Study the QCD Phase Structure in High-Energy Nuclear Collisions

Nu Xu

(GSI, LBNL)

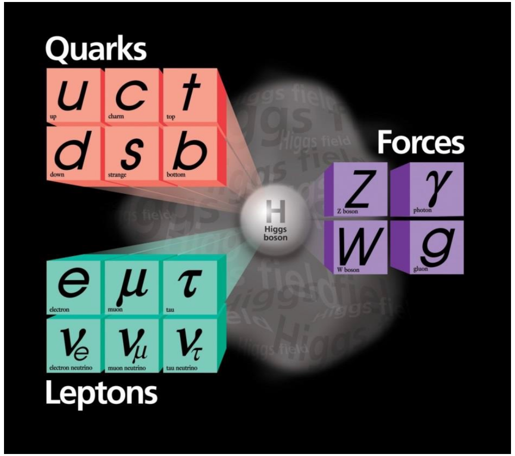
Outline

1) Introduction

2) Selected Recent Results
   - Collectivity
   - Criticality
   - Hyper-nuclei Production

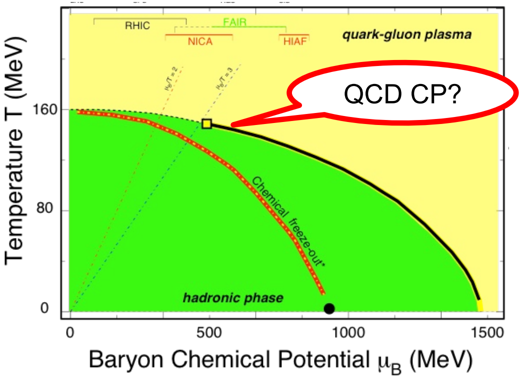
3) Future Physics Programs

Strong Interaction and QCD Phase Structure



2004 asymptotic freedom (QCD)

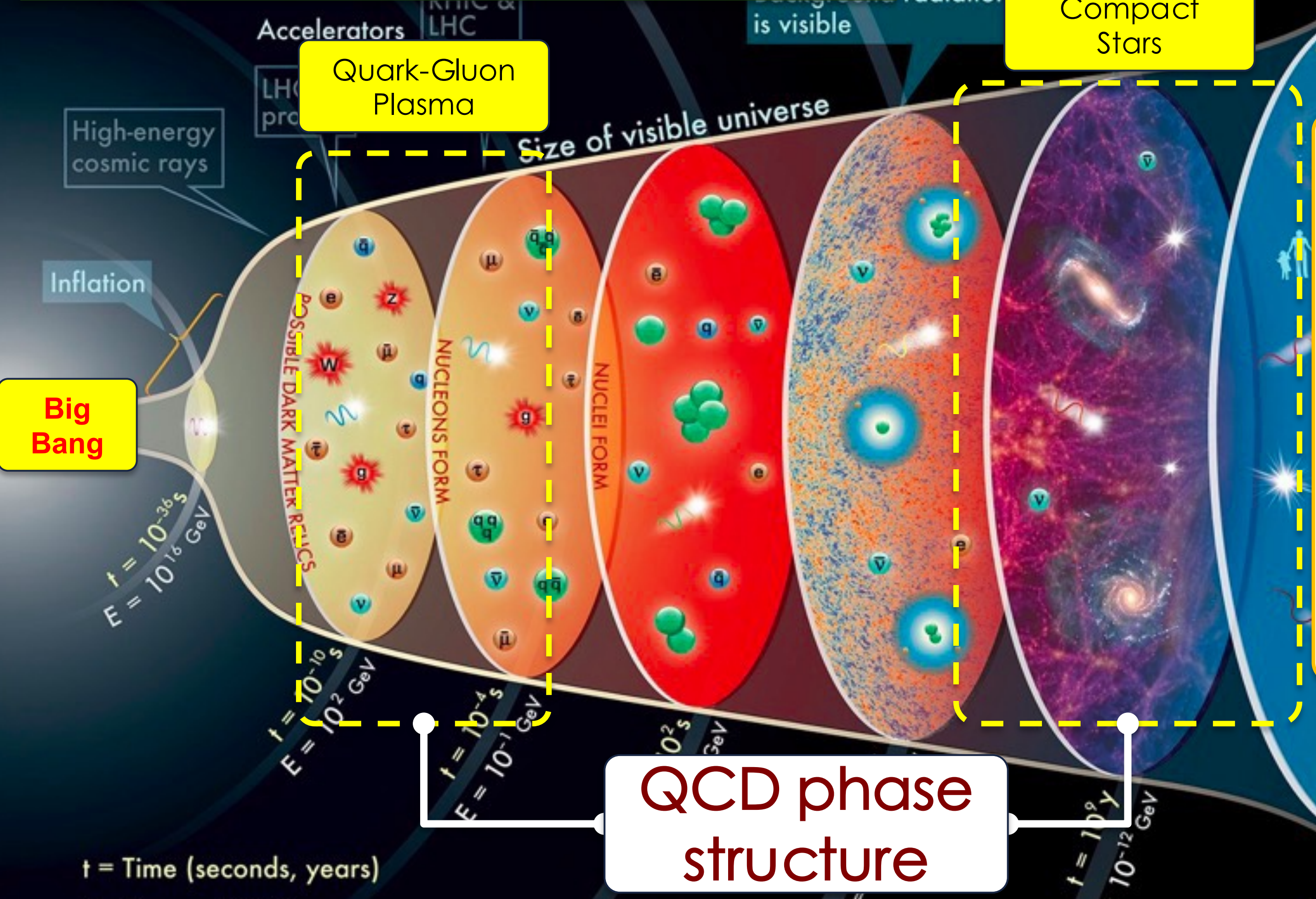
2013 Higgs



- **Discovery of the Higgs boson**
  - ✓ Origin of mass
  - ✓ Standard Model ➔ Theory
- **QCD Phase Structure (?)**
  - Confinement
  - SCB: mass of hadrons and the visible world
  - QCD phase boundary and critical point …

Emergent Properties of QCD

History of the Universe



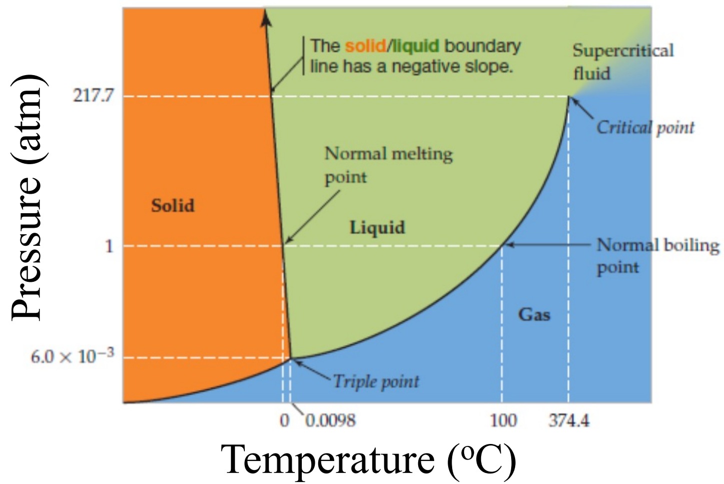
Using controlled experiments to understand:

- Emergent properties of the QCD
- Evolution of the Universe

Phase Structure of Strong Interactions

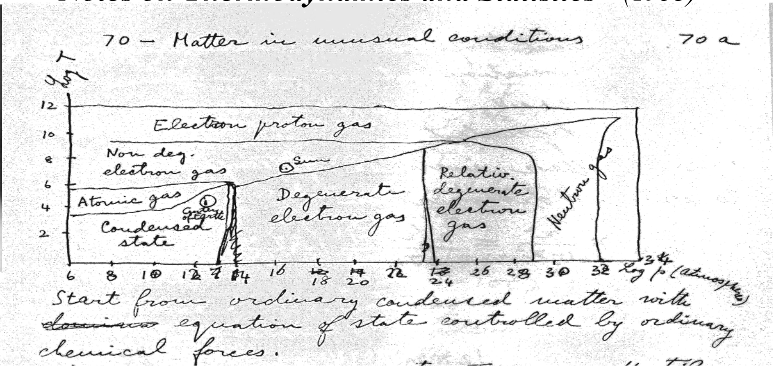
Phase Diagram: For given degrees of freedom, how matter (re)organizes itself under external conditions

Phase Diagram of Water: QED at Work



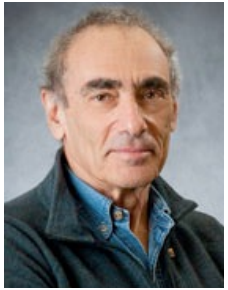
E. Fermi

"Notes on Thermodynamics and Statistics" (1953)

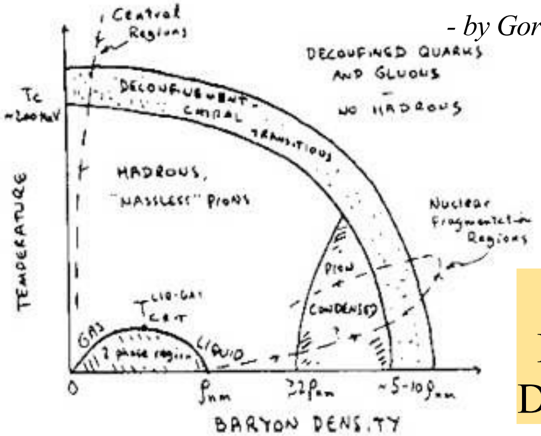


1983 US NP LRP

- by Gordon Baym



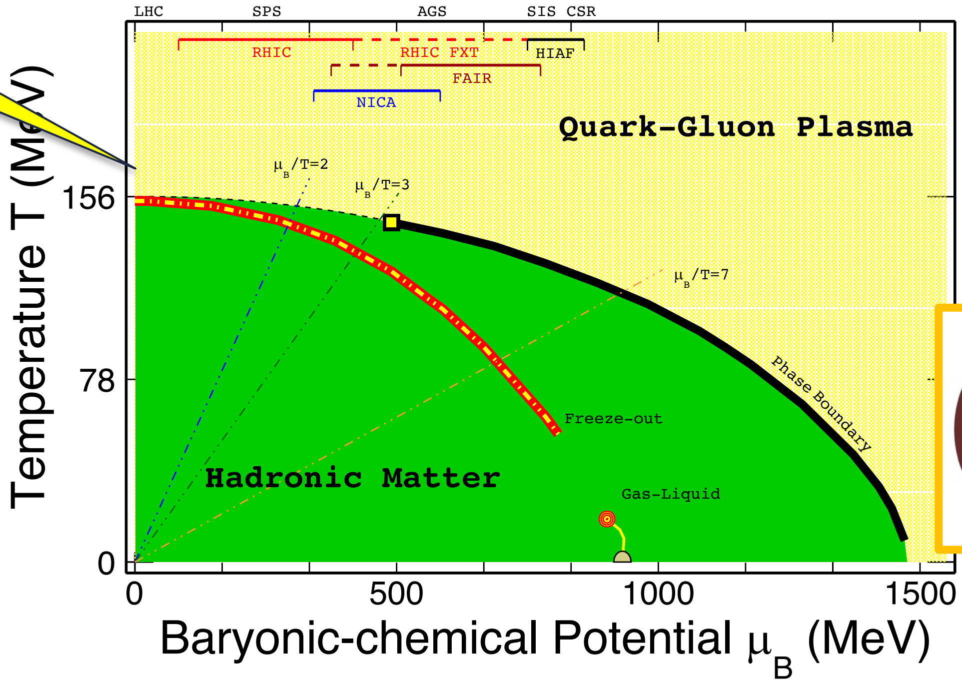
Gordon Baym



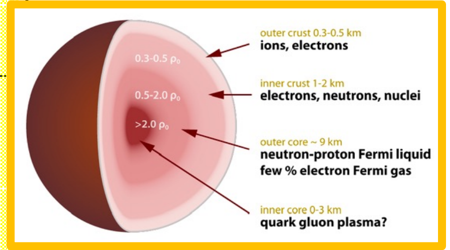
QCD Phase Diagram

High-Energy Nuclear Collisions and QCD Phase Diagram

Early Universe



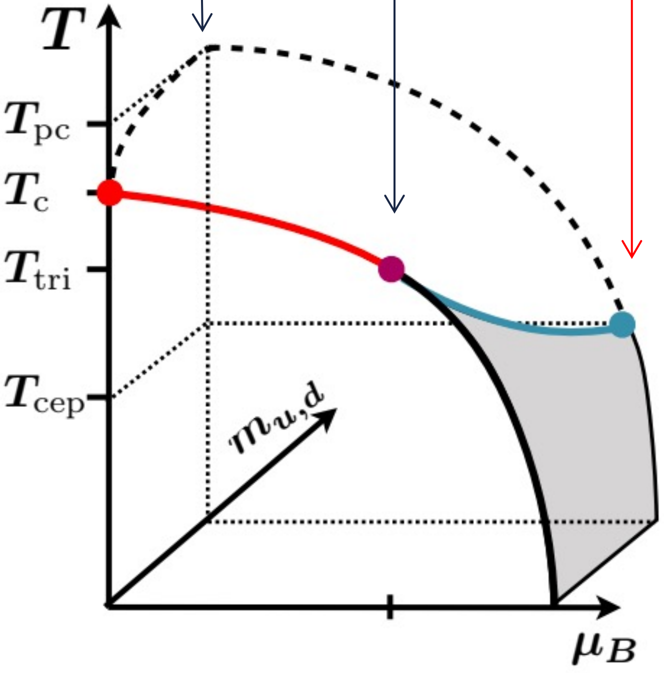
High baryon density: Inner structure of compact stars



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

LGT Calculation: QCD Phase Structure

T_C^0 | T_{PC} | T^{TriC} | T^{CEP}



F. Karsch *et al.*, 2020

1) QCD transition temperature:
$T_{PC} = 156.5 \pm 1.5$ MeV

2) Chiral crossover line

$$T_{PC}(\mu_B) = T_{PC}^0 \left[1 - \kappa_2 \left(\frac{\mu_B}{T_{PC}^0} \right)^2 - \kappa_4 \left(\frac{\mu_B}{T_{PC}^0} \right)^4 \right]$$

$\kappa_2 = 0.012(4)$, $\kappa_4 = 0.00(4)$

3) Chiral transition temperature:
$T_C = 132^{+3}_{-6}$ MeV

4) QCD critical end point:
$T^{CEP} < T_C$, $\mu_B^{CEP} \gtrsim 3T_C$

HotQCD: Phys.Lett.**B795**, 15(2019);
Phys. Rev. Lett. **123**, 062002(2019)

High-Energy Nuclear Collisions and QCD Phase Diagram

At LHC and RHIC top energy:

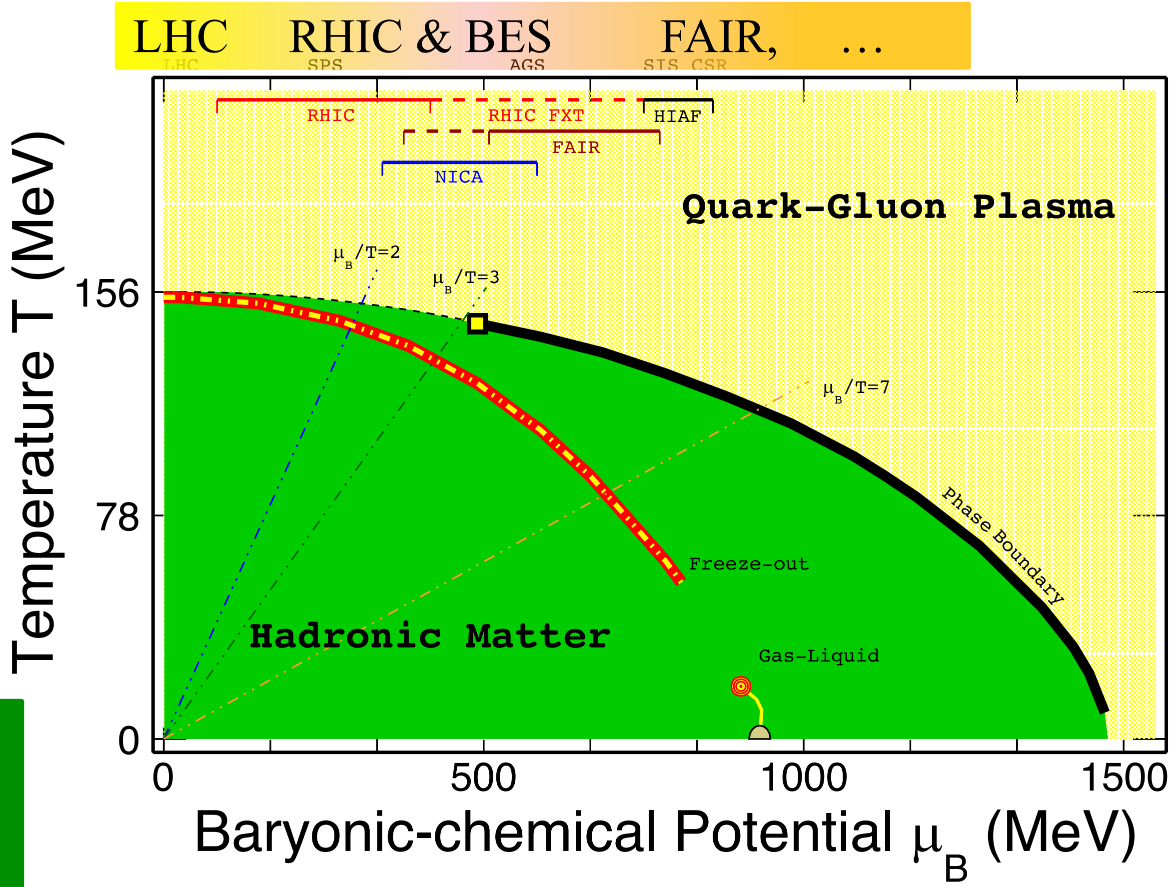
- Jet quenching;
- Collectivity data;
- Net-p C_6/C_2

→

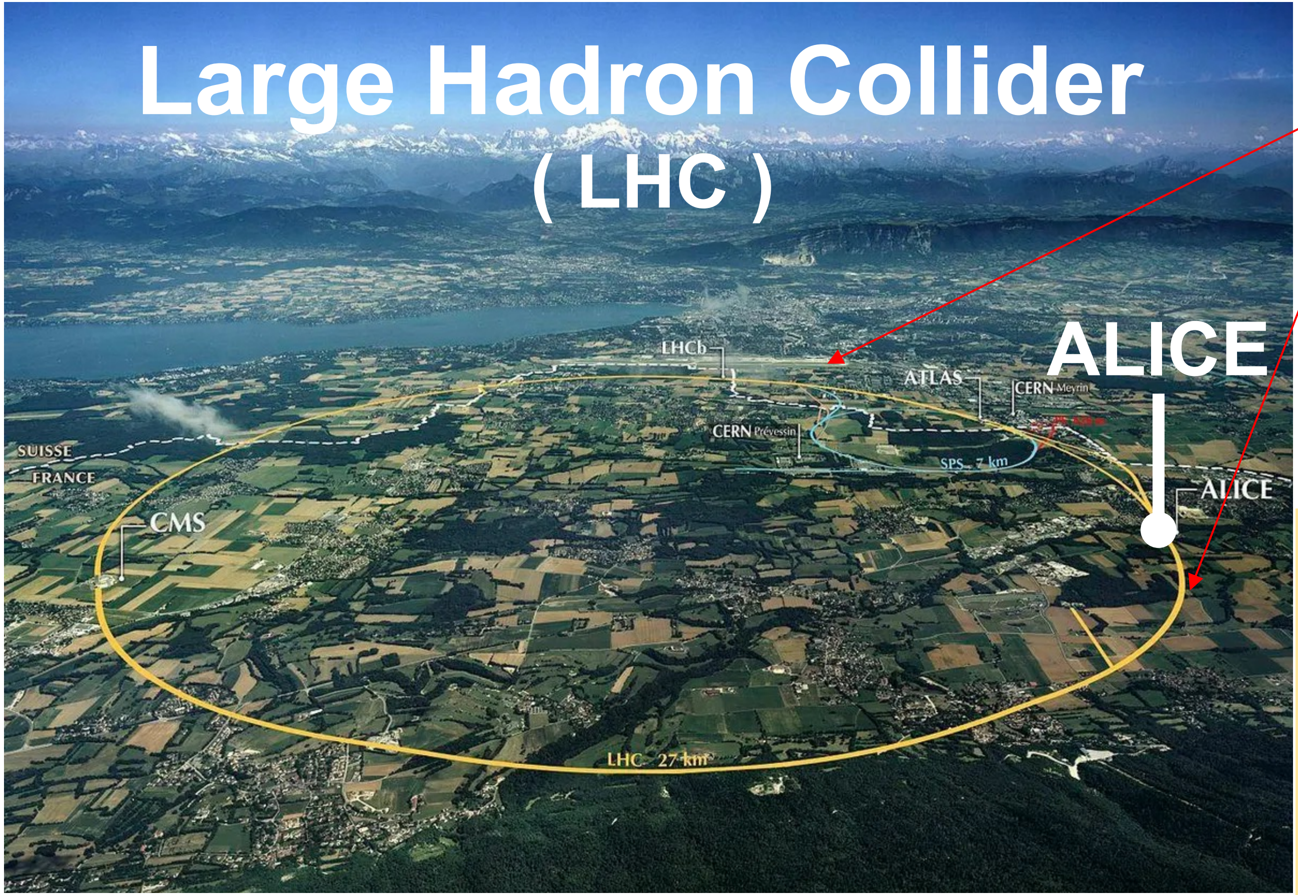
1) **At $\mu_B \sim 0$, smooth crossover. $\mu_B/T \leq 2$ (LGT);**

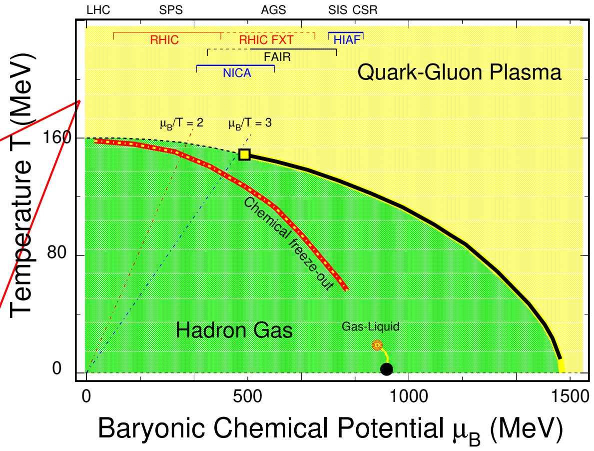
2) **CP at $\mu_B/T > 3$**

1) STAR: Phys.Rev. **C79**, 034909(2009);
2) P. Braun-Munzinger *et al.* Nature, **561**, 321(2018);
3) A. Bzdak *et al.* Phys. Rep., **853**, 1(2020);
4) ALICE: 2211.04384 (review)



High-Energy Nuclear Collisions and QCD Phase Diagram

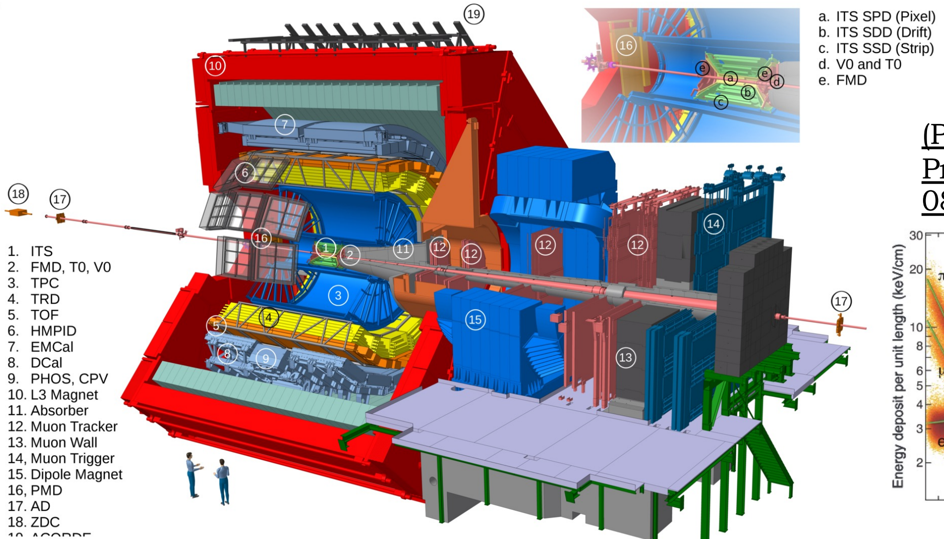




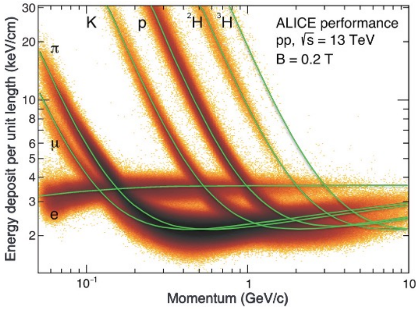
LHC collision energies:

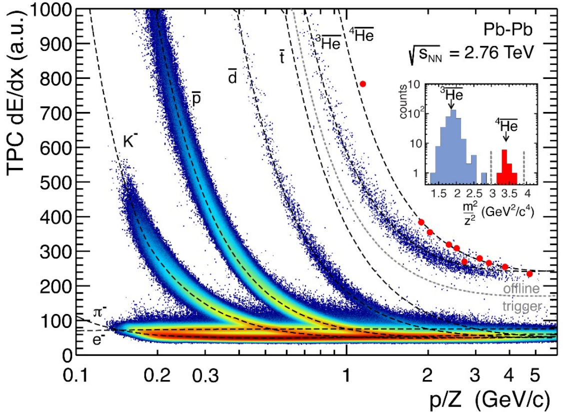
- $\sqrt{s_{NN}}$ = 0.9, 2.76, 5.02, 5.44 TeV
  Xe+Xe, Pb+Pb
- $\sqrt{s}$ = 0.9 – 13 TeV p+p
- $\mu_B \rightarrow 0$

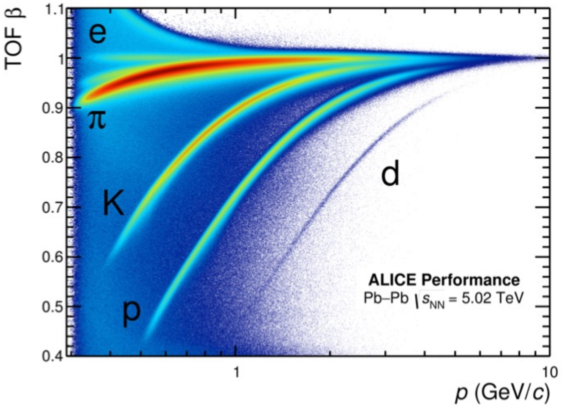
ALICE DETECTOR SYSTEM

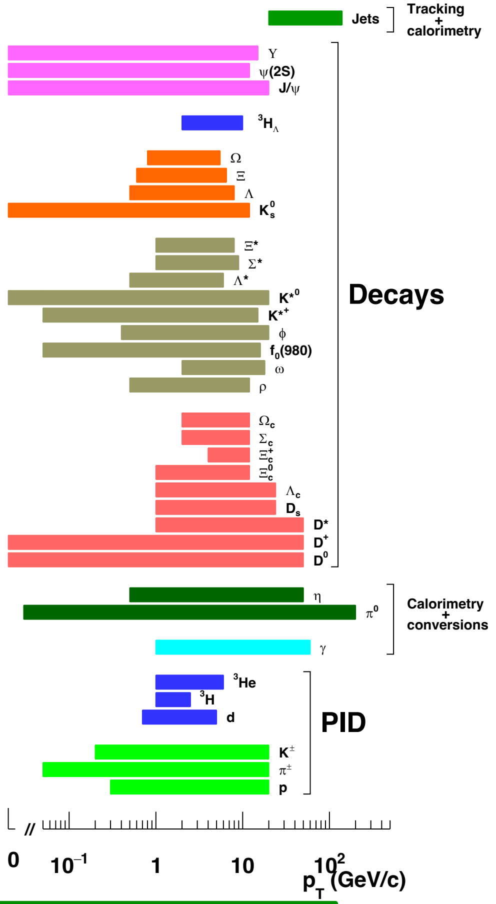


[(Particle Data Group), Prog. Theor. Exp. Phys., 083C01 (2022)]



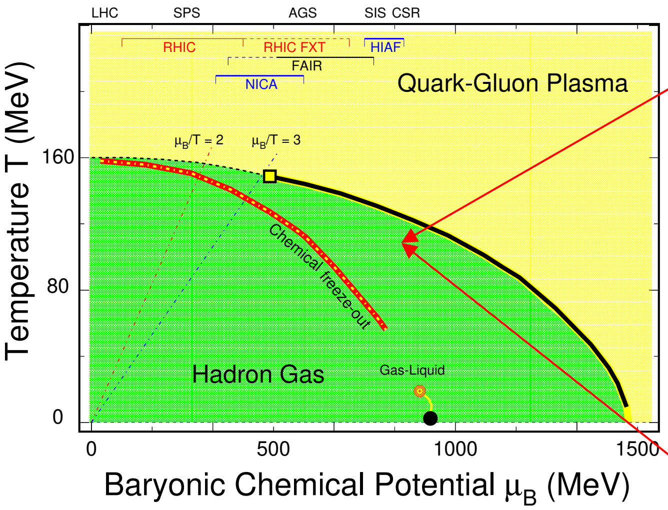


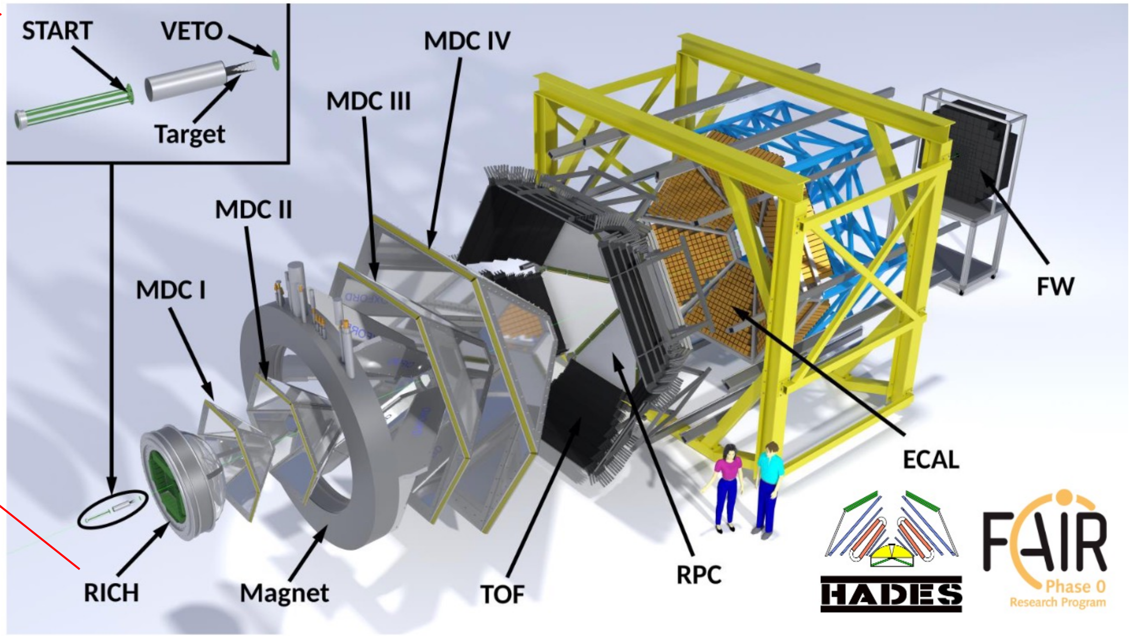




ALICE: 2211.04384

HADES DETECTOR SYSTEM





SIS18 Collisions:

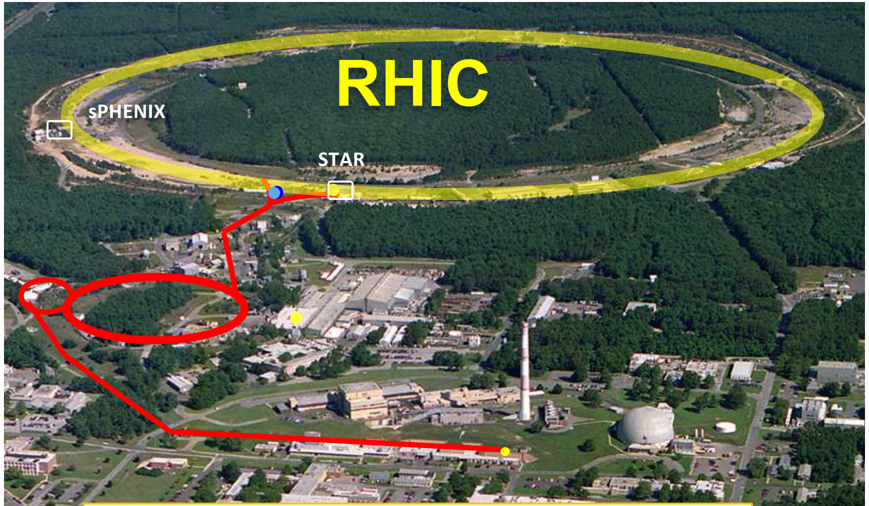
- E_K = 1.76 AGeV Ar+KI
- E_K = 1.58/1.23 AGeV Ag+Ag
- E_K = 1.23 AGeV Au+Au
- **$\mu_B \rightarrow 800$ MeV**

- E_K = 4.5 GeV p+p
- E_K = 3.5 GeV p+Nb
- E_K = 1.7 GeV π+W / +C / +PE

Properties of nuclear matter at high baryon potential and nuclear density:

1) Correlations and fluctuations;
2) Strangeness production;
3) **Di-lepton signals from various sources**

Nuclear Collisions and QCD Phase Diagram



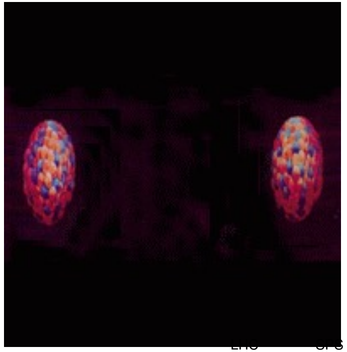
Relativistic Heavy Ion Collider (RHIC)

RHIC top collision energies:

- ➢ $\sqrt{s_{NN}}$ = 200 GeV U+U / Au+Au / Zr+Zr / Ru+Ru / O+O
- ➢ $\sqrt{s}$ = 510 GeV p+p

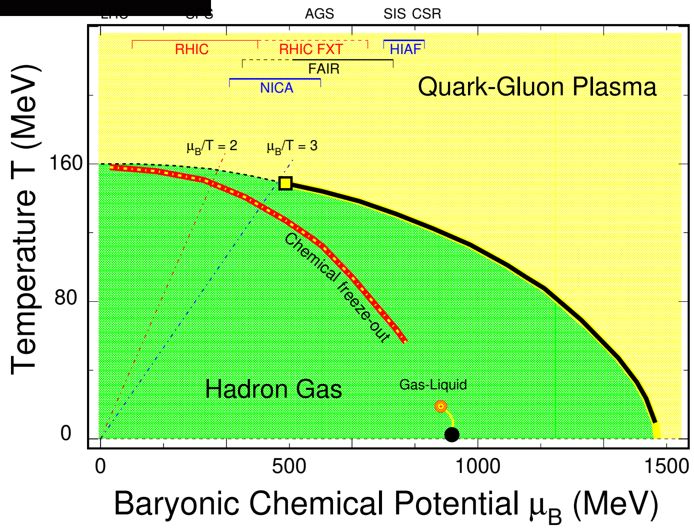
RHIC Beam Energy Scan (BES):

- ➢ $\sqrt{s_{NN}}$ = 200 – 7.7 GeV (collider mode)
- ➢ $\sqrt{s_{NN}}$ = 17.3 – 3 GeV (fixed-target mode)

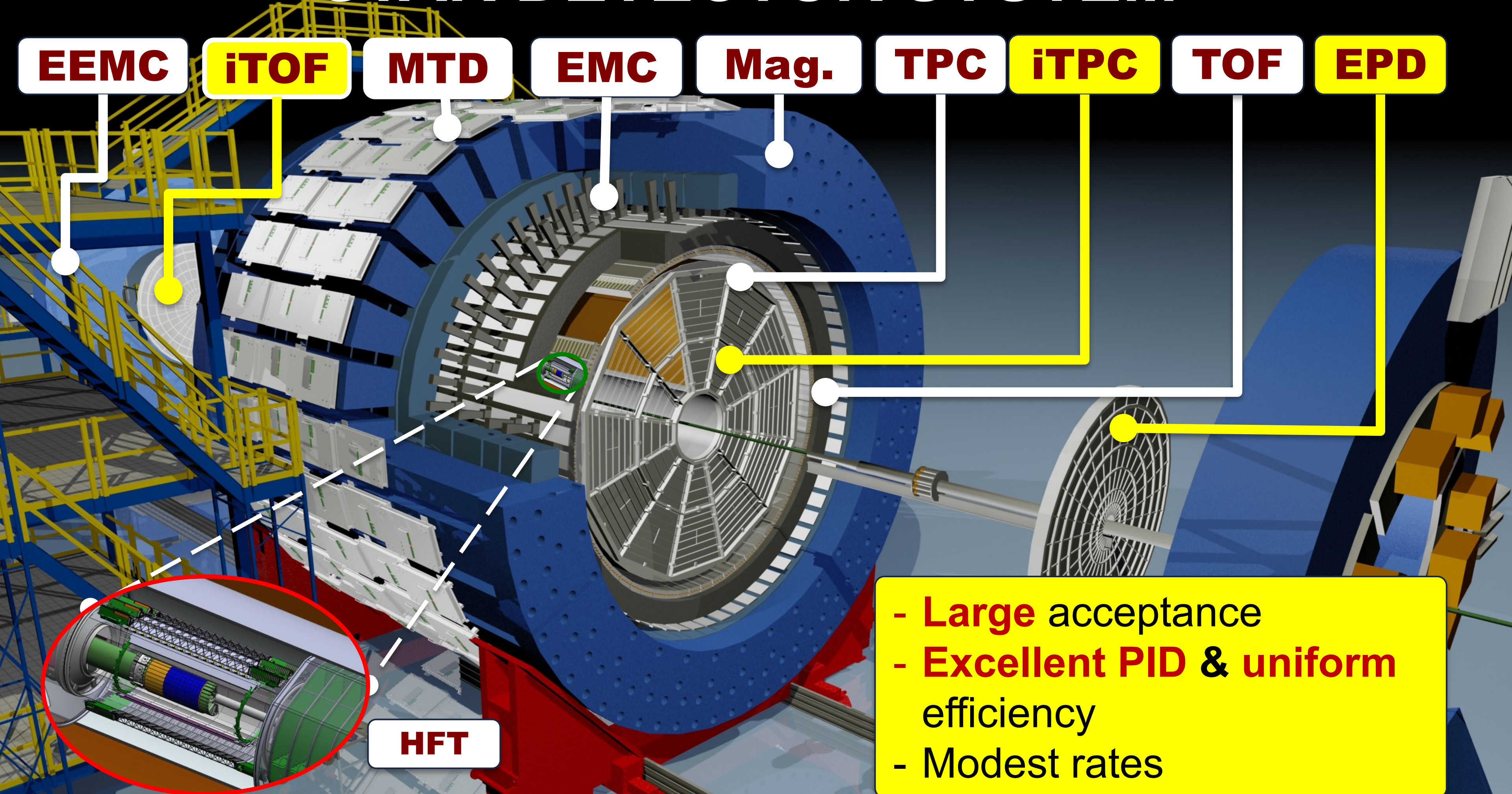


Quark-Gluon Plasma
(QGP)

QCD Phase Diagram

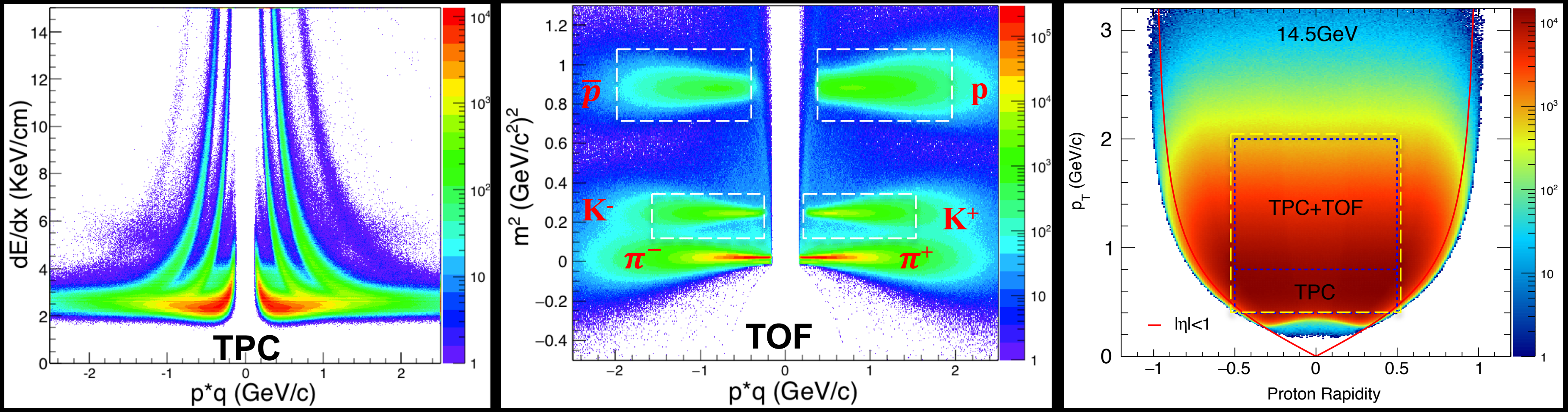


STAR DETECTOR SYSTEM



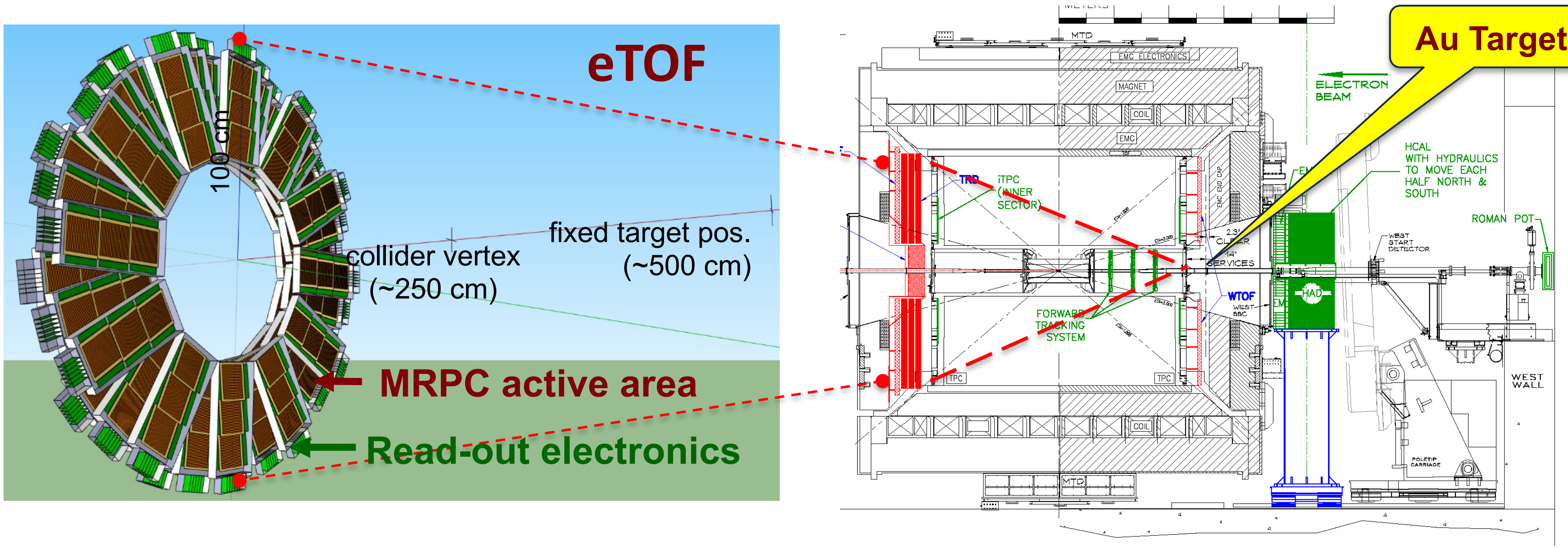
- **Large** acceptance
- **Excellent PID** & **uniform** efficiency
- Modest rates

Particle Identification and Acceptance



	Net-charge	Net-Kaon	Net-proton
Kinetic cuts	$0.2 < p_T < 2.0$ GeV/c, $\lvert\eta\rvert < 0.5$	$0.2 < p_T < 1.6$ GeV/c, $\lvert y_K\rvert < 0.5$	$0.2 < p_T < 1.6$ GeV/c, $\lvert y_p\rvert < 0.5$
Particle identifications	Reject spallation p at $p_T < 2.0$ GeV/c	TPC: $0.2 < p_T < 0.4$ GeV/c TPC/TOF: $0.4 < p_T < 1.6$ GeV/c	TPC: $0.4 < p_T < 0.8$ GeV/c TPC/TOF: $0.8 < p_T < 2.0$ GeV/c
Efficiency corrections		TPC: **$\varepsilon_{TPC} \sim 0.8$;** TPC+TOF: **$\varepsilon_{TPC+TOF} \sim 0.5$**	
Centrality Definitions	Un-corrected charge particles $0.5 < \lvert\eta\rvert < 1.0$	Un-corrected charge particles and reject Kaons, $\lvert\eta\rvert < 1.0$	Un-corrected charge particles and reject p and anti-p, $\lvert\eta\rvert < 1.0$

STAR Fixed Target Setup



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

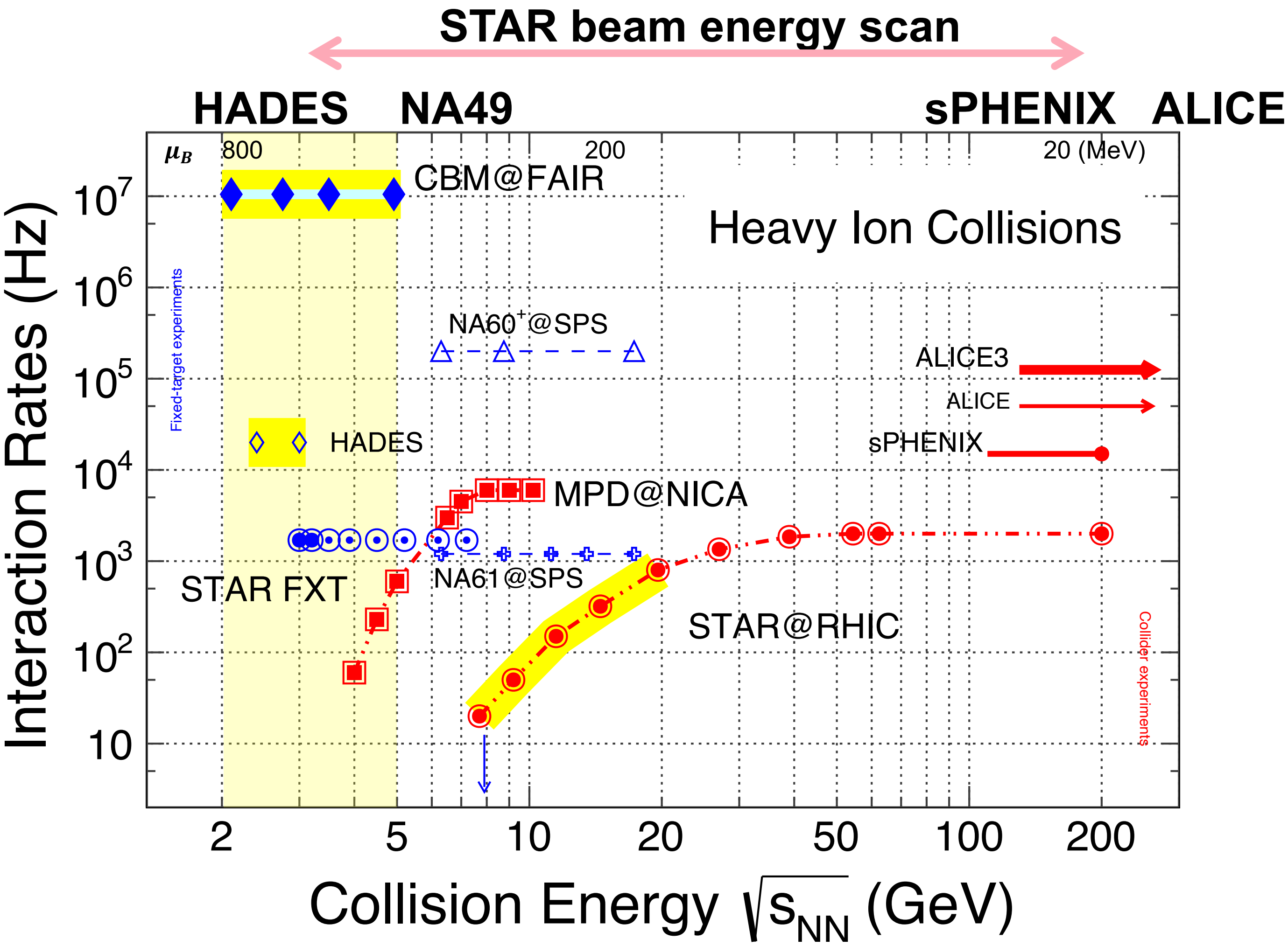
STAR BES-I and BES-II Data Sets

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 beam energy scan
HADES
NA49
sPHENIX
ALICE
μ_B
800
200
20 (MeV)
CBM@FAIR
Heavy Ion Collisions
Fixed-target experiments
NA60+@SPS
ALICE3
ALICE
HADES
sPHENIX
MPD@NICA
NA61@SPS
STAR FXT
STAR@RHIC
Collider experiments
Interaction Rates (Hz)
10
10^2
10^3
10^4
10^5
10^6
10^7
2
5
10
20
50
100
200
Collision Energy $\sqrt{s_{NN}}$ (GeV)

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3) Future Physics Programs

Collectivity

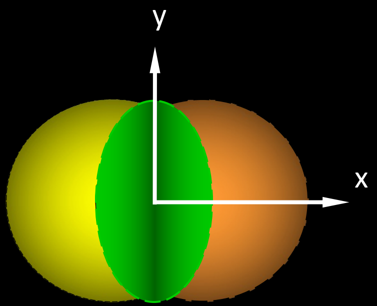
$$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - p g^{\mu\nu}] = 0$$
$$\partial_\mu[s\, u^\mu] = 0$$

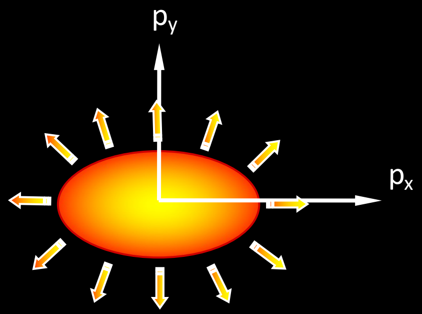
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos[n(\varphi - \Psi_R)]\right\}$$

$- v_1$ Directed flow;
$- v_2$ Elliptic flow; $- v_3$ Triangle flow

Anisotropy Parameter v_2

coordinate-space-anisotropy ➡ momentum-space-anisotropy

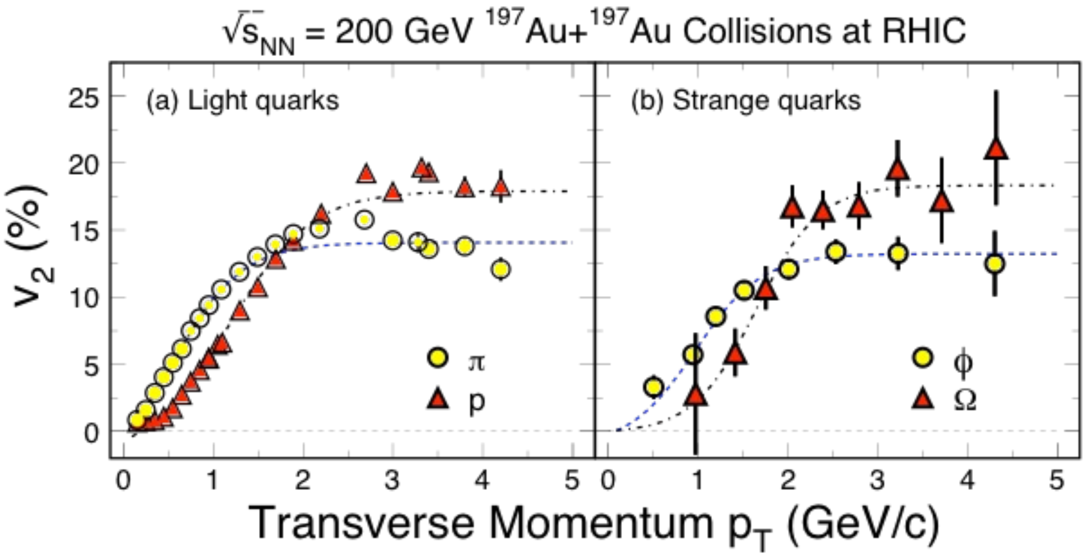




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle cos2\varphi \rangle, \qquad \varphi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Sensitive to initial/final conditions, EoS and degrees of freedom

Partonic Collectivity at RHIC



STAR: PRL**116**, 62301(2016)

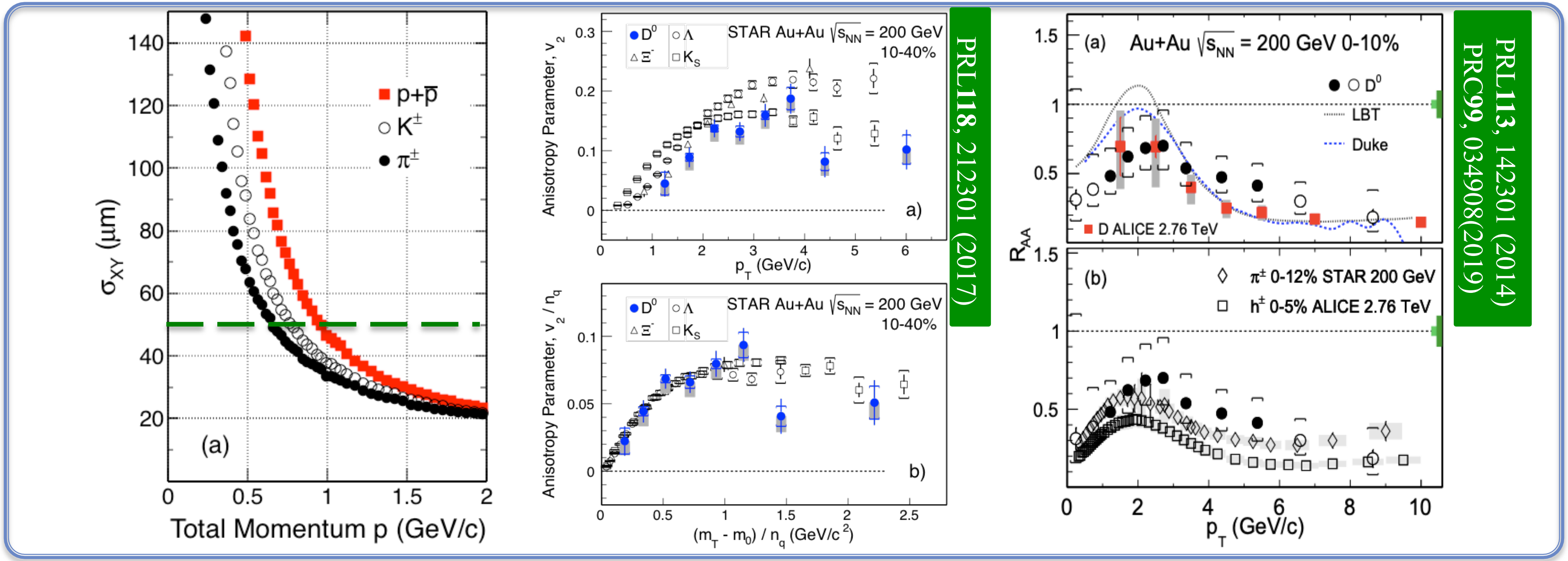
- ✓ Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
- ✓ High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

u-, d-, and s-quarks flow!

- ➢ **Partonic Collectivity!**
- ➢ **De-confinement Au+Au collisions at RHIC!**

STAR: PRL**116**, 62301(2016)

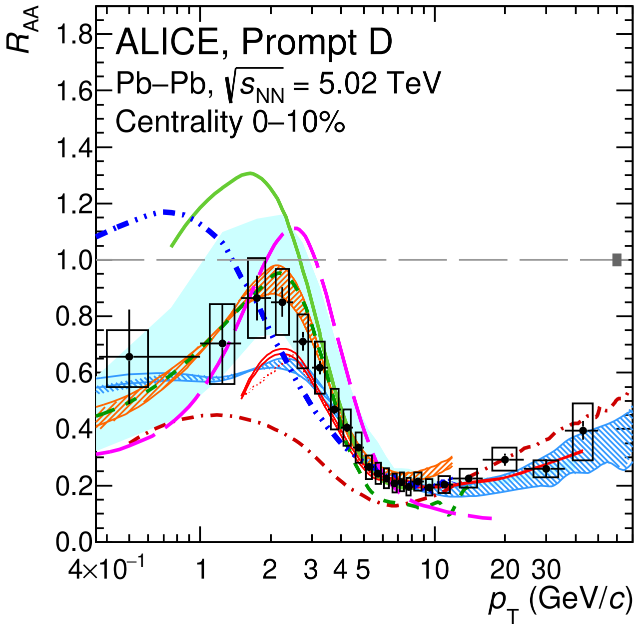
Heavy Flavor Hadron D^0 Collectivity at HRIC

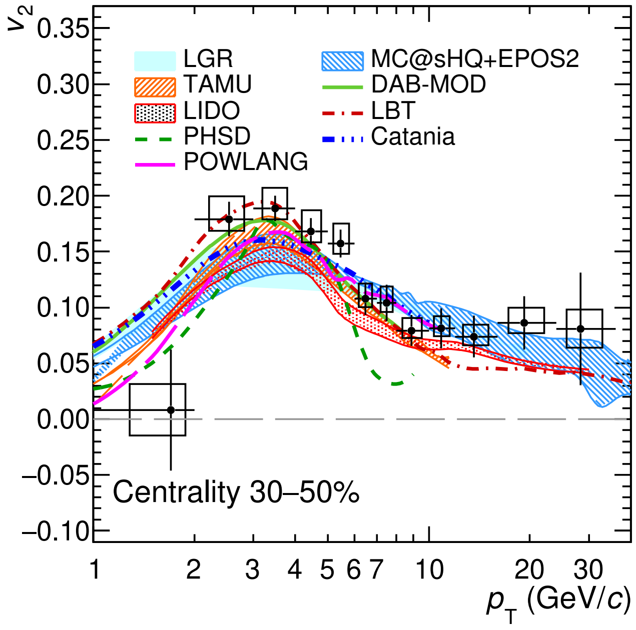


1) First application of MAPS technology in high energy collisions, excellent position resolution;
   - "These results suggest that charm quarks have achieved **local thermal equilibrium** with the medium created in such (200GeV Au+Au) collisions"
   - Hadronization via **quark coalescence** process

STAR: PRL**113**, 142301(14); PRC**99**, 034908(19); PRL**118**, 212301(17); PRL**123**, 162301(19); PRL**124**, 172301(20)

D^0 Partonic Energy Loss and Collectivity at LHC

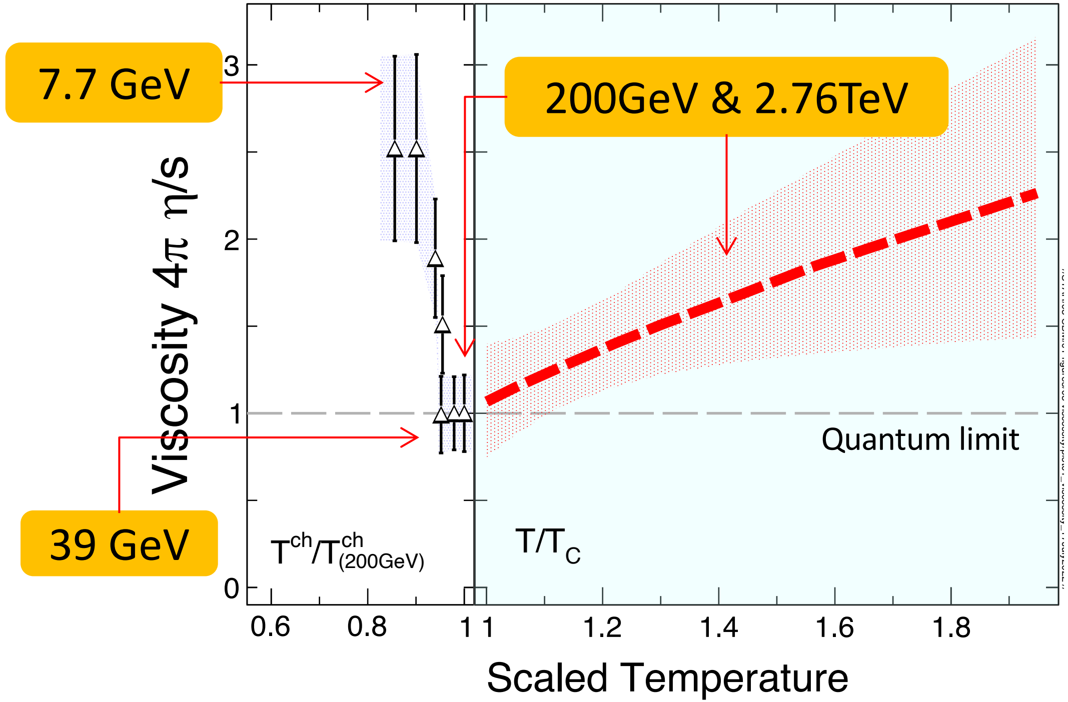


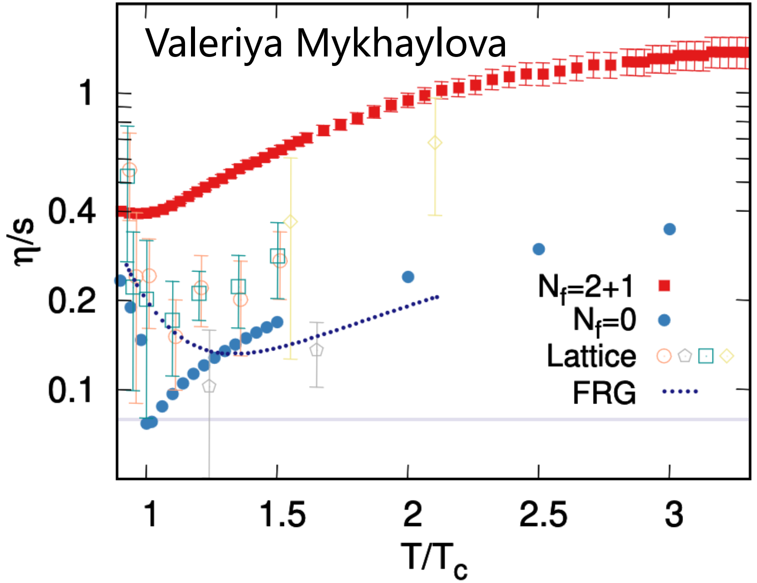


ALICE:
1) 2211.04384;
2) JHEP **01** (2022) 174
3) Phys. Lett. **B813** (2021) 136054

- D^0 strong suppress in R_{AA} and collectivity v_2 are evident at LHC;
- Calculations: Charm-transport in hydrodynamically expanding QGP

Equation of State for Strong Interaction

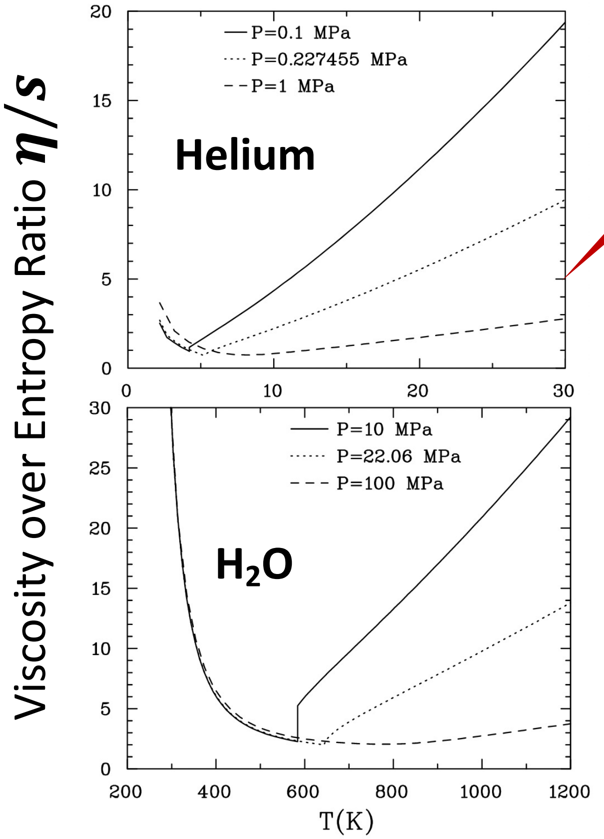




4) Evidence of the QCD transition!

- L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL **97** (2006) 152303
- X.Dong, Y.J. Lee & R.Rapp, ARNPS, **69** (2019) 417
- J.E.Bernhard, J.S.Moreland & S. Bass, Nat. Phys. **15** (2015) 1113
- I. Karpenko, P. Huovinen, H. Petersen, and M. Bleicher, Phys.Rev.**C91**, 064901 (2015).
- G.Nijs, W.van der Schee, U. Gürsoy and R. Snellings, PRL**126**, (2021) 202301

Strongly-Interacting Low-Viscosity Matter

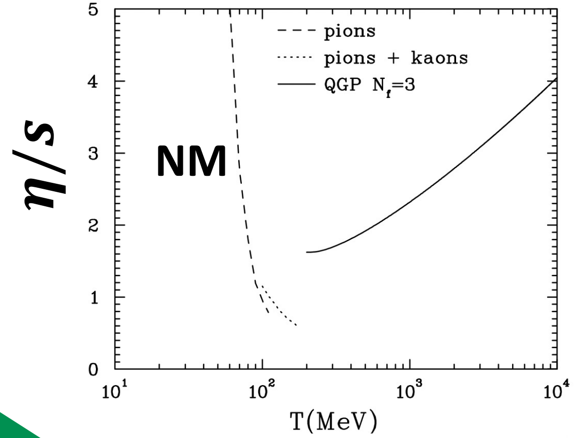


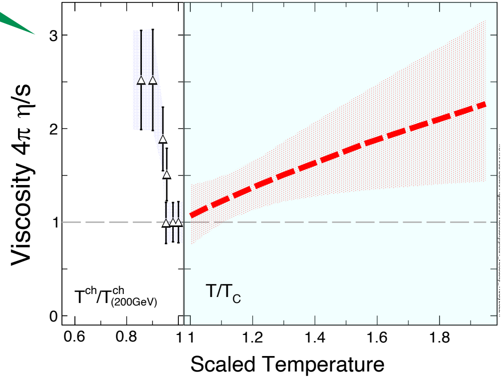
EM interaction
η/s ~ 1

L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL **97** (2006) 152303

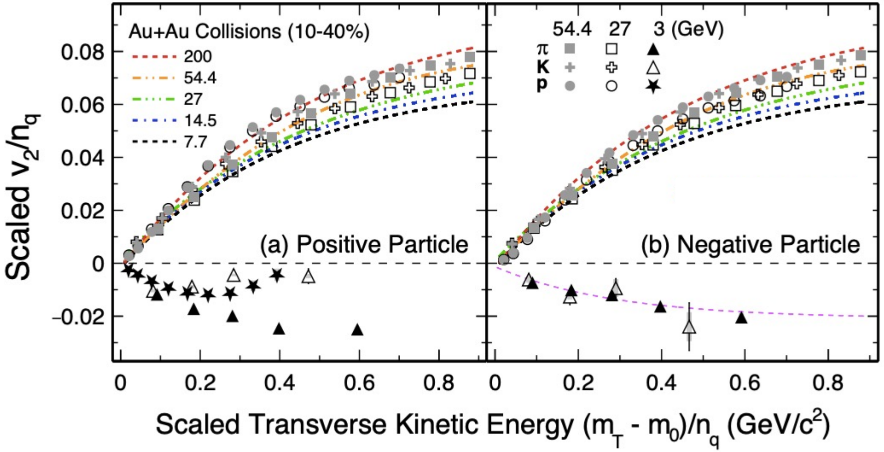
Strong Interaction
η/s ~ 0.1

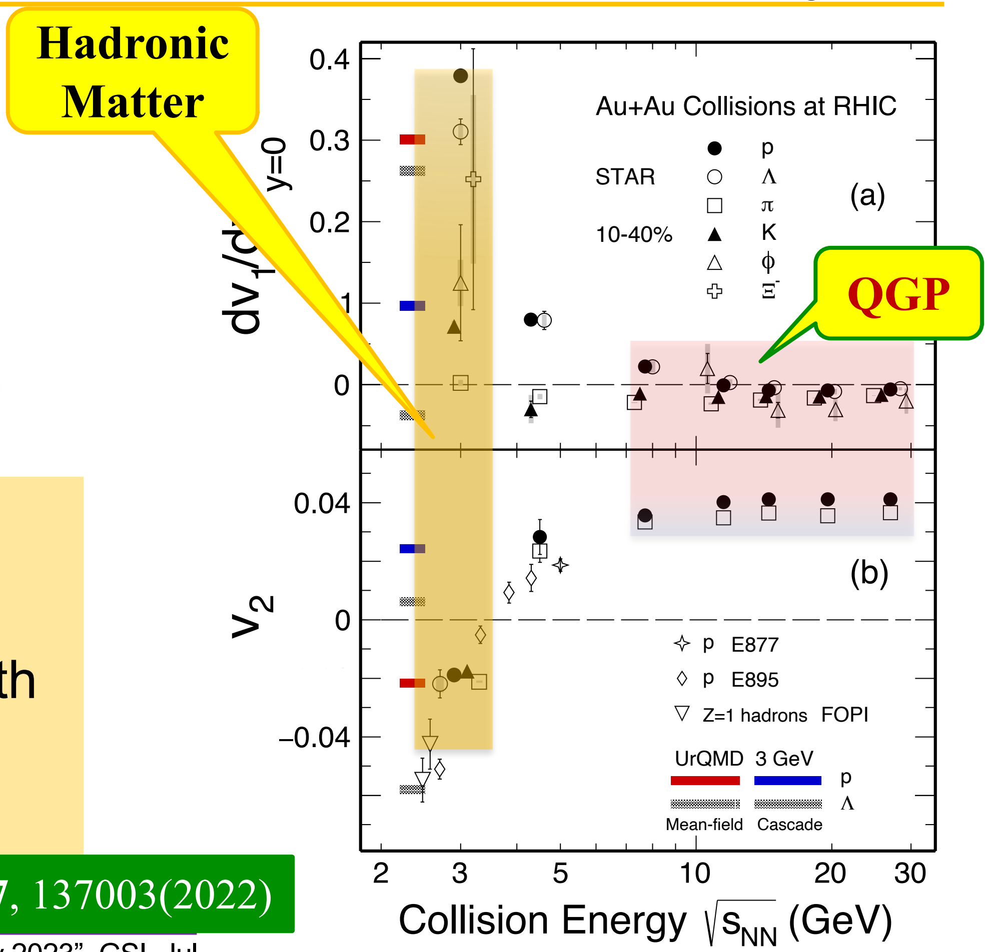
- QGP matter in $\sqrt{s_{NN}} \geq$ 39 GeV collisions!
- Universal behavior for phase transition!





Disappearance of Partonic Collectivity

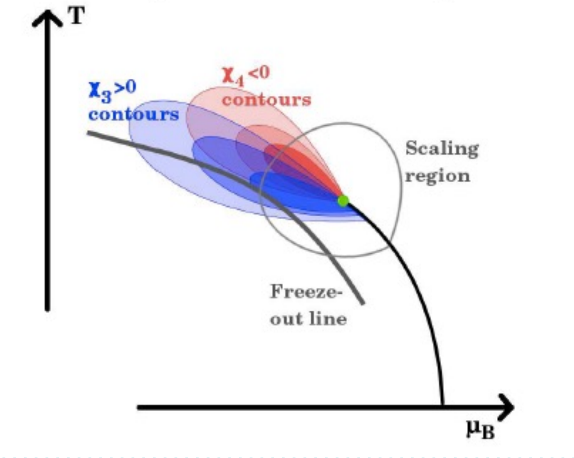




- At **3 GeV**, NCQ scaling is absent ;
- Transport model calculations, with baryonic mean field, reproduce both v_1 and v_2 results ;
- **hadronic interactions dominant!**

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

Criticality



Conserved Quantities (B, Q, S)

1) In strong interactions, baryons (B), charges (Q) and strangeness (S) are conserved;
2) Higher order moments/cumulants describe the shape of distributions and quantify fluctuations. They are sensitive to the correlation length ξ, phase structure;
3) Direct connection to theoretical calculations of susceptibilities.

Measured multiplicity N, $\langle \boldsymbol{\delta N} \rangle = \mathbf{N} - \langle \boldsymbol{N} \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

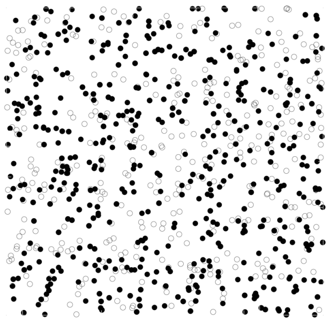
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

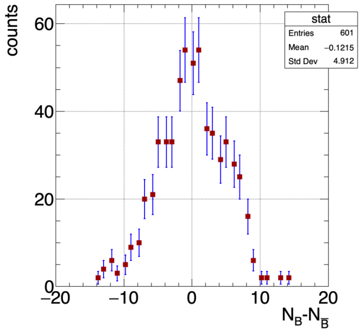
Moments, cumulants and susceptibilities:

2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

3rd order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

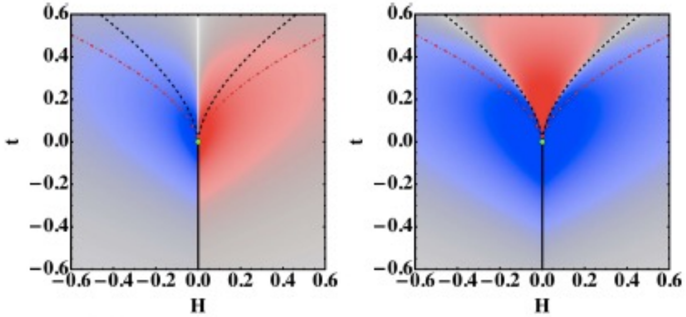
4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

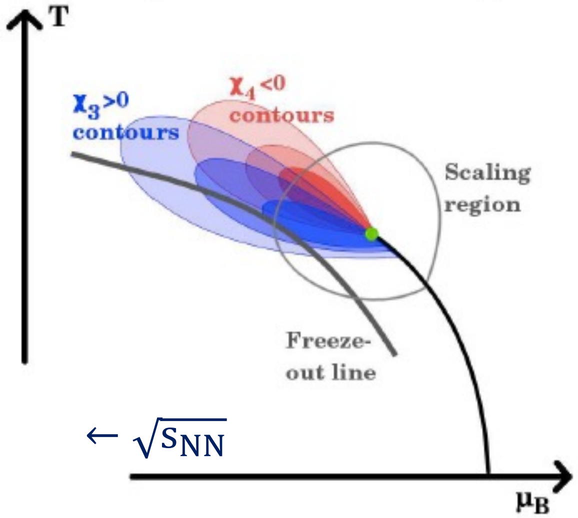


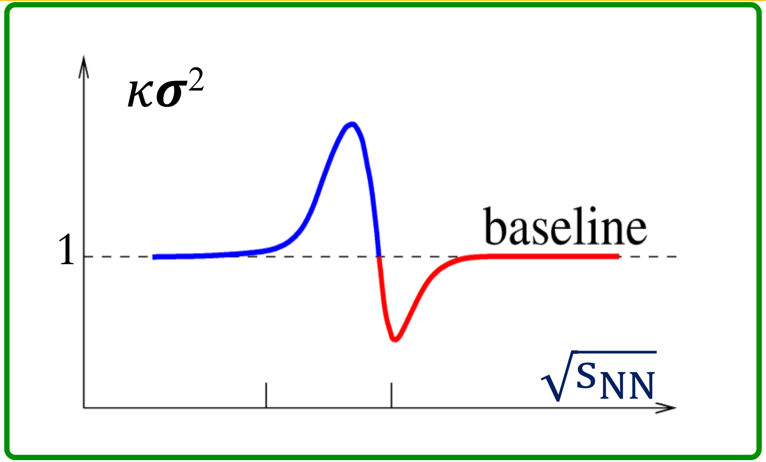


INT 2008-2b : The QCD Critical Point

Expectations for Models



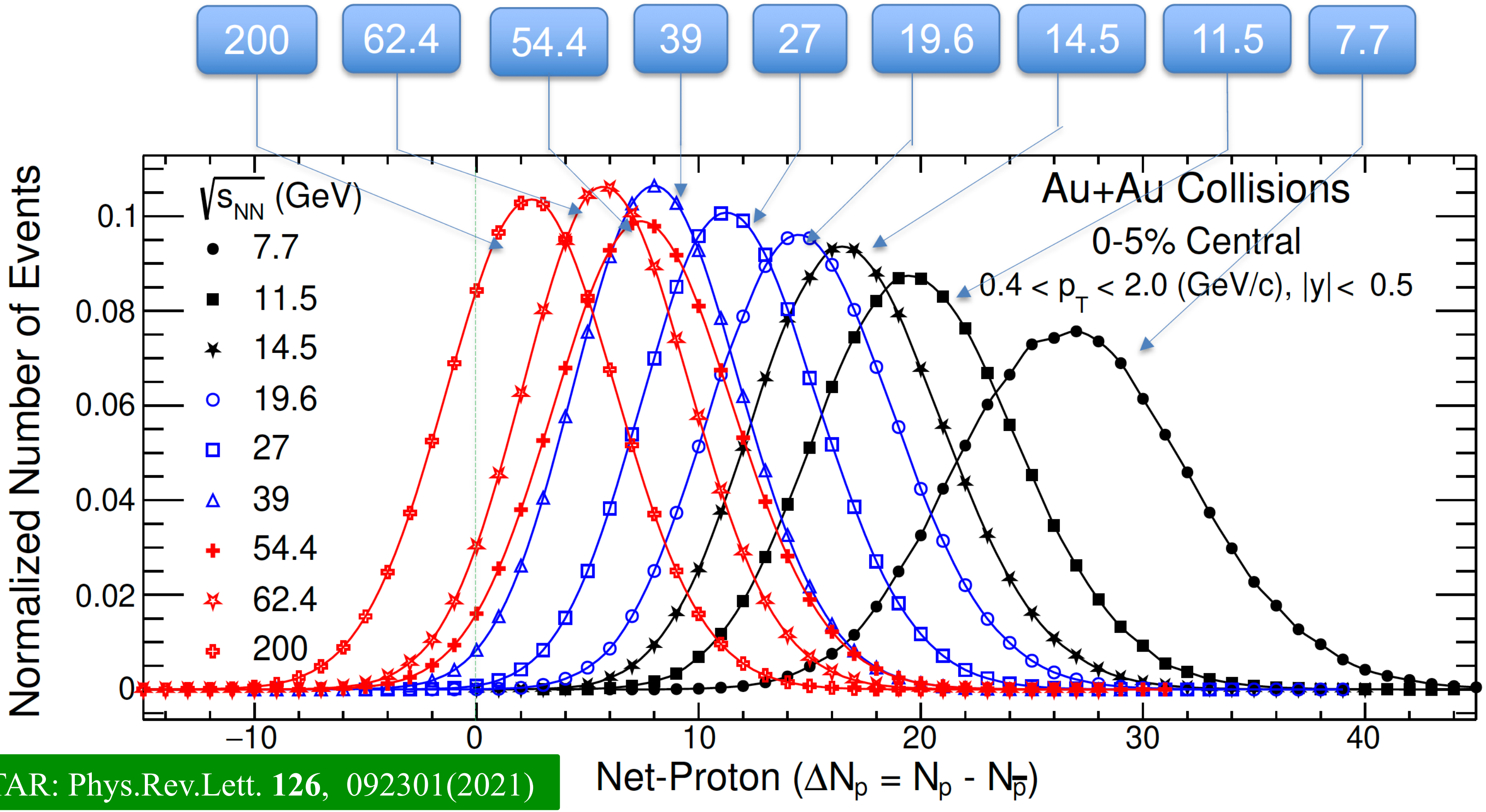




- Characteristic "Oscillating pattern" is expected for the QCD critical point but the exact shape depends on the location of freeze-out with respect to the location of CP
- Critical Region (CR)

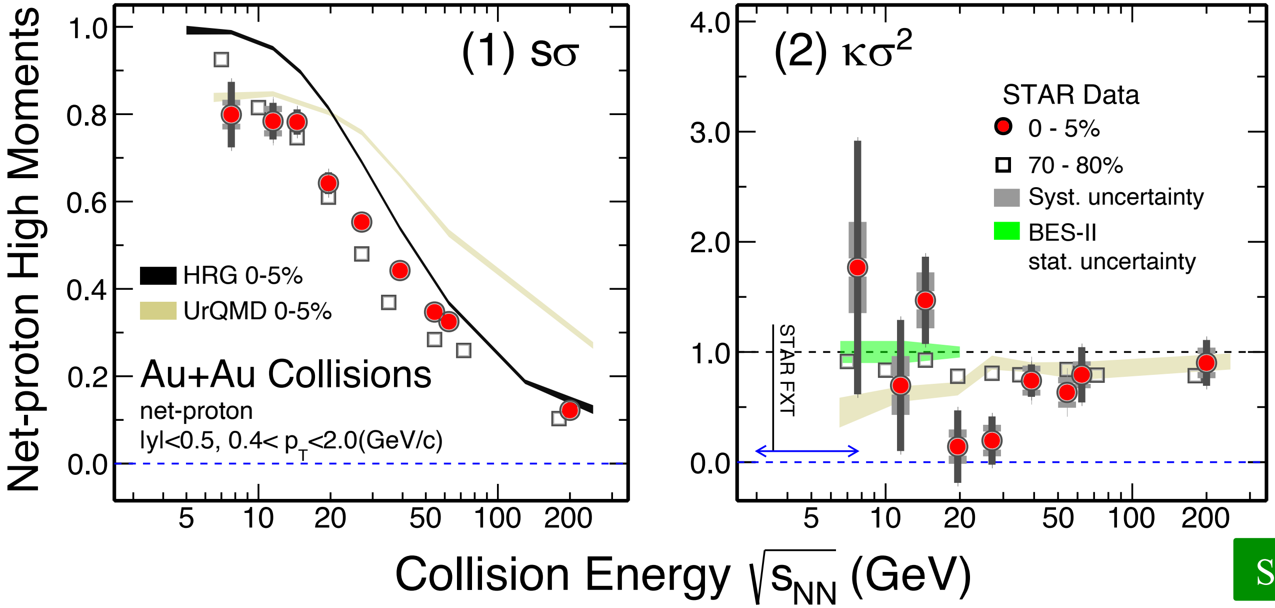
- M. Stephanov, PRL**107**, 052301(2011) - V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, Phys. Rev. **D93** (2016) 034037

Event-by-Event Net-Proton Distributions (raw)



STAR: Phys.Rev.Lett. **126**, 092301(2021)

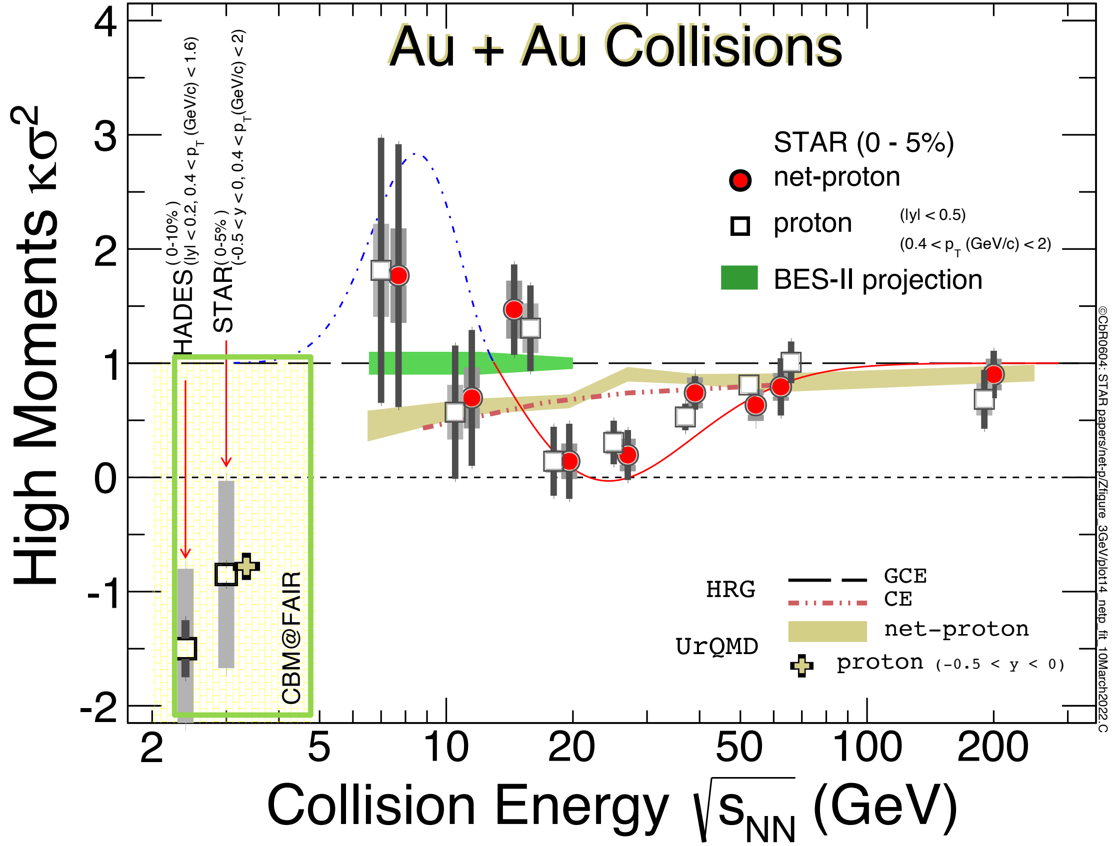
"Nonmonotonic Energy Dependence of Net-Proton Number"



STAR: PRL**126**, 092301(21)

1) HRG and transport model predicted monotonical energy dependence: AMPT, JAM, UrQMD. Suppression at low energy due to conservation;
2) The 3rd and 4th orders: **deviate from the Poisson limit** in the most central collisions!

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)

Thermalization in Heavy-Ion Collisions

S. Gupta *et al.* Phys. Lett. **B829**, (2022) 137021


Physics Letters B 829 (2022) 137021

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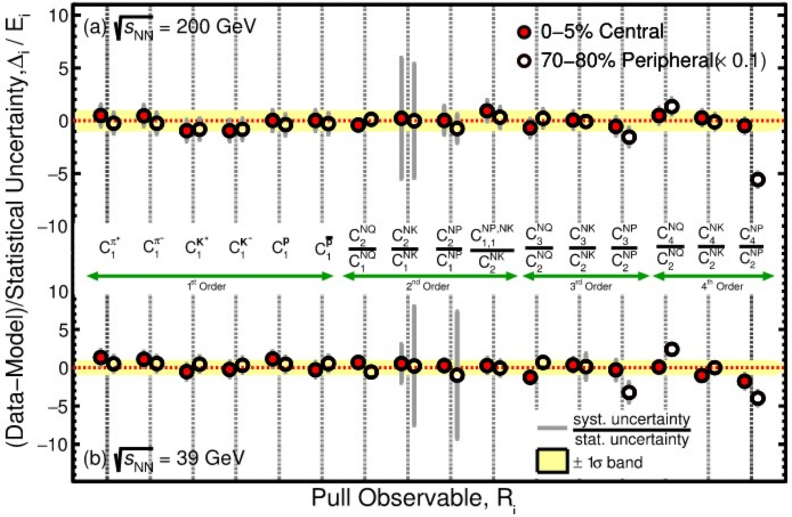
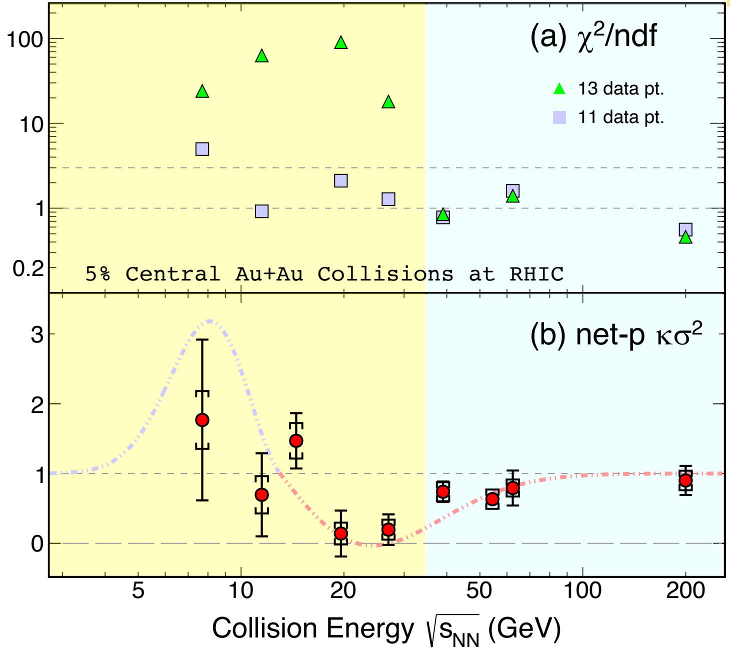
Limits of thermalization in relativistic heavy ion collisions

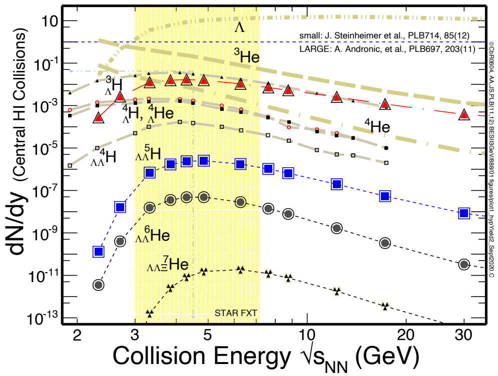
Sourendu Gupta[a], Debasish Mallick[b,c], Dipak Kumar Mishra[d], Bedangadas Mohanty[b,c,*], Nu Xu[e]

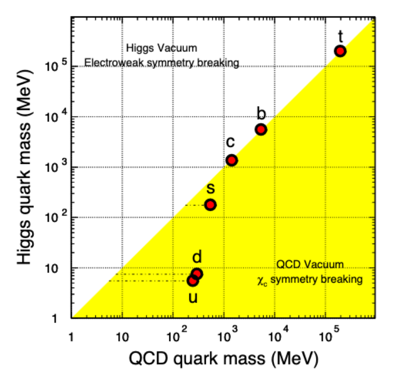


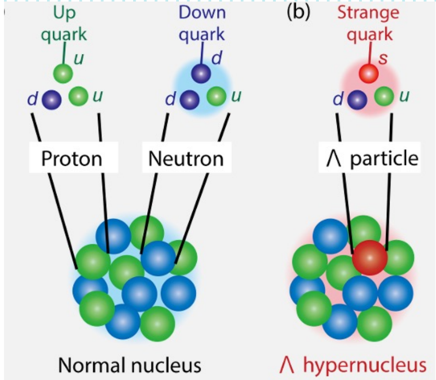
1) Test of the thermal model with high moments data: 4^{TH} order;
2) Below 39 GeV, **data is not consistent with equilibrium.**



Strangeness and Hyper-Nuclei



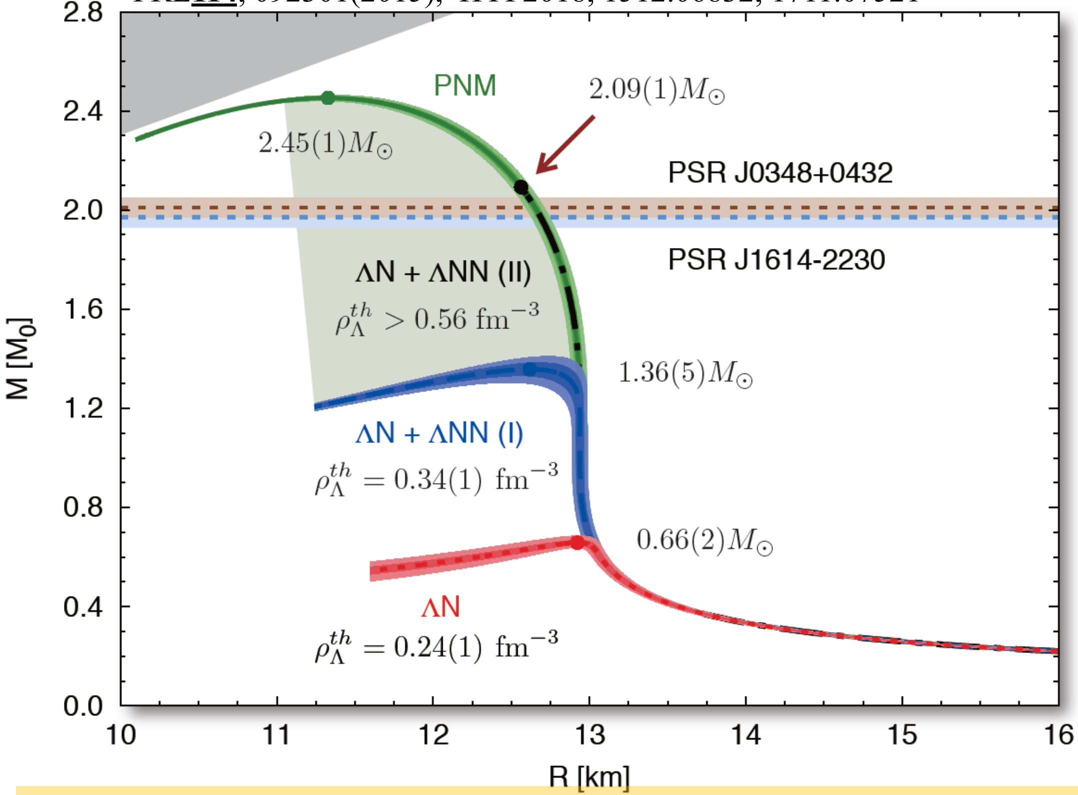


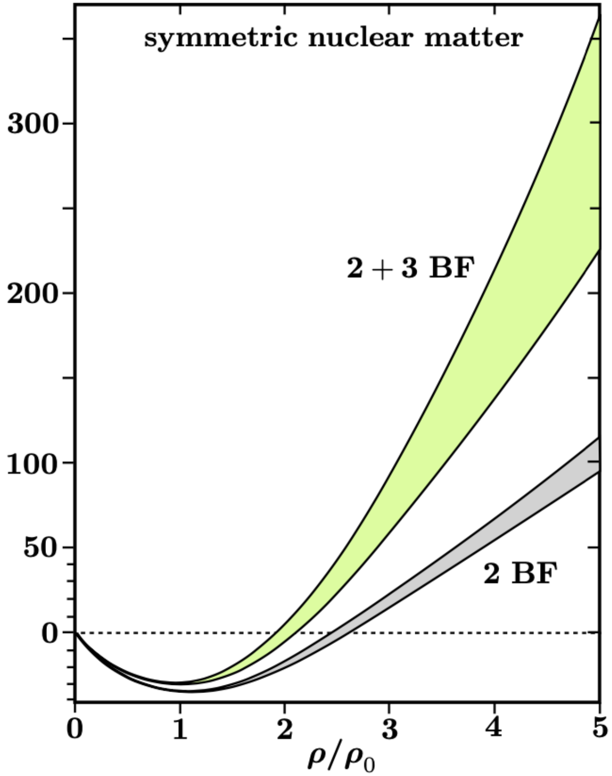


A. Andronic *et al*. PL**B697**, 203(2011)
J. Steinheimer *et al*. PL**B714**, 85(2012)

Λ-N Interaction inside Compact Stars

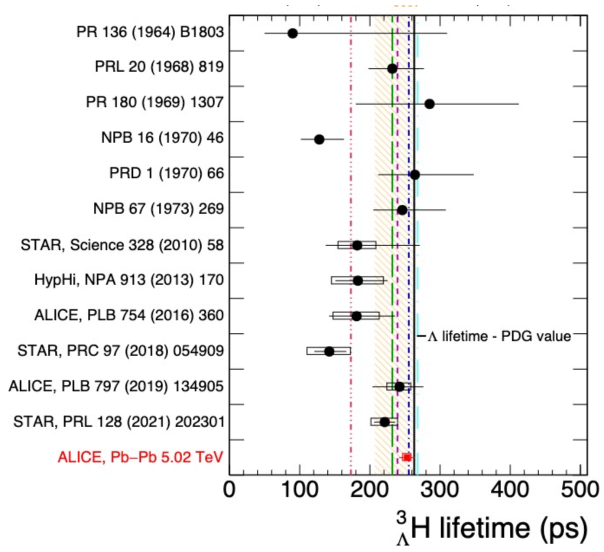
PRL**114**, 092301(2015), HYP2018, 1512.06832, 1711.07521

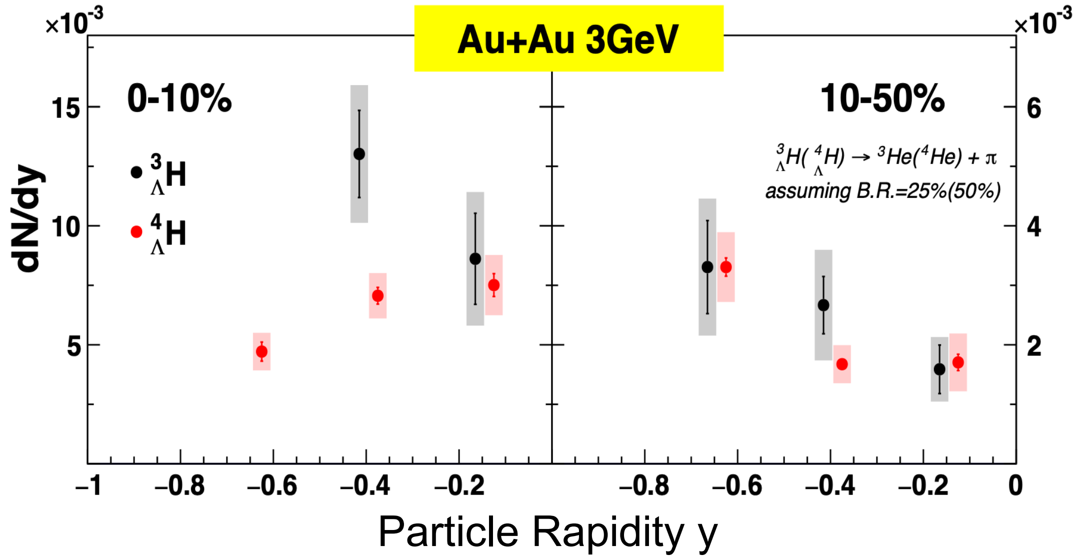




Y-N interaction: key to understand the inner structure of compact stars

Hyper-Nuclei Lifetime and Yields





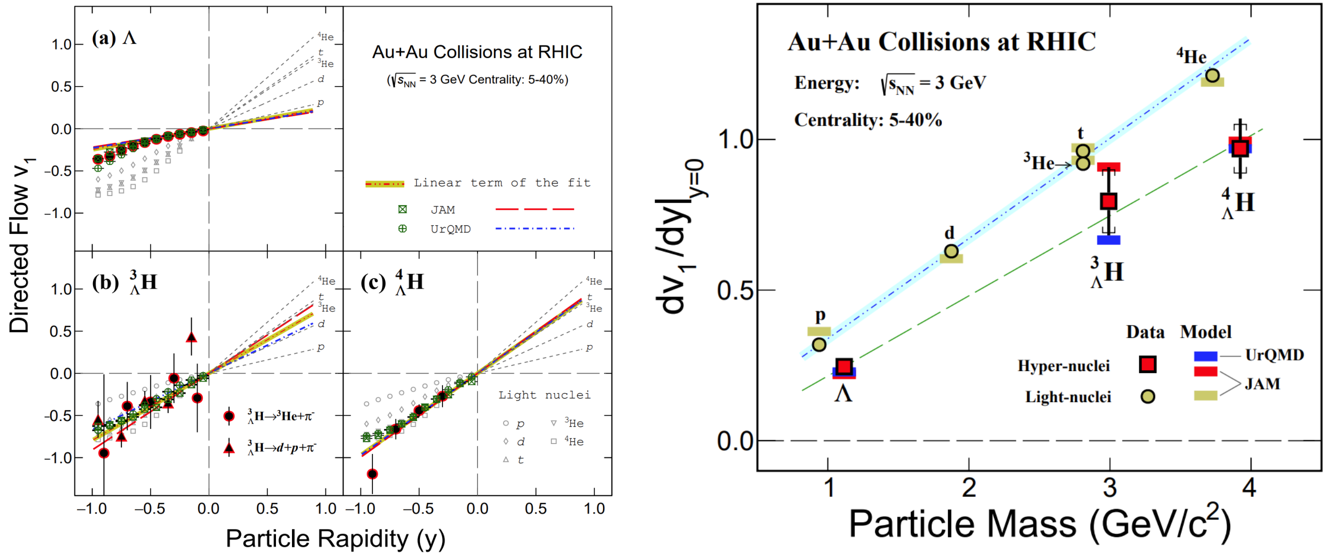
1) Precision results on lifetime;

ALICE: 2209.07360; STAR: PRL**128** 202301(2022)

2) Abundant hyper-nuclei at the high baryon density region;

3) Coalescence calculations seem work for hyper-nuclei yields

Collectivity of Hyper-Nuclei



STAR: PRL 130, 212301(2023)

- Coalescence: the dominant procedure for hyper nuclei production;
- Hyper nuclei collectivity (e.g. v_1 and v_2) → ***Y-N*** and ***Y-Y*** interactions under finite pressure gradient;
- **Questions:** Connection to the EOS of compact stars? Effect of isospin?

Outline

1) Introduction

2) Selected Recent Results

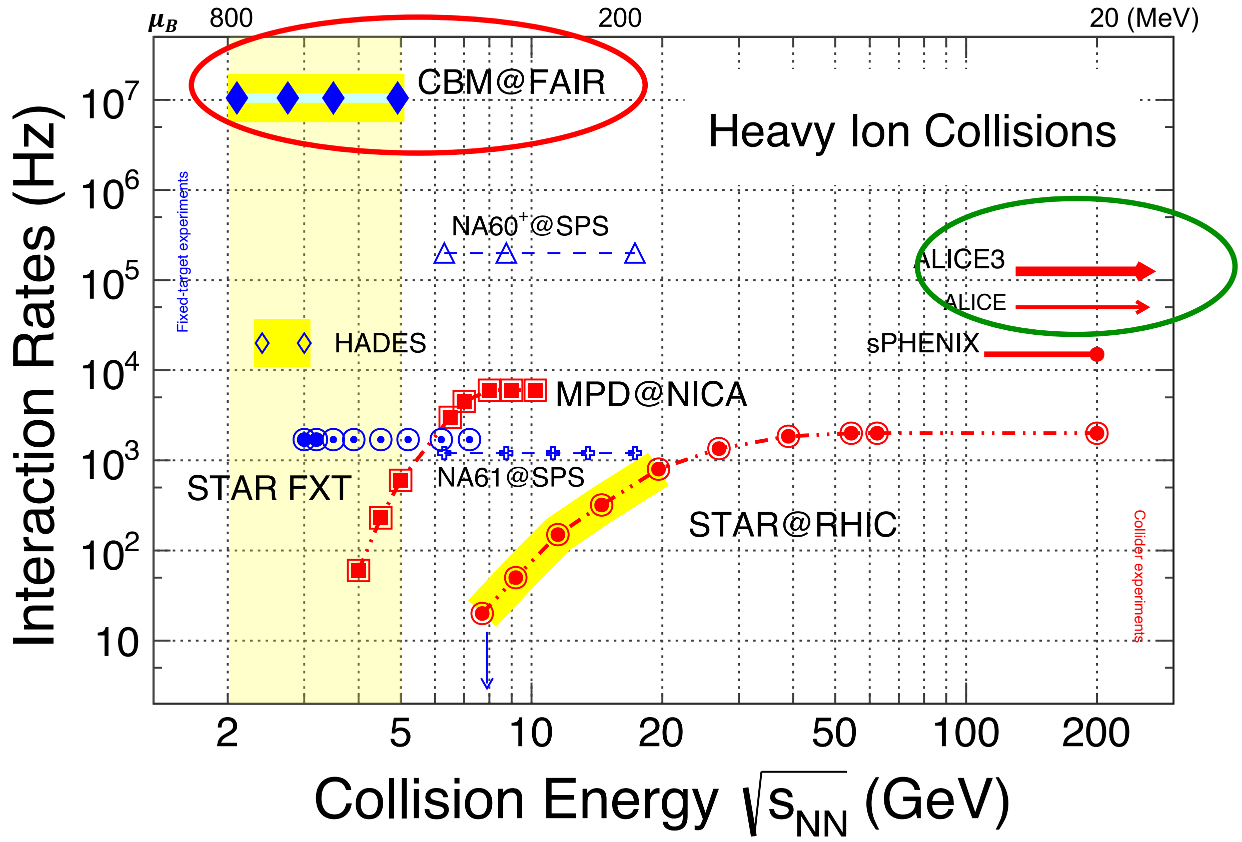
- Collectivity
- Criticality
- Hyper-nuclei Production

3) Future Physics Programs

Future High Rates Experiments

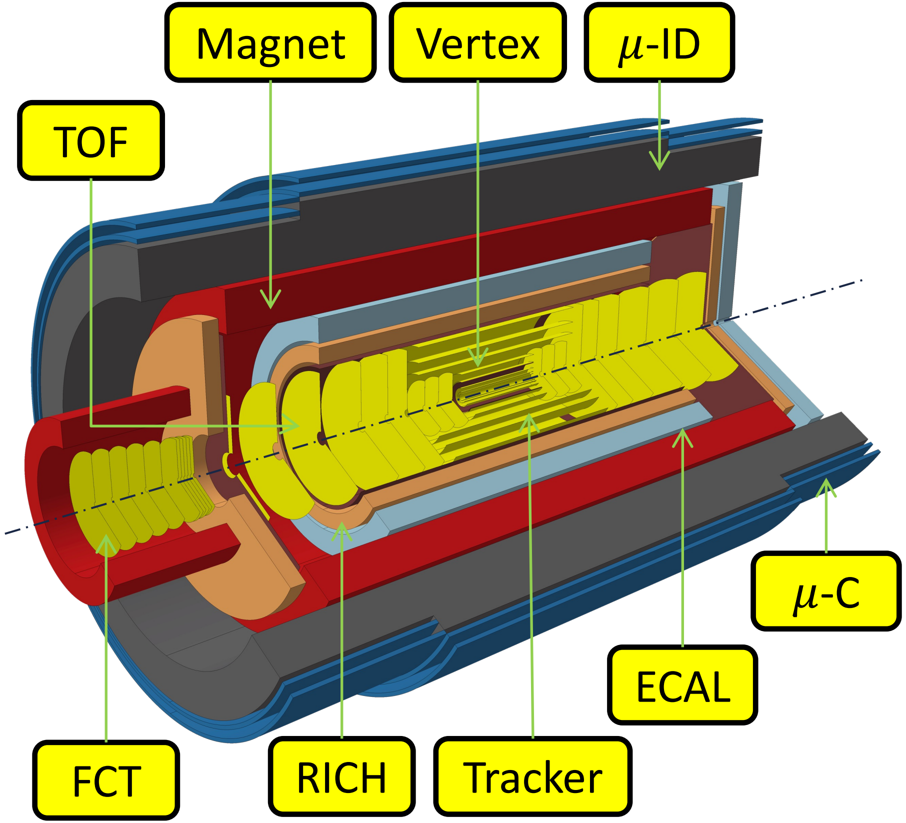
- **ALICE3:** μ_B ~ 0 Properties of QGP!
- **CBM:** Unprecedented rate capability and μ_B ~ 800 MeV

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



ALICE3

https://cds.cern.ch/record/2803563/files/LHCC-I-038.pdf



ALICE3: Low Mass, Large Rapidity Coverage

Key Physics Measurements:

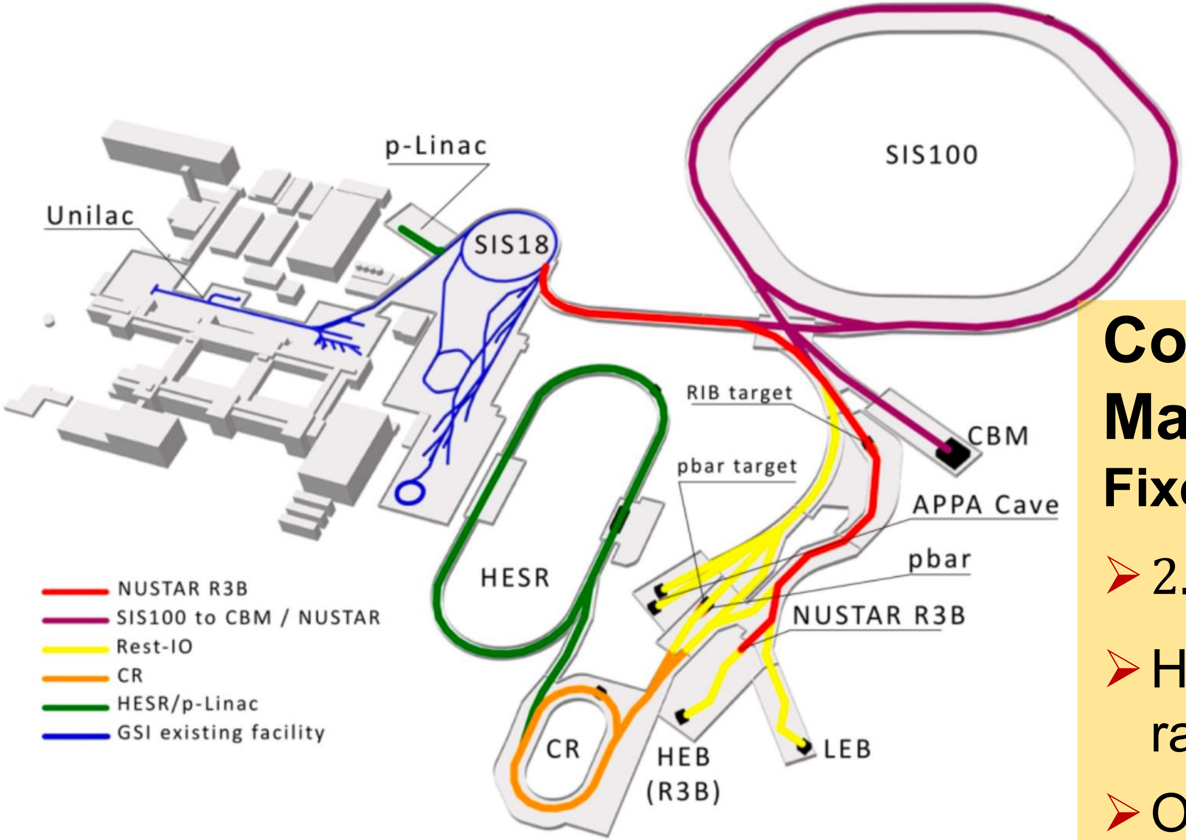
1) Heavy flavor: Medium effects and hadronization;

cumulants, …

State-of-the-art detector!
Great potentials for physics!

A dream experiment!

CBM Experiment at FAIR

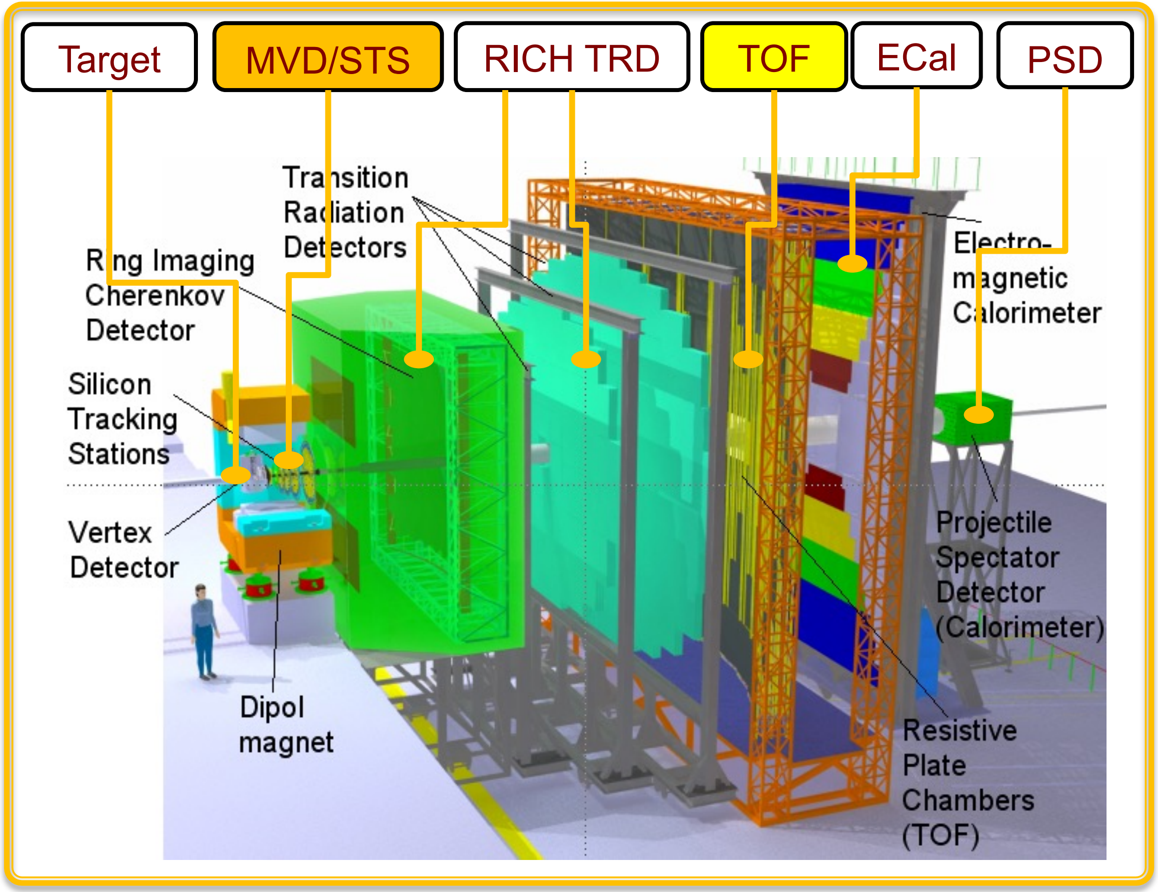


Compressed Baryonic Matter (CBM)

Fixed-target experiment:

- $2.4 < \sqrt{s_{NN}} < 4.9$ GeV
- High intensity & collision rates up to 10MHz
- Operation starts in 2028

CBM Experiment at FAIR

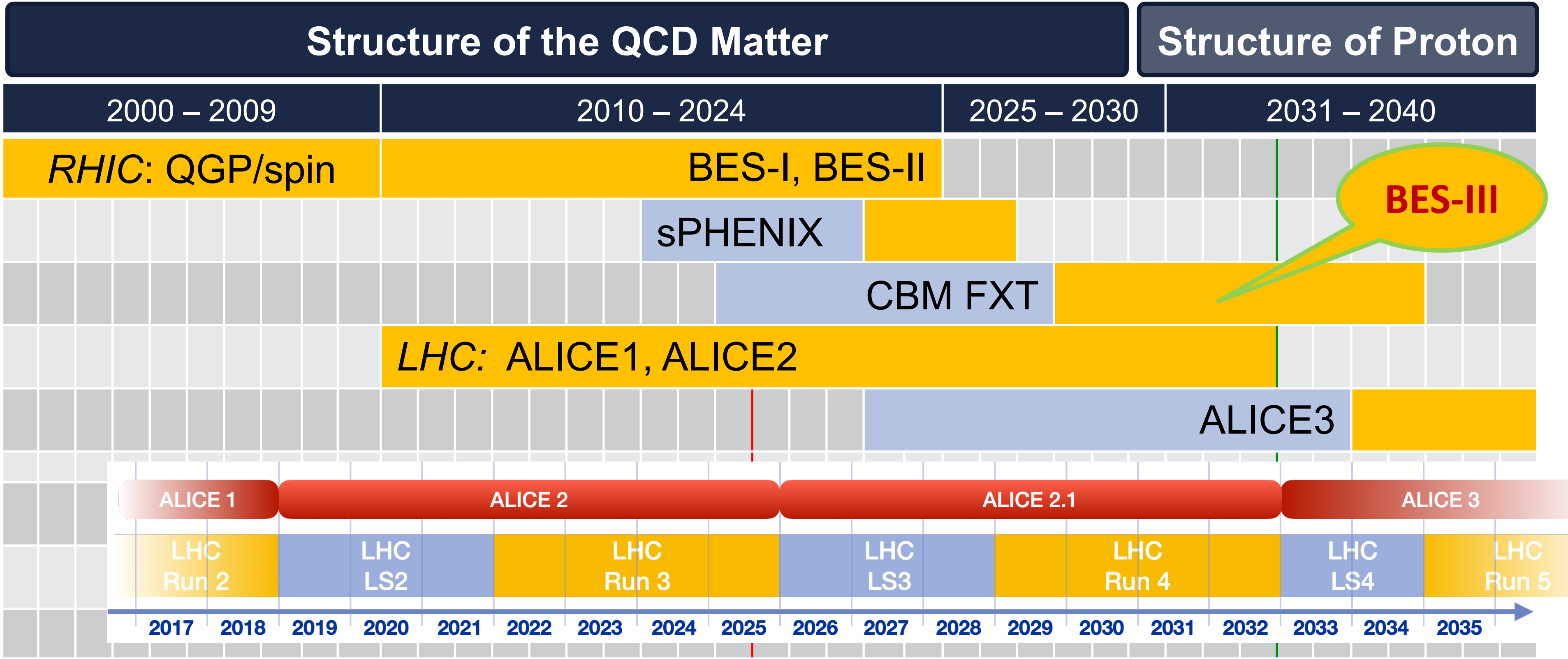


- FAIR: One of the brightest accelerator complexes
- Precision measurements at high baryon density region:
  (i) Dileptons (*e*, *μ*);
  (ii) High order correlations;
  (iii) Flavor productions (*s*, *c*) and hyper-nuclei

Beam on target in 2028

Projects and Timelines

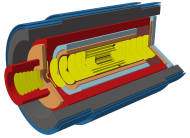
Emergent Properties of QCD: Confinement & Mass of VM

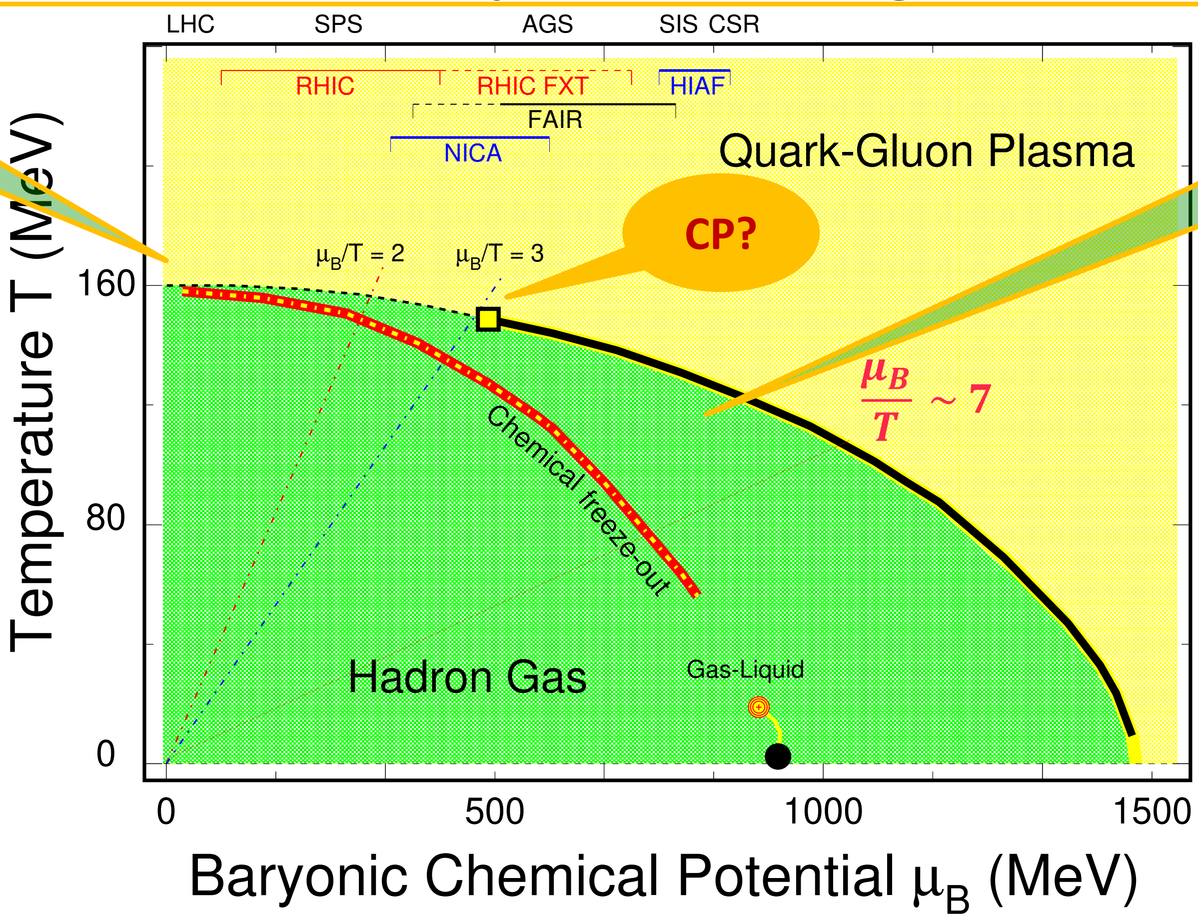


Future Physics Programs

ALICE

- Properties of the smooth cross-over;
- p+p collisions;
- Full lepton distributions with **ALICE3**

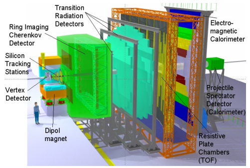




BES-II

CBM

- Critical point and phase boundary;
- Nuclear matter EOS at high baryon density;
- Y-N interactions



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// BLUE: Theory // **RED**: Experiment // **GREEN**: student

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Thank you for your attention!