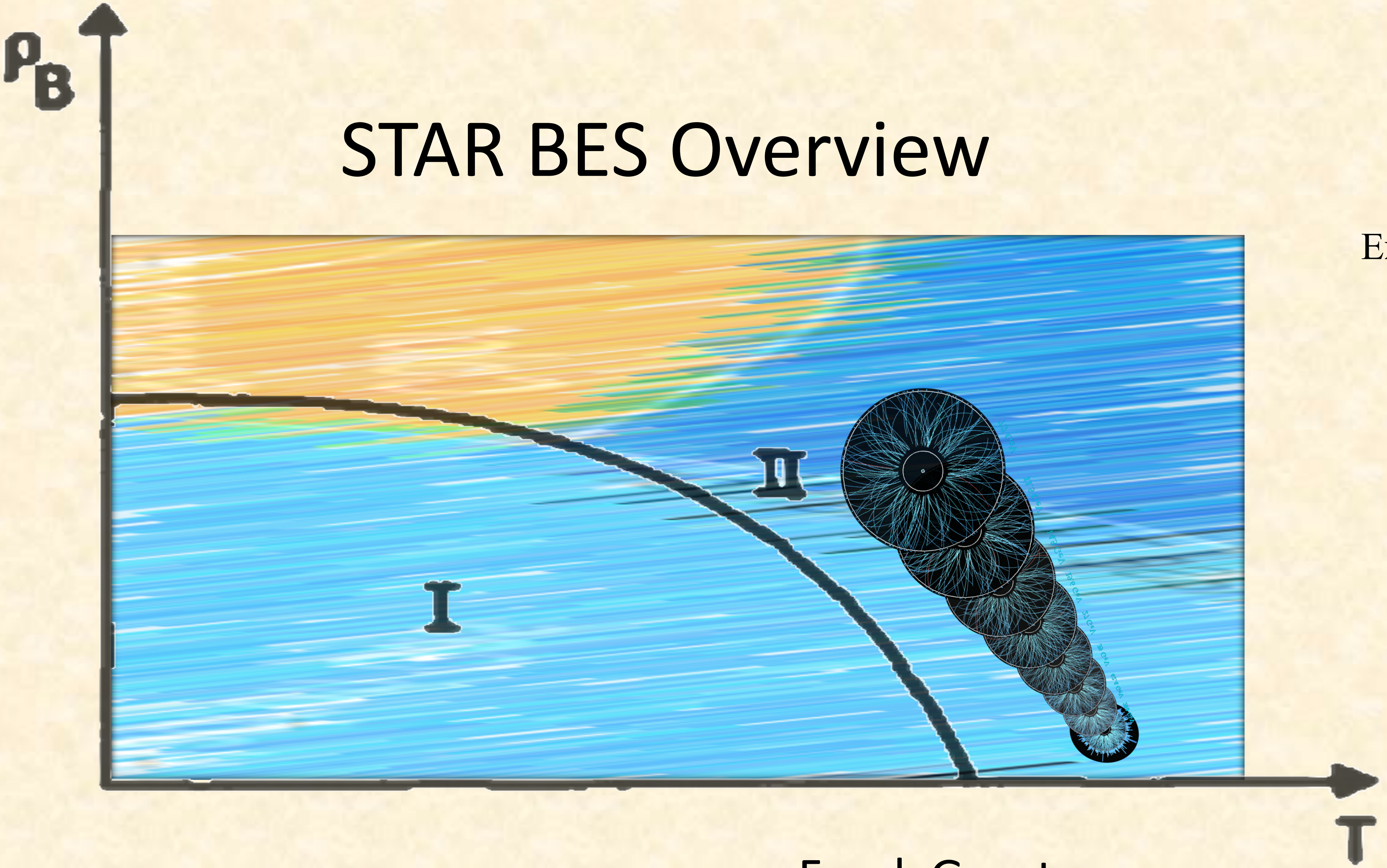
STAR BES Overview



Exploring High-μ_B Matter
with Rare Probes
ECT*, Trento,
Oct. 11 – 15, 2021

Frank Geurts
Rice University

U.S. DEPARTMENT OF ENERGY | Office of Science
FONDAZIONE BRUNO KESSLER
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QCD Phase Diagram

Experimentally, one can access different regions of phase diagram by varying centre-of-mass energy

- experimental data over 3-4 orders of magnitude in $\sqrt{s_{NN}}$

LHC and RHIC provide access to low μ_B region

- cross-over region

Several experiments/facilities give access to μ_B regions that both cover cross-over, possible 1st order PT and a conjectured CP

- AGS, SPS
- Hades
- NA61/SHINE
- RHIC beam energy scan (BES)

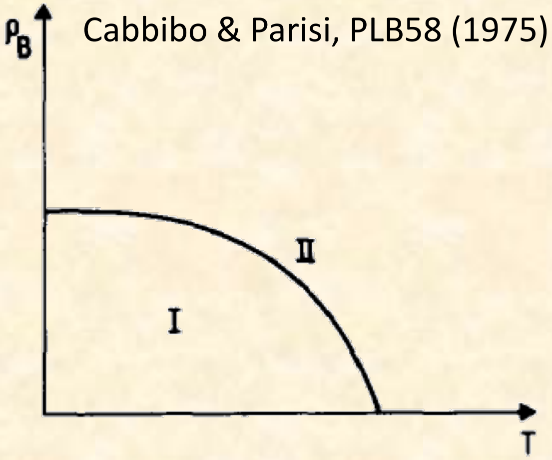
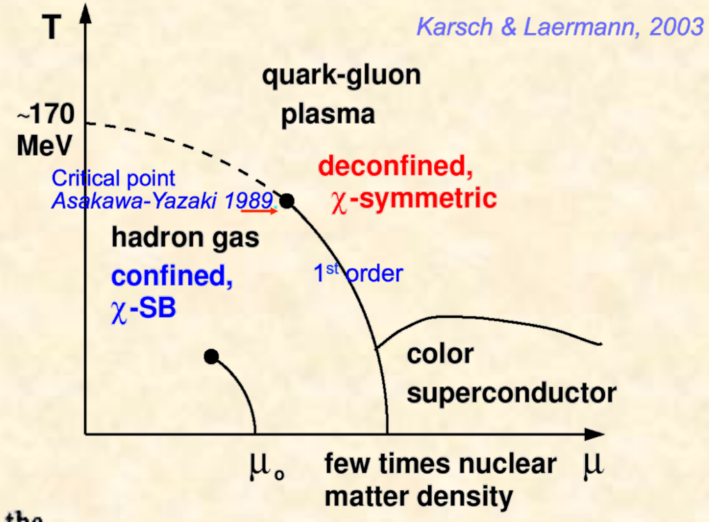
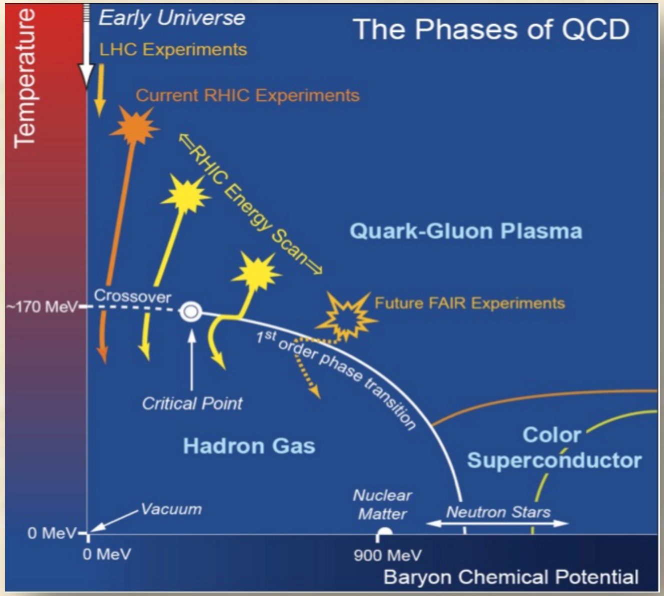


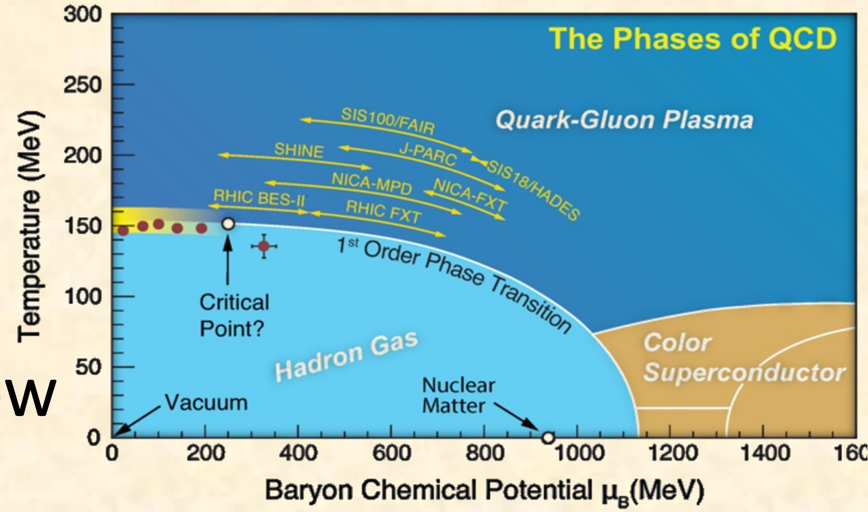
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.





BES-2 White Paper – STAR Note 598

Charting the QCD Phase Diagram



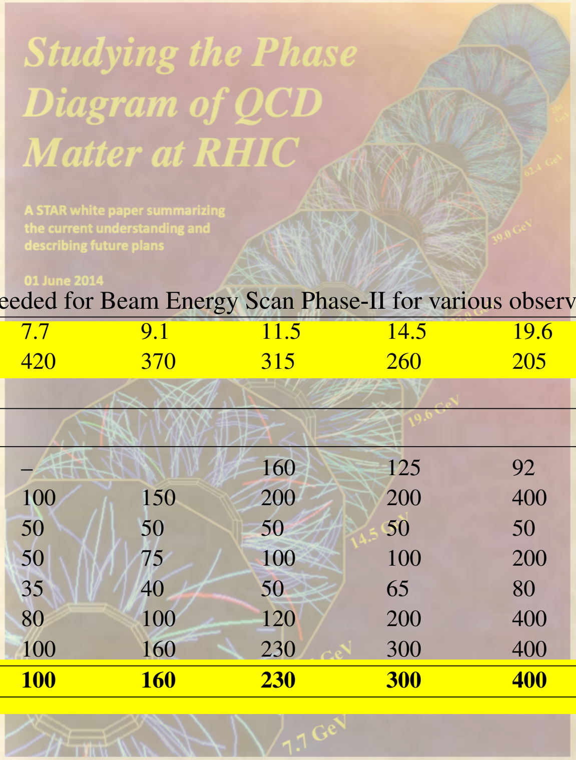
- Turn-off of QGP signatures - suppression, elliptic flow

- First-order phase transition - changes in EoS due to attractive force (softest point)
  - "step" in mean transverse mass of identified particles
  - non-monotonic behavior of directed flow slope at mid-rapidity $(dv_1/dy|_{y=0})$

- Critical point - divergence of the correlation length ⇒ non-monotonic behavior of higher moments of conserved quantities
  - experimentally, skewness S, and kurtosis κ of event-by-event net-particle distributions

STAR Beam Energy Scan Program

- Phase 1: 2010 – 2011, 2014
  - base line detectors: TPC and BTOF
  - $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39 GeV
  - hints at low $\sqrt{s_{NN}}$ of QGP turn-off, ordered phase transition, and critical point
- Phase 2: 2019 – 2021
  - specific focus on lower $\sqrt{s_{NN}}$
  - ❖ include FXT program to reach lower energies
  - improve statistical significance
    - RHIC electron cooling for low beam energies
  - improve systematics
    - detector upgrades: iTPC, EPD, eTOF

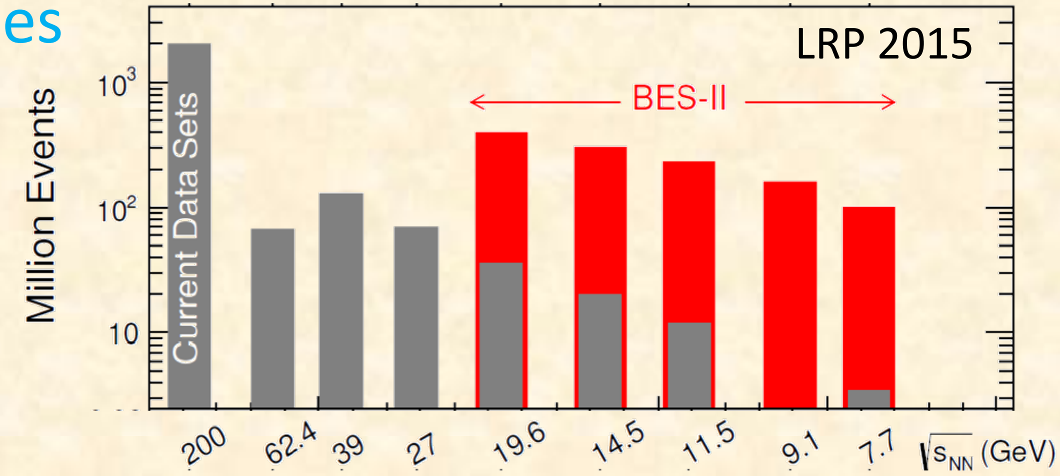


STAR Note 598

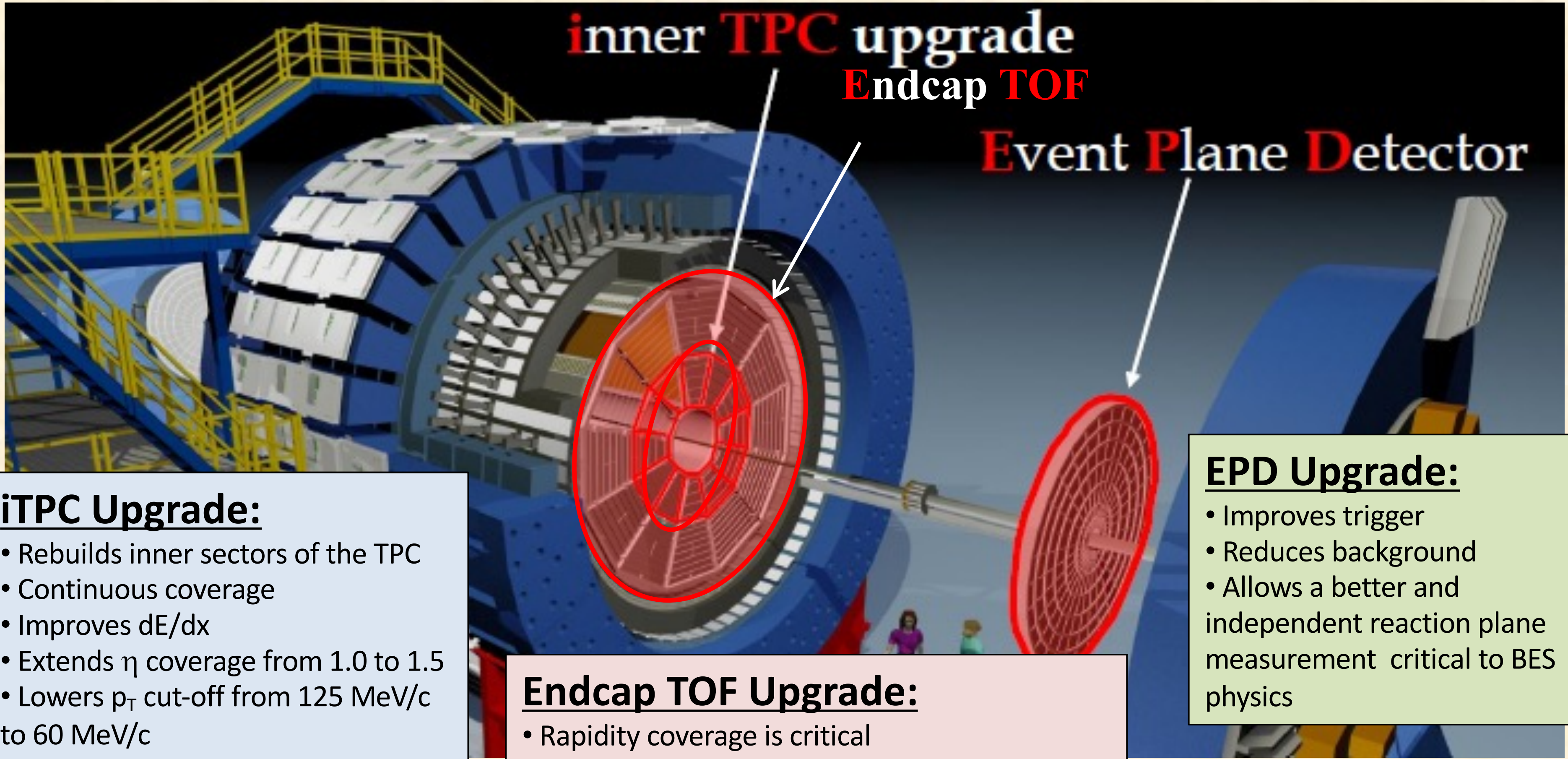
Table 2. Event statistics (in millions) needed for Beam Energy Scan Phase-II for various observables.

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to p_T = 5 GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	80	100	120	200	400
Dileptons	100	160	230	300	400
Required Number of Events	**100**	**160**	**230**	**300**	**400**

http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf



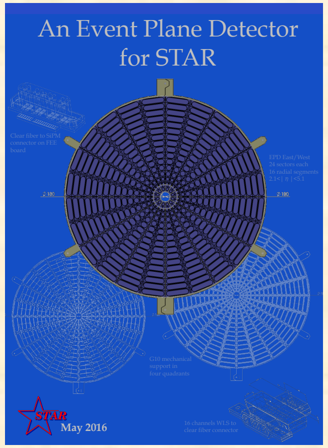
BES Phase-2: STAR Detector Upgrades



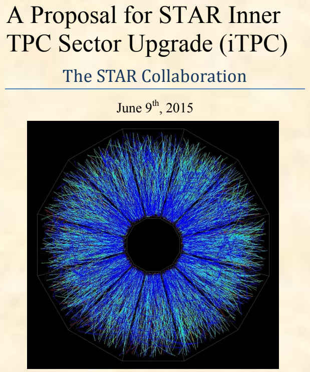
iTPC Upgrade:
- Rebuilds inner sectors of the TPC
- Continuous coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-off from 125 MeV/c to 60 MeV/c

Endcap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1.1 to 1.5
- Improves the fixed target program
- Provided by CBM at FAIR

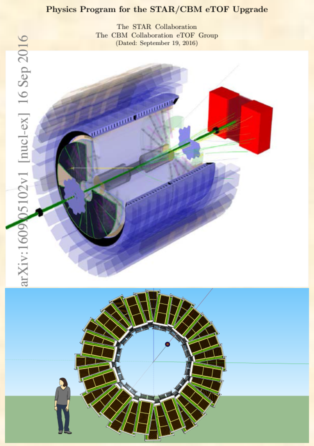
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics



https://drupal.star.bnl.gov/STAR/system/files/EPD_Construction_Proposal.pdf



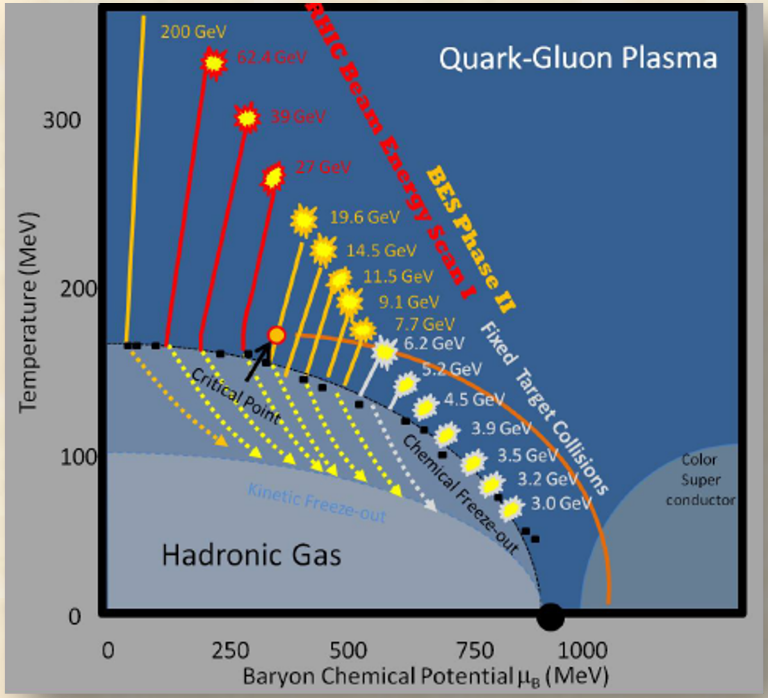
STAR Note 619

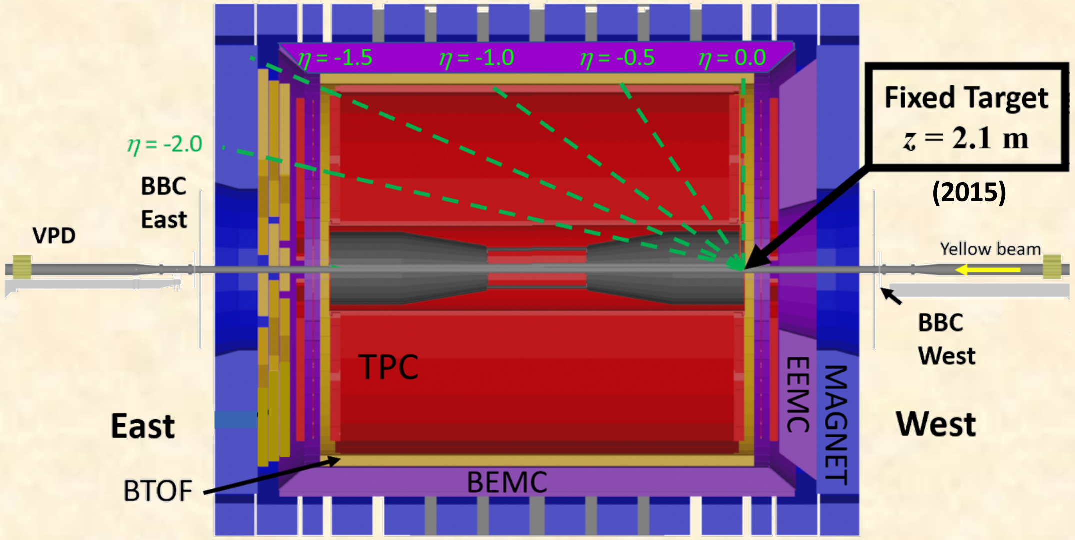


arXiv:1609.05102v1

Fixed Target Mode

- Extending $\sqrt{s_{NN}}$ from 7.7 down to 3.0 GeV
  - ➢ increase μ_B range from 420 to 720 MeV
- Au-target mounted z=2.01m
  - – 250 µm foil (~2% interaction rate)
  - – 2cm below nominal beam axis





STAR, PRC 103 (2021) 34908

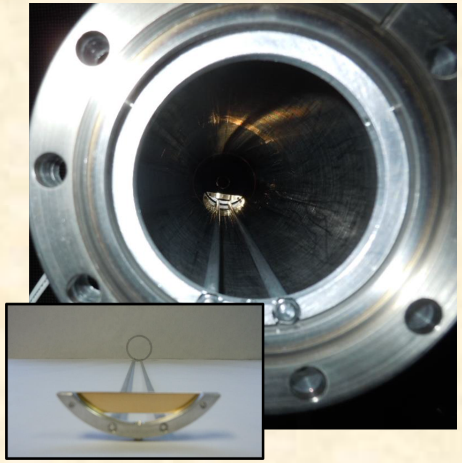
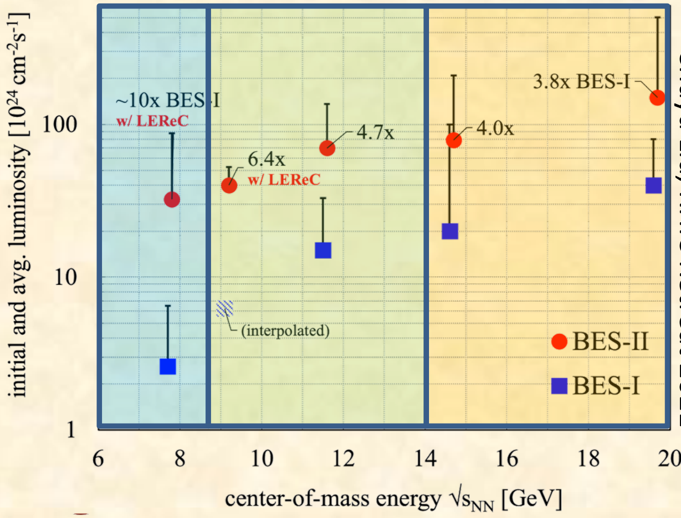


TABLE V. The collider and fixed-target center-of-mass energies ($\sqrt{s_{NN}}$), projectile kinetic energies (AGeV), center-of-mass rapidity offset (y_{CM}), and baryon chemical potentials (μ_B) for the proposed fixed-target program.

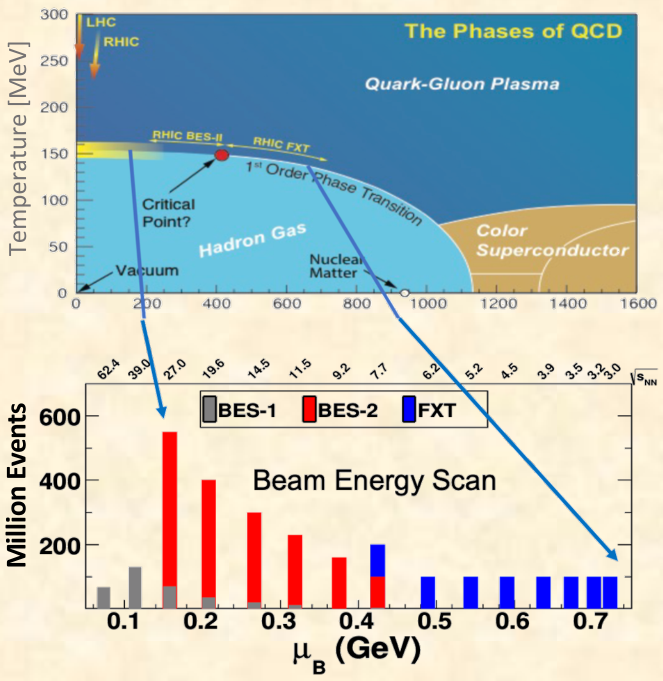
Collider	Fixed Target	AGeV	y_{CM}	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721

STAR Note 665, arXiv: 1609.05102

Phase-2 Datasets



Chuyu Liu, RHIC Retreat 2021



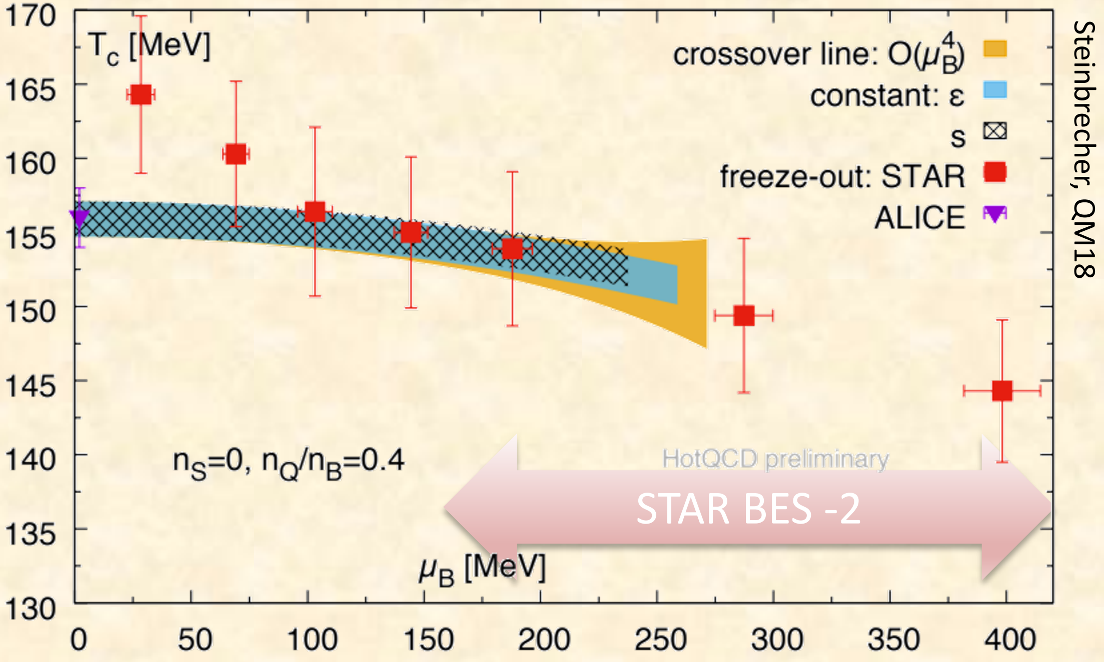
Haiyan Gao, RHIC Retreat 2021

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

Helen Caines, LBNL BES Workshop 2021

Charting the QCD Phase Diagram

- From theory:
  - cross-over starts at T_0=156.5±1.5 MeV
  - for μ_B < 250 MeV (and n_S=0, n_Q/n_B=0.4)
    - cross-over along constant ε and *s* densities
    - no indication for CP
- BES-1 data:
  - (T_{chem},μ_B) with large systematic uncertainties

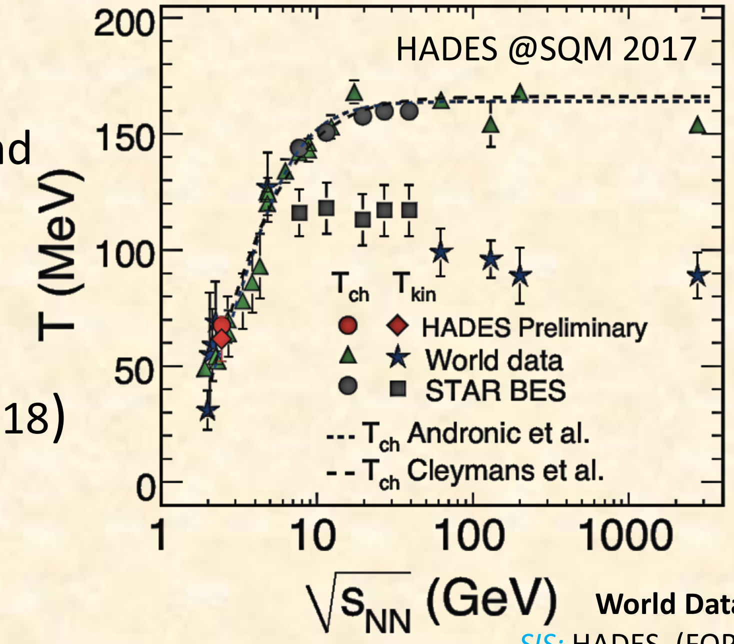


➢ BES-2 data:
  - reduce systematics in extrapolations
    - ➢ smaller uncertainties in chemical fits
  - additional data points for μ_B > 150 MeV
  - update $\sqrt{s_{NN}}$=200 GeV (Run-19)

Bulk Properties: Kinetic Freeze-out

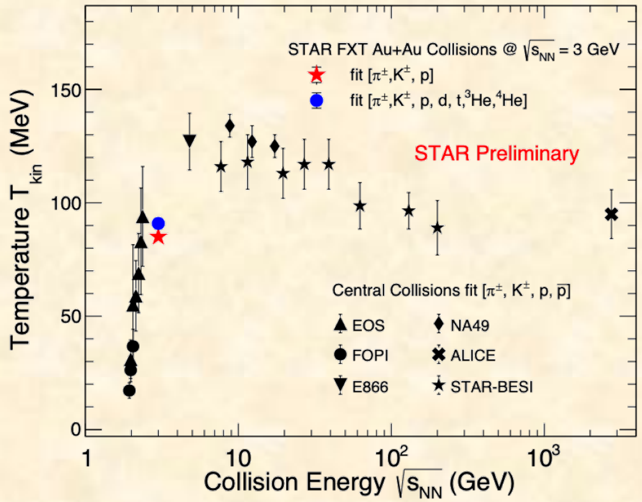
- separation between T_{kin} and T_{chem} grows with increasing energy
  - might suggest effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies
- radial flow velocity $\langle\beta\rangle$ shows rapid increase at very low energies and slower increase at higher energies

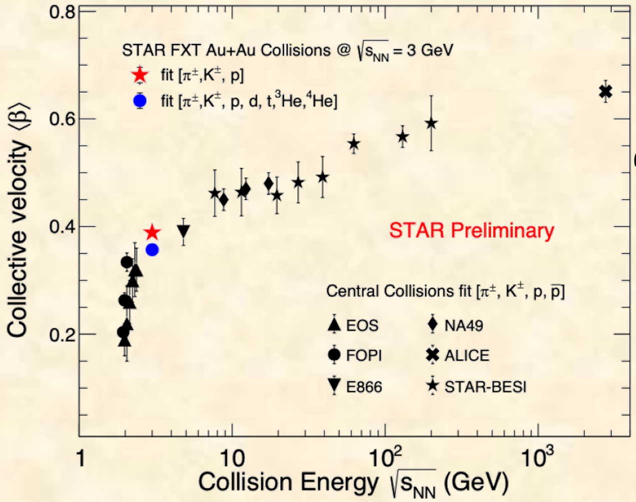
➢ recent inclusion of light nuclei (d, t, ^{3}He, ^{4}He) from $\sqrt{s_{NN}}$=3 GeV (FXT-2018)



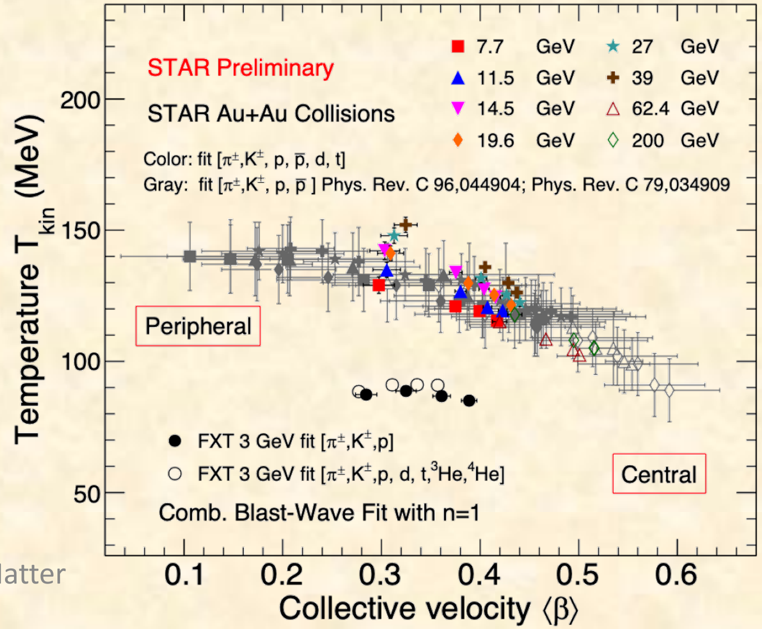
H. Schuldes, EPJ Web of Conf. 171 (2018) 01001

World Data:
SIS: HADES, (FOPI)
AGS: E802,E866, E877,E895, E917
SPS: NA49
RHIC: STAR
LHC: ALICE





H. Liu @ ISMD2021



H. Liu @ ISMD2021

- For central collisions: T_{kin} and $\langle\beta\rangle$ follow world $\sqrt{s_{NN}}$ trend

➢ Centrality differential shows different trend
  - compared to higher $\sqrt{s_{NN}}$

Onset of deconfinement

NA49 [PRC 77 (2008) 024903]: onset of deconfinement at $\sqrt{s_{NN}}$ =7.7GeV

STAR BES-1: Nuclear modification factor R_{CP}

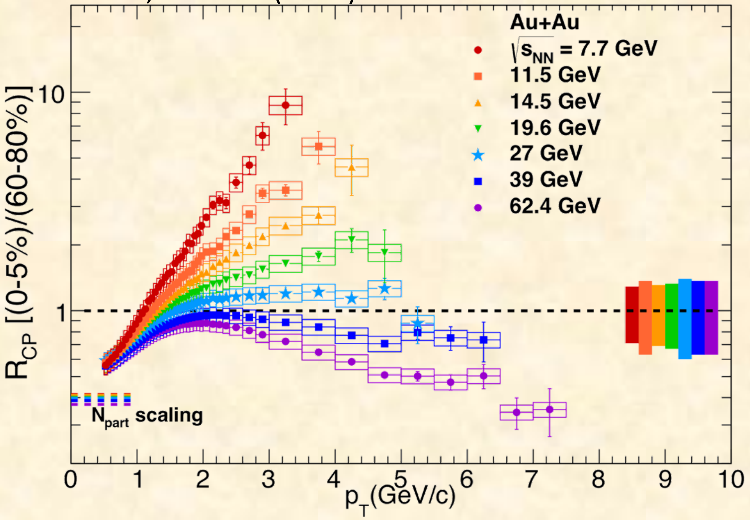
- smooth transition from suppression (high $\sqrt{s_{NN}}$), to enhancement (low $\sqrt{s_{NN}}$)
- below $\sqrt{s_{NN}}$ = 39 GeV no suppression? Turn-off?

  or, competition with enhancements from Cronin effect, flow, etc.

➢ R_{CP} > 1 does not mean "no QGP"

$$Y(\langle N_{part} \rangle) = \frac{B}{\langle N_{coll} \rangle} \frac{d^2N(\langle N_{part} \rangle)}{dp_T d\eta}$$

STAR, PRL 121 (2018) 032301

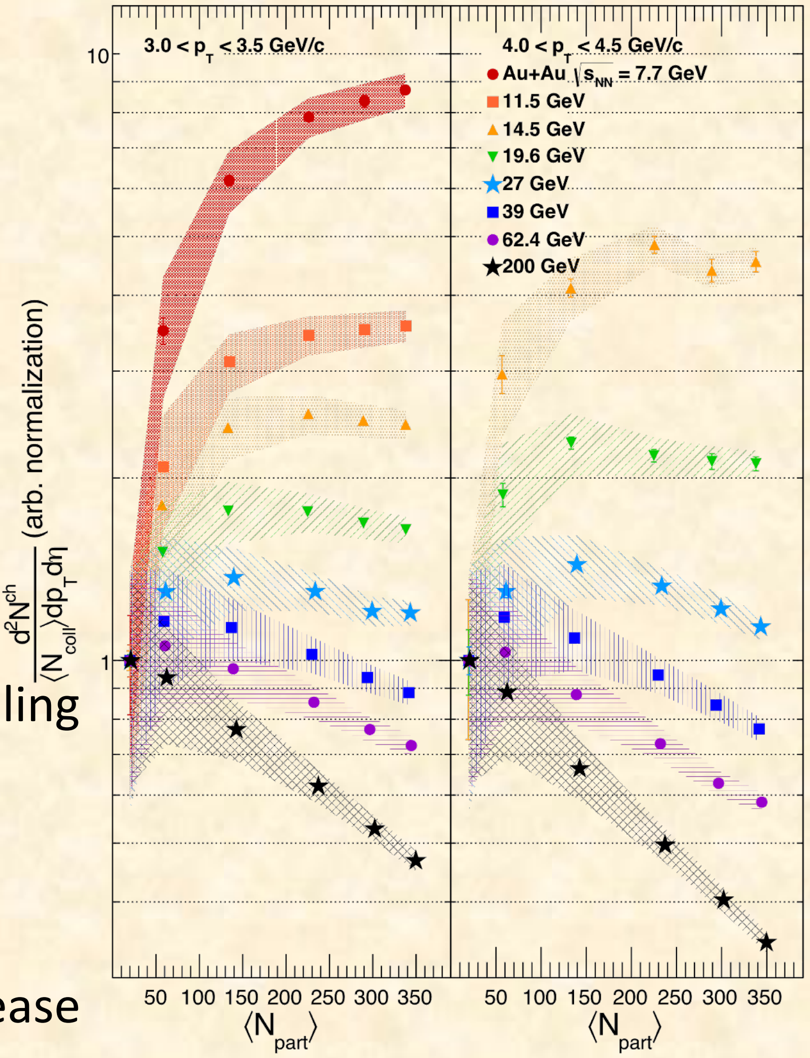


A more differential approach, look at N_{part} scaling

- ≥ 39 GeV : monotonic decrease
  - ➢ suppression > enhancement
- ≤ 11.5 GeV: monotonic increase
  - ➢ enhancement > suppression
- 14.5 – 27 GeV: increase, followed by decrease
  - ➢ enhancement grows fast, but
  - ➢ suppression dominates

➢ Suppression observed down to $\sqrt{s_{NN}}$ =14.5 GeV

STAR, PRL 121 (2018) 032301

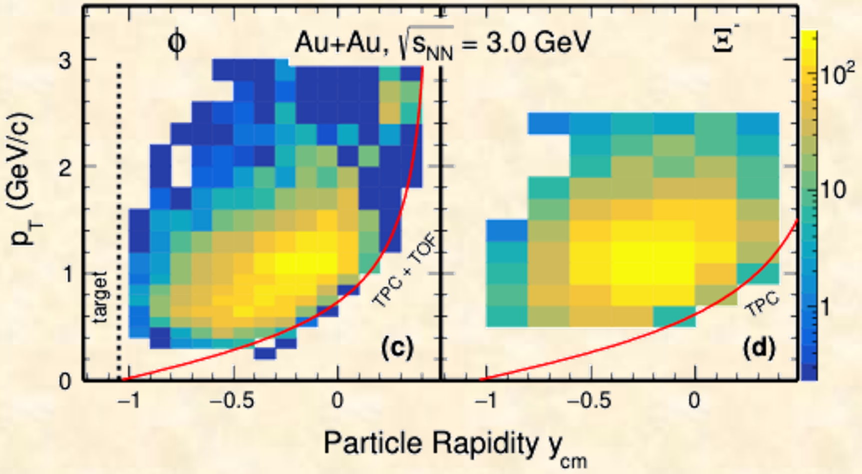


❖ BES-2: expect precision to disentangle

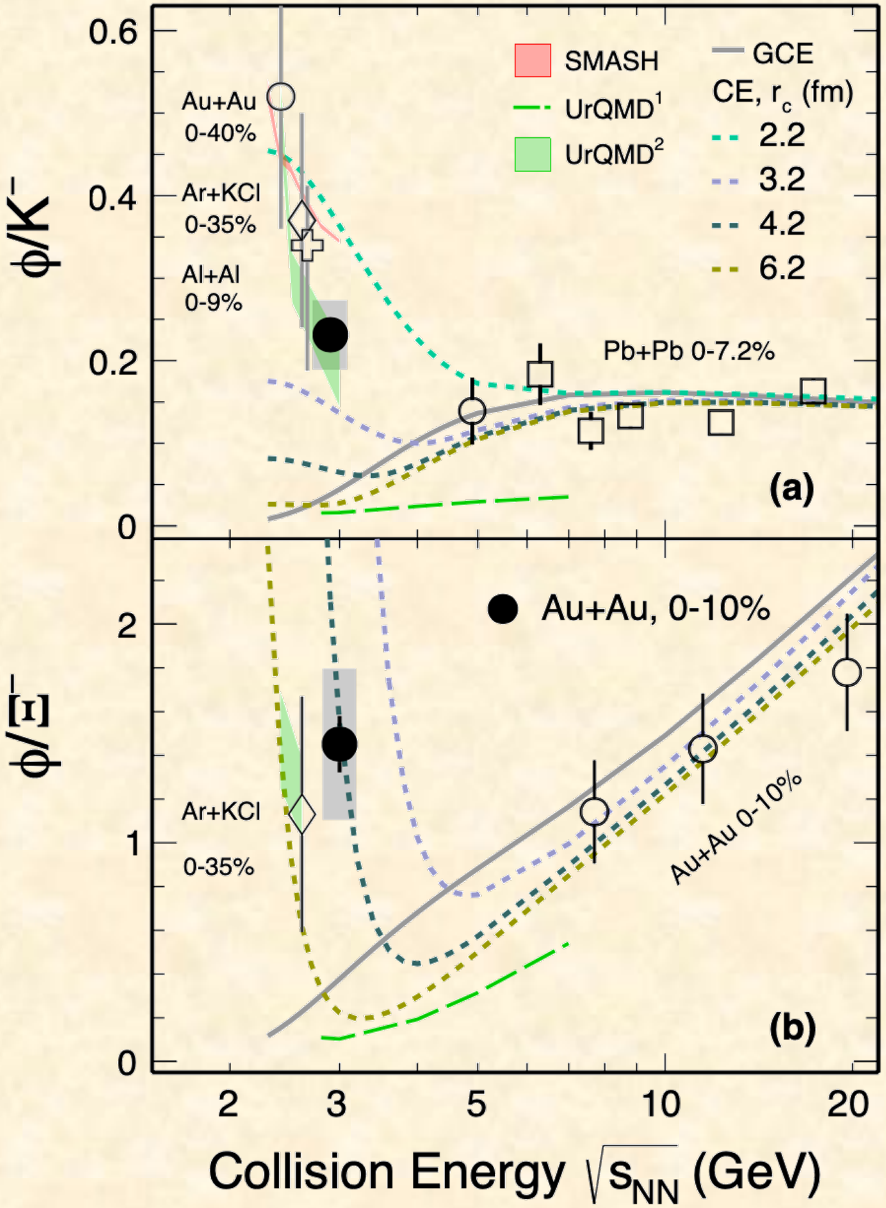
Probing Canonical Production

STAR, arXiv:2108.00924

- First multi-differential φ and Ξ at $\sqrt{s_{NN}}$= 3 GeV (FXT)
  - ➢ p_T and *y* spectra

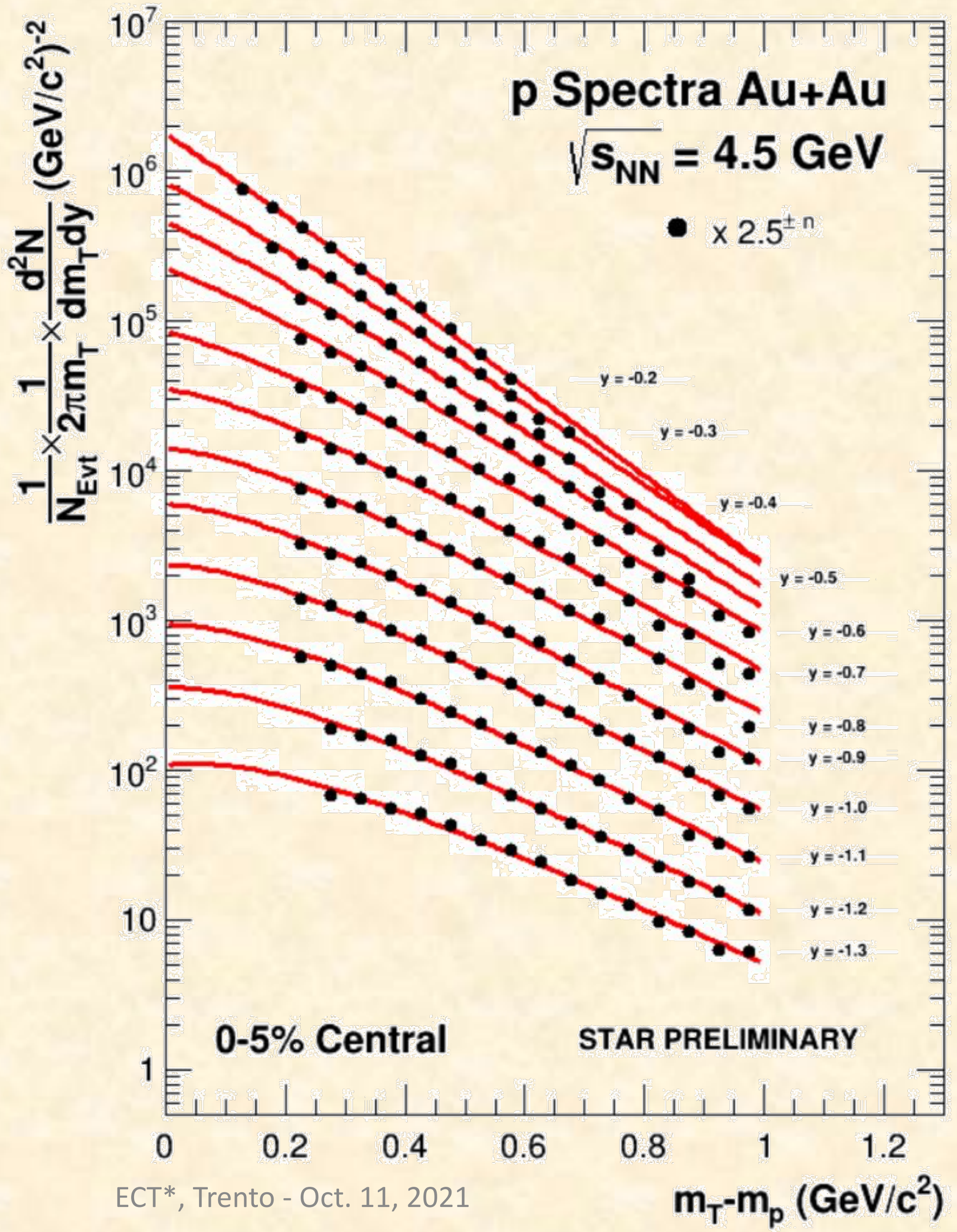


- Collision energy is close to threshold for φ and below threshold for Ξ
  - ➢ local treatment of strangeness conservation is very important
- thermal particle phase space far from GCE limit
- Canonical ensemble prefers small r_C < 4.2 fm
  - – cannot simultaneously describe φ/K⁻ and φ/Ξ⁻

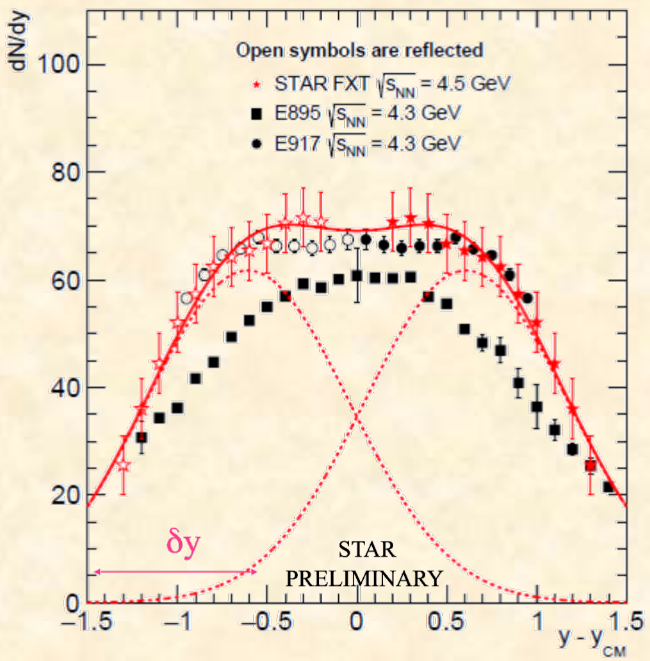


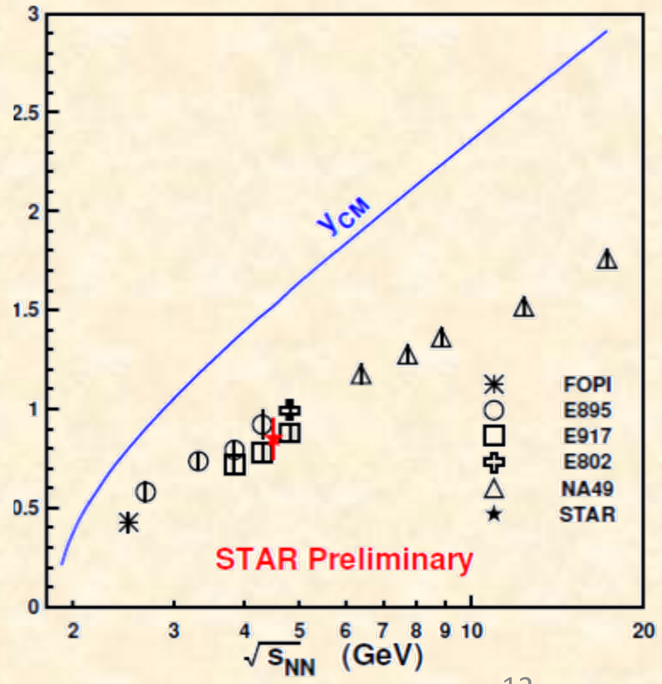
Expanding Rapidity Coverage

D. Cebra, April APS 2021



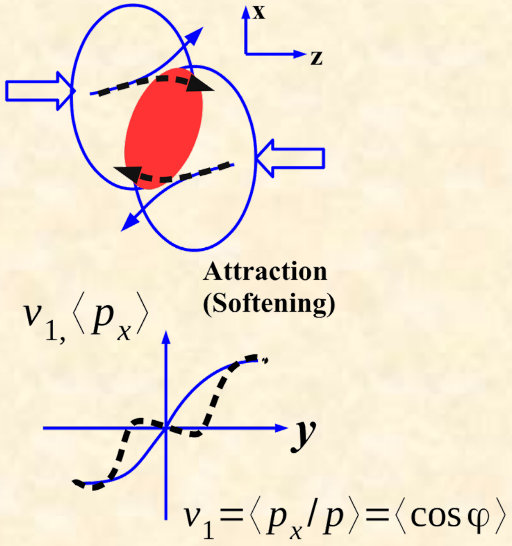
- BES-2 plans on reporting rapidity distributions
  - protons from $\sqrt{s_{NN}}$=4.5GeV (FXT) consistent with E917
- baryon stopping systematics
  - amount of stopping determines μ_B
  - Ivanov (PRC87 (2013) 064904): potentially reveal 1st order PT, softening of EoS
  - more precision measurements needed :: BES-2





Proton Directed Flow

[Akira Ohnishi, CPOD 2016]



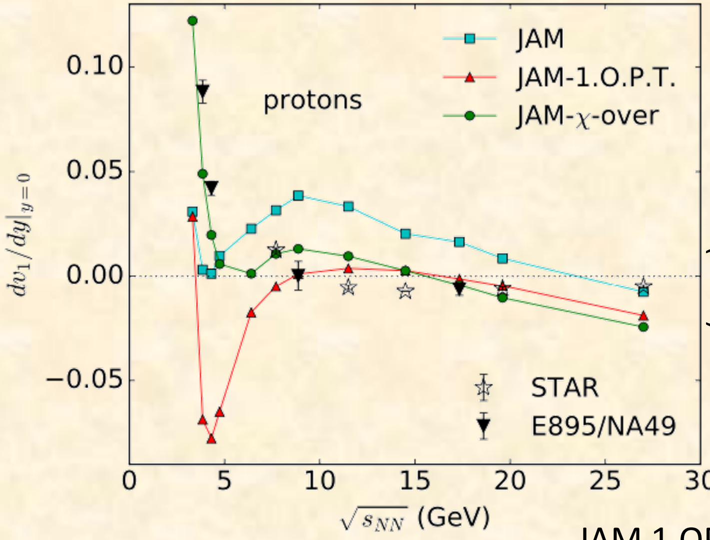
- directed flow v_1 describes sideward collective motion
  - sensitive to the EoS

[Yasushi Nara *et al.*, PRC 94 034906 (2016)]

- non-monotonic dependence
  - softening (crossover or 1st order phase transition)
  - geometry (tilted ellipsoid expansion)
    - ➢ relevant at $\sqrt{s_{NN}} \gtrsim 27$ GeV)
  - transport

➢ minimum in slope dv_1/dy of baryons in presence of 1st order PT

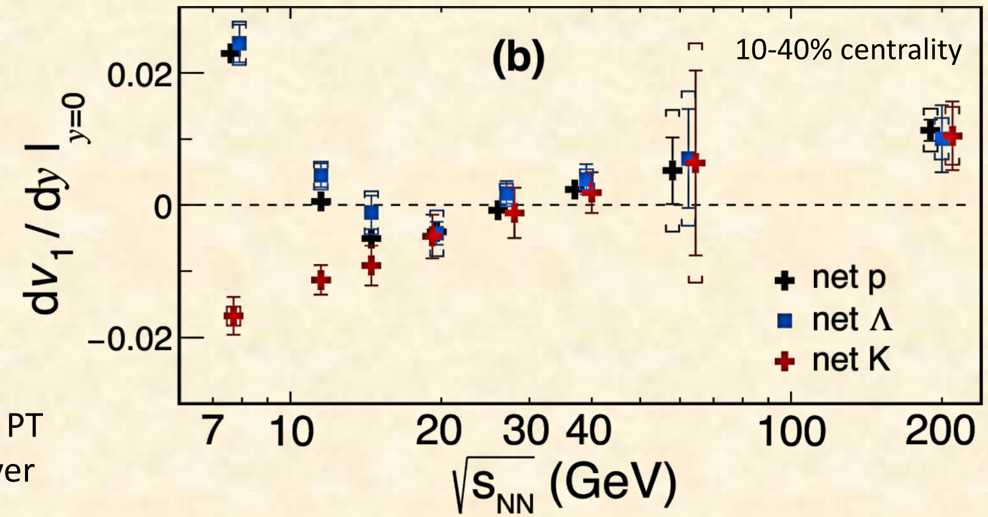
- "net-protons" help isolate transported baryons



Nara *et al.* PLB769(2017)543

JAM 1.OPT :: 1st order PT
JAM-X-over :: cross-over
JAM :: no transition

STAR, PRL 120 (2018) 062301



- Double sign change around 15 GeV

➢ BES-2 :: more statistics
  - fine centrality binning (~5%)

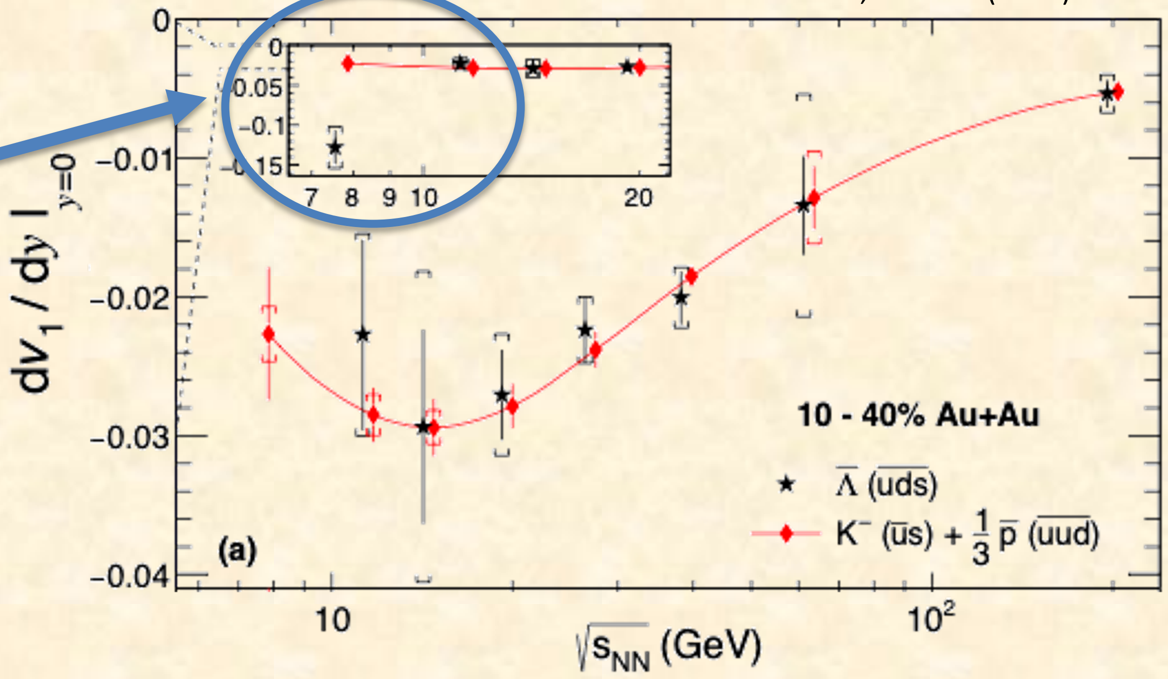
Testing the Coalescense Sum Rule

- If v_1 develops in a pre-hadronic stage
  - *and* hadrons are formed via coalescence
  - *and* $v_1(\bar{u}) = v_1(\bar{d})\,,\;\; v_1(s) = v_1(\bar{s})$
- then expect $\bar{\Lambda}$ v_1 from K and p:

  $K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\overline{uud})$

➢ picture breaks down below 11.5 GeV

STAR, PRL 120 (2018) 62301

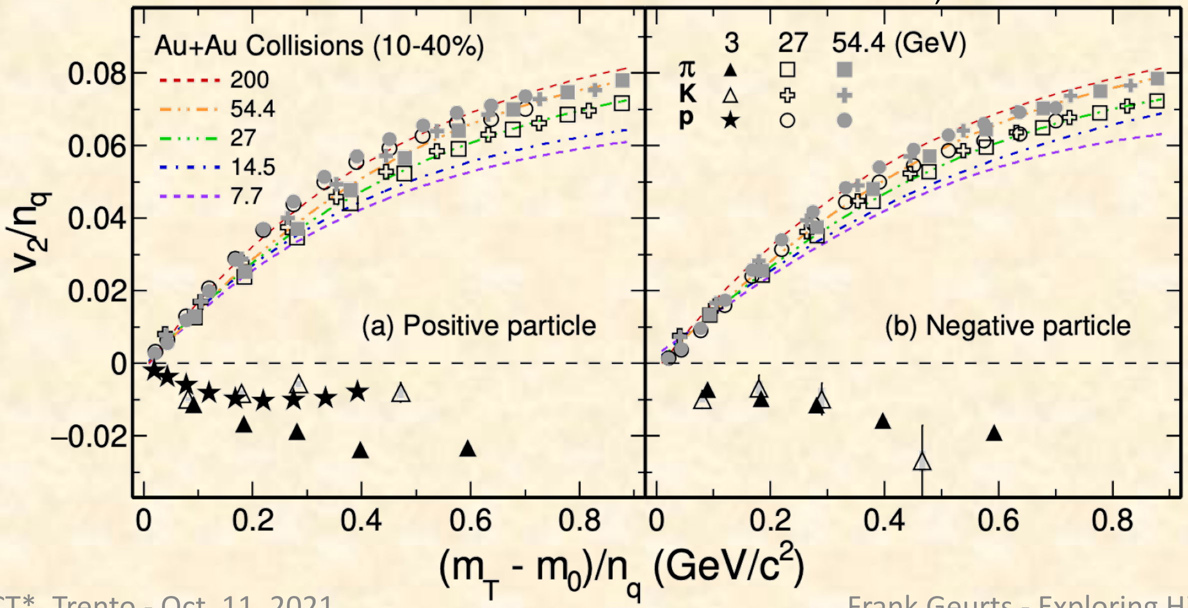


❖ BES-2 :: additional energy between 7.7 and 11.5GeV + lower FXT energies

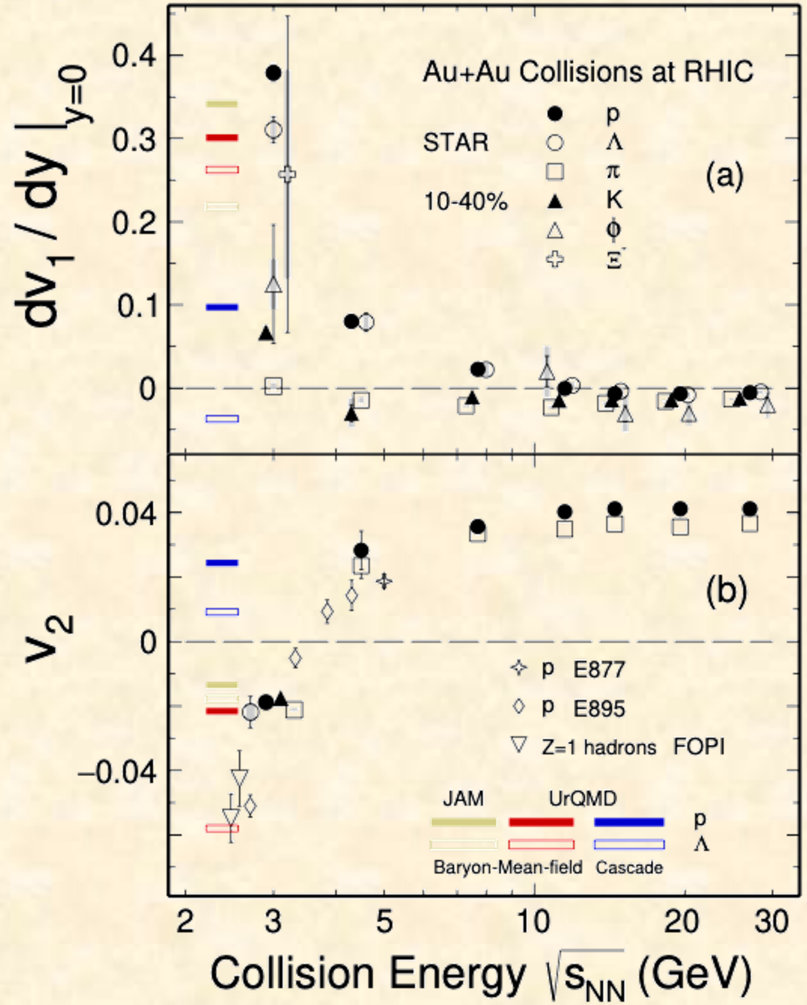
The Disappearance of Partonic Collectivity

- NCQ scaling not observed at $\sqrt{s_{NN}}$= 3 GeV
- v_2 is negative for all particles (out of plane)
  - positive for $\sqrt{s_{NN}} \geq 4.5$ GeV
- v_1 slopes are positive for all particles
  - negative for $\sqrt{s_{NN}} \geq 10$ GeV
- Qualitatively reproduced by transport models that include baryonic mean-fields

STAR, arXiv:2108.00908



STAR, arXiv:2108.00908

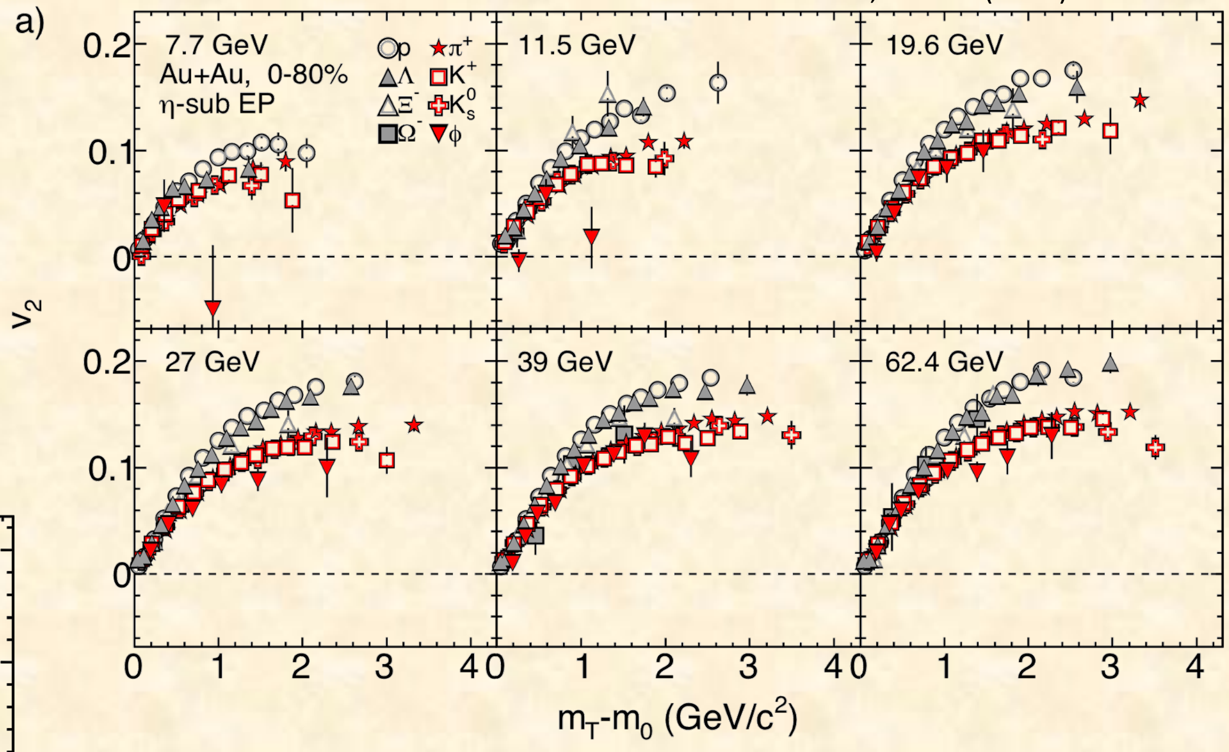


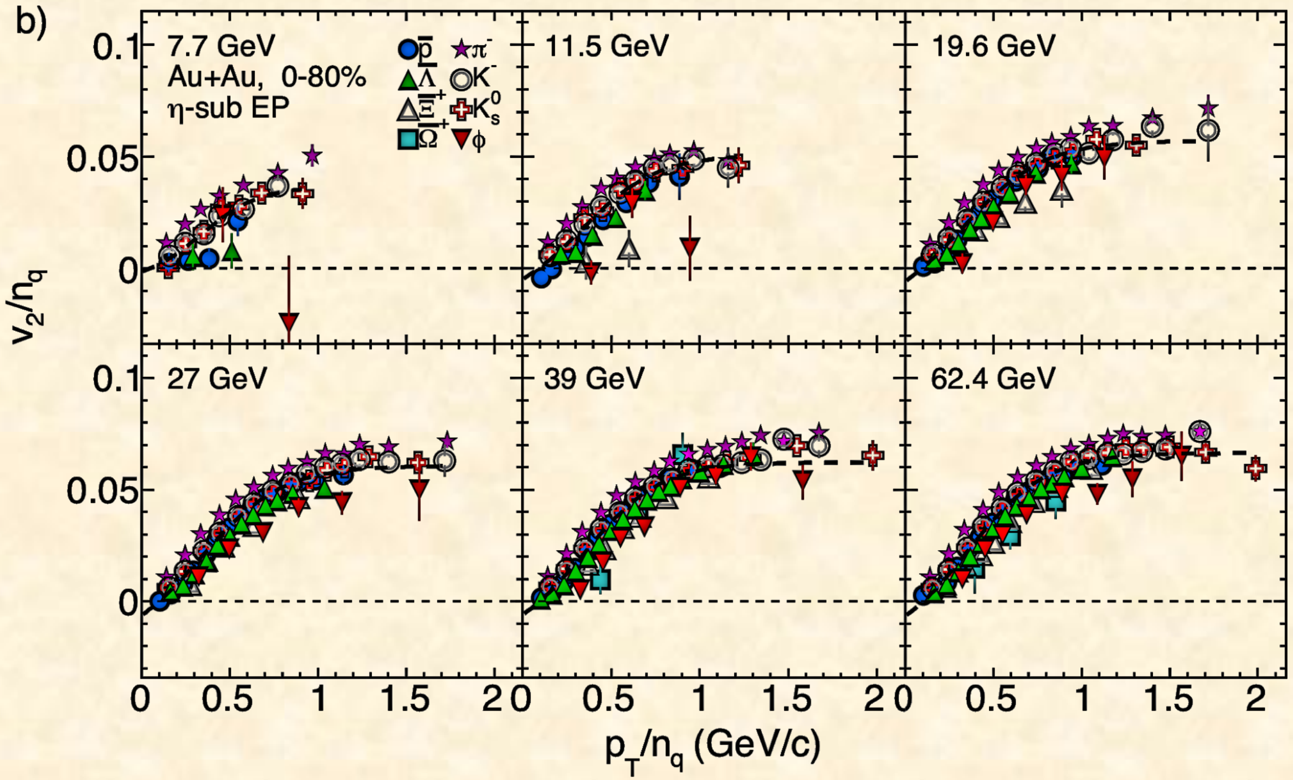
Baryonic interactions dominate, not partonic

The case for the ϕ meson

STAR, PRC 88 (2013) 014902

- v_2 shows mass ordering for $p_T < 2$ GeV/c
- baryon-meson splitting for $p_T > 2$ GeV/c
  - ➢ indicative of partonic collectivity, NCQ-scaling





But, at low energies:

- ϕ meson hints at a departure
- ϕ has a small hadronic scattering cross section
  - ➢ hadronic interactions more important for $\sqrt{s_{NN}}$ =7.7 and 11.5 GeV?
  - ❖ BES-2 will provide for more statistics

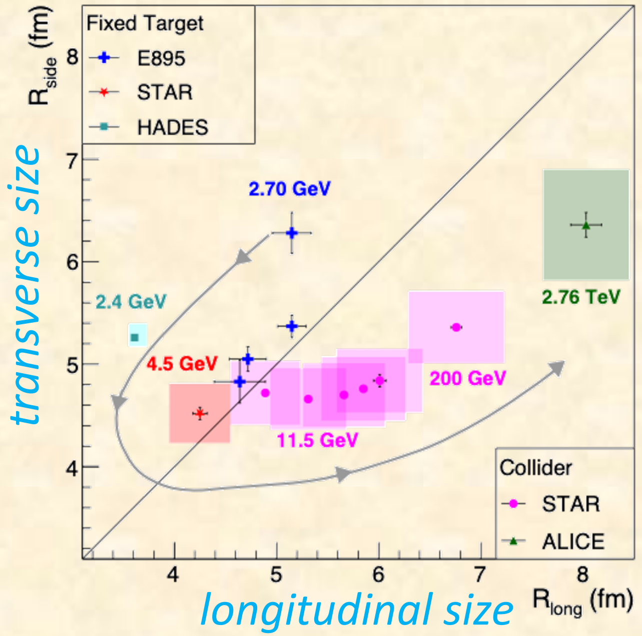
Femtoscopic Probes

- Show transition from stopping (oblate) to boost-invariant (prolate source) dynamics
  - at $\sqrt{s_{NN}}$= 4.5 GeV : $R_{side}\approx R_{long}\approx$ 4.5 fm
- R_{out} = transverse size + emission duration
  $\beta^2 t^2 = R_{out}^2 - R_{side}^2$ (if no collective flow)

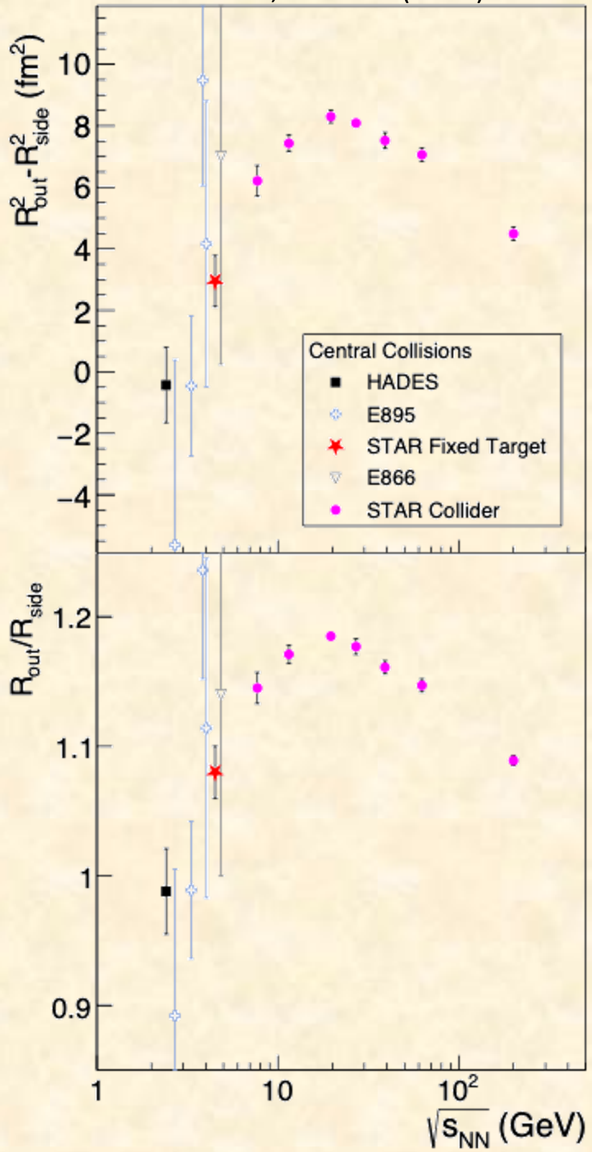
Expect increase of R_{out} relative to R_{side} to reflect extended emission time scale

- may occur if system evolves through 1st order phase transition

➢ combination of STAR and HADES data reveals peak structure

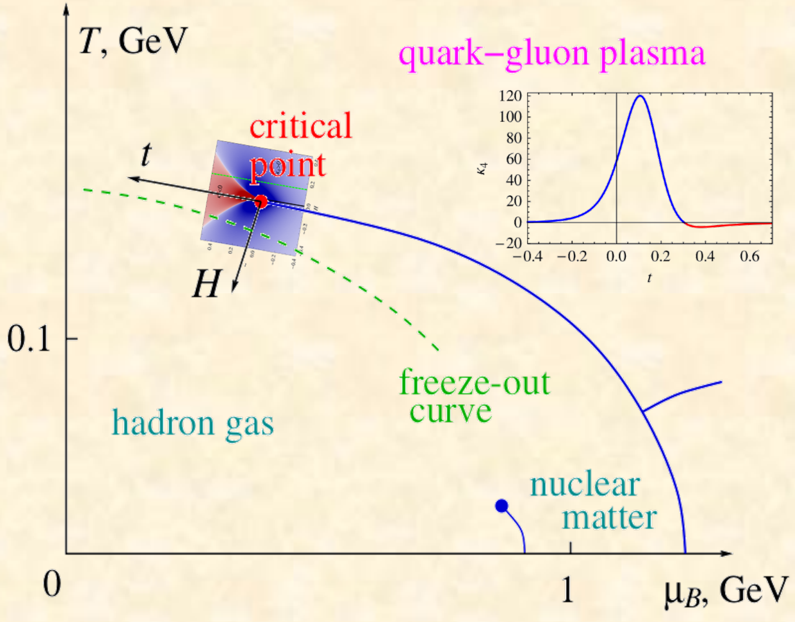


STAR, PRC 103 (2021) 034908



Critical Fluctuations

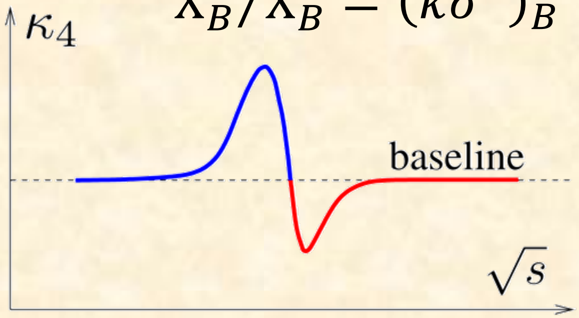
- ➢ At low μ_B: smooth cross-over
  - – test with higher-order cumulants
- ➢ At high μ_B : indications of 1st order phase transition
- Critical Point in a region accessible by heavy-ion collisions?
  - – can it be experimentally discovered?
- Look for the divergence of susceptibilities
  - – or divergence of correlation lengths
  - – non-monotonic behavior of correlations/fluctuations related to conserved quantities, *e.g.* baryon number
- Relate moments of experimentally measurable multiplicity distributions to ratios of susceptibilities



Stephanov, PRL 107 (2011) 052301

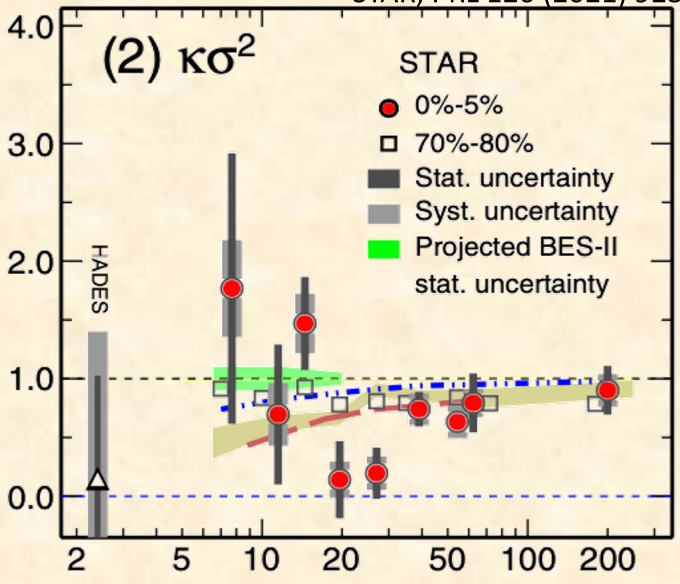
$$X_B^{(n)} = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\Big|_T$$

$$X_B^4 / X_B^2 = (\kappa\sigma^2)_B$$



Stephanov, CPOD2014

STAR, PRL 126 (2021) 92301



➢ Hints of critical fluctuations

BES-2 data sets with iTPC & EPD

- increase Δy_p acceptance with iTPC
- improve centrality selection with EPD
  - use TPC for measurements
- access to net-kaon

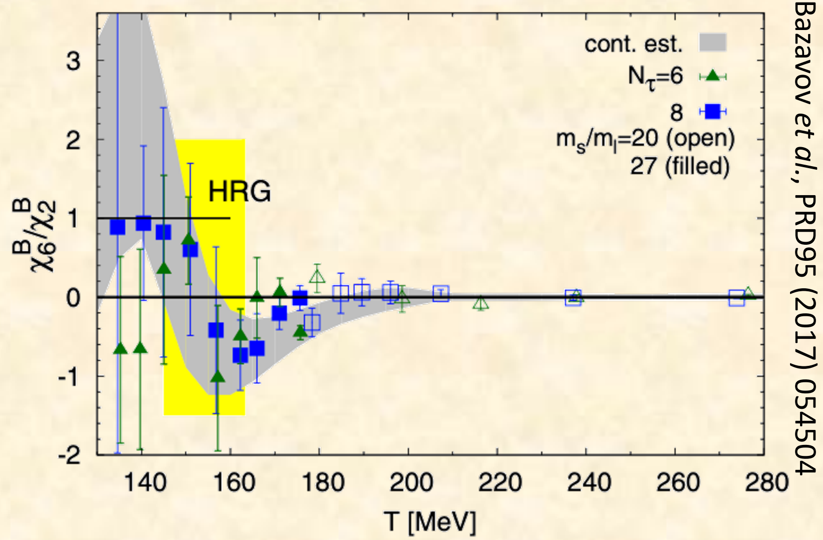
❖ STAR will only release final results

Critical Fluctuations

- At low μ_B: smooth cross-over
  - test with higher-order cumulants: expected to be negative

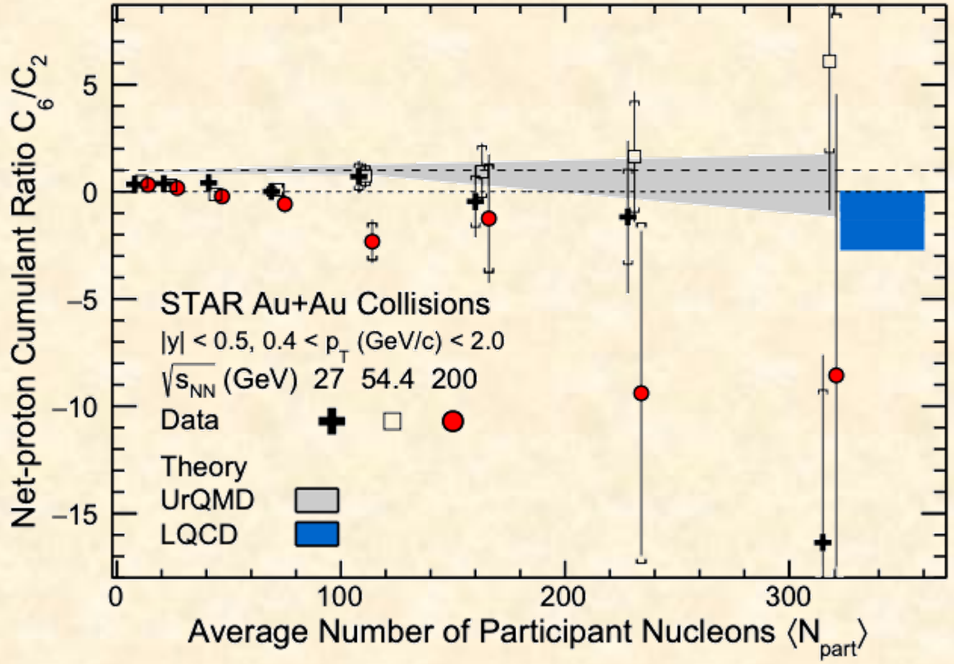
➢ First measurement of net-proton C6/C2
  - statistics limited
  - consistent with 0 for $\sqrt{s_{NN}}$= 27 and 54.5 GeV
  - negative in more central collisions for $\sqrt{s_{NN}}$=200 GeV
    - *caveat*: exp. data involves kinematic cuts that are not incorporated in the lattice calculations

❖ Suggestive of a smooth cross-over at top RHIC energies



Bazavov *et al.*, PRD95 (2017) 054504

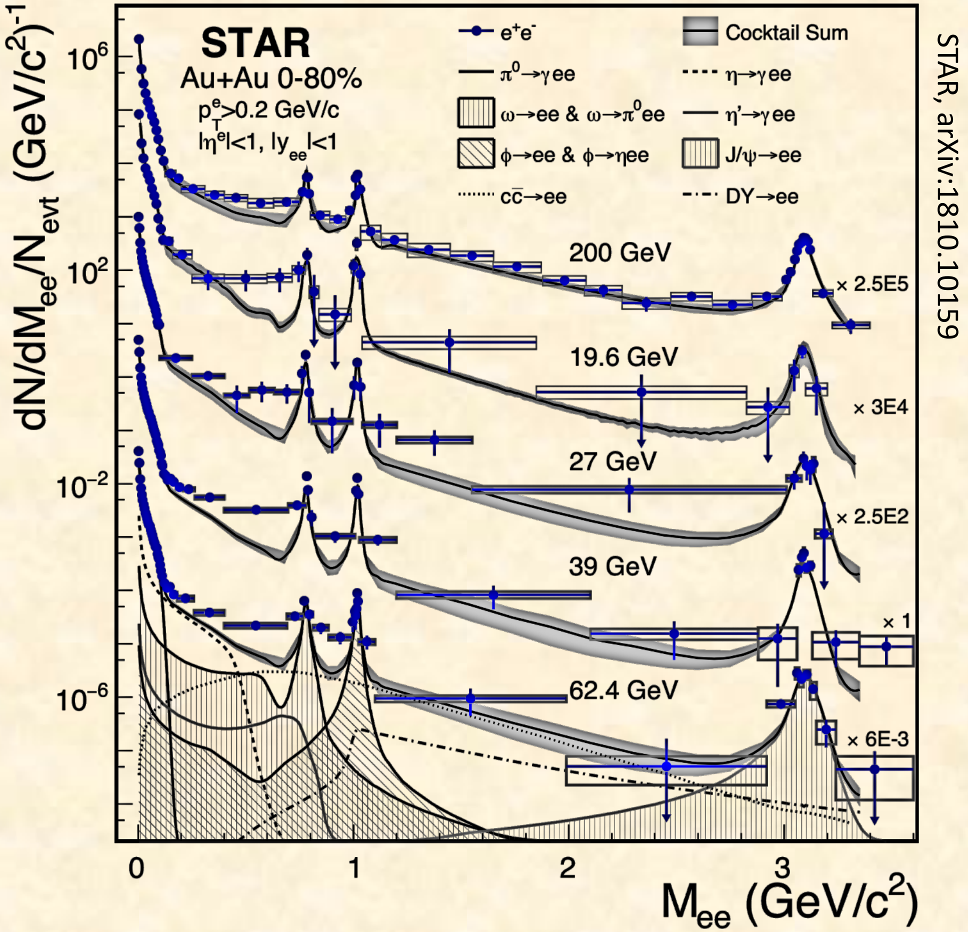
STAR, arXiv:2105:14698

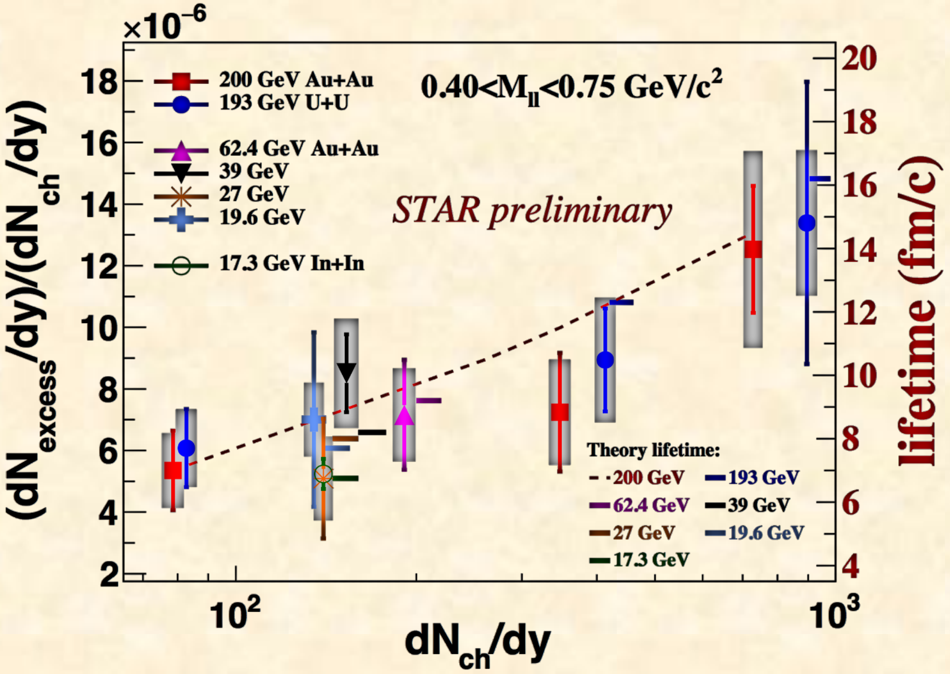


Critical Point: Lifetime Increase

- Dilepton yields sensitive to lifetime of the system
  - close to Critical Point expect increase in correlation lengths
  - critical slowing down? *anomalous* increase in the lifetime of the fireball?

➢ Can we observe this in an increase of e^+e^- rates?





NA60 life time measurement with uncertainty ±1 fm/c (“ρ clock”) [Rapp, Adv. High Energy Phys. 2013 148253]

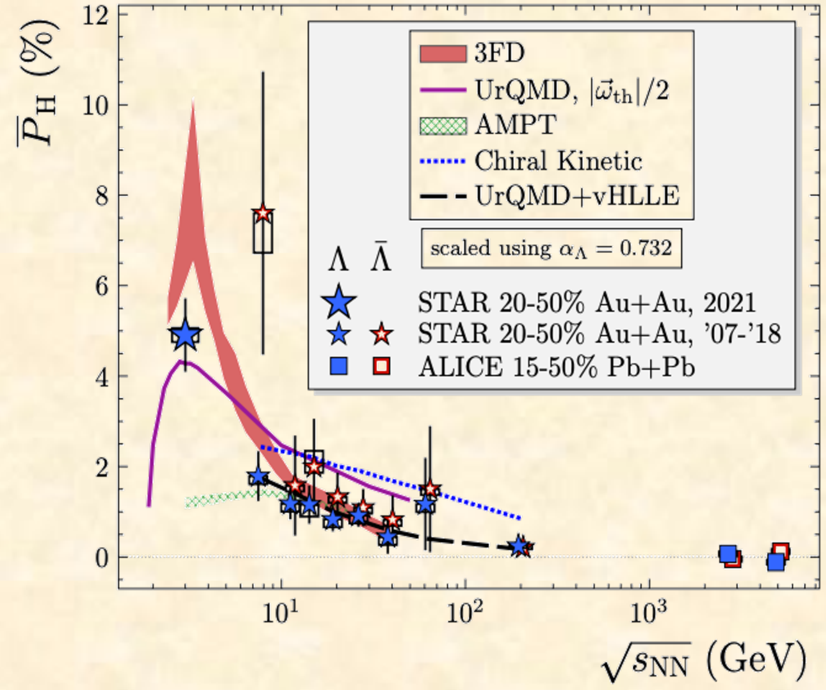
➢ STAR BES (19.6 – 200 GeV)

- no critical slowing-down in calculations
- smooth increase from 8 – 10 fm/c

Global Hyperon Polarization in FXT

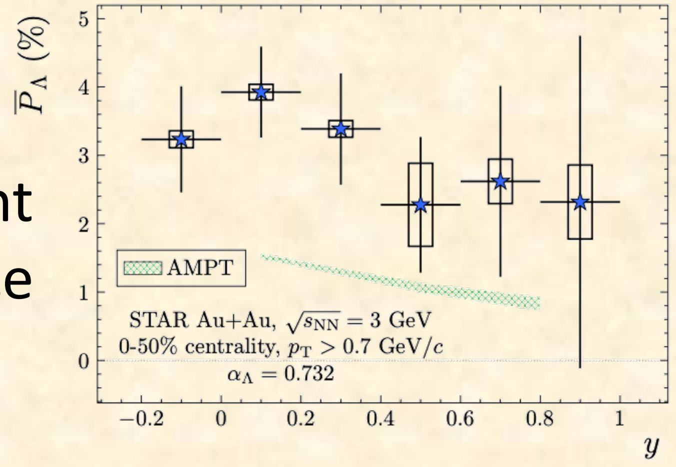
STAR, arXiv: 2108:00044

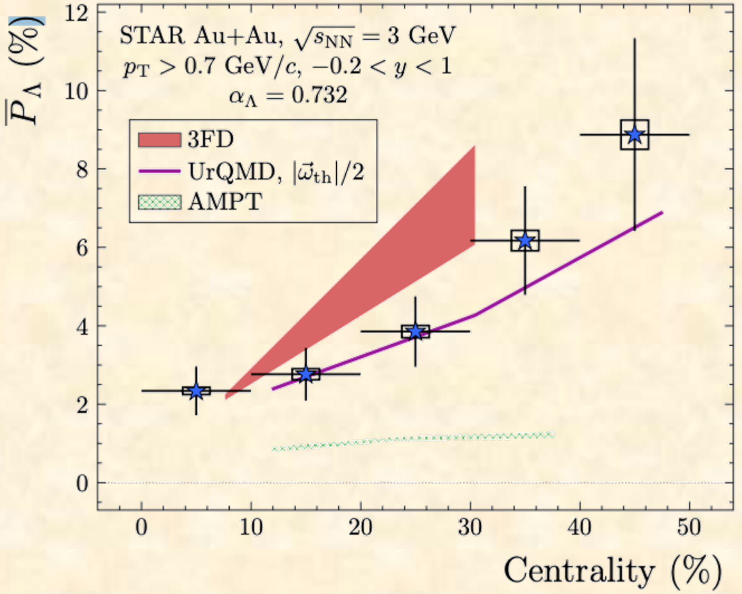
- At $\sqrt{s_{NN}}$= 3 GeV largest global Λ polarization
  - $\bar{P}_\Lambda = 4.91 \ \pm 0.81(\text{stat}) \pm 0.15 \ (\text{syst}) \ \%$
- Observation is consistent with 3FD and UrQMD (hadronic transport)
  - inconsistent with AMPT (partonic transport)
  - while UrQMD overestimates at higher $\sqrt{s_{NN}}$



➢ Does formation of vortical flow not depend on presence of QGP?

➢ No statistically significant rapidity dependence

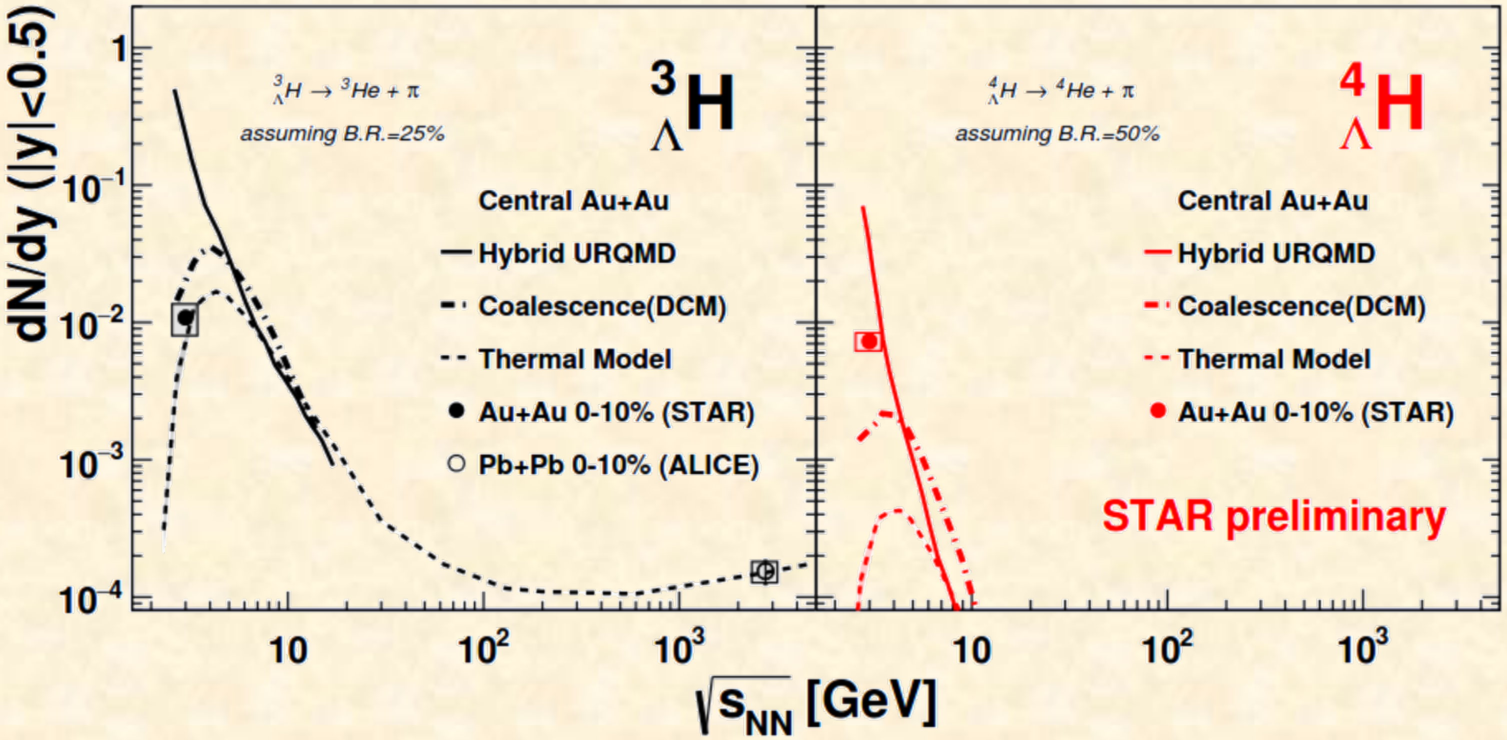


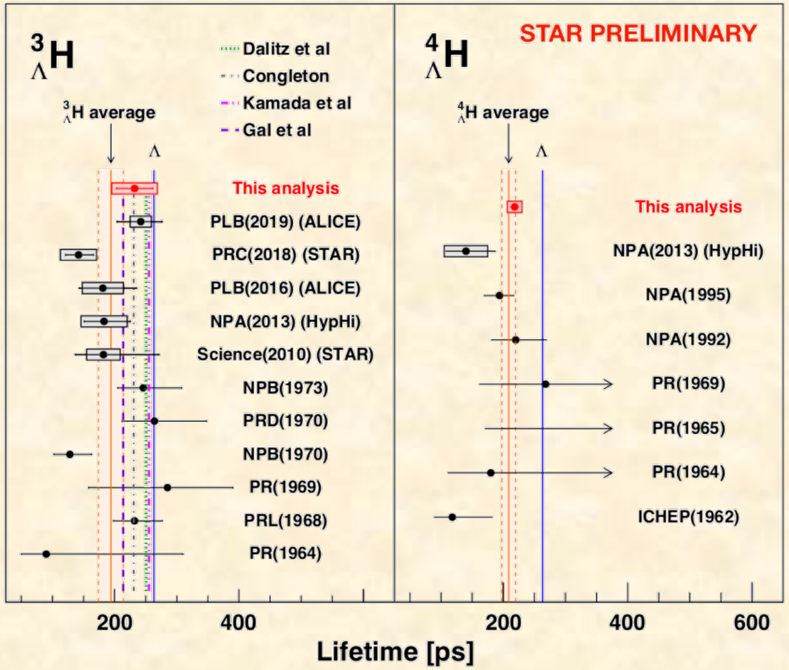


Hypernuclei Yields from Au+Au @ $\sqrt{s_{NN}}$=3 GeV

Expect significant increase in production of hypernuclei

- Thermal model with canonical ensemble (GSI-Heidelberg) and coalescence model (DCM) describe ${}^{3}_{\Lambda}H$
- ➢ Yields of ${}^{4}_{\Lambda}H$ not described by both models





Lifetime measurements from 3GeV:

- ${}^{3}_{\Lambda}H$ consistent with previous results
- ${}^{4}_{\Lambda}H$ most precise measurement to day, and consistent with previous results

Summary

- RHIC Beam Energy Scan plays an essential role in charting the QCD phase diagram
  - Phase-1: hints at low $\sqrt{s_{NN}}$ of QGP turn-off, ordered phase transition, and a critical point
  - Phase-2 including a fixed-target program: specific focus on lower $\sqrt{s_{NN}}$
- Excellent performance from Phase-2 upgrades
  - both at STAR and RHIC
- All BES-2 datasets have been successfully collected
  - providing 17 unique energies from 3 – 200 GeV
  - overlapping collider and FXT energies allow for analysis cross-checks
- First (preliminary) results from Au+Au @ $\sqrt{s_{NN}}$=3GeV submitted
  - Expect more exciting results from precision analyses to follow soon