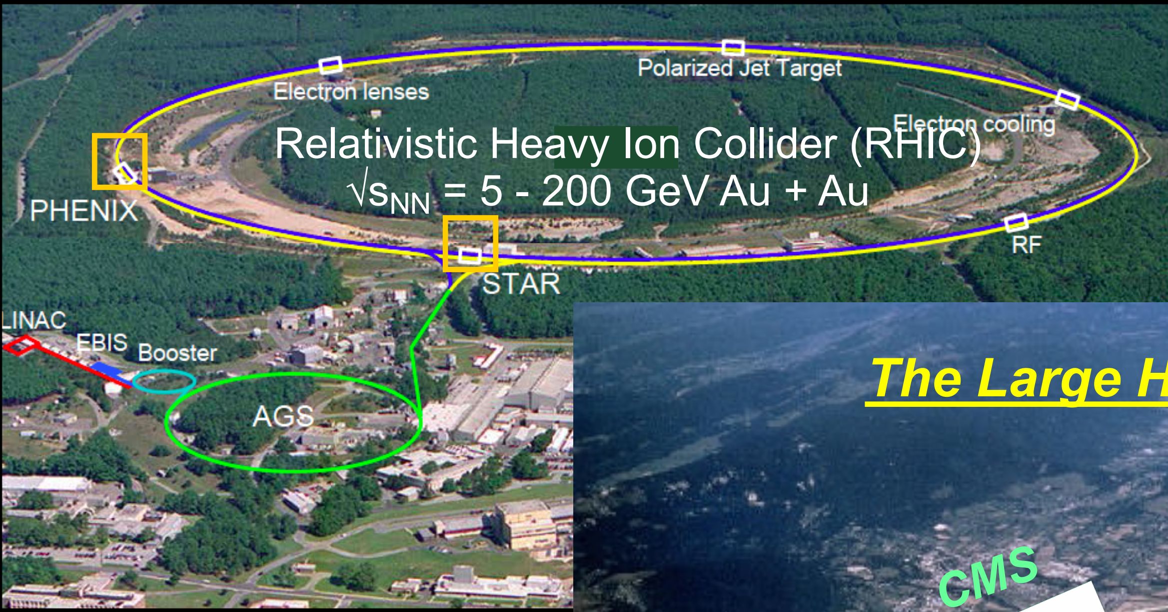
Sound connect & check!

UltraRelativistic Heavy Ion Physics Intro & Overview



$\sqrt{s_{NN}}$ = c.m. energy
per colliding nucleon pair

On the First "Day"

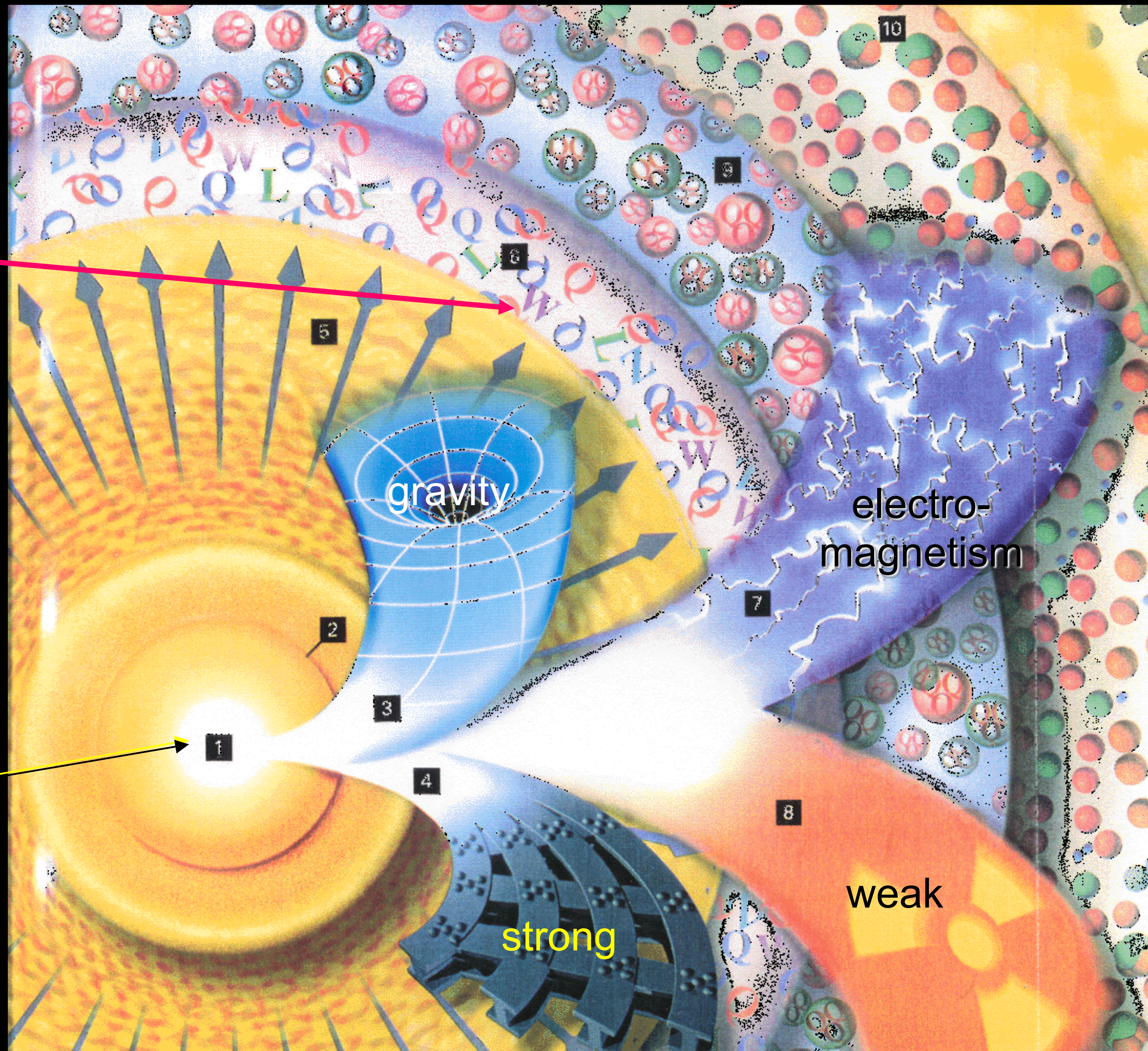
at 10 μ-seconds
~200,000 x T_{sun}
Quark-to-hadron*
phase transition

Quark-Gluon Soup

Rapid inflation

4 forces separate

at 10^{-43} seconds



Courtesy Nat. Geographic, Vol. 185, No. 1, 1994 – Graphics by Chuck Carter
Consultants – Michael S. Turner and Sandra M. Faber

* hadrons = nuclear particles

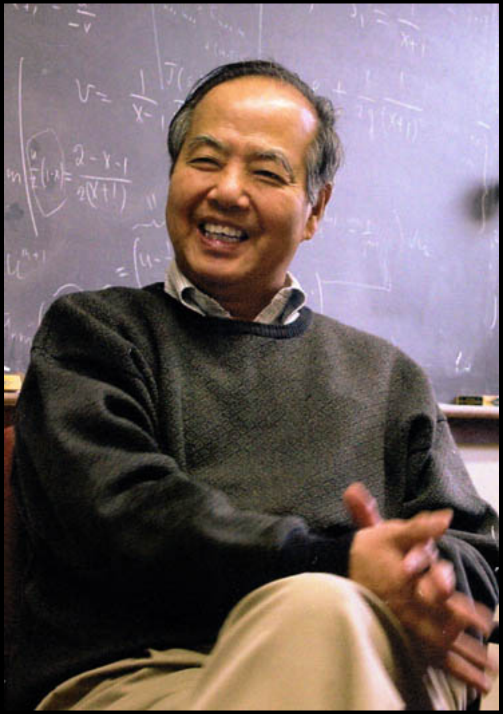
Distinguishing Heavy Ion Approach from HE Physics & Recreating the Primordial Quark-Gluon Soup

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

But, in order to study the question of 'vacuum', we must turn to a different direction; we should investigate 'bulk' phenomena

by

distributing high energy over a relatively large volume."



T.D. Lee (Nobel Laureate)
Rev. Mod. Phys. 47 (1975) 267.

Nobel Prize 2004

D. Gross
H.D. Politzer
F. Wilczek

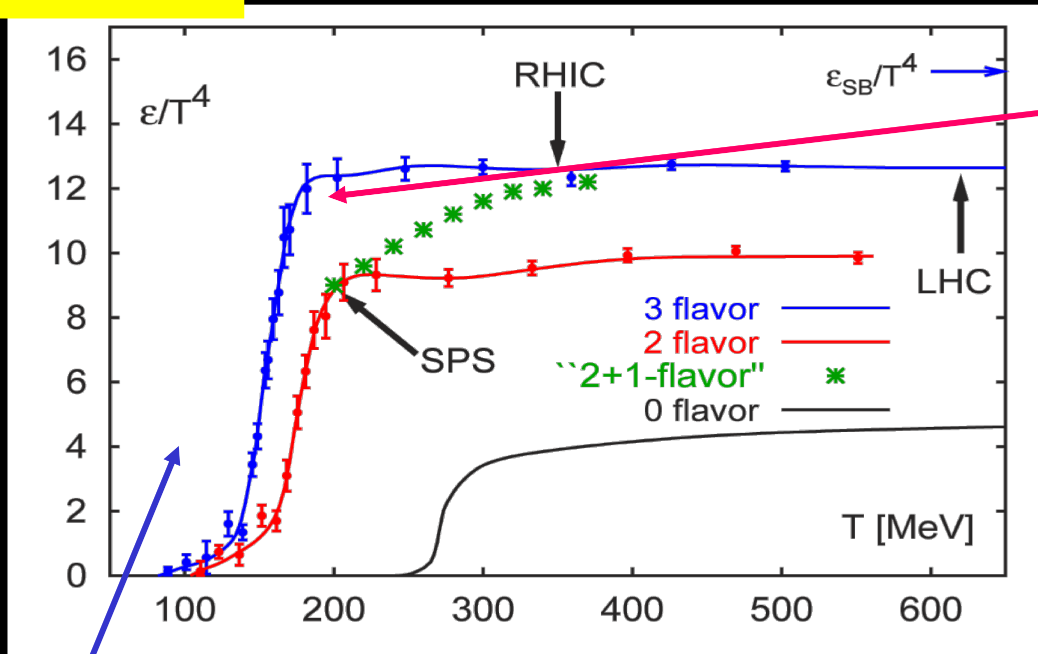
QCD Asymptotic Freedom (1973)

"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma."
David Gross, Nobel Lecture (RMP 05)

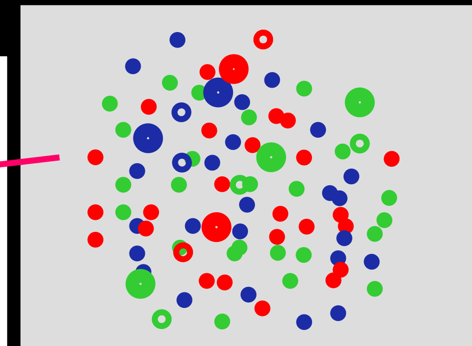
Behavior of QCD* at High Temperature

ε/T^4 ~ # degrees of freedom

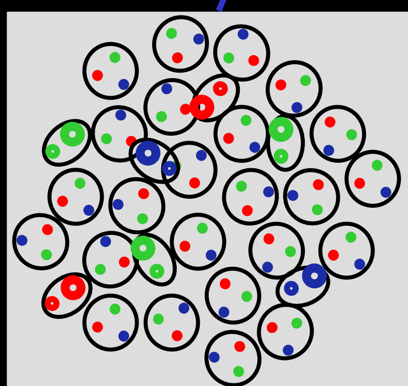
* Quantum Chomo-Dynamics



F. Karsch, et al. Nucl. Phys. B605 (2001) 579



many d.o.f.→**deconfined**



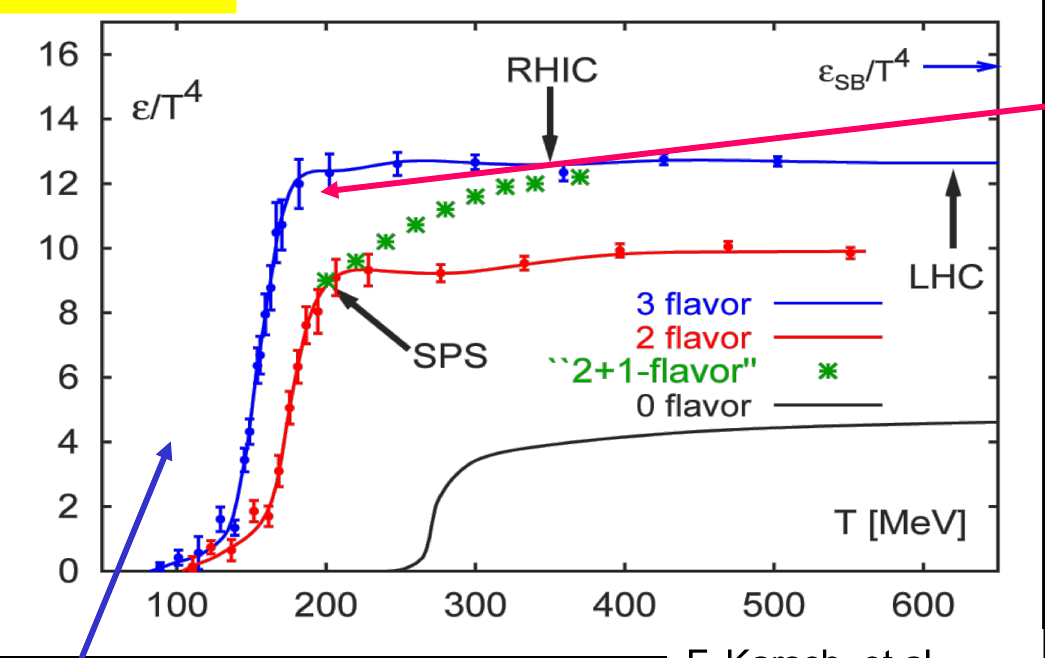
few d.o.f.→**confined**

$T_C \sim 175 \pm 8$ MeV → $\varepsilon_C \sim 0.3 - 1$ GeV/fm^3

Behavior of QCD* at High Temperature

ε/T^4 ~ # degrees of freedom

* Quantum Chomo-Dynamics



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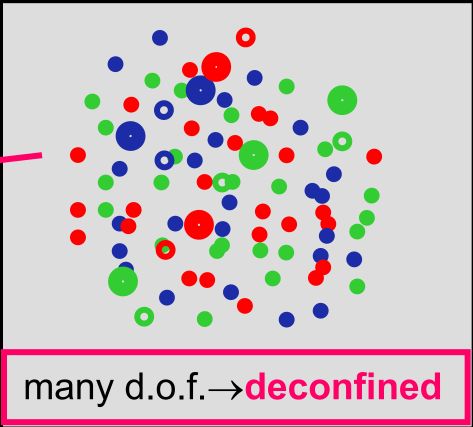
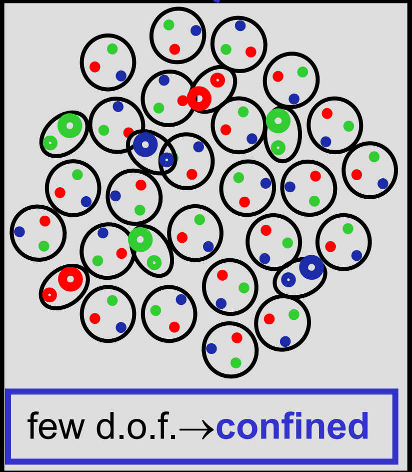




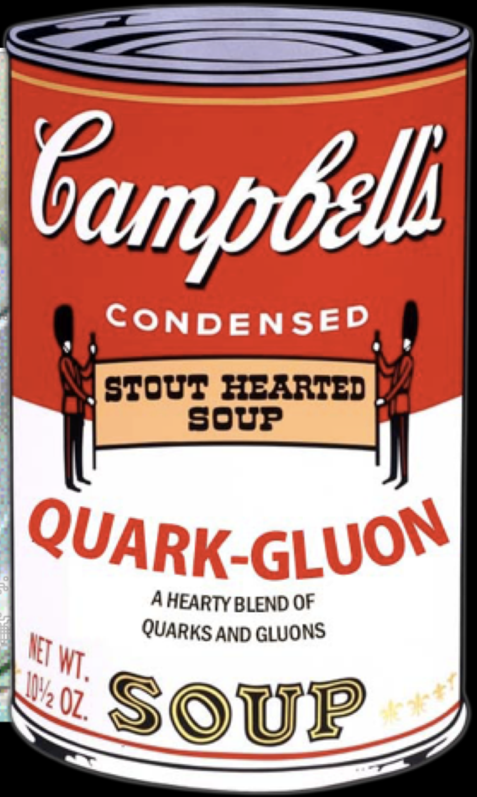
Recent LQCD results with improved actions:

- S. Borsanyi et al. JHEP 1009, 073 (2010) Tc = 155(6) MeV
- A. Bazavov et al., PRD 85, 054503 (2012) Tc = 154(9) MeV
- P. Steinbrecher, Quark Matter 2018 Tc = 156.5+/-1.5 MeV

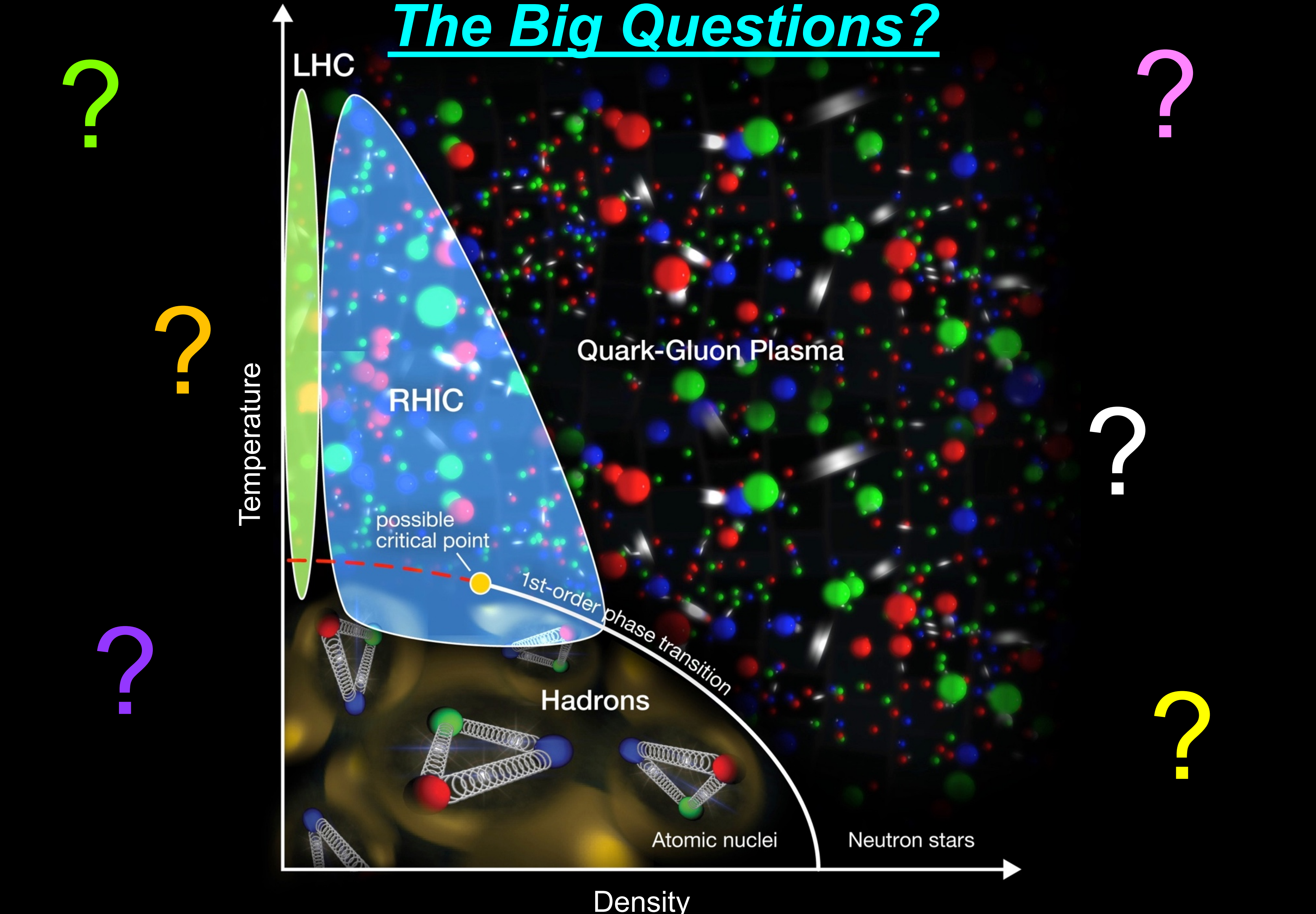
T_C ~ 154 – 157 MeV → ε_C ~ 0.3 - 1 GeV/fm^3

Quark-Gluon Plasma (Soup)

- The Standard Model (QCD) predicts at high temperature & density
  → Quark-hadron phase transition at T ~ 170 – 190 MeV
- Cosmology → Quark-hadron phase transition in early Universe
- Astrophysics → Cores of dense stars (?), neutron-star mergers!
- Can we make it in the lab? Establish its properties at high T!



The Big Questions?



The BIG Questions

What are the properties & states of matter that exist at high T & density?

- Can we explore the phase structure of a fundamental gauge (QCD) theory?

  → Can we use this to understand other gauge theories (like gravity!)?

- Is the Phase Diagram of QCD featureless above Tc?

  → What are the constituents (are there quasi-particles, exotic states, others)?

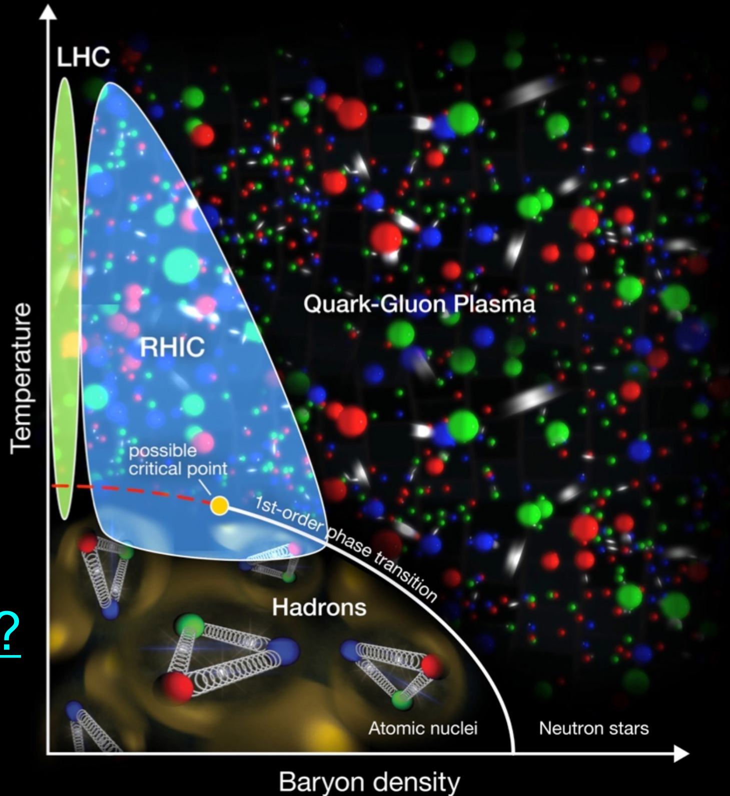
  → When does the "quark-gluon soup" become resolvable into quarks / gluons?

  → Is there a critical point (scan in energy)?

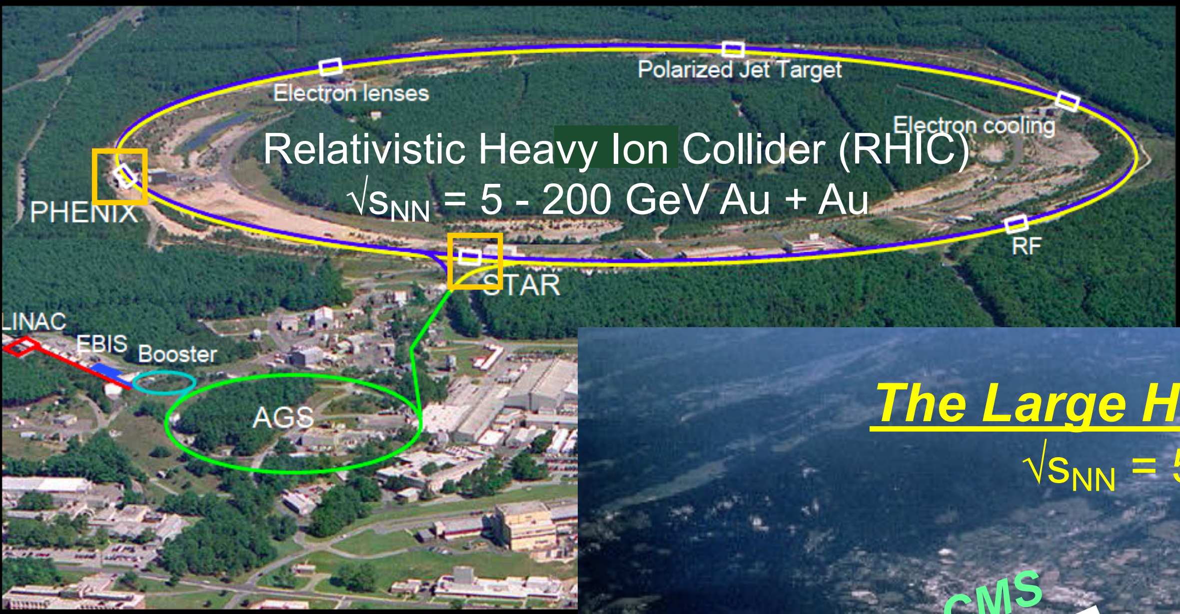
What are the properties of the QGP?

transport properties, α_s (T),
sound attenuation length,
sheer viscosity/entropy density,
formation time (τ_f),
excited modes, ….EOS?

Are there new phenomena, new states of matter?



“Experimental Mission”



Cover 3 decades
of energy
in center-of-mass

* $\sqrt{s_{NN}}$ = c.m. energy per colliding nucleon pair

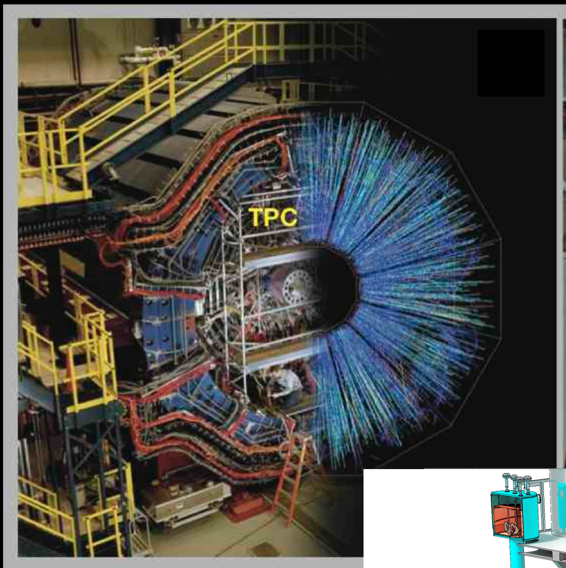
The Large Hadron Collider (LHC)

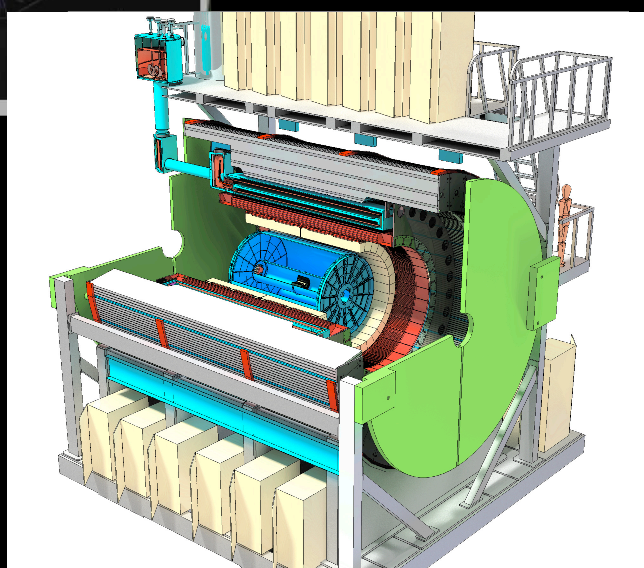
from the Control Room

RHIC Program

RHIC Collider Detectors

STAR, PHENIX → SPHENIX (~2022)





RHIC Data-taking

2001 → 2014

2015: p + p, Au + Au

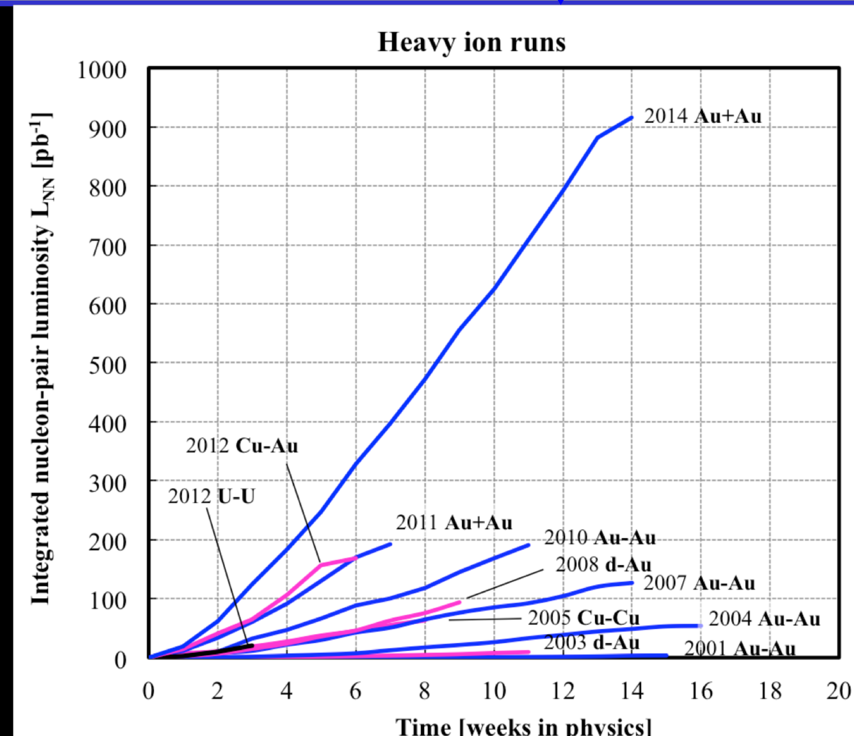
2016: Au + Au, d + Au

2017: polarized p + p, PHENIX ends

2018: Ru + Ru, Zr + Zr isobar run

2019 - 2020: Beam Energy Scan 2

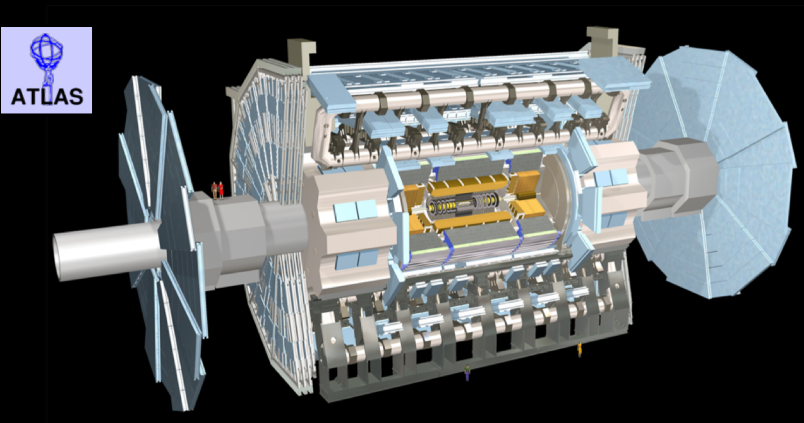
2022 → sPHENIX

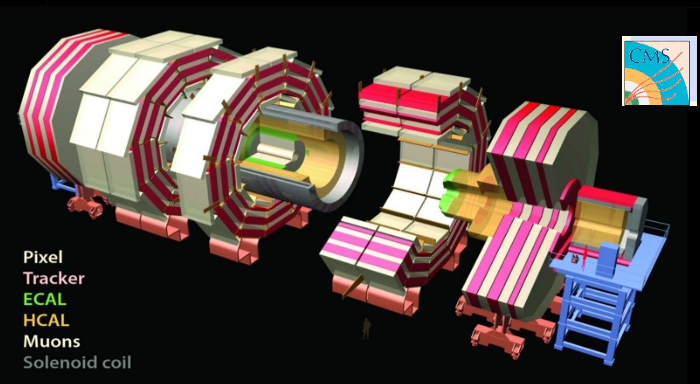


LHC Heavy Ion Program

LHC Collider Detectors in HI Physics

ATLAS CMS ALICE LHCb





LHC Heavy Ion Data-taking

Design: Pb + Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

(1 month per year)

2010-11: Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

2013: p + Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

2015: p + p, Pb + Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

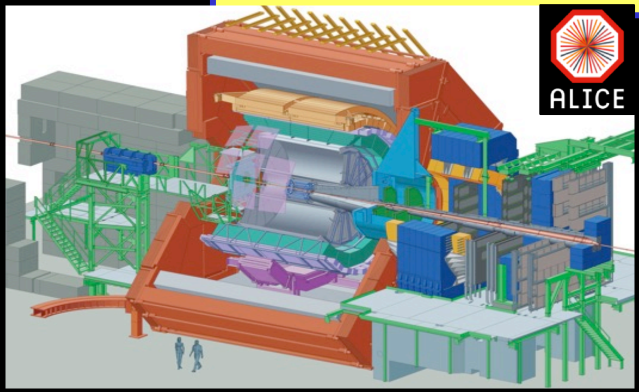
2016: p + Pb, $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV

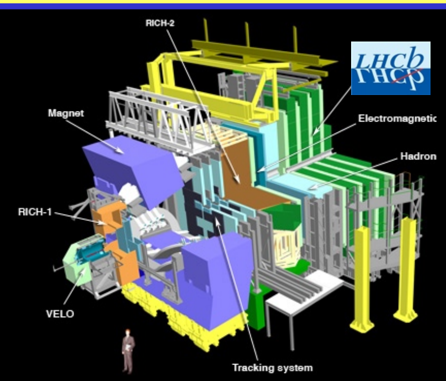
2017: p + p, $\sqrt{s_{NN}}$ = 5.02 TeV

2018: Pb + Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

2019, 2020, LHC Long Shutdown 2

2021 → Run 3





Ultra-Relativistic Heavy Ion Collisions at RHIC & LHC

Lead nucleus
diameter ~ 14 fm

γ = 100 $\rightarrow$ 2,500
(Lorenz contracted)

$\tau \sim (14\ \mathrm{fm/c}) / \gamma < 0.1 \rightarrow \sim 0.01\ \mathrm{fm/c}$

<u>General Orientation</u>

Hadron masses ~ 1 GeV

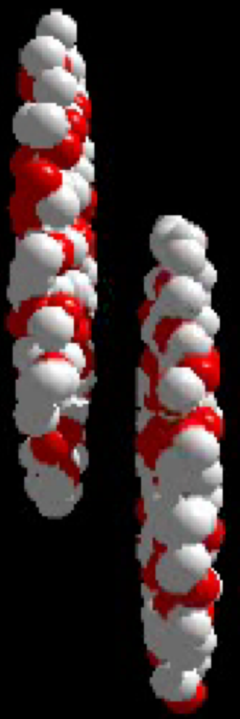
Hadron sizes ~ fm

<u>Heavy Ion Collisions</u>

RHIC: E_{cm} = 0.2 TeV per nn-pair

LHC: E_{cm} = 5.0 TeV per nn-pair

Ultra-Relativistic Heavy Ion Collisions
Example – Side View at RHIC



What We've Learned about Heavy Ion Collisions

System evolves rapidly from the initial collision to a thermalized state

Particles yields → equilibrium abundances → universal hadronization $T_{critical}$ 1

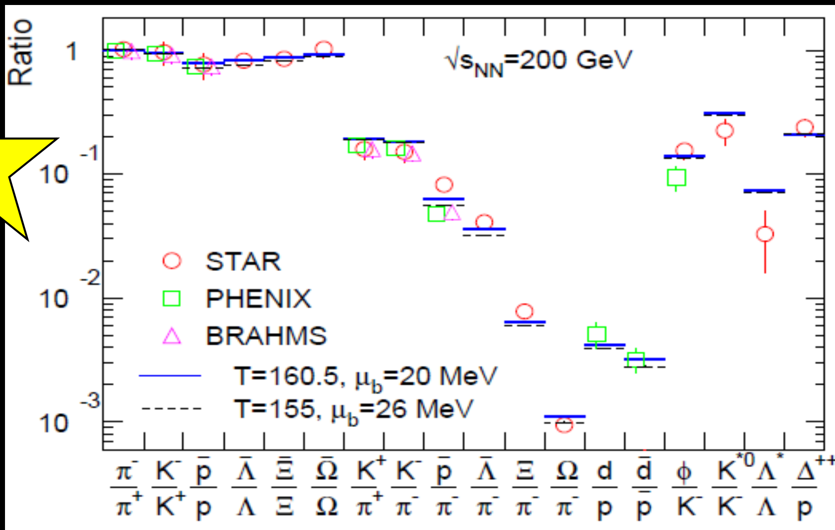
There is a thermal component of direct photon spectra → Thermal radiation from the quark-gluon plasma 2

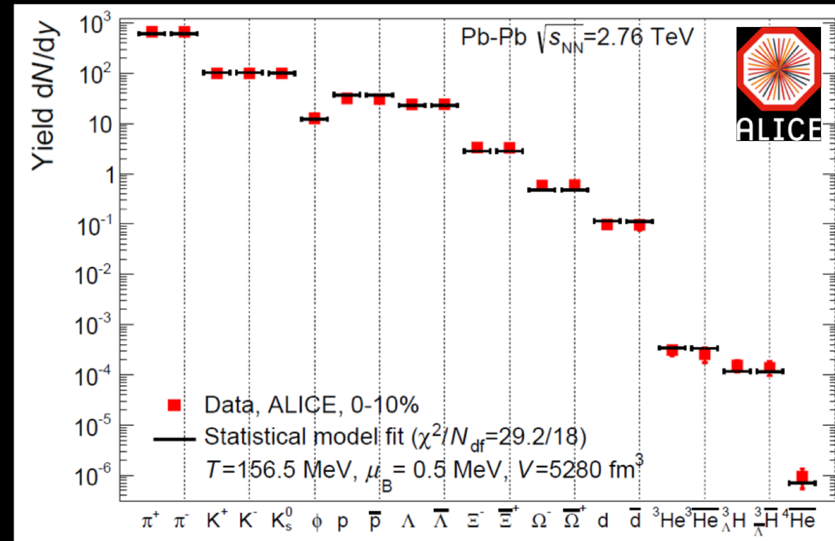
Collective flow observed Consequences → a Strongly-Coupled Medium with ultra-low shear viscosity / entropy 3

High transverse momentum (p_T) hadrons are suppressed, jets quenched
→ due to parton energy loss in the quark-gluon plasma 4

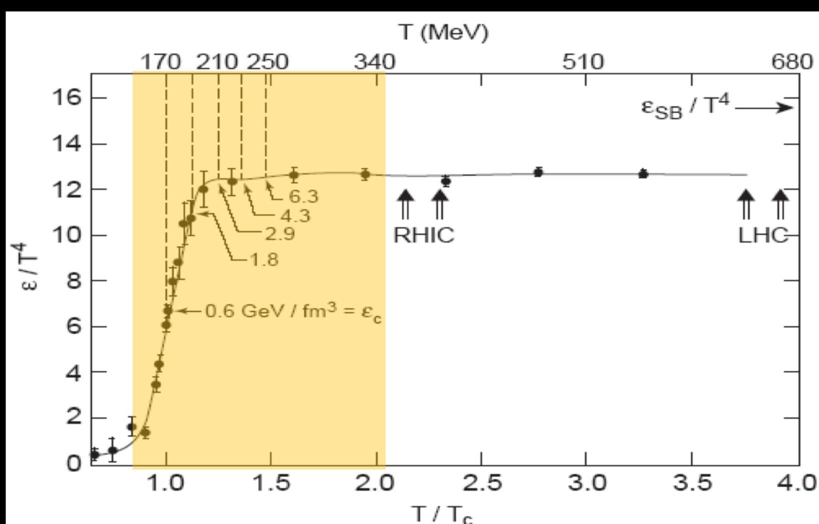
J/Ψ and Υ (quarkonia) suppressed
→ indicate color screening of $c\bar{c}$ and $b\bar{b}$ quarks resulting in quarkonium (***J/Ψ and Υ***) suppression 5

Particles Formed at Universal Hadronization T

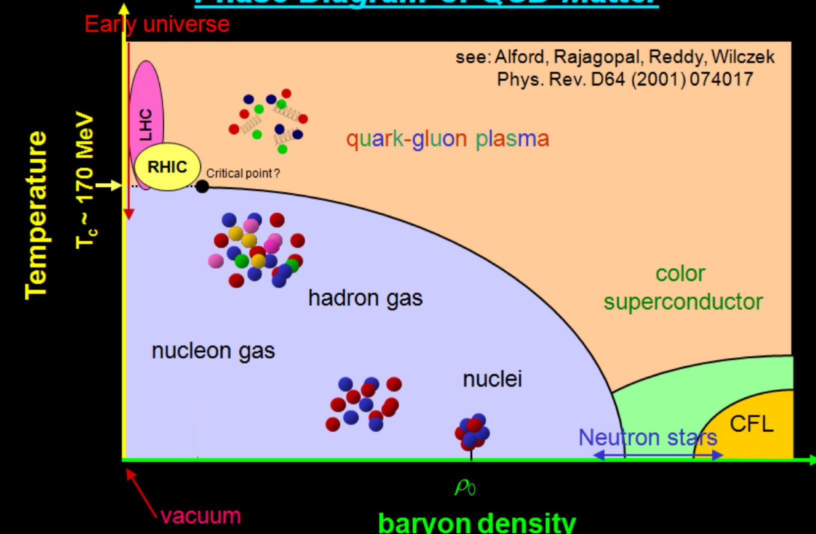




Particles yields → equilibrium abundances → T ~ universal hadronization T_c



Phase Diagram of QCD Matter



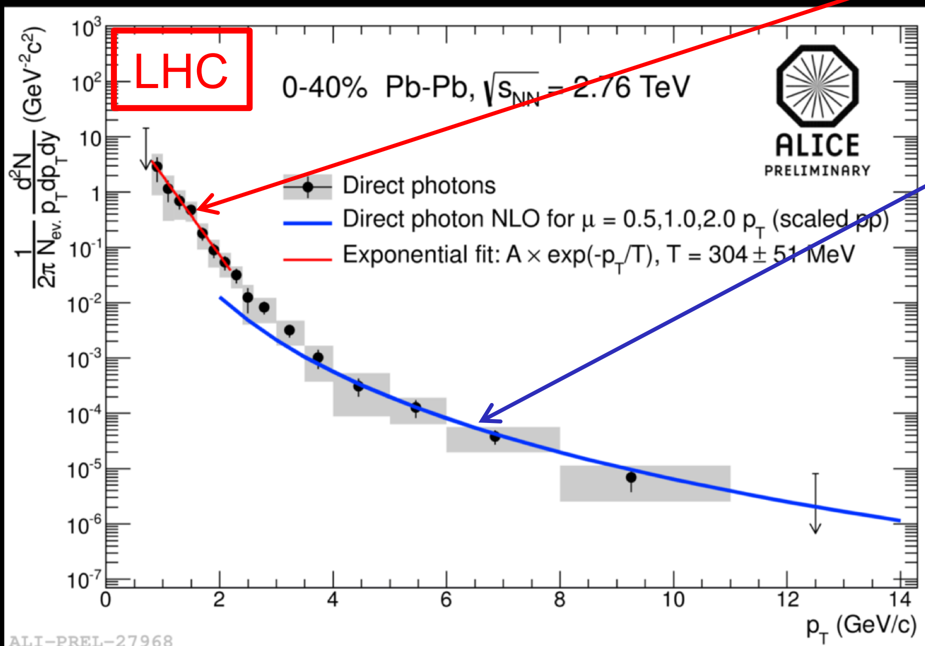
2

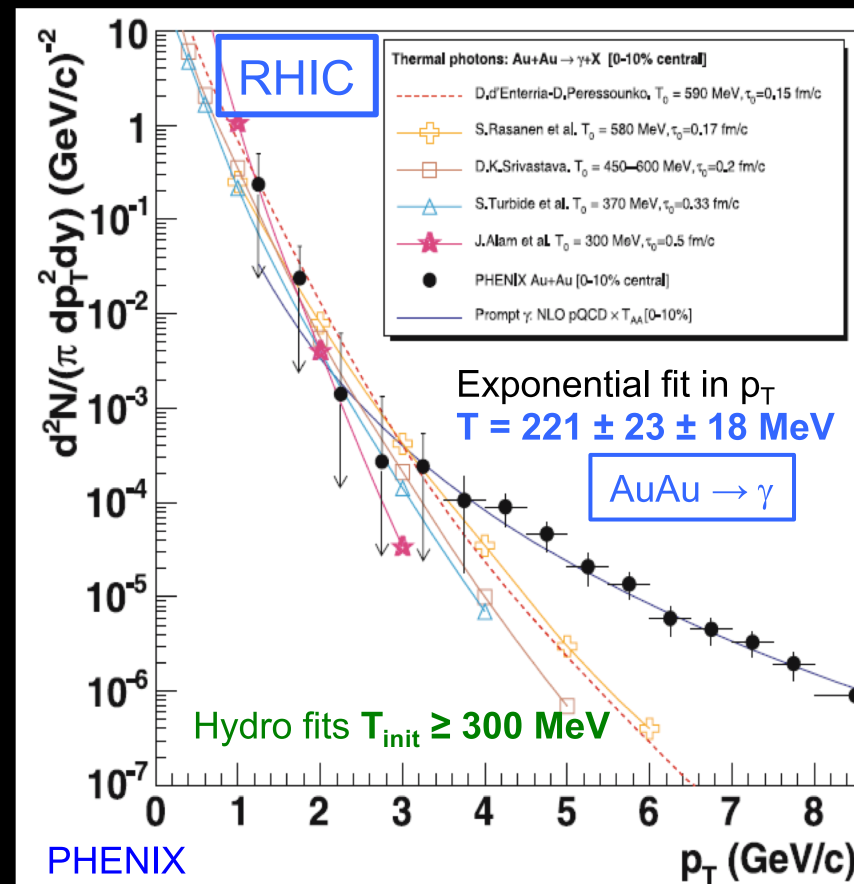
Thermal Radiation from the QGP

A thermal component of direct photons:

Exponential fit for p_T < 2.2 GeV/c
inv. slope T = 304 ± 51 MeV

N_{coll}-scaled NLO pQCD





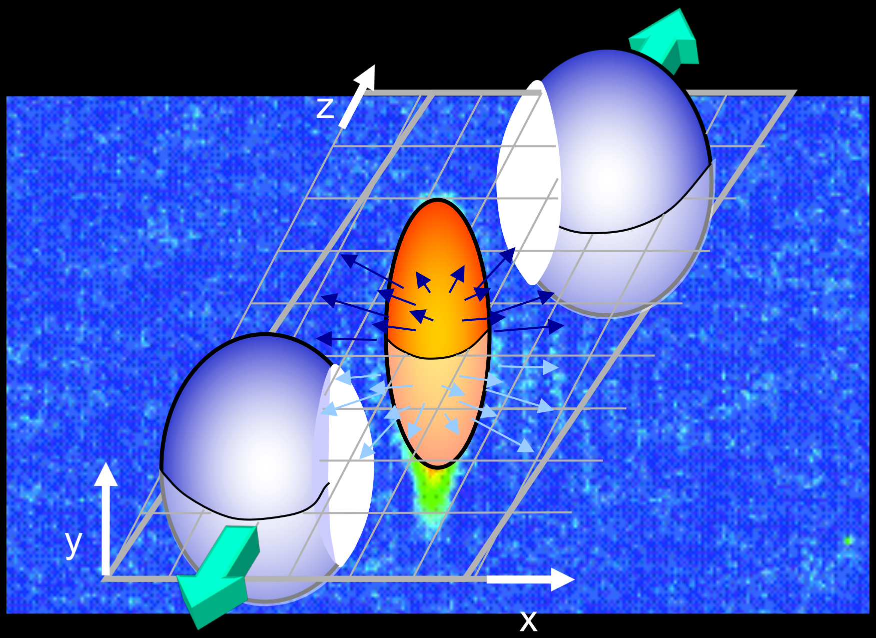
LHC (ALICE): T = 304±51 MeV
for $\sqrt{s_{NN}}$ = 2.76 TeV Pb-Pb

RHIC(PHENIX): T = 221±19±19 MeV
for $\sqrt{s_{NN}}$ = 0.2 TeV Au–Au

Note: T is integral over entire evolution!

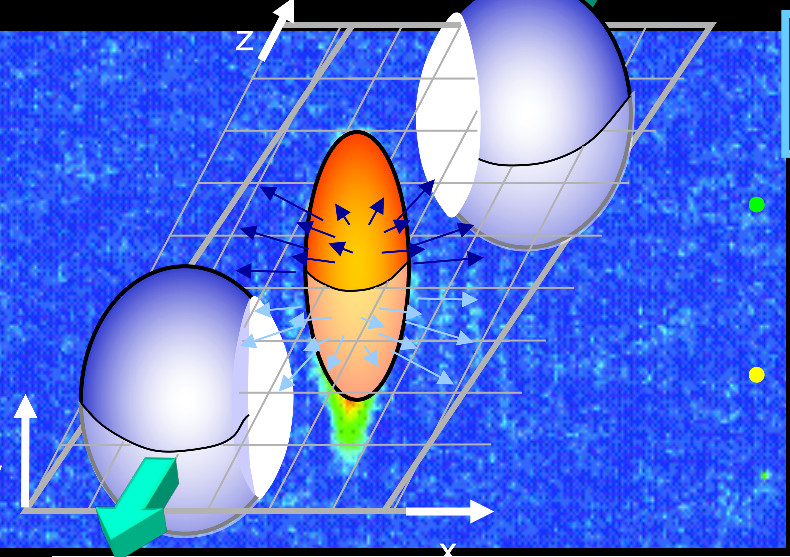
3

Strong Collective Flow is Observed



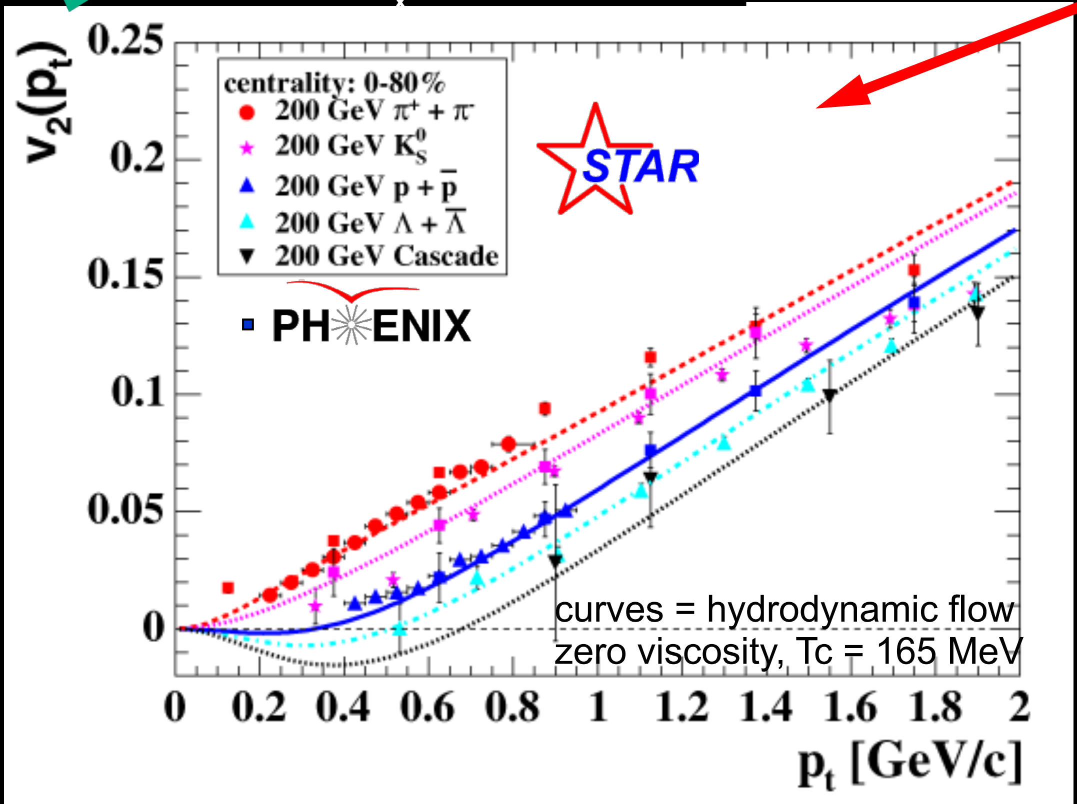
- Attributed to extremely low shear viscosity / entropy ratio

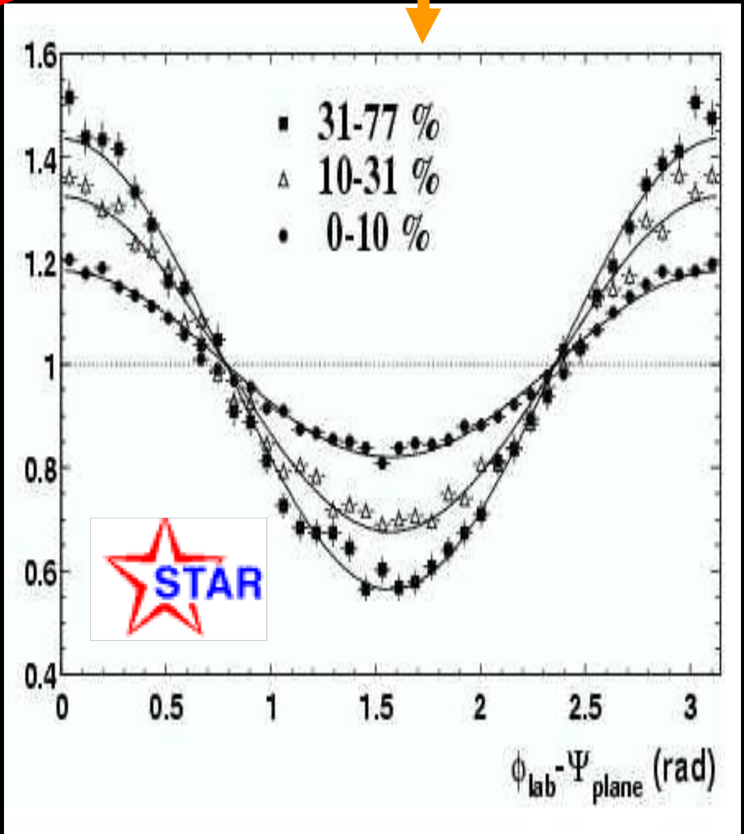
Elliptic Flow

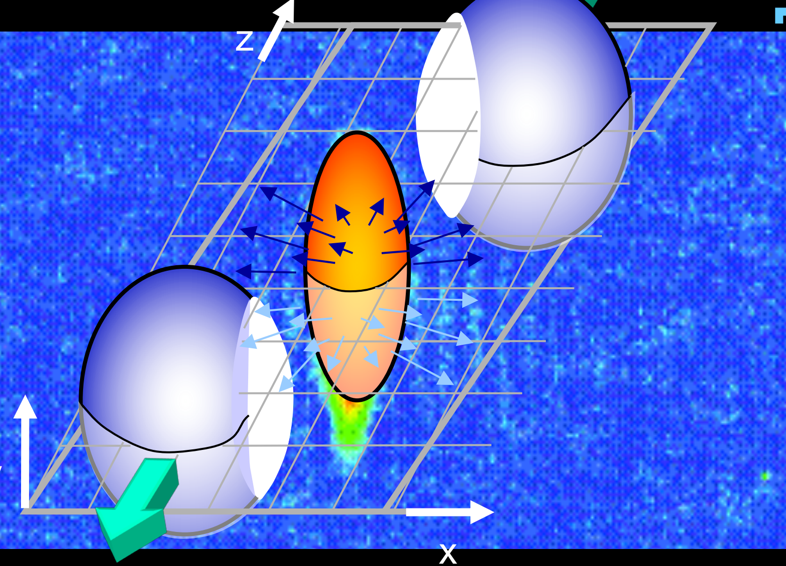


- Fourier decomposition of identified particle distributions event-by-event.
- **Azimuthal** elliptic **asymmetry found**

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$$







Elliptic Flow

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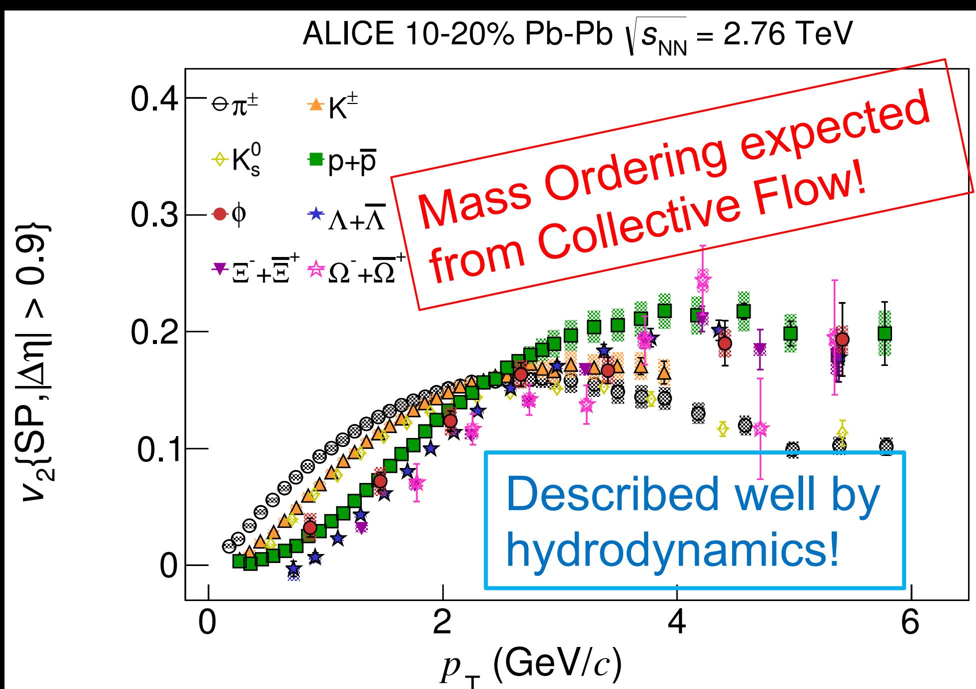
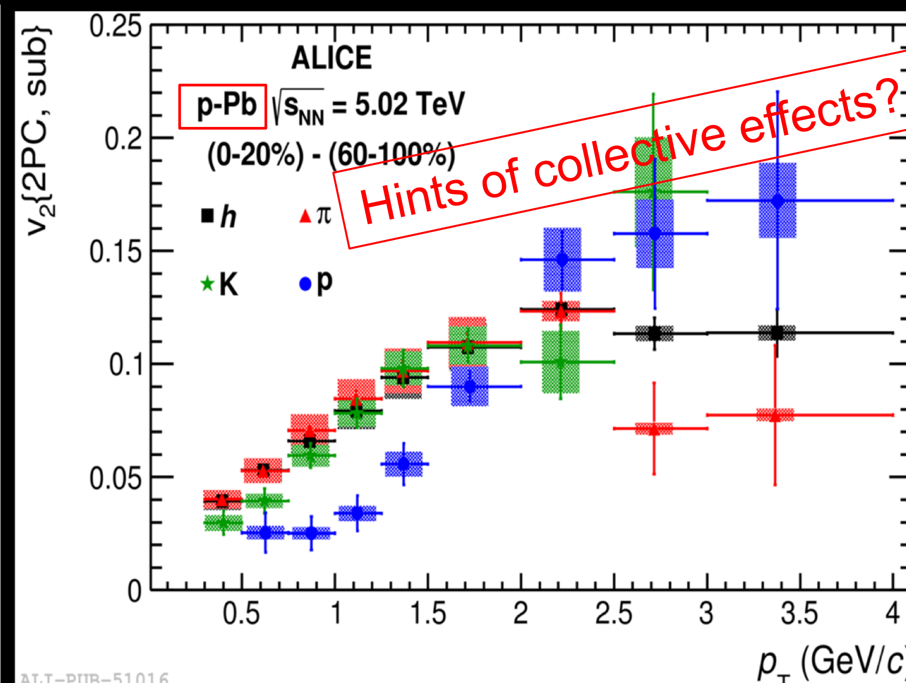
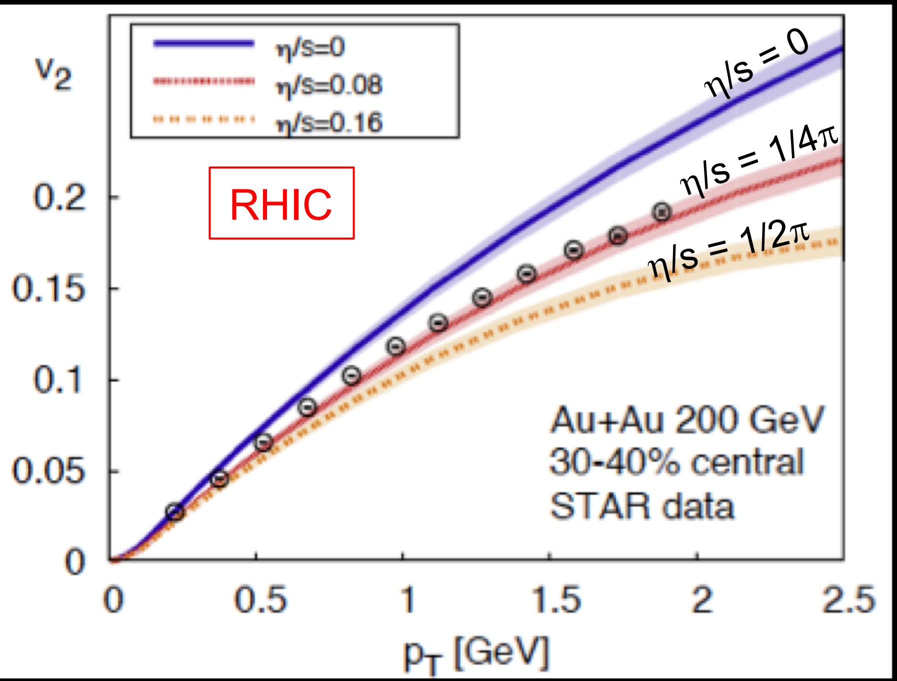
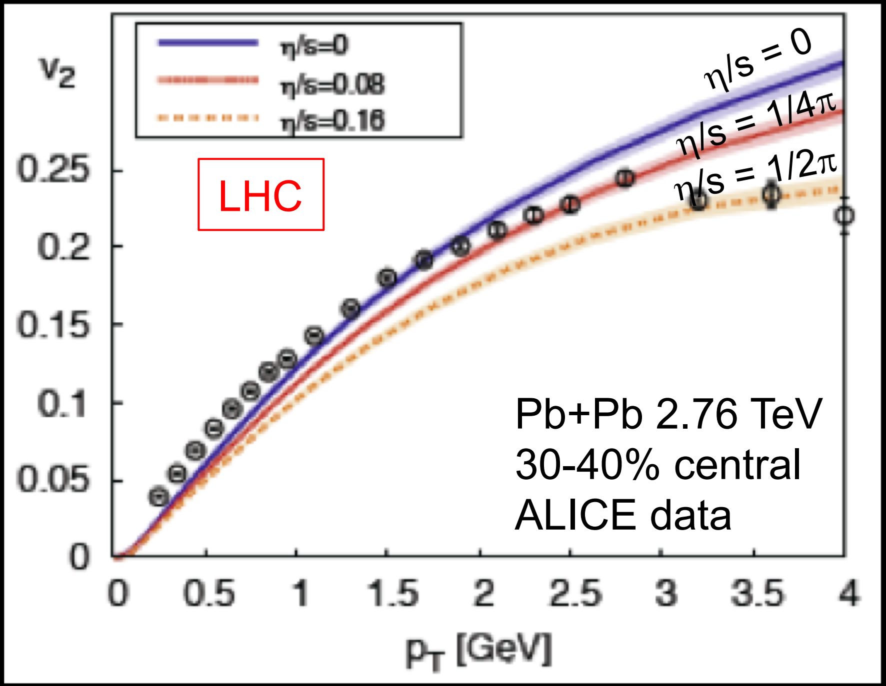




Flow Consequences → a Strongly-Coupled Medium with Ultra-low η/s (shear viscosity / entropy)





Viscous hydrodynamics calculations: Schenke, et al. PRL 106 (2011) 042301

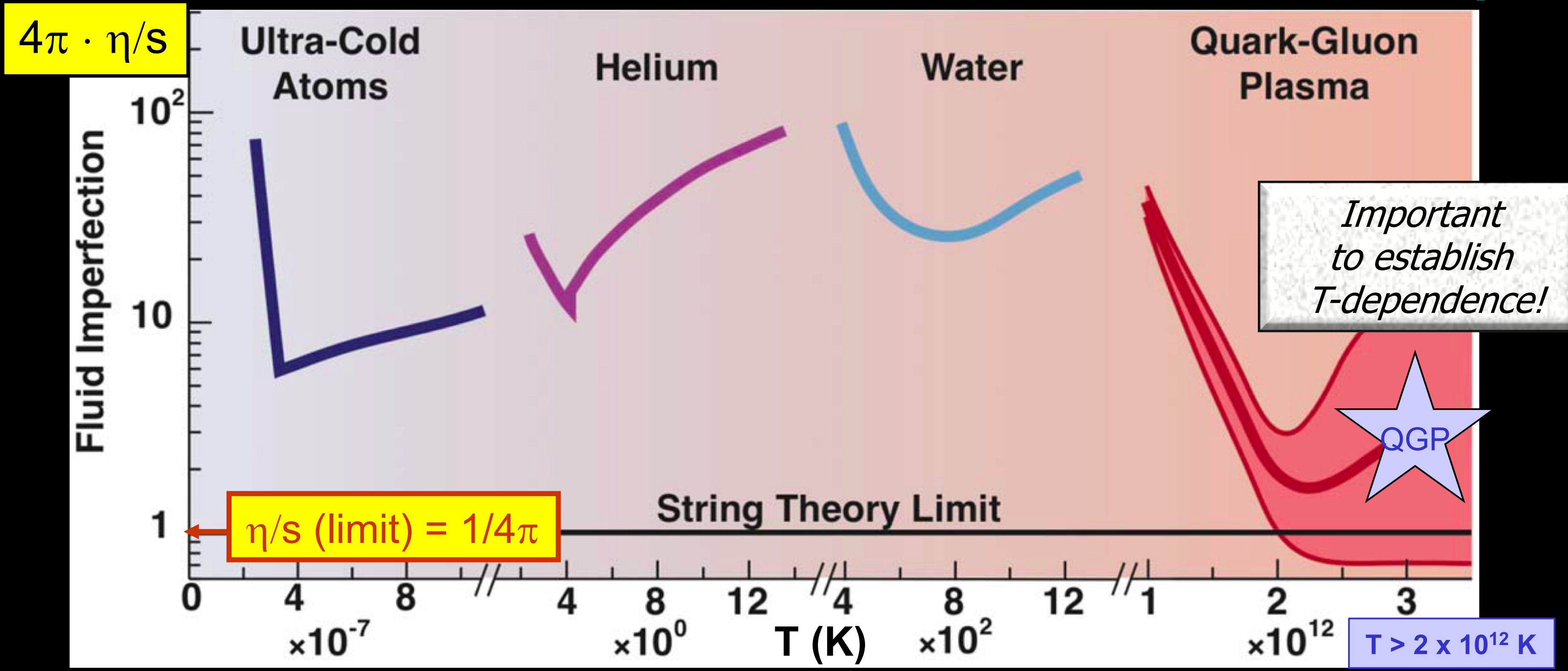
→ $1/4\pi < \eta/s < 1/2\pi$

Universal lower bound on shear viscosity / entropy ratio (η/s)

→ $\eta/s = 1/4\pi$ for a "perfect liquid"

from strong-coupling limit of non-Abelian gauge theories with a gravity dual
(ref: Kovtun, Son, Starinets, PRL 94, 111601 (2005))

Approaches Universal Lower Bound on η/s



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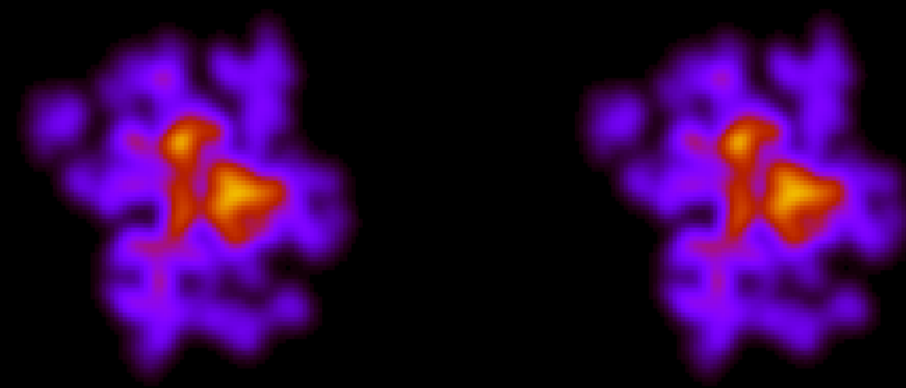
Effect of η/s Event-by-Event

Initial conditions vary event-to-event.

Overlap region (1 event): Kowalski, Lappi, Venugopalan, PRL 100:022303

Ideal $\eta/s = 0$ $\eta/s = 0.16\ (1/2\pi)$



t = 0.5 fm/c

Hydro evolution of overlap region: Schenke, et al. PRL 106:042301

Final observation

Final observation

Sound attenuation length:
$\Gamma_s = \eta/s * 1/T$
governs linear fluctuations.

Reynolds # ~ $1/\Gamma_s$
governs non-linear fluctuations.

Azimuthal RHI harmonics provide information on viscous damping & spatial correlations:

$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

Now let's turn from the study of

bulk phenomena

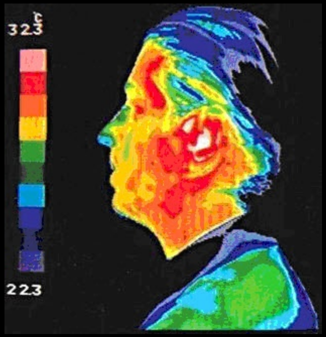
to

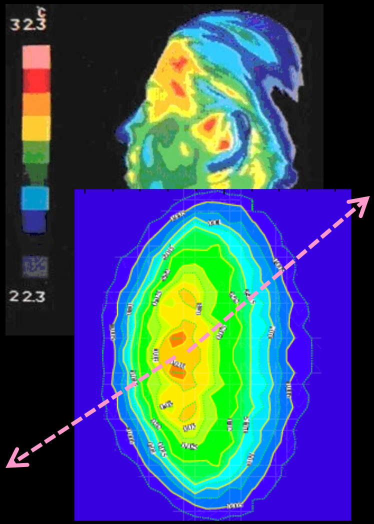
the use of penetrating probes!

i.e. high transverse momentum (p_T) particles and jets

The Use of Penetrating Probes (Hard Probes)

Highly penetrating observables (particles, radiation)
can be used
to explore properties of matter
that cannot be viewed directly!
→ "tomography"

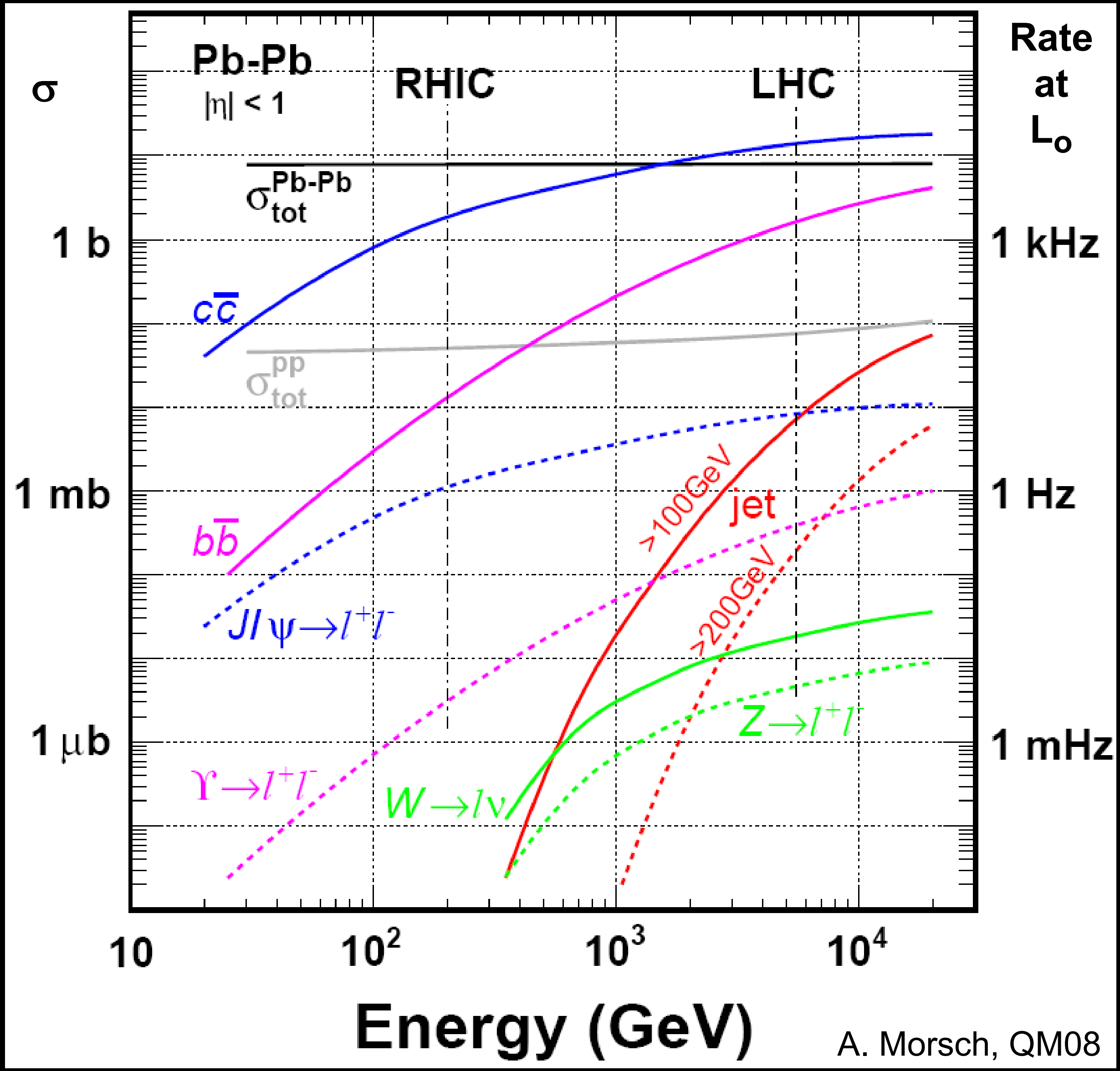




In QCD: Hard (highly penetrating) probes originate from hard scattering processes (where perturbative QCD applicable) and characterized either by:

- large 4-momentum transfer (Q^2)
- large transverse momentum (p_T)
- large mass scale (e.g. heavy quark production also at low p_T)

Yields of Hard Processes at LHC & RHIC

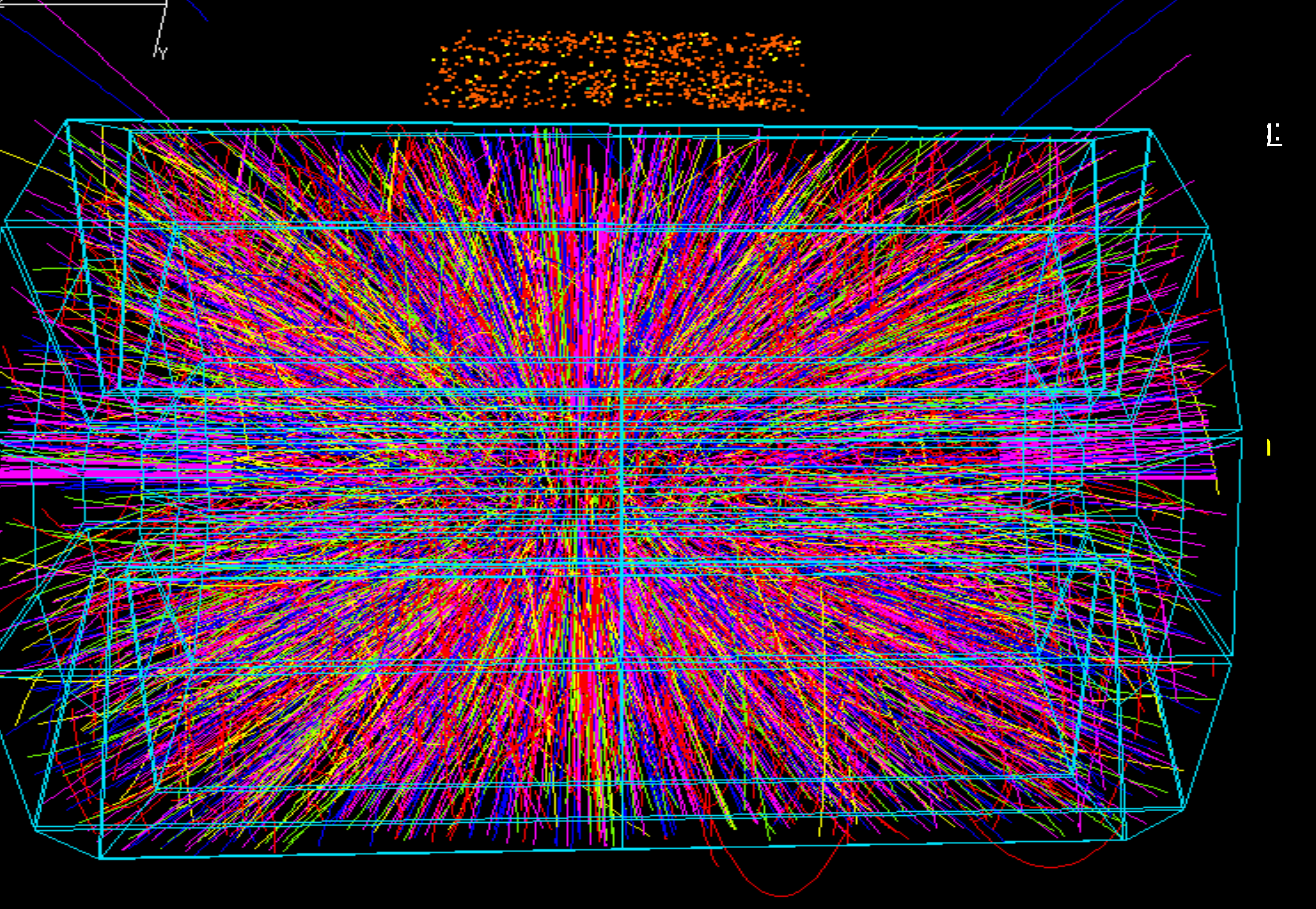


at LHC:

Strong onset of jets

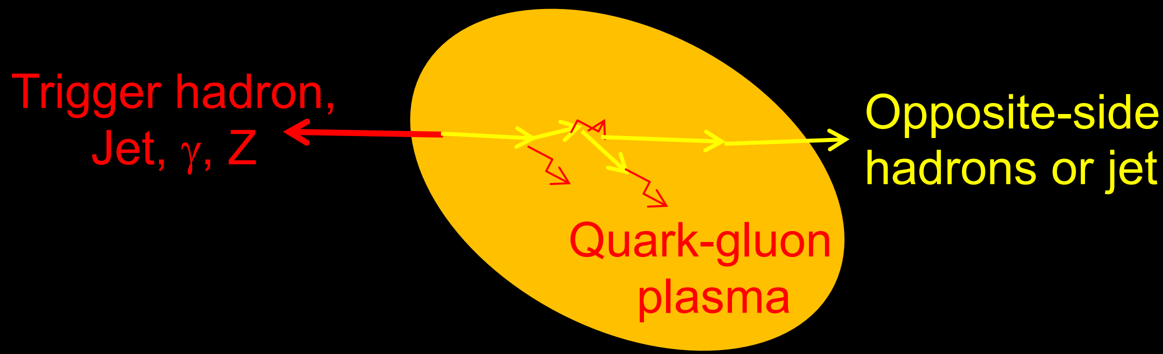
$\sigma_{cc} \to \sim 10\ \sigma_{cc}$ RHIC

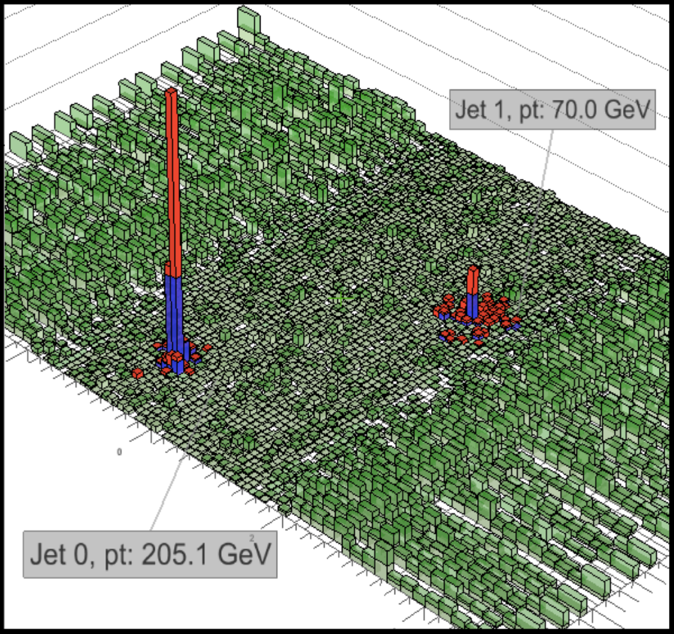
$\sigma_{bb} \to \sim 100\ \sigma_{bb}$ RHIC



High transverse momentum (p_T) particles are suppressed, jets are quenched (lose energy)

Trigger on jet or γ or Z-boson
Measure jet (or hadrons) on opposite side
→ determine energy difference



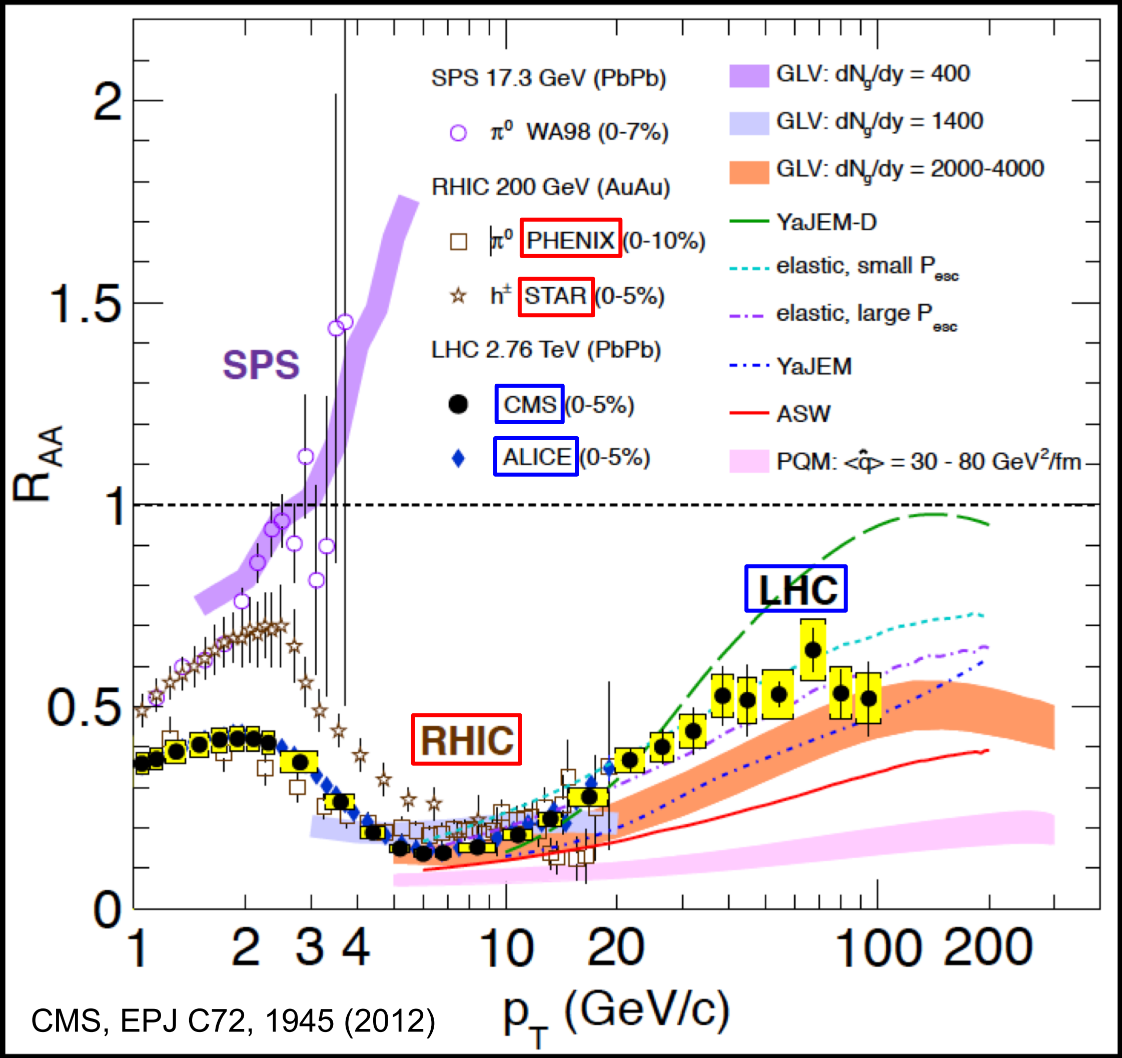


Measure pathlength L dependence

→ due to parton energy loss in the quark-gluon plasma

High p_T Hadrons Are Suppressed!

Pb-Pb (Au-Au) Central Collisions



$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

$R_{AA} = 1$

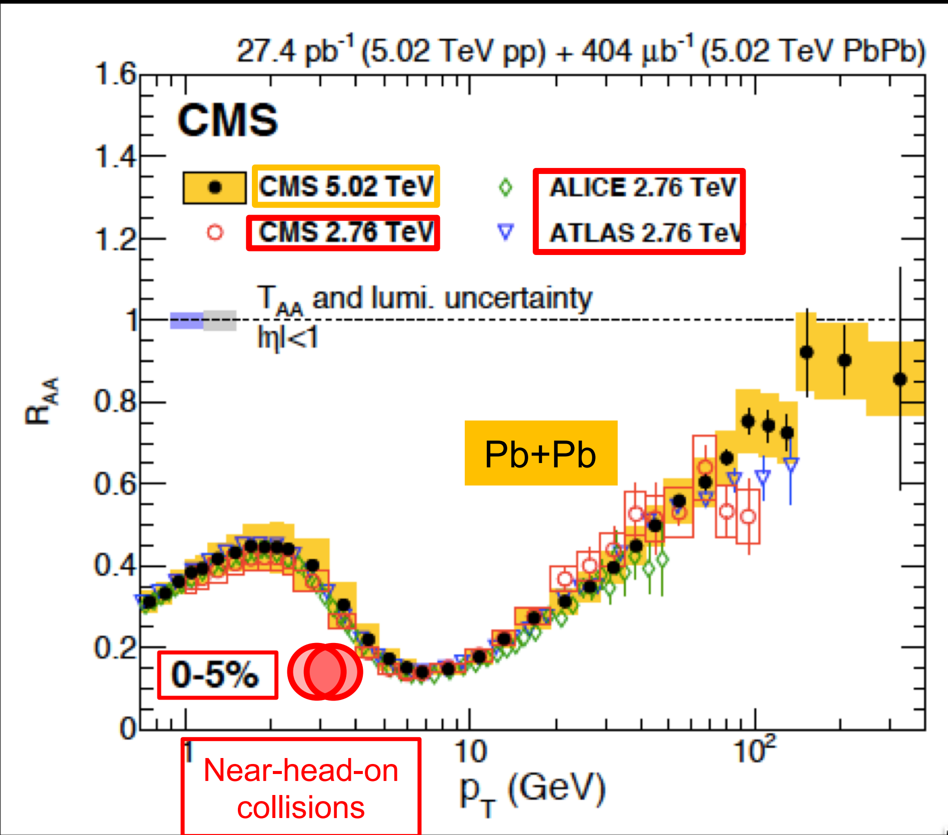
Suppression at RHIC & LHC
→ parton energy loss
in hot QCD medium

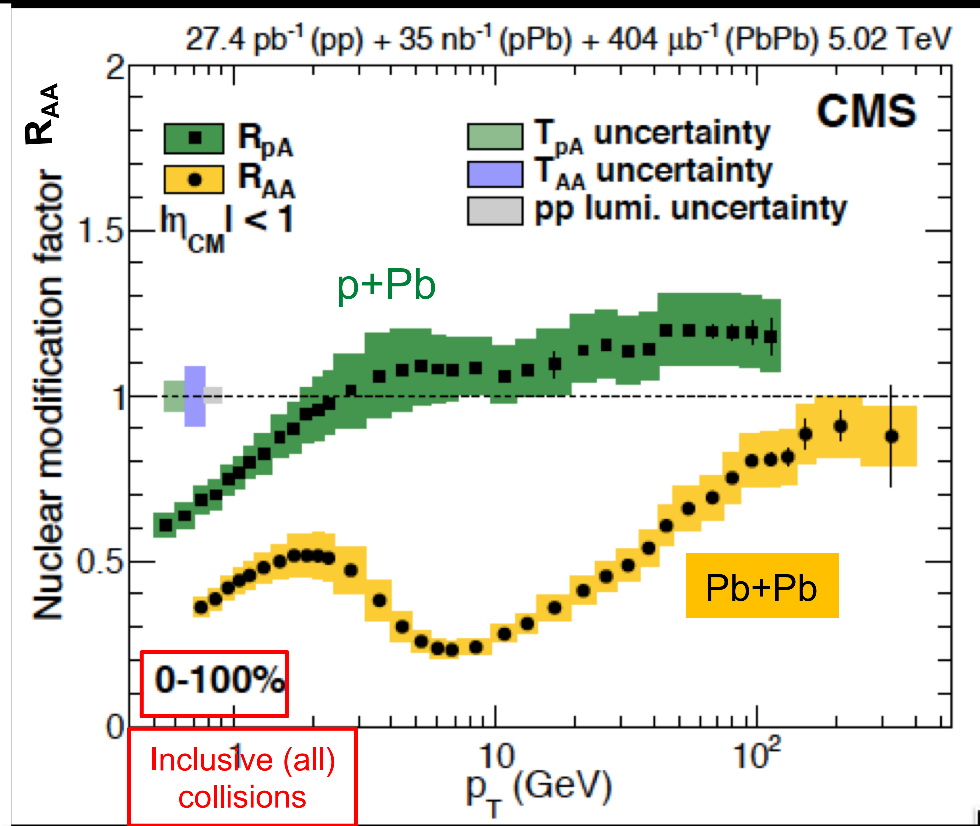
High p_T Hadrons Are Suppressed!

$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

$R_{AA} < 1$ Suppression wrt pp

$R_{AA} \sim 1$ similar to pp





→ *Pb+Pb suppression similar at 2.76 and 5.02 TeV*

→ *nearly goes away at highest p_T*

→ *p+Pb not suppressed slightly enhanced?*

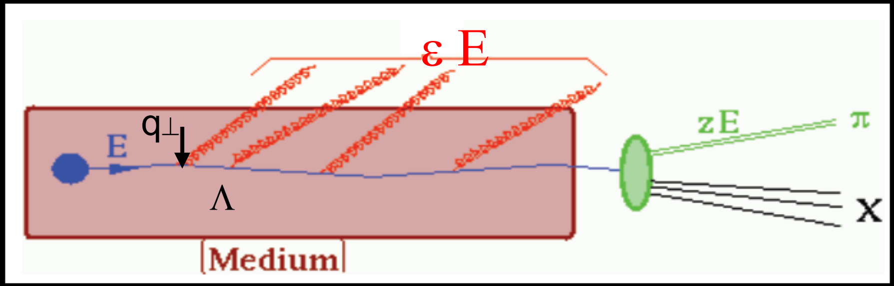
CMS arXiv: 1611.01664

Mechanisms of Parton Energy Loss?

Measure Parton Energy Loss & Disentangle effects!

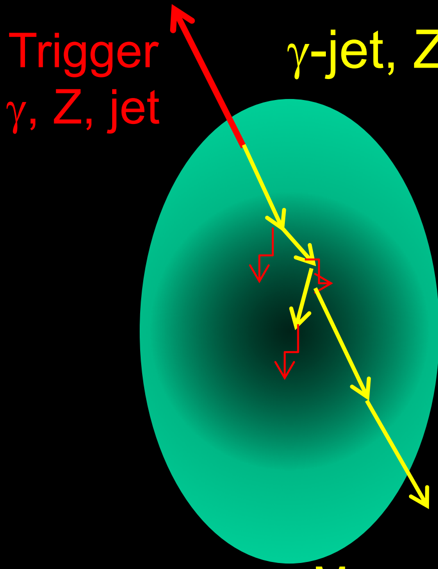
- Mass and color effects: $\Delta E_{gluon} > \Delta E_{quark,\ m=0} > \Delta E_{quark,\ m>0}$

  b-quark vs c-quark vs light-quark suppression!



- Establish initial parton kinematics for jets (before parton energy loss!):

  γ-jet, Z-jet, di-jets – γ and Z non-interacting in QGP!



Gluon vs quark suppression (color factor)

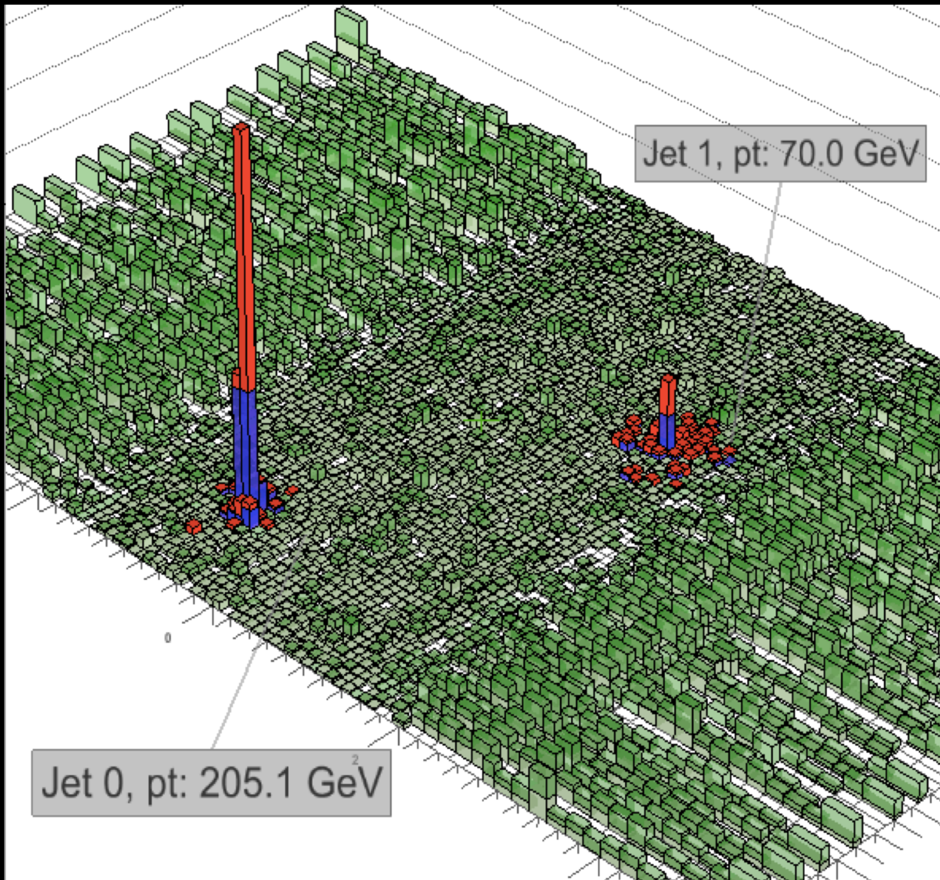
Measure dE/dx (color charge in QCD ala QED!)

Virtuality of partons different at RHIC & LHC?

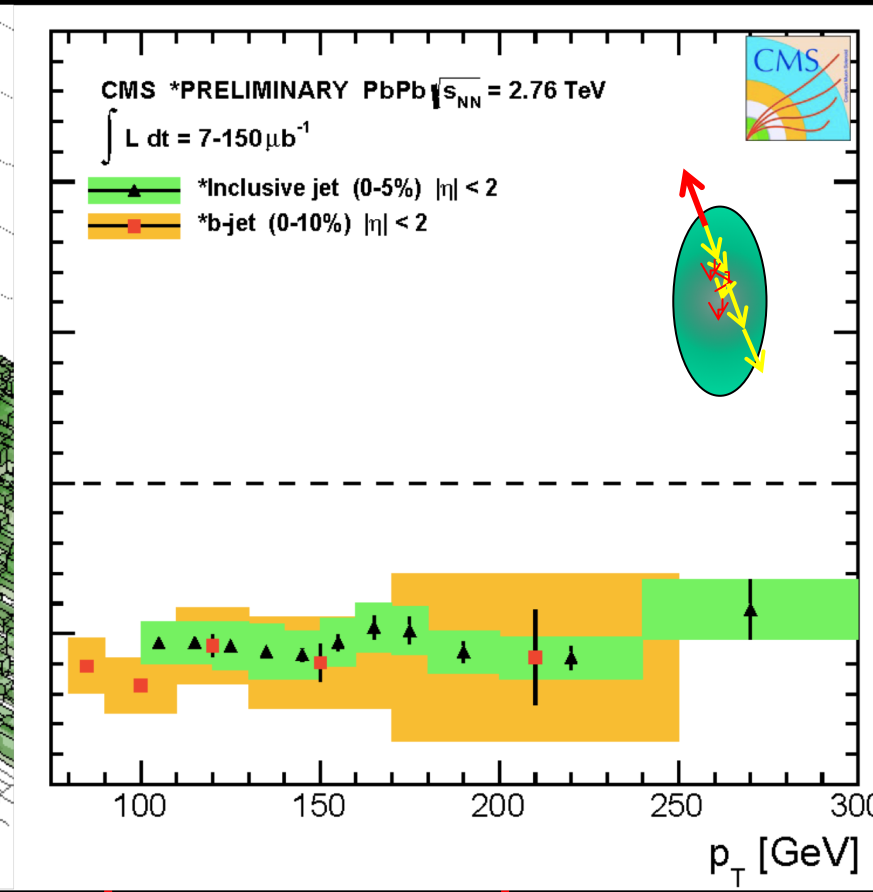
Measure pathlength L dependence

Jets Are Quenched – Flavor Independence?

High p_T Particles



High p_T Jets



Same range of parton p_T

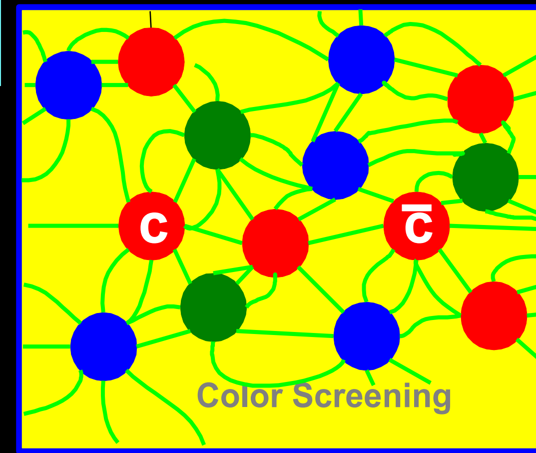
EPJC 72 (2012) 1945
PLB 715 (2012) 66
PLB 710 (2012) 256

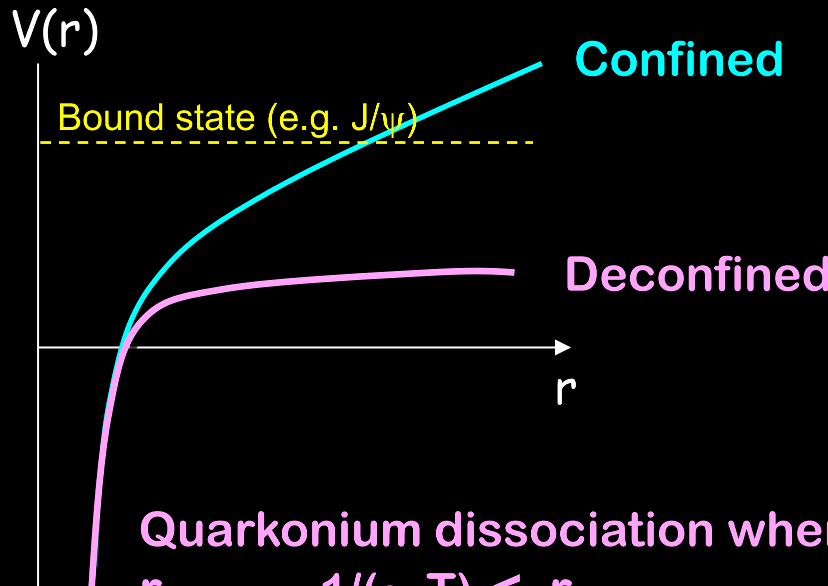
Jets quenched – even at largest jet p_T (250 GeV/c)

5 Quarkonium Suppression

Quarkonia: $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: ϒ'', ϒ', ϒ

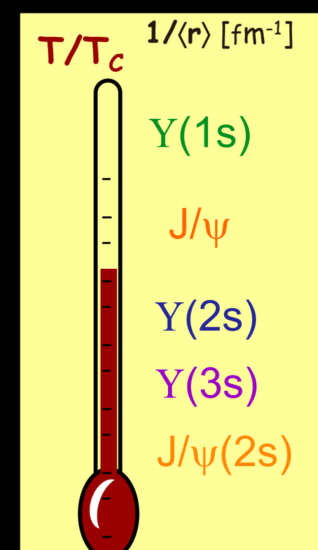
Debye color screening in the QGP →





Color screening of $c\bar{c}$ pair results in J/ψ ($c\bar{c}$) suppression!

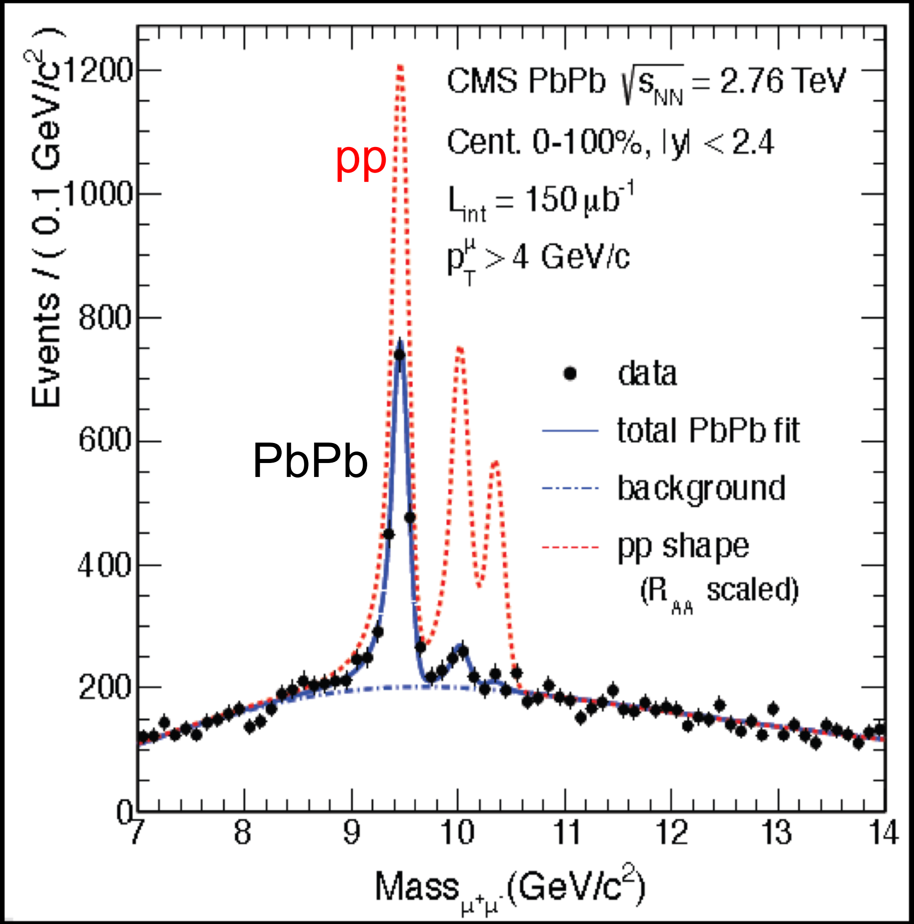
Quarkonium dissociation when $r_{Debye} \sim 1/(\alpha_s T) < r_{qq}$

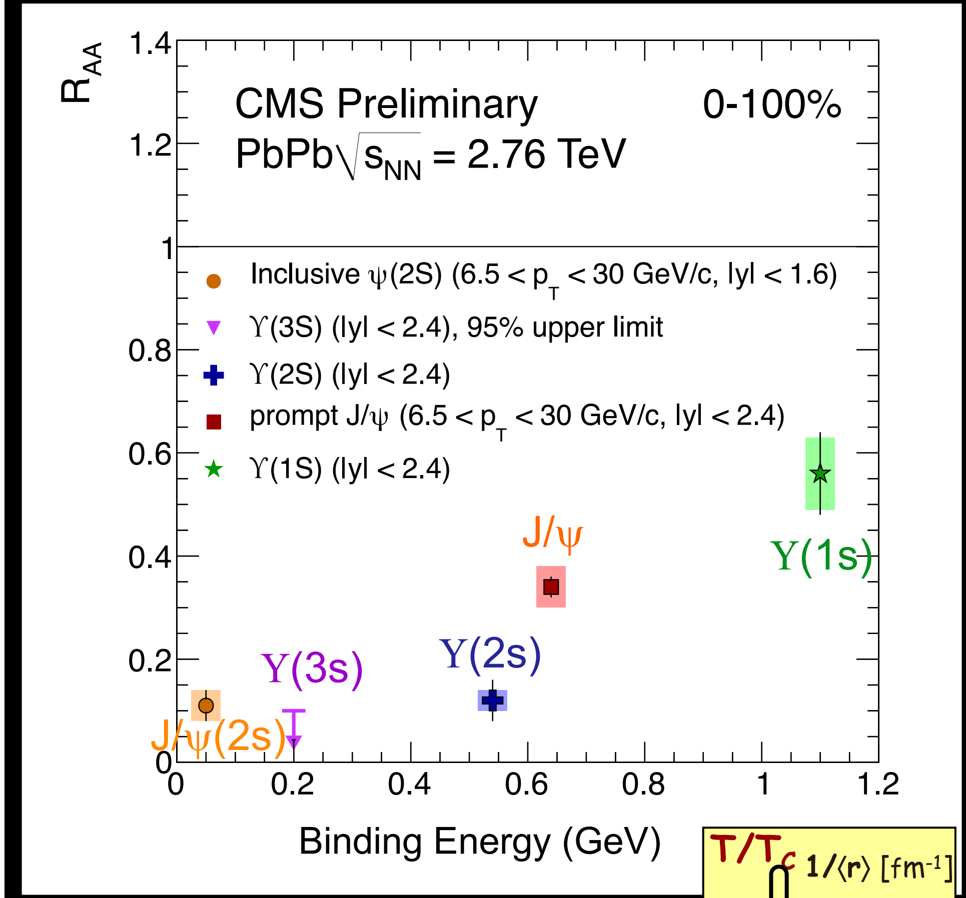


Measure melting order of $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: ϒ'', ϒ', ϒ

Quarkonia – J/Ψ and Υ – Are Suppressed

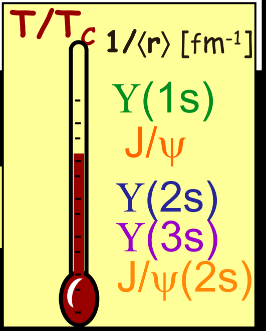
CMS, PRL 107 (2011) 052302





Suppression of Quarkonium States Expected from color screening in a hot QCD Medium!

Quarkonium Thermometer!

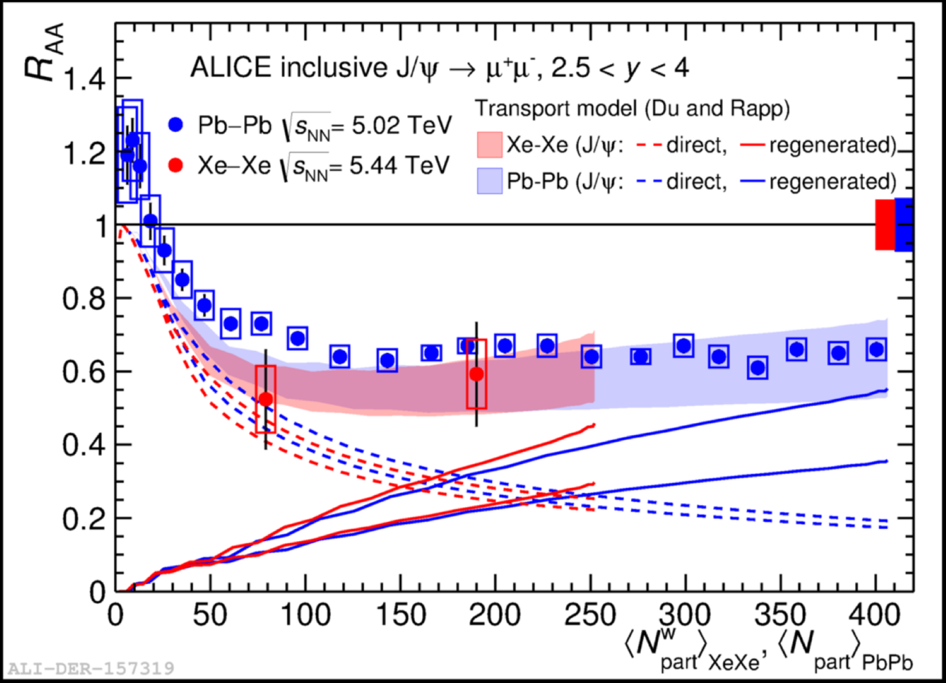


J/Ψ Suppression at LHC Compared to RHIC

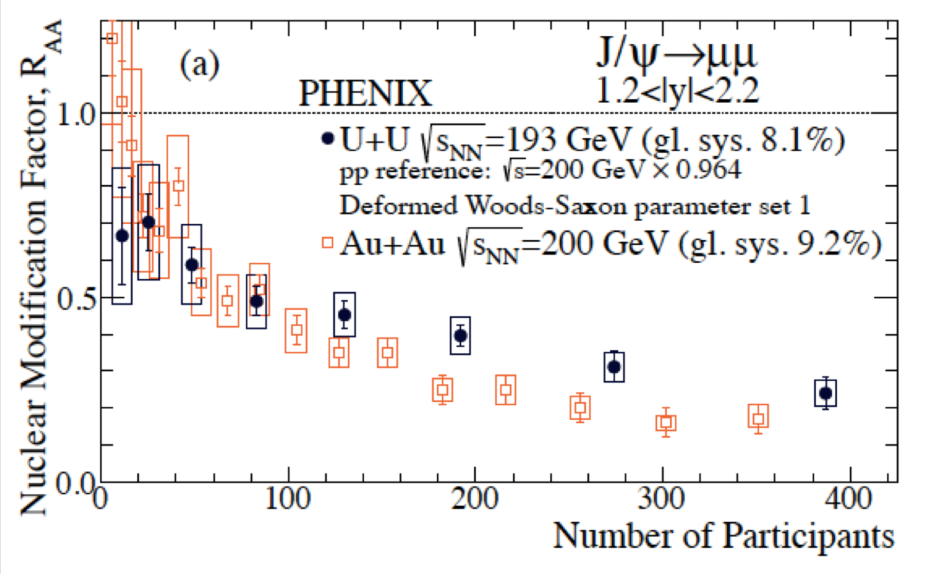
J/Ψ: R_{AA} (LHC) > R_{AA} (RHIC)

→ less apparent suppression at LHC?

ALICE, arXiv:1805.04383



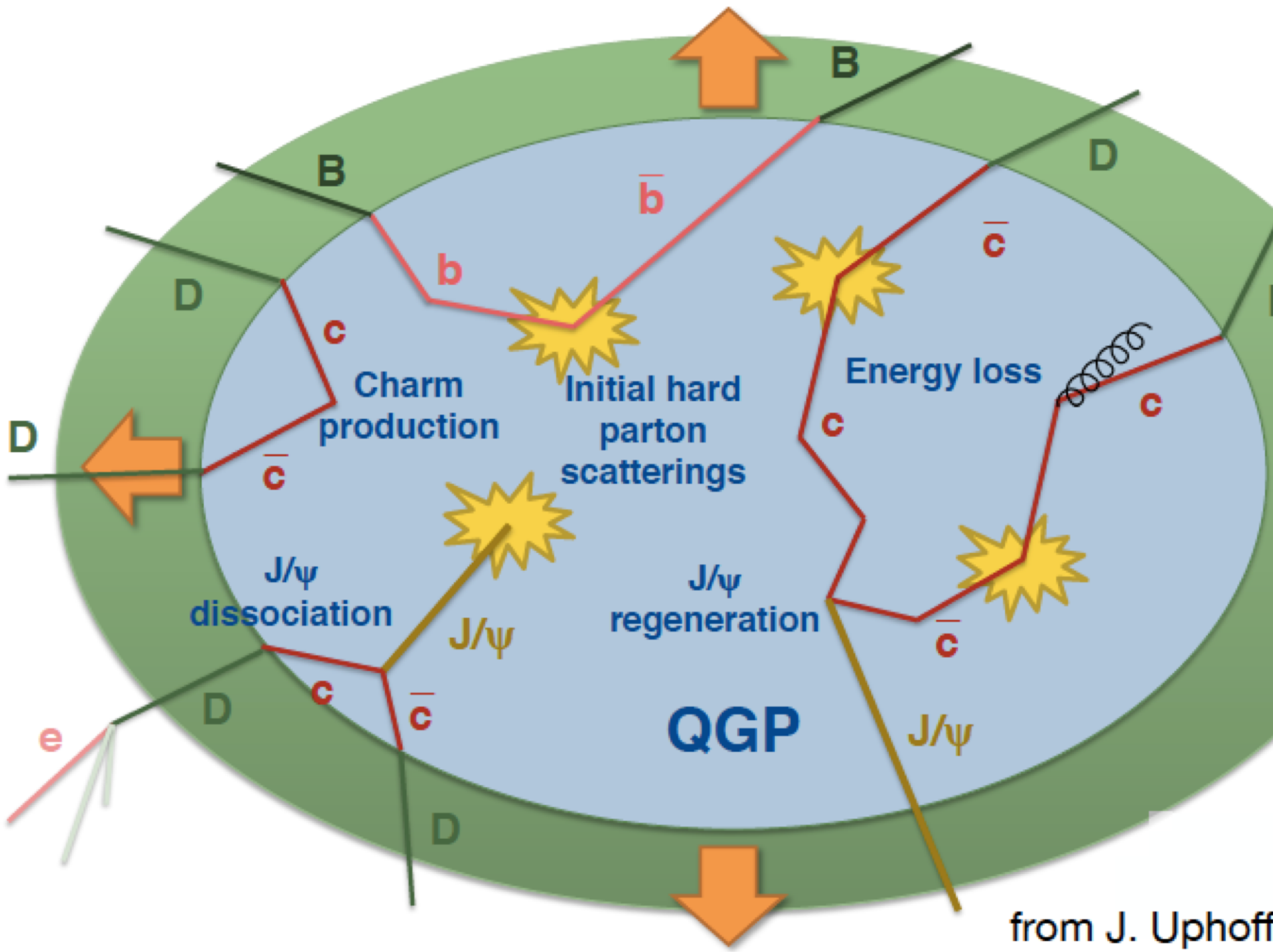
PHENIX, Phys. Rev. C 93, 034903 (2016)



Pb-Pb and Xe-Xe at LHC:
Transport models ~ stronger suppression & more regeneration in Xe-Xe vs Pb-Pb

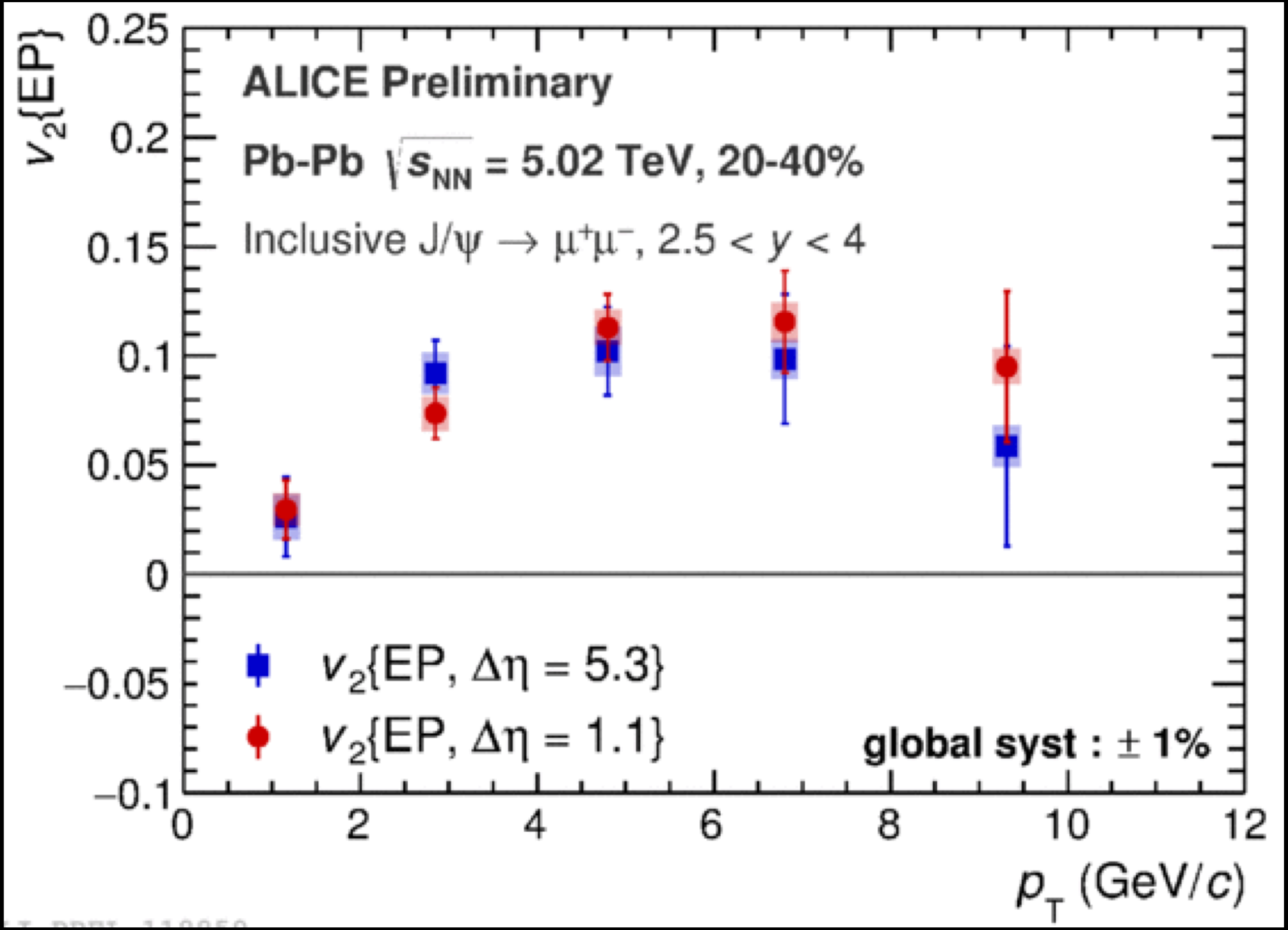
J/y in fact has significant regeneration (recombination of c c-bar quarks) at LHC

J/Ψ Suppression at LHC Compared to RHIC



J/y in fact has significant regeneration (recombination of c c-bar quarks) at LHC

J/Ψ Exhibits Collective Flow



New ALICE J/Ψ results at 5.02 TeV in Pb+Pb exhibit significant J/Ψ flow (v_2).

It appears that the J/ψ ($c\bar{c}$) suppression leads to c and $\bar{c}$ quarks that recombine later after picking up the collective motion of the system!

Quark Matter 2017-18

Big Take-aways from Heavy Ions at the LHC

Pb+Pb

System evolves rapidly to a thermalized state where particle yields reflect equilibrium abundances near universal hadronization $T_{critical}$

Collective flow observed a Strongly-Coupled quark-gluon plasma is created with ultra-low shear viscosity / entropy (i.e. a nearly perfect hot liquid of quarks and gluons)

High transverse momentum (p_T) hadrons are suppressed, jets quenched
→ partons lose energy in the quark-gluon plasma (leads to properties!)

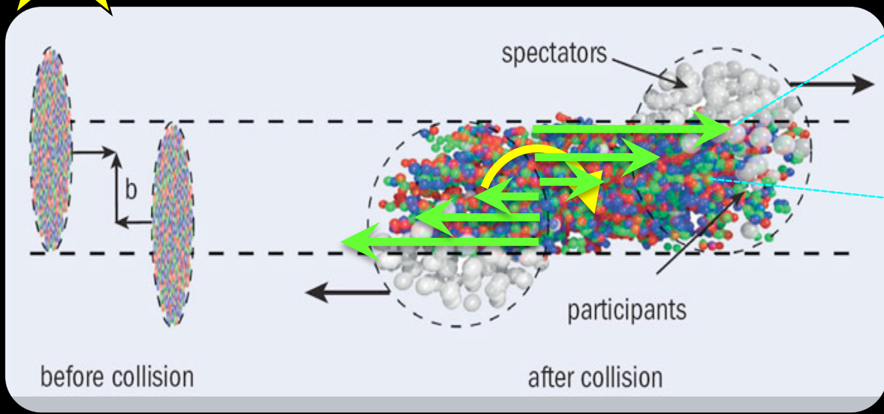
J/Ψ and Υ suppressed
→ indicate color screening of $c\bar{c}$ and $b\bar{b}$ quarks leading to suppression and deconfinement of quarks [modulo LHC vs RHIC Differences]

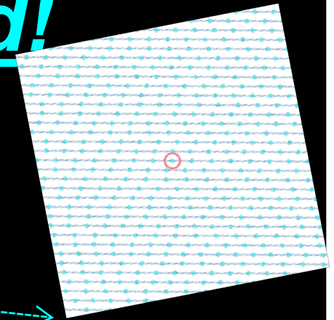
High multiplicity p+p, p+Pb

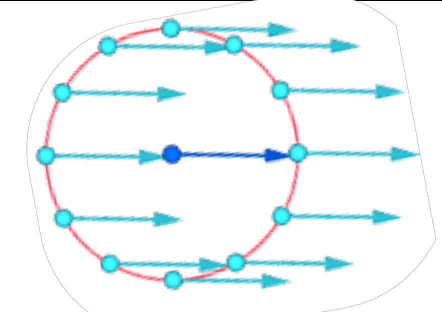
"What are the properties of the quark-gluon plasma & what is the smallest droplet of QCD matter that behaves like a liquid?"

Some Very New & Exciting Results

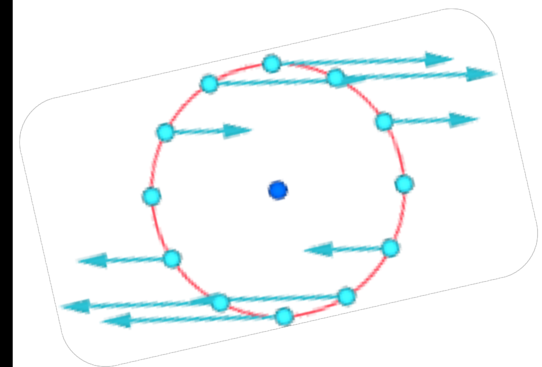
A Spinning QGP Fluid!







Global c.m. frame



Local fluid cell frame

Non-central collisions
angular momentum ~ 1000 ħ

Vorticity: $\vec{\omega} = \frac{1}{2}\vec{\nabla}\times\vec{v}$

Collision generates a "spinning QGP"

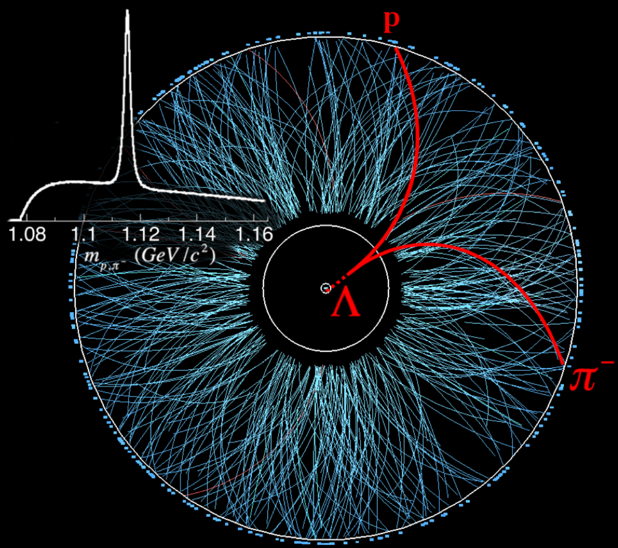
A large vorticity is measured!

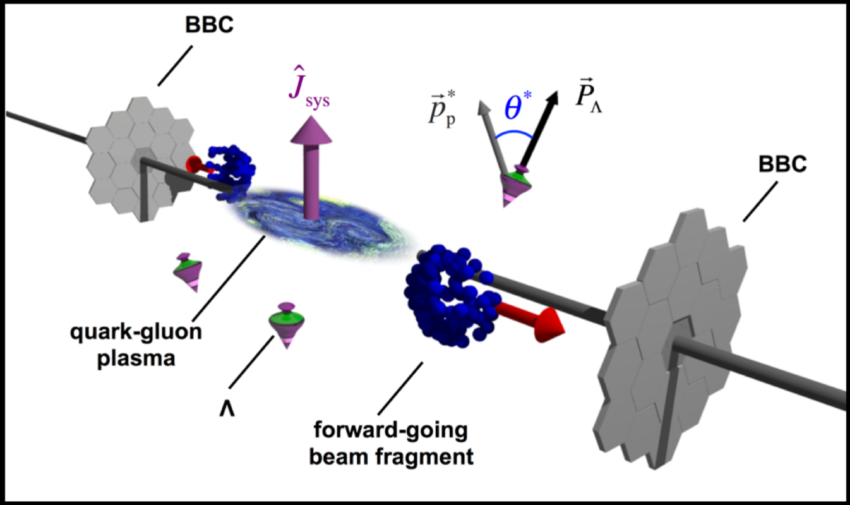
Nature 548, 62–65 (2017),
STAR Collaboration

Local orbital angular momentum (vorticity), transferred to spin degree of freedom of final-state hadrons, is measured!

Graphics courtesy M. Lisa and Wikipedia

STAR



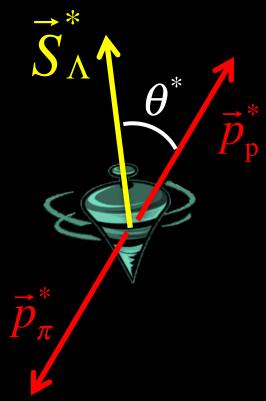


Forward BBCs estimate Reaction Plane: $\vec{B} \parallel \vec{\omega} \parallel \hat{J}_{sys}$

Λ Baryon is "self-analyzing"

- reveals its polarization by preferentially emitting daughter proton in spin direction

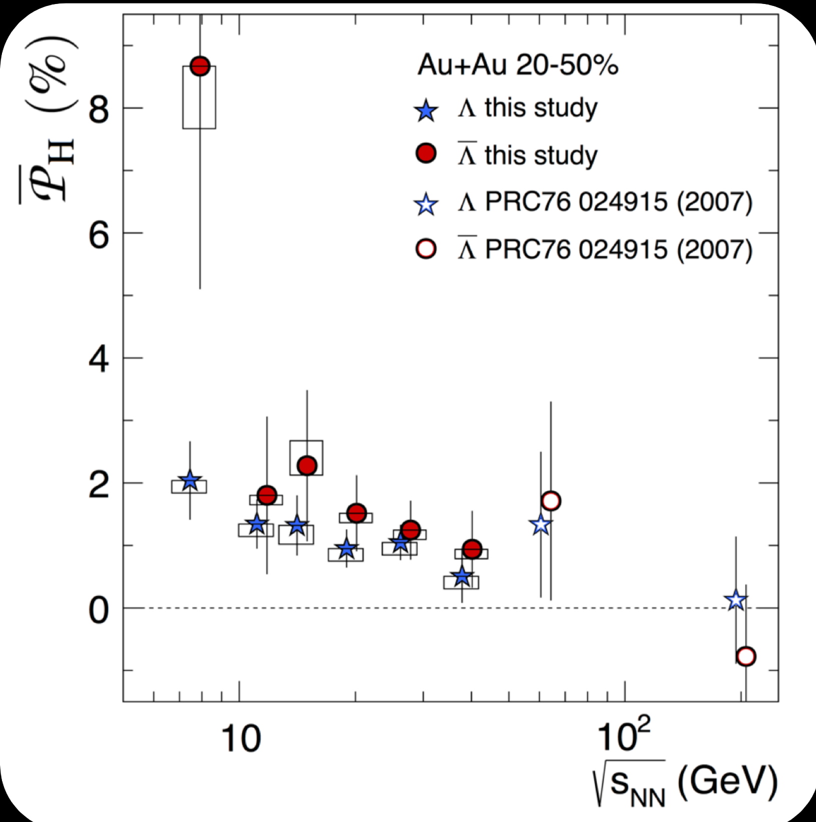
E. Cummins, Weak Interactions (McGraw-Hill, 1973)



$$\Lambda \rightarrow p + \pi^-$$

Correlate $\vec{p}^{\,*}_{p}$ and $\hat{J}_{sys}$

STAR Nature Result



$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	14.5	19.6	27	39
Λ	3.6σ	3.5σ	2.4σ	3.1σ	3.5σ	1.1σ
anti-Λ	2.2σ	2.1σ	1.1σ	2.4σ	2.9σ	1.6σ

	BES average
Λ	6.8σ
anti-Λ	3.7σ

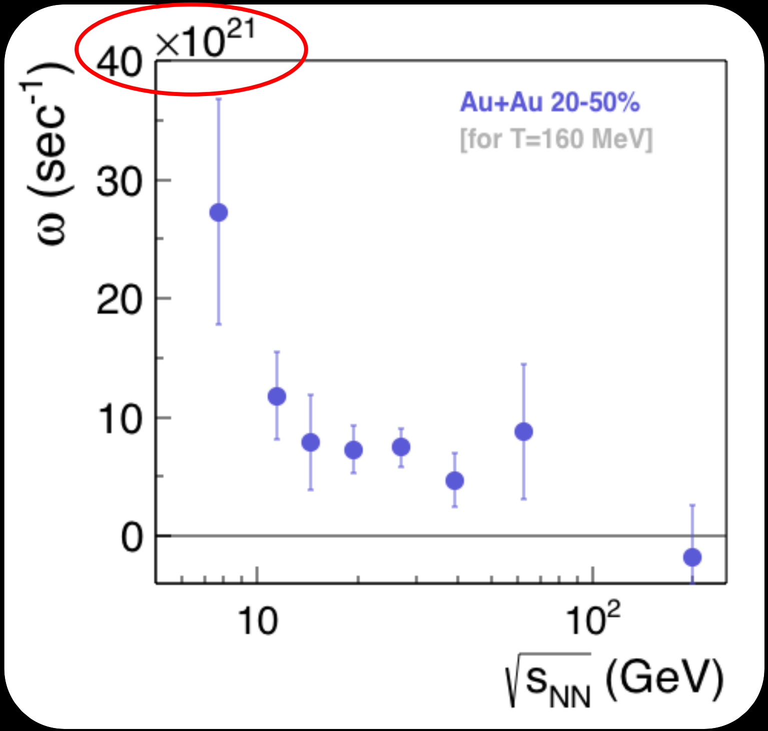
How is fluid/transport affected?

- Localized vortex generation
- Viscosity dissipates vorticity at larger scale

Vorticity – a fundamental (sub-femtoscopic) structure of the QGP and its generation

Nature 548, 62–65 (2017), STAR Collaboration

From a Global Perspective

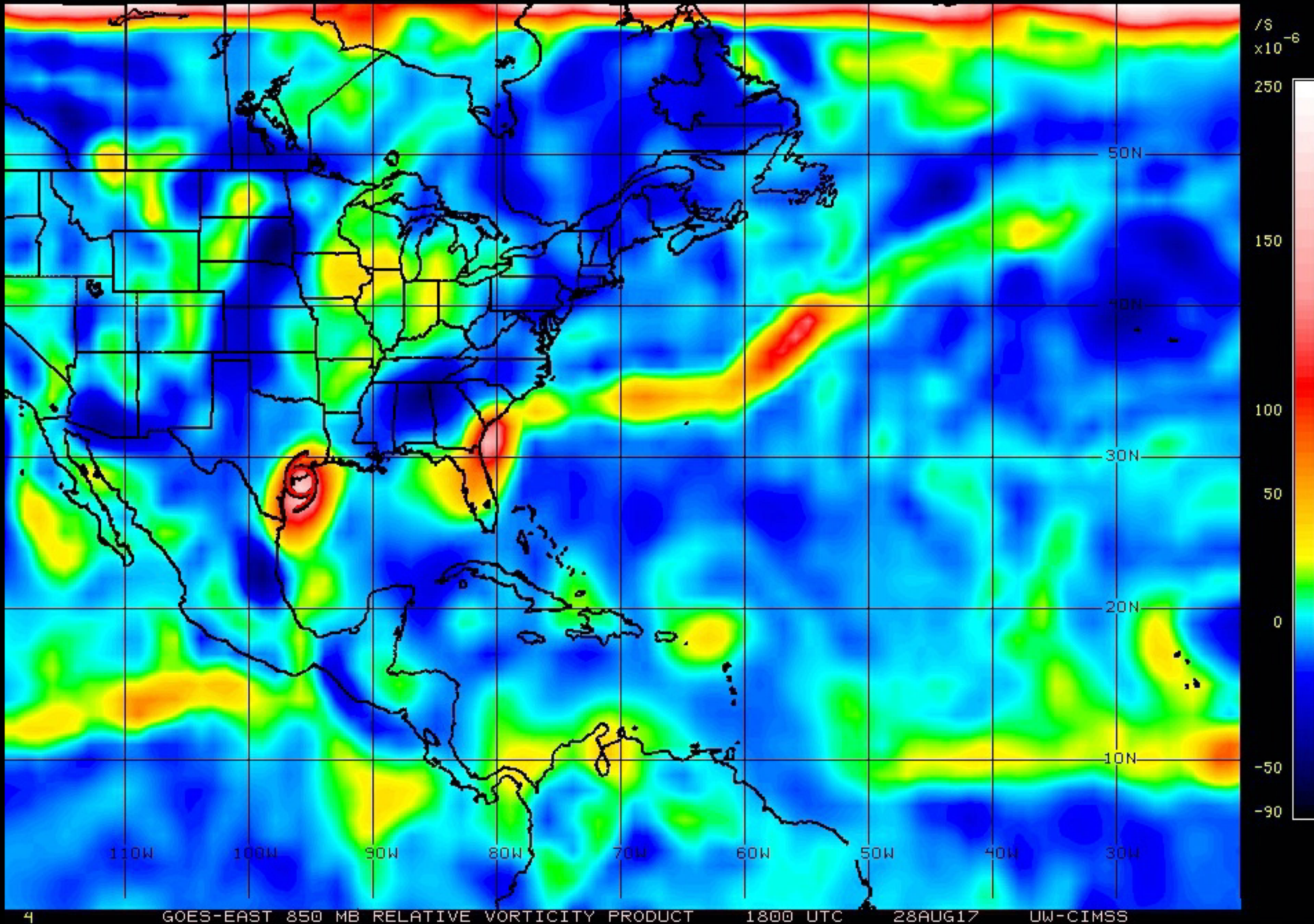


- Solar subsurface flow: $\omega \sim 10^{-6}$ s^{-1}
- Ocean flows: $\omega \sim 10^{-5}$ s^{-1}
- Terrestrial atmosphere: $\omega \sim 10^{-4}$ s^{-1}
- High vorticity (10^{-4} s^{-1}) in the "collar" of Jupiter's Great Red Spot
- Core of supercell tornado : $\omega \sim 10^{-1}$ s^{-1}
- Heated, rotating soap bubbles: $\omega \sim 10^{2}$ s^{-1}

- Max vorticity in bulk superfluid He: $\omega \sim 150$ s^{-1}
  - R. Donnelly, Ann. Rev. Fluid Mech. 25, 325 (1993)
- Max vorticity in nanodroplets of superfluid He: 10^{6} s^{-1}
  - Gomez et al, Science 345 (2014) 906

Nature 548, 62–65 (2017), STAR Collaboration

An Aside – a Global Perspective

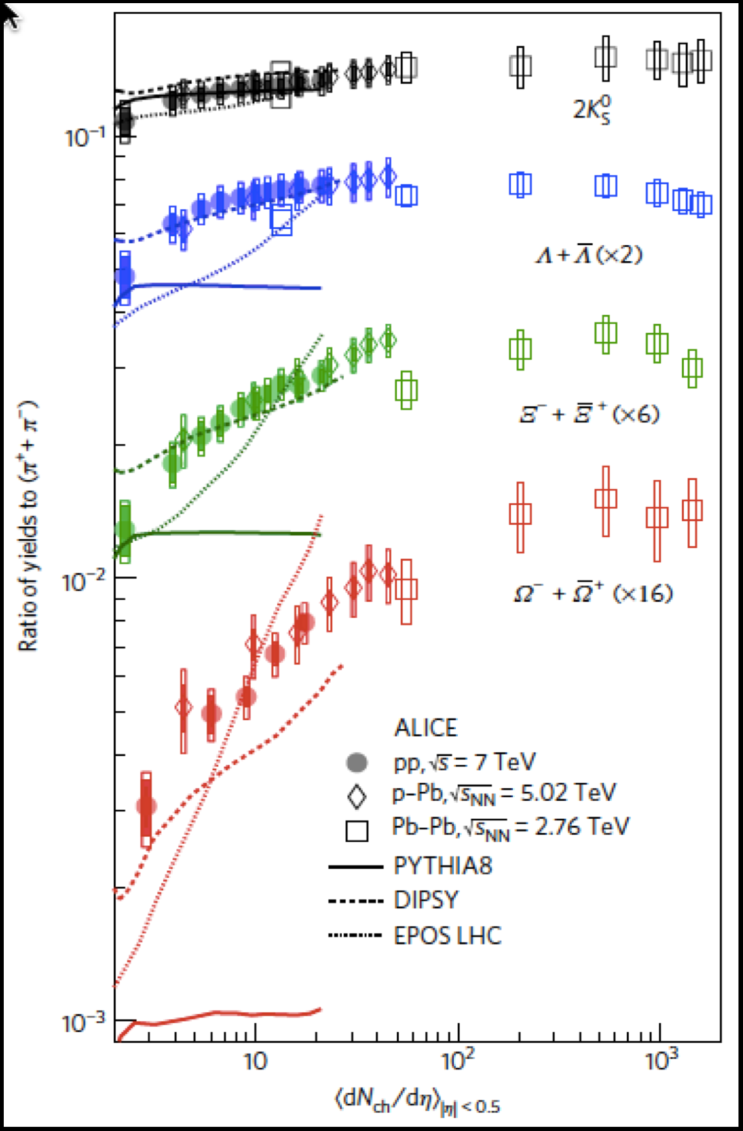


Atmospheric vorticity 31 Aug – 2 Sept 2017 (Harvey)
http://tropic.ssec.wisc.edu/real-time/windmain.php?&basin=atlantic&sat=wg8&prod=vor&zoom=&time=

★ Enhanced production of multi-strange hadrons in high-multiplicity pp collisions

Nature Physics 13, 535–539 (2017), ALICE Collaboration

- Strangeness enhanced in high multiplicity pp
- At high multiplicity pp reaches values where Pb-Pb saturates
- pp and p-Pb ratios have similar behavior and values
- No apparent dependence on cm energy
- Models cannot reproduce pp data!

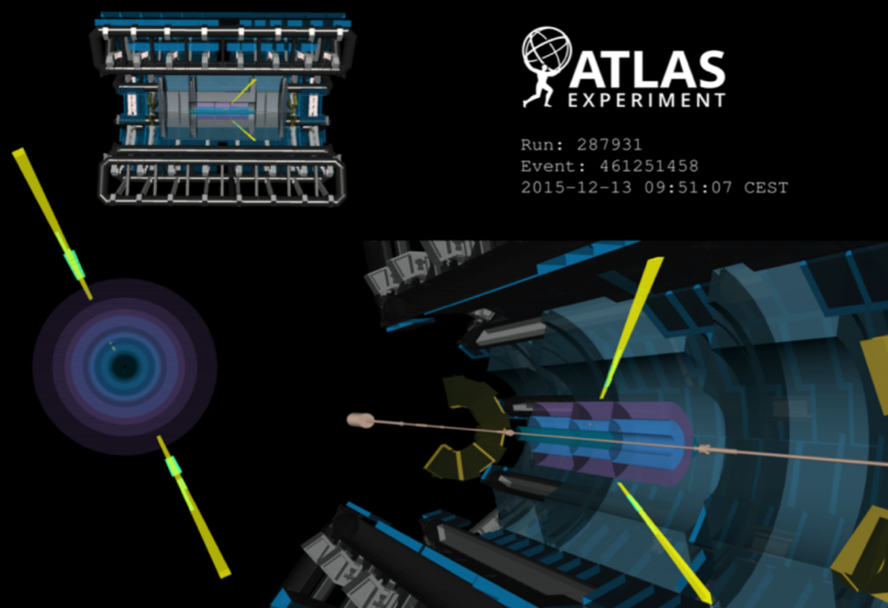


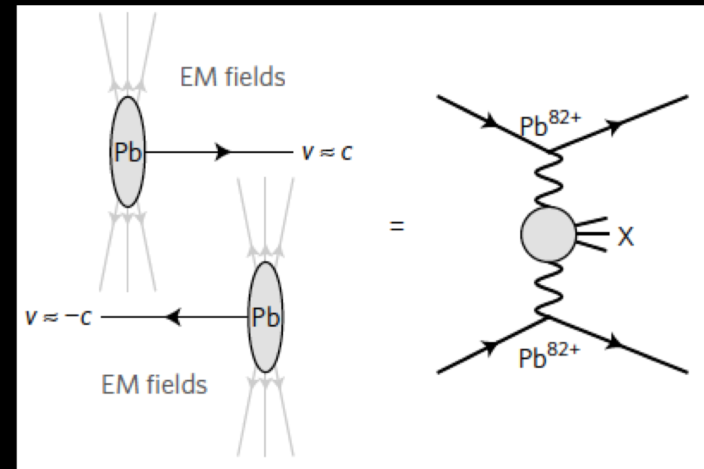
Photon-photon Scattering in Pb-Pb

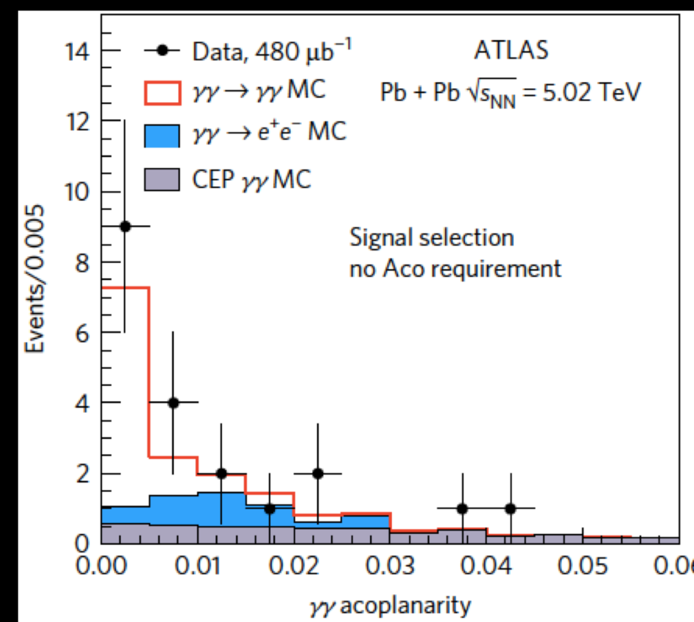
Nature Physics 13, 852–858 (2017), ATLAS Collaboration

5.02 TeV Pb-Pb “Ultra-peripheral Collisions”

Coherent production enhanced by
$Z^4 \sim 4.5\text{x}10^7$ in Pb-Pb relative to pp





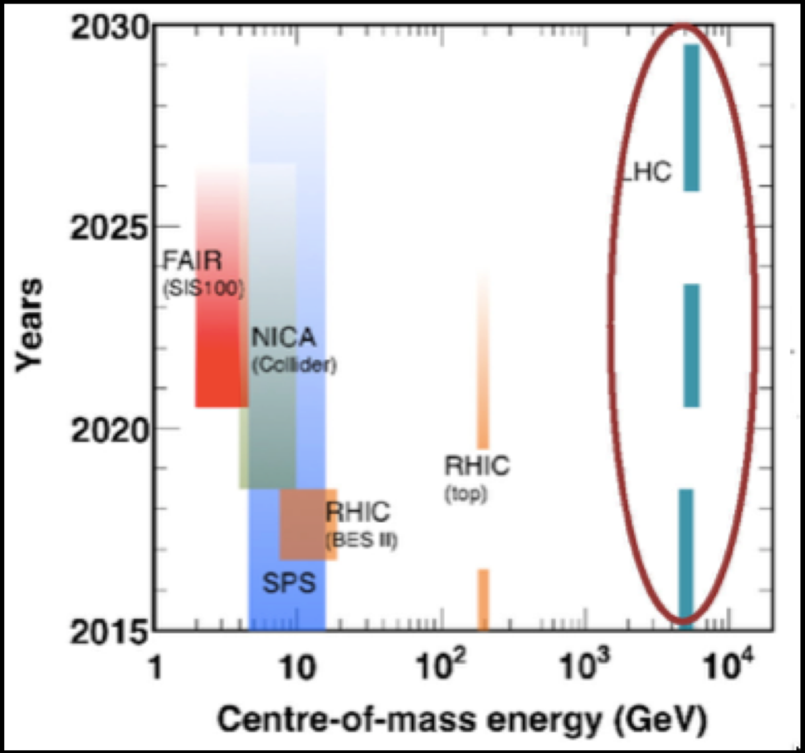


Back-to-back γ ($m_{\gamma\gamma}$=24 GeV)
with no other production

Significance vs background = 4.4

Future

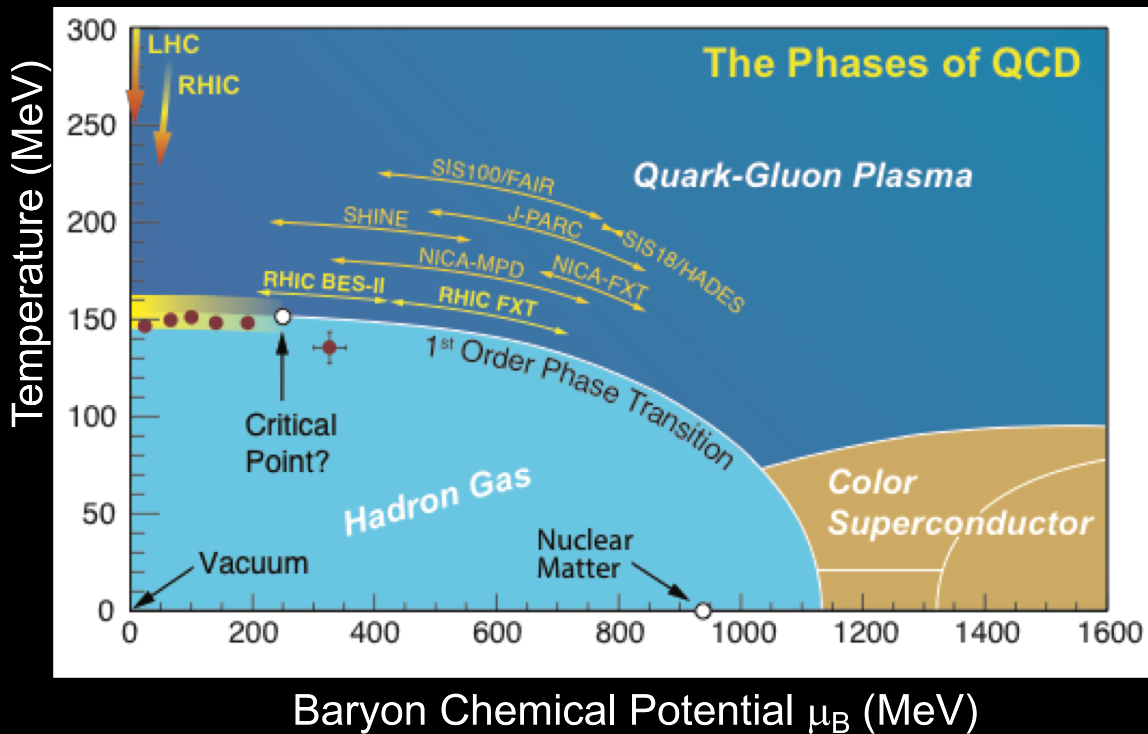
“Near Term” Heavy Ion Data



Unofficial Heavy Ion Operation (data taking) Periods

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
LHC	pp (5 TeV)	Pb-Pb (5 TeV)	Long Shutdown 2	Long Shutdown 2	Pb-Pb (50 kHz)	Pb-Pb (50 kHz)	Pb-Pb (50 kHz)	Long Shutdown 3	Long Shutdown 3	Run-4
RHIC	completed	Isobar Run Ru+Ru, Zr+Zr (200 GeV)	Beam Energy Scan 2 Au+Au (3 - 20 GeV)	Beam Energy Scan 2 Au+Au (3 - 20 GeV)	tbd	Shutdown for sPHENIX installation	sPHENIX	sPHENIX?	EIC construction!	EIC construction!

Investigating Phase Diagram - Lower Energies



Results from RHIC BES 1 suggest:

- QGP "turns off" at low √s
- 1st order phase transition?
- Presence of critical point?
- Chiral restoration?

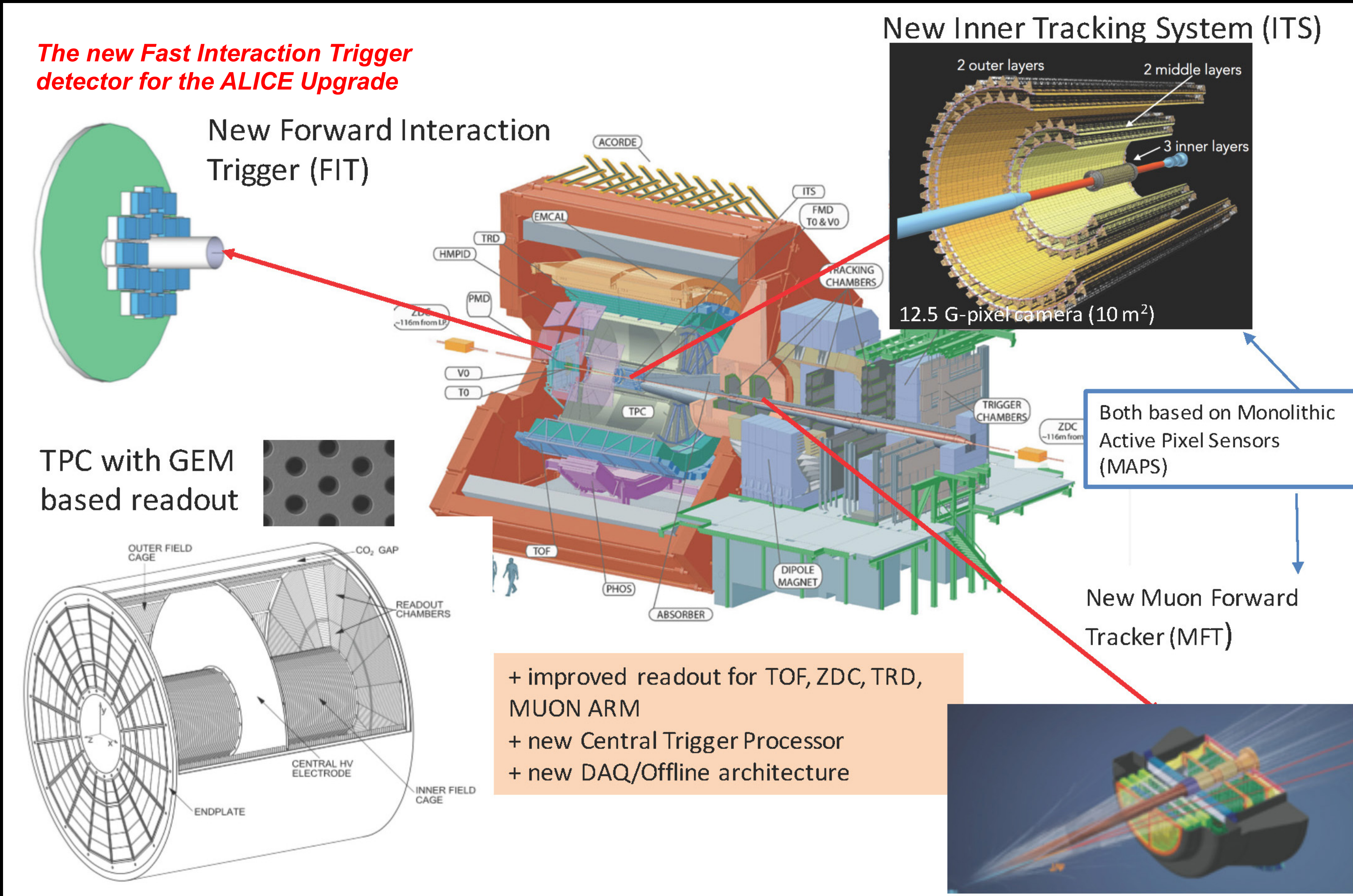
BES 2 and other exp's seek:

- Detailed map of the phase diagram
- Go to lower √s
- Maximize acceptance & new detectors

Similar physics at RHIC (BES II), FAIR (Germany) and NICA (Russia)

Scan in energy → alter initial T and μ_B

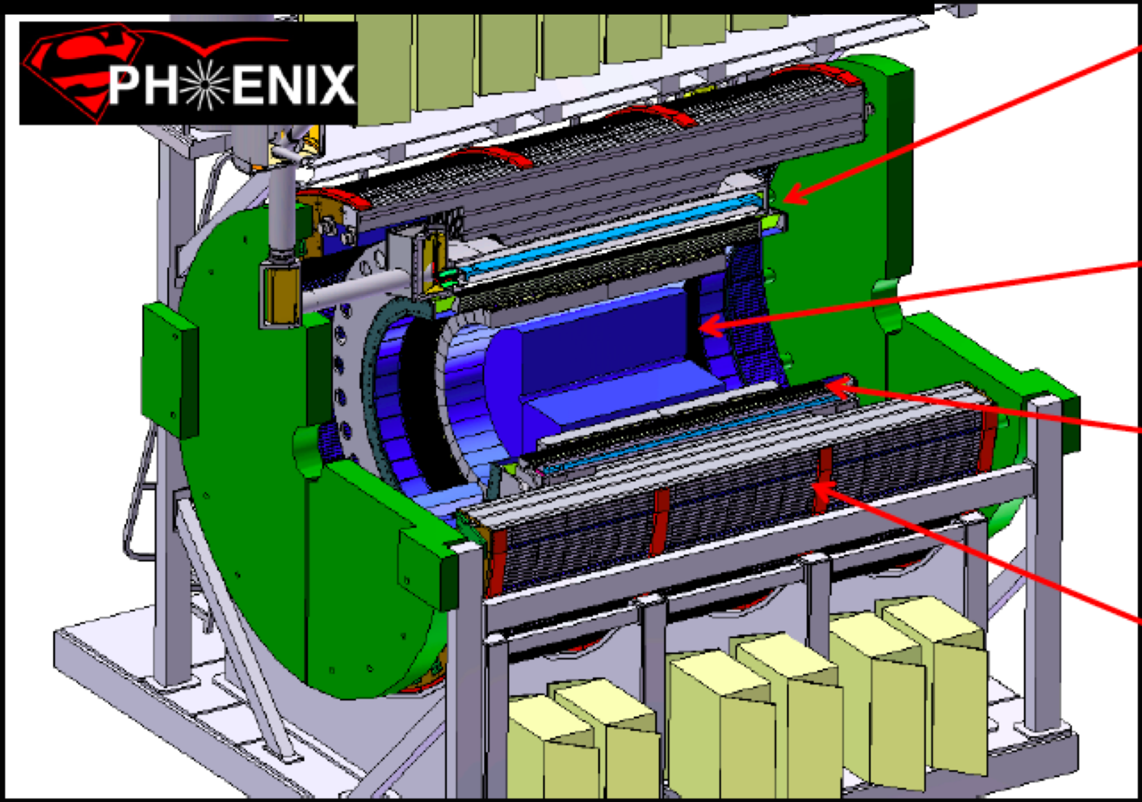
ALICE Upgrades for Run-3



sPHENIX – A New RHIC Detector

To measure Jets & Upsilon states

arXiv:1501.06197



BaBar Magnet 1.5 T

Coverage |η| < 1.1

All silicon tracking (tbd)
Heavy flavor tagging

Electromagnetic Calorimeter

Hadronic Calorimeter

c. 2023 – 2024….

High data acquisition rate capability, 15 kHz

Sampling 0.6 trillion Au+Au interactions in one-year
Maximizing efficiency of RHIC running

Electron Ion Collider – a QCD Laboratory

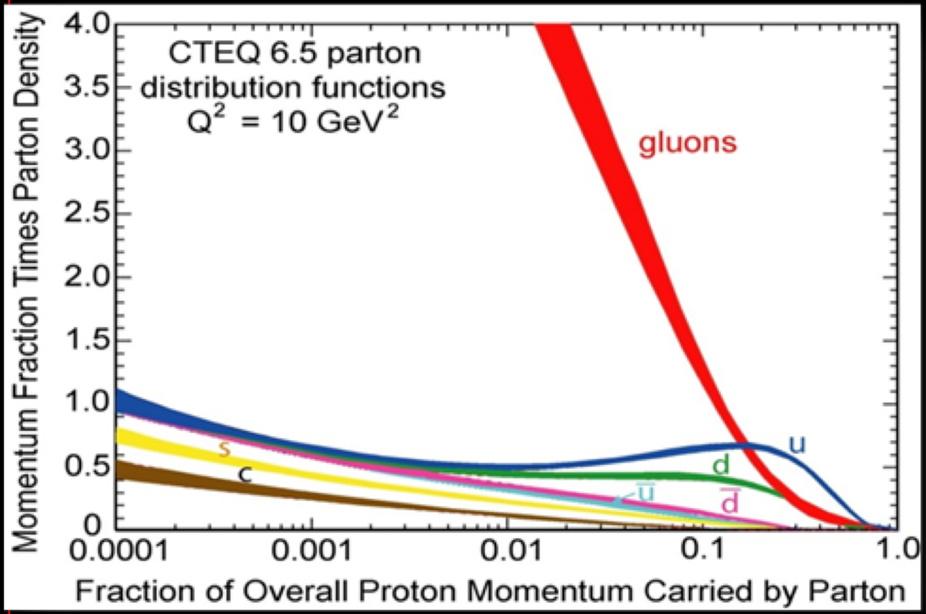
In general:

- HERA (1990's) discovered a huge abundance of soft gluons inside the proton.

  → What is the role of gluons in nucleon structure and in dynamics?

  → What is the origin of nucleon spin? and

  → What are the distributions of quarks and gluons in nuclei?



Electron Ion Collider – a QCD Laboratory

Scientific American, May 2015

In general:

- HERA (1990's) discovered a huge abundance of soft gluons inside the proton.

  → What is the role of gluons in nucleon structure and in dynamics?

  → What is the origin of nucleon spin? and

  What are the distributions of quarks and gluons in nuclei?


PARTICLE PHYSICS

the glue that binds us

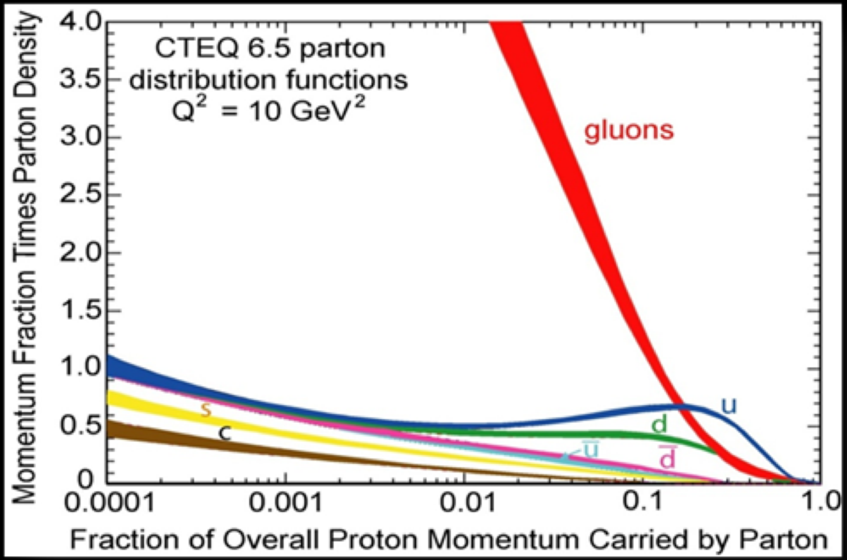
Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan

Why an Electron Ion Collider?

SCIENCE QUESTIONS:

- What is the transverse spatial and momentum structure of the gluons and sea quarks? Are there non-perturbative structures and can one image them?
- How much do the gluons contribute to the nucleon spin? Is there significant orbital angular momentum?
- How is the gluon distribution in nuclei different than in the nucleon? How does this relate to nuclear binding or short range nucleon-nucleon correlations?
- Can one find evidence for saturation of the gluon density? A Color Glass Condensate?
- How do quarks & gluons propagate in nuclear matter & join to form hadrons?



Requirements of EIC

To answer these questions requires a new versatile facility (never before available) with:

- Access to very low x~0.0001, which requires collisions of high energy electrons with high energy nucleons and nuclei.
- Highly polarized beams of nucleons and light ions, and polarized electrons to access the spin and orbital motion of the partons.
- High luminosity to enable 3D tomography of the distributions of partons.
- Collisions of electrons with atomic nuclei, up to the heaviest available, to provide information on the effect of the nuclear medium on the parton distributions as well as properties of partons traversing the nuclear medium.

Also, a new phenomenology has been developed
- Generalized Parton Distributions (GPDs) and Transverse Momentum Dependent (TMDs) distributions to "image" quarks and gluons and access orbital angular momentum.

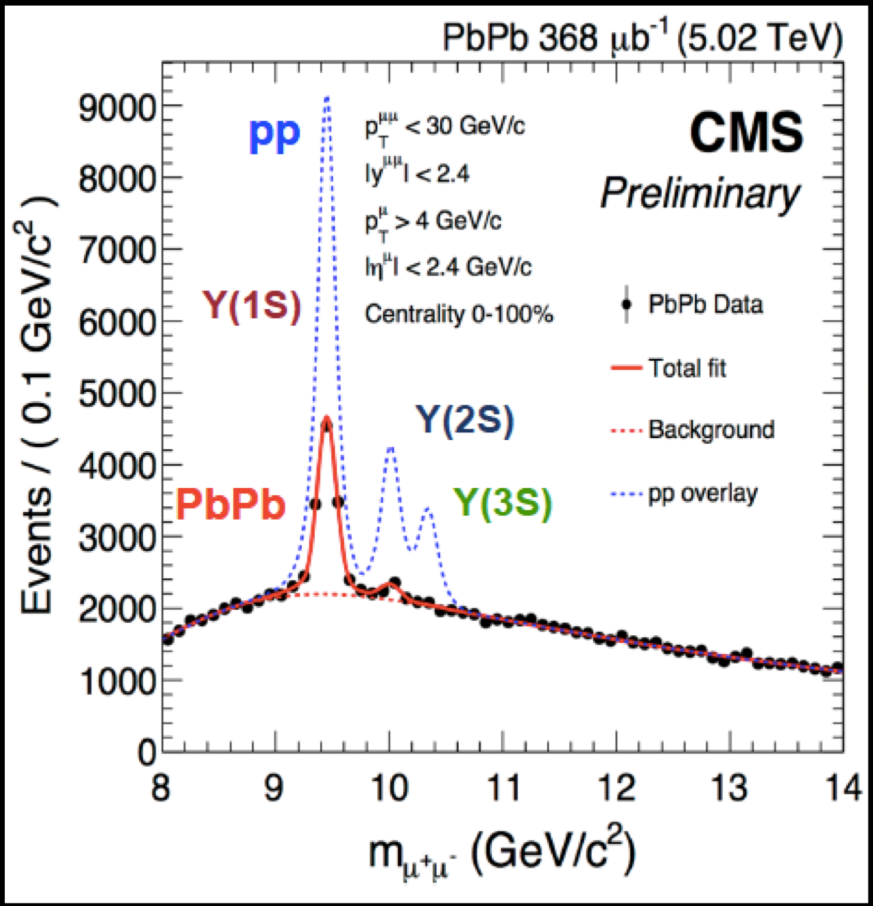
Remaining BIG Questions for the Field!

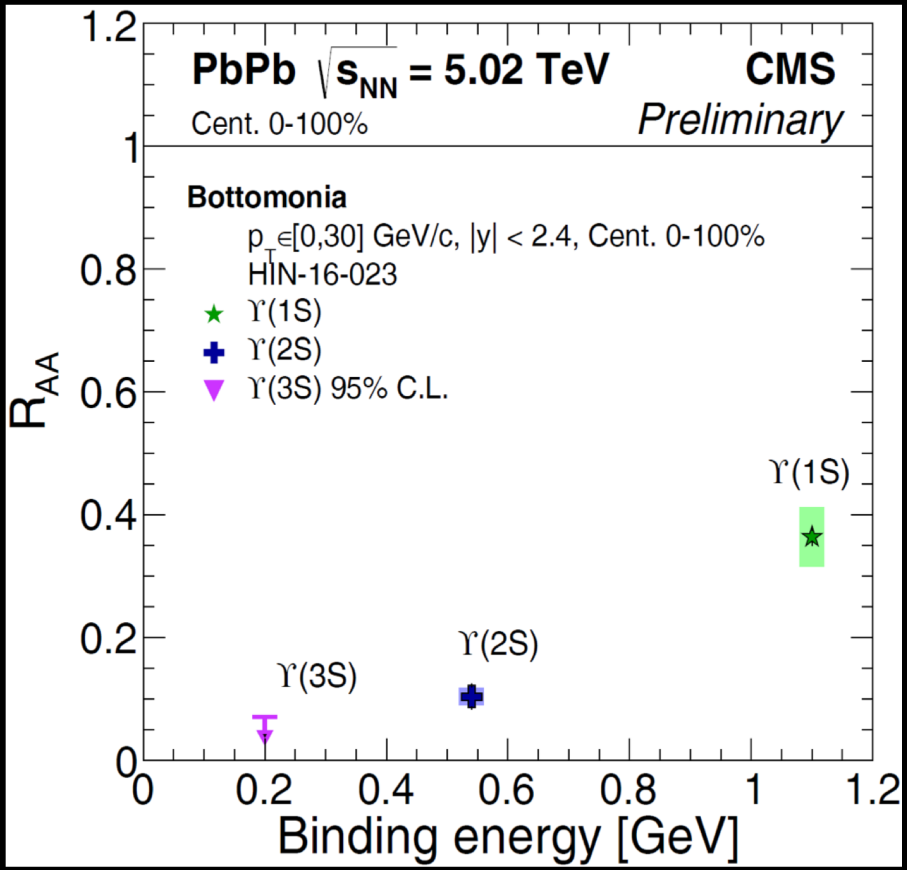
- How does the system evolve and thermalize from its initial state?
  What is the initial state (Color-Glass Condensate?)
- Can we understand parton propagation & energy loss at a fundamental level?
  What can we learn about the response of the QGP?
- Can we understand quarkonium melting (suppression) at the basic level?
  Cold matter effects? Is the melting vs T consistent with LQCD?
- Can we determine properties of the QGP? e.g. : η/s, sound attenuation length,
  parton energy loss (q-hat), α_s (T), formation time (τ_f), excited modes, ….EOS?
- Is the QCD Phase Diagram featureless above Tc?
  → RHIC BES 2, FAIR & NICA   What is the coupling strength vs T….?
- Are there new phenomena, new states of matter? χ-sym. restoration?....
- Can there be new developments in theory? (lattice, hydro, parton E-loss,
  string theory…) and understanding……across fields……?
- Did not go into detail about the pPb, dAu data where similar “flow” effects seen!
  This has yet to be understood! Hydrodynamics in high multiplicity pp, pA?
  What is the smallest droplet of QGP possible? Under heavy investigation!

Thanks for your attention!

Archive

J/Ψ and Υ suppressed



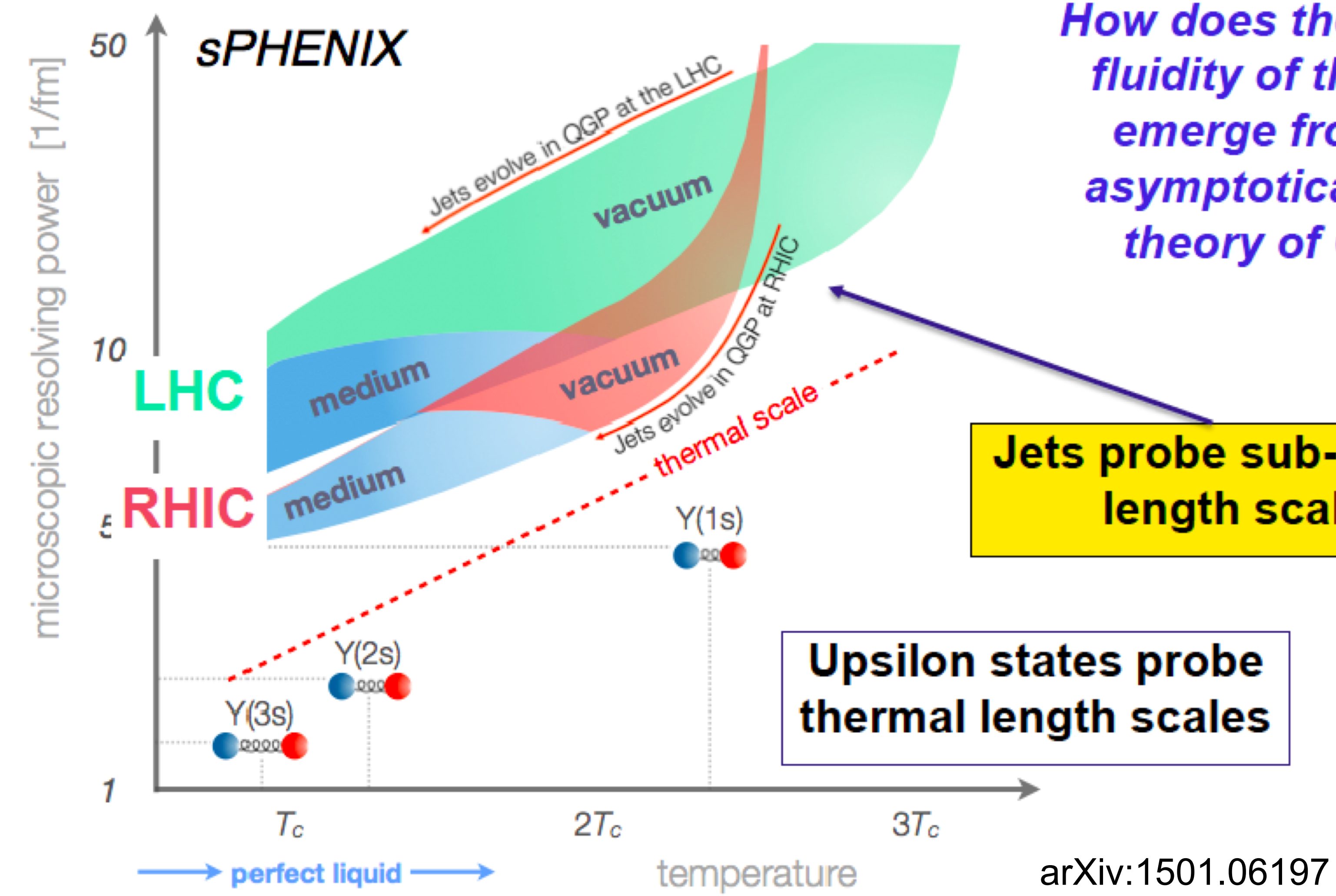


New CMS results at 5.02 TeV in Pb+Pb confirm Υ(2S,3S) suppression relative to the strongly bound Υ(1S) and to p+p

Υ(1S+2S+3S) suppression observed by STAR at RHIC

Quark Matter 2017

Probing Scales in the Medium



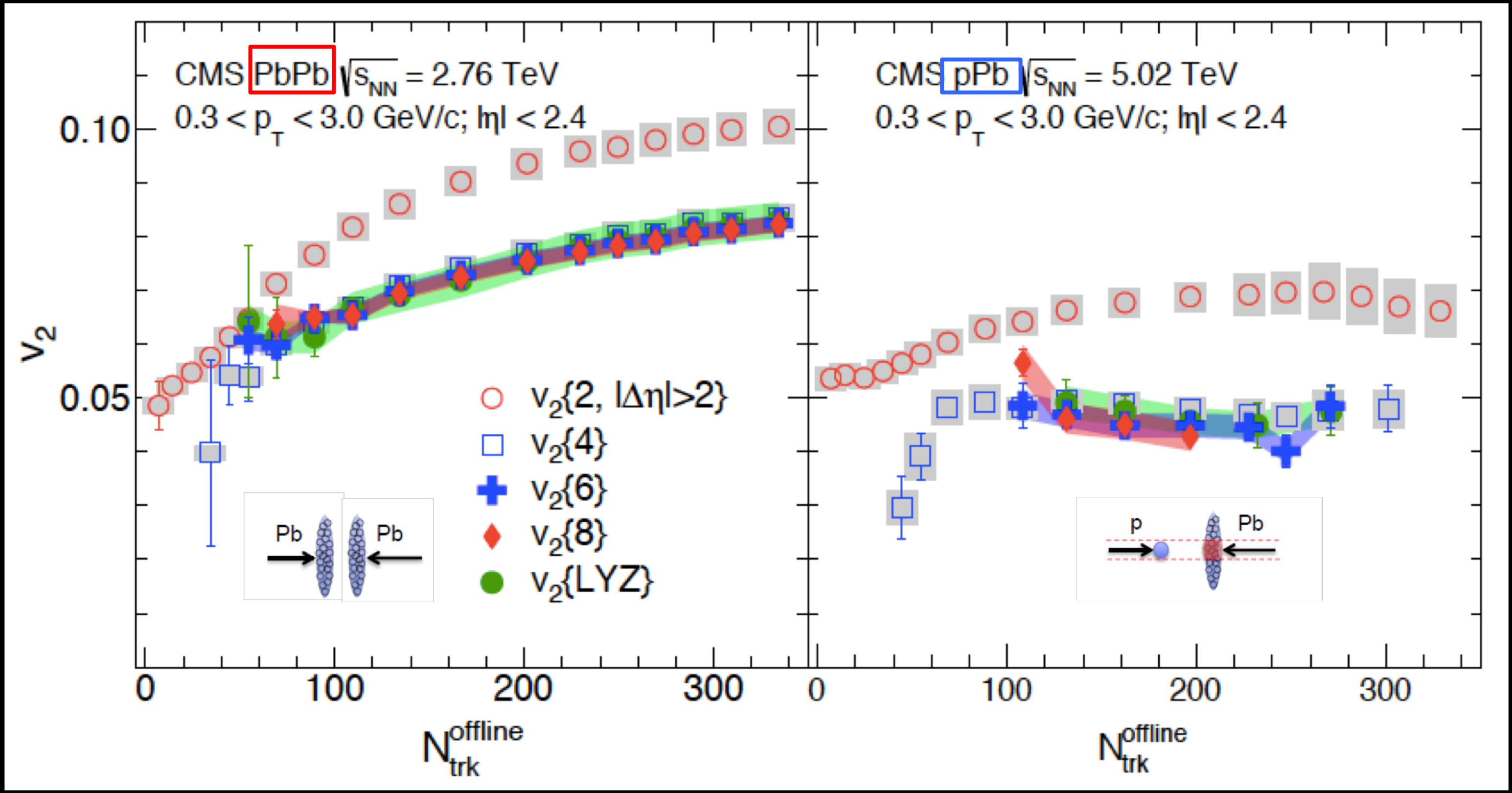
How does the perfect fluidity of the QGP emerge from the asymptotically free theory of QCD?

Jets probe sub-thermal length scales

Upsilon states probe thermal length scales

Collective Flow $v_2(n)$ & $v_{n>2}$ (n) in Pb-Pb, p-Pb

CMS, Phys. Rev. Lett. 115 (2015) 012301arXiv:1502.05382



For PbPb and pPb – Collective effects!

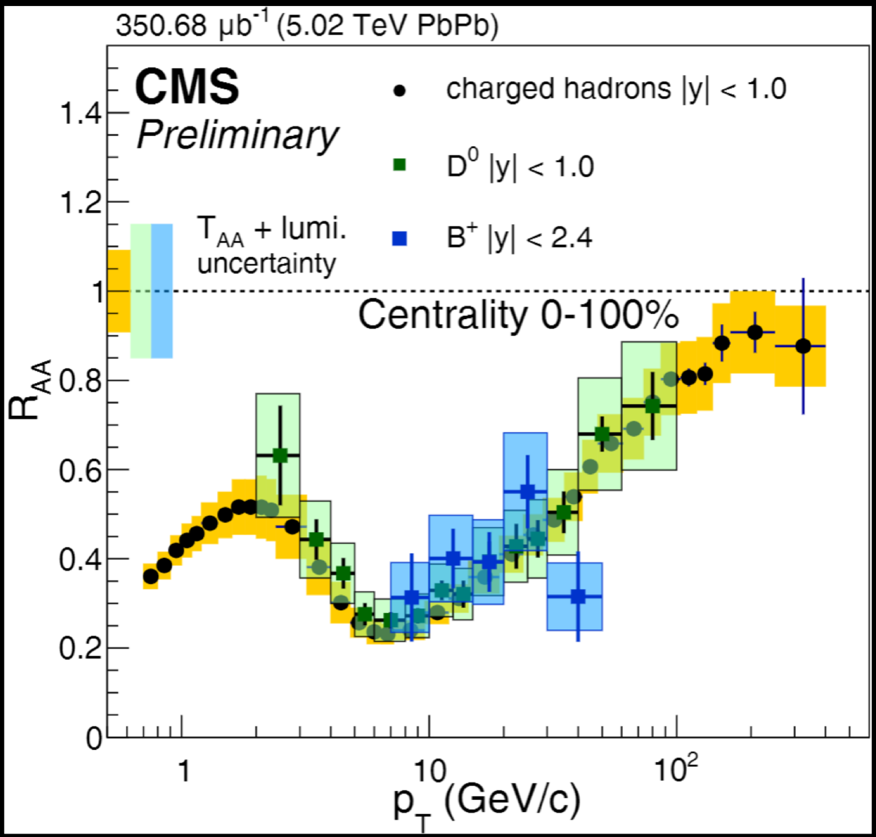
v_2 (n) remains large when using more (n) particles

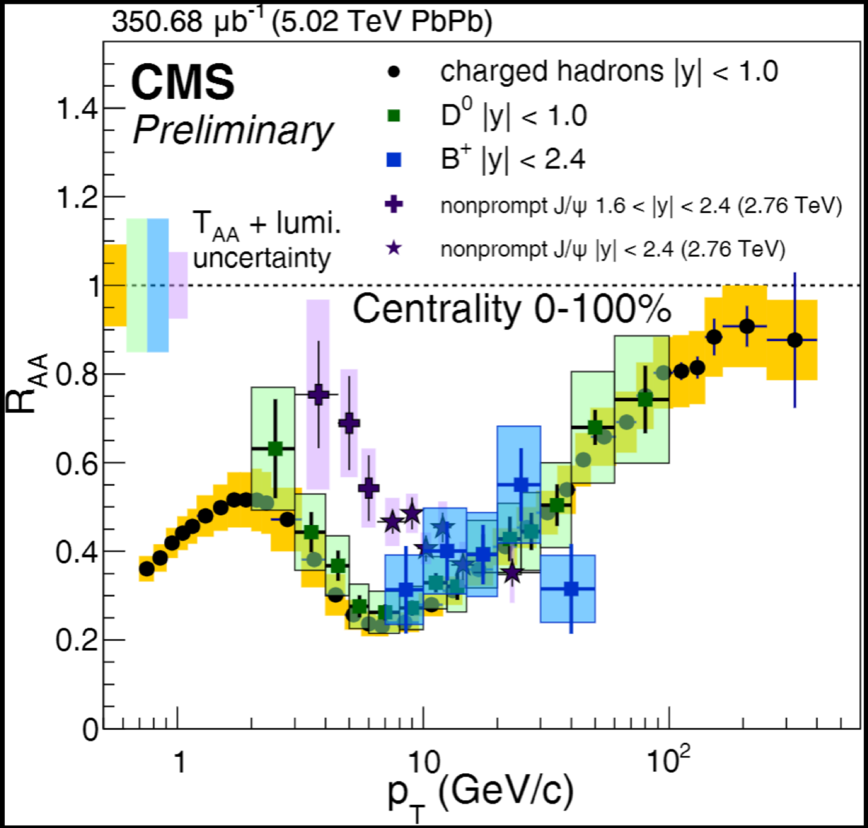
v_2 (4) = v_2 (6) = v_2 (8) = v_2 (LYZ) within 10%

Flavor Dependence of Hadron Suppression

$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

$R_{AA} < 1$ Suppression wrt pp





→ No flavor dependence seen in 5.02 TeV Pb-Pb data

CMS-PAS-HIN-16-001
CMS arXiv: 1611.01664

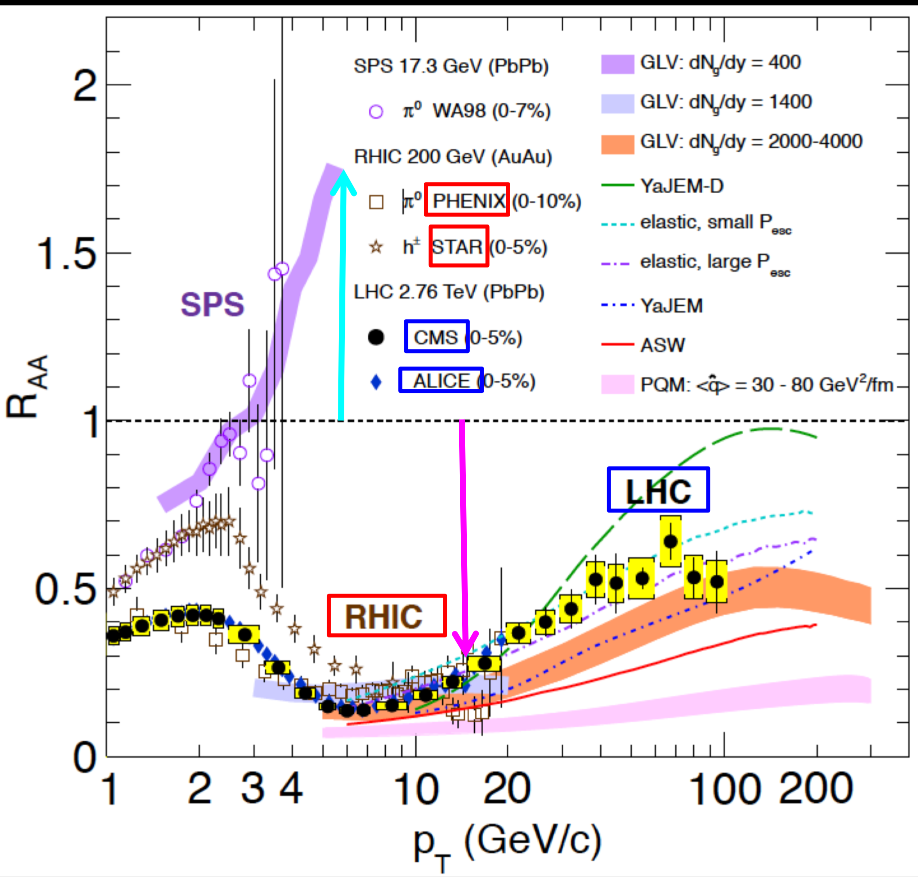
→Flavor dependence seen in 2.76 TeV data at p_T < 10 GeV/c

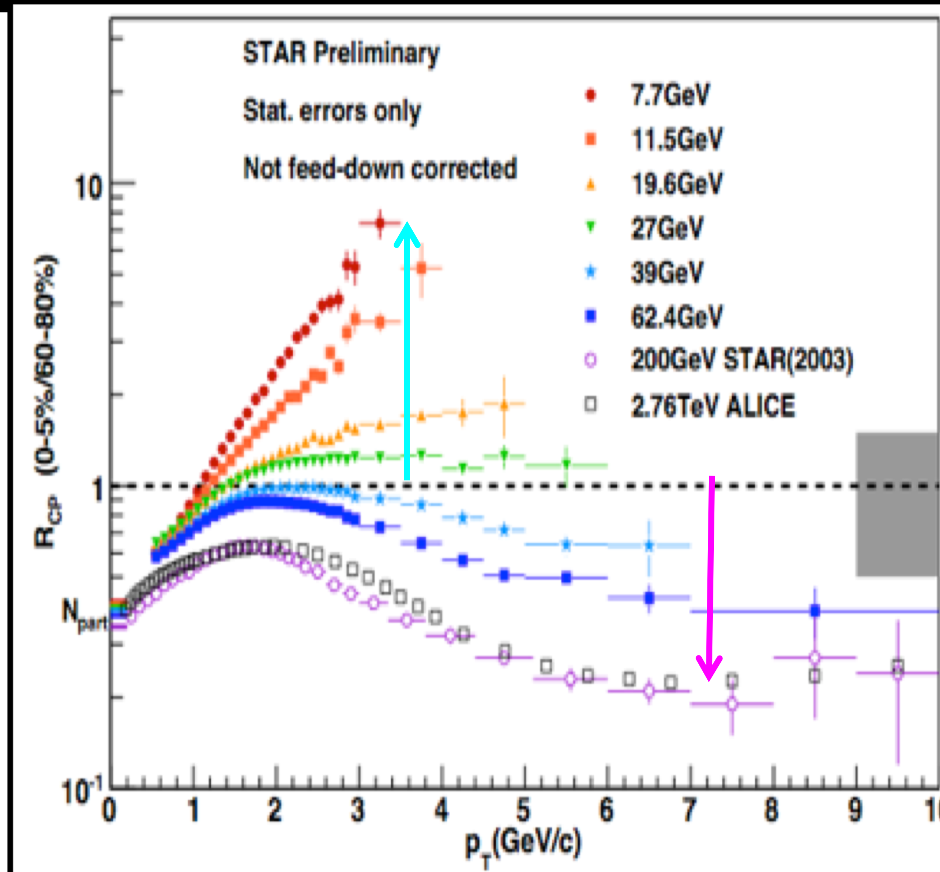
CMS J/ψ arXiv: 1610.00613

Suppression of High p_T Hadrons

Central Pb-Pb and Au-Au Collisions

Suppression → parton energy loss in hot QCD medium





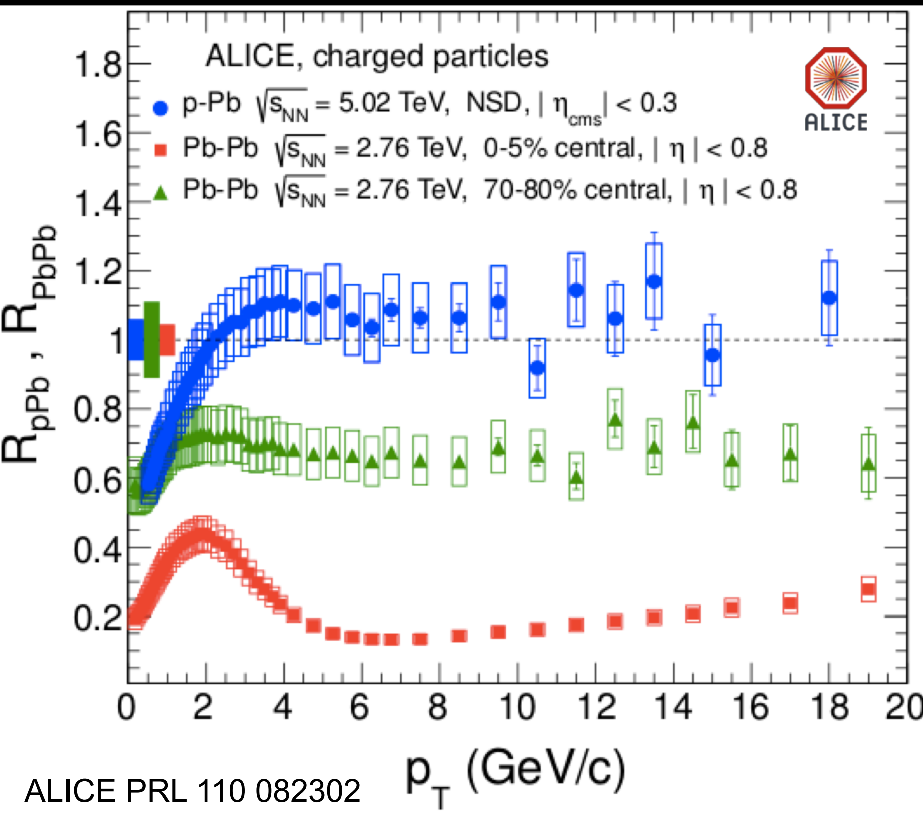
$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

Also enhancement at lower energies
→ initial state effects
(Cronin enhancement)

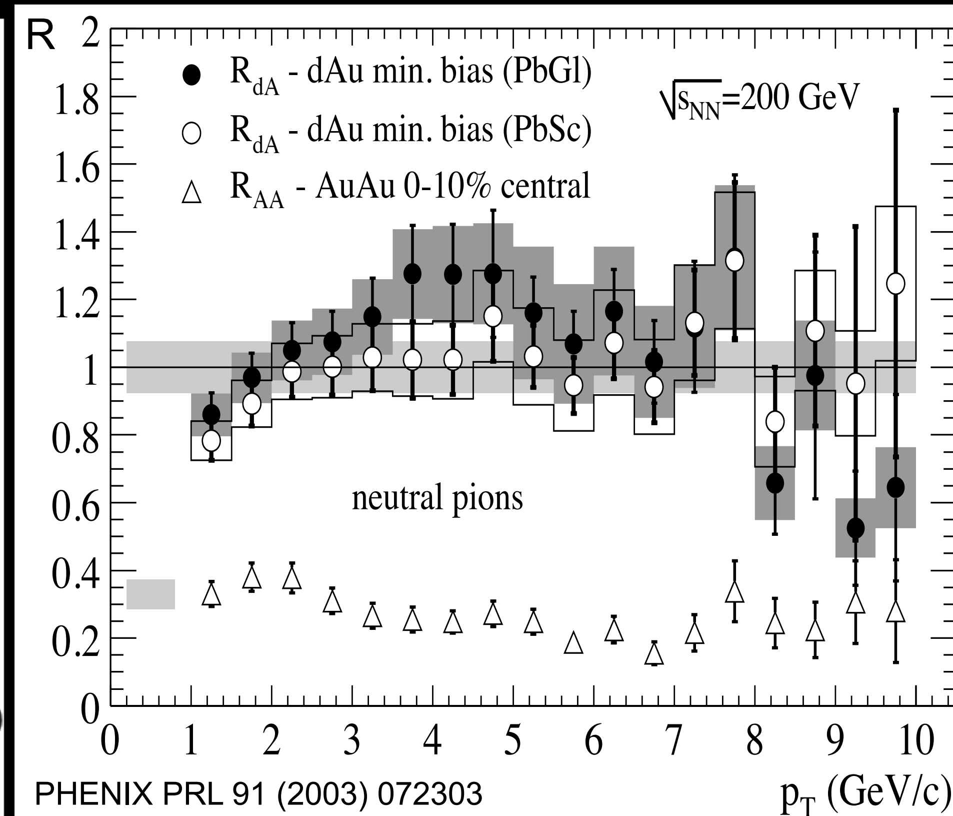
$R_{CP} = N_{central} / N_{peripheral}$

$\rightarrow R_{AA}$

R_{pPb} at LHC



R_{dAu} at RHIC



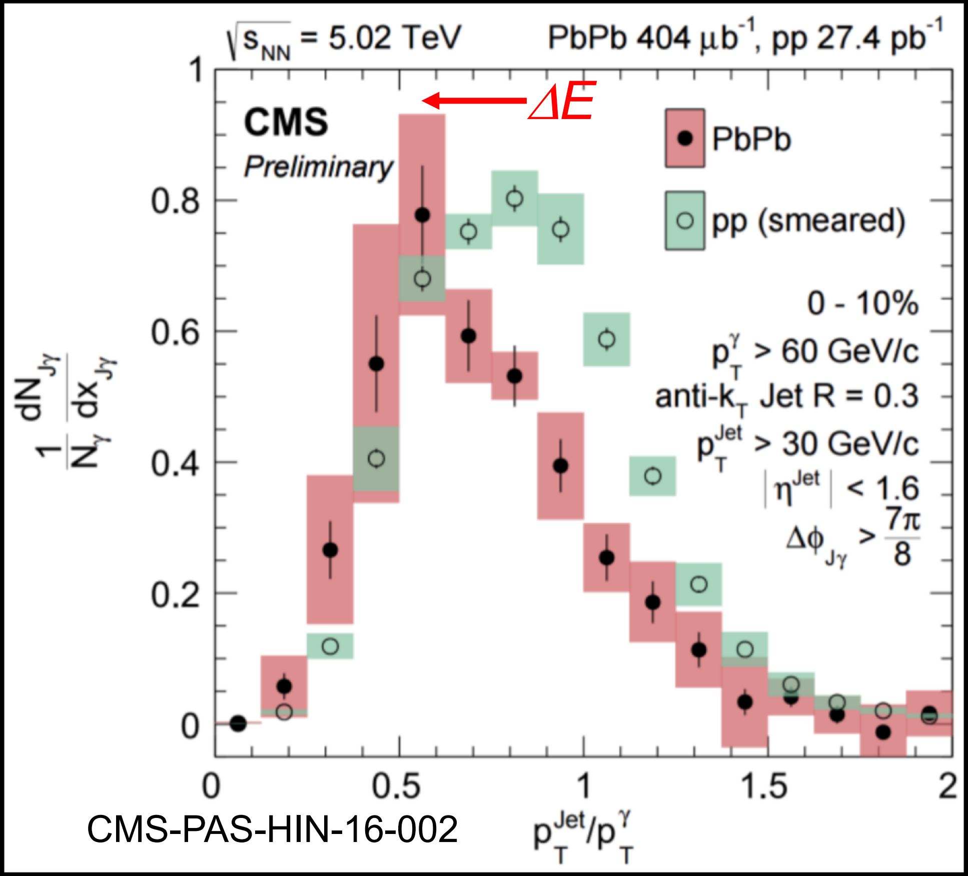
LHC p-Pb and RHIC d-Au (p_T > 2 GeV/c)

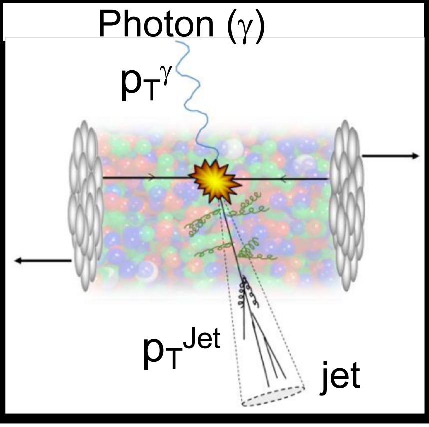
- Binary scaling (R_{dAu} ~ R_{pPb} ~ 1), except note “bump” at ~ 4 GeV/c
- Absence of Nuclear Modification → Initial state effects small

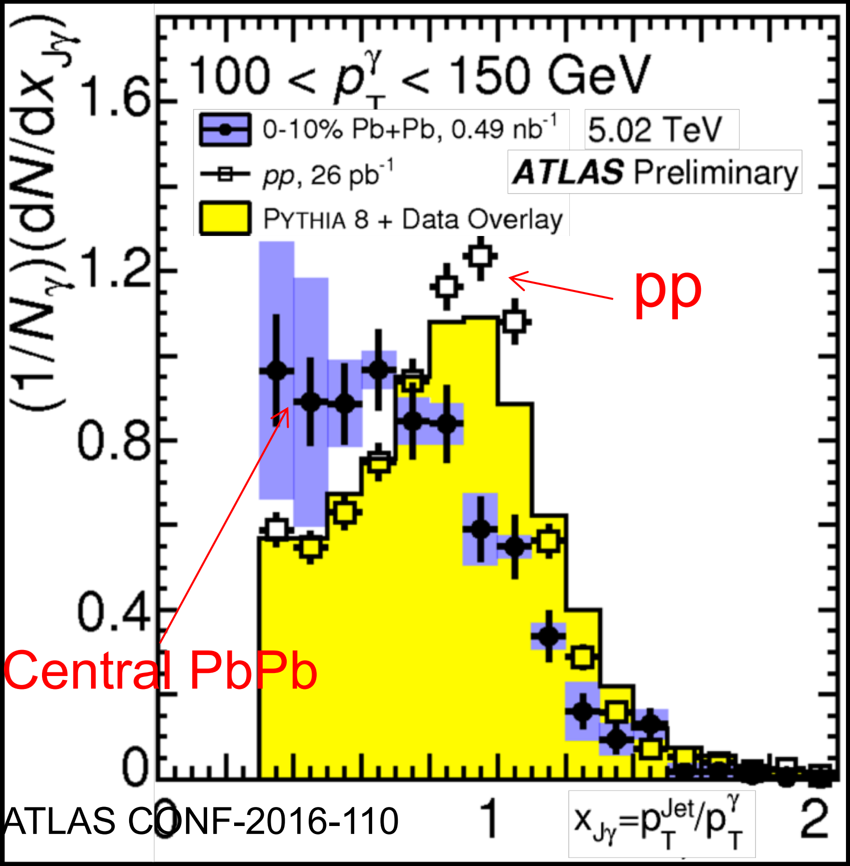
LHC Pb-Pb and RHIC Au-Au

- Suppression (R_{AuAu} << 1, R_{PbPb} << 1) → Final state effects (hot QCD matter)

Jets are Quenched







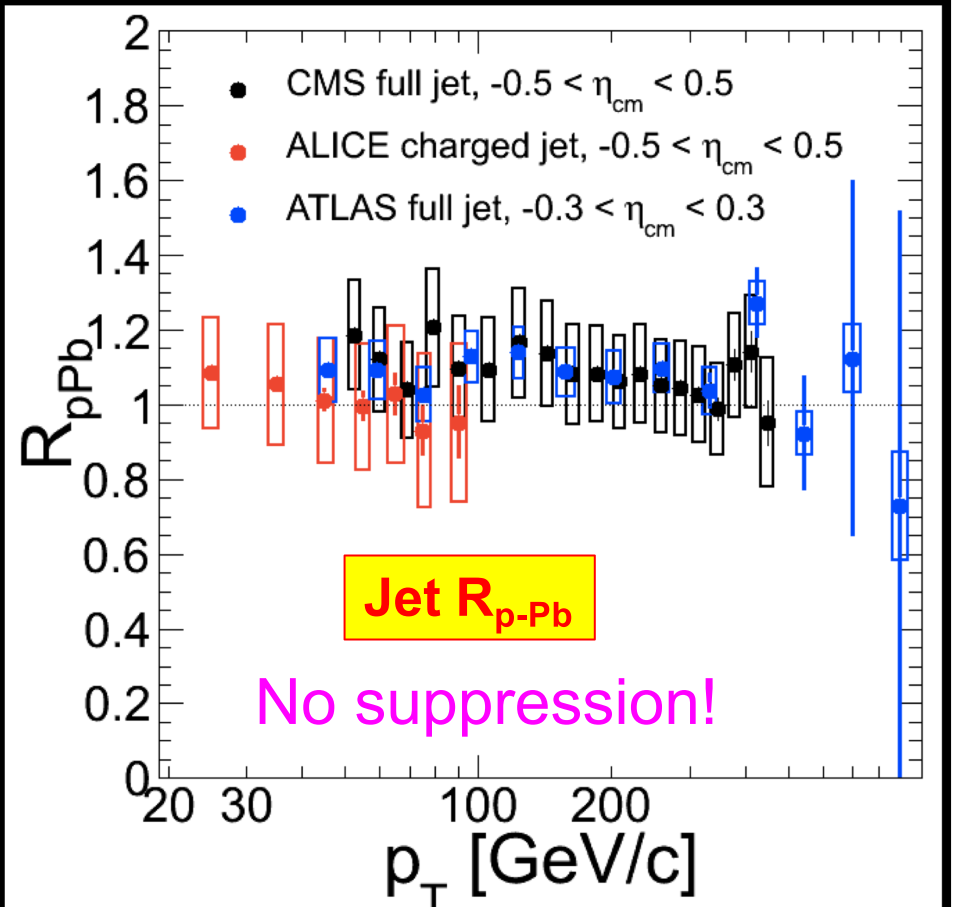
→ *Observed Pb+Pb energy loss (ΔE) relative to p+p*

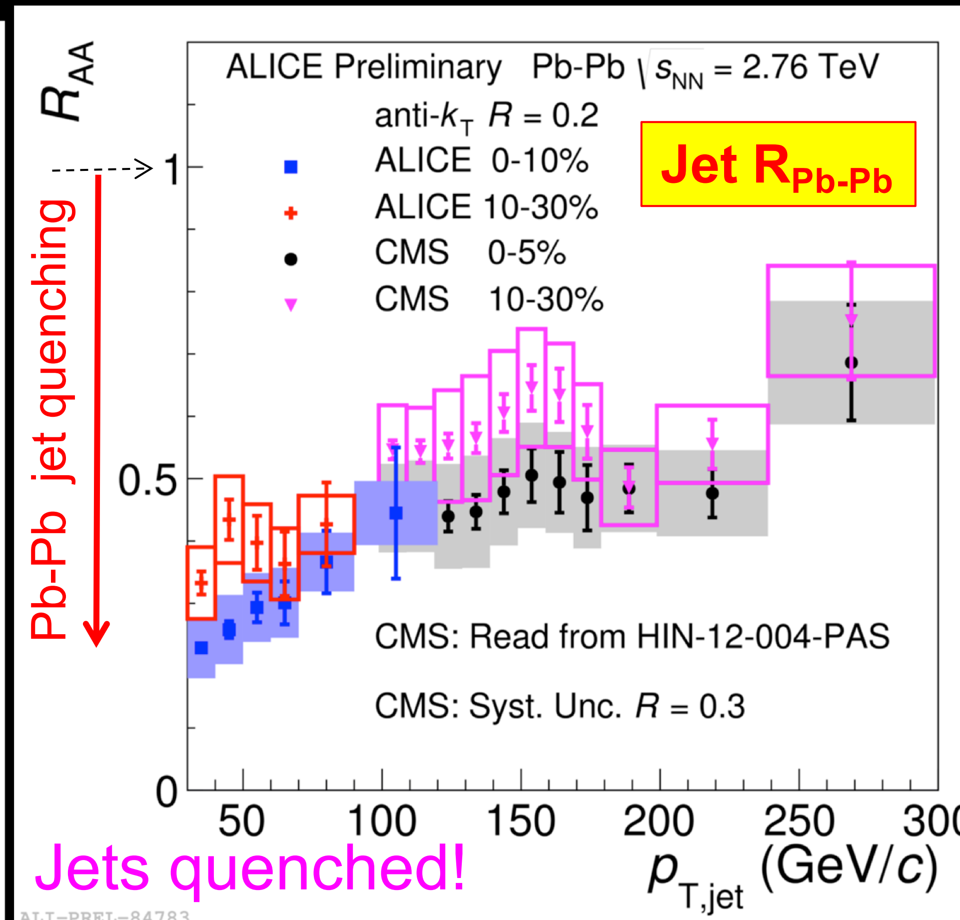
→ *Also measured for first time Z-jet Momentum imbalance – consistent with γ-jet (arXiv: 1702.01060)*

Jets in p-Pb & Pb-Pb at LHC

QM2014: ALICE ATLAS CMS (black)

ALICE QM 2014

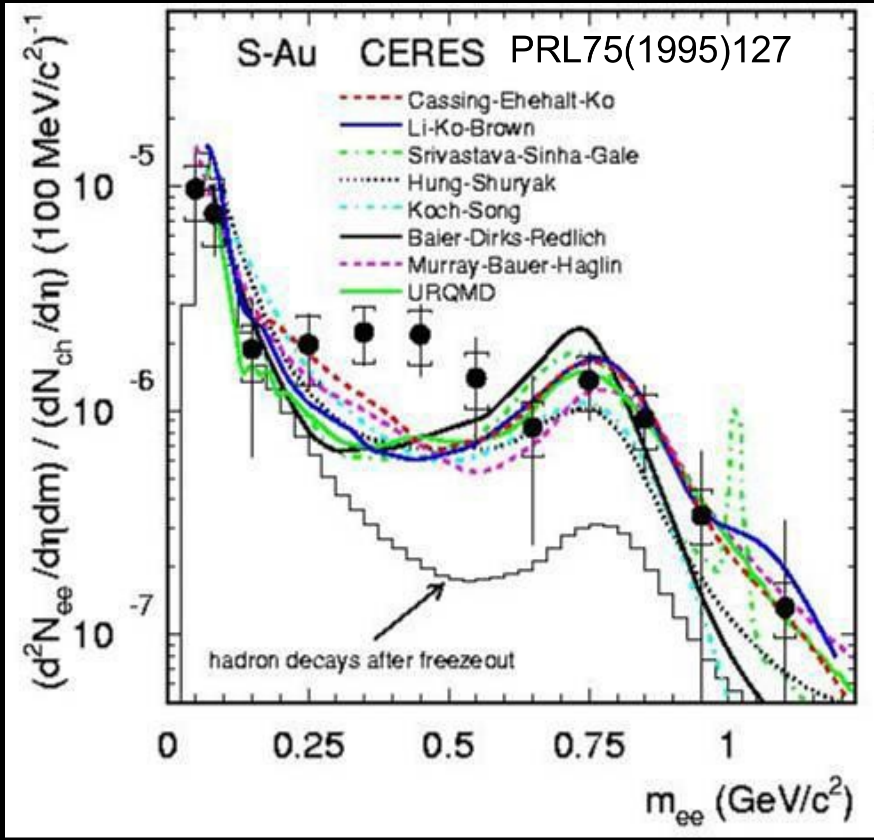


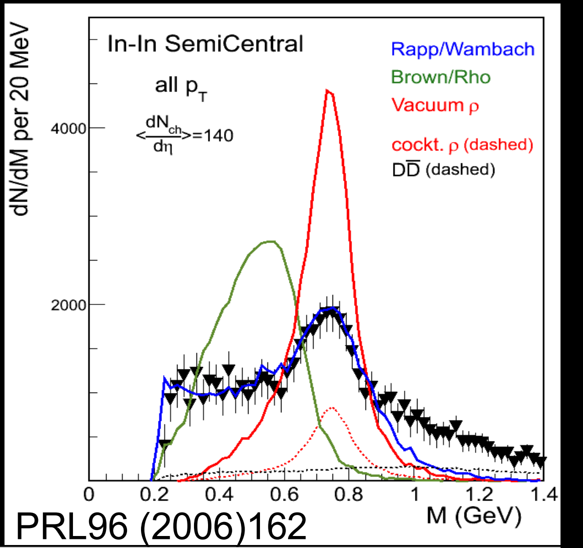


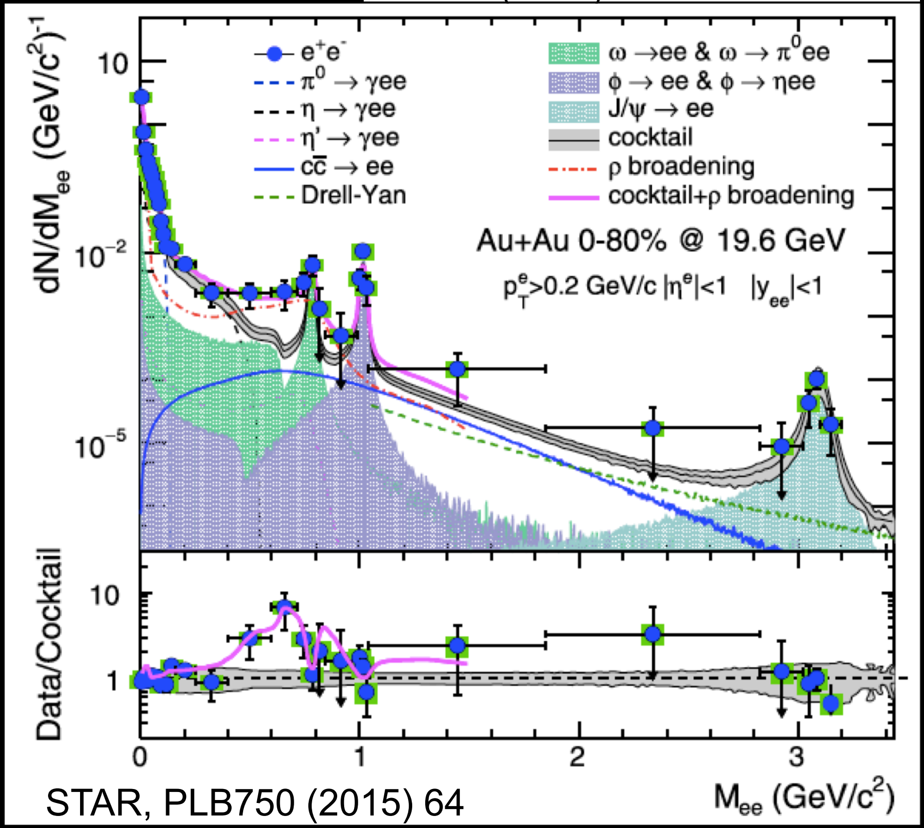
ALICE ≈ ATLAS ≈ CMS: R_{p-Pb} (jet) ≈ 1
Binary scaling, no initial state effects!

ALICE ≈ ATLAS ≈ CMS: R_{Pb-Pb} (jet)<<1
Jets quenched in Pb-Pb collisions

Indications of Chiral Symmetry Restoration in Low-mass e^+e^-







Rotational & Irrotational Vortices

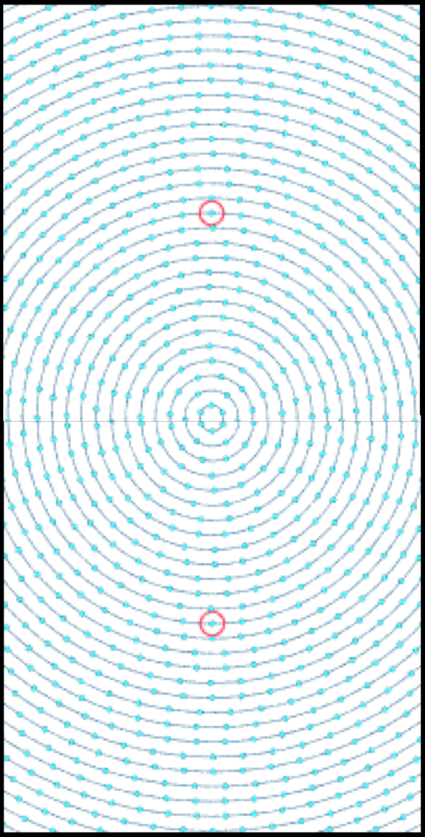
Rigid-body-like vortex

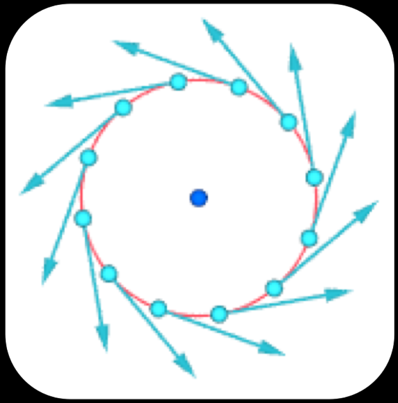
$v \propto r$

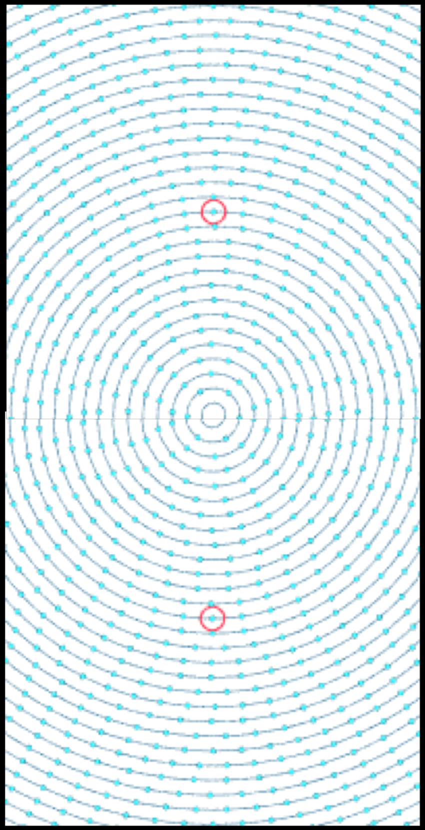
$$\vec{\omega} = \frac{1}{2} \nabla \times \vec{v}$$

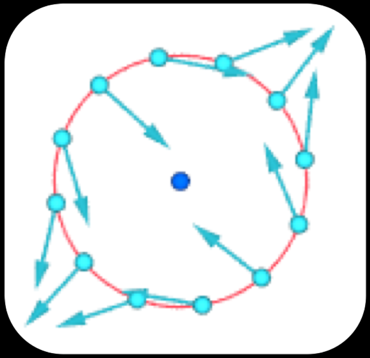
Irrotational vortex – e.g. tub drain

$v \propto 1/r$









Orbital angular momentum of cell given by its c.m. motion.
Internal angular momentum by its vorticity

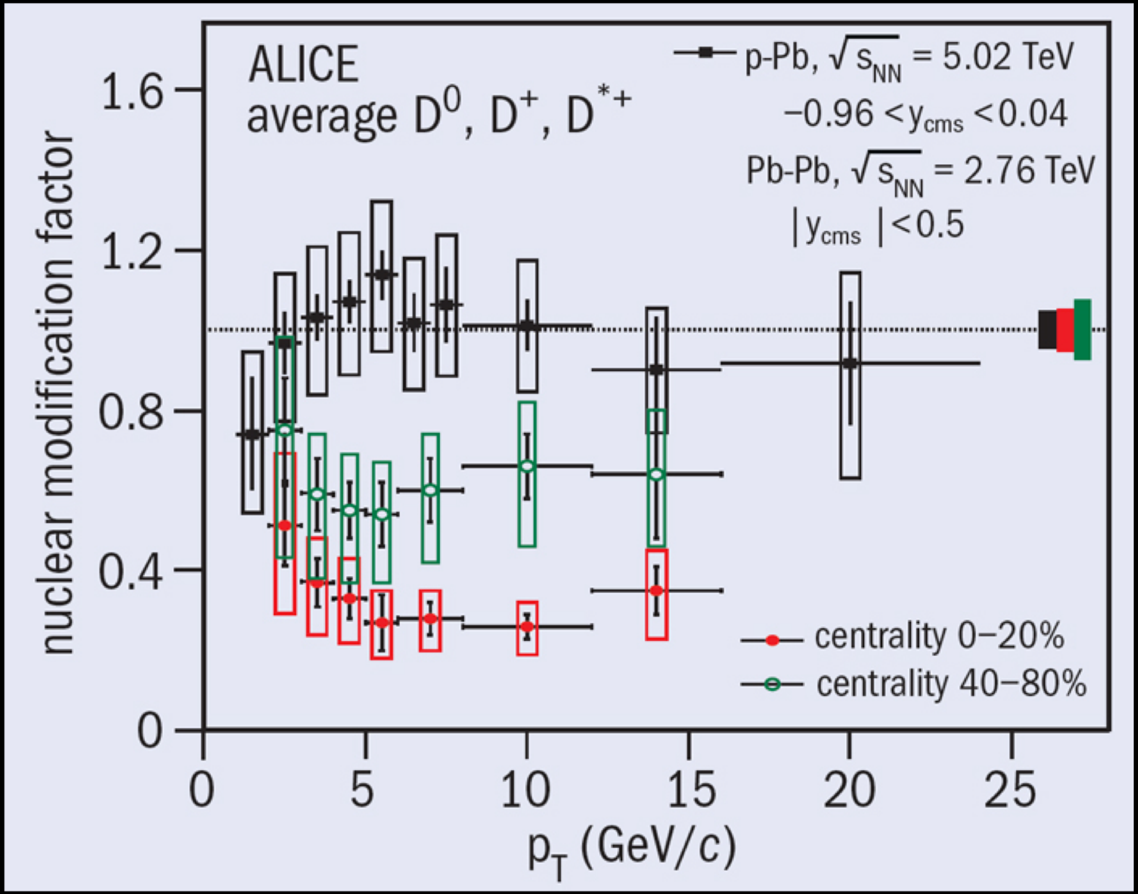
Effects in Small Systems (p-A, high multiplicity pp)

- High p_T measurements (hard probes) in pp, p-A described by pQCD-inspired models
  - No suppression of particles at high p_T
  - No jet quenching
  - No suppression of quarkonia (complicated also by cold matter effects)
  - Confirm quenching/suppression in A-A collisions is a final state effect
- Spectra, correlations in p-A, high multiplicity pp exhibit effects attributed to collective (flow) behavior
  - Strong particle mass ordering
  - Similar (though weaker) trends in flow harmonics

"What is the smallest size and density of a droplet of QCD matter that behaves like a liquid?"

Heavy Flavor – D-Mesons: R_{pPb} & R_{PbPb}

ALICE Collaboration, *Phys. Rev. Lett.* **113** (2014) 232301



D-meson NOT suppressed in p-Pb
R_{pPb} consistent with ≈1
Initial state effects small!

D-meson central R_{PbPb} suppressed!
Centrality dependence
Not initial state effect!

R_{pPb} Summary & Conclusions I

Experiments have measured

- Peudo-rapidity $dn_{ch}/d\eta$ and p_T distributions
  Described by pQCD-based MC models (HIJING, DPMJET)

- $R_{pPb}^{hadrons}$ ~ 1 for p_T > 2 GeV/c, consistent with binary scaling
  Absence of nuclear modification → small initial state effects
  R_{PbPb} suppression (previously measured) → a final state effect
  Described by Saturation (CGC) models, EPS09 with shadowing.

- $R_{pPb}^{D\text{-}mesons}$ ~ 1 for p_T = 1.5 - 20 GeV/c
  R_{pPb}^{jet} ~ 1 for p_T = 20 - 200 GeV/c
  Absence of nuclear modification → small initial state effects
  R_{PbPb} suppression (previously measured) → a final state effect
  Hard probes consistent with pQCD-based predictions.

- $R_{pPb}^{J/\psi}$ (y)
  Observes suppression that increases towards forward rapidity (y)
  $R_{FB}^{J/\psi}$ (p_T) ratio decreases (more suppressed) at low p_T
  In reasonable agreement with models including coherent energy loss
  Nuclear shadowing and/or energy loss describe the data, indicates that final state absorption may be negligible at LHC energies.

Potential of Higher Order Harmonics

Gaussian width of harmonic distributions related to length scale such as mean free path & horizon.

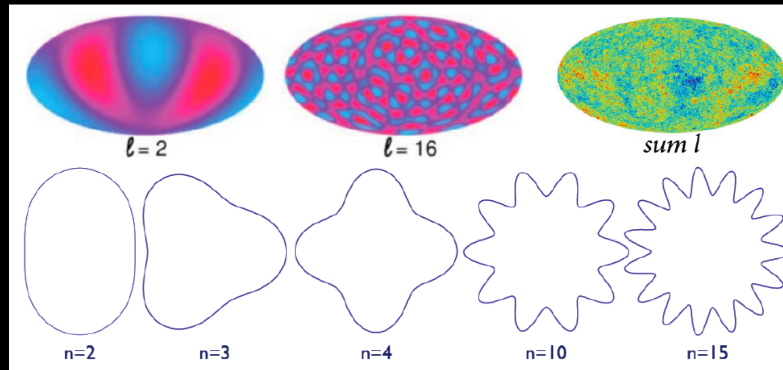
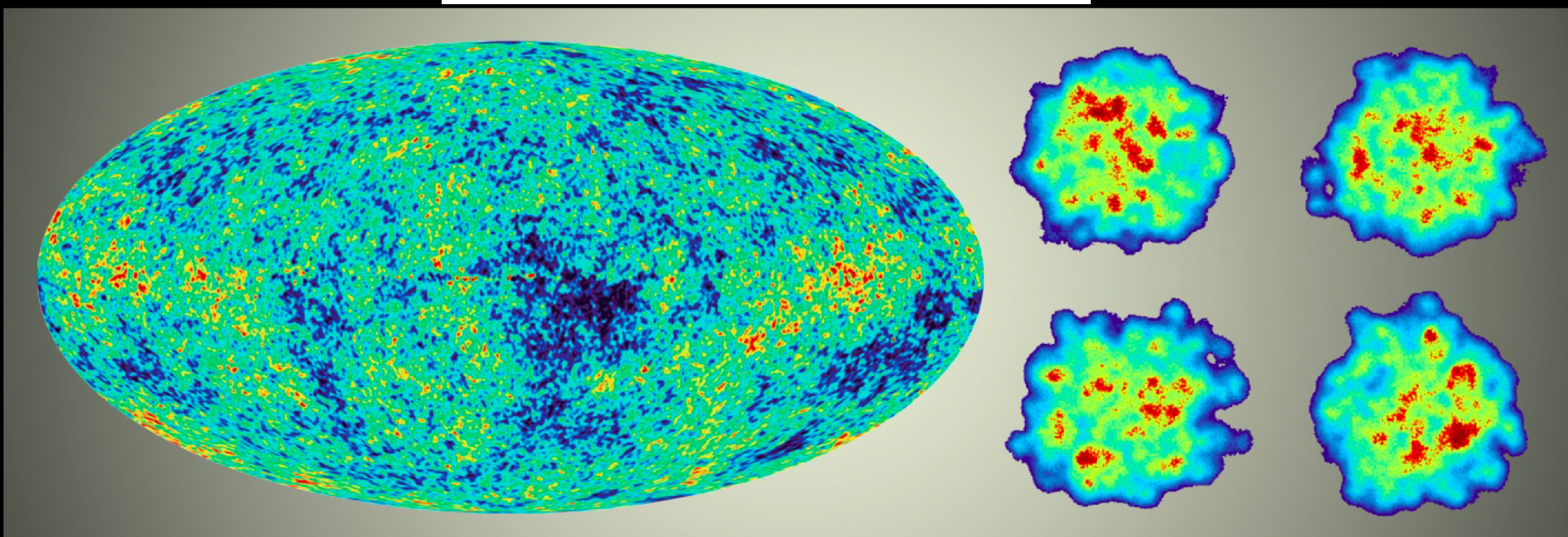
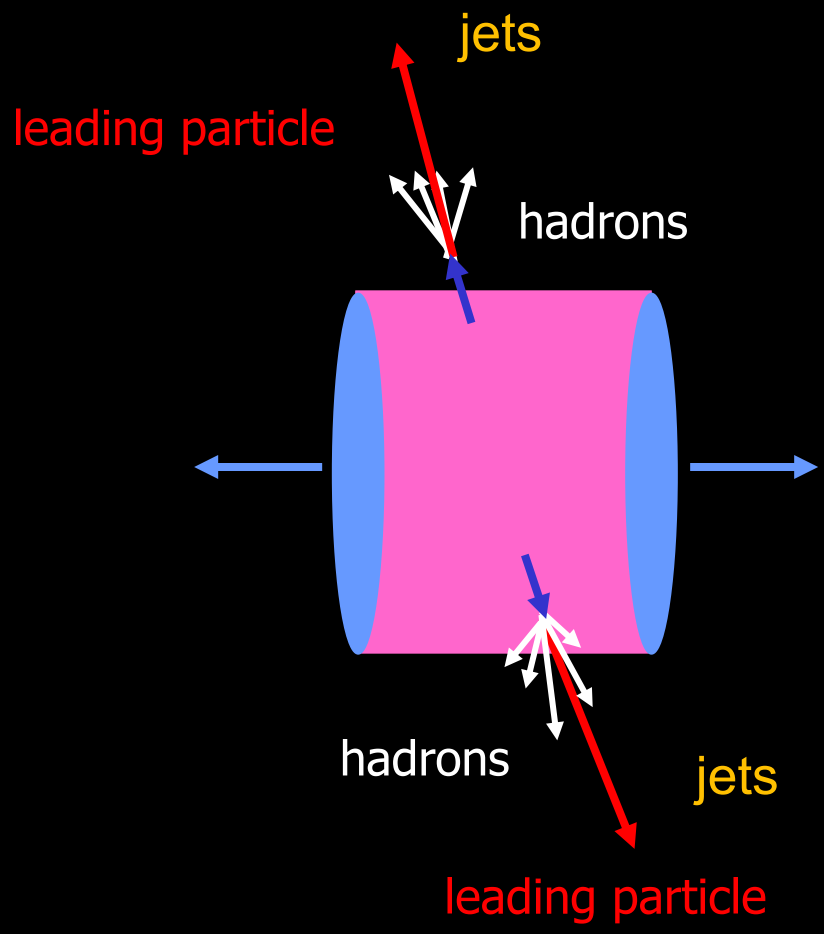


Figure 1: Top: the length scales in the CMB. Bottom: the length scales probed with higher n in heavy-ion collisions.



Probing Hot QCD Matter with Hard Probes

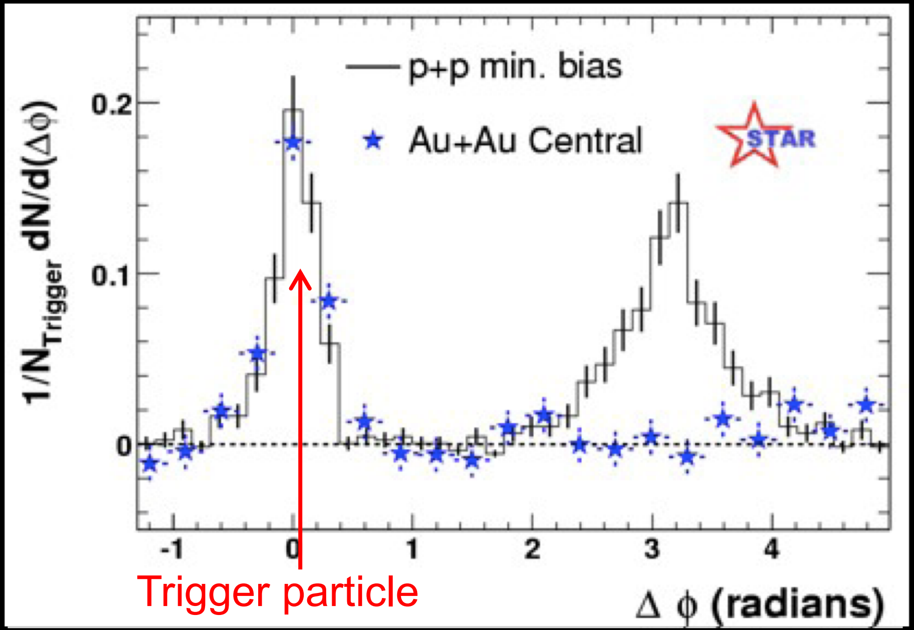


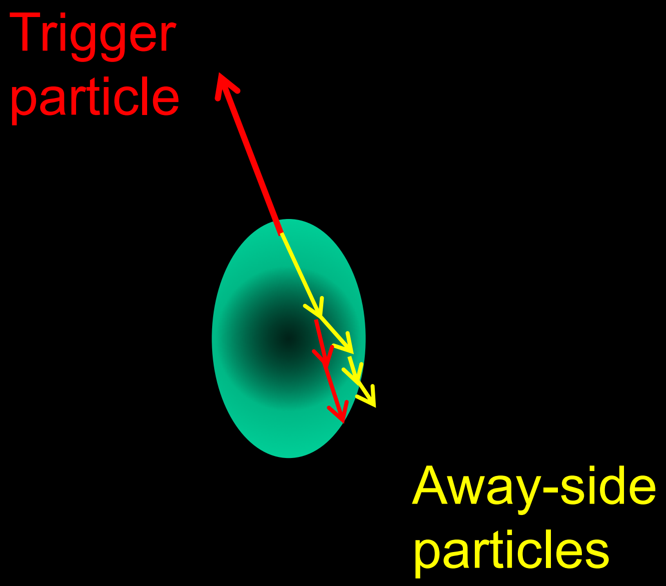
Hard Probes (from initial parton scattering):

- Large "p_T" partons
- Heavy quark production

→ parton energy loss:
modification of jets and leading particles & jet-correlations

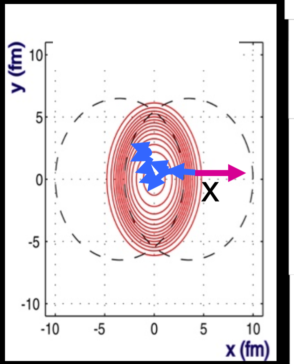
High Momentum Particle Correlations (Jet Proxy)

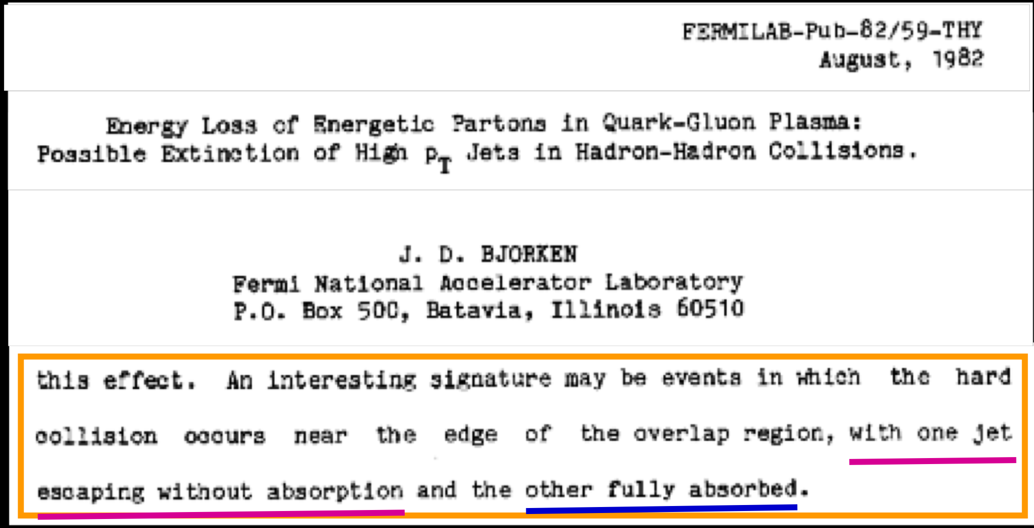




Back-to-back Jets

Away-side jets quenched
in central Au + Au





FERMILAB-Pub-82/59-THY
August, 1982

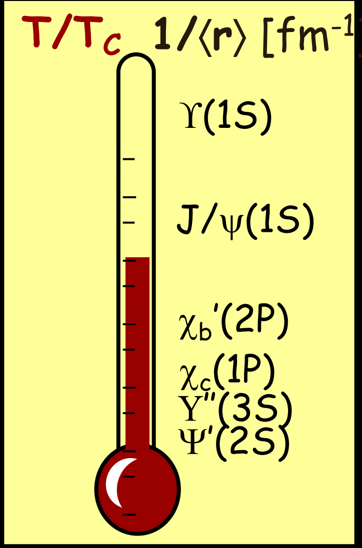
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

→ *trigger particle origin near surface*
→ strongly interacting medium

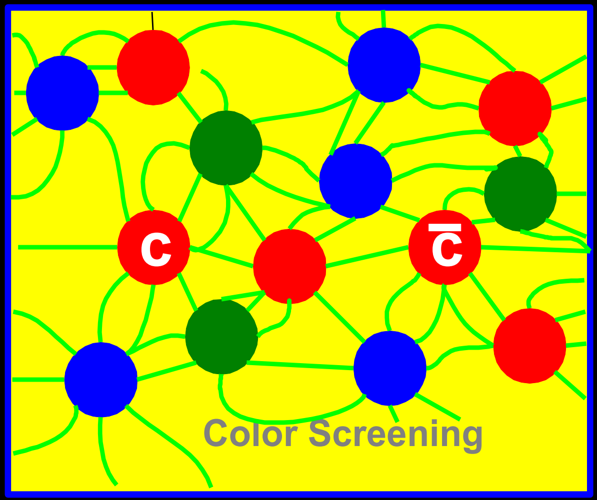
Quarkonia in the QGP



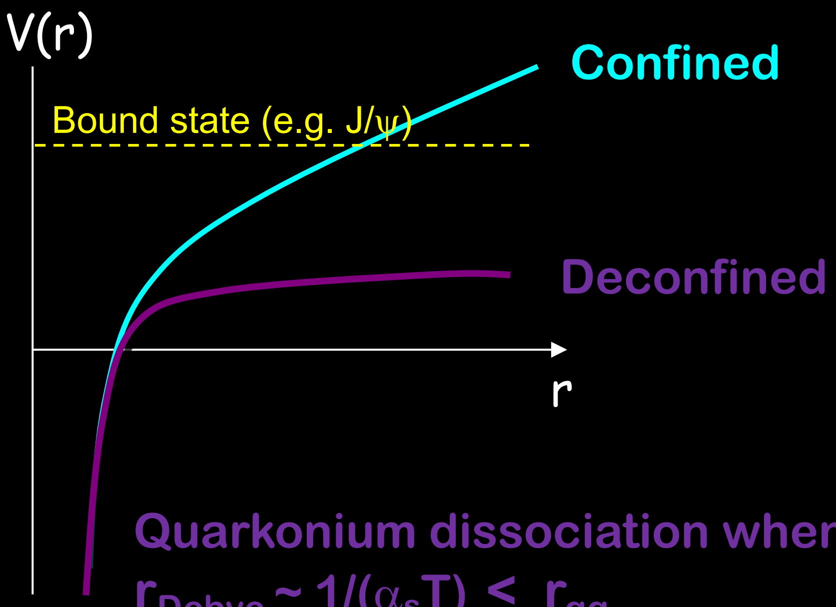
Quarkonia: $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: Υ'', Υ', Υ

(Debye color screening, recombination)

Measure melting order of $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: Υ'', Υ', Υ



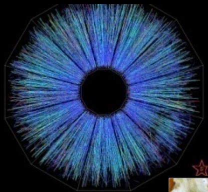
Color screening of $c\bar{c}$ pair results in J/ψ ($c\bar{c}$) suppression!



Quarkonium dissociation when $r_{Debye} \sim 1/(\alpha_s T) < r_{qq}$

"Big Picture Summary" of Results from RHIC & LHC

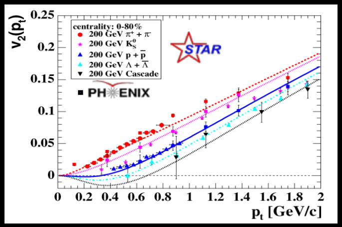
Hottest matter ever on Earth (T > 2 x 10^{12} K)…….



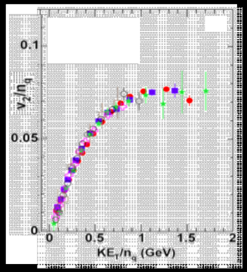
It has characteristics of a soup of quarks and gluons

Identified Particle Elliptic Flow:

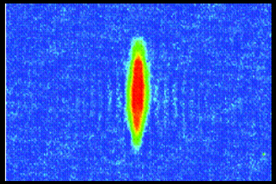
Elliptic flow v_2 mass splitting



& quark scaling

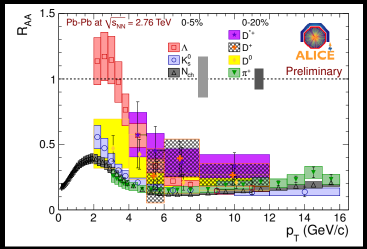


Flows like a liquid, with ultra-low shear viscosity



It's opaque to the most energetic probes:

Light & heavy quark suppression

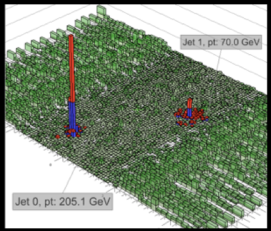


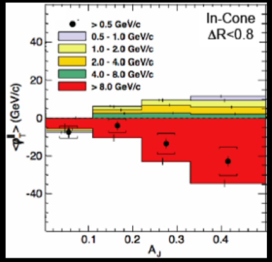
NOT Weakly-interacting QGP

(as expected from Lattice QCD)

NOT $\alpha_s \sim 0$

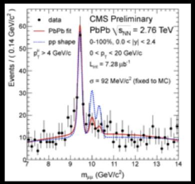
Away-side jet quenched & jet E imbalance





Suppression of quarkonia (J/ψ and Υ states)

Deconfinement….



Still much to be done on last three topics!

Questions – Quark-Gluon Plasma at RHIC & LHC

- How does the system evolve and thermalize from its initial state? What is the initial state (CGC?)?
- What are the properties & constituents (vs. T) of the QGP?
- Can we understand parton energy loss at a fundamental level? What can we learn about the medium response?
- How does hadronization take place?
- Can we understand and extract contributions to quarkonium suppression? What does it tell us?
- Is the QCD Phase Diagram featureless above Tc? Coupling strength vs T….
- Are there new phenomena? A critical point? Others?
- Can there be new developments in theory (lattice, hydro, parton E-loss, string theory…) and understanding……across fields……?