STAR Beam Energy Scan II

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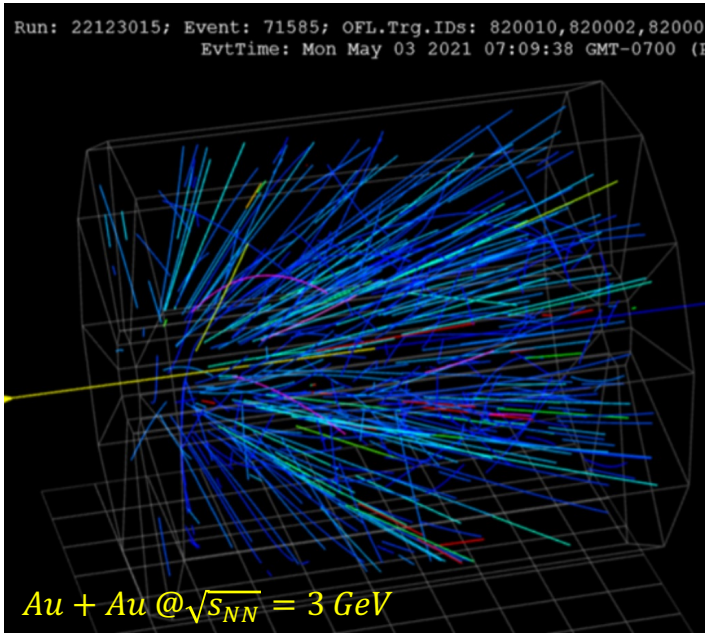
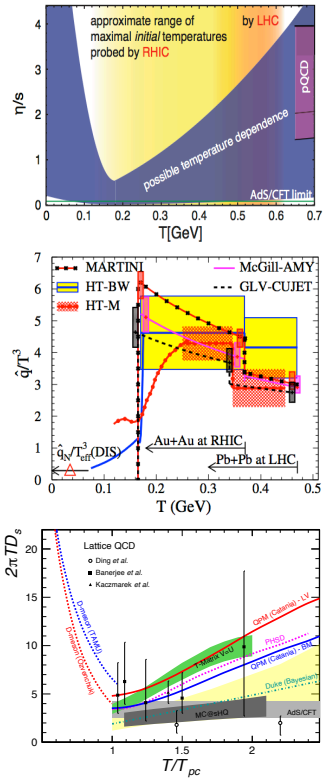
- Introduction
- Highlights from BES-I/II Results
- BES-II Prospects
- Summary



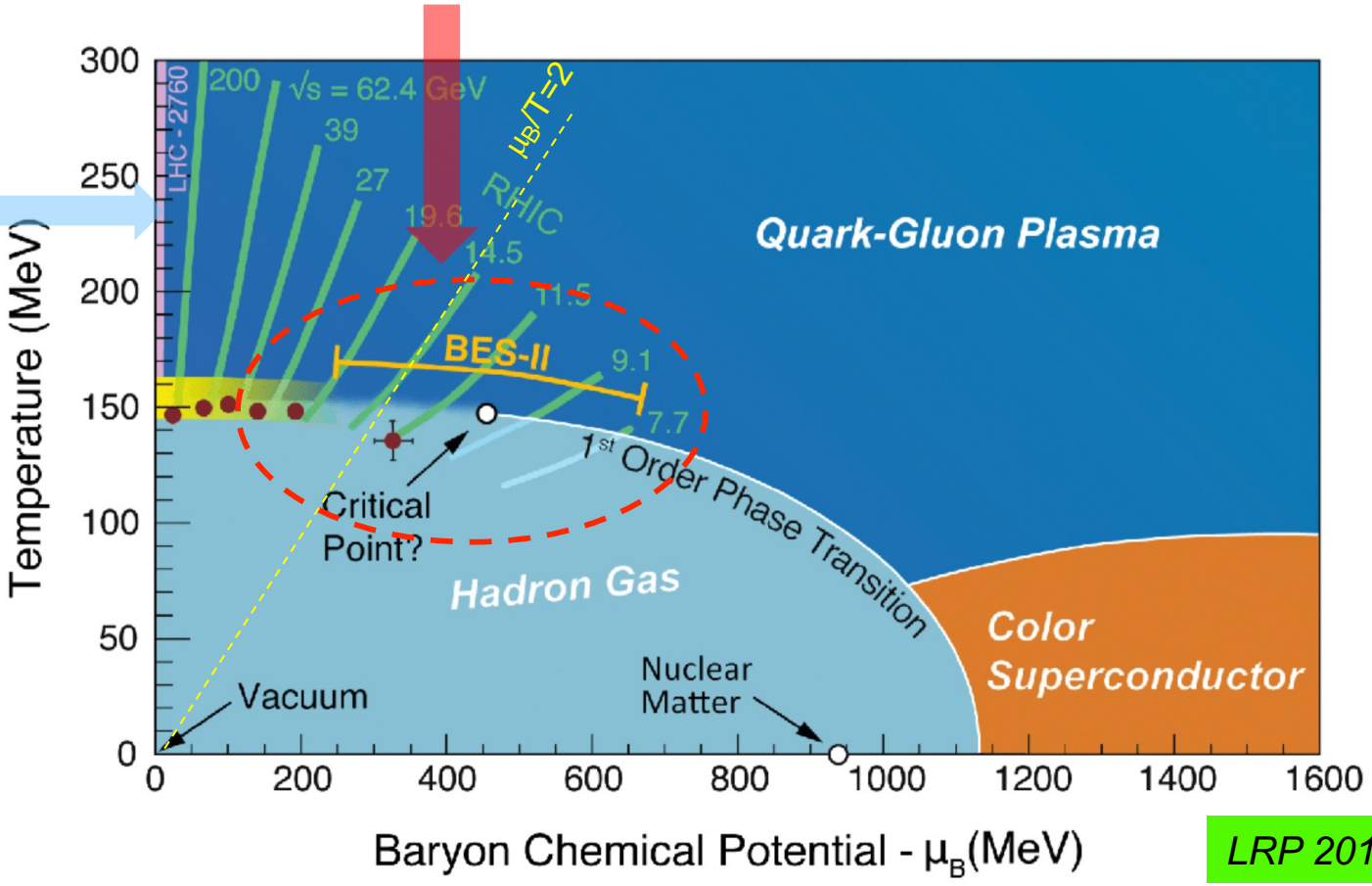
QCD Phase Diagram and Heavy-Ion Frontiers

QGP Properties
@ $\mu_B \sim 0$



QCD Phase Structure
@ finite μ_B

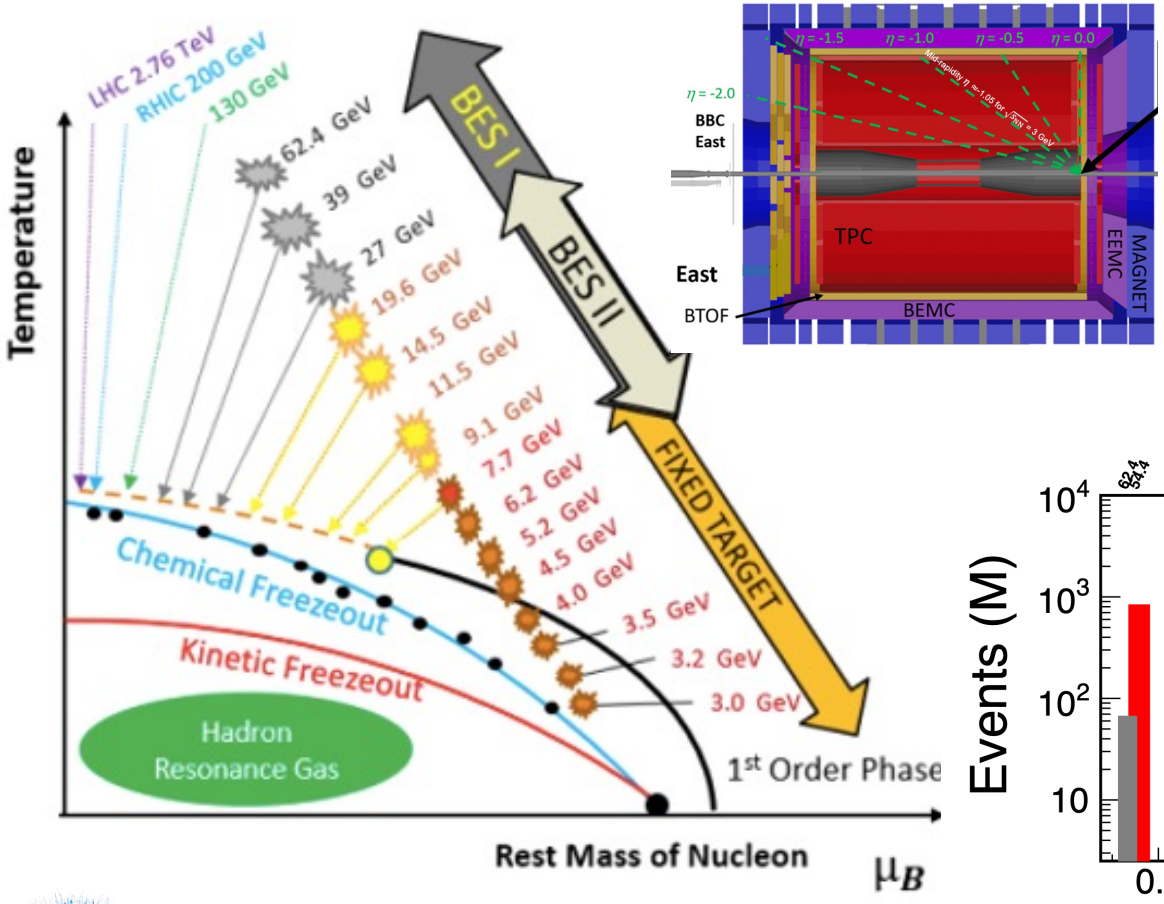
Lattice: crossover at $\mu_B/T<2$



LRP 2015

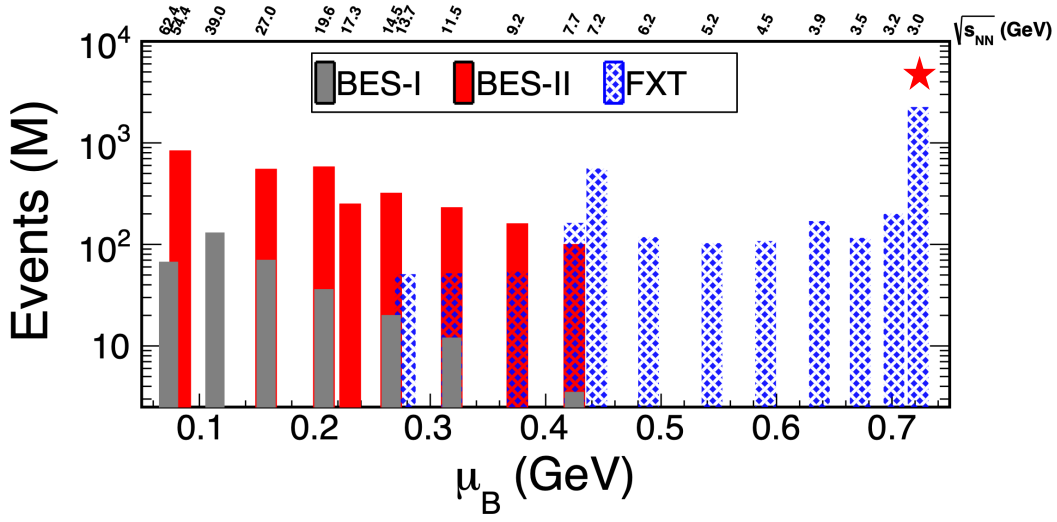
RHIC Beam Energy Scan (BES) Program

STAR as a Fixed Target Experiment

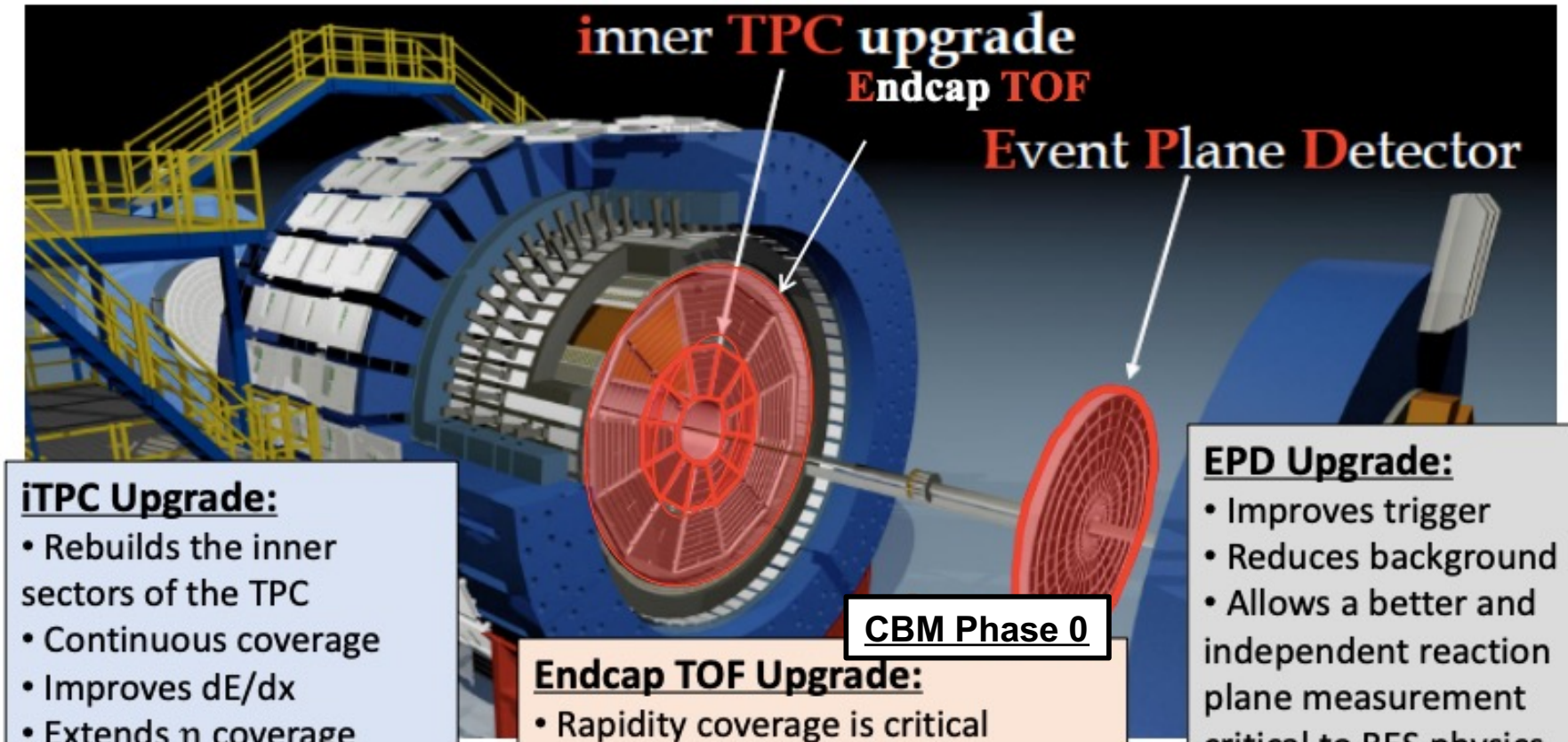


BES-II Datasets

- 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)



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

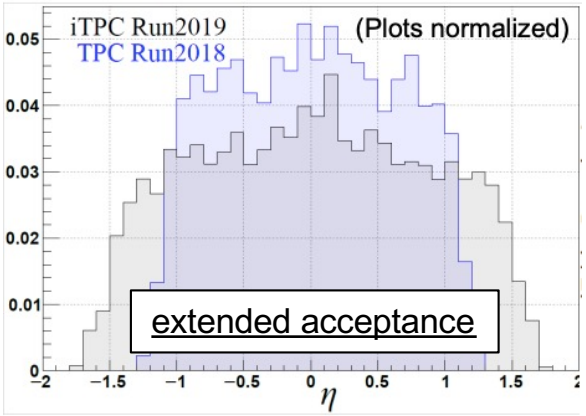
Endcap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1.1 to 1.5
- Improves the fixed target program
- Provided by CBM at FAIR

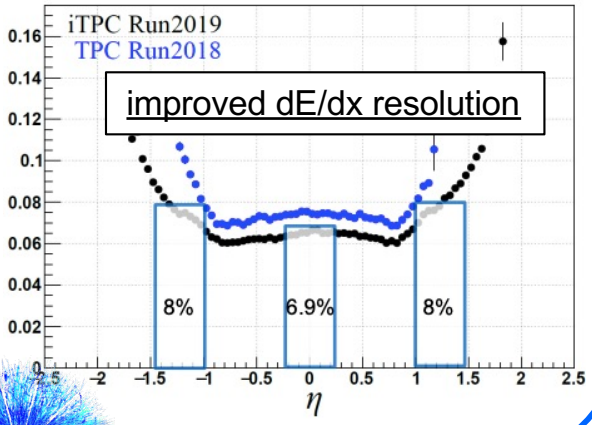
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

Extended coverage Enhanced PID

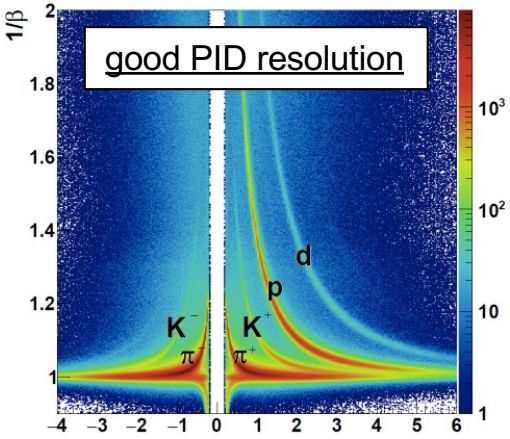
Detector Performance

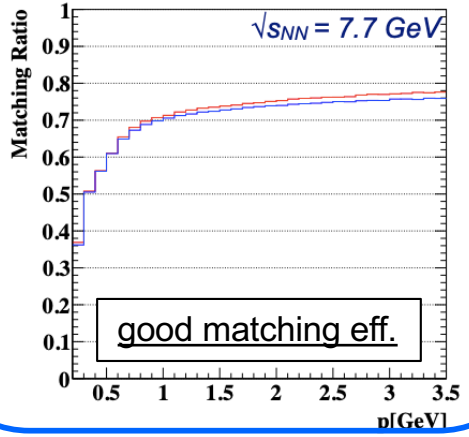
iTPC (2019+)



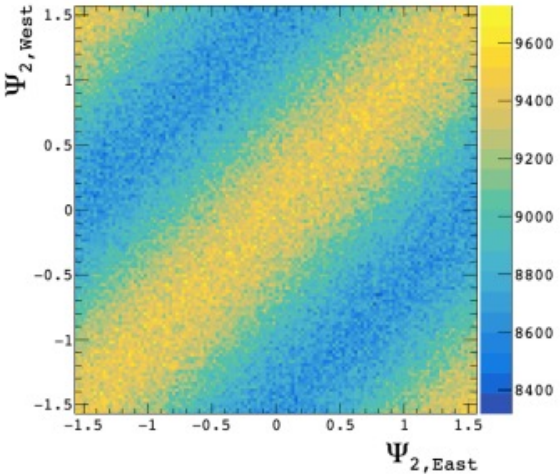


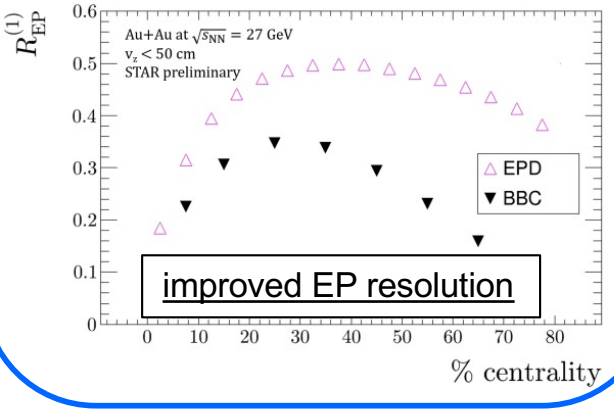
eTOF (2019+)





EPD (2018+)





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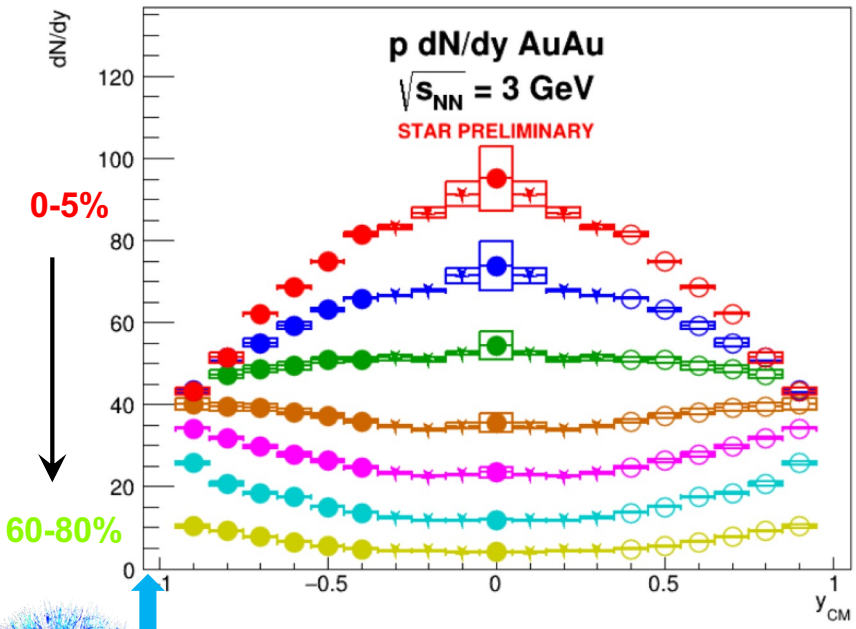
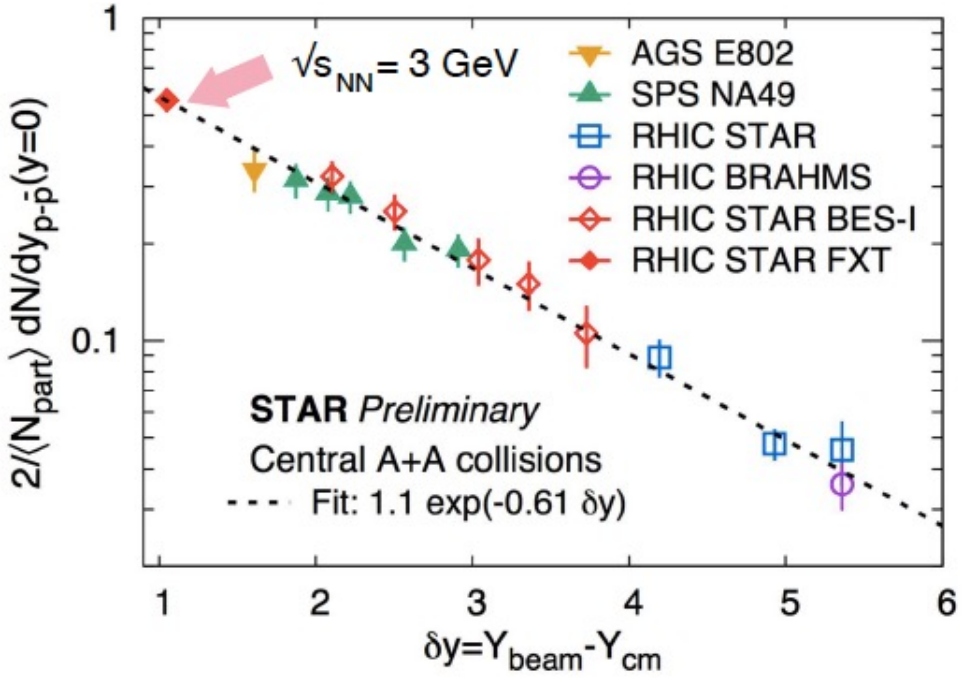
** Results from final BES-I + first sets of BES-II data (3.0, 14.6, 19.6 GeV)*

4π Measurement of Baryon Production

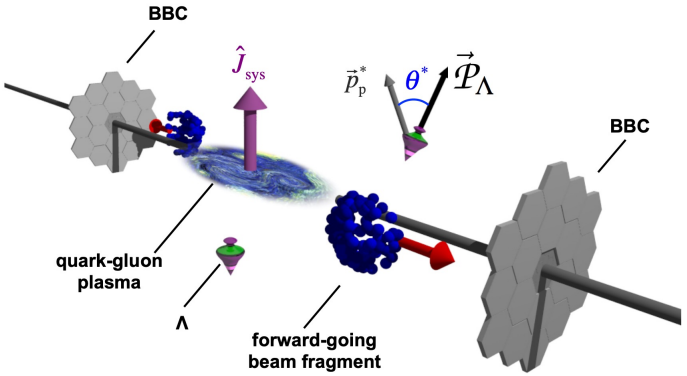
Proton dN/dy from 3 GeV covers mid to target rapidity region
strong centrality dependence in proton rapidity loss

Exponential dependence of net-proton density with rapidity shift





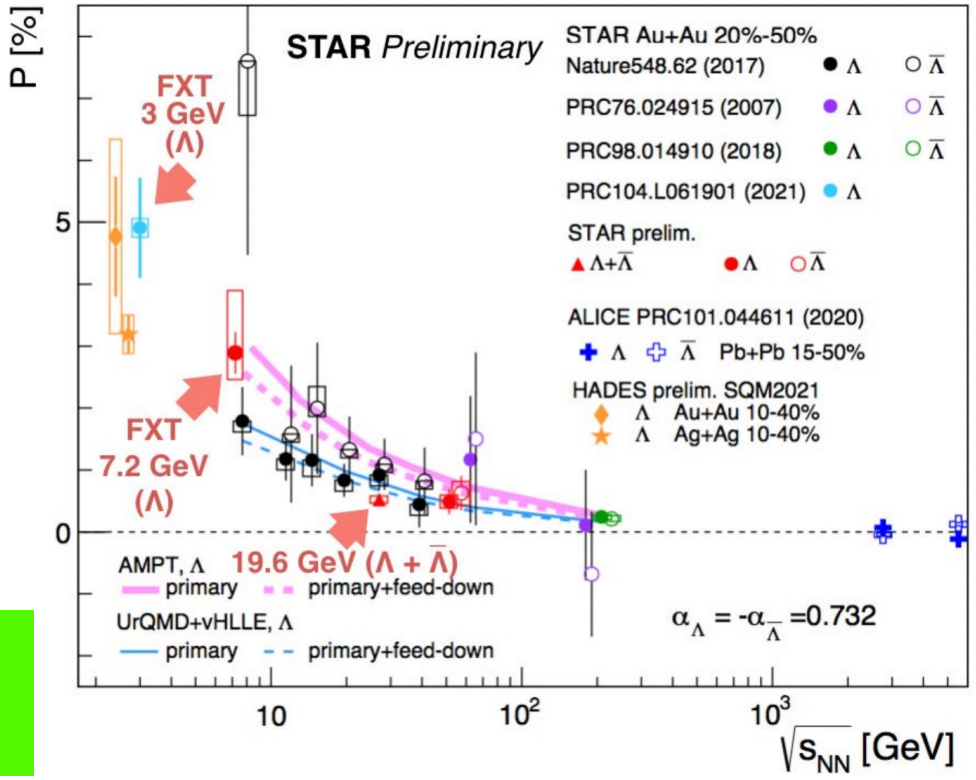
Global Polarization of Hyperons



Large angular momentum → large vorticity → global polarization

- Significant Λ global polarization
  - ***Most vortical fluid***

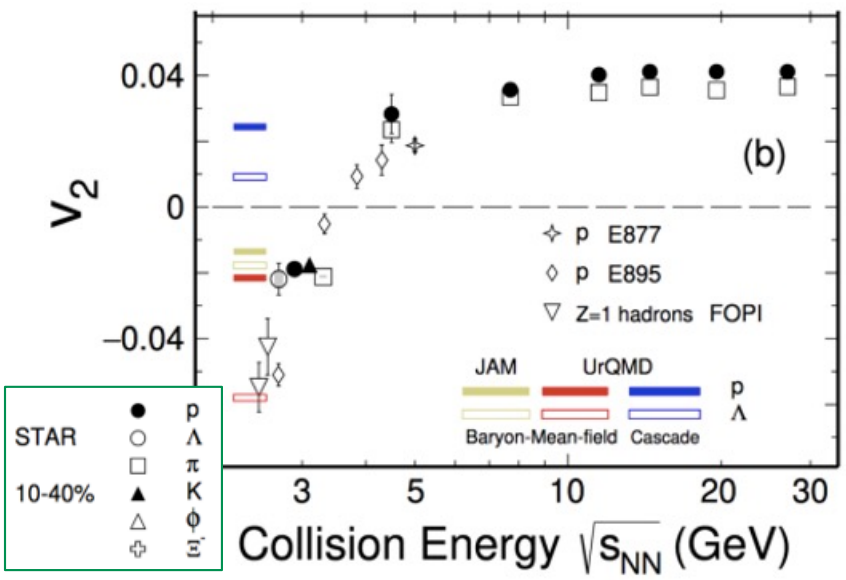
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

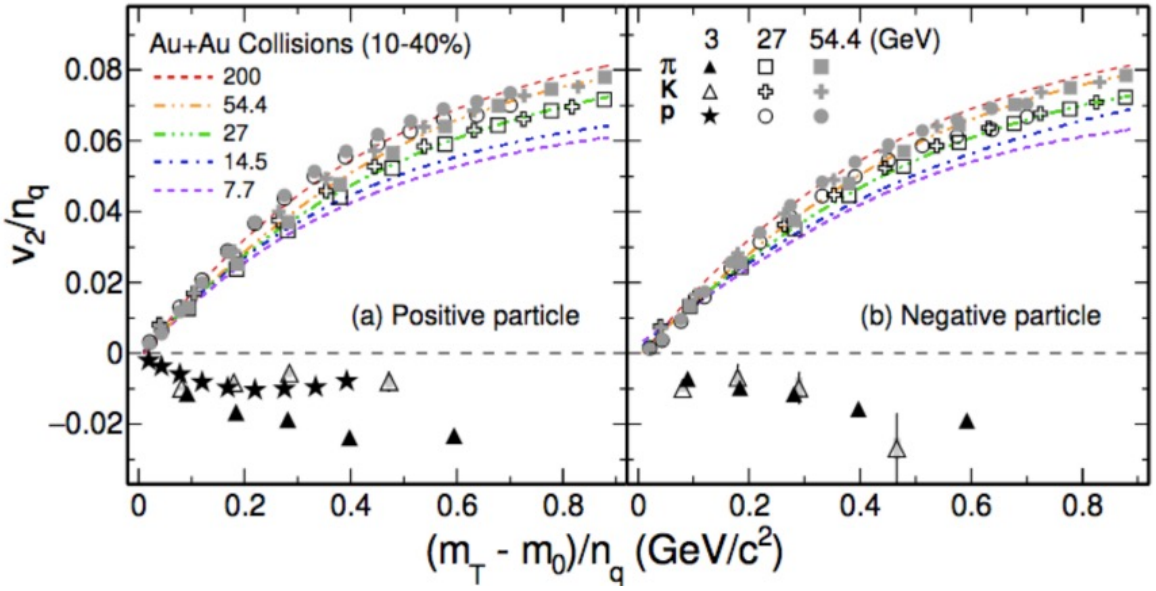


STAR, Nature 548 (2017) 62, PRC 104 (2021) 061901, arXiv: 2204.02302

Collectivity Measurements from BES

PLB 827 (2022) 137003





- EPD used for EP determination

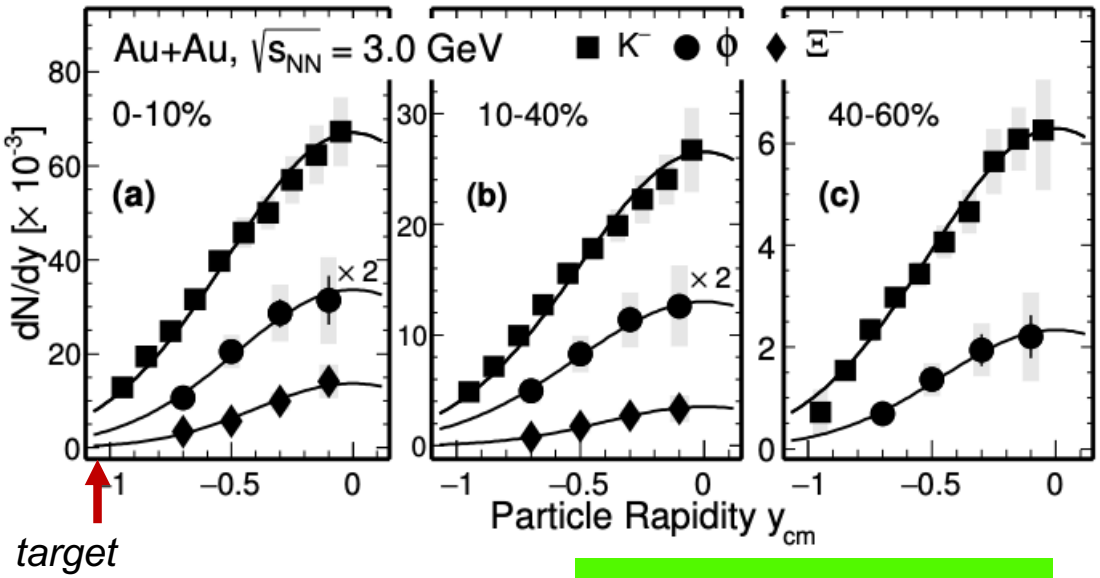
Light nuclei collectivity at 3 GeV follows the baryon number scaling – coalescence production

PLB 827 (2022) 136941

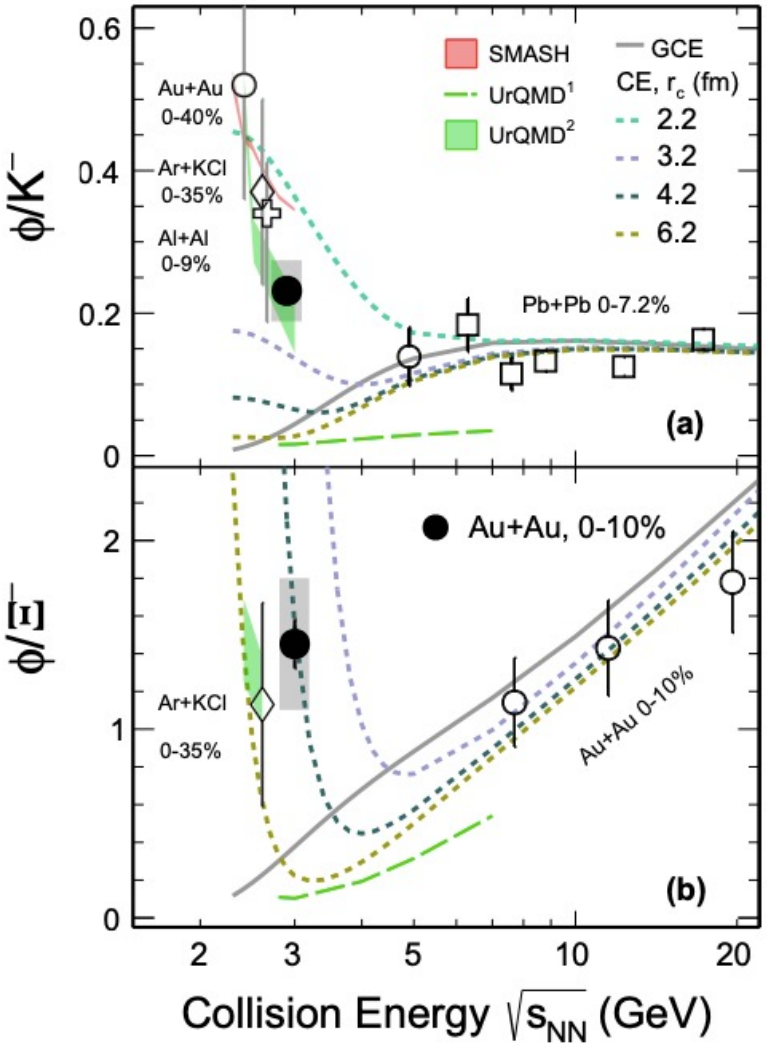
- No Number-of-Constituent-Quark scaling at 3 GeV Au+Au collisions
  - *UrQMD with baryonic mean-field potential qualitatively consistent with data*

→ Equation-of-State dominated by baryonic interactions at 3 GeV

Strange/Multi-Strange Hadron Production at 3 GeV

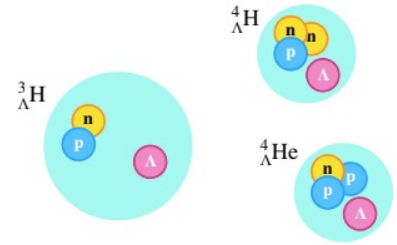


PLB 831 (2022) 137152

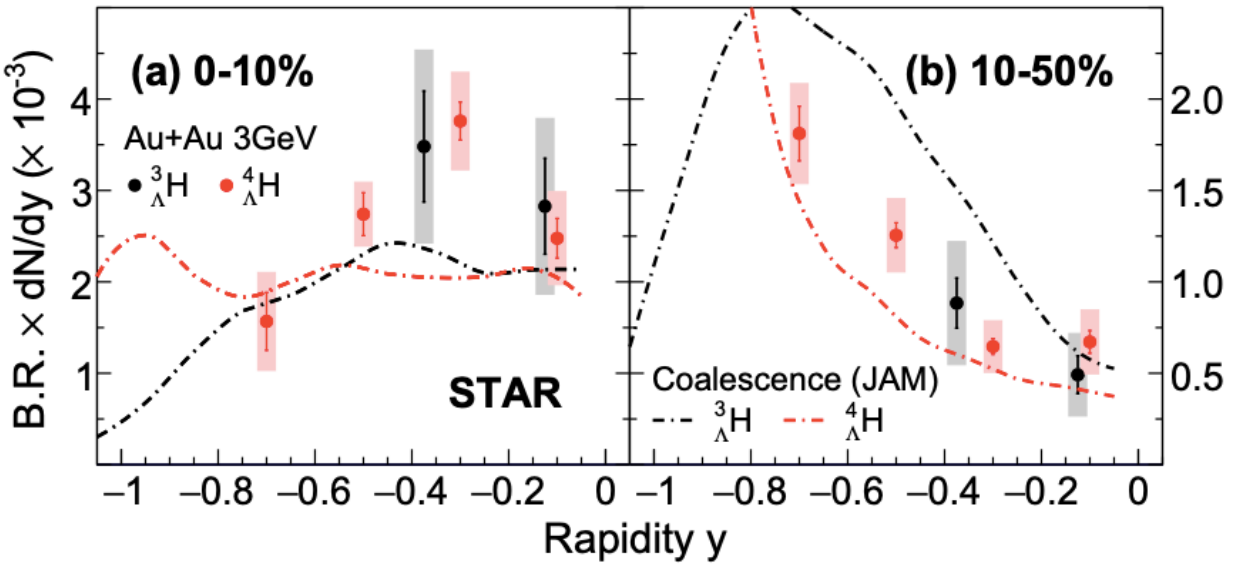


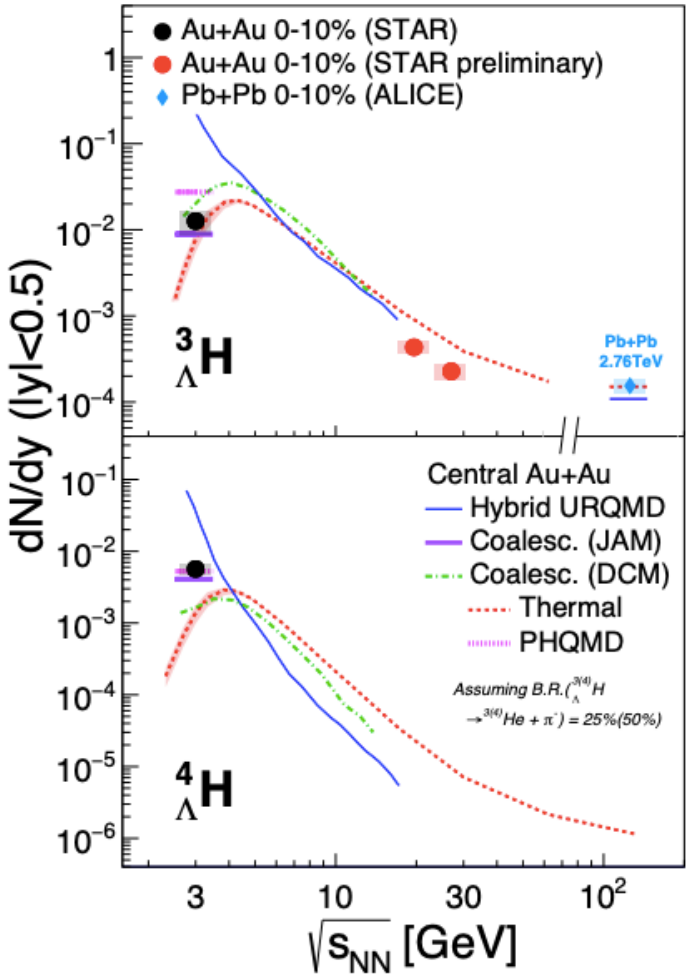
- ϕ/K ratio ~5σ > 0 (~ GCE)
- ϕ/K and ϕ/Ξ favors Canonical Ensemble
  - *favors hadronic models w/ resonance decays*

Hypernuclei Production from BES-II



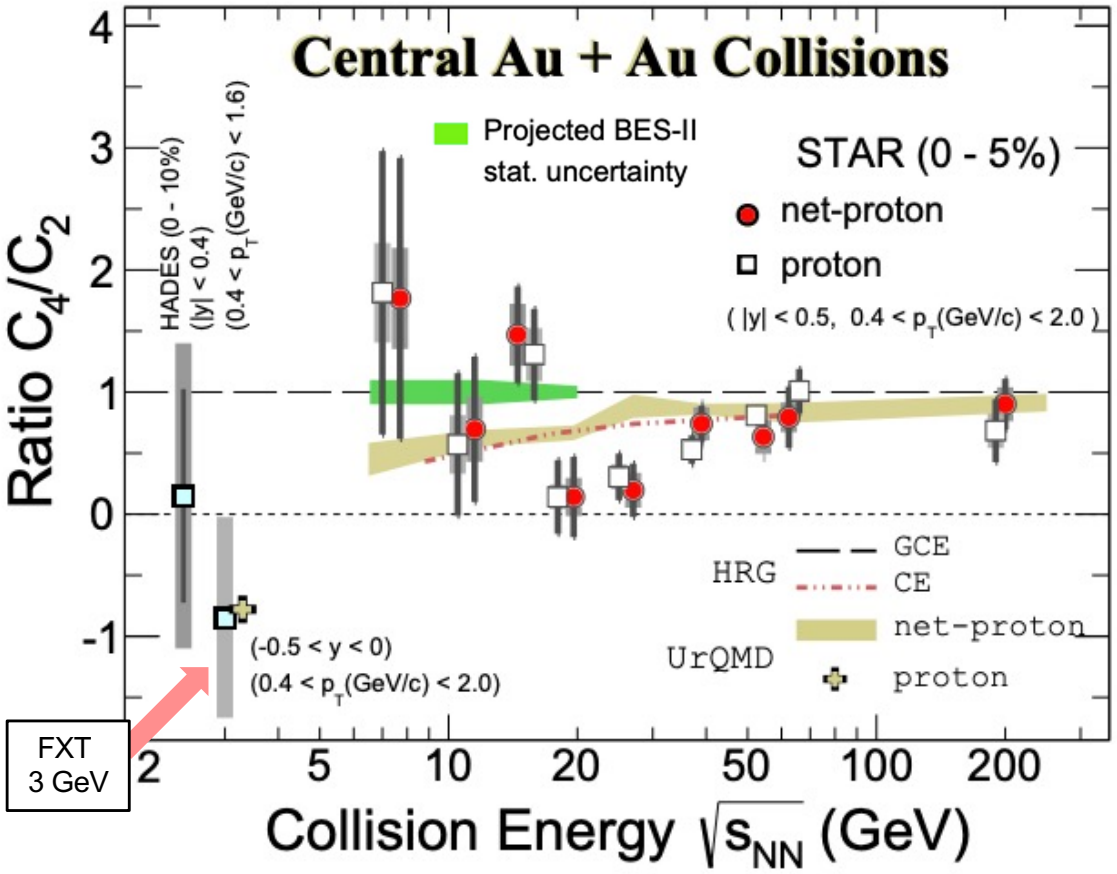
PRL 128 (2022) 202301

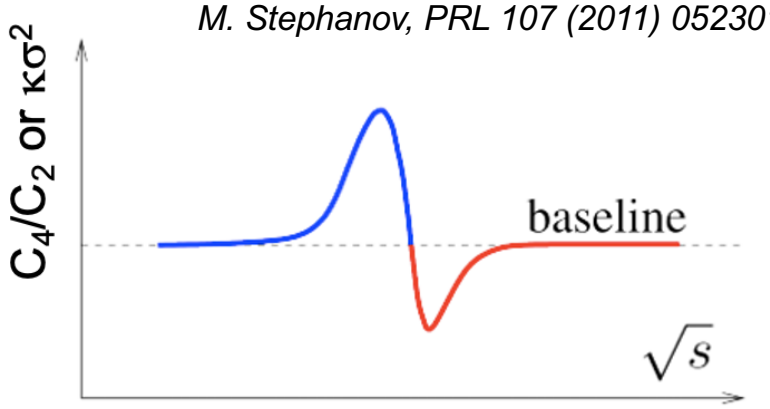




- Precision hypernuclei data from BES-II
- Towards quantitative understanding on ***Y-N*** interaction and high baryon density region

Energy Dependence of (Net-) Proton High Moments





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

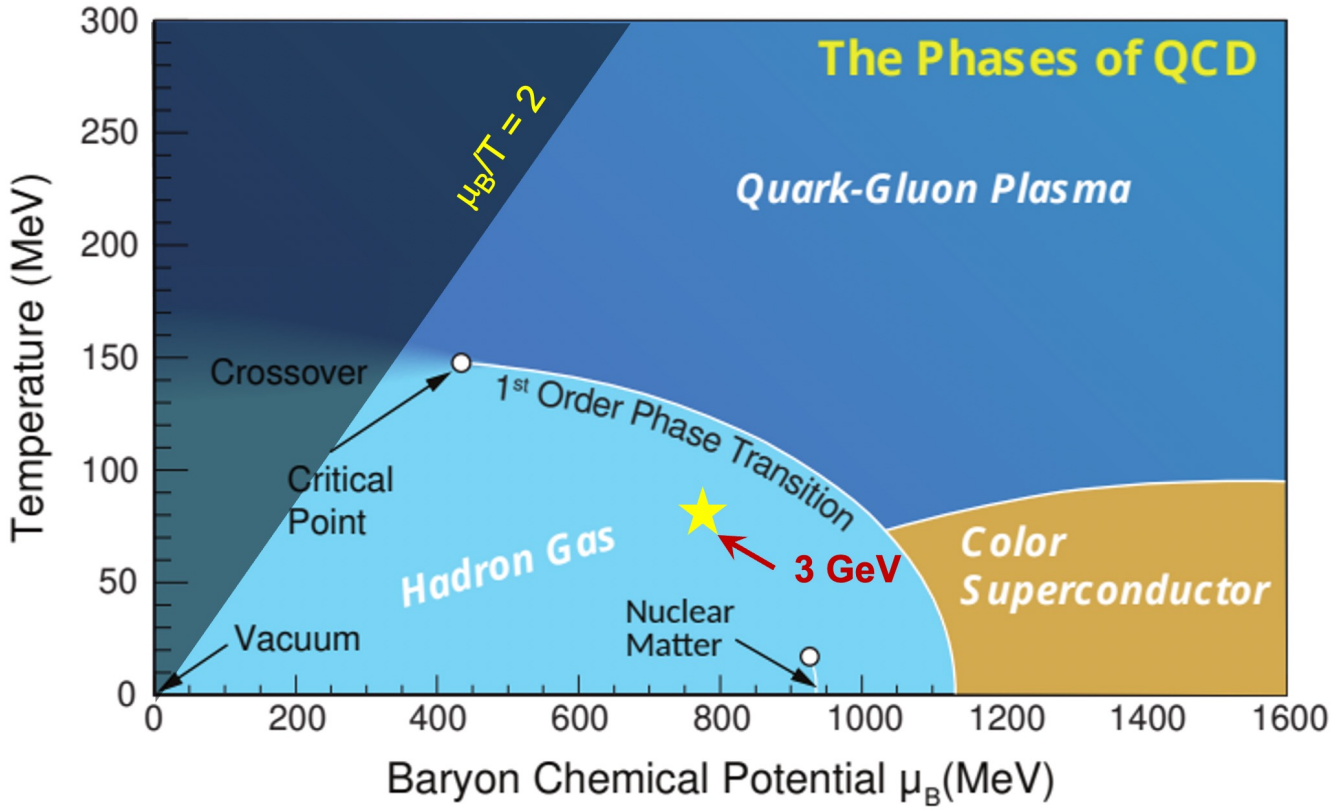
BES-I: PRL 126 (2021) 092301
3 GeV data: PRL 128 (2022) 202303

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*



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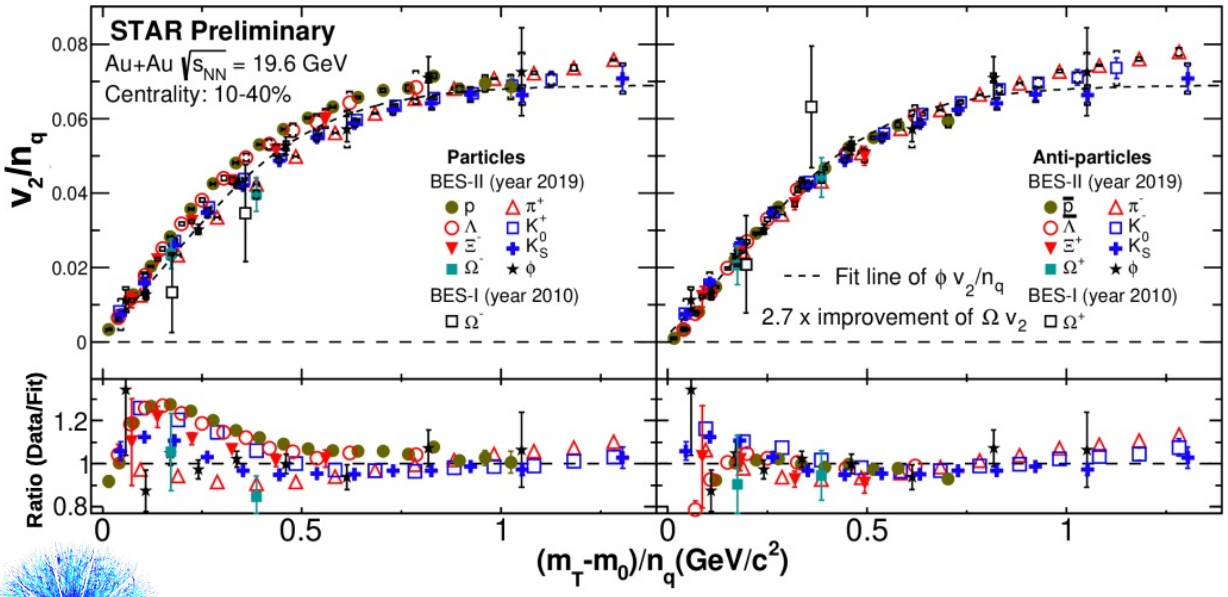
Collective Flows from BES-II 19.6 GeV

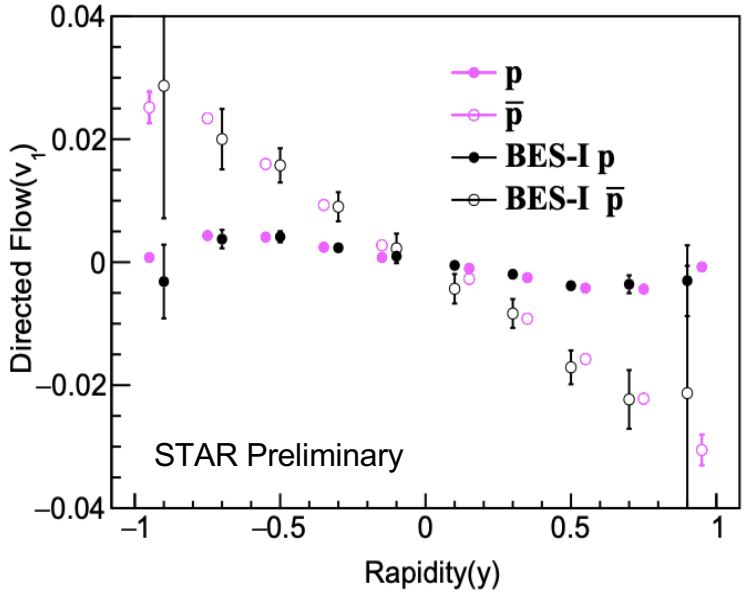
- x2.5-4 reduction in v_1/v_2 statistical uncertainties @ 19.6 GeV

NCQ-scaling holds for particles (20%) while better for anti-particles @ 19.6 GeV

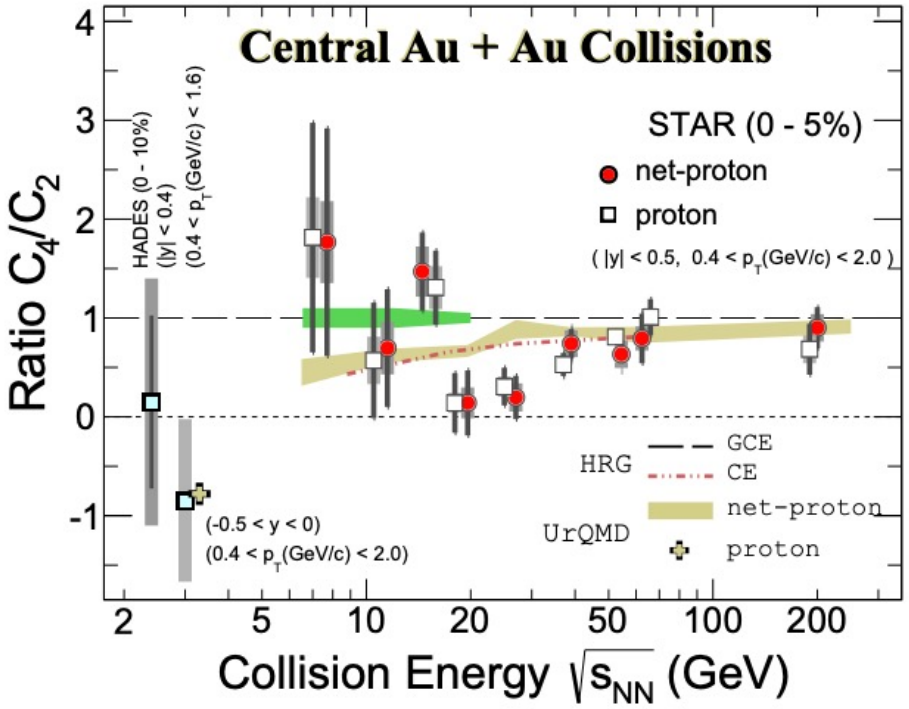
- transport quark effect



Au+Au @19.6 GeV

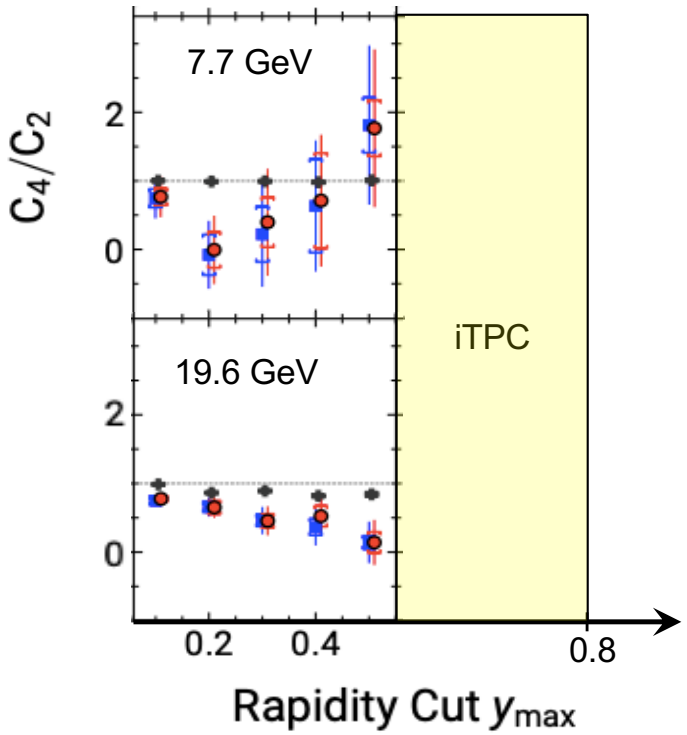


Prospects from BES-II



PRL 126 (2021) 092301, PRL 128 (2022) 202303

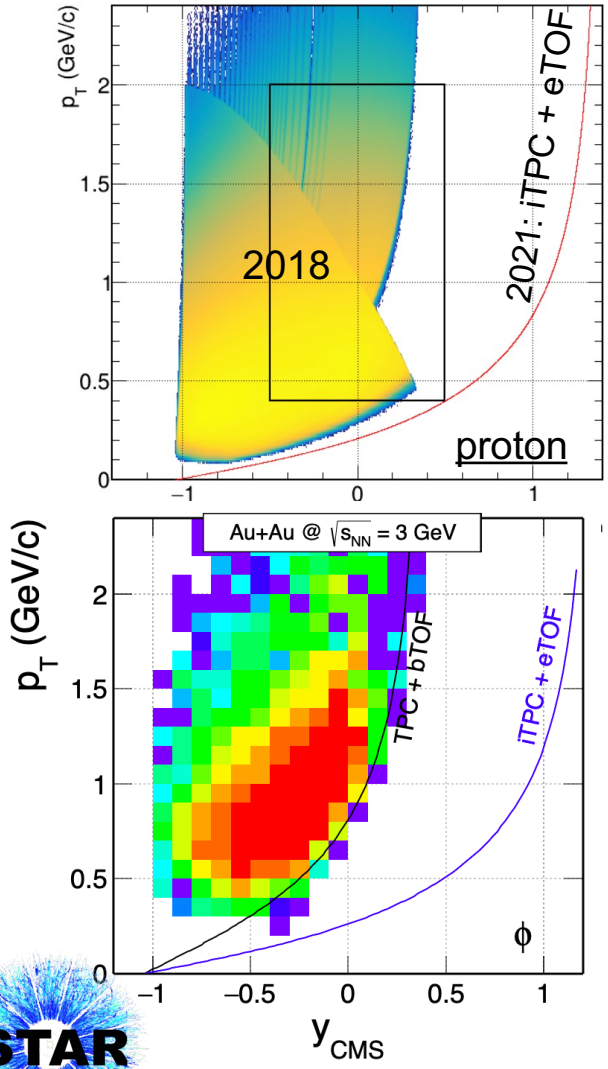
Rapidity coverages at BES-II
Collider: |y|<0.8
FXT: -1.0<y<0.5 @ 3 GeV



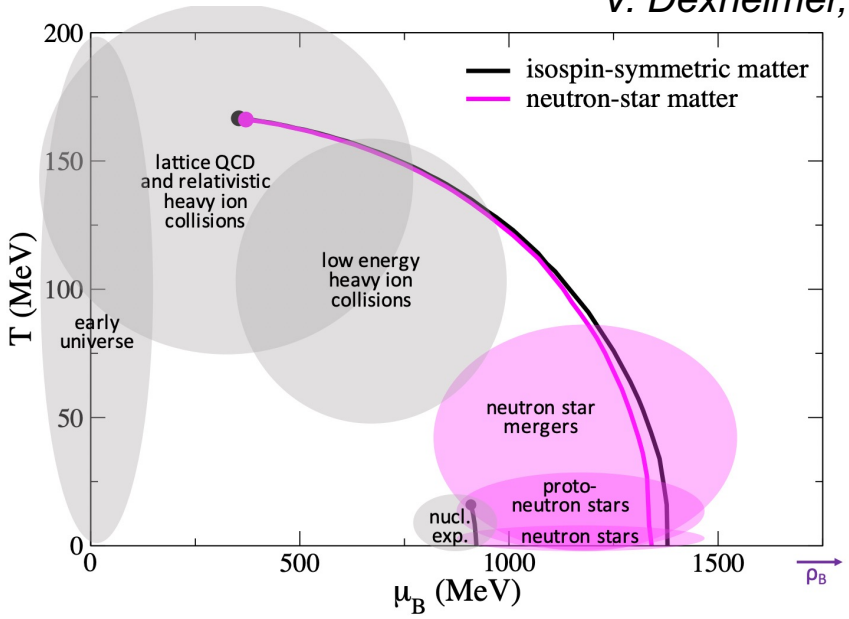
PRC 104 (2021) 024902

Significantly improved statistics
Better systematic control
Extended acceptance and PID

Prospects from BES-II – 3.0 GeV Dataset



V. Dexheimer, 1708.08342

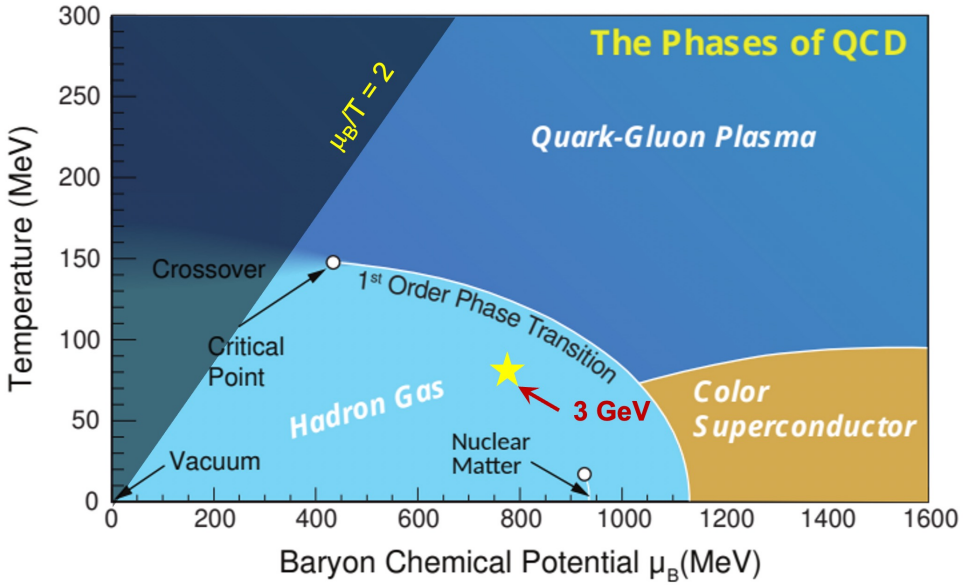


2.0 B data with iTPC+eTOF at 3.0 GeV (μ_B ~ 780 MeV)

- proton cumulants (C_1-C_6) in full mid-rapidity (|y|<0.5)
- (sub-)threshold strangeness production
- baryon-baryon/hyperon correlations

→ **Equation-of-State (EoS) at high density region**

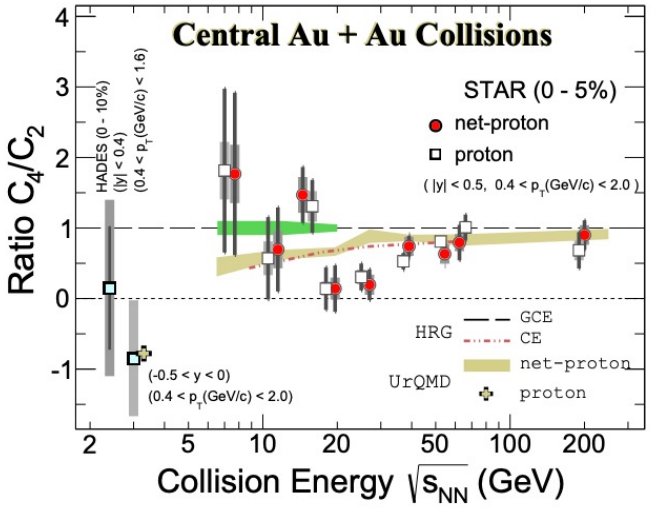
Summary



- QCD critical point or 1st-order phase transition
- Equation-of-State of nuclear matter at high μ_B
  - *connection to nuclear astrophysics*

First set of BES-II results

- FXT 3 GeV data (2018) demonstrate the dominance of hadronic phase
- Preliminary v_1/v_2 from 19.6/14.6 GeV: much improved precision compared to BES-I

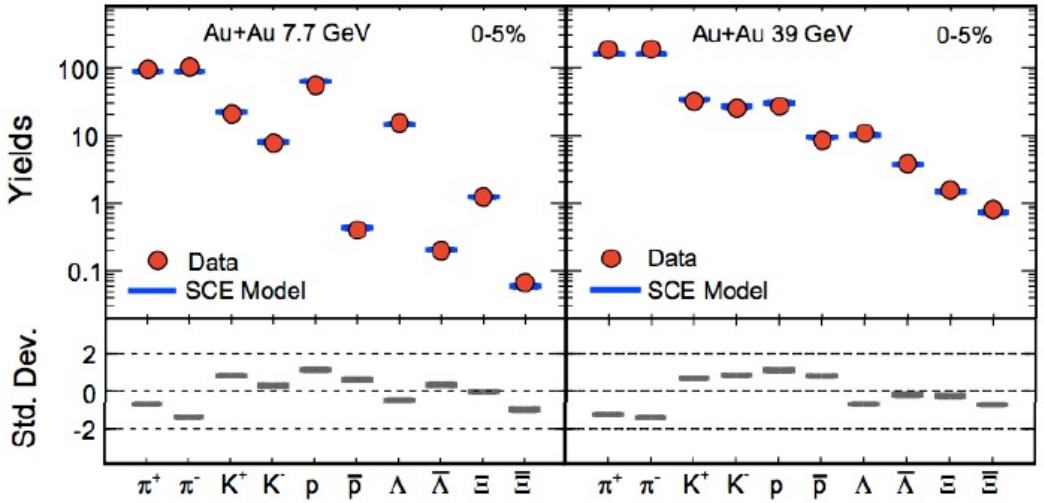


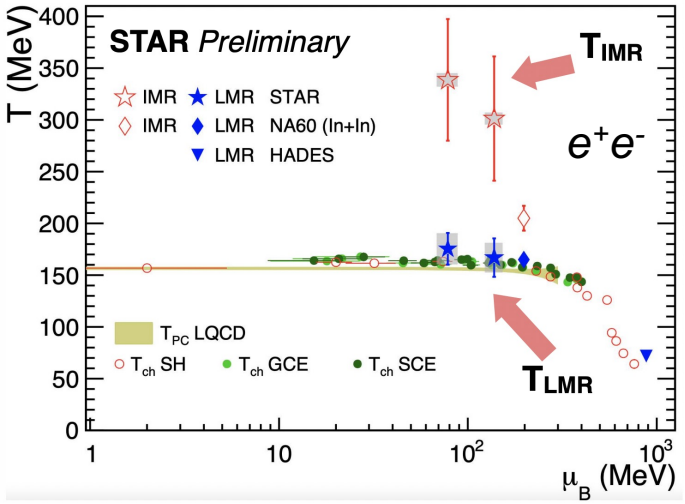
Results from full BES-II datasets to come

- Backup

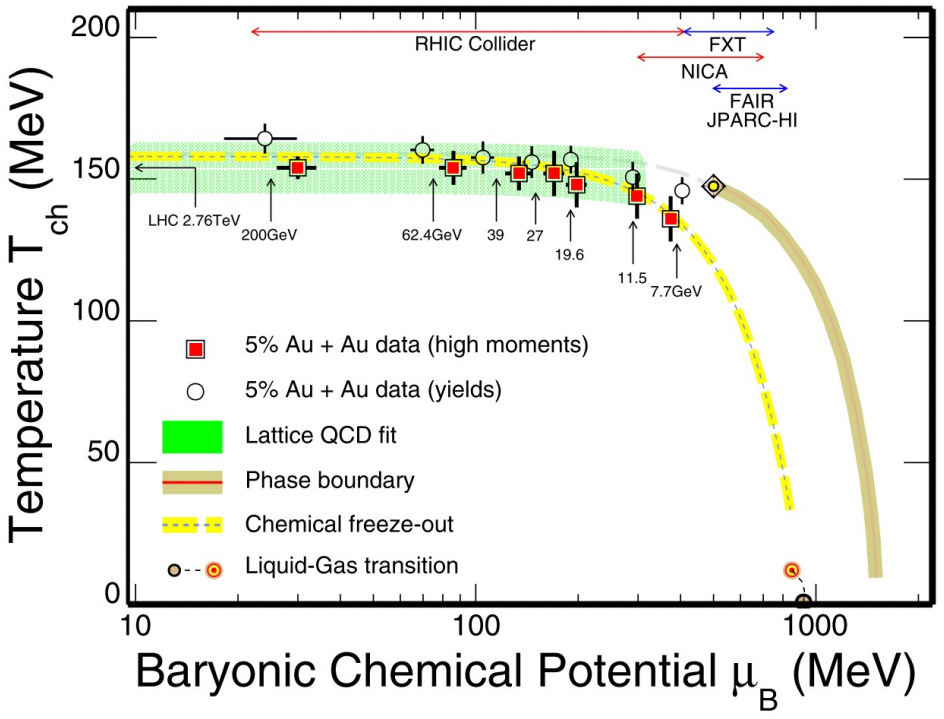
Chemical Freeze-out on Phase Diagram

STAR, PRC 96 (2017) 044904, QM2022





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

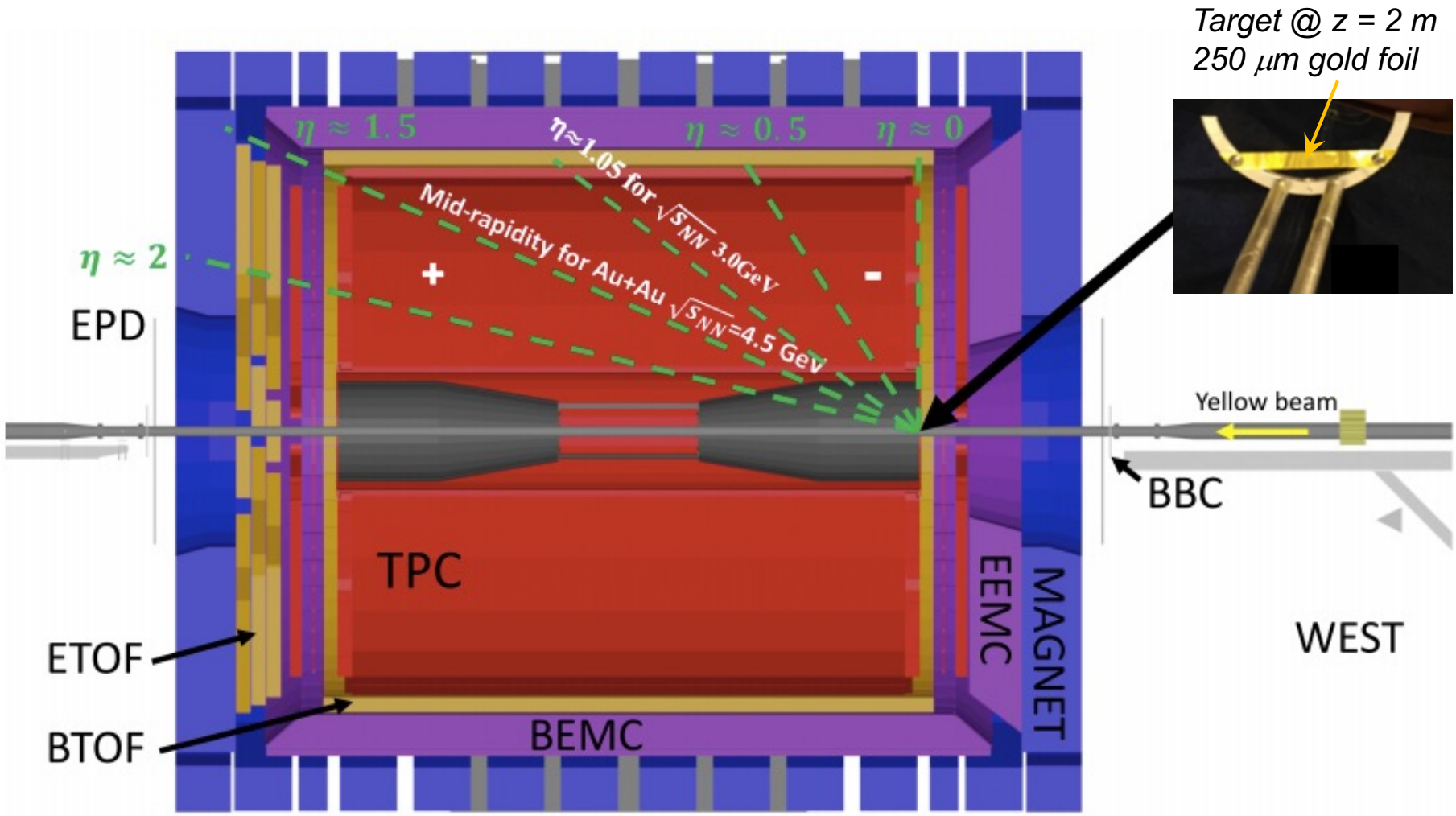


- Thermal model fit to extract freeze-out parameters
  - *consistent with those extracted from high moments and dileptons*

Status of BES-II Analyses

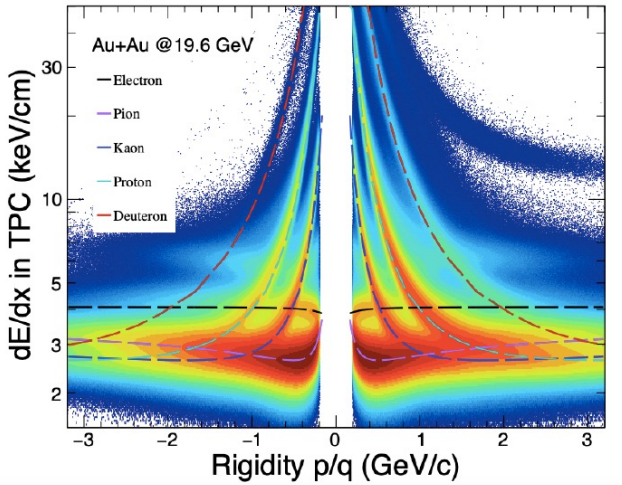
Year	Datasets	Calibration	Production	Analysis
2017/2018	54.4/27	Done	Done	Final
2018	FXT 3.0/7.2	Done	Done	Final
2019	19.6/14.6	Done	Done	Prel. @ QM22
	FXT	Done	Done	Post-prod QA
2020	11.5/9.2	in progress	Fall 2022	
	FXT	Done	Done	Post-prod QA
2021	7.7	Done	Done	Post-prod QA
	17.3	in progress	Winter 2022	
	FXT	in progress	Winter 2022	

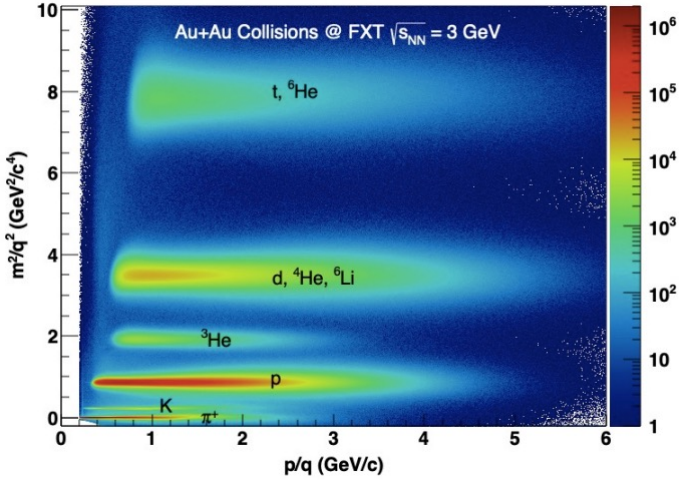
STAR Fixed-Target (FXT) Configuration

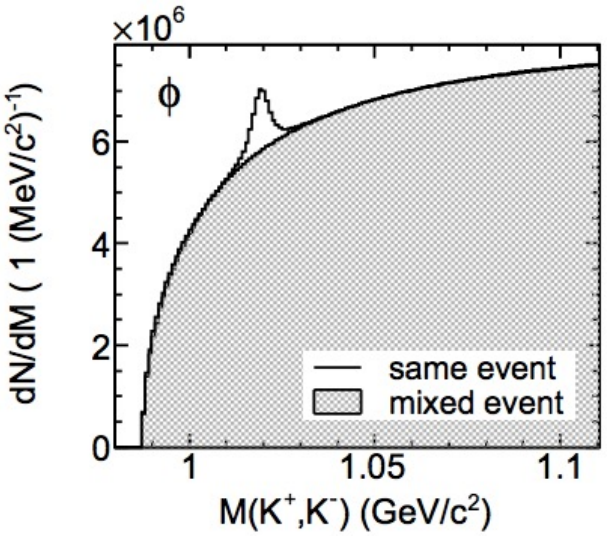


Courtesy of Benjamin Kimelman

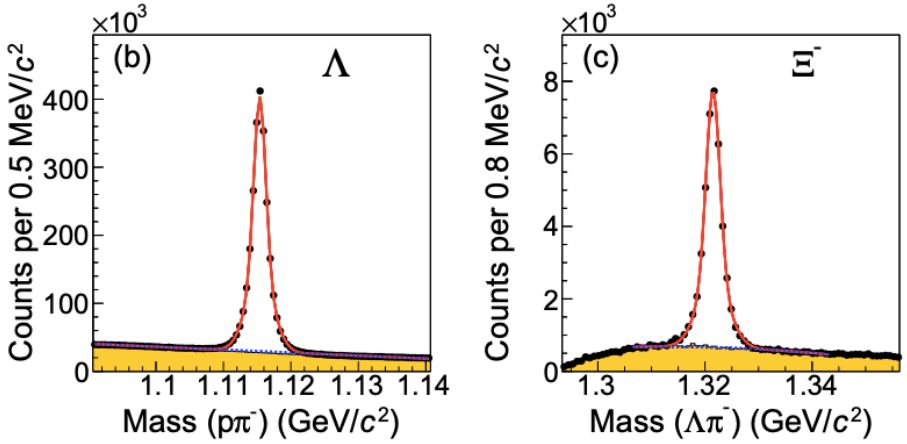
Particle Identification



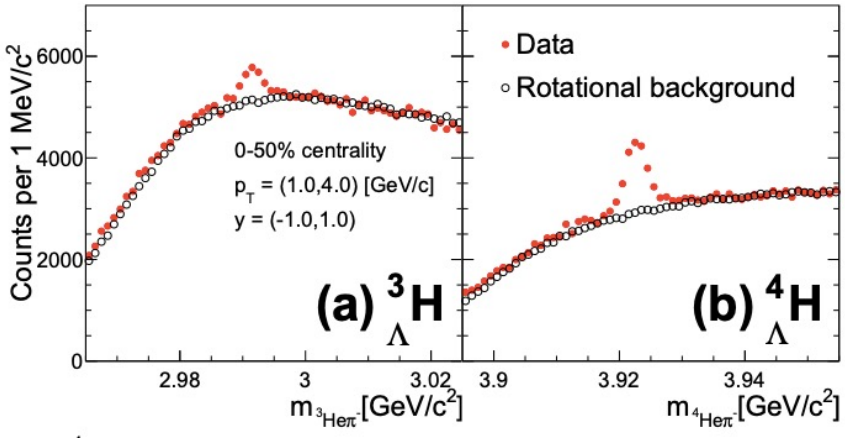




STAR, $\sqrt{s_{NN}}$ = 7.7 GeV Au+Au (0-80%), |y|<0.5



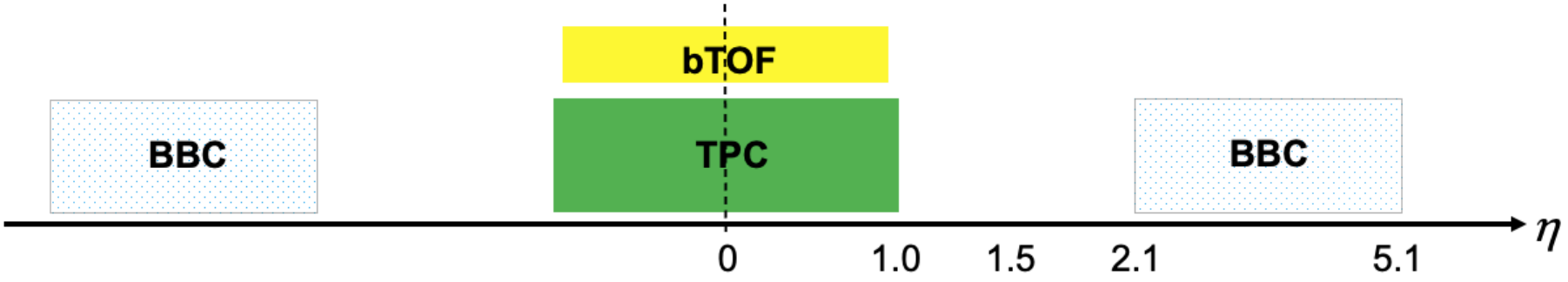
Au+Au $\sqrt{s_{NN}}$ = 3.0 GeV



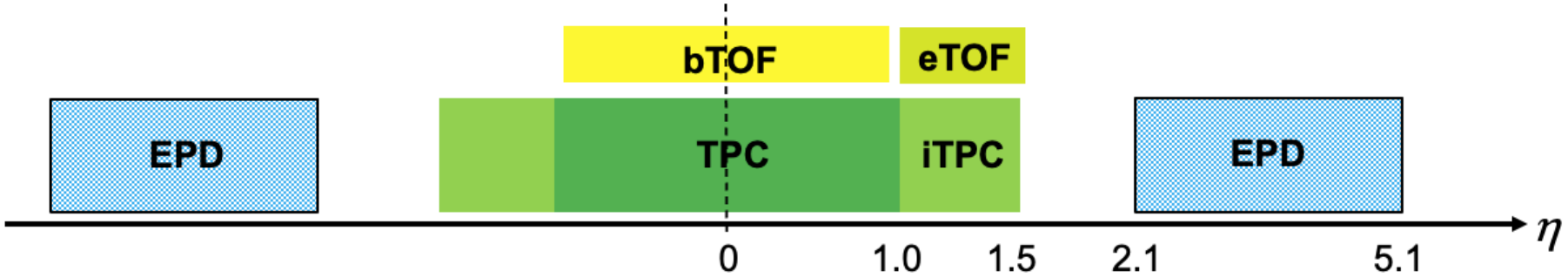
Detector Acceptance Coverage

STAR @ BES-I

Collider Mode



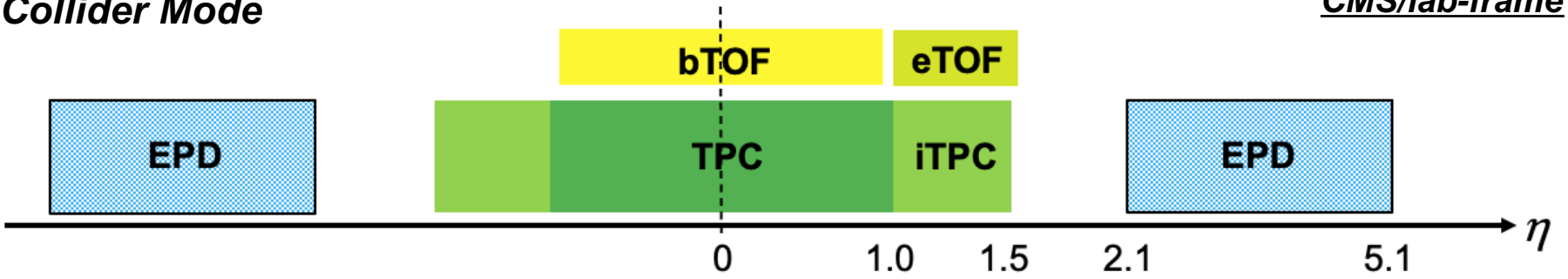
STAR @ BES-II



STAR Acceptance: Collider vs. Fixed-target

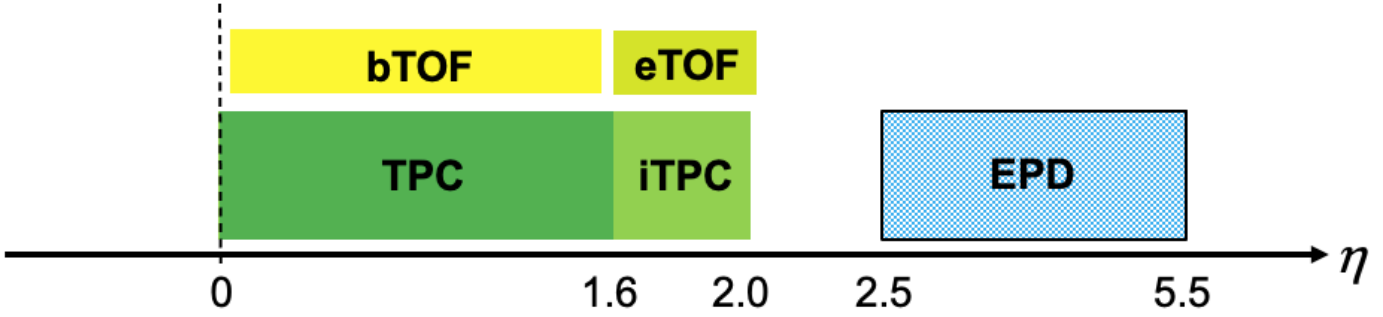
Collider Mode

CMS/lab-frame



Fixed-target Mode

lab-frame



y_{mid}	1.05	1.53	2.1
$\sqrt{s_{NN}}$ (GeV)	3.0	4.5	7.7

Critical Point Search

Lattice calculation of QCD critical point (CP) at finite μ_B is still challenging.

- Recent development (Tyler series) predicts CP location:

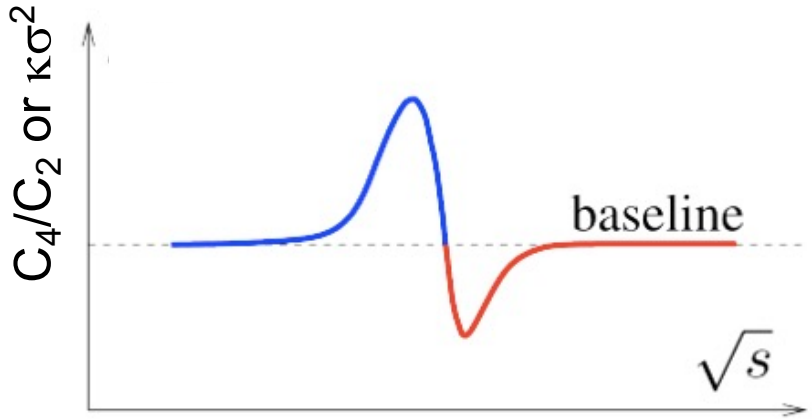
μ_B > ~400 MeV or μ_B/T > ~2.5 (*F. Karsch, 2021*)

Proposed Experimental Observables:

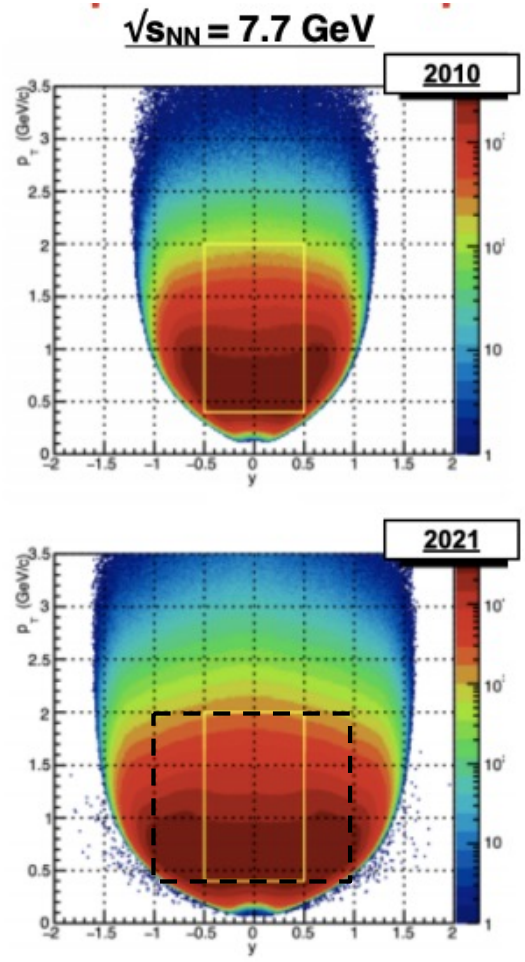
Moments of conserved quantities: net-baryon number, net-strangeness, net-charge etc.

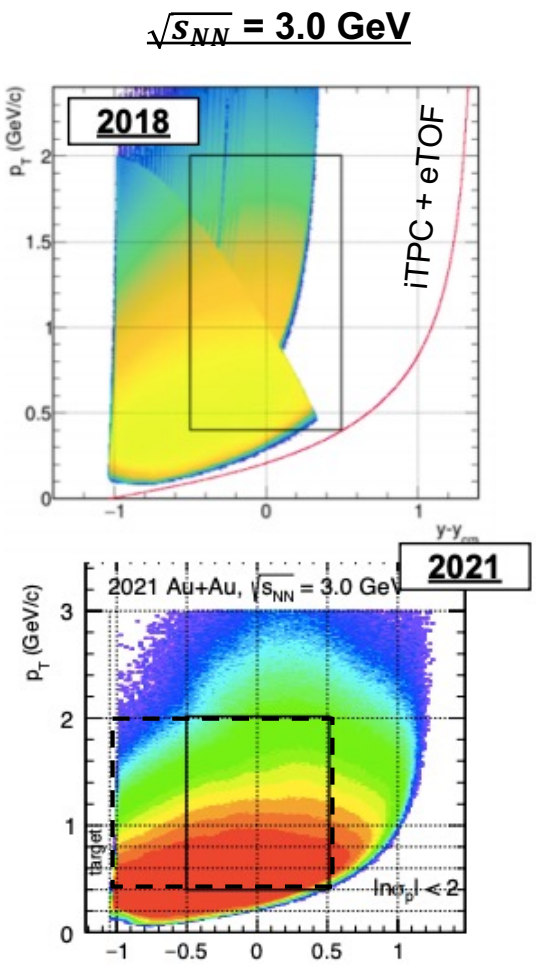
- directly related to the susceptibility ratios (calculable from Lattice QCD)
- sensitive to correlation lengths (*M. A. Stephanov, PRL 102 (2009) 032301)*

$$\begin{aligned}
\text{mean} : \mathrm{M} &= \langle N \rangle &&= C_1, \\
\text{variance} : \sigma^2 &= \langle (\delta N)^2 \rangle &&= C_2, \\
\text{skewness} : \mathrm{S} &= \langle (\delta N)^3 \rangle / \sigma^3 &&= C_3/C_2^{3/2}, \\
\text{kurtosis} : \kappa &= \langle (\delta N)^4 \rangle / \sigma^4 - 3 &&= C_4/C_2^2.
\end{aligned}$$

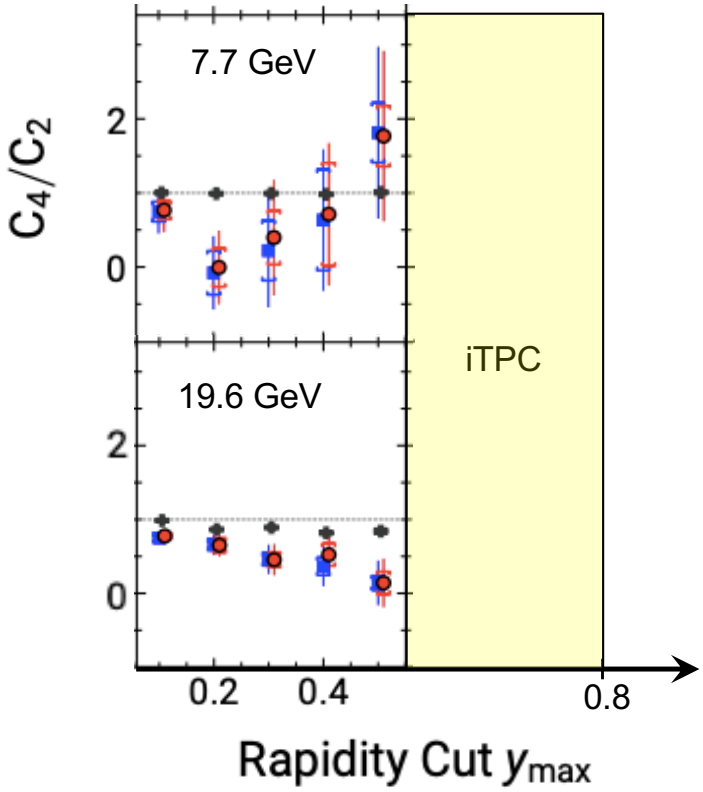


Rapidity Window Scan of (Net-)Proton Fluctuations

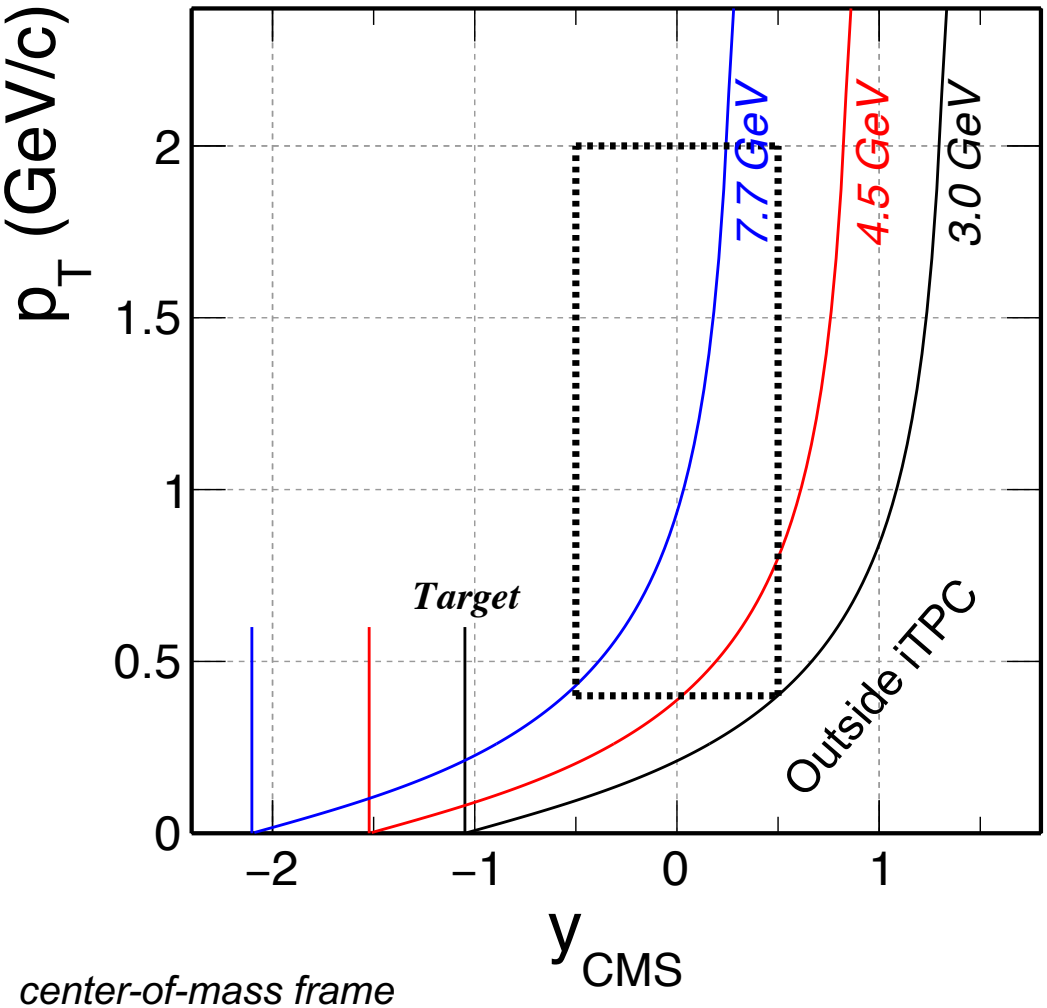




Rapidity windows at BES-II
Collider: |y|<0.8 (1.0)
FXT: -1.0<y<0.5 @ 3 GeV



Proton Acceptance in Center-of-Mass Frame in FXT



center-of-mass frame

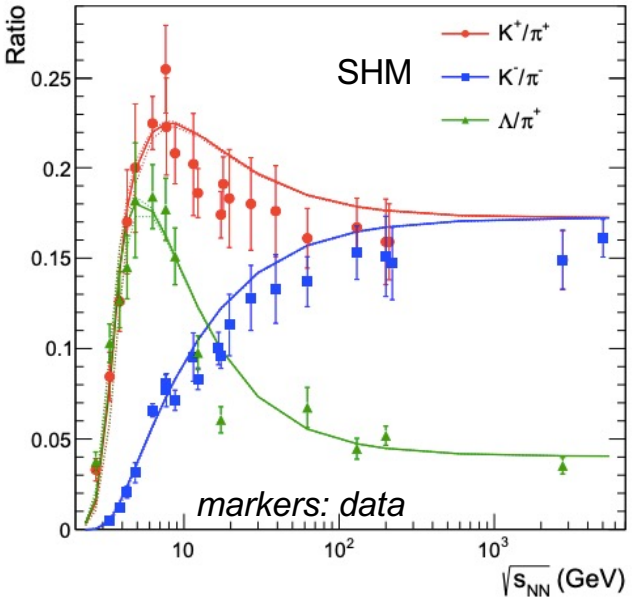
Dashed box:
- $0.4<p_T<2.0$ GeV/c
- $|y|<0.5$

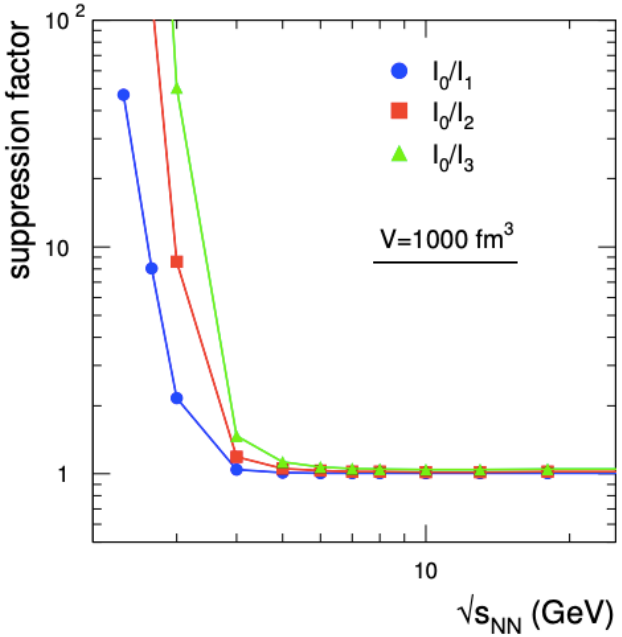
- Used in collider net-proton cumulant measurements

At 3.0 GeV, STAR with iTPC+eTOF covers full range of $0.4<p_T<2.0$, $|y|<0.5$ for proton cumulants measurements.

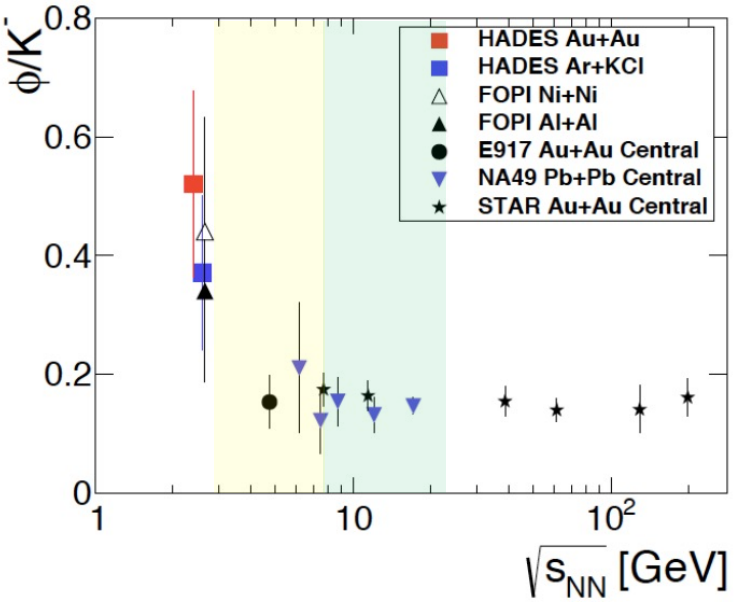
Strange Production and "Canonical Suppression"

SHM: A. Andronic et al, Nature 561 (2018) 321





HADES, PLB 778 (2018) 403



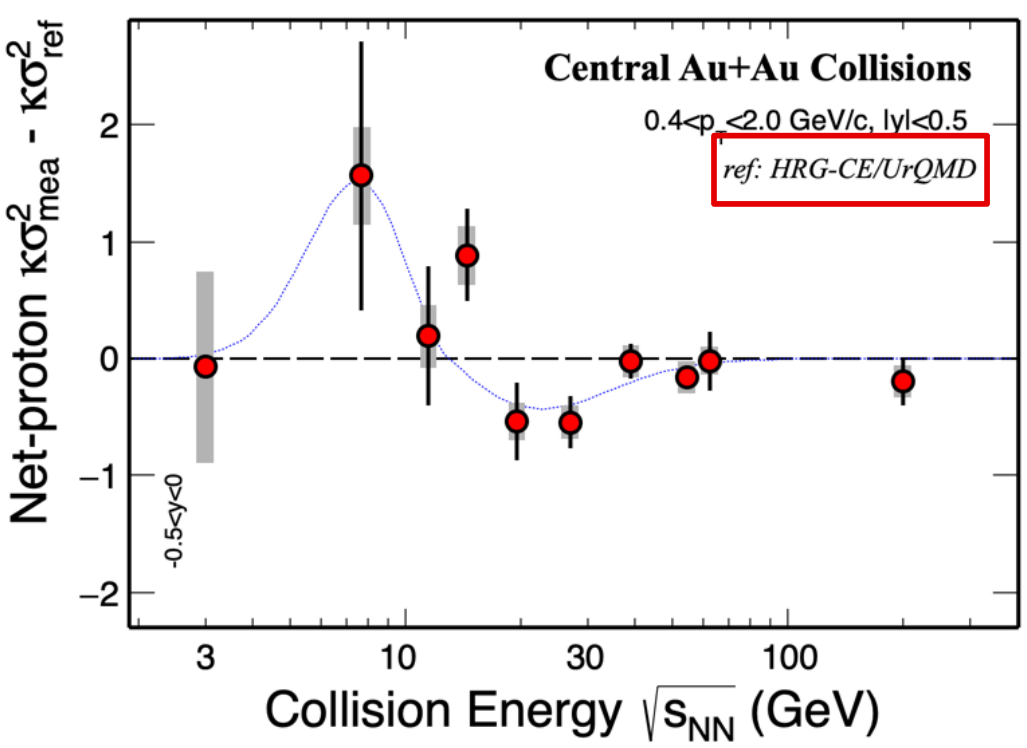
canonical suppression (correction) factor for open strange hadrons

$$n^C_{K,\Lambda} = n^{GC}_{K,\Lambda} \cdot \frac{I_1(N_S)}{I_0(N_S)},$$
$$n^C_{\phi} = n^{GC}_{\phi}$$

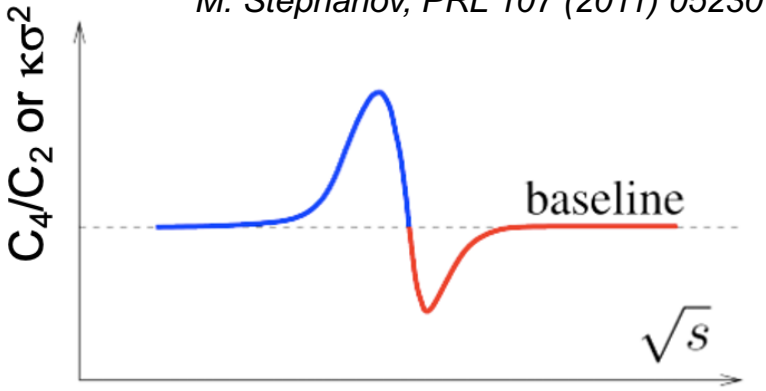
ϕ/K, ϕ/Ξ – probe canonical ensemble

- Hint of ϕ/K enhancement at SIS energies

Energy Dependence of (Net-) Proton High Moments



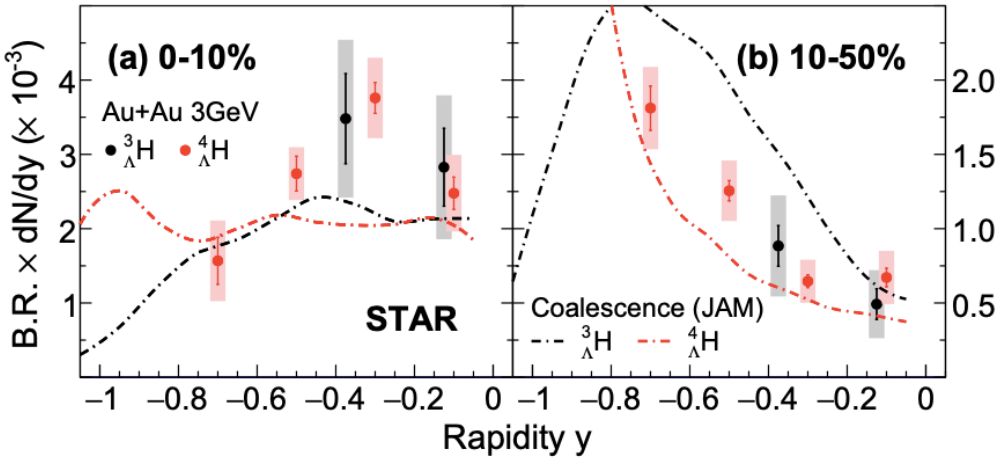
M. Stephanov, PRL 107 (2011) 052301



- 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*

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

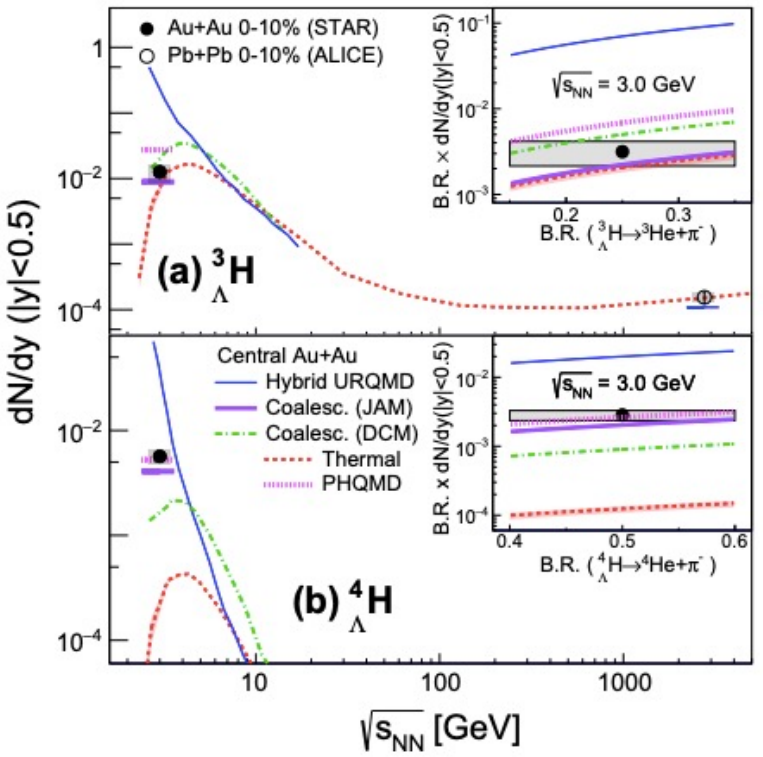
Hypernuclei Production dN/dy in Heavy-Ion Collisions



- JAM + coalescence reasonably consistent with data
- Coalescence parameters ↔ Y-N interaction

nuclei	*(r_C/fm, p_C/GeV)*	*B/A (B_Λ) (MeV)*
d	*(4.5, 0.3)*	*1.1*
t	*(4.0, 0.3)*	*2.8*
$^3_\Lambda H$	***(4.0, 0.12)***	***~0.3***
$^4_\Lambda H$	*(4.0, 0.3)*	*~2.6*

arXiv: 2110.09513



- Thermal model w/ CE consistent with $^3_\Lambda H$, but underestimate $^4_\Lambda H$
- Transport models (JAM or PHQMD) reasonably consistent with data