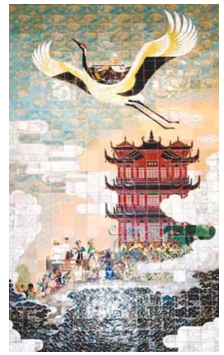
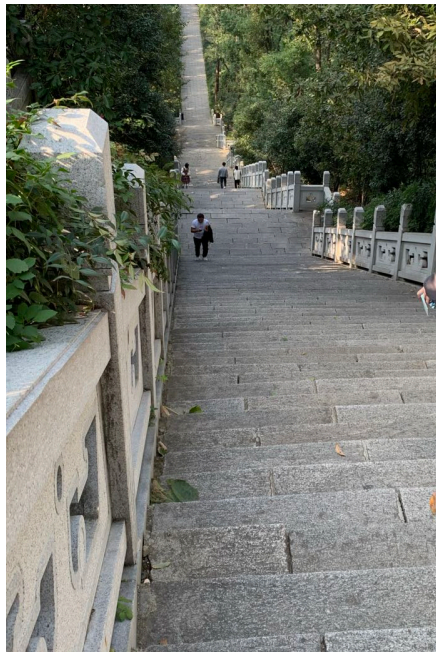
The 1st International Workshop on Physics at High Baryon Density (PHD2024)
College of Physical Science and Technology, Central China Normal University, Wuhan, 1-4/Nov/2024

Overview of Flow Measurements at RHIC-BES

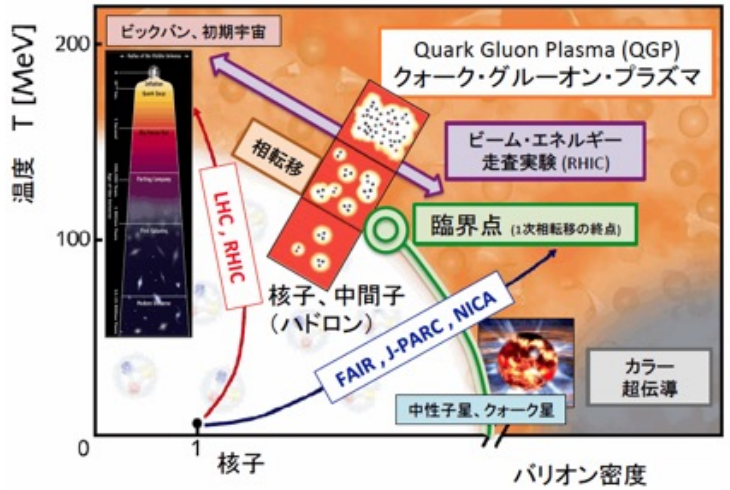


ShinIchi Esumi, University of Tsukuba
Institute of Physics, Faculty of Pure and Applied Sciences
Tomonaga Center for the History of the Universe (TCHoU)



Contents

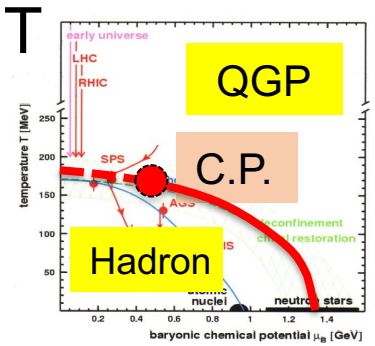
- Thermal freeze-out and radial flow
- Source size/shape via femto-scopy
- Directed, elliptic and vortical flow
- Small system and higher order flow



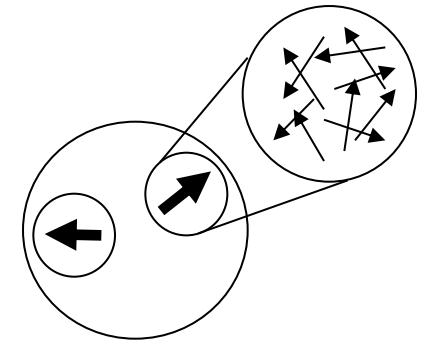
The STAR experiment
at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

筑波大学 University of Tsukuba

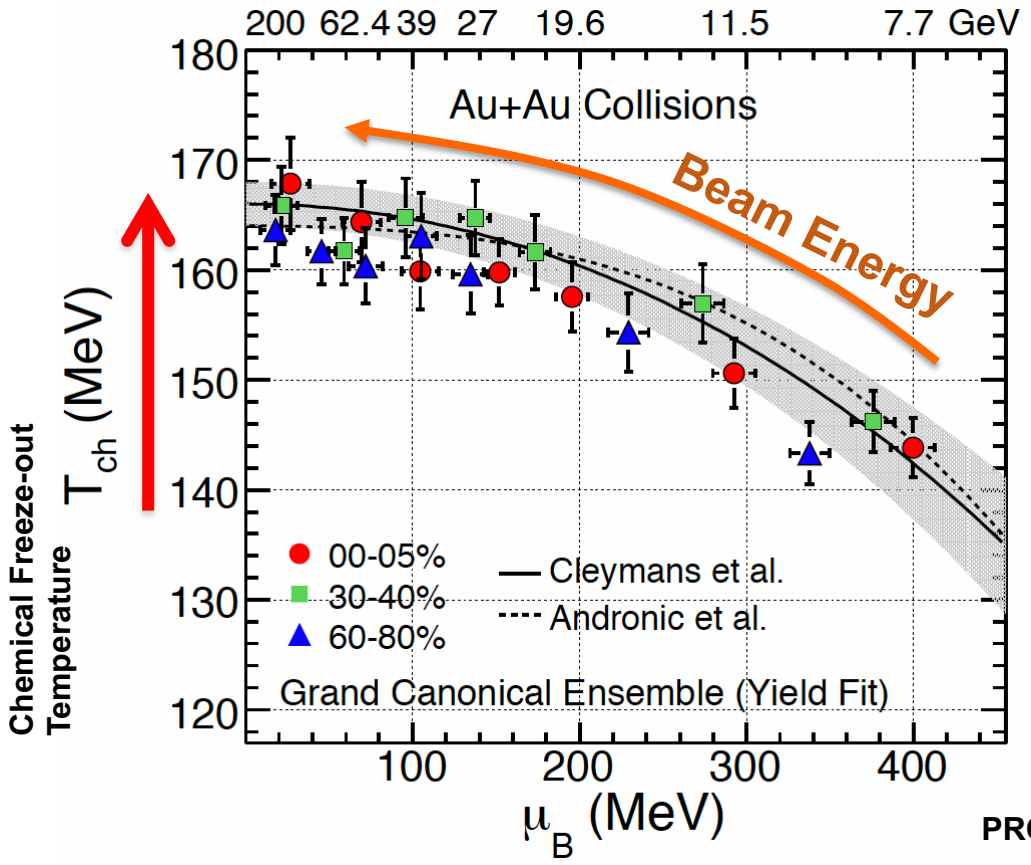
筑波大学 宇宙史研究センター Tomonaga Center for the History of the Universe



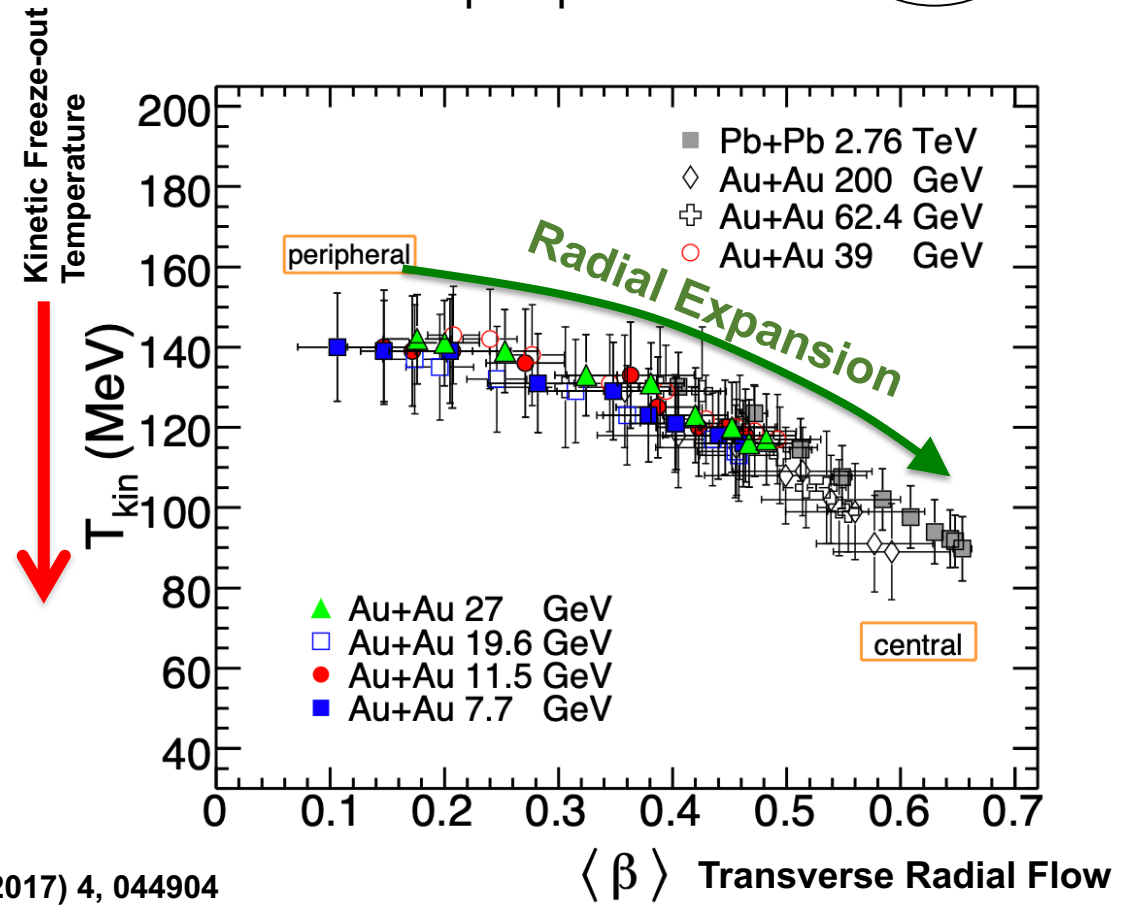
Chemical and Kinetic Thermal Freeze-out



μ_B via hadron yields, ratios

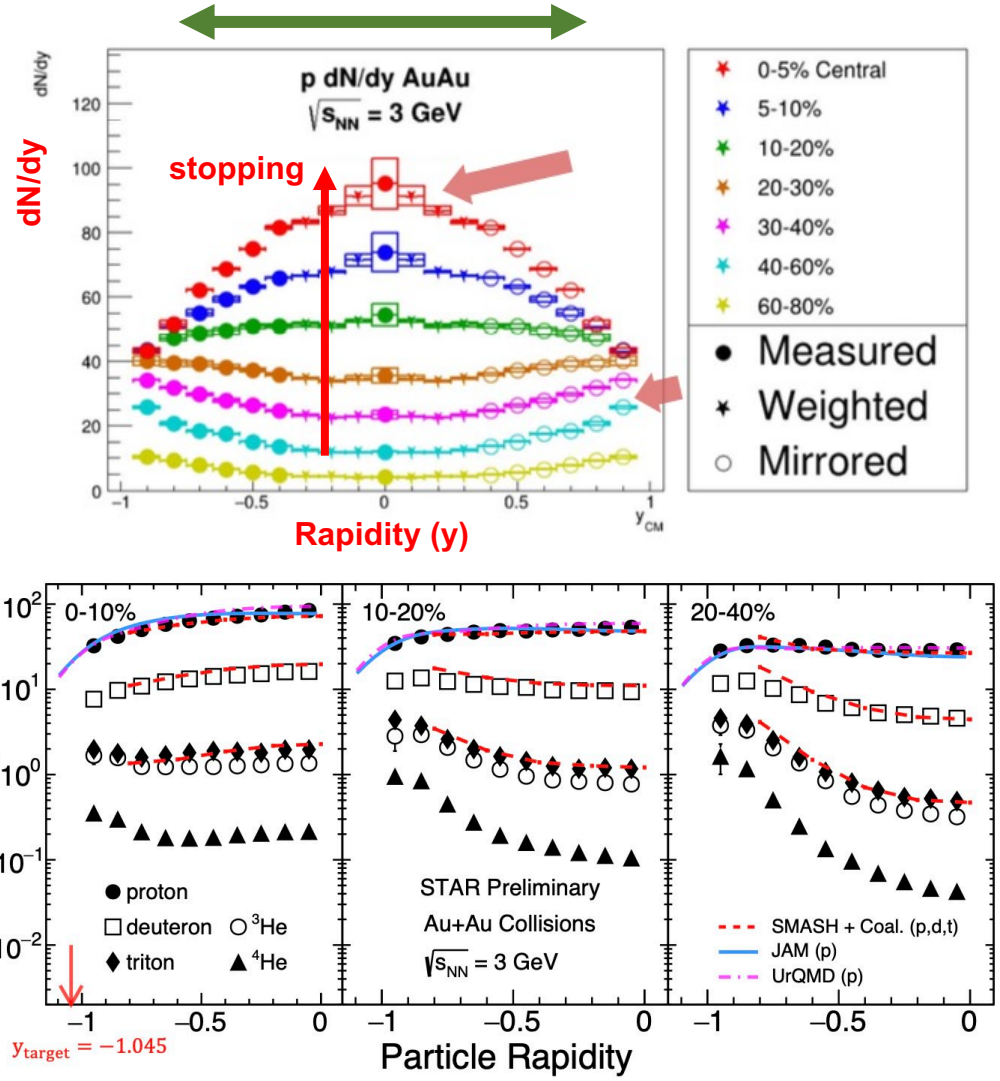


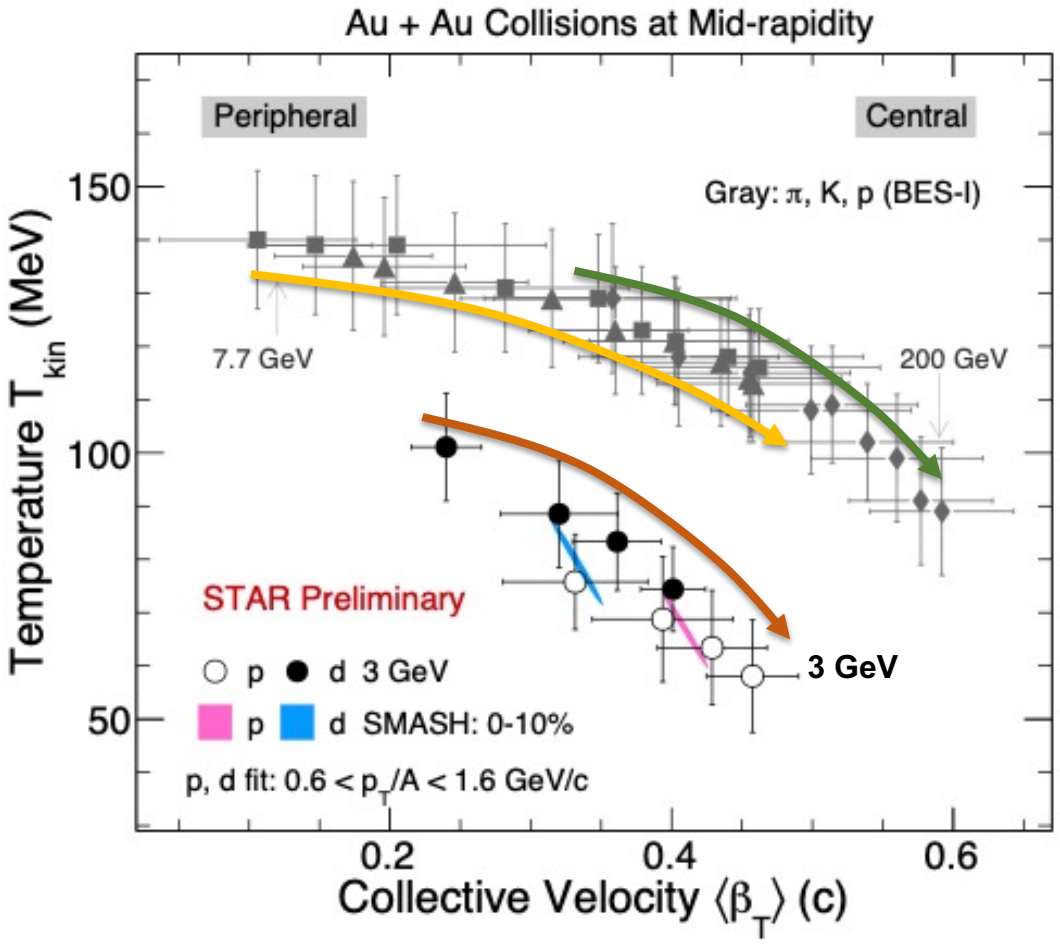
via hadron pT spectra



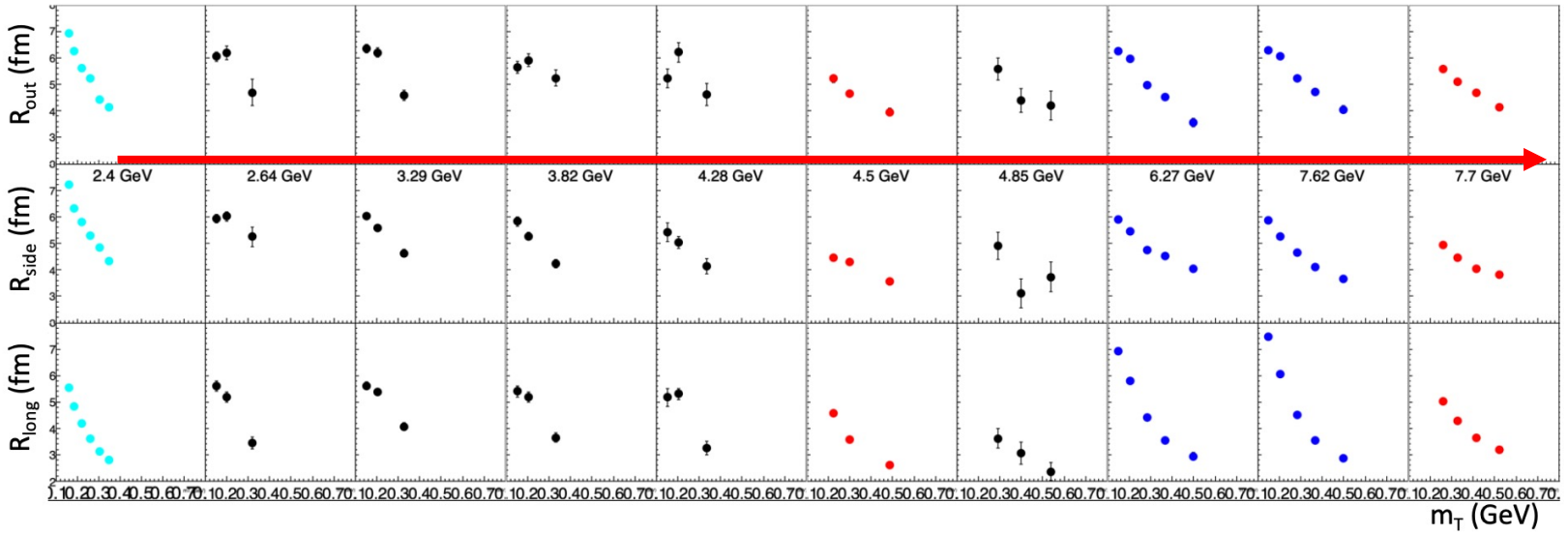
PRC 96 (2017) 4, 044904

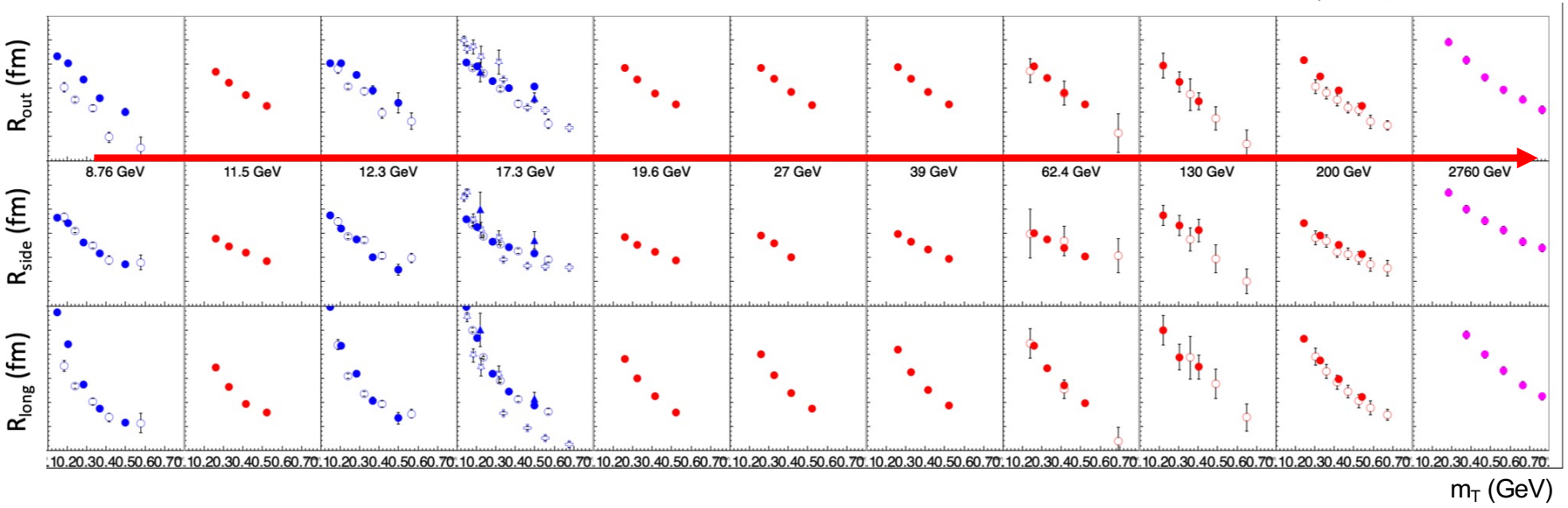
Longitudinal and Transverse Expansion



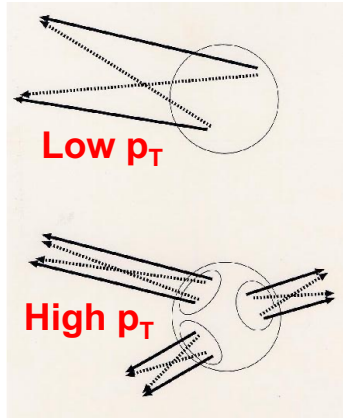


HBT: Femto-scopic correlation (quantum interferometry, coulomb and final state interactions)





- SIS: HADES
- AGS: E895, E866
- SPS: WA98, NA44, NA49, CERES, WA97, WA98, NA61
- RHIC: STAR, PHENIX, PHOBOS
- LHC: ALICE

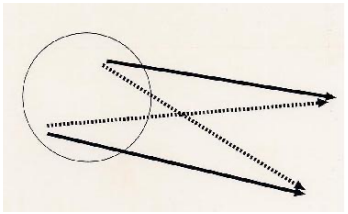


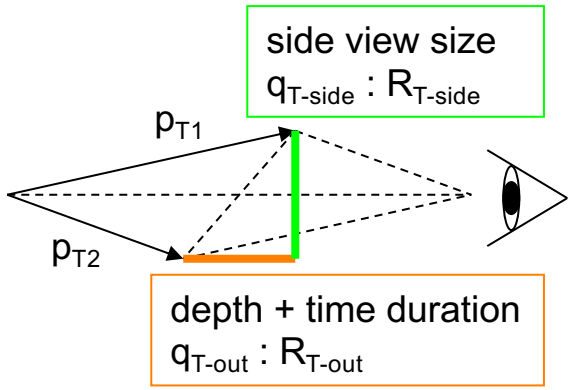
Source radius : length of homogeneity

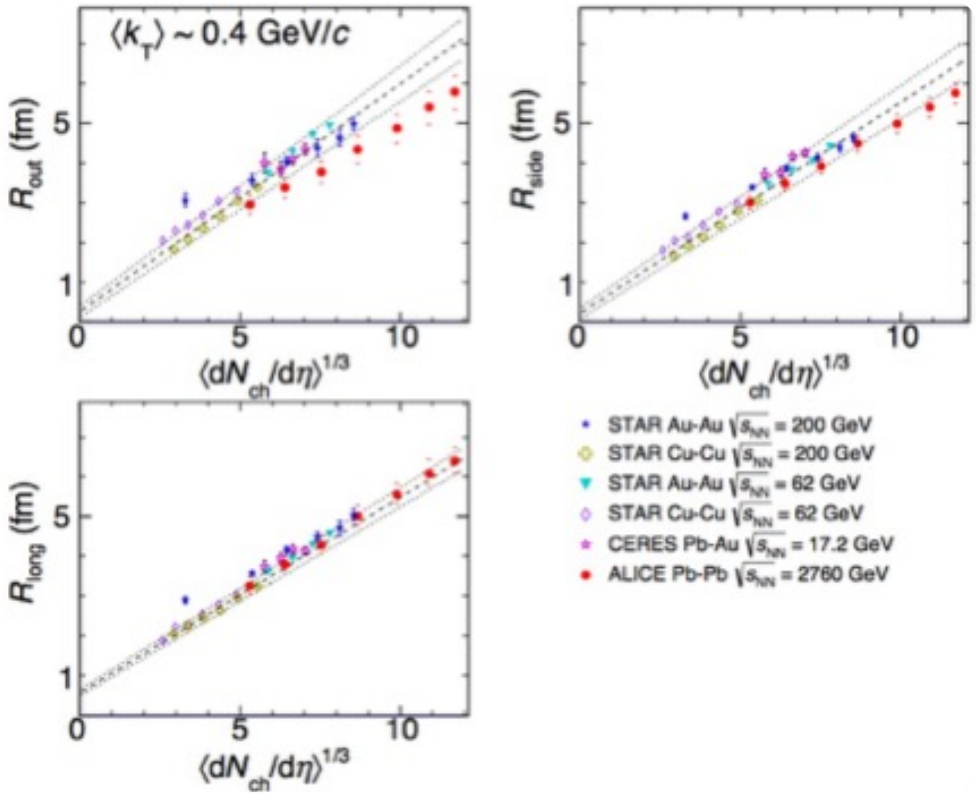
Radial flow : $1/m_T$ dependence of R

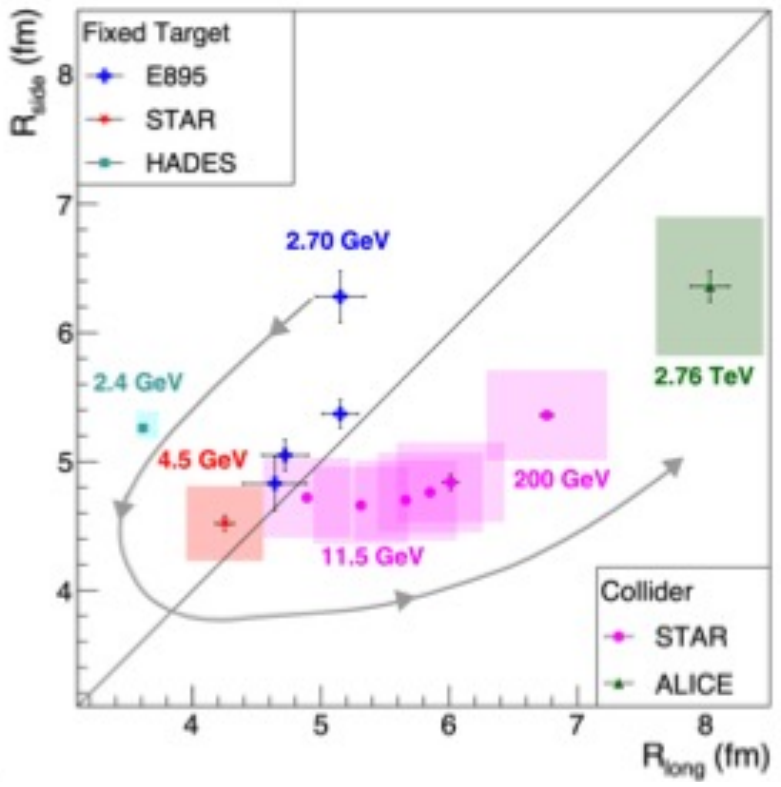
HBT 3D-radii

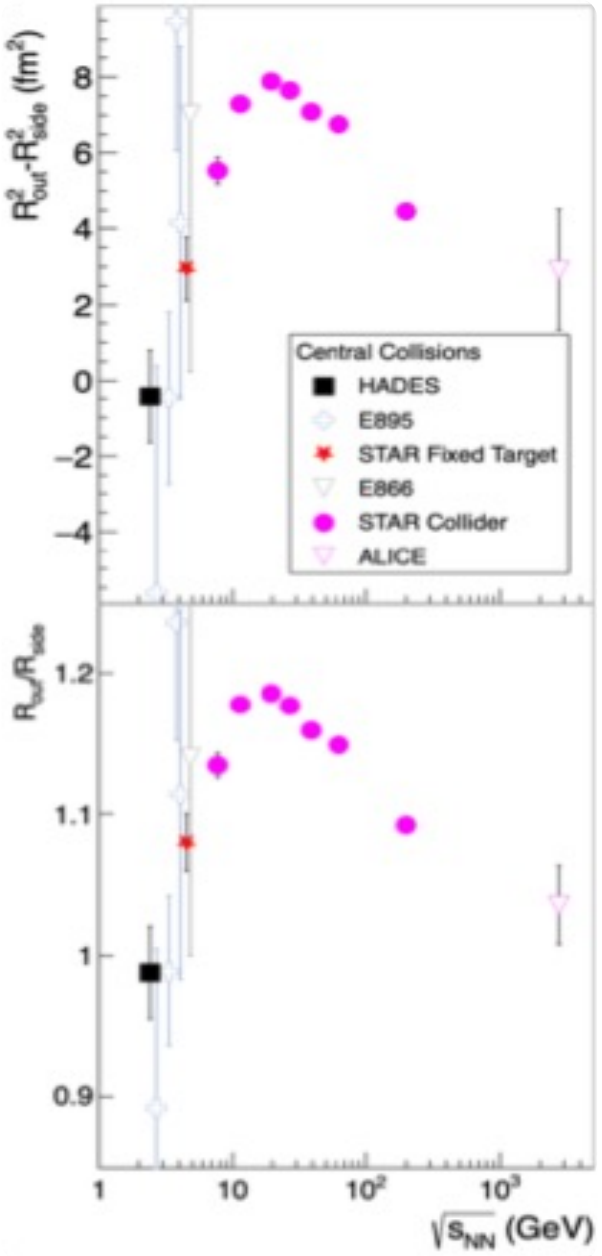
- **Longitudinal (beam) R_{long}**
- **Two Transverse R_{side} , R_{out}**





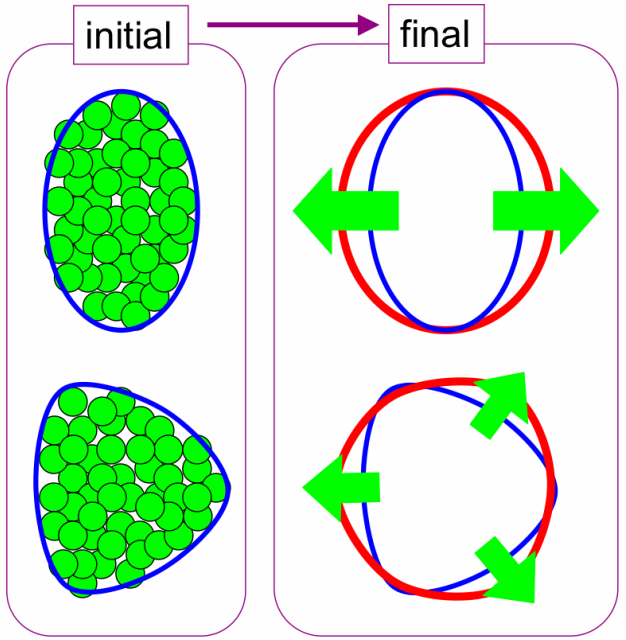




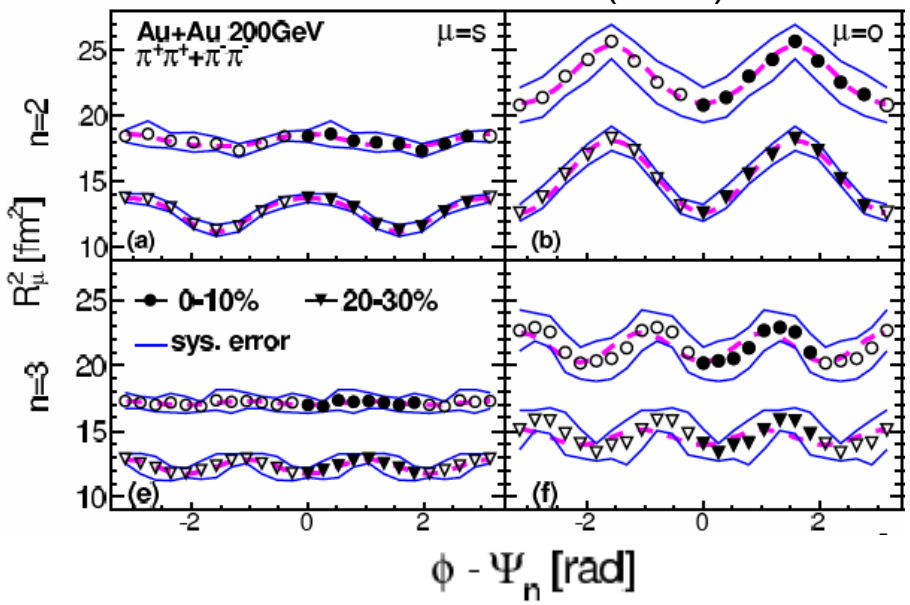


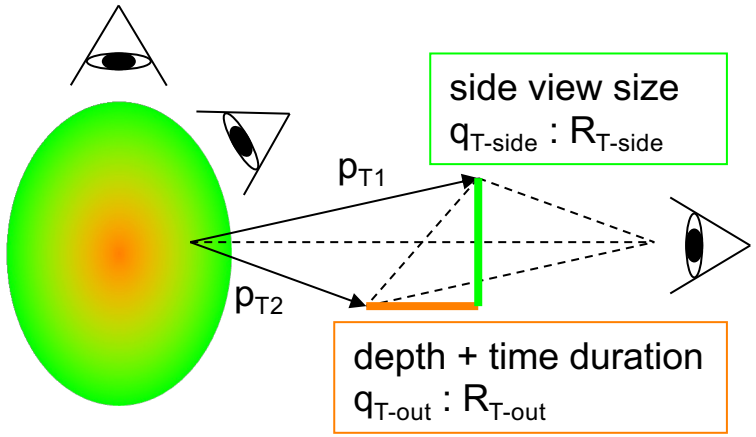
HBT Azimuthal 3D radii w.r.t. Φ_n

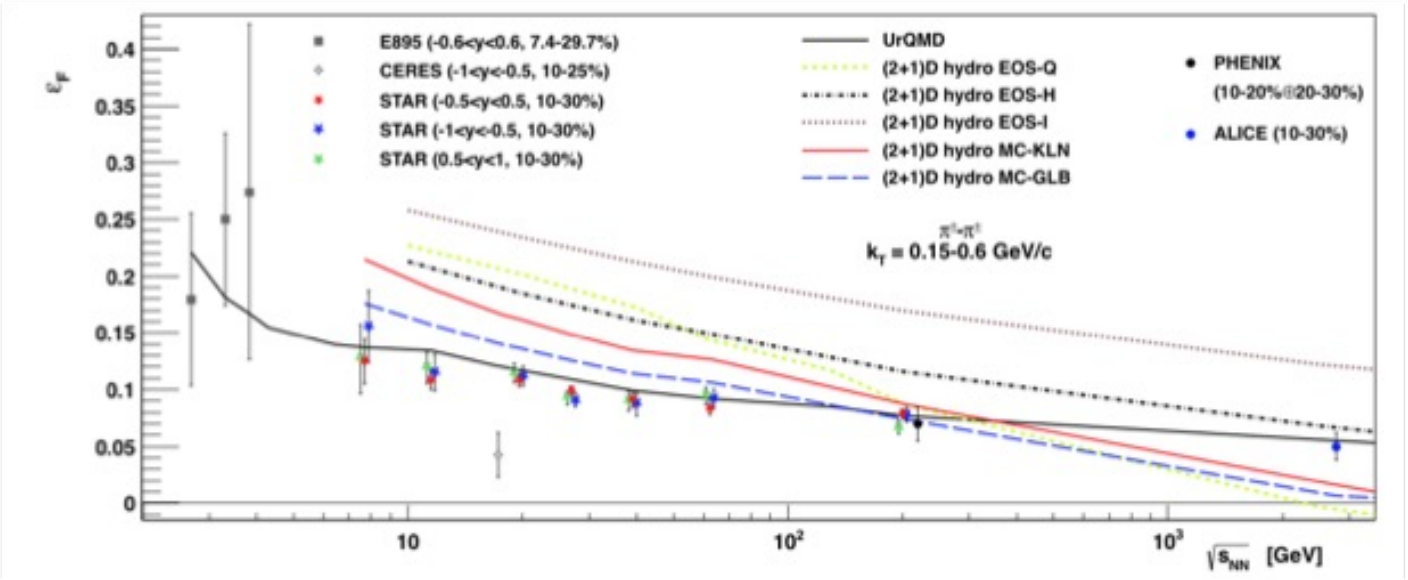
- **Final Eccentricity**
- **Final Triangularity**
- **Freeze-out Shape**



PRL 112 (2014) 222301

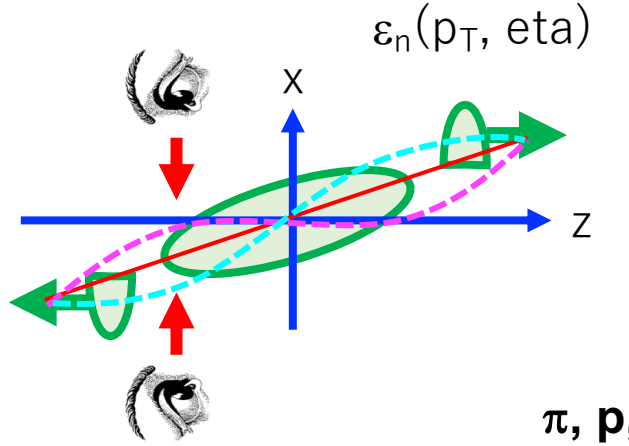


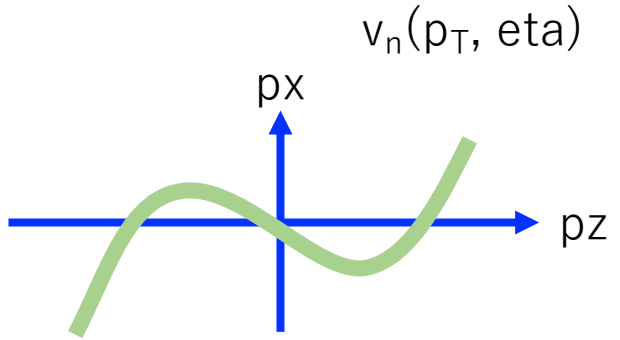




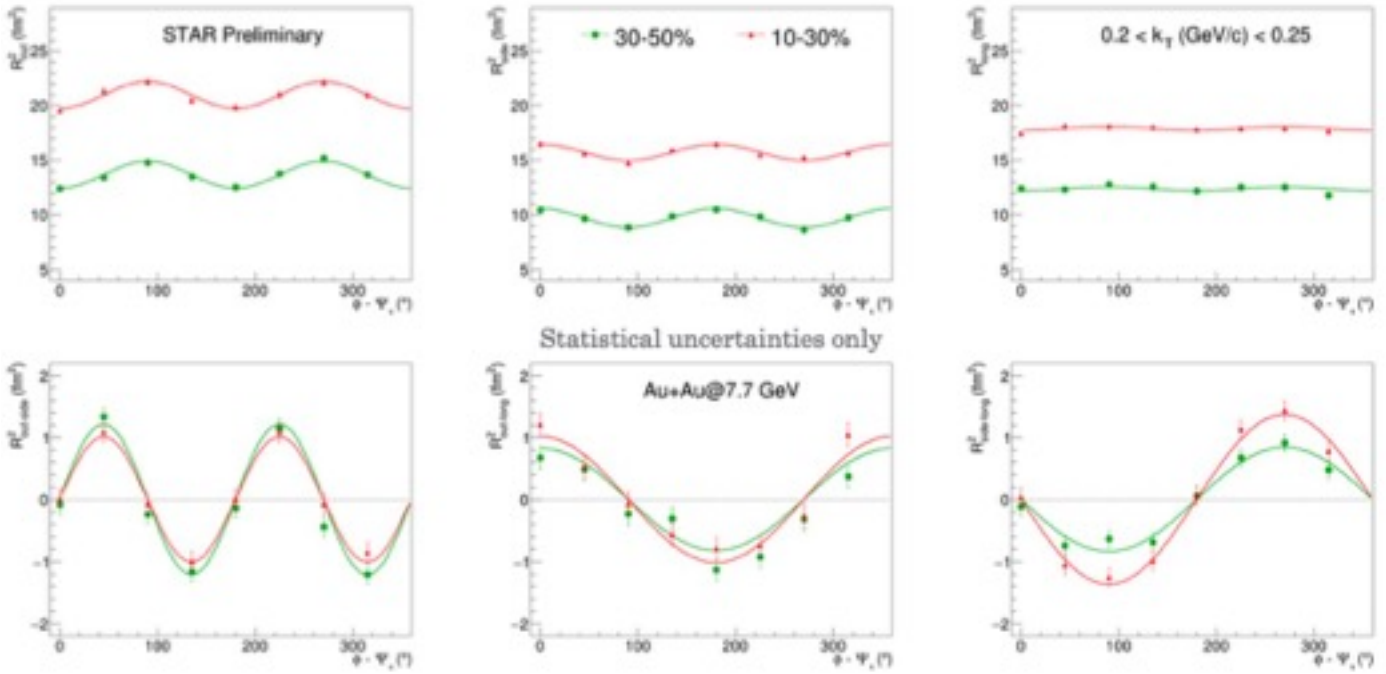
HBT Azimuthal 3D radii w.r.t. Φ_1 and η Dependence

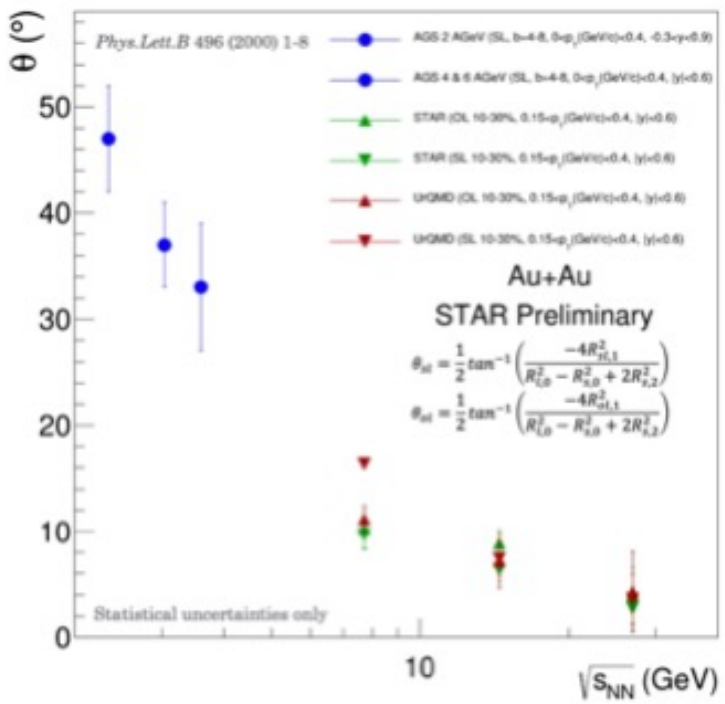
- 3D-structure at Freeze-out
- geometrical Slope w.r.t. z-axis
- include multi-strange Baryon correlation for final state interaction with 3D-Geometry
- relation to v1 and global polarization



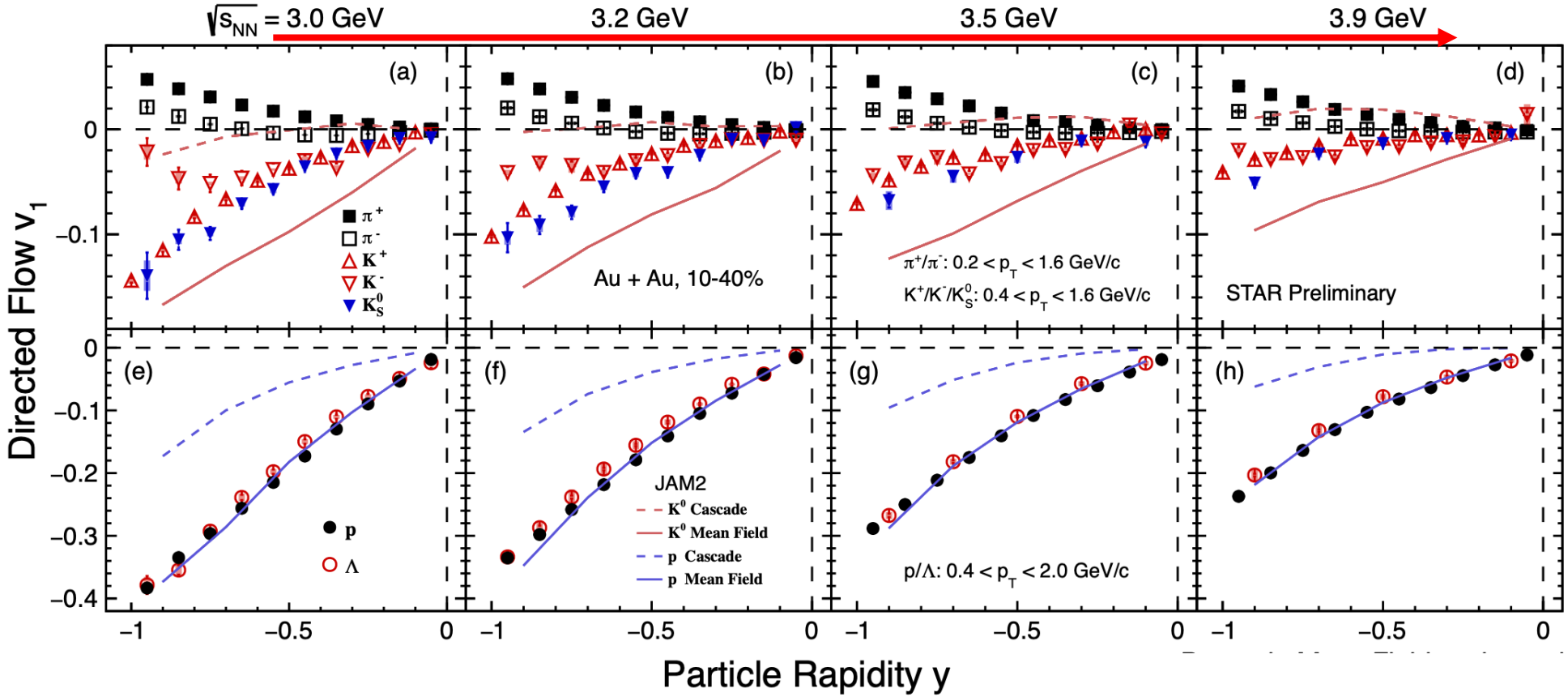


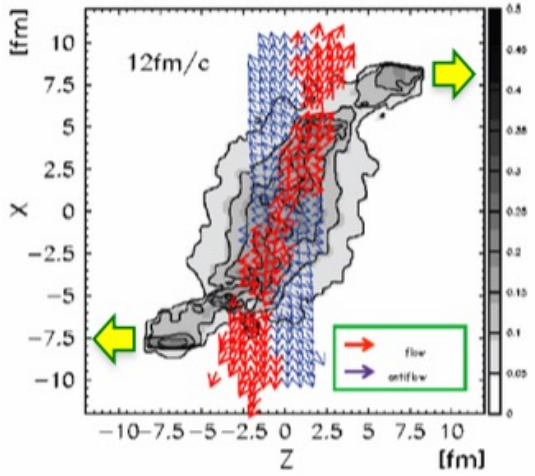
π, p, d, Λ correlations in full 3D



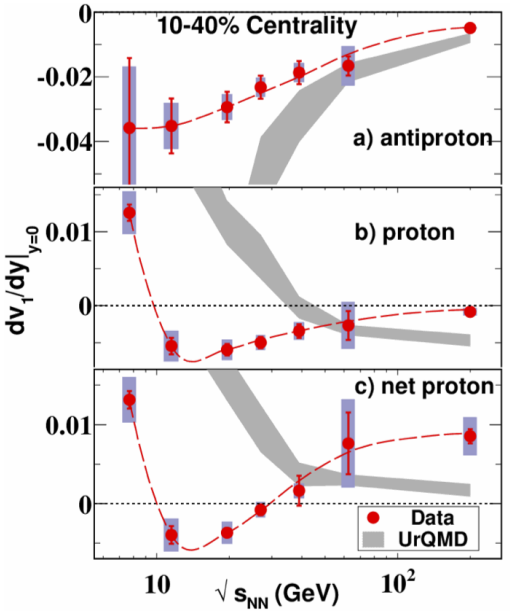


Directed Flow Expansion v_1
Medium Response to Pressure, EOS

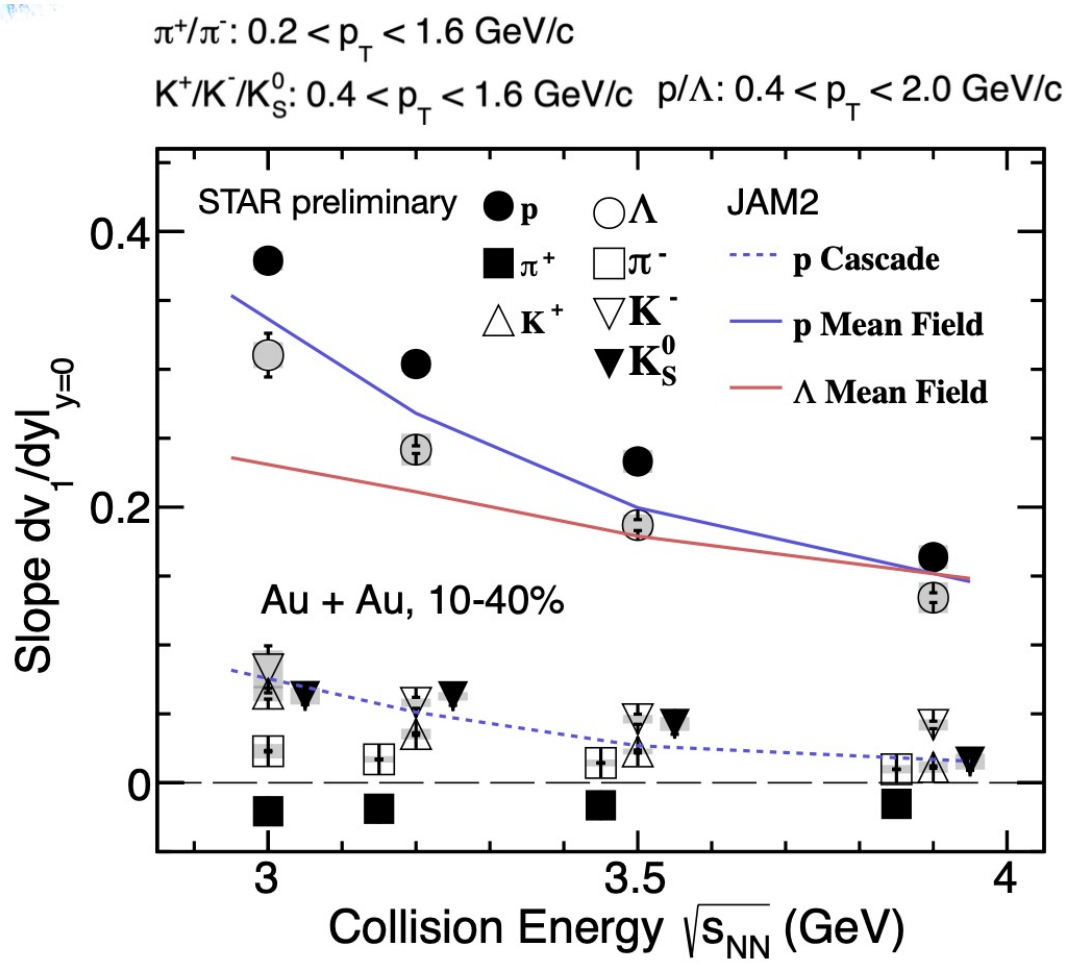


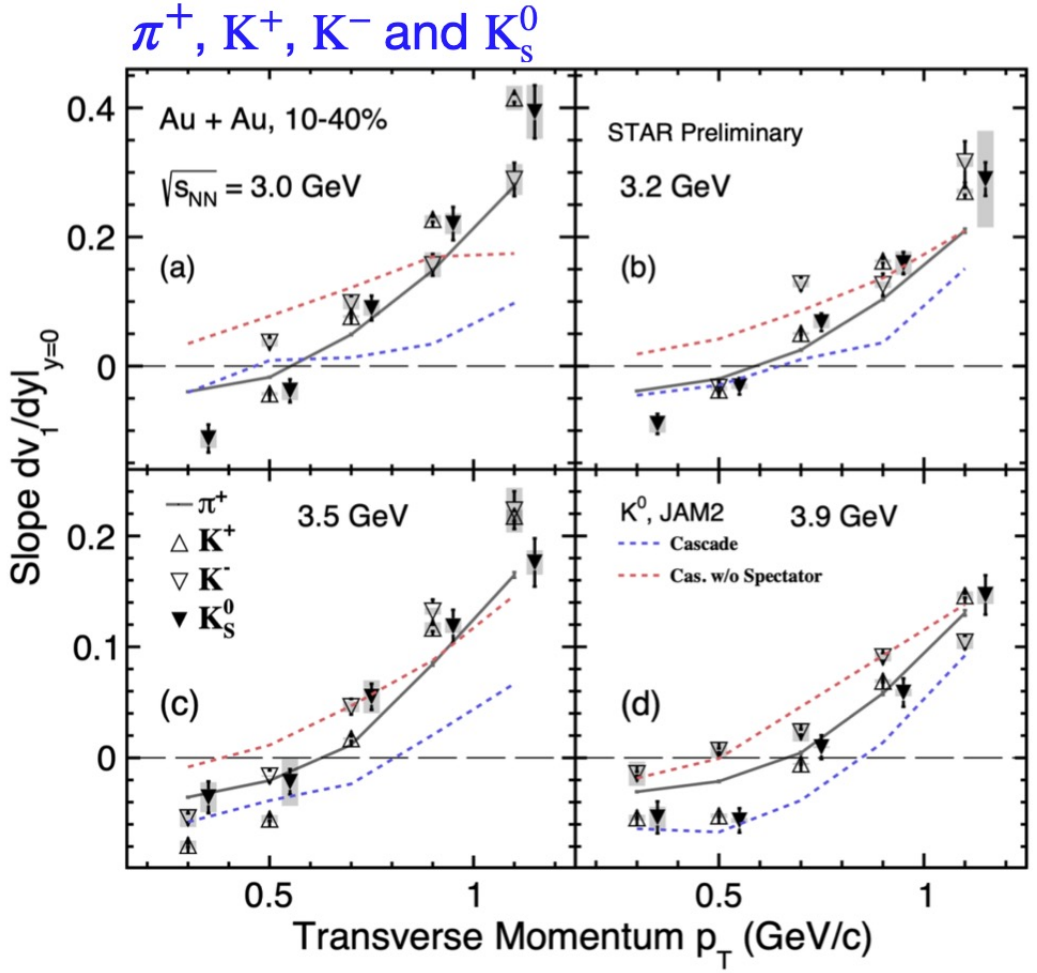


positive v_1 slope
negative v_1 slope



Directed Flow v_1 Slope w.r.t. Rapidity (Collision Energy, Transverse Momentum, Particle ID)

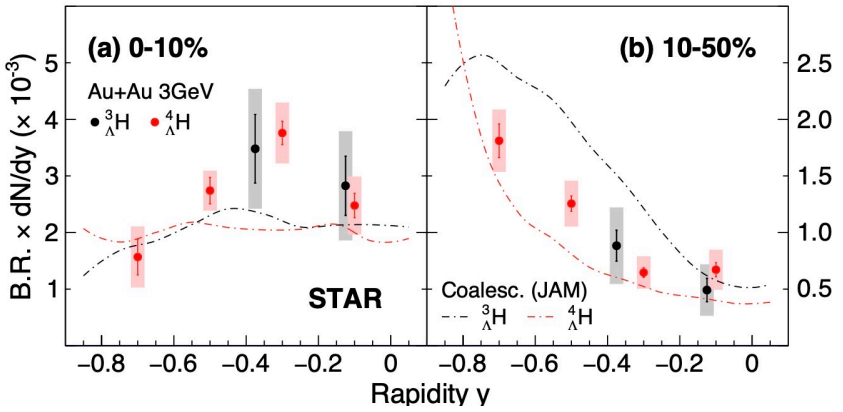


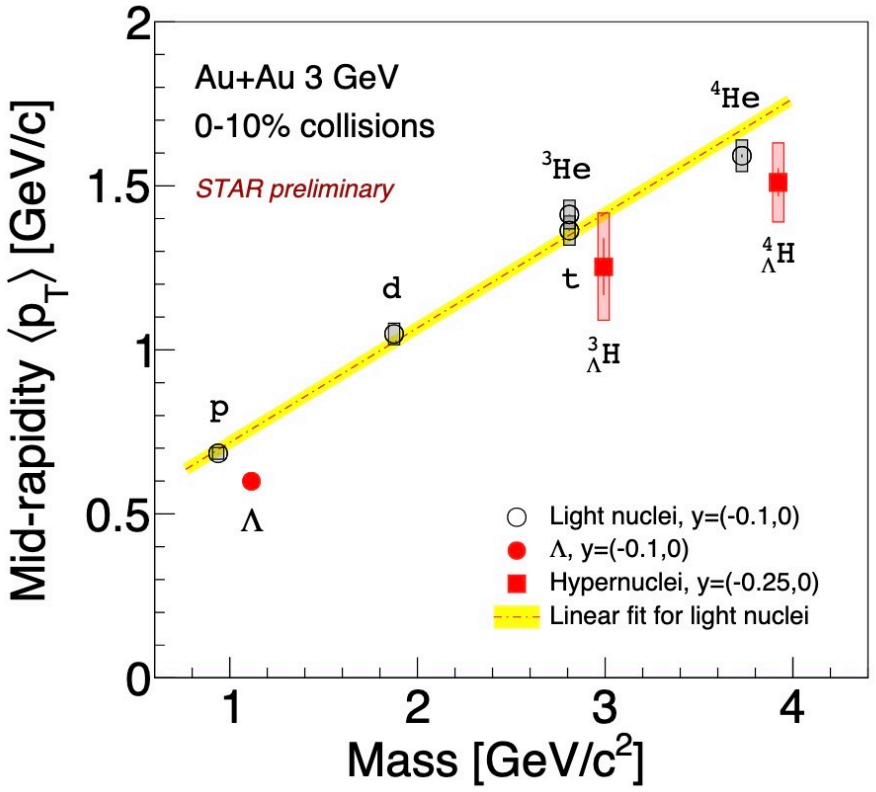


Mass Number Scaling in v_1 Slope for Light and Hyper-Nuclei

(including p_T and rapidity distributions)

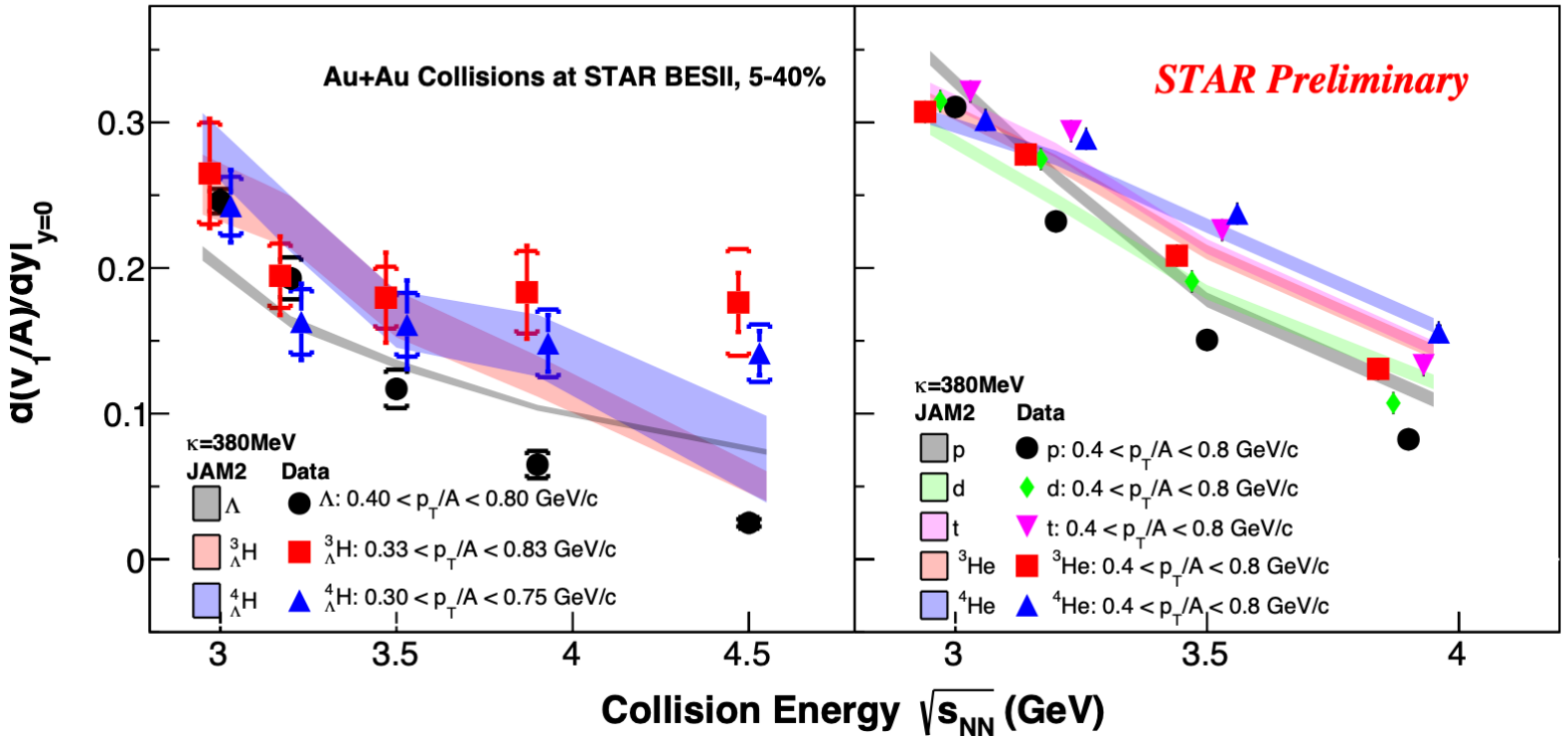
PRL 128 (2022) 202301





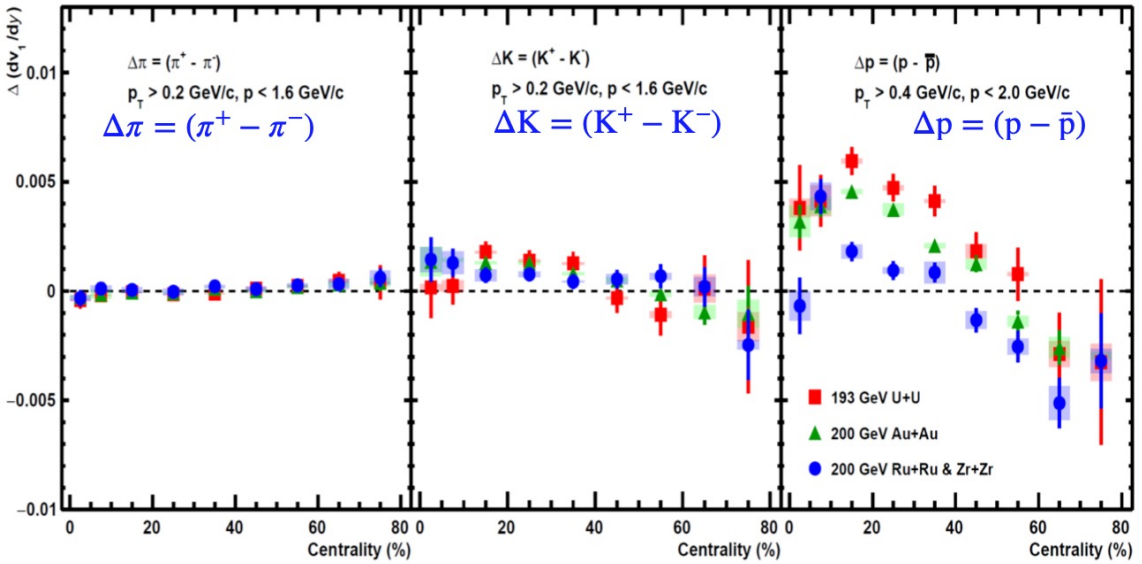
Λ,$^3_\Lambda$H and $^4_\Lambda$H

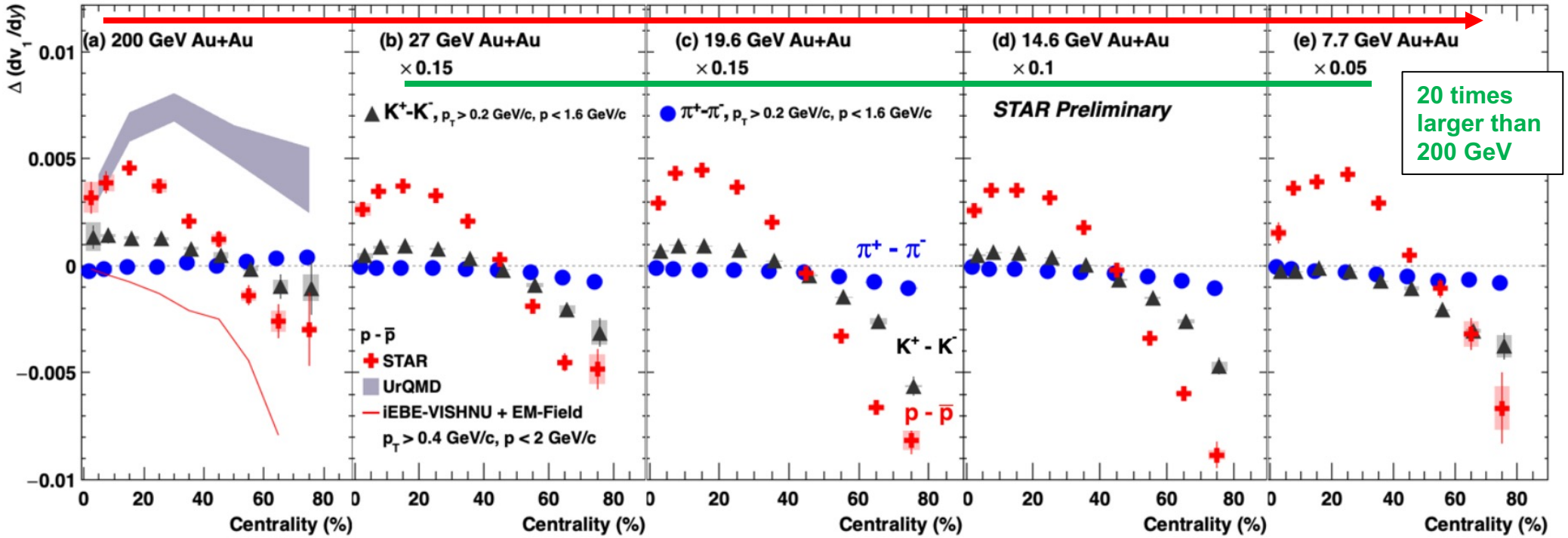
p,d,t,^{3}He and ^{4}He



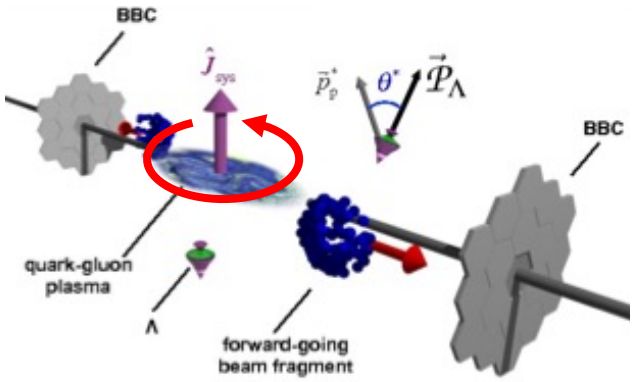
Charge Dependence of v_1 Slope

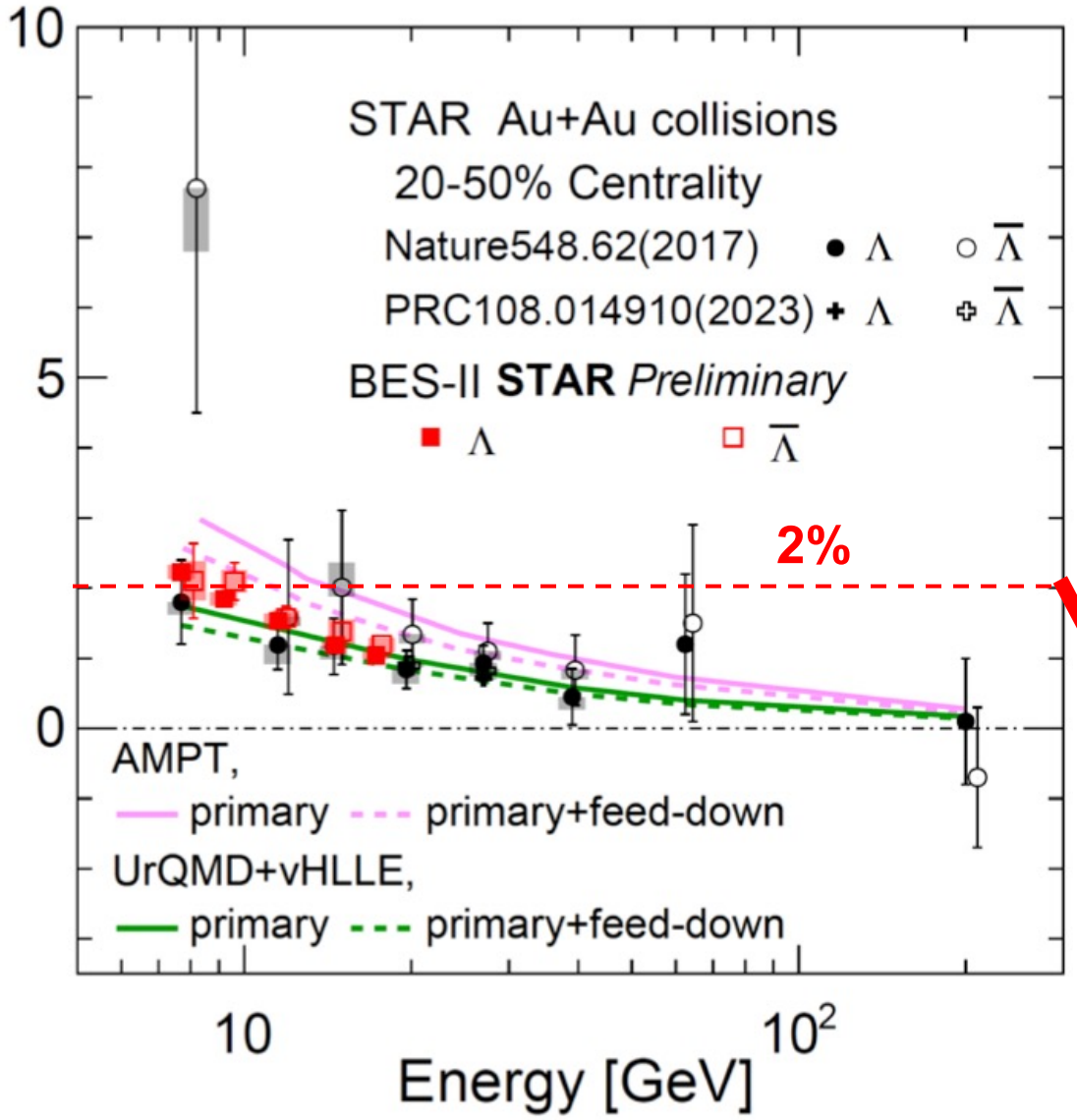
- Particle ID, System Size Dependence
- Collision Energy, Centrality Dependence
- Possible relation with EM-fields

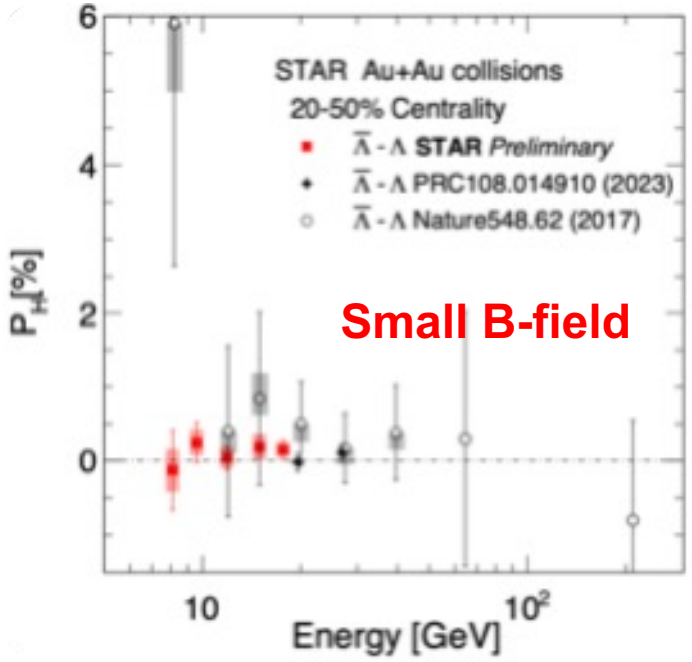




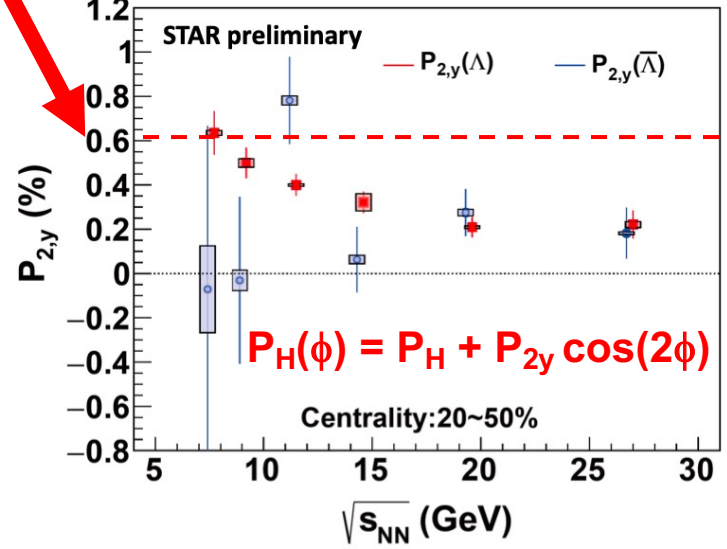
Vortical Fluid : Global Polarization via Λ, anti-Λ

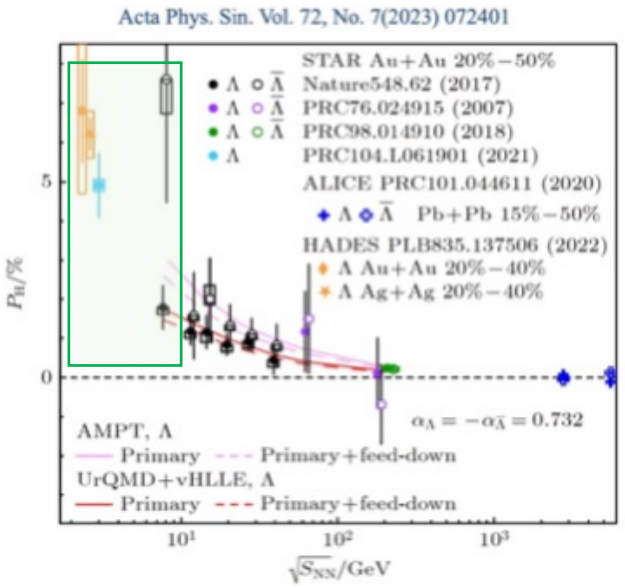




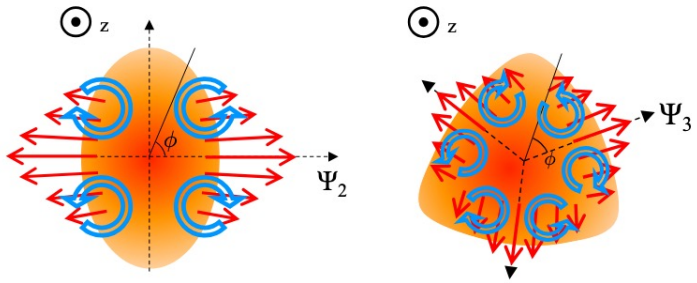


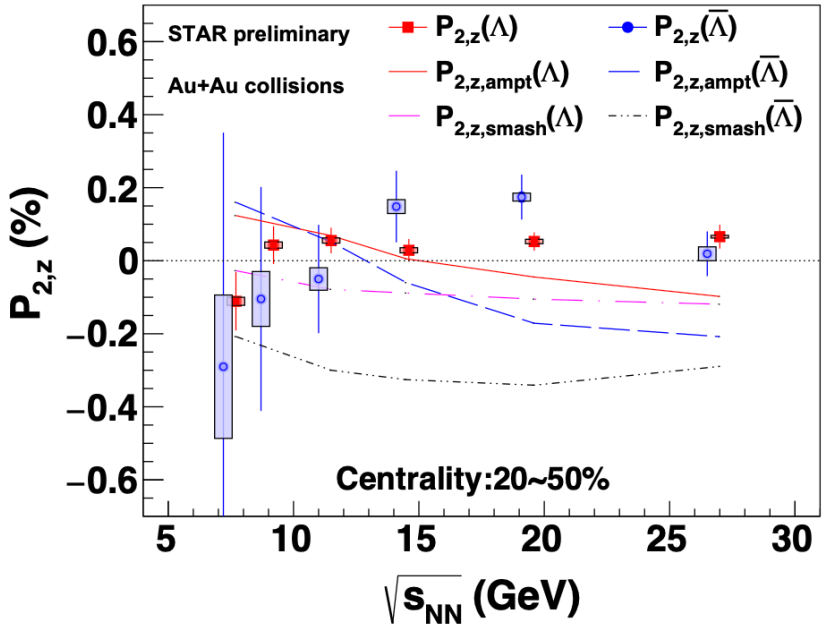
~30%

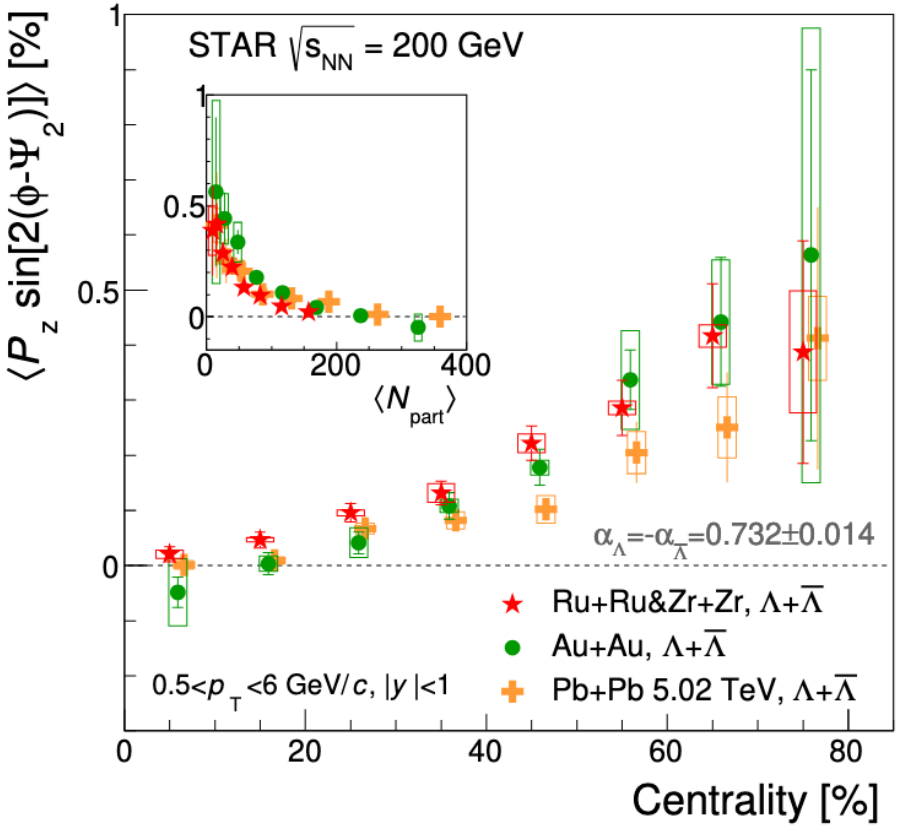


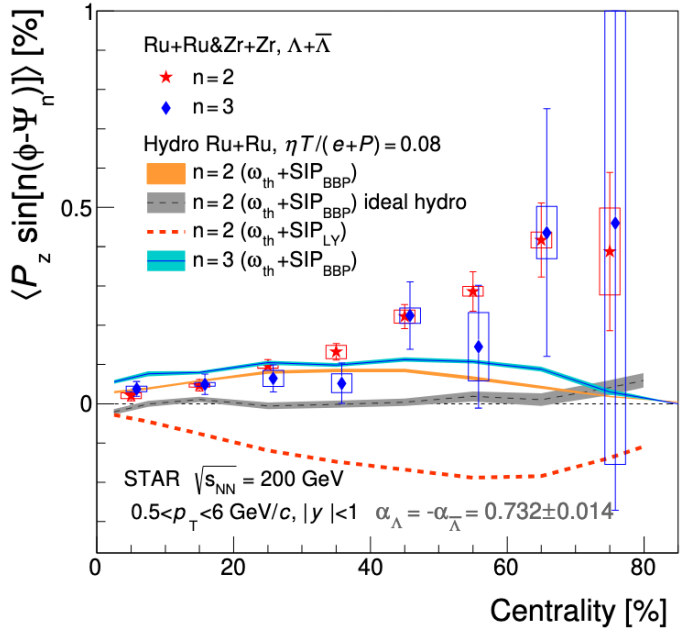


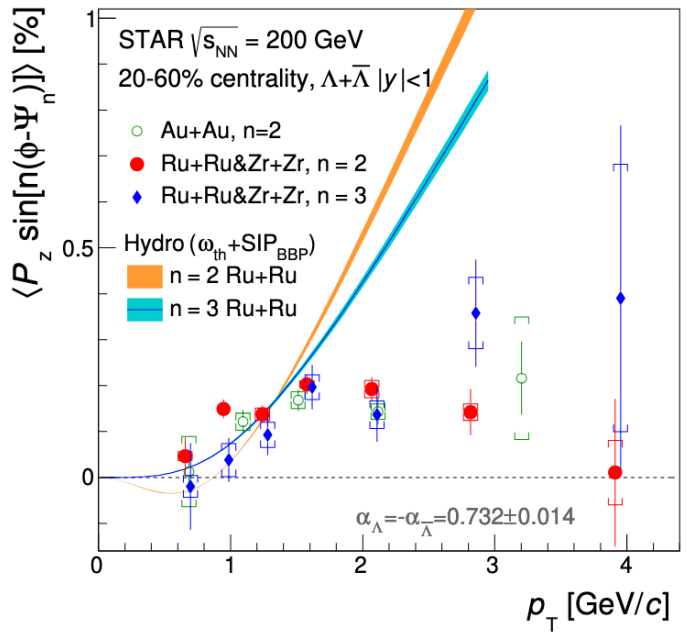
Longitudinal Polarization along the Beam Direction caused by v_2 and v_3 Expansion





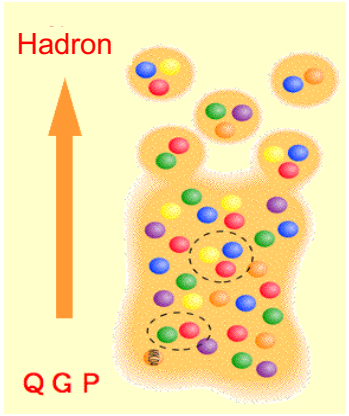




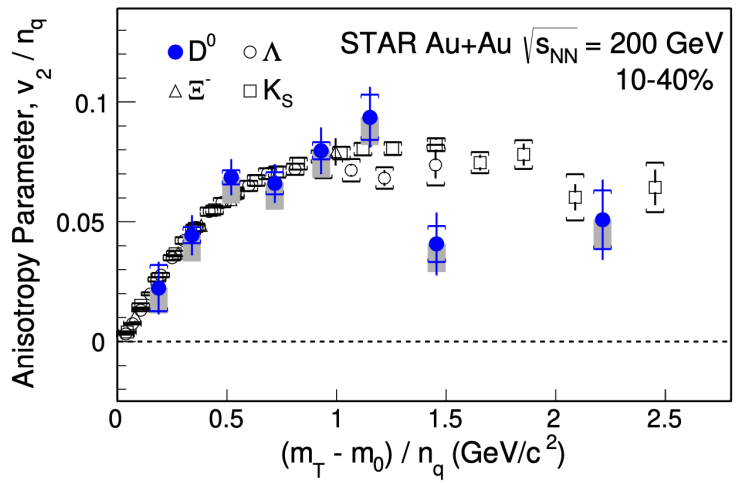


Elliptic Flow Expansion v_2

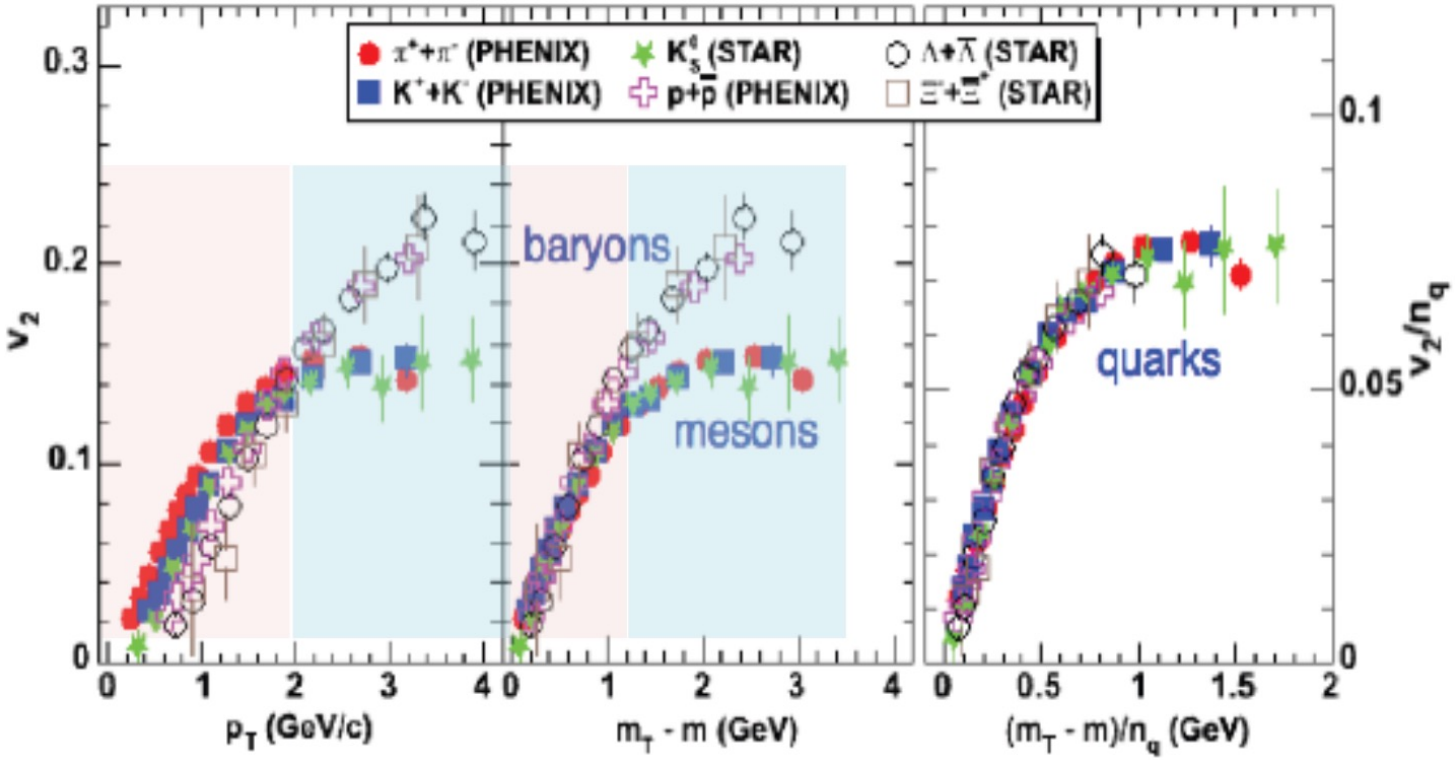
- **Number of Quark Scaling**
- **Partonic Degree of Freedom**



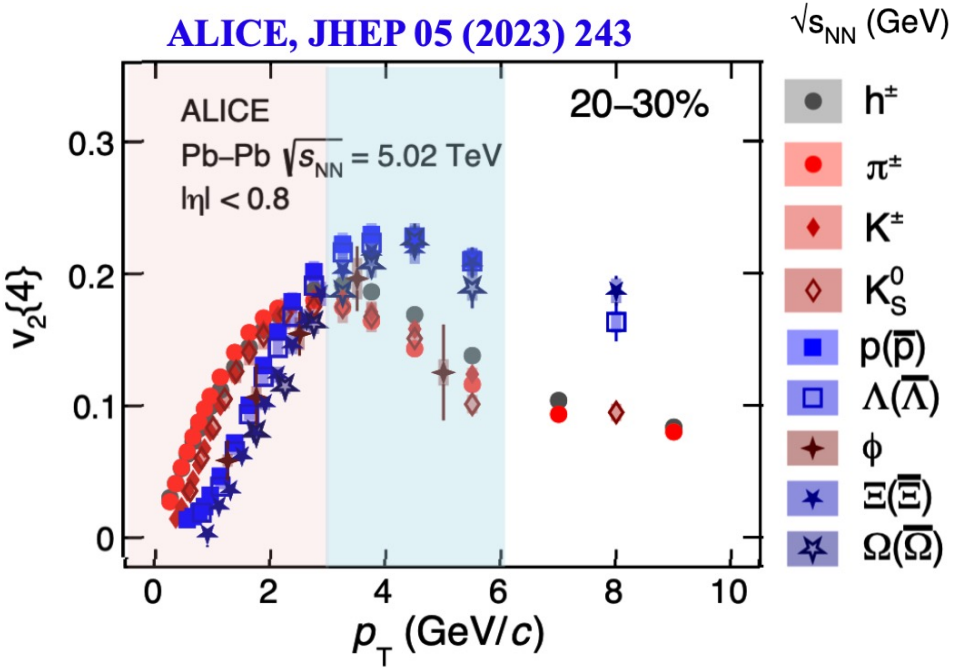
STAR Collaboration, Phys. Rev. Lett. 118, 212301 (2017)



PHENIX, PRL98, 162301 (2007)



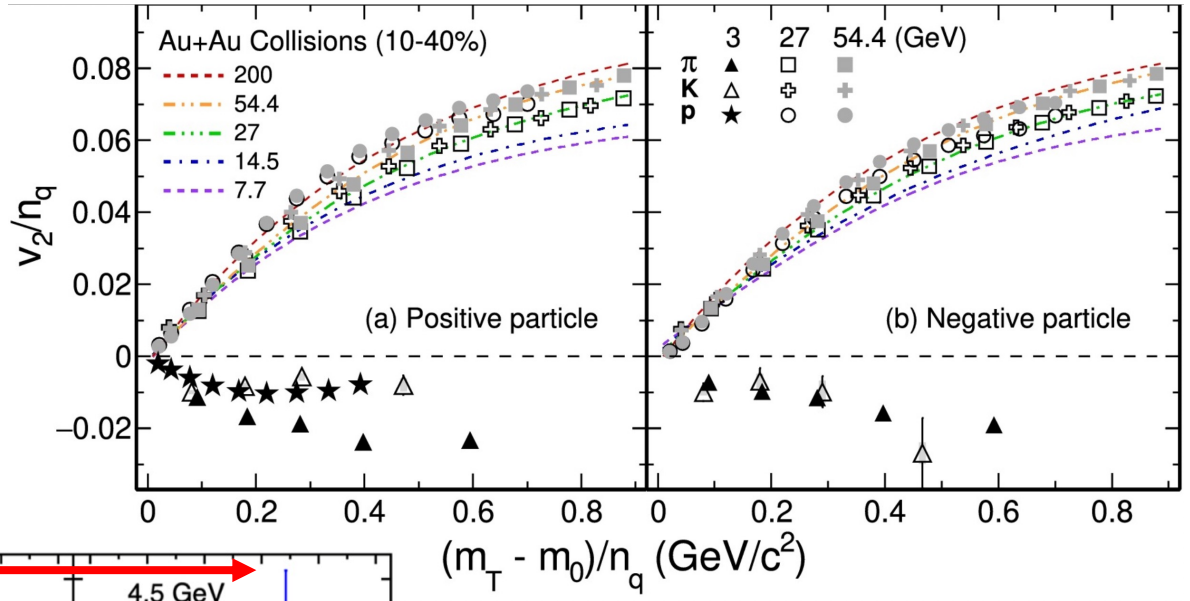
ALICE, JHEP 05 (2023) 243

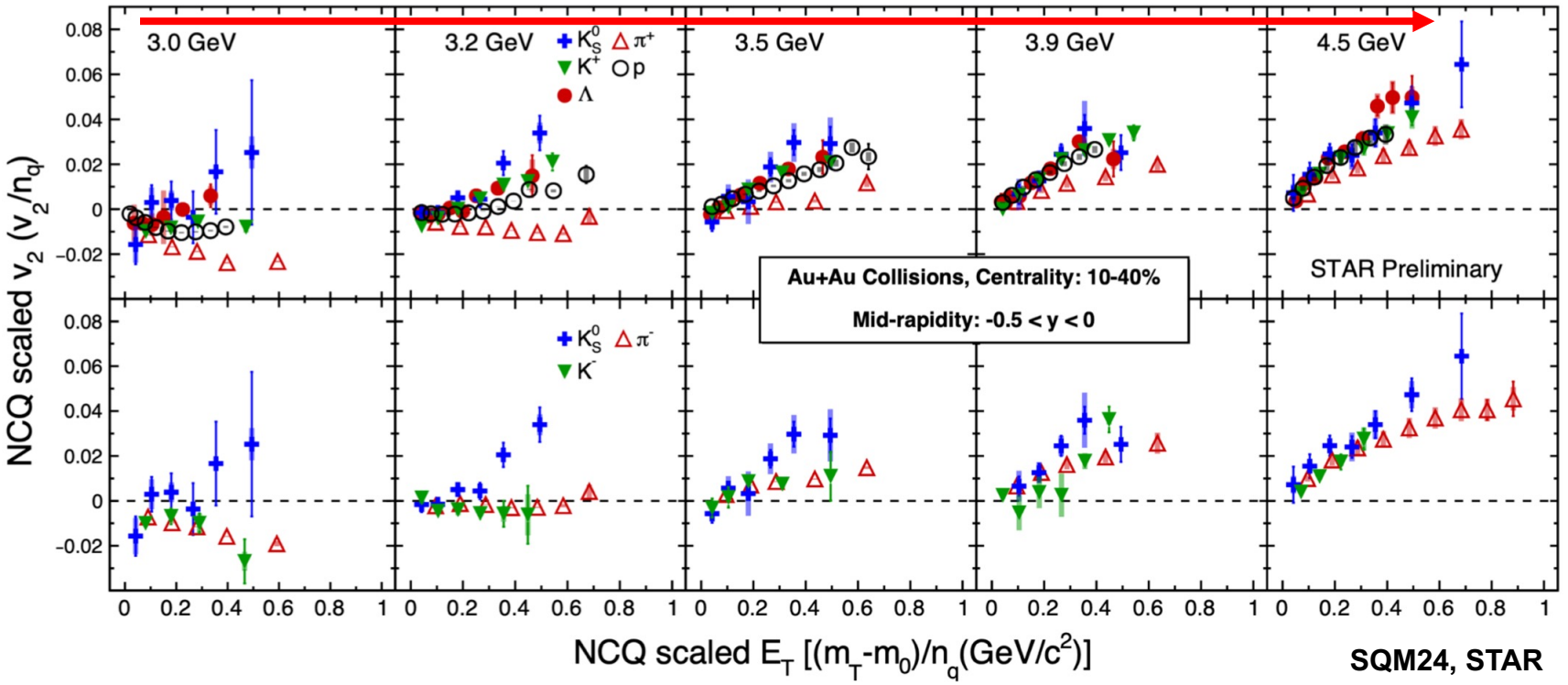


STAR, Phys. Lett. B 827, 137003 (2022)

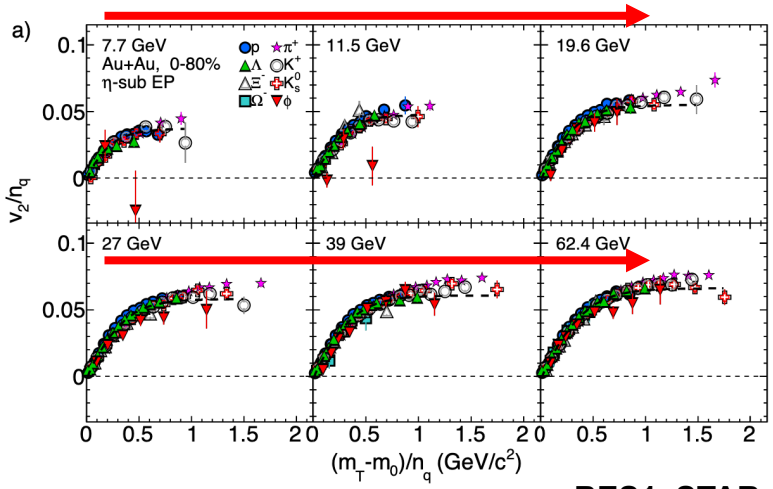
Test of Hadronic/Partonic Phase Quark Number of Scaling in v_2

- **breaking at low or middle p_T ?**



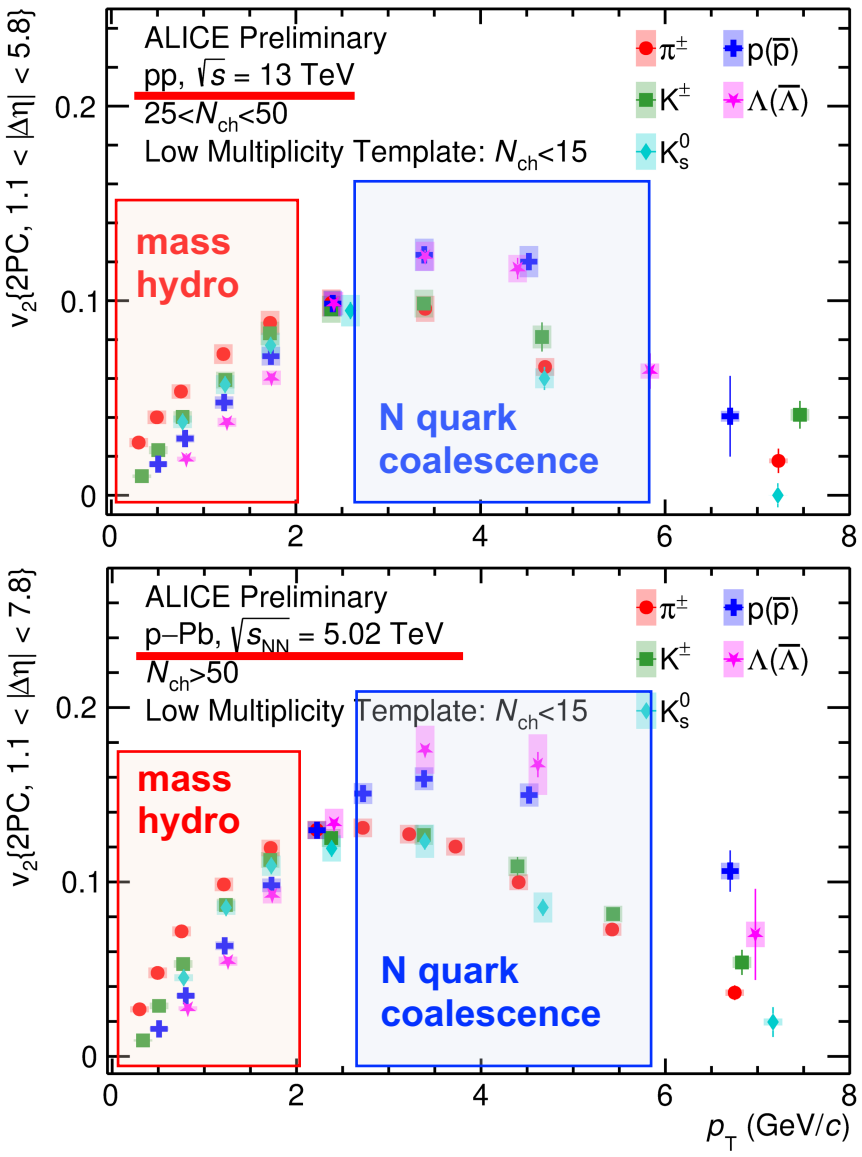


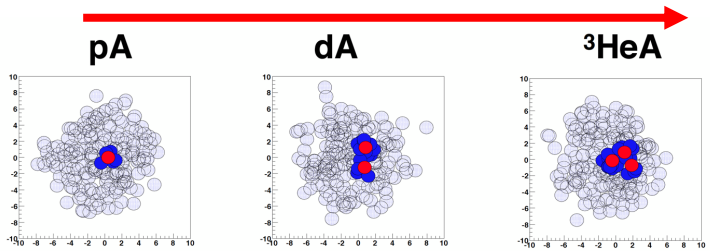
SQM24, STAR

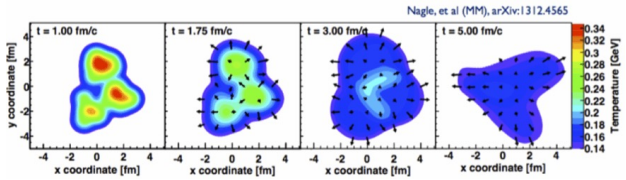


BES1, STAR

Flow in small system (pp and pA at LHC/RHIC)

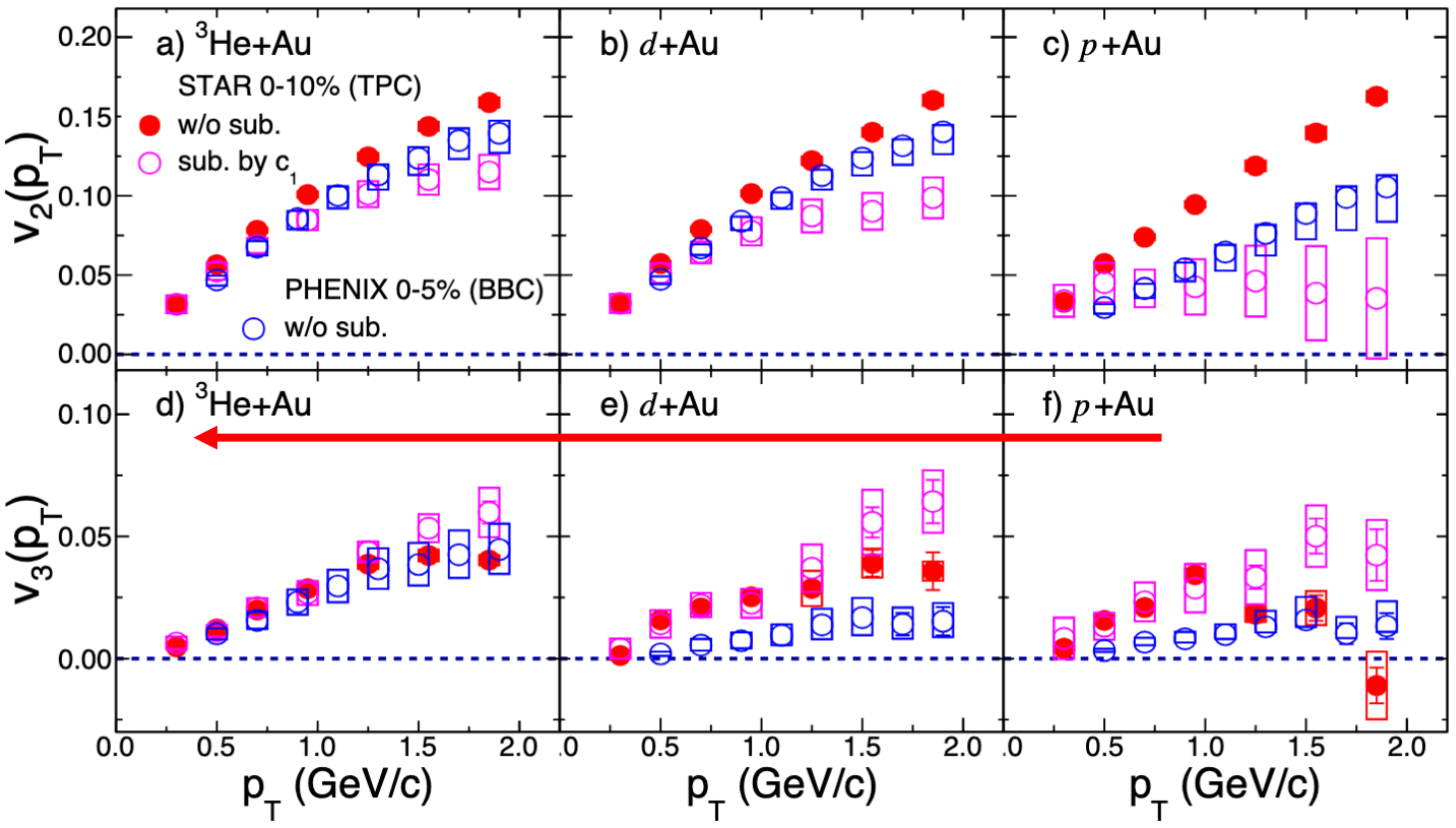




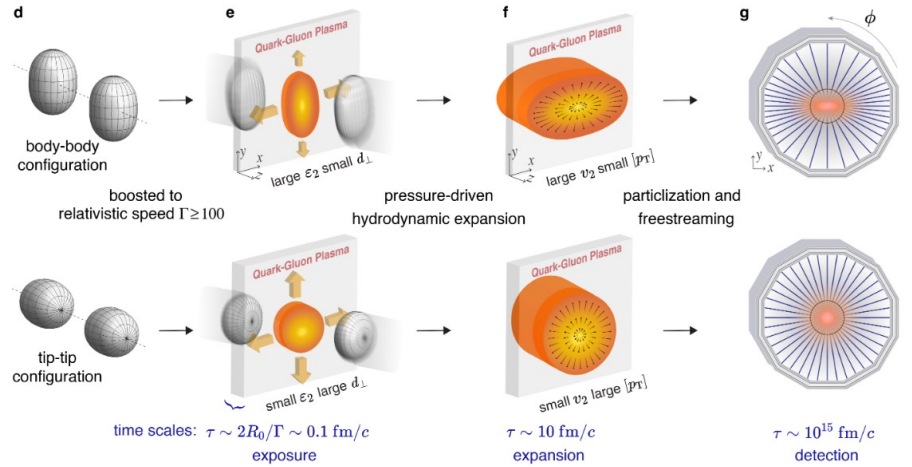


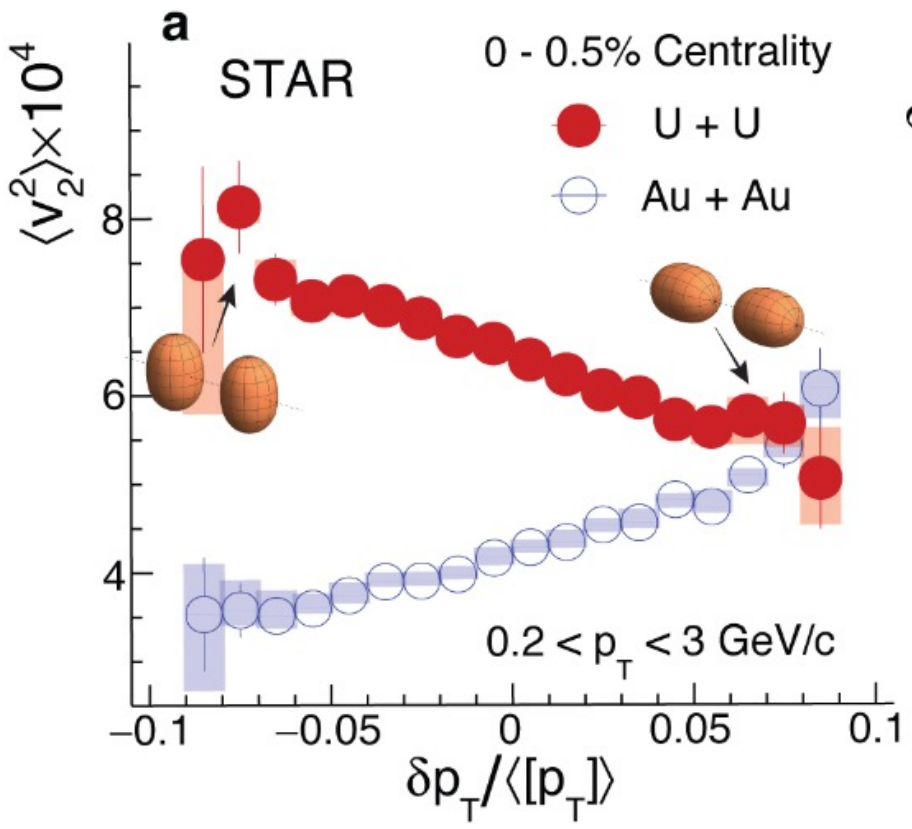
shape or multiplicity

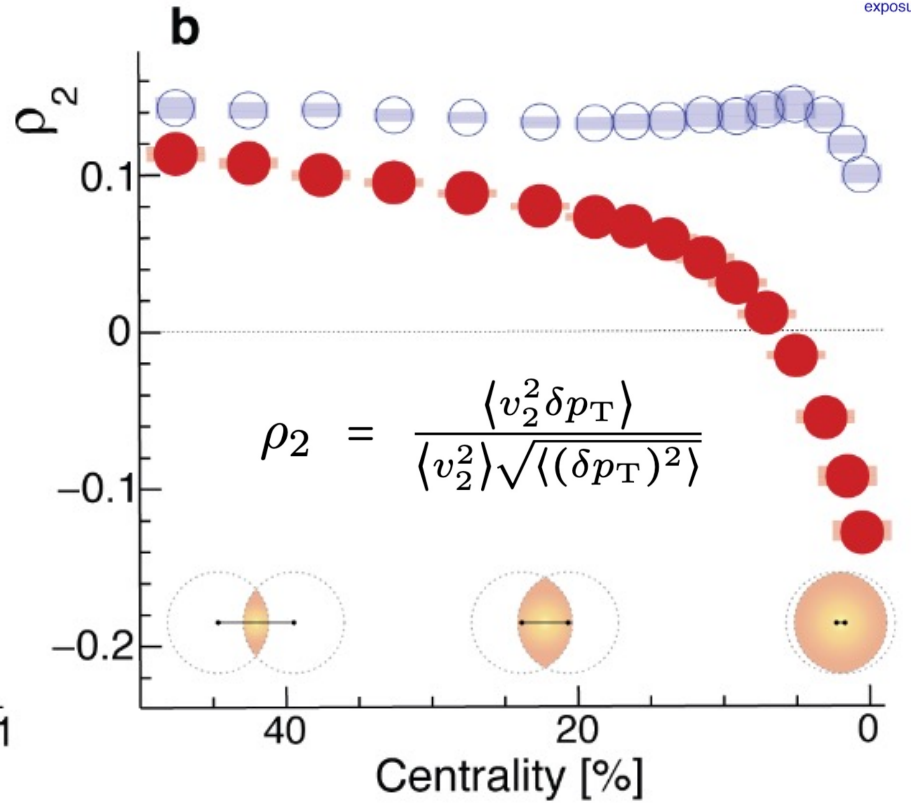
arXiv: 2312.07464



Flow application for Nuclear Structure Imaging with v_2-p_T correlation

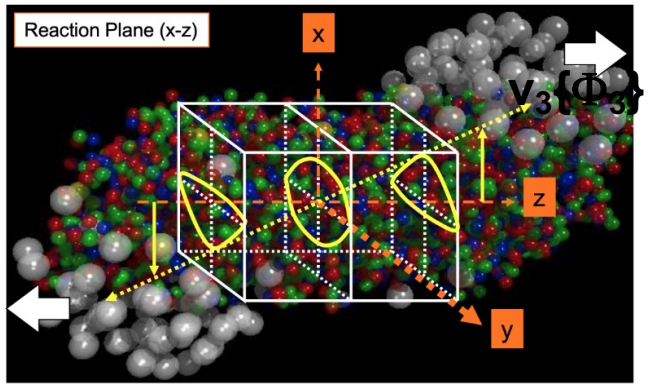


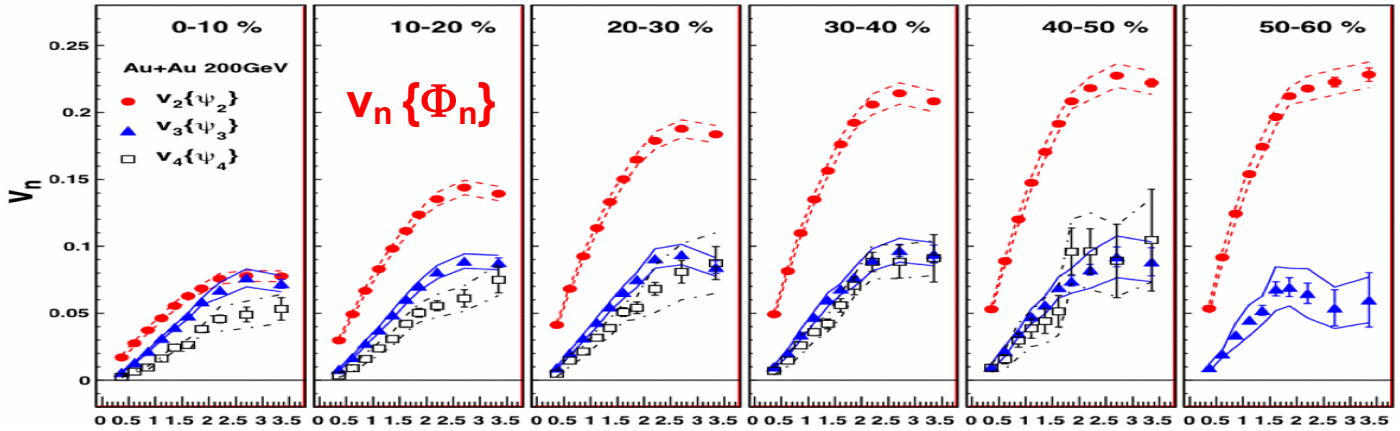


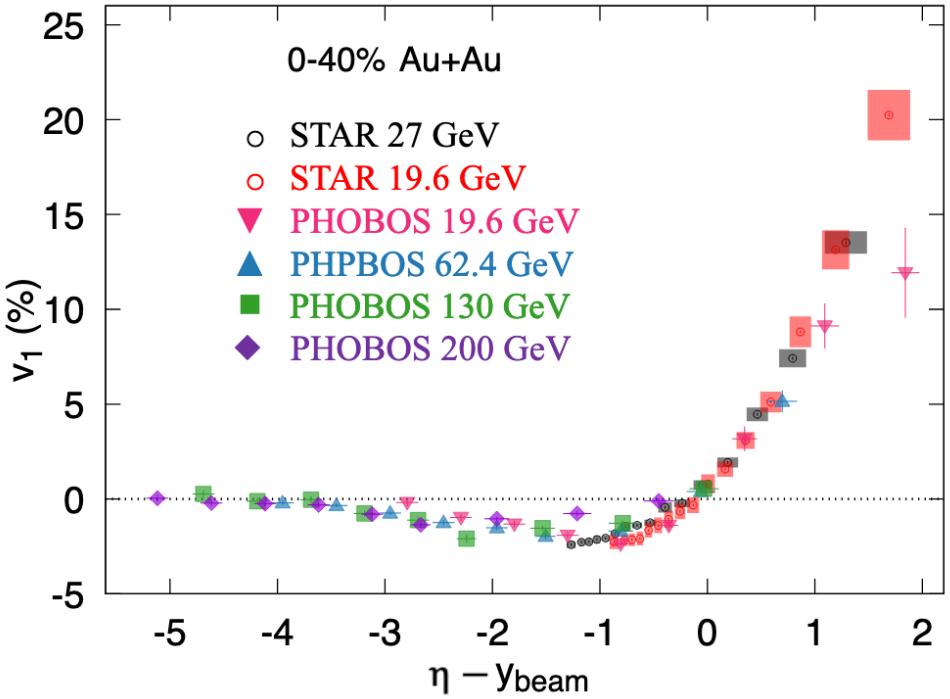


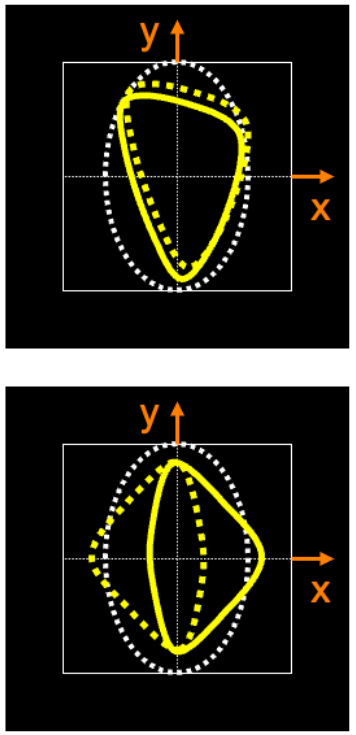
arXiv: 2401.06625

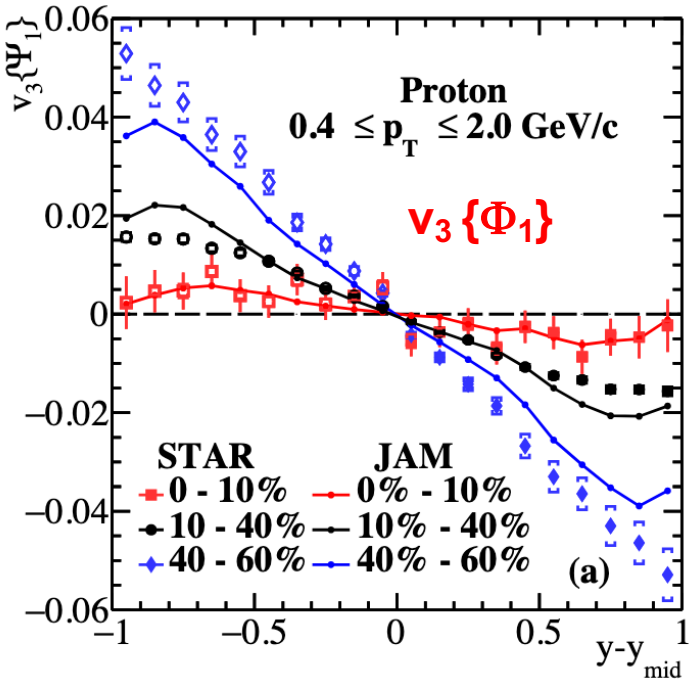
$v_3\{\Phi_3\}$ and $v_3\{\Phi_1\}$



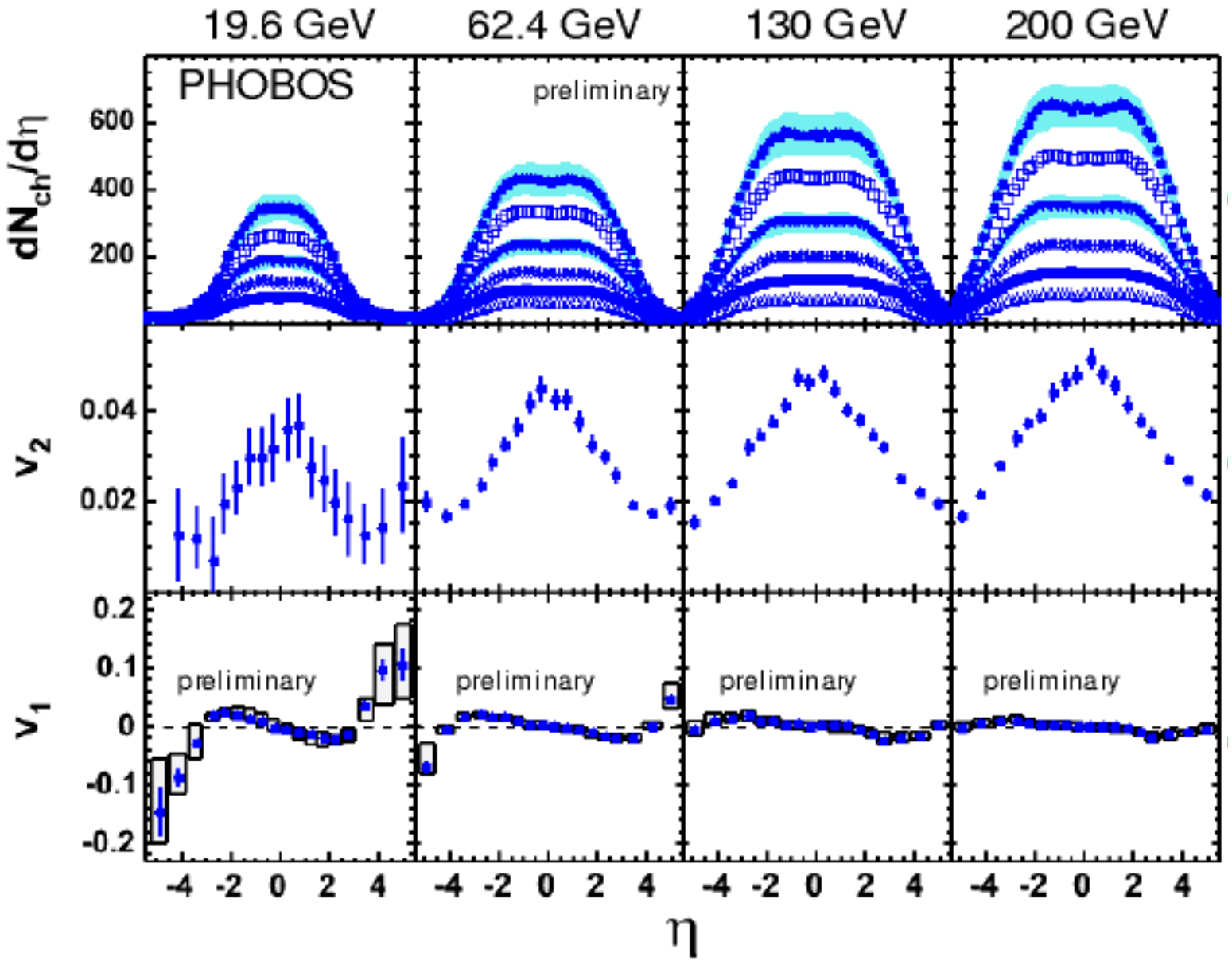






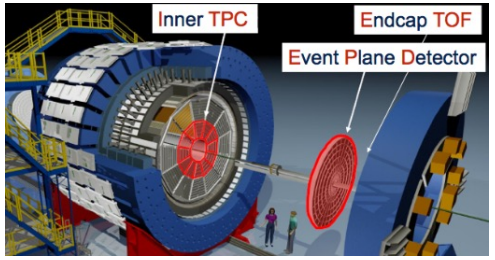


Rapidity (Eta) Dependence of Yield and Flow

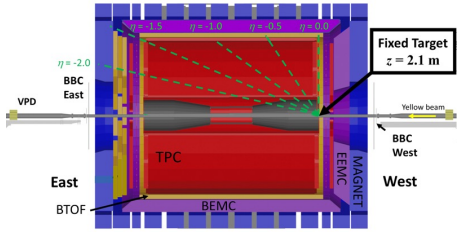


Tsukuba Univ. Group Current Activities and Future Plans

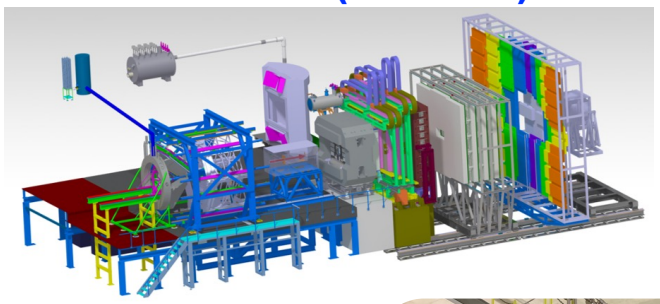
RHIC-STAR

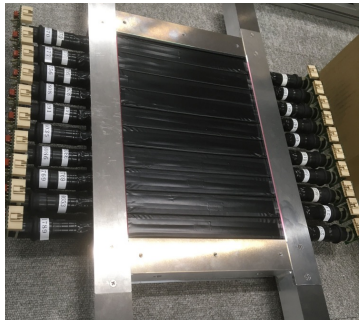


STAR (FXT)



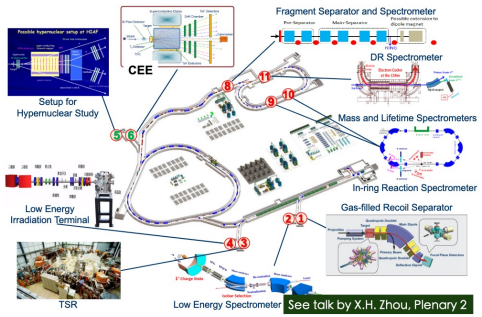
FAIR-CBM (HADES)





Neutron Detector

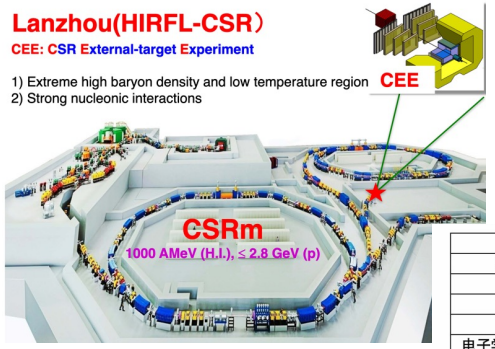
HIAF-CEE



Lanzhou(HIRFL-CSR)

CEE: CSR External-target Experiment

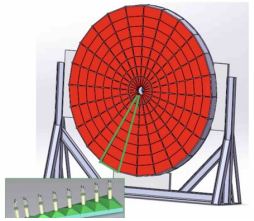
1) Extreme high baryon density and low temperature region
2) Strong nucleonic interactions

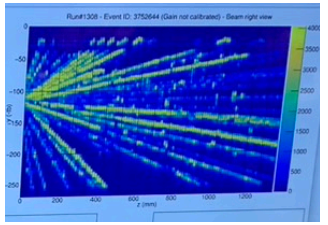


HIRFL-CSR-CEE

Centrality, RP(EP) ZDC/EPD

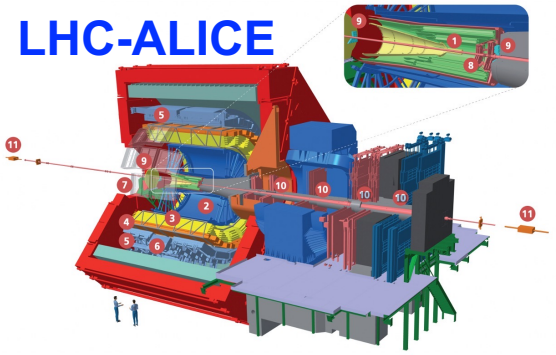
ZDC探测器的几何参数	
距磁铁中心距离	2.95 m
ZDC轮盘内径	5 cm
ZDC轮盘外径	100 cm
探测模块数	192 (24扇区 × 8模块/扇区)
电子学道数(双打拿极输出)	384
ZDC主要技术指标	
探测效率	> 95%
通道占有度	< 15%
有效面积	> 1m²



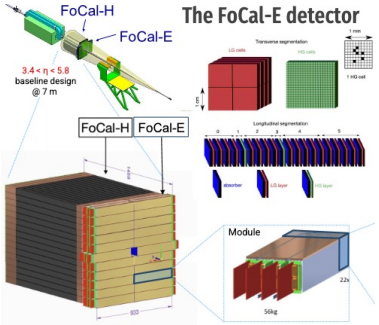


RIKEN-RIBF SAMURAI-SPIRIT

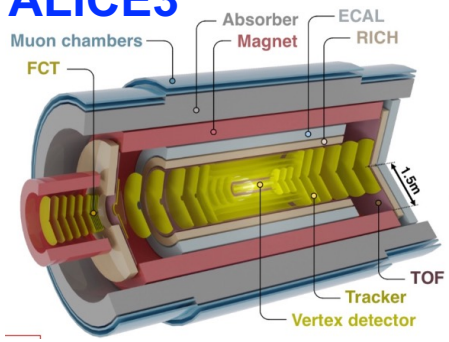
LHC-ALICE



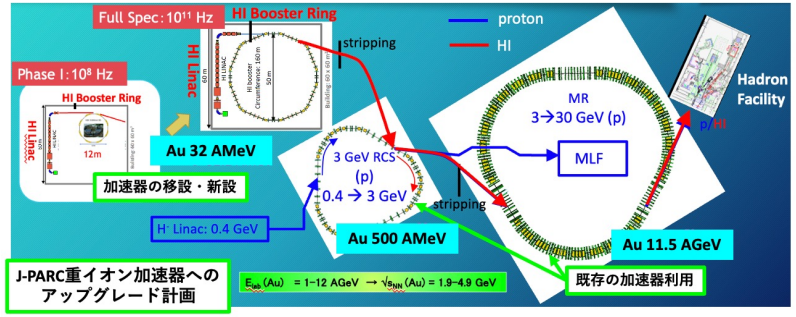
FoCal



ALICE3



J-PARC-HI

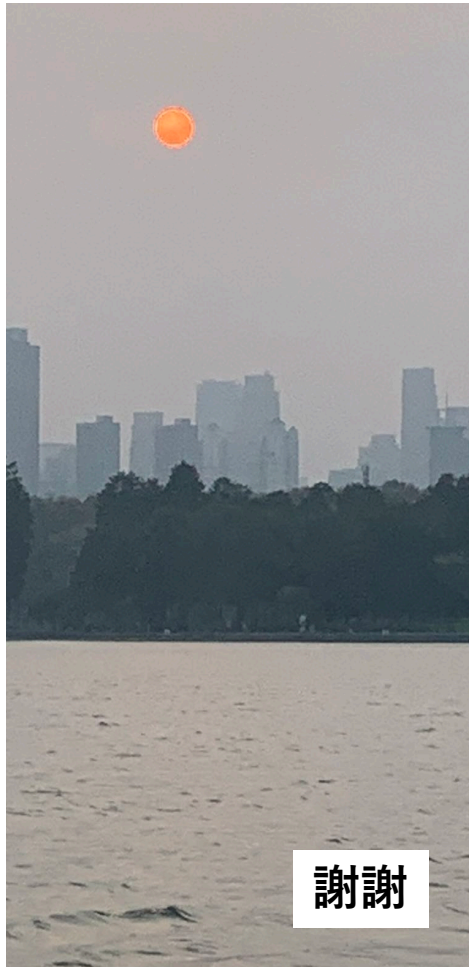


Summary and Outlook

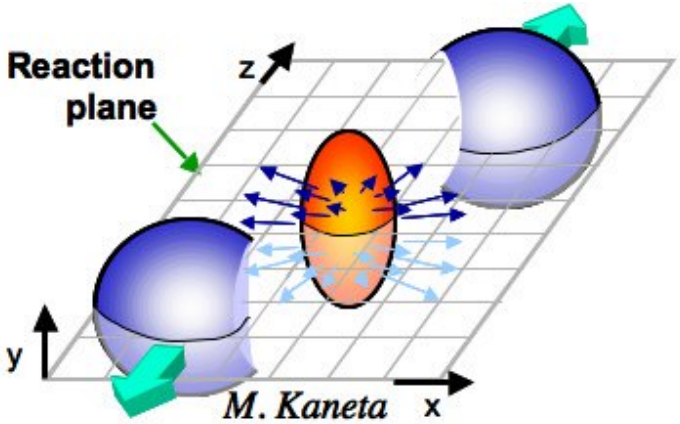
- Thermal freeze-out and radial flow
- Source size/shape via femto-scopy
- Directed, elliptic and vortical flow
- Small system and higher order flow

(my own outlooks)

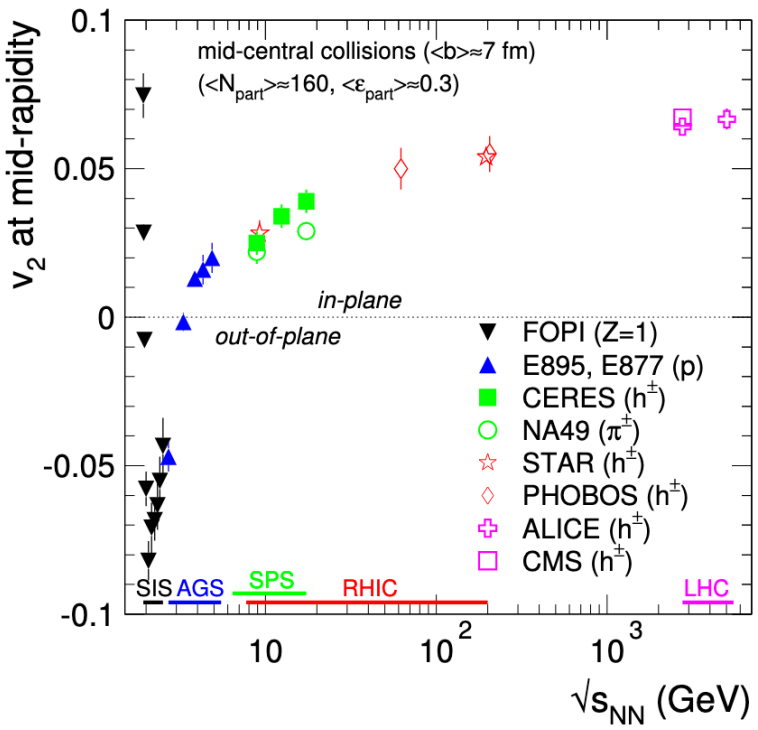
- correlation among flow, temperature and fluctuation
- from RHIC-STAR (FXT) to FAIR-CBM, HIAF-CEE (HIRFL-CSR)
- ZDC/EPD for Centrality and E.P. definition
- Neutron Detector R&D for CBM upgrade and J-PARC heavy-ion for net-Baryon measurements

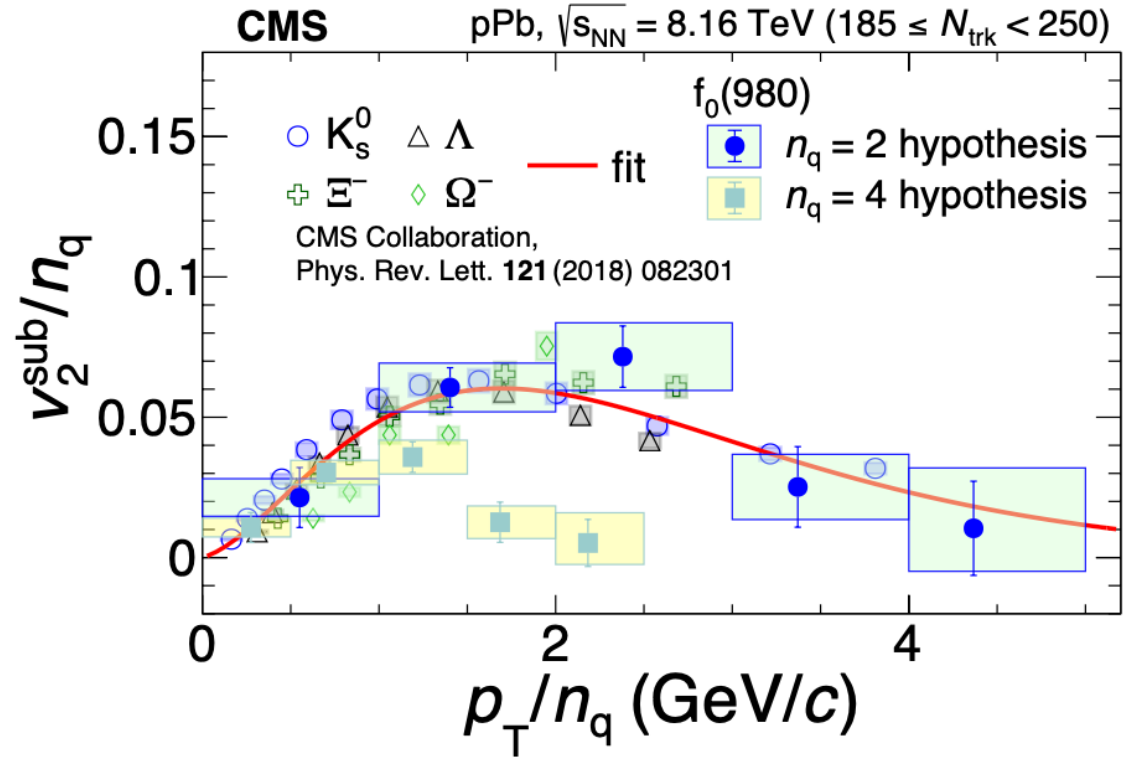


Partonic Degree of Freedom
Number of Quark Scaling in v_2

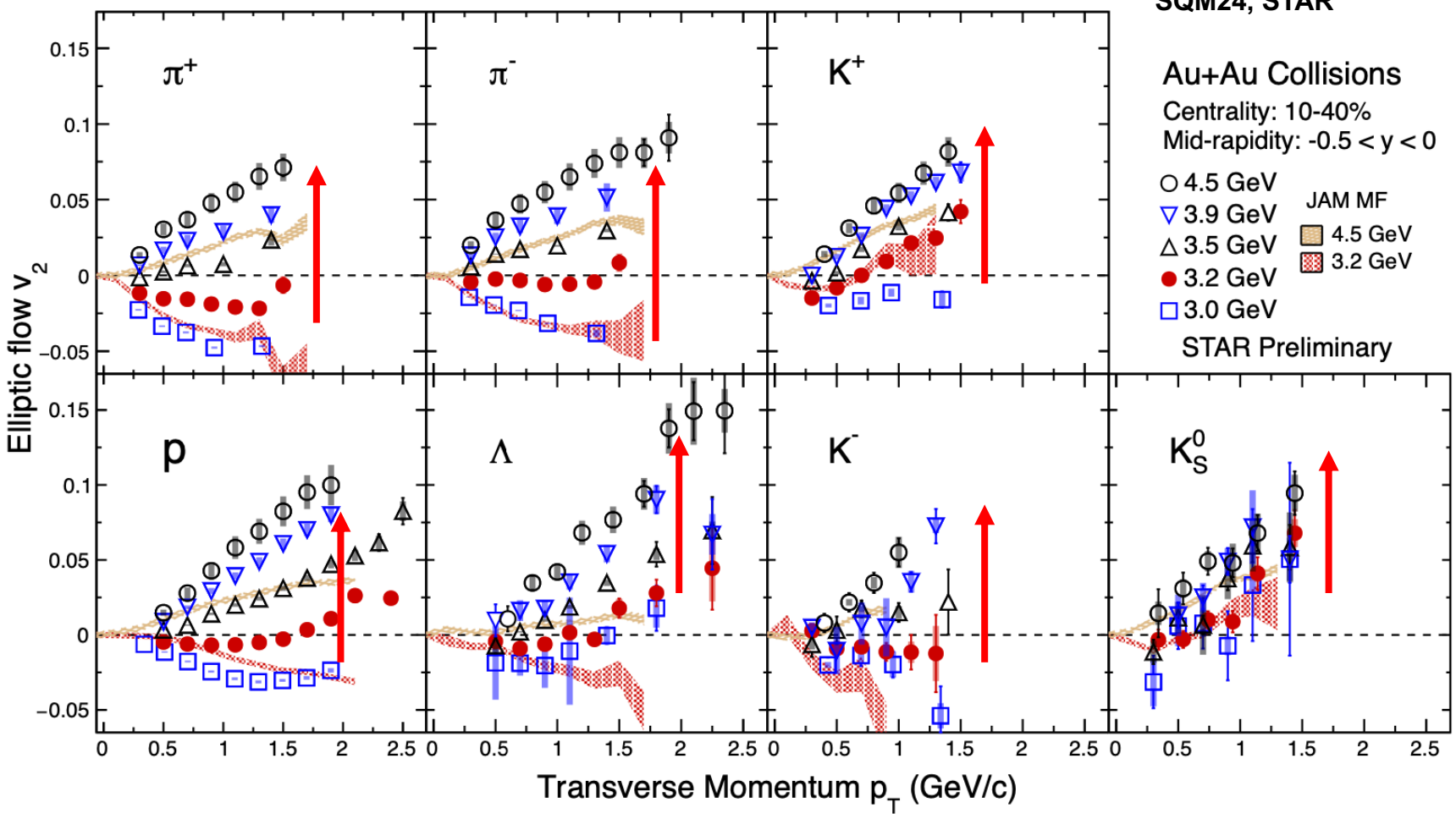


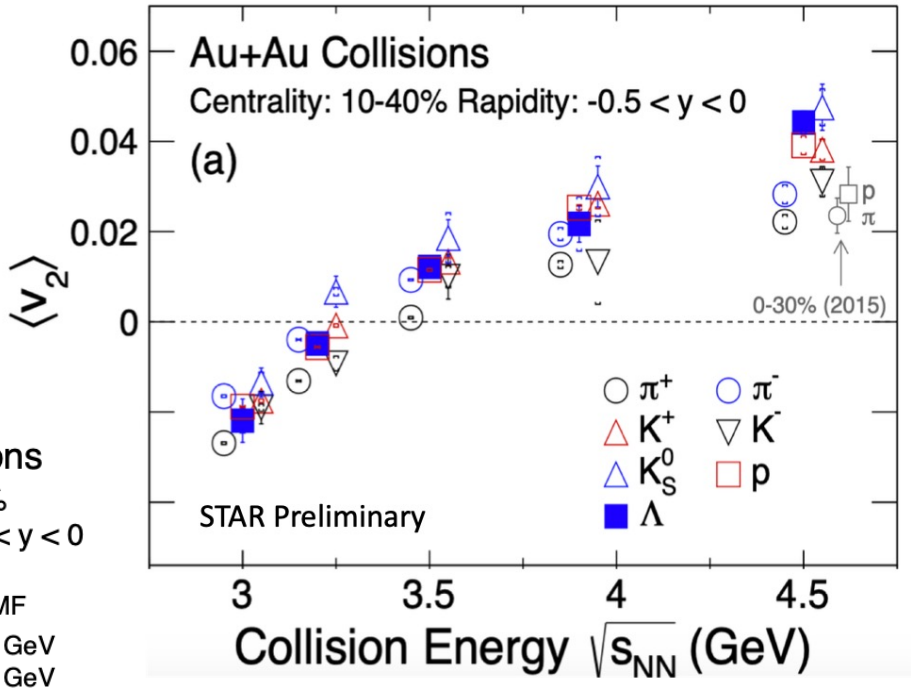
Test of exotic state with v_2 scaling





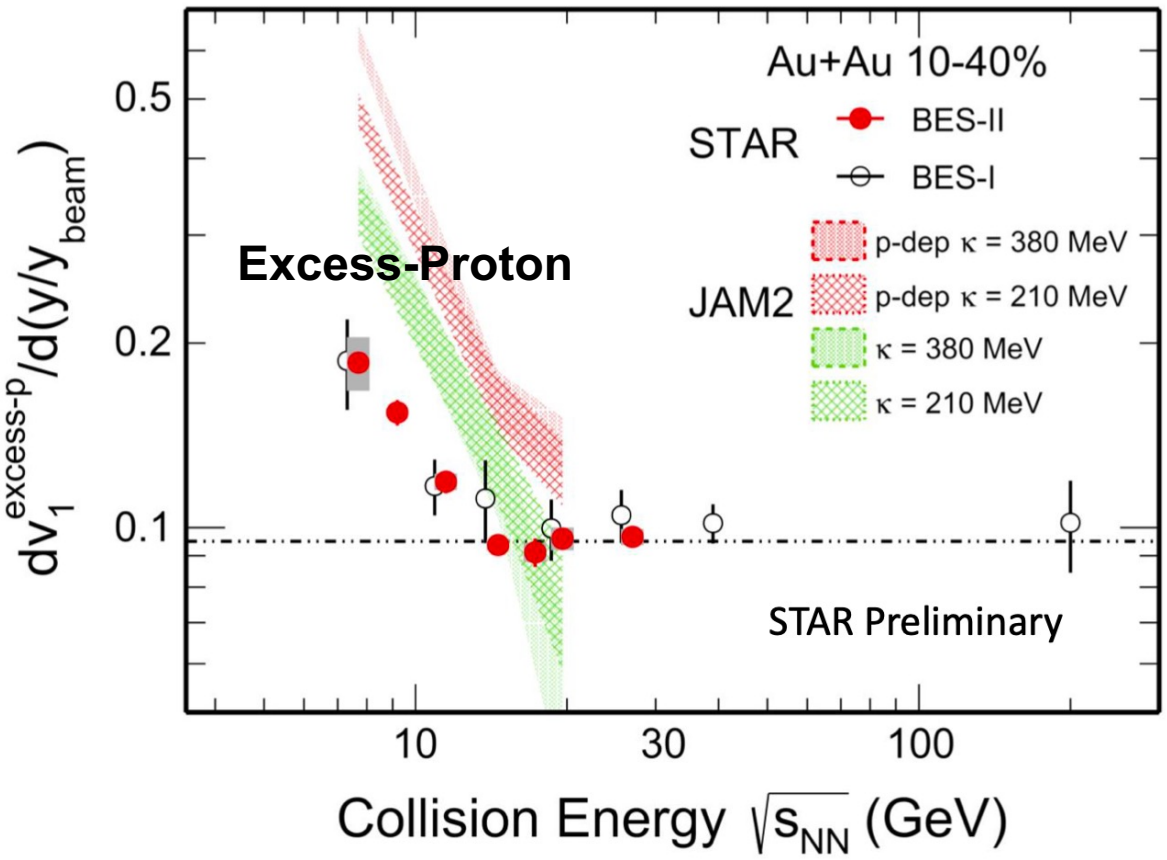
From Squeeze-out to Elliptic Expansion

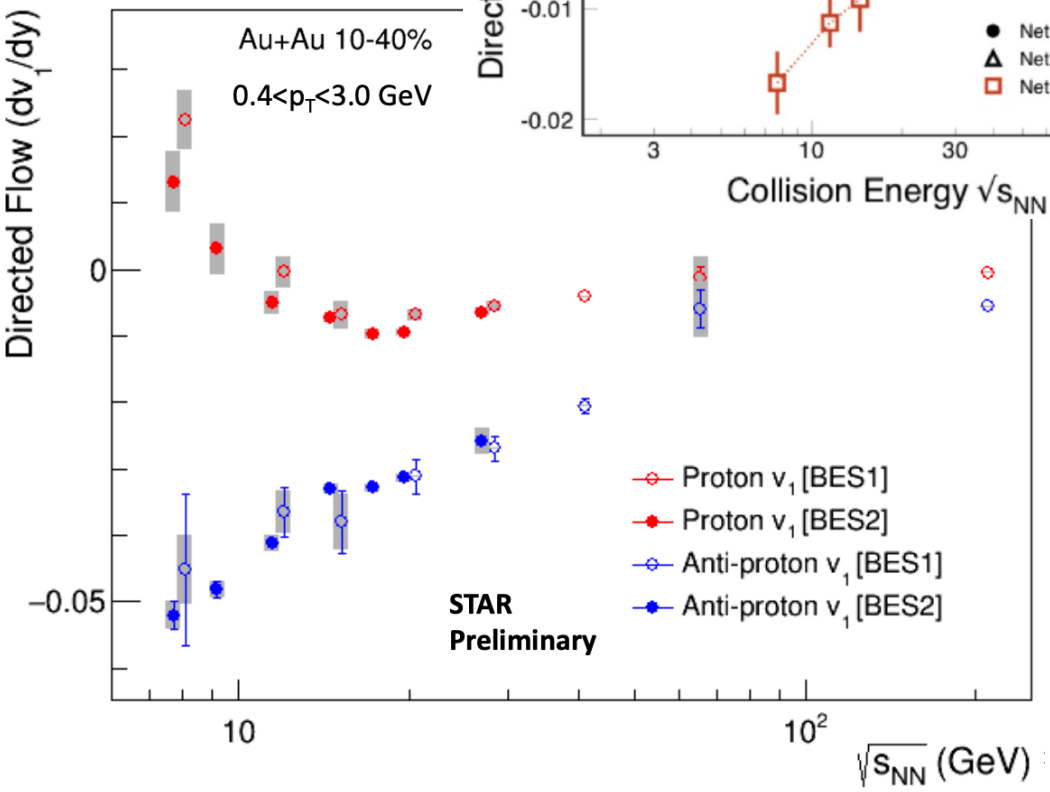


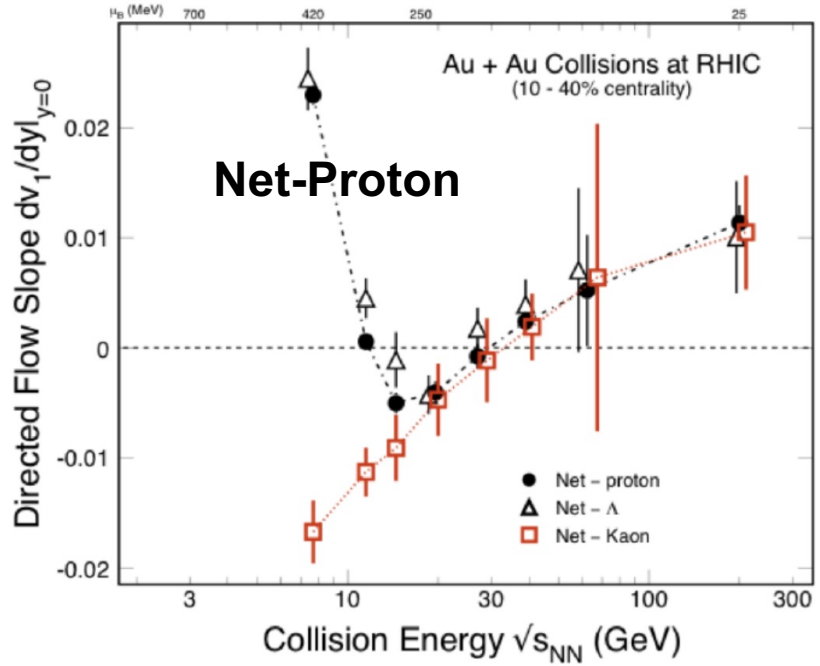


Net-Proton or Excess-Proton v_1 Slope as a Function of Collision Energy

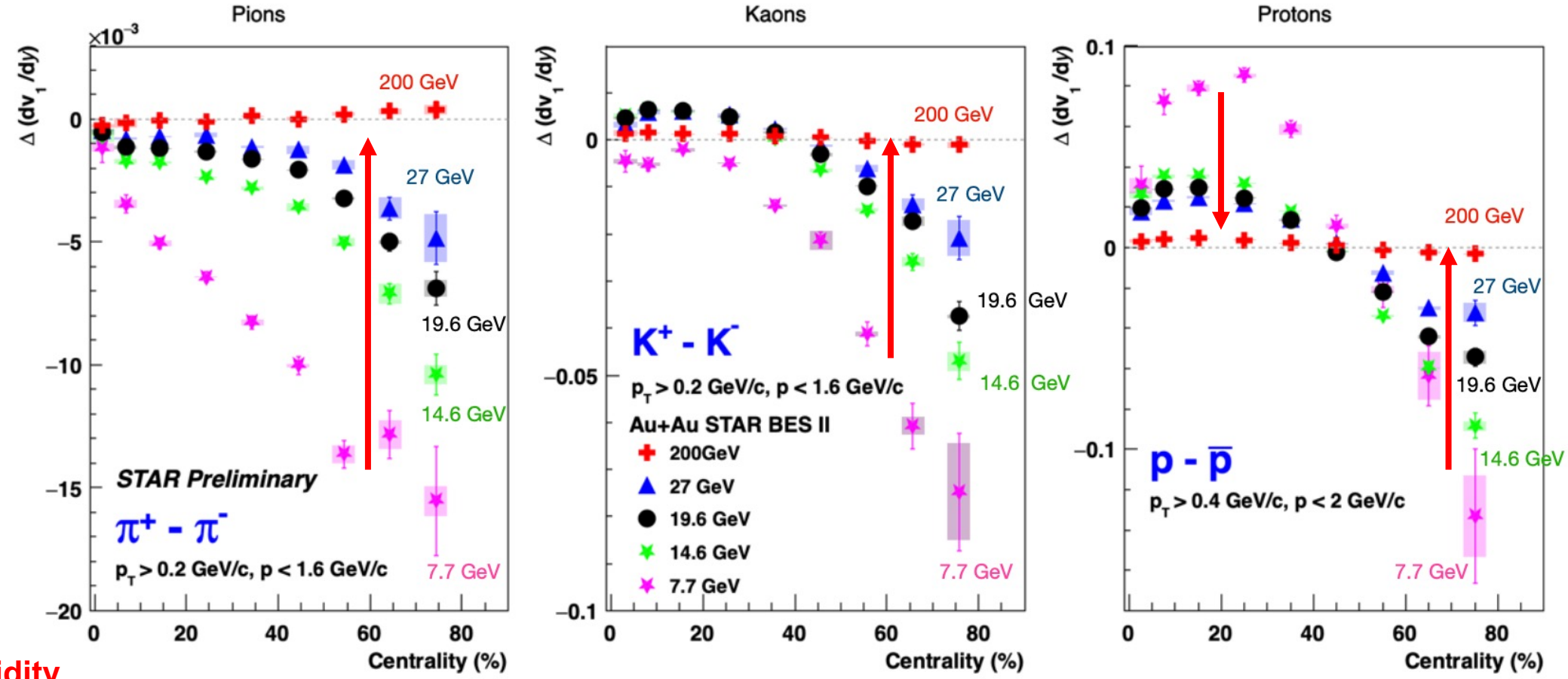
CPOD24, STAR







Charge Dependence of v_1 Slope (Collision Centrality, Energy Dependence)



p_T, rapidity differential studies