Probes of High Density QCD

Xin Dong

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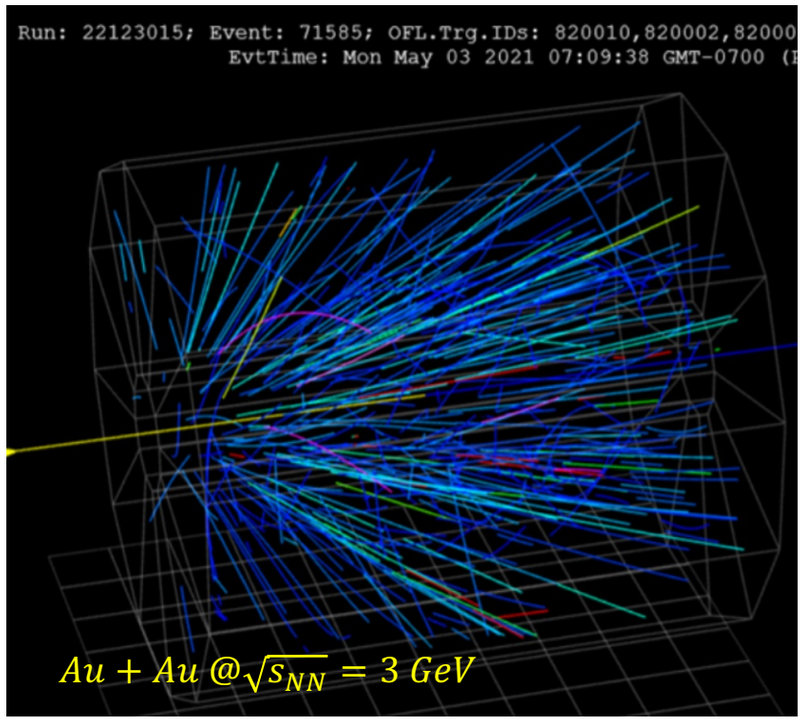
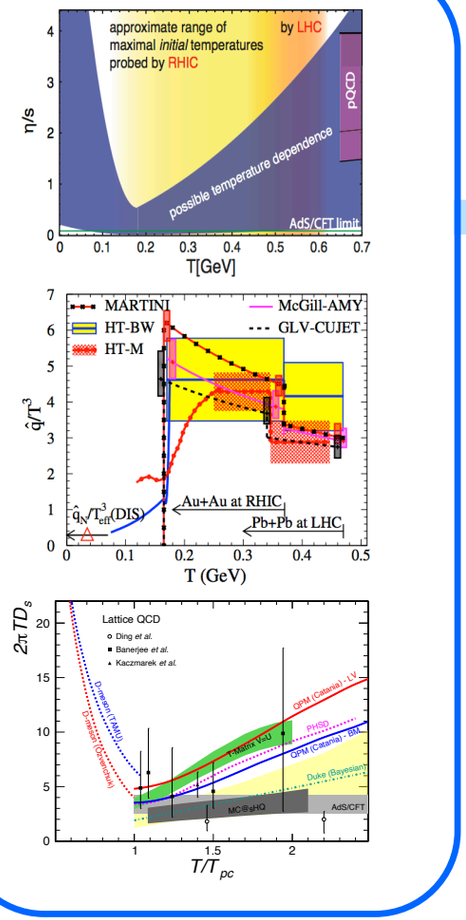


- Introduction
- RHIC Beam Energy Scan Phase-II
- Physics Highlights from RHIC BES
- Future Program at FAIR/CBM
- Summary

QCD Phase Diagram and Heavy-Ion Frontiers

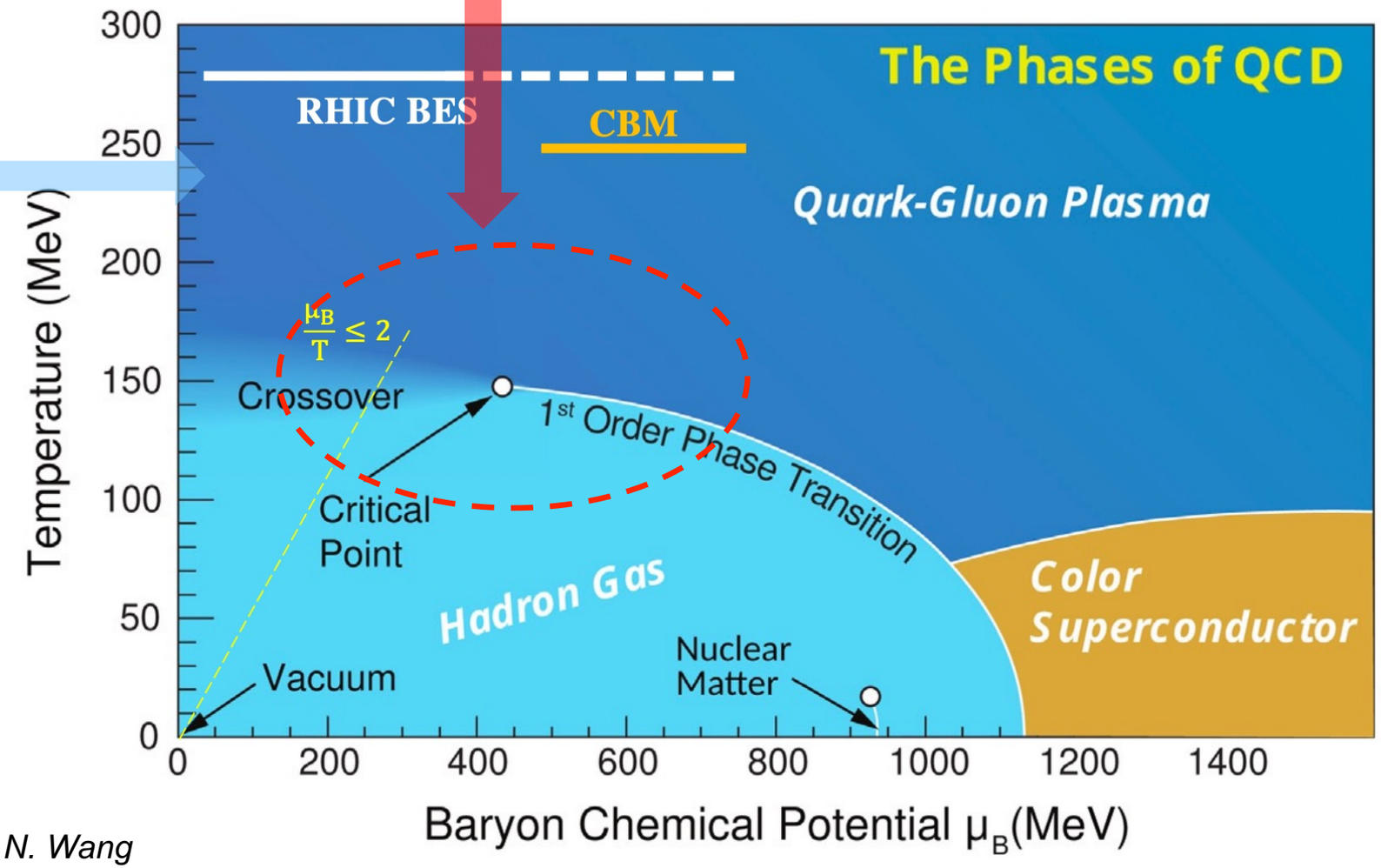
QGP Properties @ $\mu_B \sim 0$



QCD Phase Structure @ finite μ_B

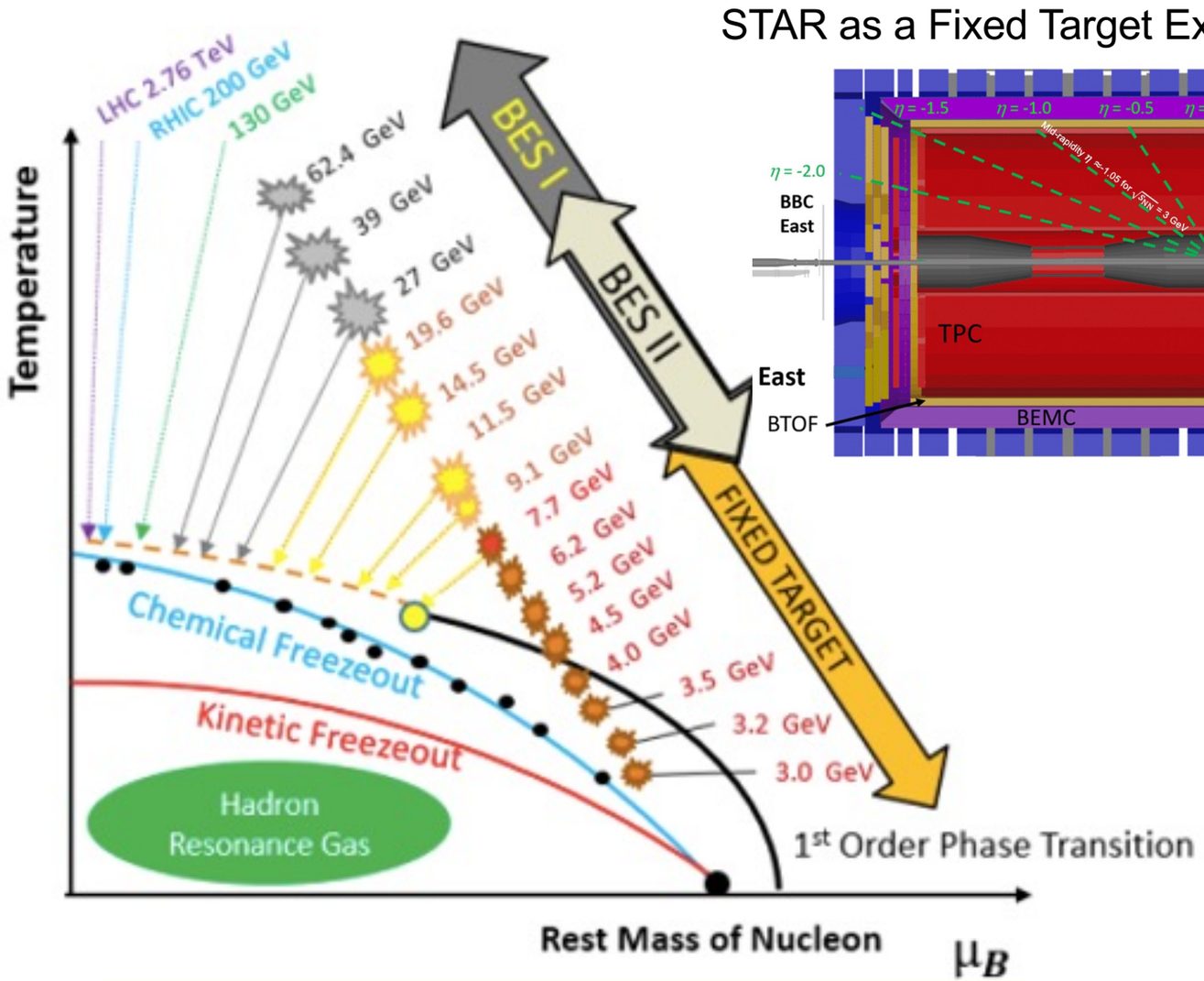
Lattice: crossover at $\mu_B/T<2$

See talks by J. Noronha-Hostler and C. Ratti

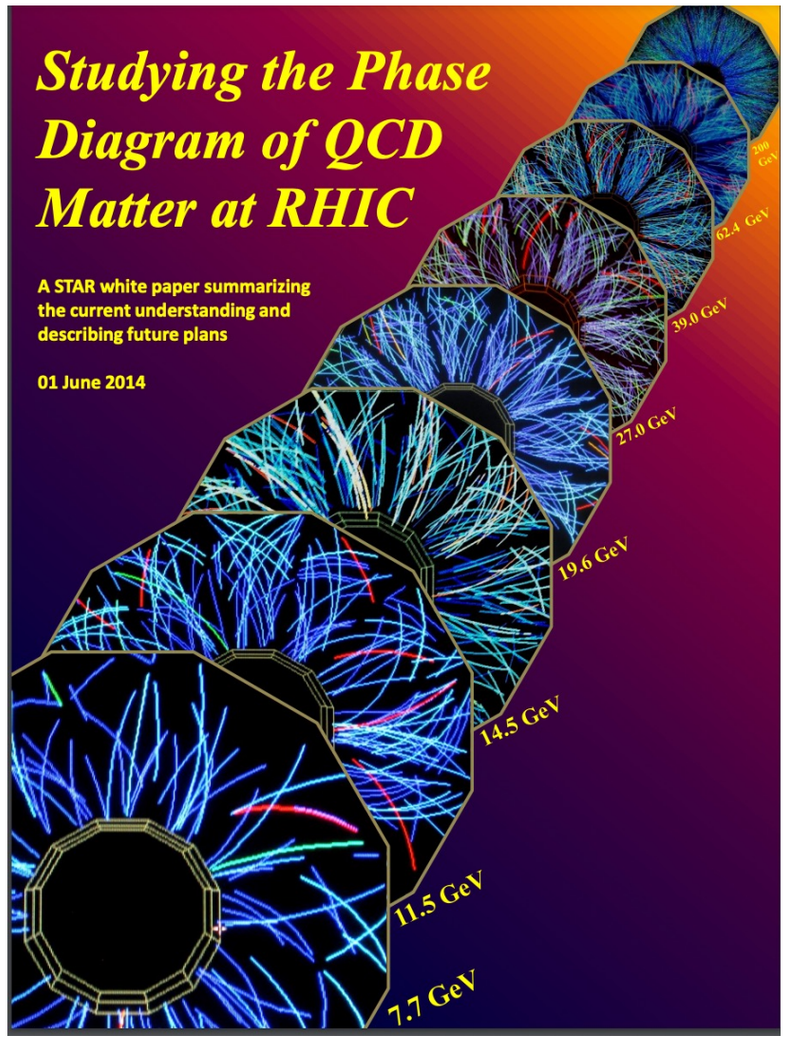


See talks by D. Perepelitsa and X.N. Wang

RHIC Beam Energy Scan (BES) Program



STAR as a Fixed Target Experiment

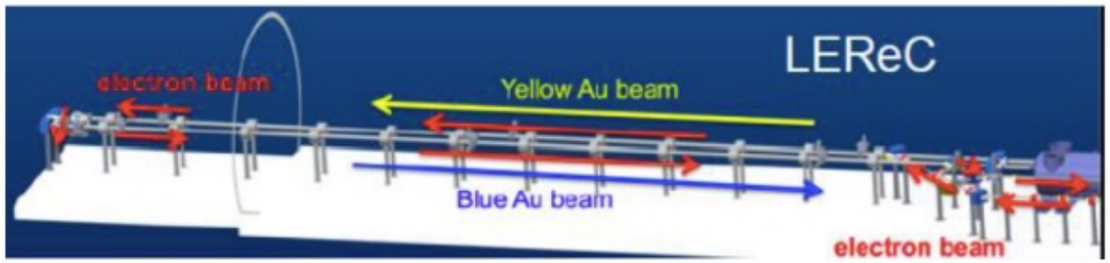


BES-II with high statistics at 7.7-19.6 GeV
- Recommendation from LRP 2015

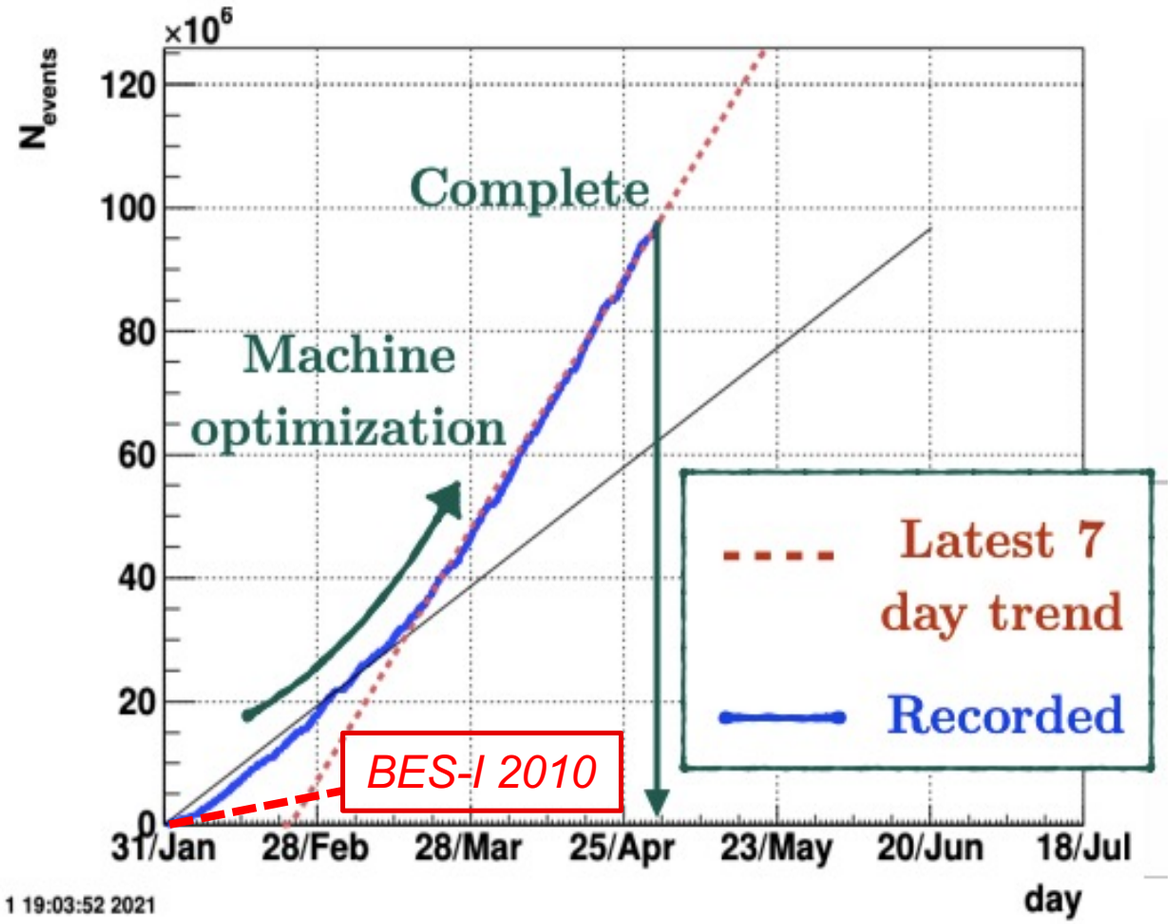
STAR note 0598
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Beam Energy Scan Phase-II: Successful Data Taken

LEReC – Low Energy RHIC electron Cooling



Au+Au 7.7 GeV in 2021



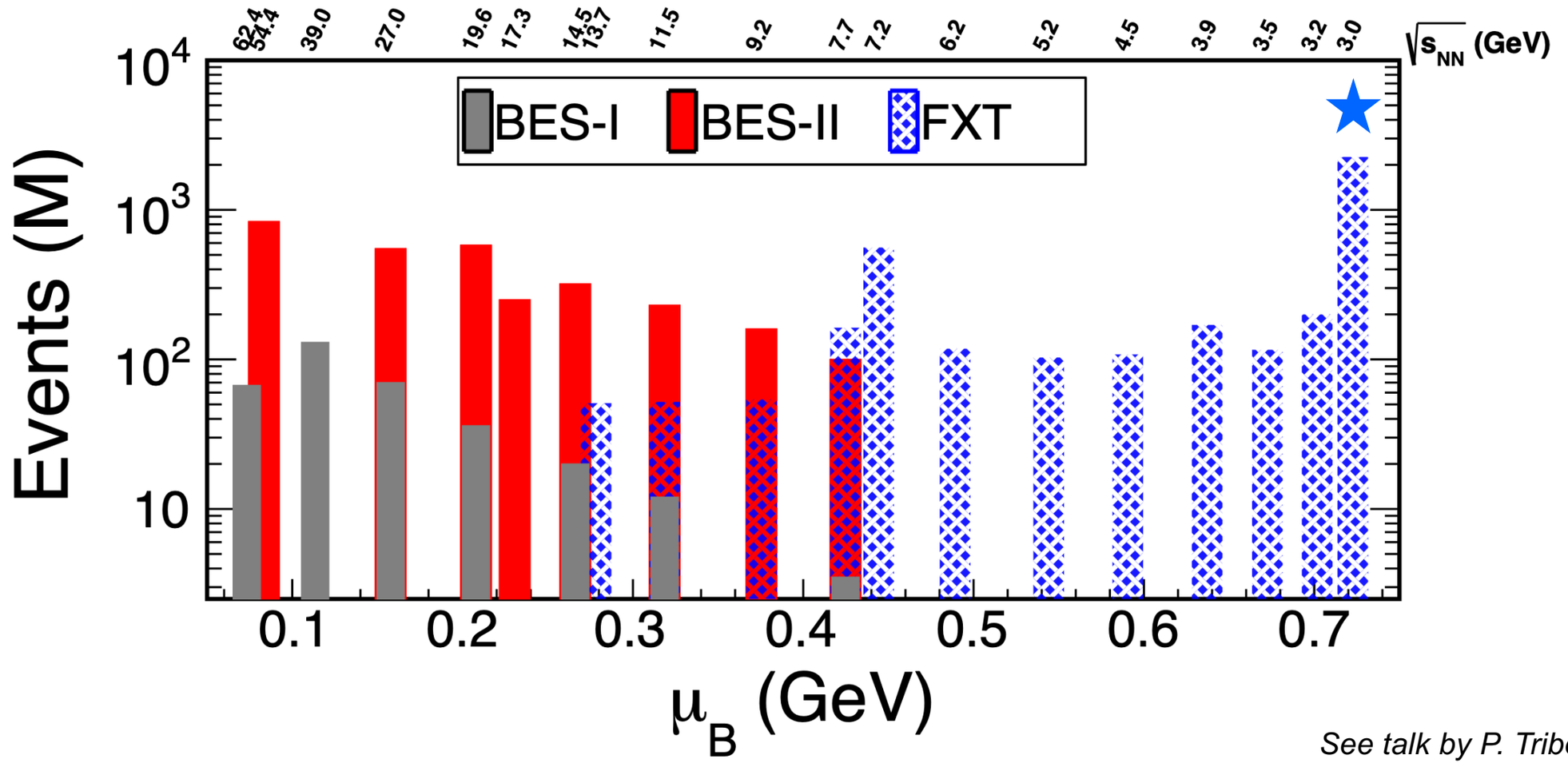
Significantly improved luminosities

Good events rate at 7.7 GeV
- BES-II: ~10M / week
- BES-I: ~1M / week

Many thanks for DOE, BNL/CAD operation team

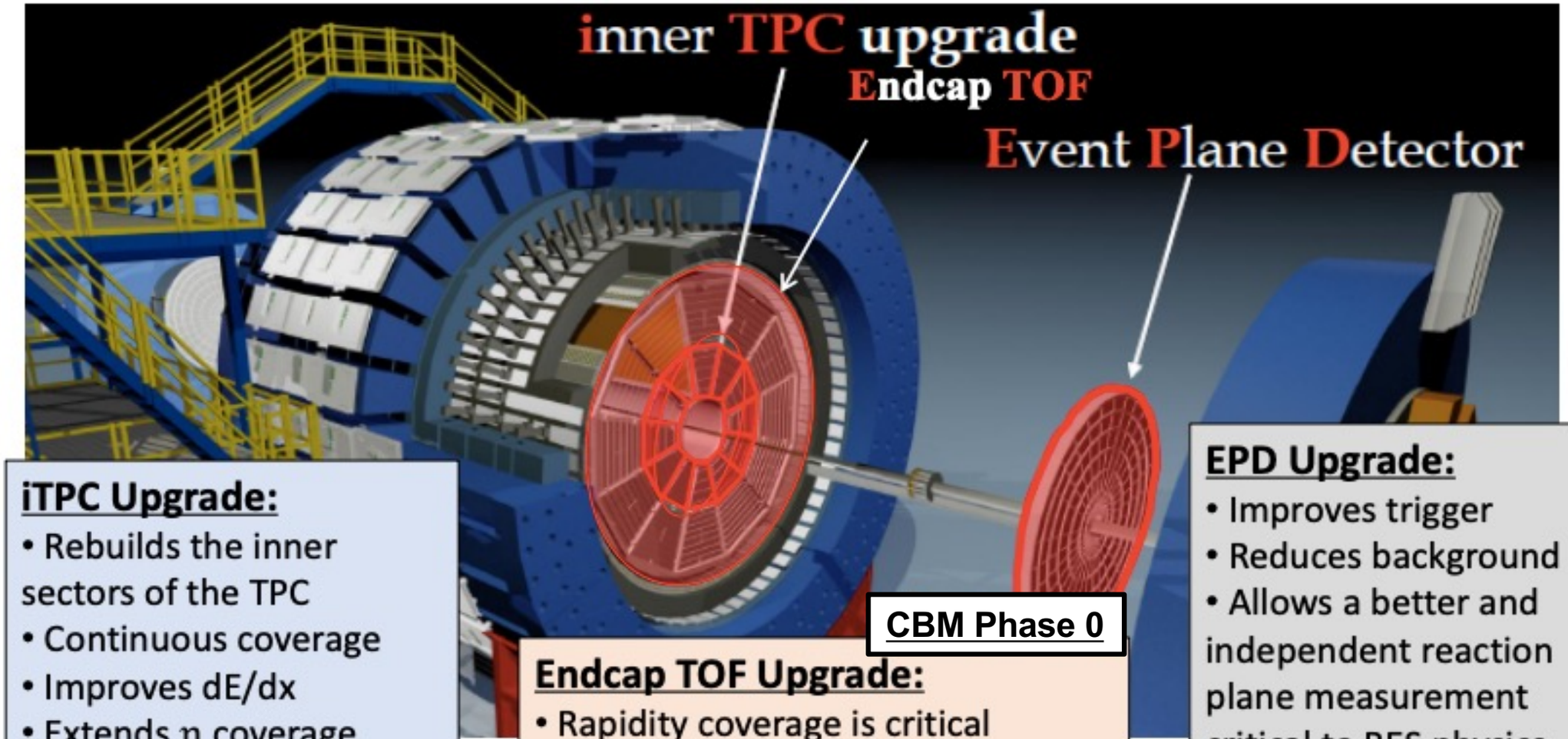
Datasets from Beam Energy Scan Phase-II

- x10-20 more statistics compared to BES-I at collider energies
- 8 collider energies (7.7 – 54.4 GeV) / 12 fixed-target energies (**3.0** - 13.5 GeV)



See talk by P. Tribedy

STAR Detector Upgrades for BES-II



iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5

MWPC modules built at Shandong Univ., China

CBM Phase 0

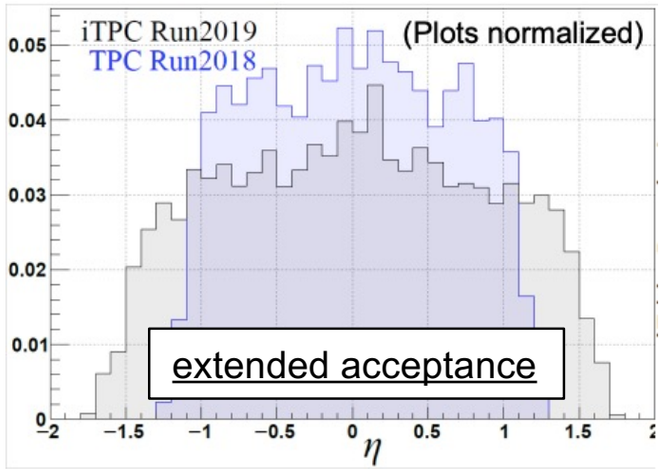
Endcap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1.1 to 1.5
- Improves the fixed target program
- Provided by CBM at FAIR

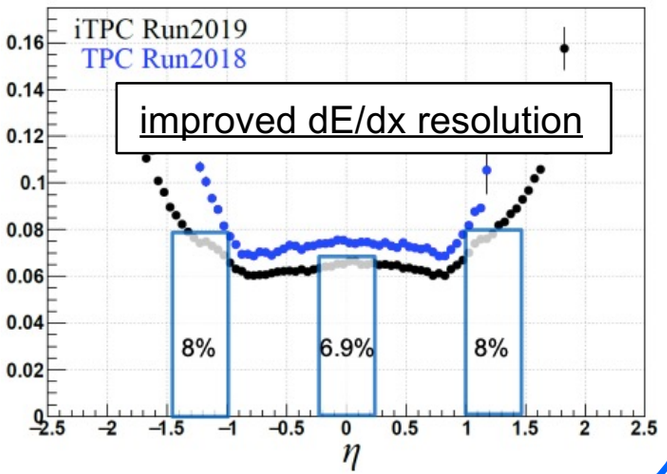
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

Extended coverage Enhanced PID

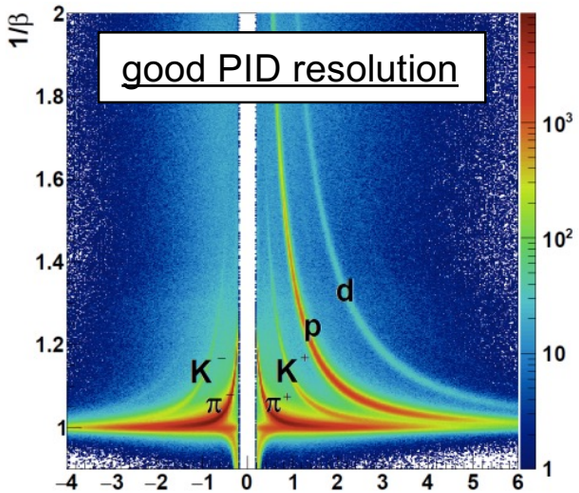
Detector Performance

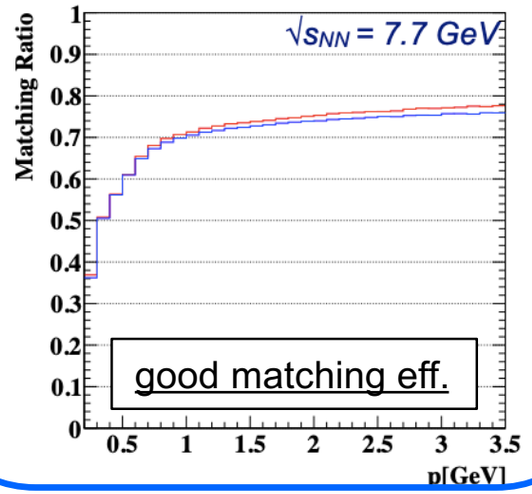
iTPC (2019+)



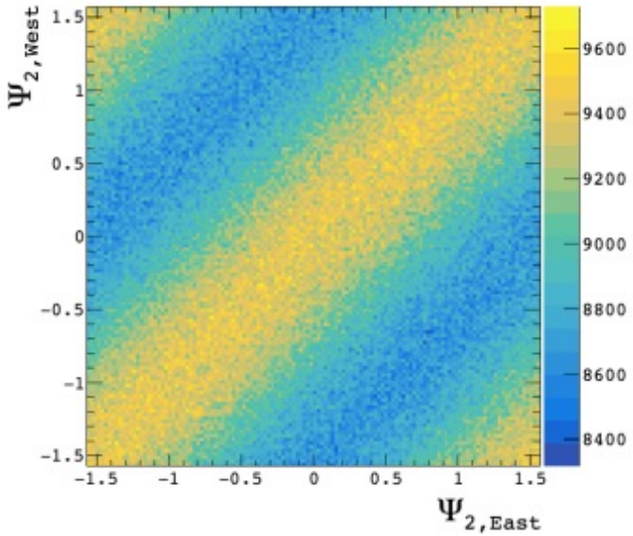


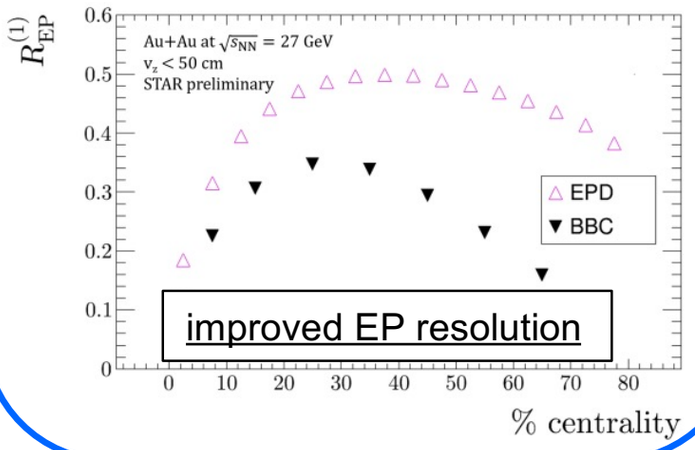
eTOF (2019+)





EPD (2018+)





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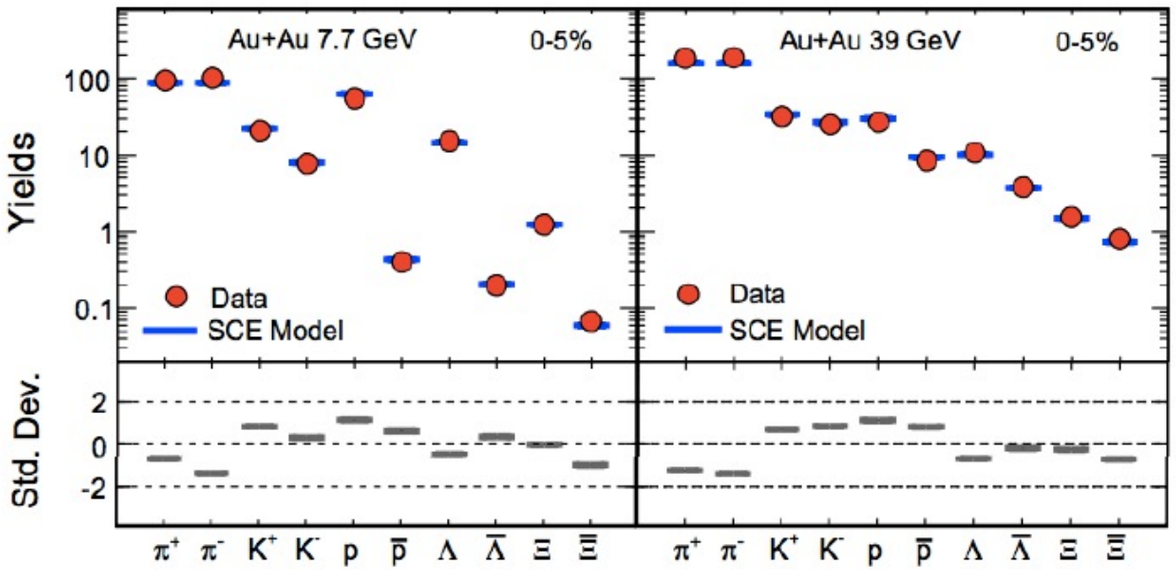
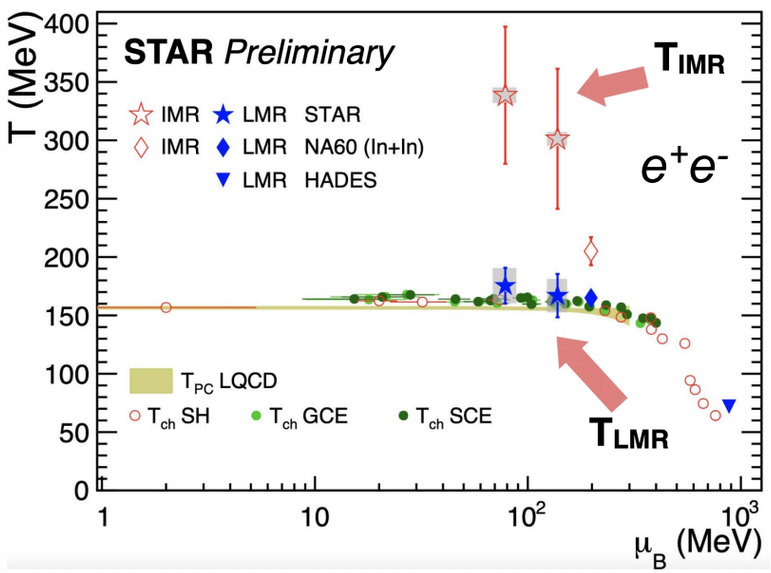
** Results from final BES-I + first set of BES-II data (3.0 GeV)*

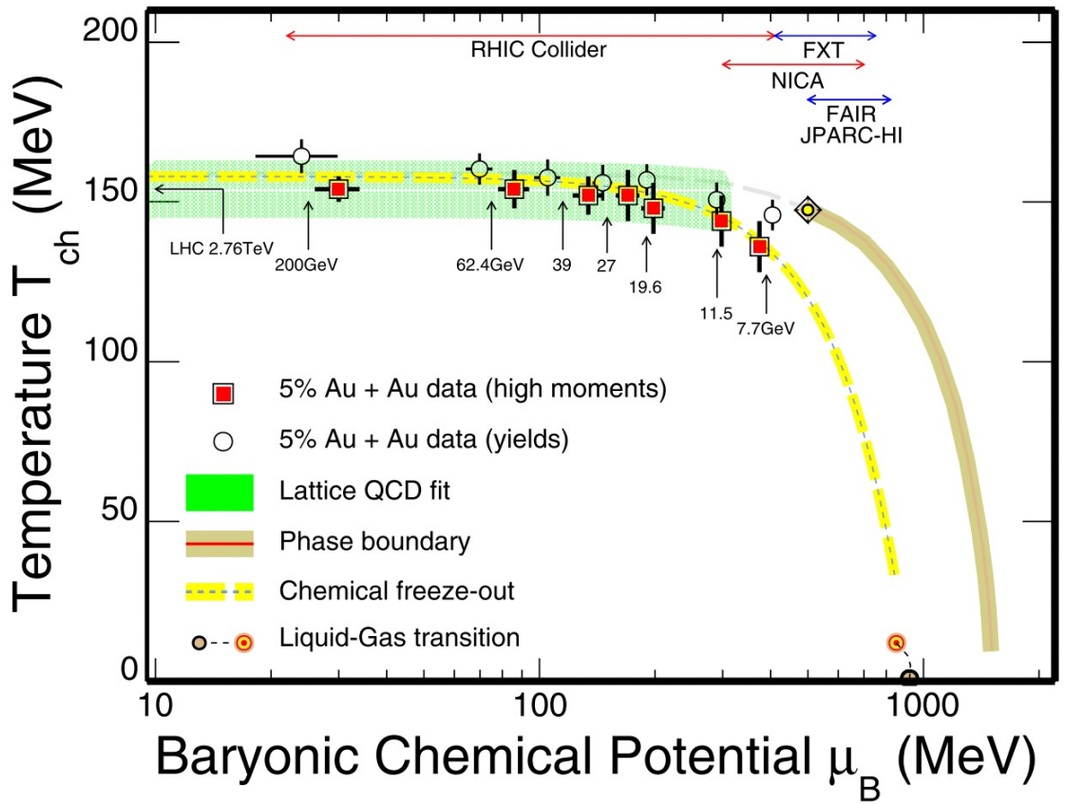
Chemical Freeze-out on Phase Diagram

STAR, PRC 96 (2017) 044904, QM2022



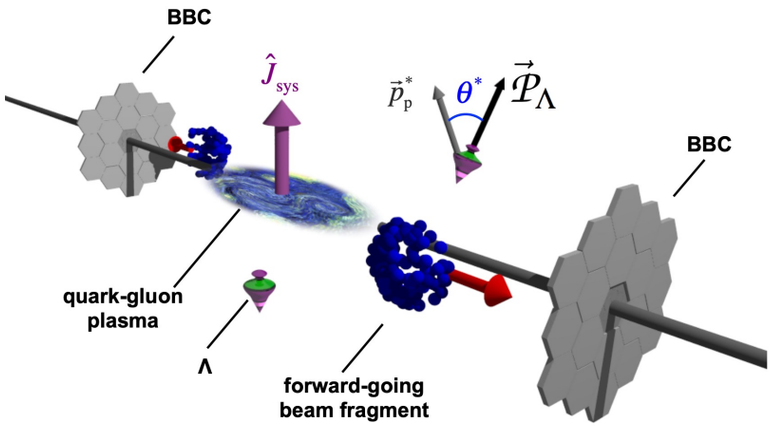


N. Xu et al., AAPPS Bulletin 31 (2021) 1



- Thermal model fit to extract freeze-out parameters
  - *consistent with those extracted from high moments and dileptons*

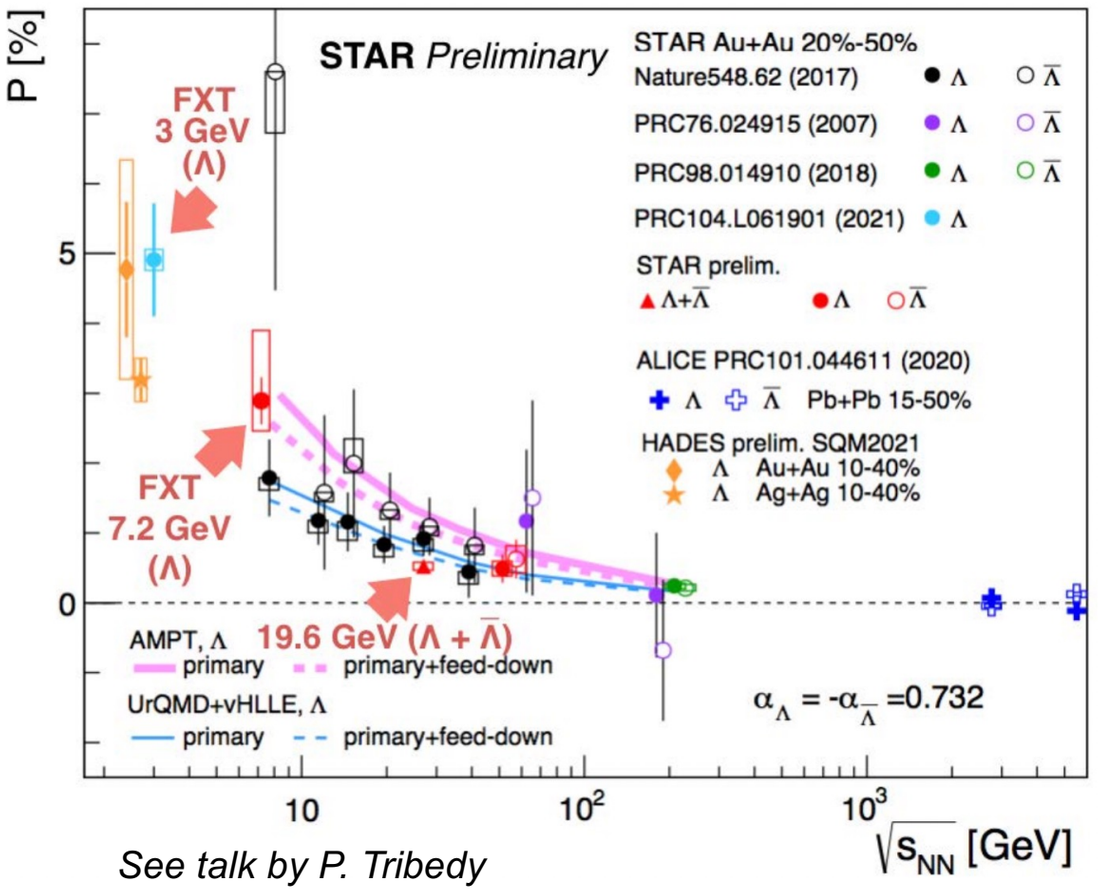
Global Polarization / Spin Alignment



Large angular momentum → large vorticity
→ global polarization / spin alignment

- Significant Λ global polarization / ϕ spin alignment
  - Most vortical fluid

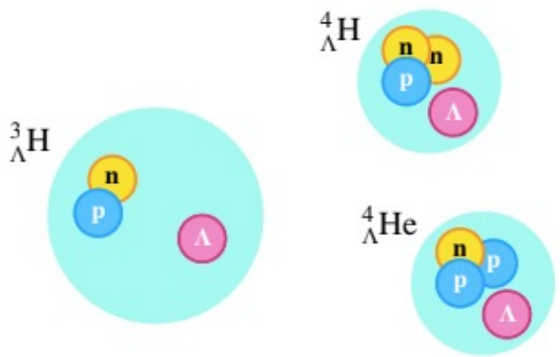
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$



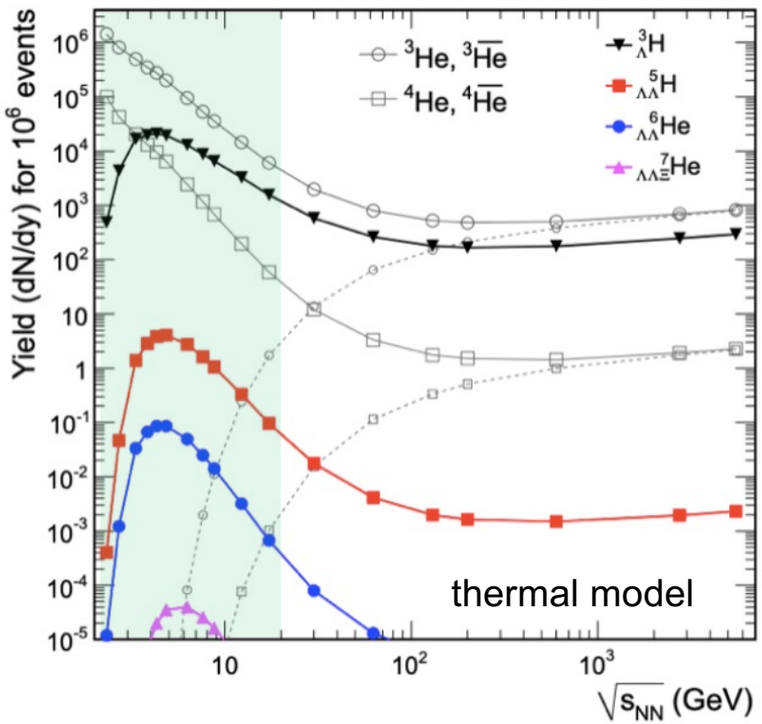
STAR, Nature 548 (2017) 62,
PRC 104 (2021) 061901,
arXiv: 2204.02302
QM2022

See talk by P. Tribedy

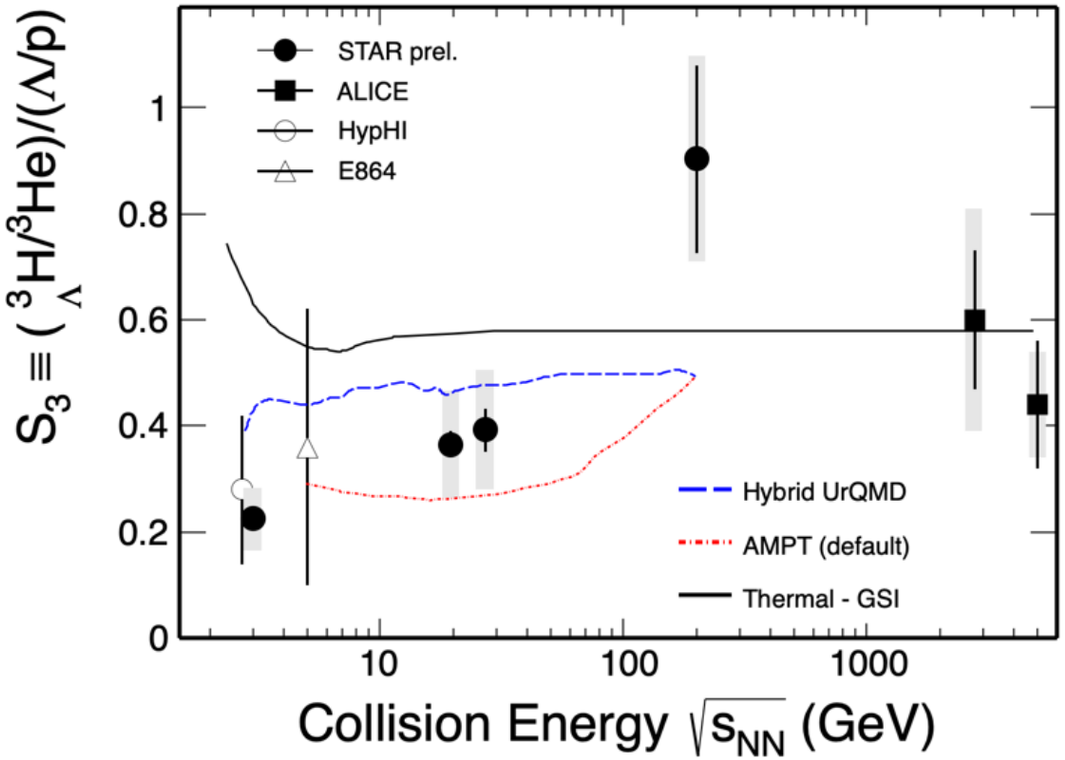
Hypernuclei – Y-N Interaction and Equation-of-State



- hyperon-nucleon (Y-N) interaction, Equation-of-State (EoS) under high baryon density
  - See talk by J. Noronha-Hostler
- New S_3 results: gradual increase vs. energy, approaching thermal limit at LHC
  - deviation at low energies?

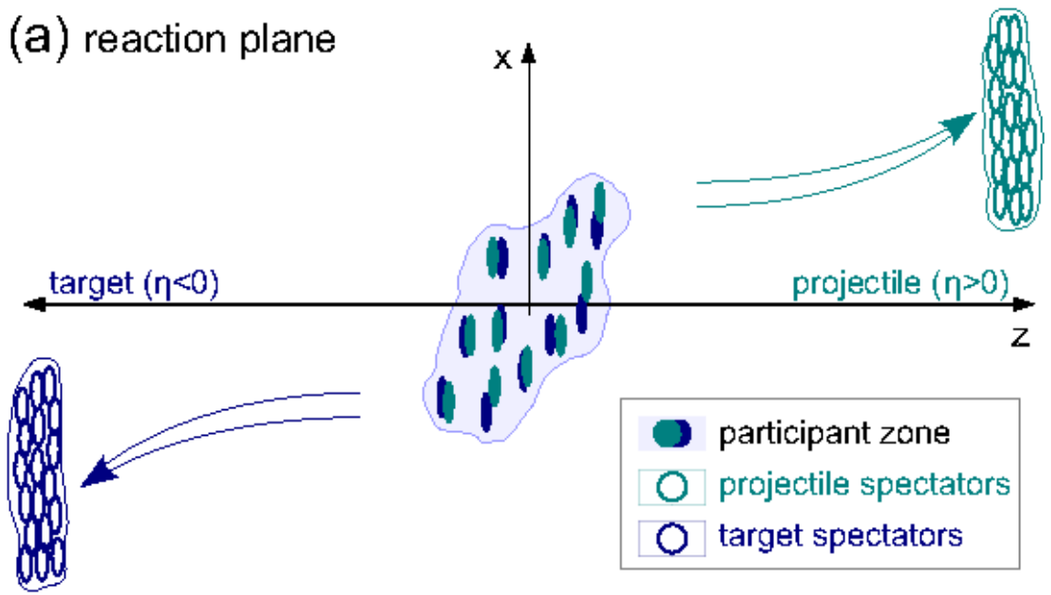


A. Andronic et al., PLB 697 (2011) 203

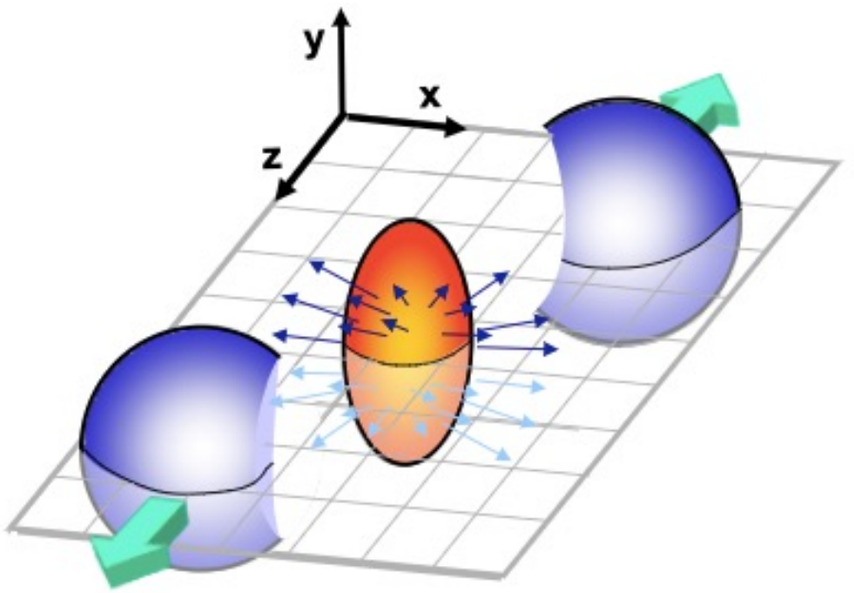


Azimuthal Anisotropic Collectivity

Directed Flow (v_1)



Elliptic Flow (v_2)

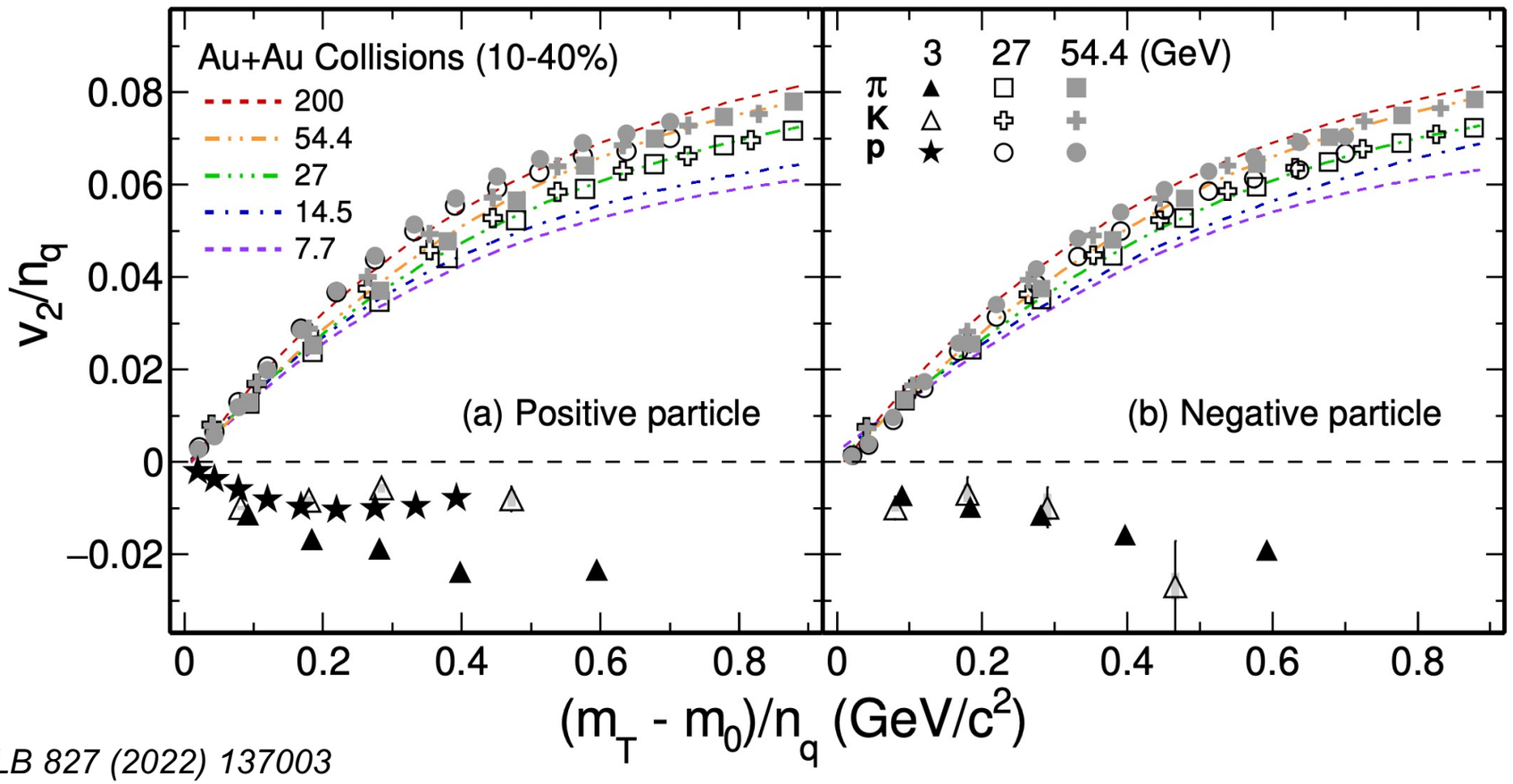


momentum space anisotropy ↔ pressure gradient in system evolution

v_1, v_2 … Equation-of-State (EoS)

See talk by J. Noronha-Hostler

Disappearance of Partonic Collectivity at Au+Au 3 GeV



STAR, PLB 827 (2022) 137003

- Number-of-Constituent-Quark (NCQ) scaling holds at 14.5 GeV and above
- No apparent NCQ scaling at 3 GeV
  - UrQMD with baryonic mean-field potential qualitatively consistent with data

  → *Baryonic interactions dominate in 3 GeV collisions.*

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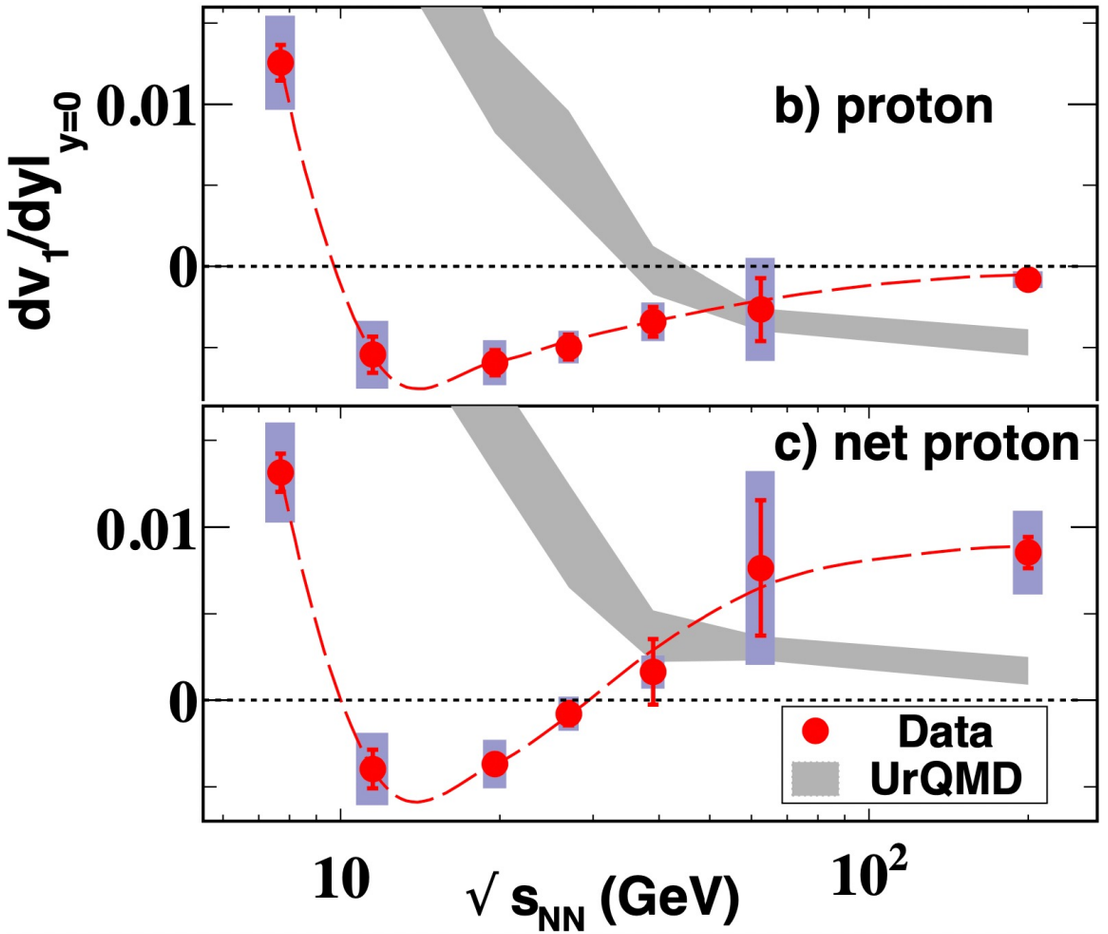
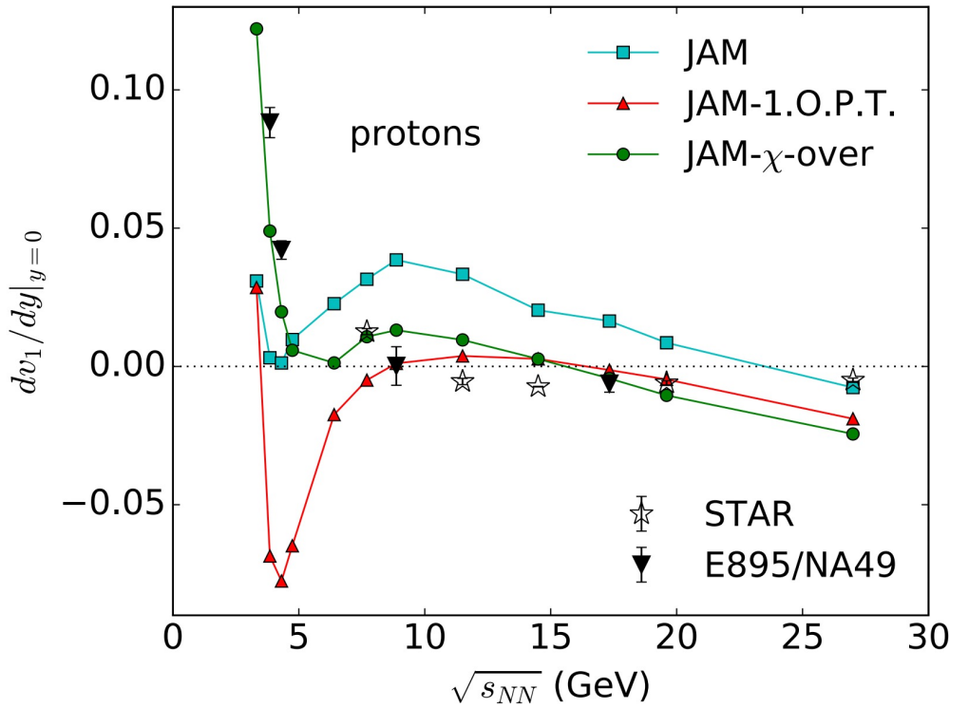
(Net-)Proton Directed Flow

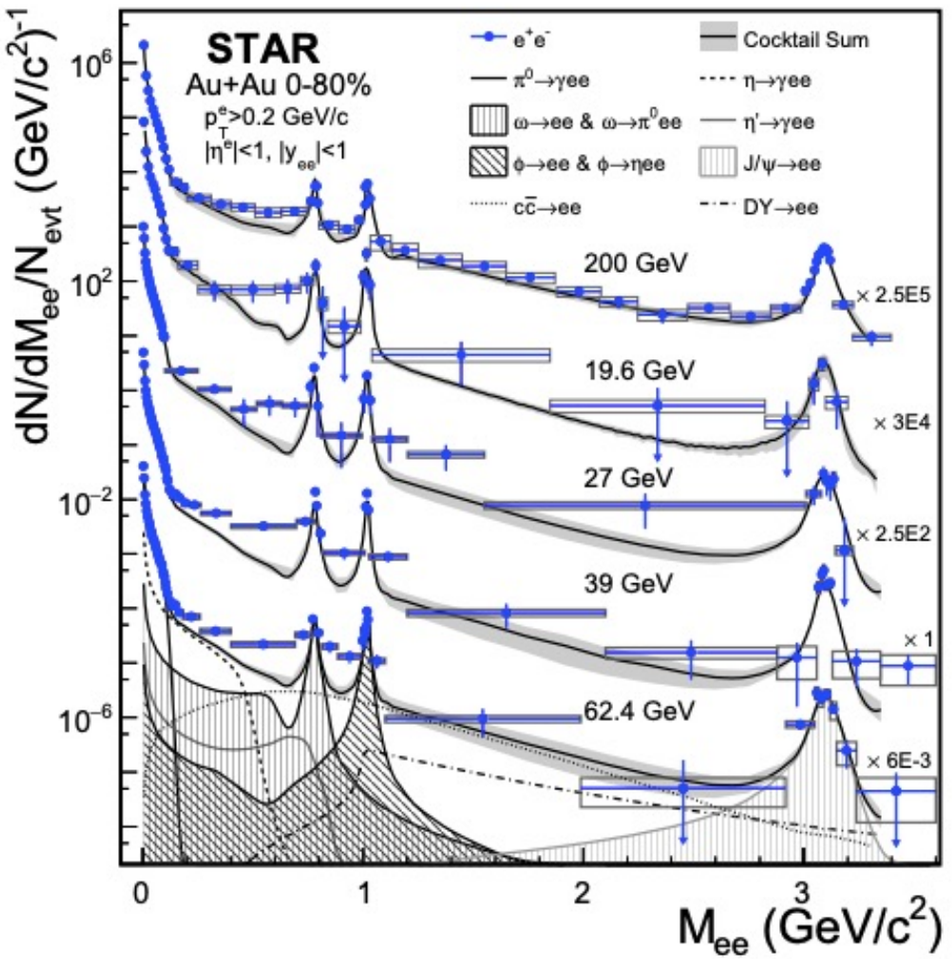


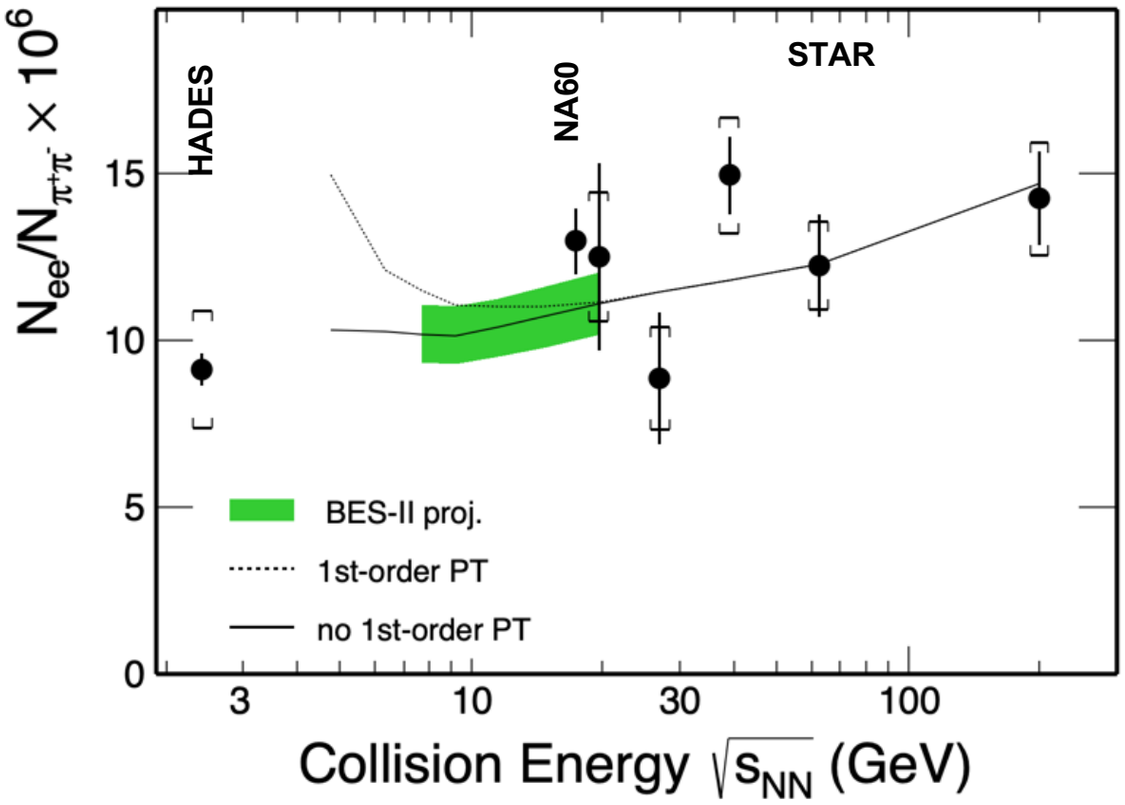


STAR, PRL 112 (2014) 162301
Y. Nara et al, PLB 769 (2017) 543

- Proton/net-proton v_1 vs. energy show a minimum
  - *Connection to 1st order phase transition?*
  - *model predicts a dip at much lower energy*

Dielectron Production





STAR, PRL 113 (2014) 022301, PLB 750 (2015) 64, arXiv: 1810.10159
Model: R. Rapp, CPOD 2021

- Dilepton yield excess at 0.3-0.7 GeV/c^2 from 17.3 – 200 GeV
  - consistent with in-medium ρ-broadening
  - *enhancement due to the 1st-order phase transition? location?*

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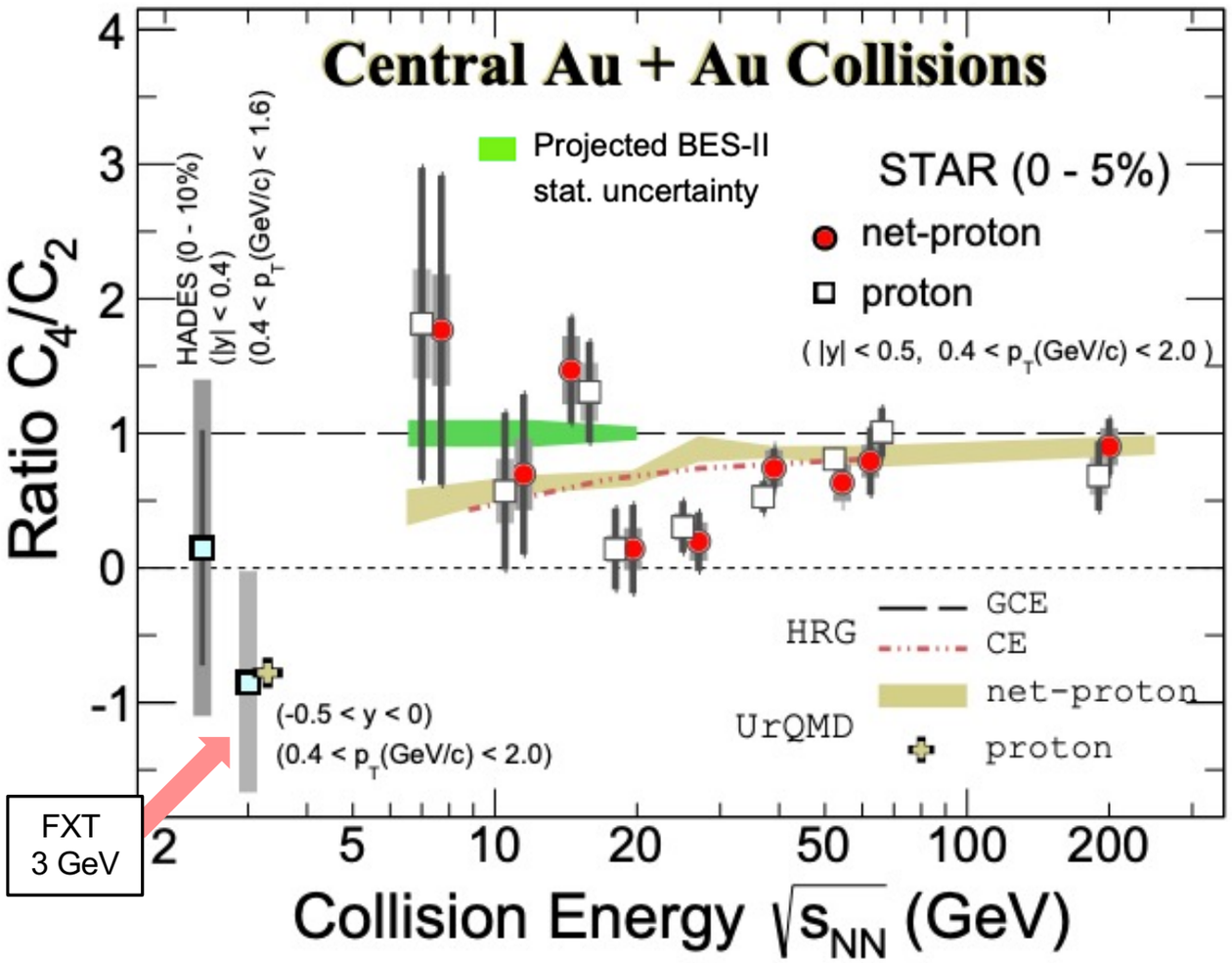
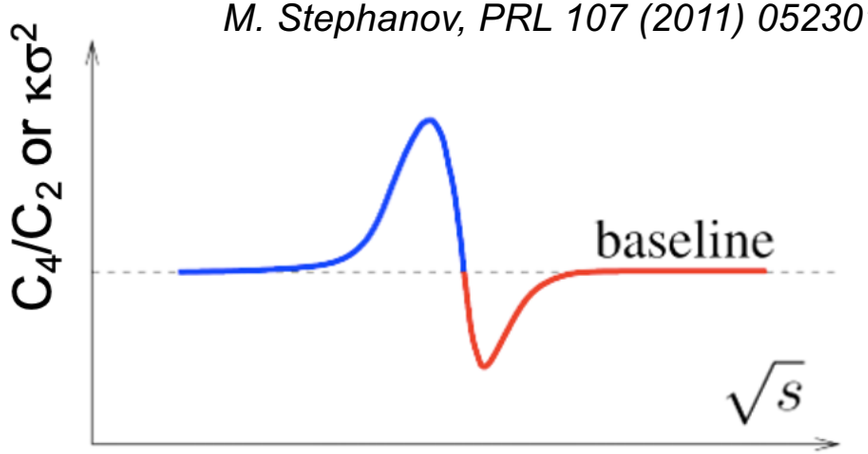
Energy Dependence of (Net-) Proton High Moments



BES-I: PRL 126 (2021) 092301
3 GeV data: PRL 128 (2022) 202303

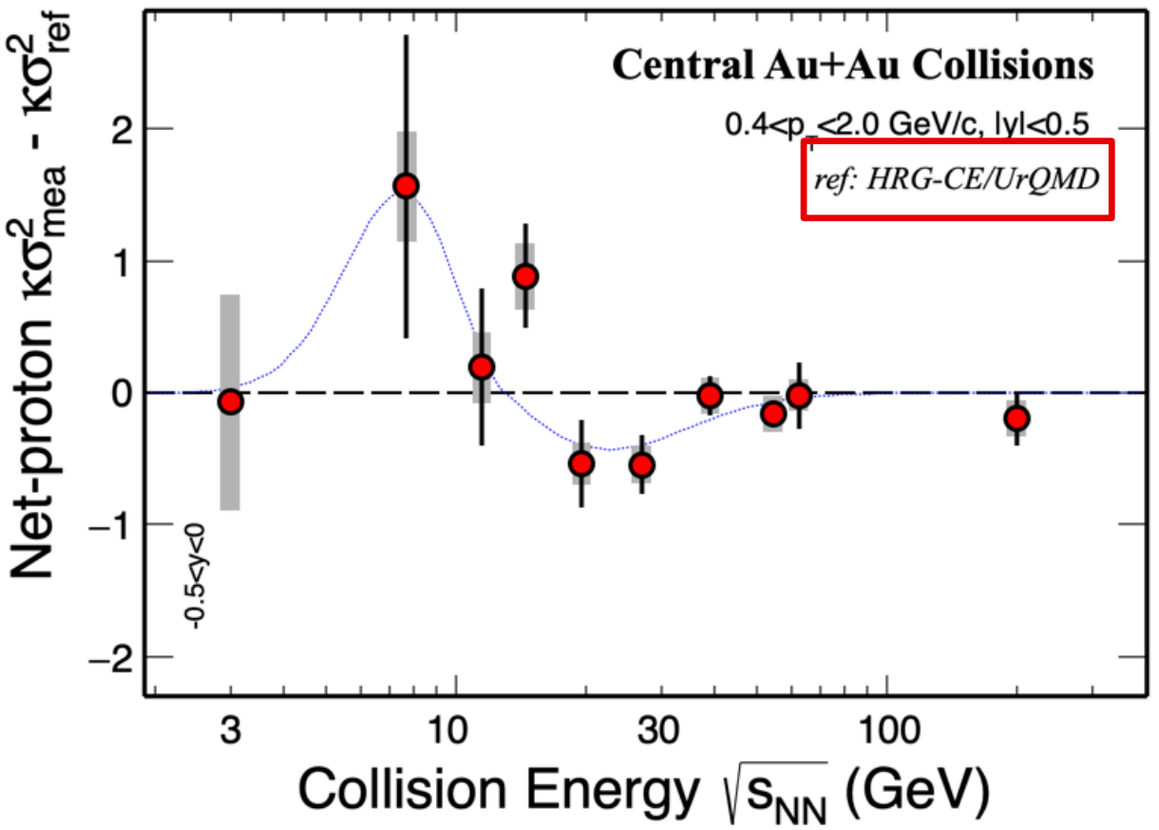
See talks by P. Tribedy and N. Xu

M. Stephanov, PRL 107 (2011) 052301

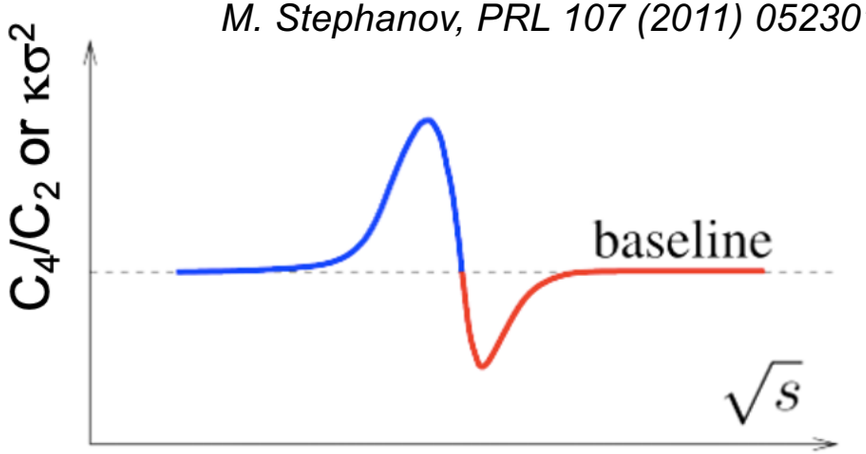


- Non-monotonic energy dependence in central Au+Au collisions (3.1σ)
- Strong suppression in proton C_4/C_2 at 3 GeV
  - *consistent with UrQMD hadronic transport model calculation*

Energy Dependence of (Net-) Proton High Moments



M. Stephanov, PRL 107 (2011) 052301



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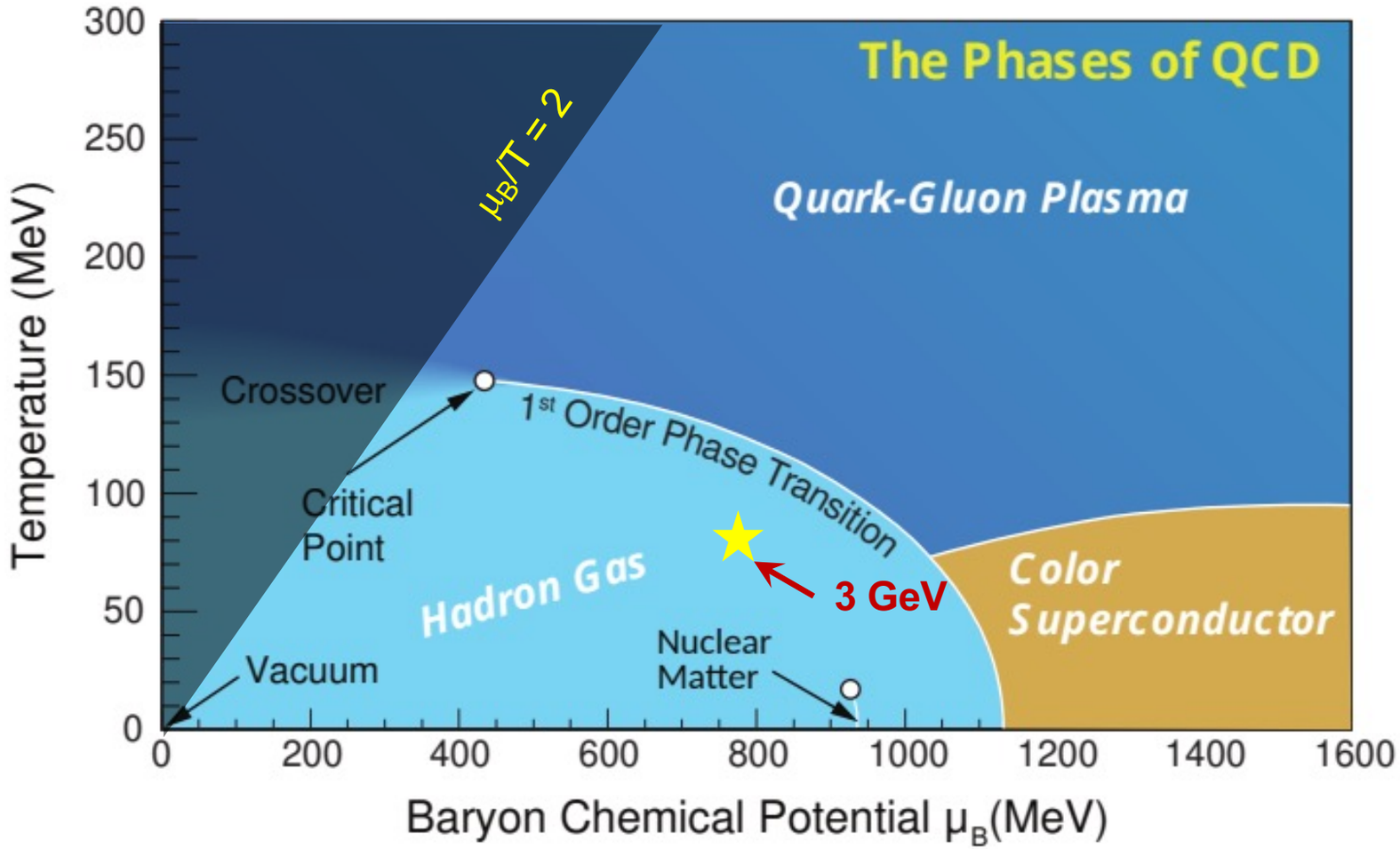
BES-I: PRL 126 (2021) 092301
3 GeV data: PRL 128 (2022) 202303
Other ref: V. Vovchenko et al. PRC 105 (2022) 014904

Current Knowledge of Phase Diagram



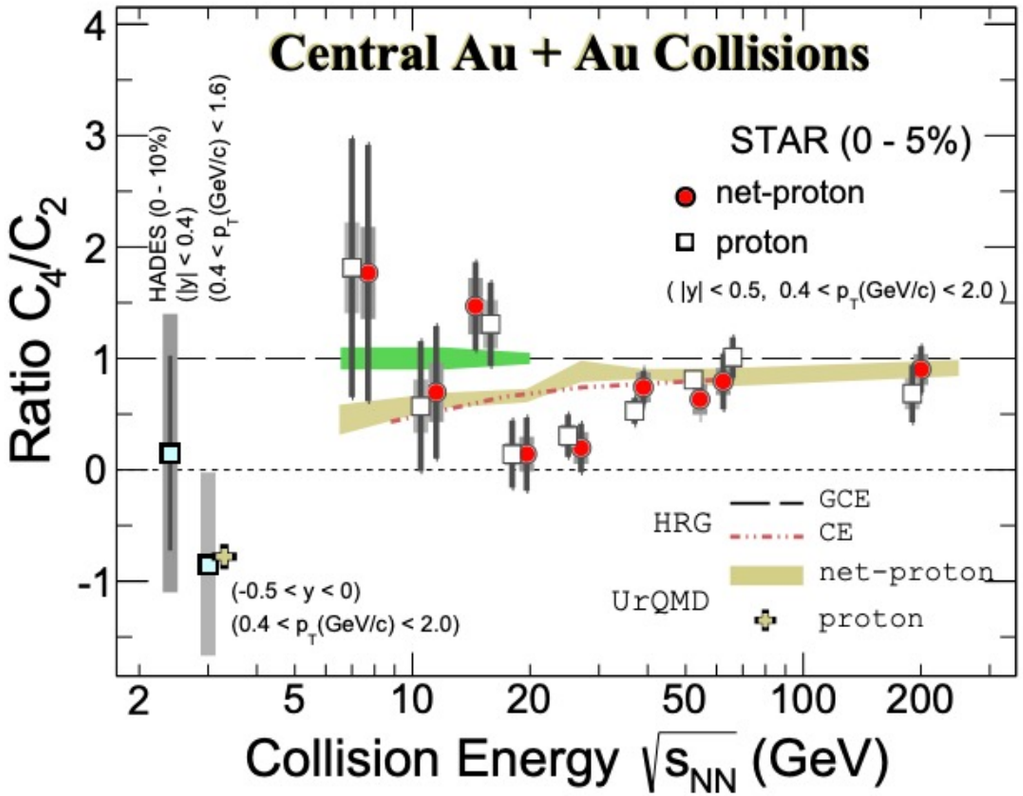
Lattice QCD predicts μ_B(CEP) > ~300 MeV

Critical point? 1st-order PT?

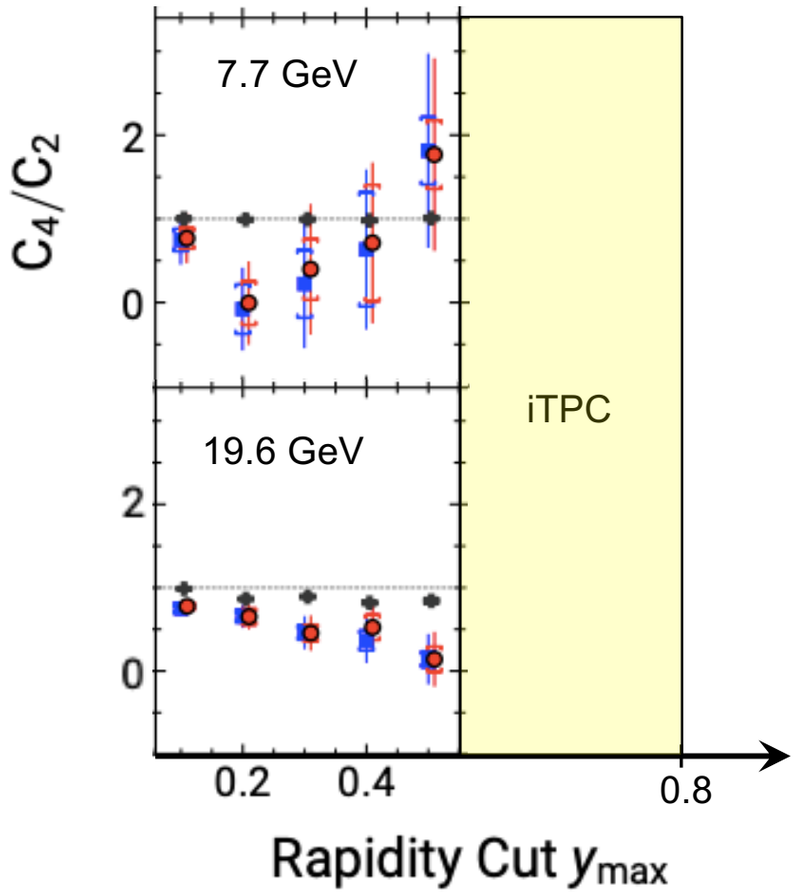
AuAu @ **3 GeV – hadronic phase**

- *Proton C_4/C_2 consistent with UrQMD*
- *v_1/v_2 dominated by baryonic mean field*
- *ϕ/Ξ driven by Canonical Ensemble*

Prospects from BES-II



Rapidity windows at BES-II
Collider: |y|<0.8
FXT: -1.0<y<0.5 @ 3 GeV



Significantly improved statistics
Better systematic control
Extended acceptance and particle identification

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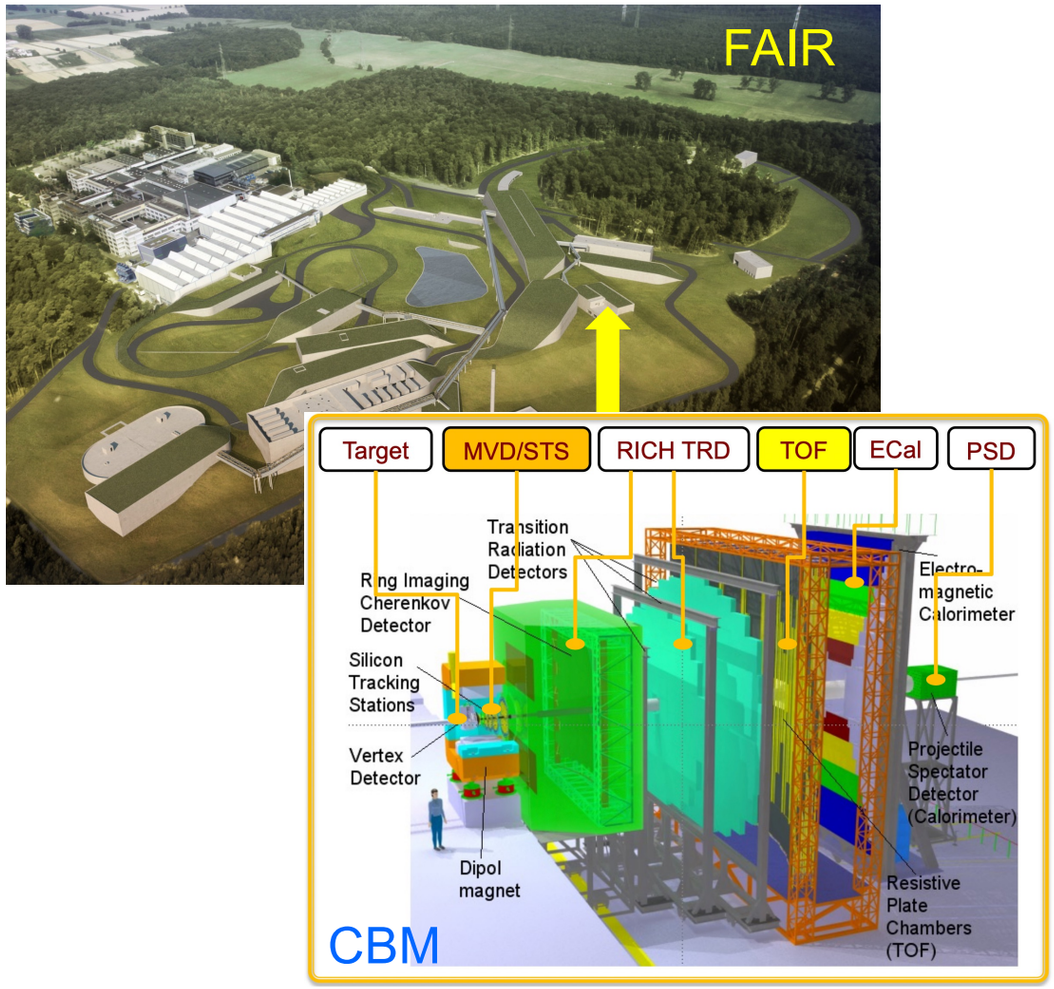
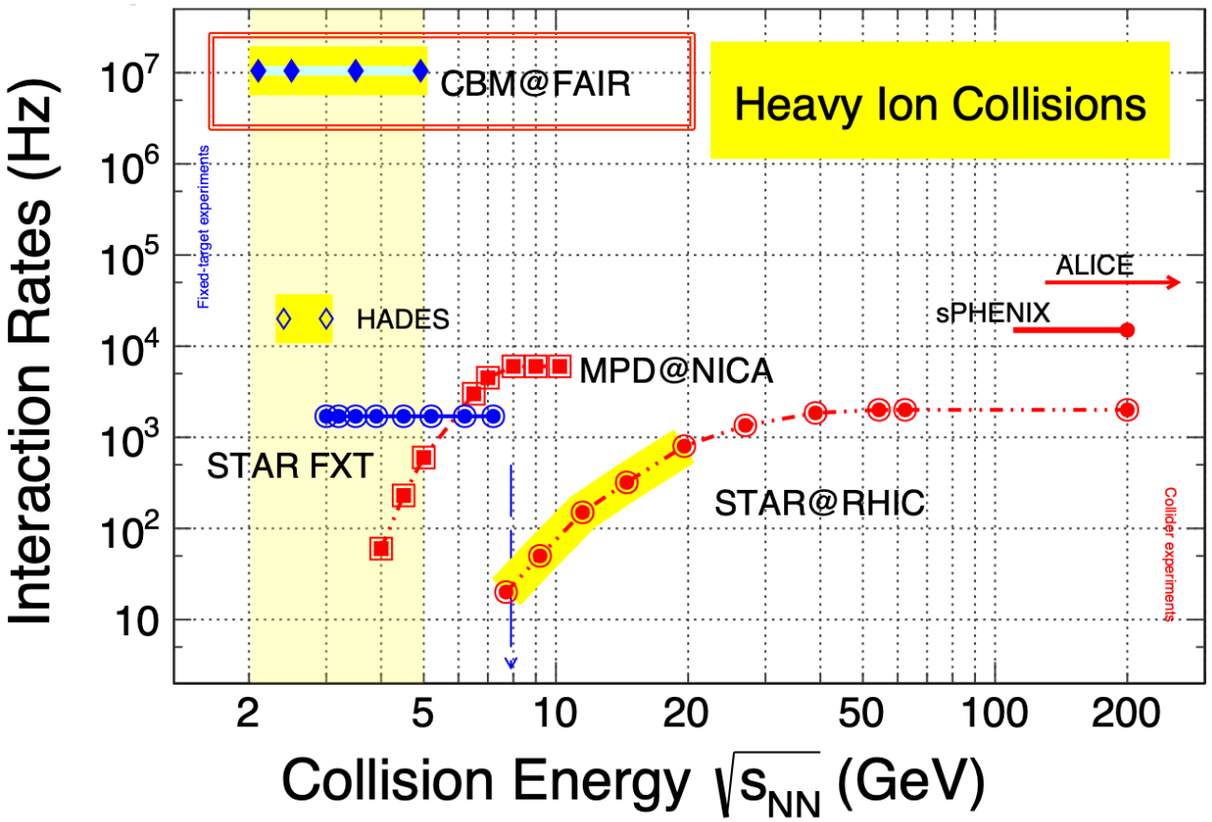
Next Phase BES Program at CBM@FAIR





See talk by N. Xu

Compressed Baryonic Matter (CBM) @ FAIR facility, Germany ($\sqrt{s_{NN}}$ = **2.9 – 4.9 GeV**)

physics anticipated to start in ***~2025+***

Collision rate ~ 10 MHz, dedicated detectors enabling unprecedented statistics

Next Phase BES Program at CBM@FAIR

Proton full midrapidity at BES-II:

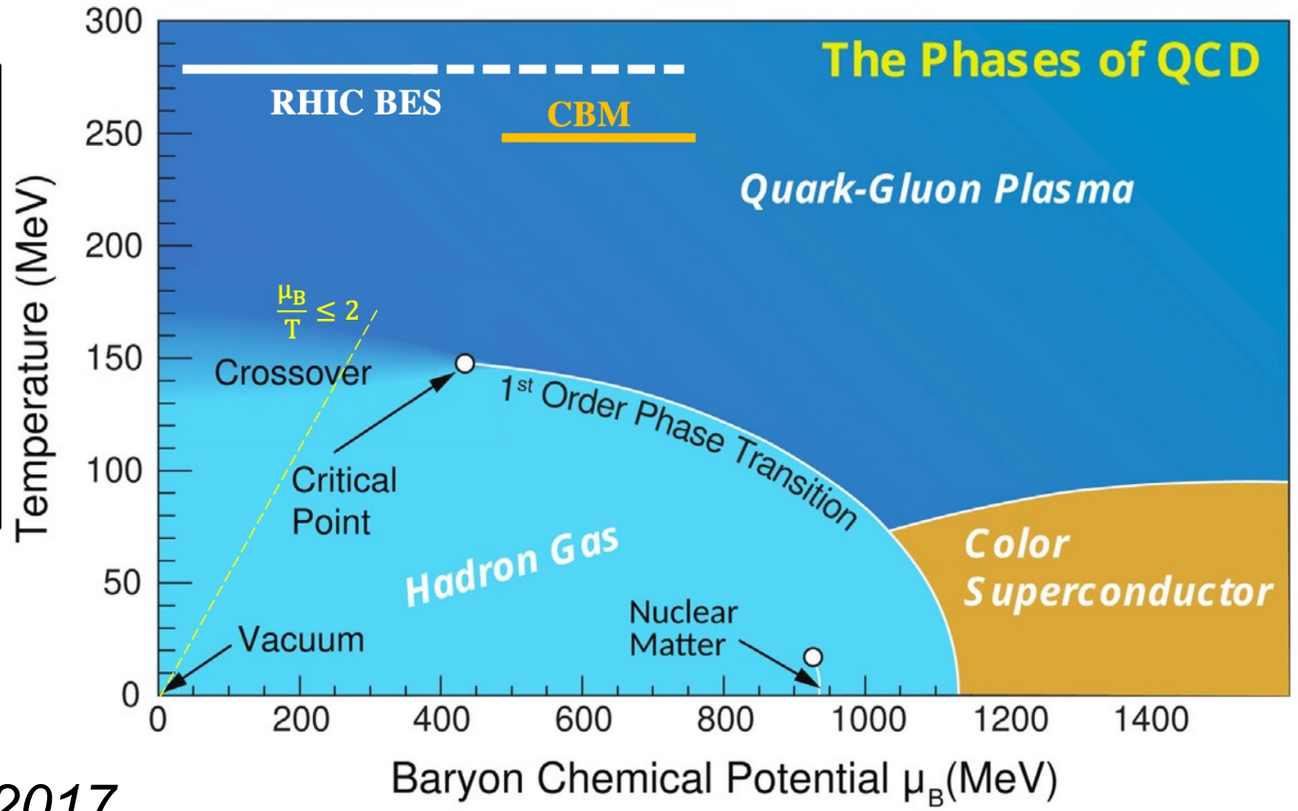
$\sqrt{s_{NN}}$ (GeV): 3.0, 7.7 – 19.6

μ_B (MeV): 750, 400 - 200

CBM@FAIR:

$\sqrt{s_{NN}}$ (GeV): **2.9 --- 4.9**

μ_B (MeV): **800 --- 540**

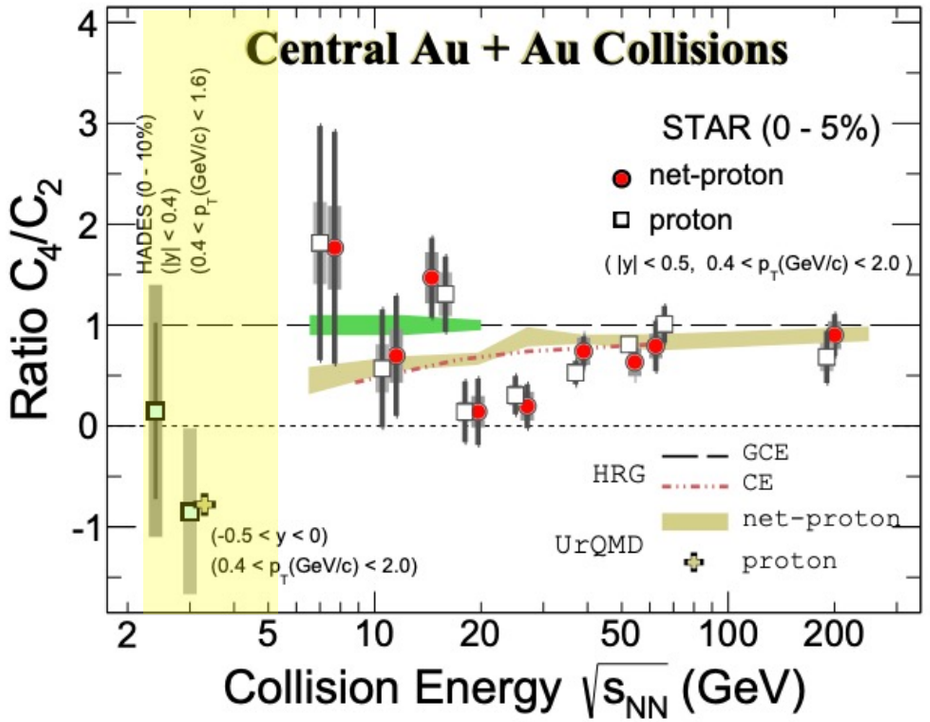


#1 priority in Europe NuPECC LRP 2017

Complete urgently the construction of the ESFRI flagship FAIR and develop and bring into operation the experimental programme of its four scientific pillars APPA, CBM, NUSTAR and PANDA.

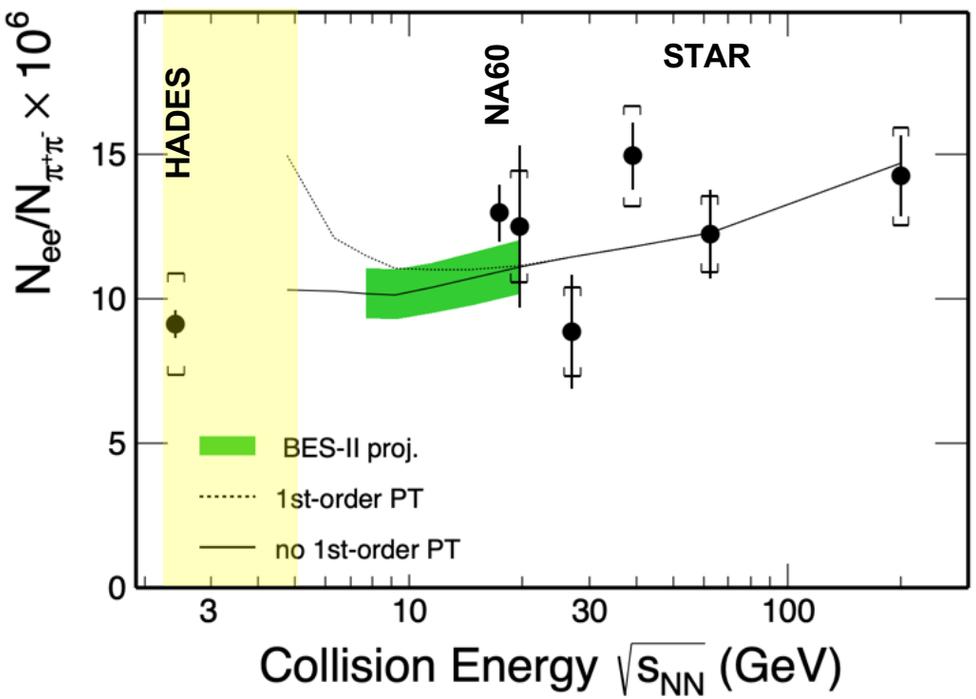
CBM Scientific Goals - I

Baryon Fluctuations/Correlations



- critical point search
- $\sqrt{s_{NN}}$ (μ_B) coverage for full mid-rapidity coverage
- dedicated instrument for controlling initial volume fluctuation

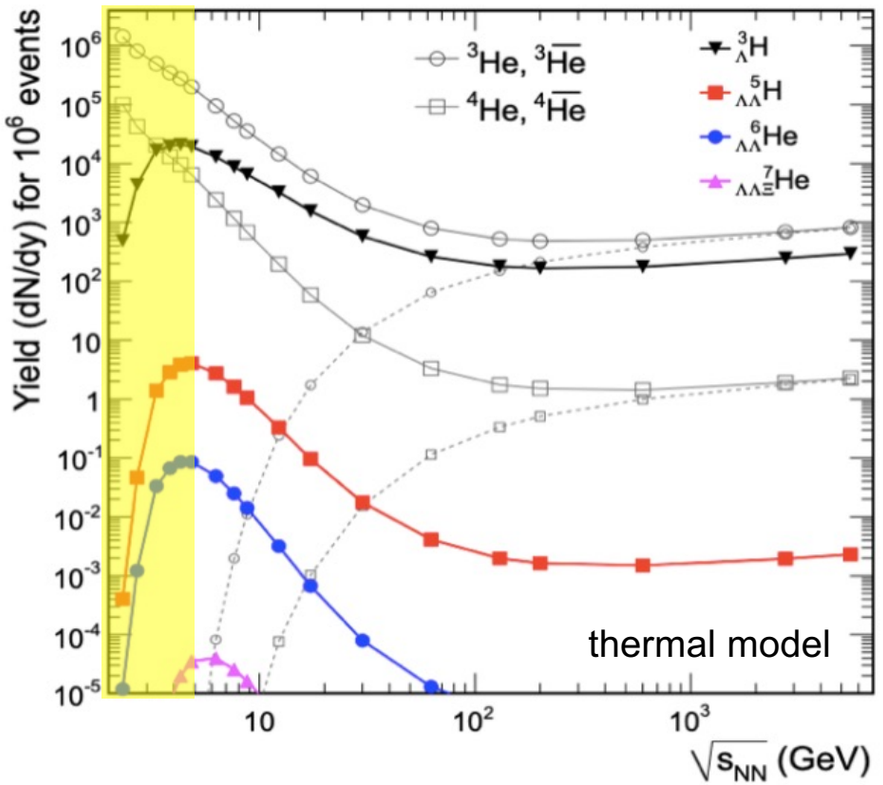
Dileptons



- 1st order phase transition / chiral property
- significantly high statistics
- dedicated instruments for both dielectron / dimuon channels

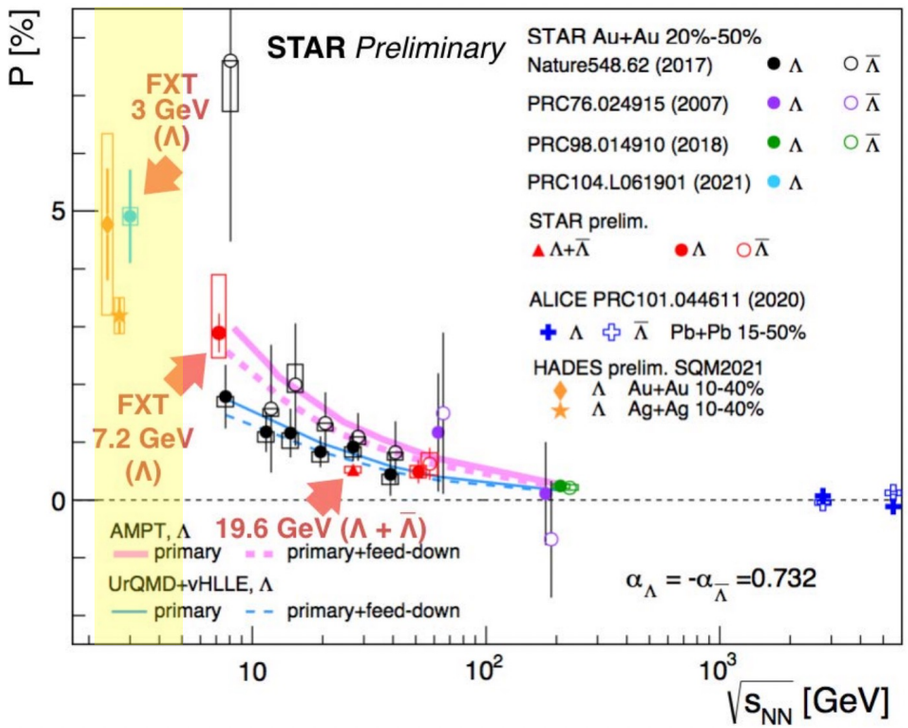
CBM Scientific Goals - II

Hypernuclei



- Y-N/Y-Y interaction / EoS
- high statistics enabling *S*=-*2* hypernuclei
- dedicated tracker for reconstruction

Polarization / Spin Alignment



- medium properties / EoS at high μ_B
- high statistics for multi-dimension analysis

US-CBM White Paper

arXiv: 2209.05009

QCD Phase Structure and Interactions at High Baryon Density: Completion of BES Physics Program with CBM at FAIR

BNL, UC Davis, UCLA, UCR, Duke, UH, UIC, UIUC, IU, KSU, LBNL, MSU, UNC, NCSU, OSU, Pepperdine, Purdue, SBU, Rice, UW, WSU

Executive Summary

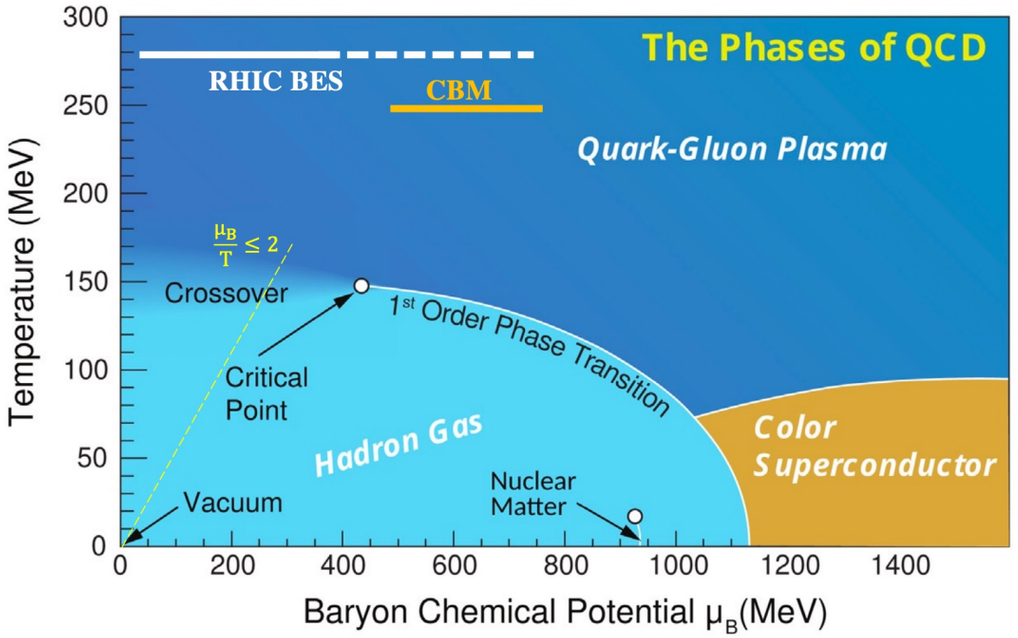
In order to complete the Beam Energy Scan (BES) physics program, including the search for the QCD critical point, the extraction of the hyperon-nucleon interaction, and the determination of constraints on the nuclear matter equation of state at high baryon density, **active US participation in the international collaboration of the Compressed Baryonic Matter (CBM) experiment at FAIR*** is scientifically necessary and cost effective.

…

Without these measurements in the FAIR/CBM energy region, the scientific program pioneered at RHIC with the BES program would risk to be terminated prematurely in the US, and some of the key physics questions may remain unanswered. … *US participation in CBM will not only greatly enhance its physics program, but will also strengthen US leadership in nuclear physics*.

**recommendation as new initiative*

Summary: QCD at High Baryon Density



- QCD critical point or 1st-order phase transition
- Equation-of-State of nuclear matter at high μ_B
  - *connection to nuclear astrophysics*
- Successful data taken for BES-II at RHIC
  - *critical to secure resources to allow timely results*
- Next phase exp. at high μ_B: ***CBM@FAIR***
  focused energies
  dedicated instruments
  unprecedented statistics

2010 — 2018 — ~2025+

BES-I STAR@RHIC (62.4 – 7.7 GeV)

BES-II STAR@RHIC (19.6 – 3.0 GeV)

BES-III CBM@FAIR (4.9 – 2.9 GeV)

Flagship QCD Facilities in Next Decades