STAR COLLABORATION OVERVIEW

7TH INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS IN THE LHC ERA

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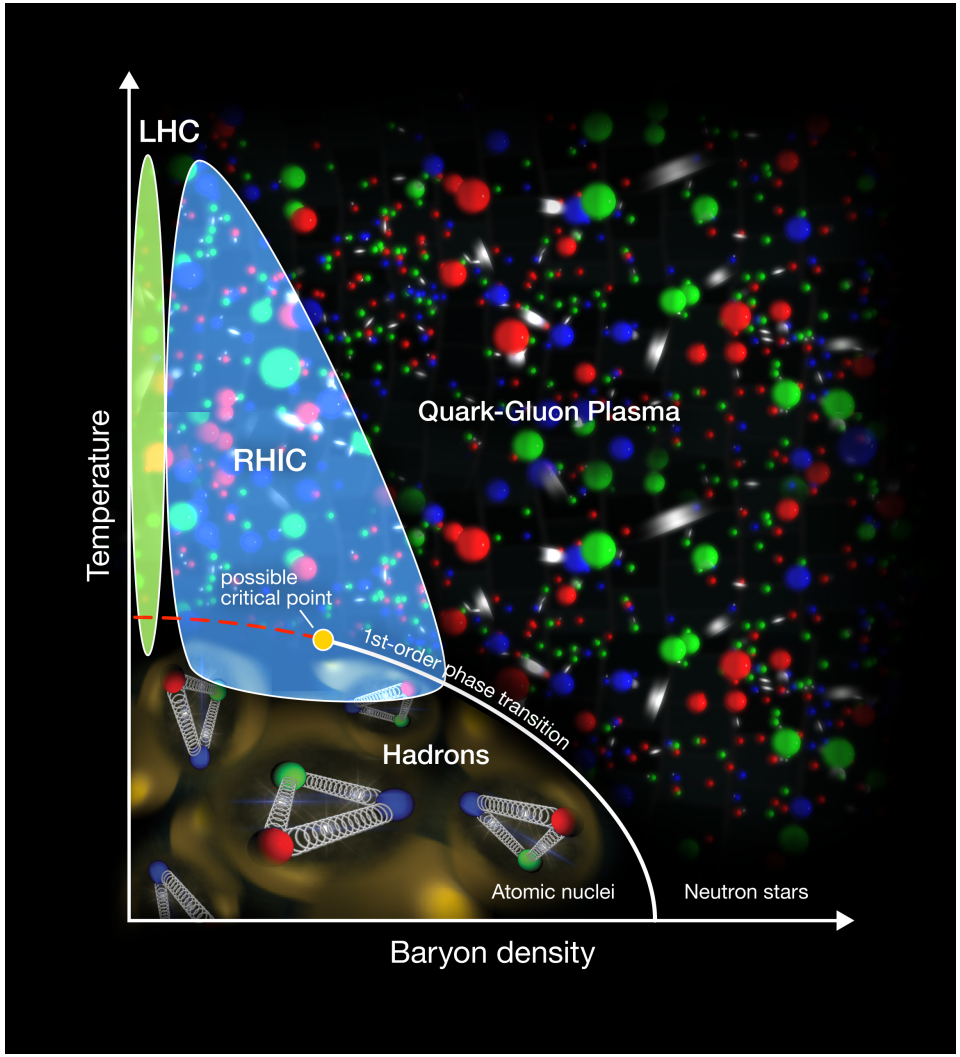
WHY RELATIVISTIC HEAVY ION COLLISIONS?

A way to explore QCD matter at extreme conditions of temperature and/or baryonic density

An important tool to investigate the QCD phase diagram

- Search for different phases of QCD matter
- Understand phase transitions
- Look for critical phenomena

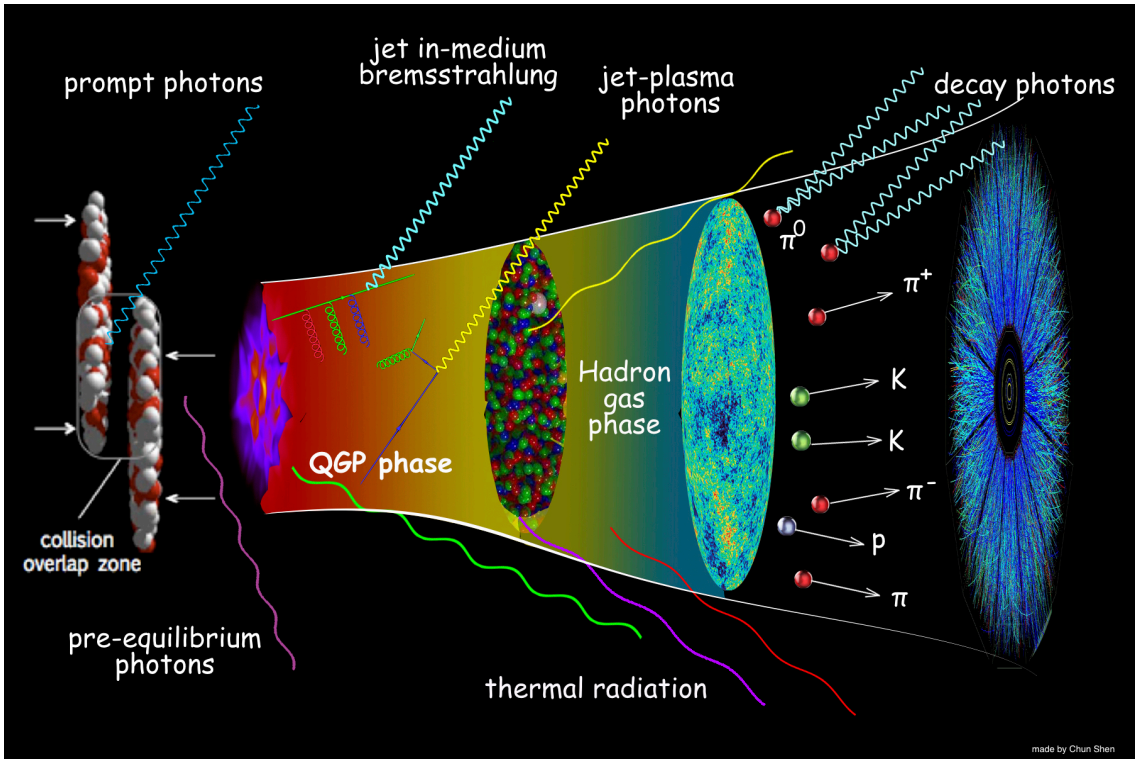


DIFFERENT OBSERVABLES, DIFFERENT EVOLUTION STAGES

A nucleus-nucleus (A-A) collision is a very complex dynamic system

- Different observables permit the investigation of different evolution stages and their properties.

To better understand what is happening in A-A collisions, it is often necessary to compare to p-p and p(d)-A collisions



OVERVIEW OF THIS TALK

The STAR experiment

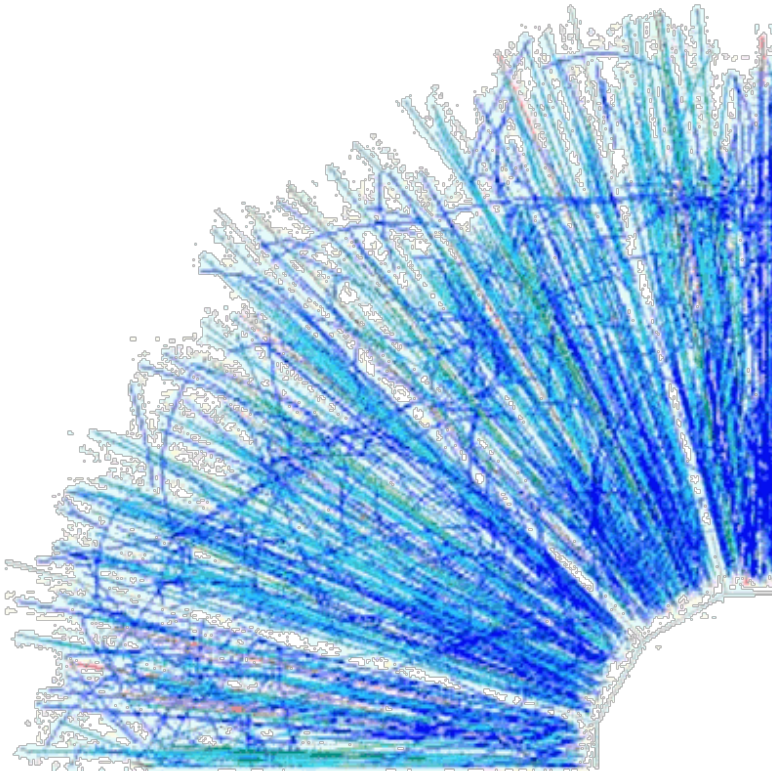
Bulk observables

- Spatial anisotropies – flow harmonics
- Hyperon polarization and vorticity
- Exploration of QCD phase diagram

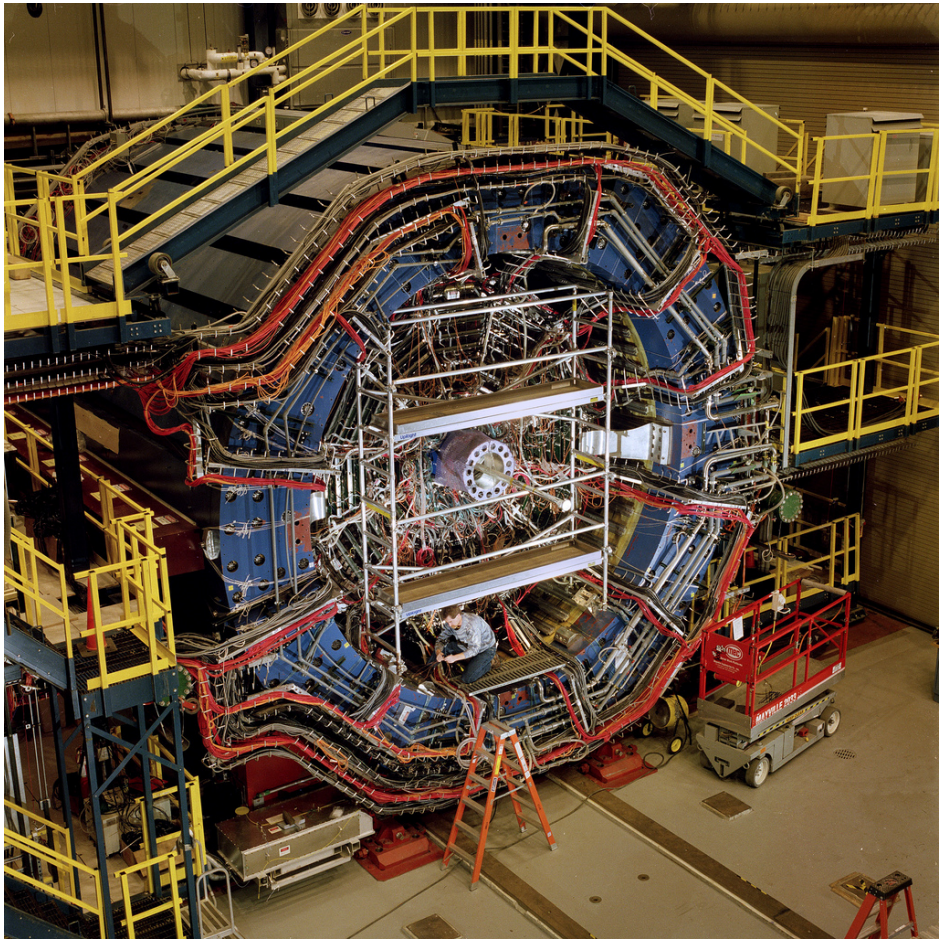
Heavy flavor measurements in STAR

- Heavy flavor meson production and flow
- J/ψ and Υ production

Future measurements and perspectives



THE STAR EXPERIMENT



Large acceptance:

- $|\eta|<1$; $0 < \phi < 2\pi$

Time Projection Chamber

- tracking, particle identification, momentum

Time of Flight detector

- particle identification

Electromagnetic Calorimeters

- electron identification, triggering

Muon Telescope detector

- muon identification, triggering

Heavy Flavor Tracker

- track pointing resolution ~50 μm at p_T~0.8 GeV/c

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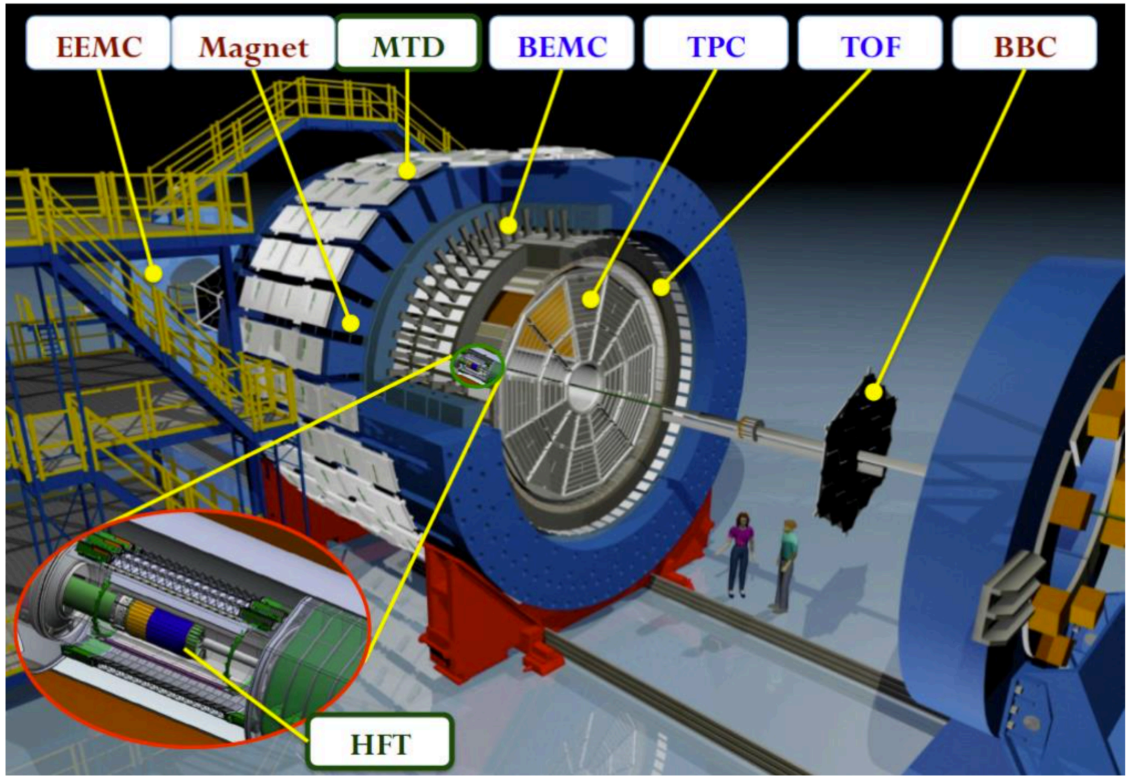

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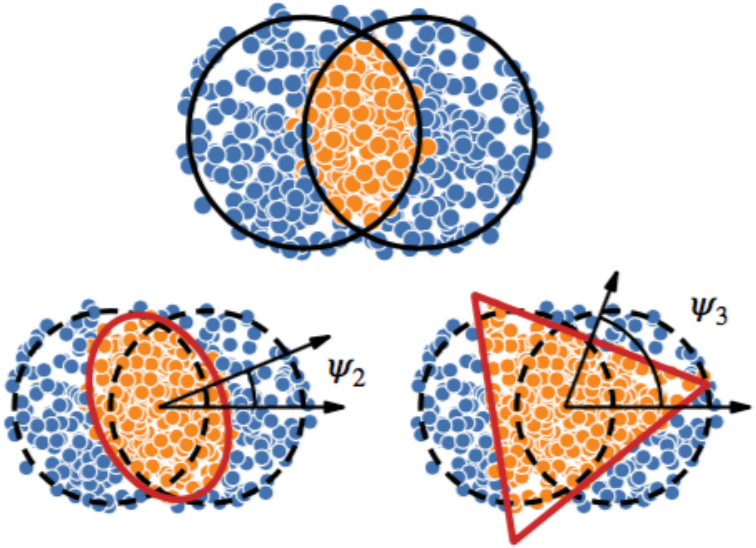
FLOW HARMONICS

Non-zero impact parameter and quantum fluctuations of initial state generates anisotropies in the spatial distribution of partons

Different pressure gradients transfer these anisotropies to the momentum space in the final distribution

Flow harmonics v_n are used to study these anisotropies

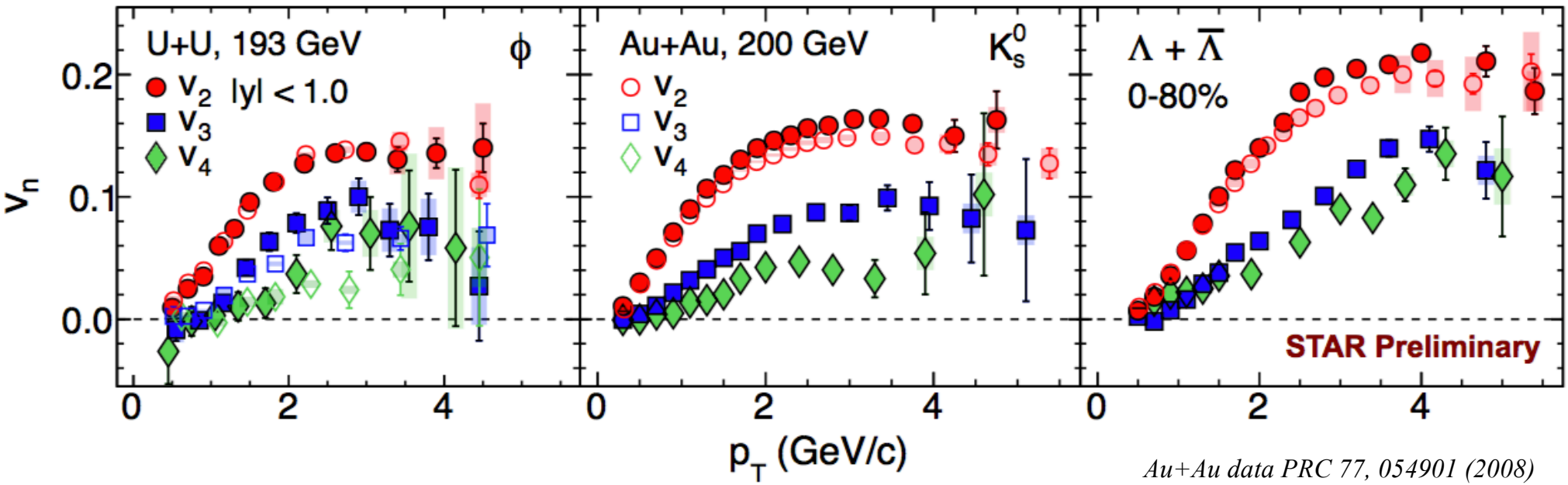


$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\varphi - \psi_n)\right)\right)$$

CENTRALITY DEPENDENCE OF FLOW HARMONICS

v_2, v_3 and v_4 of ϕ, K and Λ in Au+Au and U+U collisions

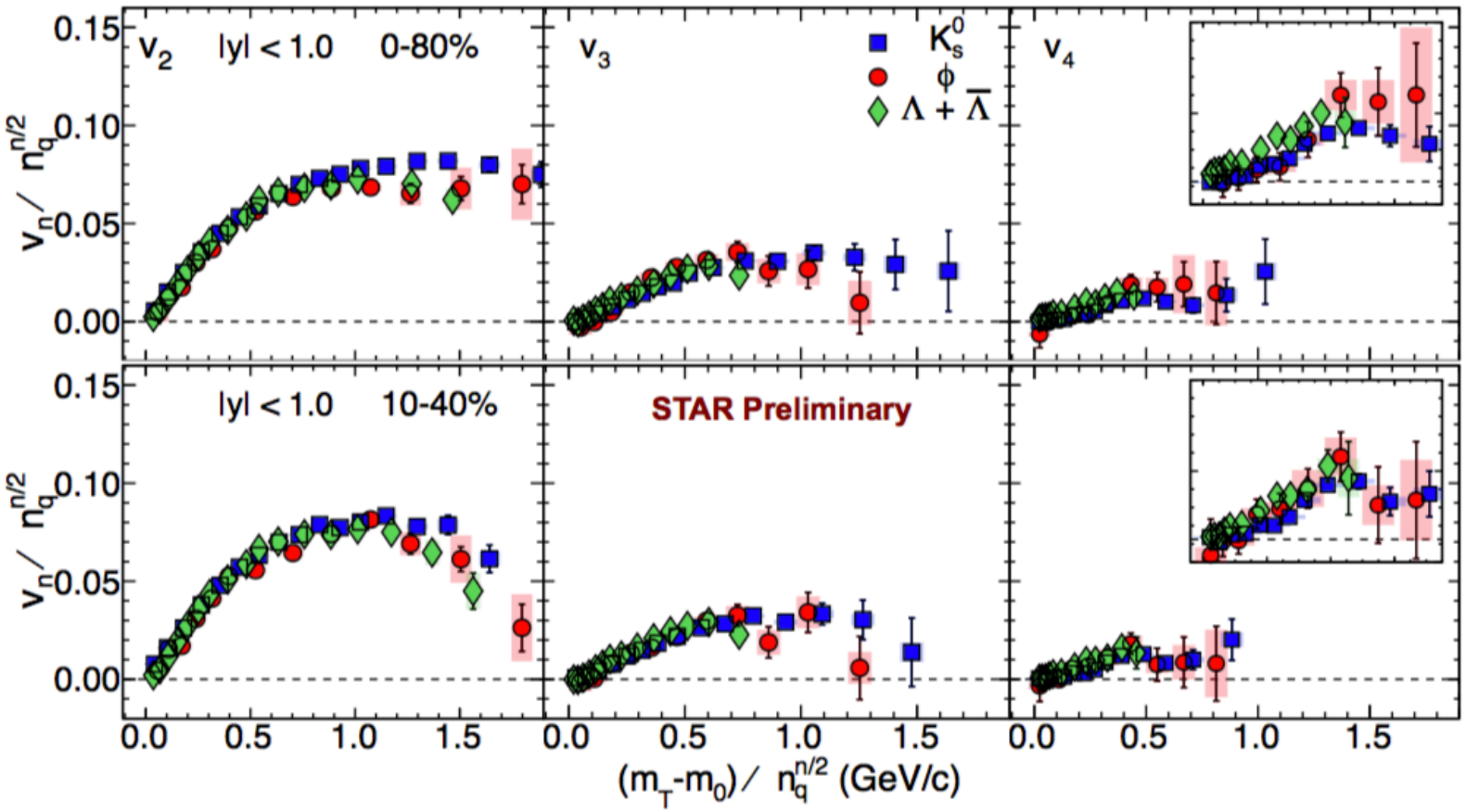
- Similar p_T dependence in both collision systems



Au+Au data PRC 77, 054901 (2008)

NCQ SCALING IN U+U

Flow coefficients in U+U follows number of constituent quarks (NCQ) scaling

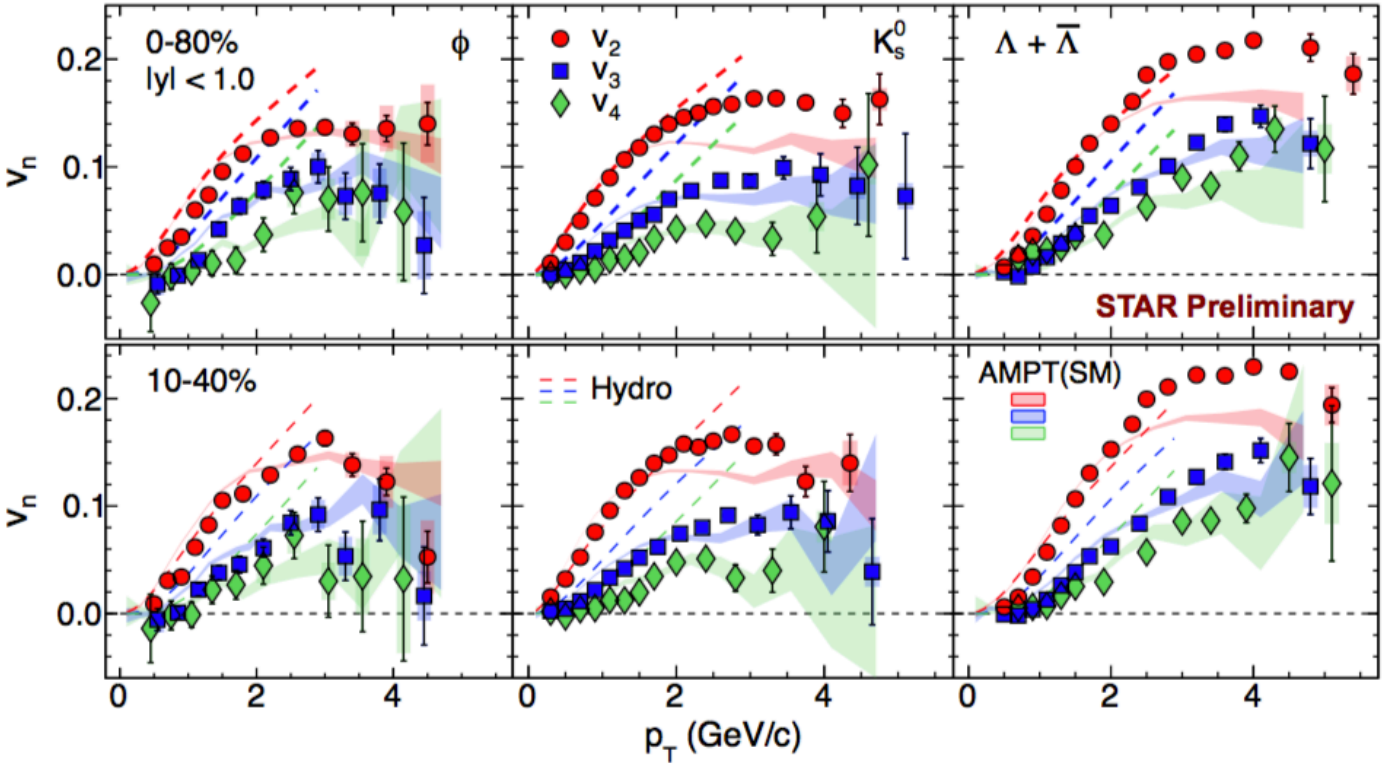


FLOW HARMONICS IN U+U: COMPARISON WITH MODELS

AMPT (string melting) describes data at low-p_T region

Dashed line – Ideal hydro with LQCD+HGR EOS

- Over predicts data. Viscous hydro is needed



AMPT: Z. W. Lin et al. PRC 72, 64901 (2005)
Hydro calculations done by V. Roy, NISER, India

SPIN ALIGNMENT, POLARIZATION AND VORTICITY IN THE QGP

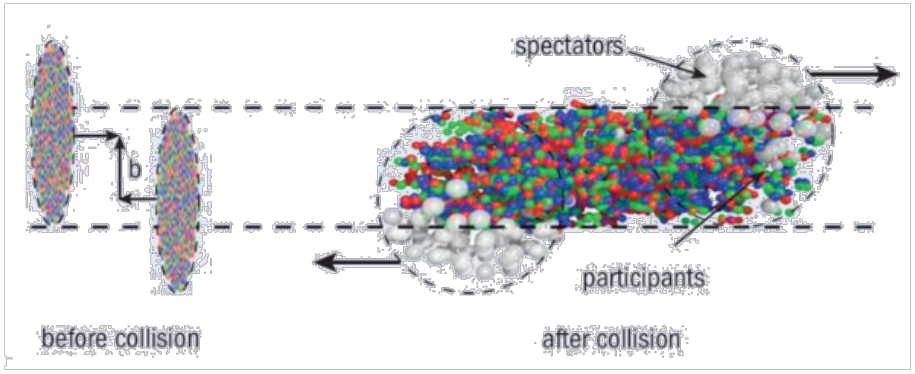
Very large initial angular momentum ($L \sim 1000\hbar$) in non-central A+A collisions

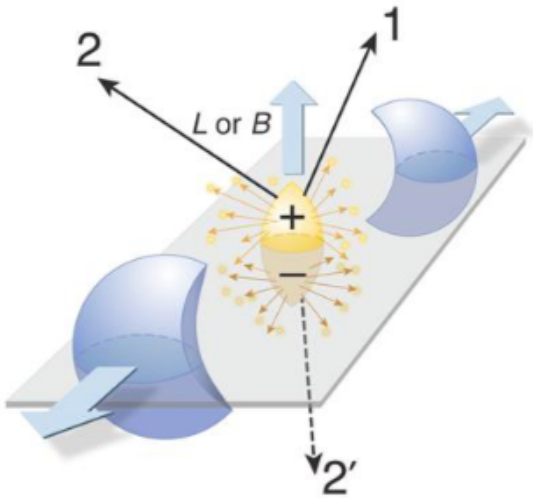
Baryon stopping may transfer this angular momentum to the QGP

Spin-orbit coupling may align spin of the particles with angular momentum

Magnetic field coupling may align (anti-align) $\bar{\Lambda}$ (Λ) spin with B field

Vorticity of the fluid may generate larger in-plane than out of plane Λ polarization



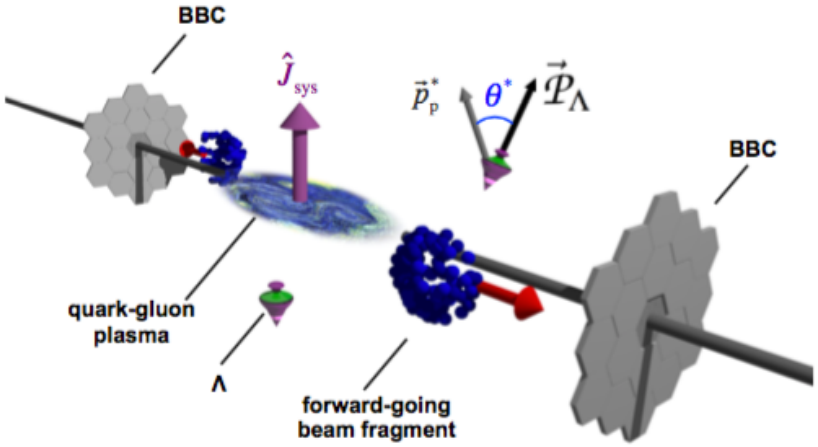


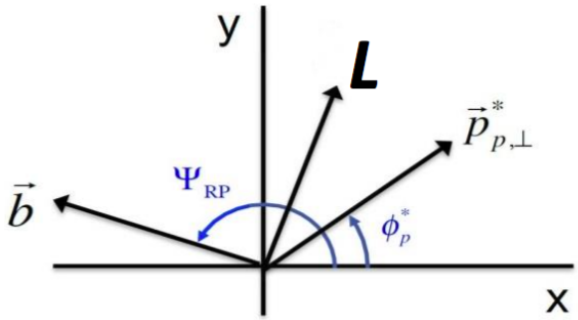
MEASURING Λ POLARIZATION

Global polarization can be measured from the angular distribution of Λ decay products relative to the system angular momentum

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H \left|\vec{P}_H\right| \cos\theta^*\right)$$

$$P_H = \left\langle \vec{P}_H \cdot \hat{J}_{syst} \right\rangle = \frac{1}{Res(\Psi)} \frac{8}{\pi\alpha_H} \left\langle \sin\left(\Psi - \phi_p^*\right)\right\rangle$$





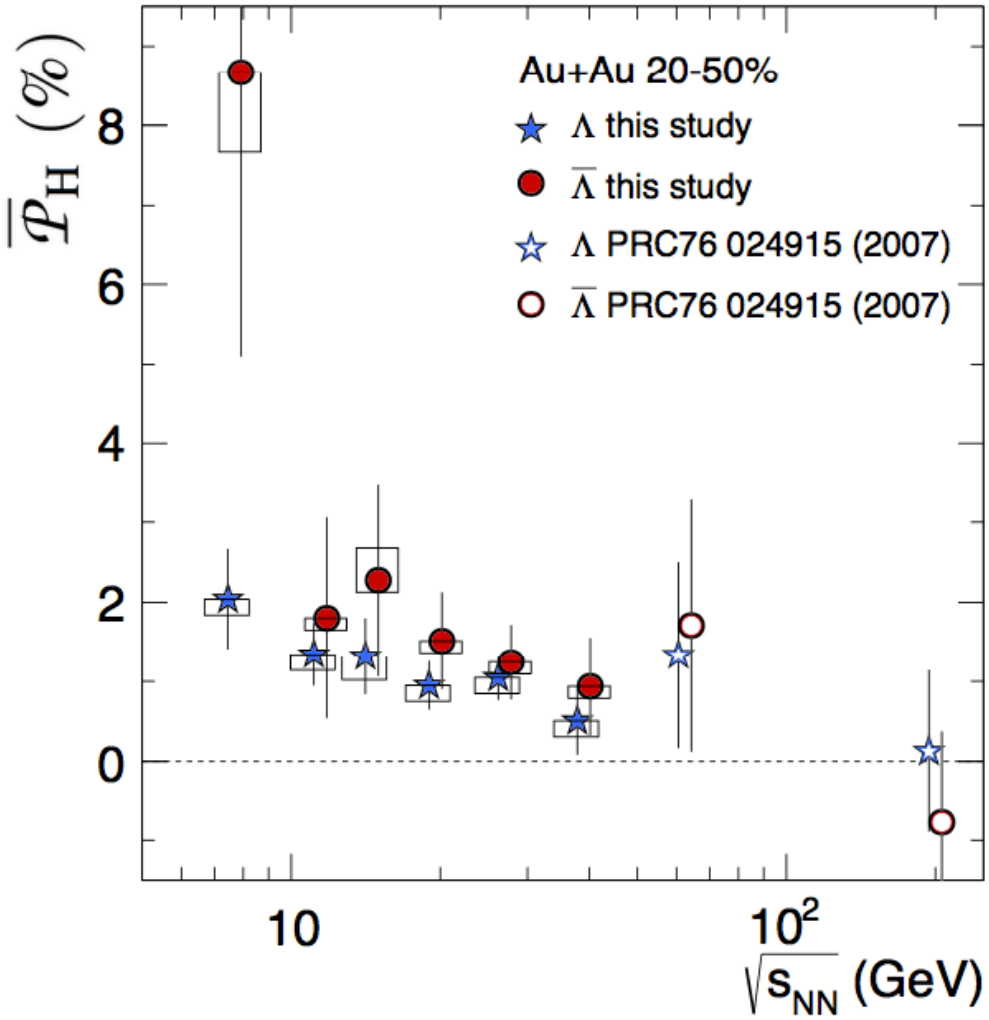
Λ AND $\overline{\Lambda}$ POLARIZATION

Nature ***548*** *(2017) 62*

Significant non-zero polarization for energies bellow 40 GeV

Both $\overline{\Lambda}$ and Λ show positive polarization implying that spin-orbit coupling and vorticity in the QGP are present

Systematic lower values of polarization for Λ than for $\overline{\Lambda}$ indicates magnetic coupling with the medium B field



EXPLORING THE QCD PHASE DIAGRAM

Our understand of the QCD phase diagram

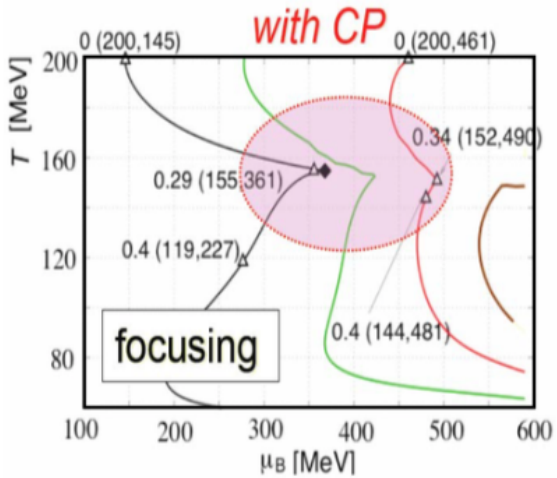
- Smooth crossover at large T and $\mu_B \sim 0$
- 1st-order phase transition at large μ_B

Location of critical point is a theoretical challenge

The STAR beam energy scan (BES) program

- Explore the phase diagram to discover the possible critical point

Evolution of system focuses near the critical point causing change of behavior in many observables



$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	1300	2017
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010

BES phase I

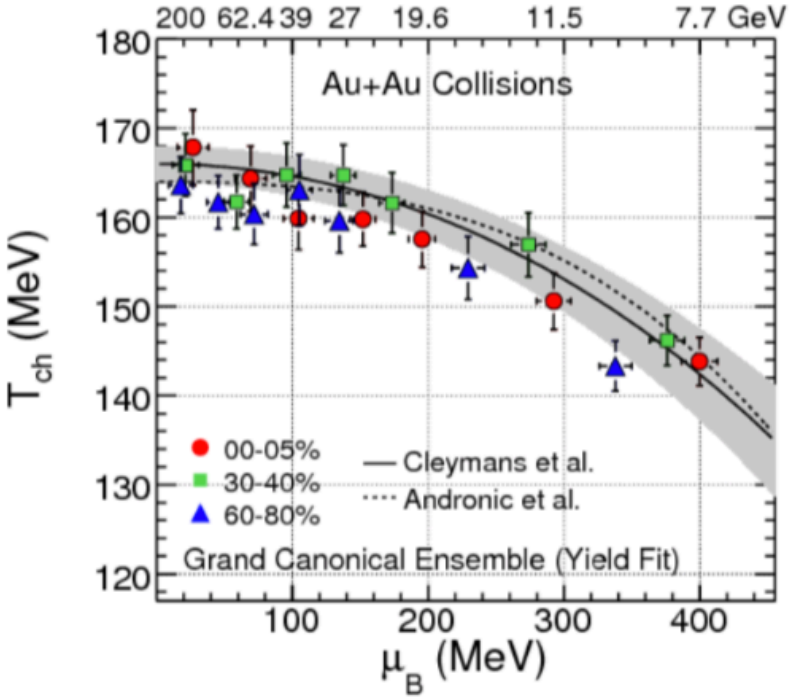
FREEZE-OUT PARAMETERS

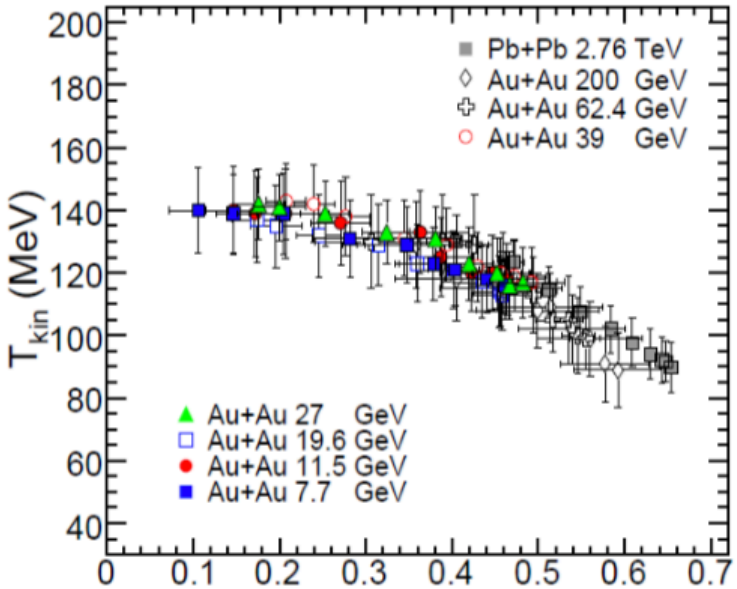
From particle ratios in the final state it is possible to infer chemical freeze-out parameters T_{ch} and μ_B

- Smooth evolution
- Well described by empirical models

From particle momentum distribution it is possible to extract kinetic freeze-out parameters T_{kin} and $\langle\beta\rangle$

- Explosive collective expansion
- More radial flow for higher energies



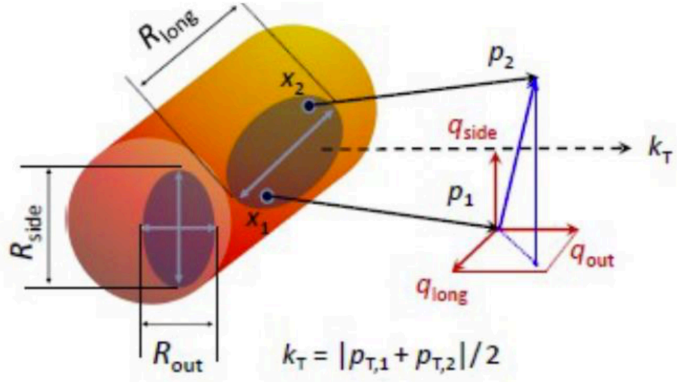


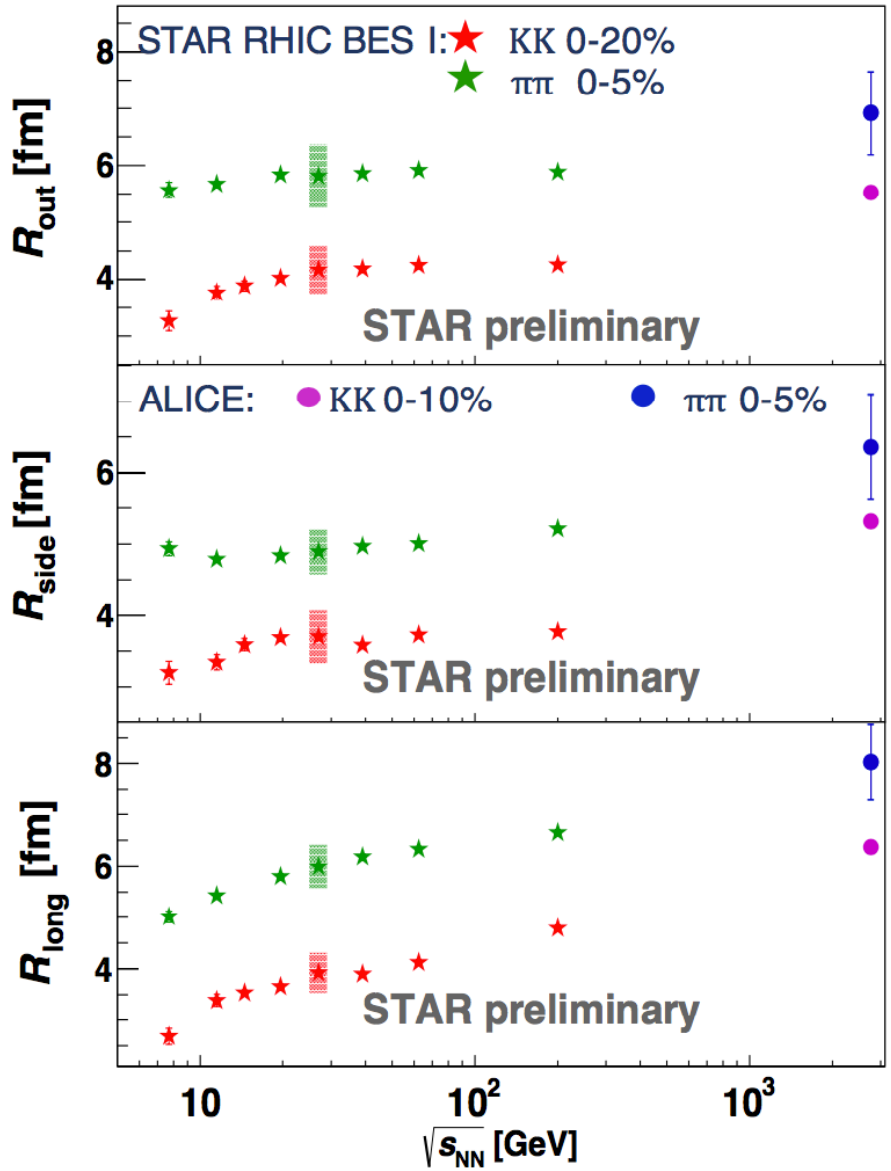
Phys. Rev. C 96 (2017) 44904

SOURCE SIZE

Increase of source radii with collision energy for kaons and pions

- Increase of R_{long} – increase on emission duration
- Increase in R_{out} and R_{side} – large system at particle emission





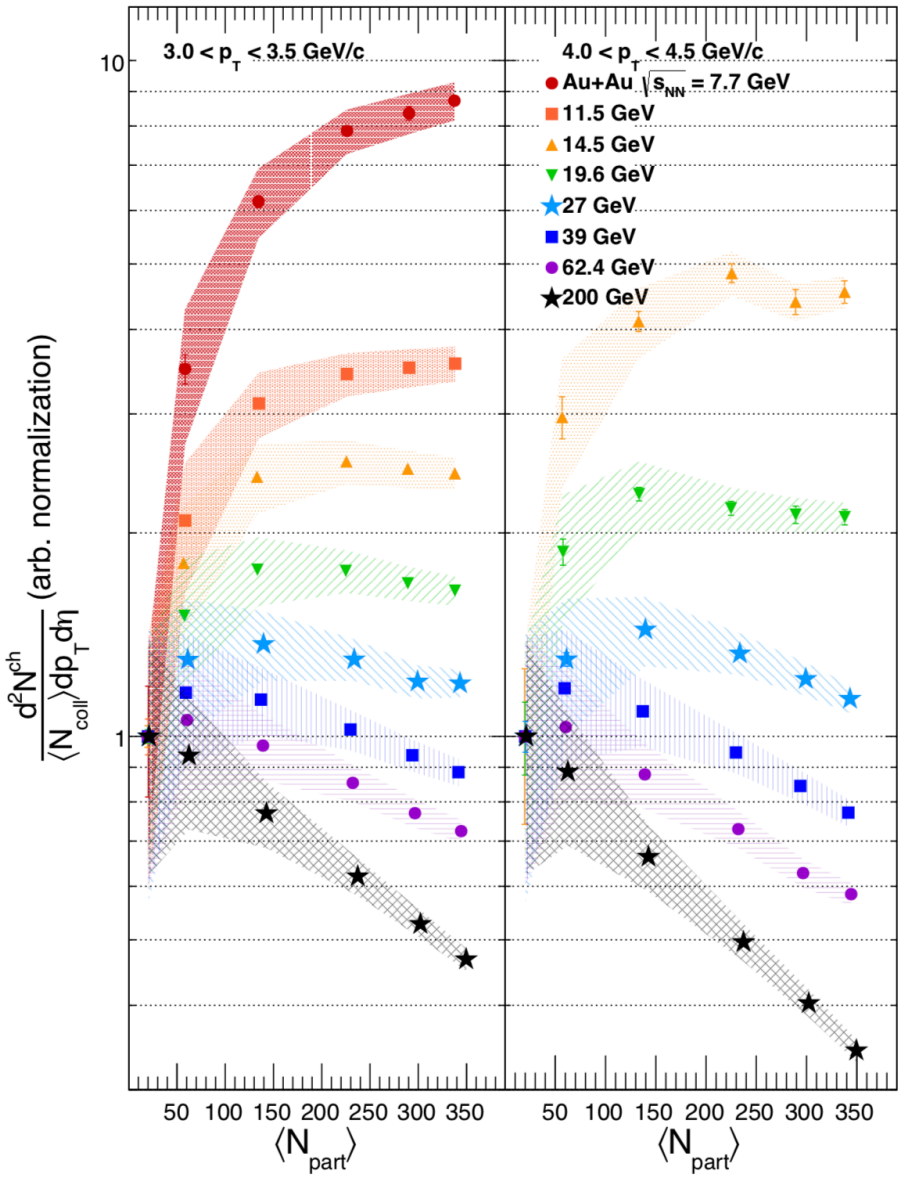
EVOLUTION OF JET QUENCHING

One of the most striking result from RHIC is jet quenching

- The suppression of high-p_T particles being one of the characteristic observable

The BES-I data allow to investigate the evolution of particle suppression with energy

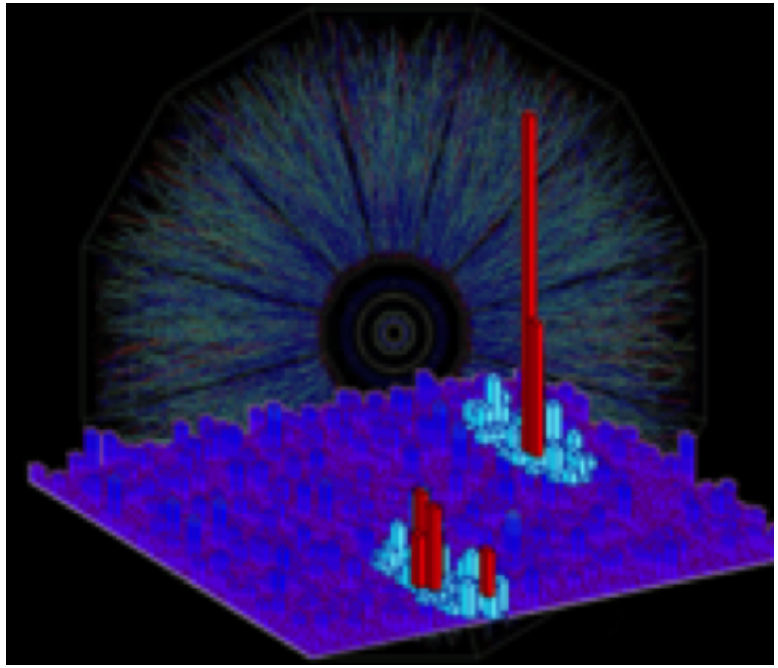
- Suppression turns off around 17 GeV



arXiv:1707.01988v1

IN FACT…

Significantly enhanced understanding of jet modifications at RHIC



High p_T hadron suppression at BES (*arXiv:1707.01988*)

pp in very good agreement with theory (*PRD 95 (2017) 71103 (R)*)

Unbiased recoil jets highly suppressed due to medium induced broadening

Total E_{loss} less than at LHC (*PRC 96 (2017) 24905*)

Lost energy re-emerges at low p_T not z_T (*PLB 760 (2016) 689*)

Di-jet energy imbalance largely recovered within R=0.4 when low p_T hadrons included (*PRL 119 (2017) 062301* - Editor's suggestion)

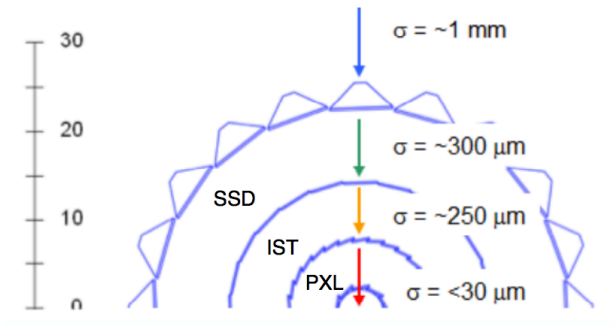
z_g unmodified for hard core jets (preliminary release)

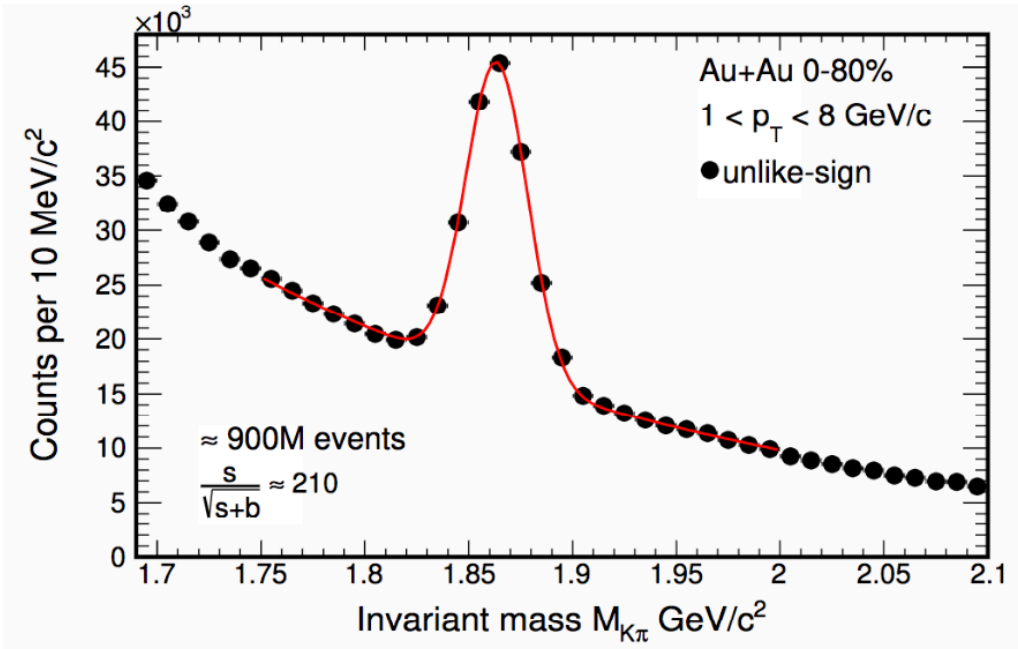
γ-jet, jet in small systems, flavor jet … (soon available)

OPEN HEAVY FLAVOR HADRONS

The STAR Heavy Flavor Tracker was installed for data taking during 2014-2016

- Excellent track pointing resolution
- Topological reconstruction of heavy flavor hadrons
- Significantly improved signal to background ratio





STAR PRL 118, 212301 (2017)

D^0 ELLIPTIC FLOW

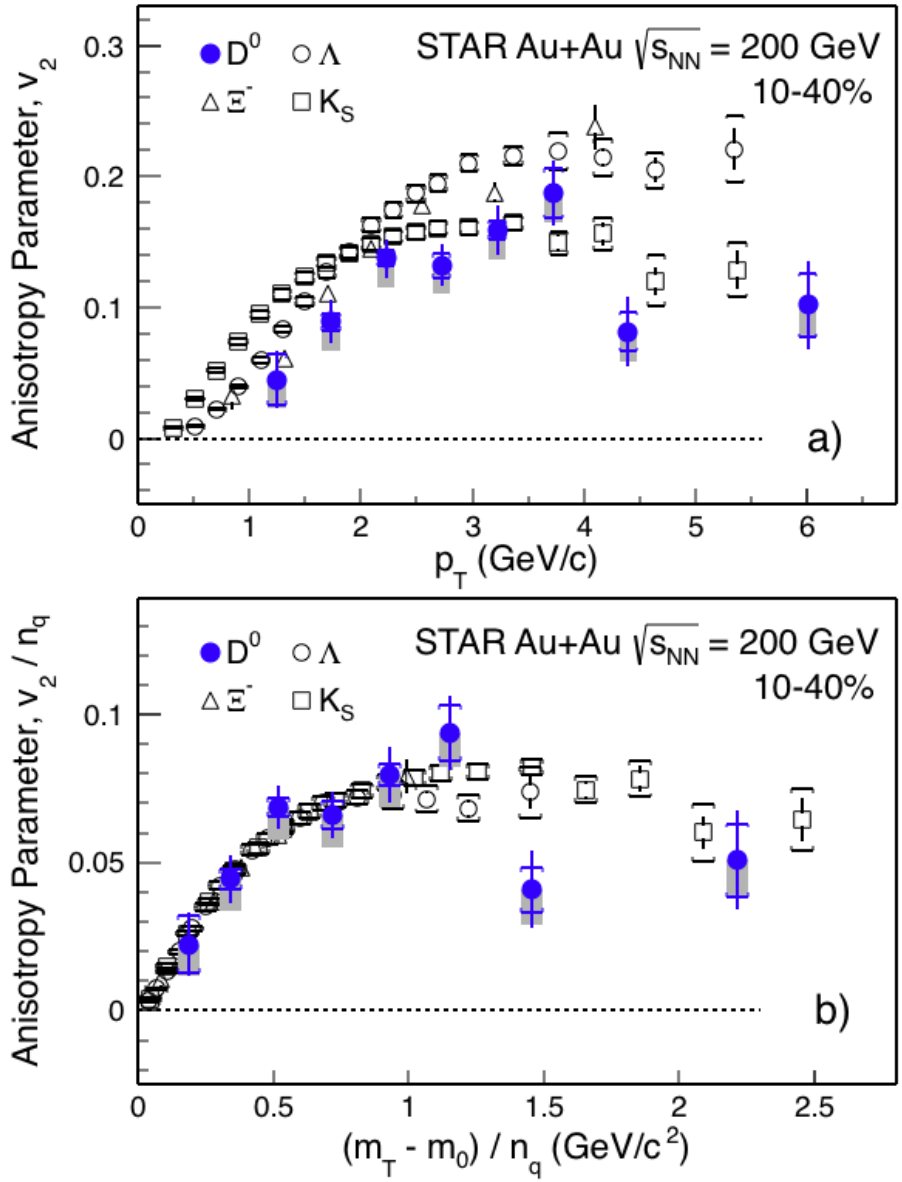
STAR PRL 118, 212301 (2017)

D^0 mesons exhibit large v_2, comparable to what is seen for light hadrons

- Mass ordering is seen for $p_T < 2$ GeV/c

Number of constituent quark (NCQ) scaling is seen for D^0 mesons

- Same behavior as for light hadrons
- Suggests that charm quarks flow with the medium

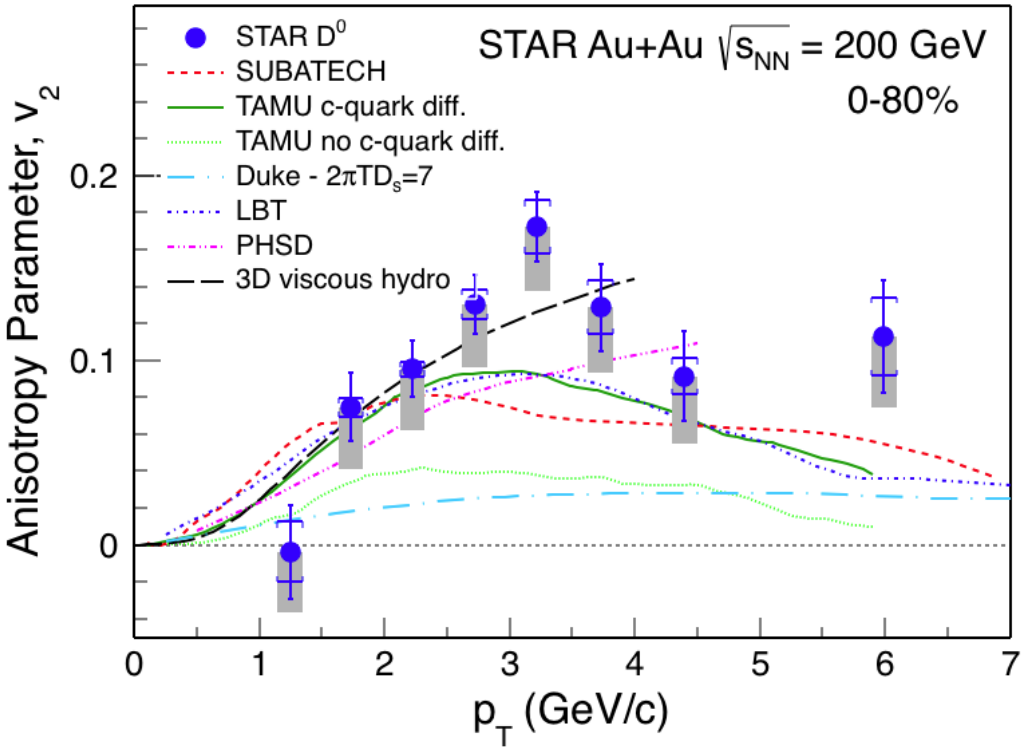


D^0 ELLIPTIC FLOW

STAR PRL 118, 212301 (2017)

3D hydrodynamic simulation describes the data at low-p_T region, bellow ~4 GeV/c

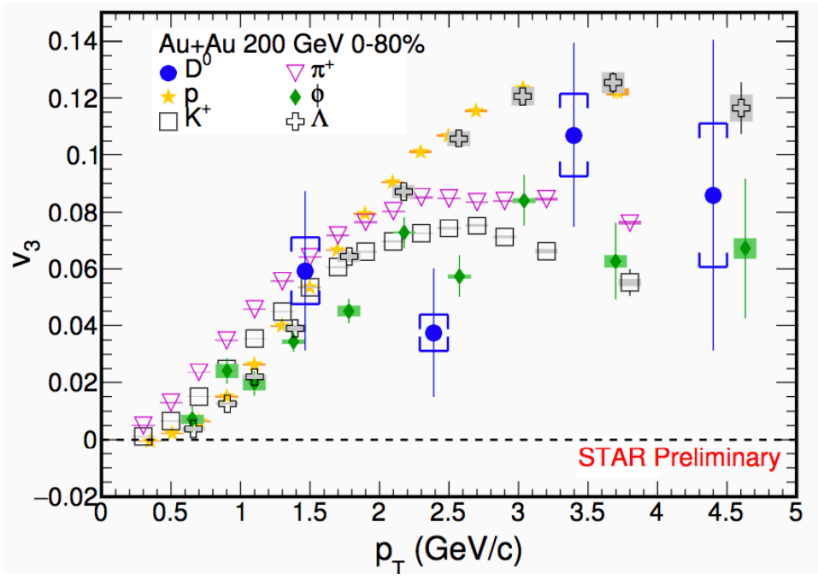
Indication that charm quarks are thermalized with the medium created in 200 GeV Au+Au collisions



D^0 TRIANGULAR FLOW

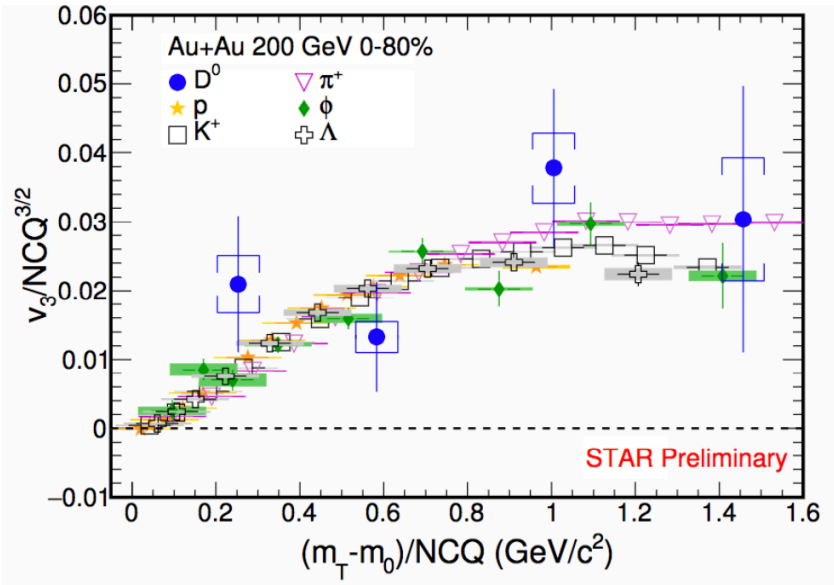
Non-zero v_3 values are observed for D^0 mesons in minimum-bias Au+Au collisions at 200 GeV

- Compatible to what is observed for light flavor hadrons



Consistent with NCQ scaling (be aware of large uncertainties)

- Strong interactions of heavy quarks with the QGP

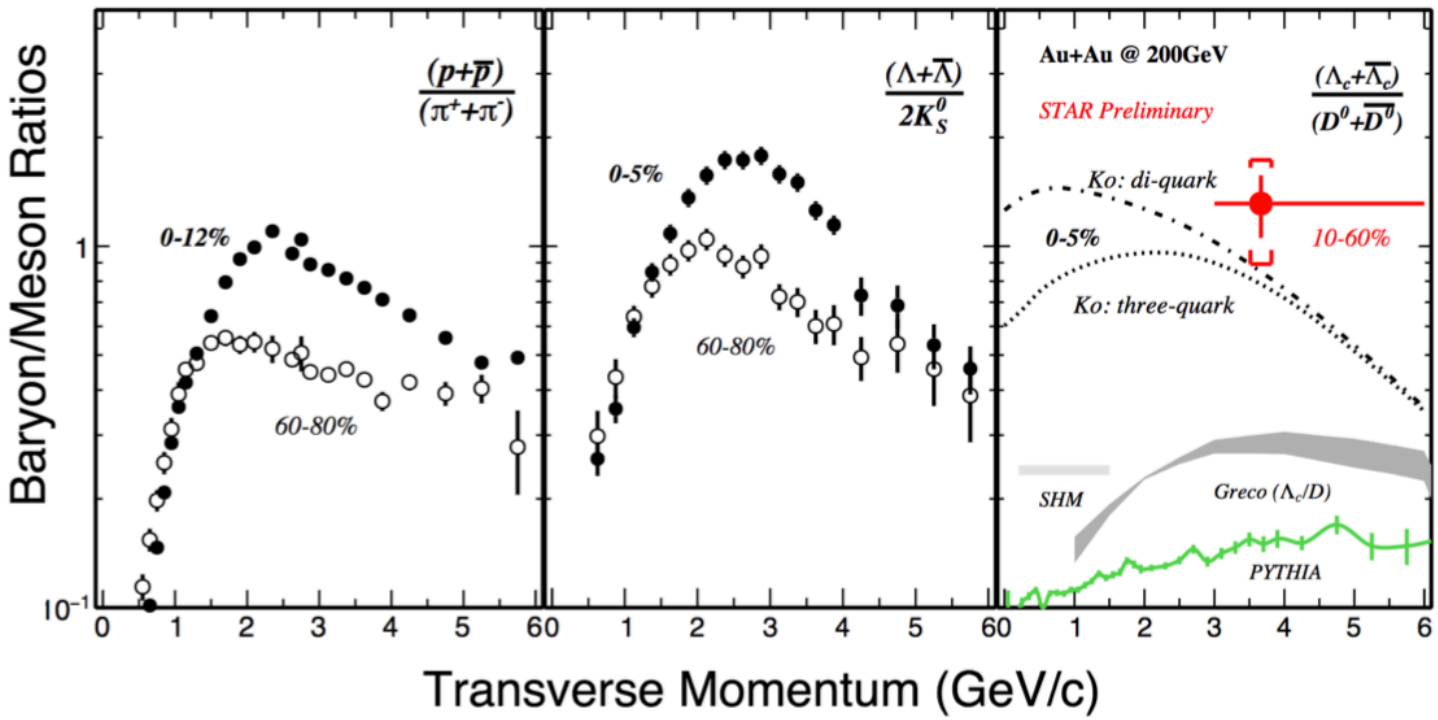


Λ_c PRODUCTION

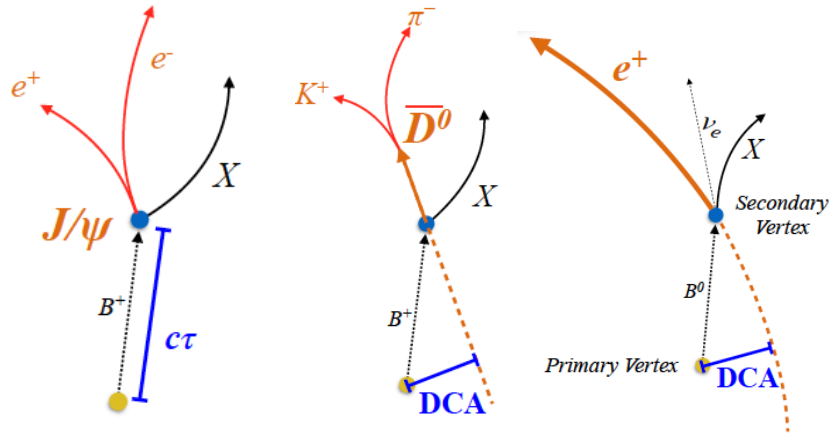
Large baryon to meson ratio in heavy flavor sector

- Similar to the ratio observed for light hadrons

Consistent with model calculations including coalescence hadronization and thermalized heavy quarks in the medium

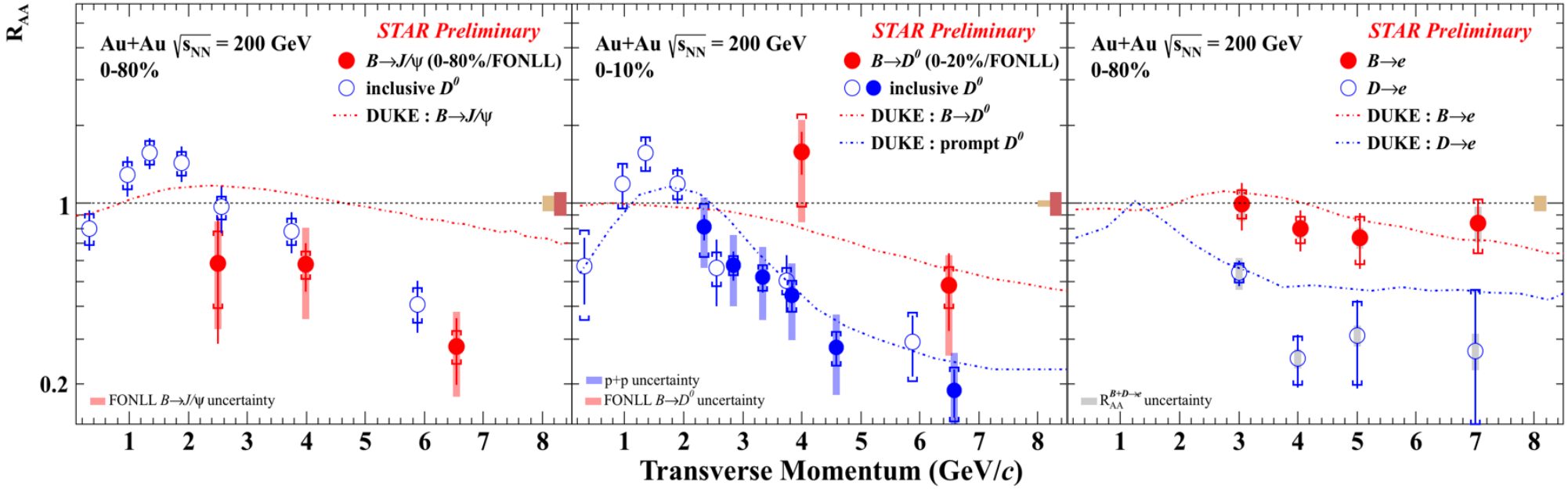


B MESON PRODUCTION



Suppression of B mesons is observed in three different decay channels

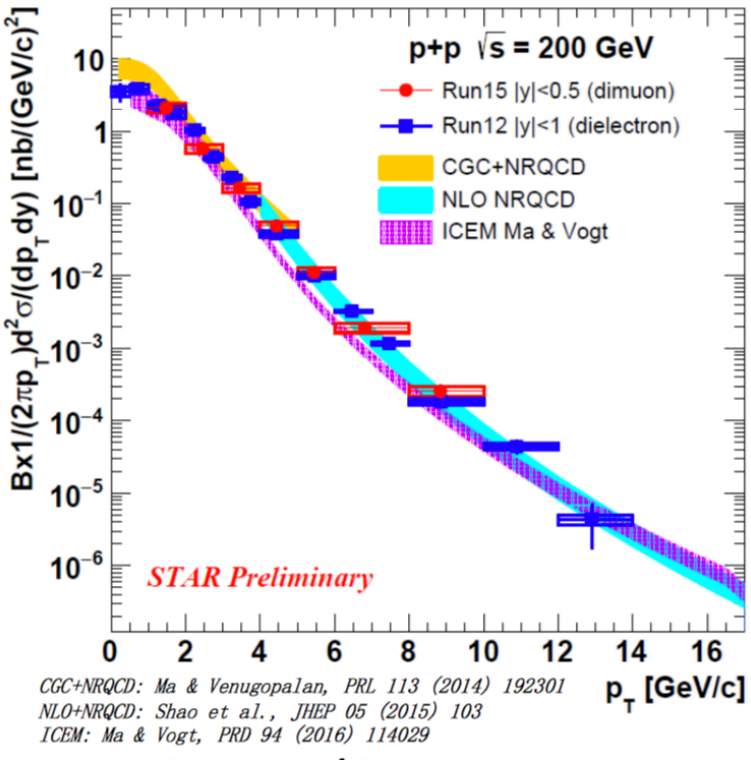
B is less suppressed than D mesons (2 sigma effect in electron channel)

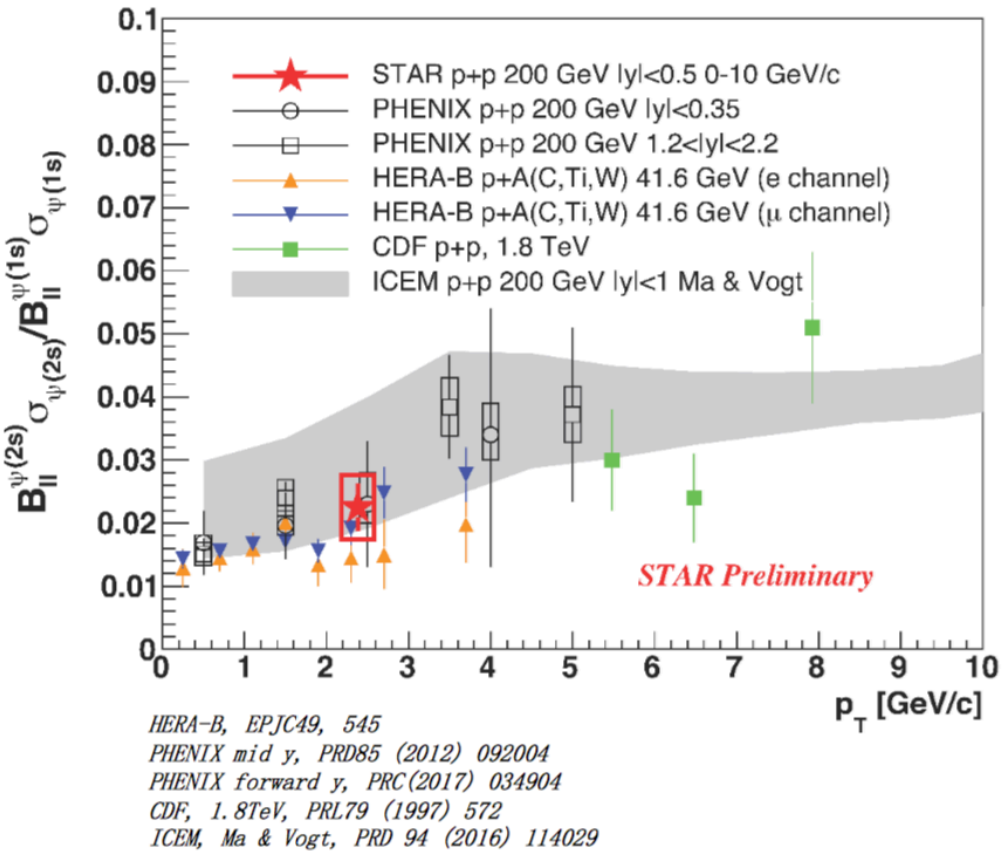


J/ψ AND ψ(2S) PRODUCTION

Consistent with CGC + NRQCD and NLO NRQCD

ψ(2s)/ ψ(1s) ratio consistent with world data

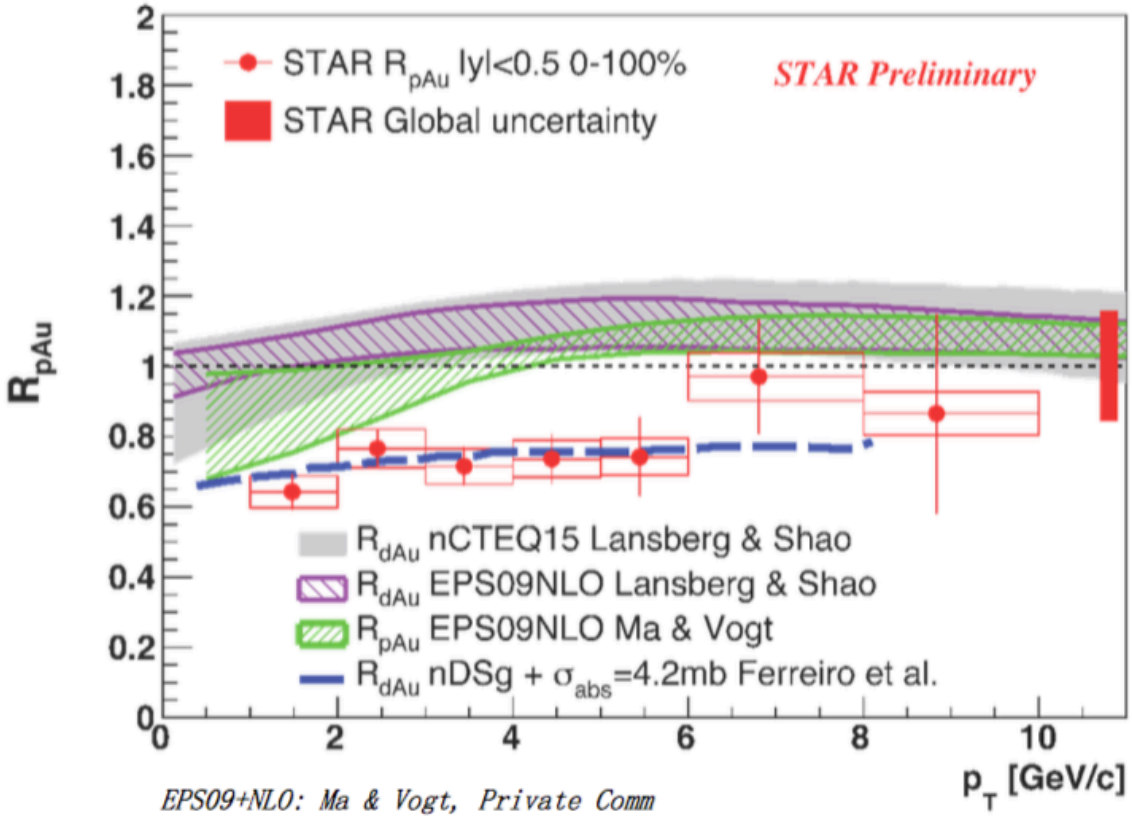




J/ψ PRODUCTION IN p+Au COLLISIONS

R_{pAu} consistent with unity at high-p_T (large uncertainties)

Production of J/ψ in p+Au collisions favors models with an extra nuclear absorption on top of PDF modification



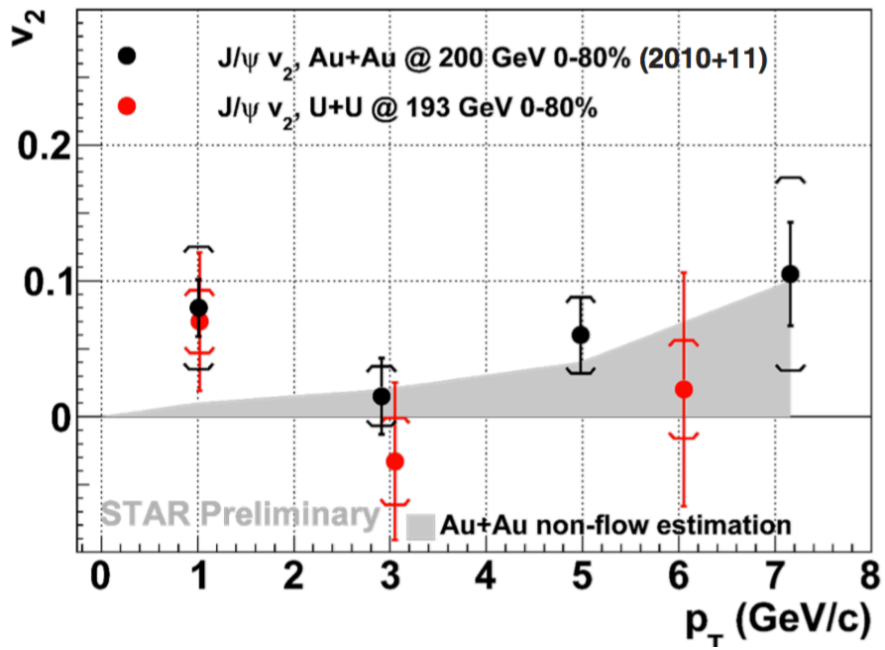
EPS09+NLO: Ma & Vogt, Private Comm
nCTEQ, EPS09+NLO: Lansberg Shao,
Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570
Ferreriro et al., Few Body Syst. 53 (2012) 27

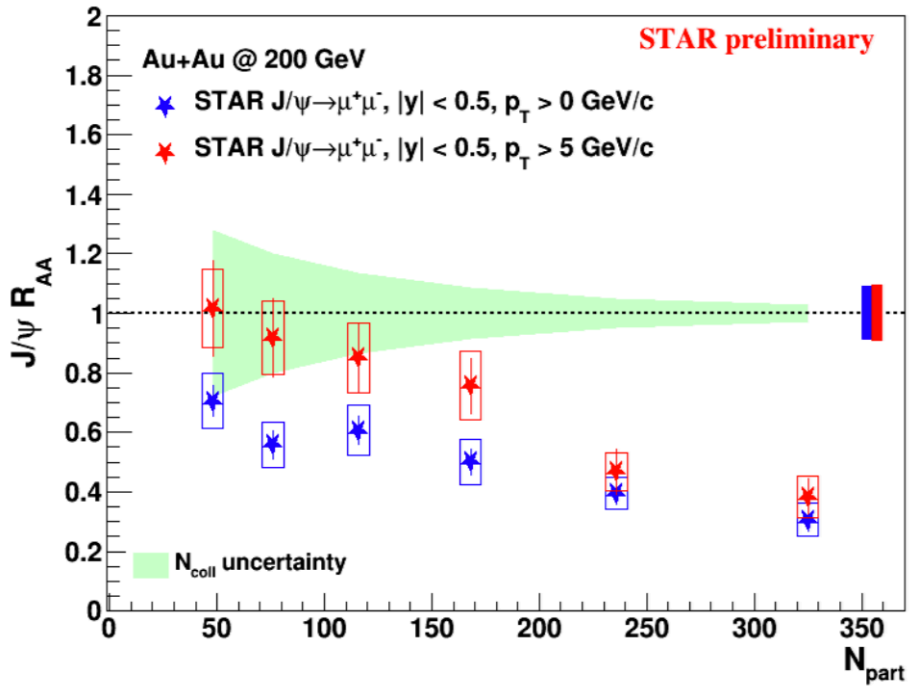
J/ψ IN A+A

Measurements of J/ψ v_2 in U+U collisions are consistent with the previous Au+Au results

- Consistent with zero v_2 above 2 GeV/c disfavoring a dominating regeneration contribution in this kinematics range

R_{AA} measurements indicate a strong suppression for $p_T > 5$ GeV/c in central collisions, a strong evidence of J/ψ dissociation in the medium



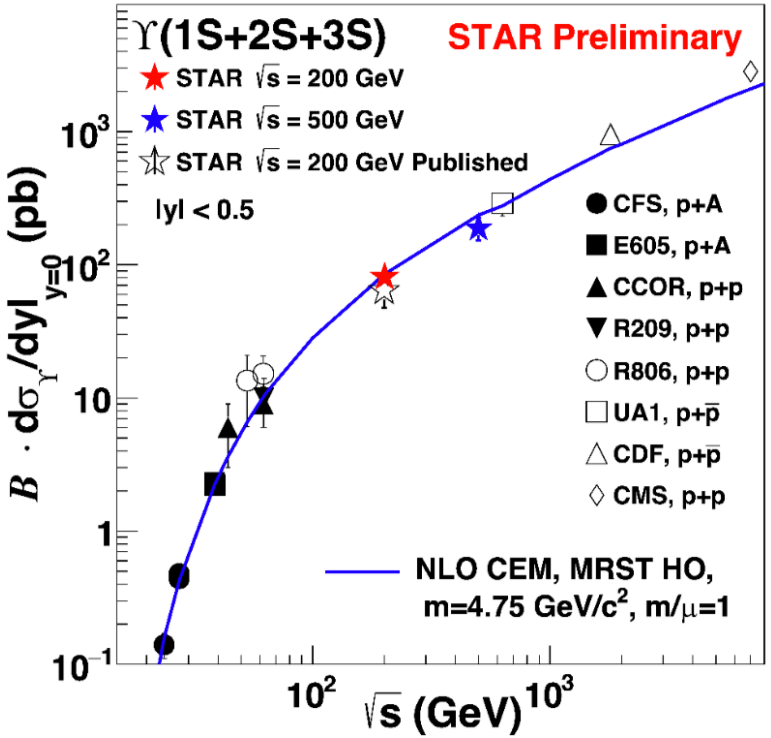


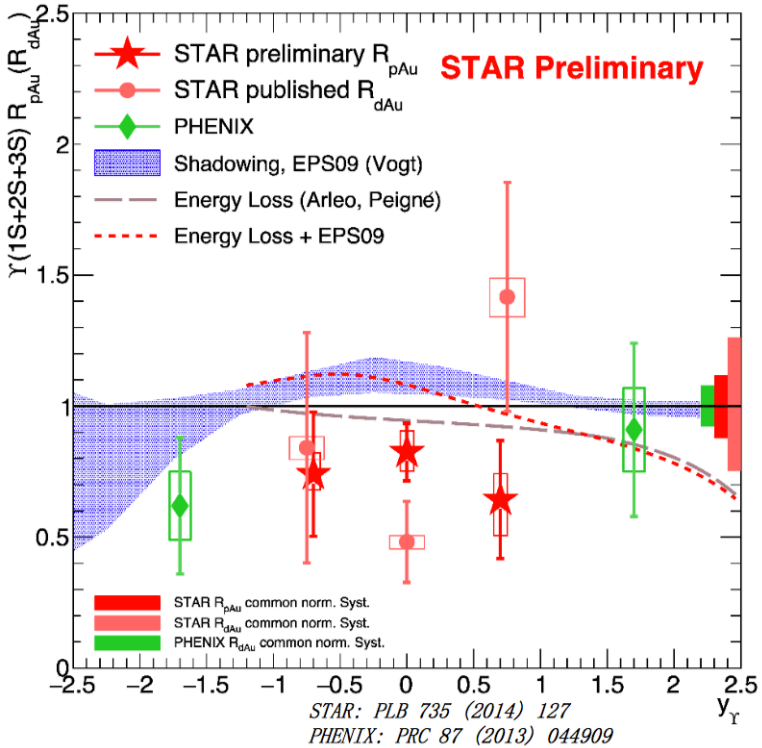
ϒ PRODUCTION IN p+p AND p+Au

Production in p+p collisions consistent with world data trend

Measurements in p+Au collisions can be used to quantify CNM effects

- $R_{pAu} = 0.82 \pm 0.10(stat) \pm 0.08(syst) \pm 0.10(global)$





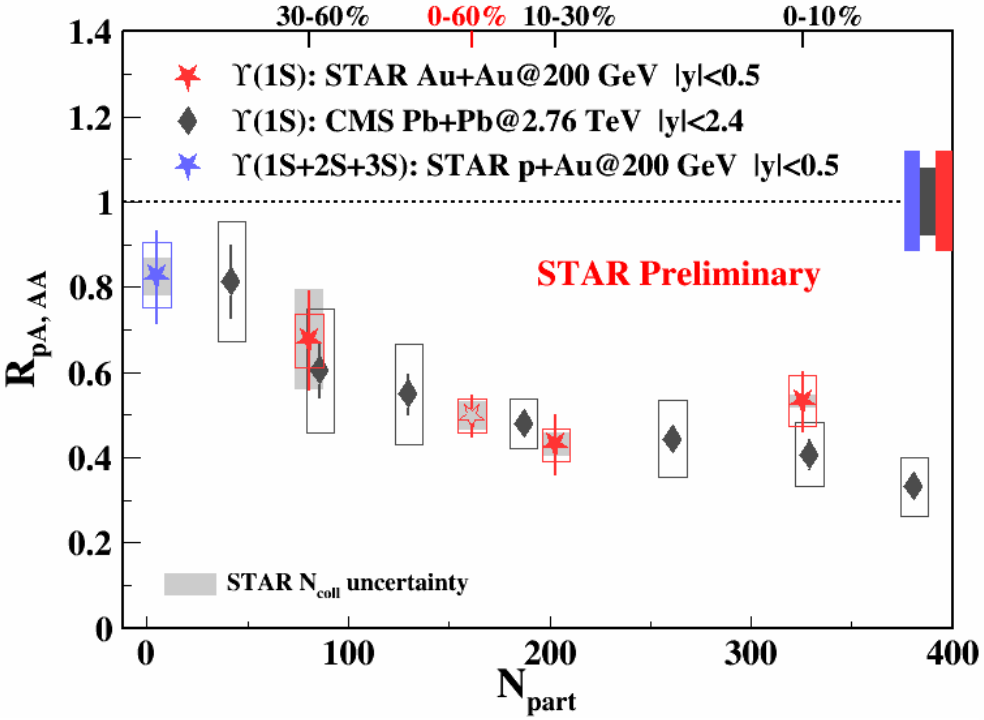
STAR: PLB 735 (2014) 127
PHENIX: PRC 87 (2013) 044909
R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065

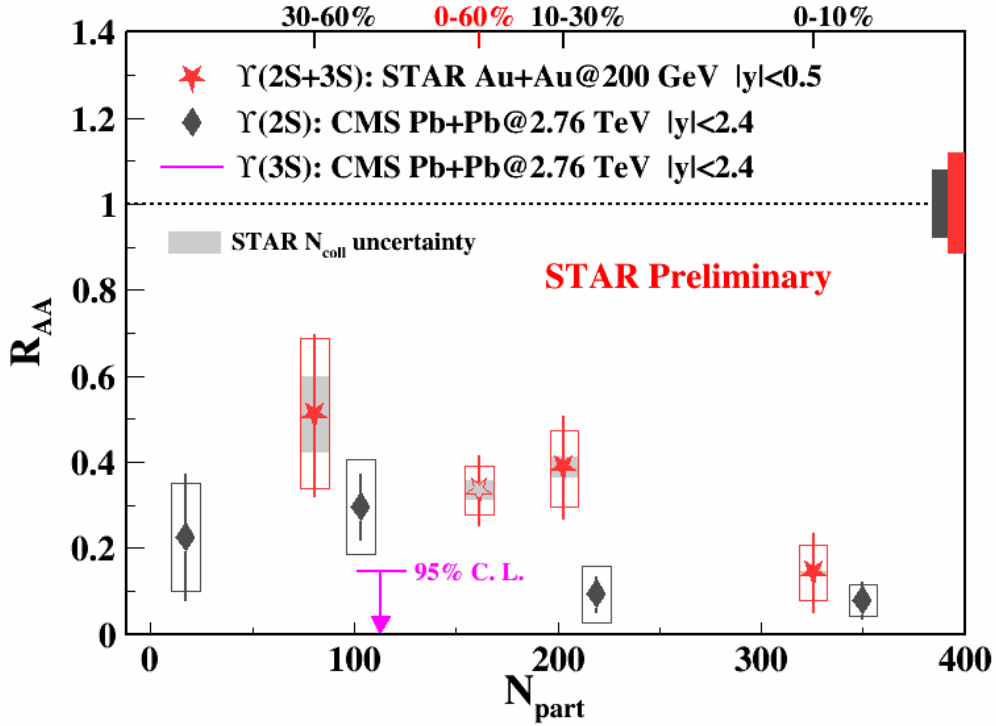
ϒ PRODUCTION IN Au+Au

Indication of increasing suppression with centrality

- Similar suppression to that at the LHC for ϒ(1S)

ϒ(2S+3S) is more suppressed than ϒ(1S) → sequential melting





FUTURE PERSPECTIVES

STAR has a striking physics and upgrade program for the upcoming years

2018 data taking

- Isobaric run (Ruthenium-96 (Ru+Ru) and Zirconium-96 (Zr+Zr)) to address chiral magnetic effect
- Au+Au collisions at 27 GeV to improve statistics on Λ polarization
- Fixed target run at 3 GeV

BES – II (Beam Energy Scan phase II) (2019-2020)

- Several measurements at different energies in collider mode and fixed target mode to explore the QCD phase diagram
  - $\sqrt{s} = 9.1, 11.5, 14.5$ and 19.6 GeV in collider mode
  - $\sqrt{s} = 3.0, 3.5, 3.9, 4.5, 5.2, 6.2$ and 7.7 GeV in fixed target mode
- Several upgrades to improve STAR capabilities for the BES-II data taking

FUTURE UPGRADES

iTPC

- Continuous pad rows
- Replace all inner TPC sectors
- $|\eta| < 1.0 \rightarrow |\eta| < 1.5$
- Improved dE/dx and momentum resolution

EPD

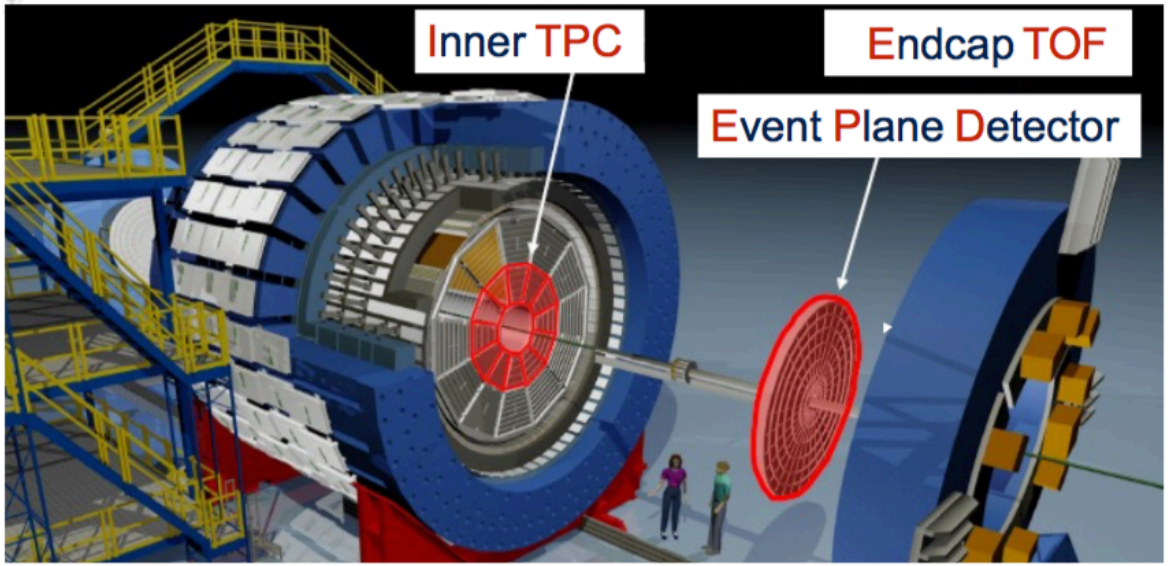
- Replace beam-beam counter
- Better trigger and EP resolution
- $2.1 < |\eta| < 5.1$

eTOF

- $-1.6 < \eta < -1.1$
- Extend PID capability (FXT)

From RHIC

- Low energy electron cooling
- Improved luminosity by a factor of 3 for BES-II



	iTPC	EPD	eTOF
2017	-	1/8 installed	1 prototype
2018	One sector	Full Installation	3 modules at one sector
2019	Full Installation	Full Installation	Full Installation