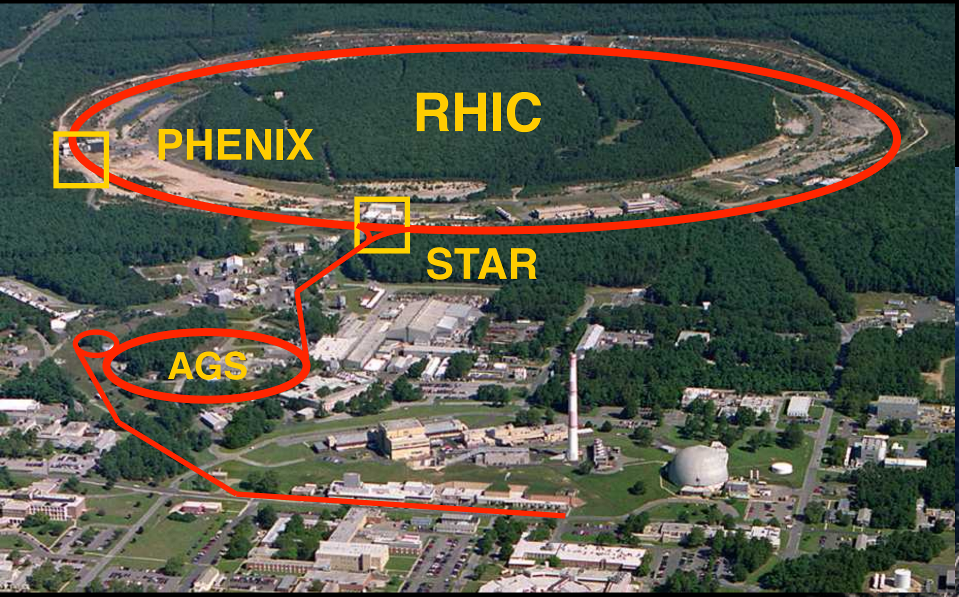
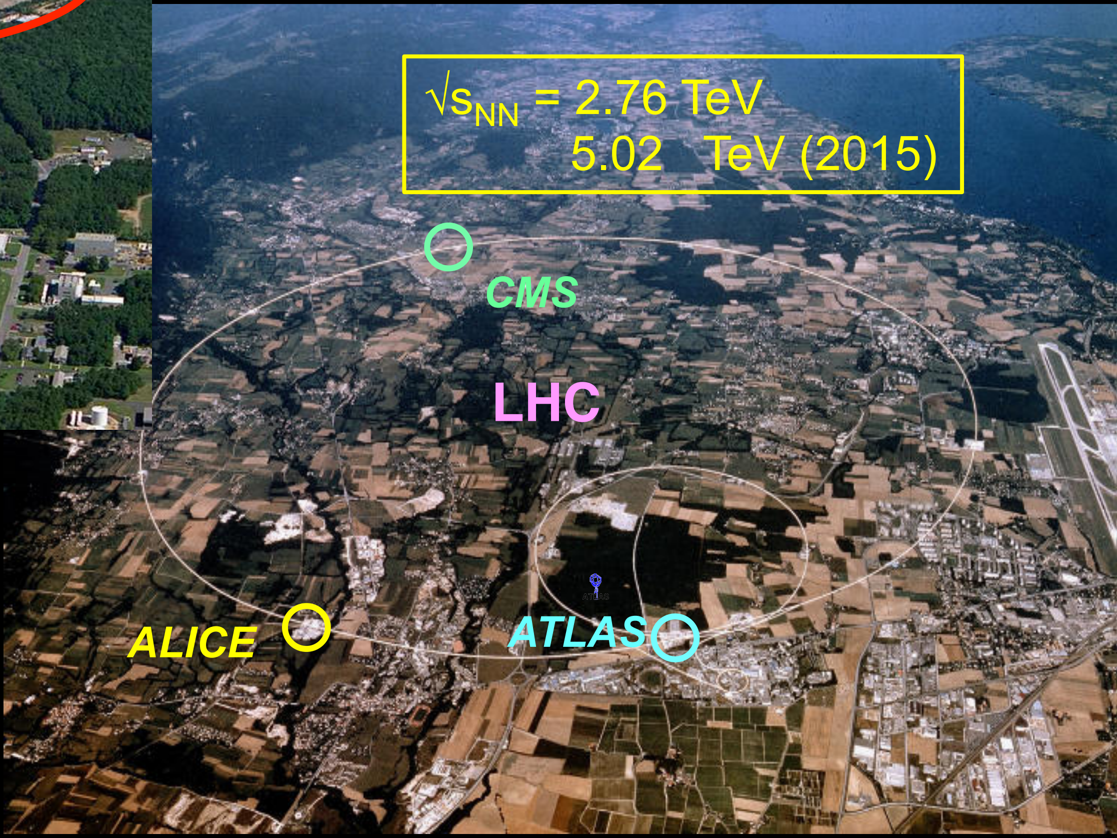
Ultra-relativistic Heavy-Ion Physics and Experiments



$\sqrt{s_{NN}}$ = 7 - 200 GeV

Cover 3 decades of energy in center-of-mass



$\sqrt{s_{NN}}$ = 2.76 TeV
5.02 TeV (2015)

Investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!

Ultra-relativistic Heavy-Ion Physics and Experiments

Outline:

Introduction to Heavy Ion Physics

Machines and Experiments

How Do Heavy Ion Collisions Evolve?

Important Physics Results

Future

Top Ten Physics Newsmakers of 2000 – 2010

http://www.aps.org/publications/apsnews/201002/newsmakers.cfm

"Stories with the most lasting physical significance & impact in physics"

*The **Large Hadron Collider (LHC)*** – modern marvel of science, last piece of standard model.

*The **Decade of Carbon*** – carbon nanotubes & graphene, will revolutionize electronics.

Negative Index of Refraction Materials – meta-materials make objects seem to disappear.

The Wilkinson Microwave Anisotropy Probe – leftover heat from Big Bang.

Quantum Teleportation – quantum information transport across macroscopic distances.

Quark-Gluon Plasma – first instances after Big Bang, all matter as hot quarks & gluons.

Gravity Probe B – observed the geodetic effect (to look for frame dragging in general relativity).

Light Stopped – actually stopped altogether and stored for up to 20 milliseconds.

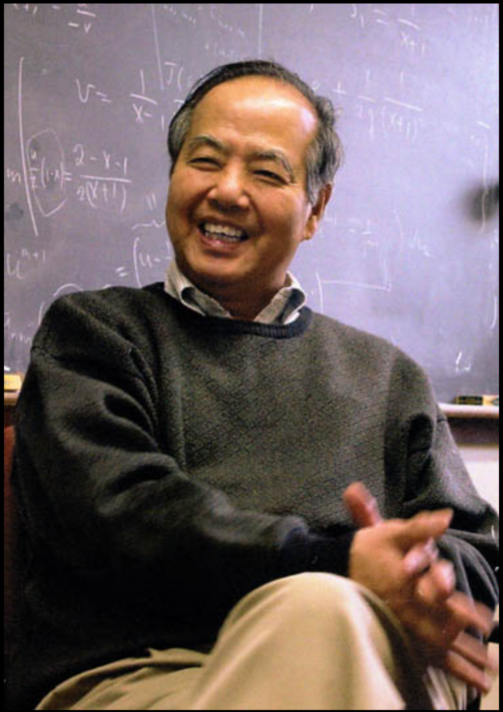
Direct Evidence for Dark Matter – two colliding galaxies confirm presence of dark matter.

Advances in Computing – > 10^{15} calculations / sec., map bio-structures, supercomputers.

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.

In order to study the question of 'vacuum', we must turn to a different direction; we should investigate some 'bulk' phenomena by distributing high energy over a relatively large volume."



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

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

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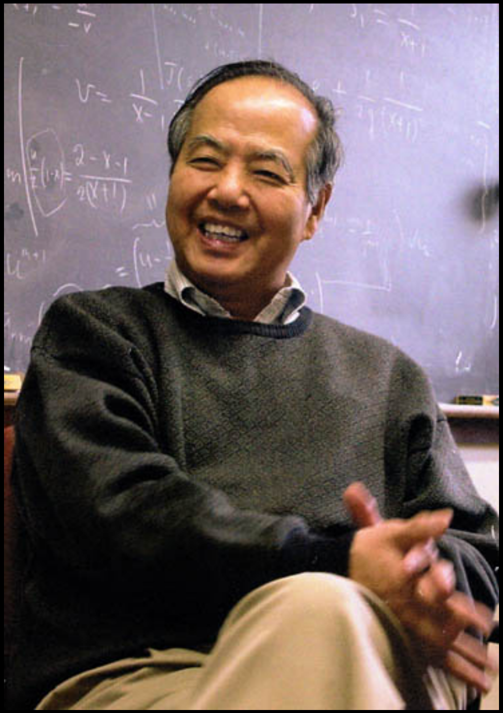
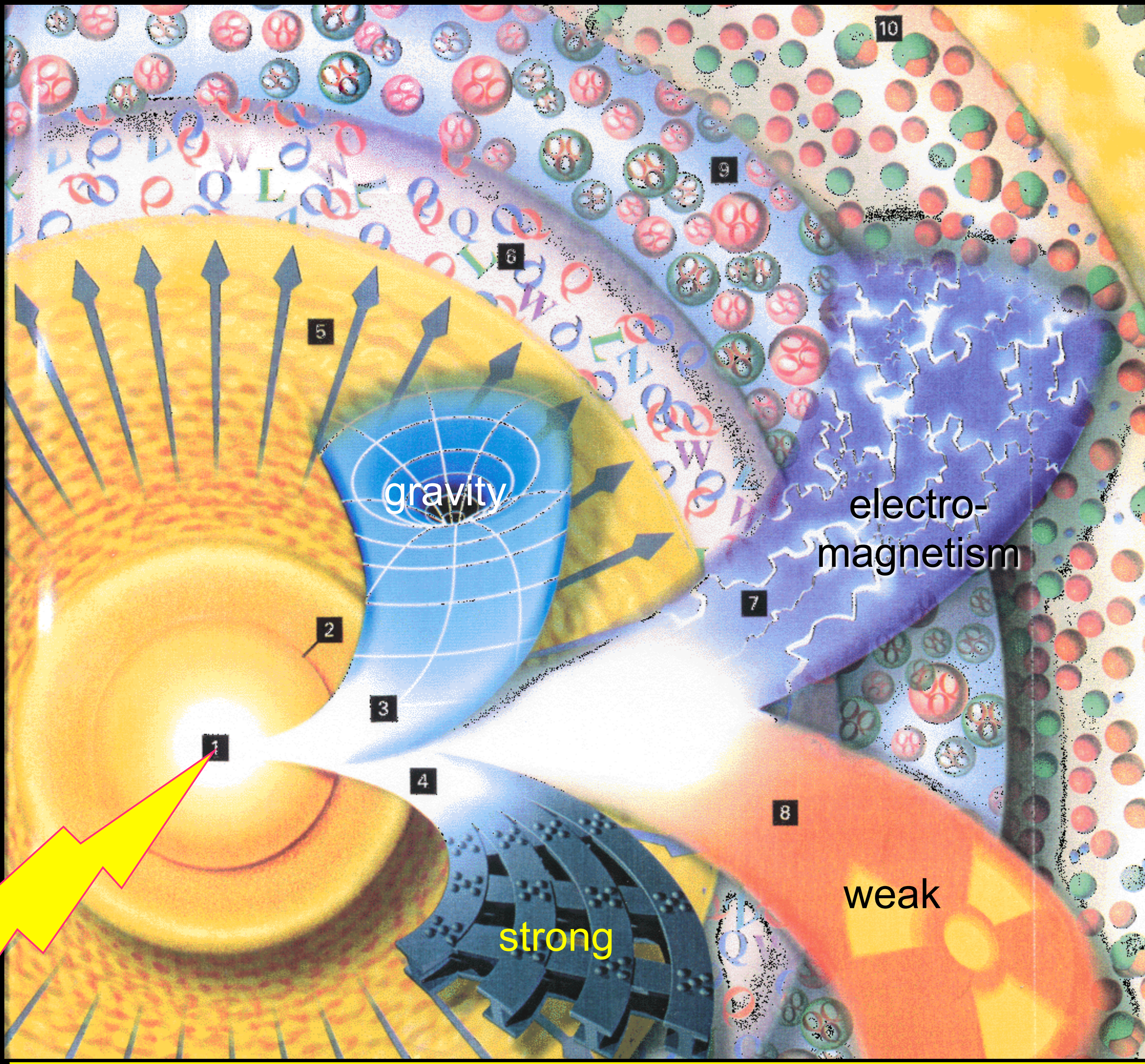


Question – What do you think T.D. Lee meant by studying the 'vacuum'? What happens in these collisions to make that possible?

On the "First Day"



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

There was light!

John Harris (Yale)

On the "First Day"

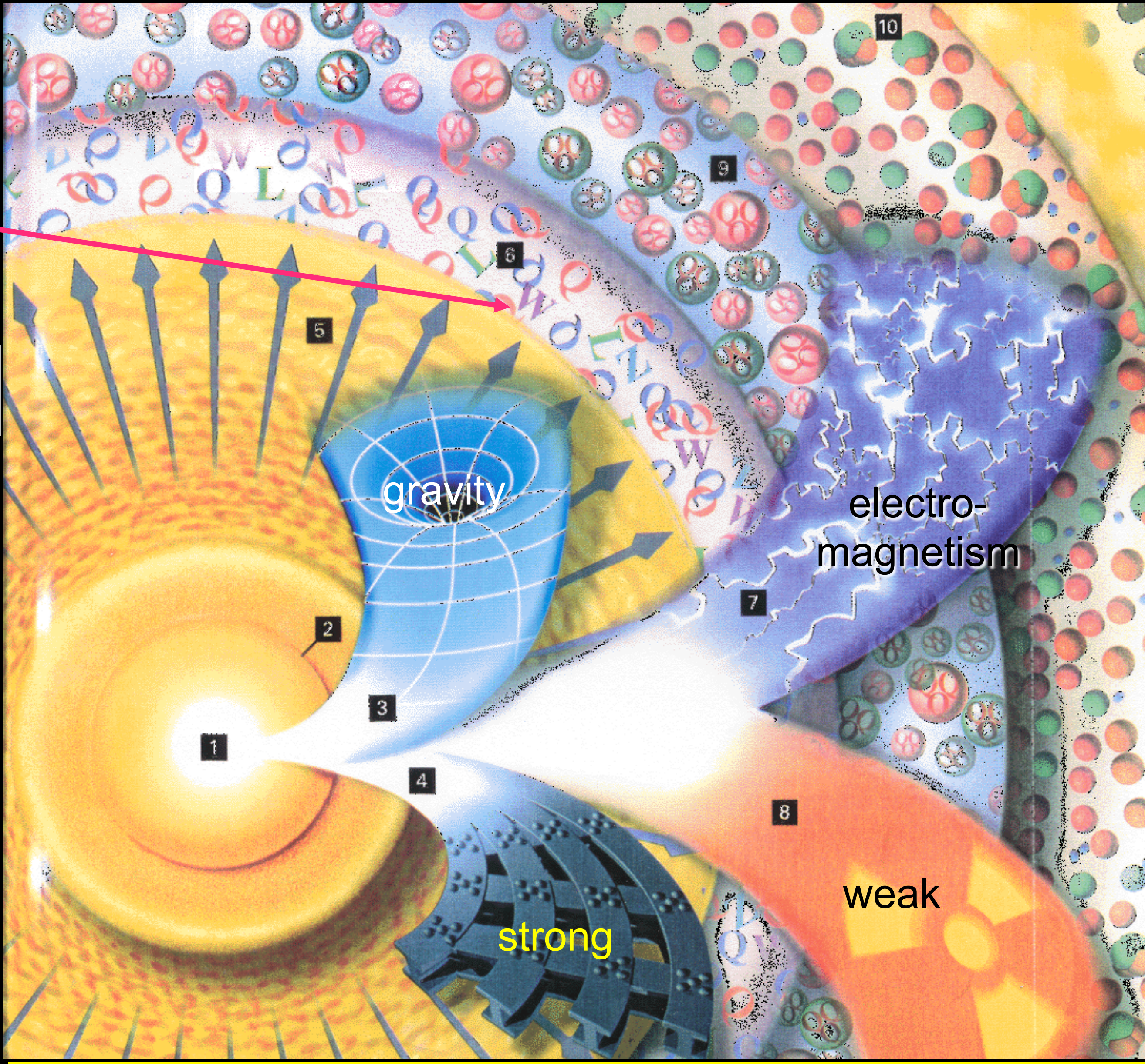
then at 10 μ-seconds
& 2 x 10^{12} Kelvin
Quark-to-hadron*
phase transition

Quark-Gluon Plasma

Rapid inflation

gravity, strong & E-W
forces separate

at 10^{-43} seconds



Courtesy Nat. Geographic, Vol. 185, No. 1, 1994 – Graphics by Chuck Carter
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* hadrons = nuclear particles
= mesons, baryons

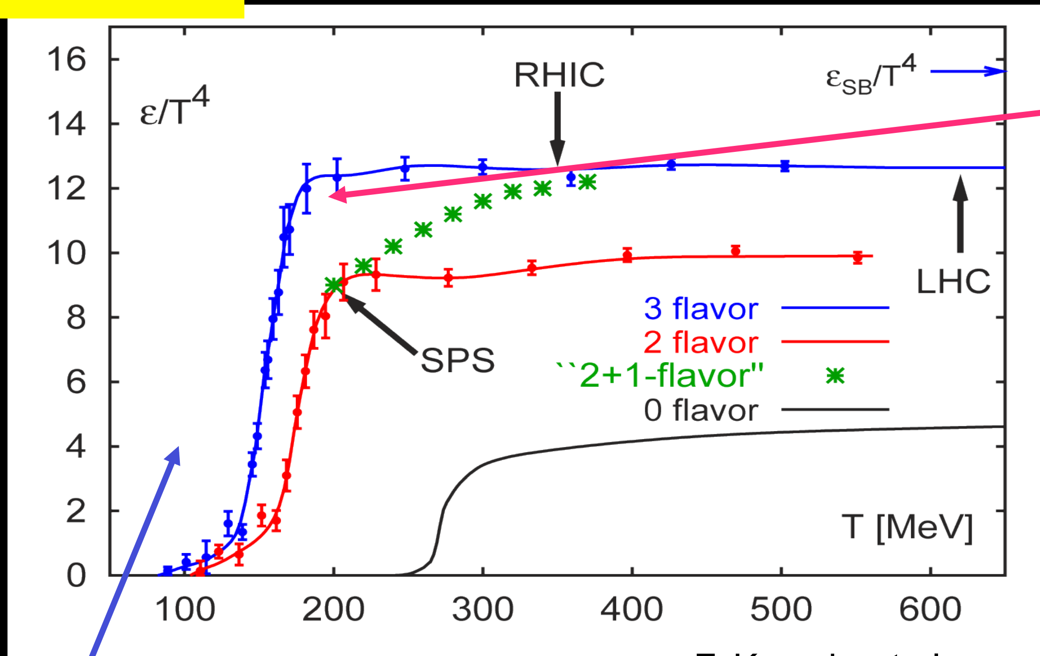
John Harris (Yale)

Behavior of QCD* at High Temperature

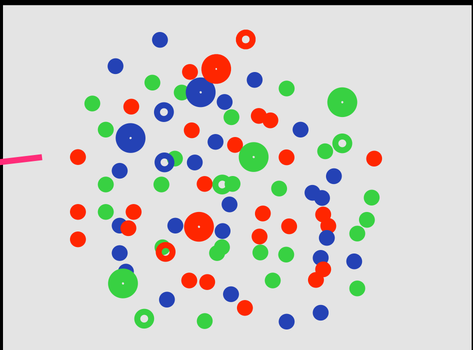
* Quantum Chomo-Dynamics

ε/T⁴ ~ # degrees of freedom

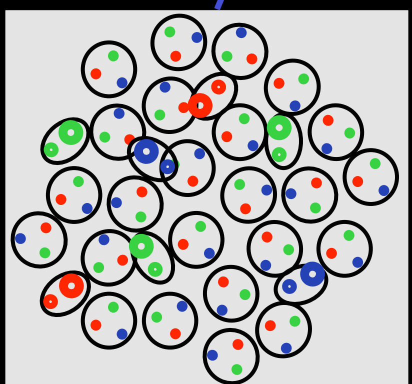
$$\varepsilon = \frac{\nu\pi^2}{30}T^4$$



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



many d.o.f.→**deconfined**



few d.o.f.→**confined**

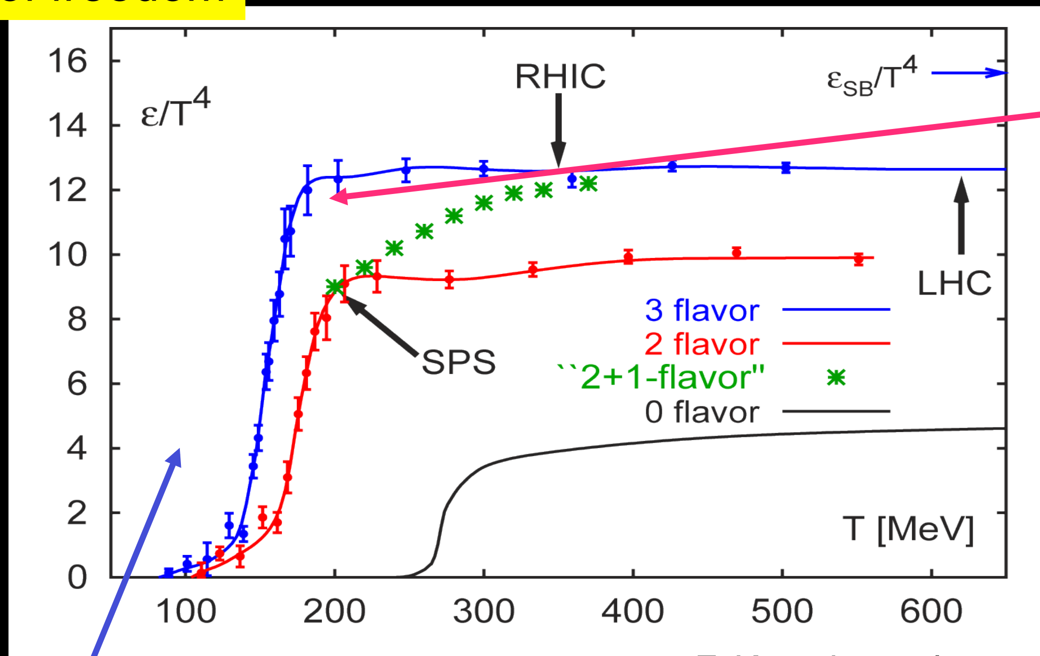
$T_C \sim 175 \pm 8$ MeV → $\varepsilon_C \sim 0.3 - 1$ GeV/fm^3

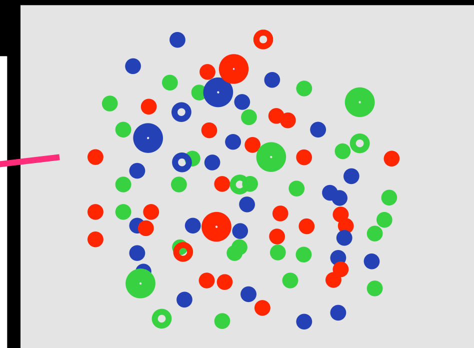
Behavior of QCD* at High Temperature

* Quantum Chomo-Dynamics

ε/T^4 ~ # degrees of freedom

$$\varepsilon = \frac{\nu \pi^2}{30} T^4$$





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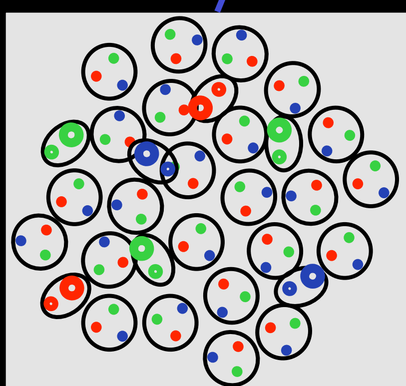


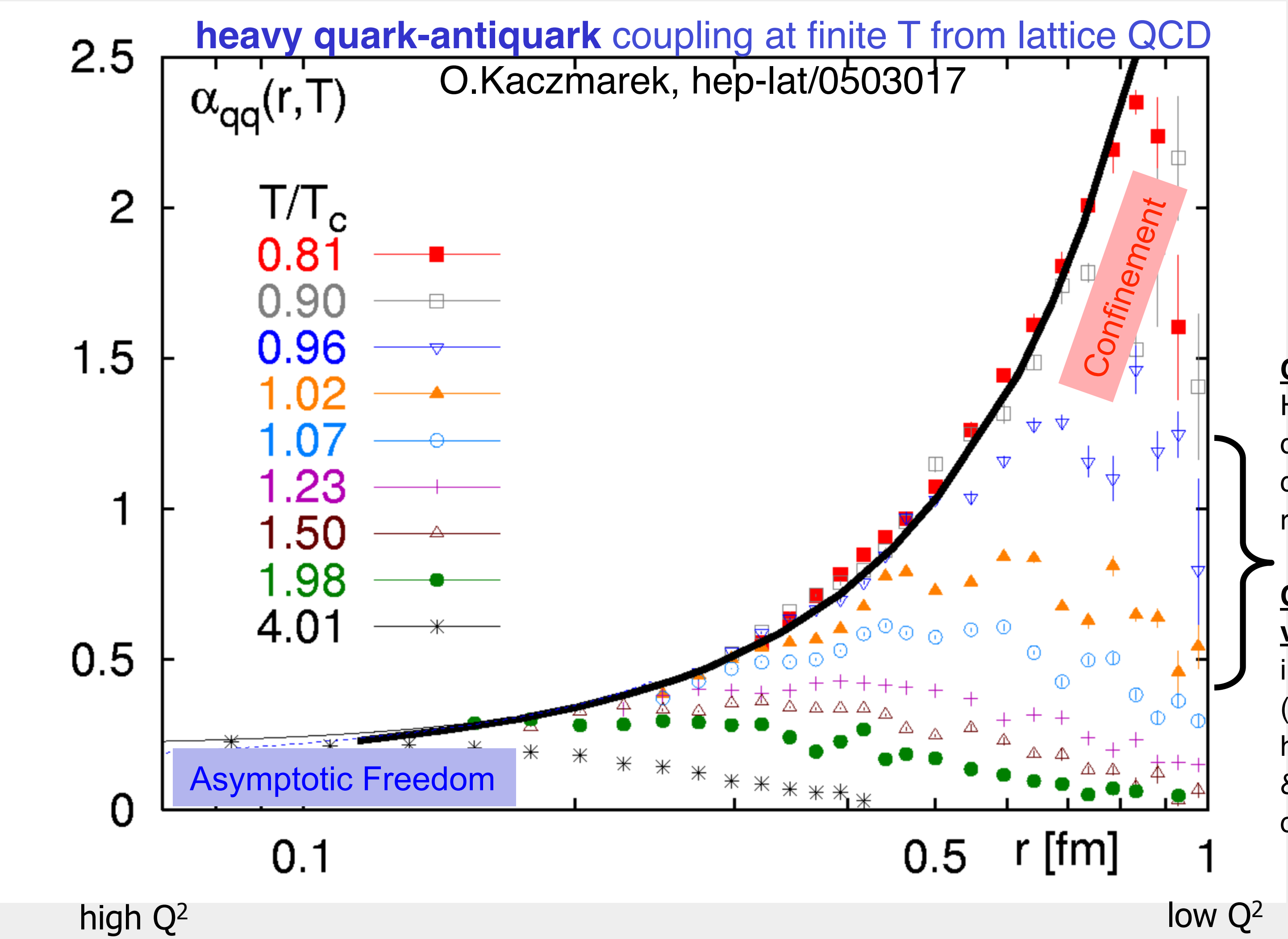
few d.o.f.→**confined**

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

Recent LQCD results with improved actions:
A. Bazavov et al, Phys. Rev. D80 (2009) 014504
P. Petreczky, Journal of Physics G39 (2012) 093002

T_C ~ 185 – 195 MeV → ε_C ~ 0.3 - 1 GeV/fm^3

Modifications to QCD Coupling Constant α_s



Constituents - Hadrons, dressed quarks, quasi-hadrons, resonances?

Coupling strength varies investigates (de-)confinement, hadronization, & intermediate objects.

Modifications to QCD Coupling Constant α_s

Nobel Prize 2004

D. Gross
H.D. Politzer
F. Wilczek

QCD Asymptotic Freedom (1973)

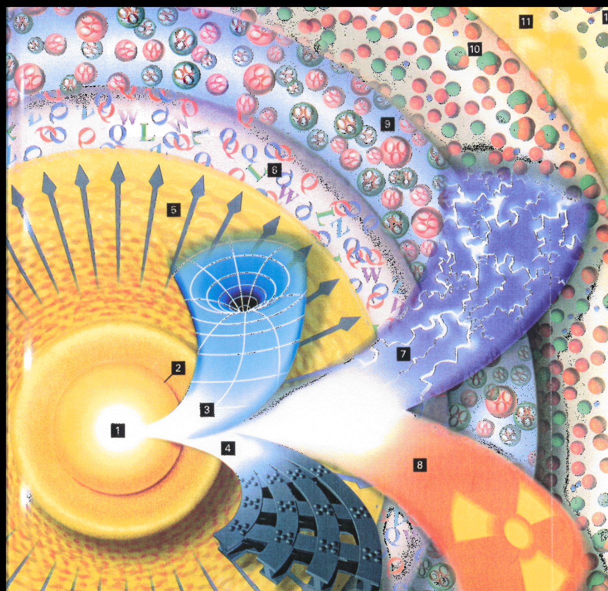
"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma."
David Gross, Nobel Lecture (RMP 05)

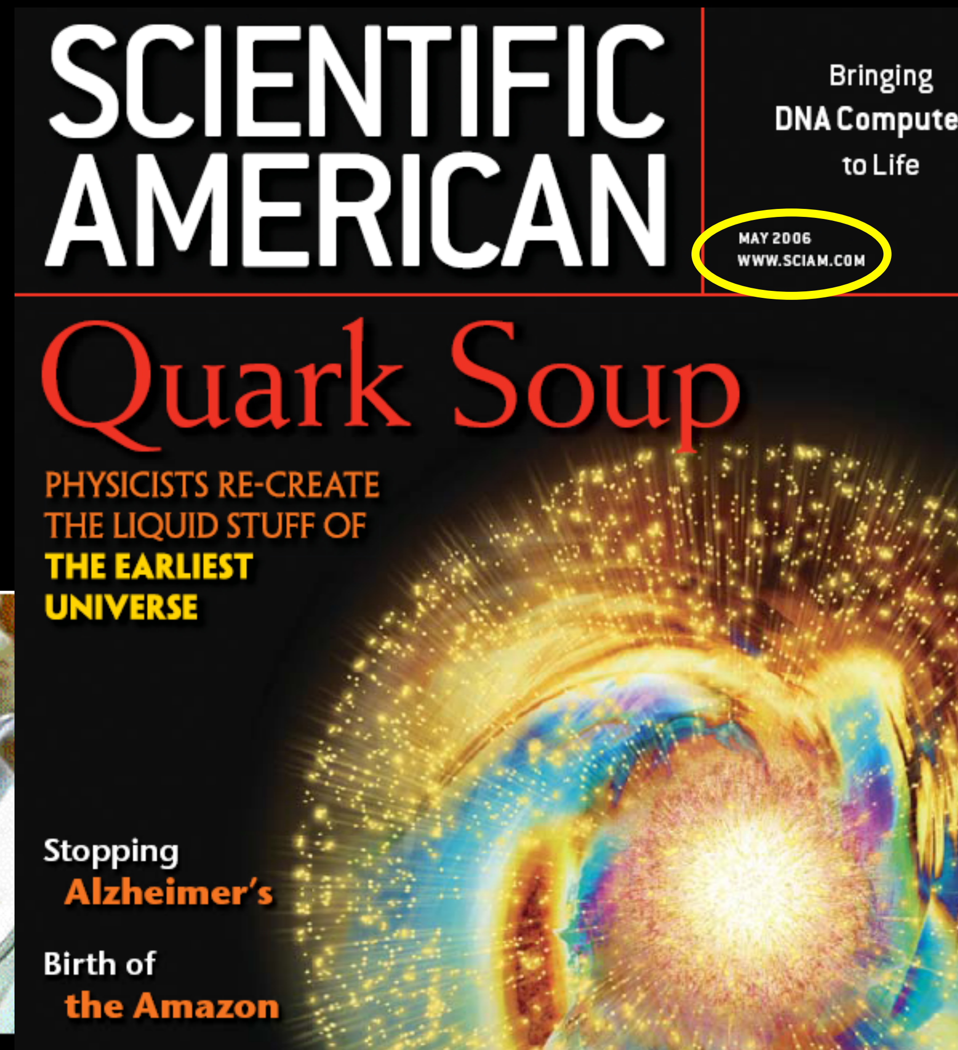
Quark-Gluon Plasma (Soup)

- **Standard Model** → Lattice Gauge Calculations predict
  QCD Deconfinement phase transition at T = 175 – 190 MeV
- **Cosmology** → Quark-hadron phase transition in early Universe
- **Astrophysics** → Cores of dense stars (?)
- Can we make it in the lab?

- Establish properties of QCD at high T

Re-creating the Primordial Quark-Gluon Plasma at RHIC and LHC





BIG PICTURE Questions

What are the states of matter that exist at high temperature and density?

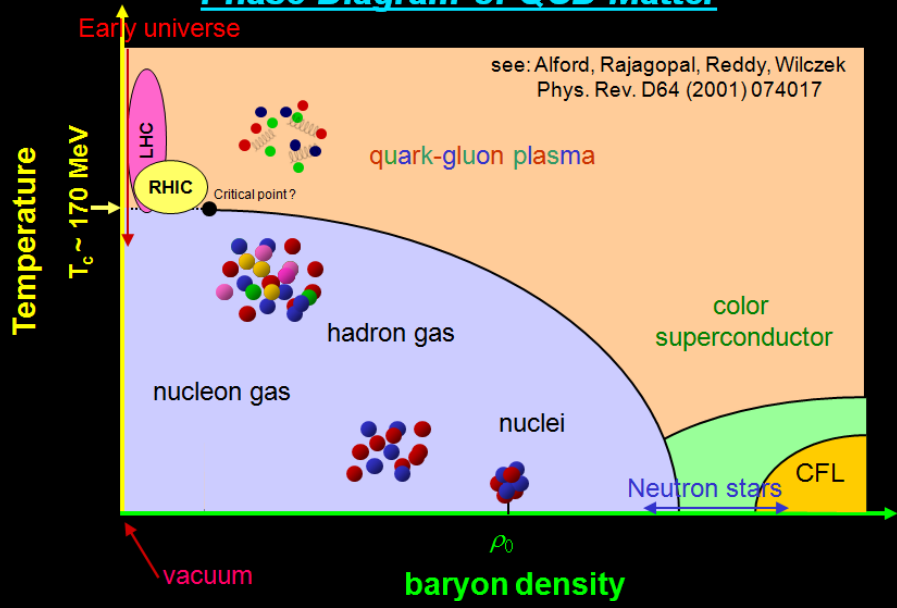
- Can we explore the phase structure of a fundamental gauge (QCD) theory?
  - → Can we use this to understand other gauge theories (like gravity!)?
- Is the Phase Diagram of QCD featureless above Tc?
  - → What are the constituents (are there quasi-particles, exotic states, others)?
  - → When does the "quark-gluon soup" become resolvable into quarks and gluons?
  - → Is there a critical point (RHIC Energy Scan)?

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?

Phase Diagram of QCD Matter



Ultra-relativistic Heavy-Ion Physics and Experiments

Introduction to Heavy Ion Physics

Machines and Experiments

How Do Heavy Ion Collisions Evolve?

Important Physics Results

Future

Where and How Do We Do This?

- STAR & PHENIX experiments at the Relativistic Heavy Ion Collider (RHIC)

  at Brookhaven National Laboratory, Long Island, New York

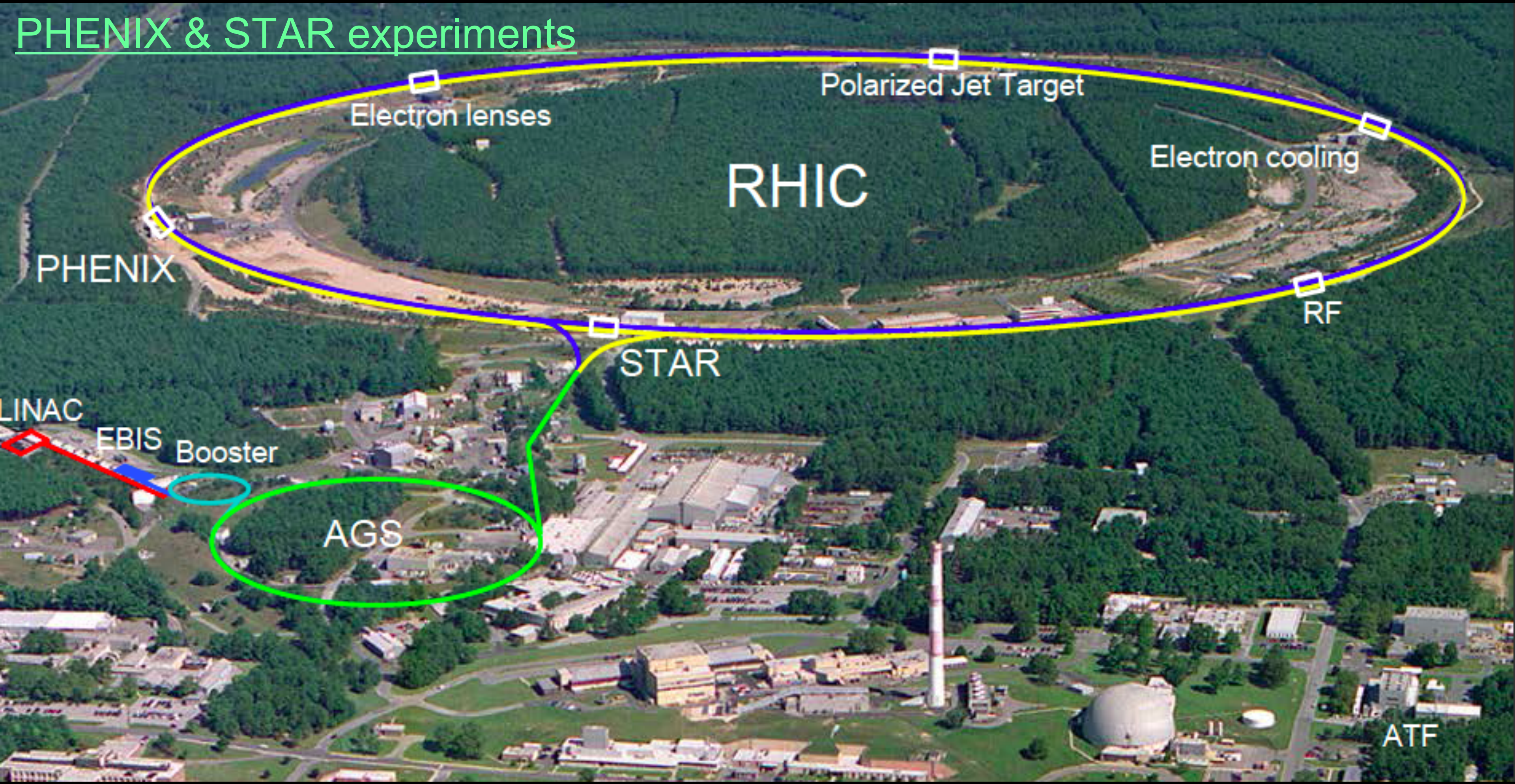
  $\sqrt{s_{NN}}$ = Au + Au at 7 – 200 GeV per colliding nucleon pair

- ALICE. ATLAS, CMS, LHCb experiments at the Large Hadron Collider (LHC)

  at CERN, Geneva, Switzerland

  $\sqrt{s_{NN}}$ = Pb + Pb at 2.76 & soon 5.0 TeV per colliding nucleon pair

Relativistic Heavy Ion Collider (RHIC) since 2000



$\sqrt{s_{NN}}$ = 7 – 200 GeV (15 energies) Au+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, U+U

$\sqrt{s_{NN}}$ = 200 & 500 GeV protons (polarized)

The Two "Large" Experiments at RHIC

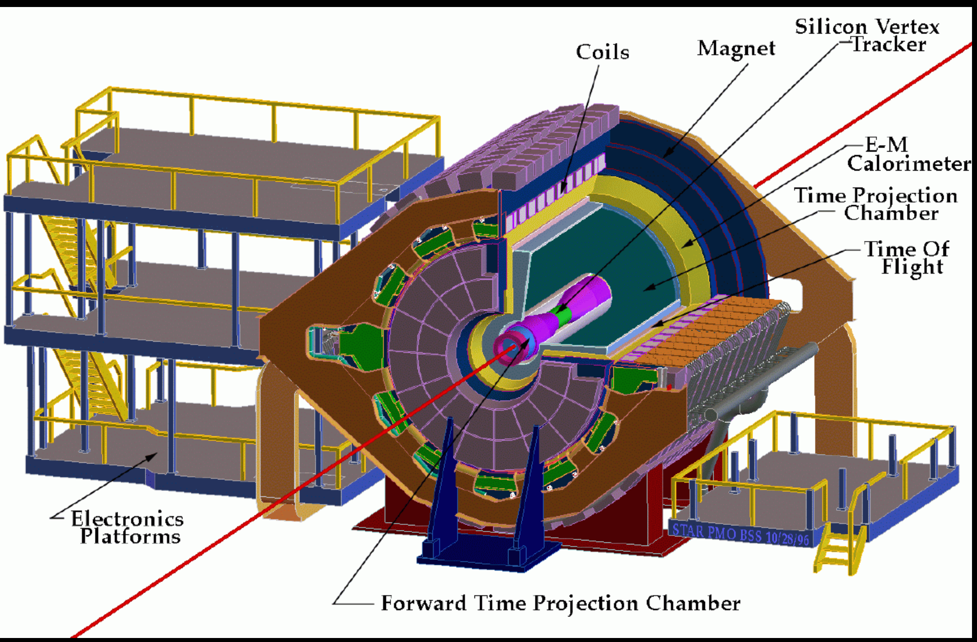
STAR

Solenoidal field $0 < \varphi < 2\pi$, $|\eta| < 1$

Large-Ω Tracking

TPC's, Si-Vertex Tracking

RICH, EM Cal, TOF



- Hadronic Observables
- Large Acceptance, Jets
- Event-by-Event Analyses

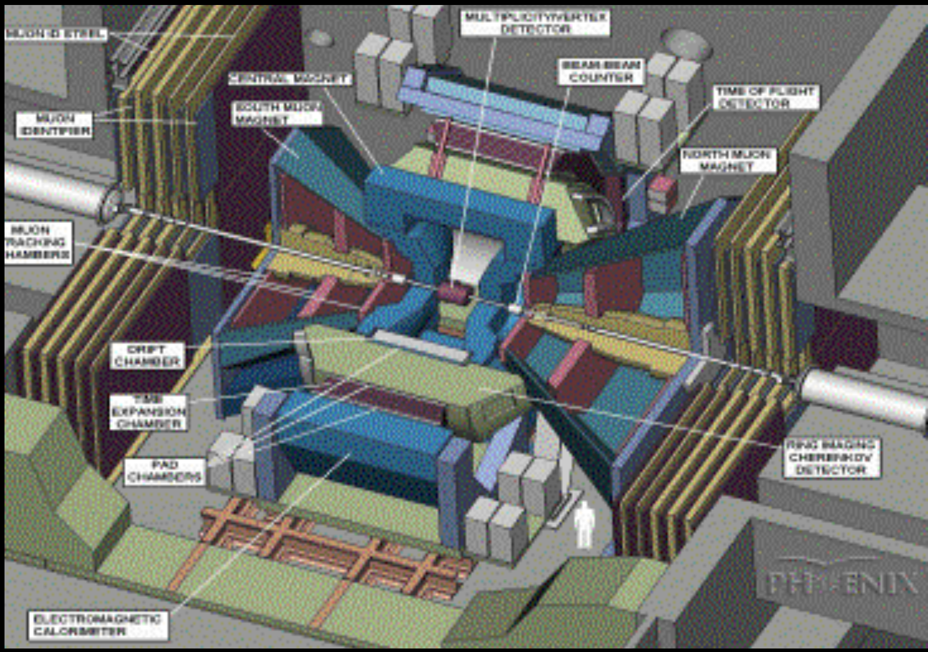
PHENIX

Axial Field

High Resolution & Rates

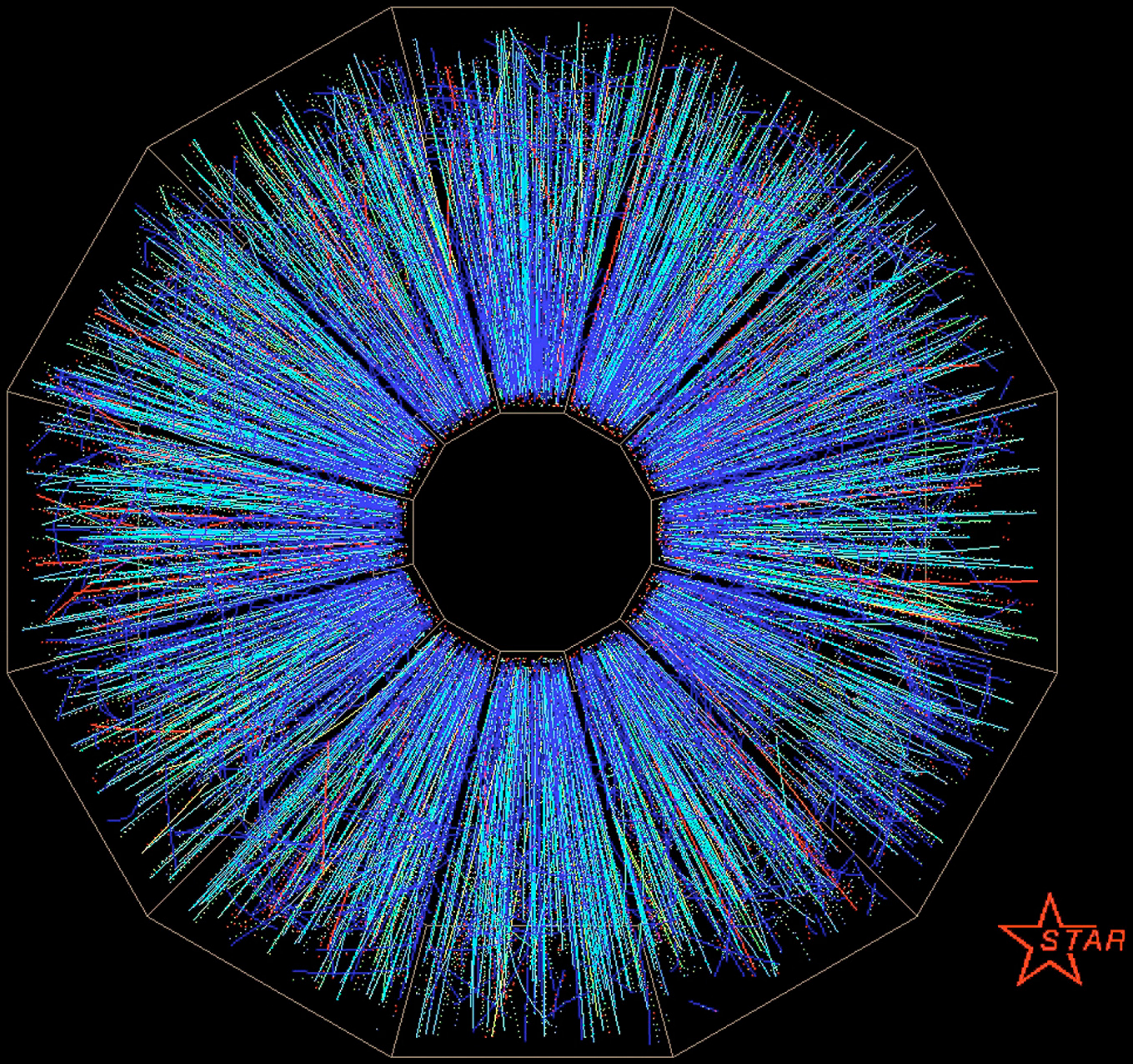
2 Central Arms, 2 Forward Arms

TEC, RICH, EM Cal, Si, TOF, μ-ID



- Leptons, Photons, & Hadrons
- Simultaneous Detection of Various Transition Phenomena

Head-on Collision



The Large Hadron Collider (LHC)

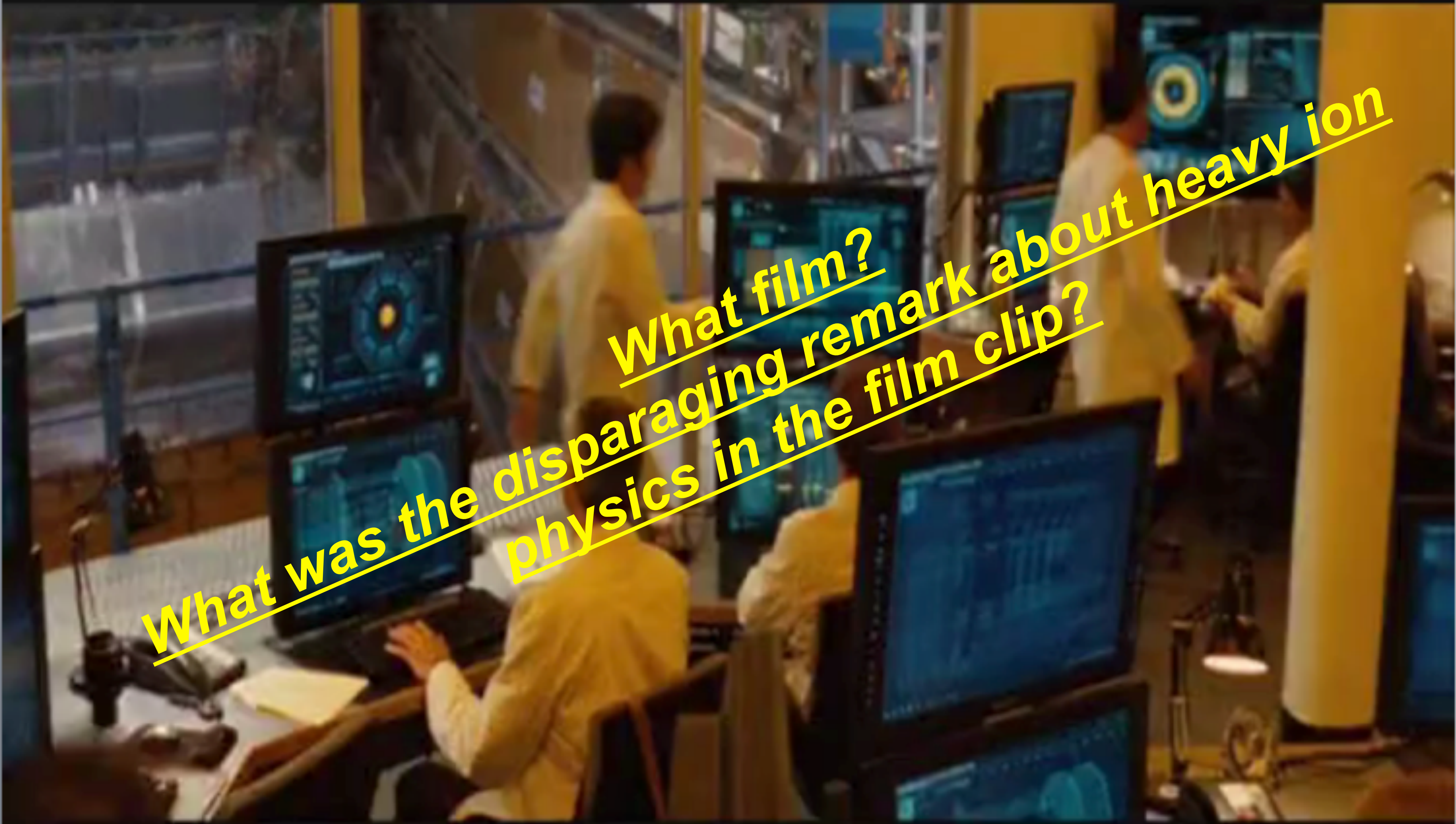
Lead nuclei each with 207 protons + neutrons are accelerated.
Lead nuclei collide at 0.999995 x speed of light (2760 GeV/nucleon pair).

The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC)

from the Control Room

The Large Hadron Collider (LHC)



from the Control Room

Scientists create hottest substance on Earth

Stuart Gary for ABC Science Online

Posted Tue Jun 14, 2011 12:37pm AEST

Scientists using the world's largest atom smasher have made some of the hottest and densest matter ever achieved on Earth.

The state of matter called a quark gluon plasma existed in the milliseconds after the big bang 13.7 billion years ago.

Physicists using the Large Hadron Collider (LHC) at CERN, the European Centre for Nuclear Research, smashed heavy lead ions together at close to the speed of light.

They generated temperatures of more than 1.6 trillion degrees Celsius, 100,000 times hotter than the centre of the Sun.

In the process they recreated the densest material ever observed - only black holes are denser.

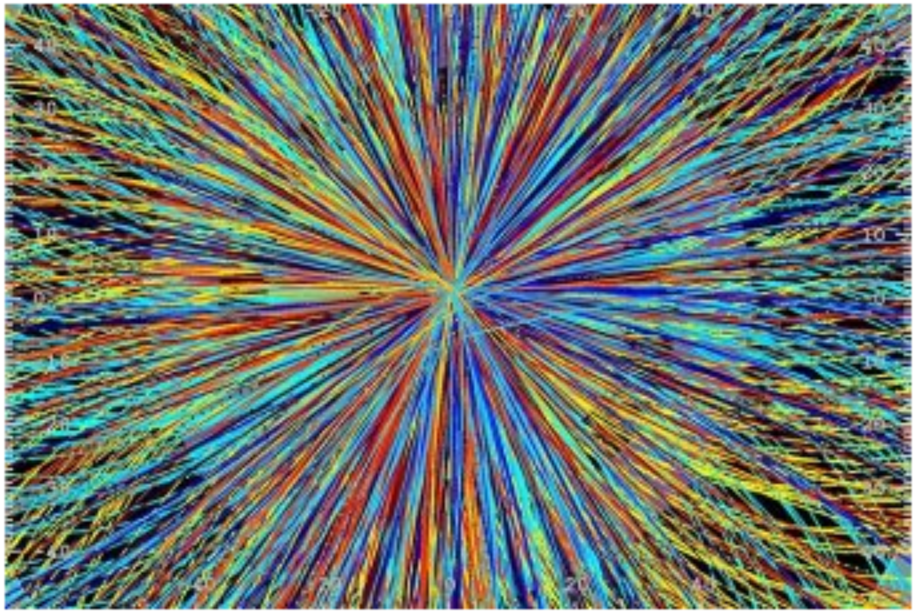
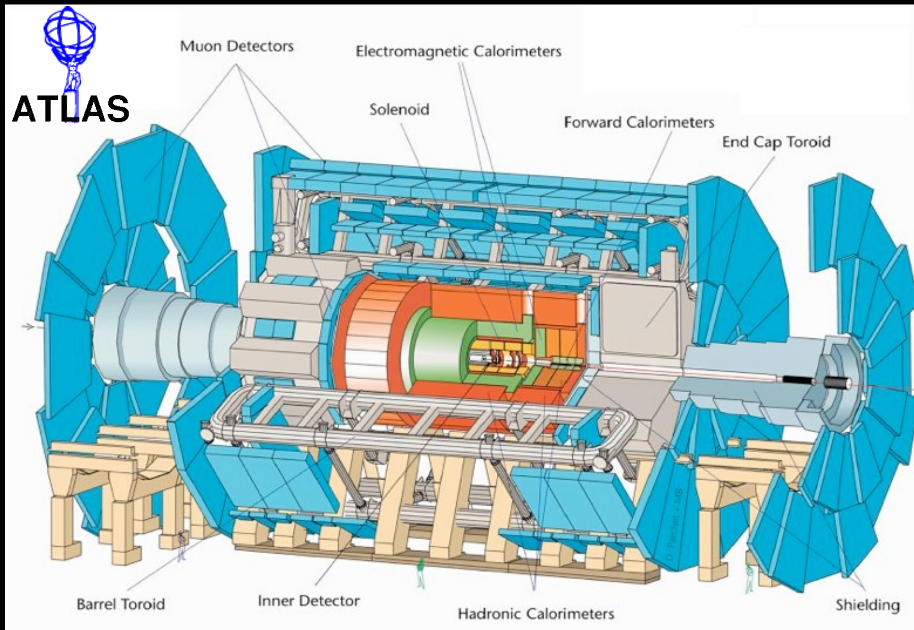


PHOTO: Events recorded by the ALICE experiment from the first lead ion collisions at a centre-of-mass energy of 2.76 TeV per nucleon pair.

MAP: Switzerland

LHC Heavy Ion Program



LHC Heavy Ion Data-taking

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

(1 month per year)

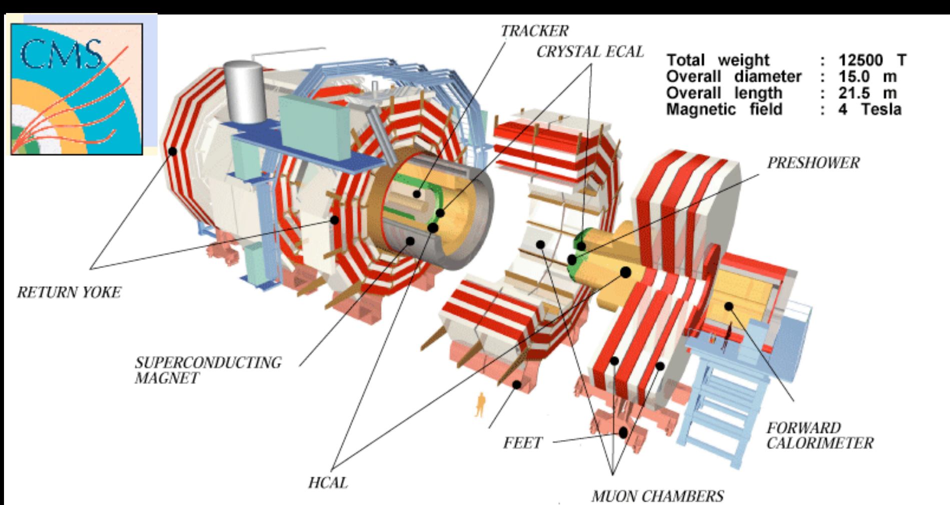
2010-11: Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

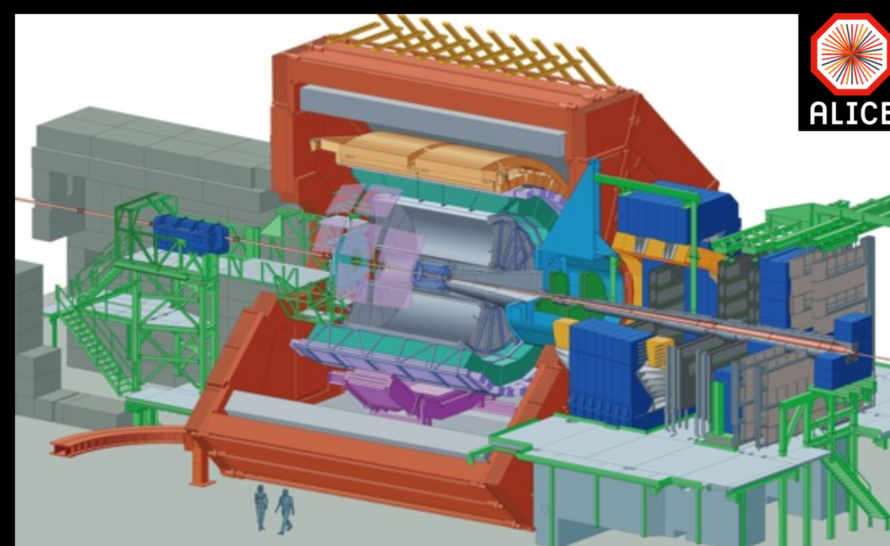
2013 : p + Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

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

LHC Collider Detectors for HI's

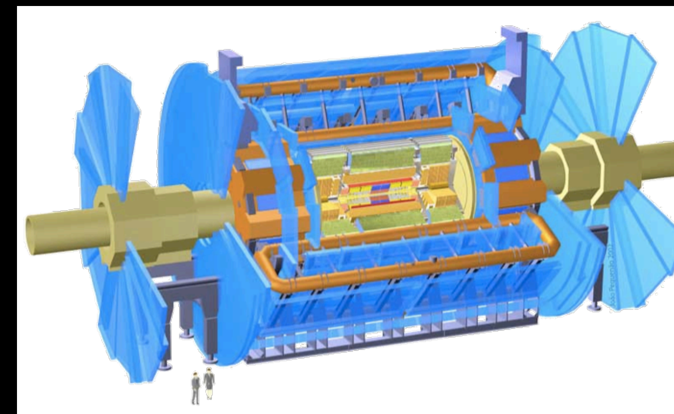
ATLAS CMS ALICE





ATLAS Heavy Ion Program

Overview:

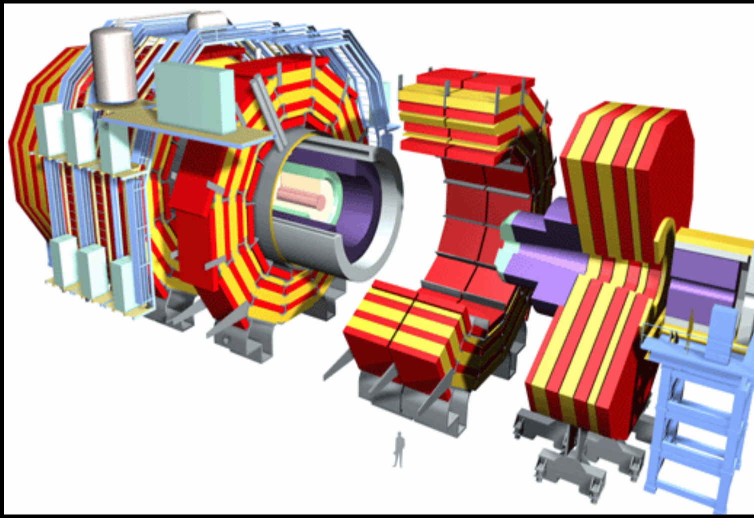


ATLAS has a broad heavy ion physics program
- soft physics, correlations
- excels at jet and photon measurements

Jets
- reconstruct jets in a large kinematical range
  E_T > 40 GeV and $|\eta|<5$
- perform key fragmentation measurements
- jet shape and FF modifications
- multi-jet studies

Photons
- isolate / measure photons in large range, E_T > 10 GeV and $|\eta|<2.5$
- unique calorimeter design allows additional rejection beyond isolation

CMS Heavy Ion Program



Overview:

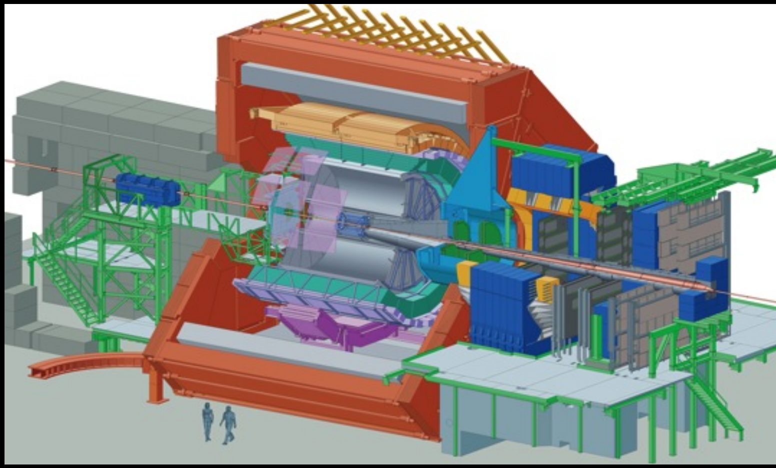
CMS has a broad heavy ion physics program

- precision tracking $|\eta| < 2.5$
- muon identification $|\eta| < 2.5$
- high-res calorimetry $|\eta| < 5$
- forward coverage

CMS excels at

- jets and di-jets
- photon-tagged jet measurements
  (FF modifications)
- quarkonium measurements

ALICE – Heavy Ion Experiment



Overview:

Soft Probes – "ala RHIC"

- Expansion dynamics different from RHIC
- Soft physics measurements ala RHIC
  + extended PID
- Day 1 physics +

Hard Probes – Jet Quenching

- Jets, γ , pi-zeros, leading particles to large p_T

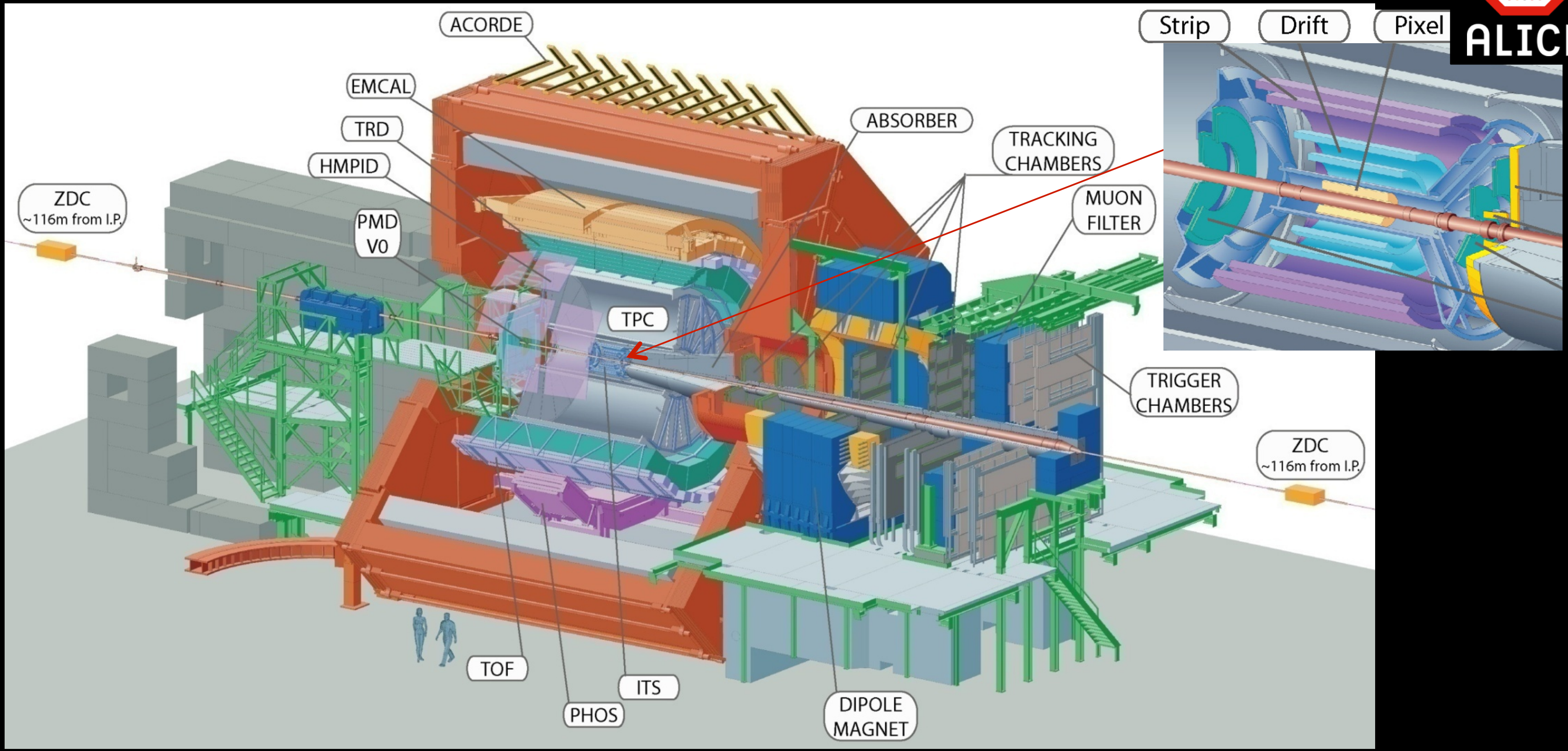
Hard Probes – Heavy Quarks

- Displaced vertices ($D^o \rightarrow K^- \pi+$) from TPC/ITS
- Electrons in Transition Radiation Detector (TRD)

Hard Probes – Quarkonia

- J/ψ, Υ, Υ' (excellent), Υ''(2-3 yrs), ψ' ???

The ALICE Heavy Ion Experiment



- **Fully Installed & Commissioned – Hadron & μ Capabilities**

  ITS, TPC, TOF, HMPID, MUONS, V0, T0, ZDC, ACORDE, TRIGGER, HLT

- **EM (e and γ) Partial Capabilities**

  TRD (50%, 100% in 2015), PHOS, EMCAL, DCal (new in 2015)

ALICE Detectors & Acceptance

ALICE

central barrel ***-0.9 < η < 0.9***

- $\Delta\phi = 2\pi$ tracking, PID **(TPC/ITS/ToF)**
- single arm RICH **(HMPID)**
- single arm e.m. cal **(PHOS)**
- electron id **(TRD)**
- EM calorimeter arms **(EMCal + DCal)**

forward muon arm ***-4 < η < -2.4***

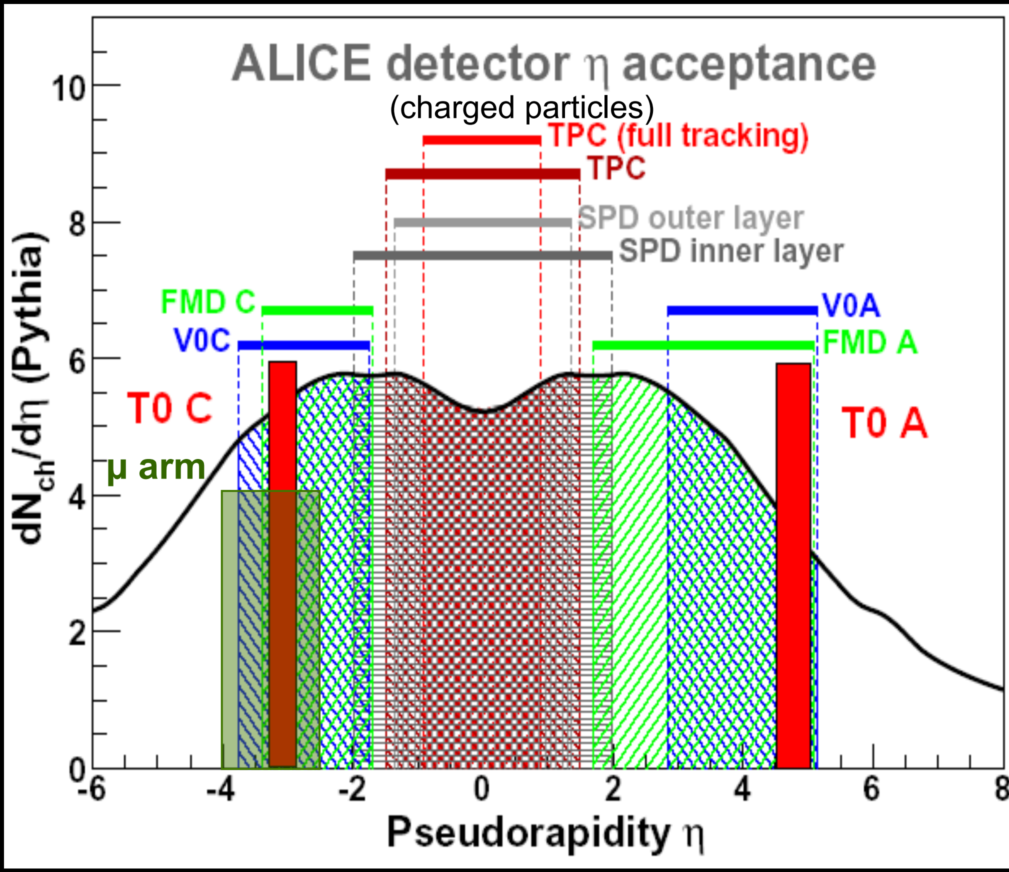
- absorber, 3 T-m dipole magnet
10 tracking + 4 trigger chambers

multiplicity detectors ***-5.4 < η < 3***

- including photon counting in **PMD**

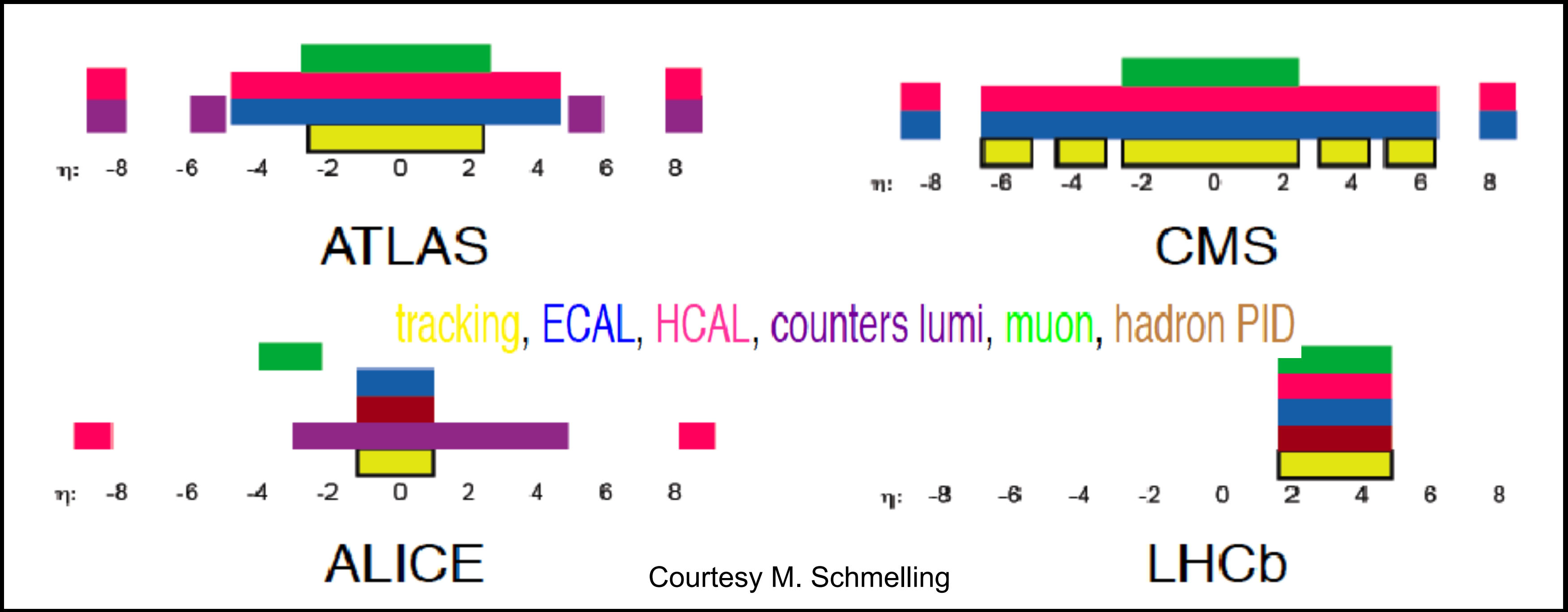
trigger & timing detectors

- 6 **Z**ero **D**egree **C**alorimeters
- **T0:** ring of quartz window PMT's
- **V0:** ring of scint. Paddles



$\eta = -1/2 \ln (\tan \theta/2)$

Angular Acceptance of LHC Experiments



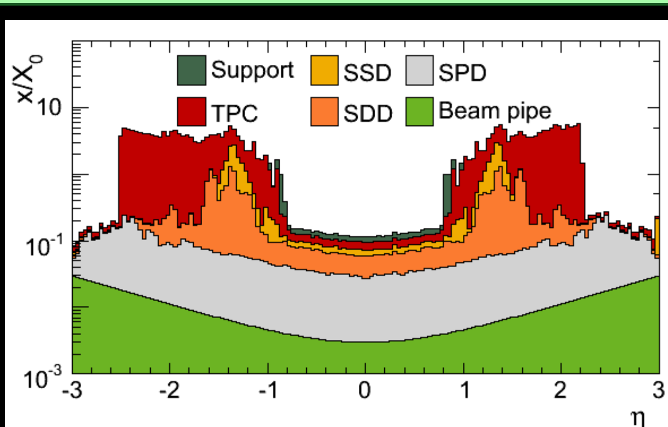
Complementary measurements

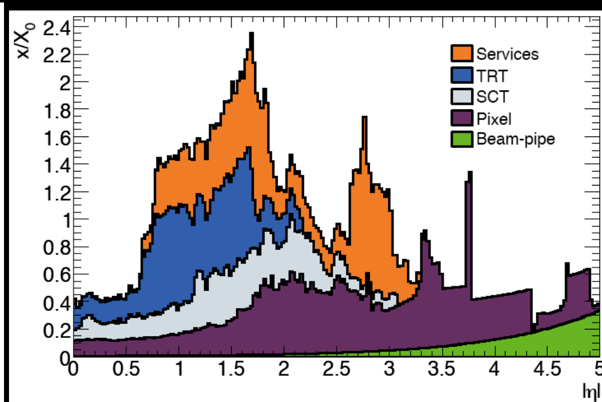
- ATLAS, CMS: Large acceptance for charged hadrons, leptons and neutral energy
- Hadron PID ALICE $|\eta| < 1$ and LHCb $2 < \eta < 5$
- ALICE/LHCb: Full tracking down to very low p_T (100 MeV)
- ATLAS, CMS also reach low p_T with vertex detectors
- ALICE: FAST-OR Pixel multiplicity trigger

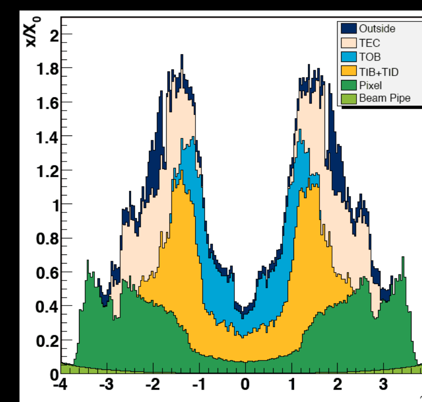
Material Budget of LHC Experiments

Cumulative mid-rapidity material budget for ALICE, ATLAS and CMS

ALICE	x/X_0 (%)	ATLAS	x/X_0 (%)	CMS	x/X_0 (%)
Beam pipe	0.26	Beam pipe	0.45	Beam pipe	0.23
Pixels (7.6 cm)	2.73	Pixels (12 cm)	4.45	Pixels (10.2 cm)	7.23
ITS (50 cm)	7.43	SCT (52 cm)	14.45	TIB (50 cm)	22.23
TPC (2.6 m)	13	TRT (1.07 m)	32.45	TOB (1.1 m)	35.23







⇨ Reconstruction and identification at low p_T due to low material budget

Ultra-relativistic Heavy-Ion Physics and Experiments

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Machines and Experiments

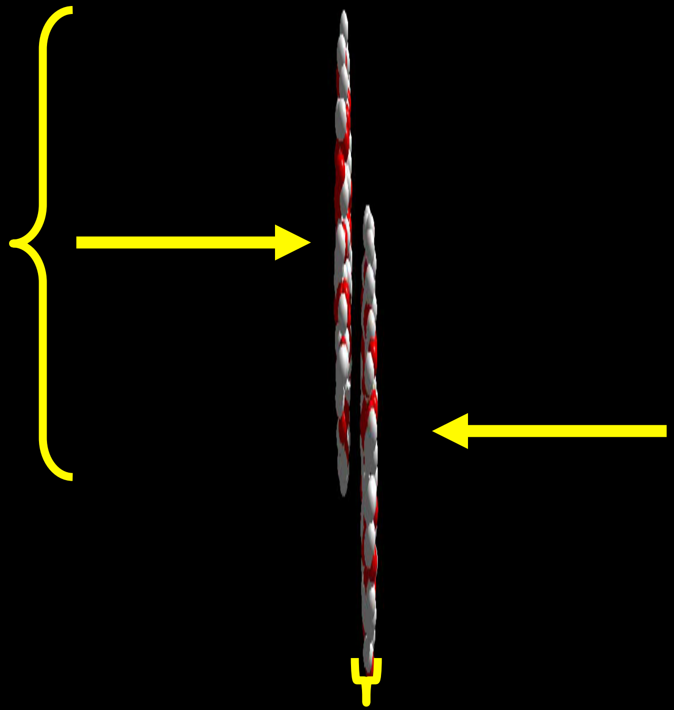
How Do Heavy Ion Collisions Evolve?

Important Physics Results

Future

Heavy Ion Collisions at RHIC & LHC

Lead nucleus
diameter ~ 14 fm



γ = 100 → 2,500
(Lorenz contracted)

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

General Orientation

Hadron masses ~ 1 GeV

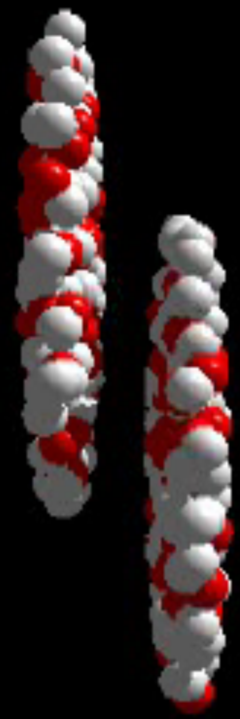
Hadron sizes ~ fm

Heavy Ion Collisions

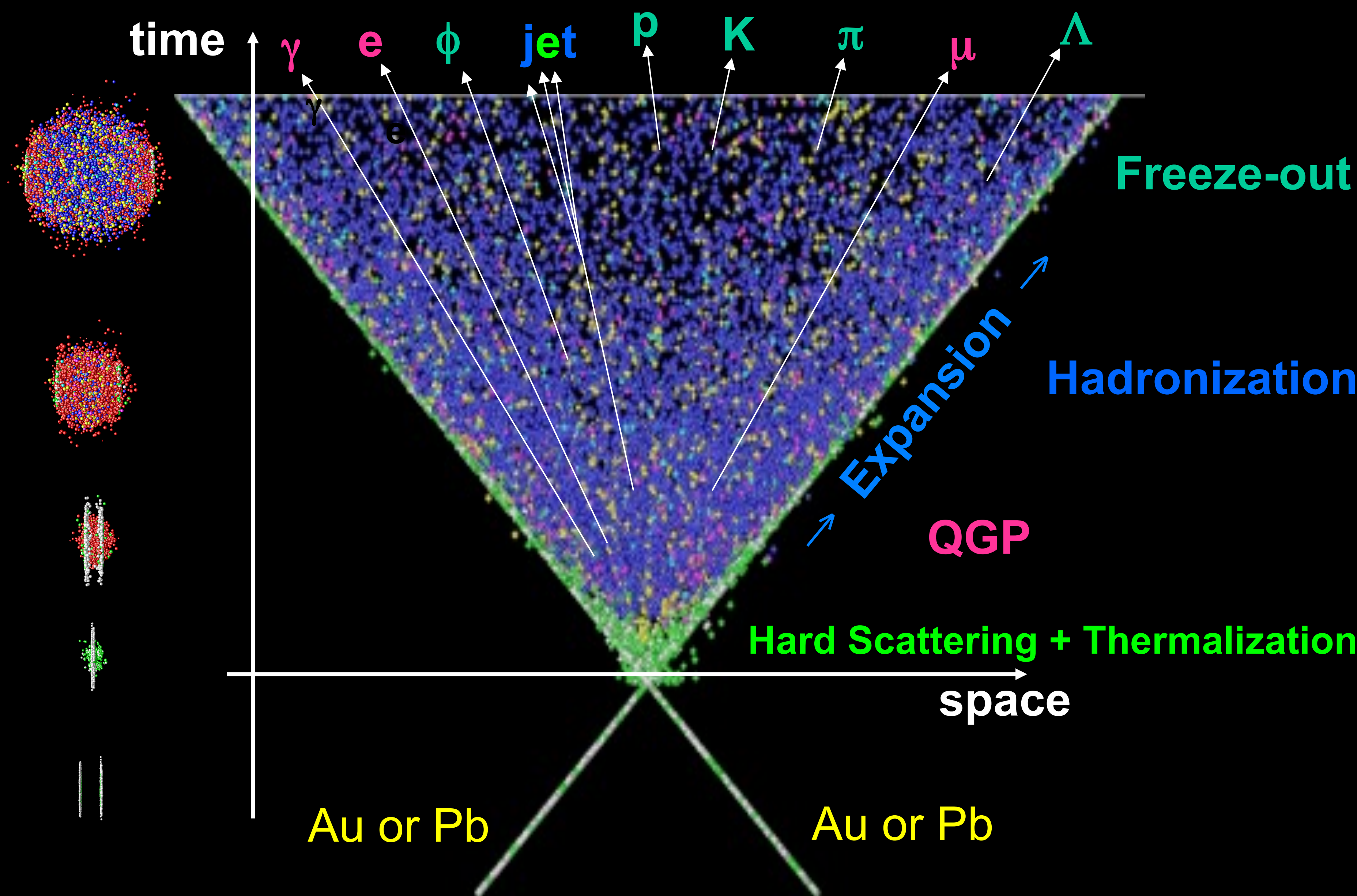
RHIC: E_{cm} = 0.2 TeV per nn-pair

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

How do Heavy Ion Collisions Evolve? – Side View at RHIC



Space-time Evolution of HI Collisions



Definitions

- **Relativistic treatment**

Energy

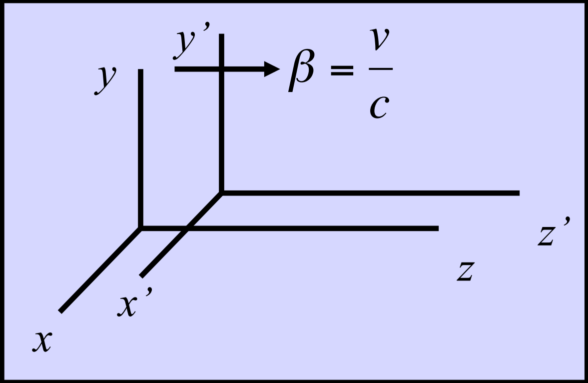
$$E^2 = p^2 + m^2 \quad \text{or} \quad E = T + m \quad \text{or} \quad E = \gamma m$$

where,

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \quad \text{and} \quad \beta = \frac{v}{c} = \frac{p}{E}$$

- **Lorentz transforms**

$$E' = \gamma(E + \beta p_z)$$
$$p'_z = \gamma(p_z + \beta E)$$



- **Longitudinal and transverse kinematics**

$$p_L = p_z$$

$$p_T = \sqrt{p_x^2 + p_y^2}, \quad m_T = \sqrt{p_T^2 + m^2}$$ **Transverse mass**

$$y = \frac{1}{2}\ln\left[\frac{E + p_L}{E - p_L}\right]$$ **Rapidity**

$$y' = y + \tanh^{-1}\beta$$

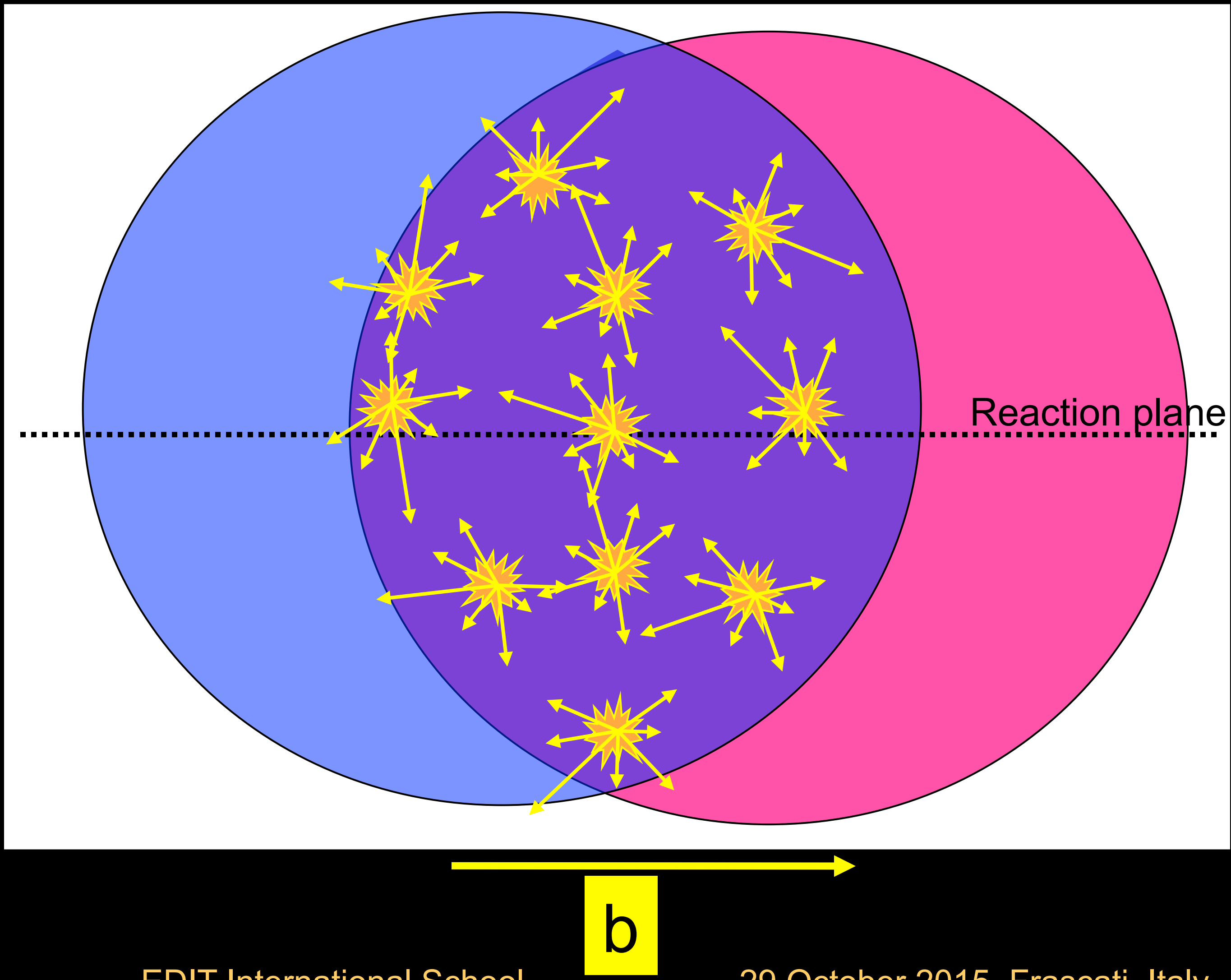
$\eta = -\ln(\tan\theta/2)$ **Pseudo-rapidity**

Useful relations

$$\gamma = \cosh y$$
$$\beta = \tanh y$$
$$E = m_T \cosh y$$
$$p_L = m_T \sinh y$$

How do Heavy Ion Collisions Evolve? – Beam View

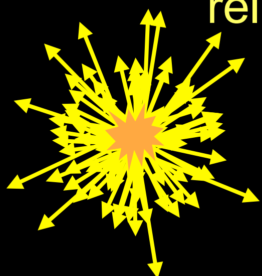
Question – What is the azimuthal angular distribution of independent nucleon-nucleon collisions?

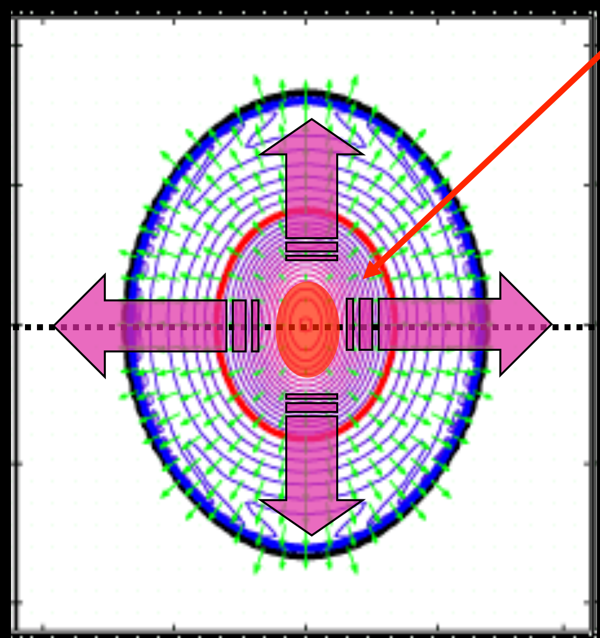


How do Heavy Ion Collisions Evolve?

1) Superposition of independent p+p:

momenta random
relative to reaction plane

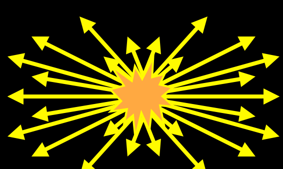




High density
pressure
at center

2) Evolution as a **bulk system**

Pressure gradients (larger in-plane)
push bulk "out" → flow"



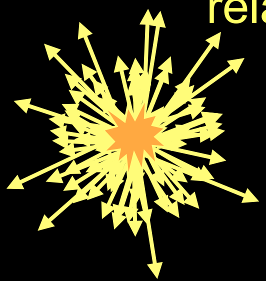
more, faster particles
seen in-plane

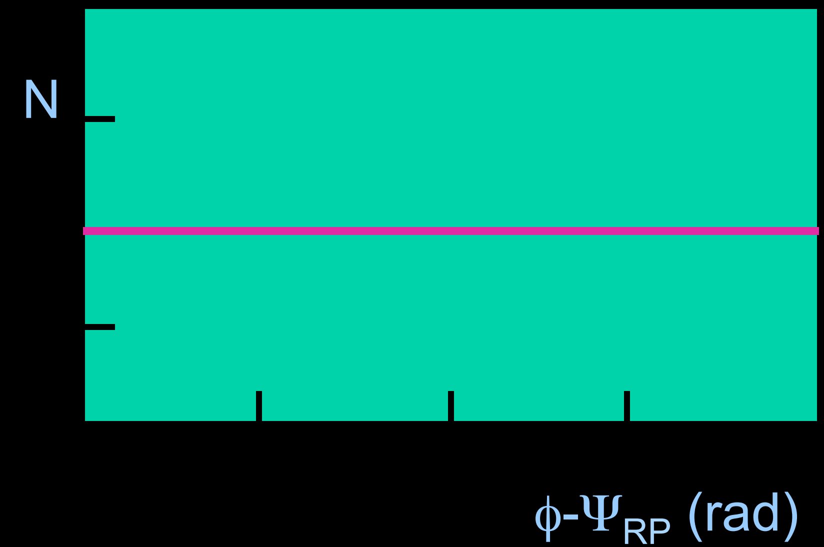
"zero" pressure
in surrounding vacuum

Azimuthal Angular Distributions

1) Superposition of independent p+p:

momenta random
relative to reaction plane





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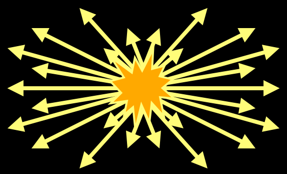

more, faster particles
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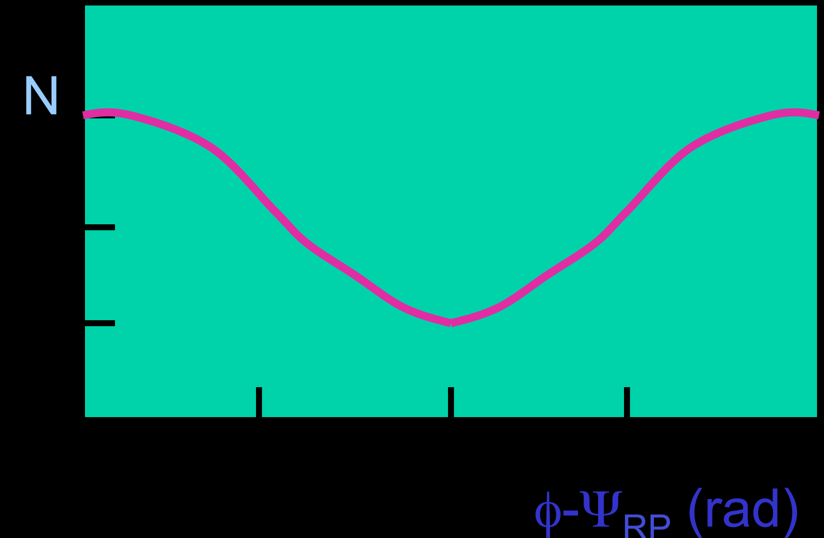


Ultra-relativistic Heavy-Ion Physics and Experiments

Introduction to Heavy Ion Physics

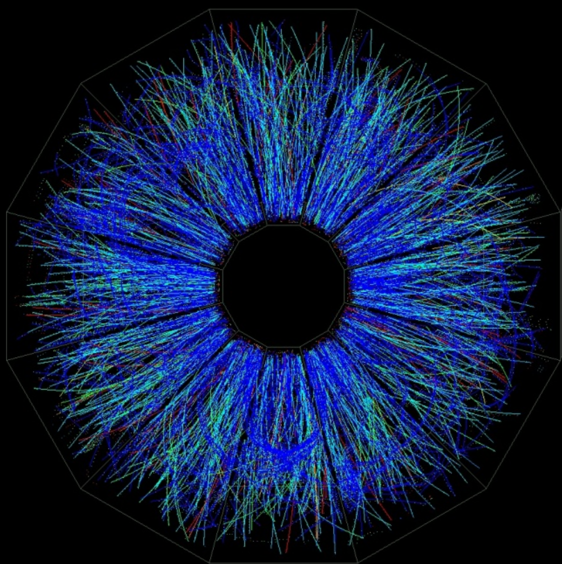
Machines and Experiments

How Do Heavy Ion Collisions Evolve?

Important Physics Results – an Appetizer from RHIC

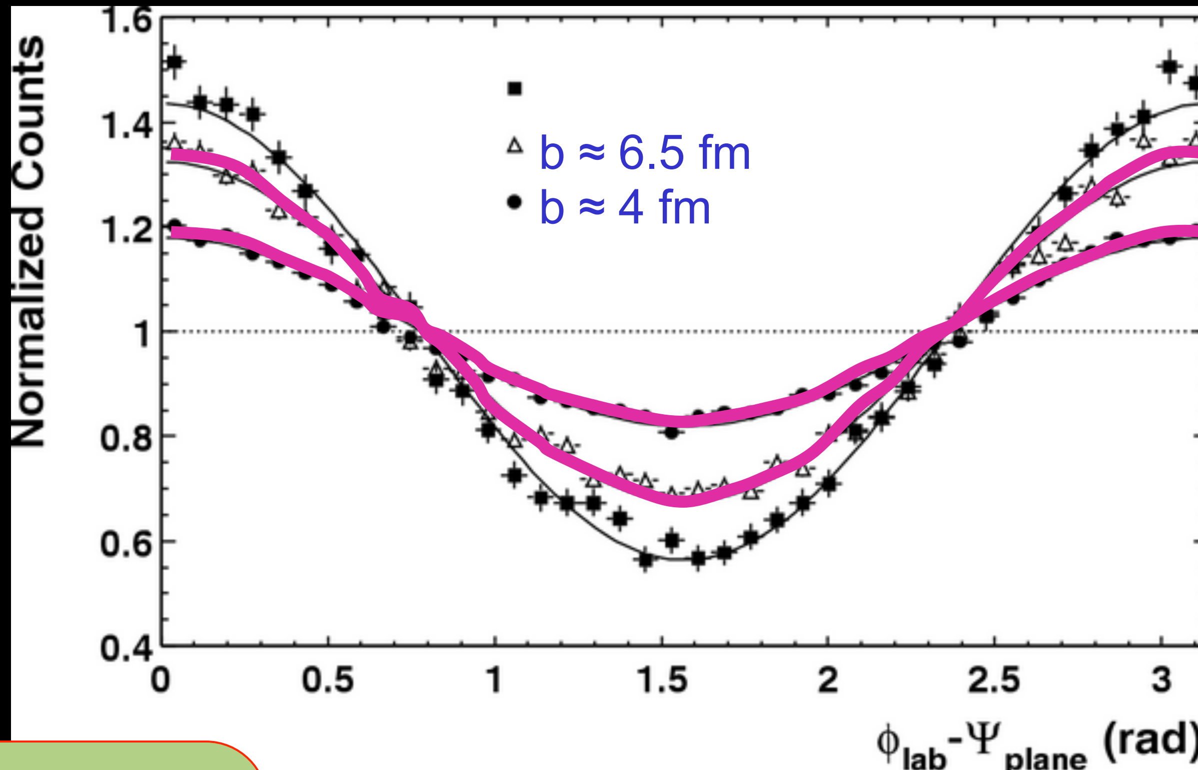
Future

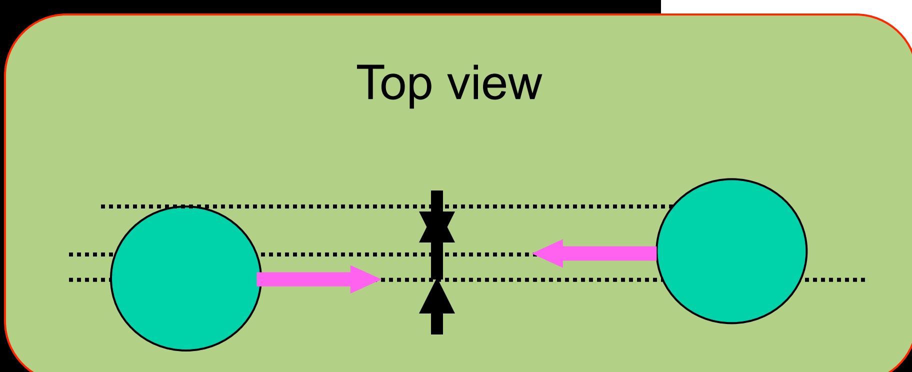
On the First Day at RHIC - Azimuthal Distributions

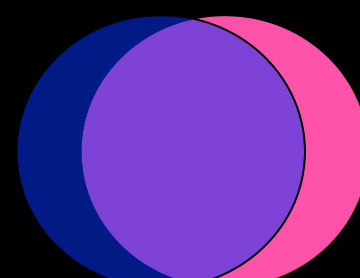


"central" collisions

STAR, PRL**90** 032301 (2003)

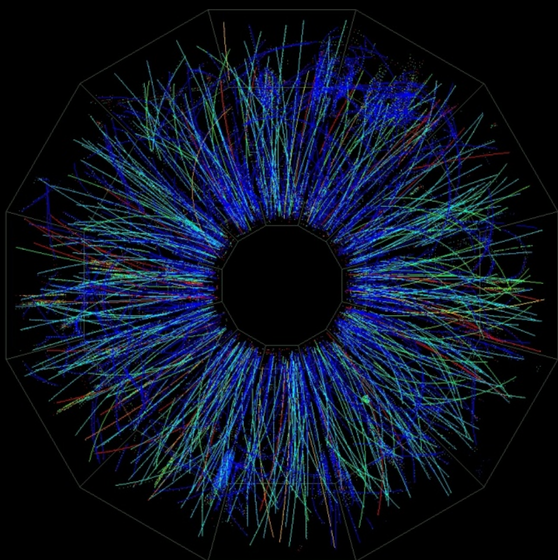






Beams-eye view

On the First Day at RHIC - Azimuthal Distributions



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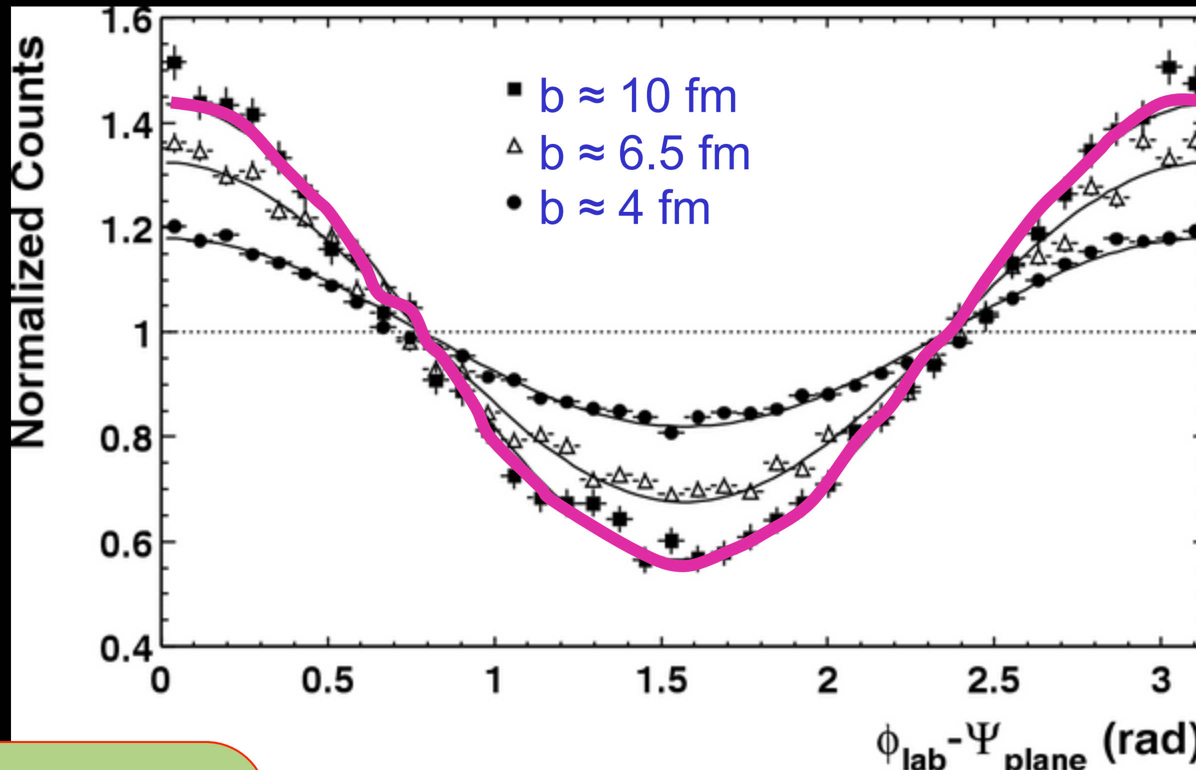
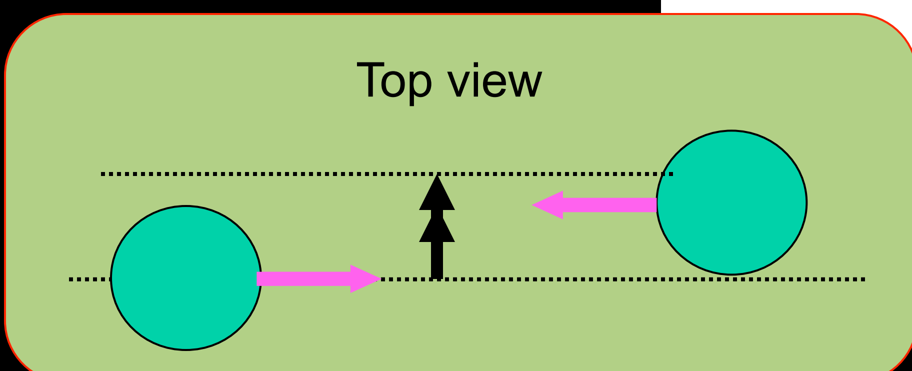
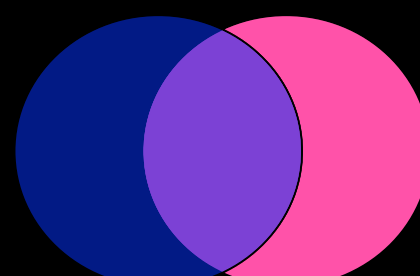


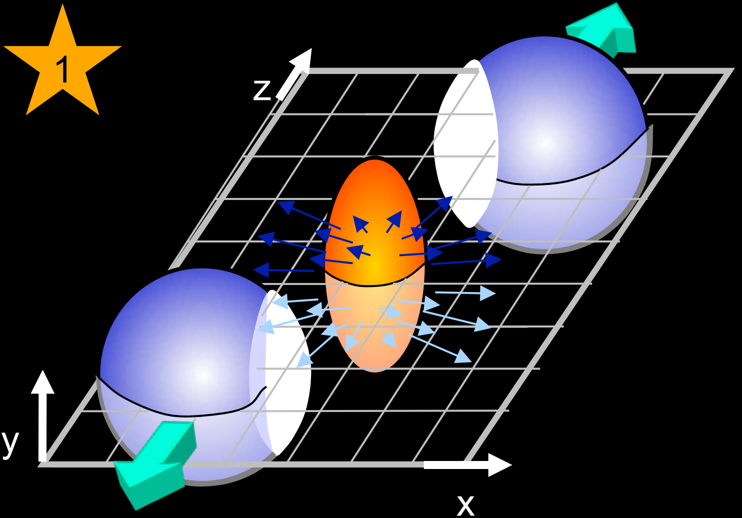
peripheral collisions





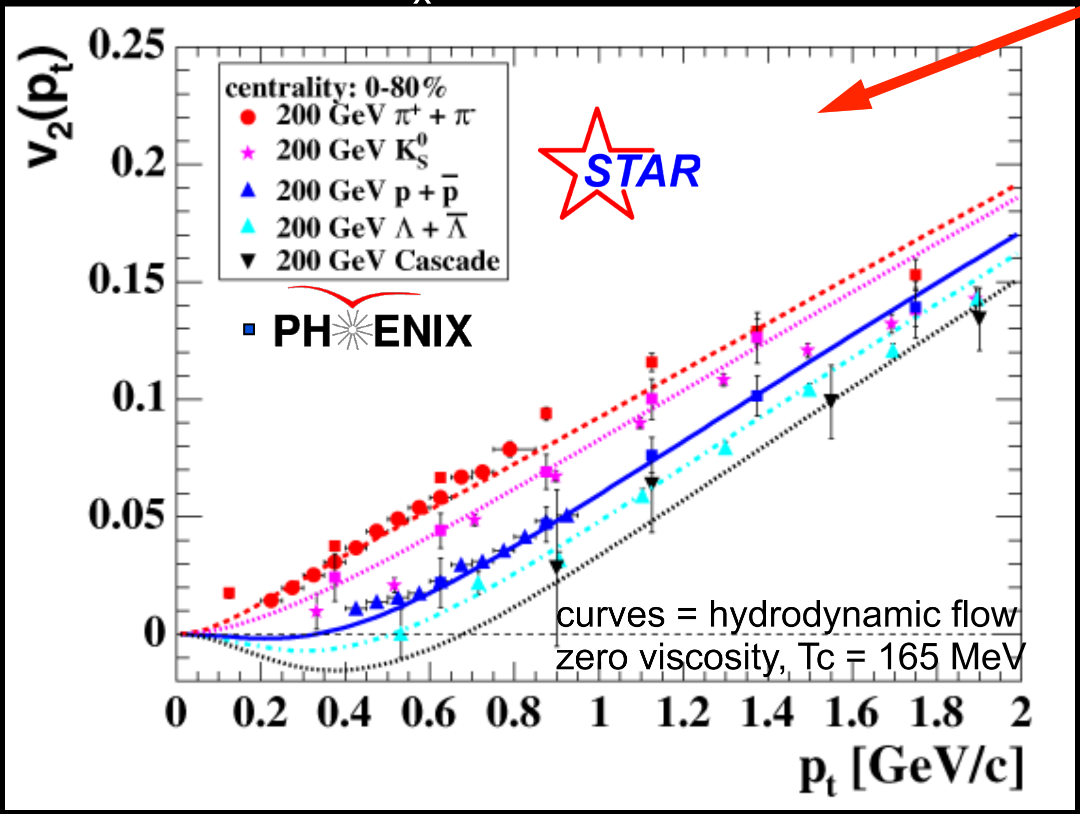
Beams-eye view

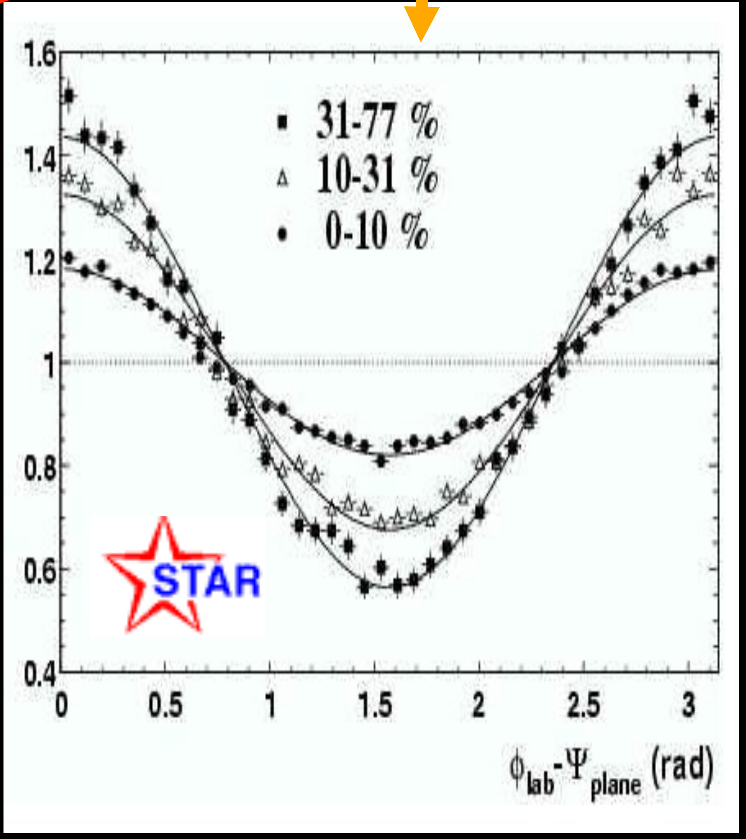
Elliptic Flow Saturates Hydrodynamic Limit

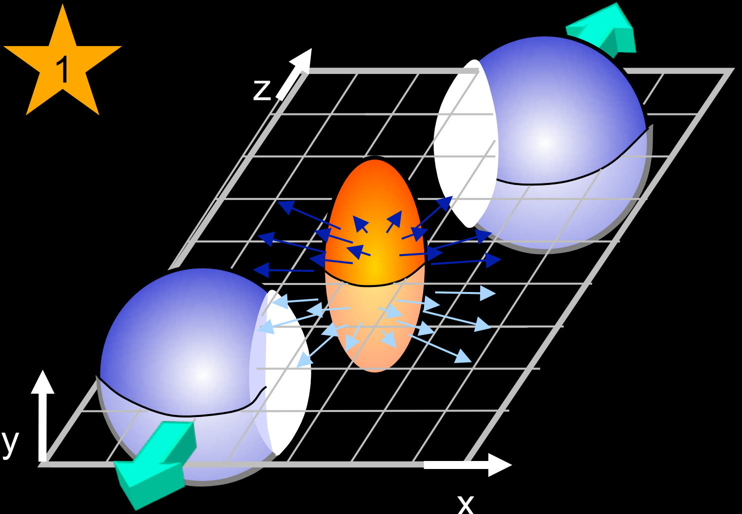


- Azimuthal asymmetry of charged particles:

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







Elliptic Flow Saturates Hydrodynamic Limit

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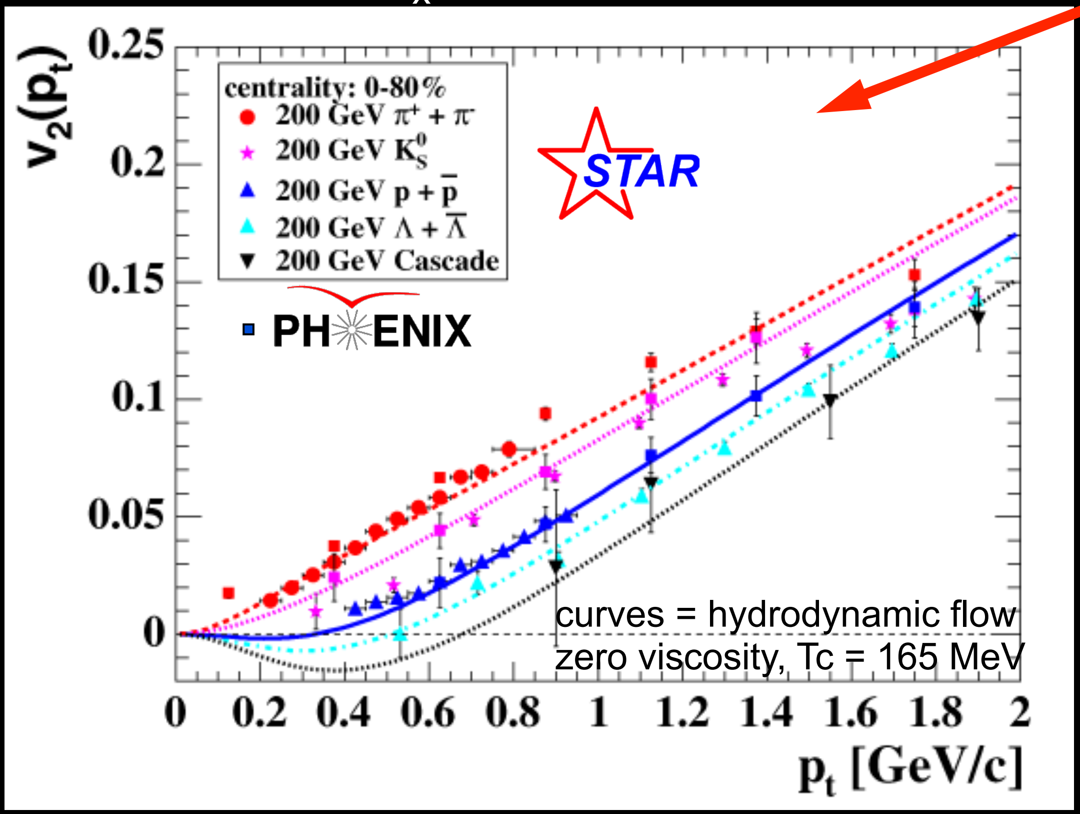
  $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$



Mass dependence of v_2

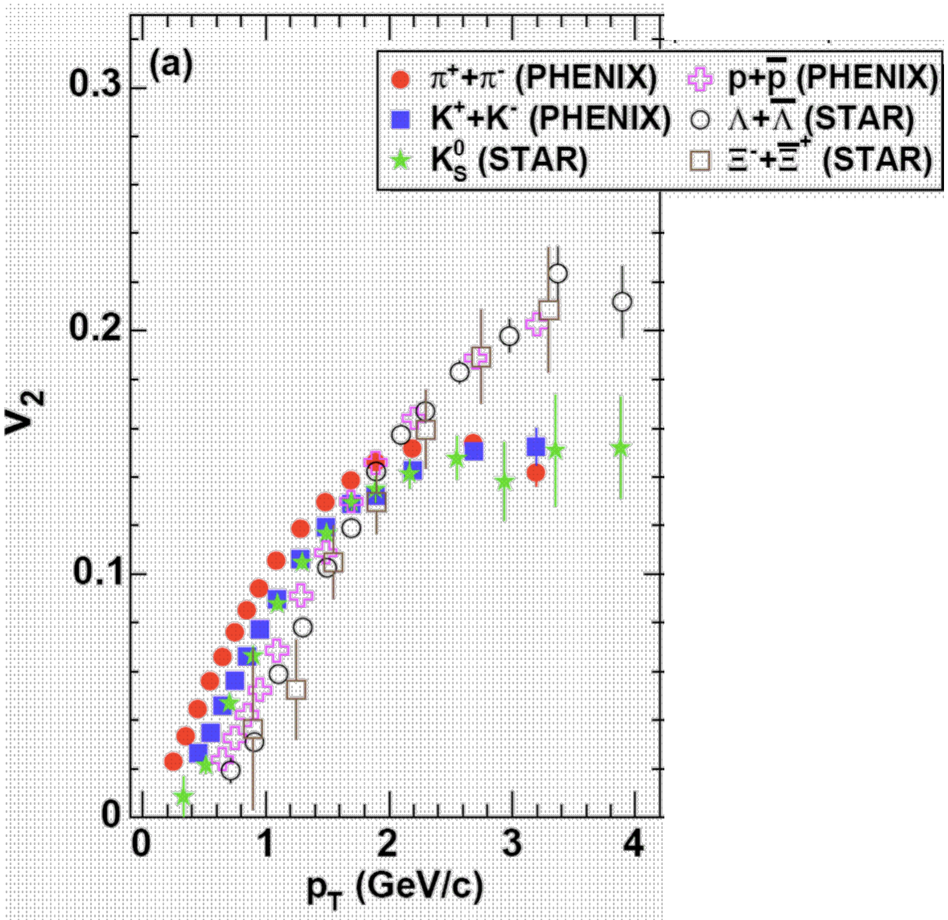
Requires -

- **Early thermalization (0.6 fm/c)**
- **Ideal hydrodynamics (zero viscosity)**
  → **"nearly perfect fluid"**
- **$\varepsilon \sim 25$ GeV/fm^3 (>> $\varepsilon_{critical}$)**
- **Quark-Gluon Equ. of State**

Identified Hadron Elliptic Flow Complicated

Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons →

$d^2n/dp_T d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$



If flow established at quark level, it is predicted to be *simple* →

$KE_T \rightarrow KE_T / n_q$, $v_2 \rightarrow v_2 / n_q$, n_q = (2, 3 quarks) for (meson, baryon)

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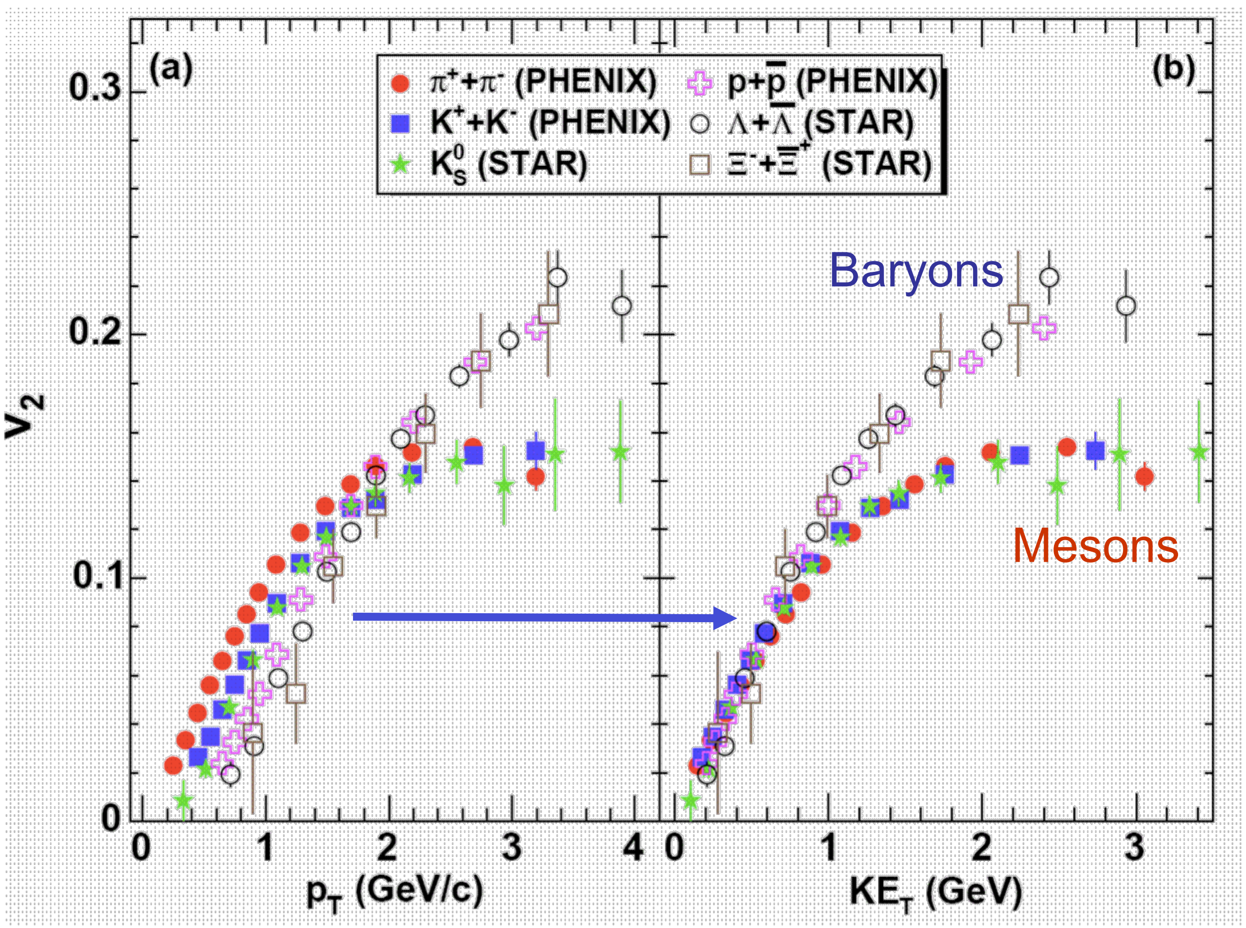

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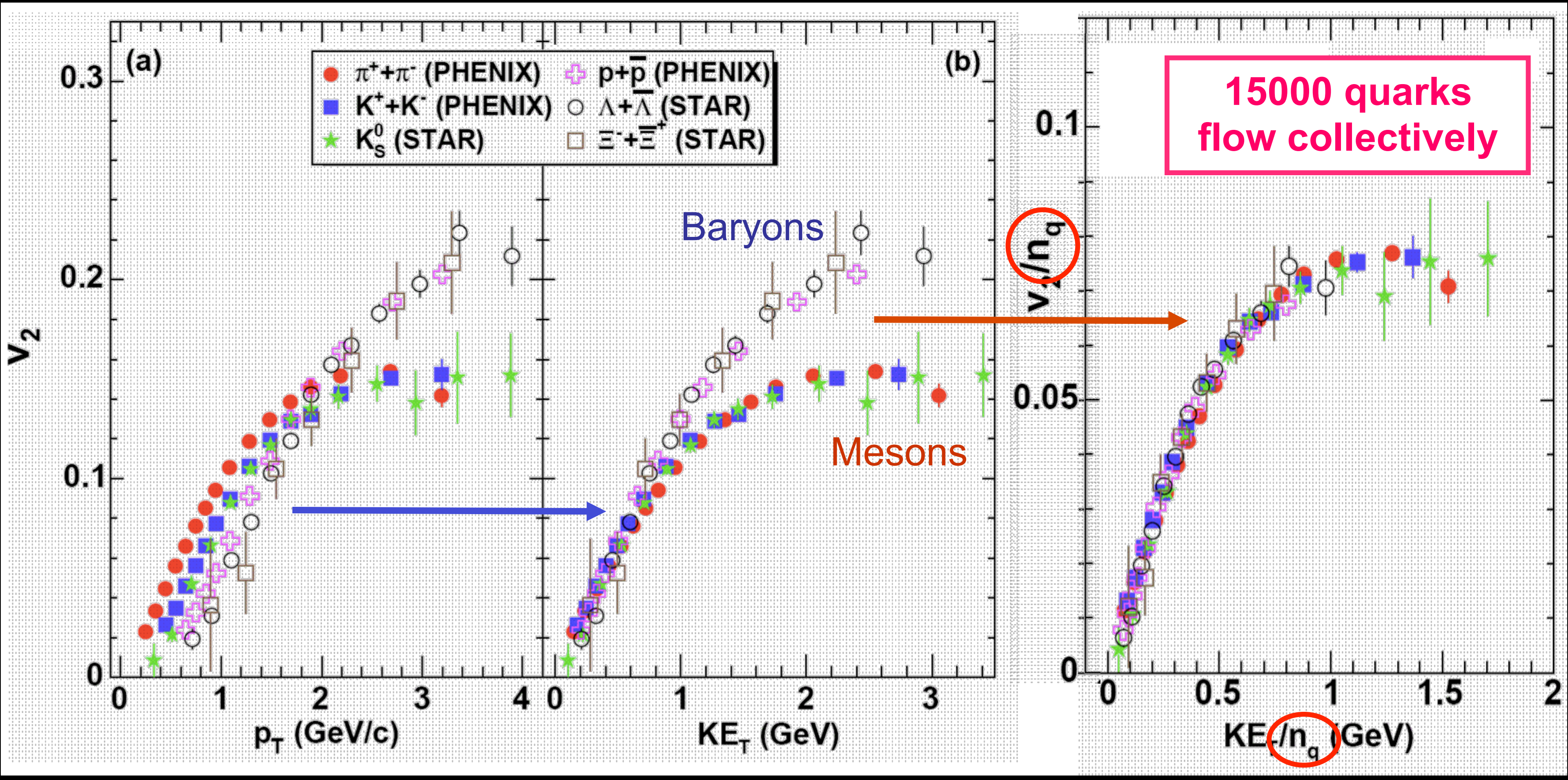

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Un Intervallo!

Ultra-relativistic Heavy-Ion Physics and Experiments

Outline:

Introduction to Heavy Ion Physics

Machines and Experiments

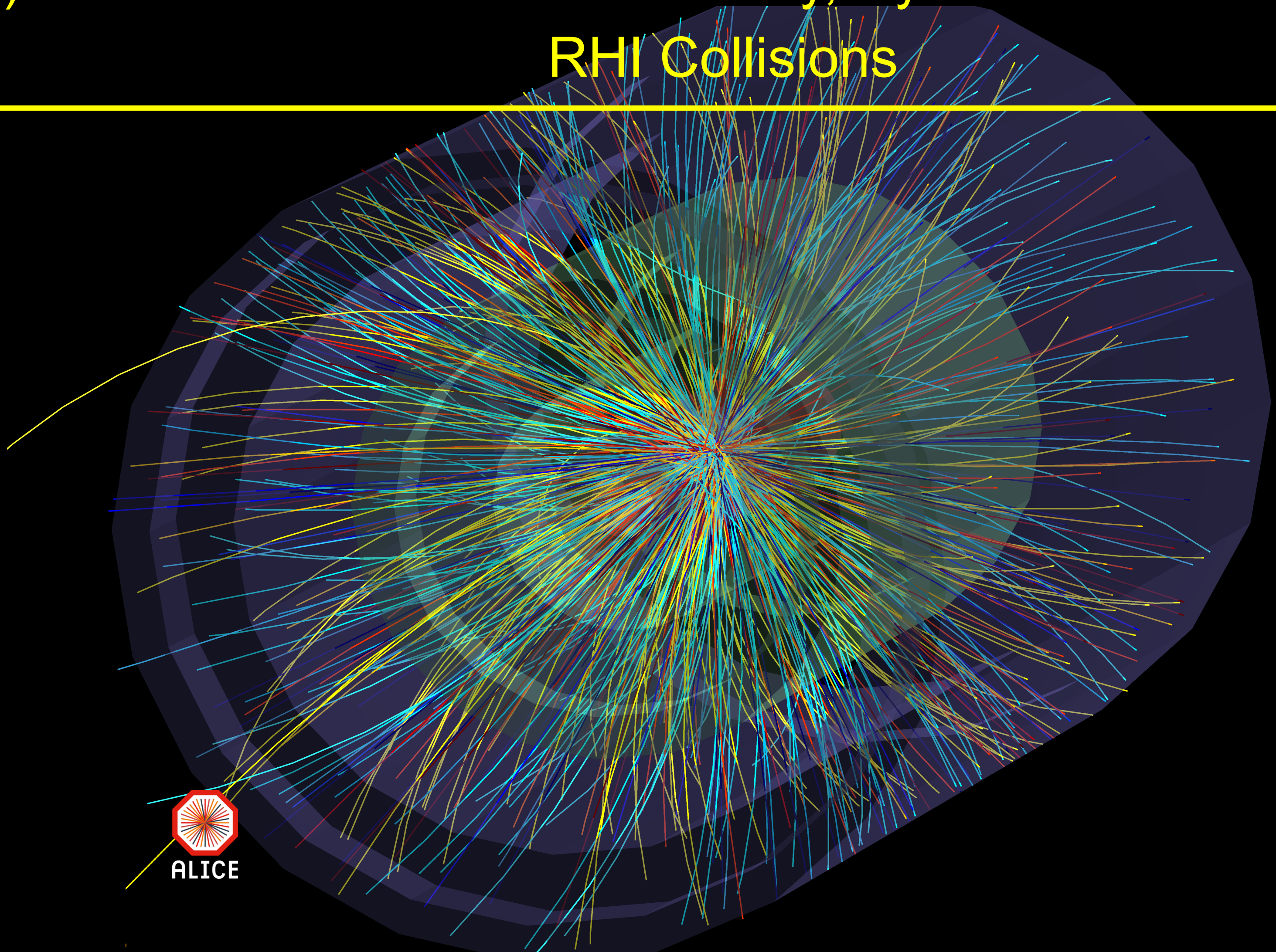
How Do Heavy Ion Collisions Evolve?

Important Physics Results from RHIC and LHC

Future

“What Have We Learned” from RHIC & LHC

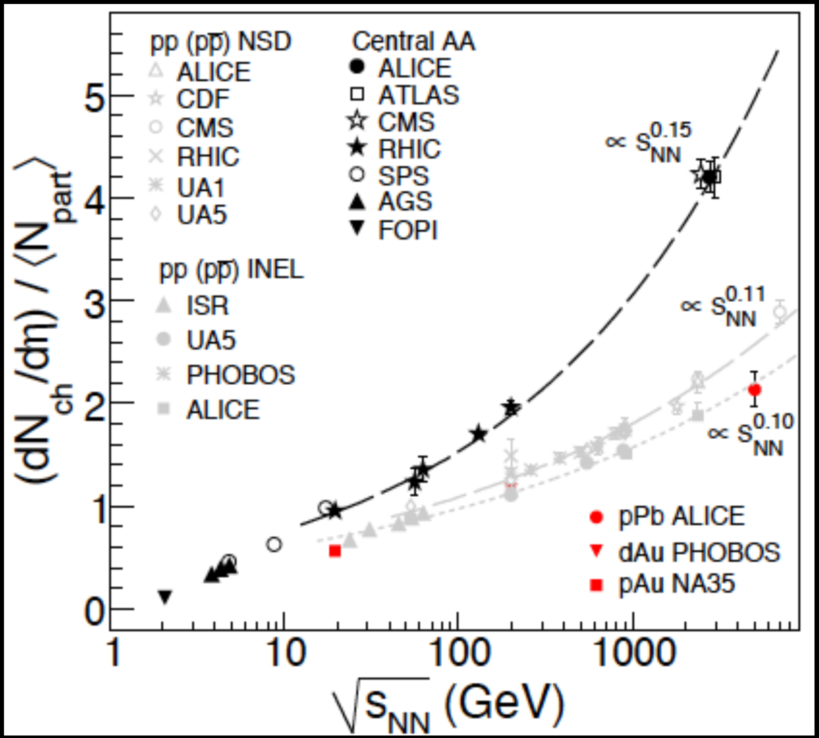
1) Consistent Picture of Geometry, Dynamics & Evolution of RHI Collisions



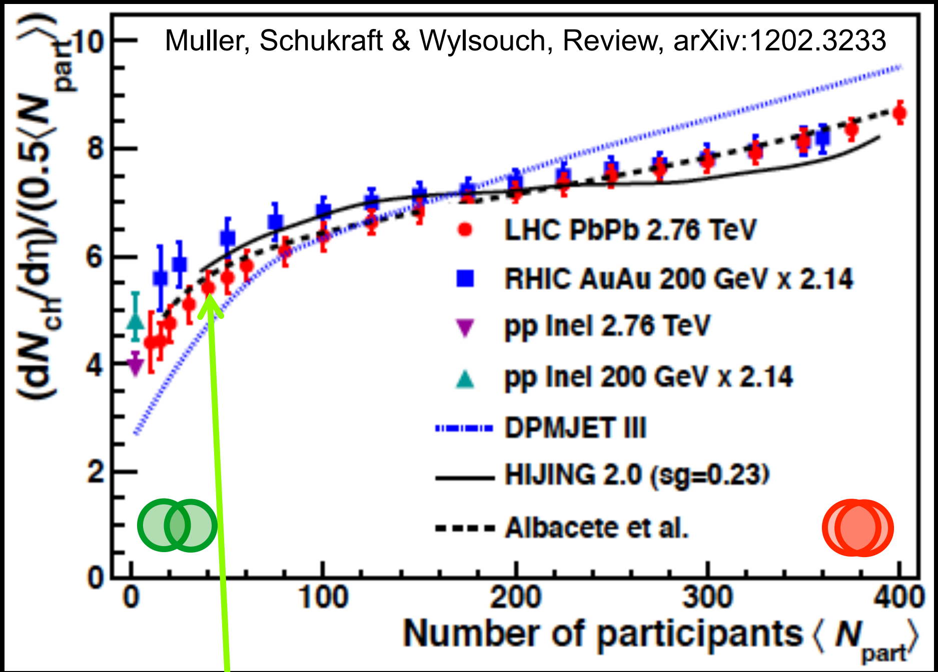
Dynamics & Evolution of RHI Collisions

Multiplicities (per participant nucleon) from RHIC to LHC

vs. C.M. energy



vs. # of participants



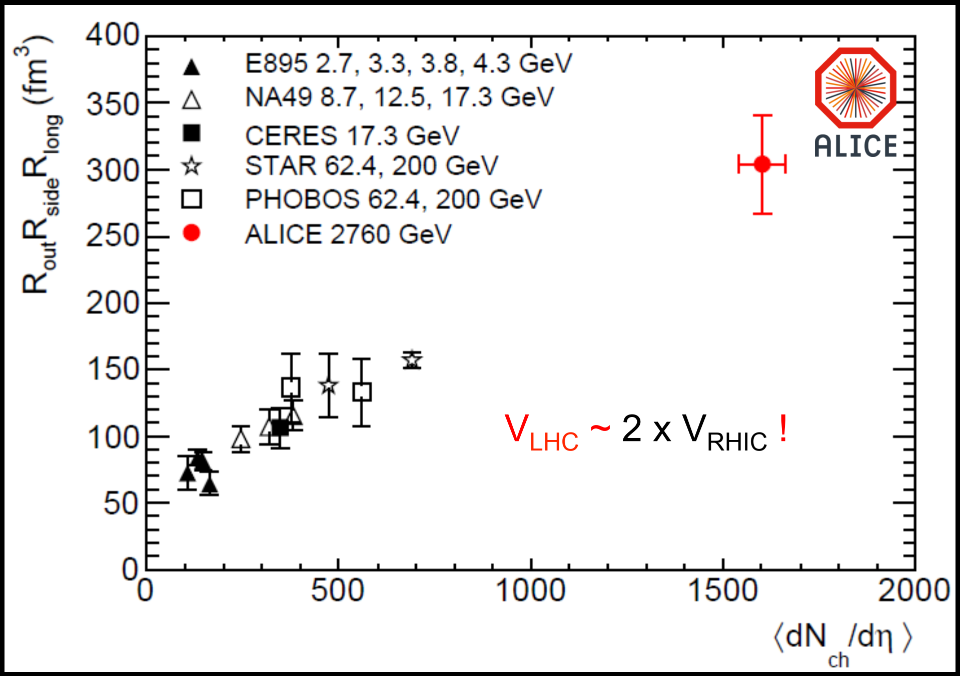
Initial state fluctuations? Degree of shadowing?
→ details in data from LHC p-Pb run?

Small differences due to initial conditions?
Gluon shadowing vs geometry,
Hard processes ~ # binary collisions
Differences at LHC /RHIC?

System Size & Lifetimes

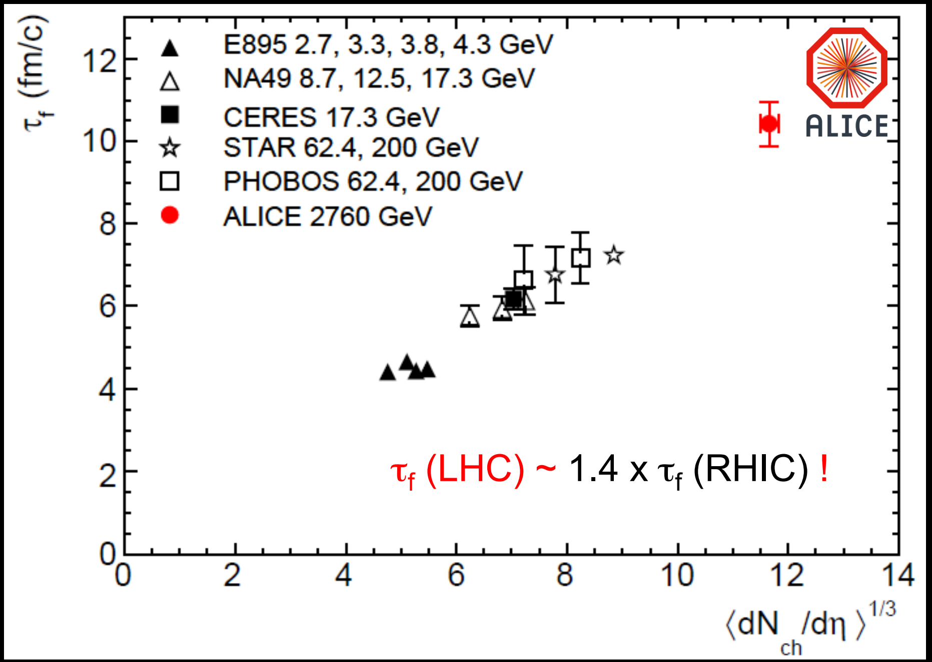
ALICE, Phys.Lett. B696 (2011) 328

System size



Size → Volume ~ dN/dη

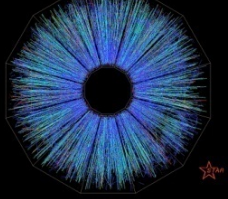
Lifetimes



$\tau_f \sim \langle dN_{ch}/d\eta \rangle^{1/3}$

τ_f (central PbPb) ~ 10 – 11 fm/c

Lifetime → hydrodynamic expansion



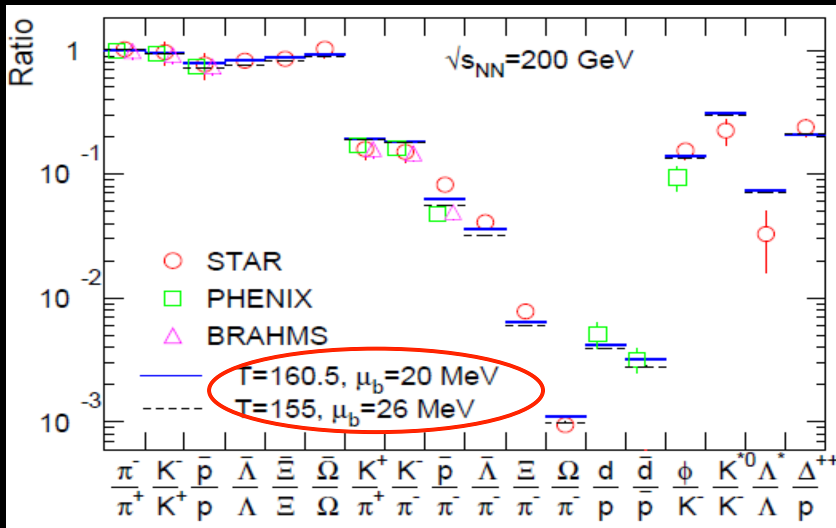
“What Have We Learned” from RHIC & LHC

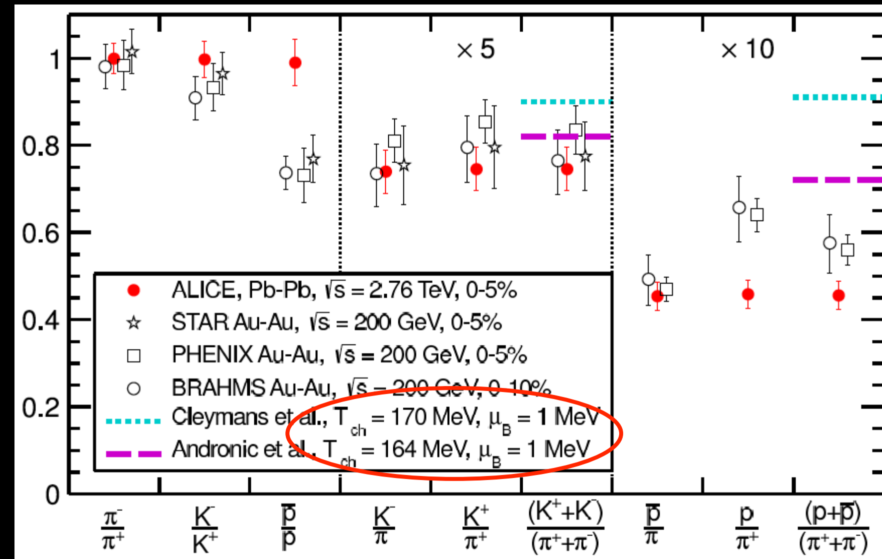
2) Particle ratios reflect equilibrium abundances

→ universal hadronization $T_{critical}$

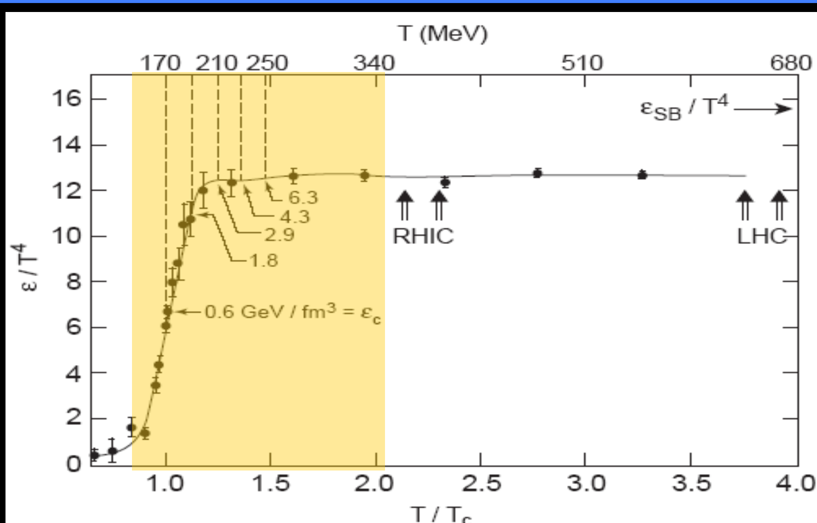
→ Confirm lattice predictions for $T_{critical}$, μ_B

Particles Formed at Universal Hadronization T

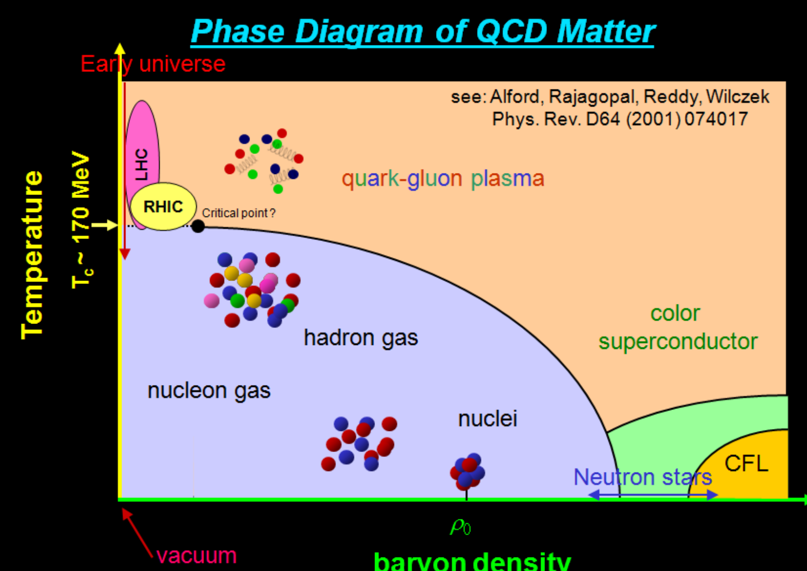


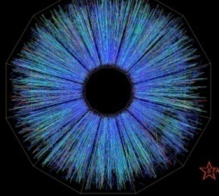


Particles yields → equilibrium abundances → universal hadronization $T_{critical}$



Confirm lattice predictions for $T_{critical}$, μ_B



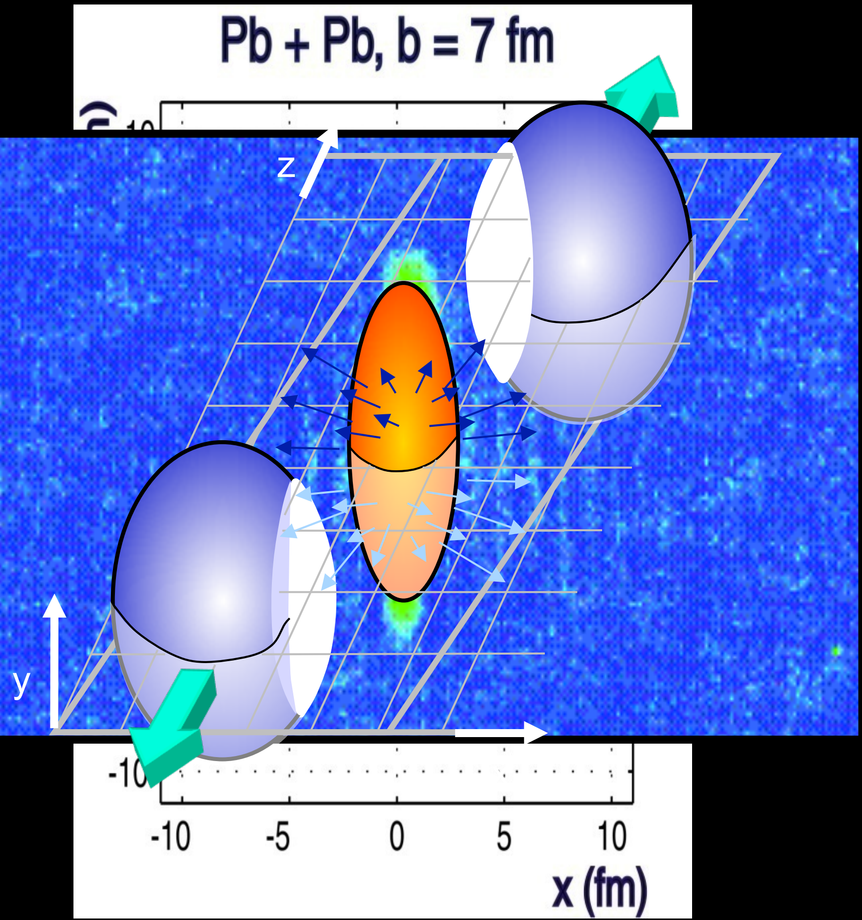


“What Have We Learned” from RHIC & LHC

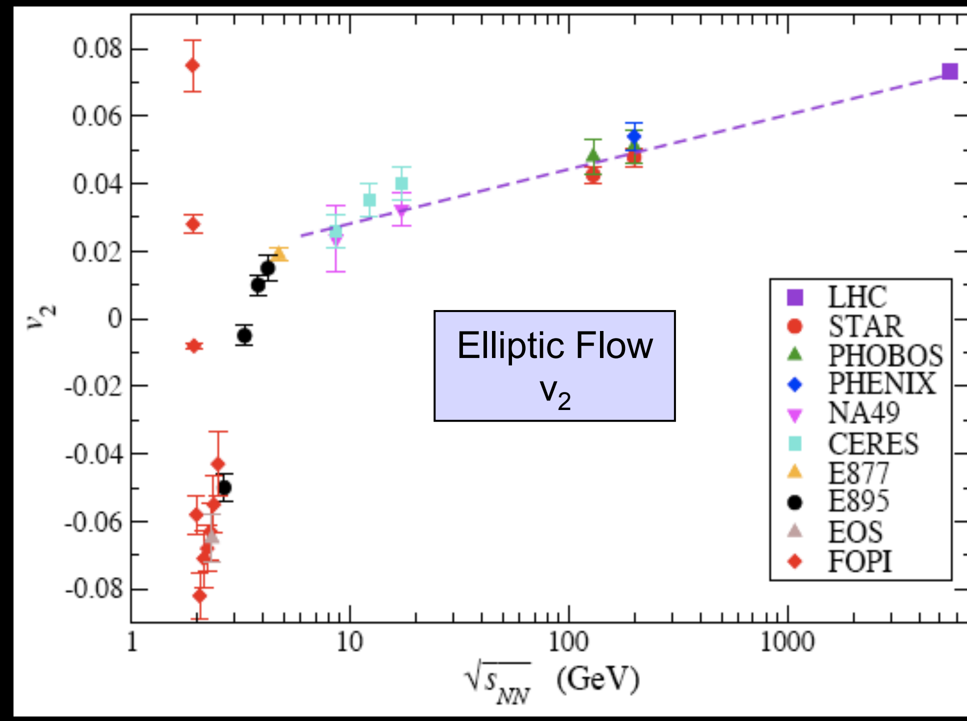
3) Strong flow observed → ultra-low shear viscosity

Strongly-coupled liquid → quark-gluon plasma

Large Elliptic Flow Observed at RHIC and LHC!



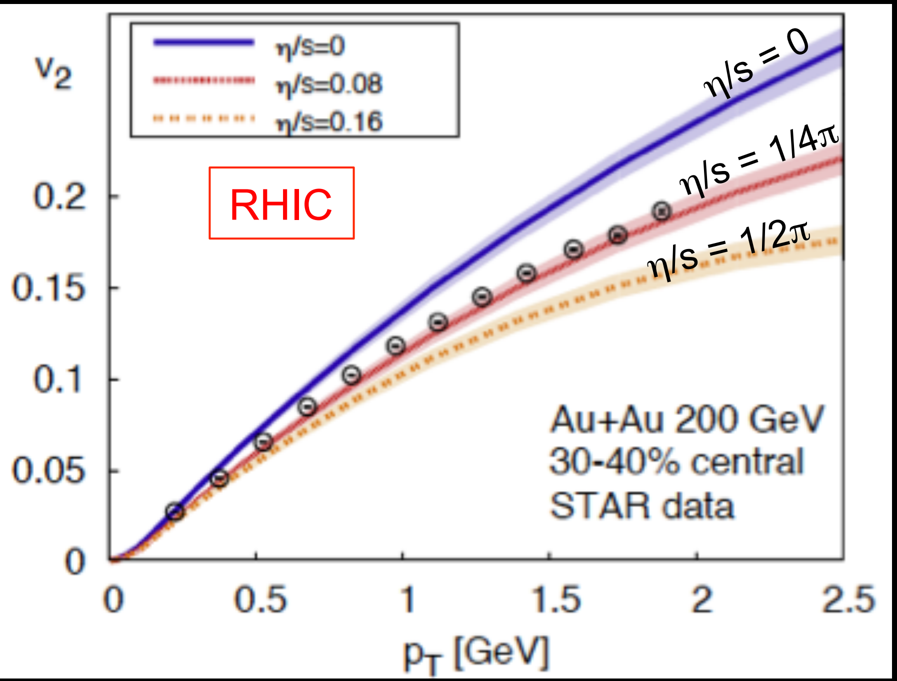
Azimuthal asymmetry of particles:
$dn/d\phi \sim 1 + 2\ v_2(p_T)\ \cos(2\ \phi) + \ldots$

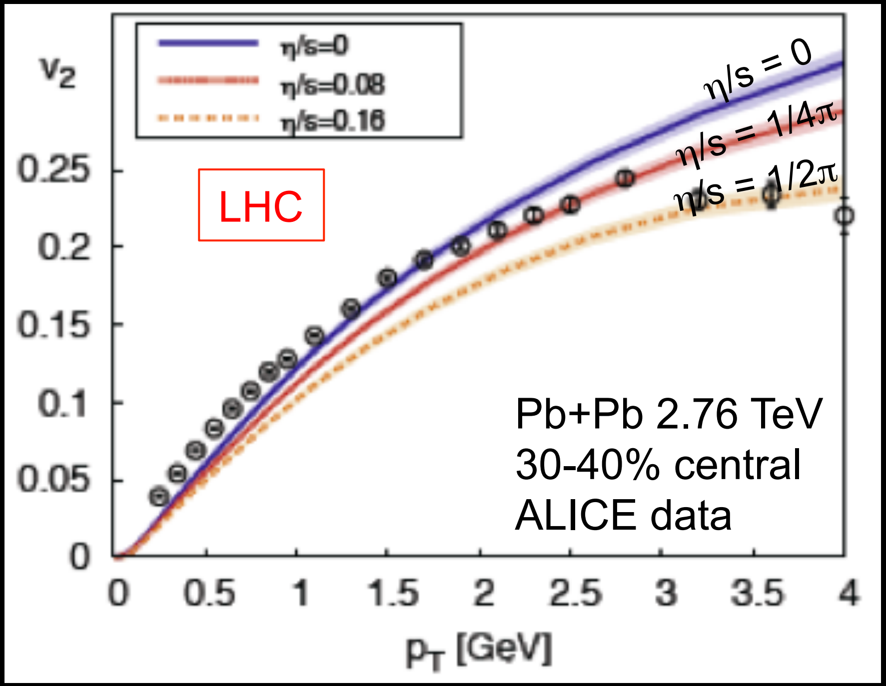


Predicted by hydrodynamics with very low shear viscosity

Increase in v_2 from RHIC to LHC

It's a Strongly-Coupled Medium with Ultra-Low Shear Viscosity





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

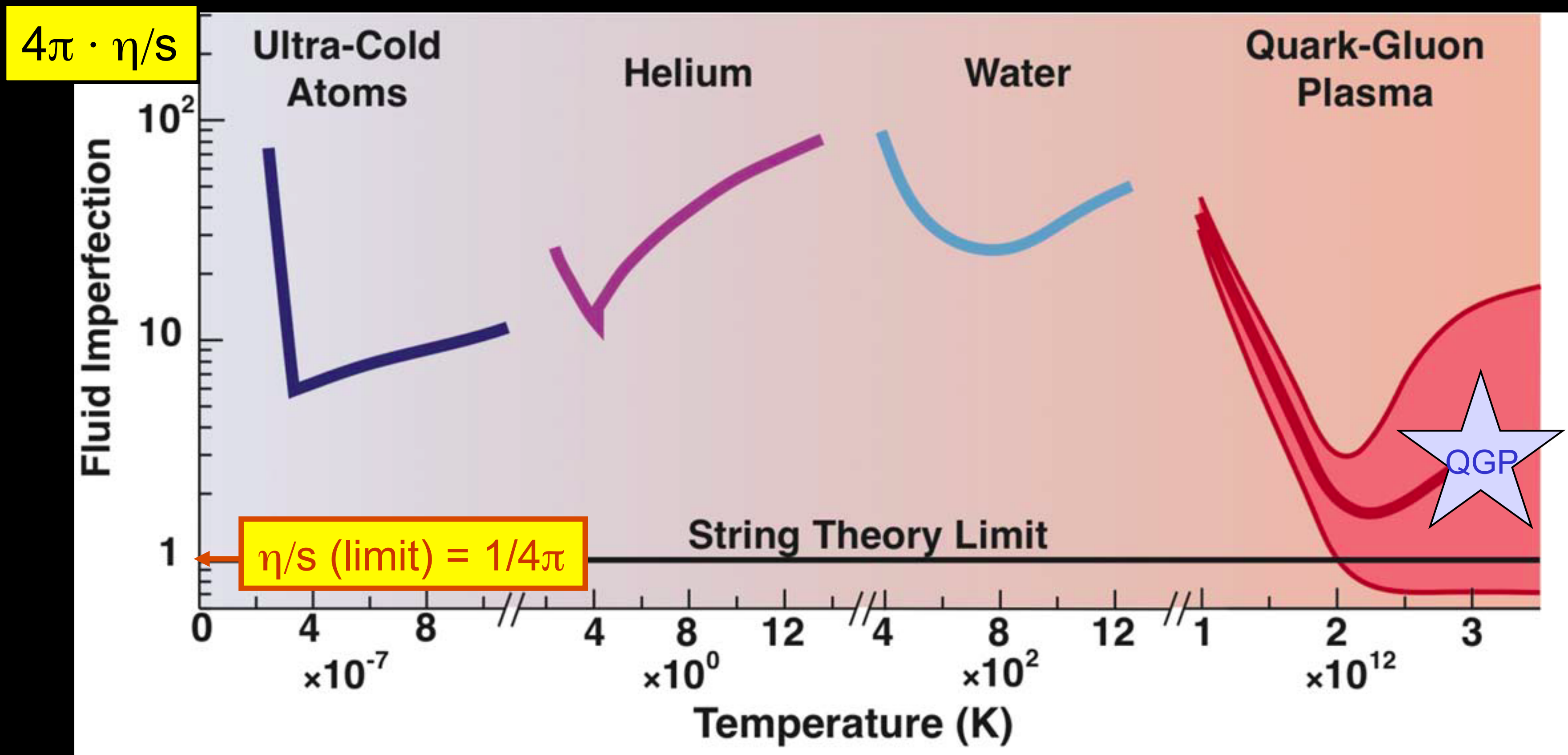
$\rightarrow 1/4\pi < \eta/s < 1/2\pi$

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

$\rightarrow \eta/s = 1/4\pi$ for the "perfect liquid"

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

Ultra-low (Shear)Viscosity Fluids



T = 2 x 10^{12} K

Quantum lower viscosity bound: $\eta/s > 1/4\pi$ (Kovtun, Son, Starinets)

From strongly coupled *N* = 4 SUSY YM theory.

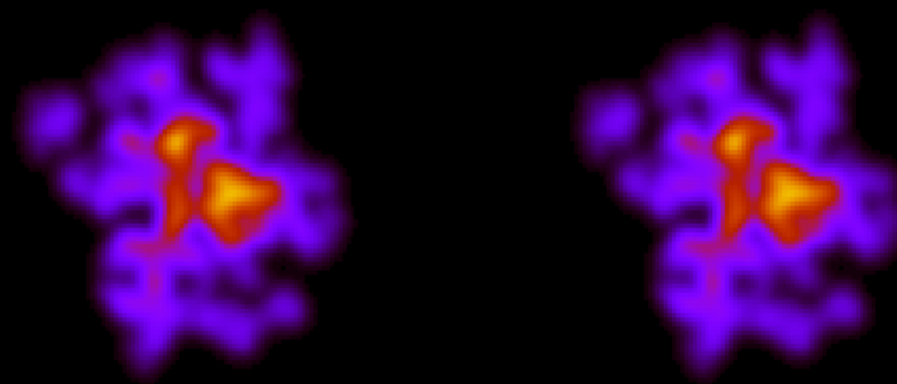
3-d Rel. Hydro describes RHIC/LHC v_2 data with $\eta/s \sim 1/2\pi$ near lower bound!

Event-by-Event Initial Conditions Vary!

Initial conditions vary event-to-event.

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

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

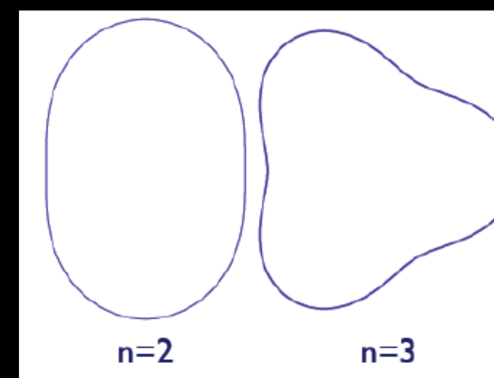


t = 0.5 fm/c

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

Final observation

Final observation

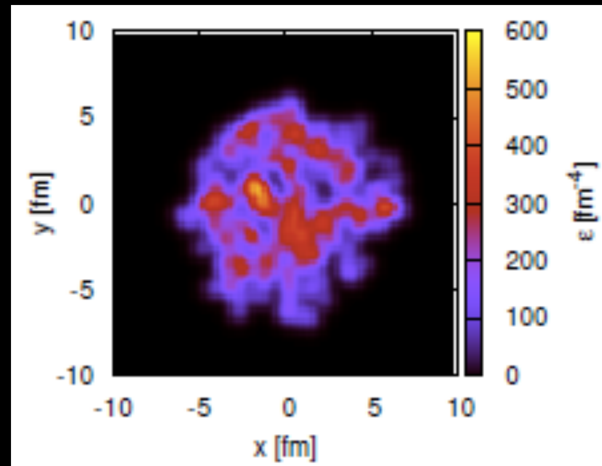


Azimuthal RHI harmonics provide information on viscous damping & spatial correlations:

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

Higher Order Harmonics → Properties of QGP

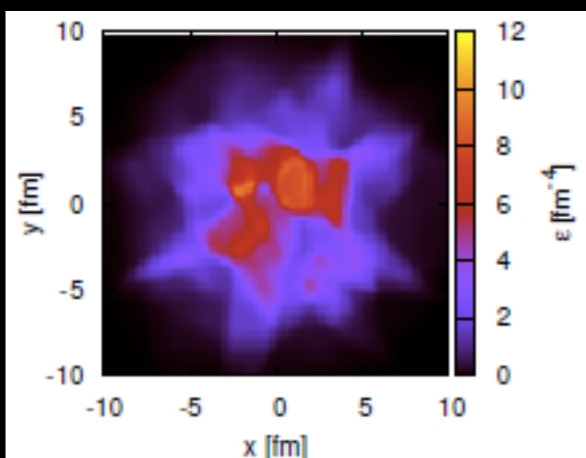
Initial State



Ideal η/s = 0

η/s = 1 /4π

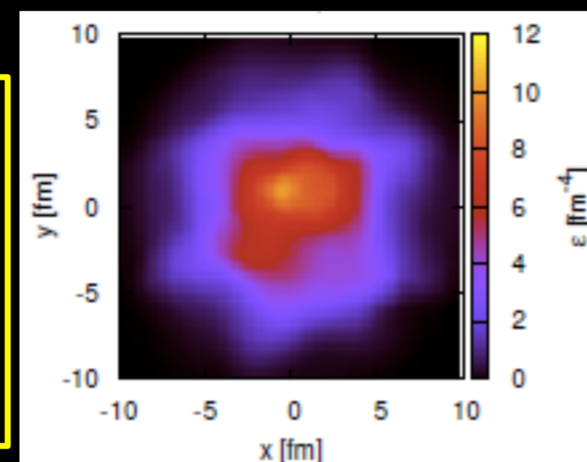
Final observation



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

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

Final observation



Higher order harmonics provide extent to which initial inhomogeneity propagates thru the QGP:

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

Potential of Higher Order Harmonics

Gaussian width of harmonic distributions related to length scale

such as mean free path & horizon.

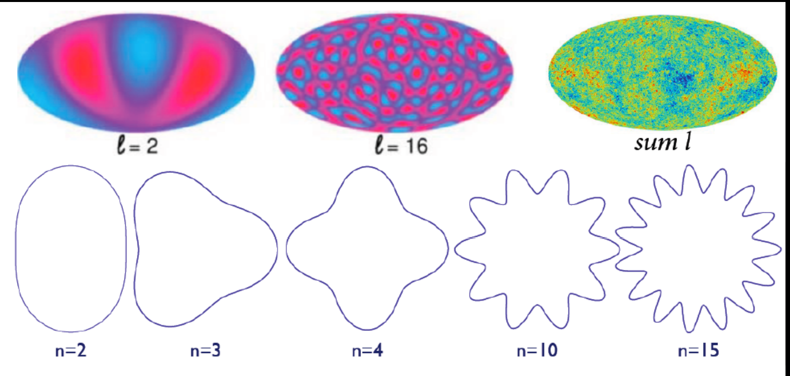
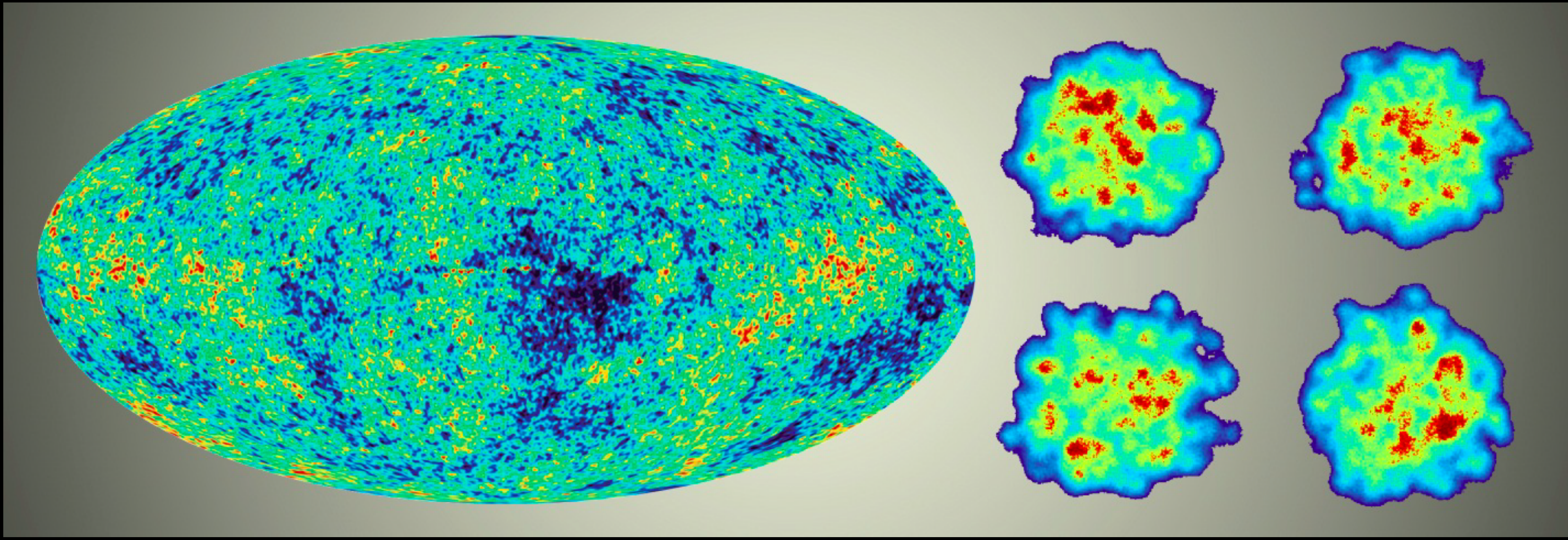
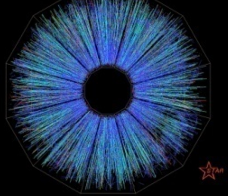


Figure 1: Top: the length scales in the CMB. Bottom: the length scales probed with higher n in heavy-ion collisions.





“What Have We Learned” from RHIC & LHC

4) QGP radiation (direct photons)

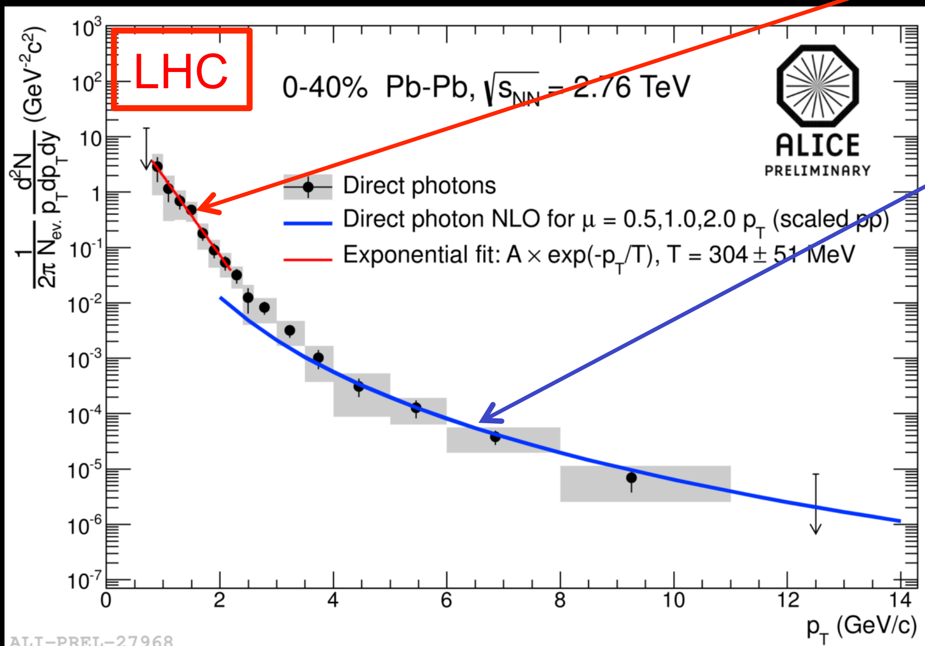
→ exhibit time-integrated temperatures >> $T_{critical}$

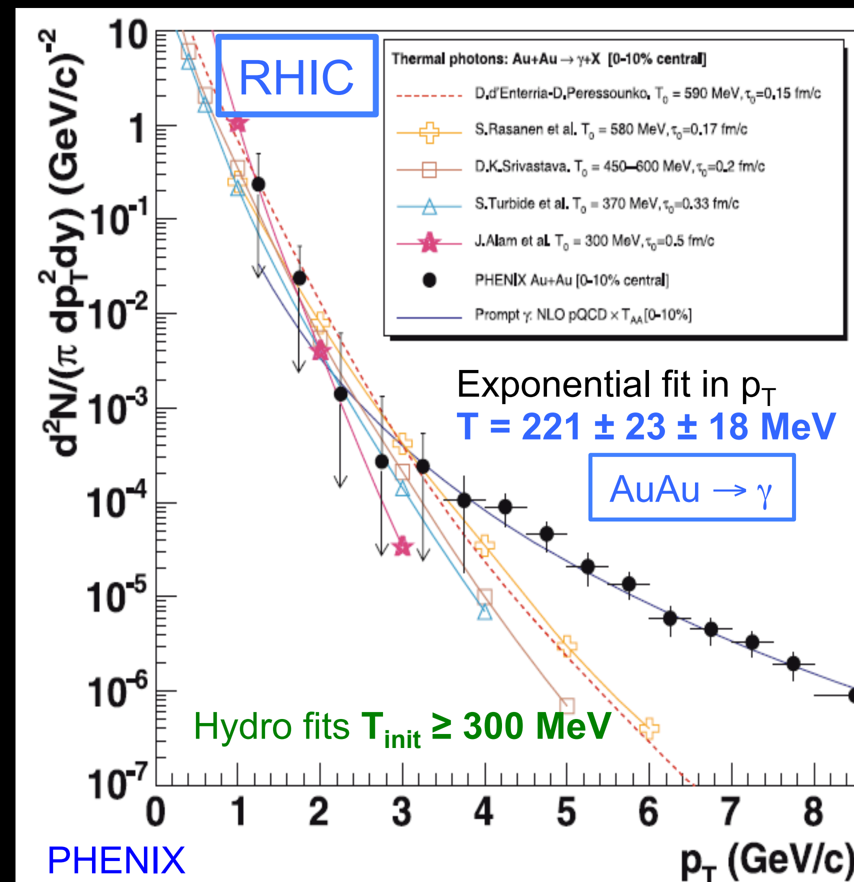
Thermal Photons – Shining of the QGP

A thermal component of direct photons:

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

N_{coll}-scaled NLO pQCD

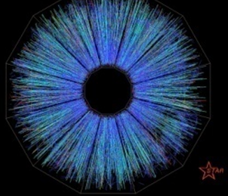




LHC (ALICE): T = 304±51 MeV
for $\sqrt{s_{NN}}$ = 2.76 TeV Pb-Pb

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

Note: T is integral over entire evolution!



"What Have We Learned" from RHIC & LHC

5) It's opaque to the most energetic ("hard") probes:

Light & heavy quarks are suppressed at large p_T

Away-side jets quenched and jet energy imbalance

p-Pb studies confirm quenching/suppression is final state effect

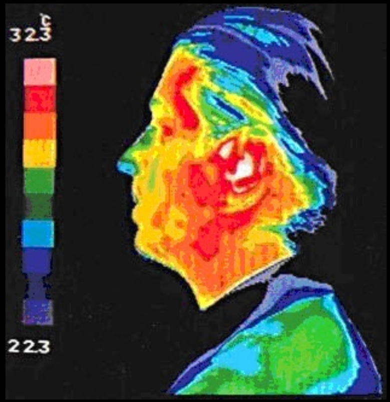
Definition of "Hard Probes"

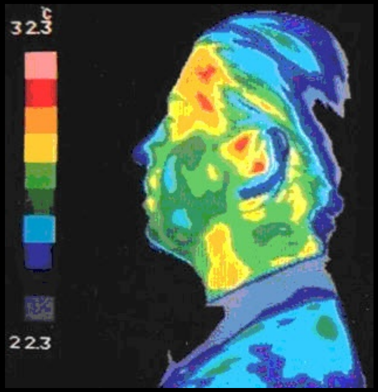
Definition of "Hard" – "relating to radiation that is highly penetrating or energetic"

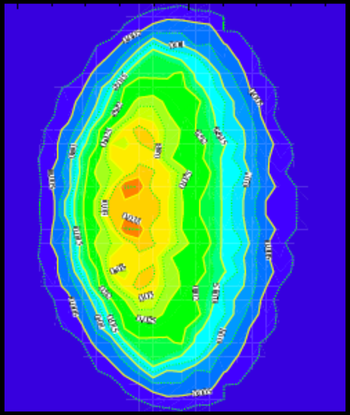
Definition of "Probe" – "device to explore properties of something that cannot be viewed directly"

"Hard Probes" –

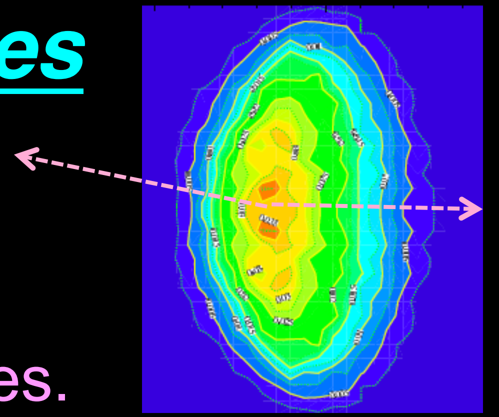
"highly penetrating observables (particles, radiation) used to explore properties of matter that cannot be viewed directly!"







Hard Scattering Processes



In QCD:

Hard (highly penetrating) probes originate from hard scattering processes.

Hard processes are those where perturbative QCD is applicable and are characterized either by:

- large momentum transfer (Q^2)

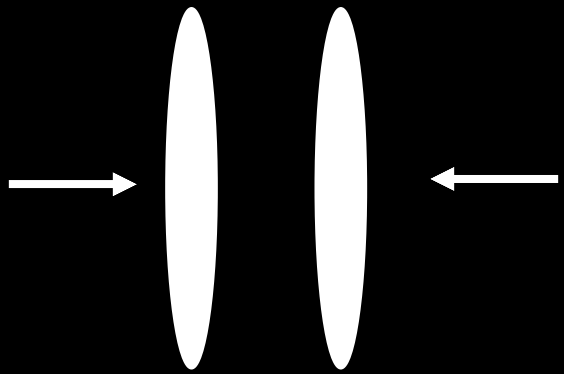
  (→ large 4-momentum transfer squared)

- large transverse momentum (p_T)

- large mass (m) scale

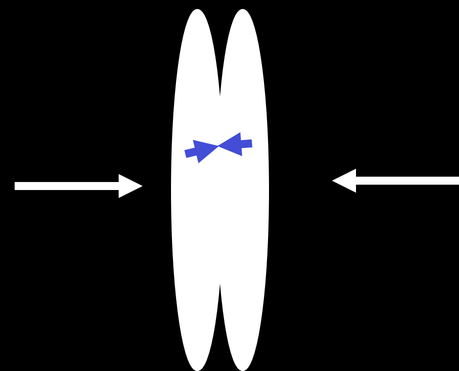
  (e.g. heavy quark production also at low p_T)

Probing Hot QCD Matter with Hard Probes

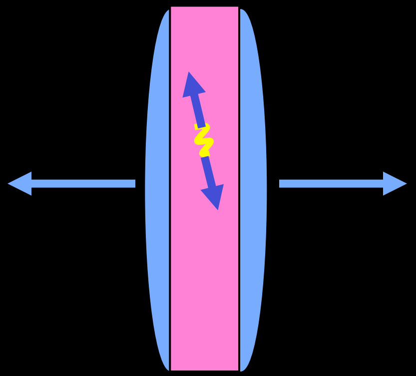


Probing Hot QCD Matter with Hard Probes

Initial Hard Parton Scattering:
- gluon-gluon
- gluon-quark
- quark-quark



Probing Hot QCD Matter with Hard Probes



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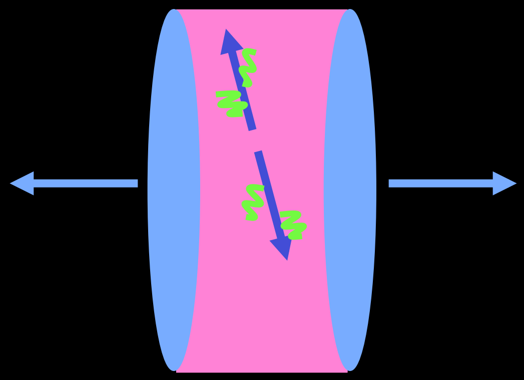
Hard Probes:
- Large "p_T" partons
- Heavy quark production

→ parton energy loss:
- reconstruct jets to determine parton kinematics.
- measure modification of jets, leading particles & jet-correlations

Probing Hot QCD Matter with Hard Probes



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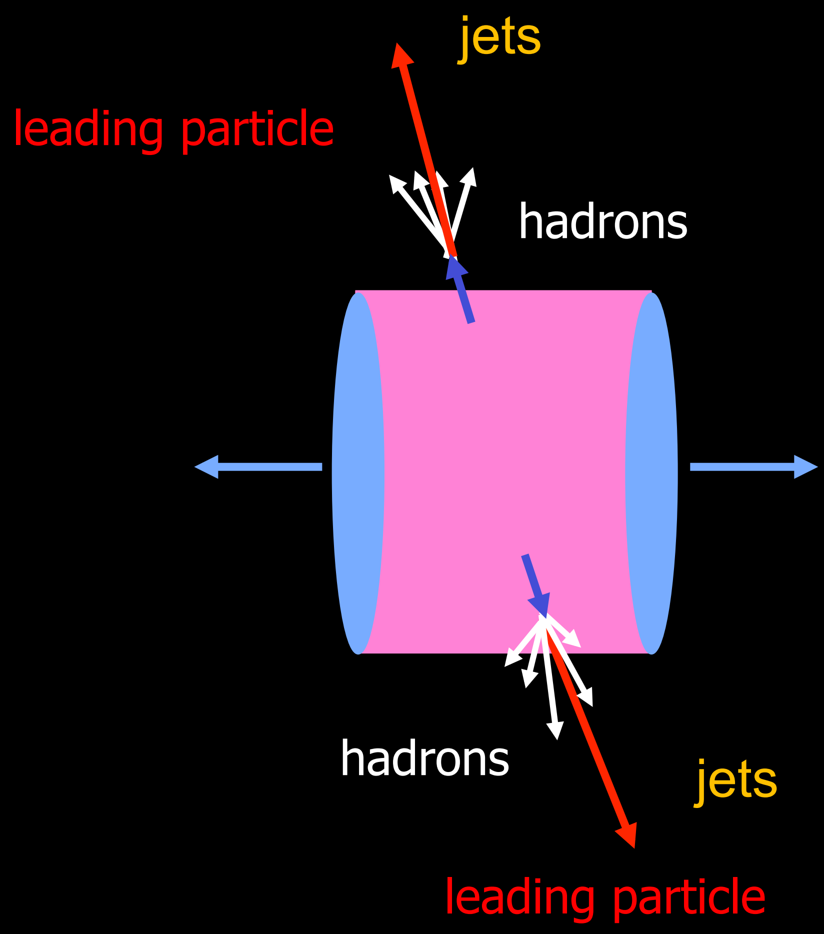
Probing Hot QCD Matter with Hard Probes



Initial Hard Parton Scattering:

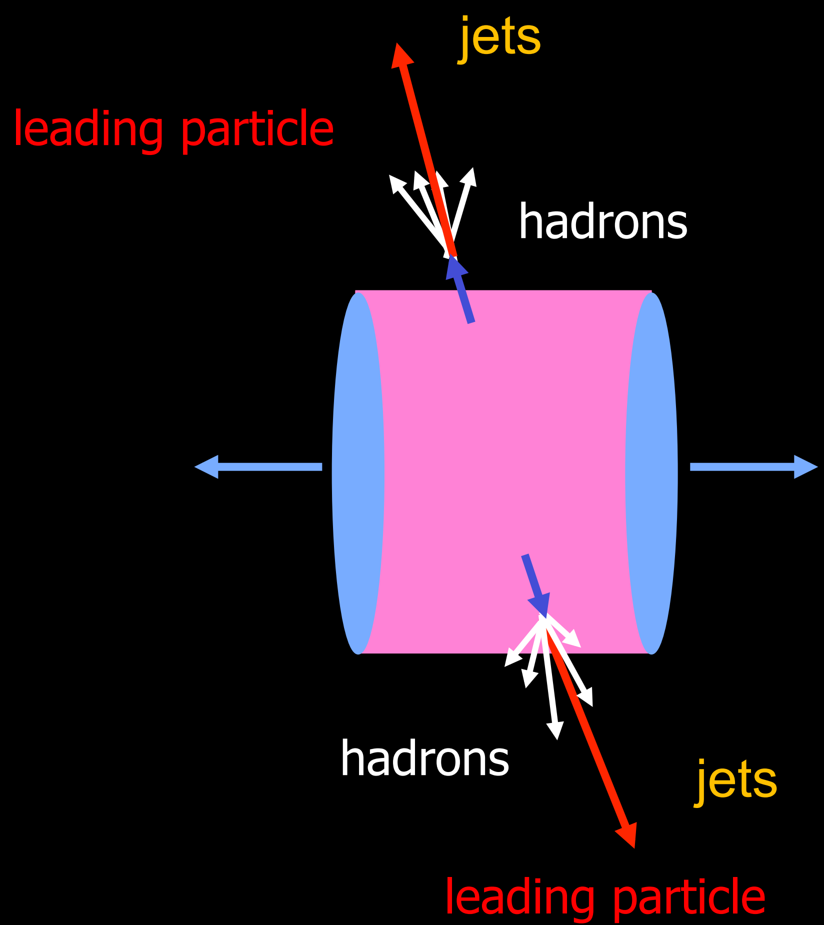
- gluon-gluon
- gluon-quark
- quark-quark

Hard Probes:

- Large “p_T” partons
- Heavy quark production

This is what we wish to “see” and investigate!

Probing Hot QCD Matter with Hard Probes



Initial Hard Parton Scattering:

gluon-gluon
gluon-quark
quark-quark

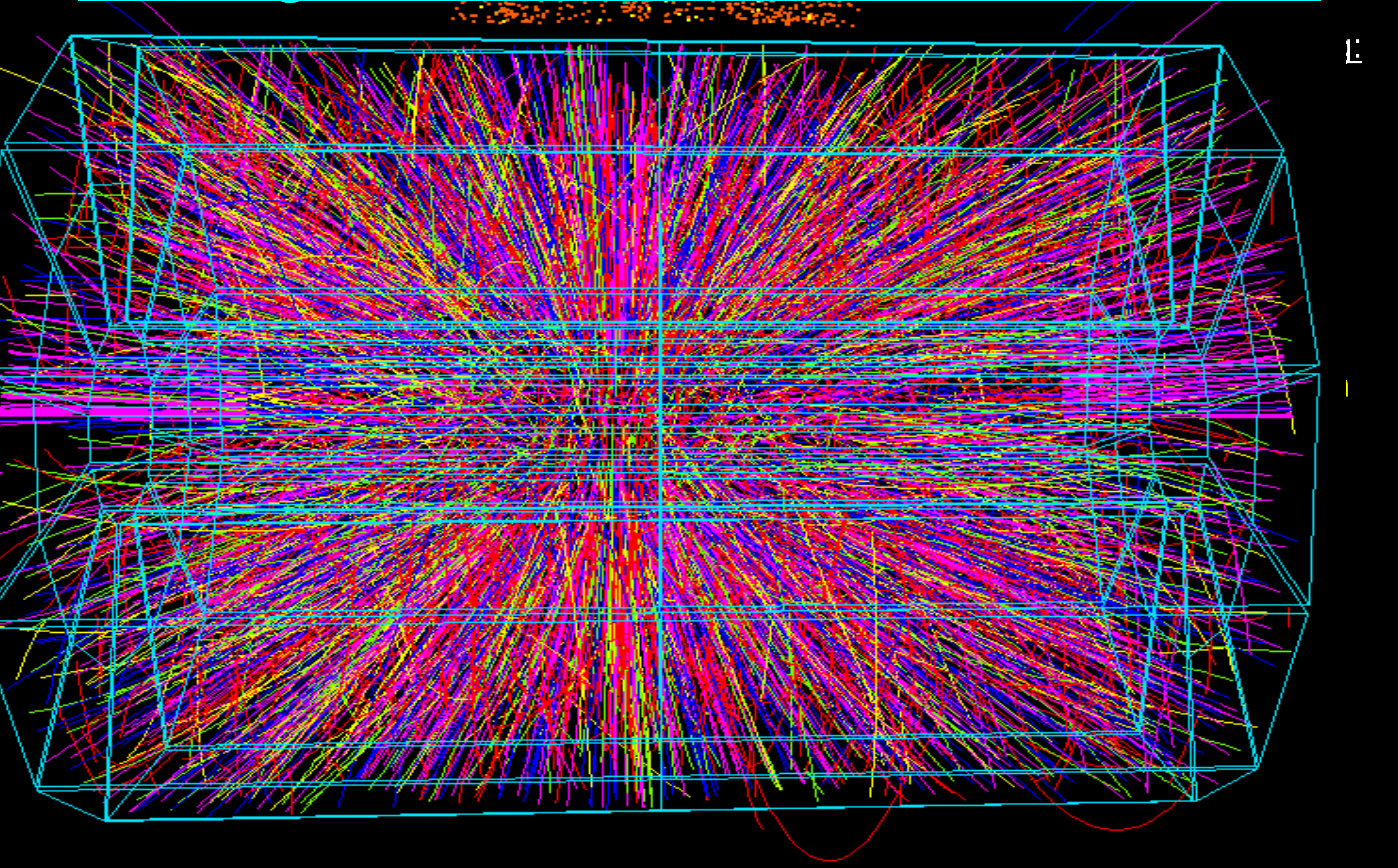
Hard Probes:

Large "p_T" partons

Heavy quark production

Question – What happens to partons as they traverse the QGP and why? Think of QED analog!

Probing Hot QCD Matter with Hard Probes



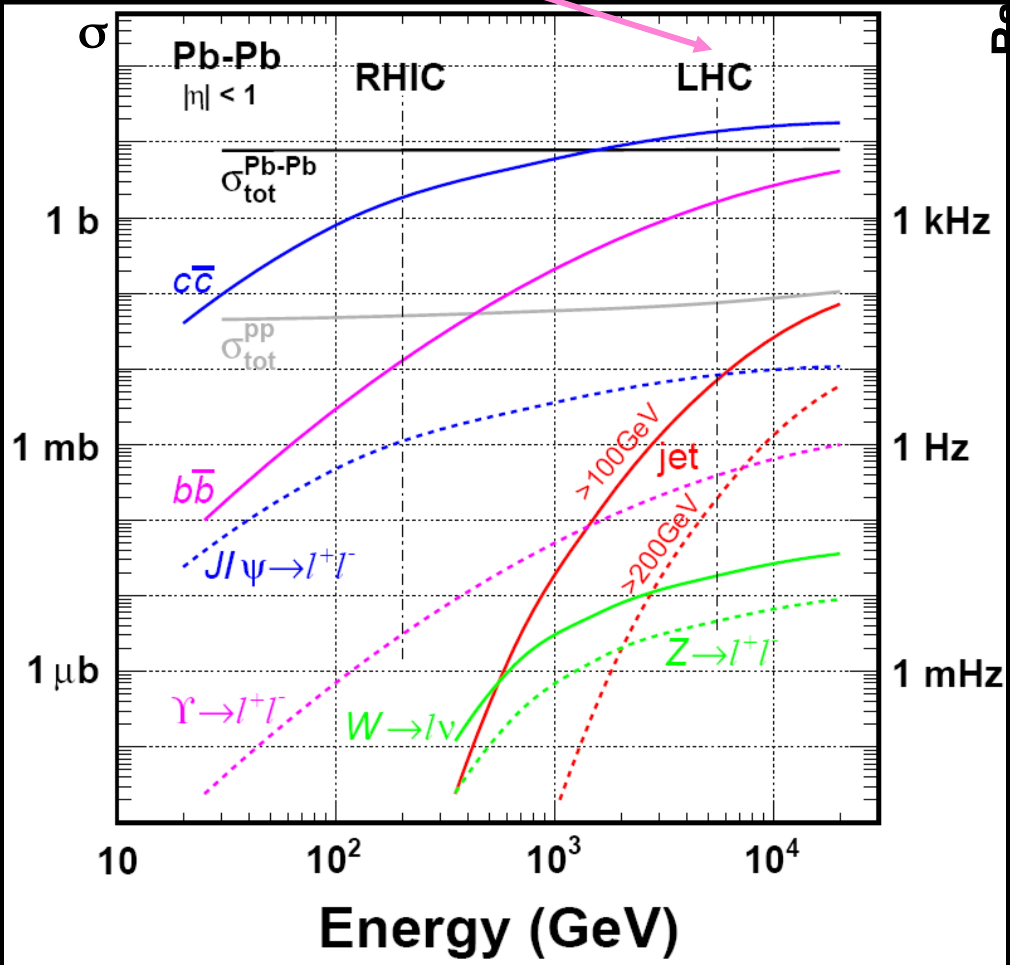
Hard Probes with LHC Heavy Ions

Significant increase in hard cross sections (p_T or mass > 2 GeV/c) at LHC

- "real" jets, large p_T processes
- abundance of heavy flavors
- probe early times, calculable

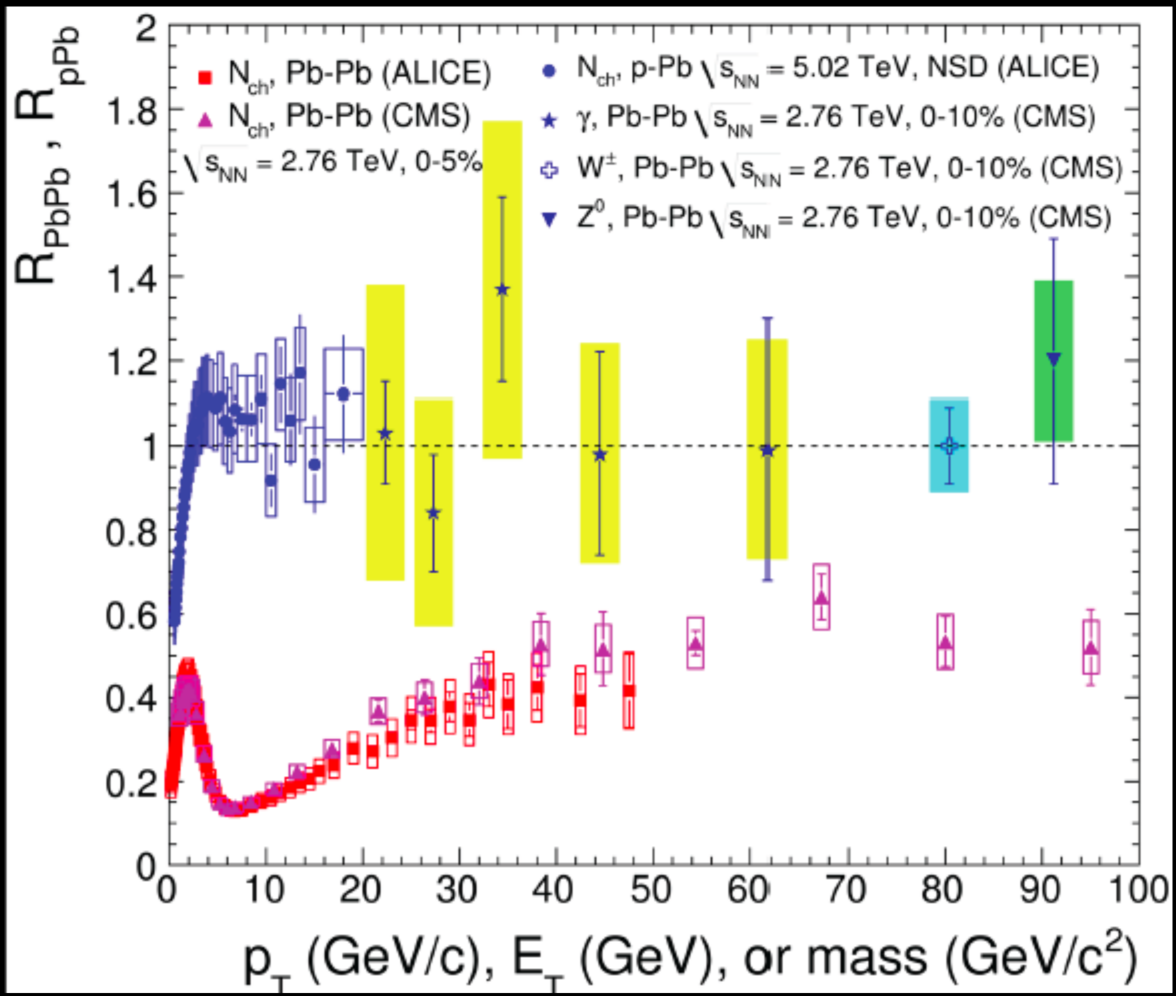
σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)

σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)



Summary: Pb-Pb→Hadrons Suppressed at Large p_T, Pb-Pb→ γ, W, Z NOT Suppressed p-Pb→Hadrons NOT Suppressed

Deviations from binary scaling of hard collisions:



$$R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$$

Pb-Pb → Photons, W, Z

(p-Pb → charged)

Pb-Pb → charged (factor 2 – 5 suppression)

Similar results at RHIC for hadrons & γ up to p_T = 20 GeV/c

Summary: Pb-Pb→Hadrons Suppressed at Large p_T, Pb-Pb→ γ, W, Z NOT Suppressed p-Pb→Hadrons NOT Suppressed

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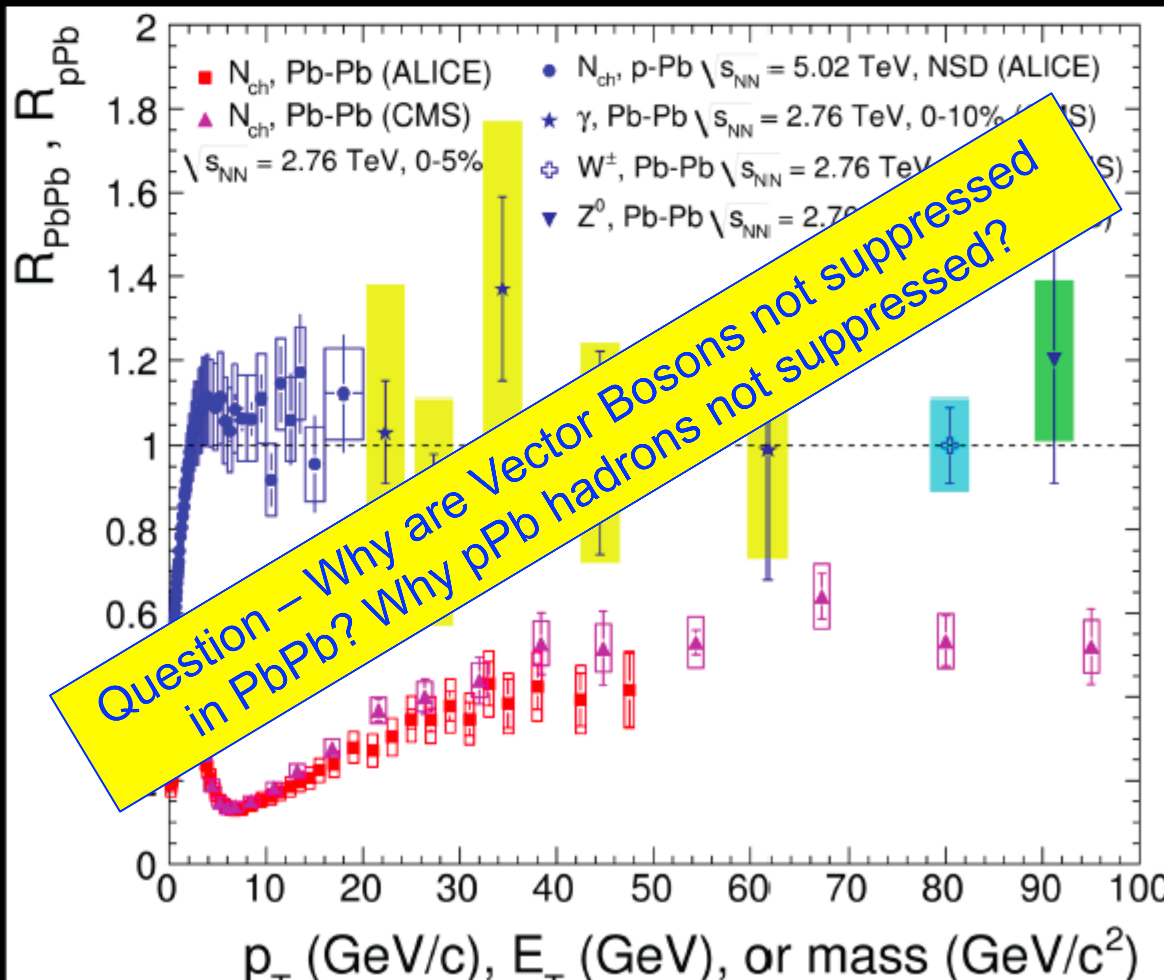

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(p-Pb → charged)

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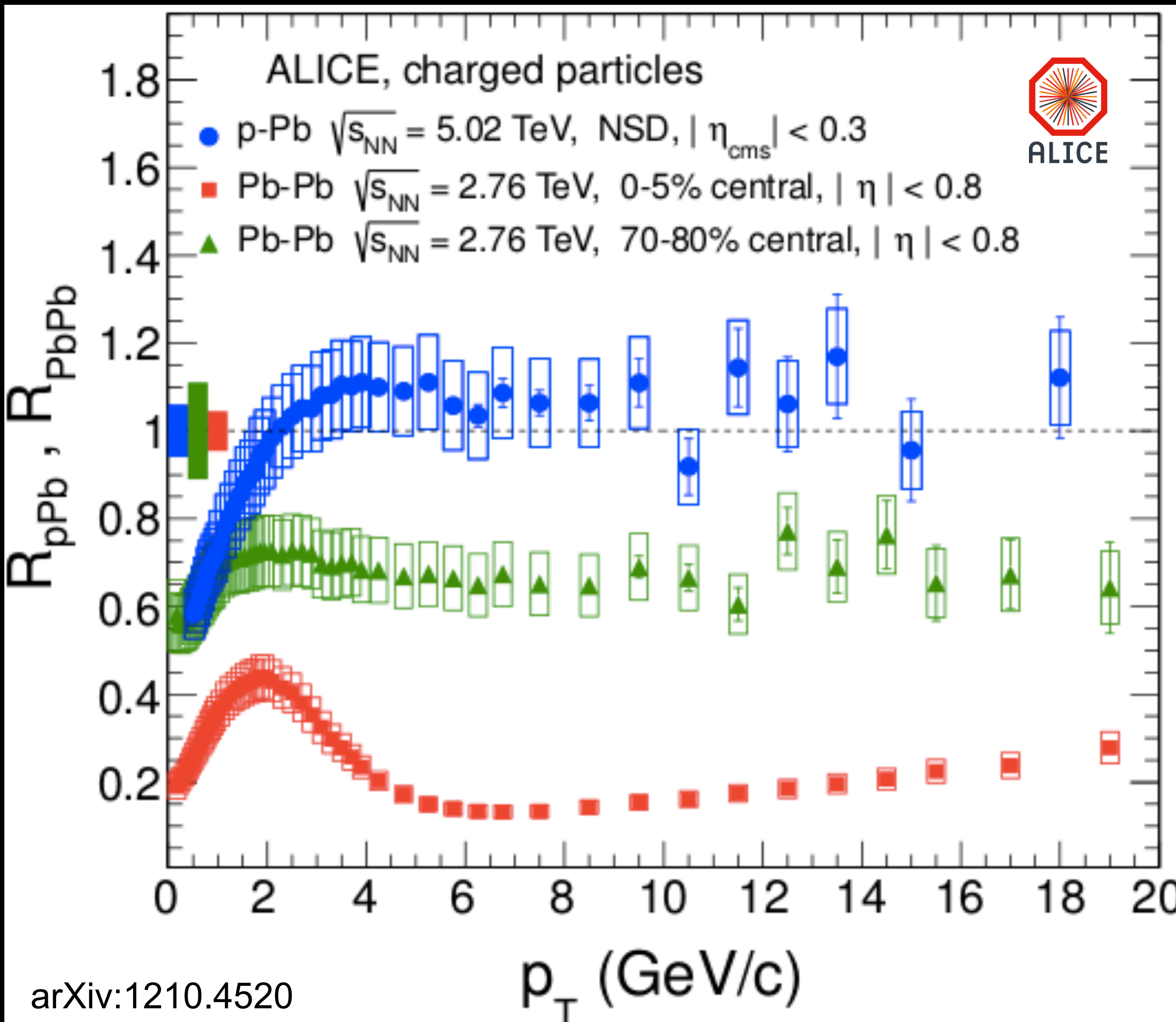
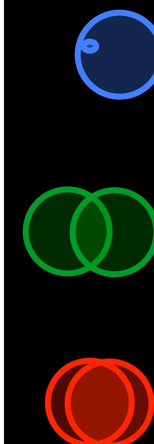
Similar results at RHIC for hadrons & γ up to p_T = 20 GeV/c

Comparison p-Pb and Pb-Pb → Hadrons at LHC



arXiv:1210.4520

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



p-Pb (p_T > 2 GeV/c)

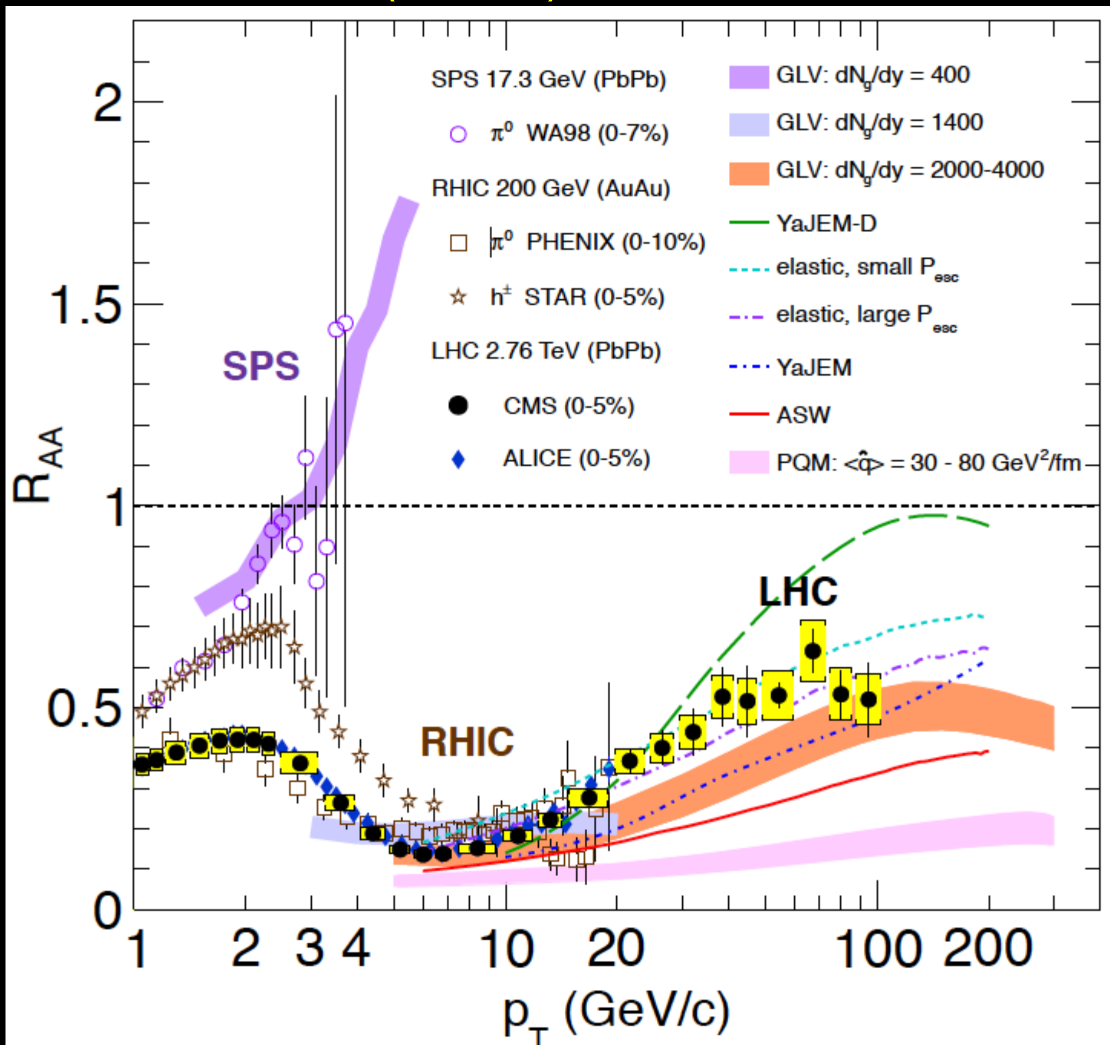
- Binary scaling (R_{pPb} ~ 1)
- Absence of Nuclear Modification
- Initial state effects small

Pb-Pb – Suppression!

- Increases with centrality
- Not initial state
- Final state effect (hot QCD matter)

RHIC and LHC Suppression of Charged Particles

Pb-Pb (Au-Au) Central Collisions



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

$R_{AA} = 1$

Suppression

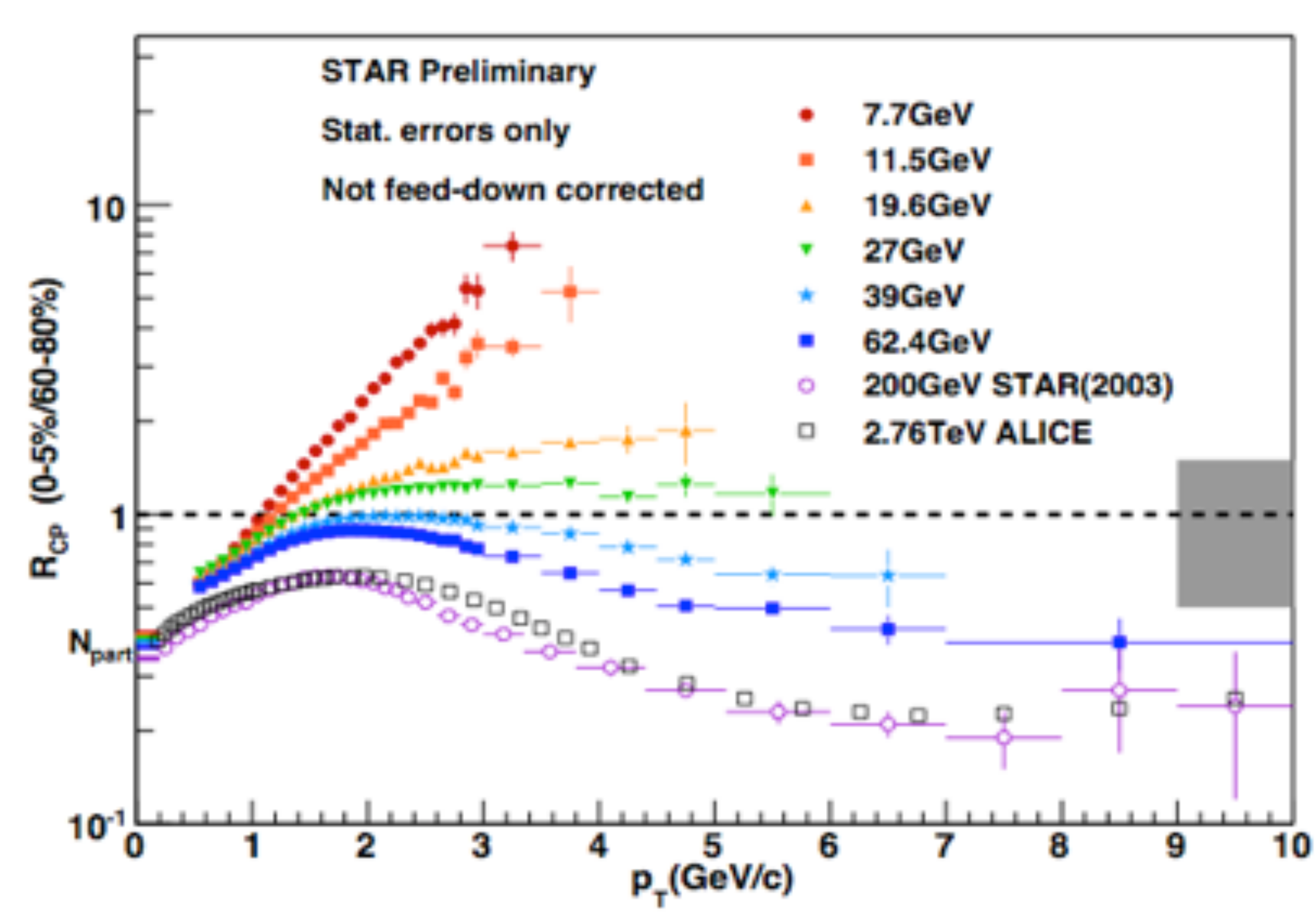
CMS, arXiv:1202.2554v1

(Lower Energy) RHIC High p_T Charged Particles

Au-Au (Pb-Pb) Central Collisions

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

$\rightsquigarrow R_{AA}$



Enhancement

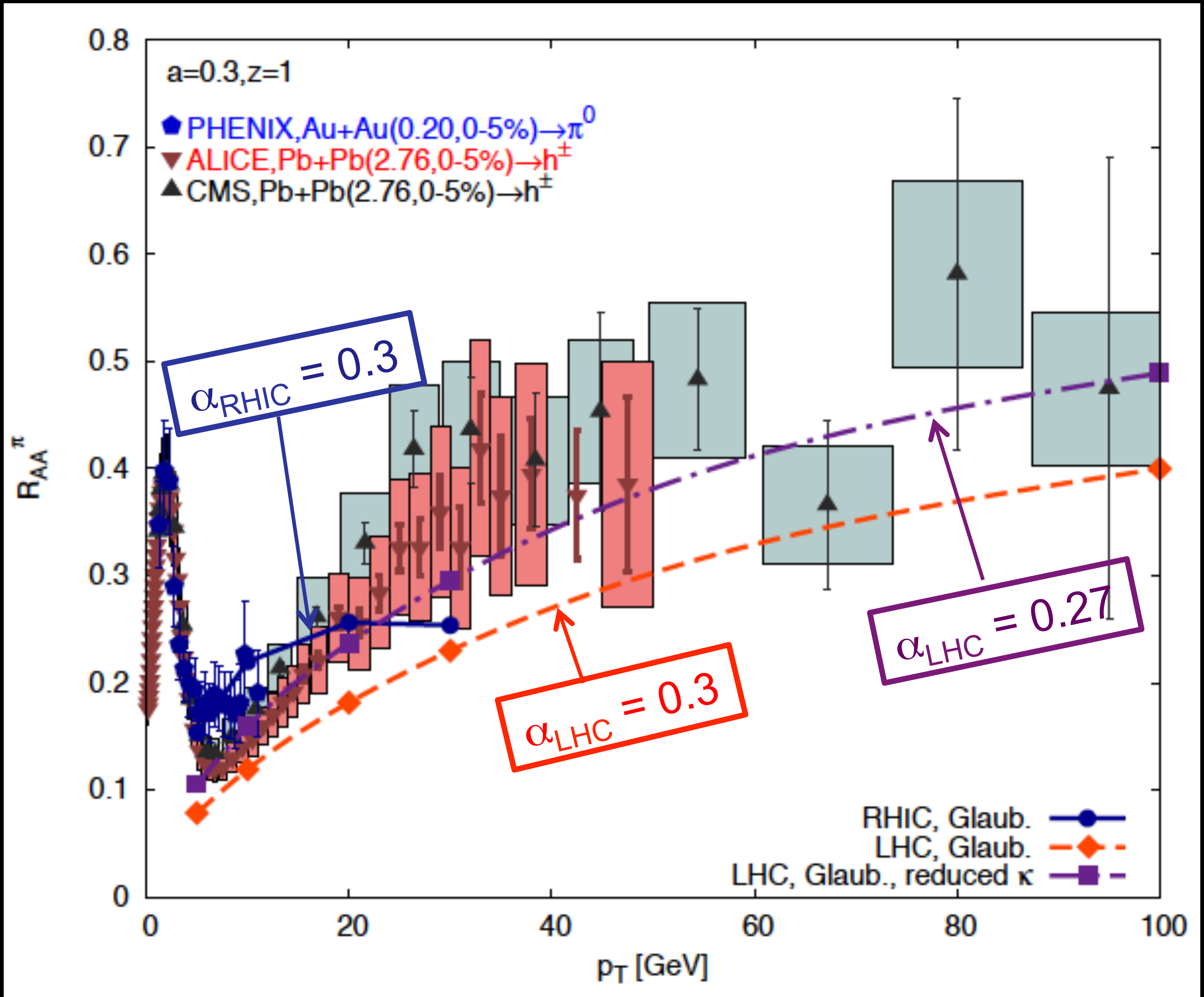
$R_{CP} = 1$

Suppression

Enhancement (Cronin, initial state effects) below 39 GeV. Above quenching starts to dominate!

Models comparisons to data are in progress.

Reduced α_s Describes LHC Trend



B. Betz & M. Gyulassy, arXiv:1201.0281

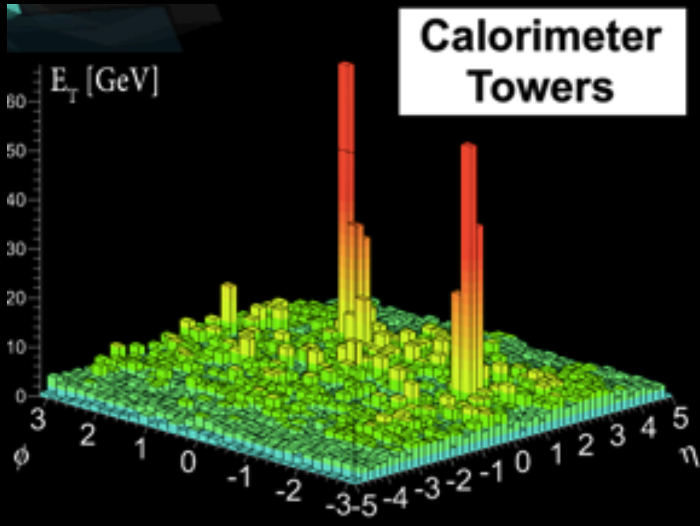
$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

R_{AA} at LHC in pQCD:

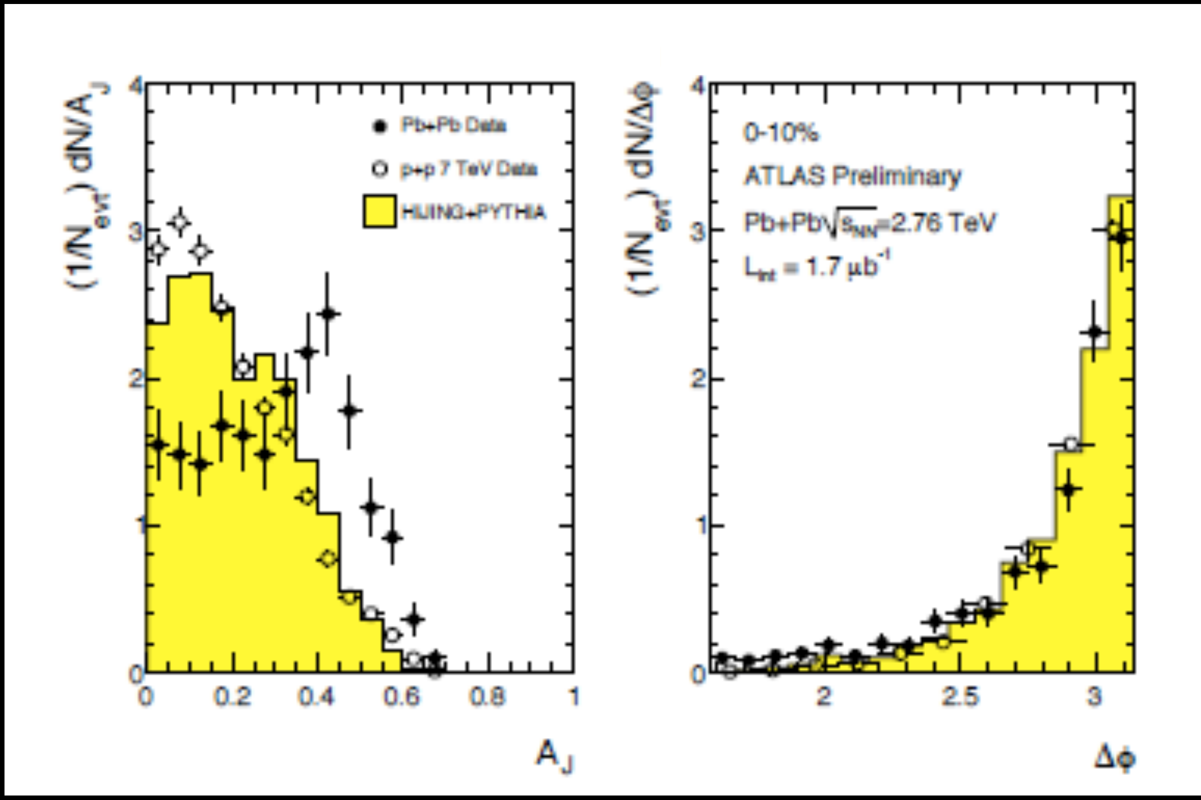
Suppression described with reduced α_s!

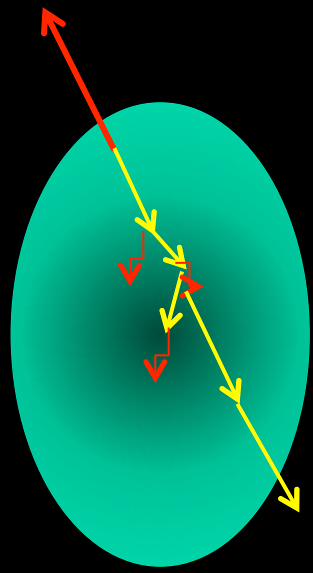
Some details remain.

Jets at the LHC – Di-Jet Energy Imbalance!



ATLAS, Phys. Rev. Lett. 105 (2010) 252303





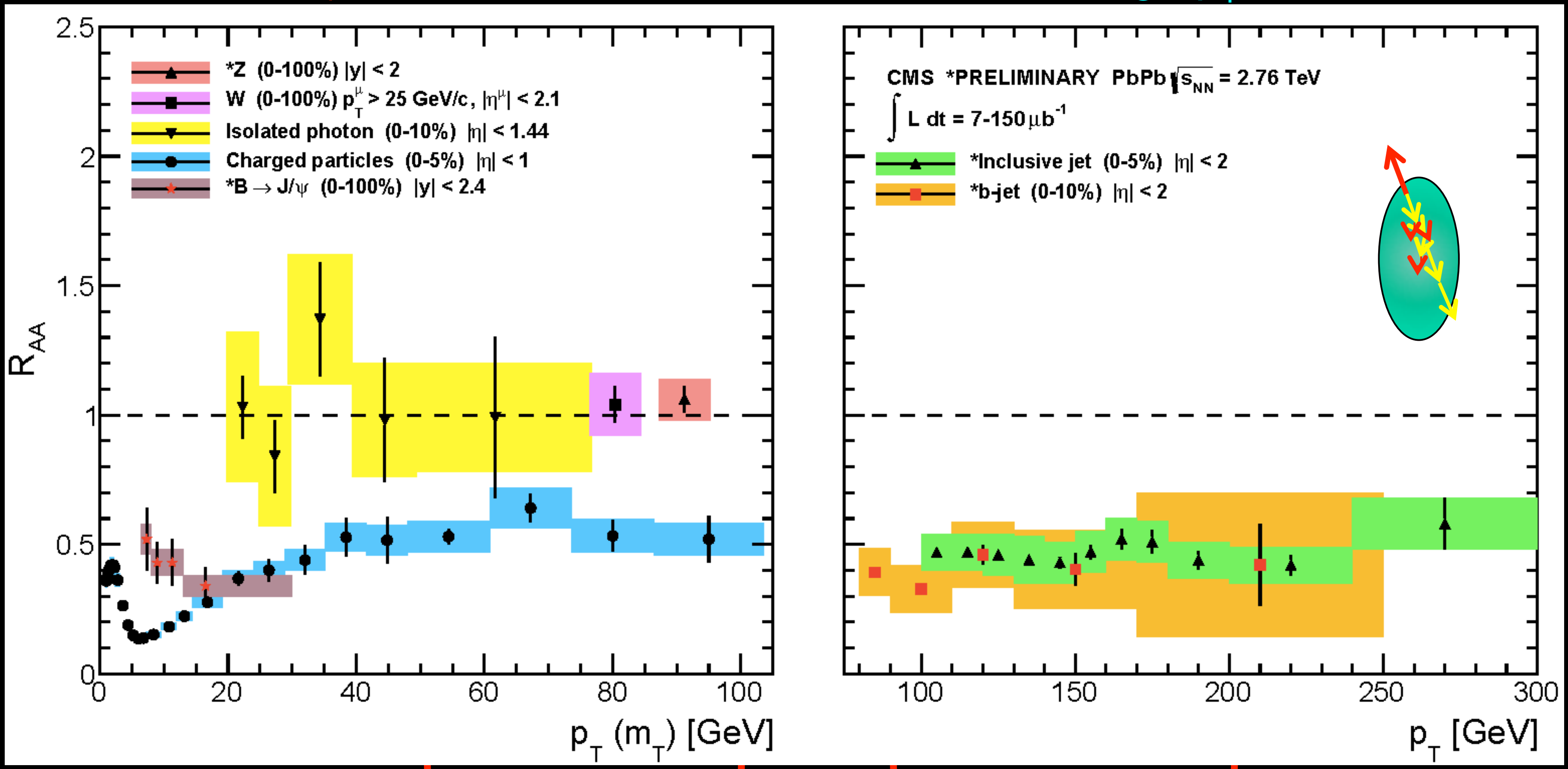
Energy Asymmetry: $A_J = E_{T1} - E_{T2} \;/\; E_{T1} + E_{T2}$

for $\Delta\phi > \pi/2$

(E_{T1} > 100 GeV, E_{T2} > 25 GeV)

Flavor (In-)Dependence of Jet Quenching at the LHC!

High p_T Particles — High p_T Jets



Same range of parton p_T

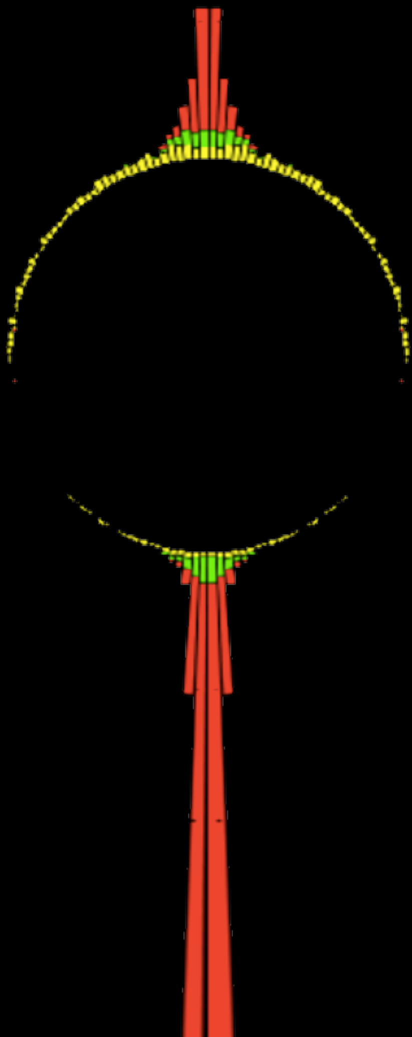
J. Velkovska (CMS) HP 2013

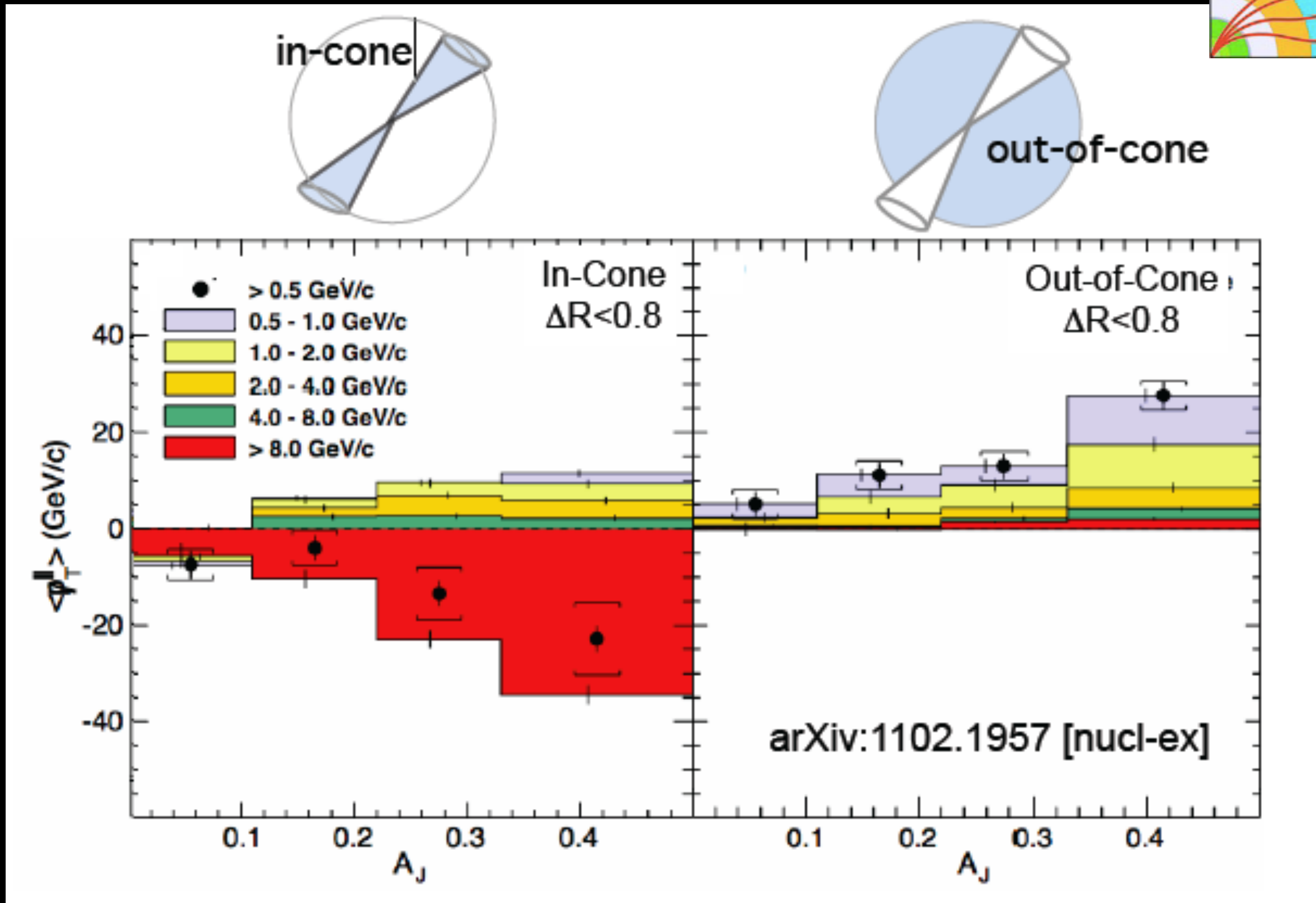
EPJC 72 (2012) 1945
PLB 715 (2012) 66
PLB 710 (2012) 256

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

Where does the Energy Go? – LHC

PRC 84 (2011) 024906





Energy/momentum balance in event is carried by low momentum particles at large angles to jets!

pQCD, vacuum fragmentation, thermalization of lost energy?

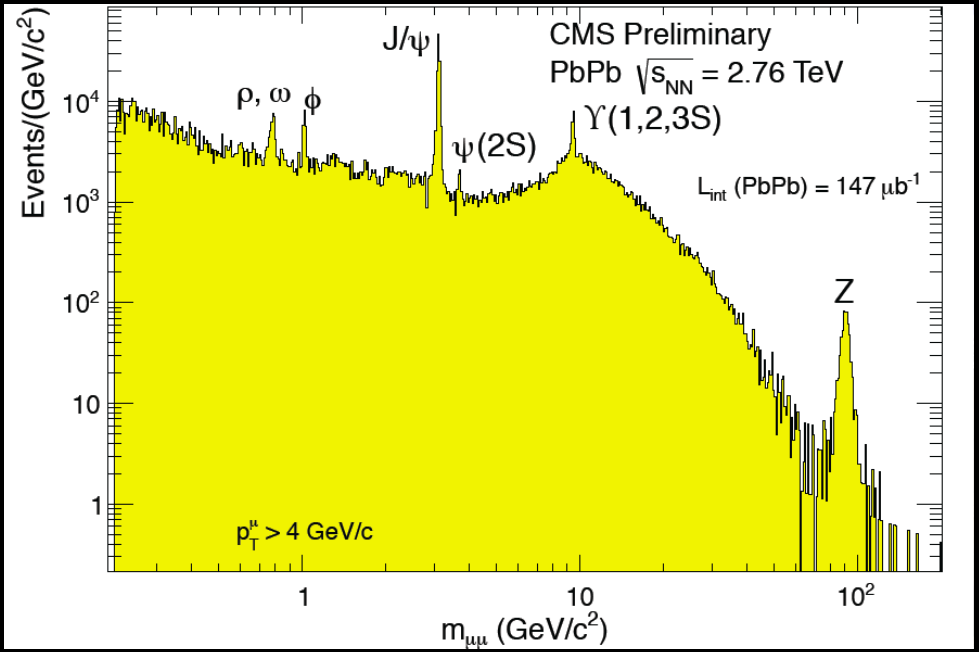
"What Have We Learned" from RHIC & LHC

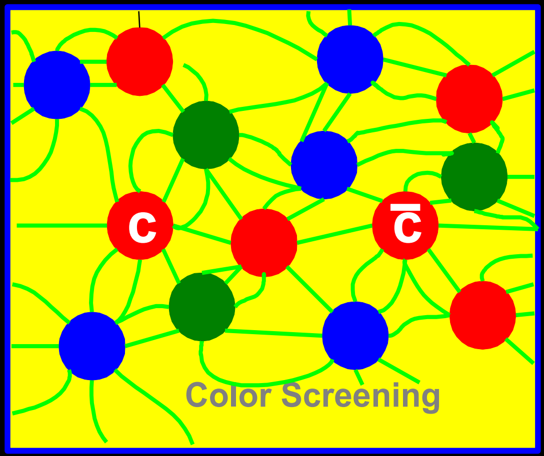
6) Suppression of quarkonia (J/ψ and Υ states)
Has properties of color-screening

Quarkonia in the QGP

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

Debye color screening in the QGP →



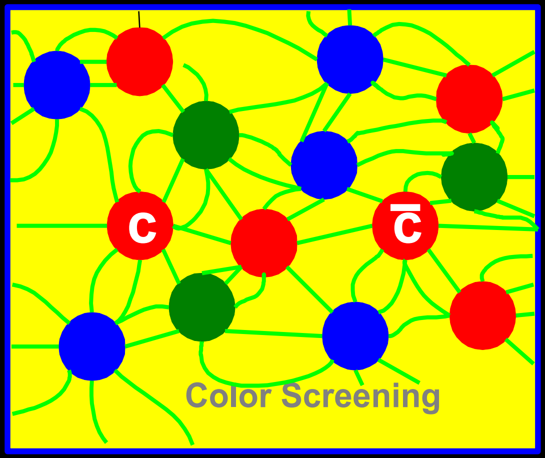


Color screening of $c\bar{c}$ pair results in J/ψ ($c\bar{c}$) suppression!

Quarkonia in the QGP

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

Debye color screening in the QGP →



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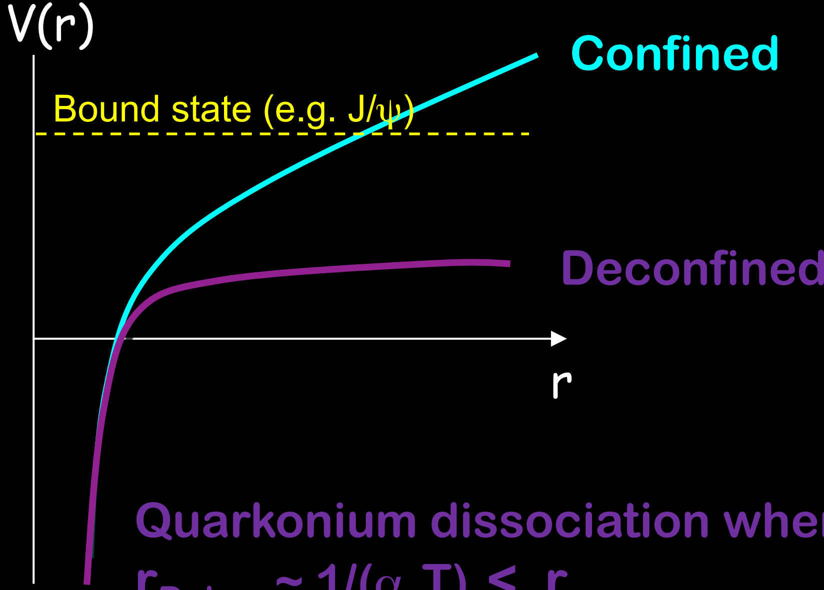
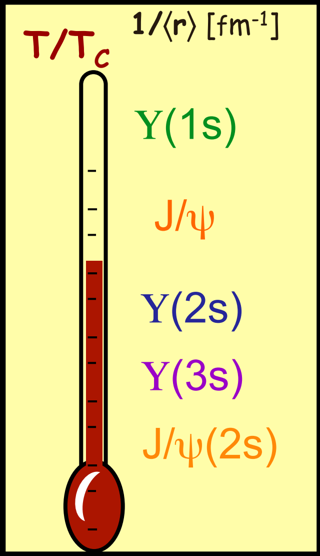


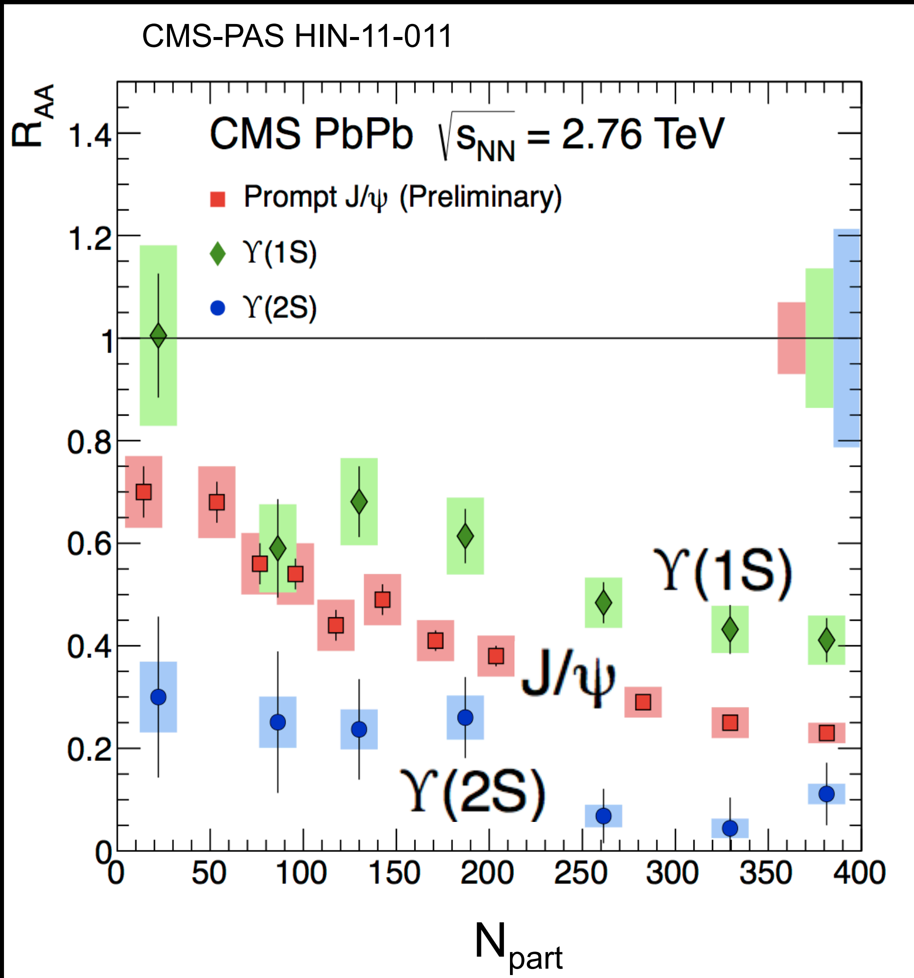
Quarkonium dissociation when $r_{Debye} \sim 1/(\alpha_s T) < r_{qq}$

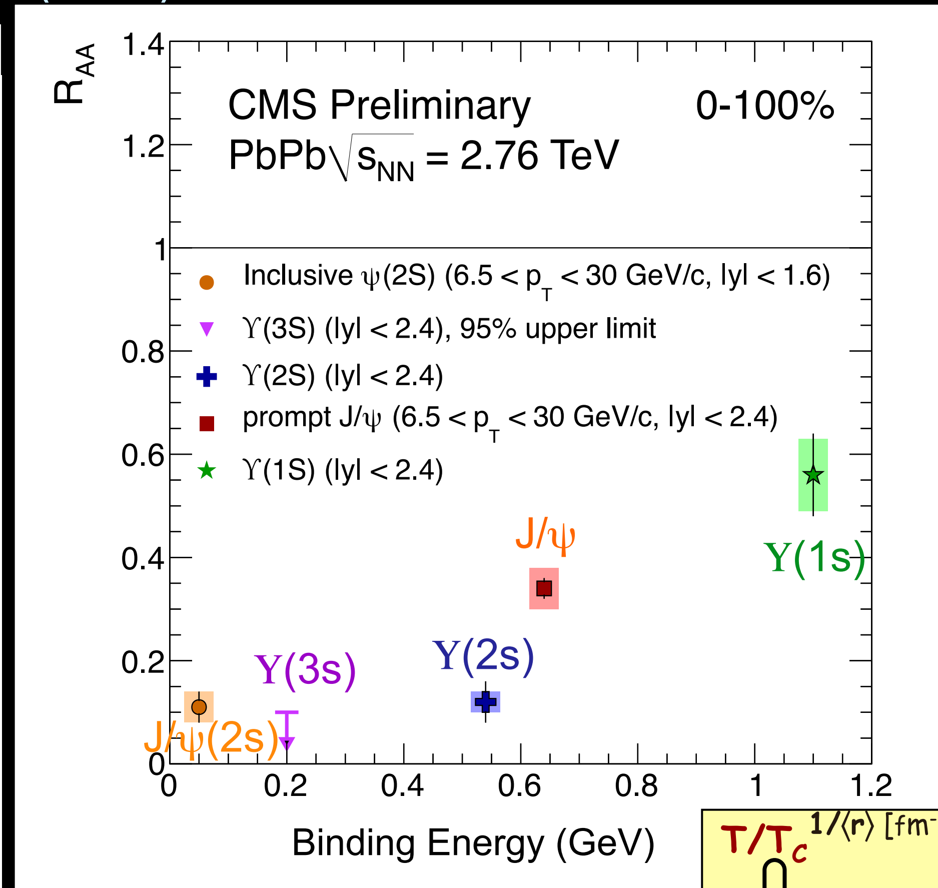


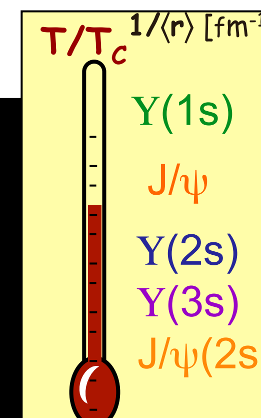
Measure melting order of $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: Υ'', Υ', Υ

J/Ψ and Υ Suppression at the LHC

CMS, PRL 107 (2011) 052302







Suppression of Quarkonium States As Expected!

Quarkonium Thermometer!

"What Have We Learned" from RHIC & LHC

1) Consistent Picture of Geometry, Dynamics and Evolution of RHI Collisions

2) Particle ratios → equilibrium abundances → universal hadronization $T_{critical}$

Confirm lattice predictions for $T_{critical}$, μ_B

3) It has characteristics of a quark-gluon plasma

Flows with ultra-low shear viscosity

Strongly-coupled liquid

4) QGP radiation (direct photons) → time-integrated temperatures >> $T_{critical}$

5) It's opaque to the most energetic probes

Light & heavy quarks are suppressed at large p_T

Away-side jet quenched and jet energy imbalance

p-Pb indicates quenching/suppression is effect of QCD medium

6) It has properties of color-screening

Suppression of quarkonia (J/ψ and Υ states)

Still much to be done experimentally and theoretically…..

Ultra-relativistic Heavy-Ion Physics and Experiments

Introduction to Heavy Ion Physics

Machines and Experiments

How Do Heavy Ion Collisions Evolve?

Important Physics Results from RHIC and LHC

Future

Heavy Ion Upgrades, New Machine & Detector Plans

Will not go into details about:

RHIC Detector Upgrades (recent and RHIC Run plans)

LHC Upgrades for Long Shutdown 2 (or HI Run Plans)

Will mention in final slides:

- A new RHIC Experiment
- New Machine (EIC) plans

A New RHIC Detector (currently known as sPHENIX)

How do asymptotically free quarks and gluons create the near-perfect liquidity of the QGP?

– or –

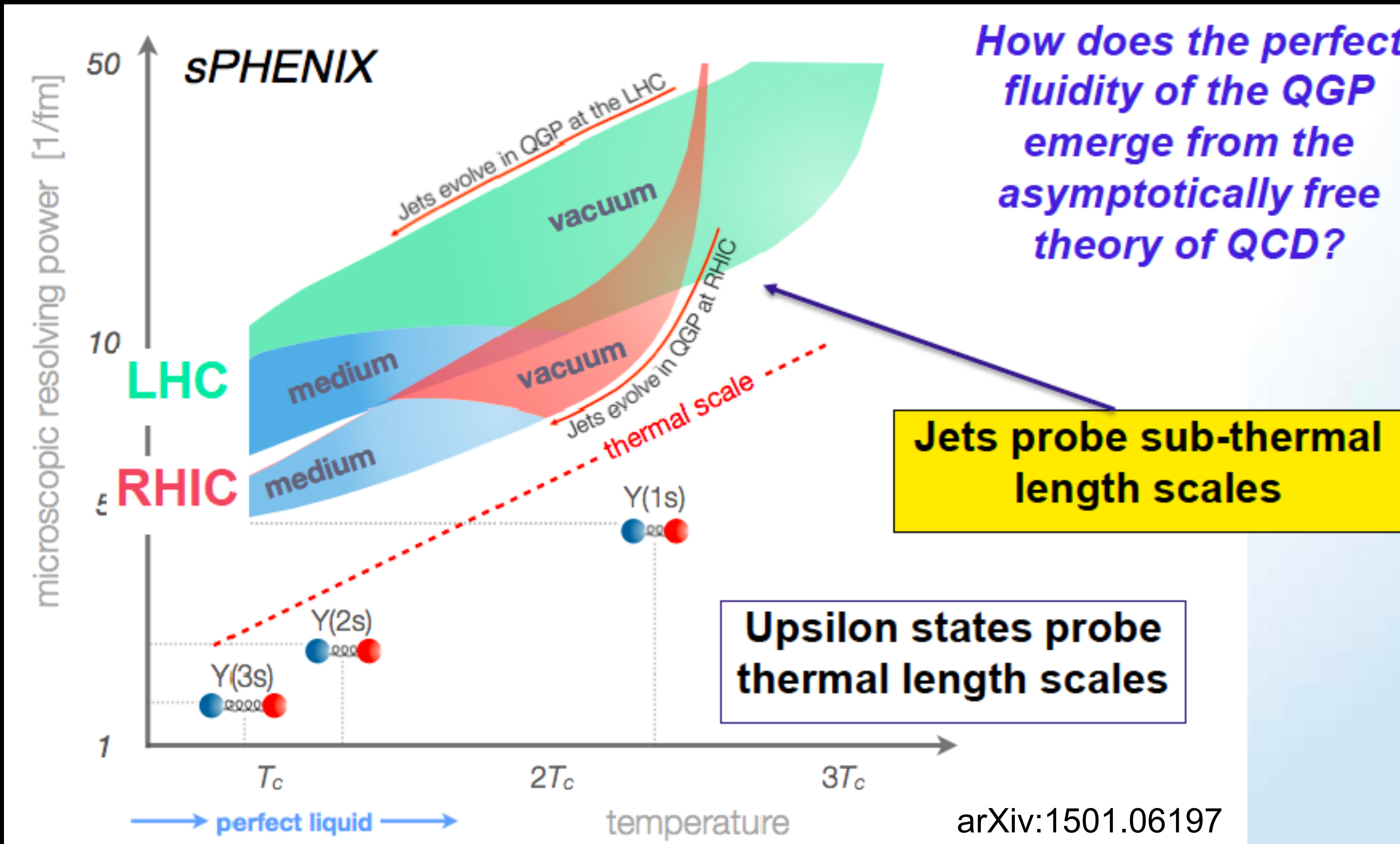
What degrees of freedom not manifest in the QCD Lagrangian produce the near-perfect liquidity of the QGP?

<u>The answer:</u>

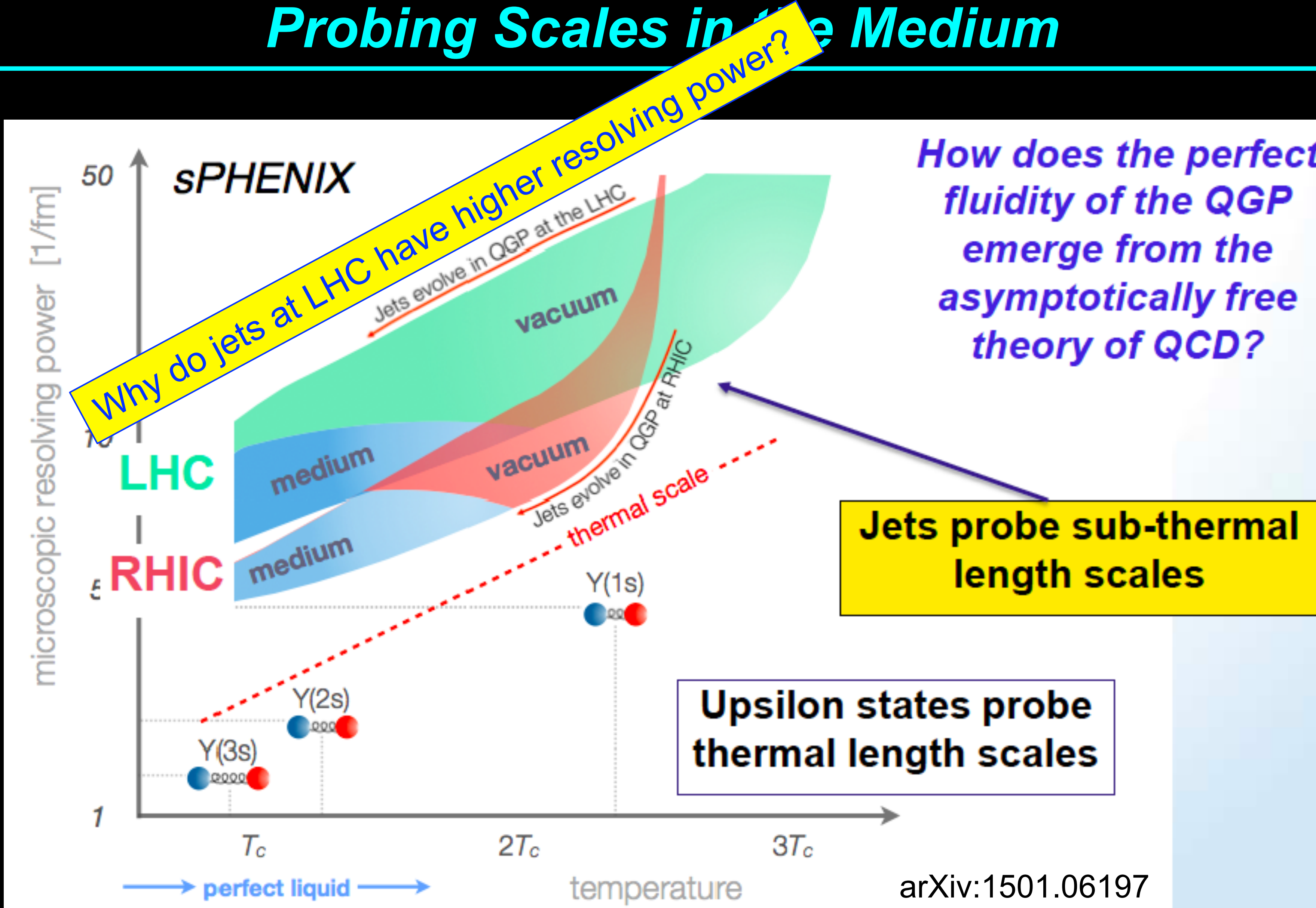
Deploy probes in experiment with a resolution reaching well below the thermal scale (~ 1 fm) of the QGP, i.e.

Jets & Upsilon states

Probing Scales in the Medium



Probing Scales in the Medium

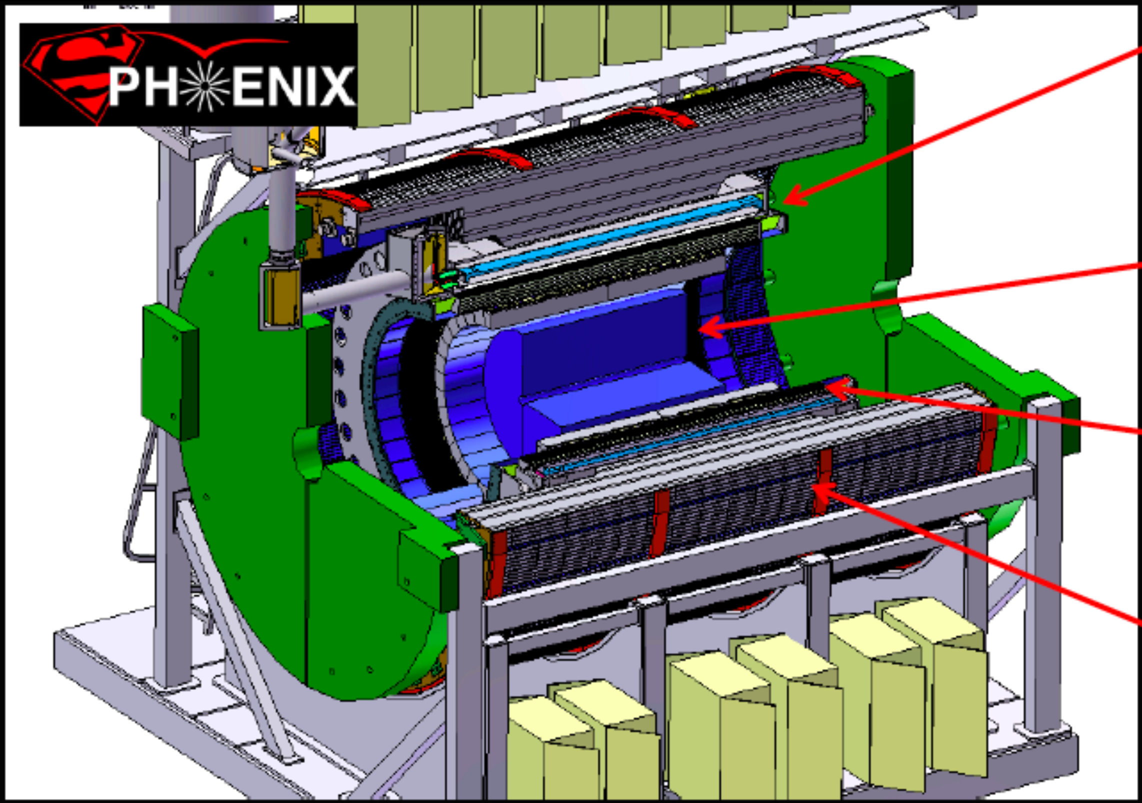


A New RHIC Detector (currently known as sPHENIX)

To measure Jets & Upsilon states

arXiv:1501.06197

c. 2021 – 2023



BaBar Magnet 1.5 T

Coverage |η| < 1.1

All silicon tracking (tbd)
Heavy flavor tagging

Electromagnetic Calorimeter

Hadronic Calorimeter

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

Scientific American, May 2015

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

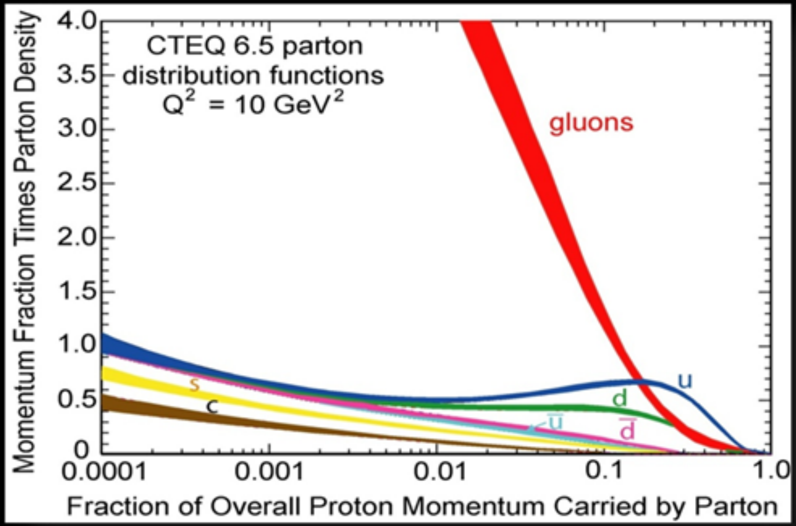
By Rolf Ent, Thomas Ullrich and Raju Venugopalan

In general:

- HERA (1990's) discovered a huge abundance of soft gluons inside the proton. Role of gluons in nucleon structure and dynamics in general is unknown.
- The origin of nucleon spin and the distributions of quarks and gluons in nuclei are still mysteries after decades of study!

Why We Need 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 CGC? ⟶
- How do quarks and gluons propagate in nuclear matter and join together to form hadrons?

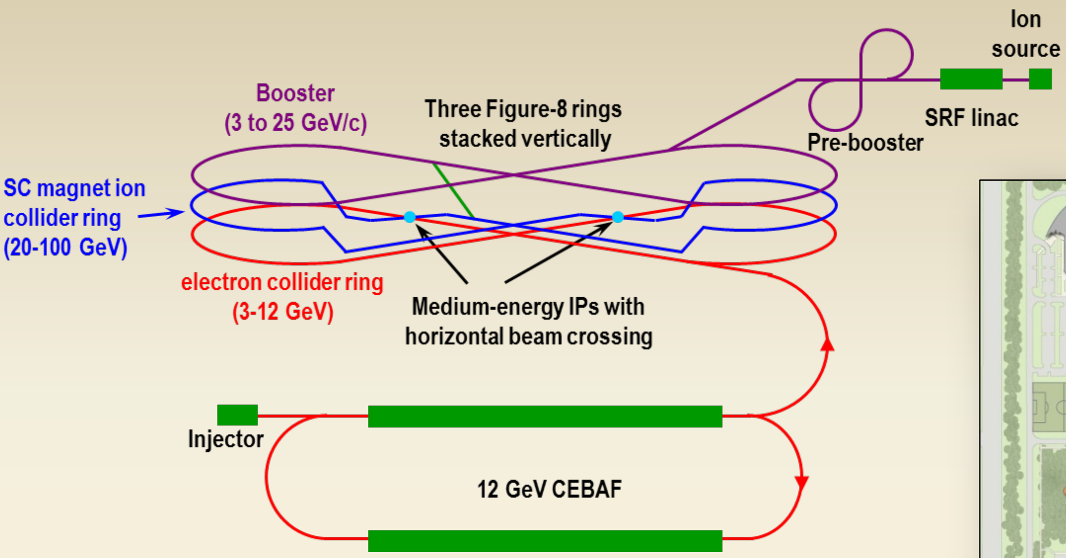
Requirements of EIC

To answer these questions will 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 the properties of partons traversing the nuclear medium.

Also, there exists new phenomenology - Generalized Parton Distributions (GPDs) and Transverse Momentum Dependent (TMDs) distributions to “image” quarks and gluons and access orbital angular momentum.

Medium Energy EIC@JLab



JLab Concept

- Initial configuration (MEIC):
  - 3-12 GeV on 20-100 GeV ep/eA collider
  - Fully-polarized, longitudinal and transverse
  - Luminosity:

    up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- Upgradable to higher energies

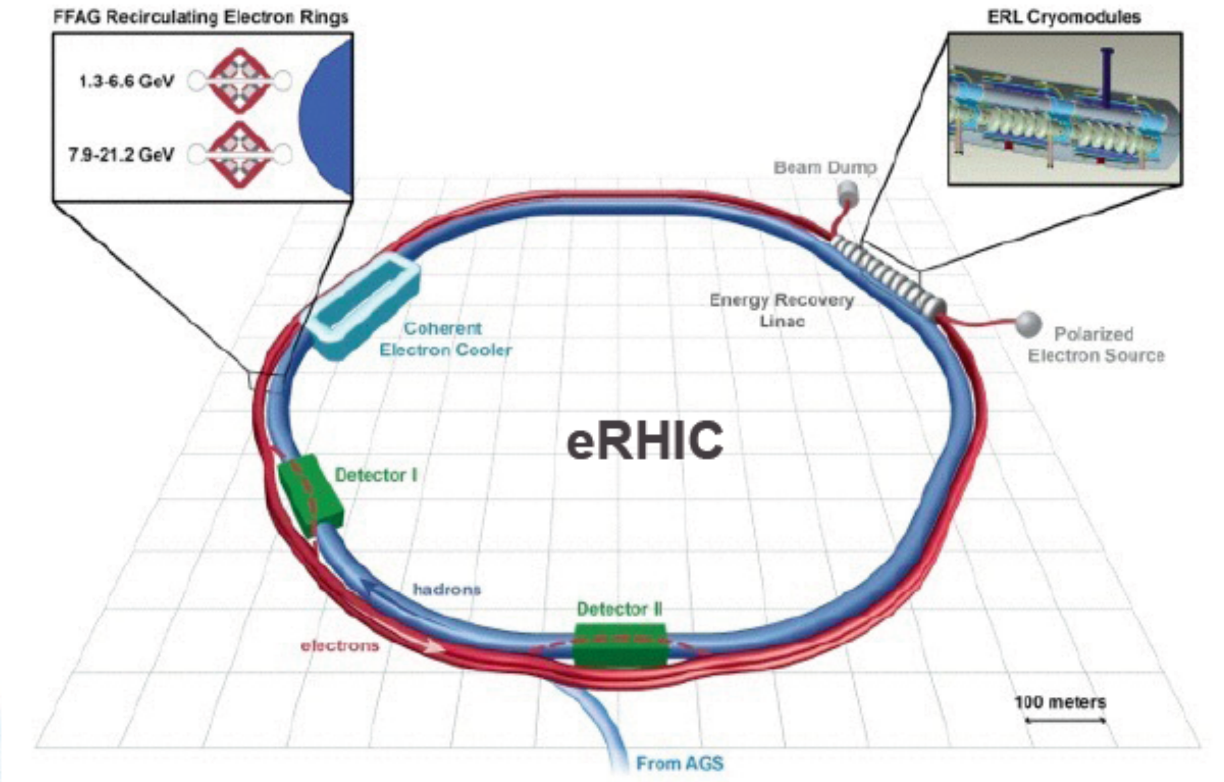
  250 GeV protons + 20 GeV electrons

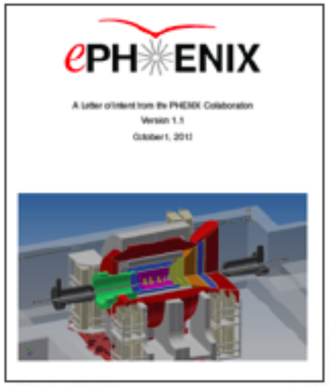
EIC Design

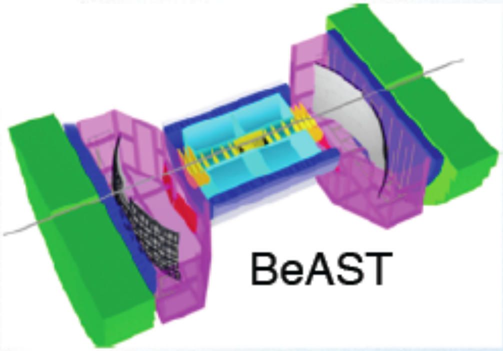
Detector Options

eRHIC ERL + FFAG ring design @ $10^{33}/cm^2s$

15.9 GeV e^- + 255 GeV p or 100 GeV/u Au.







When completed, eRHIC will be the most advanced and energy efficient accelerator in the world

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 learn from pPb?
- Can we understand parton propagation & energy loss at a fundamental level?
  What can we learn about the response of the QGP?
  How does hadronization take place as the parton propagates?
- 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?
  → Low energy RHIC, 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 is not understood! Hydro? What is the smallest droplet of QGP possible?

The Future of High Energy Density QCD is Bright!

Thanks for your Attention