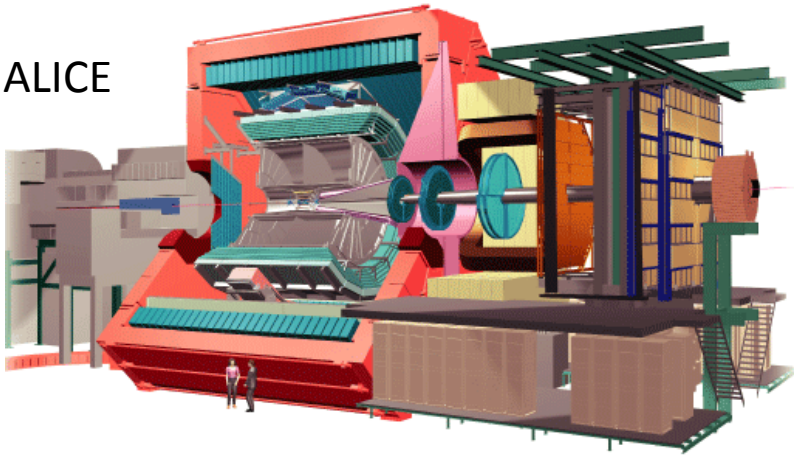

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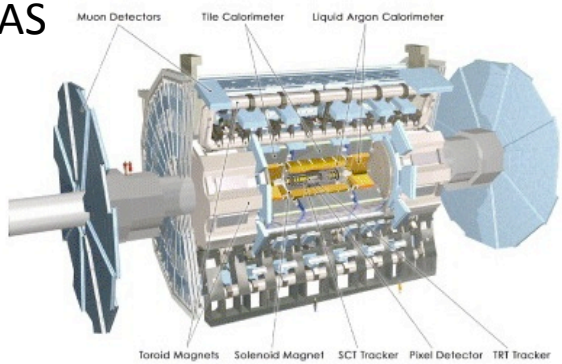

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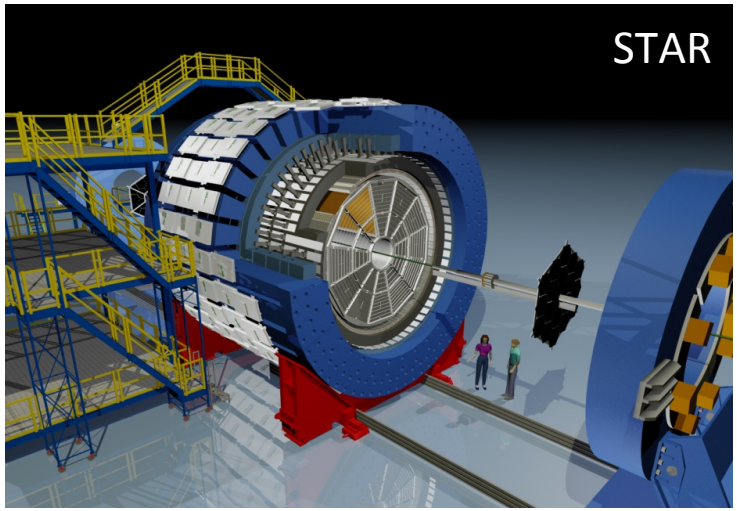
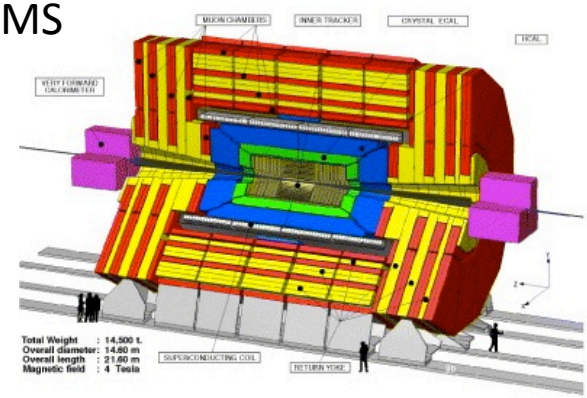
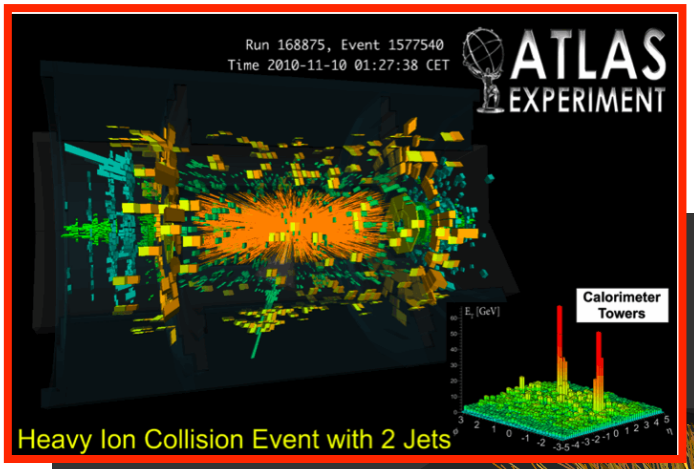
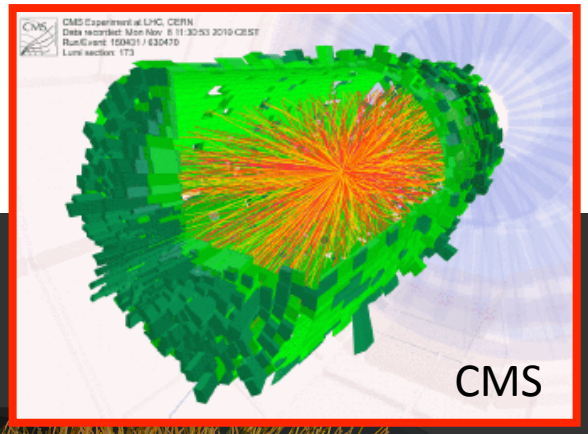
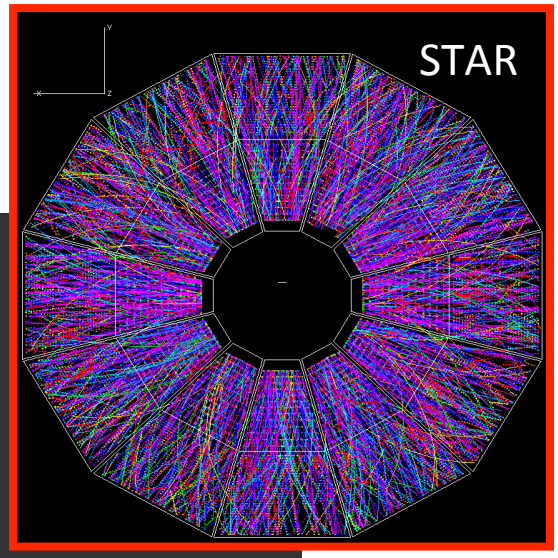


CMS



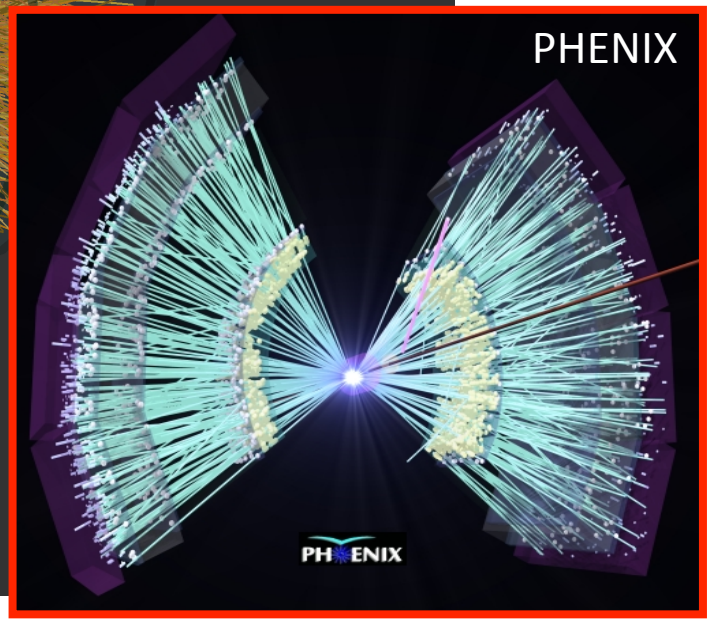




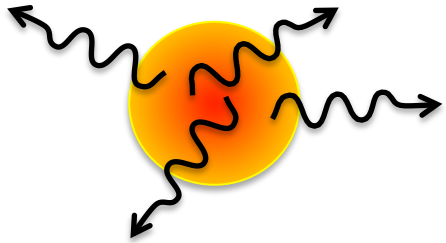


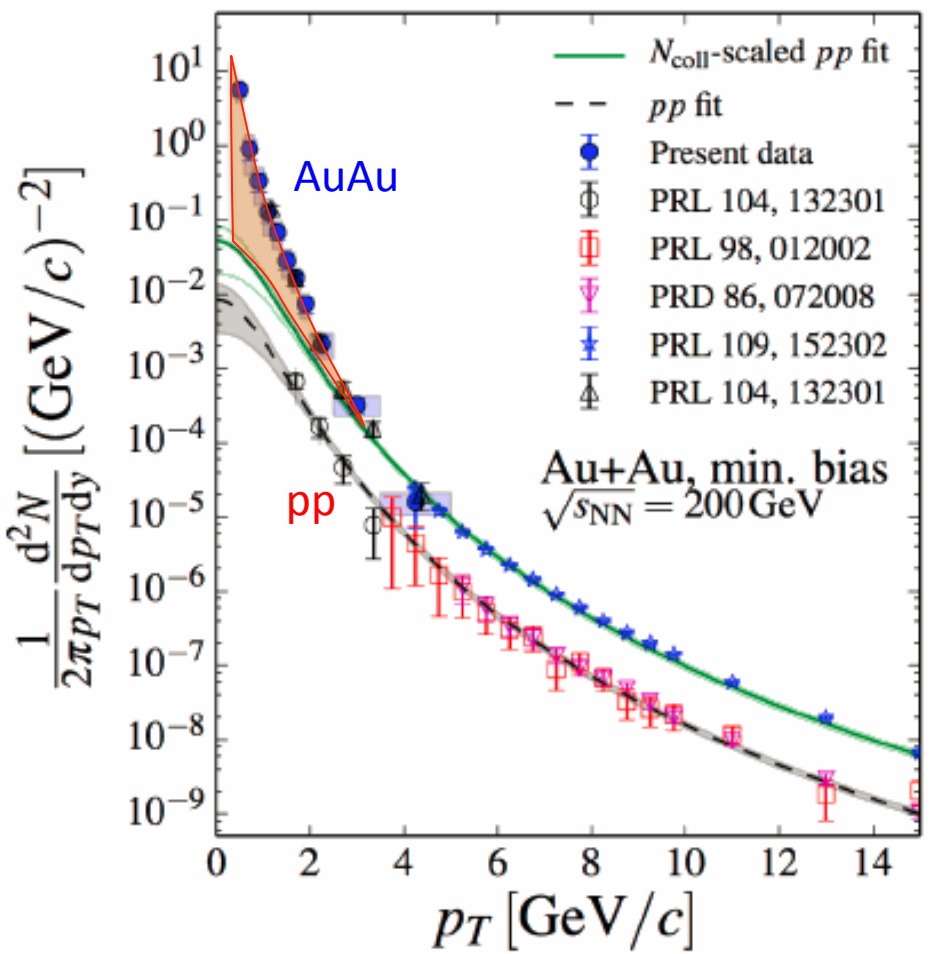
Experimental data

a few k to 10k particles per collision



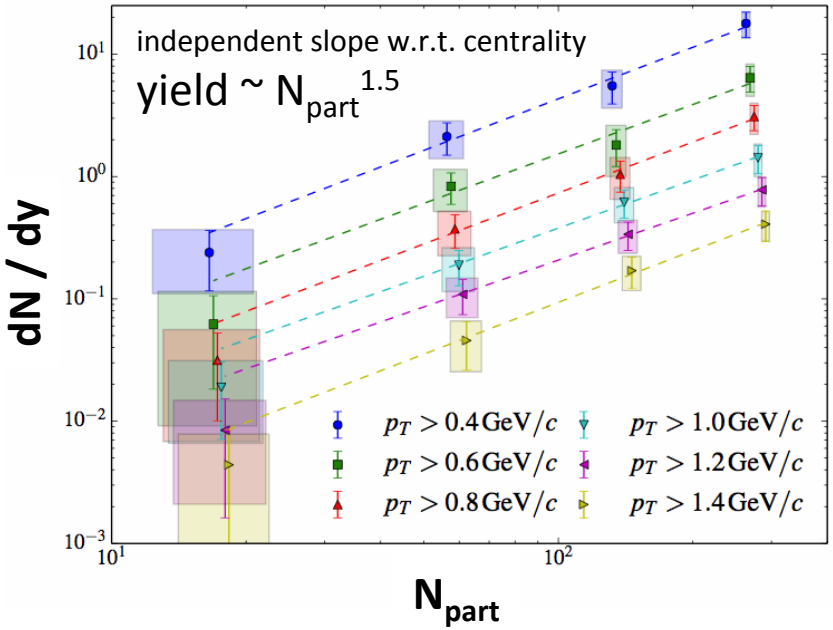
Enhanced thermal photon production at low p_T



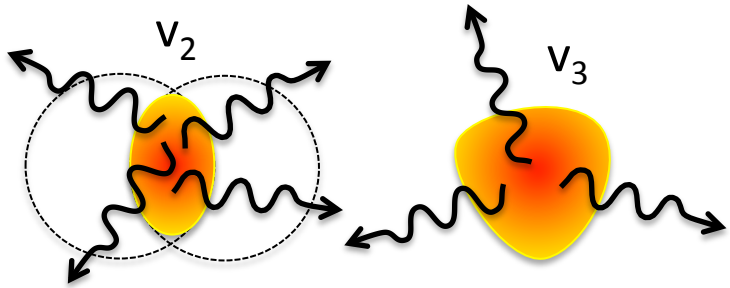


- Virtual and real photon measurements via internal and external conversion methods with electron pair measurements
- Real photon measurements with EMcal
- Initial temperature of 300~600MeV

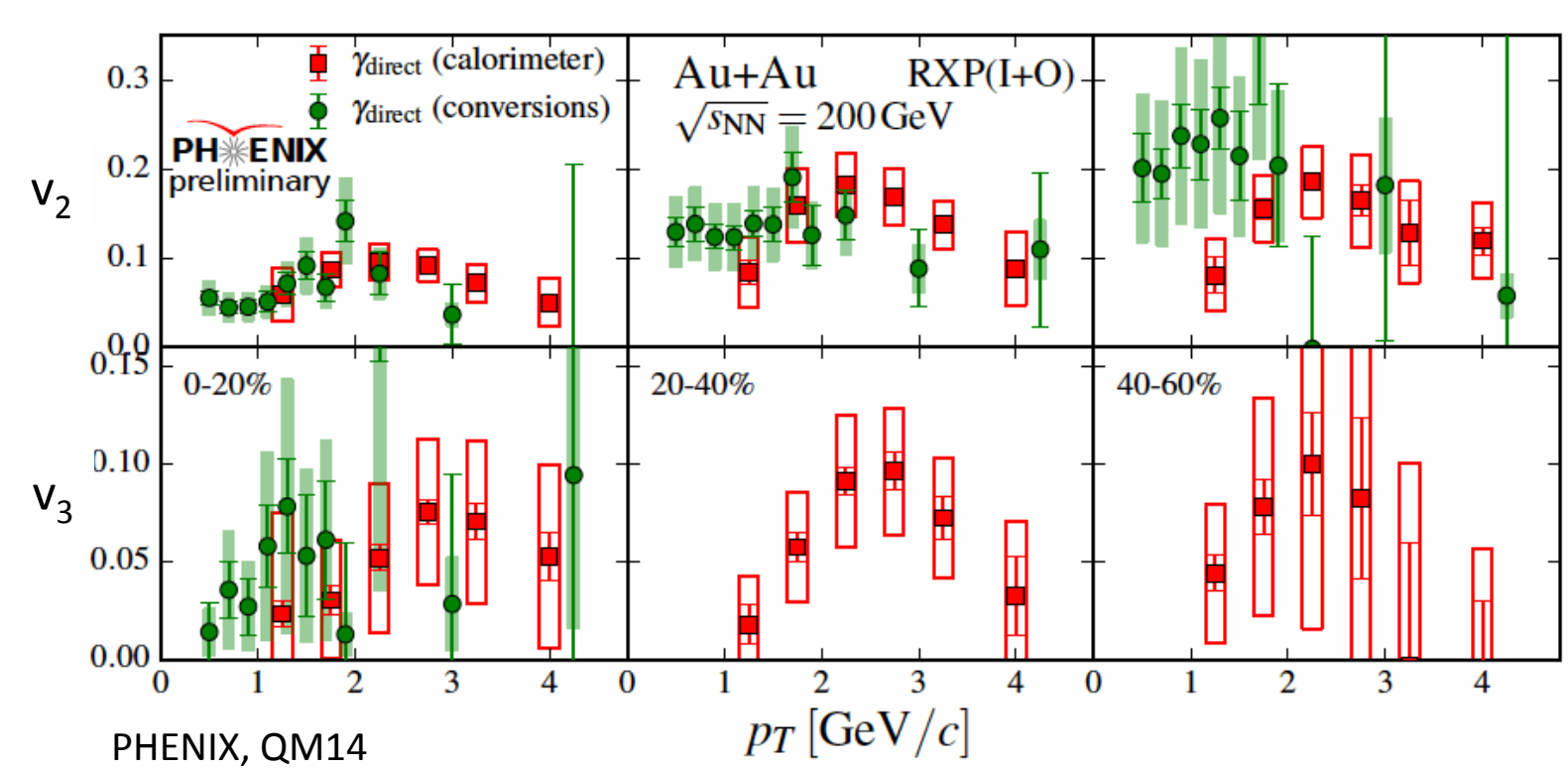
arXiv:1405.3940



Direct (thermal) photon v_2 and v_3



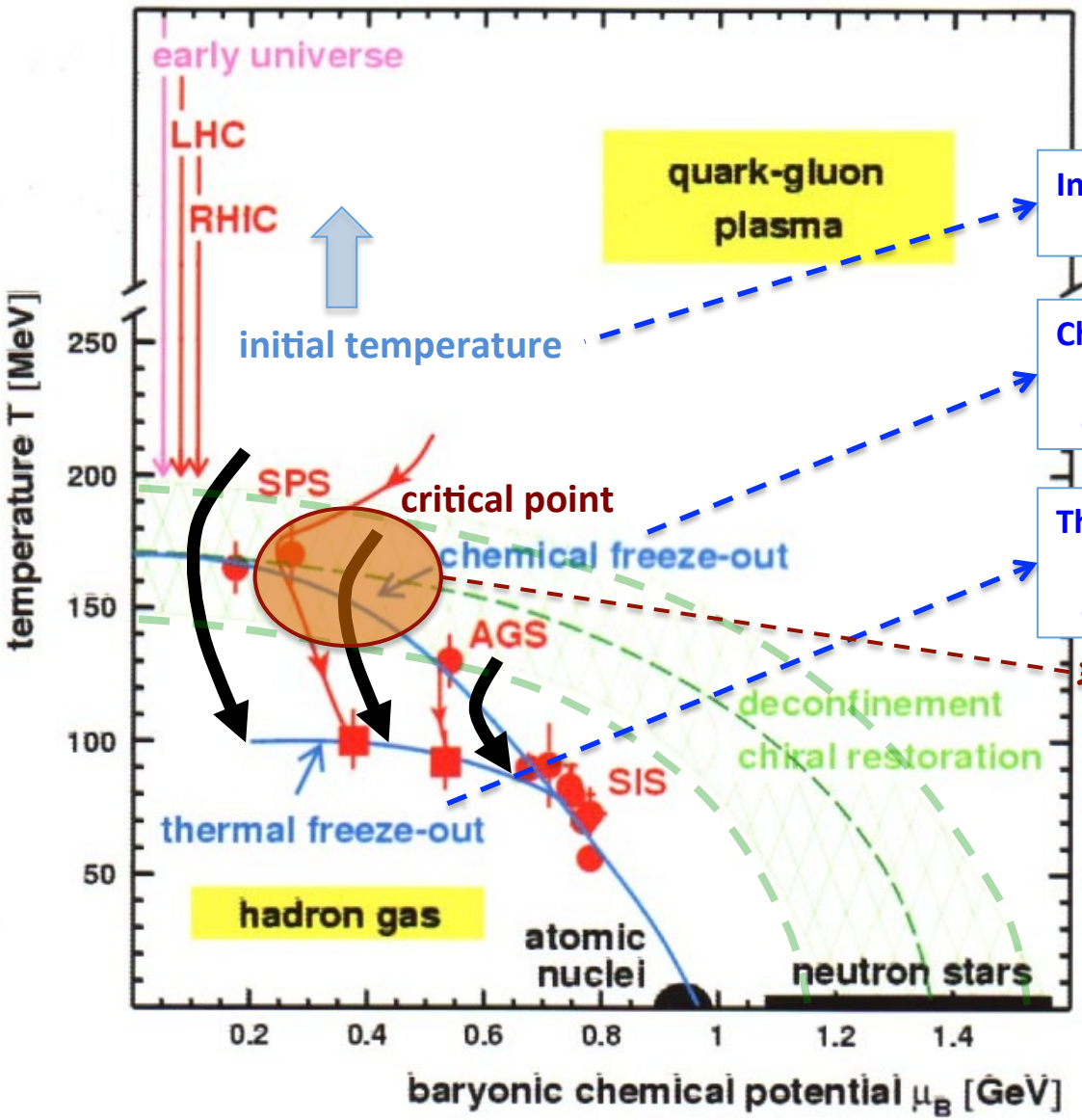
$v_n = < \cos n(\phi^{particle} - \Phi_n^{plane}) >$
(n=2 : elliptic flow), (n=3 : triangular flow)



PHENIX, QM14

- comparable to hadron for both v_2 and v_3 at 2~3GeV/c
- significant contribution from photons from later stages (inconsistent with early photons from hotter period)
- flatter p_T dependence of v_2 at low p_T

History of temperature before/after the phase transition



Initial temperature :
Direct thermal photon measurement

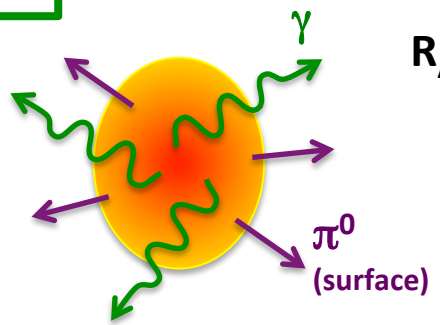
Chemical Freeze-out temperature :
Particle species, ratios are fixed
at the end of inelastic interactions

Thermal Freeze-out temperature :
Particle spectra are fixed
at the end of elastic interactions

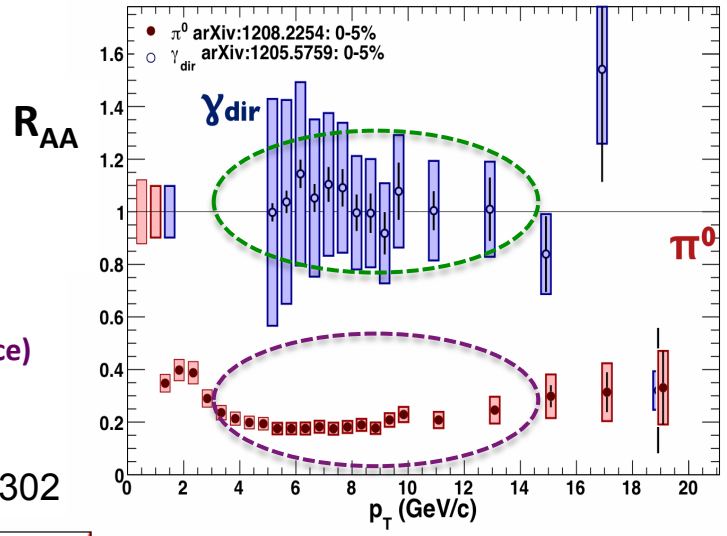
Critical Point :
1st order phase transition
non-monotonic behavior
expected fluctuation to diverge

High p_T direct photon as penetrating probe

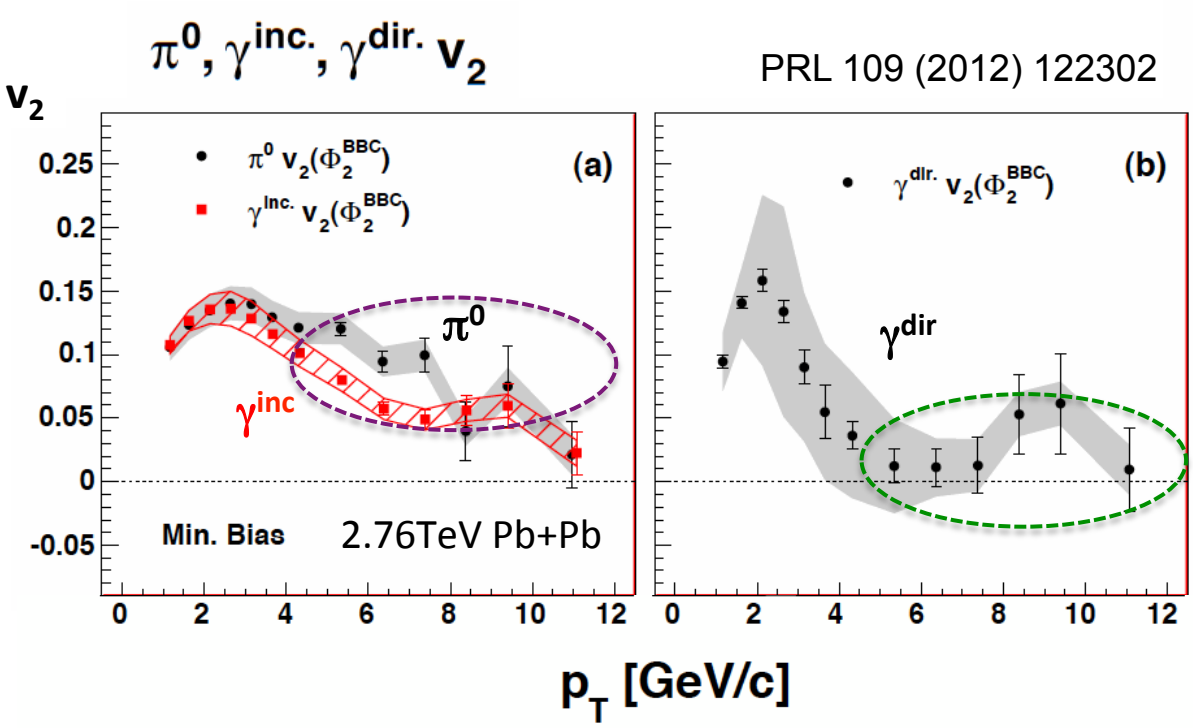
$p_T > 5$ GeV/c	hadron	γ^{dir}
R_{AA}	< 1	~ 1
v_2	> 0	~ 0



PRL 109 (2012) 152302



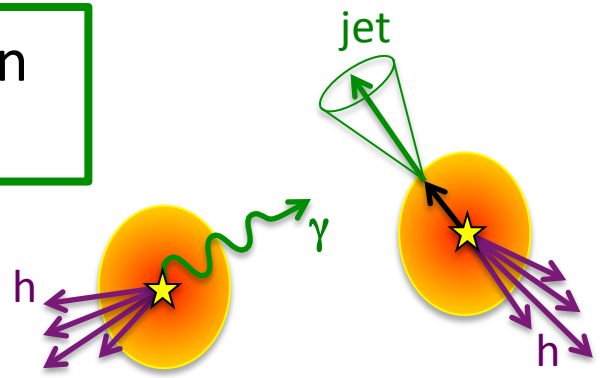
PRL 109 (2012) 122302



$$R_{AA} = \frac{N\,(A+A)}{N_{coll}\,N(p+p)}$$

relative yield with respect to a simple independent superposition of pp data

Energy loss at high p_T and re-distribution of the lost-energy at low p_T at RHIC



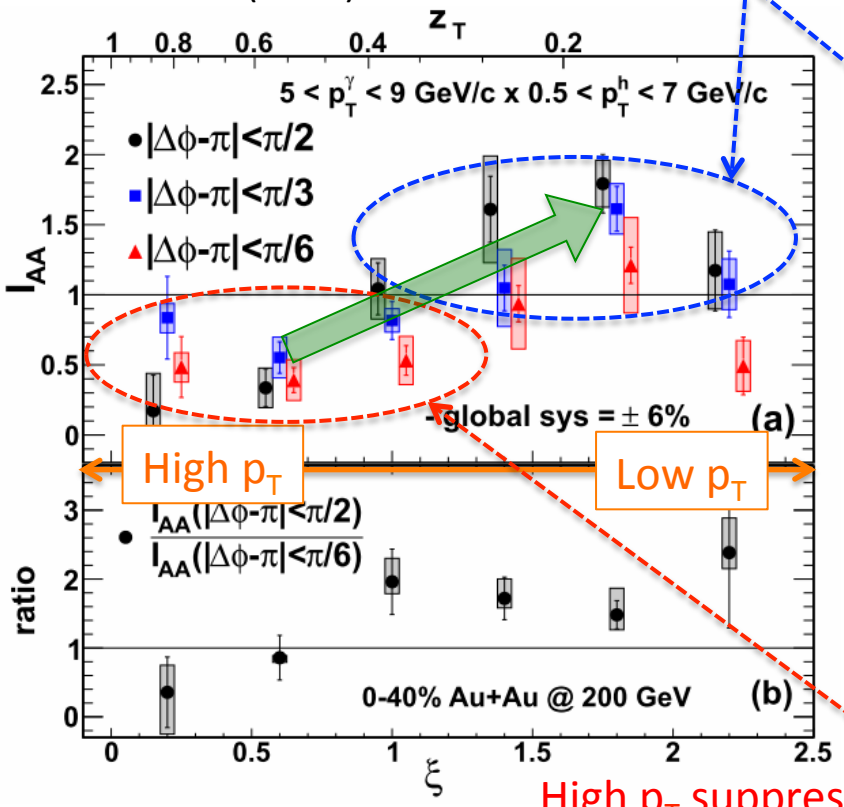
prompt photon - hadron correlation

N_{PTY} = associate hadron yield per trigger γ

$I_{AA} = N_{PTY}(AA) / N_{PTY}(pp)$

Low p_T enhancement

PRL 111 (2013) 032301

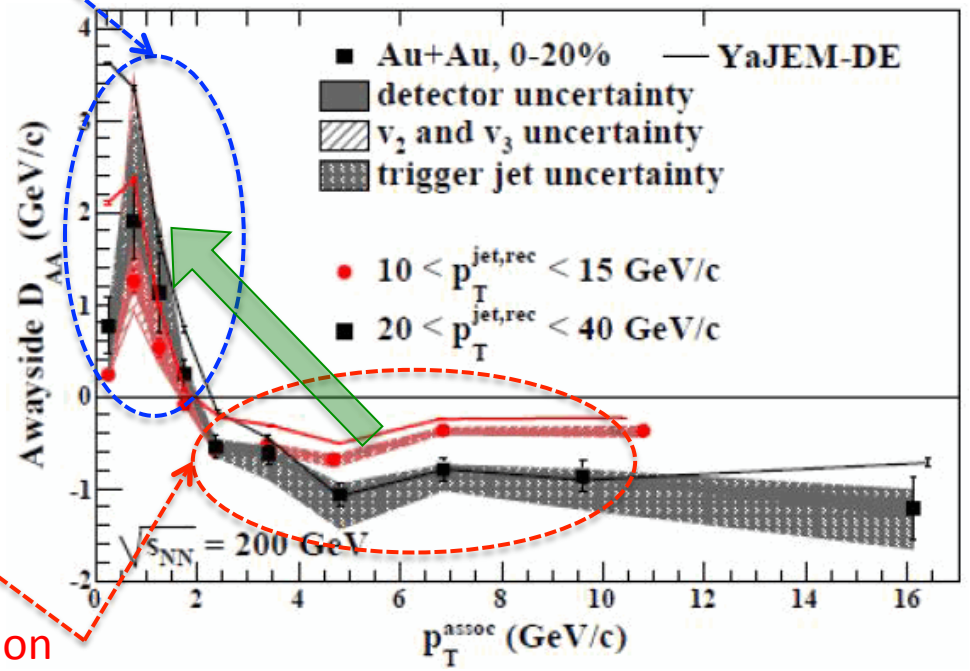


jet - hadron correlation

S_{PT} = associate hadron p_T sum per jet

$D_{AA} = S_{PT}(AA) - S_{PT}(pp)$

PRL 112 (2014) 122301

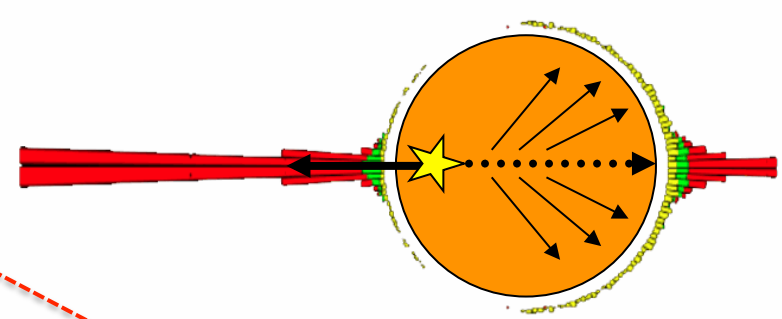


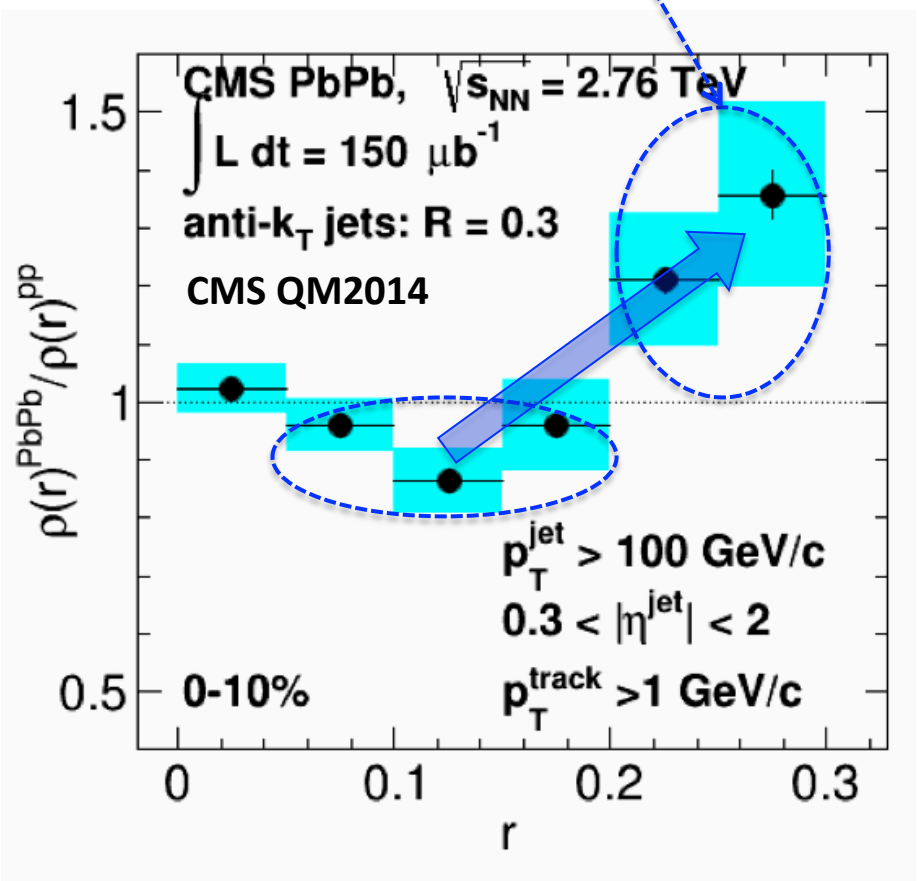
High p_T suppression

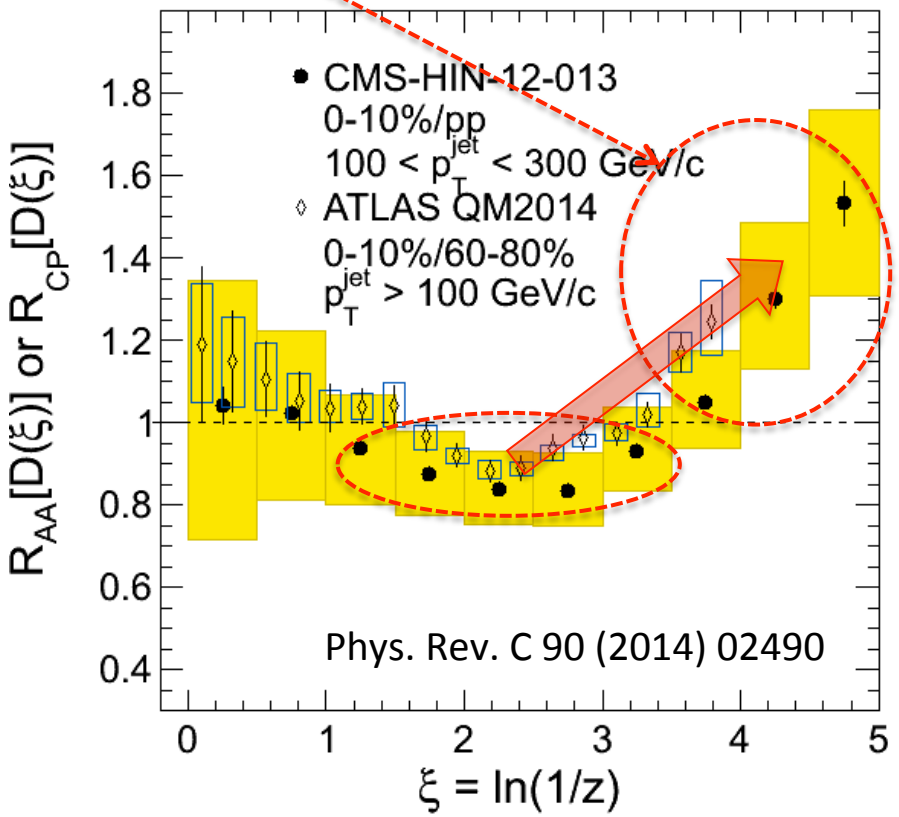
Modification of jet F.F. at LHC

re-distribution to lower p_T

and to larger angle



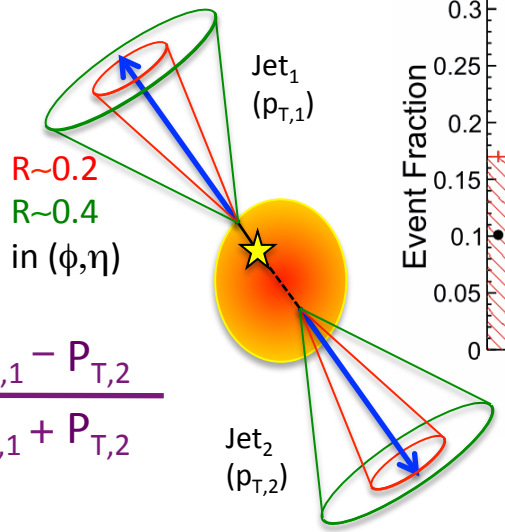


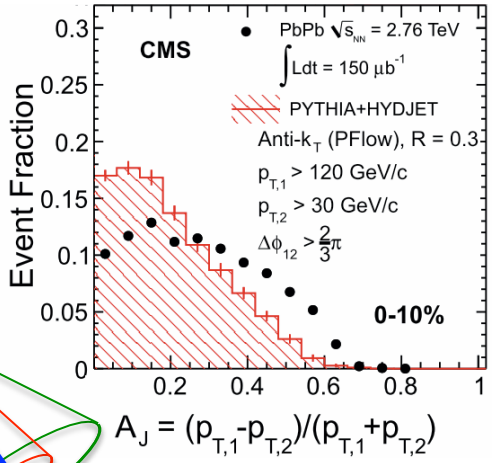


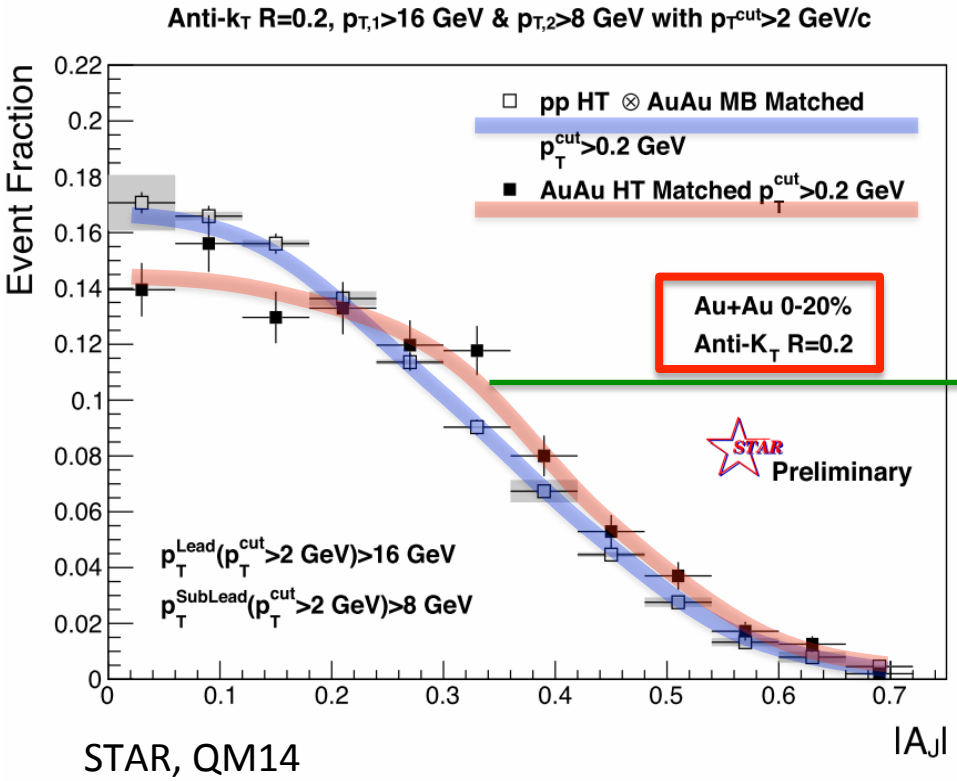
Jet quenching at RHIC vs LHC (A_J : di-jet energy asymmetry)

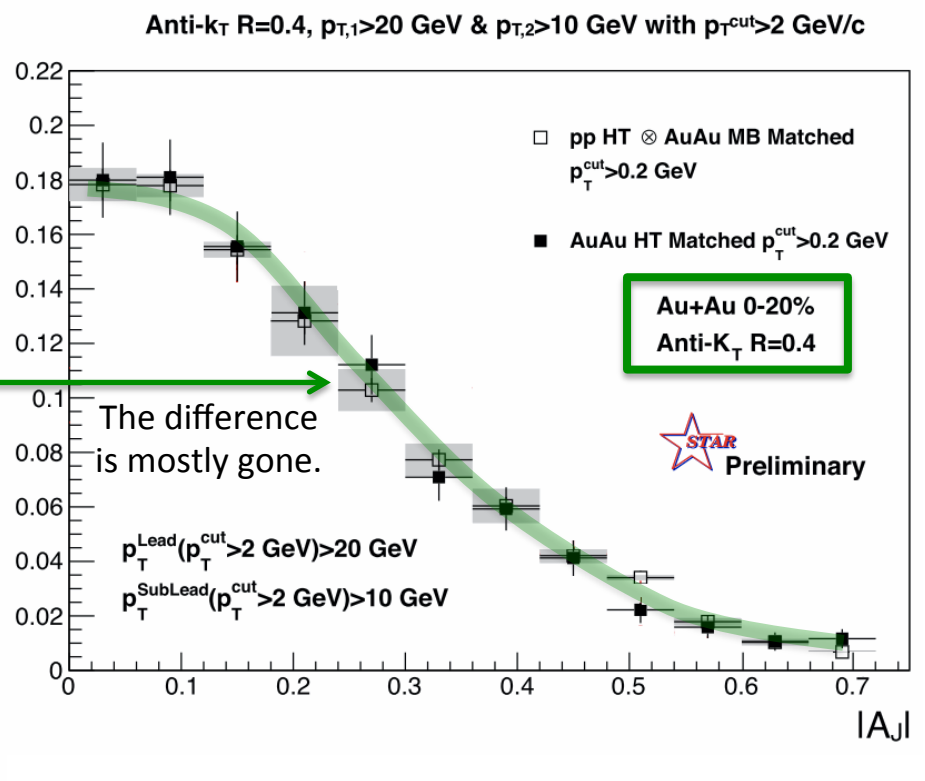
- visible effect with smaller jet cone R~0.2 at RHIC
- lower jet energy than LHC, smaller effect than LHC
- mostly recovered jet energy within larger jet cone R~0.4
- Somewhat contradicting with large angle emission of low p_T particles (jet selection bias…)

$$A_J = \frac{P_{T,1} - P_{T,2}}{P_{T,1} + P_{T,2}}$$









STAR, QM14

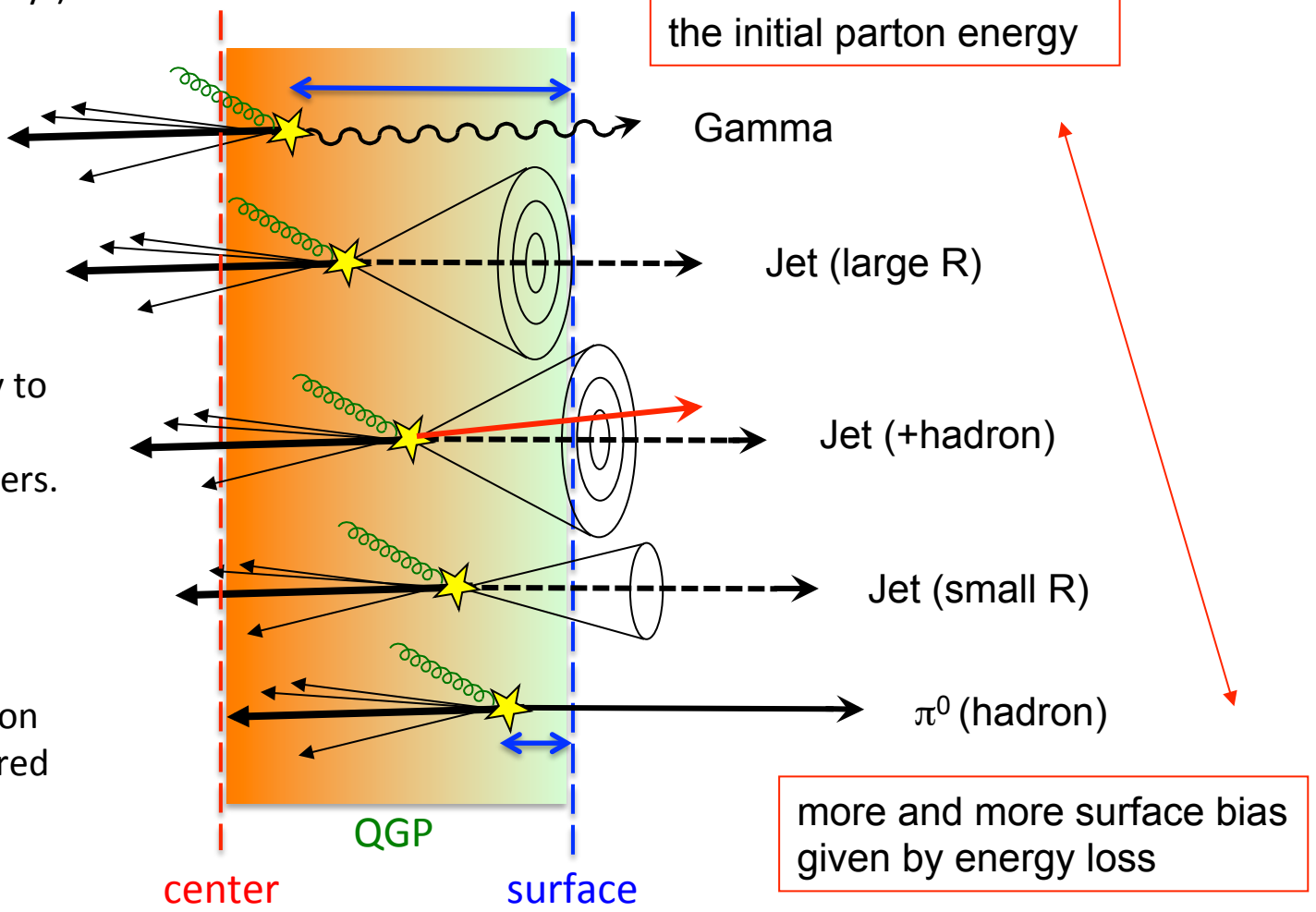
jet-suppression by partonic energy loss and/or modification of fragmentation function

(These two can not be clearly separated experimentally!)

Jet reconstruction is to recover the lost energy to get the original parton depending on parameters.

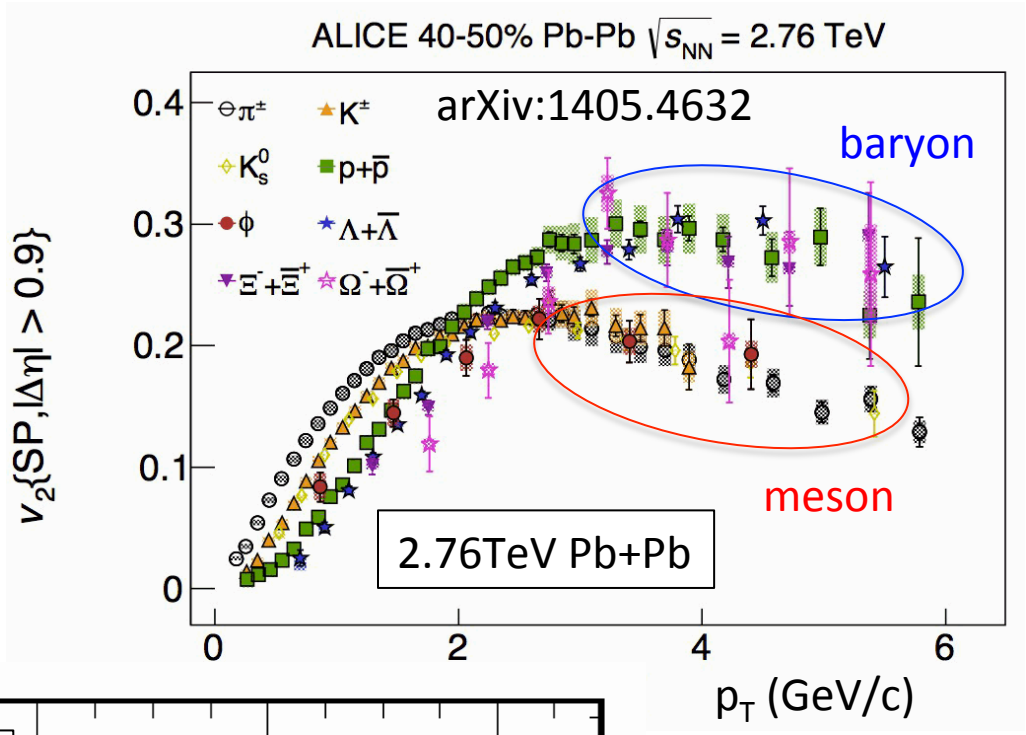
Jet as a control tool to define path length

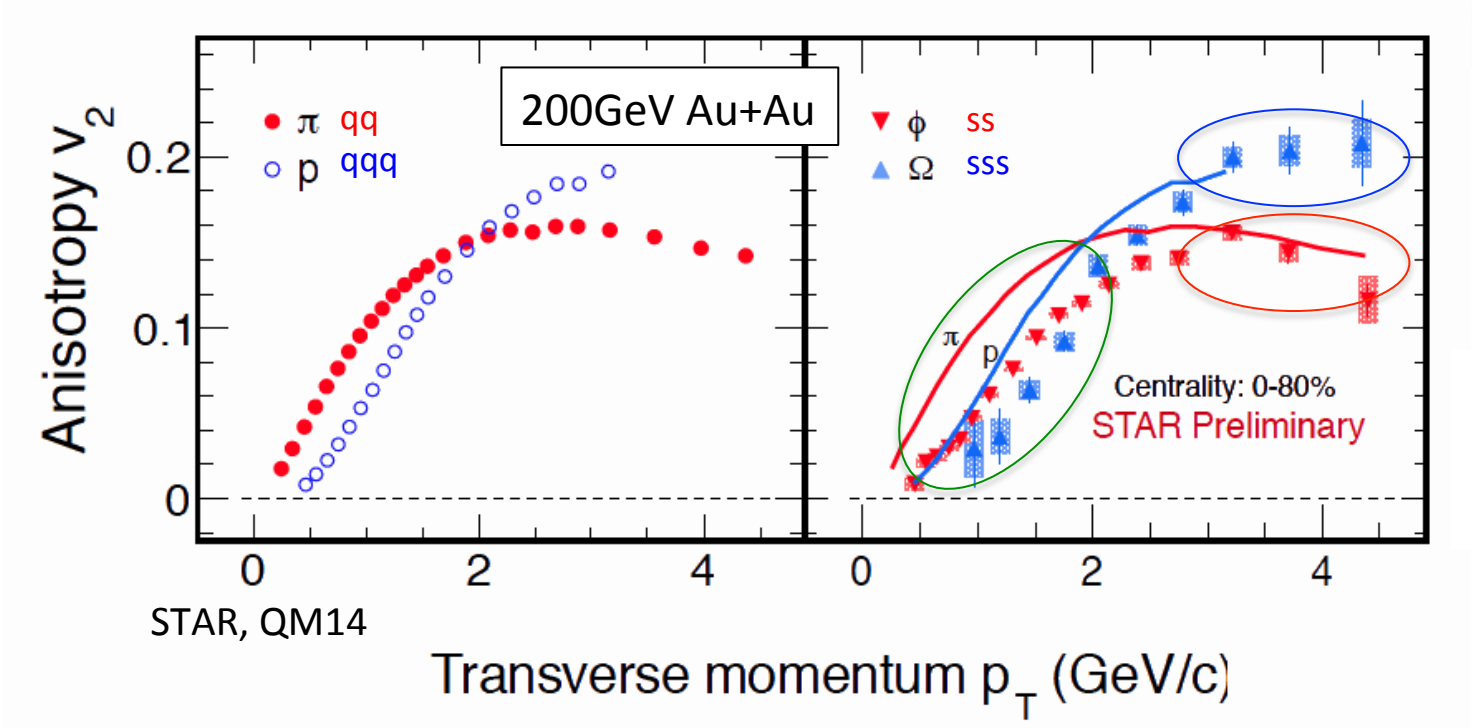
quark/gluon contribution should also be considered



Elliptic flow with PID at RHIC and LHC

- High statistics measurements allow a precise comparison of $v_2(p)$ and $v_2(\phi)$.
- Some small deviation from hydro-like mass dependence of v_2 at low p_T
- ϕ puzzle between peripheral and central at LHC



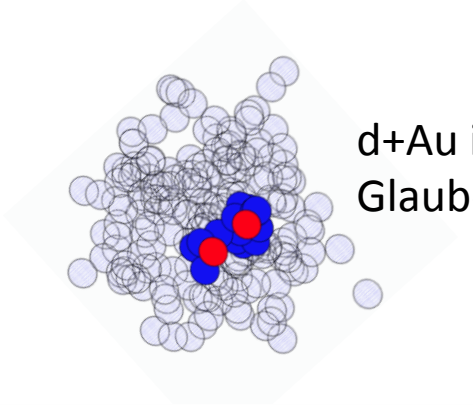


baryon

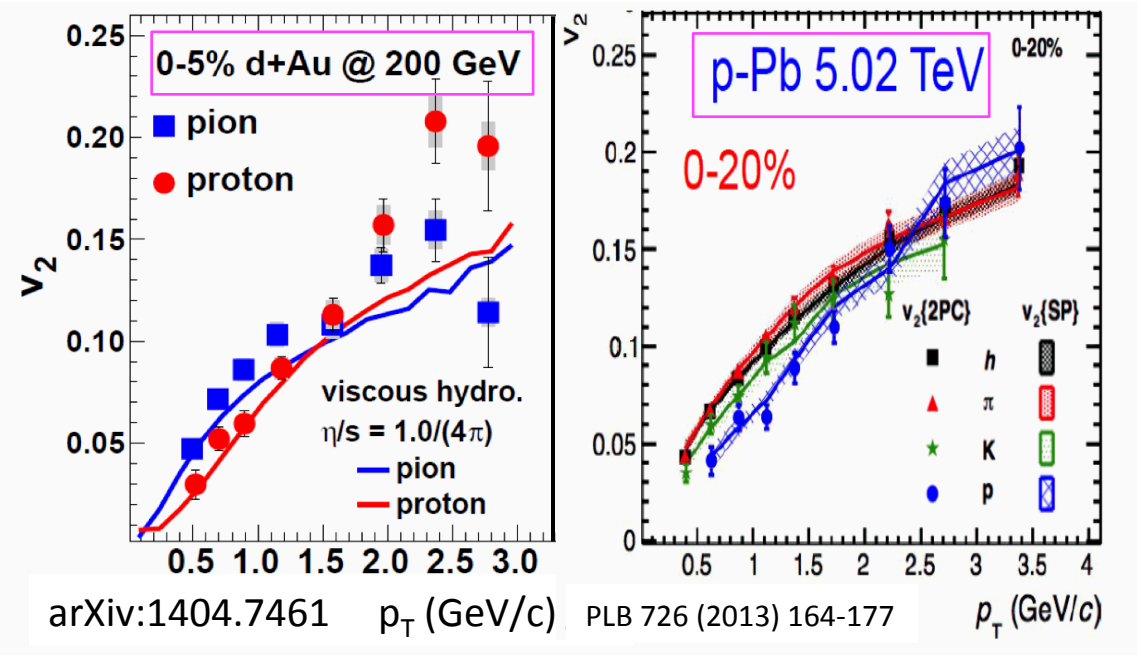
meson

Number of quark scaling as a signal of partonic phase

Elliptic flow in a small system?

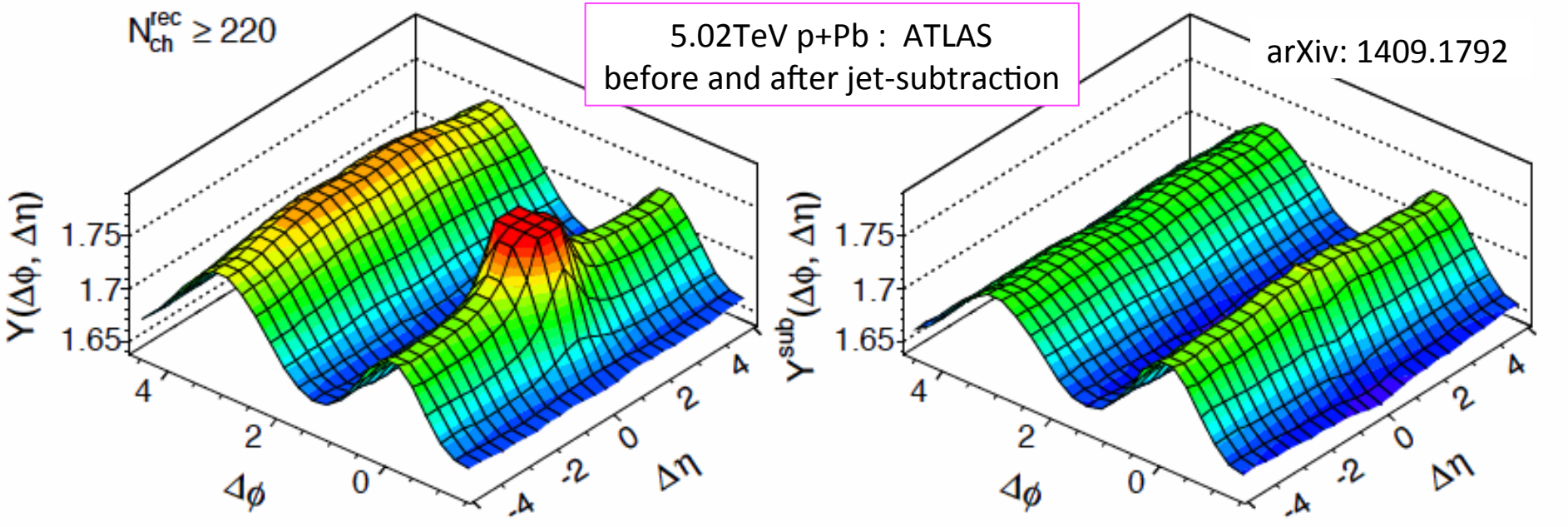


d+Au in Glauber model

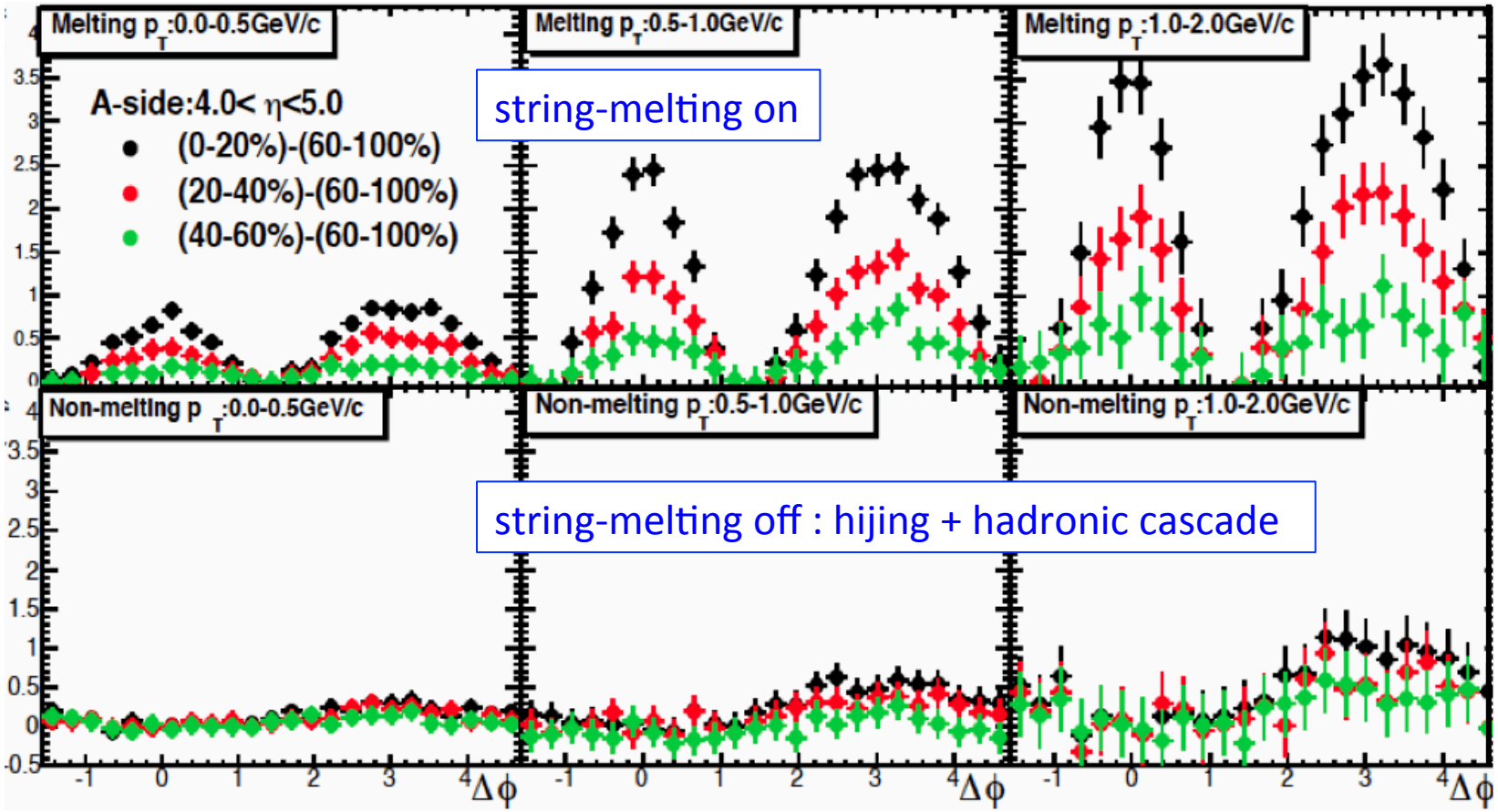


arXiv:1404.7461

PLB 726 (2013) 164-177



AMPT simulation p+Pb 5TeV (string-melting on/off) for ALICE backward-central $\Delta\phi$ correlation ($|\Delta\eta|$=3~6)



Associate yield / trigger

effectively partonic cascade : on/off

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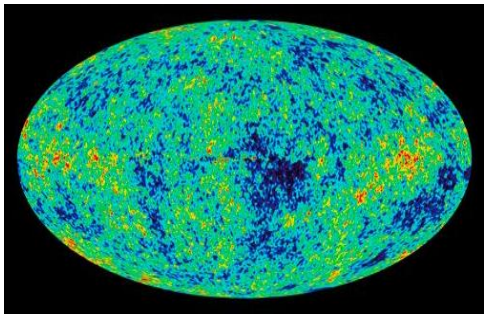
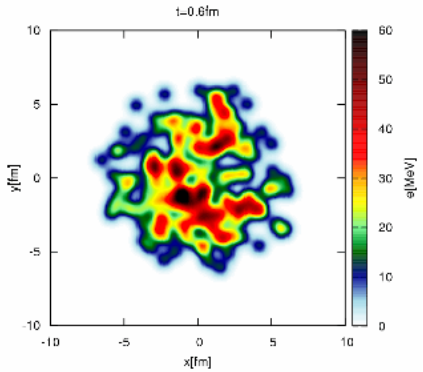
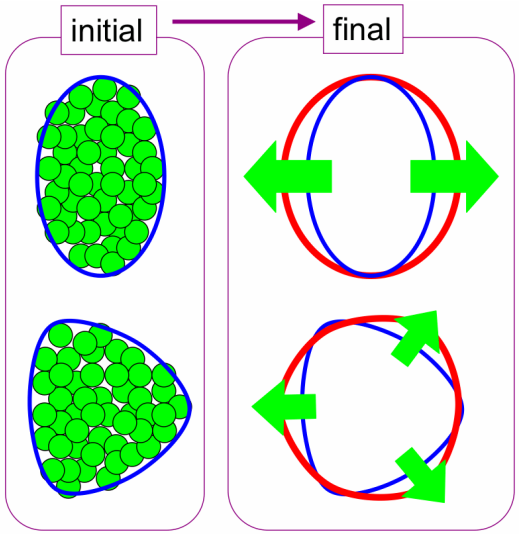
p_T/η cuts are chosen for ALICE TPC-V0A acceptance.

TPC : $|\eta|<1$
V0A: $3<\eta<5$ (Pb-going side)
V0C : $-4<\eta<-2$ (p-going side)

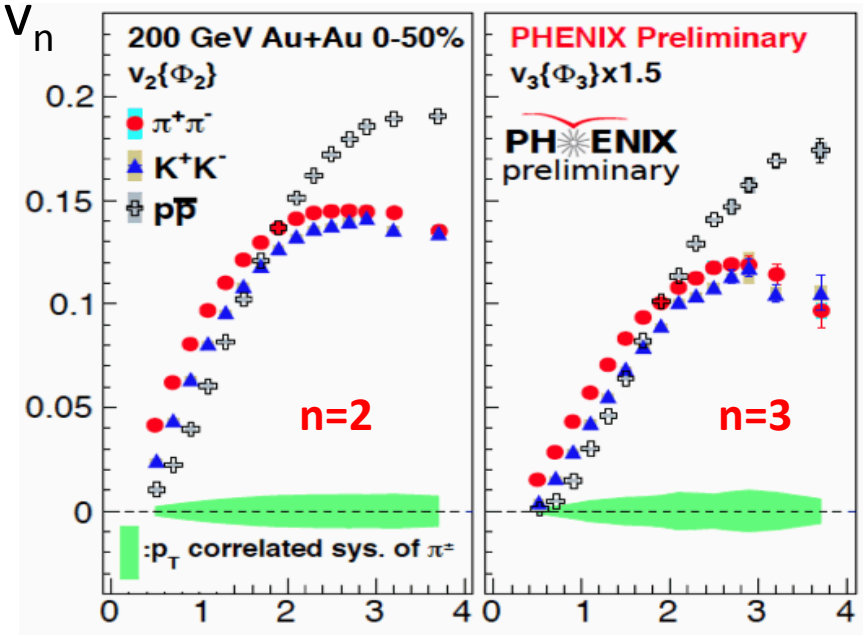
Triangular expansion and shape





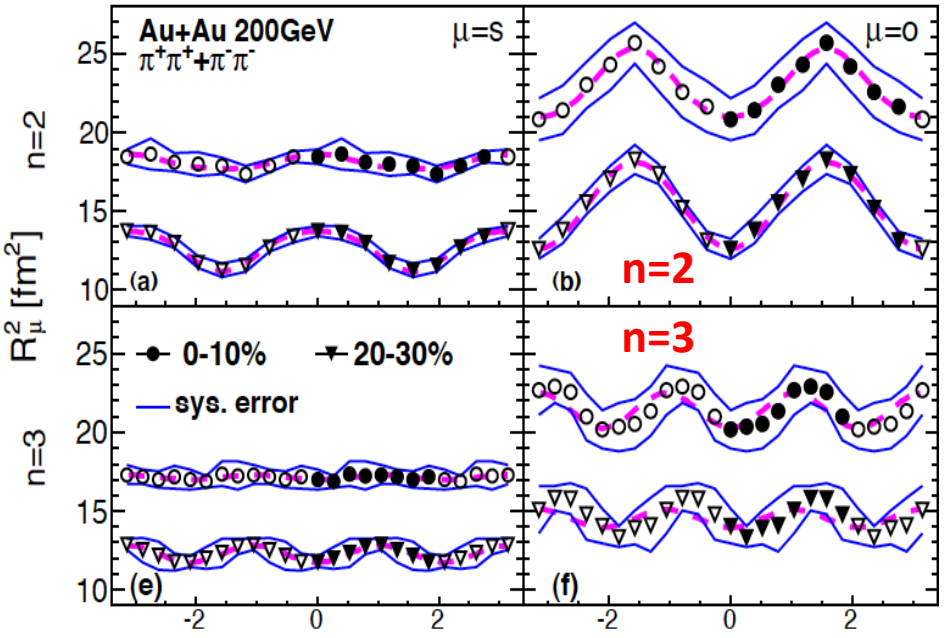


Elliptic and Triangular expansion : v_2, v_3



PHENIX, QM12

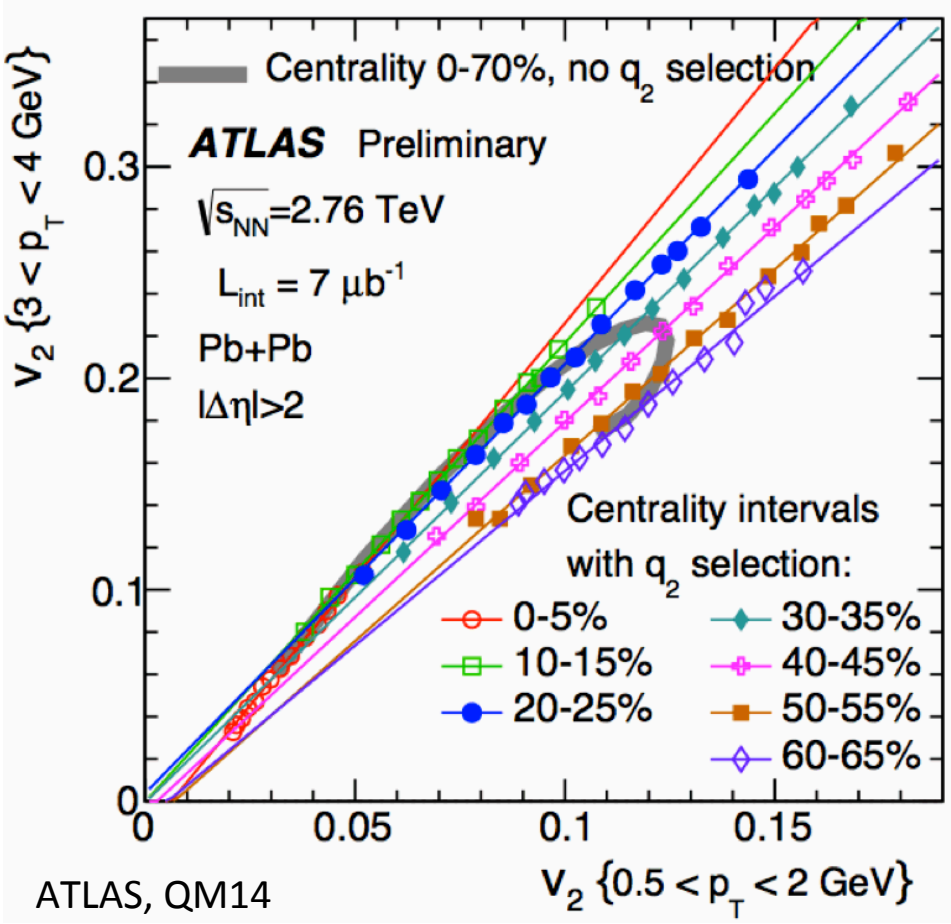
Elliptic and Triangular shape : $R^{HBT}_{\Phi 2}$, $R^{HBT}_{\Phi 3}$



PRL112 (2014) 222301

Cross harmonics correlation with Q_2 selection

$v_2^{(\text{Low pT})}$ vs $v_2^{(\text{high pT})}$



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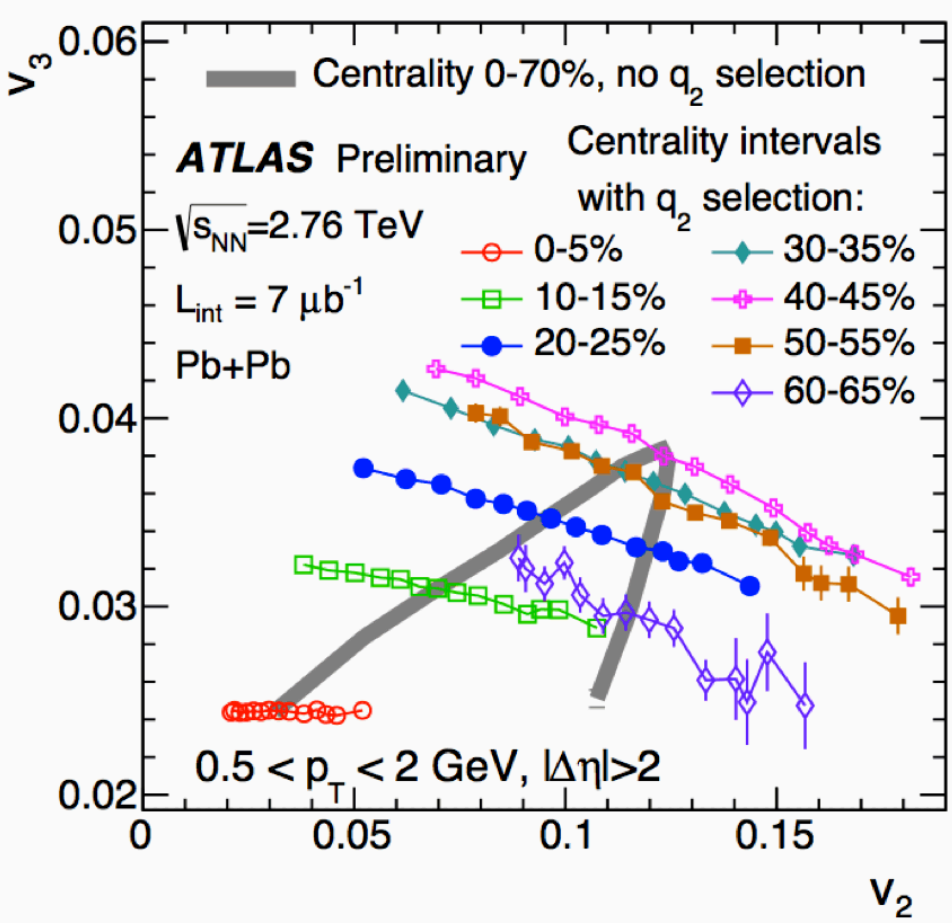
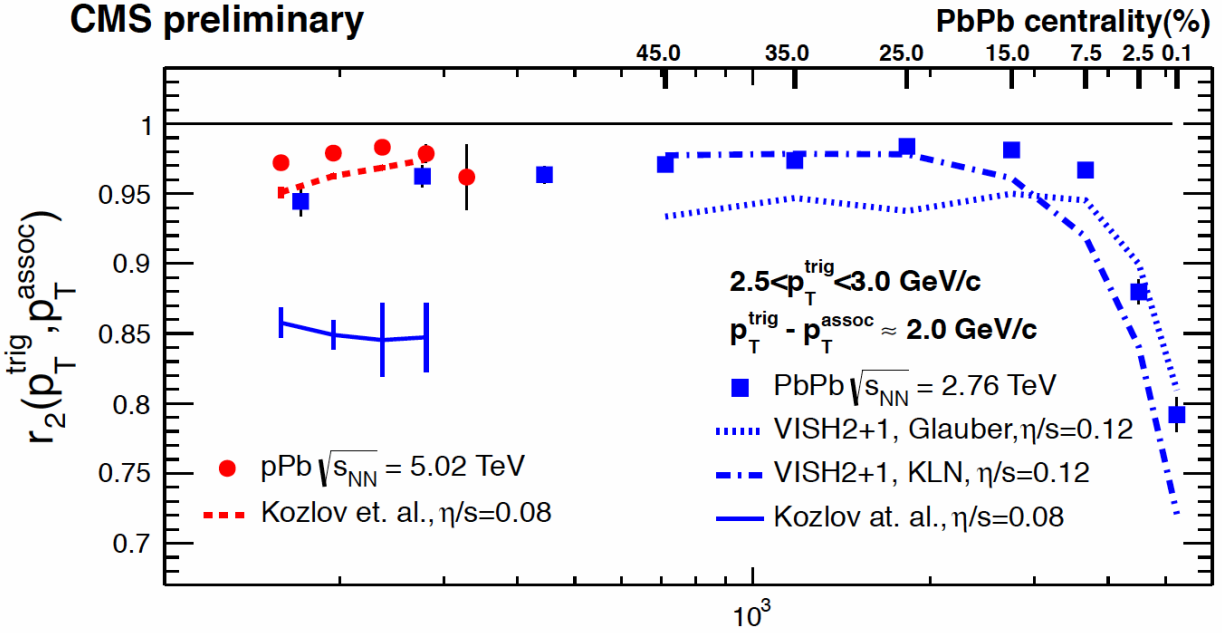
v_2 vs v_3



p_T dependent flow fluctuation

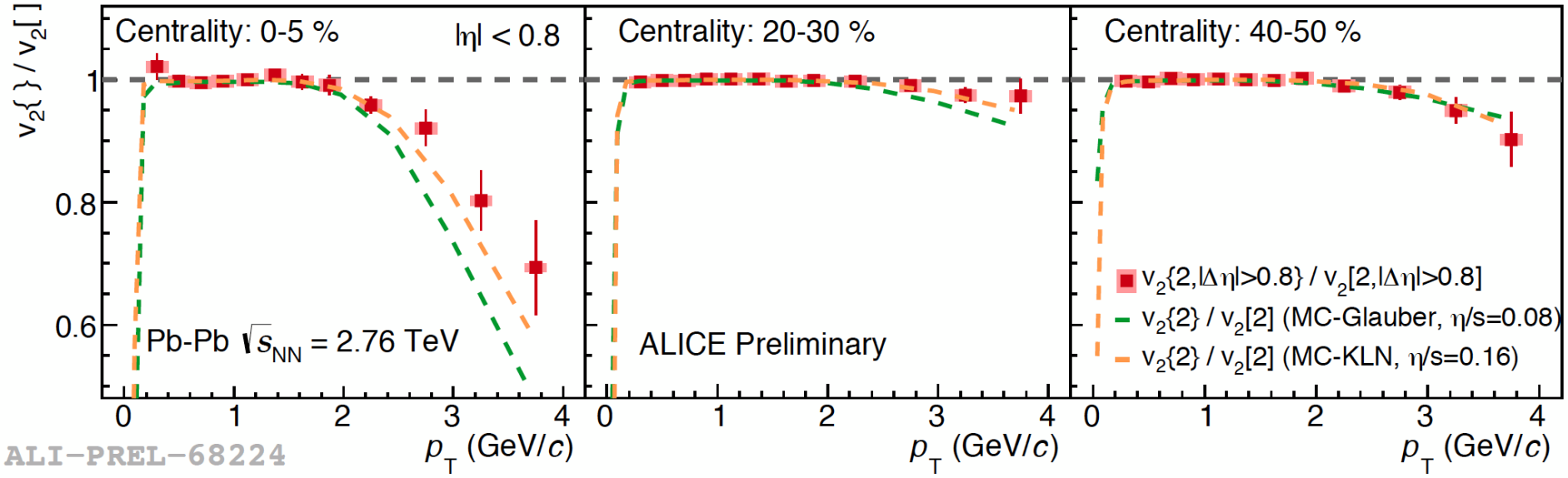
- measure of factorization
- amazing similarity in hydro-models especially in central and at mid-p_T
- despite of hydro-failure to explain v_n in central…



CMS PAS HIN-14-012 CMS, QM14 *Kozlov et.al.:arXiv:1405.3976*

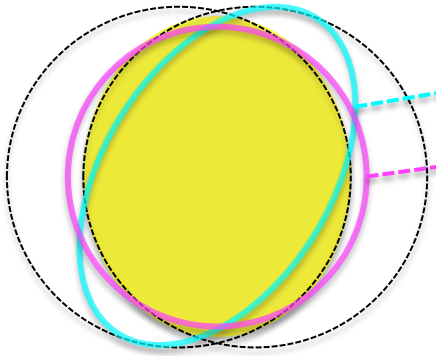
VISH2+1:PRC 87, 034913 (2013)

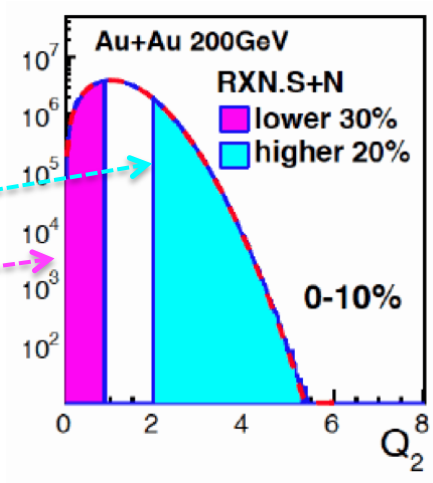
ALICE, QM14



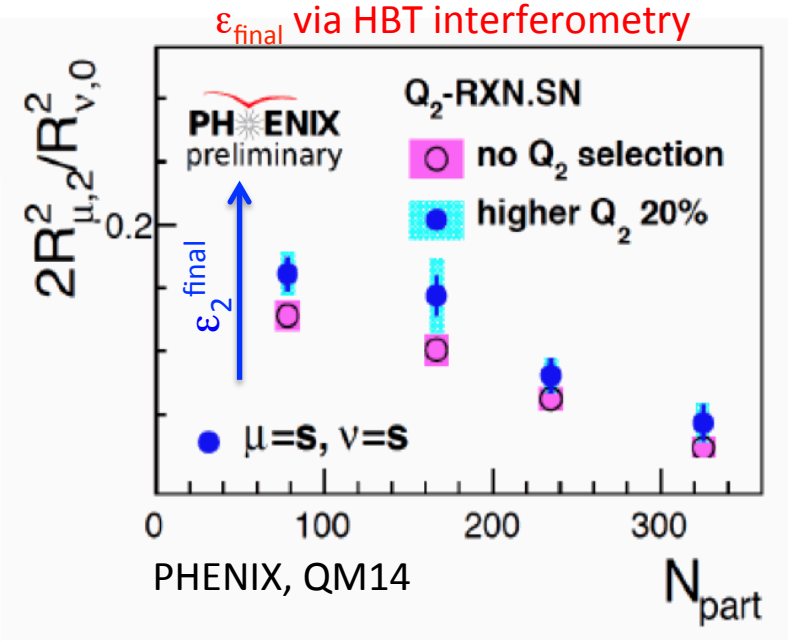
Event shape selection by Q_2 (~v_2)

relation of $\varepsilon_2^{initial} - v_2 - \varepsilon_2^{final}$ for a given centrality

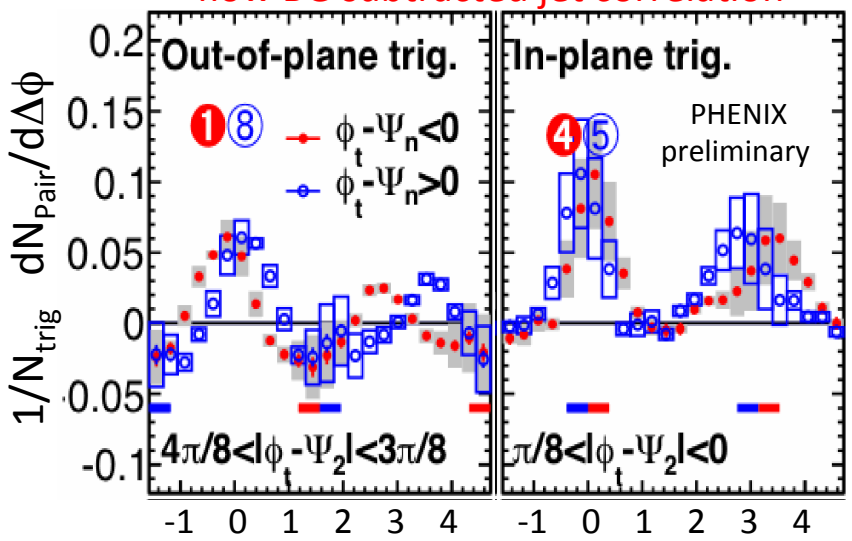


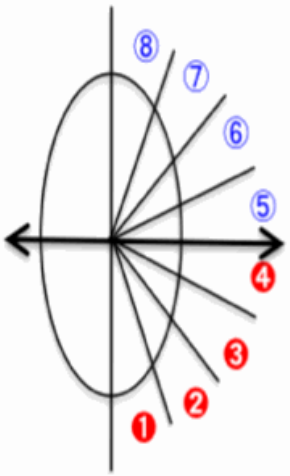


ε_{final} via HBT interferometry



flow BG subtracted jet correlation

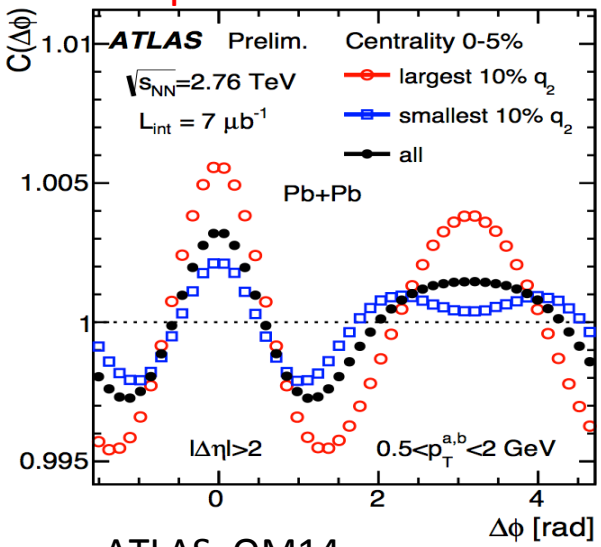




PHENIX, QM12

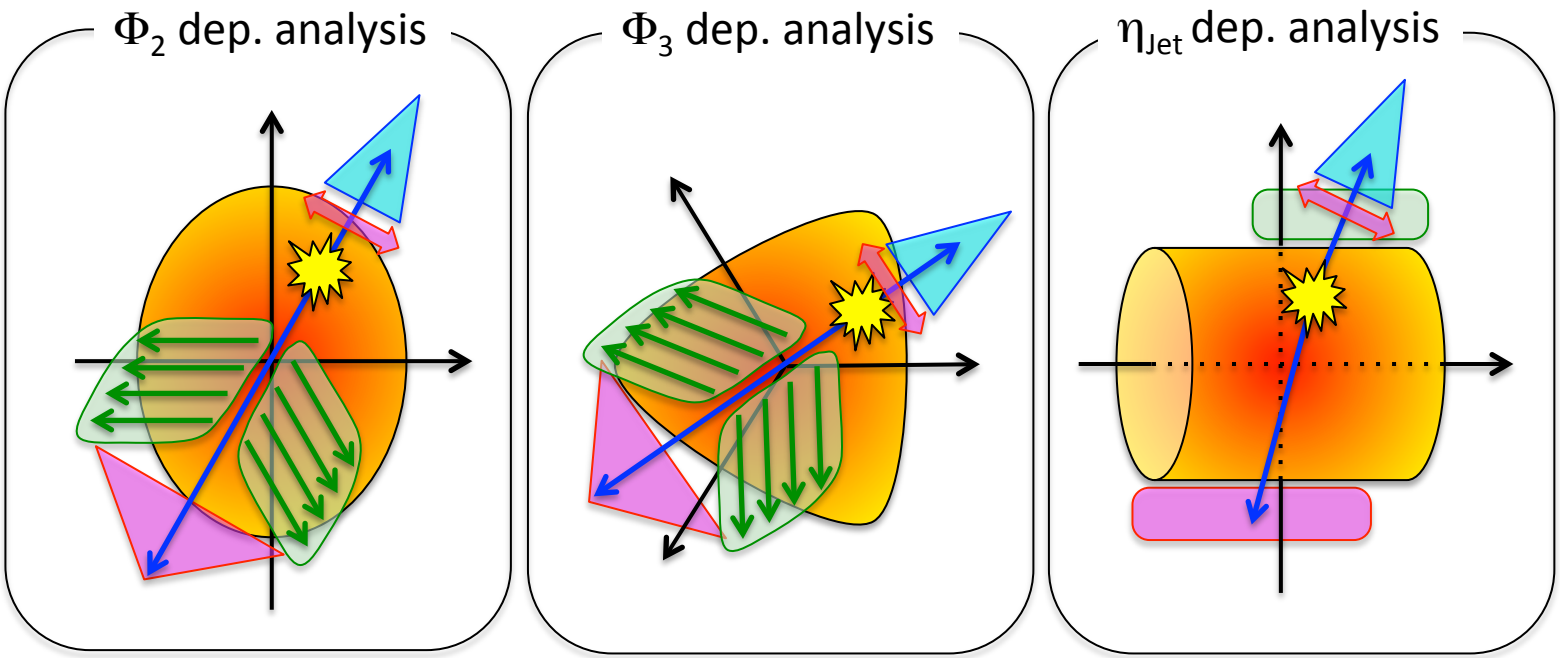
$\Delta\phi = \phi_{Asso.} - \phi_{Trig.}$

2-particle correlation



ATLAS, QM14

More differential studies of hard-soft interplay, jet-medium interaction, jet-flow correlation

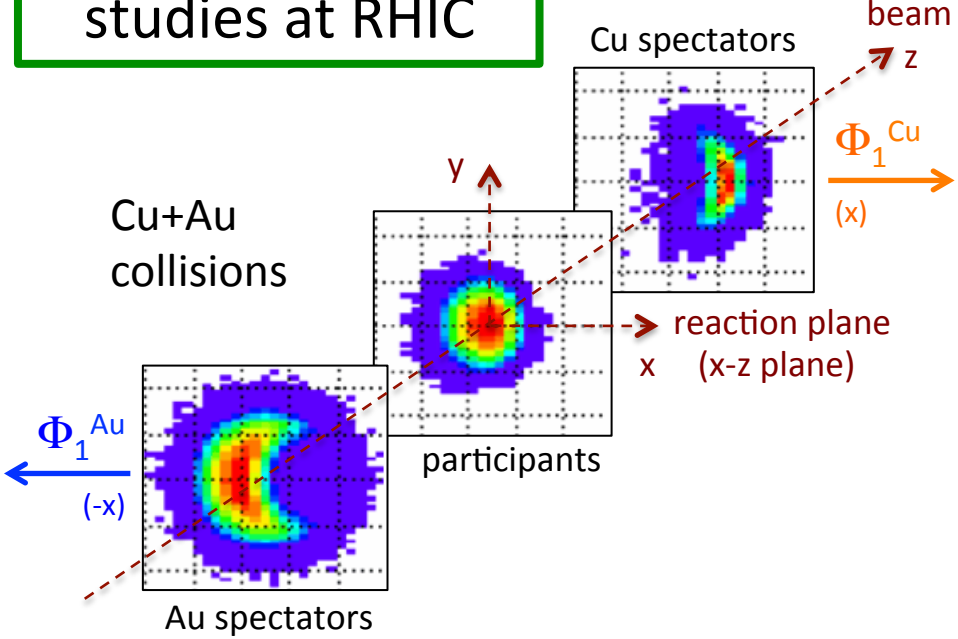


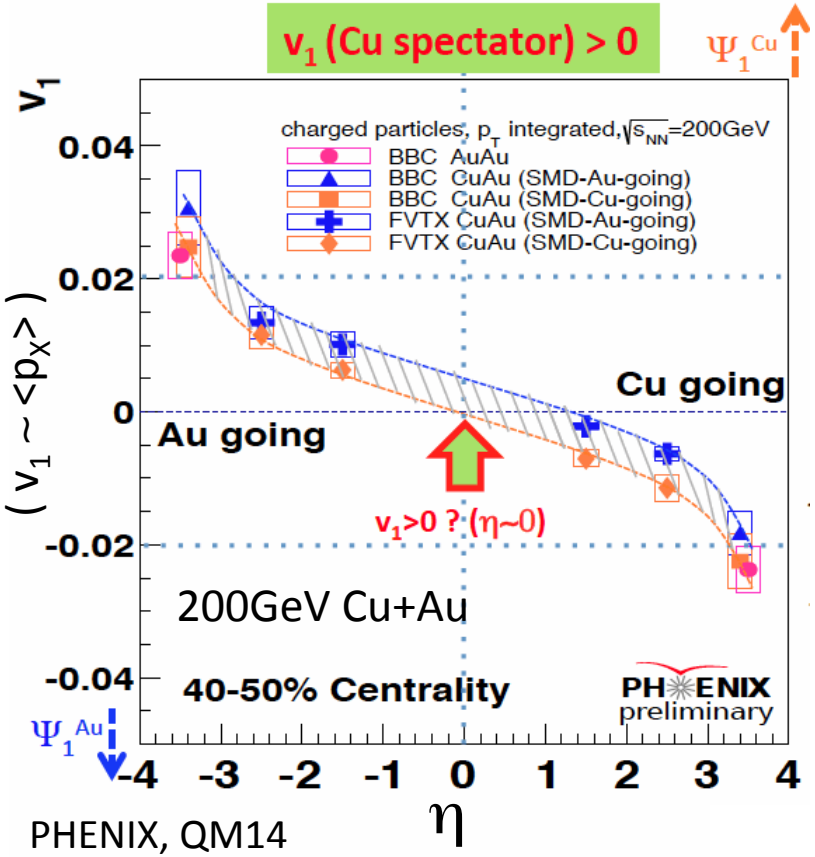
methods

- Multi-particle correlation
- Jet-hadron / γ-hadron correlation
- Jet fragmentation function
- Di-jet distribution

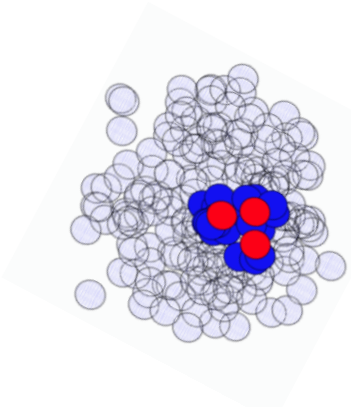
Yet another axis as a control parameter to define path length, geometry and expansion. Please join me, if you agree…

Various flow studies at RHIC



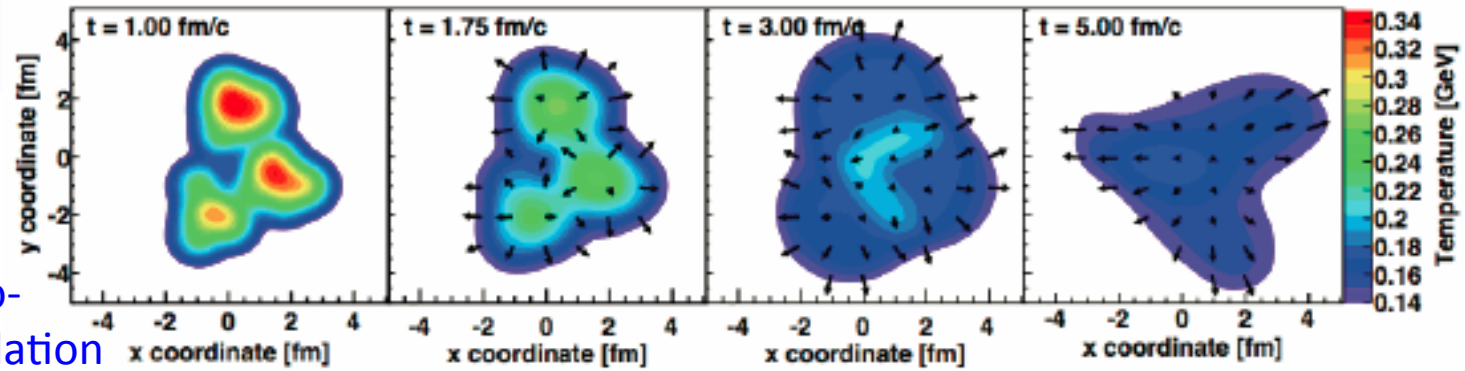


PHENIX, QM14



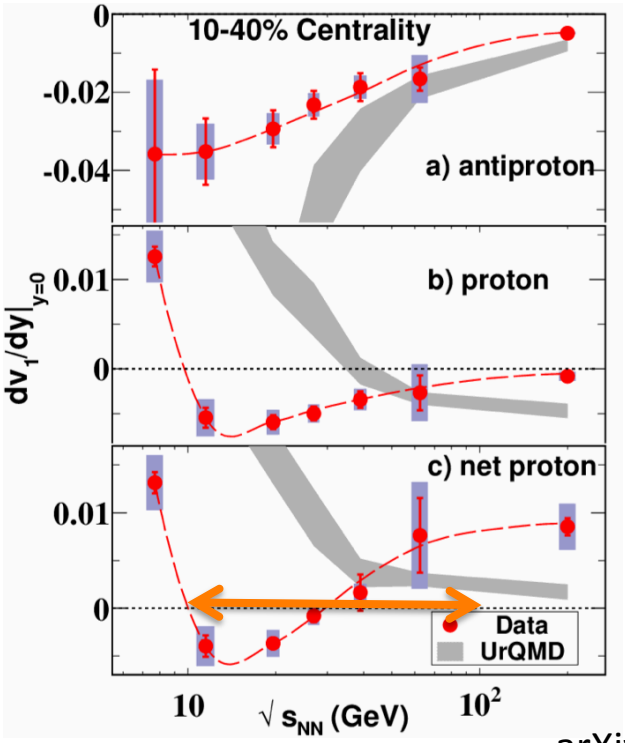
^{3}He+Au collision data
on tape in RHIC-RUN14

arXiv: 1312.4565



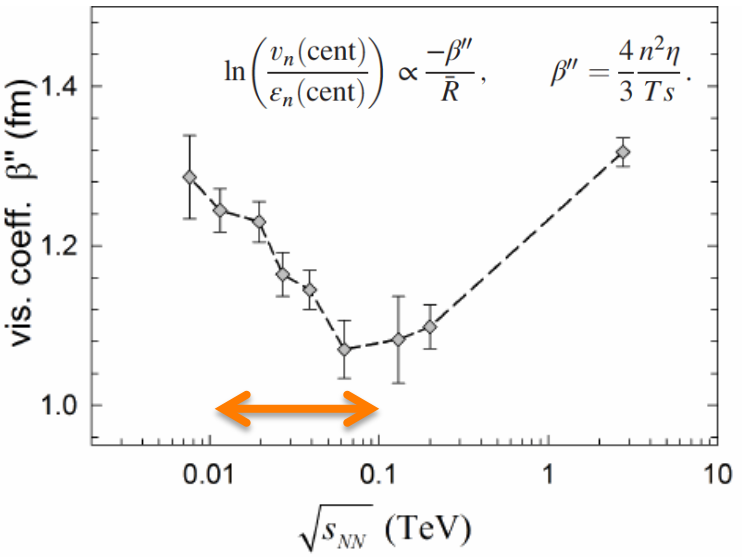
hydro-calculation

PRL112 (2014) 162301

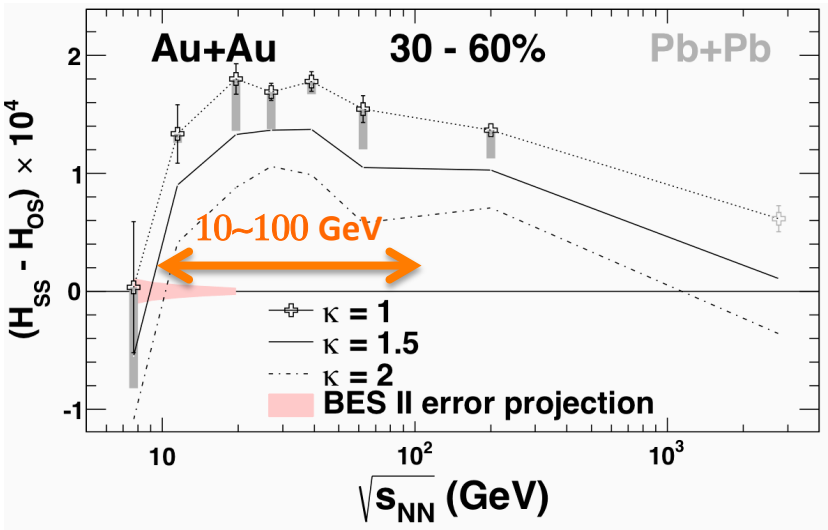


Beam energy dependence of v_1, v_2, HBT and charge asymmetry

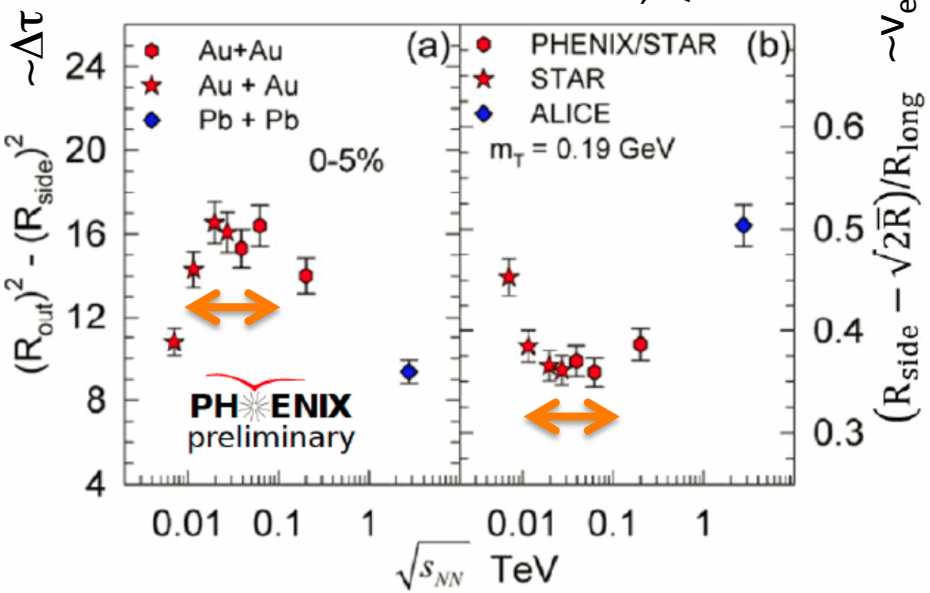
PRL 112 (2014) 082302



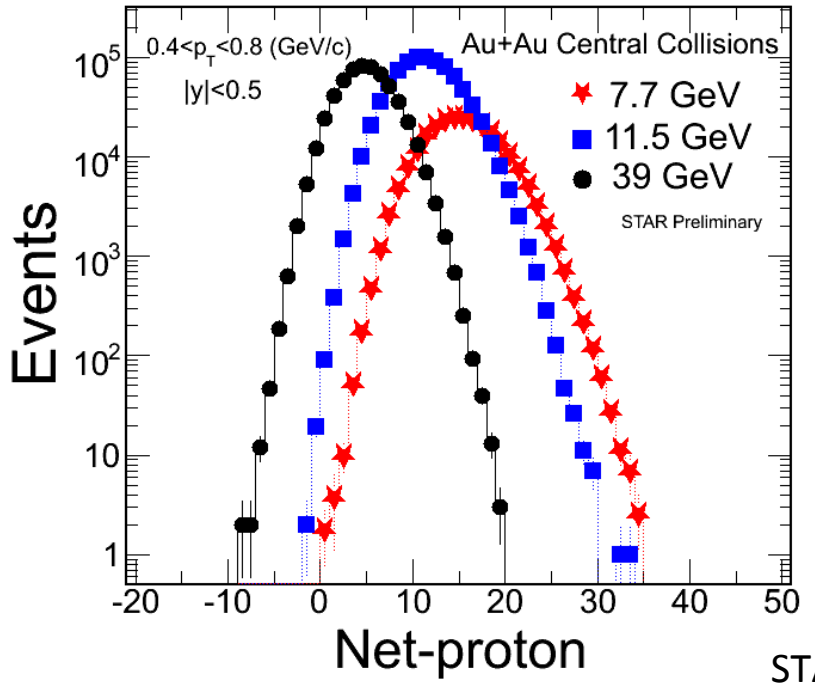
arXiv:1404.1433

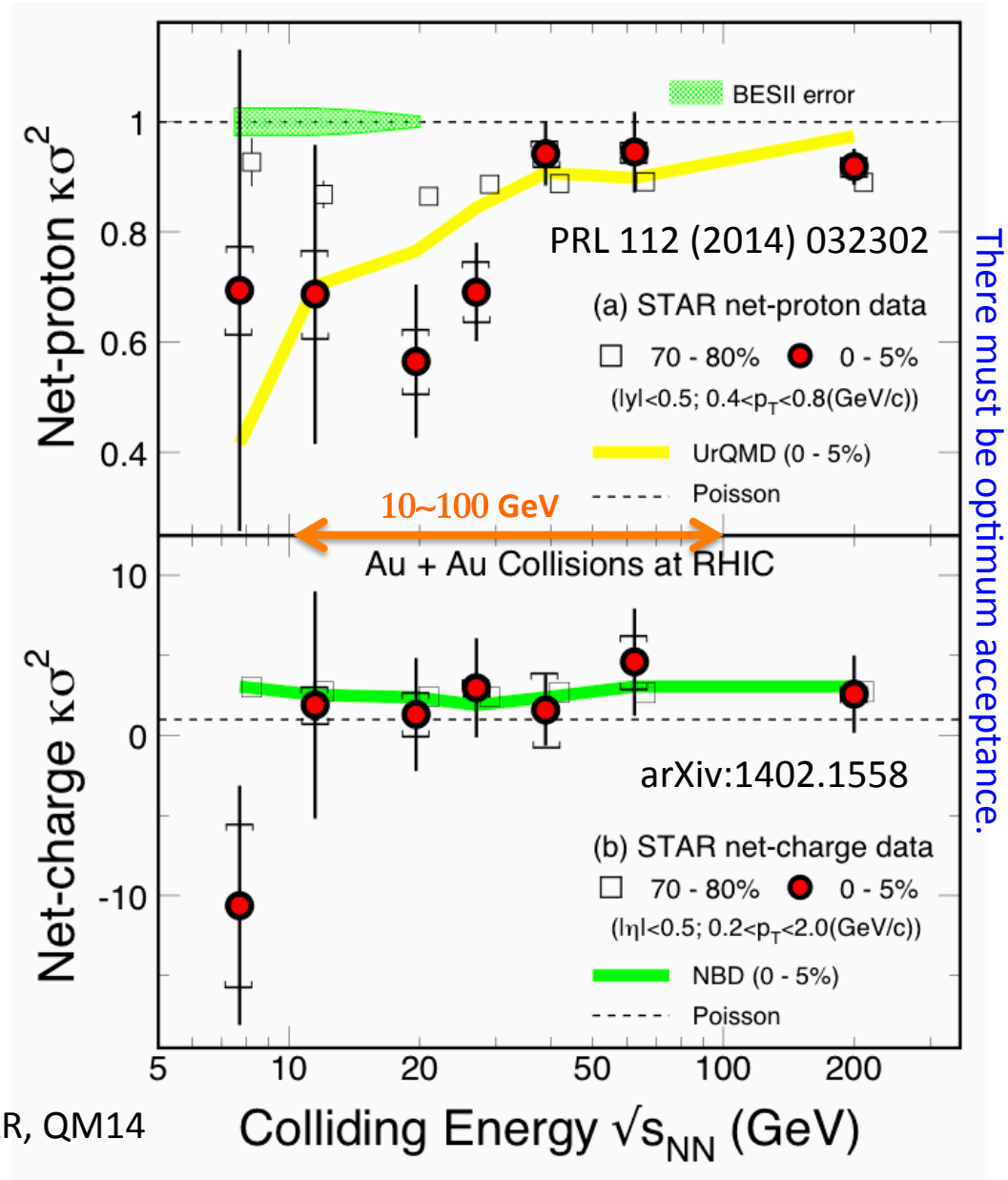


PHENIX, QM14



Fluctuation of conserved quantities such as net-baryon, net-charge distribution



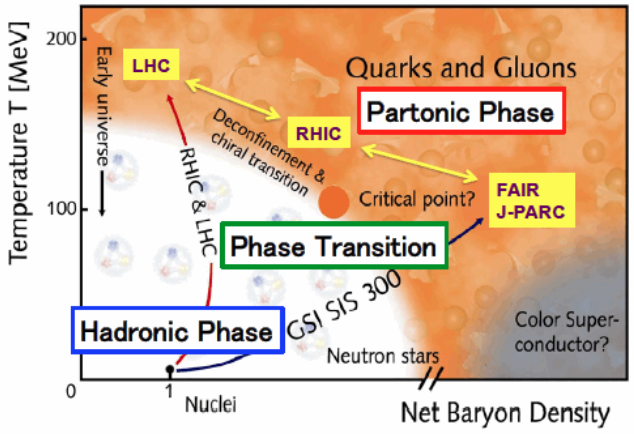


STAR, QM14

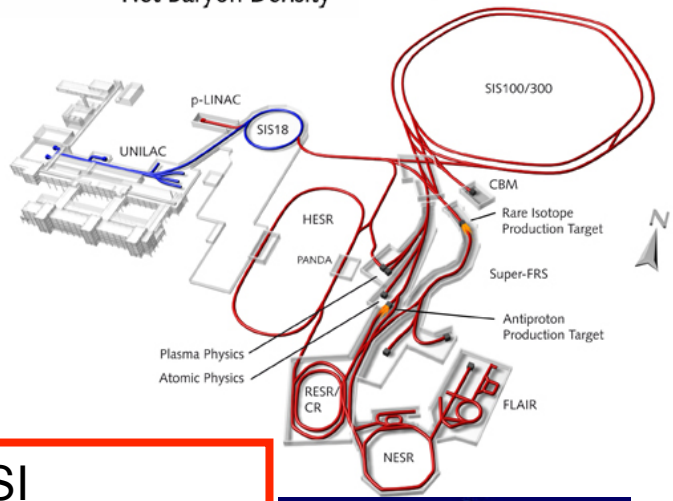
There must be optimum acceptance.

Future plan

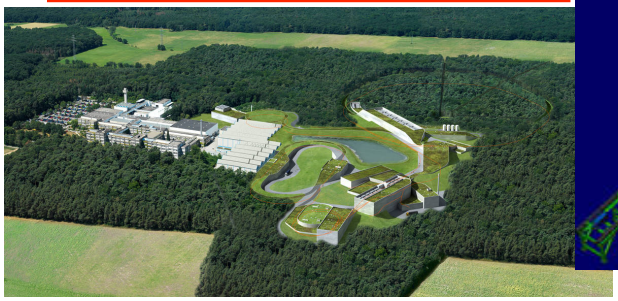
Full energy Pb+Pb collisions at LHC
Luminosity upgrade at LHC
Beam energy scan II at RHIC
A state-of-art jet detector at RHIC
Future facilities

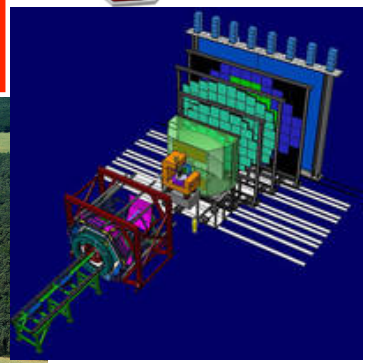


J-PARC at JAEA/KEK
for heavy-ion collisions
(Tokai, Japan)



FAIR at GSI
(Darmstadt, Germany)





Summary

- Initial temperature and collective flow via thermal photons
- Partonic energy-loss using jets and prompt photons
- Collective flow even in small system
- Event shape selection as another control parameter
- Beam energy scan to search for a critical point
- Future facilities