Strong Interaction, emergent phenomena and heavy-ion collisions

Gunther Roland
MIT

Symposium on QCD and Nuclei

Past

Present

Future

Beginning of time

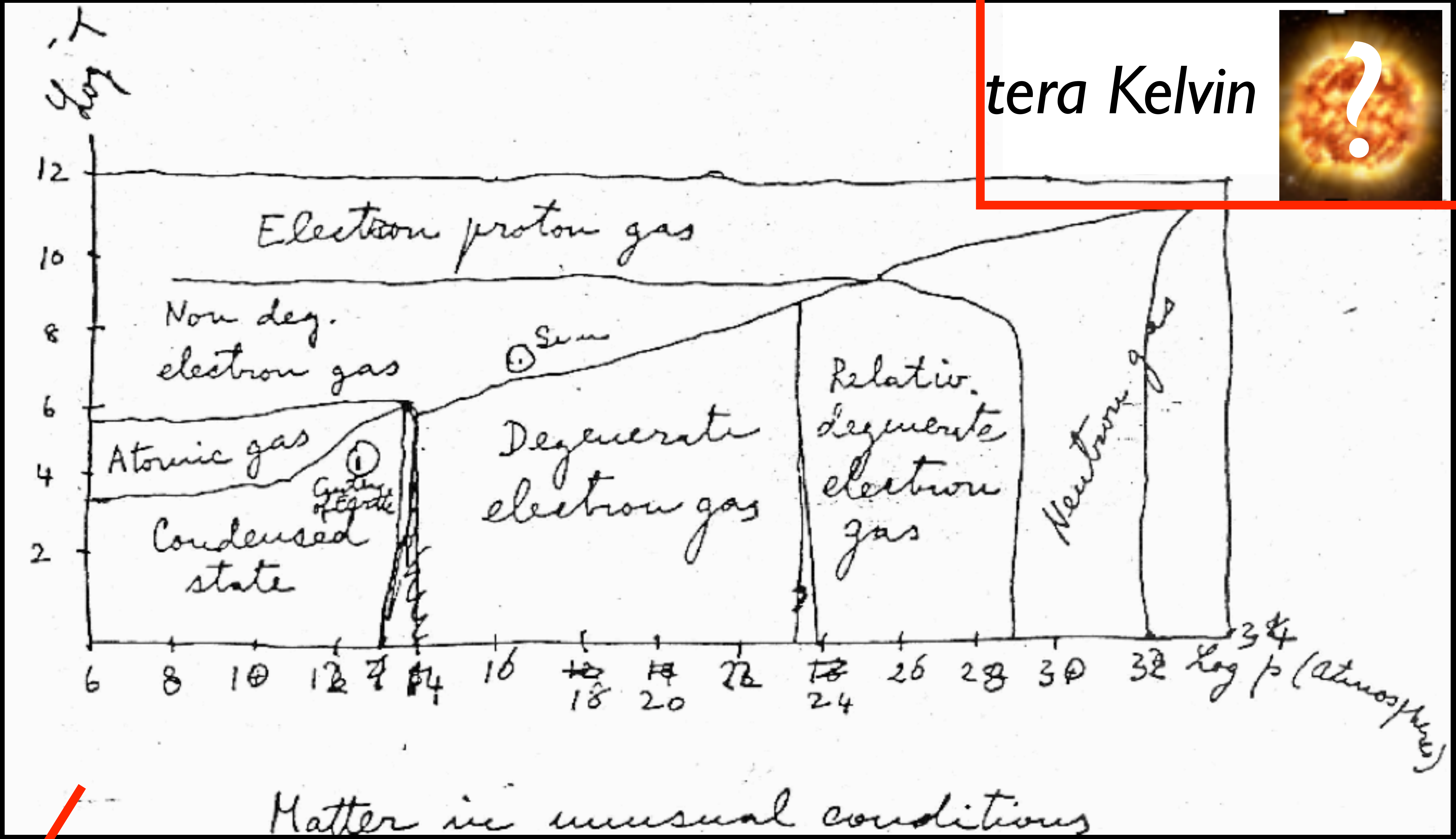
Beginning of time
ca. 1950

1946

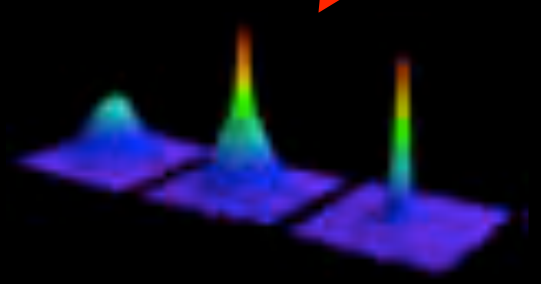
LNS: 75 Years and Counting

Jerrold R. Zacharias	Peter T. Demos	Martin Deutsch	Francis E. Low	Jerome I. Friedman	Arthur K. Kerman	Robert P. Redwine	June L. Matthews	Richard G. Milner	Boleslaw Wyslouch
1946 to 1956	1961 to 1973	1973 to 1979	1979 to 1980	1980 to 1983	1983 to 1992	1992 to 2000	2000 to 2006	2006 to 2015	2015 to present

The Big Question: Nature of matter at highest temperature and density

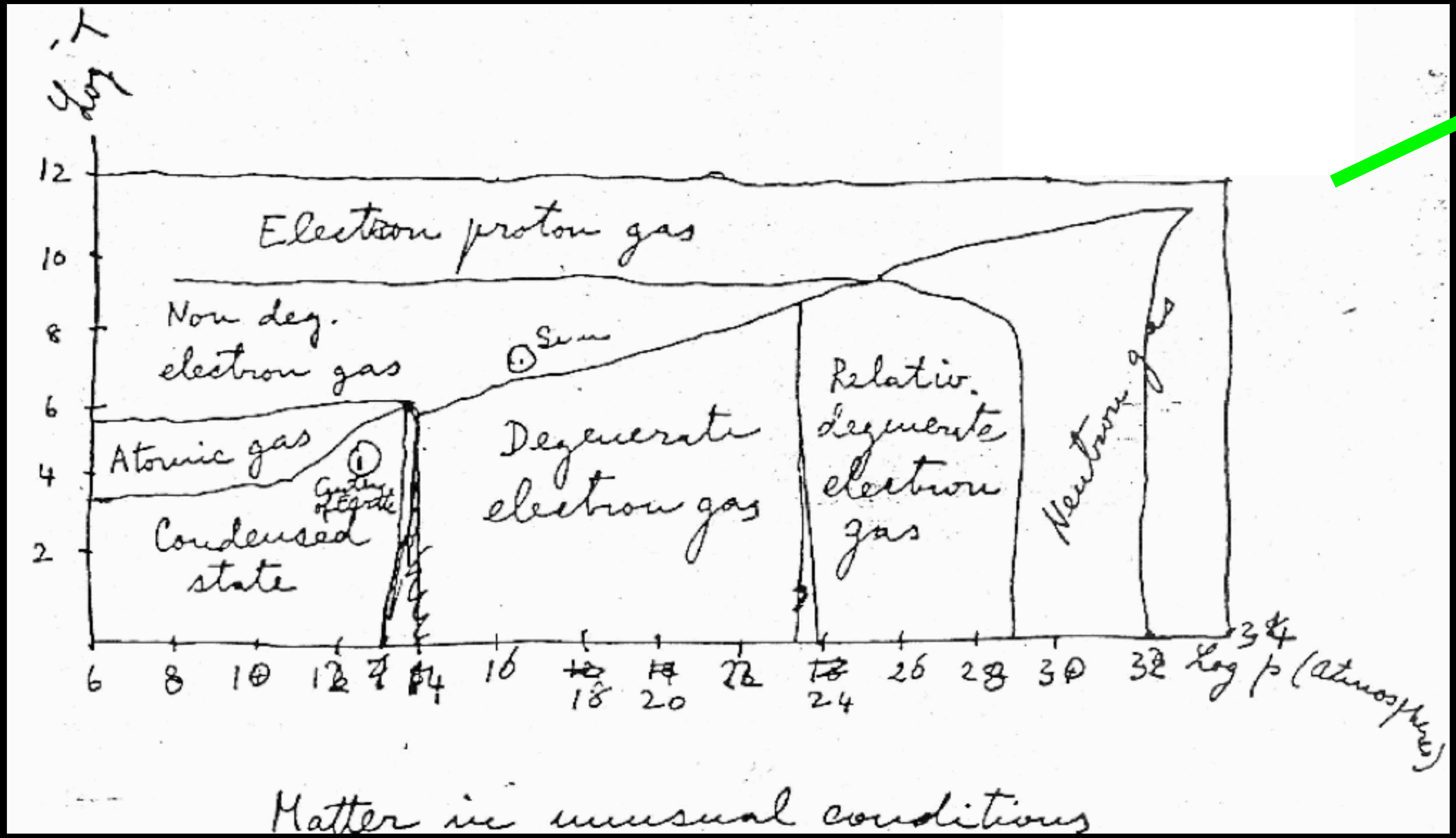


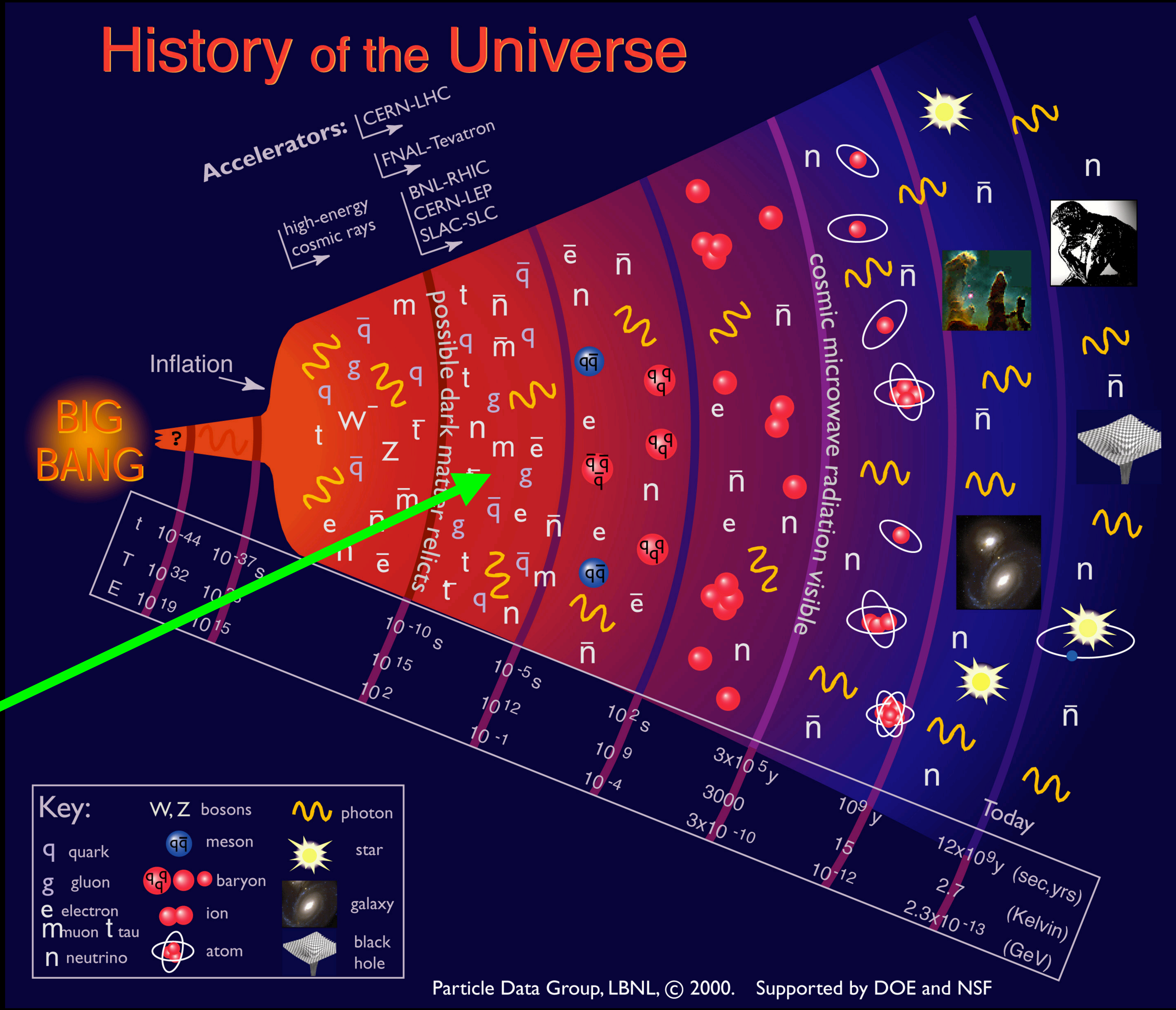
tera Kelvin



nano Kelvin

Fermi
“Notes on thermodynamics and Statistics”, 1953


Log T
Electron proton gas
Non deg. electron gas
Sun
Atomic gas
Condensed state
Degenerate electron gas
Relativ. degenerate electron gas
Neutron gas
Log ρ (atmospheres)
Matter in unusual conditions


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)
T 1032 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

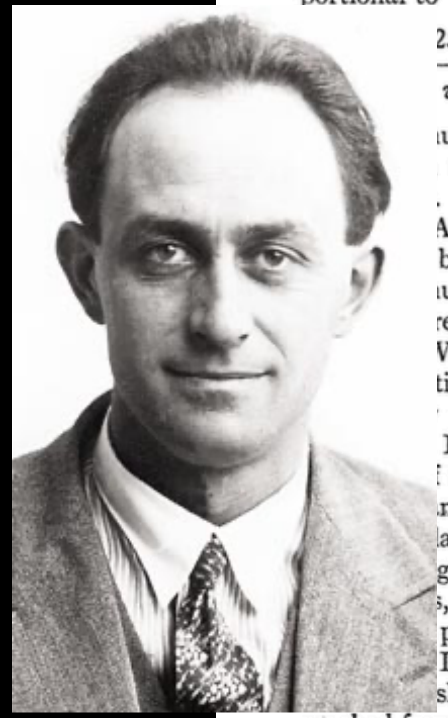
PHYSICAL REVIEW VOLUME 92, NUMBER 2 OCTOBER 15, 1953

Multiple Production of Pions in Nucleon-Nucleon Collisions at Cosmotron Energies*

E. FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received July 3, 1953)

The statistical theory of multiple pion production is applied in some detail to the discussion of nucleon-nucleon collisions for primary energies of 1.75 Bev and 2.2 Bev. Probabilities are given for single and multiple productions of pions and nucleons with different charges.

THE availability of high-energy nucleons from the Brookhaven cosmotron makes it now possible to compare the results of the statistical theory[1] of multiple pion production with experiment.[2] In Table I of A, a tentative estimate of the relative probabilities that in a nucleon-nucleon collision various numbers n of pions are emitted together with two nucleons was given. According to formula (22) of A, these probabilities for for bombarding energies of a few Bev should be proportional to



$$\ldots\frac{251}{w}(w-2)^3\Big\}^n\Big/\Big(\frac{3}{2}\times\frac{5}{2}\times\cdots\times\frac{6n+1}{2}\Big). \quad (1)$$

…ula w is the total energy of the two colliding … the center-of-mass system including their … . The nucleon rest energy is taken as unit … A number of crude simplifying approxima- … been introduced in A in deriving the pre- …ula. One of them was to neglect the effects …rent possible charges of the nucleons and of … Ve propose to improve the earlier results by …tion of this factor. This will be done for low … production up to a maximum number of … In doing this we shall make use of the con- … isotopic spin as a limitation to the possible …nsitions.

…amental hypothesis of the statistical calcu- …gh-energy nuclear events is that in a colli- …, all possible final states are formed with a … proportional to the statistical weight of the … In listing all the possible final states, how- … should exclude all those that cannot be reached from the ground state because of conservation theorems. In addition to the classical conservation theorems of energy, momentum, and angular momentum, one should include in the present discussion also the conservation of isotopic spin and, of course, of charge. To be sure, the conservation of isotopic spin is not exact. It is believed, however, that only weak transitions are possible between states of different isotopic spin. Therefore, the statistical equilibrium postulated in A will normally not have time to be established except for states of equal isotopic spin.

In a collision of two nucleons, the initial state may have either isotopic spin $T=1$ or $T=0$. In computing the final states, only those with isotopic spin 1 or 0 shall have to be counted. For each final state characterized, for example, by the momenta of its particles, there are a number of different charge possibilities. Let p_n be the number of such possibilities for states of isotopic spin 1 with the given total charge, and q_n the similar number for isotopic spin 0. In Table I, we list the numbers p_n and q_n for states of two nucleons and n pions.

For example, in the collision of two high-energy protons, the isotopic spin of the initial state is $T=1$. A final state will be formed abundantly only when its isotopic spin is also 1 and we may assume that the probability of its formation will be proportional to $f_n(w)$ given by Eq. (1). In computing the relative probabilities for the formation of n pions, we shall take into account, however, that there are p_n states of isotopic spin 1. Therefore, the probabilities to form n pions will be proportional to p_nf_n and be given by

$$P_n=p_nf_n/\sum p_nf_n. \quad (2)$$

If the two colliding nucleons are a neutron and a proton, the initial state is a mixture of 50 percent isotopic spin 1 and 50 percent isotopic spin 0. If the initial state has $T=1$, the probability to form n pions will again be given by Eq. (2). For $T=0$, the probability will be given by a similar expression with p_n replaced by q_n:

$$Q_n=q_nf_n/\sum q_nf_n. \quad (3)$$

The resultant probability will be, therefore, the arithmetic average of Eqs. (2) and (3).

In discussing the comparison of these figures with experiment, it is important to give not only the number of pions that accompany the two nucleons in the final state, but also their charges. In order to do this, we must subdivide the numbers p_n and q_n of states with n pions into numbers of states corresponding to the

TABLE I. Number of states of isotopic spin 1 and 0 for a system of two nucleons and n pions.

n	0	1	2	3
p_n	1	2	4	9
q_n	1	1	2	4

* Research supported by a joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
[1] E. Fermi, Progr. Theoret Phys. (Japan) 5, 570 (1950), quoted as A; Phys. Rev. 81, 683 (1951).
[2] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. (to be published).

Statistical particle production from a thermal system

SUPPLEMENTO AL VOLUME III, SERIE X DEL NUOVO CIMENTO N. 1, 1956 1° Semestre

Hydrodynamic Theory of Multiple Production of Particles.

S. Z. BELEN'KJI and L. D. LANDAU
Institute of Physical Problems of the Academy of Sciences of the USSR - Moscow
Institute of Physics of the Academy of Sciences of the USSR - Moscow

CONTENTS. —

1. – Introduction.

It is known experimentally that in the collision of very f… large number of new particles is created (nuclear events). FERMI… the idea of using thermodynamic methods in investigating the … high-energy collision. The basic postulates of his theory are…

1) When two very fast nucleons collide the energy, in the … system, is released in a very small volume V. As the nuclea… very great and the volume small, the energy distribution will be… statistical laws. This permits to examine the collision of high-… without using any particular theory of nuclear interaction.

2) The volume V in which the energy is released is determ… mensions of the nucleon meson cloud, whose radius is of … where μ is the pion (π-meson) mass. But since the nucleons move at high velocity, the meson cloud surrounding them undergoes Lorentz contraction in the direction of the nucleon's motion. Thus, the volume will be of the order of magnitude

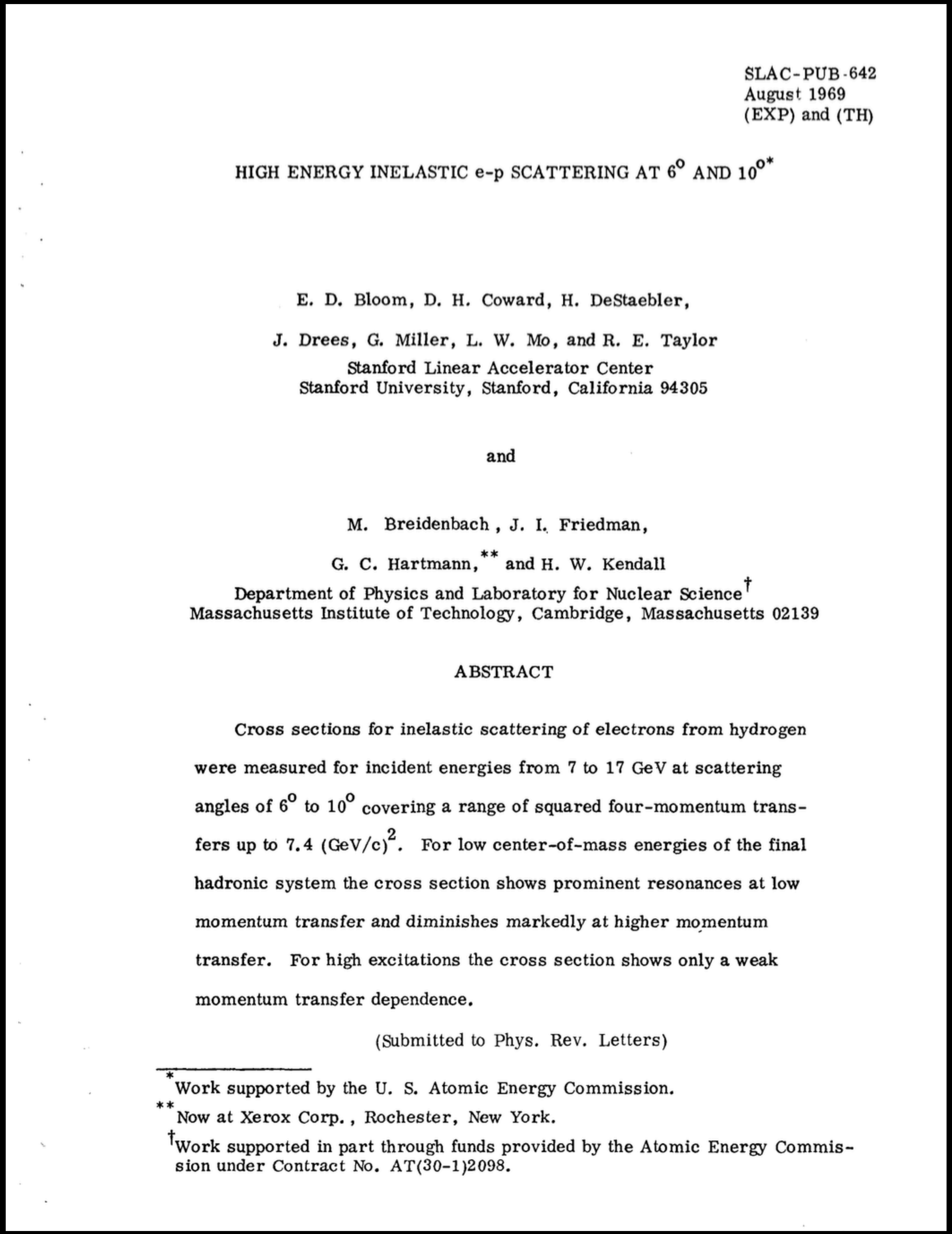
$$V=\frac{4\pi}{3}\left(\frac{\hbar}{\mu c}\right)^3\frac{2Mc^2}{E'}, \quad (1)$$

where M is the nucleons mass, and E' is the total energy of the two colliding nucleons in the center of mass system.

Hydrodynamic evolution of dense, hot system

ca.1970

Underlying degrees of freedom of strong interaction



SLAC-PUB-642
August 1969
(EXP) and (TH)

HIGH ENERGY INELASTIC e-p SCATTERING AT 6° AND 10°*

E. D. Bloom, D. H. Coward, H. DeStaebler,

J. Drees, G. Miller, L. W. Mo, and R. E. Taylor

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

and

M. Breidenbach, J. I. Friedman,

G. C. Hartmann,** and H. W. Kendall

Department of Physics and Laboratory for Nuclear Science†
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

ABSTRACT

Cross sections for inelastic scattering of electrons from hydrogen were measured for incident energies from 7 to 17 GeV at scattering angles of 6° to 10° covering a range of squared four-momentum transfers up to 7.4 $(\mathrm{GeV}/c)^2$. For low center-of-mass energies of the final hadronic system the cross section shows prominent resonances at low momentum transfer and diminishes markedly at higher momentum transfer. For high excitations the cross section shows only a weak momentum transfer dependence.

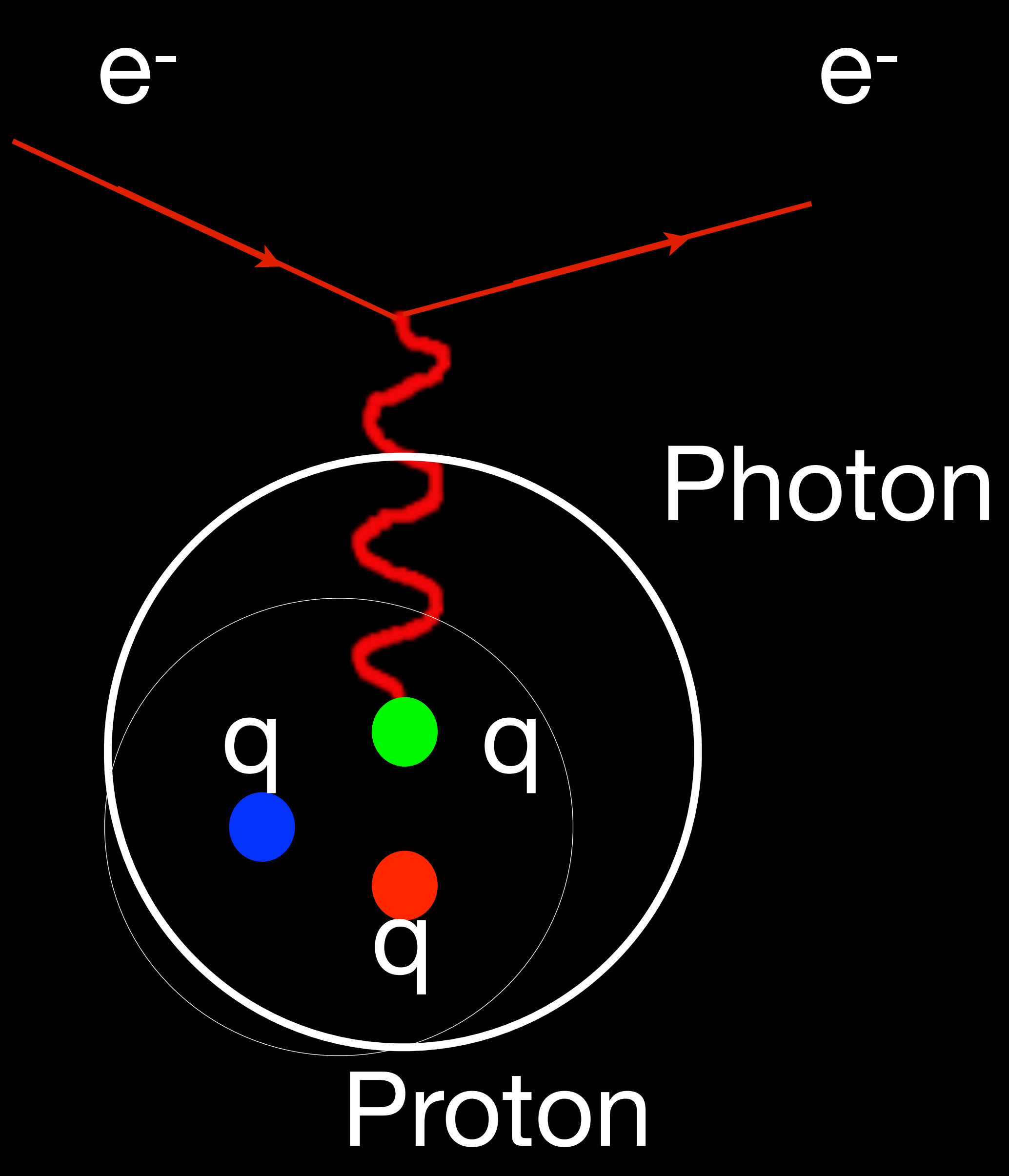
(Submitted to Phys. Rev. Letters)

*Work supported by the U. S. Atomic Energy Commission.

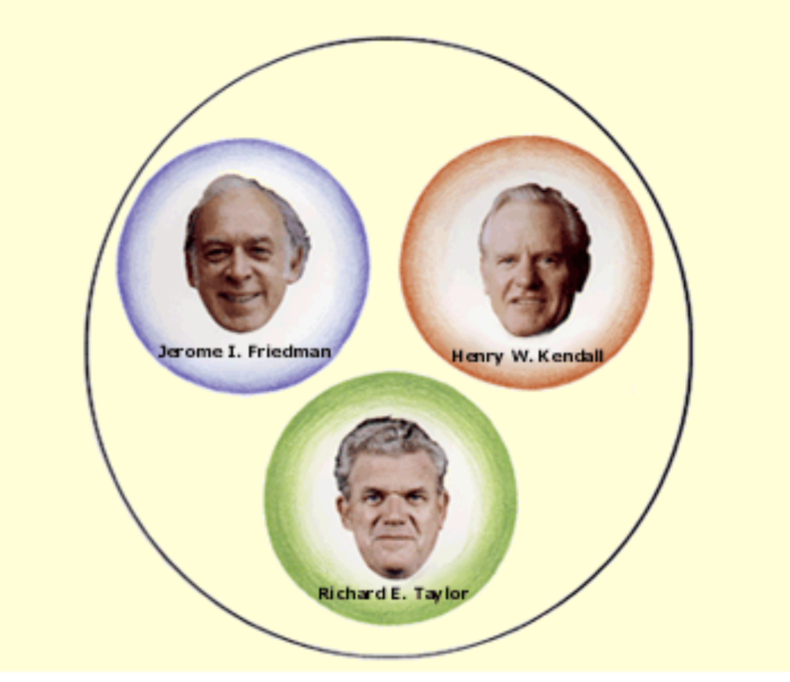
**Now at Xerox Corp., Rochester, New York.

†Work supported in part through funds provided by the Atomic Energy Commission under Contract No. AT(30-1)2098.

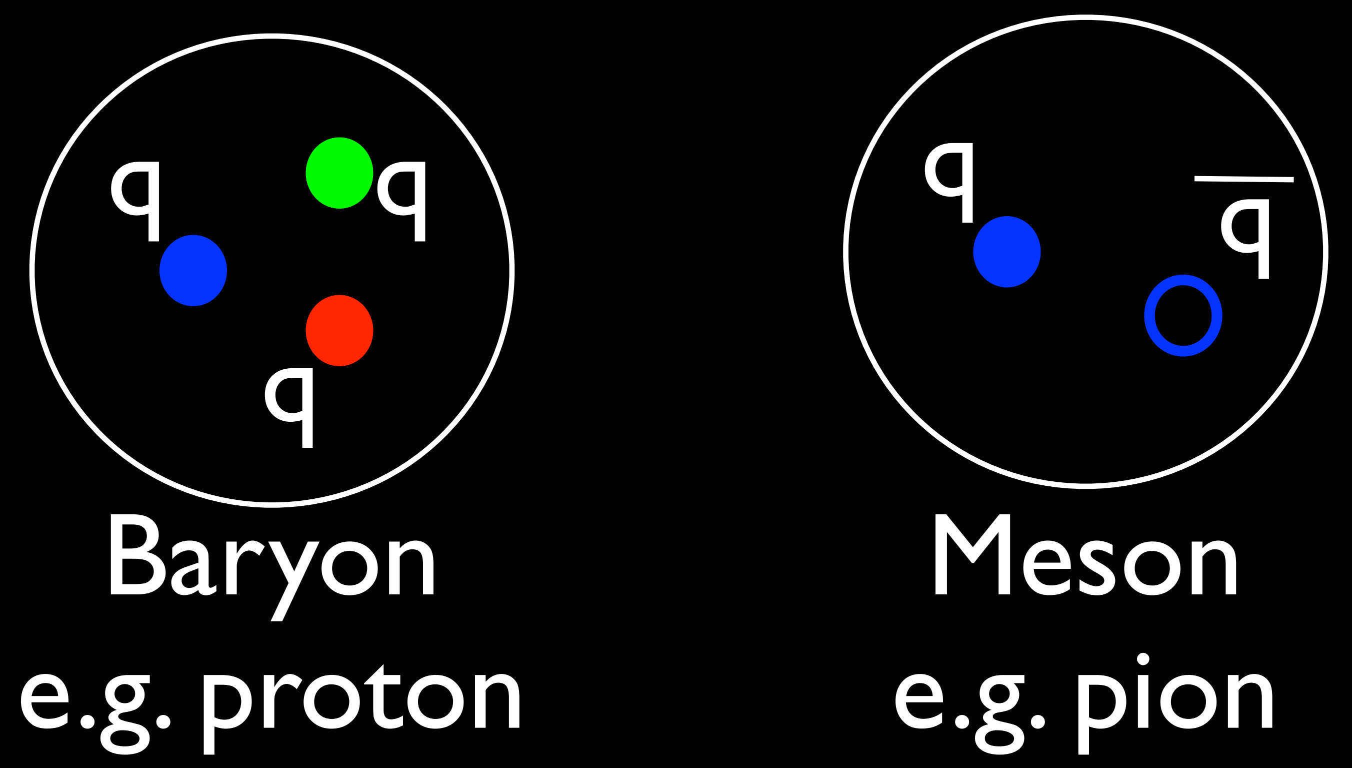
late 1960's

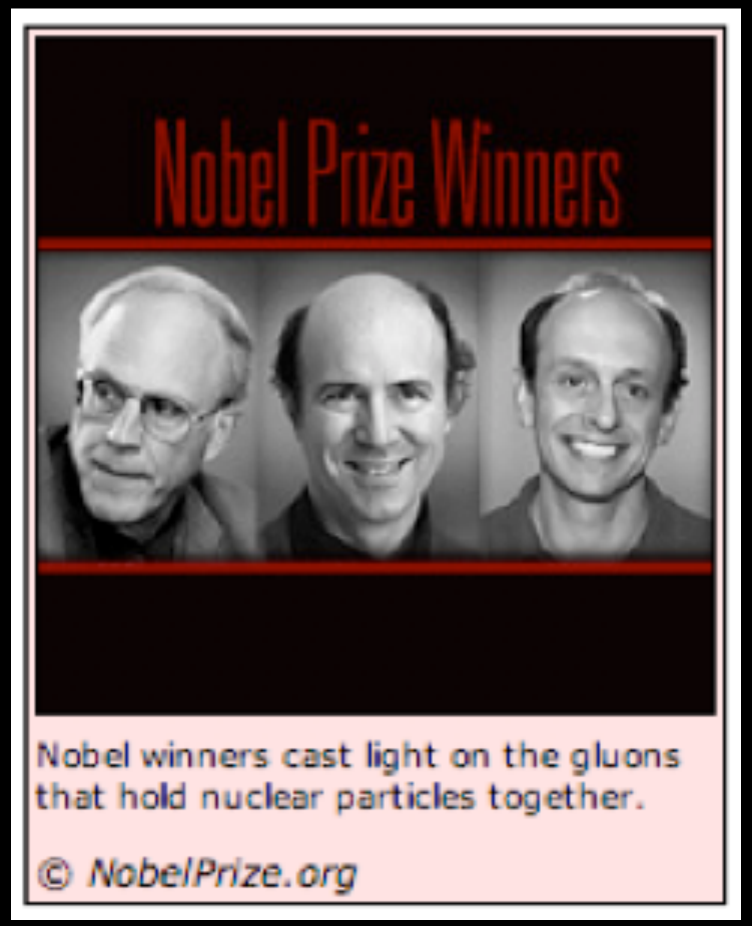


1990 Nobel Prize to
Jerry Friedman (MIT), Henry Kendall (MIT),
Richard Taylor (SLAC)



Hadrons are composite particles

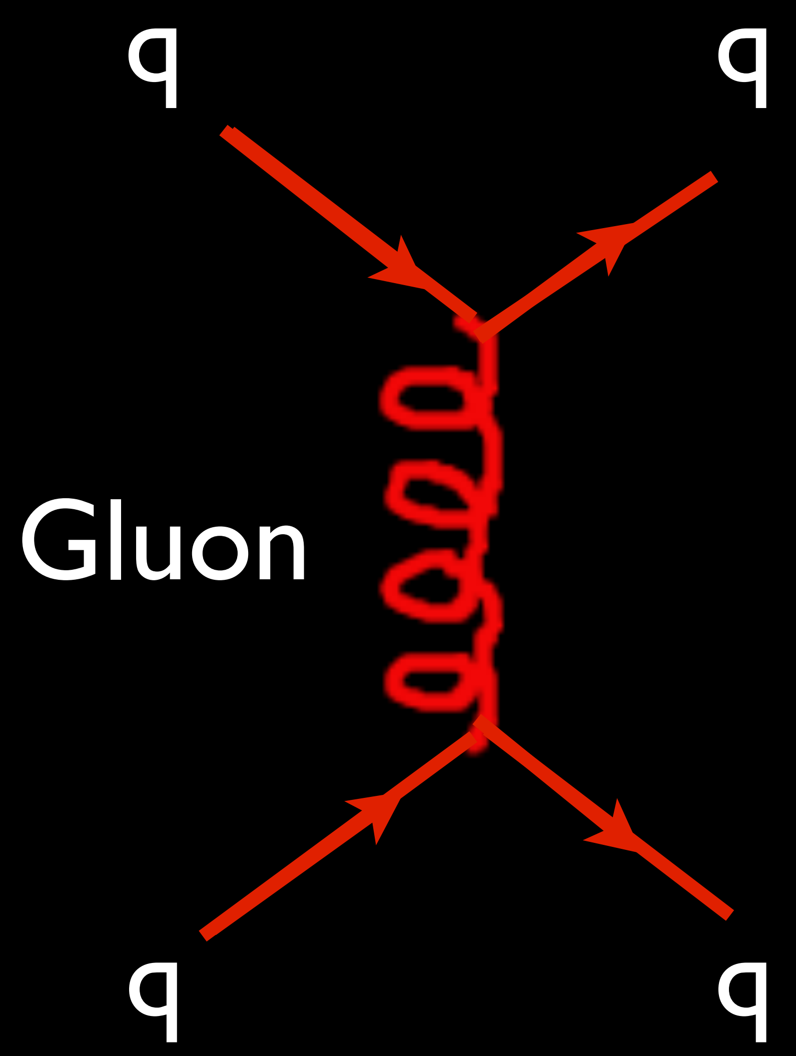




Quantum Chromodynamics theory (early 1970's)

- QFT like QED
- Point-like fermions (Quarks)
- Massless bosons (Gluons)

Quarks **and** gluons carry 'Color' charge



Colored particles can not propagate through the vacuum: **Confinement** bers of these bands are also plotted. Comparison of experiment with theory suggests that the 2.87-MeV state is likely the 3^- member of the 1^- band and that the new member of the 2.97-MeV doublet is likely the 4^- member of the 2^- band. The comparison also suggests that either the 3.59- or 3.68-MeV state is the 4^+ member of the 1^+ band, with perhaps a slight preference for the 3.59-MeV level.

Clearly, one or both members of the 4.20-MeV doublet have high spin. In any case, one member must have $J^\pi \geqslant 4^-$ or $\geqslant 5^+$. Thus a state here is a candidate for identification as the 4^- member of the 1^- band or the 5^- member of the 2^- band, or the 5^+ member of the 1^+ band or the 6^+ or 7^+ member of the 2^+ band. If one member is 4^-, the other is probably 5^-, 6^+, or 7^+, while if one is 5^-, the other is probably either 4^-, 4^+, 5^+, or 6^+. It is thus very likely that one of the members of this doublet is a 6^+ state.

The 4.51-MeV state appears to be a good candidate for the 4^- member of the 1^- band, or the 6^+ member of the g.s. band. One of the members of the 4.6-MeV doublet may be the 5^- member of the 2^- band, or the 5^+ member of the 1^+ band, or the 7^+ member of the g.s. band. If the 7^+ state is not contained in the 4.20-MeV doublet, then one of the 4.6-MeV states is the only other good candidate below 5 MeV. However, if the two 4.6-MeV states have comparable spins, then neither need be larger than 3. The 4.73- and 4.76-MeV states are candidates for either the 4^- member of the 1^- band, or the 5^+ member of the 1^+ band, or the 6^+ member of the g.s. band. If one of the 4.9-MeV states has low spin, the other might be the 5^+ member of the 1^+ band. Clearly, the γ decays of these levels must be studied in order to pin down their spins. But the present reaction provides a powerful tool for determining which states may have high spin.

†Work supported by the National Science Foundation.

*Present address: Center for Nuclear Studies, University of Texas, Austin, Tex. 78712.

[1]E. C. Halbert, J. B. McGrory, B. H. Wildenthal, and S. P. Pandya, in *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum, New York, 1971), Vol. 4, p. 315.
[2]B. H. Wildenthal, private communication.
[3]J. B. McGrory and B. H. Wildenthal, Phys. Rev. C 7, 974 (1973).
[4]F. Ajzenberg-Selove, Nucl. Phys. A190, 1 (1972).
[5]R. R. Betts, H. T. Fortune, and R. Middleton, Phys. Rev. C 8, 660 (1973).
[6]R. R. Carlson and R. L. McGrath, Phys. Rev. Lett. 15, 173 (1965).
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[9]H. T. Fortune and H. G. Bingham, Phys. Rev. C 10, 2174 (1974).
[10]H. T. Fortune and R. R. Betts, Phys. Rev. C 10, 1292 (1974).
[11]D. J. Crozier and H. T. Fortune, Phys. Rev. C 10, 1697 (1974).

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

There are several astrophysical and cosmological situations where one needs the equation of state for matter of densities greater than 10^{15} g cm^{-3}: in particular, the center of a neutron star,[1,2] the early phases of the big-bang universe,[3] and black-hole explosions.[4] However, such densities might at first sight appear to be outside the range of normal physics, so that nothing can

Deconfined quarks as DOFs of superdense matter

QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

QCD calculations of the production rate in a quark–gluon plasma and account of the space–time picture of hadronic collisions lead to estimates of the dilepton mass spectrum, $p_\perp$ distributions of $e^\pm$, $\mu^\pm$, γ, $\pi^\pm$, production cross sections of charm and psions.

Hadronic reactions, taking place at small and large distances, are treated on quite different theoretical grounds. While the former are well described by the parton model based on asymptotic freedom of QCD, the latter are still discussed in more phenomenological way. I should like to argue in this paper, that a very important intermediate region exists, namely reactions taking place far from the collision point and not obeying the parton model, but at the same time treatable by perturbative QCD methods. This region corresponds to production of particles with mass M or transverse momentum $p_\perp$ such that 1 GeV $\lesssim M, p_\perp \ll \sqrt{s}$ ($\lesssim$ 4–5 GeV at ISR energies).

The best known example is dilepton production ($\mu^+\mu^-$, e^+e^-), in which deviations from the Drell–Yan model [1] for dilepton mass $M \lesssim 5$ GeV reach a factor 10^1–10^2. Bjorken and Weisberg [2] proposed a qualitative explanation for it: such pairs are produced at later stages of the collision, when antiquarks are more numerous and can interact repeatedly. Much earlier, Feinberg [3] ascribed them to the charge-current fluctuations in the hydrodynamical model [4] and also stressed the importance of the space–time aspect of the problem.

We assume that in hadronic collisions after some time a *local* [7] *thermal equilibrium* is established in the sense that all properties are determined by a single parameter, the temperature T, depending on time and coordinates. The schematic space–time picture of the collisions is shown in fig. 1. We are interested in the final state interaction region, limited by two lines: $T(x, t) = T_i$, the initial temperature at which the thermodynamical description becomes reasonable, and $T(x, t) = T_f \sim m_\pi$, where the system breaks into secondaries [4,7]. The medium is assumed to be the quark–gluon

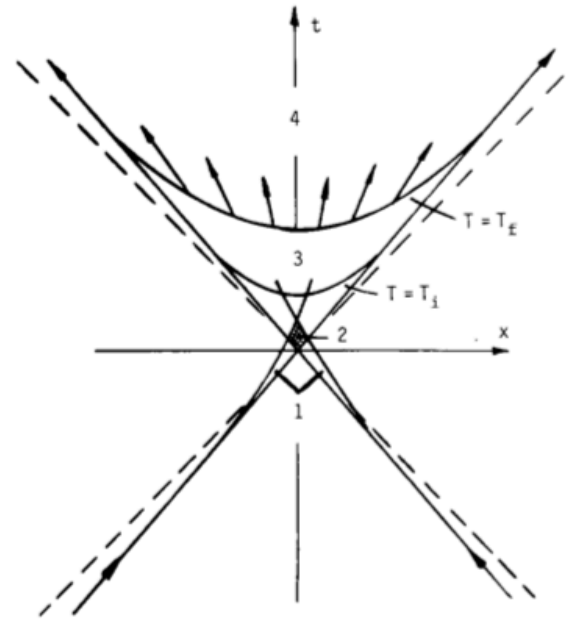
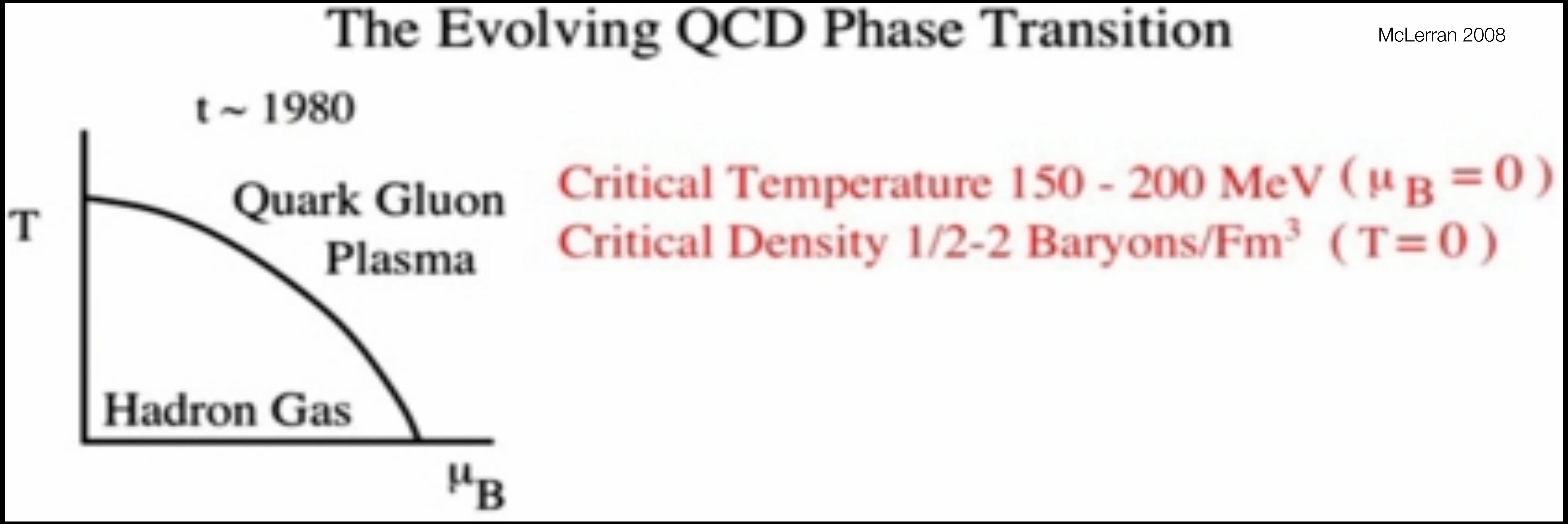


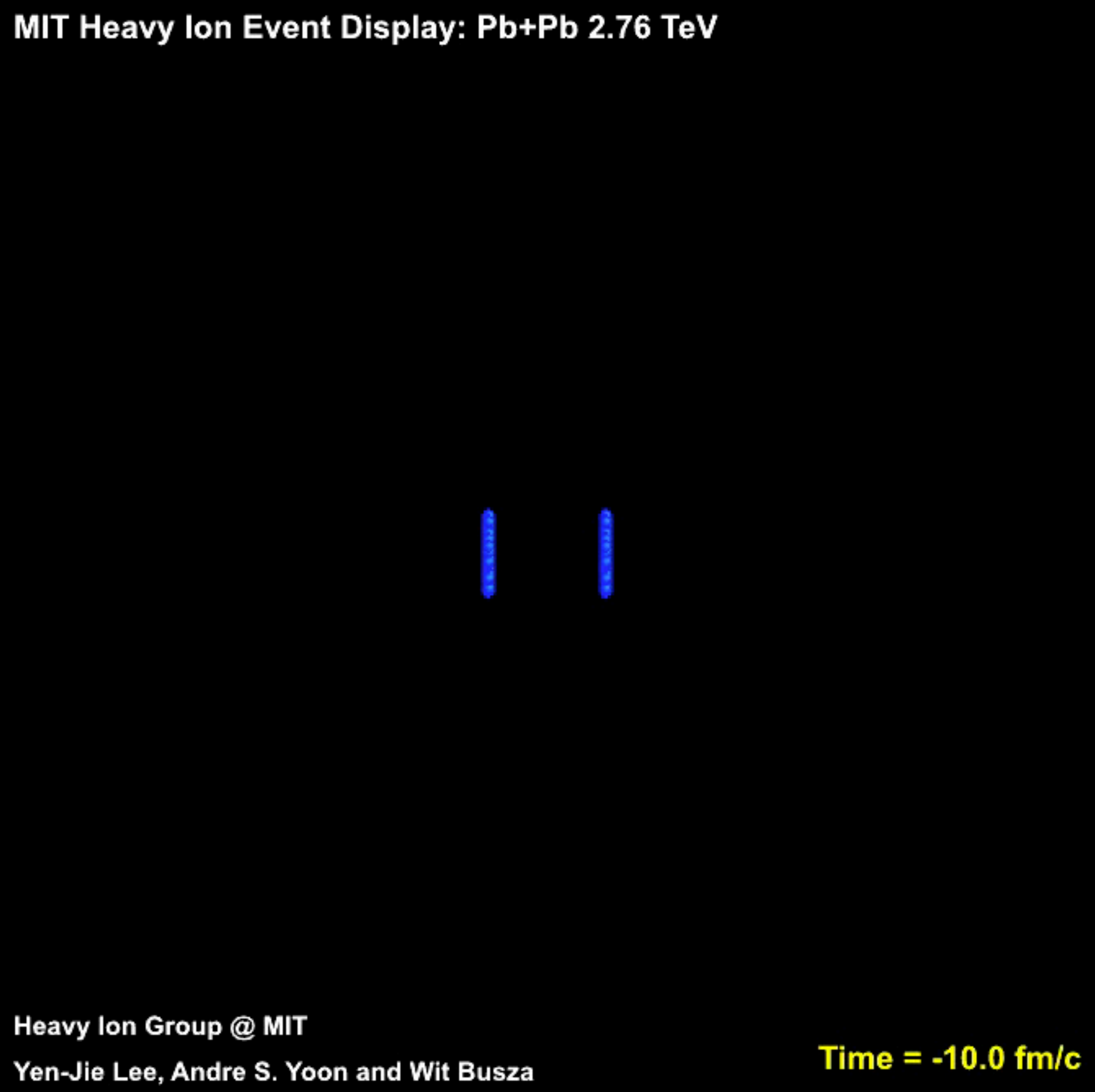
Fig. 1. The space–time picture of hadronic collisions, proceeding through the following stages: (1) structure function formation; (2) hard collisions; (3) final state interaction; (4) free secondaries.

Space-time structure of Quark-Gluon Plasma

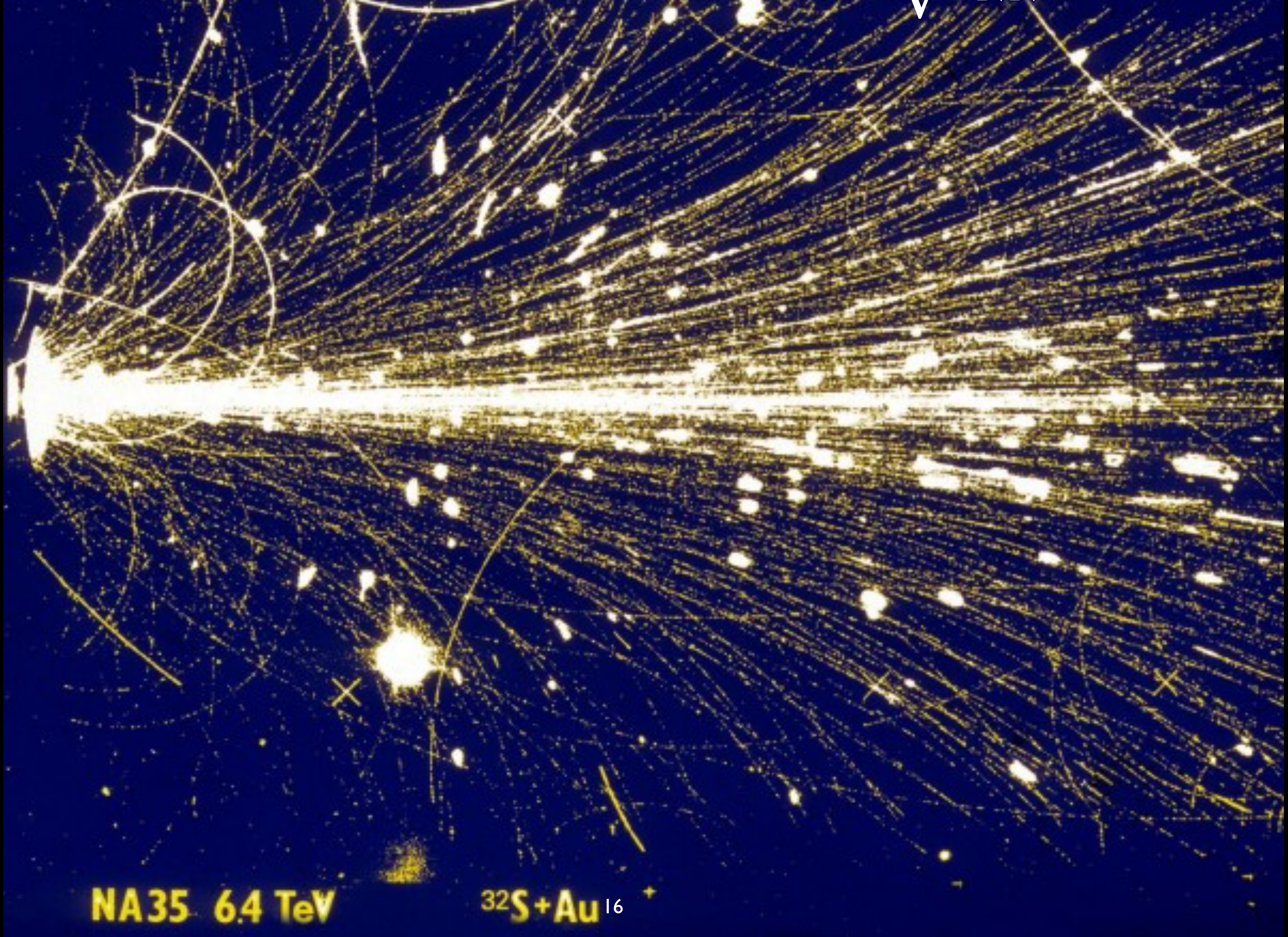


Can we observed this phase transition
in experiment and study its nature?

1980s

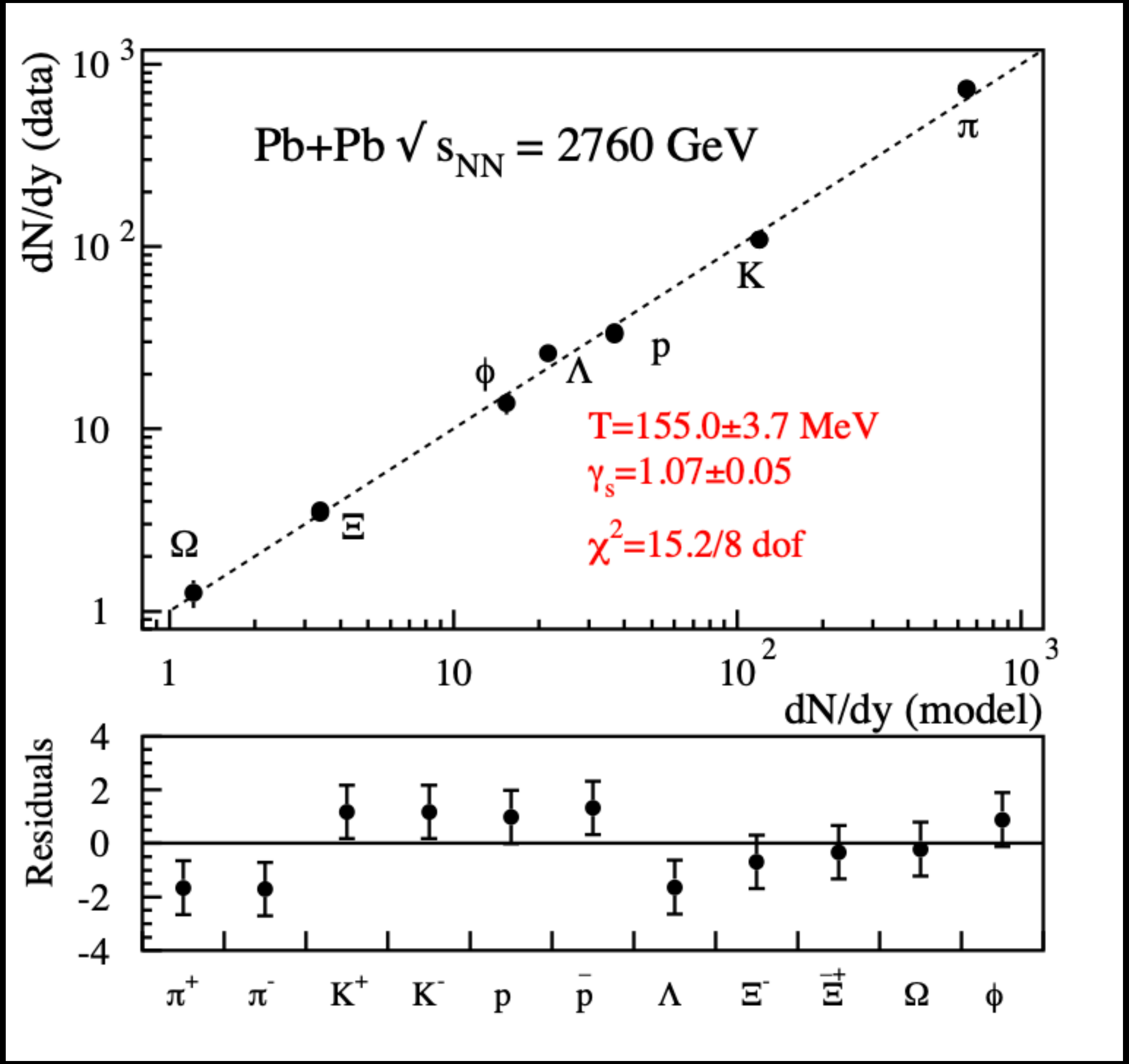

MIT Heavy Ion Event Display: Pb+Pb 2.76 TeV
Heavy Ion Group @ MIT
Yen-Jie Lee, Andre S. Yoon and Wit Busza
Time = -10.0 fm/c

AGS and SPS fixed target programs @ $\sqrt{s_{NN}} \approx$ 2-20GeV



Statistical model of particle production

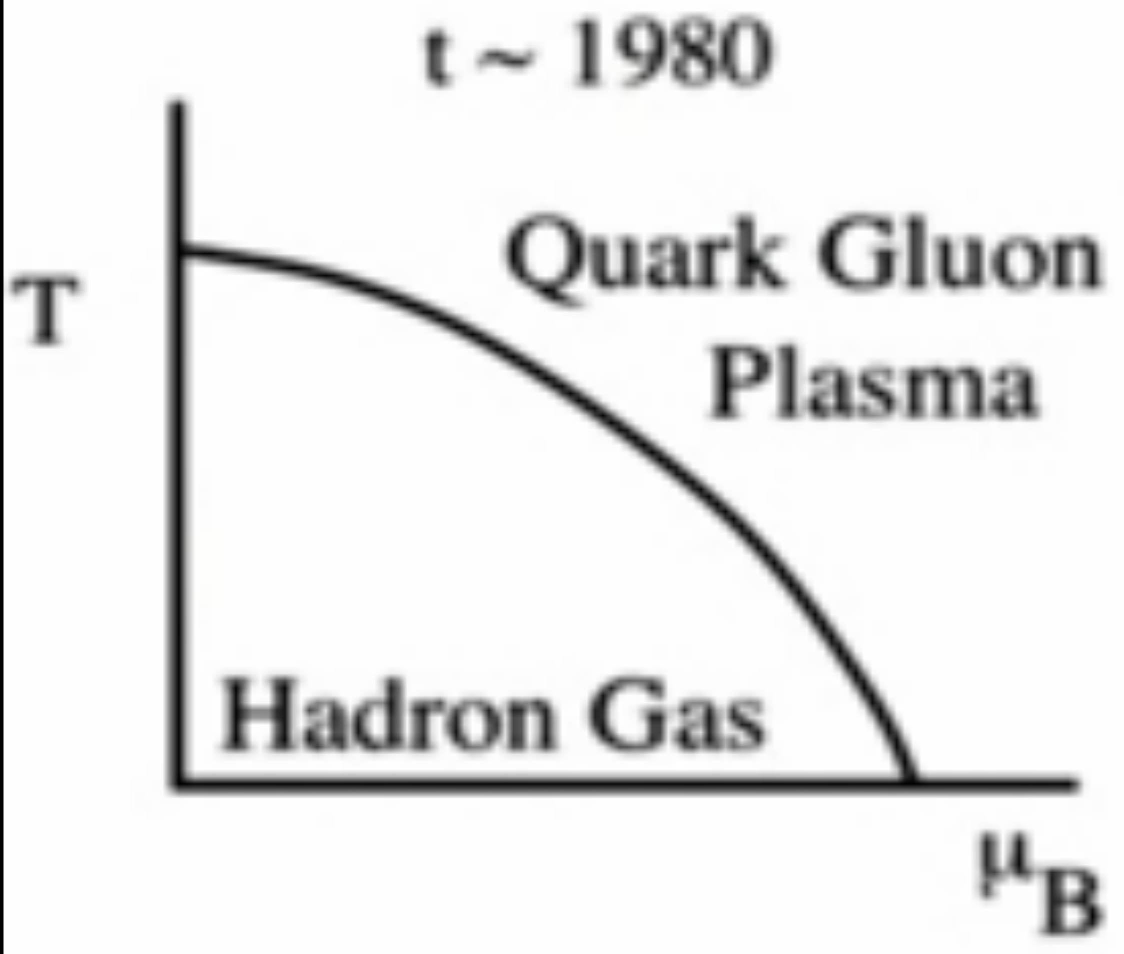
Becattini et al (2004)



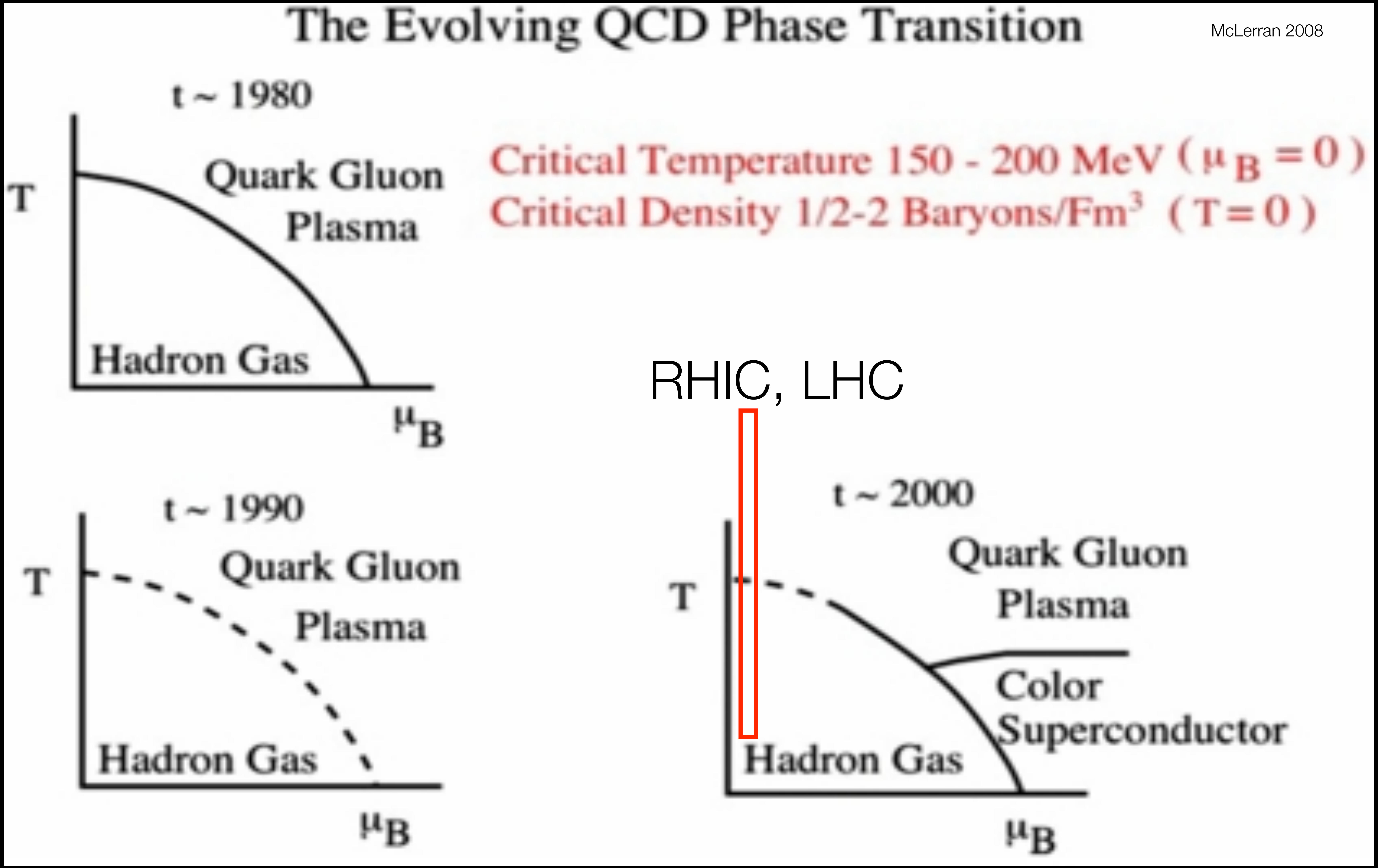
Relative yields of hadrons consistent with global thermal equilibrium at T ~160MeV

The Evolving QCD Phase Transition

McLerran 2008



Critical Temperature 150 - 200 MeV ($\mu_B = 0$)
Critical Density 1/2-2 Baryons/Fm^3 ($T = 0$)

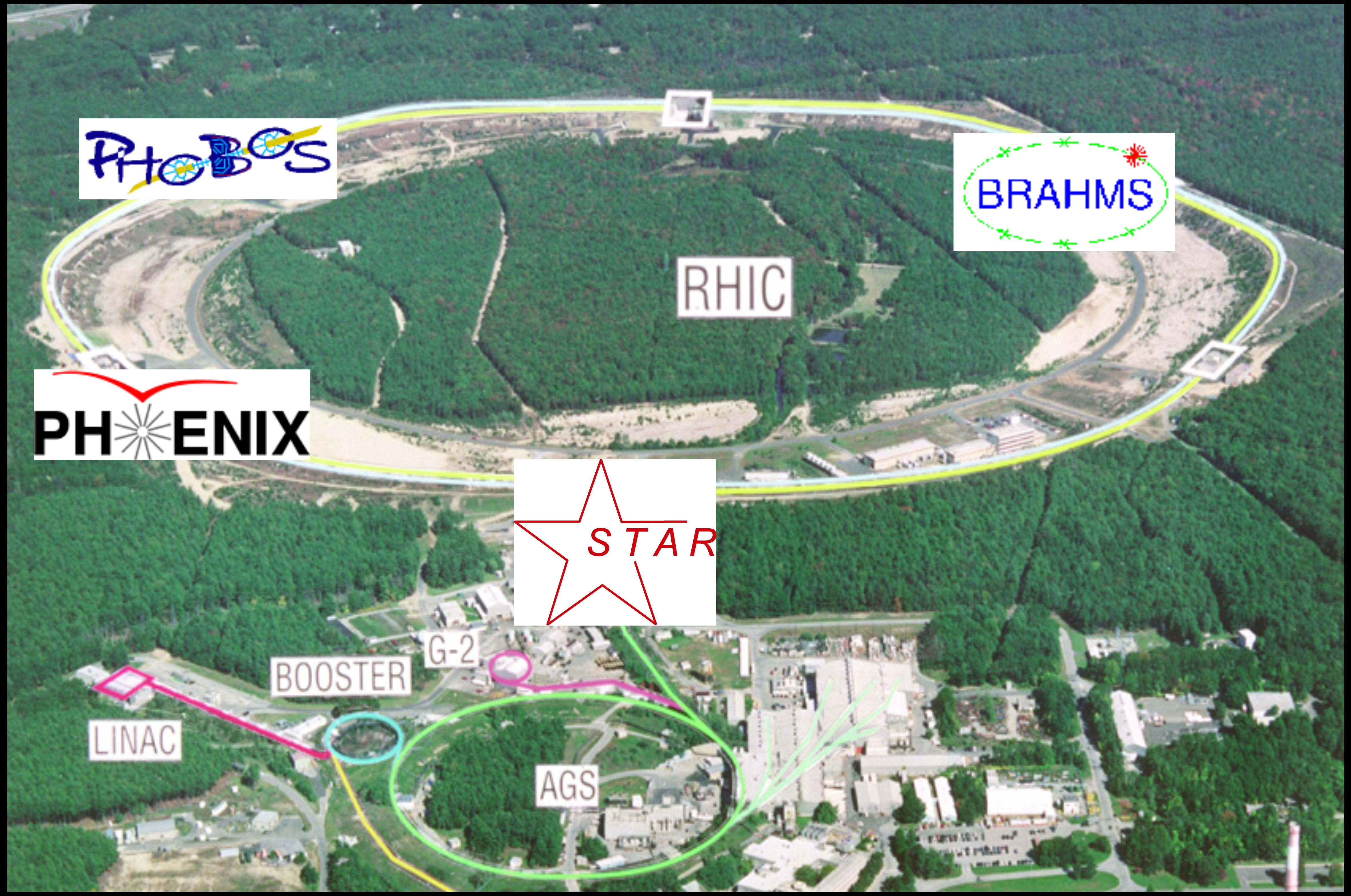


Nature of phase transition? → Nature of matter above T_C?

2000

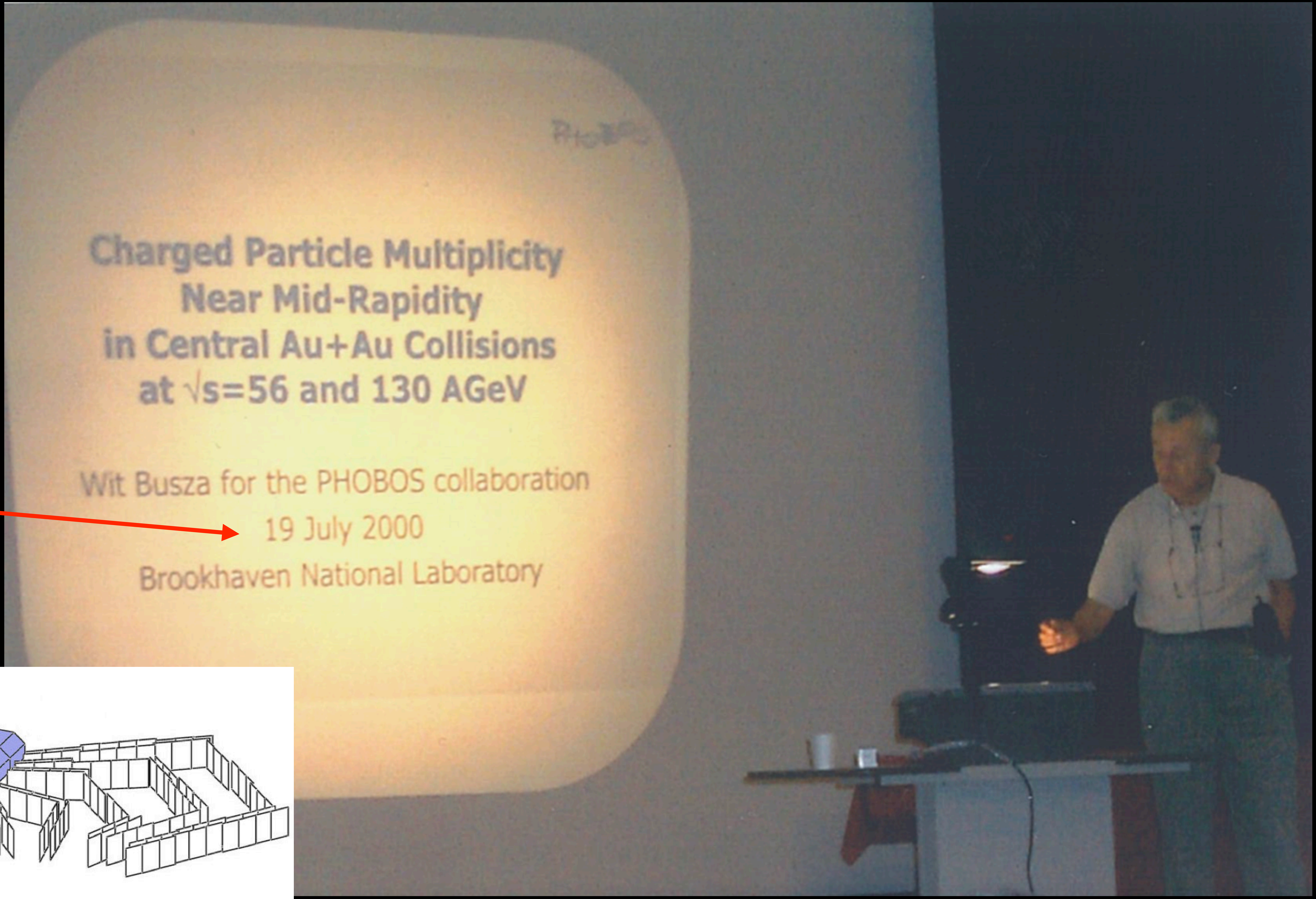
First Heavy Ion Collider

RHIC

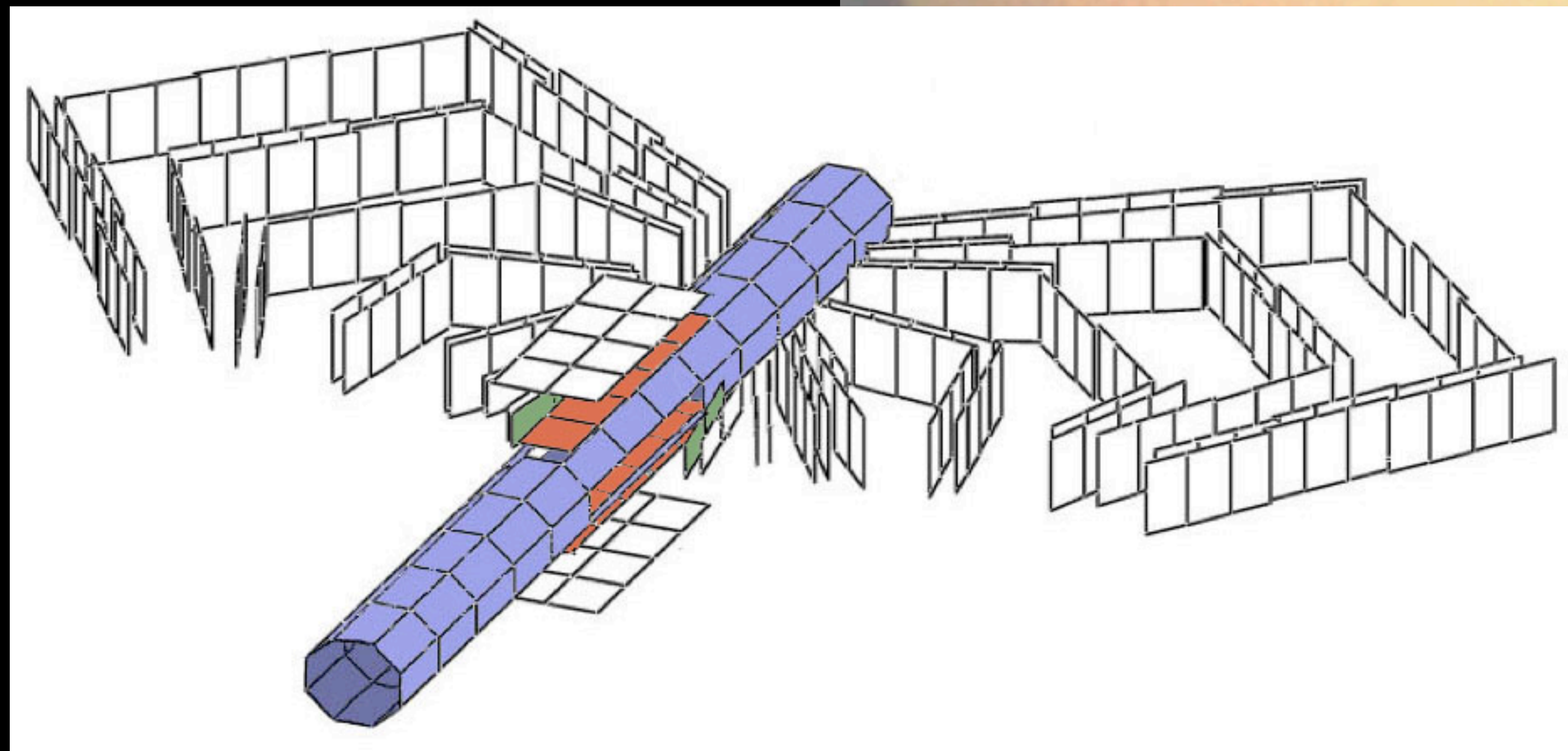


First Au beams in 2000
Top energy $\sqrt{s_{NN}} = 0.2$TeV

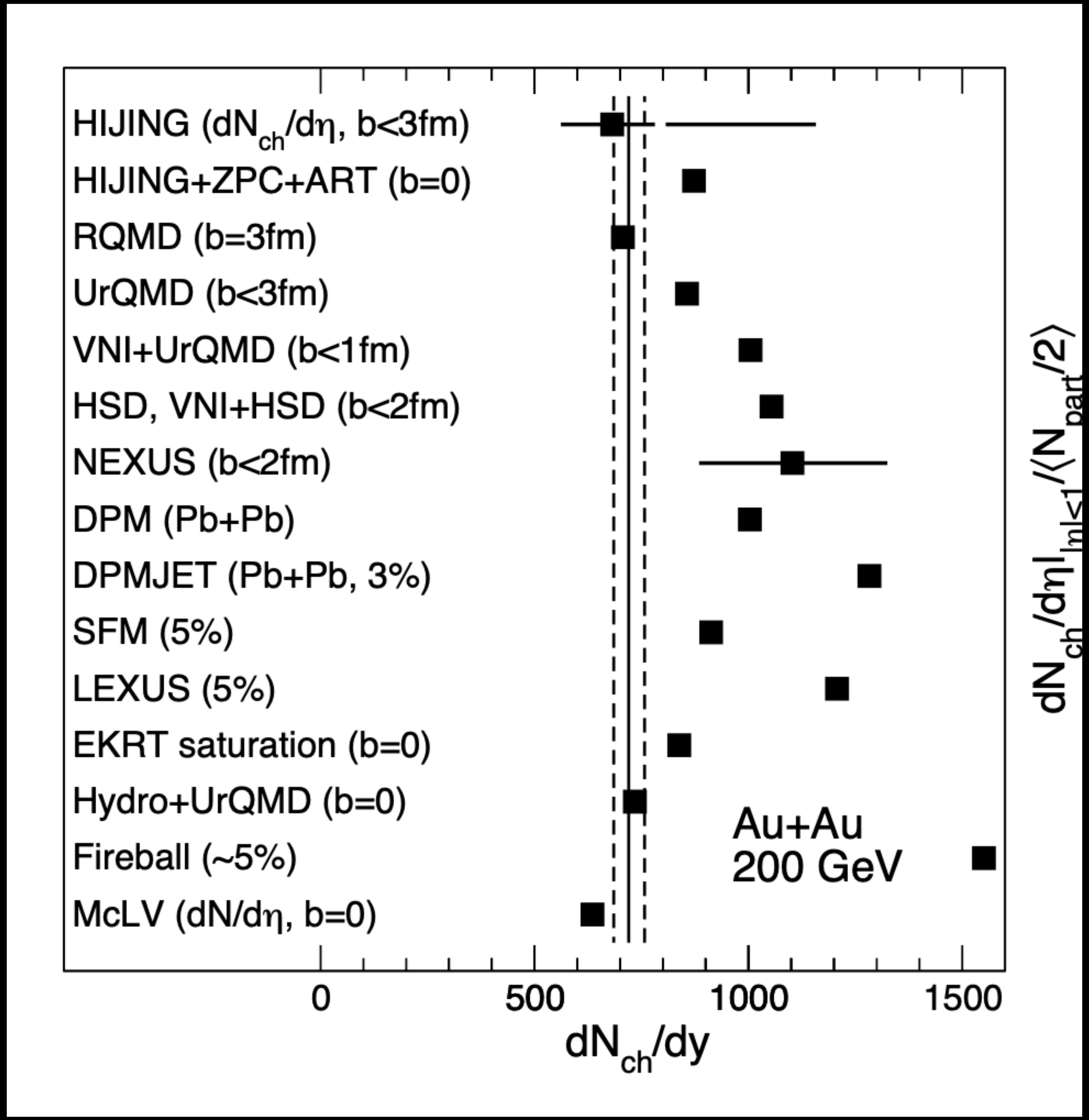
Wit Busza presents first physics results at RHIC



First collisions:
June 12, 2000

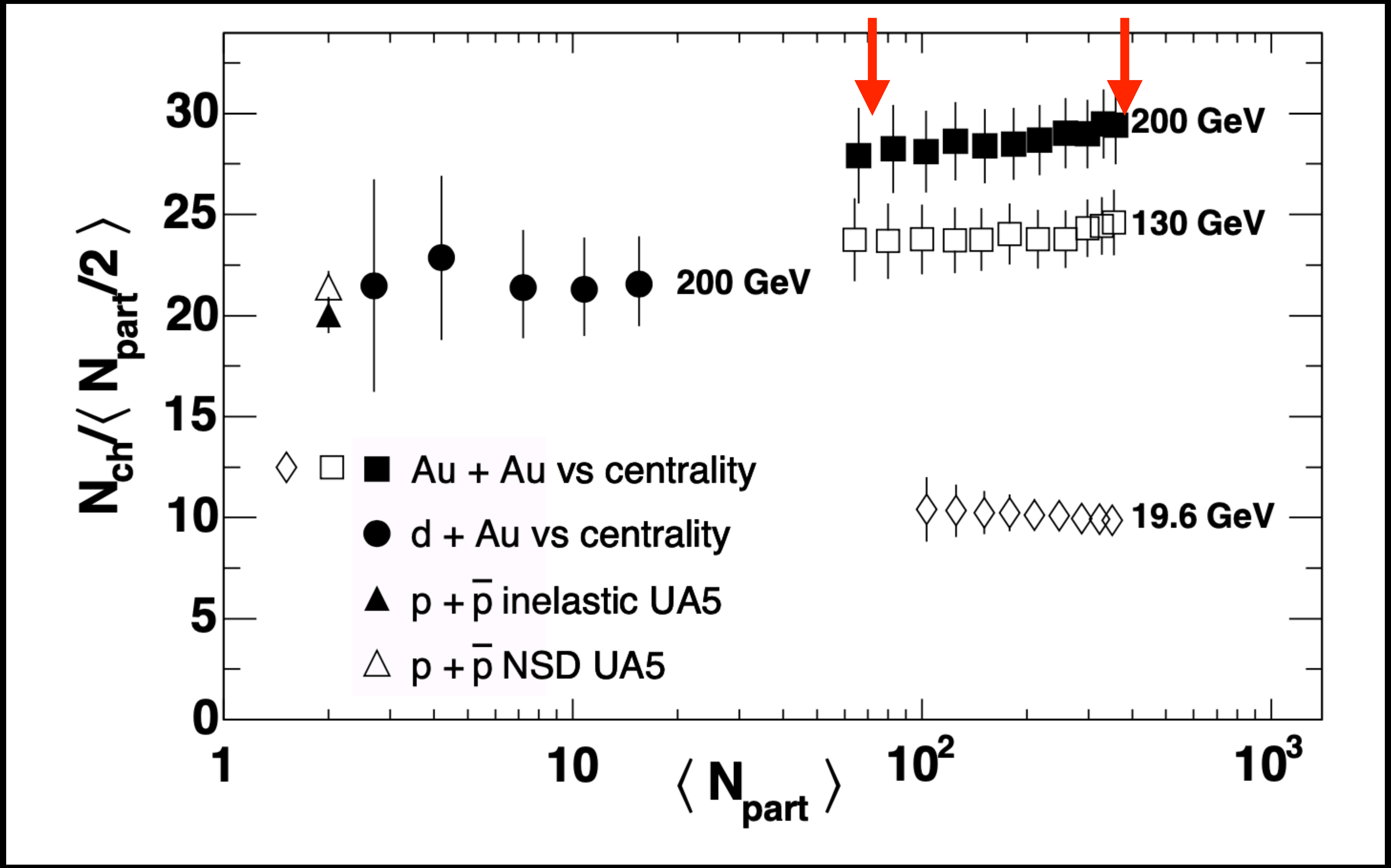


First surprise at RHIC



Multiplicity much lower than expected in most models

$\nu \approx 1$ $\nu \approx 6$

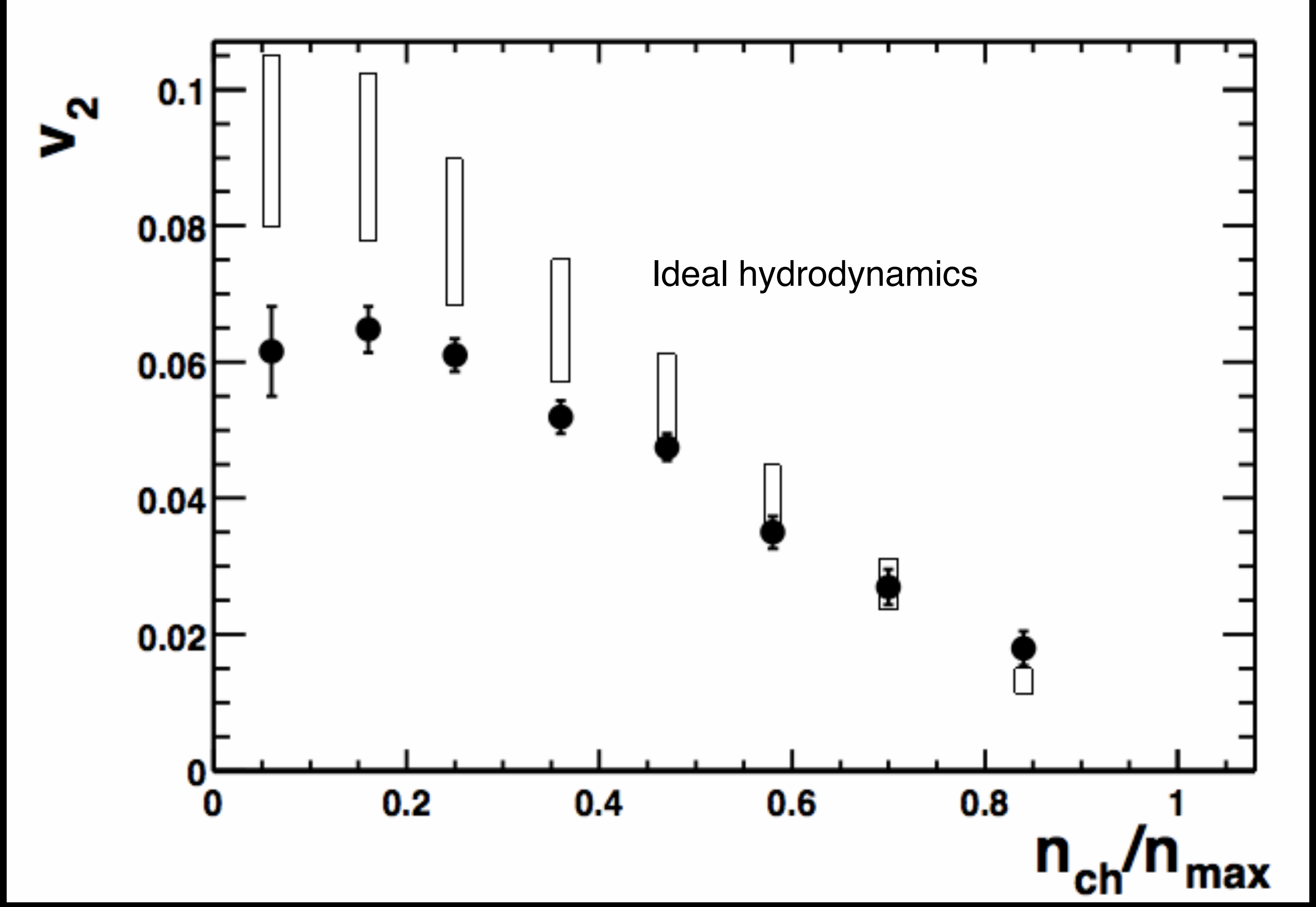


Centrality dependence much weaker than expected

Particles are not produced independently: Parton saturation

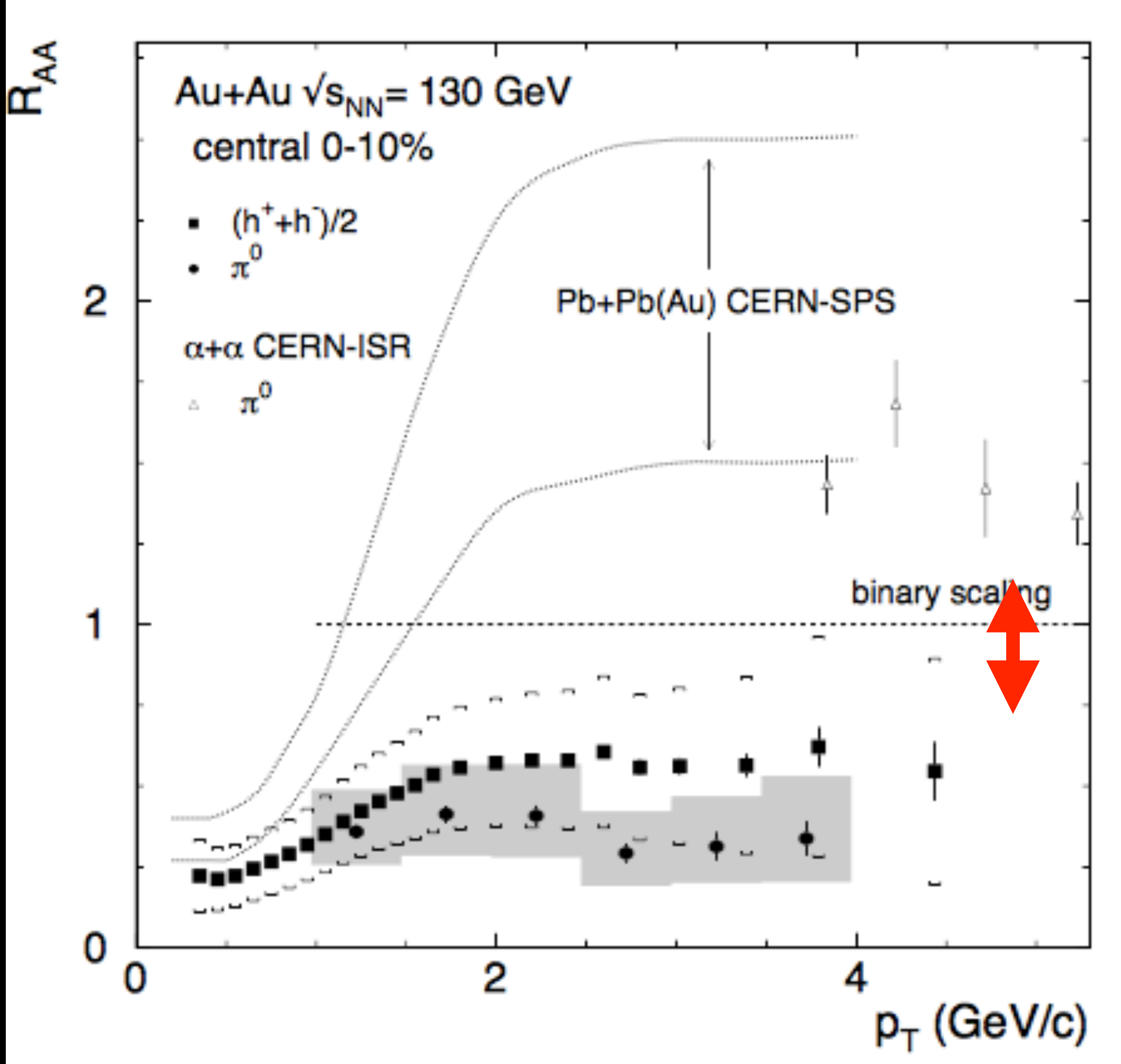
Two early discoveries

STAR PRL (2001)



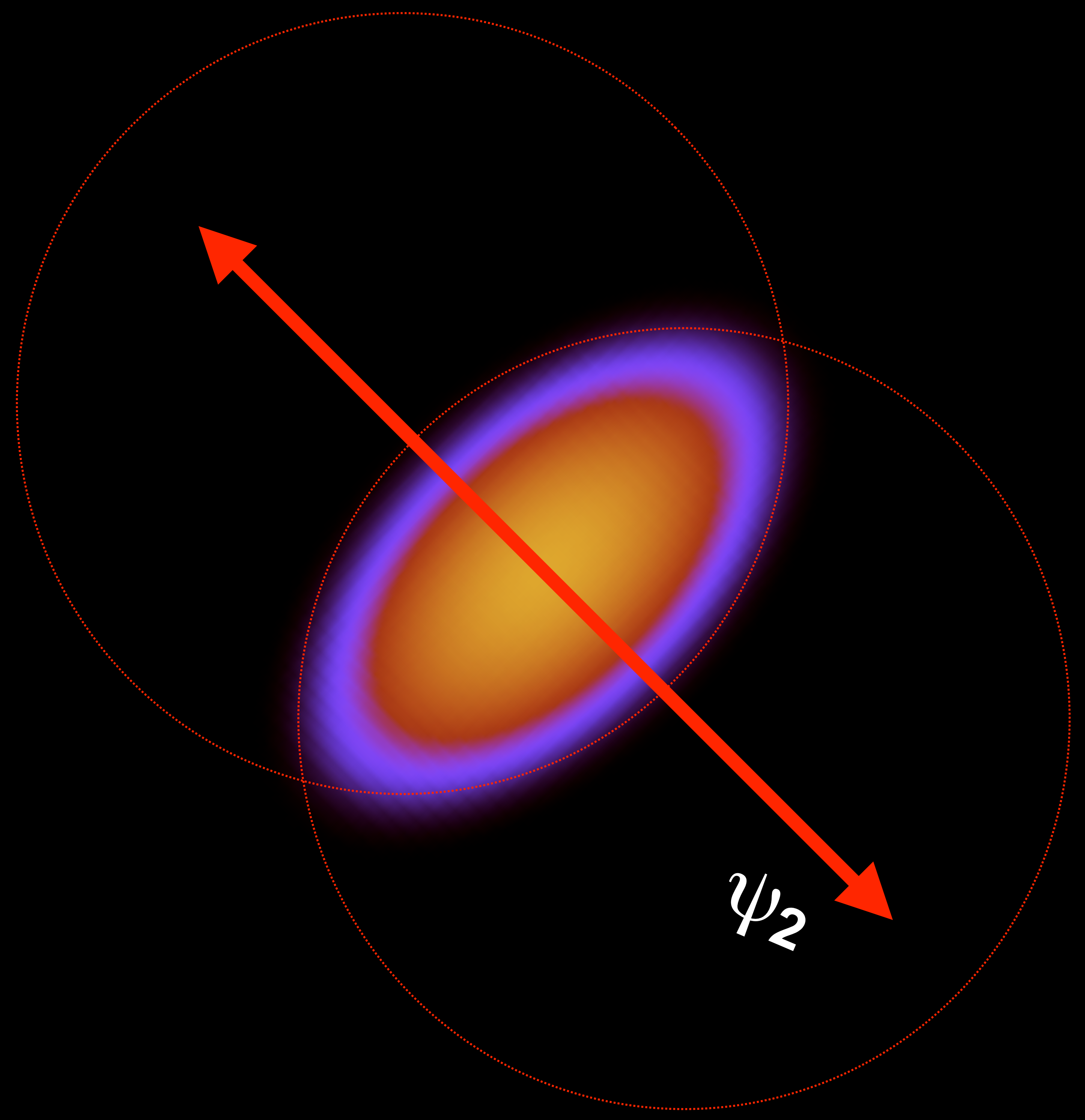
Strong azimuthal anisotropy in particle production (“**Elliptic Flow**”) reaching limit obtained in ideal hydrodynamics

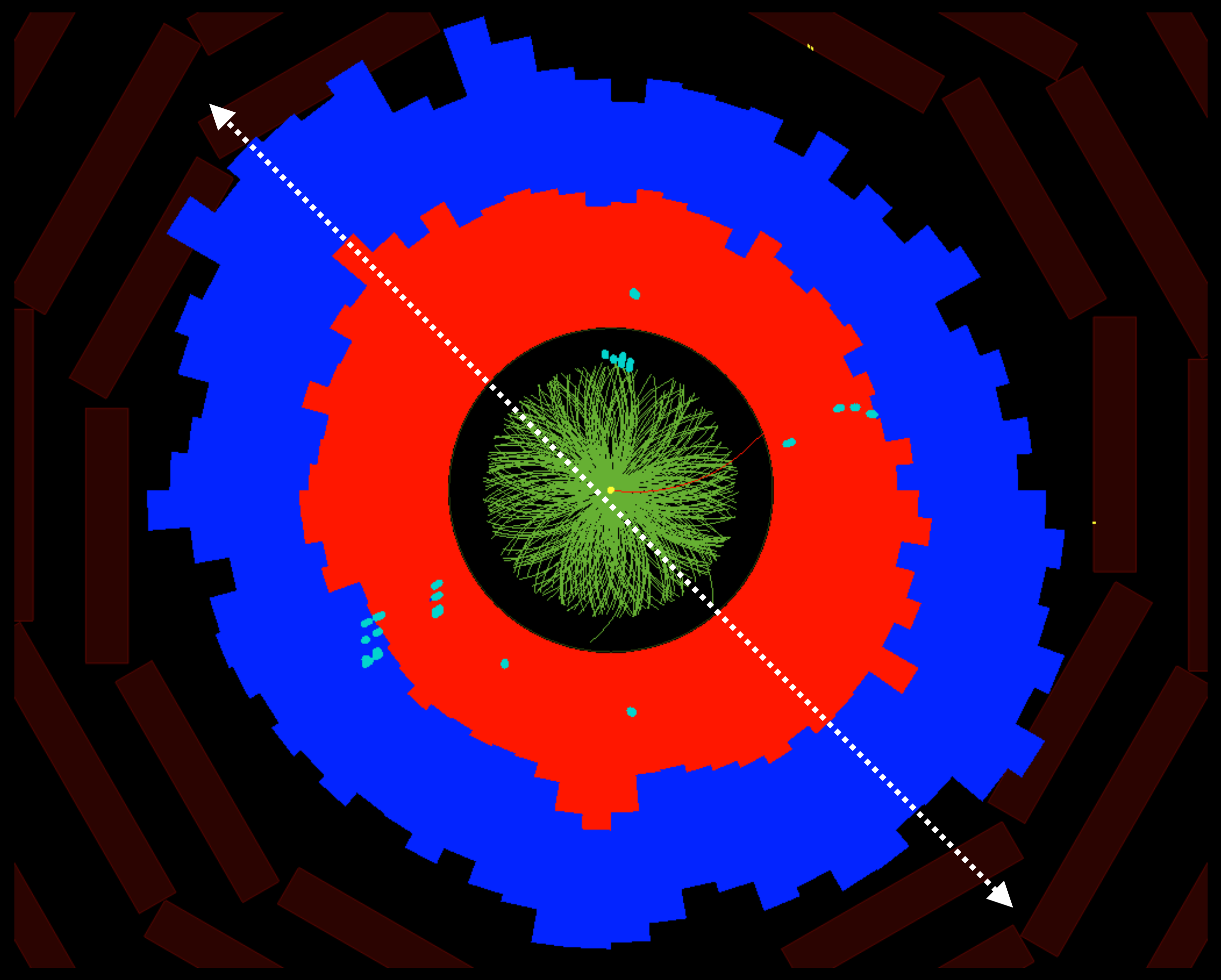
PHENIX PRL (2001)



Suppression of high-p_T particle production vs pp: **Jet Quenching**

Pressure driven hydrodynamic expansion





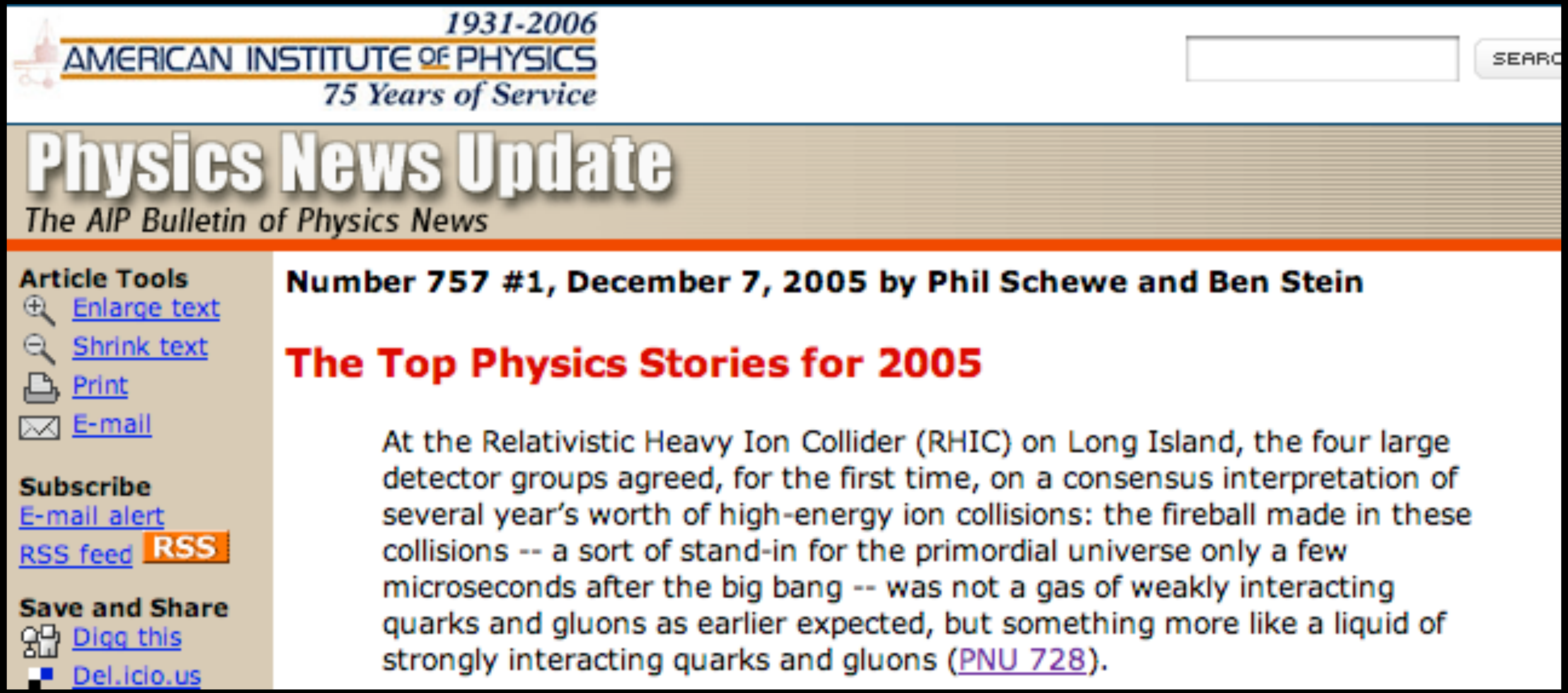
Initial nuclear overlap defines direction
(anisotropic pressure gradients)

Final state momentum distribution
reflects initial overlap geometry

Hydrodynamic expansion translates initial configuration space
anisotropy into final state momentum distribution

ca. 2005

"Something more like a liquid"



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Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

The Top Physics Stories for 2005

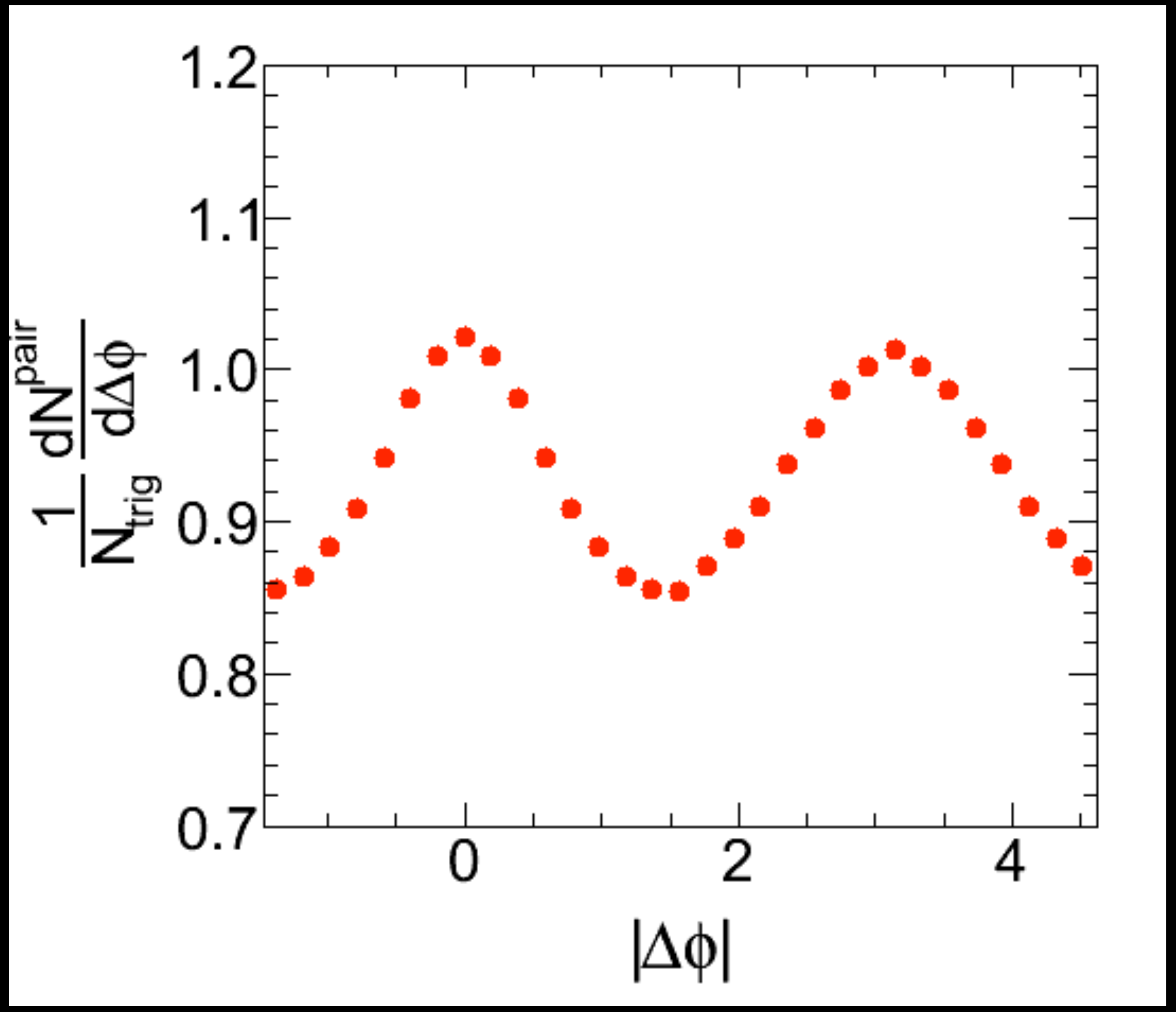
At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

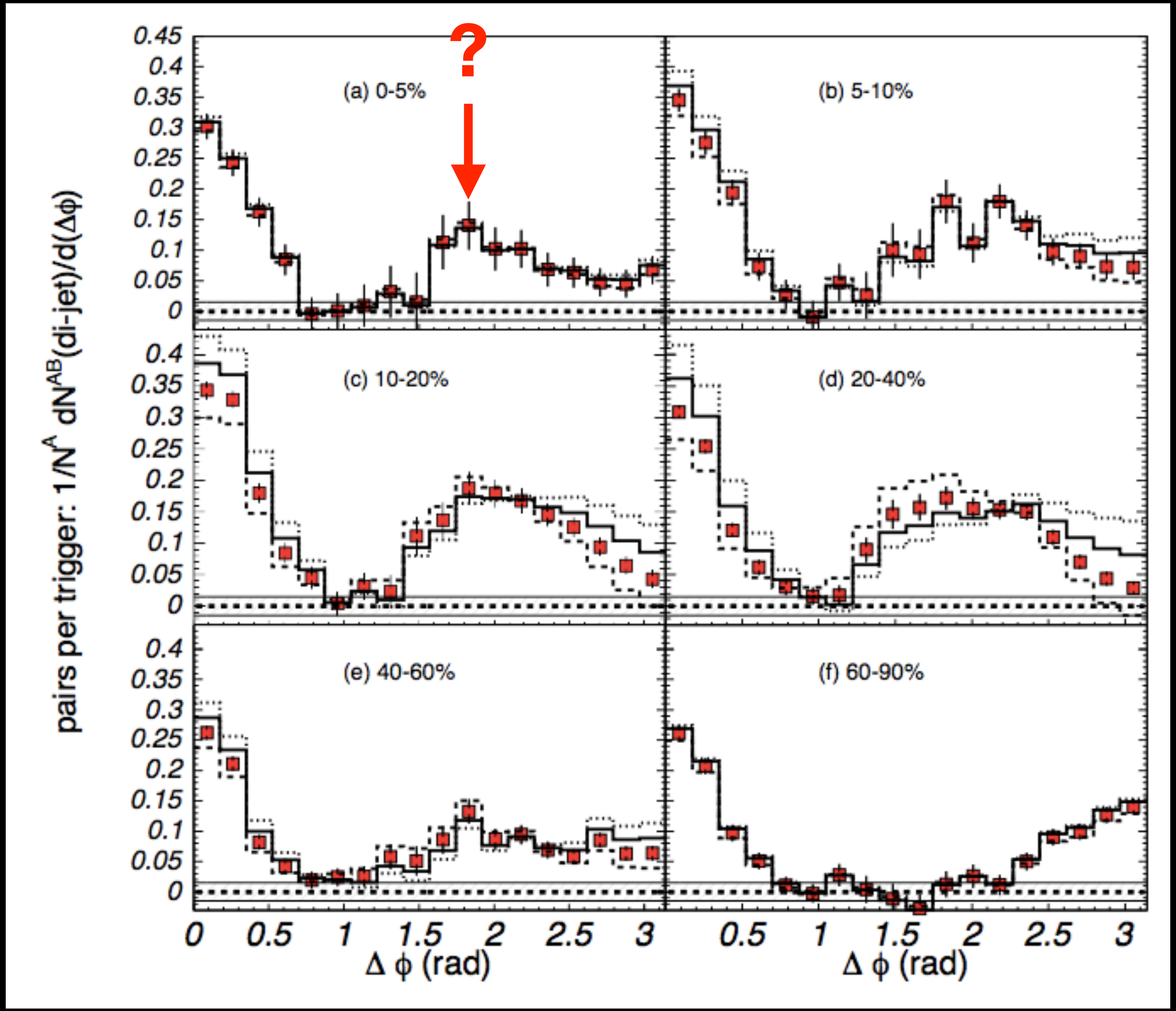
"...the fireball made in these [heavy-ion] collisions...was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid..."

based on Whitepapers by BRAHMS, PHENIX, PHOBOS and STAR collaborations at RHIC

Discovery of Mach cones?

PHENIX, STAR (2005)



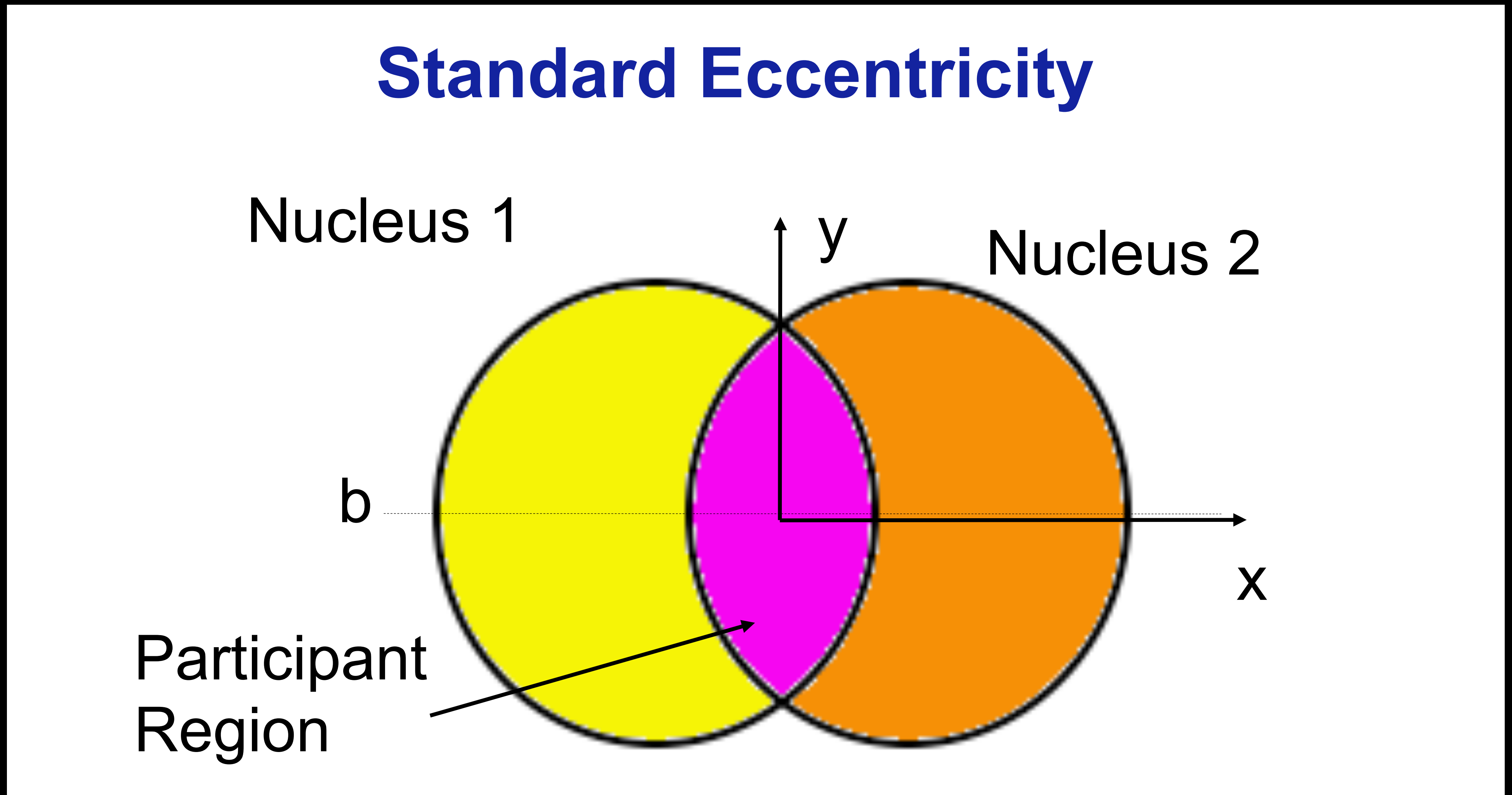


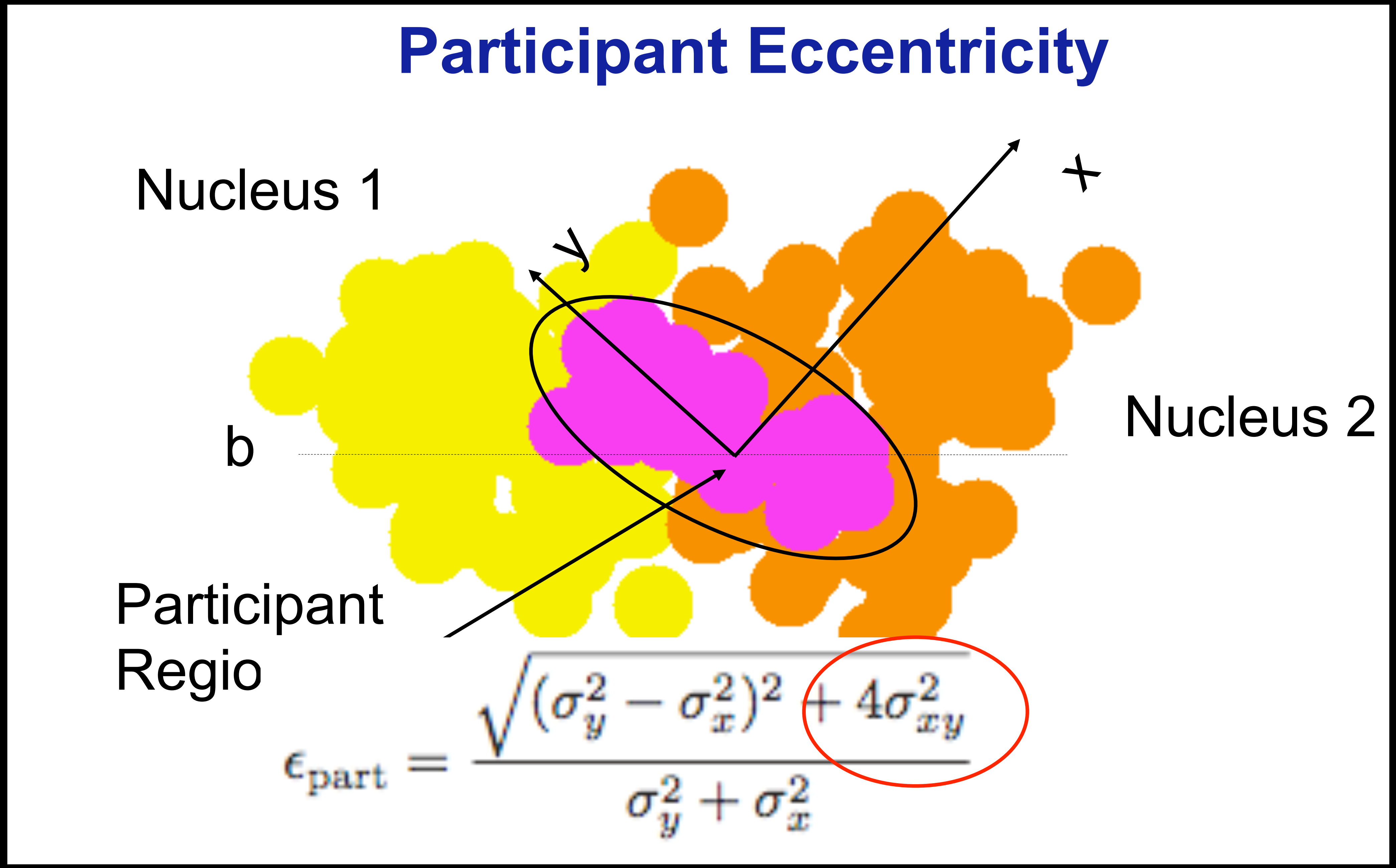
Take 2-particle angular correlation function and subtract "elliptic flow" $\cos(2\Delta\phi)$ term

Residual correlations at $\Delta\phi \approx 0$ and $\Delta\phi \approx \pi \pm 60^\circ$

A new look at nuclear collisions

PHOBOS QM ‘05



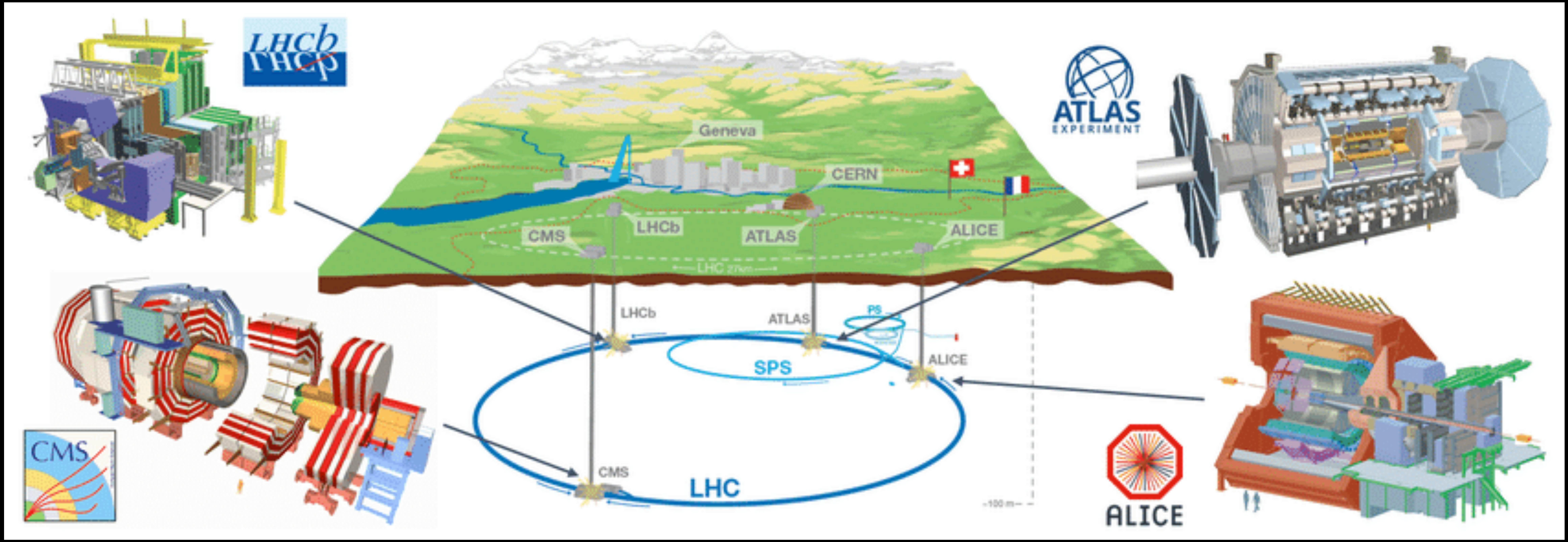


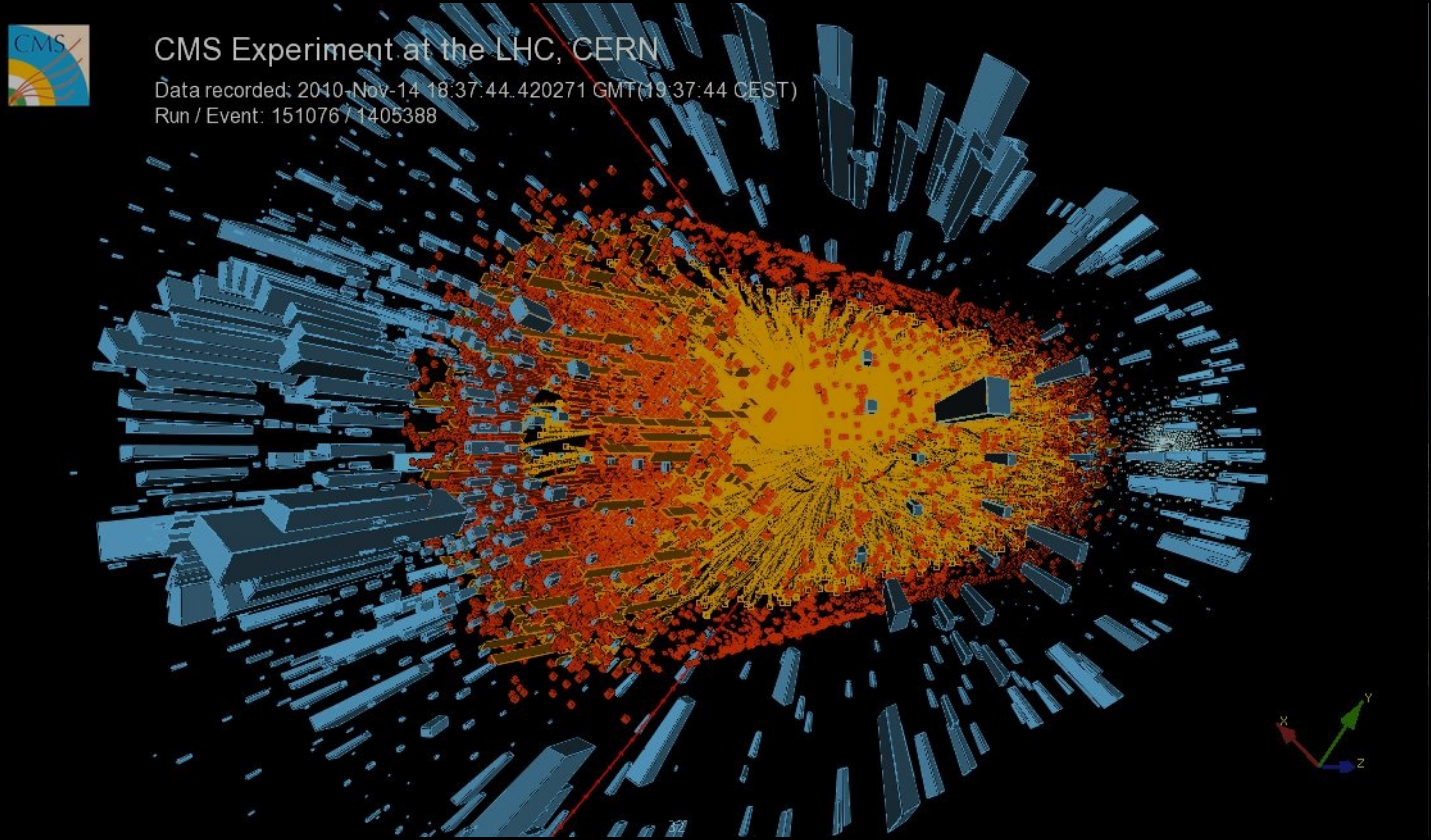
Initial geometry given by overlap of smooth nuclear density distributions

Initial geometry determined by positions of individual colliding nucleons (participants)

2010

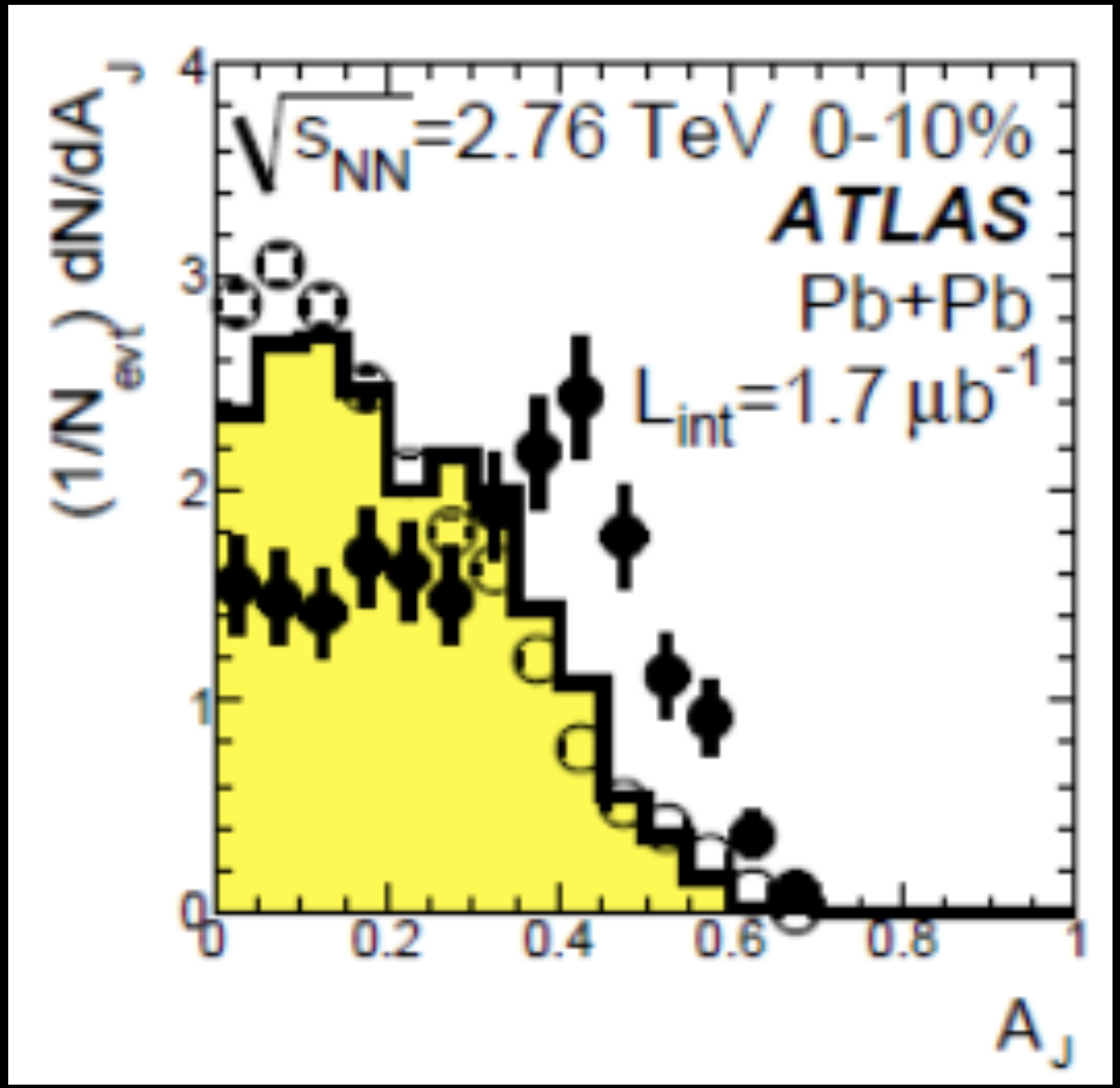
2nd Heavy Ion Collider: LHC



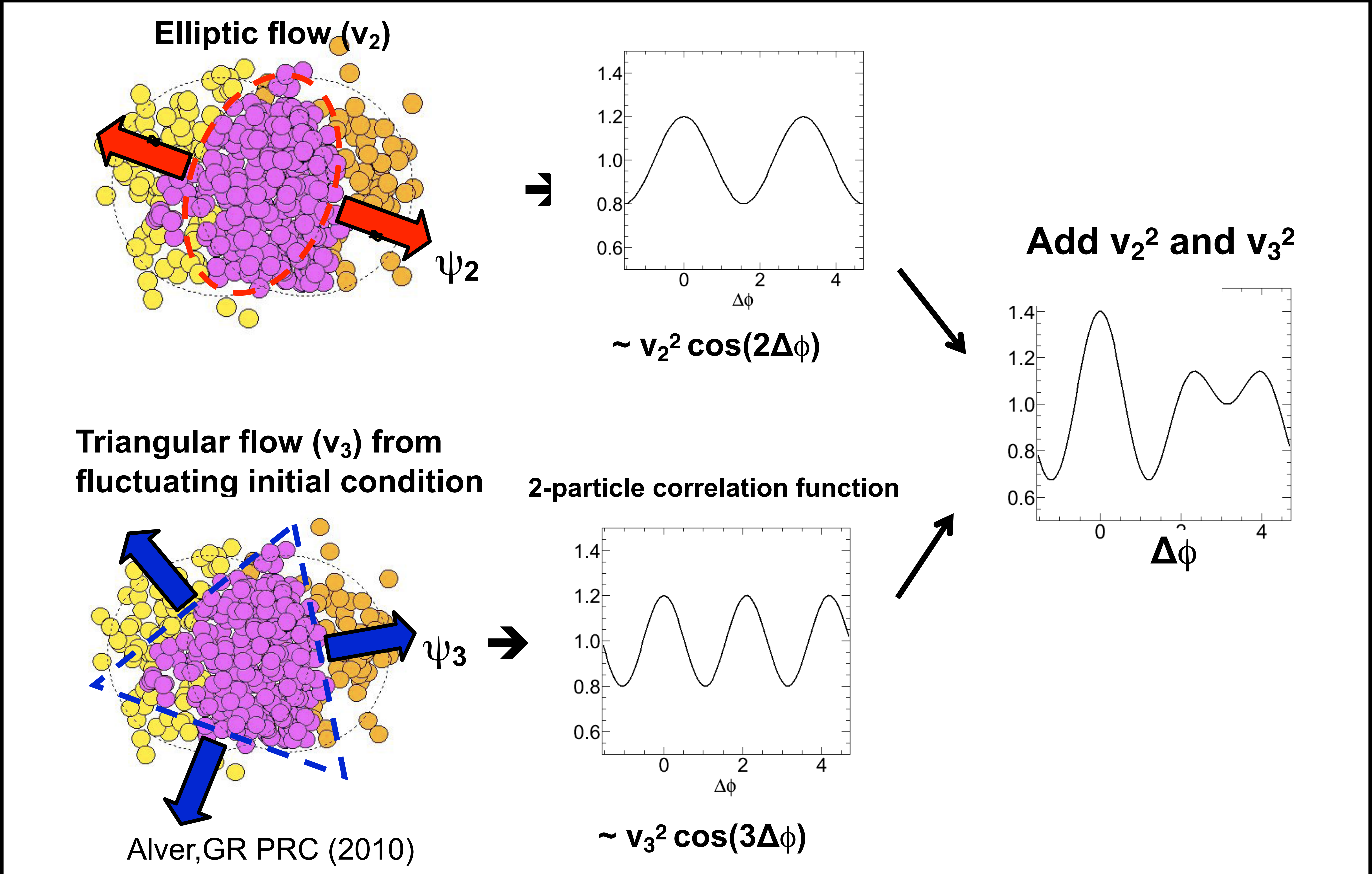

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST)
Run / Event: 151076 / 1405388
X
Y
Z

ATLAS PRL (2010)

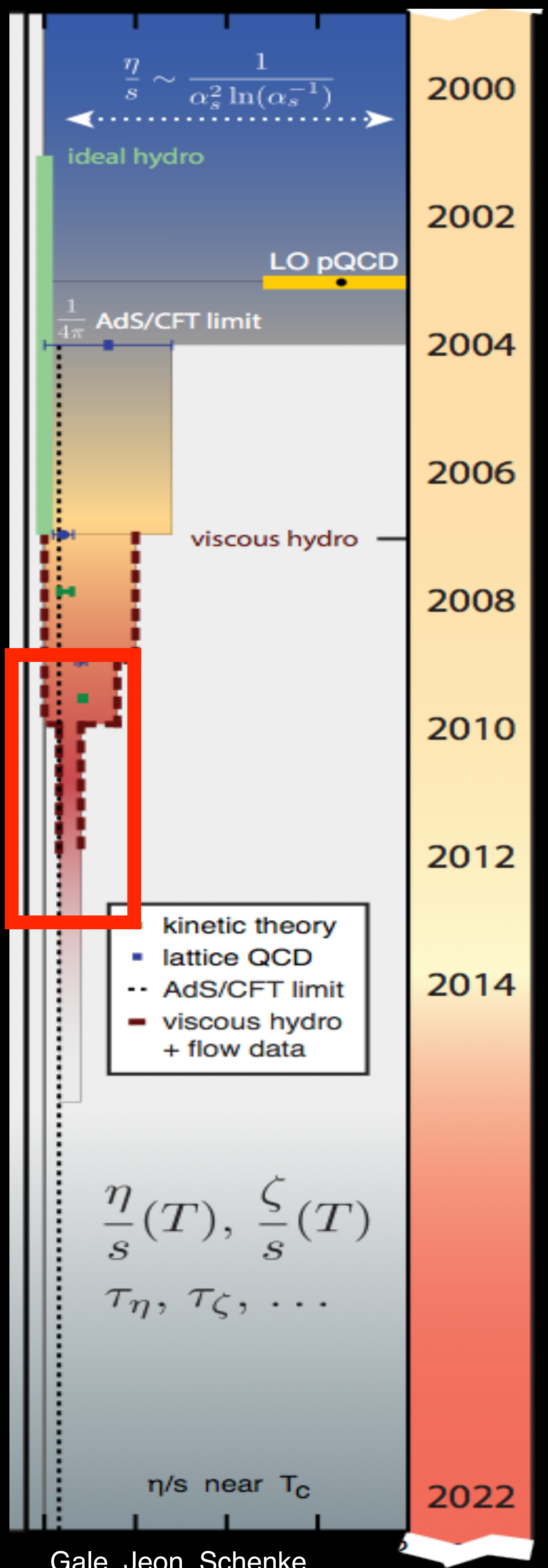
Jet energy loss in QGP leads to dijet momentum imbalance



Demise of Mach cones…

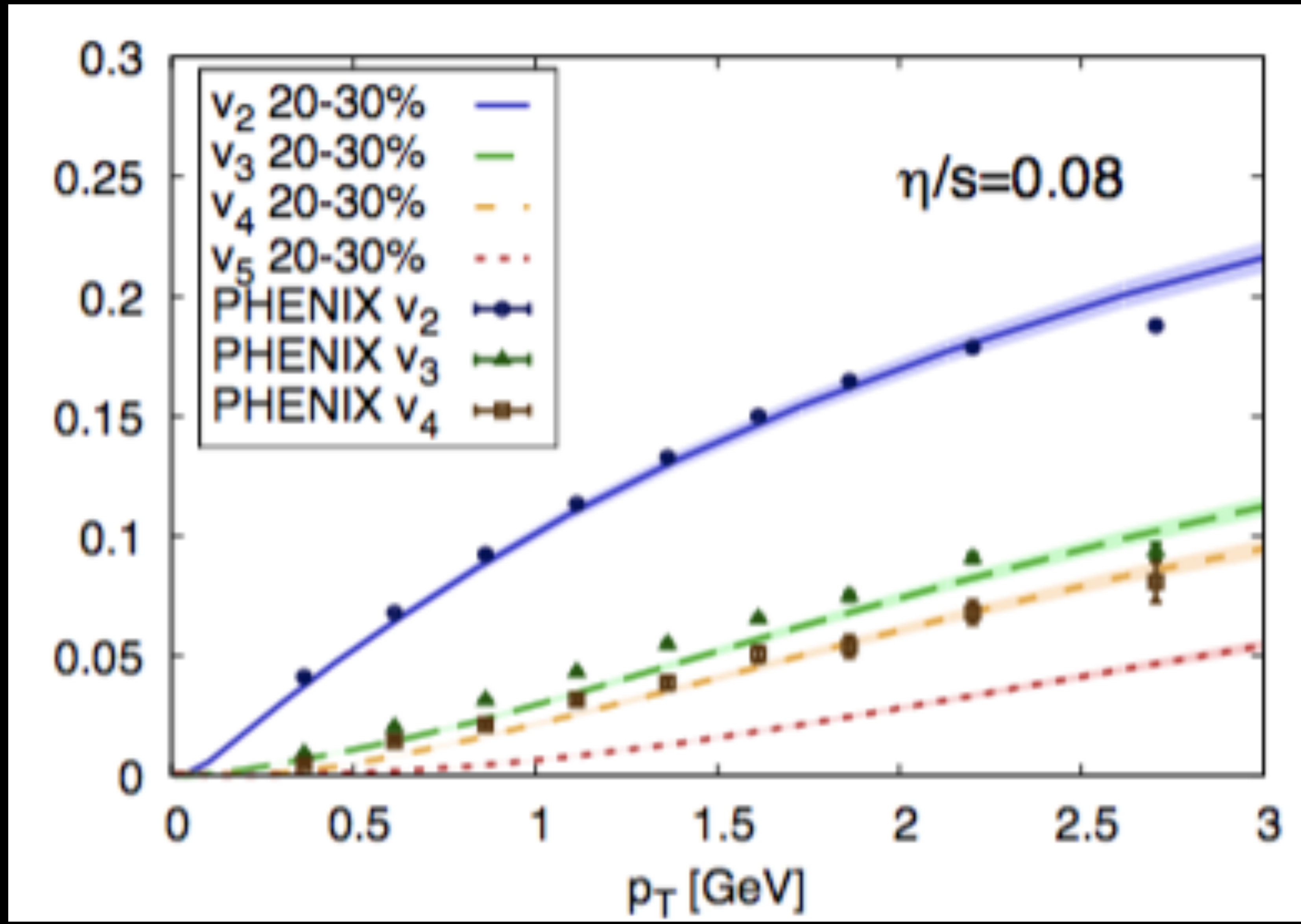


…precise determination of QGP transport coefficient



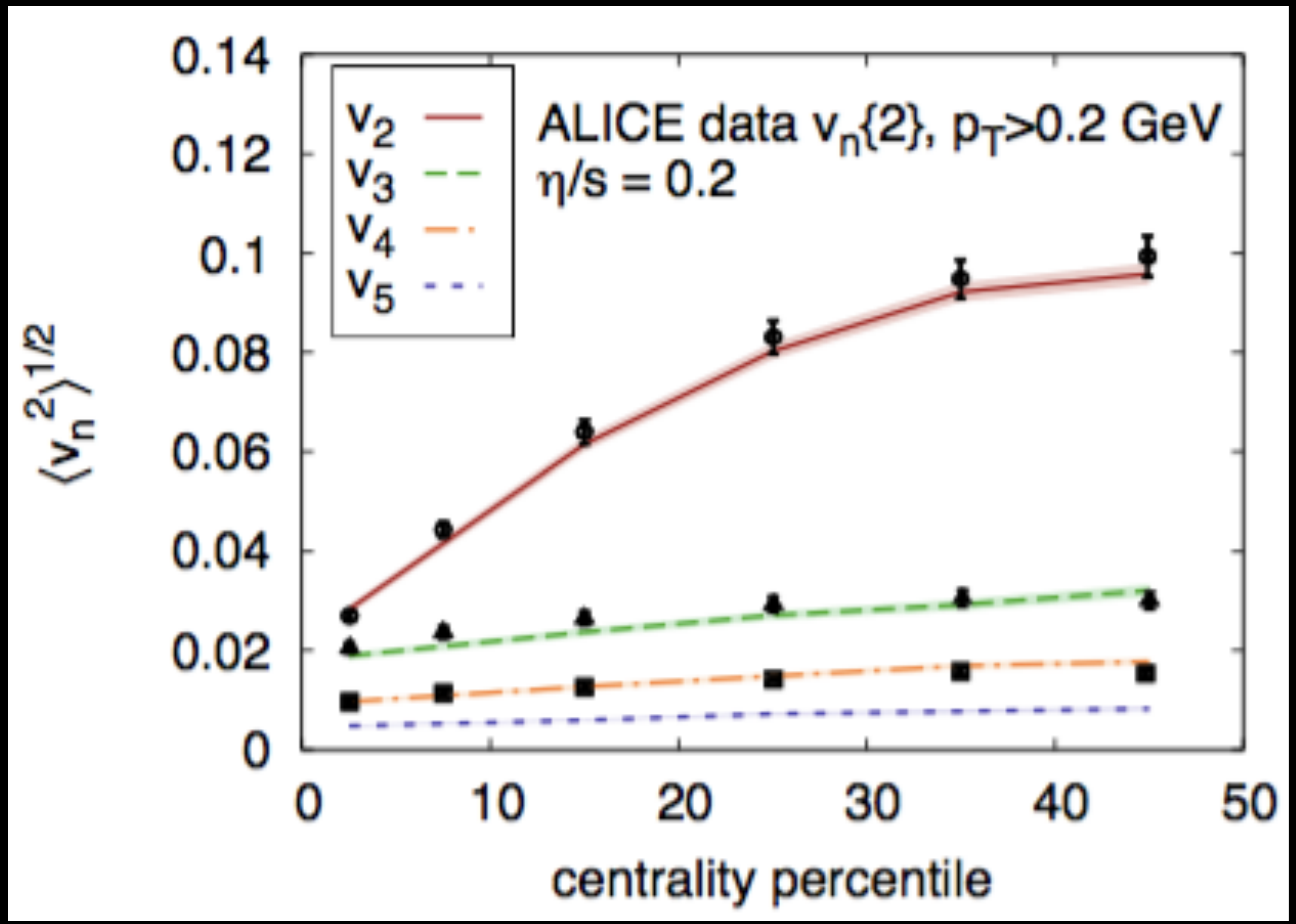
Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011

Gale, Jeon Schenke Phys.Rev. C85 (2012) 024901

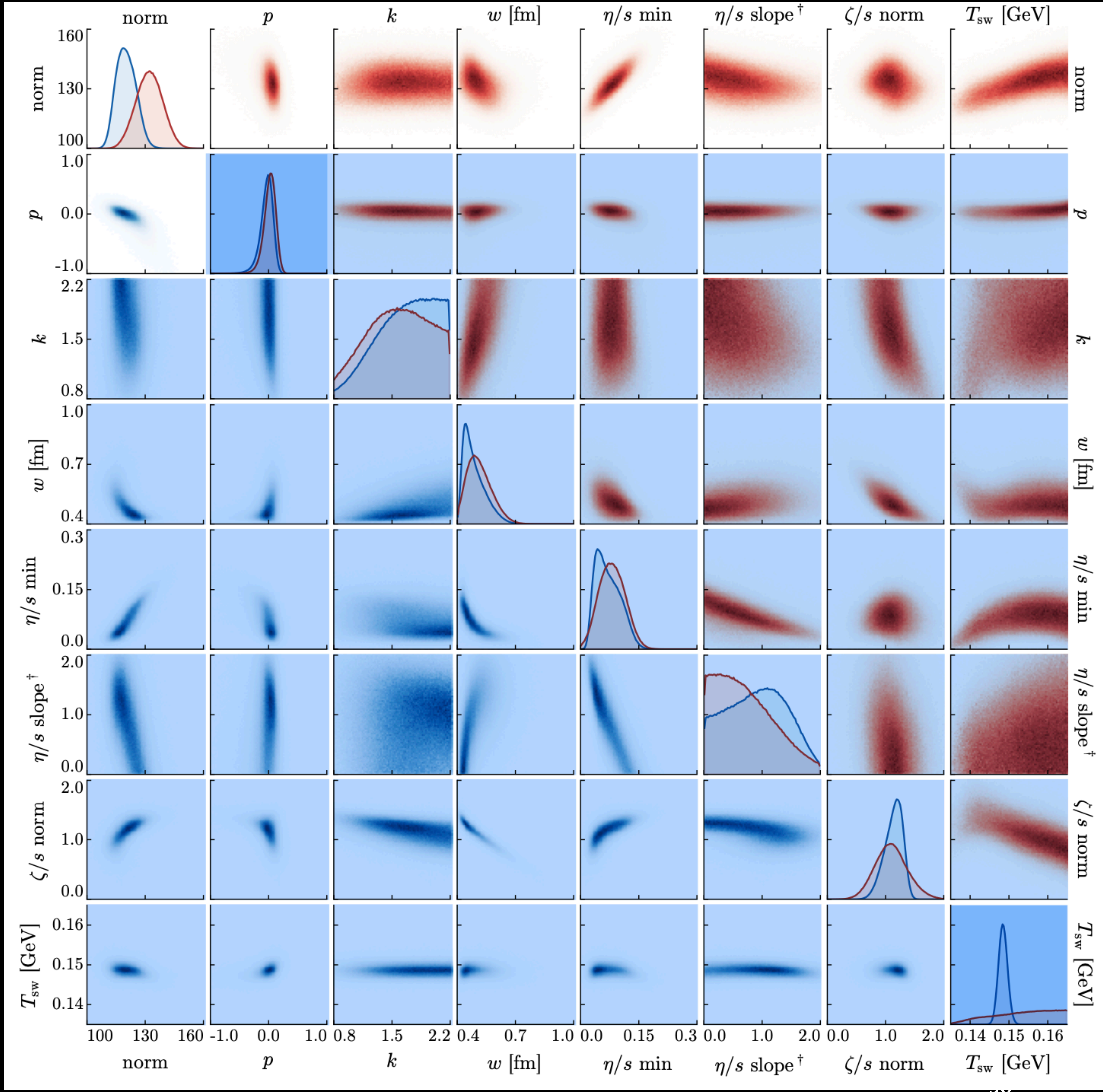


Higher order Fourier components constrain initial geometry and transport coefficient η/s simultaneously

Gale et al, Phys.Rev.Lett. 110 (2013)

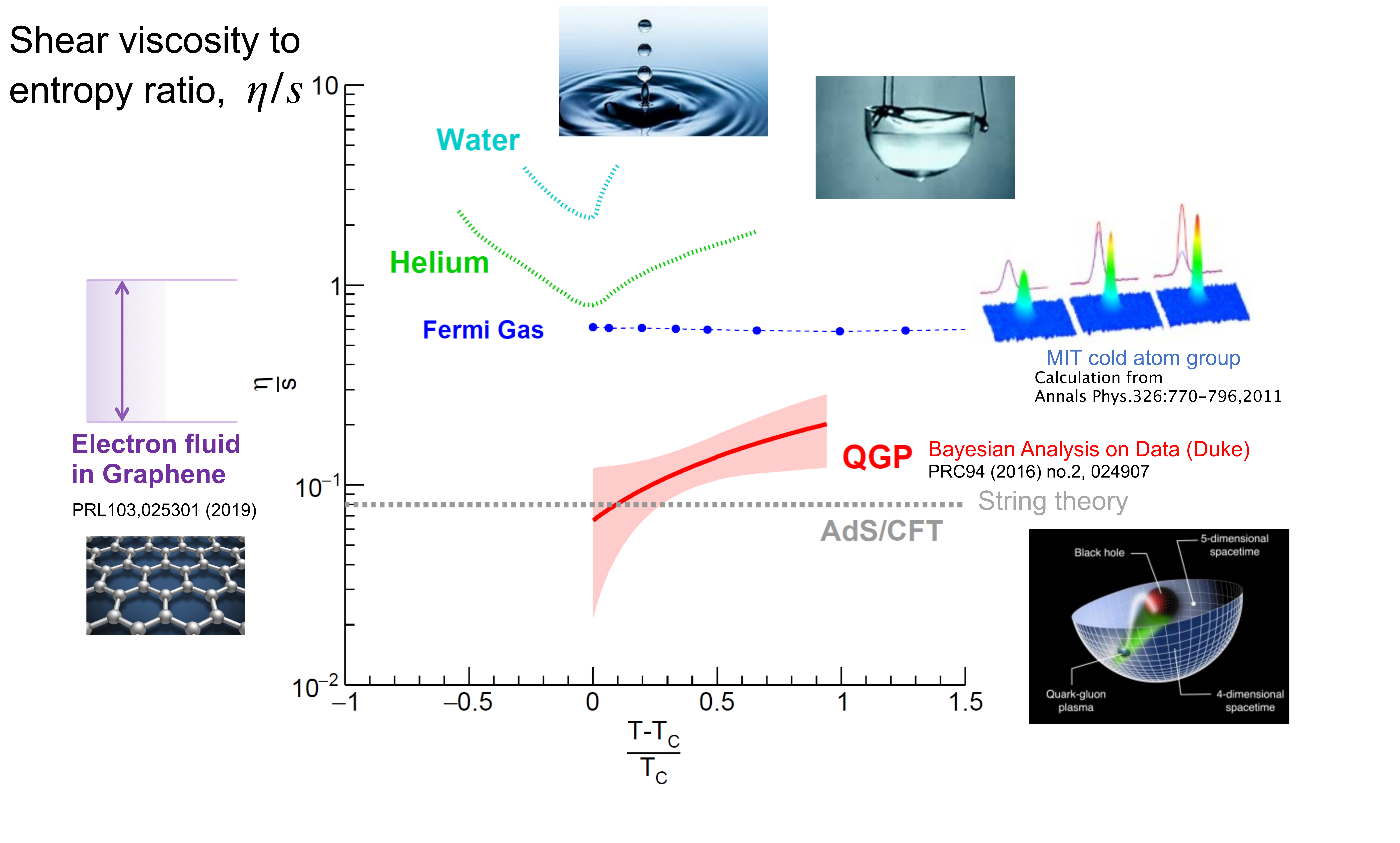


Bass et al, Heinz et al



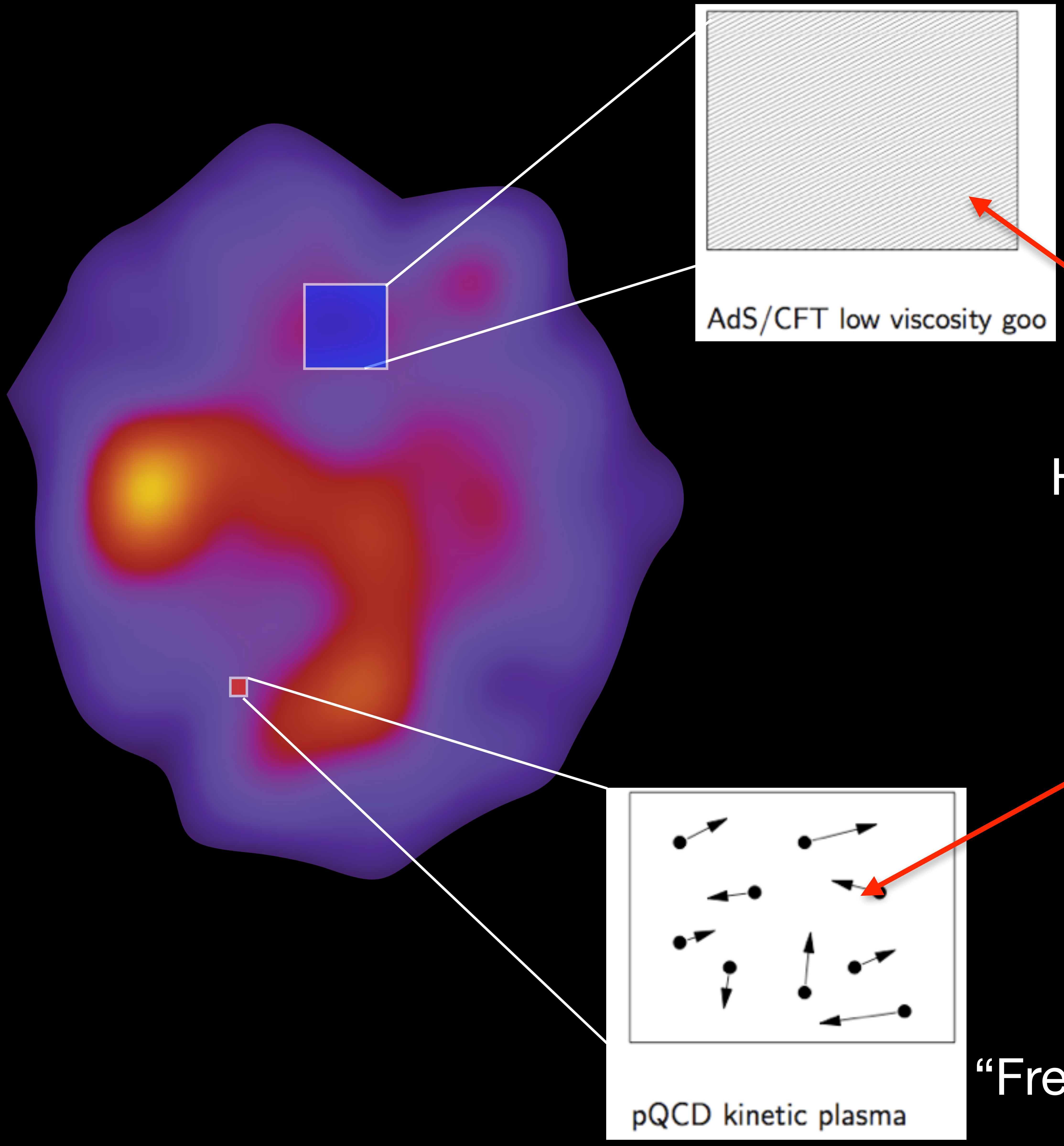
State of the art: Bayesian analysis of multiple observables at multiple energies to extract QGP properties

QGP vs other fluids in nature



2015

How does QGP work?



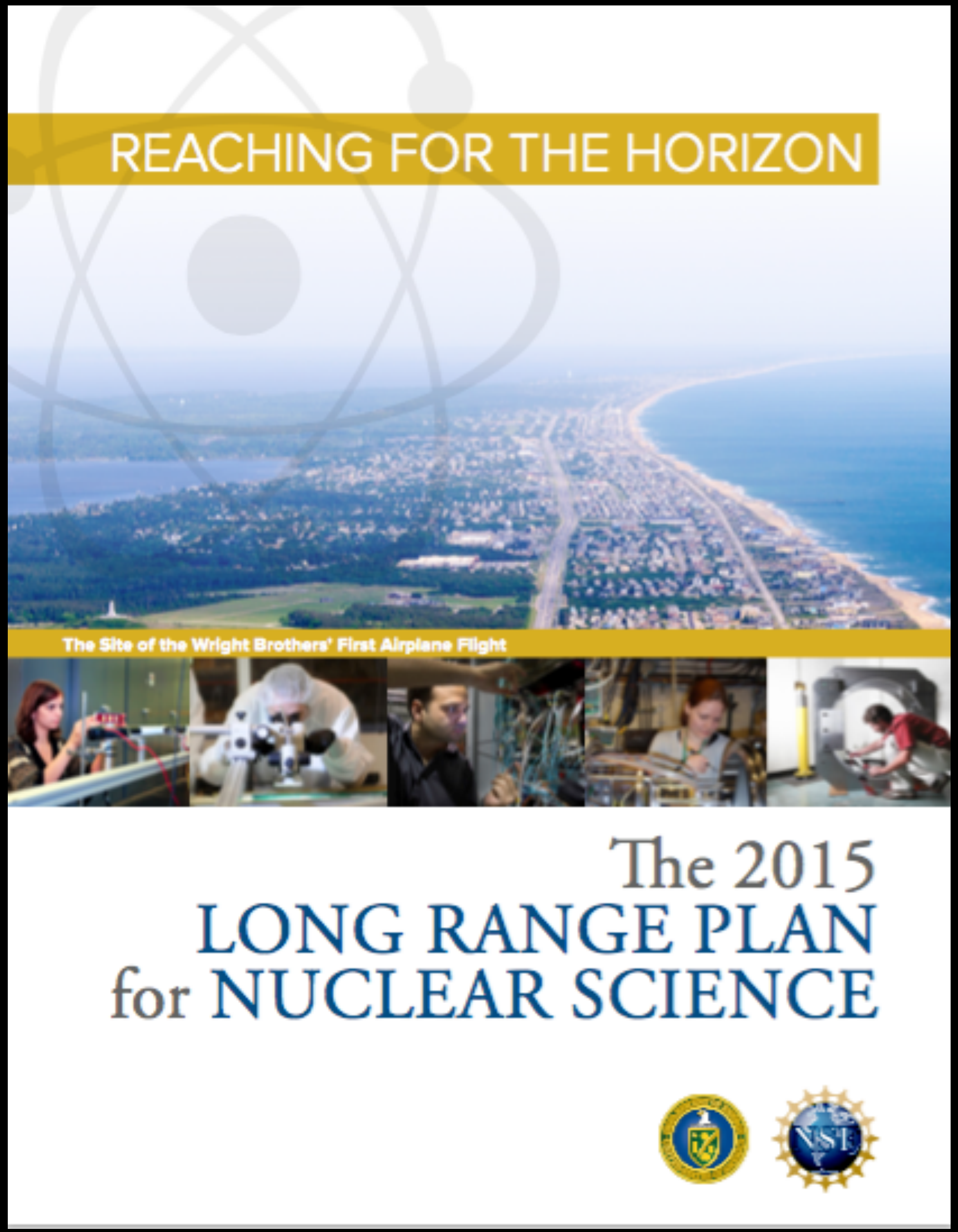
$\Delta x \approx 1\text{fm}$
$\Delta p \lessapprox 200\text{MeV}$

“Perfect Liquid”

How does long-wavelength behavior emerge from asymptotically free interaction at high T?

$\Delta x \ll 1\text{fm}$
$\Delta p >> 1\text{GeV}$

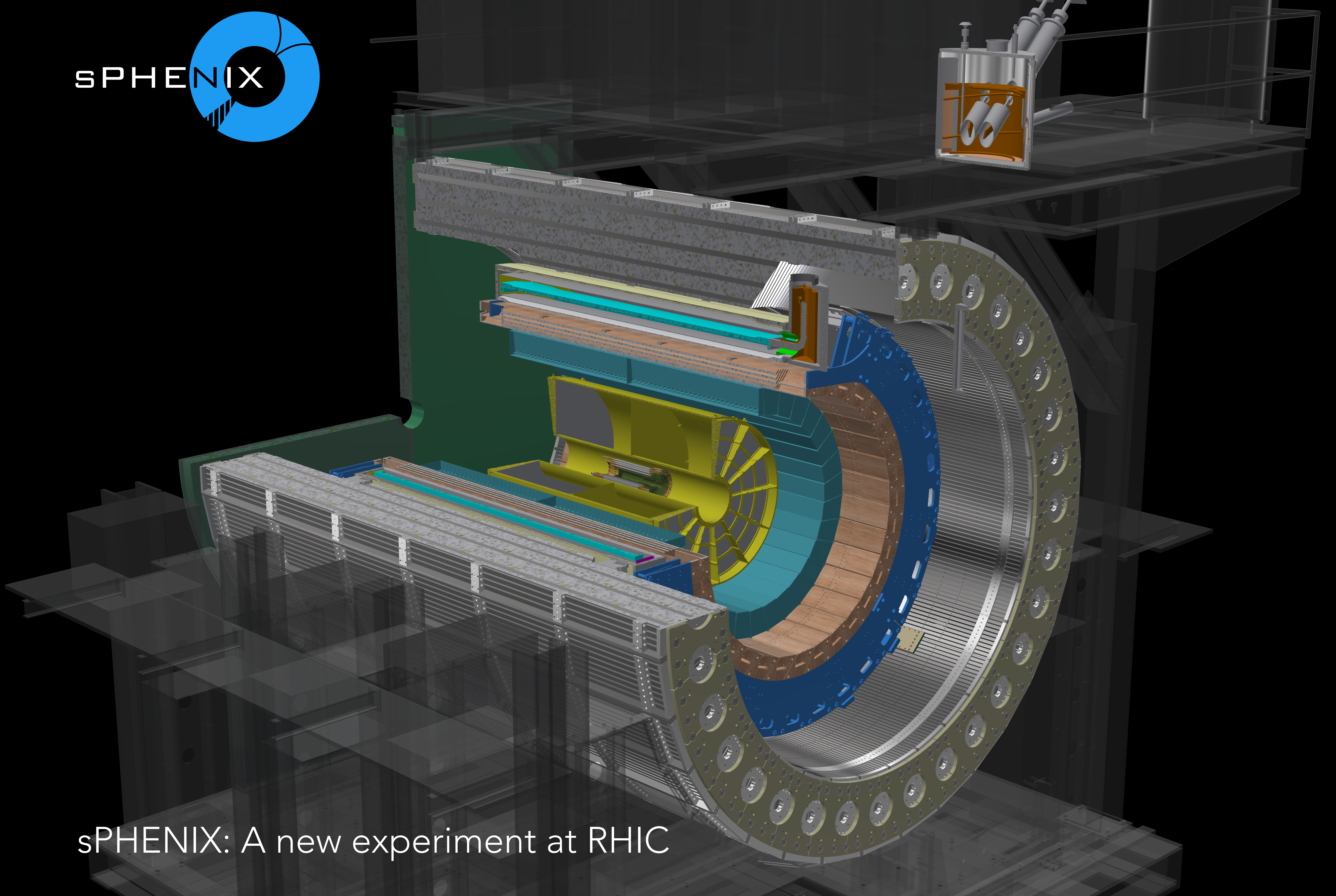
“Free quarks and gluons”



US Nuclear Physics
Long range plan

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

c.f. 2014 Hot QCD White Paper (arXiv:1502.02730) sPHENIX



sPHENIX: A new experiment at RHIC

2022+

LHC and RHIC timeline

LHC

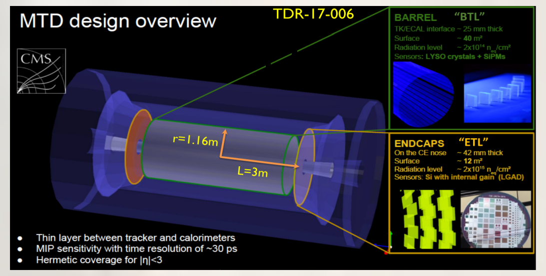
pO, OO, pPb

HL-LHC

PbPb 1.8 nb^{-1} | PbPb 7 nb^{-1} | PbPb 7 nb^{-1}

Run 2 | Long shutdown 2 | Run 3 | LS 3 | Run 4

CMS Phase 1 Upgrade | CMS Phase 2 Upgrade

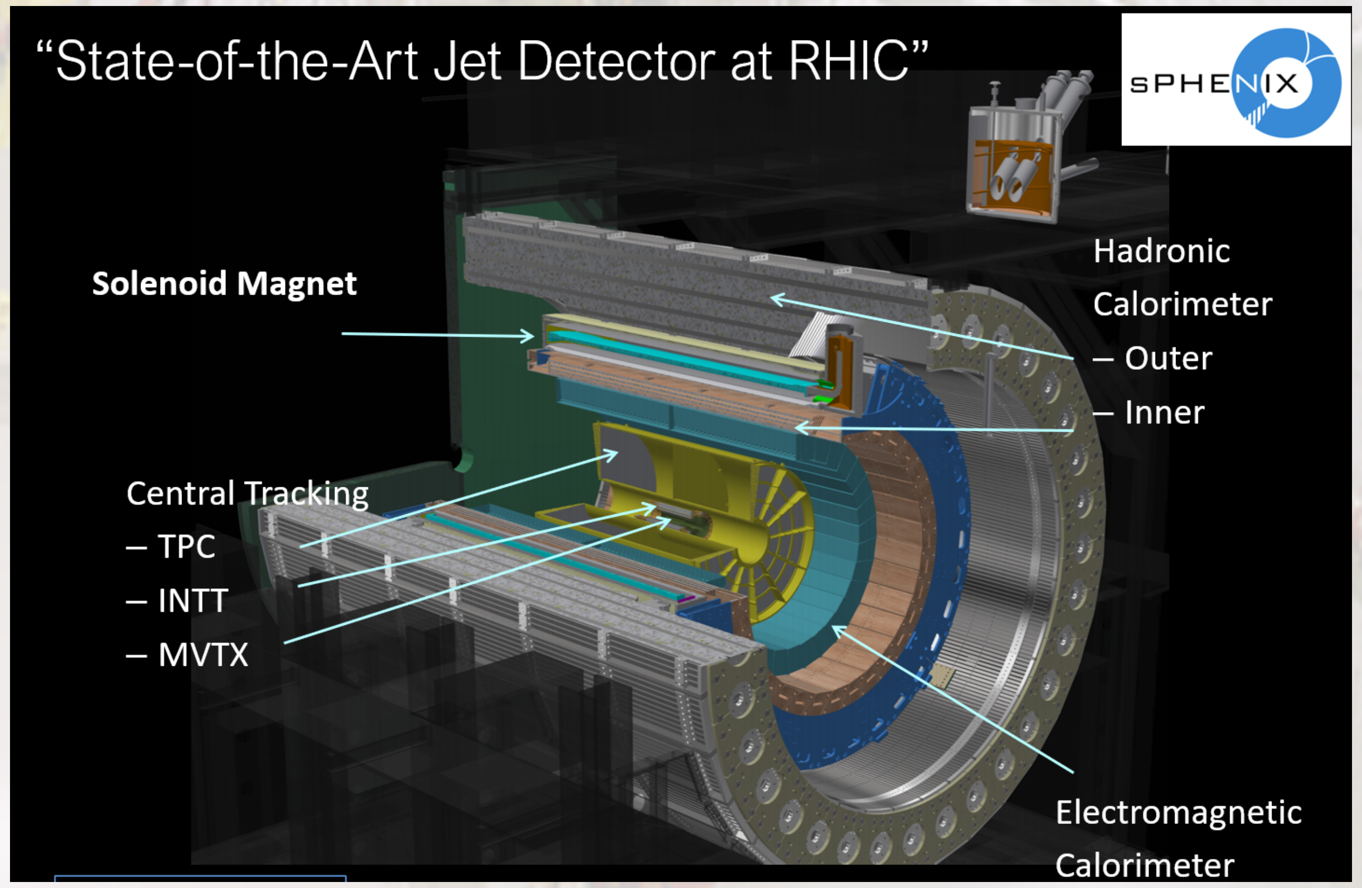


	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

PD-2/3

sPHENIX construction

sPHENIX Installation commissioning



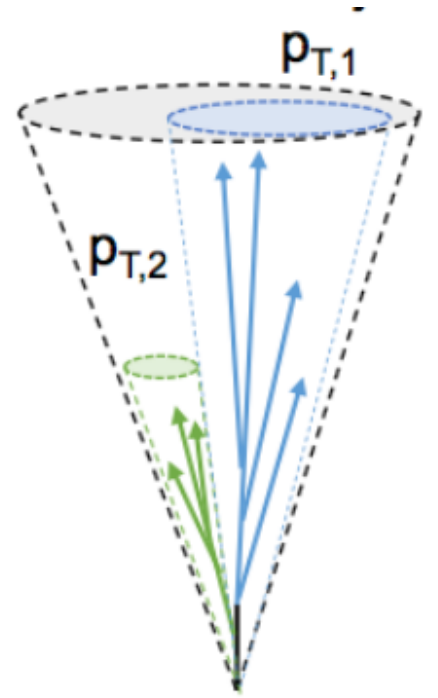
Run 23-25

RHIC

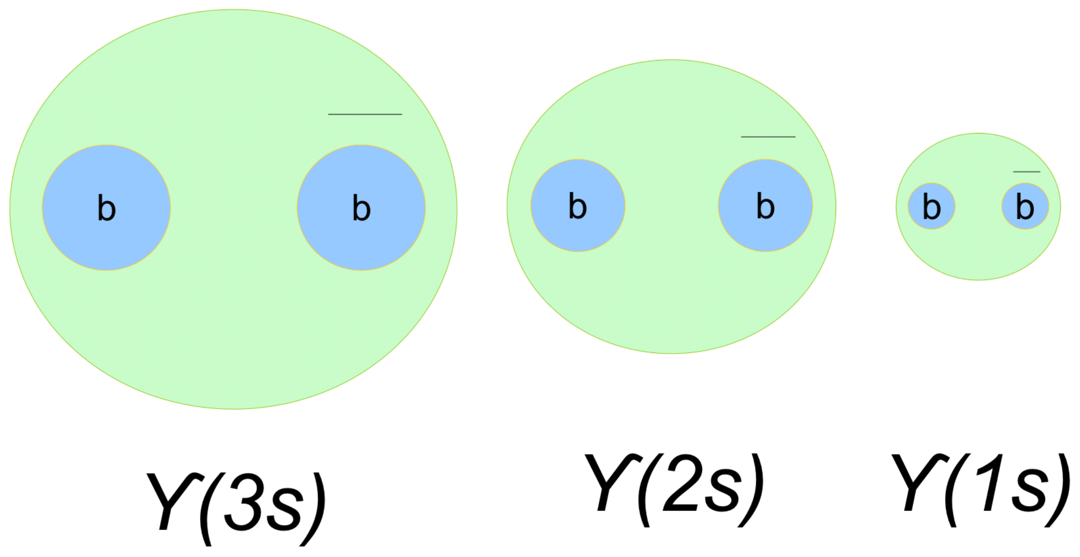
pp, pAu, AuAu 20 nb^{-1}

EIC

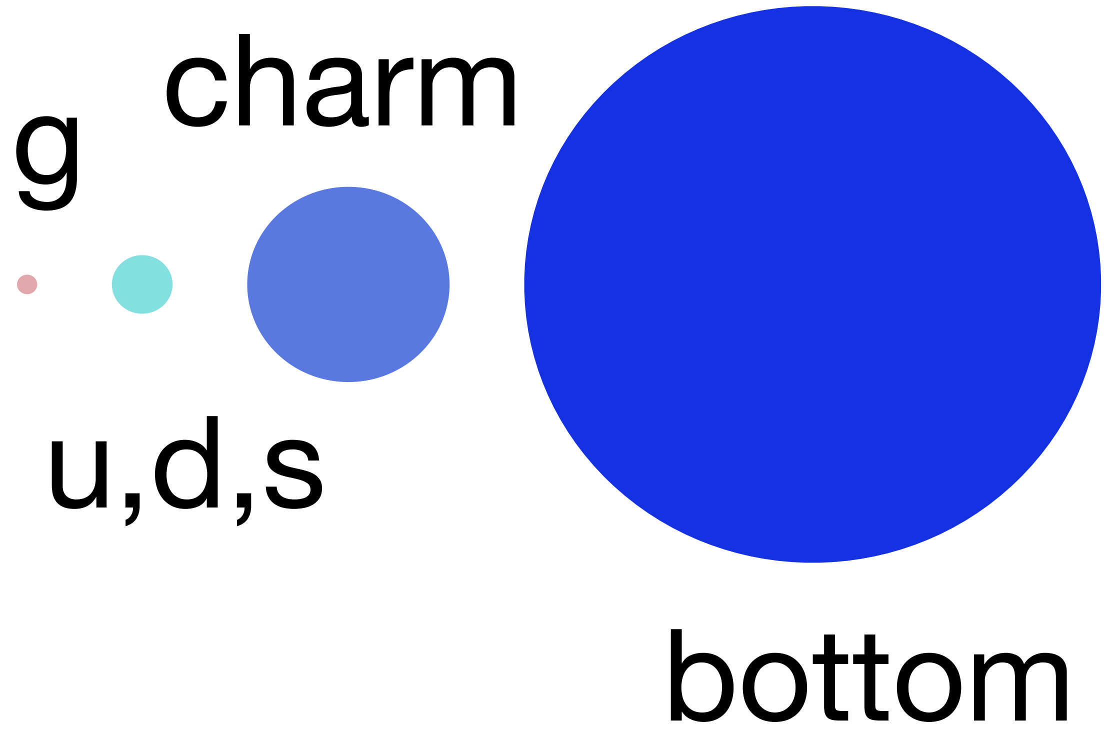
QGP Diagnosis toolkit



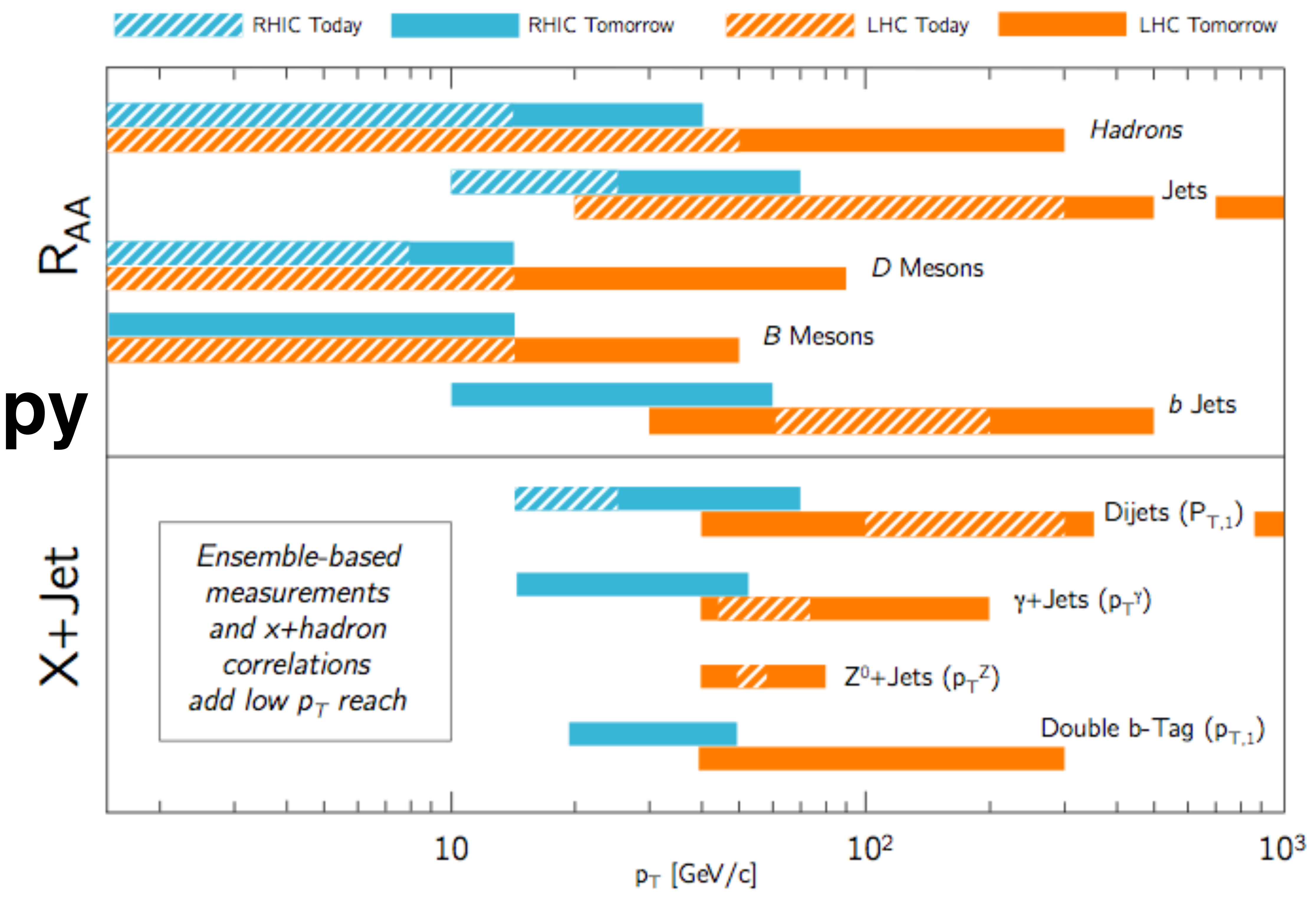
Jet structure
vary momentum/ angular scale of probe



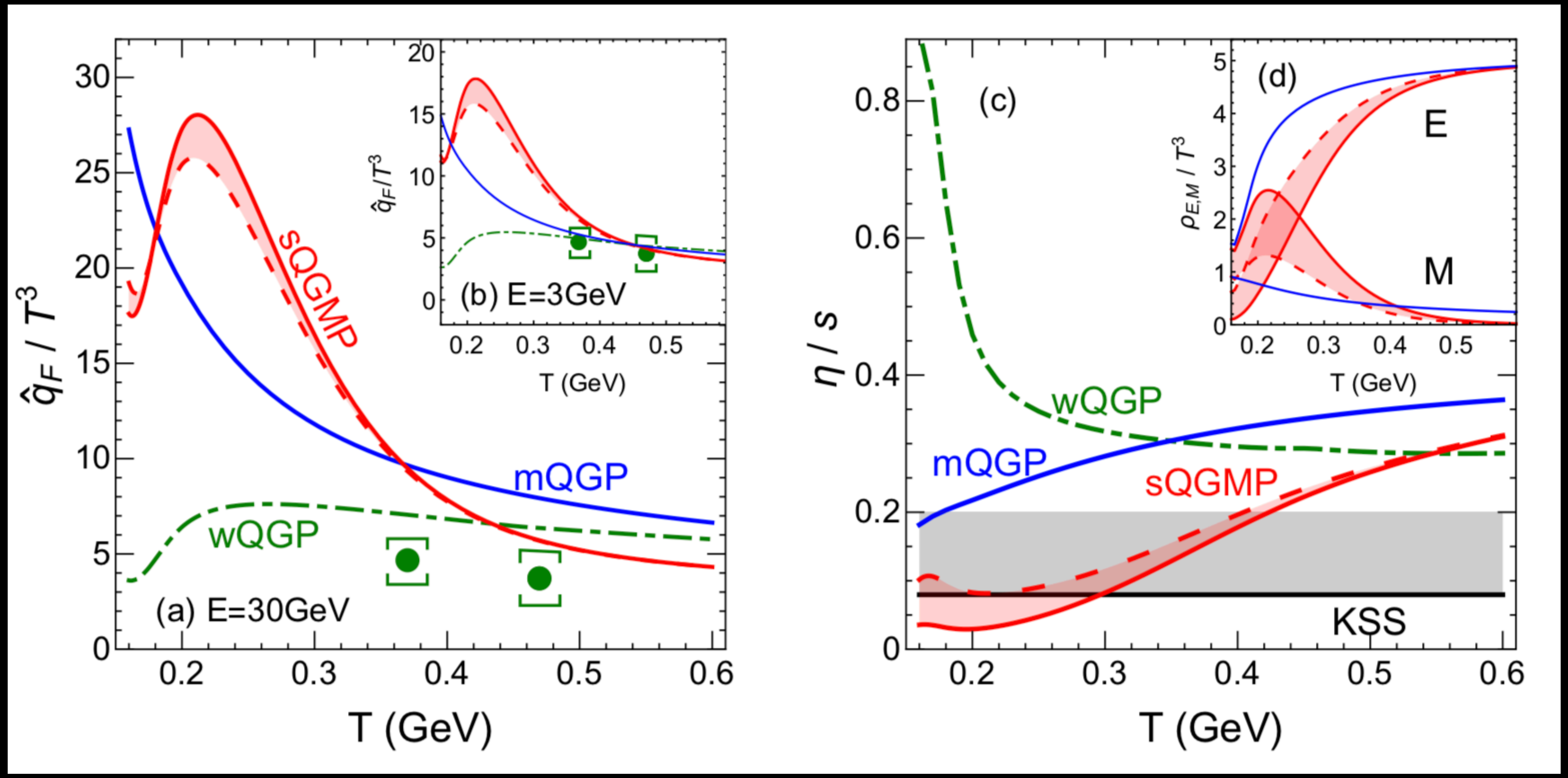
Quarkonium spectroscopy
vary size of probe



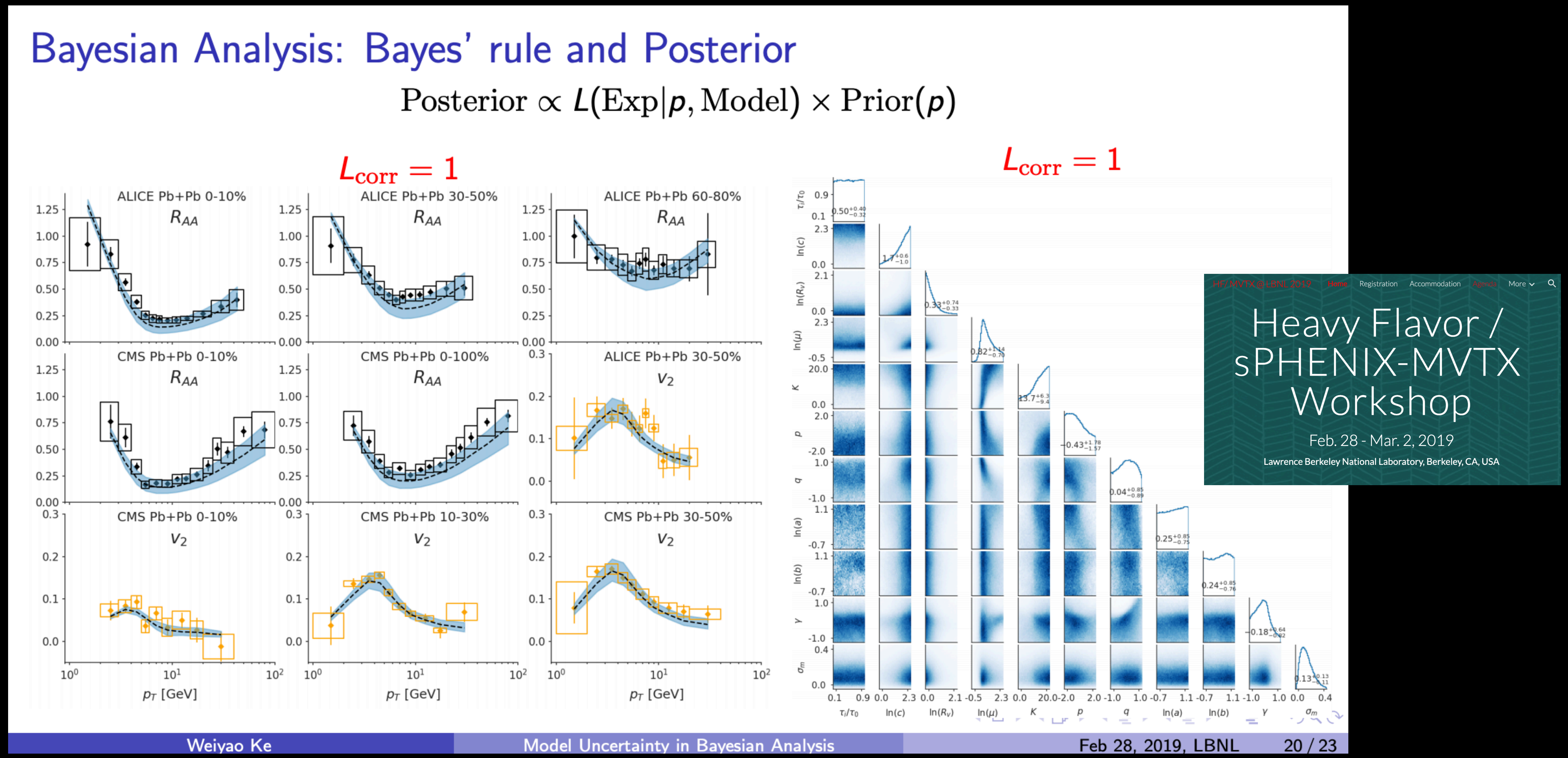
Parton energy loss
vary mass/momentum of probe



Use RHIC and LHC to study QGP properties vs temperature



T-dependence of QGP structure, as reflected e.g. in transport coefficients can reveal new physics

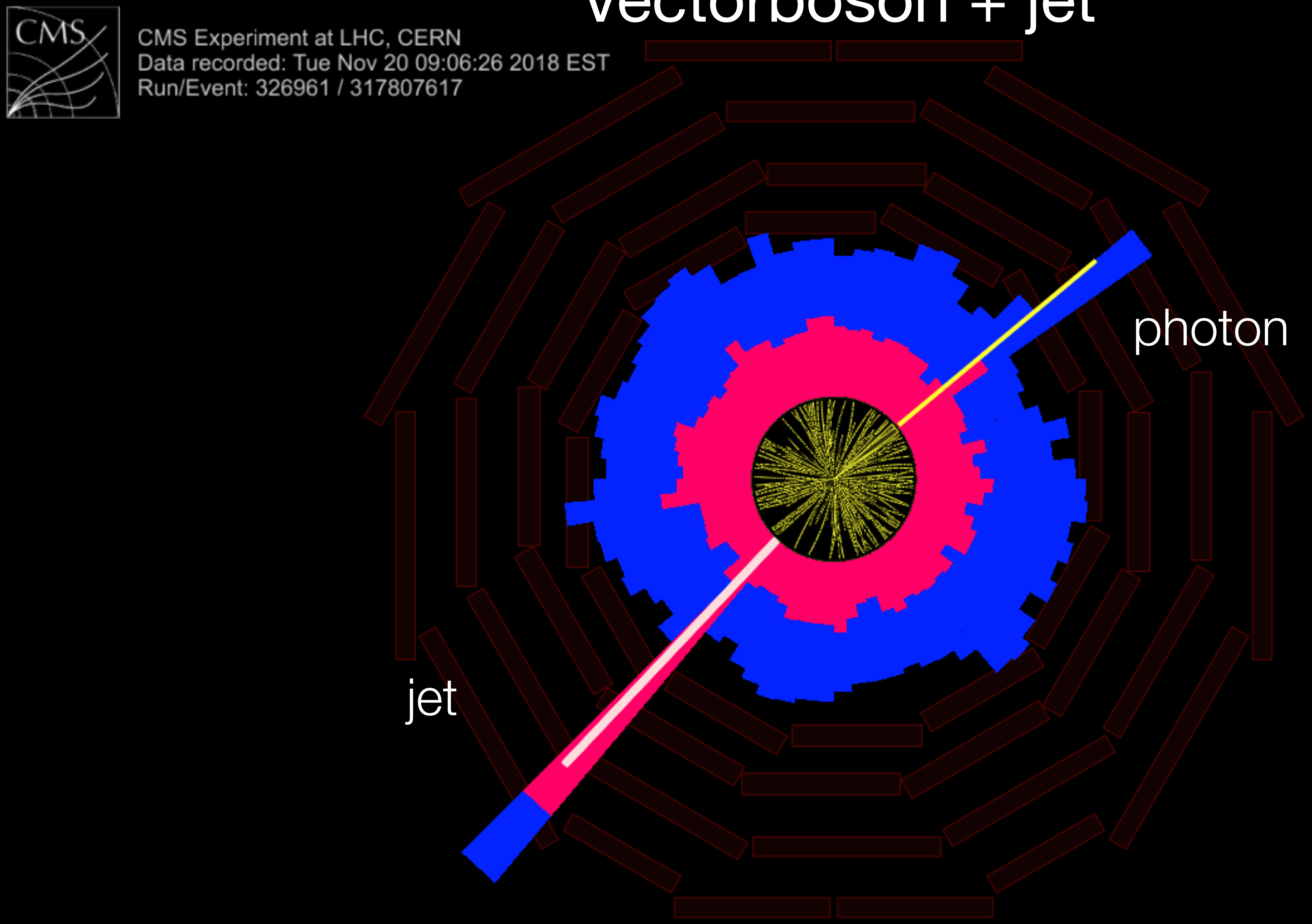


Bayesian inference key approach for extracting temperature dependence

Data from two energy regimes, RHIC & LHC, essential to constrain T dependence

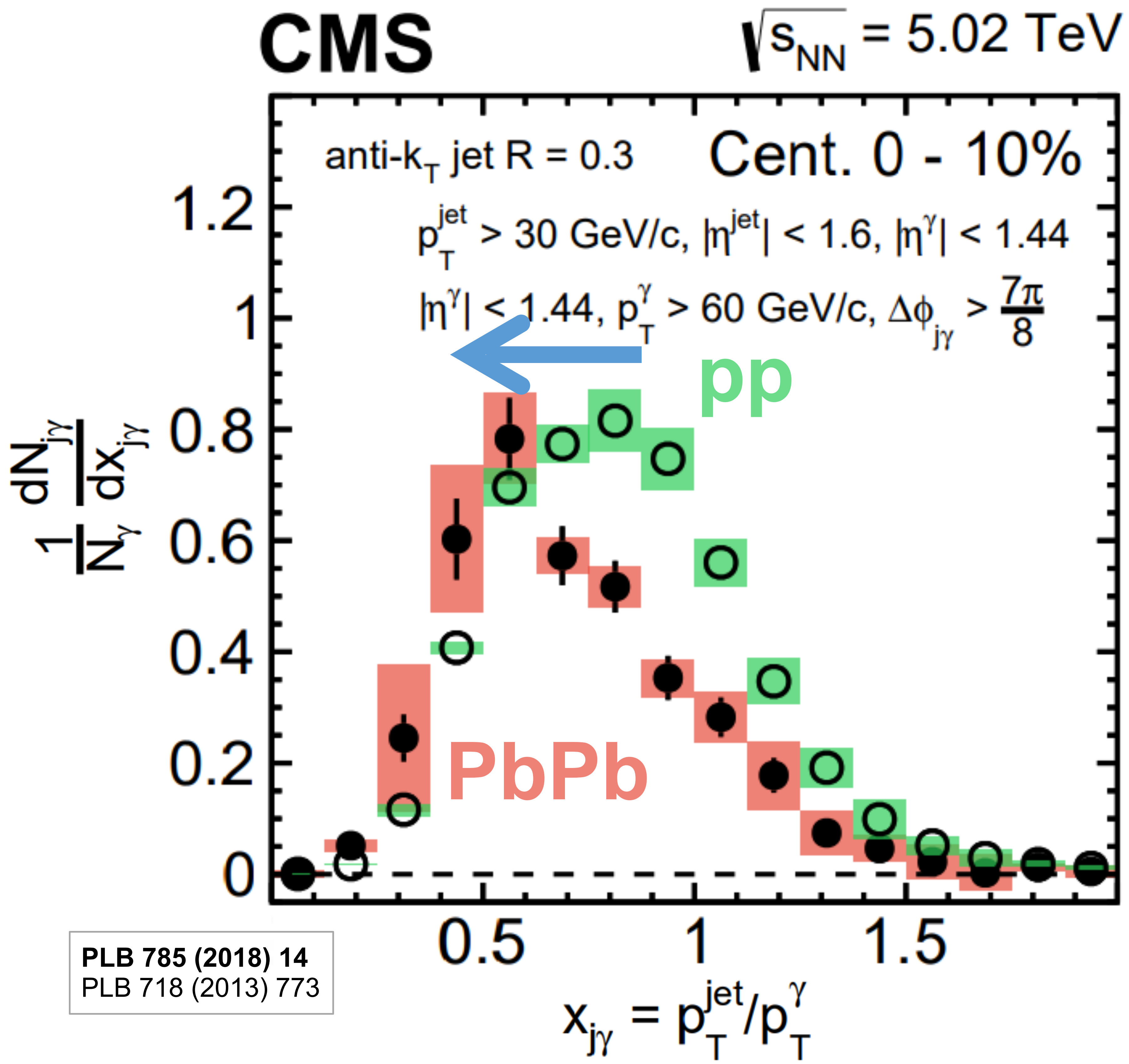
Close collaboration of experiments and theory required

Golden channel for studying QGP structure: Vectorboson + jet

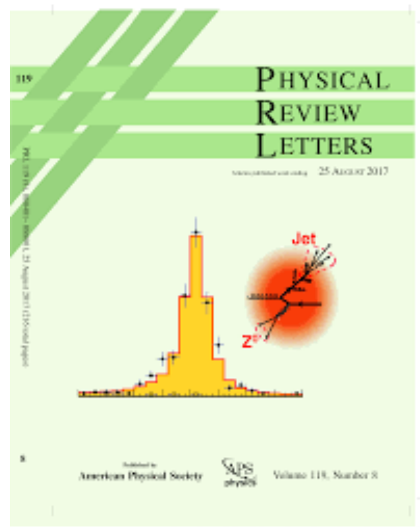


Pioneering measurements at LHC

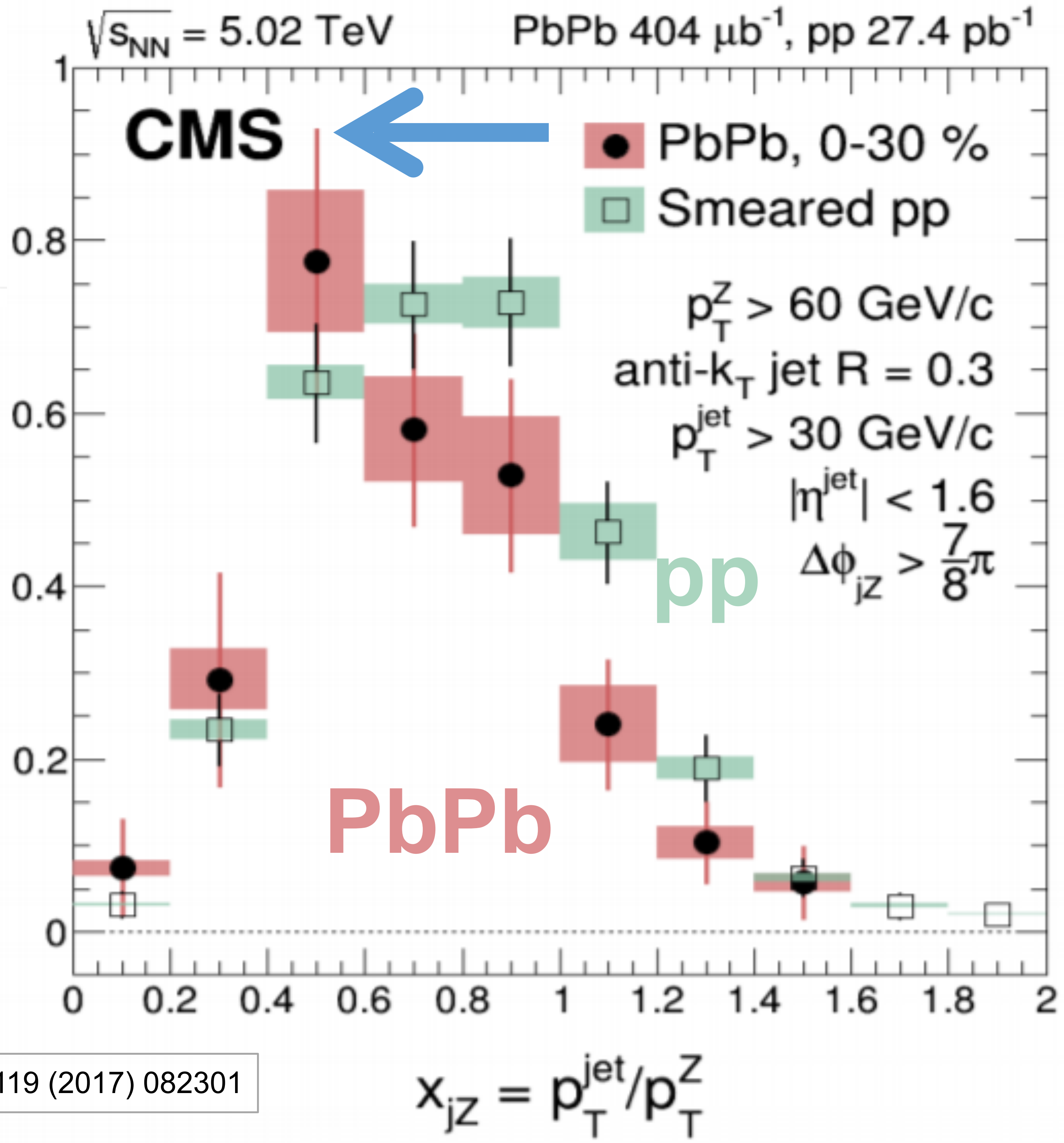
Photon + Jet



PRL cover (2017)

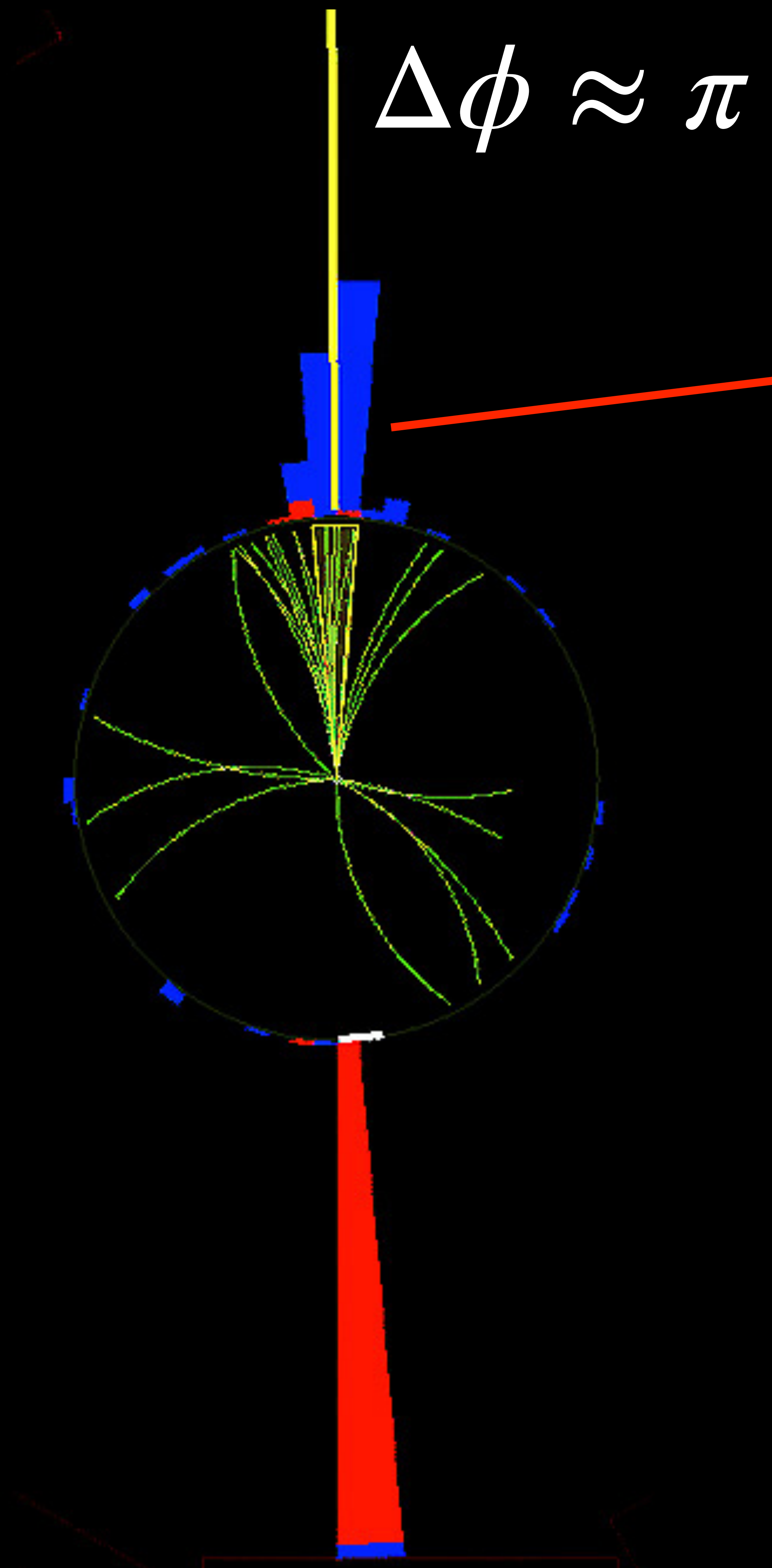


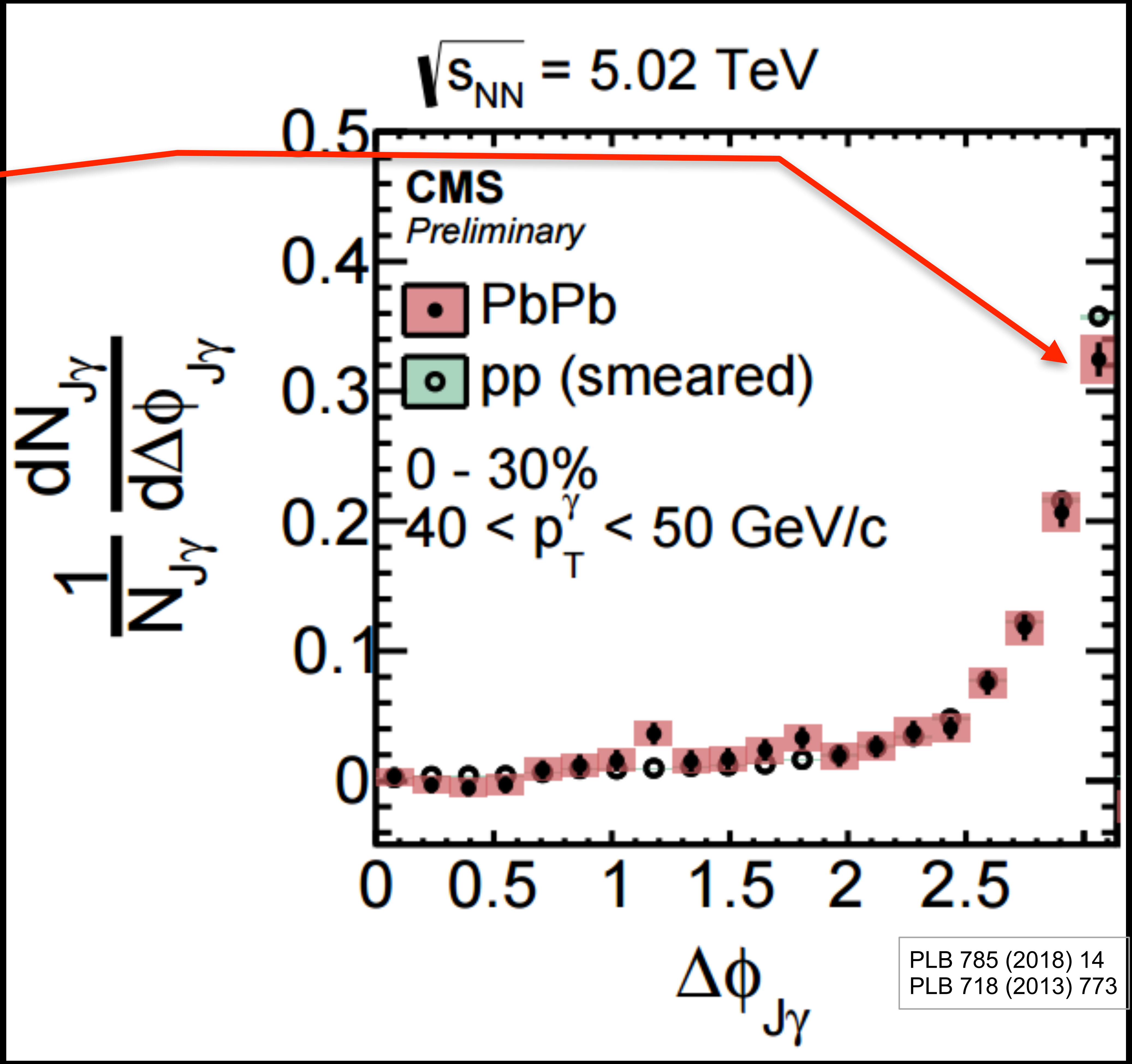
Z^0 boson + Jet



Energy loss (transport of energy out of jet cone) changes jet/photon (Z^0) momentum balance

QGP "Rutherford scattering"



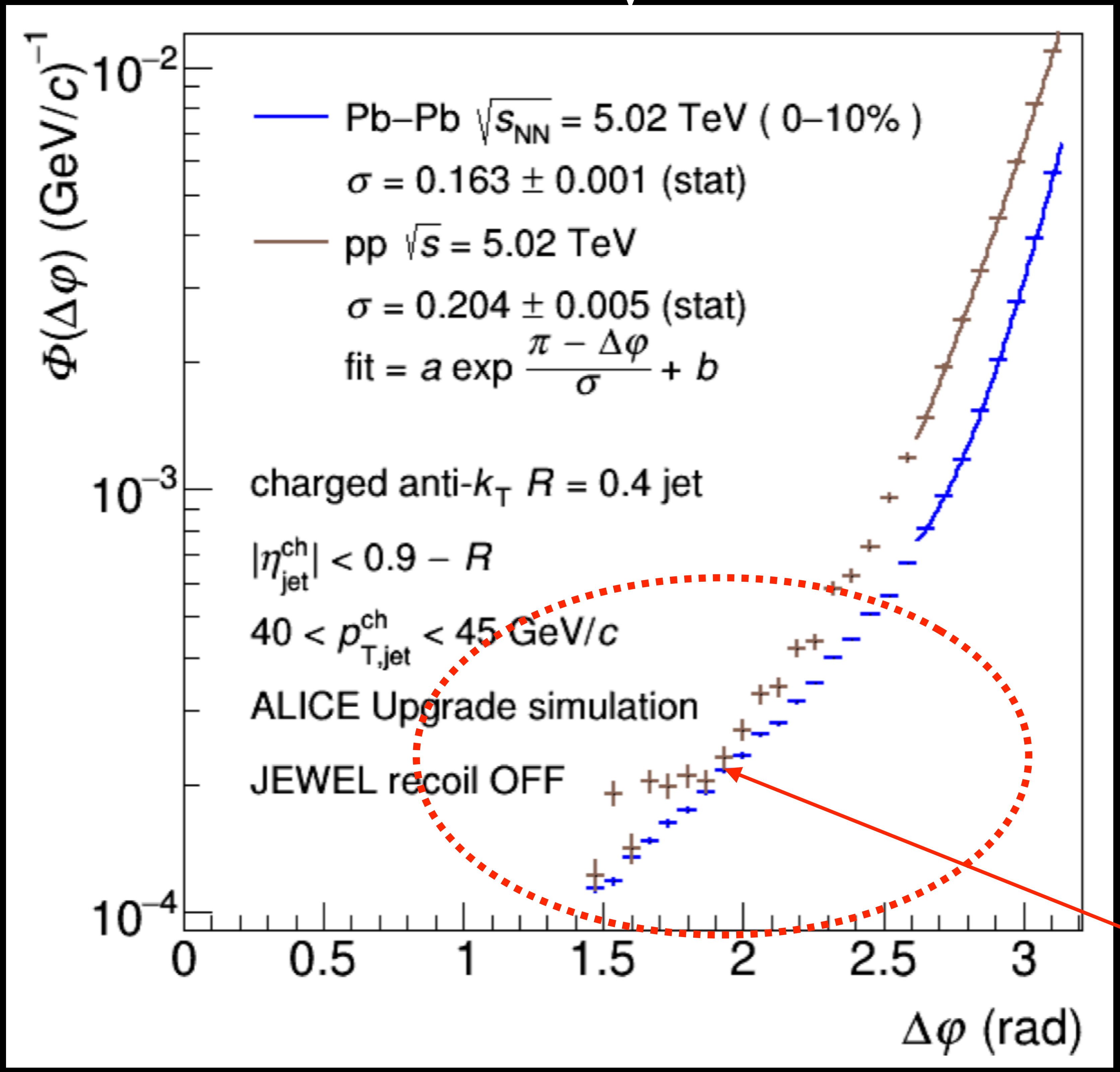


Does scattering in QGP deflect jet relative to the photon?

Distribution similar with QGP (PbPb) and without (pp)

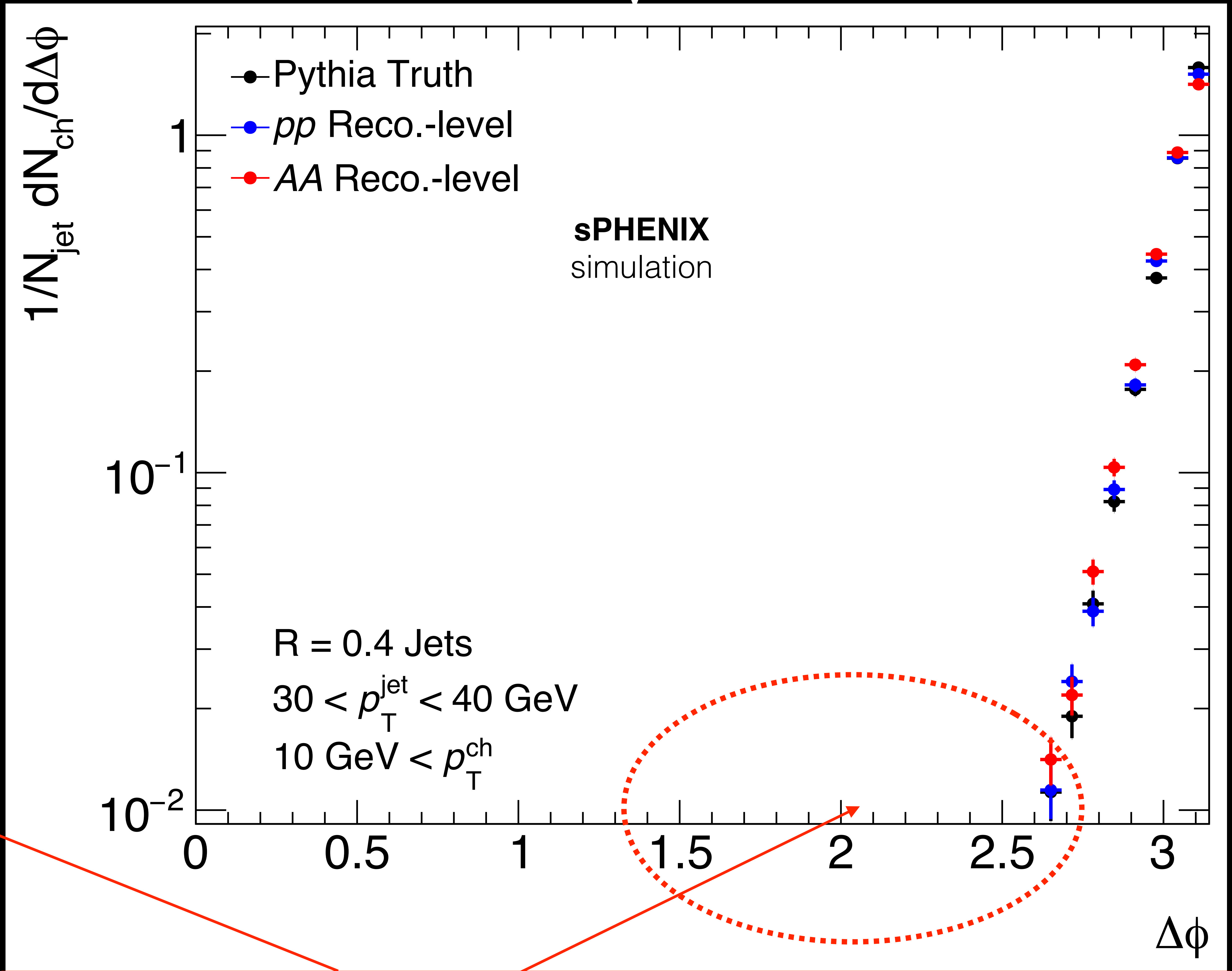
Jet broadening: Better at RHIC (lower energy)!

LHC projection $\sqrt{s_{NN}} = 5.02$ TeV



Final State Radiation

RHIC projection $\sqrt{s_{NN}} = 0.2$ TeV



At comparable jet energies, much smaller contribution from ISR/FSR at RHIC, as well as smaller smearing from UE fluctuations

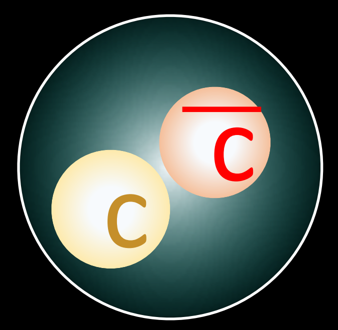
New opportunity: Exotica (use QGP as tool)

BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

X(3872): Observed by BELLE (2003)

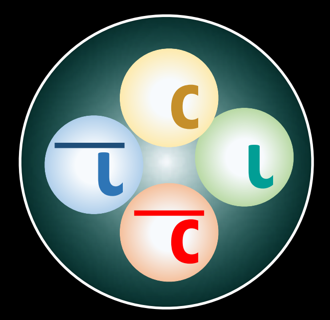
- Quantum number determined by CDF and LHCb data: JPC=1++
- internal structure is still under debate

Charmonium



PLB 590 209-215 (2004)

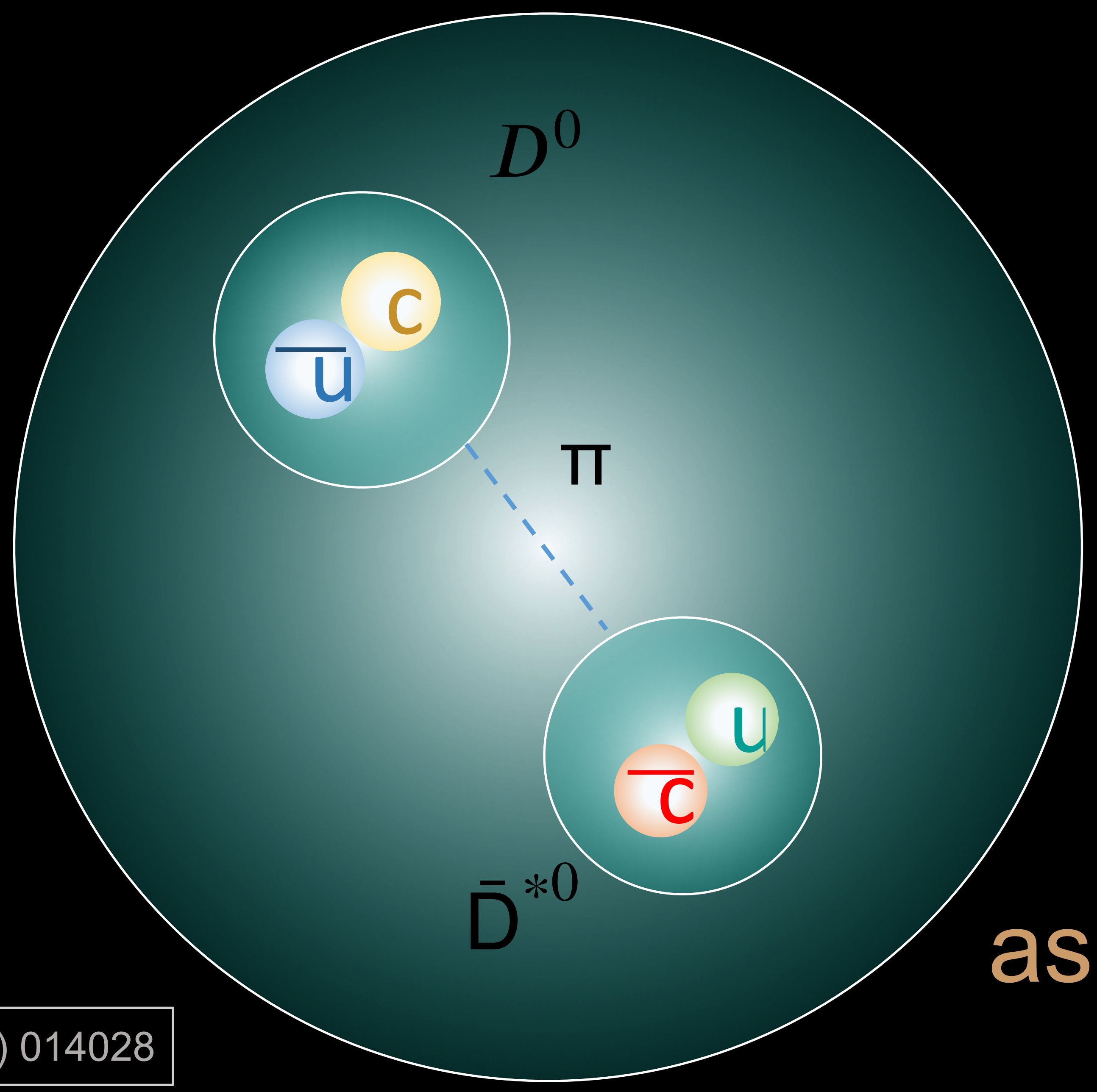
Tetraquark (4q)



$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

PRD 71 (2005) 014028

$D^0 - \bar{D}^{*0}$ molecule

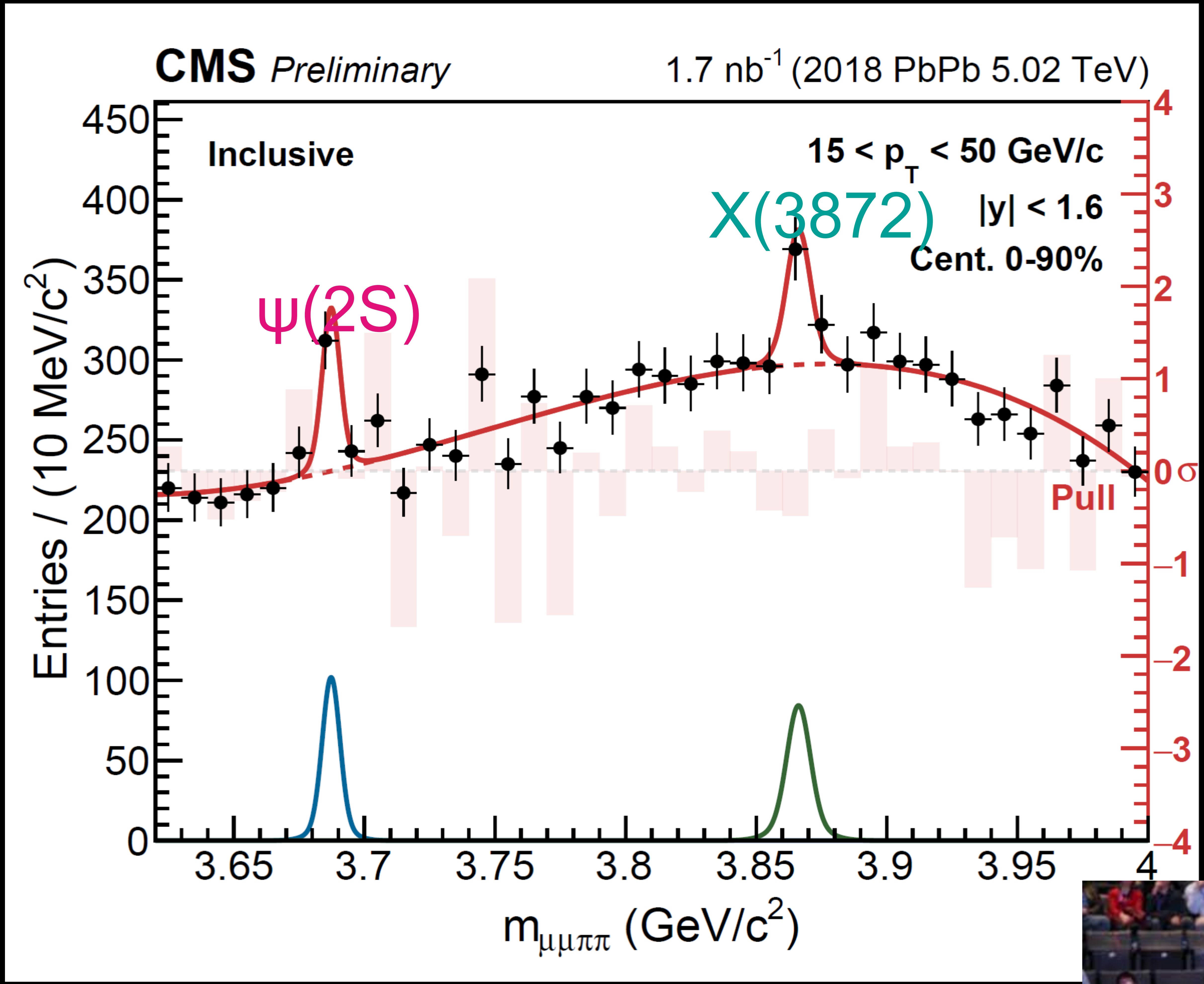


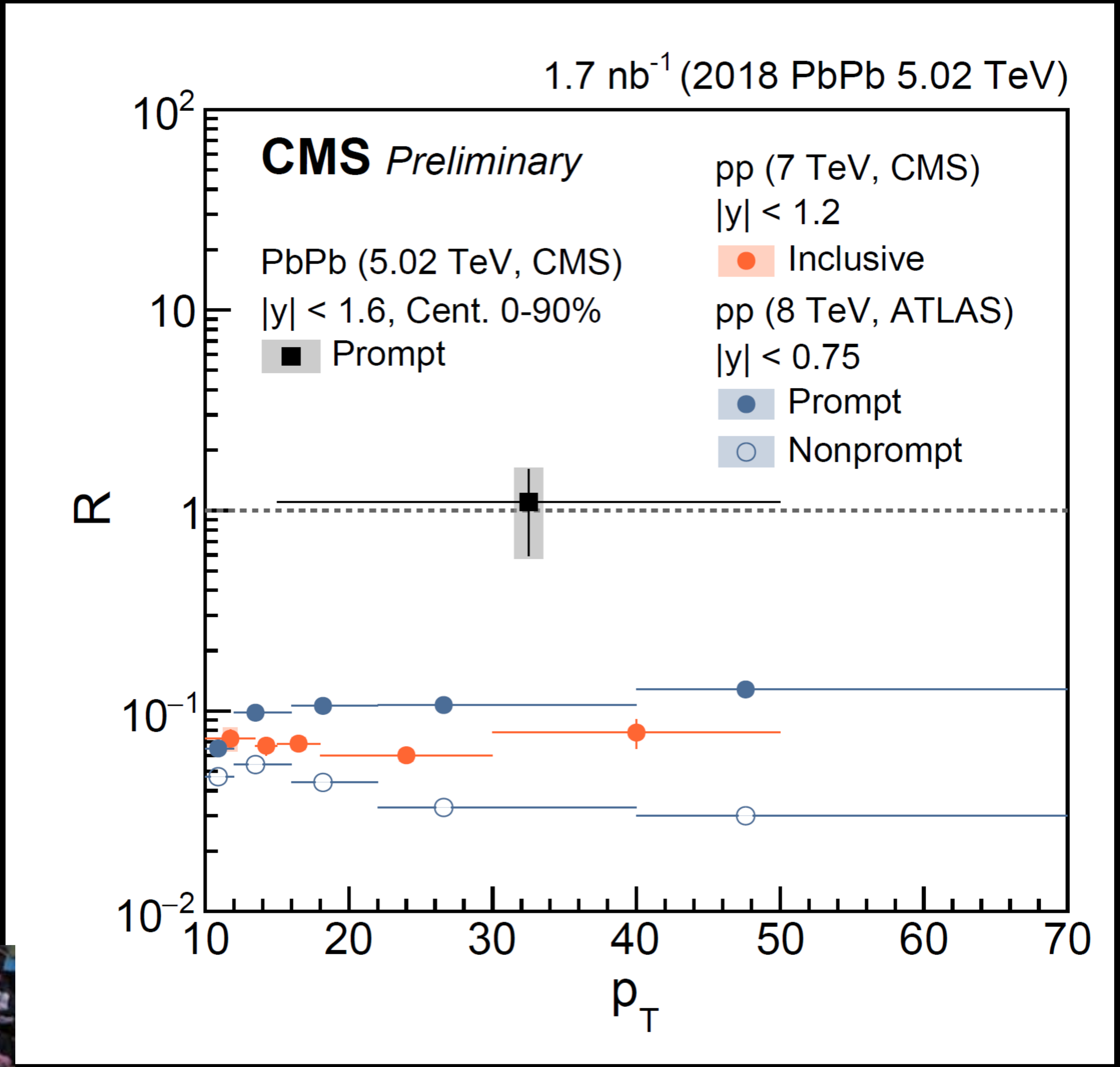
PRD71 (2005) 014028

$r_{molecule}$
as large as 5 fm

Hybrid

EPJA47 (2011) 101





First evidence for X(3872) production in heavy ion collisions

Jing Wang + Yen-Jie Lee

Indication of enhancement in X(3872)/$\psi(2S)$ ratio in PbPb

2025+

LHC Run 4

daft punk
HARDER BETTER
FASTER STRONGER
YACO REMIX
WWW.YACODJ.COM.NU

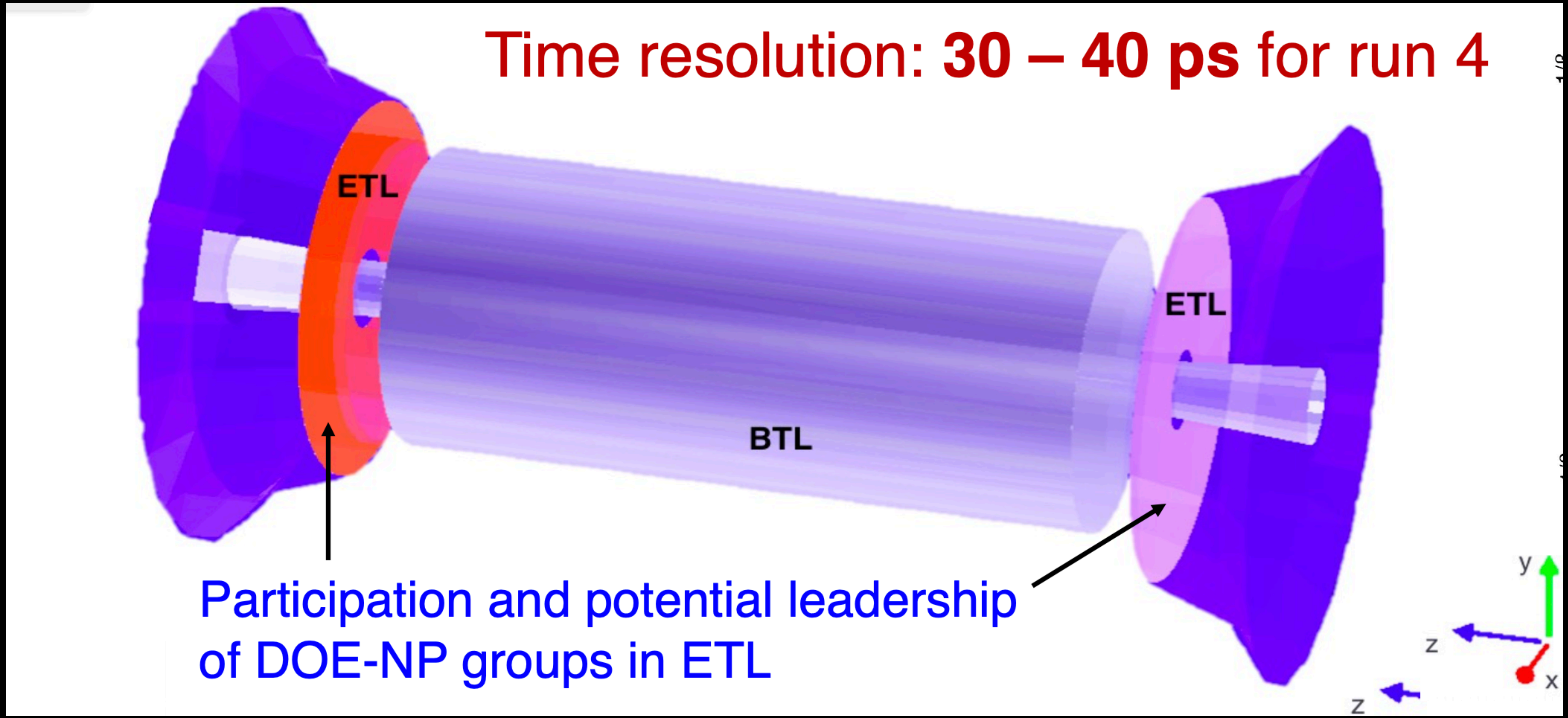
LHC Run 4: Phase 2 upgrades

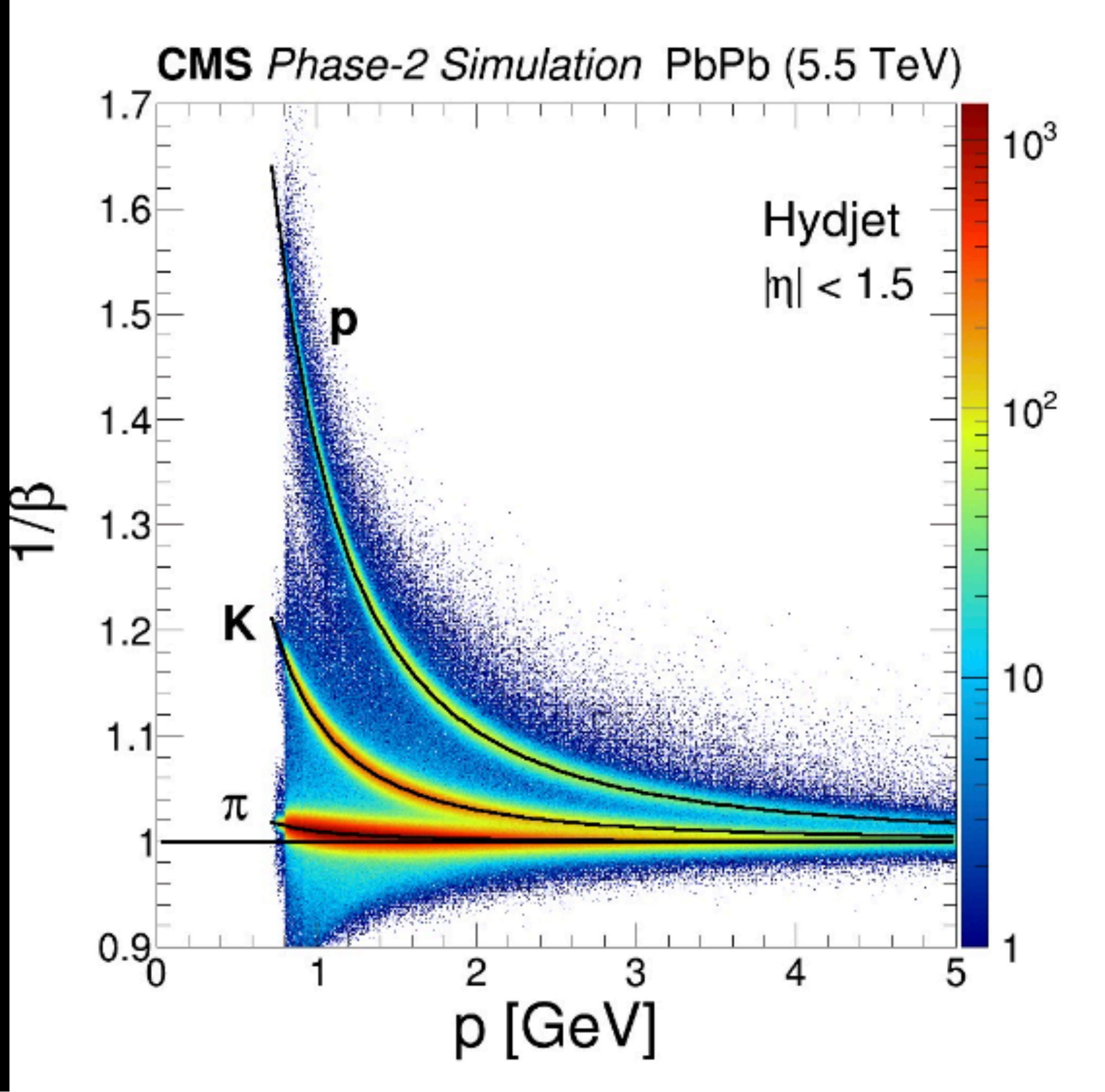
Wider coverage, better precision, higher rate, and …

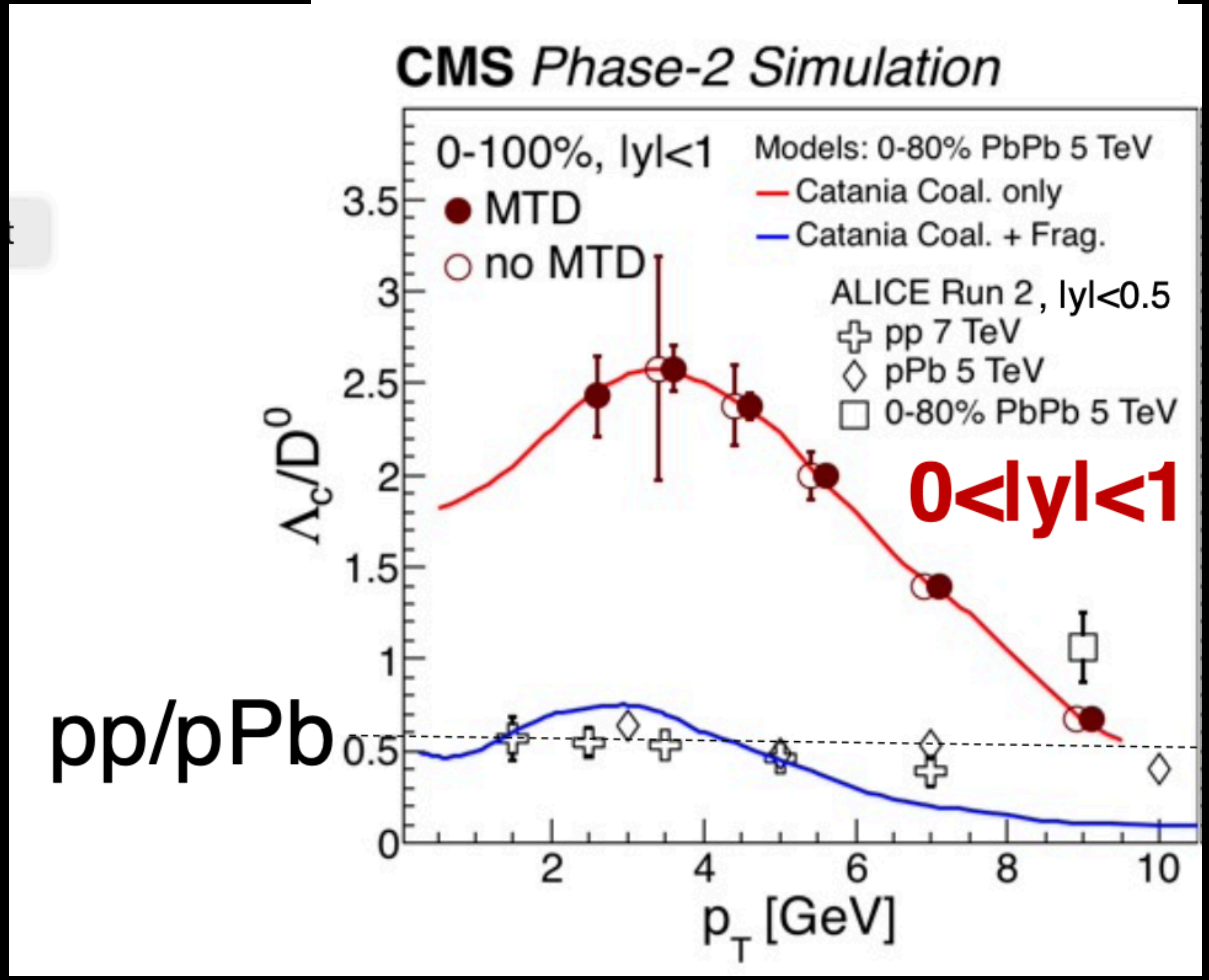
Table 1: Main features of CMS detector at present and Phase 2 upgrades.

Subdetector	CMS present	CMS Phase-2
Inner Tracker	$\|\eta\| < 2.4$, $100\times150\ \mu m^2$ pixel size	$\|\eta\| < 4$, $50\times50\ \mu m^2$ pixel size
Calorimeter	Low-granularity	High-granularity end-cap with silicon sensors
Muon detector	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$
L1 trigger bandwidth	30 kHz for PbPb, 100 kHz for pp and pPb	750 kHz (pass through all PbPb events)
DAQ throughput	6 GB/s	60 GB/s
Time-of-flight for Particle ID	**N/A**	**MTD for charged hadron PID over $\|\eta\| < 3.0$**

MIP Timing Detector

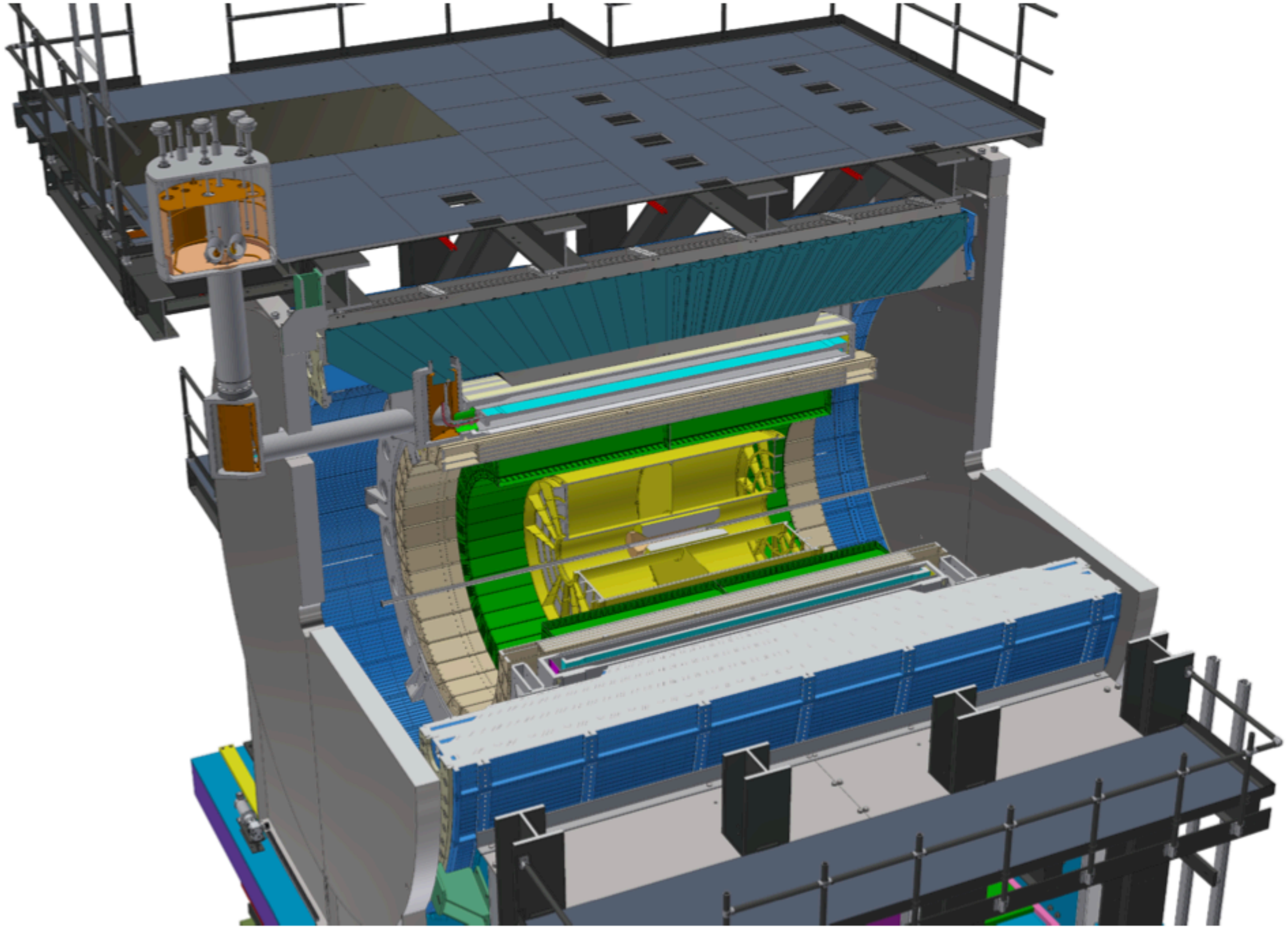




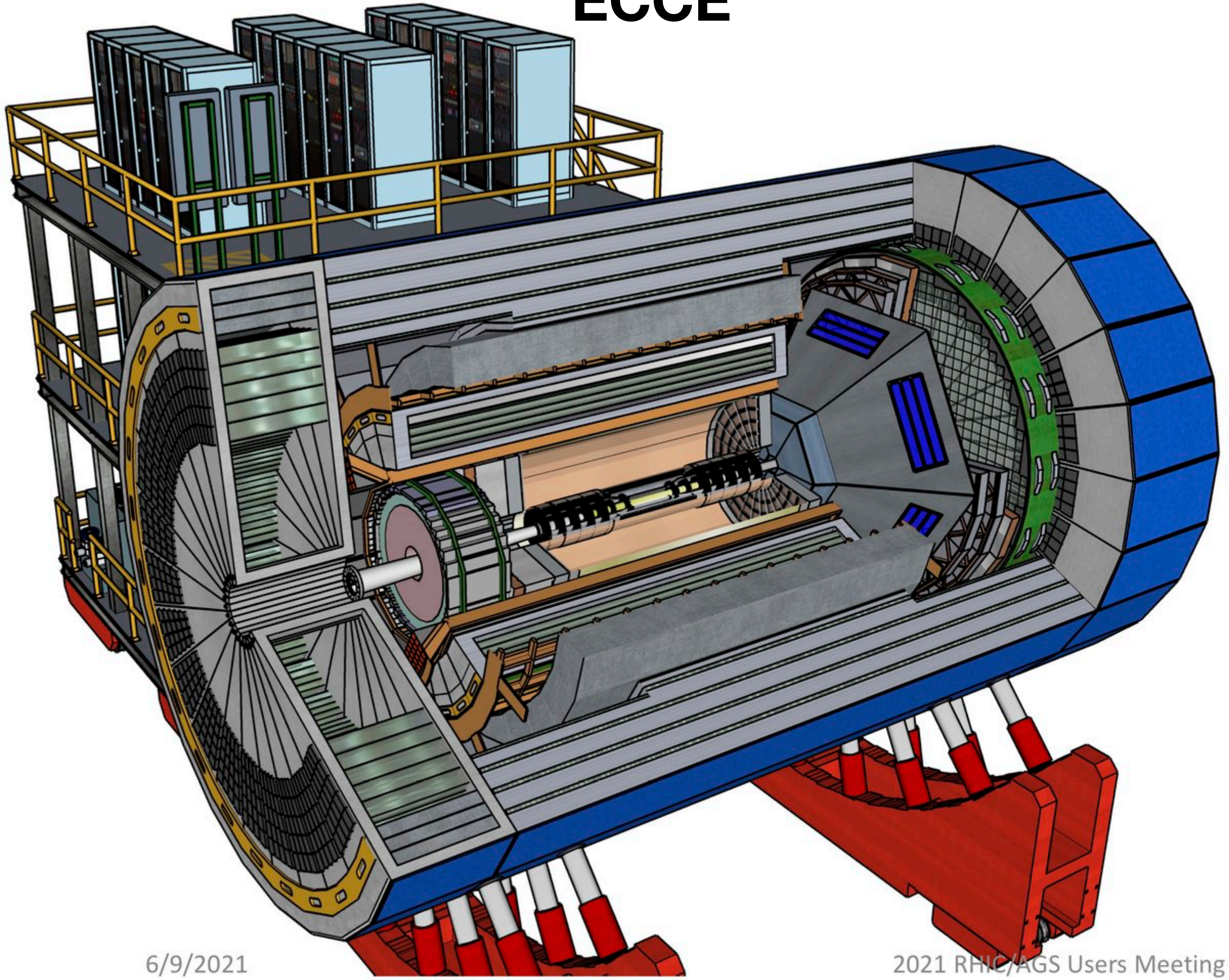


Particle identification improves S/B for many existing measurements (HF, Exotica) and opens new opportunities

sPHENIX



ECCE



6/9/2021

2021 RHIC/AGS Users Meeting