Stony Brook University | The State University of New York

Center for Frontiers in Nuclear Science

Explorations of Quark Gluon Matter: a world ruled by the strong force

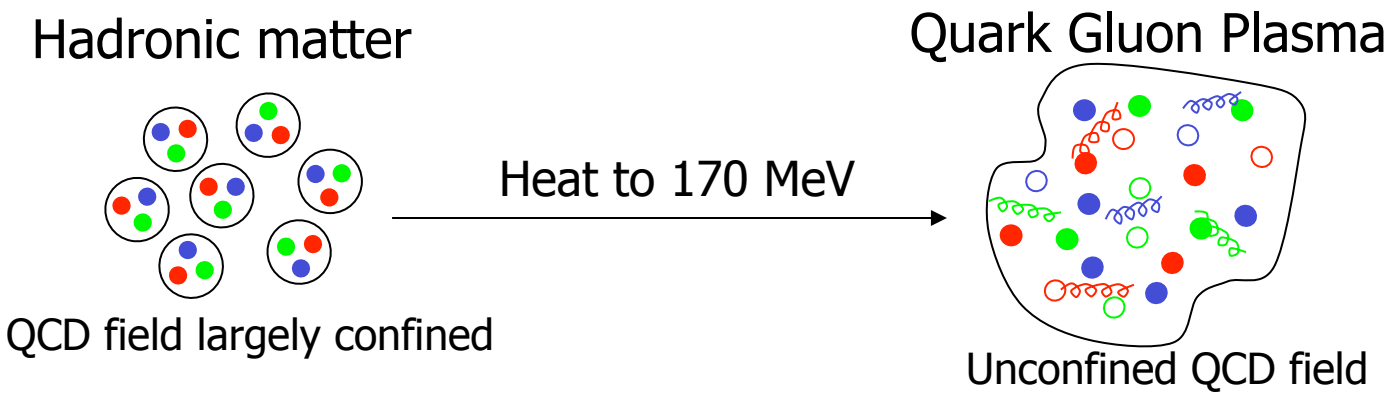
Prof. Jiangyong Jia and Prof. Roy Lacey

Stony Brook University & Brookhaven National Laboratory

Feb 8, 2019

Physics of Quark Gluon Matter

- Study of non-Abelian QCD matter
  - Consists of nucleons, hadrons, quarks or gluons
  - Occupy extended volume, has finite lifetime

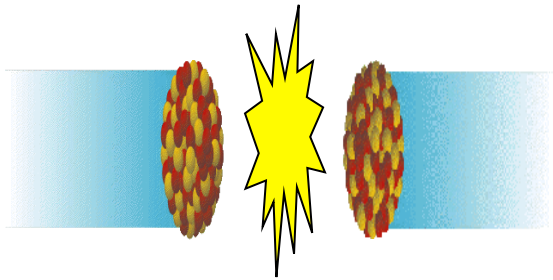


Condense matter physics, but with QCD force instead of QED

Emergent phenomena of multi-body strongly-interacting QCD system

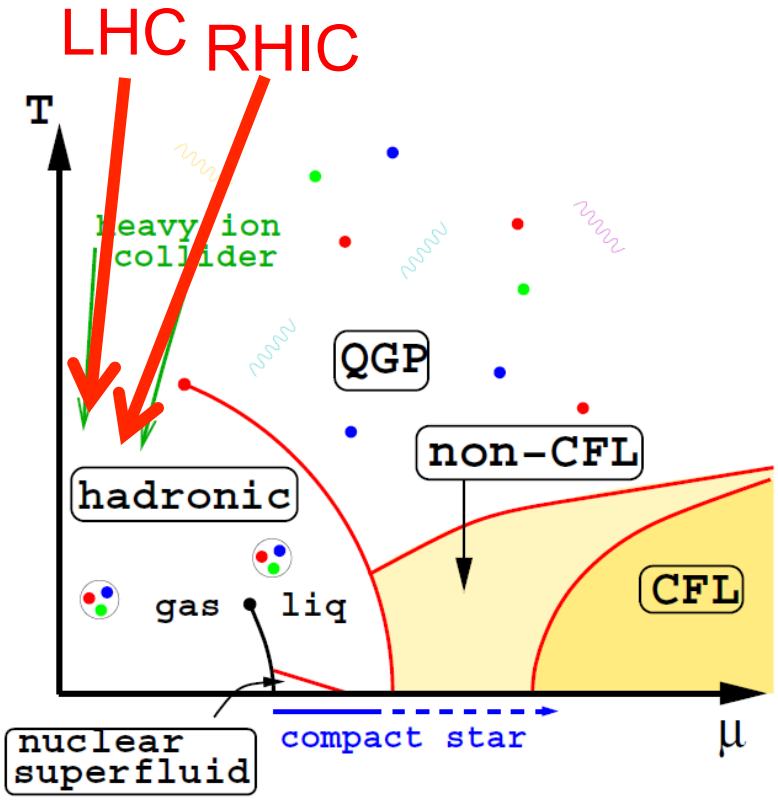
Phases of QCD Matter

- Regions reached by varying √s
  - Changing temperature (T~0.2-0.4 GeV) and chemical potential μ_b.

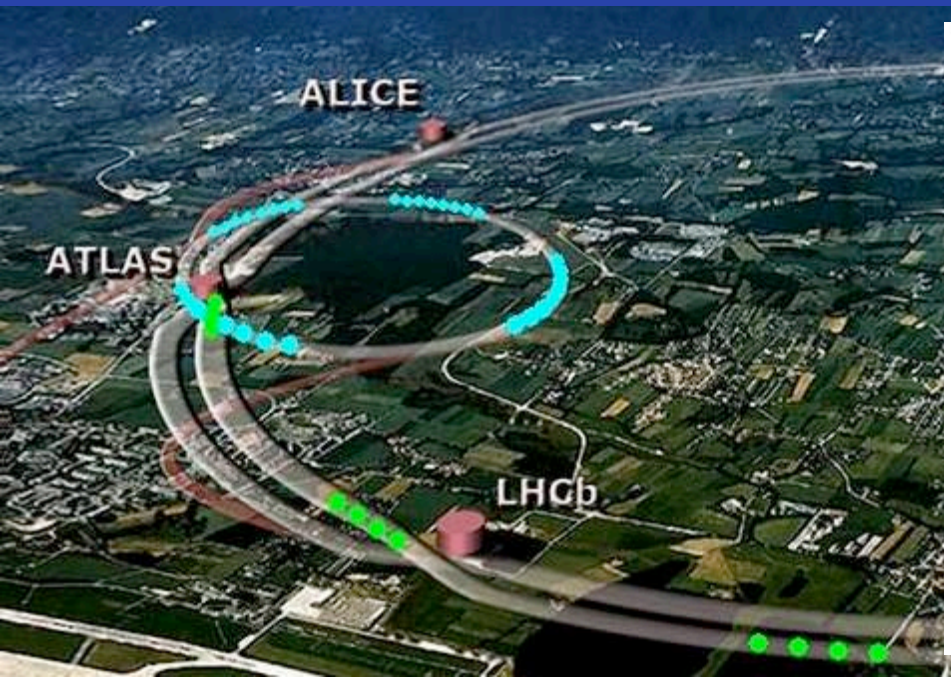


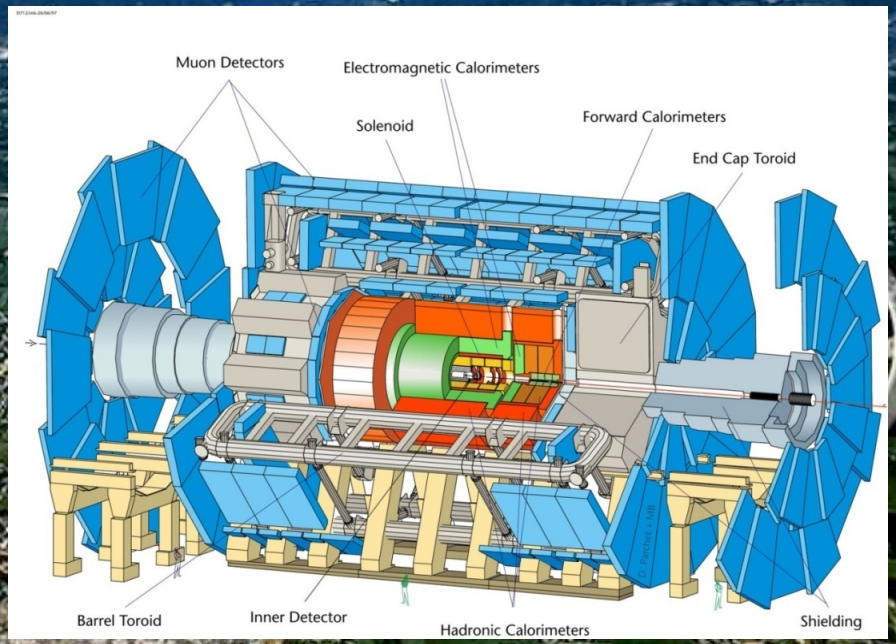
Kinetic energy ➔ heat/matter

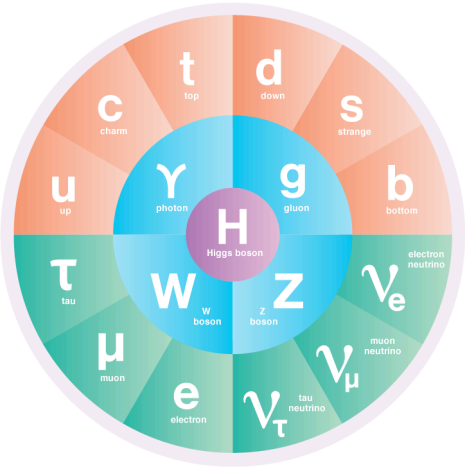
- Some big questions:
  - Confinement and Chiral symmetry restoration.
  - Phase boundaries & Phase transitions.
  - QGP equation of state & various transport properties.
  - QCD at finite T: local parity violation and polarization.
  - …



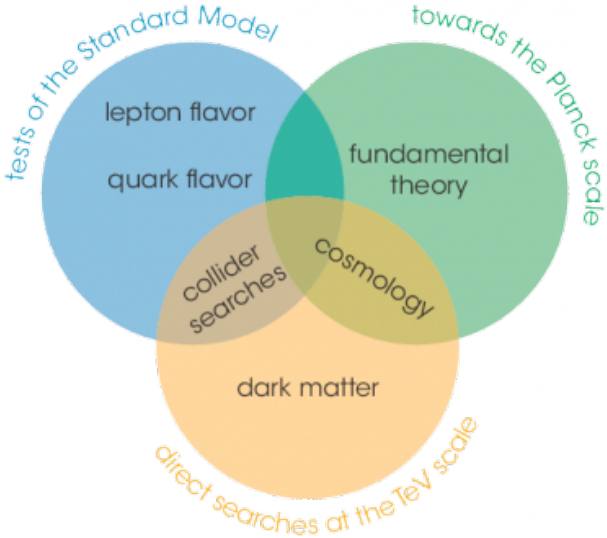
ATLAS and Large Hadron Collider





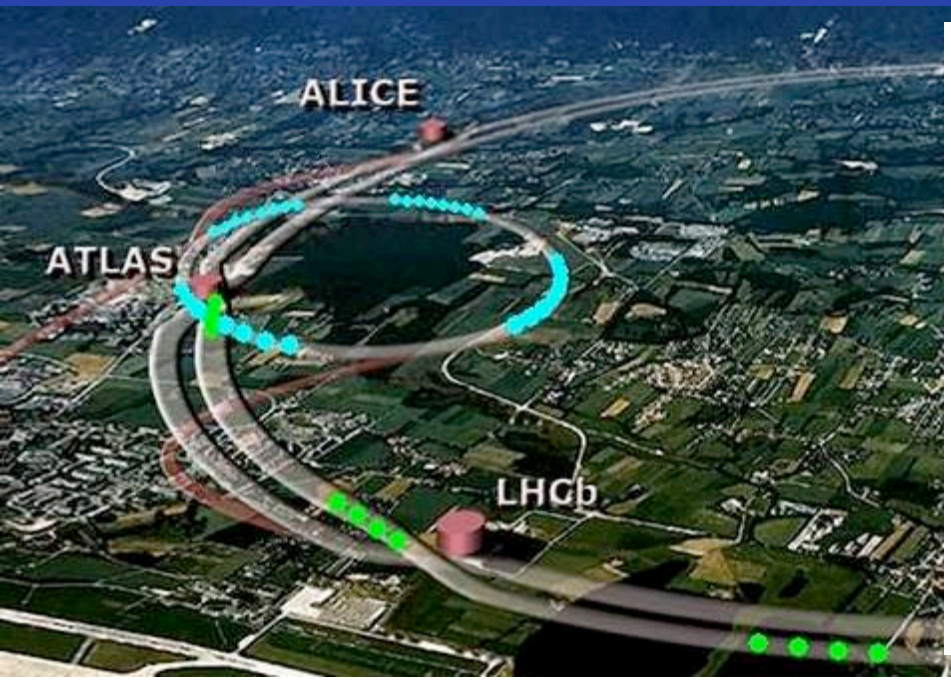


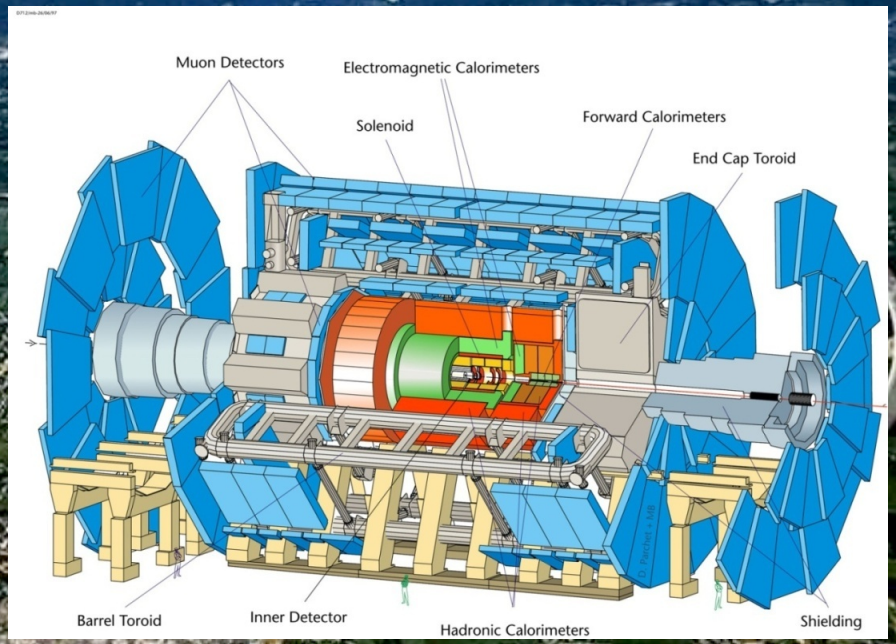
Precision standard model physics



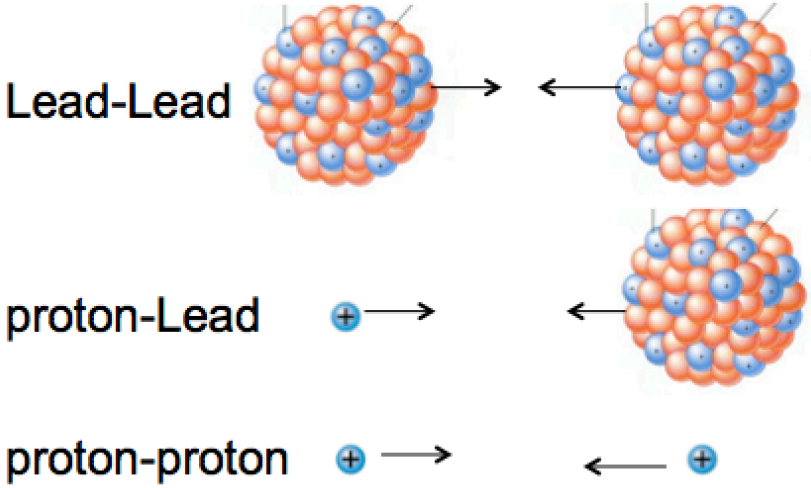
Beyond standard model physics

ATLAS and Large Hadron Collider

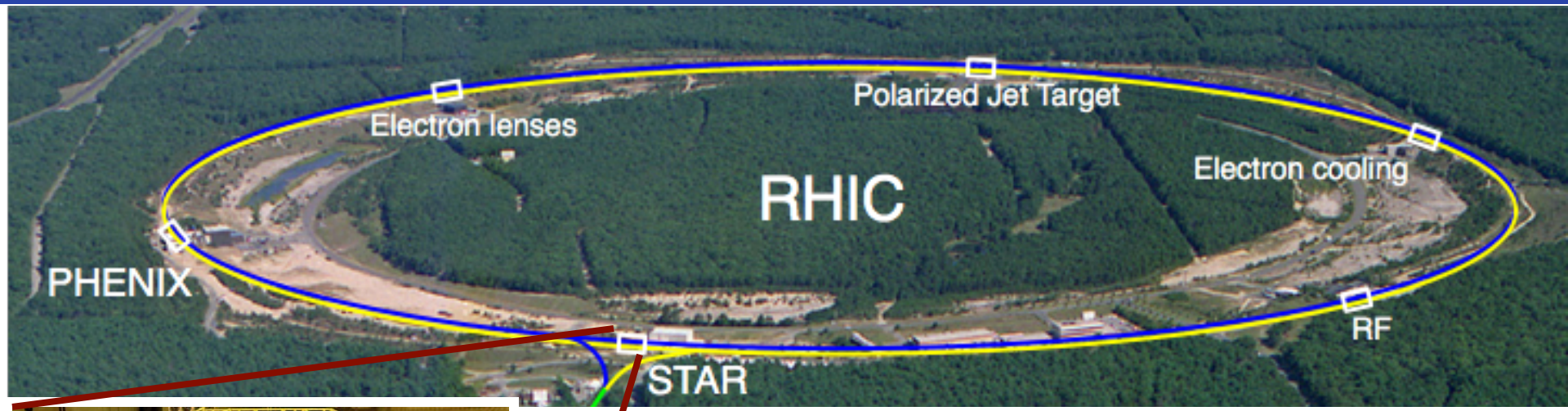


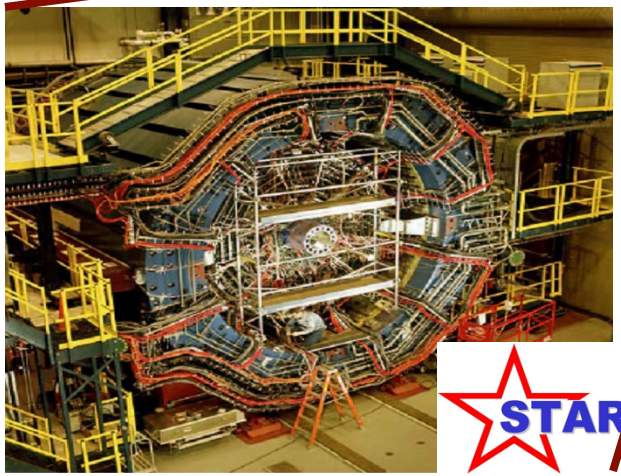


- Collide heavy-ions 1 month/year
  - Produce extended dense partonic matter, Quark-Gluon Plasma (QGP)
- Mostly lead-lead, but also proton-lead, and special proton-proton runs
  - Switching off the QGP effects.



STAR and Relativistic Heavy-Ion Collider





Most versatile collider machine

➔Dedicated heavy-ion machine

➔Any pair of nucleus is possible: A+B

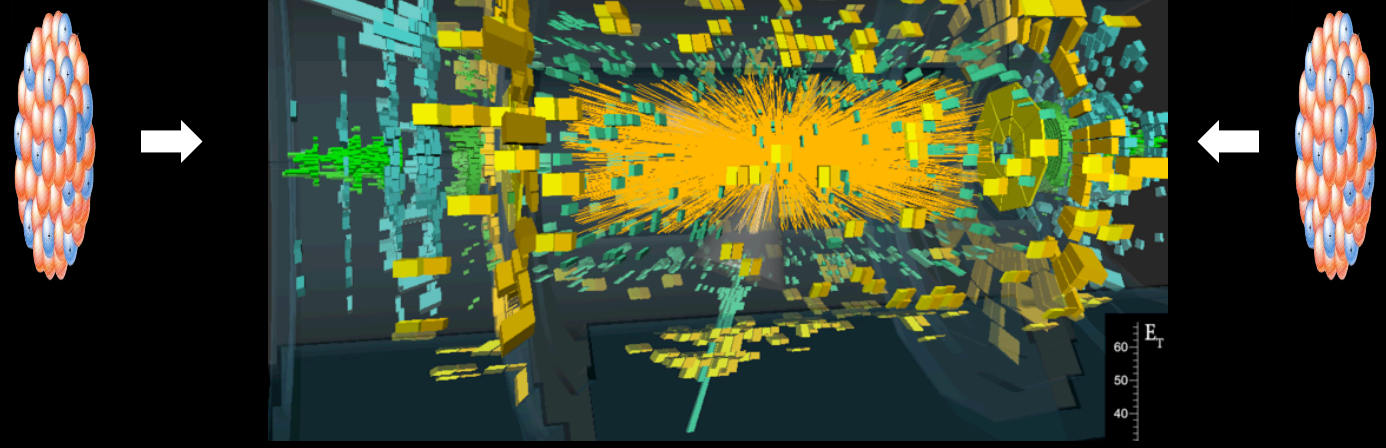
p+p,p+Al, p+Cu,p+Au,
d+Au, He^3+Au, Cu+Au
Au+Au, Zr+Zr, Ru+Ru, U+U, so far

➔Broad energy range 3.9-200 GeV

➔Stepping stone to Electron-Ion Collider

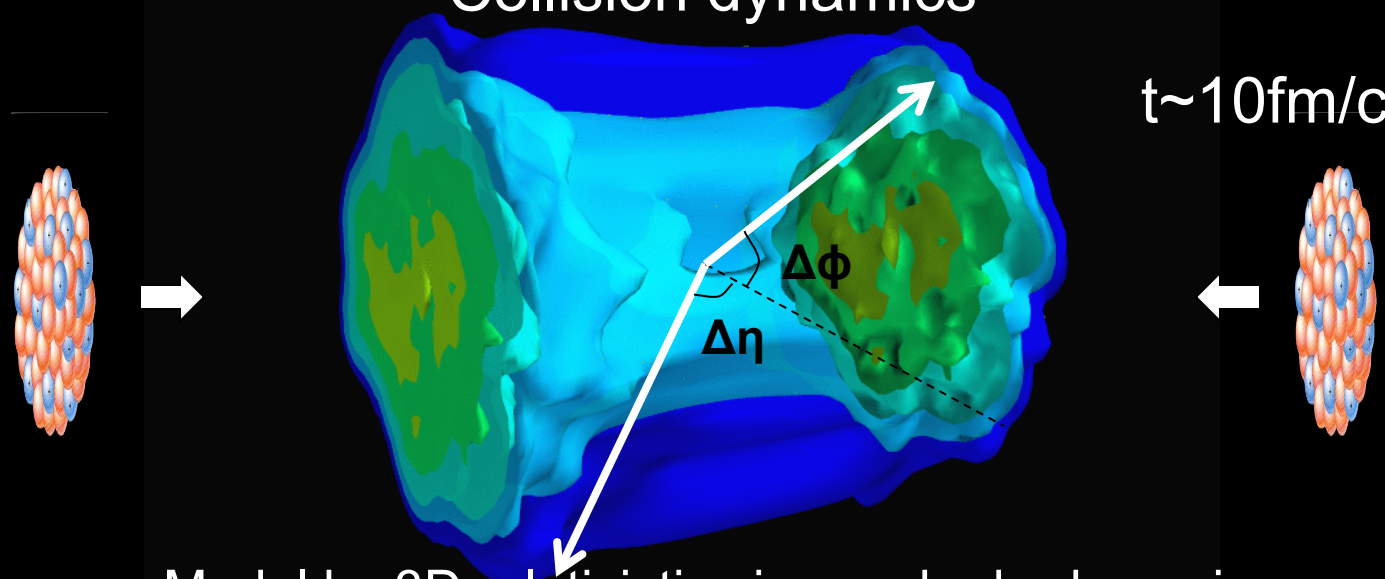
Seen by detector

$t \sim 10 m/c = 10^{-8}$ s



Collision dynamics

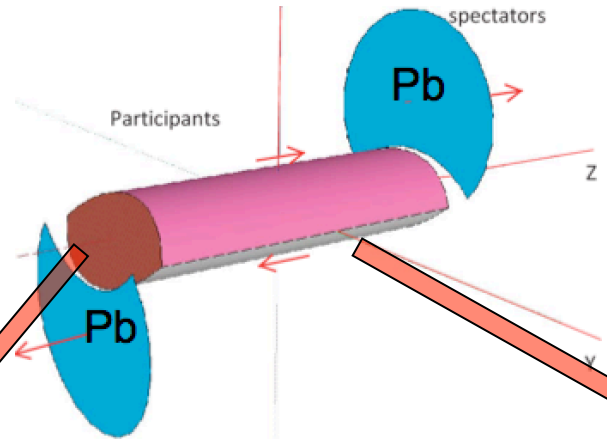
$t \sim 10 fm/c = 10^{-22}$ s



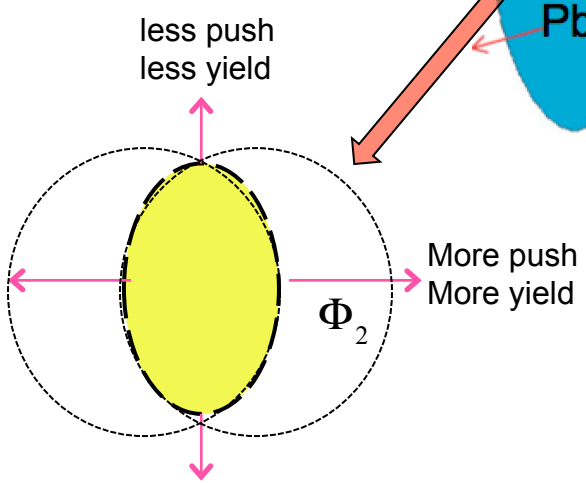
Model by 3D relativistic viscous hydrodynamics

Credit: Bjoern Schenke

Transverse collective flow



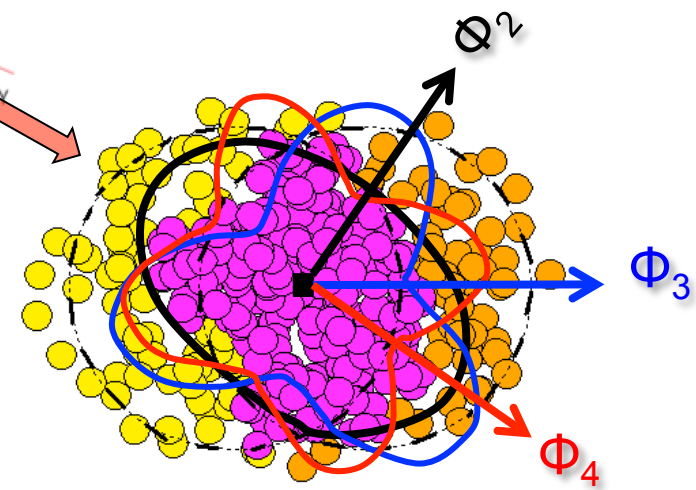
Simplified



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_2)$$

Elliptic flow

Realistic



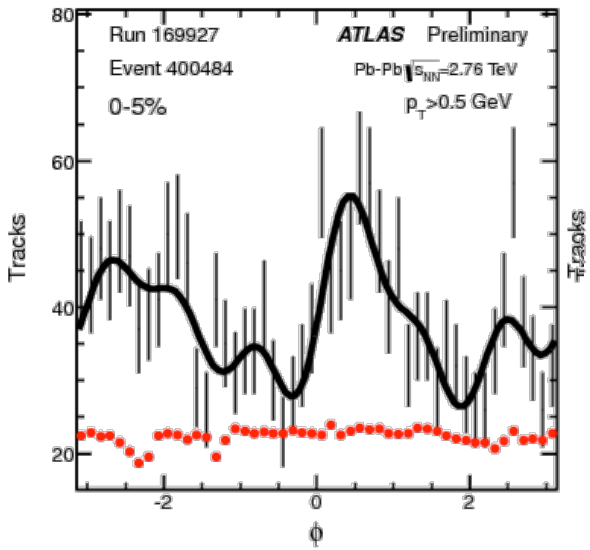
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

+directed flow, triangular flow+..

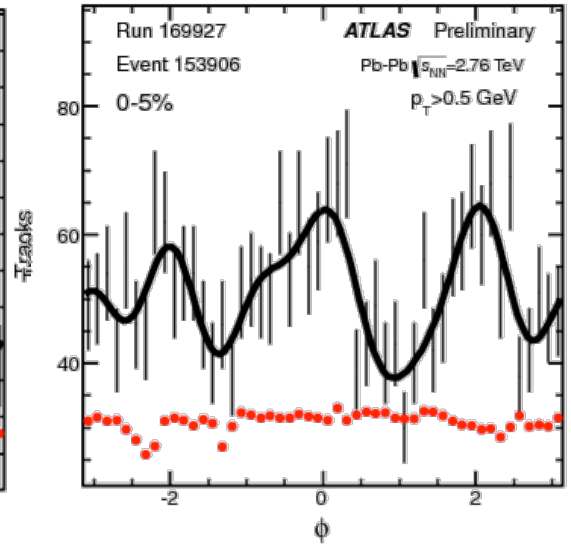
Hydrodynamic fluid behavior

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n\left(\phi - \Phi_n\right)$$

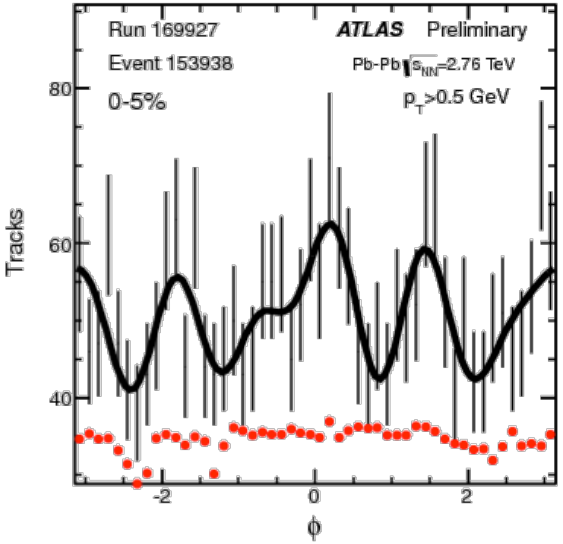
Event 1



Event 2



Event 3



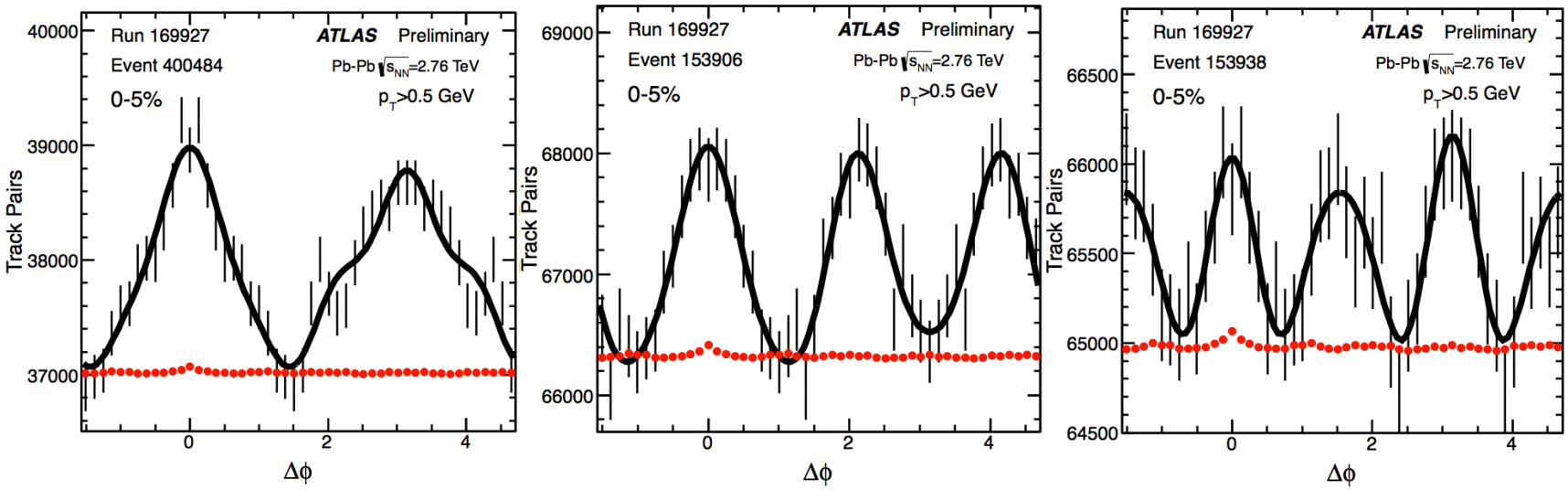
- v_n sensitive to initial perturbation and viscosity (η/s).
  - Bigger initial fluctuation lead to bigger v_n
  - Small viscosity ensure efficient transfer of initial fluctuation to final state flow.

$\eta/s \sim 1/4\pi$, the lower bound from string theory via AdS/CFT

Pair distributions in same events

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_n v_n^a v_n^b \cos(n\Delta\phi)$$

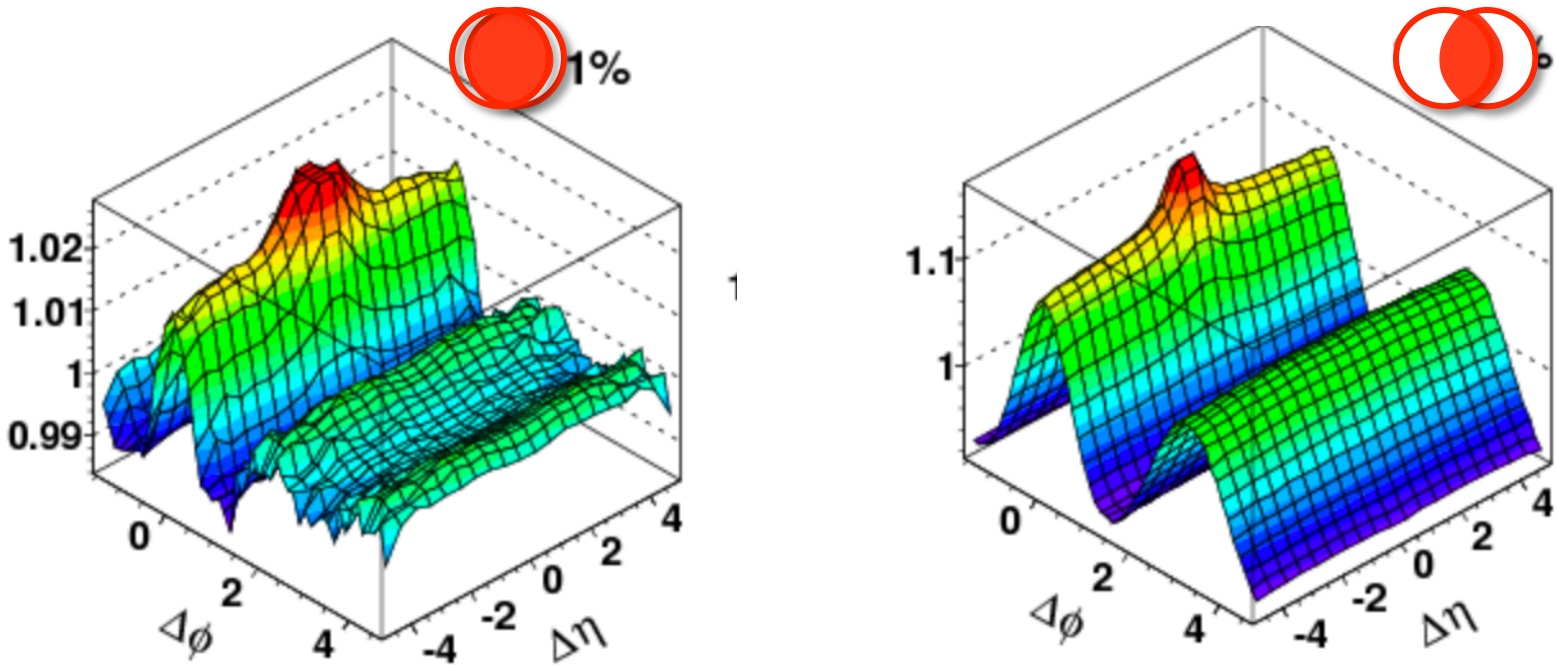
Event 1 Event 2 Event 3



- v_n sensitive to initial perturbation and viscosity (η/s).
  - Bigger initial fluctuation lead to bigger v_n
  - Small viscosity ensure efficient transfer of initial fluctuation to final state flow.

$\eta/s \sim 1/4\pi$, the lower bound from string theory via AdS/CFT

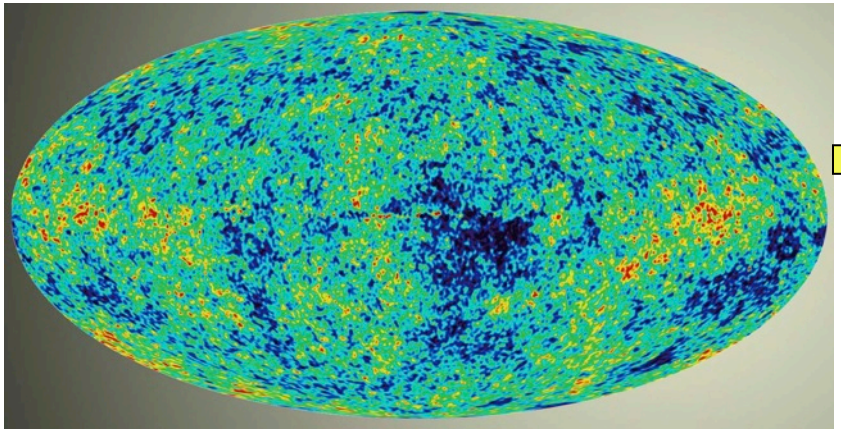
Pair distribution averaged over many events

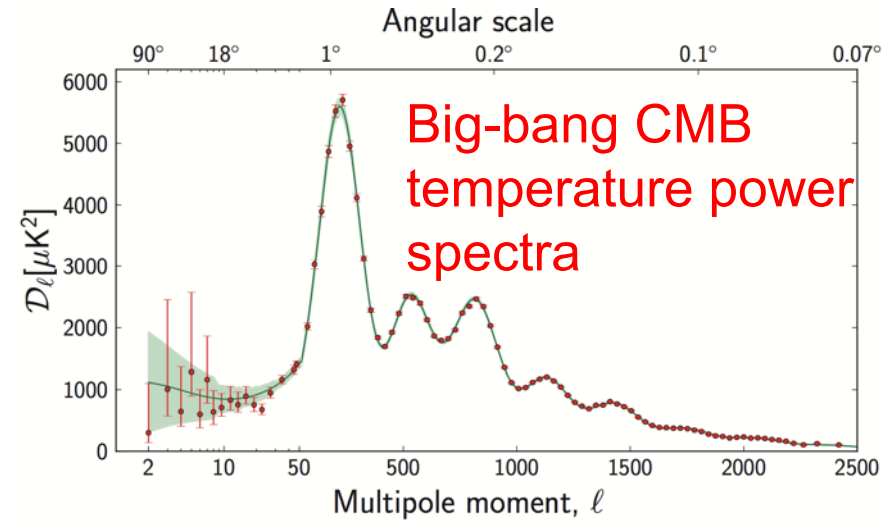


- Δφ shape extended over wide Δη, the so-called "ridge"
  - Δη=5 means pair from 10° and 170° → correlation must arise from early time
  - Confirmed the hydrodynamic response to initial quantum fluctuations.

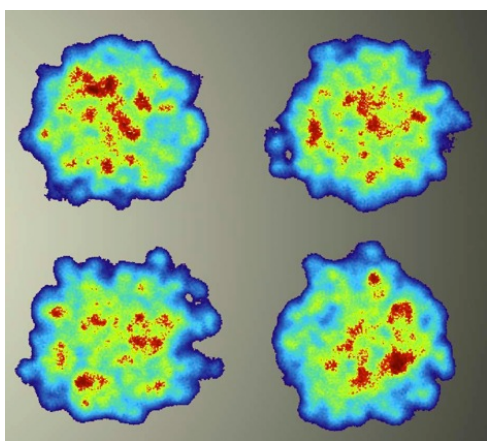
Analogy to the big-bang

One big-bang event

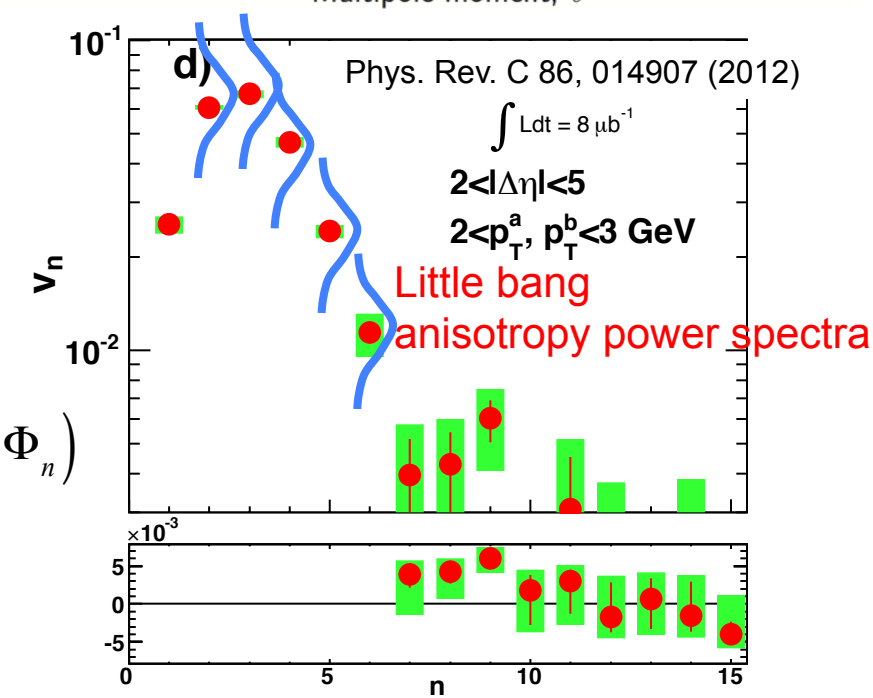




Many little-bang events

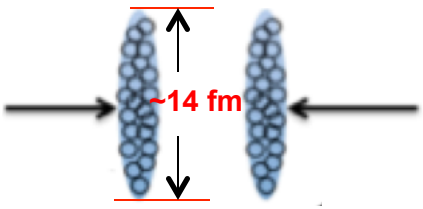


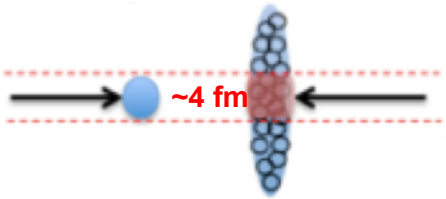
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n\left(\phi - \Phi_n\right)$$

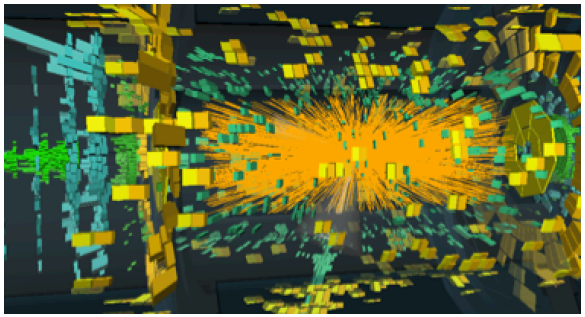


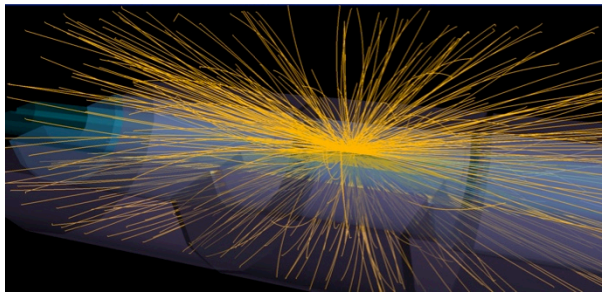
Probability distribution: $p(v_n, v_m, \ldots, \Phi_n, \Phi_m \ldots)$; **Effort 1**

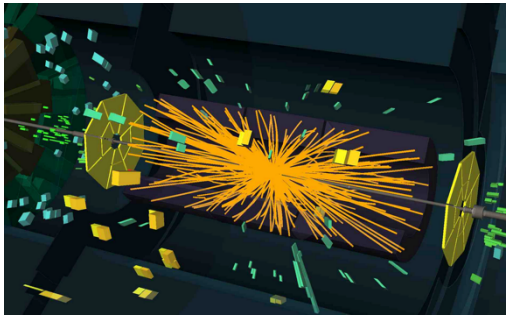
What is the smallest droplet of QGP?









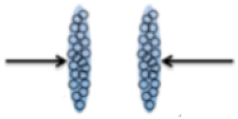


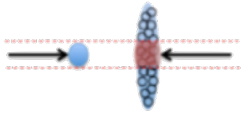
~30000 particles* ~2000 particles* ~ 600 particles*

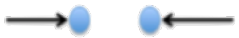
→ Change matter size, life-time and space-time dynamics

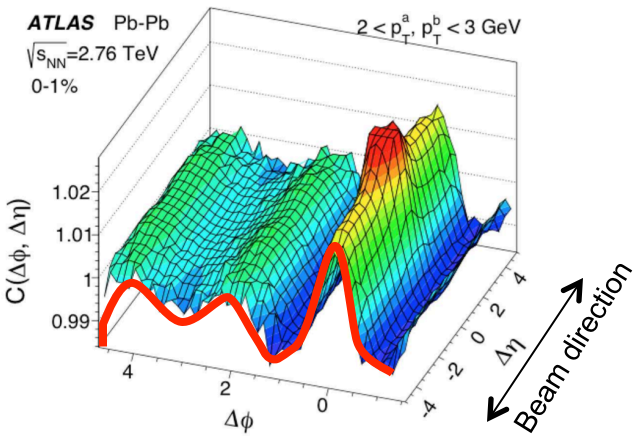
* Rough number in very high-multiplicity events, integrated over full phase space

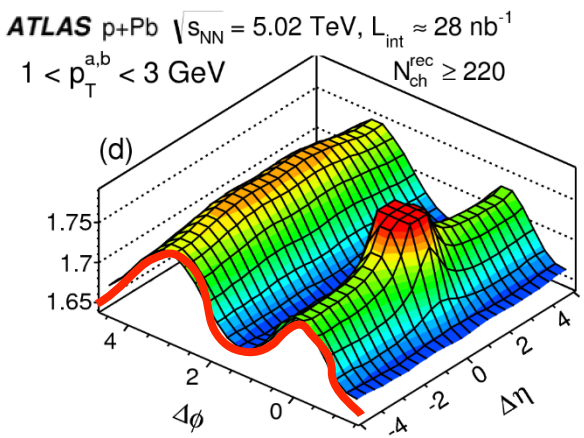
Big surprise: collective feature seen in small systems!

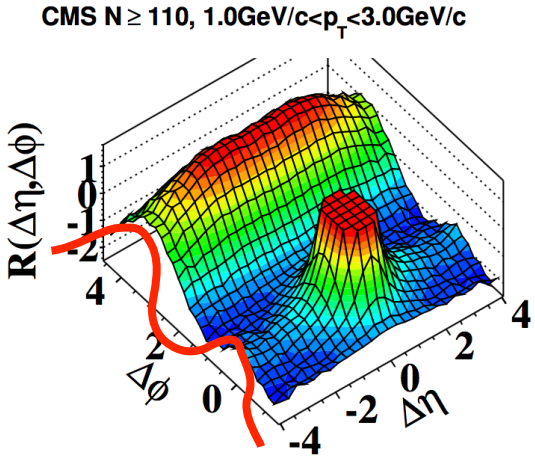






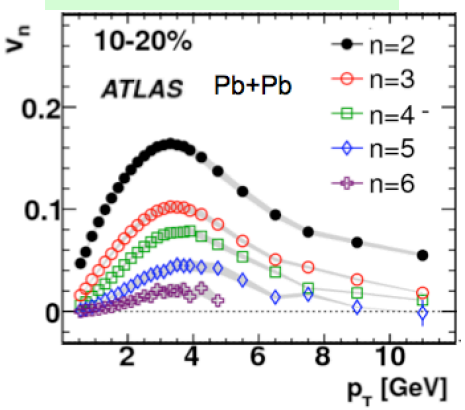




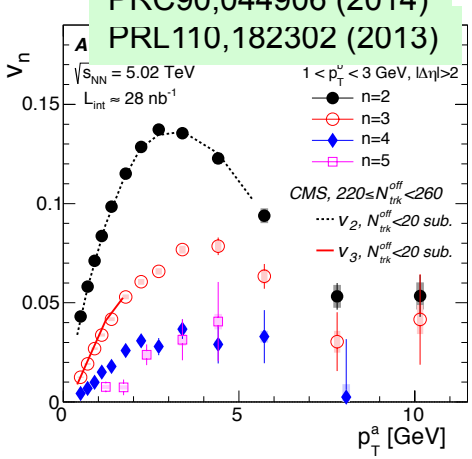


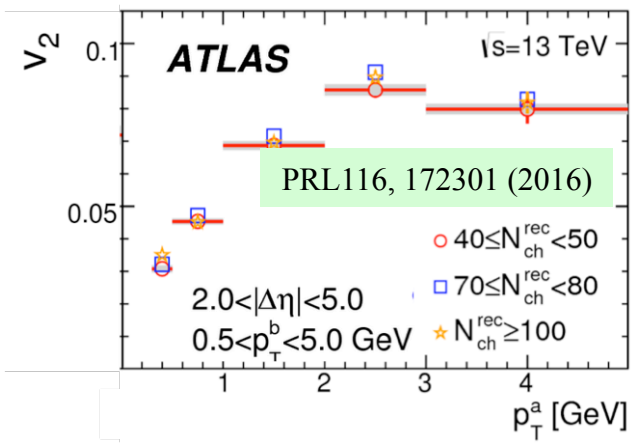
- Long-range ridge observed in all collision systems $\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2 v_n^a v_n^b \cos n\Delta\phi$

PRC86,014907(2012)



PRC90,044906 (2014)
PRL110,182302 (2013)

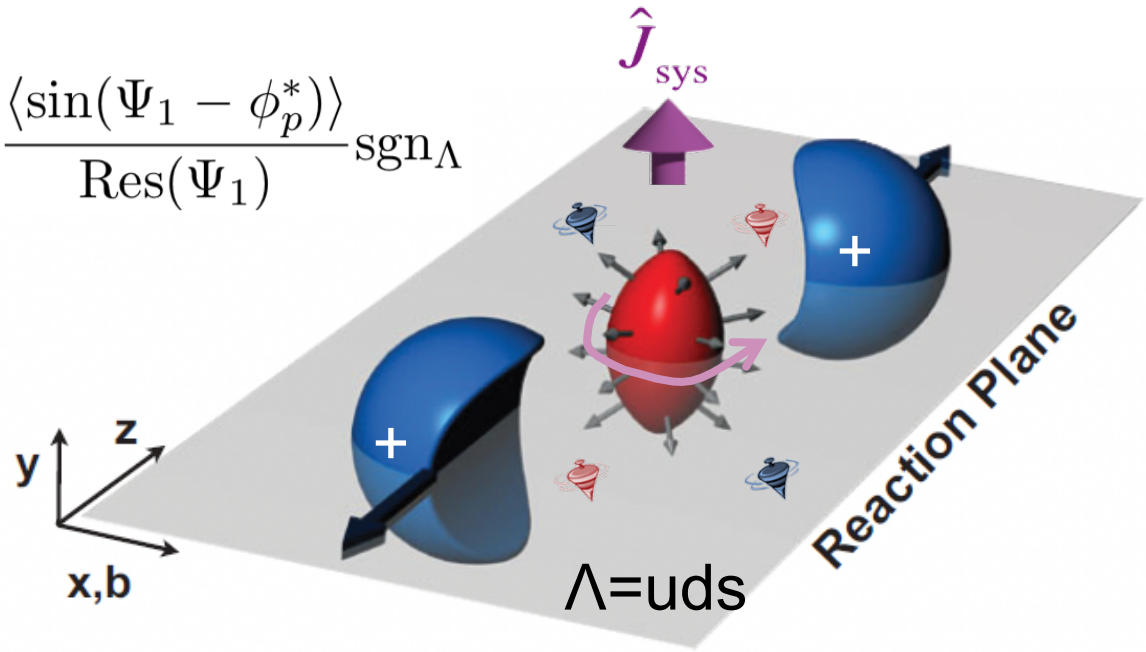




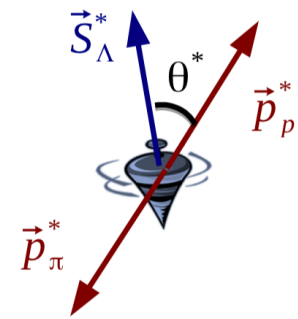
How QCD multi-body non-perturbative interactions lead to this? **Effort 2**

Vorticity of the Quark-Gluon Matter

$$P_H = \frac{8}{\pi\alpha}\frac{\langle \sin(\Psi_1 - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}\mathrm{sgn}_\Lambda$$



$$\vec{S}_\Lambda \propto \vec{\omega}$$



Daughter proton preferentially decays into the direction of Λ's spin (opposite for anti-Λ)

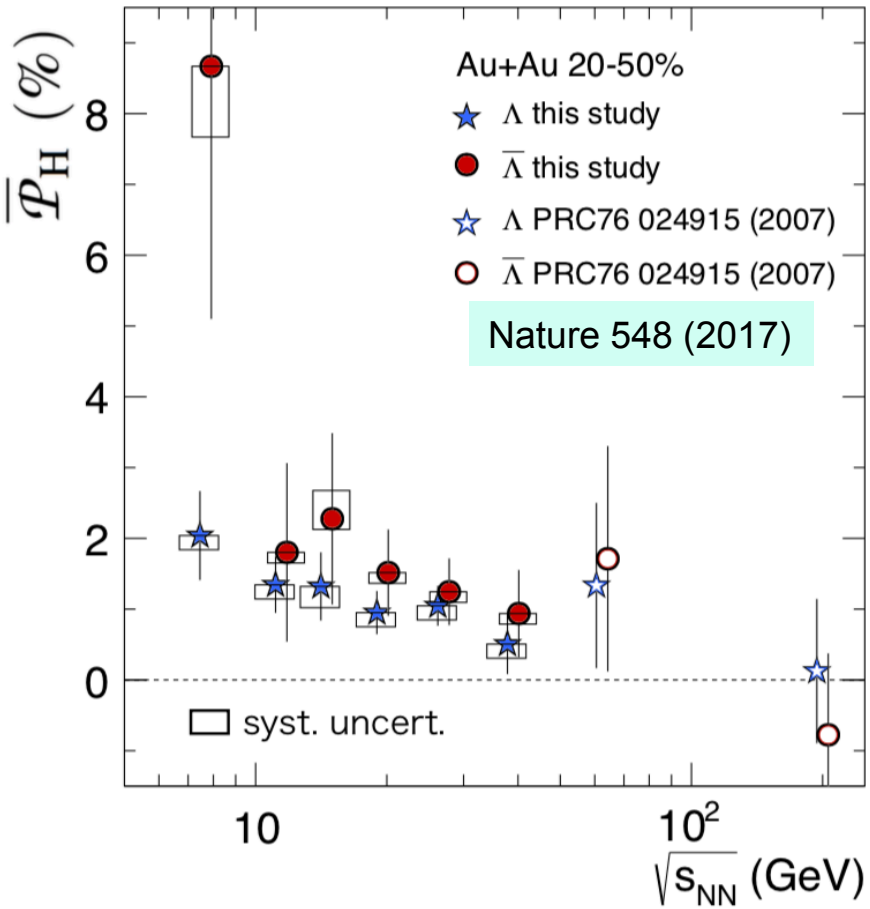
α=0.642

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

- Initial longitudinal flow asymmetry ➔ Global angular momentum
- J_{sys} transfer to Λ (=uds) polarization S_Λ via spin-orbit coupling.
- Parity-violating decay Λ→π+p, transfer to proton polarization

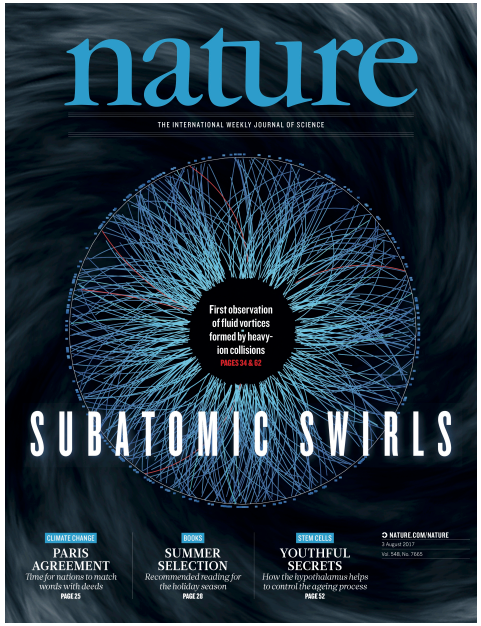
➔Direct probe of "QGP vorticity" from measured p_H.

Quantifying the QGP vorticity



Hydrodynamic relation:

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'}\right)/\hbar \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

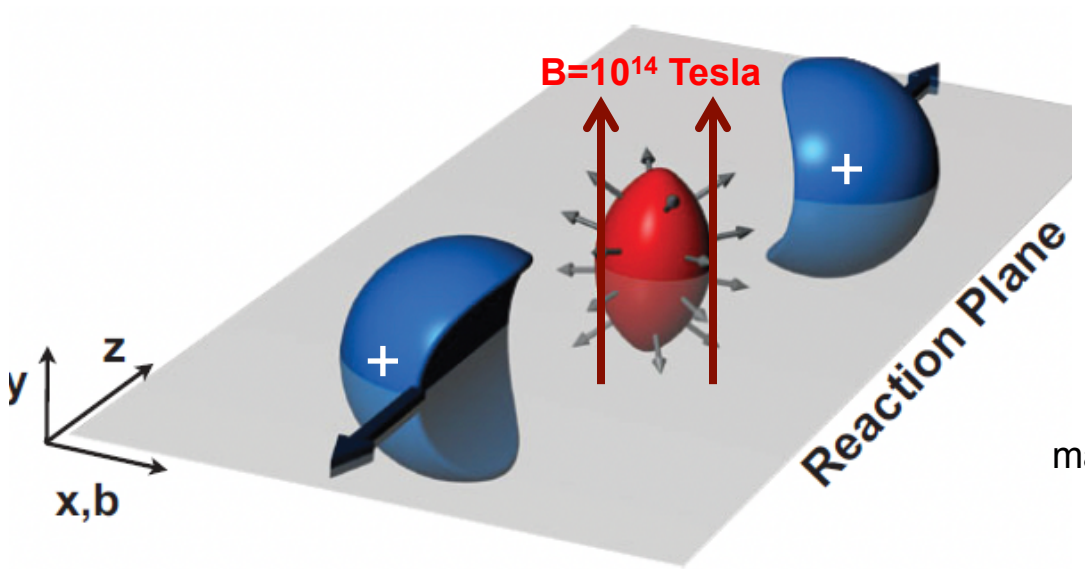


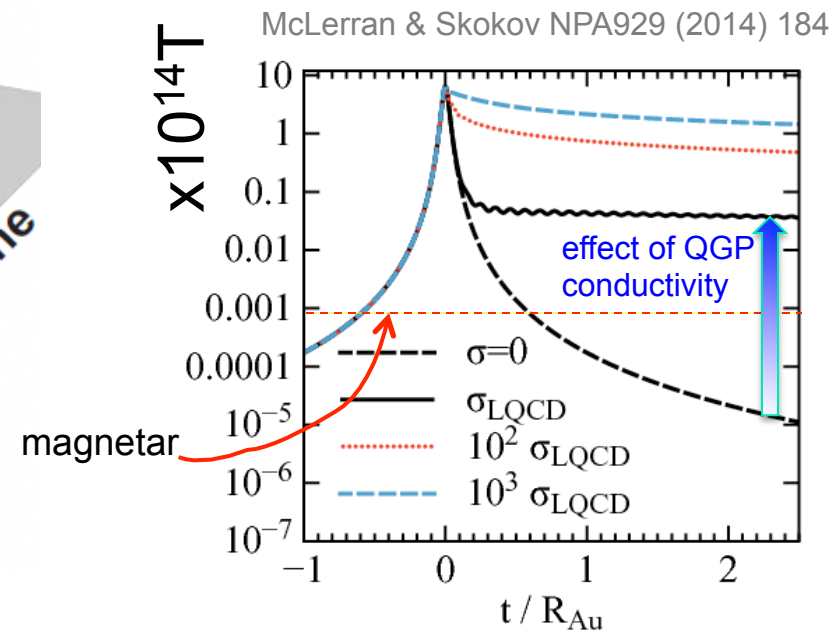
Perfect QGP fluid is also the most vortical fluid

- ϖ expect to increase for lower energy → Beam Energy Scan (2019-2021)

Effort 3

HI collision as source of magnetic field

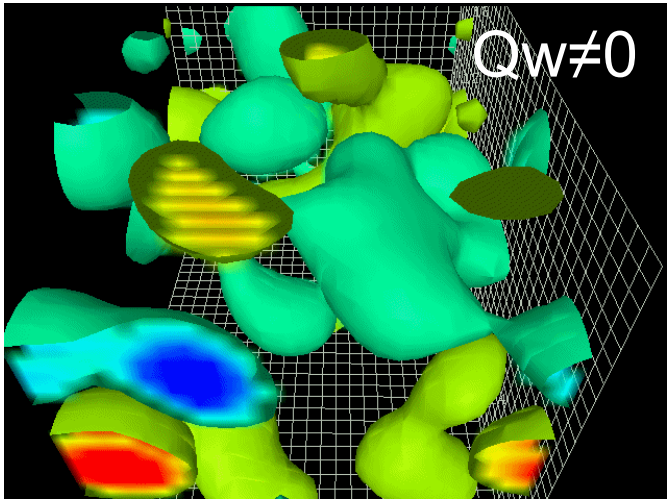




Create strong yet short-lived B-field

Chiral magnetic effect

Lattice QCD

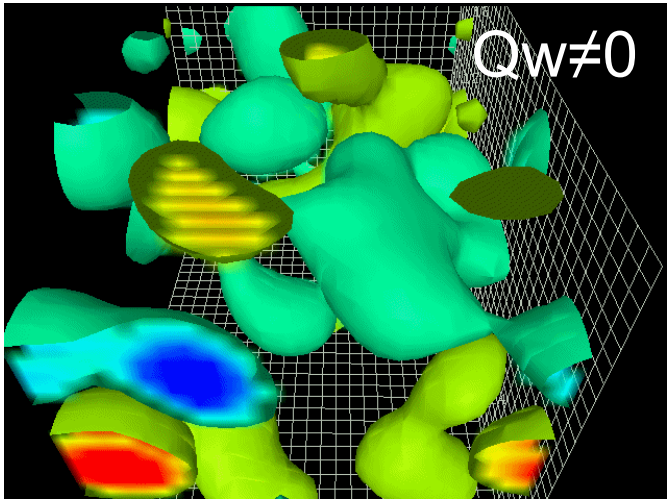


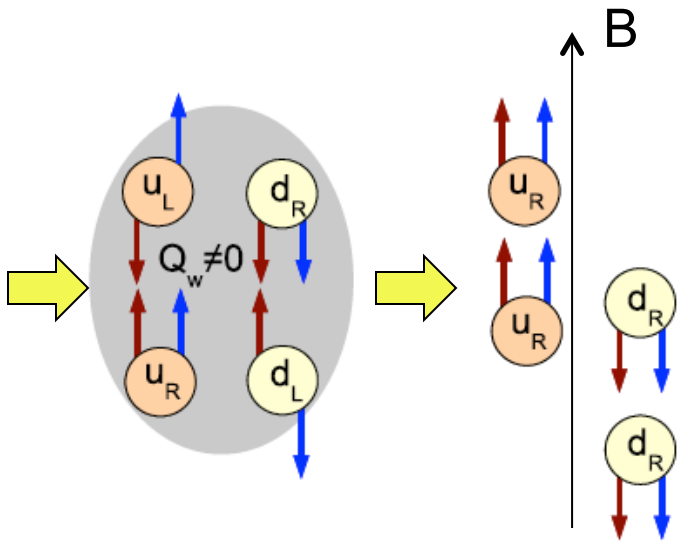
- The chiral anomaly of QCD

  ➔ topological charge fluctuation of Gauge field Qw≠0

Chiral magnetic effect

Lattice QCD





Spin

Momentum

$$\langle \mu_5^2 \rangle \neq 0$$

$$\langle J J \rangle \neq 0$$

spin alignment in B-field:
opposite direction for
opposite charges

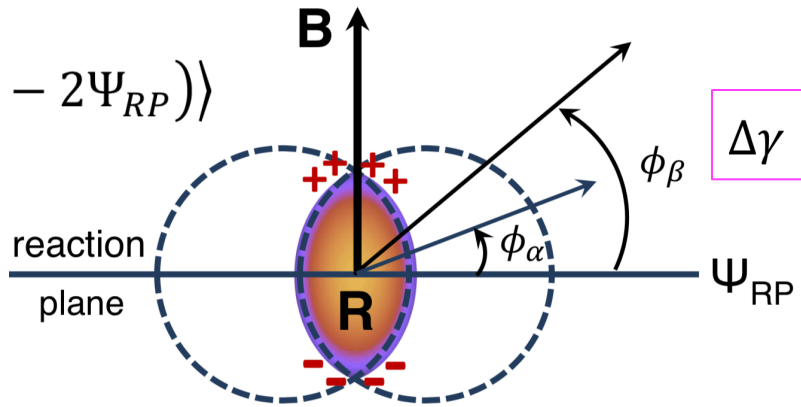
$$\vec{J} = \frac{e^2}{2\pi^2}\, \mu_5\, \vec{B}$$

handedness:
momentum and spin,
aligned or anti-aligned

- The chiral anomaly of QCD
  - ➔ topological charge fluctuation of Gauge field Qw≠0
  - ➔ creates differences in the number of left and right handed quarks.
  - ➔ excess of right /left handed quarks lead to current flow along magnetic field

Experimental observation

$$\gamma^{(\pm,\pm)} \equiv \langle \cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\Psi_{RP}) \rangle$$



Expectation:

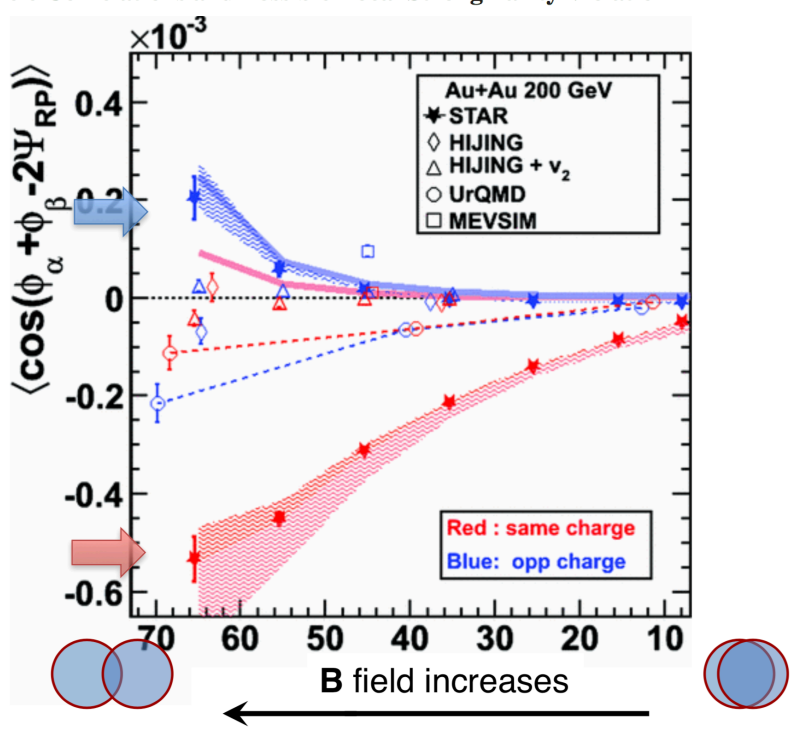
$$\Delta\gamma \equiv 2\gamma^{(+,-)} - \gamma^{(+,+)} - \gamma^{(-,-)} > 0$$

PRL 103, 251601 (2009)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

+- pairs

++,-- pairs



If this is true:

- First observation of QCD topological charge
- Deconfinement and chiral symmetry restoration
- Strong B field & perfect conductivity of Quark-gluon plasma

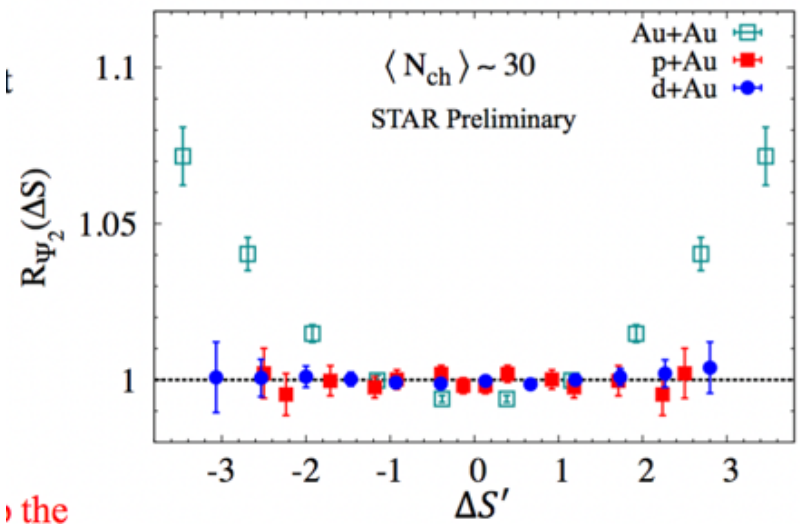
Controlling the background

But: Δγ= signal + flow-background

Recent studies suggest background could be >80%

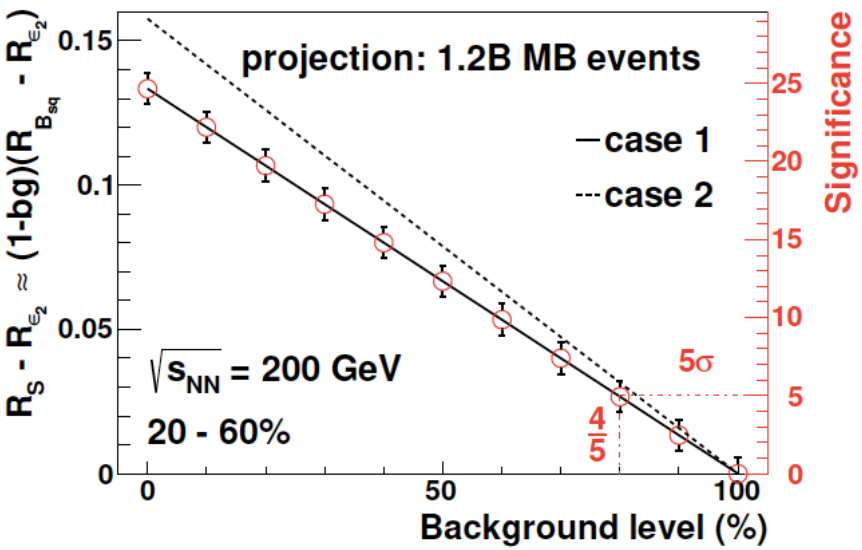
Solution:

Alternative observable



Better Control experiment

$^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$ vs. $^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$



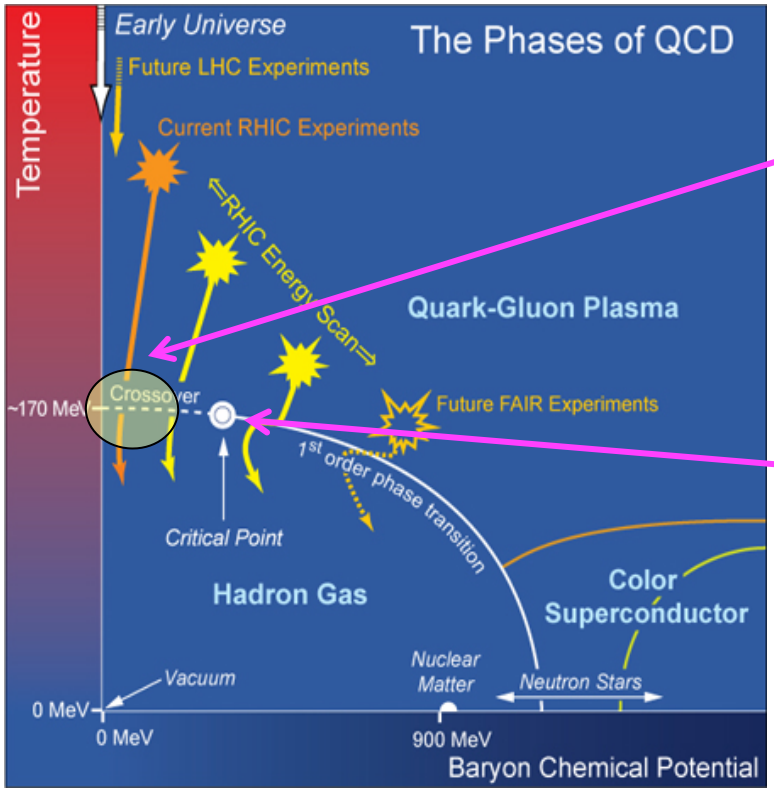
Effort 4

Same collision geometry, but 10% diff. in B field

Phase diagram & Critical point

A map of the QCD matter under different conditions (T,μ_b)

Understand this phase diagram is a central focus of our field



<u>A Known known from lattice QCD:</u>

- Cross-over transition leading to the QGP

  → Necessary requirement for CEP

<u>Known unknowns</u>

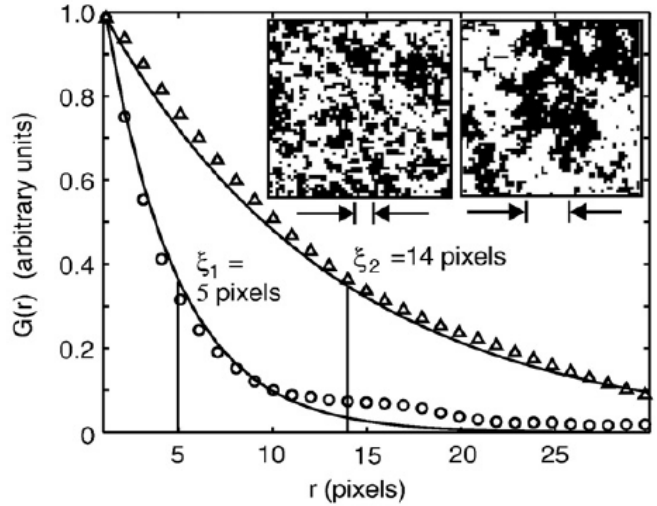
- **Location of phase boundaries?**
- **Location of the critical End point (CEP)?**

Require measurements spanning a broad range of the (T,μ_b)-plane

Goal of Beam energy scan!

Feature of the critical point

Critical opalescence



Corr. Length $\xi(T) \propto |T - T_c|^{-\nu}$

Mag. Sucep. $\chi_M(T) \propto |T - T_c|^{-\gamma}$

Heat Cap. $C_V(T) = \frac{1}{V}\frac{d\langle E\rangle}{dT} \propto |T - T_c|^{-\alpha}$

Large scale fluctuation of order parameter

→ correlation length ξ diverge

→ fluctuation of conserved charges (baryron, s-quark, charge etc)

Observables:

$$C_2 = \langle \delta X^2 \rangle \qquad \delta X = X - \langle X \rangle$$

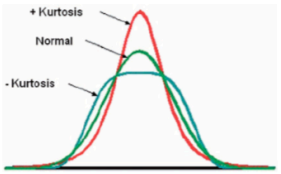
$$C_3 = \langle \delta X^3 \rangle$$

$$C_4 = \langle \delta X^4 \rangle - 3\langle \delta X^2 \rangle^2$$

$$C_5 = \langle \delta X^5 \rangle - 10\langle \delta X^3 \rangle \langle \delta X^2 \rangle$$

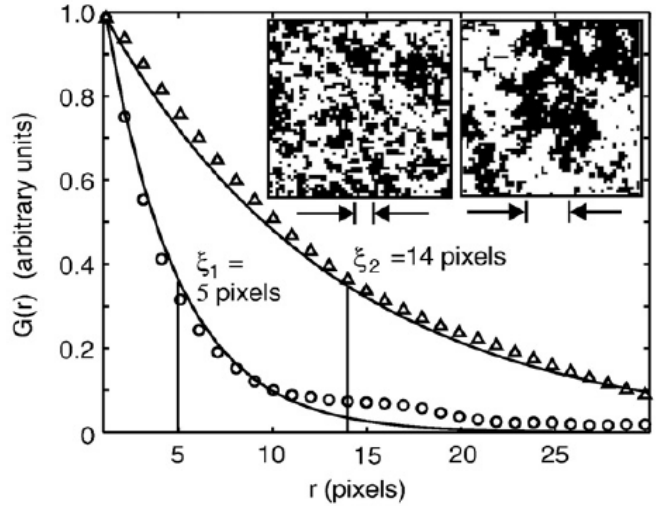
Quantifies the shape of p(x)

C_2 variance, C_3 Skewness, C_4 Kurtosis



Feature of the critical point

Critical opalescence



Corr. Length $\xi(T) \propto |T - T_c|^{-\nu}$

Mag. Sucep. $\chi_M(T) \propto |T - T_c|^{-\gamma}$

Heat Cap. $C_V(T) = \frac{1}{V}\frac{d\langle E\rangle}{dT} \propto |T - T_c|^{-\alpha}$

Large scale fluctuation of order parameter

→ correlation length ξ diverge

→ fluctuation of conserved charges (baryron, s-quark, charge etc)

Expectation:

Higher-order cumulants grow as power of ξ

$$\langle(\delta N)^2\rangle_c \approx \xi^2, \quad \langle(\delta N)^3\rangle_c \approx \xi^{4.5}, \quad \langle(\delta N)^4\rangle_c \approx \xi^7$$

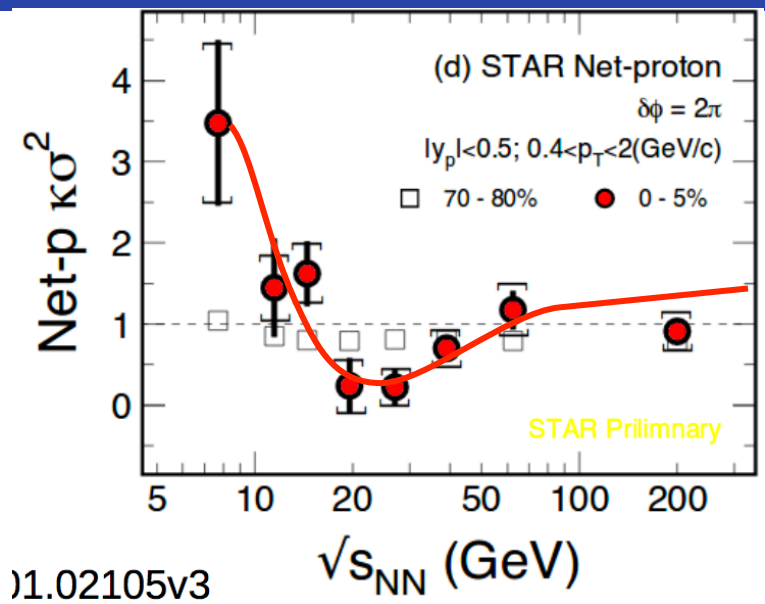
Anomalous value at √s where CEP influence is maximized

→ non-monotonic behavior?

STAR Observation

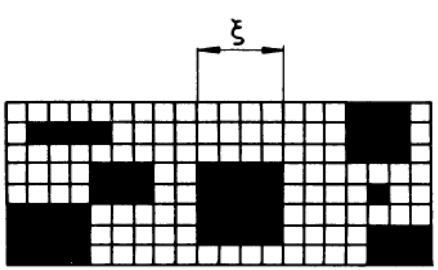
▷ Kurtosis

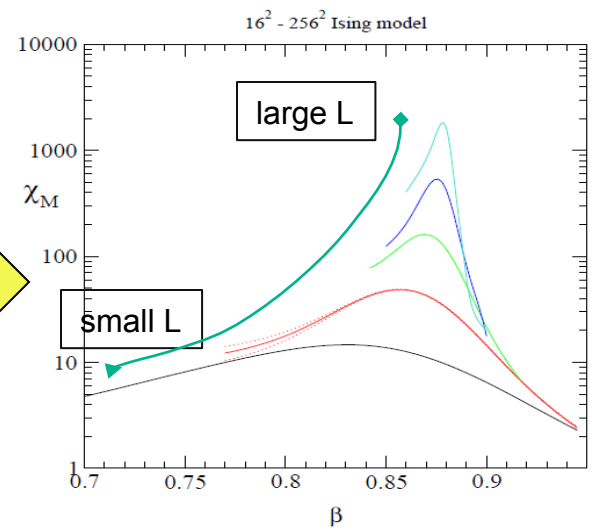
$$k\sigma^2 = C_4/C_2$$



)1.02105v3

- Non-monotonic pattern observed in net-proton 4th-order cumulants
- Current focus: non-Critical effects & finite size/time effects





$$\xi \sim |T - T_c|^{-\nu} \leq L$$

Developed comprehensive scaling strategy to account for these effects

see arXiv:1606.08071

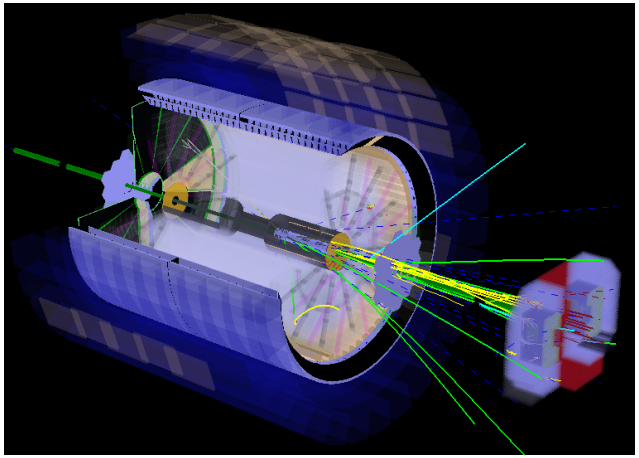
Effort 5

STAR: huge physics opportunities in next 5 years

- ***Run 2018: → data is just being produced.***
  - Isobar system (^{96}Ru - ^{96}Zr) comparison run (>1.2B events each)
  - 27 GeV Au+Au run, 3 GeV Au+Au fixed target run
  - Test of signatures of Chiral Magnetic Effect and measurement of vorticity

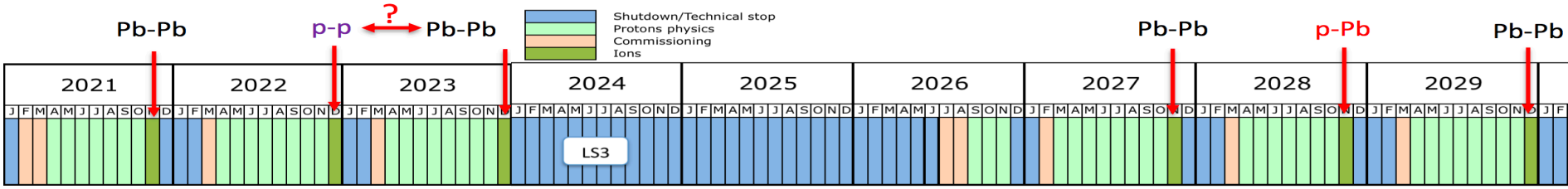
- ***Beam Energy Scan II (2019-2021):***
  - Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity at lowest energies
  - Fixed target runs at $\sqrt{s_{NN}}$ = (3.0), 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for signs of critical phenomena in event-by-event fluctuations

- ***Forward detector upgrade (2022-2025):***
  - Concurrent running with sPHENIX
  - Much better control on global event properties
  - Explore QCD structure probes
  - Good technical experience for students



Outlook in ATLAS@LHC

- Just took x10-100 more data for correlations in 2017-2018
  - 200pb^{-1} @ 5 TeV and 100 pb^{-1} at 13 TeV, comparing to 0.19pb^{-1} and 0.9pb^{-1}
  - Sampled 10 billion Pb+Pb events @ 5 TeV
- Robust HI program planned out for next 10 years
  - >x30 L_{int} for Pb+Pb and p+Pb with tracking extended to $|\eta|<4$
  - Light ions: Xe+Xe, Ar+Ar,O+O? bridge between small & large system



1812.06772, 200+ page

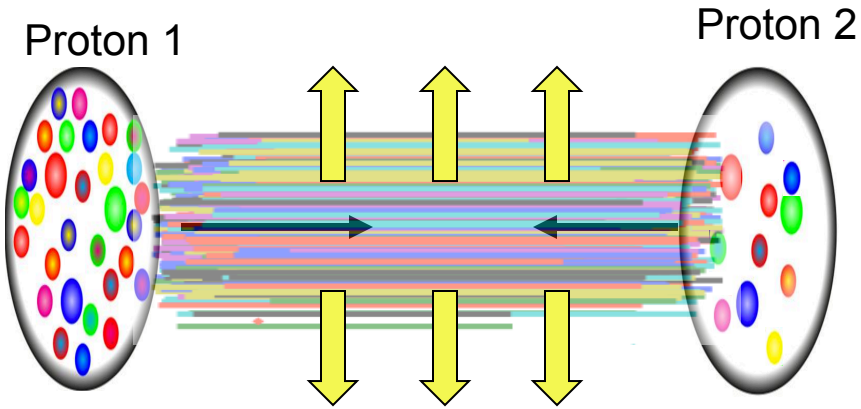
CERN-LPCC-2018-07
December 18, 2018

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

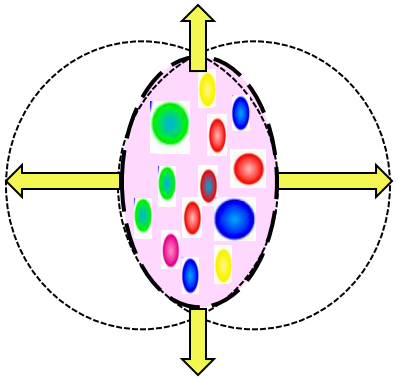
Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

Even further down the road

Longitudinal view

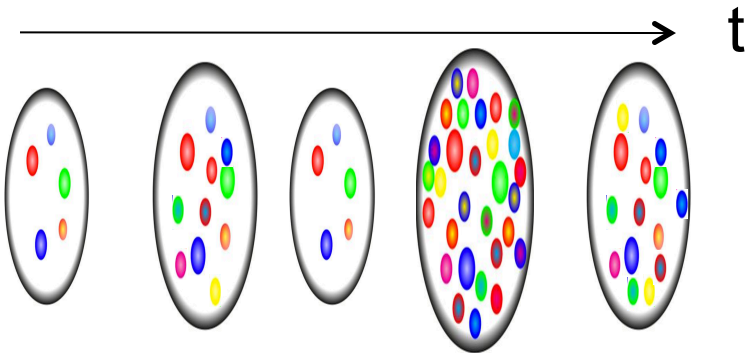


Transverse view

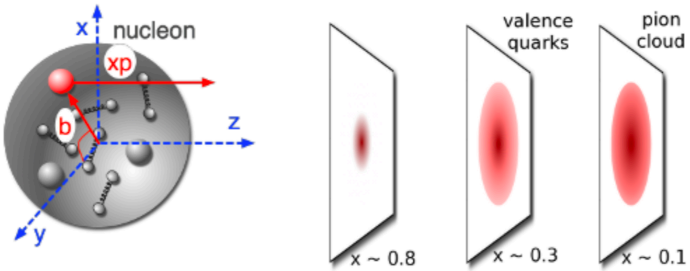


- Understand the internal structures of objects that we are colliding

Proton:

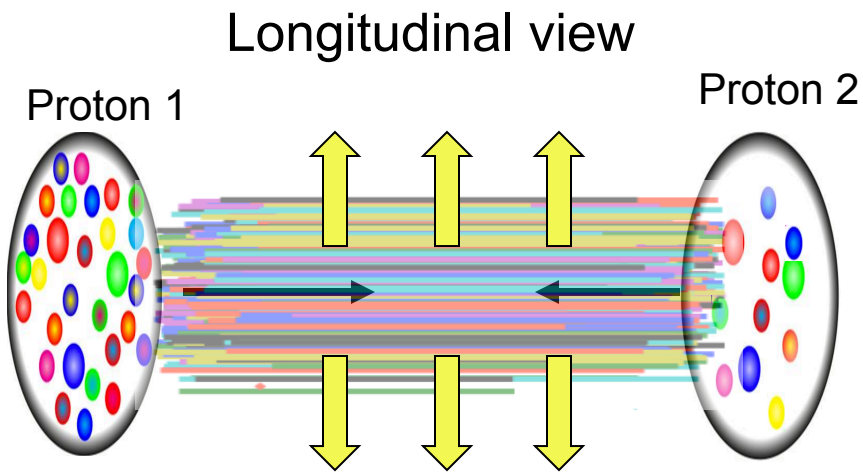


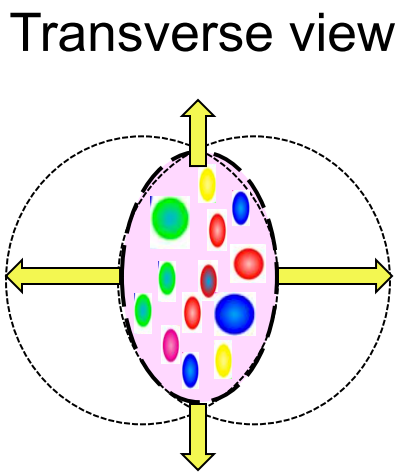
Proton/nuclei are in a superposition of infinite number of configurations



What one see depend on scale of probes

Even further down the road



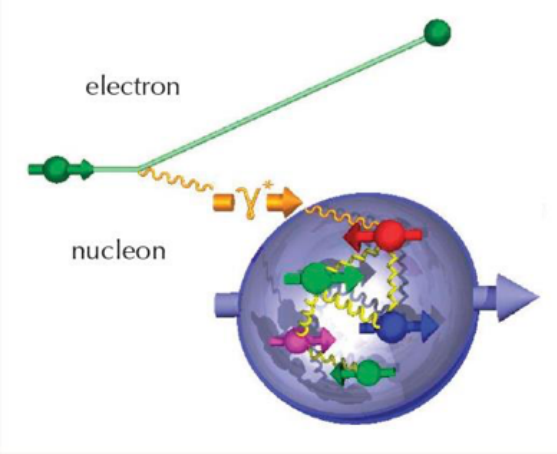


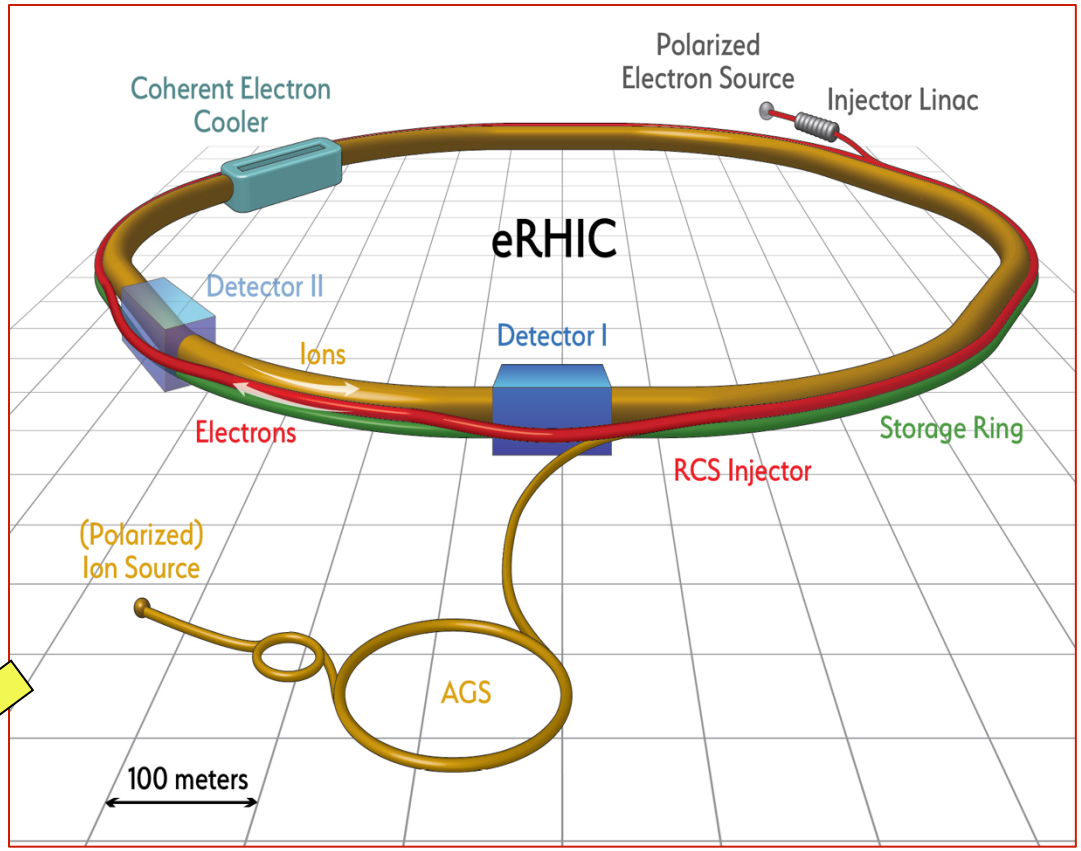
- Understand the internal structures of objects that we are colliding

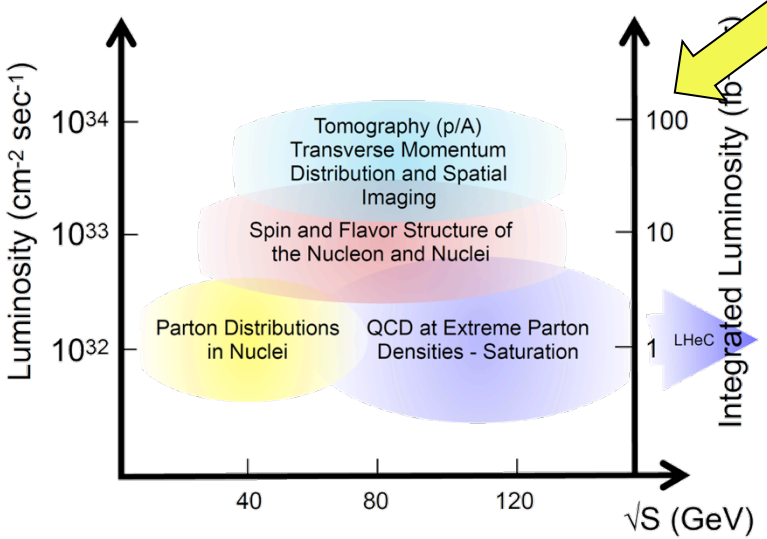
What are the internal degrees of freedom of proton?
How they give rise to proton mass and spin?
How dense environment affects quark/gluons and their correlations?

Need to measure the 3D structure of proton and nuclei

Electron-Ion Collider







Re-uses the large investment in RHIC
Cost ~ $800M
Construction ~ 2025-2030
Physics ~ 2030+

There are, indeed,

Exciting Times Ahead!

Our group

https://www.star.bnl.gov/~jjiastar

Home | News | Members | Papers | Talks | Links

Group Members