Highlights from STAR

Leszek Kosarzewski
for the STAR collaboration

Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague

RHIC & AGS Users Meeting 2021

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ČVUT
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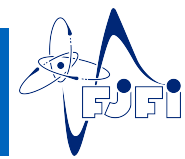
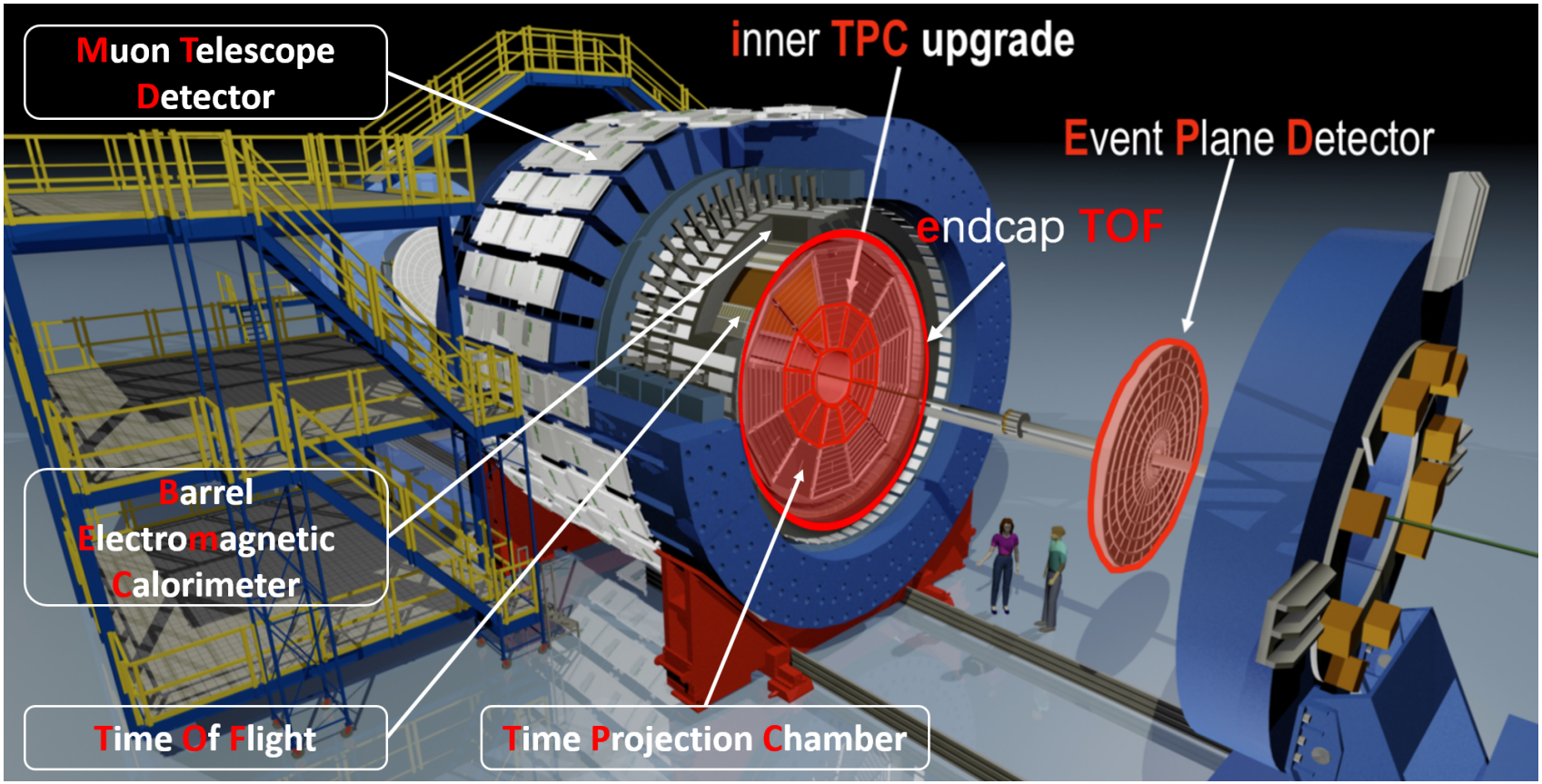


The work was also supported from European Regional Development Fund-Project "Center of Advanced Applied Science" No. CZ.02.1.01/0.0/0.0/16-019/0000778 and by the grant LTT18002 of Ministry of Education, Youth and Sports of the Czech Republic.

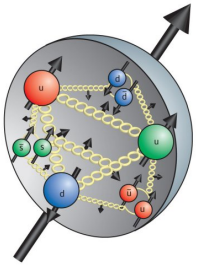
Outline

STAR experiment



- TPC+**iTPC** $|\eta| < 1.5$, $0 \leq \phi < 2\pi$
  - Tracking, p, $\frac{dE}{dx}$ - now improved!
- TOF+**eTOF** $-1.5 < \eta < 1$, $0 \leq \phi < 2\pi$
  - Particle identification based on time-of-flight
- **EPD** $2.14 < |\eta| < 5.09$, $0 \leq \phi < 2\pi$
  - Independent event plane estimation
- BEMC $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Electron identification via E/p and EM shower shape
  - Trigger on high-p_T electrons
- MTD $|\eta| < 0.5$, 45% in ϕ
  - Muon identification utilizing position and time-of-flight information
  - Dimuon trigger

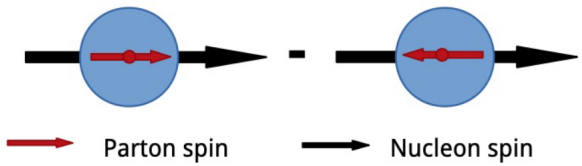
Gluon helicity



Gluon helicity contribution ΔG to proton spin S:

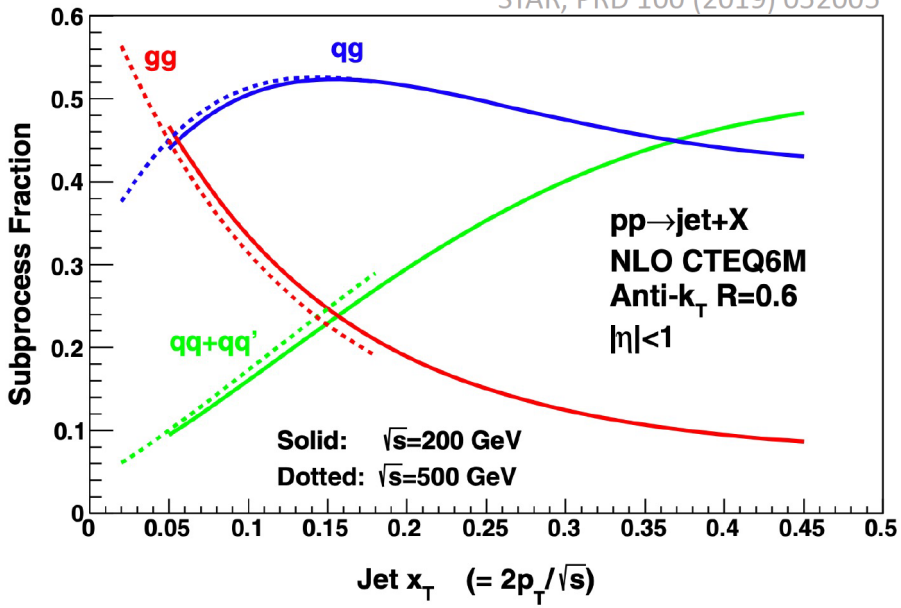
$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- Studied using collisions of longitudinally polarized proton beams
- Different spin configurations allow to measure longitudinal double spin asymmetry A_{LL}:



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a_{\hat{LL}}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}$$

STAR, PRD 100 (2019) 052005

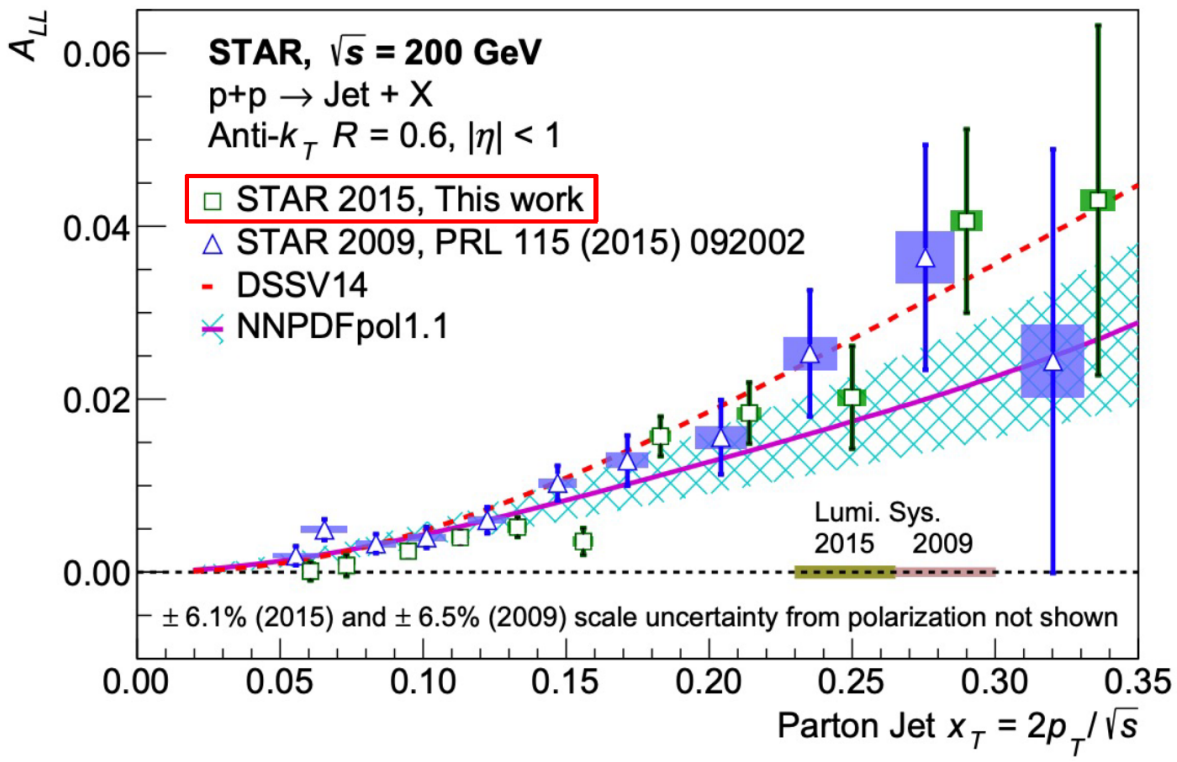


- At RHIC, a large fraction of jets come from qg and gg at low x_T
  - Sensitive to gluon distributions
  - Use jets to study gluon helicity

See talk by:

Xiaoxuan Chu, 8 June 2021, 09:50

Gluon helicity



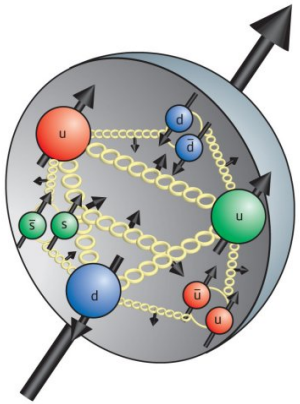
STAR: [Phys. Rev. D 103, L091103 (2021)]

- Largest longitudinal p+p dataset at 200 GeV taken in 2015 used
  - Improved statistical and systematic uncertainties
- Once added to global fits, it can **reduce the uncertainty for polarized gluon distribution at** $x_T > 0.05$

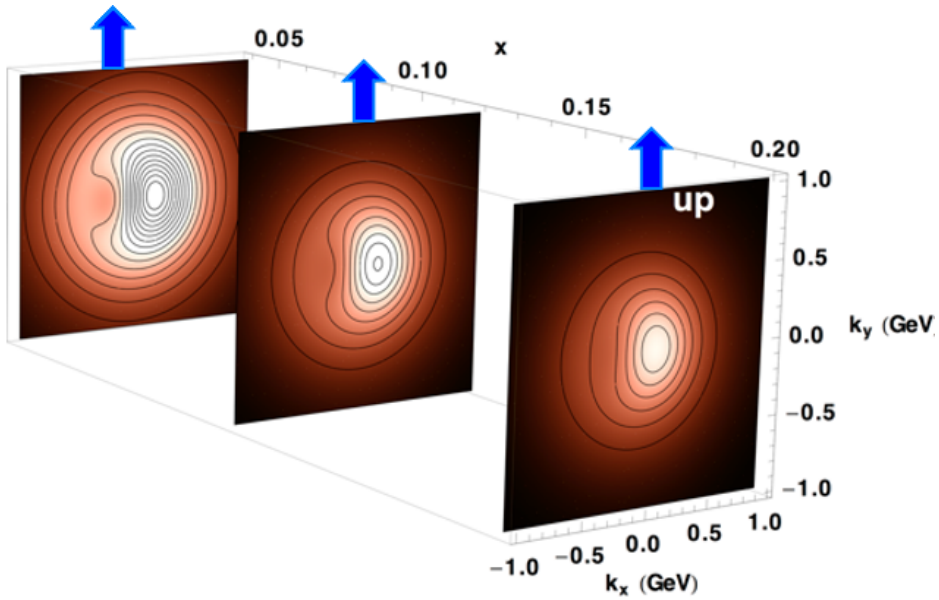
See talk by:

Xiaoxuan Chu, 8 June 2021, 09:50

Transverse structure of the proton



3D image $\longmapsto$



- Described by Transverse Momentum Dependent PDFs (TMDs, $f(x, k_T)$)
- Accessed by measuring Transverse Single Spin Asymmetry (TSSA)

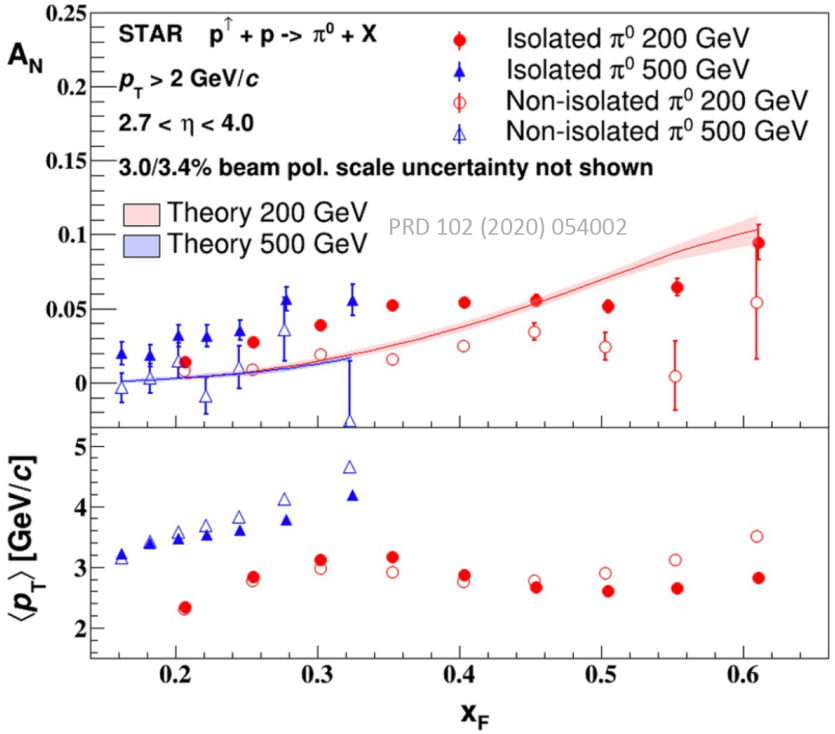
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- TSSA affected by:
  - Initial state effects, k_T of a parton - Sivers function
  - Final state effects, fragmentation - Collins function

See talk by:

Xiaoxuan Chu, 8 June 2021, 09:50

TSSA of π^0 in jets



STAR: [Phys. Rev. D 103, 092009 (2021)]

- x_F - longitudinal momentum fraction of π^0 with respect to the beam energy
- TSSA studied for π^0 in jets vs. isolated in p+p collisions at 200 GeV and 500 GeV
- **Larger asymmetry for isolated than non-isolated π^0**
  - Indication of diffractive process contribution to isolated π^0 A_N
- **Weak energy dependence**

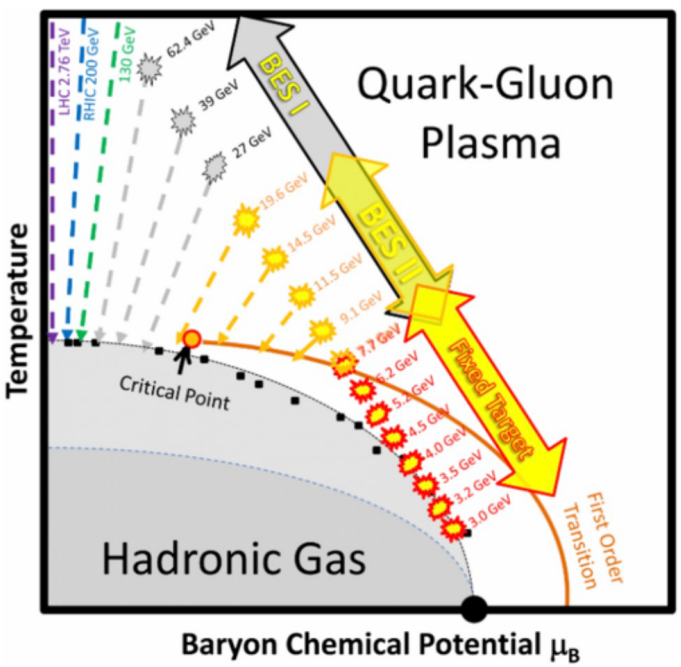
See talk by:

Xiaoxuan Chu, 8 June 2021, 09:50

Cold-QCD future talk by:

Ting Lin, 8 June 2021, 11:20

Study of QCD matter phases



J. Cleymans [Phys. Rev. C 73, 034905 (2006)]

Goals:

- Study phase transition
  - Hadron gas $\rightarrow$ QGP
- Search for Critical Point
  - 1-st order phase transition $\rightarrow$ crossover
- Search for turn-off of QGP signatures

How to study?

- Study various observables vs. $\sqrt{s_{NN}}$ and μ_B
  - fluctuations
  - particle ratios
  - particle flow
- Beam Energy Scan - BES
  - Collider mode
  - FXT - fixed target mode
    - More efficient data taking at low-$\sqrt{s_{NN}}$
    - Lower $\sqrt{s_{NN}}$ and higher μ_B reach

BES I

$\sqrt{s_{NN}}$ [GeV]	Events [10^6]	Year	μ_B [MeV]
200	900	2010	25
62.4	43	2010	73
54.4	550	2017	83
39	92	2010	112
27	70	2011	156
19.6	36	2011	206
14.6	12.6	2014	264
11.5	11.7	2010	315
7.7	4.3	2010	420

BES II

$\sqrt{s_{NN}}$ [GeV]	Events [10^6]
27	560
19.6	582
17.1	TBD
14.6	324
11.5	235
9.1	162
7.7	101

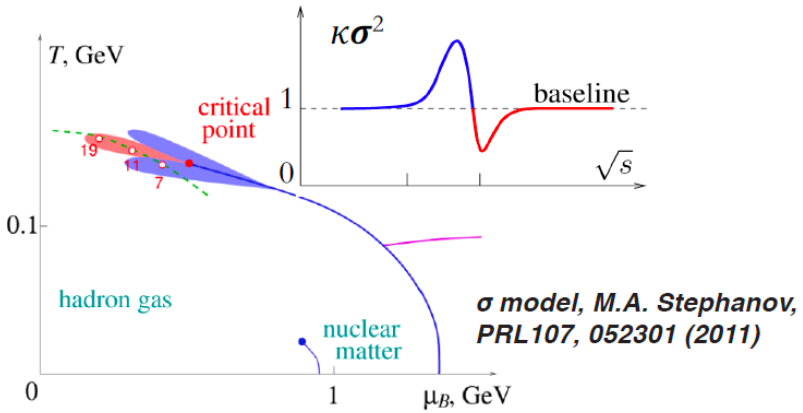
FXT

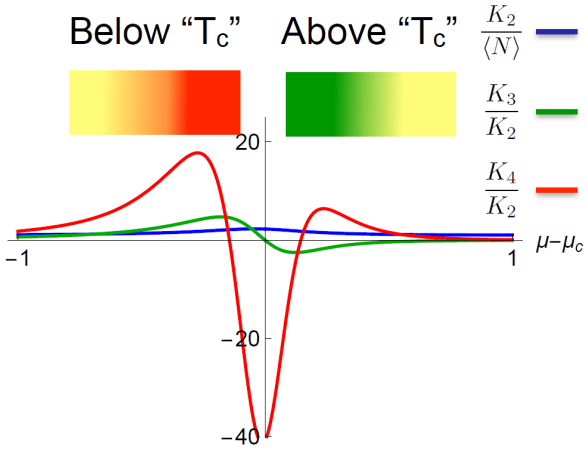
$\sqrt{s_{NN}}$ [GeV]	Events [10^6]
13.7	50.7
11.5	51.7
9.1	53.9
7.7	162.6
7.2	472+
6.2	118

$\sqrt{s_{NN}}$ [GeV]	Events [10^6]
5.2	103
4.5	108
3.9	169.7
3.5	115.6
3.2	200.6
3	565+

Fluctuations

- Fluctuations are expected to be large around the Critical Point
  - The correlation length diverges



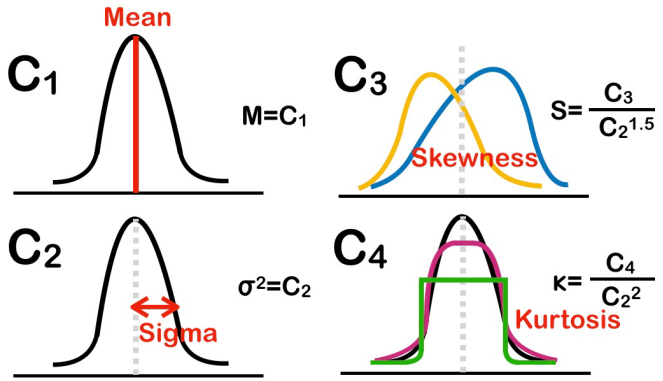


[V. Koch, QM2019]

- Can be measured with cumulants C_n, K_n of conserved quantities (Q,B,S)
  - C_n are sensitive to the correlation length - higher orders more sensitive!
  - Ratios factor out the volume dependence
  - C_n follows Skellam distribution in absence of critical phenomena, so $\frac{C_4}{C_2} = \frac{C_6}{C_2} = 1$ as a statistical baseline
  - C_n are calculated using moments:

$$< m^n >= \sum_m m^n P(m)$$
$$< \delta m^n >=< (m - < m >)^n >$$

$$< \delta N >= N - < N >$$
$$C_1 =< N >$$
$$C_2 =< (\delta N)^2 >$$
$$C_3 =< (\delta N)^3 >$$
$$C_4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

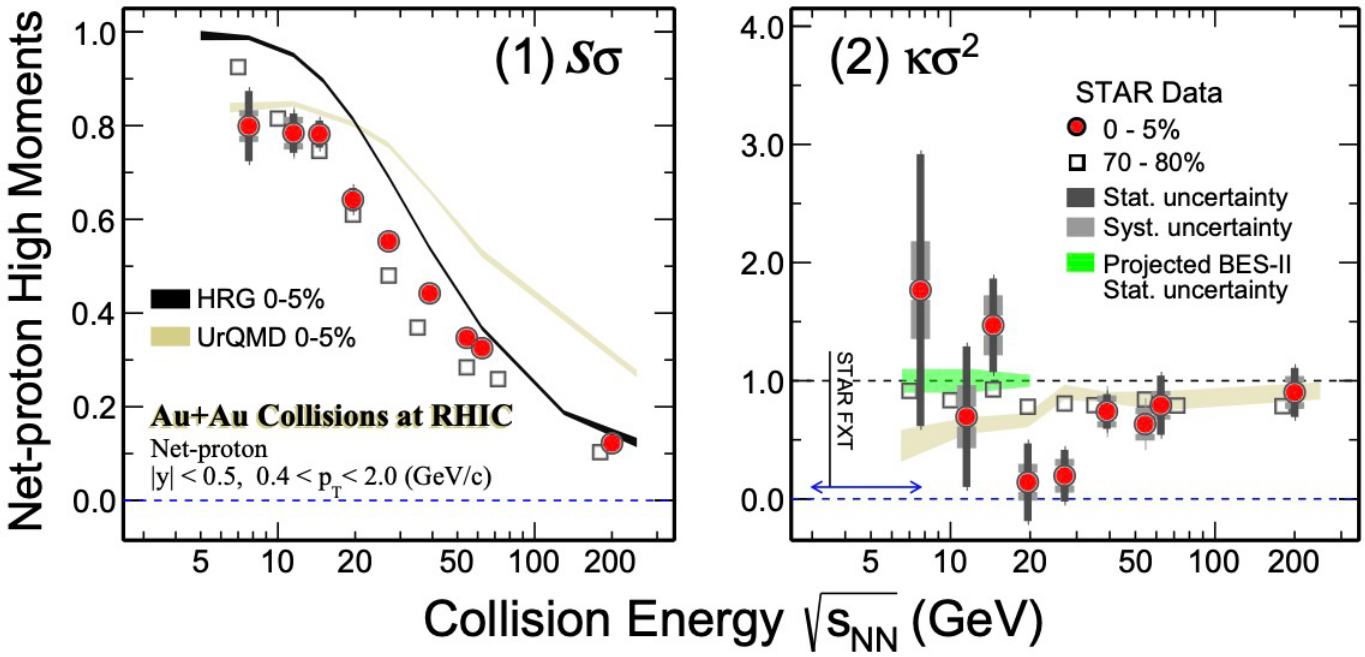


See talk by:

Risa Nishitani
8 June 2021, 12:40

Fluctuations - net proton

- Net protons are a proxy for net baryons
- Related to baryon number conservation



$$S\sigma = \frac{C_3}{C_2}$$
$$\kappa\sigma^2 = \frac{C_4}{C_2}$$

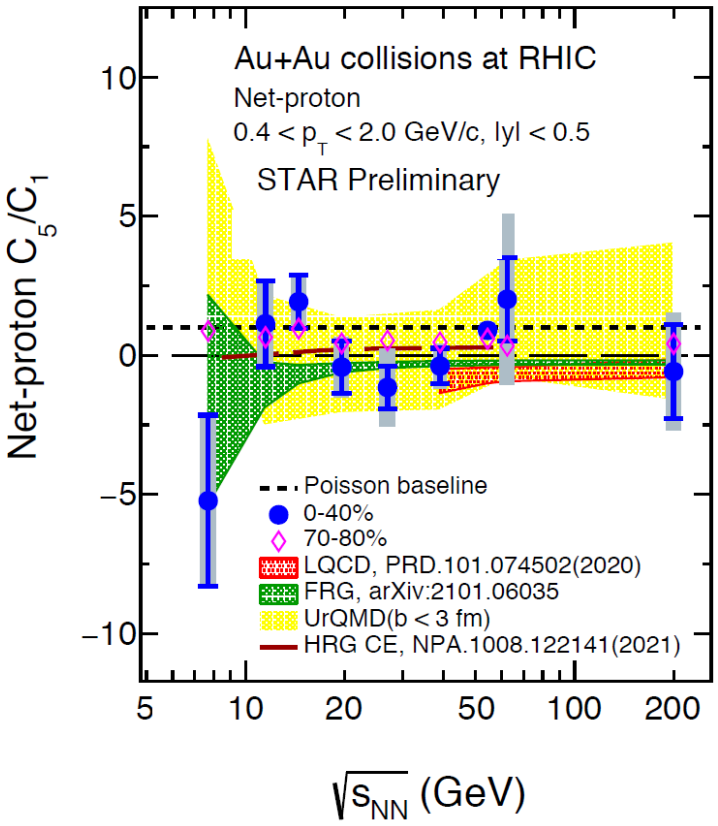
See talk by:

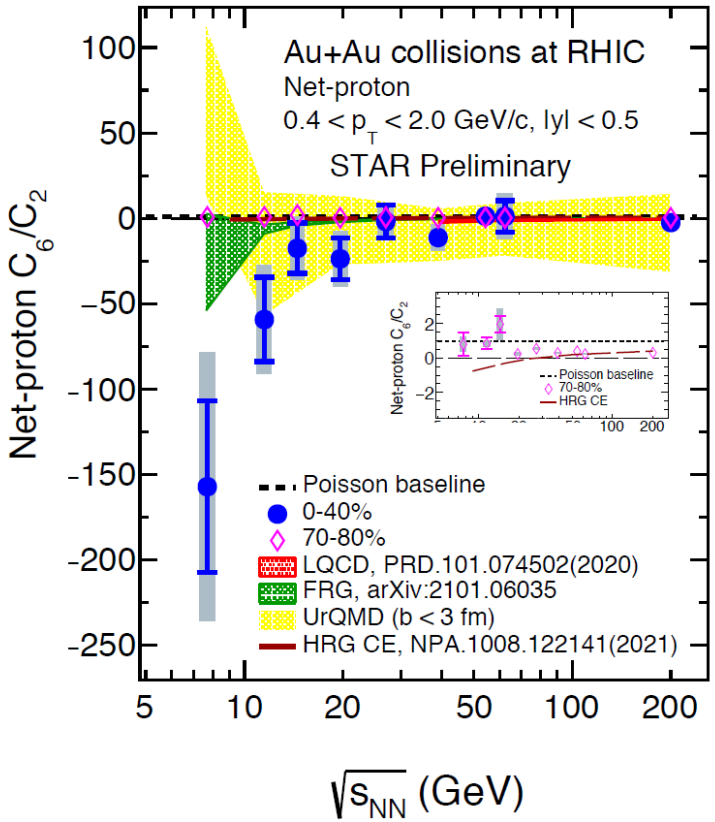
Risa Nishitani
8 June 2021,
12:40

STAR: [Phys. Rev. Lett. 126, 092301 (2021)]

- Non-monotonic dependence of net proton $\kappa\sigma^2$ on $\sqrt{s_{NN}}$ observed
  - 3.1σ significance
- **A possible signature of Critical Point**
- Better precision will be available with BES II data!

Fluctuations - net proton C_5 and C_6



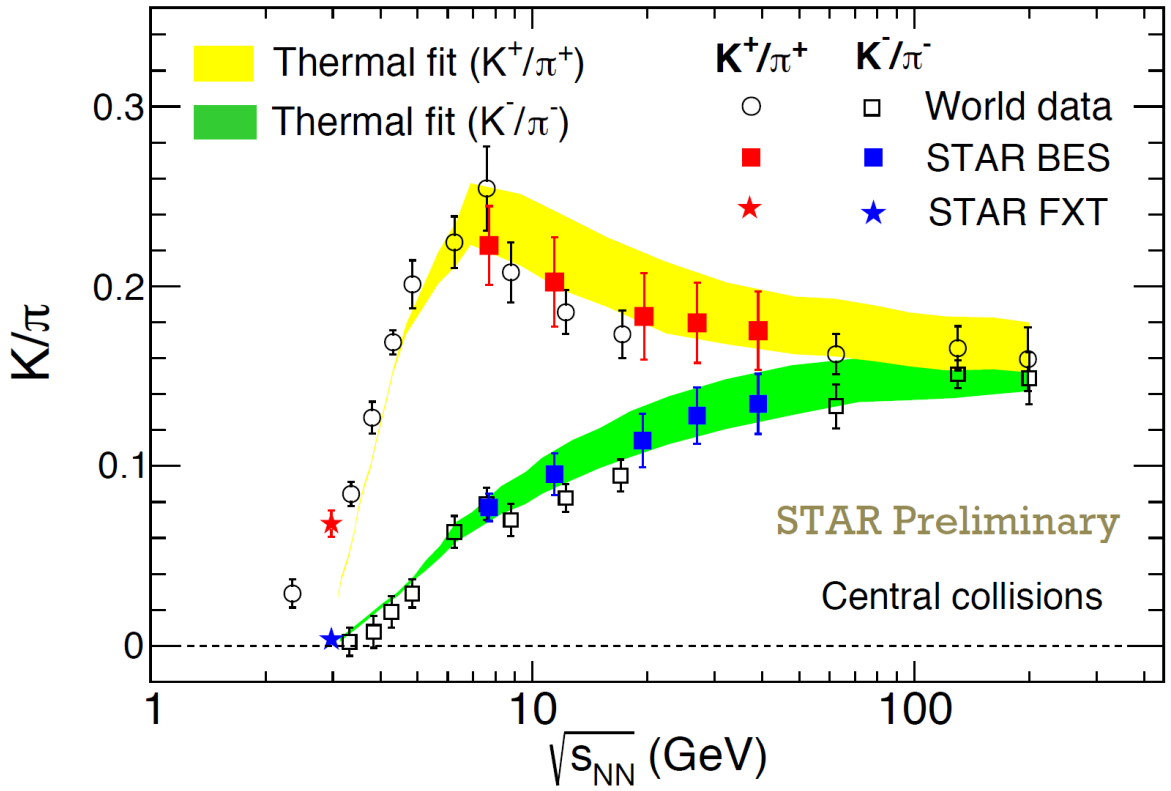


See talk by:

Risa Nishitani
8 June 2021,
12:40

- LQCD and FRG models predict negative values of higher cumulant ratios due to phase transition between partonic and hadronic phases
- STAR data show positive ratios for peripheral collisions (70-80% centrality)
- Data from 0-40% central Au+Au collisions:
  - $\frac{C_5}{C_1}$ negative at some energies (but large uncertainties $< 2\sigma$)
  - $\frac{C_6}{C_2}$ mostly negative
- **Indication of increasing fluctuations at low energies**

K/π vs. $\sqrt{s_{NN}}$



KaoS: [J. Phys. G 28, 2011 (2002)]

E866/E917: [Phys. Lett. B490, 53 (2000)]

NA49: [Phys. Rev. C 77, 024903 (2008)]

NA49: [Phys. Rev. C 66, 054902 (2002)]

STAR: [Phys. Rev. C 96, 044904 (2017)]

E866/E917: [Phys. Lett. B476, 1 (2000)]

Thermal: [Phys. Lett. B, 673, 142 (2009)]

J. Cleymans: [Phys. Lett. B, 615, 150 (2005)]

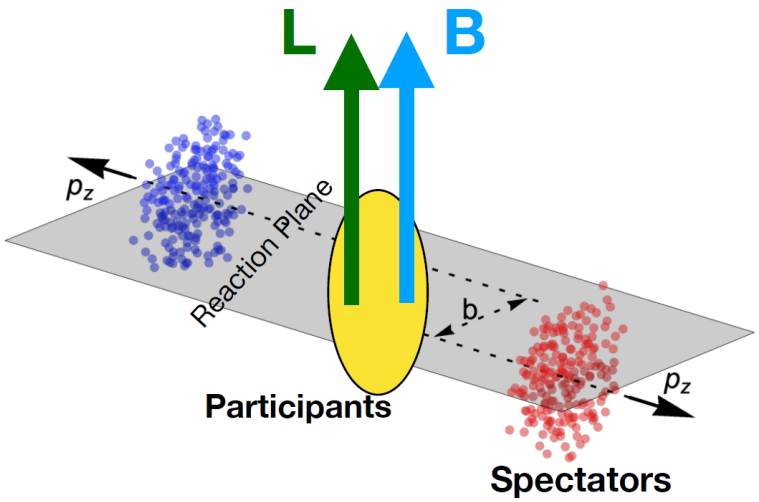
M. Gazdzicki: [Acta Phys Polon. B30,2705 (1999)]

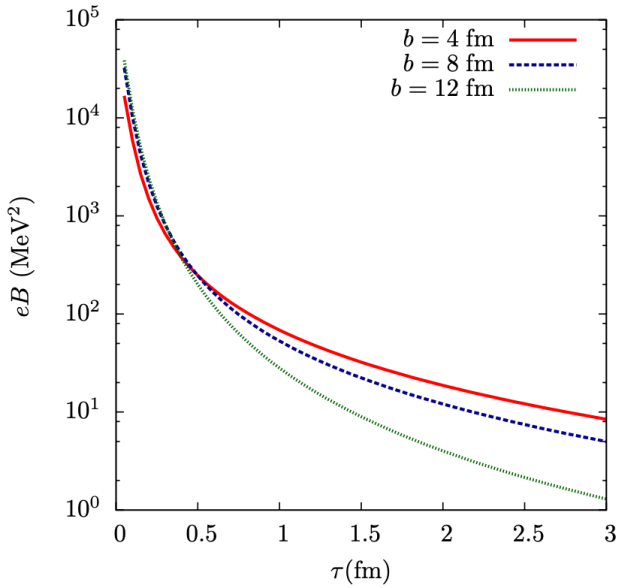
Motivation: Strangeness/entropy ratio - Is there a change in degrees of freedom?

- **Smooth K^+/π^+ ratio vs. collision energy**
- STAR BES I data follow the trend vs. $\sqrt{s_{NN}}$
- Data well described by thermal model

Vortices in medium

- Large orbital angular momentum is produced in non-central heavy-ion collisions
- Strong initial magnetic field $eB \sim m_\pi^2 \sim 10^{14}\,T$ created mostly by the spectators





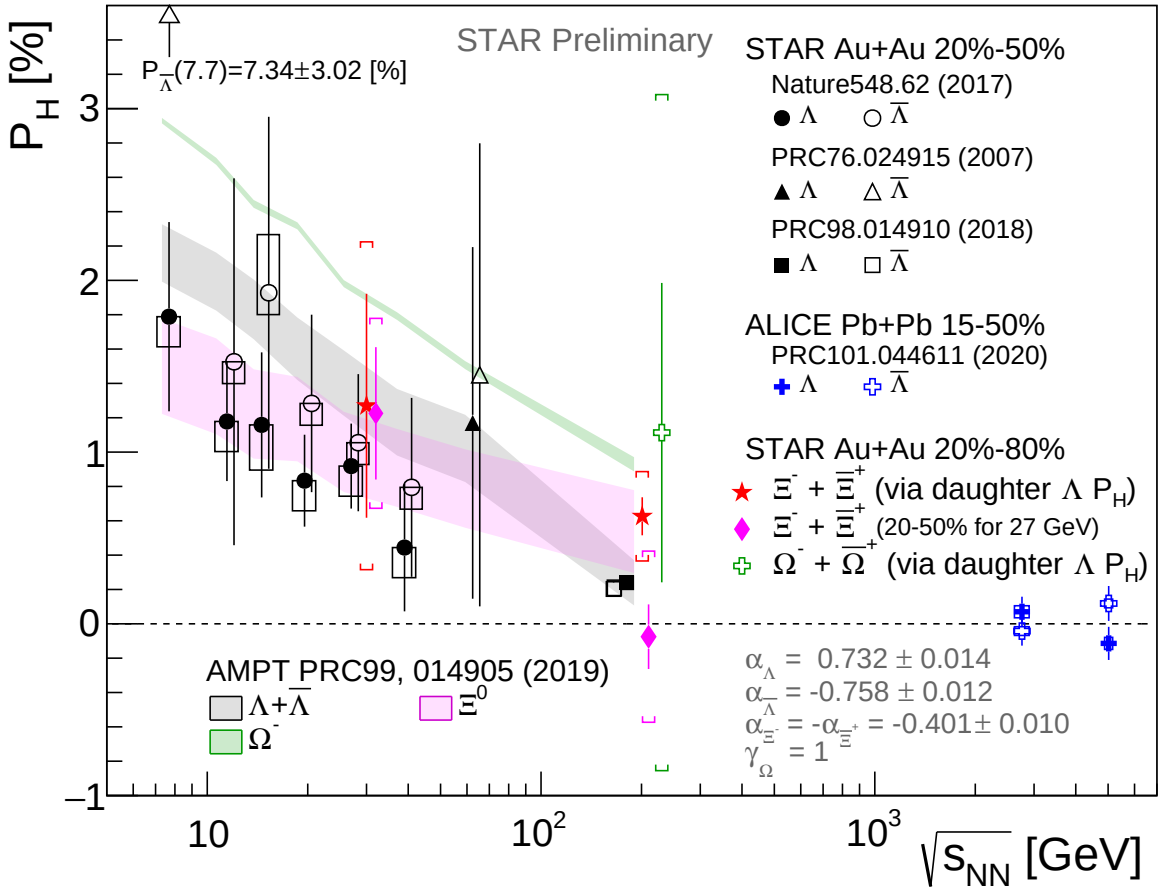
D. Kharzeev [Nucl Phys A803, 227 (2008)]

- Vorticity in medium aligns spins of quarks through spin-orbit coupling
  - Same effect on q and $\bar{q}$
- Magnetic field also interacts with quark magnetic moments
  - Opposite effect on q and $\bar{q}$
- Use angular distributions of "self analyzing" hyperons to study B and L by measuring polarization:

$$P_H = \frac{8}{\pi \alpha_H} \frac{<sin(\Psi_1 - \phi_d^*)>}{\sigma_{\Psi_1}}$$

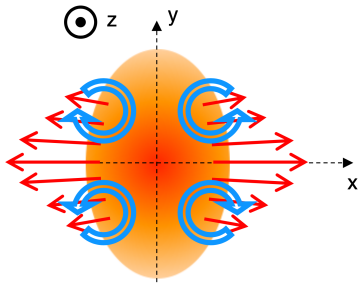
- Most vortical fluid in nature observed by STAR *STAR: [Nature 548, 62 (2017)]*

Energy dependence



STAR: [Phys Rev Lett 126, 162301 (2021)]

- For more on:
  - Local spin polarization



  - Global spin alignment of vector mesons

See talk by:

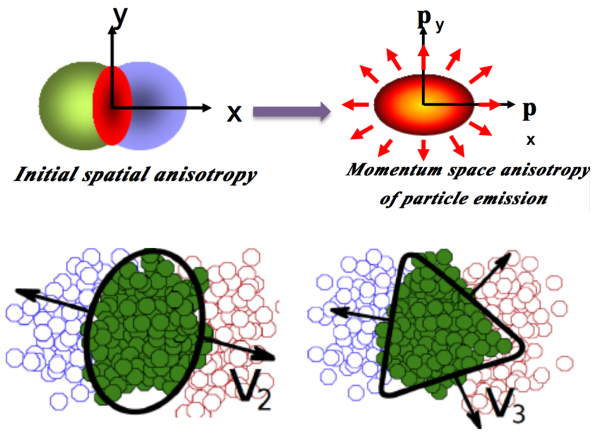
Subhash Singha
8 June 2021, 13:45

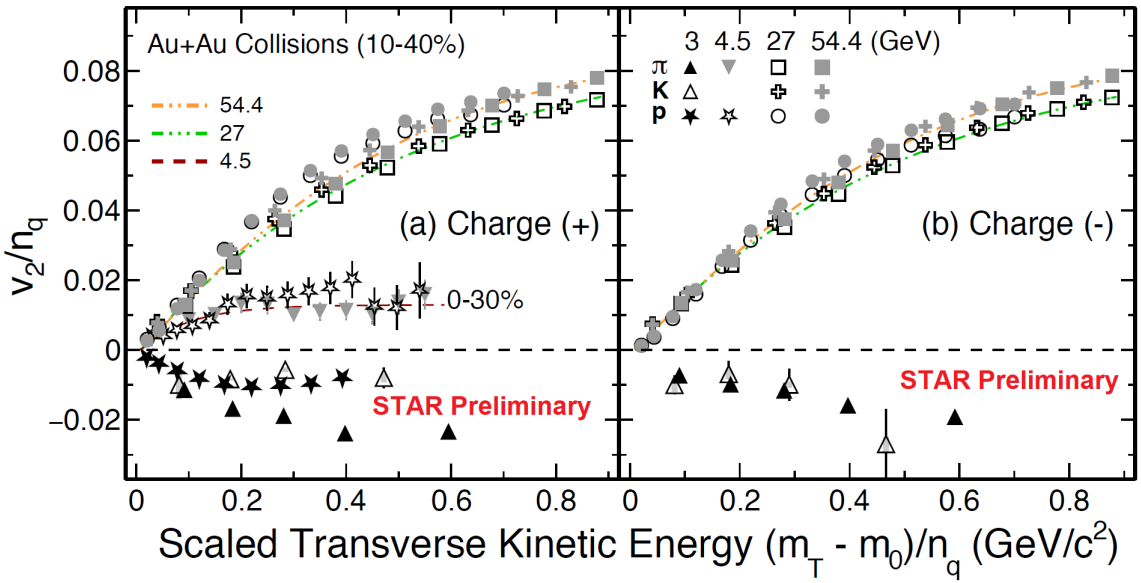
- First measurement of P_Ξ and P_Ω - global polarization
  - $P_\Xi = 0.47 \pm 0.10(stat.) \pm 0.23(syst.)$
  - $P_\Omega = 1.11 \pm 0.87(stat.) \pm 1.97(syst.)$
  - $P_\Lambda = 0.24 \pm 0.03(stat.) \pm 0.03(syst.)$
- **Energy dependence of P_Ξ follows the same trend as P_Λ**

- Initial state spatial anisotropy is transformed into momentum anisotropy by the resulting pressure gradients

$$\frac{dN}{d\phi} = 1 + 2\sum_n v_n cos(n(\phi - \Psi_n)) \qquad v_n = < cos(n(\phi - \Psi_n)) >$$

- Flow coefficients are sensitive to both the medium's initial shape and the nature of interactions in it





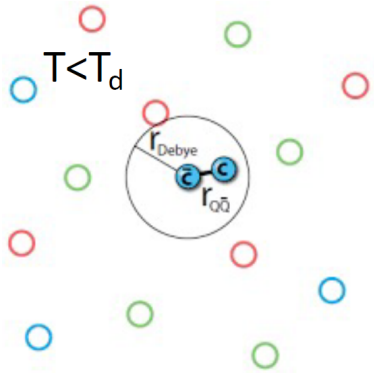
- Fixed target data at $\sqrt{s_{NN}} = 3\,\mathrm{GeV}$
  - v_2 is negative for all particles
  - **NCQ scaling breaks - hadronic interactions dominate**

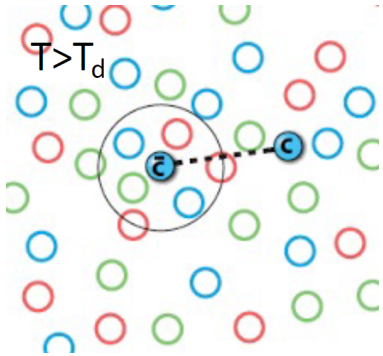
See talk by:

Md Nasim
8 June 2021, 14:35

Heavy Flavor production - J/ψ suppression

- J/ψ can be used as a probe of QGP
  - Suppression of J/ψ production due to Debye-like screening of color charges
    T. Matsui [Phys. Lett. B, 178(4), 416–422 (1986)]

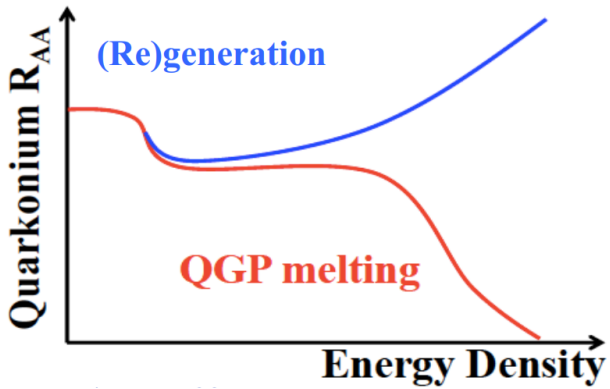




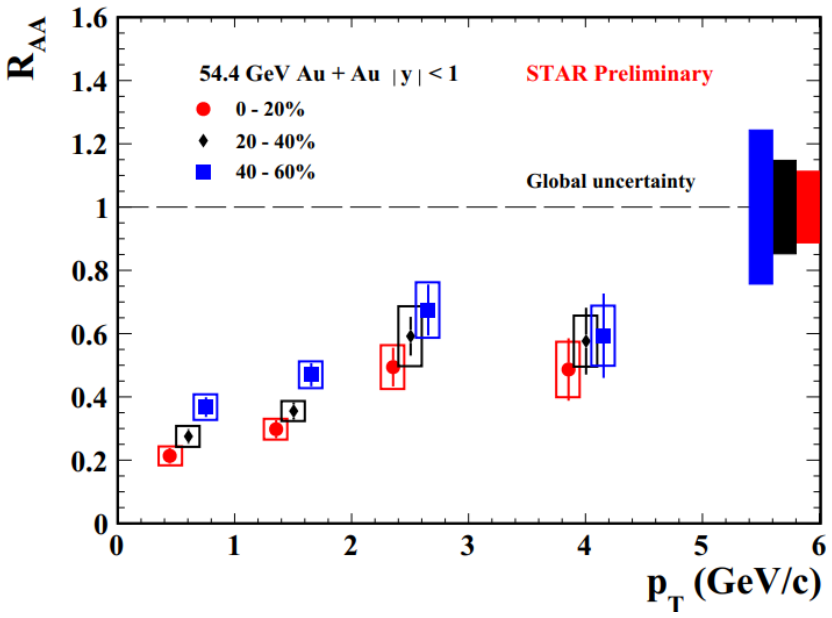
- Measured using nuclear modification factor R_{AA}

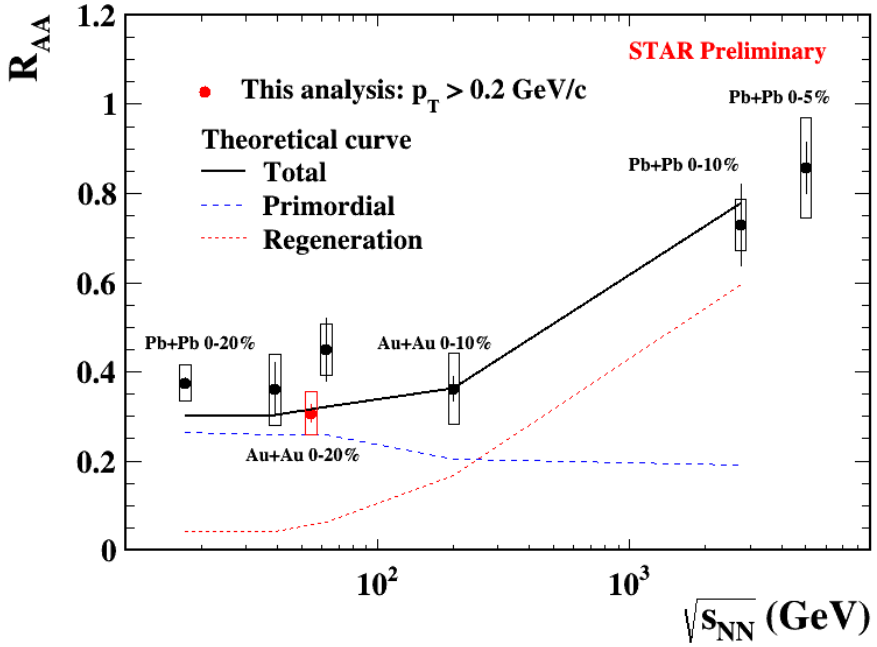
$$R_{AA} = \frac{\sigma_{inel}}{<N_{coll}>} \frac{\mathrm{d}^2 N_{A+A}/\mathrm{d}p_T\mathrm{d}y}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}p_T\mathrm{d}y}$$

- Other effects also play a role
  - Feed-down contributions
  - Modified nuclear PDFs
  - Comover interactions
  - Regeneration



J/ψ production at $\sqrt{s_{NN}} = 54.4$ GeV





- p_T dependence of R_{AA}
  - R_{AA} **increases with** p_T
  - More suppression in central collisions
- $\sqrt{s_{NN}}$ dependence of R_{AA}
  - **No dependence is observed up to** $\sqrt{s_{NN}} = 200$ GeV **within uncertainties**
  - Model calculations are consistent with the data trend

X. Zhao, R. Rapp: [Rev. C 82 (2010) 064905 (private communication)]

L. Kluberg: [Eur. Phys. J. C 43 (2005) 145]

NA50: [Phys. Lett. B 477 (2000) 28]

ALICE: [Phys. Lett. B 734 (2014) 314]

STAR: [Phys . Lett. B 771 (2017) 13 20]

STAR: [Phys. Lett. B 797 (2019) 134917]

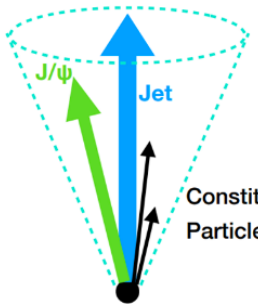
ALICE: [Nucl. Phys. A 1005 (2021) 121769]

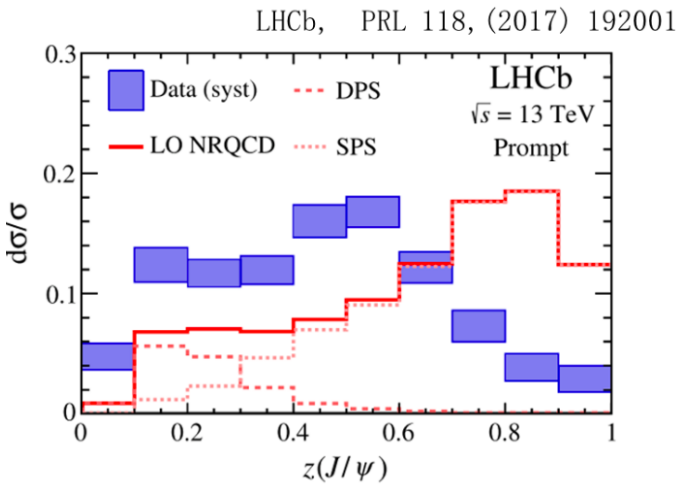
See talk by:

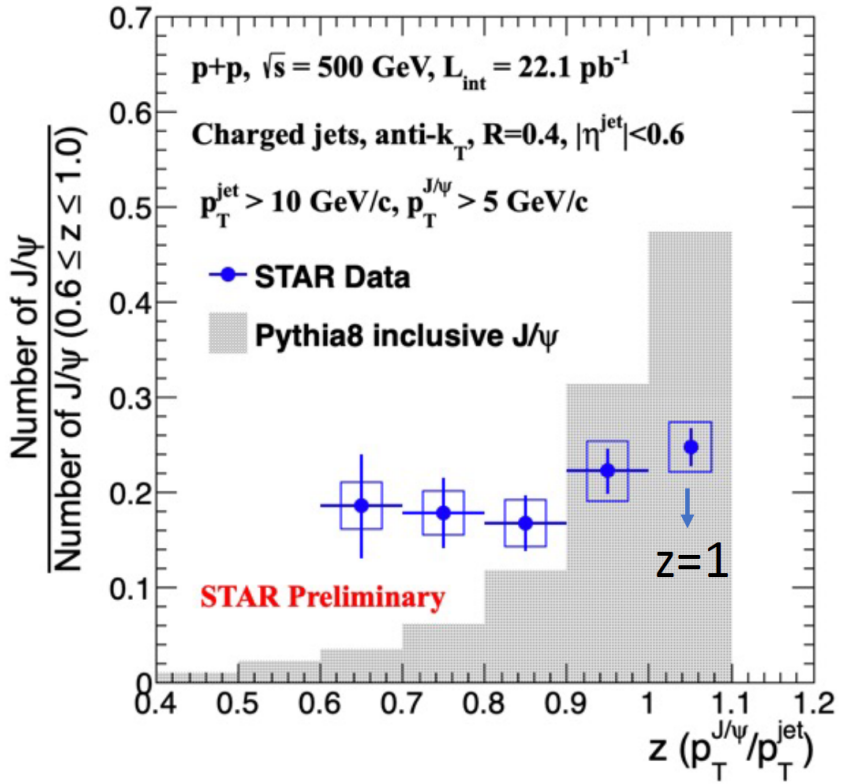
Yuanjing Ji
8 June 2021, 14:10

J/ψ production in a jet in p+p at $\sqrt{s} = 500$ GeV

- J/ψ production mechanism not well understood
- Are J/ψ produced directly or in association with a parton shower (jet)?







- **No significant z dependence observed within uncertainties**
- Less isolated J/ψ than predicted by PYTHIA8

See talk by:

Yuanjing Ji
8 June 2021, 14:10

Summary

- Cold-QCD and Spin
  - New published measurements of jet A_{LL} and π^0 TSSA
  - Larger asymmetry for isolated π^0 than those in jets - diffractive process contribution?
- Study of QCD phase diagram
  - Net proton fluctuations show non-monotonic dependence on $\sqrt{s_{NN}}$ - indicative of critical point
  - Cumulant ratios $\frac{C_5}{C_1}$ and $\frac{C_6}{C_2}$ in central collisions mostly negative due to transition to partonic phase
  - $\frac{K^+}{\pi^+}$ ratio vs. $\sqrt{s_{NN}}$ described by thermal model
- Global hyperon polarization
  - New data for Ξ and Ω show similar trend as Λ
- Flow: negative v_2 measured at $\sqrt{s_{NN}} = 3\,\mathrm{GeV}$ using FXT data
  - Breaking of NCQ scaling - hadronic interactions play an important role
- J/ψ production
  - New precise R_{AA} at $\sqrt{s_{NN}} = 54.4\,\mathrm{GeV}$
    - Increases with p_T and decreases with centrality
    - No dependence on $\sqrt{s_{NN}}$ seen up to 200 GeV
  - J/ψ production in jet in p+p $\sqrt{s} = 500\,\mathrm{GeV}$
    - No significant z dependence observed for the measured kinematics

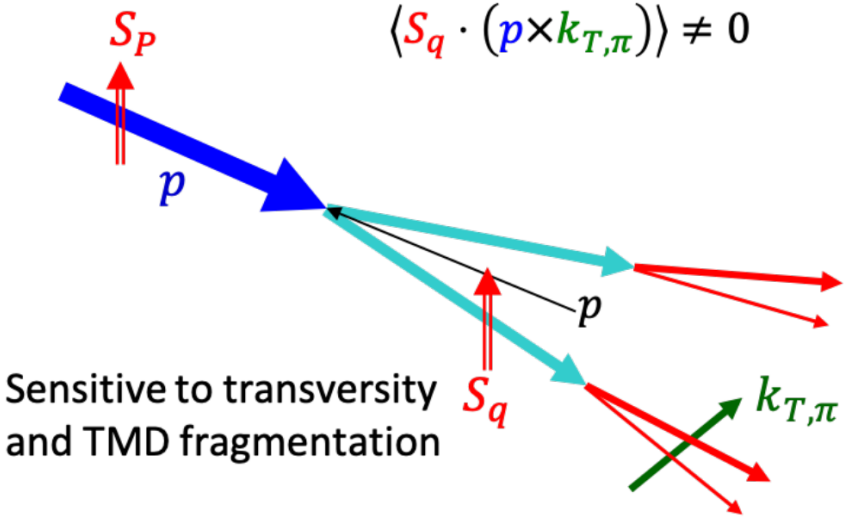
Thank you for your attention!

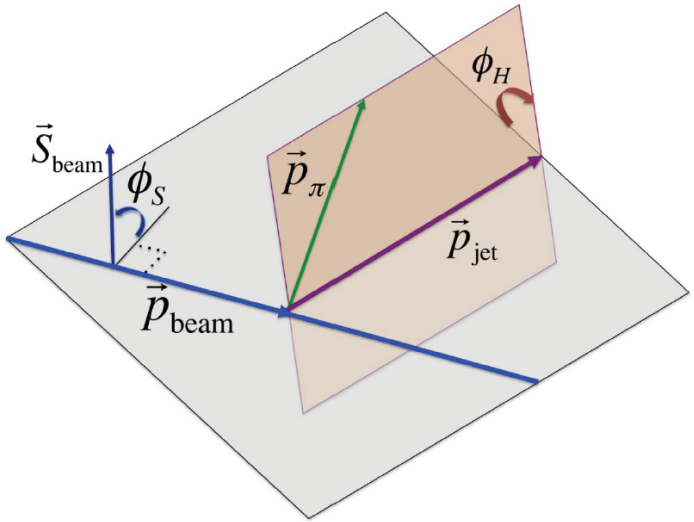
STAR presentations at RHIC & AGS Users Meeting 2021

- Recent Highlights from the STAR Cold-QCD Physics Program
  - Xiaoxuan Chu (BNL), 8 June 2021 (Tuesday), 09:50
- Future Cold-QCD Physics Program with STAR
  - Ting Lin (Shandong University), 8 June 2021 (Tuesday), 11:20
- Net-particle Cumulants Measurement from STAR BES
  - Risa Nishitani, 8 June 2021 (Tuesday), 12:40
- Polarization Measurements from STAR BES
  - Subhash Singha (Kent State University), 8 June 2021 (Tuesday), 13:45
- Recent Open Heavy Flavor and Quarkonia Measurements from STAR
  - Yuanjing Ji (LBNL), 8 June 2021 (Tuesday), 14:10
- Yield Production and Flow Measurements from STAR BES
  - Md Nasim (IISER Berhampur, India), 8 June 2021 (Tuesday), 14:35

BACKUP

Collins asymmetry





$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)} \qquad \phi = \phi^S - \phi^H$$

- indicates the azimuthal asymmetry of a hadron originating from the fragmentation of a transversely polarized quark
- directly probes the fragmentation process contribution to the single spin asymmetry

See talk by:

Xiaoxuan Chu, 8 June 2021, 09:50