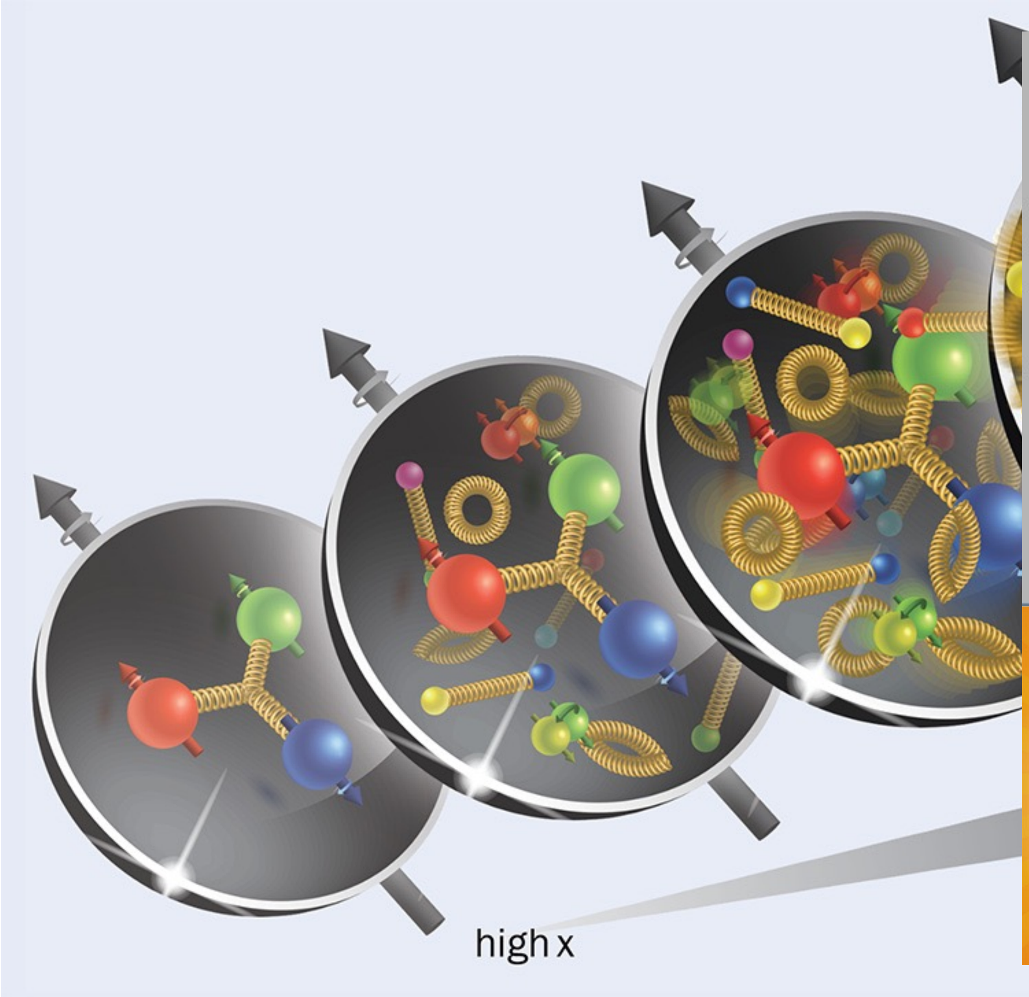
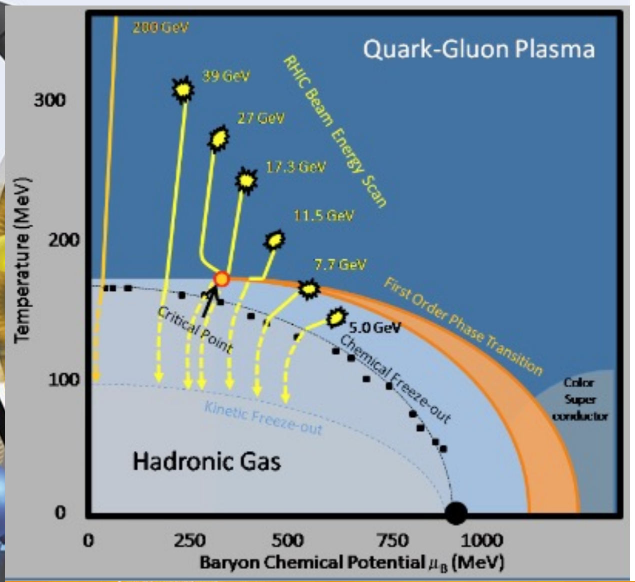
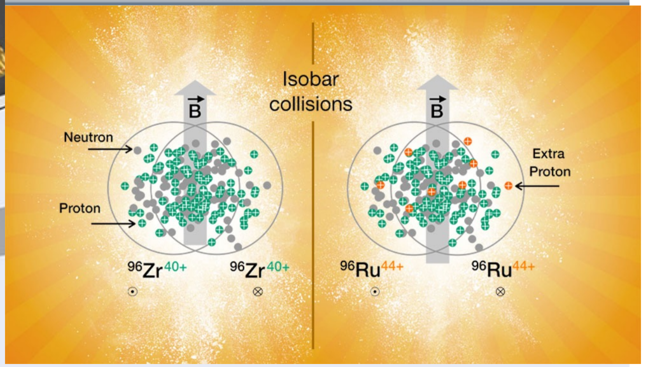
STAR toward EIC







Zhangbu Xu

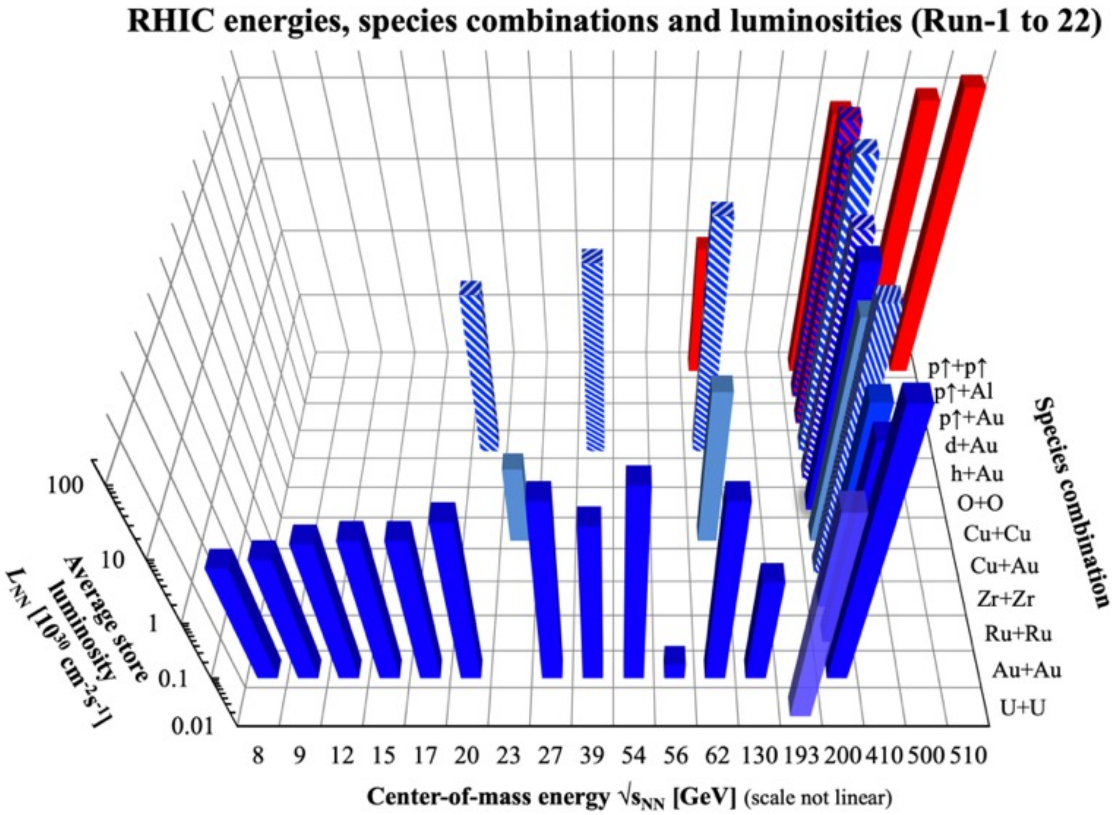
https://indico.bnl.gov/event/20331/contributions/79937/attachments/49634/84868/BUR2024to25_STAR.pdf

EIC-Asia Workshop, 01/29/2024

Brookhaven National Laboratory
In part supported by U.S. DEPARTMENT OF ENERGY Office of Science

Example of versatile colliders and detectors

major upgrades over the last twenty years to improve particle identification and vertex reconstruction and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM.
Estimate 35M(initial) +75M(upgrades)$.



Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\|\eta\| <1$ Tracking		1999-
Barrel EMC	$\|\eta\| <1$ jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	$1< \eta <2$ jets/π^0/e	(NSF)	2005-
Roman Pots	diffractive		2009-
TOF	PID	(China)	2009-
FMS/Preshower	$2.5< \eta <4.2$	(Russia)	2008-2017
DAQ1000	x10 DAQ rate		2008-
HLT	Online Tracking	(China/Germany)	2012-
FGT	$1< \eta <2$ $W^{\pm}$		2012-2013
GMT	TPC calibration		2012-
HFT/SSD	open charm	(France/UIC)	2014-2016
MTD	muon ID	(China/India)	2014-
EPD	event plane	(China)	2018-
RHICf	$\eta >5$ π^0	(Japan)	2017
iTPC	$\|\eta\| <1.5$ Tracking	(China)	2019-
eTOF	$-2< \eta <-1$ PID	(Germany/China)	2019-
FCS	$2.5< \eta <4$ calorimeter	(NSF)	2021-
FTS	$2.5< \eta <4$ Tracking	(NCKU/SDU)	2021-

8 new detectors added to STAR in last decade

Eras defined in STAR

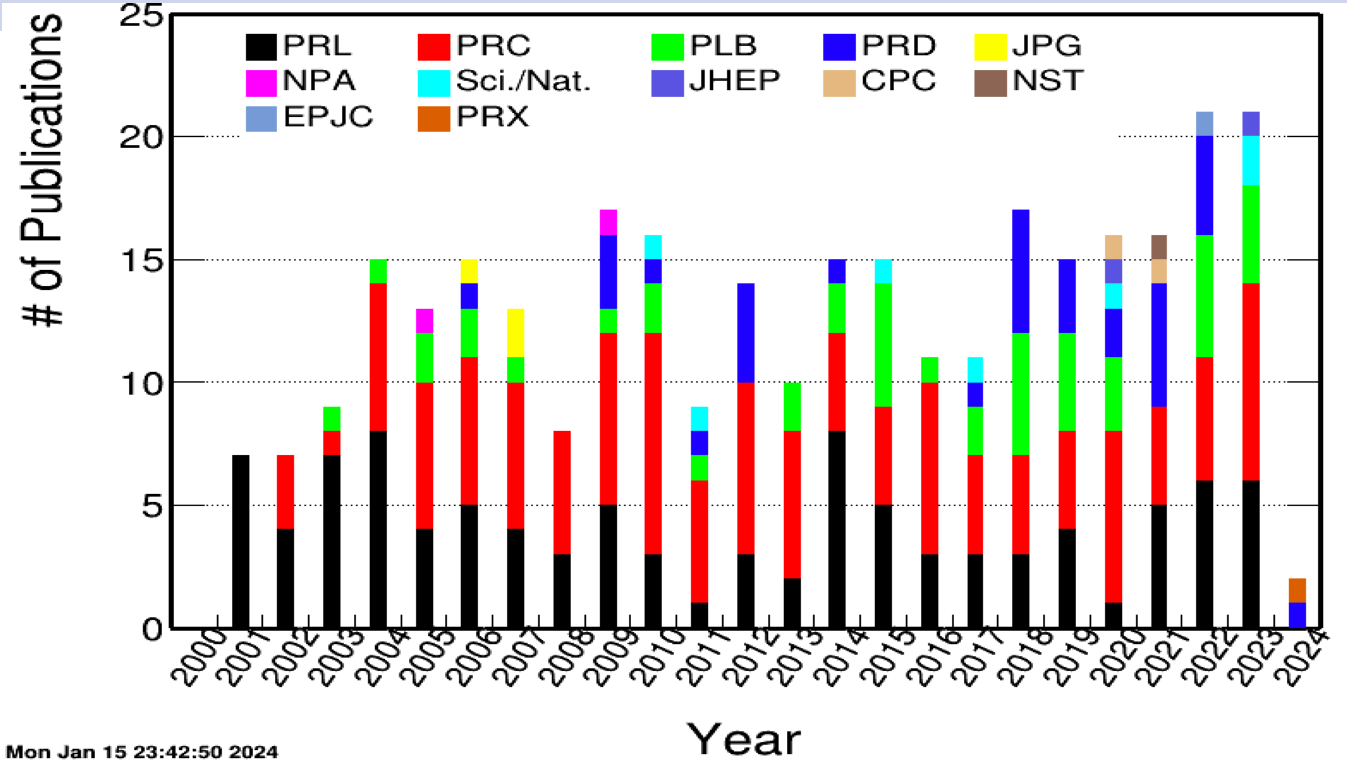
2000-2004	2005-2009	2010-2014	2014-2016	2017-2021	2022-2025
TPC	EMC	TOF+DAQ1K	HFT+MTD	iTPC+EPD+eTOF	fSTAR
QGP discovery	Jet, NPE, flow harmonics	BES-I (Critical Point); Symmetries: CME, EM probes	Open charm and Quarkonia	BES-II (Critical Point); Symmetries+DOF (isobar, Vorticity); Small Systems; FXT	Early-time dynamics; Imagining (2EIC); Statistics/precision nPDF

Transverse Spin Asymmetry

Universality (sign change)

Non-zero Gluon Spin Contribution to proton spin

Precise TMD over large phase space



Early-time dynamics:

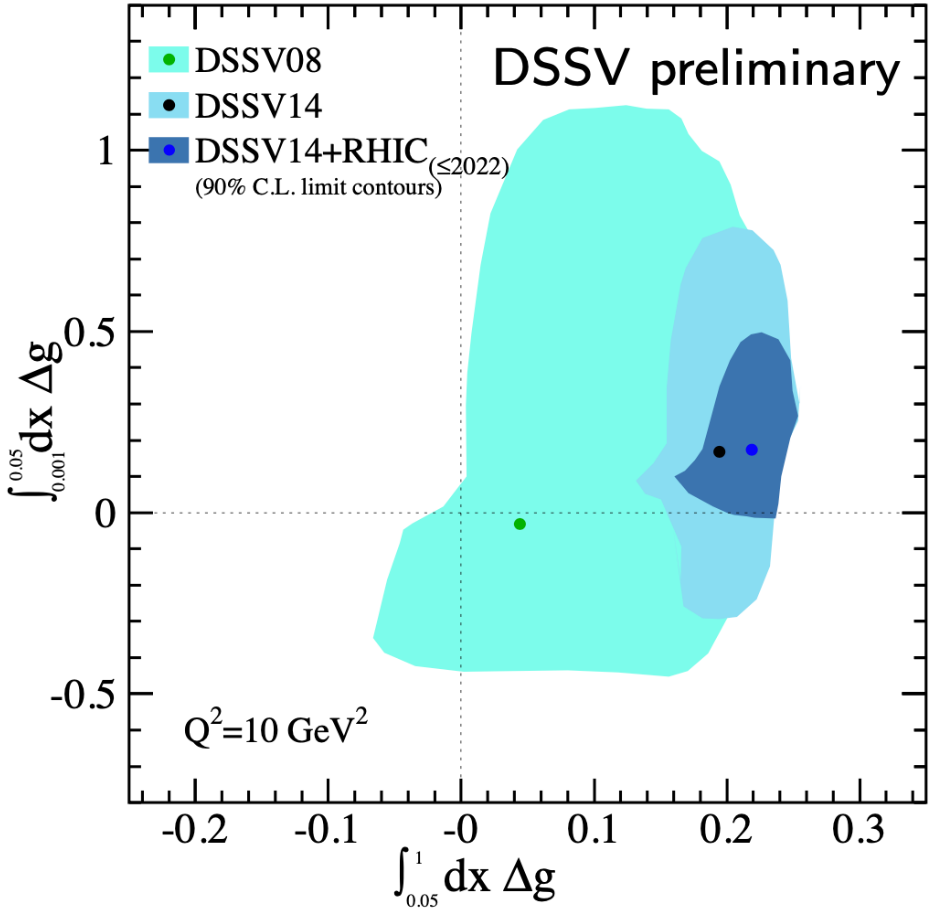
- Rapidity (de)correlations,
- Global Polarization in rapidity,
- Photon collisions;

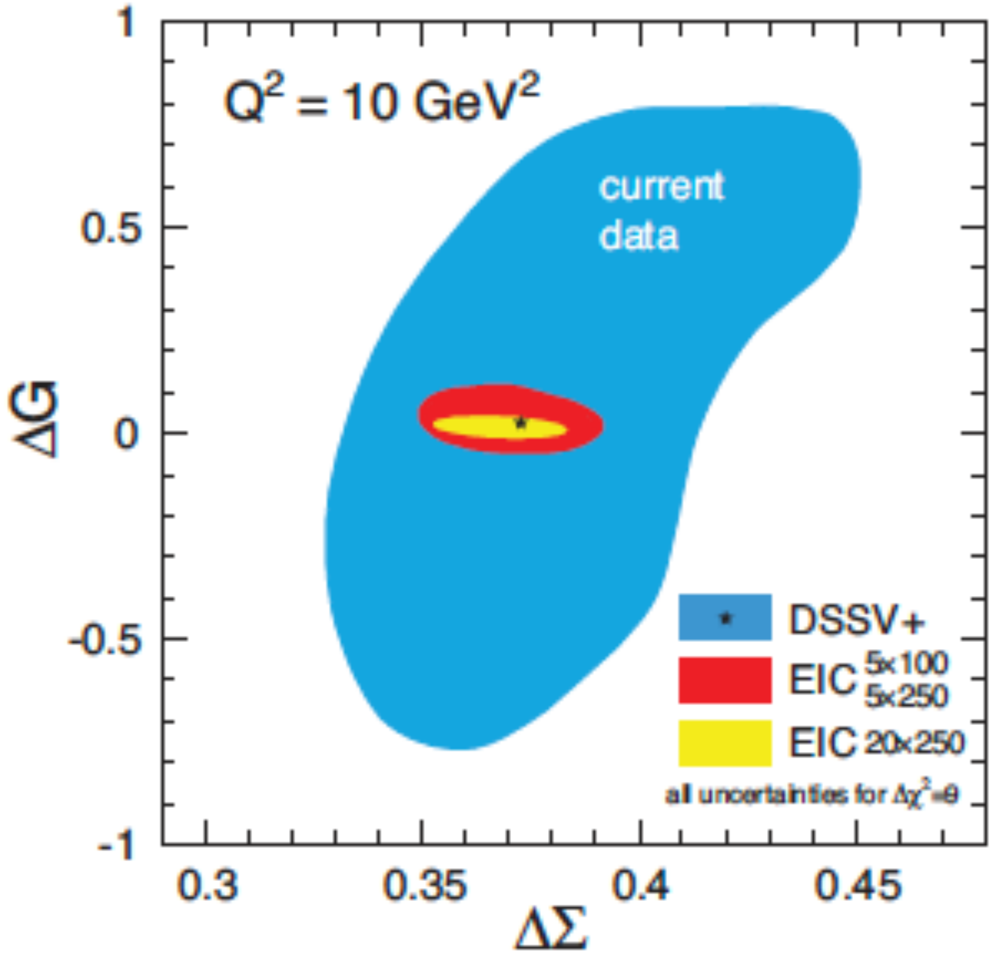
High statistics and precision:

- Higher order cumulants,
- Data points in Phase diagram,
- Jet structures and angles,
- Quarkonium flow

Connections to EIC and FAIR

One of the most direct connections to EIC physics





- RHIC data significantly improve ΔG compared to 2008 results: $\int_{0.05}^{1} dx\Delta g = 0.22 \pm 0.03$, for $x > 0.05$ and $Q^2 = 10\ \text{GeV}^2$
- The white paper of the RHIC cold QCD program: E.C. Aschenauer et al., arXiv:2302.00605
- The EIC white paper: A. Accardi et al., arXiv:1212.1701

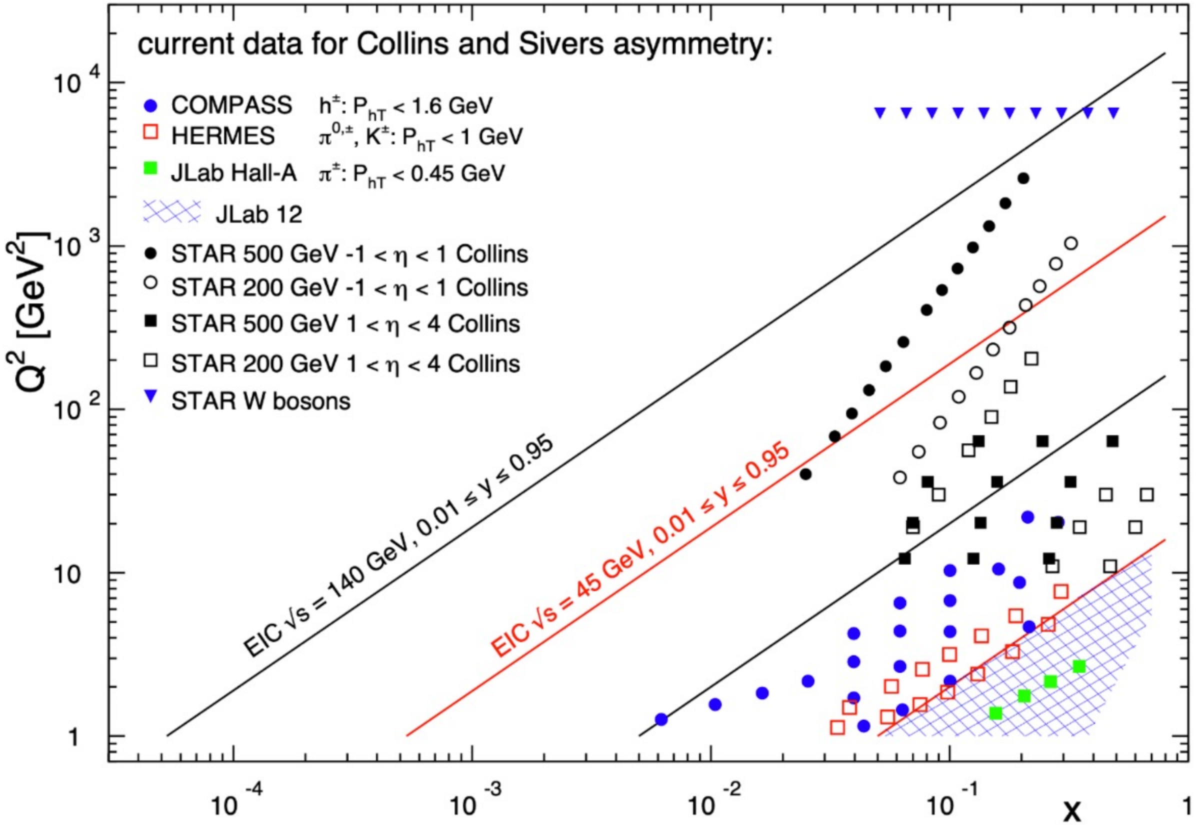
Transverse Momentum Dependence (TMD) Parton Distribution Function (PDF) and Fragmentation Function (FF)

- ❑ **quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions for initial and final state TMDs**

  Test of Sivers non-universality: $Sivers_{SIDIS}$ = -- $Sivers_{DY, W+/-, Z0}$; Full jet and dijet Sivers asymmetry

  Probe final state TMDs: Collins asymmetry for hadrons in jet
  - ➢ **Requirement:**
    - ➢ **large data sets √s = 200 and 500 GeV p↑p**
      → **low to high x, highest and lowest x with fSTAR**
    - ➢ **A_{UT} for $W^{+/-}$ Z^0, A_{UT} for hadrons in jet**
- ❑ **First look Gluon GPD → E_g**
  - ❑ **Requirement:**
    - ➢ **data sets √s = 500 GeV p↑p and √s = 200 GeV p↑A**
    - ➢ **A_{UT} for J/ψ in UPC**
- ❑ **Physics driving the large A_N at forward rapidities and high x_F**
  - ➢ **Requirement:**
    - ➢ **large data sets √s = 200 and 500 GeV p↑p**
      → **low to highest x_F → fSTAR**
    - ➢ **charge hadron A_N at forward rapidities**
- ❑ **Nuclear dependence of PDFs, FF, and TMDs**
  - ➢ **Requirement:**
    - ➢ **large equal data set of √s = 200 p↑p and p↑Au**
      → **low to high x, highest and lowest x with fSTAR**
    - ➢ **R_{pA} direct photons and DY, hadrons in jet A_{UT}**
- ❑ **non-linear effects in QCD**
  - ➢ **Requirement:**
    - ➢ **large equal data set of √s = 200 p↑p and p↑Au**
      → **lowest-x through fSTAR**
    - ➢ **dihadron correlations for $h^{+/-}$, γ-jet, di-jets**

- STAR@RHIC Unique Kinematics
- Cover large Q^2 and x range
- Significant overlap with EIC kinematics
- Different tools and beam energies:
  $W^{\pm}/Z$, DY g, jet, $p^{\pm}/p^0$, two-hadron correlations



Transverse Momentum Dependence (TMD) Parton Distribution Function and Fragmentation Function

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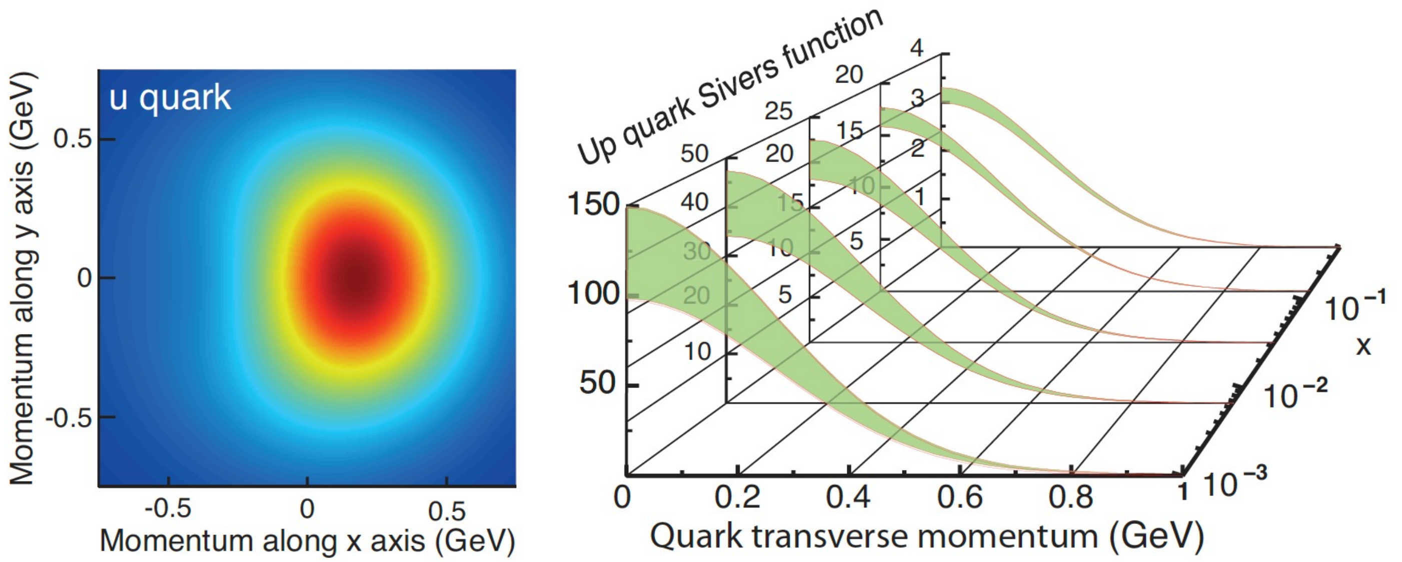


Figure 1.3: **Left:** The transverse-momentum distribution of an up quark with longitudinal momentum fraction $x = 0.1$ in a transversely polarized proton moving in the z-direction, while polarized in the y-direction. The color code indicates the probability of finding the up quarks. **Right:** The transverse-momentum profile of the up quark Sivers function at five x values accessible to the EIC, and corresponding statistical uncertainties.

EIC White paper

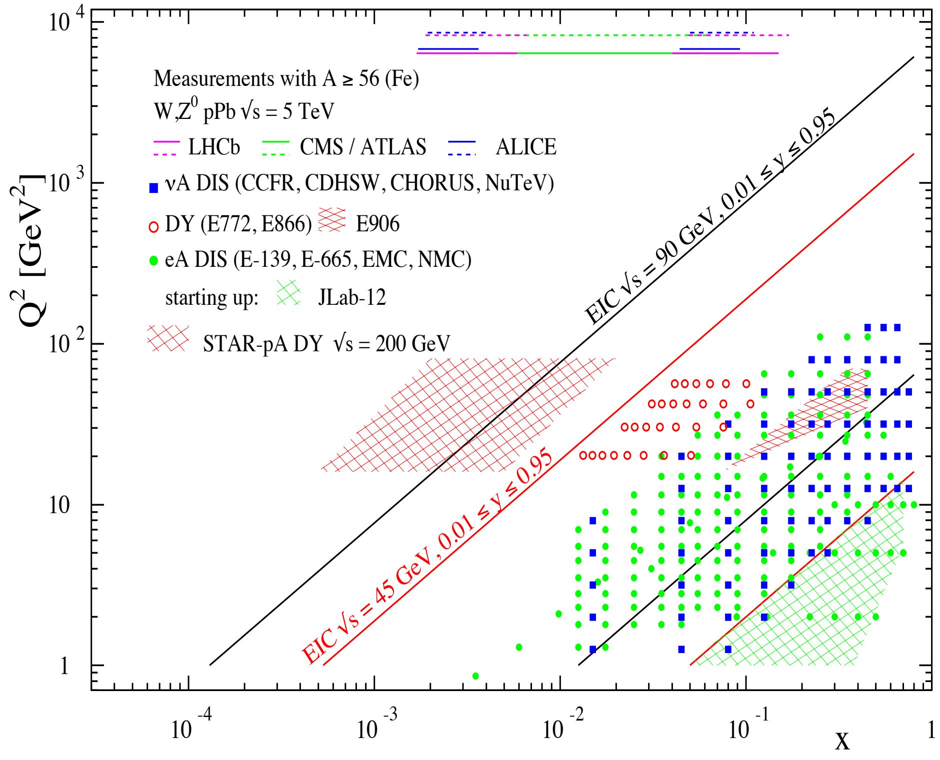
Nuclear PDF and Initial Conditions for A+A collisions

measure nPDF in a x-Q^2 region where nuclear effects are large

$Q^2 > Q_s^2$ over a wide range in x

STAR Forward upgrade with tracking and calorimeters
Cold QCD/ Spin physics

pA@RHIC: unique kinematics

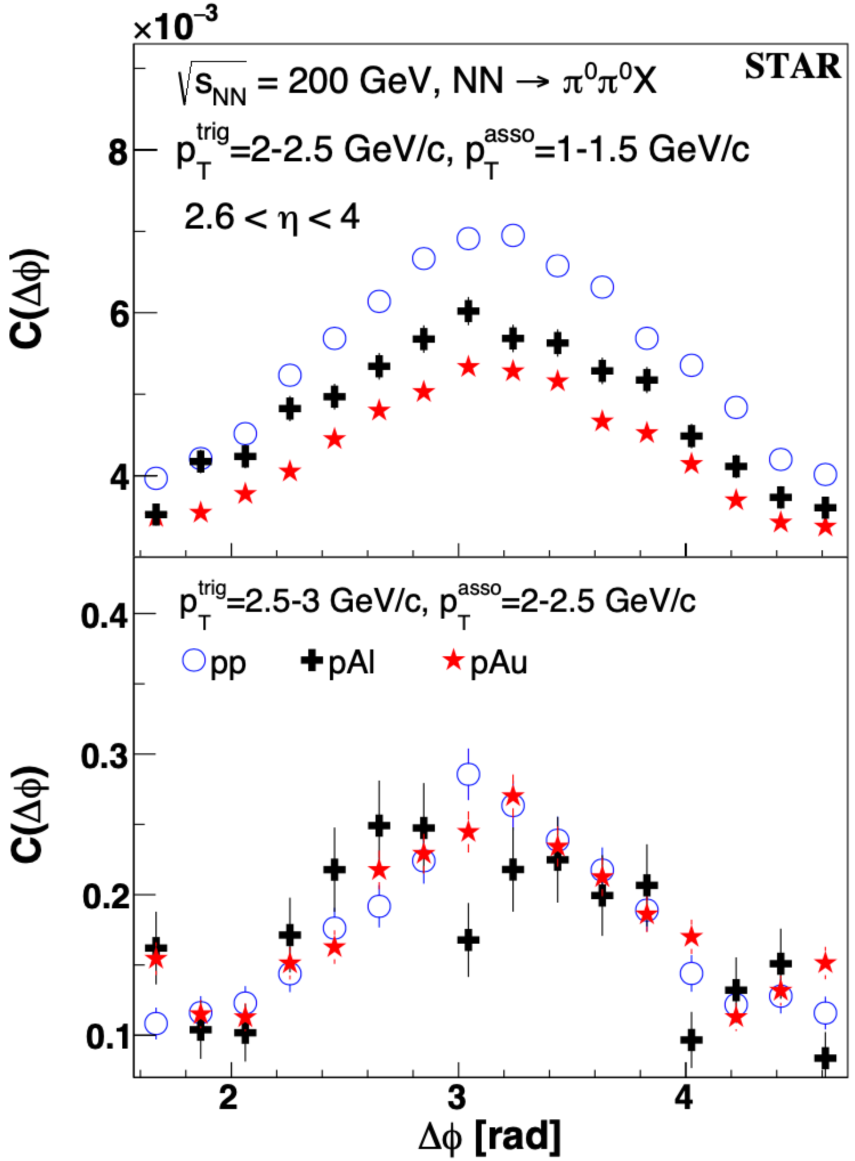


	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023 to 2025	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
		$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
		$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
		AuAu @ 200	1 Billion Minbias Events	Longitudinal de-correlation	$C_n(\Delta\eta)$ and $r_n(\eta_a,\eta_b)$	Forward instrum. ECal+HCal or Tracking
				η/s(T) and ζ/s(T)	$V_{n\Delta}(\eta)$	Forward instrum. Tracking
				Mixed flow Harmonics	$C_{m,n,m+n}$	Forward instrum. ECal+HCal or Tracking
				Rapidity dependence of Hyperon Polarization	$P_H(\eta)$	Forward instrum. Tracking
				Ridge	$dN/d(\Delta\eta)d(\Delta\phi)$ & $V_{n\Delta}$	Forward instrum. ECal+HCal or Tracking
Potential future running	2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal

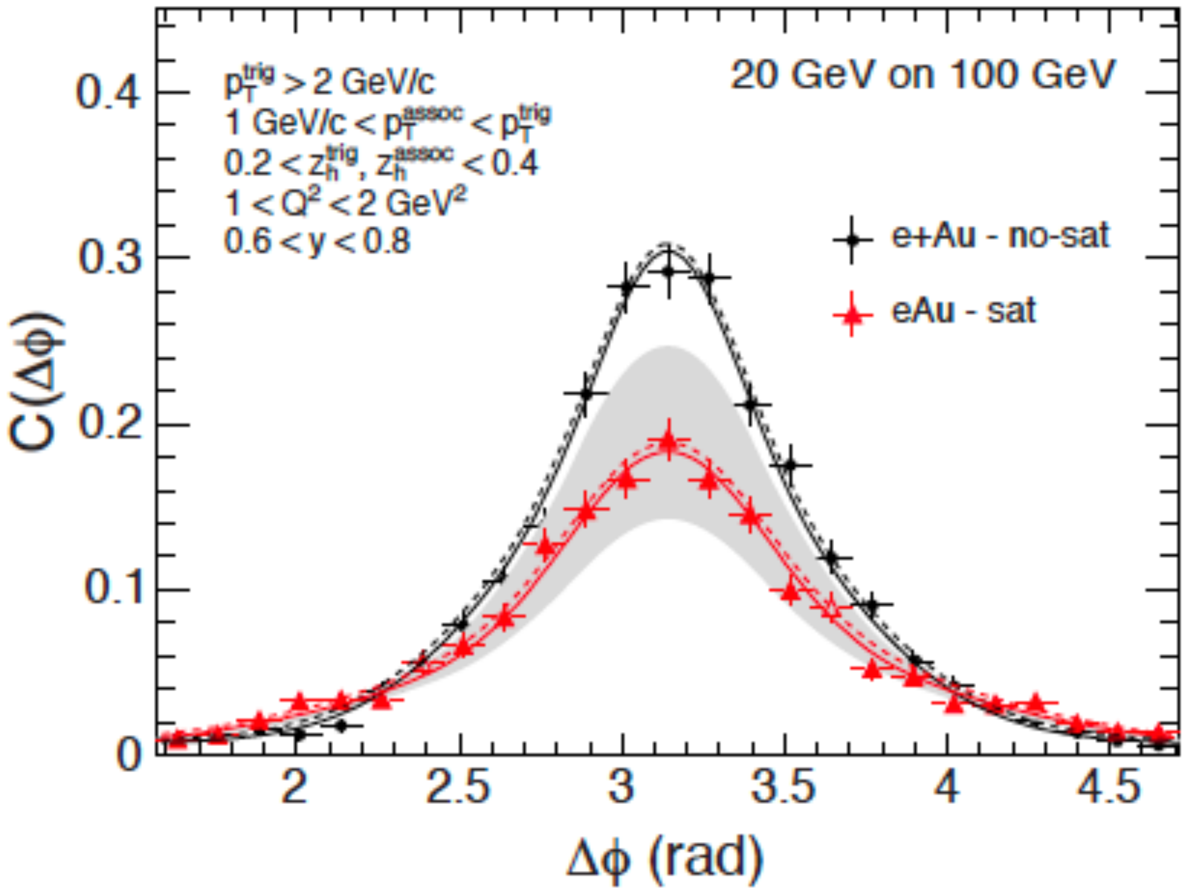
SN0648 - January 2016, STAR Forward Calorimeter and Forward Tracking Systems beyond BES-II

Gluon Non-linear/Saturation Effect

STAR, Phys. Rev. Lett. **129** (2022) 92501;
arXiv: 2111.10396

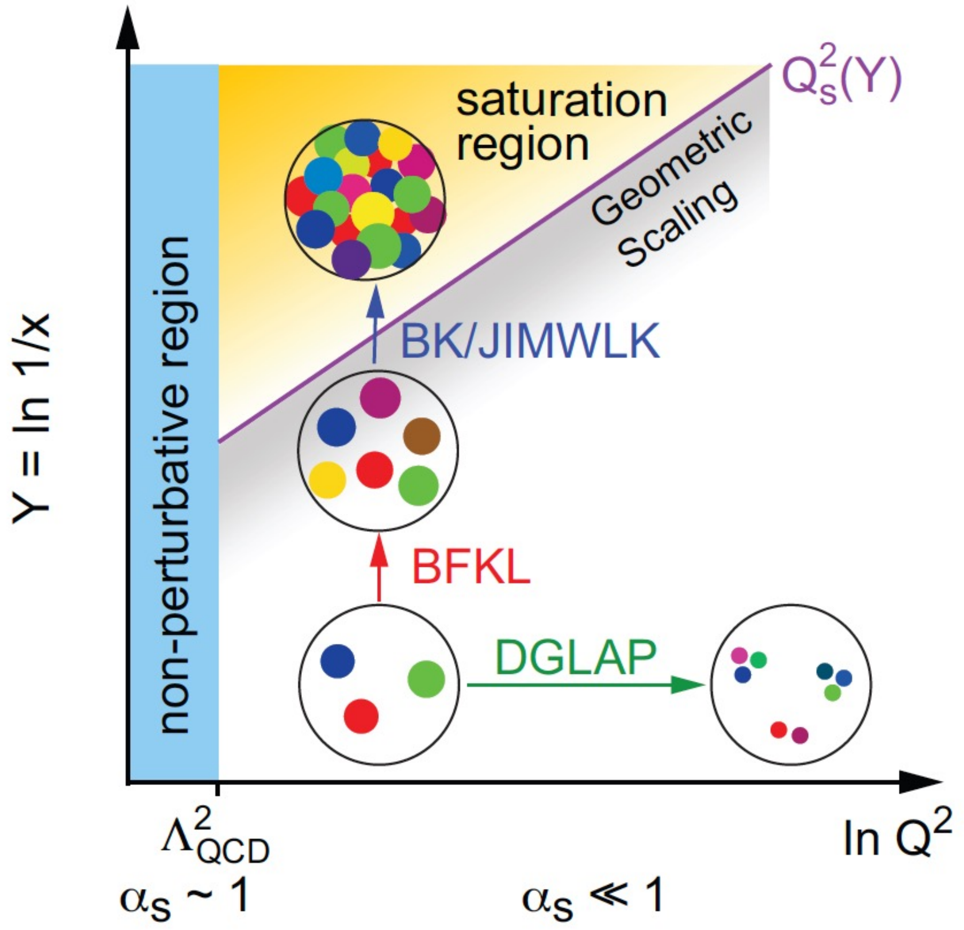


Projection: EIC Whitepaper Fig.3.18



2π correlations at STAR forward shows suppression of yield with increase nuclear mass A
shape does not change

A picture is worth a thousand words



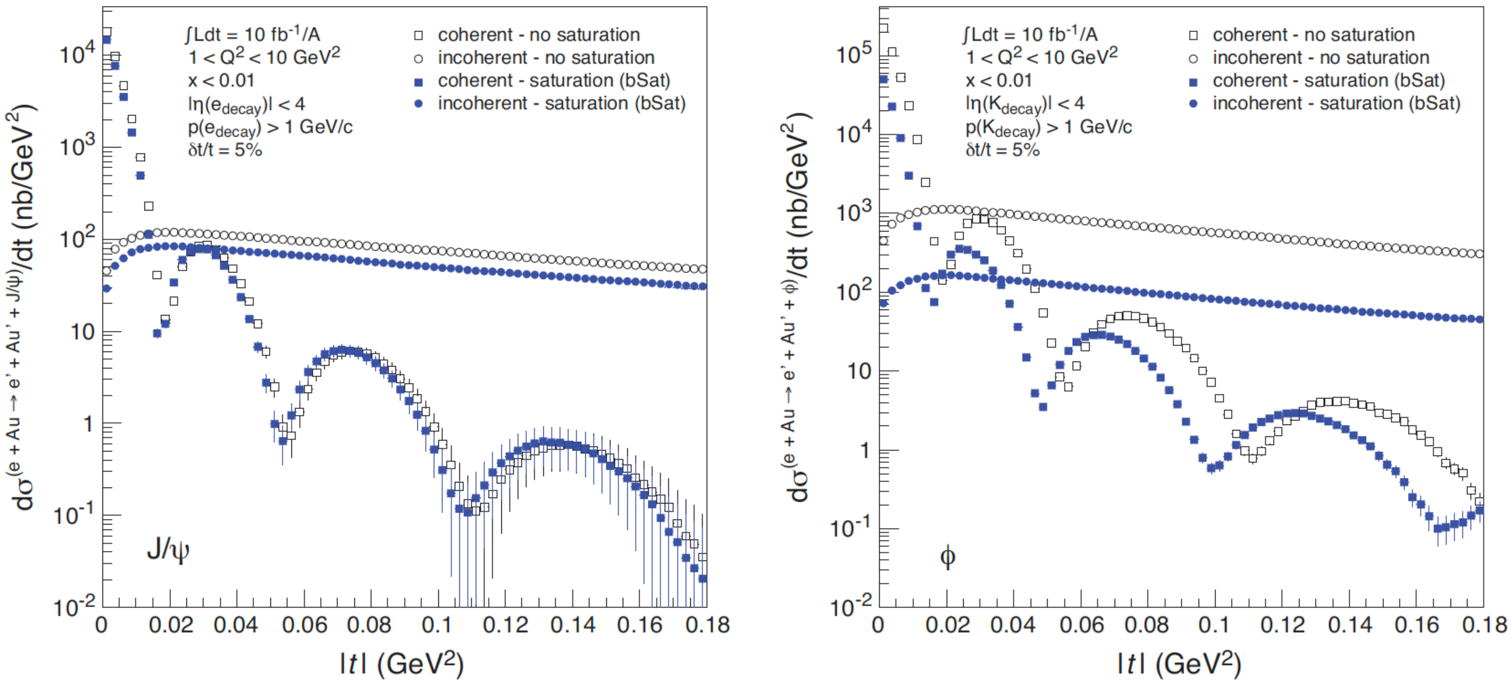
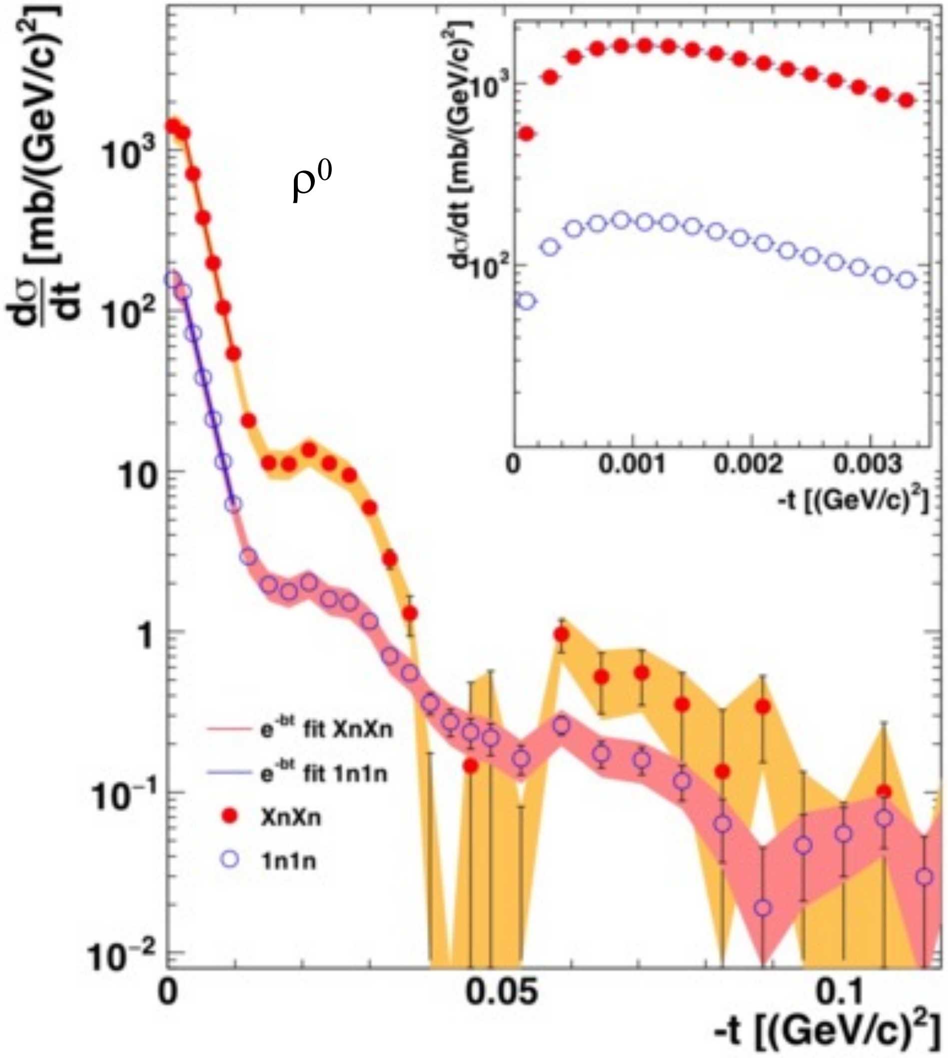


Figure 3.23: $d\sigma/dt$ distributions for exclusive J/ψ (left) and ϕ (right) production in coherent and incoherent events in diffractive e+Au collisions. Predictions from saturation and non-saturation models are shown.

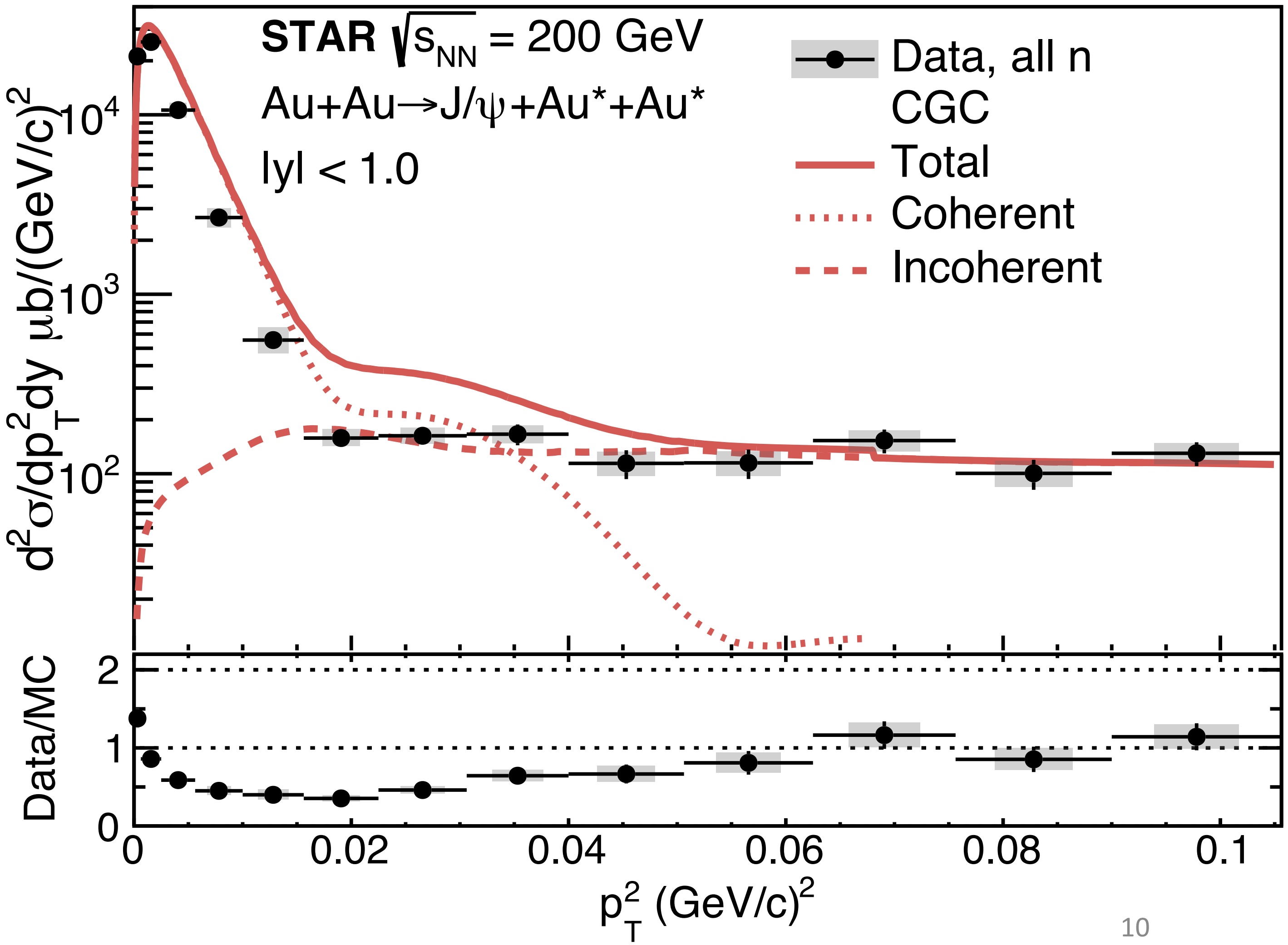
Imaging of 3D gluon distribution of heavy ion at high density (low-*x*)

Vector Meson diffractive production in UPC

STAR, Phys. Rev. C **96** (2017) 54904



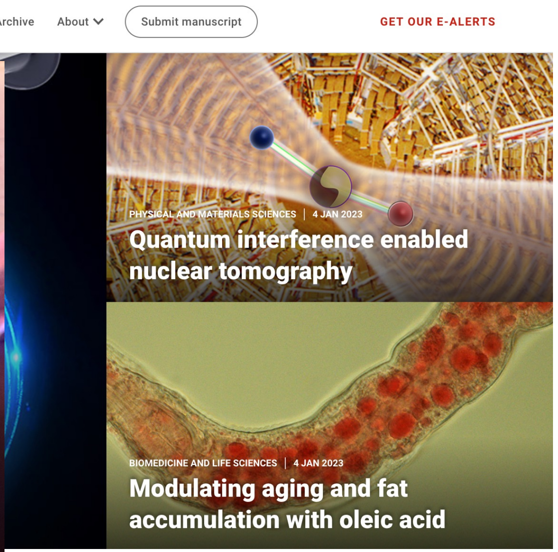
STAR, arXiv:2311.13632, 2311.13637

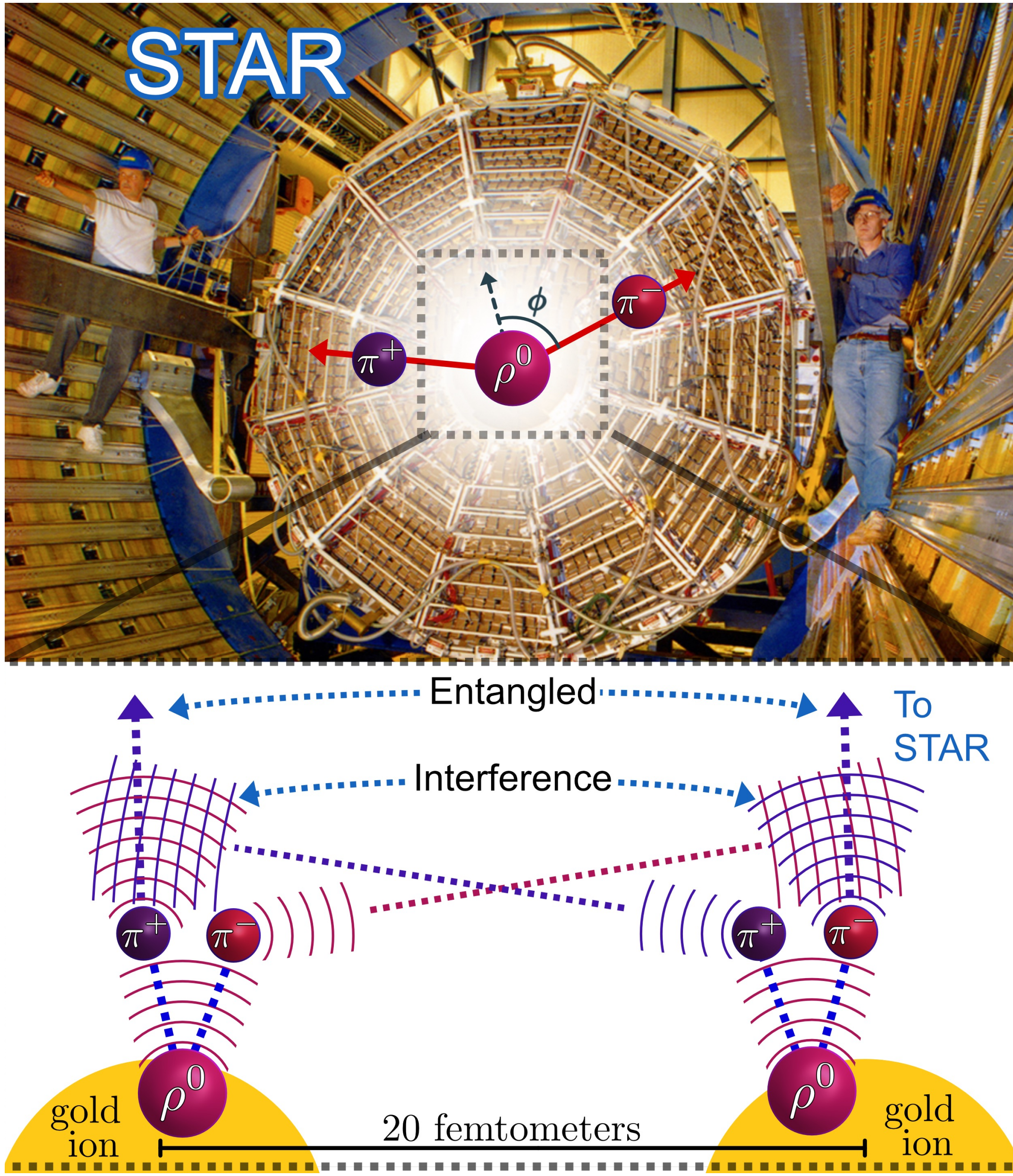


Spin Interference Enabled Nuclear Tomography

STAR, arXiv:2204.01625

- Teaser:
  Polarized photon-gluon fusion reveals quantum wave interference of non-identical particles and shape of high-energy nuclei



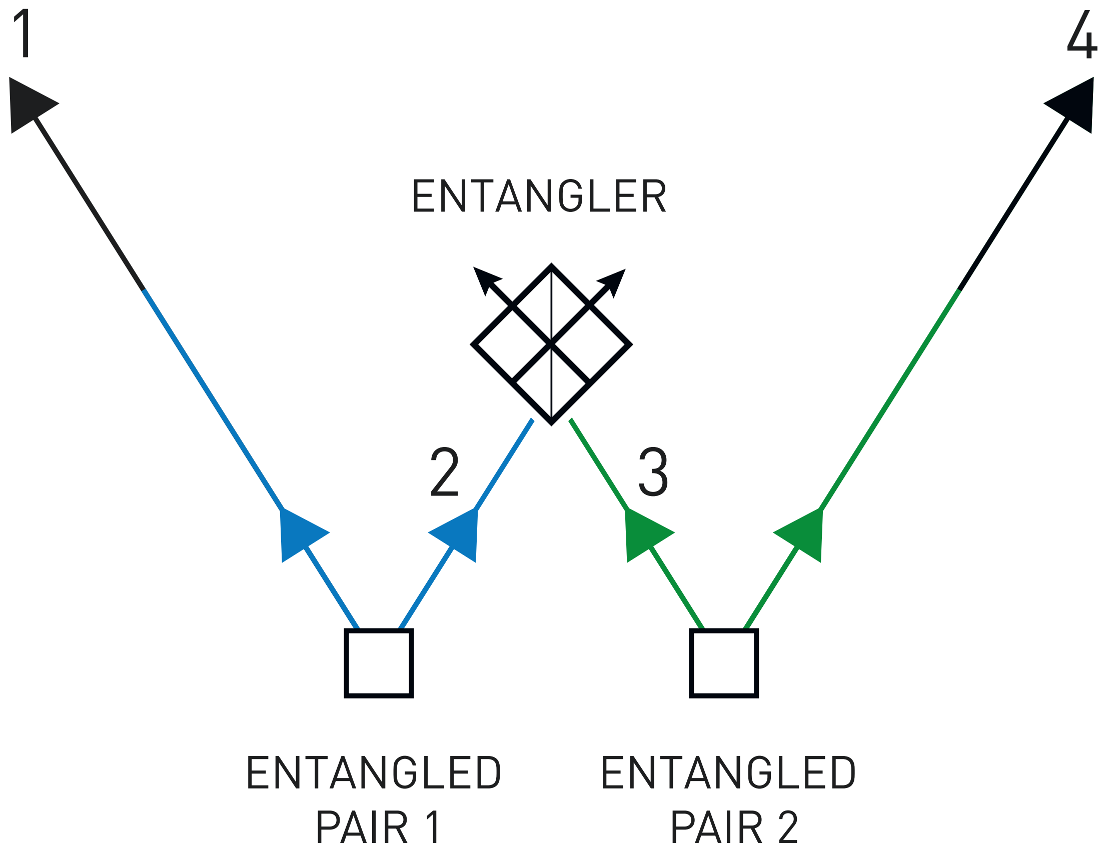


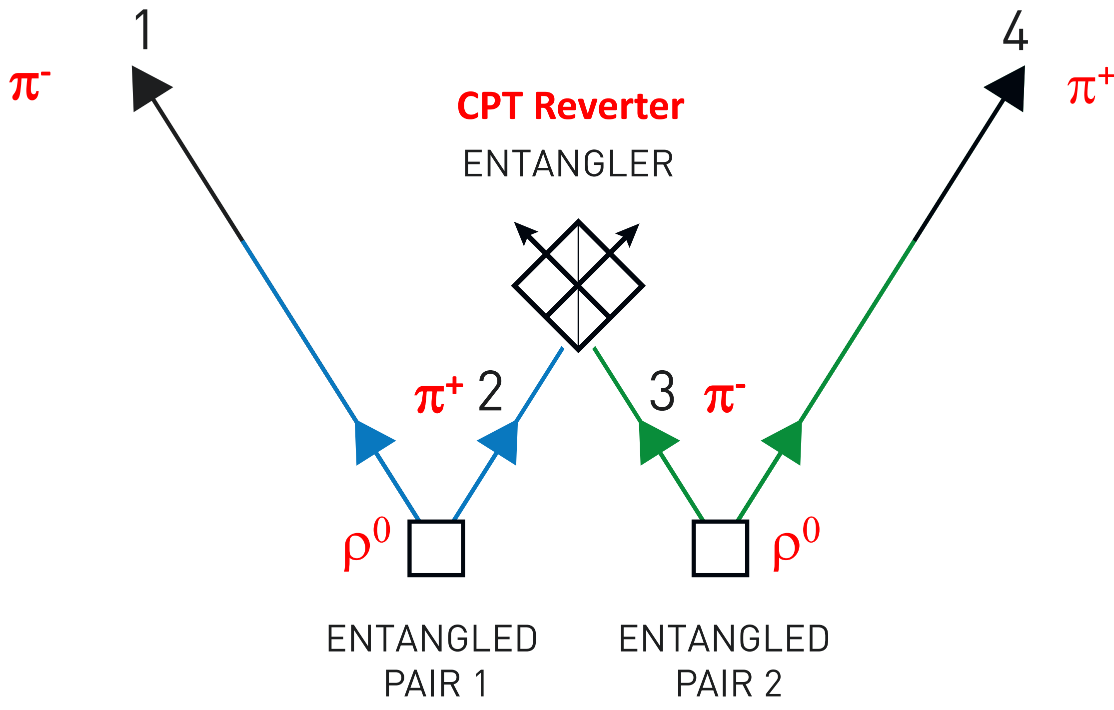
Entangled particles that never met

Two pairs of entangled particles are emitted from different sources. One particle from each pair is brought together in a special way that entangles them. The two other particles (1 and 4 in the diagram) are then also entangled. In this way, two particles that have never been in contact can become entangled.

Since π^+ and π^- are particle and antiparticle of each other, their wavefunctions could "annihilate"?

Nobel Prize in Physics 2022





Entangled particles that never met

Two pai… ces. One particle
from ea… s them. The two
other pa… In this way, two
particle…

$$|\pi^-\rangle = |\pi_1^-\rangle e^{i\phi_1} + |\pi_2^-\rangle e^{i\phi_2}$$

$$|\pi^+\rangle = |\pi_1^+\rangle e^{i\phi_1} + |\pi_2^+\rangle e^{i\phi_2}$$

$$|\pi^-\rangle|\pi^+\rangle = (|\pi_1^-\rangle e^{i\phi_1} + |\pi_2^-\rangle e^{i\phi_2})(|\pi_1^+\rangle e^{i\phi_1} + |\pi_2^+\rangle e^{i\phi_2})$$

$$= (|\pi_1^-\rangle|\pi_1^+\rangle e^{i2\phi_1} + |\pi_2^-\rangle|\pi_2^+\rangle e^{i2\phi_2} + |\pi_1^-\rangle|\pi_2^+\rangle e^{i(\phi_1+\phi_2)} + |\pi_2^-\rangle|\pi_1^+\rangle e^{i(\phi_1+\phi_2)})$$

$$(\langle\pi^-|\langle\pi^+|)(|\pi^-\rangle|\pi^+\rangle)$$

$$= (\langle\pi_1^-|\langle\pi_1^+| e^{-i2\phi_1} + \langle\pi_2^-|\langle\pi_2^+| e^{-i2\phi_2} + \langle\pi_1^-|\langle\pi_2^+| e^{-i(\phi_1+\phi_2)} + \langle\pi_2^-|\langle\pi_1^+| e^{-i(\phi_1+\phi_2)})$$

$$(|\pi_1^-\rangle|\pi_1^+\rangle e^{i2\phi_1} + |\pi_2^-\rangle|\pi_2^+\rangle e^{i2\phi_2} + |\pi_1^-\rangle|\pi_2^+\rangle e^{i(\phi_1+\phi_2)} + |\pi_2^-\rangle|\pi_1^+\rangle e^{i(\phi_1+\phi_2)})$$

$$= \langle\pi_1^-|\pi_1^-\rangle\langle\pi_1^+|\pi_1^+\rangle + \langle\pi_2^-|\pi_2^-\rangle\langle\pi_2^+|\pi_2^+\rangle$$

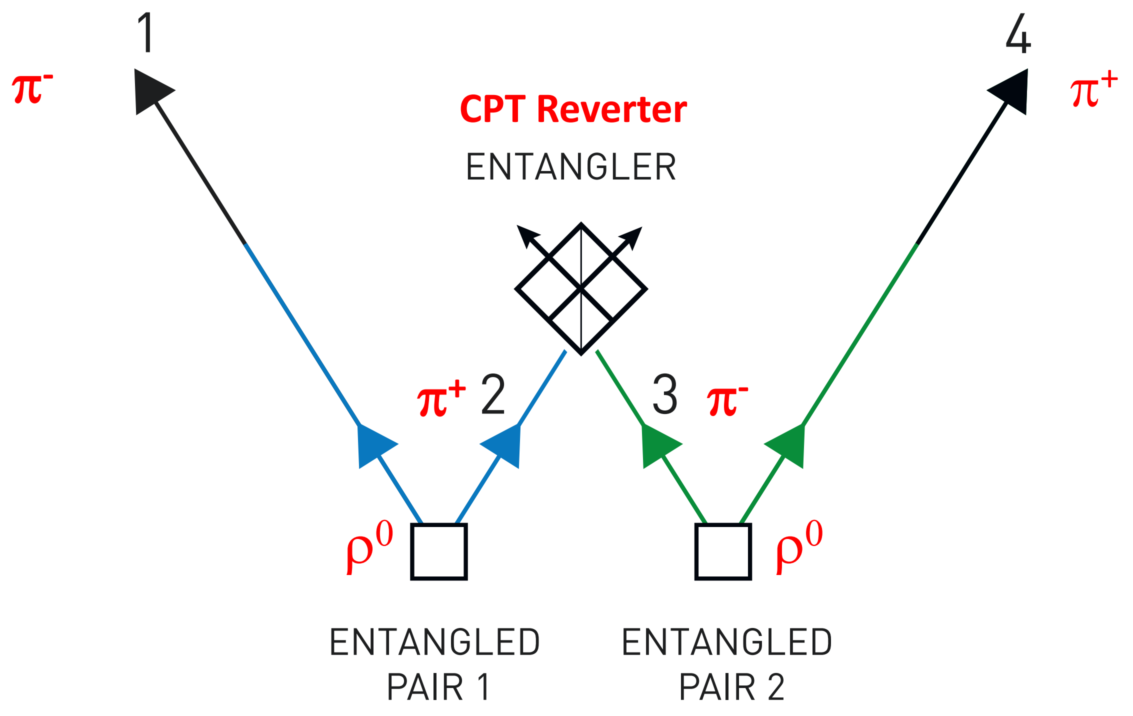
$$+ \langle\pi_1^-|\pi_1^-\rangle\langle\pi_1^+|\pi_2^+\rangle + \langle\pi_1^-|\pi_2^-\rangle\langle\pi_2^+|\pi_1^+\rangle$$

$$+ \langle\pi_2^-|\pi_1^-\rangle\langle\pi_1^+|\pi_2^+\rangle + \langle\pi_2^-|\pi_2^-\rangle\langle\pi_1^+|\pi_1^+\rangle$$

1

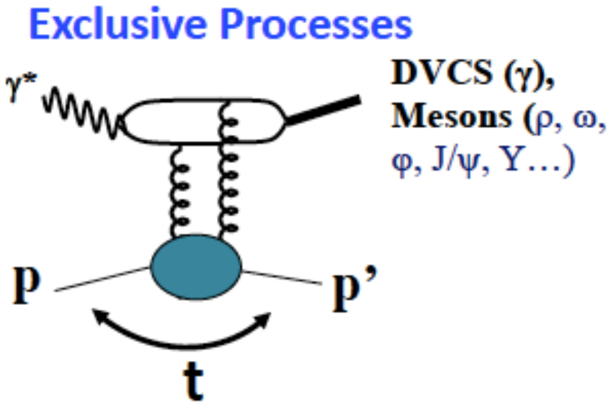
4

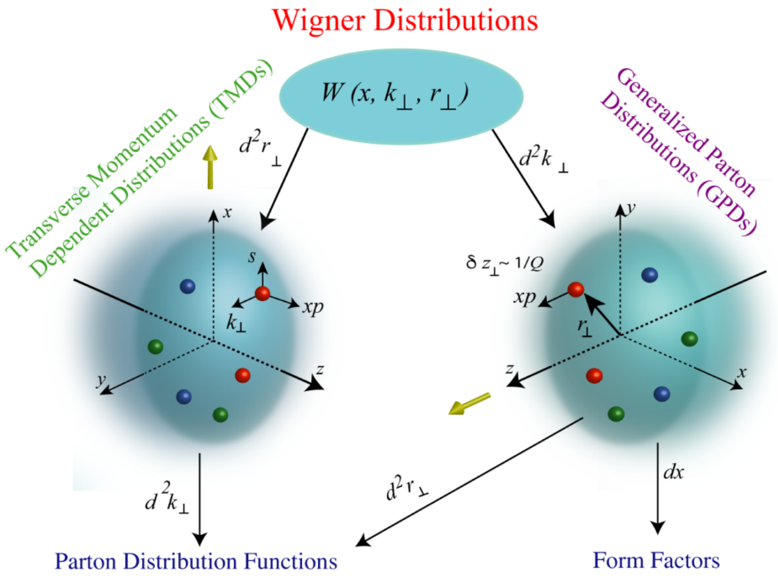
Since π^+ and π^- are particle and antiparticle of each other, their wavefunctions could "annihilate"?



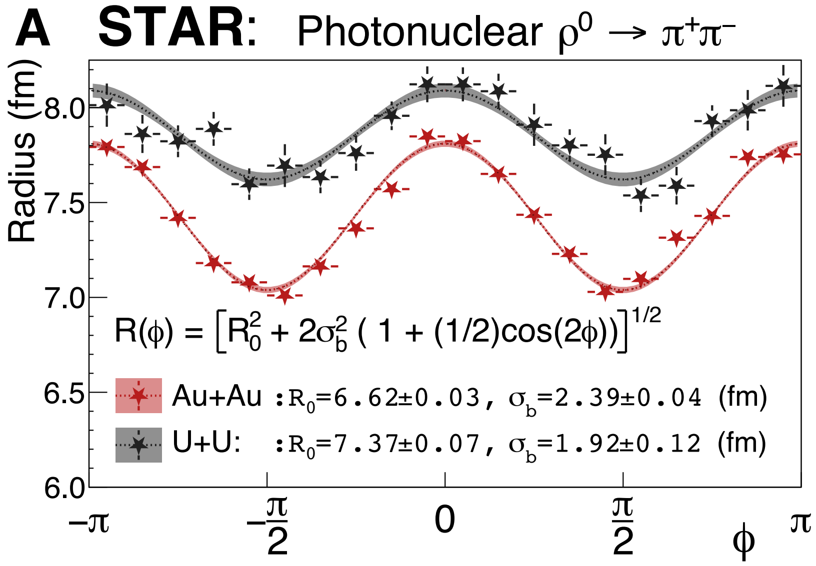
New observable in ρ photoproductior

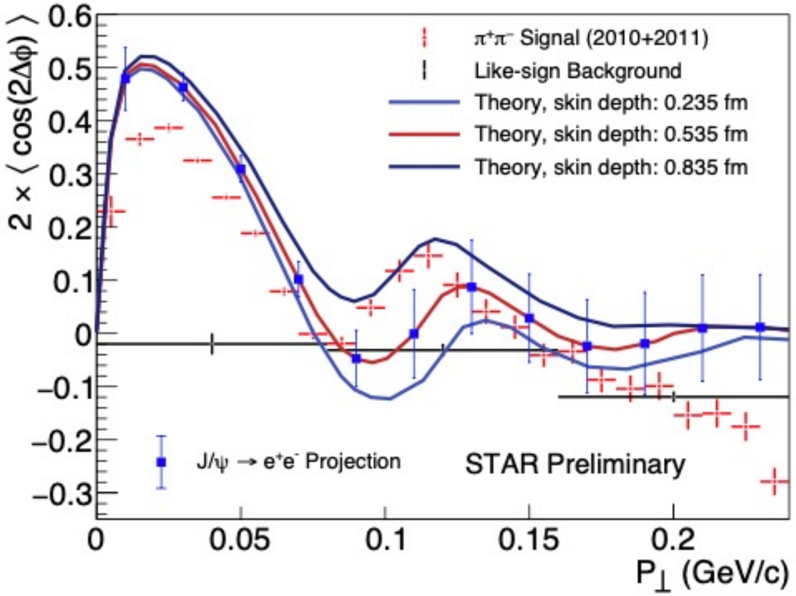
- Predicted to be sensitive to Generalized Transverse Momentum Distribution (GTMD):
  "offer direct access to the second derivative of the saturation scale w.r.t gluon spatial distribution"





- Expected magnitude scales with $(P_\perp/M_\rho)^2$
- Tensor Pomeron …





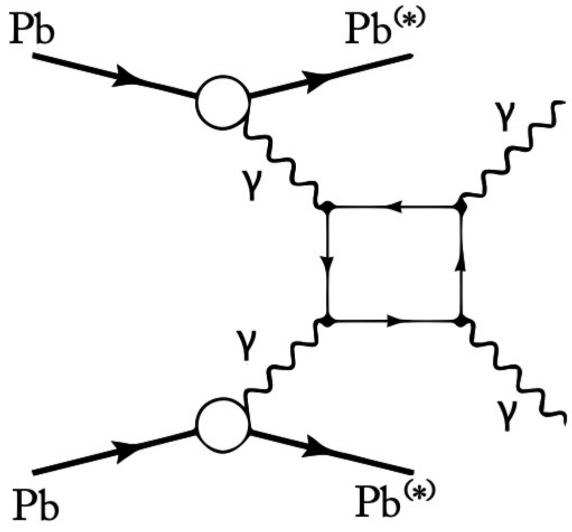
[1] J. Zhou, Phys. Rev. D 94 (2016) 114017;

A. Metz *et al., PRD 84 (2011) 051503* "Distribution of linearly polarized gluons inside a large nucleus"

Observations of cos(2ϕ) modulation➔photons are polarized
Observations of cos(4ϕ) modulation ➔Linear polarized gluons have spatial gradient

Recent Discoveries in Ultra-peripheral collisions:

2017: Light-by-Light



Open Access | Published: 14 August 2017

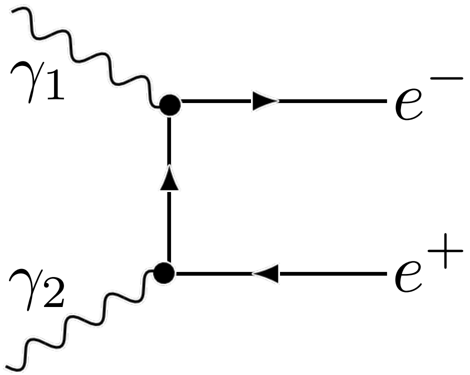
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration

Nature Physics **13**, 852–858 (2017) | Cite this article

41k Accesses | **185** Citations | **521** Altmetric | Metrics

2021: Breit-Wheeler



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2023: Entanglement Enabled Interference

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Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

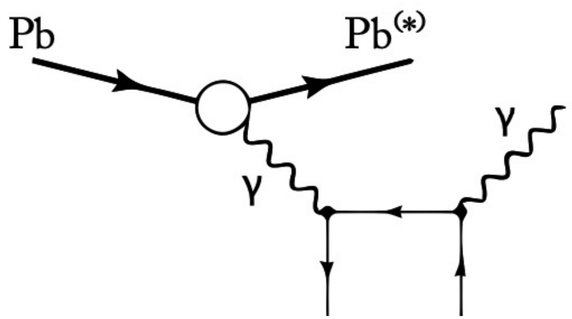
Overview of attention for article published in Science Advances, January 2023

Scientists See Quantum Interference between Different Kinds of Particles for First Time

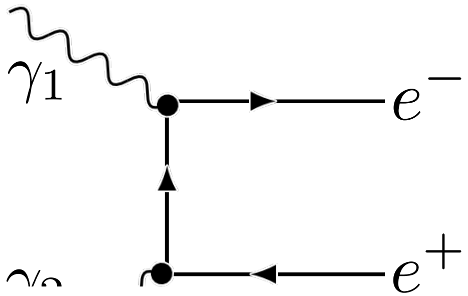
A newly discovered interaction related to quantum entanglement between dissimilar particles opens a new window into the nuclei of atoms

Recent Discoveries in Ultra-peripheral collisions:

2017: Light-by-Light



2021: Breit-Wheeler



2023: Entanglement Enabled Interference

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Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

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PHYS ORG — **Understanding photon collisions could aid search for physics beyond the Standard Model**
Phys.org, 20 Sep 2021
Hot on the heels of proving an 87-year-old prediction that matter can be generated directly from light, Rice University...

PChome — **成大高能核物理實驗室 參與愛因斯坦著名公式驗證**
PC Home, 08 Sep 2021
【大成報/記者于郁金/臺南報導】國立成功大學高能核物理實驗室參與位在美國布魯克海文國家實驗室(Brookhaven National Laboratory，BNL)STAR實驗，首次驗證從純能量(光子)產生正反物質對，這就是愛因斯坦最著名的質能互換公式：E...

HiNet 生活誌 — **成大高能核物理實驗室 參與愛因斯坦著名公式驗**
HiNet, 08 Sep 2021
【勁報/記者于郁金/臺南報導】國立成功大學高能核物理實驗室參與位在美國布魯克海文國家實驗室(Brookhaven National Laboratory，BNL)STAR實驗，首次驗證從純能量(光子)產生正反物質對，這就是愛因斯坦最著名的質能互換公式：E=m...

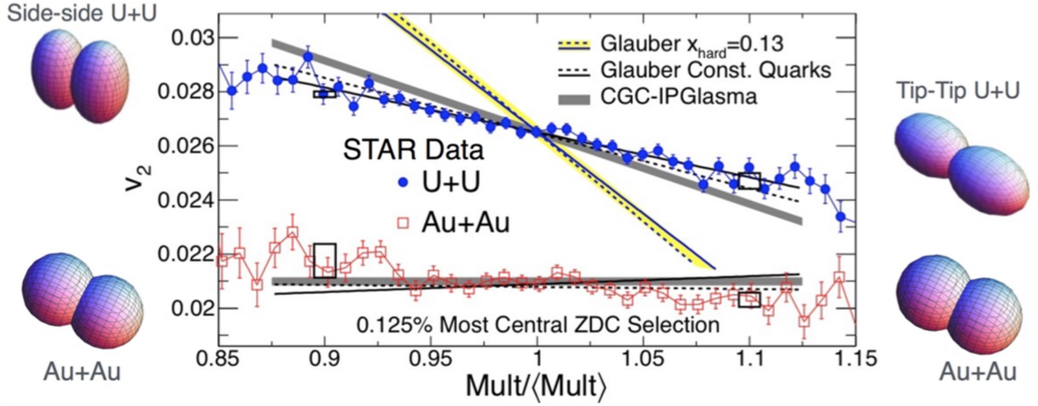
Trends der Zukunft — **Revolutionäre Physik bestätigt 80 Jahre alte Theorie: Forscher wandeln Licht in Materie um**
Trends Dezukunft, 23 Aug 2021
E=mc² – die berühmte Formel von Albert Einstein kennt so gut wie jeder. Die Erkenntnis dahinter ist wiederum wahrscheinlich...

scinexx — **Forscher erzeugen Materie aus Licht - Experiment im Teilchenbeschleuniger bestätigt fast 90 Jahre alte Theorie - scinexx.de**
Scinexx, 22 Aug 2021
Einstein im Beschleuniger: Physiker haben Materieteilchen aus purem Licht erzeugt – durch die Kollision von energiereichen...

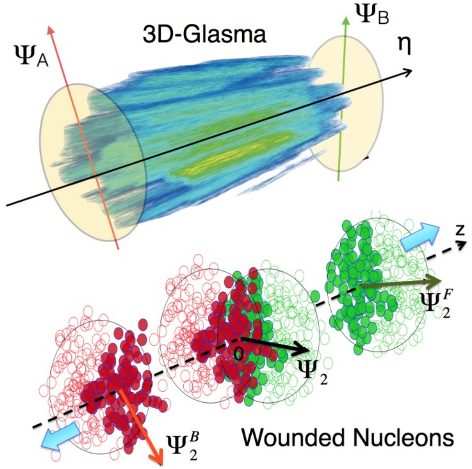
HYSICAL REVIEW LETTERS
42
322 outputs

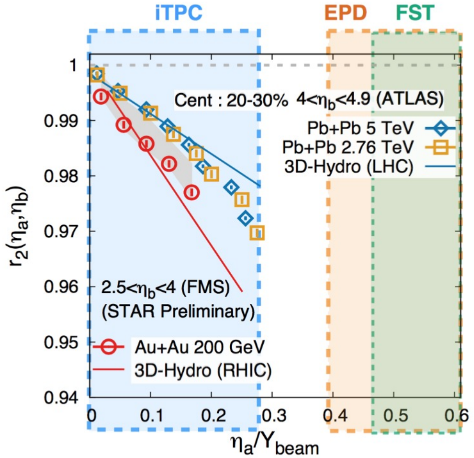
Imaging the initial stages of heavy ion collisions

Extensive measurements from RHIC on different harmonics of azimuthal correlations have strongly constrained the modeling of initial stages of heavy ion collisions.



STAR Collaboration (L. Adamczyk et al.), **Phys. Rev. Lett. 115, 222301 (2015)**, **Phys. Rev. C 98, 034918 (2018)** ,**Phys. Lett. B 790 (2019) 81-88**



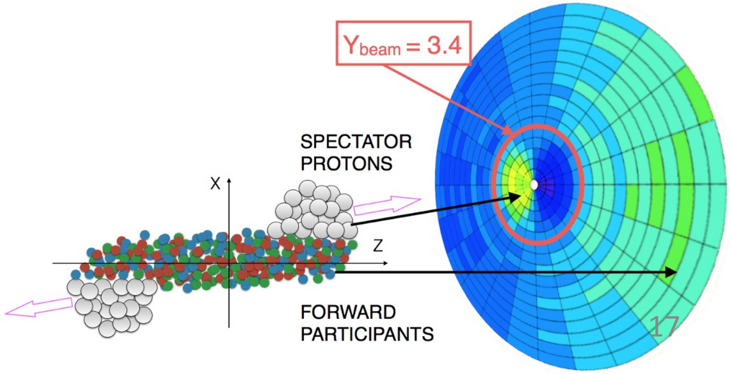


Past half decade (Au+Au, U+U, Cu+Au): The shape of nuclei, geometry of collisions, various sources of initial state fluctuations, dynamics of initial state. **Constraints on state-of-the art modeling** of colliding nuclei before the era of EIC.

Ongoing (Light-heavy ion, pAu, dAu, 3He+Au): Role of subnucleon fluctuations in small collision systems:

Ongoing (Measurements with Beam Energy Scan-II upgrades):

Initial statges of colliding nuclei at lower energies (7.7-27 GeV), the role of valence dof or nucleon wavefunction inside a nucleus



Imaging of nuclear shape at RHIC

STAR, arXiv:2401.06625, submitted to Nature

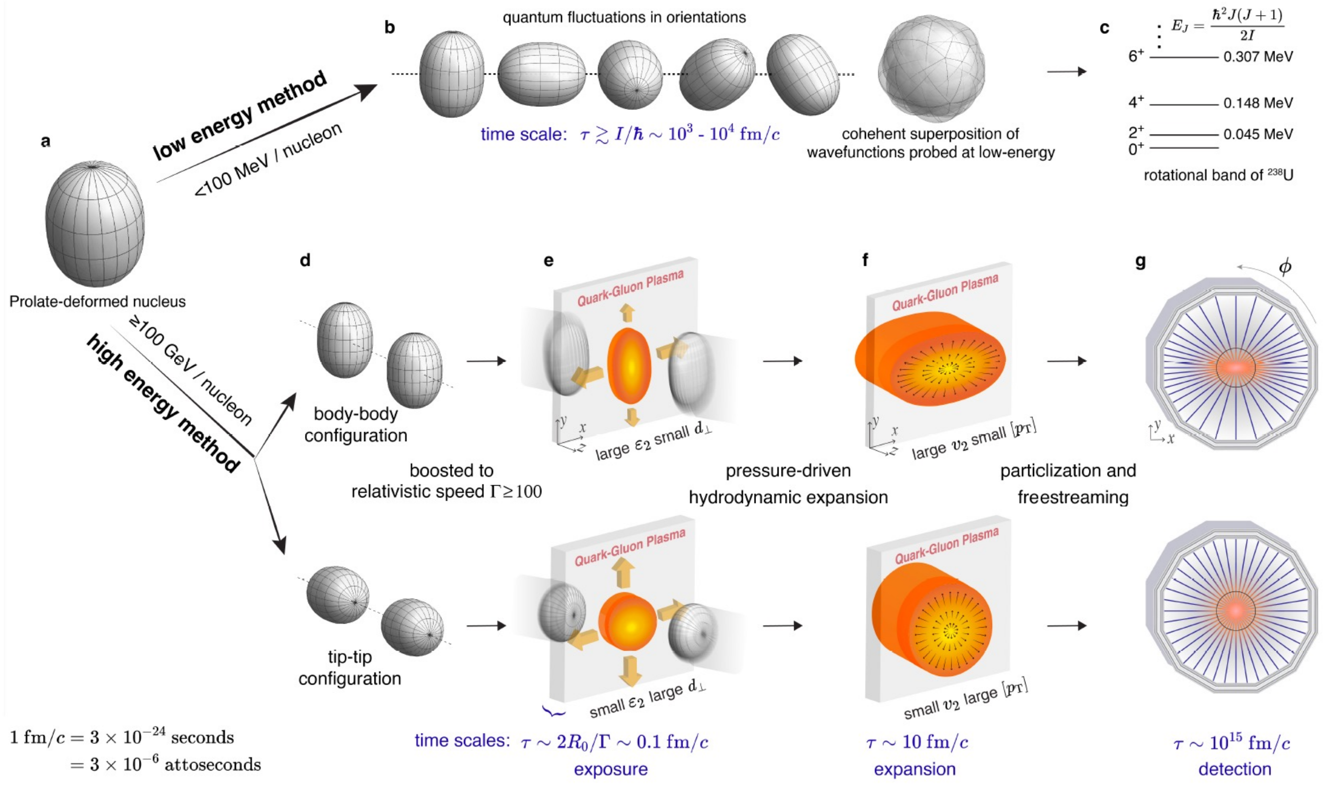


Fig. 1 | Methods for determining the nuclear shape in low and high energies. a, cartoon of a

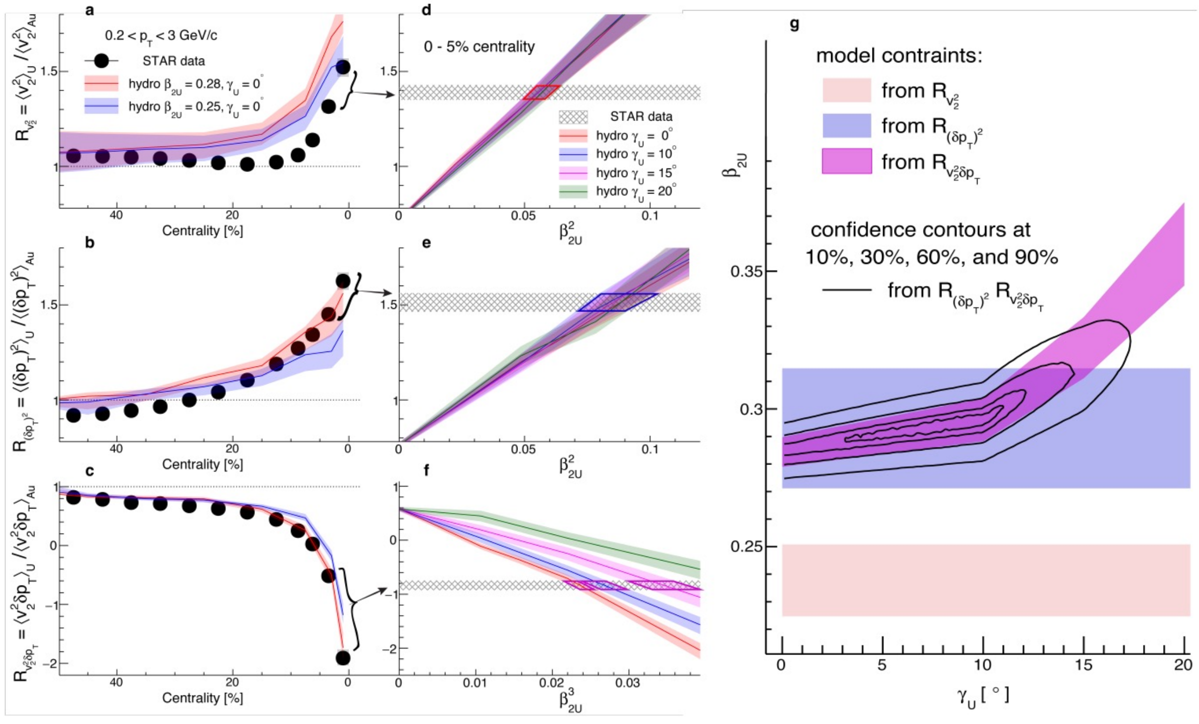


Fig. 3 | Constraining the shape of ^{238}U. Left column: ratios of $\langle v_2^2 \rangle$ (**a**), $\langle (\delta p_T)^2 \rangle$ (**b**), and $\langle v_2^2 \delta p_T \rangle$ (**c**) between U+U and Au+Au collisions as a function of centrality. The data are compared to the IP-Glasma+MUSIC hydrodynamic model calculation assuming β_{2U} = 0.28 (red) and β_{2U} = 0.25 (blue), whose shaded bands denote the

- This technique captures a collision-specific snapshot of the spatial matter distribution in the nuclei
- through the hydrodynamic expansion, leaves imprints on the particle momentum distribution
- U-238 an overall deformation broadly consistent, also a small deviation from axial symmetry
- Is nuclear structure at low energy directly applicable to gluon snapshot at high energy?

Search for heavy antimatter and baryon objects

Rapid Communication

Strangelet search

B. I. Abelev *et al.* (STAR Collab
Phys. Rev. C **76**, 011901(R) – Pu

nature

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Published: 24 April 2011

Observation of the antimatter helium-4 nucleus

The STAR Collaboration

Nature **473**, 353–356 (2011) | Cite this article

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Letter | Published: 09 March 2020

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration

Nature Physics **16**, 409–412 (2020) | Cite this article

Science

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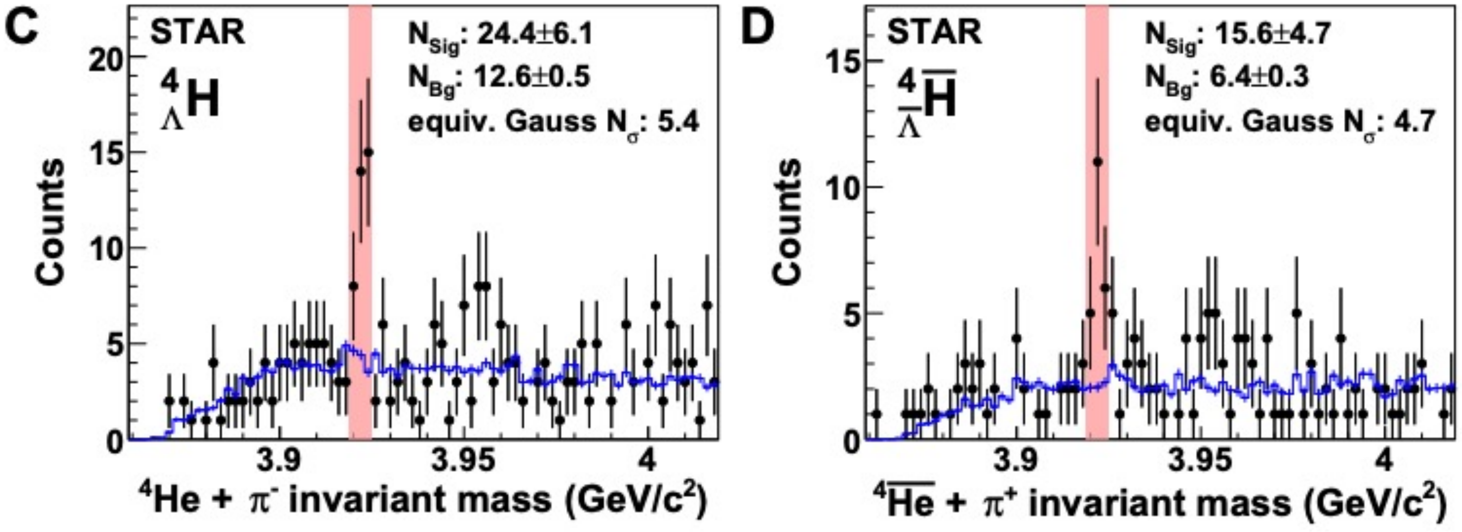
HOME > SCIENCE > VOL. 328, NO. 5974 > OBSERVATION OF AN ANTIMATTER HYPERNUCLEUS

RESEARCH ARTICLE

Observation of an Antimatter Hypernucleus

THE STAR COLLABORATION , B. I. ABELEV, M. M. AGGARWAL, Z. AHAMMED, A. V. ALAKHVERDYANTS, I. ALEKSEEV, B. D. ANDERSON, D. ARK
Y. ZOULKARNEEVA +382 authors Authors Info & Affiliations

SCIENCE • 4 Mar 2010 • Vol 328, Issue 5974 • pp. 58-62 • DOI: 10.1126/science.1183980



Submitted to Nature; arXiv:2310.12674

Search for Stable Charmed Mesic Nucleus $_{D^-}{}^4He$ in Heavy-Ion and EIC

Possibility of Charmed Hypernuclei

C. B. Dover and S. H. Kahana
Phys. Rev. Lett. **39**, 1506 – Published 12 December 1977

Article | References | Citing Articles (38) | PDF | Export Citation

ABSTRACT

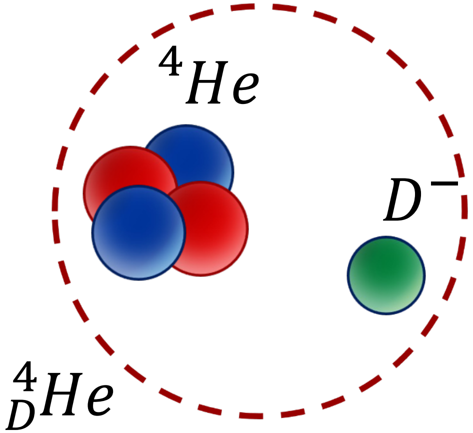
We suggest that both two-body and many-body bound states of a charmed baryon and nucleons should exist. Estimates indicate binding in the $^1S_0$ state of C_1N ($I=\frac{3}{2}$) and SN ($I=1$). We further estimate the binding energy of C_0, C_1 in various finite nuclei.

Received 10 August 1977

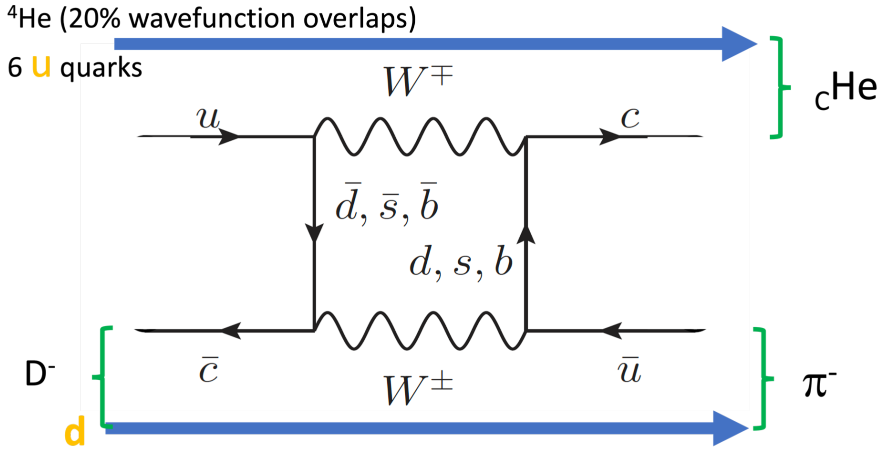
Zhangbu Xu (BNL)
Cheng-Wei Lin, Yi Yang (NCKU)
DNP (2022), EMMI (2023)

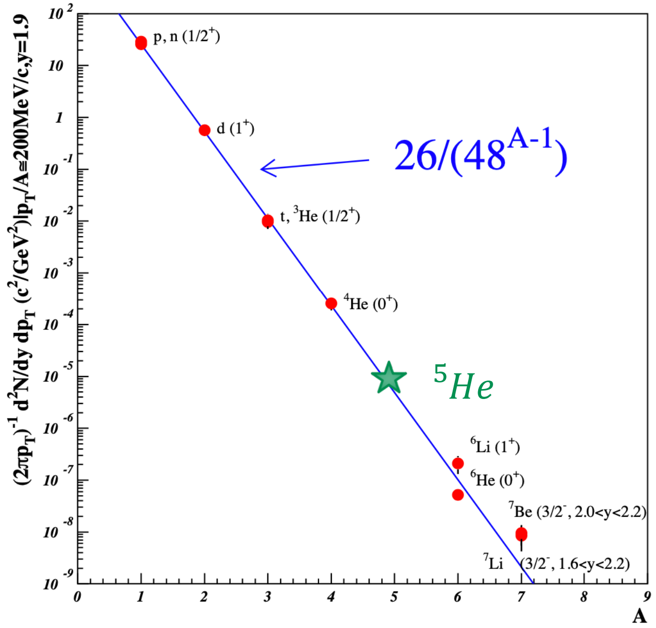
STAR@RHIC:
Estimate 1×10^5/year in forward acceptance
But without vertex detector

EIC ion forward direction:
clean environment
Large boost factor for charm decay vertex
Nuclear cluster



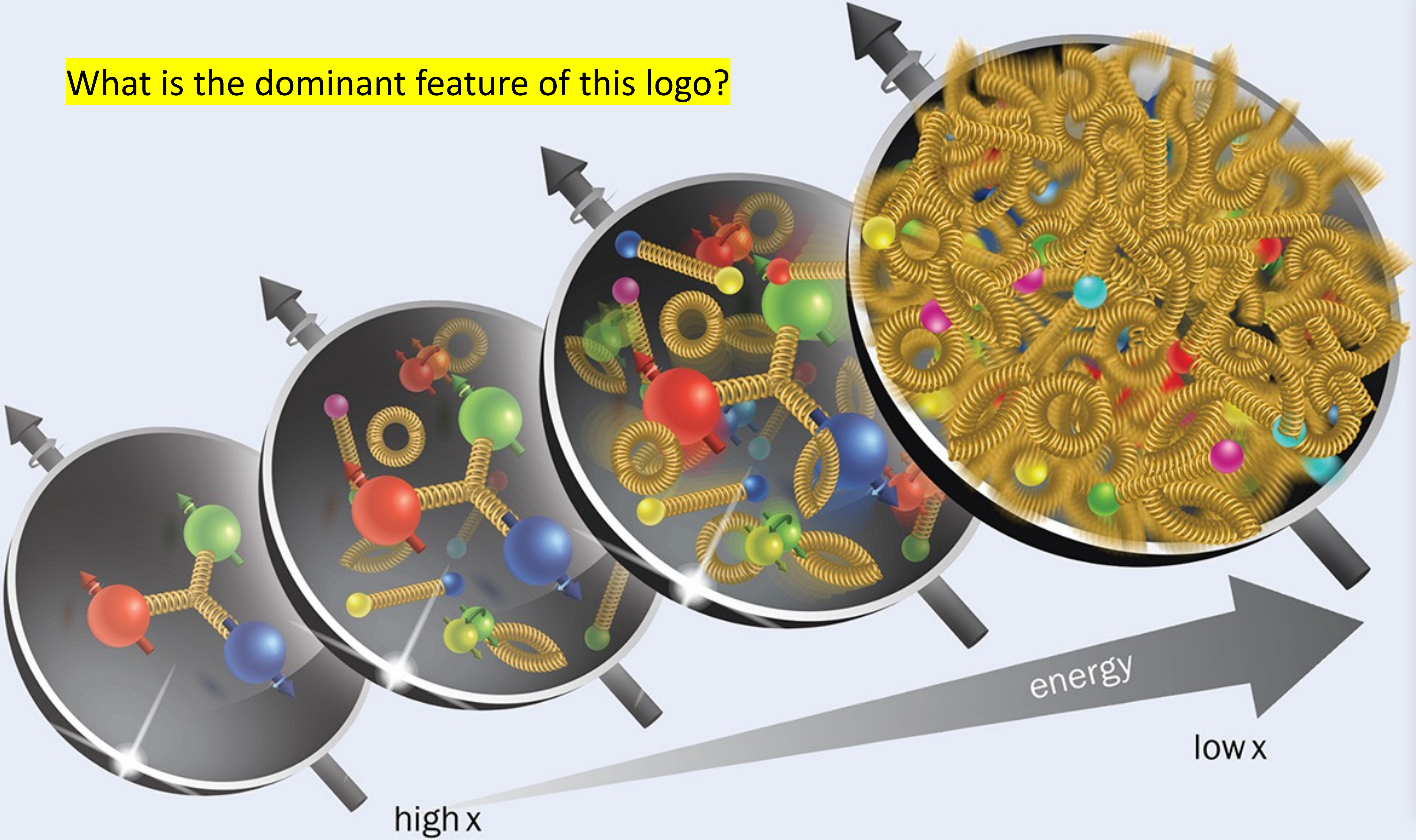
Charm Quark Oscillation with large mass difference





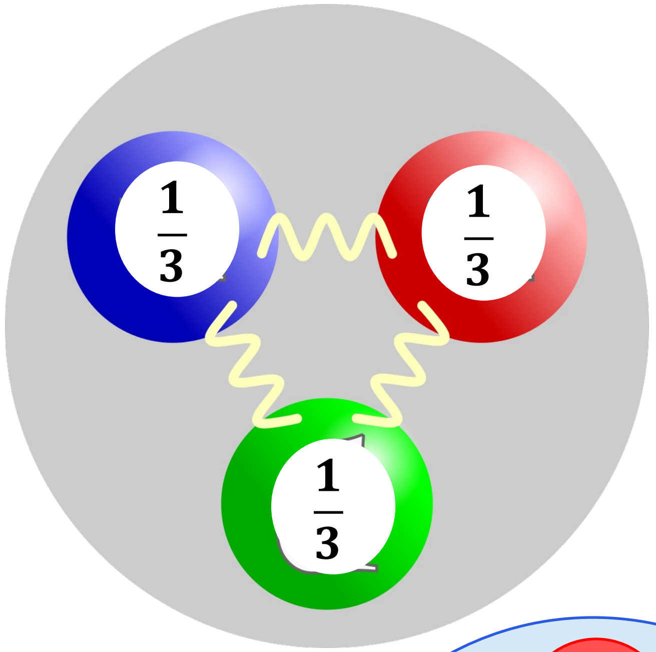
Phys. Rev. C **61**, 064908

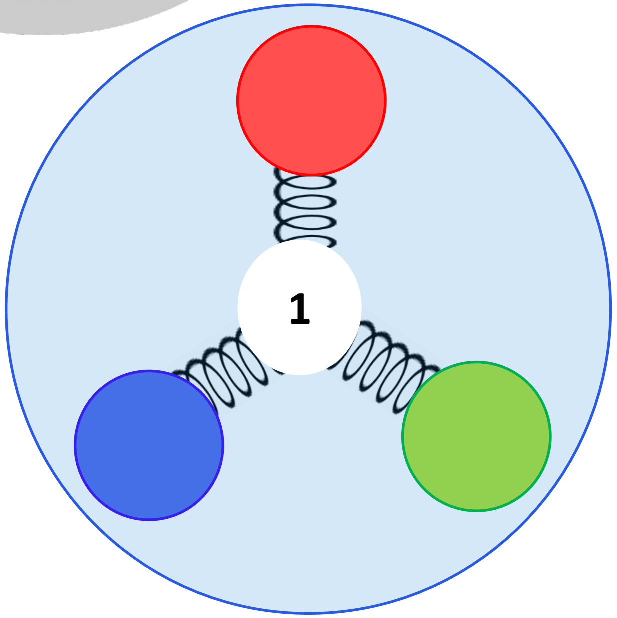
What is the dominant feature of this logo?



Baryon Number (B) Carrier

- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
  - Each valence quark carries 1/3 of baryon number
  - Proton lifetime >10^{34} years
  - Quarks are connected by gluons
- Alternative picture of a proton
  - Proposed at the Dawn of QCD in 1970s
  - A Y-shaped gluon junction topology carries baryon number (B=1)
  - The topology number is the strictly conserved number
  - Quarks do not carry baryon number
  - Valence quarks are connected to the end of the junction always
- Neither of these postulations has been verified experimentally





[1]: Artru, X.; String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (**1975**).
[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (**1977**)

N·H
ELSEVIER

20 June 1996

PHYSICS LETTERS B

Physics Letters B 378 (1996) 238–246

Can gluons trace baryon number?

D. Kharzeev

Theory Division, CERN, CH-1211 Geneva, Switzerland
and Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

Received 15 March 1996
Editor: R. Gatto

Abstract

QCD as a gauge non-Abelian theory imposes severe constraints on the structure of the baryon wave function. We point out that, contrary to a widely accepted belief, the traces of baryon number in a high-energy process can reside in a non-perturbative configuration of gluon fields, rather than in the valence quarks. We argue that this conjecture can be tested experimentally, since it can lead to substantial baryon asymmetry in the central rapidity region of ultra-relativistic nucleus-nucleus collisions.

In QCD, quarks carry colour, flavour, electric charge and isospin. It seems only natural to assume that they also trace baryon number. However, this latter assumption is not dictated by the structure of QCD, and there-

There is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons

state vector which is gauge-invariant – the constraint which is ignored in most of the naive quark model formulations. This constraint turns out to be very severe; in fact, there is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons [1] (note however that there is a large amount of freedom in choosing the paths connecting x to x_i):

$$B = \epsilon^{ijk}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu dx^\mu\right)q(x_1)\right]_i \times \left[P\exp\left(ig\int_{x_2}^{x} A_\mu dx^\mu\right)q(x_2)\right]_j \times \left[P\exp\left(ig\int_{x_3}^{x} A_\mu dx^\mu\right)q(x_3)\right]_k . \quad (1)$$

of gauge invariant operators representing a baryon in QCD. With properly optimised parameters it is used extensively in the first principle computations ... lattice Monte Carlo attempting to determine the nucleon mass. The purpose of this work is to study ... nomenological impact on baryon number production in the central region of nucleus-nucleus collisions.

It is evident from the structure of (1) that the trace of baryon number should be associated not with the valence quarks, but with a non-perturbative configuration of gluon fields located at the point x – the "string junction" [1]. This can be nicely illustrated in the string picture: let us pull all of the quarks aw...

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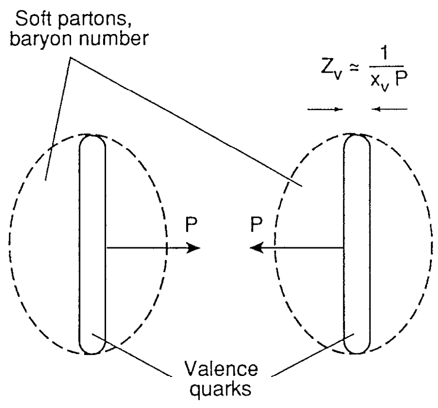

Fig. 2.

of the produced baryons will in general differ from the composition of colliding protons.

Why then is the leading baryon effect a gross feature of high-energy pp collisions? The reason may be the following. The string junction, connected to all three of the valence quarks, is confined inside the baryon, whereas pp collisions become on the average more and more peripheral at high energies. Therefore, in a typical high-energy collision, the string junctions of the colliding baryons pass far away from each other in the impact parameter plane and do not interact. One can however select only central events, triggering on high multiplicity of the produced hadrons. In this case, we expect that the string junctions will interact and

[4]. These two observations combined indicate the existence of an appreciable baryon stopping in central pp collisions even at very high energies [3].

Where else do we encounter central baryon-baryon collisions? In a high energy nucleus-nucleus collision, the baryons in each of the colliding nuclei are densely packed in the impact parameter plane, with an average inter-baryon distance

$$r \simeq (\rho\, r_0)^{-1/2} A^{-1/6}, \quad (4)$$

where ρ is the nuclear density, $r_0 \simeq 1.1$ fm, and A is the atomic number. The impact parameter b in an individual baryon-baryon interaction in the nucleus-nucleus collision is therefore effectively cut off by the packing parameter: $b \leq r$. In the case of a lead nucleus, for example, r appears to be very small: $r \simeq 0.4\ fm$, and a central lead-lead collision should therefore be accompanied by a large number of interactions among the string junctions. This may lead to substantial baryon stopping even at RHIC and LHC energies.

We shall now proceed to more quantitative considerations. In the topological expansion scheme [1], the separation of the baryon number flow from the flow of valence quarks in baryon-(anti)baryon interaction can be represented through a t-channel exchange of the quarkless junction-antijunction state with the wave function given by

$$M_0^J = \epsilon_{ijk}\epsilon^{i'j'k'}\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu dx^\mu\right)\right]_{i'}^{i} \times \left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu dx^\mu\right)\right]_{j'}^{j} \times \left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu dx^\mu\right)\right]_{k'}^{k} . \quad (5)$$

The structure of the wave function (5) is illustrated in Fig. 1b – it is a quarkless closed string configuration composed from a junction and an antijunction. In the topological expansion scheme, the states (5) lie on a Regge trajectory; its intercept can be related to the baryon and reggeon intercepts [1]:

$$\alpha_0^J(0) \simeq 2\alpha_B(0) - 1 + 3(1-\alpha_R(0)) \simeq \frac{1}{2}, \quad (6)$$

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Physics Letters B 378 (1996) 238–246

PHYSICS LETTERS B

Can gluons trace baryon number?

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In QCD, quarks carry colour, flavour, electric charge and isospin. It seems only natural to assume that they also trace baryon number. However, this latter assump-tion is not dictated by the structure of QCD, and there-

There is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons

the baryon number $B = 1/3$) to quarks is based merely on the naive quark model classification. But any phys-

state vector which is gauge-invariant – the constraint which is ignored in most of the naive quark model formulations. This constraint turns out to be very severe; in fact, there is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons [1] (note however that there is a large amount of freedom in choosing the paths connecting x to x_i):

$$B = \epsilon^{ijk}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu dx^\mu\right)q(x_1)\right]_i \times \left[P\exp\left(ig\int_{x_2}^{x} A_\mu dx^\mu\right)q(x_2)\right]_j \times \left[P\exp\left(ig\int_{x_3}^{x} A_\mu dx^\mu\right)q(x_3)\right]_k . \quad (1)$$

$q(x_n)$ make it transform as a quark field at point x instead of at x_n. The ϵ tensor then constructs a local

quark fields (see Fig. 1a). The B in Eq. (1) is a set of gauge invariant operators representing a baryon in QCD. With properly optimised parameters

extensively in the first principle computations

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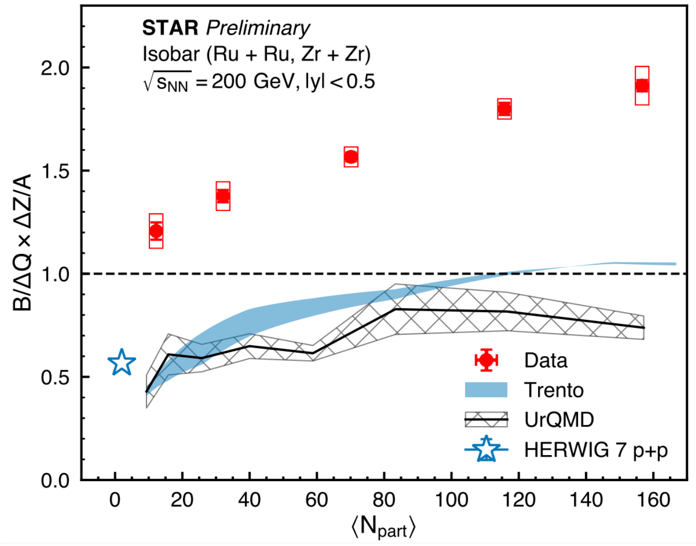
PII S0370-2693(96)00435-2

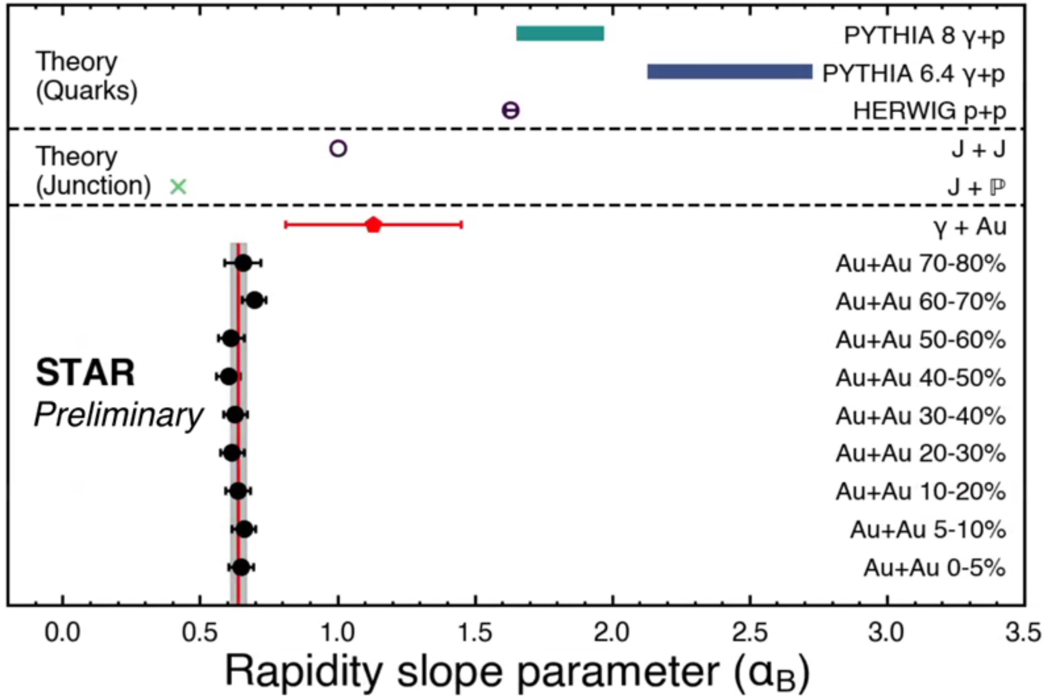
Three approaches toward tracking the origin of the baryon number

1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity
   B/Q=2
2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory
   α_B=0.61
3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin
   $\alpha_B(A+A)=0.61 < \alpha_B(\gamma+A)=1.1 < \alpha_B(PYTHIA)$

$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5





EIC simulation of baryon vs charge transports

Summary of the 1st workshop on 2nd EIC detector (05/15/23)

Golden Channels Strawman

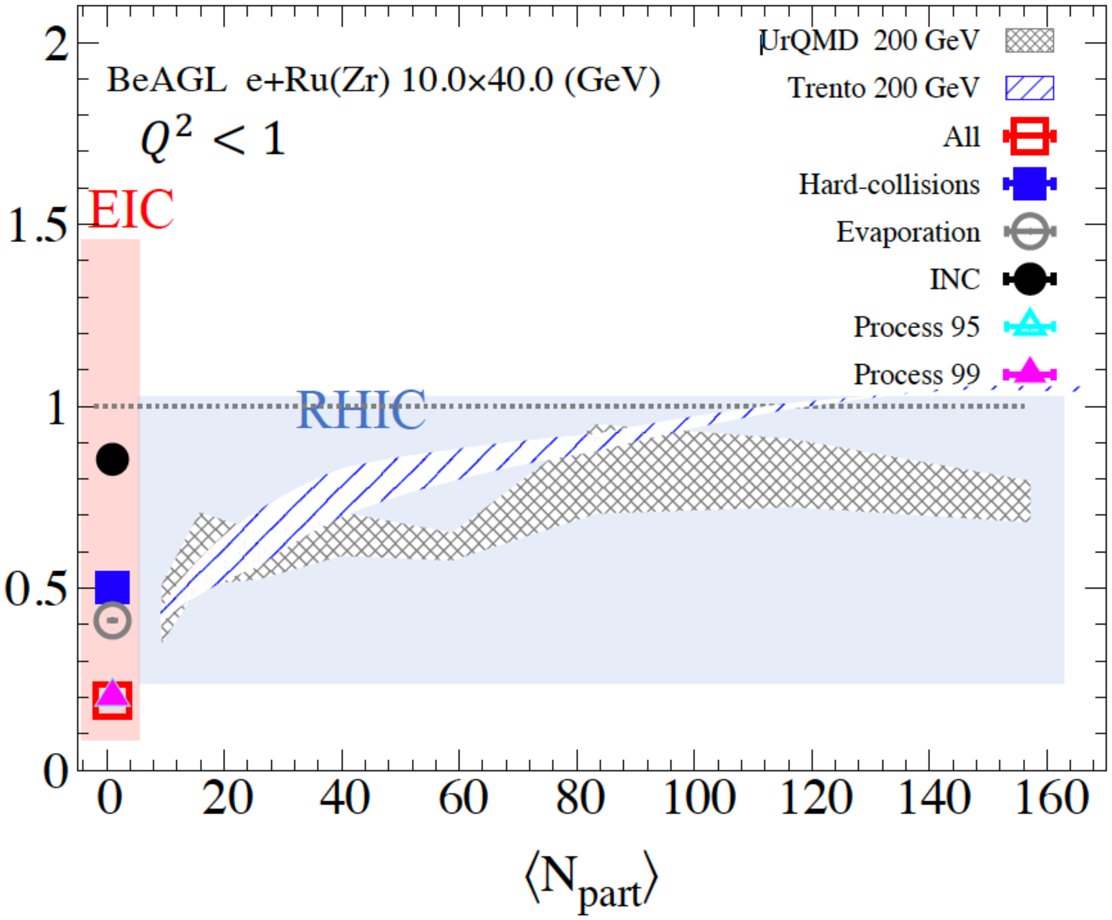
CHANNEL	PHYSICS	DETECTOR II OPPORTUNITY
Diffractive dijet	Wigner Distribution	detection of forward scattered proton/nucleus + detection of low p_T particles
DVCS on nuclei	Nuclear GPDs	High resolution photon + detection of forward scattered proton/nucleus
Baryon/Charge Stopping	Origin of Baryon # in QCD	PID and detection for low p_T pi/K/p
F_2 at low x and Q^2	Probes transition from partonic to color dipole regime	Maximize Q^2 tagger down to 0.1 GeV and integrate into IR.
Coherent VM Production	Nuclear shadowing and saturation	High resolution tracking for precision t reconstruction

These channels are just a starting point, a way to initially focus activities within the group. Additional ideas and efforts are welcome!

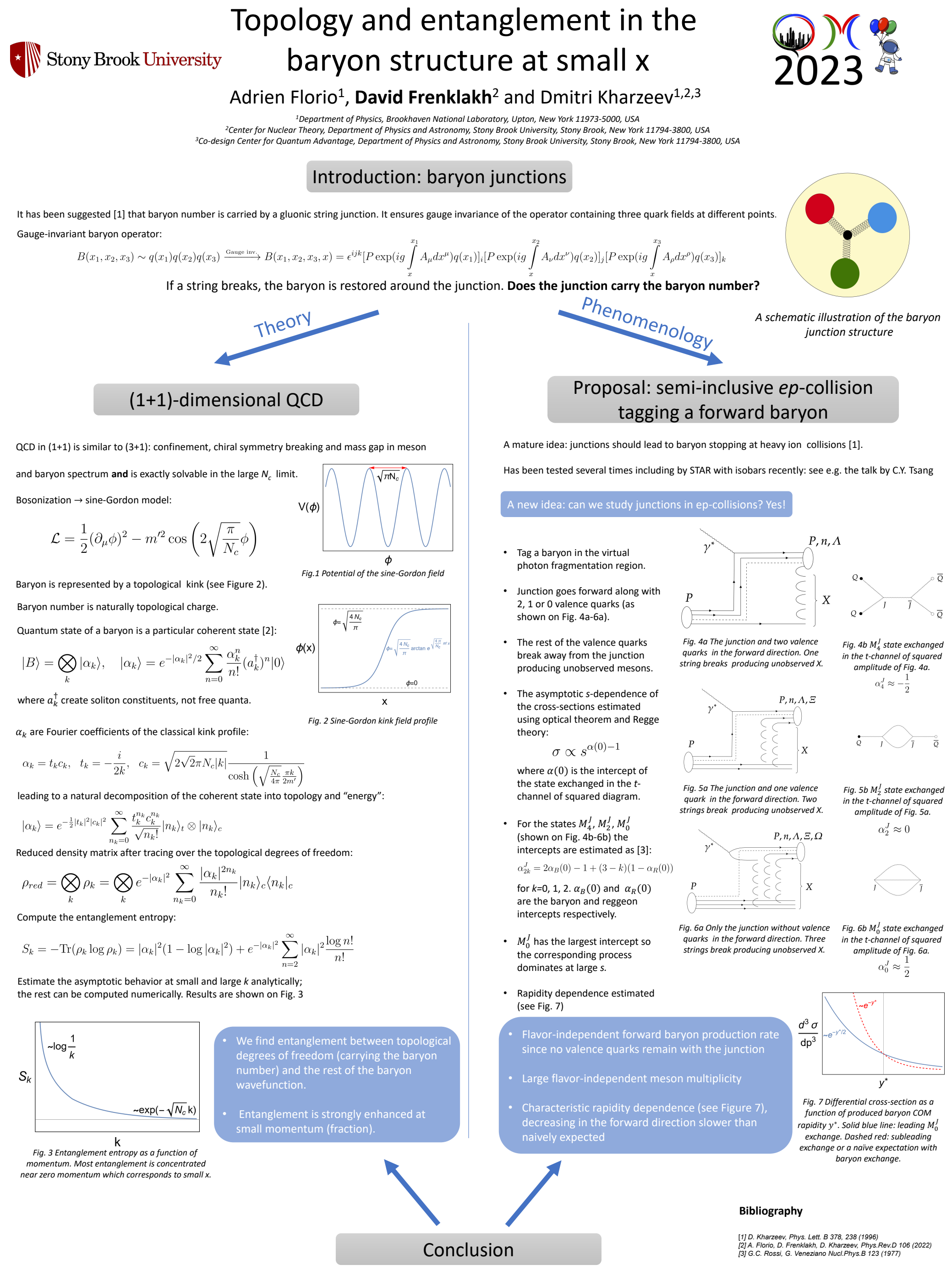
- Need small Q^2, large rapidity coverage and low-momentum hadron particle identification
  $Q^2 \leq 1\ GeV^2$; π/k/p PID $p_t \geq \sim 100\ MeV$

- Isobar collisions to measure charge transport (quark transports), Zr/Ru; $^7Li/^7Be$

Niseem Magdy (SBU)



EIC can measure the baryon junction distribution function



Topology and entanglement in the baryon structure at small x

Stony Brook University

2023

Adrien Florio[1], **David Frenklakh**[2] and Dmitri Kharzeev[1,2,3]

[1]Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
[2]Center for Nuclear Theory, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
[3]Co-design Center for Quantum Advantage, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

Introduction: baryon junctions

It has been suggested [1] that baryon number is carried by a gluonic string junction. It ensures gauge invariance of the operator containing three quark fields at different points.

Gauge-invariant baryon operator:

$$B(x_1,x_2,x_3) \sim q(x_1)q(x_2)q(x_3) \xrightarrow{\text{Gauge inv.}} B(x_1,x_2,x_3,x) = \epsilon^{ijk}[P\exp(ig\int_x^{x_1} A_\mu dx^\mu)q(x_1)]_i[P\exp(ig\int_x^{x_2} A_\nu dx^\nu)q(x_2)]_j[P\exp(ig\int_x^{x_3} A_\rho dx^\rho)q(x_3)]_k$$

If a string breaks, the baryon is restored around the junction. **Does the junction carry the baryon number?**

A schematic illustration of the baryon junction structure

Theory

Phenomenology

(1+1)-dimensional QCD

QCD in (1+1) is similar to (3+1): confinement, chiral symmetry breaking and mass gap in meson and baryon spectrum **and** is exactly solvable in the large N_c limit.

Bosonization → sine-Gordon model:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)^2 - m'^2\cos\left(2\sqrt{\frac{\pi}{N_c}}\phi\right)$$

$V(\phi)$, $\sqrt{\pi N_c}$, ϕ

Fig.1 Potential of the sine-Gordon field

Baryon is represented by a topological kink (see Figure 2).

Baryon number is naturally topological charge.

Quantum state of a baryon is a particular coherent state [2]:

$$|B\rangle = \bigotimes_k |\alpha_k\rangle, \quad |\alpha_k\rangle = e^{-|\alpha_k|^2/2}\sum_{n=0}^{\infty}\frac{\alpha_k^n}{n!}(a_k^\dagger)^n|0\rangle$$

where $a_k^\dagger$ create soliton constituents, not free quanta.

$\phi(x)$, $\phi=\sqrt{\frac{4N_c}{\pi}}$, $\phi=0$, x

Fig. 2 Sine-Gordon kink field profile

α_k are Fourier coefficients of the classical kink profile:

$$\alpha_k = t_k c_k, \quad t_k = -\frac{i}{2k}, \quad c_k = \sqrt{2\sqrt{2}\pi N_c|k|}\frac{1}{\cosh\left(\sqrt{\frac{N_c}{4\pi}}\frac{\pi k}{2m'}\right)}$$

leading to a natural decomposition of the coherent state into topology and "energy":

$$|\alpha_k\rangle = e^{-\frac{1}{2}|t_k|^2|c_k|^2}\sum_{n_k=0}^{\infty}\frac{t_k^{n_k}c_k^{n_k}}{\sqrt{n_k!}}|n_k\rangle_t \otimes |n_k\rangle_c$$

Reduced density matrix after tracing over the topological degrees of freedom:

$$\rho_{red} = \bigotimes_k \rho_k = \bigotimes_k e^{-|\alpha_k|^2}\sum_{n_k=0}^{\infty}\frac{|\alpha_k|^{2n_k}}{n_k!}|n_k\rangle_c\langle n_k|_c$$

Compute the entanglement entropy:

$$S_k = -\mathrm{Tr}(\rho_k\log\rho_k) = |\alpha_k|^2(1-\log|\alpha_k|^2) + e^{-|\alpha_k|^2}\sum_{n=2}^{\infty}|\alpha_k|^2\frac{\log n!}{n!}$$

Estimate the asymptotic behavior at small and large k analytically; the rest can be computed numerically. Results are shown on Fig. 3

S_k, $\sim\log\frac{1}{k}$, $\sim\exp(-\sqrt{N_c}k)$, k

Fig. 3 Entanglement entropy as a function of momentum. Most entanglement is concentrated near zero momentum which corresponds to small x.

- We find entanglement between topological degrees of freedom (carrying the baryon number) and the rest of the baryon wavefunction.
- Entanglement is strongly enhanced at small momentum (fraction).

Proposal: semi-inclusive *ep*-collision tagging a forward baryon

A mature idea: junctions should lead to baryon stopping at heavy ion collisions [1].

Has been tested several times including by STAR with isobars recently: see e.g. the talk by C.Y. Tsang

A new idea: can we study junctions in ep-collisions? Yes!

- Tag a baryon in the virtual photon fragmentation region.
- Junction goes forward along with 2, 1 or 0 valence quarks (as shown on Fig. 4a-6a).
- The rest of the valence quarks break away from the junction producing unobserved mesons.
- The asymptotic s-dependence of the cross-sections estimated using optical theorem and Regge theory:

  $$\sigma \propto s^{\alpha(0)-1}$$

  where $\alpha(0)$ is the intercept of the state exchanged in the t-channel of squared diagram.
- For the states M_4^J, M_2^J, M_0^J (shown on Fig. 4b-6b) the intercepts are estimated as [3]:

  $$\alpha_{2k}^J = 2\alpha_B(0) - 1 + (3-k)(1-\alpha_R(0))$$

  for k=0, 1, 2. $\alpha_B(0)$ and $\alpha_R(0)$ are the baryon and reggeon intercepts respectively.
- M_0^J has the largest intercept so the corresponding process dominates at large s.
- Rapidity dependence estimated (see Fig. 7)

Fig. 4a The junction and two valence quarks in the forward direction. One string breaks producing unobserved X.

Fig. 4b M_4^J state exchanged in the t-channel of squared amplitude of Fig. 4a. $\alpha_4^J \approx -\frac{1}{2}$

Fig. 5a The junction and one valence quark in the forward direction. Two strings break producing unobserved X.

Fig. 5b M_2^J state exchanged in the t-channel of squared amplitude of Fig. 5a. $\alpha_2^J \approx 0$

Fig. 6a Only the junction without valence quarks in the forward direction. Three strings break producing unobserved X.

Fig. 6b M_0^J state exchanged in the t-channel of squared amplitude of Fig. 6a. $\alpha_0^J \approx \frac{1}{2}$

- Flavor-independent forward baryon production rate since no valence quarks remain with the junction
- Large flavor-independent meson multiplicity
- Characteristic rapidity dependence (see Figure 7), decreasing in the forward direction slower than naively expected

Fig. 7 Differential cross-section as a function of produced baryon COM rapidity y^*. Solid blue line: leading M_0^J exchange. Dashed red: subleading exchange or a naïve expectation with baryon exchange.

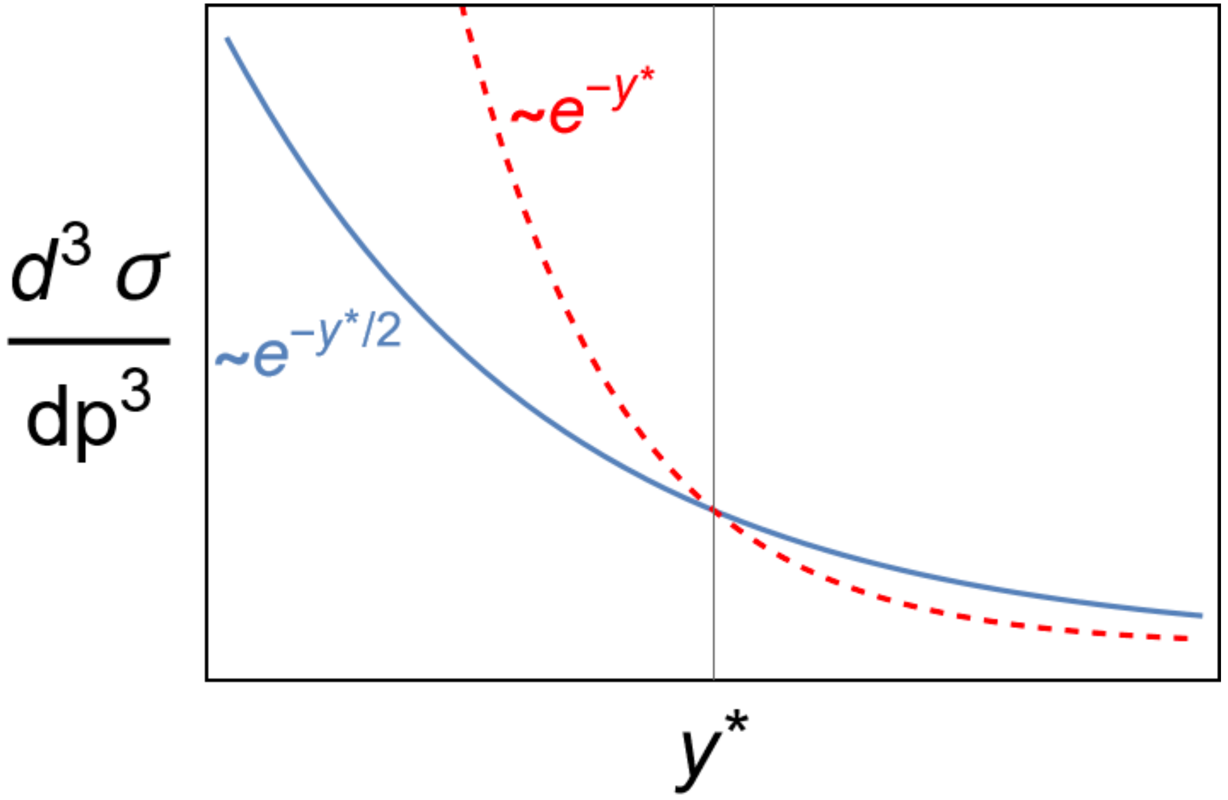
Conclusion

Bibliography

[1] D. Kharzeev, Phys. Lett. B 378, 238 (1996)
[2] A. Florio, D. Frenklakh, D. Kharzeev, Phys.Rev.D 106 (2022)
[3] G.C. Rossi, G. Veneziano Nucl.Phys.B 123 (1977)

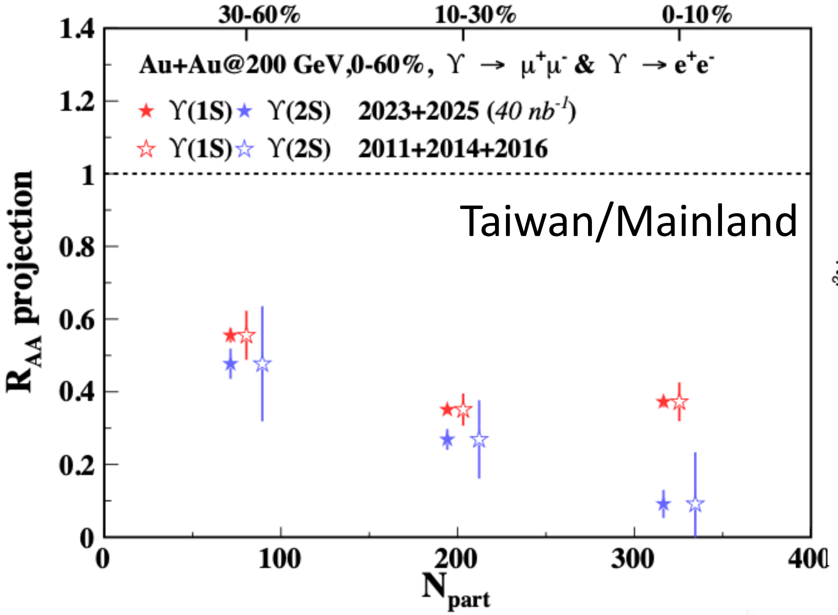
Electron-Ion Collider at BNL (2030+)

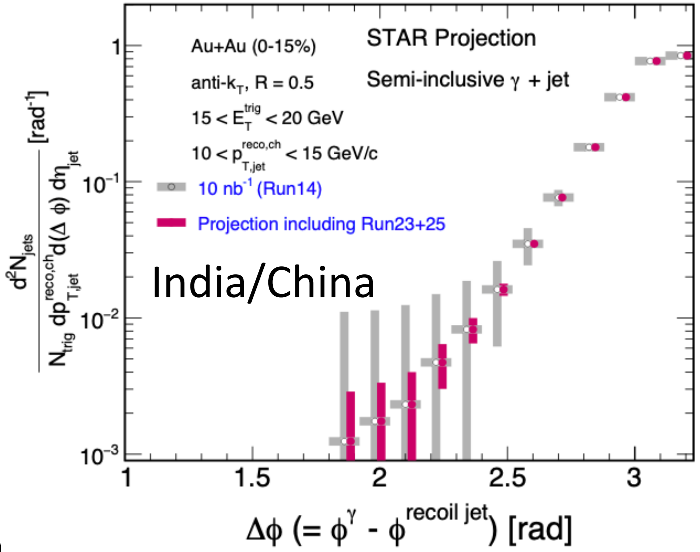
arXiv: 2312.15039



Similar to γ+Au collisions?

Heavy-ion programs less related to EIC





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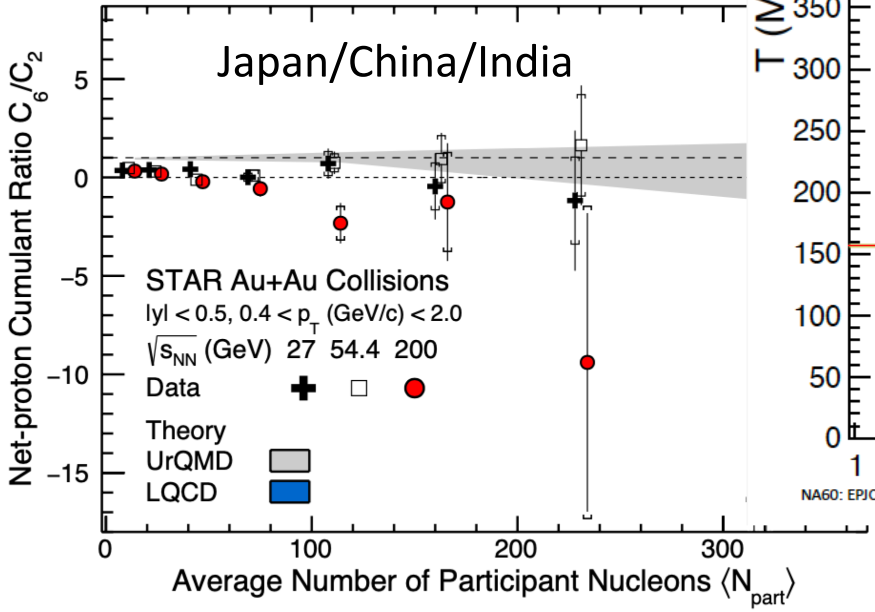
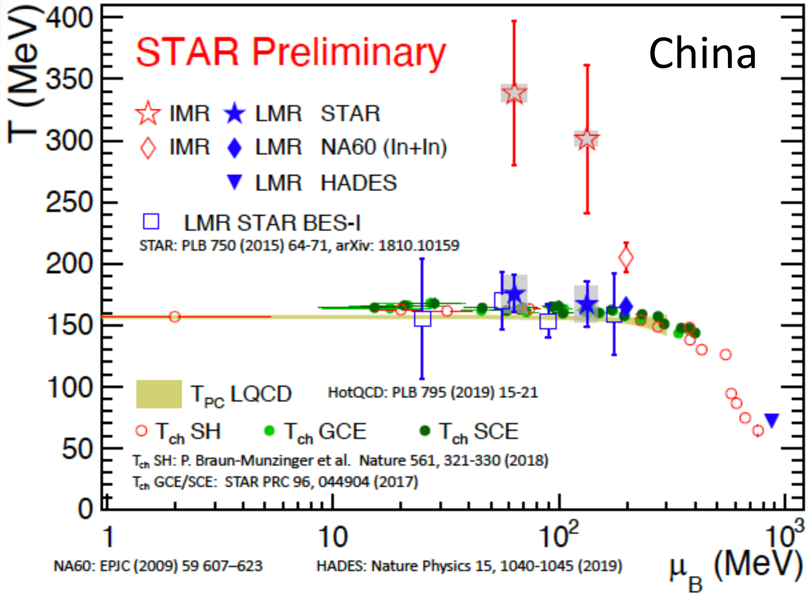




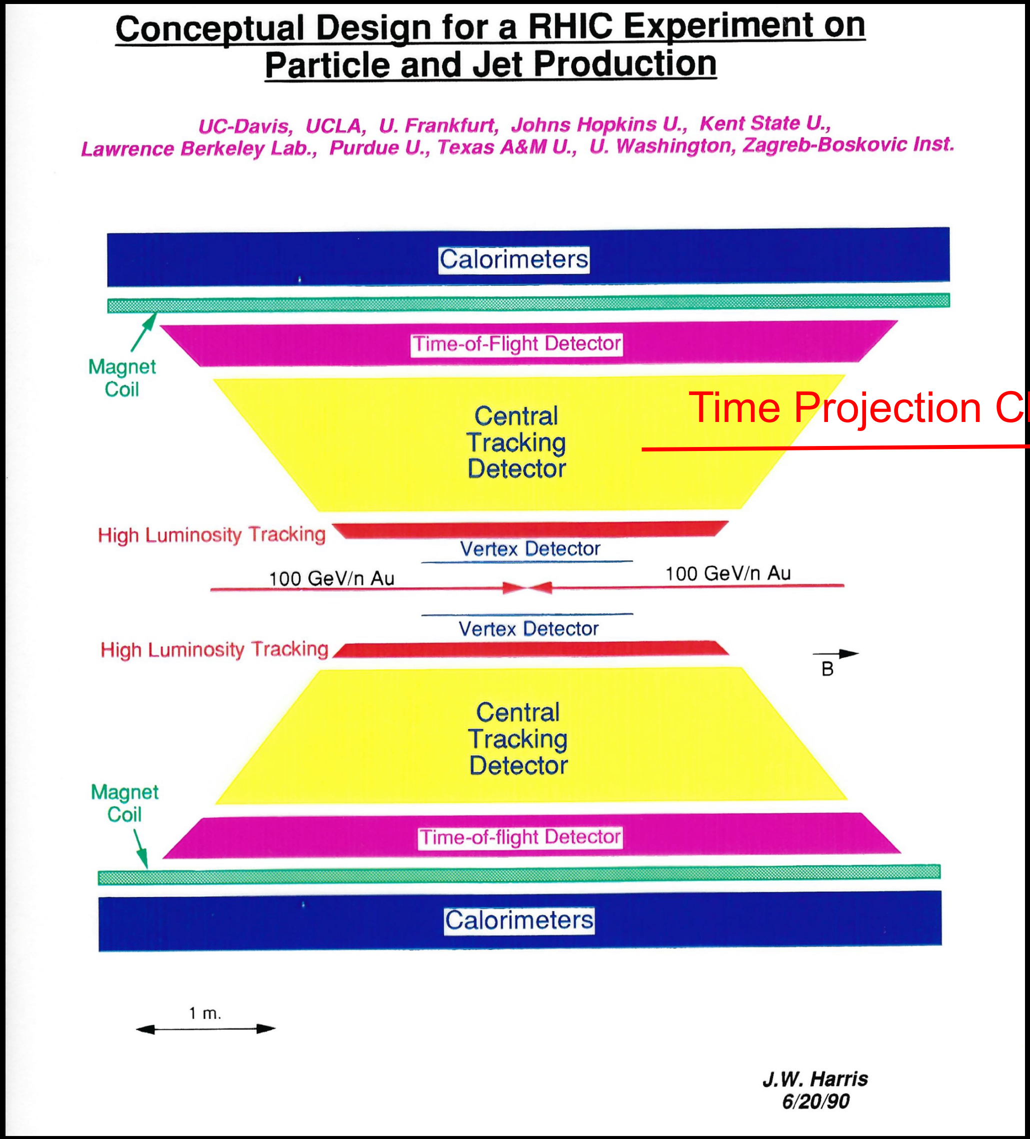
To address important questions about the inner workings of the QGP

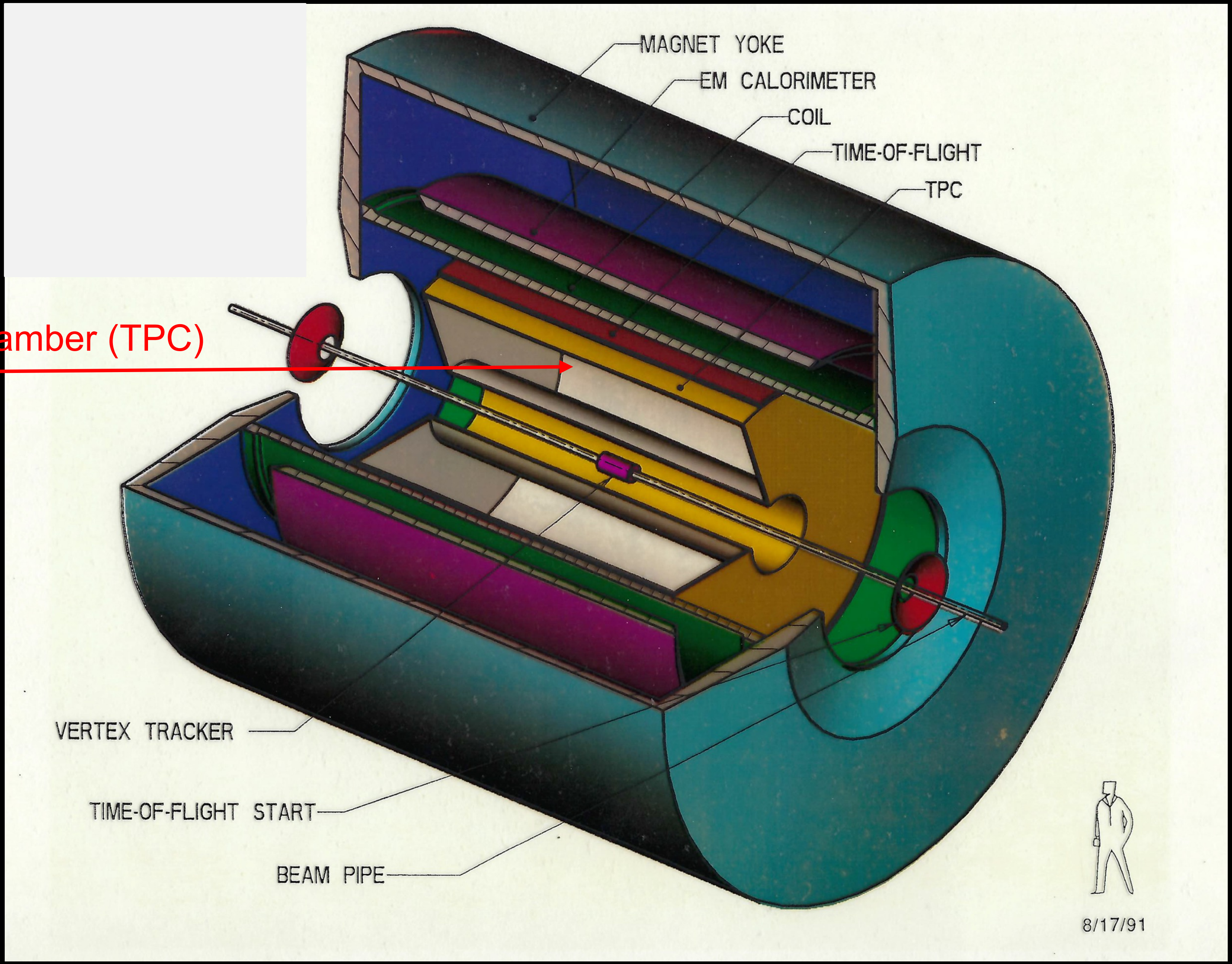
- **What is the nature of the 3-dimensional initial state at RHIC energies?** r_n over a wide rapidity, J/ψ v_1, photon Wigner distributions
- **What is the precise temperature dependence of shear and bulk viscosity?** v_n as a function of η
- **What can be learned about confinement from charmonium measurements?** J/ψ v_2
- **What is the temperature of the medium?** Different ϒ states, ψ(2S), thermal dileptons
- **What are the electrical, magnetic, and chiral properties of the medium?** Λ, Ξ, Ω P_H and K*, ϕ, J/ψ ρ_{00}, thermal dileptons, CME observables
- **What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale?** γ_{dir}+jet I_{AA}, γ_{dir}+jet acoplanarity, jet substructure
- **What is the precise nature of the transition near μ_B=0?** Net-proton C_6/C_2
- **What can we learn about the strong interaction?** Correlation functions

To inform EIC physics with photon induced processes:

- **Probe gluon distribution inside the nucleus:** vector mesons (J/ψ), dijets (?)
- **Search for collectivity and signatures of baryon junction:** inclusive charge particles and cross sections, v_n, identified particle spectra

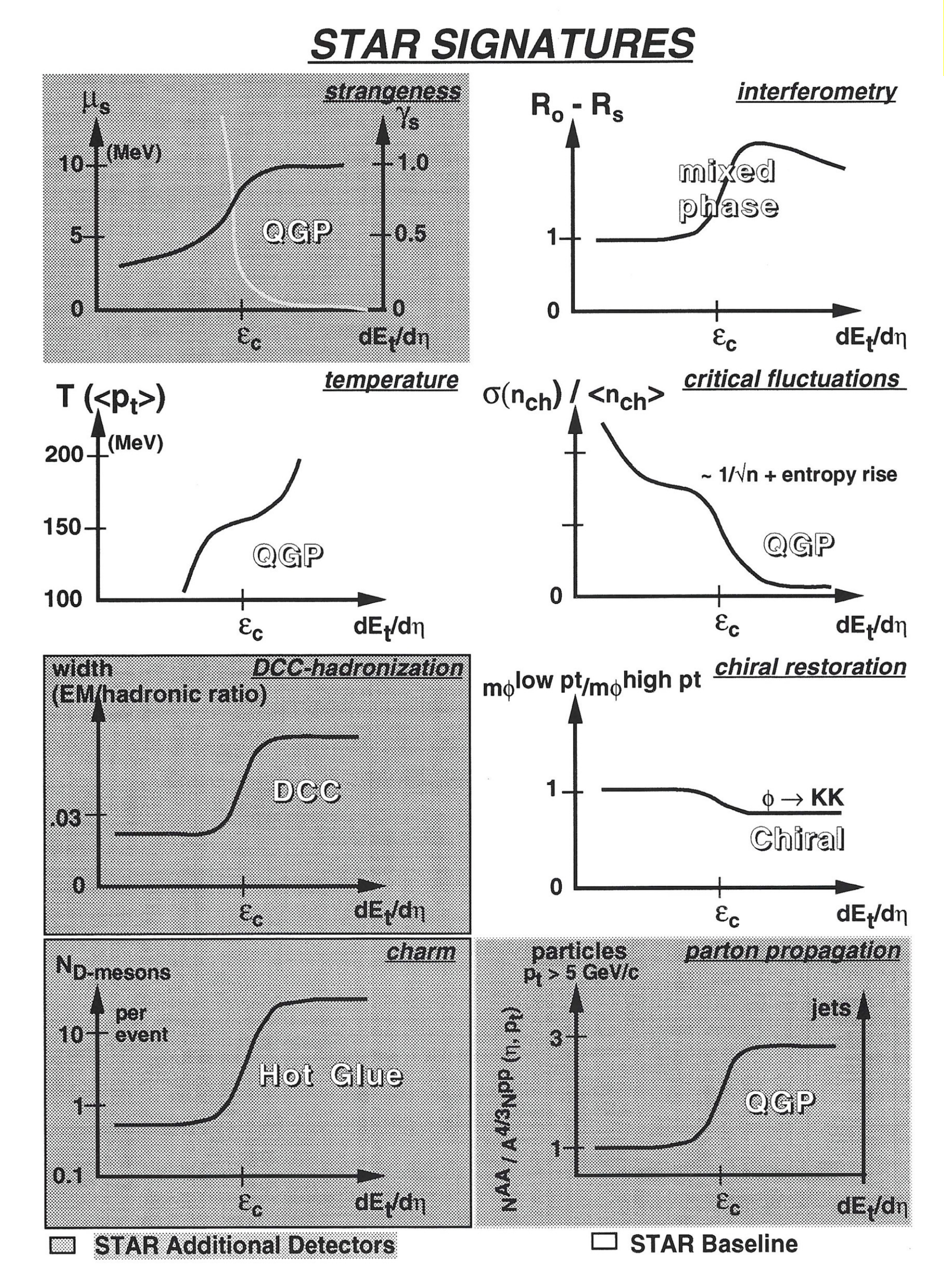
Design Evolution for Experiment at RHIC



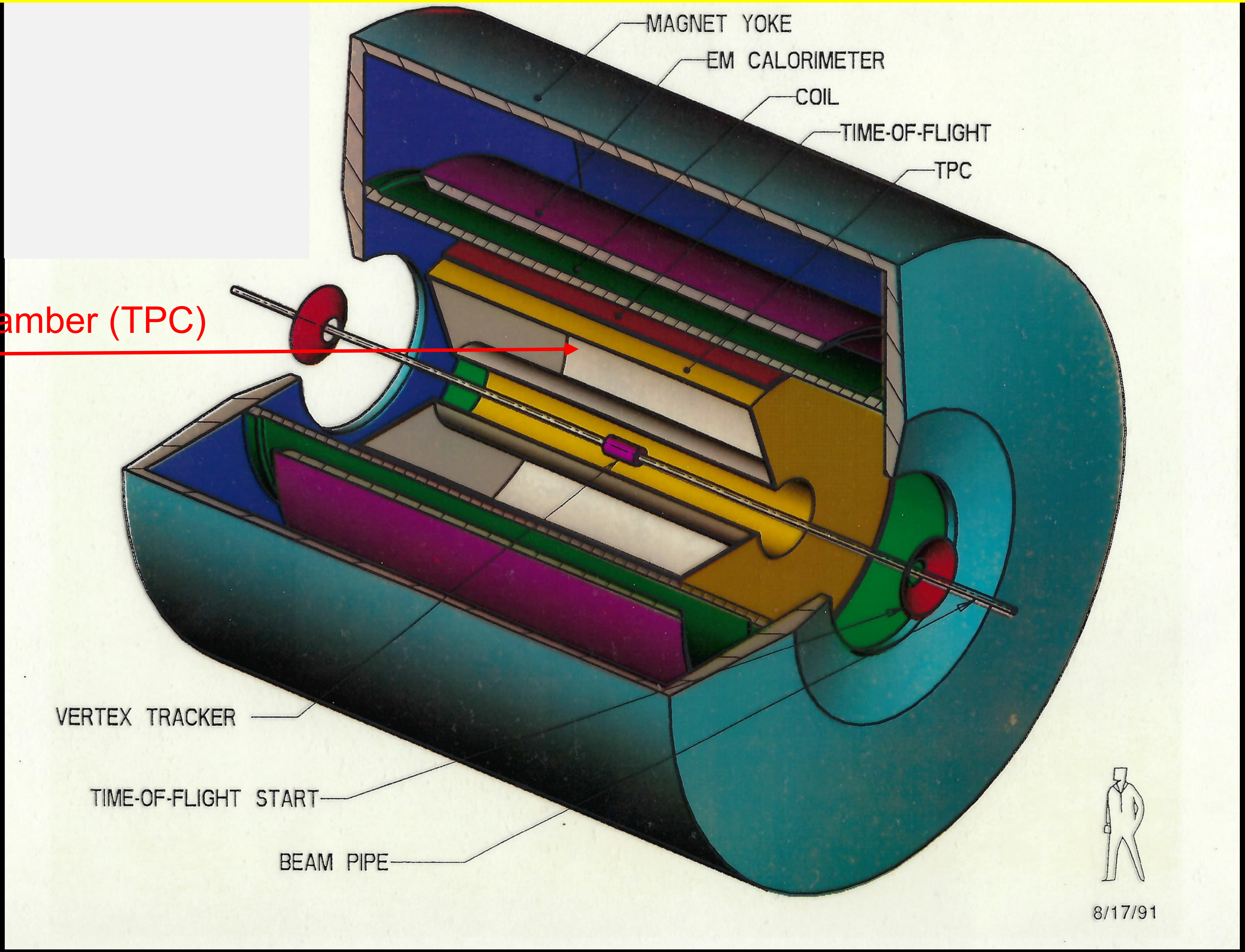


Design Evolution for Experiment at RHIC

NONE of the signatures came true, but we went on to discover greater things!



on Chamber (TPC)



STAR physics is well connected to EIC