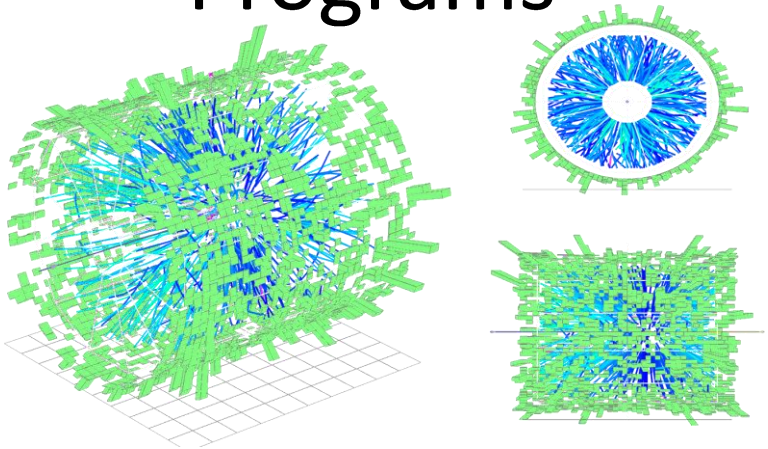
Recent STAR Results from Heavy-Ion and Polarized Proton Programs



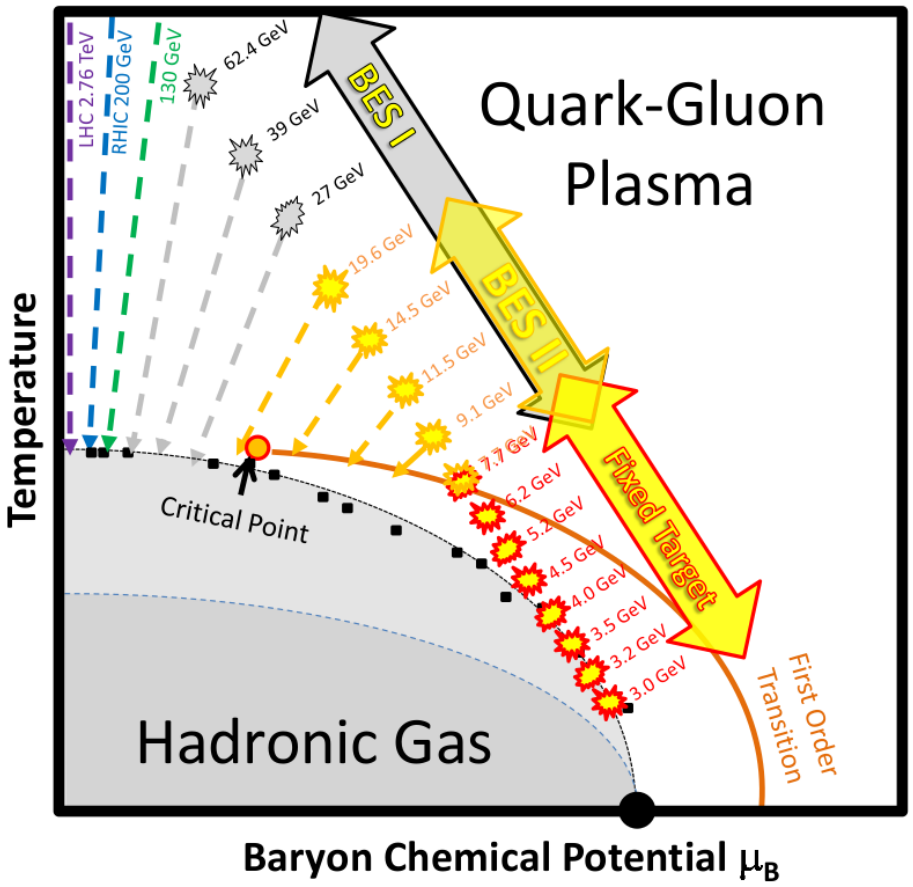
Grigory Nigmatkulov (for the STAR Collaboration)
National Research Nuclear University MEPhI

The XXIV International Workshop
High Energy Physics and Quantum Field Theory

Outline

- Heavy-ion program
  - Soft probes
  - Hard probes
  - Ultra-peripheral collisions (UPC)
- Polarized proton program
- Summary

STAR ☆ Heavy-Ion Program



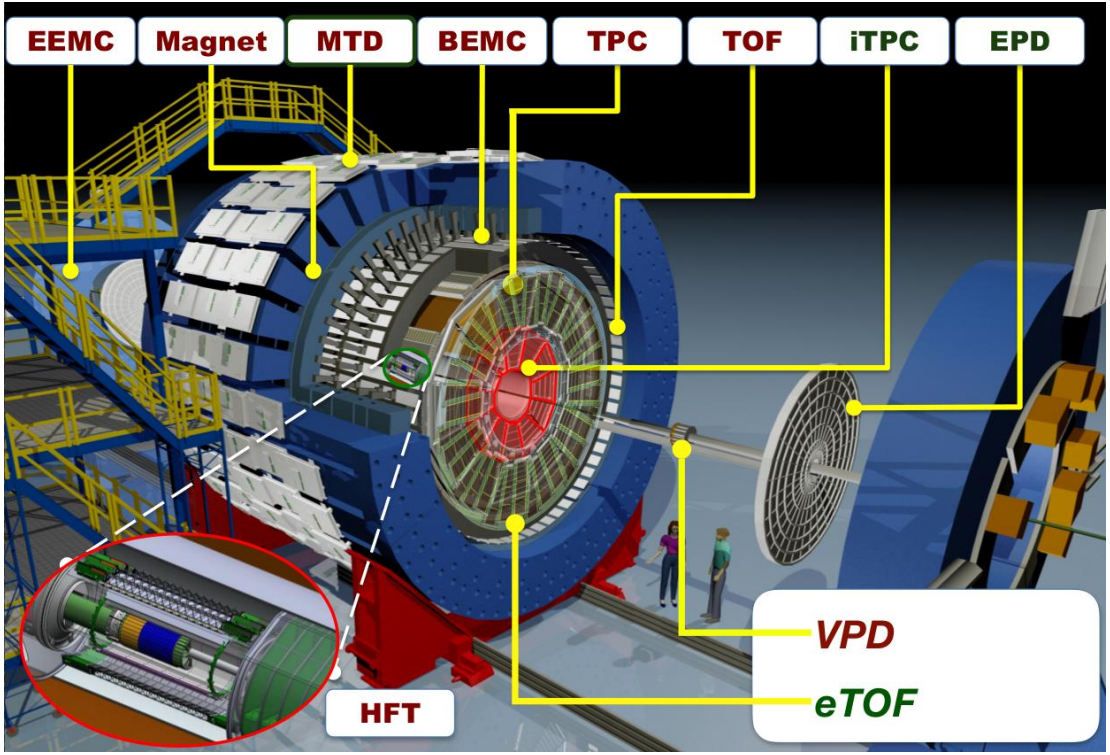
Main goals

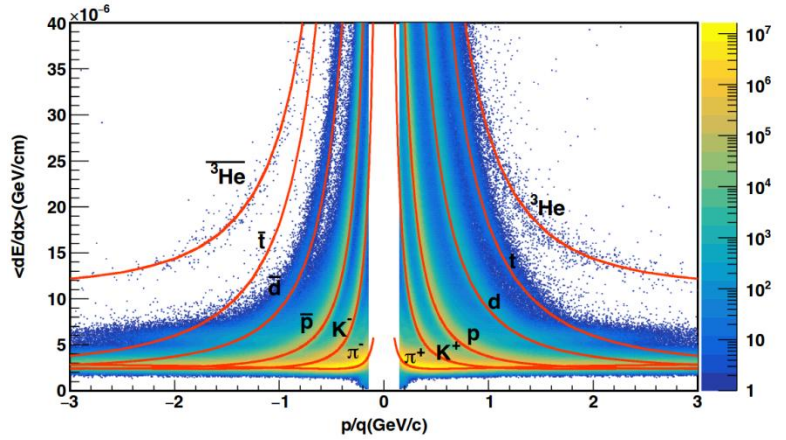
- Explore QCD phase diagram, study the Equation of State (EoS) and transport properties of the medium
- Search for the 1st-order phase transition and critical point

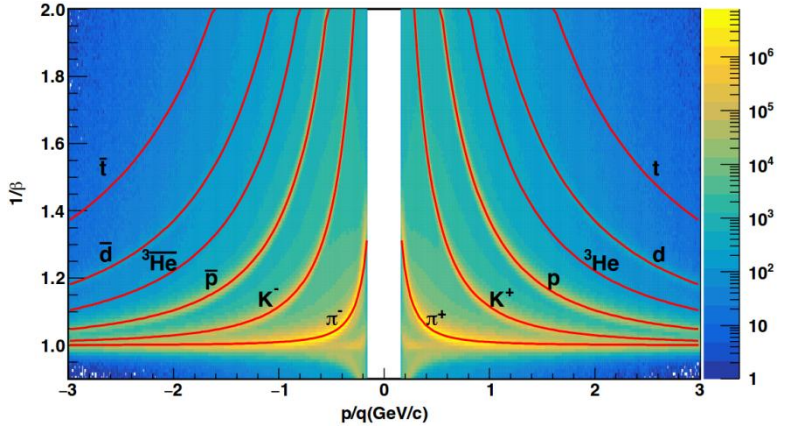
Tools to study various properties

- p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U at top RHIC energy ($\sqrt{s_{NN}}$=200 GeV)
- Au+Au at $\sqrt{s_{NN}}$=7.7-62.4 GeV from Beam Energy Scan I and II
- Au+Au at $\sqrt{s_{NN}}$=3.0-7.7 GeV from Fixed-Target Program (FXT)

The STAR ☆ Experiment





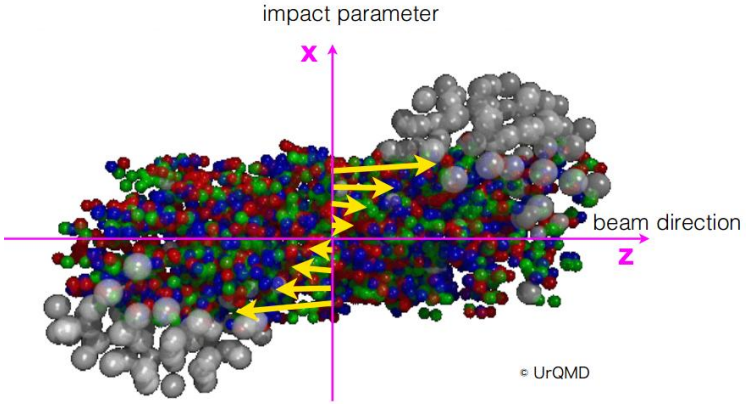


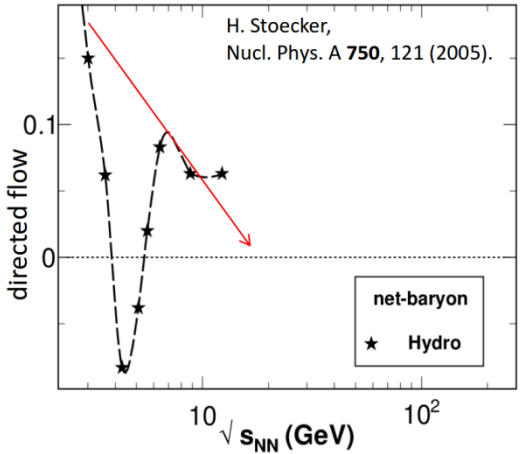
- Tracking of charged particles in full 2π azimuth
- Good particle identification using TPC and TOF

Outline

- Heavy-ion program
  - Soft probes
  - Hard probes
  - Ultra-peripheral collisions (UPC)
- Polarized proton program
- Summary

Azimuthal Anisotropy in Heavy-Ion Collisions





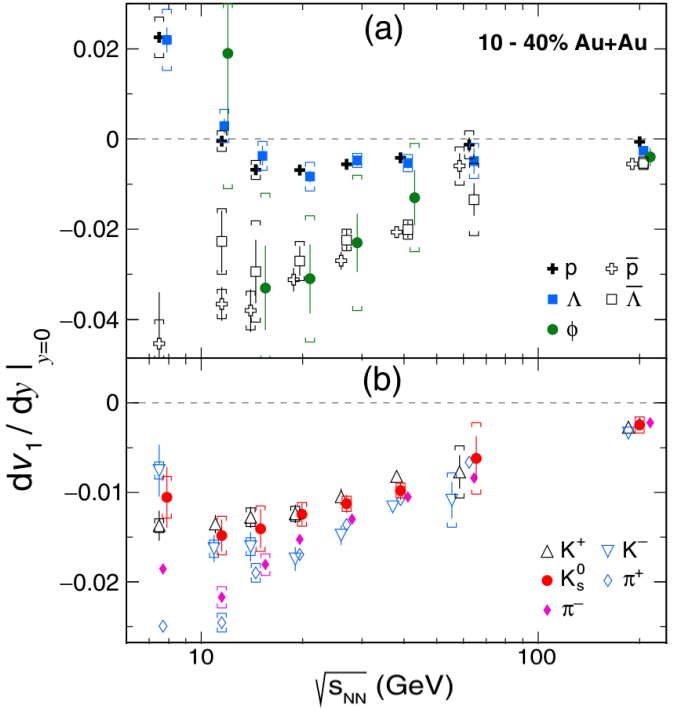
Nara, Niemi, Steinheimer, Stöker. Phys. Lett. B 769 (2017) 543
Ivanov, Soldatov. Phys. Rev. C 91 (2015) 024915

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right)$$

Voloshin , Zhang. Z. Phys. C 70 (1996) 665
Poskanzer, Voloshin. Phys. Rev. C 58 (1998) 1671

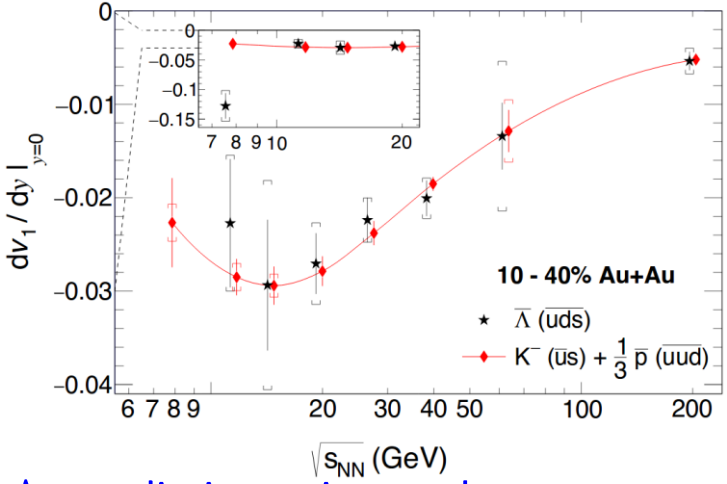
- $v_1 = \langle p_x/p_t \rangle$ – directed flow
  - Describes the sideward collective motion of particles within the reaction plane (x-z)
  - Probe of the softening of the EoS:
    - Strong softening: consistent with the 1st-order phase transition
    - Weaker softening: more likely due to crossover
- v_2 – elliptic flow
  - Sensitive to the properties of the medium
- v_3 – triangular flow
  - Event-by-event fluctuation-driven anisotropy

Beam-Energy Dependence of Directed Flow



- dv_1/dy for Λ and p agree within uncertainties
- dv_1/dy slope for baryons changes sign in the region $\sqrt{s_{NN}}$<14.5 GeV
- Particles (anti-p, anti-Λ, and ϕ) with produced quarks show similar behavior for $\sqrt{s_{NN}}$>14.5 GeV
- Mesons show negative dv_1/dy

STAR. Phys. Rev. Lett. 120 (2018) 062301



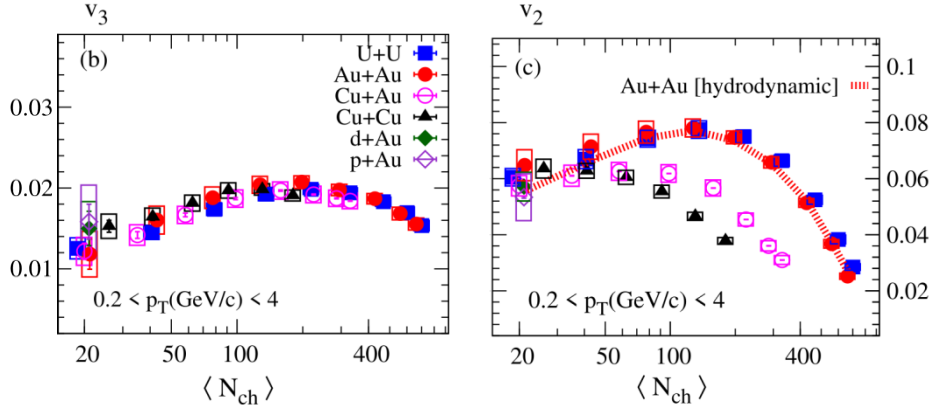
For anti-Λ, prediction using coalescence sum rule agrees with measured v_1 above $\sqrt{s_{NN}}$=11.5 GeV

Assumptions for coalescence sum rule:

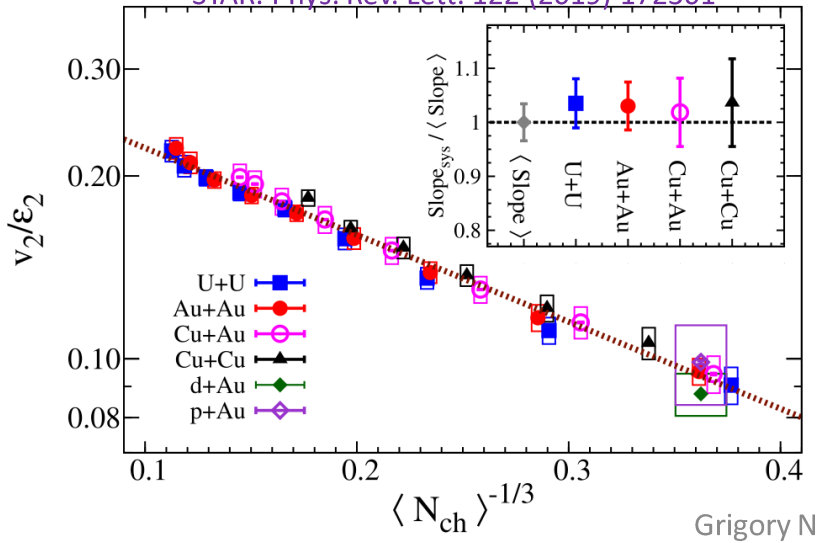
1. v_1 is developed at prehadronic stage
2. Specific types of quarks have the same v_1
3. Hadrons are formed via coalescence

$$(v_n)_{hadron} = \Sigma(v_n)_{\text{constituent quarks}}$$

Azimuthal Harmonics in Small and Large Systems



STAR. Phys. Rev. Lett. 122 (2019) 172301

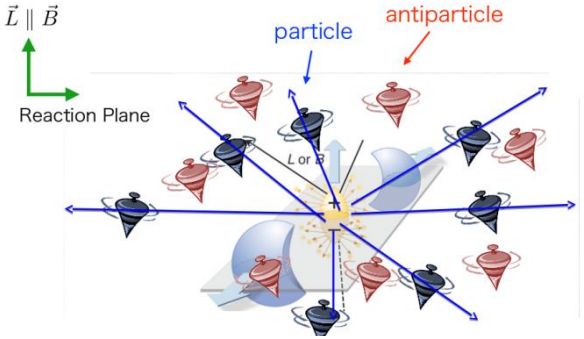


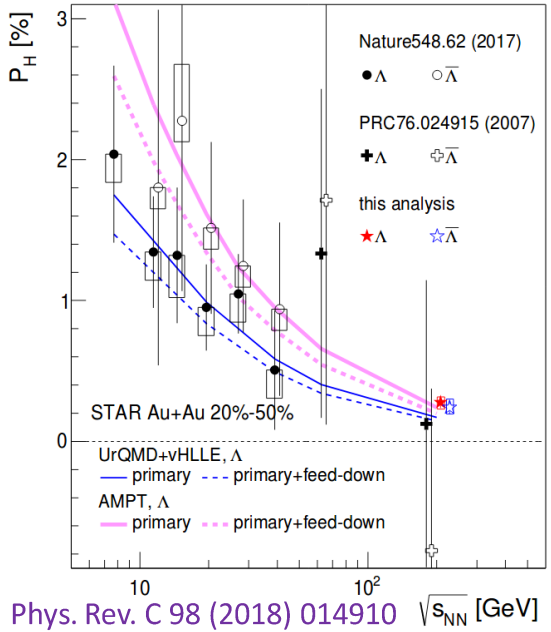
- The $\langle N_{ch} \rangle$ dependence of v_2 and v_3 are compared for p+Au, d+Au, Cu+Cu, Cu+Au, Au+Au and U+U
- For $\langle N_{ch} \rangle \gtrsim 170$, the v_n values show decrease with increasing $\langle N_{ch} \rangle$, consistent with decrease of ε_n (for central collisions)
- Decrease of v_2 for $\langle N_{ch} \rangle \gtrsim 170$ shows the dominant role of size-driven viscous attenuation of flow harmonics (ε_2 increases for $\langle N_{ch} \rangle \lesssim 170$)
- v_3 shows system-independent behaviour

$\ln(v_2/\varepsilon_2)$ vs. $\langle N_{ch} \rangle^{-1/3}$ shows similar trend for all colliding species

STAR ☆ Global Polarization

S. Voloshin, nucl-th/0410089 (2004)
Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94 (2005) 102301





STAR. Phys. Rev. C 98 (2018) 014910

- Non-zero angular momentum transfers to the spin degrees of freedom (polarization)
  - Particles' and antiparticles' spins are aligned with angular momentum **L**
- Magnetic field aligns particle's spin
  - Particles' and antiparticles' spins are aligned oppositely along the **B** due to the opposite sign of the magnetic moment

Positive polarization signal at lower energies!

- polarization looks to increase at lower energies
- anti-Λ looks larger than Λ, possible effect of B-field?

Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar$$

$$\sim 0.02\text{-}0.09\ \mathrm{fm}^{-1}$$

$$\sim 0.6\text{-}2.7 \times 10^{22}\mathrm{s}^{-1}$$

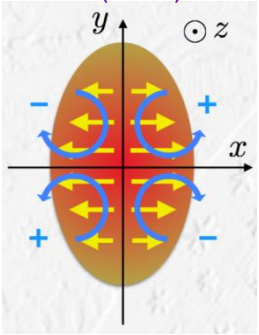
(T=160 MeV)

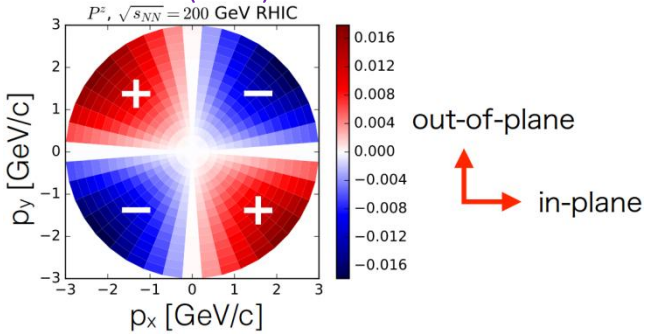
The most vortical fluid ever observed!

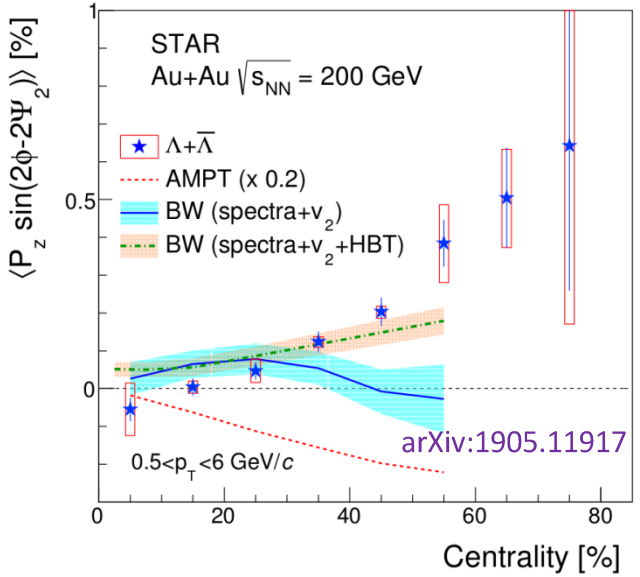
Polarization Along the Beam Direction

S. Voloshin. EPJ. Web Conf. 171 (2018) 07002

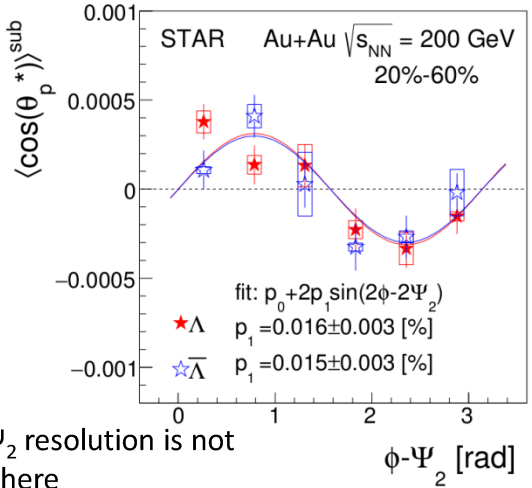
F. Becattini and I. Karpenko. Phys. Rev. Lett. 120 (2018) 012302







Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis



Effect of Ψ_2 resolution is not corrected here

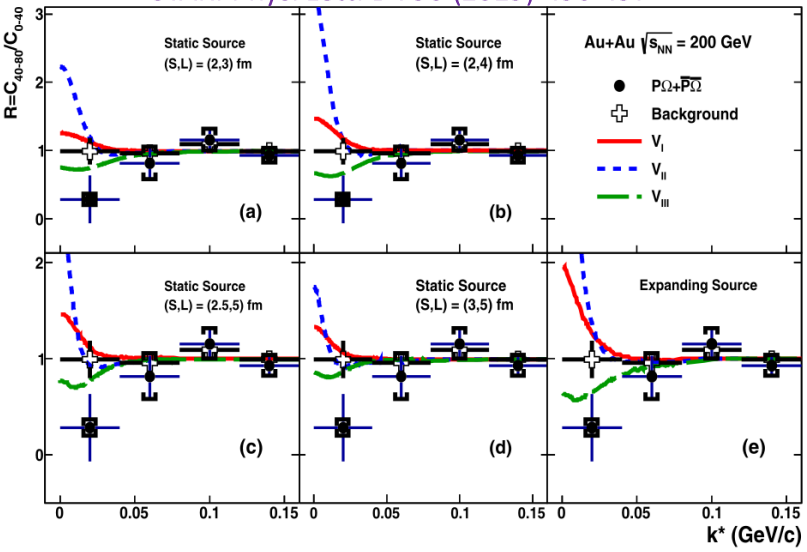
- Sine structure is observed at top RHIC energy
  - Opposite sign to hydrodynamic and transport models
- Strong centrality dependence as for v_2
  - Can be described by Blast-Wave model with HBT

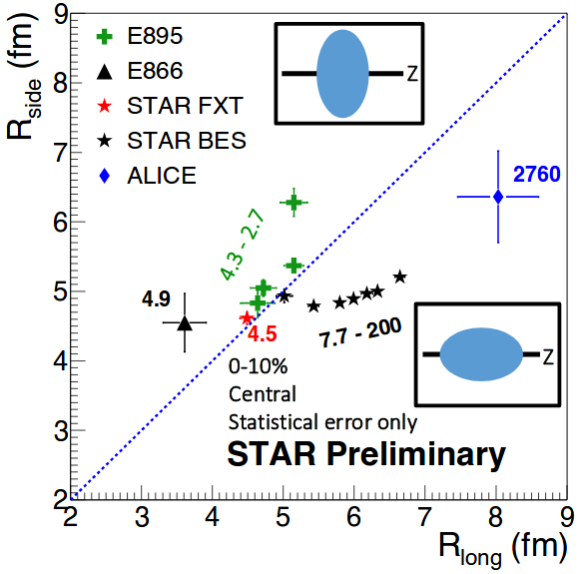
Correlation Femtoscopy

The positive scattering length and the measured ratio of the pΩ correlation function from peripheral to central collisions less than unity for k* <40 MeV/c (within 1σ) favors the pΩ interaction potential V_{III} with $E_b \sim 27$ MeV for proton and Ω

Data favor a positive scattering length for the pΩ interaction

STAR. Phys. Lett. B 790 (2019) 490-497





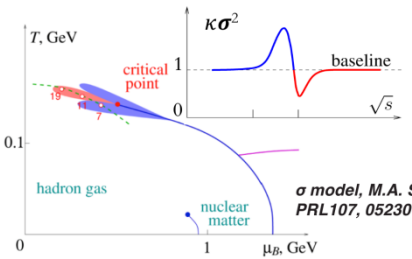
Fixed-target program in STAR: pion femtoscopic radii measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 4.5 GeV are consistent with results from AGS experiments

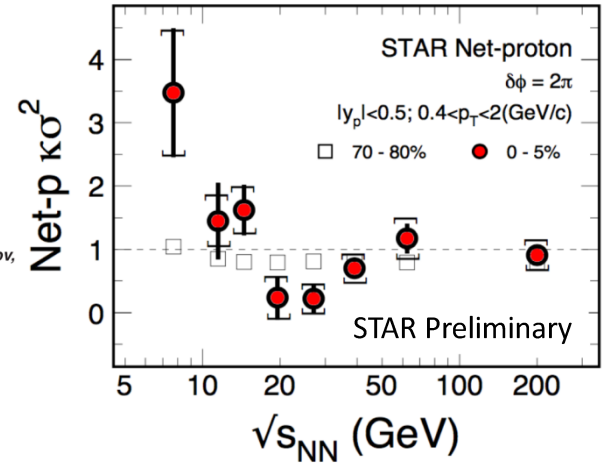
Apparent source shape evolves from oblate to prolate, as energy increases

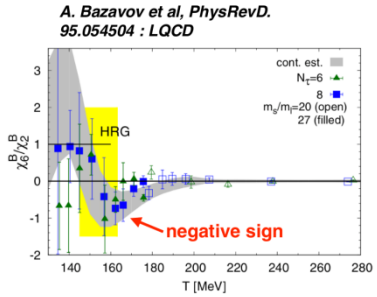
Fluctuations of Conserved Quantities

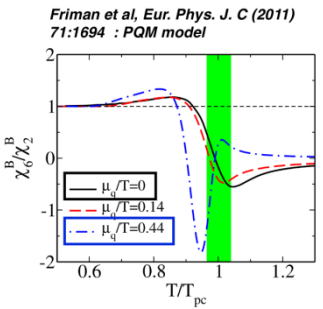
- Fluctuations of conserved quantities (B,Q,S) are sensitive to the correlation length of the system and directly connected to the susceptibilities.

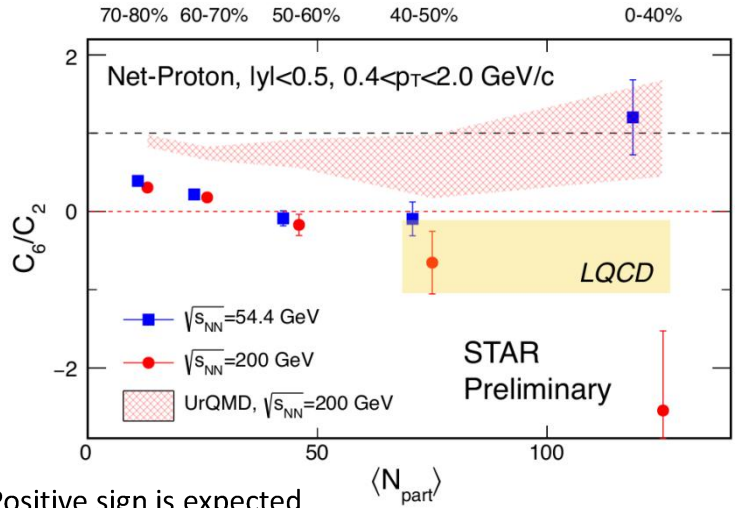
Net proton $k\sigma^2$ (C_4/C_2) shows a non-monotonic behaviour











Positive sign is expected for $\sqrt{s_{NN}}$<60 GeV

- Clear separation and opposite signs between two energies in 0-40%
- UrQMD cannot describe the experimental data at $\sqrt{s_{NN}}$ = 200 GeV
- 200 GeV results are consistent with LQCD calculations

First evidence for the smooth cross over at $\sqrt{s_{NN}}$ = 200 GeV?

Nucleon Freeze-Out Volume

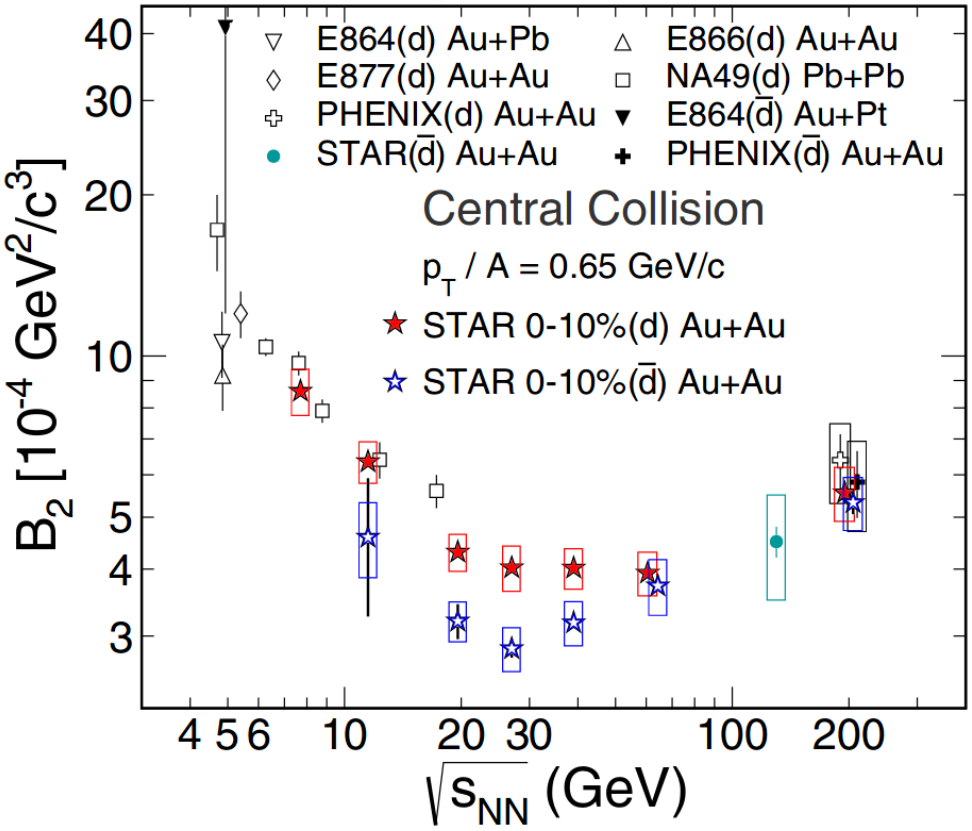
- Production of (anti)deuteron light nuclei can be used to extract information of nucleon distributions at freeze-out
- Coalescence picture: $E_A \frac{d^3N_A}{d^3p_A} \approx B_A \left(E_p \frac{d^3N_p}{d^3p_p} \right)^A$
- The nuclear correlation volume, V_{eff}, is related to the coalescence parameter, B_A:

$$B_A \propto V_{\text{eff}}^{1-A}$$

- At $20<\sqrt{s_{NN}}<40$ GeV:
  - B_2: antideuterons < deuterons
  - V_{eff}: antideuterons > deuterons

Broad minimum: implications for change in Equation of State?

STAR. Phys. Rev. C 99 (2019) 064905

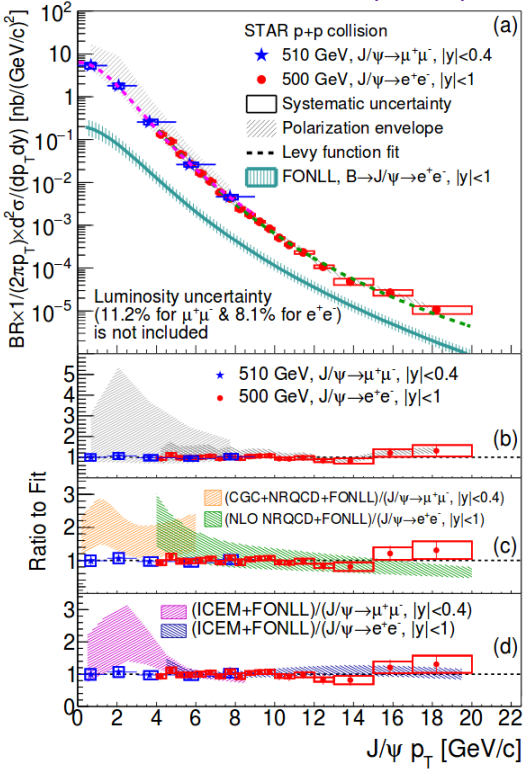


Outline

- Heavy-ion program
  - Soft probes
  - Hard probes
  - Ultra-peripheral collisions (UPC)
- Polarized proton program
- Summary

STAR ☆ J/ψ Production in p+p and Au+Au collisions

arXiv: 1905.06075, Accepted by PRD



Include MTD data from 2013-2014

Suppression increases with increasing collision centrality

- Color screening at RHIC

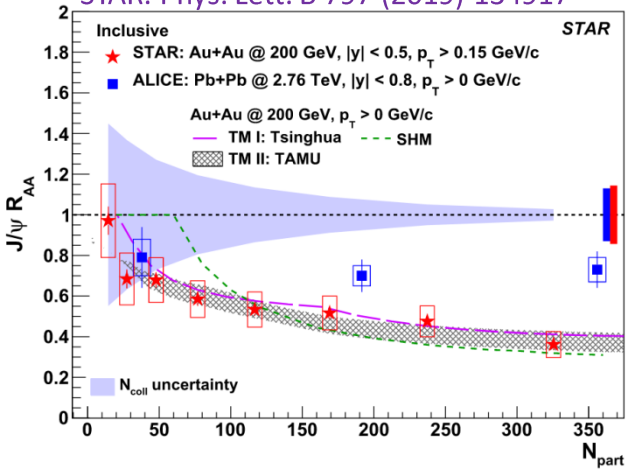
Significant excess at low p_T in peripheral Au+Au and U+U collisions

- Coherent photo-nucleus interactions?

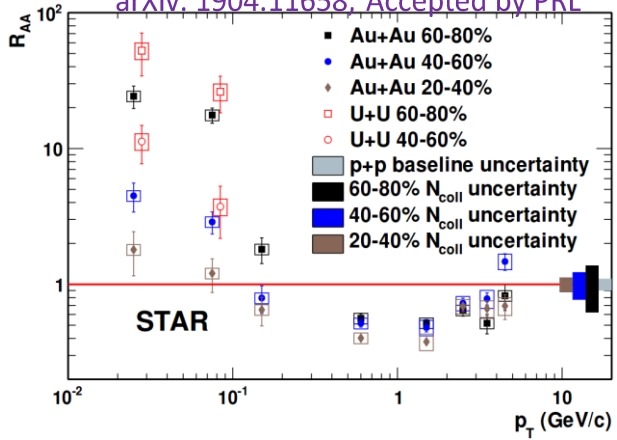
Differential cross section in p+p collisions reasonably reproduced by theory

$\psi(2S)/J/\psi$ - no obvious collision energy dependence

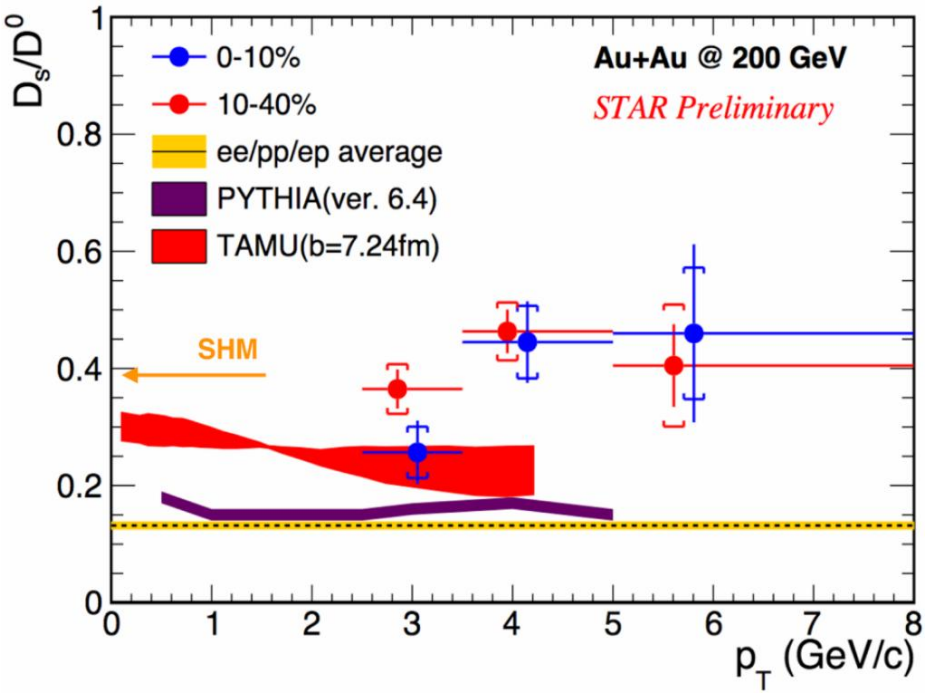
STAR. Phys. Lett. B 797 (2019) 134917



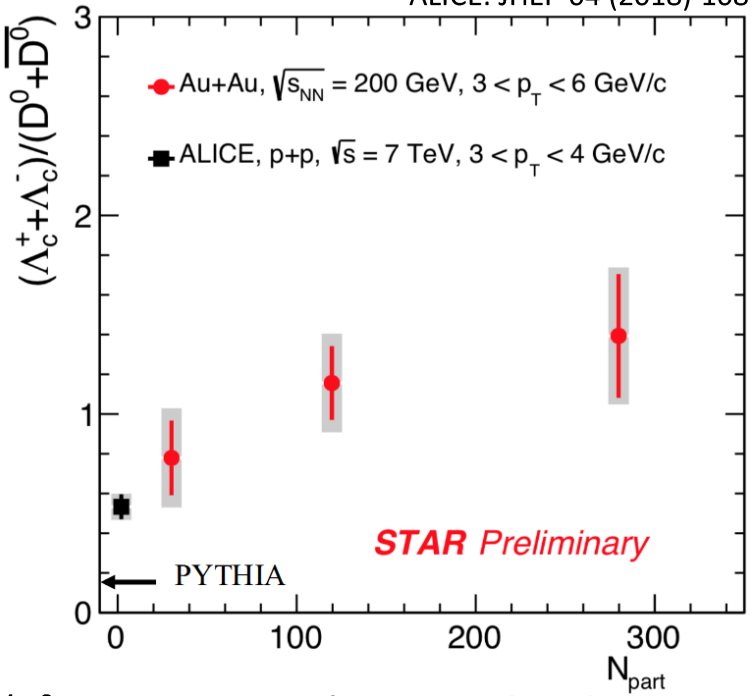
arXiv: 1904.11658, Accepted by PRL



STAR ☆ D_s/D^0 and Λ_c/D^0 Ratios



ALICE: JHEP 04 (2018) 108



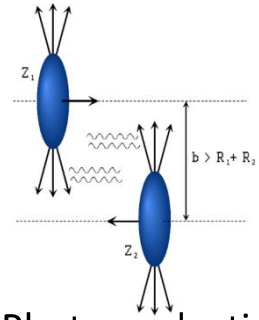
- Strong D_s/D^0 enhancement in central A+A collisions w.r.t fragmentation baseline
  - Strangeness enhancement and coalescence hadronization
- Enhancement is larger than model predictions

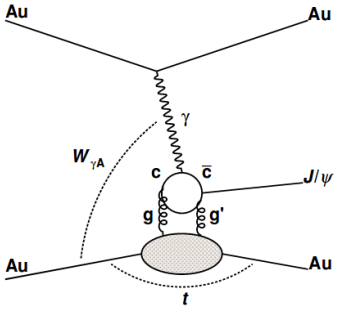
- Λ_c/D^0 ratio increases from peripheral to central collisions, indicative of hot medium effects
- Ratio for peripheral Au+Au comparable with p+p value at 7 TeV

Outline

- Heavy-ion program
  - Soft probes
  - Hard probes
  - Ultra-peripheral collisions (UPC)
- Polarized proton program
- Summary

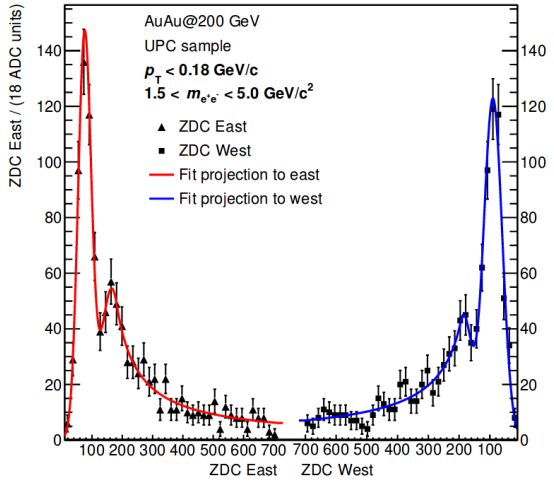
Coherent J/ψ production in UPC

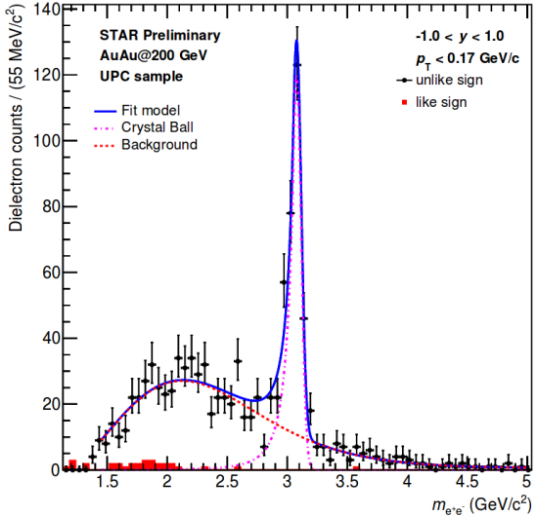


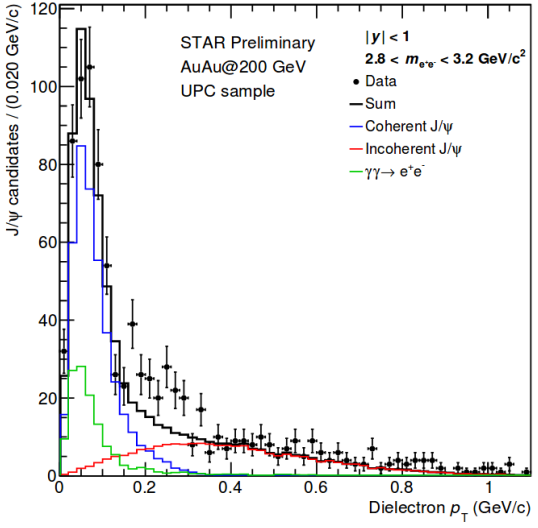


- Just two tracks from a low-p_T vector meson and forward neutrons
- Signal of J/ψ and continuum from γγ→e^+e^-
- Coherent and incoherent J/ψ have different shapes of p_T spectrum

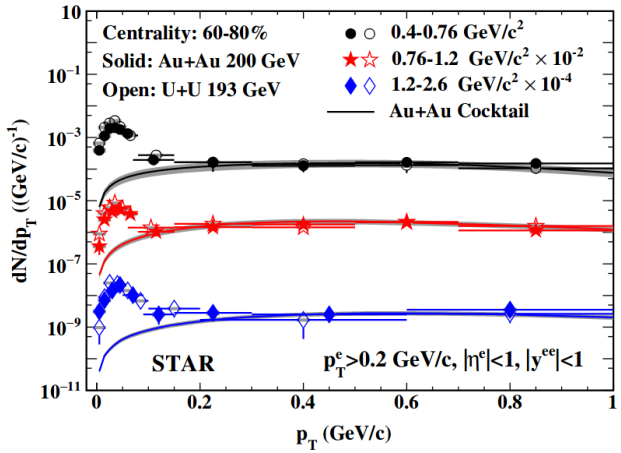
Photoproduction of heavy vector mesons can be described by perturbative QCD as two-gluon exchange







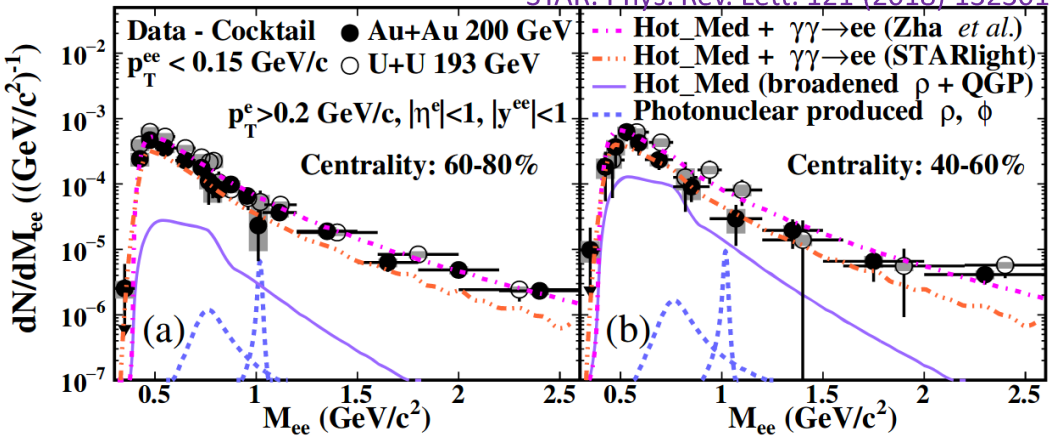
Low-p_T e^+e^- Pair Production in Au+Au and U+U

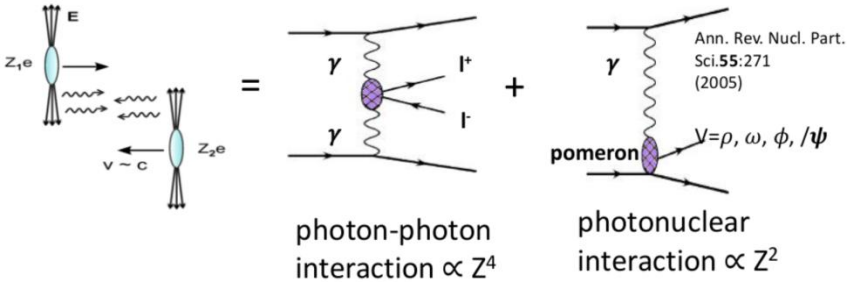


- Significant dielectron enhancement at low p_T
- The invariant mass, M_{ee}, shape of the low-p_T dielectron pairs can be described with addition of photon-photon interactions

  Zha et al. Phys. Lett. B 781 (2018) 182
  STARlight. Phys. Rev. C 97 (2018) 054903
  - No effect of hadronic interactions on virtual photon production
  - The excess is dominated by photon-photon interactions

STAR. Phys. Rev. Lett. 121 (2018) 132301





Outline

- Heavy-ion program
  - Soft probes
  - Hard probes
  - Ultra-peripheral collisions (UPC)
- Polarized proton program
- Summary

STAR ☆ Sea Quark Contribution to Proton Spin

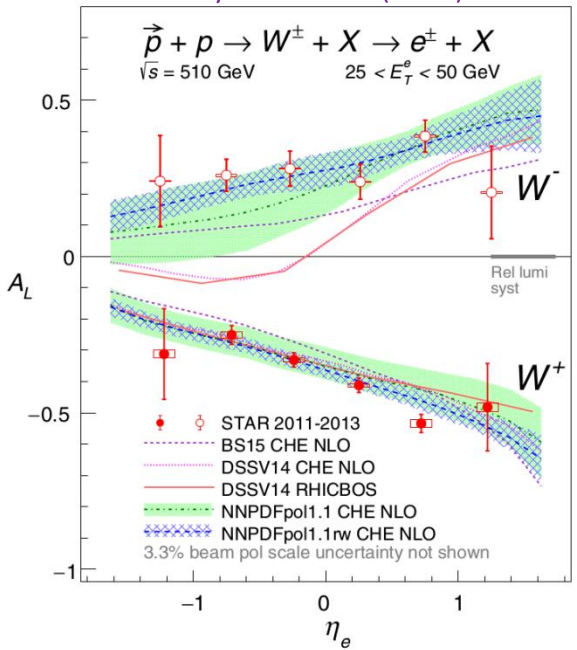
$W^{\pm}$ production can access flavored quark and antiquark polarizations via measurement of single-spin asymmetry:

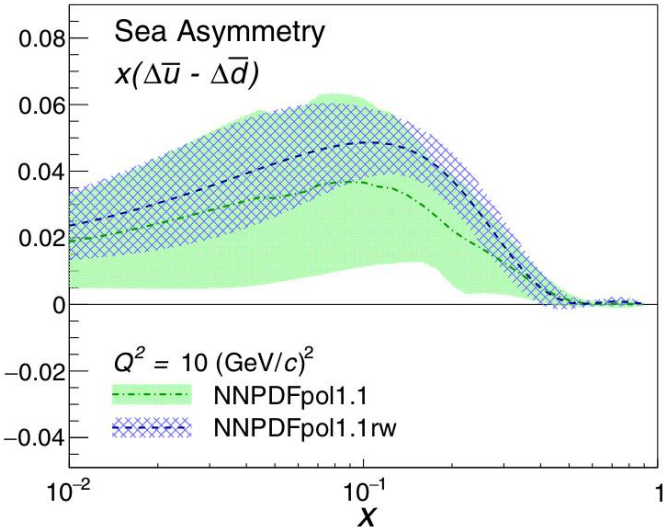
$$A_L \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)},$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)},$$

STAR. Phys. Rev. D 99 (2019) 051102





Significant preference for $\Delta\bar{u}(x, Q^2) > \Delta\bar{d}(x, Q^2)$ over 0.05<x <0.25 at Q^2=10 (GeV/c)^2

Opposite to the flavor asymmetry observed in the spin-averaged quark-sea distributions

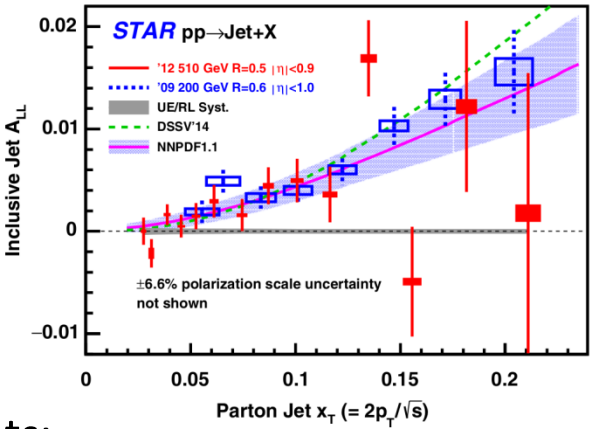
Gluon Polarization via Inclusive Jets and Dijets

Access gluon polarization via measurement of longitudinal double-spin asymmetry, A_{LL}:

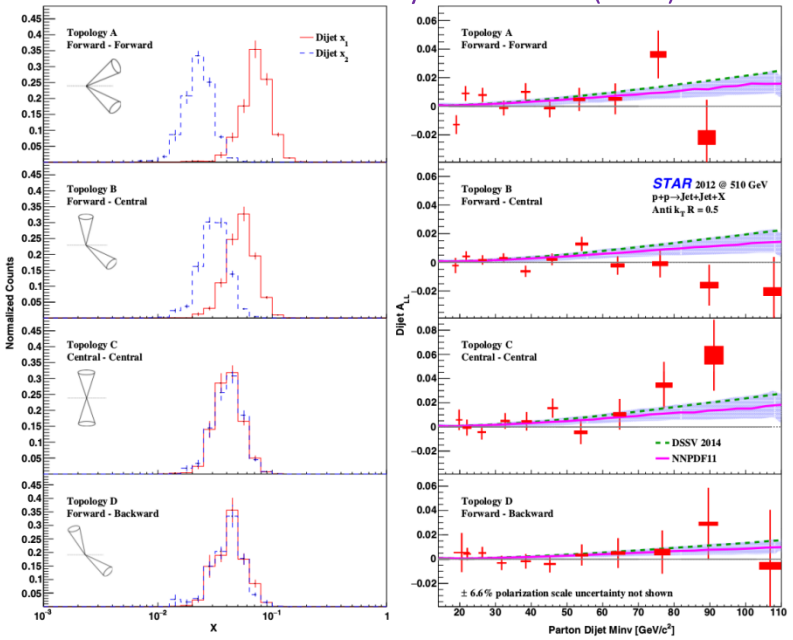
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

A_{LL} results sensitive of 0.015<x<0.2

Inclusive jets: new constraints on magnitude of gluon polarization



STAR. Phys. Rev. D 100 (2019) 052005



Dijets:

- Different topologies access different x regions
- Important new constraints on shape of $\Delta g(x)$

Region x <0.05 previously largely unconstrained by data in global analyses of polarized PDFs

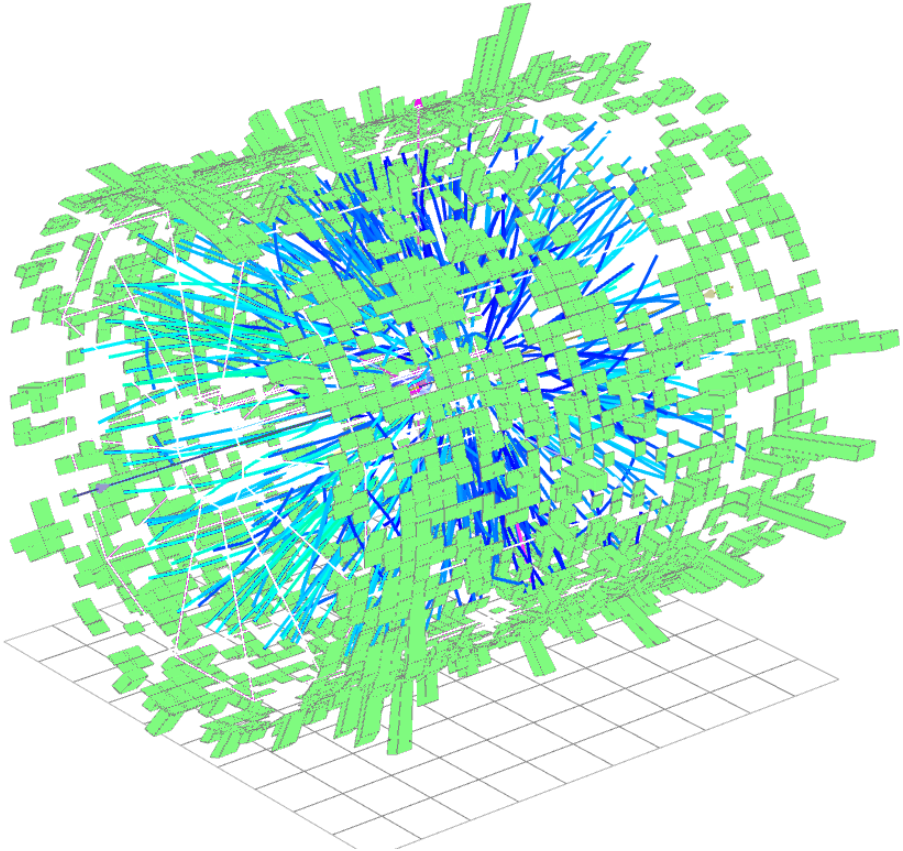
Outline

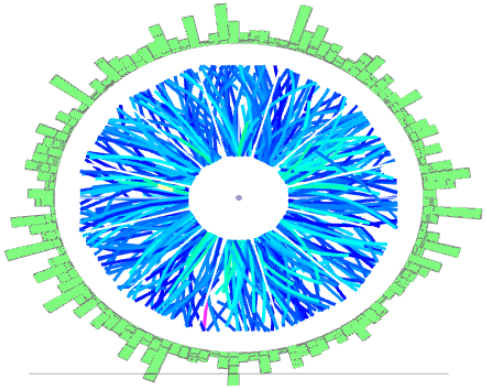
- Heavy-ion program
  - Soft probes
  - Hard probes
  - Ultra-peripheral collisions (UPC)
- Polarized proton program
- Summary

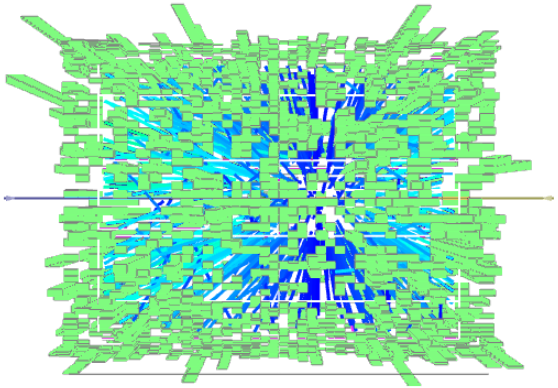
STAR ☆ Summary

- Azimuthal anisotropy
  - Collectivity plays an important role in large and small systems
- Global and local polarization
  - Global polarization increases with decrease of beam energy
  - First observation of polarization along the beam direction
- Net-proton multiplicity distributions
  - Non-monotonic behaviour of $k\sigma^2$ (criticality?)
  - Indication for the cross over phase transition at top RHIC energy
- Indication of positive scattering length for $p\Omega$
- (Anti)Deuteron production
  - Change of the Equation of State at $20<\sqrt{s_{NN}}<40$ GeV?
- J/ψ Production
  - p+p: precise cross section measured over a wide p_T range is reasonably described by theory
  - Au+Au: suppression increases with increasing collision centrality
- Enhancement of low-p_T dielectron production
  - Consistent with photoproduction
- Proton spin
  - Measurement of sea antiquark contribution to the proton spin ($\Delta\bar{u}(x,Q^2) > \Delta\bar{d}(x,Q^2)$)
- Gluon polarization
  - New constraints via measurements of longitudinal double-spin asymmetries

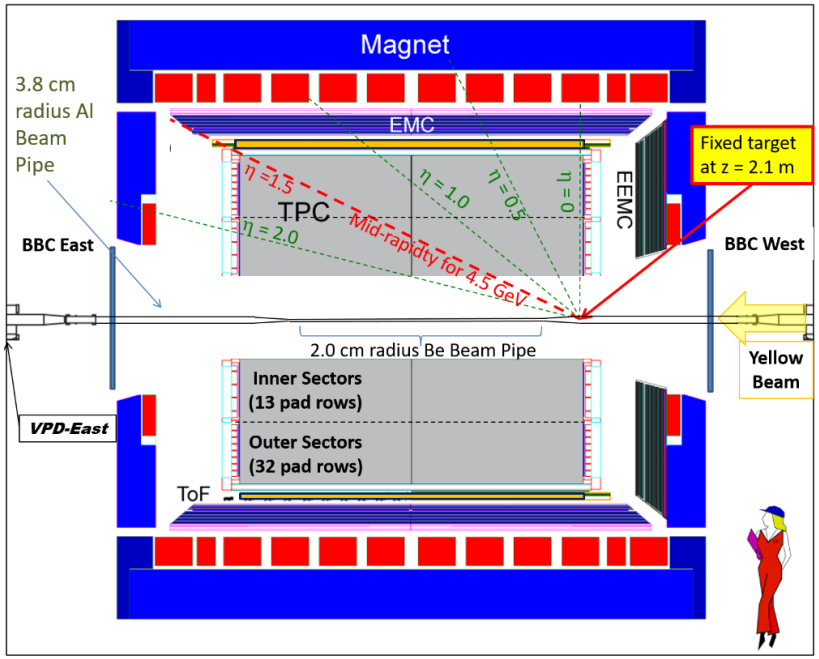
Backup Slides



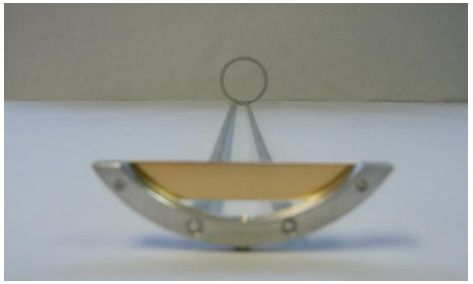


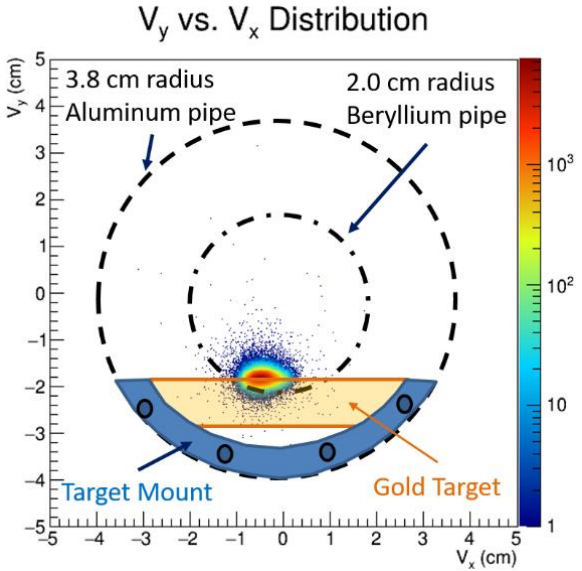


STAR Fixed-Target (FXT) Program



A 1 mm thick (4% inter. prob.) gold target





- 1.3M events from half hour test run (2014), top 30% central trigger, Au+Au $\sqrt{s_{NN}}$=4.5 GeV
- Full data taking $\sqrt{s_{NN}}$=3.0-7.7 GeV starting 2018

RHIC Beam Use Request For Runs 18 and 19 (The STAR Collaboration)

Fluctuations of Conserved Quantities

STAR . Phys. Rev. Lett. 112 (2014) 032302

✦ Net baryon, net charge and net strangeness

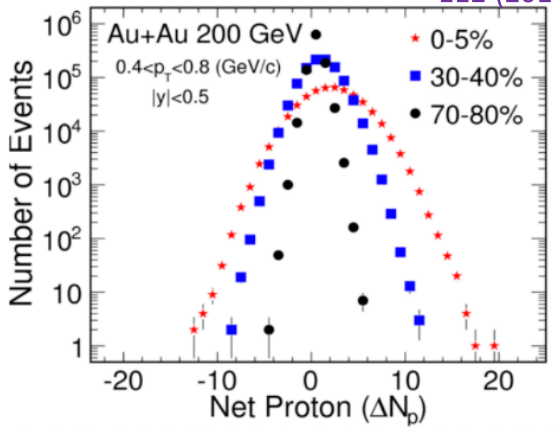
"Net" : positive - negative

$$\Delta N_q = N_q - N_{\bar{q}}, \quad q = B, Q, S$$

No. of positively charged particles in one collision

No. of negatively charged particles in one collision

Fill in histograms over many collisions



→neutrons cannot be measured

(1) Sensitive to correlation length

$$C_2 =< (\delta N)^2 >_c \approx \xi^2 \qquad C_5 =< (\delta N)^5 >_c \approx \xi^{9.5}$$
$$C_3 =< (\delta N)^3 >_c \approx \xi^{4.5} \qquad C_6 =< (\delta N)^6 >_c \approx \xi^{12}$$
$$C_4 =< (\delta N)^4 >_c \approx \xi^7$$

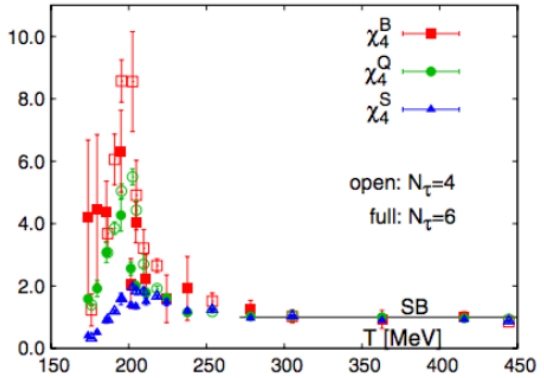
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
MAsakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009)

(2) Direct comparison with susceptibilities.

M. Cheng et al, PRD 79, 074505 (2009)

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

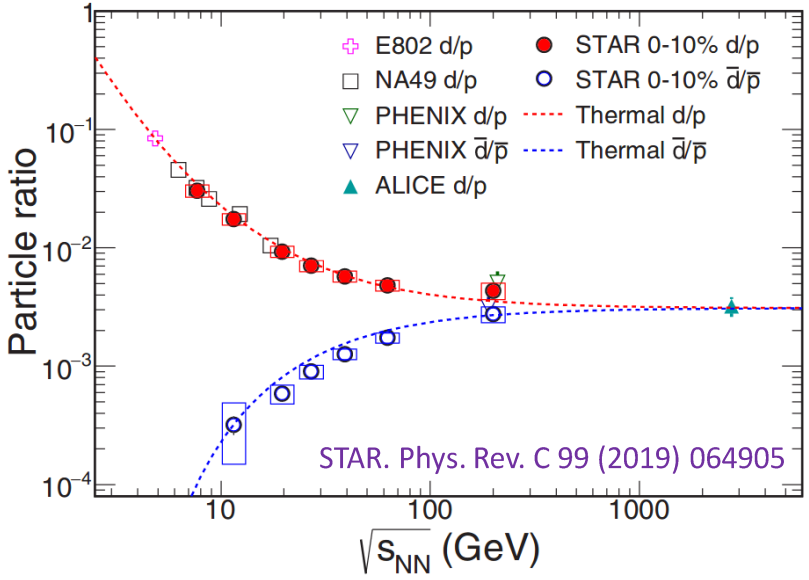
$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

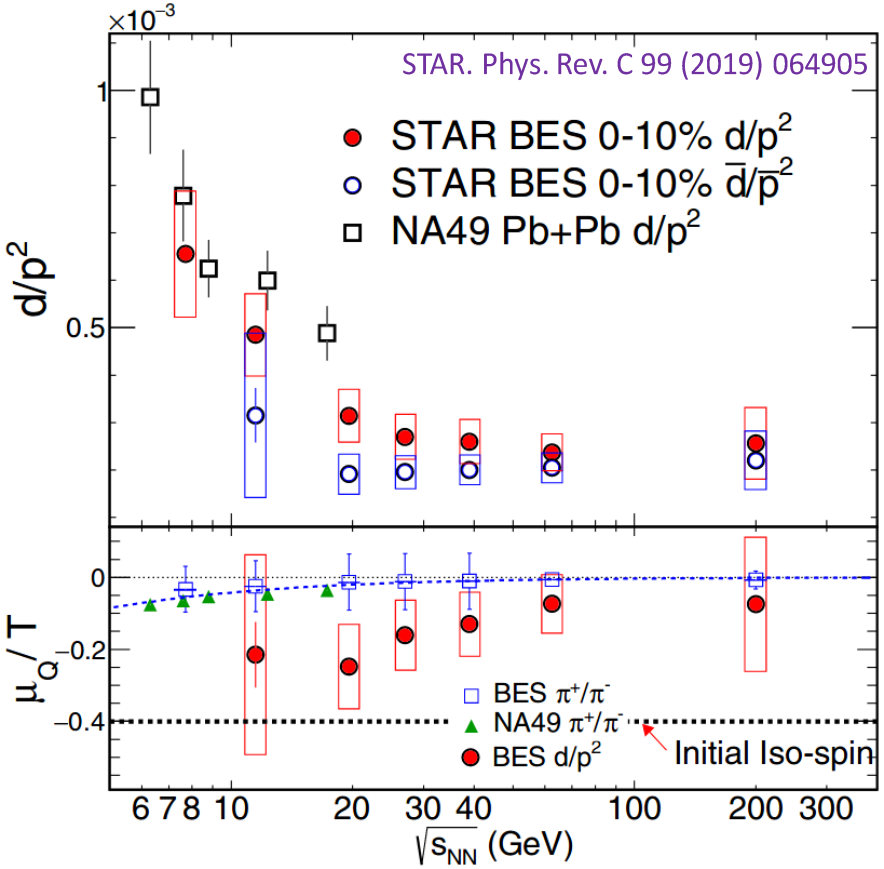


M. Cheng et al, PRD 79, 074505 (2009)

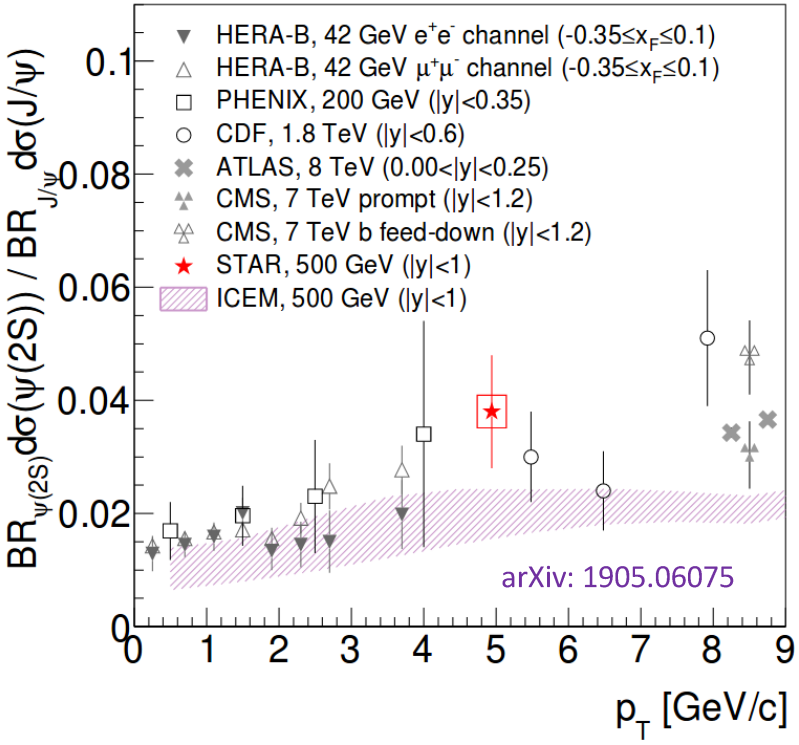
Toshihiro Nonaka, XQCD2019, Tokyo, Japan

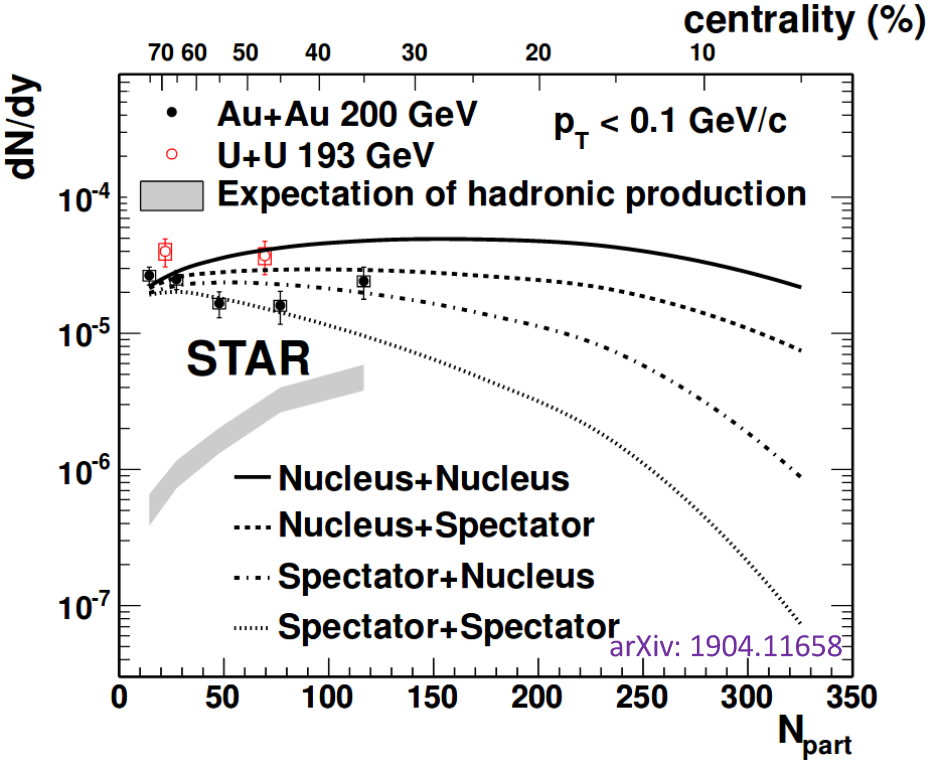
Beam-Energy Dependence of (Anti)Deuteron Production



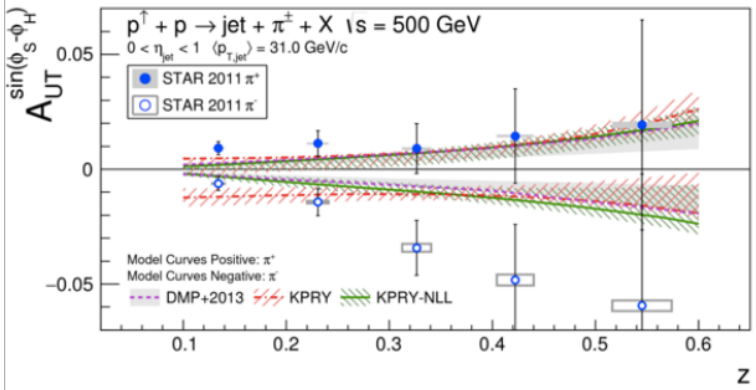


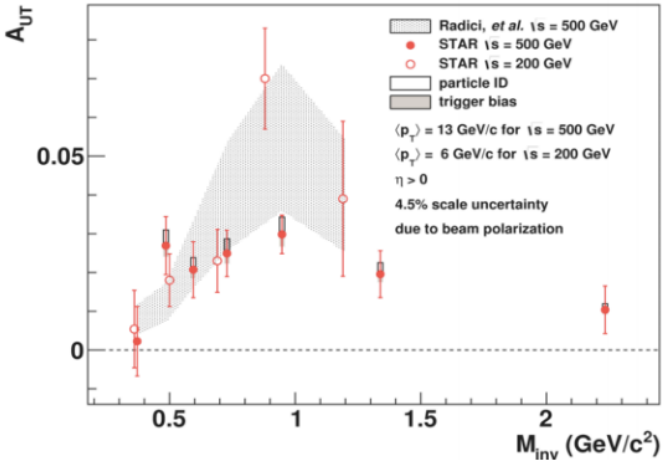
STAR ☆ J/ψ Production in p+p and Au+Au collisions





Transverse spin measurements





W and Z A_N and Drell-Yan from Run 17
510 GeV - data being analyzed

PRD **97** (2018) 032004
First observation of non-zero Collins Effect in pp collisions and first limit on linearly polarized gluons in polarized proton

Models-based entirely on SIDIS
- π^+ reasonable description of despite being 1-2 order magnitude higher Q^2
- π^- new constraints - d-quark transversity not well determined previously

TMD evolution effects appear small

Suggests factorization and universality of Collins function

PLB **780** (2018) 332
Interference fragmentation functions at 200 and 500 GeV

First inclusion of RHIC data in transversity determination at high Q^2

(Radici and Bacchetta PRL 120, 192001 (2018))

STAR data significantly reduces uncertainties

Proton spin: gluon helicity contribution

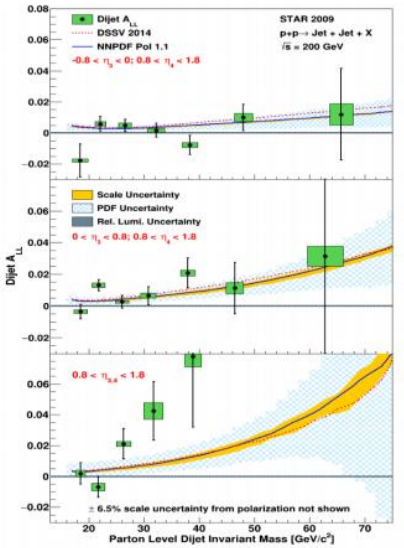
~0.2 for x>0.05: Unconstrained at low-x

First extension of gluon polarization measurements beyond mid-rapidity

PRD **98** (2018) 032011

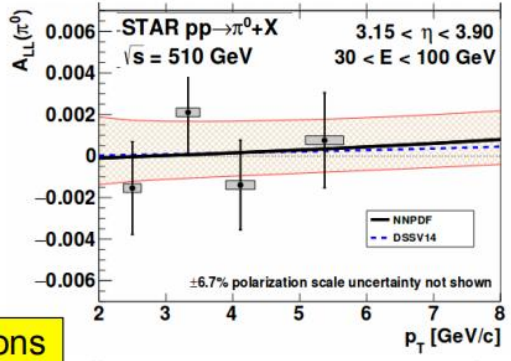
Pushing forward access down to x=0.01

First forward dijet A_{LL} with 3 different topologies



PRD **98** (2018) 032013

Moving to higher √s access down to x=0.001



Good agreement with theory

Constrains unexplored low-x region - abundant soft gluons