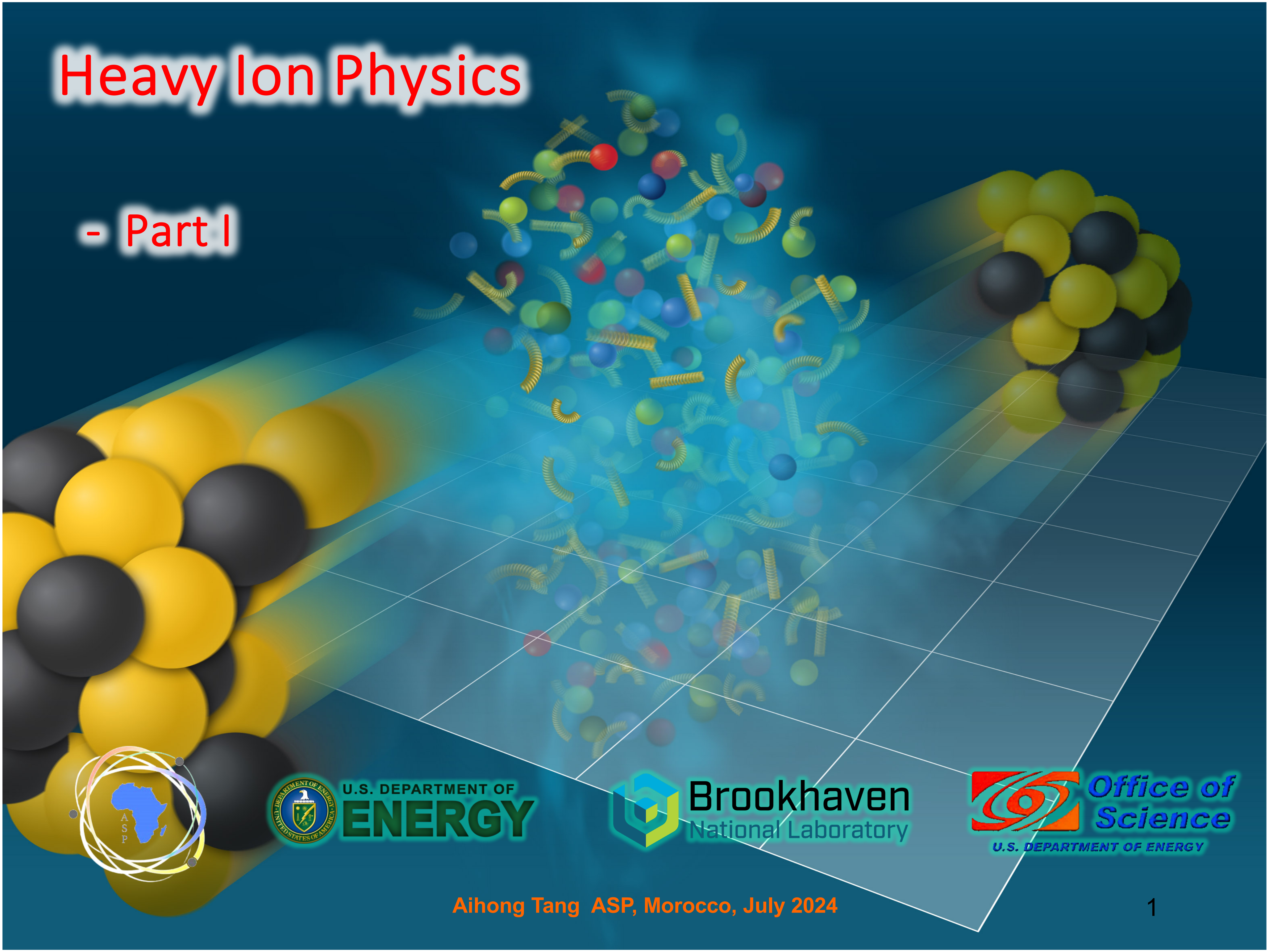
Heavy Ion Physics

- Part I



U.S. DEPARTMENT OF ENERGY

Brookhaven National Laboratory

Office of Science
U.S. DEPARTMENT OF ENERGY

Aihong Tang ASP, Morocco, July 2024

Part I : Introduction to heavy ion physics

Part II : In-depth discussion on two selected topics (flow and antimatter)

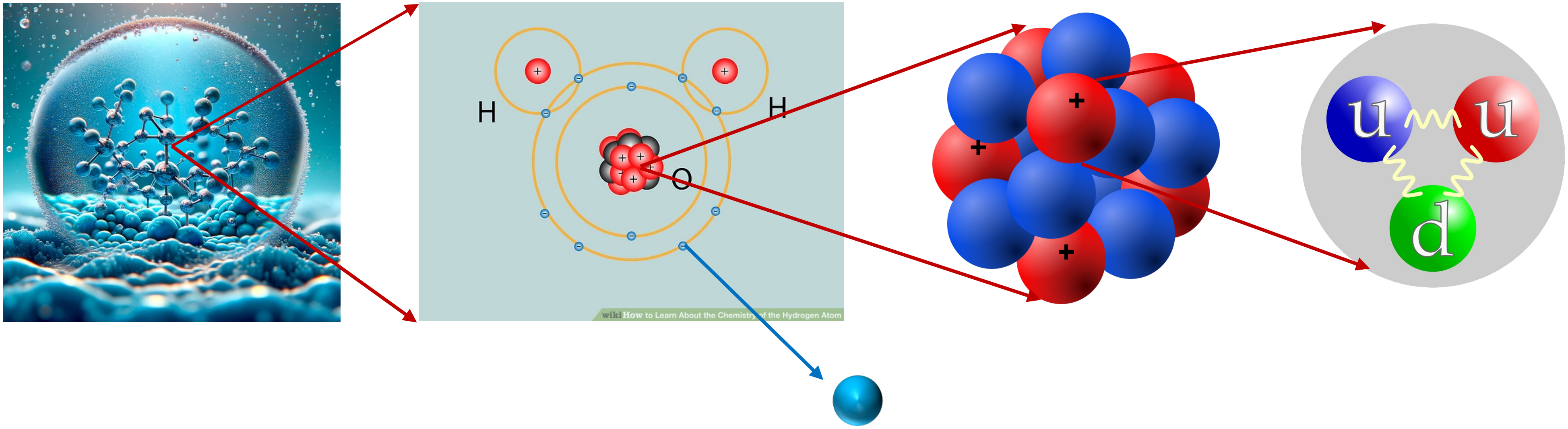
Building Block of the Universe

Molecule
10^{-9} m

Atom
10^{-10} m

Nucleus
10^{-15}-10^{-14} m

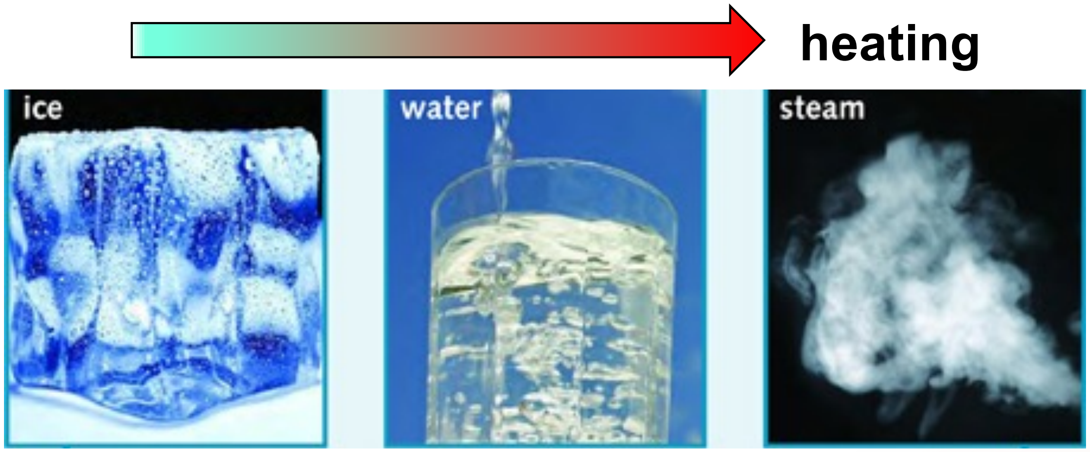
Quarks & Gluons
$<10^{-18}$ m

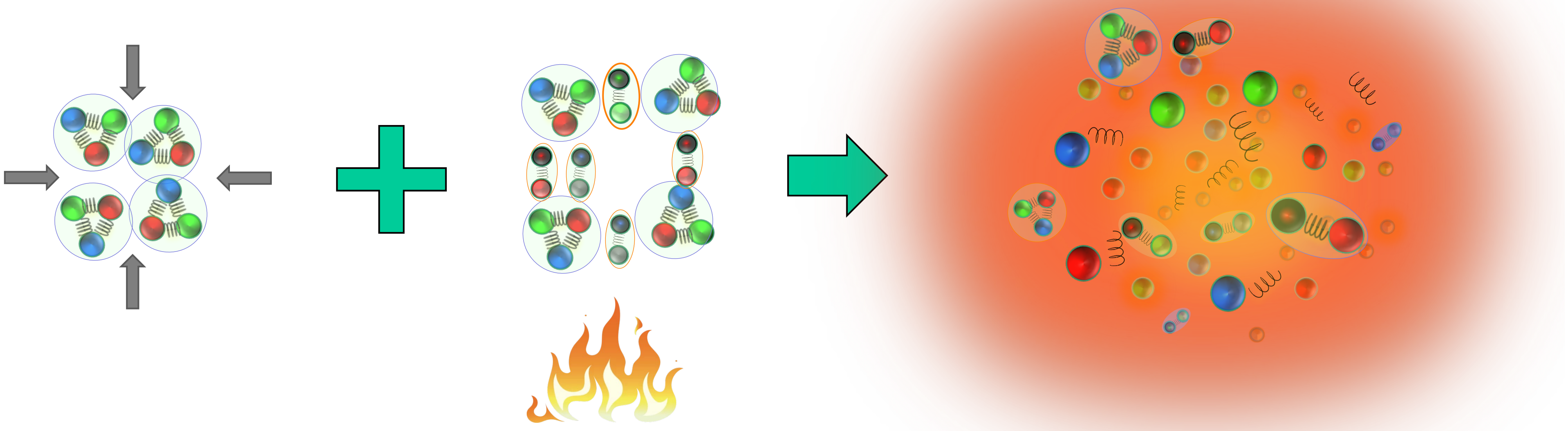


electron

Slide Credit R. Ma. Images:
https://scitechdaily.com/rethinking-h2o-water-molecule-discovery-contradicts-textbook-models/
https://www.wikihow.life/Learn-About-the-Chemistry-of-the-Hydrogen-Atom
https://en.wikipedia.org/wiki/Nucleon

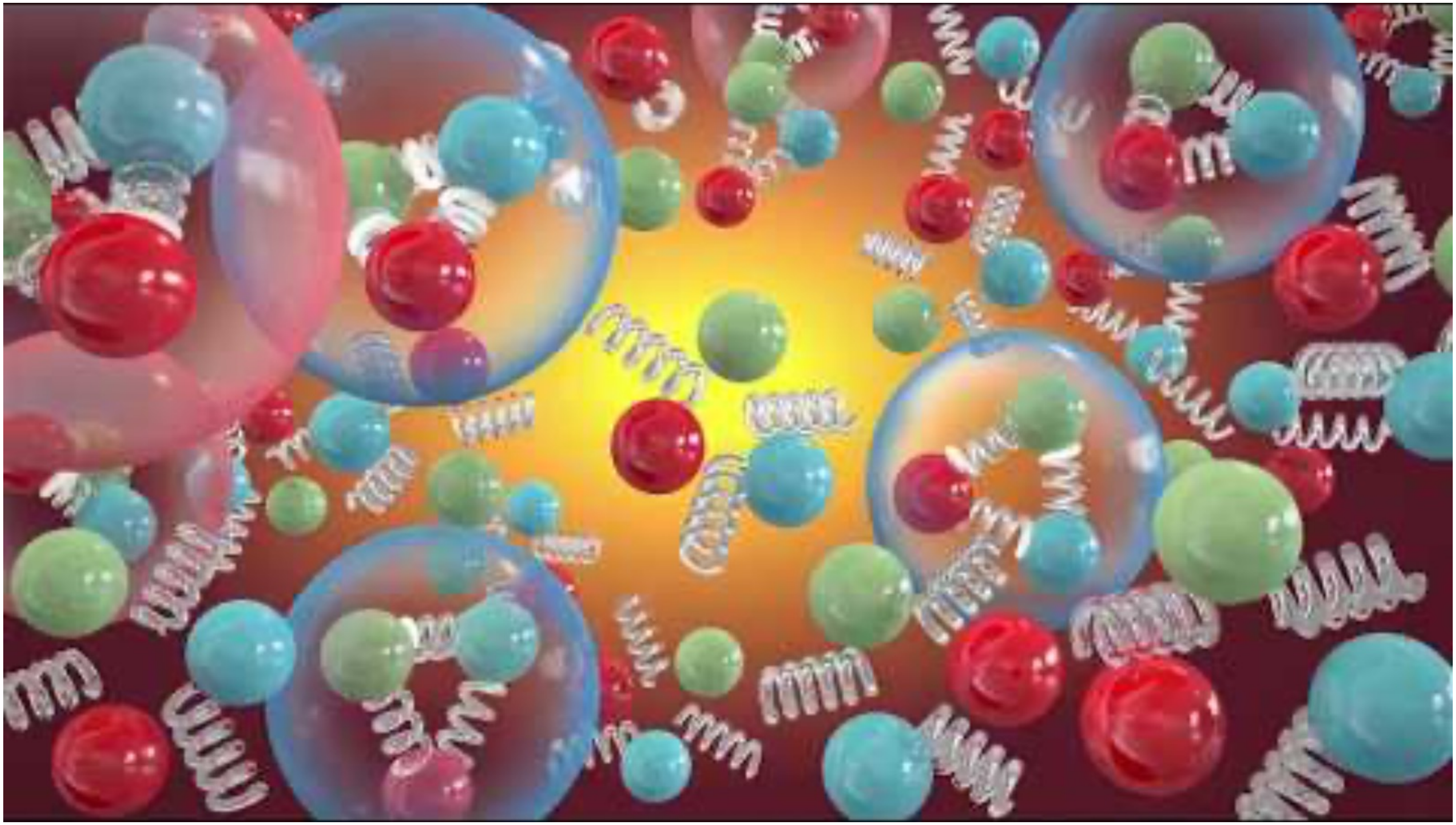
Quark-Gluon Plasma


heating

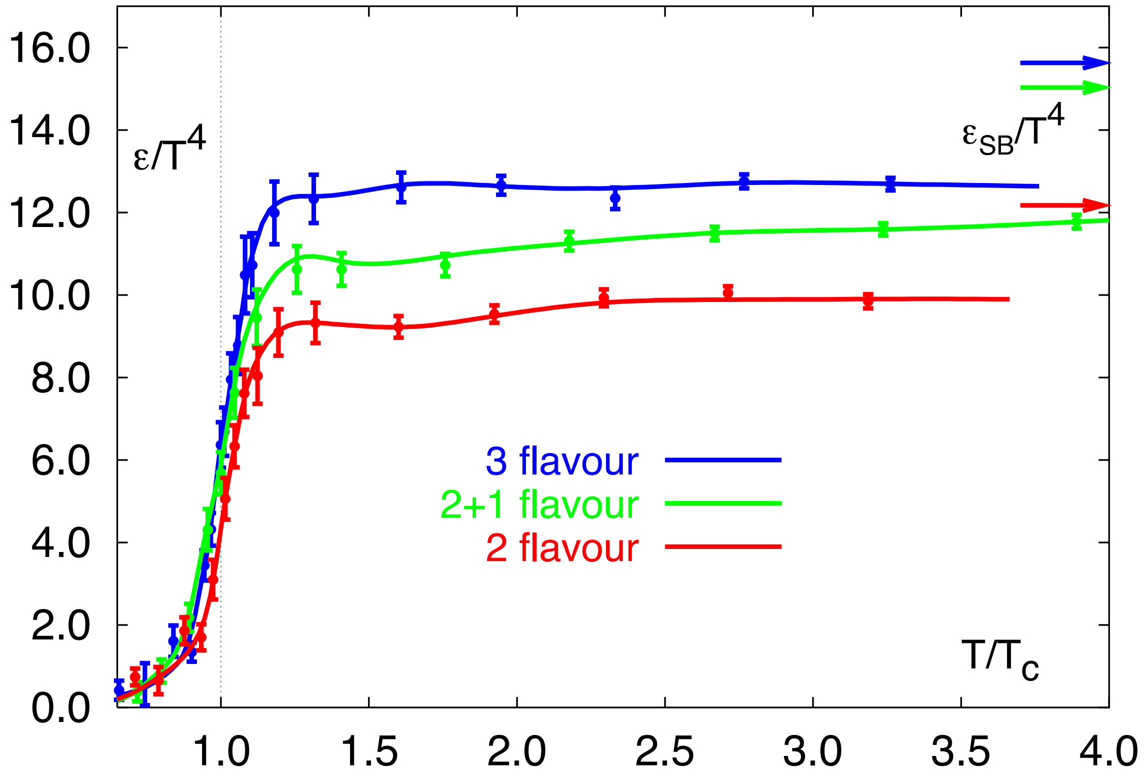


Pressure + Heat ⇒ Quark-Gluon Plasma

Quark-Gluon Plasma



Quark-Gluon Plasma



F.Karsch, Lect.Notes Phys. 583 209 (2002)

$\varepsilon_c \sim 1$ GeV / fm^3

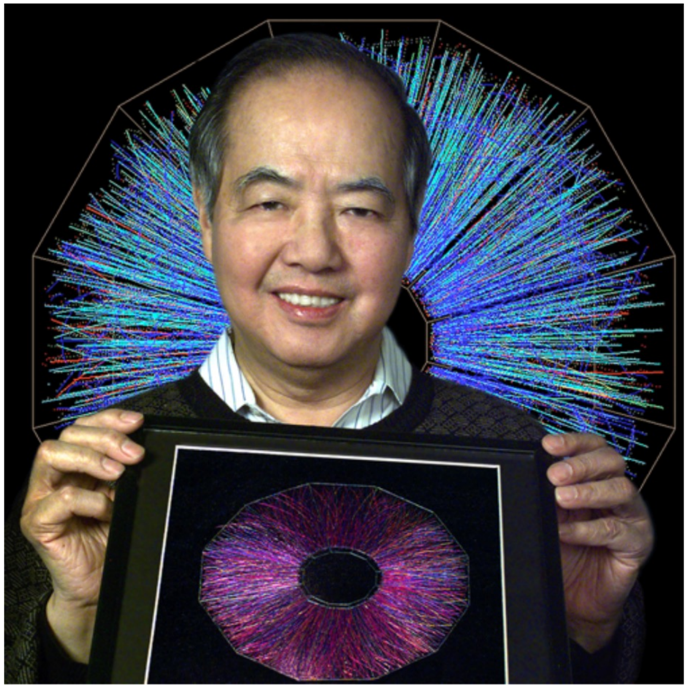
$T_c \sim 165$ MeV (2e12 K)

[For reference, core of sun : 1.5e7K]

A Brief History

1974 : Workshop on “GeV/nucleon collisions of heavy ions”

“We should investigate some “bulk” phenomena by distributing high energy over a relatively large volume. That fact that this direction has never been explored should, by itself, serve as an incentive for doing such experiments”
– Tsung-Dao Lee (Nobel Prize laureate 1957)



1984 : SPS started (ended in 2003)

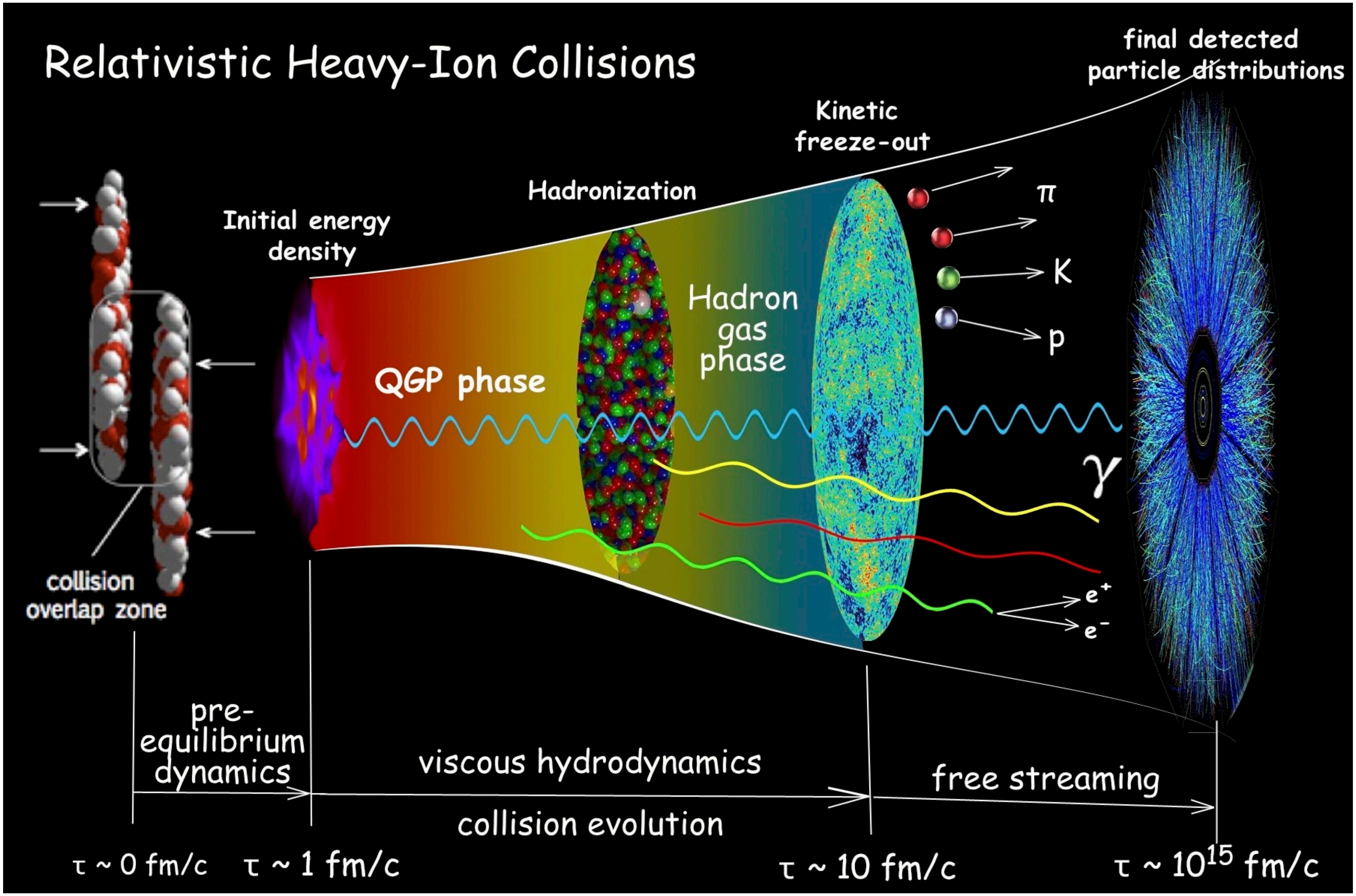
1986 : AGS started (ended ~ 2000)

2000 : RHIC started (to end in 2025)

2010 : LHC started.

In preparation : FAIR & NICA

Big Bang and Little Bangs



Cosmic Origins in a Collider

Image Credit : Wiki and C. Shen

Relativistic Heavy Ion Collisions

1. QCD phase diagram

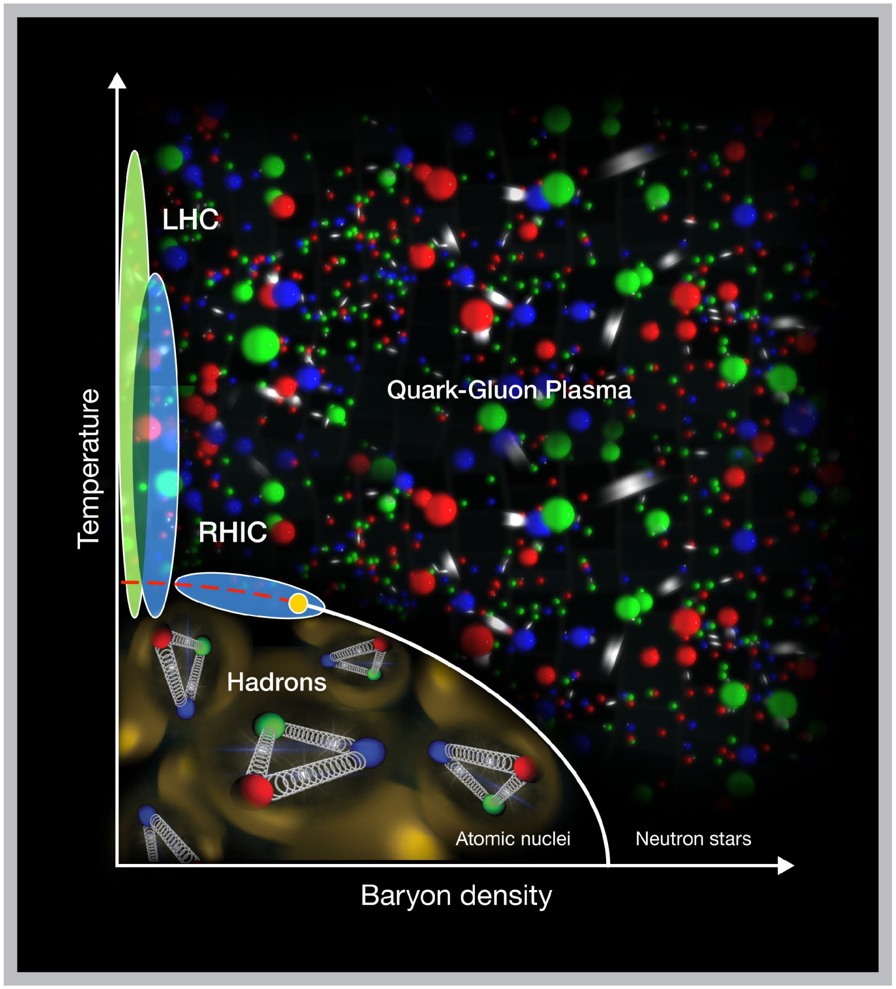
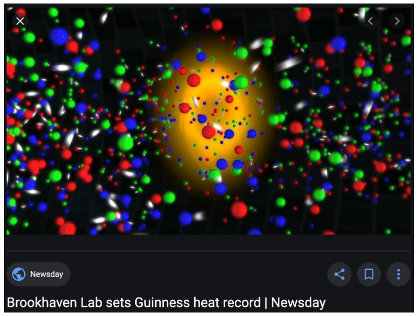


Image Credit : Brookhaven Lab

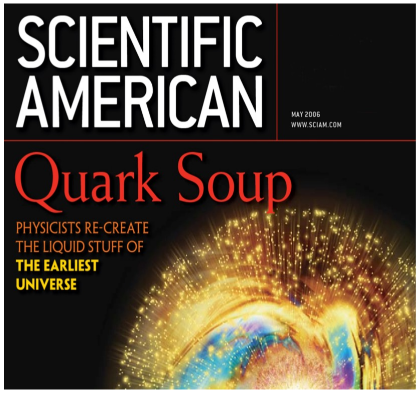
Relativistic Heavy Ion Collisions : Excellent QCD test ground

Relativistic Heavy Ion Collisions

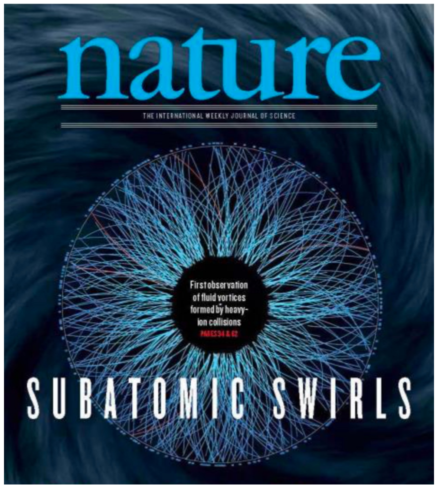


Brookhaven Lab sets Guinness heat record | Newsday

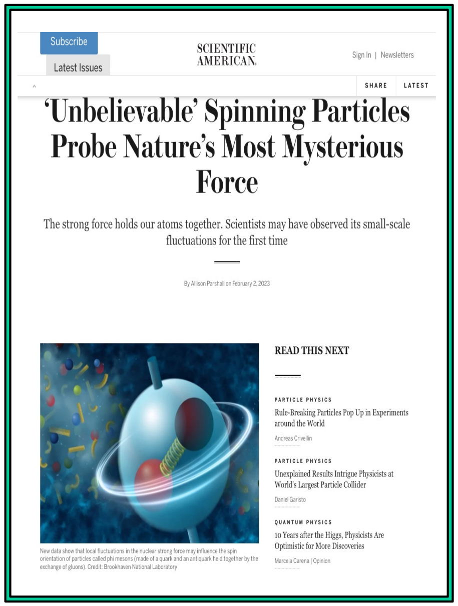
Hottest



Least viscous



Most vortical



‘Unbelievable’ Spinning Particles Probe Nature’s Most Mysterious Force

The strong force holds our atoms together. Scientists may have observed its small-scale fluctuations for the first time

By Allison Parshall on February 2, 2023

New data show that local fluctuations in the nuclear strong force may influence the spin orientation of particles called phi mesons (made of a quark and an antiquark held together by the exchange of gluons). Credit: Brookhaven National Laboratory

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Andreas Crivellin

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Daniel Garisto

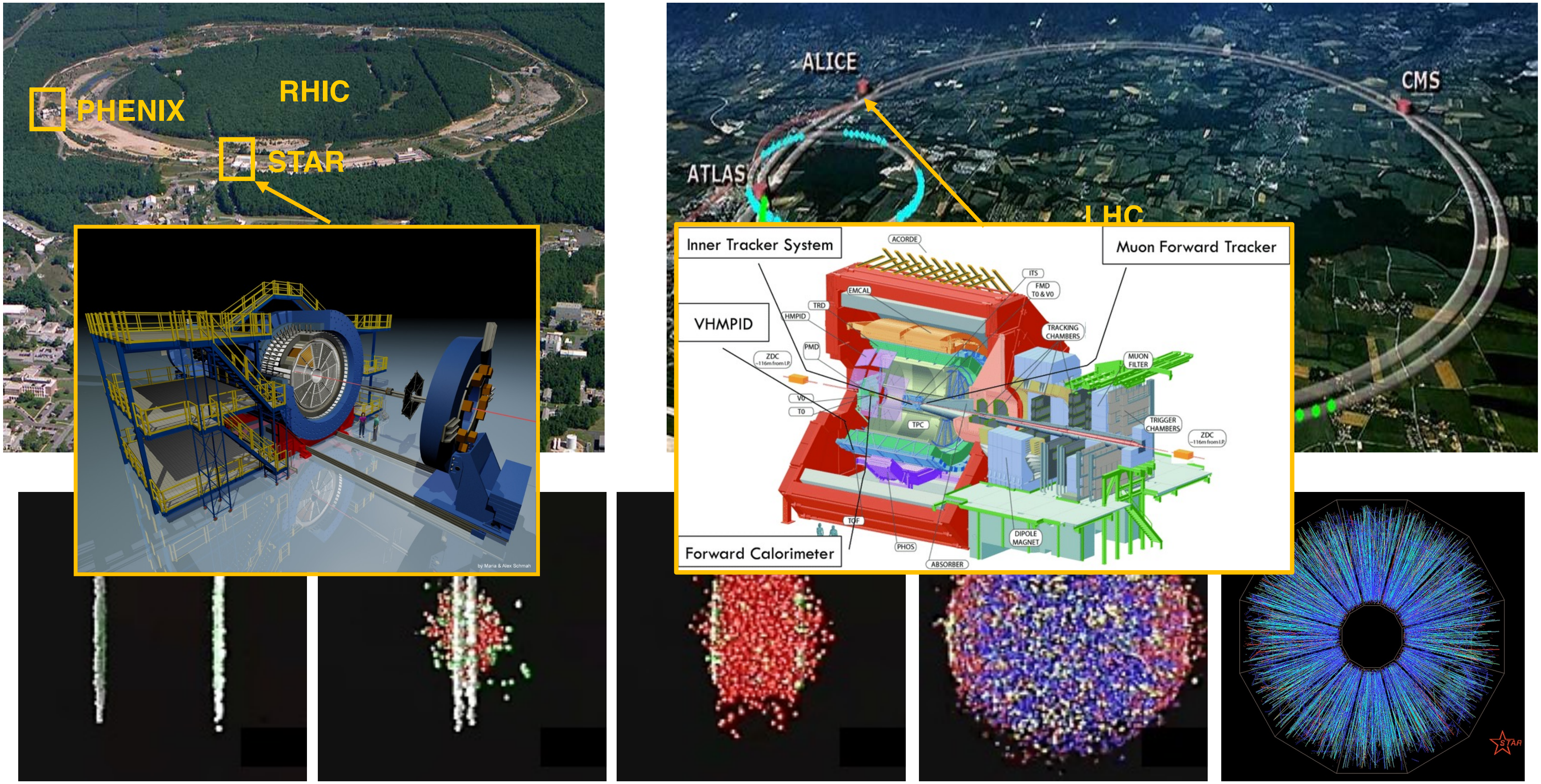
QUANTUM PHYSICS
10 Years after the Higgs, Physicists Are Optimistic for More Discoveries
Marcela Carena | Opinion

Strongly Fluctuating ?

1. QCD phase diagram
2. Dynamic properties of QCD matter

Relativistic Heavy Ion Collisions : Excellent QCD test ground

Heavy Ion Experiments

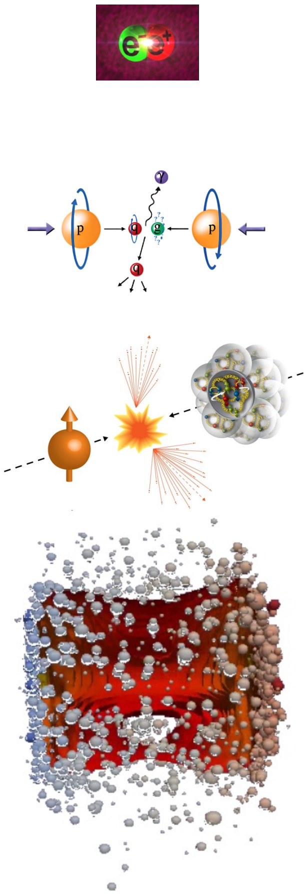


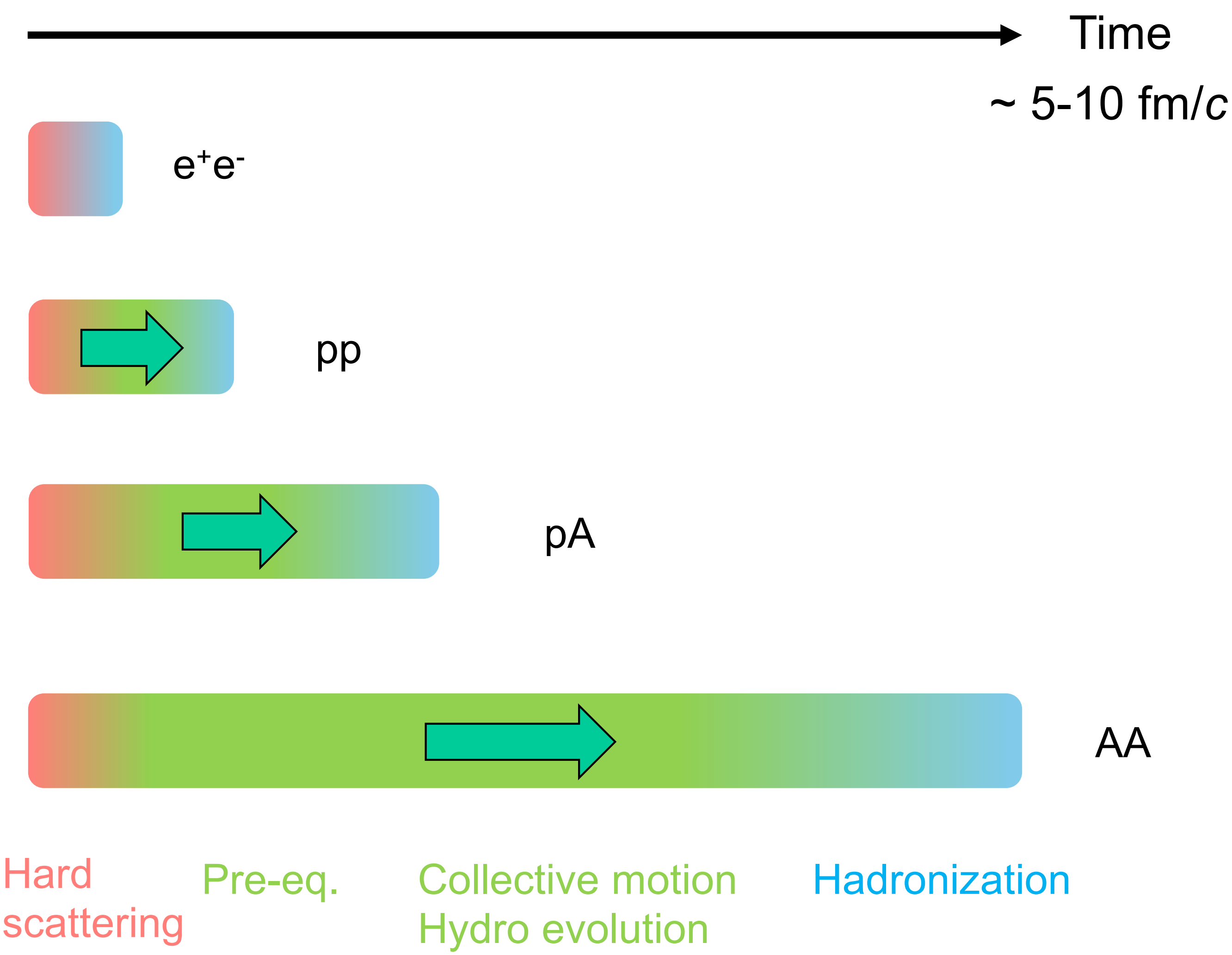
Ions about to collide   Ion collision   Plasma formation   Freeze out   What we “see”

Heavy Ion Experiment in a Nutshell

RHIC

Compare to Elementary Collisions





Time

~ 5-10 fm/c

e^+e^-

pp

pA

AA

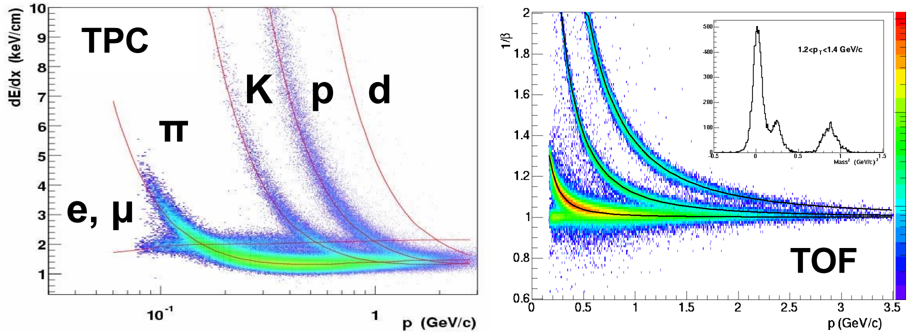
Hard scattering

Pre-eq.

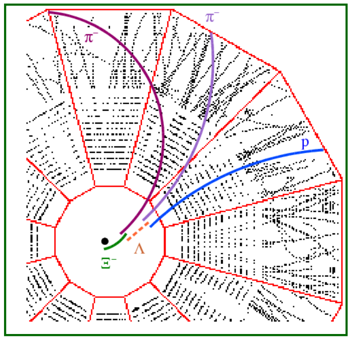
Collective motion
Hydro evolution

Hadronization

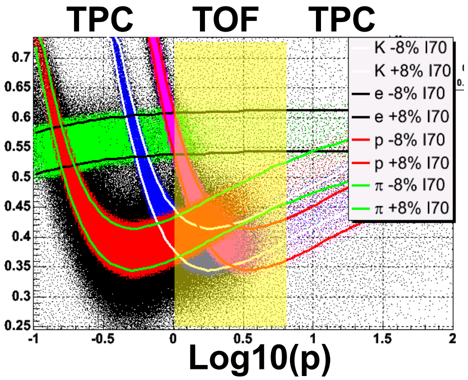
Requirements for Detectors

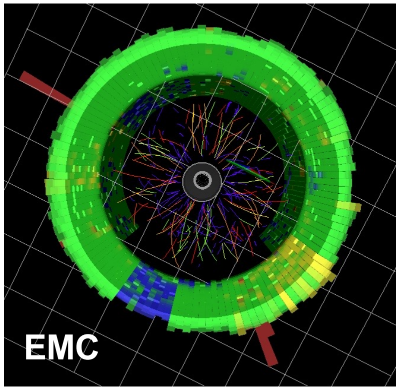


Charged hadrons

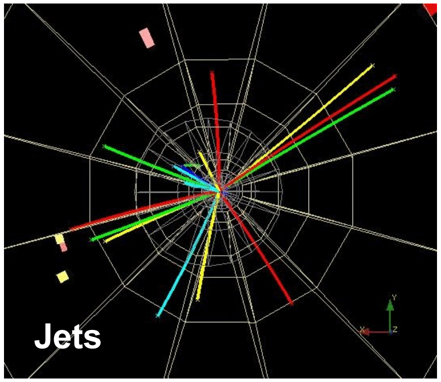


Hyperons & Hyper-nuclei

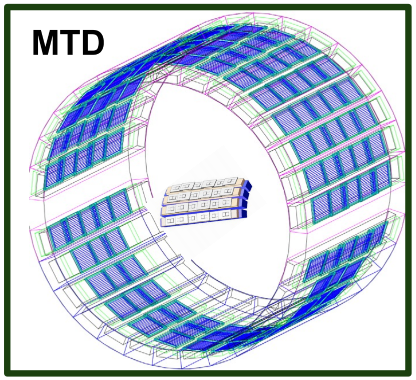




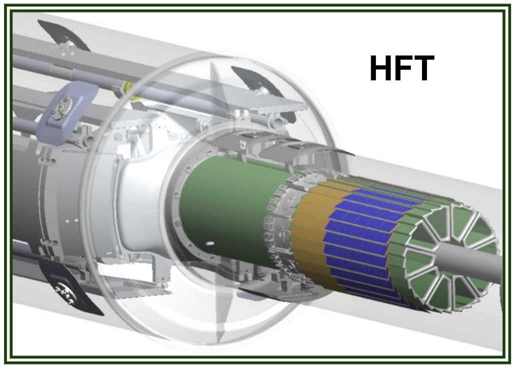
Neutral particles



Jets & Correlations



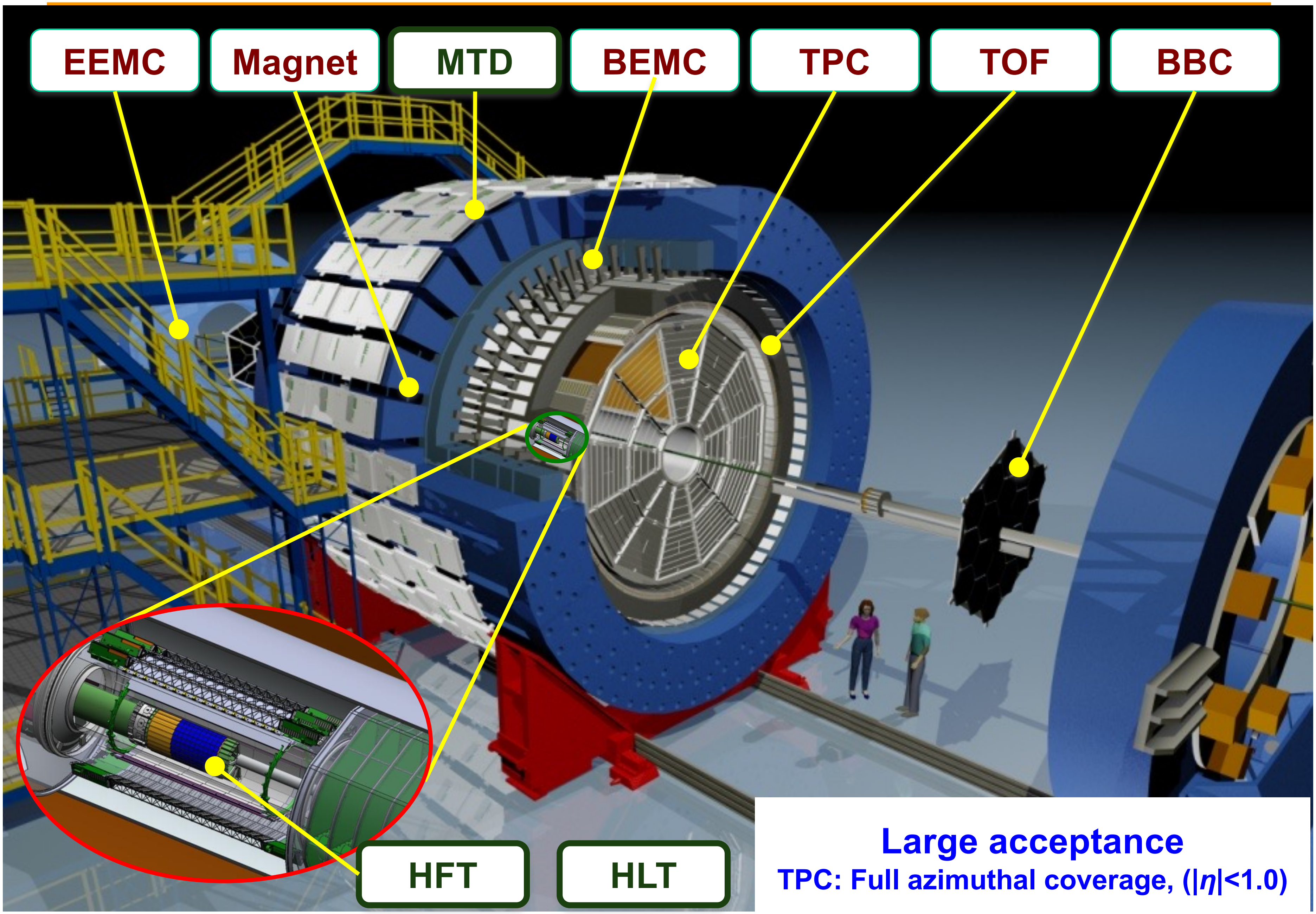
High pT muons



Heavy-flavor hadrons

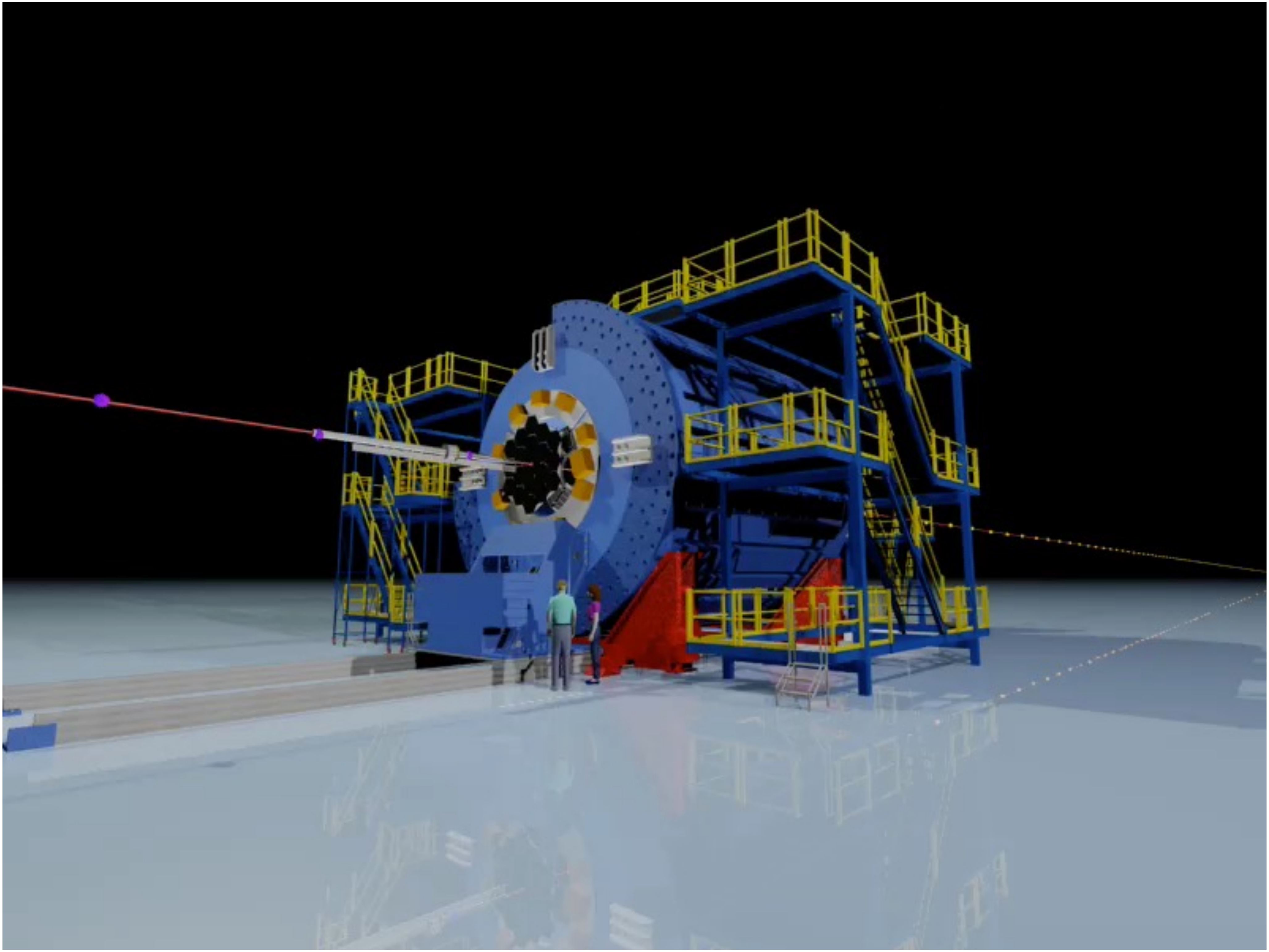
Large acceptance. High efficiency. High resolution. Particle identification capability.

Requirements for Detectors

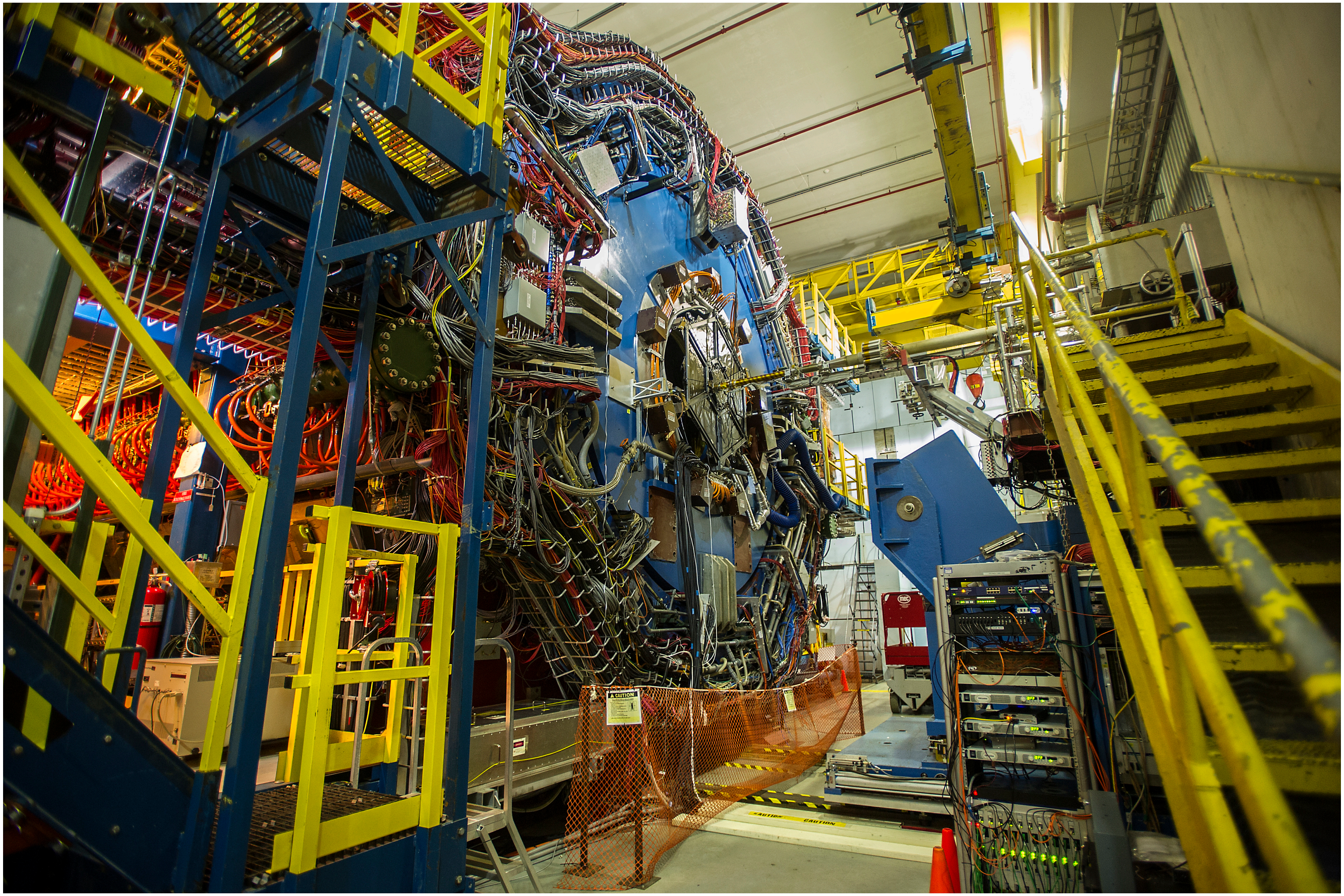


Large acceptance

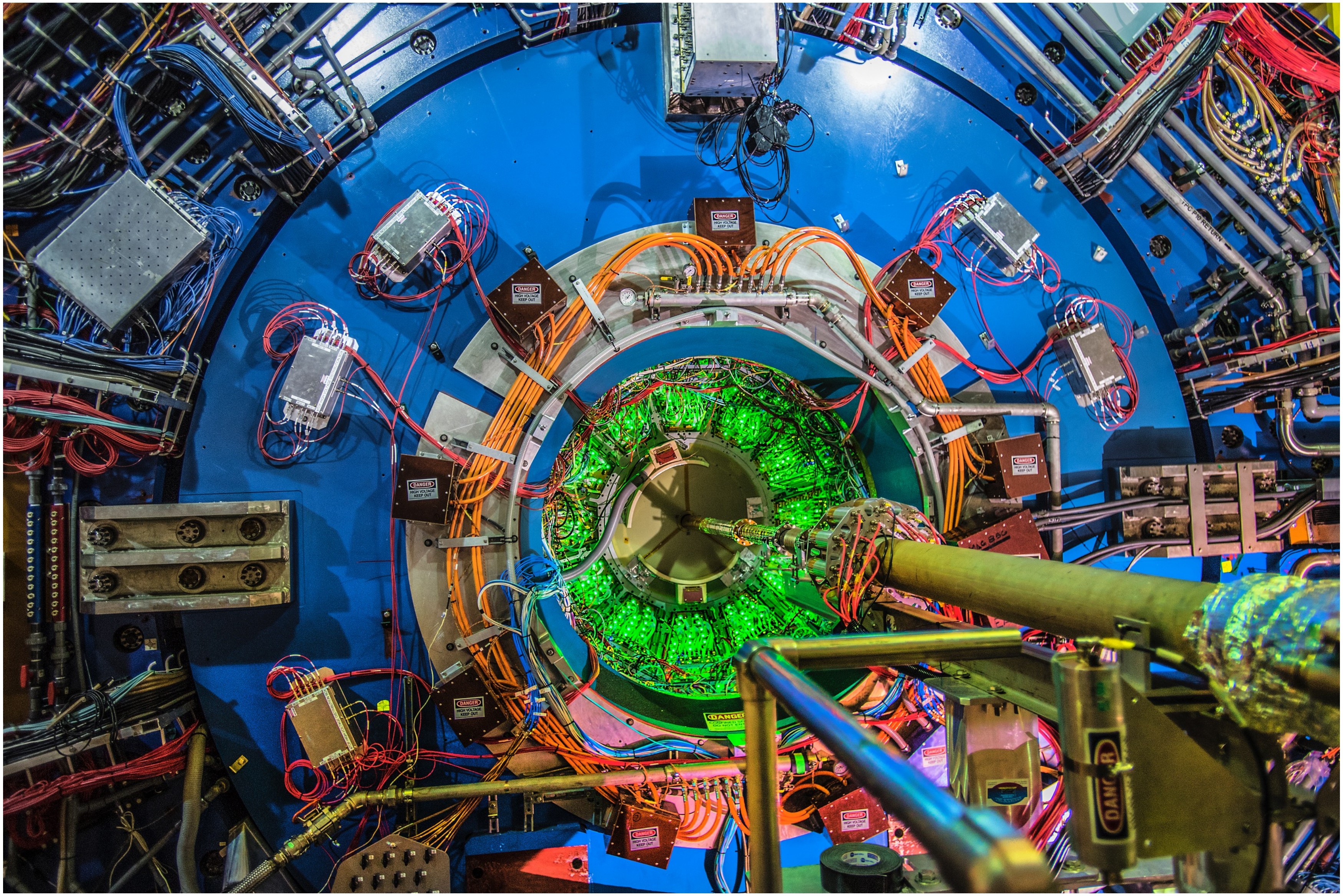
TPC: Full azimuthal coverage, (|η|<1.0)



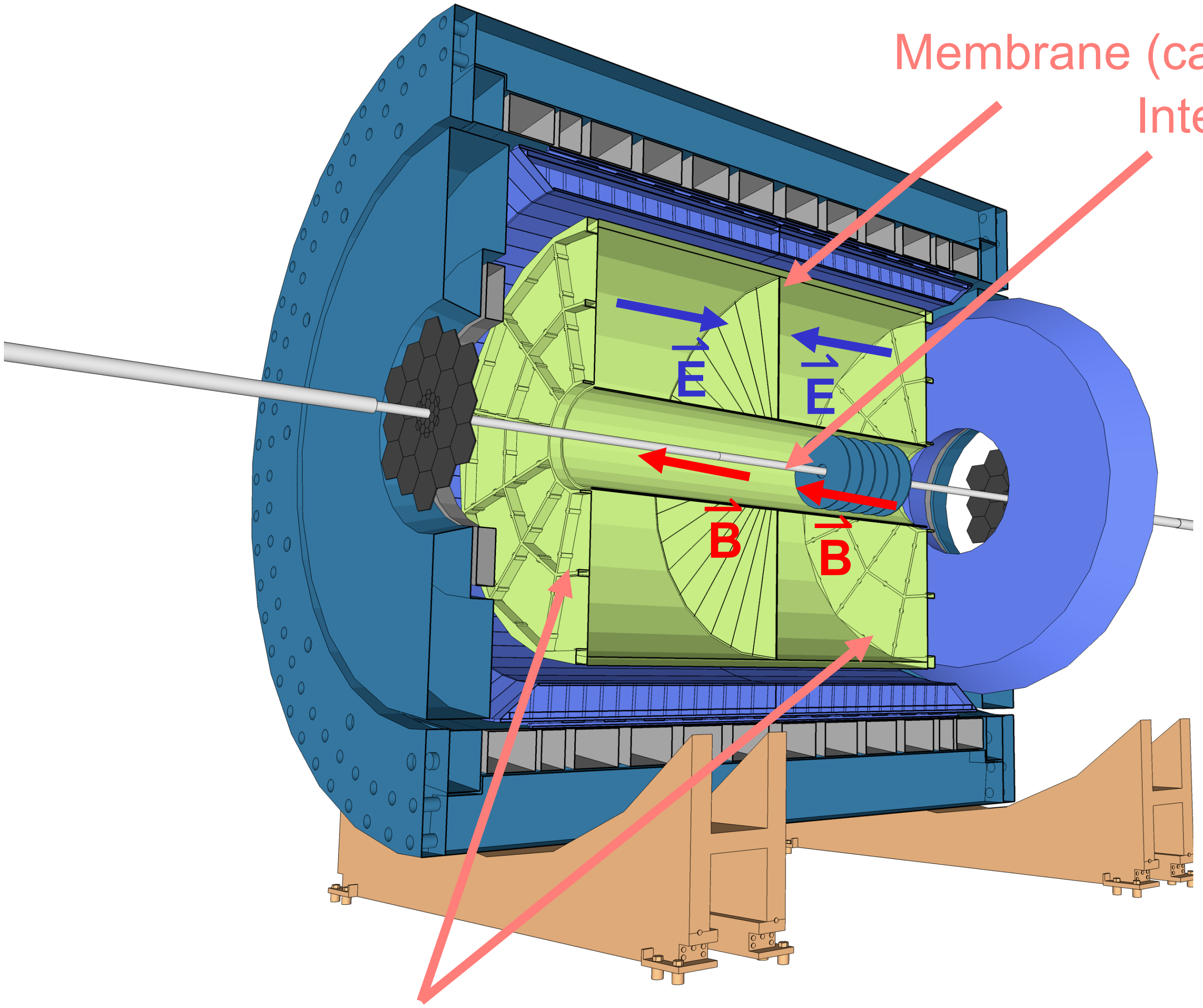
Time Projection Chamber

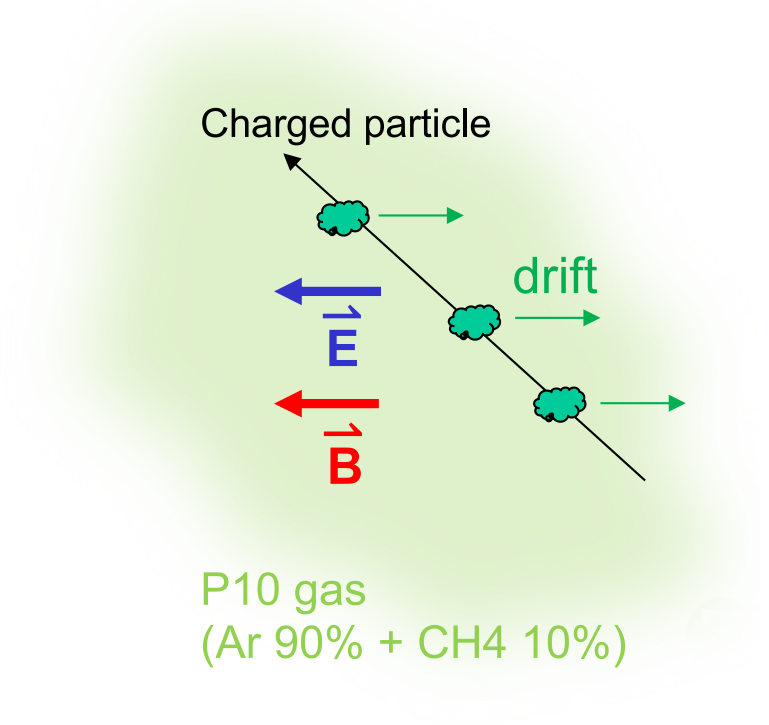


Time Projection Chamber



Time Projection Chamber

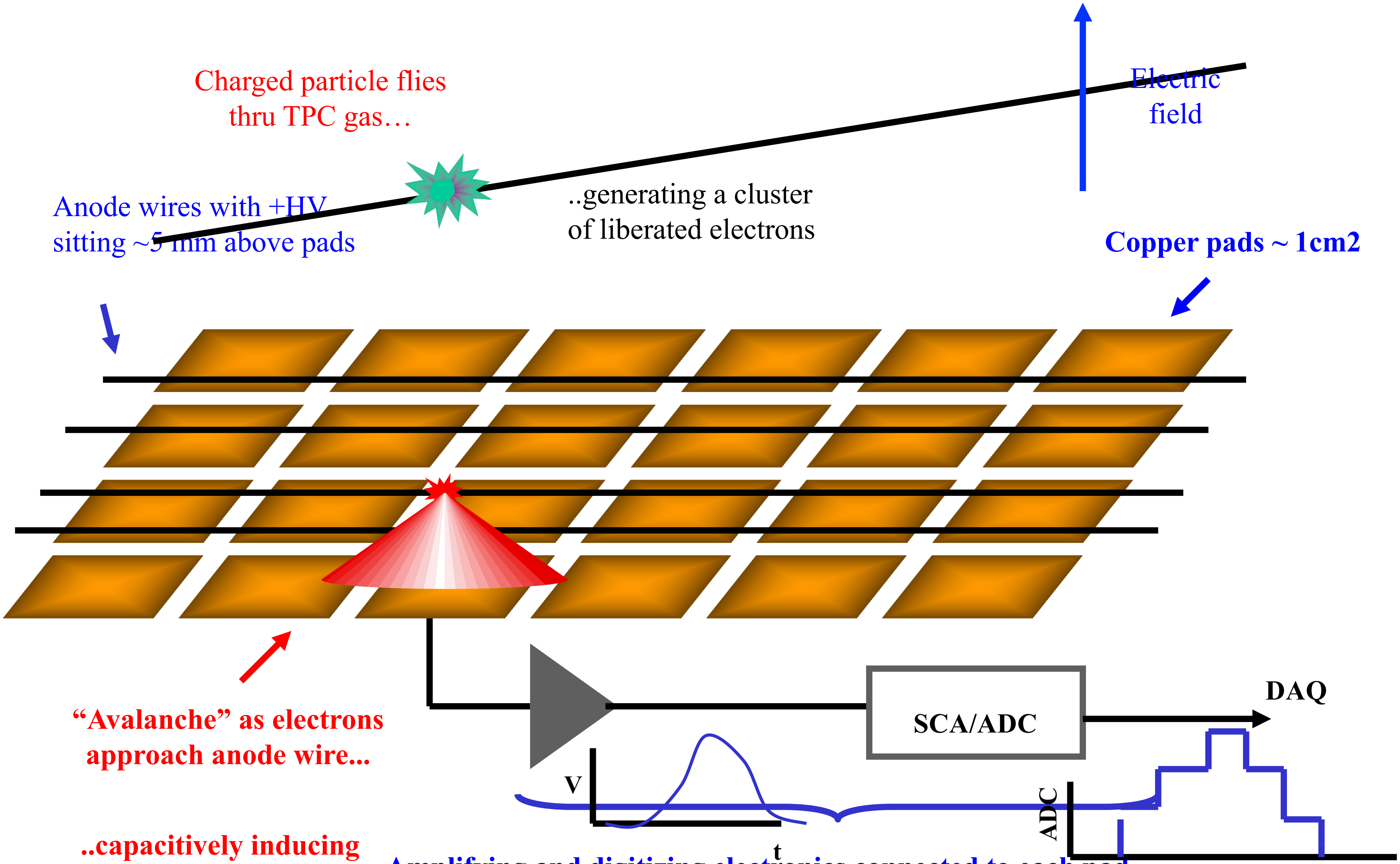




$$p_T = mv_T = qBr$$

Gas detector taking 3D photos of the tracks of passing charged particles

Time Projection Chamber



Charged particle flies
thru TPC gas…

Electric
field

Anode wires with +HV
sitting ~5 mm above pads

..generating a cluster
of liberated electrons

Copper pads ~ 1cm2

**“Avalanche” as electrons
approach anode wire...**

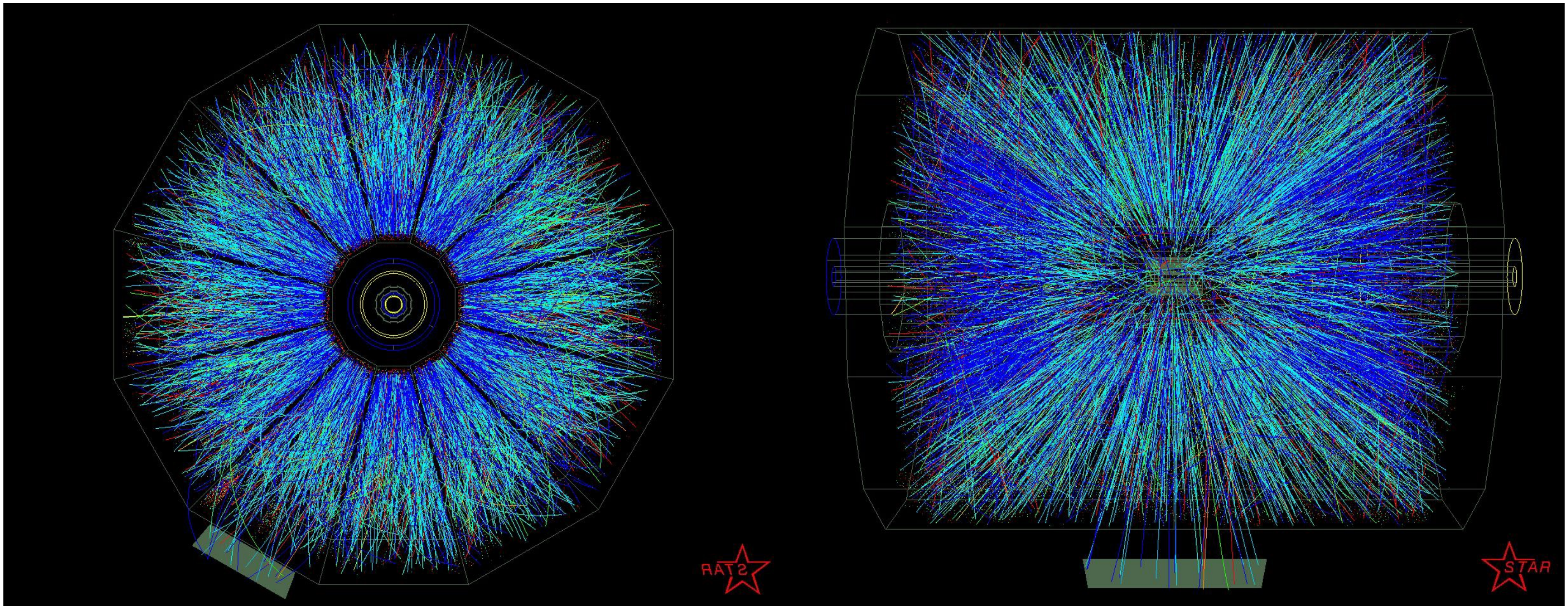
**..capacitively inducing
asignal on nearby pads...**

Amplifying and digitizing electronics connected to each pad

..which is amplified, digitized, and recorded for later analysis

Cartoon credit : Mike Lisa

Time Projection Chamber



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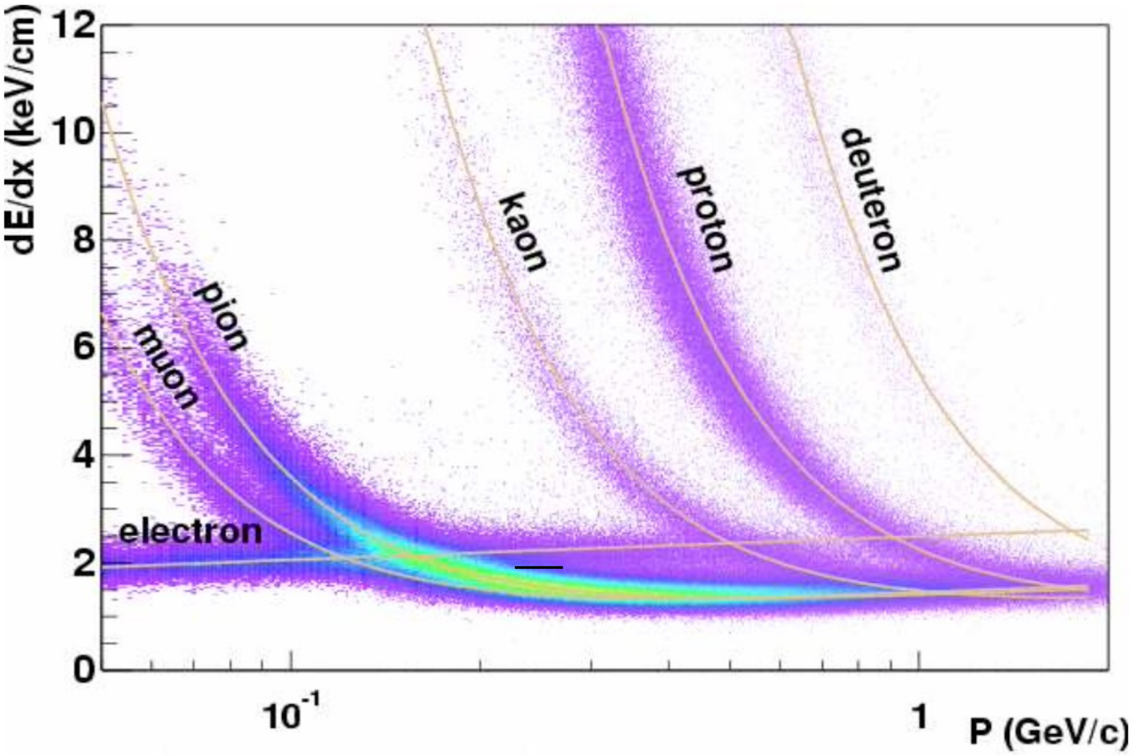
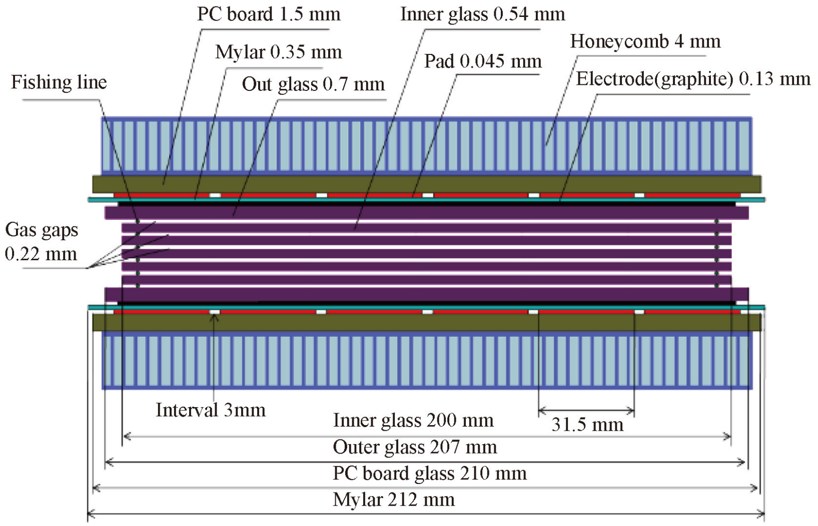


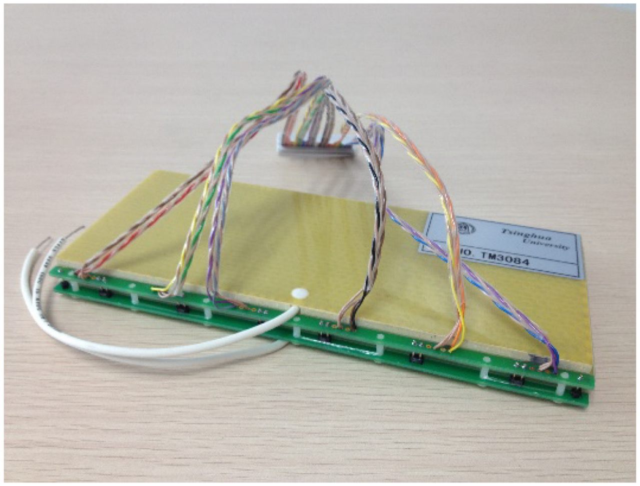
Number of drifted electron is proportional to the energy loss (dE/dx).

dE/dx depends on velocity. $\beta\gamma = \frac{p}{m}$

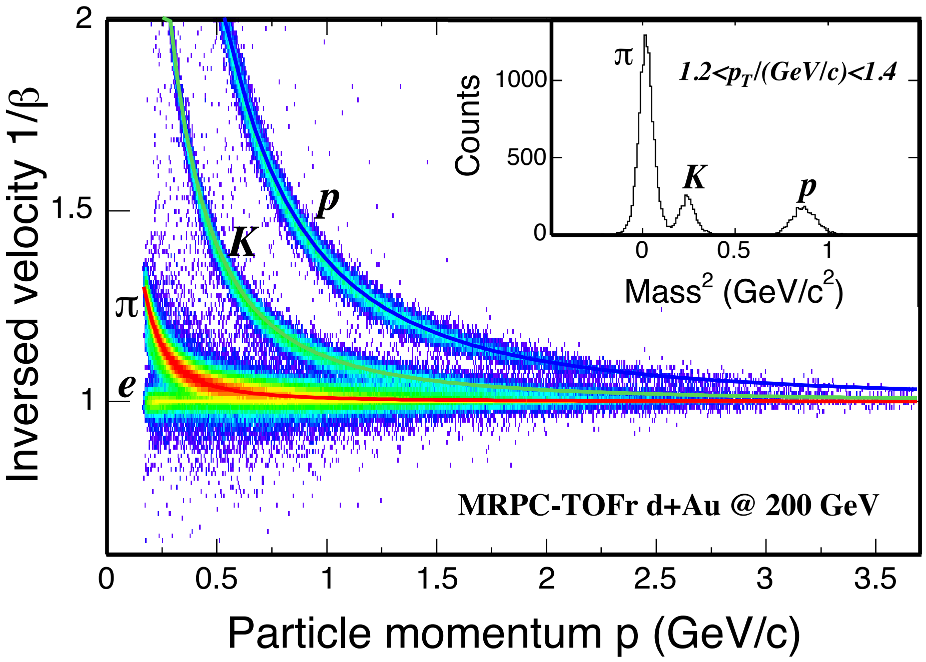
At same momentum, different particle type has different velocities, thus different dE/dx ⇒ **Particle separation.**

Time of Flight Detector





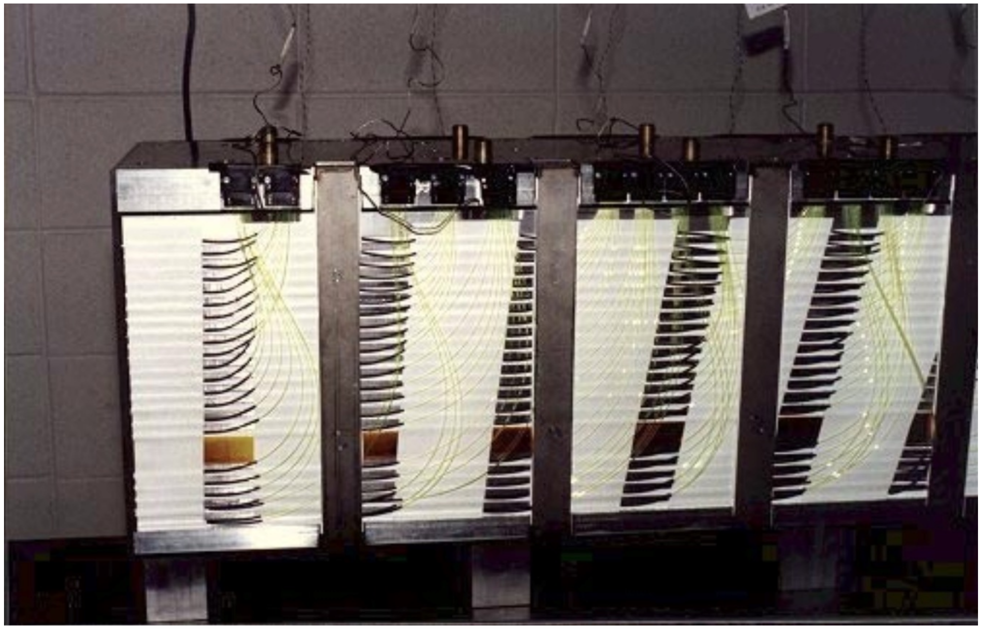
MRPC (Multi-gap Resistive Plate Chamber) with timing resolution ~ 95 ps

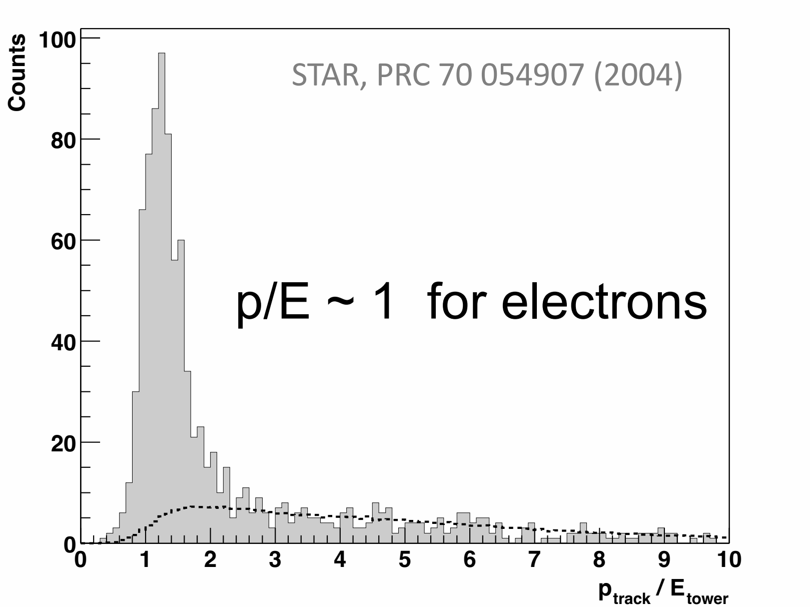


$$\frac{1}{\beta} = \frac{c\Delta t}{L}$$

At same momentum, different particle type has different velocities, thus different travel time ⇒ **Particle separation.**

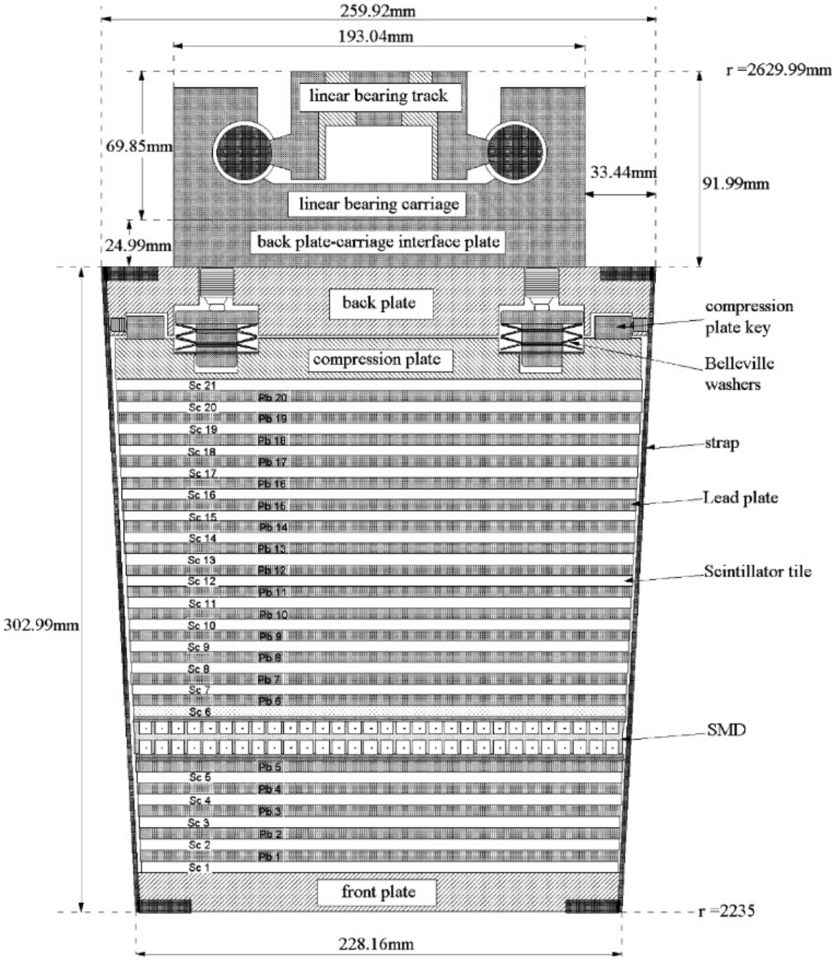
Barrel ElectroMagnetic Calorimeter





STAR, PRC 70 054907 (2004)

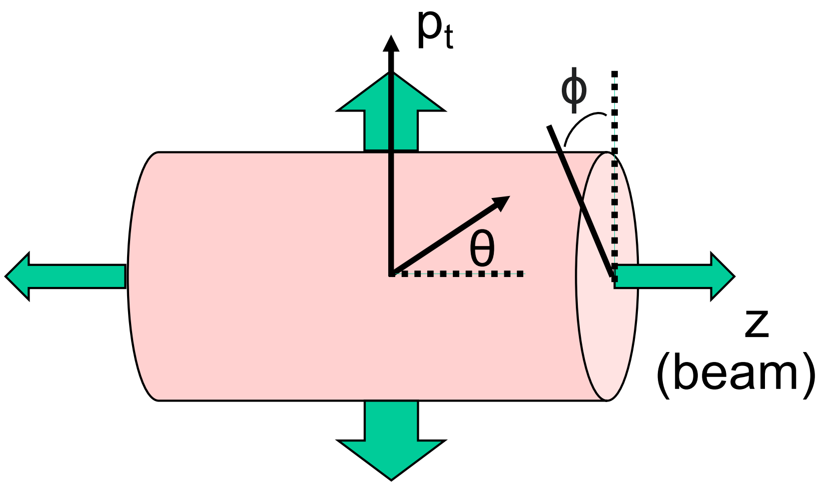
p/E ~ 1 for electrons



Matching momentum and energy

⇒ **Electron identification**

Collision Geometry and Basic Kinematics



Transverse momentum $$p_t \equiv \sqrt{p_x^2 + p_y^2}$$

p_t is unchanged by boost along z

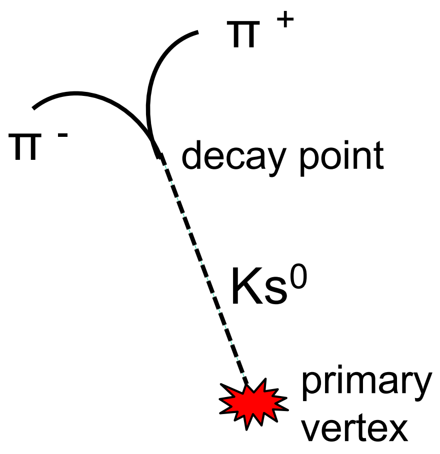
Rapidity $$y \equiv \ln\left(\frac{E + p_z}{E - p_z}\right)$$

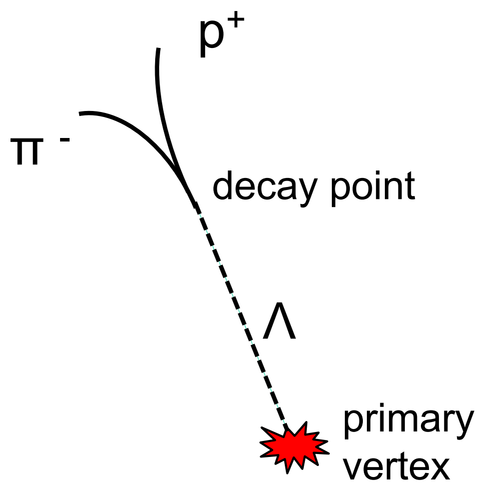
y is additive under Lorentz transformation along z. This means that rapidity spectra shape is preserved under Lorentz transformation.

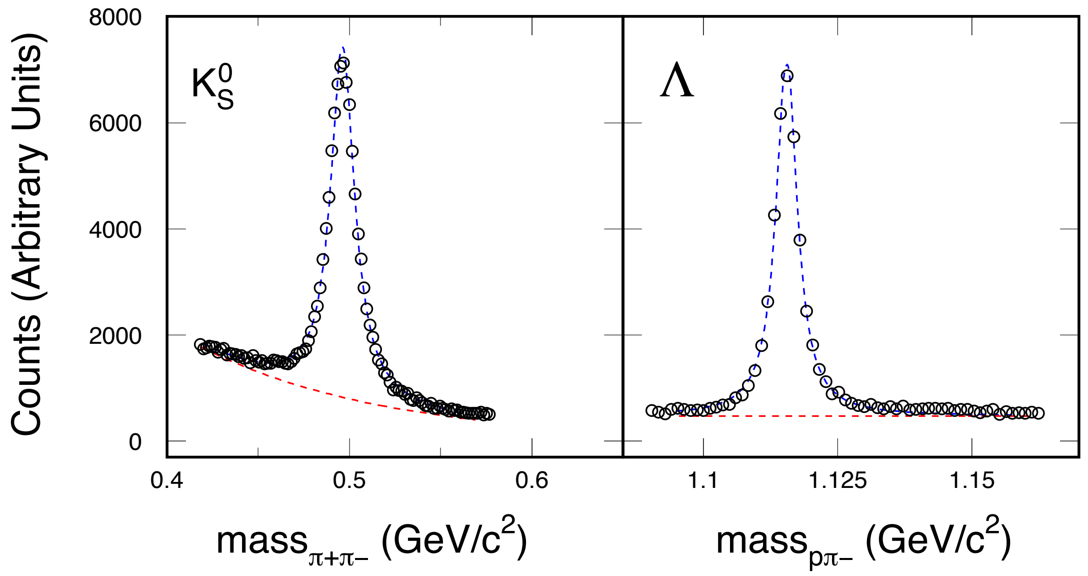
Pseudorapidity $$\eta \equiv -\ln\tan\left(\frac{\theta}{2}\right)$$

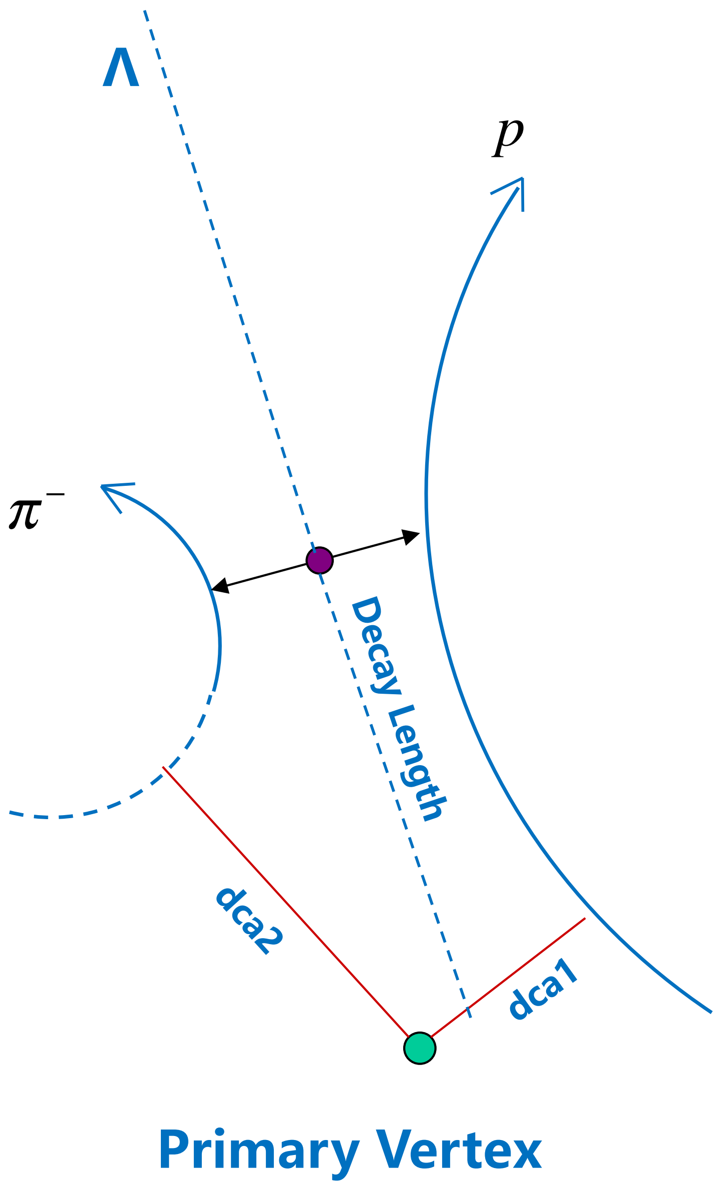
η = y for massless particles

PID via Topology and Invariant Mass









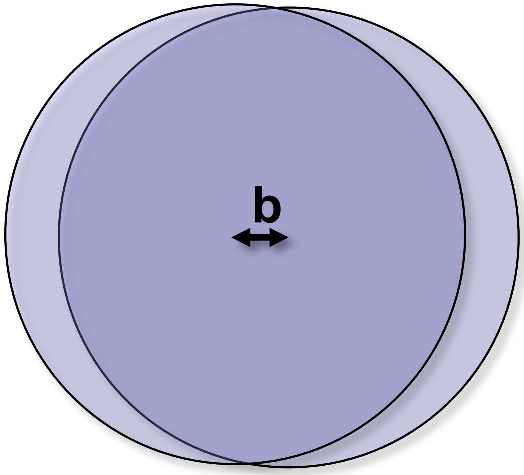
STAR, PRL 89 132302 (2002)

$$\begin{aligned} M^2 &= (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2 \\ &= m_1^2 + m_2^2 + 2\,(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)\,. \end{aligned}$$

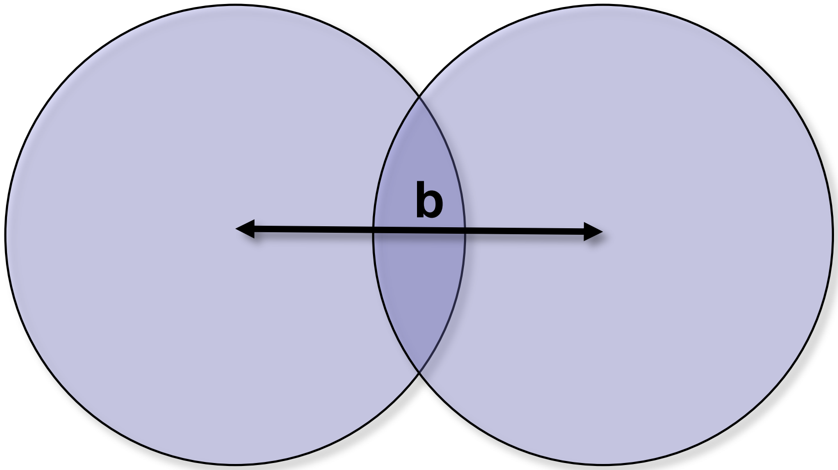
Centrality

Centrality : characterizes a collision by the degree of overlap

central



peripheral



Head-on
Large overlap (small b)
Produce the maximum number of particles
Large and hotter medium

Graze each other
Small overlap (large b)
Produce the least number of particles
Small / no medium

Let’s Characterize QGP

My presentation will focus on a few key areas.

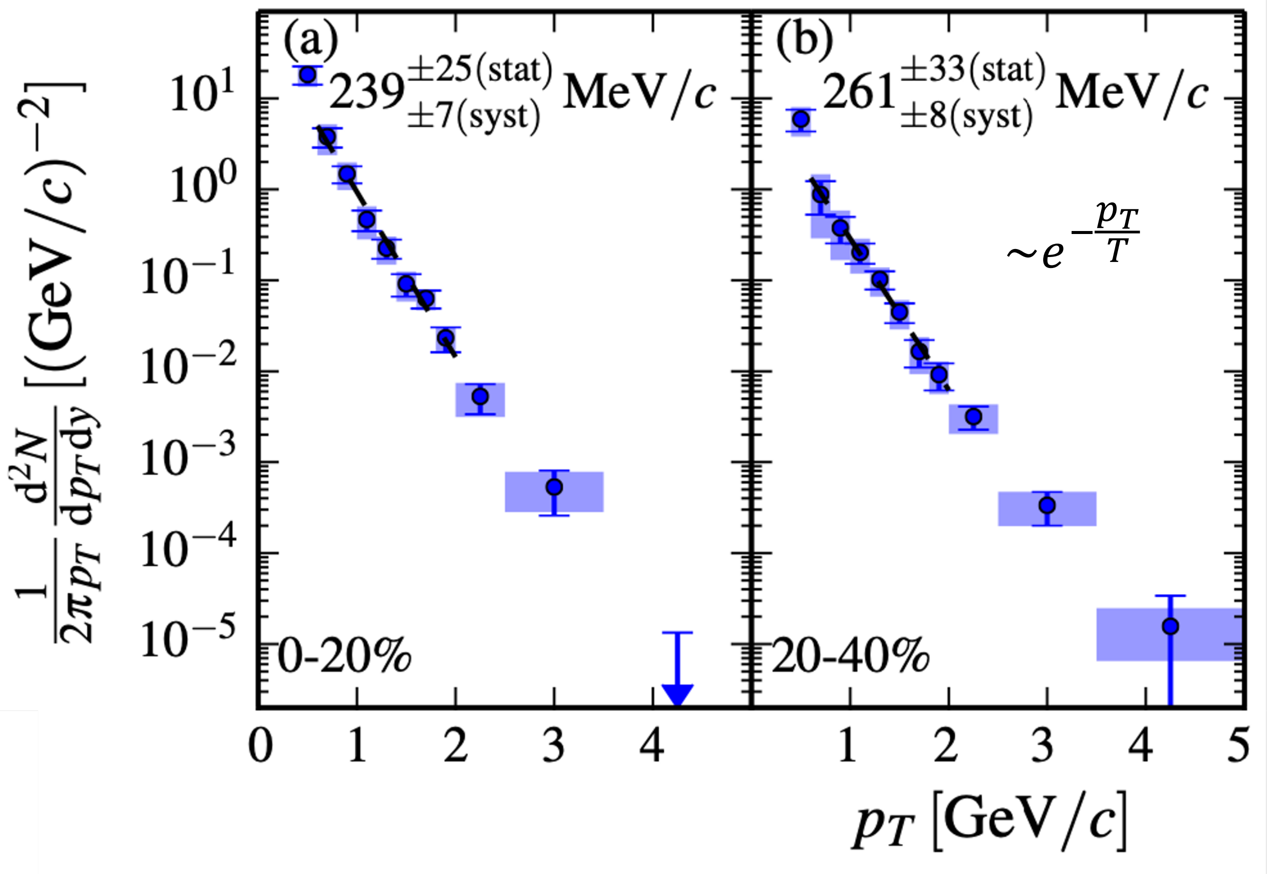
It’s hot

Hundreds of thousands of times hotter than the Sun !

Image credit : NASA

Temperature

p_T slope ⇒ Temperature



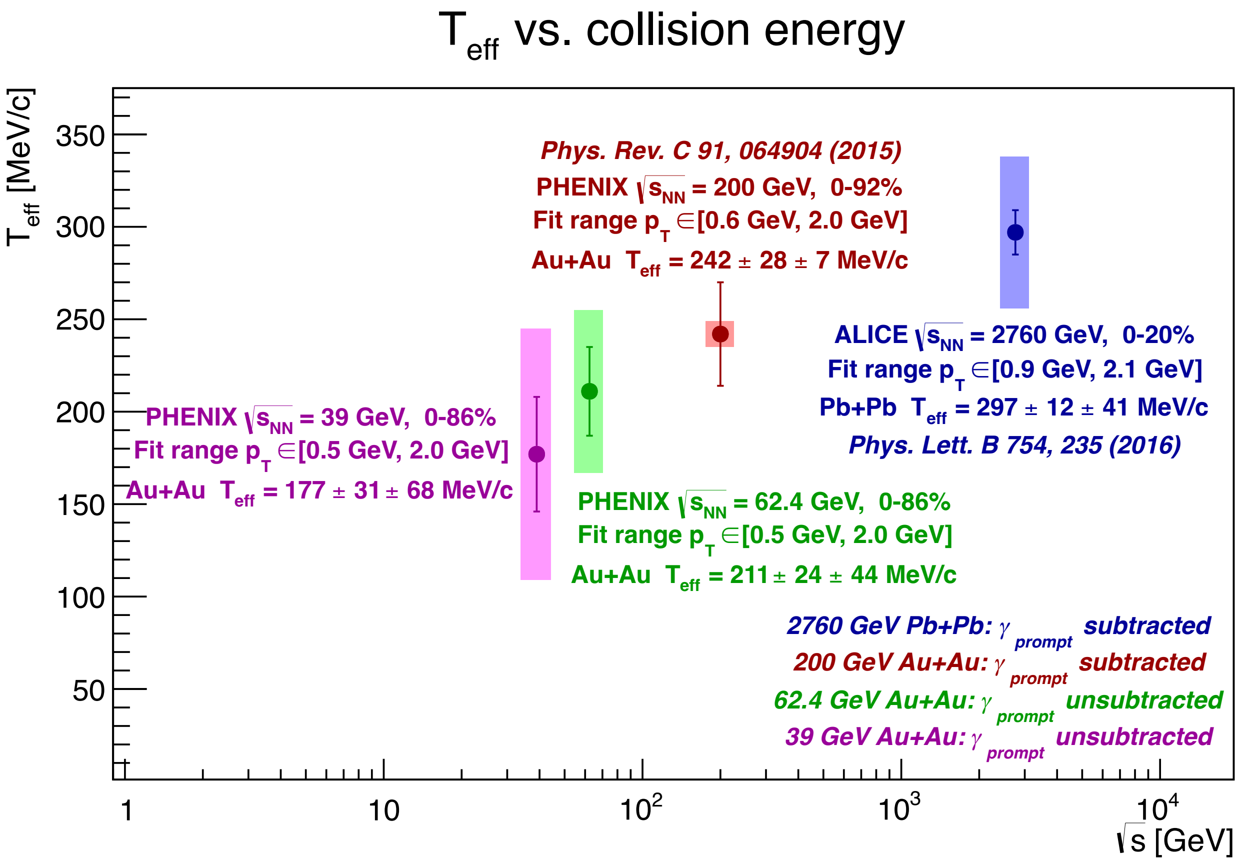
Phenix, PRC 91 064904 (2015)
Phenix,PRL 104 132301 (2010)

T_c ~ 240 (MeV) for central collisions

Critical condition for QGP satisfied.

Temperature

p_T slope ⇒ Temperature



PoS CPOD 2017 079 (2018)

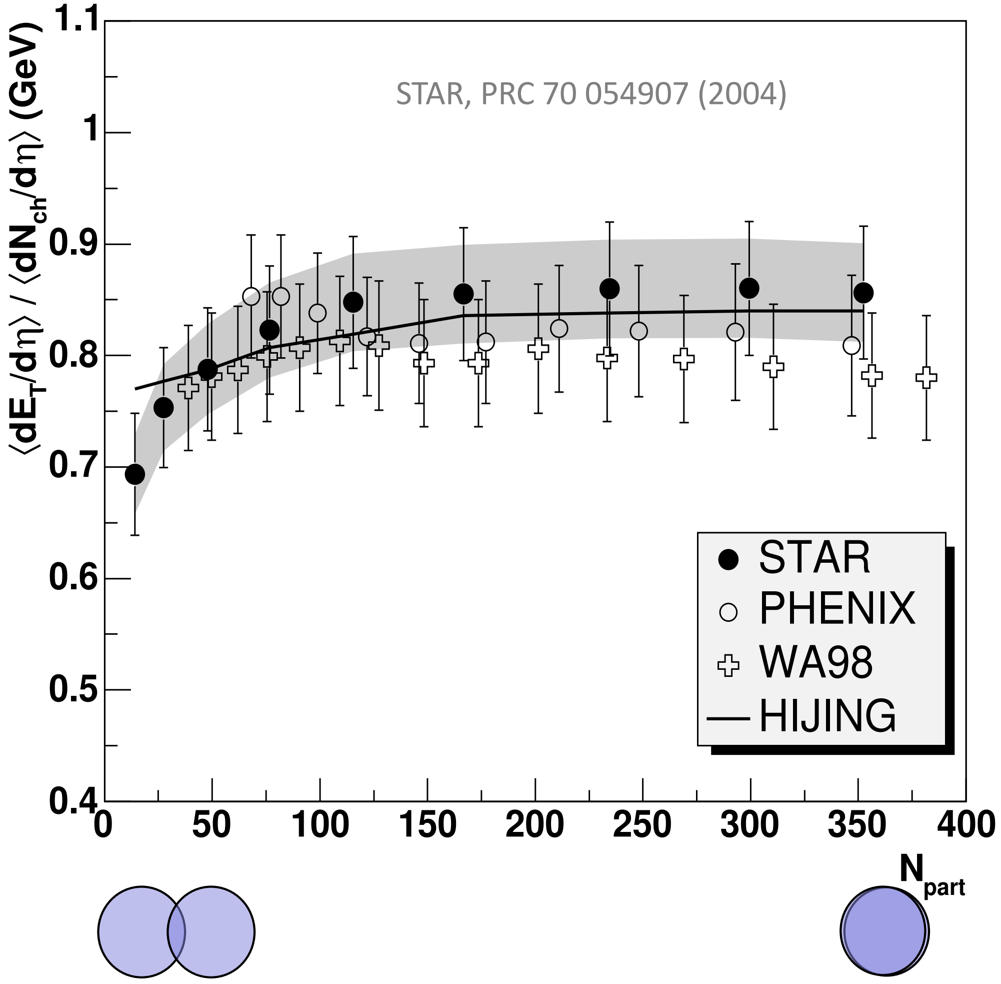
Critical condition for QGP satisfied.

It’s dense

Pack the entire Earth inside a stadium !

Energy Density

Particle yield ⇒ Energy density



STAR, PRC 70 054907 (2004)

$$\varepsilon_0 = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

$$\tau_0 \sim 1 \text{ fm}/c,\ R \approx 1.2 A^{1/3} \text{ fm}$$

$$\varepsilon_0 = 4.9 \pm 0.3 \text{ GeV/fm}^3$$

Recall : ε_c ~ 1 GeV / fm^3;
T_c ~ 165 (MeV)

Critical condition for QGP satisfied.

Temperature and Energy Density

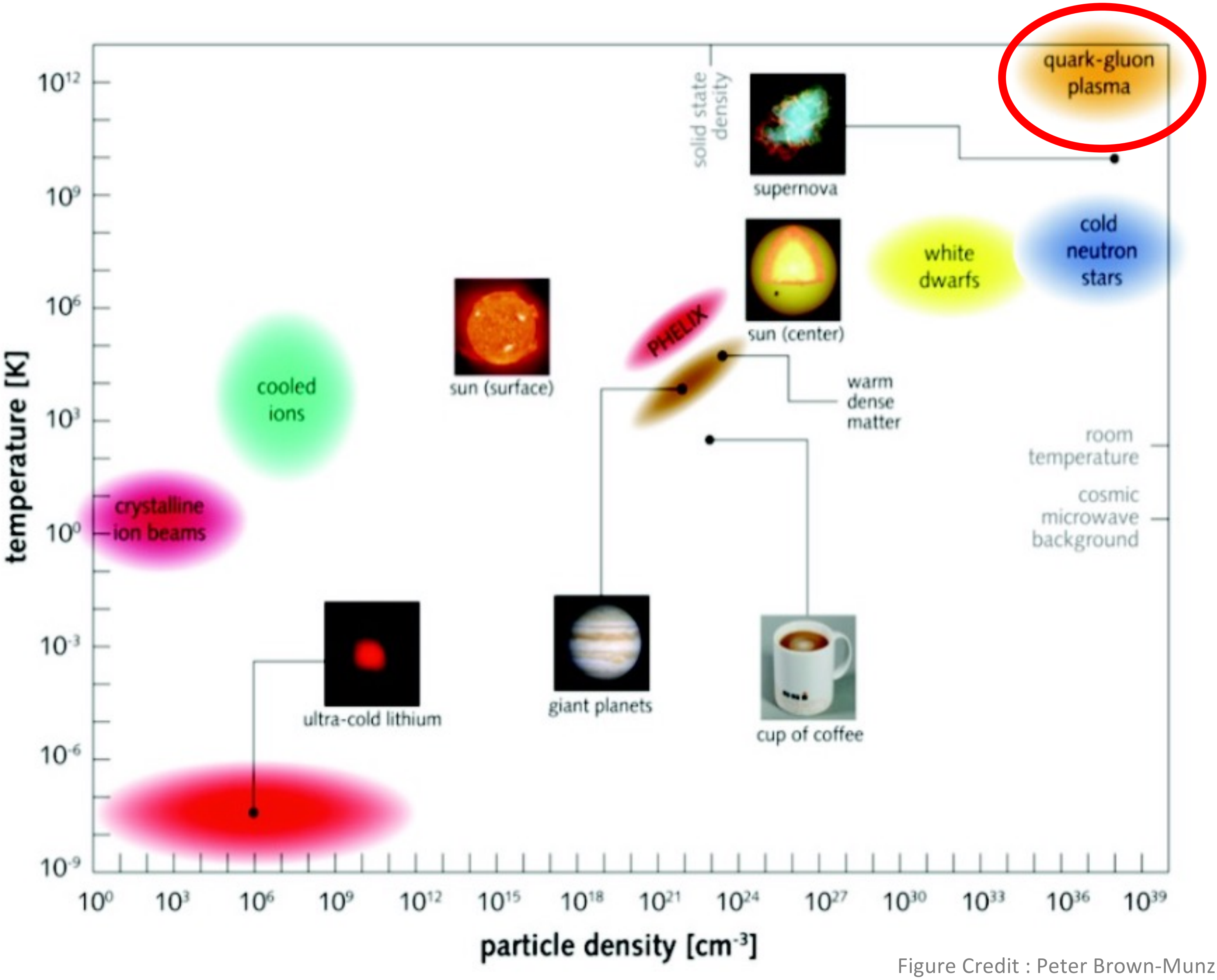
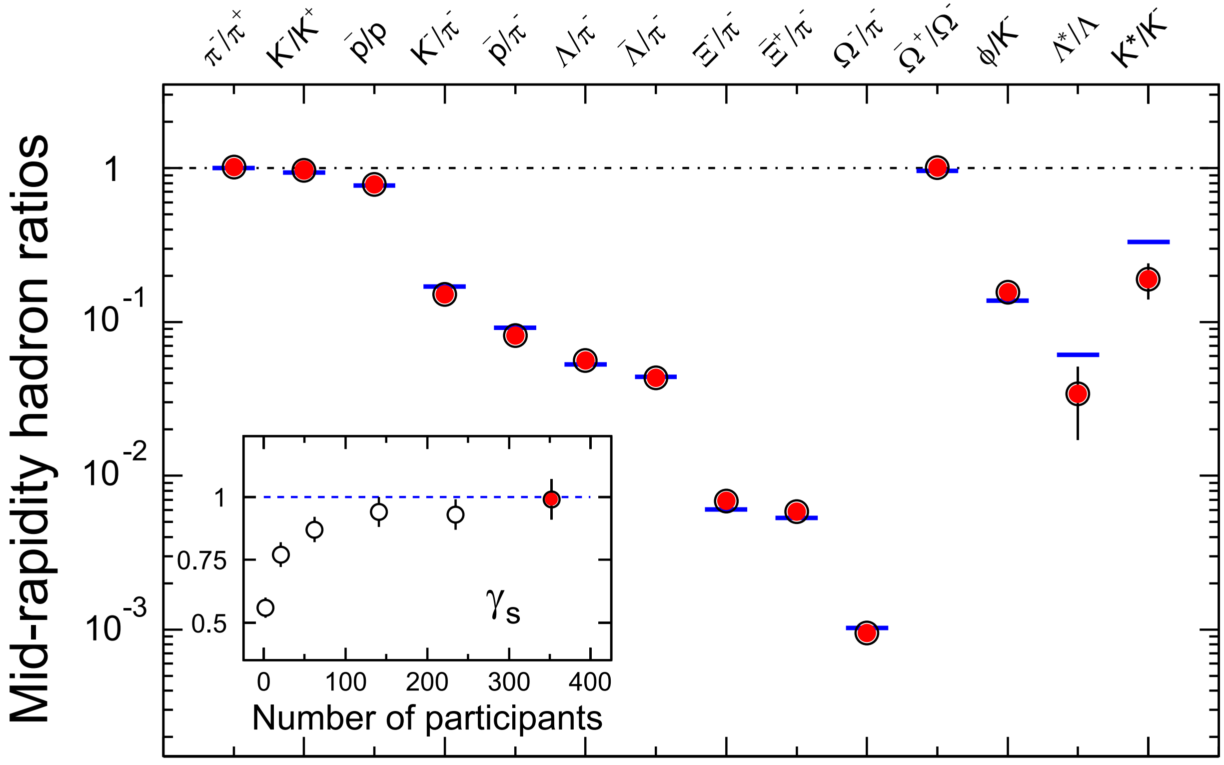


Figure Credit : Peter Brown-Munzinger

Chemical and Thermal Equilibrium

Particle yields freeze



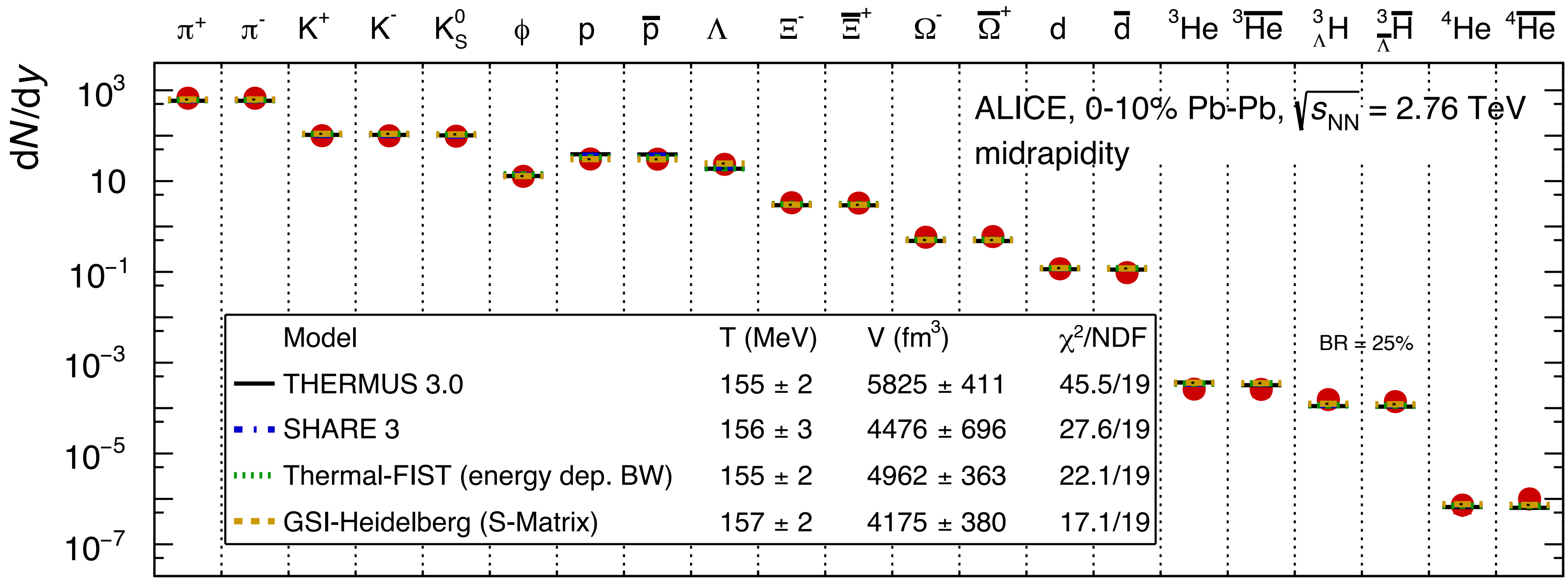
200 GeV ^{197}Au + ^{197}Au central collision

STAR, NPA 757 102 (2005)

Particle ratios described very well by statistical model assuming thermal and chemical equilibrium

Chemical and Thermal Equilibrium

Particle yields freeze

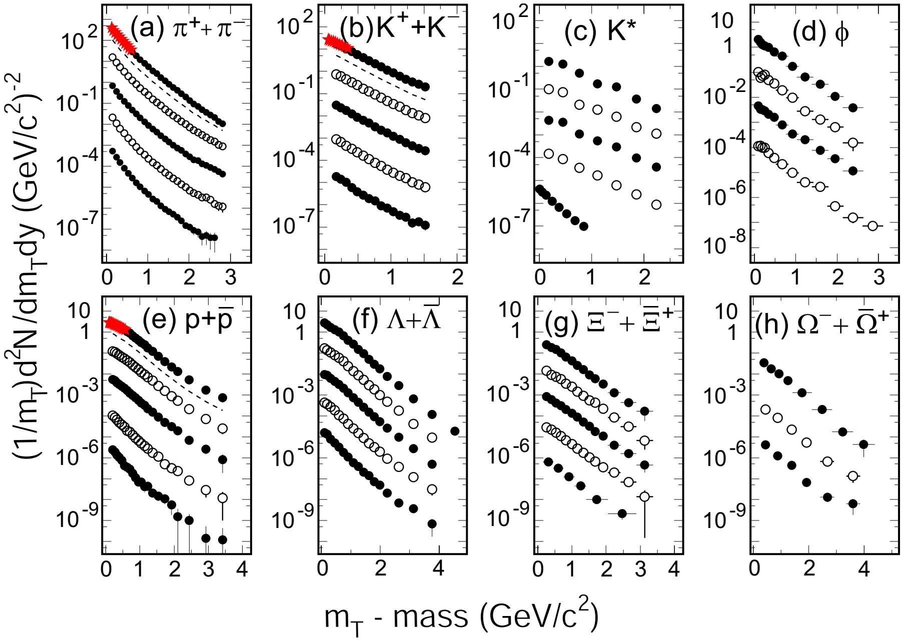


Alice, arXiv:2211.04384

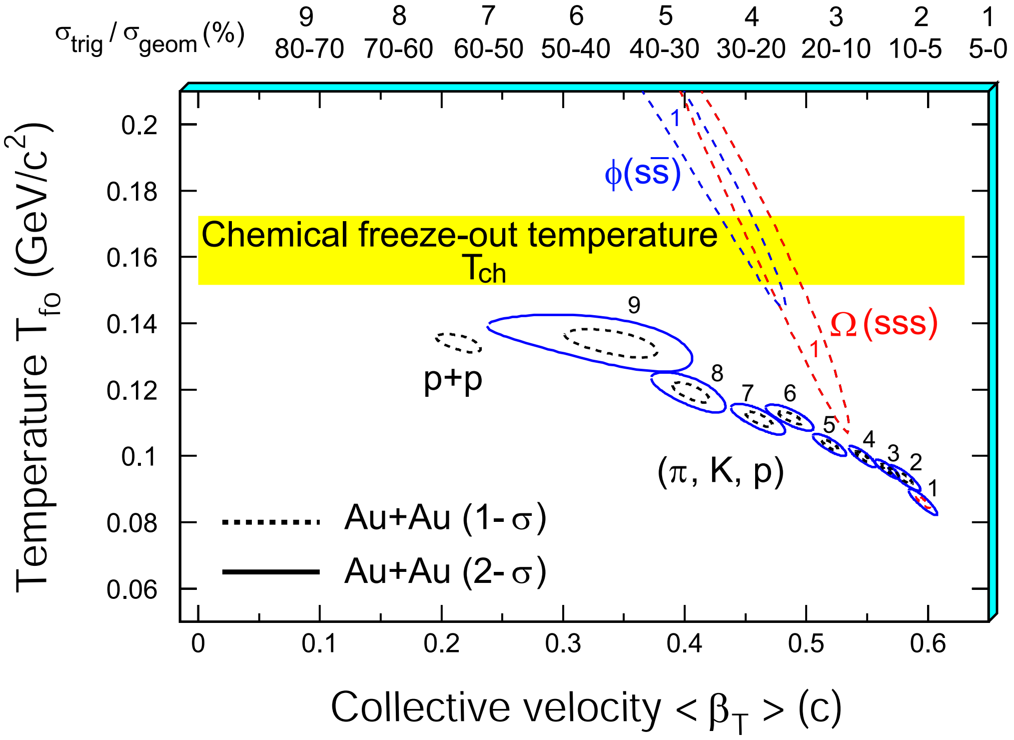
Particle ratios described very well by statistical model assuming thermal and chemical equilibrium

Chemical and Thermal Equilibrium

Particle kinematics freeze



STAR, NPA 757 102 (2005)



$$m_T = \sqrt{m_0^2 + p_T^2}$$

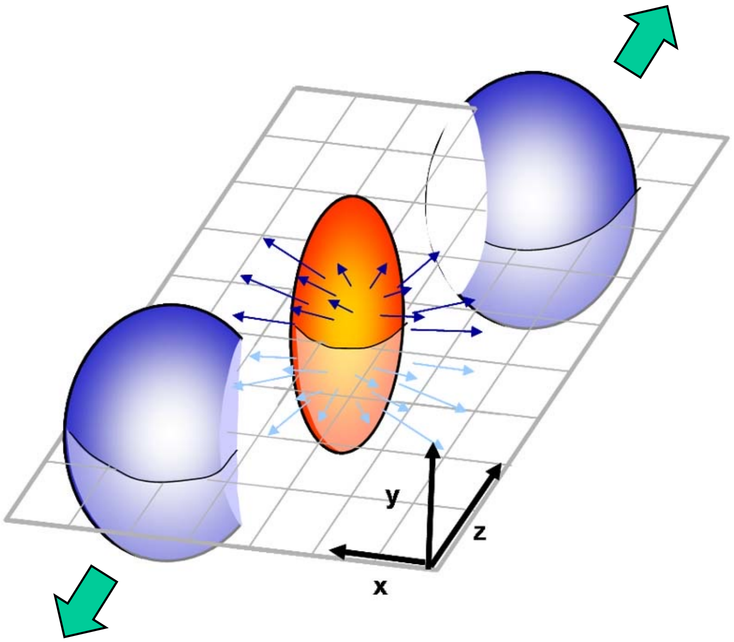
Peripheral to central collisions : the system expands faster and becomes cooler when reaching kinetic freeze-out

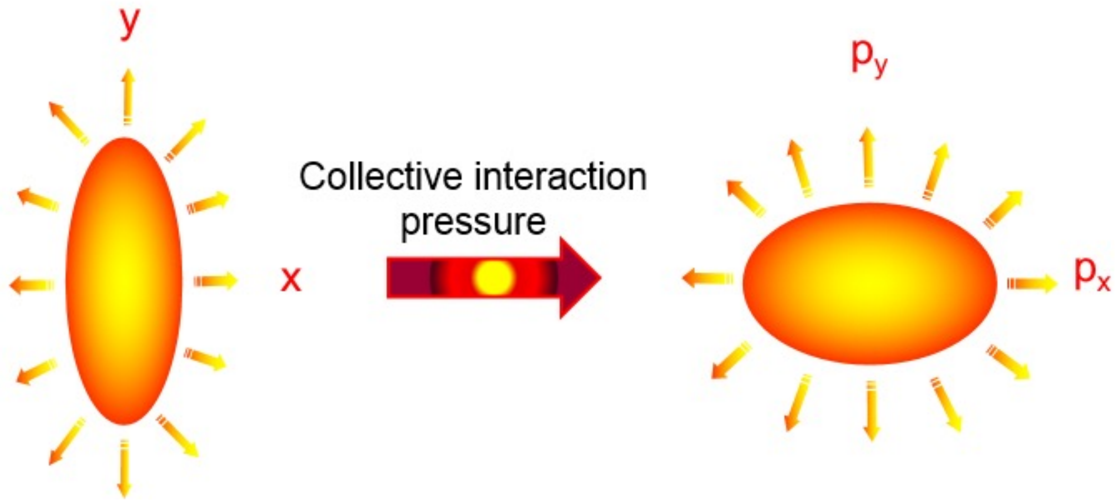
It’s perfect liquid

Lowest viscosity possible !

Image credit : SmileTemplates

Reaction Plane and Flow Observables





Reaction plane ψ : Defined by the beam and the line connecting two colliding nuclei

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_t dp_t d(\phi - \psi)}$$

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

Coordinate space : initial asymmetry

$$\varepsilon = \frac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle}$$

Momentum space: final asymmetry

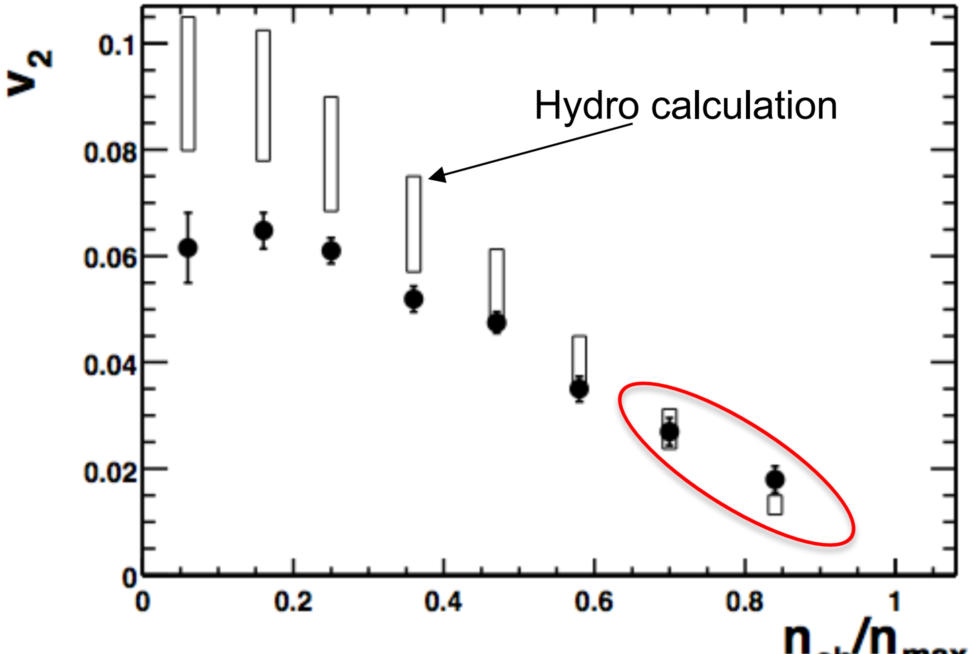
$$v_2 = \left\langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \right\rangle$$

$$= \langle \cos^2(\phi - \psi) - \sin^2(\phi - \psi)\rangle$$
$$= \langle \cos 2(\phi - \psi)\rangle$$

v_n : flow measurements

Perfect Liquid

System behaves “fluid-like”



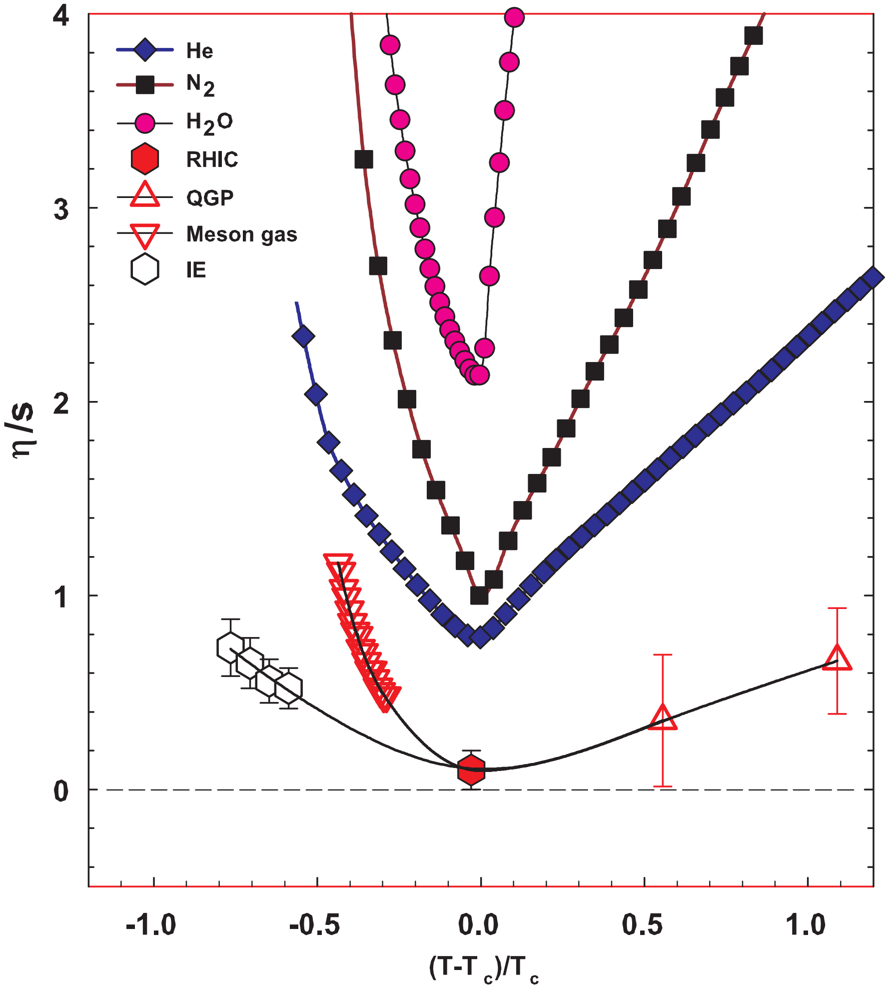
STAR, PRL 86 402 (2001)

Data approaching Hydro for central collisions

This topic will be discussed in depth in the second part

Perfect Liquid

System behaves "fluid-like"



R. Lacey et al., PRL 98 092301 (2007)

Data approaching Hydro for central collisions viscosity extracted close to the lowest value set by quantum limit.

This topic will be discussed in depth in the second part

It’s partons unchained

Partonic degree of freedom at work !

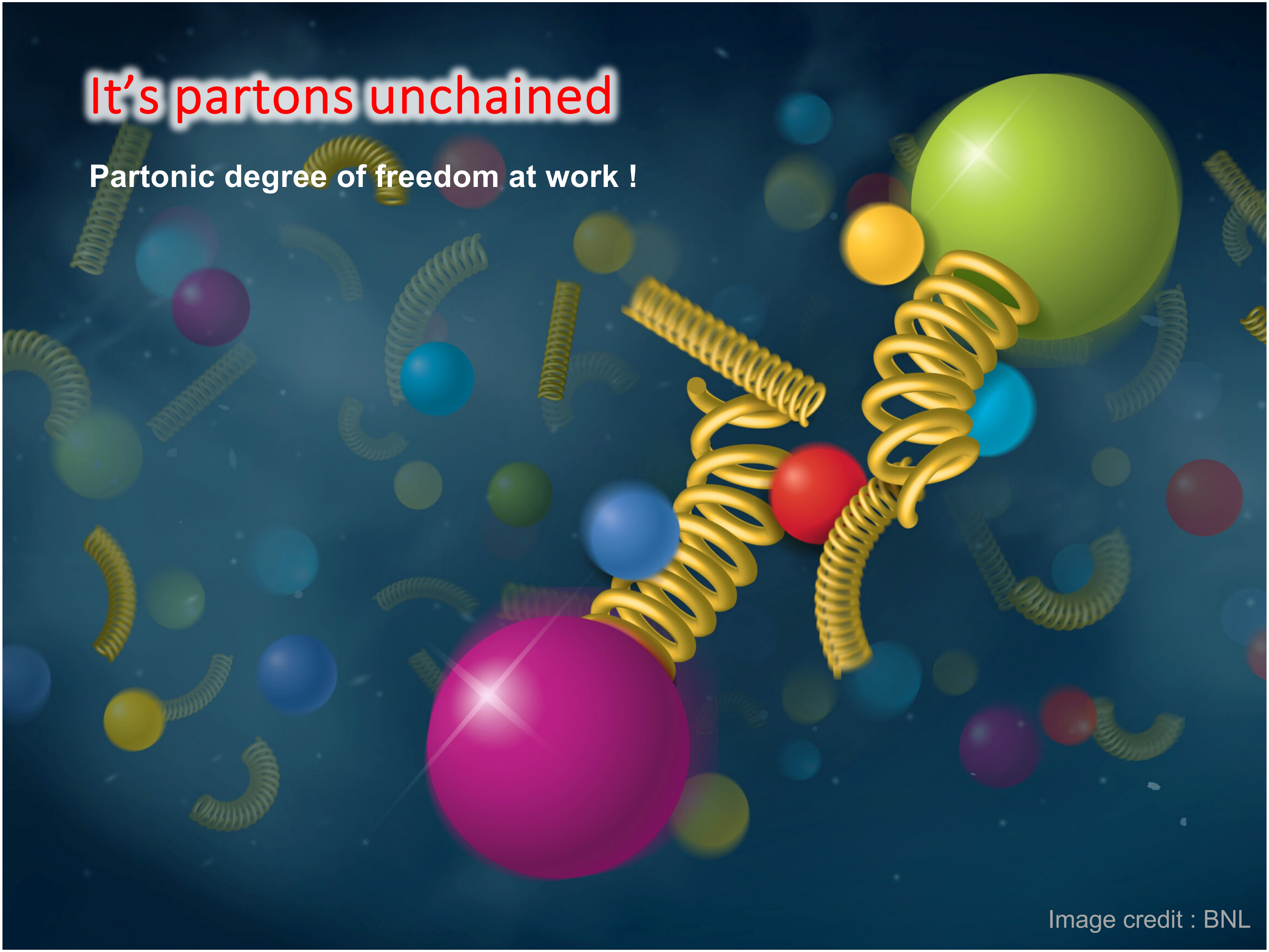


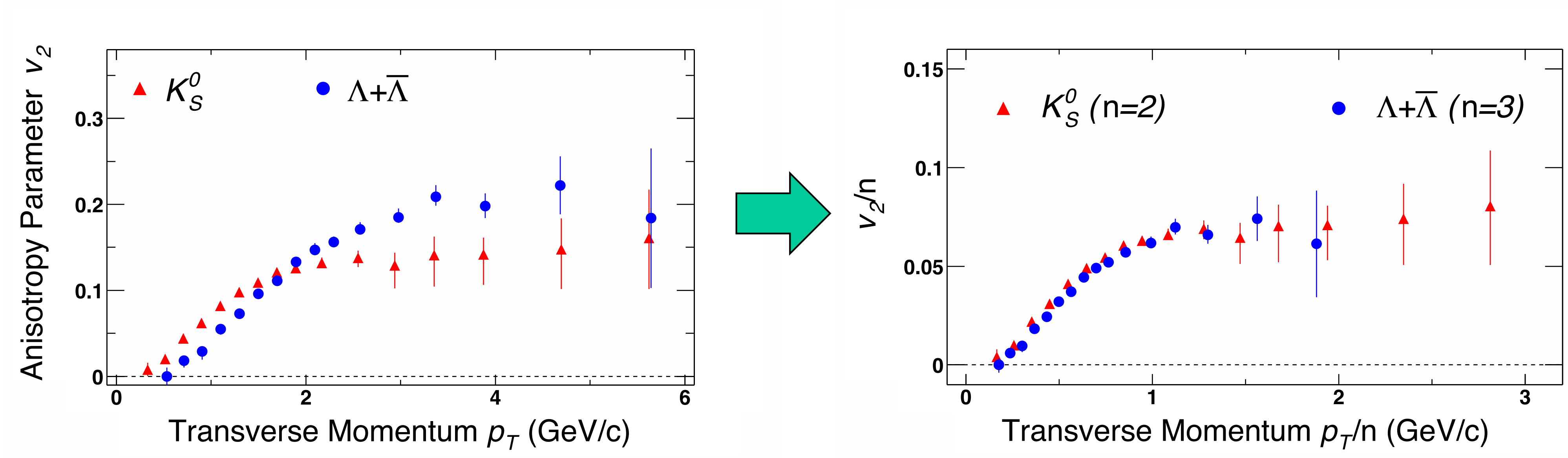
Image credit : BNL

Number of Constituent Quark Scaling

Hadron formation by quark-coalescence

$$K_s^0\left(\frac{\mathrm{d\bar{s}-s\bar{d}}}{\sqrt{2}}\right) \rightarrow \pi^+ + \pi^-$$

$$\Lambda(uds) \rightarrow p + \pi^-$$



STAR, PRL 92 052302 (2004)

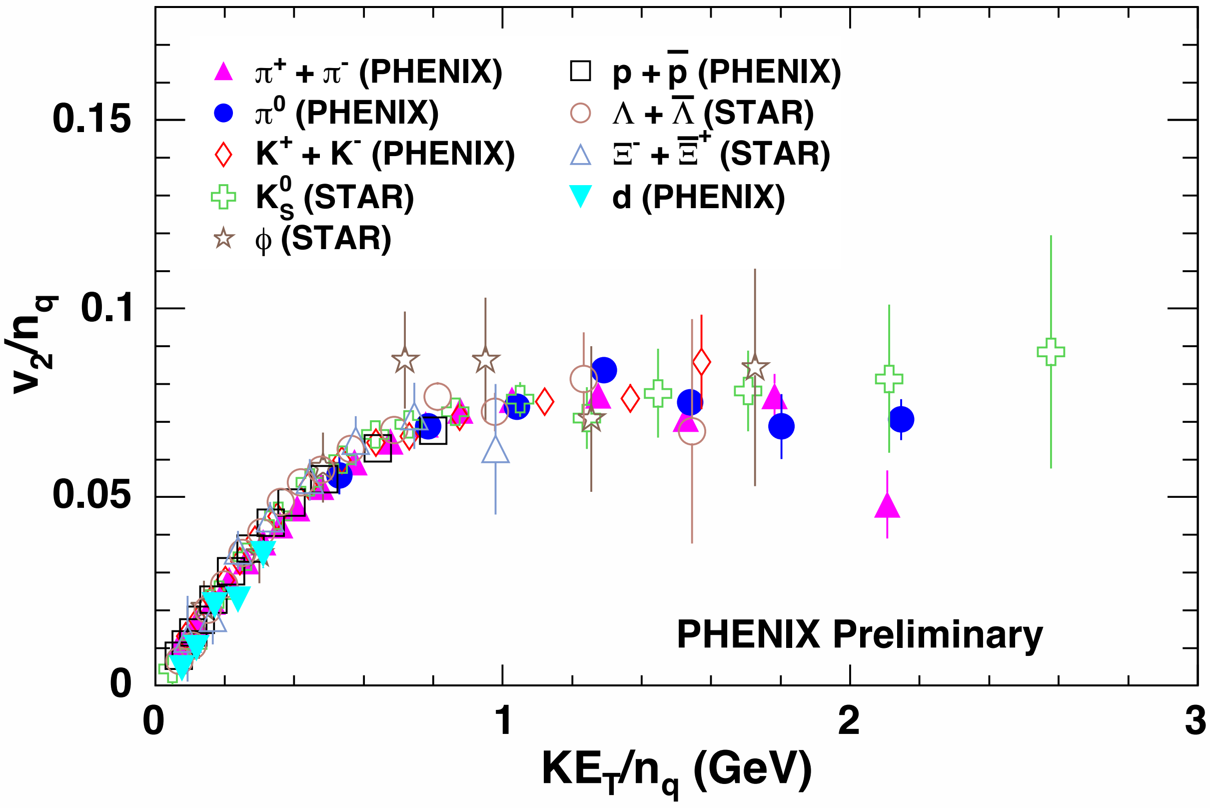
$$v_2^M(p_t) = 2v_2^q\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3v_2^q\left(\frac{p_t}{3}\right)$$

Evidence of partonic degree of freedom at work !

Number of Constituent Quark Scaling

Hadron formation by quark-coalescence

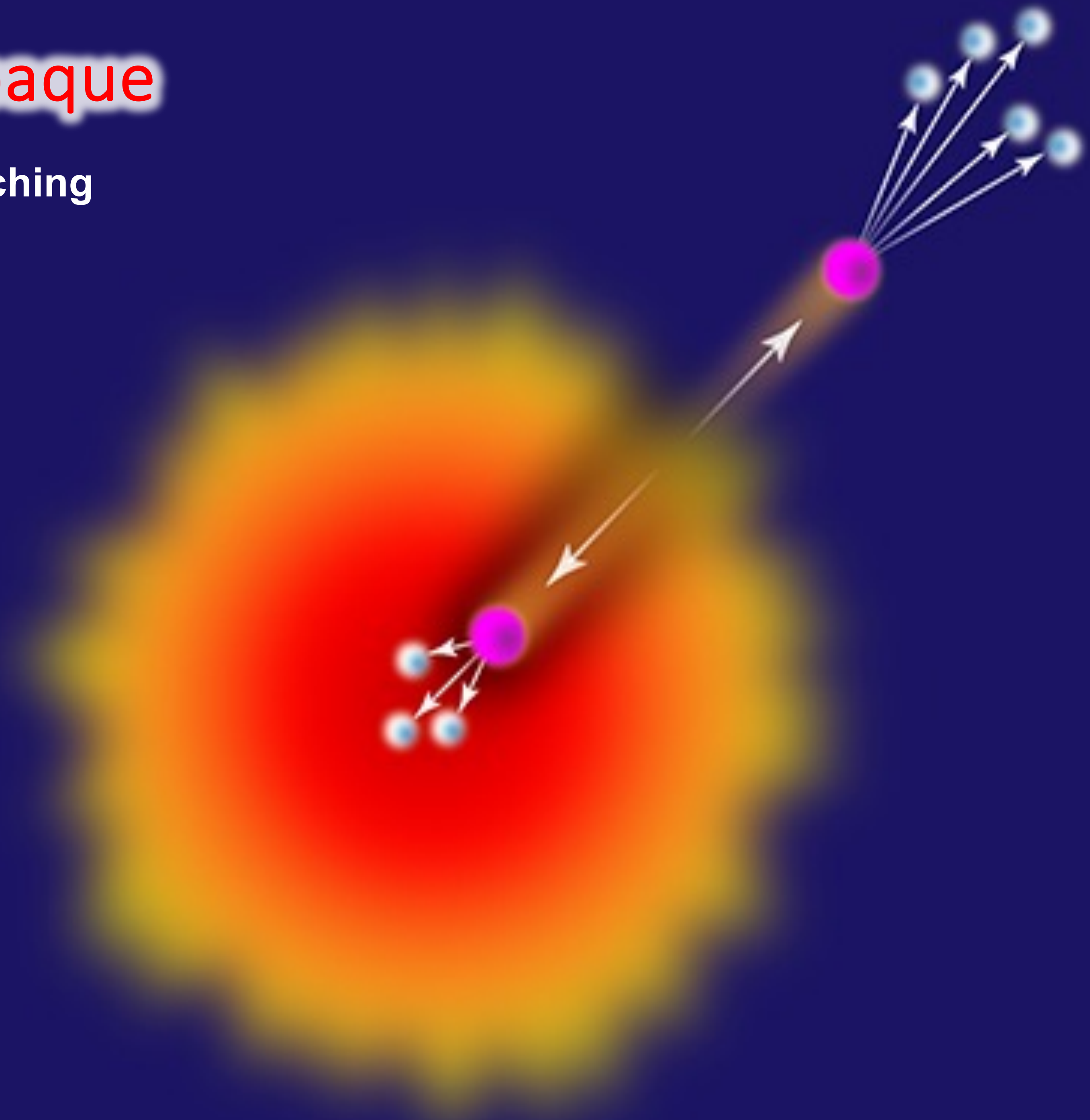


Phenix, PRL 98 162301 (2007)
Phenix, arXiv:nucl-ex/0604011

Evidence of partonic degree of freedom at work !

It’s opaque

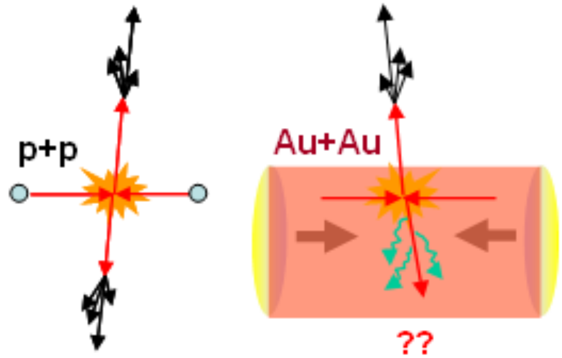
Jet quenching

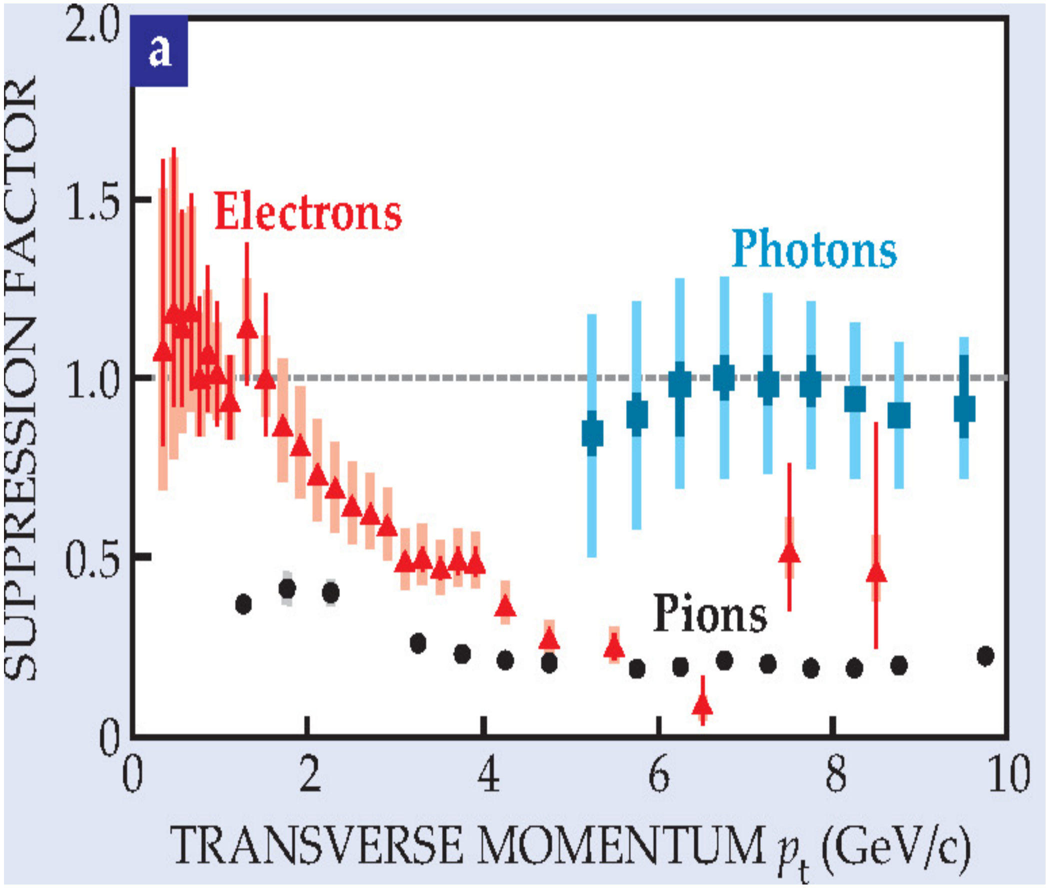


Jet Quenching

$$R_{\mathrm{AA}} = \frac{\sigma_{\mathrm{inel}}}{\langle N_{\mathrm{coll}} \rangle} \frac{d^2 N_{AA}/dydp_t}{d^2 \sigma_{pp}/dydp_t}$$

$R_{\mathrm{AA}} < 1$: suppression
$R_{\mathrm{AA}} = 1$: no medium effects
$R_{\mathrm{AA}} > 1$: enhancement





B. Jacak and P. Steinberg, Physics Today 63 39-43 (2010)

Partons lose energy in the medium
This lost energy makes jets broader and softer

Medium is opaque !

Jet Quenching

$$R_{\mathrm{AA}} = \frac{\sigma_{\mathrm{inel}}}{\langle N_{\mathrm{coll}}\rangle} \frac{d^2 N_{AA}/dydp_t}{d^2\sigma_{pp}/dydp_t}$$

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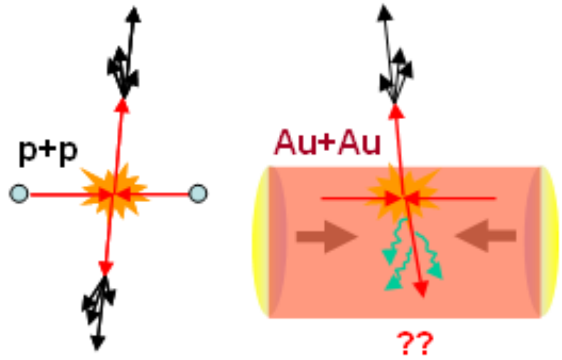
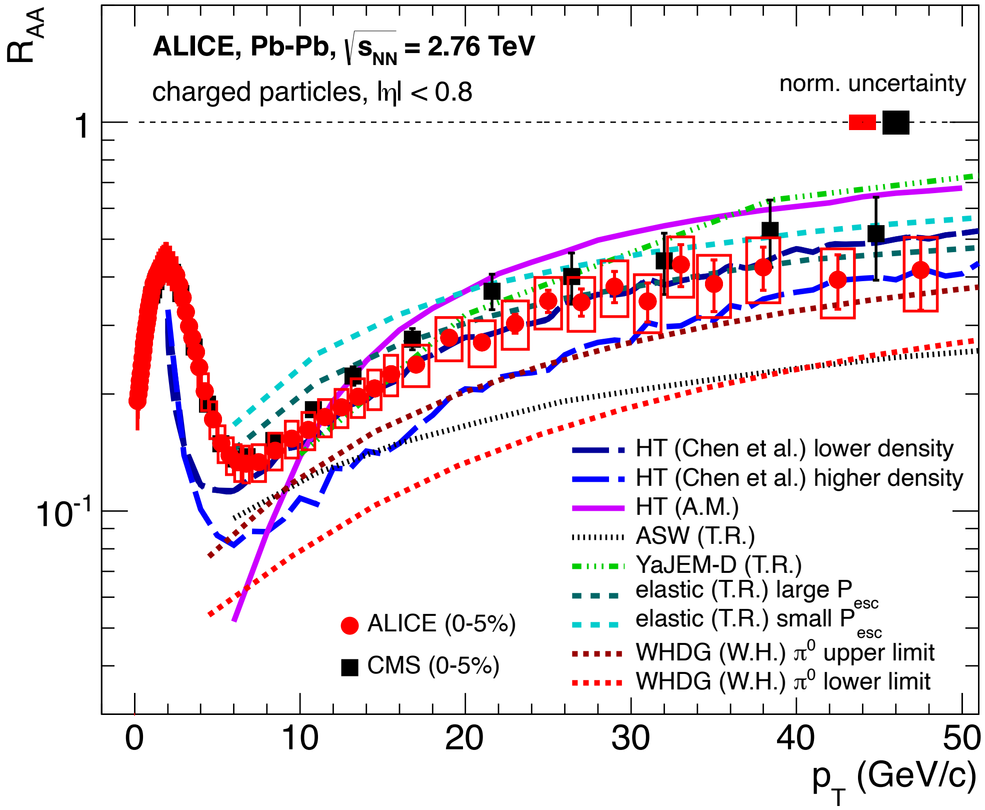




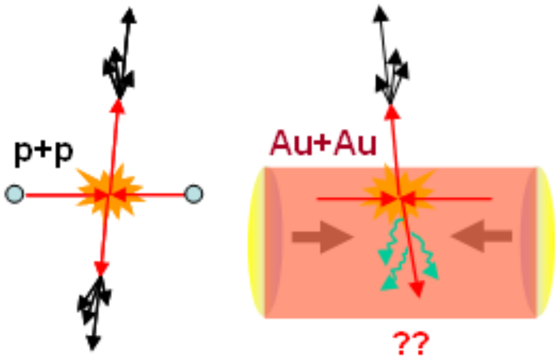
ALICE PLB 720 52 (2013)

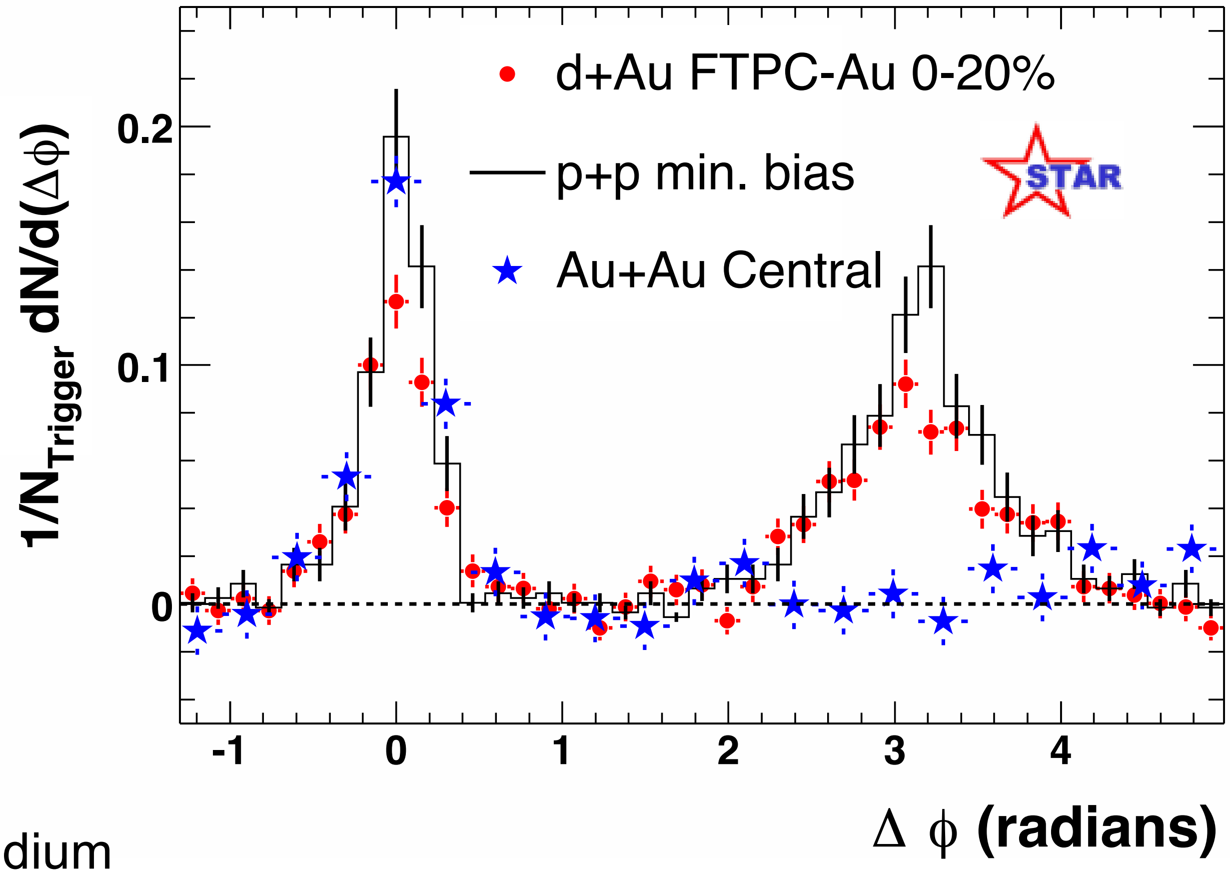
Partons lose energy in the medium
This lost energy makes jets broader and softer

Medium is opaque !

Jet Quenching

Strong suppression of back-to-back correlations





Partons lose energy in the medium
This lost energy makes jets broader and softer

STAR, PRL 90 082302 (2003)

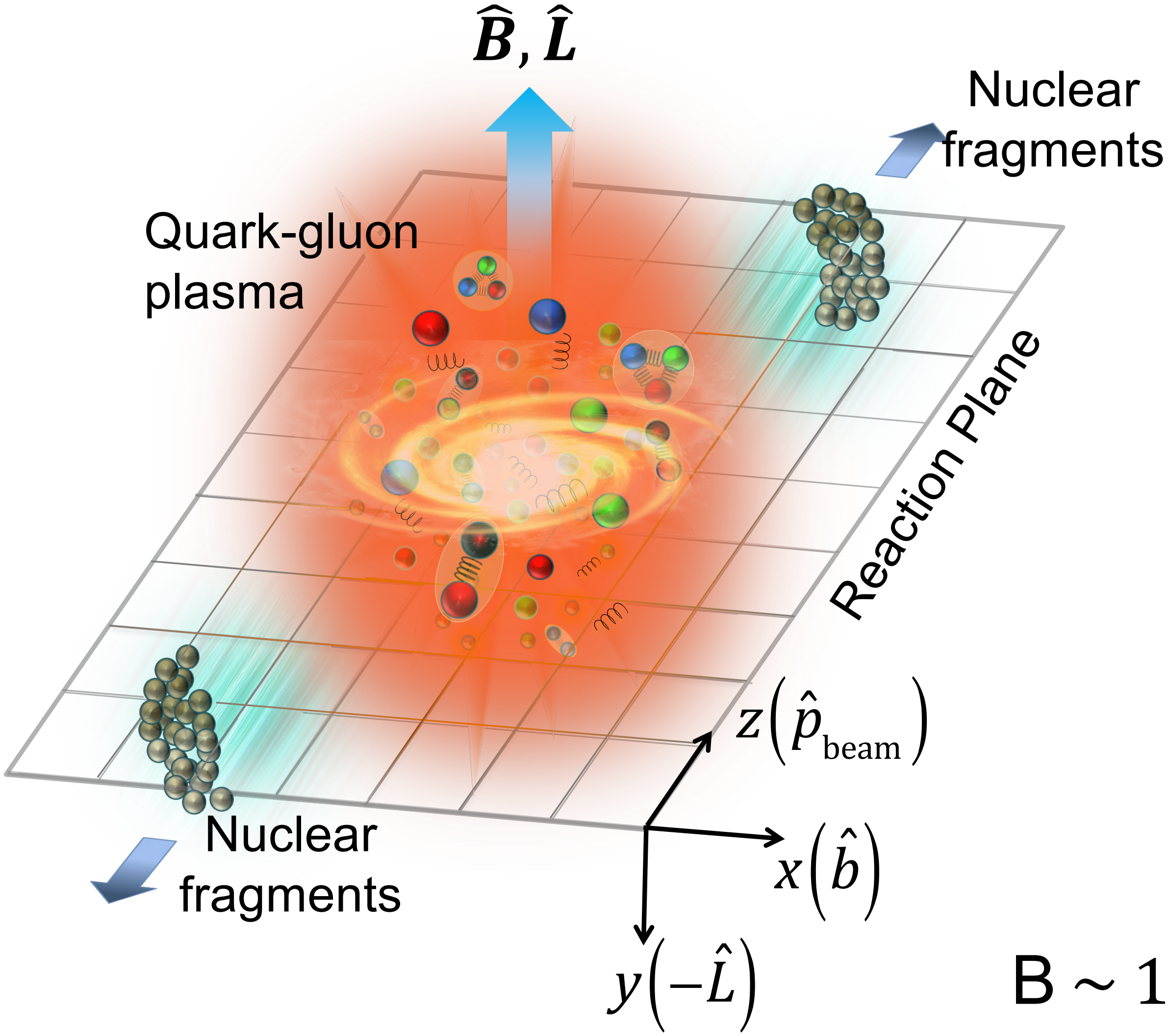
Medium is opaque !

It’s swirling fast

Most vortical fluid !

Image credit : BNL

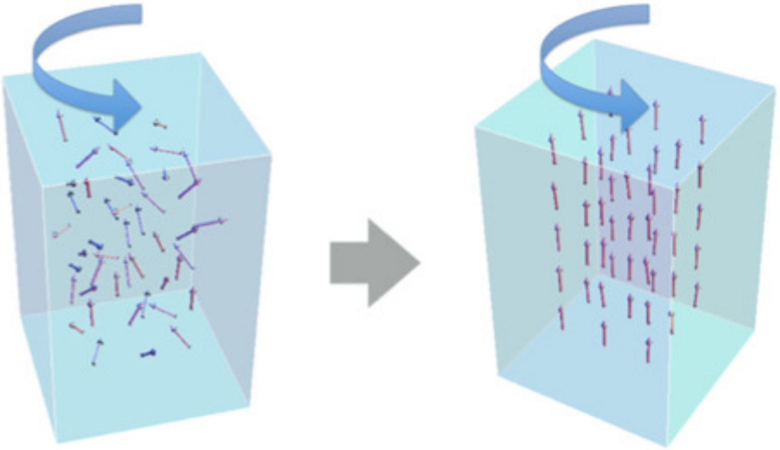
QGP Under Rotation

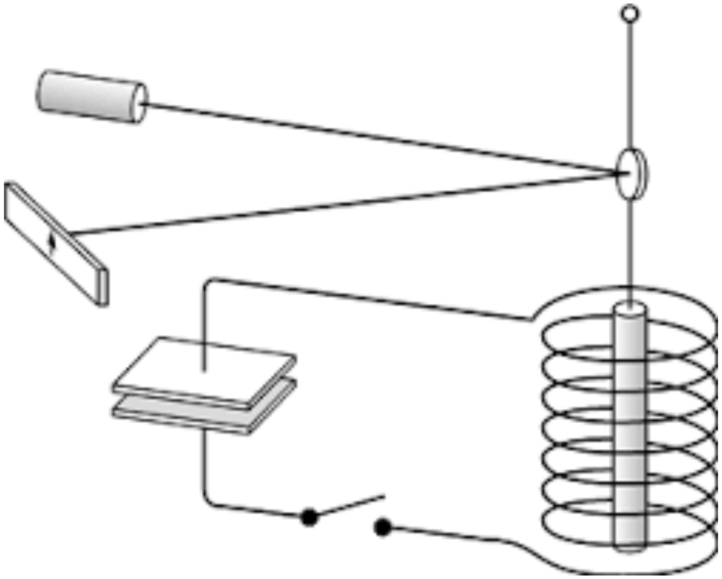


$\text{B} \sim 10^{18}$ Gauss

$L \sim 10^3 - 10^7 \hbar$

Barnett Effect and Einstein-de Haas Effect





Rotation ➔ Polarization

- Spontaneous magnetization
- Polarizaton (spin-orbital coupling)

Barnett, Rev. Mod. Phys. 7, 129 (1935)

Polarization ➔ Rotation

- Magnetic field causes polarization of electrons
- $\Delta L_{\text{mechanical}} = - \Delta L_{\text{electron}}$

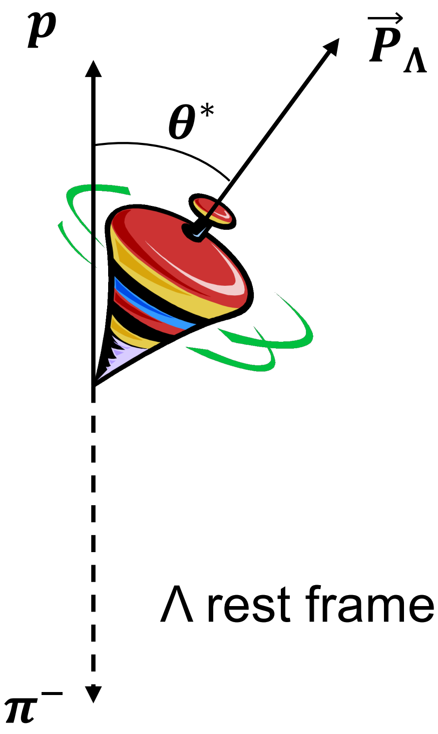
Einstein, de Hass, DPG Vanhandlungen 17, 152 (1915)

Classical world ⇔ Quantum world

Λ Global Polarization

Parity-violating weak decay of hyperons ("self-analyzing")

Daughter baryon is preferentially emitted in the direction of hyperon's spin (opposite for anti-particle)

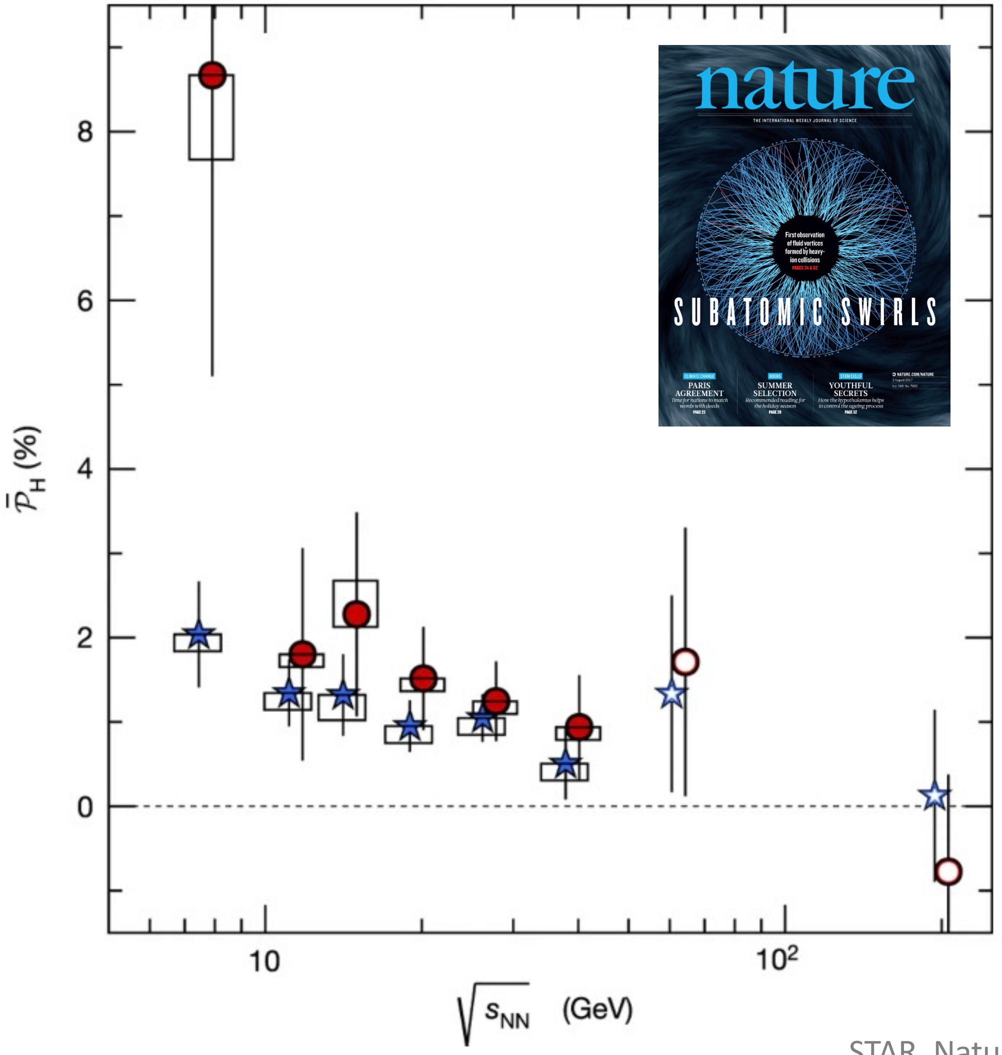


$$\Lambda(uds) \rightarrow p + \pi^-$$

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H P_H \cos\theta^*)$$

P_H : Λ polarization
θ^* : polar angle of daughter w.r.t. polarization direction
α_H : Λ decay parameter (0.732 ± 0.014)

Λ Global Polarization



STAR, Nature 548 62 (2017)

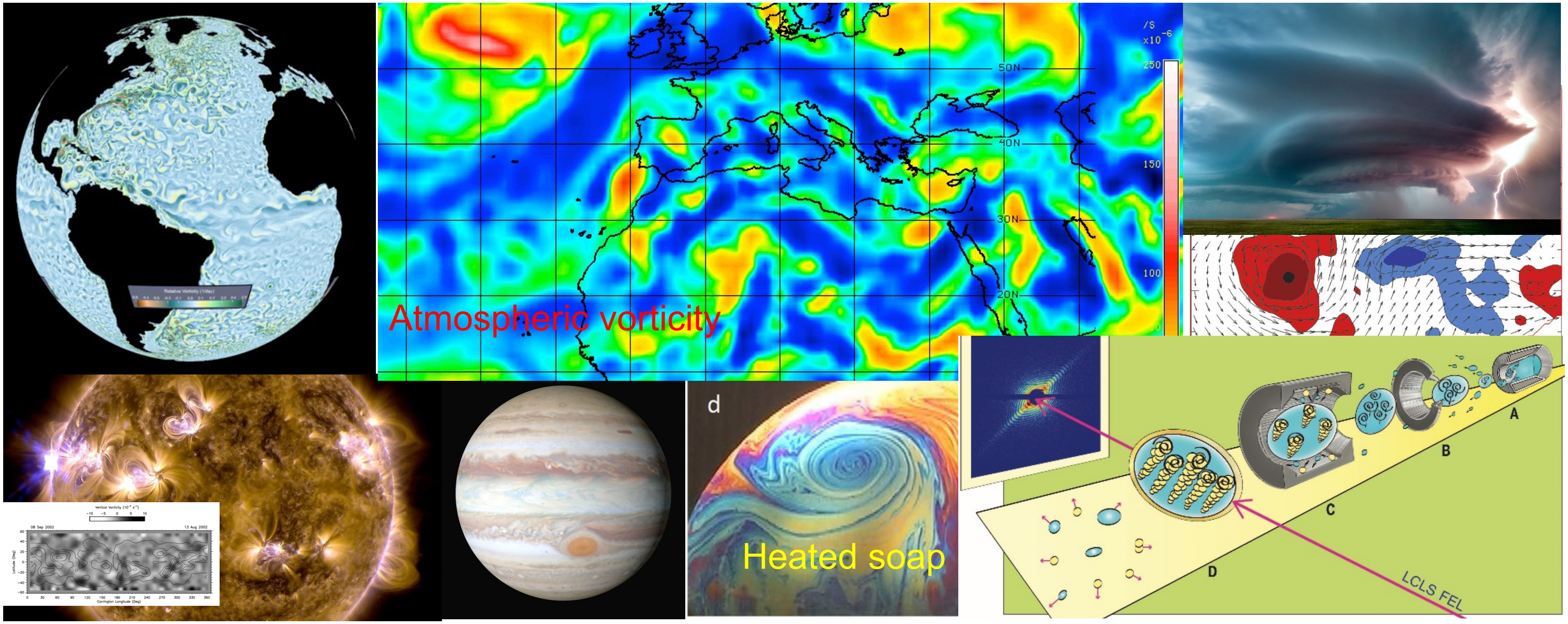
$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \qquad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

⇓

$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T/\hbar \sim 10^{22} s^{-1}$$

RHIC : ω ~ 10^{22} s^{-1}
Most vortical fluid !

Most vortical fluid



ocean flows: ω ~ 10^{-5} s^{-1}

terrestrial atmosphere: ω ~ 10^{-4} s^{-1}

core of supercell tornado : ω ~ 10^{-1} s^{-1}

solar subsurface flow: : ω ~ 10^{-6} s^{-1}

high vorticity (10^{-4} s^{-1}) in the “collar” of Jupiter’s Great Red Spot

heated, rotating soap bubbles (10^{2} s^{-1})

max vorticity in nanodroplets of superfluid He-II 10^{6} s^{-1}(Gomez et al., Science 345 903 (2014)).

RHIC : ω ~ 10^{22} s^{-1}
Most vortical fluid !

It’s EM vibrant

EM field stronger than magnetar !

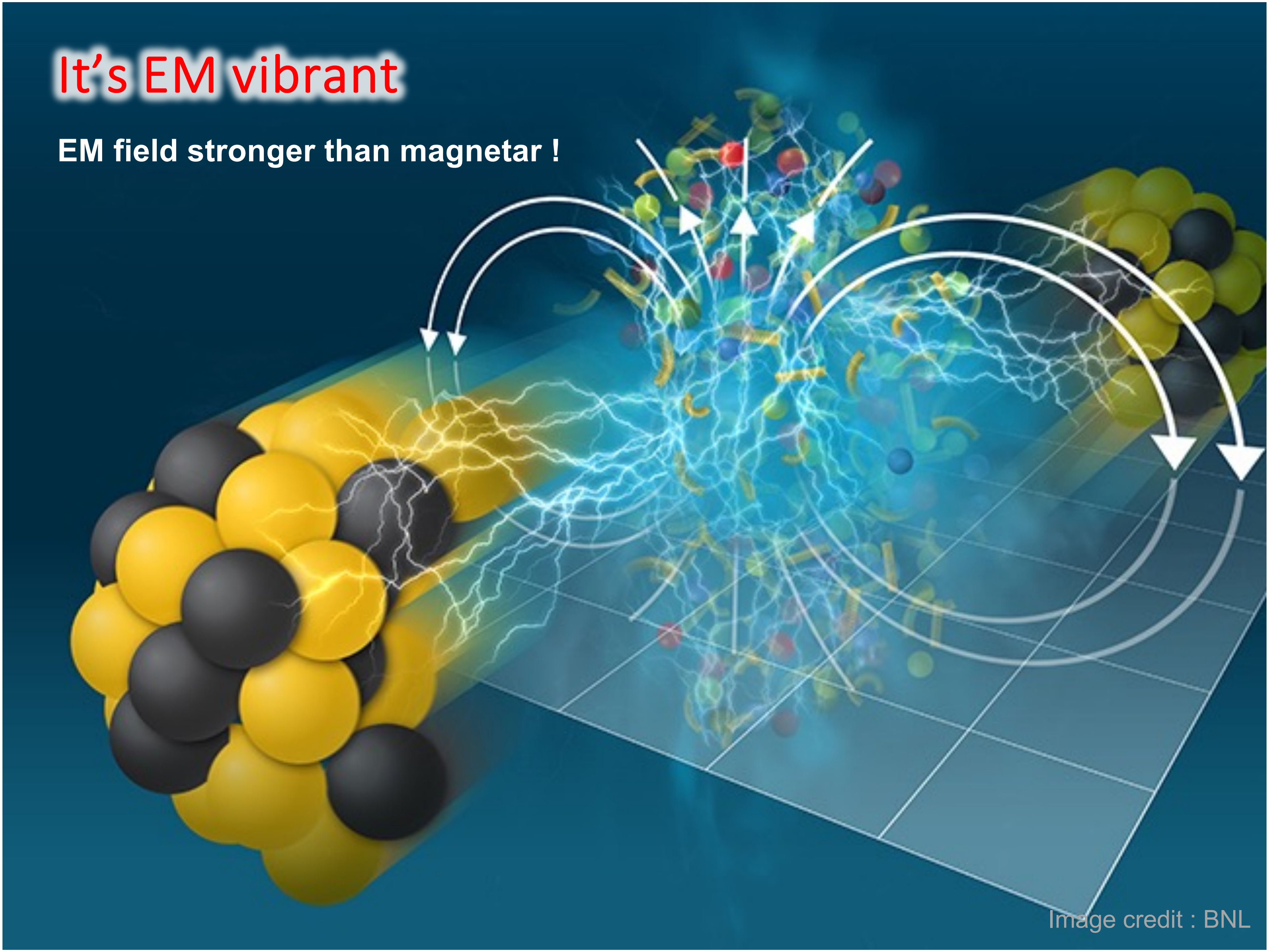
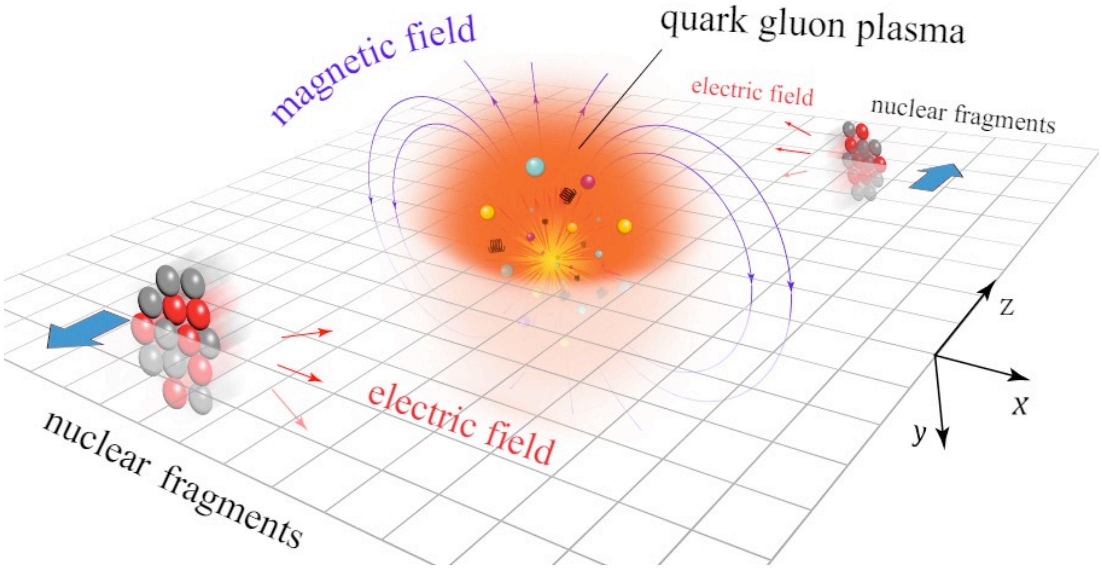


Image credit : BNL

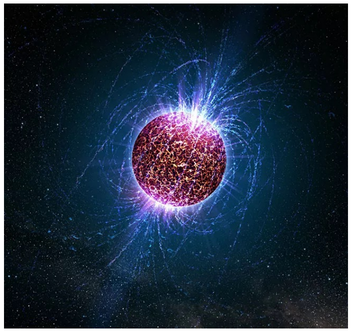
Ultra-strong EM field



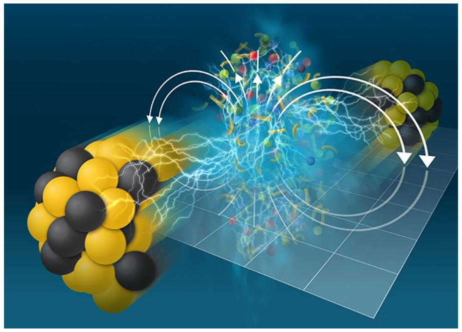
Strongest man-made magnetic field : peak value of eB ~ 10^{18} Gauss at top RHIC energy.

Earth
~ 0.5 Gauss

Lightning
~ 10^3 - 10^4 Gauss

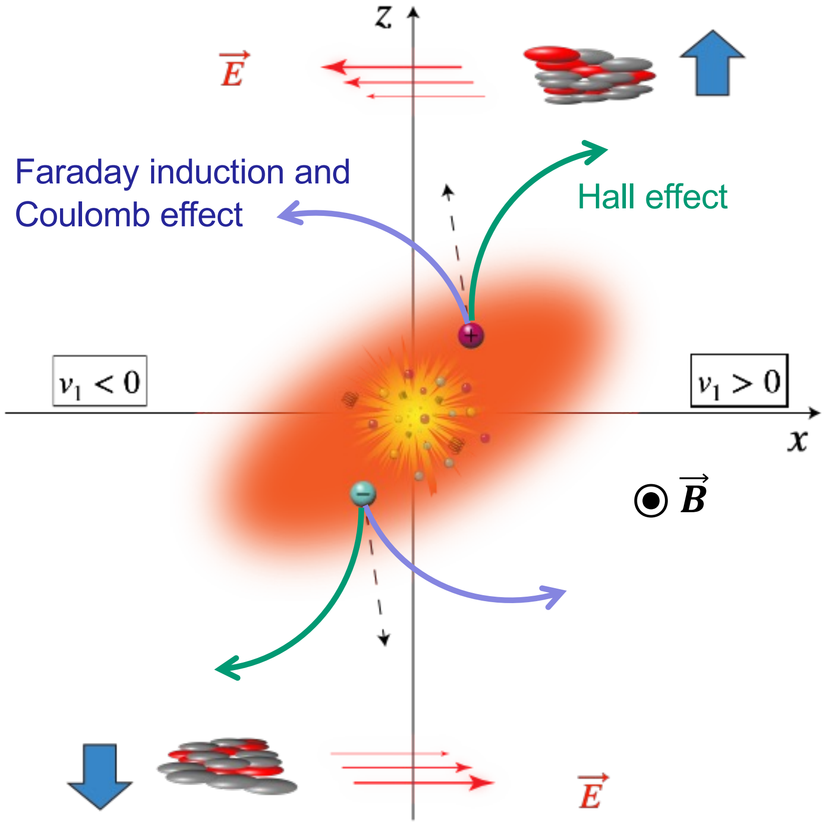


Neutron Star (Magnetar)
~ 10^{14} Gauss



Heavy ion collisions
~ 10^{18} Gauss

Ultra-strong EM field



Hall effect (Lorentz force) and Faraday + Coulomb effect compete each other.

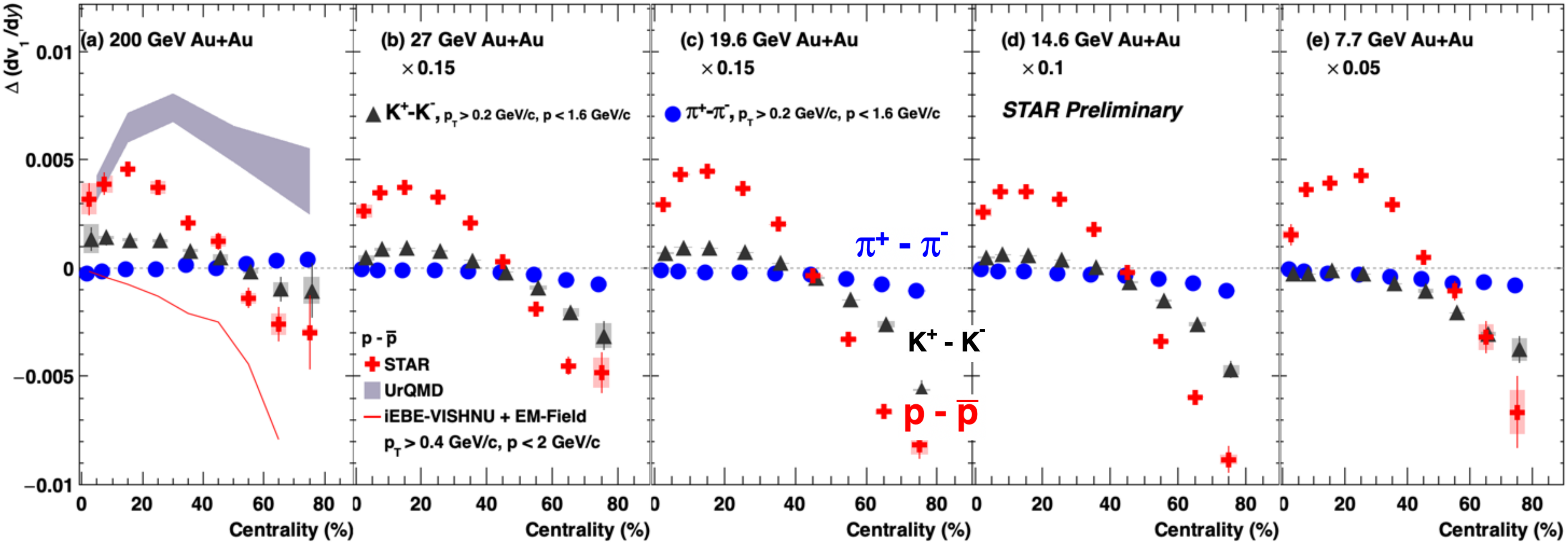
Hall effect is more relevant for heavy quarks at early stage.

Calculations indicate Faraday + Coulomb effect dominate over Hall effect for light hadrons.

Gursoy, Kharzeev and Rajagopal, PRC 89 054905 (2014)
S.K. Das et al., PLB 768 260 (2017)
Umut Gursoy, et al., PRC 98 055201 (2018)
K. Nakamura et. al., PRC 107 034912 (2023)
K. Nakamura et. Al., PRC 107 014901 (2023)

EM field cause splitting in collective motion (v_1)

Ultra-strong EM field



STAR, PRX 14 11028 (2024)

Feature consistent with EM field effects.

Key Takeaways

Extreme Conditions : Heavy ion collisions recreate conditions similar to those just after the Big Bang.

Quark-Gluon Plasma : A state of matter where quarks ang gluons are deconfined, providing insights to the early universe and serving as a test ground for QCD, helping to map the QCD phase diagram.

Innovative Techniques : Advanced measurement and theoretical methods drive discoveries in understanding the fundamental nature and dynamics of matter.

Dynamic Exploration : Exciting and continuous efforts at RHIC and LHC to explore new phenomena and unravel the mysteries of QGP properties.

Ultimate Goal : To uncover the fundamental building blocks of matter and the forces that govern their interactions, enhancing our understanding of the universe.

Apologies to those not mentioned