MARIA STEFANIAK

THE SOUP THAT IS NOT TOO HOT



FAIRNESS

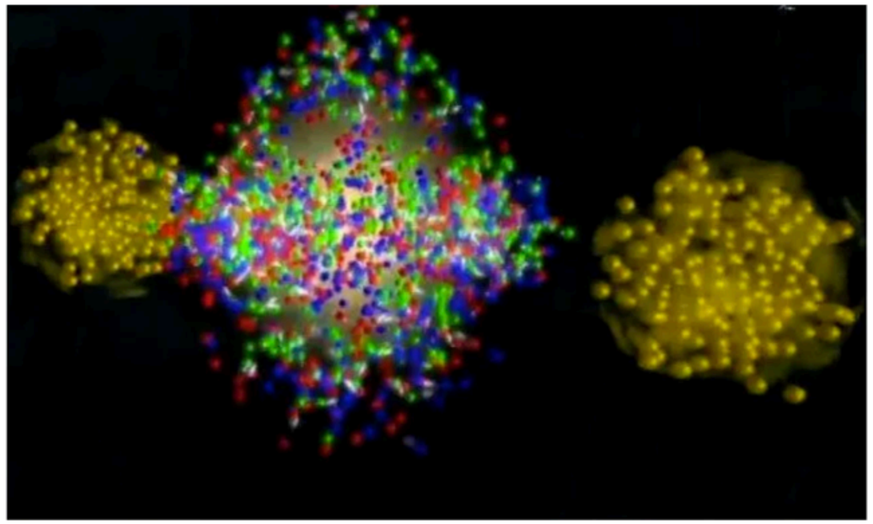
Paralia, Greece 24.05.2022

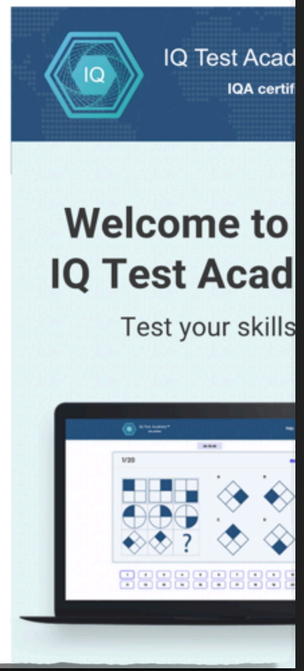
THE HOTTEST SOUP

SCIENCE

Hottest Temperature Ever Made By Humans? 'Subatomic Soup' Is About 9.9 Trillion Degrees, CERN Scientists Speculate

Aug. 14, 2012, 05:24 PM EDT | **Updated** Feb. 25, 2013





The Large Hadron Collider scientists at CERN claim to have created the hottest man-made

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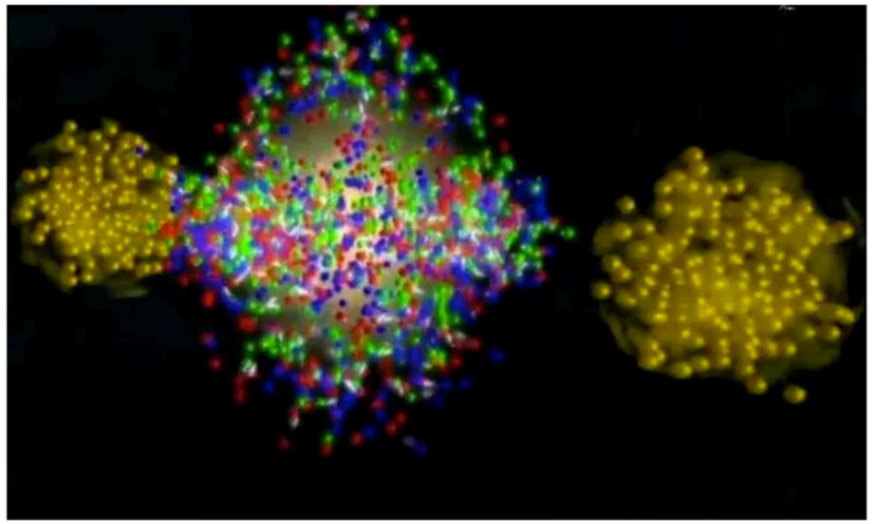

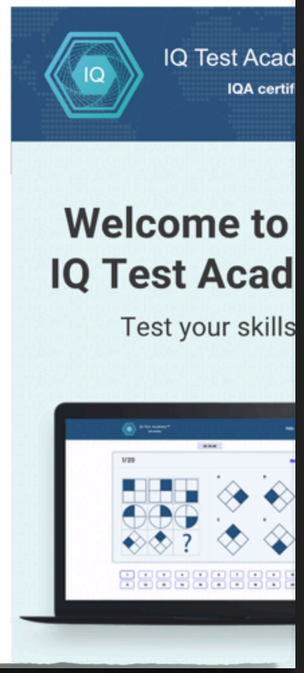

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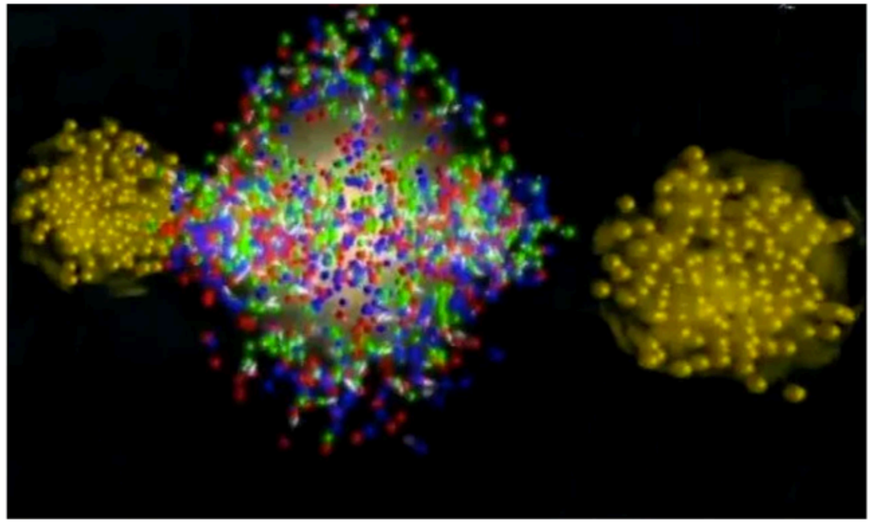

The Large Hadron Collider scientists at CERN claim to have created the hottest man-made

NEWS

Hottest soup in the universe

COSMIC LOG

Hottest soup in the universe

Feb. 15, 2010, 11:15 PM CET

By Alan Boyle, Science Editor, NBC News

BNL

Click for video: This artist's conception shows two gold ions blasting into each

other in the Relativistic Heavy Ion Collider, leaving behind a spray of particles that

includes quark-gluon plasma. Such conditions naturally existed in the universe a

microsecond after the big bang. Click on the image to watch a YouTube video.

Scientists say the tiny bubbles of plasma they've created in a "big bang machine" are the hottest dollops of soup ever seen in the universe, reaching temperatures of several trillion degrees.

What's more, the weird properties of that soup may help scientists

THE HOTTEST SOUP

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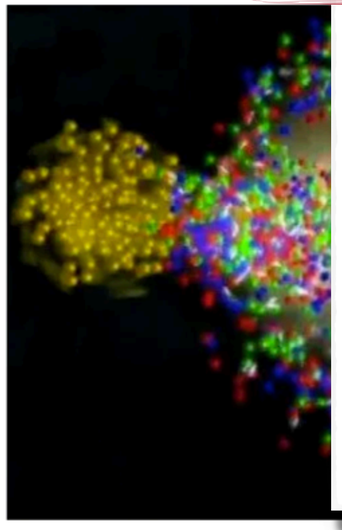
Aug. 14, 2012, 05:24 PM EDT | Updated Fe



The Large Hadron Collider scientists at CERN claim to have created the hottest man-made

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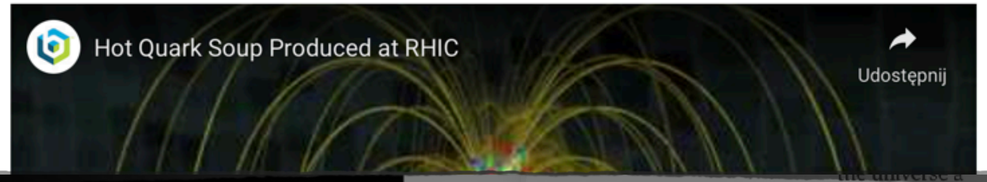
Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631)

'Perfect' Liquid Hot Enough to be Quark Soup

Protons, neutrons melt to produce 'quark-gluon plasma' at RHIC

February 15, 2010

UPTON, NY — Recent analyses from the Relativistic Heavy Ion Collider (RHIC), a 2.4-mile-circumference "atom smasher" at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, establish that collisions of gold ions traveling at nearly the speed of light have created matter at a temperature of about 4 trillion degrees Celsius — the hottest temperature ever reached in a laboratory, about 250,000 times hotter than the center of the Sun. This temperature, based upon measurements by the PHENIX collaboration at RHIC, is higher than the temperature needed to melt protons and neutrons into a plasma of quarks and gluons. Details of the findings will be published in *Physical Review Letters*.



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News

BNL

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Aug. 14, 2012, 05:24 PM



The Large Hadron Col

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Cooking Up Hot Quark Soup

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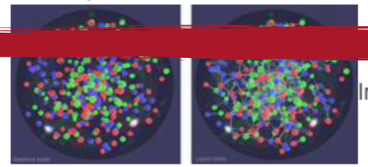

Image courtesy of Brookhaven National Laboratory

These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure on left, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure on right, see mpeg animation). The green "force lines" and collective motion (visible on the animated version only) show the much higher degree of interaction and flow among the quarks in what is now being described as a nearly "perfect" liquid.

Imagine the hottest "soup" on the planet—250,000 times hotter than the center of the sun. You won't find any letter-shaped noodles or bits of veggies and chicken. Under these conditions, all regular matter melts—even the protons and neutrons that make up atoms! Instead, you'll find the tiniest known pieces of matter—quarks and the gluons that ordinarily hold them together—zipping around and interacting as they did some 14 billion years ago, before they coalesced to form protons, neutrons, atoms, stars, planets, and galaxies.

Physicists are cooking up just such a soup at the Relativistic Heavy Ion Collider (RHIC), a 2.4-mile circular atom smasher at the U.S. Department of Energy's Brookhaven National Laboratory. Inside RHIC's twin accelerator rings, two beams of gold ions travel in opposite directions at nearly the speed of light, smashing into one another millions of

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THE HOTTEST SOUP

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nature

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nature > news > article

Published: 16 February 2010

Subatomic soup is hot stuff

Eric Hand

Nature (2010) | Cite this article

58 Accesses | 12 Altmetric | Metrics

Twisting vortices seen in fireballs could unravel matter-antimatter conundrum.

Physicists have measured the temperature inside the hottest fireball on Earth, a four-t
degree jumble of melted protons and neutrons.

This soup of subatomic particles, created in collisions of gold nuclei at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, New York, is yielding other intriguing discoveries. Chief among them is evidence of tiny bubbles in the soup that could help explain a fundamental

coalesced to form protons, neutrons, atoms, stars, planets, and galaxies.

Physicists are cooking up just such a soup at the Relativistic Heavy Ion Collider (RHIC), a 2.4-mile circular atom smasher at the U.S. Department of Energy's Brookhaven National Laboratory. Inside RHIC's twin accelerator rings, two beams of gold ions travel in opposite directions at nearly the speed of light, smashing into one another millions of

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SCIENCE

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Aug. 14, 2012, 05:2

The Large Hadro

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Why hot soup is tastier than cold soup? [closed]

Asked 3 years, 2 months ago Modified 3 years, 2 months ago Viewed 747 times

Ask Question

2

1

Closed. This question is off-topic. It is not currently accepting answers.

Want to improve this question? Update the question so it's on-topic for Physics Stack Exchange.

Closed 3 years ago.

Improve this question

My physics teacher recently asked me this question. Can anyone answer the question?

temperature physical-chemistry biology perception food

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edited Feb 15, 2019 at 14:38

Qmechanic ♦

167k ● 33 ● 416 ● 1932

asked Feb 15, 2019 at 14:26



CodeXxxx

47 ● 1 ● 2

How do you measure "taste"? – NickD Feb 15, 2019 at 14:35

5 I'm voting to close this question as off-topic because it isn't about physics. – Jon Custer Feb 15, 2019 at 14:35

2 Assumes facts not in evidence. There are soups you eat cold. – StephenG - Help Ukraine Feb 15, 2019 at 14:36

@JonCuster Agreed. Probably a better fit for biology.se? – Apoorv Feb 15, 2019 at 14:39

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18 Hot water freezing faster than cold water

3 Do sodium chloride(ions) melt the ice or not?

4 Why do we feel hot when temperature is relatively high even though it might be lower than our normal body temperature

0 How much of a difference does it make whether you blow on hot soup indoor vs outdoor?

0 Why does a gunpowder makes sound when it burns but not like a candle?

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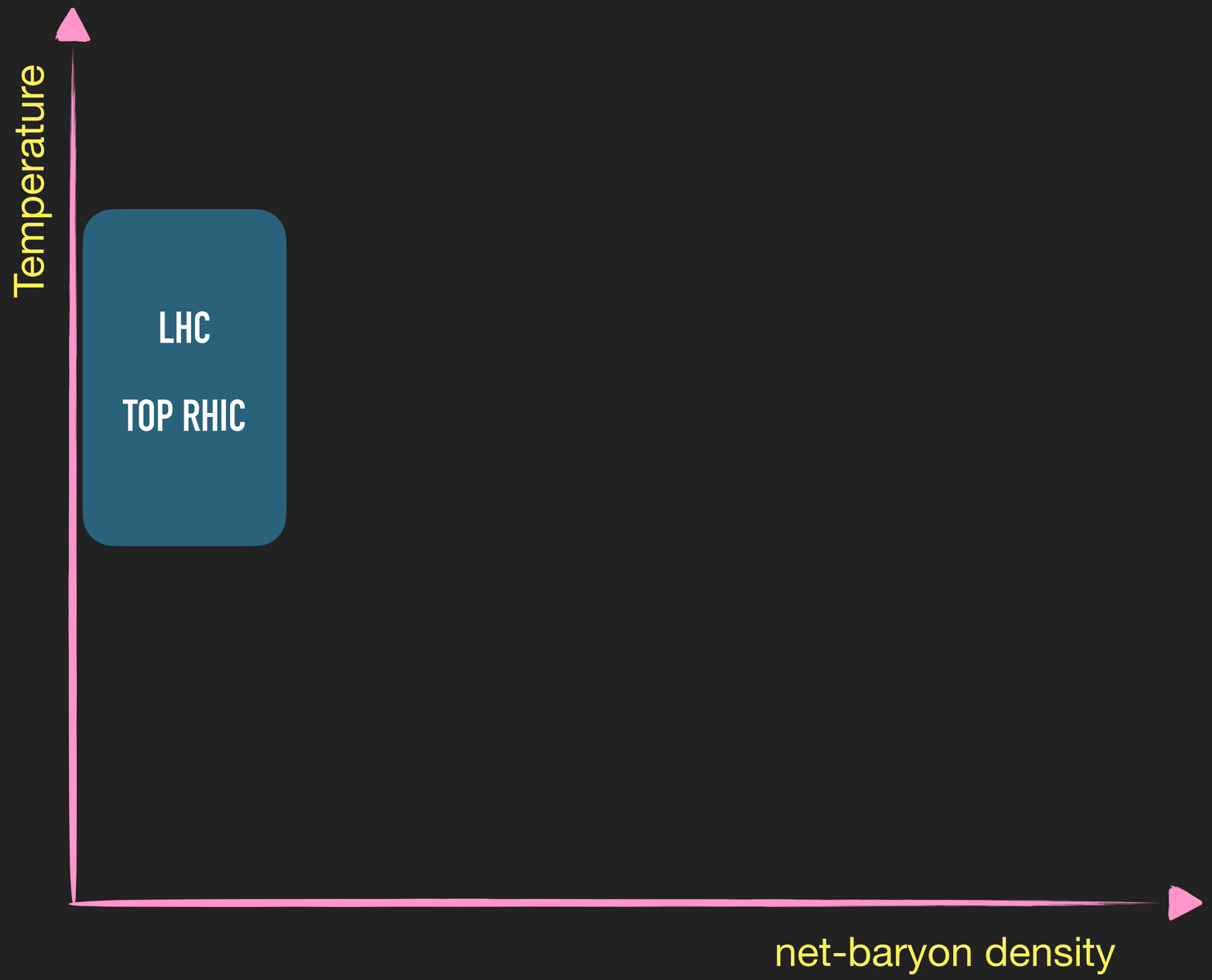
THE HOT SOUP



THE HOT SOUP

Temperature

LHC

TOP RHIC



net-baryon density

THE HOT SOUP

Lattice QCD

Temperature

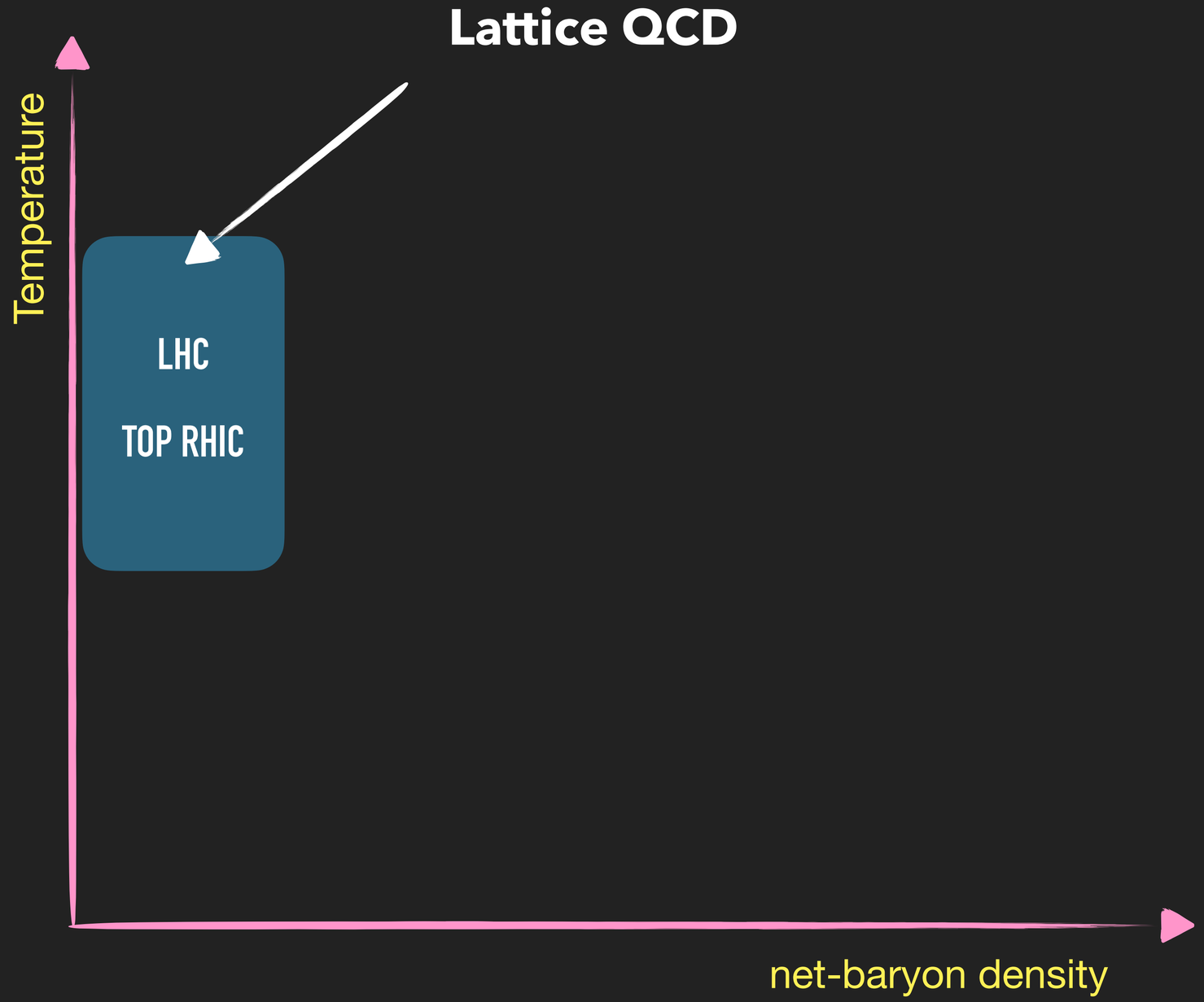
LHC

TOP RHIC



net-baryon density

THE HOT SOUP



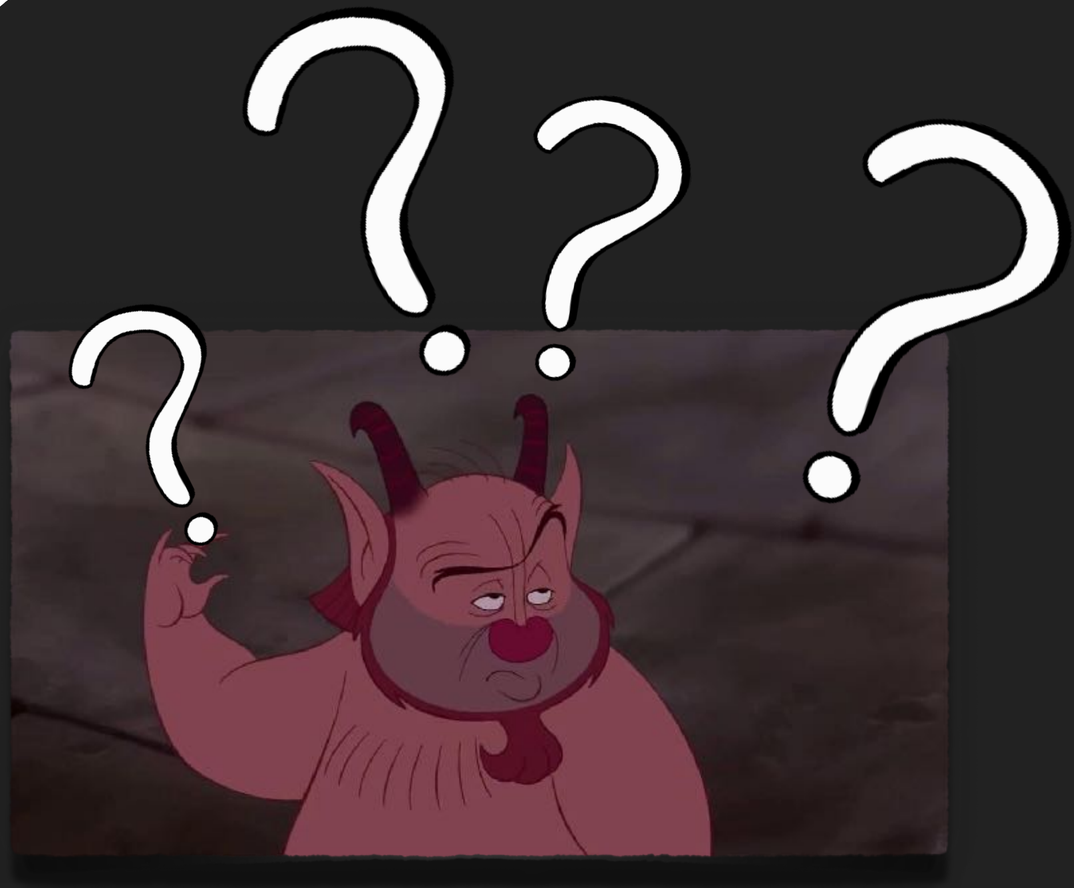
THE HOT SOUP

Lattice QCD

Temperature

LHC

TOP RHIC



net-baryon density

THE COLDER SOUP

Lattice QCD

Temperature

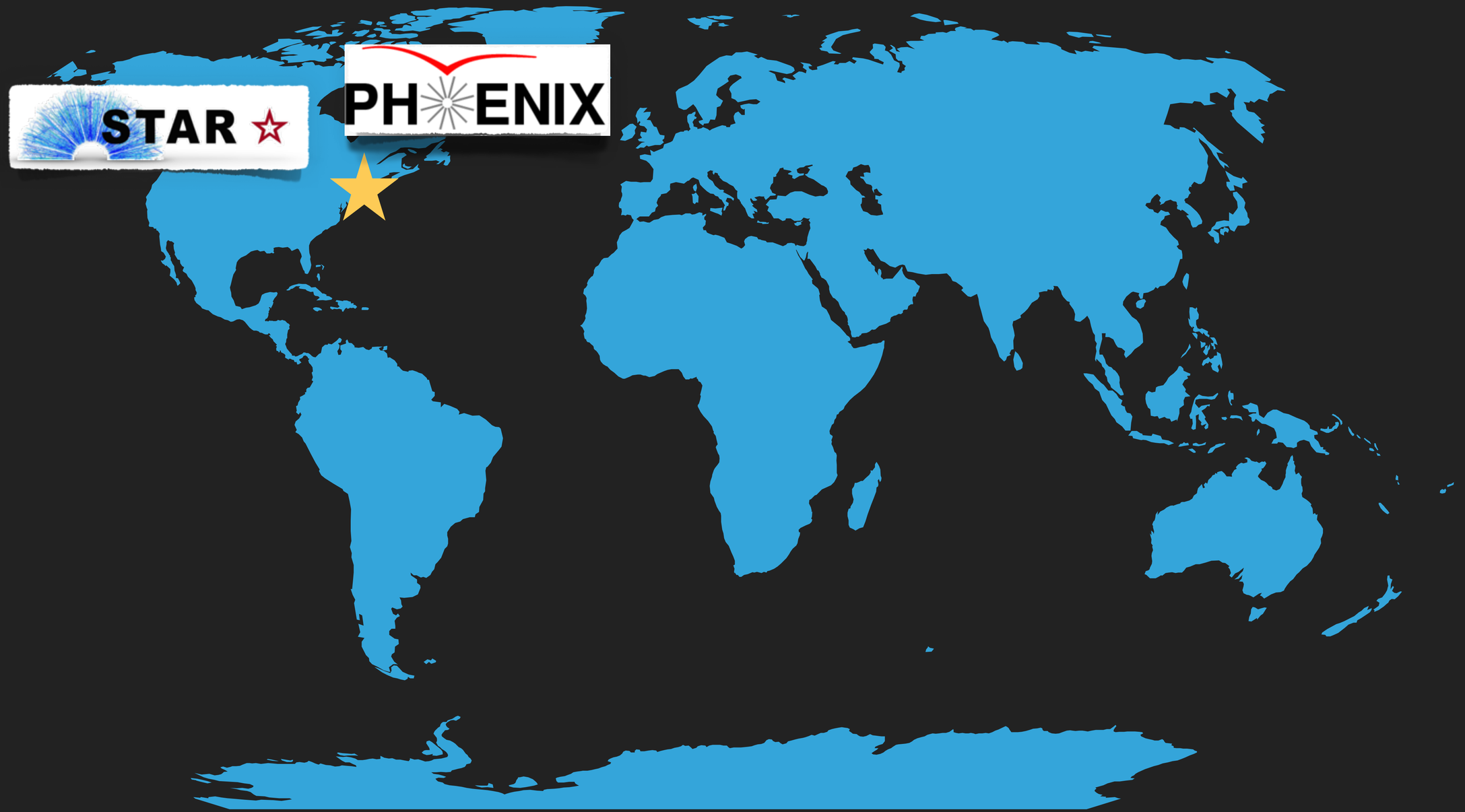
LHC

TOP RHIC

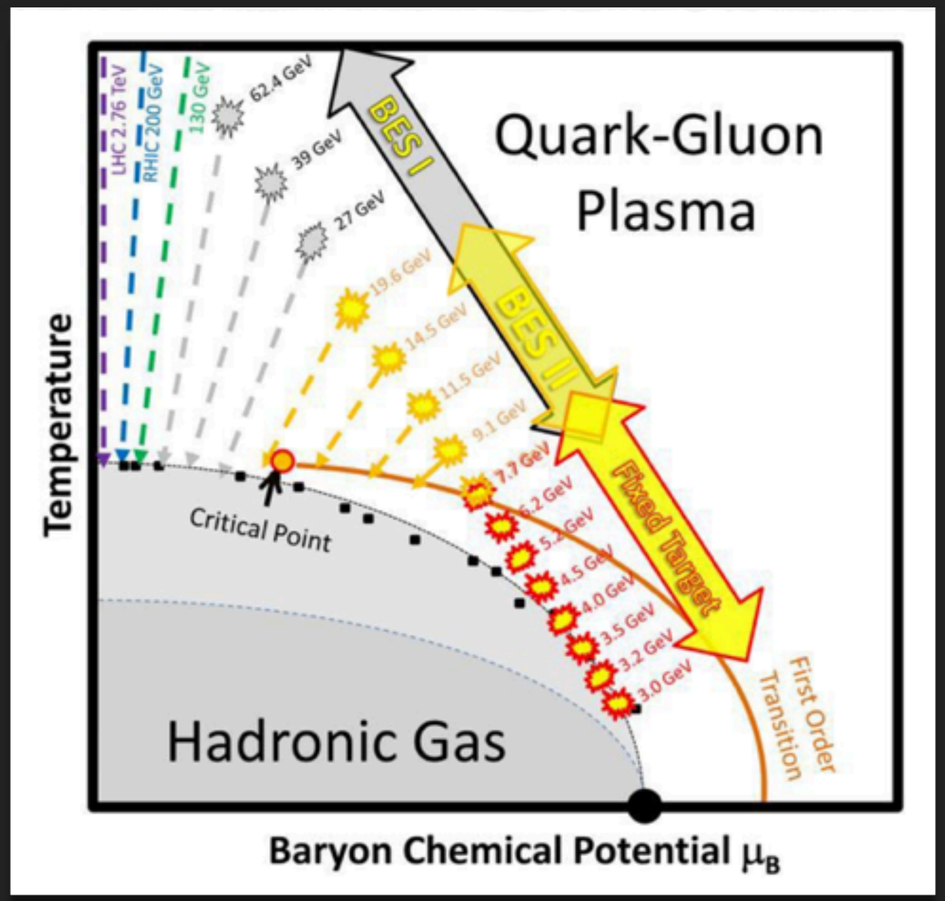


net-baryon density

EXPERIMENTS



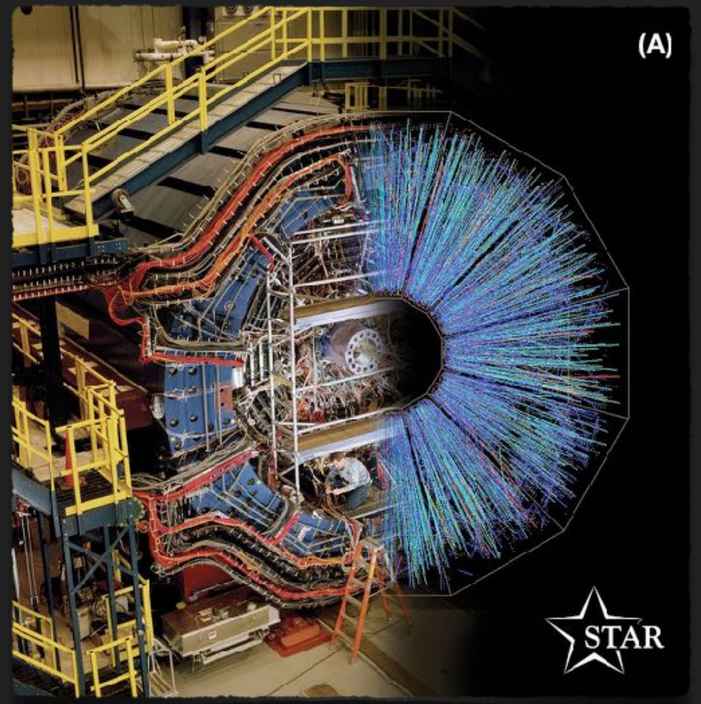
BEAM ENERGY SCAN I AND II

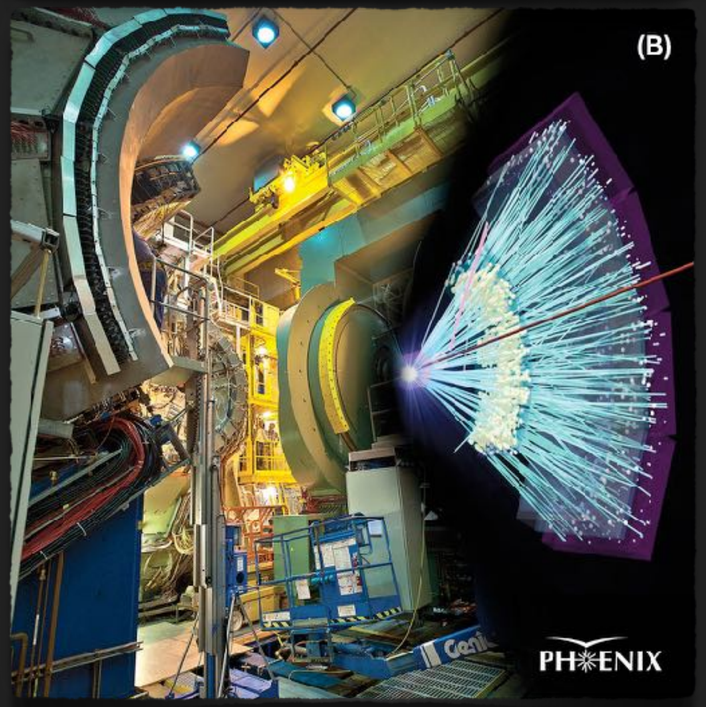


Goals of the Beam Energy Scan Program:

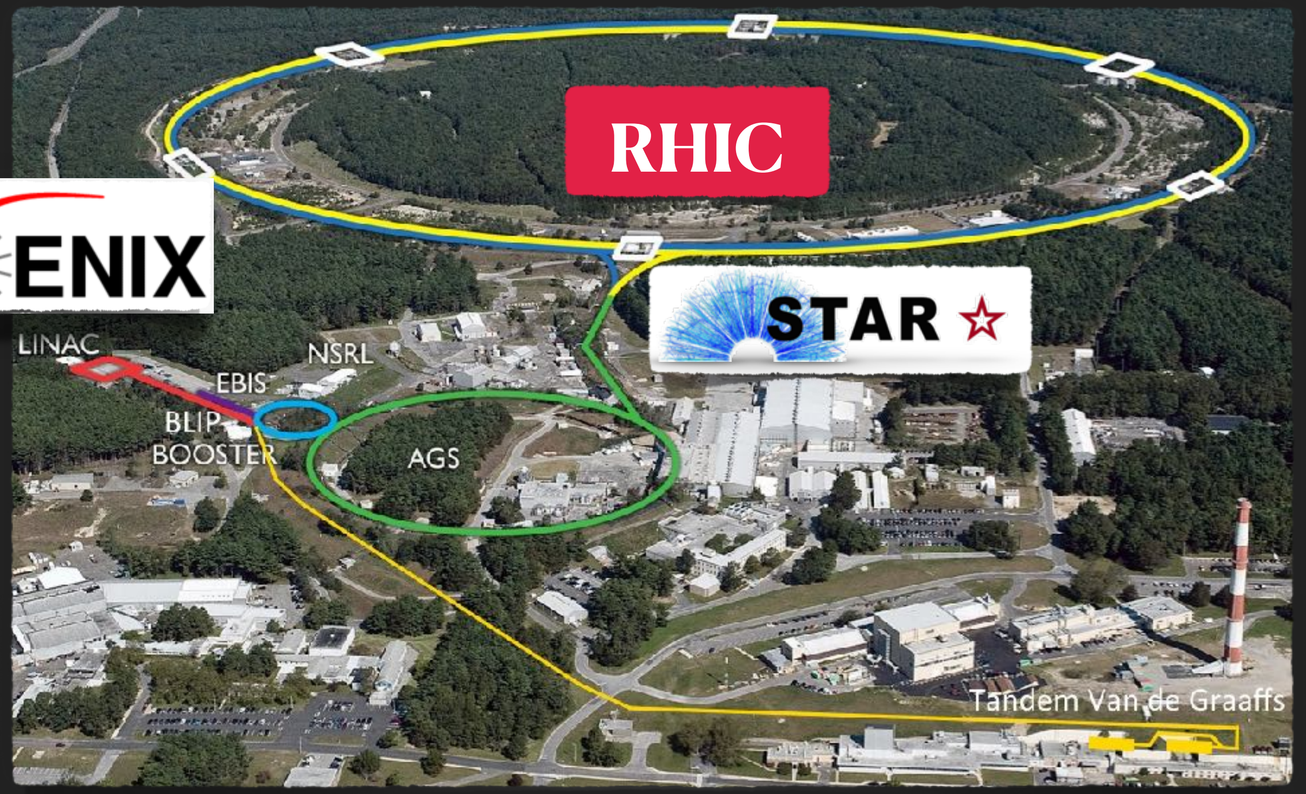
- Search for turn-off of QGP signatures
- Search for signals of the first-order phase transition
- Search for QCD critical point

EXPERIMENTS



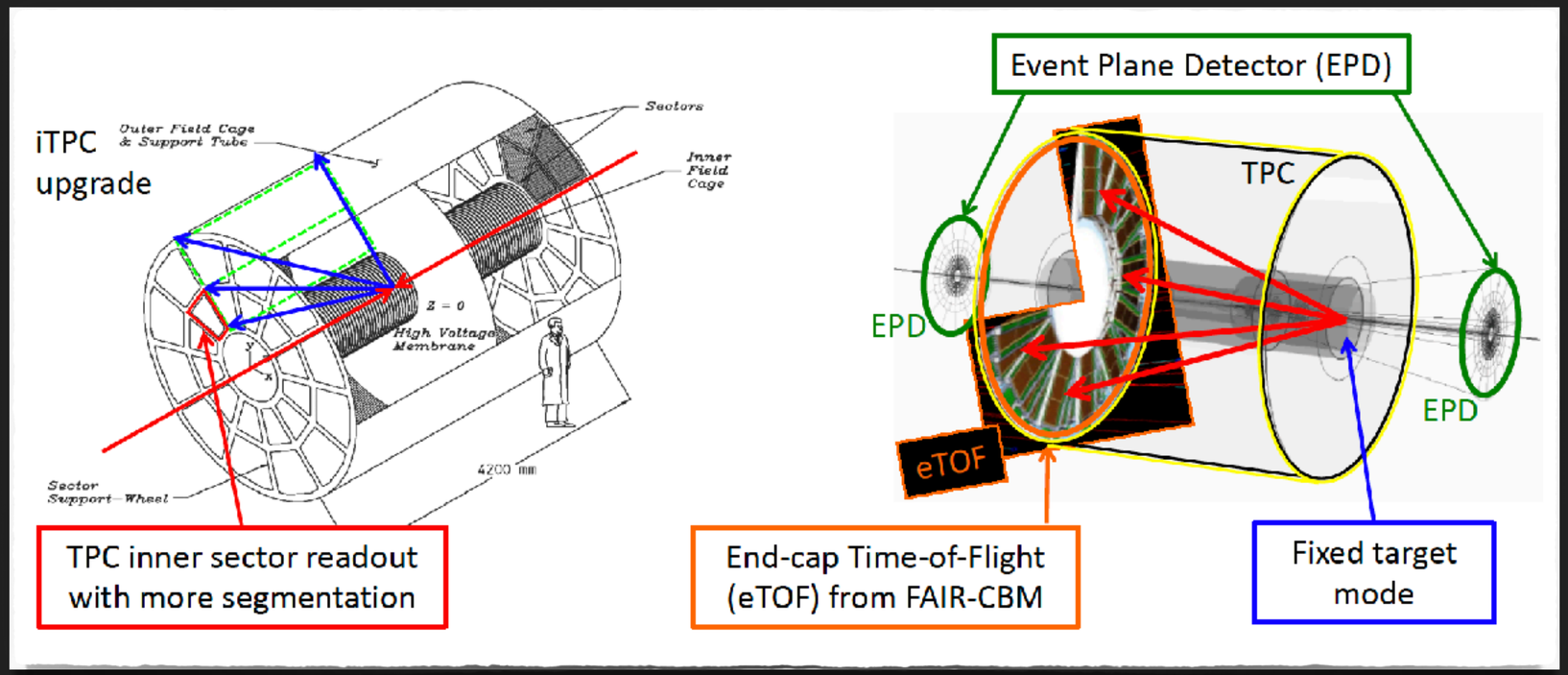


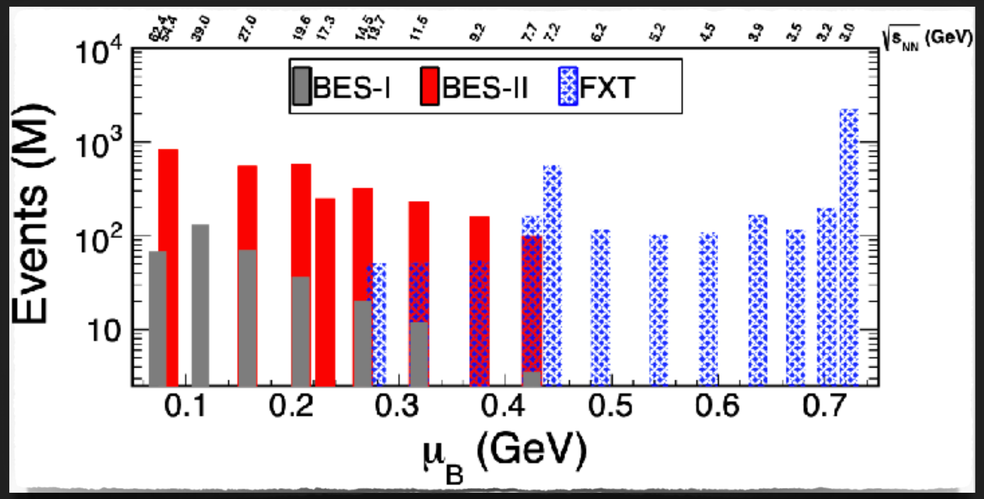
PHENIX



https://science.osti.gov/np/Facilities/User-Facilities/RHIC

STAR DETECTOR SYSTEM





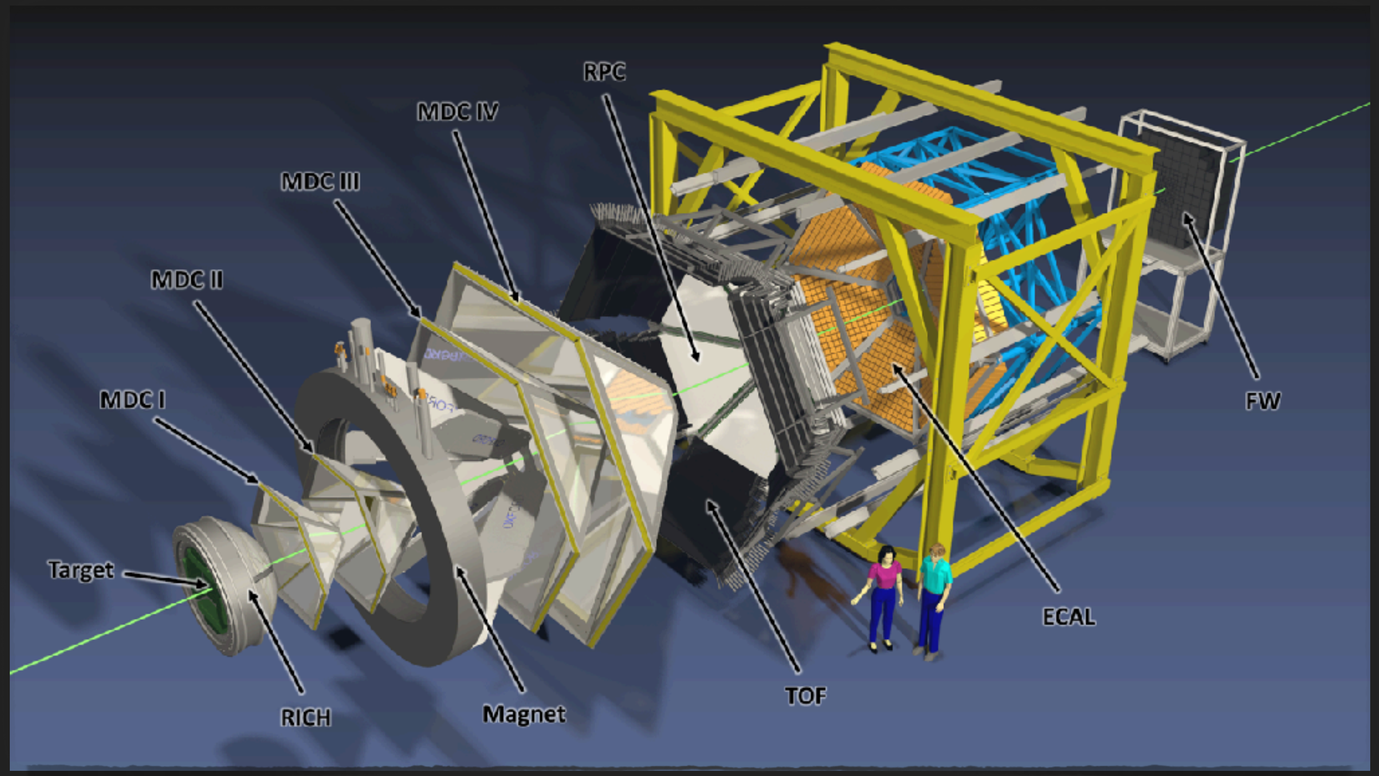
- **Solenoidal Tracker At RHIC originally designed to search for Quark Gluon Plasma.**
- *BES program started at 2010.*
- *Luminosity of the RHIC collider-mode is unusable for $\sqrt{s_{NN}}$<7.7 GeV.*
- *Fixed-target (FXT) program extends the collision energy and μ_B coverage.*

H. Zbroszczyk: QM 2022

EXPERIMENTS



HADES DETECTOR SYSTEM



- **High Acceptance Di-Electron Spectrometer**
- *Fixed target setup provides higher interaction probability than in the collider mode*

Two main scientific goals:

1) Heavy-ion collisions at $\sqrt{s_{NN}}$ = 2-2.4 GeV:

- *Microscopic properties of baryon dominated matter*
- *Equation-of-State*

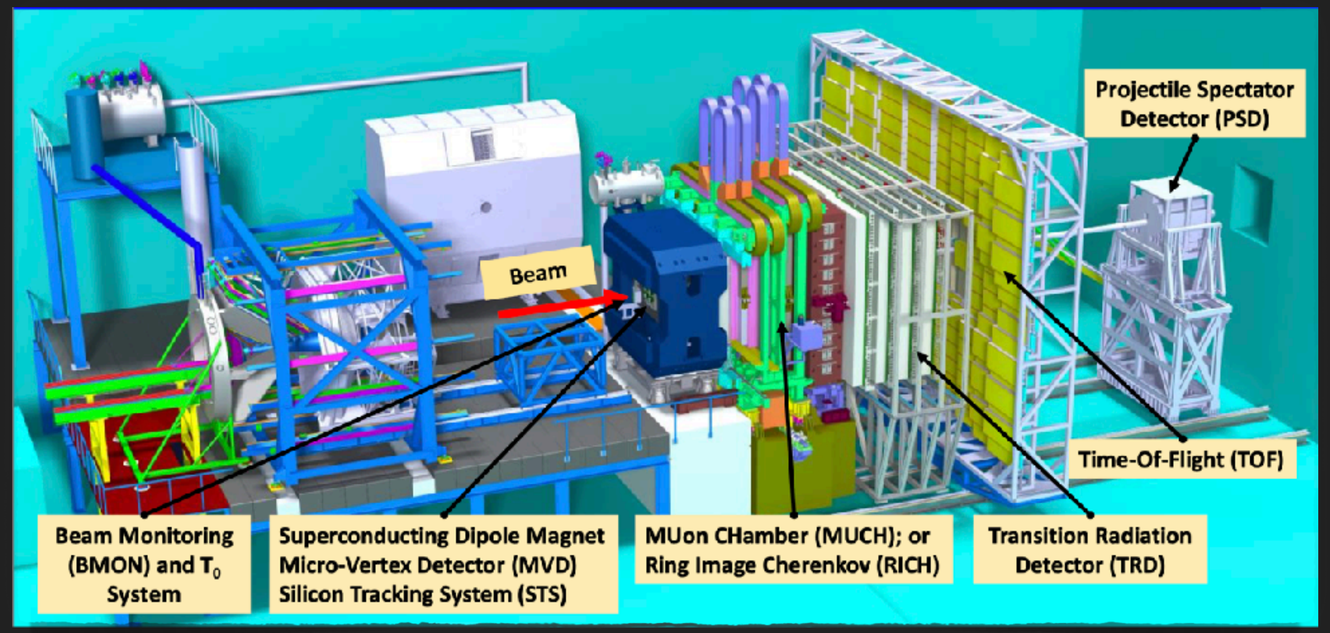
2) Pion and nucleon beams:

- *Reference measurements (vacuum, cold QCD matter)*
- *Electromagnetic structure of baryons and hyperons*

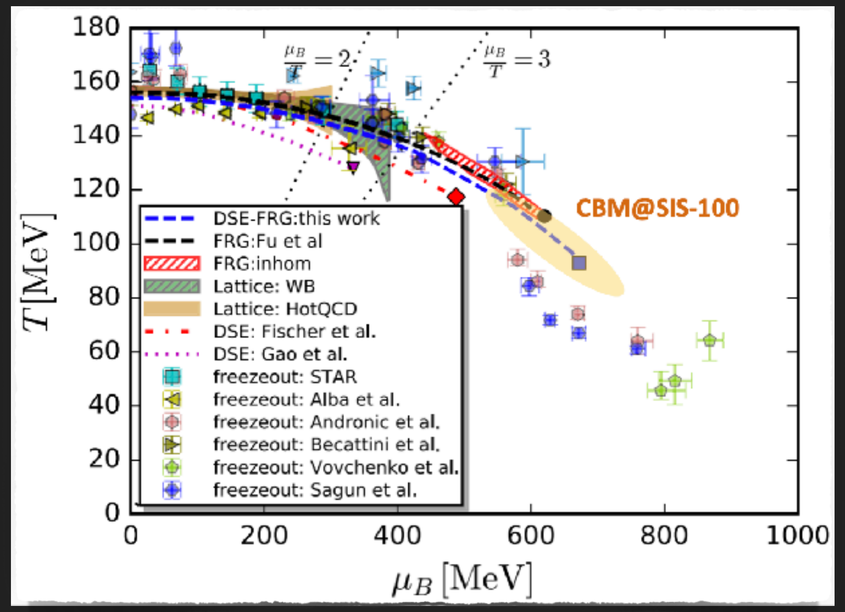
Sz. Harabasz: QM 2022

FUTURE CBM DETECTOR SYSTEM

✱ Compressed Baryonic Matter



F. Gao, J.M. Pawlowski, Phys.Rev.D 102 (2020) 3, 034027



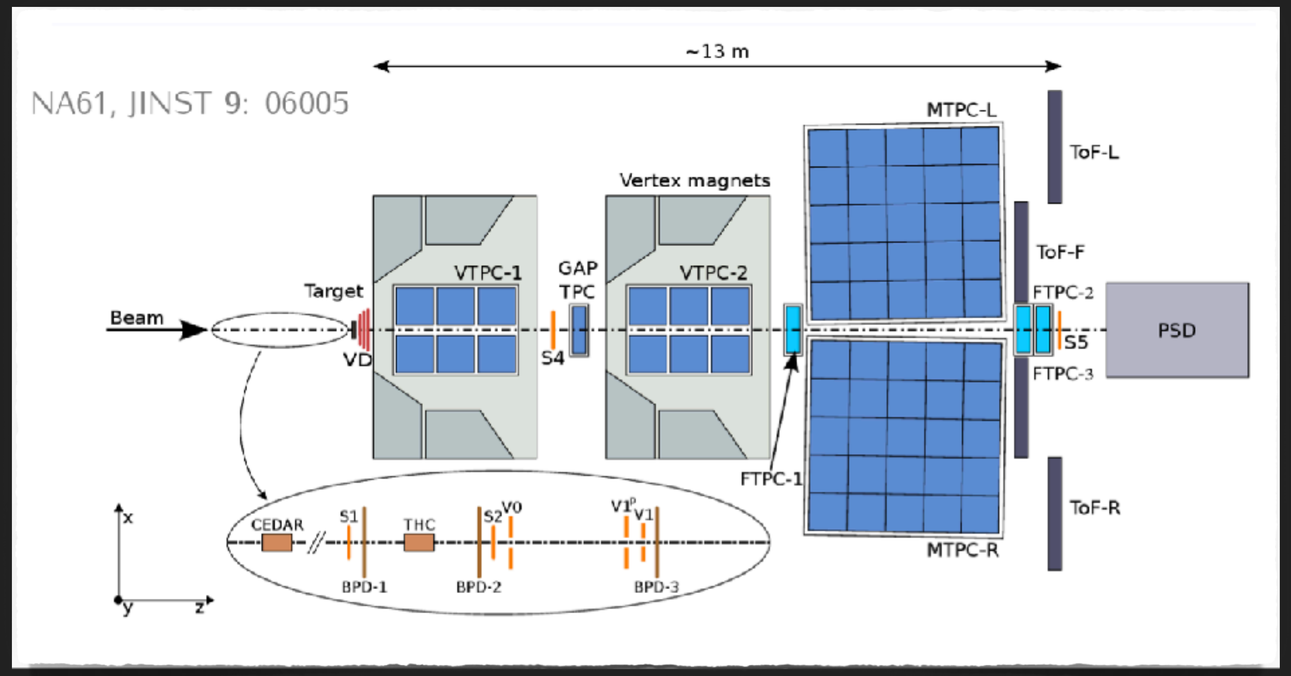
The CBM research program aims to decipher dense QCD matter properties:
Microscopic (CBM) + Macroscopic Collisions (Astro) = New Multi-Messenger Physics

K. Agarwal: QM 2022

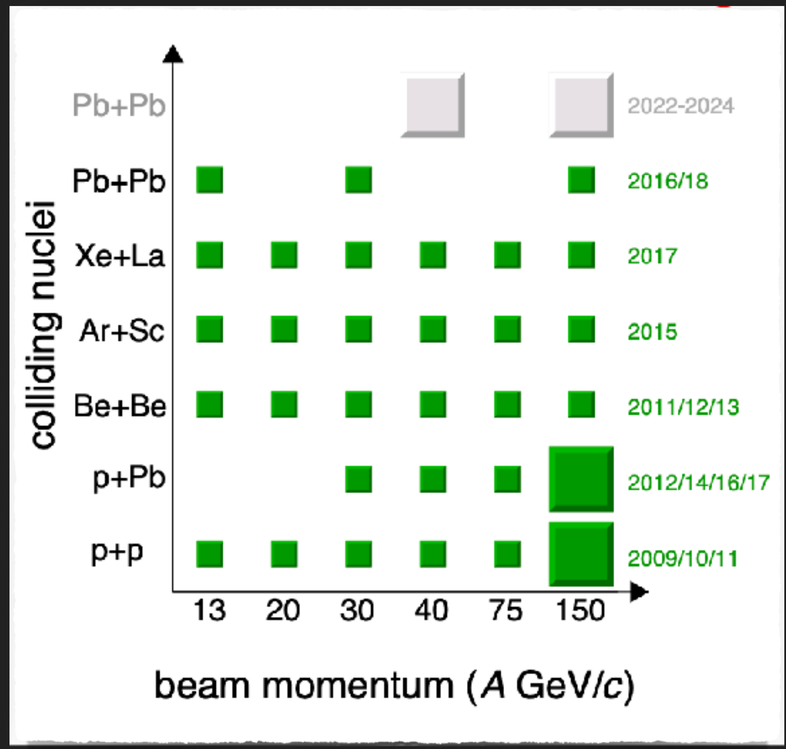
EXPERIMENTS



NA61–SHINE DETECTOR SYSTEM



- **SPS Heavy Ion and Neutrino Experiment**
- *Various collision systems*
- *$\sqrt{s_{NN}}$ = 5.1-17.3(27.4) GeV*
- *large acceptance: full forward hemisphere, down to p_T = 0*



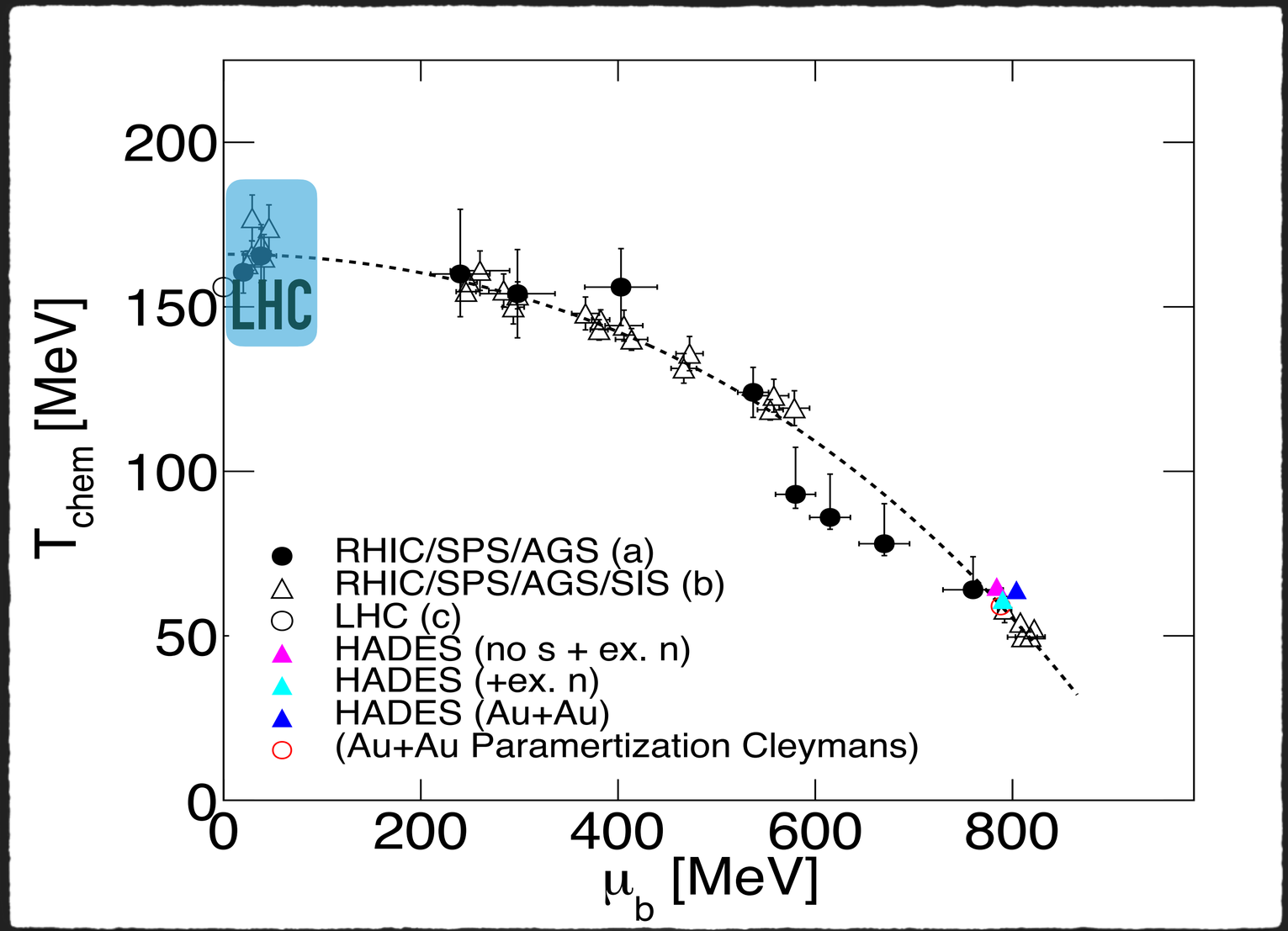
Studies of strong interactions:

- *Onset of deconfinement*
- *Search for Critical Point*

Cosmic rays and neutrinos

A. Marcinek: QM 2022

WHERE THE EXPERIMENTS „ARE"



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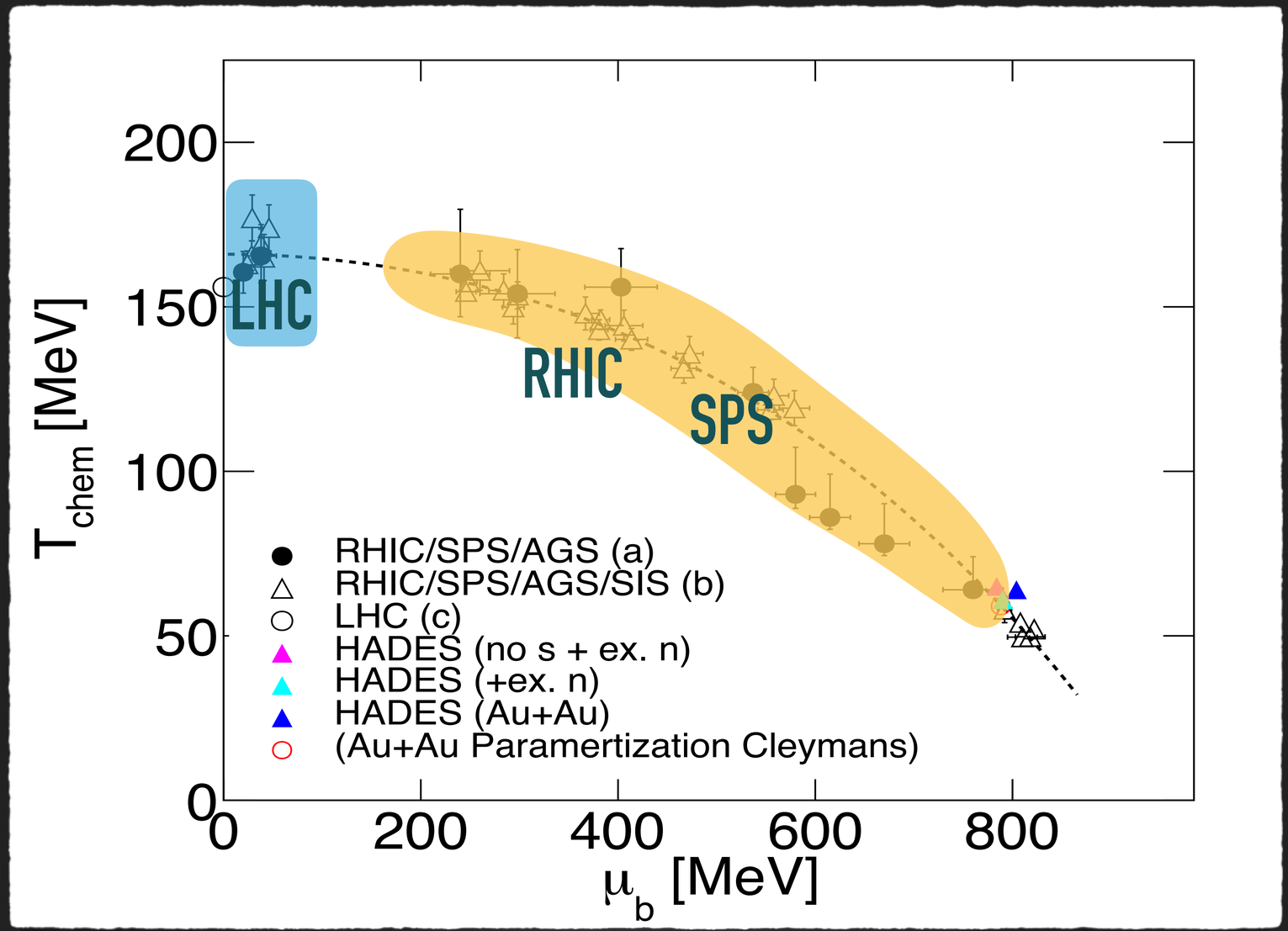

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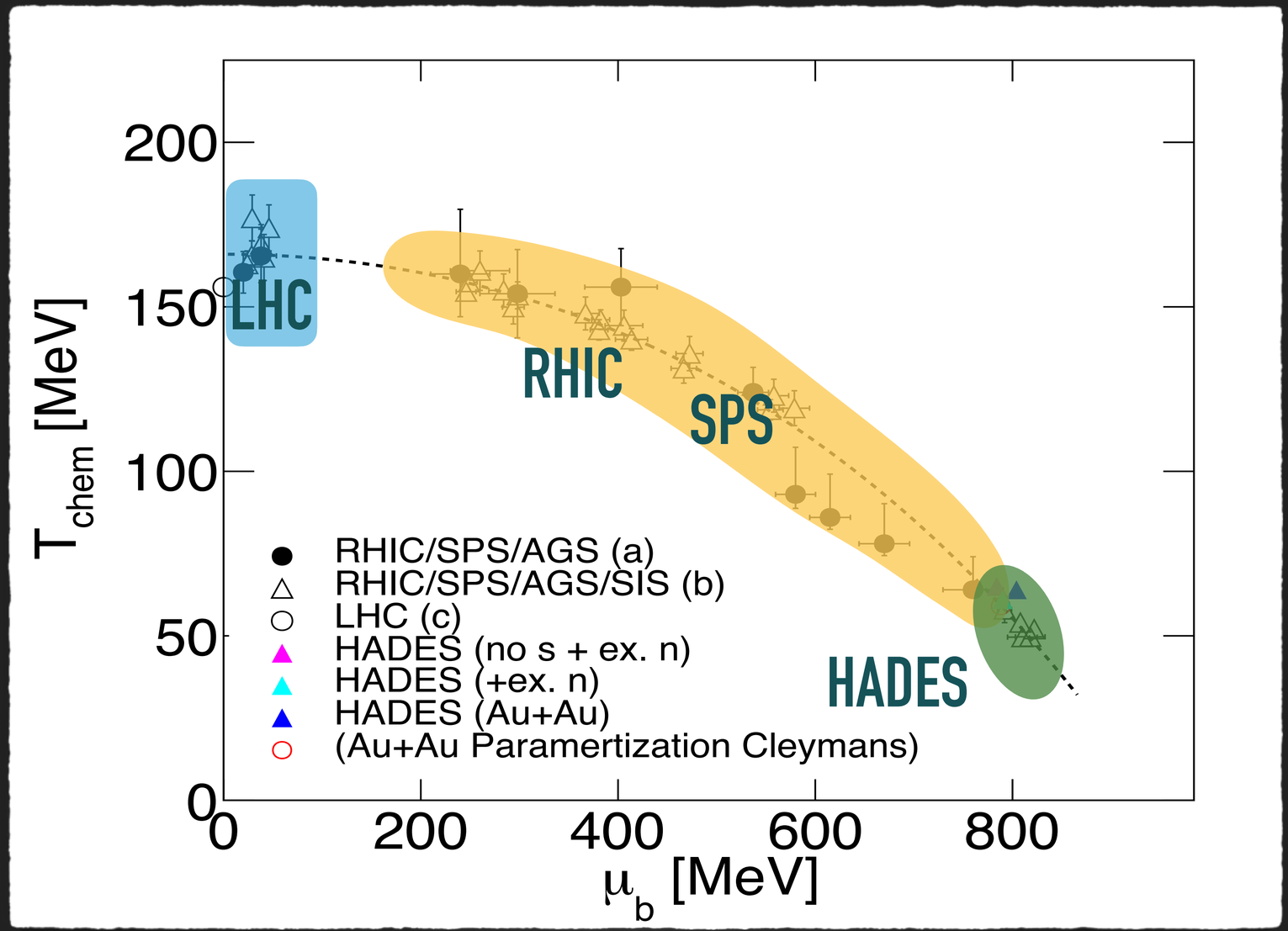
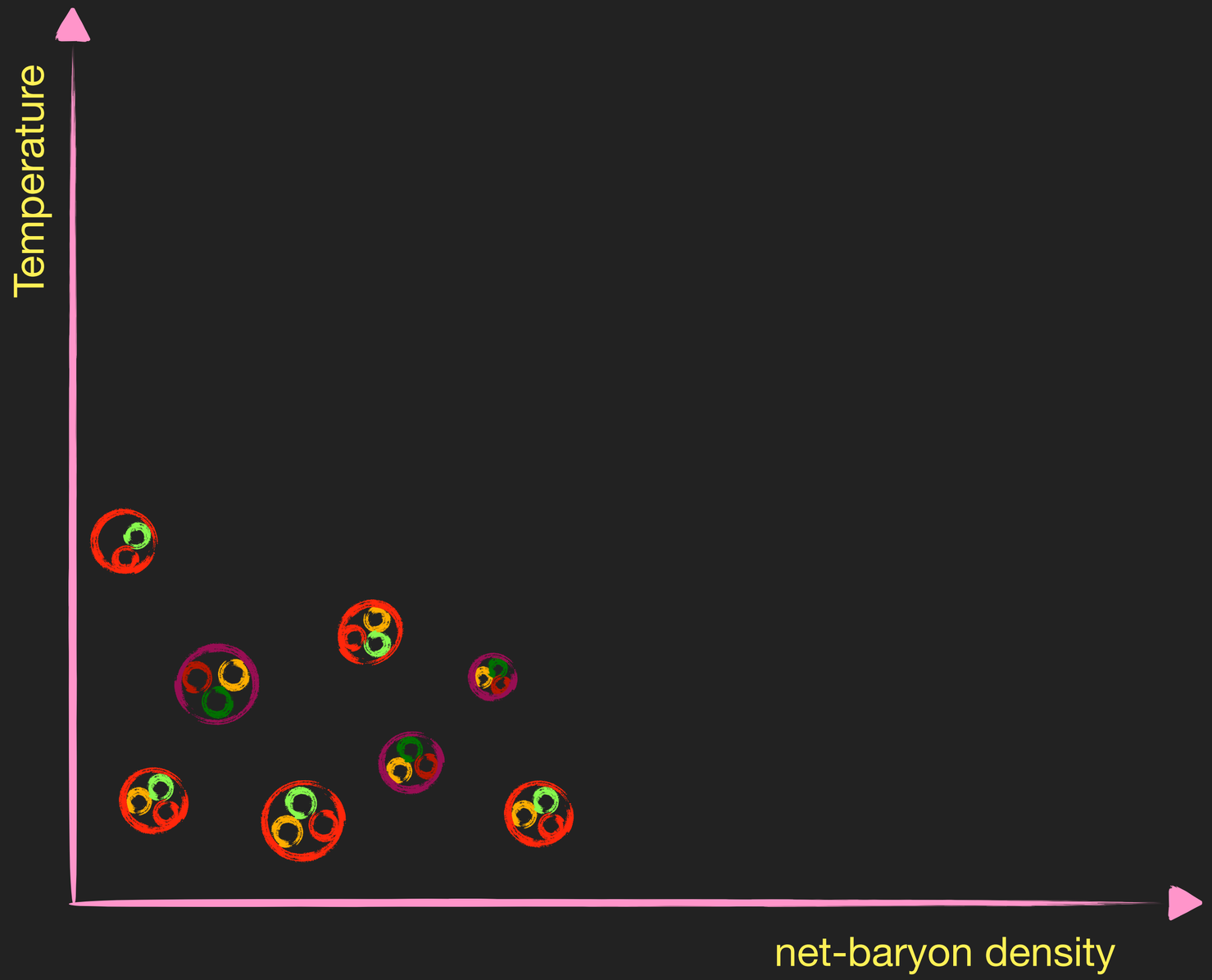


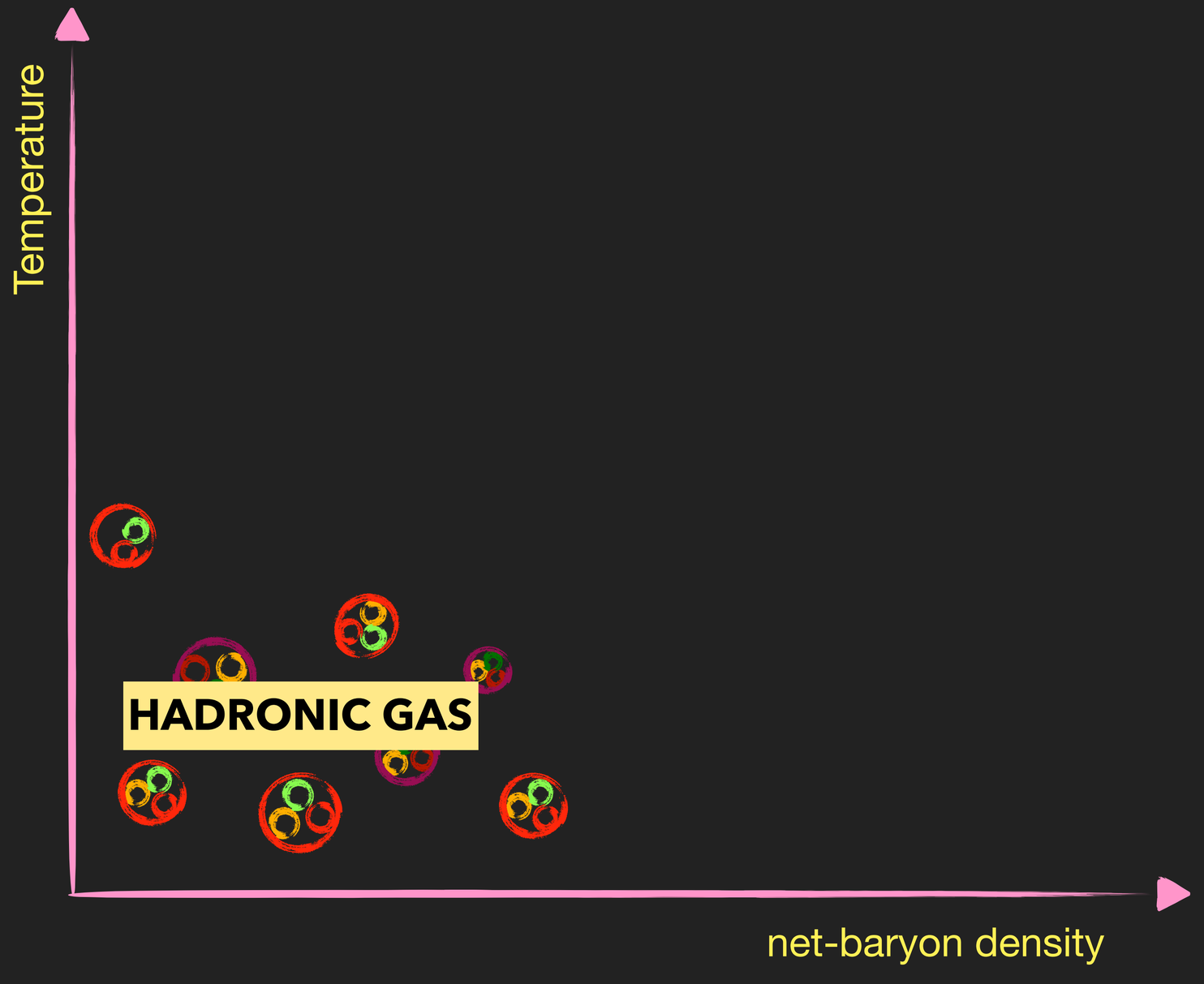
THE COLDER SOUP

WHAT WE KNOW:



THE COLDER SOUP

WHAT WE KNOW:



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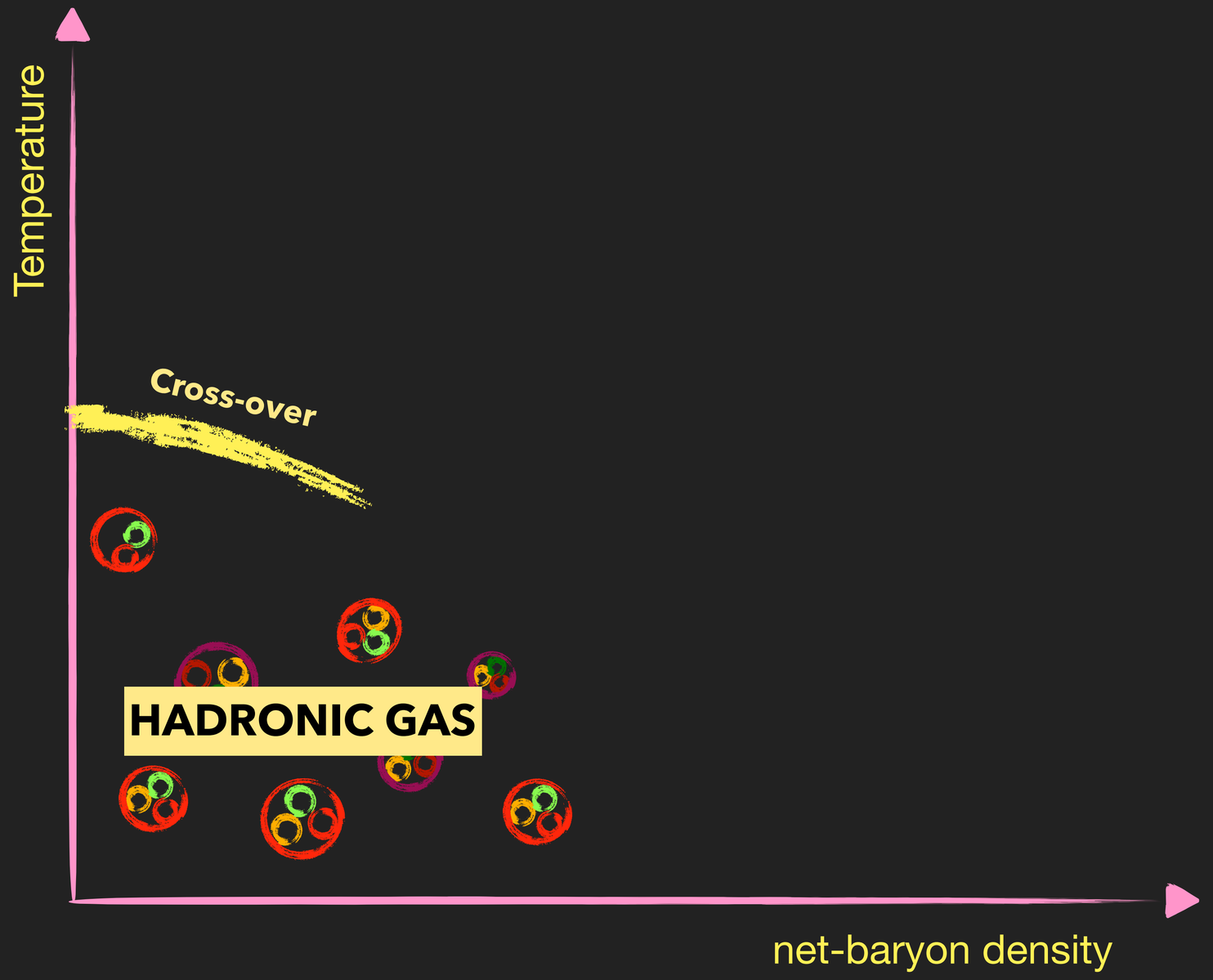
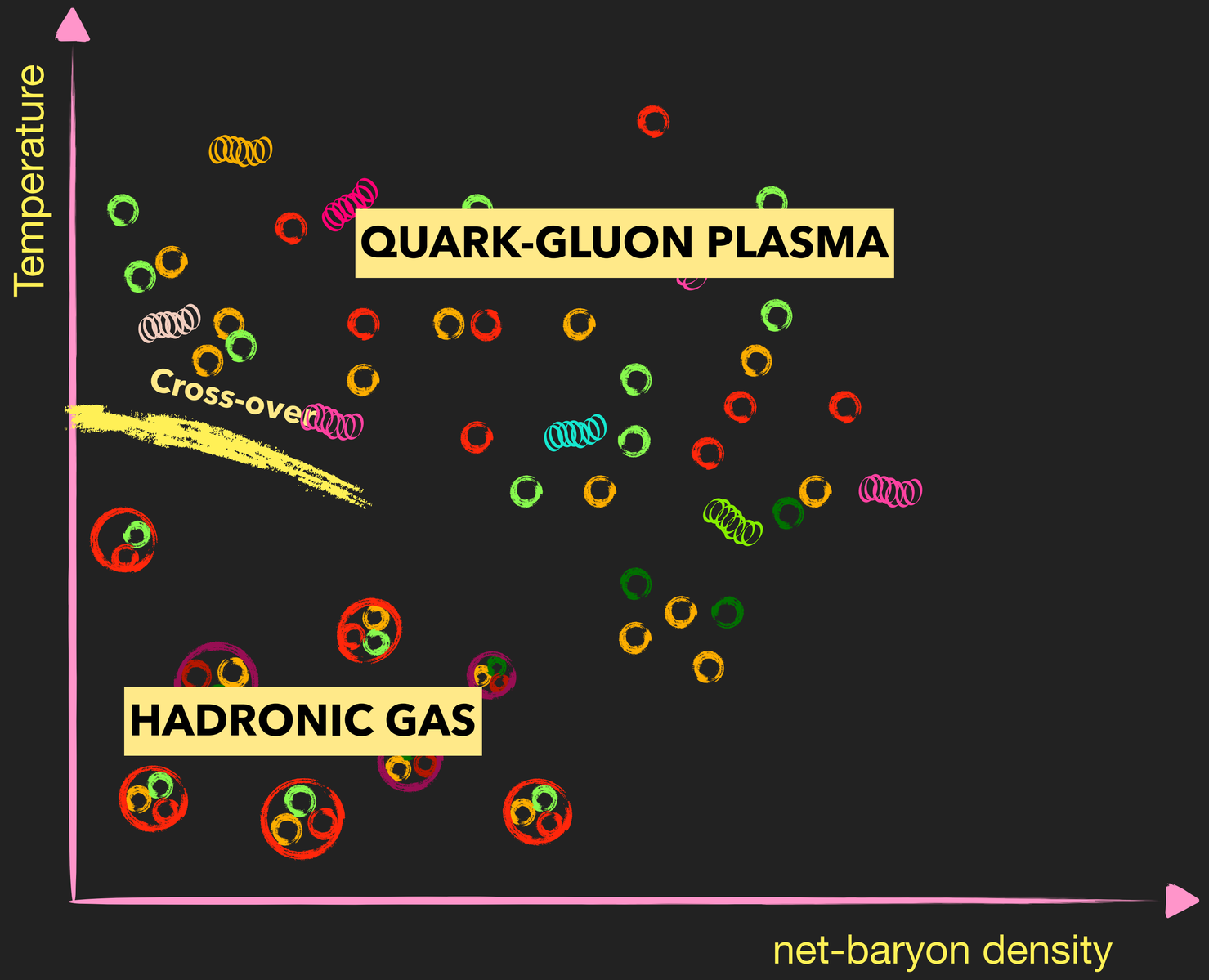


WHAT WE KNOW:

- **Lattice QCD:**
  - ✳ Cross-over transition

THE COLDER SOUP



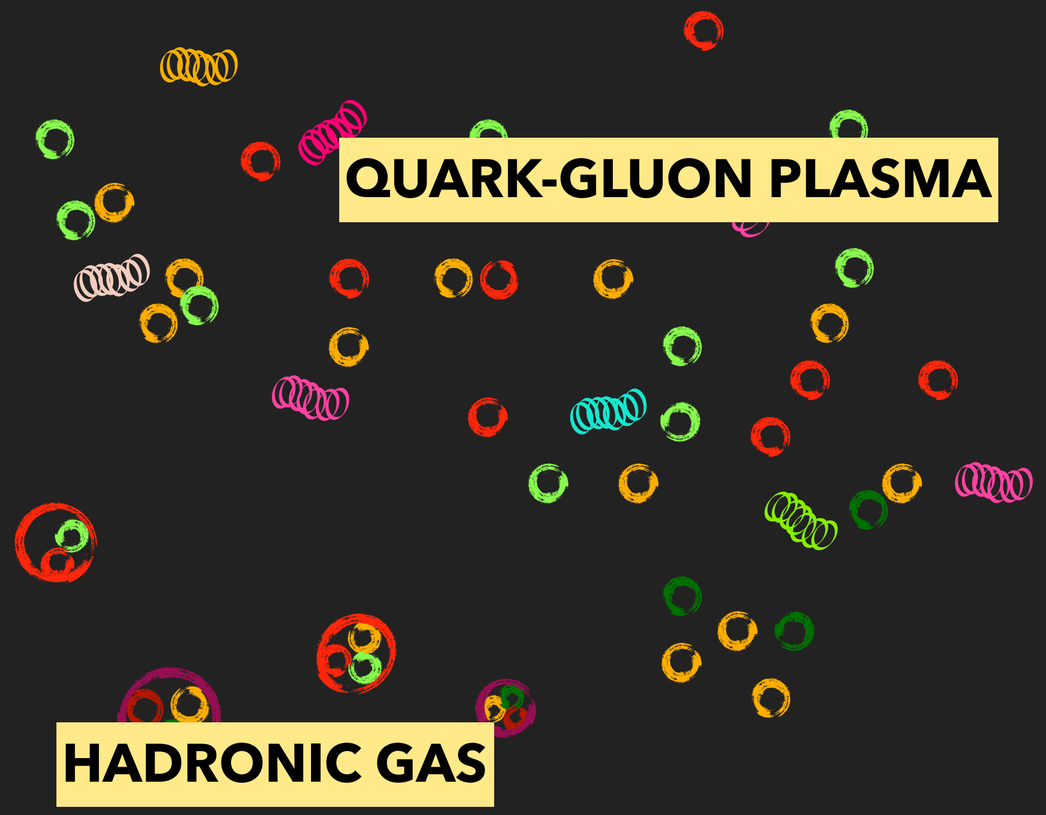
WHAT WE KNOW:

- **Lattice QCD:**
  - ✳ Cross-over transition
- **Experiment:**
  - ✳ Onset of QGP

ONSET OF QGP

Disappearance of signals of partonic degrees of freedom

- Nuclear modification factor Rcp
- Charge separation w.r.t. EP
- NCQ scaling of elliptic flow

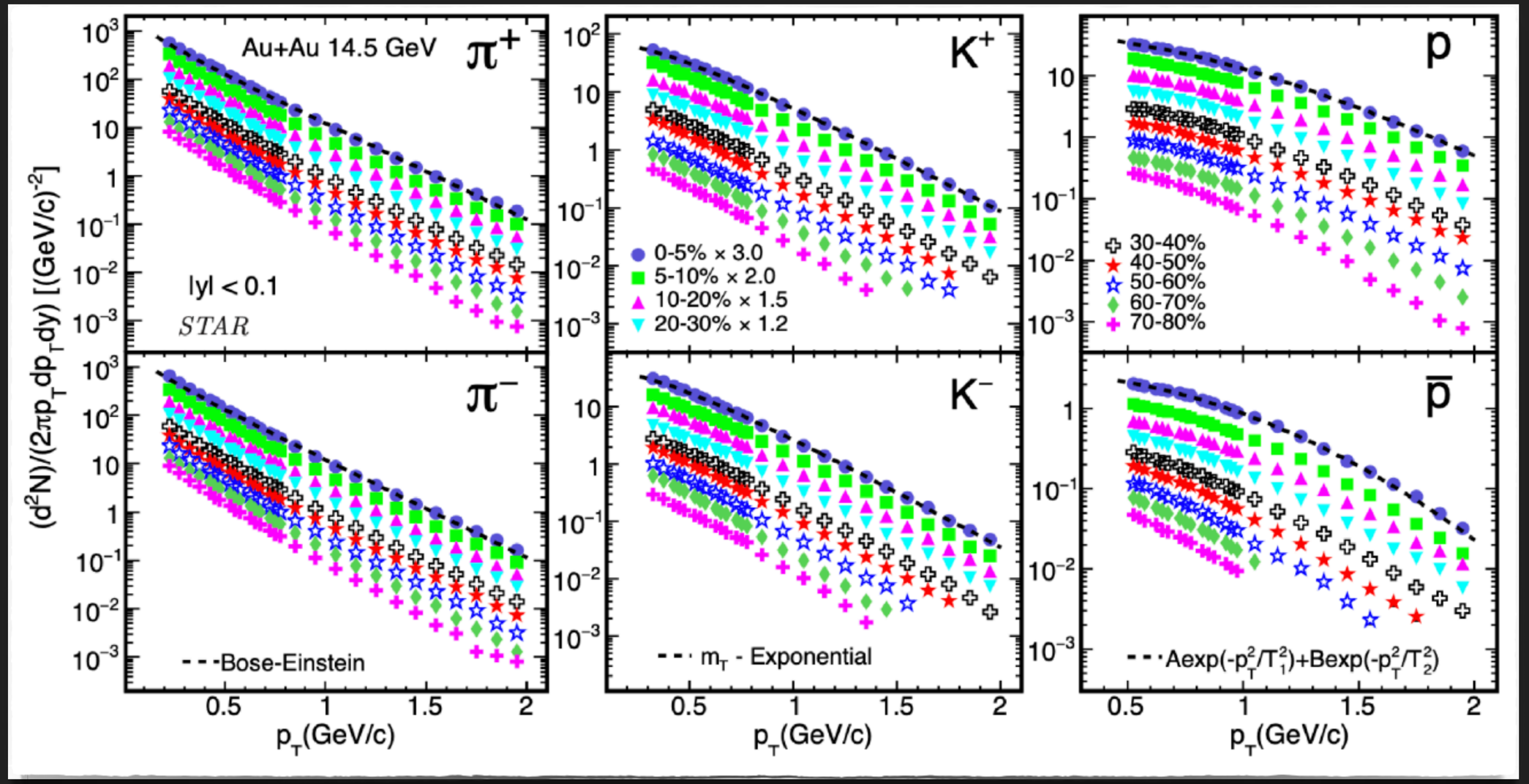


ONSET OF QGP

Transverse momentum spectra

$$p_T = \sqrt{p_x^2 + p_y^2}$$

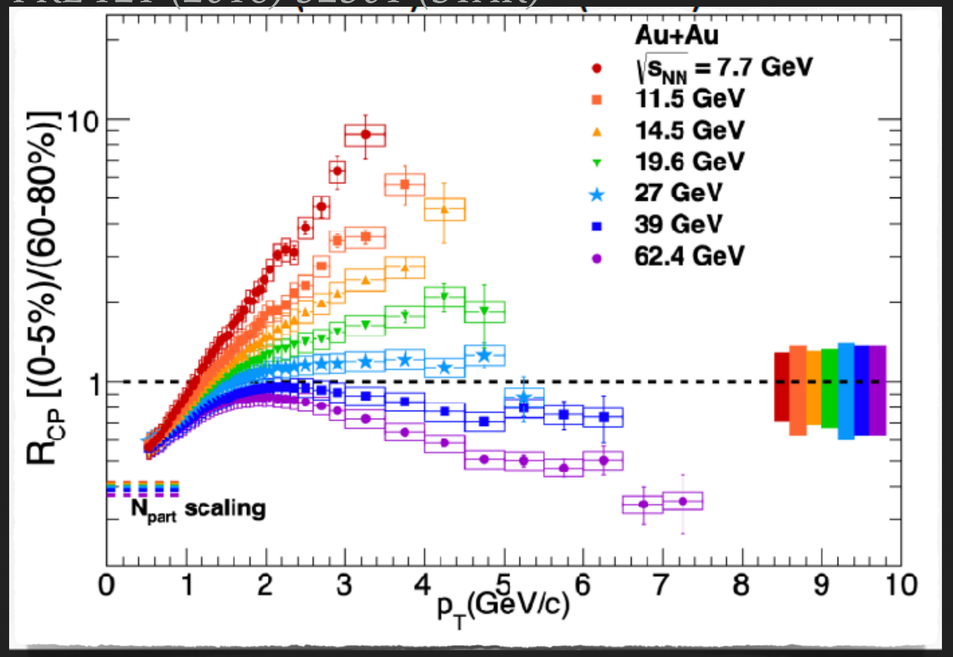
STAR: PHYSICAL REVIEW C 101, 024905 (2020)



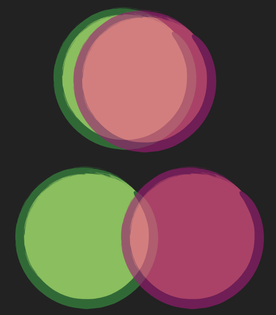
ONSET OF QGP

Nuclear modification factor R_{cp}

PRL 121 (2018) 32301 (STAR)



$$R_{CP} = \frac{< N_{bin}^{per} > d^3N_{AA}^{cen}/d\eta d^2p_T}{< N_{bin}^{cen} > d^3N_{AA}^{per}/d\eta d^2p_T}$$



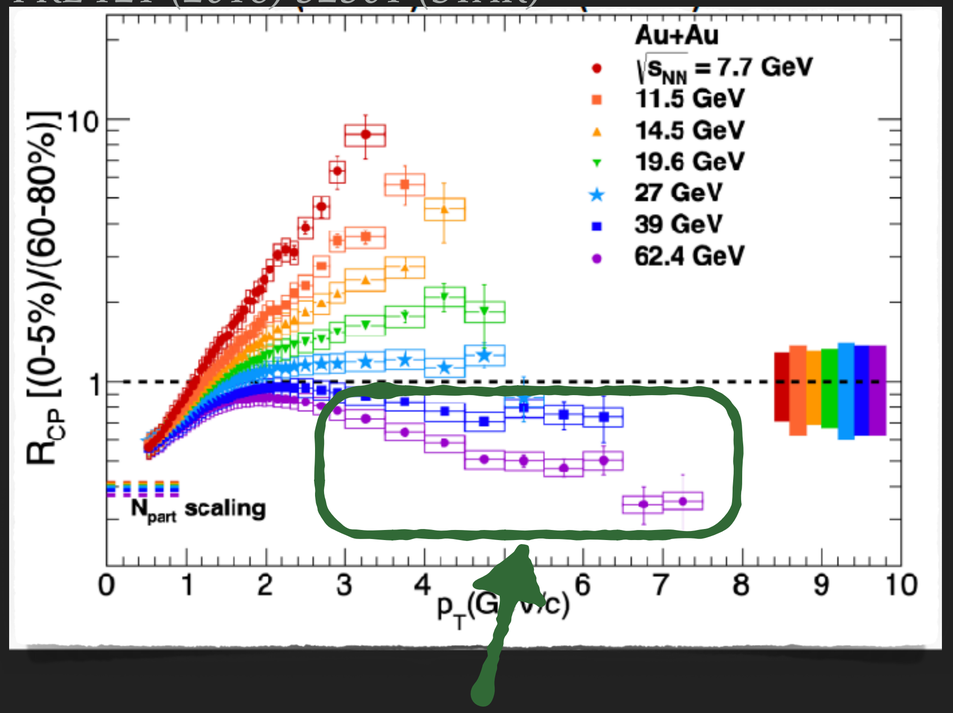
central

peripheral

ONSET OF QGP

Nuclear modification factor R_{cp}

PRL 121 (2018) 32301 (STAR)



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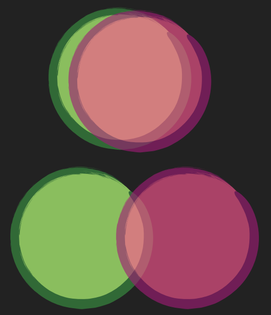


central

peripheral

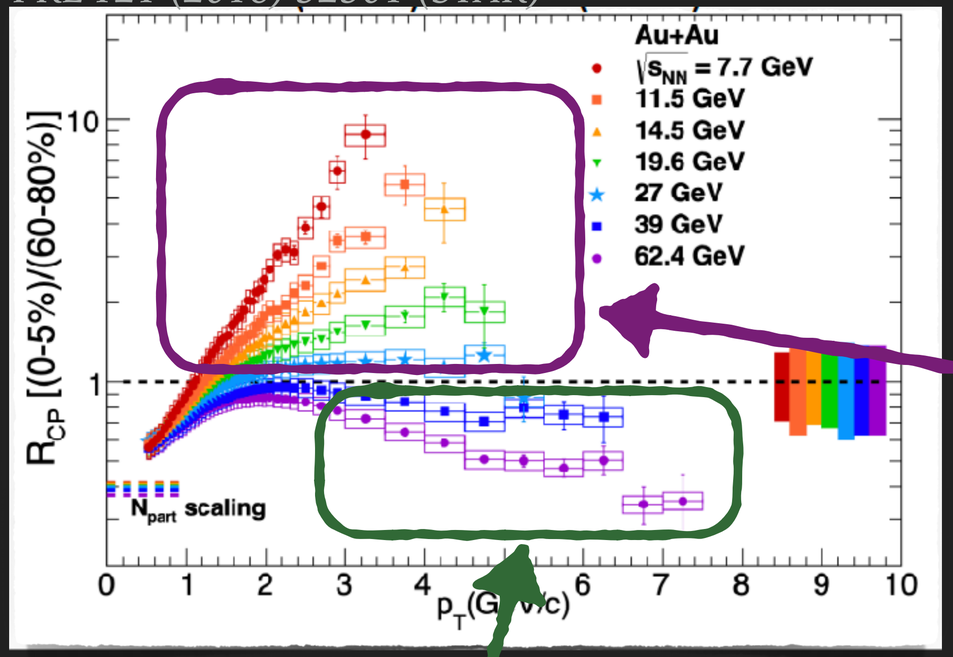
Suppression $R_{cp} < 1$:

Opacity of partonic deconfined medium

ONSET OF QGP

Nuclear modification factor R_{cp}

PRL 121 (2018) 32301 (STAR)



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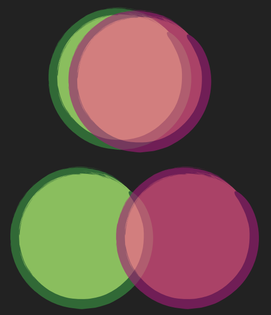


central

peripheral

Enhancement $R_{cp} > 1$:

Hadronic interactions dominate *(Cronin, cold matter effect, radial flow)*

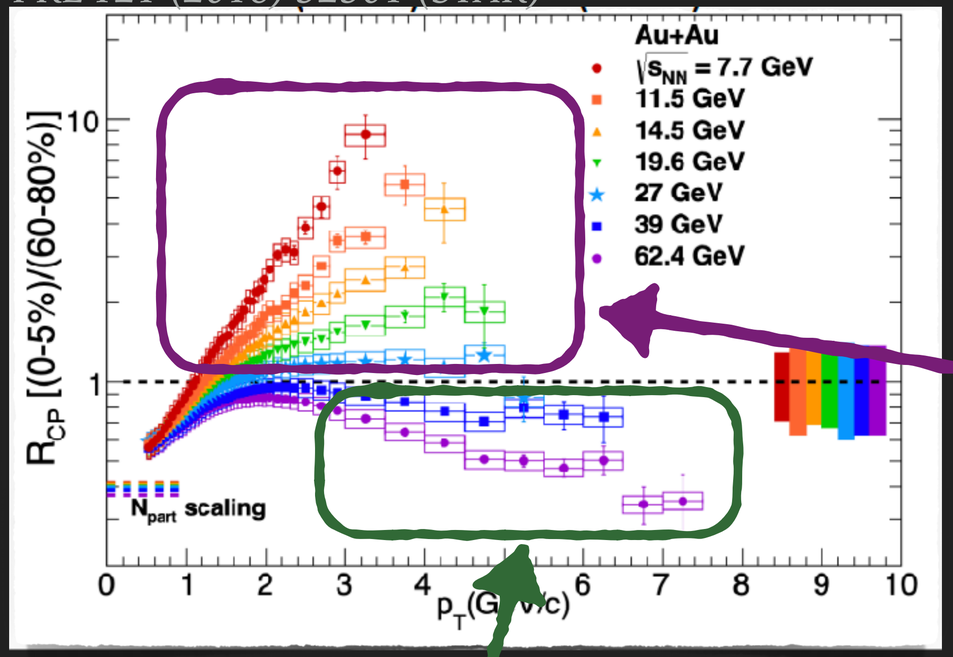
Suppression $R_{cp} < 1$:

Opacity of partonic deconfined medium

ONSET OF QGP

Nuclear modification factor R_{cp}

PRL 121 (2018) 32301 (STAR)



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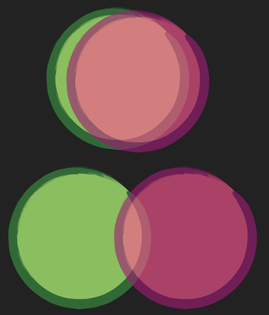

central

peripheral

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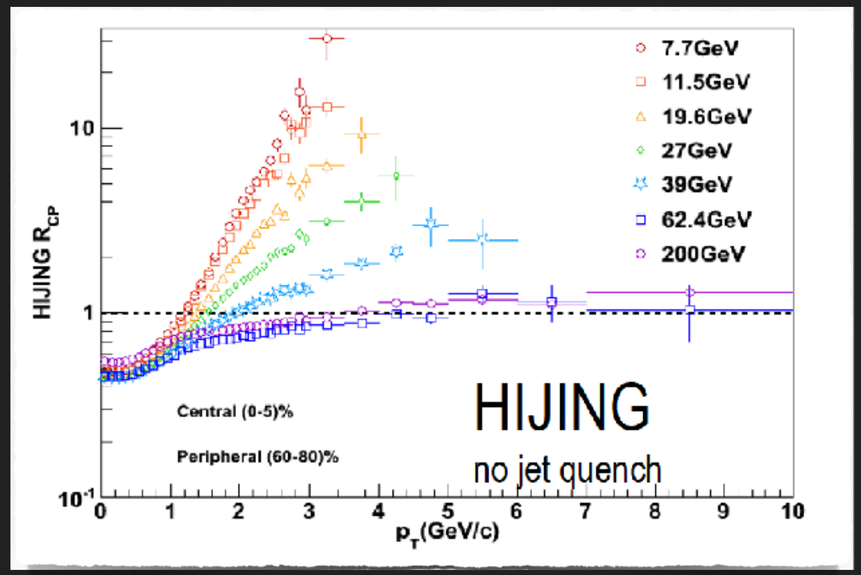
Hadronic interactions dominate *(Cronin, cold matter effect, radial flow)*

Suppression $R_{cp} < 1$:

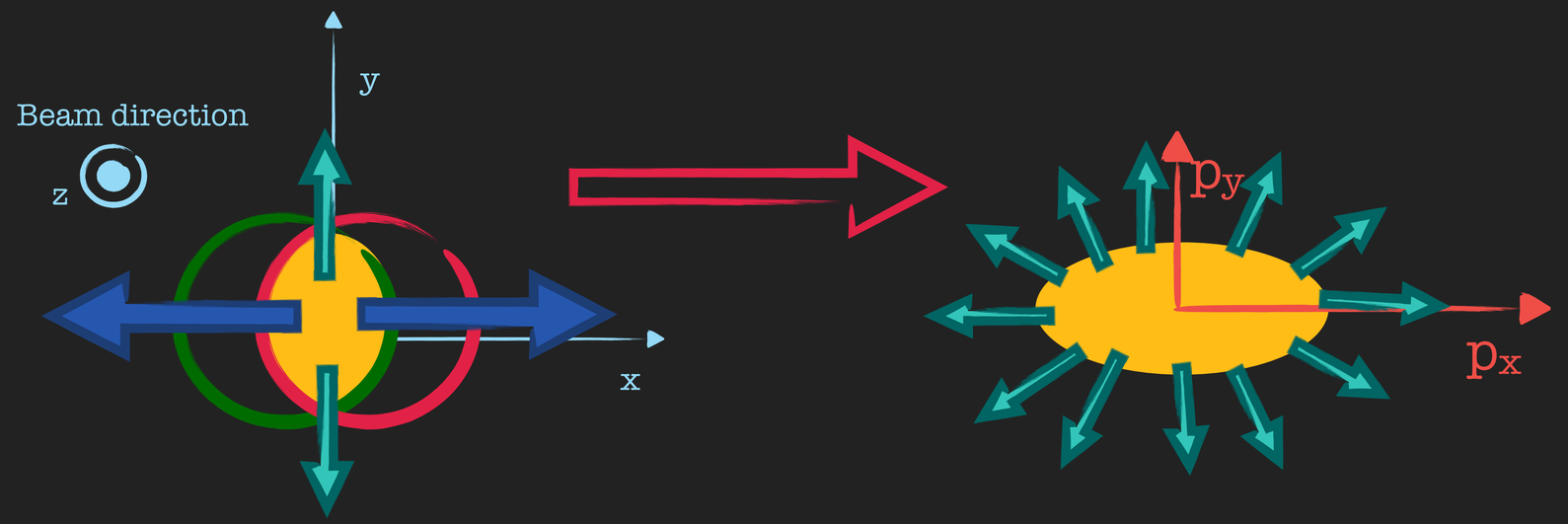
Opacity of partonic deconfined medium



HIJING (including Cronin effect) shows similar dependence like for STAR lower $\sqrt{s_{NN}}$

ONSET OF QGP

Anisotropy in the expansion of matter

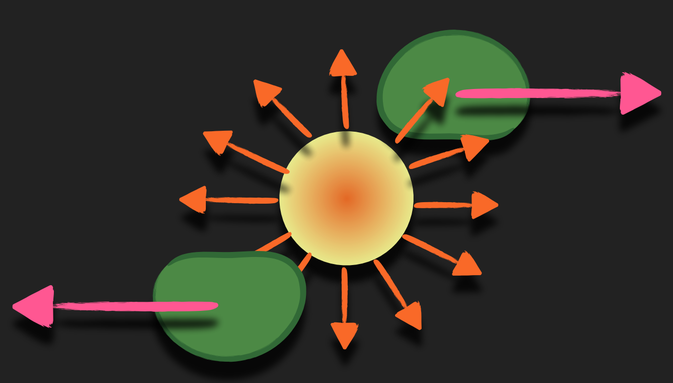


Anisotropy in initial geometry → **Final-state momentum anisotropy**

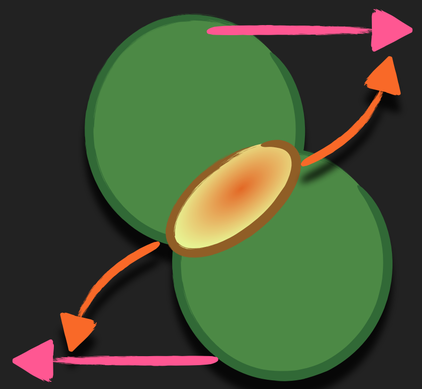
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n cos[n(\varphi - \Psi_{RP})]\right)$$

ONSET OF QGP

Anisotropy in the expansion of matter

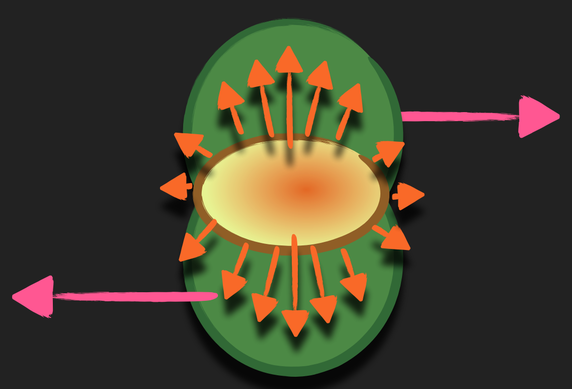


radial flow



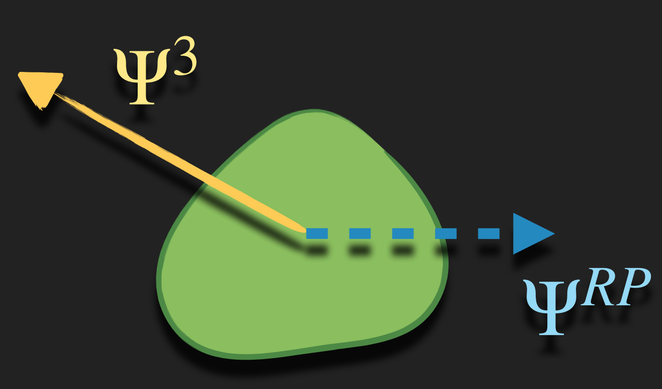
directed flow

$v_1 = \langle cos(\phi) \rangle$



elliptic flow

$v_2 = \langle cos(2\phi) \rangle$

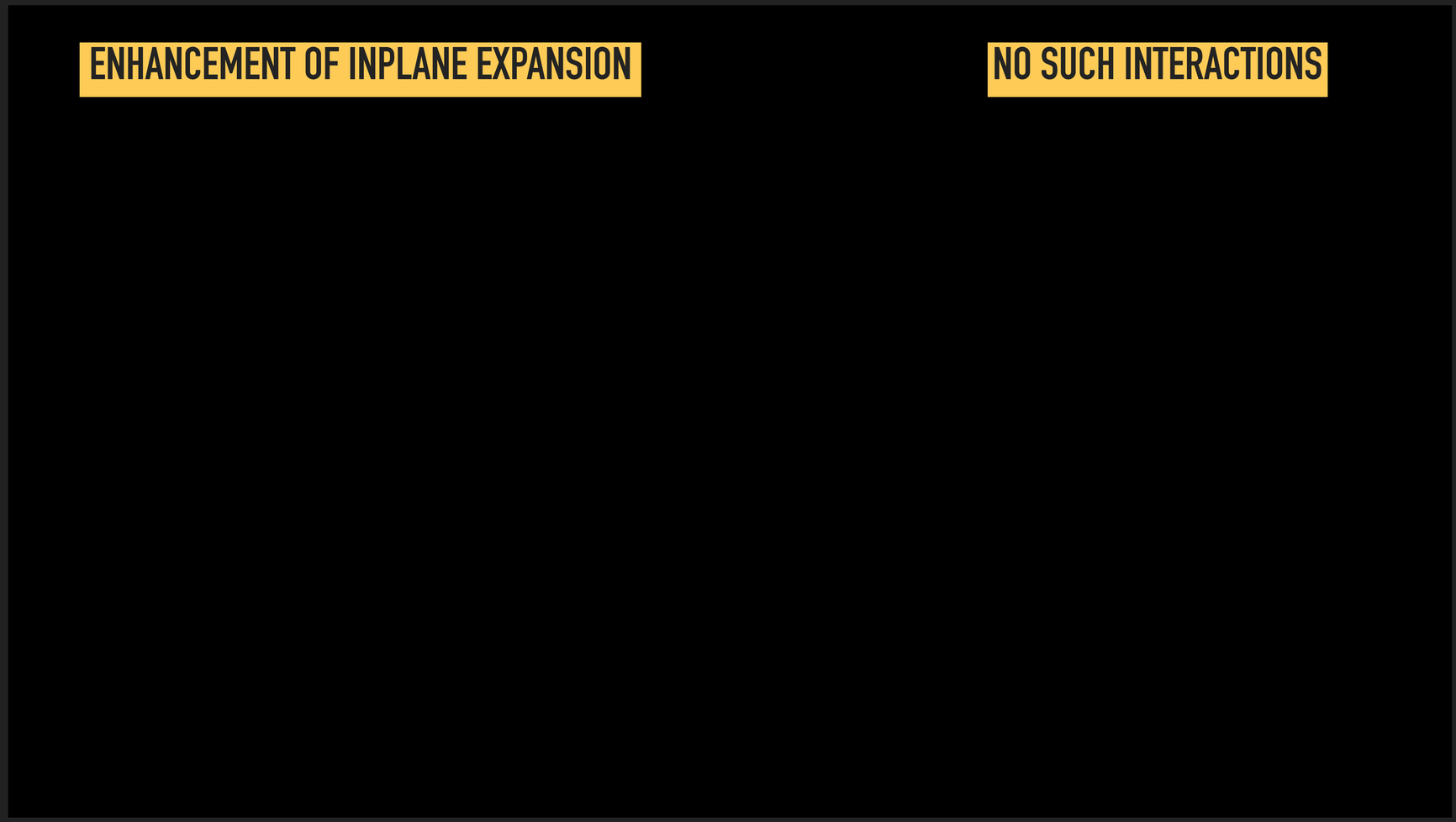


triangular flow

$v_3 = \langle cos(3\phi) \rangle$

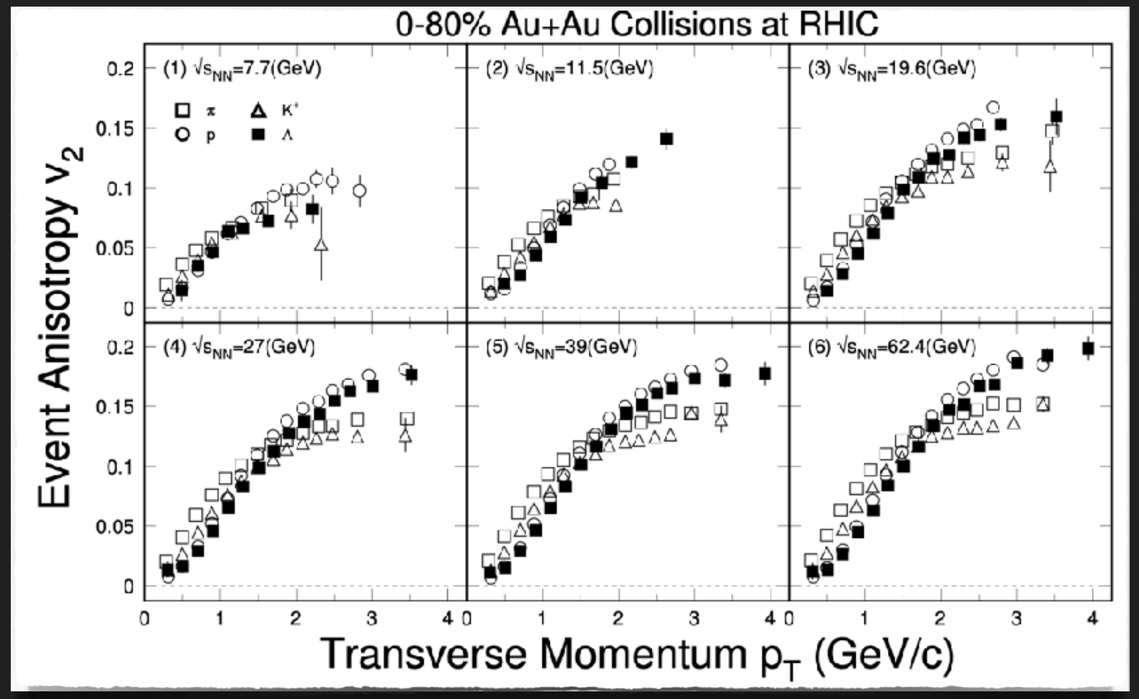
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n cos[n(\varphi - \Psi_{RP})]\right)$$

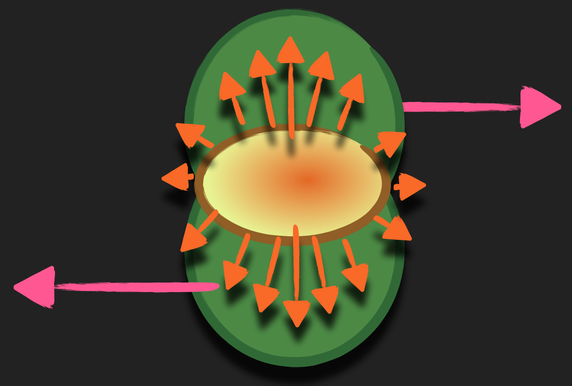
FLUID? Anisotropy in the expansion of matter



https://www.youtube.com/watch?v=xrL2ELkQOiE

ONSET OF QGP NCQ scaling of elliptic flow





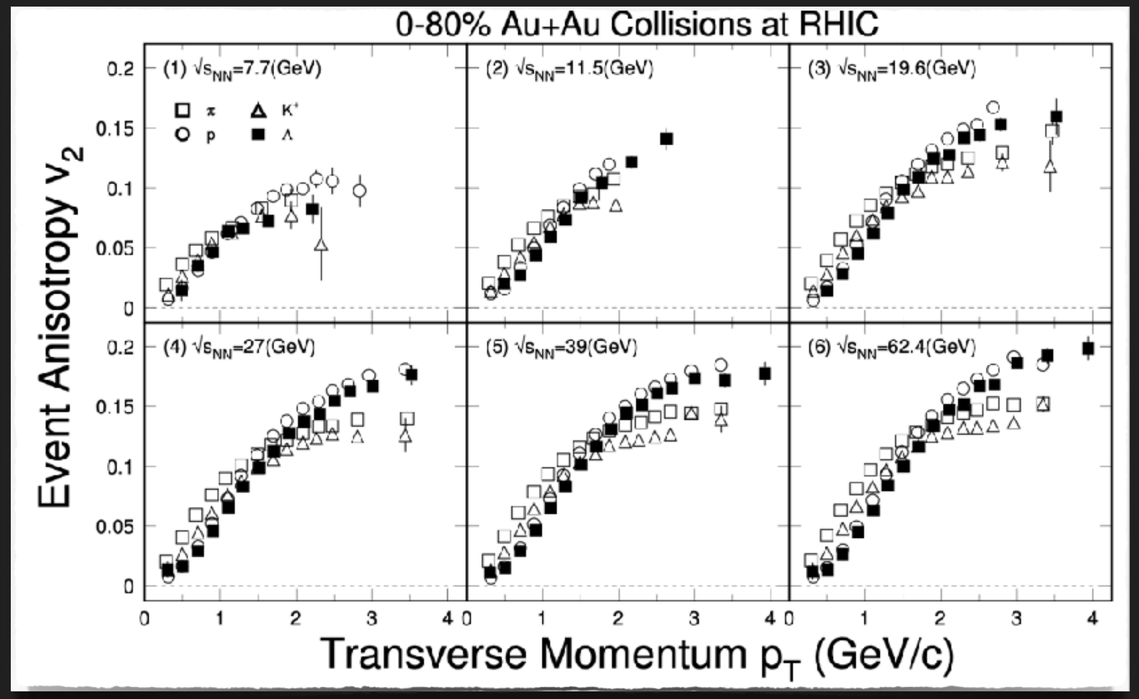
elliptic flow

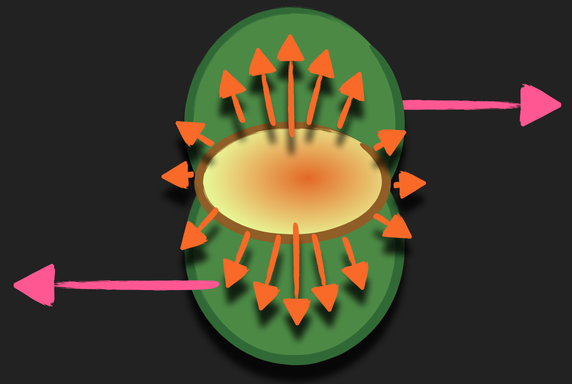
$v_2 = \langle cos(2\phi) \rangle$

STAR: PRC 88 (2013) 14902
Phys. Rev. C 93, 014907 (2016)
Phys. Rev. Lett. 116, 062301 (2016)

Mass ordering of elliptic flow

ONSET OF QGP NCQ scaling of elliptic flow





elliptic flow

$v_2 = \langle cos(2\phi) \rangle$

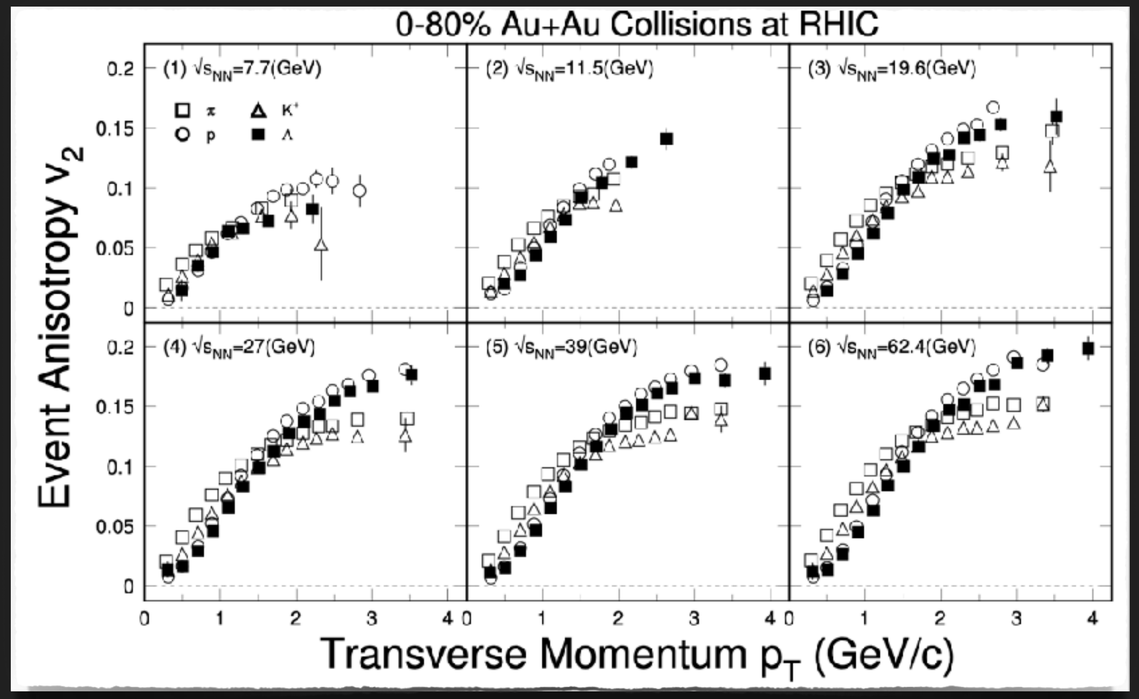
STAR: PRC 88 (2013) 14902
Phys. Rev. C 93, 014907 (2016)
Phys. Rev. Lett. 116, 062301 (2016)

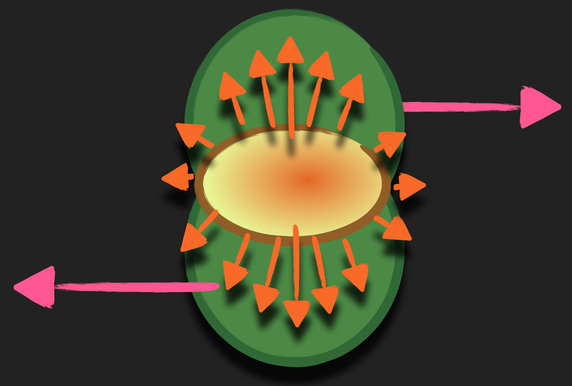
Mass ordering of elliptic flow



baryons **mesons**

ONSET OF QGP NCQ scaling of elliptic flow





elliptic flow

$v_2 = \langle cos(2\phi) \rangle$

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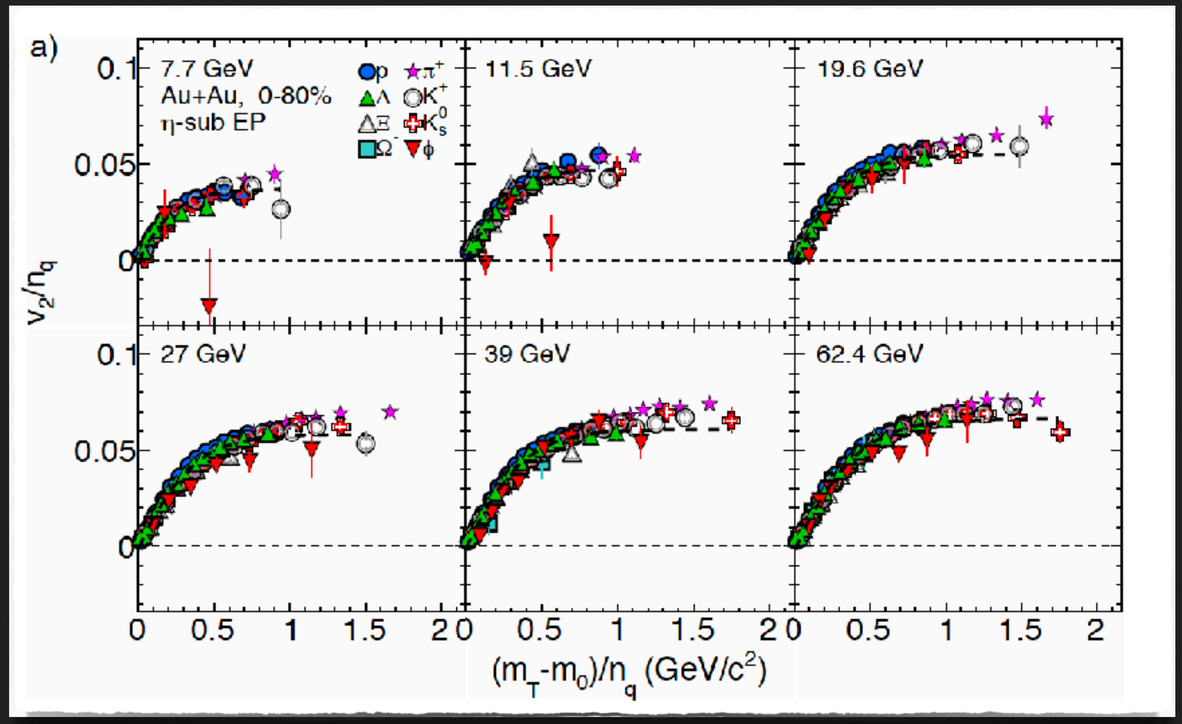


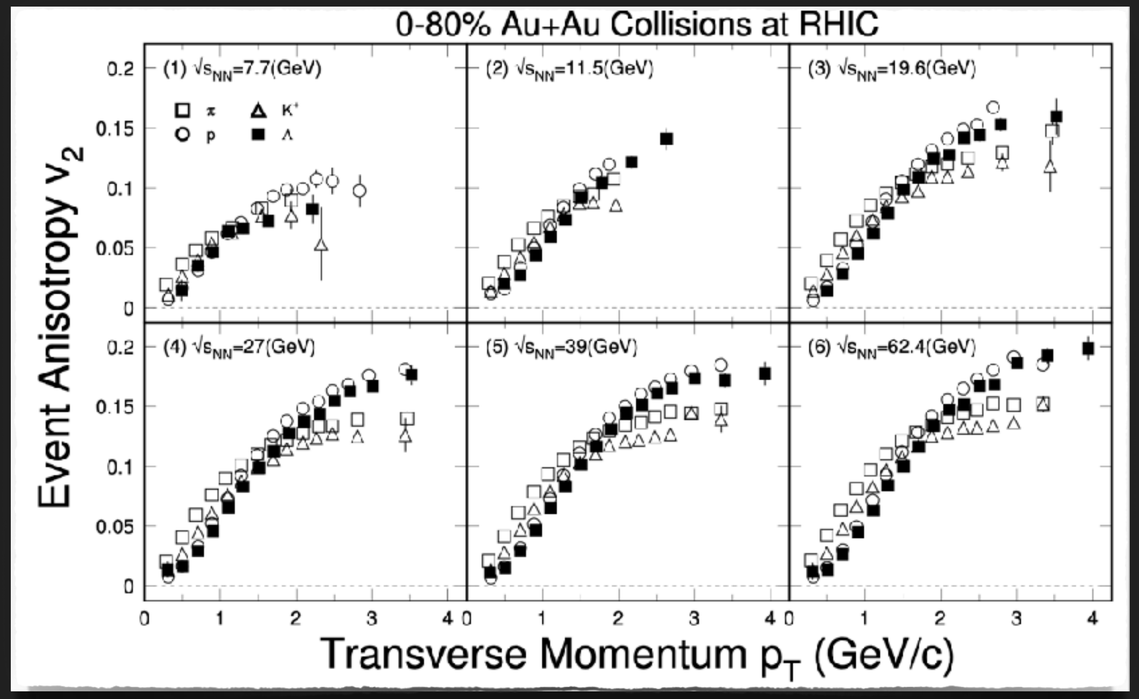


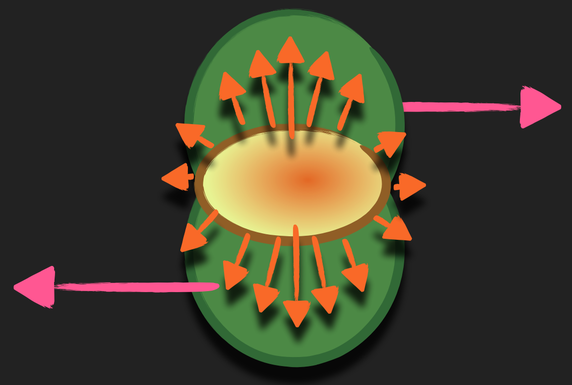
baryons



mesons

ONSET OF QGP NCQ scaling of elliptic flow





elliptic flow

$v_2 = \langle cos(2\phi) \rangle$

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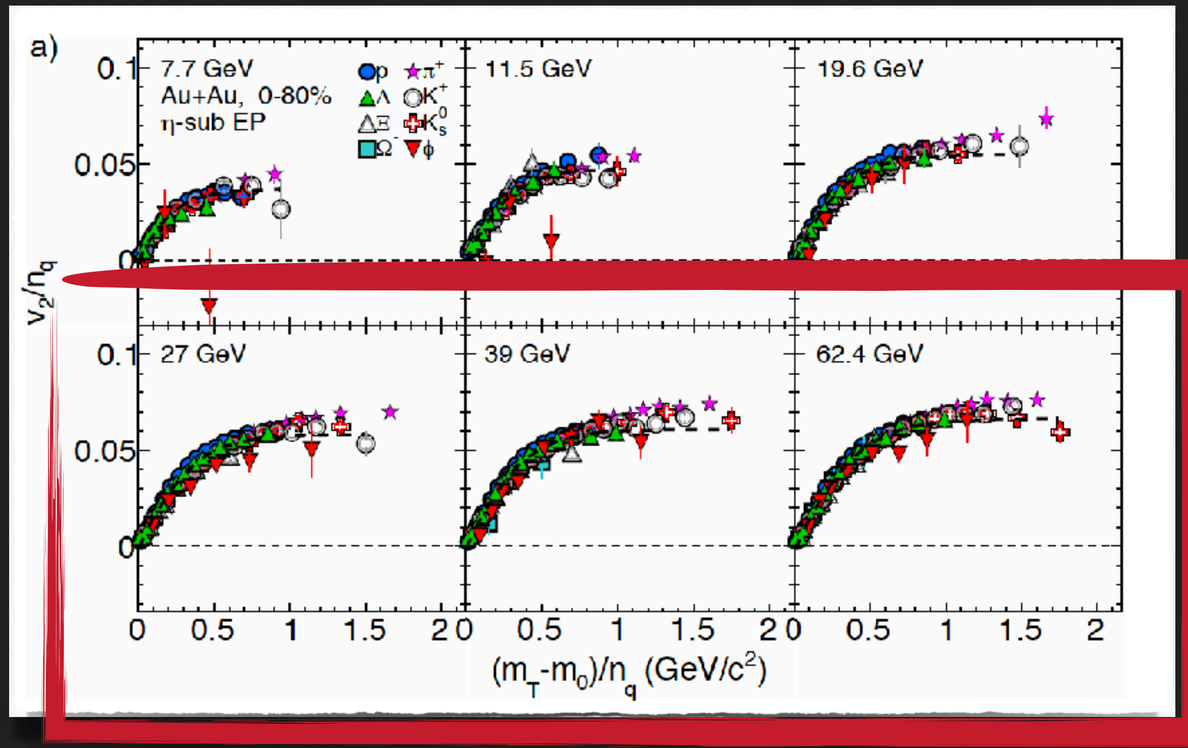
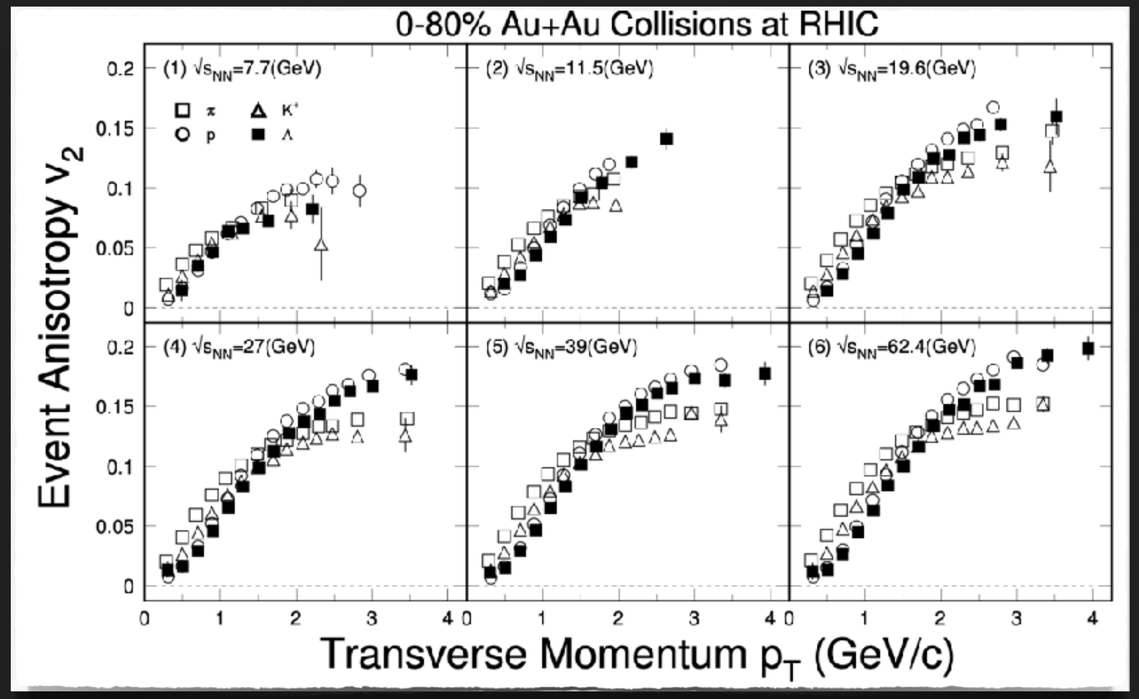
Scaled v_2 by the number of constituent quarks overlap for all particle species

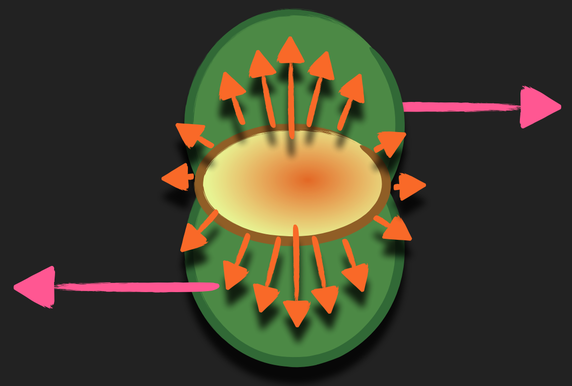
↓

Flow built in the partonic phase



ONSET OF QGP NCQ scaling of elliptic flow





elliptic flow

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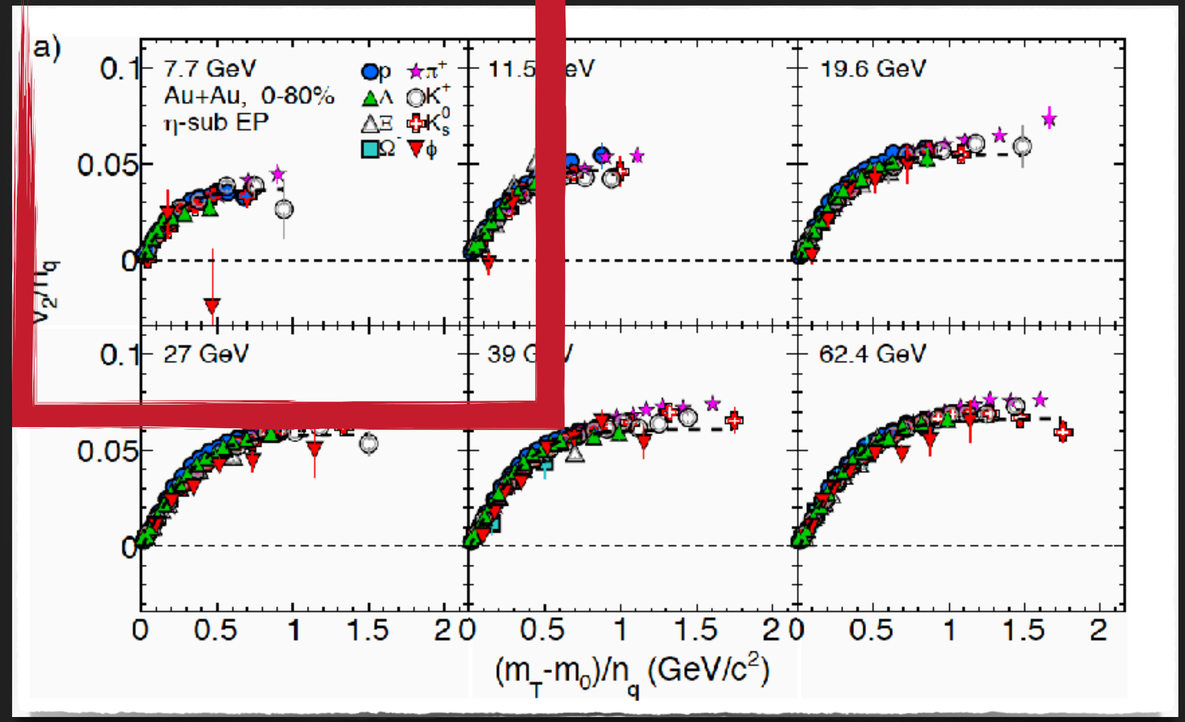


NCQ scaling broken for lover $\sqrt{s_{NN}}$

↓

The hadronic interactions become dominant

ONSET OF QGP

$$F = \left[\frac{(\sqrt{s_{NN}} - 2m_N)^3}{\sqrt{s_{NN}}}\right]^{\frac{1}{4}} \simeq \sqrt{\sqrt{s_{NN}}},$$

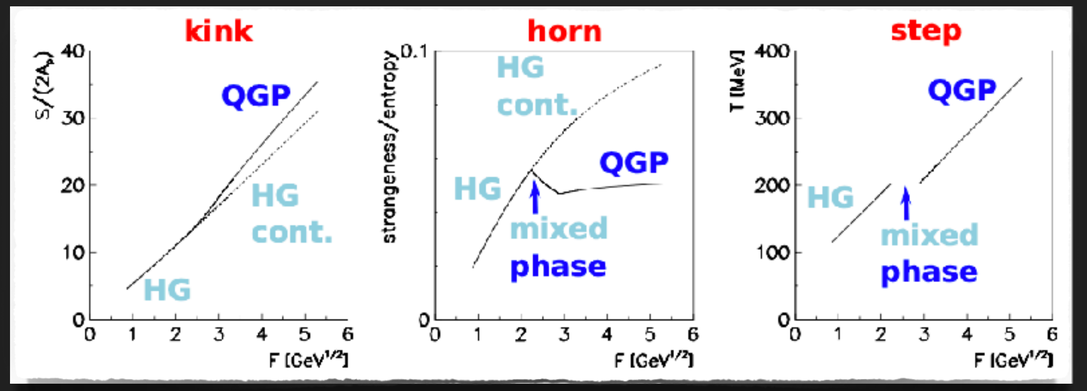
Fermi energy

Number of heavy flavors and whole entropy same before and after hadronization

According to Statistical Model of the Early Stage (SMES)

(Gaździcki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705)

NA61/SHINE Collaboration:
Nucl. Phys., vol. A967, pp. 35–42, 2017
Eur. Phys. J., vol. C77, no. 10, p. 671, 2017
PoS, vol. CPOD2014, p. 010, 2015
Acta Phys. Polon., vol. B50, pp. 1765–1770, 201



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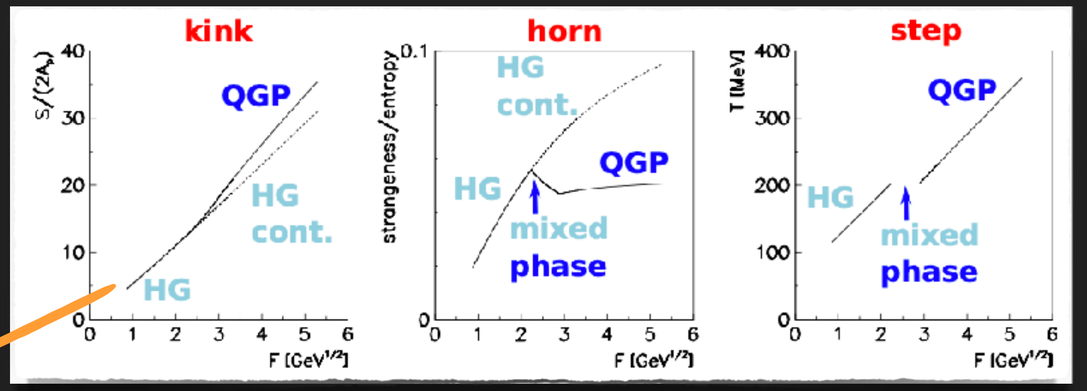
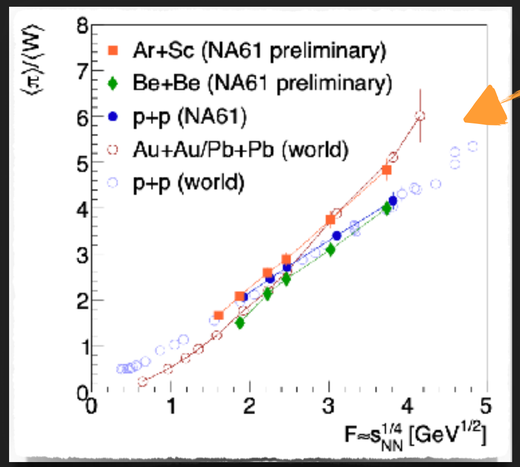


Pions as proxy of **entropy**



Slope change due to the activation of partonic degrees of freedom

ONSET OF QGP

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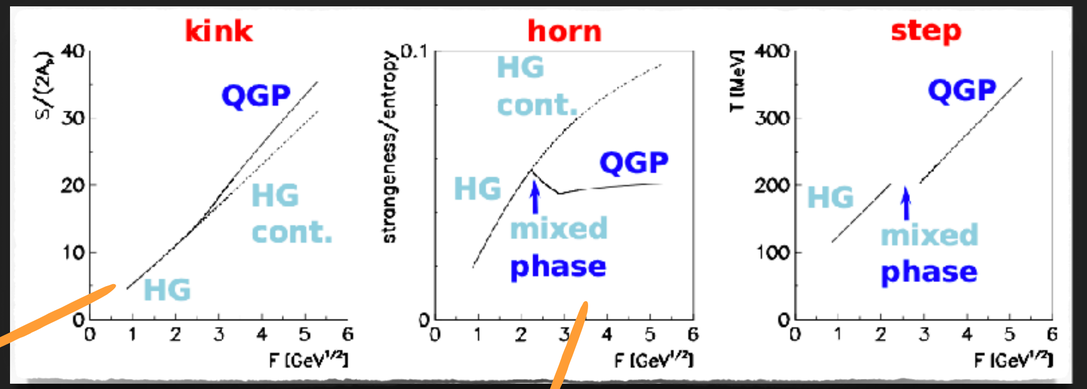

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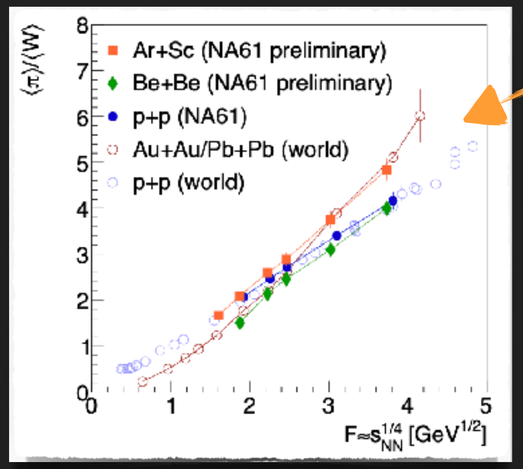

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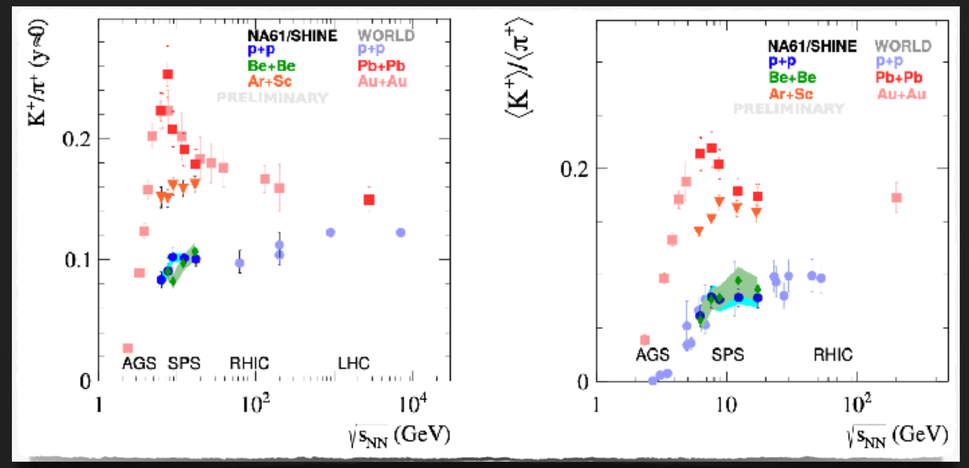

Charged **kaon to pion ratio** proxy of **strangers to entropy**

ONSET OF QGP

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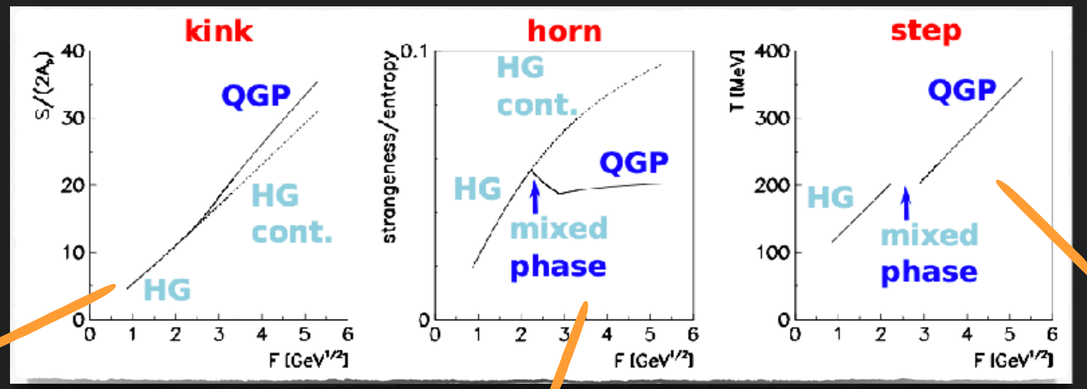
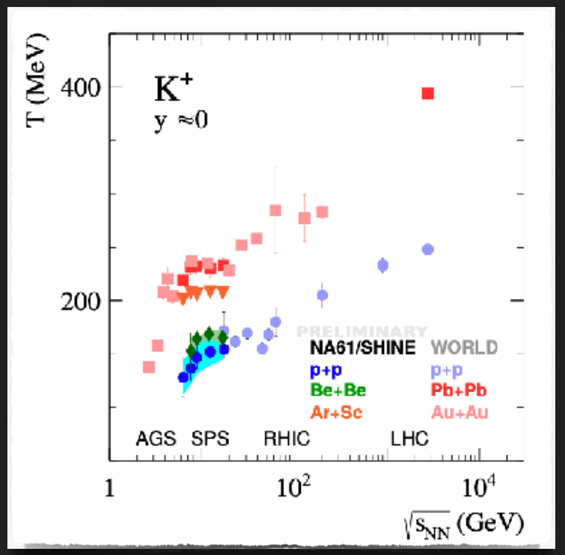
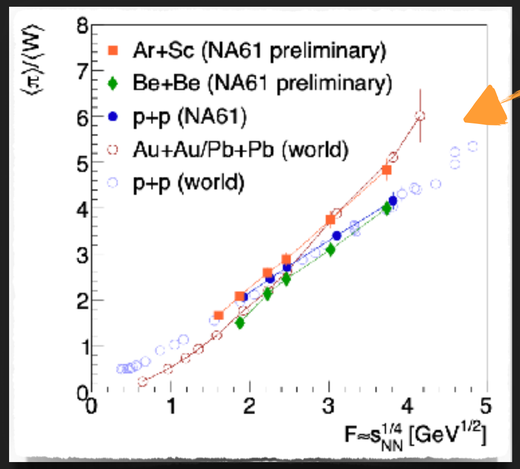


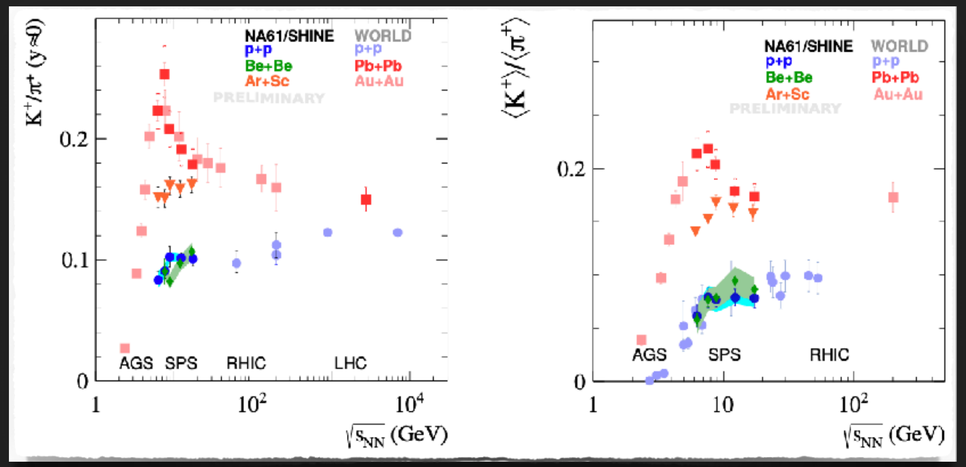
Temperature extracted from inverse slope parameter of **transverse mass** spectra



Pions as proxy of **entropy**



Slope change due to the activation of partonic degrees of freedom



$$\frac{dN}{dm_T} \sim m_T exp(-\frac{m_T}{T})$$

Charged **kaon to pion ratio** proxy of **strangers to entropy**

ONSET OF QGP

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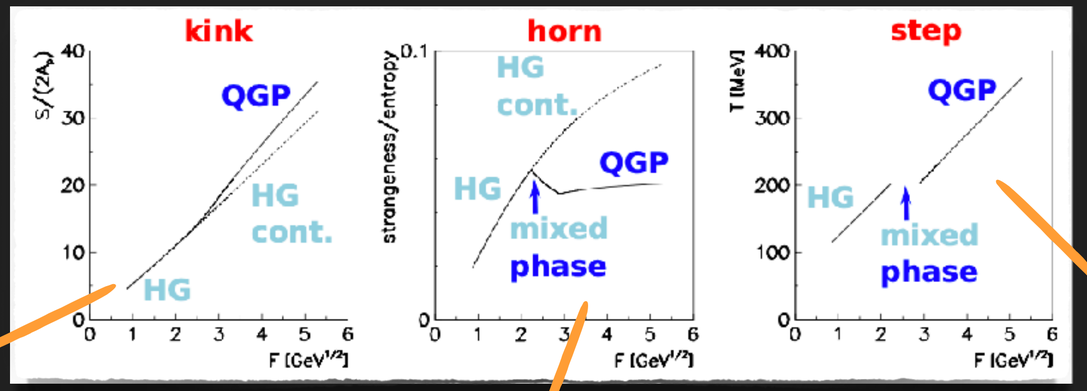

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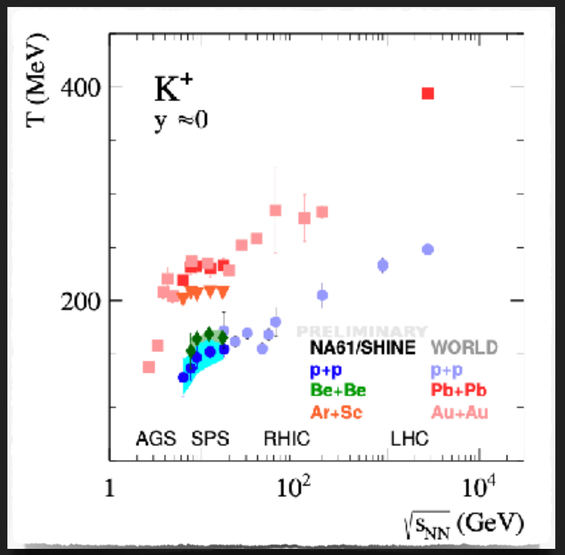
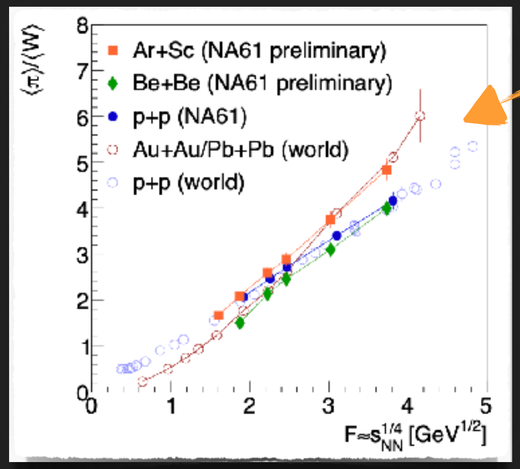
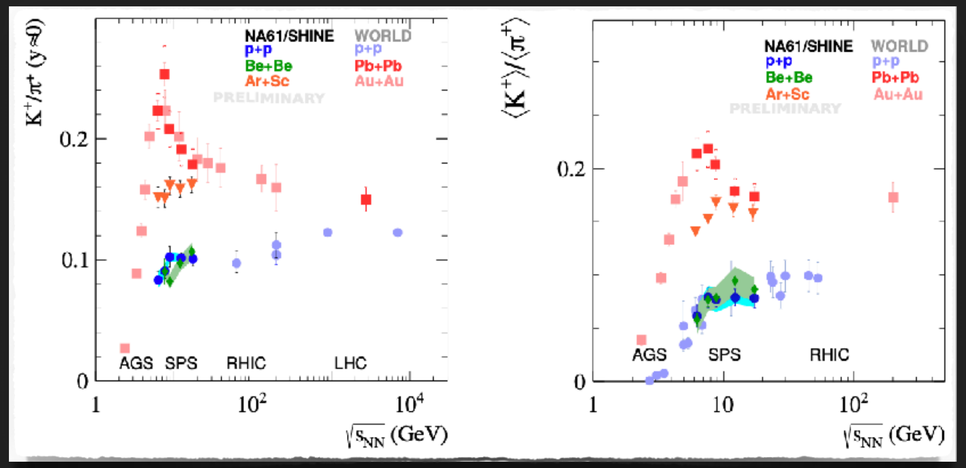


Pions as proxy of **entropy**



Slope change due to the activation of partonic degrees of freedom

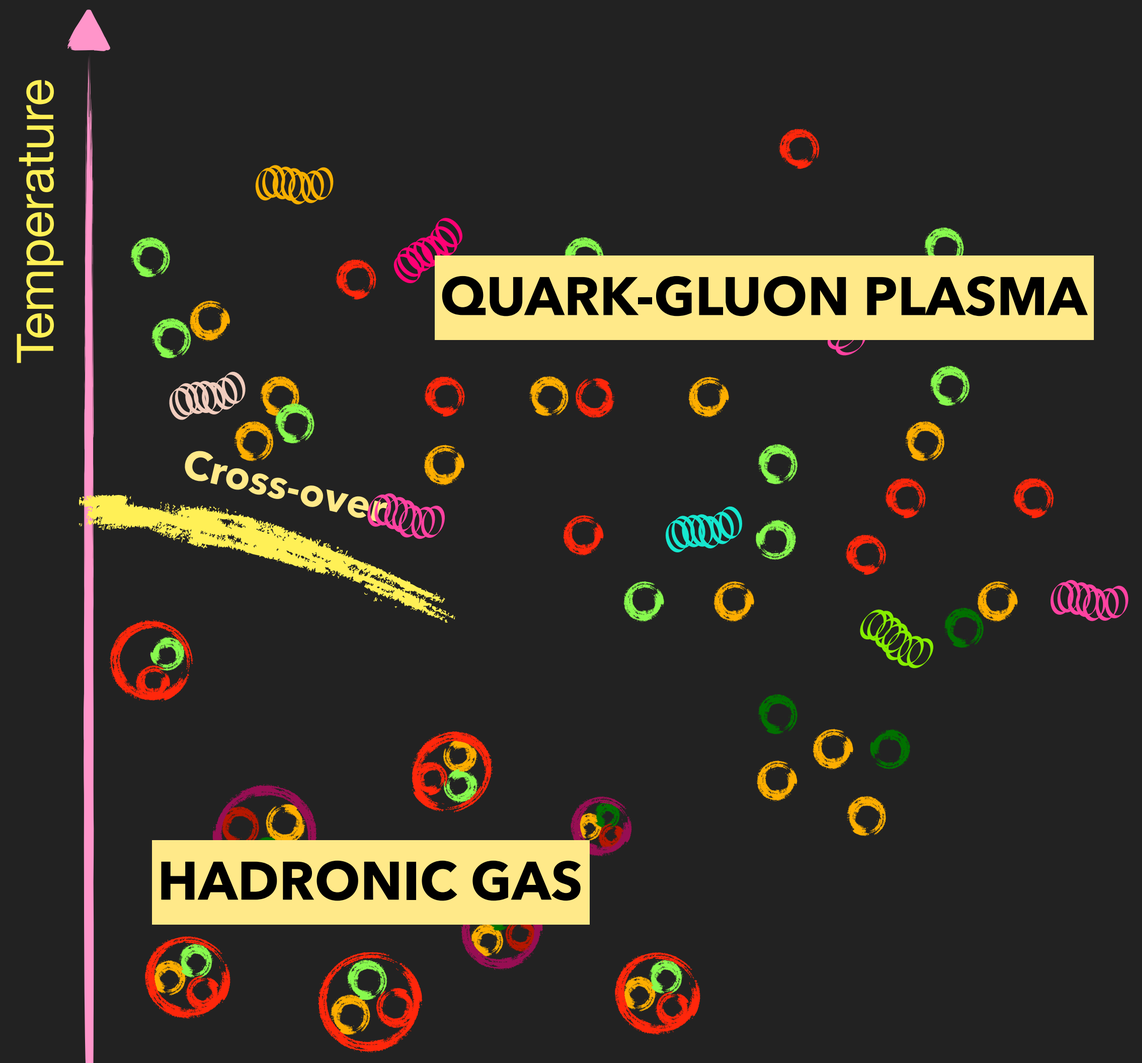


Charged **kaon to pion ratio** proxy of **strangers to entropy**

$$\frac{dN}{dm_T} \sim m_T exp(-\frac{m_T}{T})$$

ONSET OF DECONFINEMENT:
PBPB@ $\sqrt{s_{NN}} \approx 7.6$ GEV

THE COLDER SOUP



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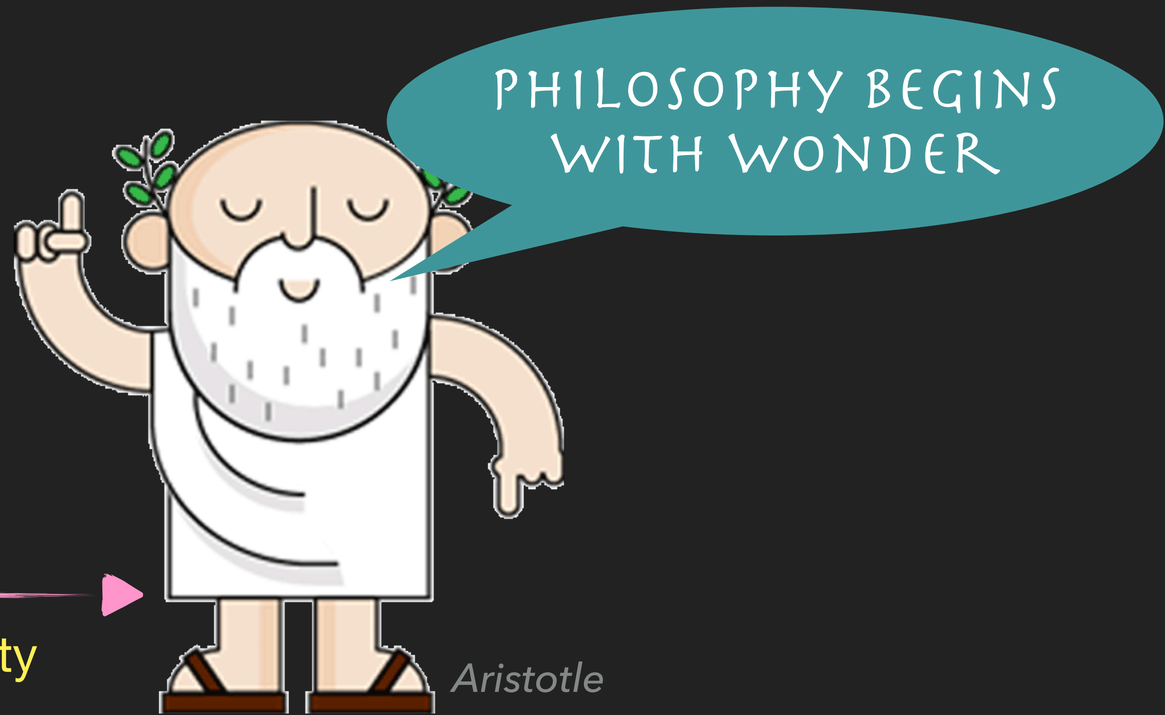
- **Lattice QCD:**
  - ✳ Cross-over transition
- **Experiment:**
  - ✳ Onset of QGP



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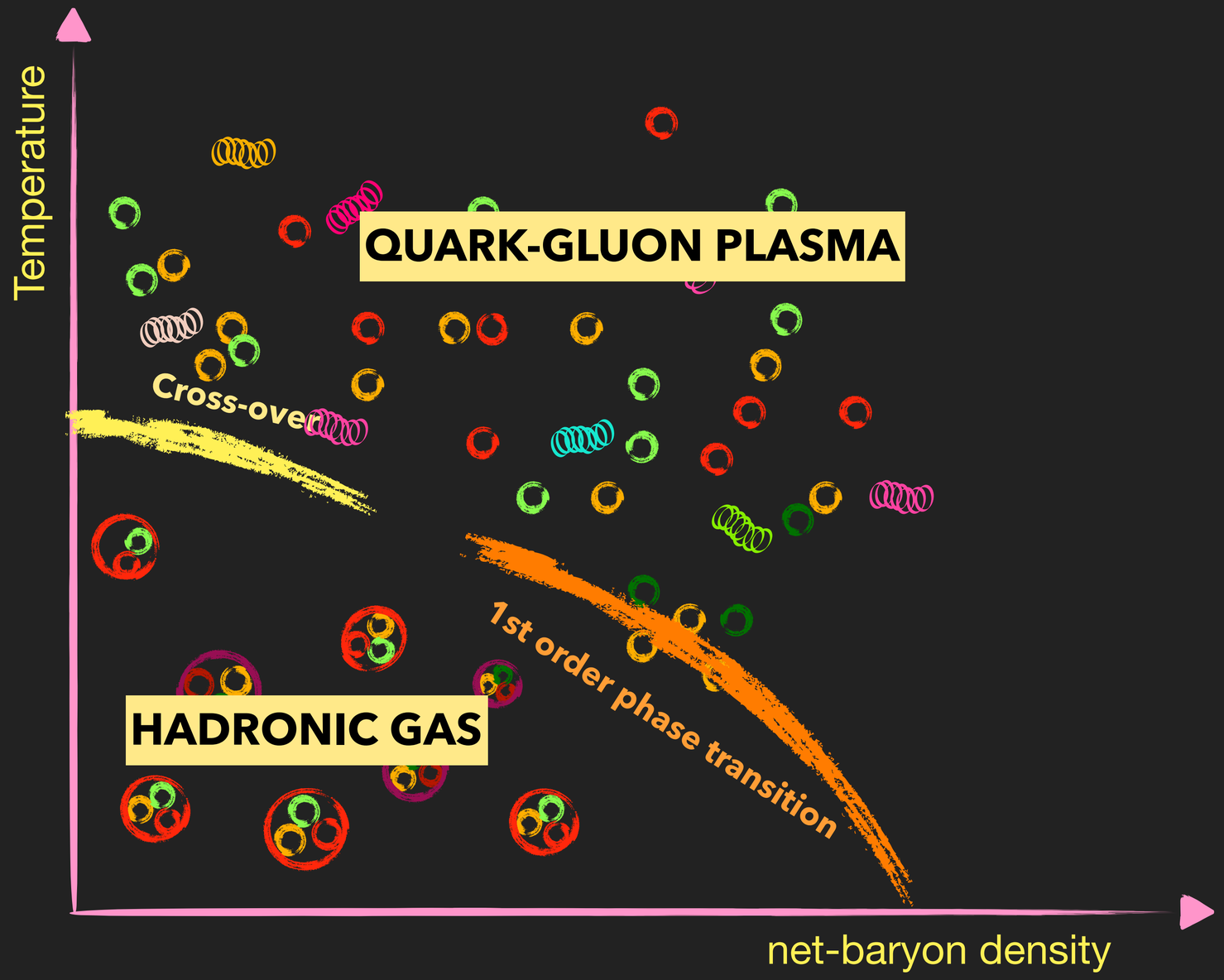

WHAT WE KNOW:

- **Lattice QCD:**
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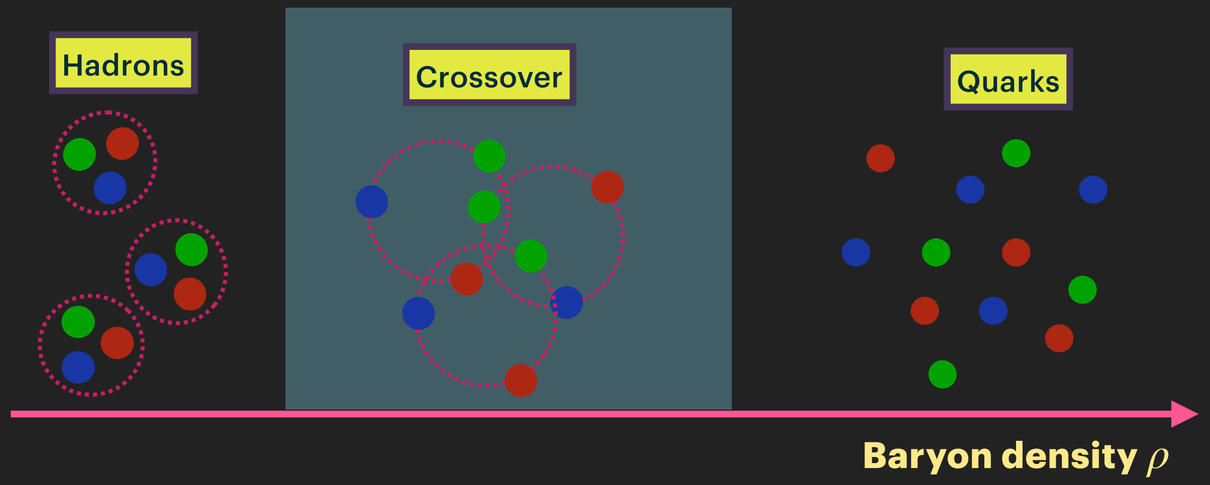
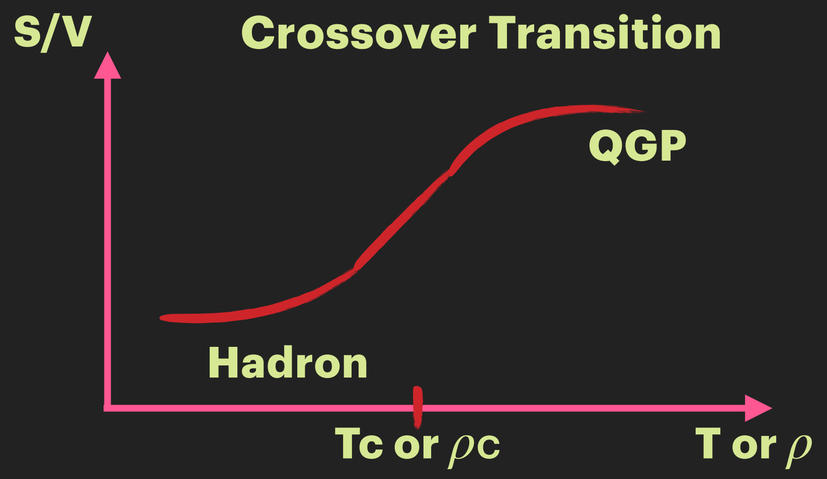
- **Experiment:**
  - ✳ Onset of QGP

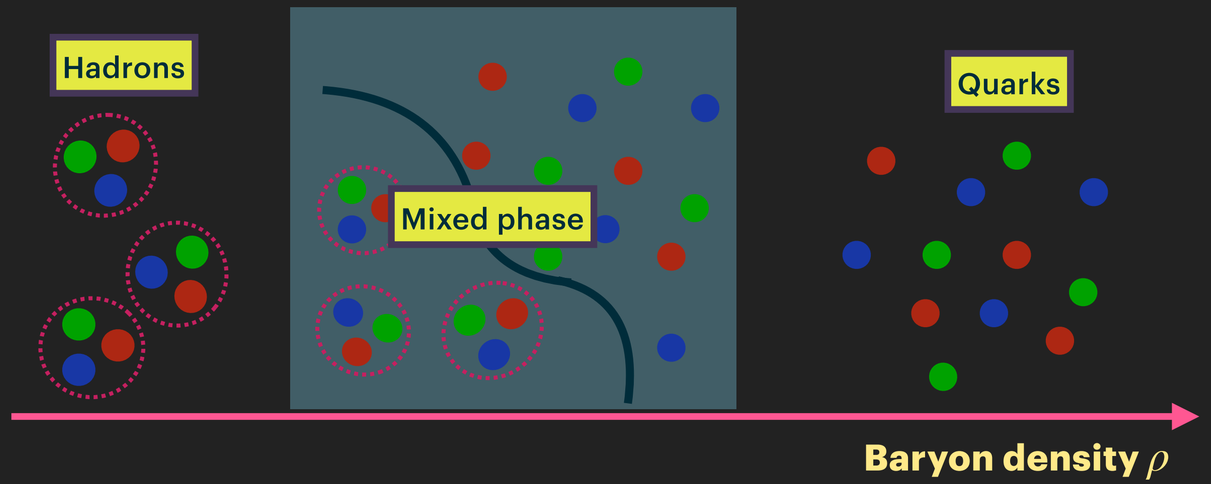
WHAT WE EXPECT:

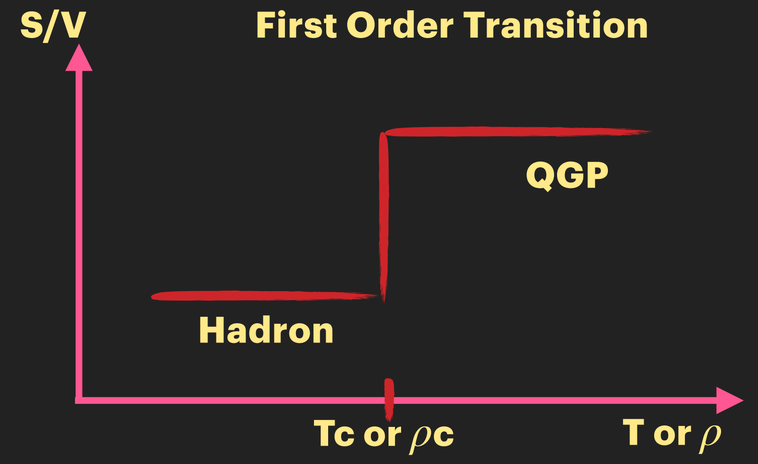
- **First order phase transition?**

1ST ORDER PHASE TRANSITION





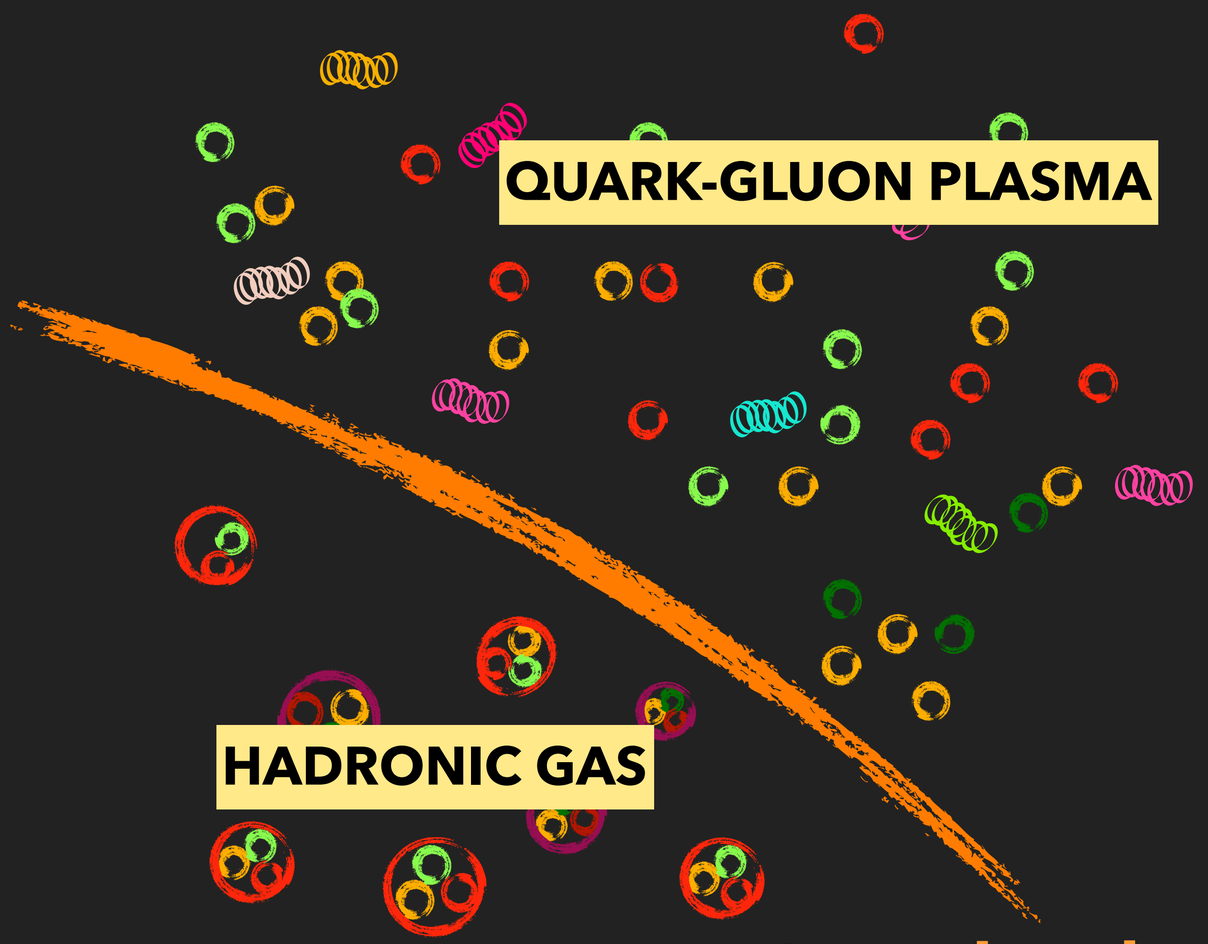




1ST ORDER PHASE TRANSITION

EoS softening at Lower collision energies

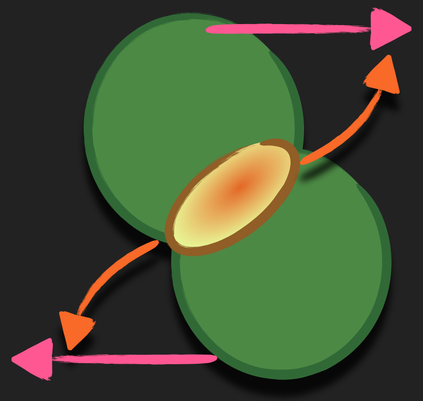
- Directed flow v_1
- Femtoscopy
- Higher order cumulants



1st order phase transition

1ST ORDER PHASE TRANSITION Directed flow v_1

Sensitive to the early stage of collision and compression of medium



STAR, PRL 112, 162301 (2014)

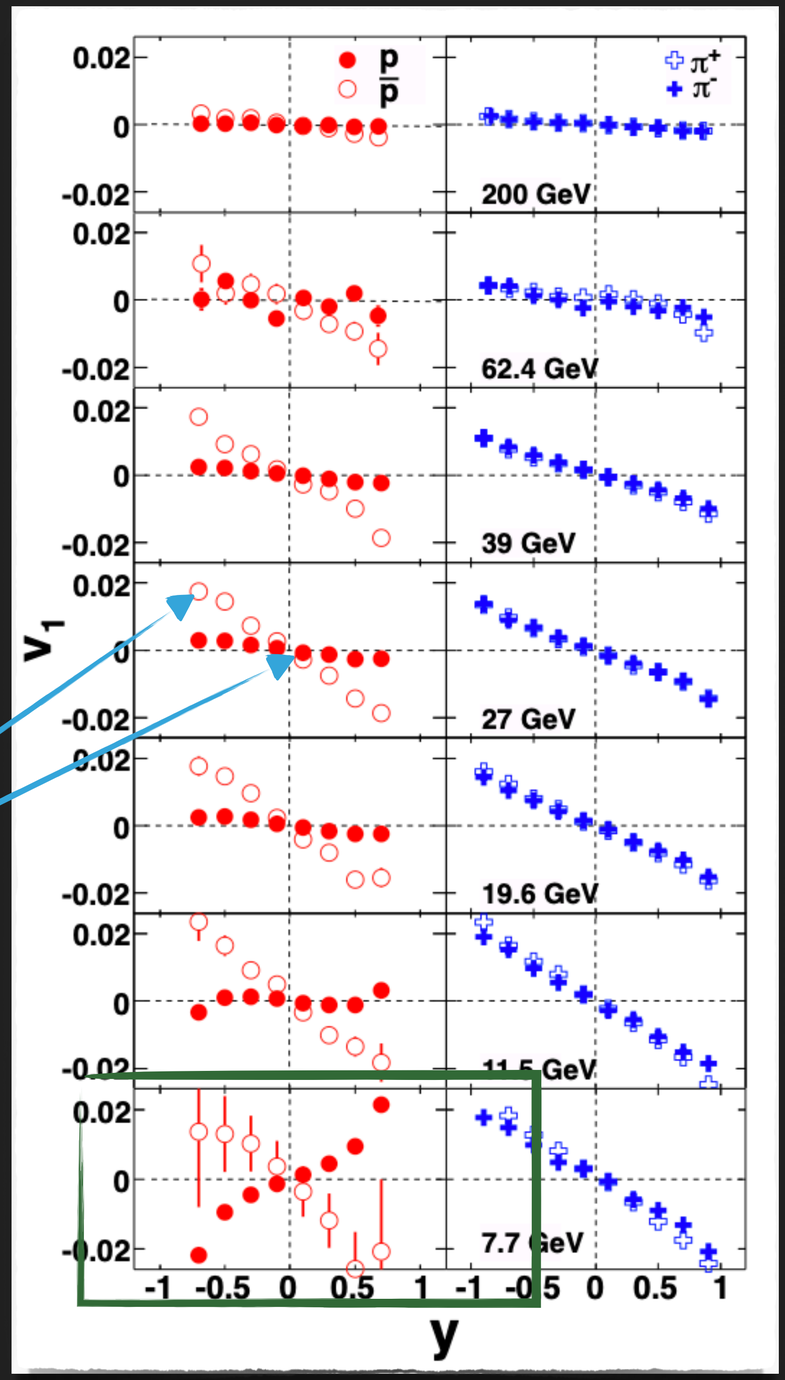
directed flow

$v_1 = \langle cos(\phi) \rangle$

Clear differences in slopes of protons and antiprotons

Negligible for pions

Only fo $\sqrt{s_{NN}} = 7.7$ GeV the slope of $v_1(y)$ of protons positive!



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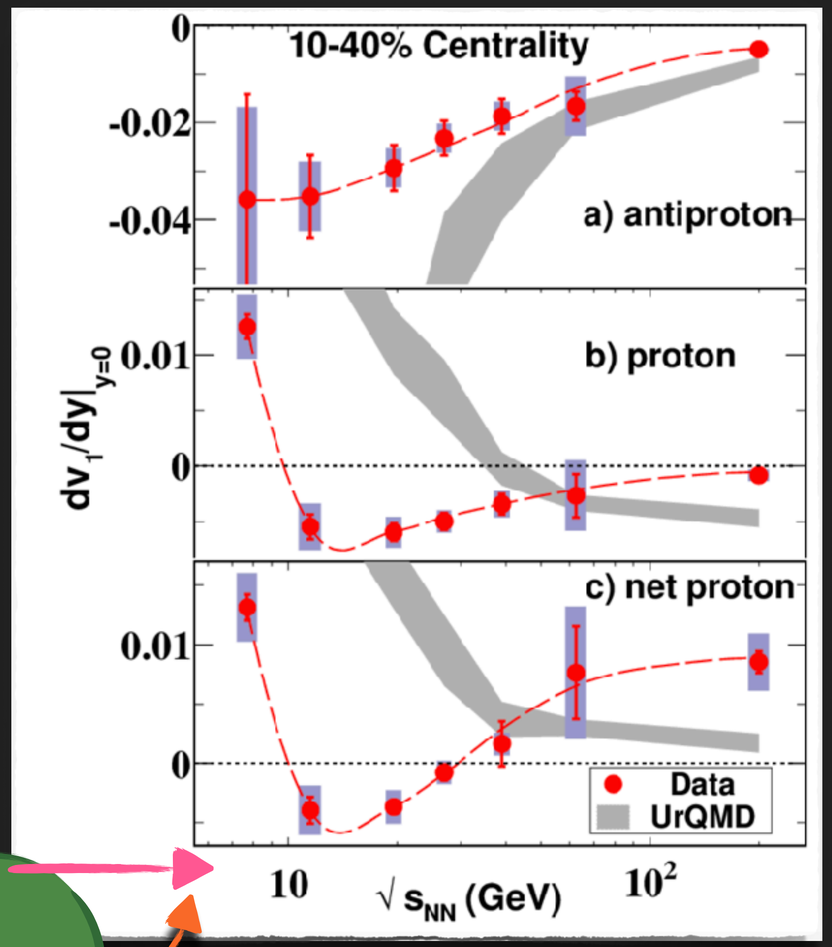

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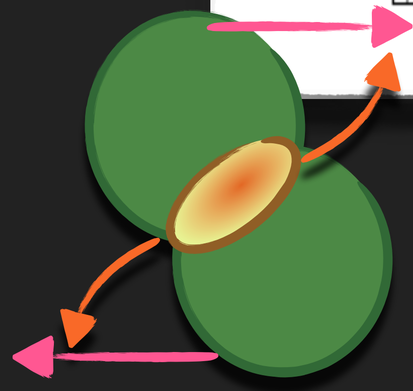


directed flow

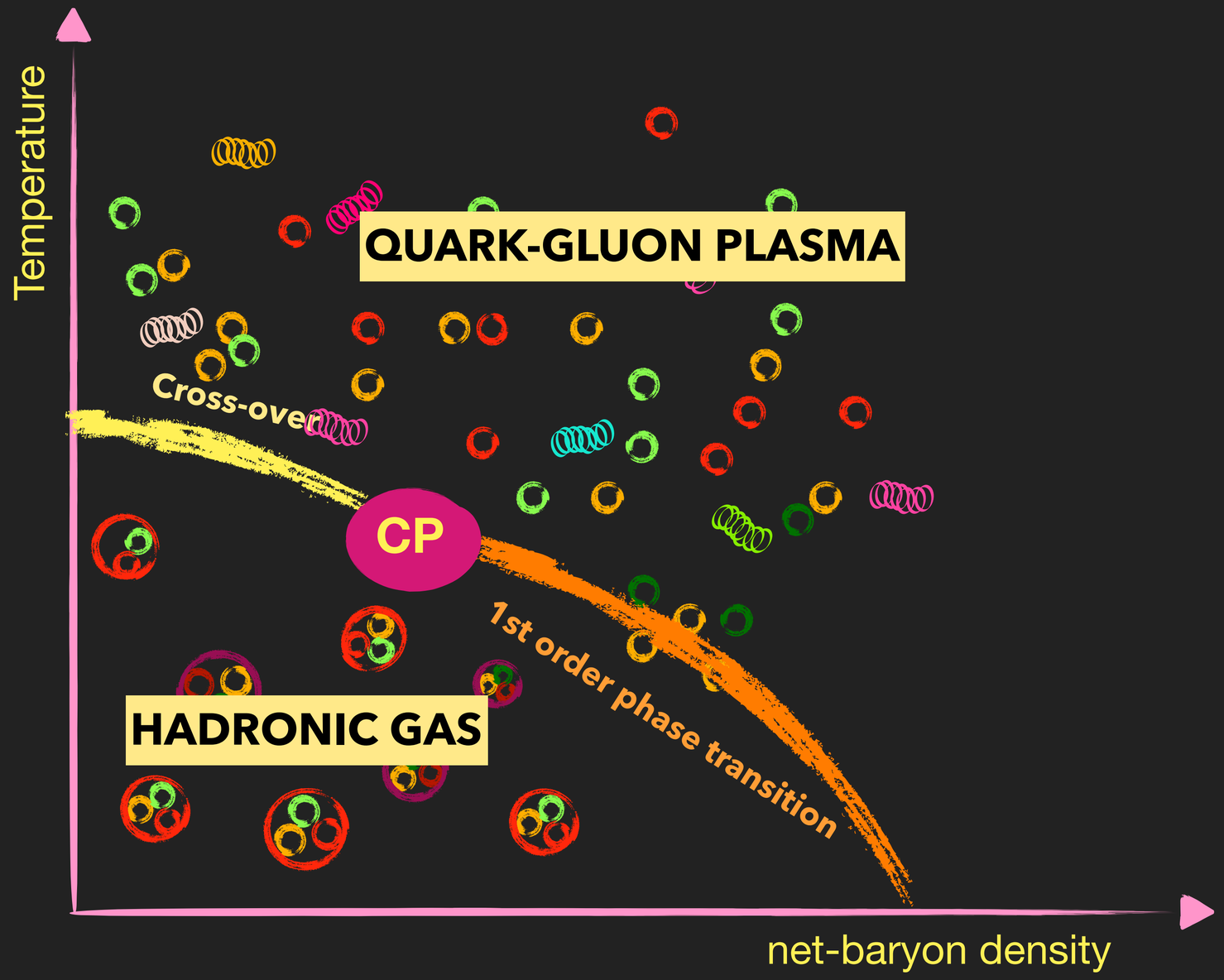
$v_1 = \langle cos(\phi) \rangle$

Change of sign in the slope of $\frac{dv_1}{dy}$ (for (net-) baryons)

System undergoing a 1st order phase transition characterized by the small pressure gradient due to mix phase formation

Softening of EoS and/or the **first-order phase transition**

THE COLDER SOUP



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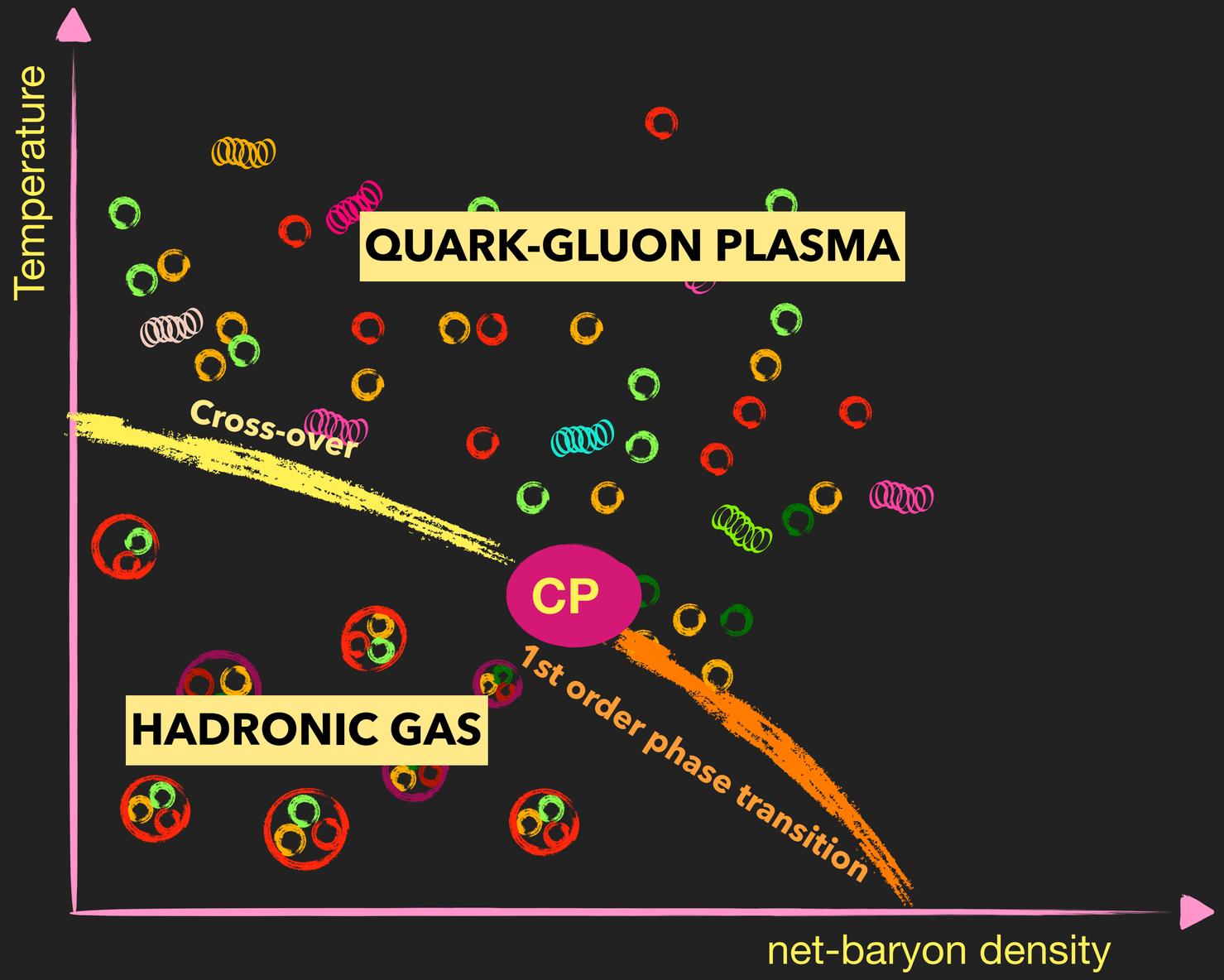
THE COLDER SOUP



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Fluctuations and correlations

$$\delta N = N - < N >$$

$$C_1 = < N >$$

$$C_2 = < (\delta N)^2 > = \sigma^2$$

$$C_3 = < (\delta N)^3 >$$

$$C_4 = < (\delta N)^4 > - 3 < (\delta N)^2 >^2$$

$$S\sigma = \frac{C_3}{C_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2}$$

$$C_2 \sim \xi^2 \quad C_3 \sim \xi^{4.5} \quad C_4 \sim \xi^7$$



The higher cumulant order, the more sensitive to the correlation length

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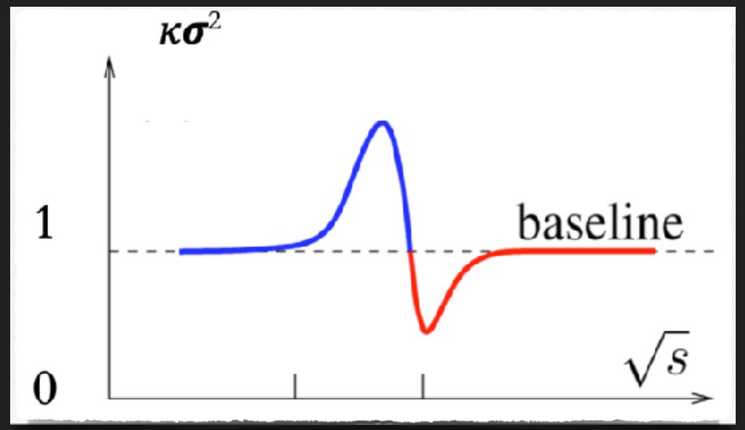

4th order: predicts a non-monotonic energy dependence due to contribution from QCD critical point

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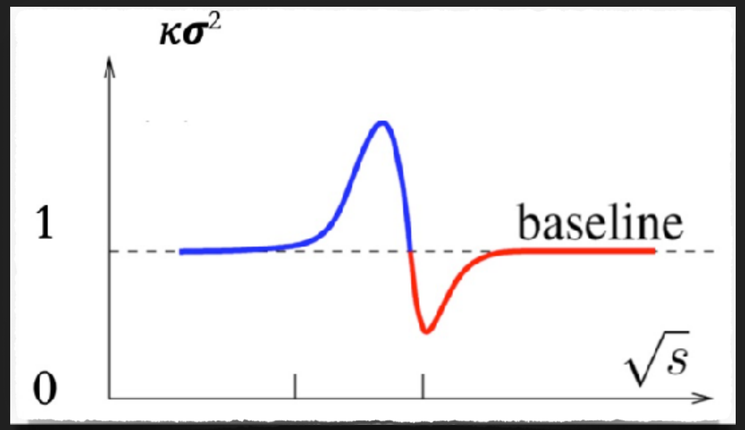

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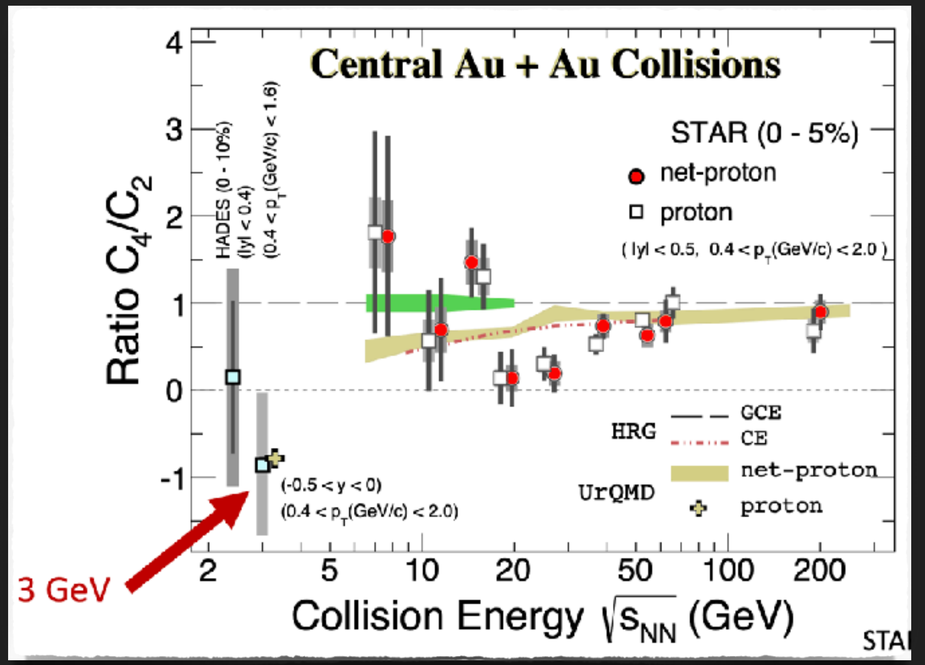

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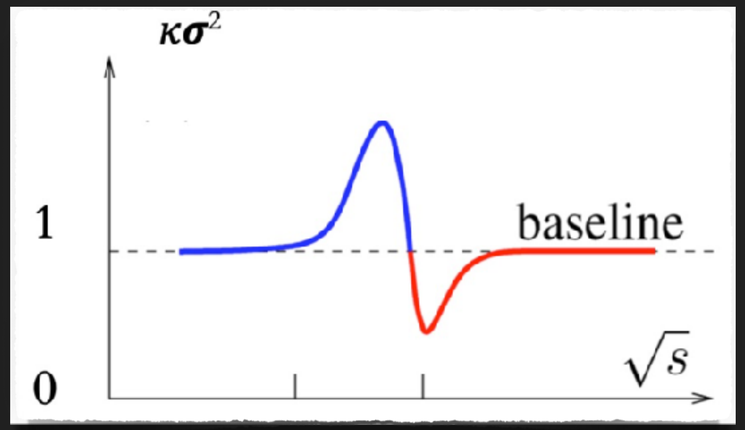

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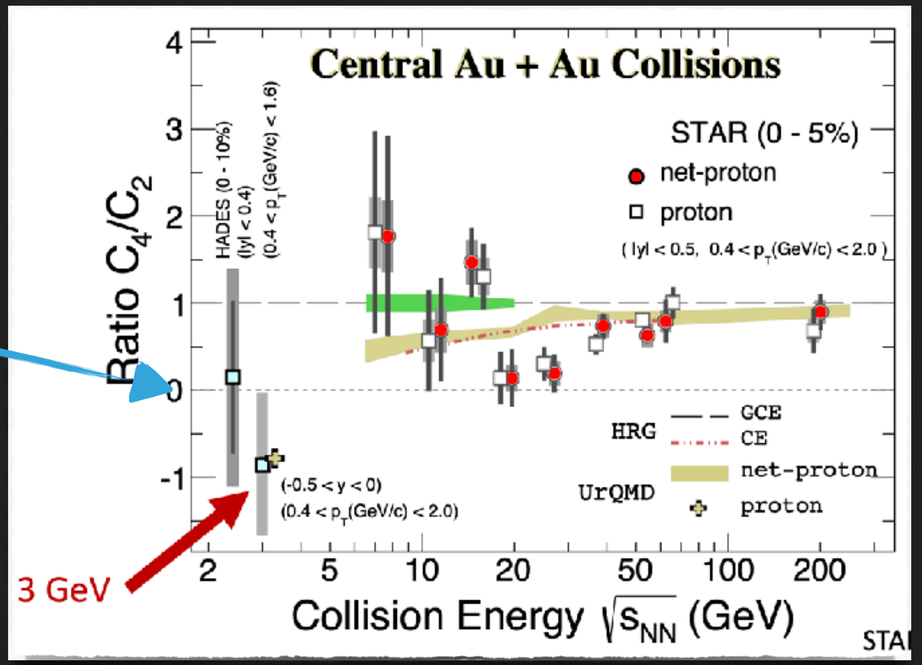
The C4/C2 suppression consistent with fluctuations driven by baryon number conservation indicating domination of hadronic interaction



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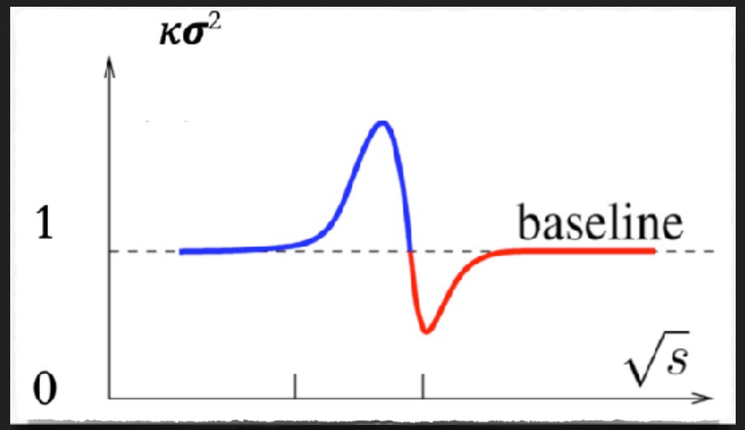
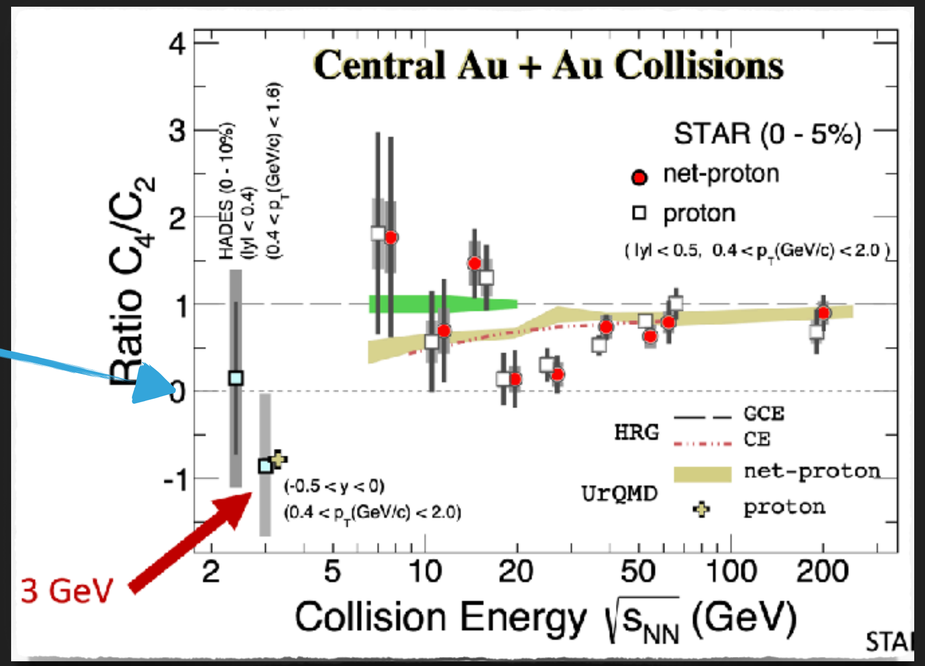


4th order: predicts a non-monotonic energy dependence due to contribution from QCD critical point

The C4/C2 suppression consistent with fluctuations driven by baryon number conservation indicating domination of hadronic interaction

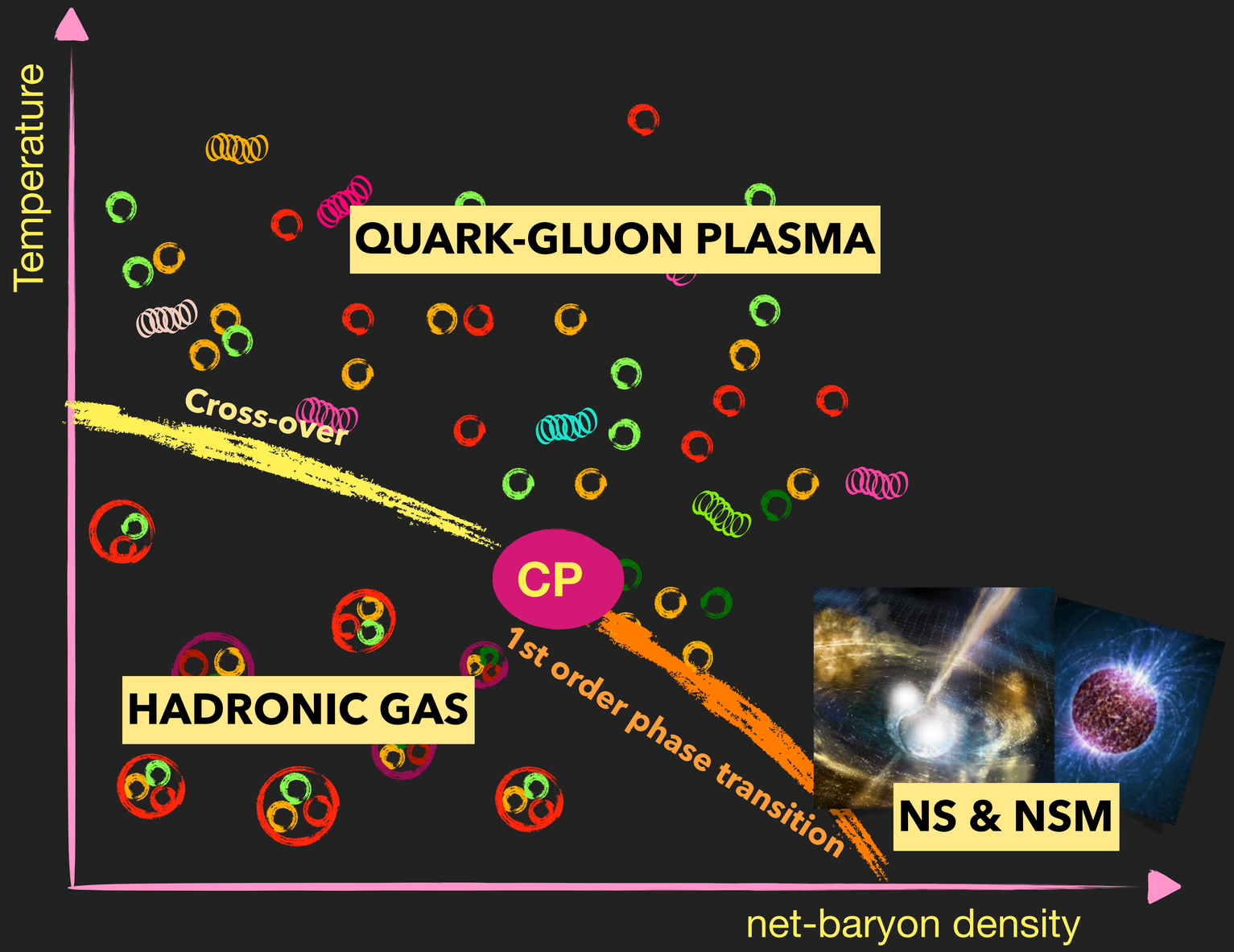
The QCD critical point, could be located at

$\sqrt{s_{NN}}$> 3 GeV



STAR, arXiv:2112.00240

THE COLDER SOUP



WHAT WE KNOW:

- **Lattice QCD:**
  - ✳ Cross-over transition
- **Experiment:**
  - ✳ Onset of QGP
  - ✳Neutron Stars & NS Mergers

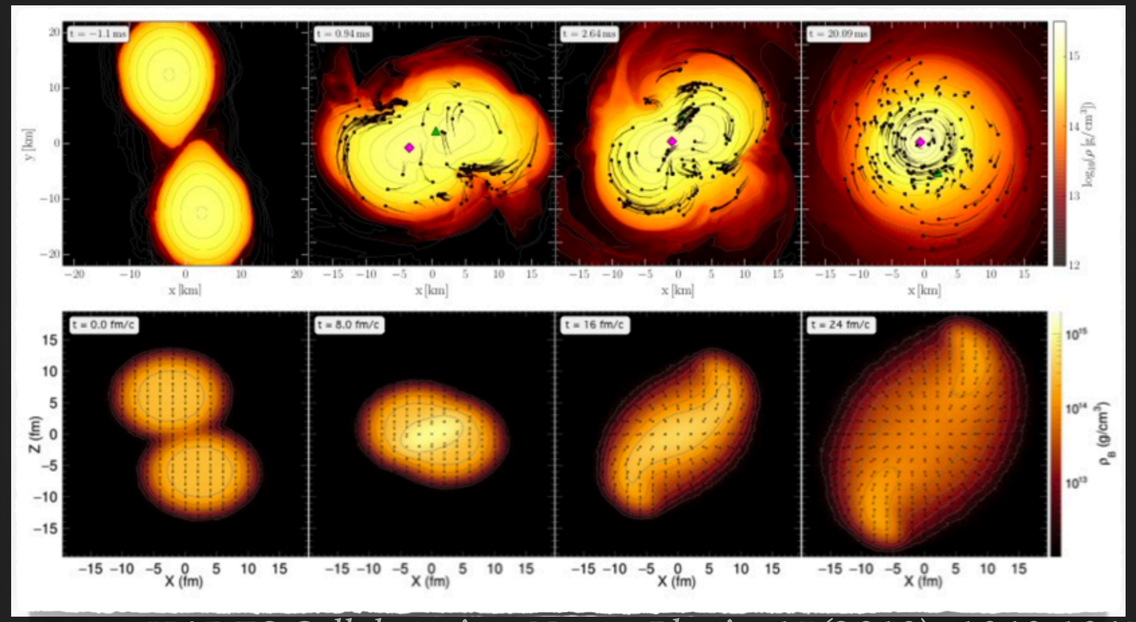
WHAT WE EXPECT:

- **First order phase transition?**
- **Critical Point?**
- **Universal EoS LHC->NS**
- **Characterization of NSM**

NEUTRON STARS AND NEUTRON STAR MERGERS

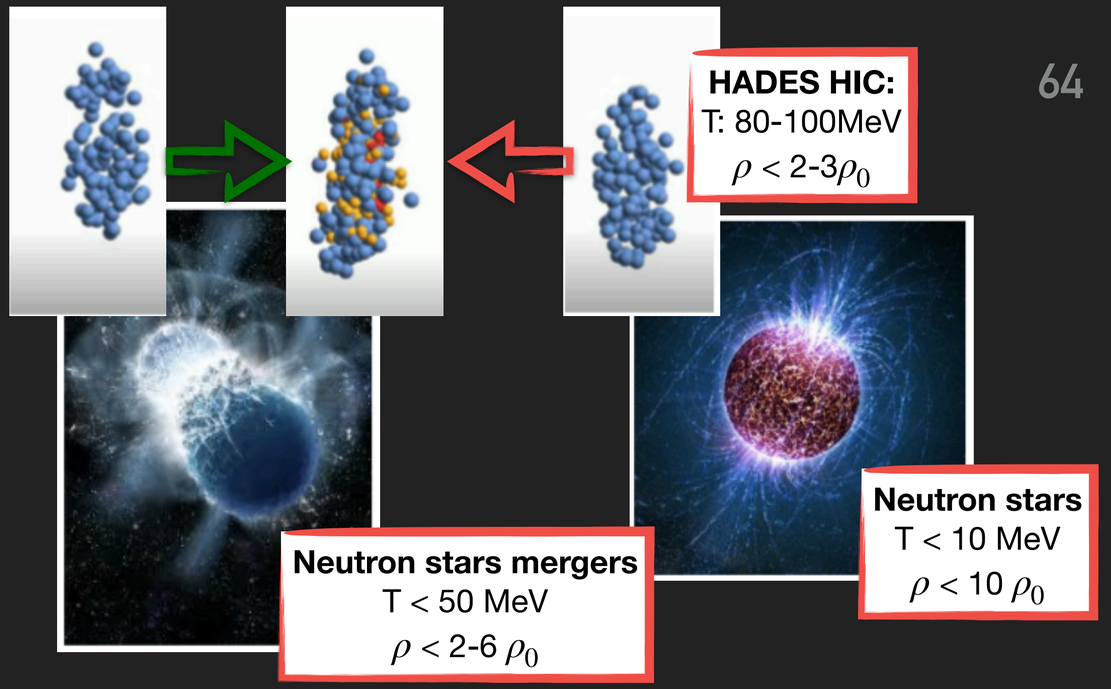
DENSITY EVOLUTION IN:

Two merging neutron stars



HADES Collaboration: Nature Physics 15(2019), 1040-1045

Two colliding gold nuclei



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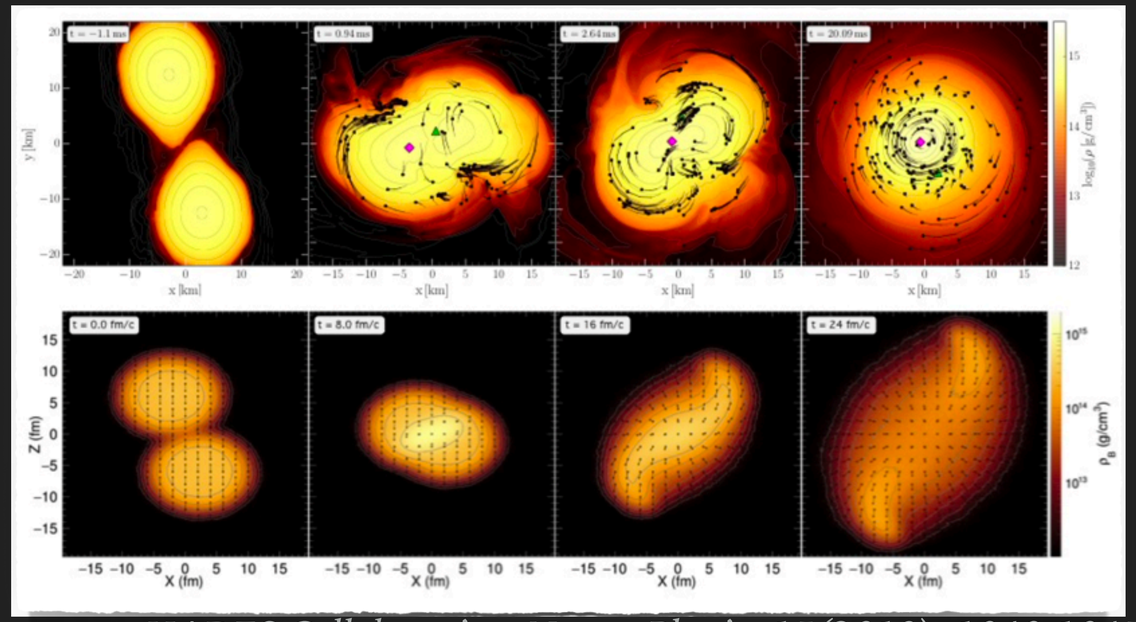

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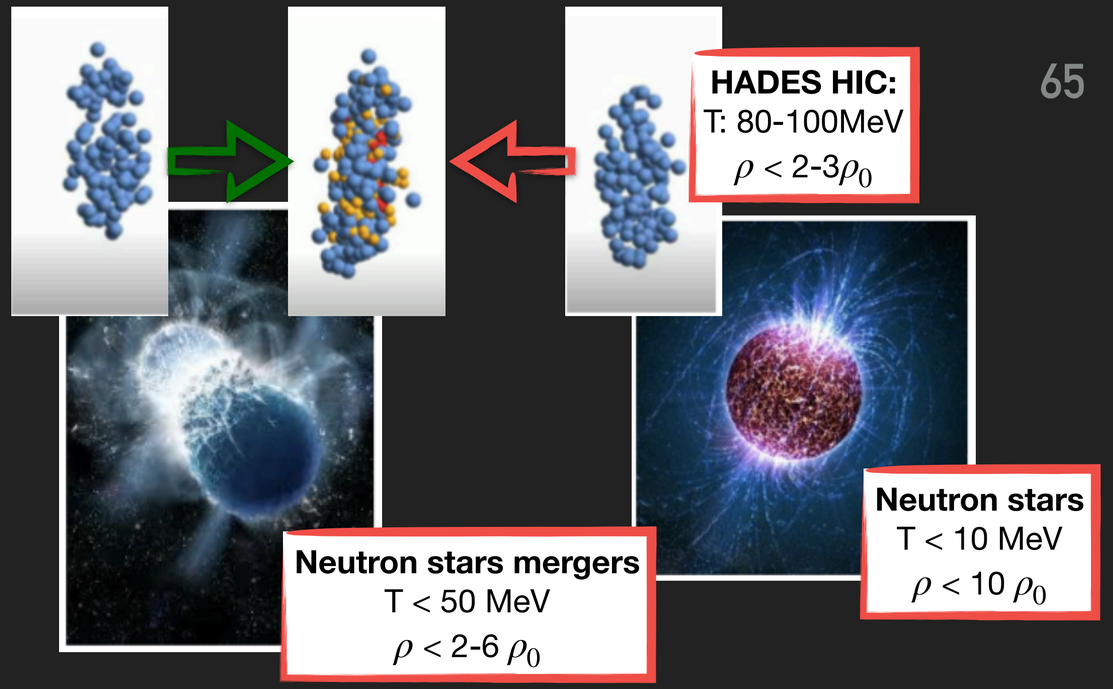
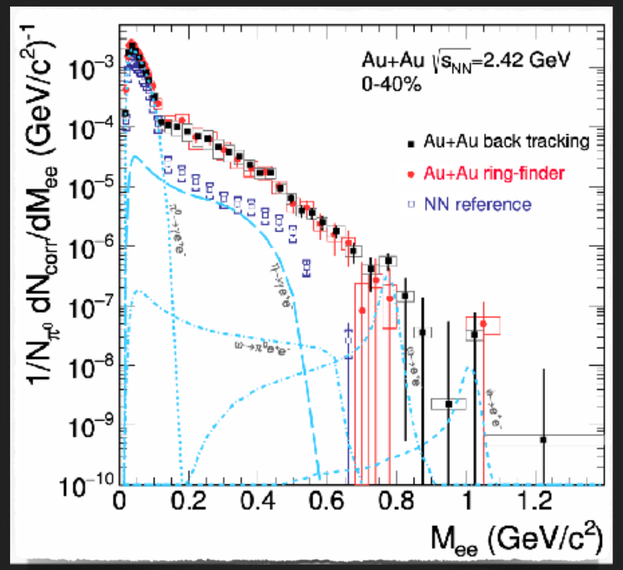


- Different scales
- Similar matter properties:
  - Relation pressure - energy density - temperature - density

NEUTRON STARS AND NEUTRON STAR MERGERS

HADES Collaboration: ***Nature Physics*** *15(2019), 1040-1045*



Reconstructed e^+e^- mass distribution
- manifestation of virtual photons

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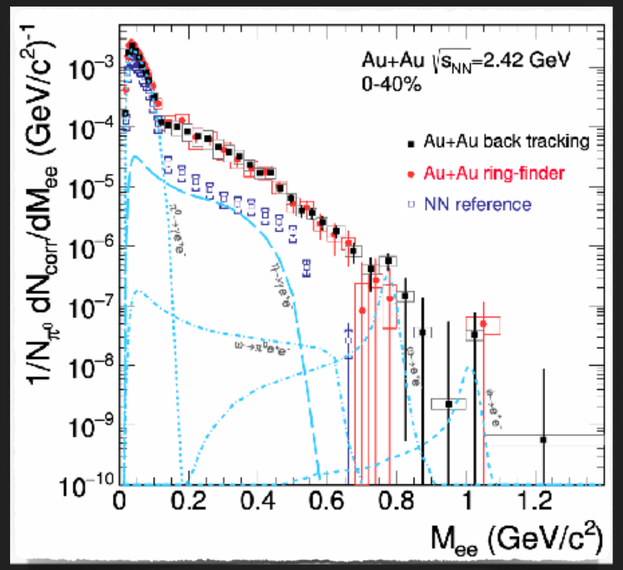

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Correction of acceptance in dilepton excess yield, subtraction of:

- η, ω contributions
- *NN* reference normalized to the number of neutral pions

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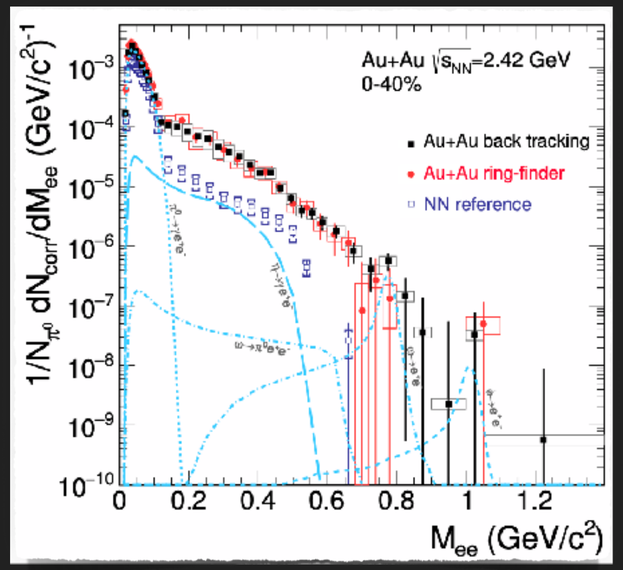

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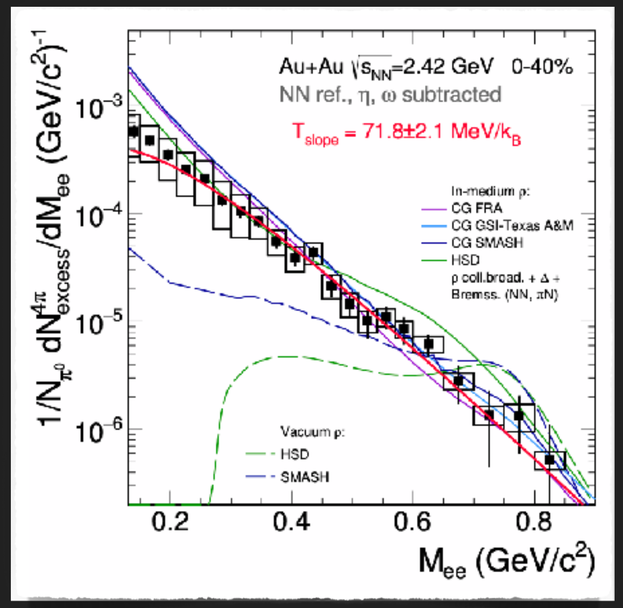

The excess radiation:

- Nearly-exponential fall-off
- Extraction of temperature: $T = 71.8 \pm 2.1$ MeV/k_B

Models predict the $T = 50 - 80$ MeV of the post-merger neutron star around the dense remnant core

NEUTRON STARS AND NEUTRON STAR MERGERS

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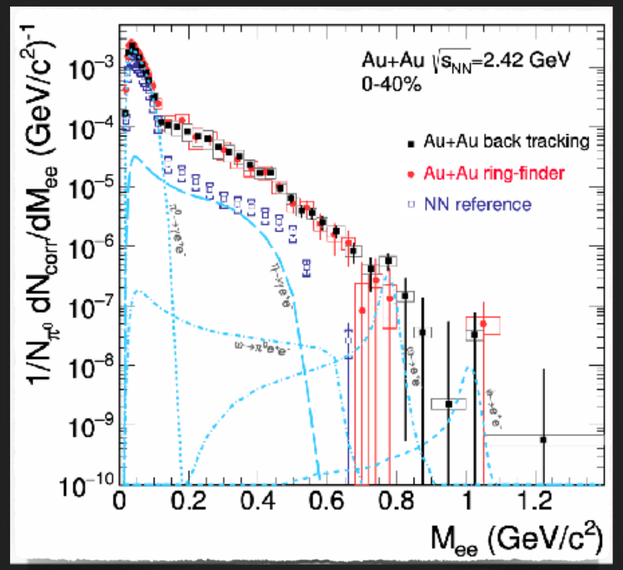

Reconstructed e^+e^- mass distribution - manifestation of virtual photons

theoretical basis. Therefore, the observation of thermal (virtual) photon emission off dense baryon matter in relativistic heavy-ion collisions serves as a benchmark for accessing other bulk properties.

Correction of acceptance in dilepton excess yield, subtraction of:

- η, ω contributions
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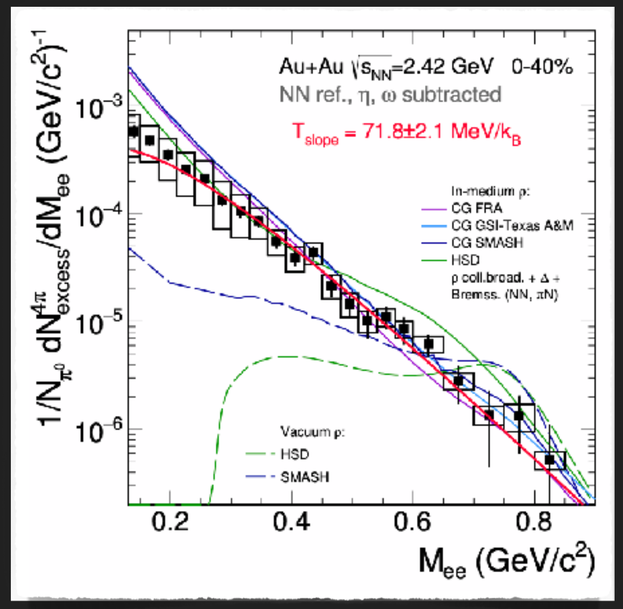
Like Neutron Star Mergers



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More in Niklas Schild talk today at 16:40

SUMMARY AND OUTLOOK

- Fascinating physics is being studied at the QCD phase diagram region of finite μ_B.
- Many observables were investigated providing excellent reference for the theoretical studies of properties of the strongly interacting matter and its transitions.
- The significant improvement of the data quality leads to the ground-breaking discoveries!
- We are able to *„bring the universe in the laboratory"*, at the HADES and future FAIR experiments.
- About more recent, exciting research we will hear from our colleagues in next few days of our meeting!



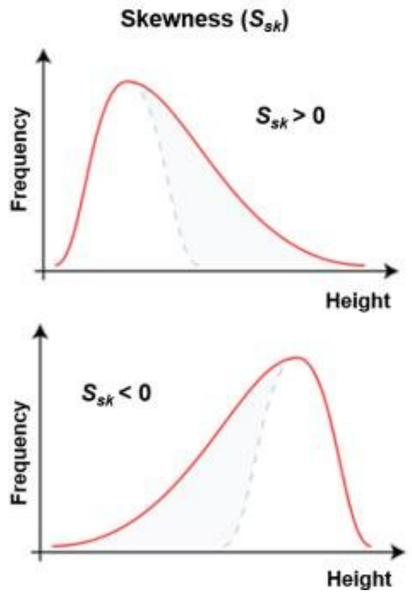
THANK YOU!

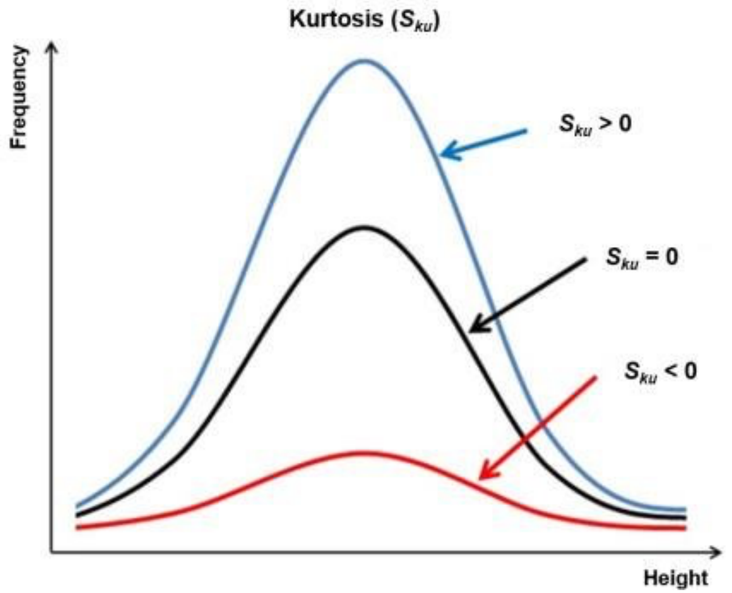


BACK UP

Moments of net proton distributions

- **Mean** (M)
- **Standard deviation** (σ)
- **Skewness** (S), which corresponds to the asymmetry of the distribution
- **Kurtosis** (κ), reflecting the degree to which the distribution is peaked relative to the normal distribution.





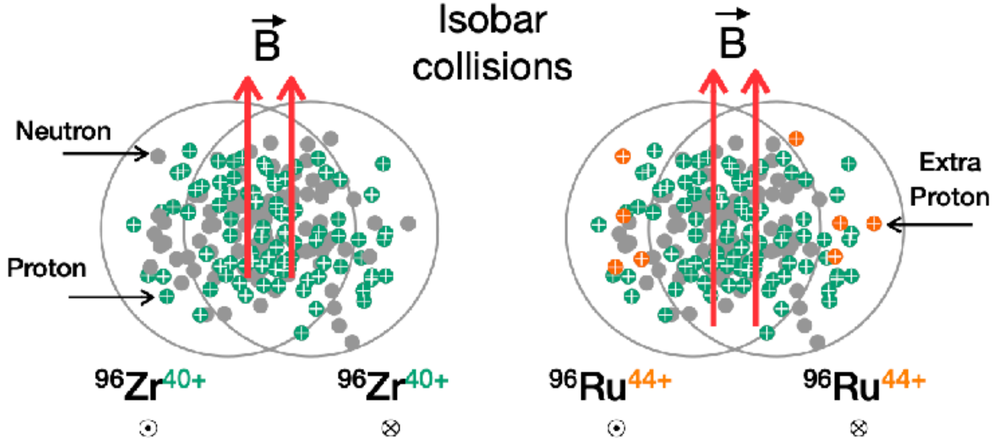
Decisive Tests Of CME Using Isobar Collisions

Phys.Rev.Lett. 105 (2010) 172301

Testing the Chiral Magnetic Effect with Central $U+U$ collisions

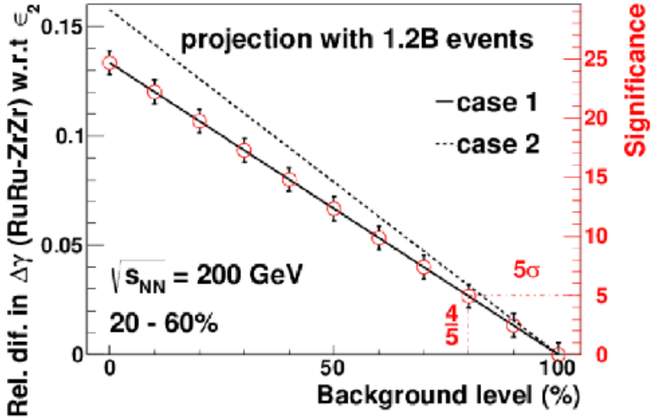
Sergei A. Voloshin
Wayne State University, Detroit, Michigan 48201, USA

The charge separation dependence on the strength of the magnetic field can be further studied with collision of isobaric nuclei, such as $^{96}_{44}Ru$ and $^{96}_{40}Zr$. These nuclei have the same mass number, but differ by the charge.



STAR's proposal and projections

https://drupal.star.bnl.gov/STAR/system/files/STAR_BUR_Run1718_v22_0.pdf



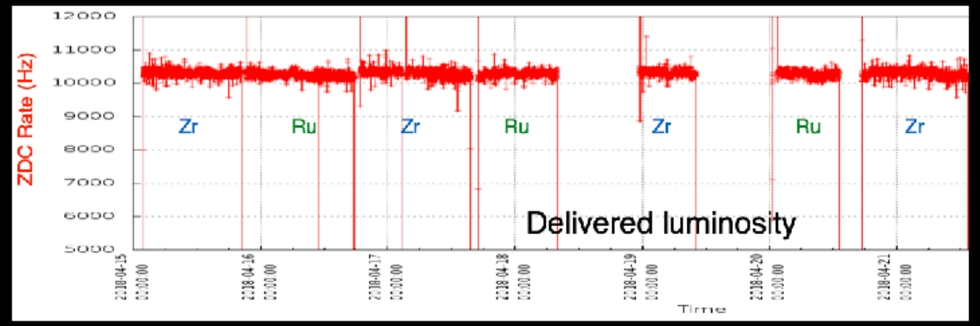
5σ difference in Δγ observable if signal is at 20% level

~10% larger B-field in Ru+Ru but similar background as Zr+Zr makes isobar collisions ideal to make a decisive test of CME

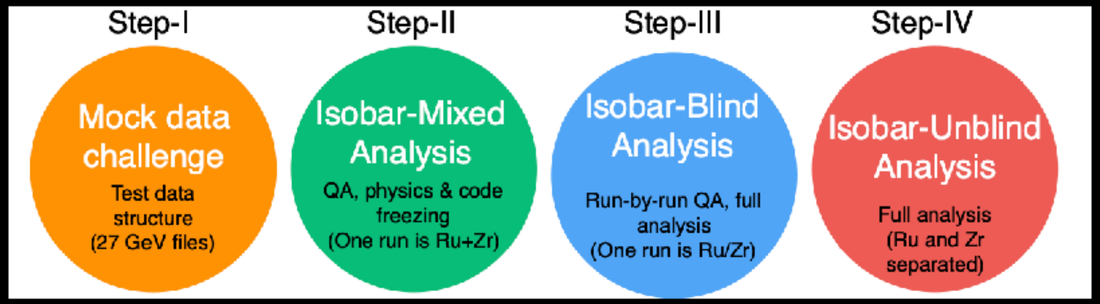
Many more model studies on the observability of CME with Isobar collisions have come up

Shi et al. Annals Phys. 394 (2018) 50-72 arXiv:1711.02496 [nucl-th]
Sun et al. Phys.Rev. C98 (2018) no.1, 014911 arXiv:1803.06043 [nucl-th]
Xu et al. Phys.Rev.Lett. 121 (2018) no.2, 022301 arXiv:1710.03086 [nucl-th]
Deng et al. Phys.Rev. C97 (2018) no.4, 044901 arXiv:1802.02292 [nucl-th]
Schenke et al., Phys.Rev. C99 (2019), 044908 arXiv:1901.04378 [nucl-th]
Hammelmann et al, arXiv:1901.04378

Isobar Run & Blind Analysis From STAR



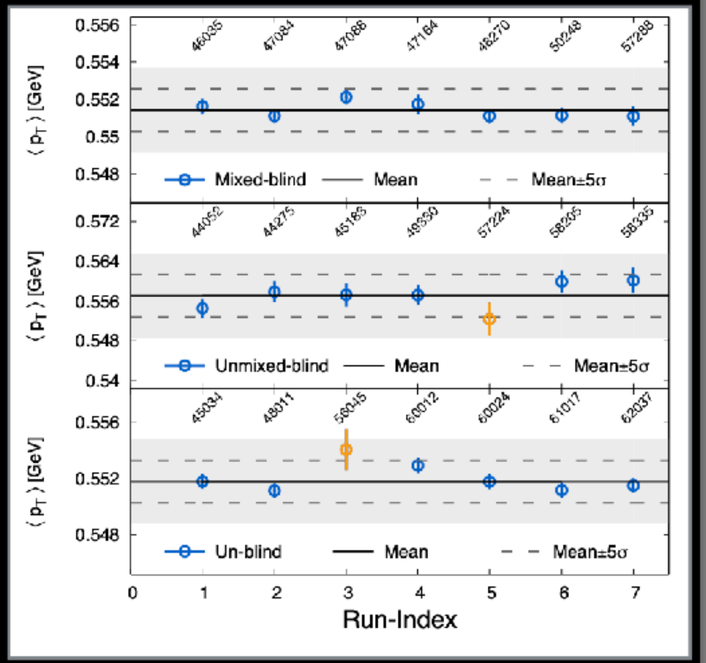
Multiple institutions actively participating in the blind analysis which is done in four steps
Goal is to eliminate "predetermined bias"



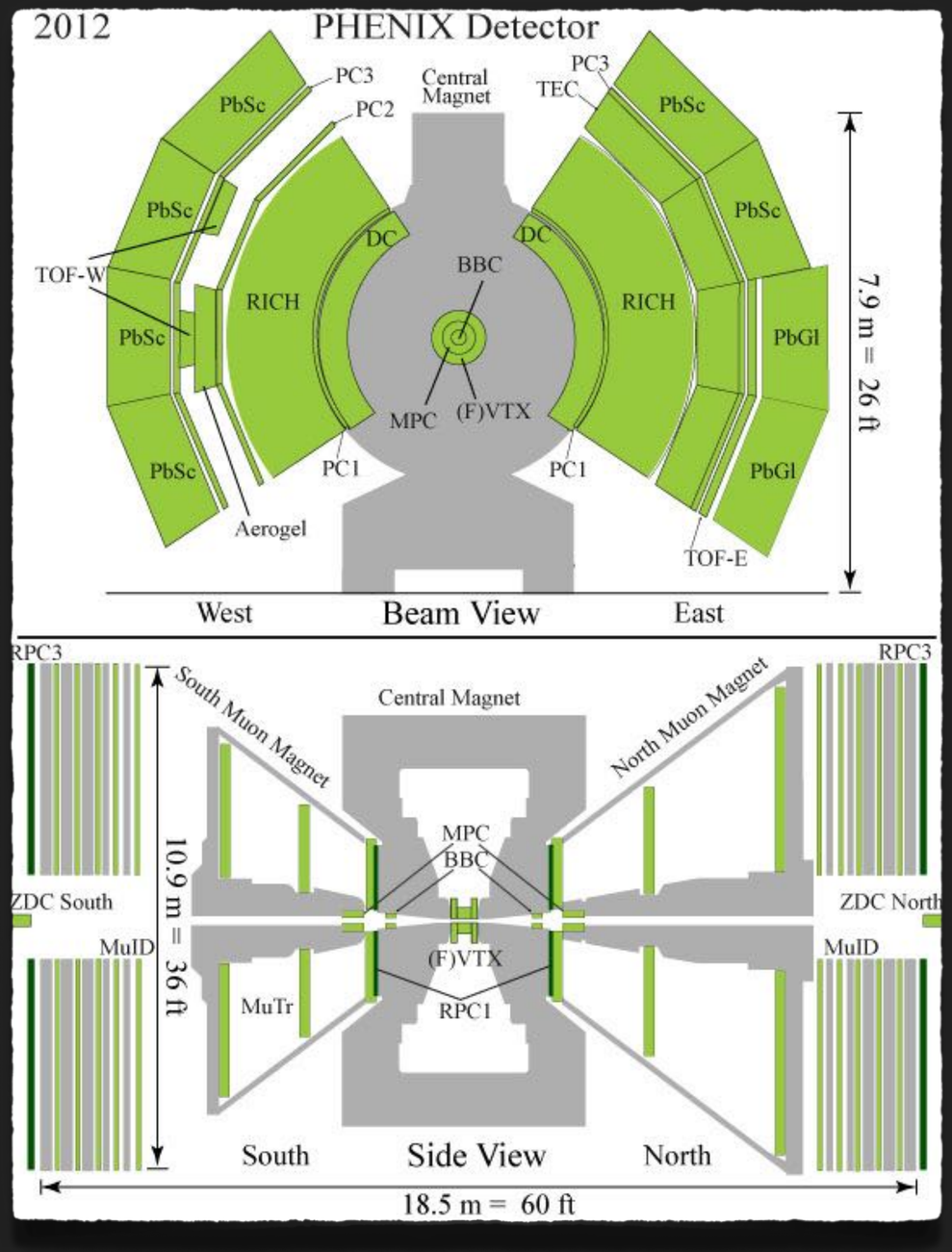
All steps of the blind analysis were tested with mock data sample and documented



STAR collaboration, arXiv:1911.00596



PHENIX DETECTOR SYSTEM



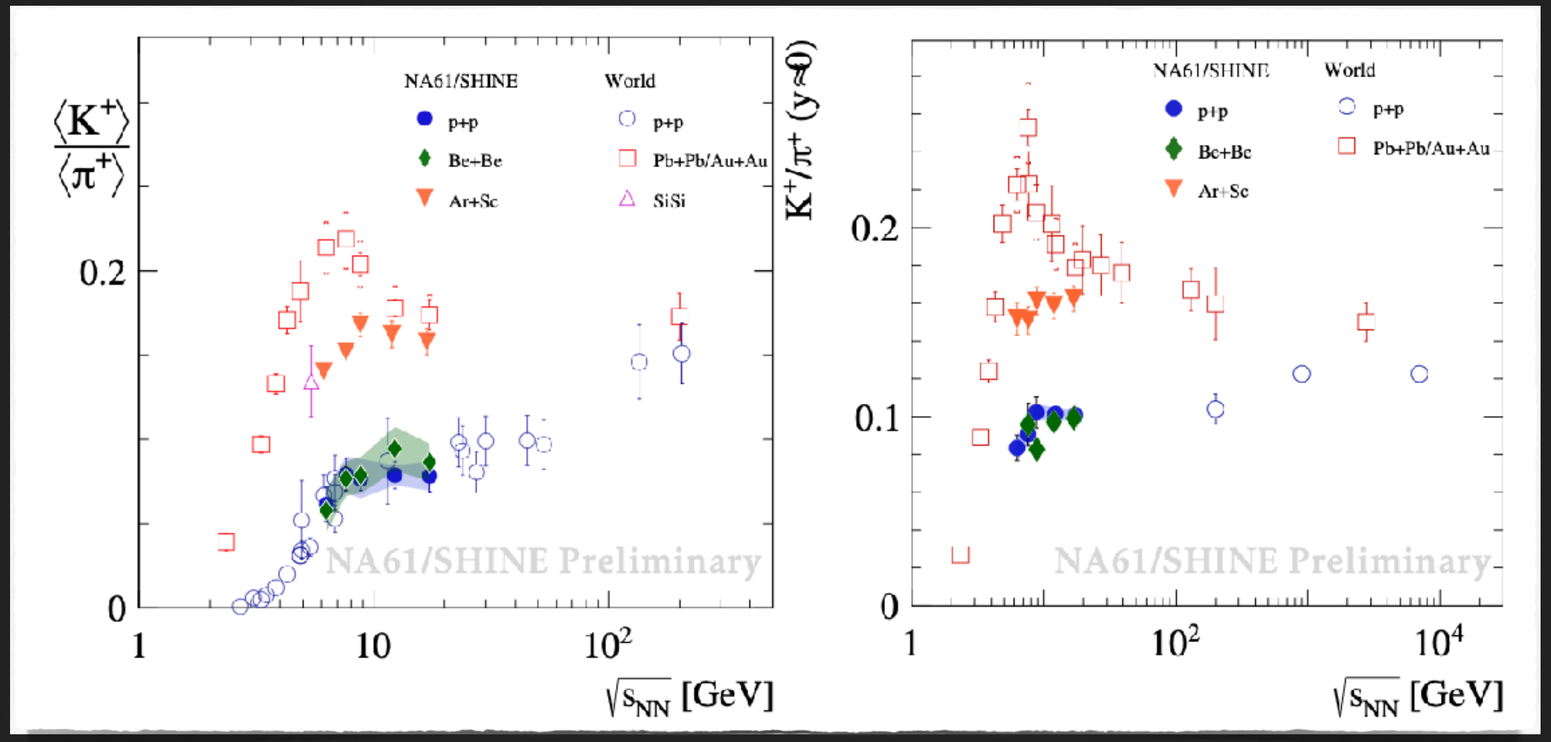
- **P**ioneering **H**igh **E**nergy **N**uclear **I**nteraction e**X**periment
- *special purpose detector to measure **rare processes** involving **leptons** and **photons** at the **highest luminosities**.*
- ***Versatile** detector to identify many particle species, recording large amount of collisions: **p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Au+Au, U+U**.*
- ***Dismantled in 2016**, to give way to sPHENIX*

1ST ORDER PHASE TRANSITION Strangeness production



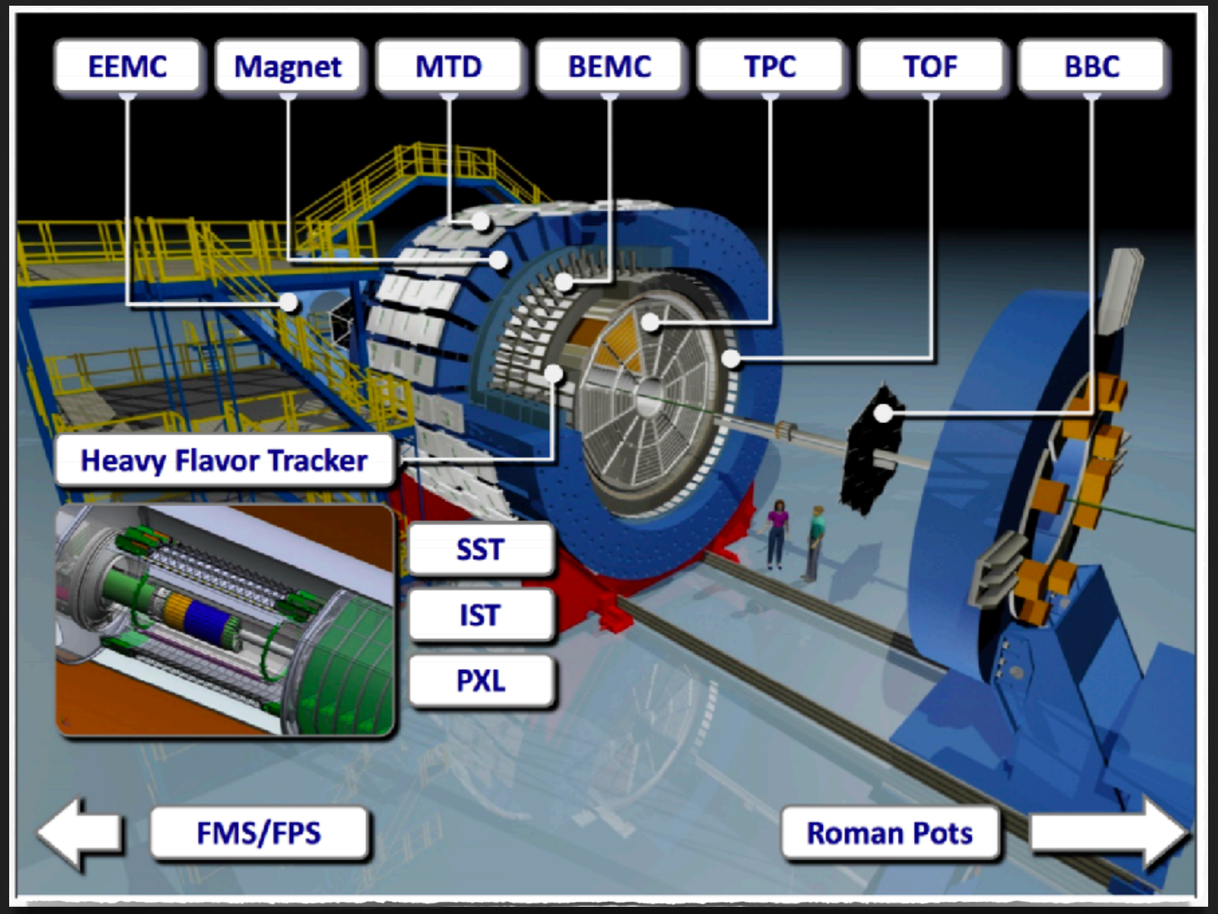
Crossing the phase transition leads to a decrease of the strange/non-strange particle ratio – the horn-like structure.

Gaździcki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705

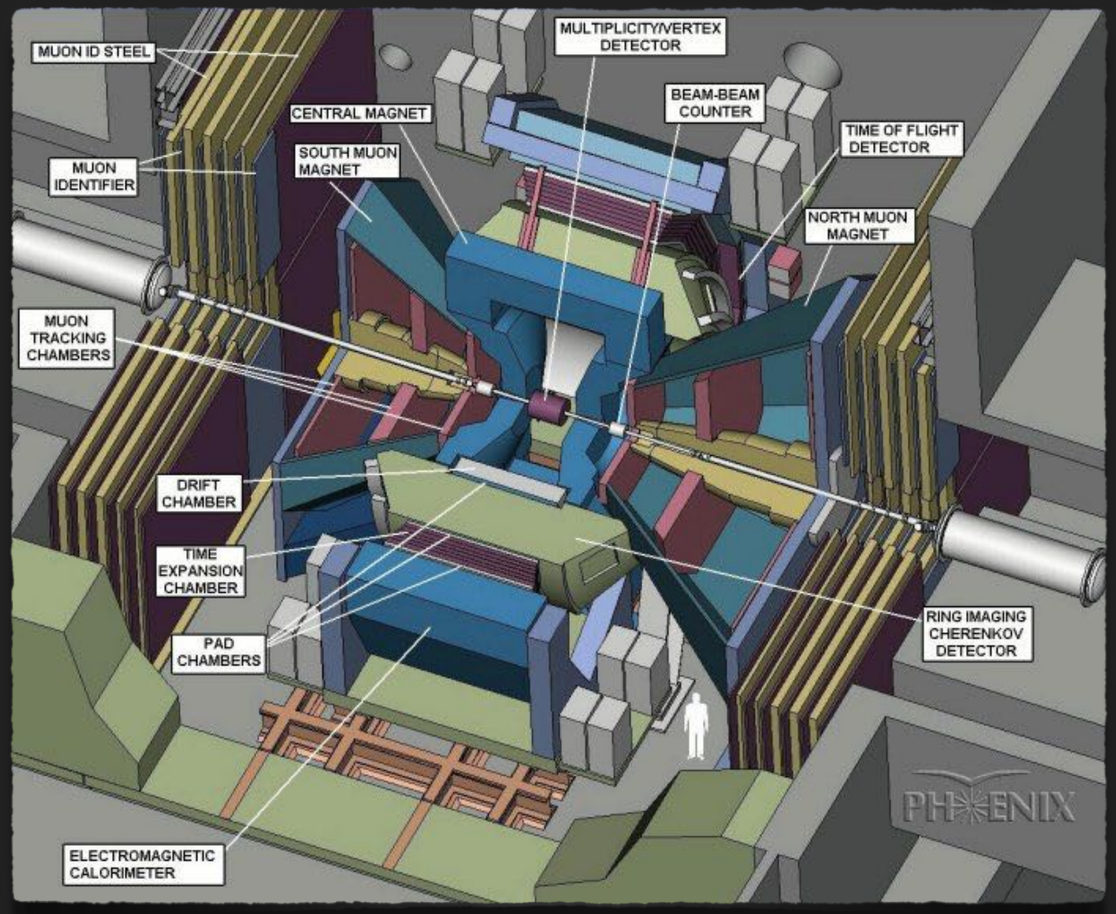


EXPERIMENTS

STAR

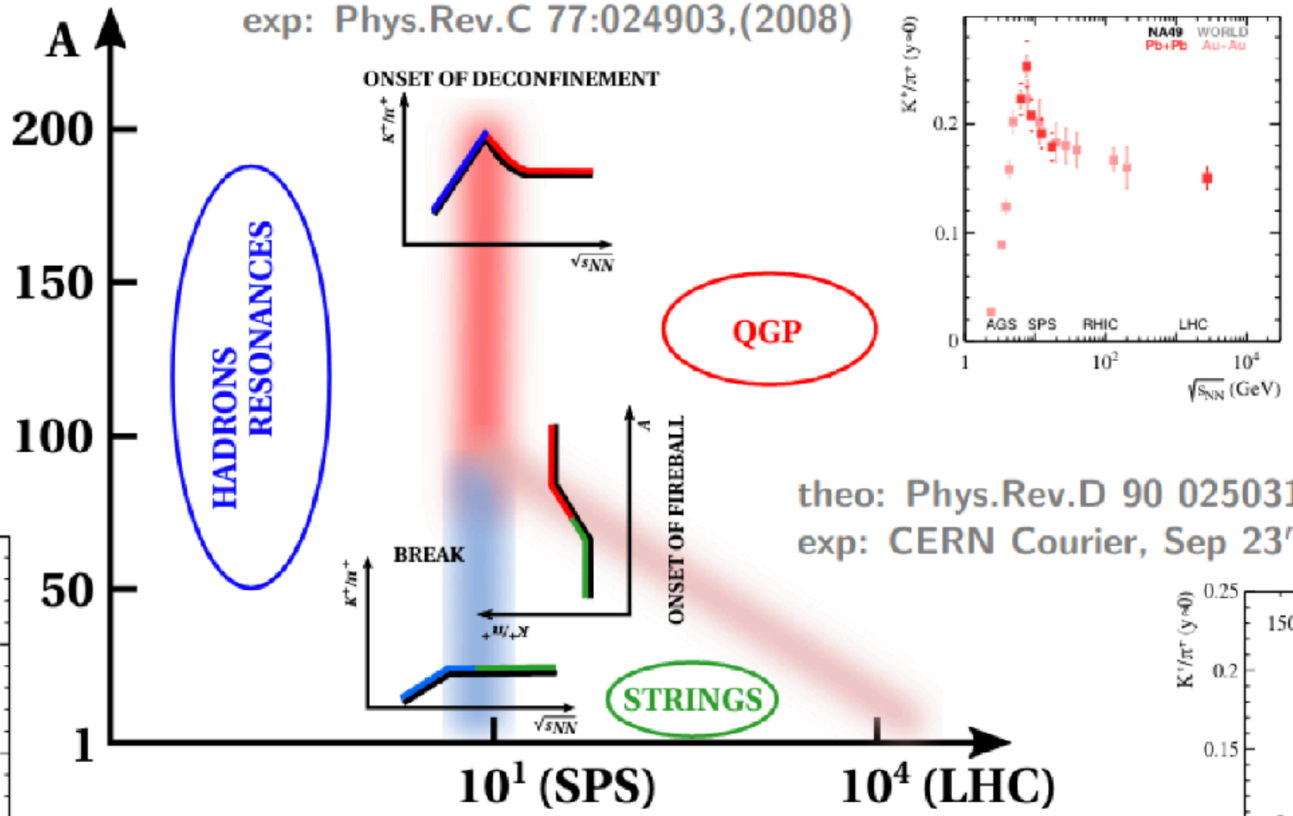


PHENIX

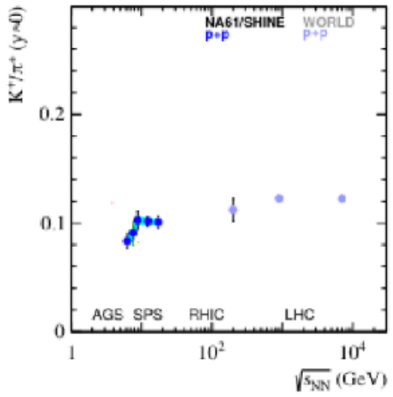


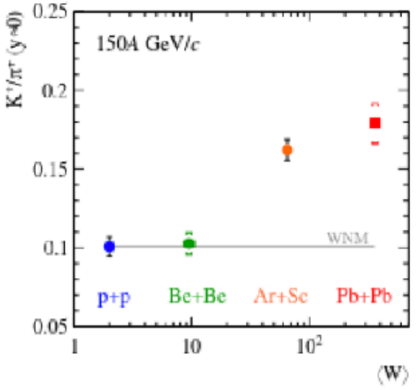
1ST ORDER PHASE TRANSITION Strangess production

theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)



theo: Phys.Rev.D 90 025031 (2014)
exp: CERN Courier, Sep 23rd, 2019





theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901