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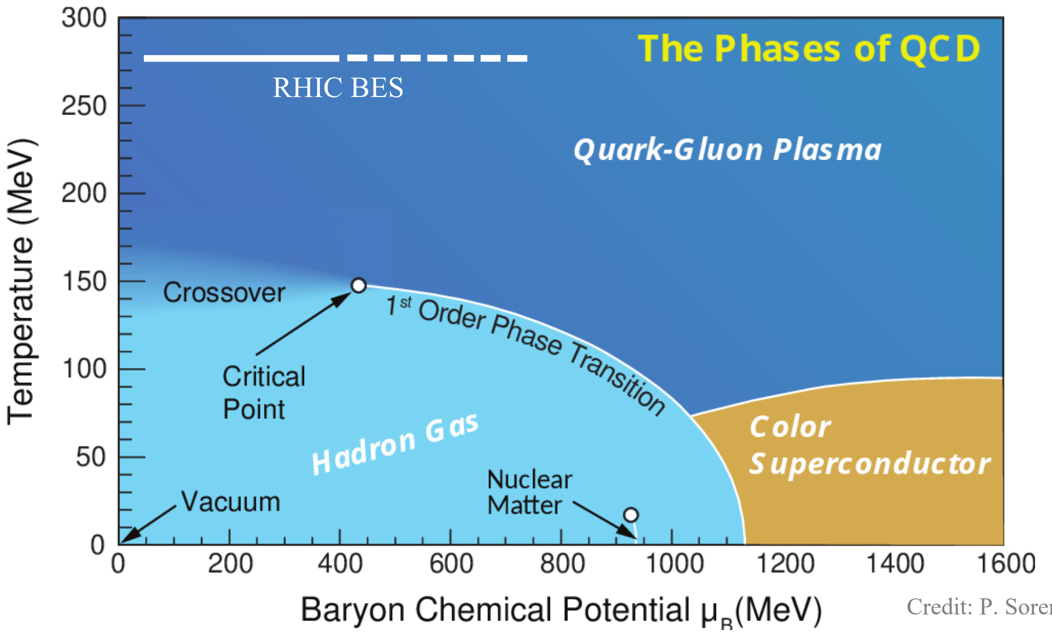
Brookhaven National Laboratory

STAR Highlights

Rongrong Ma (For the STAR Collaboration)
Brookhaven National Laboratory

STAR Physics Program

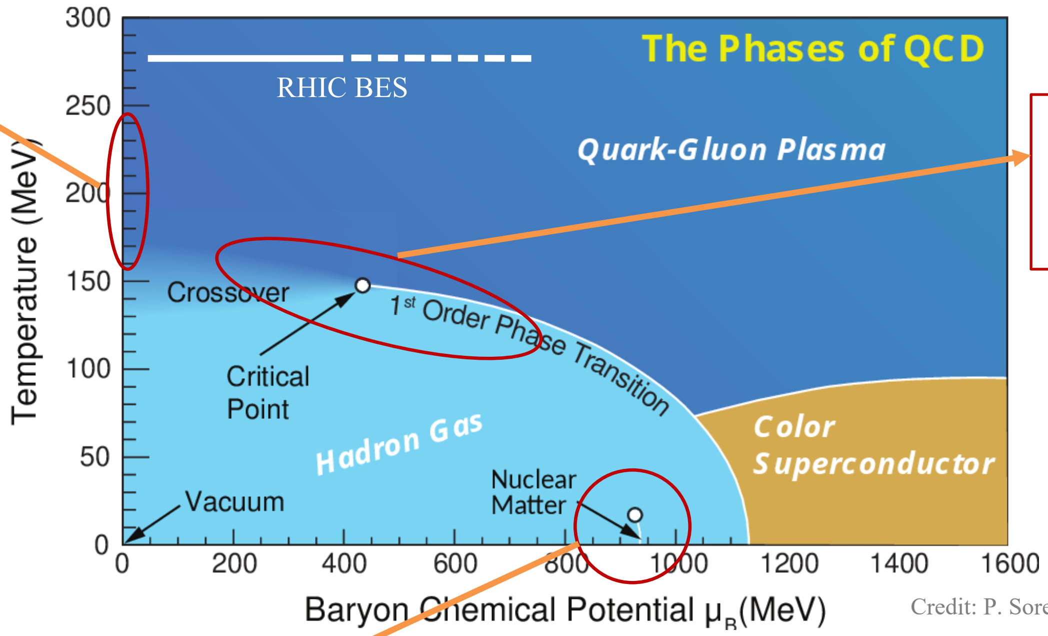


Credit: P. Sorensen, T. Ullrich

- Study QCD and QCD phase diagram with *p+p* and heavy-ion collisions

Outline

3. RHIC top energy

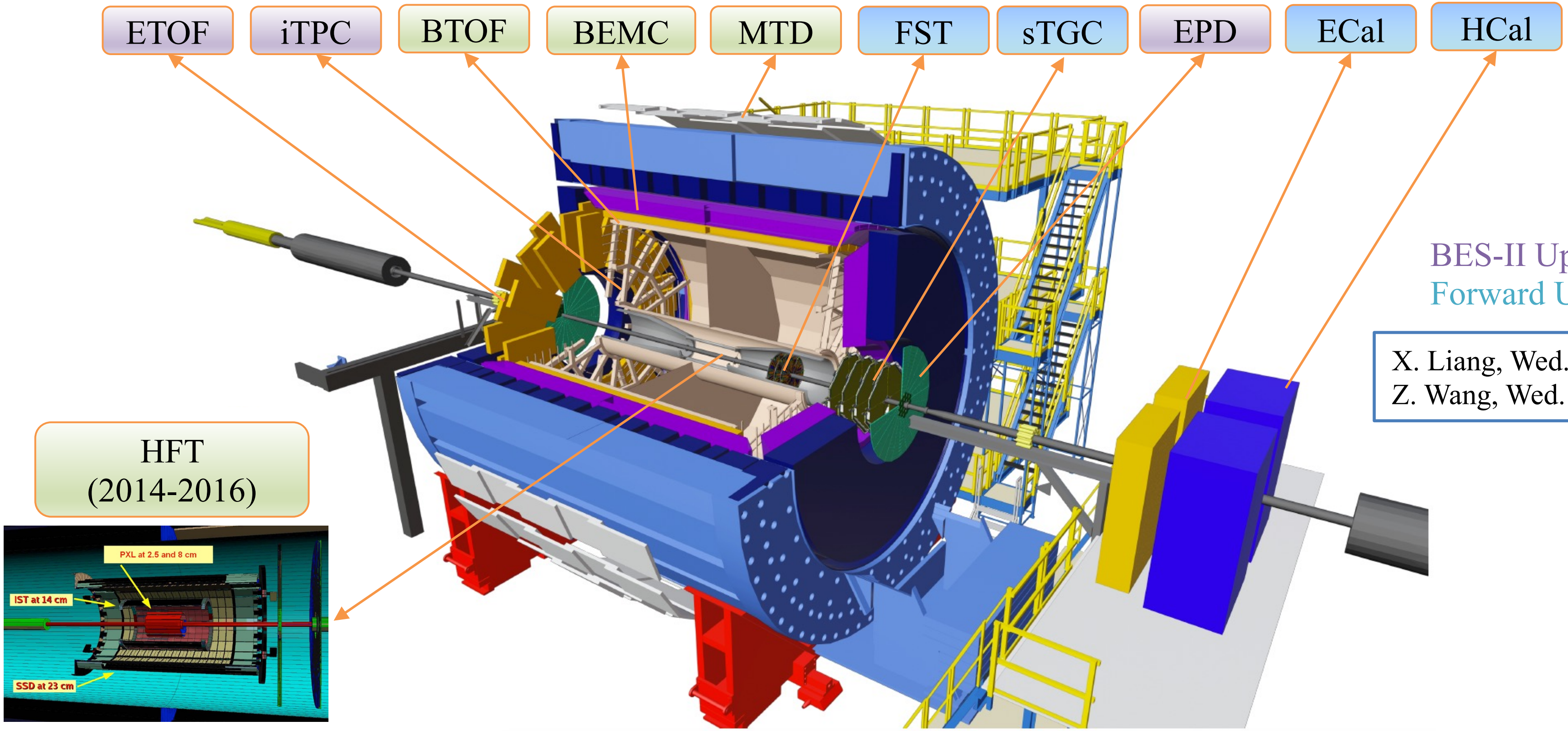


Credit: P. Sorensen, T. Ullrich

2. Beam Energy Scan

1. Cold QCD physics

STAR Detector

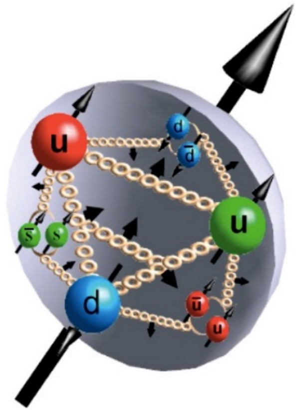


BES-II Upgrade
Forward Upgrade

X. Liang, Wed. 9:30 AM
Z. Wang, Wed. 3:50 PM

Cold QCD Physics

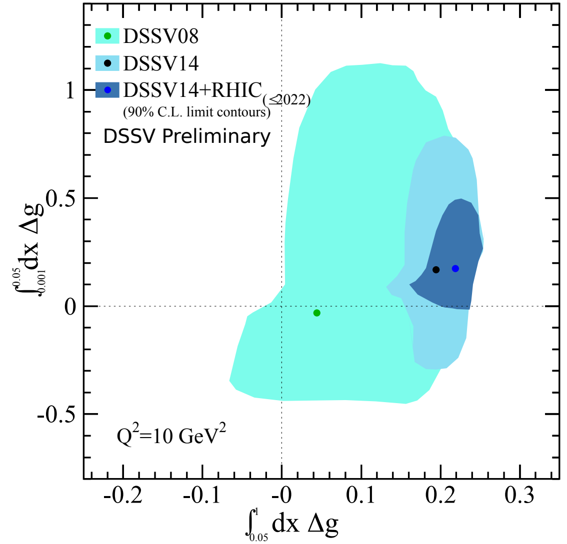
RHIC's Final Word on Gluon Helicity



R. L. Jaffe, A. Manohar, NPB 337 (1990) 509

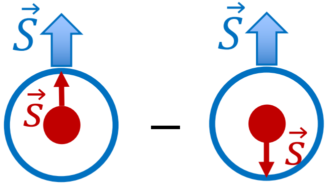
$$S = \frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quarks}} + \underbrace{\Delta G}_{\text{gluons}} + \underbrace{L}_{\text{orbital angular momentum}}$$

DSSV Preliminary



- DSSV global fit including up-to-date jet, dijet, pion, *W* data
- $\int_{0.05}^{1} dx\Delta g = 0.218 \pm 0.027$

Transversity $h_1(x)$

$h_1(x) \approx$ 

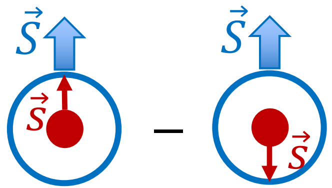
$\pi^+\pi^-$ azimuthal asymmetry; interference FF

$$A_{UT}^{sin(\phi_{RS})} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\sum_{i,j,k} \boxed{h_1^{i/p_a}(x_a)} f_1^{j/p_b}(x_b) H_1^{\sphericalangle h_1 h_2/k}(z, M_h)}{\sum_{i,j,k} f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) D_1^{h_1 h_2/k}(z, M_h)}$$

Transversity $h_1(x)$

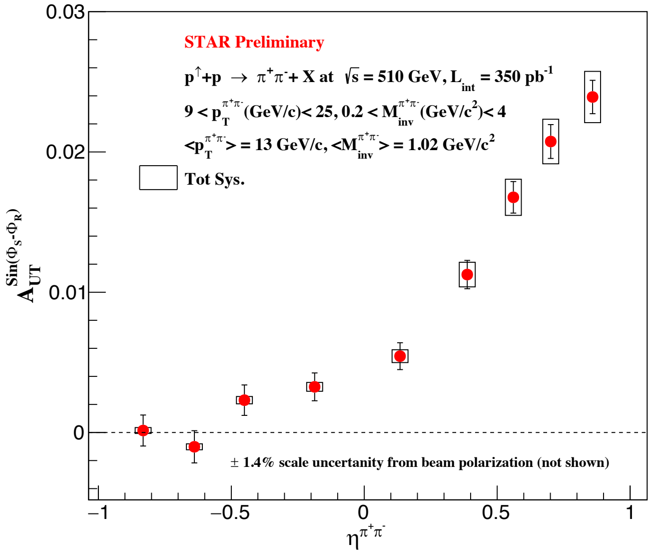
N. Ghimire, Poster

$h_1(x) \approx$



$\pi^+\pi^-$ azimuthal asymmetry; interference FF

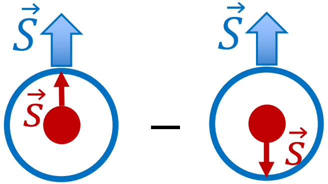
$$\boxed{A_{UT}^{\sin(\phi_{RS})}} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^{\sphericalangle h_1 h_2/k}(z, M_h)}{\sum_{i,j,k} f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) D_1^{h_1 h_2/k}(z, M_h)}$$



- Latest measurement in 510 GeV *p*+*p* collisions
- Large asymmetry at high η → significant quark transversity at large *x*
  - Small asymmetry at negative η due to small transversity at low *x*

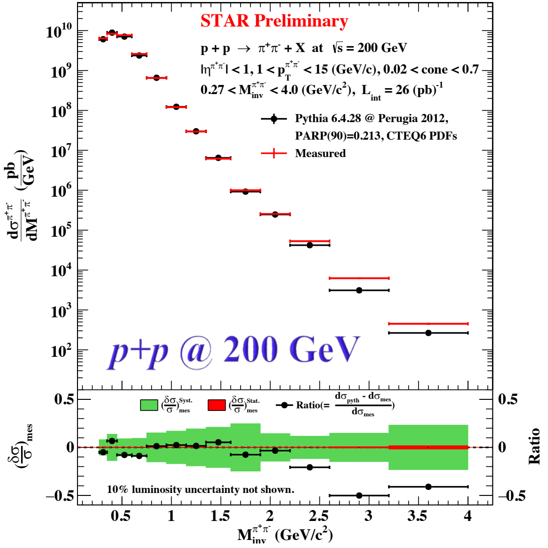
Transversity $h_1(x)$

B. Pokhrel, Poster

$h_1(x) \approx$ 

$\pi^+\pi^-$ azimuthal asymmetry; interference FF

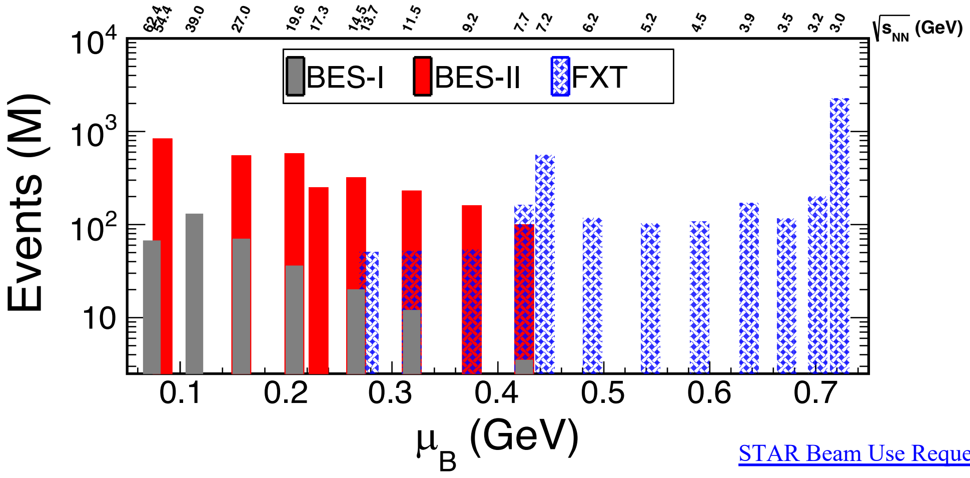
$$A_{UT}^{sin(\phi_{RS})} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^{\sphericalangle h_1 h_2/k}(z, M_h)}{\sum_{i,j,k} f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) \boxed{D_1^{h_1 h_2/k}(z, M_h)}}$$



- First measurement of unpolarized $\pi^+\pi^-$ cross section in 200 GeV *p+p* collisions
  - Good agreement with PYTHIA
  - Can constrain gluon fragmentation

- Towards a model-independent extraction of transversity

Beam Energy Scan

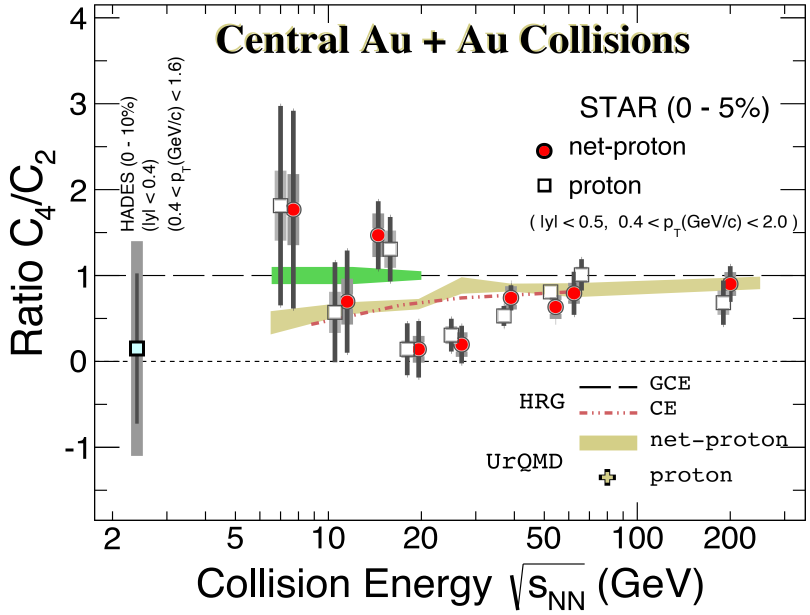


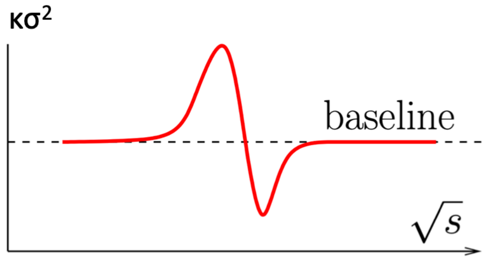
[STAR Beam Use Request]

Search for CP: Net-Proton Fluctuation

STAR, PRL 128 (2022) 202303

Z. Sweger, Wed. 11:30 AM



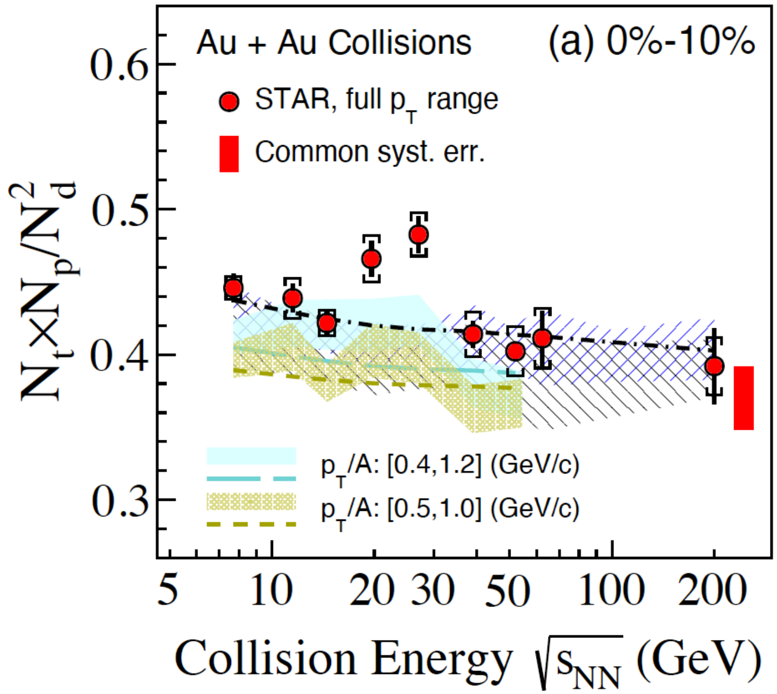


M. Stephanov. J. Physics G.: Nucl. Part. Phys. **38** (2011) 124147

- BES-I: non-monotonic trend with collision energy with 3.1σ
  - BES-II COL: significantly improve BES-I results
  - BES-II FXT: fill the gap between 3 – 7.7 GeV

Search for CP: Light Nuclei Yield Ratio

STAR, PRL 130 (2023) 202301



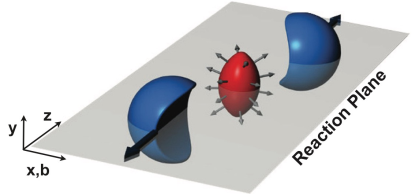
$$\frac{N_t \times N_p}{N_d^2}$$

Sensitive to neutron density fluctuation → non-smooth behavior at CP or first-order phase transition

- BES-I: in 0-10% central collisions, data deviate from coalescence baseline at 19.6 and 27 GeV with a combined significance of 4.1σ
  - *BES-II data will allow more differential measurements*

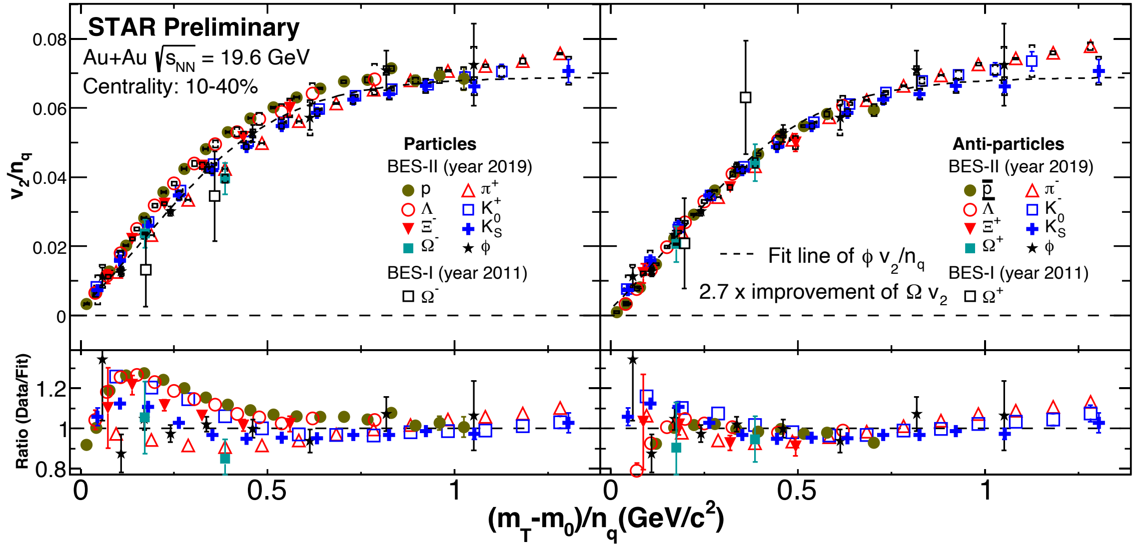
Search for QGP Signature: NCQ Scaling

C. Racz, Wed. 11:30 AM



R. Snellings, New J. Phys. 13 (2011) 055008

19.6 GeV



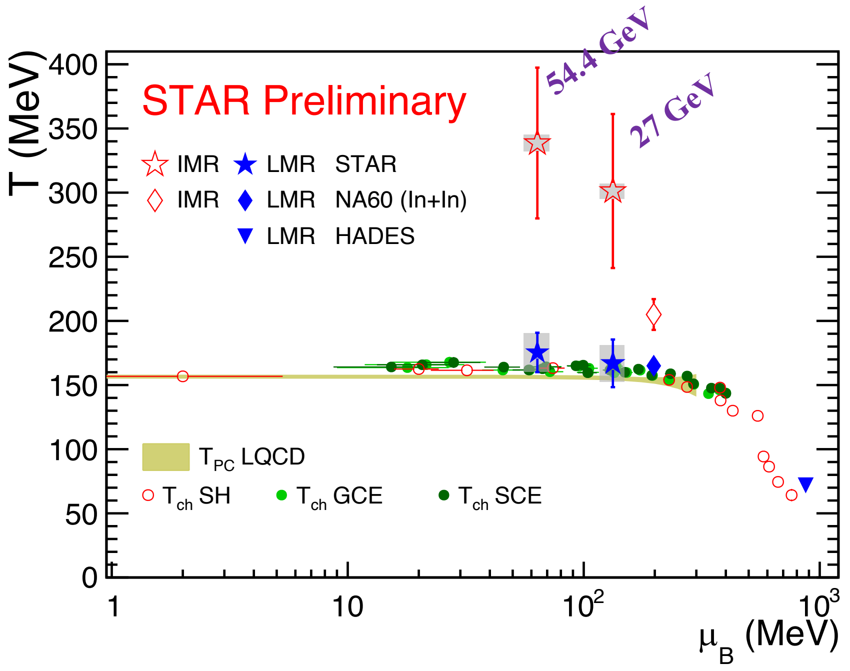
- Number-of-constituent-quark scaling holds within 10% for $(m_T-m_0)/n_q > 0.5$ GeV/c^2
  - Also observed at 14.6 GeV

→ Dominance of partonic interactions

QGP Temperature at RHIC

Z. Ye, Wed. 12:00 PM

- Thermal dileptons with mass between 1-3 GeV/c^2
  - Emitted from the QGP phase
- QGP temperature from mass spectrum slope → $T \sim 320$ MeV
  - No blue-shift effect

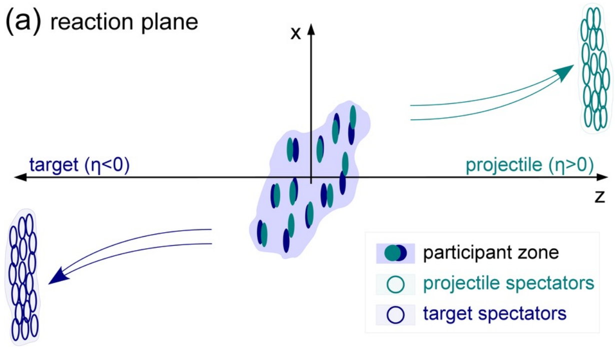


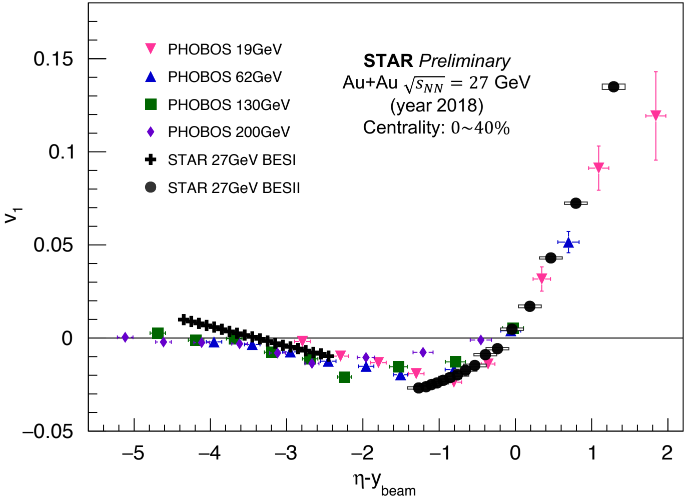
STAR, PLB 750 (2015) 64; STAR, arXiv:1810.10159; STAR, PRC 96 (2017) 044904
HotQCD: PLB 795 (2019) 15; P. Braun-Munzinger, et. al., Nature 561 (2018) 321
NA60, EPJC 59 (2009) 607; NA60, AIP Conf. Proc. 1322 (2010) 1
HADES, Nature Physics 15 (2019) 1040

Rapidity dependence of v_1 at 27 GeV

C. Racz, Wed. 11:30 AM

ALICE, PRL 111 (2013) 232302



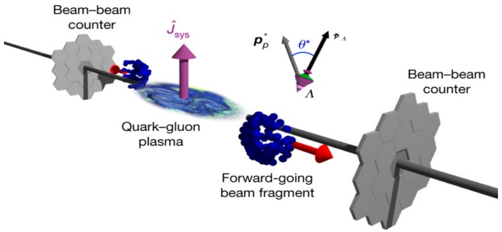


PHOBOS, PRL 97 (2006) 012301
STAR, PRC 101 (2020) 024905

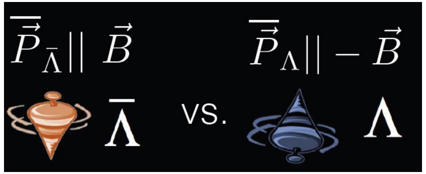
- $v_1(\eta)$: first dedicated EPD analysis
- Collapse to a common curve with other energies
- Can be used to constrain T-dependence of medium viscosity

Λ Global Polarization at 19.6 and 27 GeV

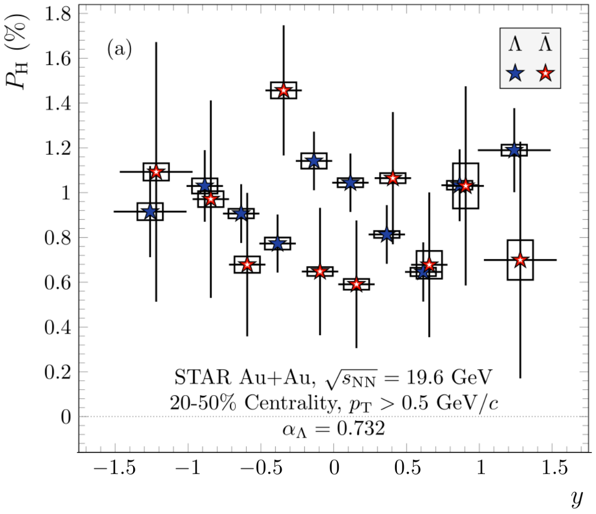
STAR, Nature 548 (2017) 62

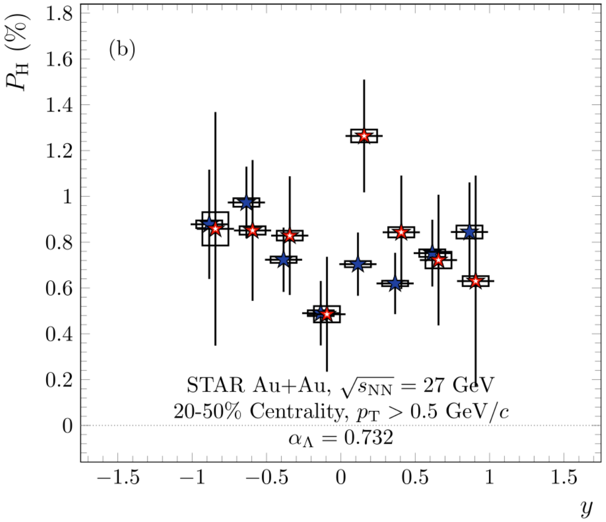


Courtesy of P. Tribedy



19.6 GeV STAR, PRC 108 (2023) 014910 **27 GeV**





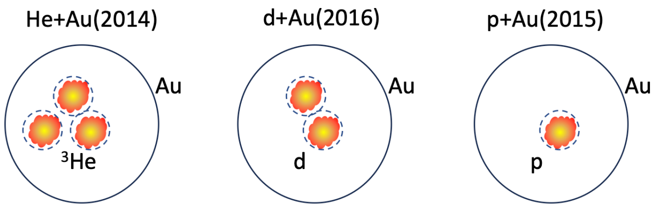
- No significant splitting between Λ and anti-Λ
  - Upper limit of difference: < 0.24% for 19.6 GeV and < 0.35% for 27 GeV with 95% confidence level
- No strong dependence on rapidity → challenge many theoretical predictions

D. X. Wei, et. al., PRC 99 (2019) 014905; Y. Guo, et. al., arXiv:2105.13481

Top RHIC Energy

Flow in Small Systems

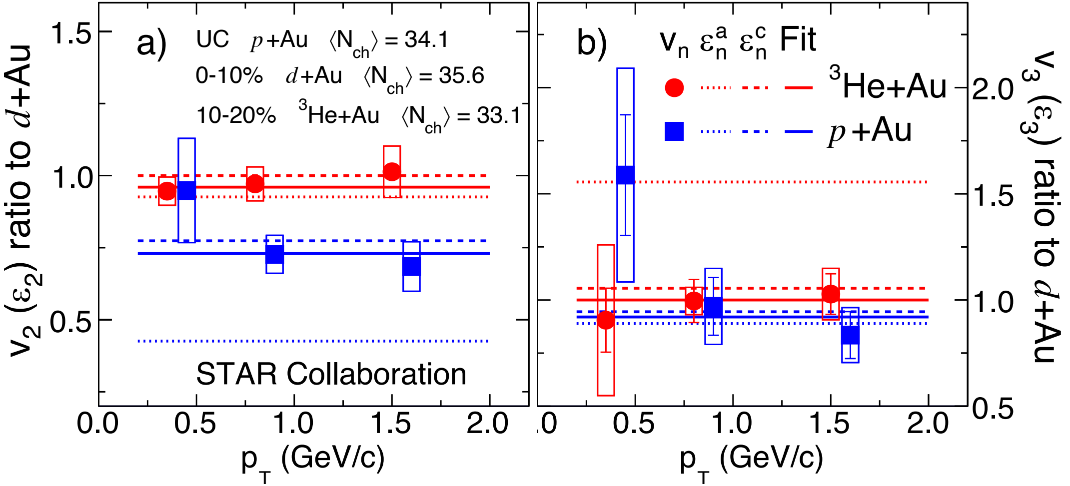
Courtesy of S. Huang



	Nucleon Glauber $\varepsilon_2(\varepsilon_3)$	Sub-Nucleon Glauber $\varepsilon_2(\varepsilon_3)$
0-5% pAu	0.23(0.16)	0.38(0.30)
0-5% dAu	0.54(0.18)	0.51(0.31)
0-5% ^{3}He+Au	0.50(0.28)	0.52(0.35)

Nucleon Glauber: J. L. Nagle, et. al., PRL 113 (2014) 112301
Sub-nucleon: K. Welsh, et. al., PRC 94 (2016) 024919

STAR, PRL 130 (2023) 242301

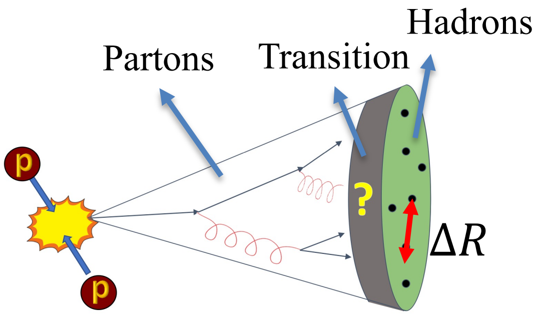


- Data at midrapidity
  - $v_2^{\text{He+Au}} \sim v_2^{\text{d+Au}} > v_2^{\text{p+Au}}$
  - $v_3^{\text{He+Au}} \sim v_3^{\text{d+Au}} \sim v_3^{\text{p+Au}}$
- Suggests significant influence of sub-nucleonic fluctuations
  - Need to study pre-flow

p+p: Jet Energy-Energy Correlator

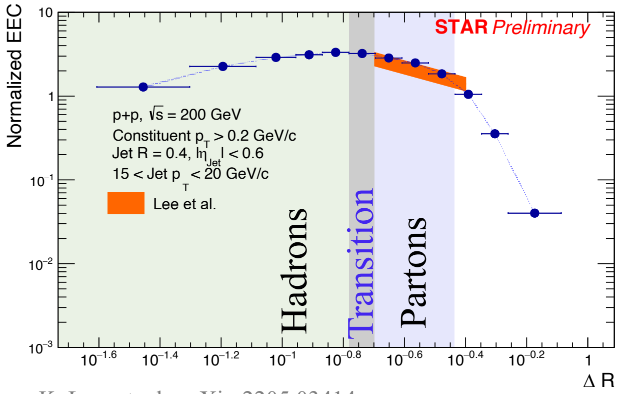
D. Roy, Wed. 9:40 AM

Courtesy of A. Tamis



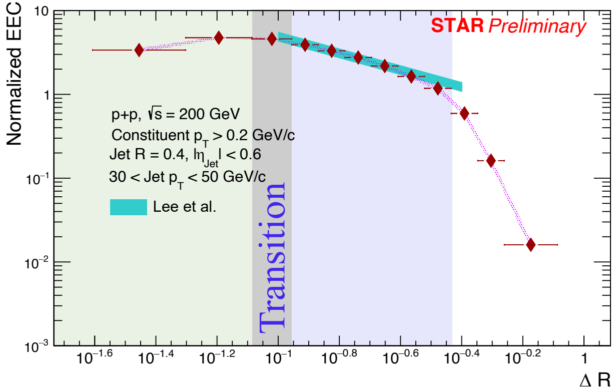
$$\mathrm{EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{p_{T,Jet}^2}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{p_{T,Jet}^2}\right)}{d\,(\Delta R)}$$

15 < Jet p_T < 20 GeV/c



K. Lee, et. al., arXiv:2205.03414

30 < Jet p_T < 50 GeV/c



- Transition region (onset of hadronization) scales with $1/p_{T,\mathrm{jet}}$ → $\Delta R^{*}p_{T,\mathrm{jet}} \sim$ 2-3 GeV/c
  - Also observed at LHC

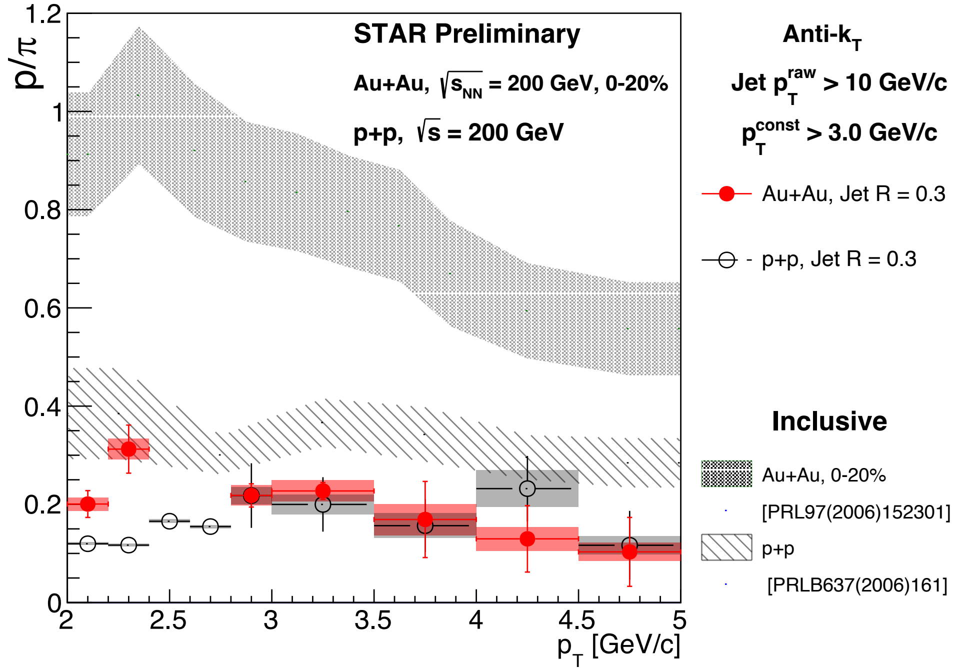
P. Komiske, et. al., PRL 130 (2023) 051901

- pQCD calculation describes partonic phase quite well

Au+Au: Hadron Chemistry in Jets

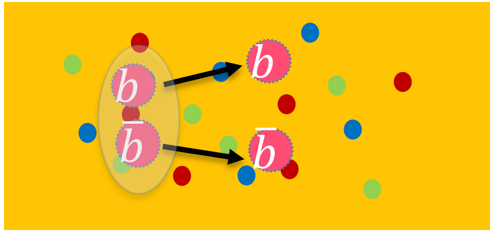
D. Roy, Wed. 9:40 AM

p+p vs. Au+Au



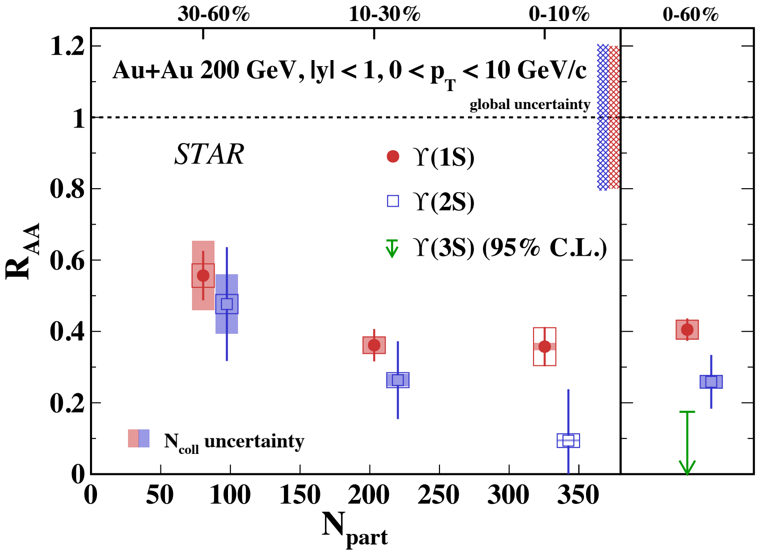
- *p/π* ratio significantly smaller in jets compared to bulk
- Similar *p/π* ratio in jets with $p_T^{const} > 3$ GeV/c in *p+p* and Au+Au collisions
- Measurements with lower p_T^{const} cuts are underway

Au+Au: Sequential ϒ Suppression



V. Prozorova, Wed. 1:45 PM

STAR, PRL 130 (2023) 112301



- ✓ First measurement of suppression of three ϒ states separately at RHIC
  - Upper limit for ϒ(3S) in 0-60%
  - $> 3\sigma$ difference for ϒ(1S) and ϒ(3S)
  - ϒ(2S) lies in between

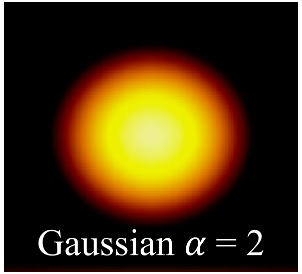
Au+Au: Emission Source Shape

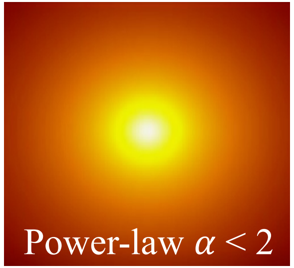
D. Kincses, Poster

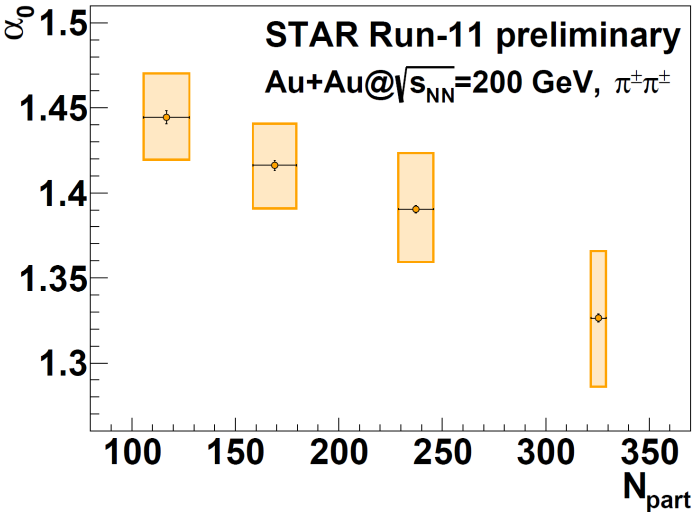
- ✓ **Source information through pion momentum correlation (femtoscopy)**

$$C_2(Q) = 1 - \lambda + \lambda * \mathcal{K}(Q;\alpha,R) * (1 + e^{-(RQ)^\alpha})$$

Q: relative momentum
R: source size
α: Lévy exponent





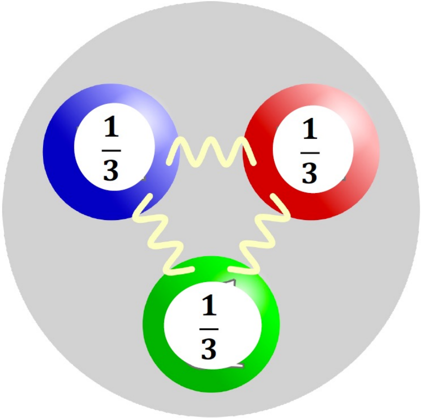


- Non-Gaussian source observed in Au+Au collisions
  - Deviates further from Gaussian in central collisions

What Carries the Baryon Number?

T. Tsang, Wed. 4:15 PM

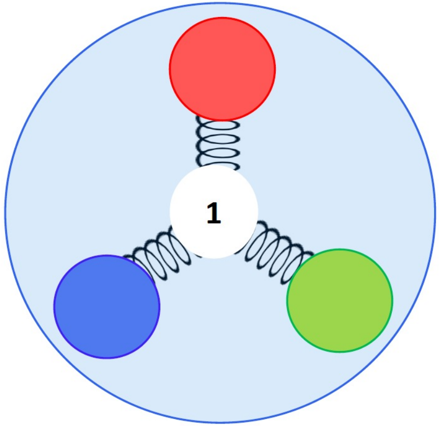
Quarks carry baryon number



https://en.wikipedia.org/wiki/Quark

vs.

Junction carry baryon number



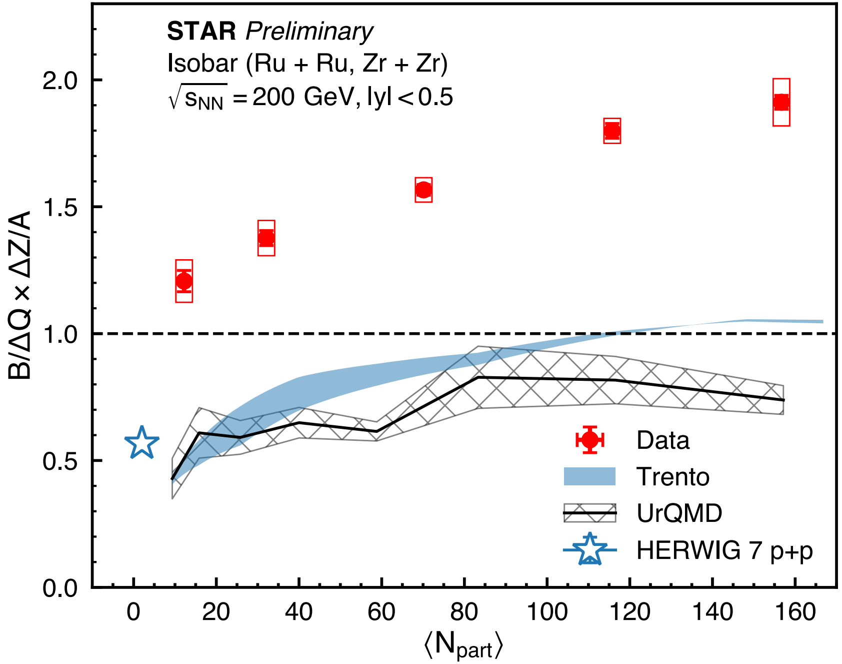
X. Artru, NPB 85 (1975) 441
G. C. Rossi, G. Veneziano, NPB 123 (1977) 507

- Test the different scenarios with charge (Q) and baryon (B) number

Quark carrier: $\frac{Q}{B} \approx \frac{Z}{A}$ **vs.** **Junction carrier:** $\frac{Q}{B} < \frac{Z}{A}$

What Carries the Baryon Number?

T. Tsang, Wed. 4:15 PM



- Measure charge difference (ΔQ) between two isobar collisions, and compare $B/\Delta Q$ vs. $A/\Delta Z$
- Significantly more baryon stopping than model calculation in which quarks carry baryon number
- Favors the scenario that baryon junction carries baryon number

Summary & Outlook

- ✓ STAR continues to produce highly impactful results for studying the QCD phase diagram and fundamental features of QCD

- ➢ *Stay tuned for more results from p+p, BES-II, top energy HI*

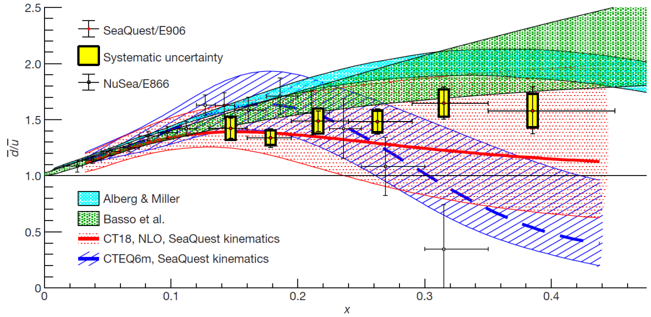
- ✓ Run23-25: entering the precision era
  - Unprecedented statistics for p+p, p+Au, Au+Au collisions
  - Low material budget
  - STAR detector with enhanced capabilities
    - Particle identification; tracking; extended coverage
  - *Measurements connecting to future EIC*

Backup

Unpolarized Anti-quark PDF

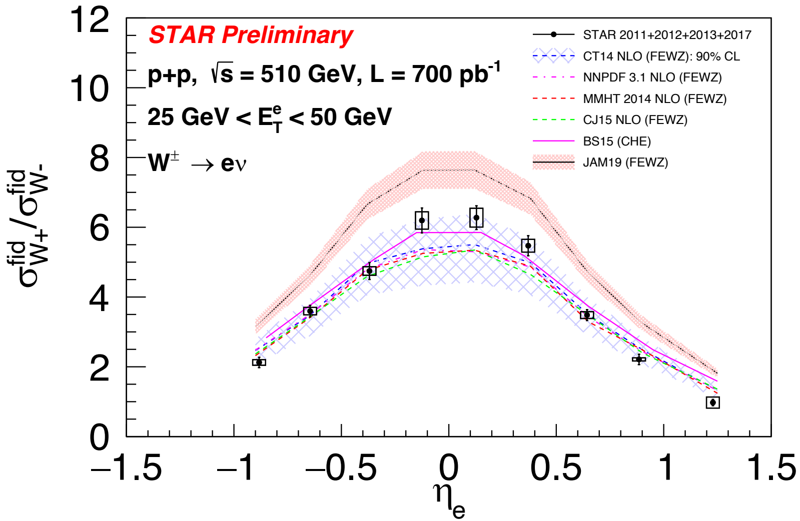
M. Posik, Poster

SeaQuest, Nature 590 (2021) 561



W cross-section ratio at RHIC can provide constraints around similar x region at high Q^2

$$R_W = \frac{\sigma^{W+}}{\sigma^{W-}} \sim \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{\bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_2)}$$



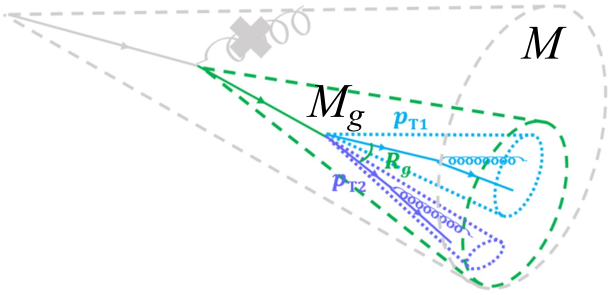
- Cross-section ratio vs. lepton rapidity
- Overall agreement with current PDF fits. Can be used to further constrain anti-quark distributions

![STAR logo]

p+p: Jet Substructure

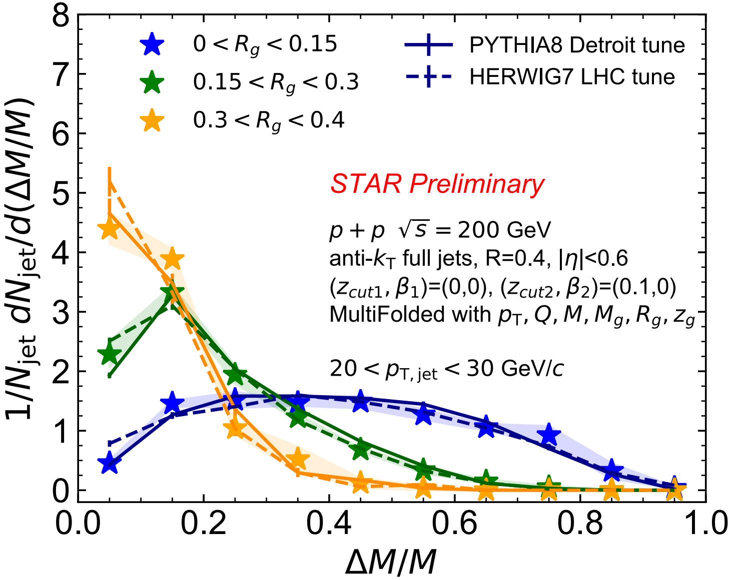
D. Roy, Wed. 9:40 AM

Courtesy of Y. Song



$$\Delta M = M - M_g$$

$$R_g = \Delta R(\mathrm{jet}_1, \mathrm{jet}_2)$$

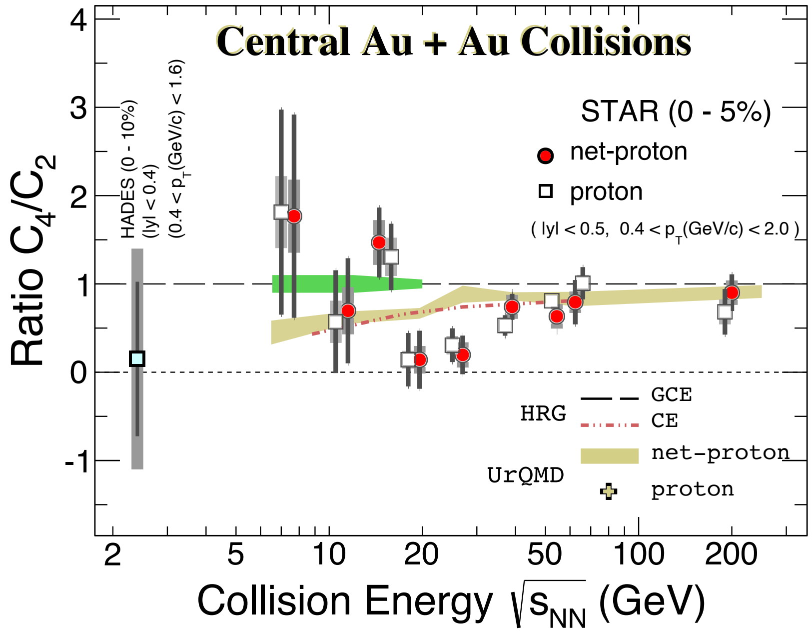


- $\Delta M/M$ anti-correlated with R_g → Early soft wide-angle radiation constrains angular phase space of late splittings
- Well described by event generators

Search for CP: Net-Proton Fluctuation

STAR, PRL 128 (2022) 202303; PRL 126 (2021) 092301

Z. Sweger, Wed. 11:30 AM



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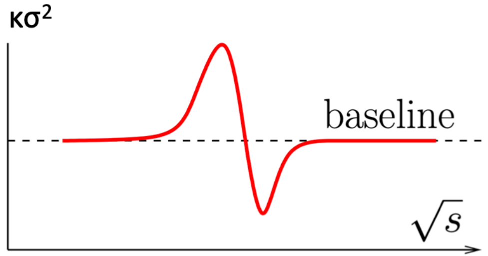
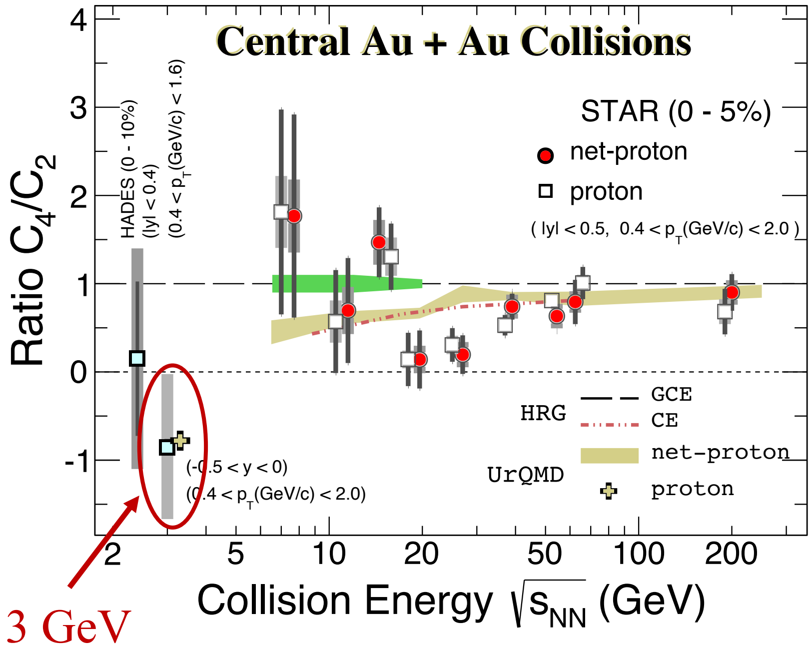


M. Stephanov. J. Physics G.: Nucl. Part. Phys. **38** (2011) 124147

Search for CP: Net-Proton Fluctuation

STAR, PRL 128 (2022) 202303; PRL 126 (2021) 092301

Z. Sweger, Wed. 11:30 AM

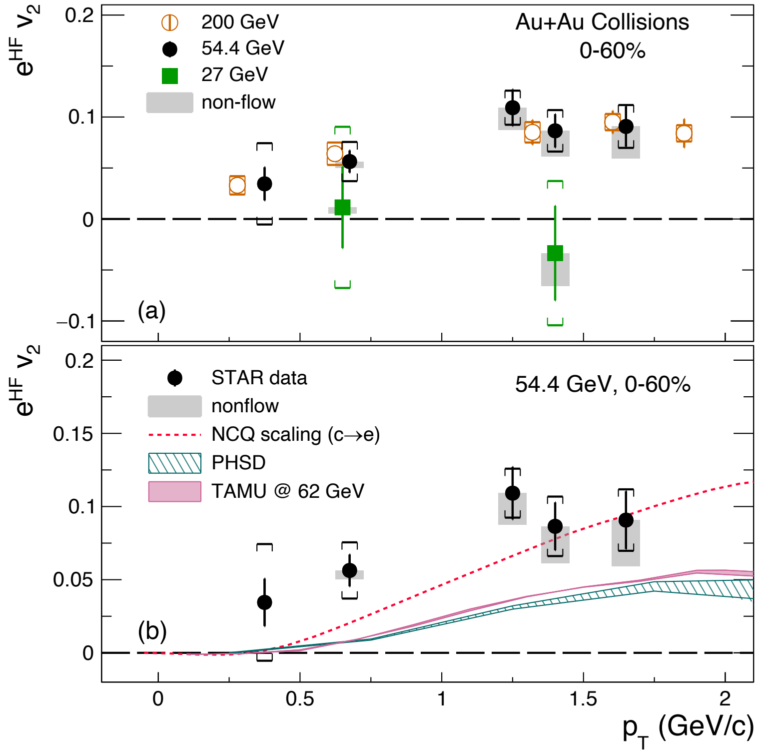


- BES-I: non-monotonic trend with collision energy with 3.1σ
  - BES-II COL: significantly improve BES-I results
  - BES-II FXT: fill the gap between 3 – 7 GeV
- BES-II: negative C_4/C_2 at 3 GeV
  - Consistent with UrQMD
  - Hadronic interaction dominates
- *Stay tuned for more BES-II results*

HF Electron v_2 at 54.4 and 27 GeV

STAR, PLB 844 (2023) 138071

V. Prozorova, Wed. 1:45 PM

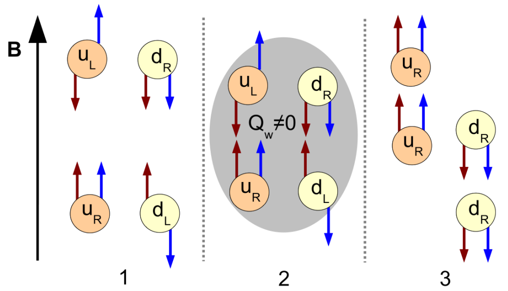


- 27 GeV: consistent with zero
- 54.4 GeV:
  - Significant v_2 comparable to that at 200 GeV
  - Charm quarks gain v_2 at T close to T_c
  - Transport models seem to underpredict v_2 (1-2σ for $p_T > 0.5$ GeV/c)
  - Consistent with NCQ scaling → may reach local thermal equilibrium with the QGP

Search for CME at 27 GeV

Y. Feng, Poster

D. Kharzeev, L. McLerran, H. Warringa, NPA 803 (2008) 227

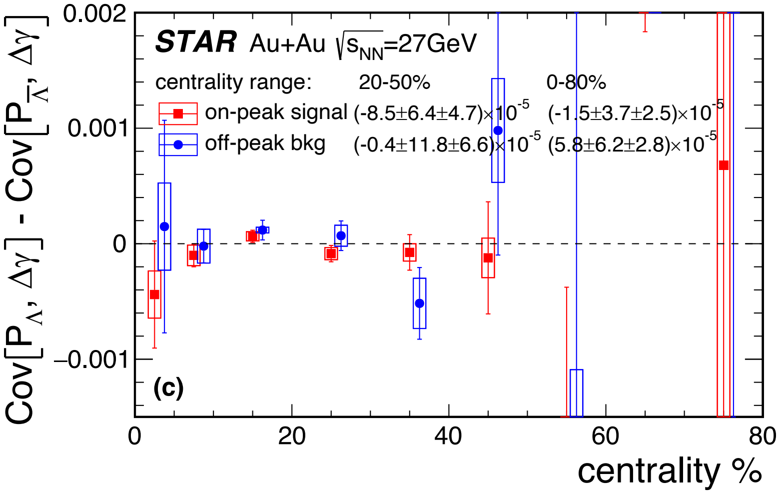


$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

$$\Delta P = P_{\Lambda} - P_{\bar{\Lambda}}$$

Expect negative event-by-event correlation in case of B and CME

STAR, PRC 108 (2023) 014909

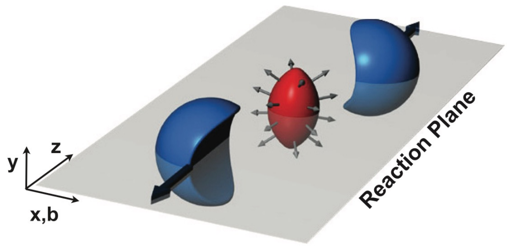


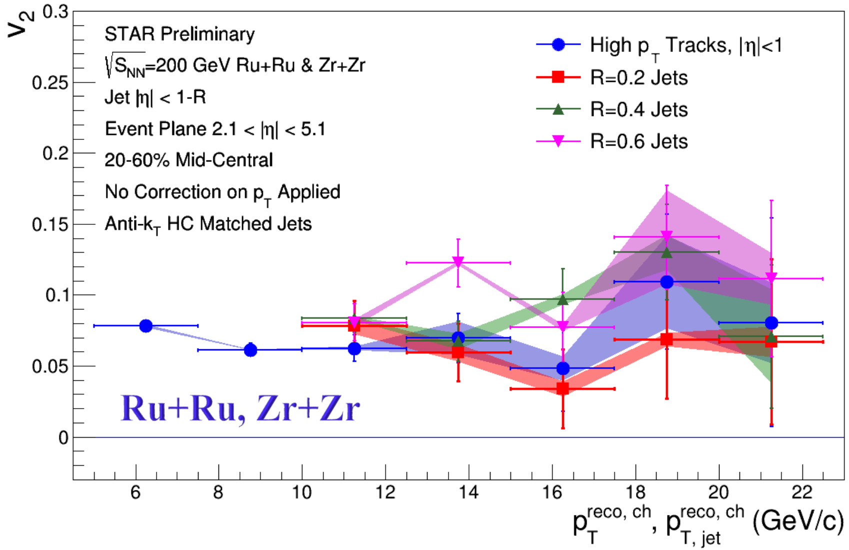
- Background does not contribute to the covariance
- No correlations observed beyond statistical fluctuations
  - *CME signal still elusive; Run23+25 Au+Au data might provide an answer*

Isobar Collisions: Jet v_2

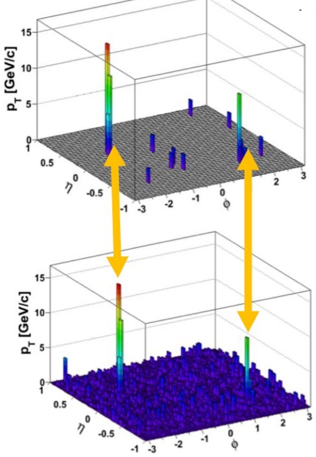
D. Roy, Wed. 9:40 AM

R. Snellings, New J. Phys. 13 (2011) 055008





Hard-core selection

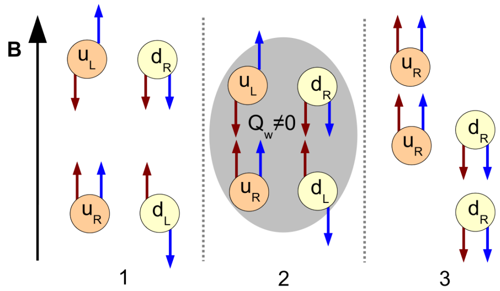


- Sizable v_2 for high p_T tracks and jets → path-length dependence of jet-medium interaction
- No obvious jet R dependence. Could be due to hard-core selection.

Search for CME at 27 GeV

Y. Feng, Poster

D. Kharzeev, L. McLerran, H. Warringa, NPA 803 (2008) 227

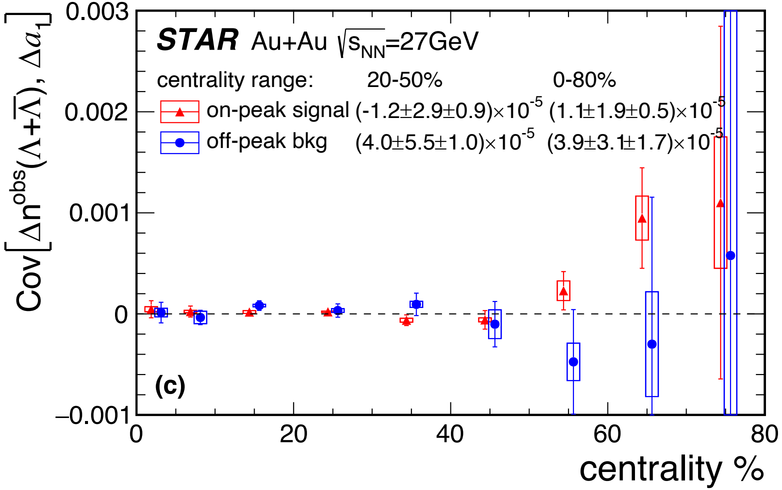


$$\Delta a_1 = \langle \sin(\phi^+ - \psi_{RP}) \rangle - \langle \sin(\phi^- - \psi_{RP}) \rangle$$

$$\Delta n^{obs}_{\Lambda+\bar{\Lambda}} = \frac{N_L^{obs} - N_R^{obs}}{\langle N_L^{obs} + N_R^{obs} \rangle}$$

Expect negative event-by-event correlation in case of B and CME

STAR, PRC 108 (2023) 014909

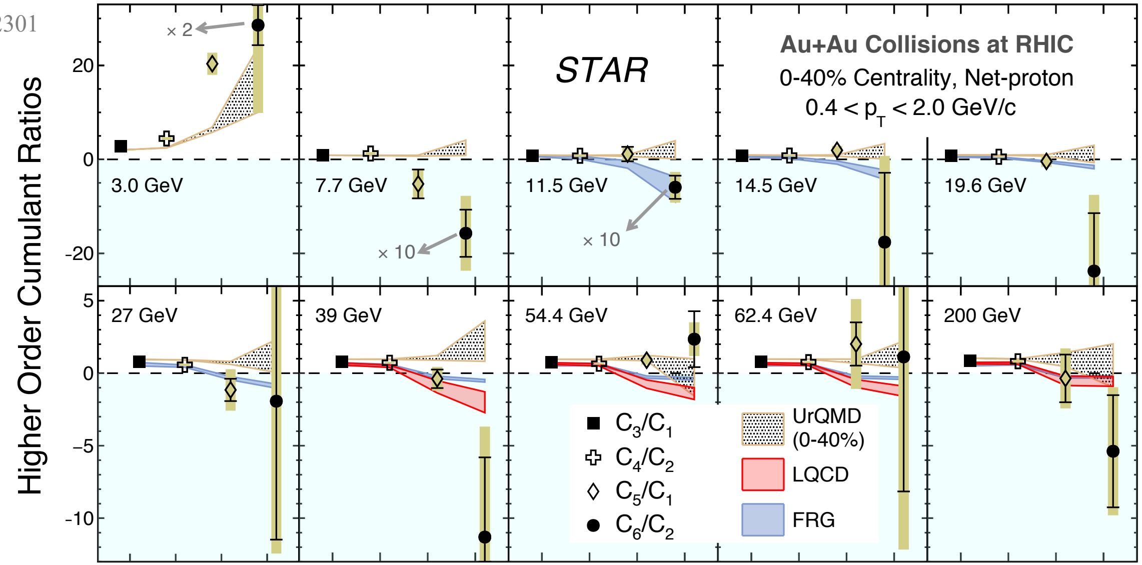


- Background does not contribute to the covariance
- No correlations observed beyond statistical fluctuations
  - *CME signal still elusive; Run23+25 Au+Au data might provide an answer*

Study Phase Structure: Net-Proton Fluctuation

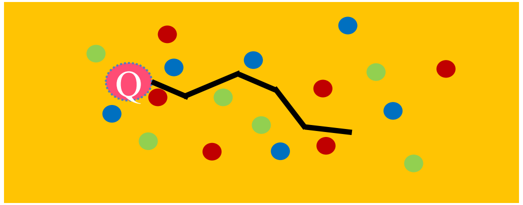
STAR, PRL 130 (2022) 082301

Z. Sweger, Wed. 11:30 AM



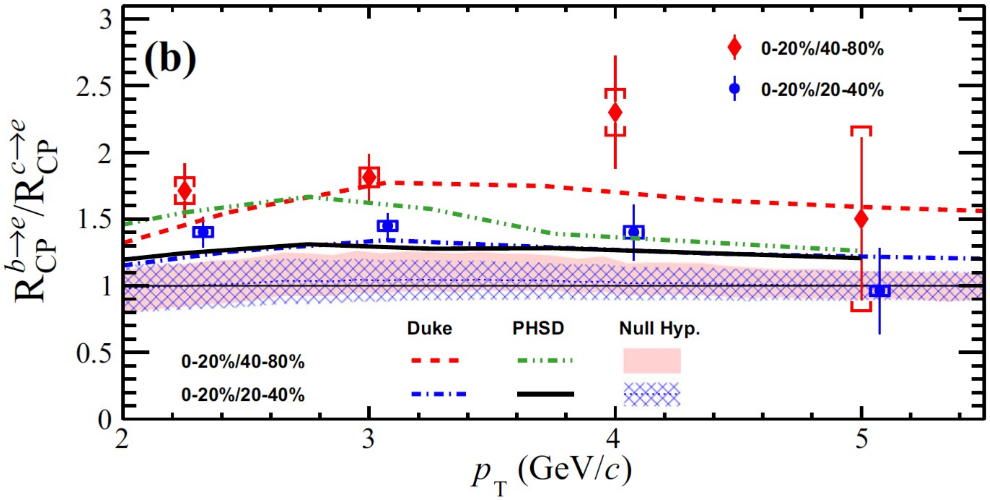
- LQCD calculation with crossover transition: $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$
- BES-I: data above 7.7 GeV consistent with expected ordering
- BES-II: opposite trend at 3 GeV → hadronic interaction dominates → CP exits above 3 GeV

Au+Au: Ordered HF Suppression



V. Prozorova, Wed. 1:45 PM

STAR, EPJC 82 (2022) 1150



- Charm quarks are significantly more suppressed than bottom quarks
  - Deviate from null hypothesis of same energy loss

✓ Parton mass dependence of energy loss in the QGP