Exploring QCD Matter

at high baryon density

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FAIRNESS : FAIR Next Generation Scientists

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Talk Outline

Introduction

- Big Questions: Why Study QCD Matter?
- The QCD Phase Diagram
- What Theory can tell us (experimentalists perspective)

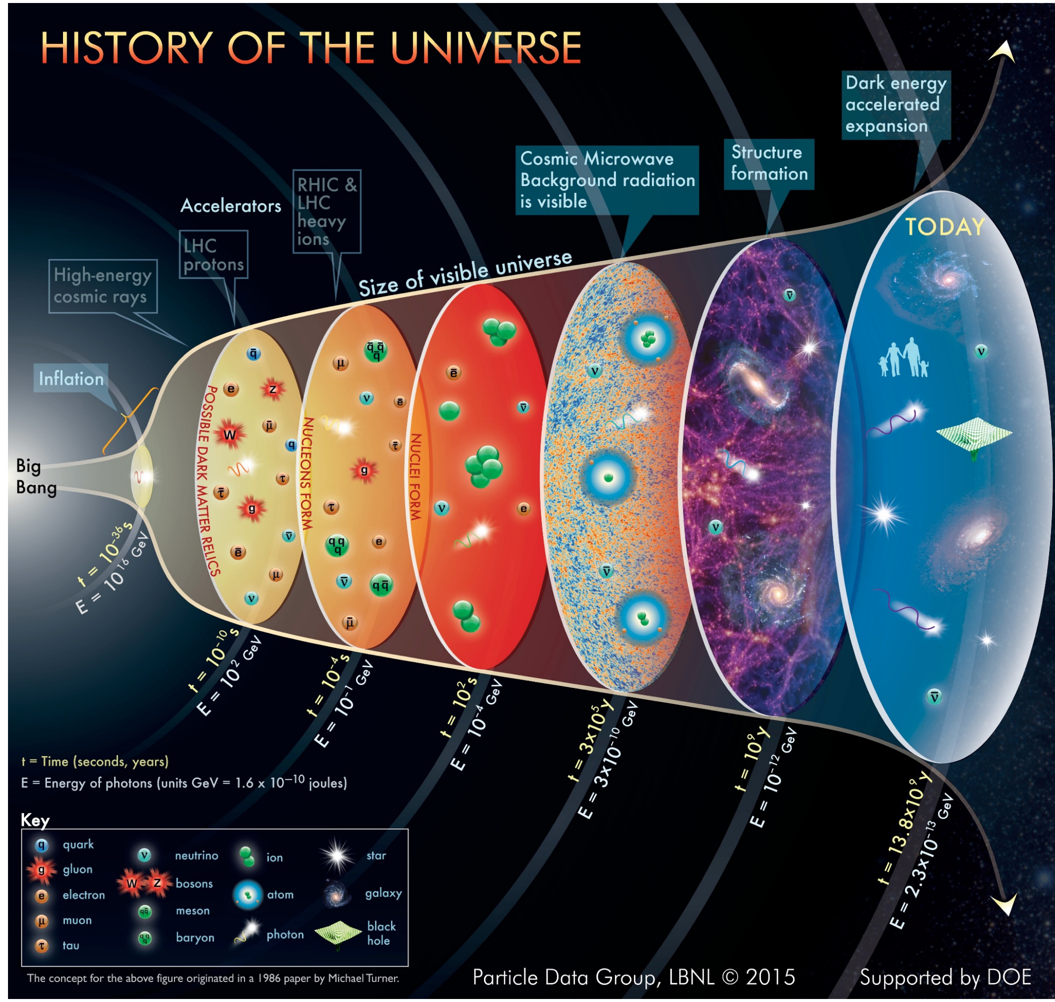
Studying QCD Matter with Heavy Ion Collisions

- Basics of Heavy Ion Collisions
- Scanning the phase diagram
- Search for 1st Order phase transition & Critical point
- Search for Chiral Symmetry Restoration

Summary & Outlook

Why study QCD Matter?

The history of the Universe
(as we currently understand it)



Early Universe :

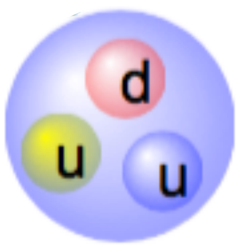
- High temperature / energy density
- low density
- Too hot for "normal" matter to form
- How did the earliest forms of normal matter form?

We study QCD matter to understand the physical evolution of the early Universe and emergence of structure

Chiral Symmetry and the Proton

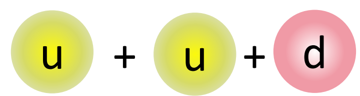
- The proton (and neutron) make up almost all visible matter
- The proton is (much) more than the sum of its parts!

p



M_p= 938 MeV

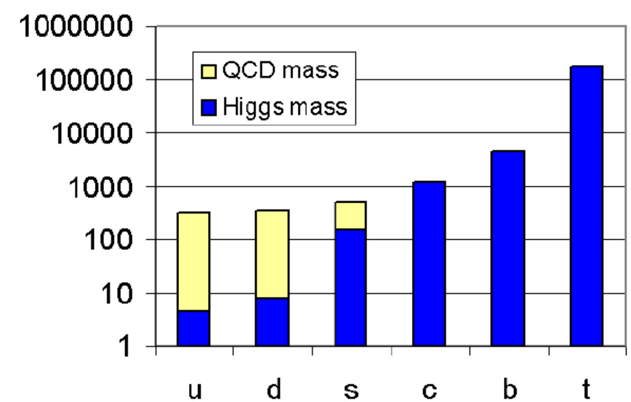
$\neq$



$M\ \approx$ 10 MeV

M_u= 2.3 MeV

M_d= 4.8 MeV

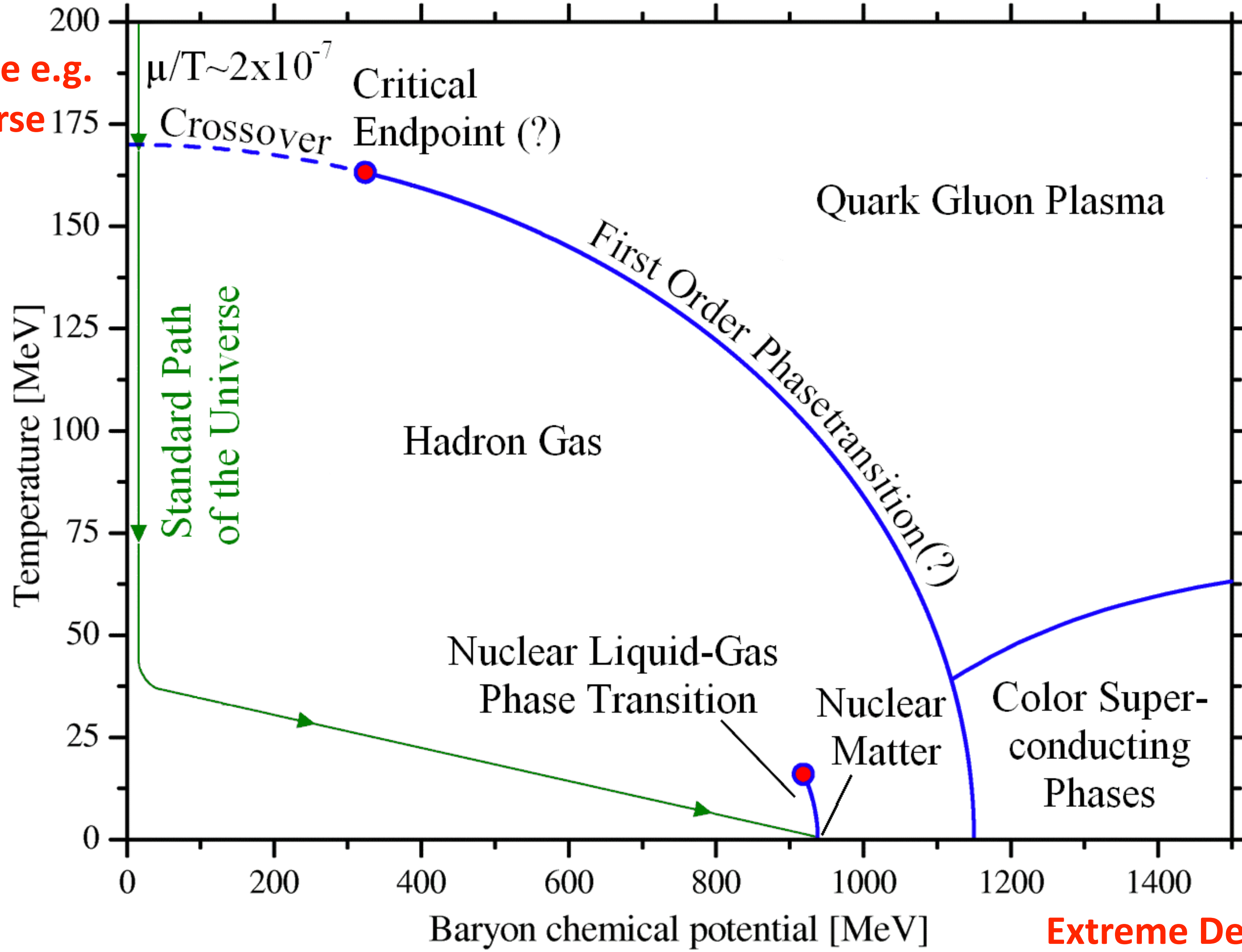


- Higgs Boson only explains the mass of fundamental particles!
- The remaining 99% of proton mass:
  - Kinetic energy
  - Gluon self interaction
  - Quark Interactions (chiral symmetry breaking)

We study QCD matter to understand the mass of normal matter

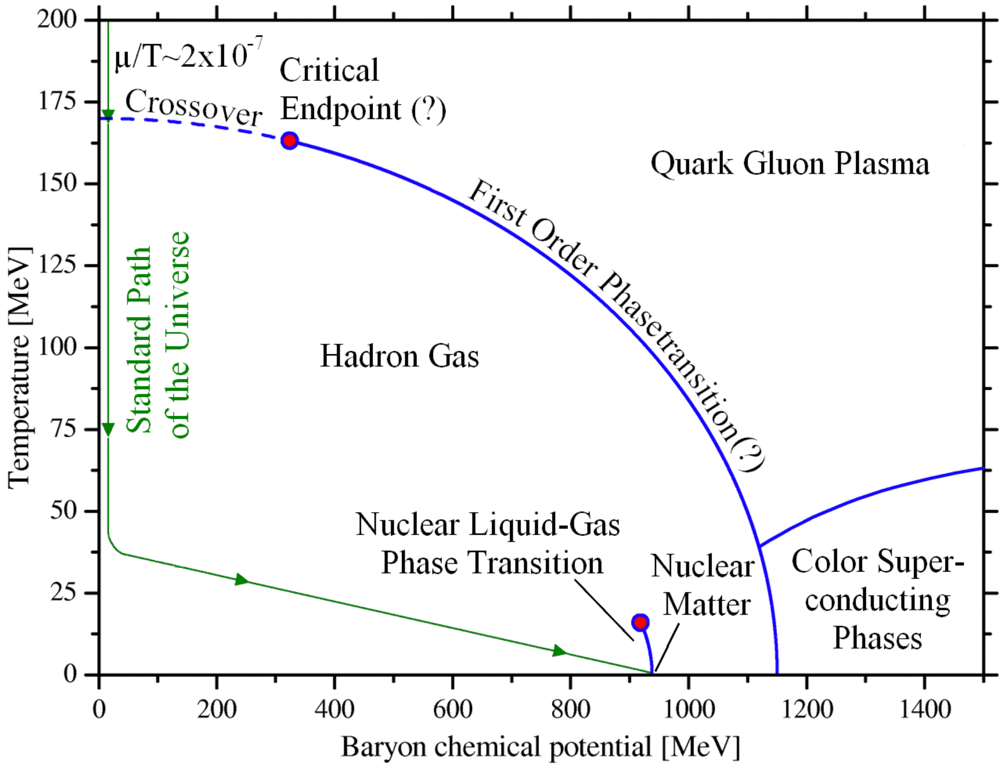
The QCD Phase Diagram

Extreme Temperature e.g. Early Universe



Extreme Density e.g. Compact Stars

The QCD Phase Diagram



$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(i\gamma^{\mu}D_{\mu} - m)q - \frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a}$$

But we know QCD, why not just calculate it!

Big questions = questions about the QCD Phase Diagram

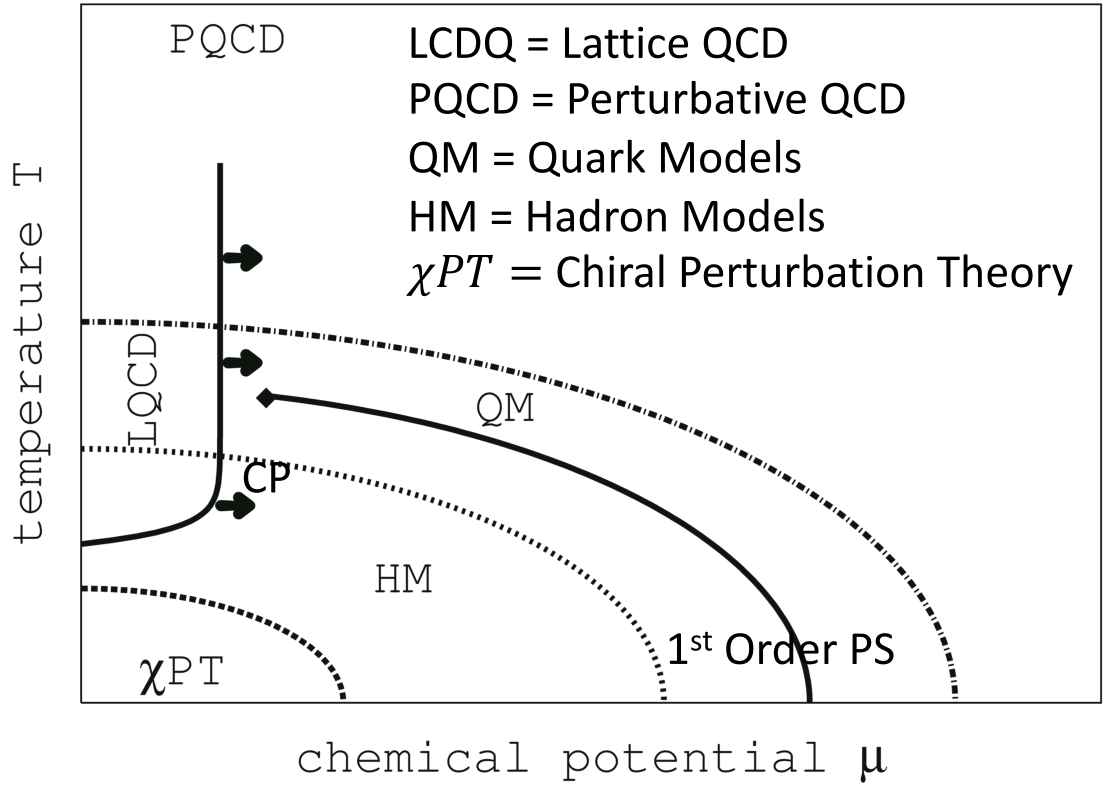
Is there a 1st Order Phase transition between the hadron gas and the Quark Gluon Plasma phases?

Is there a critical endpoint between phase transition and crossover region?

Does the transition to a chiraly symmetric phase coincide with the deconfinement transition?

What is the equation of state for these types of matter?

QCD Calculations

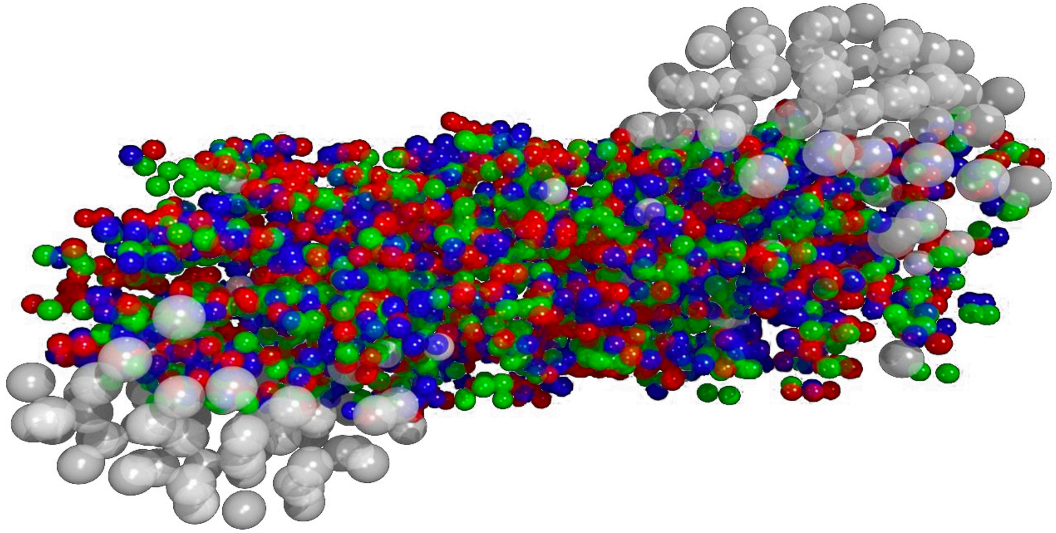


Theoretical Approaches:

- Lattice QCD : "first principles"
- Chiral Perturbation Theory : Systematic approach
- Hadron Gas Models & Quark Models : Can be verified in overlap region with LQCD and χPT
- Many other models – Sorry, I cannot possible list them all

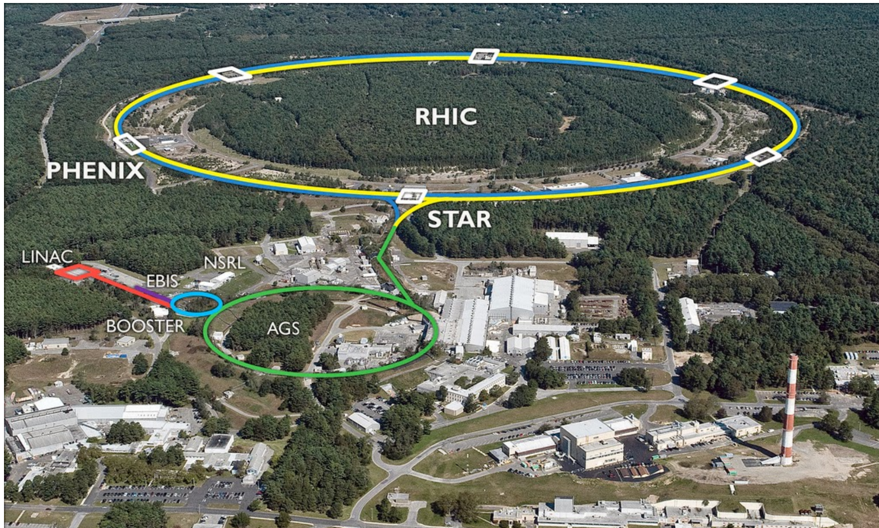
- Only Lattice QCD is really QCD from first principles – though some caveats
- Sign problem prevents direct calculations at large baryon chemical potential
  - Progress is being made
  - Regions of overlap with LQCD can help verify other models

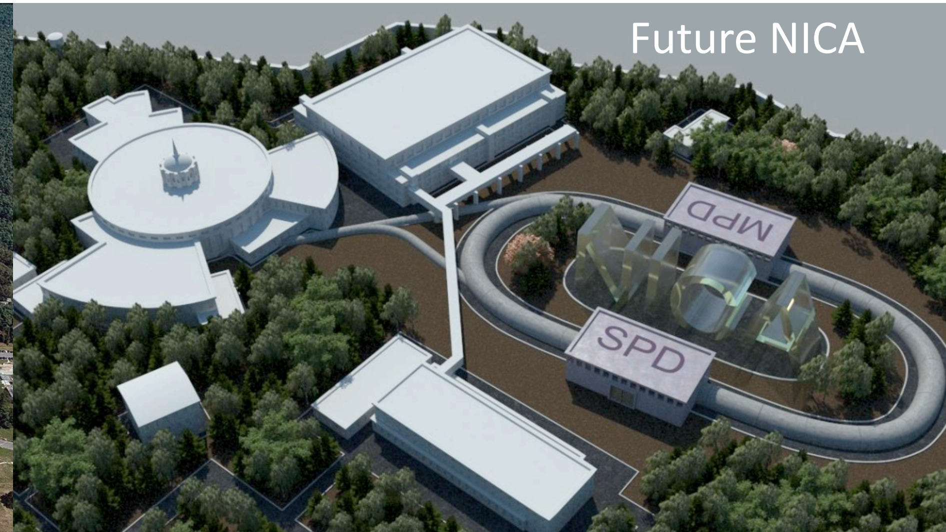
Experimental measurements are needed to determine key features of phase diagram



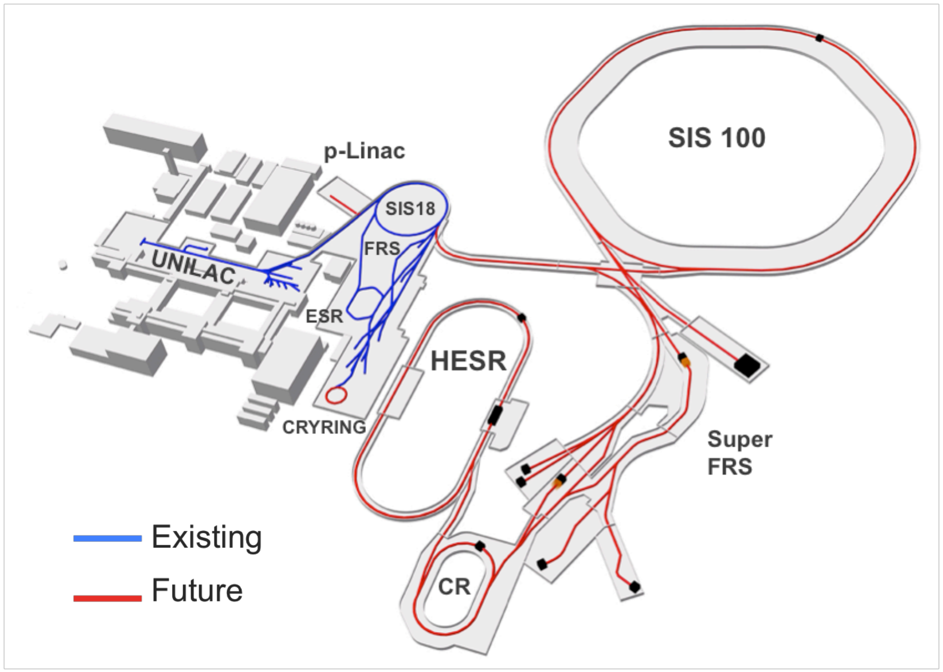
Studying QCD Matter with Heavy Ion Collisions

Facilities for Heavy Ion Collisions





FAIR Complex at GSI



Currently Running

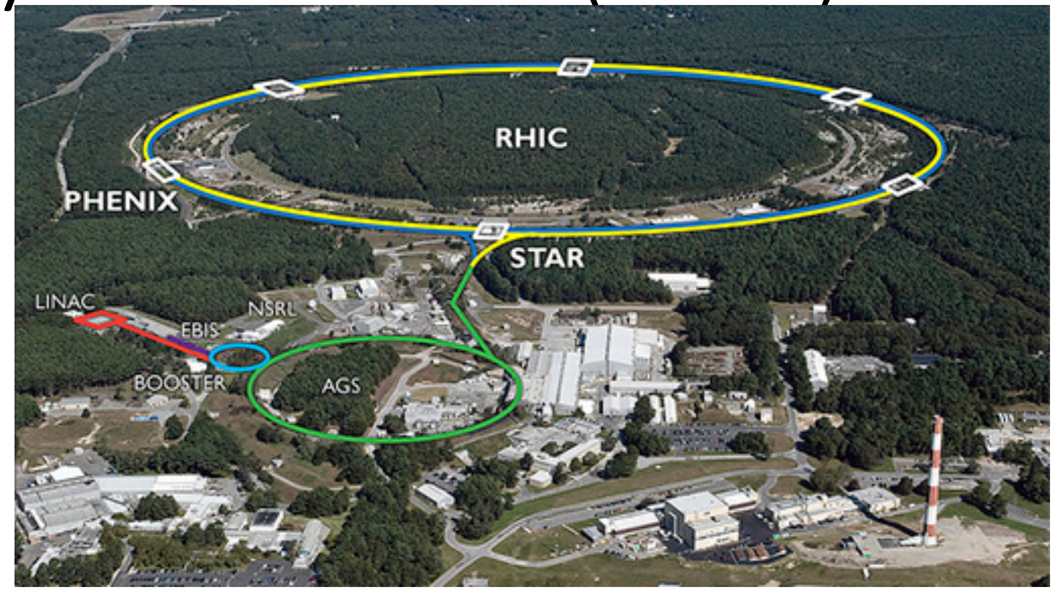
SIS18

- Fixed target with ions, protons and π beams
- $\sqrt{s_{NN}} \approx 2.4 - 2.6$ GeV
- μ_B range : ~880 – 670
- Active experiments:
  - HADES (start 2012)
  - miniCBM (start 2018)

More about the Future near the end of the talk

Relativistic Heavy Ion Collider (RHIC)

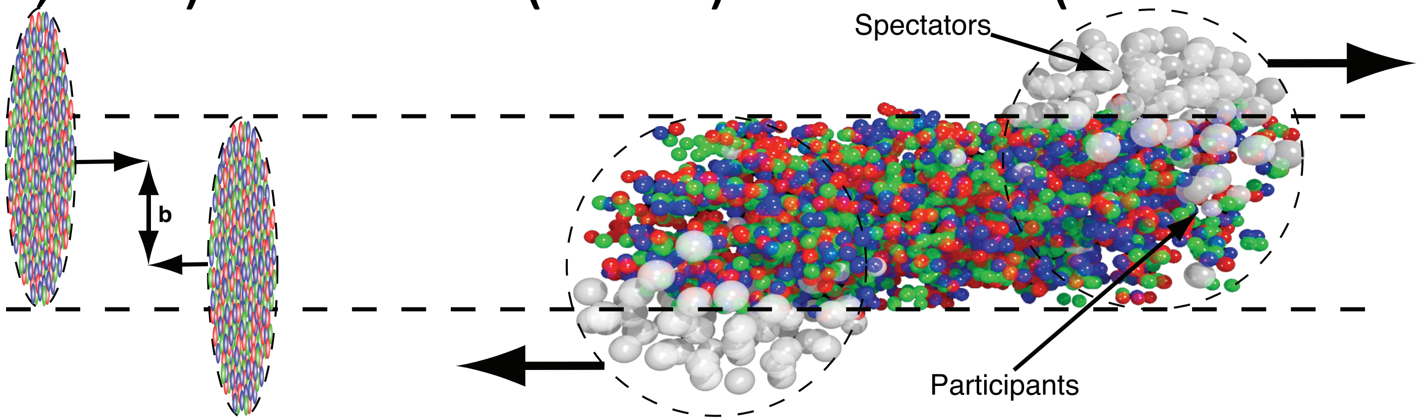
- Located at Brookhaven National Laboratory, Long Island, NY, USA
- Ions accelerated with $\vec{E}$, steered with $\vec{B}$
- Uses >1,700 dipole magnets in two 3.8 km rings



- Since beginning operation in 2000:
  - p+p, p+Au, p+Al, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Au+Au and U+U at $\sqrt{s_{NN}}$=7.7 – 200 GeV, p+p at $\sqrt{s}$ = 510 GeV
- Four experiments:
  - STAR, PHENIX(‘16), BRAHMS(‘06), PHOBOS (‘05) – STAR is only active experiment now

Studying the QCD Phase with Heavy Ion Collisions

Use SIS18 / RHIC / LHC to accelerate heavy ions (gold, lead, etc.) to >0.90c (SIS18) or >0.99c (RHIC & LHC)



$\gamma^{RHIC} \approx 108$

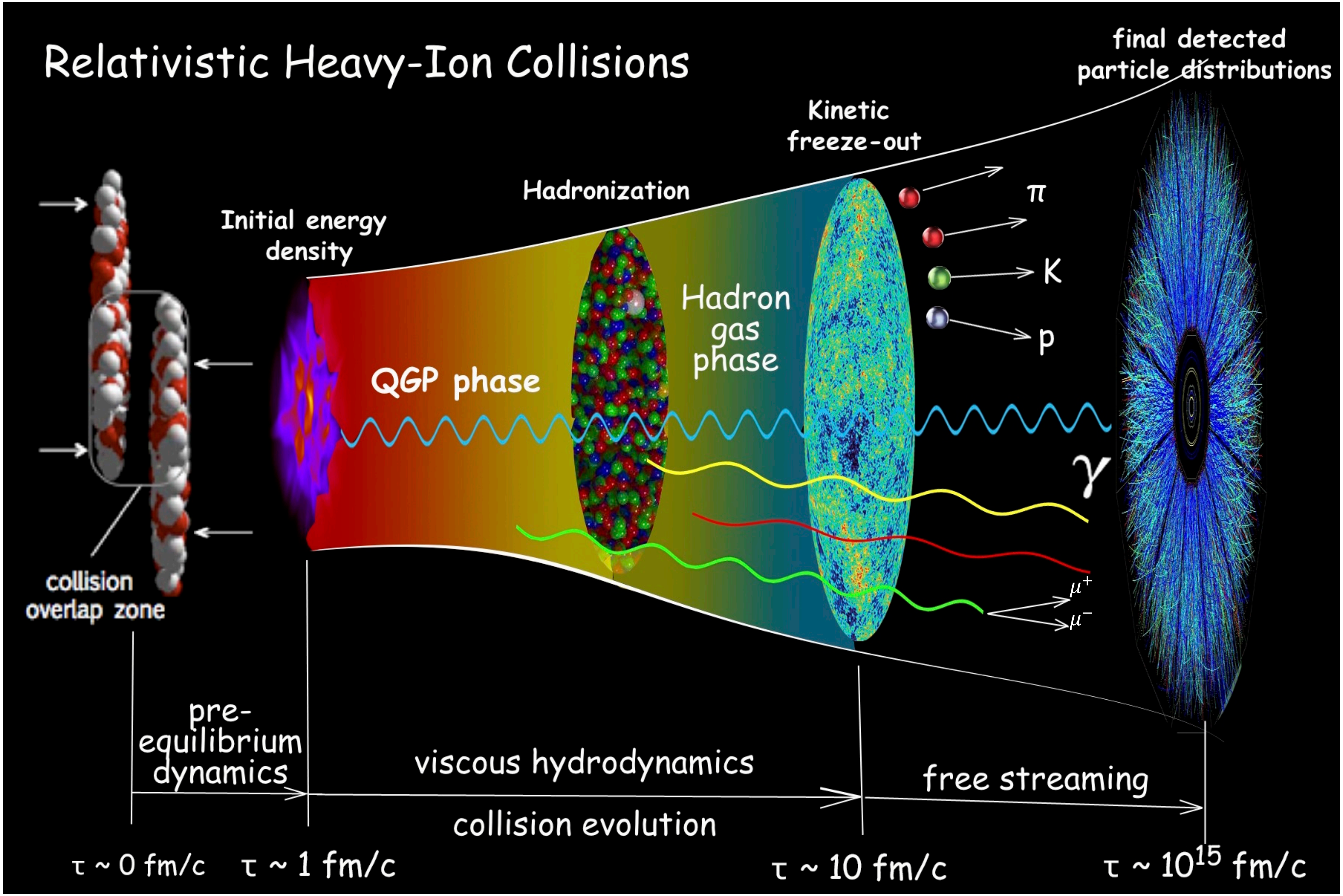
$\gamma^{LHC} \approx 7000$

At large γ - Ions are compressed into thin "pancakes"

$\gamma = \frac{1}{\sqrt{1-\beta^2}},\ L' = L/\gamma,\ \beta = v/c$

- Each HIC follows a specific trajectory through the QCD phase diagram
- Varying collision energy and impact parameter we can control:
  - Initial temperature, initial μ_B, system size, lifetime

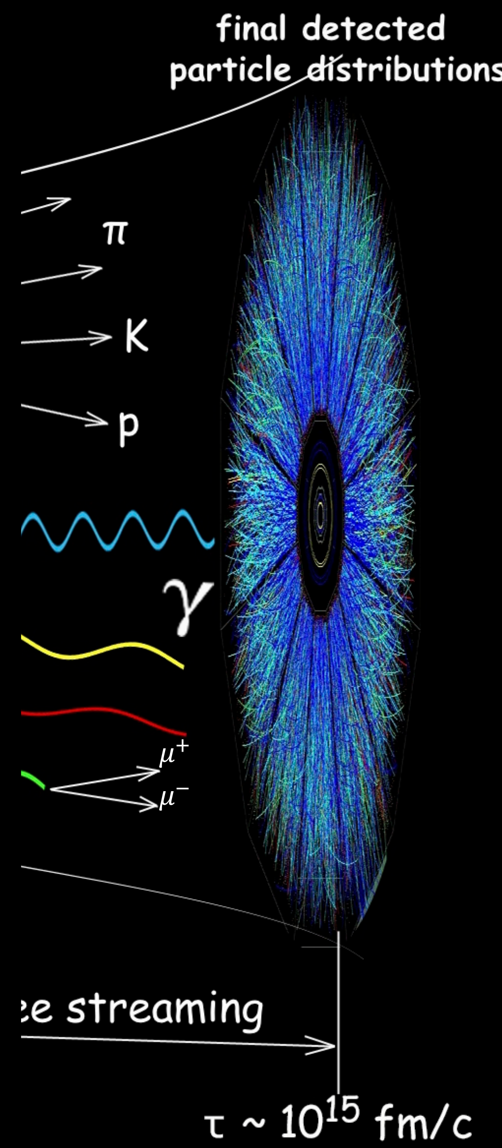
Life of a Heavy Ion Collision



Life of a Heavy Ion Collision

Relativistic Heavy-Ion Collisions

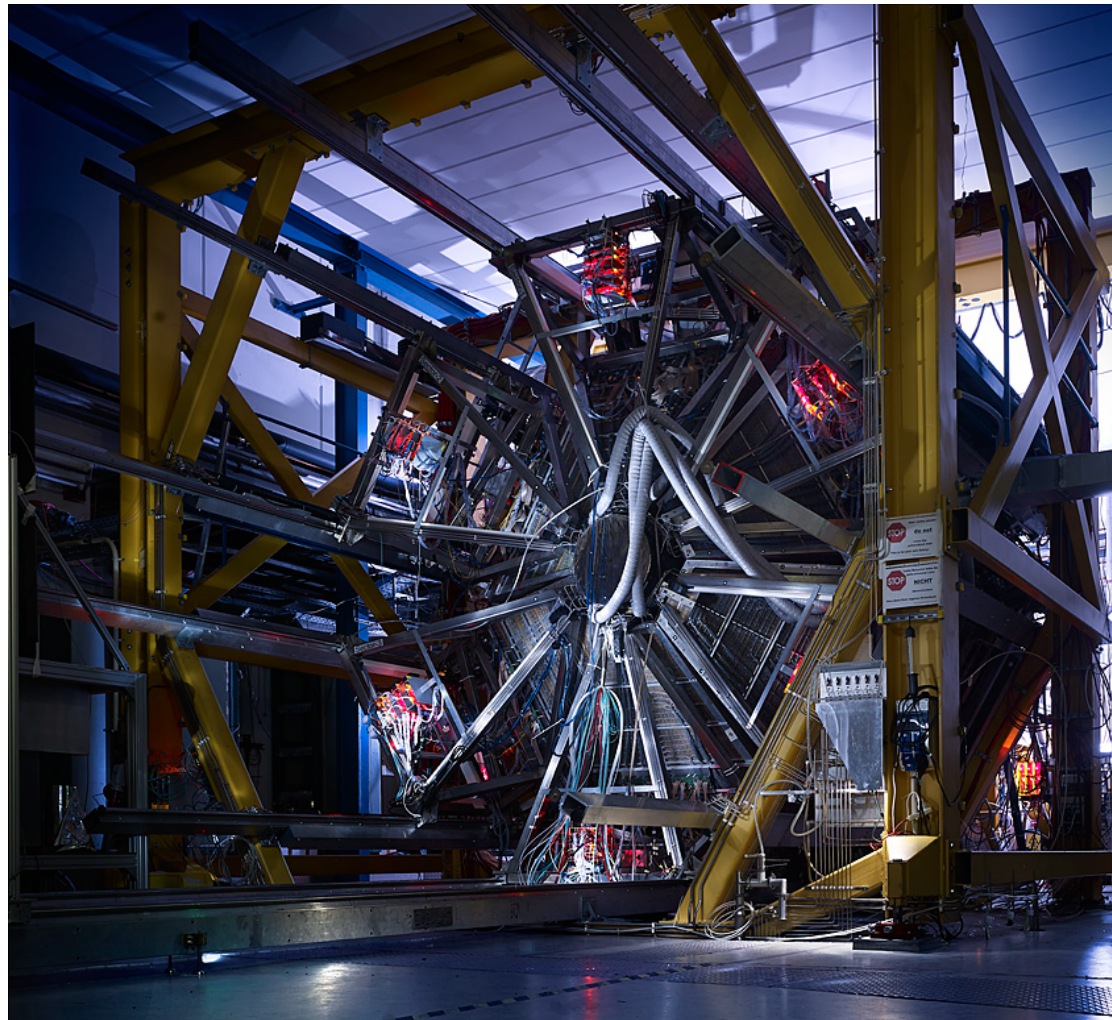
As we actually observe them



The HADES Detector

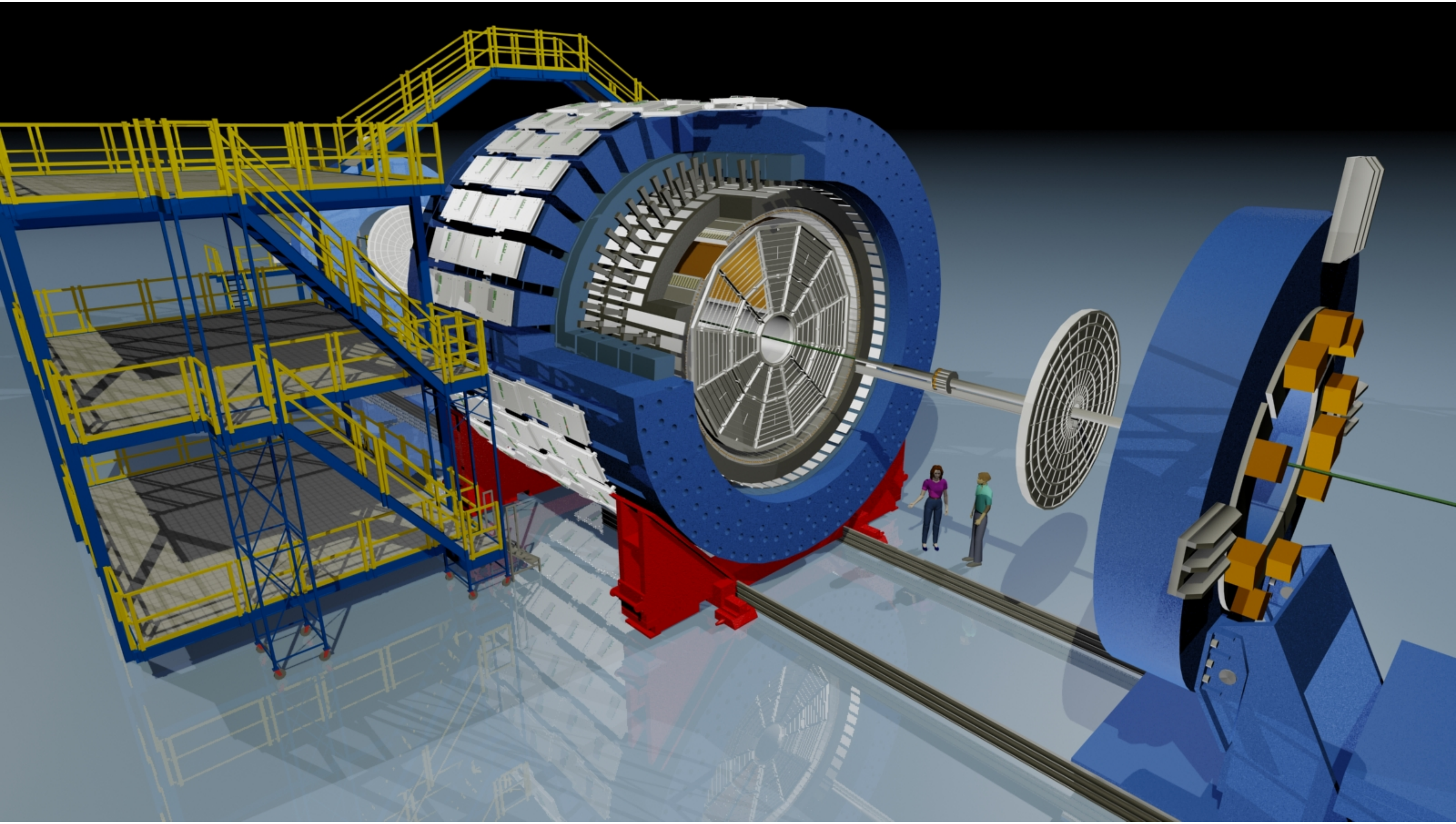
HADES = High Acceptance Dielectron Spectrometer

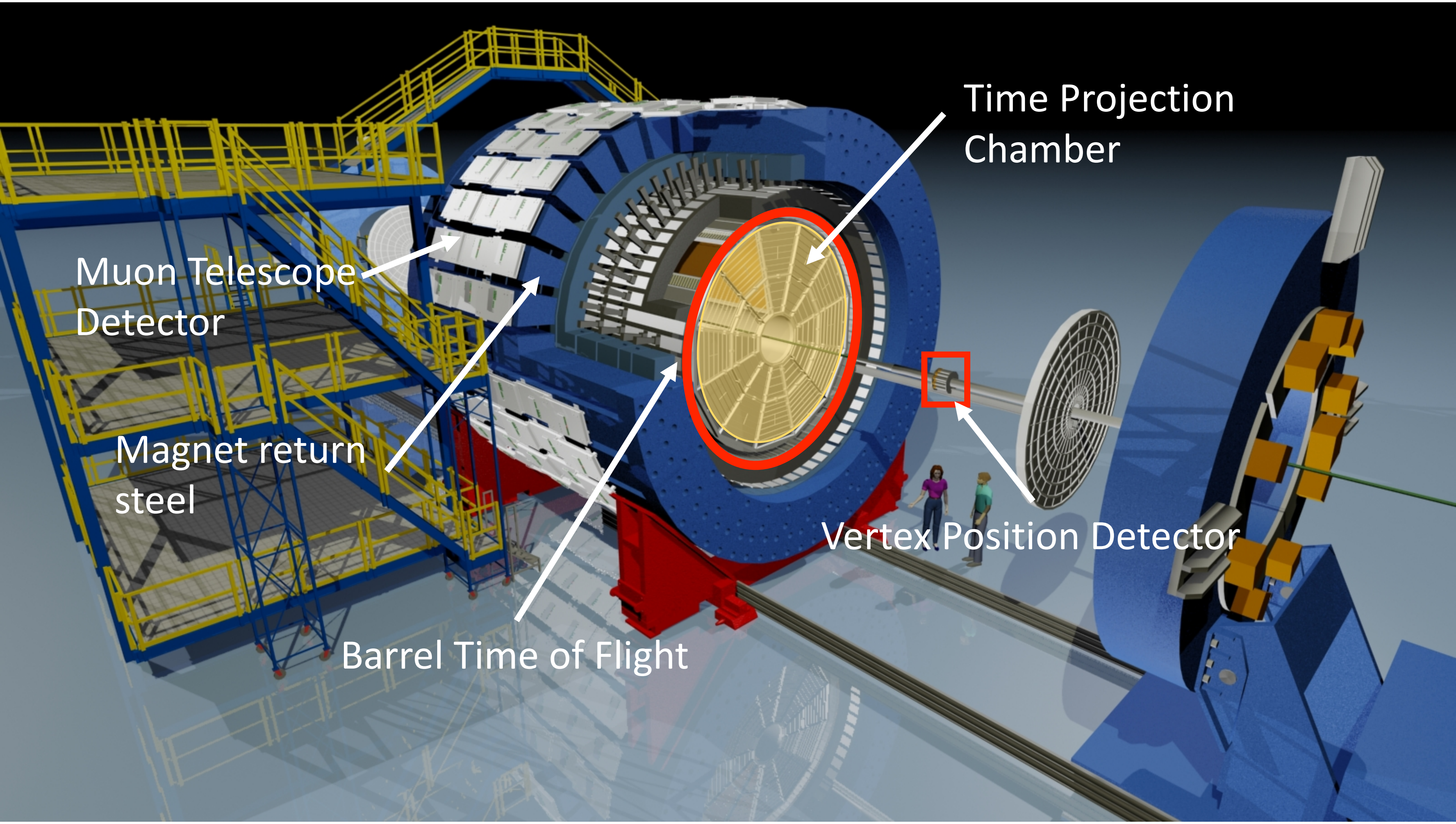
- Full azimuthal acceptance
- 18 to 85 degrees in Polar
- e^+e^- par acceptance : 35%
- Mass resolution : 2% (ρ, ω)



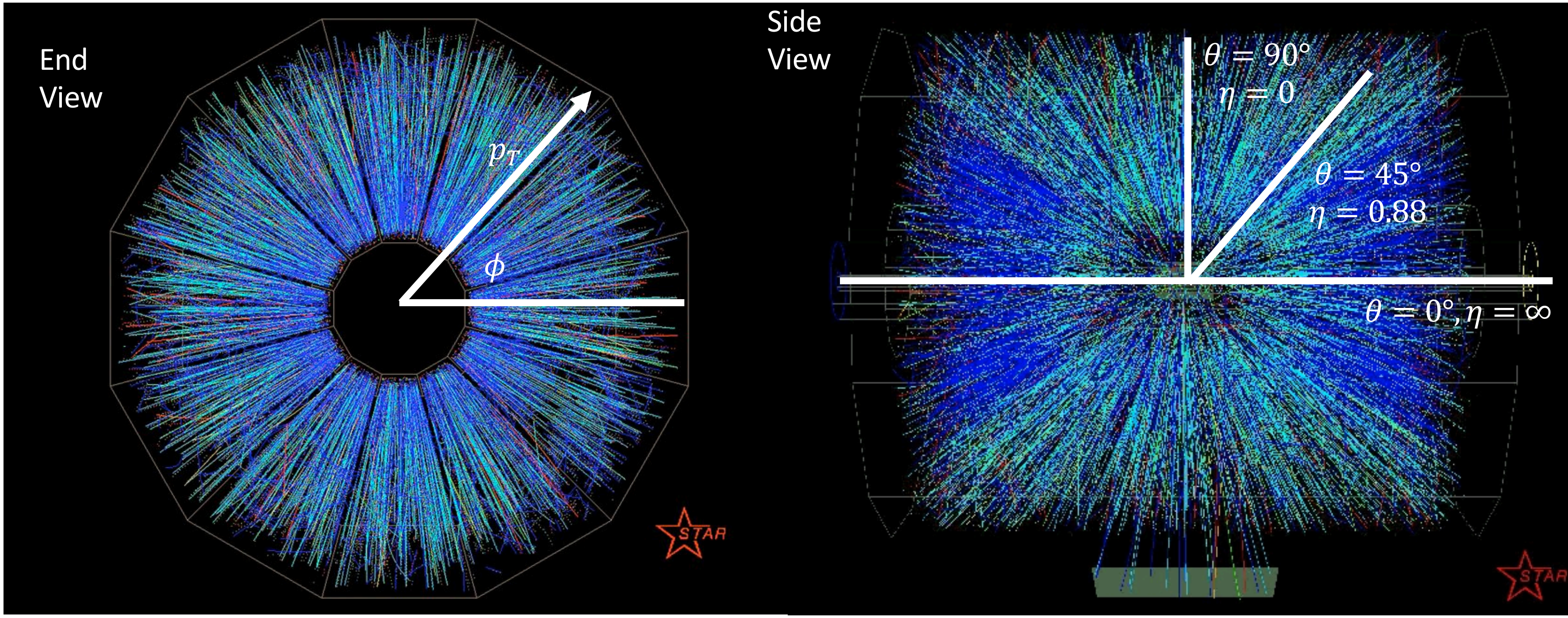
Physics Program:

- Excitation function for low-mass dielectron pairs
- Excitation function for (multi-)strange baryon/mesons




Time Projection Chamber
Muon Telescope Detector
Magnet return steel
Vertex Position Detector
Barrel Time of Flight

Heavy Ion Collision : Common Terms



Transverse Momentum:

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

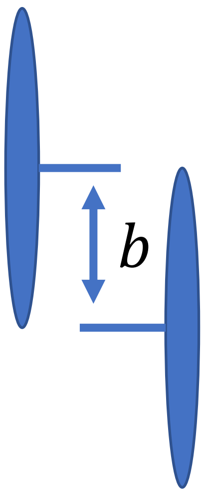
Rapidity: $y = \frac{1}{2}\ln\left(\frac{E+P_z}{E-P_z}\right)$

Additive under Lorentz boost

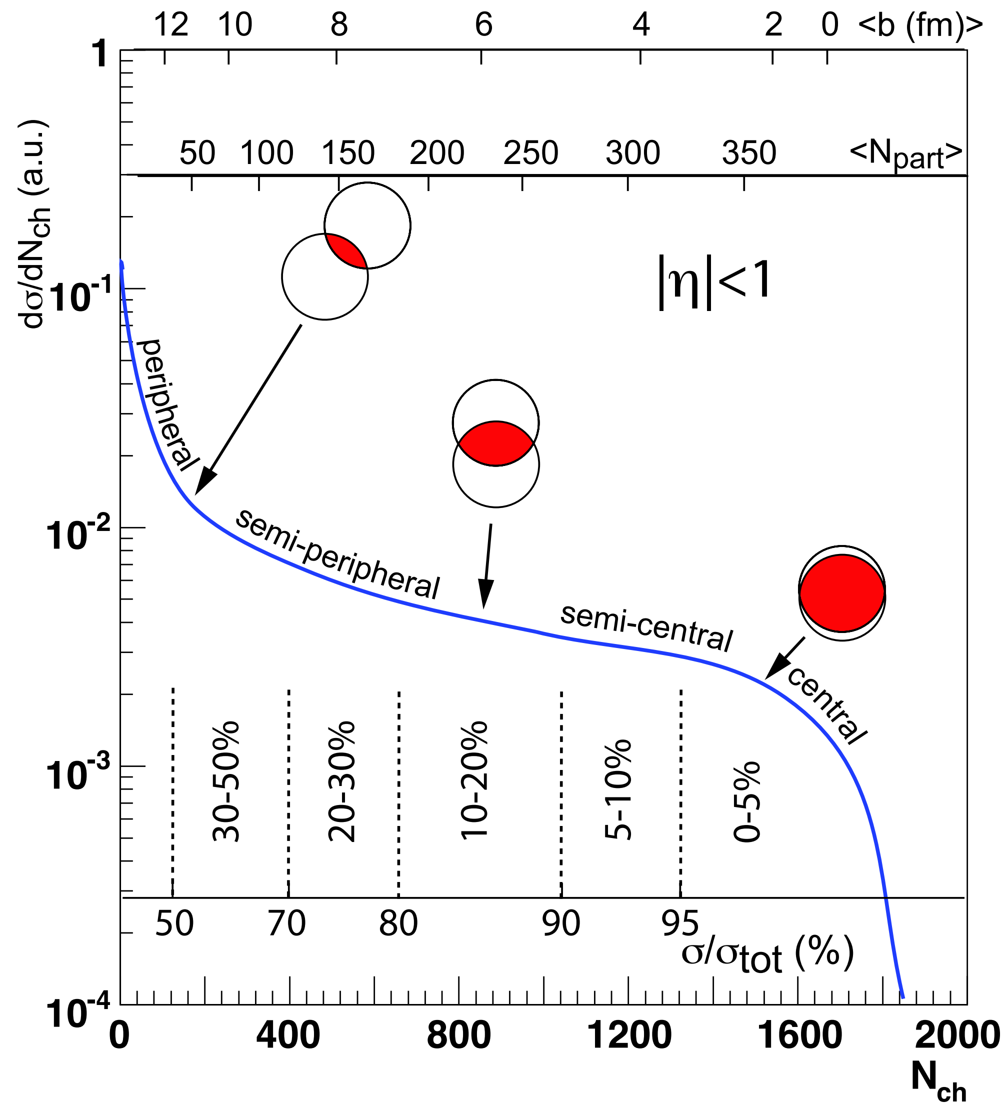
Pseudo-Rapidity (y for m=0) :

$$\eta = \frac{1}{2}\ln\left(\frac{P+P_z}{P-P_z}\right) = -\ln\left(\tan\frac{\theta}{2}\right)$$

Centrality in HICs



We cannot measure impact parameter (b) directly!

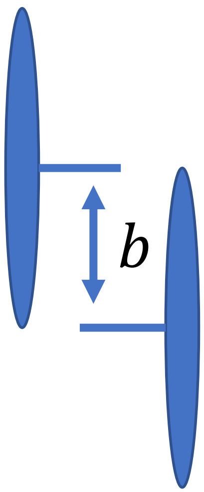


Instead we measure charged particle multiplicity (N_{ch}) and correlate to b

Same technique is used for:

- N_{part} - number of participating nucleons
- N_{coll} - number of binary collisions between nucleons

Centrality in HICs



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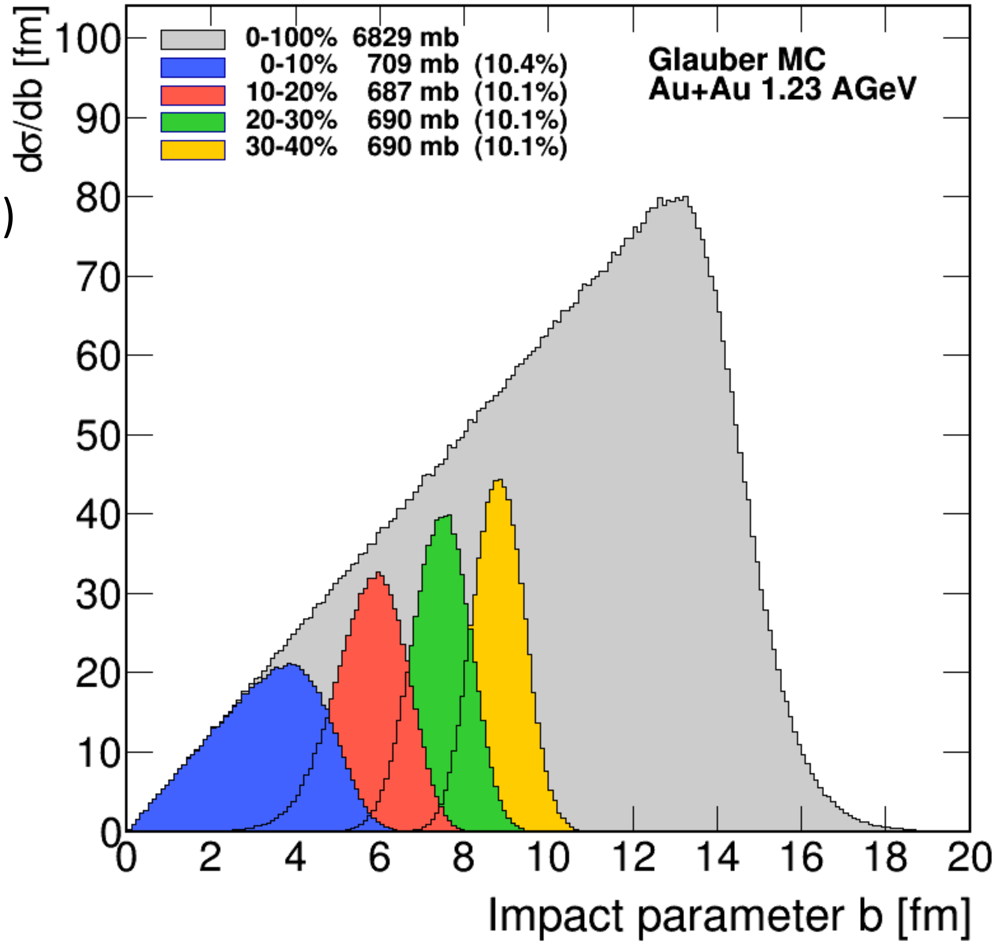

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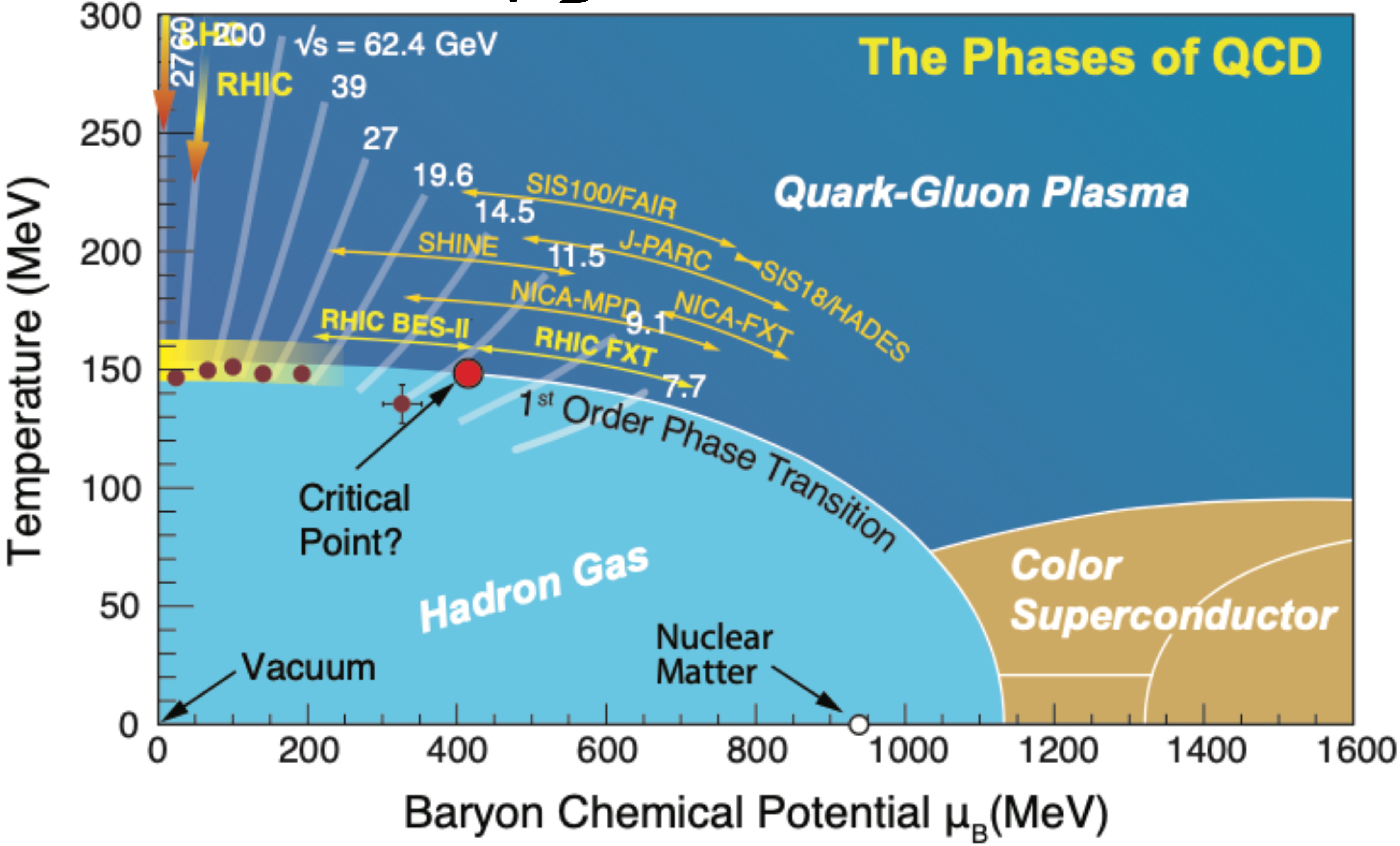
Going to high μ_B

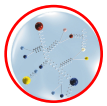


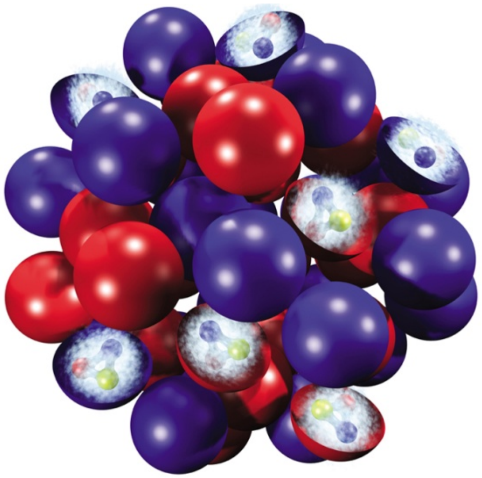
Effect of Collision Energy on μ_B

Beam energy effects deBroglie wavelength of partons.

Wavelength determines the scale observed by colliding parton :

- Whole nucleus
- Individual nucleons
- Individual partons





Low collision energy

High collision energy

Nucleons are opaque
Valence quarks are stopped
Excess quarks = high μ_B
Baryon dominated

Nucleons are transparent
Valence quarks pass through
Equal quark / anti-quarks = low μ_B
Meson dominated

Effect of Collision Energy on μ_B

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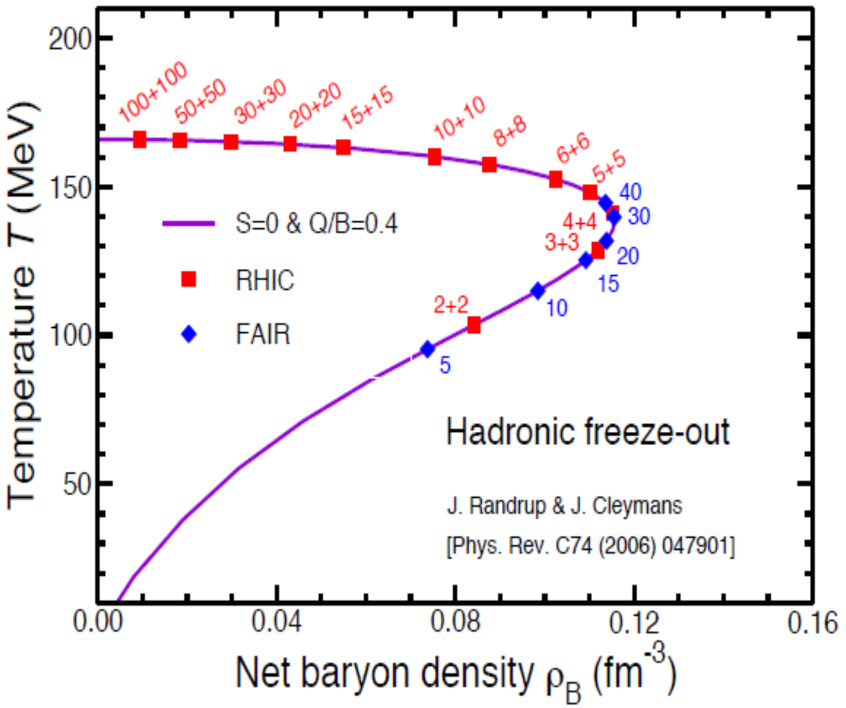


Low collision energy | High collision energy

Nucleons are opaque
Valence quarks are stopped
Excess quarks = high μ_B
Baryon dominated

Nucleons are transparent
Valence quarks pass through
Equal quark / anti-quarks = low μ_B
Meson dominated

Where in the phase diagram?

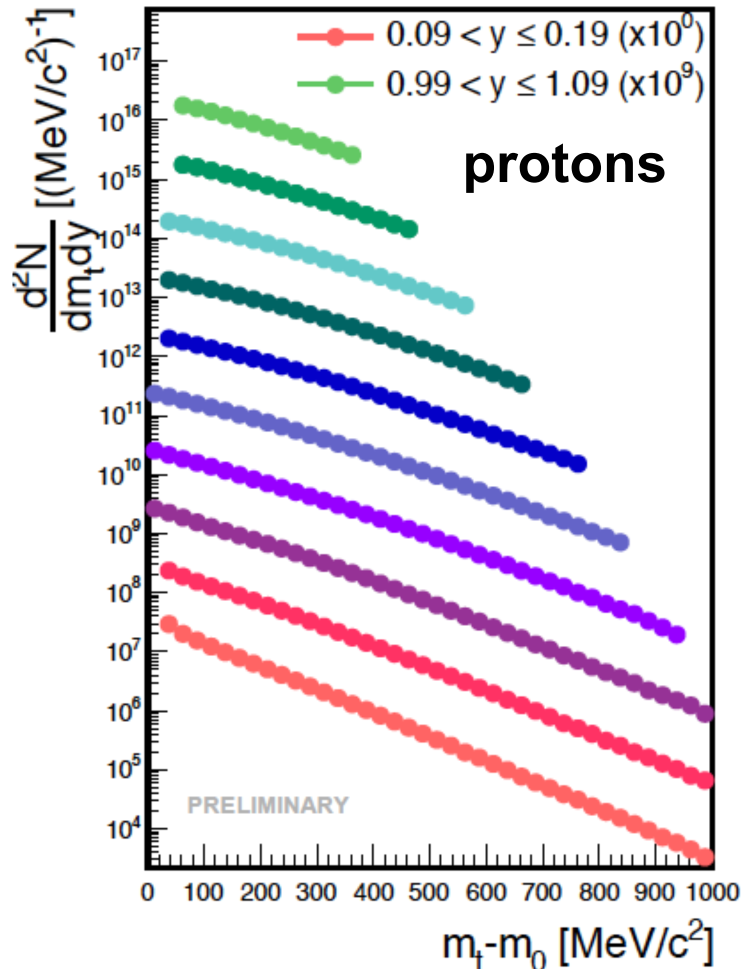
Experimentally how do we measure where we are in the phase diagram for a given:

- Collision energy
- Centrality
- Rapidity range

Using a model which assumes statistical equilibrium (Statistical Hadronization Models): Relate the measured particle yields (π, K, p, Λ, Ξ, ϕ, Ω) and their ratios, to the location in the phase diagram

$$\ln Z^{GC}(T,V,\{\mu_i\}) = \sum_{\text{species } i} \frac{g_i V}{(2\pi)^3} \int d^3p \ln\left(1 \pm e^{-\beta(E_i-\mu_i)}\right)^{\pm 1}$$

$$\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$$



Step 1 : Measure Particle Spectra

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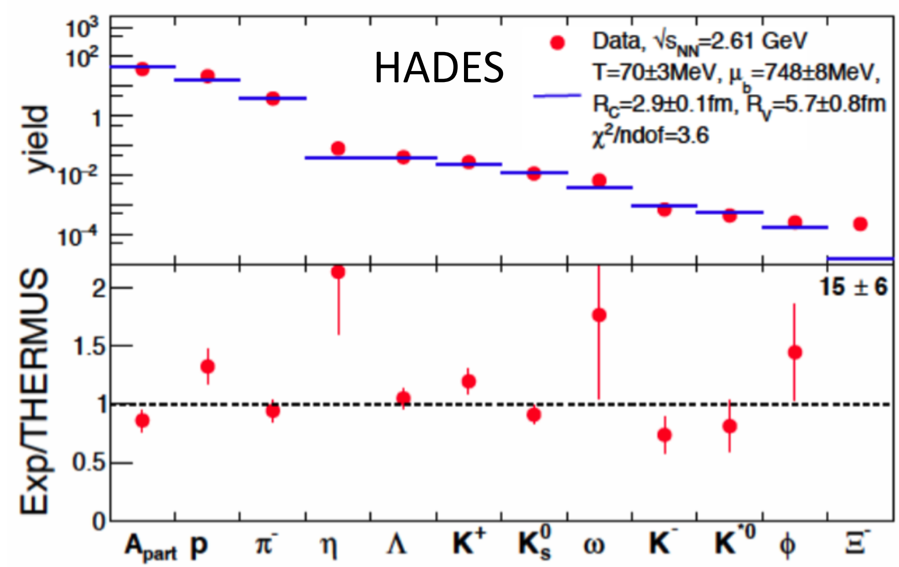

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Step 2 : Fit with SHM

Where in the phase diagram?

Experimentally how do we measure where we are in the phase diagram for a given:

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- Centrality
- Rapidity range

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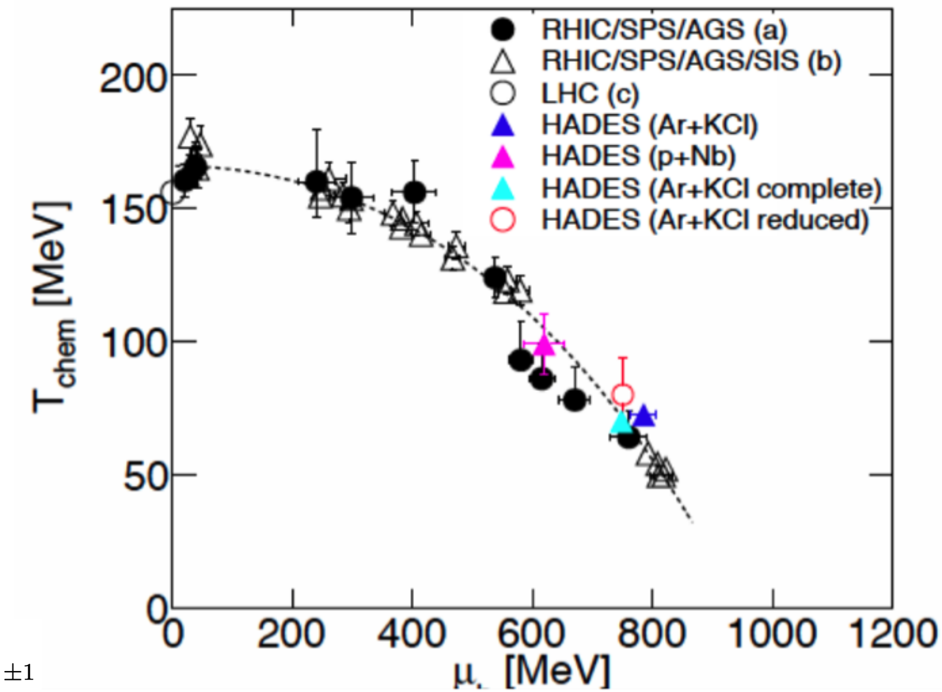

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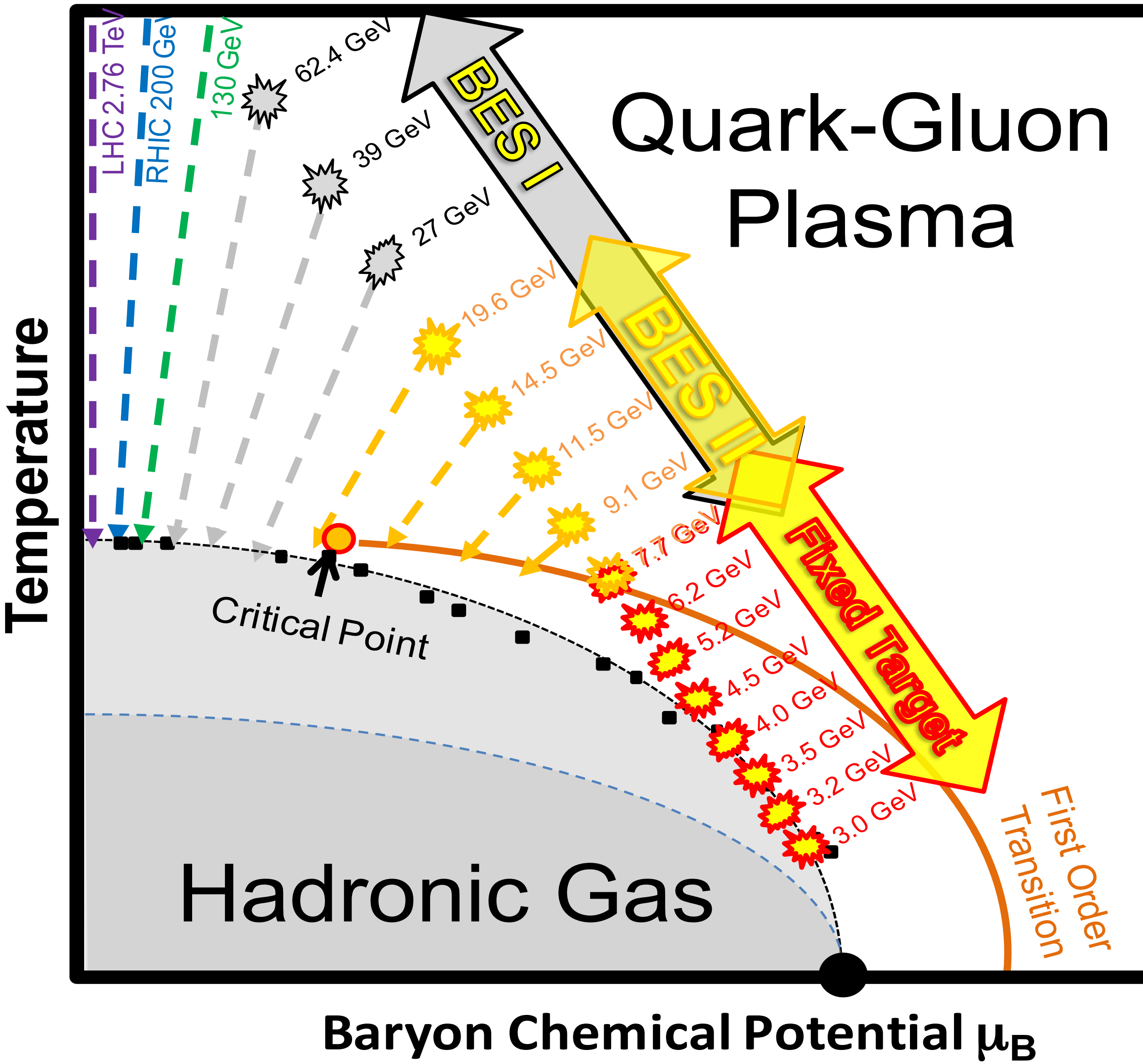
$$\mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q$$

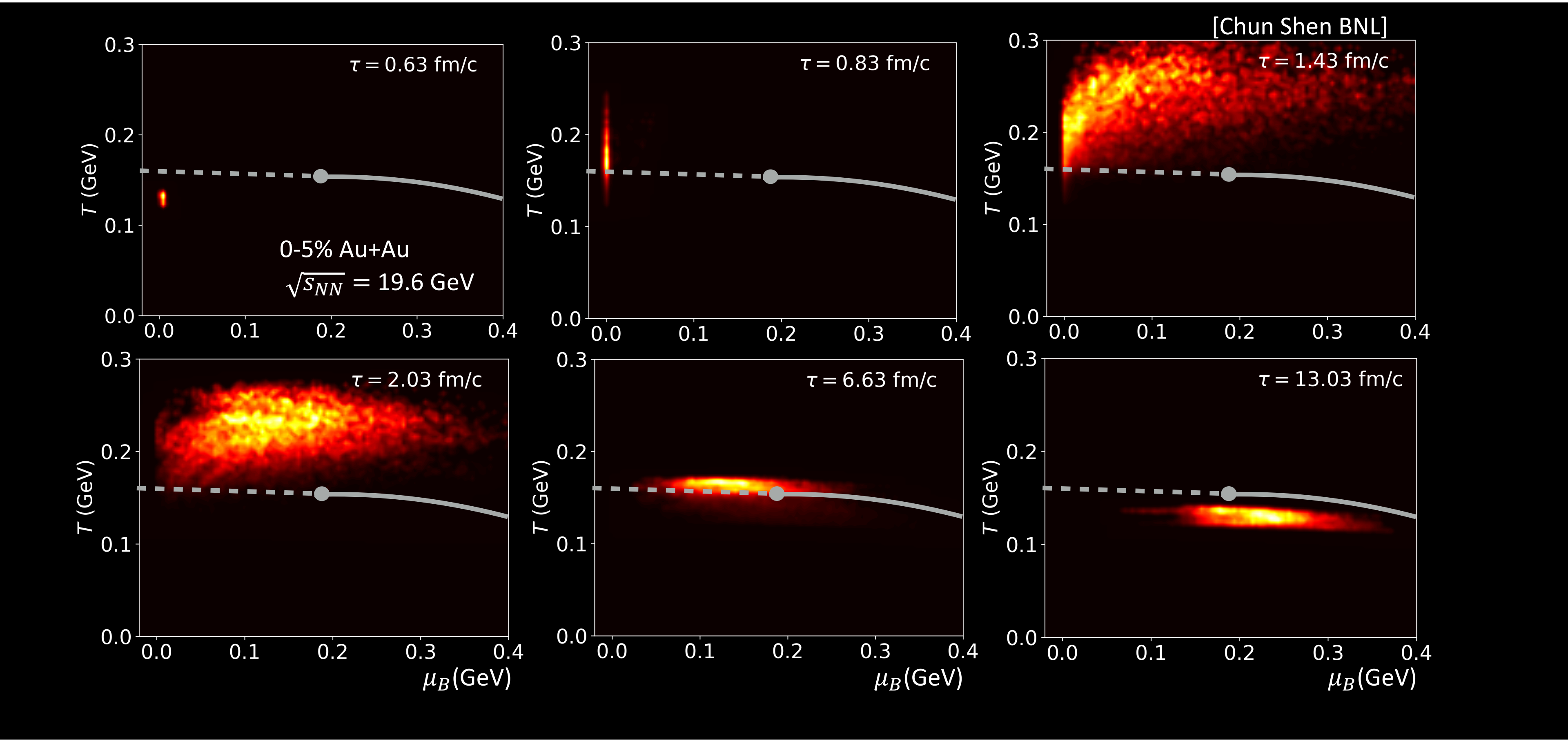
Step 3 : Get T_{chem} (chemical freeze-out temp) and μ_B

RHIC Beam Energy Scan



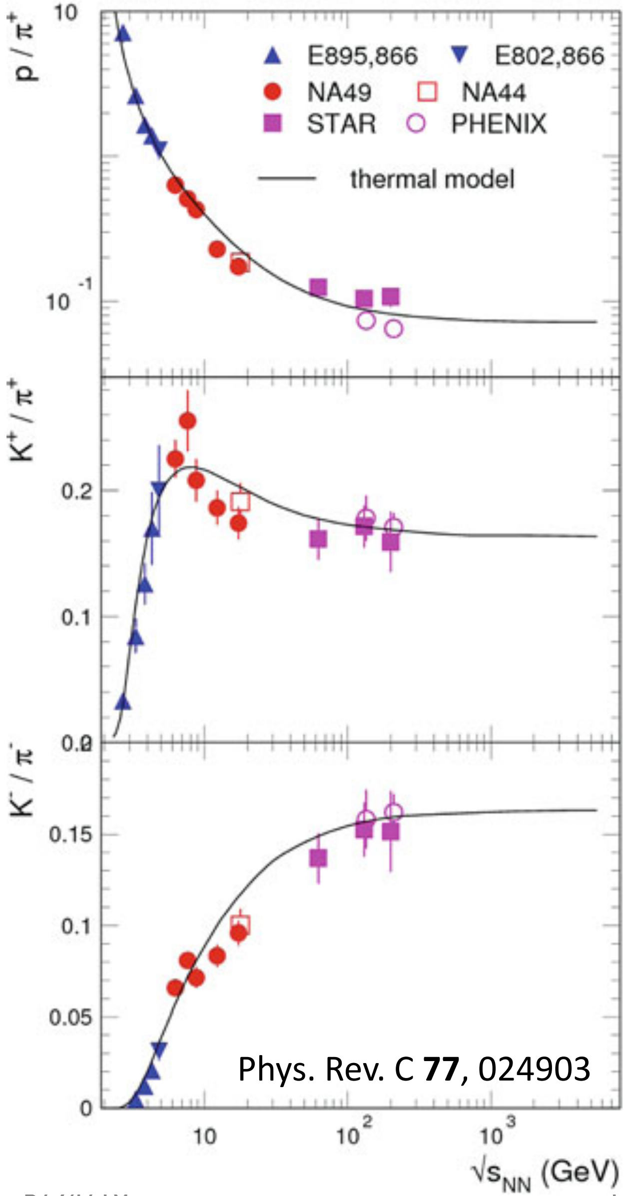
	Energy (GeV)	Chemical Potential μ_B	Pred. Temp. (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.5	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
AGS	4.7	573	114.6
AGS	4.3	602	108.8
AGS	3.8	638	100.6
AGS	3.3	686	88.9
AGS	2.7	752	70.4
SIS	2.3	799	55.8

Trajectory through Phase Diagram of a HIC



Keep in mind:
Path through the phase diagram is not as trivial and localized as we often depict

Particle Ratio



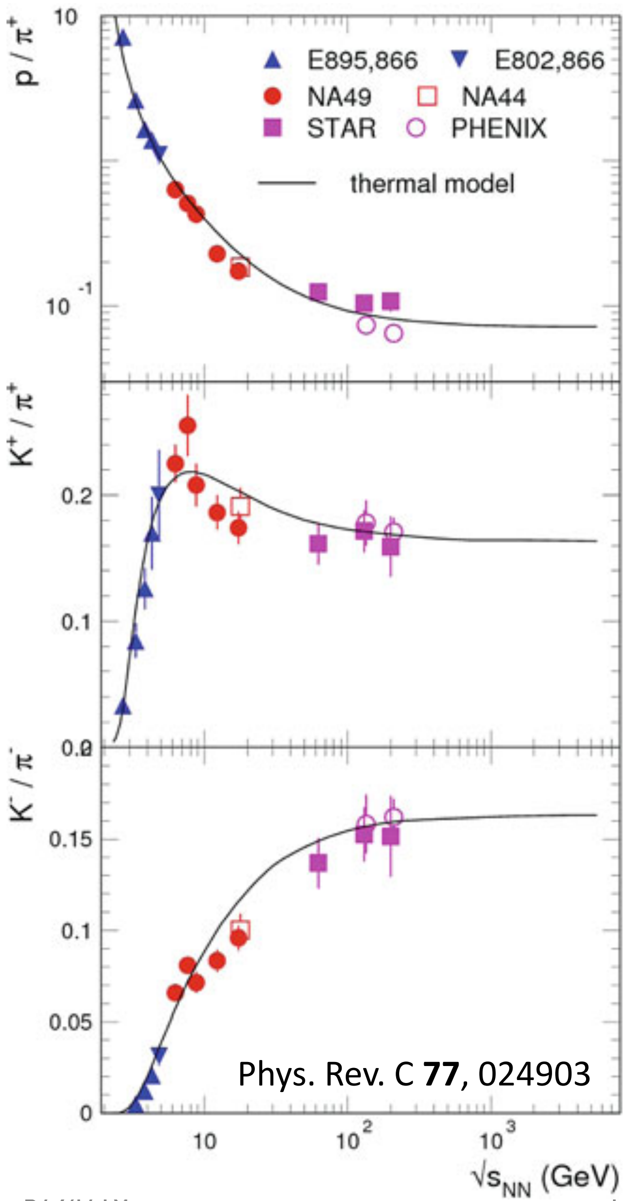
Steep decrease in p/π^+ : decreasing μ_B and transition from baryon dominated to meson dominated

Peak in K^+/π^+ : competing effects. 1) decreasing light quark fraction, 2) increasing $\bar{q}q$ production ($u\ \bar{s}$) in kaon

- Interpreted as indication of the onset of deconfinement

Peak in K^-/π^- : Both are produced particles. Steep increase corresponds to the rapid rise in temperature

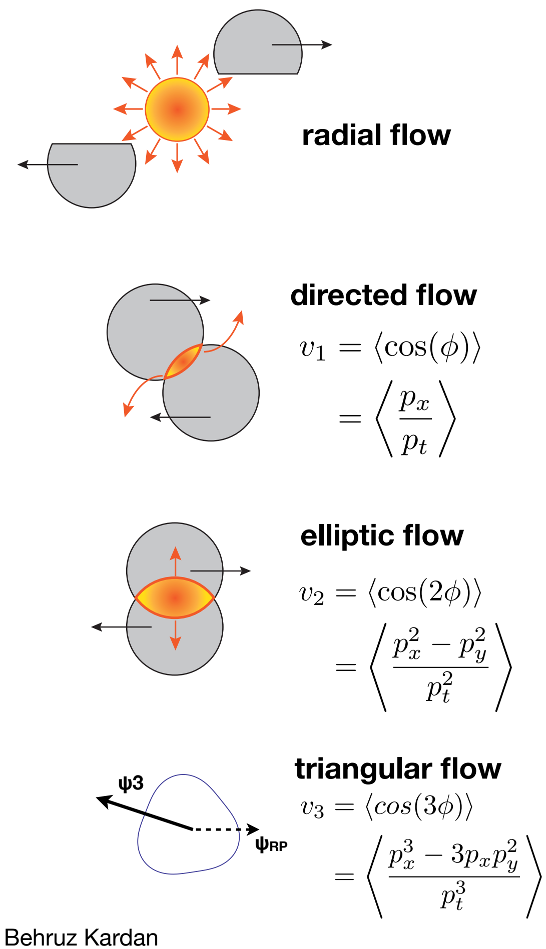
Particle Ratio



Something interesting is happening for $\sqrt{s_{NN}} < {\sim}20$ GeV

Now, Lets look for the 1st order Phase Transitions and Critical point

Measuring the Flow

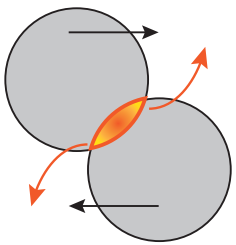


Look at the collective behavior of the medium

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\varphi - \Psi_n)\right]$$

Where ψ is the azimuthal angle and Ψ_n is the n^{th} order event plane

Proton v1



directed flow

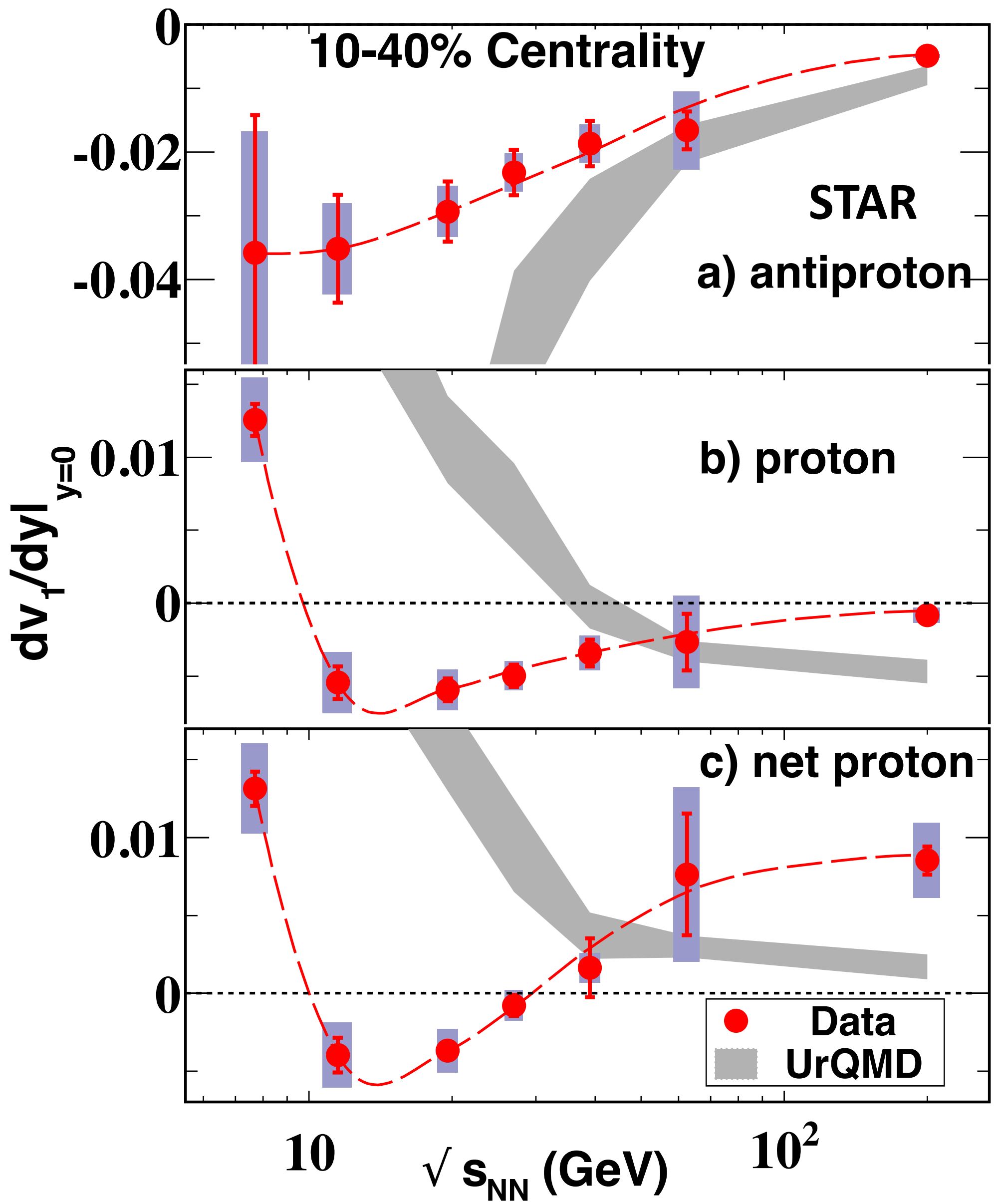
$$v_1 = \langle \cos(\phi) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$

v_1 is Sensitive to the compressibility

First order phase transition produces a **spinoidal region** – region of phase coexistence = softest point in EoS

Minimum in dv1/dy is consistent with predictions for a softest point in EoS due to 1st order phase transition

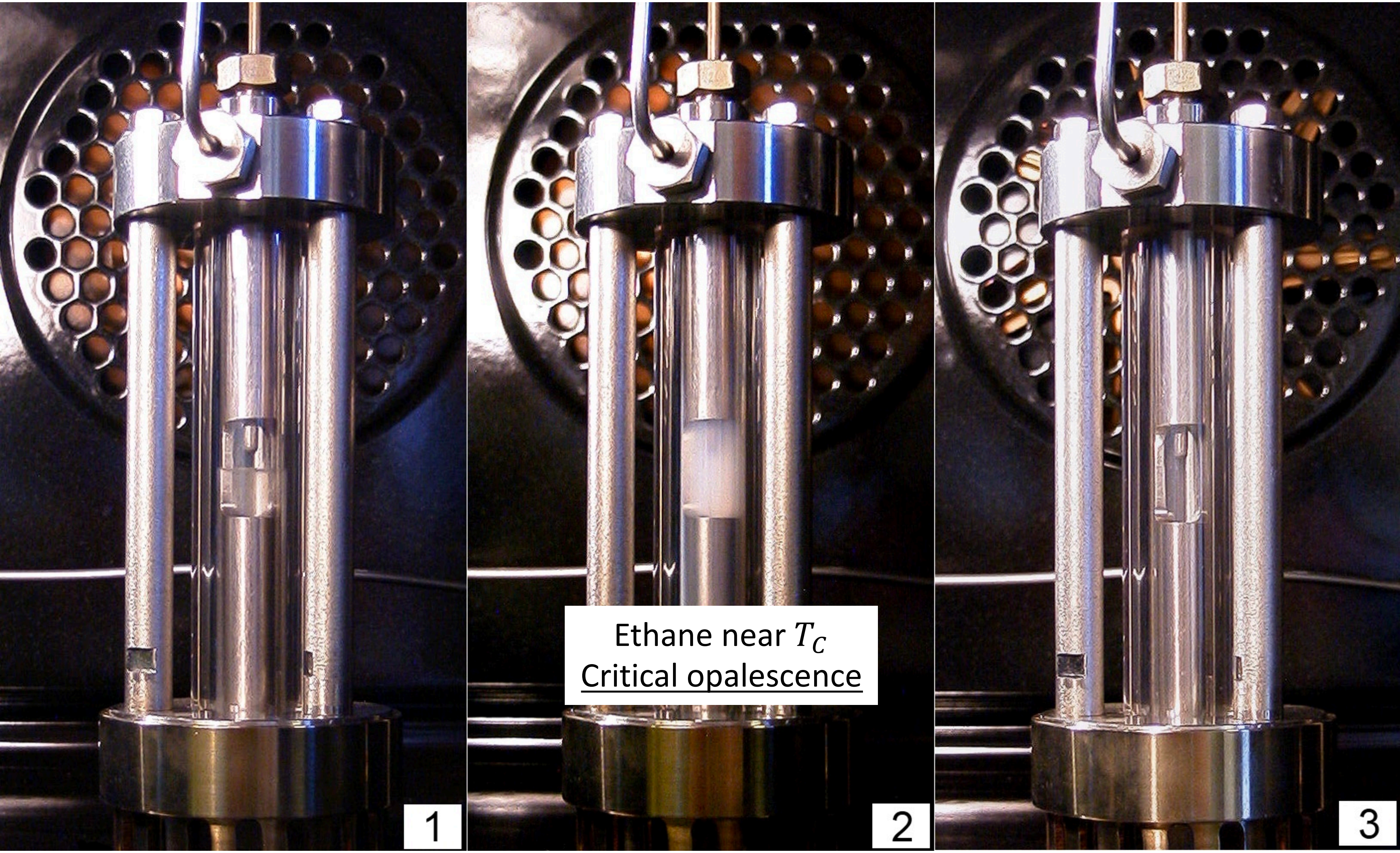
Dashed line is just to guide the eye



*v1 image: Behruz Kardan

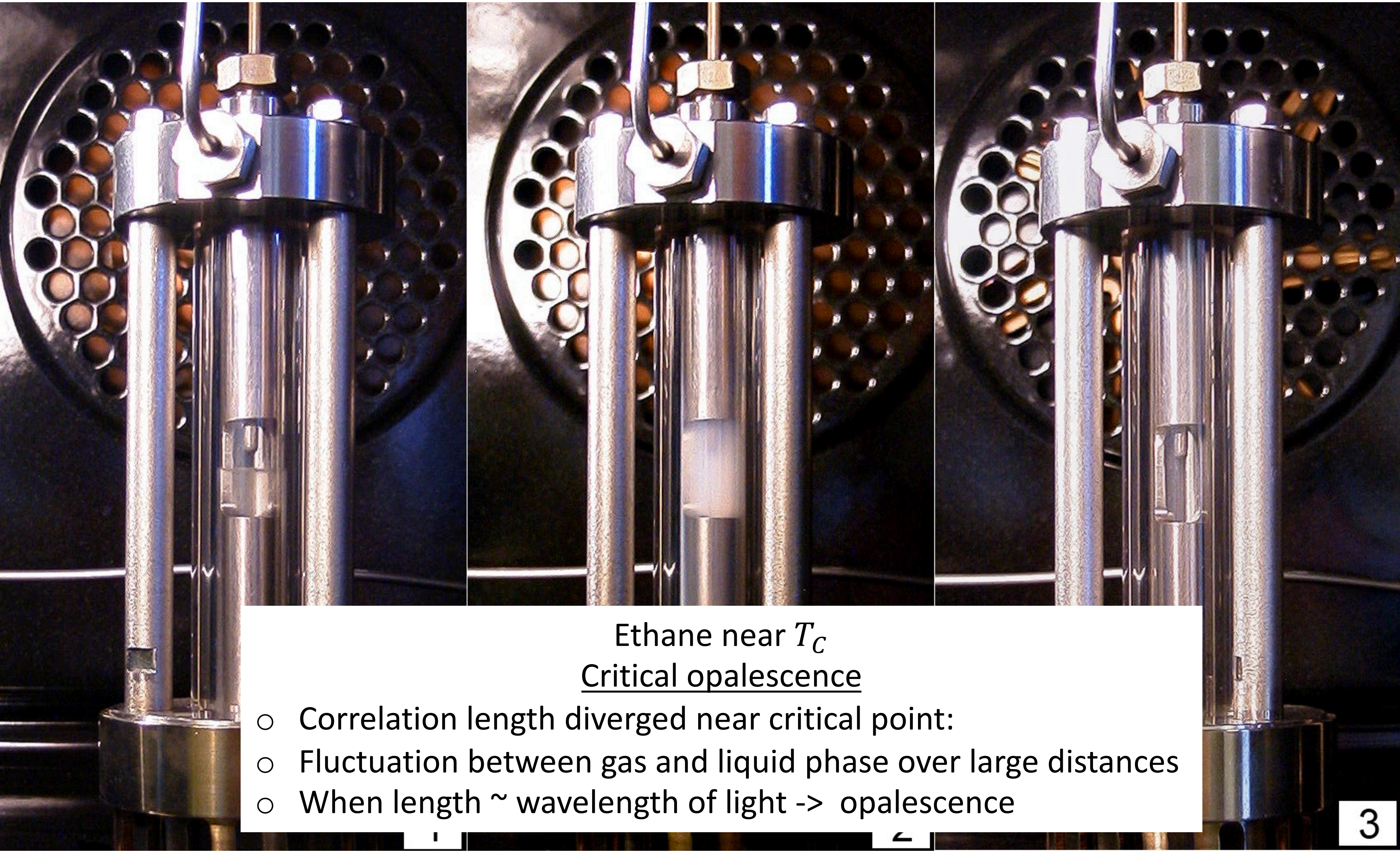
https://arxiv.org/pdf/1401.3043.pdf

Fluctuations and Criticality



T. Andrews. Phil. Trans. Royal Soc., 159:575, 1869
M. Smoluchowski, *Annalen der Physik, 25 (1908) 205 - 226*

Fluctuations and Criticality



Ethane near T_C

<u>Critical opalescence</u>

- Correlation length diverged near critical point:
- Fluctuation between gas and liquid phase over large distances
- When length ~ wavelength of light -> opalescence

Fluctuations in QCD

Q: Fluctuations of what? A: Conserved quantities

Charge(C), Baryon Number(B), Strangeness(S)

- Look for event-by-event fluctuations in a fixed volume
- Corresponds to divergence in susceptibilities

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}(P/T^4)}{\partial(\mu_B/T)^l\,\partial(\mu_S/T)^m\,\partial(\mu_S/T)^n}$$

$$\mu_i = \langle(\delta N)^i\rangle$$

$$\delta N = N - \langle N \rangle$$

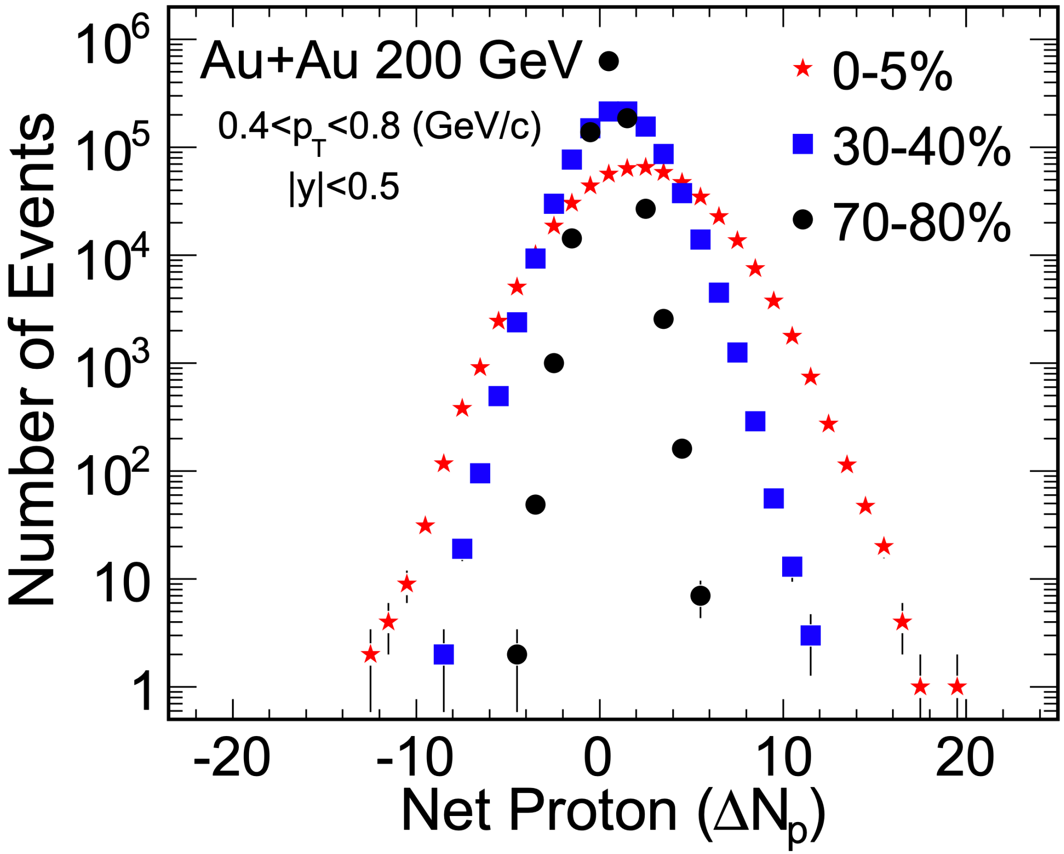
$$\begin{aligned}
M &= K_1 &&= \mu &&= \langle N \rangle &&= VT^3 \cdot \chi_1 \\
\sigma^2 &= K_2 &&= \mu_2 &&= \langle(\delta N)^2\rangle &&= VT^3 \cdot \chi_2 \\
S &= K_3/\sigma^3 &&= \mu_3/\sigma^3 &&= \langle(\delta N)^3\rangle/\sigma^3 &&= VT^3 \cdot \chi_3/(VT^3 \cdot \chi_2)^{3/2} \\
\kappa &= K_4/\sigma^4 &&= (\mu_4 - 3\mu_2^2)/\mu_2^2 &&= \langle(\delta N)^4\rangle/\sigma^4 - 3 &&= (VT^3 \cdot \chi_4)/(VT^3 \cdot \chi_2)^2
\end{aligned}$$

Susceptibilities are directly accessible in lattice QCD!

BUT – cannot predict behavior near Critical Point

Fluctuations in QCD

STAR, Phys. Rev. Lett. **105**, 2010



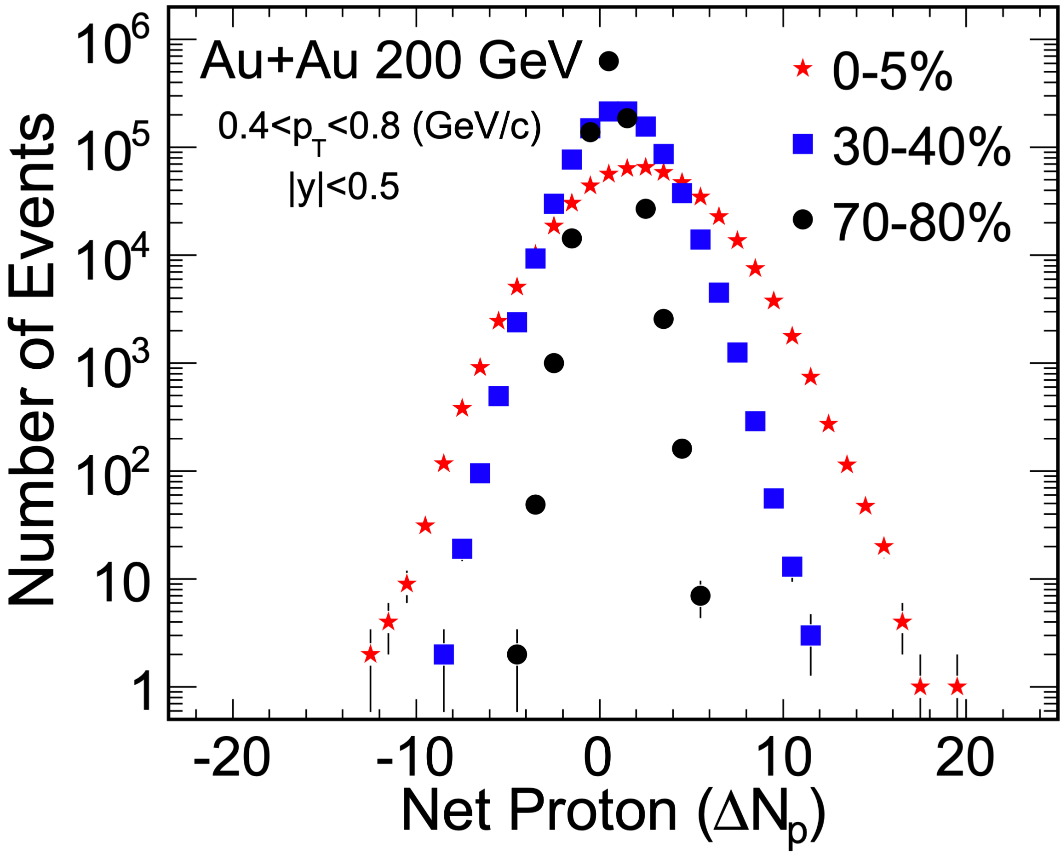
Experimentally, we cannot measure baryon number **directly**

Proxy : net-protons = $\mathrm{p} - \bar{p}$

Also, we don't know the volume…

Fluctuations in QCD

STAR, Phys. Rev. Lett. **105**, 2010



Experimentally, we cannot measure baryon number **directly**

Proxy : net-protons = $\mathrm{p} - \bar{p}$

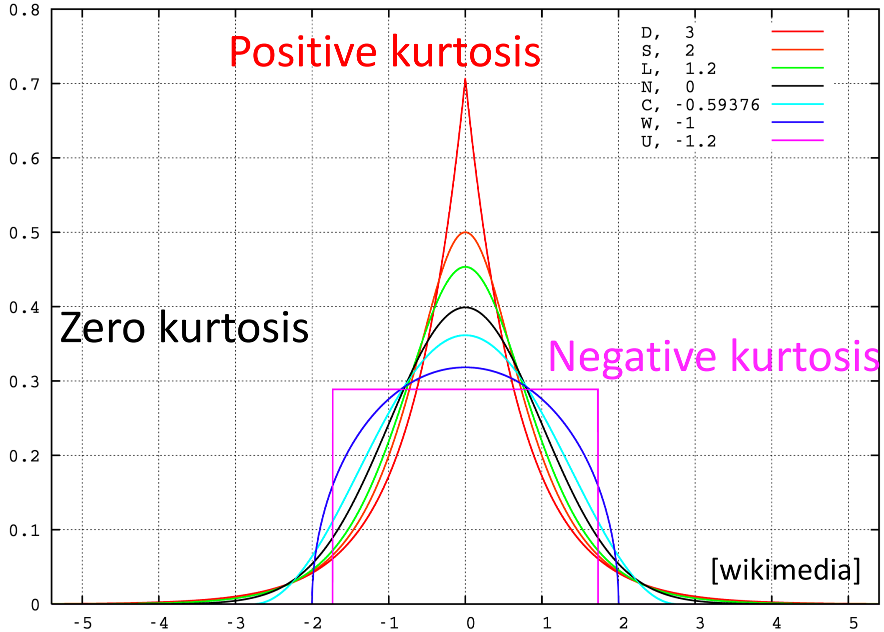
Also, we don't know the volume…

Make ratios or products that cancel volume term:

$$\kappa\sigma^2 = \frac{\chi_B^{(4)}}{\chi_B^{(2)}/T^2}$$

Independent of volume!

Fluctuations in QCD



Experimentally, we cannot measure baryon number **directly**

Proxy : net-protons = $\mathrm{p} - \bar{p}$

Also, we don't know the volume…

Make ratios or products that cancel volume term:

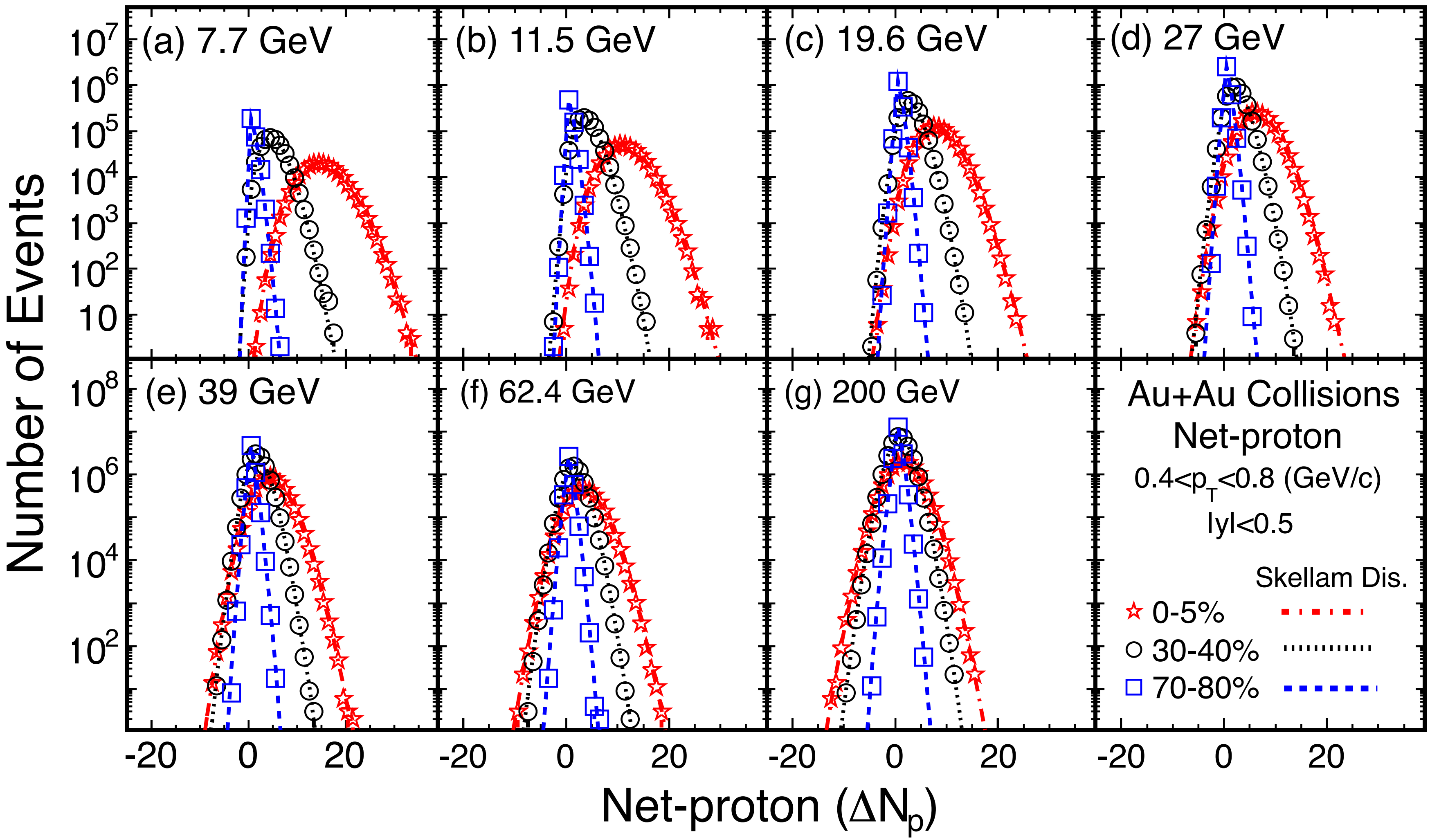
Very sensitive to the "tails" of distribution: Very statistics hungry

$$\kappa\sigma^2 = \frac{\chi_B^{(4)}}{\chi_B^{(2)}/T^2}$$

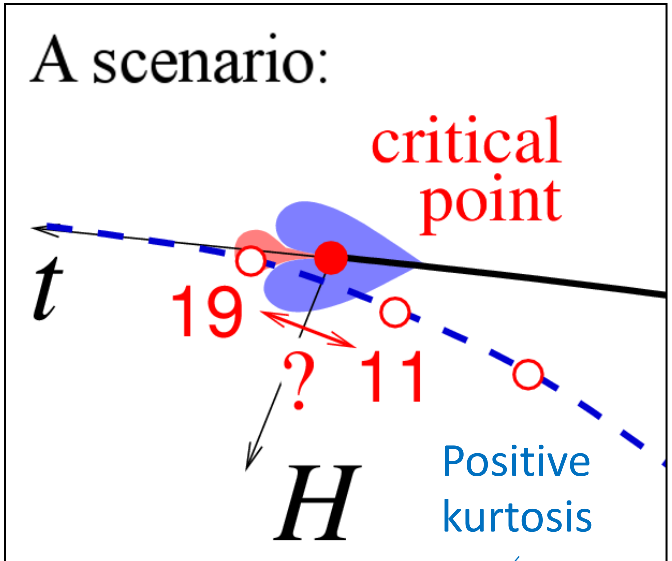
Independent of volume!

Measuring Fluctuations

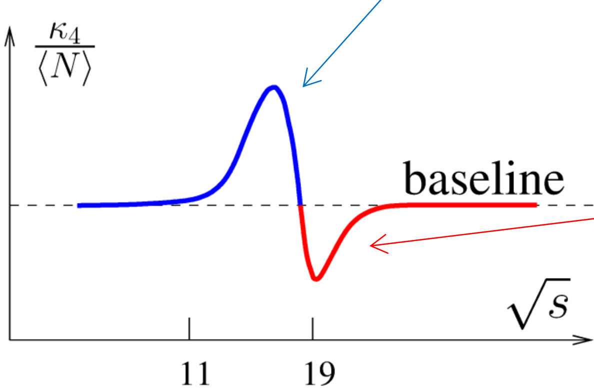
[STAR@RHIC, PRL 112 (2014)]



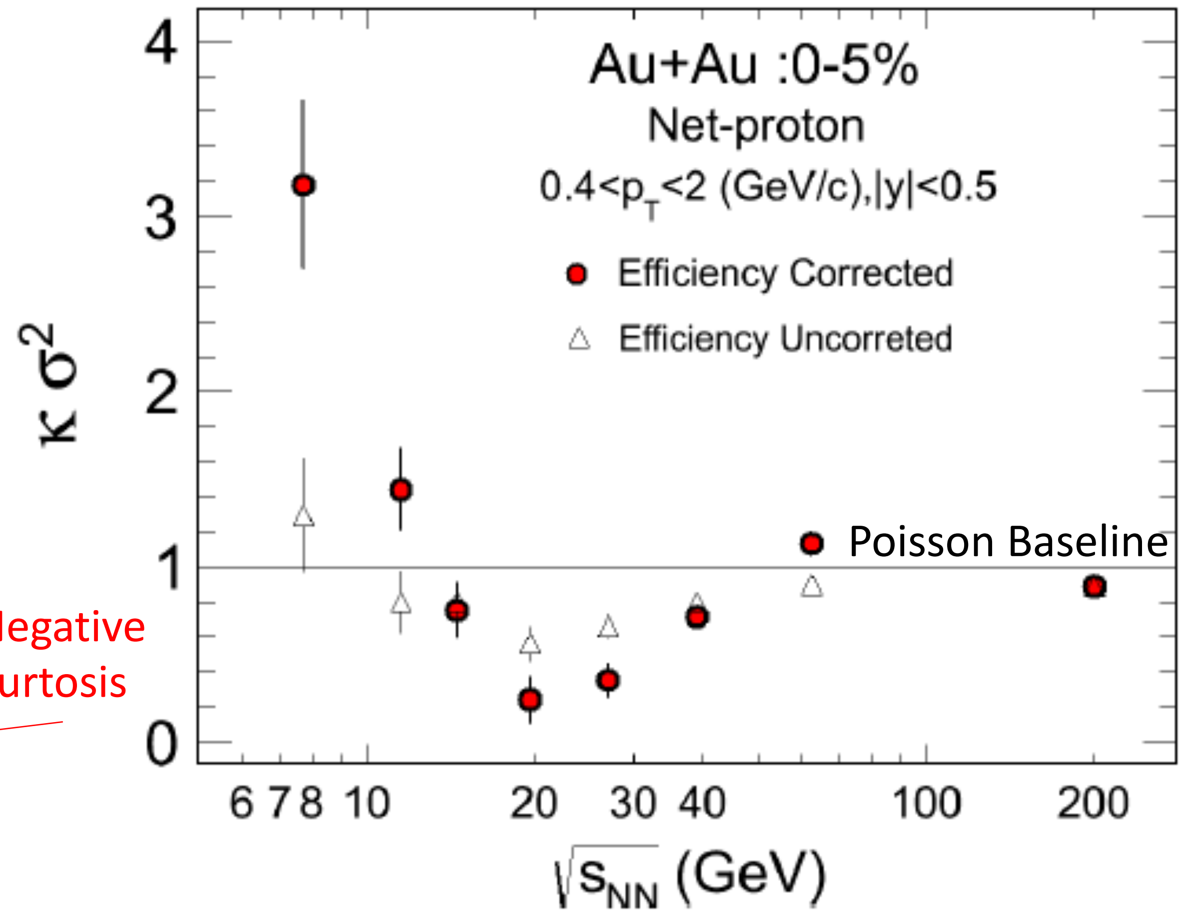
Search for the Critical Point



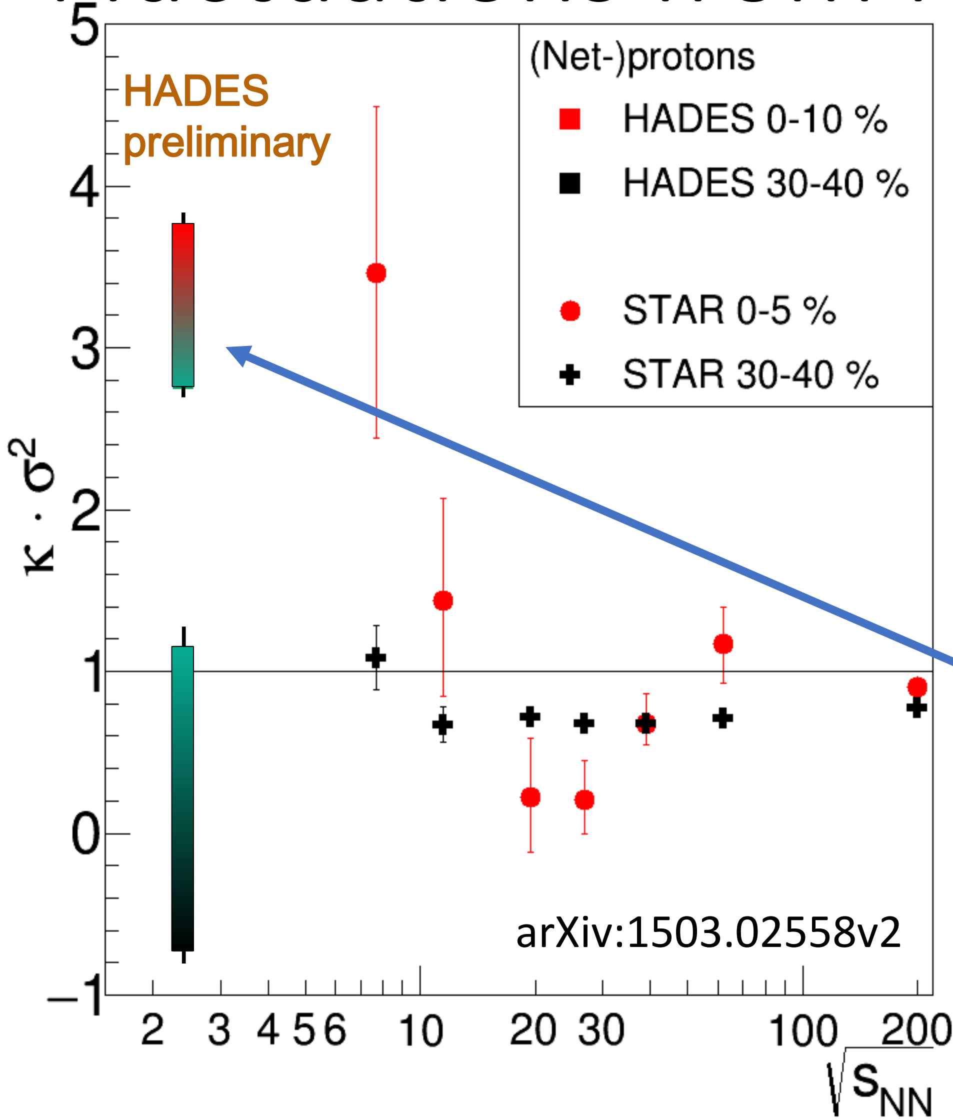
M. Stephanov

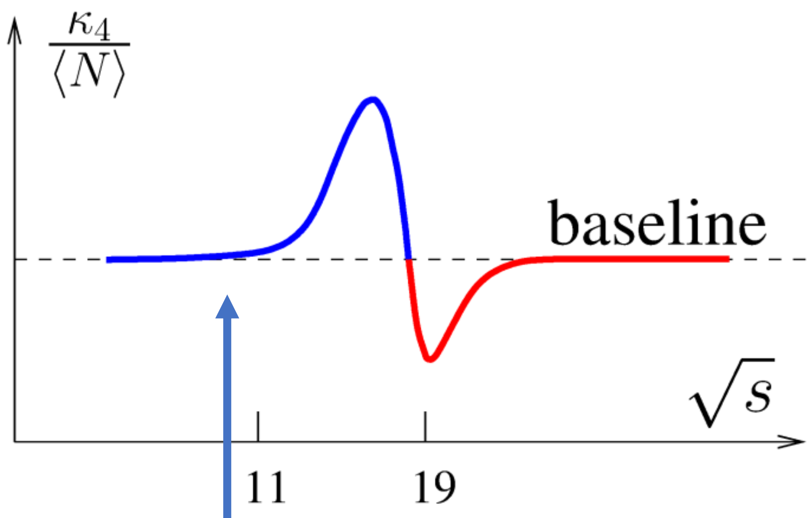


http://arxiv.org/abs/1503.02558v2



Fluctuations from HADES





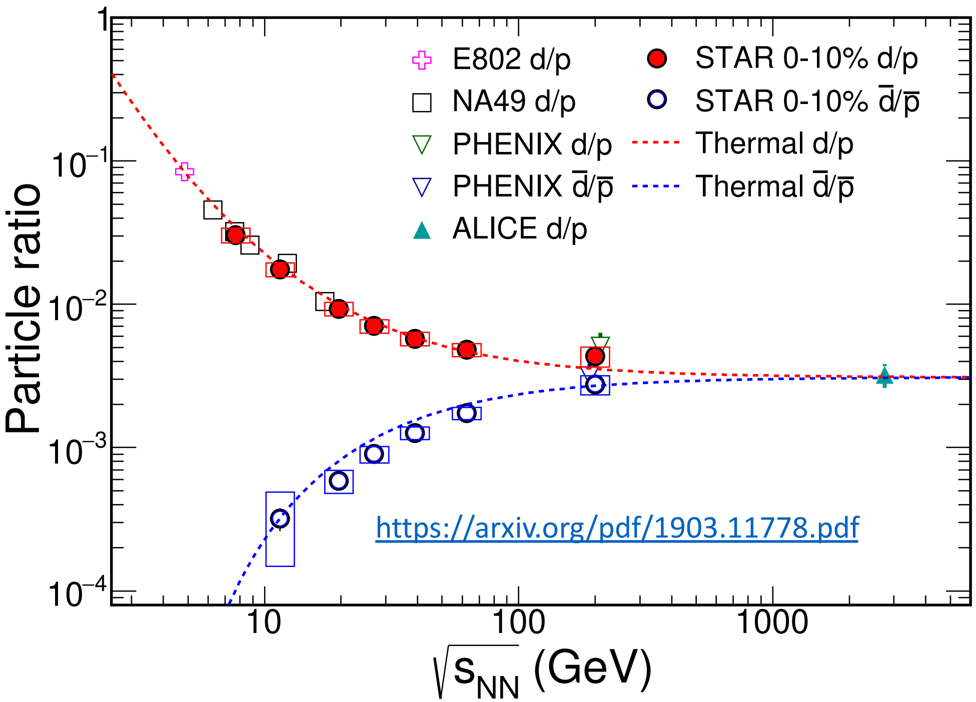
HADES point (central collisions) doesn't seem to return to the Poisson "Baseline"

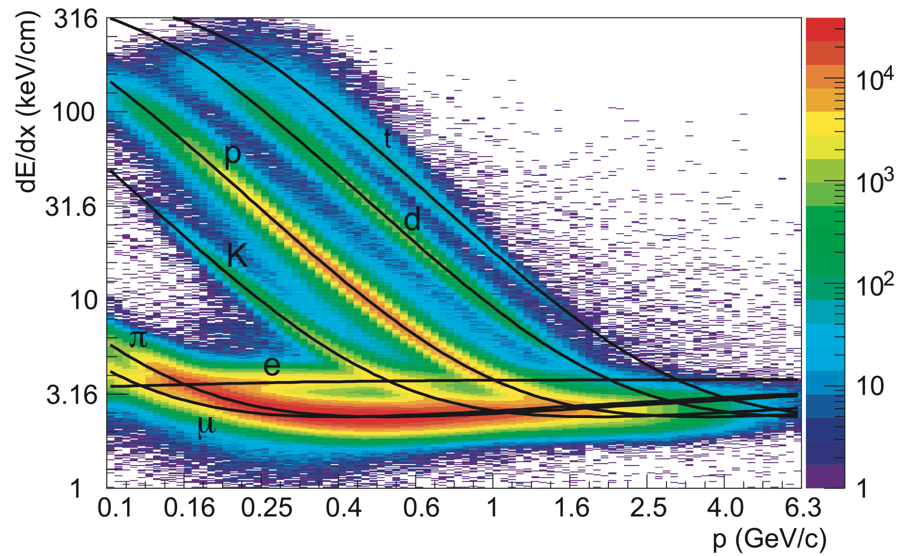
More data needed for a firm conclusion

red/black = unfolding (preferred method) + vol. flucs. corr.

green = evt-by-evt eff correction of factorial moments + vol. flucs. corr.

Experimental Complications





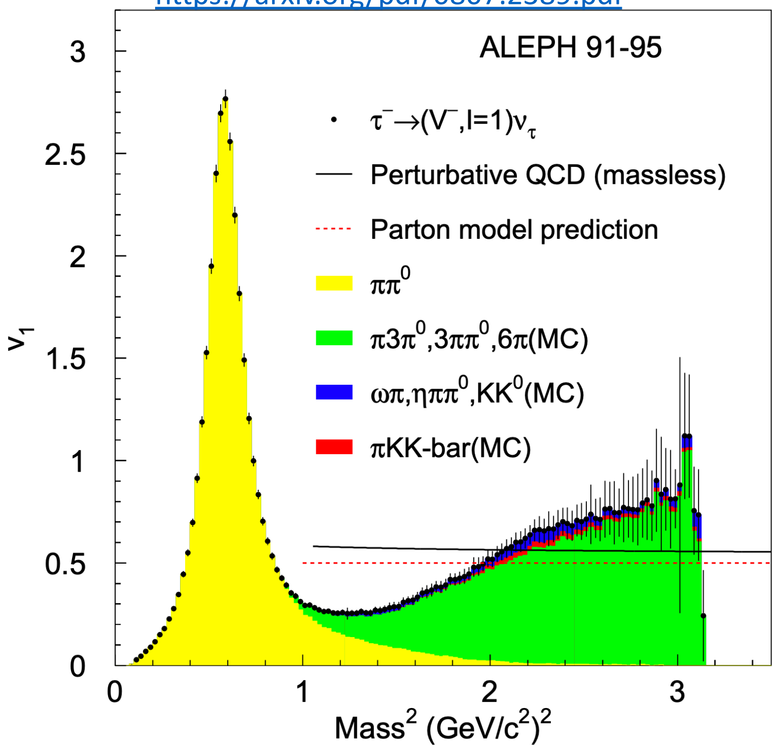
Substantial fraction of protons are bound in heavy fragments : d, t, He, etc.

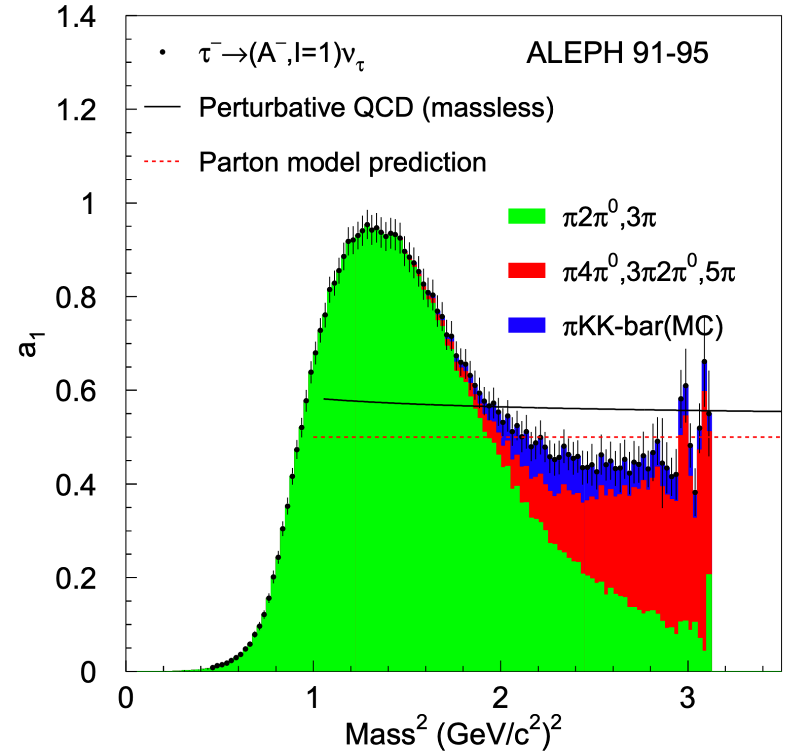
- How does this effect the baryon number fluctuations measured through protons?

Particle identification techniques do not give 100% purity/efficiency

Search for Chiral Symmetry Restoration

https://arxiv.org/pdf/0807.2389.pdf





Mass difference of light quark states : $\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$

	π^0	ρ^0	a_1
Mass (MeV/c^2)	135	770	~1260

Chiral symmetry restoration : mass of chiral partners will become the same

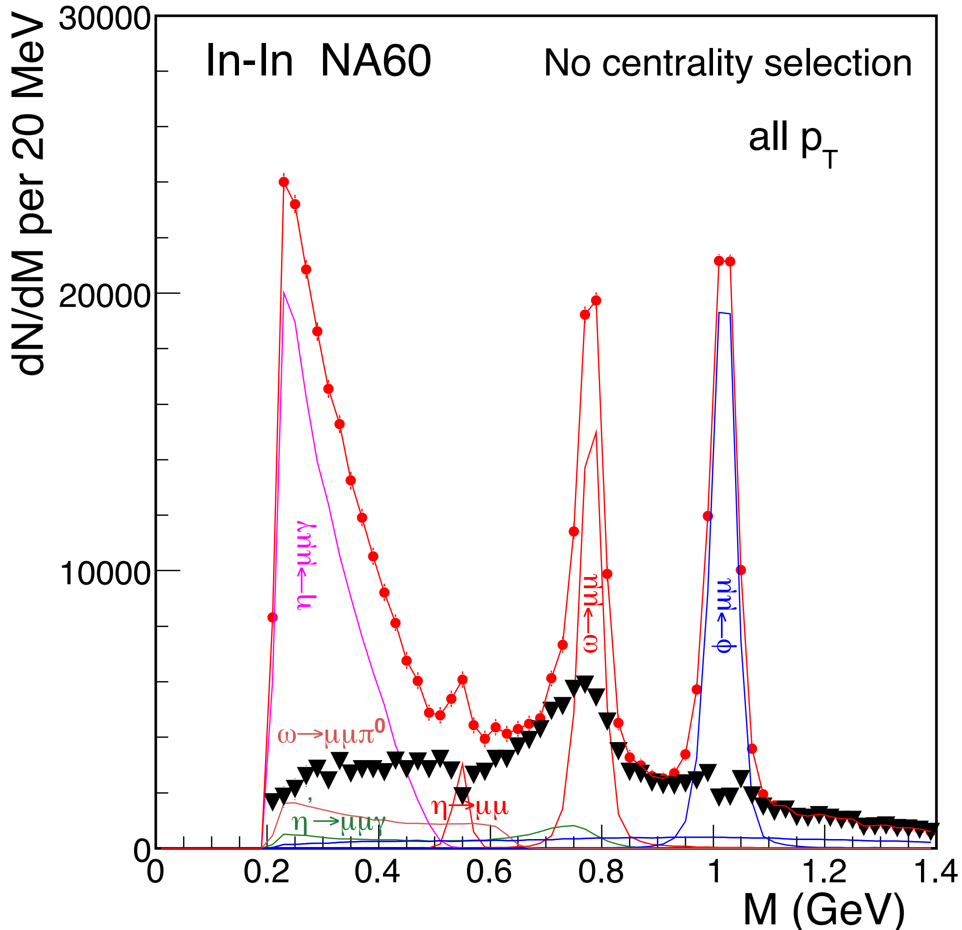
Search for Chiral Symmetry Restoration

NA60 Measured $\mu^+\mu^-$ in In+In collisions at $\sqrt{s_{NN}}$ = 17.3 GeV

Extremely high precision

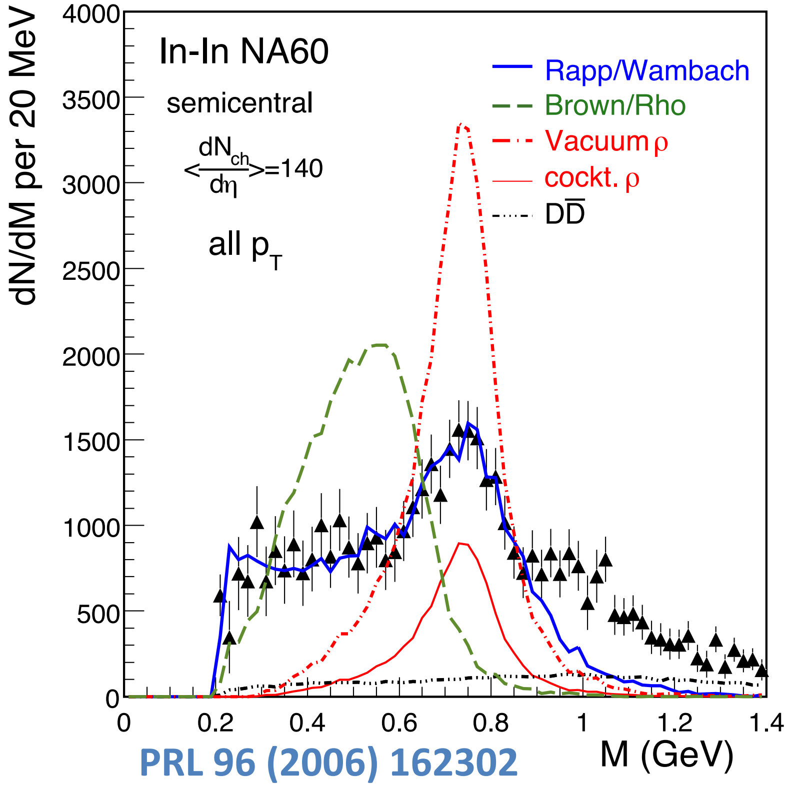
→ Isolate ρ^0 meson

→Thermal dileptons



PRL 96 (2006) 162302

NA60 Thermal Dileptons



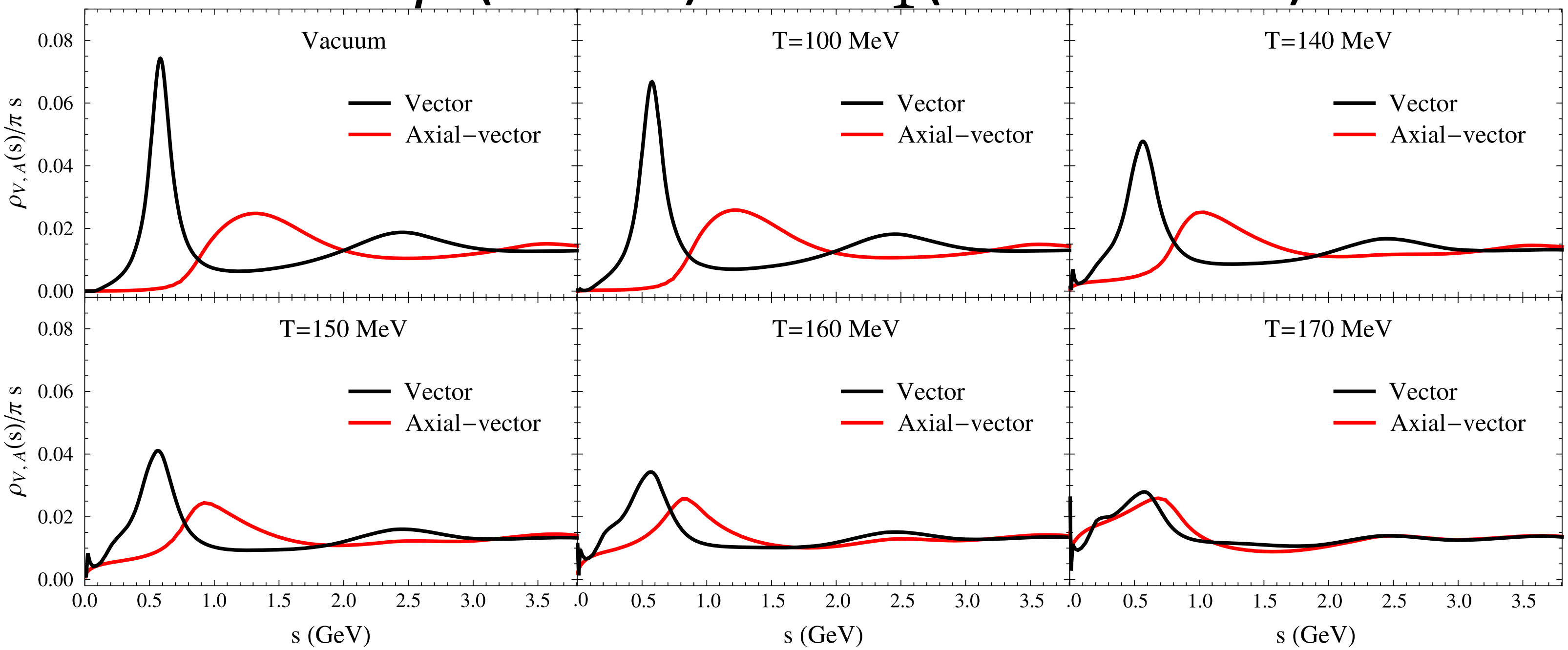
PRL 96 (2006) 162302

- ρ-meson broadening/melting through medium interactions
- Possible link to chiral symmetry restoration

How does low mass excess evolve with collision energy?

Chiral Symmetry Restoration

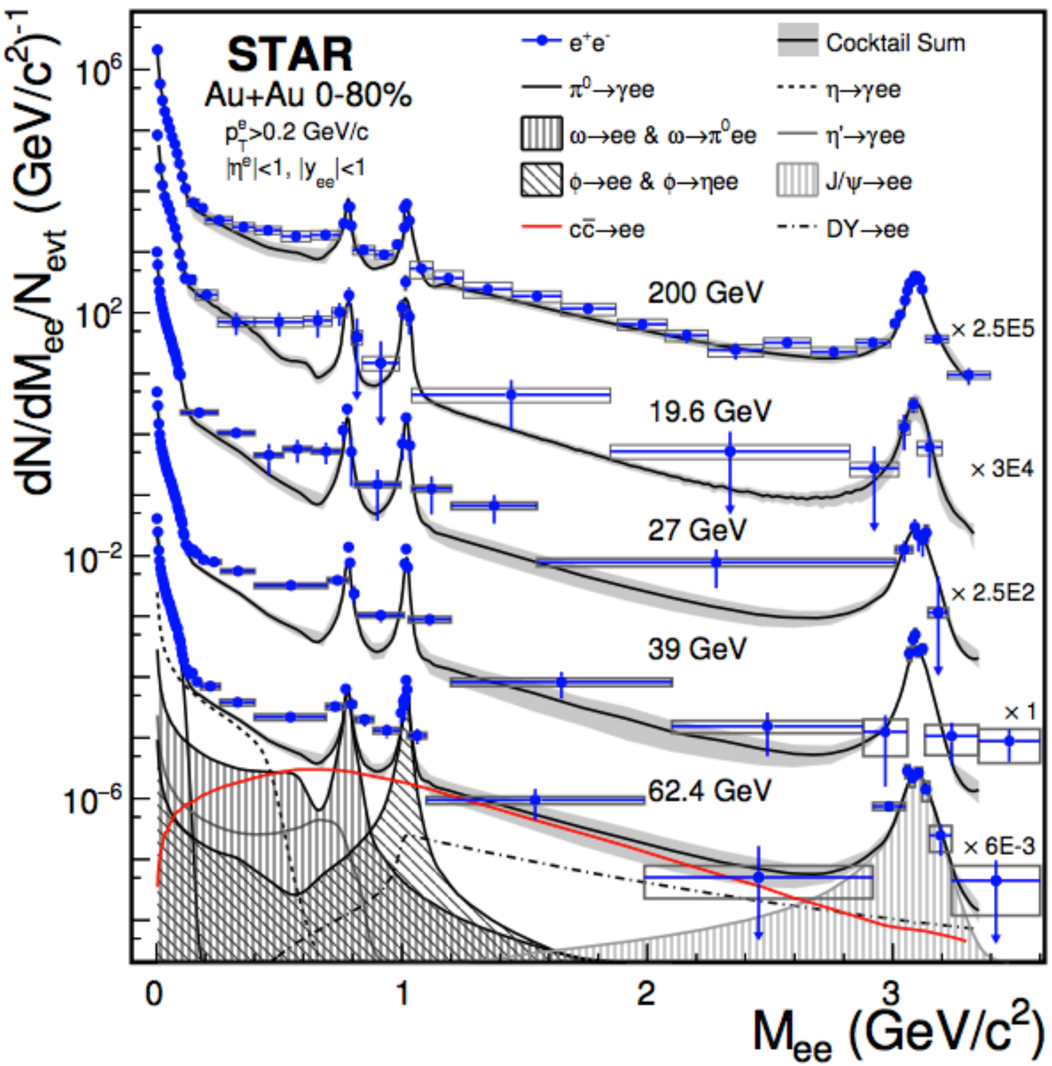
- Phenomenological description of mass splitting between ρ (vector) and a_1 (axial-vector)



- Use experimentally verified ρ spectral function(SF) → search for a_1 SF satisfying QCD & Weinberg sum rules

(QCD) $\frac{1}{M^2}\int ds \frac{\rho_{V/A}(s)}{s} e^{-s/M^2} = \sum_n C_n \langle O_n \rangle$ (Weinberg) $\int ds(\rho_{\mathrm{V}} - \rho_{\mathrm{A}})s^n = f_n$

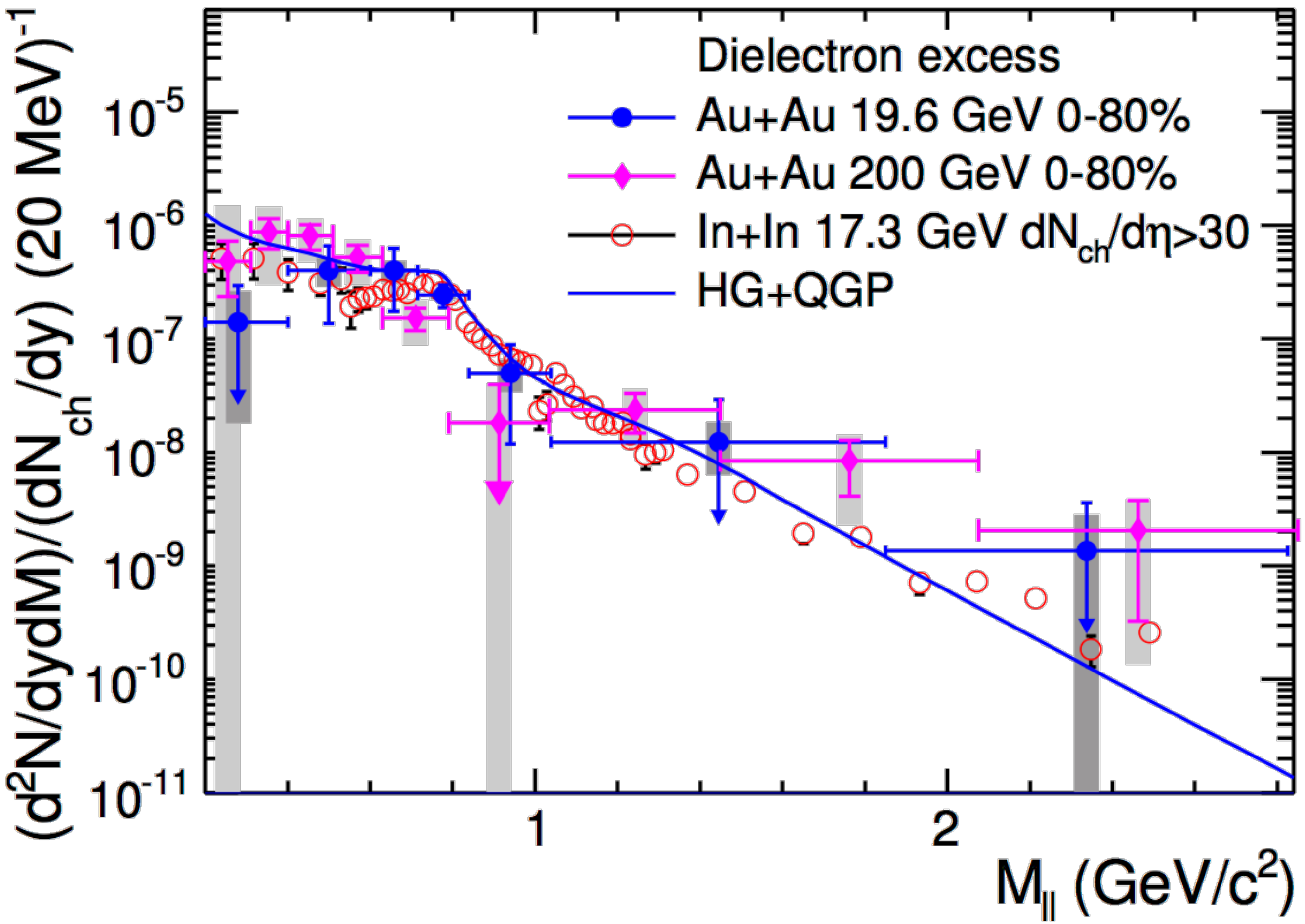
Systematic study of e^+e^-



STAR measurements of e^+e^- in BES 1

- Away from ρ – spectra well described by "hadronic cocktail"
- Sustained excess observed in ρ meson region

The Melted ρ



Model includes :

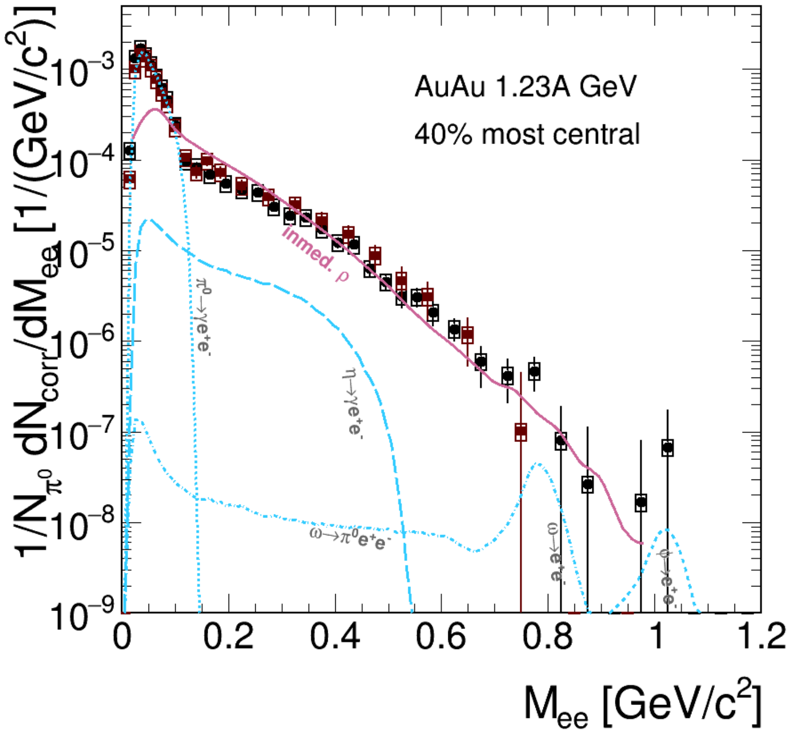
ρ^0 "melting" from chiral symmetry restoration

QGP radiating like a thermal black-body

NA60 & STAR excess yields are well described by melted ρ+QGP model

Strong experimental evidence that ρ-meson "melts" →
Hohler & Rapp: "Is ρ-meson melting compatible with chiral restoration?"

HADES High Precision Measurements



Significant excess observed over expected sources

But $T \approx 80$ MeV < T_C!

At high μ_B the Chiral transition may proceed at lower T than deconfinement transition

$$T_C^{\chi} < T_C^{QGP}$$

Excess is well described by the same in-medium broadened ρ as for higher energies

HADES in CBM: Measure the $\rho - a_1$ mixing

Summary

Heavy Ion Collisions gives us the tool we need to systematically exploring the QCD Phase Diagram

1st Order Phase Transition

Net-Proton v_1 shows double sign change → softest point in EoS (phase coexistance region)

Critical End Point

Fluctuations in conserved quantities → access susceptibilities

$\kappa\sigma^2$ for net-p shows possible deviation from Poisson Baseline

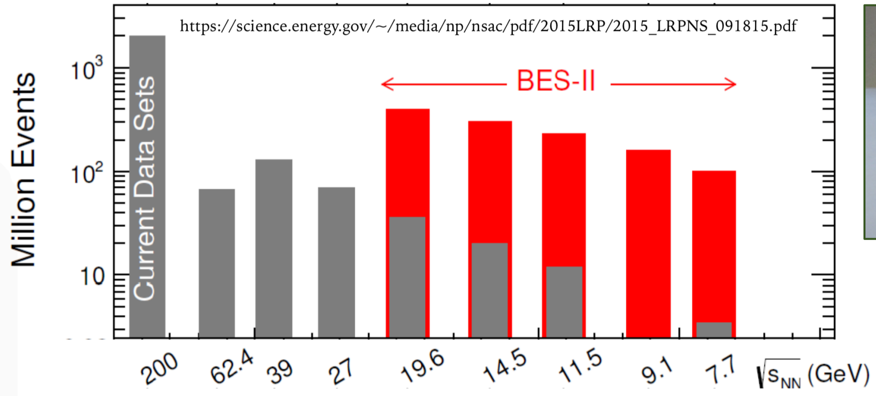
Chiral Symmetry Restoration

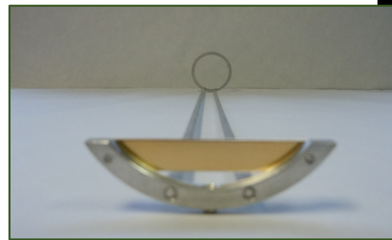
Melting of the ρ^0 meson may be linked to Chiral Symmetry restoration

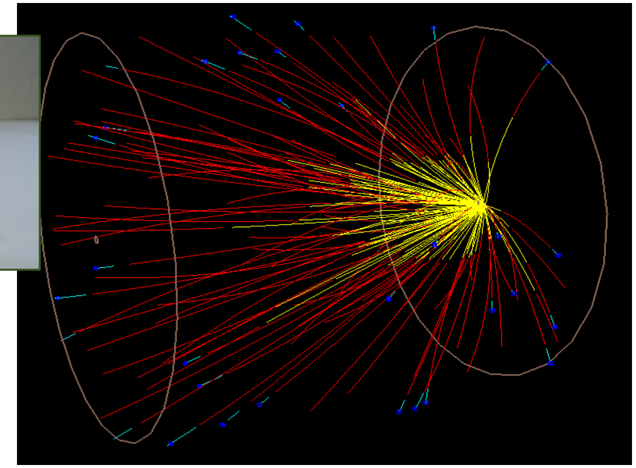
Model consistently describes excess from HADES to RHIC energies

Conclusive results need more data → Outlook

RHIC Beam Energy Scan II

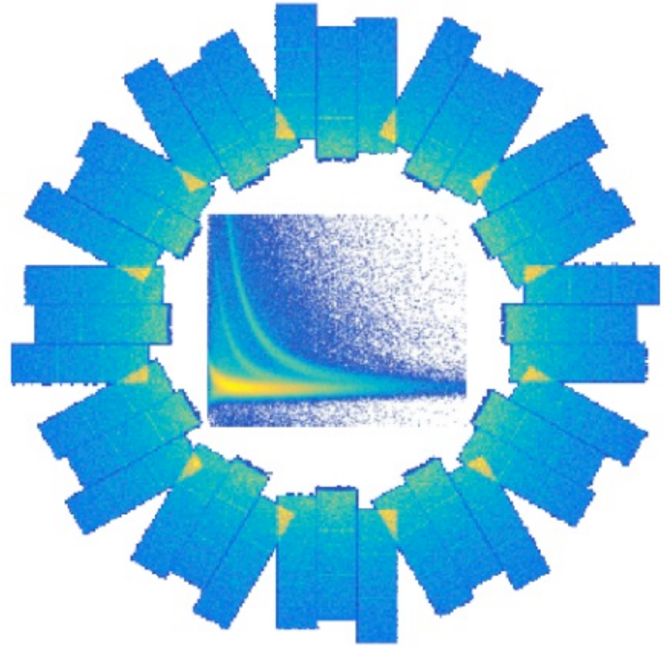




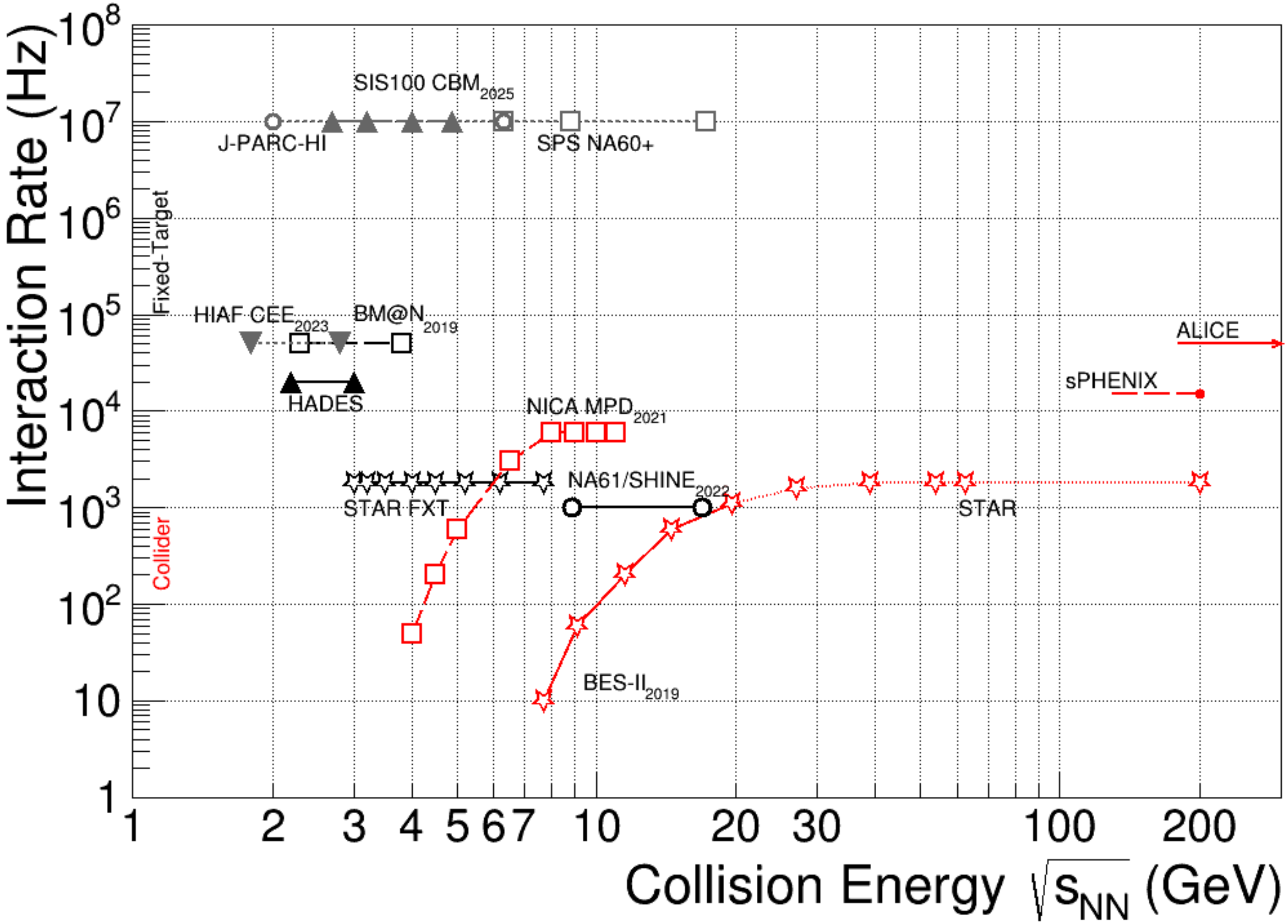


Successful collaboration with CBM!

Extended PID with eTOF for BESII

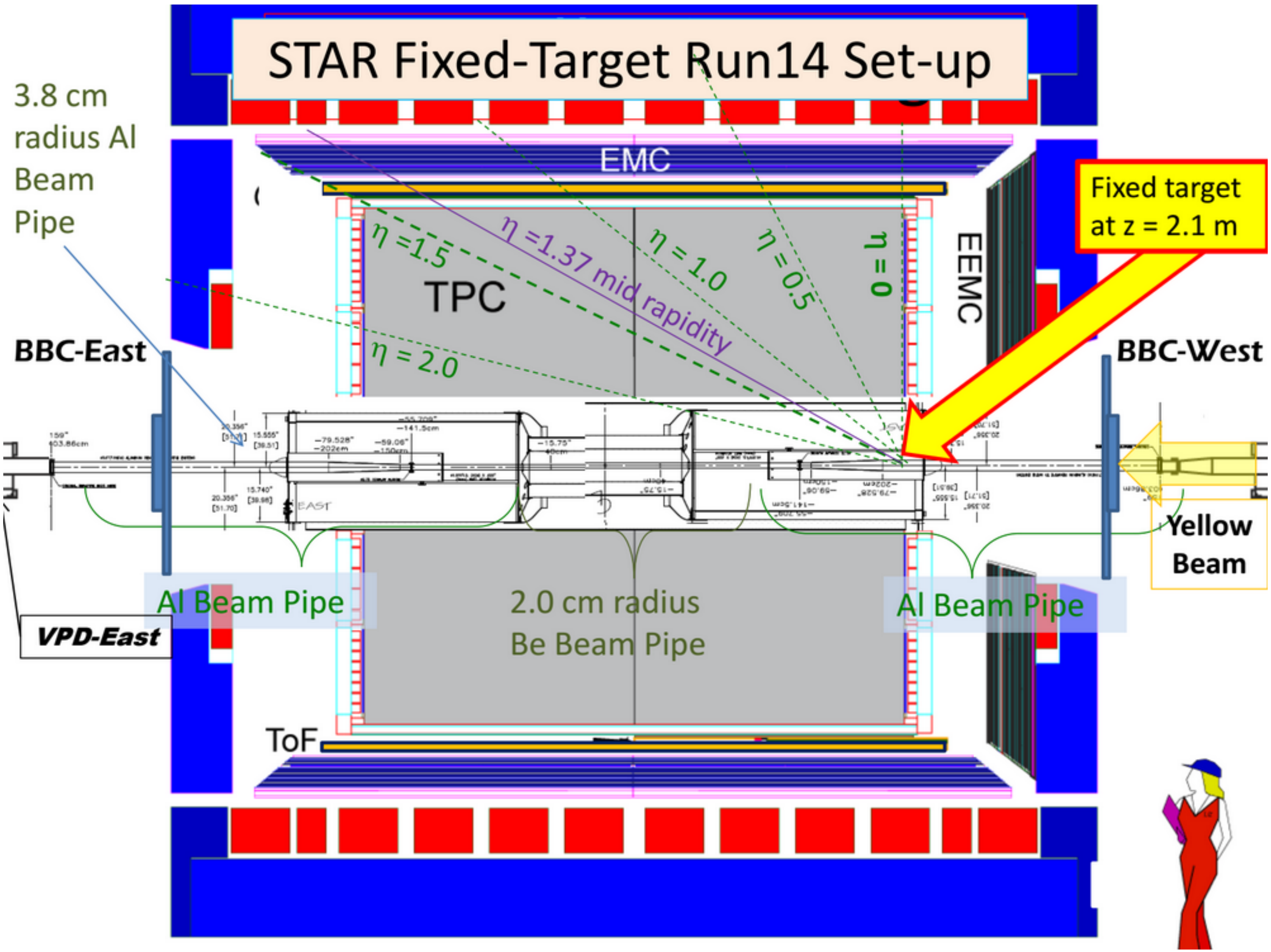


The Next Era of high-μ_B Experiments



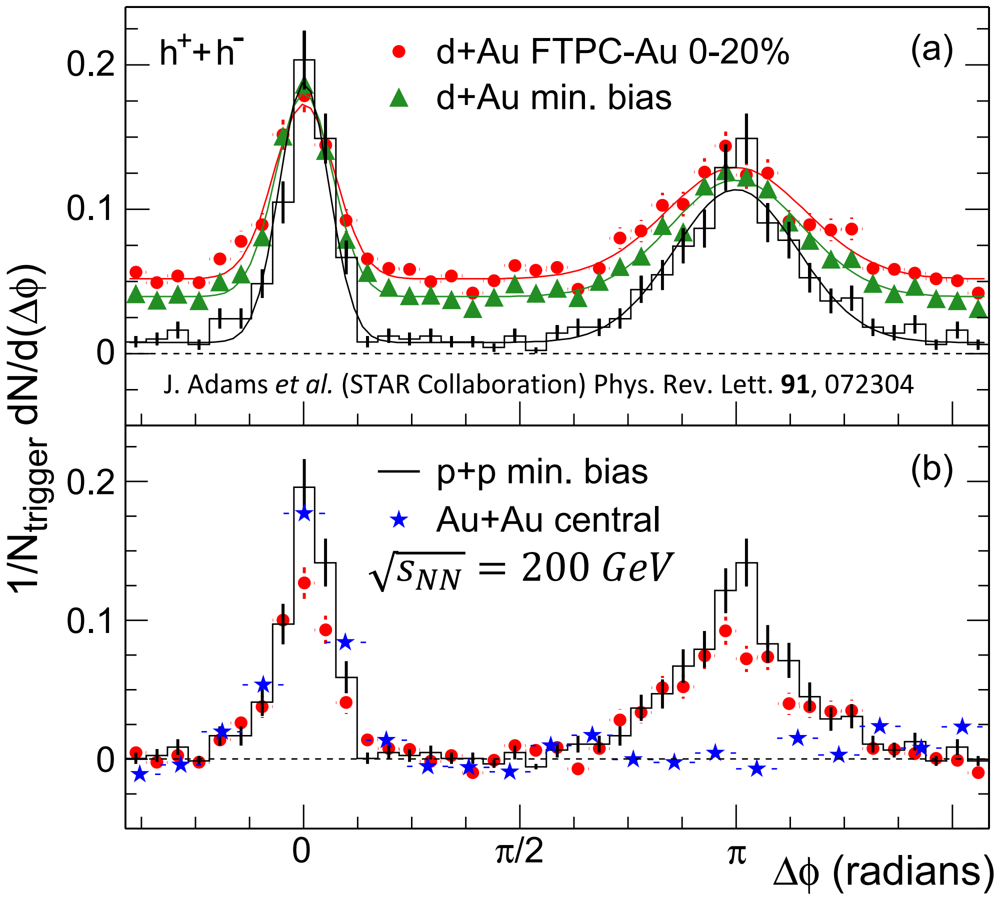
Thank you!

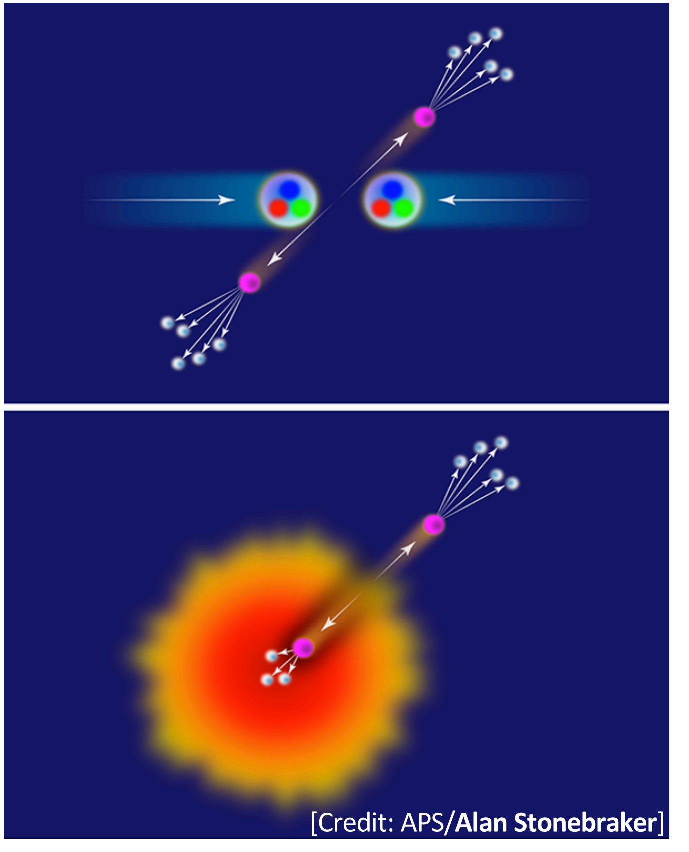
STAR Fixed Target



Setting the Scene

Jet Quenching in the Quark Gluon Plasma

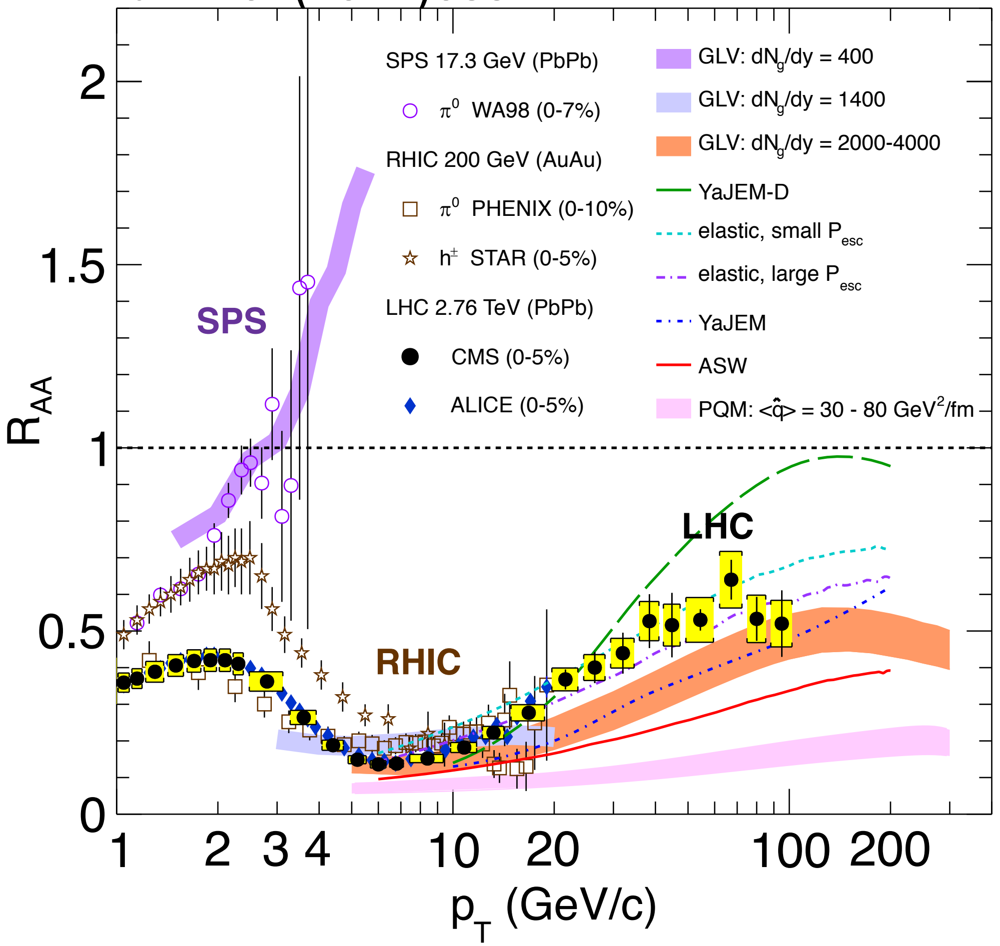




- High-p_T partons (quarks and gluons) – forebears of jets – lose energy via strong interactions with the partonic medium
- Clear signature of the Quark Gluon Plasma observed by all 4 RHIC experiments in 2003 (cover of PRL!)

Jet Quenching in the Quark Gluon Plasma

JHEP04(2017)039



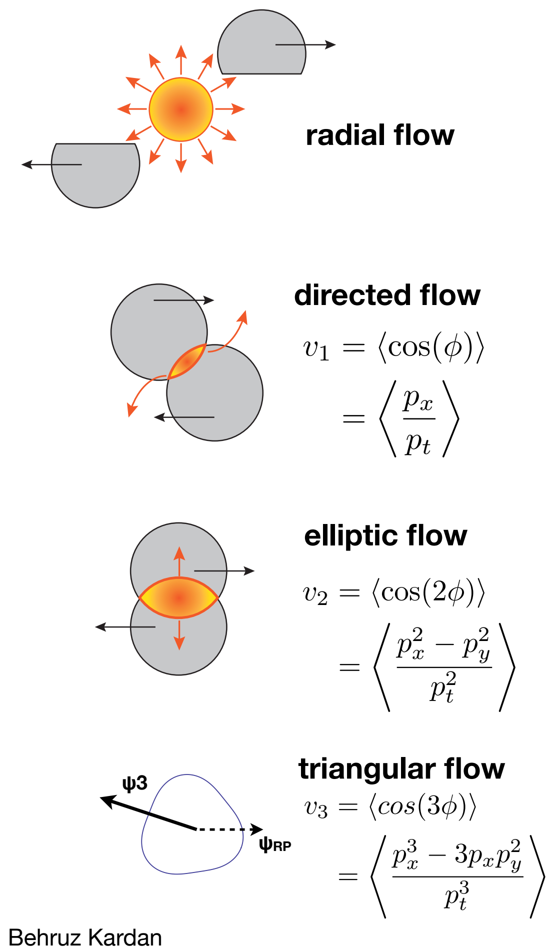
Quantify jet quenching:

$$R_{AA} = \frac{\text{Yield in AA Collisions}}{\text{Yield in pp Collisions} \times \text{\# “binary” collisions in AA}}$$

Significant Jet quenching ($R_{AA} \ll 1$) has identified as a clear signature of QGP formation

Clear evidence for QGP formation at RHIC and LHC

Finding the QGP



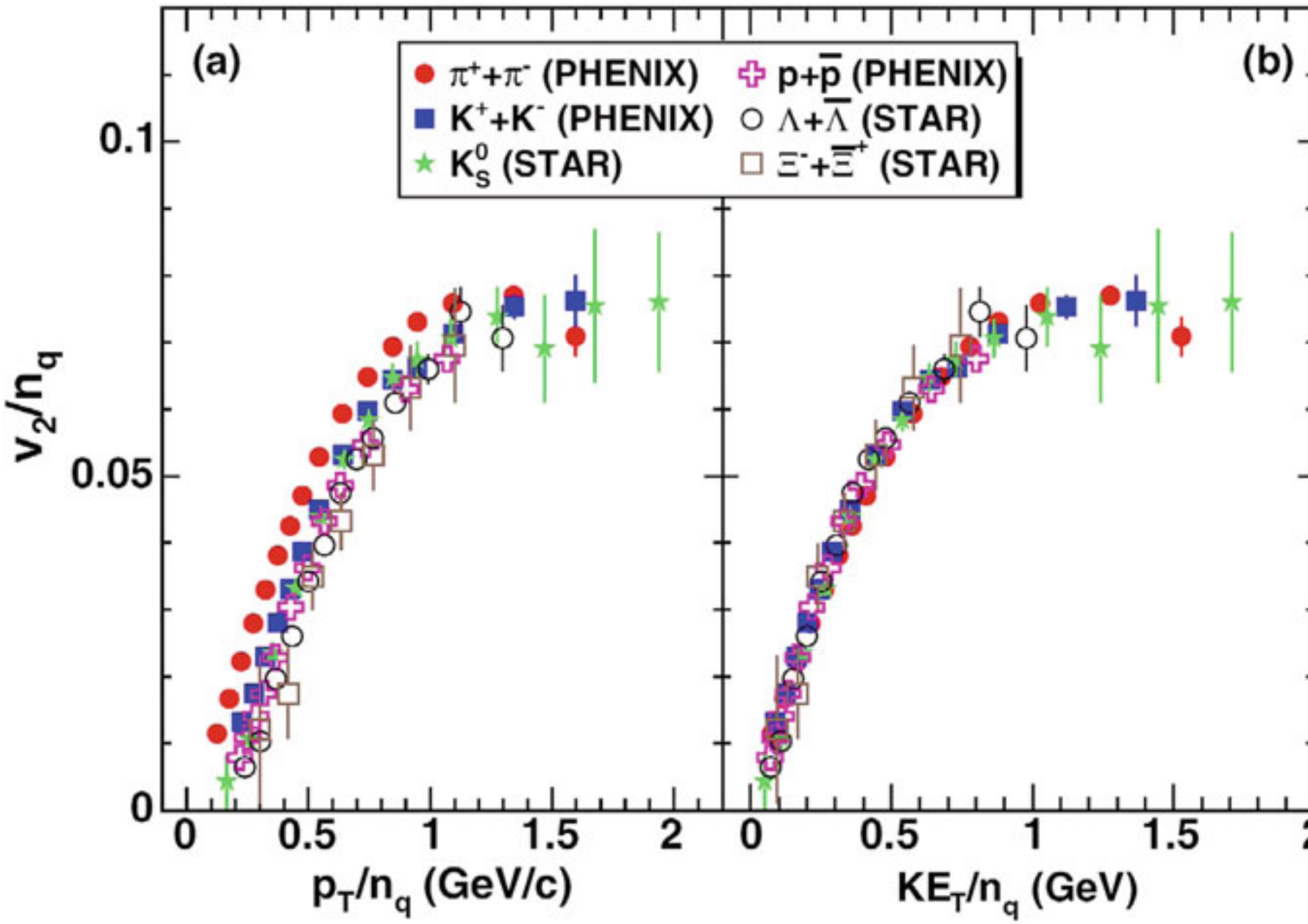
Look at the collective behavior of the medium

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\varphi - \Psi_n)\right]$$

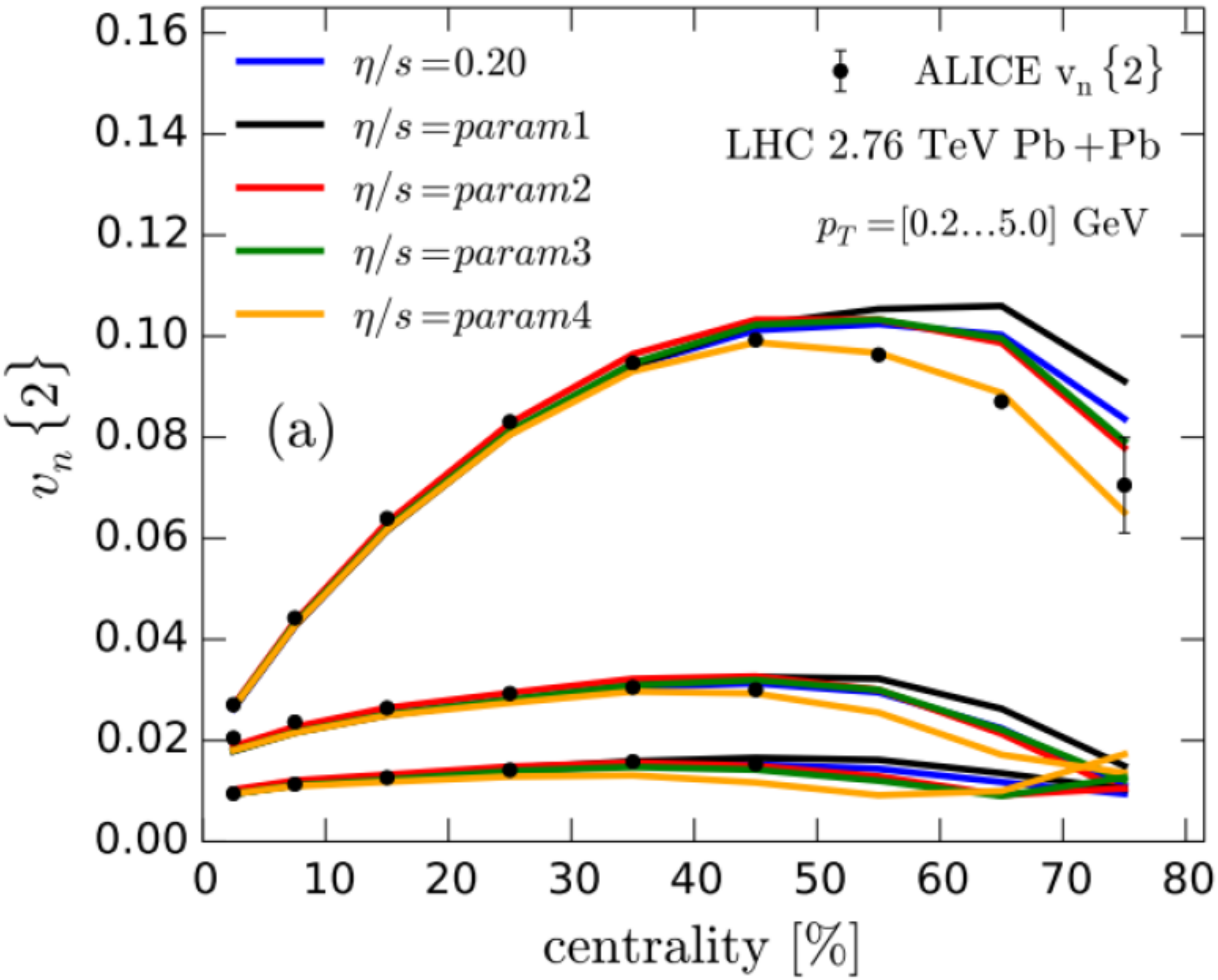
Where ψ is the azimuthal angle and Ψ_n is the n^{th} order event plane

Finding the QGP

- How do we know the medium is partonic?



QGP :Ideal Gas or Perfect Liquid?



Fit and Bayesian Analysis give most likely value of $\eta/_s \approx 0.07^{+0.05}_{-0.04} + c(T - T_c)$

Note, c is mostly unconstrained [0, 1.6] /GeV

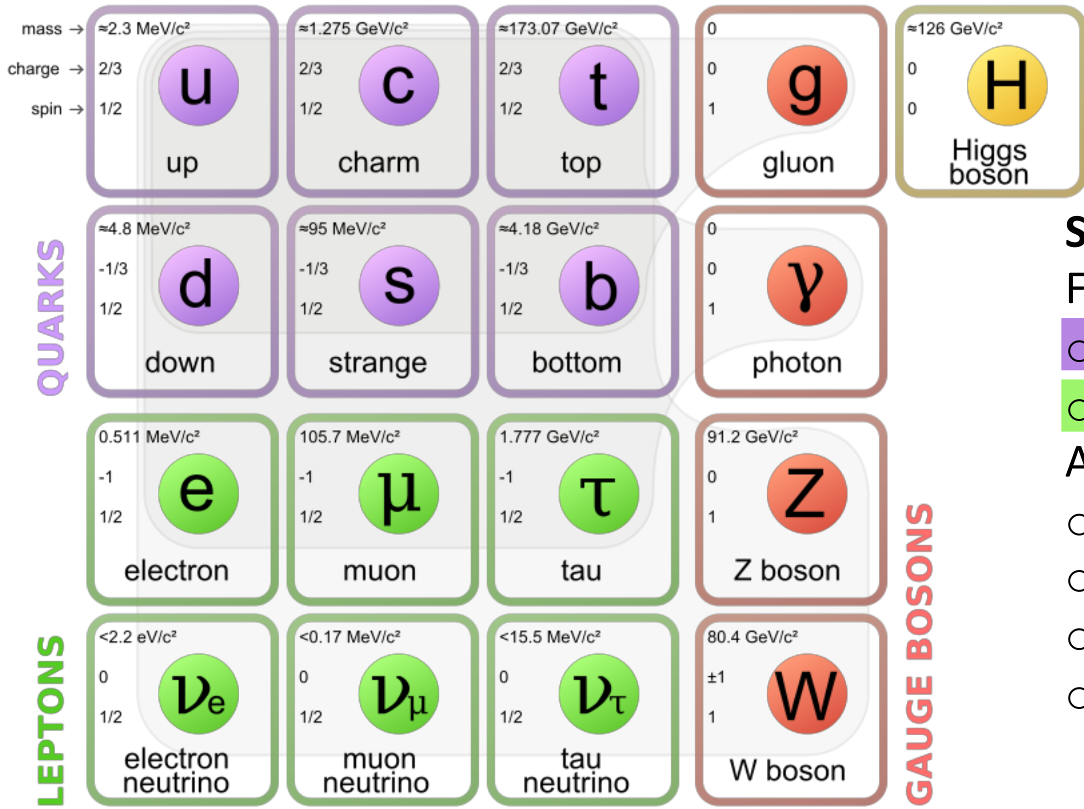
Average $\eta/_s$ strikingly close the theoretical limit from holography:

$$({}^1/_{4\pi} \approx 0.08)$$

If QGP were a weakly interacting gas of quarks and gluons : expect isotropic distribution

Hydrodynamic flow converts spatial anisotropies into momentum anisotropy

Why Study QCD Matter?



[https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg]

Standard Model of Physics

Fundamental building blocks of matter:

- Quarks
- Leptons

And their fundamental interactions:

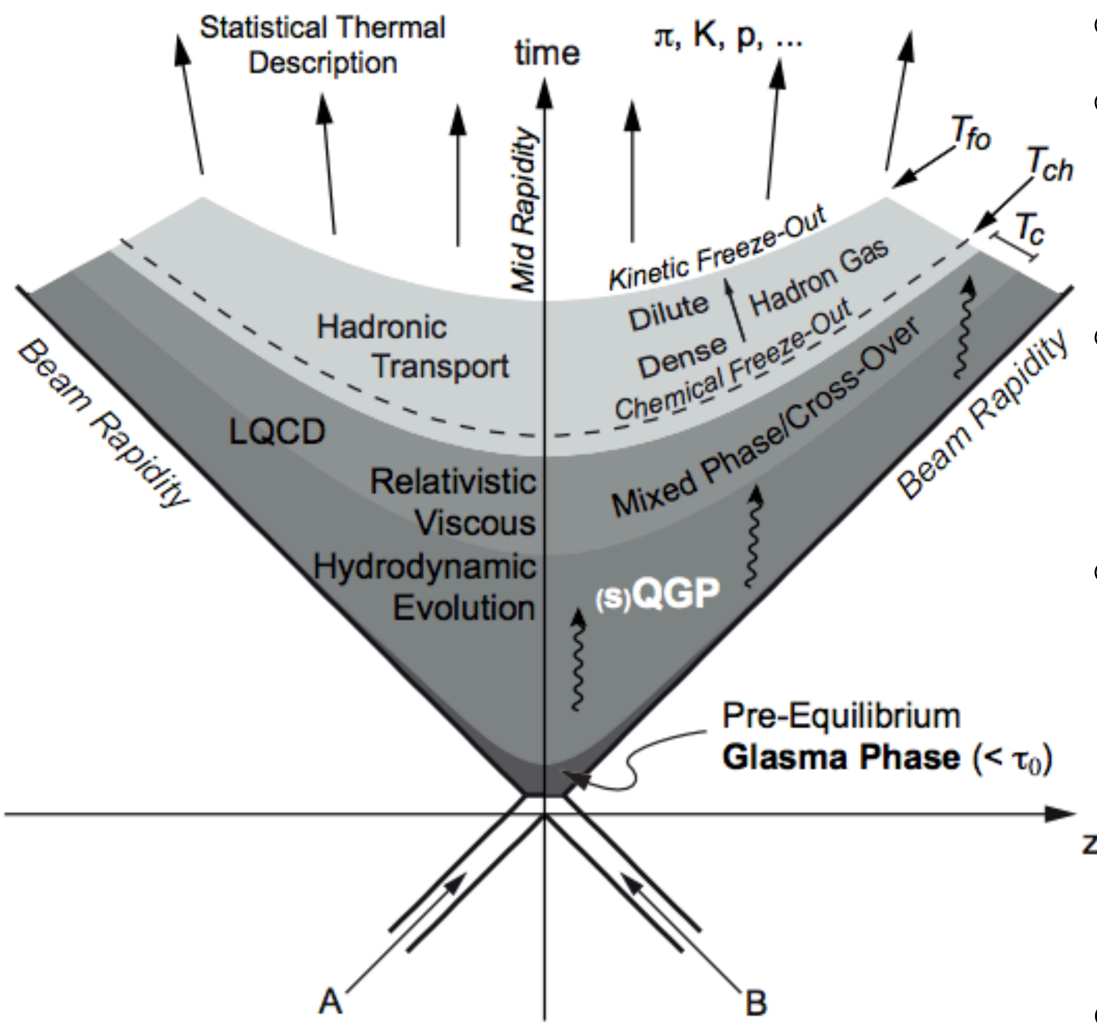
- Electromagnetic
- Weak interaction
- **Strong interaction**
- Gravity (not yet!)

But normal matter isn't just bare quarks

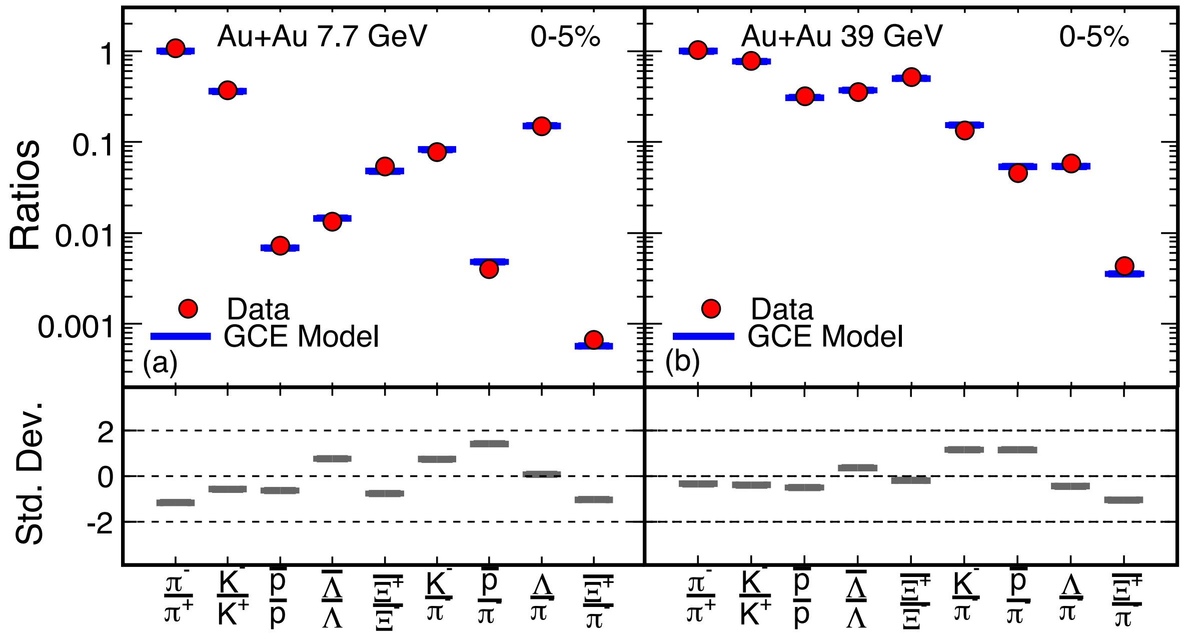
We study QCD to understand the emergence and organization of "normal" matter from quarks and gluons

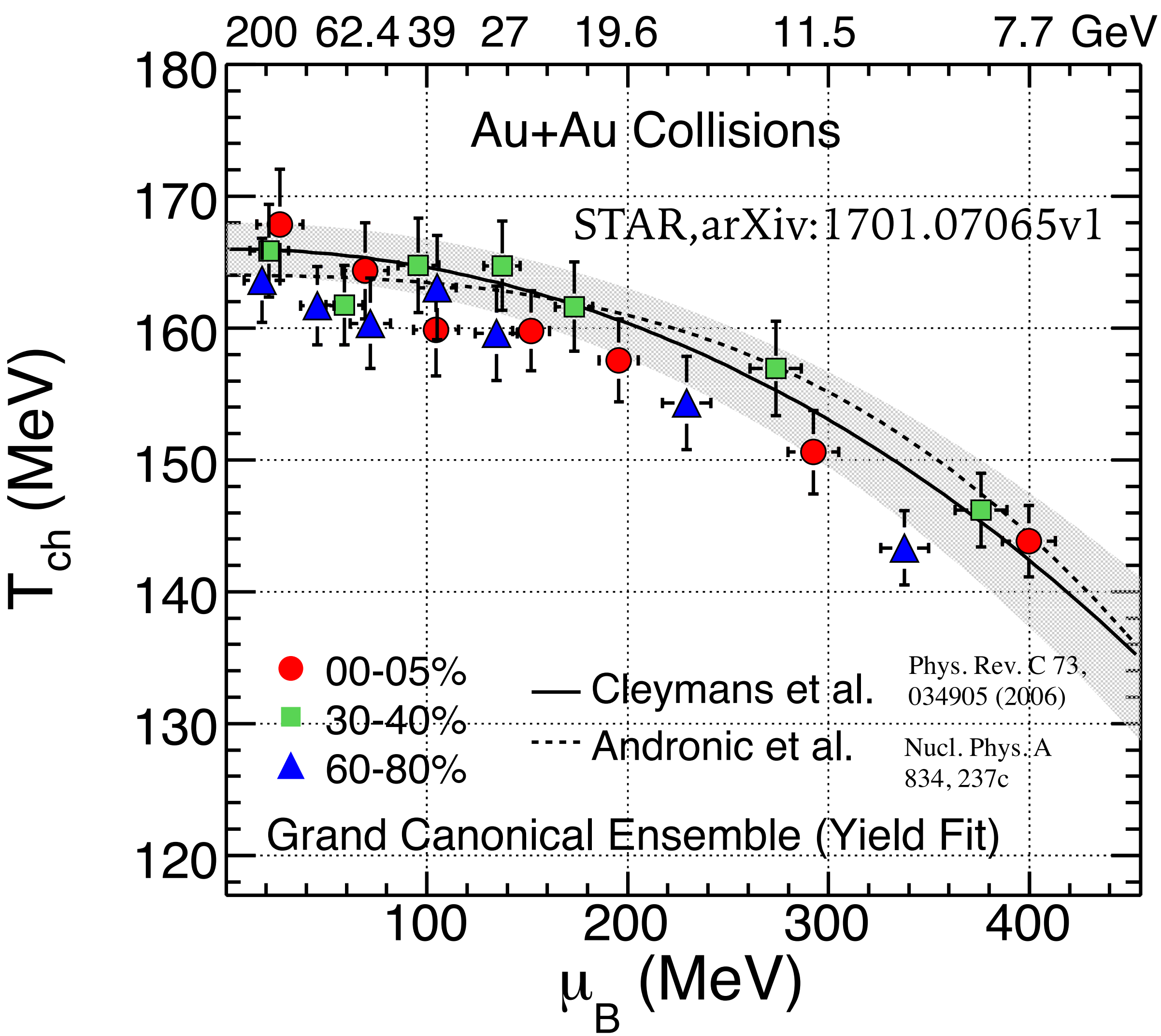
Life of a Heavy Ion Collision

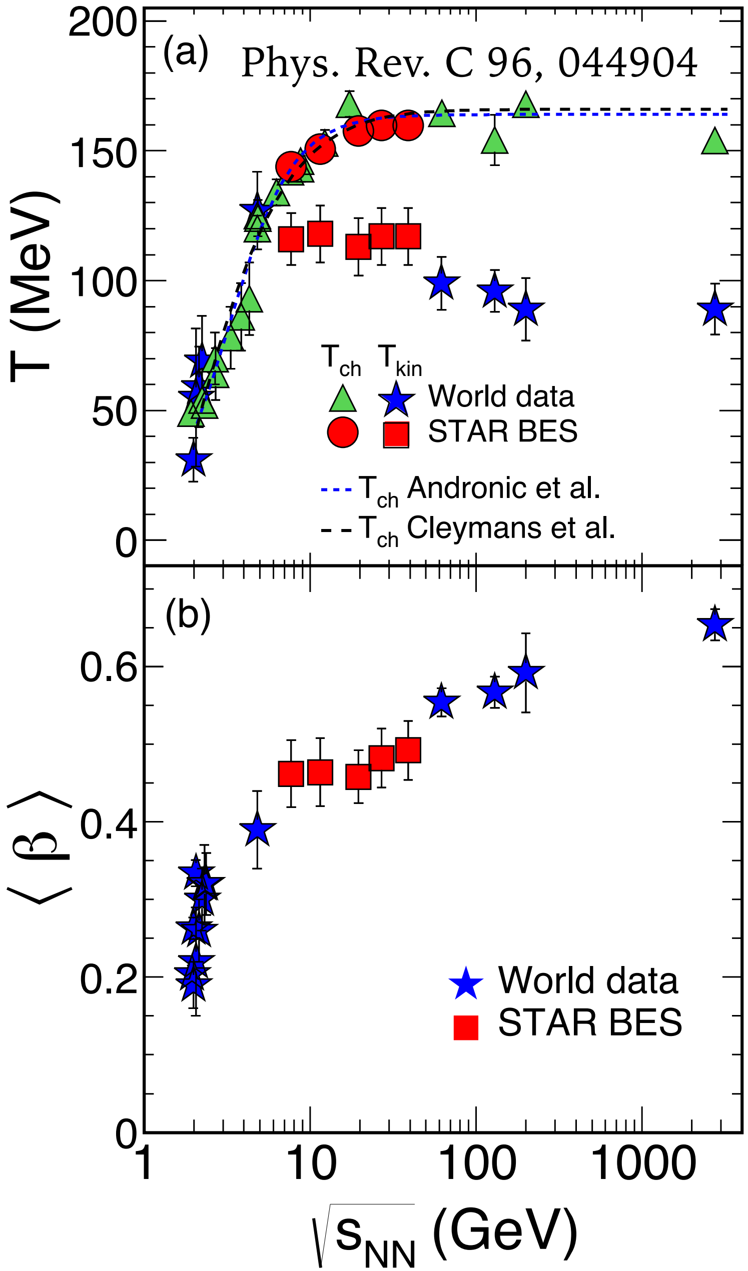
U.W. Heinz, (2004). http://arxiv.org/abs/hep-ph/0407360.



- $\tau = 0$: initial collision
- $\tau <\sim 1$ fm/c : pre-equilibrium – not much is known about the dynamics. Assume fast approach to thermal equilibrium
- $1 < \tau < \approx 15$ fm/c : QGP is formed if $\varepsilon > \varepsilon_c, T > T_c$
  - Viscous hydrodynamic expansion and cooling
- $\tau > 10 - 15$ fm/c : Freeze-out
  - T drops below T_c
  - Chemical freeze-out : inelastic scatterings cease - particle species are fixed
  - Kinetic freeze-out : elastic scatterings cease – particle momenta are fixed
- Free stream to detectors


Au+Au 7.7 GeV
0-5%
Au+Au 39 GeV
0-5%
Ratios
1
0.1
0.01
0.001
Data
GCE Model
(a)
(b)
Std. Dev.
2
0
-2

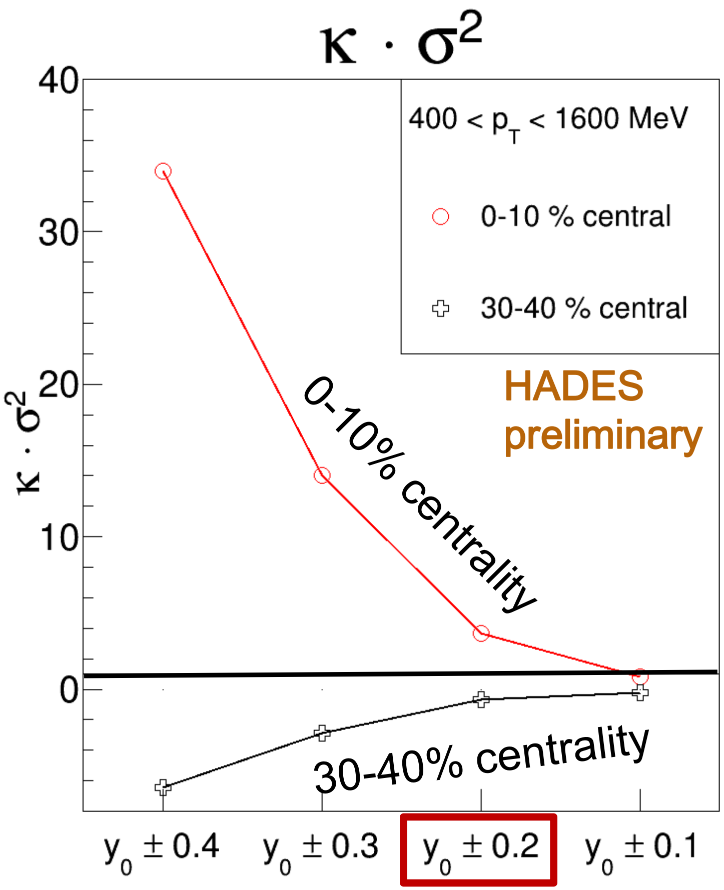

200 62.4 39 27 19.6 11.5 7.7 GeV
Au+Au Collisions
STAR,arXiv:1701.07065v1
00-05%
30-40%
60-80%
Cleymans et al.
Phys. Rev. C 73, 034905 (2006)
Andronic et al.
Nucl. Phys. A 834, 237c
Grand Canonical Ensemble (Yield Fit)
T_{ch} (MeV)
μ_B (MeV)
180
170
160
150
140
130
120
100
200
300
400

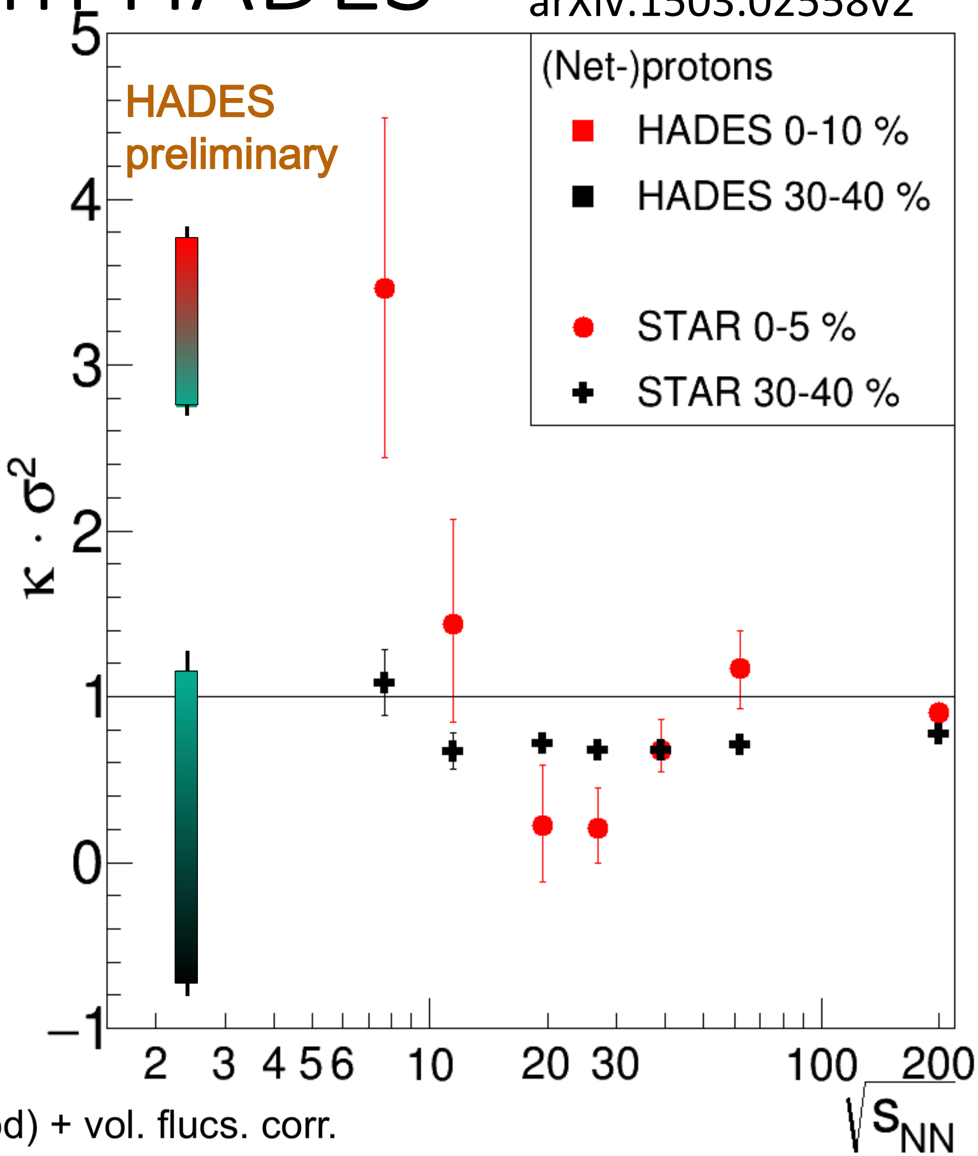


(a)
Phys. Rev. C 96, 044904
T (MeV)
200
150
100
50
0
T_{ch} T_{kin}
World data
STAR BES
T_{ch} Andronic et al.
T_{ch} Cleymans et al.
(b)
⟨ β ⟩
0.6
0.4
0.2
0
World data
STAR BES
1
10
100
1000
$\sqrt{s_{NN}}$ (GeV)

Fluctuations from HADES

arXiv:1503.02558v2



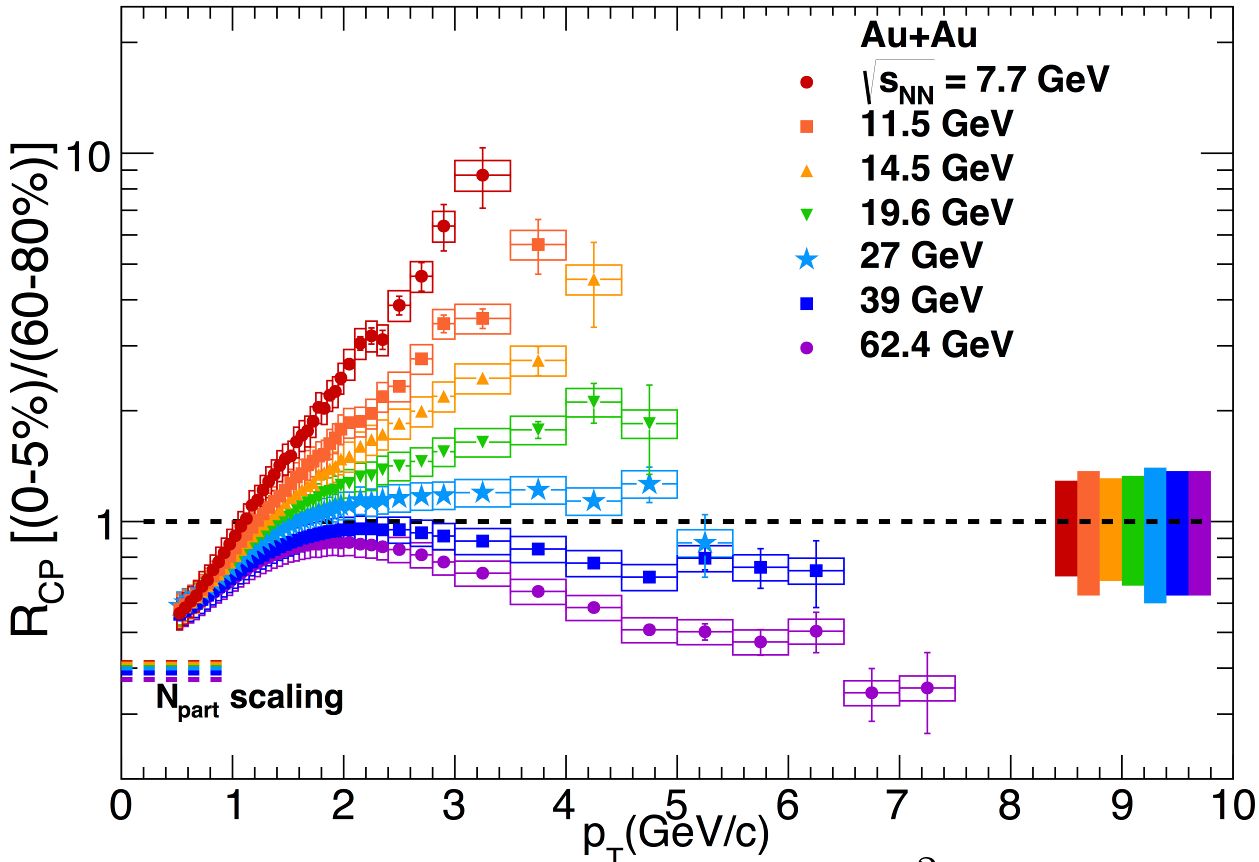


Demonstrate Poisson limit for small volume

red/black = unfolding (preferred method) + vol. flucs. corr.

green = evt-by-evt eff correction of factorial moments + vol. flucs. corr.

Nuclear Modification Factor in BES 1

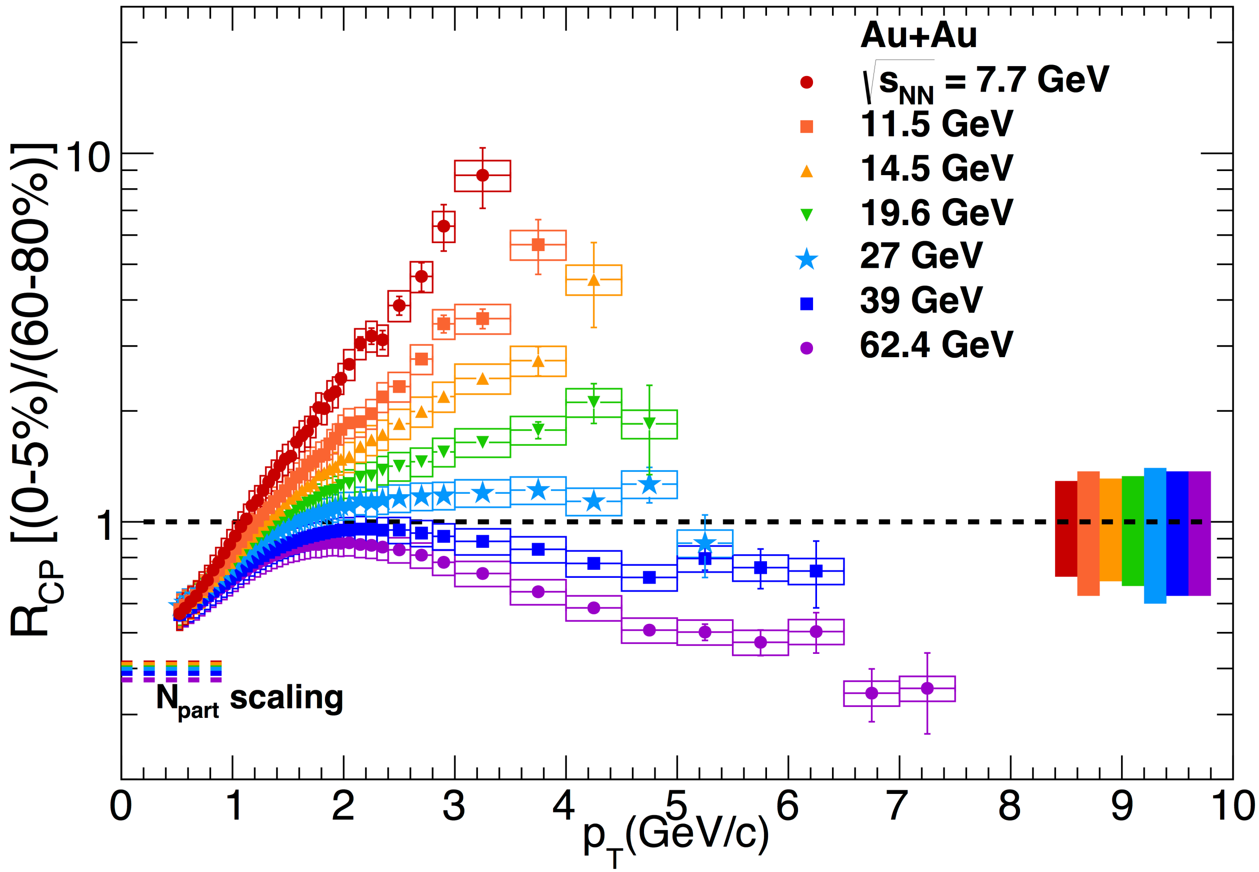


Smooth transition from suppression ($R_{CP} < 1$) at highest energies to enhancement ($R_{CP} > 1$) at lowest energies

Turn off of the QGP?

$$R_{\mathrm{CP}} = \frac{\langle N_{\mathrm{coll}} \rangle_{\mathrm{Peripheral}}}{\langle N_{\mathrm{coll}} \rangle_{\mathrm{Central}}} \frac{\left(\frac{d^2N}{dp_{\mathrm{T}}\,d\eta}\right)_{\mathrm{Central}}}{\left(\frac{d^2N}{dp_{\mathrm{T}}\,d\eta}\right)_{\mathrm{Peripheral}}}$$

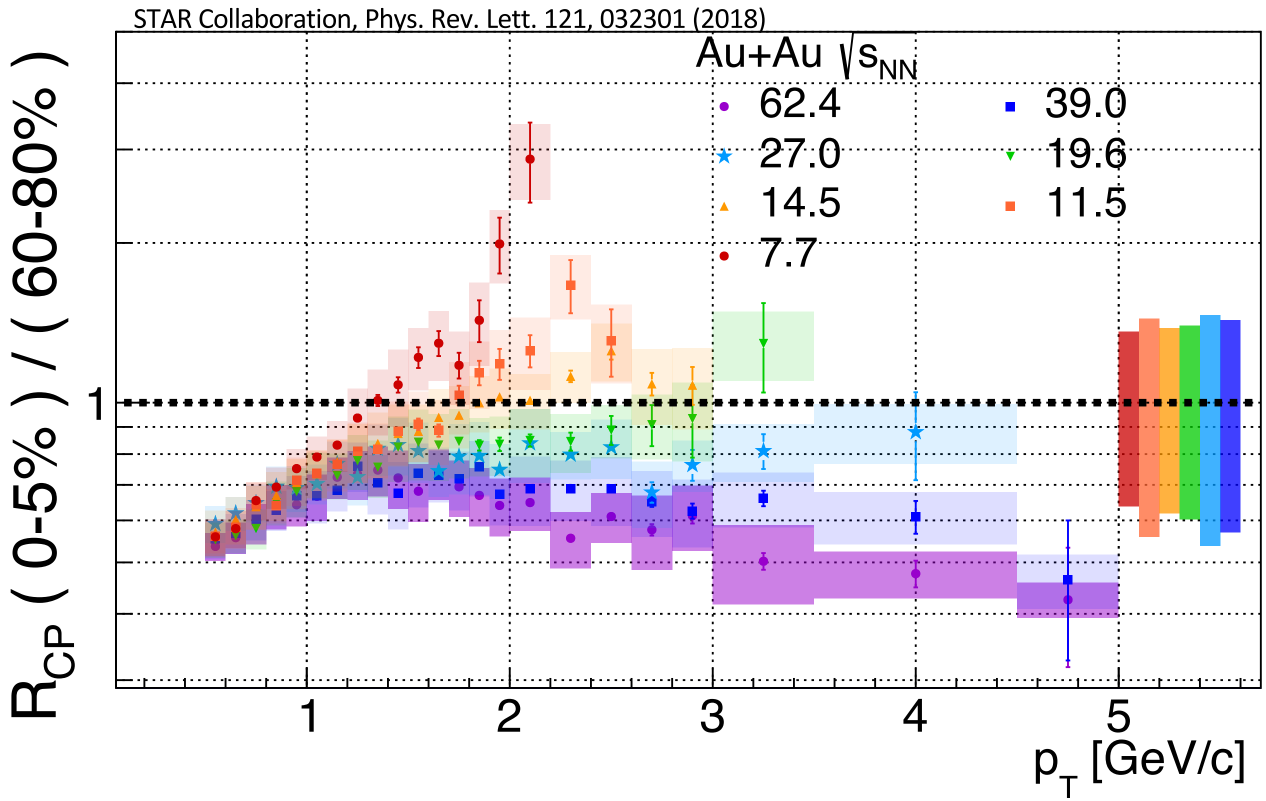
Nuclear Modification Factor in BES 1



What can we say from this measurement?

- $R_{CP} \ll 1$ (at high p_T) : QGP is definitely formed
- If $R_{CP} \geq 1$: QGP may be formed or may not - competing effects

R_{CP} for Identified Hadrons



- Pions are more sensitive probes of suppression than heavy particles
- No sign of suppression above ~19.6 GeV