Physics at High Baryon Density

- RHIC BES and **CBM@FAIR**

Nu Xu

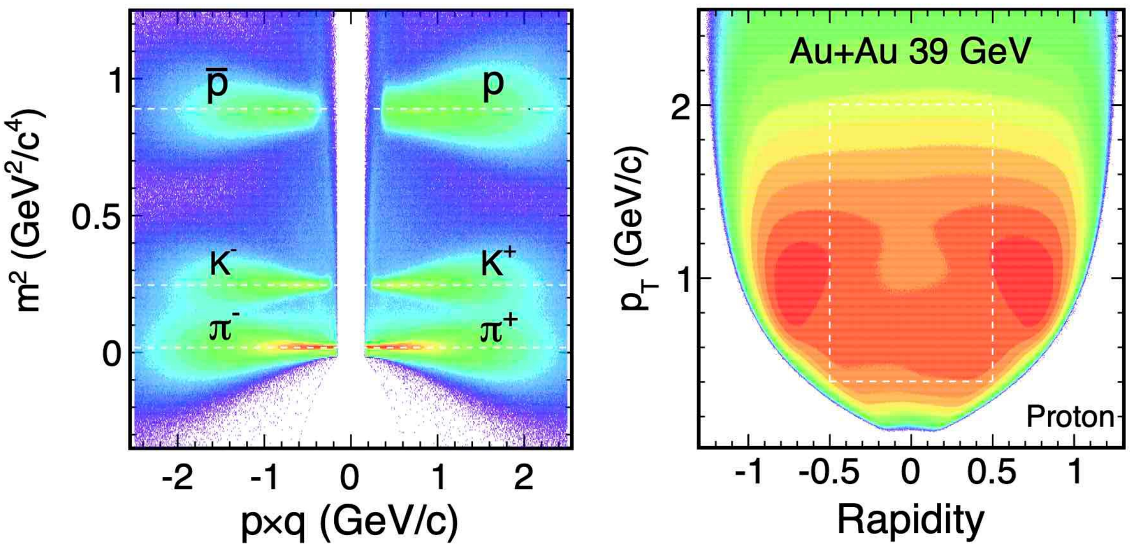
STAR BES-I and BES-II Data Sets

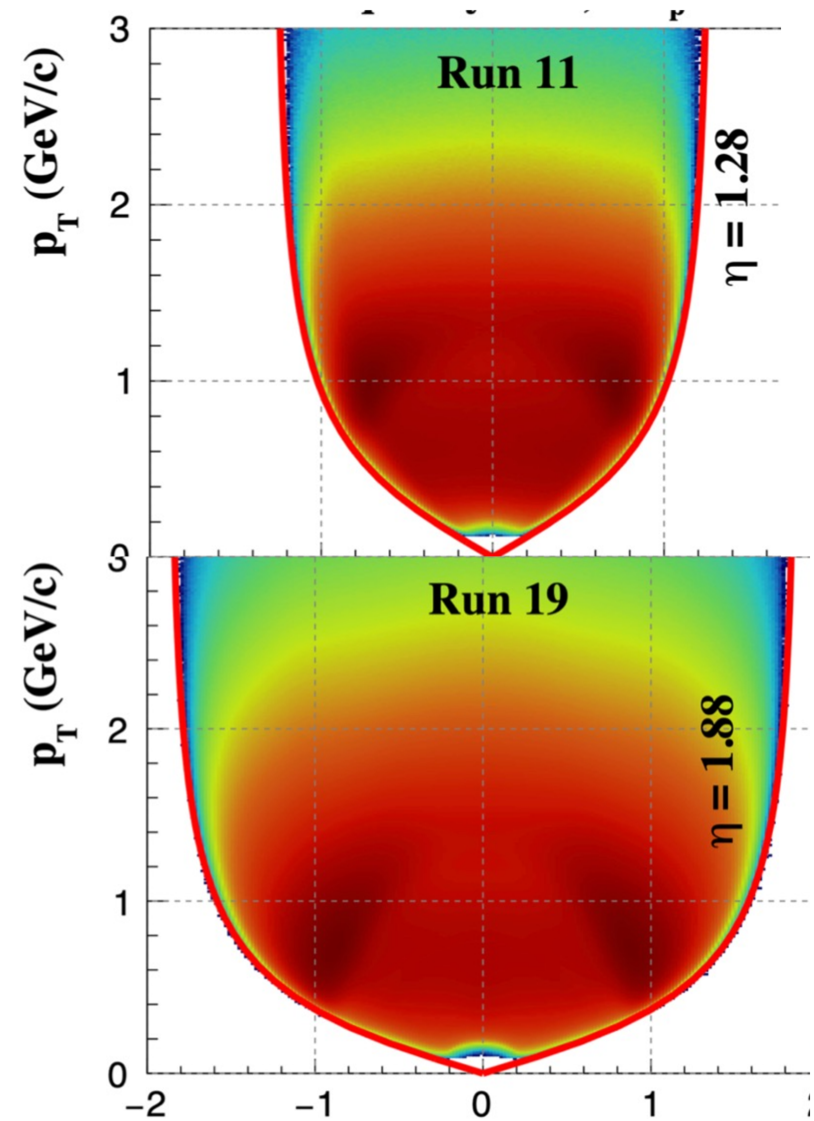
Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 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

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

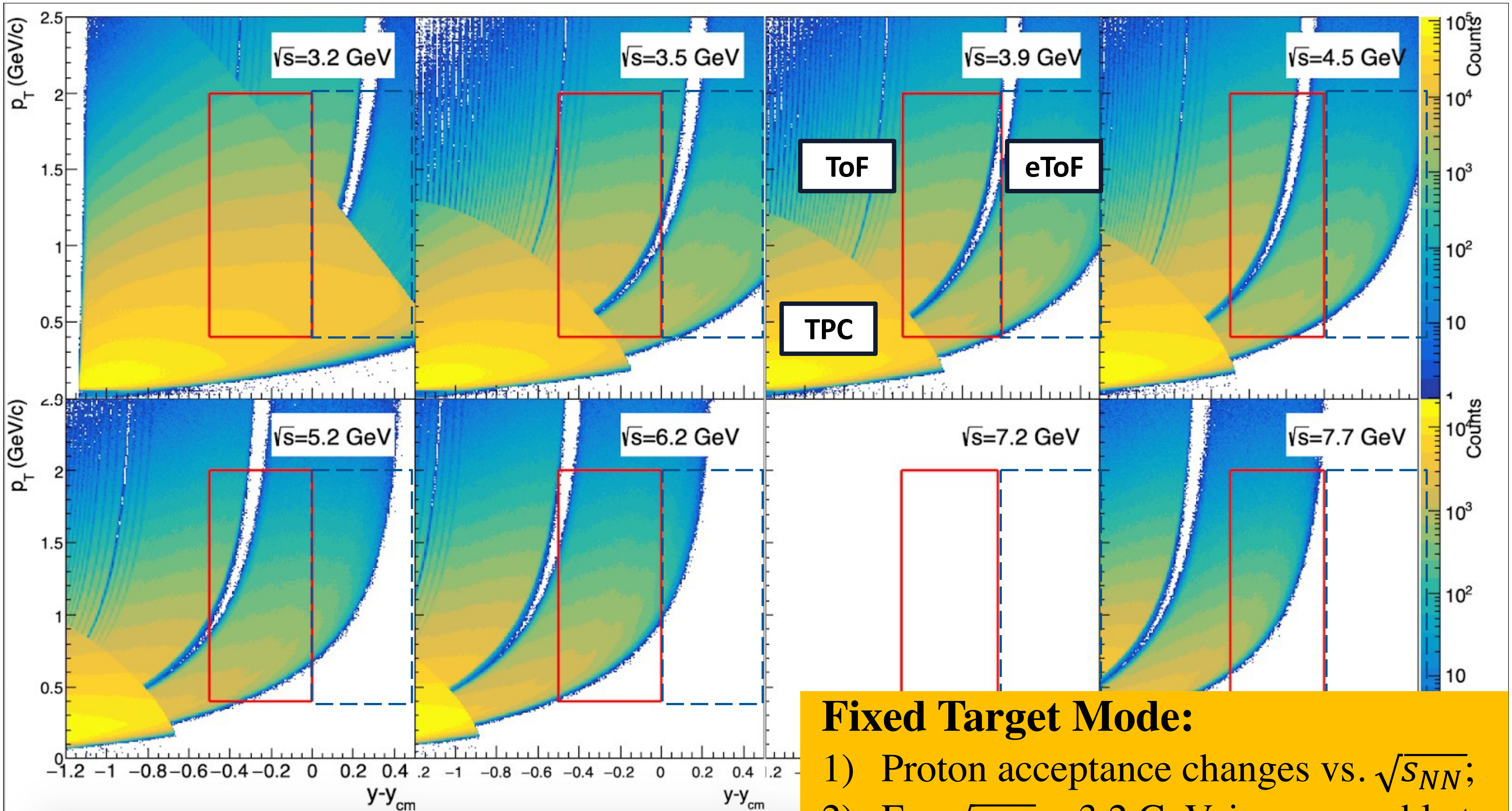
STAR Acceptance (A. Pandav, CPOD22)





Collider Mode:

1) Clean PID. Acceptance does not change vs. $\sqrt{s_{NN}}$;
2) Similar acceptance for π, K and p;
3) For protons:
   BES-I: $|y| \leq 0.5$, $0.4 < p_T < 2$ GeV/c
   BES-II: $|y| \leq 0.7^*$, $0.4 < p_T < 2$ GeV/c

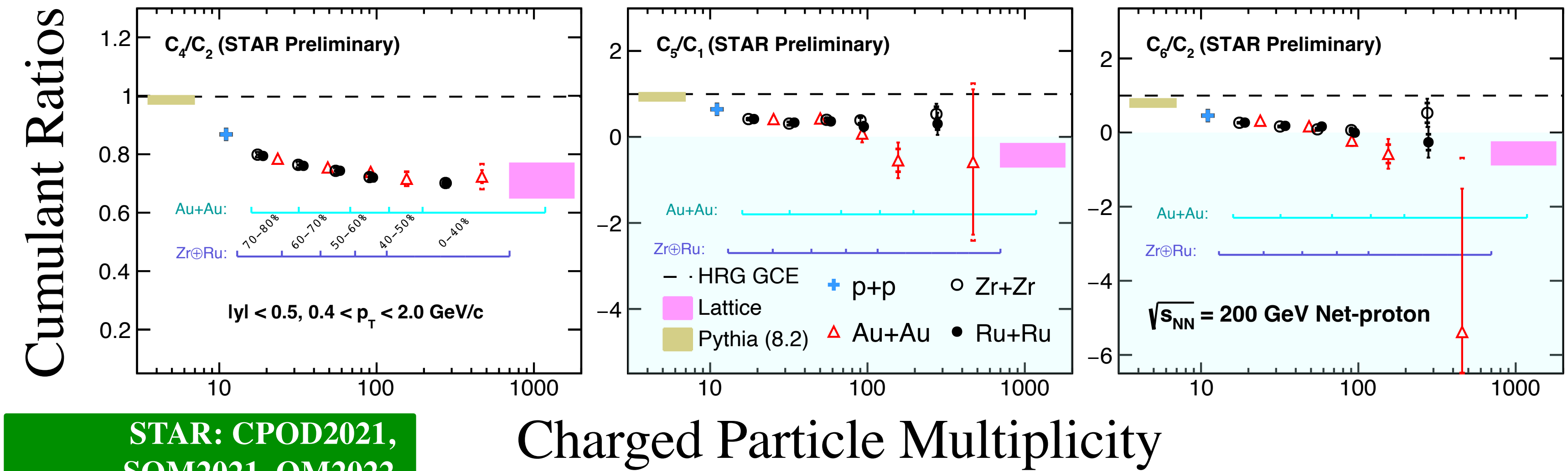


STAR: DNP2022, Zachary Sweger UC Davis

Fixed Target Mode:

1) Proton acceptance changes vs. $\sqrt{s_{NN}}$;
2) For $\sqrt{s_{NN}} < 3.2$ GeV, is comparable to results from collider mode

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



STAR: CPOD2021, SQM2021, QM2022

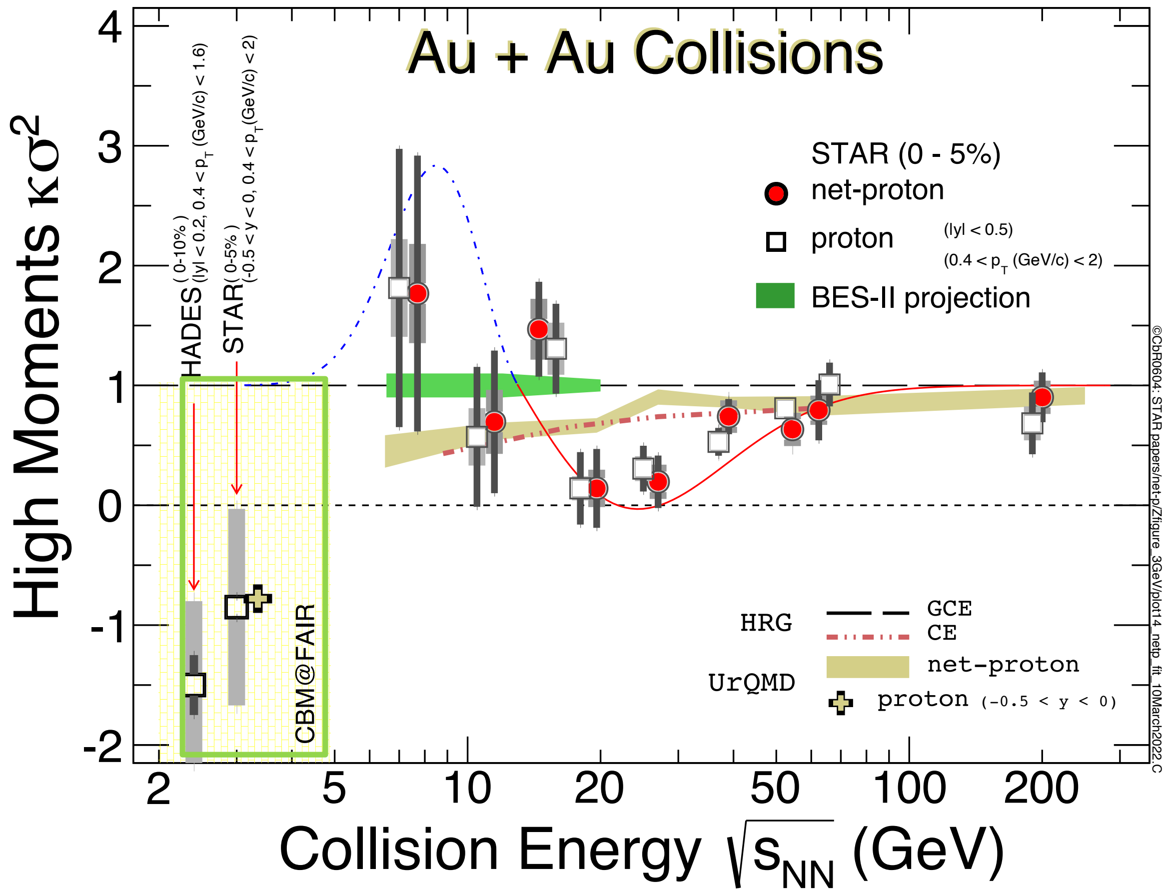
1) In 200GeV p+p collisions, high order cumulants ratios of net-protons are found to be positive for: C_4/C_2, C_5/C_2 and C_6/C_2;

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)

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: PRC**102**, 024914(2020)

High-Energy Nuclear Collisions and QCD Phase Diagram

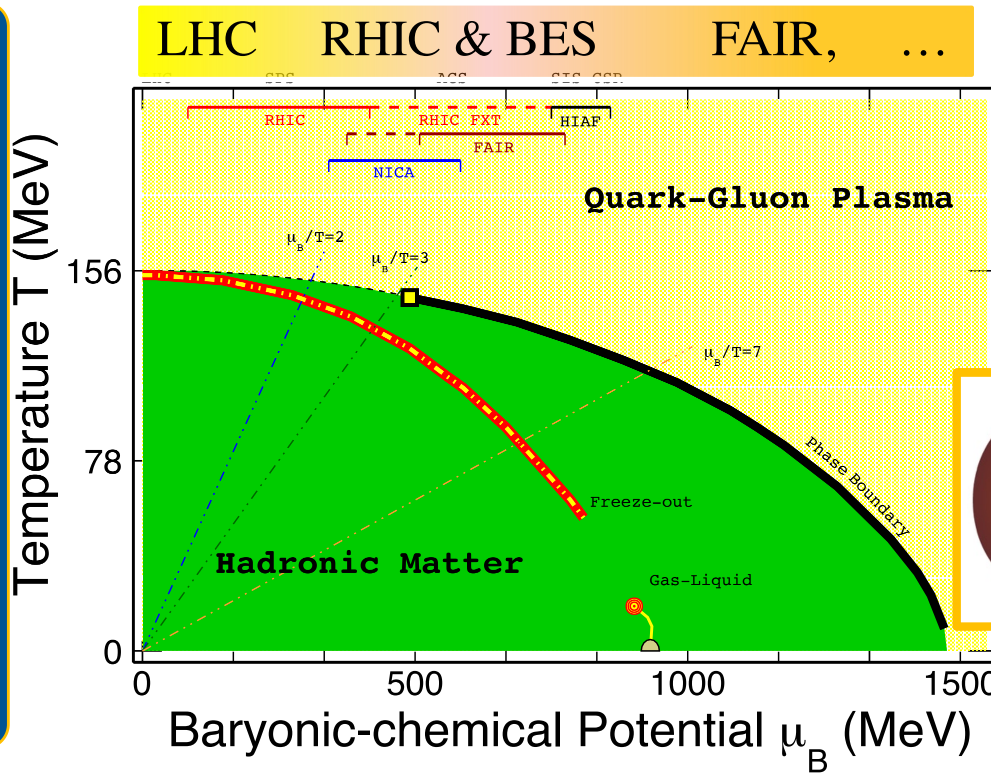
At LHC and RHIC top energy:

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

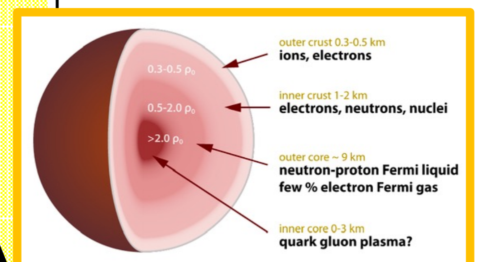
$\rightarrow$

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

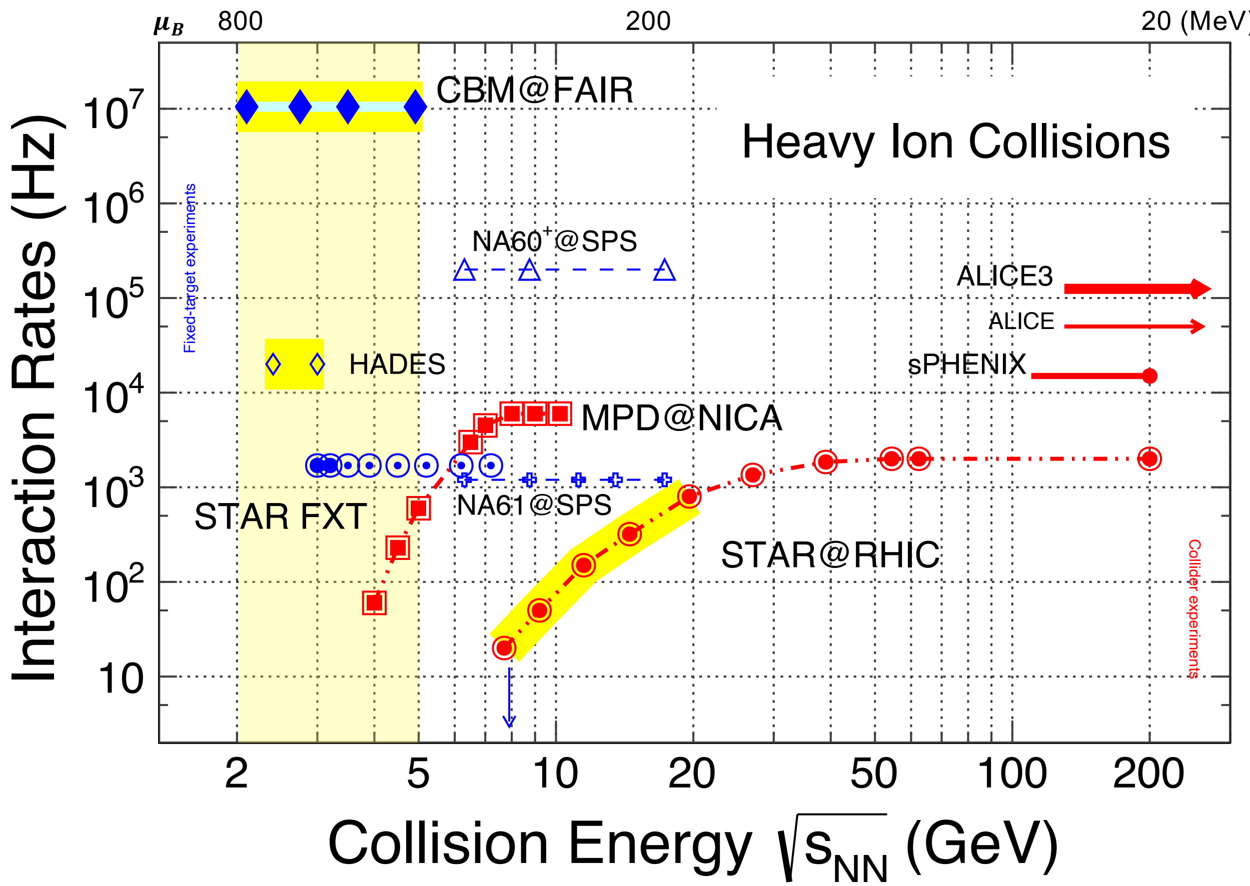


1) RHIC BES: $\rightarrow$ search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions ($e.g.$ $N - N$, $Y - N$) $\rightarrow$ inner structure of compact stars

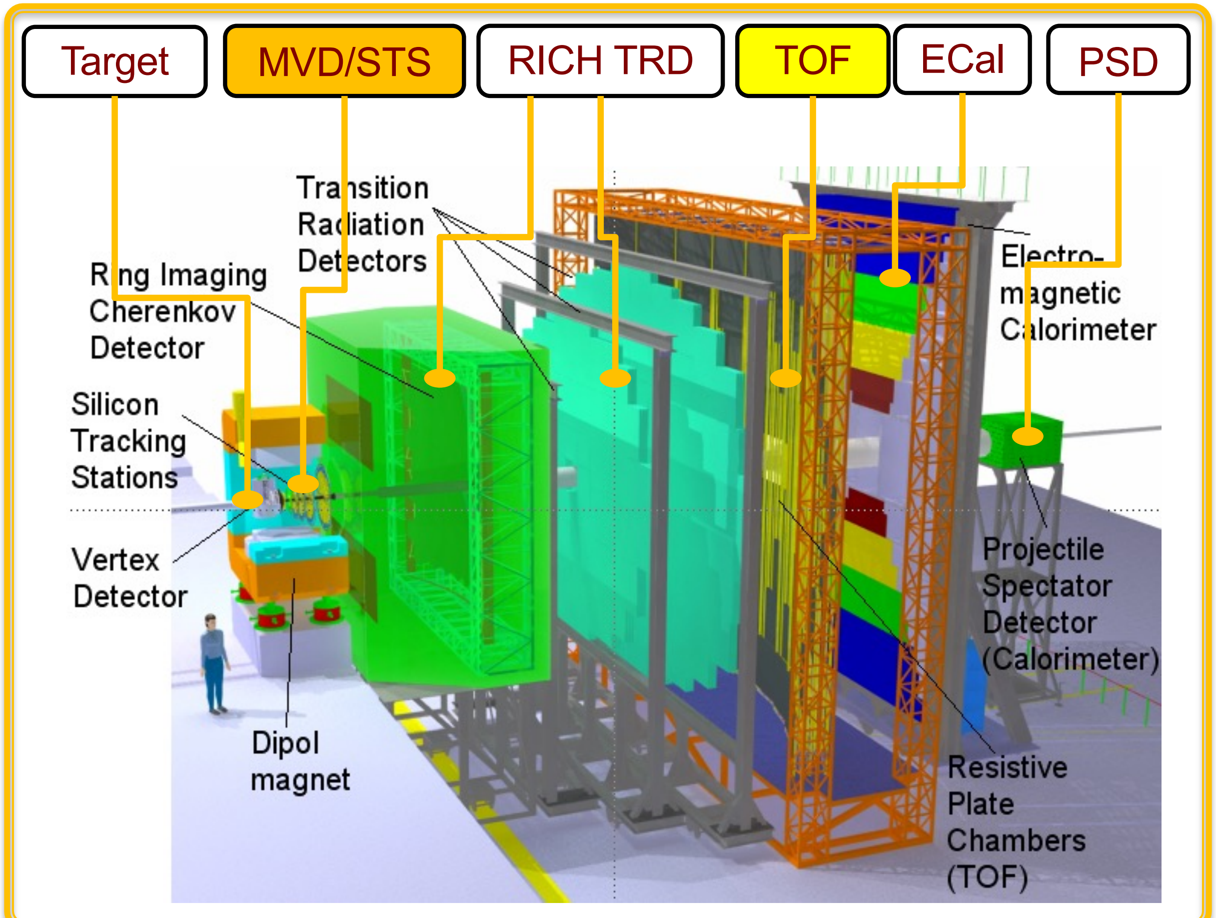
High Rates CBM Experiment

- **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



CBM Experiment at FAIR

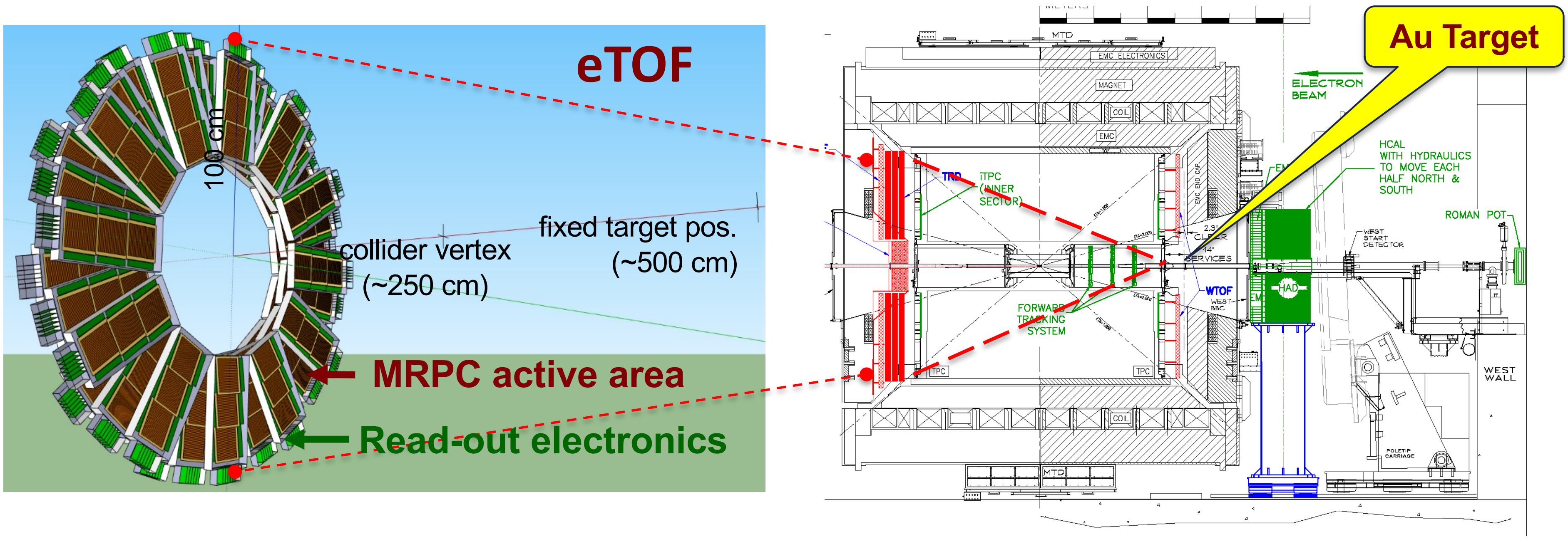


- FAIR: The brightest accelerator complex;
- Precision measurements at high baryon density region:
  (i) Dileptons (e, μ);
  (ii) High order correlations;
  (iii) Flavor production (s, c) and hyper-nuclei

CBM: BES-III experiment

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

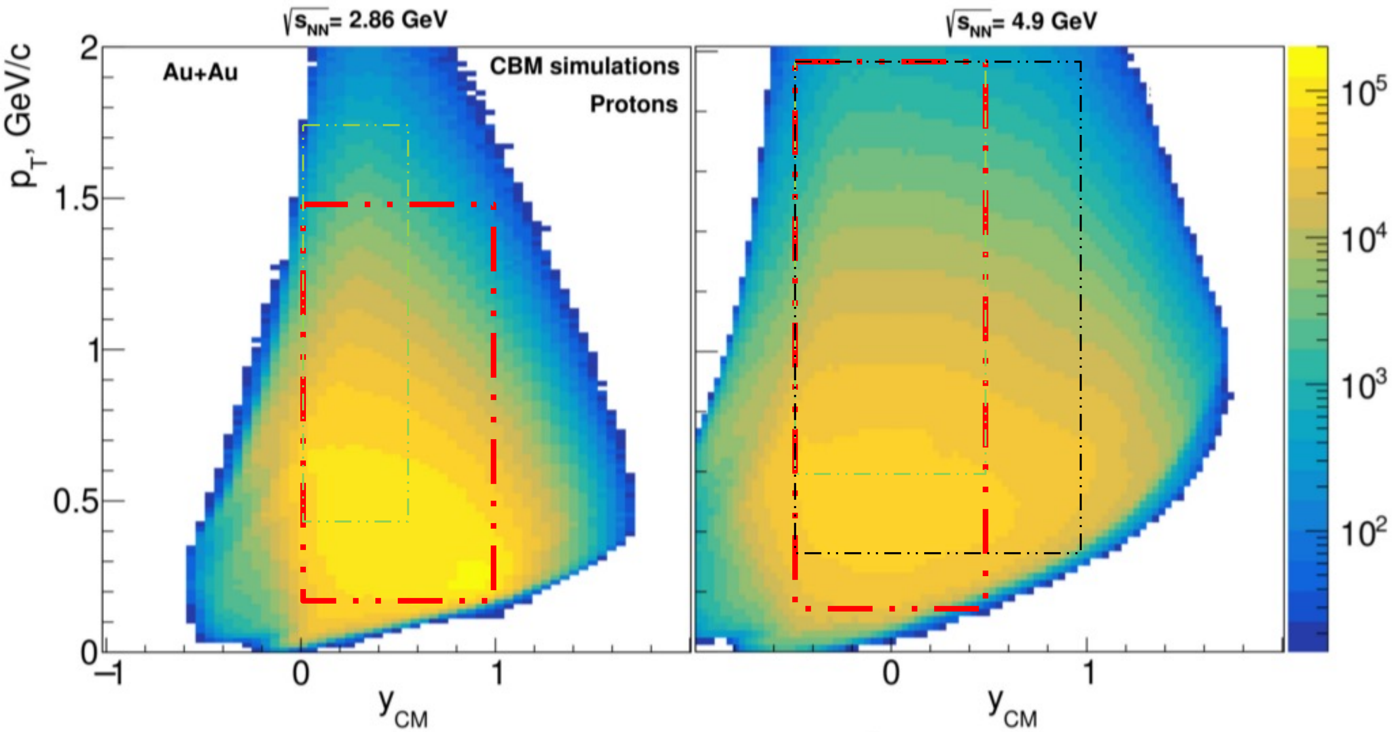
CBM TOF at STAR



CBM participates in RHIC BES-II in 2019 – 2021:

- Complementary to CBM program: $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**760 ≥ μ_B ≥ 420 MeV**)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

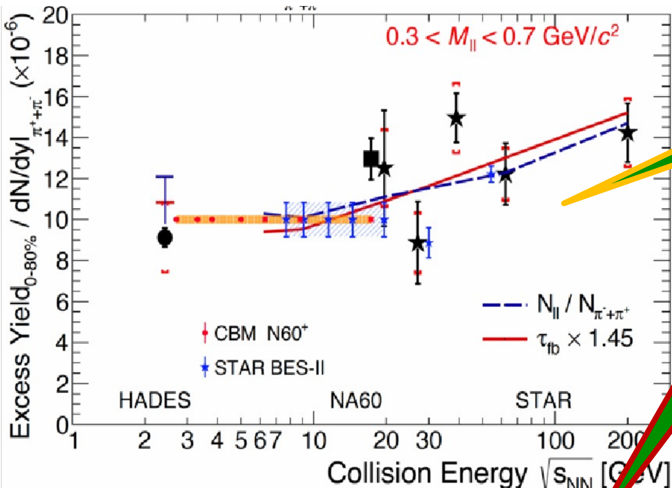
CBM Proton Acceptance



1) **CBM experiment:** Wide rapidity and low p_T proton coverages in 2.9 – 4.9 GeV AuAu collisions
2) Rapidity and p_T scan of proton high moments are possible with CBM

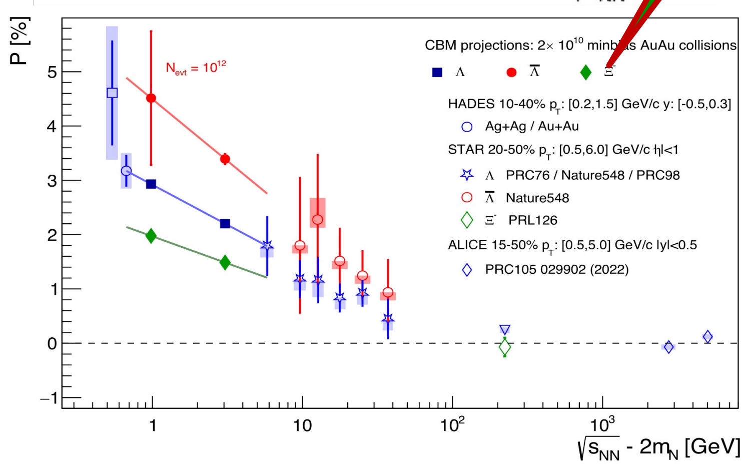
CBM Measurements

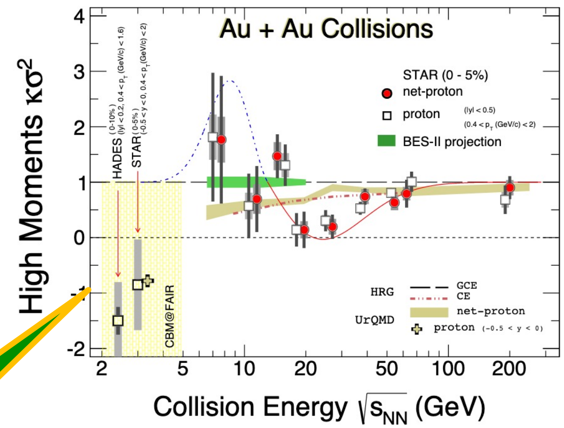
N. Herrmann
CPOD2022



Emissivity (LMR)

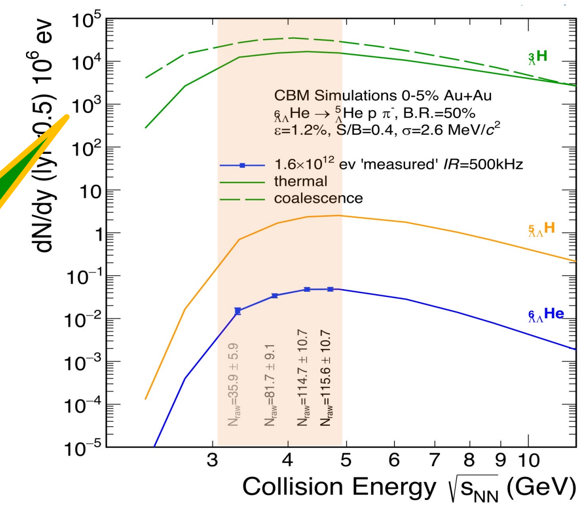
Vorticity



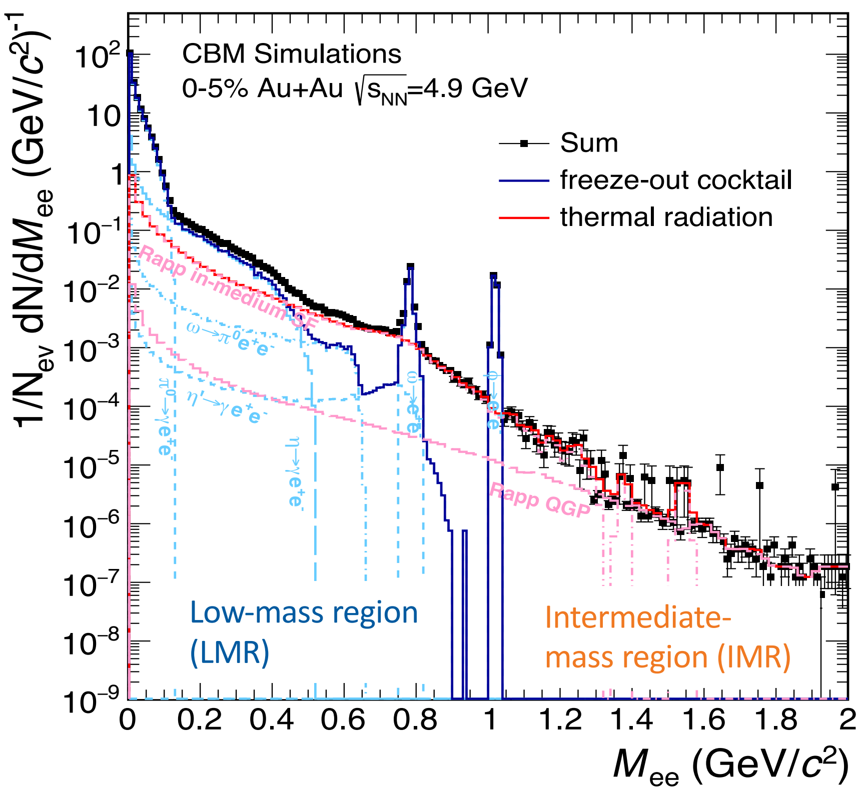


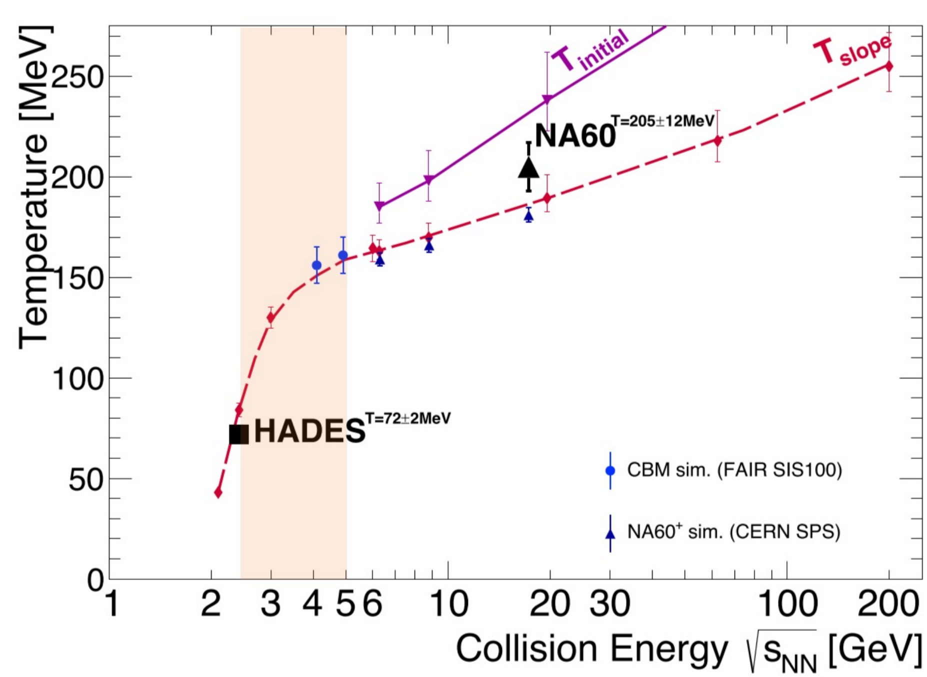
High Moments

Hyper-Nuclei



CBM Measurements (dileptons)





T_{eff} – measurements in IMR within 10% uncertainty

N. Herrmann
CPOD2022

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, TEXAS A&M, UC DAVIS, UCLA, UC RIVERSIDE, UIC, UIUC, UH, UNC, WSU

22 institutes signed on to the whitepaper!

US-CBM Whitepaper

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