Completing the STAR Scientific Mission

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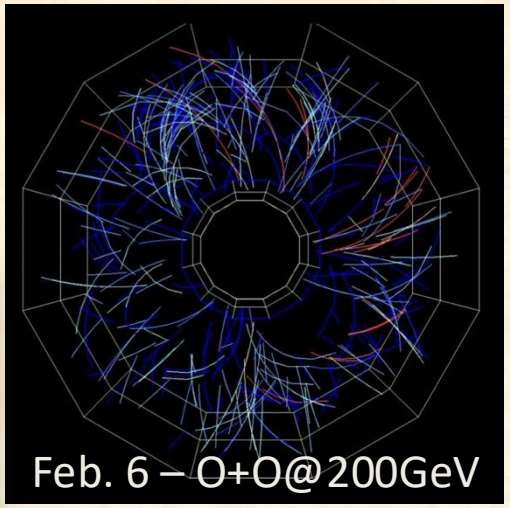
RICE UNIVERSITY

U.S. DEPARTMENT of ENERGY | Office of Science

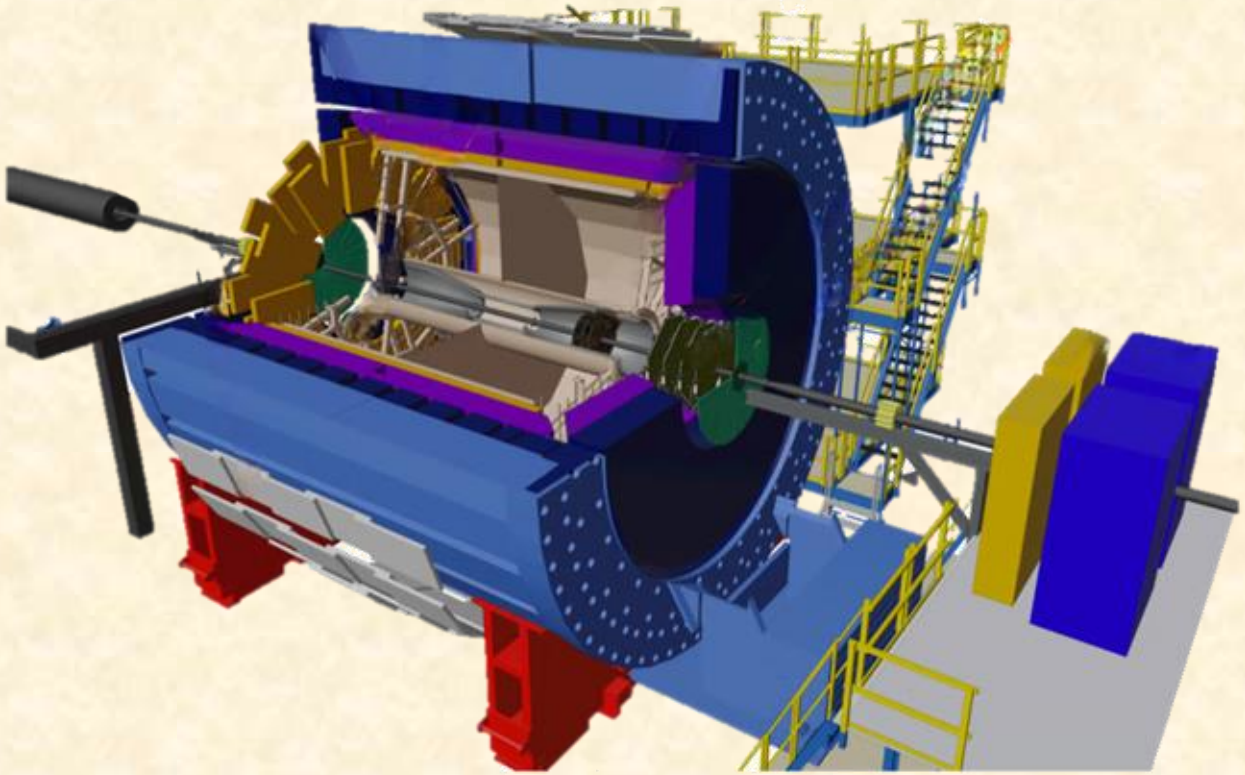
Looking back

✓ … to the Last Collision



➢ From the First …

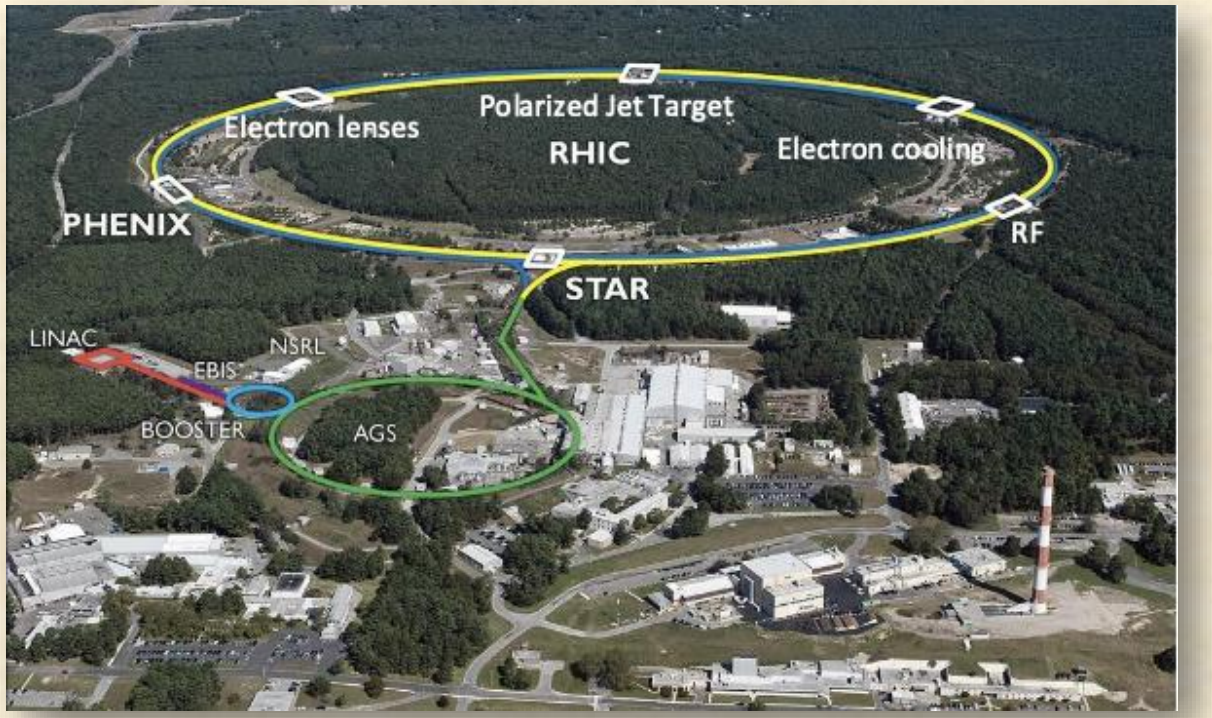
The STAR Detector at 25 years …

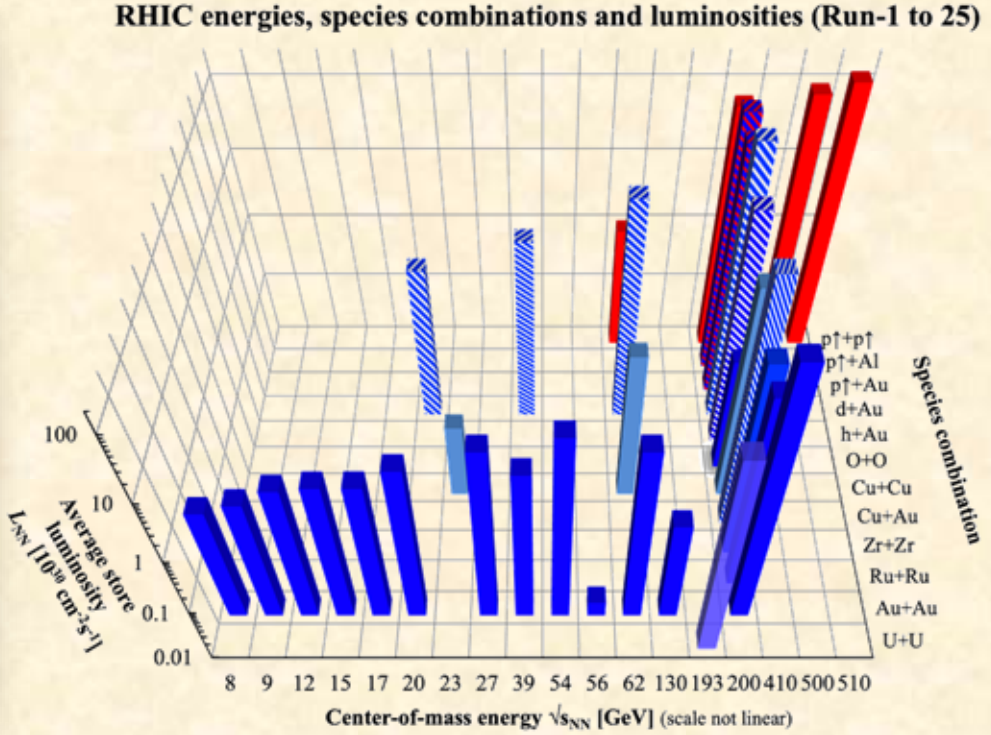


Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\|\eta\|$ <1 Tracking		1999-
Barrel EMC	$\|\eta\|$ <1 jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	1< η <2 jets/π^0/e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

❖ Extended detection capabilities following 20+ upgrades

25 years of RHIC and STAR





www.agsrhichome.bnl.gov/RHIC/Runs/

- *"RHIC: the world's first purpose-built heavy ion collider"*

➢ Wide range of beam energies and collision systems

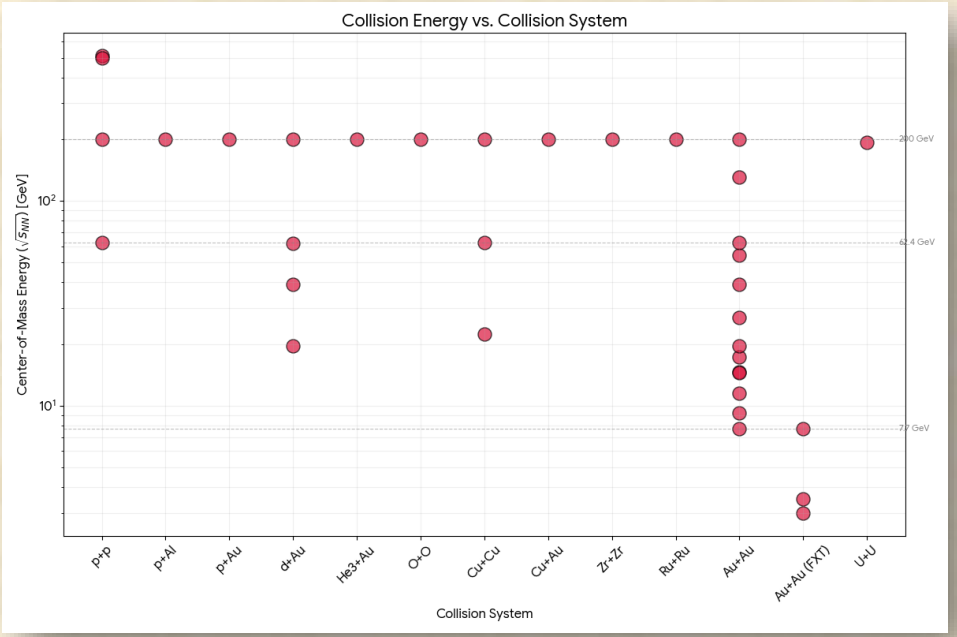
– *"The most versatile collider ever built!"*

[Bill Zajc, 2025 RHIC-AGS Users' Meeting]

✓ 25 years of STAR operations

Run	Year	System(s)	$\sqrt{s_{NN}}$ (GeV)	Notes
Run-1	2000	Au+Au	130	~1.6 M events (First data)
Run-2	2001	Au+Au p+p	200 200	~4 M ~10 M (polarized)
Run-3	2002	d+Au p+p	200 200	~15 M ~15 M
Run-4	2003	Au+Au p+p	200, 62.4 200	~80 M (200 GeV) ~40 M
Run-5	2004	Cu+Cu p+p	200, 62.4, 22.4 200	High stats Cu+Cu scan
Run-6	2006	p+p	200, 62.4	High statistics polarized proton
Run-7	2007	Au+Au	200	~80 M (Low mass dilepton focus)
Run-8	2008	d+Au p+p	200 200	Low material run
Run-9	2009	p+p	500, 200	First 500 GeV p+p run (~W physics)
Run-10	2010	Au+Au p+p	200, 62.4, 39, 11.5, 7.7 200	**BES-I Start**; ~4-250 M events/energy
Run-11	2011	Au+Au p+p	19.6, 27, 200 500	**BES-I** continuation; Heavy Flavor focus
Run-12	2012	U+U Cu+Au p+p	193 200 200, 510	First U+U and Cu+Au collisions
Run-13	2013	p+p	510	High luminosity polarized p+p (~W/Z)
Run-14	2014	Au+Au He-3 +Au	200, 14.5 200	**HFT** installed; BES-I completion (14.5)

Run	Year	System(s)	$\sqrt{s_{NN}}$ (GeV)	Notes
Run-15	2015	p+p p+Au p+Al	200 200 200	Transverse spin; Cold QCD
Run-16	2016	Au+Au d+Au	200 200, 62, 39, 19.6	Heavy Flavor program; Small system scan
Run-17	2017	p+p Au+Au	510 54.4	Transverse spin; Magnetic field study
Run-18	2018	Ru+Ru, Zr+Zr Au+Au	200 27	**Isobar Run** (>3 B/species); iTPC upgrade
Run-19	2019	Au+Au Au+Au (FXT)	19.6, 14.6 3.0 - 7.7 (scan)	**BES-II Start**; Fixed Target (FXT) initiation
Run-20	2020	Au+Au Au+Au (FXT)	11.5, 9.2 3.5, 3.9, 4.5, 5.2, 6.2, 7.7	**BES-II** Collider + FXT high stats (~100 M+)
Run-21	2021	Au+Au O+O / d+Au	7.7 200	**BES-II Finish**; Test runs for O+O
Run-22	2022	p+p	510	Forward Upgrade
Run-23	2023	Au+Au p+p Au+Au	200 200 17.3	High stats Au+Au; Forward Physics
Run-24	2024	p+p p+Au	200 200	Cold QCD & Forward Physics
Run-25	2025 2026	Au+Au Au+ Au (FXT) O+O	200 4.2, 4.5, 5.2 200	High statistics final Au+Au run High statistics final FXT run Small systems data set

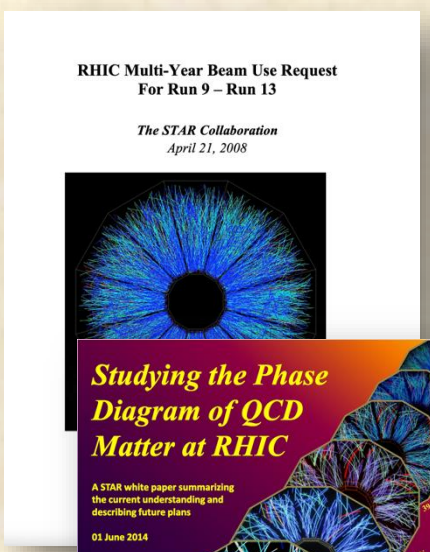


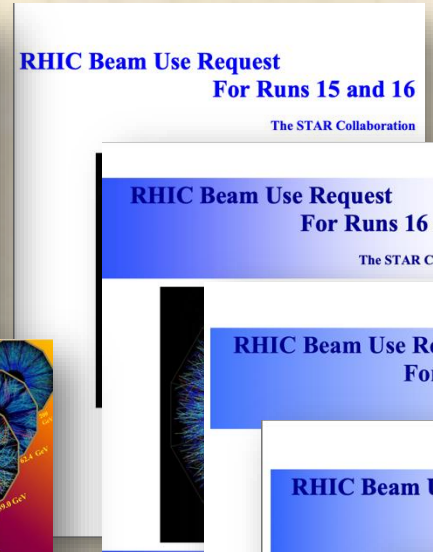
Courtesy of Google Gemini

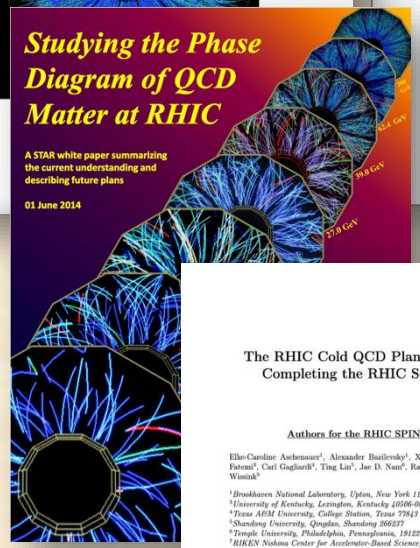
- 25 RHIC Runs
- 13 collision systems
  - Incl. Fixed Target
- 15+ energy and spin configs

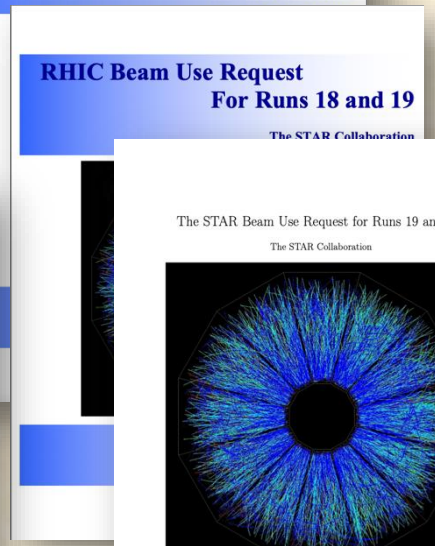
25 years of RHIC *Beam Use Requests*

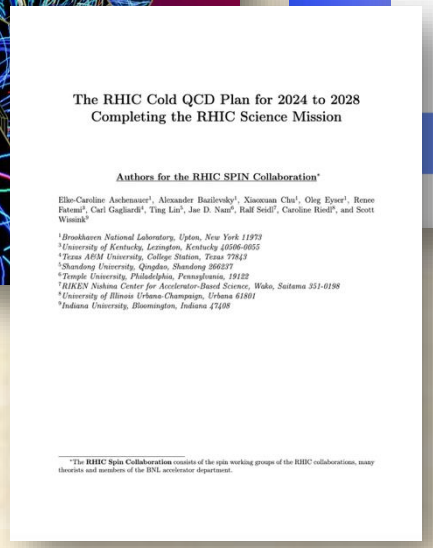
https://drupal.star.bnl.gov/STAR/starnotes

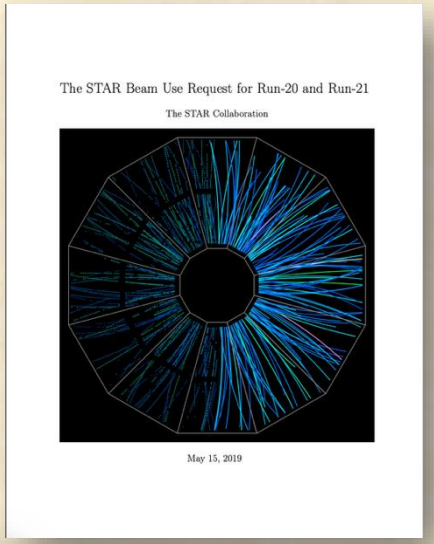


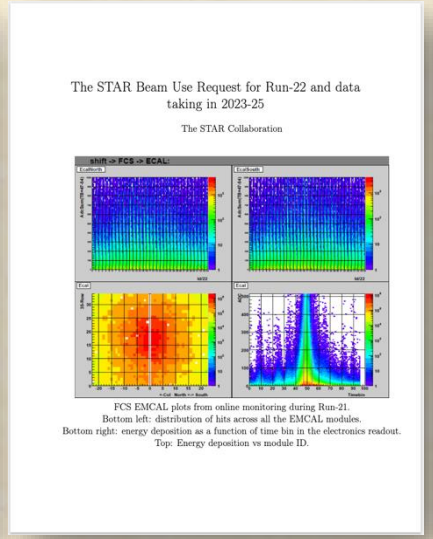


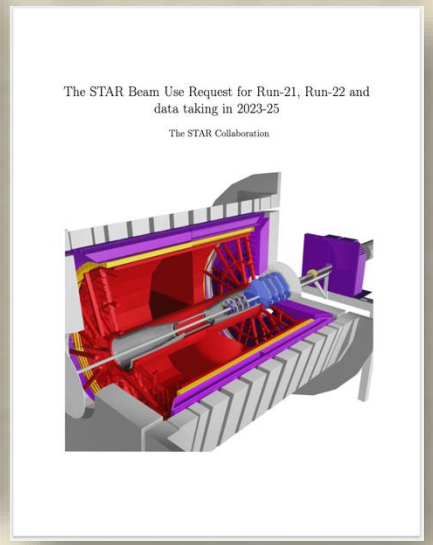


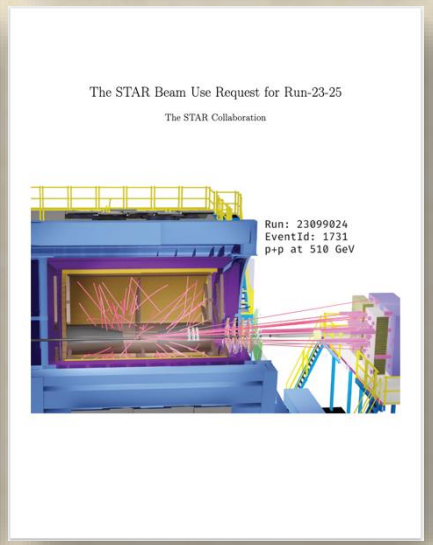


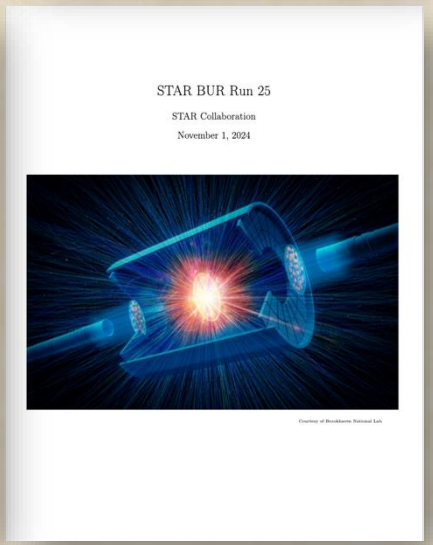








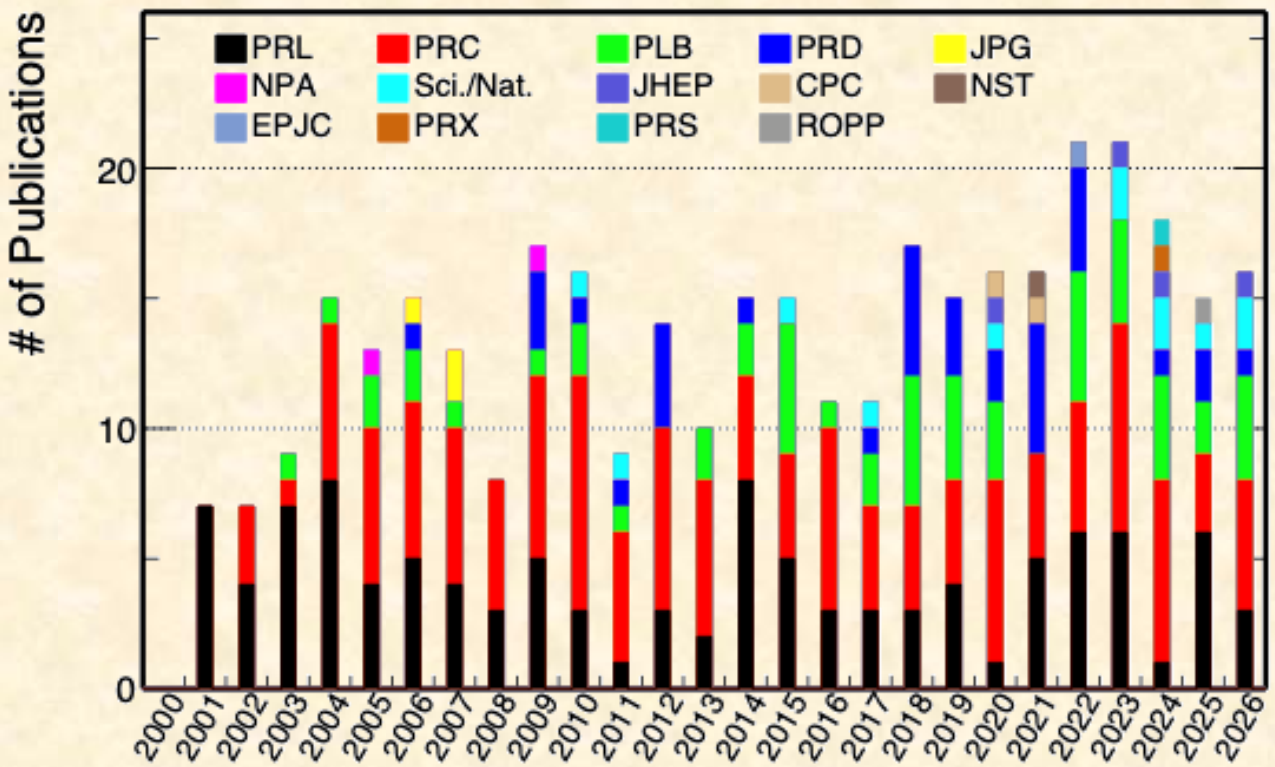




25+ years of Physics Publications

Total: 360 published physics papers

- PRL: 110, PLB: 54, Sci/Nat: 12
- PRC: 133, PRD: 35, Others: 16



STAR Theses:

- 420 PhD theses

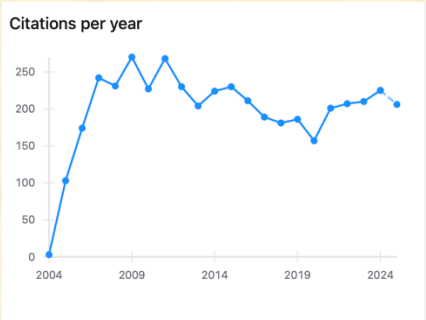
  English, Chinese, Polish, French, German, Portuguese, Russian (~349 uploaded)

- 44 Masters and Diploma theses

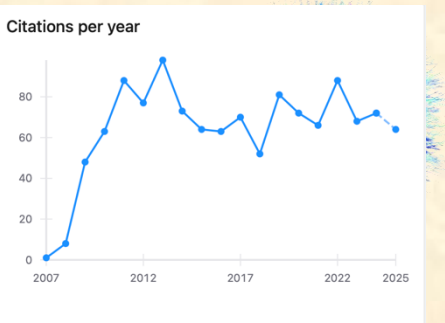
STAR Impact

src: inspirehep.net

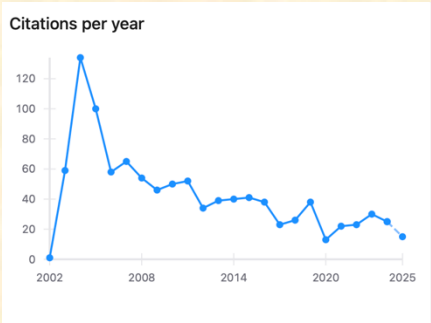
- 1000+ citations :: 5 papers
  - STAR white paper - 4379 citations
- 900 – 1000 citations :: 5 papers
  - Incl. NIM-A TPC & STAR Detector Overview



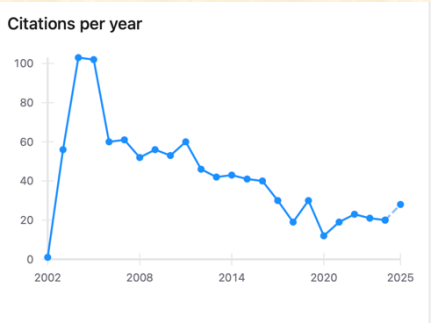
White Paper - NPA 2005



BES 1 Spectra - PRC 2009

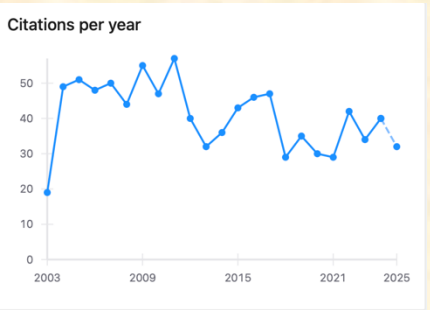


R_{dA} 200 GeV - PRL 2003

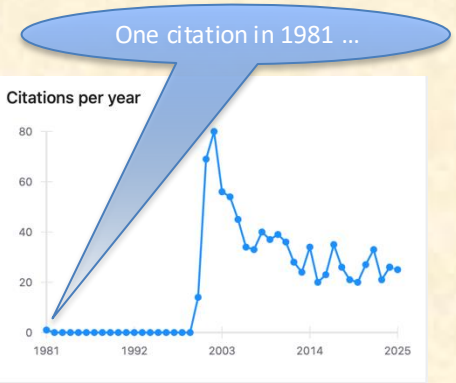


R_{AA} 200 GeV - PRL 2003

src: inspirehep.net



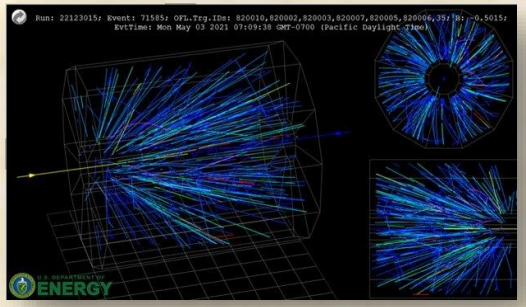
STAR Detector – NIM-A 2002



V_2 130 GeV - PRL 2001

Recent DOE Office of Science NP Highlights

December 6, 2022

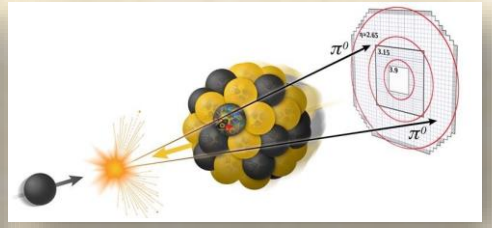


Scientists Narrow the Anchor Point in a Quantum Chromodynamics Critical Point Search

March 22, 2023

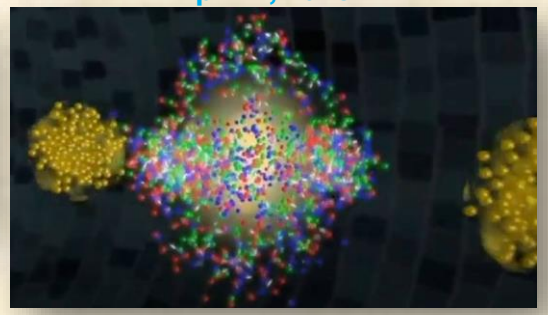
New Type of Entanglement Lets Scientists 'See' Inside Nuclei

March 24, 2023



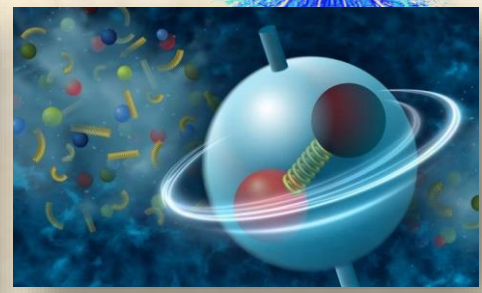
Signs of Gluon Saturation Emerge from Particle Collisions

April 7, 2023



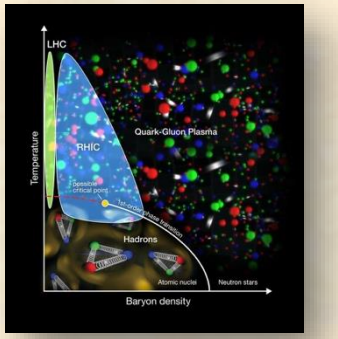
New Findings on the Flow of Particles in Heavy Ion Collisions

May 5, 2023



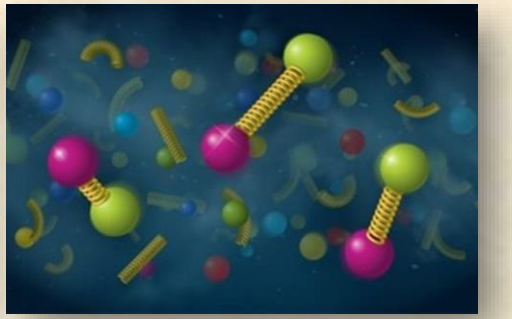
Surprising Preference in Particle Spin Alignment

June 5, 2023



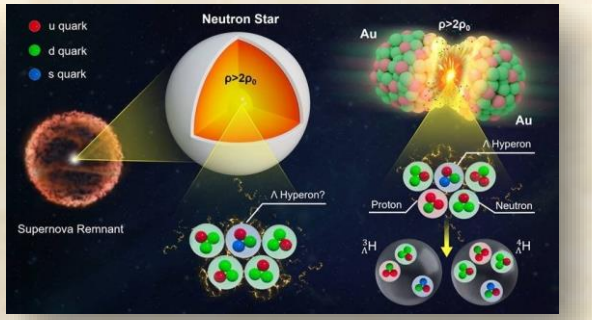
A Low-Energy 'Off Switch' for Quark-Gluon Plasma

June 15, 2023



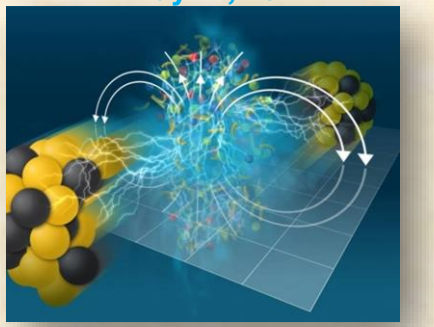
STAR Physicists Track Sequential 'Melting' of Upsilons

August 21, 2023



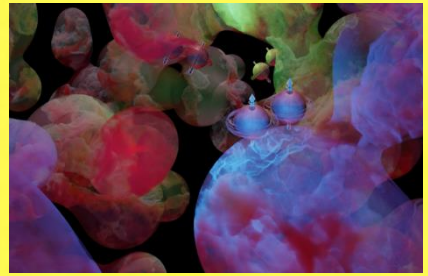
New Insights into How Strange Matter Interacts with Ordinary Matter

May 17, 2024



STAR Sees a Magnetic Imprint on Deconfined Nuclear Matter

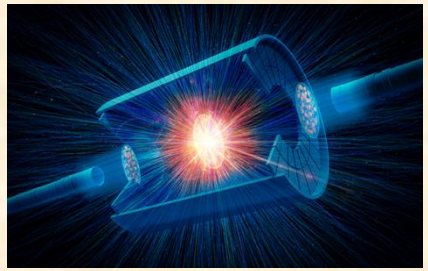
BNL News: Feb. 4, 2026

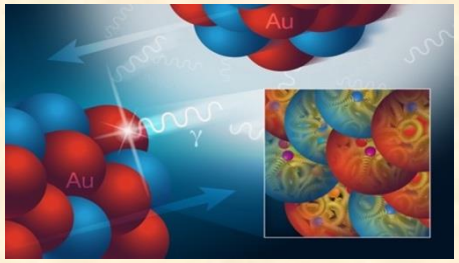


Scientists Capture a Glimpse into the Quantum Vacuum

April 7, 2025

Imaging Nuclear Shapes by Smashing Them to Smithereens





April 14, 2025

Gluons' Density Isn't the Same in Bound vs Unbound Protons and Neutrons

A Pipeline of Future Publications

- 54 Active GPCs
  - GPC = godparent committee (internal editorial committee)

– Cold-QCD/Spin - 3, Correlations & Fluctuations - 8, Hard Probes - 13,
– Flow, Chirality, Vorticity - 15, Light-Flavor Spectra & Ultraperipheral Coll. – 15

➢ Papers submitted, in journal review - 13
– Papers in collaboration review - 13
– Papers before release to collaboration - 28

– 35 new GPCs formed in 2025, 14 new GPCs formed this year
– 23 papers submitted in 2025, 10 submitted this year

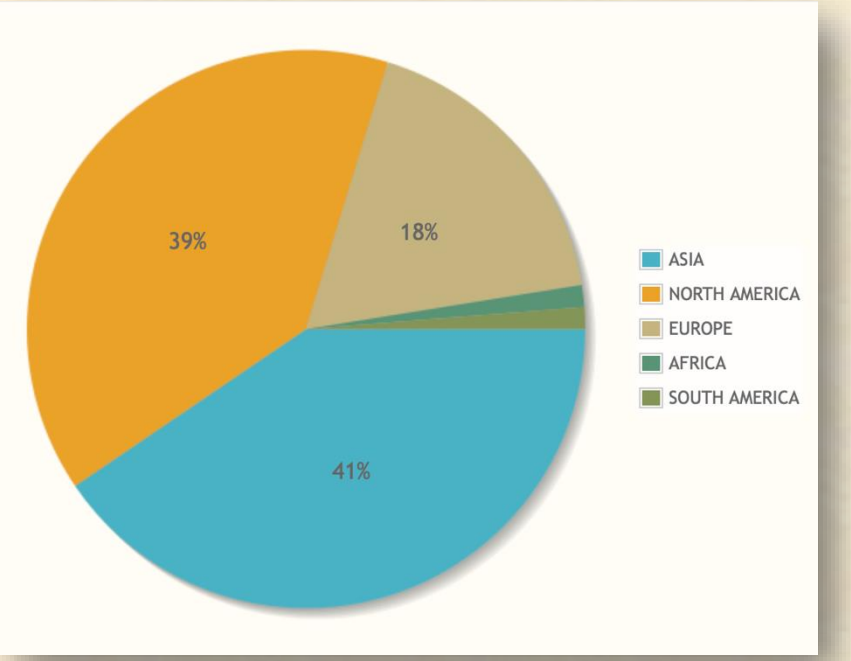
Where are we now?

Internally proposed abstracts:
QM23: 86 proposed
QM25: 84 proposed

- STAR is a very active collaboration
  - 2nd largest heavy-ion collaboration
  - 780 members, 79 institutions, 14 countries
  - 437 authors, ~~425~~ 313 juniors, 11 emeritus

➢ STAR is a young collaboration!

STAR institutions



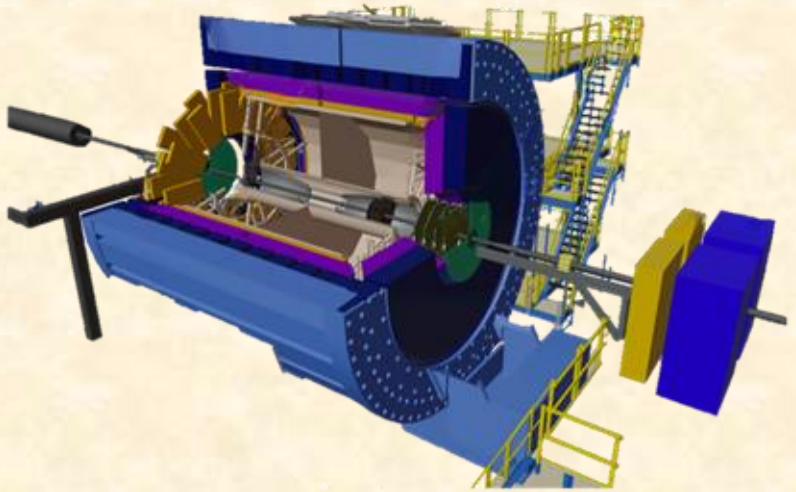
- *many* collaborators were involved in shifts
  - Runs 24 and 25 were long runs
- *many* collaborators are involved in GPCs
  - 54 active GPCs with each ~4-5 members
- in between, *many* are providing essential service work: calibration/production/embedding, QA, PWGs, paper reviews

STAR Performance 2023-2025

a *uniquely versatile* experiment at a *uniquely versatile* collider

Au+Au at $\sqrt{s_{NN}}$=200 GeV (Run 23+24+25) : 16B minimum bias events
- 26.7 nb^{-1} sampled luminosity

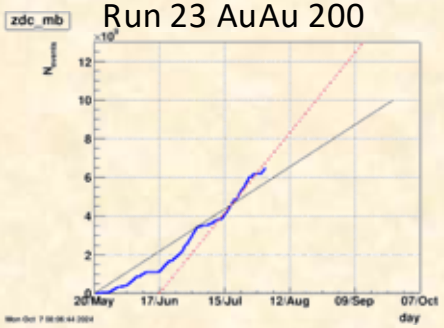
pp at $\sqrt{s}$= 200 GeV (Run 24): 164 pb^{-1} sampled luminosity
- 1.5B min. bias events and 1.5B high-mult. events



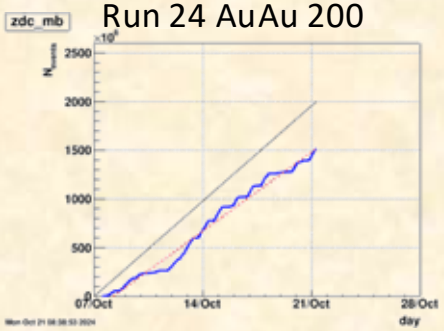
Fixed Target Au+Au at $\sqrt{s_{NN}}$=4.2, 4.5, and 5.2 GeV (Run 25) :
- $\sqrt{s_{NN}}$= 4.2 GeV : 290M min.bias events
- $\sqrt{s_{NN}}$ = 4.5 GeV : 1.04B min.bias events
- $\sqrt{s_{NN}}$ = 5.2 GeV : 370M min.bias events

O+O at $\sqrt{s_{NN}}$=200 GeV (Run 25): 136M min.bias, and 269M high-mult. events
- 34 nb^{-1} sampled luminosity

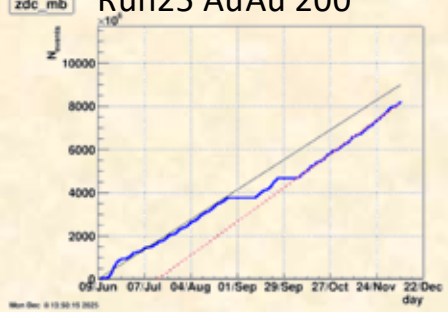
Run 23 AuAu 200



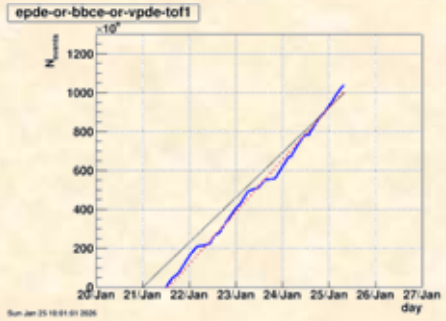
Run 24 AuAu 200



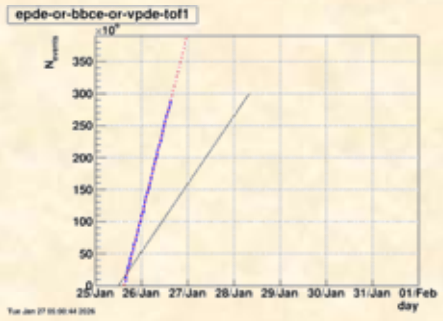
Run25 AuAu 200



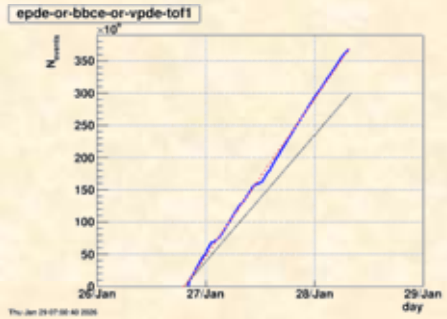
FXT AuAu 4.5



FXT AuAu 4.2



FXT AuAu 5.2



Bountiful Physics Program ahead

BUR 2025, STAR Note 850

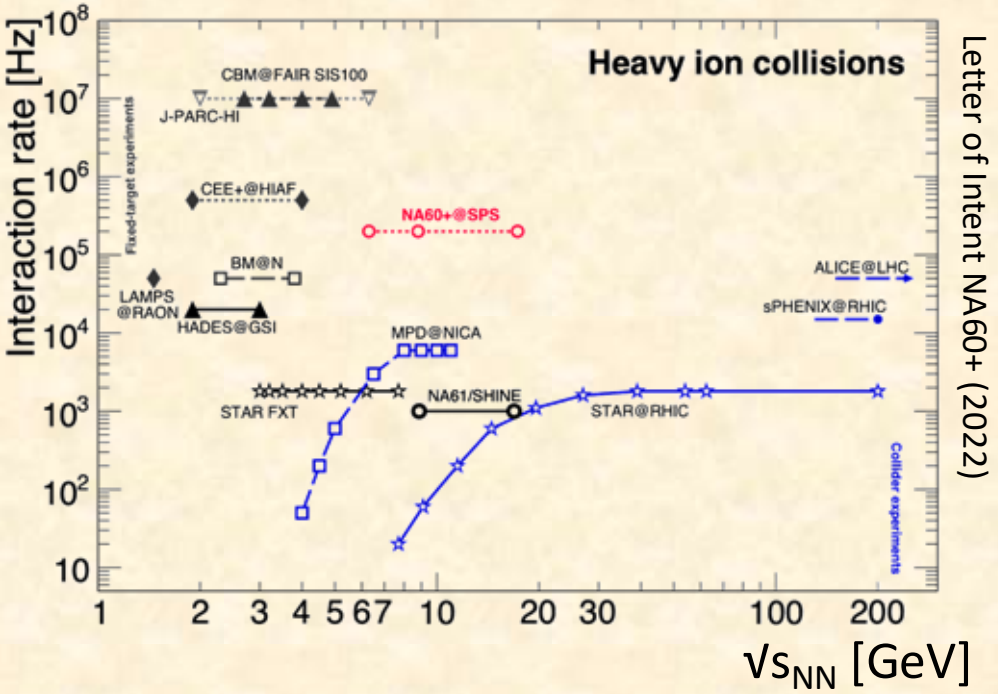
1. What is the nature of the 3-dimensional initial state at RHIC energies?
2. What is the precise temperature dependence of the shear (η/s) and bulk (ζ/s) viscosities?
3. What can we learn about [de-] confinement from charmonium measurements?
4. What is the temperature of the medium?
5. What are the electrical, magnetic, and chiral properties of the medium?
6. What are the underlying mechanisms of jet quenching at RHIC energies?
7. What is the precise nature of the transition near $\mu_B = 0$?
8. What can we learn about the strong interaction [between hadrons]?
9. [FXT] Complete the Critical Point search

Observable	Question	PWG	MB/H$\mathcal{L}$	Coverage	Trigger
$v_2(\eta)$ Twist	1) Initial State	FCV	Min bias	iTPC, TOF, EPD, FTS	MB
$r_n(\eta_a,\eta_b)$	1) Initial State	FCV	Min Bias	iTPC, TOF, EPD, FTS	MB
J/ψ v_1	1) Initial State	HP	Luminosity	iTPC, TOF, EPD	MB+BHT
Photon WF	1) Initial State	LFSUPC	Min Bias	iTPC, TOF	MB
$v_2(\eta)$	2) Viscosity	FCV	Min bias	iTPC , TOF, EPD, FTS	MB
J/ψ v_2	3) Deconfinement	HP	Luminosity	iTPC, TOF, EPD	MB+BHT
Υ Suppression	4) Temperature	HP	Luminosity	iTPC, TOF	BHT+Dimuon
ψ(2s) suppress.	4) Temperature	HP	Min Bias	iTPC, TOF	MB
Di-elec IMR	4) Temperature	LFSUPC	Min Bias	iTPC, TOF	MB
$P_H(\eta)$	5) Properties	FCV	Min Bias	iTPC, TOF, FTS, EPD	MB
P_H of J/ψ	5) Properties	FCV	Luminosity	iTPC, TOF, EPD	MB+BHT
ρ^0 a_1 mixing	5) Properties	LFSUPC	Min Bias	iTPC, TOF	MB
Di-elec LMR	5) Properties	LFSUPC	Min Bias	iTPC, TOF	MB
CME	5) Properties	FCV	Min Bias	iTPC, TOF, EPD	MB
γ_{Dir} + jet I_{AA}	6) Jet quenching	HP	Luminosity	BEMC, EEMC FCS	BHT
γ_{Dir} + jet acopl.	6) Jet quenching	HP	Luminosity	BEMC, EEMC, FCS	BHT
Jet substruct.	6) Jet quenching	HP	Luminosity	BEMC, EEMC, FCS	BHT
Net-p C_6	7) Phase Transition	CF	Min Bias	iTPC, TOF	MB
Baryon CF	8) Strong Interact.	CF	Min Bias	iTPC, TOF	MB
UPC ρ^0, ϕ, J/ψ	UPC – CNM	LFSUPC	Luminosity	iTPC, TOF, BEMC, EEMC	ZDCEW, UPC
v_2 in γ+Au (UPC)	UPC – CNM	FCV	Min Bias	iTPC, TOF, FTS	UPC
UPC di-jets	UPC – CNM	HP	Luminosity	iTPC, TOF, BEMC	UPC+BHT
UPC CP spectra	UPC – CNM	LFSUPC	Min Bias	iTPC, TOF	ZDCE(1n)+ZDCW

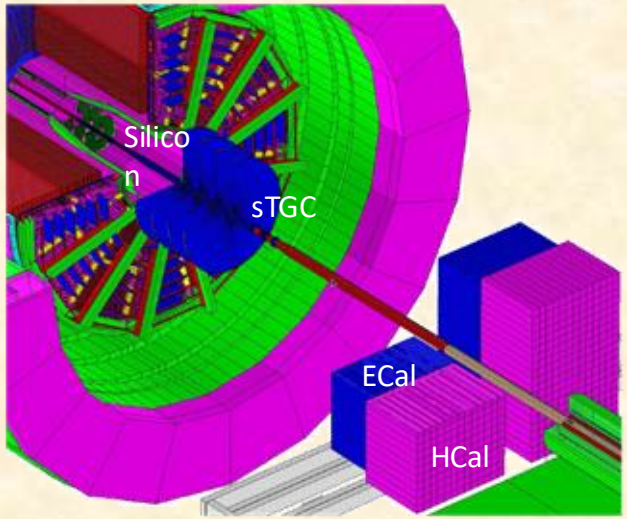
A Strategic Bridge

Hot QCD ⟶ FAIR, SPS, LHC

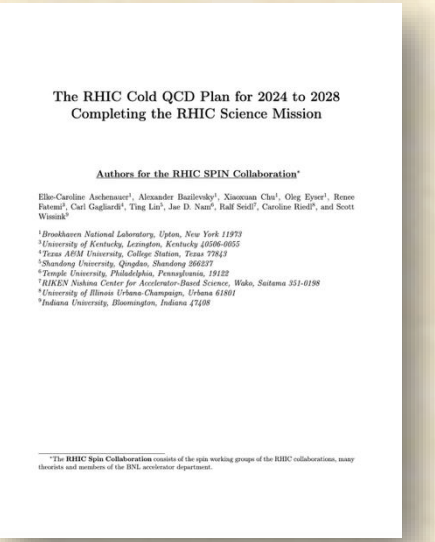
Cold QCD ⟶ EIC



Letter of Intent NA60+ (2022)



Measurement	Physics Goals	pp Data Sets (GeV)	Year
Transverse spin asymmetry (A_N) for J/Ψ and eHF production	Gluon GPD	200, 510	2022, 2024
A_N of dijet	Spin-dependent parton transverse motion	200, 510	2022, 2024
A_N of inclusive jets, hadrons, and direct photons	Sivers and Collins effects, nuclear PDFs and hadronization effects	200, 510	2022, 2024
A_N of hadron-in-jet	Collinear and TMD FF TMD evolution and universality	200, 510	2022, 2024
Forward Drell-Yan	Sivers effect and test non-universality of Sivers function	200, 510	2022, 2024
Di-hadron correlation asymmetries and cross-section	Transversity and IFF cross-section	200, 510	2022, 2024
Hyperon polarization	Spin transfer and polarizing fragmentation	200, 510	2022, 2024
W and Z cross-sections	Sea quark and TMD PDFs	510	2022
W and Z A_N	Sivers effect and test of non-universality of Sivers function	510	2022
Dijet and charged hadron yields	PDFs	200, 510	2022, 2024

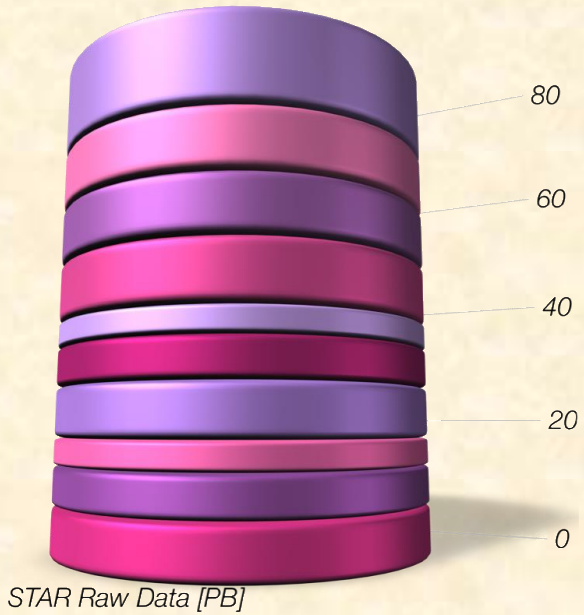


The RHIC Cold QCD Plan for 2024 to 2028
Completing the RHIC Science Mission

Authors for the RHIC SPIN Collaboration*

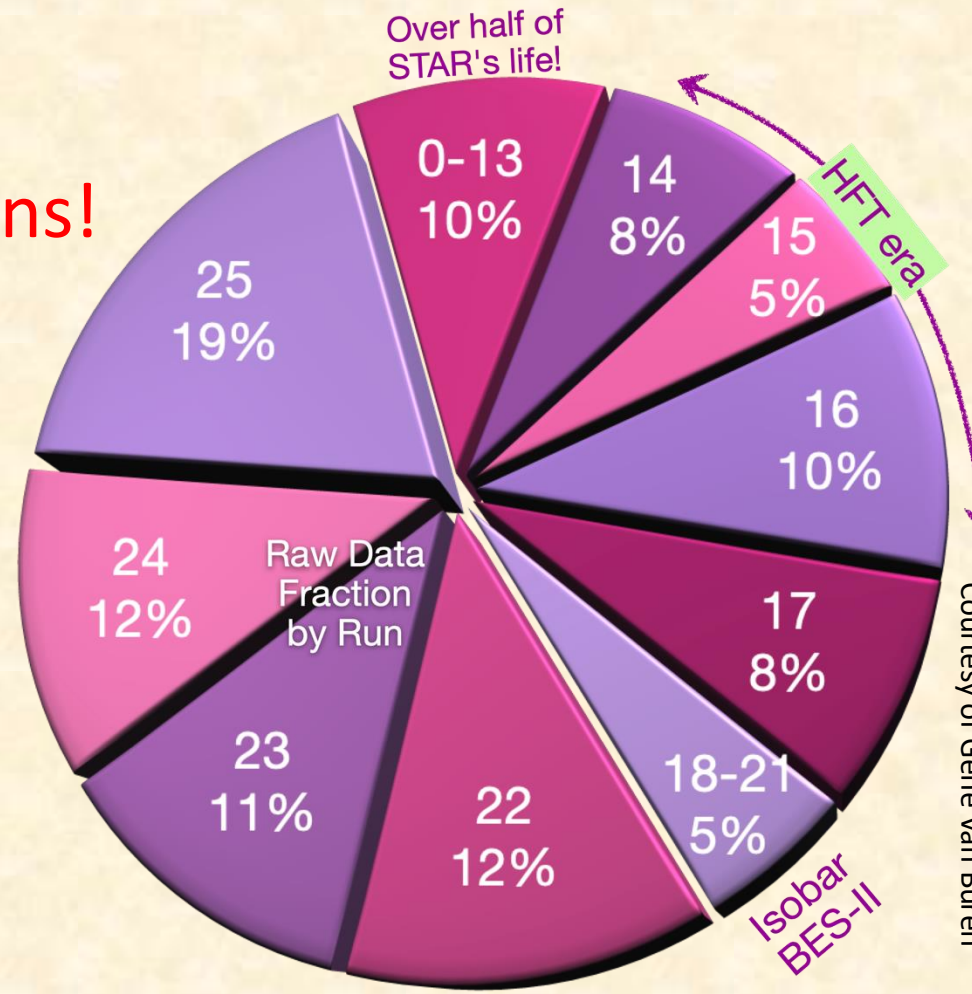
[STAR Note 837]

STAR Data – a diverse 25-year legacy



- All years combined: ~85 PB
  - raw data "on HPSS" only

➢ Half of all data in final 4 runs!



- Calibration and upcoming productions will require substantive CPU & storage resources
- Prioritize physics data streams
- Run productions parallel

➢ **Computing resources crucial for the next several years**

Data & Analysis Preservation

- STAR works closely with BNL for common strategies
  - RHIC DAP initiative
  - proactive engagement with partners at BNL (SCDF, ITD, NP) and outside BNL (HEPdata)
- STAR internal
  - integrate DAP into workflows
  - software/environment upgrades (incl. virtualization)
  - improve research-data-management and user management tools
- AI/Genesis Mission
  - training data for Physics Foundation Models
  - RAG/LLM tools to improve access to a wide range of internal knowledge
  - allow for cross-facility interoperability

➢ A strongly engaged collaboration
  - opportunities for students and postdocs to gain experience and innovate
  - opportunities for outreach

Book of the Death (a guide to help ancient Egyptians through death, on to to afterlife) - c1275 BC.

Tape units CDC-6600 computing systems - 1965

Summary

- STAR is a highly productive collaboration
  - Thanks to the engagement of many institutes and individuals
- 25 years of carefully acquired datasets
  - Runs 22 – 25 provide us with an excellent legacy, with physics potential beyond our BURs
  - 8-10 years of exciting physics ahead of us!
- Computing resources crucial for the next several years
  - Data and Analysis Preservation is essential
  - Many opportunities for the innovative use of AI
- STAR serves as an incubator of leadership talent!
  - Many opportunities for postdocs and graduate students

STAR's Future is Bright!

STAR 25 YEARS