The Relativistic Heavy Ion Collider

Status and Future

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Useful Documents

Barbara Jacak and B.M., *The Exploration of Hot Nuclear Matter*
Science **337**, 310-314 (20 July 2012)

Steven Vigdor: *The Case for Continuing RHIC Operations*
White Paper submitted to NSAC Subcommittee on Implementation of the 2007 Long Range Plan for Nuclear Science
http://www.bnl.gov/npp/docs/The%20Case%20for%20Continuing%20RHIC%20Operations%20_draft%205.pdf

Steffen Bass et al.: *Hot and Dense QCD Matter*
Community White Paper on the Future of Relativistic Heavy Ion Physics
http://www.bnl.gov/npp/docs/Bass_RHI_WP_final.pdf

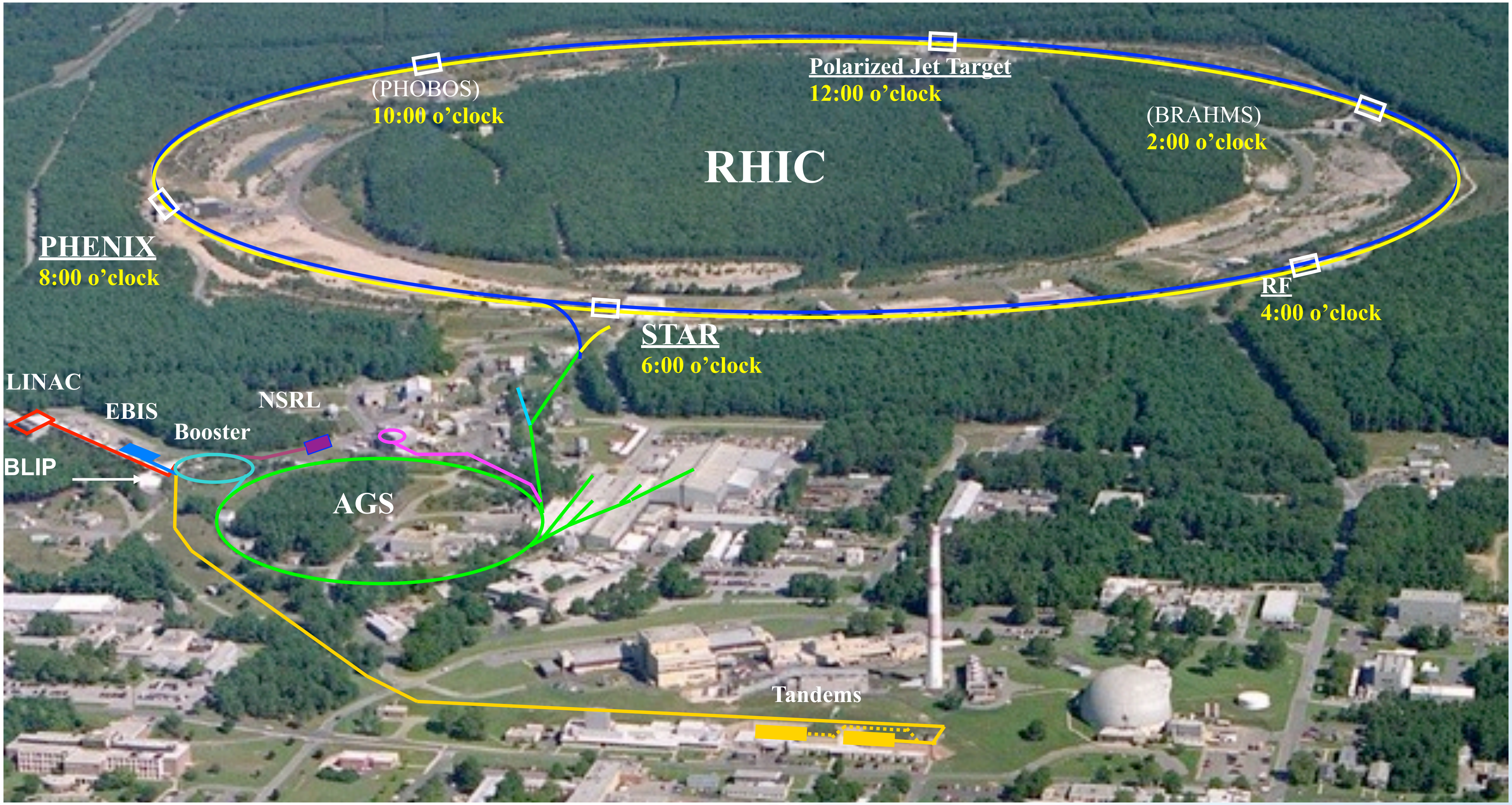
Elke Aschenauer et al.: *The RHIC SPIN Program,*
Whitepaper on Achievements and Future Opportunities
http://www.bnl.gov/npp/docs/RHIC-Spin-WriteUp-121105.pdf

Message 1

RHIC is the perfect facility to explore the phases of nuclear (QCD) matter.

If RHIC did not exist, someone would have to build it (...but no one could afford it!)

RHIC: A Discovery Machine



Brookhaven Science Associates

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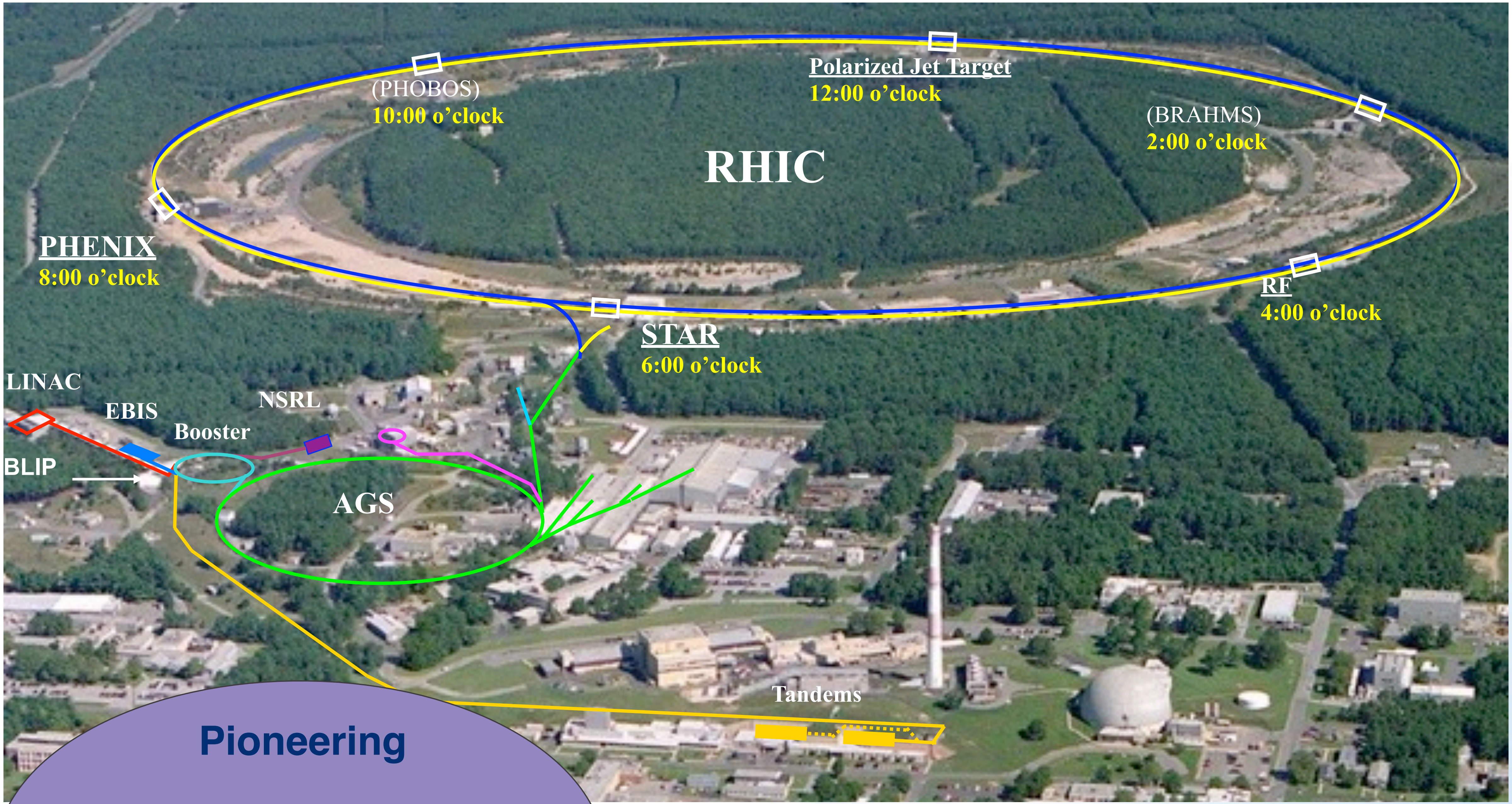

Pioneering

Perfectly liquid quark-gluon plasma; Polarized proton collider

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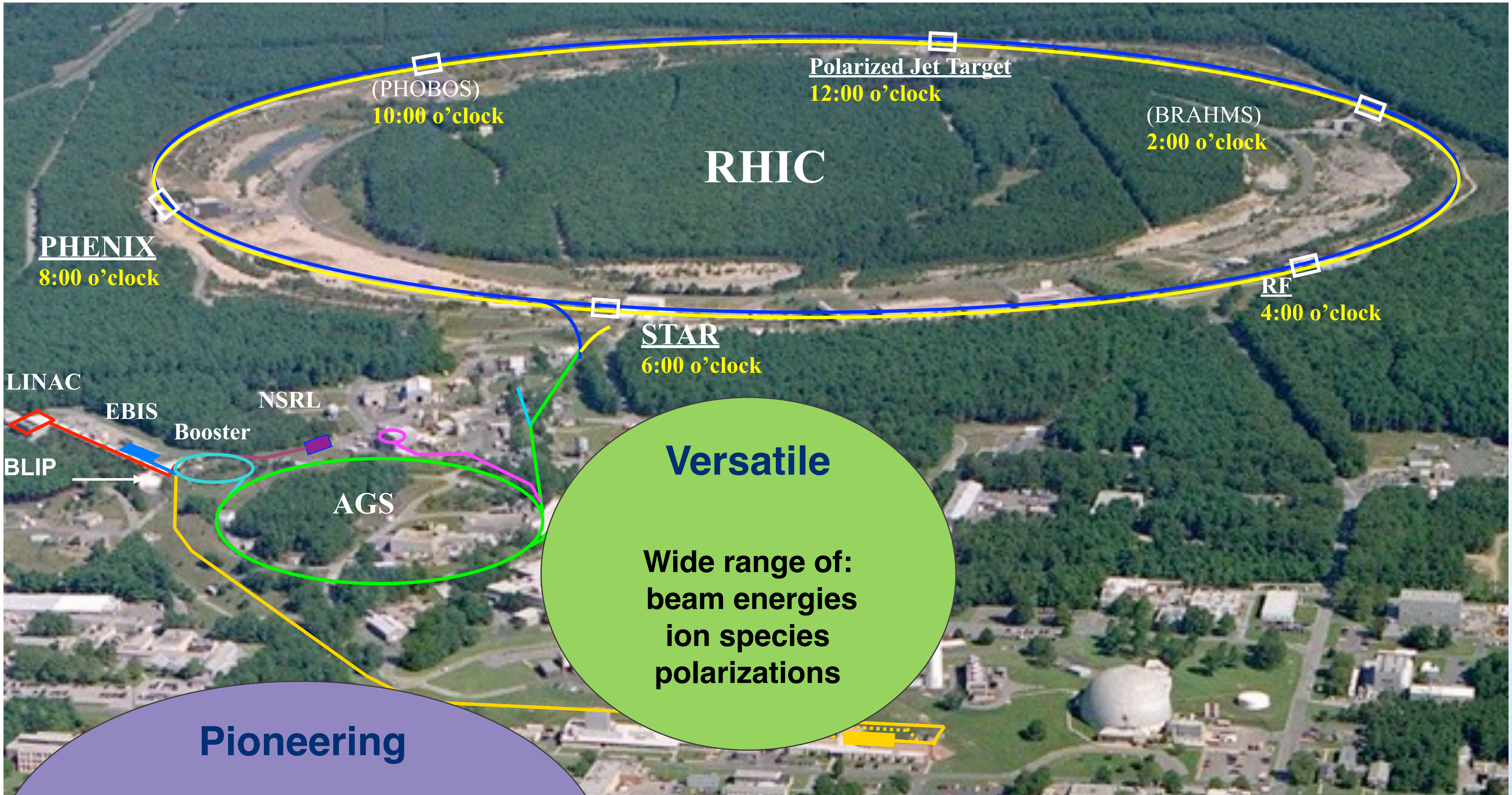

Versatile

Wide range of:
beam energies
ion species
polarizations

Pioneering

Perfectly liquid quark-gluon plasma;
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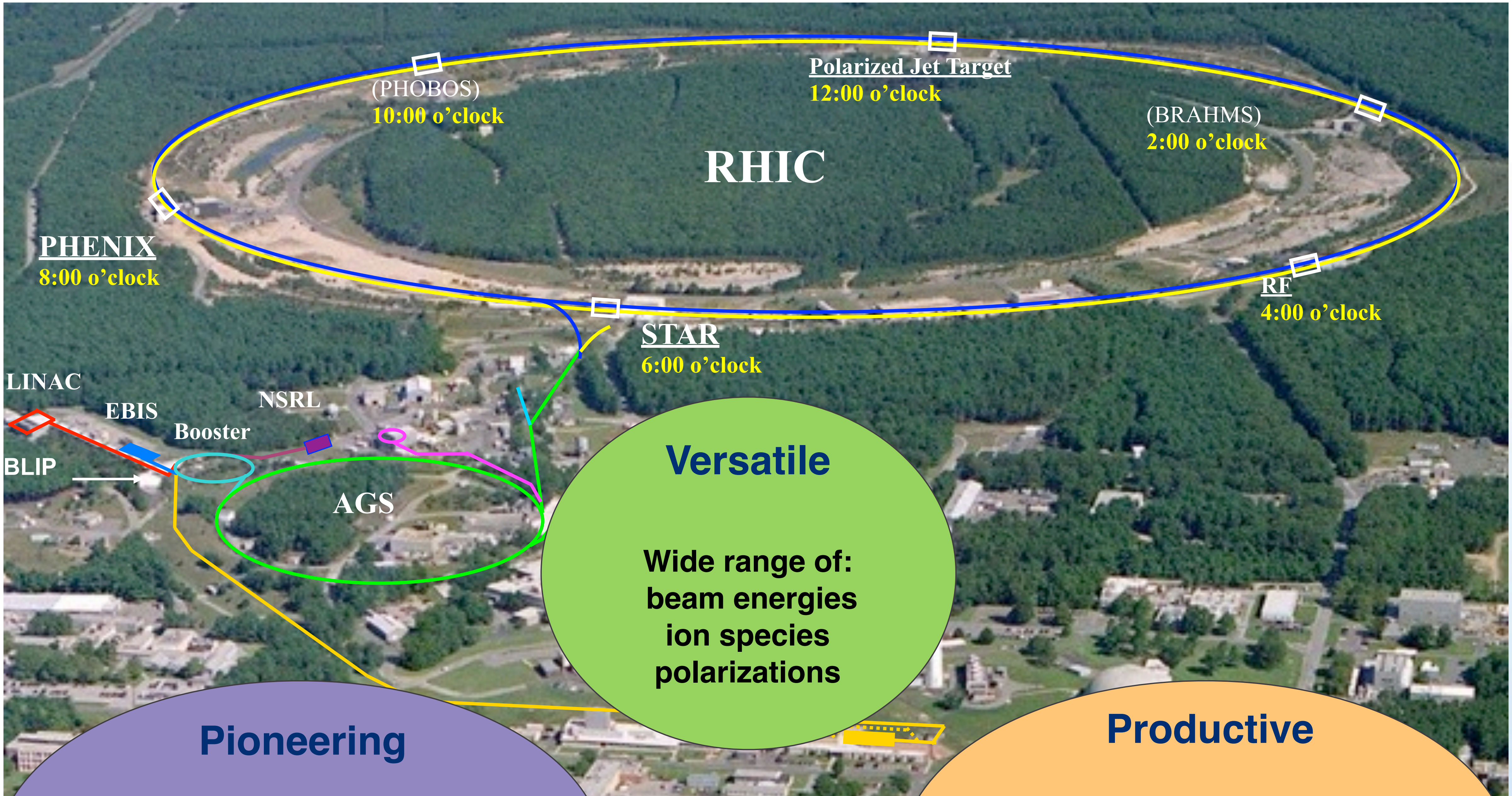
RHIC: A Discovery Machine



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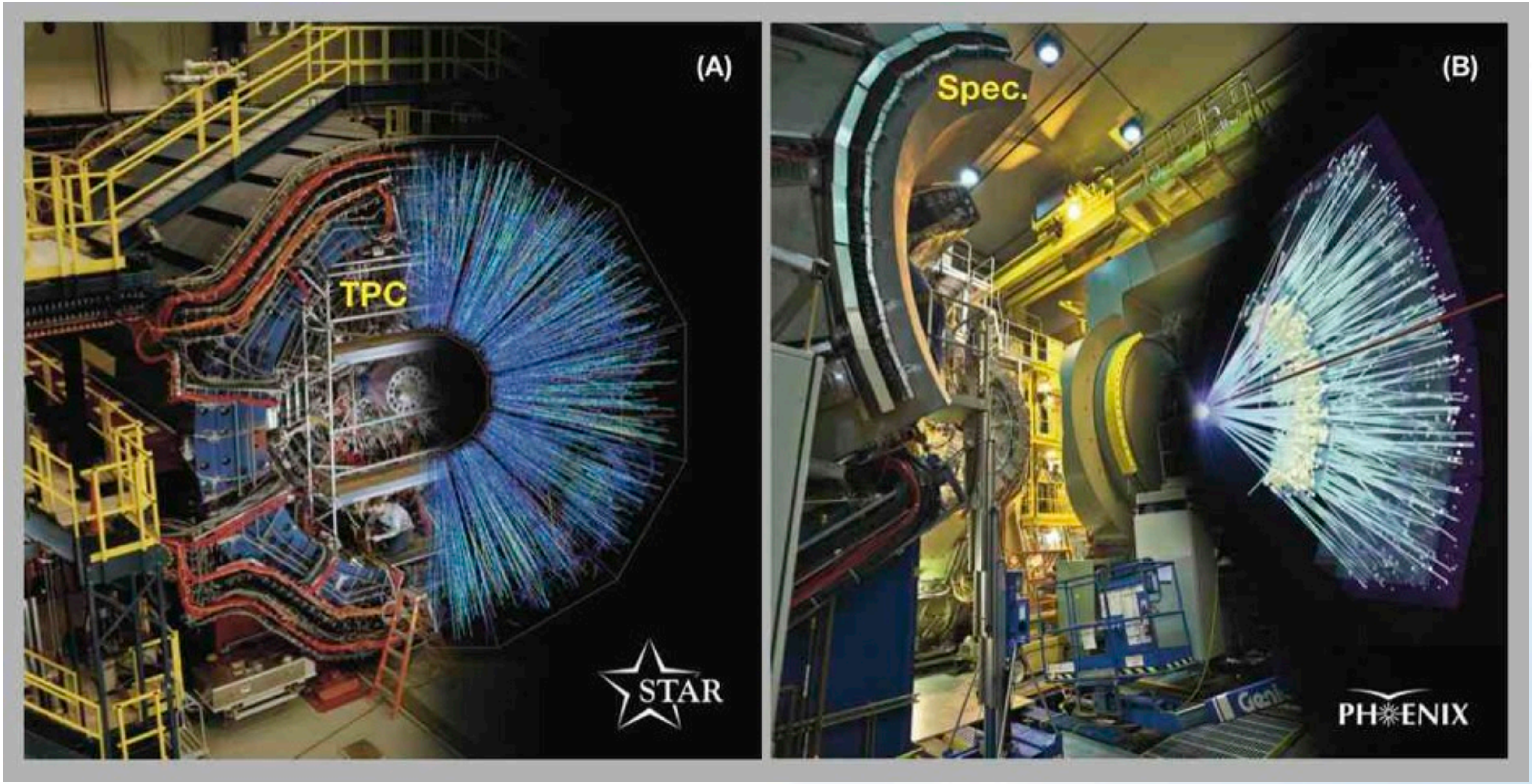
Productive

>300 refereed papers
>30k citations
>300 Ph.D.'s in 12 years
productivity still increasing

Detector Collaborations



558 collaborators from 12 countries

>430 collaborators from 12 countries

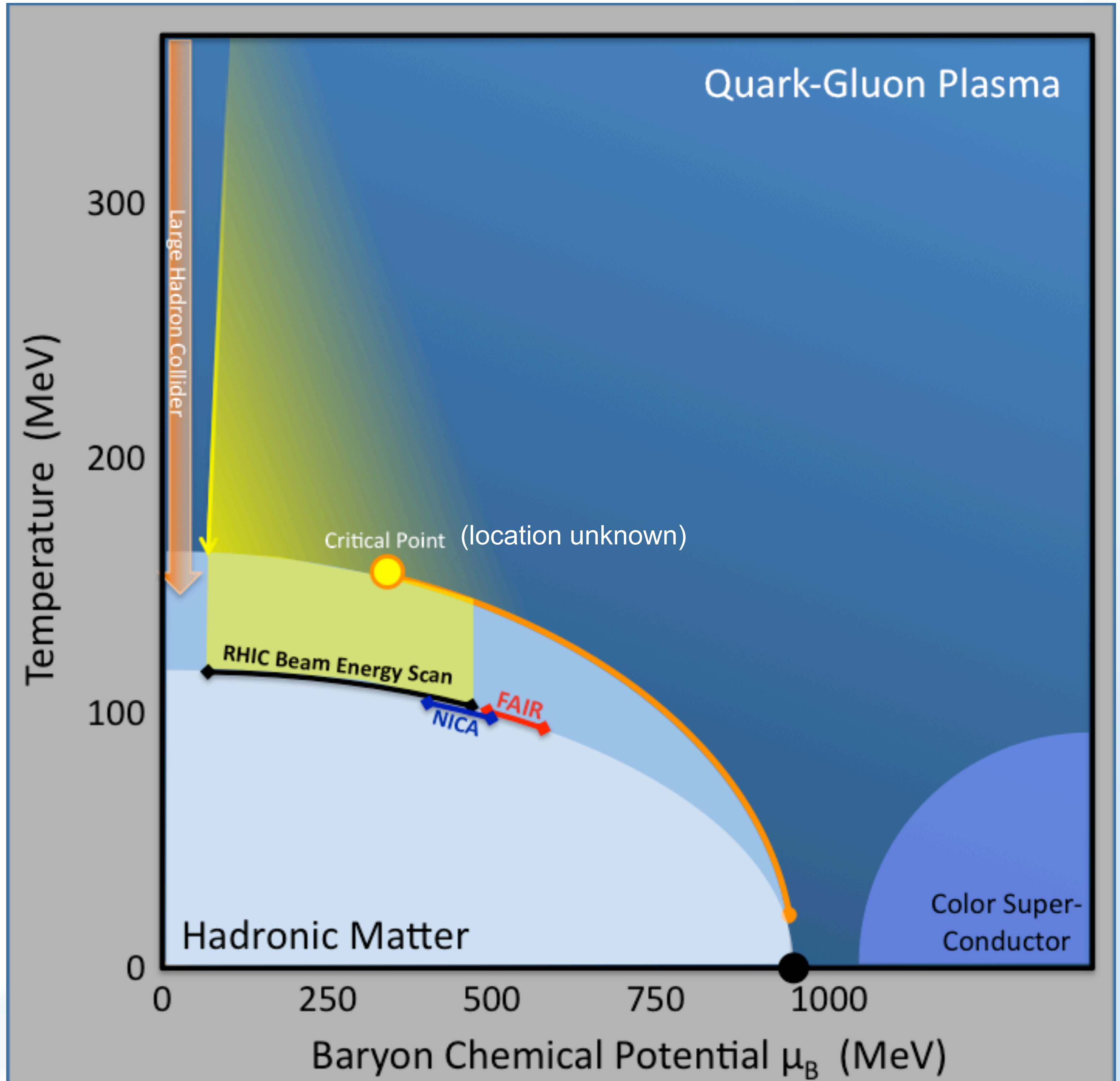
Exploring the QCD Phase Diagram

LHC: Collider at $\sqrt{s_{NN}}$=2.76 TeV, up to $\sqrt{s_{NN}}$=5.5 TeV in the future, planned beams: Pb+Pb, p+Pb, p+p only.

FAIR: Fixed target up to $\sqrt{s_{NN}}$=4.7 GeV (well below our region of interest). Online in 2018. *Fixed target mode makes energy scan experimentally challenging because acceptance changes with $\sqrt{s_{NN}}$.*

NICA: Au+Au at $\sqrt{s_{NN}}$=4-11 GeV in collider mode. Lower end of region of interest and uncertain time-table.

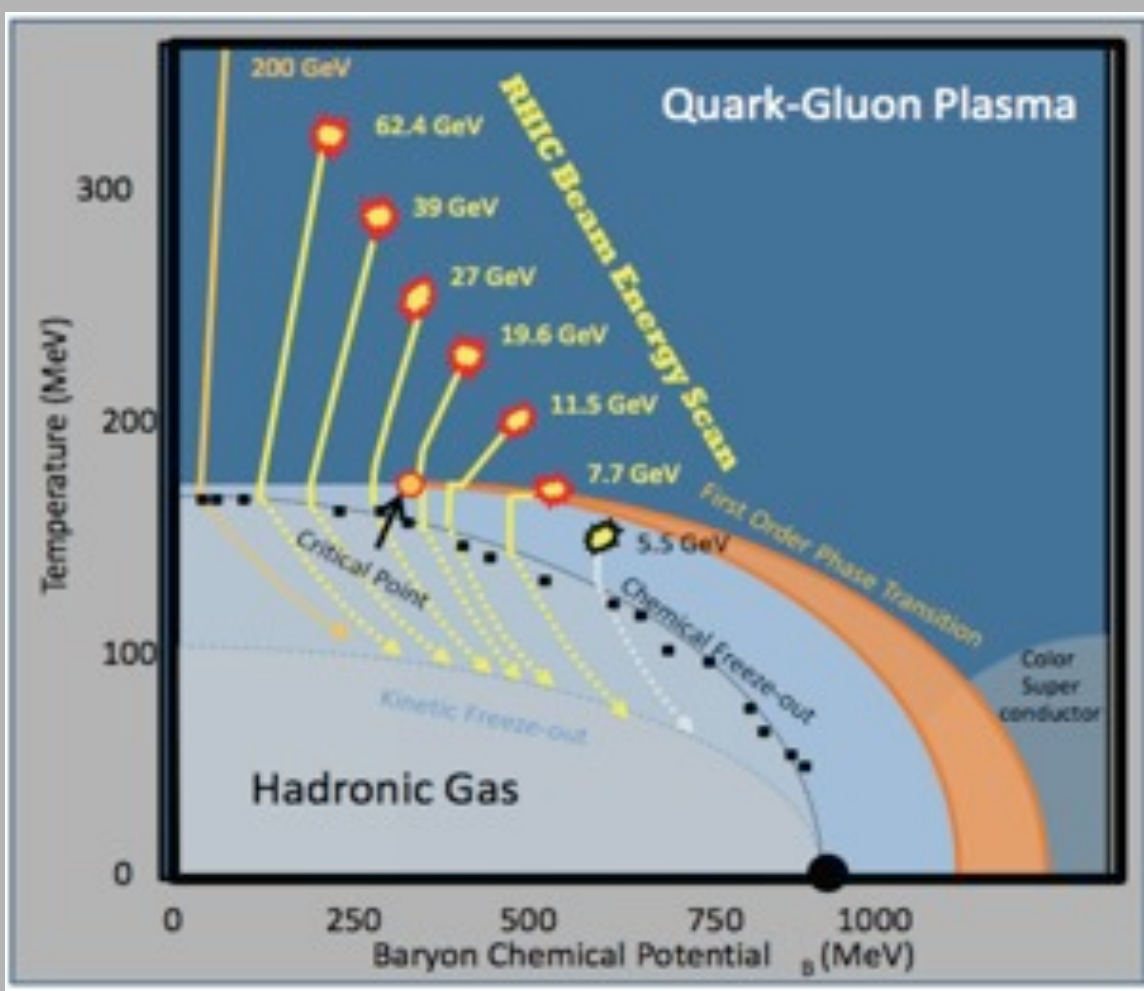
RHIC: Spans largest swath of μ_B in preferred collider mode. Proven capabilities; just needs to be run.

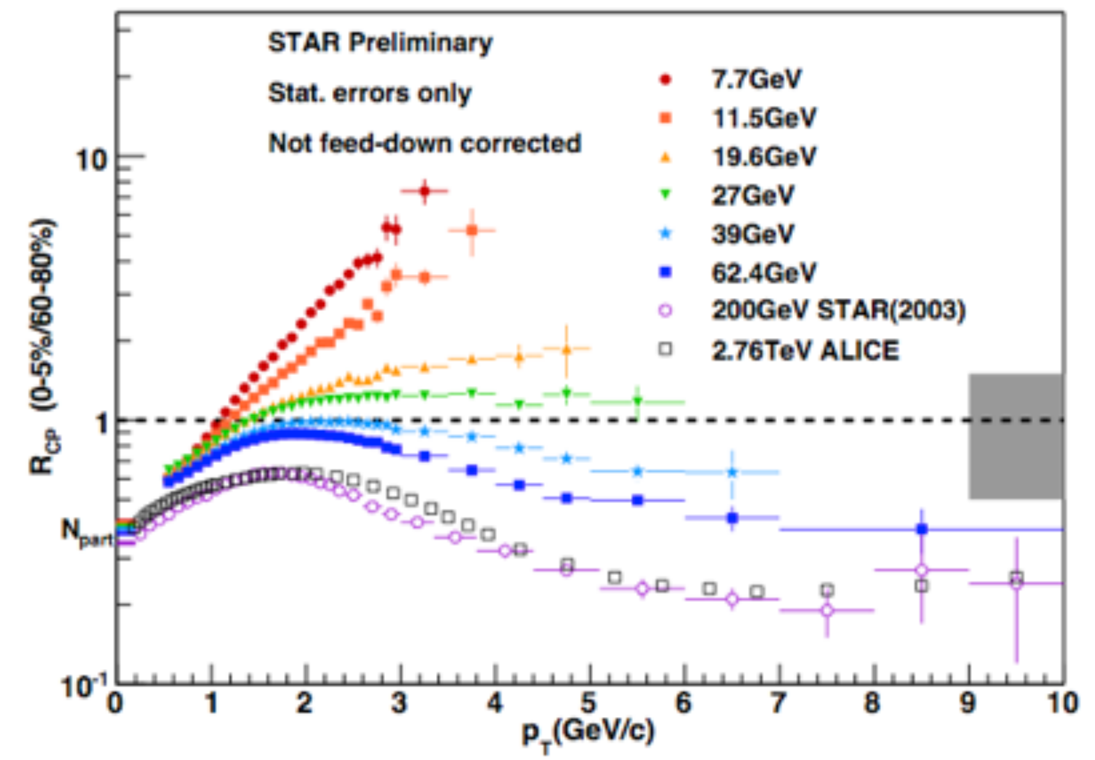


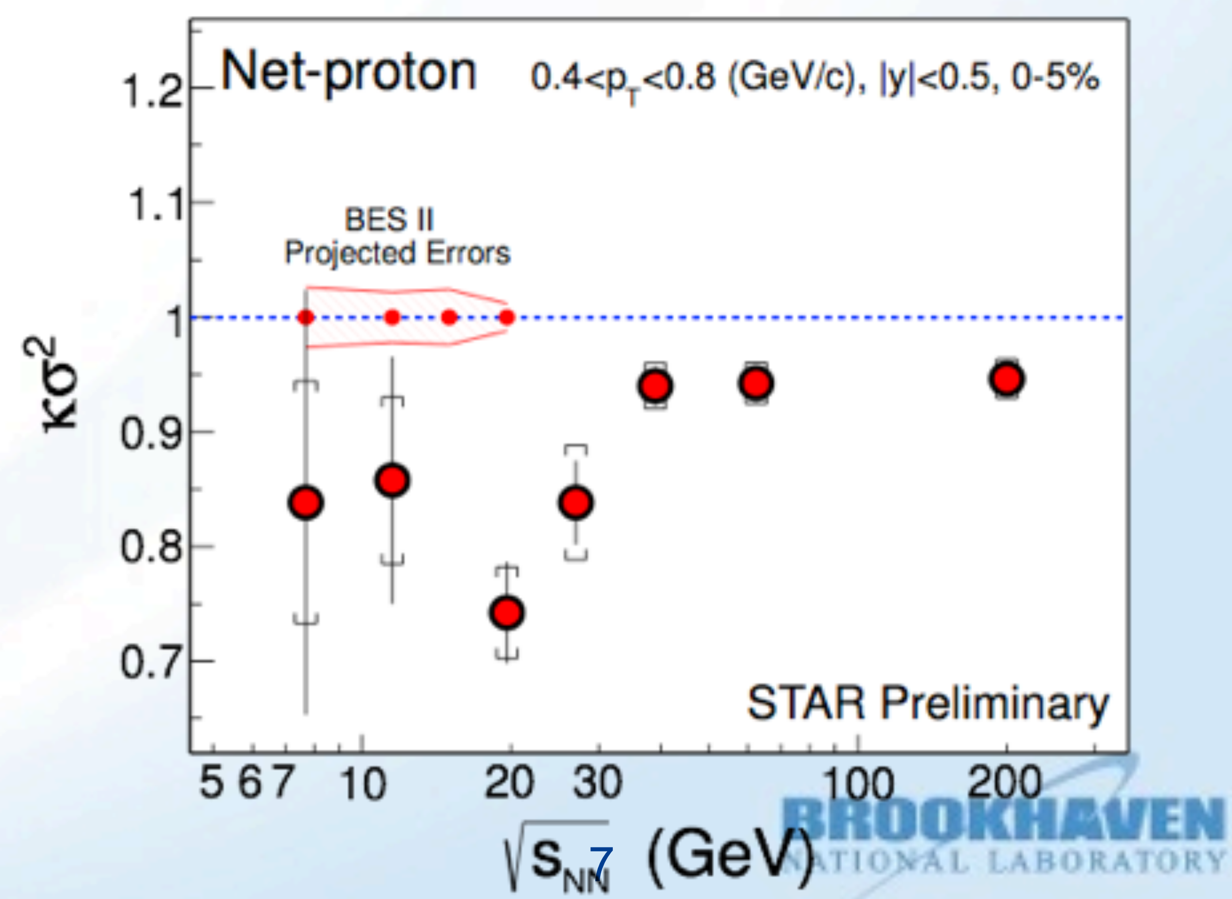
Discovery Potential: Charting the QCD Phase-Diagram

Probing the QCD Phase-Diagram

- RHIC Beam-Energy-Scan: use beam energy as control parameter to vary initial temperature and chem. potential
- beam energy range in area of relevance is unique to RHIC!
- BES-II will deliver precision required to search for signatures of the CEP





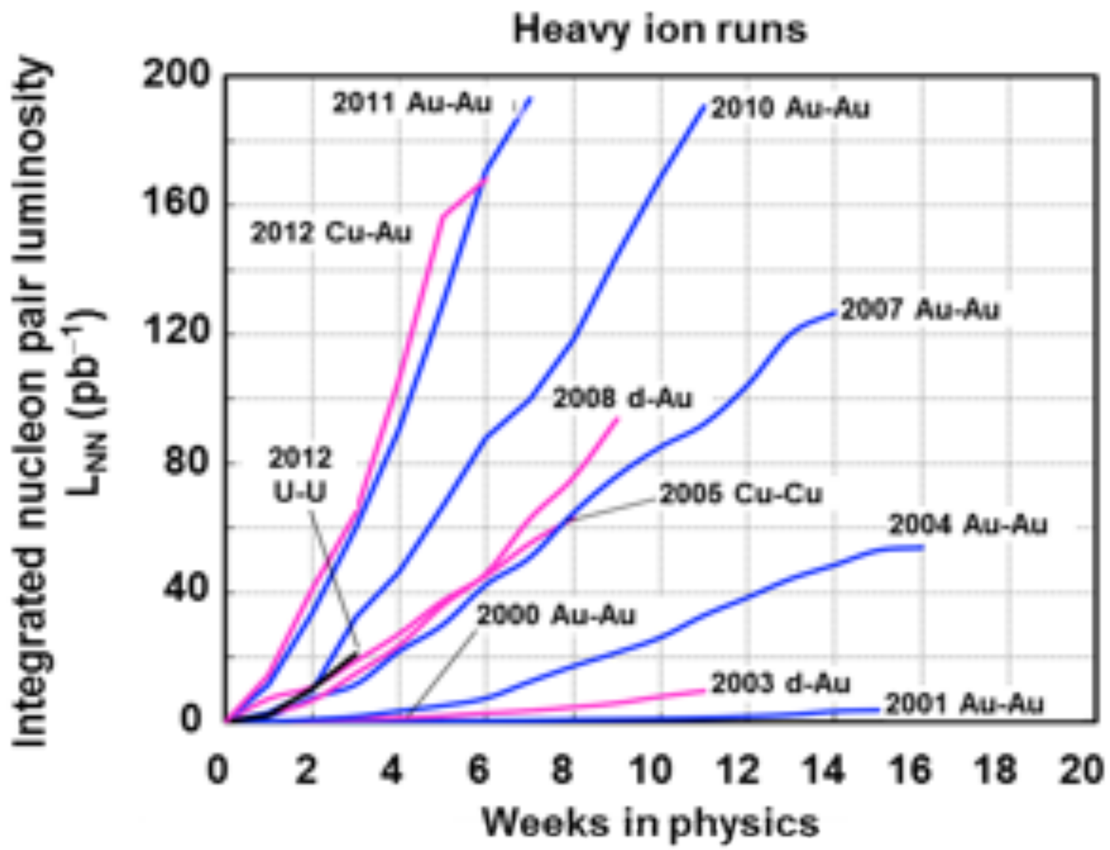


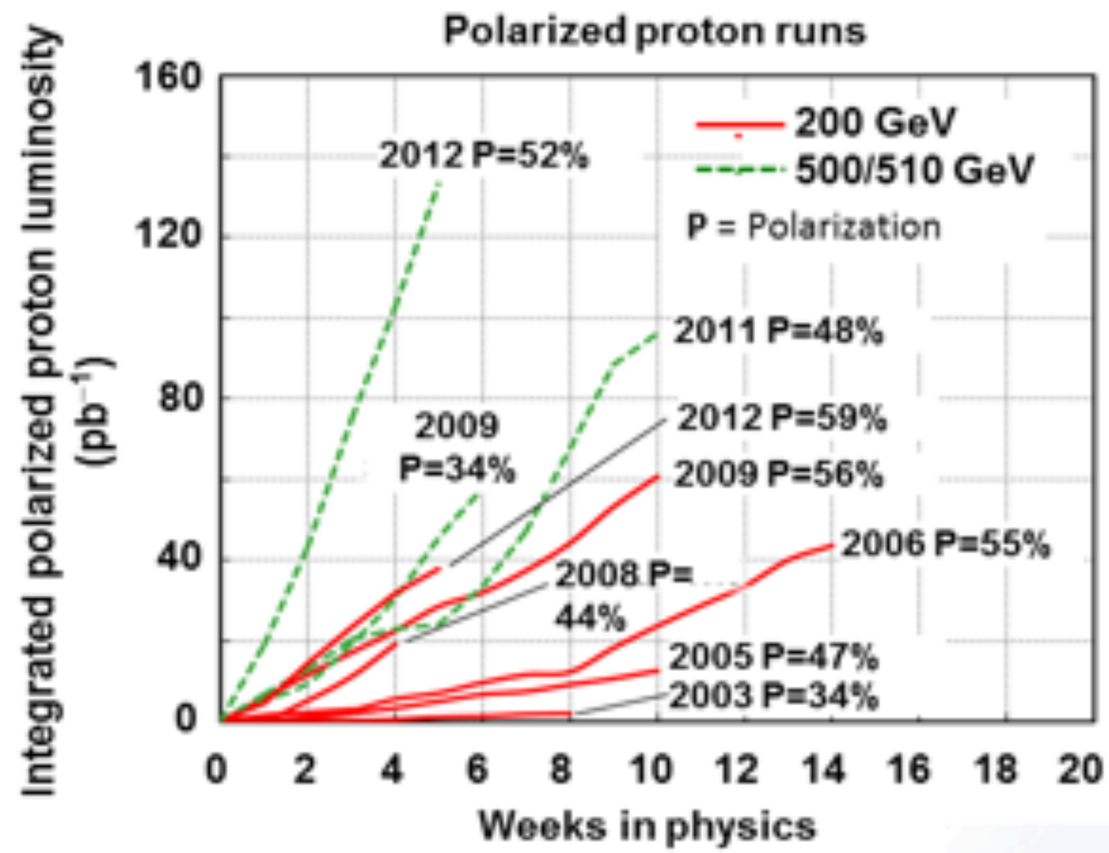
Message 2

*Today's RHIC **is** RHIC-2.*

...actually it probably is RHIC-2.3 !

Dramatic Improvements in Performance & Versatility





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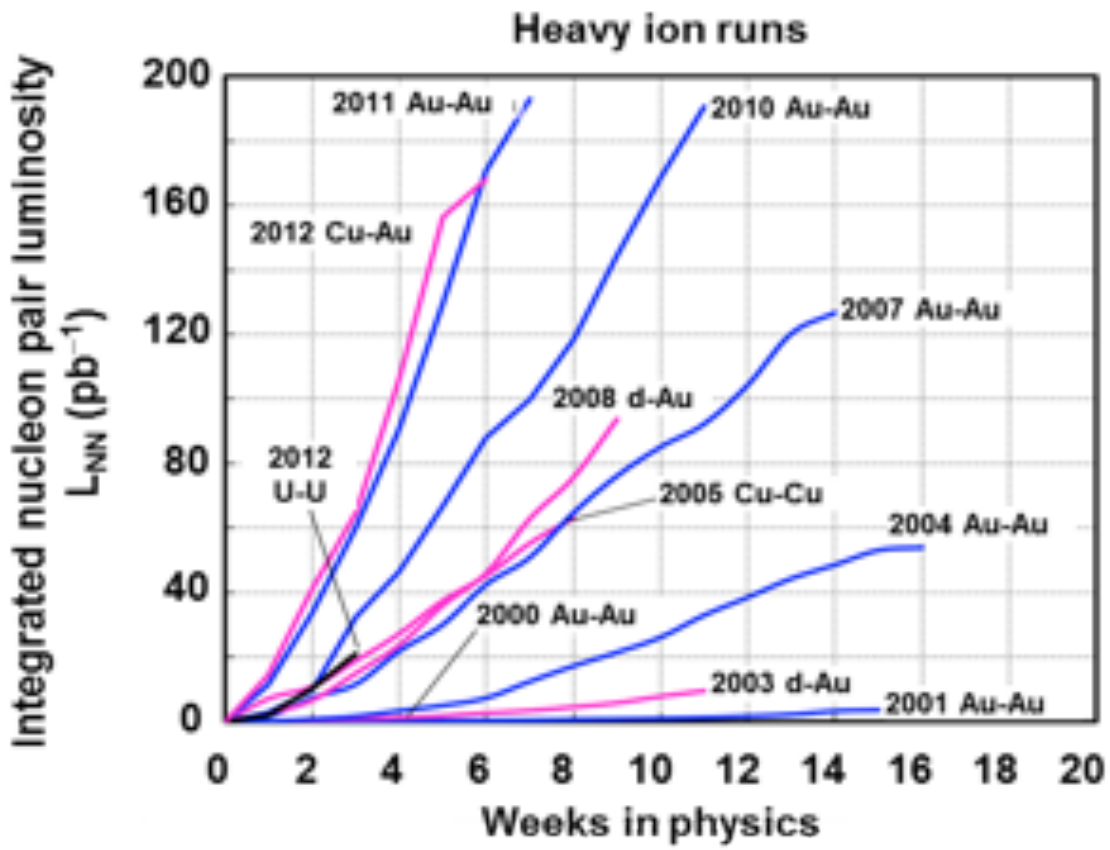

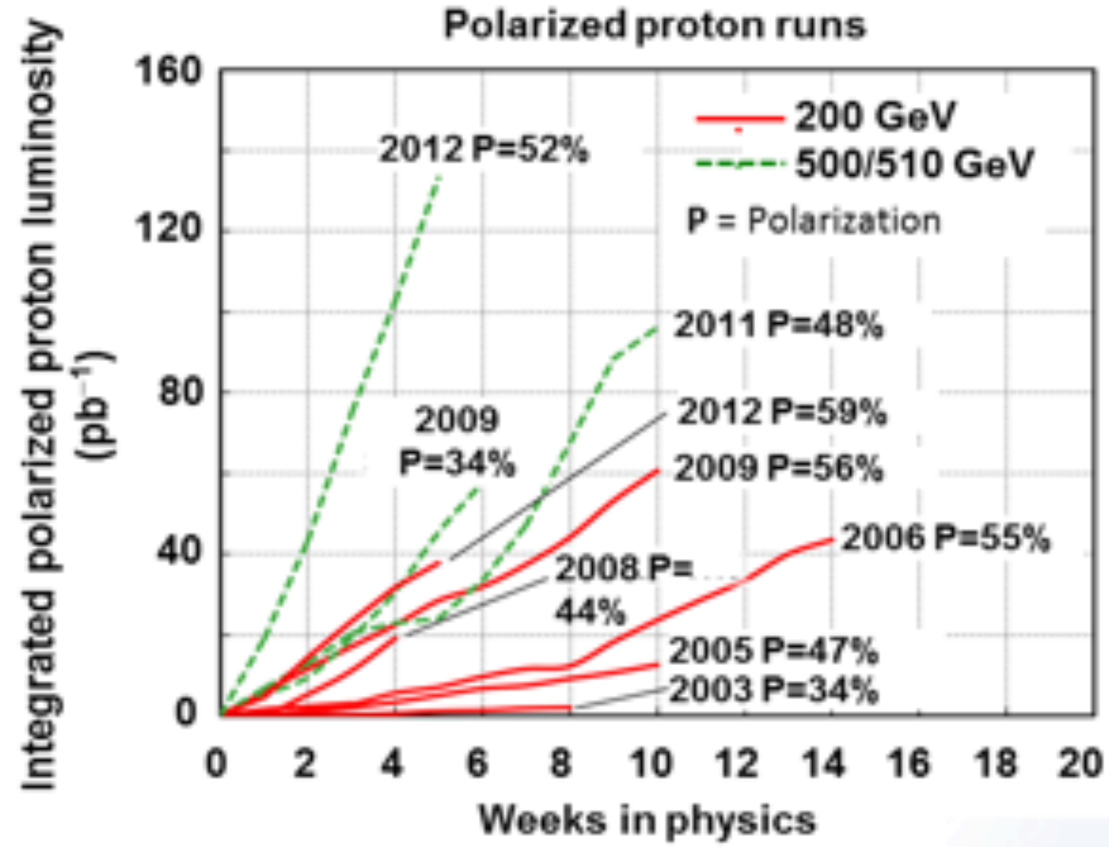

Collision partners	Beam energies (GeV/nucleon)	Peak pp-equivalent luminosities achieved to date, scaled to 100 GeV/n[b)]
Used to date		
Au+Au	3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 31, 65, 100	195×10^{30} cm^{-2}s^{-1}
d+Au[a)]	100	100×10^{30} cm^{-2}s^{-1}
Cu+Cu	11, 31, 100	80×10^{30} cm^{-2}s^{-1}
p↑+p↑ (polarized)	11, 31, 100, 205, 250, 255	165×10^{30} cm^{-2}s^{-1} at 255 GeV
Cu+Au[a)]	100	230×10^{30} cm^{-2}s^{-1}
U+U	96	60×10^{30} cm^{-2}s^{-1}
Considered for future		
Au+Au	2.5, 7.5	
p+Au	100	
p↑+ ^{3}He↑ [a)]	166	

2 new colliding beam species / combinations in 2012

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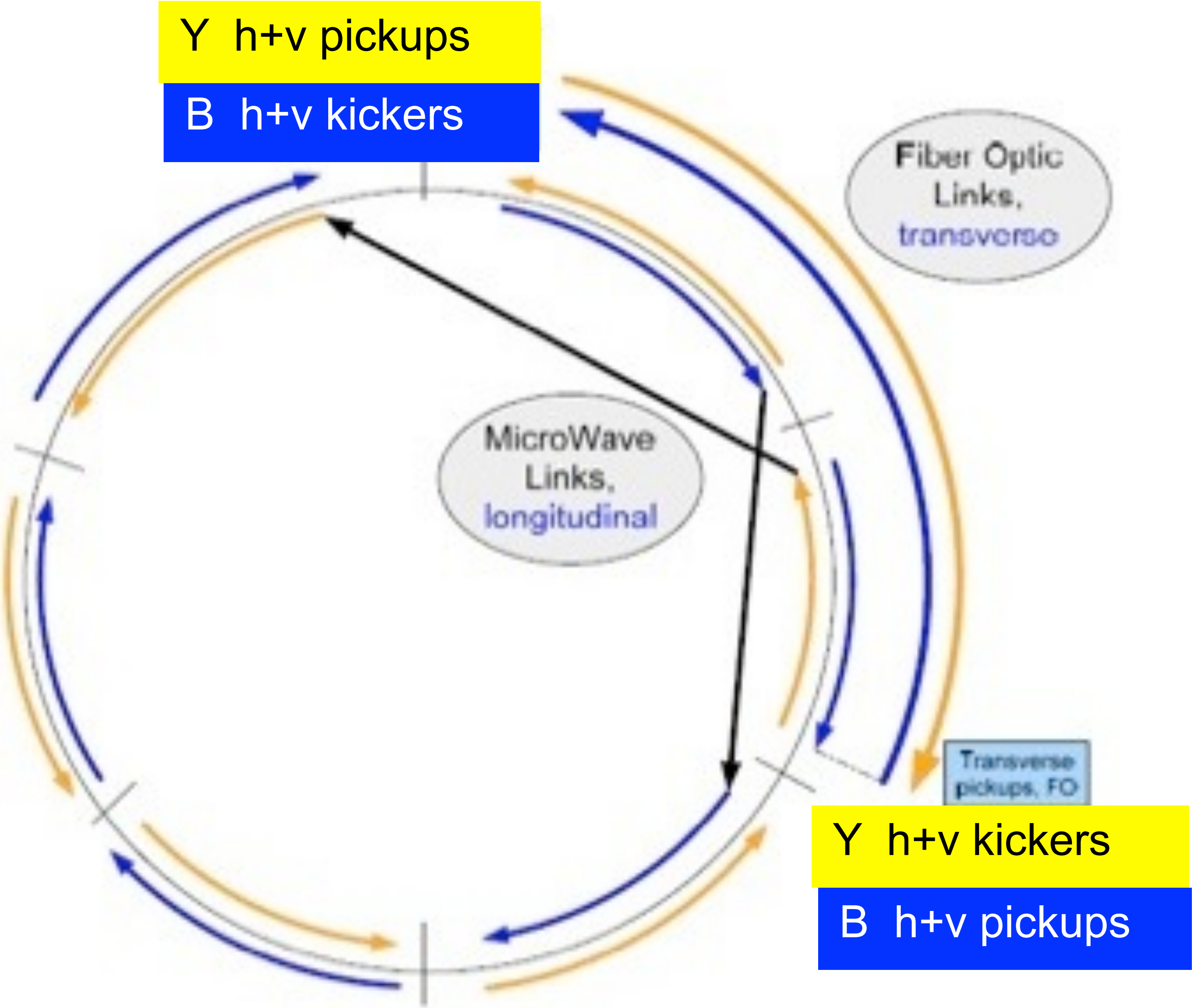
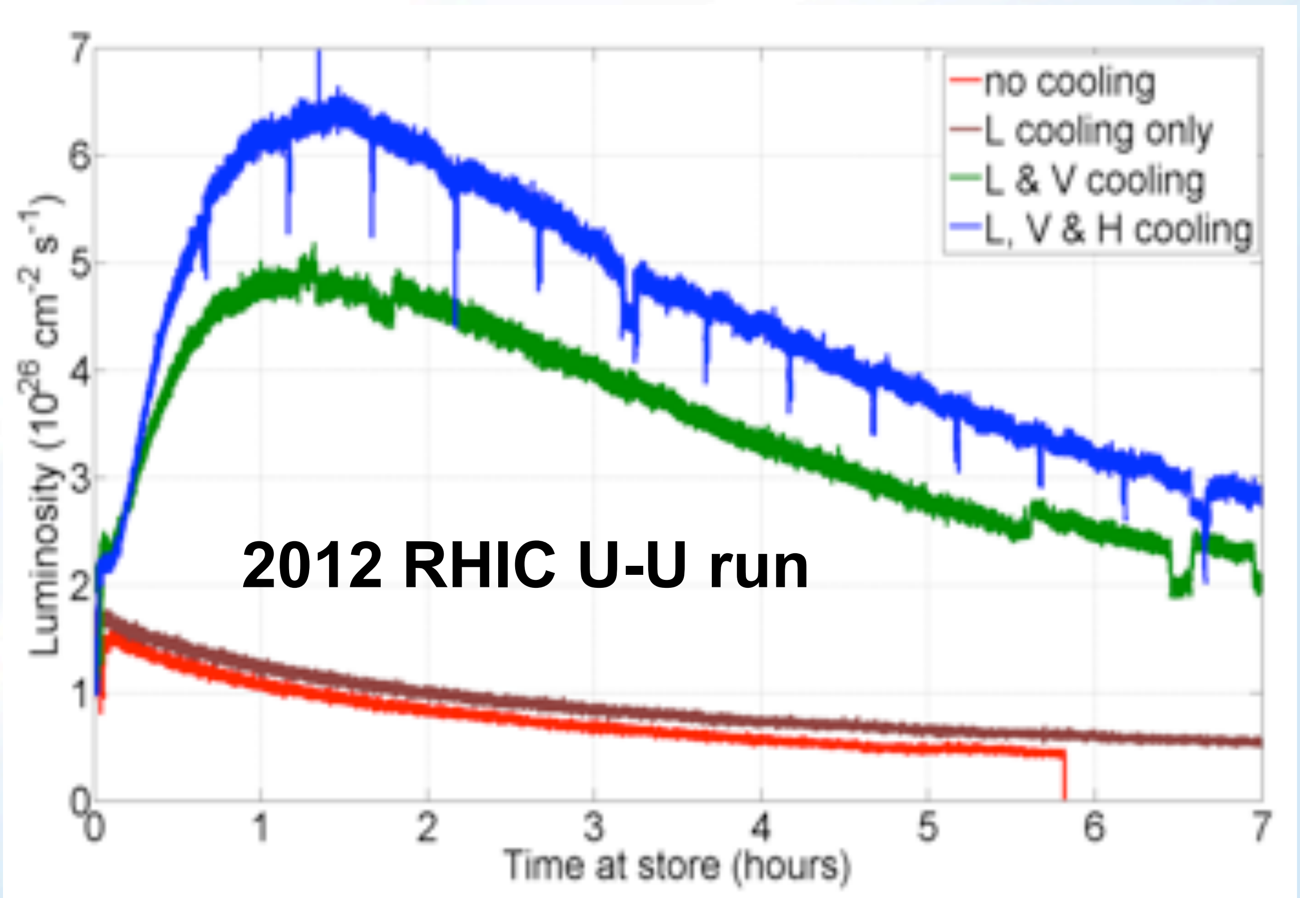
RHIC-II Era is Here, Done Very Cost-Effectively





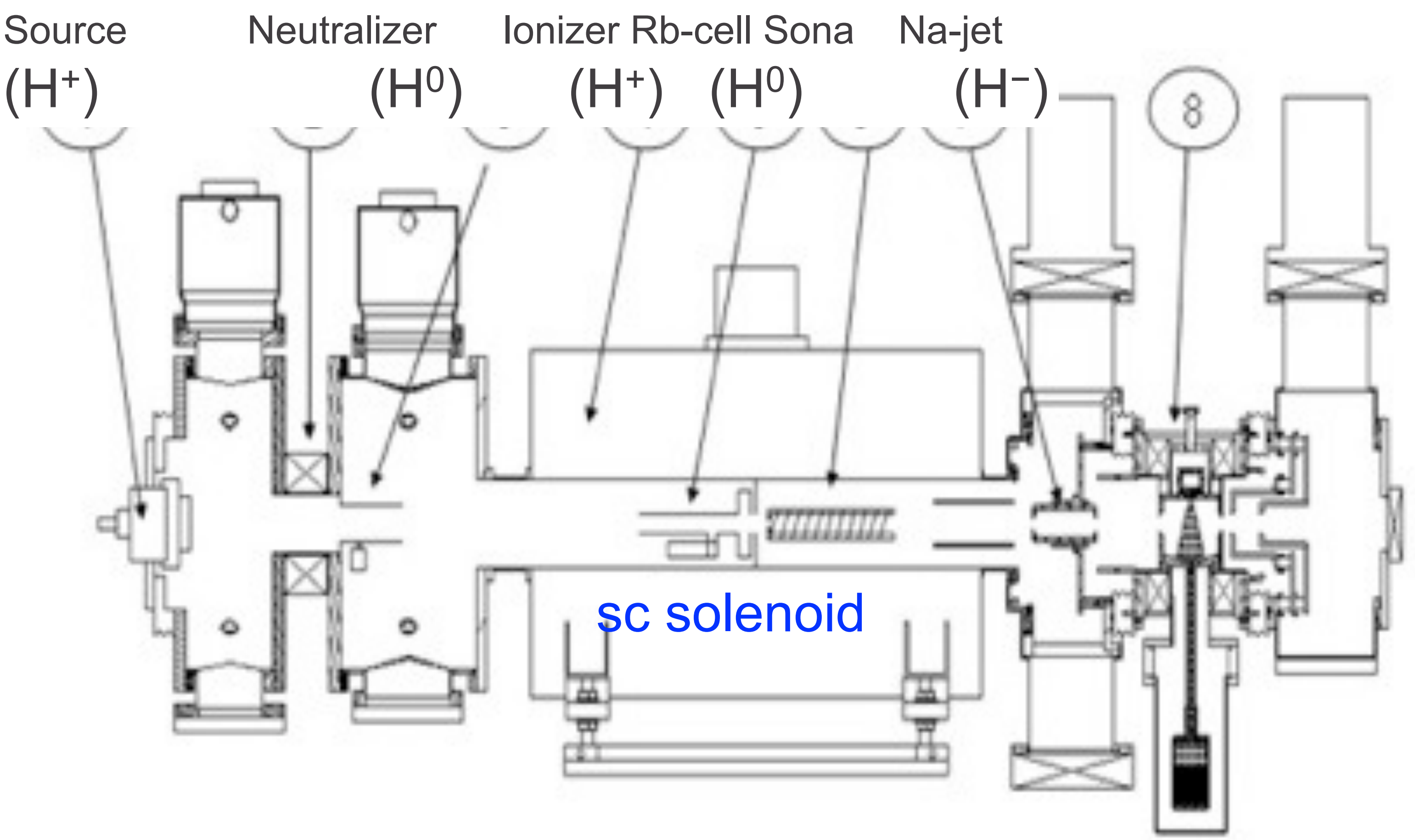
RHIC breakthrough in bunched-beam stochastic cooling: now ~18 times the original design HI luminosity, at ~1/7 the cost in 2007 NP LRP & 5 years earlier,

New Electron Beam Ion Source used in 2012 for new species, e.g., U beams

Electron lenses ready for 2013 run to double the polarized p+p luminosity

New OPPIS 1st time use in Run-13

Optically Pumped Polarized Ion Source



Goals:

1. H^- beam current increase to 10mA (order of magnitude)
2. Polarization to 85-90% (~5% increase)

Upgrade components:

1. Atomic hydrogen injector (collaboration with BINP Novosibirsk)
2. Supercond. solenoid (3 T)
3. Beam diagnostics and polarimetry

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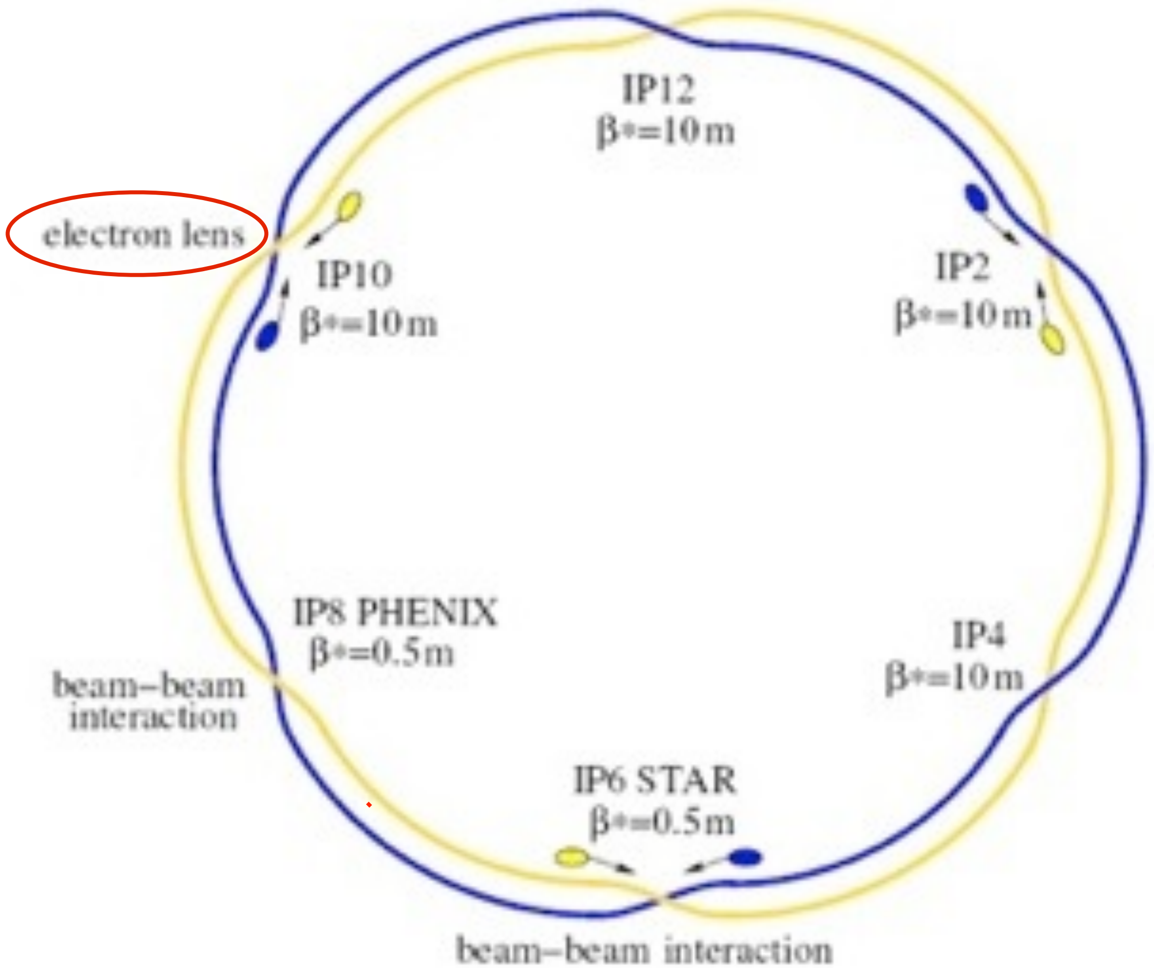
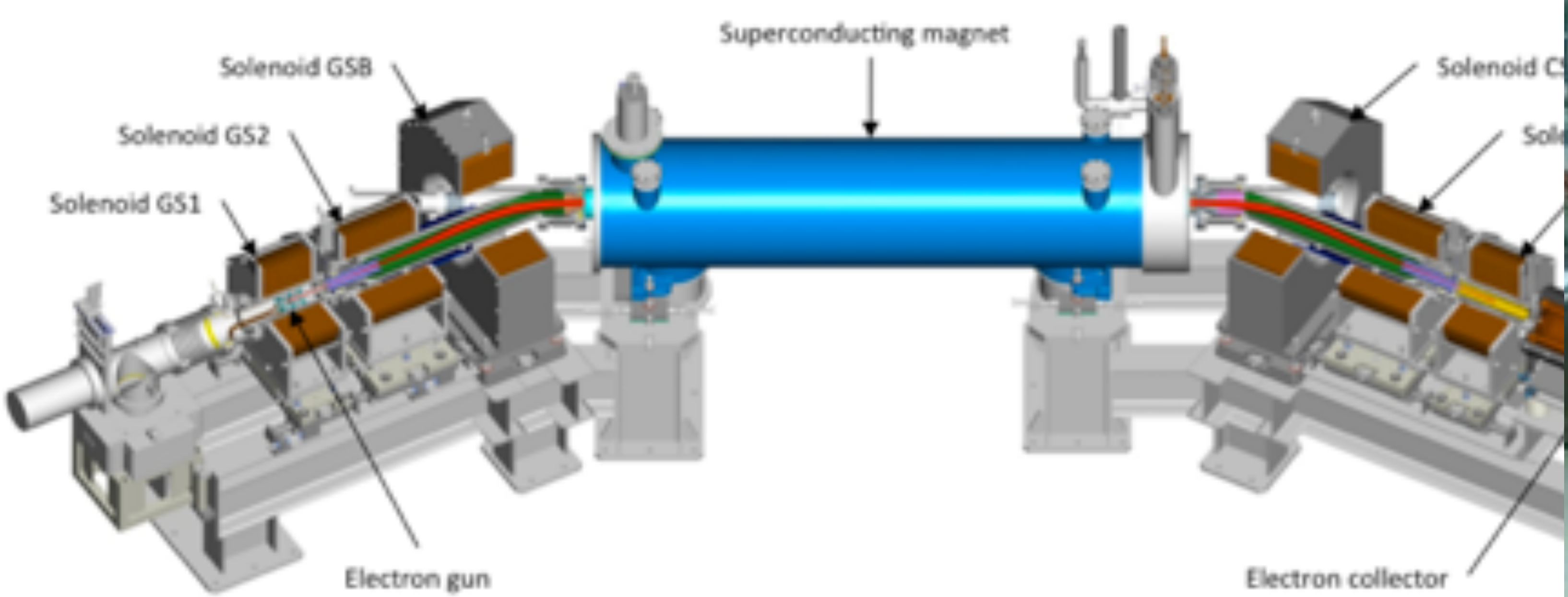
Electron lenses

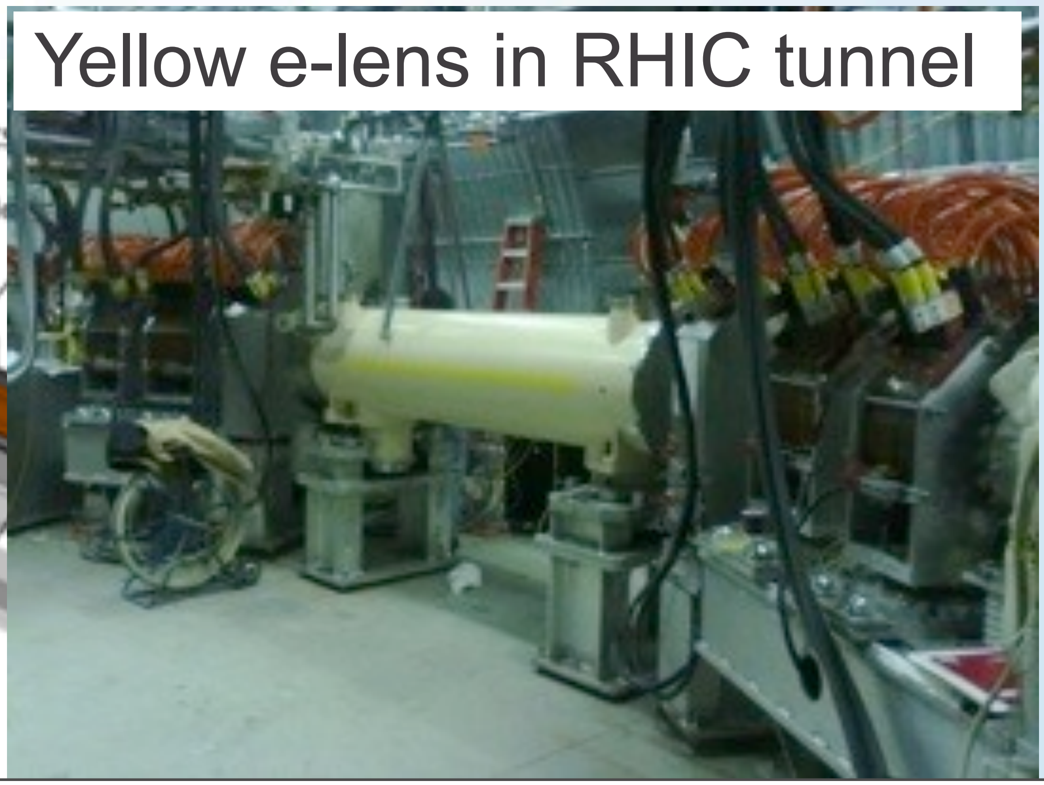


Polarized proton luminosity limited by head-on beam-beam interaction.

Compensate for beam-beam collisions with positively charged beam by another collision with a negatively charged beam with the same amplitude dependence.

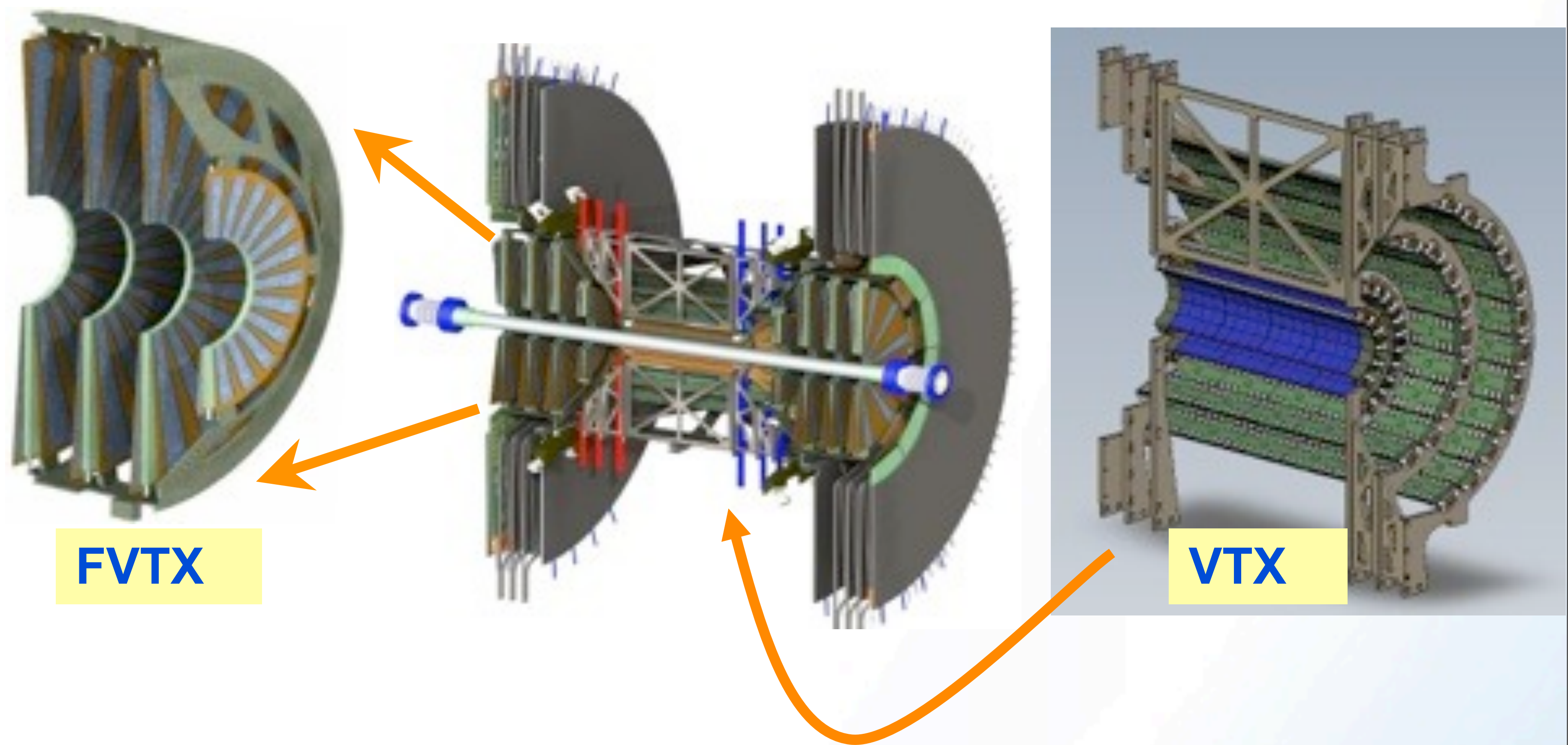
Expect approx. factor 2 luminosity increase with 2 e-lenses (partial comm. in Run-13)





A Suite of Ongoing Detector Upgrades

- ***PHENIX VTX & FVTX upgrades improve vertex resolution, heavy flavor ID***
- ***μ trigger upgrade installed in FY10-11 enhances W prod'n triggering for spin program.***



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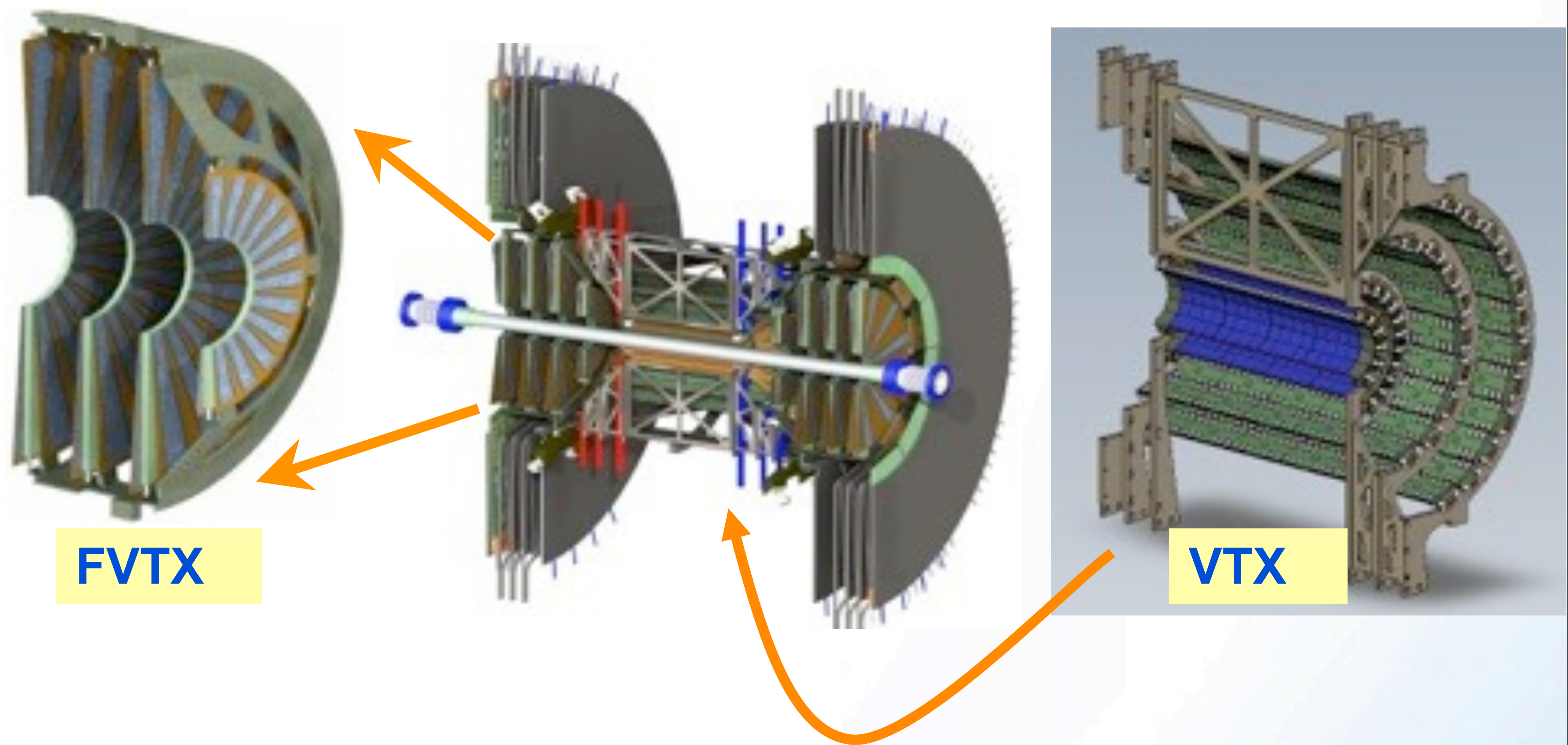
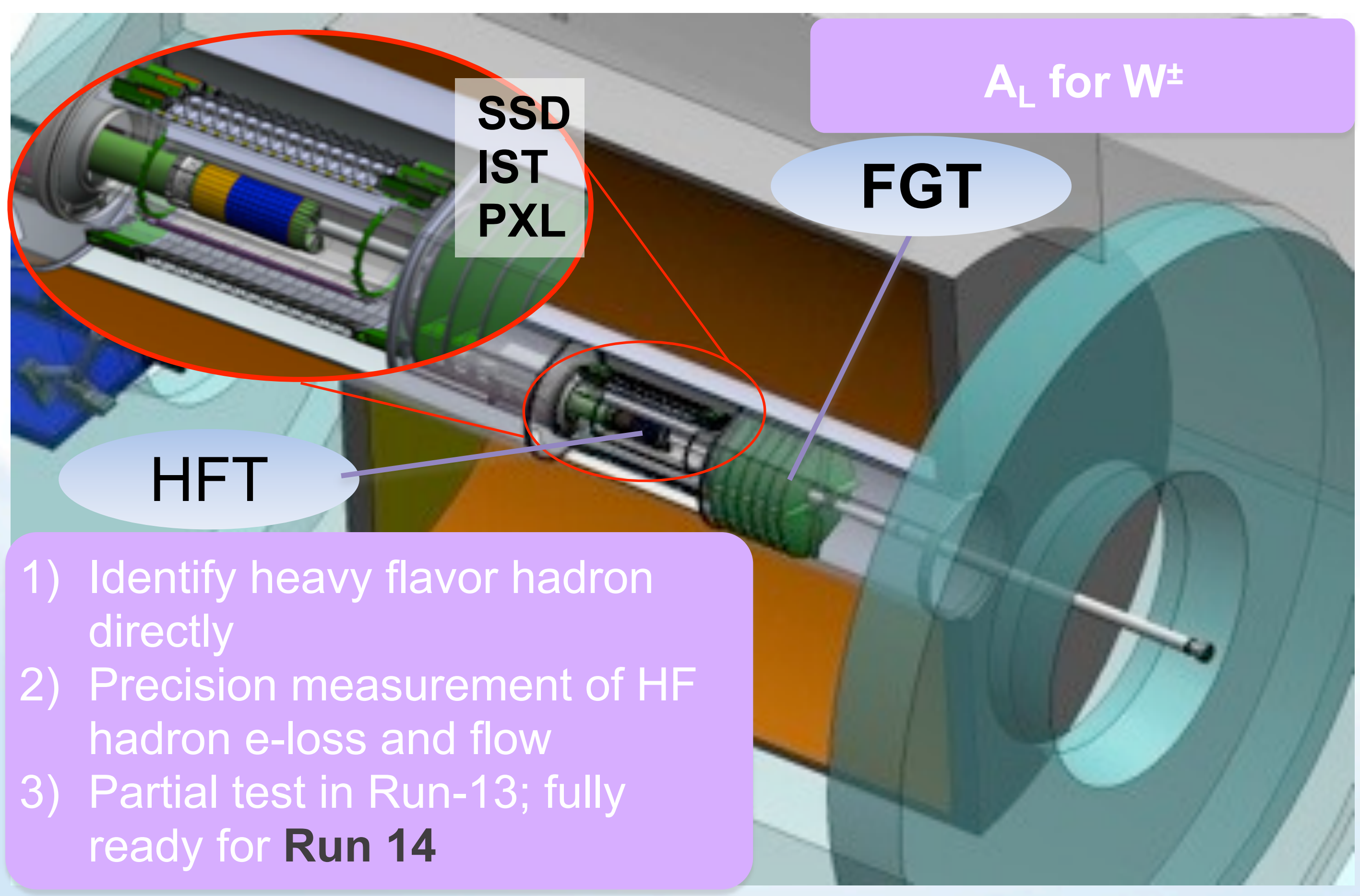




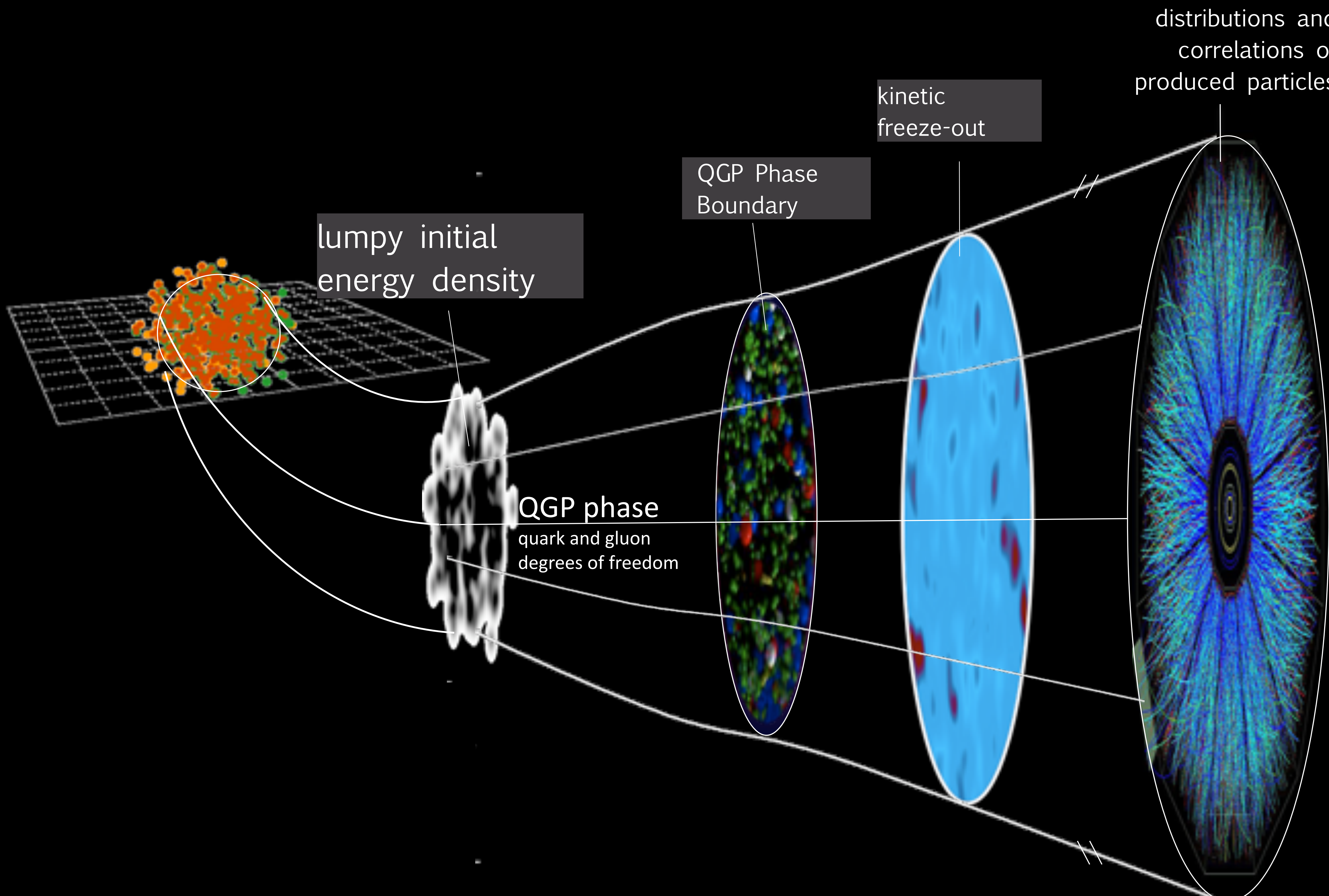
- *STAR Heavy Flavor Tracker slated for CD-4 review in 2014. HFT will permit reconstruction of charmed hadrons and b/c ID.*
- *STAR Forward GEM Tracker (FGT) enhances forward tracking, W charge sign discrimination.*
- *STAR Muon Telescope Detector (Run 14) to improve quarkonium resolution and triggering*

Message 3

RHIC's results have defined a new subfield of (nuclear) physics.

Scientists, from condensed matter physicists to string theorists, have taken note.

RHIC Has Pioneered Lab Study of Condensed QCD Matter



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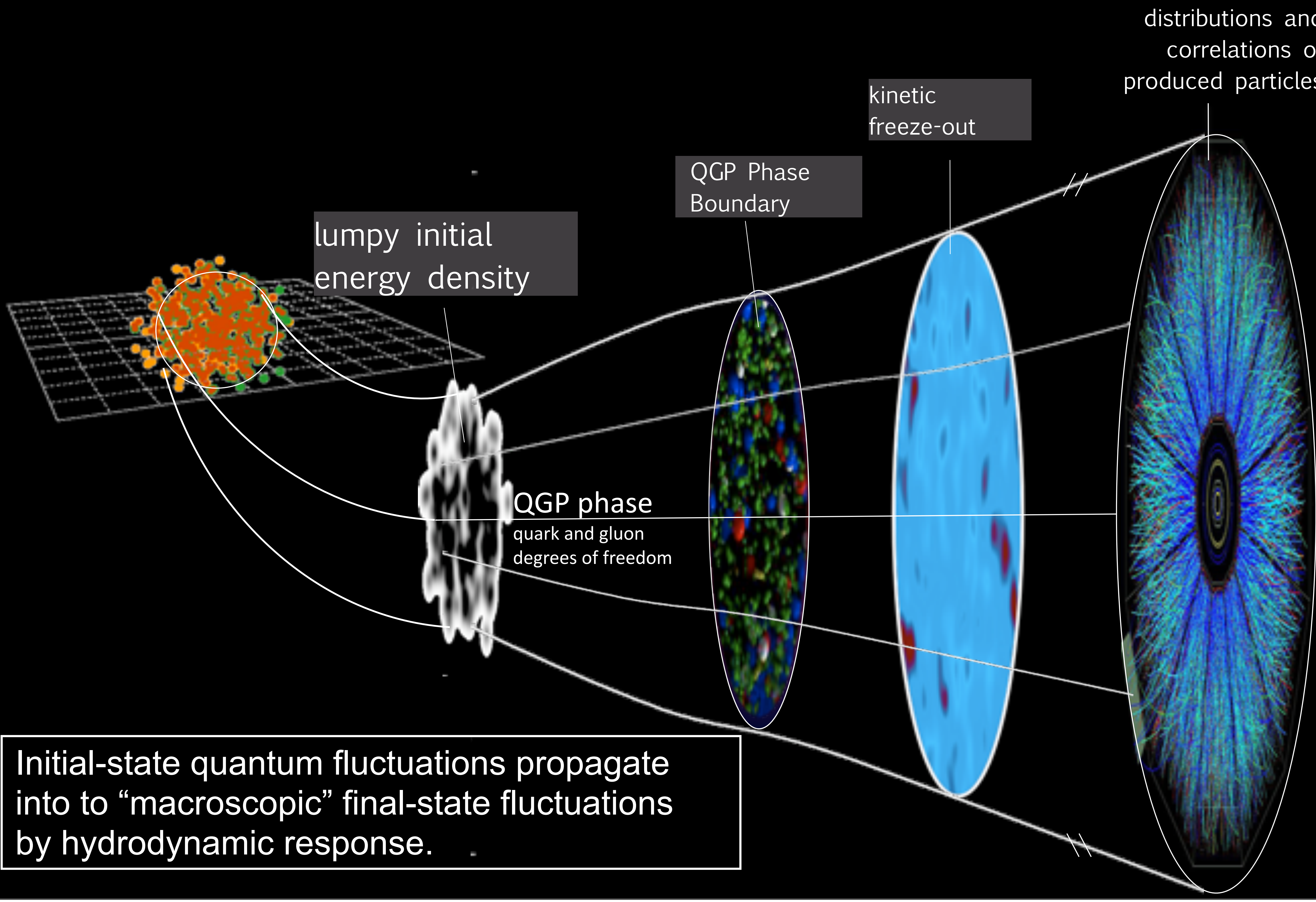
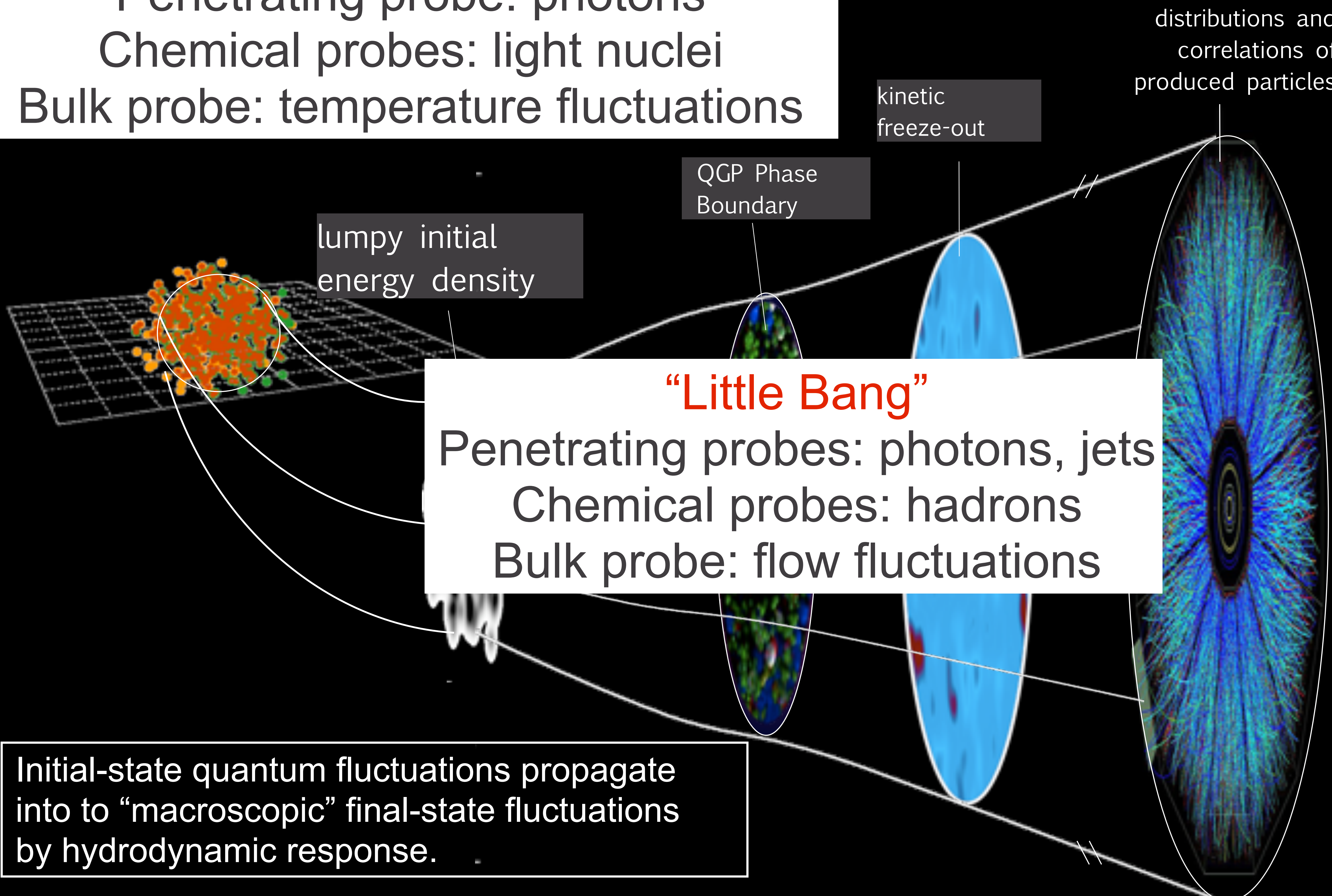


Initial-state quantum fluctuations propagate into to “macroscopic” final-state fluctuations by hydrodynamic response.

RHIC Has Pioneered Lab Study of Condensed QCD Matter

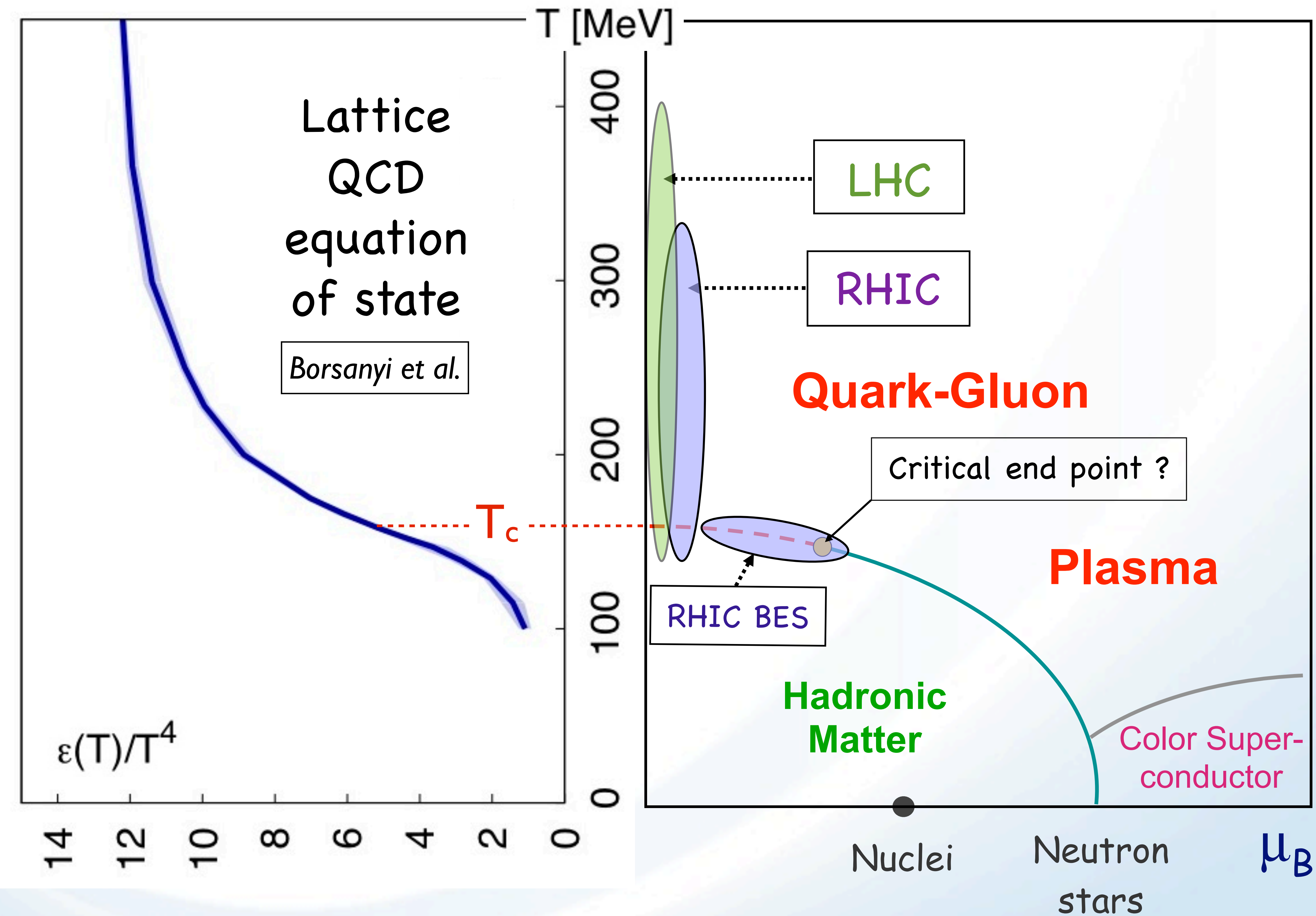
“Big Bang”
Penetrating probe: photons
Chemical probes: light nuclei
Bulk probe: temperature fluctuations



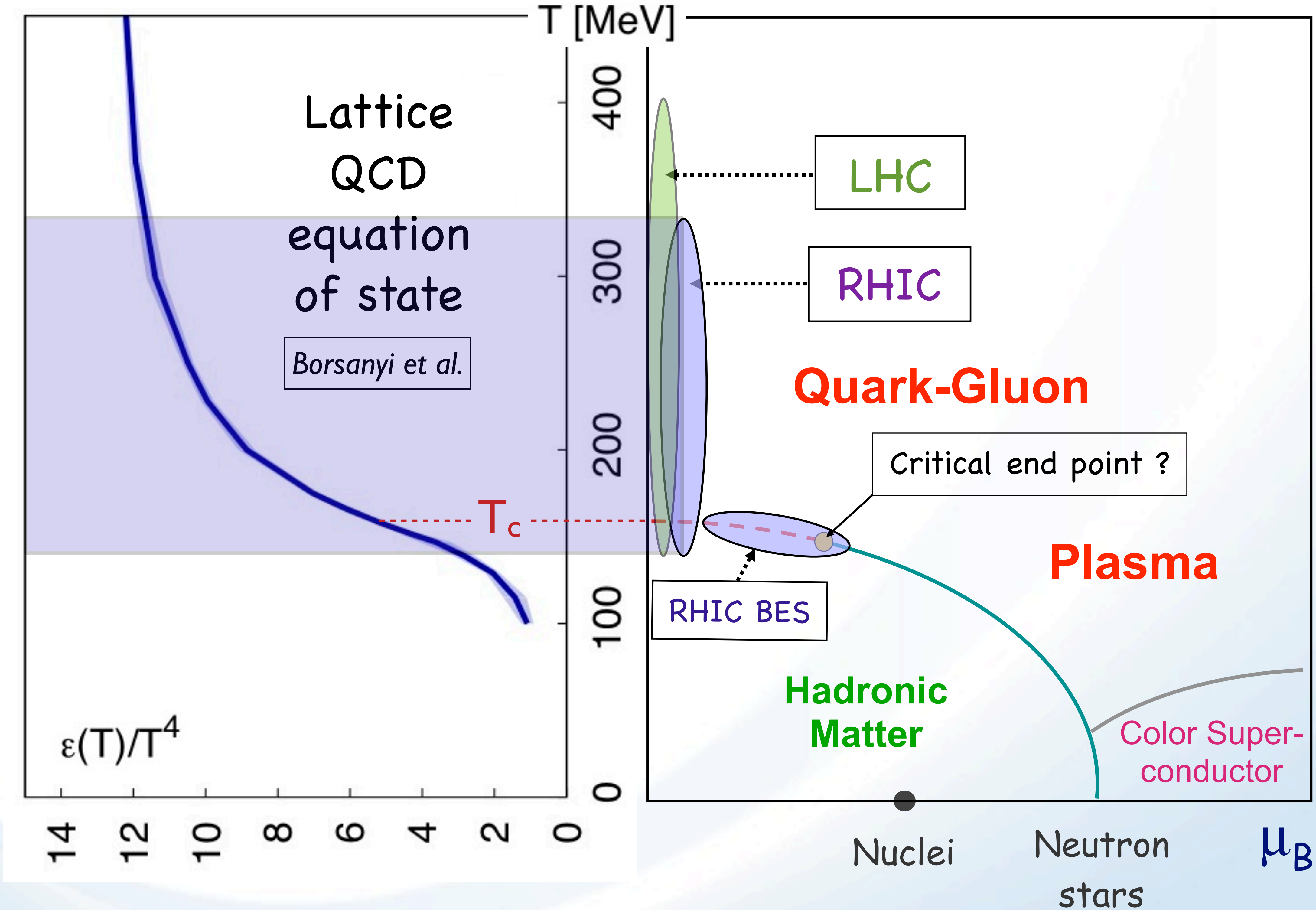
“Little Bang”
Penetrating probes: photons, jets
Chemical probes: hadrons
Bulk probe: flow fluctuations

Initial-state quantum fluctuations propagate into to “macroscopic” final-state fluctuations by hydrodynamic response.

QCD Phase Diagram



QCD Phase Diagram



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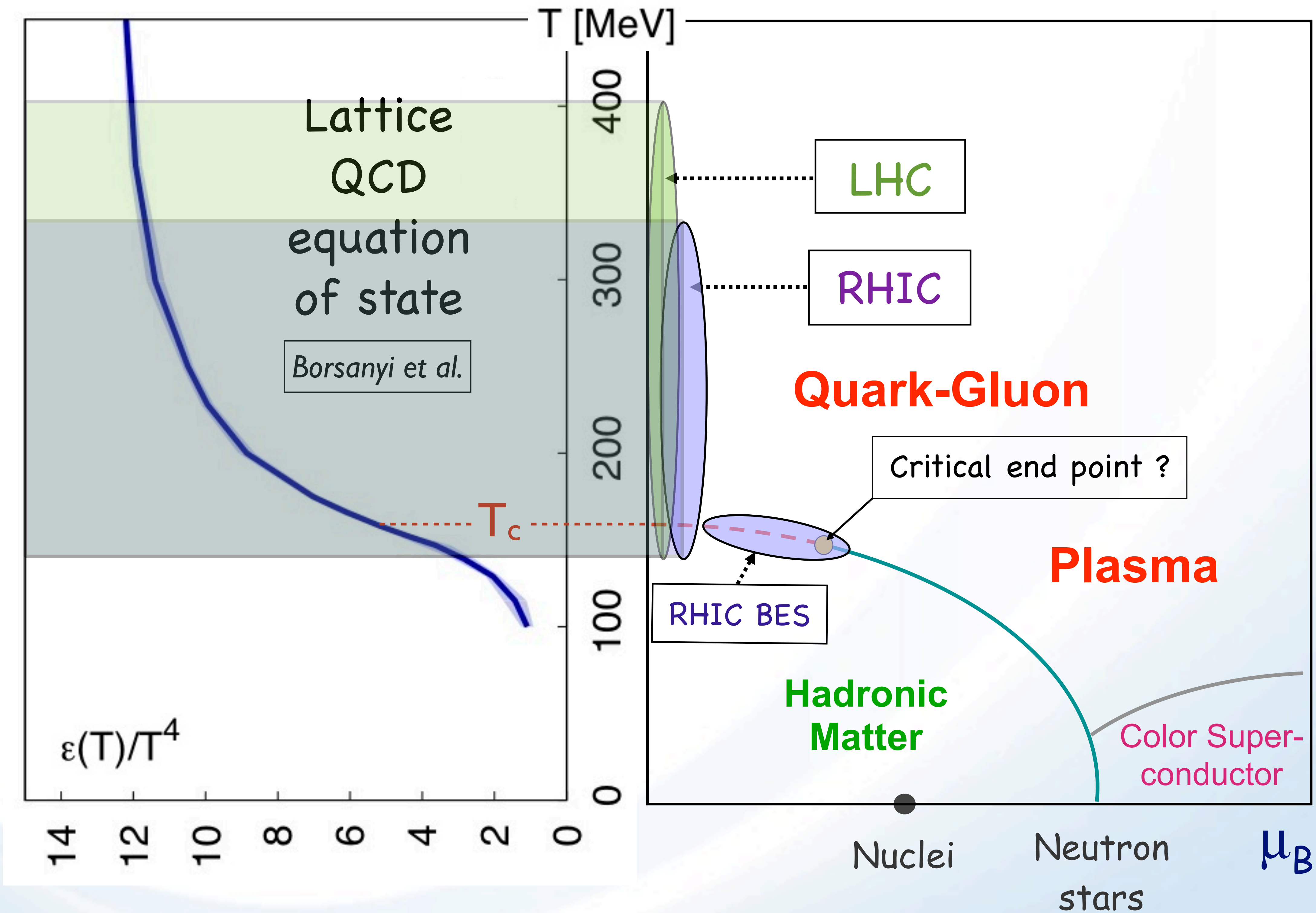
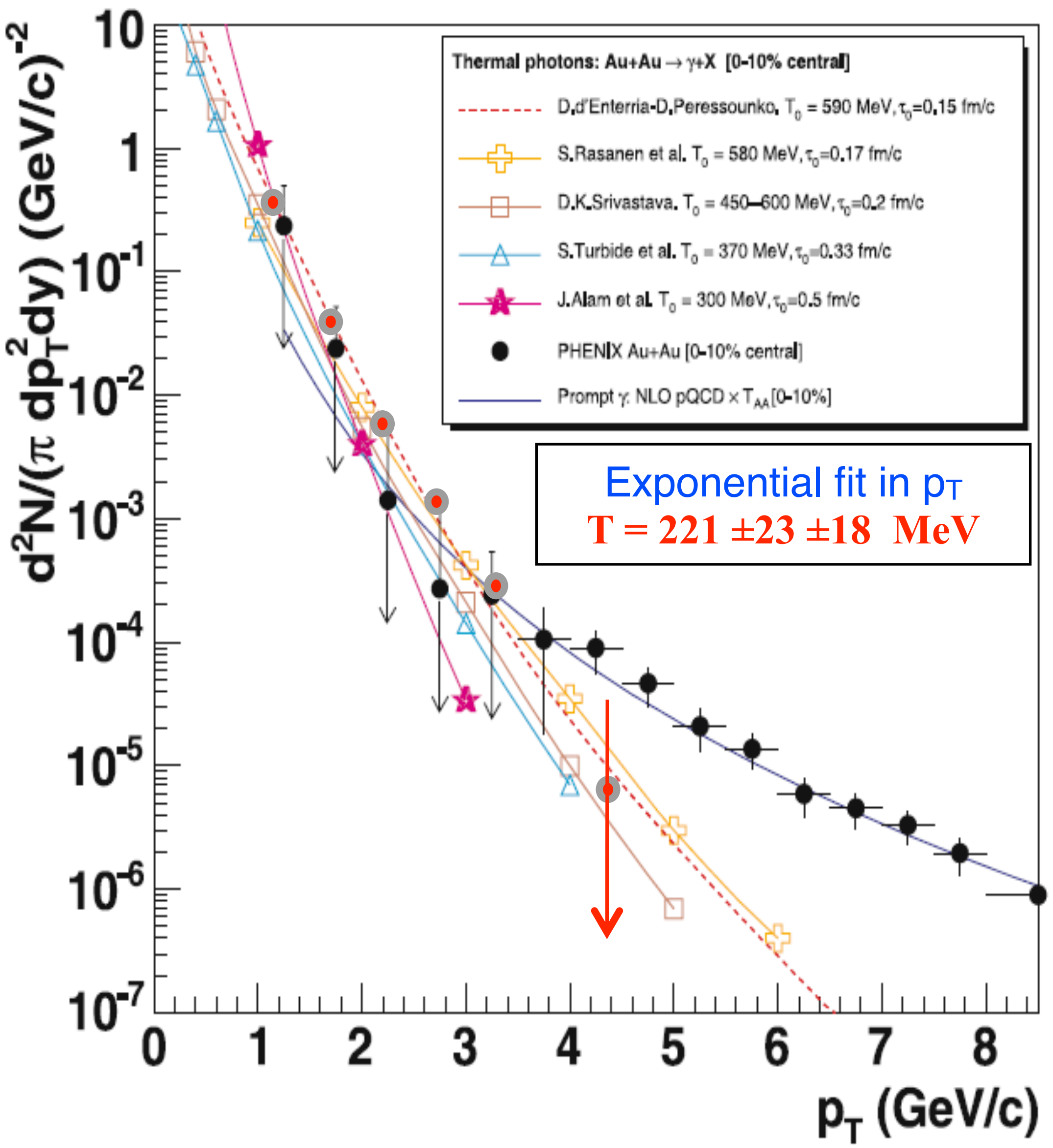
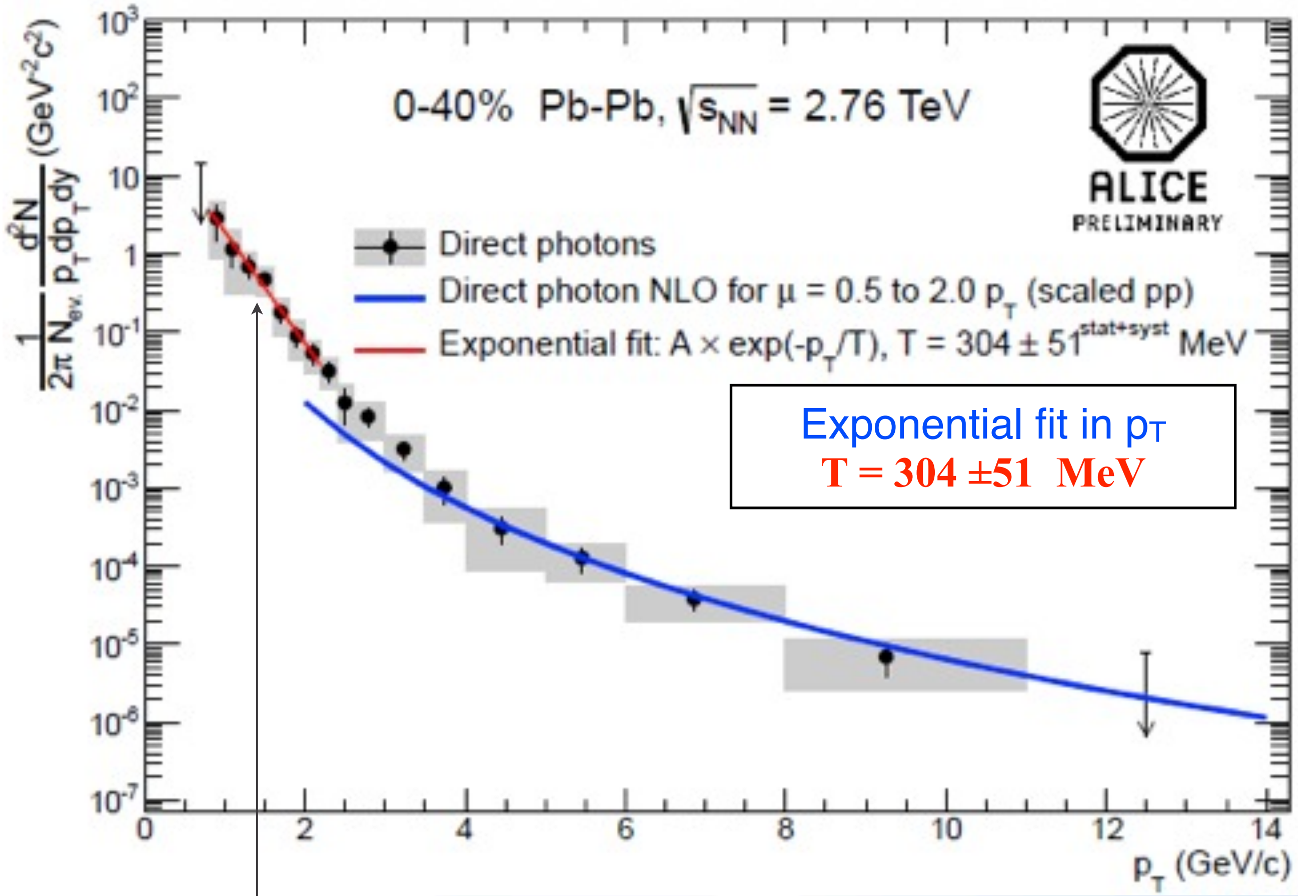
QCD Phase Diagram



A “Guinness” record



Hydro fits
$T_{init} \geq 300$ MeV



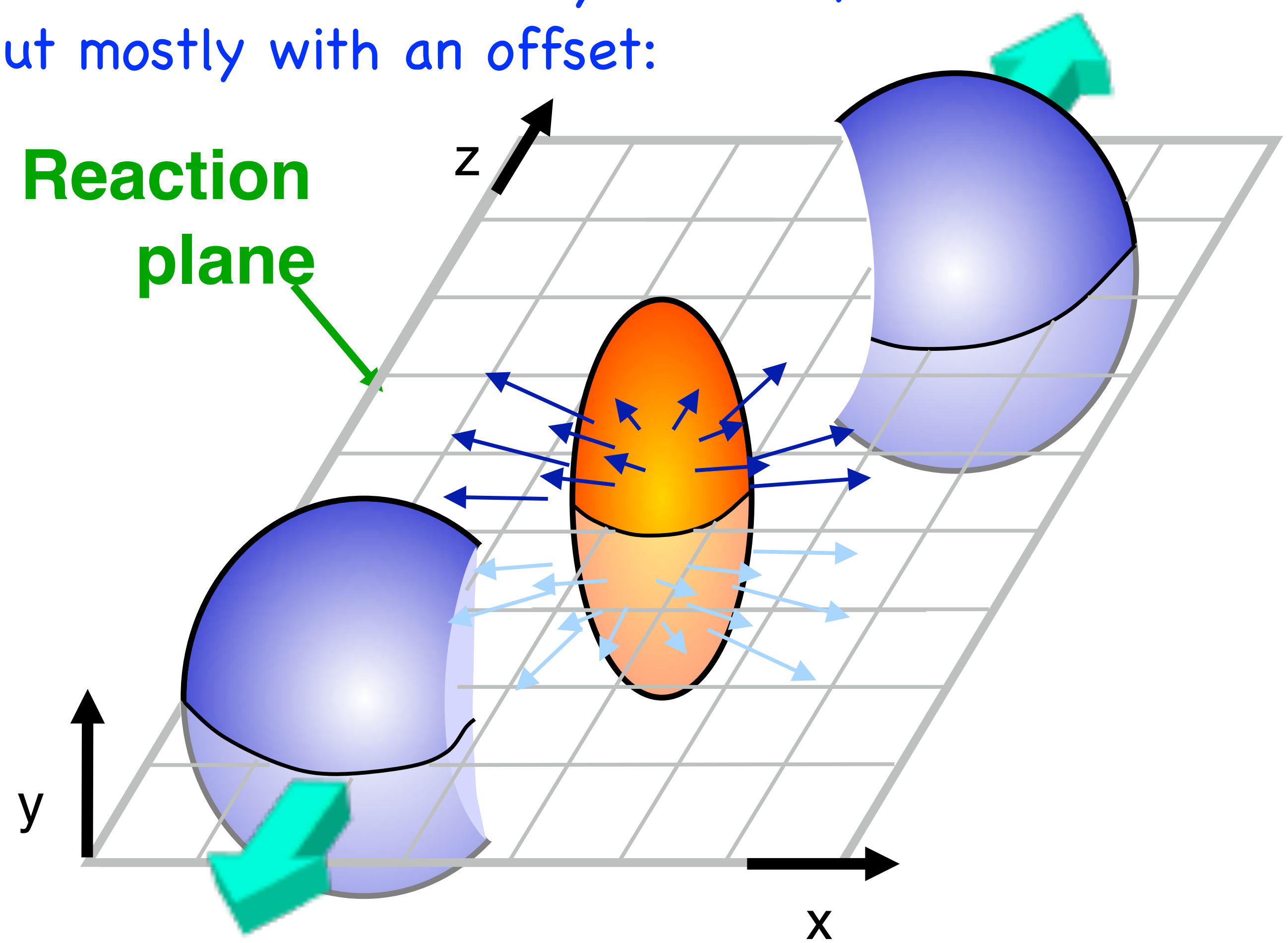
New **record “temperature”** measured in Pb+Pb at LHC:

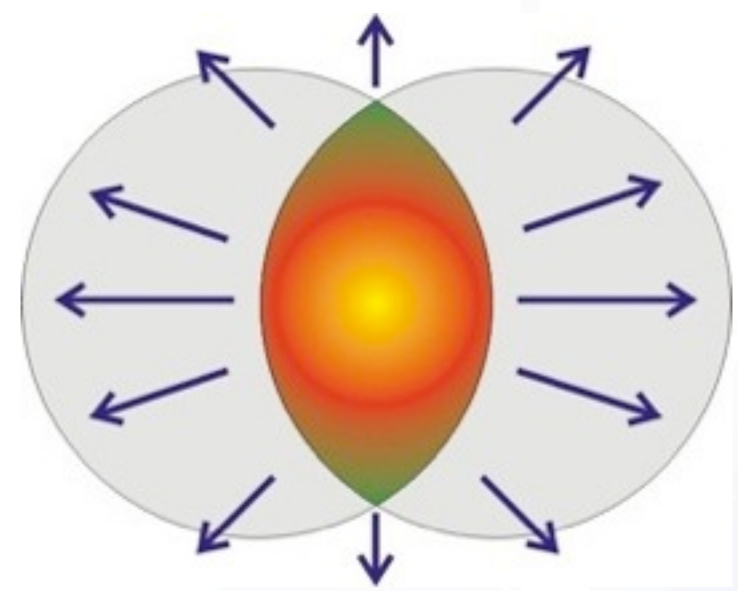
$T_{LHC} = 1.37\, T_{RHIC}$.

Reflects larger initial temperature T_{in}, but not to be identified with T_{in}.

Anisotropic flow

- two nuclei collide rarely head-on, but mostly with an offset:





only matter in the overlap area gets compressed and heated

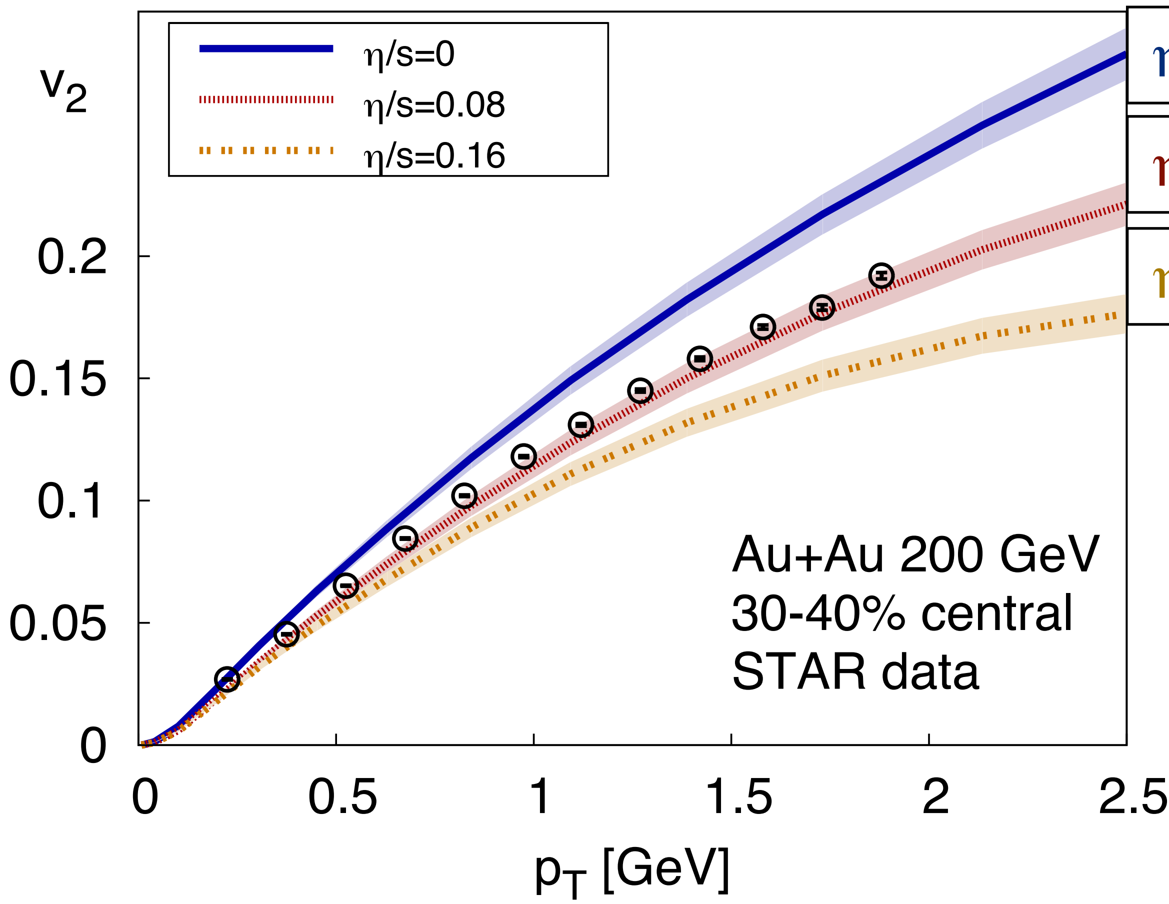
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n v_n(p_T, \eta) \cos n\left(\phi - \psi_n(p_T, \eta)\right) \right)$$

anisotropic flow coefficients (v_n)

event plane angle (ψ_n)

The Perfect Liquid

Schenke, Jeon, Gale, PRL 106 (2011) 042301
PRC 85 (2012) 024901



$\eta/s = 0$

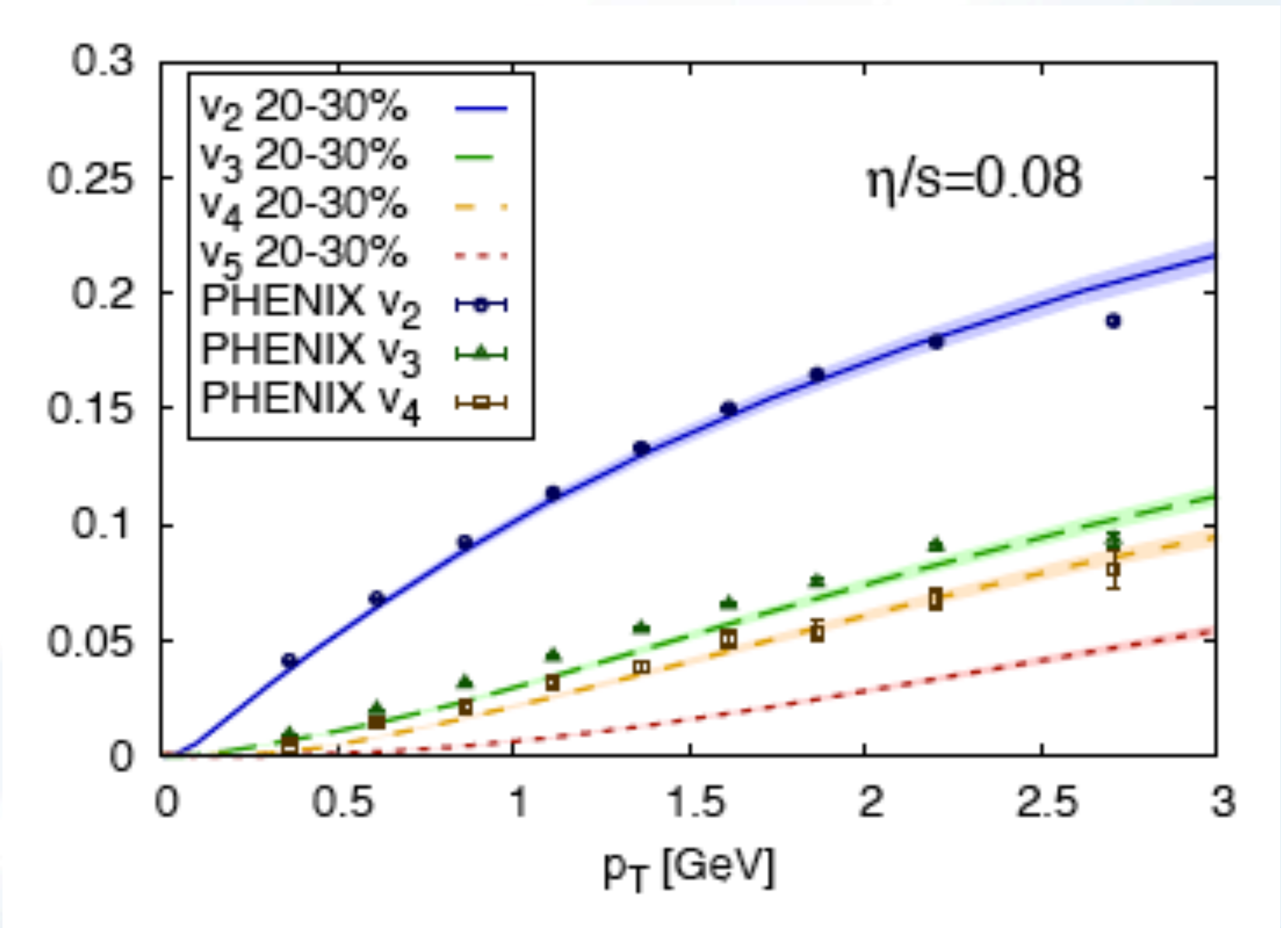
$\eta/s = 1/4\pi$

$\eta/s = 2/4\pi$

Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

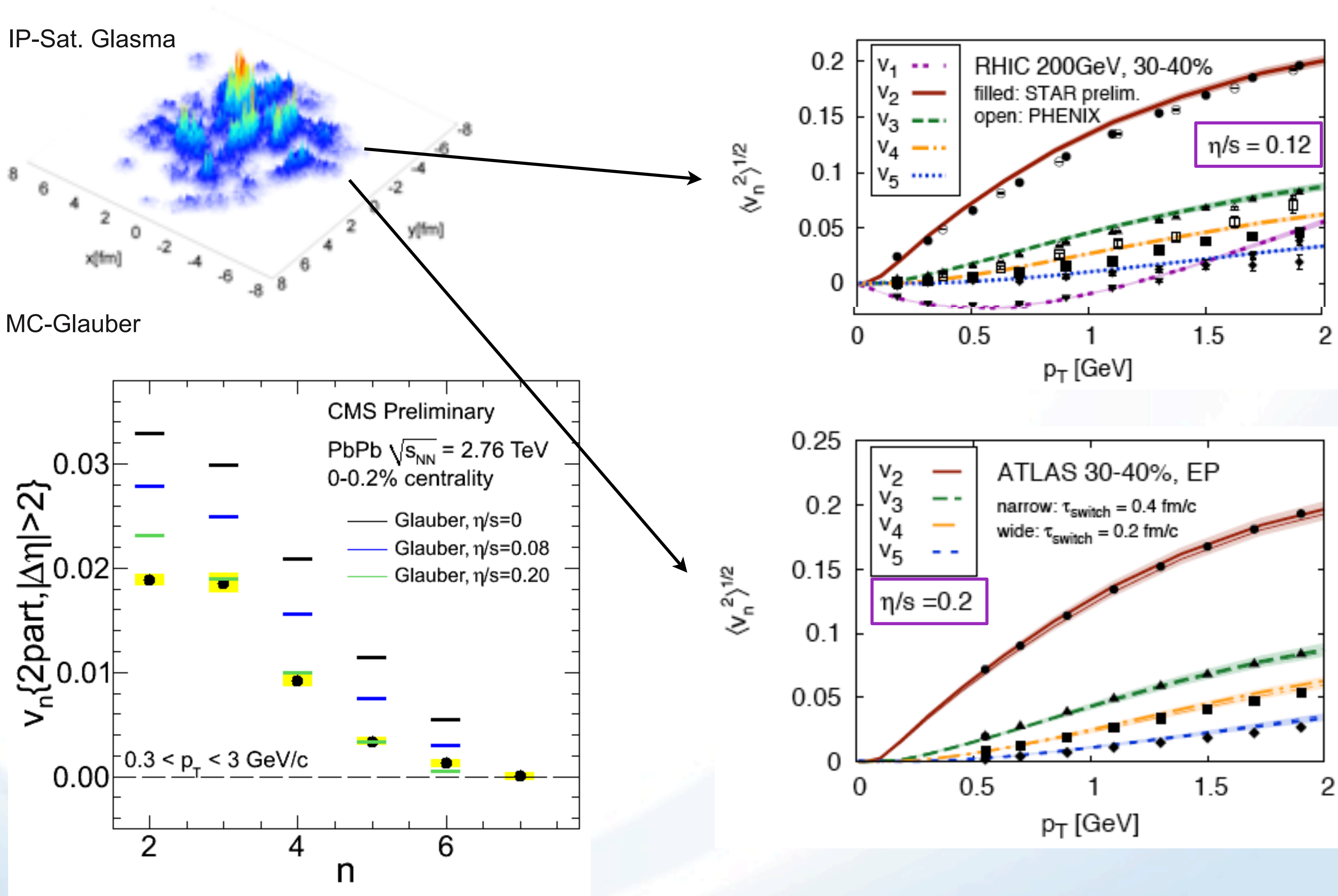
$\eta/s \rightarrow 1/4\pi$

***aka:* the "perfect" liquid**



RHIC-2: The era of precision measurements.

Ultimate probe: Flow fluctuations



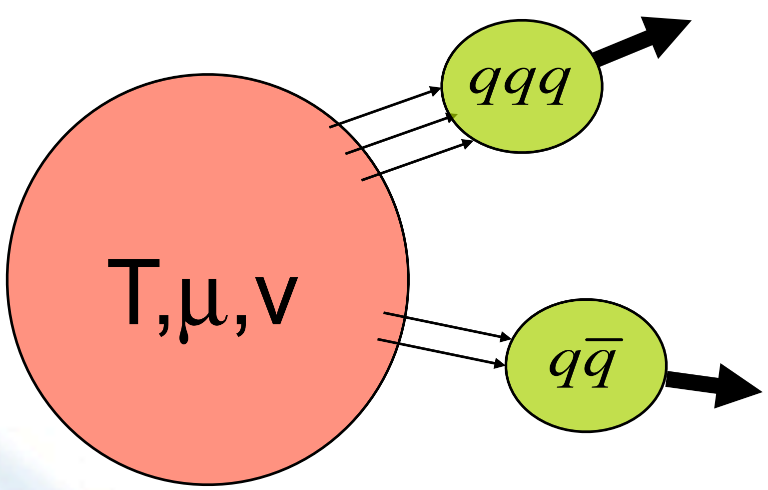
RHIC

LHC

The origin of hadrons

$$v_2^M(p_t) = 2v_2^Q\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3v_2^Q\left(\frac{p_t}{3}\right)$$



$$p_B \approx 3p_Q$$

$$p_M \approx 2p_Q$$

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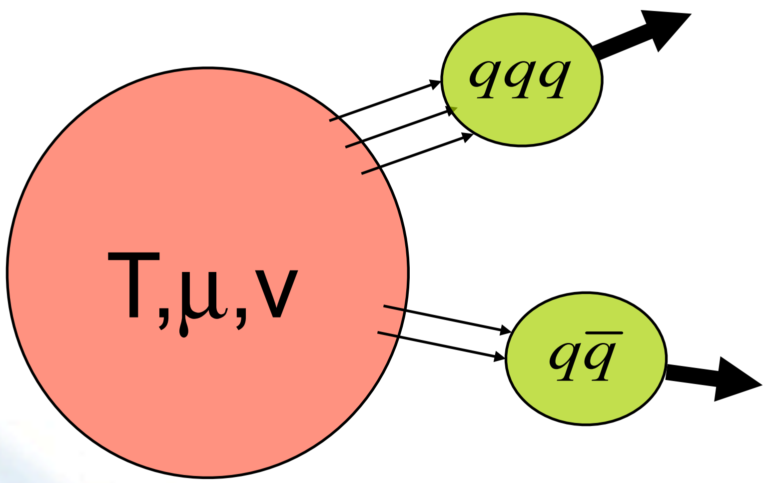
$$v_2^M(p_t) = 2v_2^Q\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3v_2^Q\left(\frac{p_t}{3}\right)$$

Emitting medium is composed of unconfined, flowing quarks.



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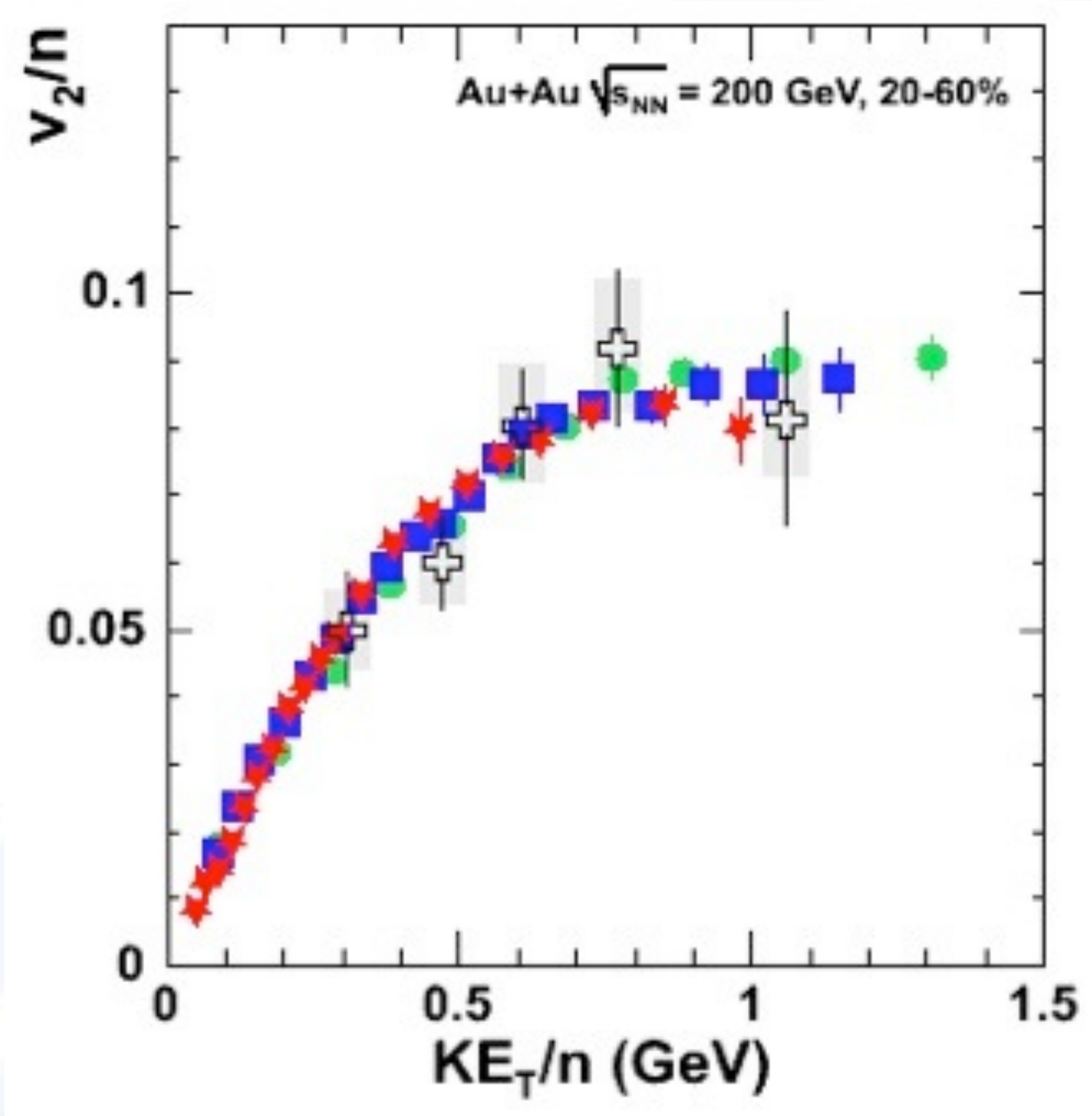
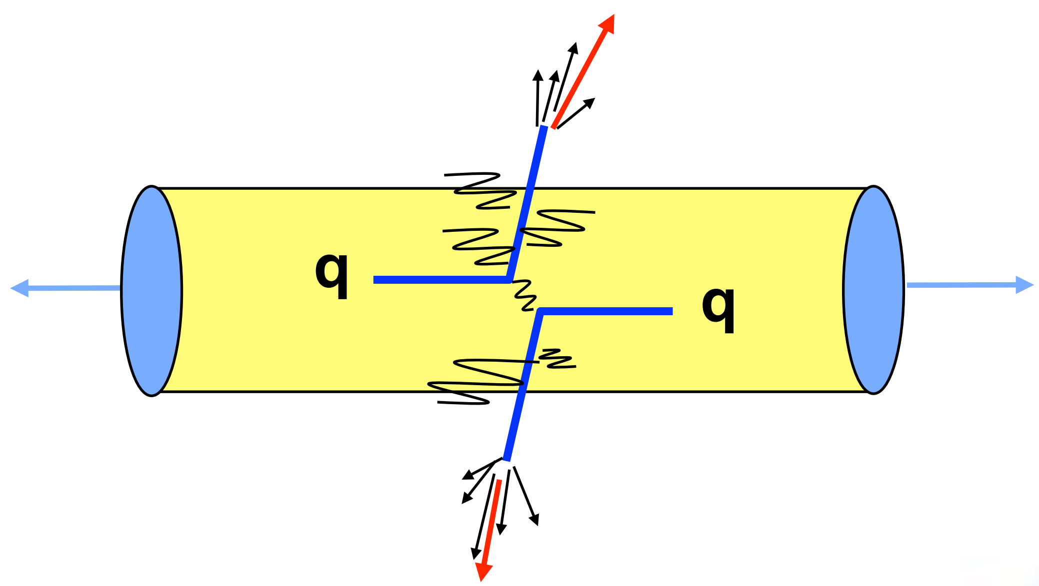
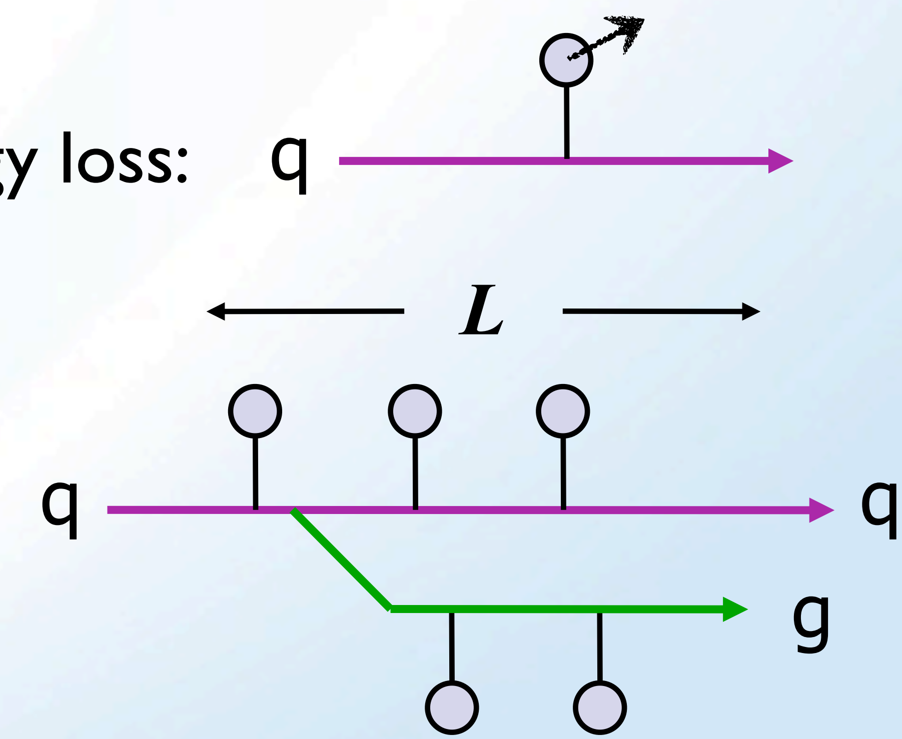


Color opacity of the QGP



Elastic energy loss:

Radiative energy loss:



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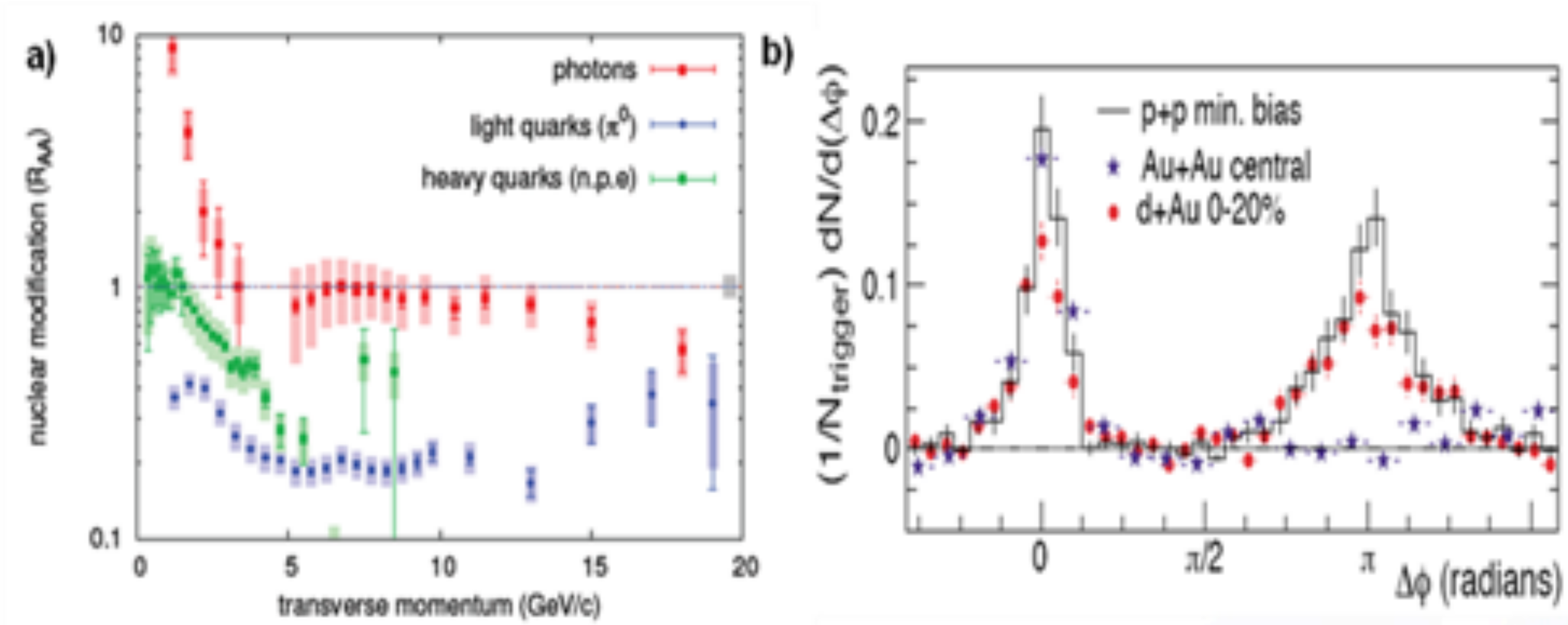

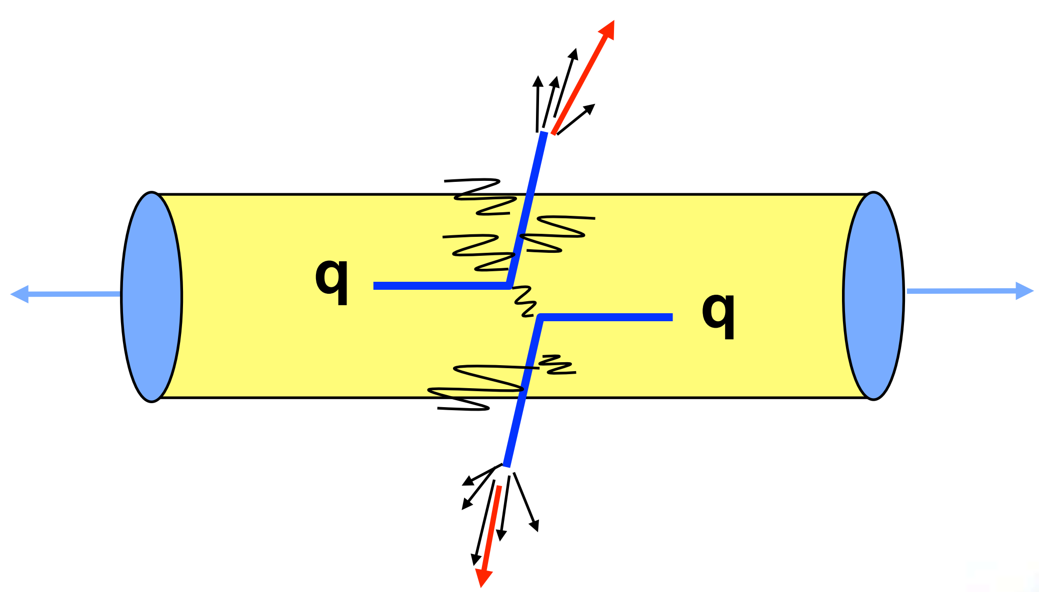

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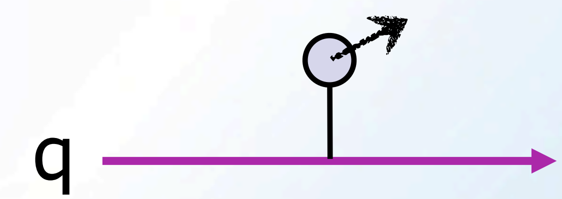
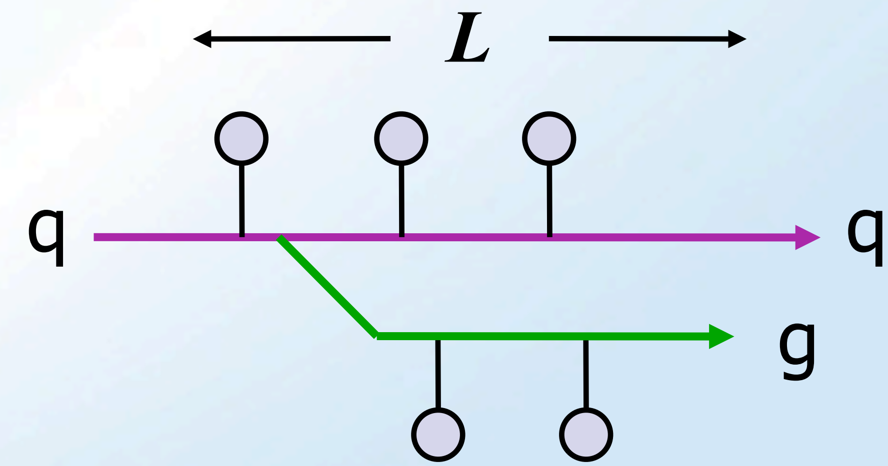




Radiative energy loss:

QGP stopping power

Nuclear suppression

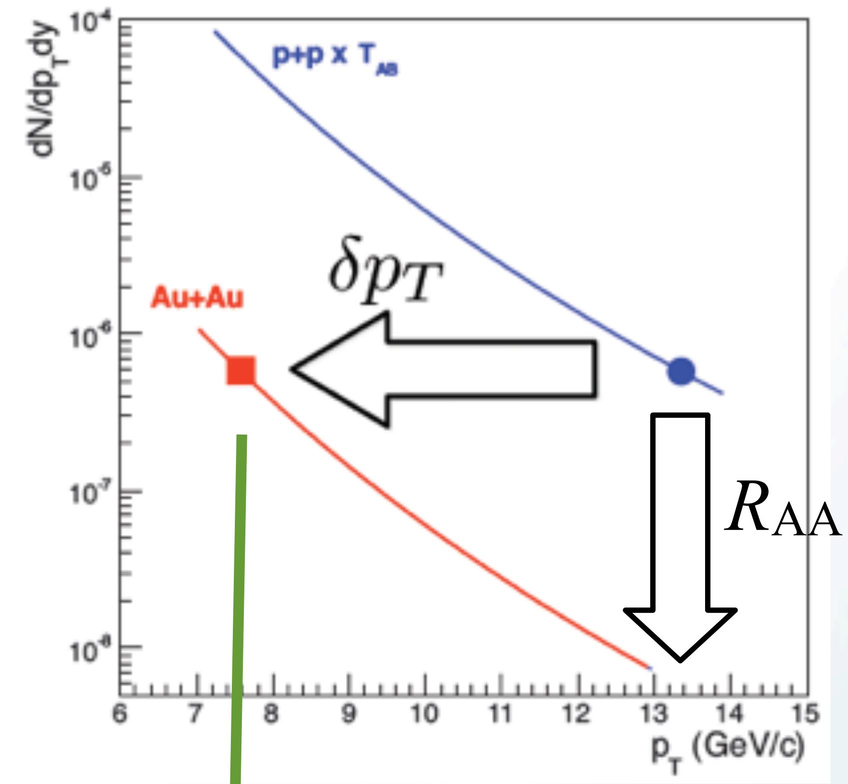
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T dy}{T_{AA}\left(d^2\sigma_{NN}/dp_T dy\right)}$$

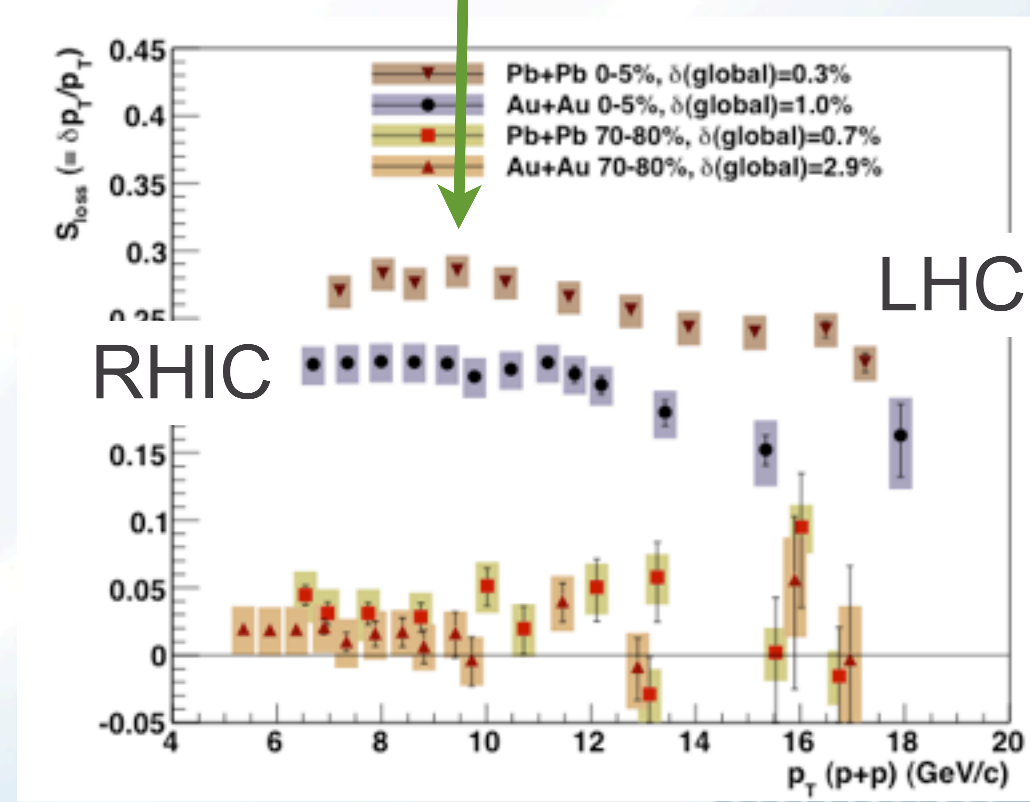
$(\delta p_T)_{\mathrm{LHC}} \approx 1.3\ (\delta p_T)_{\mathrm{RHIC}}$

but:

$(dN/dy)_{\mathrm{LHC}} \approx 2.2\ (dN/dy)_{\mathrm{RHIC}}$

⇒ **QGP at LHC is less opaque to hard partons than at RHIC**





Conclusion

RHIC sits at the "sweet spot":

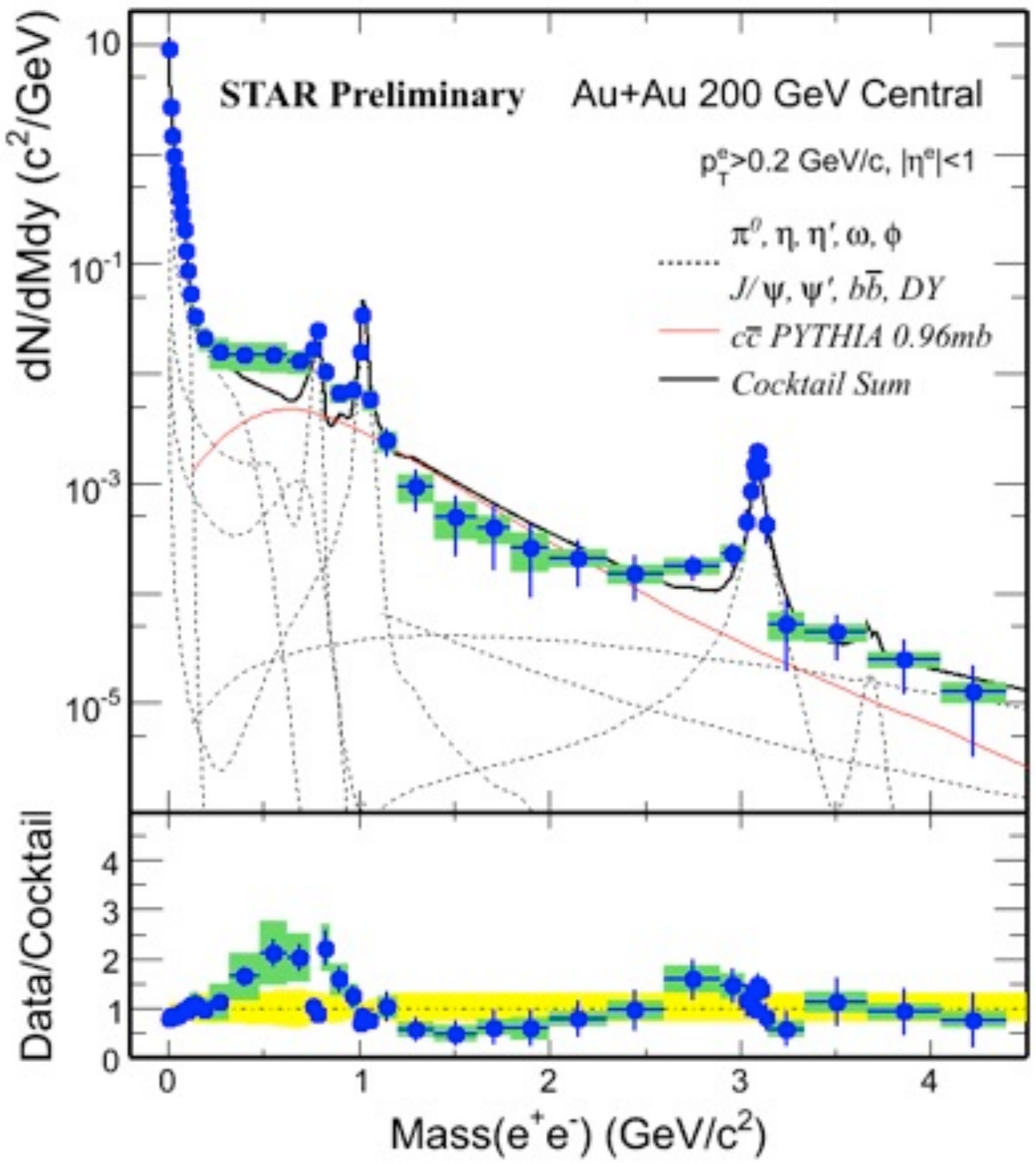
It explores the most perfectly liquid, most opaque form of the quark-gluon plasma.

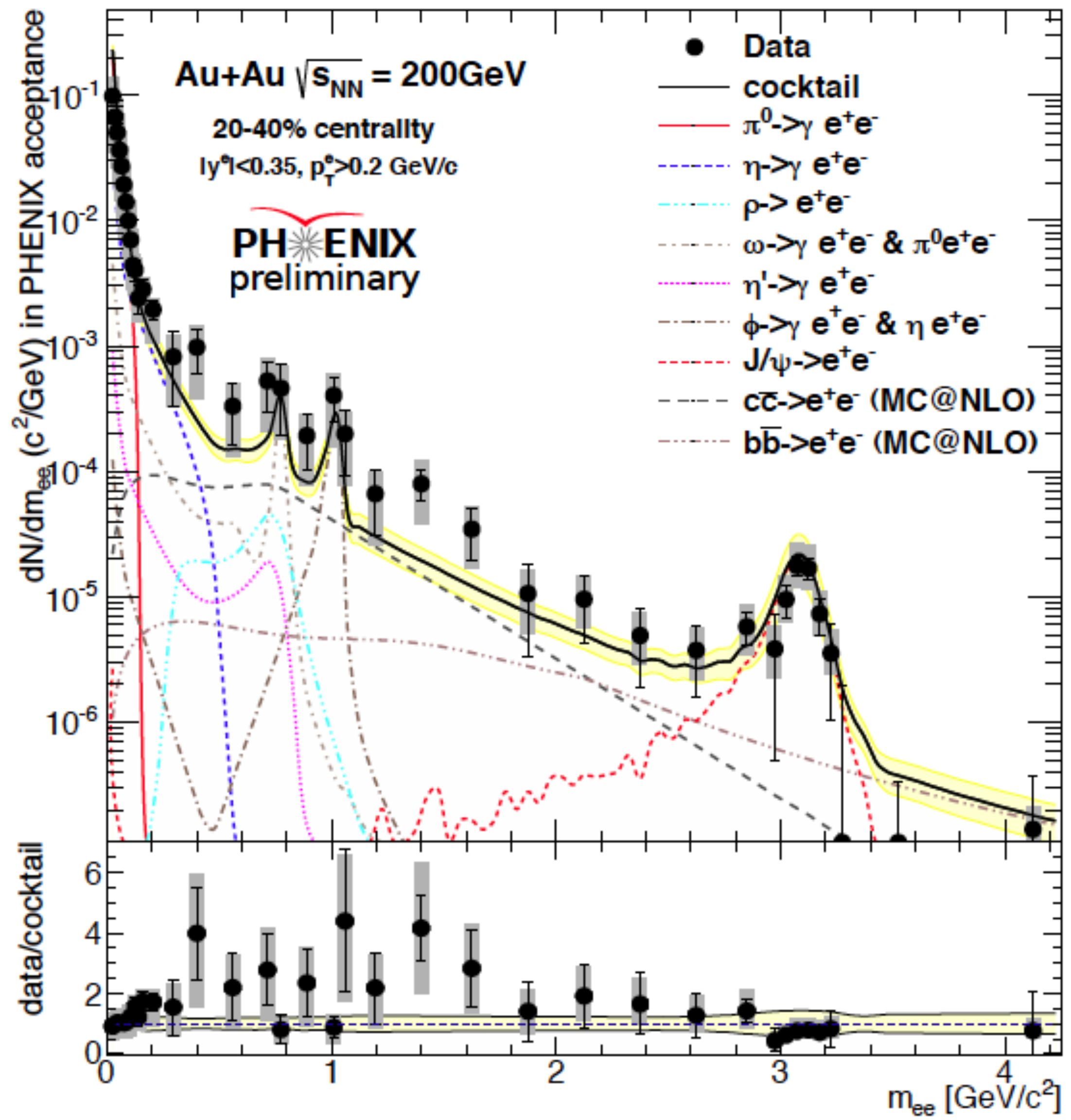
That's all fine, but what have you done for us lately?

Message 4

RHIC's productivity is higher than ever.

Di-leptons: Penetrating Probe



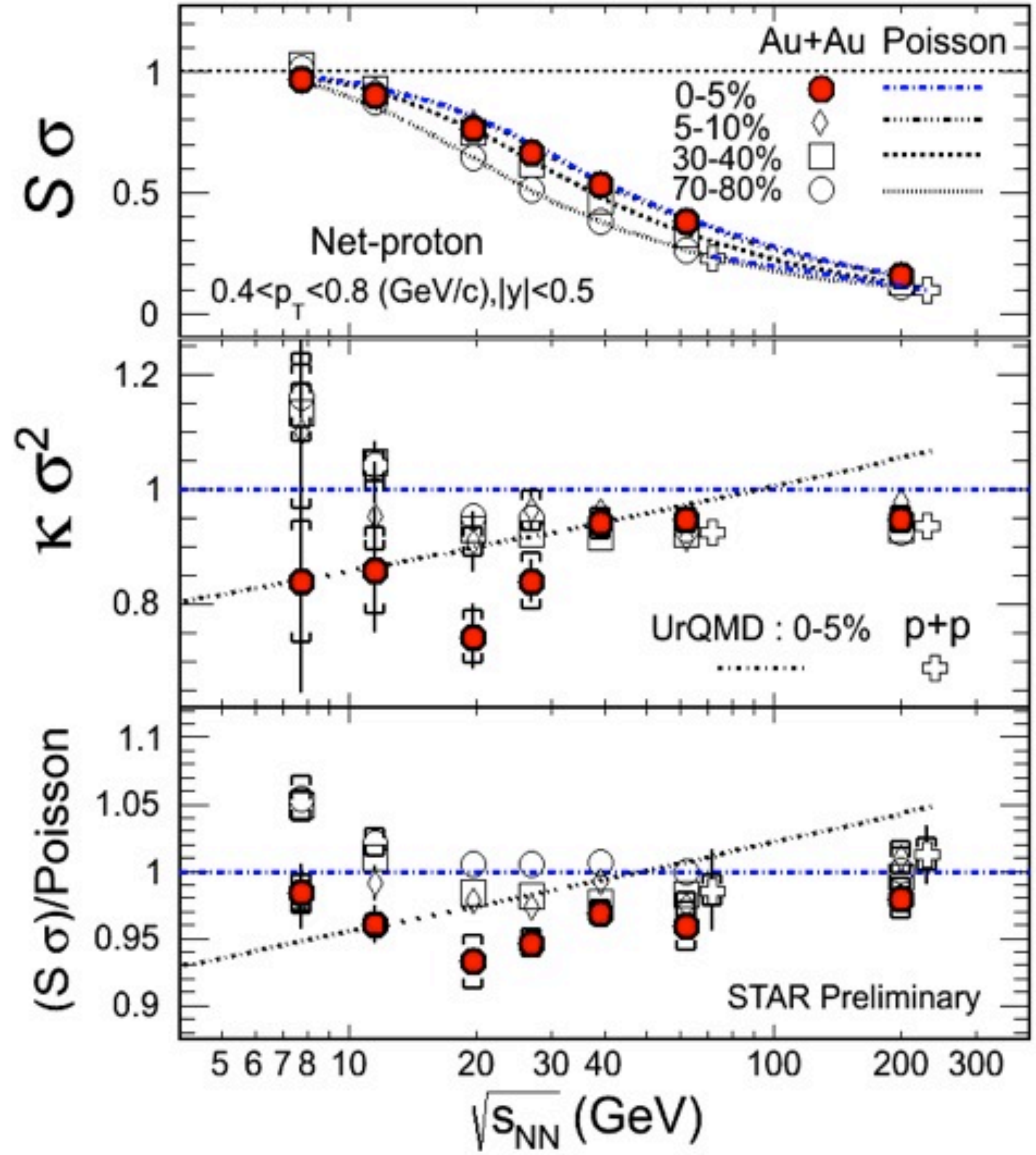


New detector capabilities of STAR (EMCal/TOF) and PHENIX (HBD)

Probing
in-medium hadron modification and chiral symmetry restoration

Uniqueness of RHIC: Beam energy scan

- BES Phase 1 analyses near final
  - Results presented at QM 2012
  - First publication, PR C 86 (2012) 54908
- Hints of exciting behavior, but higher luminosity Phase 2 necessary for definitive results
- Run at 15 GeV in Run-13 ?

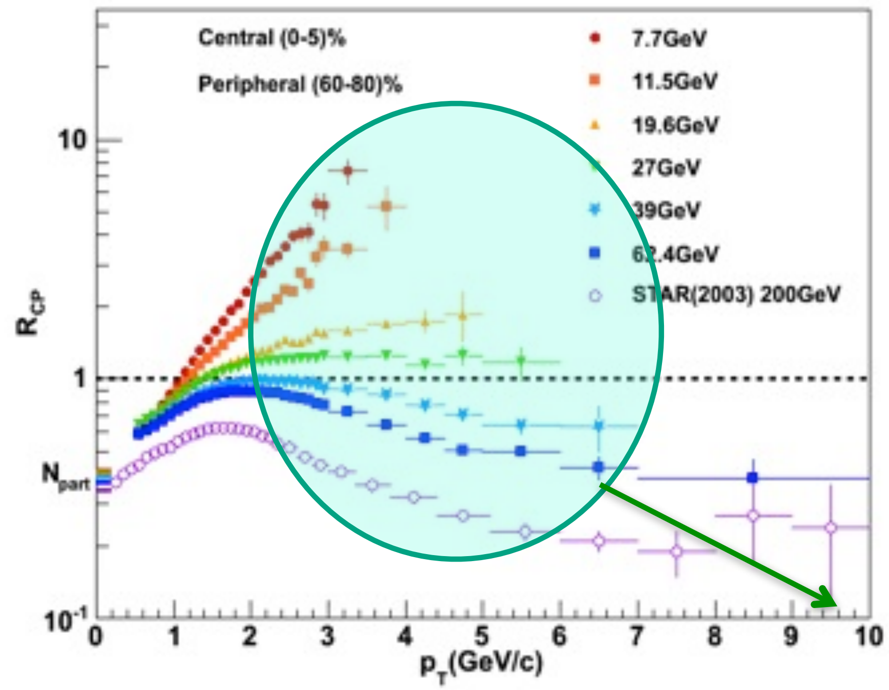


Data taken at
$\sqrt{s_{NN}}$ = 39, 27, 19.6, 11.5, 7.7 GeV

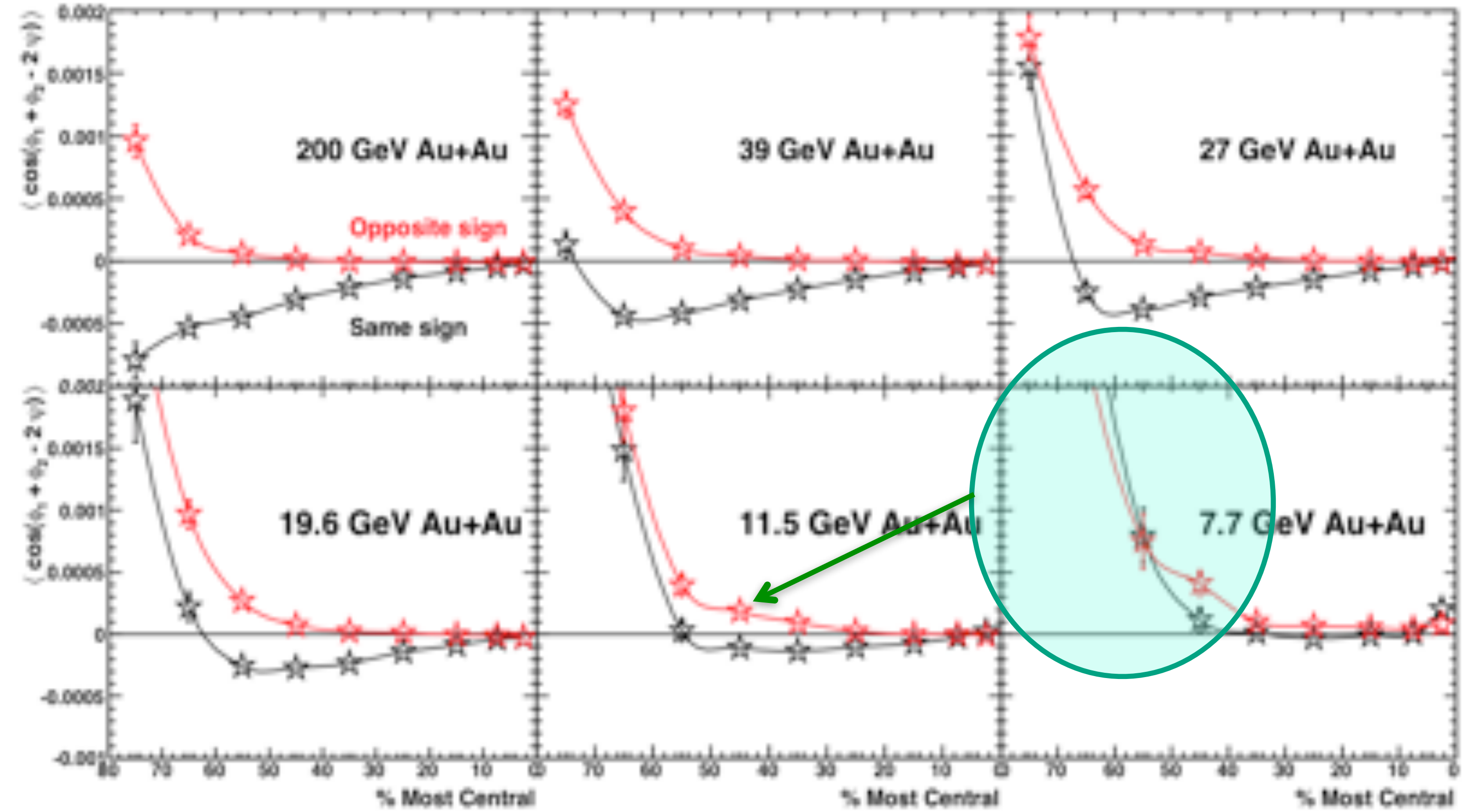
Partonic interaction dominant
at $\sqrt{s_{NN}} \geq$ 39 GeV
Hadronic interaction dominant
at $\sqrt{s_{NN}} \leq$ 11.5 GeV

More BES Highlights

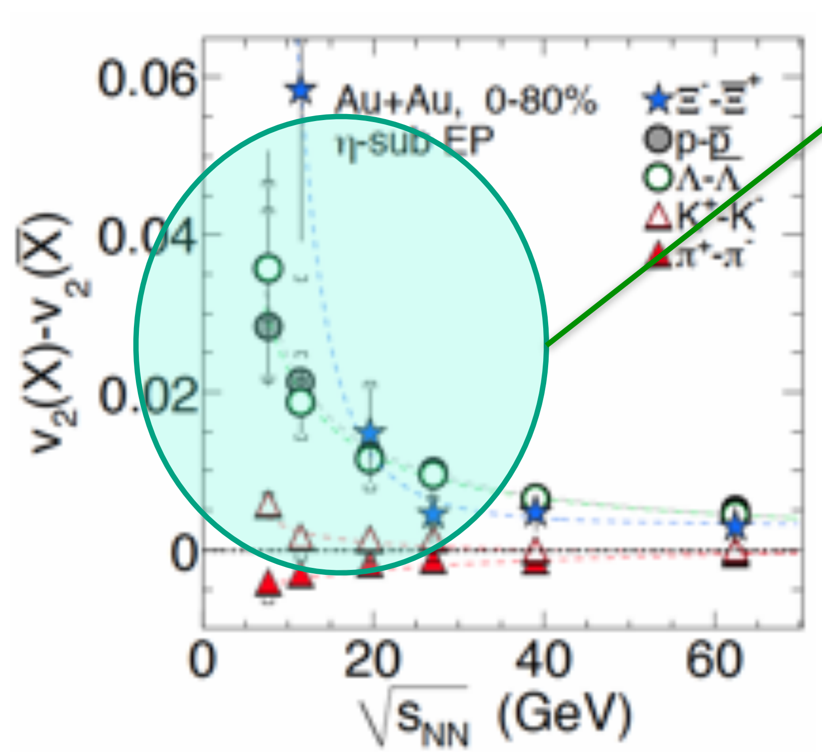
Jet-quenching



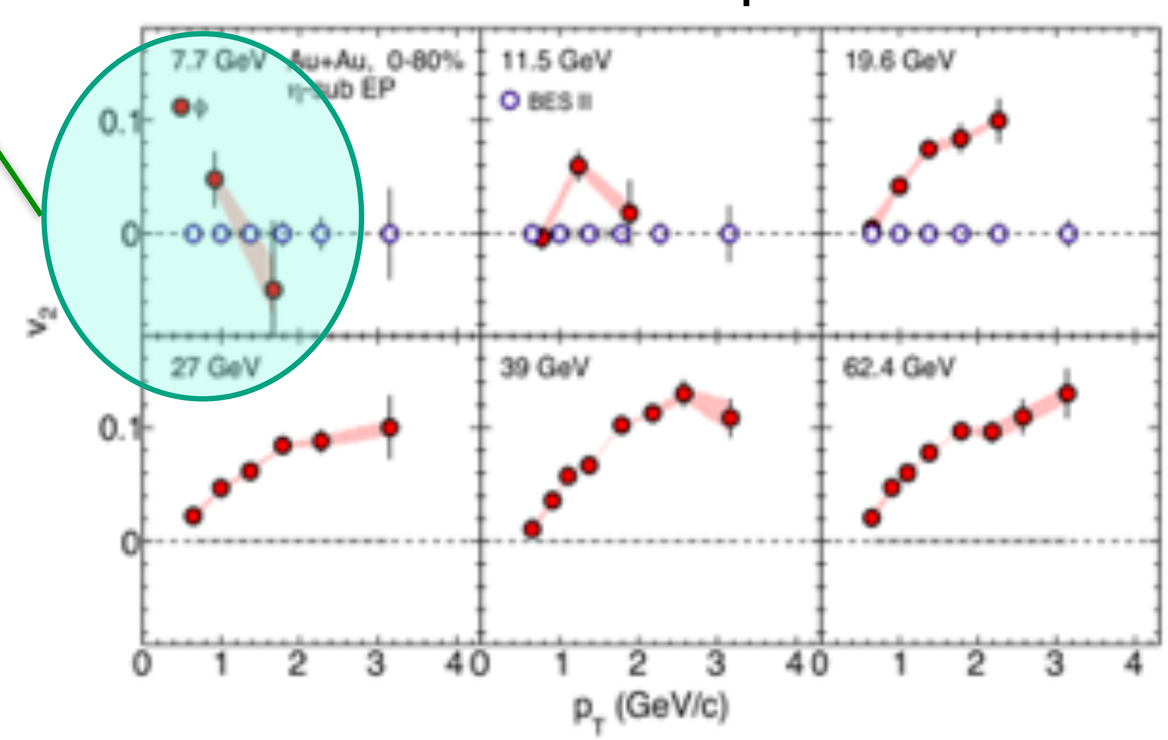
“Local Parity Violation”



NQ Scaling in v_2



ϕ-meson flow



More BES Highlights

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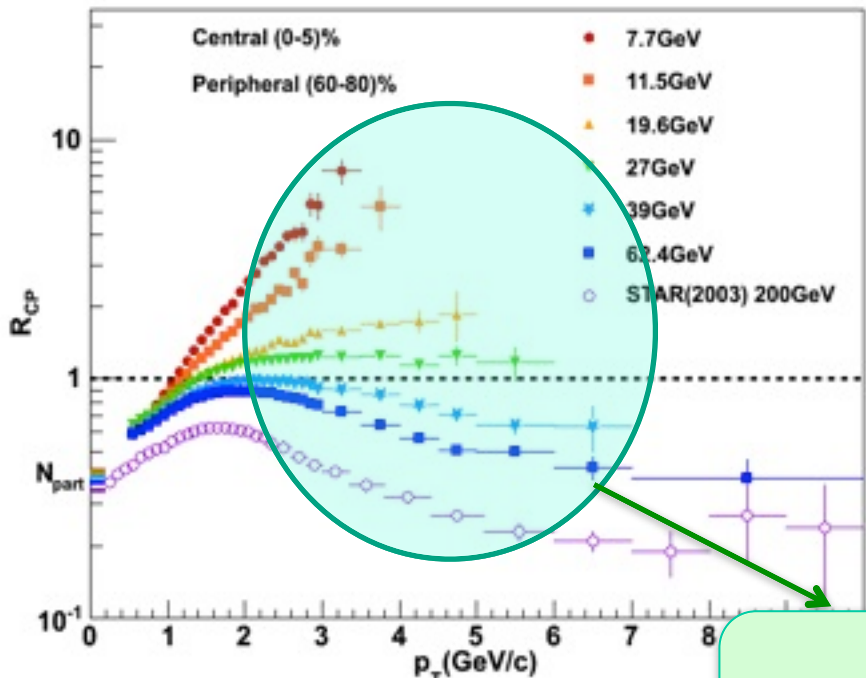

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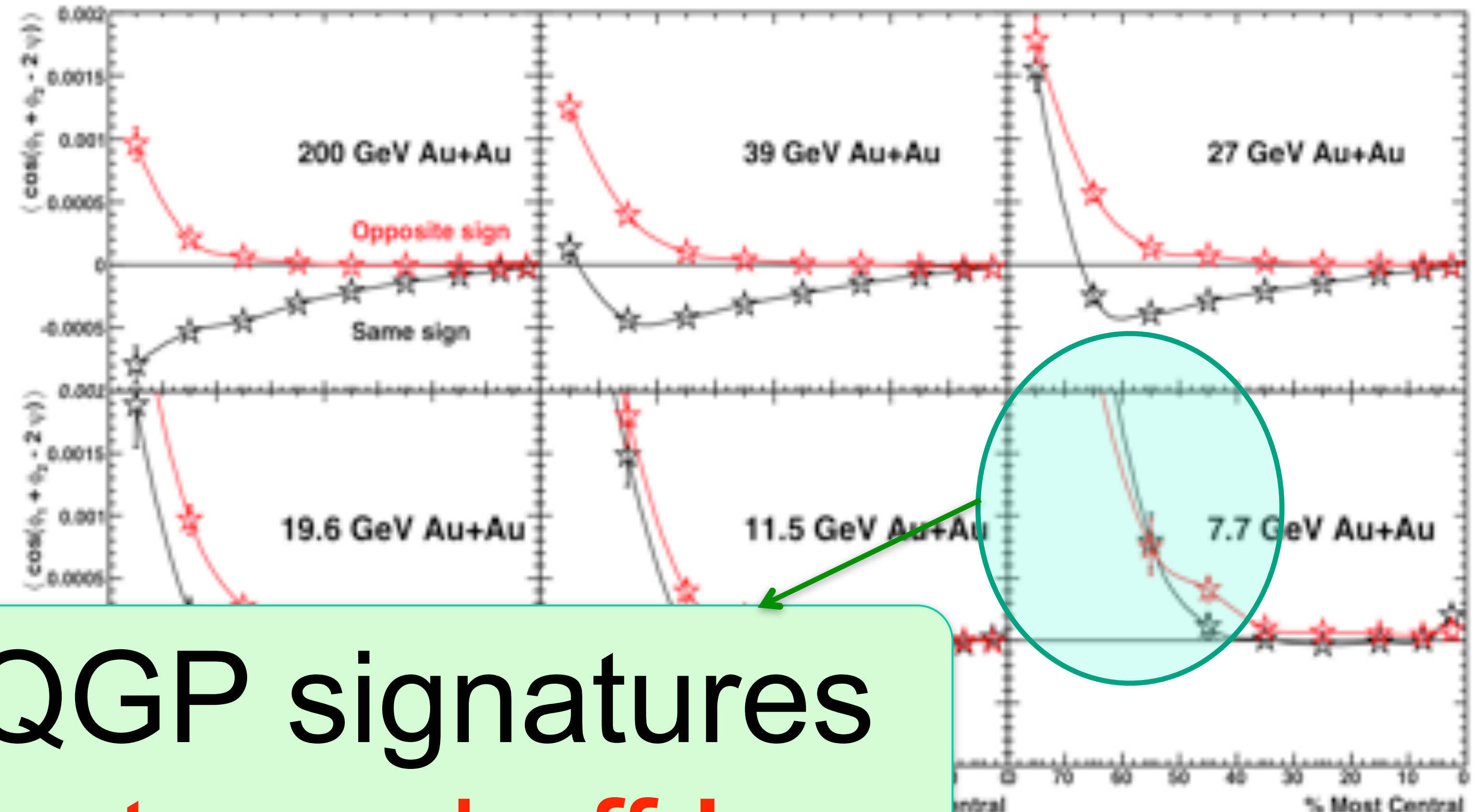
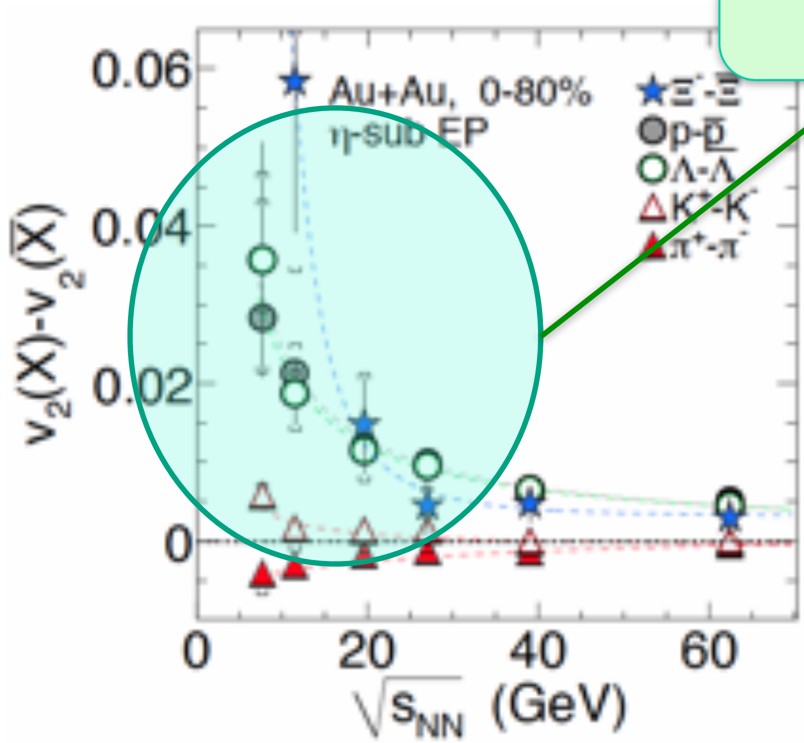


sQGP signatures

turned off !

NQ Scaling in v_2



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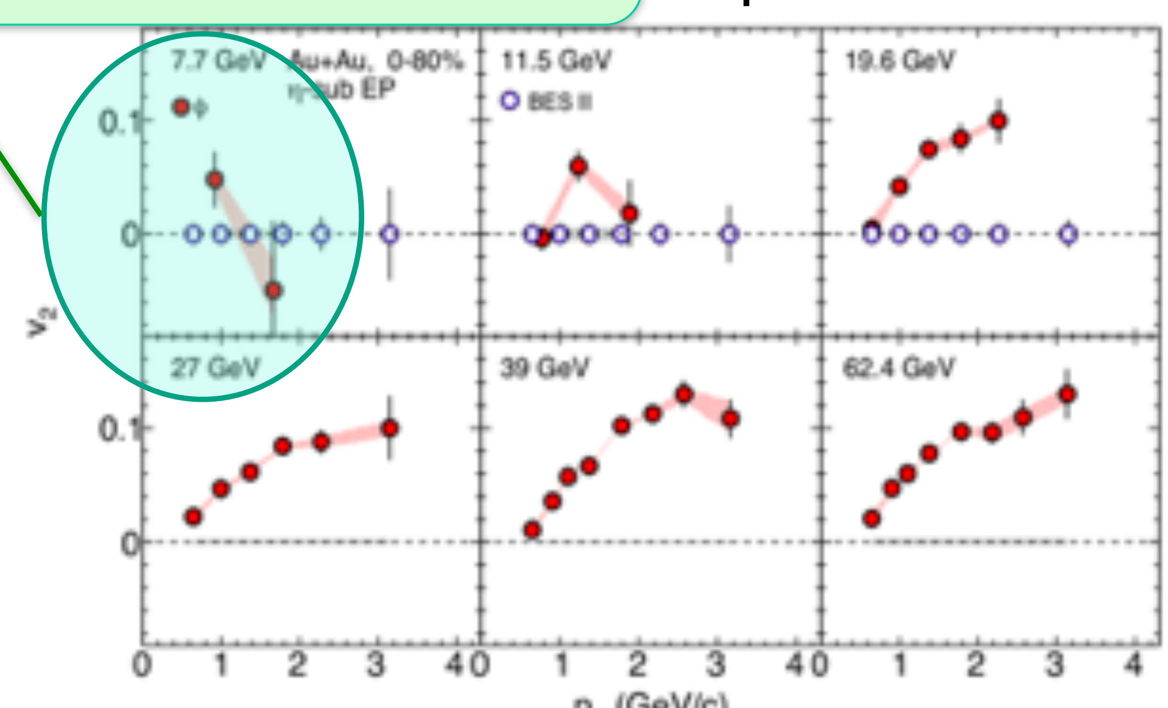
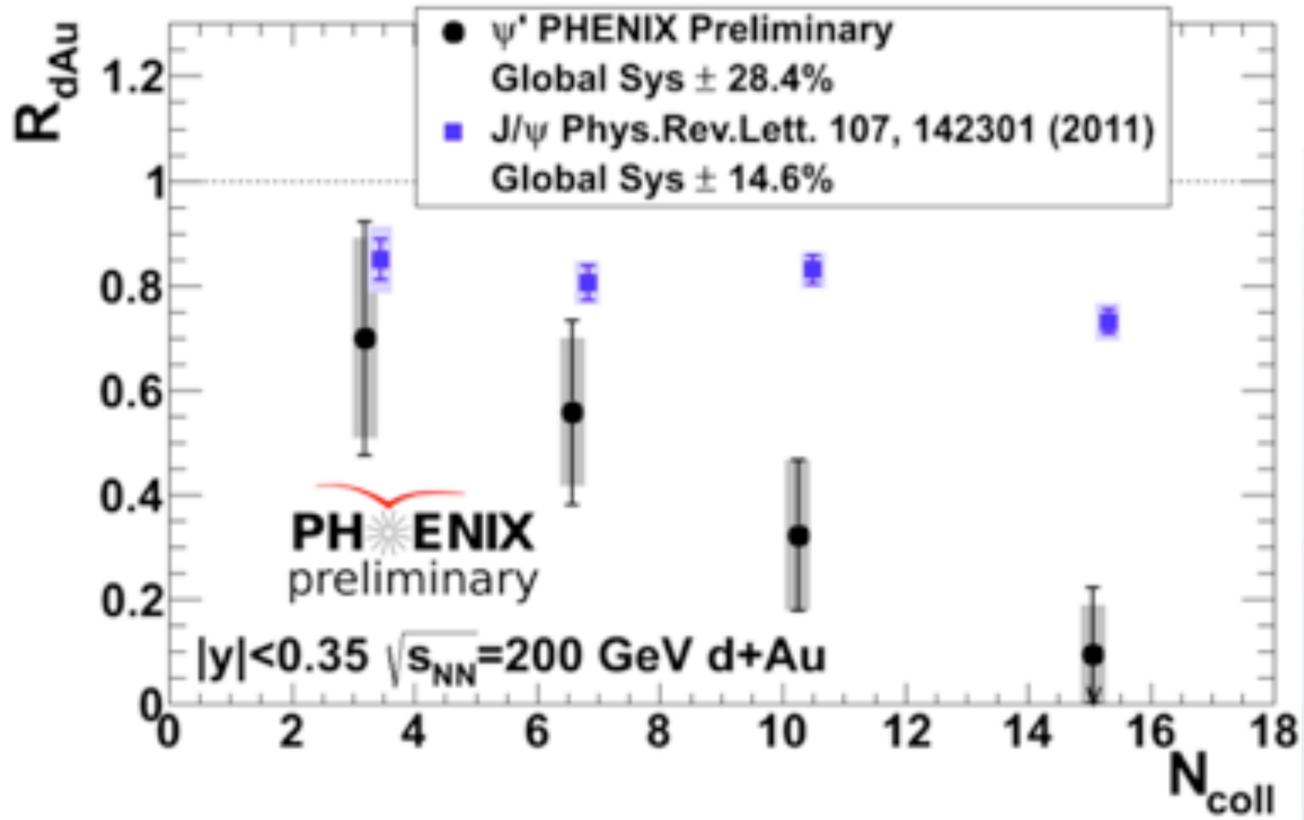


Versatility of RHIC: d+Au

Teasing apart the J/ψ story:

ψ′ is strongly suppressed in *central* d+Au collisions



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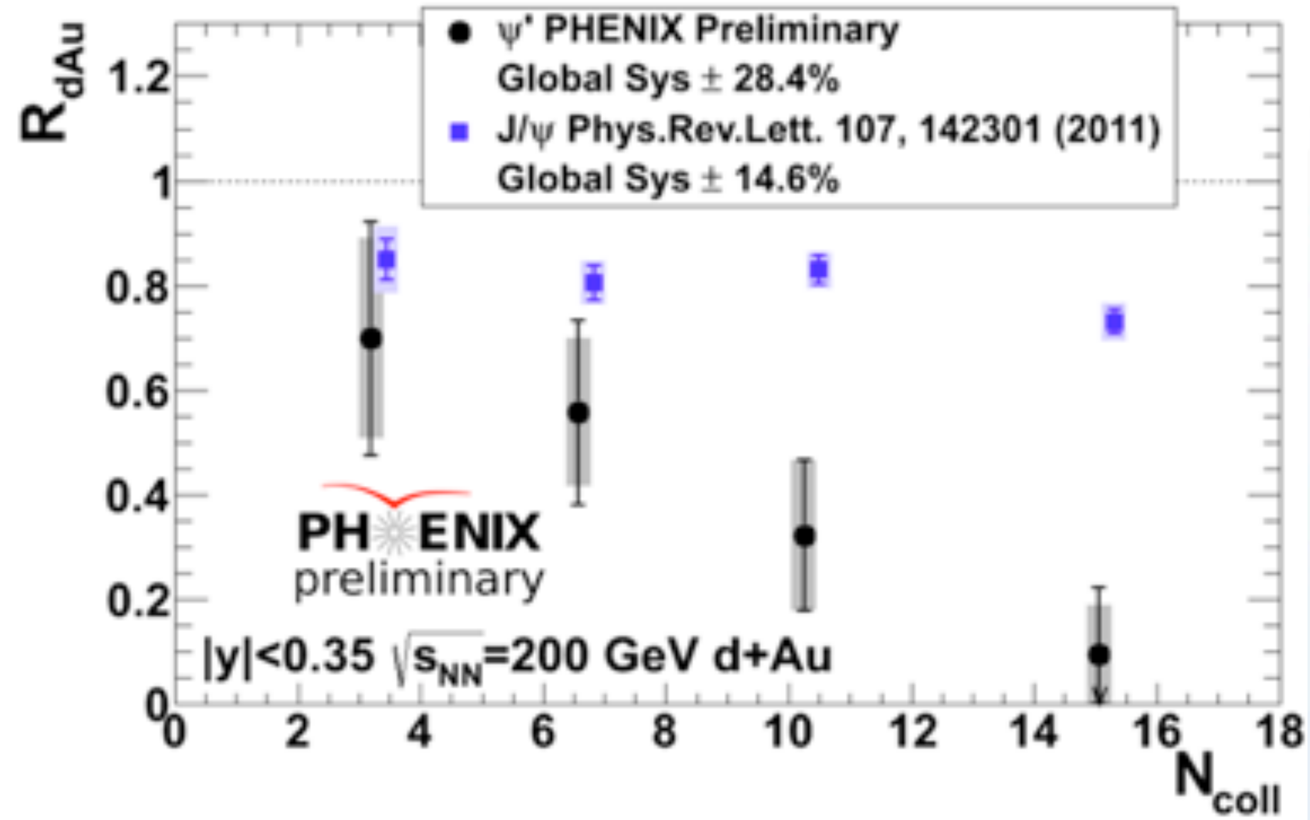
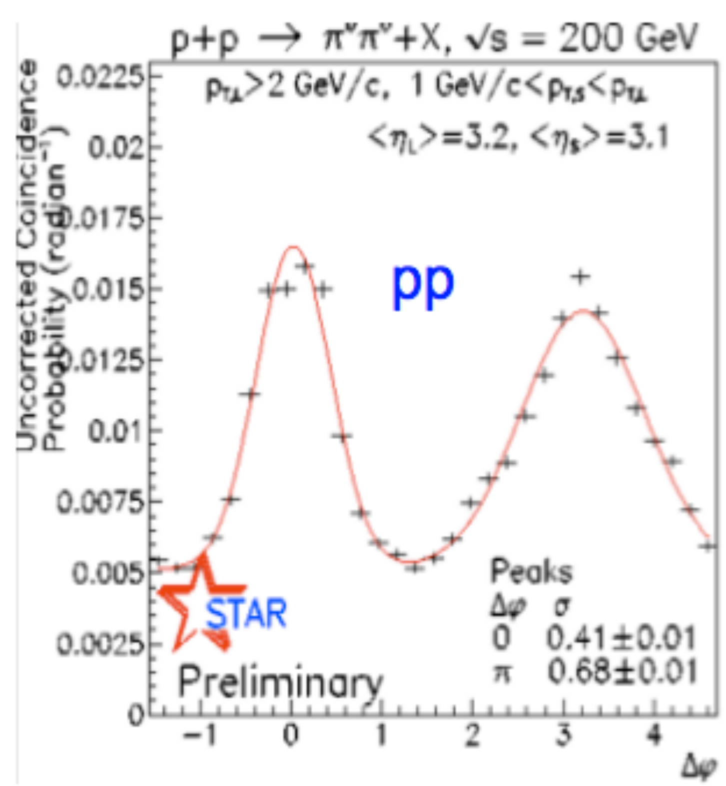
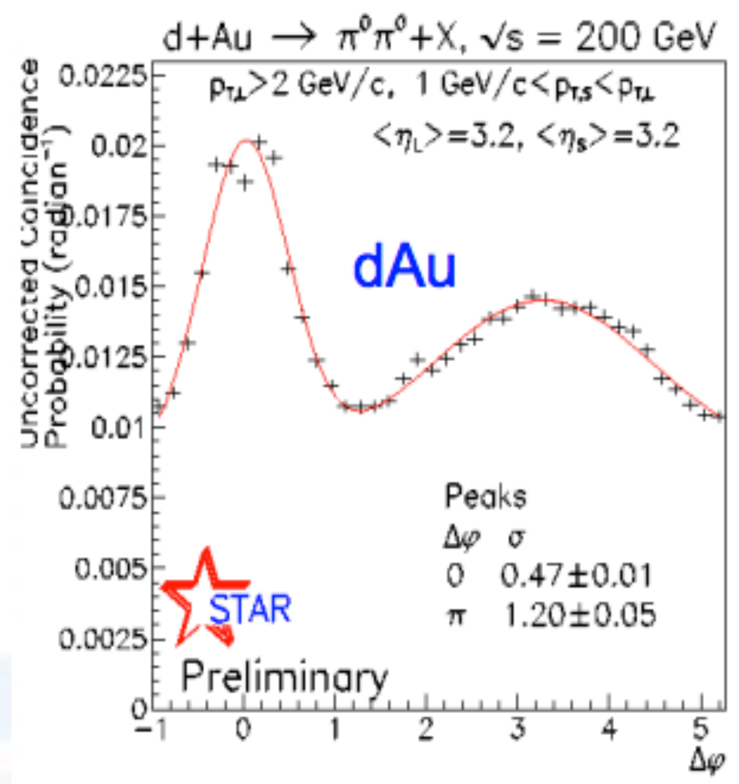


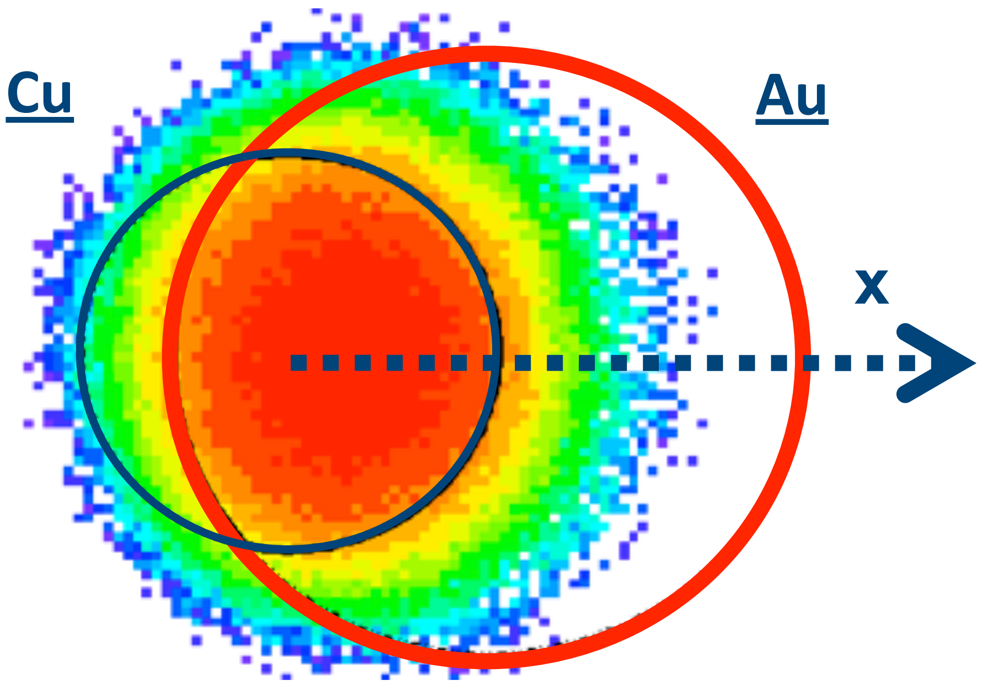


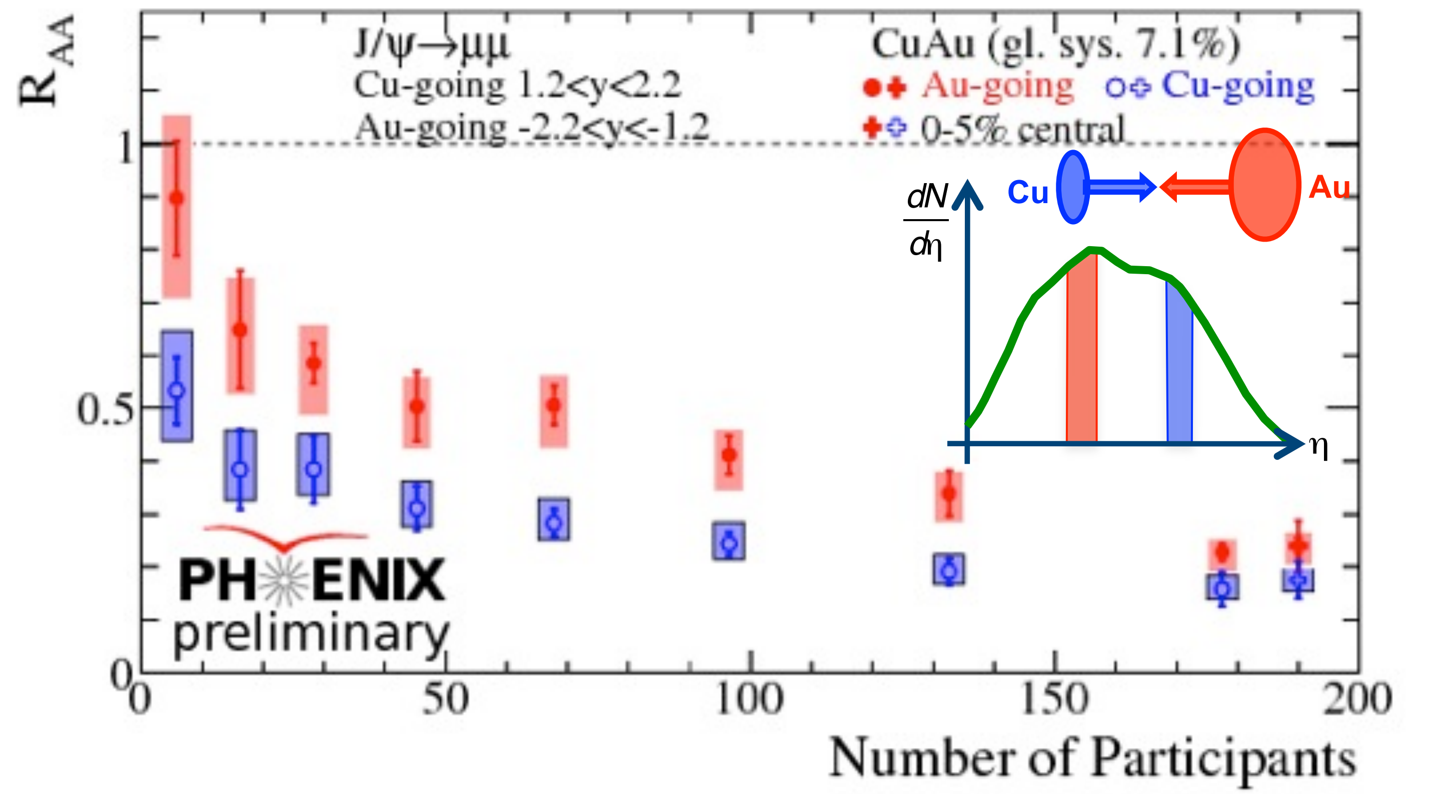


Probing saturation:

Away side broadening of $\pi\pi$ correlations is consistent with CGC expectations.

Versatility of RHIC: Cu+Au & U+U





BROOKHAVEN NATIONAL LABORATORY

Friday, February 15, 13

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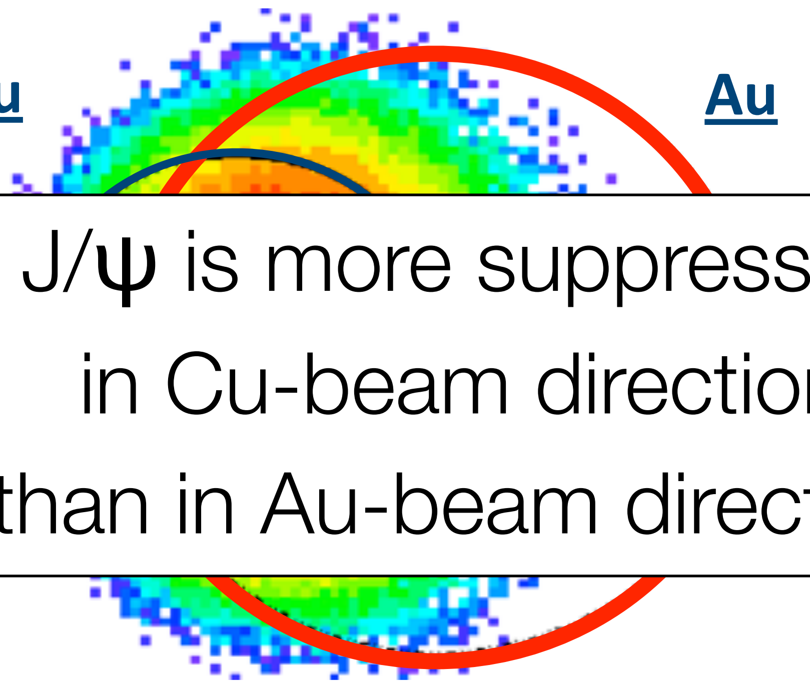
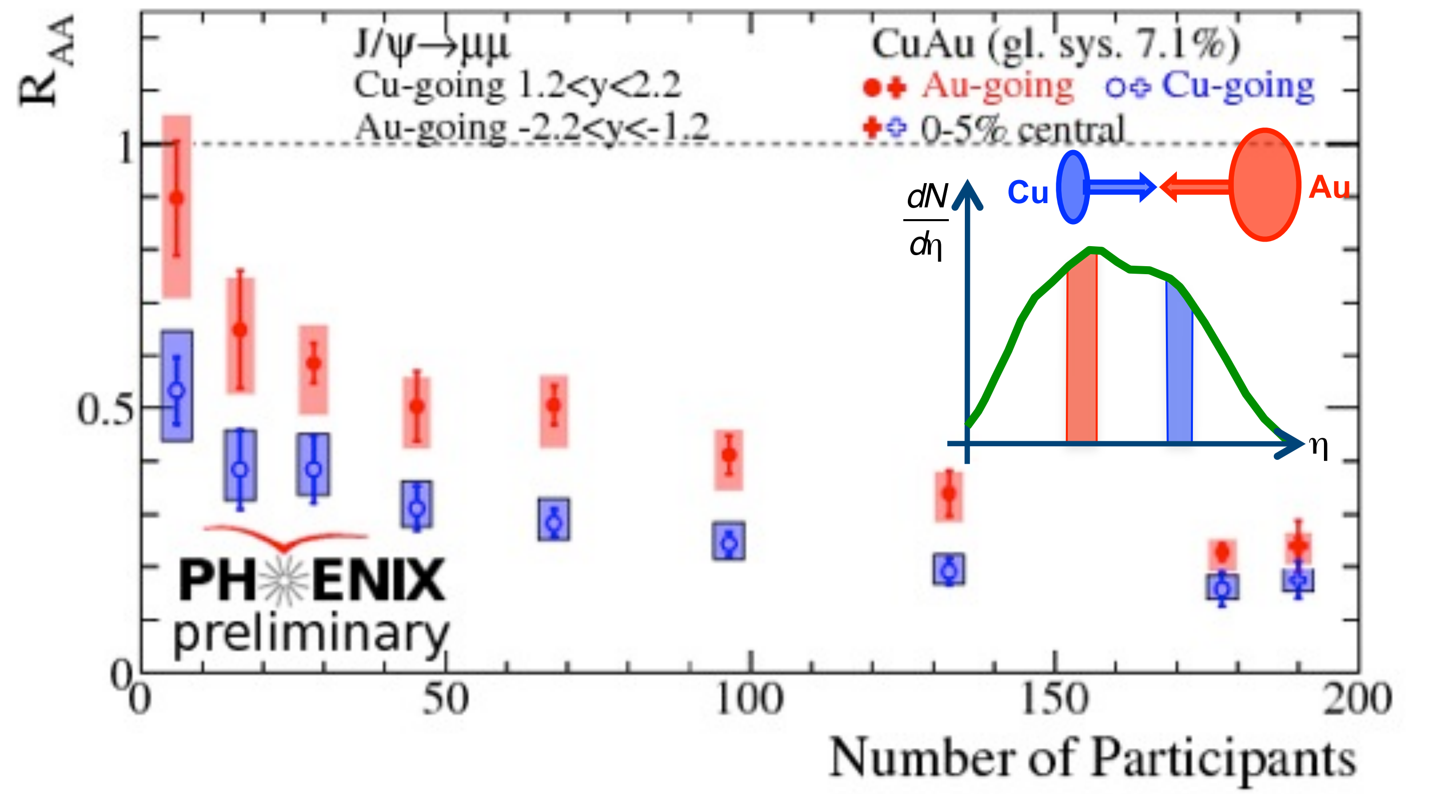


J/ψ is more suppressed in Cu-beam direction than in Au-beam direction



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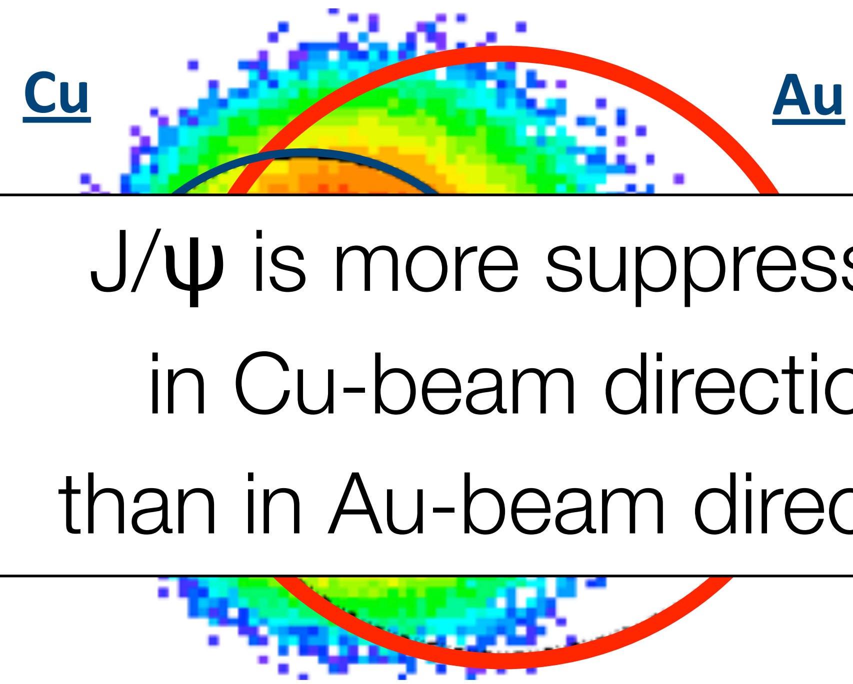

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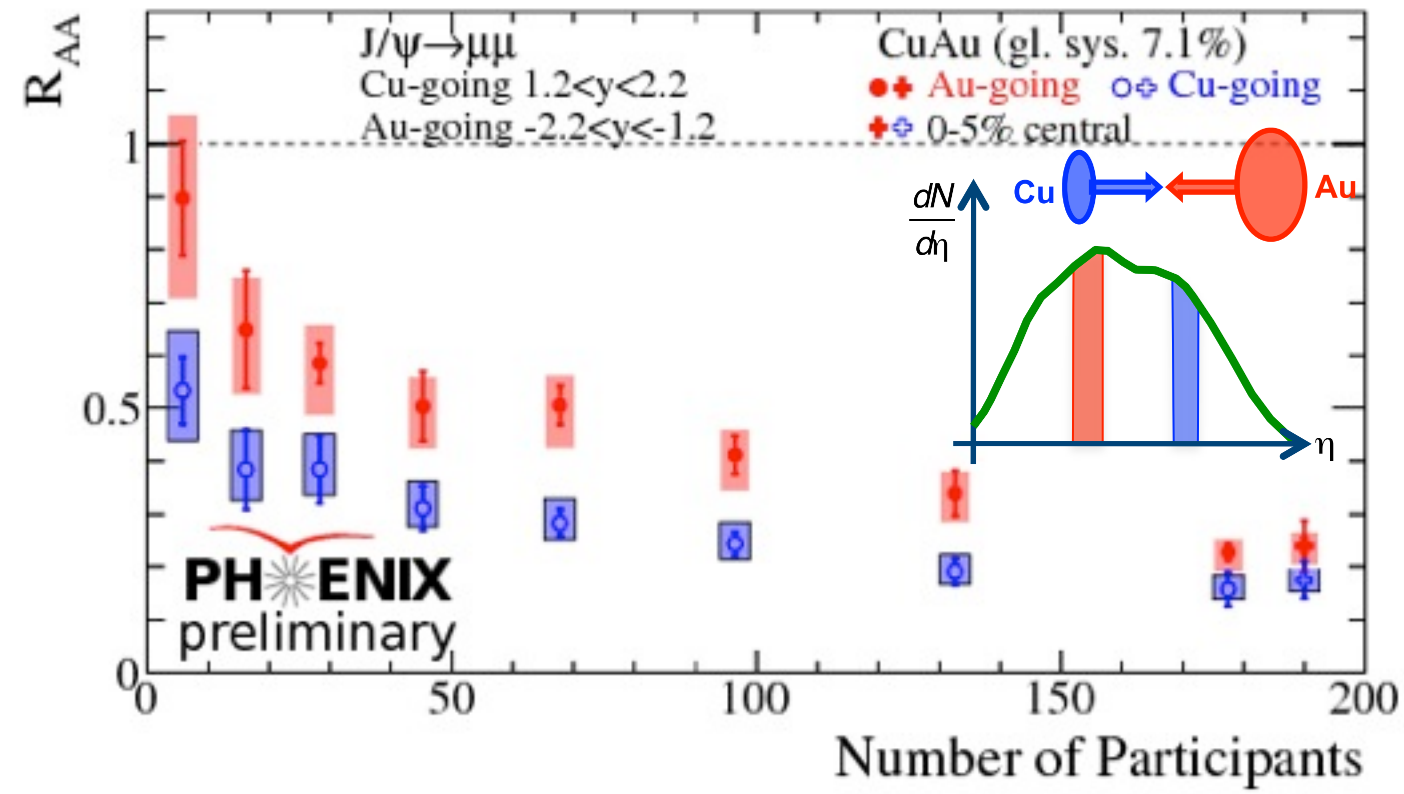
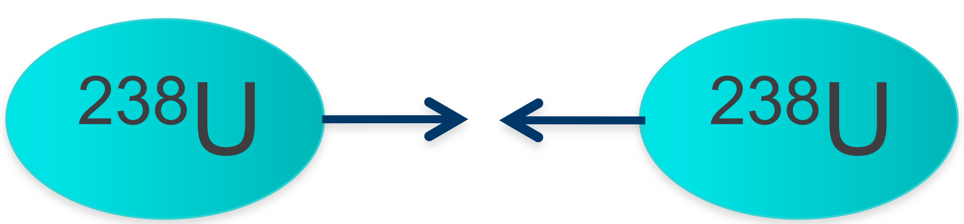
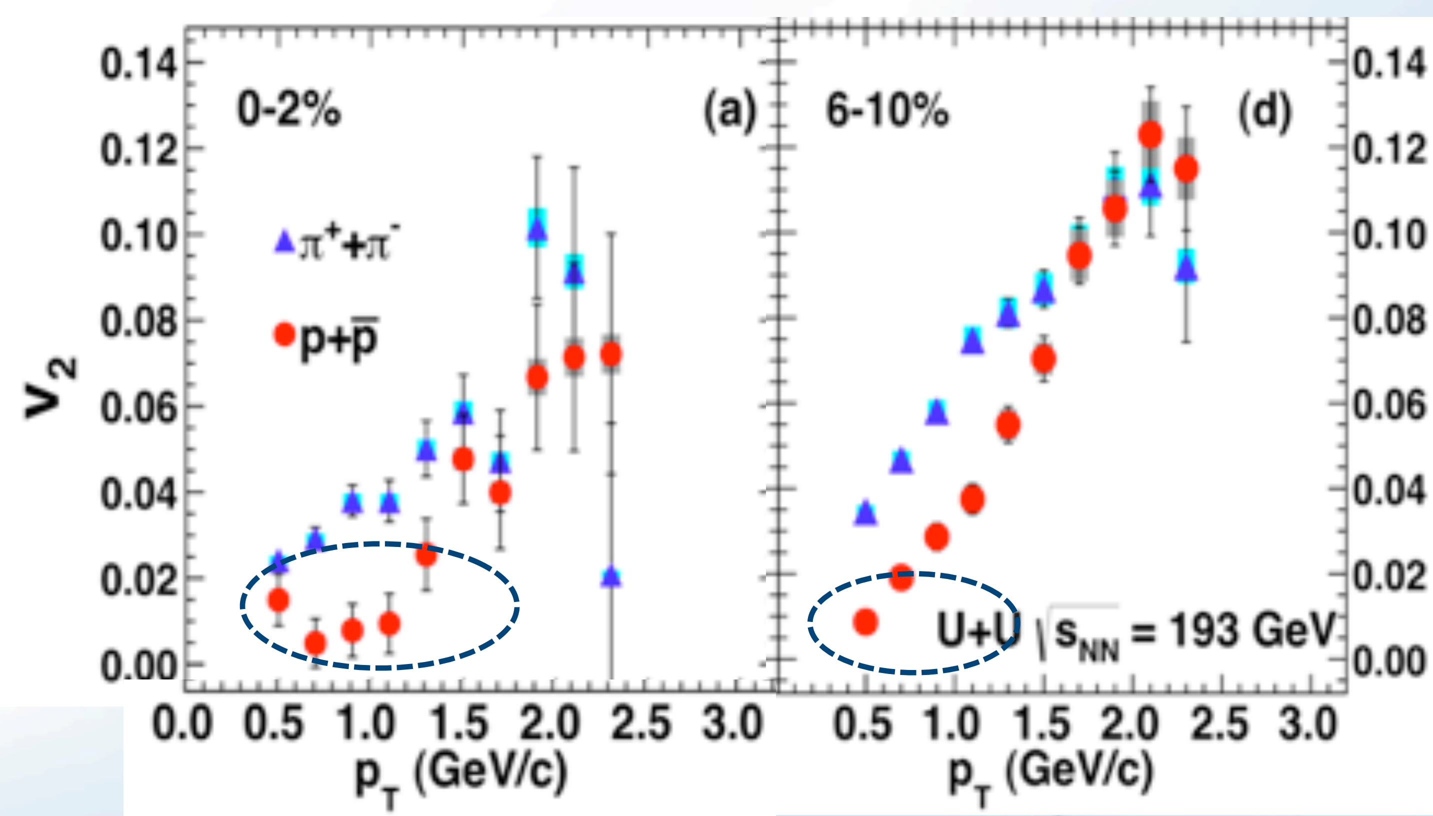


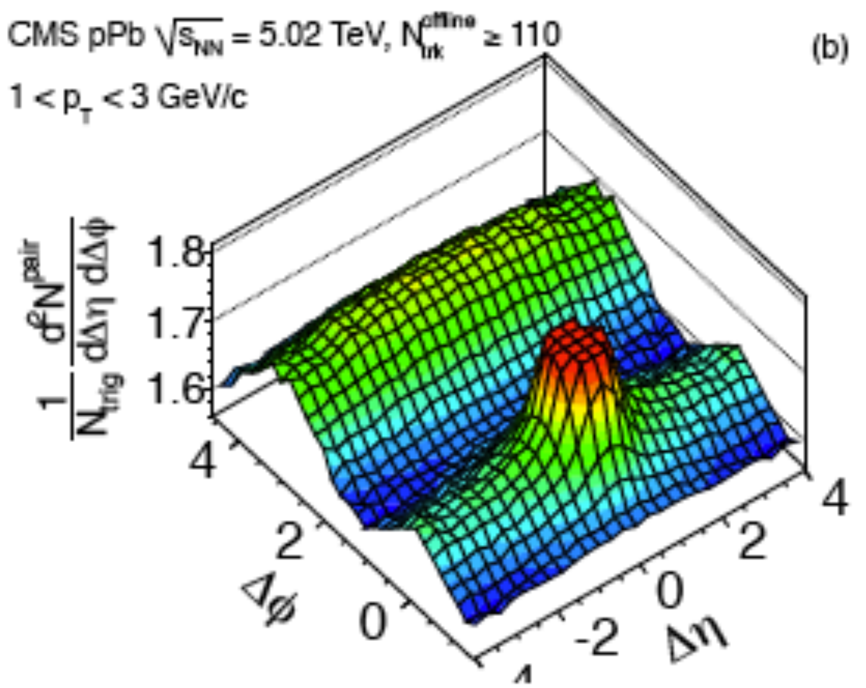


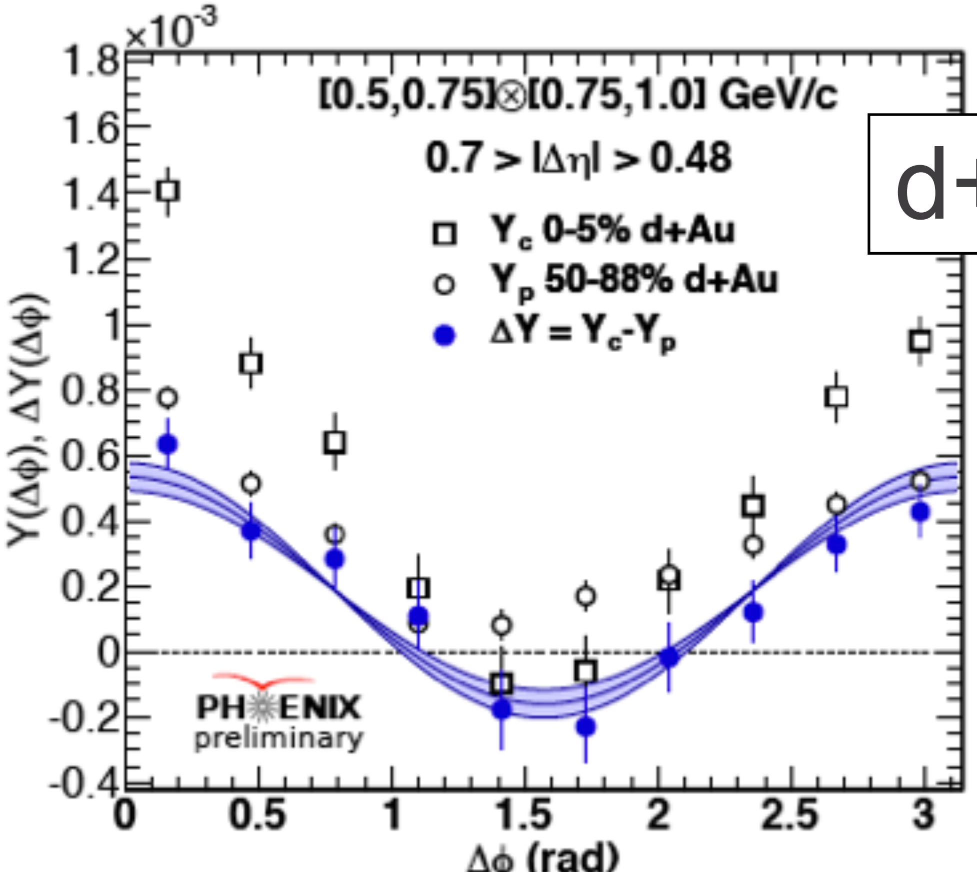
strong radial flow in U+U tip-tip collisions



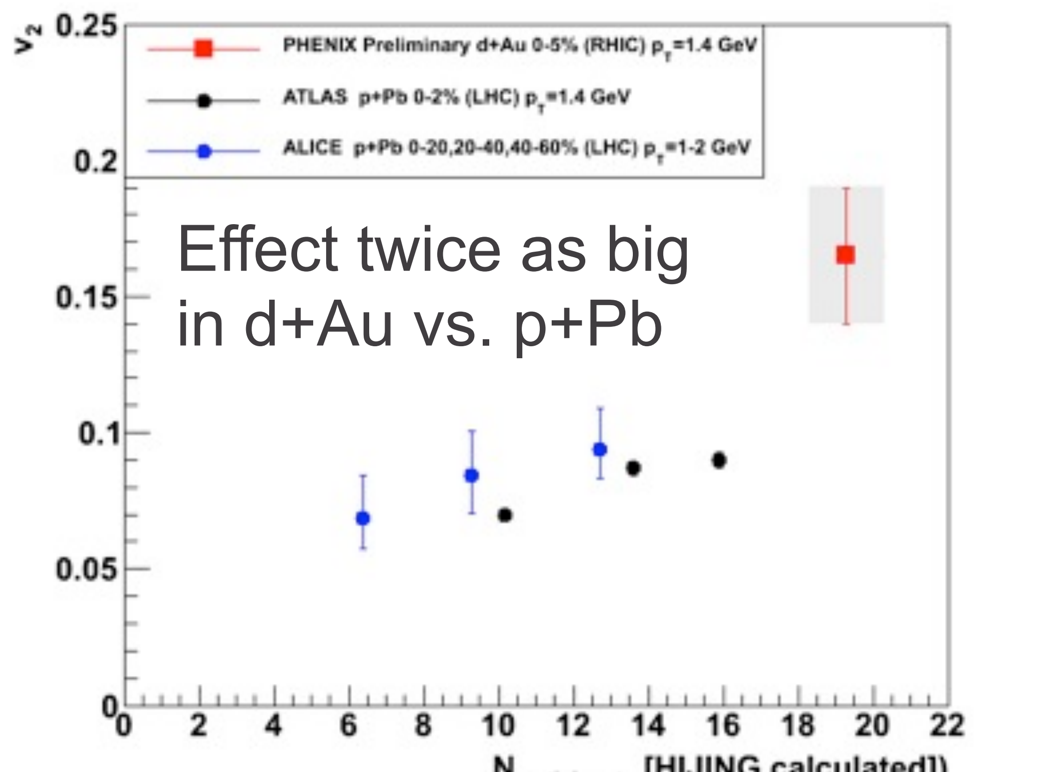
Versatility of RHIC: "Ridge" in d+Au

p+Pb @ 5.02TeV

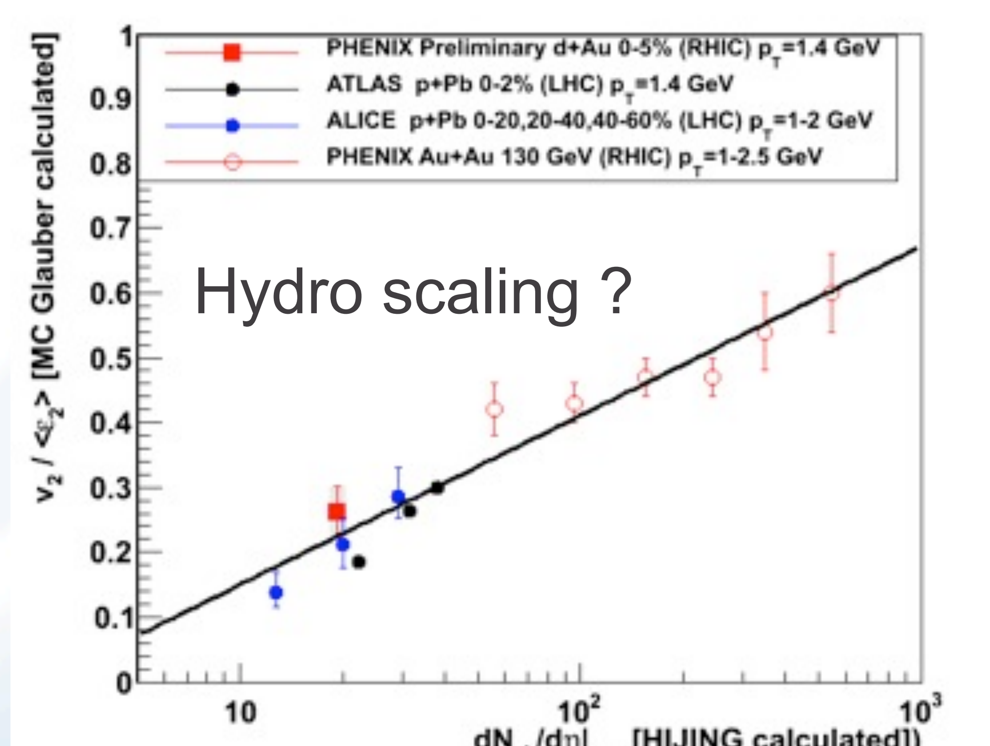




d+Au



Effect twice as big in d+Au vs. p+Pb



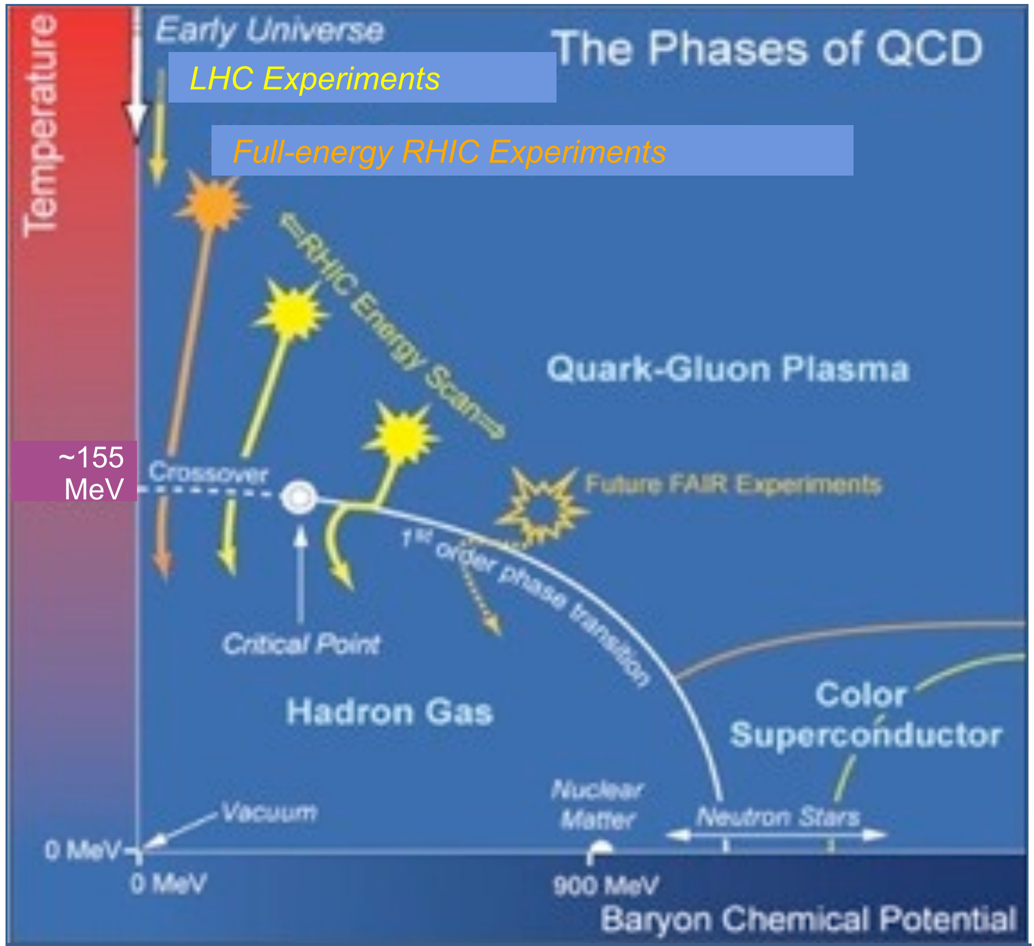
Hydro scaling ?

Message 5

RHIC has at least a decade of science to do.

RHIC: Science Goals for the Next Decade

Quantify properties of the QGP and features of the QCD phase diagram as functions of temperature and net quark density from the onset of deconfinement toward even earlier universe conditions.



Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

Exploit new discovery potential in searches for a QCD critical point and for the nature and influence of quantum fluctuations in initial densities and gluon vacuum excitations.

Continue explorations of the role of soft gluons in cold nuclear matter (gluon saturation, gluon and sea quark contributions to the proton spin).

Compelling Questions For the Next Decade…

Question	Facilities Needed to Answer	Comments
1) How perfect is "near-perfect" liquid?	RHIC & LHC (both required)	Flow power spectra, next 5 years
2) Nature of initial density fluctuations?	RHIC, LHC & EIC	Benefits from asymmetric ion collisions at RHIC
3) How does strong coupling emerge from asymptotic freedom?	RHIC & LHC	After 2017 @ RHIC; jets need sPHENIX upgrade
4) Evidence for onset of deconfinement and/or critical point?	RHIC; follow-up @ FAIR, NICA	Phase 2 energy scan after 2017, needs low-E electron cooling
5) Sequential melting of quarkonia?	RHIC & LHC	LHC higher energy a plus; RHIC detector upgrades help; $\sqrt{s}$-dependence important
6) Are sphaleron hints in RHIC data real?	Mostly RHIC	Exploits unique U+U and $\mu_B \neq 0$ reach at RHIC
7) Saturated gluon densities?	RHIC, LHC & EIC	Want to see onset at RHIC; need EIC to quantify
8) Where is missing proton spin?	RHIC & EIC	EIC will have dramatic impact

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Addressing these questions requires a 10-year program of A+A, p+p and p/d + A runs at various RHIC energies.

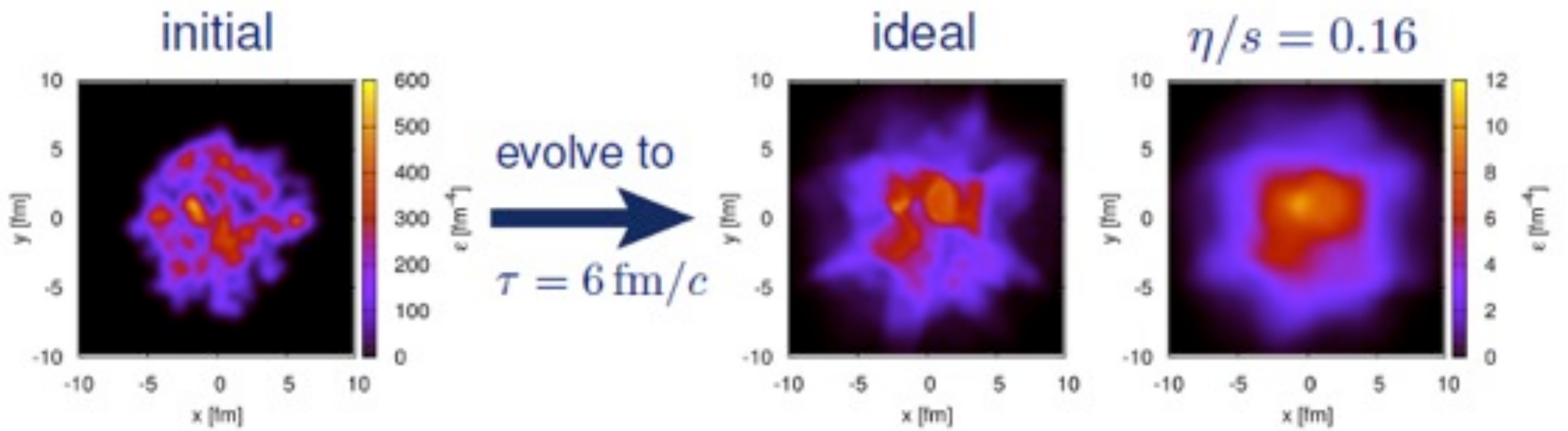
...and a Schedule for addressing them at RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 500 GeV pol p+p • 15 GeV Au+Au	• Sea antiquark and gluon polarization • QCD critical point search	• Electron lenses • upgraded pol'd source • STAR HFT
2014	• 200 GeV Au+Au and baseline data via 200 GeV p+p (needed for new det. subsystems)	• Heavy flavor flow, energy loss, thermalization, etc. • quarkonium studies	• 56 MHz SRF • full HFT • STAR Muon Telescope Detector • PHENIX Muon Piston Calorimeter Extension (MPC-EX)
2015-2017	• High stat. Au+Au at 200 GeV and ~40 GeV • U+U / Cu+Au at 1-2 energies • 200 GeV p+A • 500 GeV pol p+p	• Extract $\eta/s(T_{min})$ + constrain initial quantum fluctuations • further heavy flavor studies • sphaleron tests @ $\mu_B \neq 0$ • gluon densities & saturation • finish p+p W prod'n	• Low-energy electron cooling • Coherent electron cooling test • STAR inner TPC pad row upgrade
2018-2021	• 5-20 GeV Au+Au (BES phase 2) • Long 200 GeV Au+Au w/ upgraded detectors • baseline p+p/d+Au data at 200 GeV • 500 GeV pol p+p • 200 GeV pol p+A	• x10 sens. increase to QCD critical point and deconfinement onset • jet, di-jet, γ-jet quenching probes of E-loss mechanism • color screening for different qq states • transverse spin asymm. Drell-Yan & gluon saturation	• sPHENIX • Forward physics upgrades

Message 6

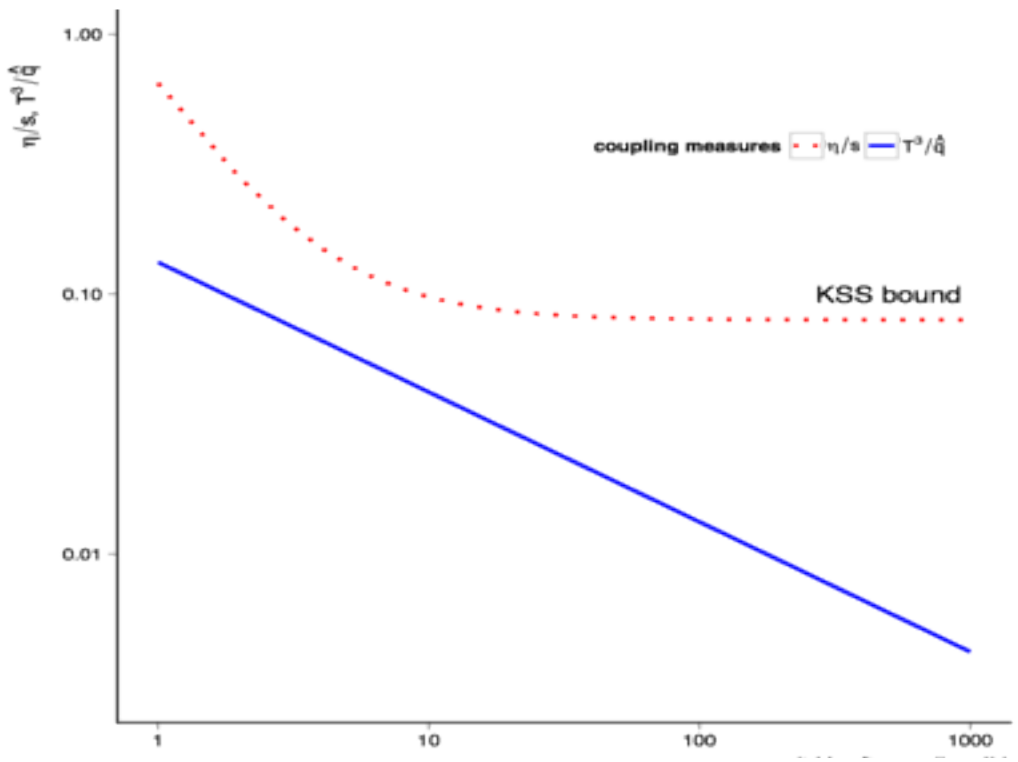
RHIC will continue to provide answers.

Providing Answers: Degree of Perfection



- Increasing sophistication viscous hydrodynamics and measurement of Fourier power spectra for collective flow ⇒ clear path to quantification
- Detailed future measurement /theory program to yield improved $[\eta/s]_{min}$ and nature of density fluctuations
- η/s minimum at transition temperature?
- Deviation from AdS/CFT bound and implications?
- Measurements over wide $\sqrt{s}$ range with particle ID and for different collision systems required

Providing Answers: Emergence of Strong Coupling



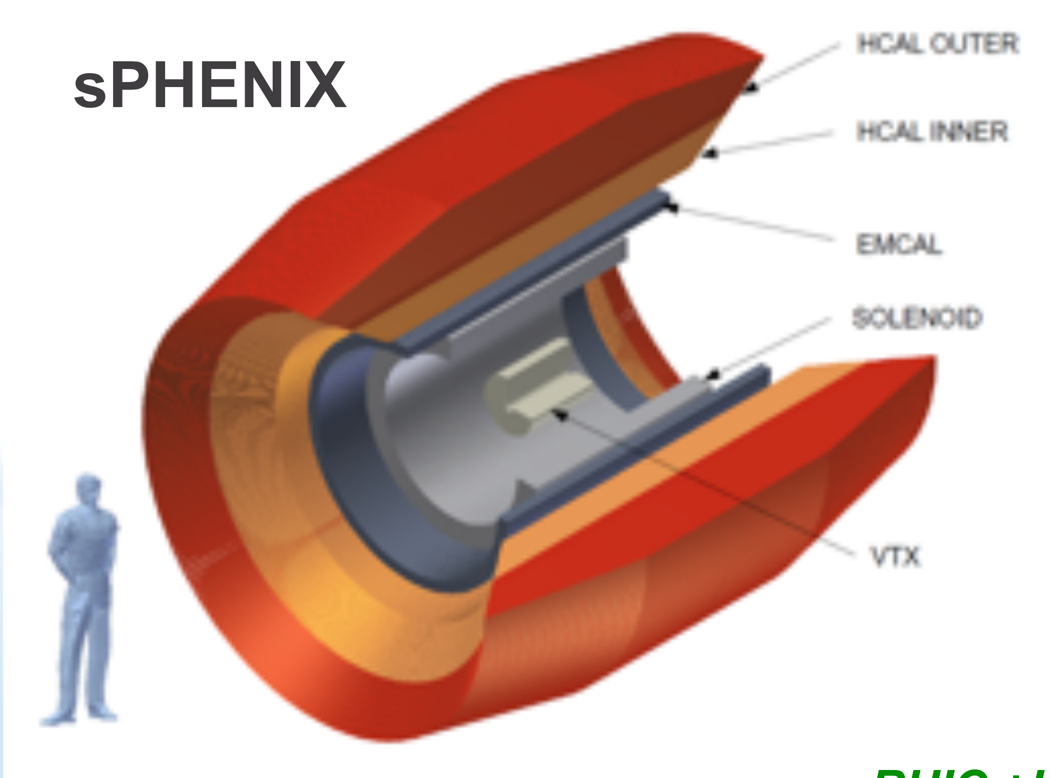
't Hooft coupling

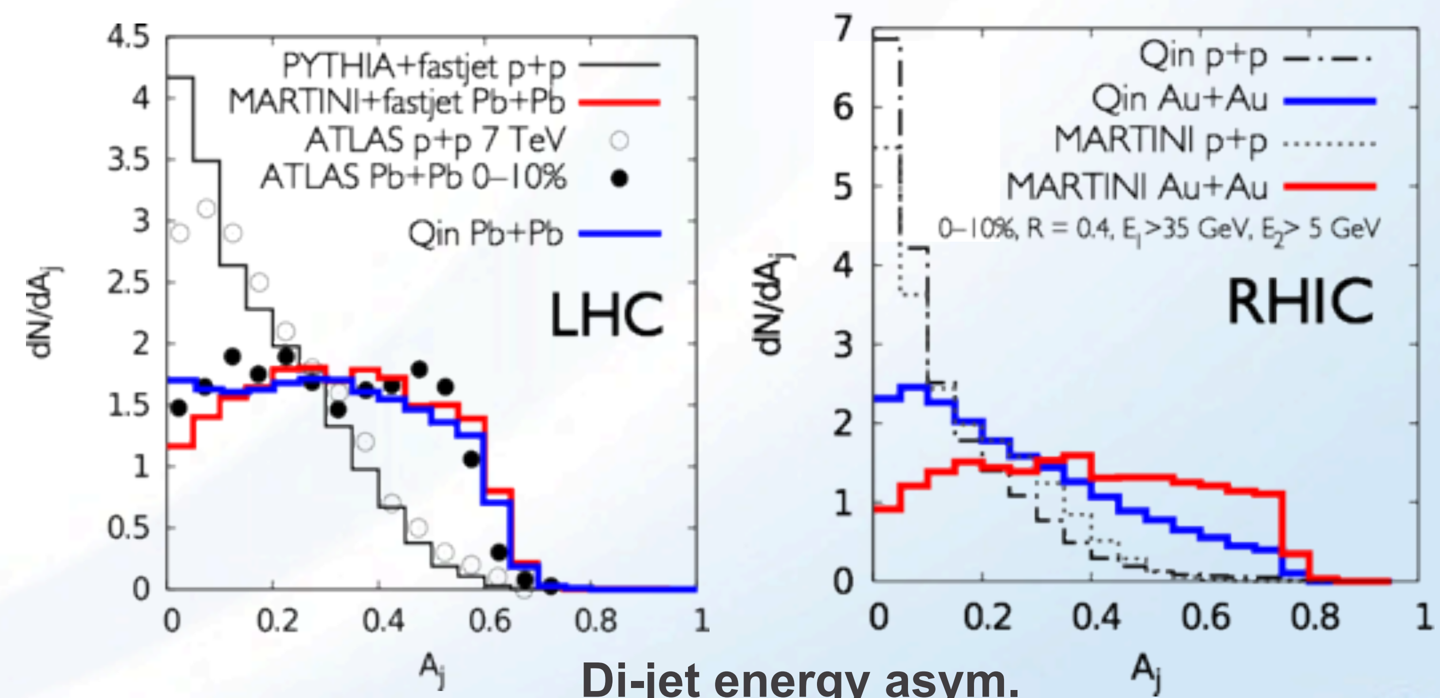
Low viscosity, rapid thermalization, and strong jet quenching are consequences of strong coupling

Determination of qhat(T), η/s(T) permits analysis of coupling strength

Requires measurements of jet, di-jet, γ-jet quenching, jet structure at multiple $\sqrt{s}$

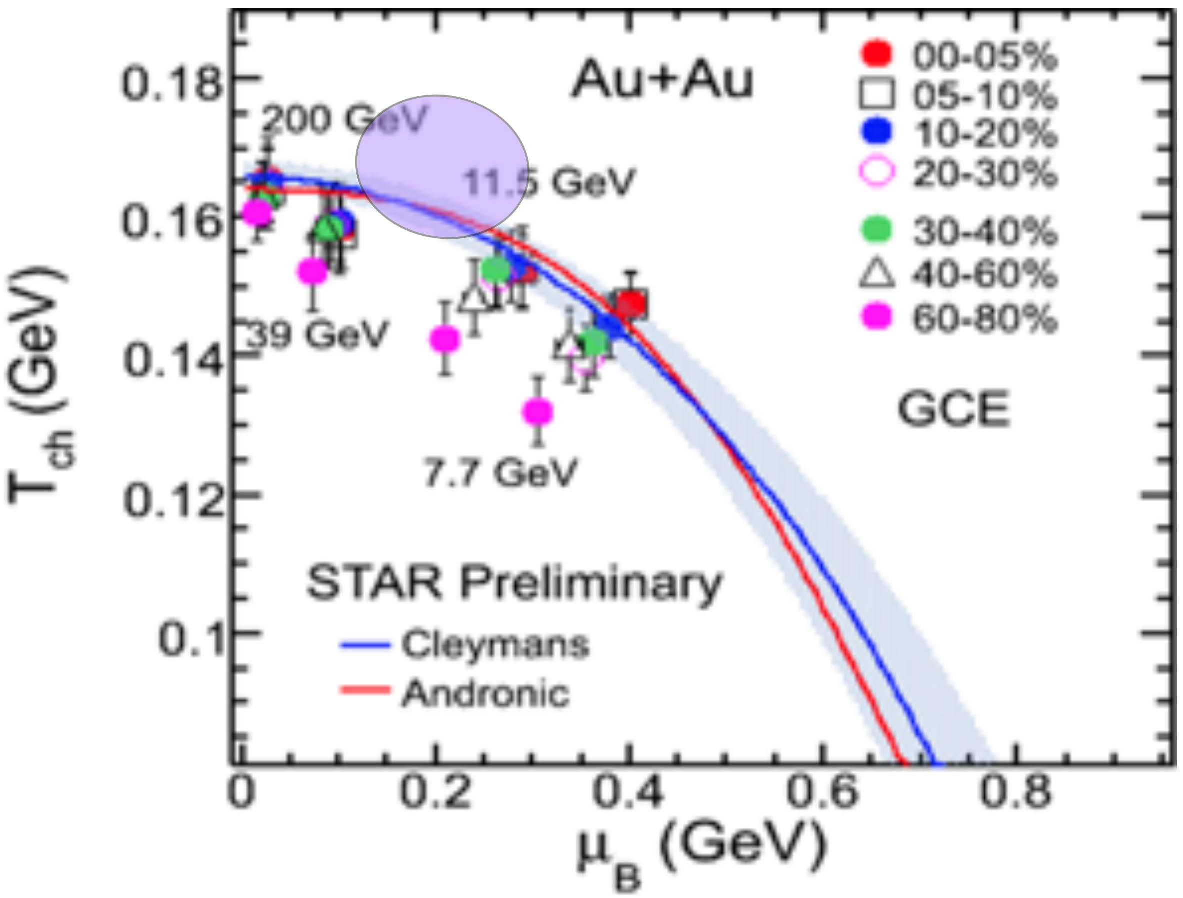
sPHENIX upgrade will enable full jet reconstruction at RHIC

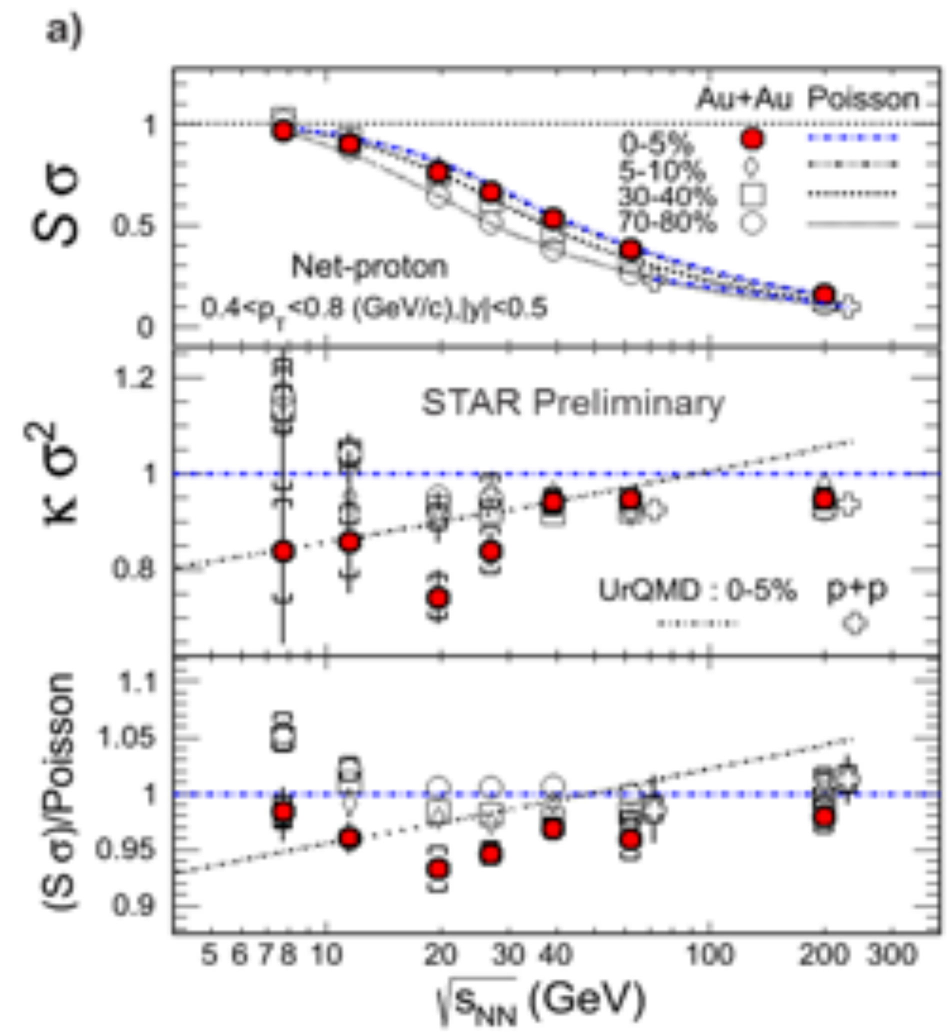




RHIC +LHC data can discriminate between models

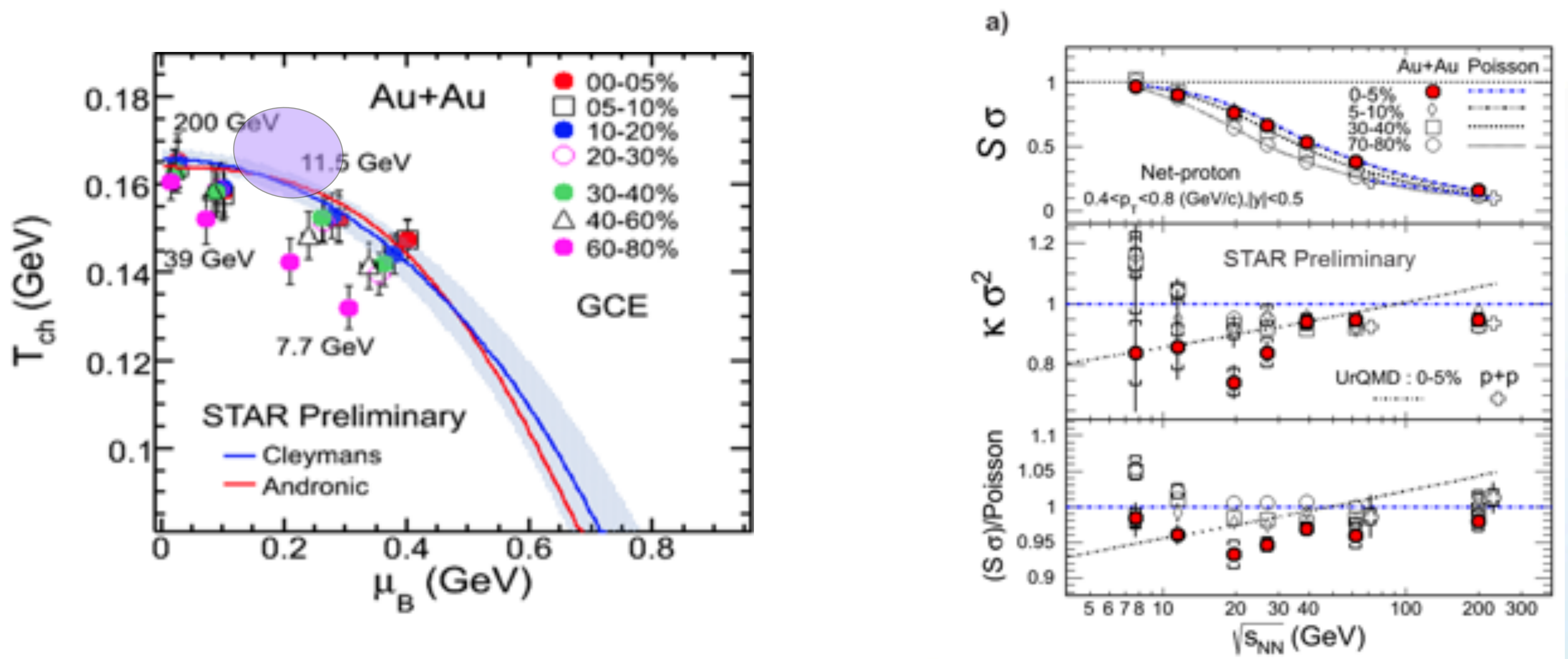
Providing Answers: Onset of Deconfinement





Phase 1 BES: Rapid changes below ~27 GeV:
single hadron suppression → enhancement; n_q scaling breaks down;
non-statistical net-proton fluctuations

Providing Answers: Onset of Deconfinement



Phase 1 BES: Rapid changes below ~27 GeV:
single hadron suppression → enhancement; n_q scaling breaks down; non-statistical net-proton fluctuations

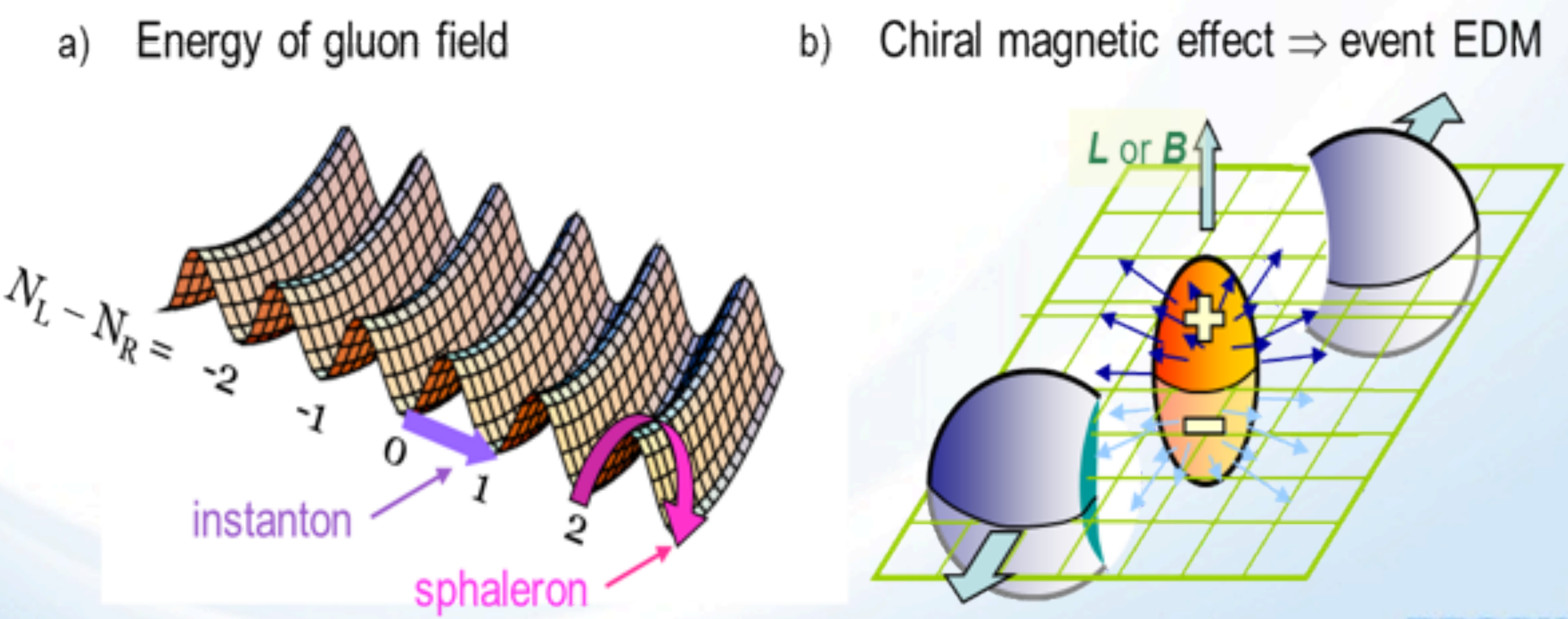
Low-energy e-cooling will improve statistics at √s < 20 GeV for detailed measurements of sensitive quantities in search for critical point

Providing Answers: Sphaleron Effects?

Transitions among degenerate vacuum (winding number) states of the gauge field, called "sphalerons" at the EW phase transition are speculated to be the origin of the baryon-antibaryon imbalance in the early universe.

RHIC offers the opportunity to search for effects of analogous QCD sphalerons, which can create spatially localized regions with chiral imbalance.

Ultra-strong magnetic field in non-central collisions generate local electric dipole moment (locally violating P, CP) and electric quadrupole moment in QCD matter which manifest themselves in certain event-by-event observables.



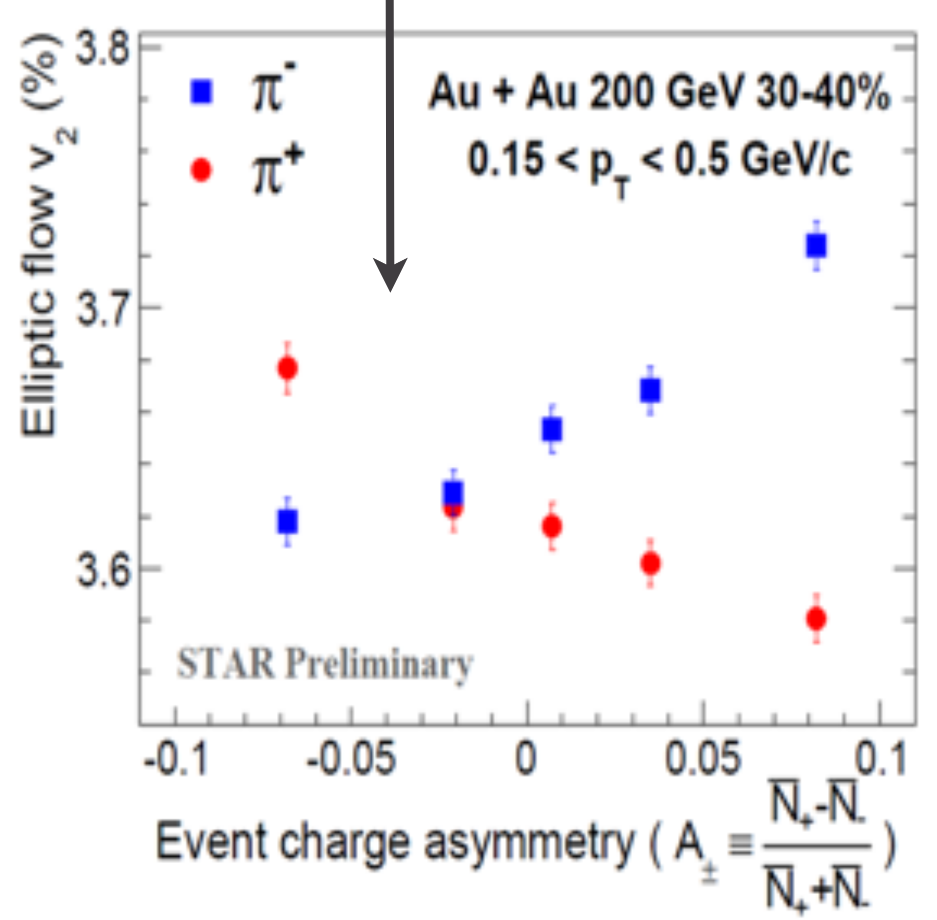
Providing Answers: Magnetic Effects?

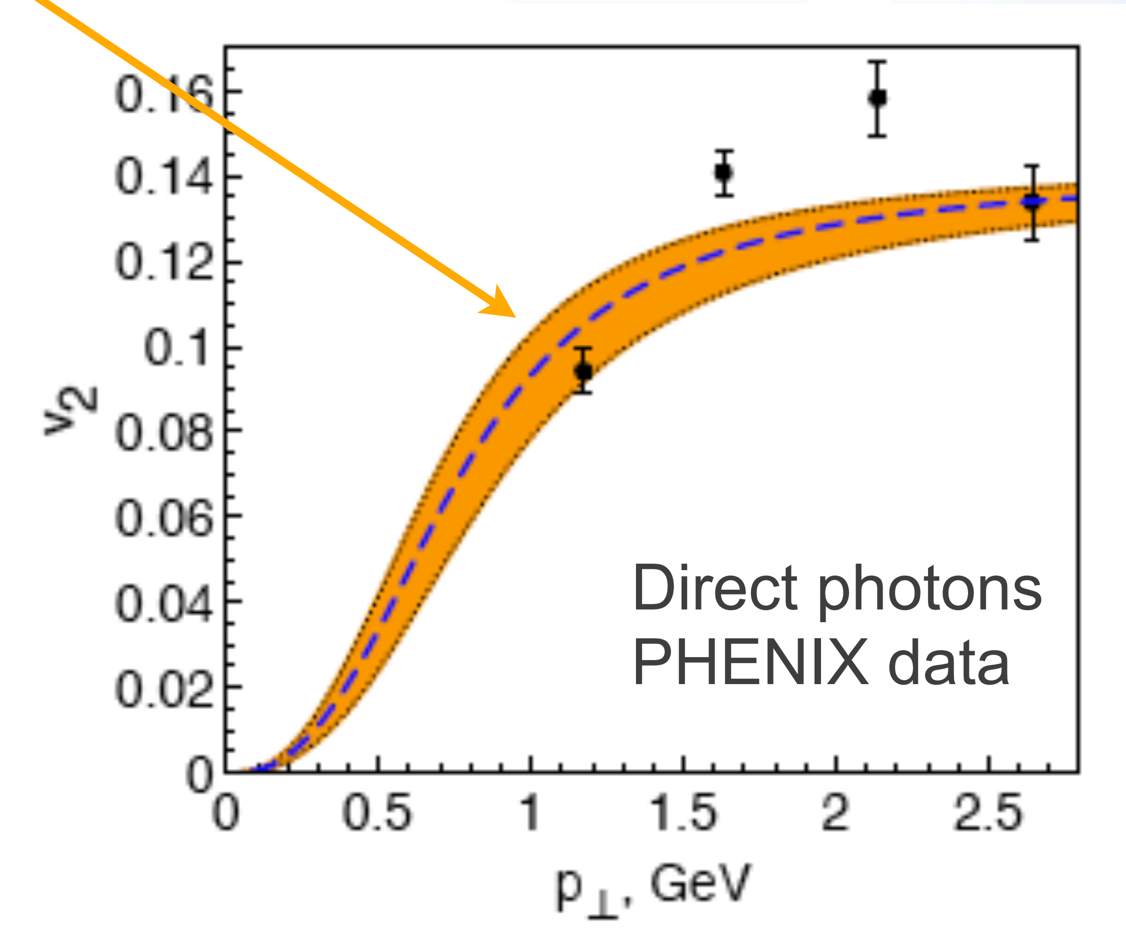
Intriguing RHIC data searching for EDM-like correlations and flow differences between pions of different charge when net charge ≠ 0.

Pursue with improved statistics for U+U, highly central and lower-energy collisions to probe dependence on magnetic field strength

Search for related effects of chiral imbalance and QCD triangle anomaly in matter with net baryon density ≠ 0 (requires RHIC energies ~40 GeV).

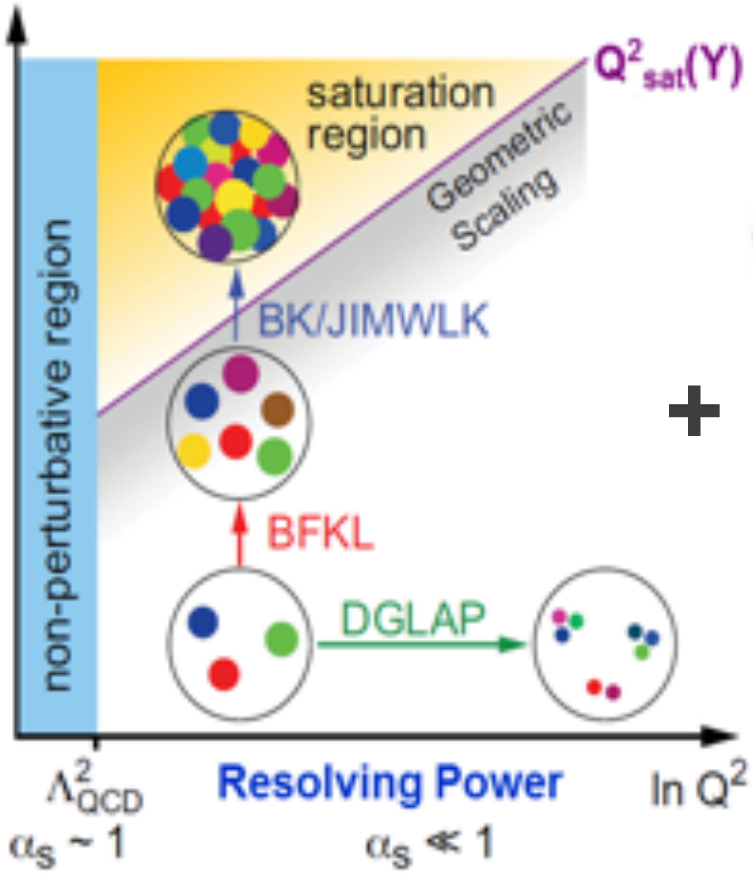
Possible non-collective v2 of photons due to effect of B-fields on conformal anomaly as explanation of surprising PHENIX data.





Providing Answers: Gluon Saturation

CGC + glasma provide for a remarkably successful 3+1-D hydro account for A+A multiplicities and flow



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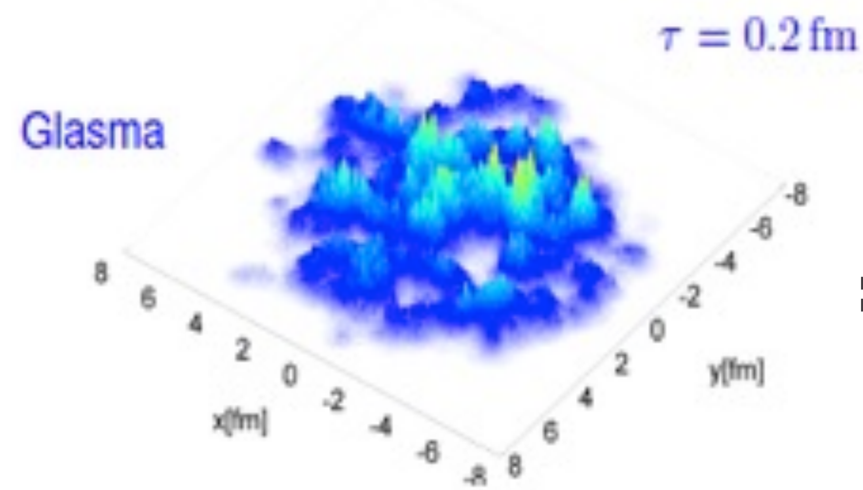

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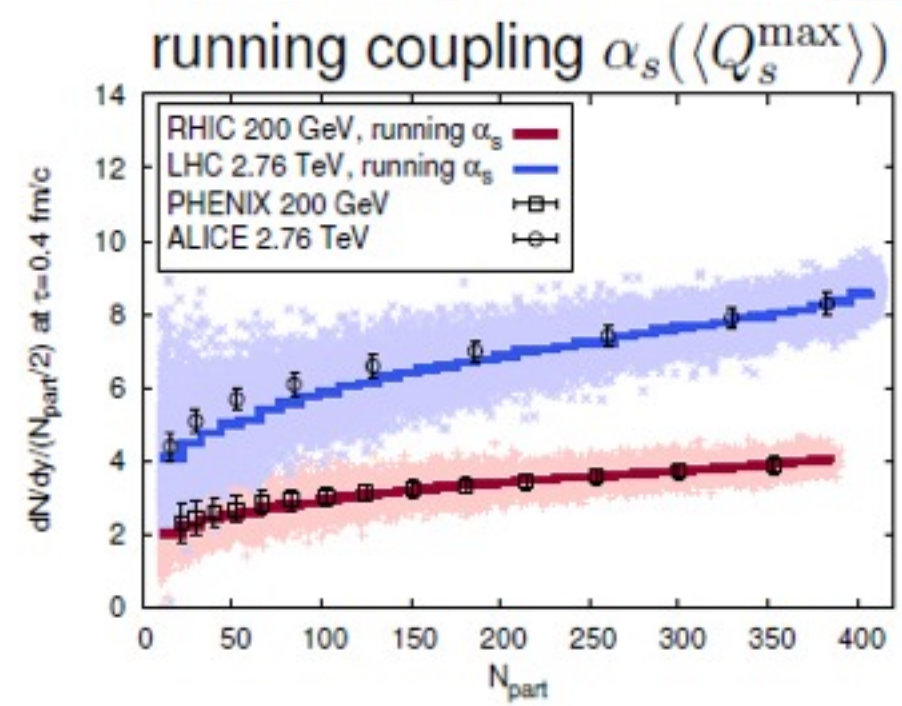
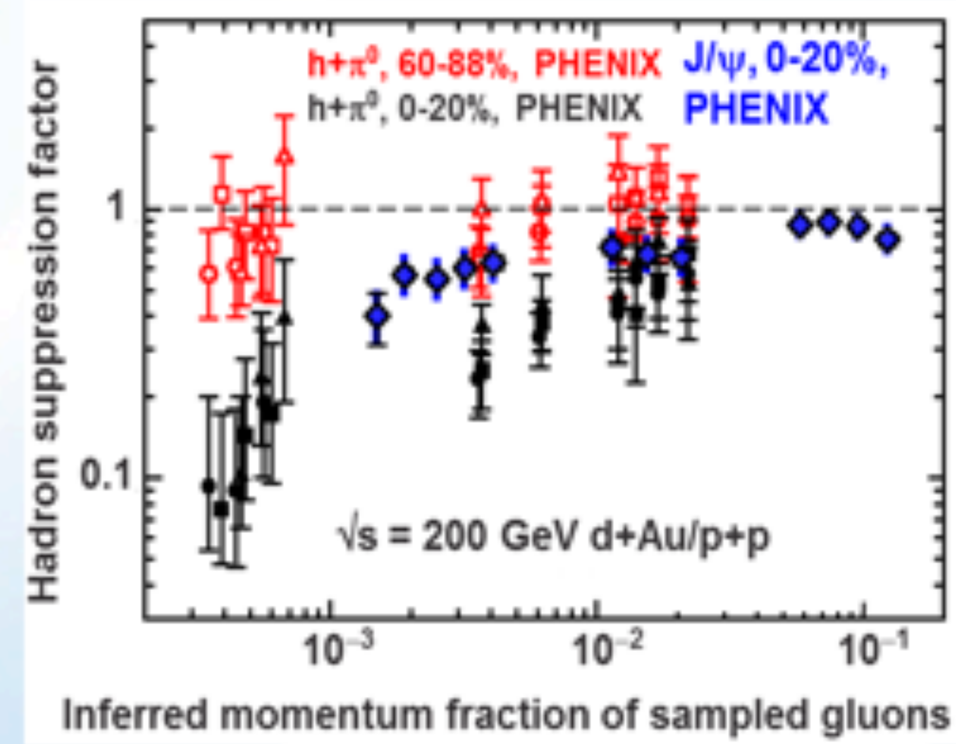


Consistent with observed suppression of forward hadron and di-hadron prod. in d+Au collisions at RHIC



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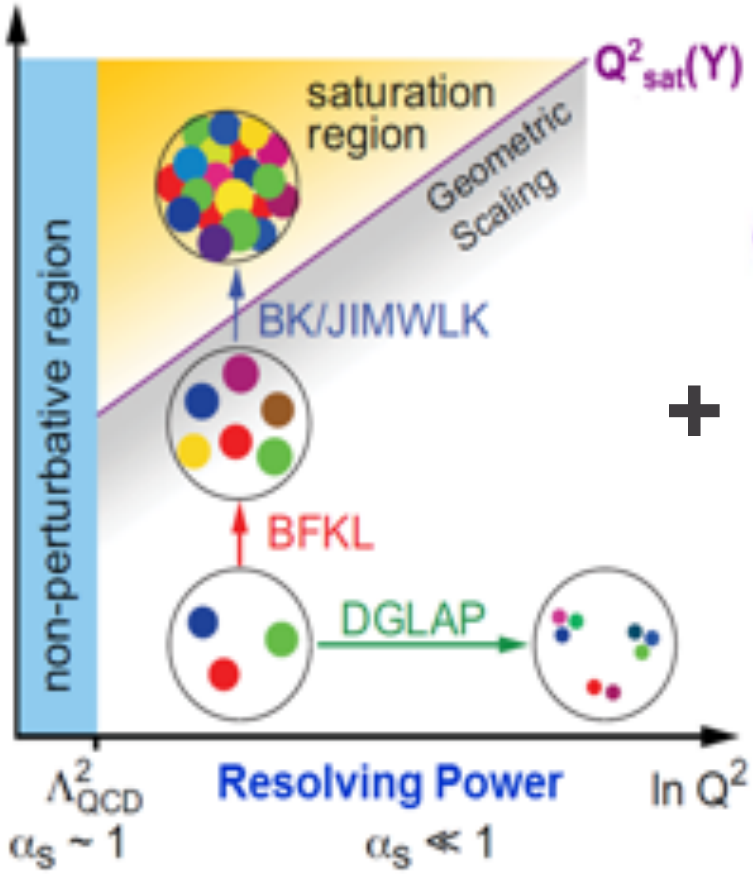

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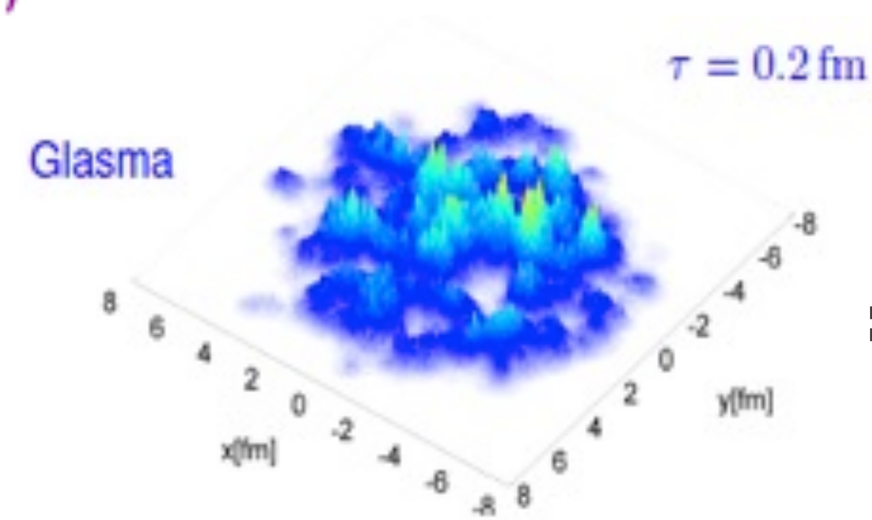

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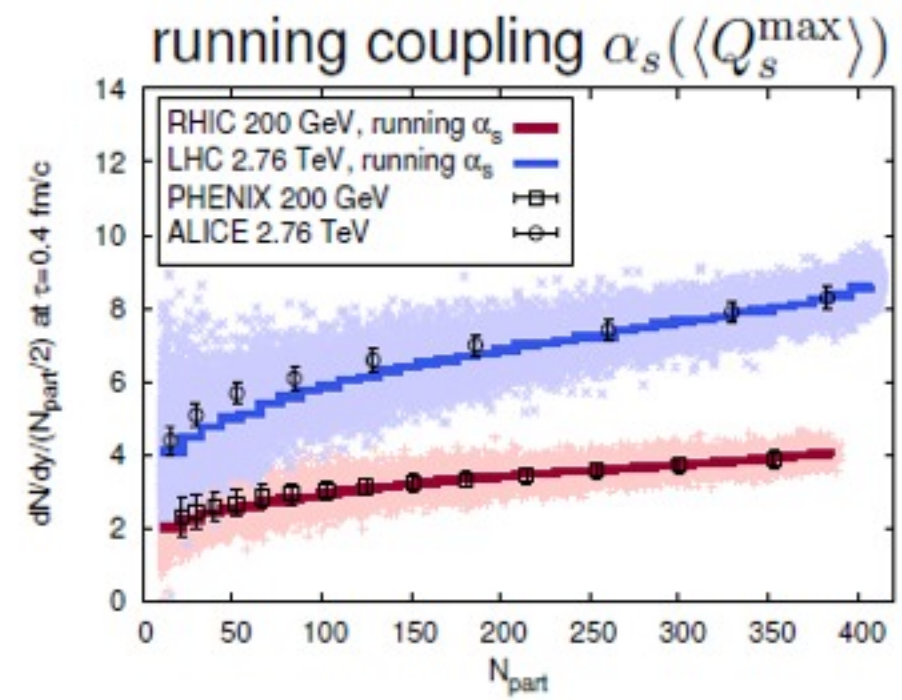

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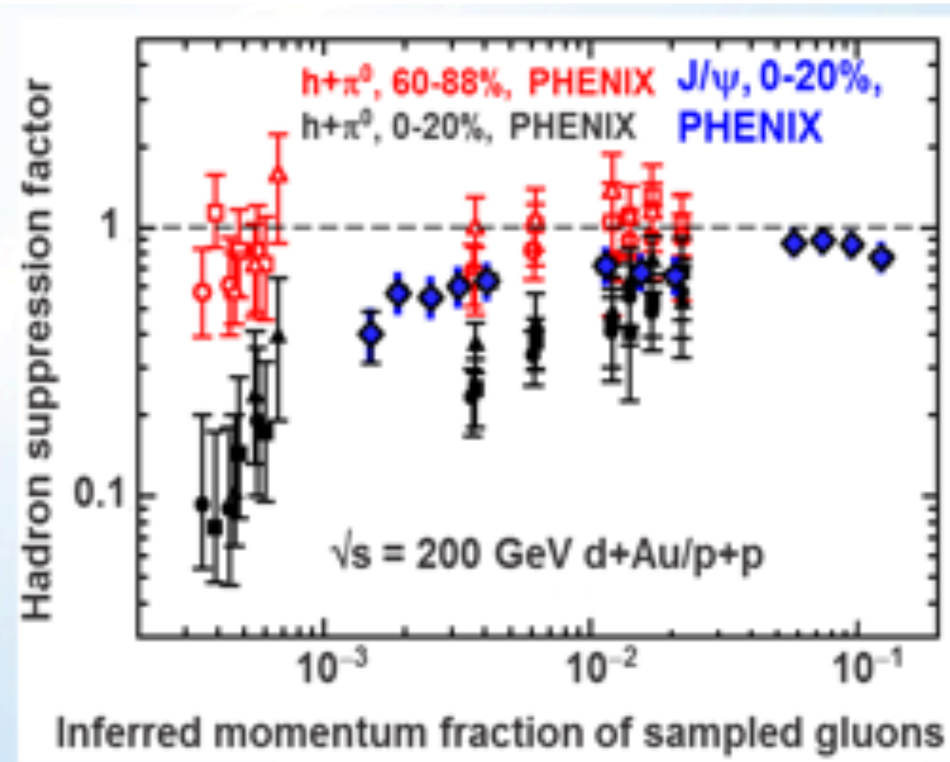
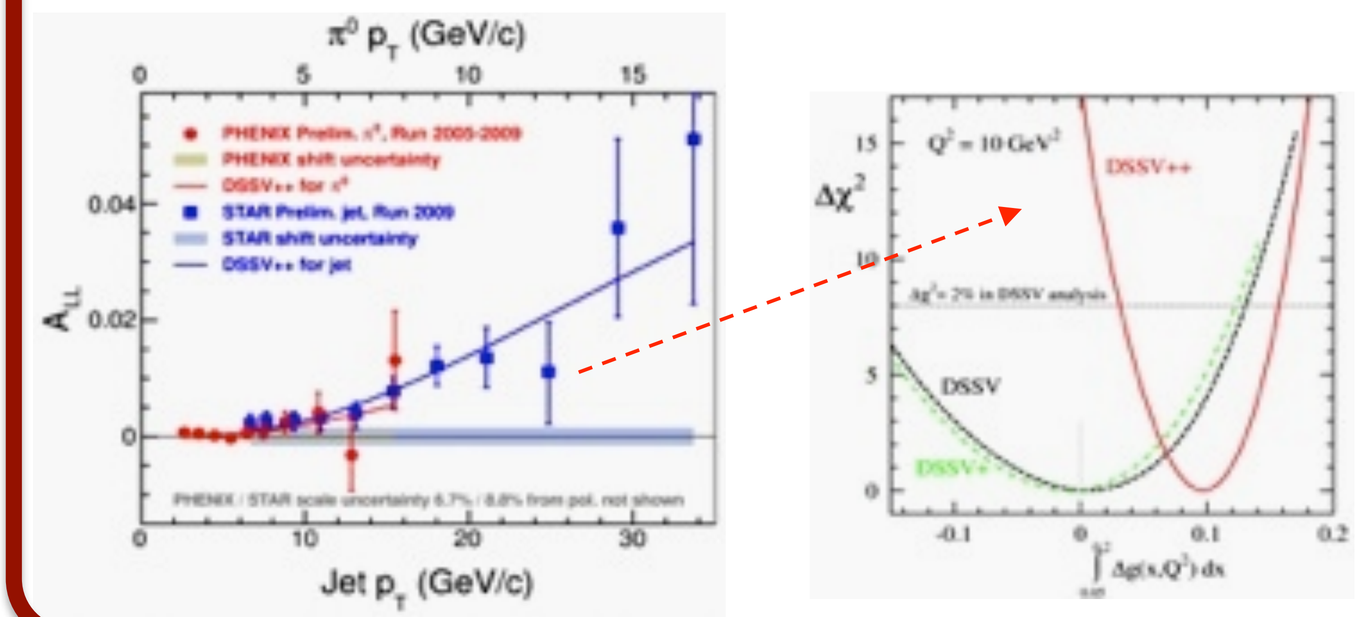


Next steps: forward $\vec{p}$+A – γ production probes gluon densities at low x; transverse spin asymmetries for hadron prod. in $\vec{p}$+A/$\vec{p}$+$\vec{p}$ probes saturation scale

Need forward detector upgrades and EIC – unifies all RHIC program aspects

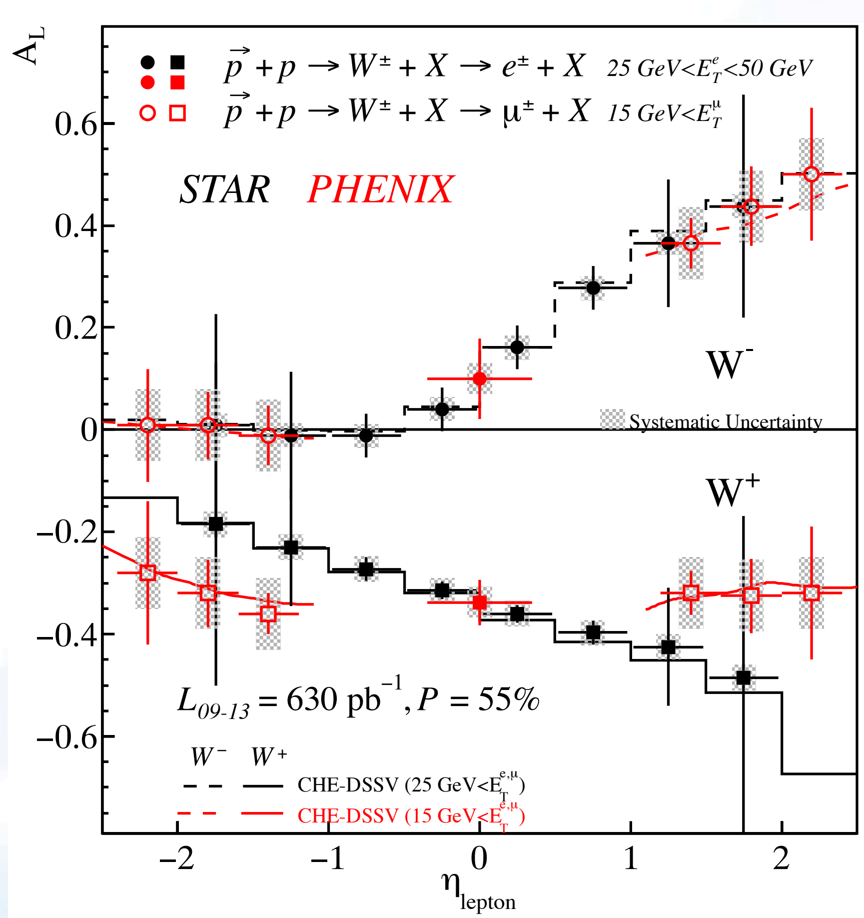
Providing Answers: Missing Proton Spin

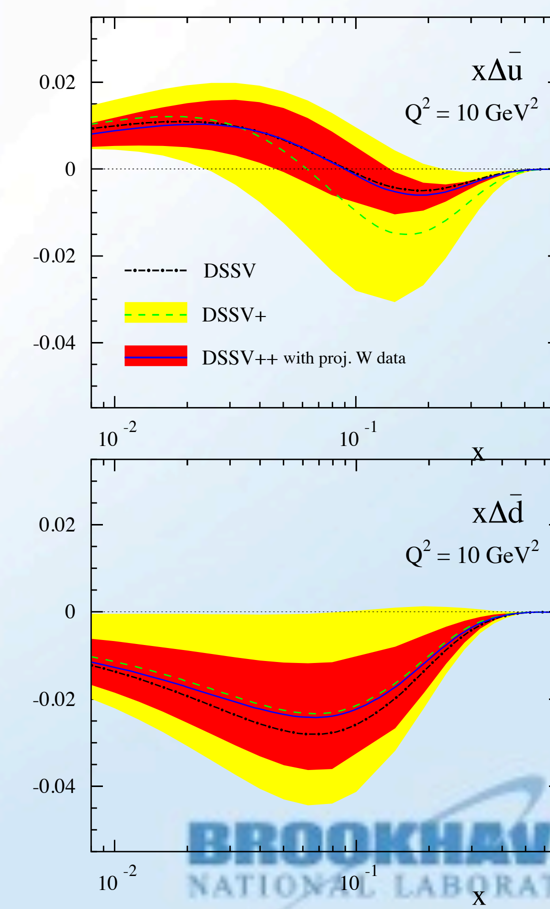
$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2)\, dx = 0.10^{+0.06}_{-0.07}$$



200 GeV data show ~20% gluon contribution of gluons to proton spin.

500 GeV p+p luminosity and polarization now sufficient for vigorous pursuit of $W^{\pm}$ prod. asymmetries constrainting sea-quark polarization

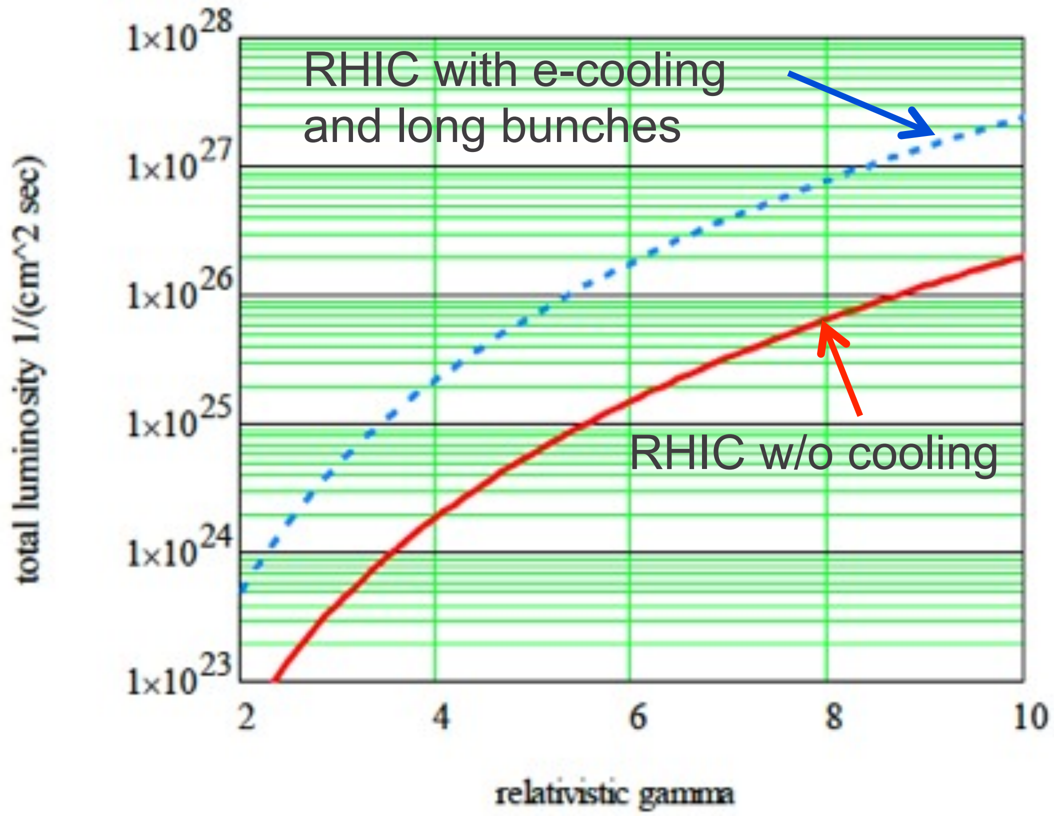




Forward upgrades will permit transverse spin asymmetries for DY dileptons to test initial-state vs. final-state effects

Future Upgrades: "RHIC-3"

Bunched beam electron cooling; ~10x luminosity; ready after 2017



Other machine options: polarized ^3He; coherent e-cooling for p+p

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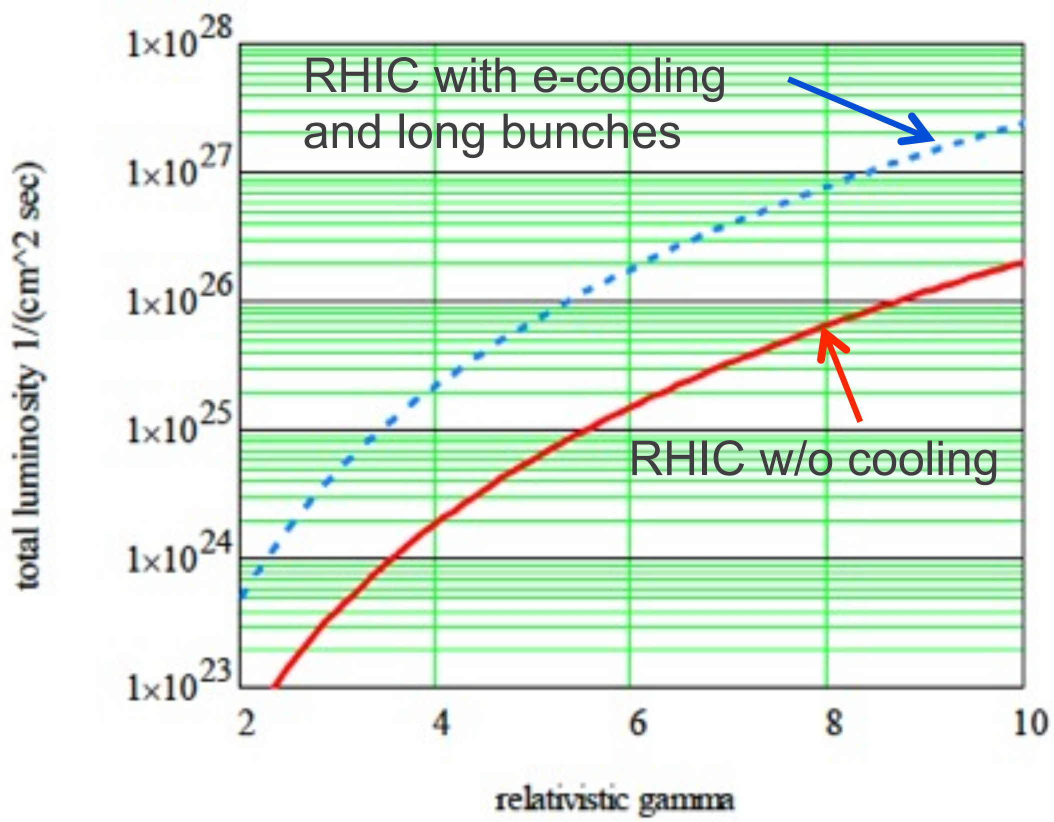
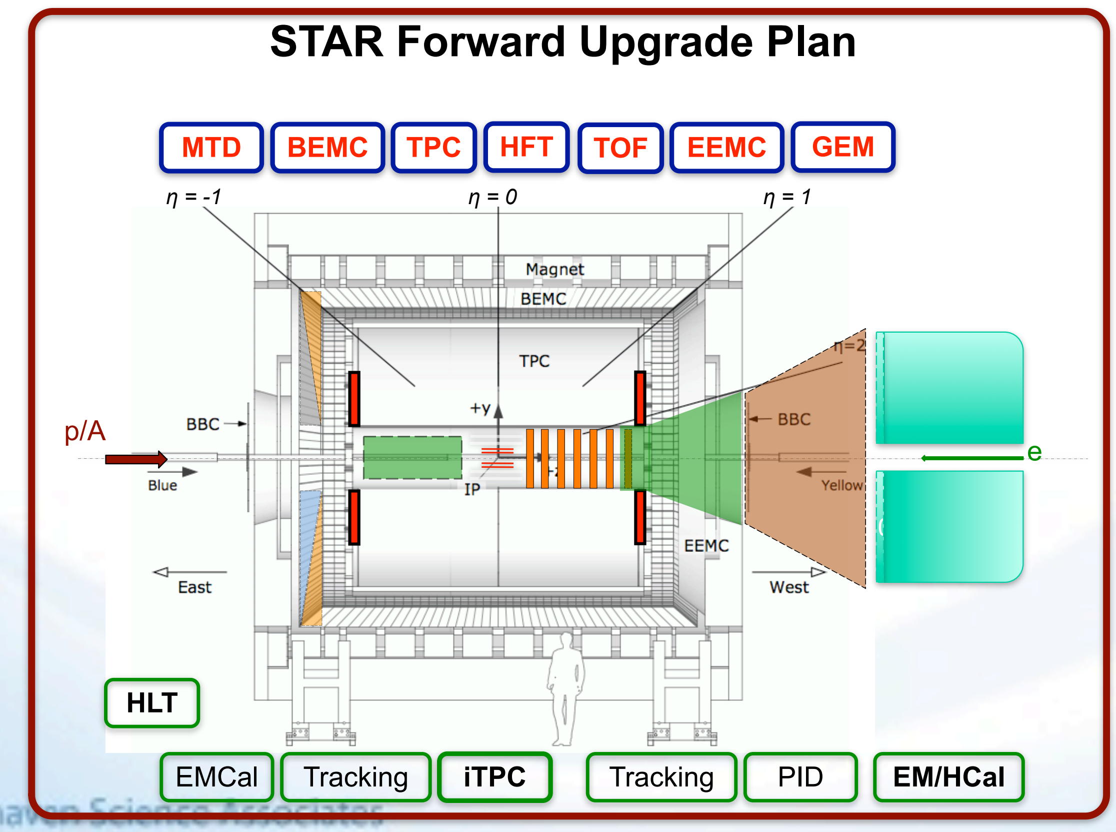
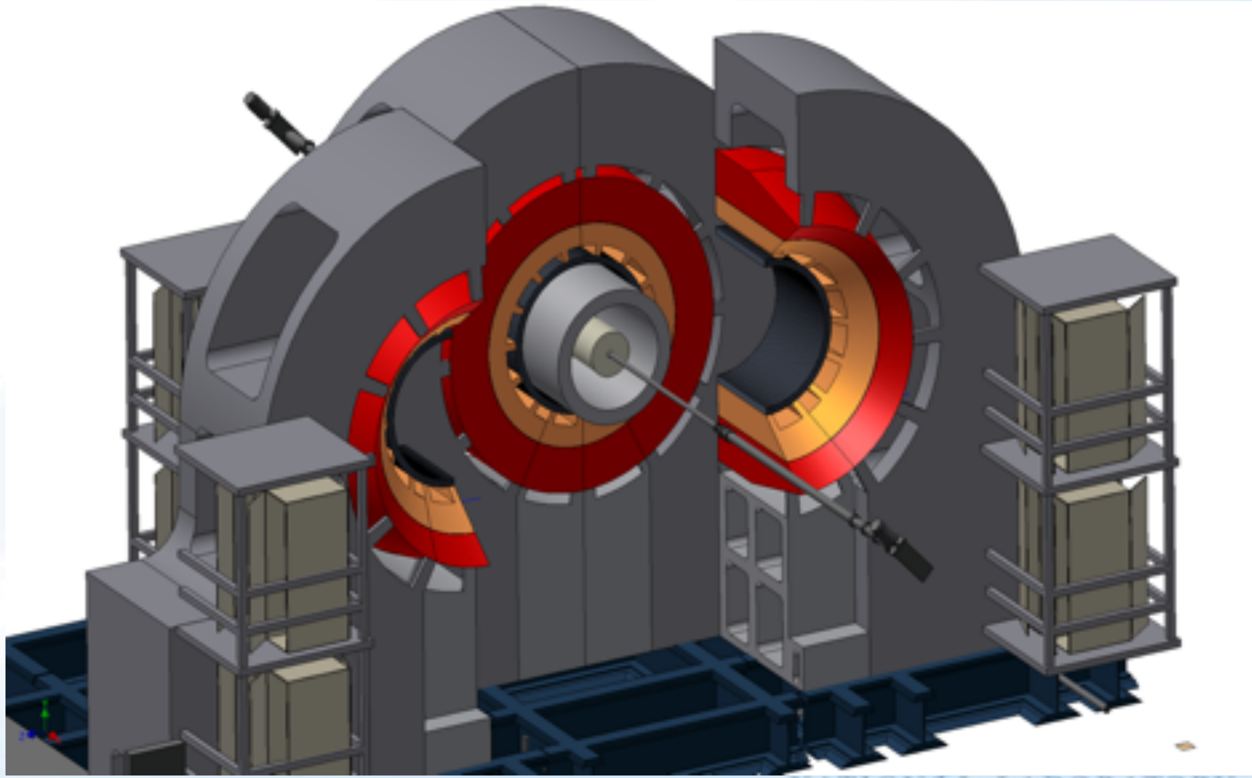


Detector upgrades:

- sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC
- STAR forward upgrade for p+A and transverse spin physics
- PHENIX MPC-EX,
- STAR TPC pad rows

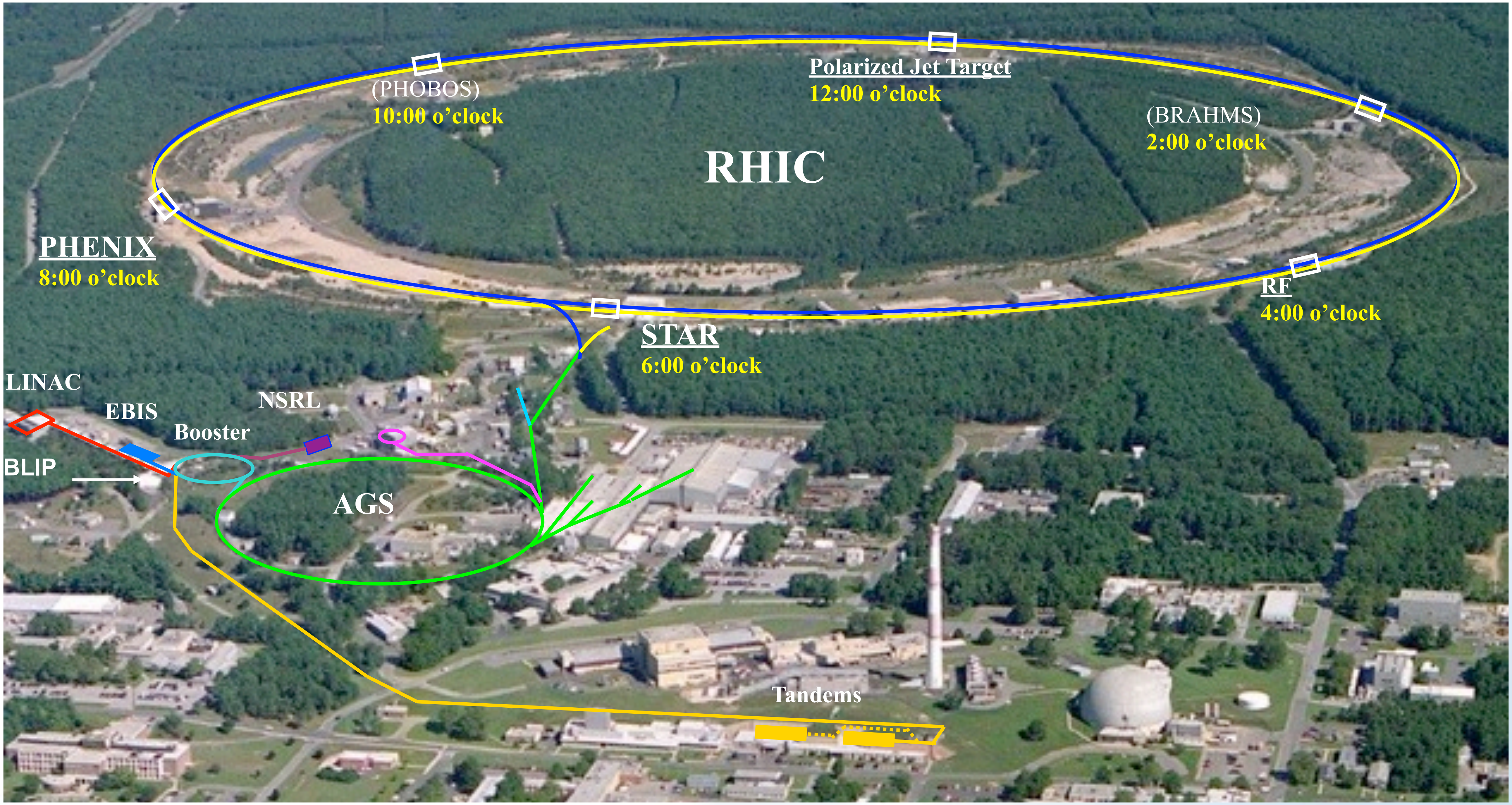




Message 7

RHIC provides a (the one and only?) cost-effective path to an EIC.

From RHIC to e-RHIC



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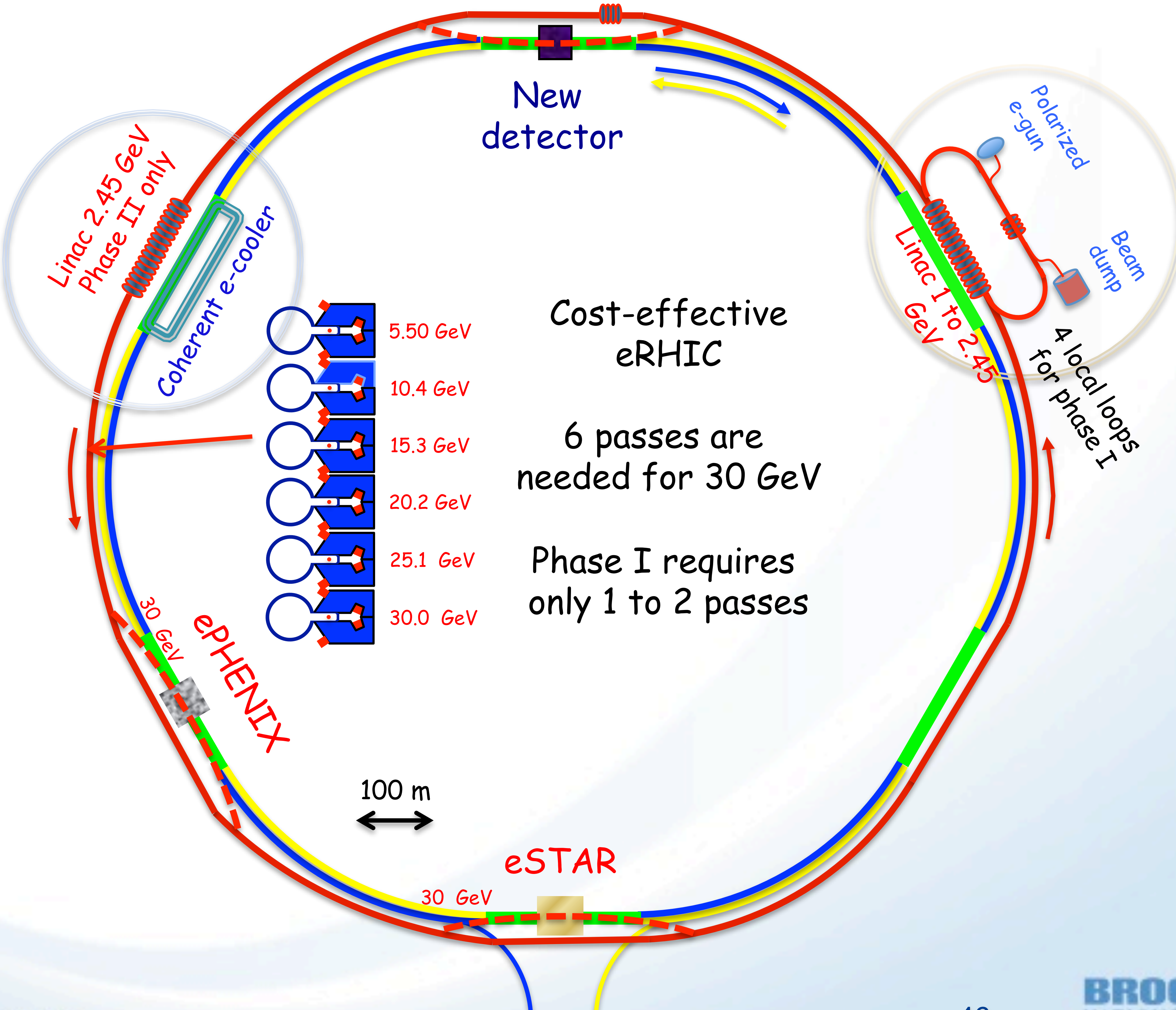
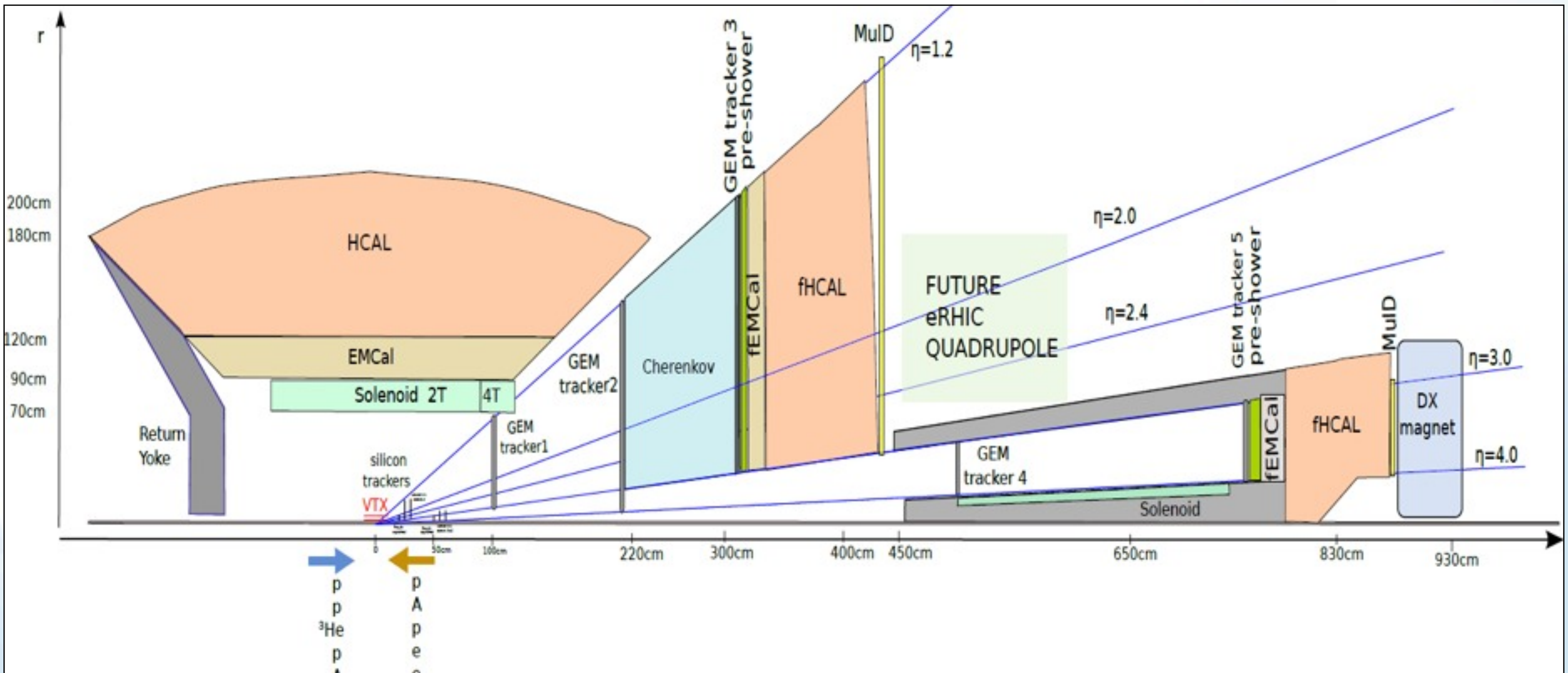


Towards ePHENIX

Design drawing with sPHENIX barrel and forward spectrometer

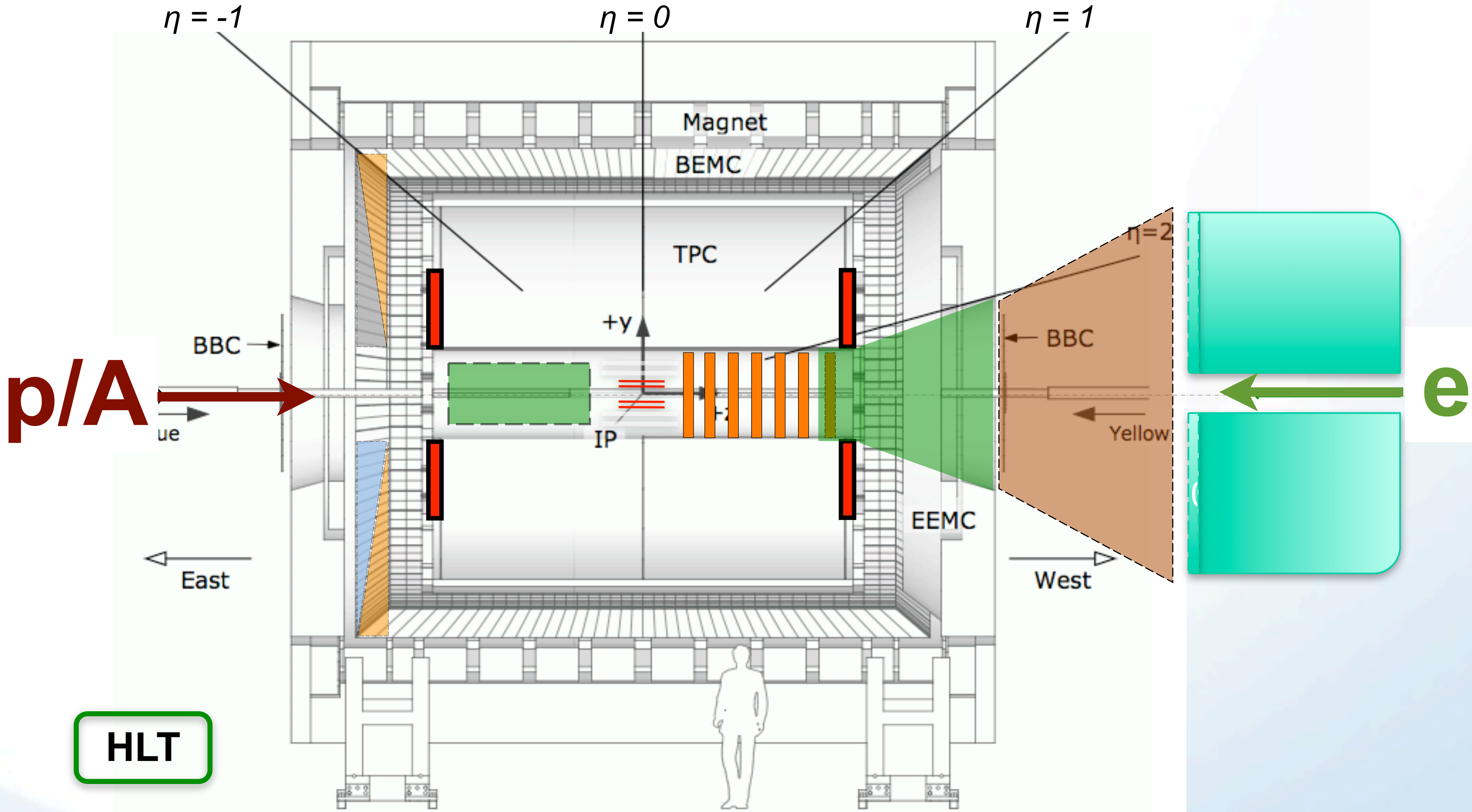
Close coupling and detailed discussions with CAD to fully incorporate eRHIC lattice and space requirements.



Towards eSTAR

STAR Forward Upgrade Plan

MTD | BEMC | TPC | HFT | TOF | EEMC | GEM



HLT

EMCal | Tracking | iTPC | Tracking | PID | EM/HCal

Final Comments

- If RHIC did not exist, it would need to be built
- $2B infrastructure uniquely capable to explore QCD matter in perfect liquid domain and across the phase diagram
- RHIC sits at the sweet spot: most liquid & opaque QGP
- The discovery potential of RHIC is not exhausted
- Next decade = era of precision measurements
- RHIC-2 exists now -- on track to RHIC-3 in 2017/18
- RHIC's path toward eRHIC is clearly delineated and provides for a cost-effective realization of the EIC
- RHIC can ensure preeminence of U.S. research on QCD for the next 2-3 decades