Beam Energy Scan

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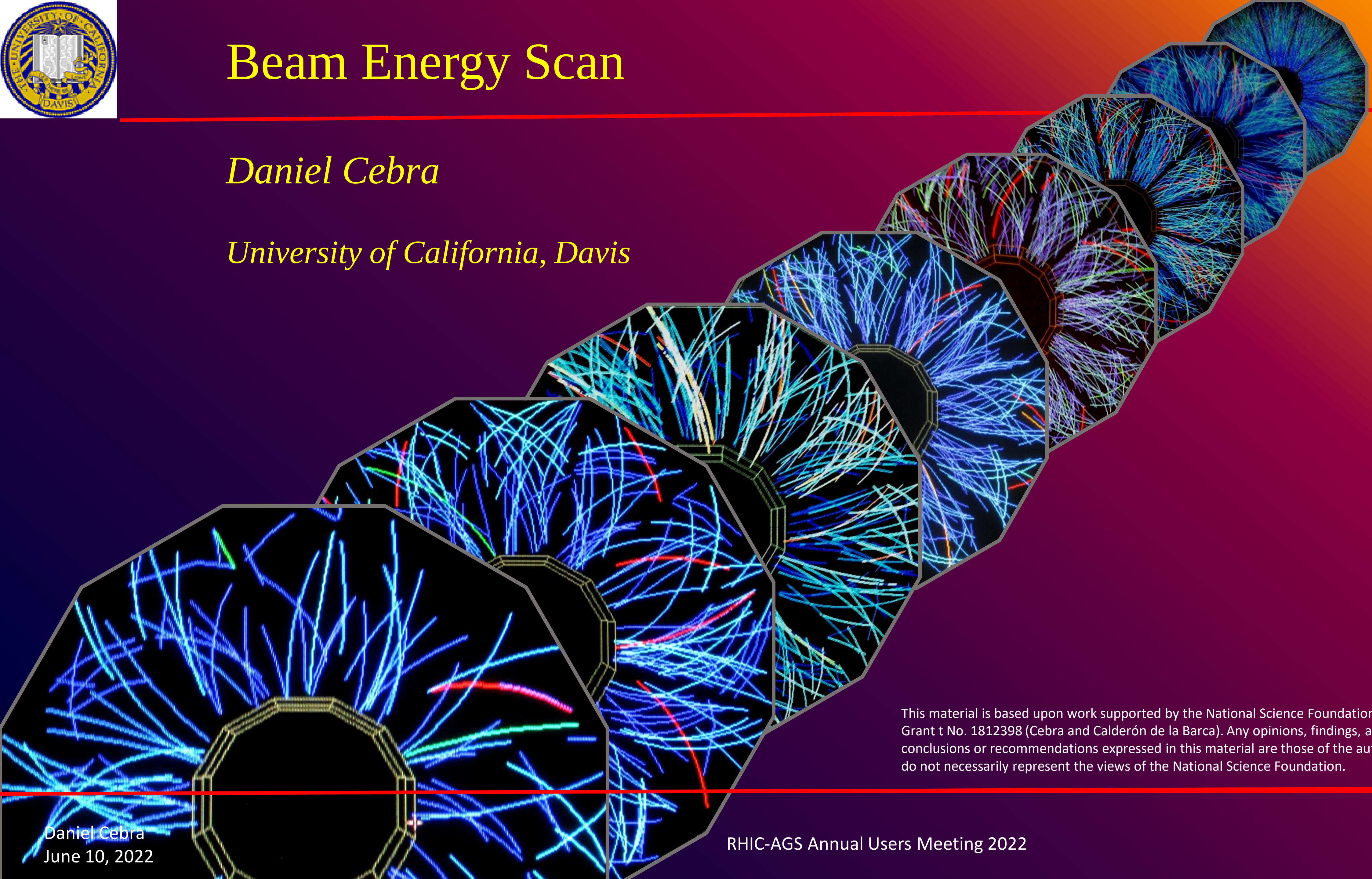

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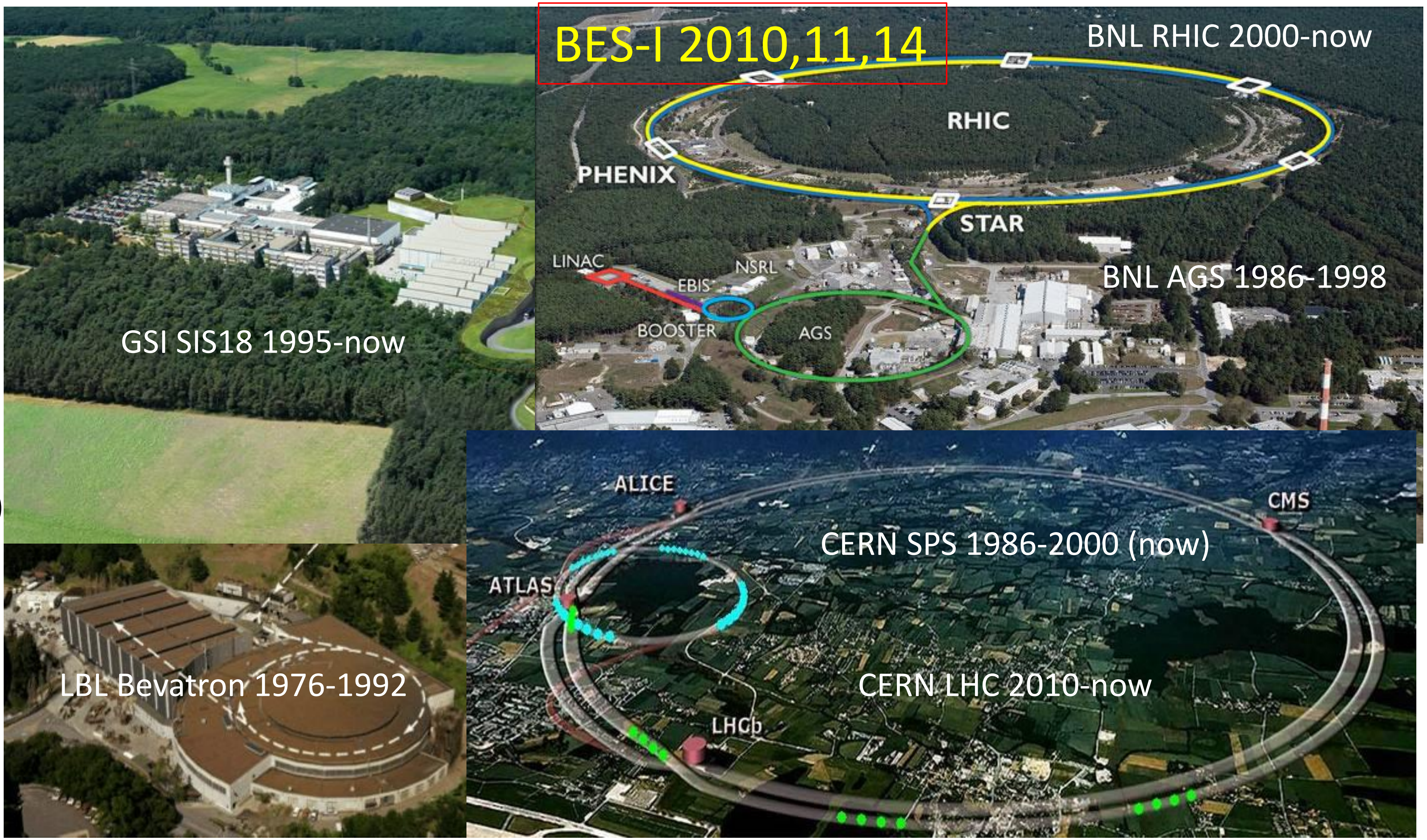
History of Heavy Ion Energy Scans

SIS18 (1997)
Energy Scan
250 AMeV
400 AMeV
600 AMeV
800 AMeV
1000 AMeV
1200 AMeV
1500 AMeV

Bevatron (1992)
Energy Scan
250 AMeV
400 AMeV
600 AMeV
800 AMeV
1000 AMeV
1150 AMeV



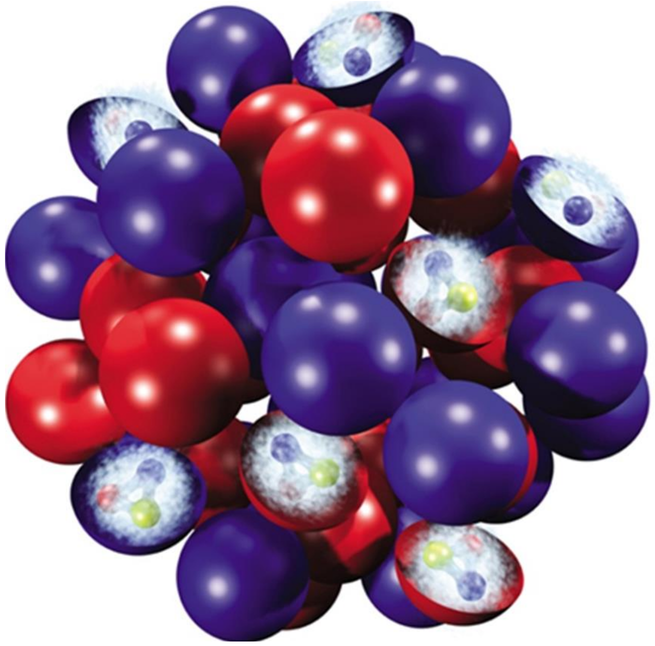
AGS (1995)
Energy Scan
2.7 GeV
3.3 GeV
3.84 GeV
4.3 GeV
4.85 GeV

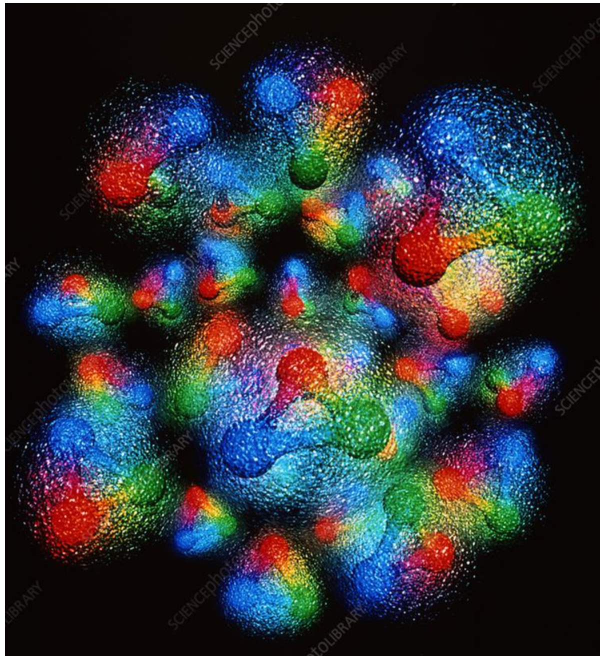
SPS (2000)
Energy Scan
6.27 GeV
7.62 GeV
8.76 GeV
12.3 GeV
17.3 GeV

LHC (ongoing)
Energy Scan
2.76 TeV
5.0 TeV
5.5 TeV

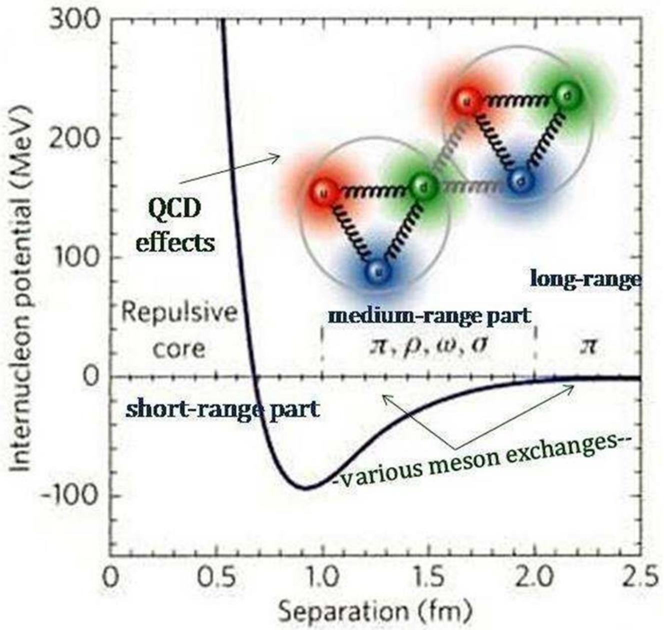
Tevatron Energy Scan (2011) ➔ 300 GeV , 900 GeV, 1.96 TeV ➔ Study of the Underlying Event

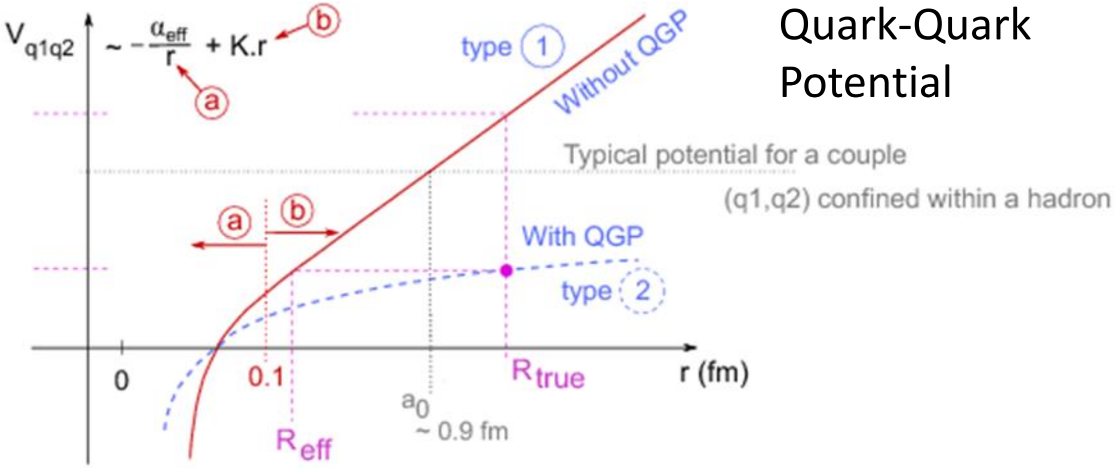
Which of these is the most accurate image of a silicon nucleus, and why?





Internucleon Potential





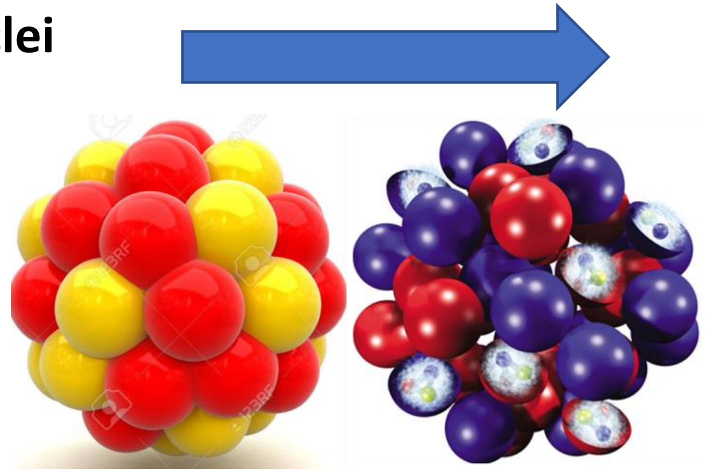
Quark-Quark Potential

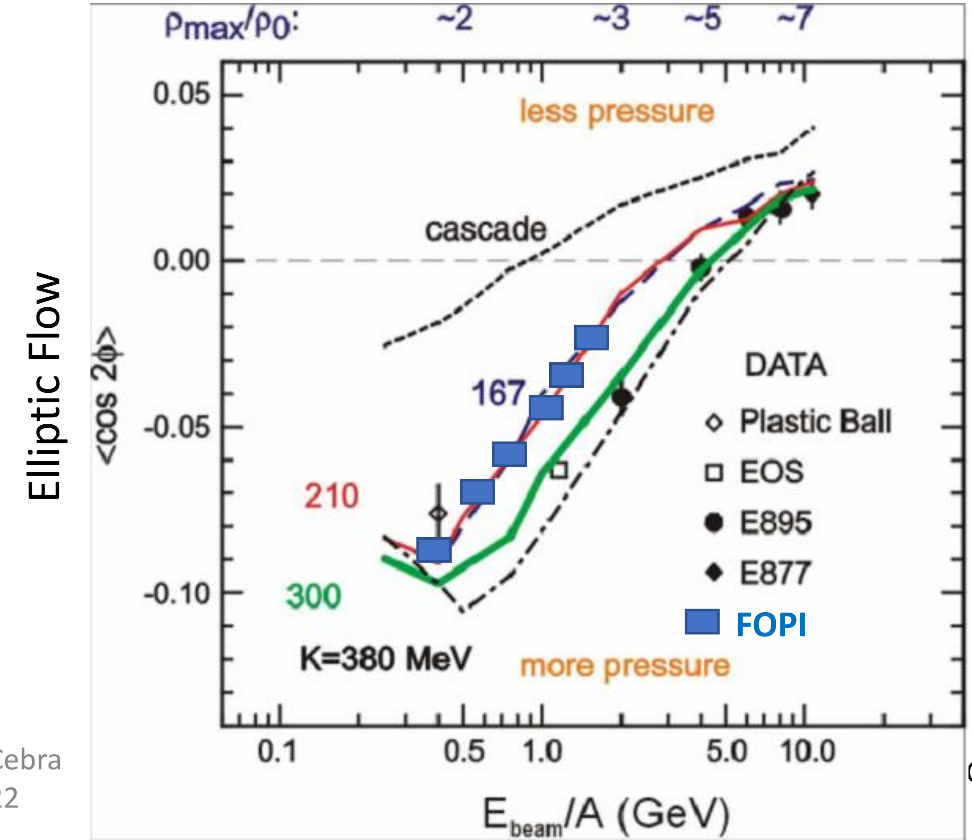
Bevatron, SIS18, and AGS Energy Scan Results: Elliptic Flow

Bevatron ➔ Observation of "squeeze-out", Liquid-Gas phase transition in nuclei

SIS18 ➔ Observation of transition from fully stopped to transparent nuclei

AGS ➔ In-plane expansion of the fireball





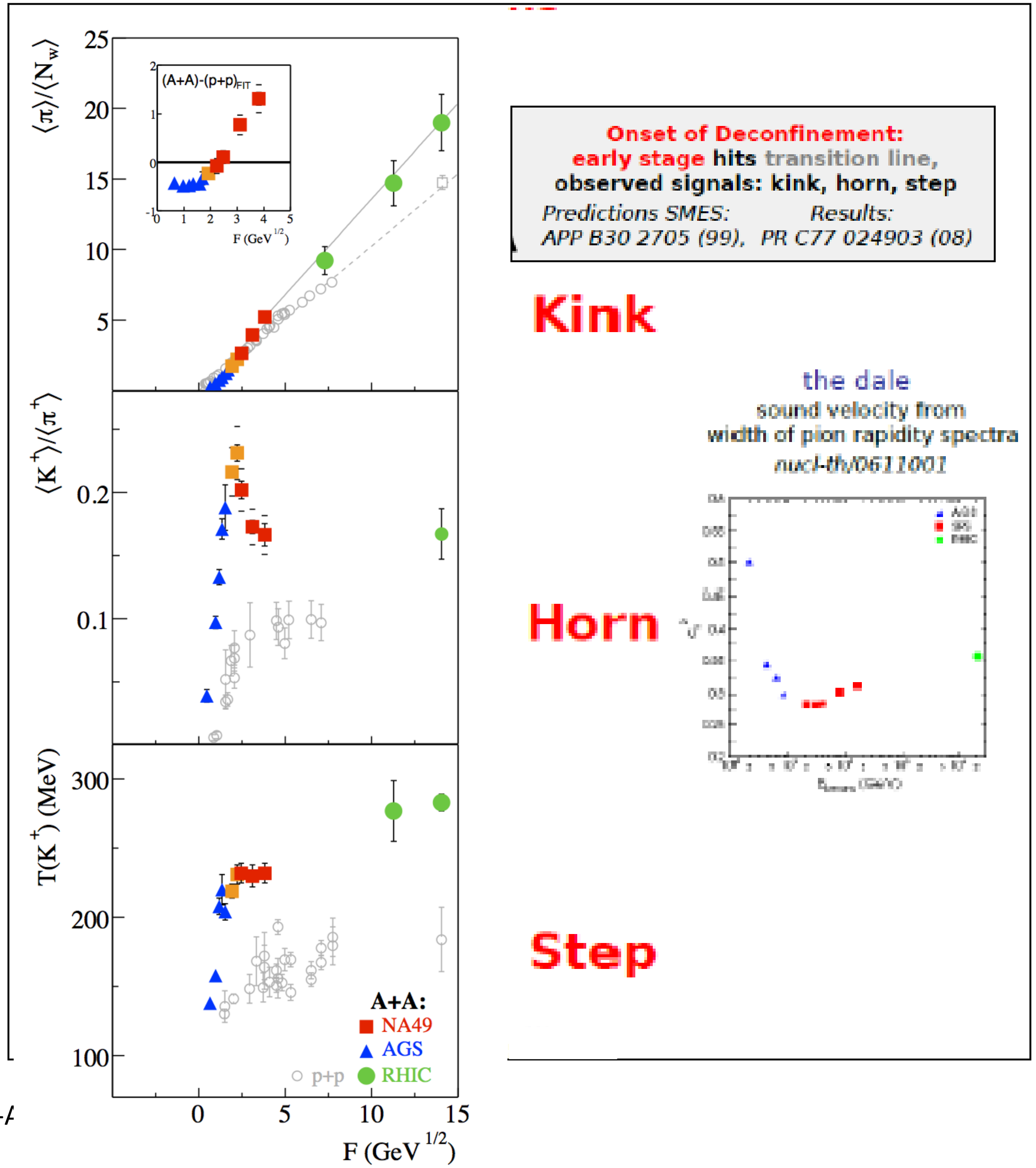
Elliptic Flow – Protons:

- E895_PRL83(1999)1295 – at 2, 4, 6, 8 AGeV
- E877_PRC56(1997)3254 – at 10.5 AGeV
- E895_PRC66(2002)021901 – at 2, 4, 6 AGeV with centrality cuts

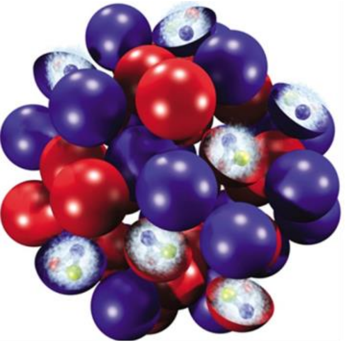
- Crossover from squeeze-out to in-plane at 4 AGeV
- Relevance to the change of stiffness of EoS?
- Or, the speed of sound versus the transit time?

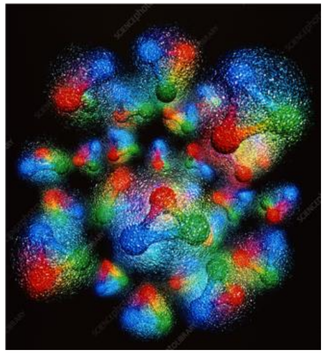
SPS Scan Results ➔ Onset of Deconfinement

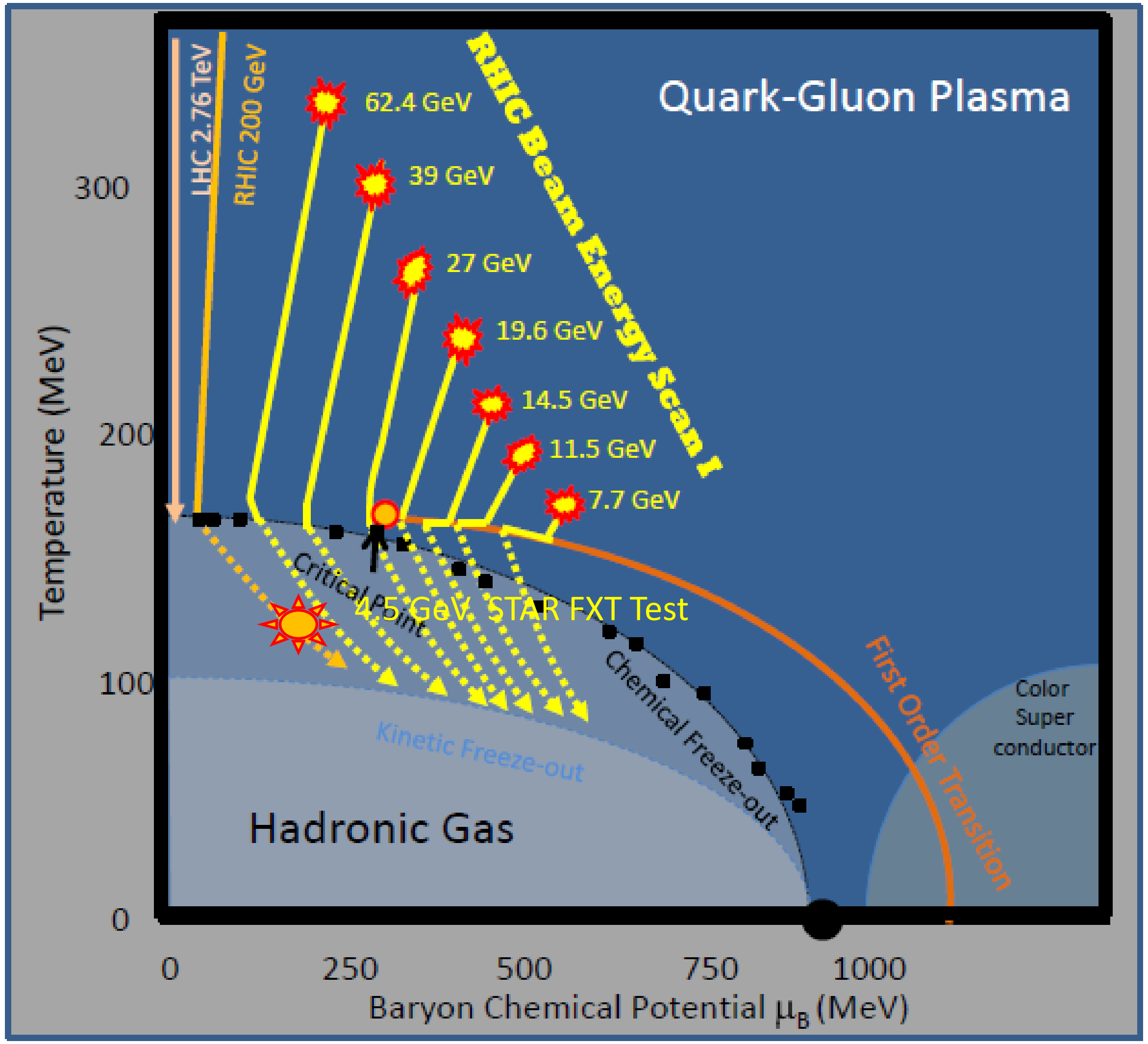
- Summary of AGS, SPS, and early RHIC Results.
- Inclusive observables ➔ *onset of deconfinement* at 7-8 GeV.
- The observables suggest a change in the nature of the system.
- More discriminating studies were needed to understand the nature of the phase transition and to search for critical behavior.
- It is best to study regions above and below the possible onset energy.



RHIC Beam Energy Scan I Results





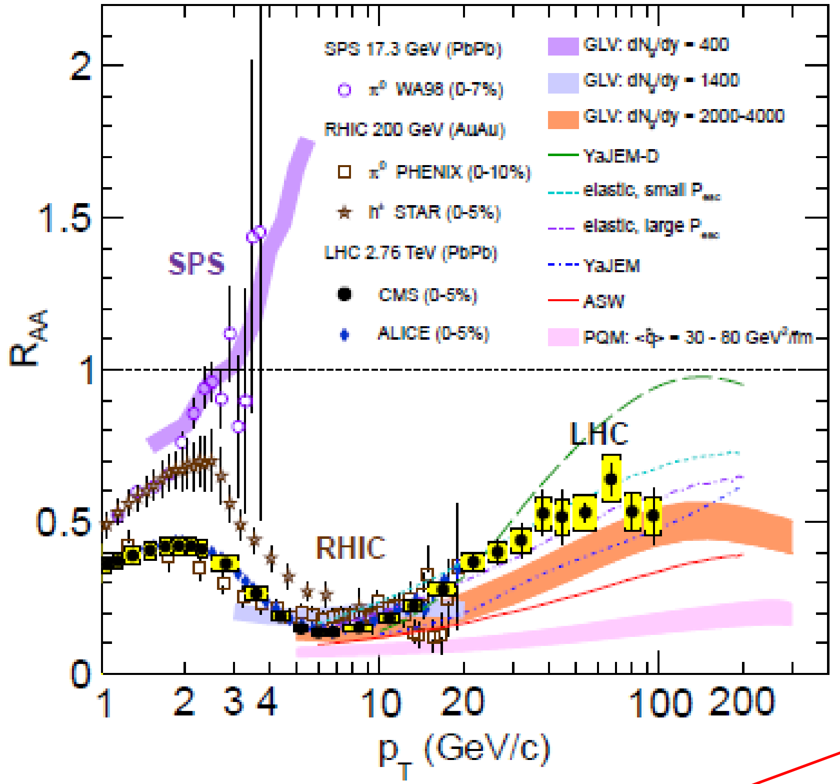


	Energy (GeV)	Chemical Potential μ_B	Pred. Temp. (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.6	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
AGS	4.7	573	114.6
RHIC	4.5	587	112.0
AGS	4.3	602	108.8
AGS	3.8	638	100.6
AGS	3.3	686	88.9
AGS	2.7	752	70.4
SIS	2.3	799	55.8

BES-I was a survey to define the questions and the search parameters for the study of the QCD phase diagram.

Turn-off of QGP Signatures

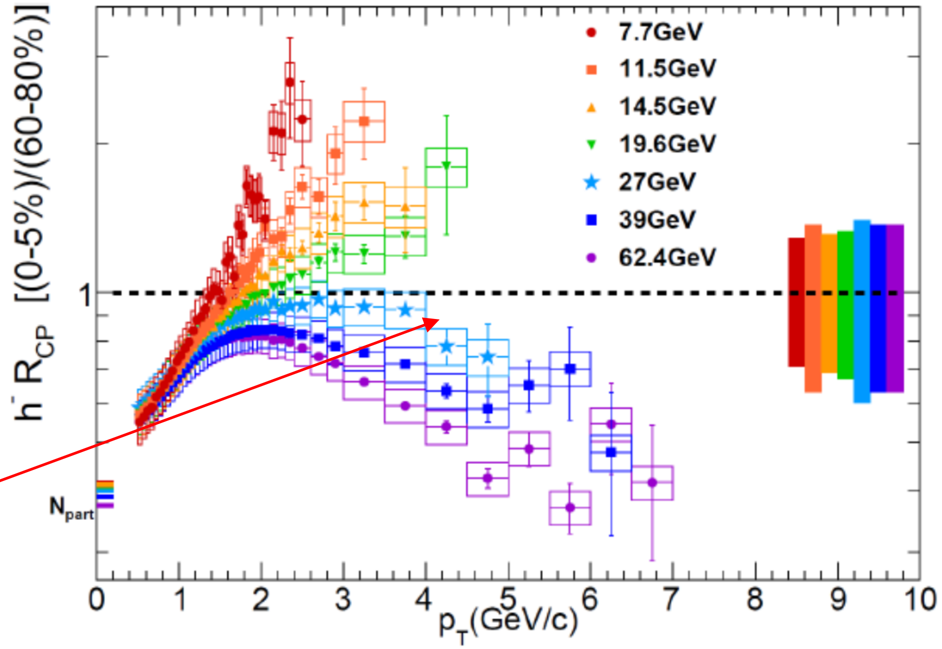
High p_T suppression has been seen as a clear manifestation of energy loss by color objects (quarks) in a color medium (QGP).



Eur.Phys.J. C72 (2012) 1945

- R_{cp} suppression NOT seen at lower energies!

➔ **The QGP signature is turned off.**



Phys. Rev. Lett. 121 (2018) 32301

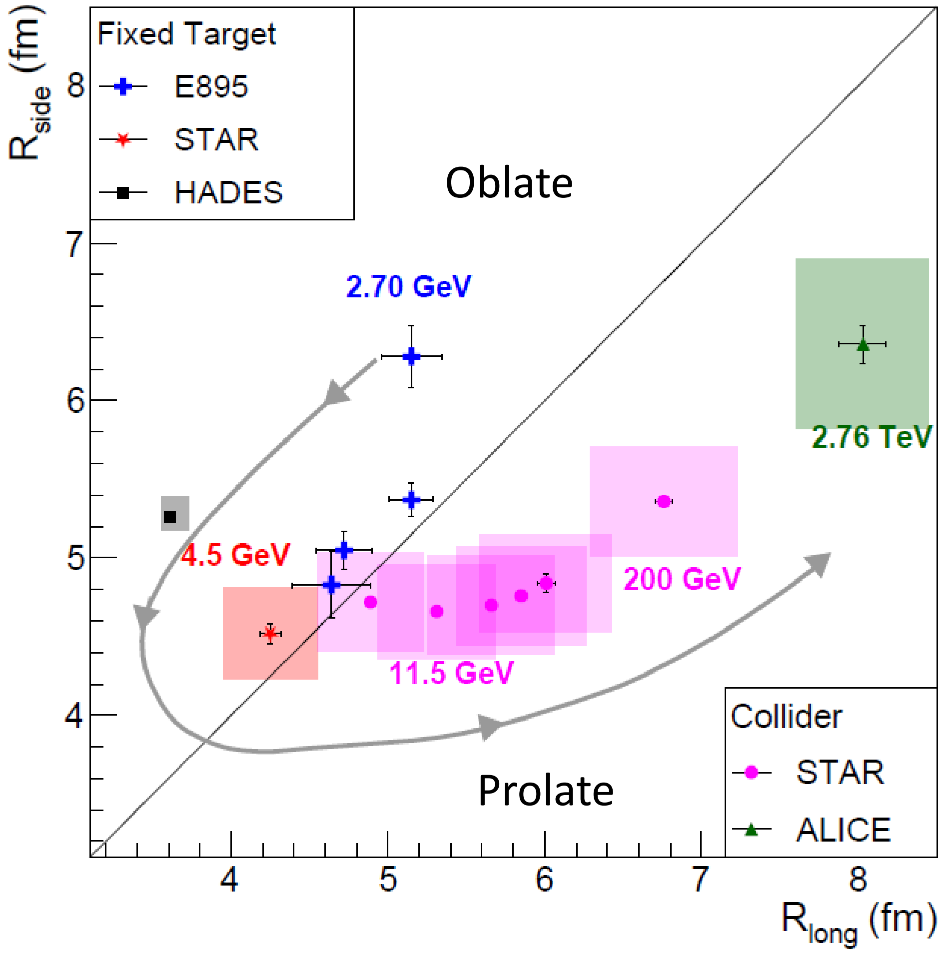
Suppression above 19.6 GeV
➔ Continuous Phase transition

Search for 1st Order Phase Transition

- Using a pion interferometry method, similar to photon interferometry developed by Hanbury Brown and Twiss (HBT) to measure the size of stars, we can measure the size and shape of the fireball.

- First fixed-target results from STAR show a minimum size in longitudinal and transverse directions at 4.5 GeV.

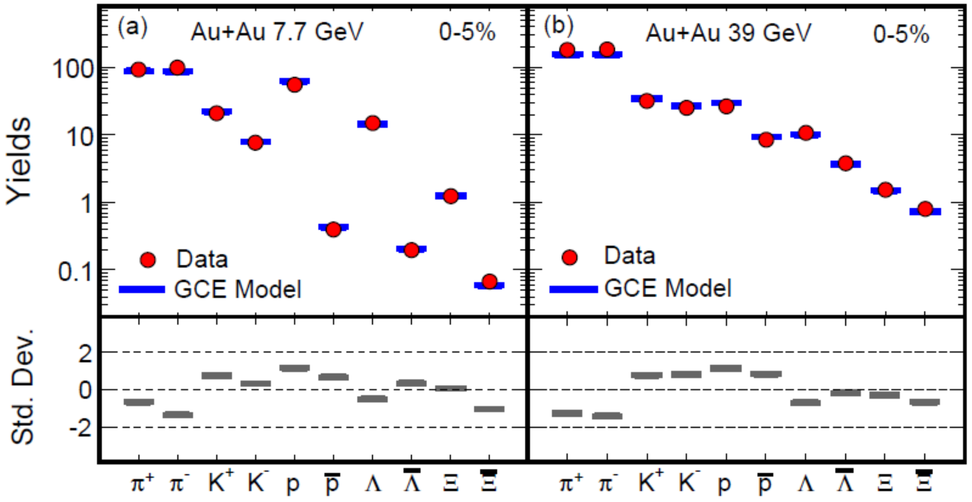
- Supports softening of the Equation of State.



Phys. Rev. C **103** (2021) 34908

Spectra and Yields

- Yields are particle spectra have been matched to thermal models to extract the chemical temperatures.

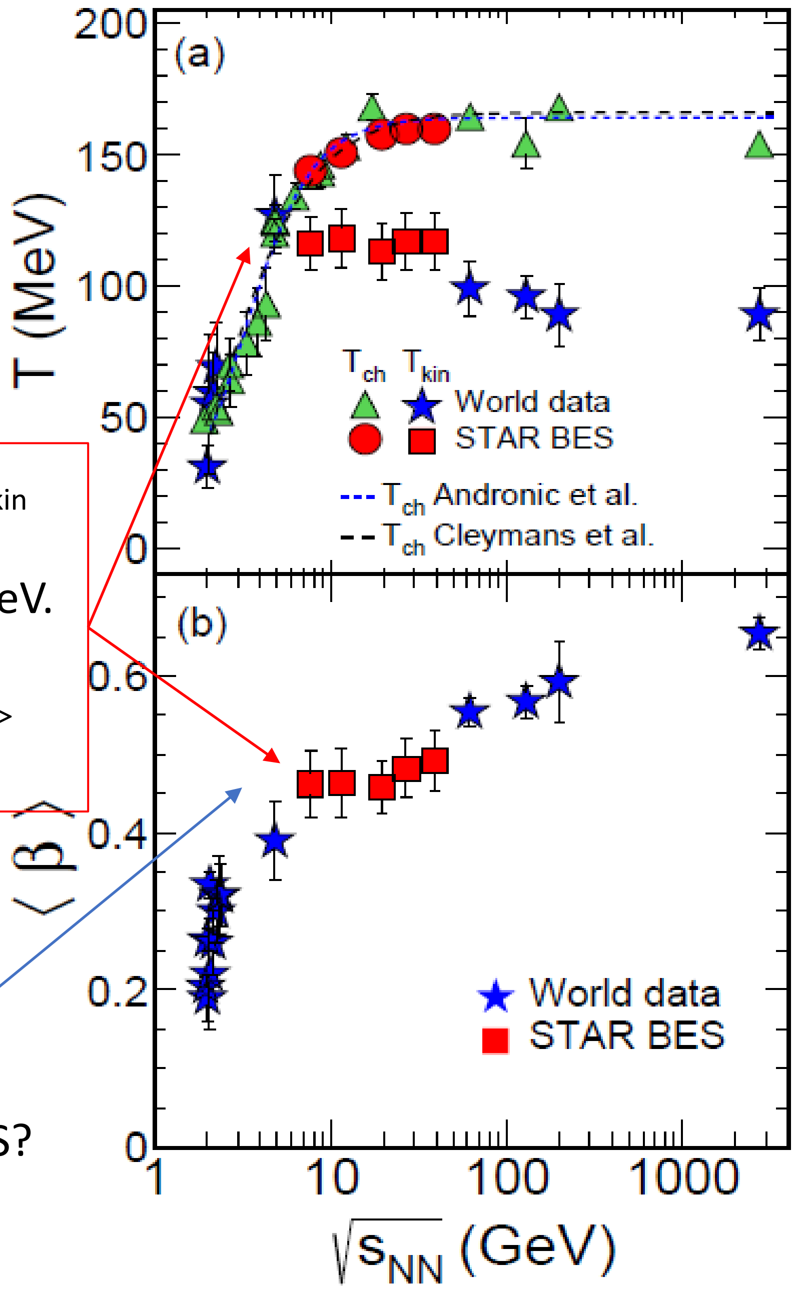


- Particle spectra show curvature, which is a feature of a radial "Hubble-style" expansion.
- Fits using the blast wave model allow extraction of the kinetic temperature and the radial flow.
- The chemical and kinetic temperatures start to diverge at the low end of the RHIC collider range.

T_{chem} and T_{kin} diverge at around 7 GeV.

T_{kin} and $\langle\beta\rangle$ flatten

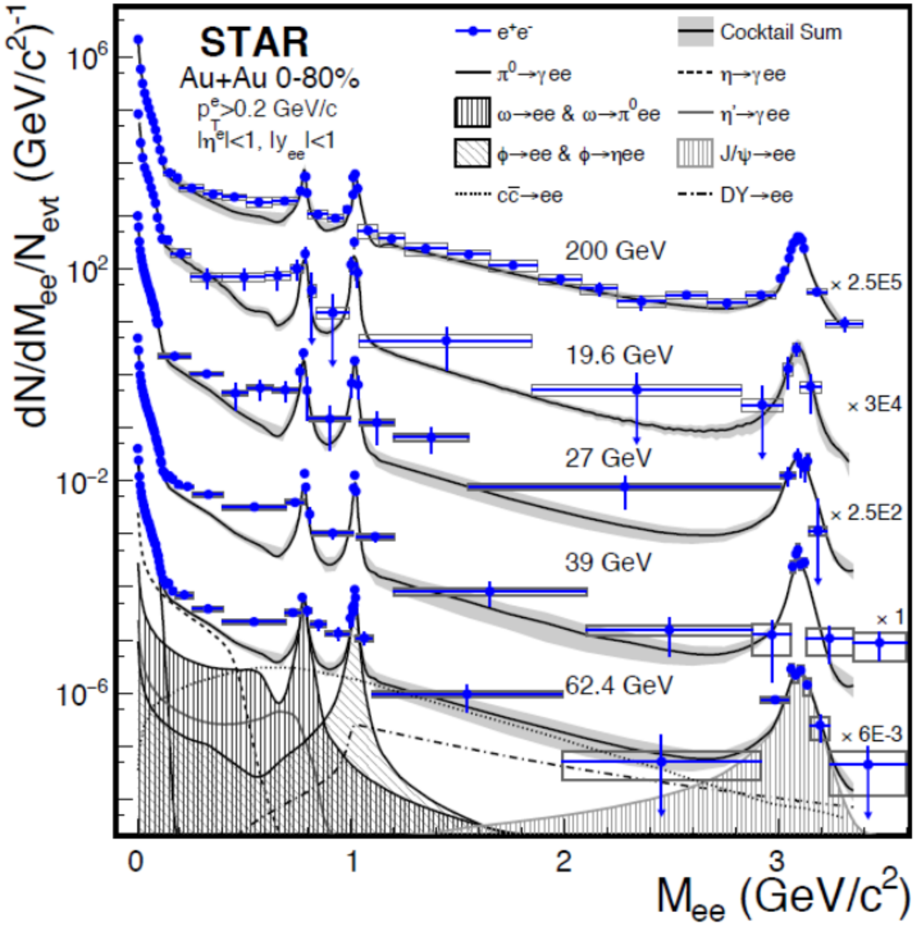
Softening of the EoS?



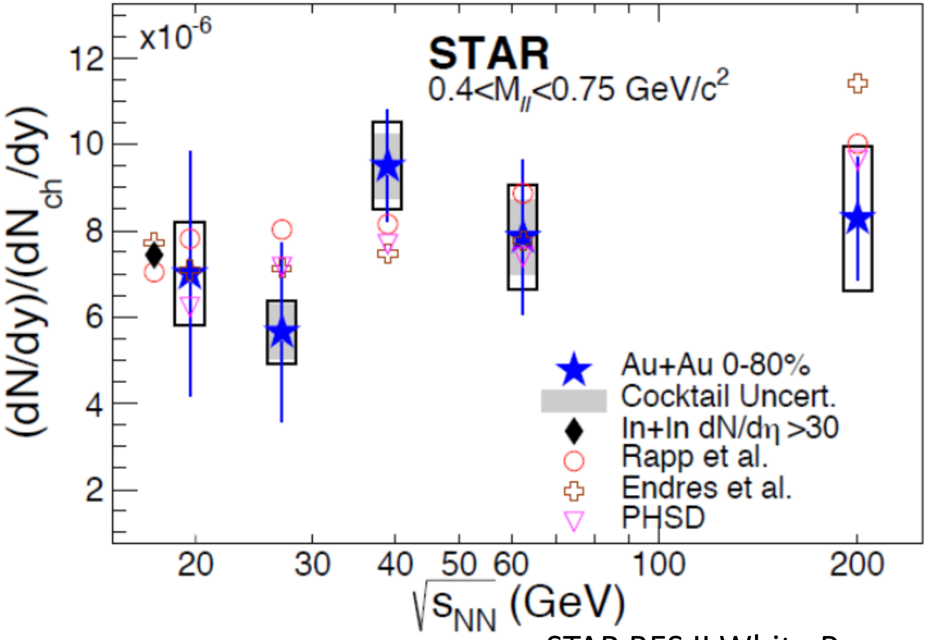
Chiral Phase Transition

Low Mass Region:
Shows broadening of ρ

Continuous Phase Transition above 19.6 GeV



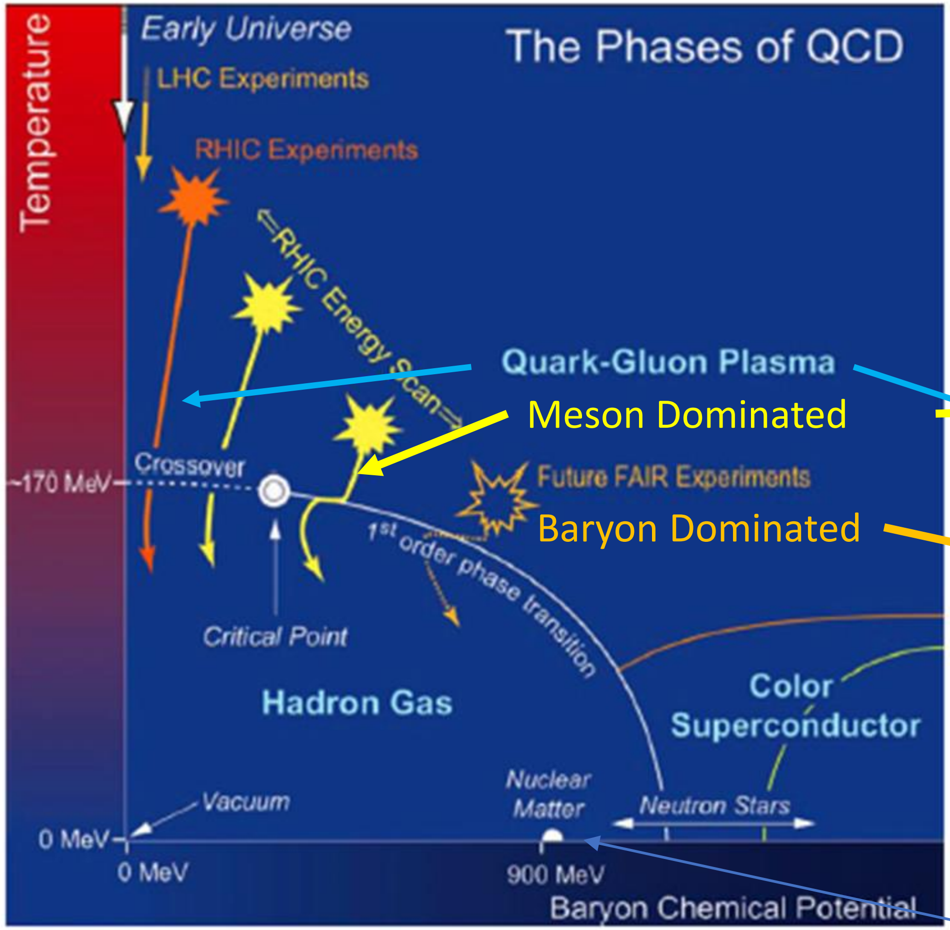
Low Mass Region:
Emission depends on T, total baryon density, and lifetime



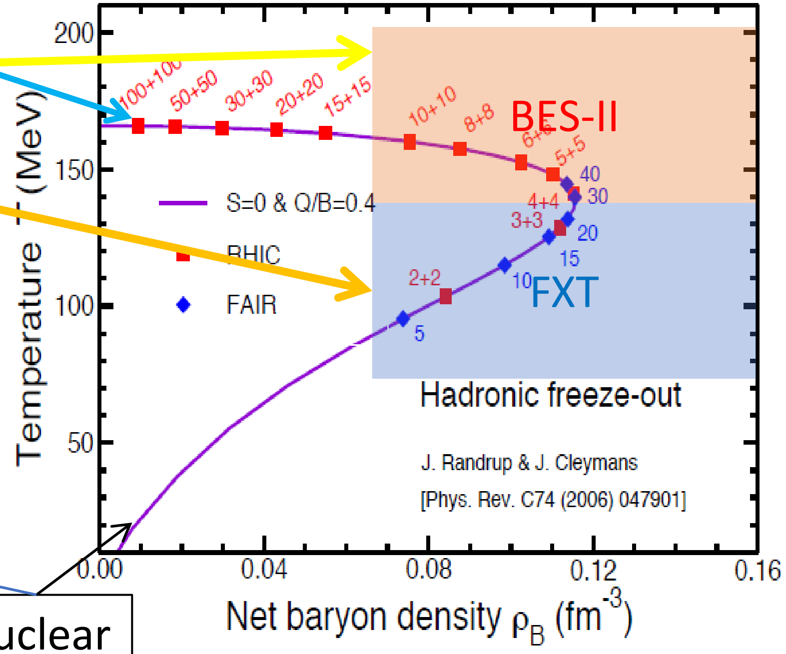
STAR BES II White Paper

Motivation for RHIC Beam Energy Scan II

Onset of deconfinement; nature of the phase transition; Critical Point; Partonic Matter



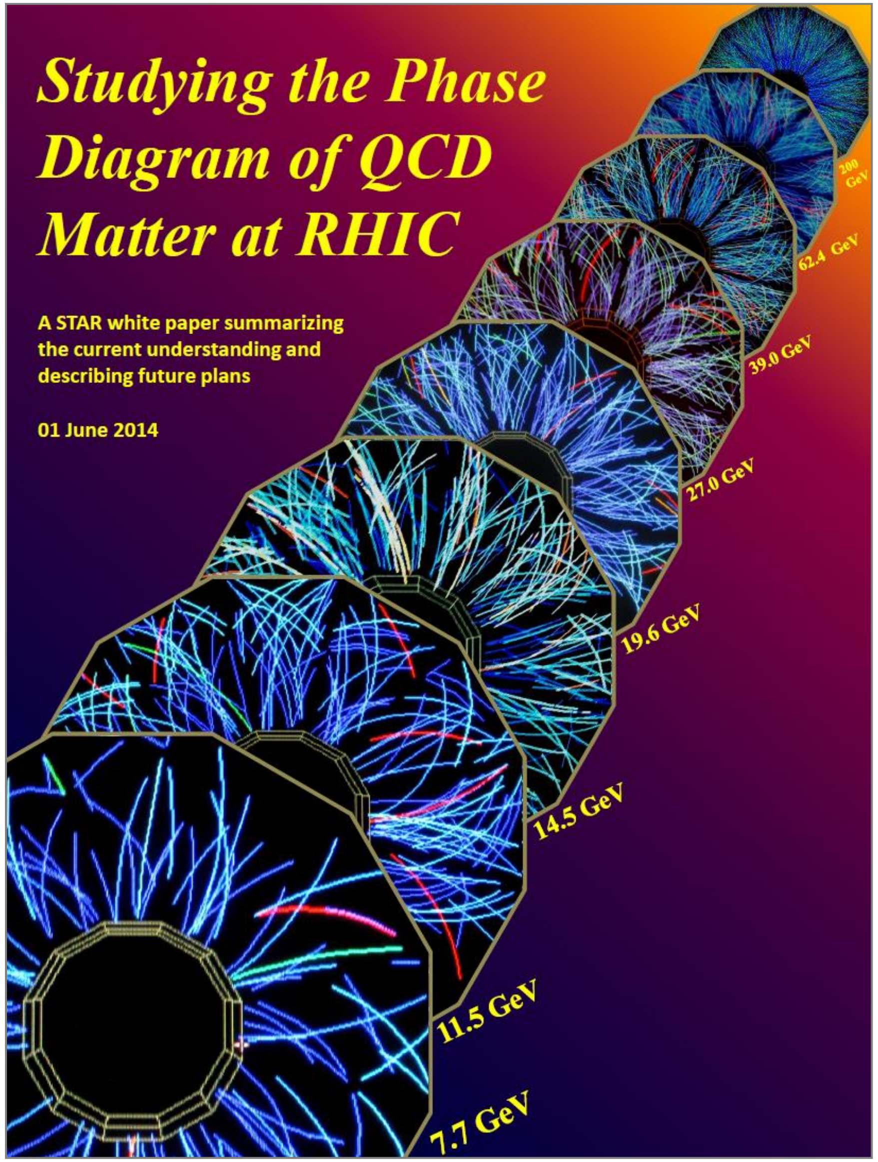
The goal of the energy scans is to study regions of the QCD which exhibit different behaviors and the transitions between such regions.



There is strong motivation to study both the baryon and meson dominated regions.

Nuclear Matter

BES-II Whitepaper 2014



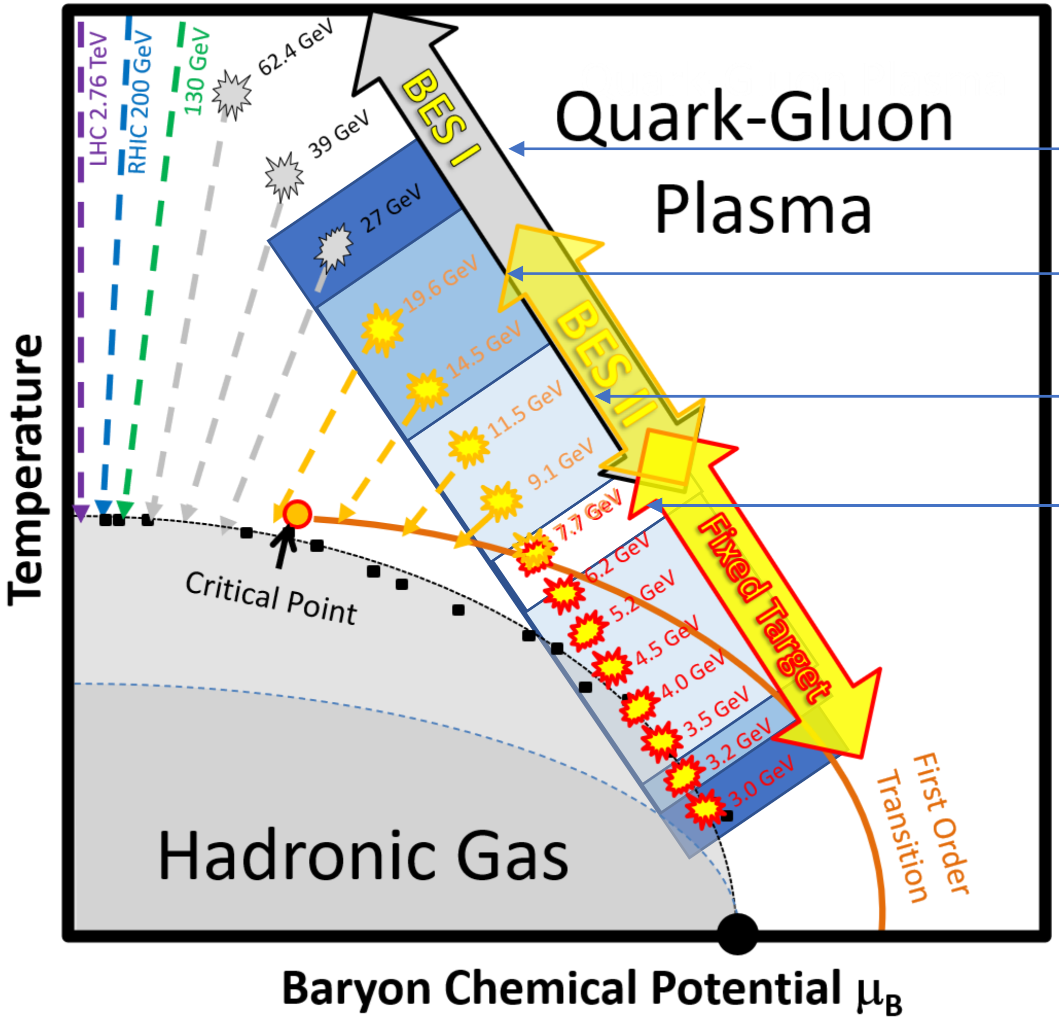
Beam Energy Scan II (2018-2021)

Select the most important energy range
➔ 3 to 20 GeV (**Add fixed-target program**)

Improve significance
➔Long runs, higher luminosity (**electron cooling**)

Refine the signals
➔ Detector improvements (**iTPC, eTOF, EPD**)

STAR Beam Energy Scan II – Mapping the QCD Phase Diagram
The Experimental Plan



Go from easiest to hardest

Run 18 -- 27 GeV, FXT 3.0, FXT 7.2
Beams are accelerated

Run 19 – 19.6, 14.6, FXT 3.2 GeV
No acceleration in RHIC

Run 20 – 11.5, 9.2, six FXT energies
Needs cooling at 9.2 GeV

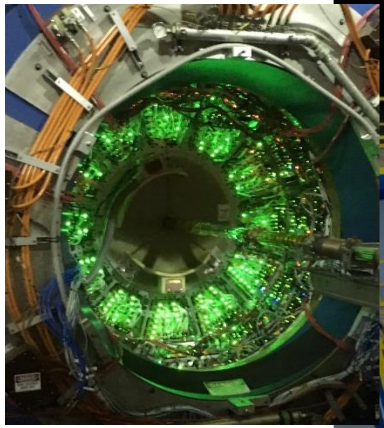
Run 21 – 7.7, 17.3 GeV Collider
FXT 9.2, 11.5, 13.5, hi stats at FXT 3

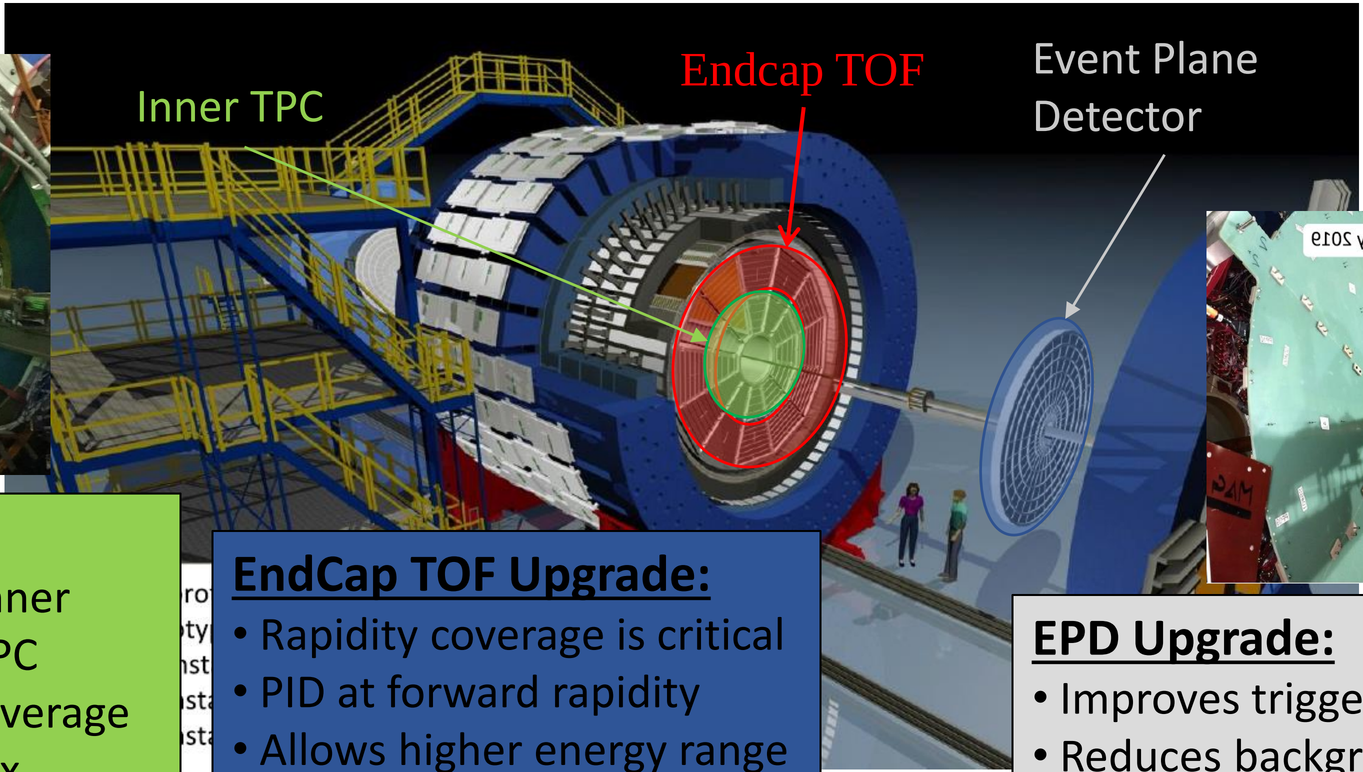
The plan went well, all items in red were extra

The BESII collider program maps the approach to the transition from the QGP side of the QCD phase diagram.

The FXT program maps the baryon-rich side of the phase diagram

The STAR Detector Upgrades → BES-II



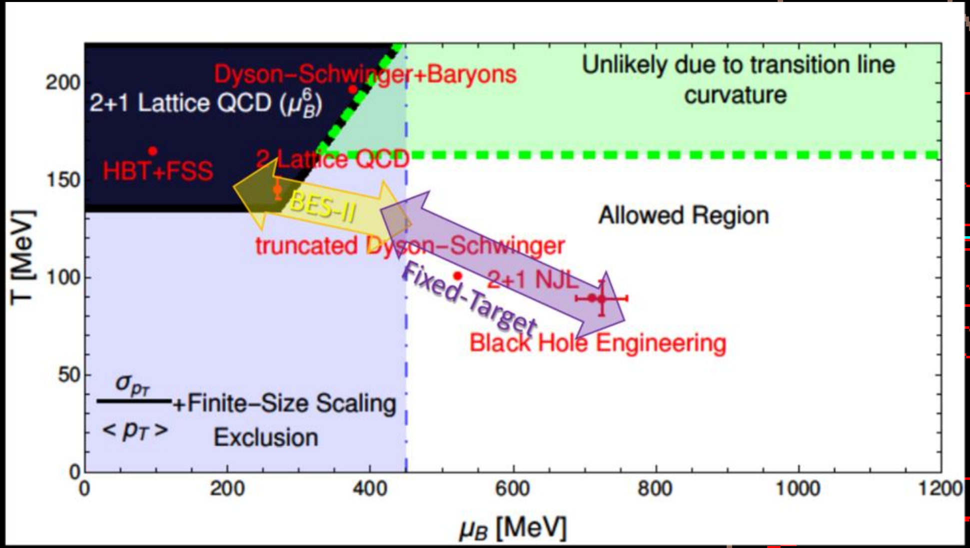


iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage to 1.5 (2.2 for FXT)
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c
- Ready in 2019

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at forward rapidity
- Allows higher energy range of FXT program
- CBM/FAIR
- Ready 2019

EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES and FXT
- Ready 2018

Why a Fixed Target Program



Theory tells us that the critical point might be below the collider region.

Need to study the high-baryon density region as a control.

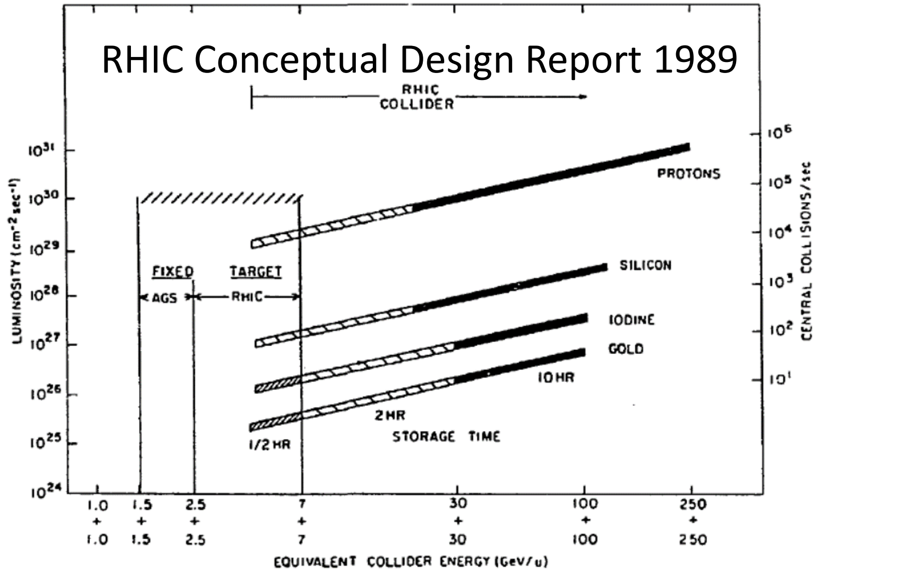
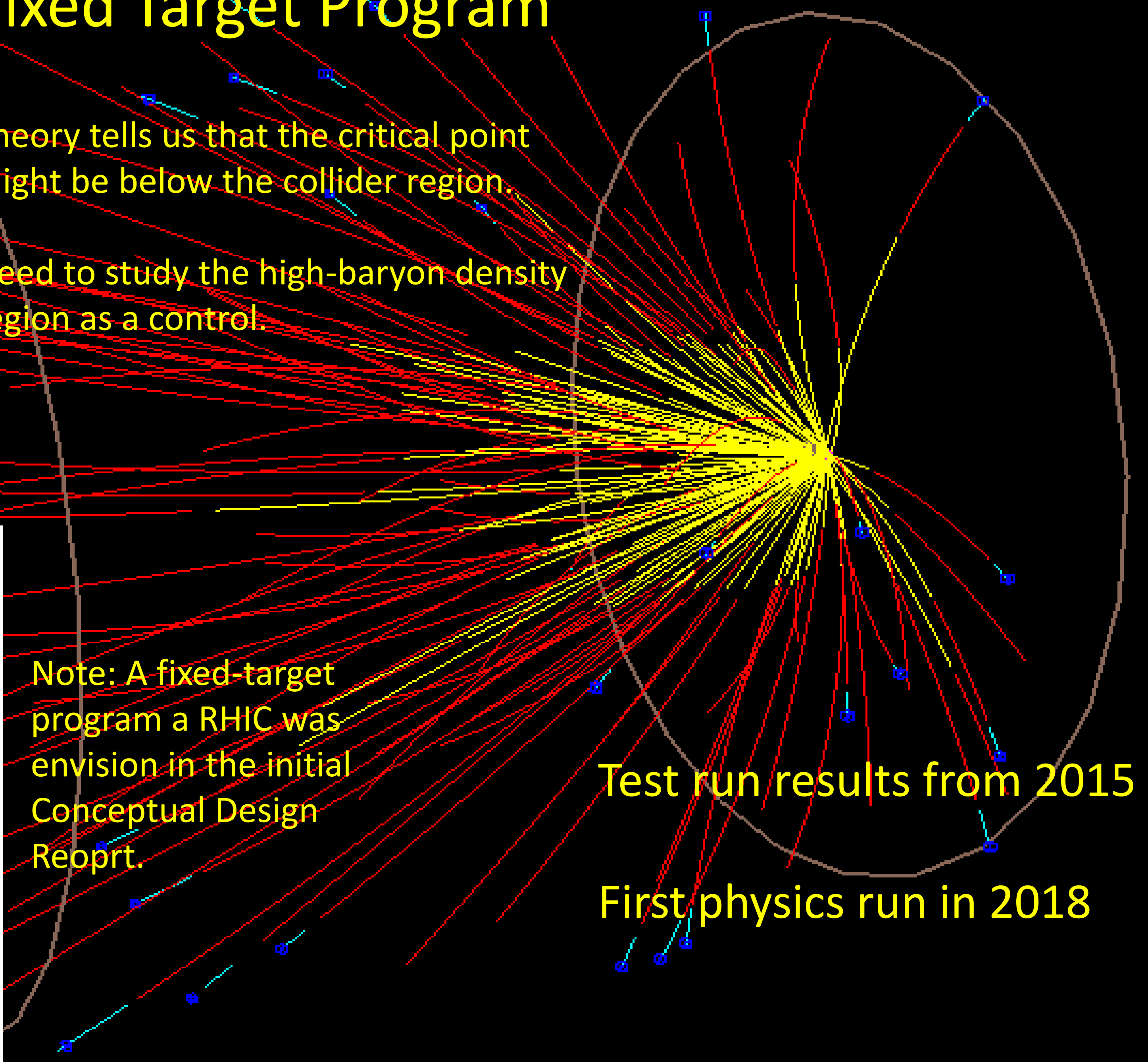


Fig. I-4. The design luminosity, for various ion masses, as a function of collision energy over the full range accessible with AGS and RHIC. On the right-hand scale, central collisions correspond to an impact parameter less than 1 Fermi.

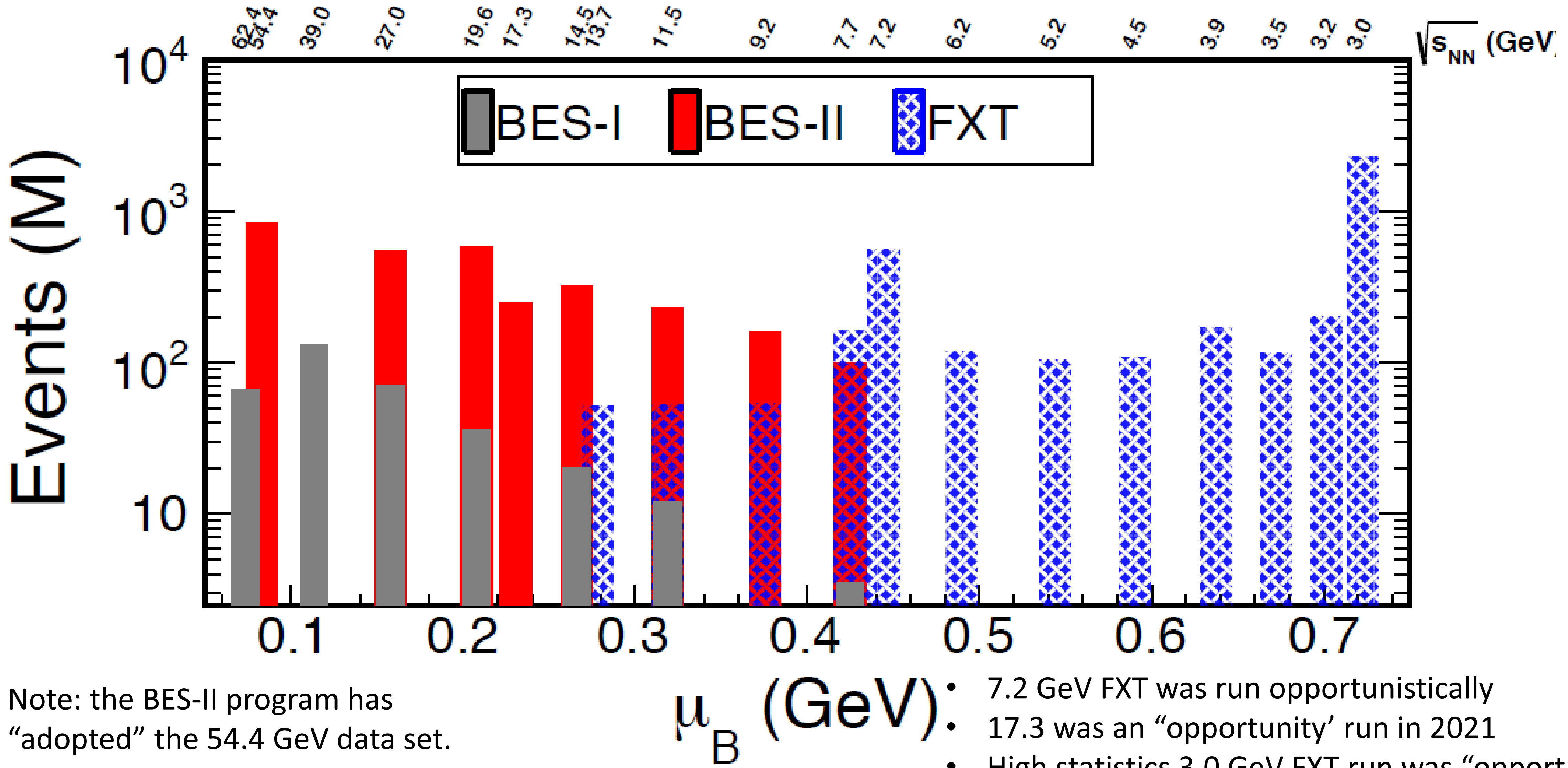
Note: A fixed-target program a RHIC was envision in the initial Conceptual Design Reoprt.



Test run results from 2015

First physics run in 2018

Beam Energy Scan II Event Statistics



Note: the BES-II program has "adopted" the 54.4 GeV data set.

- 7.2 GeV FXT was run opportunistically
- 17.3 was an "opportunity' run in 2021
- High statistics 3.0 GeV FXT run was "opportunity"

Acquisition of the BES-II/FXT data went very well, even leaving some time for some opportunity systems.

Calibration, Production, and Post-production QA take some time, but teams are in place and data sets are becoming available for the analysis teams. With all data likely available for physics analysis within a year.

STAR plans to publish final results once all energies are available (with the exception of the 3.0 GeV FXT data).

2018	Start	Stop	Good	Target	Status
27 GeV	May 10th	June 17th	555 M	700 M	Final
3.0 FXT	May 30th	June 4th	258 M	100 M	Final
7.2 FXT	June 11th	June 12th	155 M	none	Final
2019	**Start**	**Stop**	**Good**	**Target**	
19.6 GeV	Feb 25th	April 3rd	478 M	400 M	Preliminary
14.6 GeV	April 4th	June 3rd	324 M	310 M	Post-prod QA
3.9 FXT	June 18th	June 18th	52.7 M	50 M	Produced
3.2 FXT	June 28th	July 2nd	200.6 M	200 M	Post-prod QA
7.7 FXT	July 8th	July 9th	50.6 M	50 M	Produced
200 GeV	July 11th	July 12th	138 M	140 M	Produced
2020	**Start**	**Stop**	**Good**	**Target**	**Status**
11.5 GeV	Dec 10th	Feb 24th	235 M	230 M	*Summer*
7.7 FXT	Jan 28th	Jan 29th	112.5 M	100 M	Produced
4.5 FXT	Jan29th	Feb 1st	108 M	100 M	Produced
6.2 FXT	Feb 1st	Feb 2nd	118 M	100 M	Produced
5.2 FXT	Feb 2nd	Feb 3rd	103 M	100 M	Produced
3.9 FXT	Feb 4th	Feb 5th	117 M	100 M	Produced
3.5 FXT	Feb 13th	Feb 14th	115.6 M	100 M	Produced
9.2 GeV	Feb 24th	Sep 1st	161.8 M	160 M	*Summer*
7.2 FXT	Sep 12th	Sep 14th	317 M	None	*Fall*
2021	**Start**	**Stop**	**Good**	**Target**	**Status**
7.7 GeV	Jan 31st	May 1st	100.9 M	100 M	*May*
3.0 FXT	May 1st	June 28th	2103 M	2.0 B	*Fall*
9.2 FXT	May 6th	May 6th	53.9 M	50 M	*Fall*
11.5 FXT	May 7th	May 7th	51.7 M	50 M	*Fall*
13.7 FXT	May 8th	May 8th	50.7 M	50 M	*Fall*
17.3 GeV	May 25th	June 7th	256.1 M	250 M	*Fall*
7.2 FXT	June 3rd	July 3rd	88.6 M	None	*Fall*

The only “final” results are from 2018 data.

Results from the 19.6, 14.6, and 200 GeV data sets will be coming out soon.

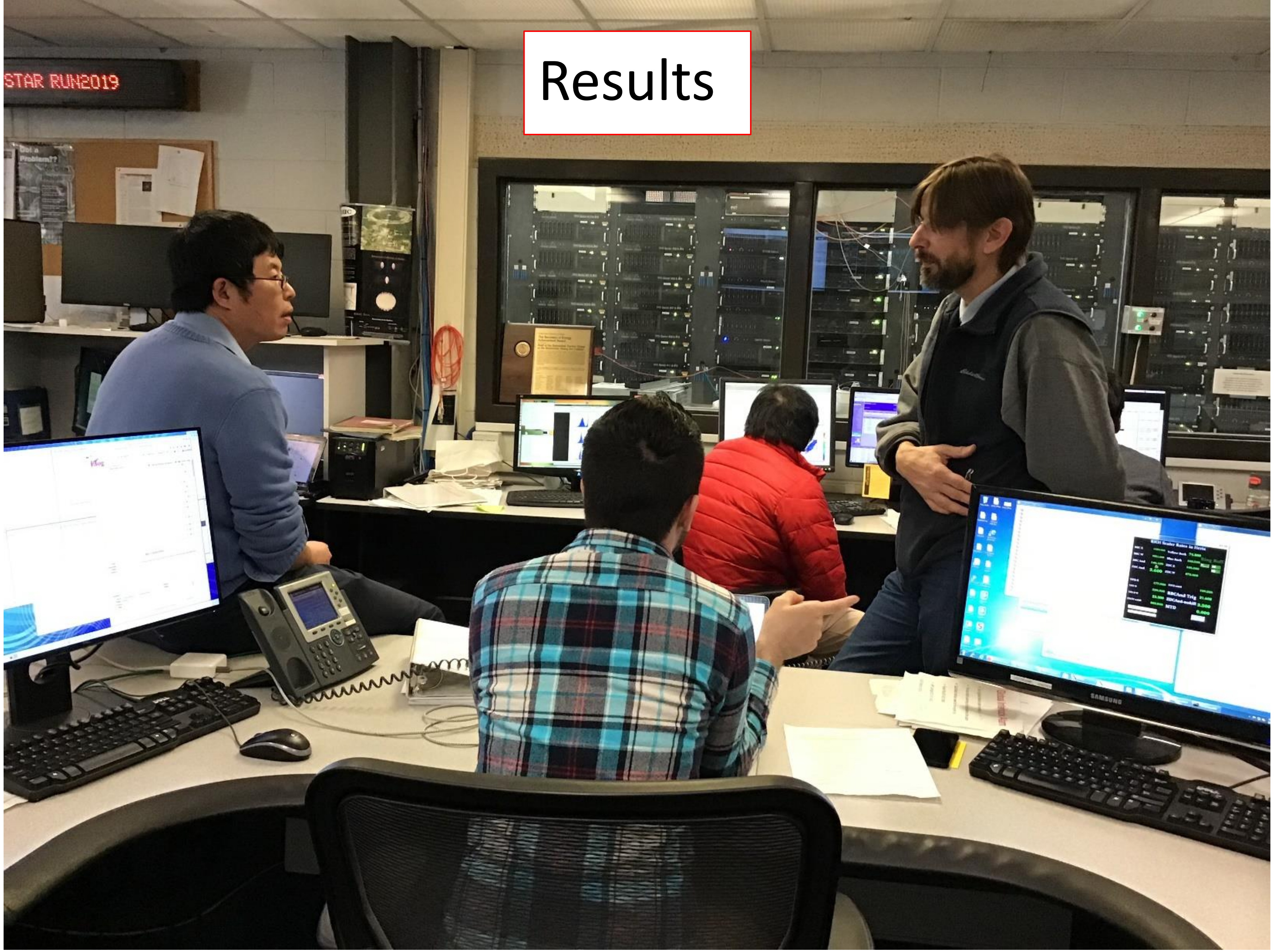
The full FXT energy scan data have been produced.

7.7 GeV Collider data have been given a high priority.

Status of Key Physics Analysis Efforts

Physics Analysis	Status of Analyses
R_{CP} up to p_T = 5 GeV/c	Physics Working Group
Elliptic Flow	Published March 10, 2022
Chiral magnetic Effect	
Directed Flow	Published February 1, 2022
Azimuthal Femtoscopy	Physics Working Group
Net-proton Kurtosis	Published Feb. 01, 2022
Di-leptons	QM2022 talk
Lambda Polarization	Published December 21, 2021
Multi-strange Baryons	Published May 31, 2022
Hyper-nuclei	Published May 17, 2022
Rapidity dependent Spectra	QM2022 talks (2)

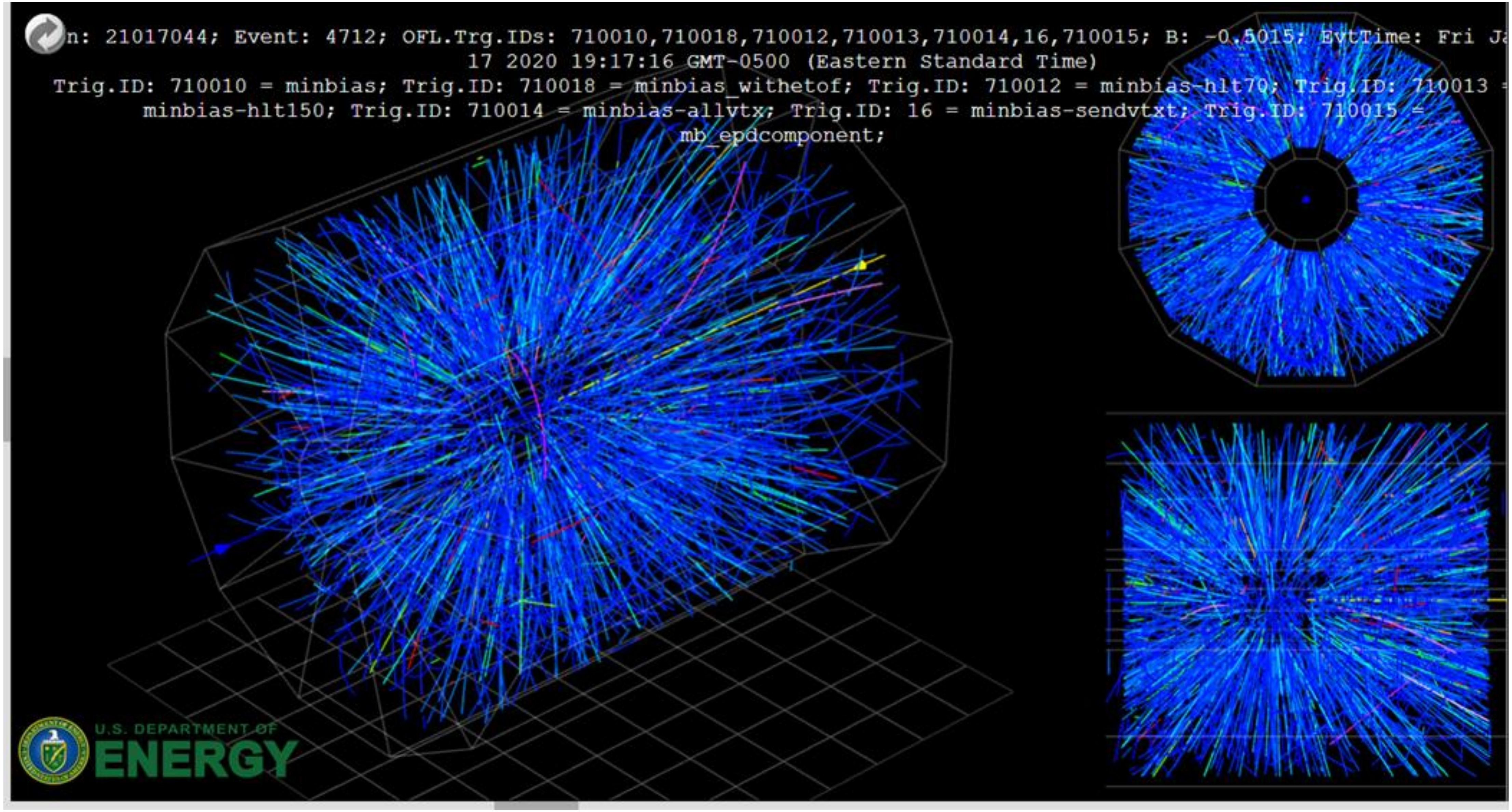
Analysis teams are in place for all key analyses (with the exception of chiral magnetic effect).



Results

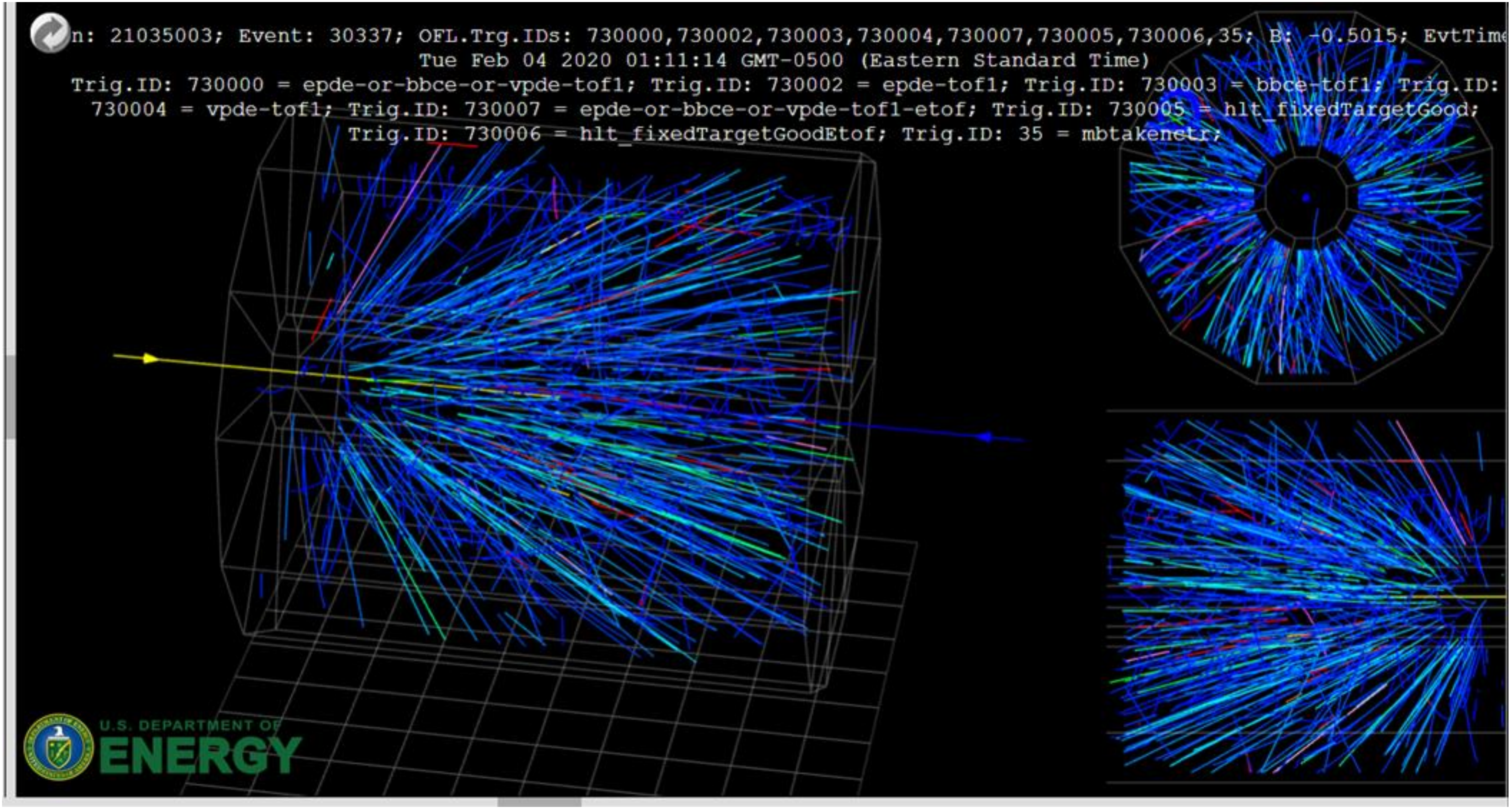
Online Event Display – Collider Event

11.5 GeV



Online Event Display – FXT Event

3.9 GeV



BES-II/FXT Publications to date (6 FXT papers, one 27/54.4 GeV paper):

Probing Strangeness Canonical Ensemble with K-, phi(1020) and Xi- Production in Au+Au Collisions at sqrt{s_NN} = 3 GeV
Submitted Dec. 23, 2021, *Published May 31, 2022,* Phys. Lett. B **831** (2022) 137152

Light Nuclei Collectivity from 3 GeV Au+Au Collisions at RHIC
Submitted Dec. 8, 2021 , Published Feb. 1, 2022, Phys. Lett. B **827** (2022) 136941

Measurements of Proton High Order Cumulants in sqrt{s_NN} = 3 GeV Au+Au Collisions and Implications for the QCD Critical Poi
Submitted Dec. 2, 2021, Published Feb 01, 2022, Phys. Rev. Lett. **128** (2022) 202303

Disappearance of partonic collectivity in 3 GeV Au+Au collisions at RHIC
Submitted Nov. 24, 2021 , Published Mar. 10, 2022, Phys. Lett. B **827** (2022) 137003

Measurements of H3L and H4L Lifetimes and Yields in Au+Au Collisions in the High Baryon Density Region
Submitted Oct. 18, 2021, Published May 17, 2022, Phys. Rev. Lett. **128** (2022) 202301

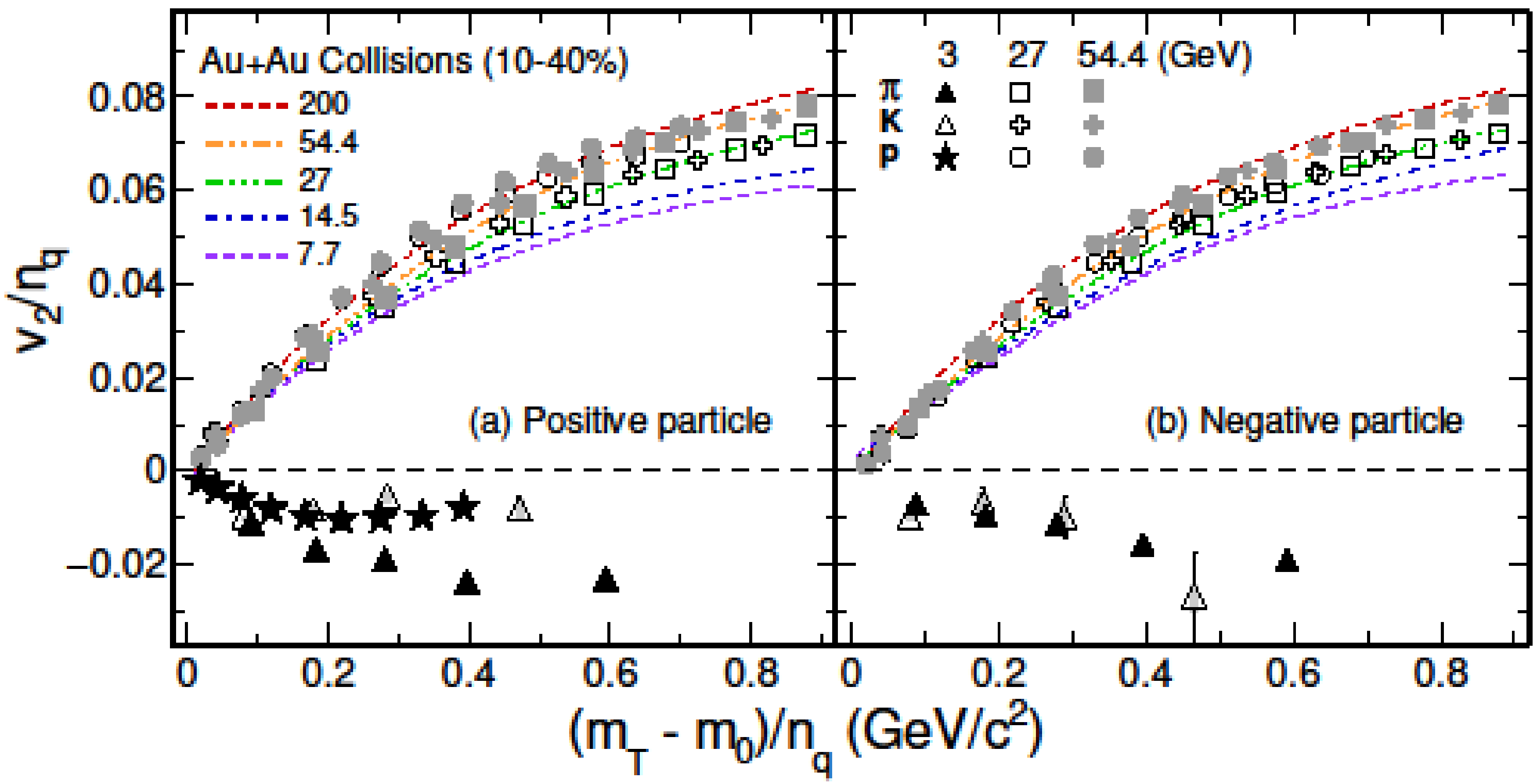
Global Lambda-hyperon polarization in Au+Au collisions at sqrt{sNN} =3 GeV
Submitted Aug. 4, 2021 , Published Dec. 21, 2021, Phys. Rev. C **104** (2021) 61901

Measurement of the Sixth-Order Cumulant of Net-Proton Multiplicity Distributions in Au+Au Collisions at sqrt{sNN} = 27 , 54.4, and 200 GeV at RHIC
Submitted May. 31, 2021 , published Dec. 20, 2021, Phys. Rev. Lett. **127** (2021) 262301

Disappearance of partonic collectivity in 3 GeV Au+Au collisions at RHIC

Submitted Nov. 24, 2021 , Published Mar. 10, 2022, Phys. Lett. B **827** (2022) 137003

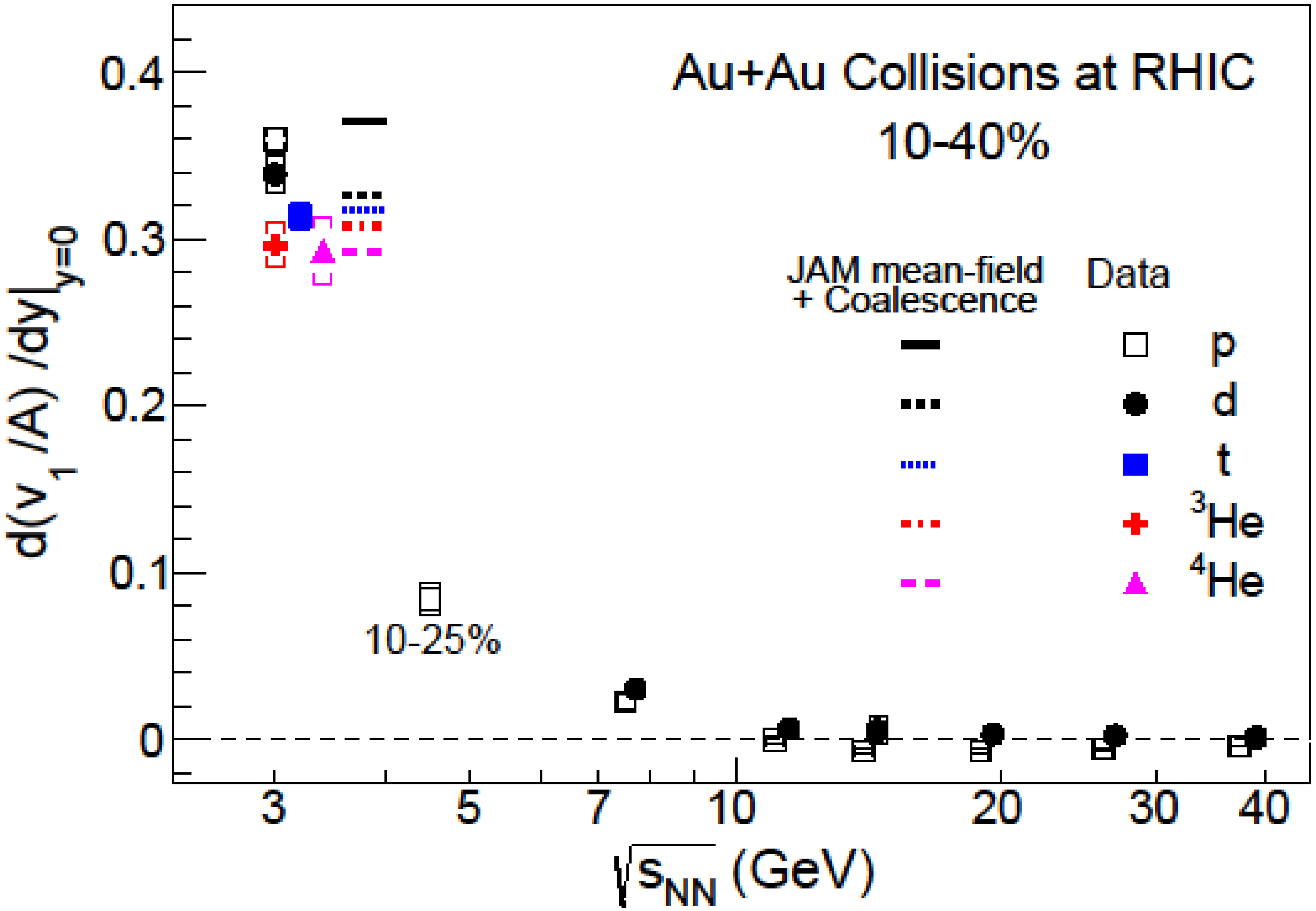
- Elliptic flow is negative (squeeze-out) at 3 GeV, as expected from the previous AGS data.
- The quark number scaling (n_q) has been used at higher energies as a signature of the QGP. At 3 Gev, the scaling has broken down ➔ hadronic gas (not QGP).
- First midrapdity pion and kaon results.



Light Nuclei Collectivity from 3 GeV Au+Au Collisions at RHIC

Submitted Dec. 8, 2021 , Published Feb. 1, 2022, Phys. Lett. B **827** (2022) 136941

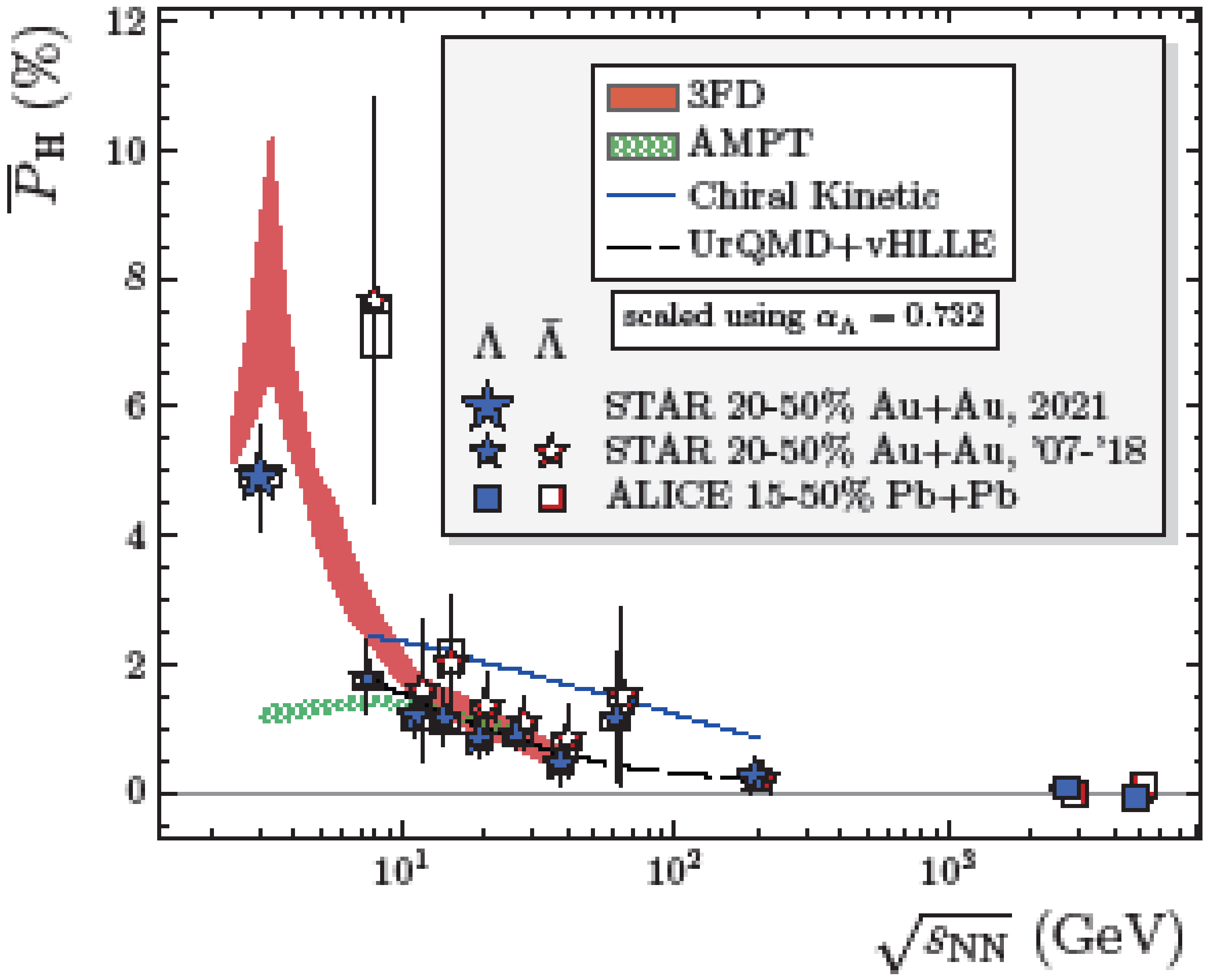
- Directed flow is large and positive for all light nuclei.
- Comparisons to JAM mean-field + Coalescence support the conclusion that this energy is in the hadronic gas regime.
- Pion and kaon results will be available.



Global Lambda-hyperon polarization in Au+Au collisions at sqrt{sNN} =3 GeV

Submitted Aug. 4, 2021 , Published Dec. 21, 2021, Phys. Rev. C **104** (2021) 61901

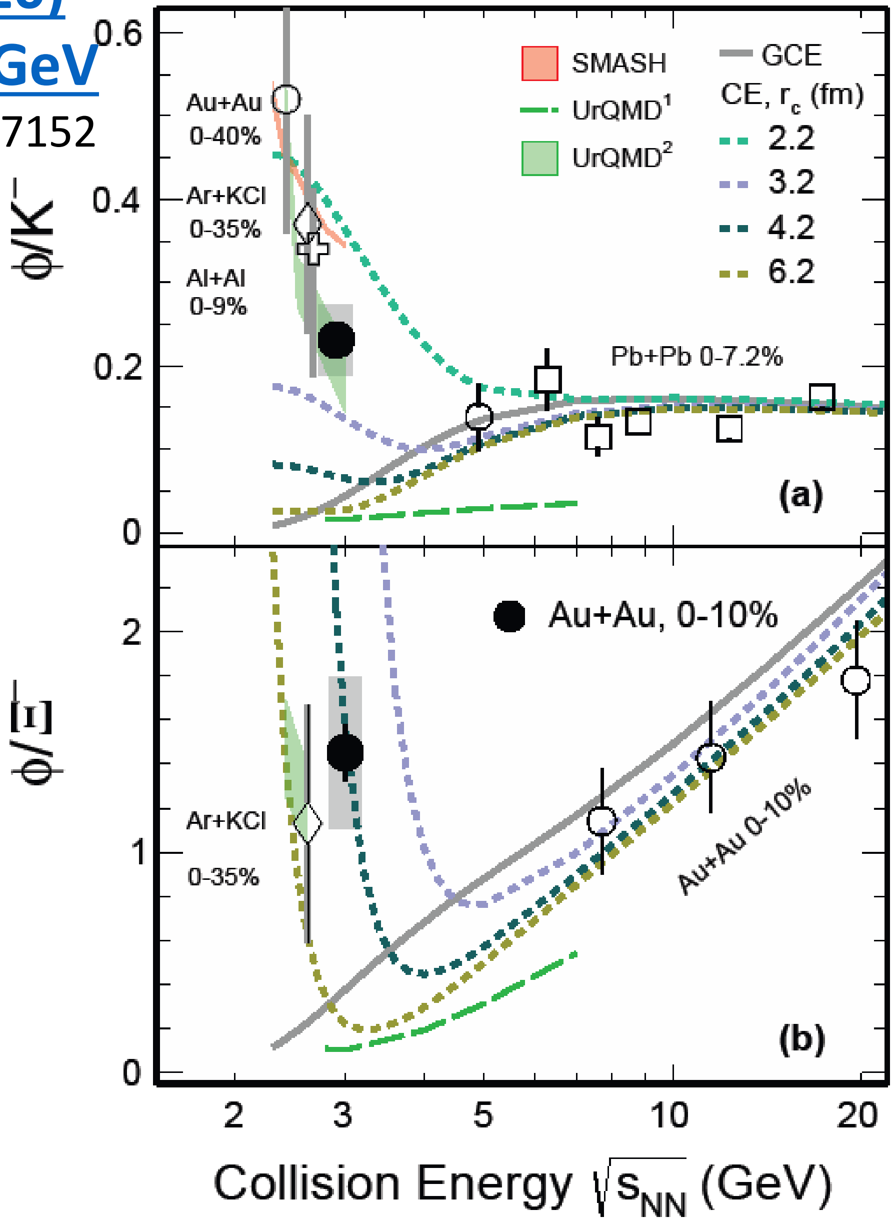
- Global hyperon polarizationover a large range of collision energy was recently measured and successfully reproduced by hydrodynamic and transport models with intense fluid vorticity of the QGP.
- The behavior of P_H at very low energy was unknown.
- The observation of substantial polarization in these collisions may require a reexamination of the viscosity of any fluid created in the collision, of the thermalization timescale of rotational modes, and of hadronic mechanisms to produce global polarization.



Probing Strangeness Canonical Ensemble with K-, phi(1020) and Xi- Production in Au+Au Collisions at sqrt{s_NN} = 3 GeV

Submitted Dec. 23, 2021, *Published Dec. 31, 2022,* Phys. Lett. B **831** (2022) 137152

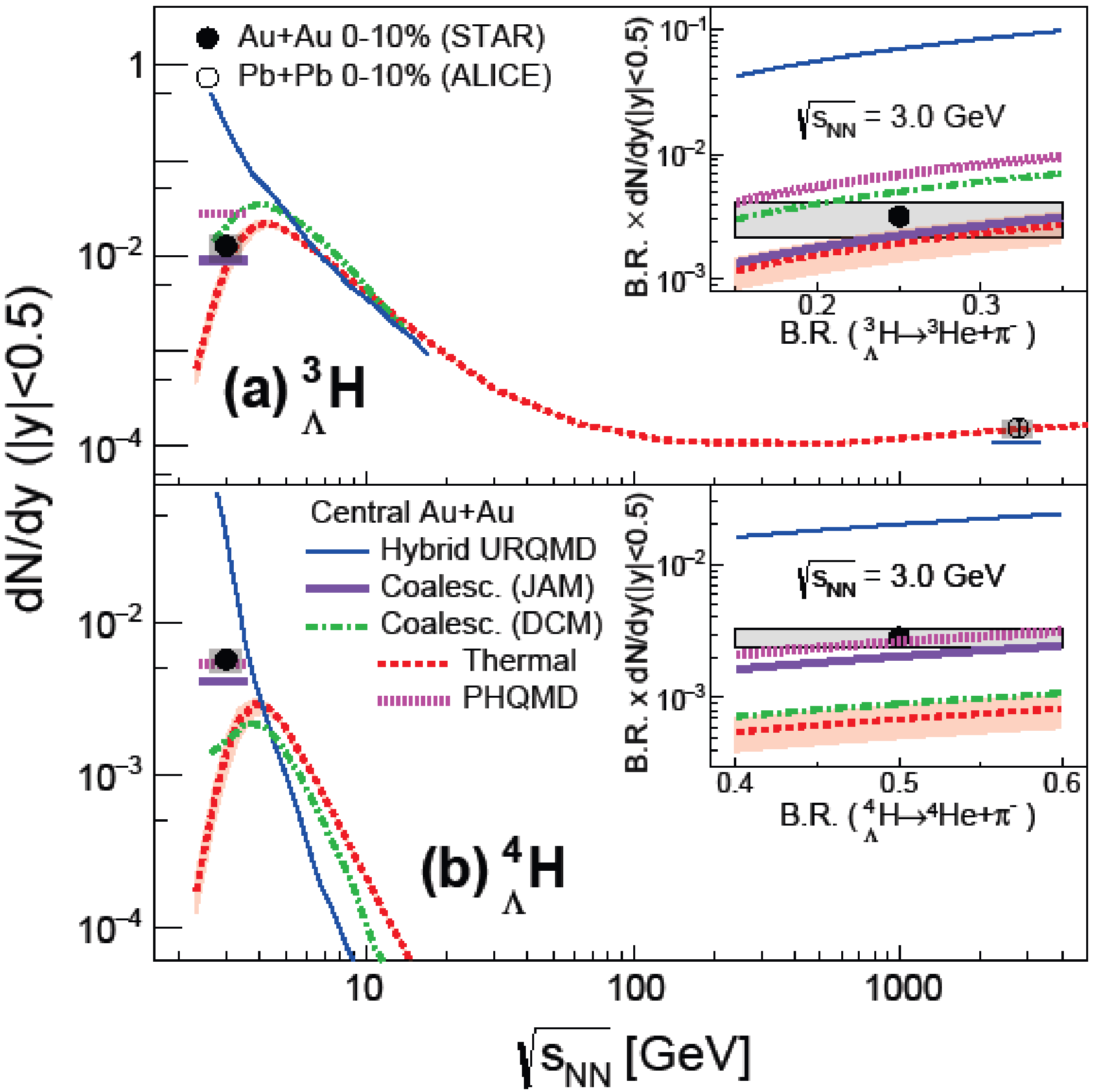
- The ϕ meson is very close to threshold in 3 GeV collisions.
- The thermal model with grand canonical ensemble (GCE) under-predicts the ratios.
- The canonical ensemble (CE) calculations reproduce the ratios with correlation lengths of 3-4 fm.
- These observations imply that the ϕ meson is produced in a system of high baryon density causing the small correlation length.



Measurements of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ Lifetimes and Yields in Au+Au Collisions in the High Baryon Density Region

Submitted Oct. 18, 2021, Published May 17, 2022, Phys. Rev. Lett. **128** (2022) 202301

- Copious hypernucleus production is seen in the FXT data.
- Thermal models had predicted that the FXT region would be the optimal for hypernucleus production.
- Hyper-triton yields, so far, match the thermal model predictions.
- An unexpectedly high $^{4}_{\Lambda}H$ is observed.
- Lifetime measurements are consistent with previous measurements and have higher precision.



Measurements of Proton High Order Cumulants in sqrt{s_NN} = 3 GeV Au+Au Collisions and Implications for the QCD Critical Point

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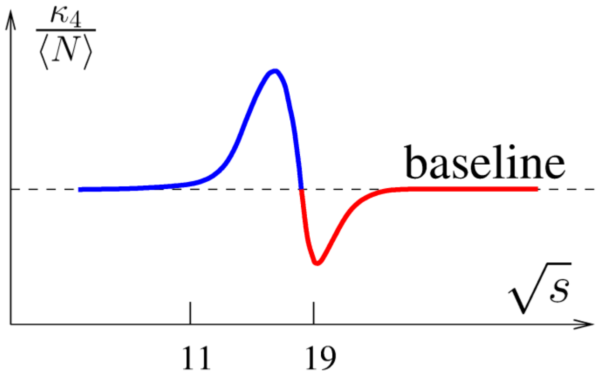
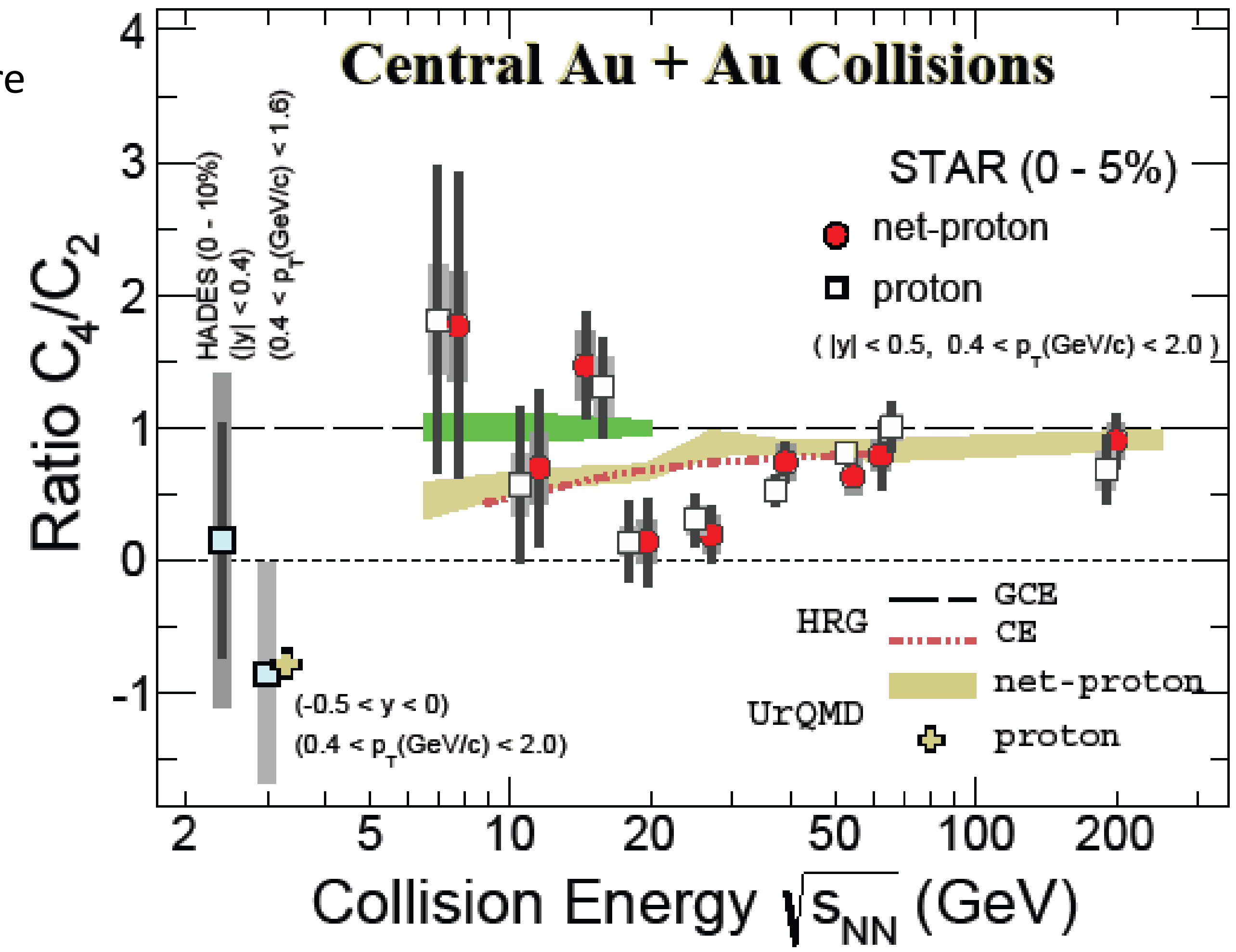
- Finding the critical point in the QCD phase transition would firmly establish our understanding of the nature of the the QCD phase diagram.

- Fluctuation analysis is the most promising methodology.

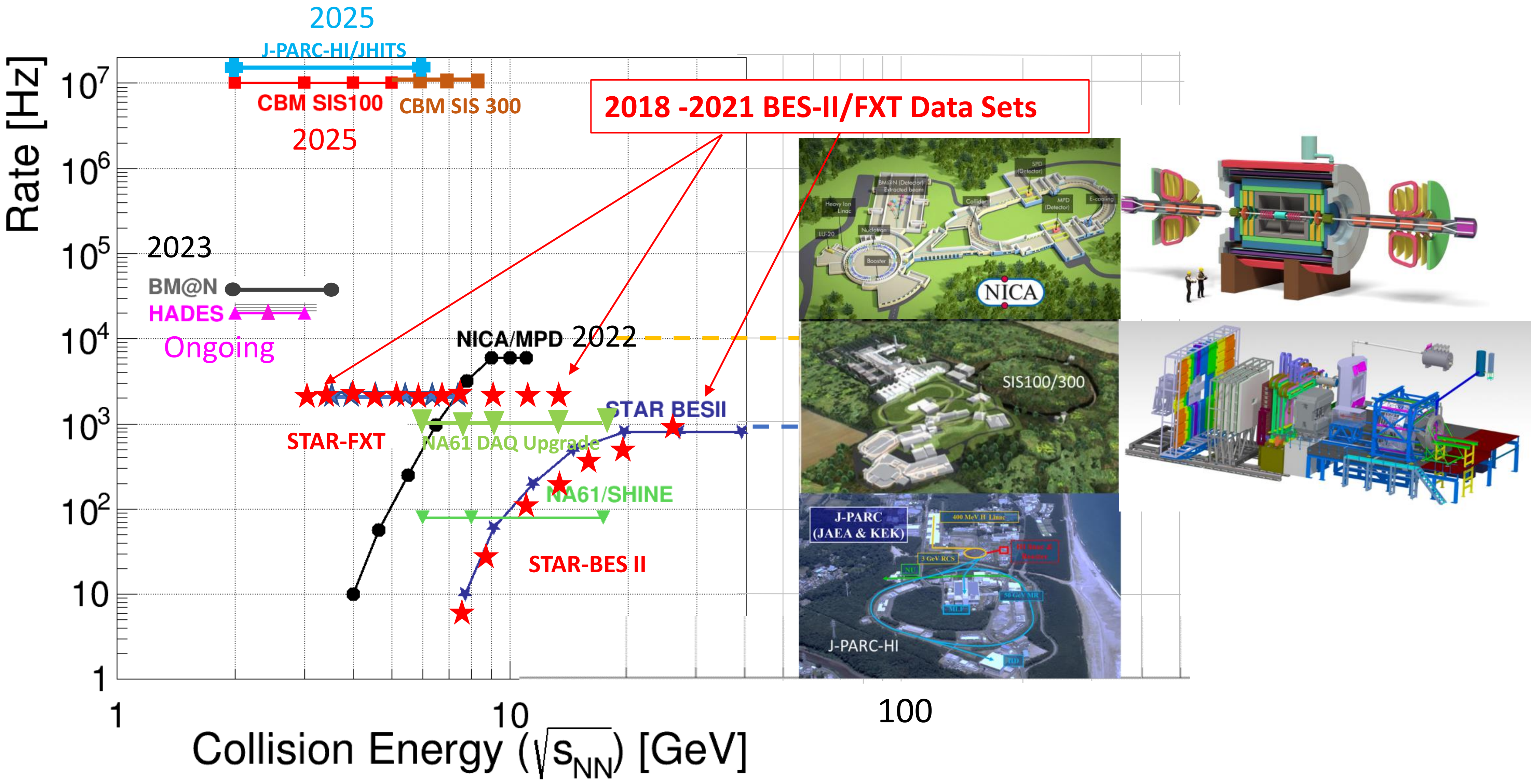


- The new 3 GeV FXT results are suppressed below the Possion baseline due to baryon conservation, as evidenced by the UrQMD model comparison.

➔ Established that 3 GeV is a dense hadonic gas.



Future Facilities to Address Phase-Diagram Physics



Conclusions

- Energy scans are have used for many years to understand the evolution of hot dense systems created in heavy ion collisions.
- Previous Energy scan had demonstrated the liquid-gas phase transition and the evolution from systems dominated by the attractive part of the inter-nucleon potential to those dominated by repulsive interactions.
- Previous scans at the SPS and RHIC had demonstrated that RHIC was in the optimal region to study the transition between hadronic gas and QGP.
- BES-II was proposed as a thorough study of the QCD phase diagram.
- Data taking has been very successfully completed and analysis is underway.
- The first results are from the lowest energy FXT system and these demonstrate that the system is clearly in the hadronic gas phase (as expected).
- Results with all energies will be available within a year.

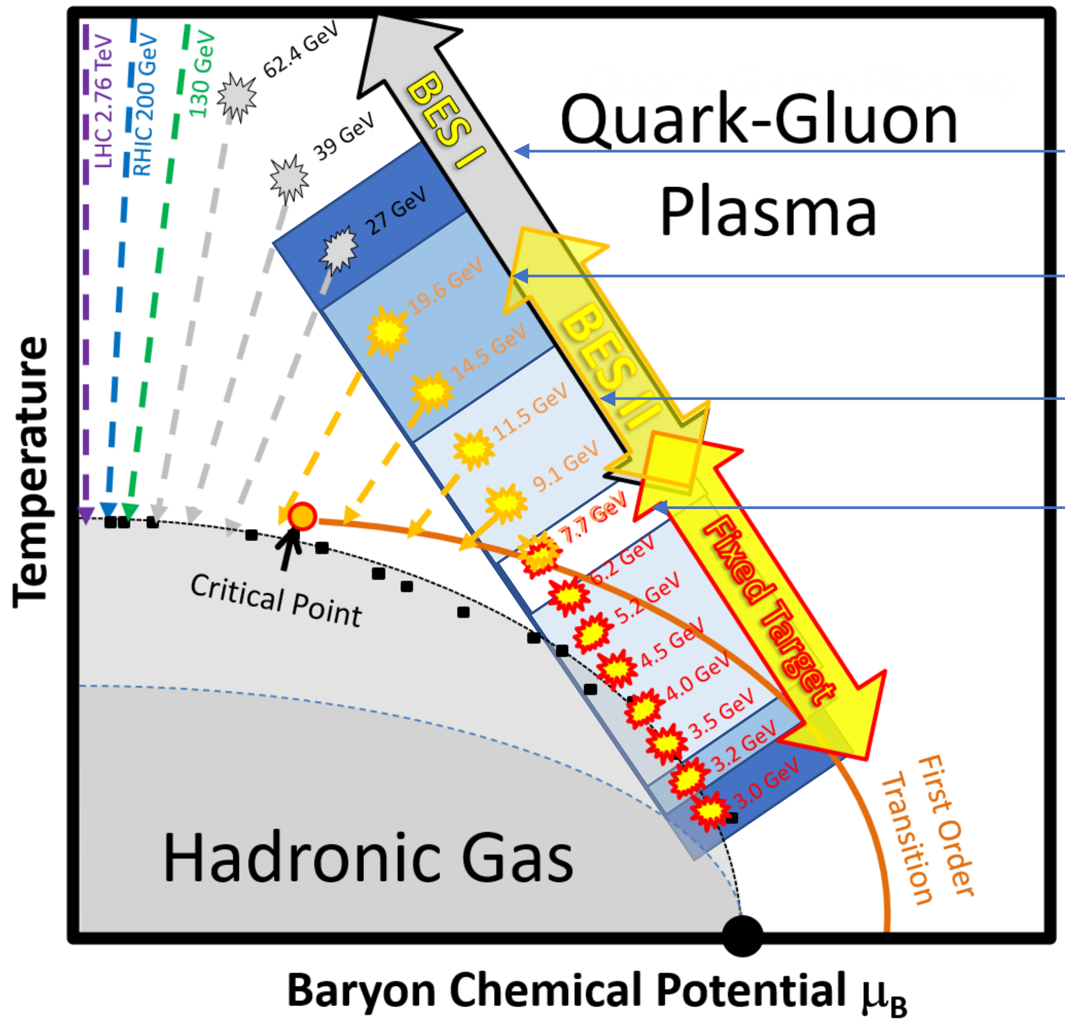
BACKUP

Comparison of Facilities

Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD +BM@N	CBM	JHITS
Start:	2019-20 2018	2009	2020 2018	2022 2025	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 3.0-7.7	4.9-17.3	2.7 - 11 2.0-3.5	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 kHz	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM	OD&DHM
	Collider Fixed Target	Fixed Target Lighter ion collisions	Collider Fixed Target	Fixed Target	Fixed Target

CP = Critical Point
OD = Onset of Deconfinement
DHM = Dense Hadronic Matter

STAR Beam Energy Scan II – Mapping the QCD Phase Diagram



Go from easiest to hardest

Run 18 -- 27 GeV, FXT 3.0

Beams are accelerated

Run 19 – 19.6, 14.6, FXT 3.2 GeV

No acceleration in RHIC

Run 20 – 11.5, 9.2, many FXT

Needs cooling at 9.2 GeV

Run 21 – 7.7 GeV Collider

The BESII collider program maps the approach to the transition from the QGP side of the QCD phase diagram.

The FXT program maps the baryon-rich side of the phase diagram

Fixed-Target Program at RHIC