Physics at High Baryon Density

- RHIC BES, HADES, NA60+ and NA61@CERN, **CBM@FAIR**

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LBNL

High-Energy Nuclear Collisions and QCD Phase Diagram

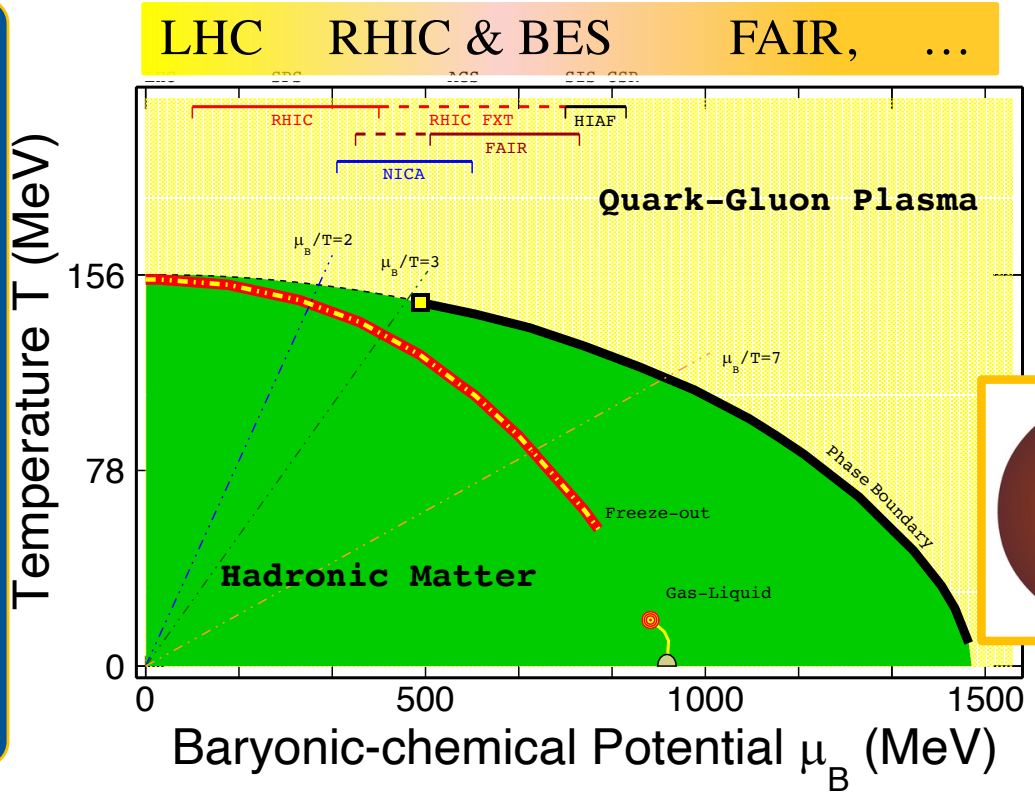
At LHC and RHIC top energy:

- Jet quenching;
- HF R_{AA} and v_2 data;
- Net-p C_6/C_2

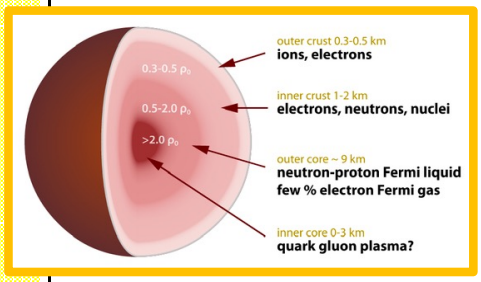
→

1) At $\mu_B \sim 0$, smooth crossover. $\mu_B/T \leq 2$ (LGT);

2) CP at $\mu_B/T \geq 2$

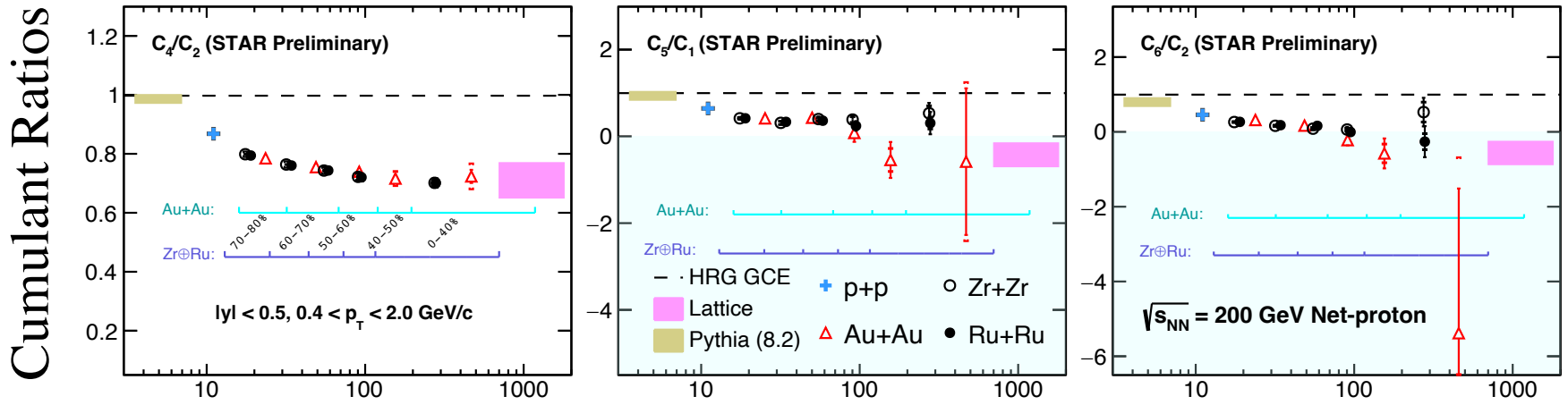


High baryon density: Inner structure of compact stars



1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions (*e.g.* $N-N$, $Y-N$) → inner structure of compact stars

Net-p in 200 GeV p+p and Au+Au Collisions



STAR: CPOD2021, SQM2021, QM2022

1) In 200GeV p+p collisions, high order cumulants ratios of net-protons are found to be positive for: C_4/C_2, C_5/C_2 and C_6/C_2;

2) For QGP matter, LGT predicted negative net-baryon C_5/C_2 and C_6/C_2;

3) **Direct evidence for the QGP formation in 200GeV Au+Au central collisions!**

HotQCD Collaboration, PR**D101**, 074502 (2020)

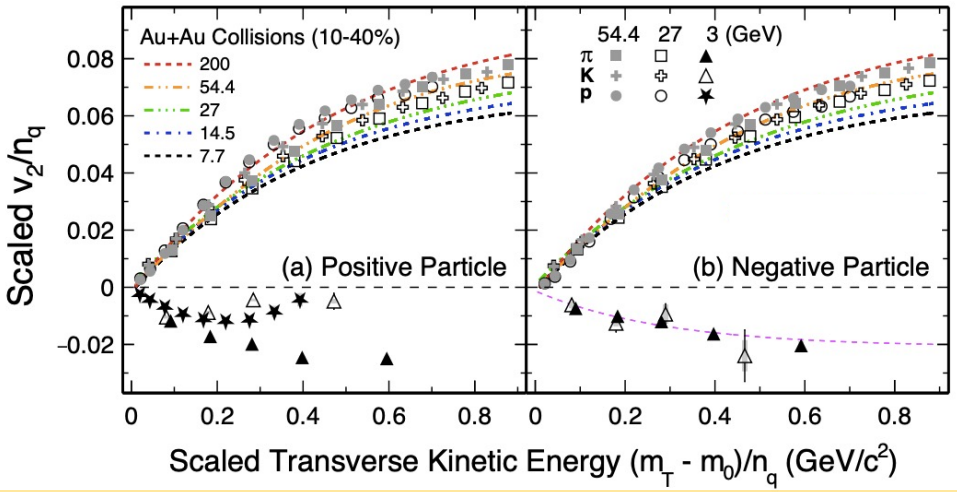
STAR BES-I and BES-II Data Sets

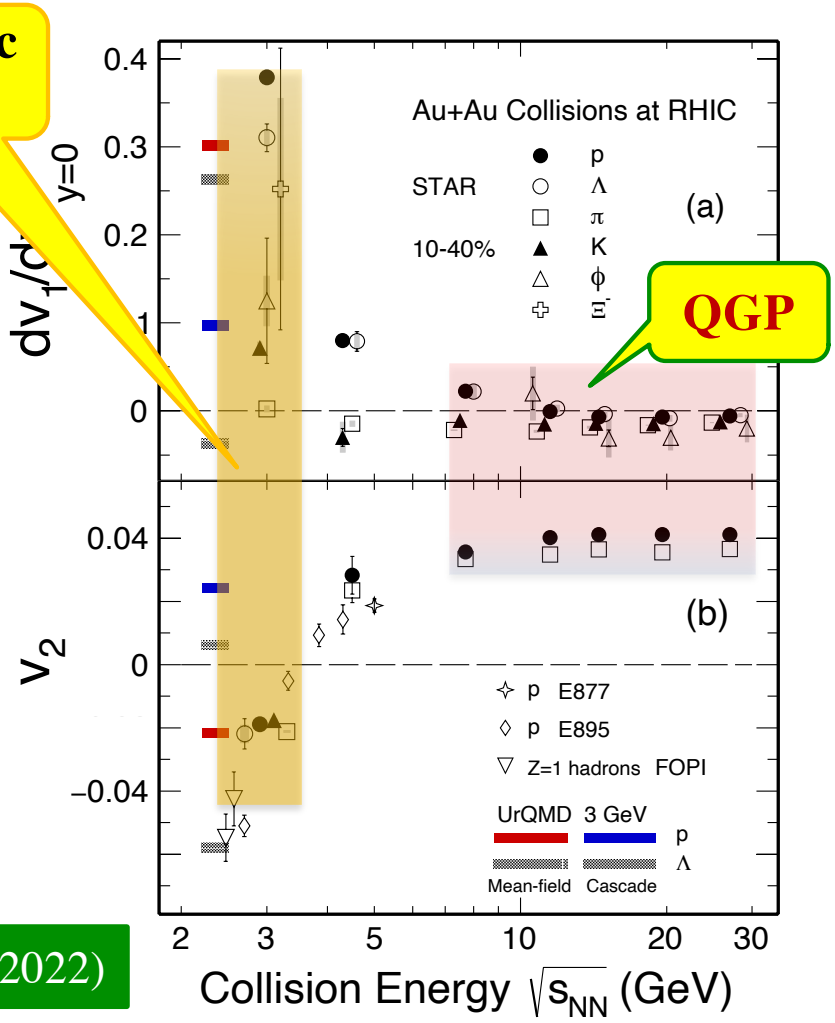
Au+Au Collisions at RHIC												
Collider Runs						**Fixed-Target Runs**						
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	57 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	**3.0** (3.85)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

$$3 < \sqrt{s_{NN}} < 200 \text{ GeV}; \quad 760 > \mu_B > 25 \text{ MeV}$$

Disappearance of Partonic Collectivity

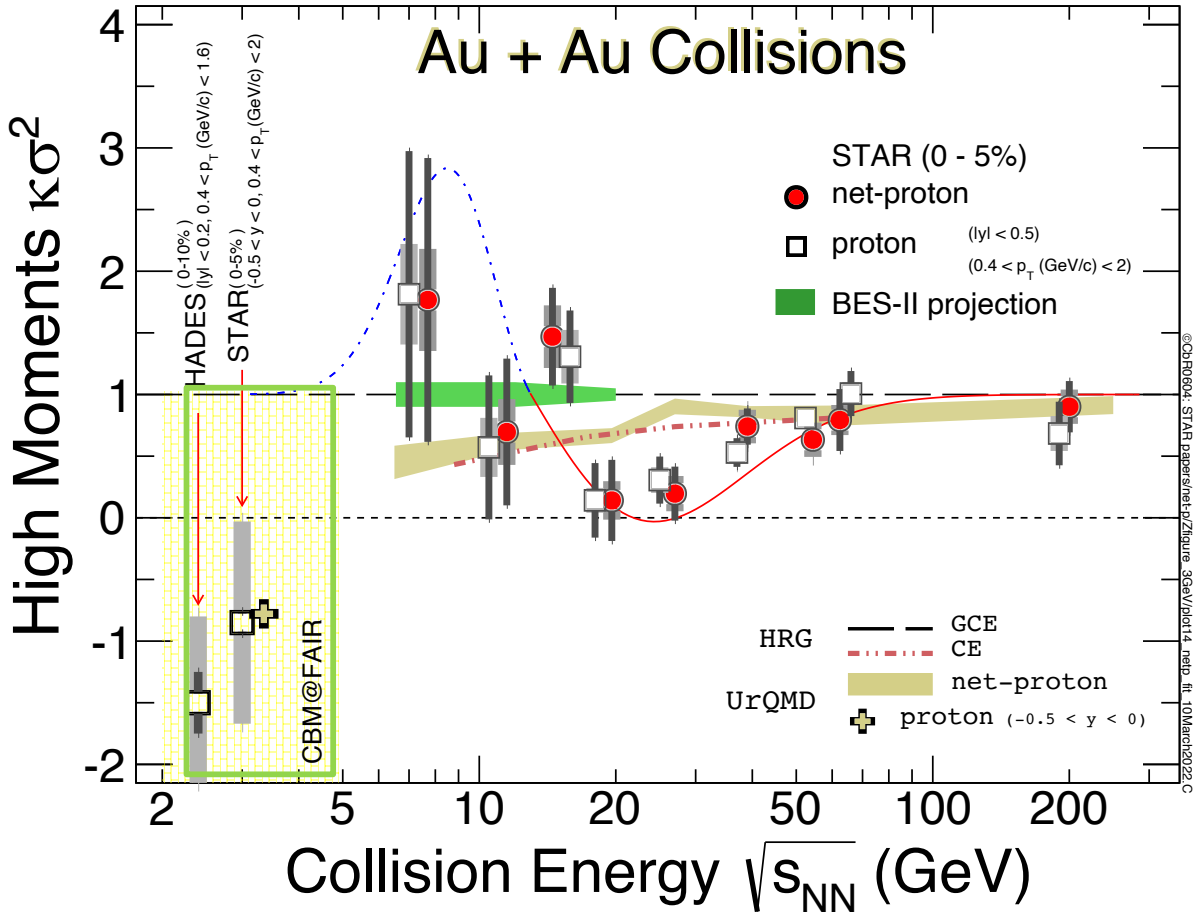




- At **3 GeV**, NCQ scaling is absent ;
- Transport model calculations, with baryonic mean field, reproduce both v_1 and v_2 results ;
- **hadronic interactions dominant!**

STAR: PLB**827**, 137003(2022)

Net-p $\kappa\sigma^2$ Energy Dependence

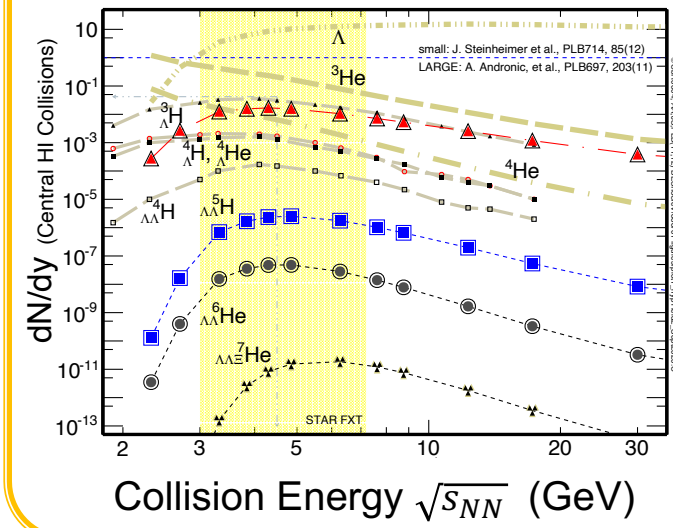


1) Non-monotonic energy dependence;
2) 3 GeV proton high moments data → **Hadronic interaction dominant!**
3) Energy gap between 3 and 7.7 GeV, important for **Critical Point search**

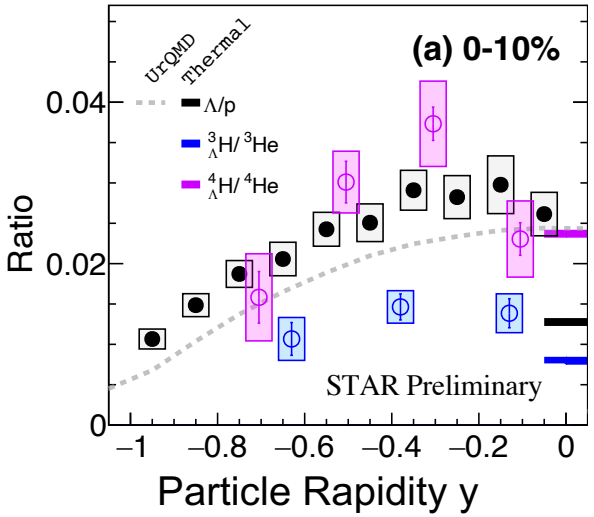
STAR: PRL**126**, 92301(2021)
PRL**128**, 202303(2022)
HADES: PR**C102**, 024914(2020)

Baryon Interactions and Hyper-Nuclei

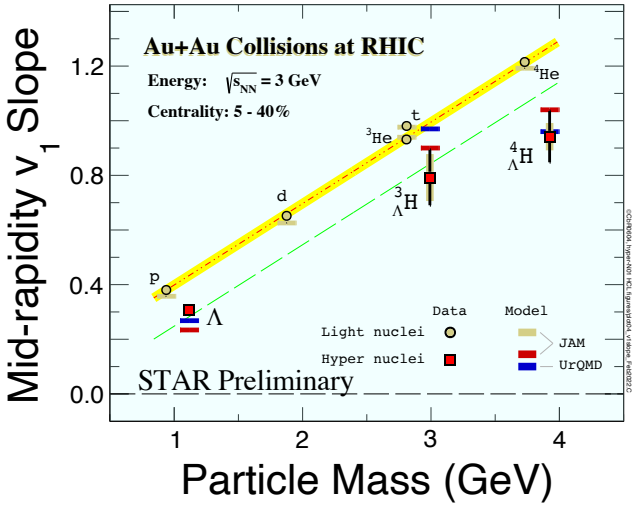
Yields



Rapidity Density



Collectivity

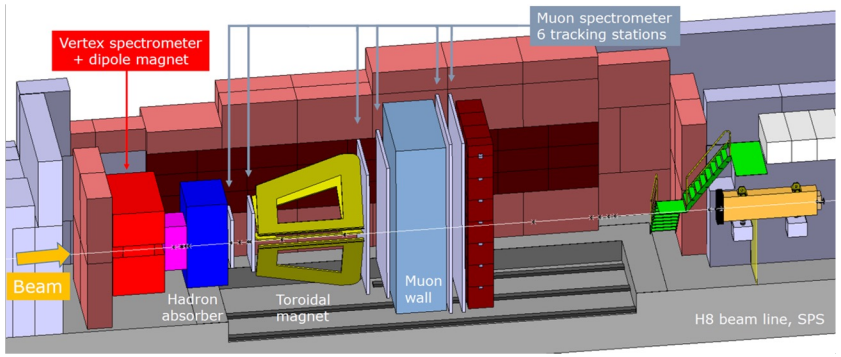


1) Hyper nuclei and double-Λ hyper-nuclei productions
2) Hyper nuclei collectivity (e.g. v_1 and v_2) → ***Y-N*** and ***Y-Y*** interactions under finite pressure

STAR: CPOD21, SQM22, SYP22

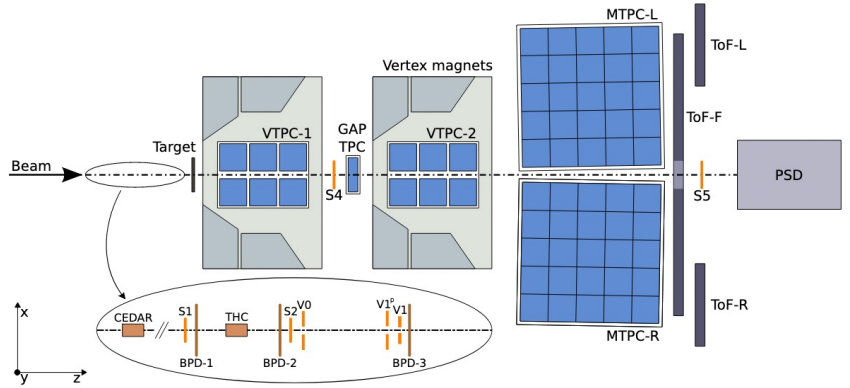
NA60+ and NA61 Experiments at SPS

NA60+ (2029)



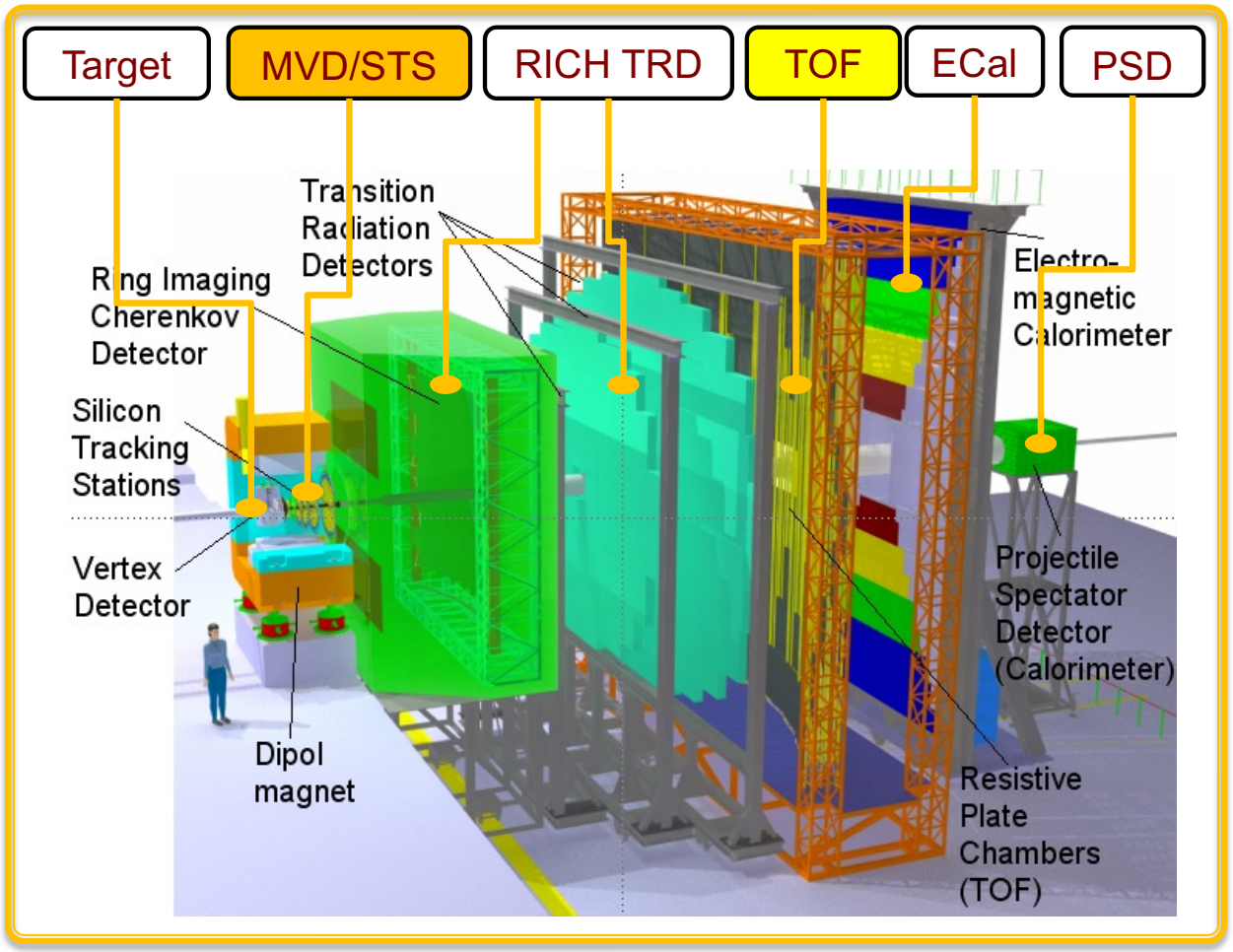
1) High rate (10^6 Hz Pb beam) di-muon spectrometer for energy scan $6 \leq \sqrt{s_{NN}} \leq 17.3$ GeV
2) **Key Physics:** (i) Temperature; (ii) Onset of deconfinement; (iii) QCD transport coefficient

NA61 (2008 - 2027)



1) Study hadronic production in p-p, p-A and A-A collisions over $5.1 \leq \sqrt{s_{NN}} \leq 17.3$ GeV
2) **Key Physics:** (i) QCD CP; (ii) Onset of deconfinement

CBM Experiment at FAIR



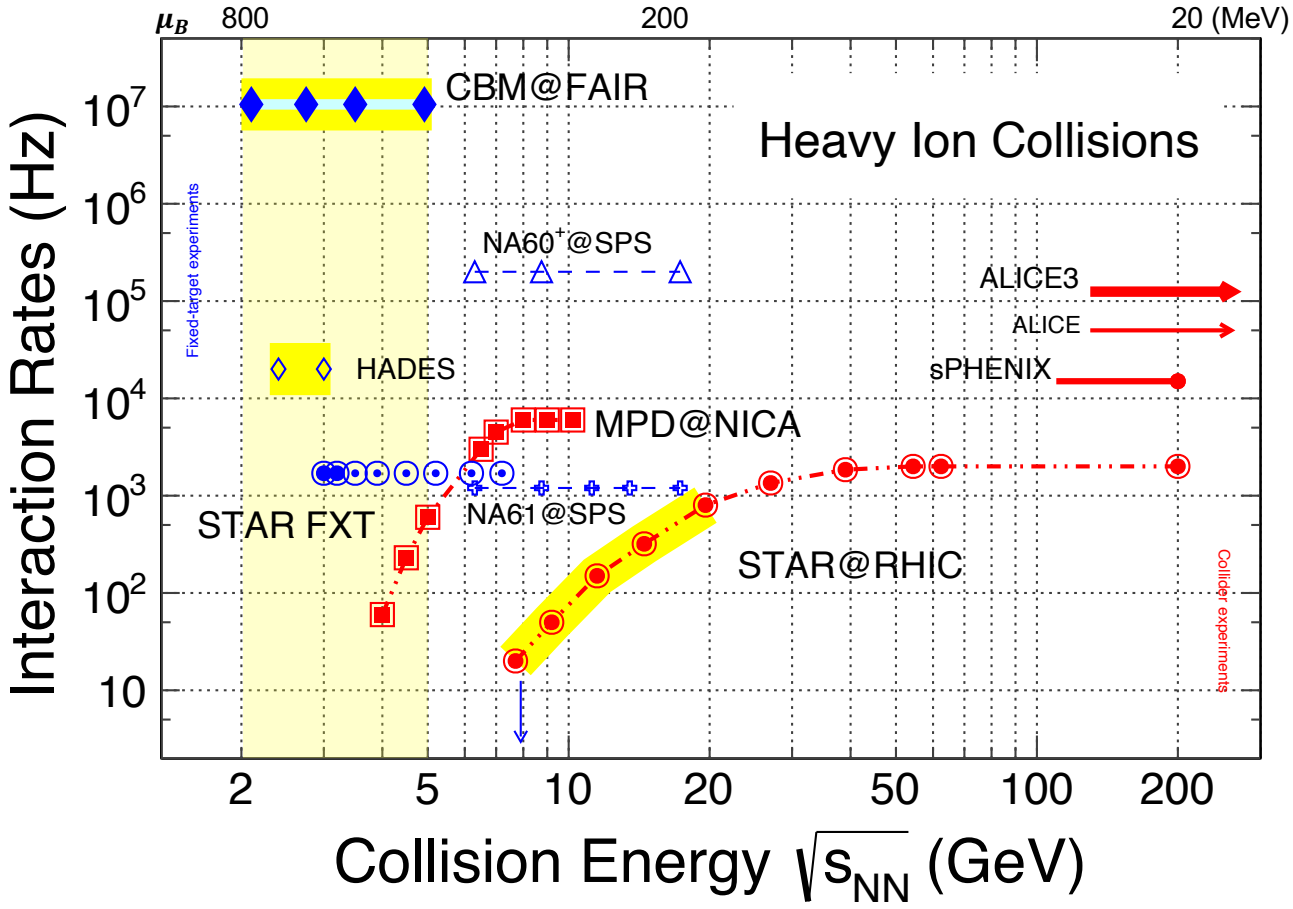
- FAIR: The brightest accelerator complex;
- Precision measurements at high baryon density region:
  (i) Dileptons (e, μ);
  (ii) High order correlations;
  (iii) Flavor production (s, c) and hyper-nuclei

CBM: BES-III experiment

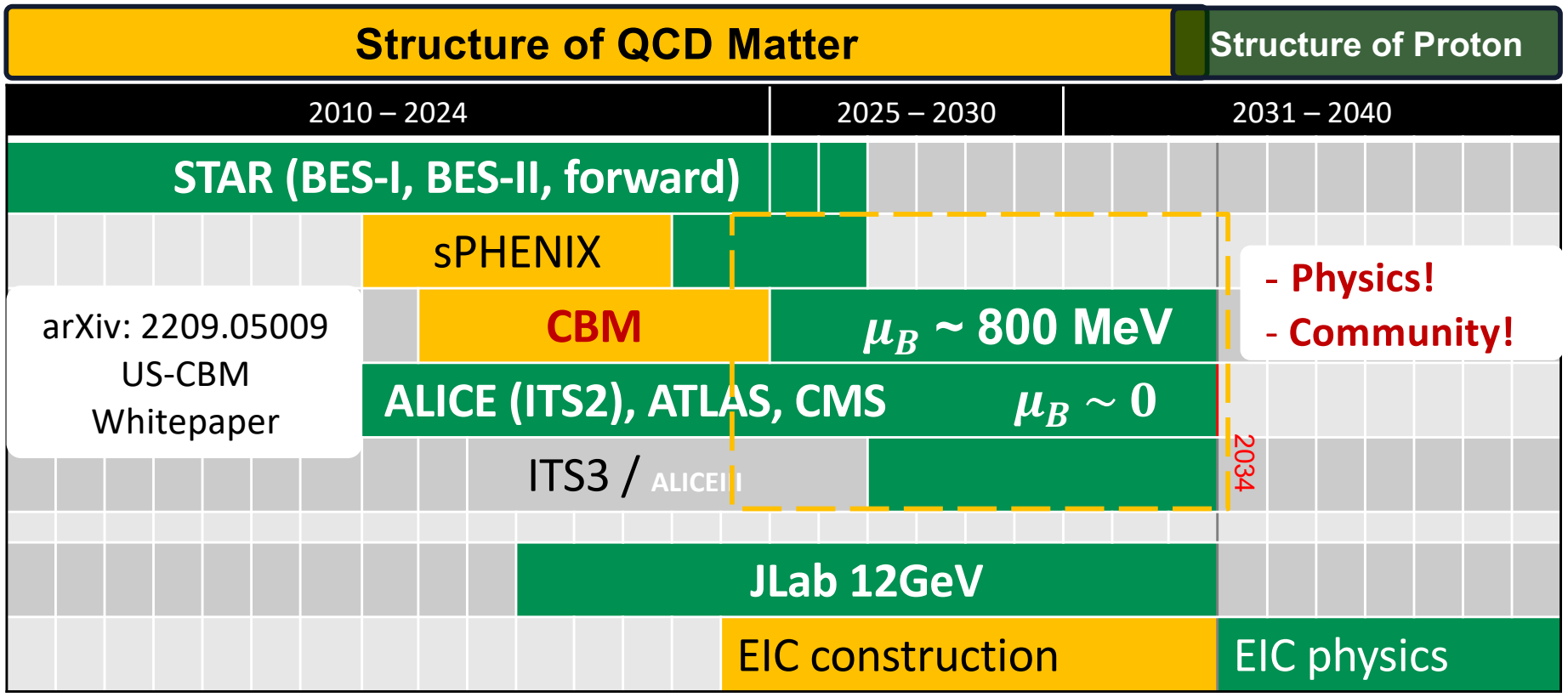
($2.5 \leq \sqrt{s_{NN}} \leq 4.9$ GeV)

High Rates CBM Experiment

- **Unprecedented rate capability at CBM;**
- **Necessary for precision measurements and search for exotics**
  1) High order baryon fluctuation and correlation;
  2) 3D di-lepton spectra (collision centrality, pair mass and p_T) ;
  3) Hyper-nuclei production and Y-N interactions



Projects and Timelines



US-CBM Whitepaper:
QCD Phase Structure and Baryonic Interactions at High Baryon Density

QCD Phase Structure and Baryonic Interactions at High Baryon Density

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.

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US-CBM Whitepaper

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(Dated: September 17, 2022)

Utilize CBM experiment at FAIR with high rates and mid-rapidity coverage and study the QCD phase structure at high baryon density:

1) Complete the search for critical point and 1st-order phase boundary in the energy range 2.9 – 20 GeV ($800 \geq \mu_B \geq 250$ MeV);
2) Dileptons: nuclear matter EOS;
3) Hyper-Nuclei, Y-N interactions and EOS at high baryon density → inner structure of compact stars

arXiv: 2209.05009

QCD Phase Structure and Baryonic Interactions at High Baryon Density

BNL, DUKE, IU, INT-UW, KSU, LBNL, MSU, NCSU, OSU, PU, PURDUE, RICE, SBU, UC DAVIS, UCLA, UC RIVERSIDE, UIC, UIUC, UH, UNC, WSU

1) More than 20 institutes signed on to the whitepaper. **The community is strongly resonating with the initiative!**
2) More talks: **C. Ratti**, J.F. Liao, R. Pisarski, A. Sorensen, **X. Dong**, **J. Noronha-Hostler**
3) NS&IC: arXiv: 2209.11042

US-CBM Team for BES-III@FAIR

- **Science:** necessary for the search of QCD critical point and completion of the beam energy scan program started at RHIC
- **Timeline:** reasonable and healthy for HI physics programs
- **Investment:** cost effective for the US heavy-ion program

Initiative for LRP: "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."

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Many thanks for your attention and support!

Acknowledgements:

HADES, NA60+, **NA61** and **STAR** Collaborations