CMS Experiment at the LHC, CERN

Heavy-Ion Physics (I)

Yen-Jie Lee

Student Lecture

2022 Asia Europe Pacific School of High-Energy Physics

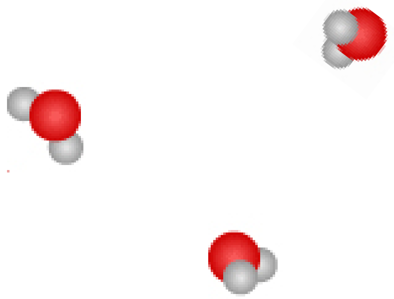
Pyeongchang, South Korea

5-18 October 2022

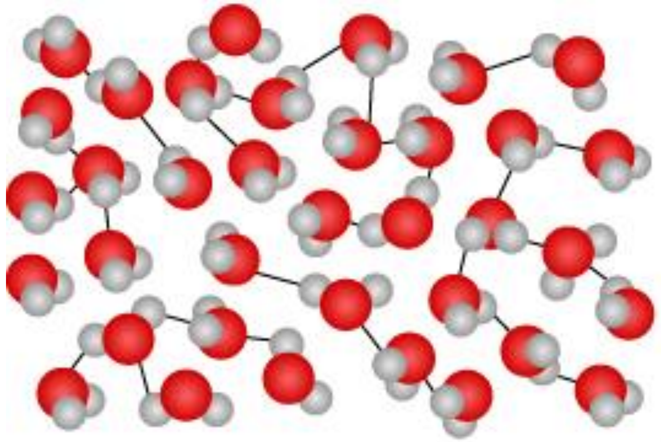
MIT HIG group's work was supported by US DOE-NP

Phases of QED (Electrons and Nuclei) Matter

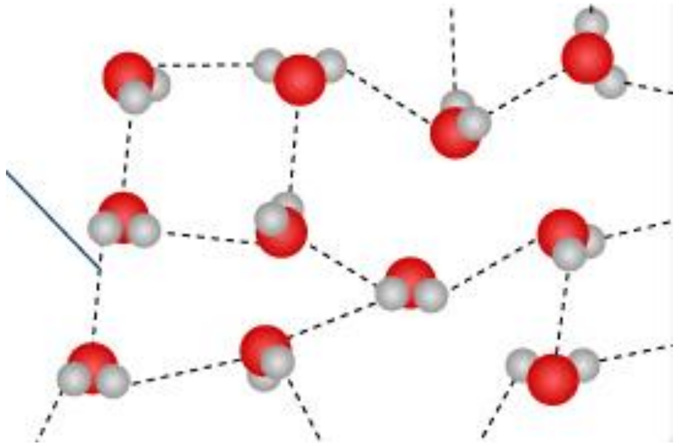
Vapor



Water



Ice



Quantum Chromodynamics

Structure of QCD driven by SU(3) color gauge symmetry

Gluon self-interaction

In principle, all is calculable from the QCD Lagrangian:

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \bar{\psi}_a \Big((i\gamma^\mu \partial_\mu - m)\delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu \Big) \psi_b - \frac{1}{4} F^A_{\mu\nu} F^{\mu\nu,A}$$

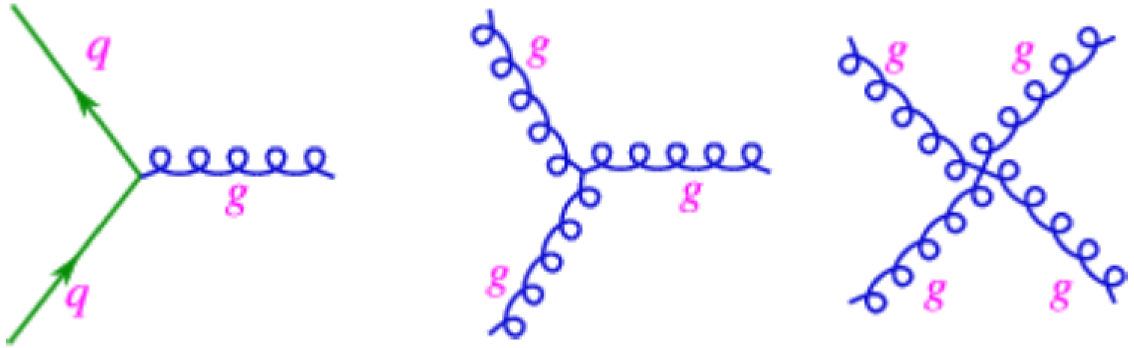
$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\nu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu$$

$$[t^A, t^B] = i f_{ABC} t^C$$

Quark propagator

Quark-gluon vertex

Field strength tensor



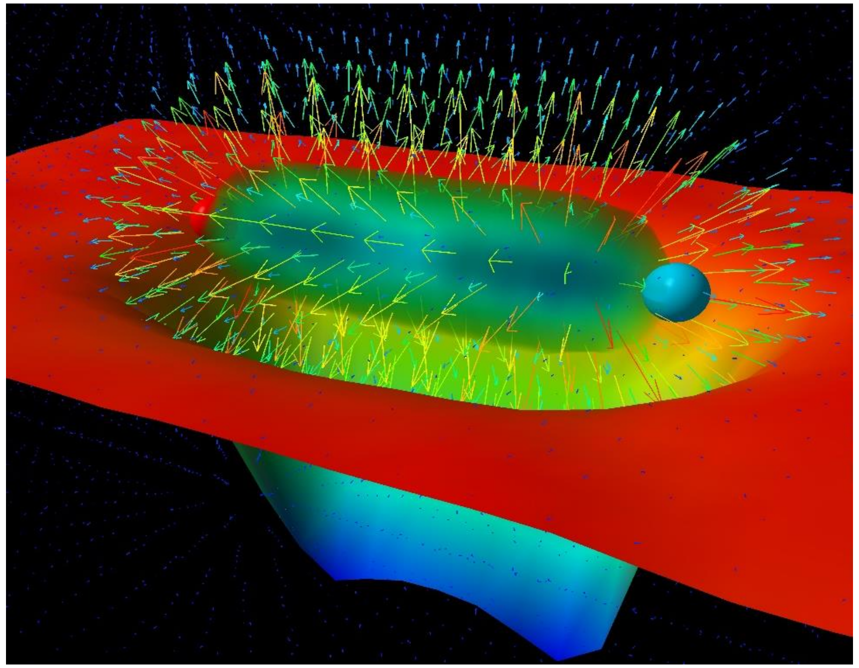
$N_c^2 - 1 = 8$ gluons
$N_c * N_f$ quarks

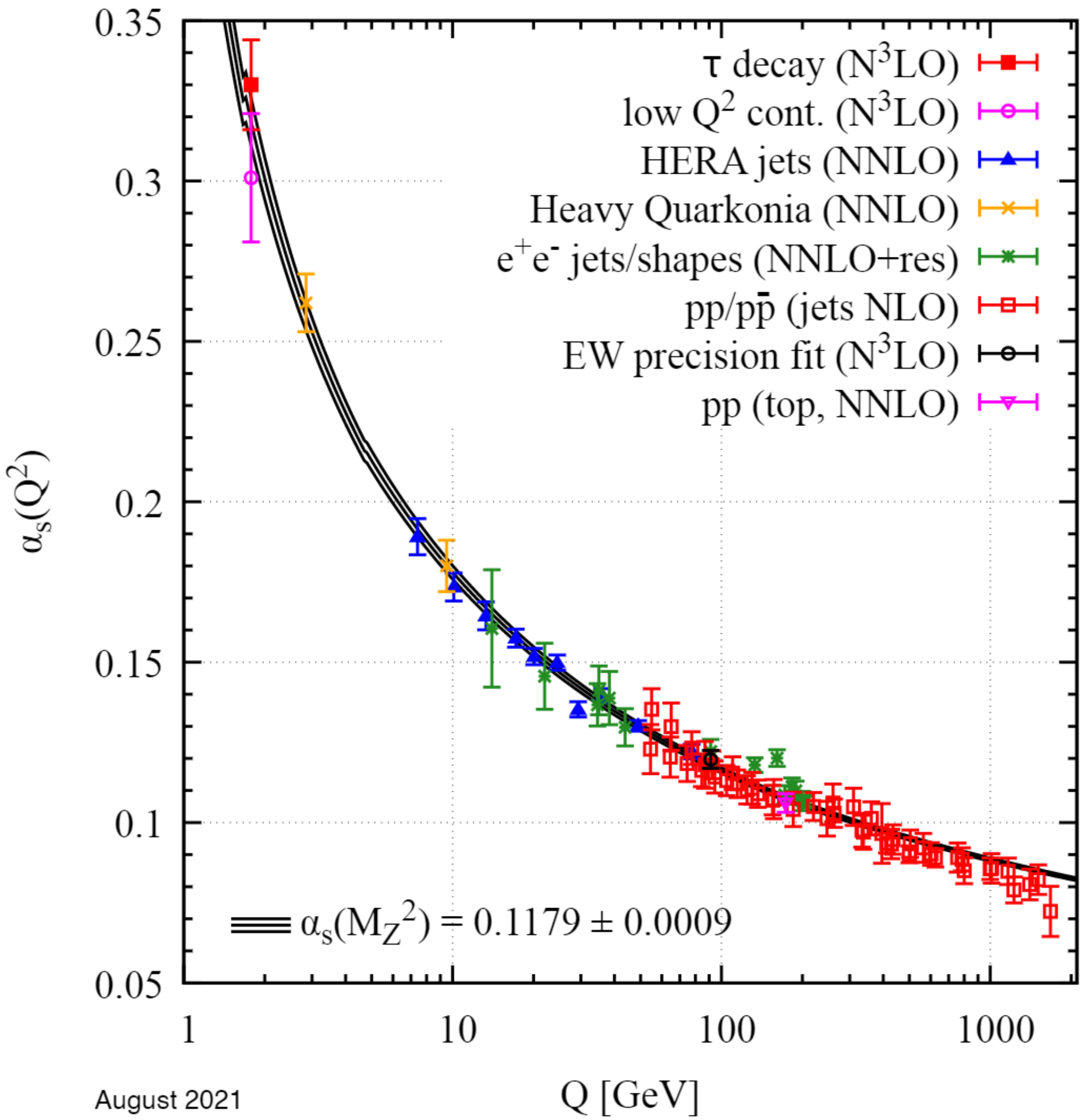
Quark masses

charge=+2/3	u (~5 MeV)	c (~1.5 GeV)	t (~175 GeV)
charge=-1/3	d (~10 MeV)	s (~100 MeV)	b (~5 GeV)

QCD Running Coupling α_s

Strong coupling
Confinement
Infrared slavery
Non-perturbative



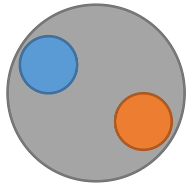


0.2 fm 0.02 fm 0.002 fm 0.0002 fm

Weak coupling
Asymptotic freedom
Perturbative

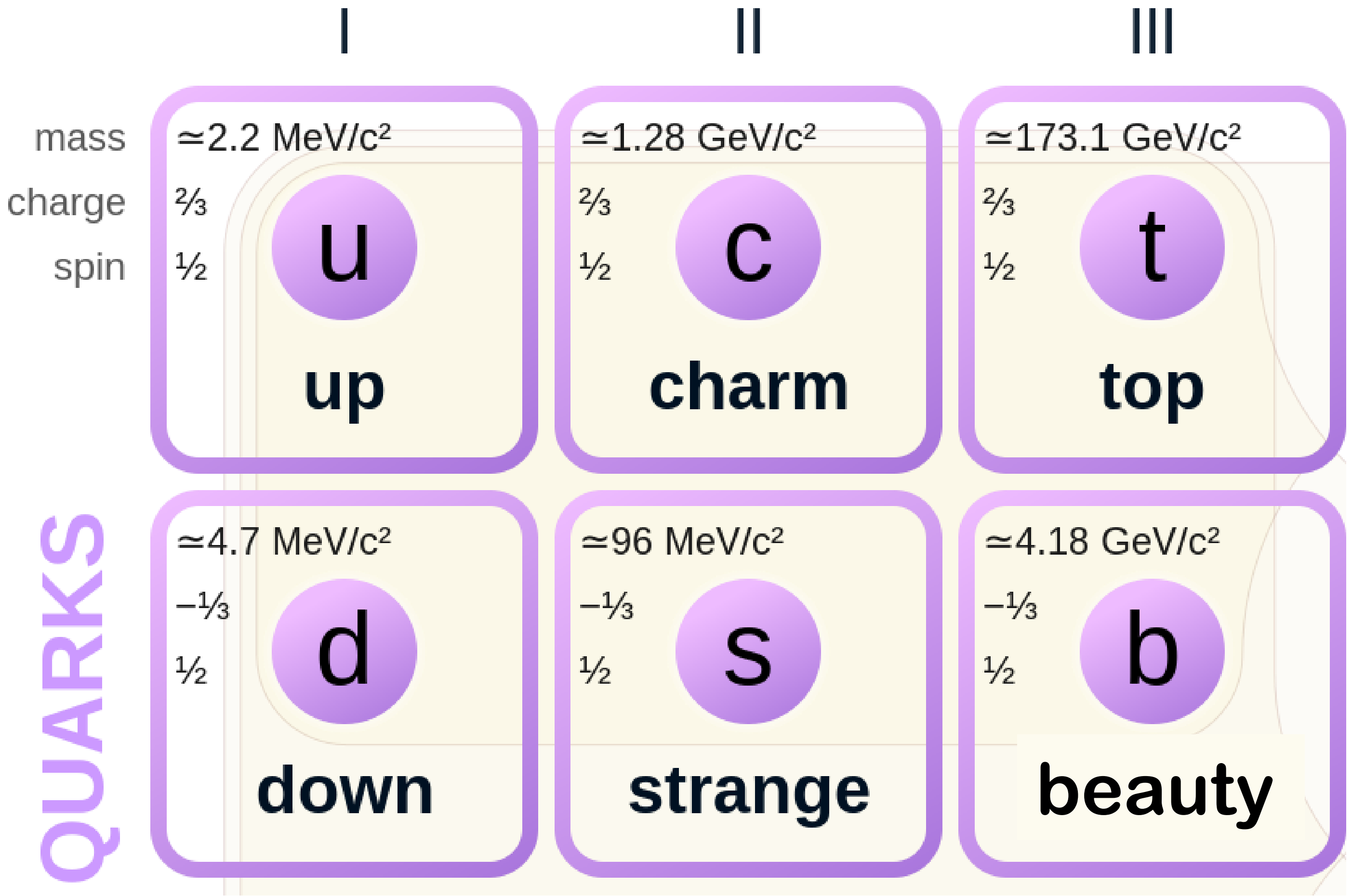
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

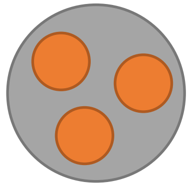
Quarks and Hadrons



Mesons
(**quark** and **anti-quark**)

Confinement





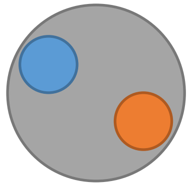
Baryons
(Three **quarks**)

When the quarks form a hadron, the total color charge needs to be neutral

Ultra-dense QCD (Quarks and Gluons) Matter

Increase the Temperature (T)

Quark
Anti-quark



Mesons
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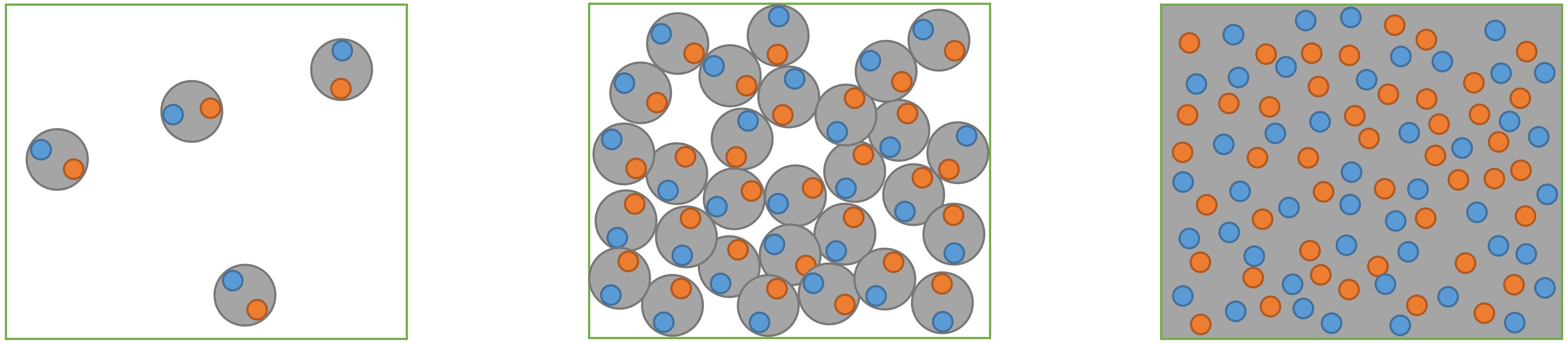
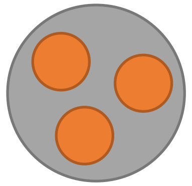


$T<T_C$ $\quad$ $T \sim T_C \sim$ 2 trillion degrees $\quad$ $T>T_C$



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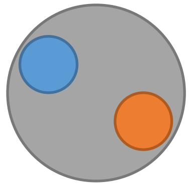

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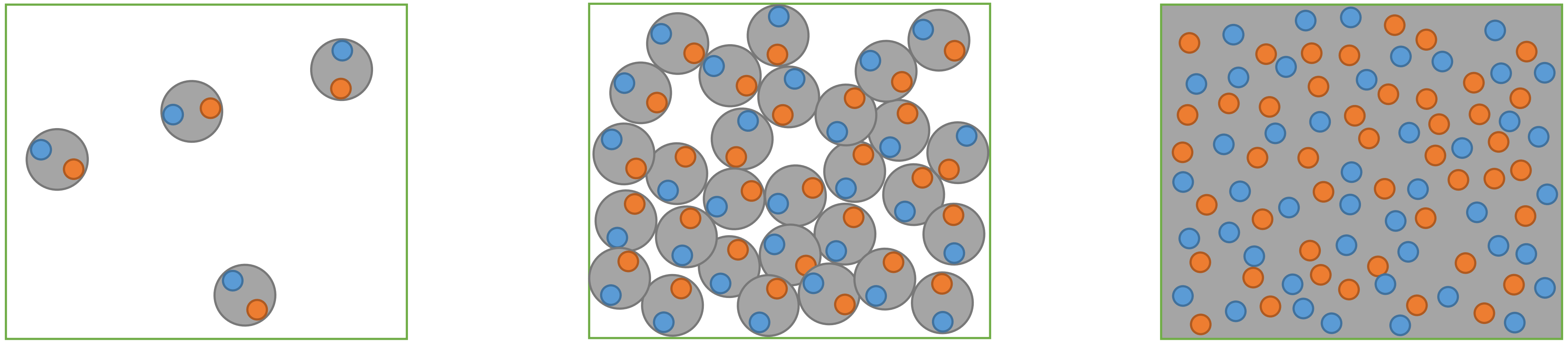
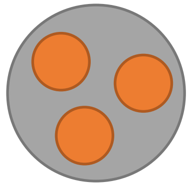
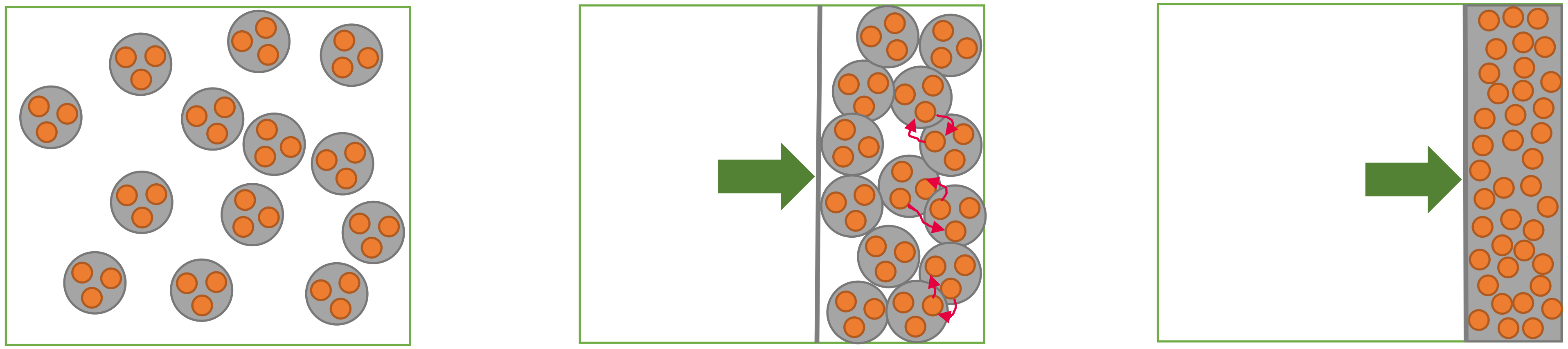


$T<T_C$ $T\sim T_C$ ~ 2 trillion degrees $T>T_C$

Increase the Density (ρ)



Baryons
(Three quarks)



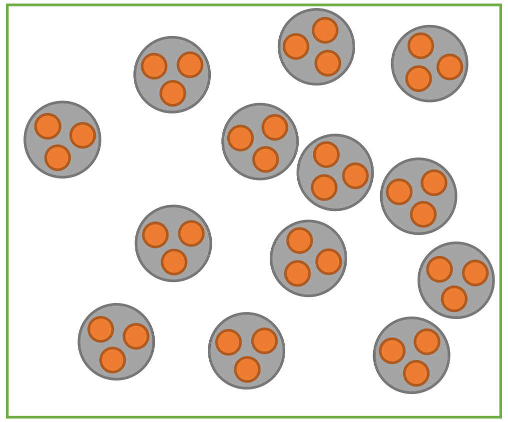
$\rho<\rho_C$ $\rho\sim\rho_C$ ~ (2 to 12) x nuclei density $\rho>\rho_C$

Rough Estimation of the Critical Density

- Normal nuclear matter
  - Baryon density

$$\rho_0 = \frac{A}{\frac{4}{3}\pi R^3} = \frac{1}{\frac{4}{3}\pi r_0^3} \approx 0.16/\mathrm{fm}^3$$

$$r_0 \equiv \frac{R}{A^{\frac{1}{3}}} \approx 1.15\ fm$$



Proton Charge Radius: Nature volume 575, pages147–150 (2019)

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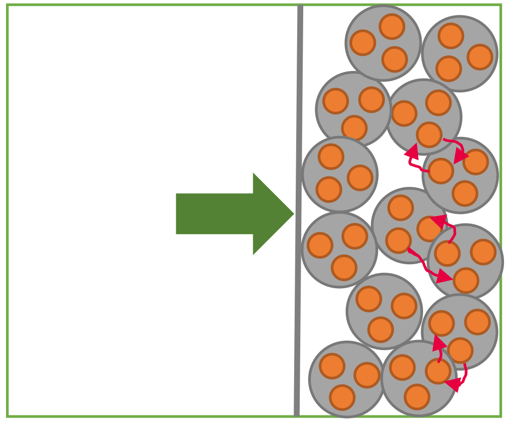
  - Compressed nuclei: nucleons start to overlap!

$$r_p = 0.84\ \mathrm{fm}$$



Rough estimation of critical density:

$$\rho_c = \frac{1}{\frac{4}{3}\pi r_p^3} \approx 0.4/fm^3$$

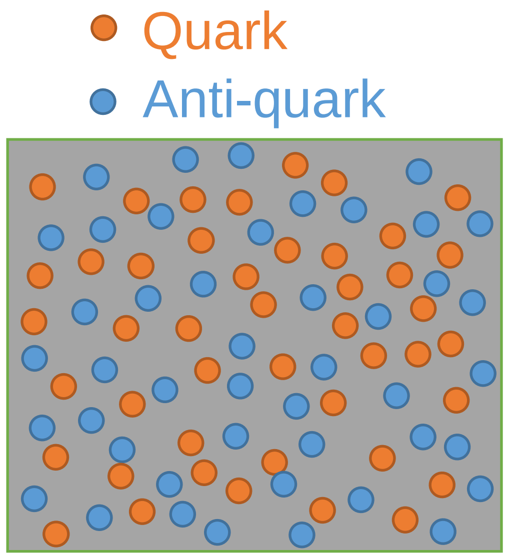
→ At least a few times of the normal nuclear matter density

Proton Charge Radius: Nature volume 575, pages147–150 (2019)

Reminder: Thermodynamics

- **At high temperature limit**:
  QGP as an ideal gas of non-interacting quarks and gluons
- Probability density: $$N(E) = \frac{D}{(2\pi)^3} \frac{1}{e^{\frac{E-\mu}{T}} \pm 1}$$ where + for Fermion, - for Boson

With degeneracy **D**, chemical potential **μ**, energy **E**, and $\hbar = c = k_B = 1$



Relativistic Bose Gas

- **At high temperature limit**:
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  With degeneracy **D**, chemical potential **μ**, energy **E**, and $\hbar = c = k_B = 1$

- For a relativistic Bose gas, neglecting the chemical potential (μ=0)
  - Energy density: $$\epsilon = \int N(E) p d^3p = \frac{4\pi D}{(2\pi)^3}\int \frac{p^3 dp}{e^{\frac{p}{T}} - 1}$$

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  - Energy density: $$\epsilon = \int N(E) p d^3 p = \frac{4\pi D}{(2\pi)^3} \int \frac{p^3 dp}{e^{\frac{p}{T}} - 1}$$

$$\Rightarrow \quad \epsilon = \frac{3D}{\pi^2} T^4 \zeta(4) = \frac{\pi^2 D}{30} T^4$$

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s} = \frac{1}{\Gamma(s)} \int_0^{\infty} \frac{x^{s-1}}{e^x - 1} \, dx \,,$$

where

$$\Gamma(s) = \int_0^{\infty} x^{s-1} e^{-x} \, dx$$

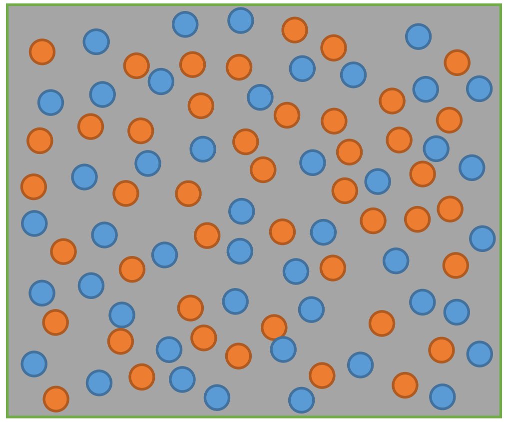
Relativistic Bose Gas

Bose gas energy density

$$\epsilon = \frac{\pi^2 D}{30} T^4$$

Pressure

$$P = \frac{1}{3}\epsilon = \frac{\pi^2 D}{90} T^4$$



Relativistic Bose Gas

Bose gas energy density

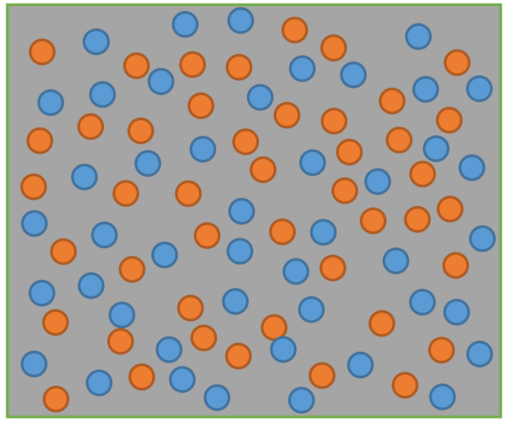
$$\epsilon = \frac{\pi^2 D}{30} T^4$$

Pressure

$$P = \frac{1}{3}\epsilon = \frac{\pi^2 D}{90} T^4$$

Entropy density

$$ds = \frac{d\epsilon}{T} = \frac{\pi^2 D}{30} \cdot \frac{4T^3 dT}{T} = \frac{4\pi^2 D}{30} \cdot T^2 dT$$



$$s = \int ds = \frac{4\pi^2 D}{30} \int T^2 dT \Rightarrow s = \frac{4\pi^2 D}{90} T^3 \qquad s = \frac{4}{3}\frac{\epsilon}{T}$$

Relativistic Bose Gas

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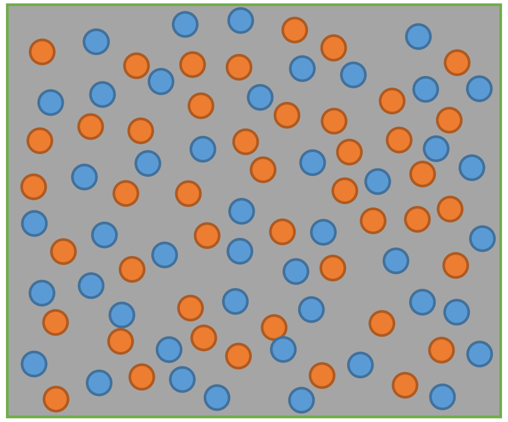

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$$s = \frac{4}{3}\frac{\epsilon}{T}$$

Number Density

$$\rho_N = \int N(E) d^3p = \frac{D}{\pi^2} T^3 \zeta(3) \approx 0.12 D T^3$$

Exercise with **Fermi Gas**

$$\epsilon_f = \frac{7}{8}\epsilon_b$$

What Have We Learned So Far?

Bose gas energy density: $$\epsilon = \frac{\pi^2 D}{30} T^4$$

Bose gas pressure $$P = \frac{\pi^2 D}{90} T^4 \qquad P = \frac{1}{3}\epsilon$$

Bose gas entropy density $$s = \frac{4\pi^2 D}{90} T^3 \qquad s = \frac{4}{3}\frac{\epsilon}{T}$$

Fermi Gas $$\epsilon_f = \frac{7}{8}\epsilon_b$$

Speed of sound c_s

$$c_s^2 = \frac{dP}{d\rho} = \frac{dP}{d\epsilon} = \frac{1}{3}$$

$$c_s \approx 0.58$$

- Energy density and pressure increases very quickly with temperature! (T^4)
- Proportional to number of degrees of freedom (degeneracy D)
- Similar dependence between Bose and Fermi gas except for a scale factor (**7/8**)!
- Speed of sound is around 0.58 c

Number of Degree of Freedom (D) for Hadron Gas

Hadron Gas:

- Suppose we focus on T< 400 MeV, it is a gas of pions
- **D = 3** for π^+, π^- and π^0 ⇨ $\epsilon = 3 \times \frac{\pi^2}{30} T^4$

Number of Degree of Freedom (D) for QGP

Hadron Gas:

- Suppose we focus on T< 400 MeV, it is a gas of pions
- **D = 3** for π^+, π^- and π^0 ➔ $\epsilon = 3 \times \frac{\pi^2}{30} T^4$

Non-interacting **Quark and Gluon gas**:

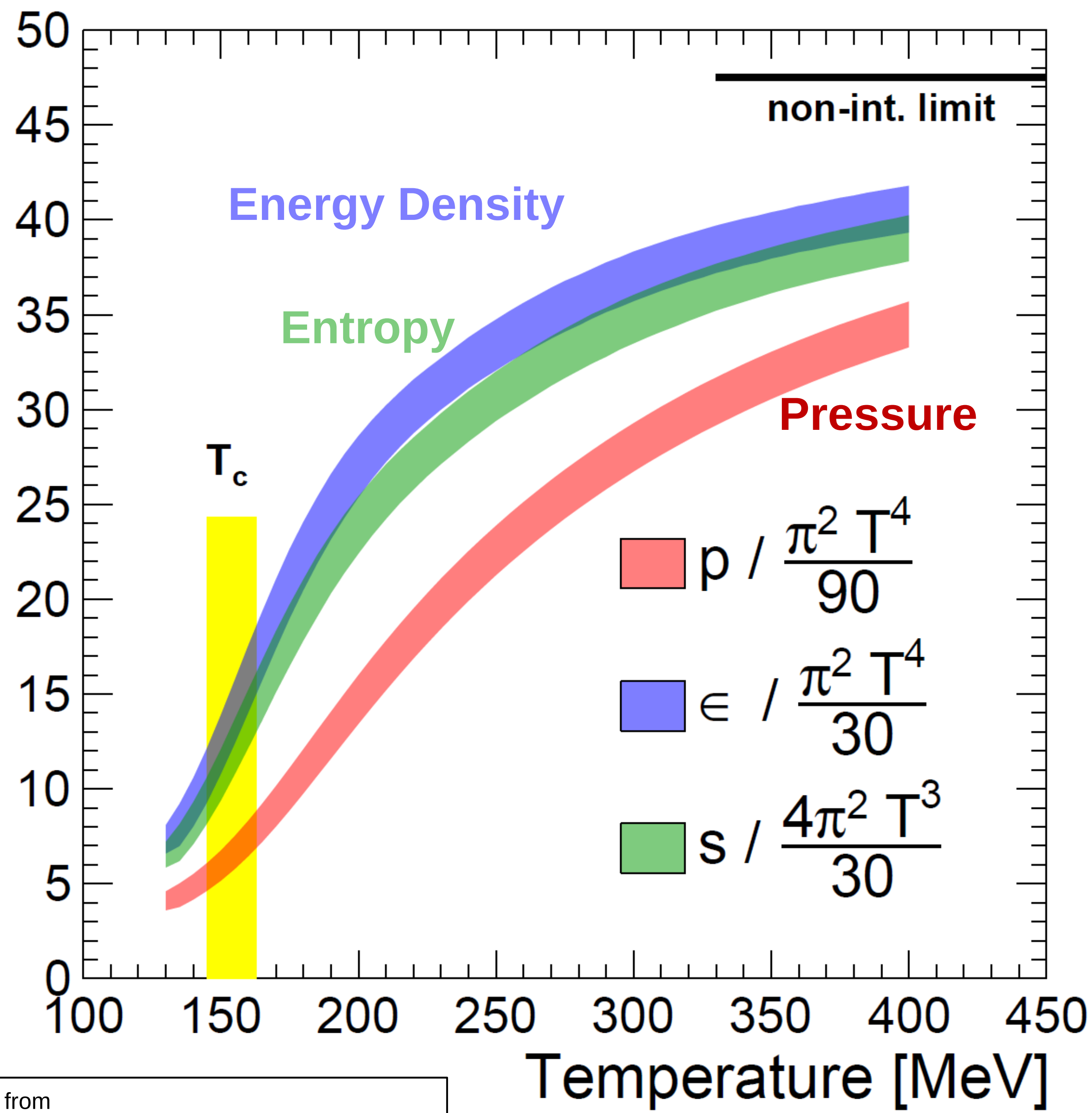
- Number of Gluons (Boson): D_g = 2 (spin) x 8 (color) = 16
- Number of Quarks (Fermion):
  D_q = 2 (spin) x 2 (particle/anti-particle) x 3 (color) x 3 (flavor u,d,s) = 36

➔ $\epsilon = (16 + \frac{7}{8} \times 36) \times \frac{\pi^2}{30} T^4 = 47.5 \times \frac{\pi^2}{30} T^4$

16x jump in energy density!!!

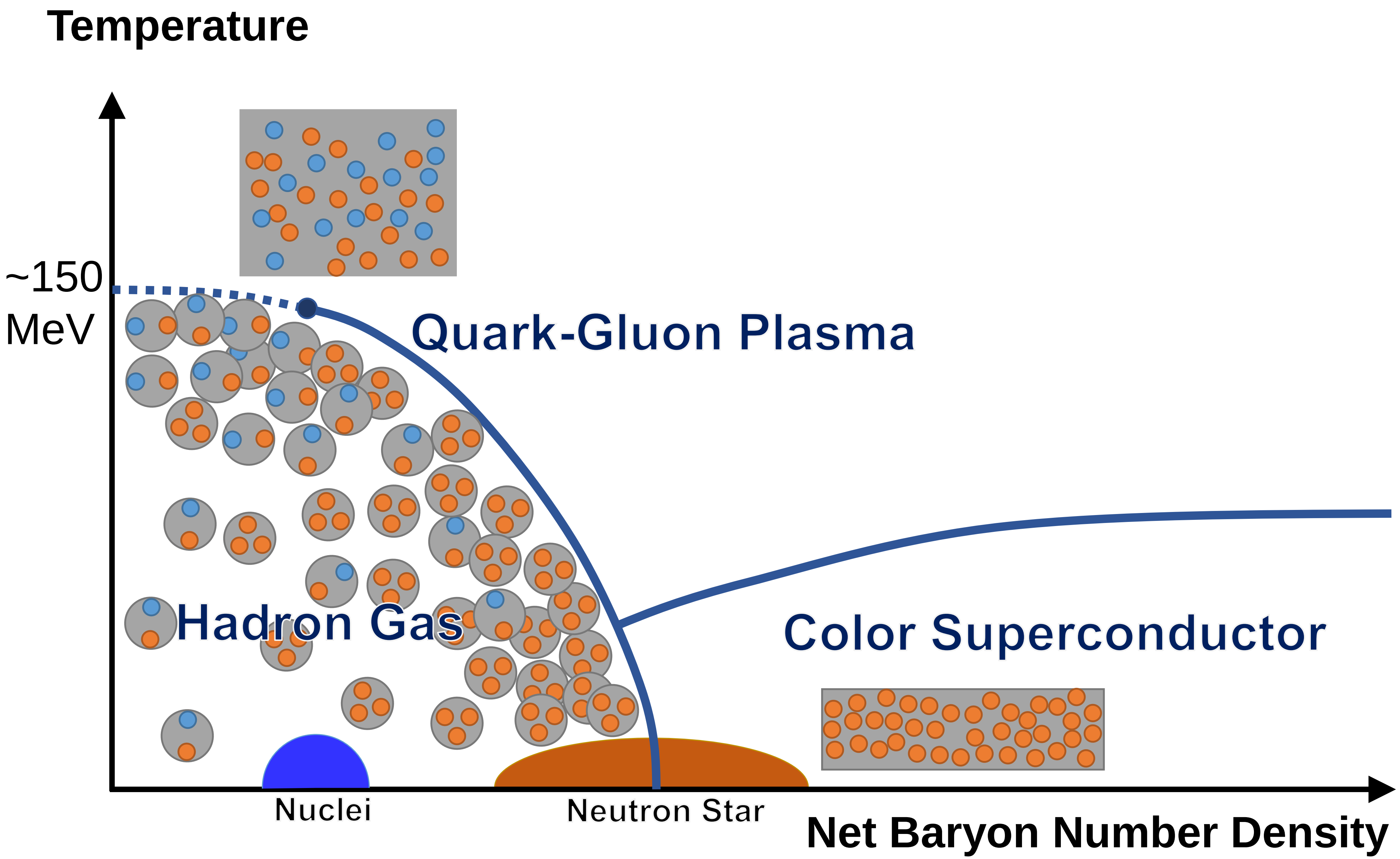
Lattice QCD Equation of State

- Solve the QCD equation of state on a discrete space-time lattice
- Reliable for zero net baryon density!
- Indeed, we see a rapid increase in the degrees of freedom!!!
- Predicts a speed of sound $c_s \approx 0.4 - 0.55$

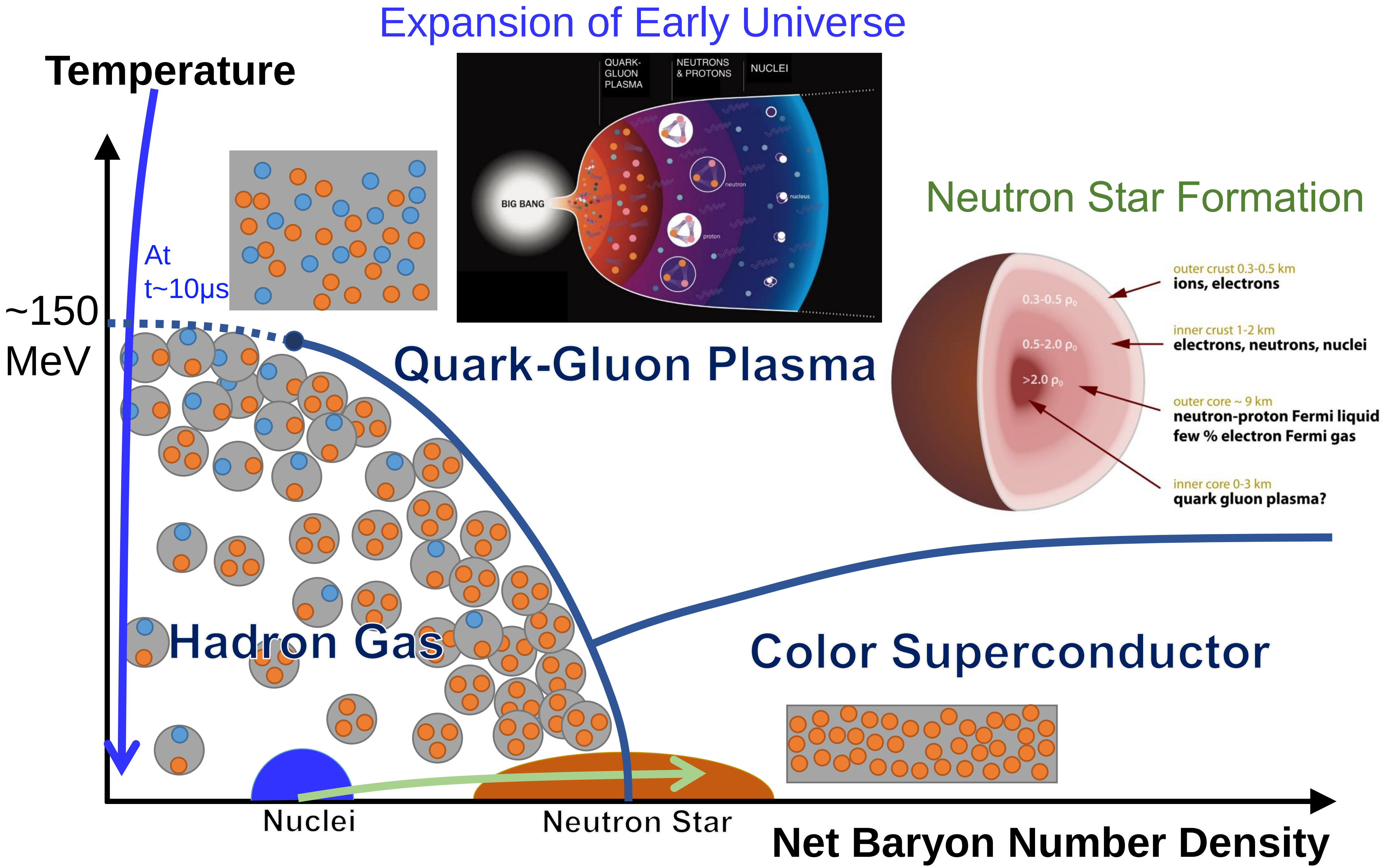


Replotted from
HotQCD Collaboration PRD90 (2014) 094503

QCD Phase Diagram

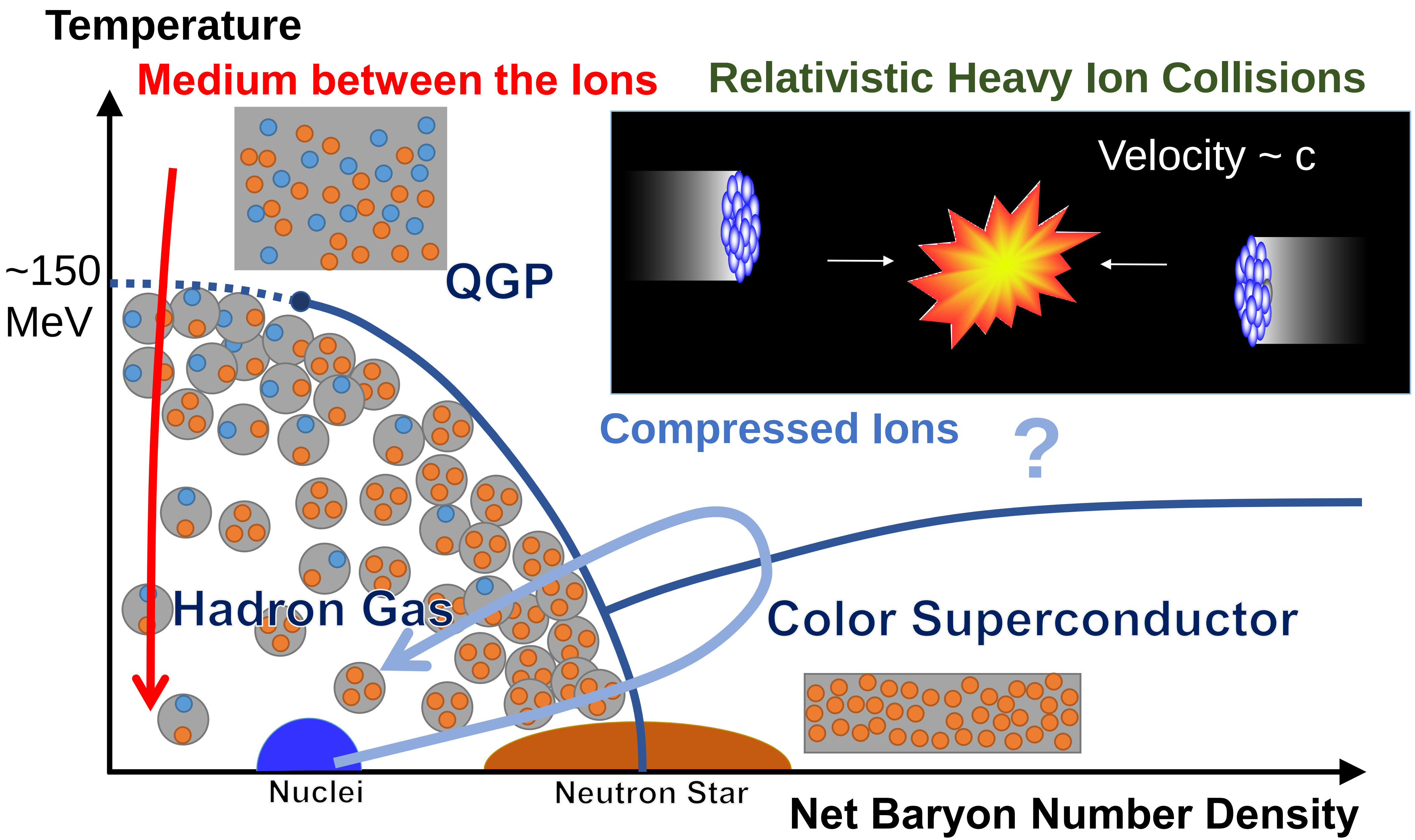


QCD Phase Diagram



How Do We Generate Quark-Gluon Plasma in a Lab?

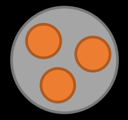
QCD Phase Diagram

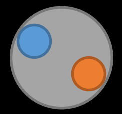


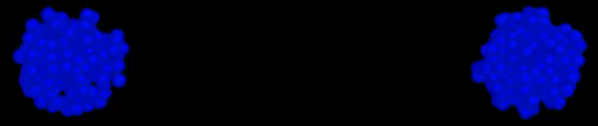
Relativistic Heavy Ion Collisions (Simulation)

MIT Heavy Ion Event Display: Pb+Pb 5.02 TeV

Quark Gluon Plasma

Baryons 

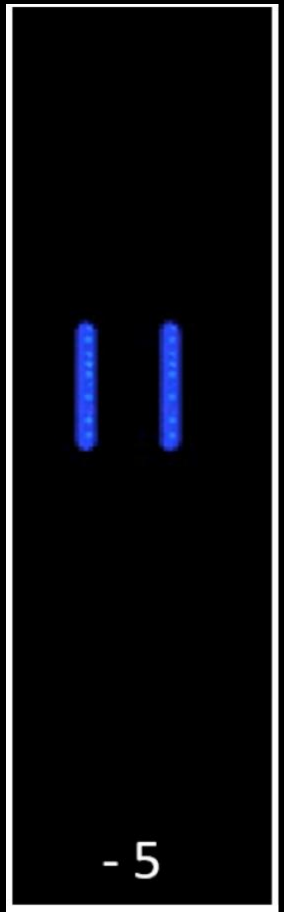
Mesons 



Yen-Jie Lee, Andre S. Yoon and Wit Busza

Acceleration

Relativistic Heavy Ion Collisions

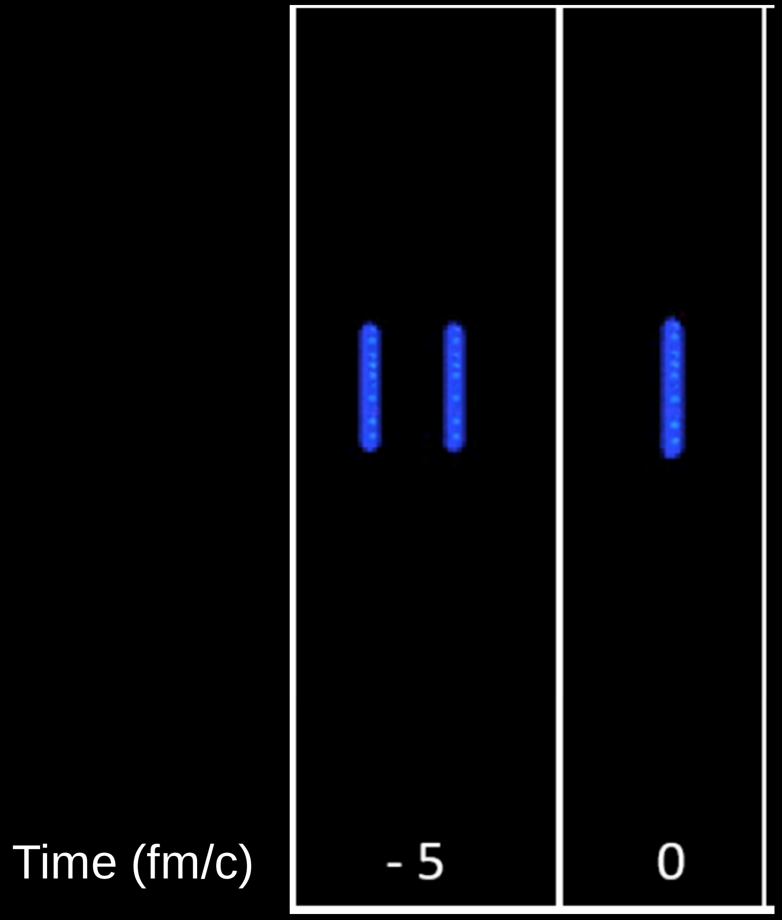


Time (fm/c)

Two discs of almost real quarks and gluons

Relativistic Heavy Ion Collisions

Collision! Highest energy density state. Huge amount of soft (low momentum transfer) scatterings.



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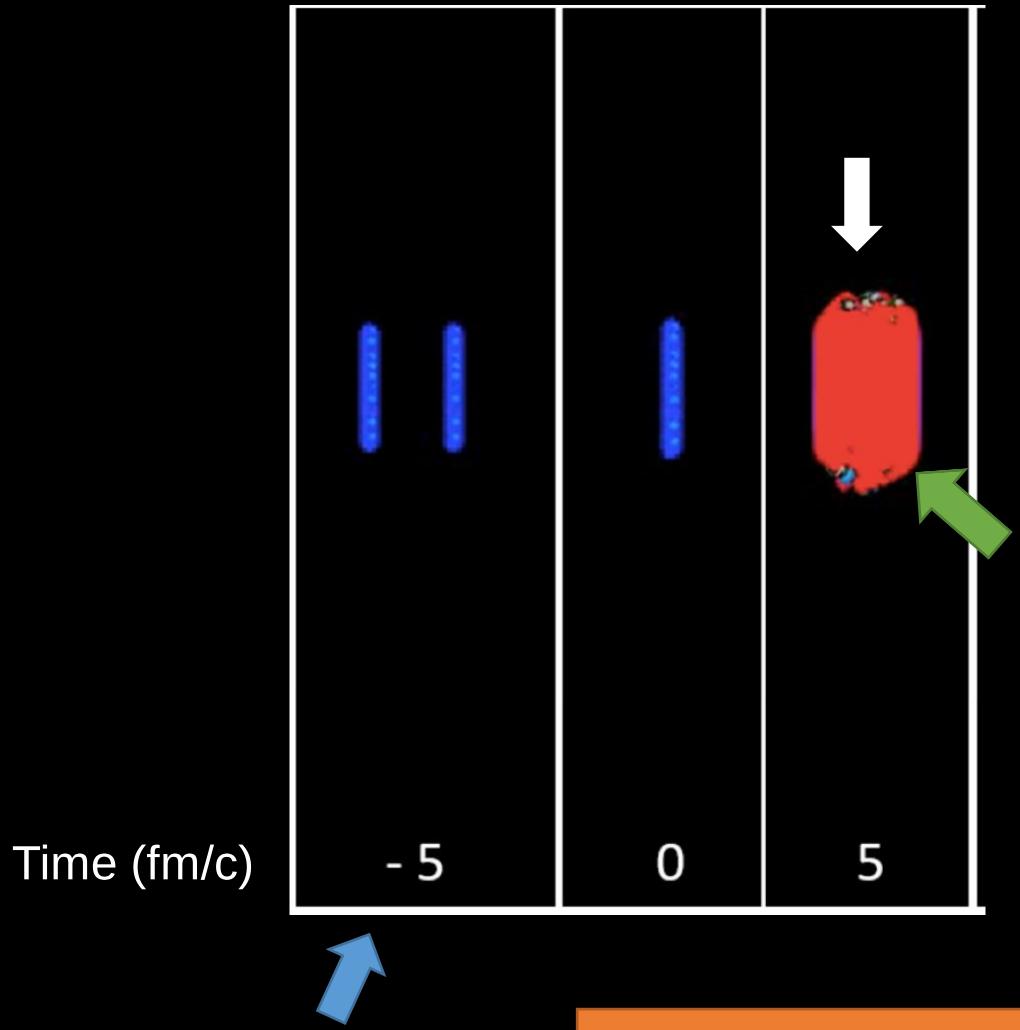


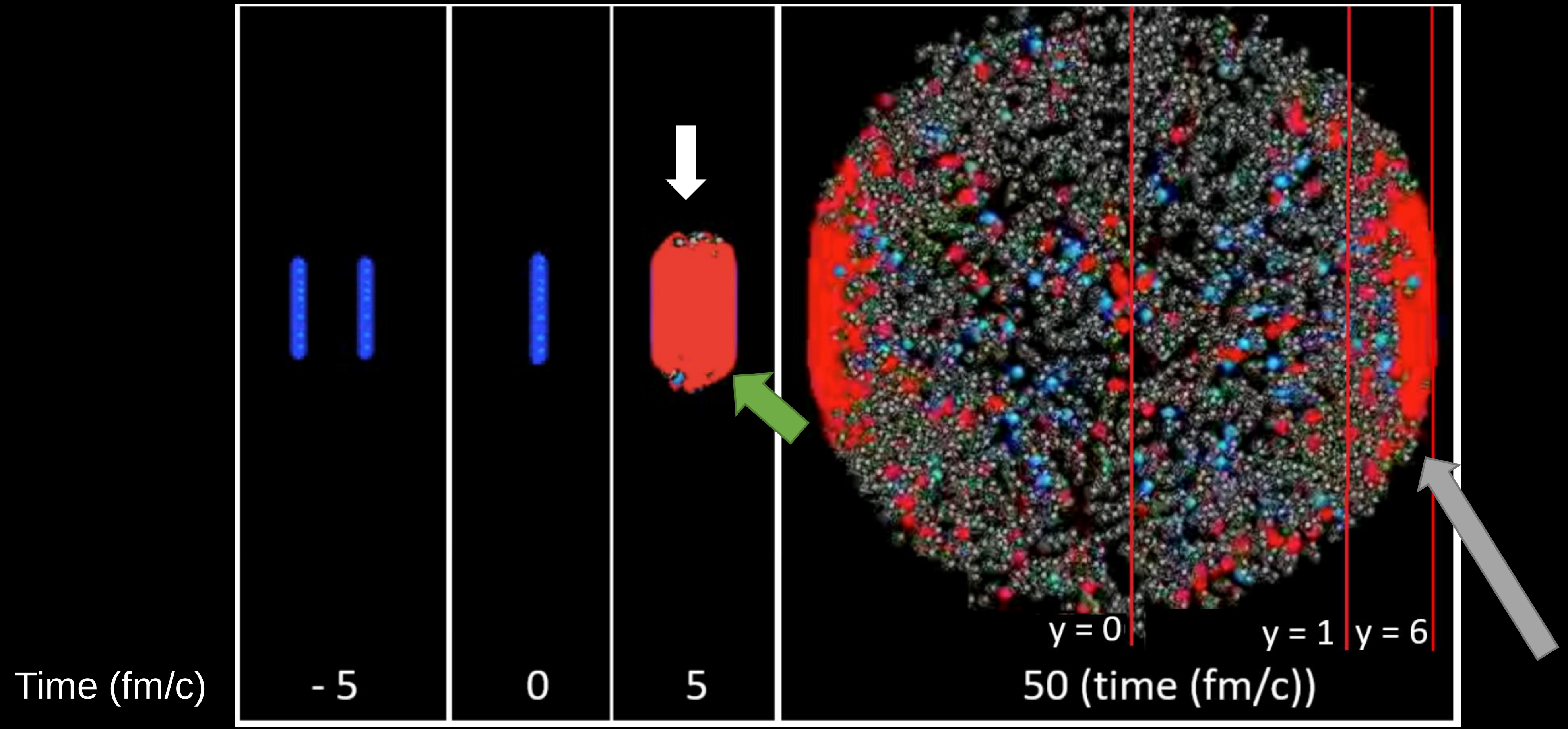
Two discs of almost real quarks and gluons

Midrapidity: thermalized QGP with very small baryon doping (μ_B)
Forward: QGP just created

Relativistic Heavy Ion Collisions

Collision! Highest energy density state. Huge amount of soft (low momentum transfer) scatterings.

Hadronization of QGP, different from elementary collisions like e^+e^- or pp collisions



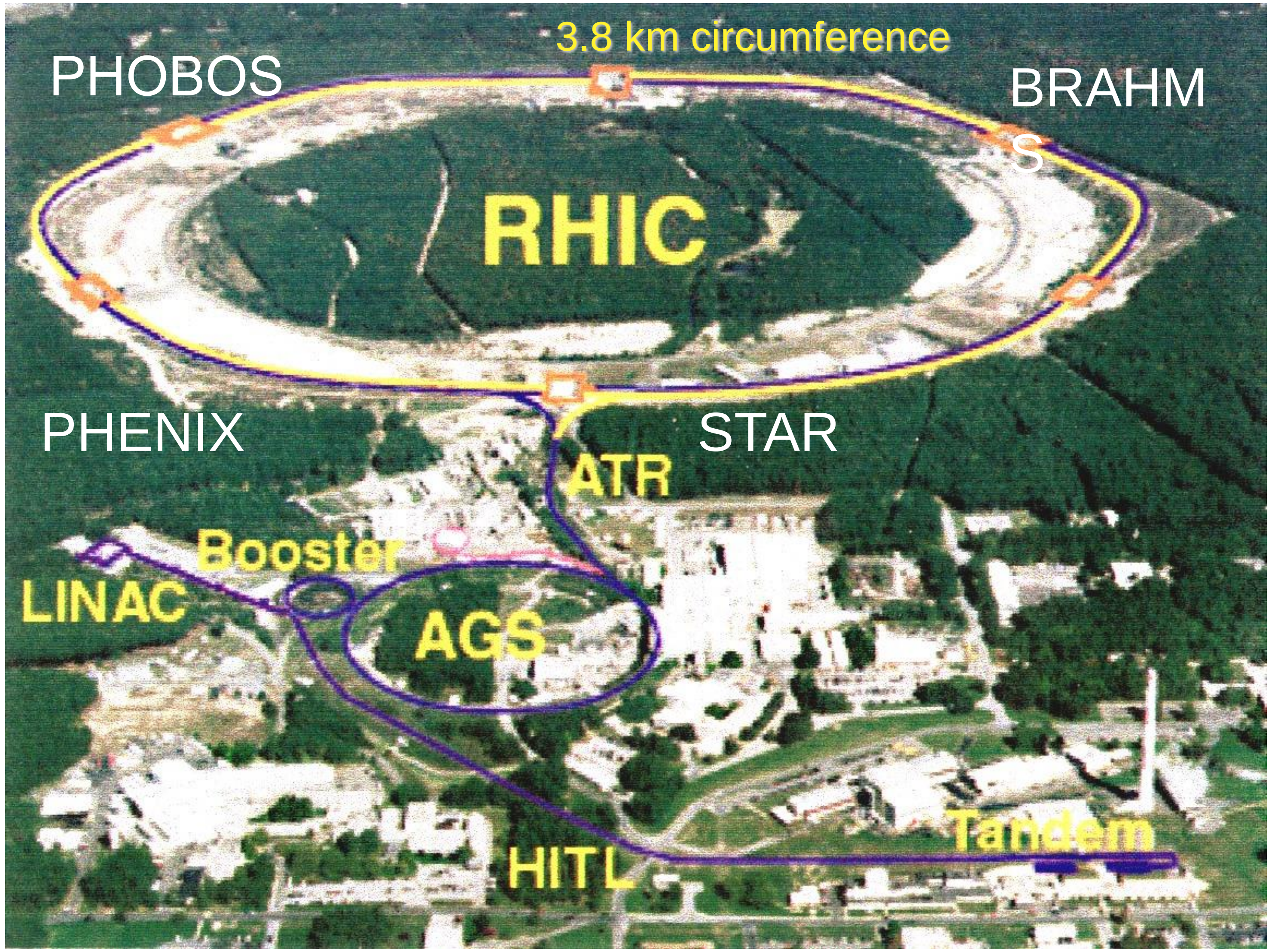
Two discs of almost real quarks and gluons

Midrapidity: thermalized QGP with very small baryon doping (μ_B)
Forward: QGP just created

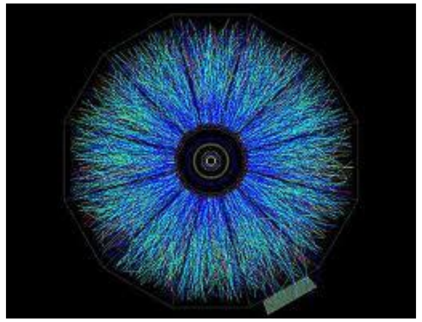
The ions lose ~ 85% of the momentum and form a compressed baryon-rich QGP (high μ_B) at large rapidity

The First Dedicated Heavy Ion Collider

Relativistic Heavy Ion Collider



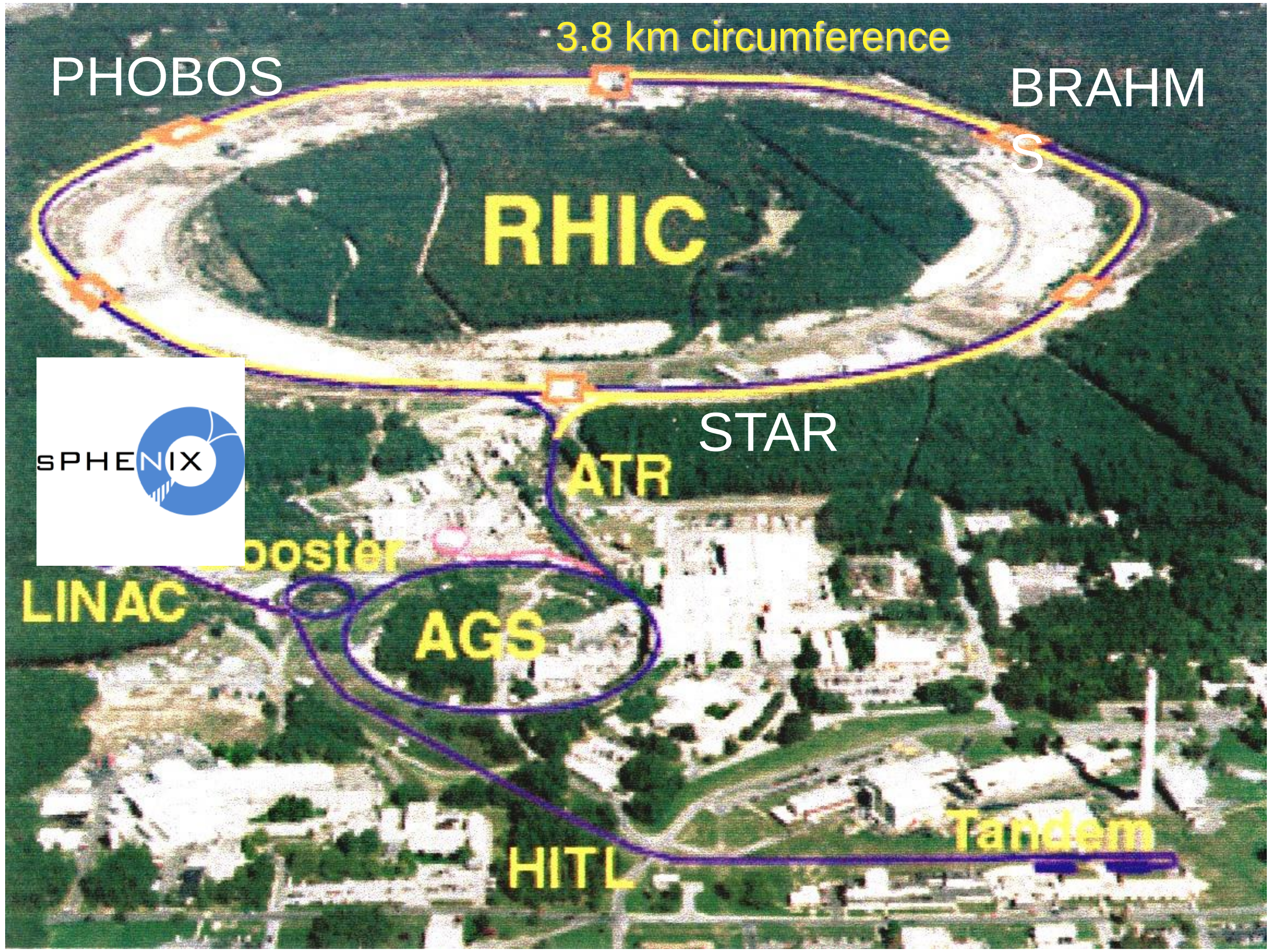
Au+Au
7.7 - 200 GeV



Since 2000~

sPHENIX Data-Taking in 2023

Relativistic Heavy Ion Collider



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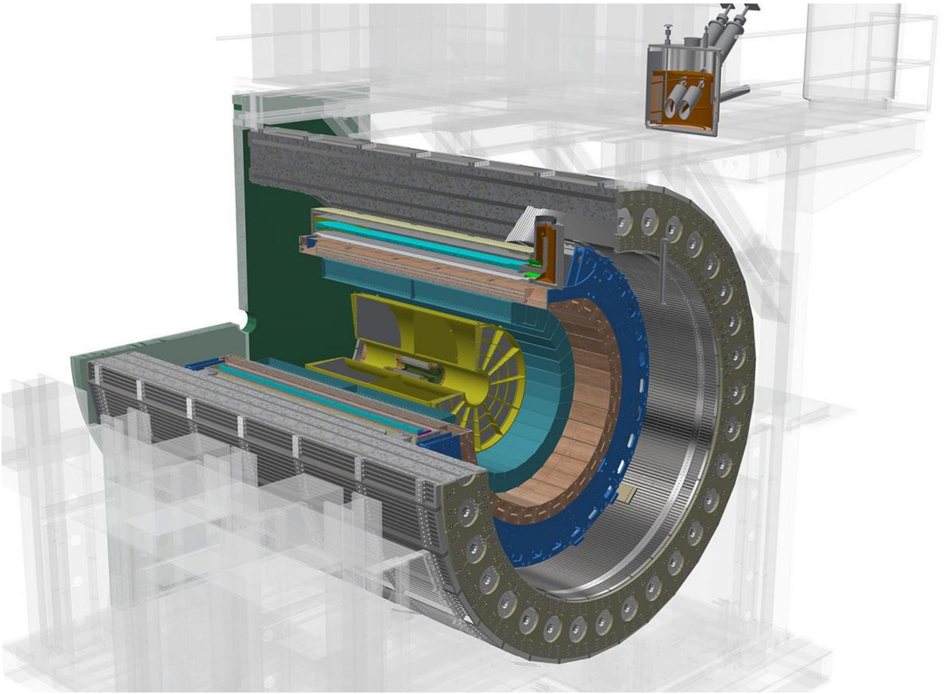
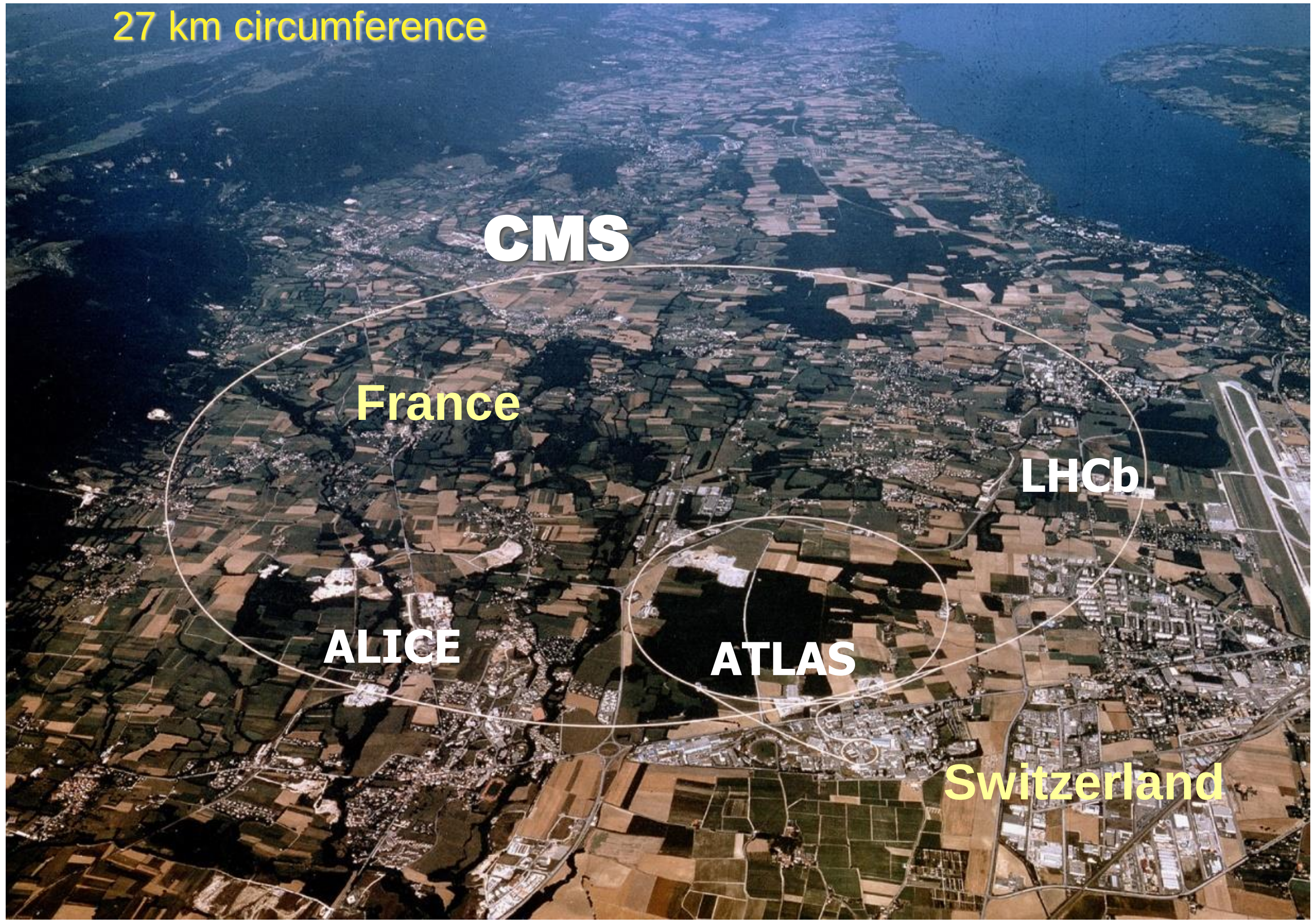


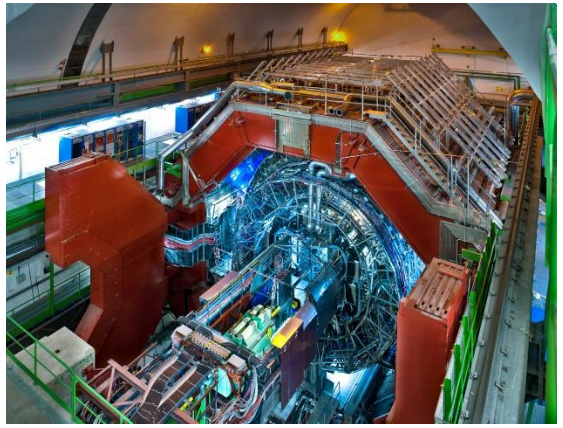
High Energy (Temperature) Frontier

Large Hadron Collider

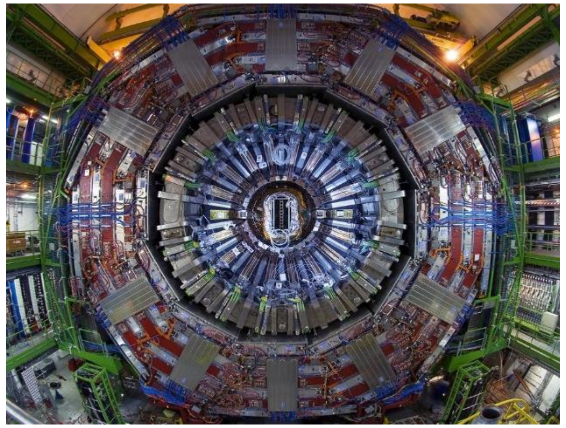


Lead+Lead (PbPb) collisions
2010-11: 2.76 TeV 0.16/nb
2015-18: 5.02 TeV 1.7/nb

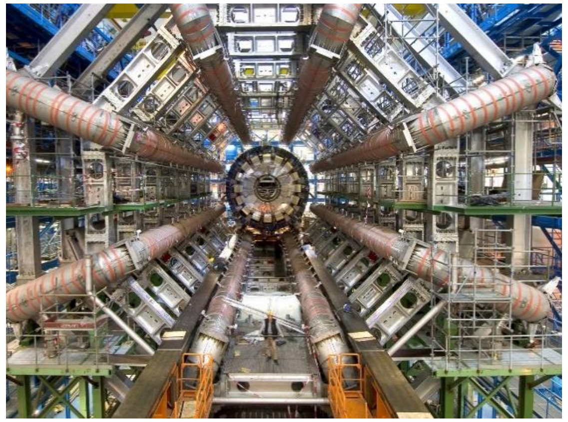
ALICE



CMS



ATLAS

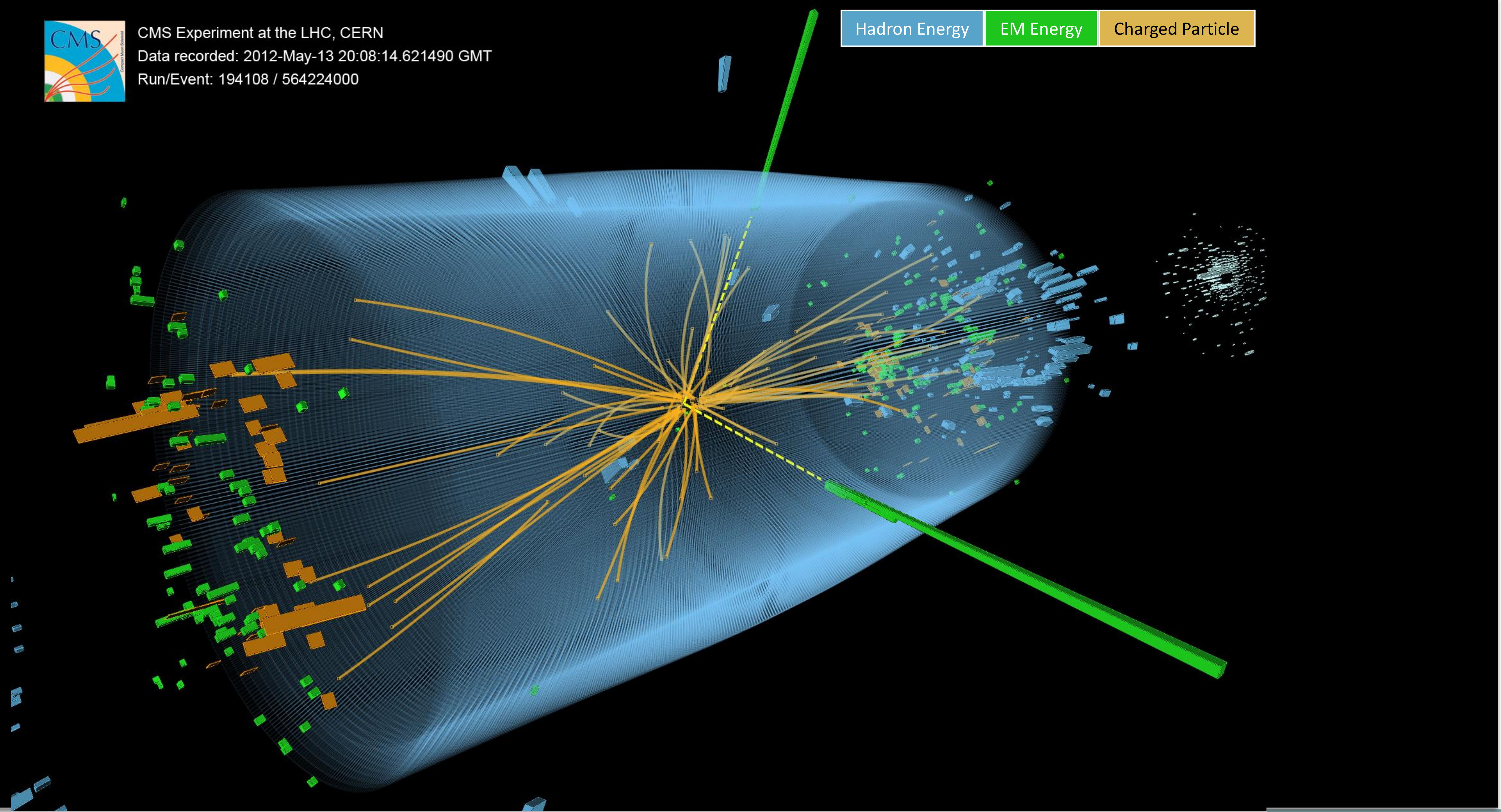


LHCb

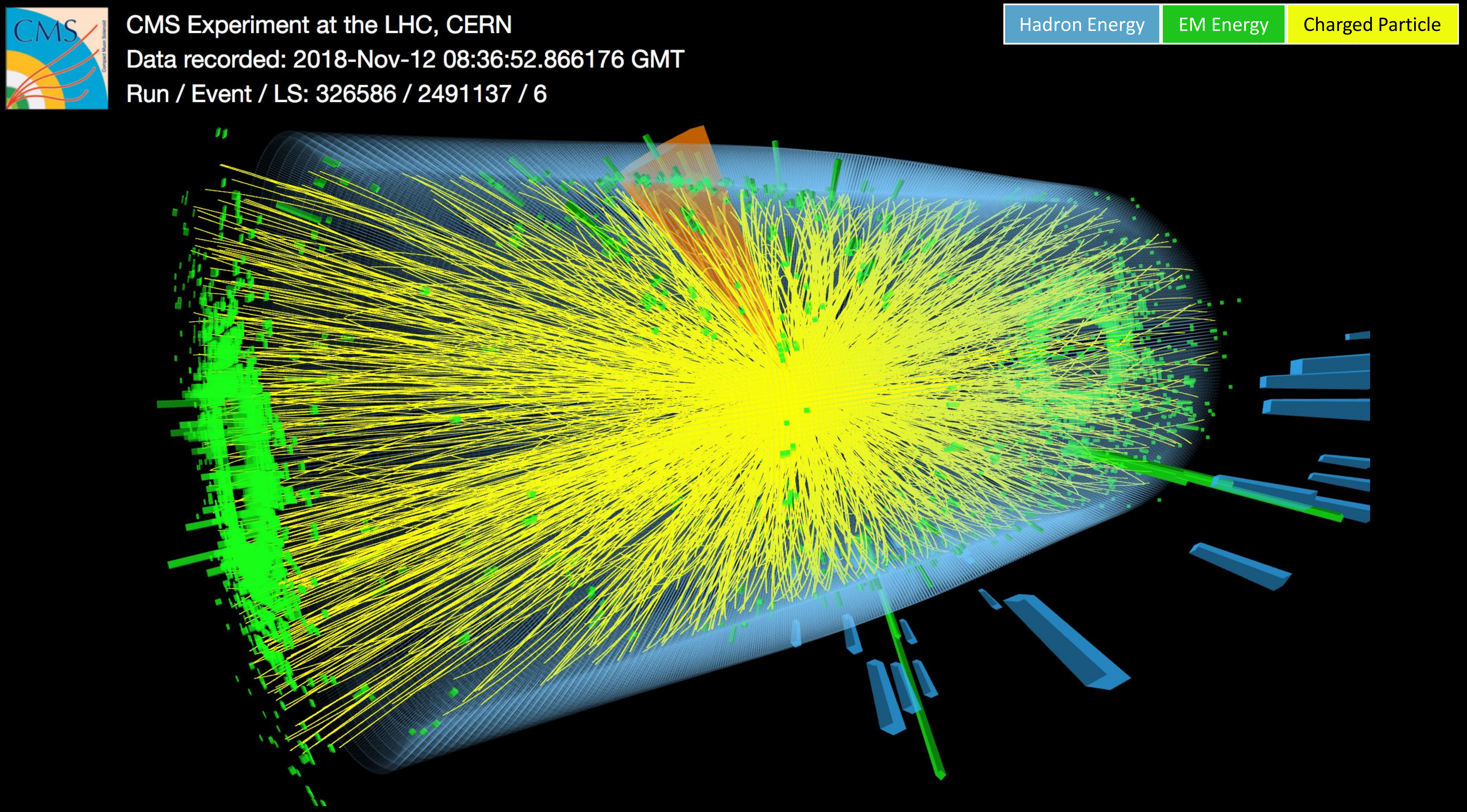
Also smaller system data:
Proton-lead (pPb) at 5.02 & 8.16 TeV
Xenon-Xenon (XeXe) at 5.44 TeV

A flying mosquito has about 4 trillion electronvolts **(4TeV)** of energy

Proton-Proton Collision Recorded by CMS

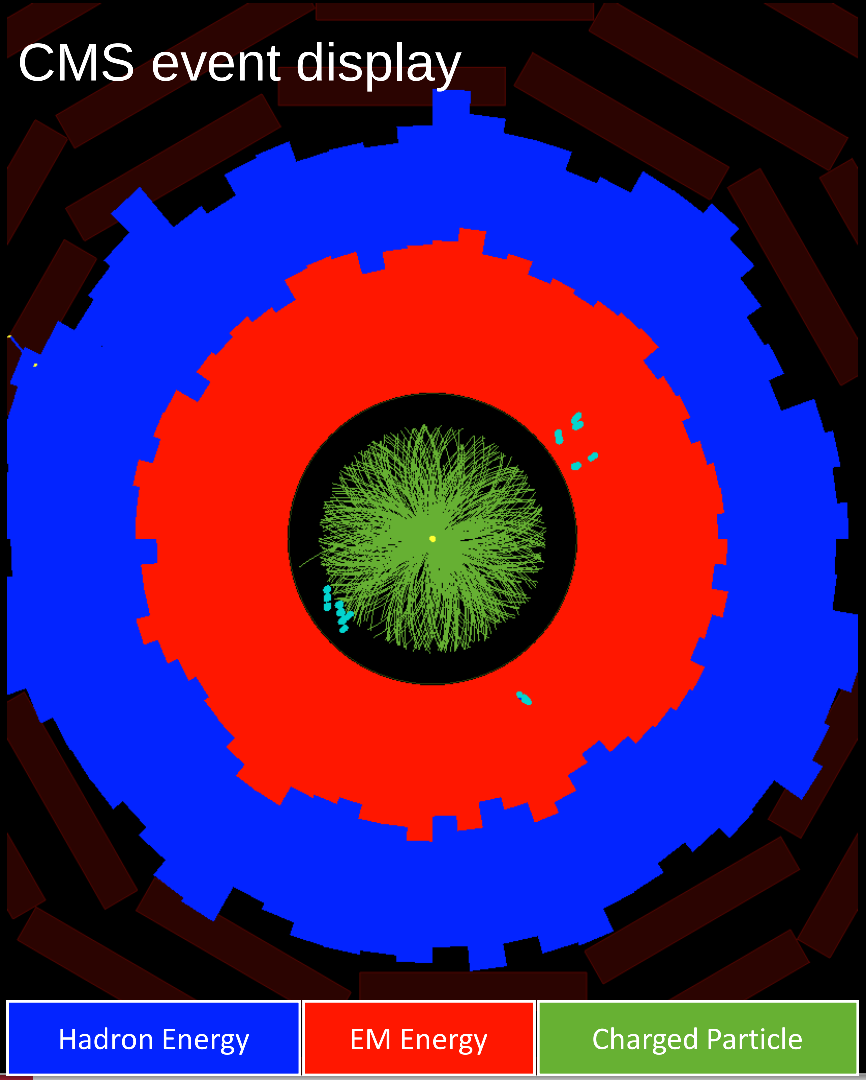


Lead-Lead Collision Recorded by CMS (2018)



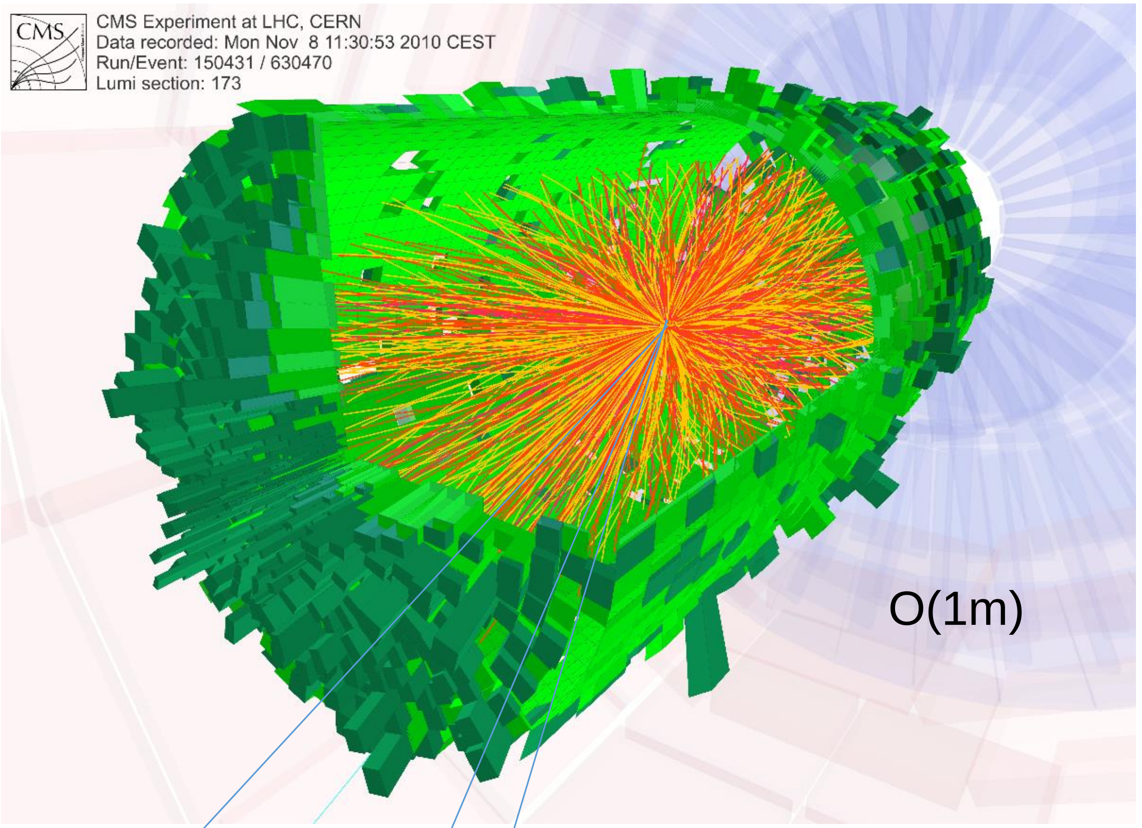
Data-Taking

- LHC delivers heavy ion collisions for around **one month per year**
- 2018: PbPb collision data rate up 50 kHz; CMS peak data throughput 9 GB/s
- We are actively preparing for the first data-taking in Run 3!

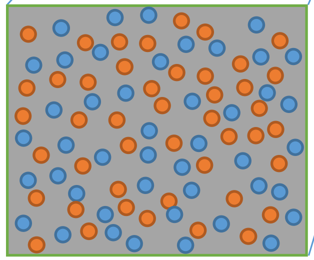


Reconstruct the Quark Soup with CMS

Size of the CMS detector



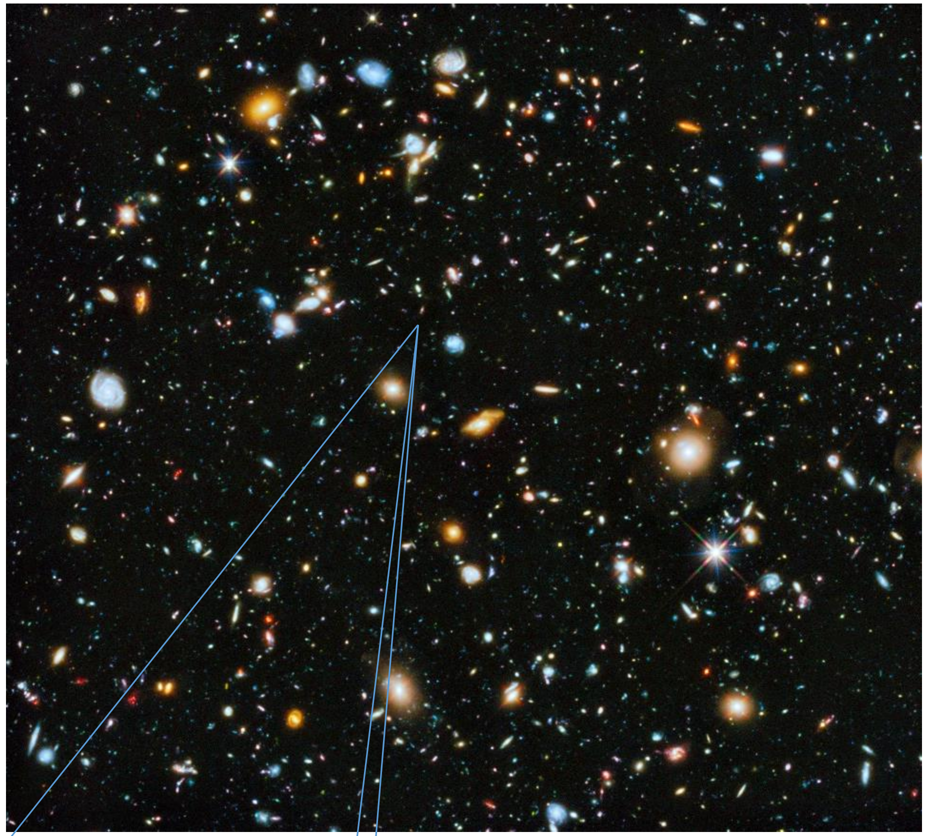
O(1m)



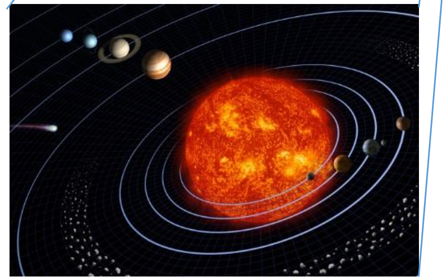
O(10^{-14} m)

Inner Structure of QGP

Size of the Universe



O(10^{27} m)

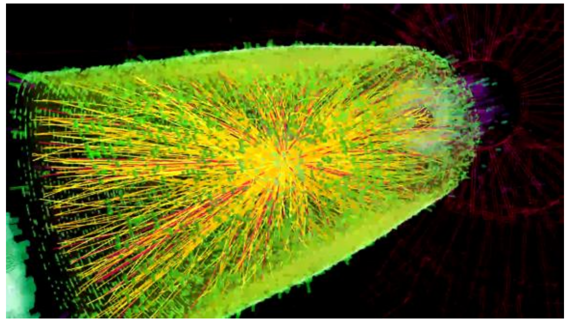


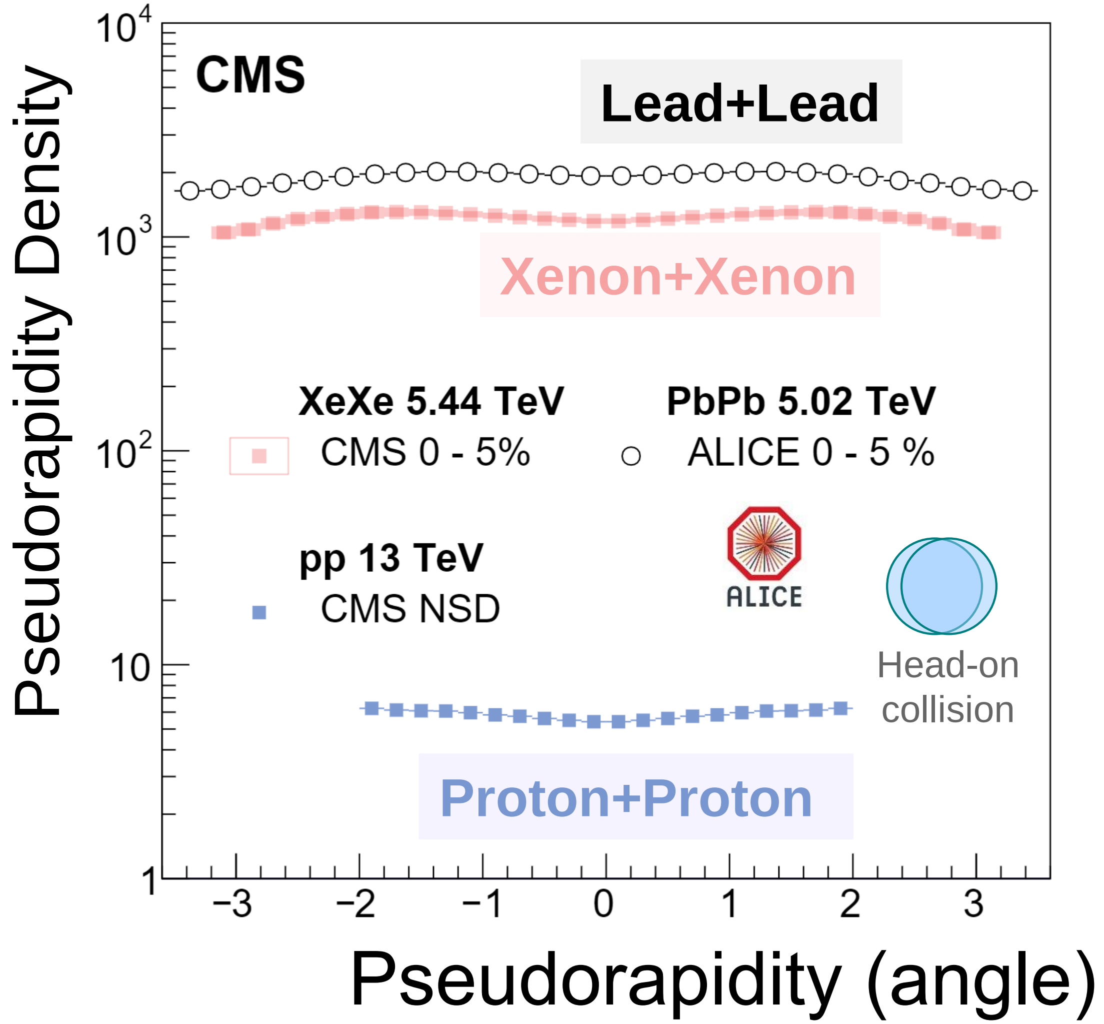
O(10^{13} m)

Inner Structure of Our Solar System

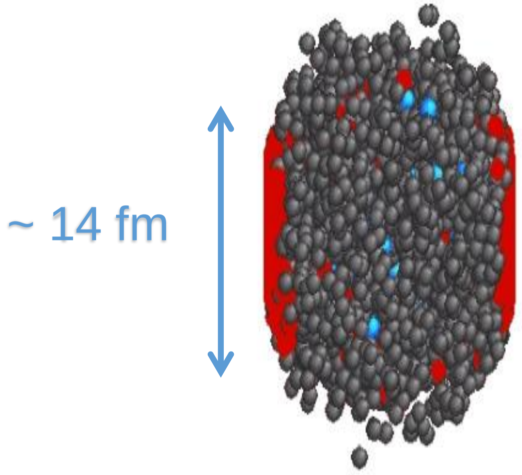
Density of the Quark Soup

Count the number of particles produced in **head-on** collisions.
Particle density in **Lead+Lead** ~ **400x** of that in **Proton+Proton**





At τ_0 ~ 0.2 fm/c:



$$\epsilon = \frac{1}{A \cdot \tau_0} \frac{dE_T}{dy}\bigg|_{y=0}$$

Energy density of the medium based on CMS dE/dη ~ 2 TeV: ~65 GeV/fm^3

> 100x denser than the proton!

At **early time** of the collision, the system can not be described by hadrons

Rough Estimation of QGP Temperature

At $\tau_0 \sim 0.2$ fm/c:

$$\epsilon = \frac{1}{A\cdot\tau_0}\frac{dE_T}{dy}\bigg|_{y=0} \approx 65\ \mathrm{GeV/fm^3}$$

$$\approx 0.5\ \mathrm{GeV^4} \quad = 47.5 \times \frac{\pi^2}{30}T^4$$

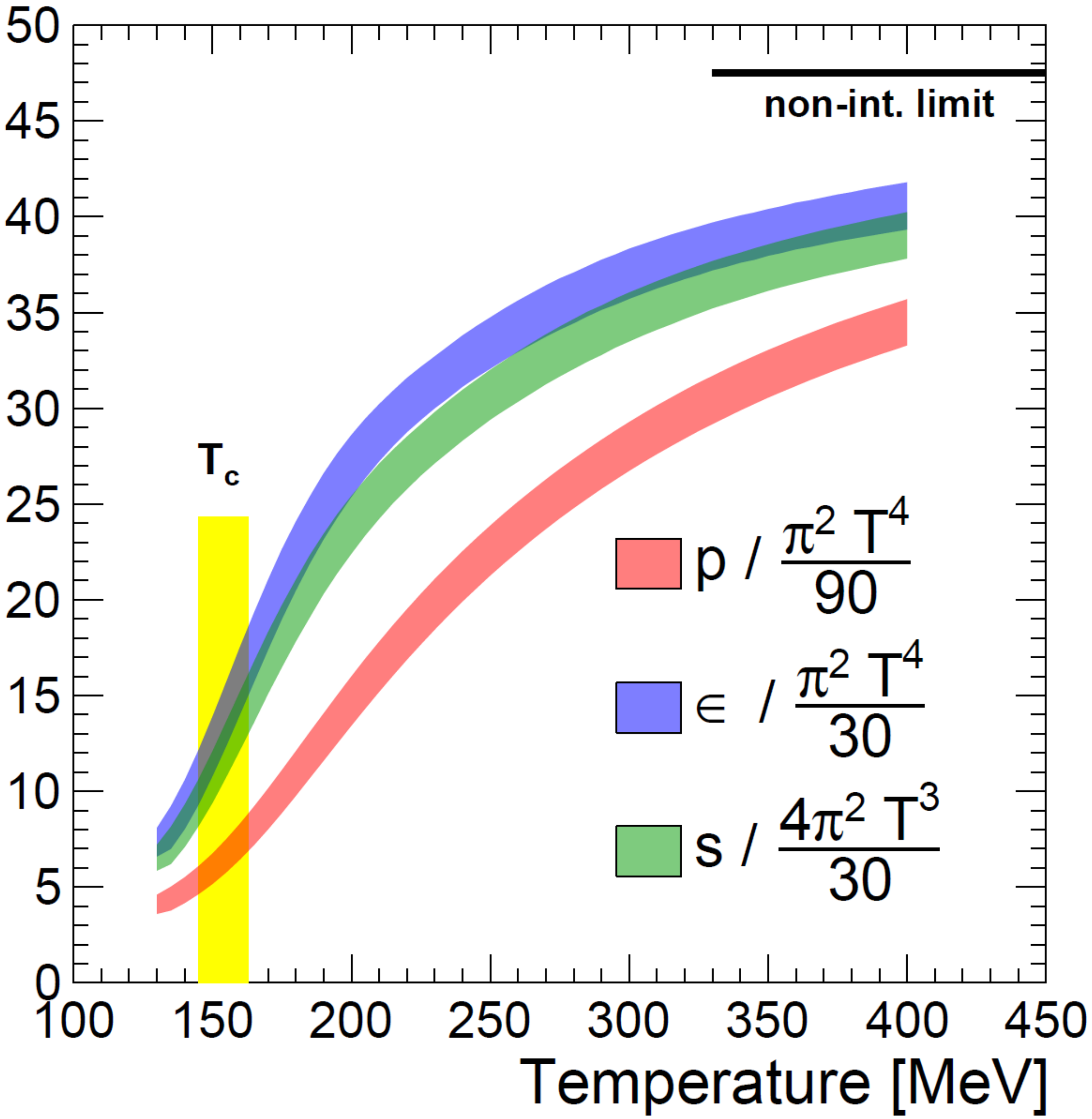
$$1\ \mathrm{fm^{-1}} = 0.1973\ \mathrm{GeV}$$

$$T \approx 0.423\ \mathrm{GeV} = 423\ \mathrm{MeV}$$

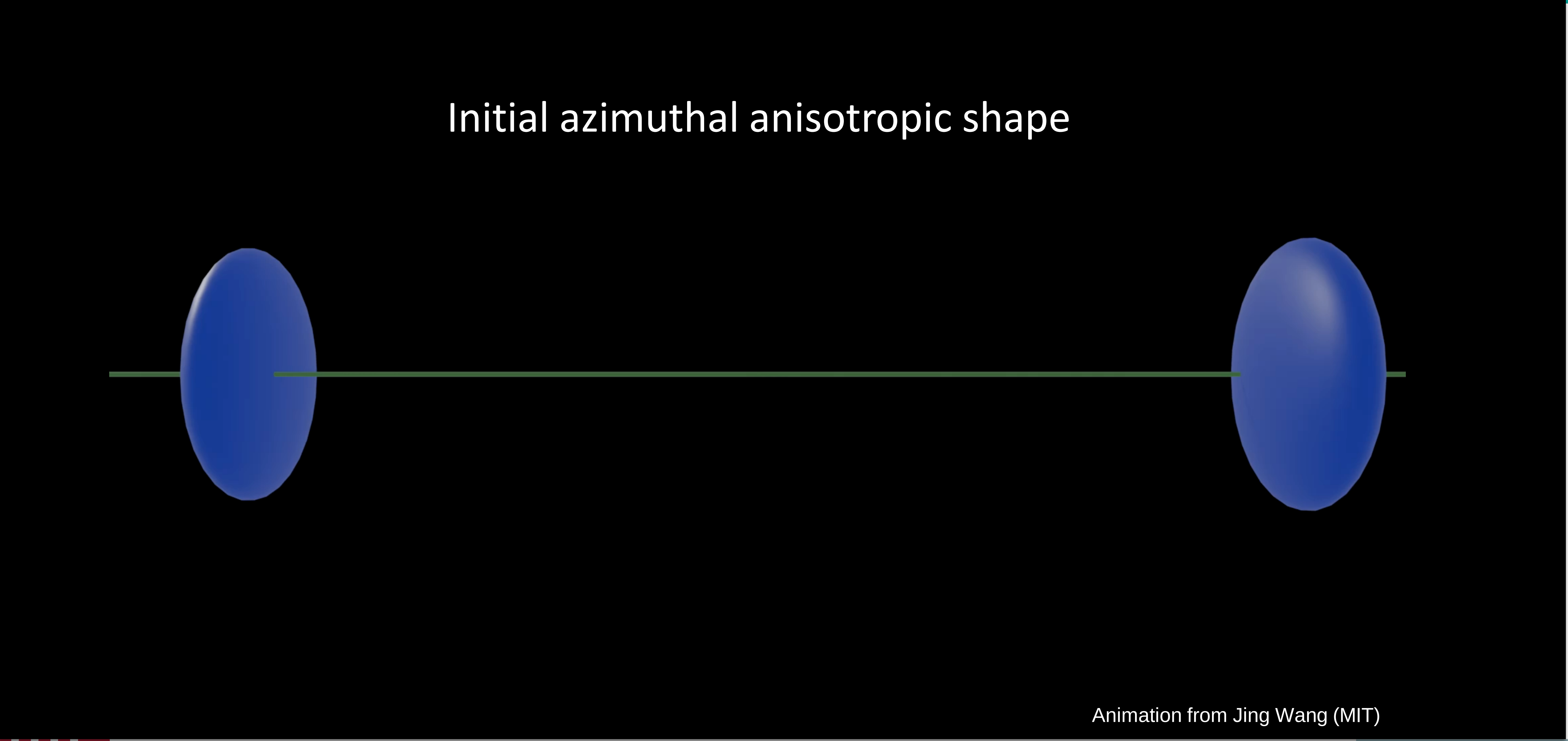
$$\approx 5\times 10^{12}\ \mathrm{K}$$

!!!

$$1\ \mathrm{GeV} = 1.16\times 10^{13}\ \mathrm{K}$$



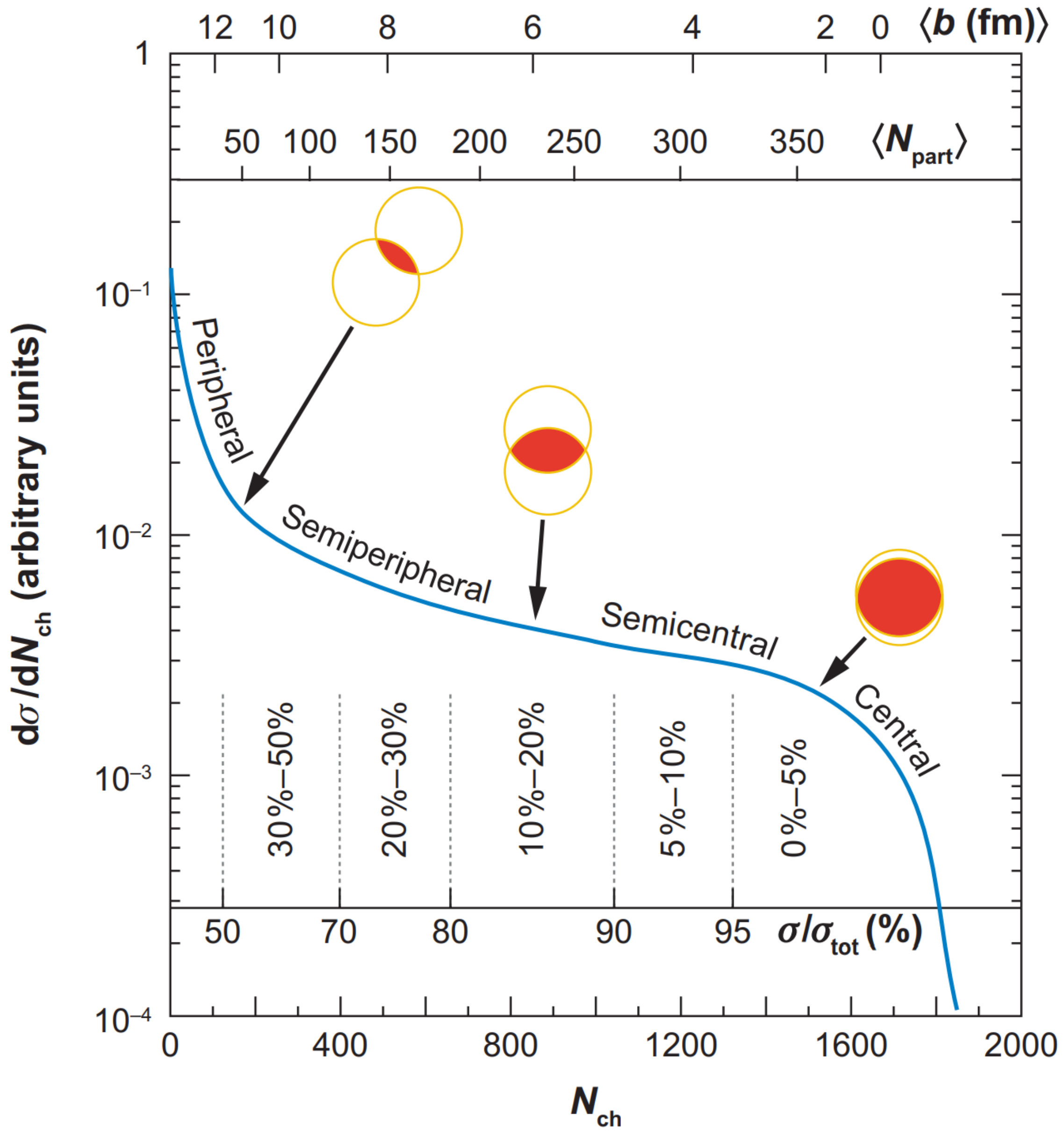
Collision with Finite Impact Parameter



Animation from Jing Wang (MIT)

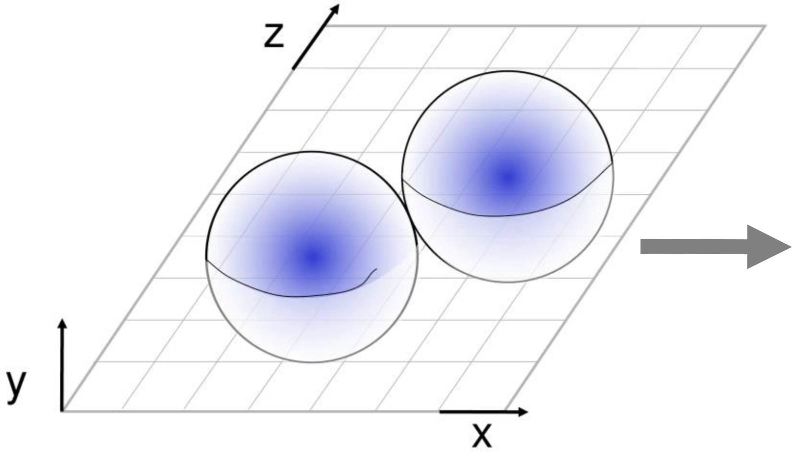
Centrality

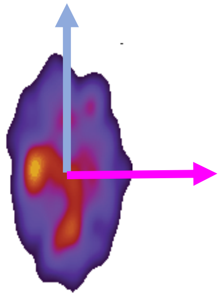
- Need experimental access to the impact parameter **b** of the collision
- Idea: use an observable which change **monotonically with b**, such as:
  - Forward calorimeter energy
  - Charged particle multiplicity (N_{ch}).
- Centrality classes: percentiles (fraction of total integral) of centrality distribution
- Convention:
  - 0% = "most central" (head-on!), b~0 (high N_{ch})
  - 100% = most peripheral (low N_{ch})

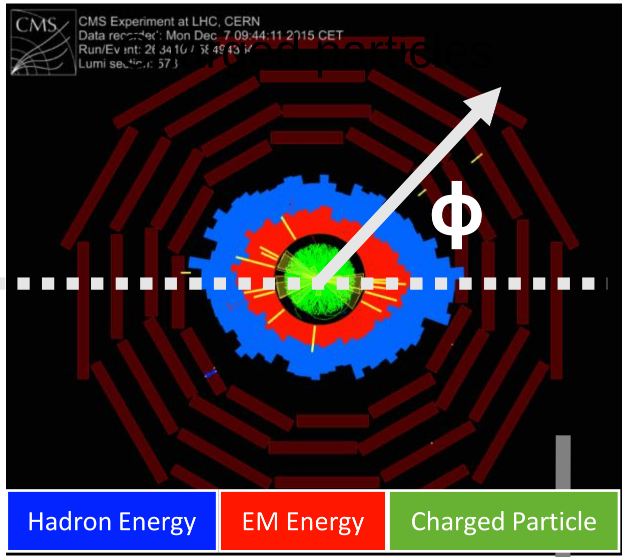


Annual Review of Nuclear and Particle Science, 57:205-243 (2007)

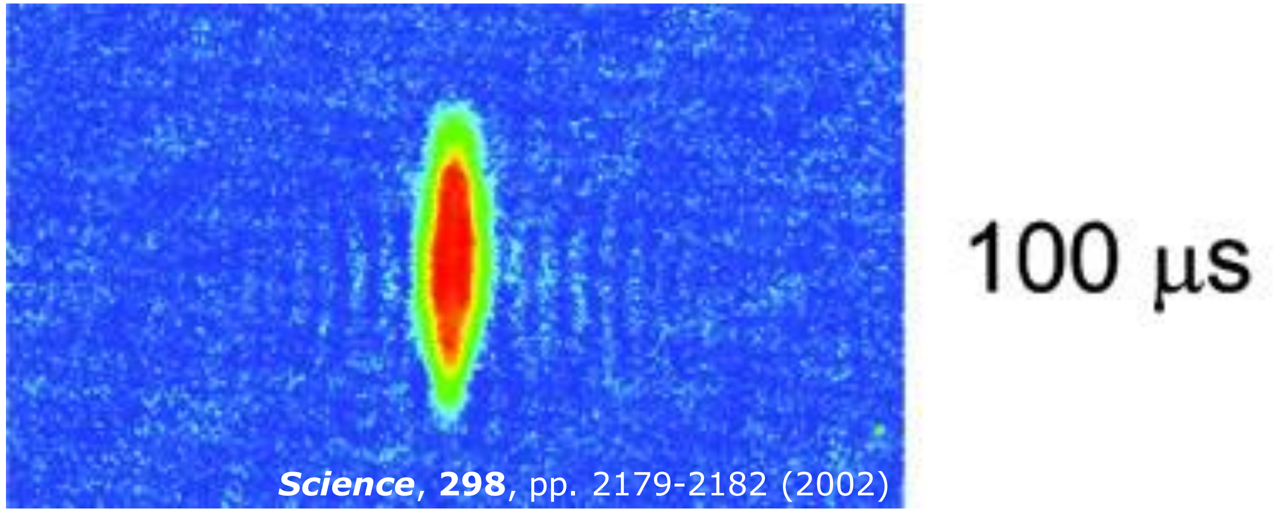
Pressure Driven Expansion of the Quark Soup



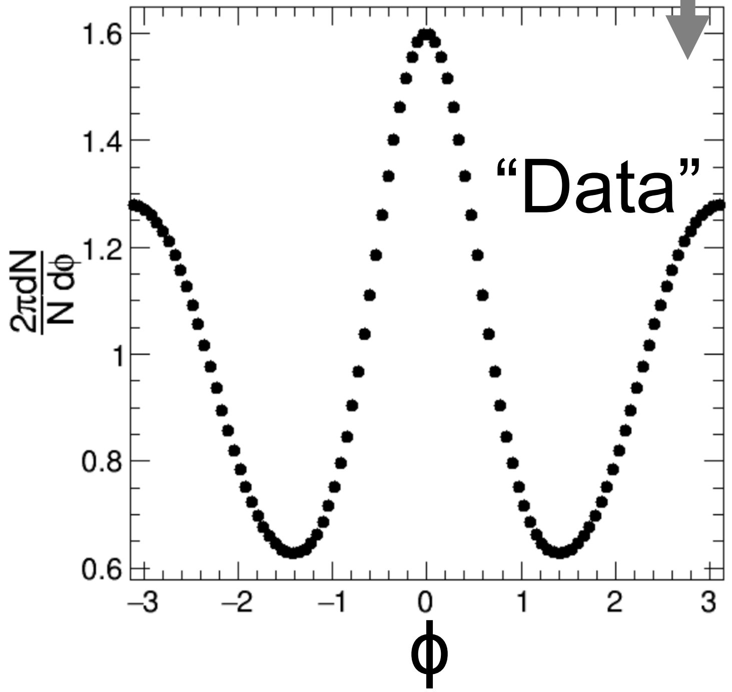




Expansion of **Ultra-cold atoms (Li-6)** released from laser trap



Science, **298**, pp. 2179-2182 (2002)

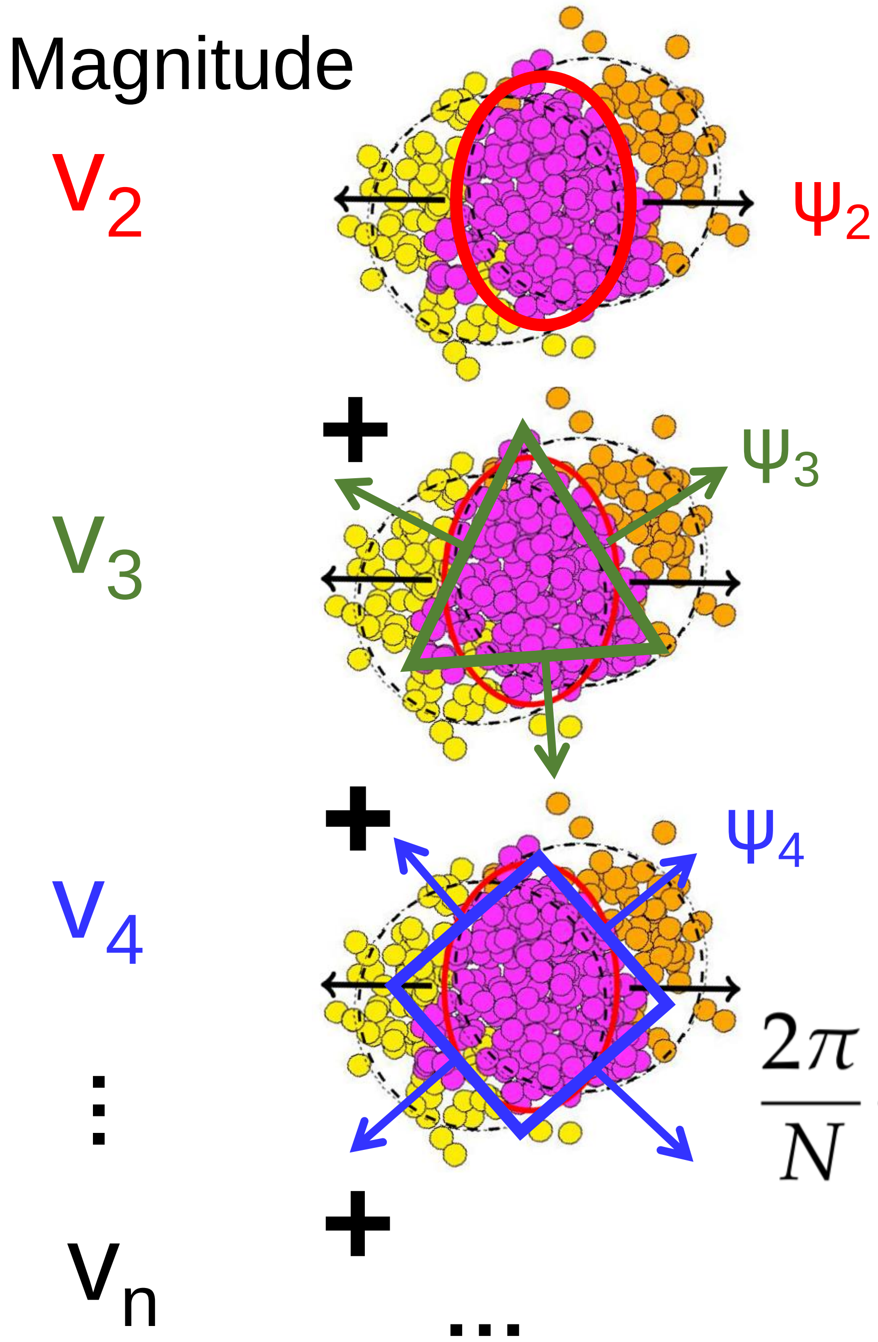


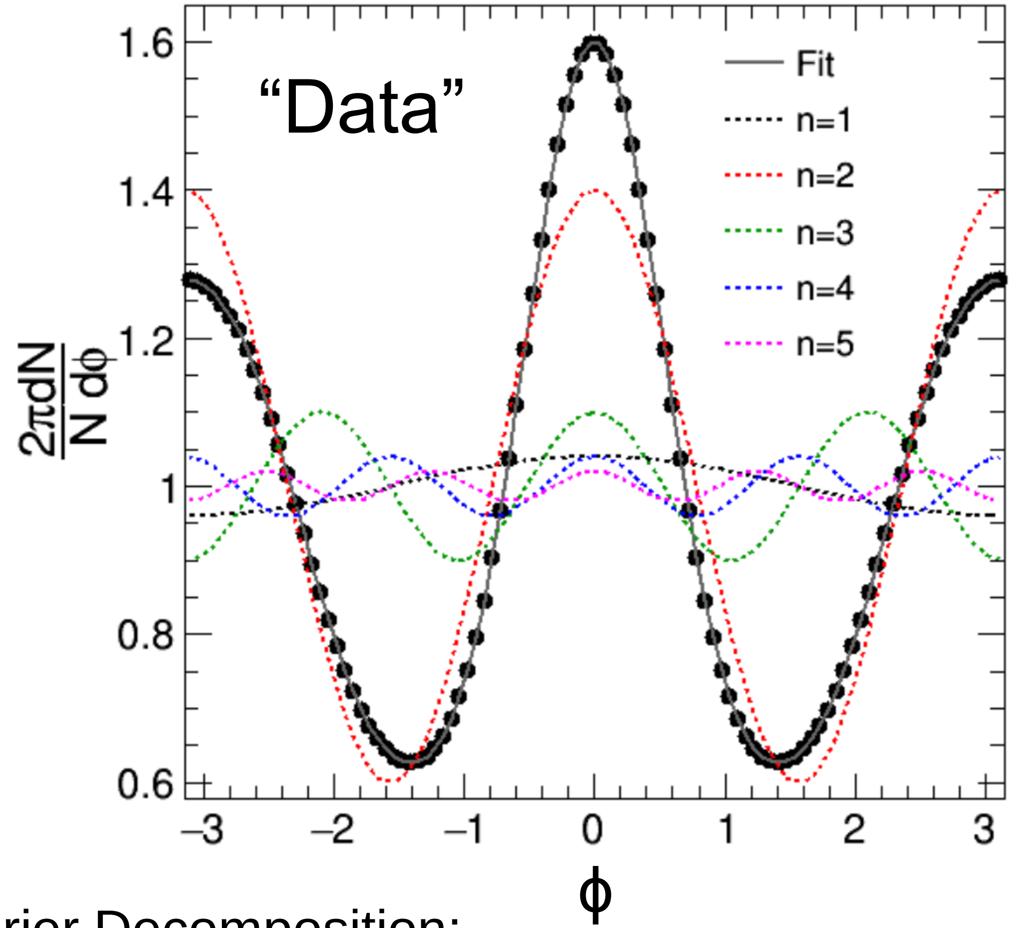
Collective motion is observed

→ **Early hydrodynamization!**

Particle Azimuth Angle Distribution

Particle Azimuthal Anisotropy



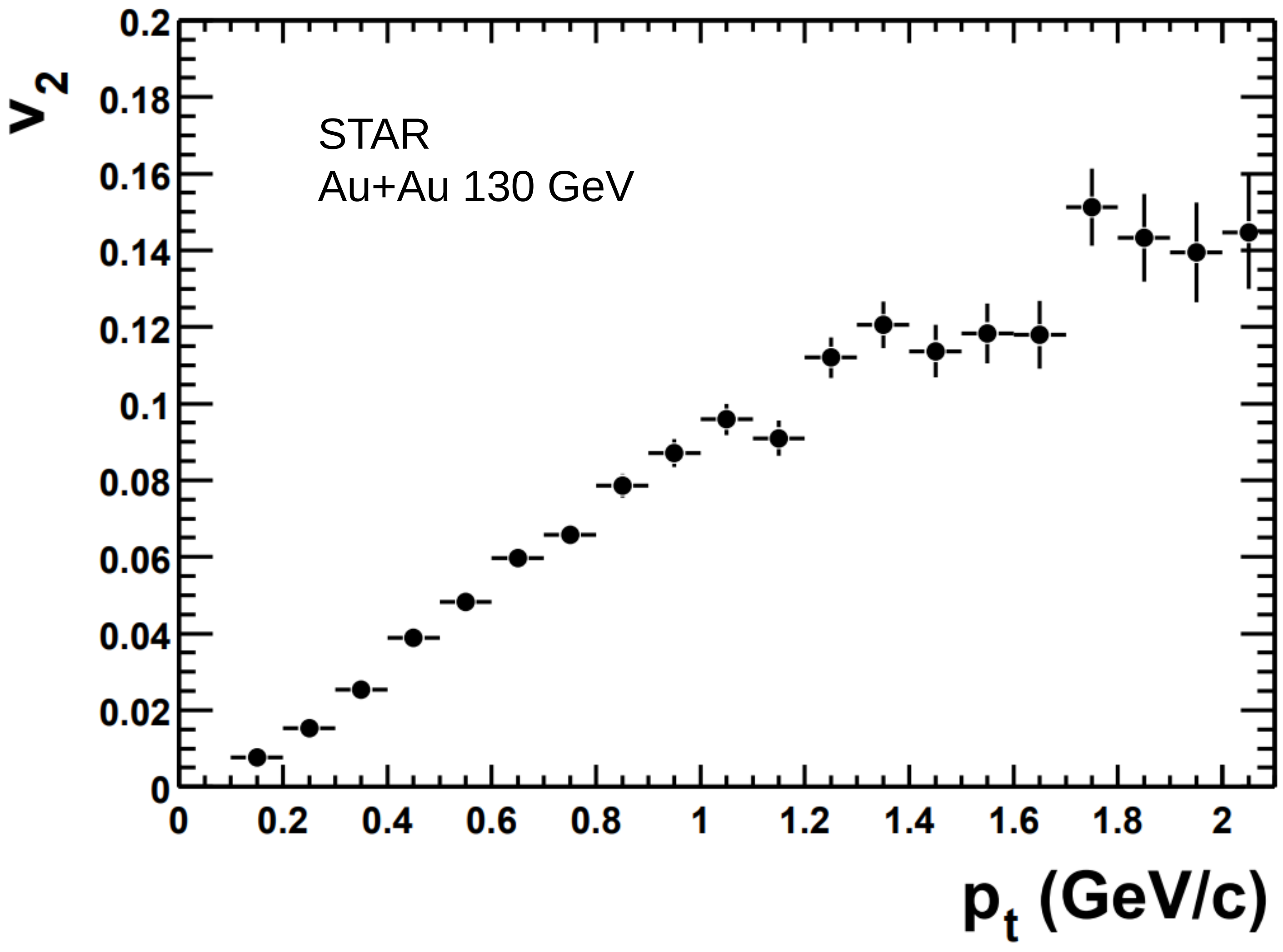


Fourier Decomposition:

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

Alver and Roland (MITHIG)
"Collision geometry fluctuation"
PRC82 (2010) 039903

Elliptic Flow

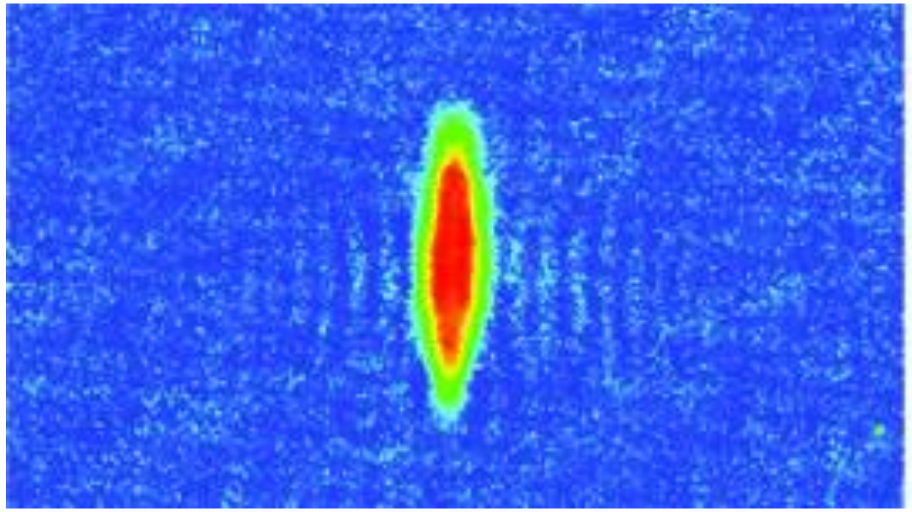


PRL 86 (2001) 402

- The first result from STAR at RHIC
- The extracted v_2 increases with transverse momentum

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

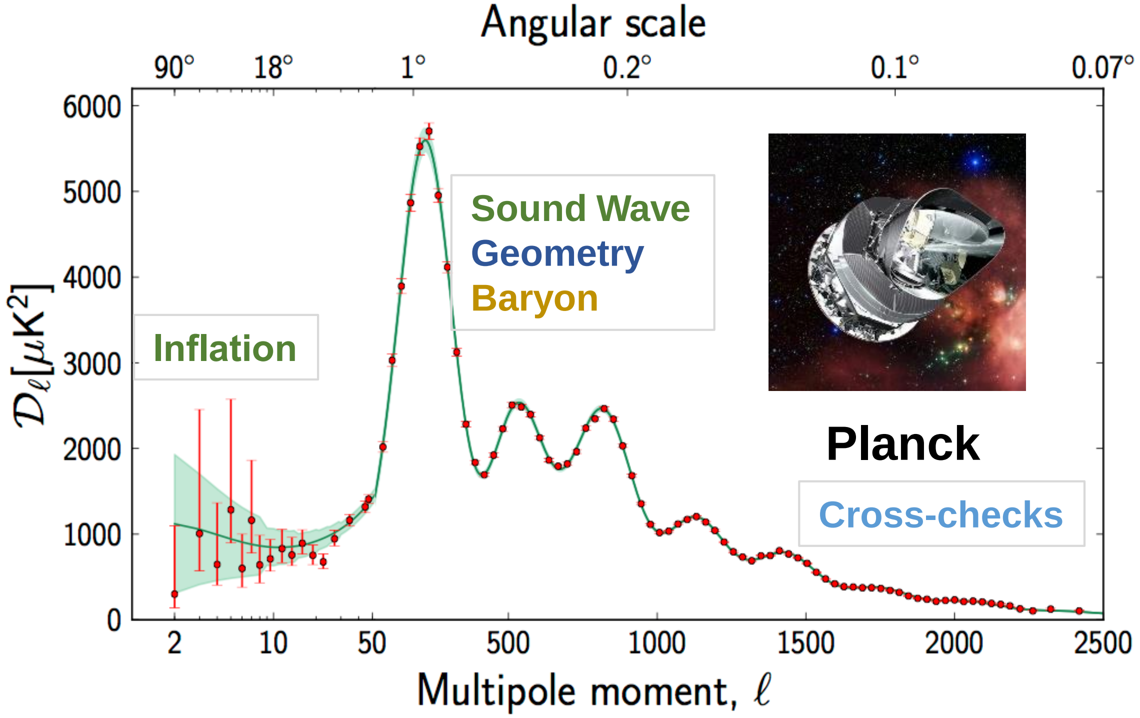
Expansion of **Ultra-cold atoms (Li-6)** released from laser trap



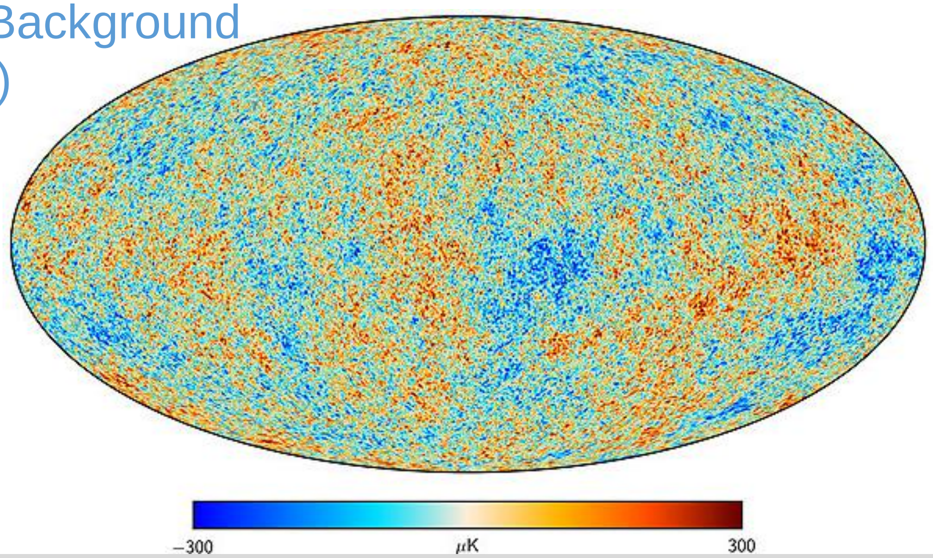
100 μs

Density Fluctuation

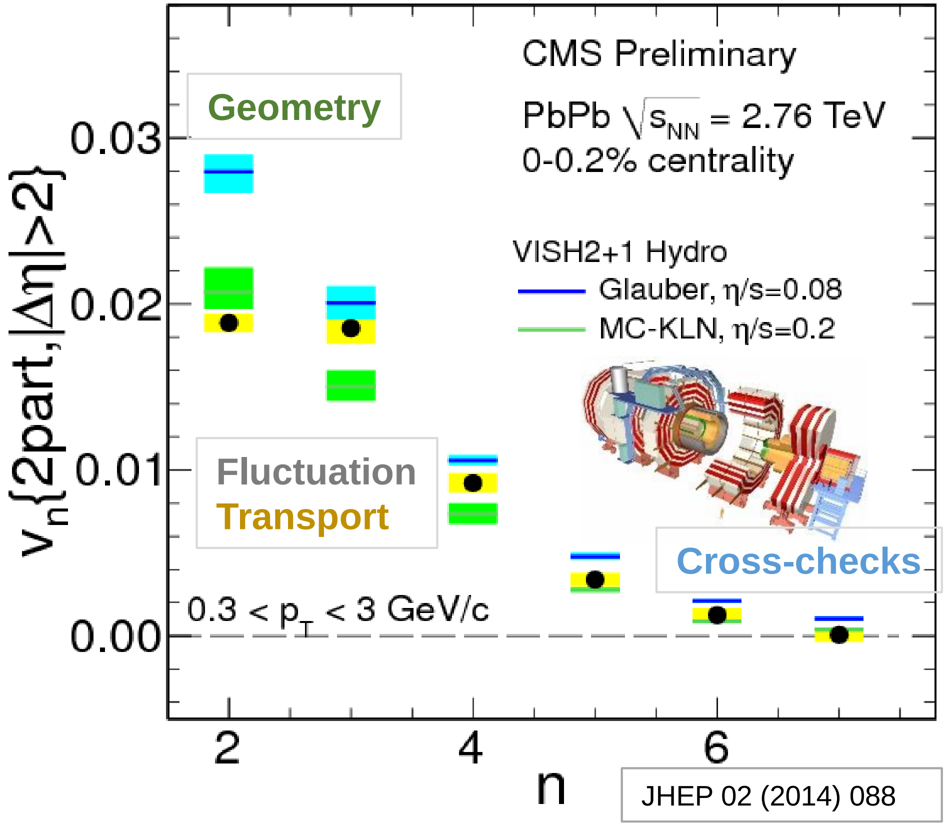
Power spectrum of **the Big Bang**



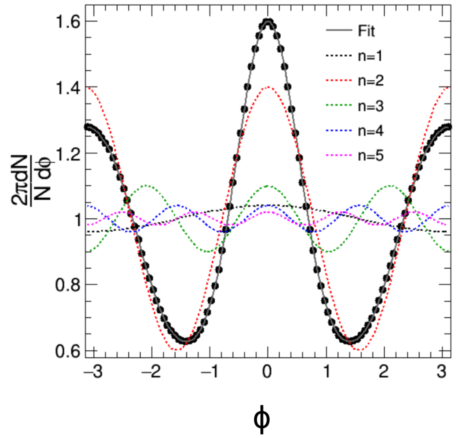
Cosmic Microwave Background (CMB)



Fourier analysis of **many little bangs**

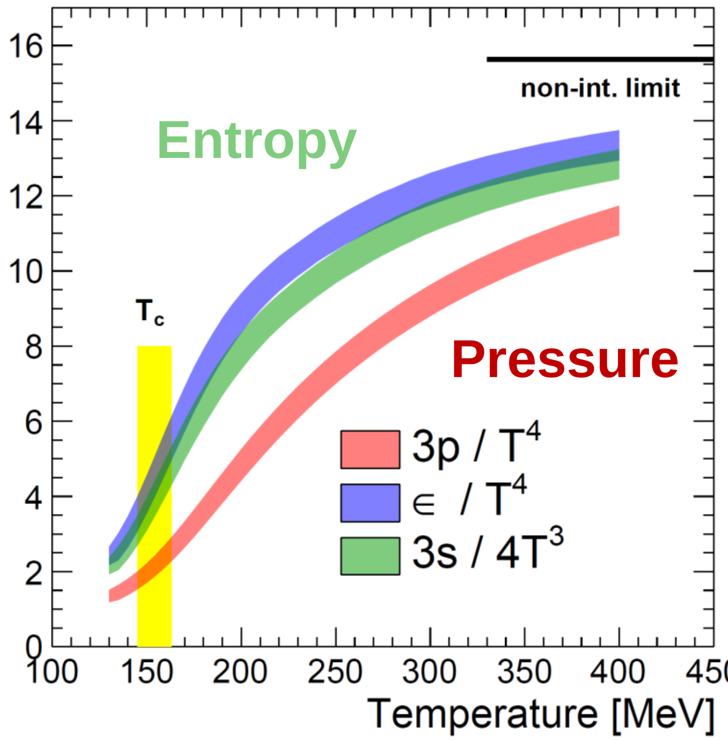


JHEP 02 (2014) 088

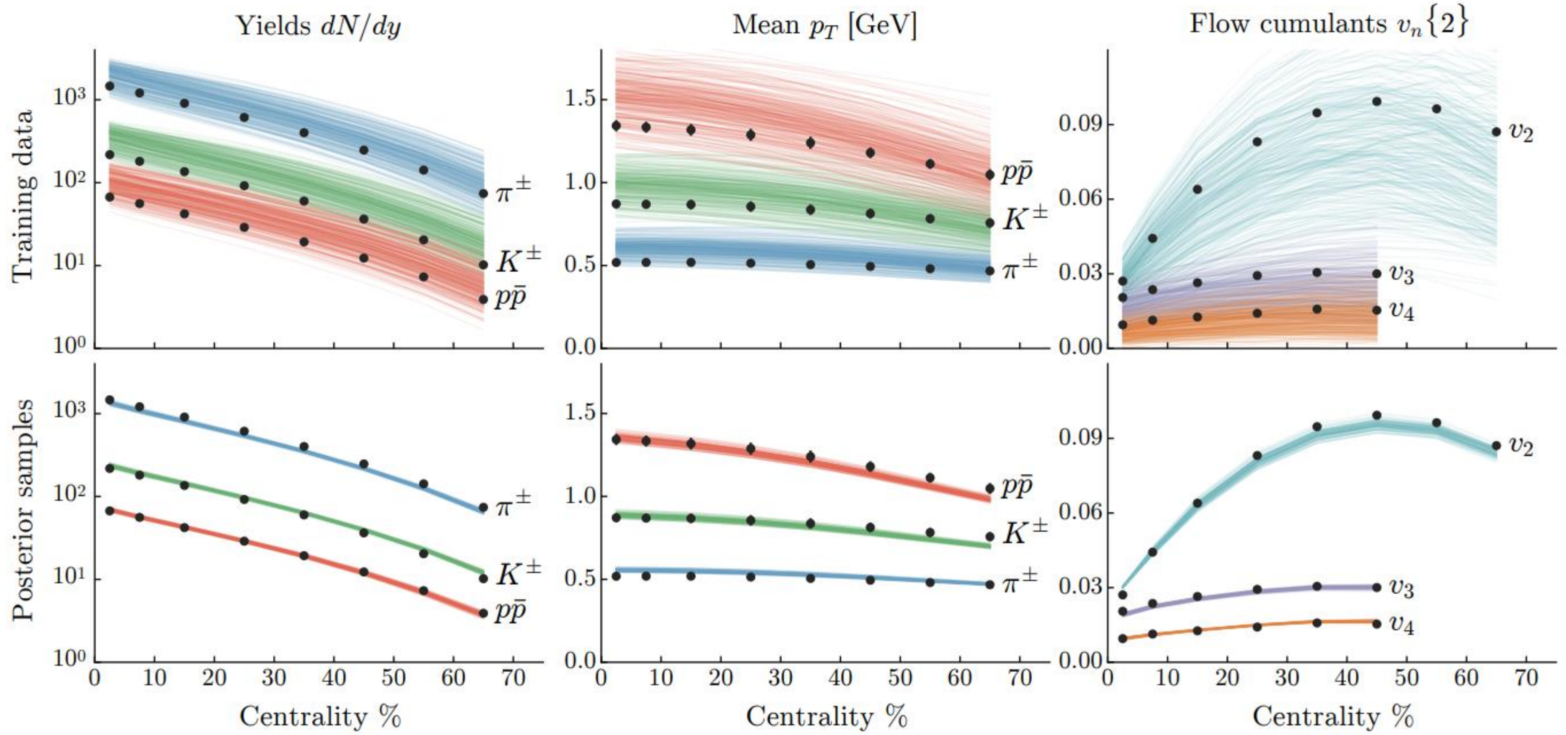


Quark Gluon Plasma (QGP)

Relativistic Hydrodynamics Calculations



HotQCD Collaboration
PRD90 (2014) 094503



Lattice QCD based
Equation of State

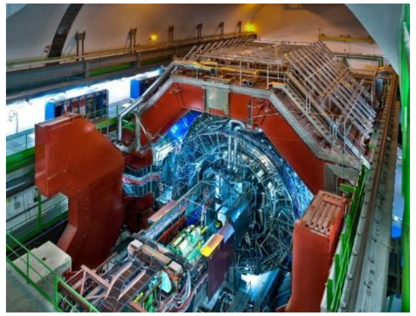
Output (from Global fit)
Medium Properties

$$T_{\mu\nu} = \varepsilon\, u_\mu u_\nu + p[\varepsilon]\Delta_{\mu\nu} - \eta[\varepsilon]\,\sigma_{\mu\nu} - \zeta[\varepsilon]\Delta_{\mu\nu}\nabla_\mu u^\mu + \mathcal{O}(\partial^2),$$

$$\sigma_{\mu\nu} = \Delta_{\mu\alpha}\Delta_{\nu\beta}(\nabla^\alpha u^\beta + \nabla^\beta u^\alpha) - \frac{2}{3}\Delta_{\mu\nu}\Delta_{\alpha\beta}\nabla^\alpha u^\beta,$$

$$\Delta_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu,$$

hydrodynamic evolution equations, $\nabla_\mu T^{\mu\nu} = 0$



ALICE

Example:
PRC 94 (2016) 2, 024907

Shear Viscosity

Viscosity η in the kinetic theory:[1] $$\eta = k\rho \langle p \rangle \lambda_f$$

p → momentum
ρ → the density of medium constituents (quarks and gluons)
σ → Cross-section
λ_f → mean free path $$\lambda_f = \frac{1}{\rho\sigma}$$

k → a constant ~ $\frac{1}{3}$ from kinetic theory calculation

Therefore, $$\eta = \frac{\langle p \rangle}{3\sigma}$$

→ **Large transport cross-section** leads to **small shear viscosity**

[1] F. Reif, Fundamentals of Statistical and Thermal Physics (McGraw-Hill, New York, 1965

Shear Viscosity to Entropy Ratio

The motivation of $\frac{\eta}{s}$: Normalize by system size

Relativistic Version of $F = ma$ results in $\frac{\eta}{\epsilon + P} \sim \frac{\text{force}}{mass}$

At zero chemical potential: $\epsilon + P = Ts$

Therefore $\frac{\eta}{\epsilon + P} = \frac{\eta}{s} \times \frac{1}{T}$

Where $\frac{\eta}{s}$ is a dimensionless number and $\frac{1}{T}$ is the natural thermal time

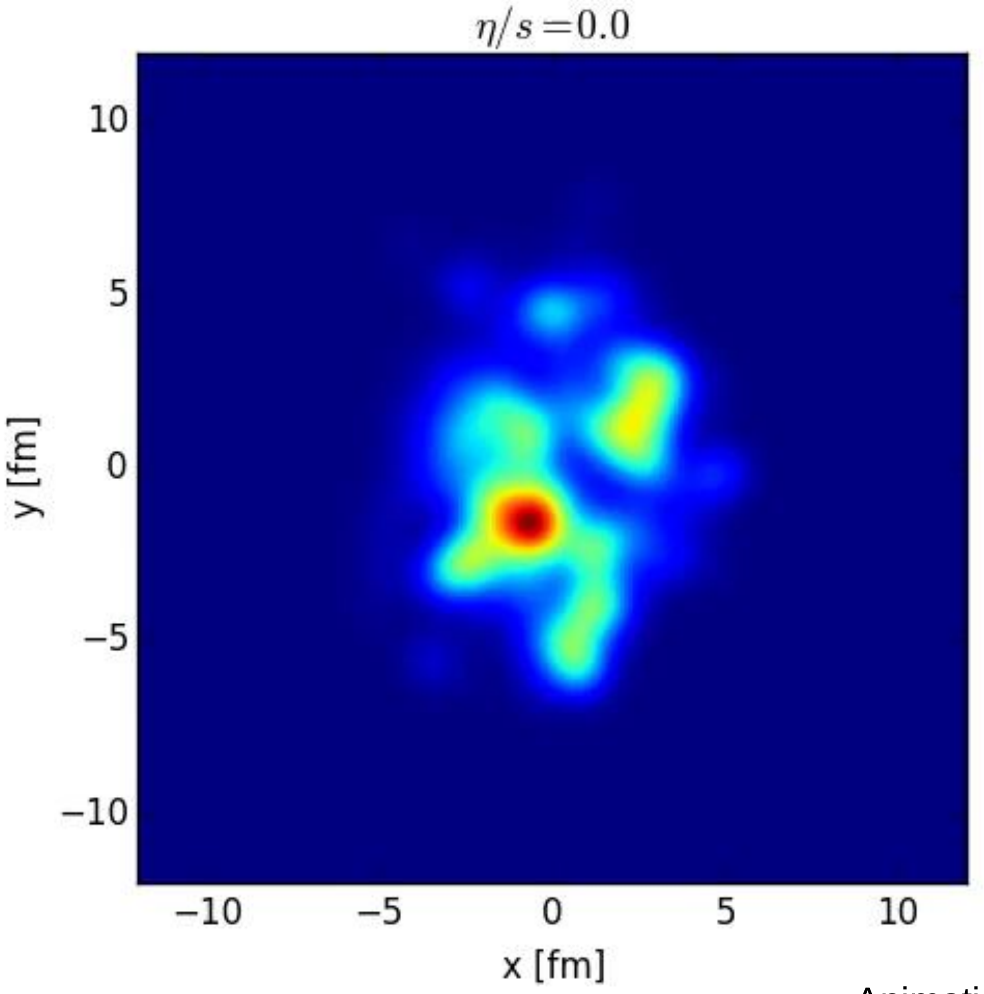
Small **specific shear viscosity** ~ very small force per inertial mass

Bill Zajc QM18'

Effect of Specific Shear Viscosity in Simulation

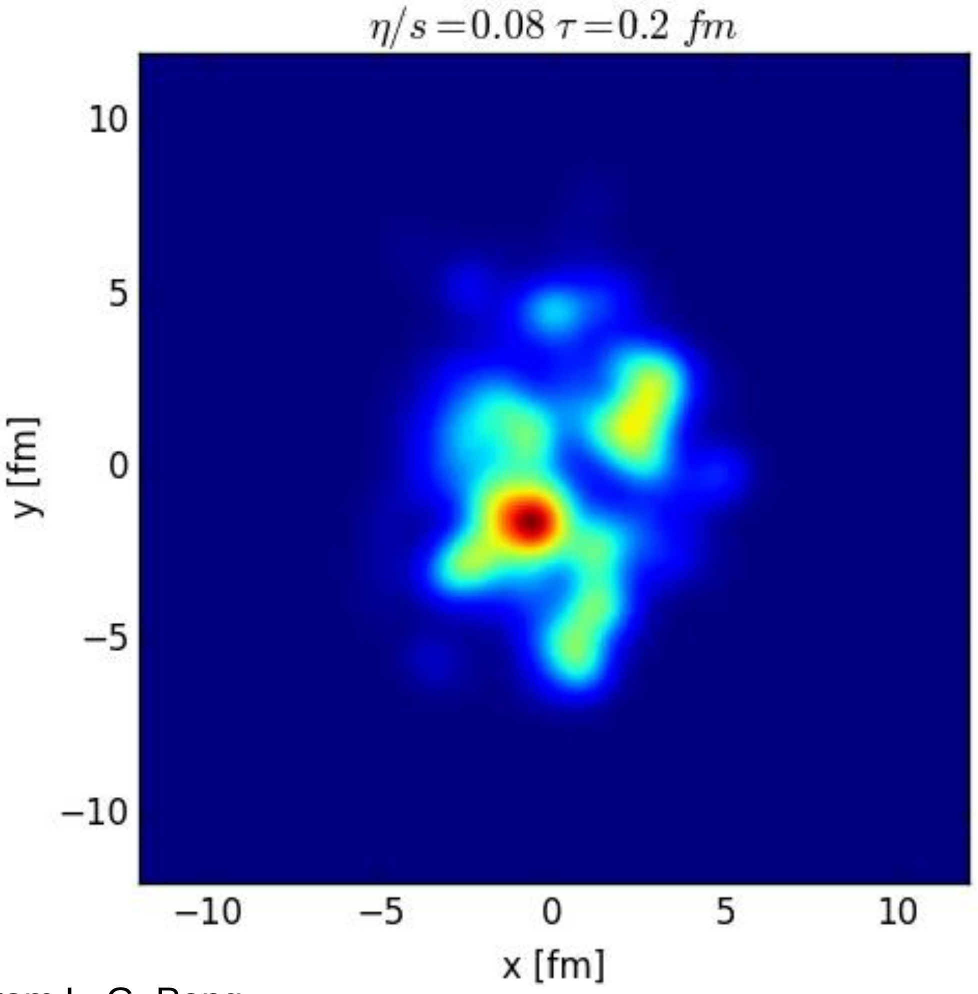
Ideal hydrodynamics

$\eta/s = 0$



Viscous hydrodynamics

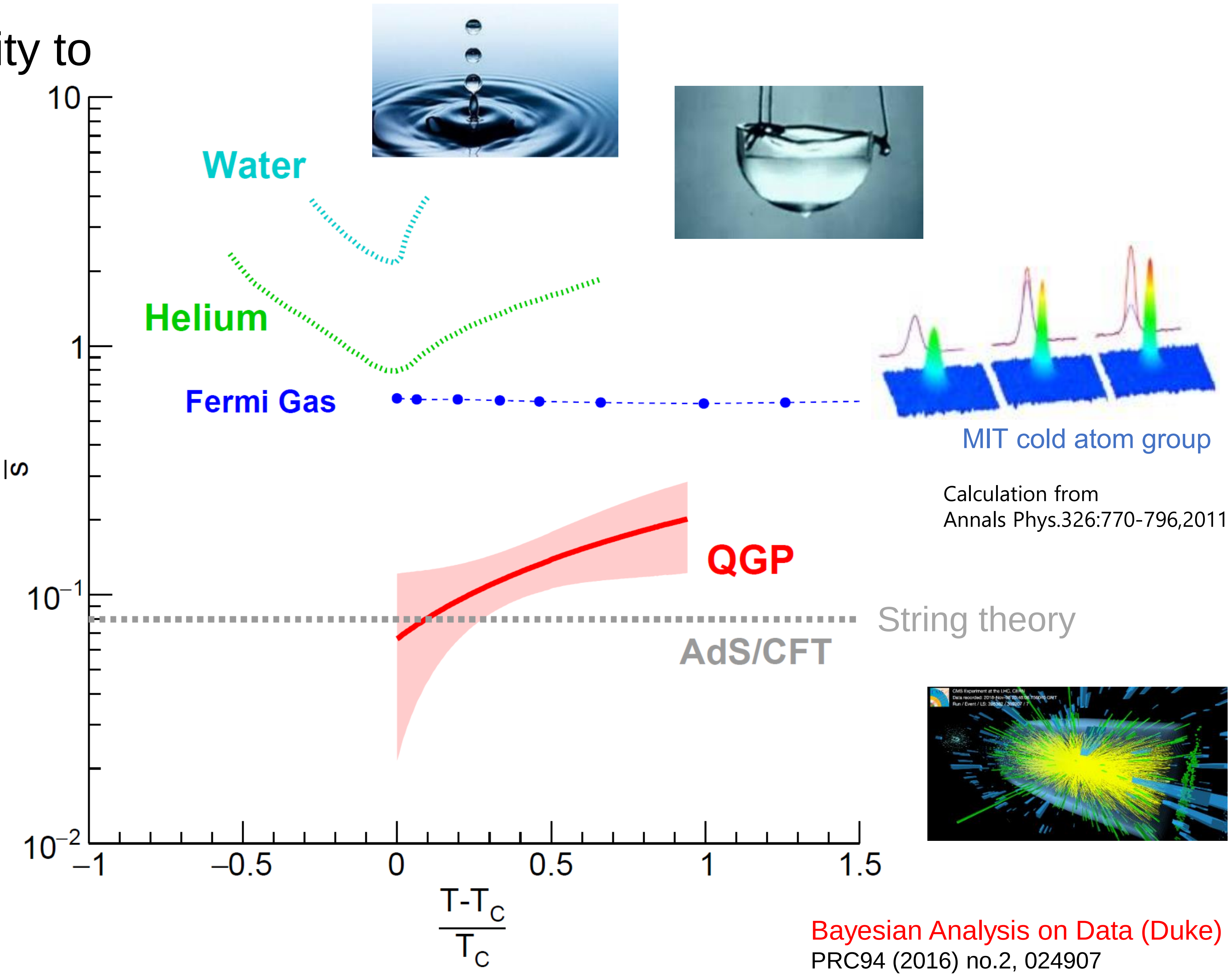
$\eta/s = 0.08$



Animation from L. G. Peng

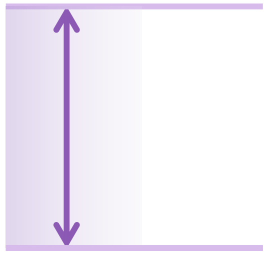
Near Perfect Fluid

Shear viscosity to entropy ratio



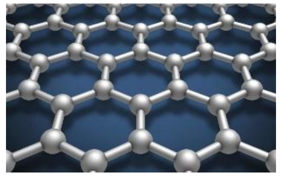
MIT cold atom group

Calculation from Annals Phys.326:770-796,2011



Electron fluid in Graphene

PRL103,025301 (2019)



Bayesian Analysis on Data (Duke)
PRC94 (2016) no.2, 024907

Shear Viscosity of the QGP

Shear viscosity of the QGP is very large

$$\eta \approx 0.1\hbar s \approx 10^{12}\ \mathrm{erg\ s/cm^3}$$
$$\approx 10^{14}\ \mathrm{centipoise}$$

Almost as large as the **glass (>10^{15} cp)**

However, due to the large QGP entropy **s,**
QGP specific viscosity η/s is very small

Table 8.4.1. *Viscosities η for some common materials in units of centipoise (10^{-2} erg s/cm^3).*

Substance	Temperature	Viscosity (cp)
Air	18°C	0.018
Water	0°C	1.8
Water	20°C	1
Water	100°C	0.28
Glycerin	20°C	1500
Mercury	20°C	1.6
n-Pentane	20°C	0.23
Argon	85K	0.28
He^4	4.2K	0.033
Superfluid He^4	< 2.1K	0
Glass		> 10^{15}

Note that, by popular convention, the designation "glass" is applied to any disordered material once its viscosity exceeds 10^{15}cp.

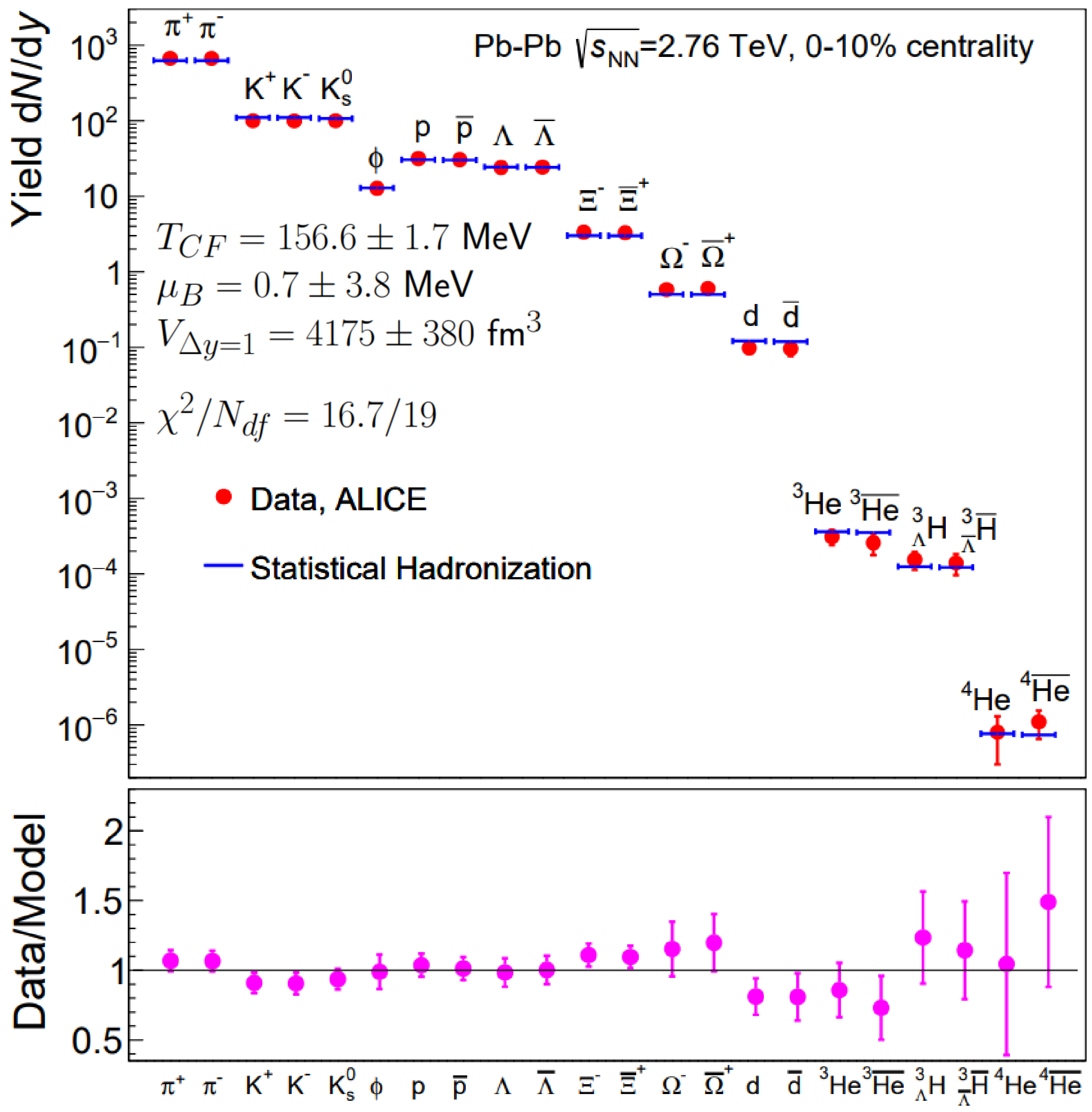
* Note that the physics picture of QGP is not like slow-moving Honey or stationary glass! The strong force acting on QGP is also way bigger (a dynamic system)

Statistical Hadronization

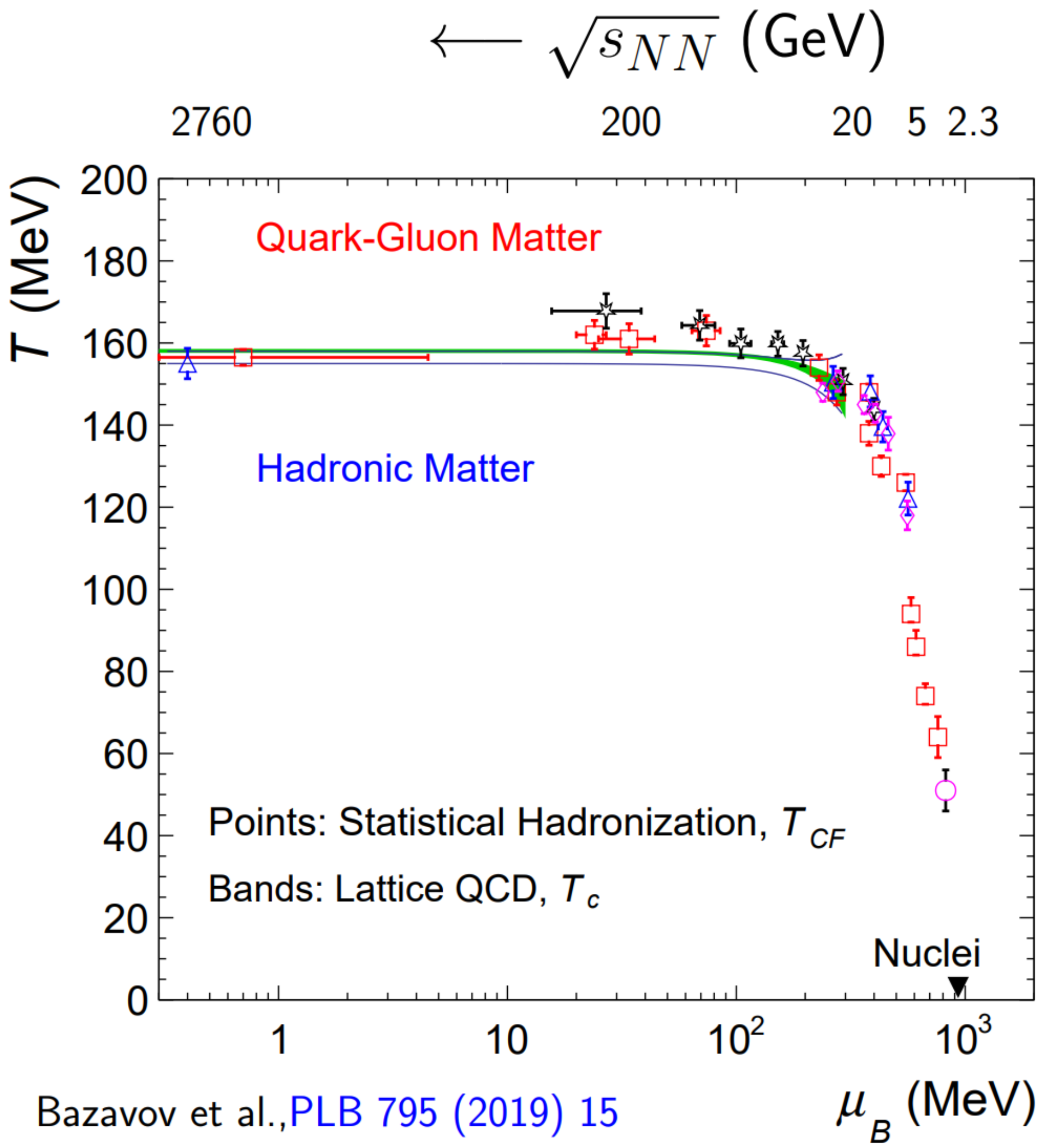
- Hadronization process: non-perturbative
- In **ee** and **pp**: string fragmentation, cluster
- Postulate: QGP cools into an equilibrated gas of hadrons
- Particle abundance produced in QGP could be described by calculation with partition function

$$n = \int N(E) d^3p \quad \text{and} \quad N(E) = \frac{D}{(2\pi)^3} \frac{1}{e^{\frac{E-\mu}{T}} \pm 1}$$

- Conserved quantum number, such as baryon number gives a chemical potential μ_B
- Temperature at the chemical freeze-out could be extracted



QGP Phase Diagram from Stat Hadronization Model



Bazavov et al.,PLB 795 (2019) 15
Borsanyi et al., PLB 370 (2014) 99

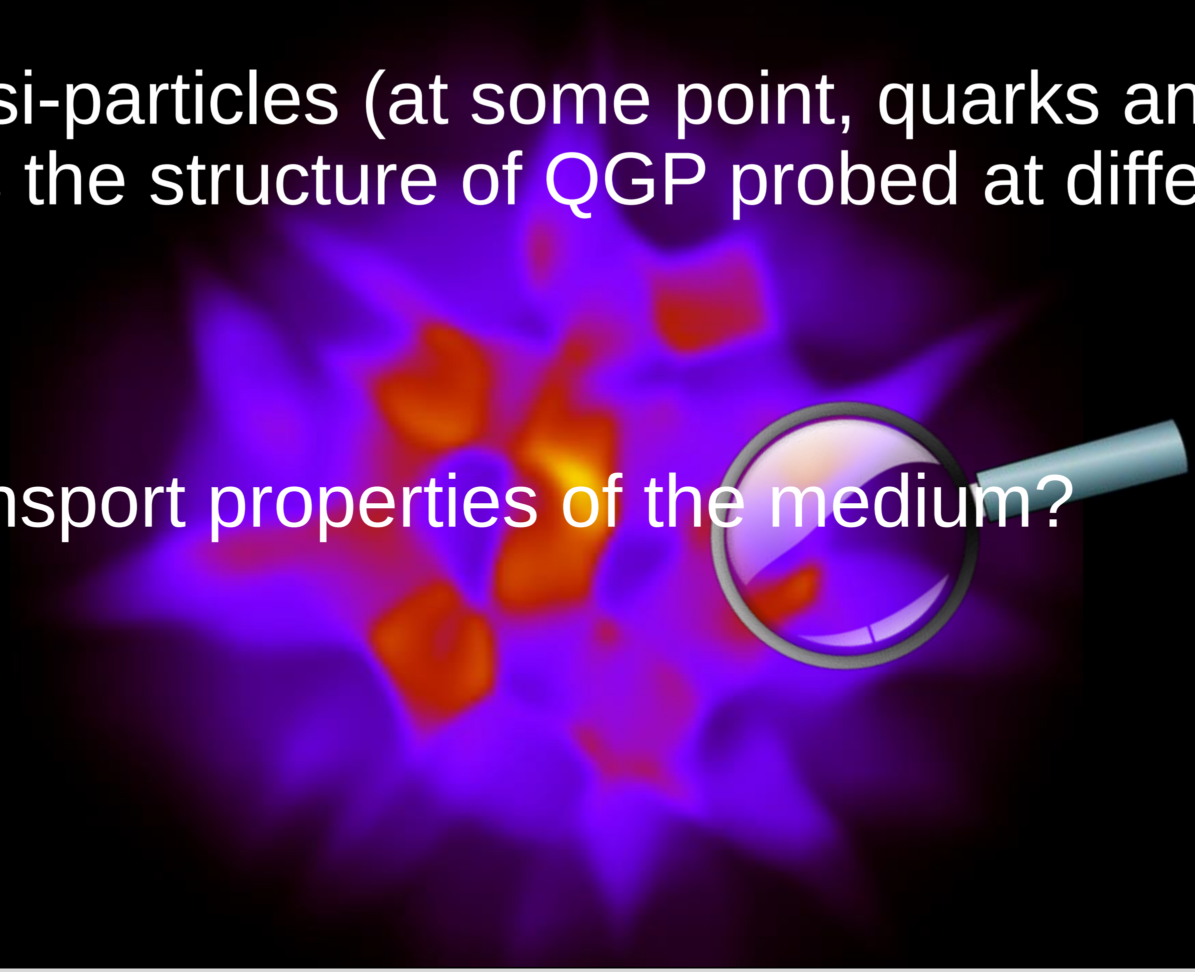
- Extracted result from LHC: remarkable coincidence with Lattice QCD results
- At LHC, baryon chemical potential μ_B~ 0: produced matter and anti-matter as in the Early Universe
- At lower collision energy: more matter from beam remnants of the colliding nuclei, larger μ_B
- Critical point still to be located (RHIC Beam Energy Scan, FAIR)

Unanswered Questions

- How does the strongly interacting medium emerge from an asymptotic free theory?

- Can we see quasi-particles (at some point, quarks and gluons) in the Quark-Gluon Plasma? What is the structure of QGP probed at different length scales?

- What are the transport properties of the medium?



Probe the Quark Soup!

- How does the strongly interacting medium emerge from an asymptotic free theory?

Start from "un-thermalized" objects and see how they are thermalized in the Quark Soup

- Can we see quasi-particles (at some point, quarks and gluons) in the Quark-Gluon Plasma? What is the structure of QGP probed at different length scales?

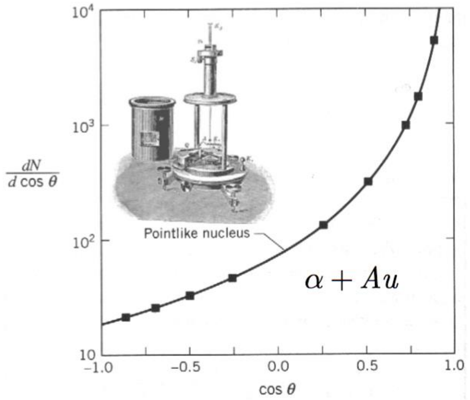
"QGP Rutherford Experiment"

- What are the transport properties of the medium?

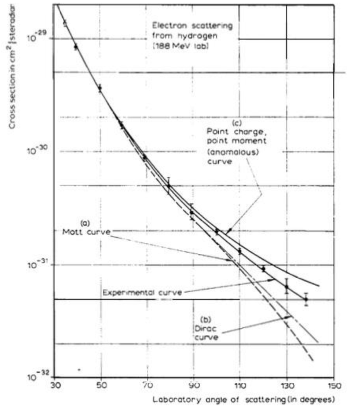
Study how Colored Probes are modified by QGP
Study how QGP respond to Colored Probes

Hard Probes

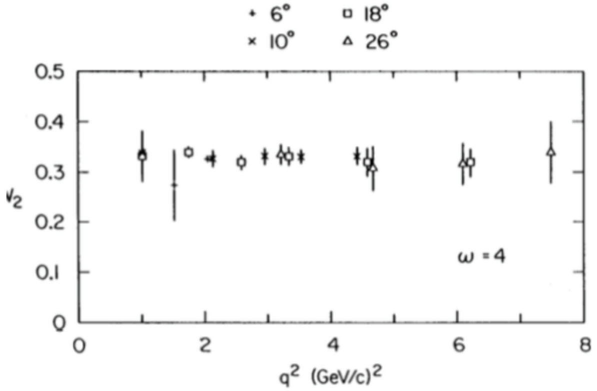
Atoms➔Nuclei



Nuclei➔Nucleons



Nucleons➔Quarks

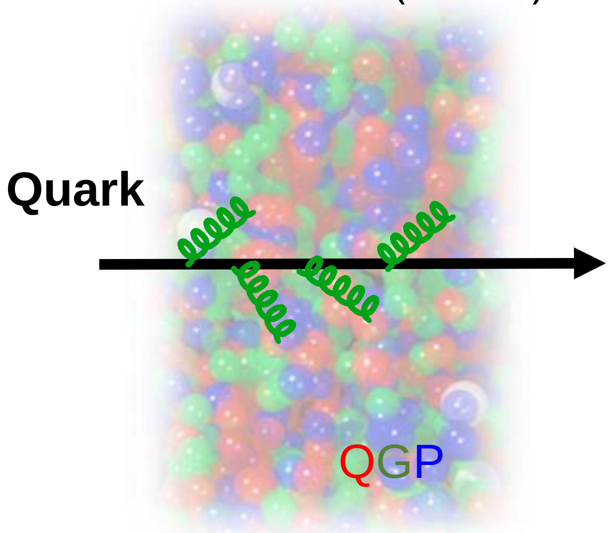


James Bjorken (1982)

FERMILAB-PUB-82-059-T

Jet Quenching

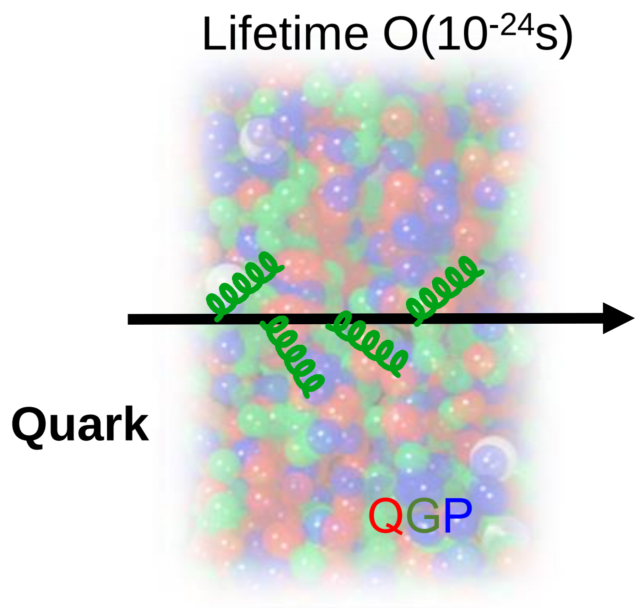
Lifetime O(10^{-24}s)



Use **Energetic Quarks** to reveal QGP structure at various length scales

The Advantage of Hard Probes

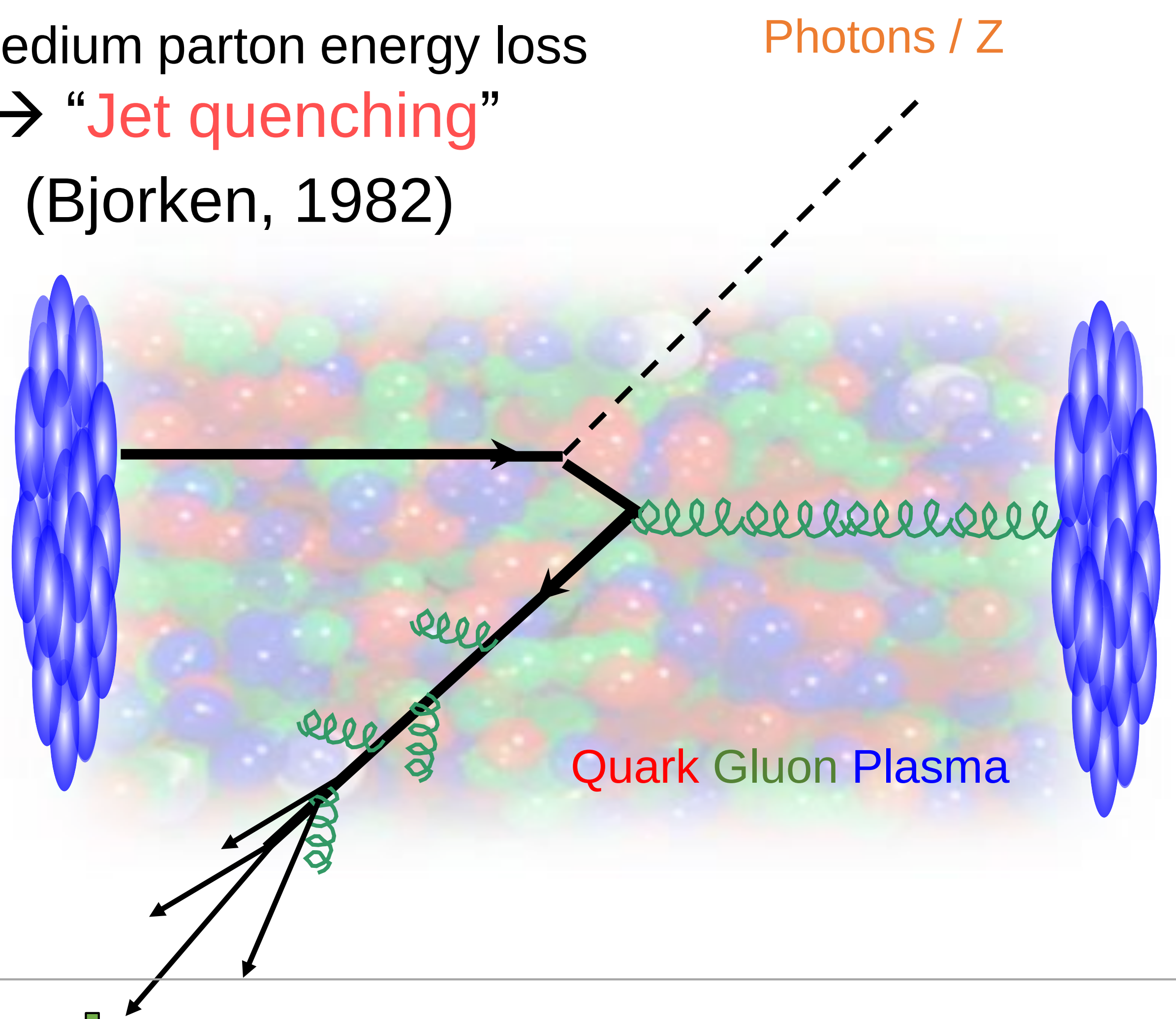
- Momentum scale is well above QCD scale Λ_{QCD} ~ 200 MeV
  - Described by perturbative methods (pQCD), calculations can be tested with pp scattering
- They are produced early: sensitive to full evolution of QGP
- Sensitive to short wave-length behavior of the medium
  - Transverse resolution of a radiated quanta: $\lambda \sim \frac{1}{Q} \ll 1\ \mathrm{fm}$
  - Example: Q=100 GeV → λ=0.05 fm



- Long relaxation time: “memory” of their initial conditions at production

Colorless and Colored Hard Probes

In medium parton energy loss
→ "Jet quenching"
(Bjorken, 1982)



Colorless Probes
Photons, electroweak bosons
Validation
Tag the initial state

Transport coefficient $\hat{q}$, stopping power dE/dx, gluon density $\frac{dN_g}{dy}$, temperature T…

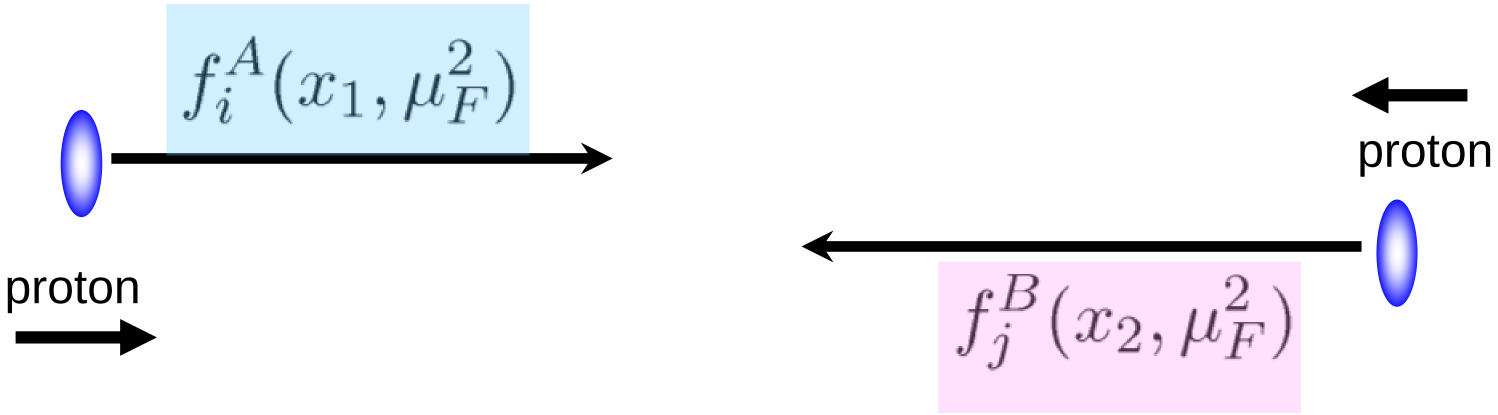
Colored Probes:
Fast-moving high energy quarks and gluons,
Heavy quarks
Studies of the medium properties

Factorization

Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1, \mu_F^2) \otimes f_j^B(x_2, \mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

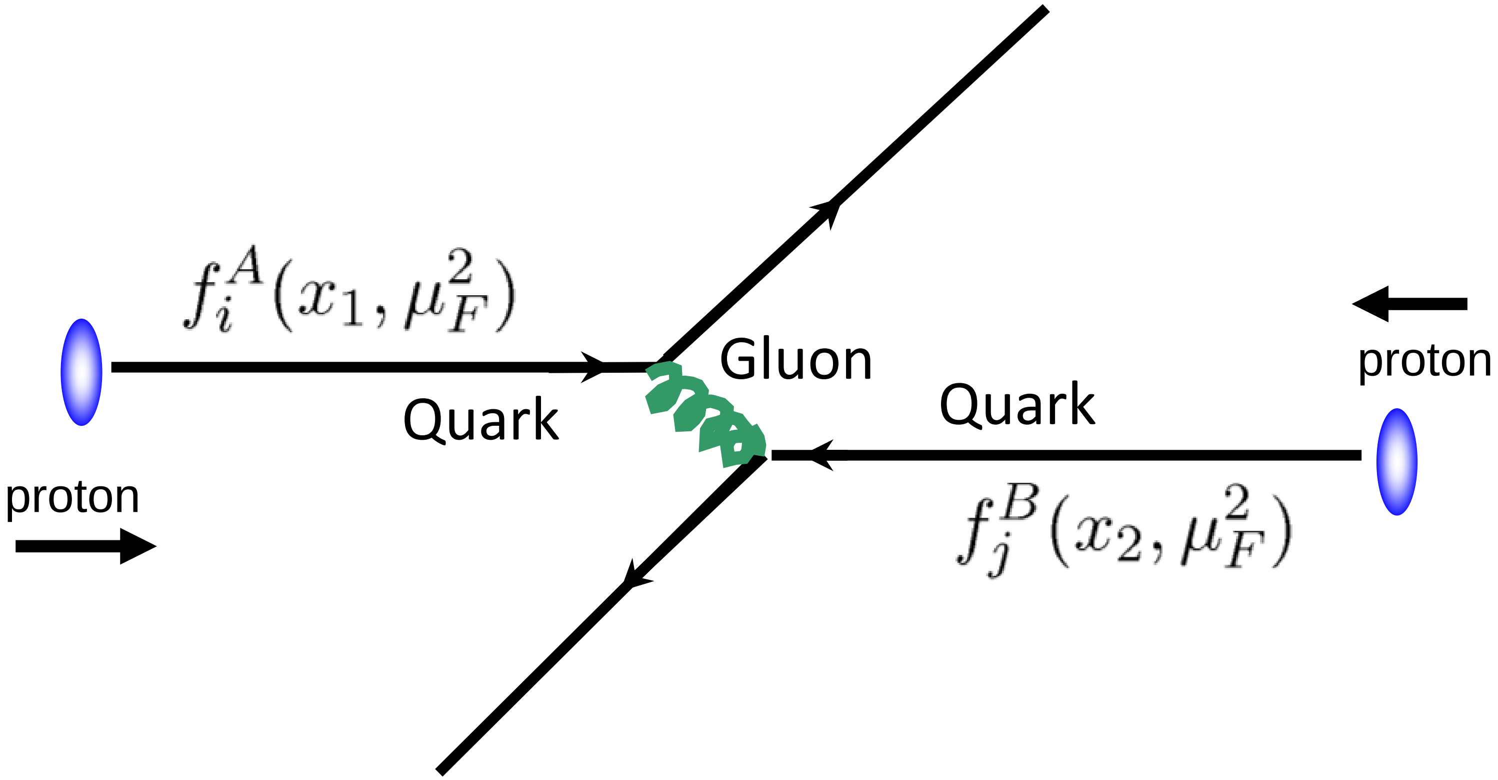
Parton Distribution Function (PDF)



Factorization

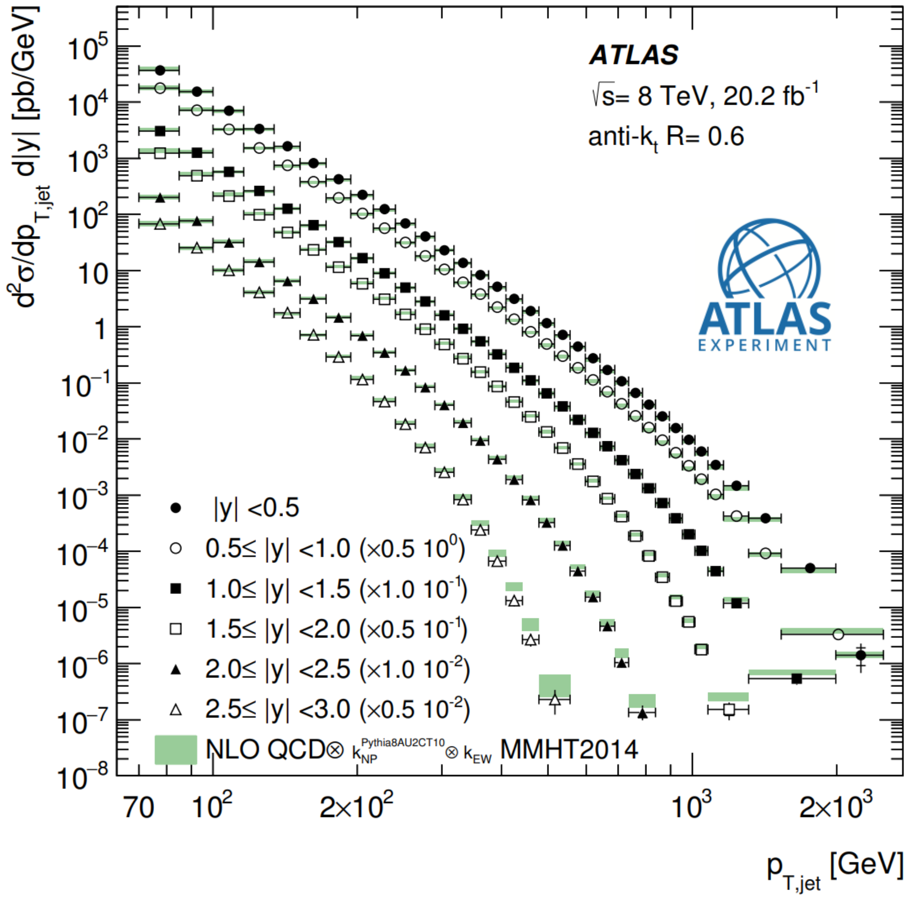
$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Parton Distribution Function (PDF)   Cross-section of 2→2 process



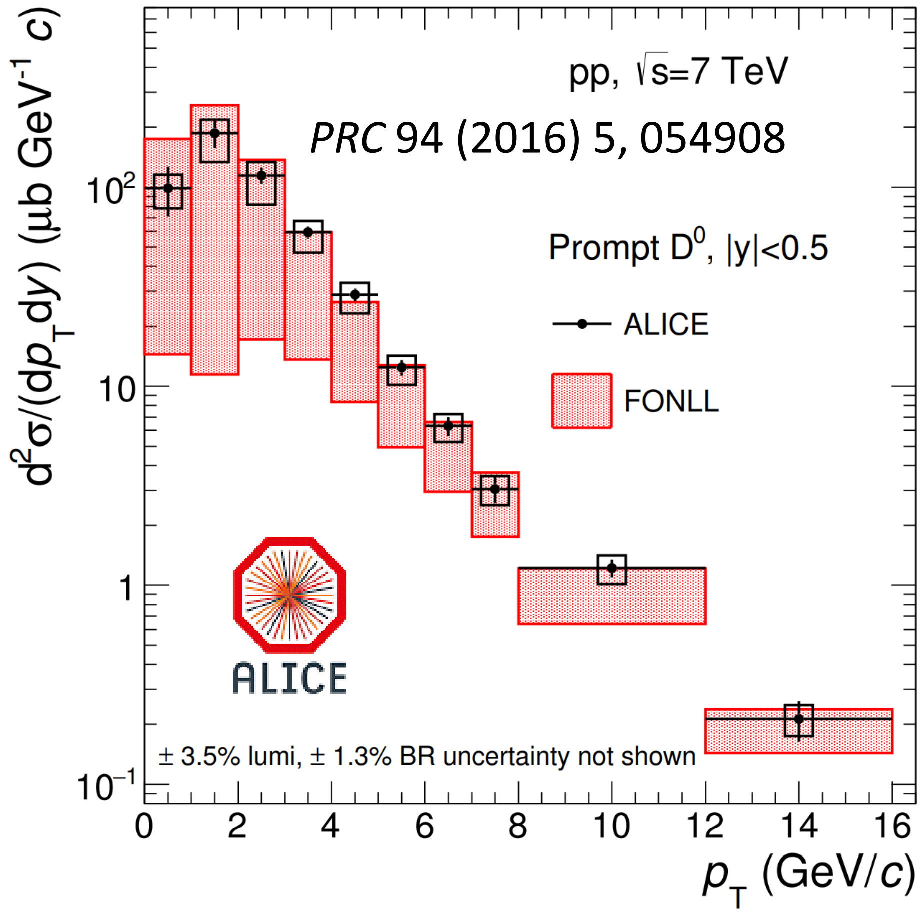
Jet and Heavy Flavor Meson Production in PP

Jet

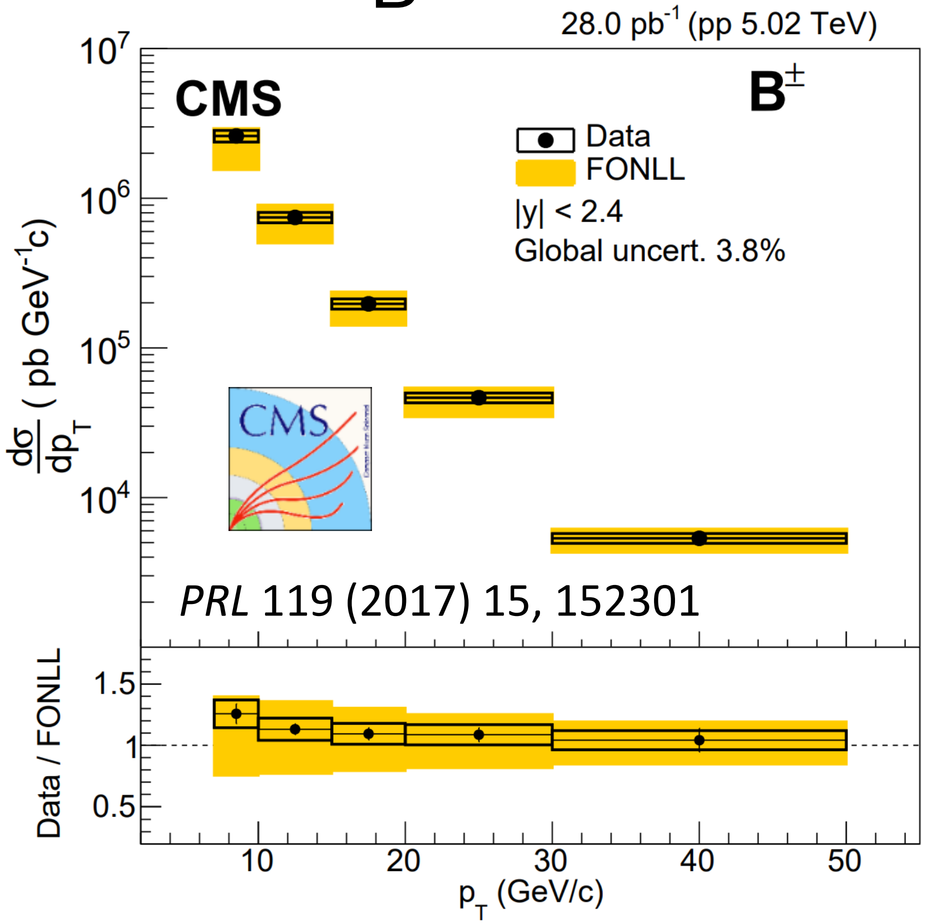


JHEP 09 (2017) 020

D^0



B^+

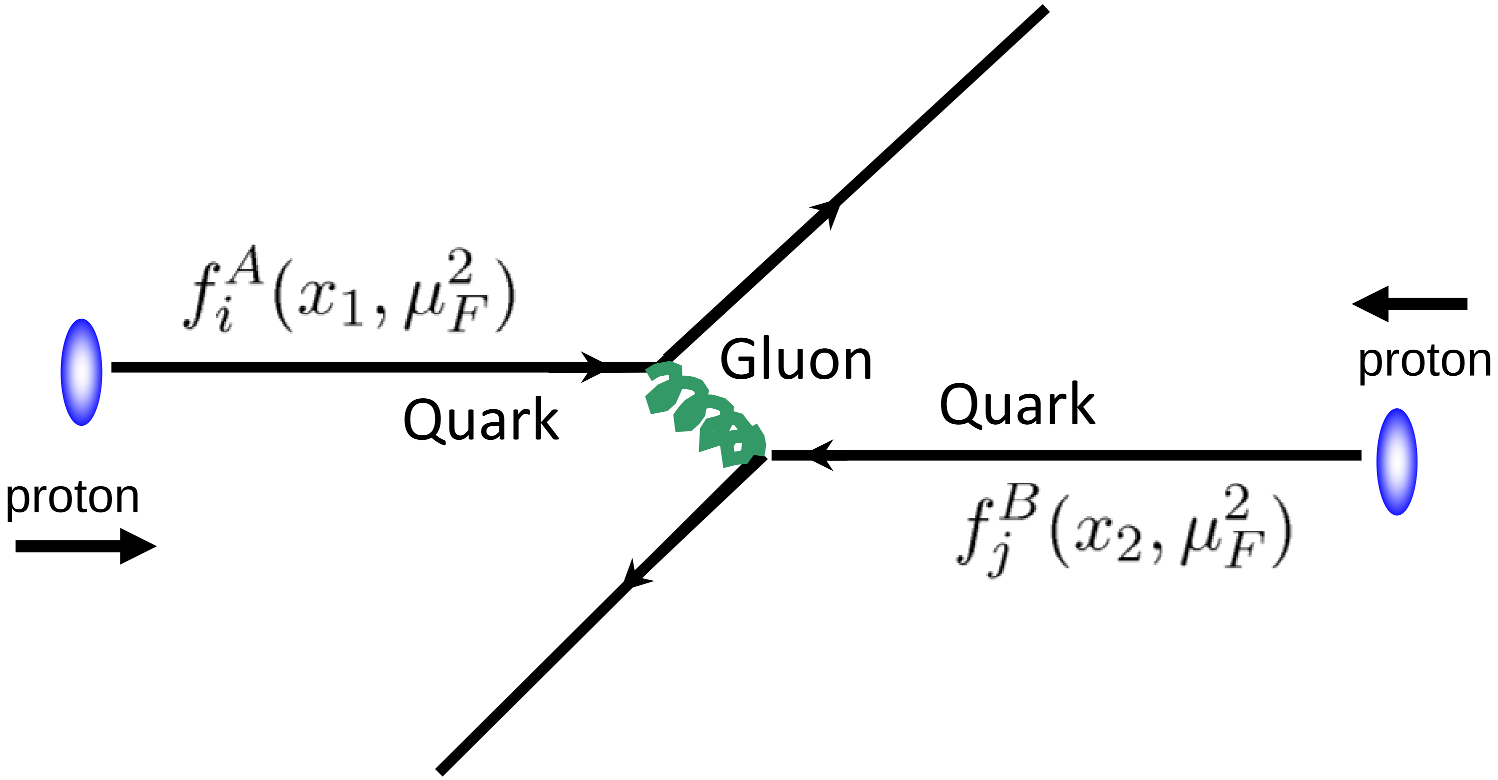


Jets and heavy flavor meson p_T spectra can be described by pQCD calculations

Factorization

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Parton Distribution Function (PDF) Cross-section of 2→2 process

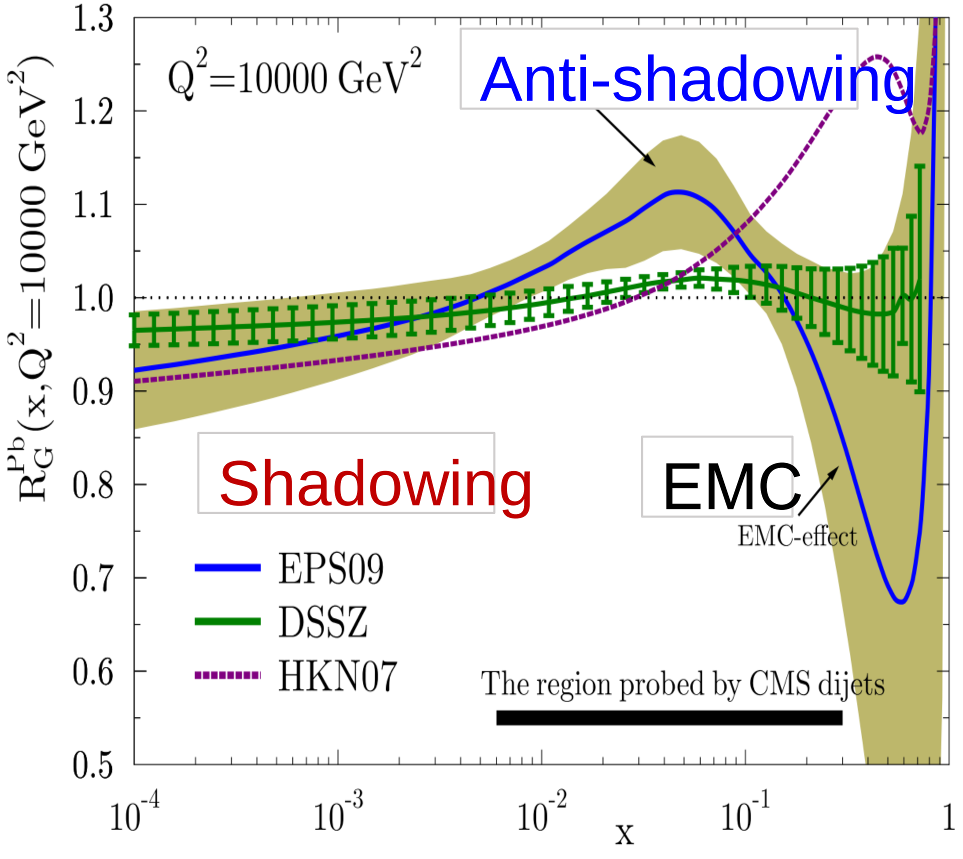


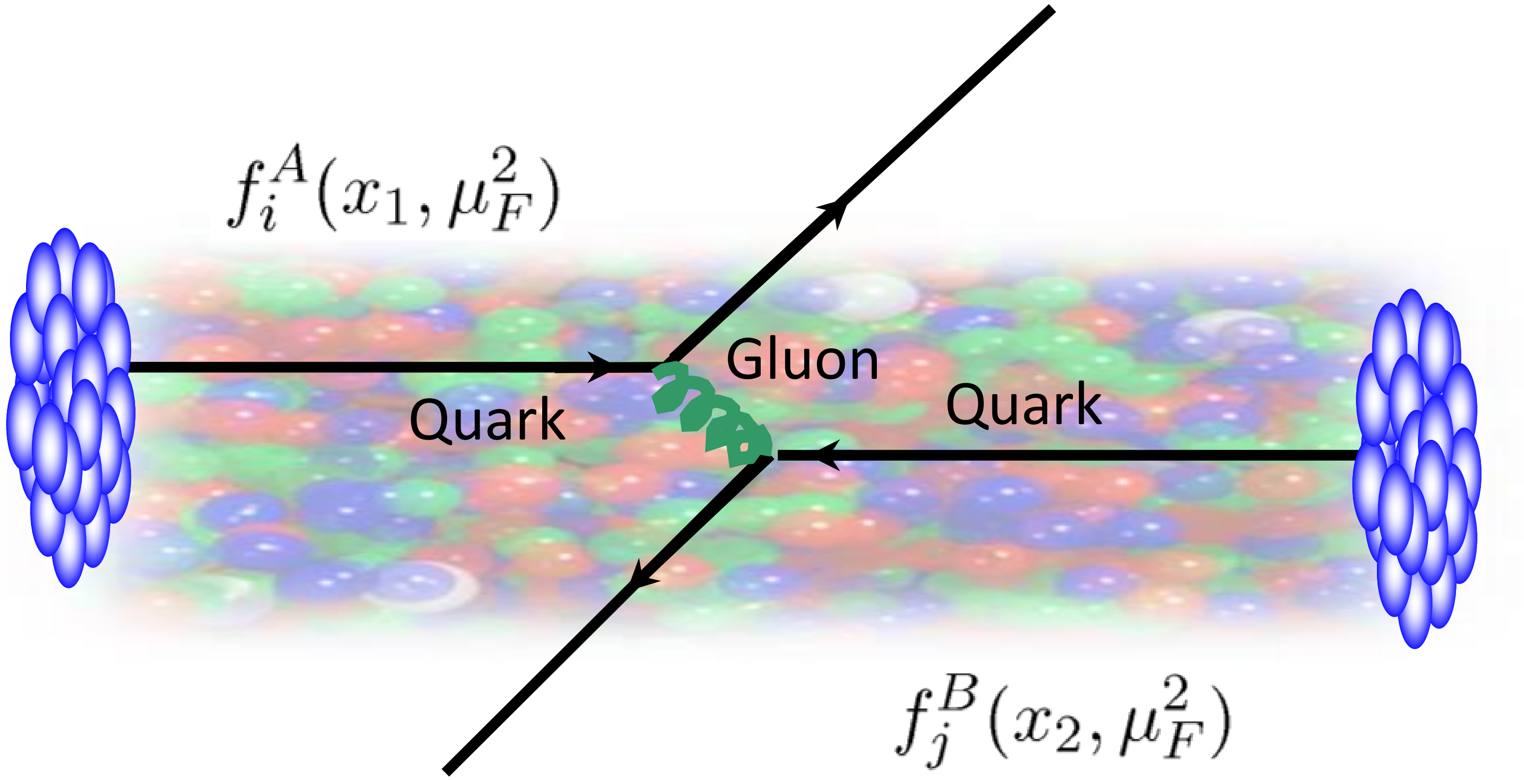
Factorization in AA collisions

$$\sigma^{AB\to kl} \sim f_i^A(x_1,\mu_F^2) \otimes f_j^B(x_2,\mu_F^2) \otimes \hat{\sigma}^{ij\to kl}$$

Nuclear Parton Distribution Function (nPDF)   Cross-section of 2→2 process

$$R = \frac{nPDF}{PDF}$$





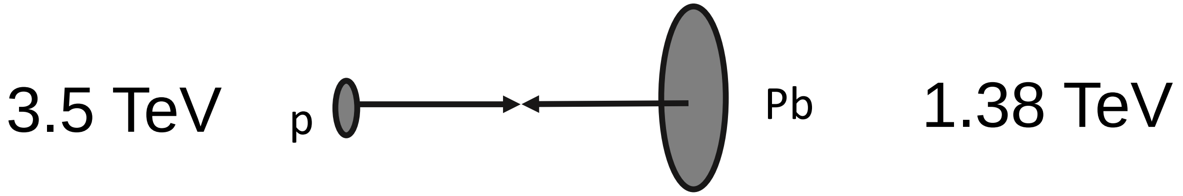
Summary

- Heavy-Ion Collisions: experiments that give access to Quark Gluon Plasma
- The medium produced in HI collisions is very dense, strongly interacting, flows like a perfect fluid.
- The abundance of the final state baryons and mesons can be described by a statistical hadronization model
- Next: Hard Probes of QGP

Bonus Material

Nuclear Parton Distribution Function

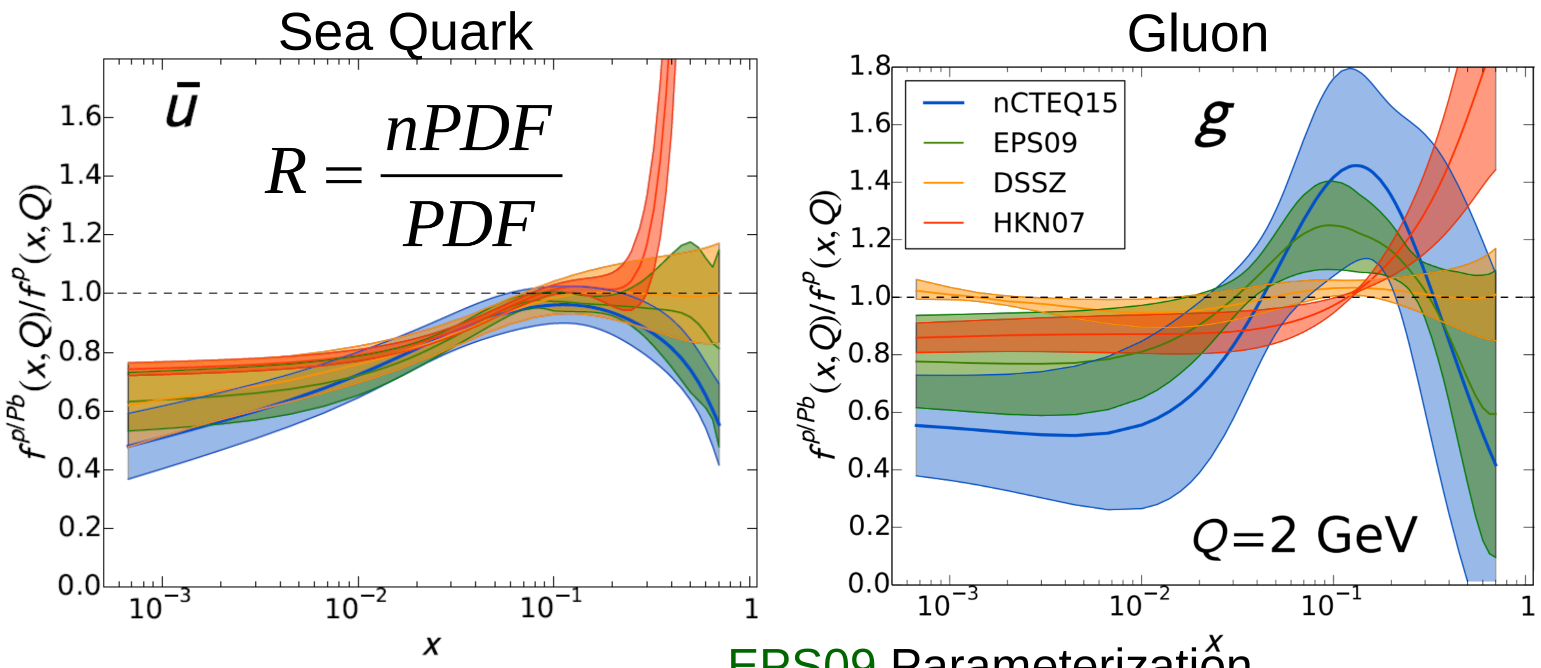
Jet for constraining the nuclear parton distribution function



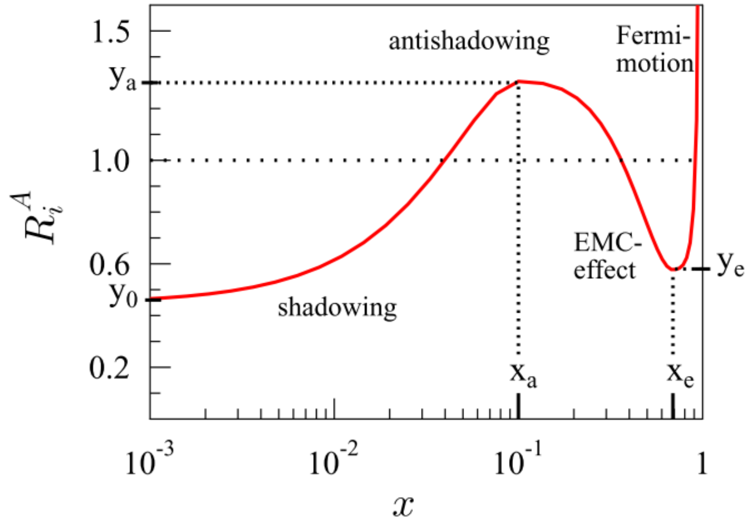
Parton Distribution Function

Nuclear Parton Distribution Functions (nPDF)

- Deep Inelastic Scattering Data
- Drell-Yan Data
- RHIC Pion Data



EPS09 Parameterization



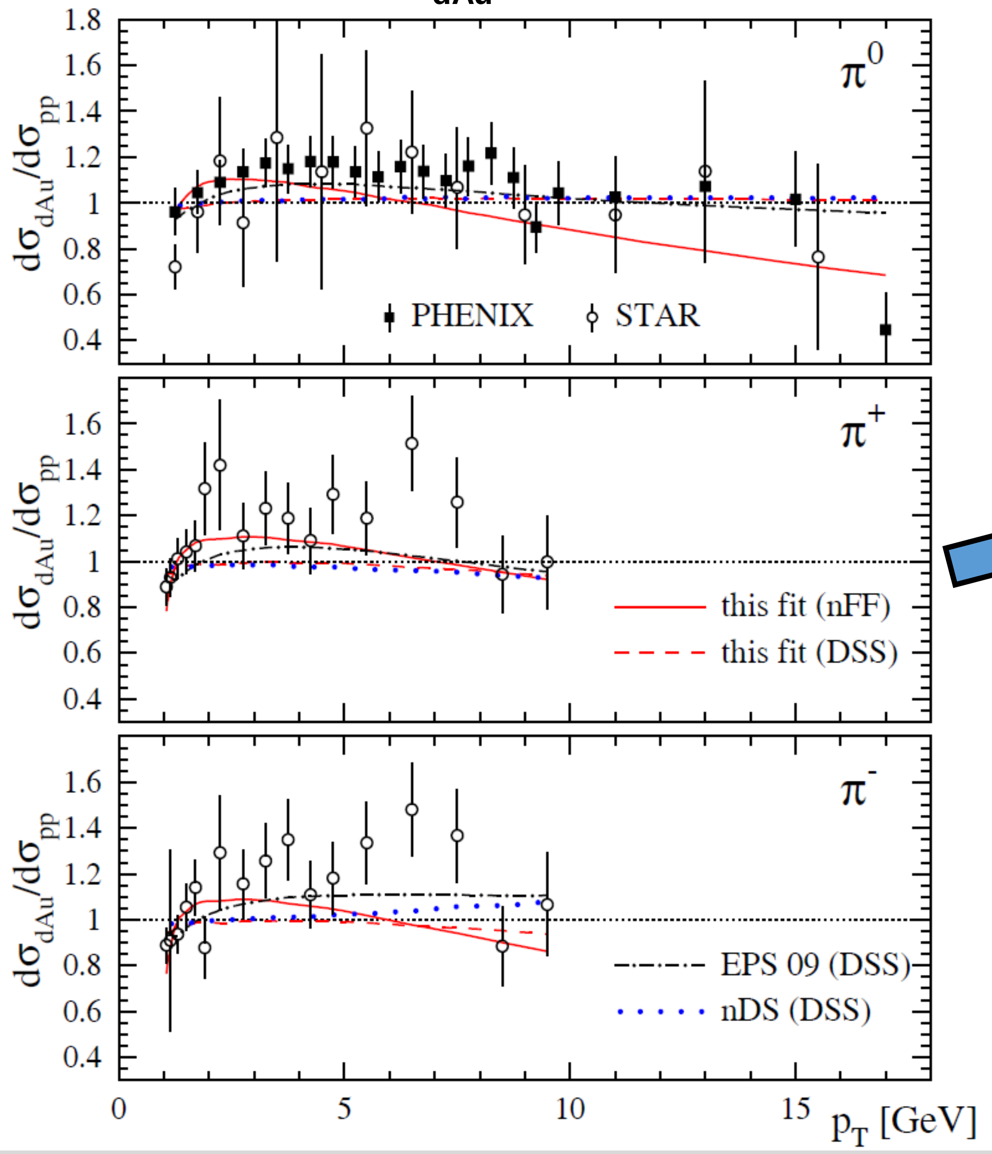
	Q^2 cutoff	DIS	DY	PHENIX Pion	STAR Pion
HKN07	1	V	V		
EPS09	1.69	V	V	V	
DSSZ	1	V	V	V	V
nCTEQ15	4	V	V	V	V

EPPS16: with LHC pPb data (W,Z, jets)

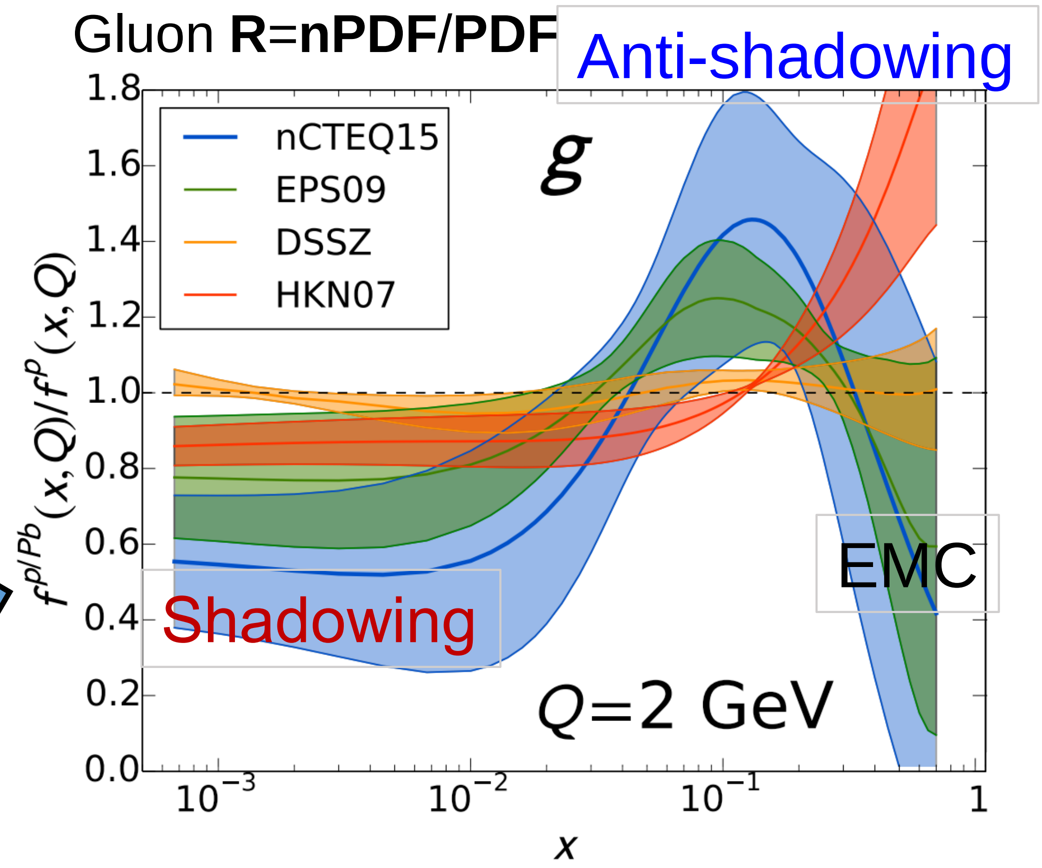
Different interpretation of the pion data

Hadron observables: sensitive to possible modifications of **fragmentation function** and **hadronization** → Different interpretation of the data!

RHIC Pion $\mathbf{R_{dAu}}$ dAu 200 GeV/c



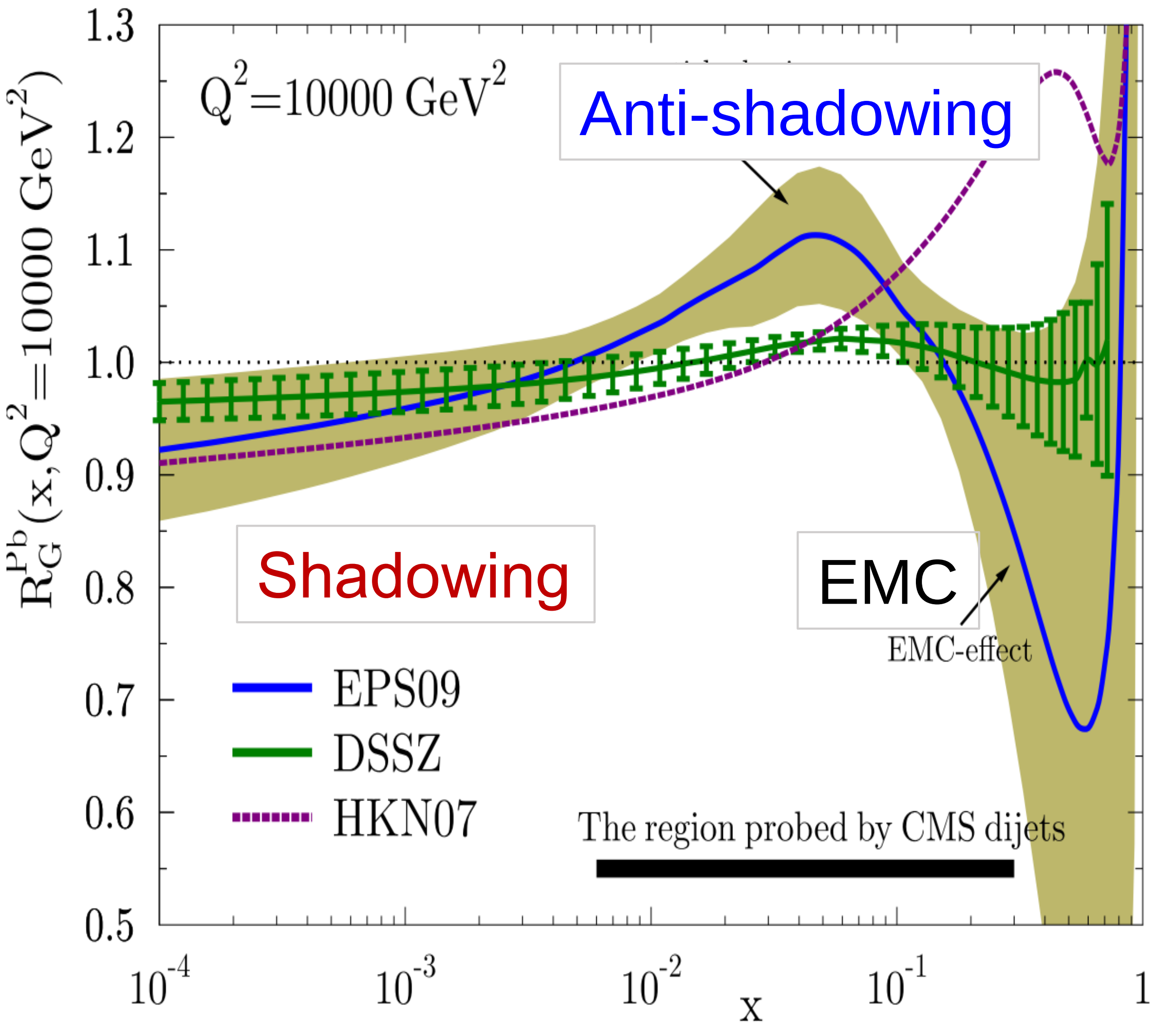
Gluon **R=nPDF/PDF**



- **EPS09** & **nCTEQ15**: hint of **anti-shadowing** and **EMC effect** of gluon nPDF
- **DSSZ**: modification of parton-to-pion fragmentation function in heavy ion collisions and no gluon anti-shadowing

nPDF modification at large Q^2

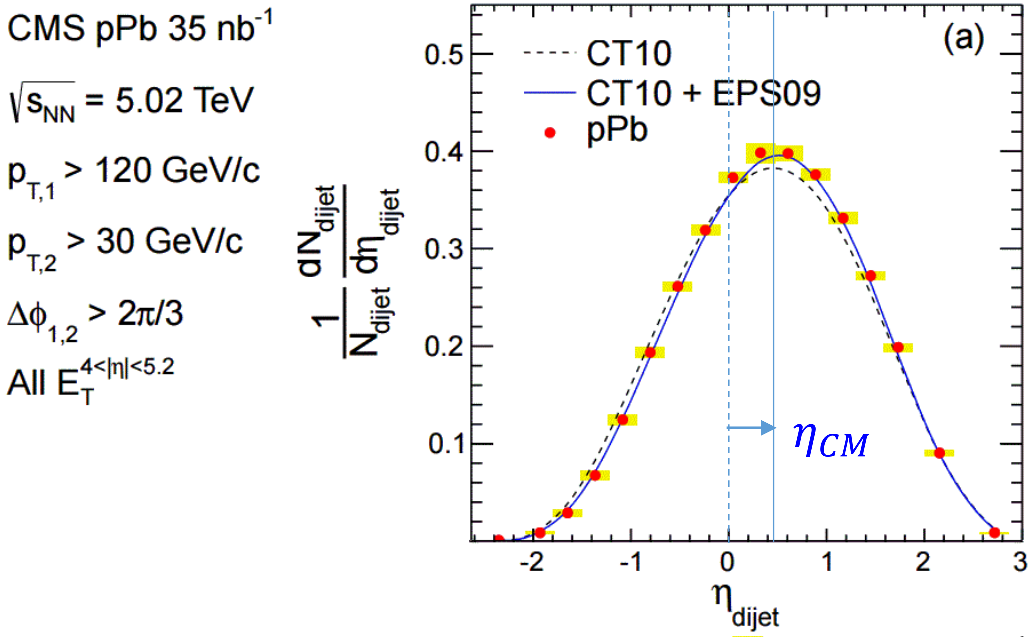
$$R = \frac{nPDF}{PDF}$$



Nuclear modification of hard scattering involving large momentum transfer due to PDF is small (at the order of 10%)

Dijet pseudorapidity in the LAB Frame

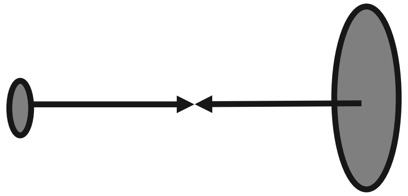
Idea: Angular distributions of high p_T dijets



$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$

$$\propto 0.5 \log\left(\frac{x_p}{x_{Pb}}\right) + \eta_{CM}$$

- Jets: Less sensitive to fragmentation functions and hadronization effects
- Can be calculated with pQCD with small theoretical uncertainties
- Normalized distribution: lead to smaller theoretical and experimental uncertainties

3.5 TeV p  Pb 1.38 TeV

Distribution shift to positive value due to asymmetric proton and lead ion beam energy

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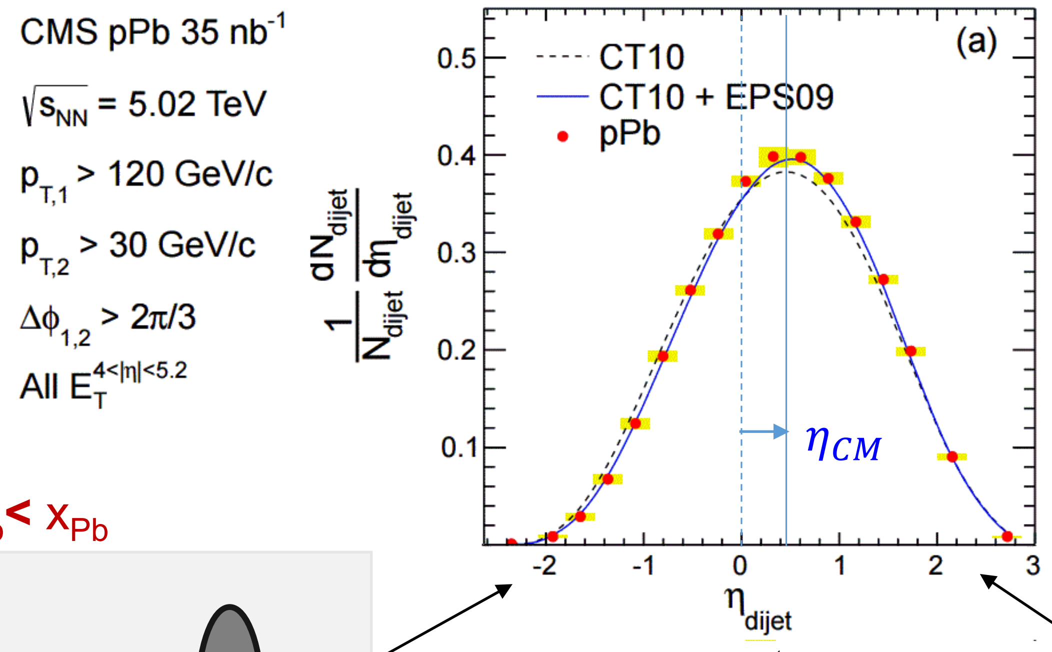
Dijet pseudorapidity in the LAB Frame

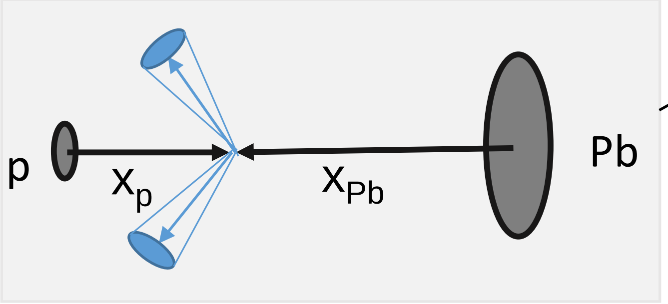
- Idea: Angular distributions of high p_T dijets

$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$

$$\propto 0.5 \log\left(\frac{x_p}{x_{Pb}}\right) + \eta_{CM}$$

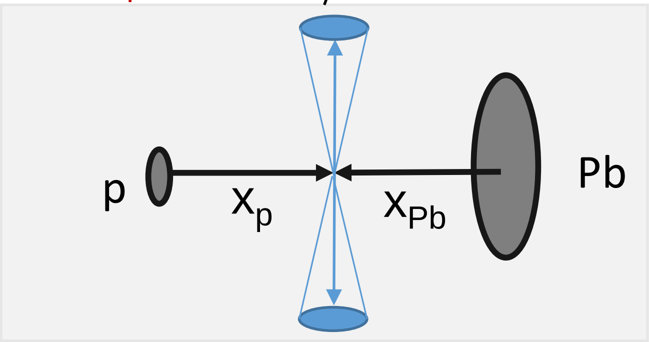


$x_p < x_{Pb}$



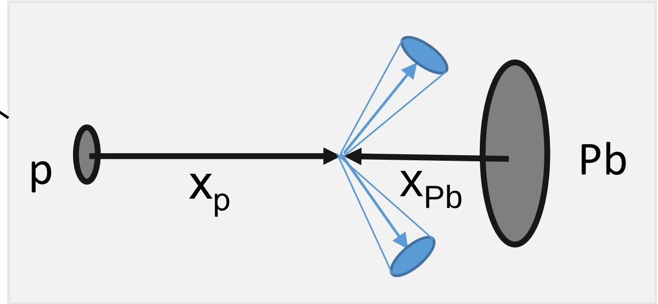
Sensitive to EMC effect

$x_p \sim x_{Pb}$



Sensitive to anti-shadowing

$x_p > x_{Pb}$



Sensitive to shadowing

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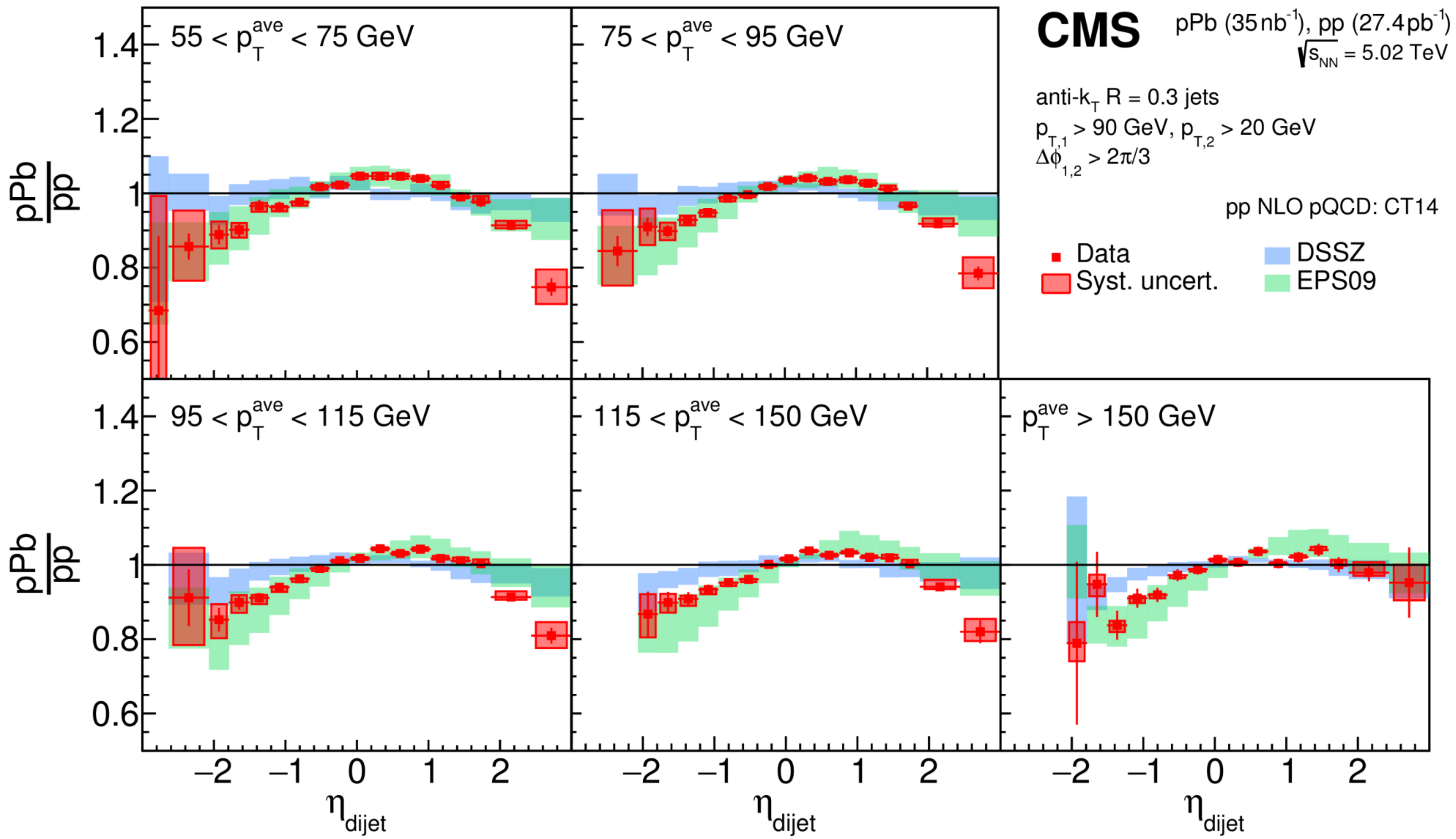
Observation of nPDF effect



- **EPS09**: hint of **anti-shadowing** and **EMC effect** of gluon nPDF
- **DSSZ**: modification of parton-to-pion fragmentation function in heavy ion collisions and no gluon anti-shadowing