Soft and hard QCD processes at RHIC

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WE-Heraeus Physics School

QCD – Old Challenges and New Opportunities

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Relativistic Heavy Ion Collider at BNL

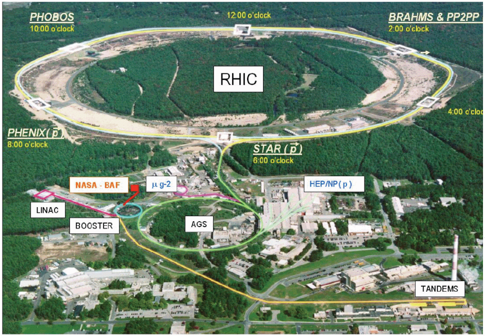
BNL - Brookhaven National Laboratory, Upton, USA: particle and photon science.

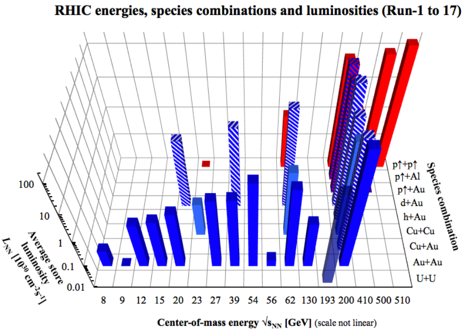
RHIC - Relativistic Heavy Ion Collider: in operation since 2000;

- the only polarized proton collider in the world (P=70%),
- maximum cms energy: 510 GeV for pp and 200 GeV for Au+Au collisions.

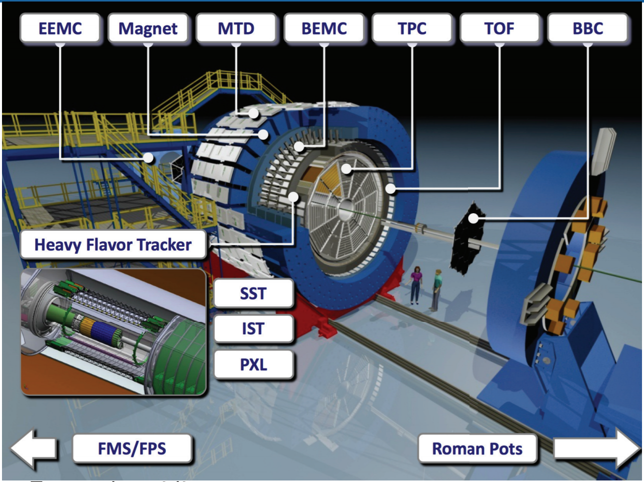
Four major experiments:

BRHAMS(2006), PHOBOS(2005), PHENIX(2016), STAR



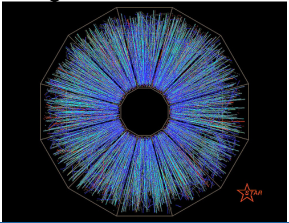


RHIC is uniquely suited to map the QCD phase diagram at finite baryon density.



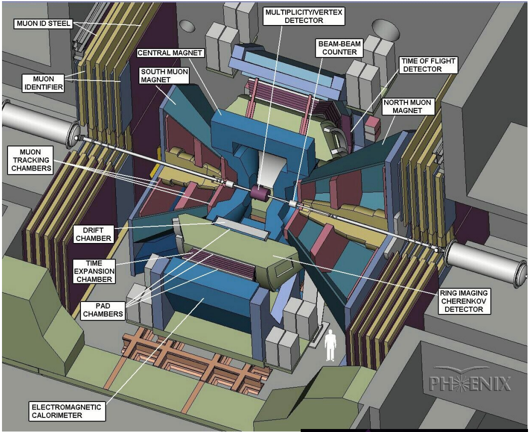
STAR detector

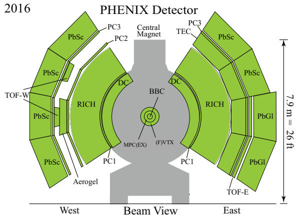
- TPC: high resolution tracking device, PI via dE/dx, $|\eta| < 1,\ 0 < \phi < 2\pi$
- ToF: measures $1/\beta$, together with TPC: $e/hadron$ separation up to 1.4 GeV/c.
- BEMC: $e/hadron$ separation via p/E at high momentum.

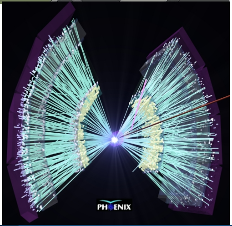


- Forward rapidity gap veto: FTPC: $2.5 < |\eta| < 4.2$, BBC: $3.8 < |\eta| < 5.2$
- ZDC: measurement of energy of spectator neutrons.
- HFT: reconstruction of heavy flavour mesons.
- RP: tagging of beam protons scattered at small angles.

Pioneering High Energy Nuclear Interaction eXperiment





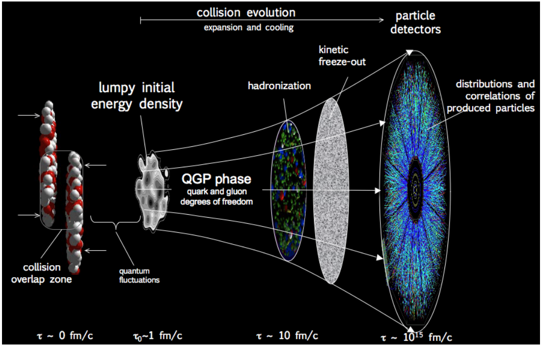


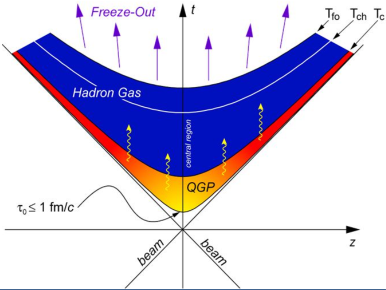
PHENIX detector

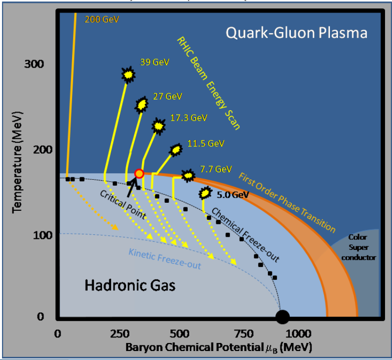
- Central arms:
  - Drift & pad chambers for measuring charged-particle tracks
  - Electromagnetic calorimeter with 18λ (PbSc) and 14λ (PbGl).
  - good mass resolution and PI.
  - $|\eta| < 0.35$, two $\Delta\phi = \pi/2$ arms,
- Muon arms cover $1.2 < |\eta| < 2.2$ and $\Delta\phi = 2\pi$
- MPC: EMC in $-3.7 < \eta < -3.1$ & $3.1 < \eta < 3.9$
- BBC $(2.1 < \eta < 3.8)$ provide MB event definition and centrality.
- F(VTX): reconstruction of heavy flavour mesons.
- ZDC: measurement of energy of spectator neutrons.

Soft and hard probes of the Quark Gluon Plasma

Quark Gluon Plasma and the QCD phase diagram







- Ultra relativistic collisions of heavy ions (HI) enable to study QCD in the deconfined state reached in the limit of high temperatures and densities - the Quark Gluon Plasma (QGP).
- Exploring the QCD phase diagram is the main aim of the experiments at RHIC (BES program).
- Two claims of priority in discovery of QGP:

SPS@CERN (2000) and RHIC@BNL (2005)

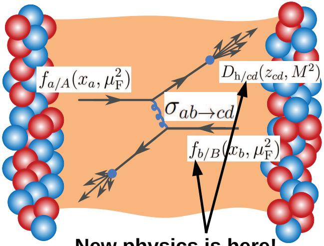
See e.g. this essay for in depth discussion.

Probing Quark-Gluon Plasma

We can study properties of QGP by using:

- hard probes of different scales: electroweak bosons, hadrons, jets, heavy quarks, ...

  Assume factorisation: hard probes are produced early in the HI collision, in a process which cross section is not changed by presence of strongly interacting medium, i.e. can by calculated in pQCD. Passing through the medium hard probes interact weakly or strongly with it providing information on its properties.



  - High transverse momentum partons, produced in hard scattering process, propagating through the medium of strongly interacting nuclear matter, lose energy, resulting in the phenomenon of 'jet quenching'.
  - Magnitude of suppresion is expected to depend on both the p_T dpendence of energy loss as well as the shape of initial jet p_T spectrum.
  - Suppression is quantified by the nuclear modification factor:

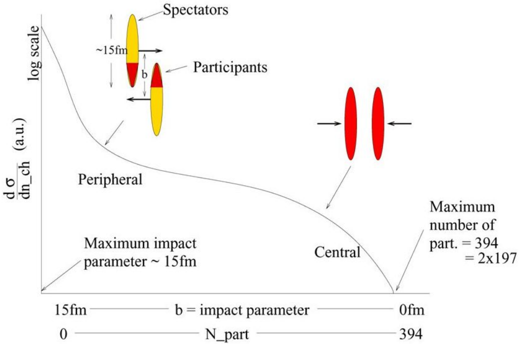
$$R_{AB} = \frac{1}{N_{\rm evt}} \frac{1}{\langle T_{AA}\rangle} \left(\left.\frac{d^2 N^{AB}_{\rm proc}}{dp_T dy}\right|_{\rm cent} \right) \Big/ \frac{d^2 \sigma^{pp}_{\rm proc}}{dp_T dy} = \frac{1}{\langle N_{\rm coll}\rangle} \left(\left.\frac{d^2 N^{AB}_{\rm proc}}{dp_T dy}\right|_{\rm cent} \right) \Big/ \frac{d^2 N^{pp}_{\rm proc}}{dp_T dy}$$

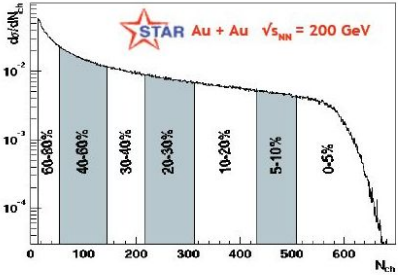
  - $T_{AA} = N_{\rm coll}/\sigma_{NN}$ is the nuclear thickness function, a measure of the nuclear overlap, i.e. the number of nucleons which can participate in the hard scattering process.

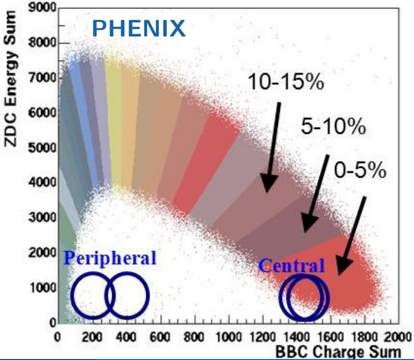
- soft probes, i.e. measuring parameters describing collective behaviour of the medium.

Centrality in heavy-ion collisions

- Yields of hard processes in HI collisions are expected to scale with the number of binary nucleon-nucleon collisions, $N_{\rm coll}$, which depends on the centrality of the collision.
- Central collisions: large overlap of nuclei $\Rightarrow$ high $N_{\rm coll}$ and high number of nucleons participating in the collision, $N_{\rm part}$.
- Peripheral collisions: small overlap of nuclei $\Rightarrow$ small $N_{\rm coll}$ and small $N_{\rm part}$.



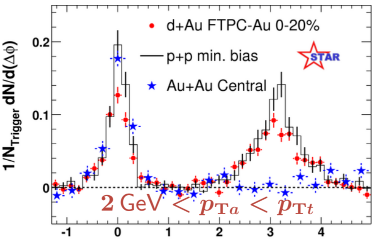


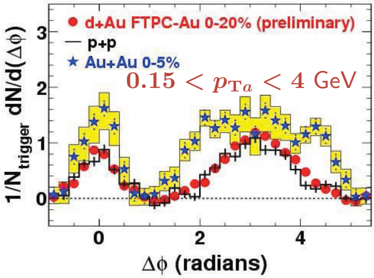


Vanishing of away-side jet in Au+Au collisions

Conditional probability two particle correlation functions - given a trigger particle with $4 < p_{Tt} < 6$ GeV - of detecting an associated particle with p_{Ta} in the range: (a) $2\,\text{GeV} < p_{Ta} < p_{Tt}$, (b) $0.15 < p_{Ta} < 4$ GeV

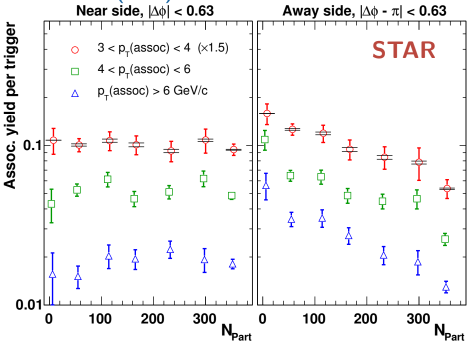
PRL 91 (2003) 072304





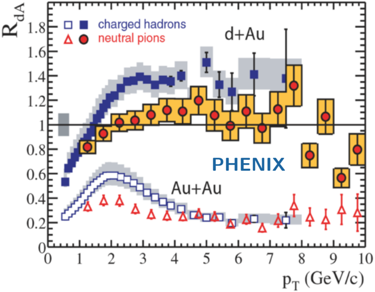
- The away-jet did not disappear, but lost energy and the away-side correlation peak became much wider than in pp collisions.

PRL 97 (2006) 162301

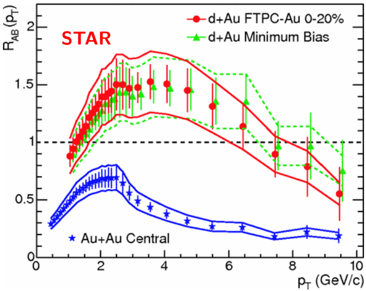


- The amount of suppresion of away-side jet increases in more central collisions.

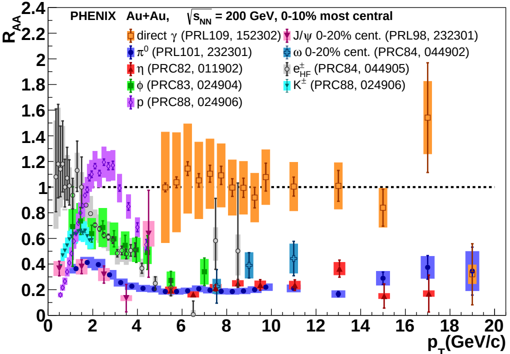
PRL 91 (2003) 072303



PRL 91 (2003) 072304

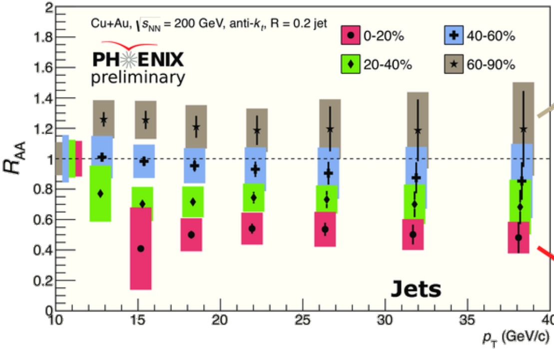


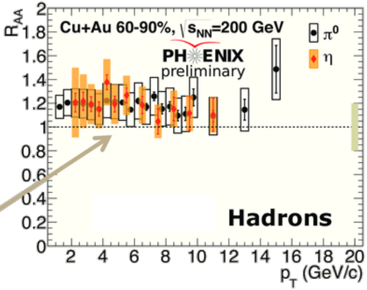
- In central Au+Au coollisions, all mesons are strongly suppressed,
- $e^{\pm}_{\mathrm{HF}}$ are suppressed for higher p_{T}.
- Protons are enhanced for $2 < p_{\mathrm{T}} < 4$ GeV.
- Direct-γ $(q + g \to q + \gamma)$ are not suppressed.
- In d+Au collisions: production of charged hadrons is enhanced (Cronin effect) and production of neutral pions is not suppressed.

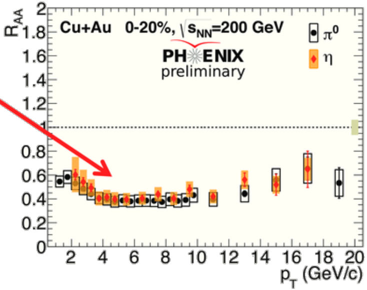


Hadrons and jets suppression in Cu+Au collisions

- In Cu+Au collisions the R_{AA} is very similar for π^0 and η mesons in all centrality intervals.
- Production of π^0 and η mesons is suppressed in central collisions and only in most peripheral bin there is a sign of enhancement.







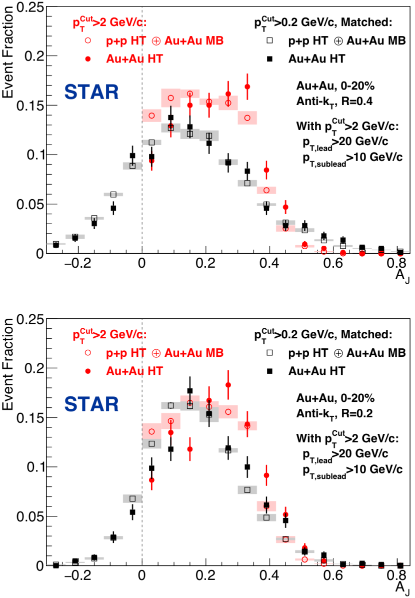
- Suppression of light mesons is very similar to the suppression of jets in the same centrality interval.

Dijet transverse momentum imbalance

- Dijet imbalance is measured in central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV and expressed in terms of the observable:

$$\mathrm{A_J} = \frac{p_{\mathrm{T,lead}} - p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

- Back-to-back dijets ($|\Delta\phi - \pi| < 0.4$) are reconstructed using anti-k_T algorithm with resolution parameter $R = 0.4$ and 0.2.
- For $R = 0.4$, clear increase in dijet imbalance is observed compared to pp baseline, when only constituents with $p_{\mathrm{T}} > 2$ GeV are considered.
- When allowing softer constituents with $p_{\mathrm{T}} > 0.2$ GeV, the imbalance becomes the same as in pp data.
- Repeating the measurement with smaller resolution parameter, $R = 0.2$, leads to significant remaining momentum imbalance even for jets with softer constituents.
- The energy lost via interactions with the medium reemerges as soft constituents, leading to small, but significant broadening of the jet.



PRL 119 (2017) 062301

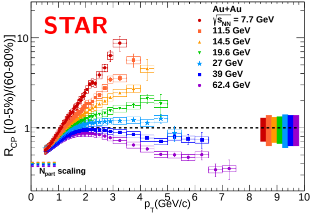
Beam energy dependence of jet-quenching

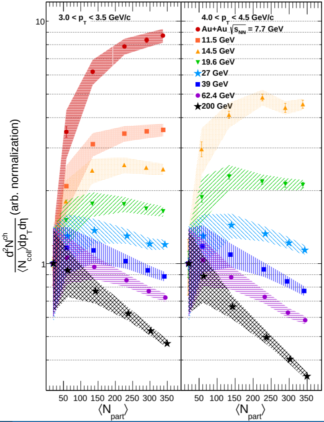
- p_{T} dependence of suppresion of charged hadrons is quantified in terms of the nuclear modification factor defined as (here C: $(0-5)\%$ and P: $(60-80)\%$):

$$R_{CP} = \frac{\langle N_{\mathrm{coll}} \rangle_{\mathrm{Peripheral}}}{\langle N_{\mathrm{coll}} \rangle_{\mathrm{Central}}} \frac{(\mathrm{d}^2 N/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)_{\mathrm{Central}}}{(\mathrm{d}^2 N/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)_{\mathrm{Peripheral}}}$$

- R_{CP} is found to be lowest at the highest energy studied, and increases from the suppresion regime to pronounced enhancement at the lowest beam energies.
- Due to strong enhancement effects, seen at lower energies, R_{CP} is not sensitive enough observable for drawing firm conclusions on quenching effects which would confirm formation of QGP at lower energies.
- Charged hadron yields scaled by $\langle N_{\mathrm{coll}} \rangle$ are measured in two p_{T} ranges as a function of centrality.
- For $\sqrt{s_{\mathrm{NN}}} = 200$ GeV the yield decreases monotonically as expected for stronger increase of quenching effects with centrality than the effects leading to enhancement.
- Quenching effects start to overcome enhancement effects in central collisions at $\sqrt{s_{\mathrm{NN}}} = 14.5$ GeV. ⇒ QGP

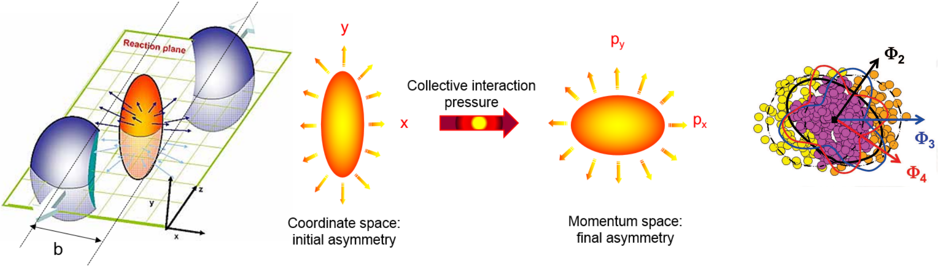
arXiv:nucl-ex/1707.01988





Collective phenomena in QGP

- Immadiately after an A+A collision, the overlap region defined by the nuclear geometry is almond shaped, with shortest axis along the impact parameter vector.
- Multiple interactions between particles in the evolving system change the initial coordinate space asymmetry into final momentum space asymmetry.



- Final state momentum anisotropy is studied via Fourier decomposition of the azimuthal angle of the particle with respect to the reaction plane:

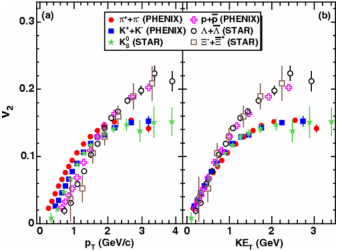
$$E\frac{d^3N}{dp^3} = \frac{1}{p_T}\frac{d^3N}{d\phi\, dp_T\, dy} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N}{dp_T\, d\eta}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)$$

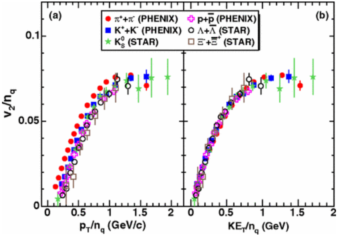
Φ_n - azimuthal angle of the n-th order symmetry plane of the initial geometry,
$v_n \equiv \langle e^{in(\phi-\Phi_n)}\rangle = \langle \cos n(\phi - \Phi_n)\rangle$ - magnitude of the n-th flow harmonics.

Flow harmonics in Au+Au collisions

- Non-zero flow observed in the final state hadrons means that thermalization is rapid, and hydrodynamics comes into play before the spatial anisotropy dissipates.
- At this early stage hadrons have not yet formed, so the quarks must flow, and the flow of hadrons should be proportional to the number of constituent quarks n_q.

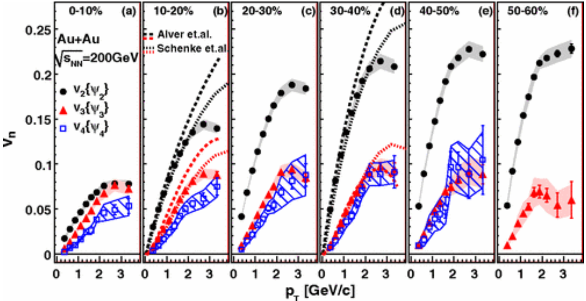
PRL 107 (2011) 252301





- v_2 for identified hadrons as a function of p_t or $KE_T \equiv m_T - m$ scales with n_q,
- v_2 tracks the change of eccentricity with centrality,
- centrality dependence of $v_{3,4}$ is weak - fluctuations,
- for the most central collisions, where the overlap region is nearly circular, they are comparable.

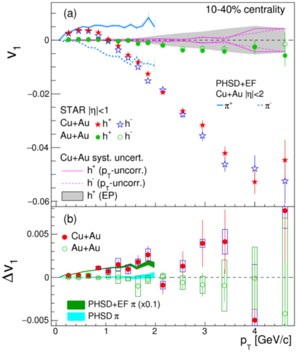
PRL 107 (2007) 162301



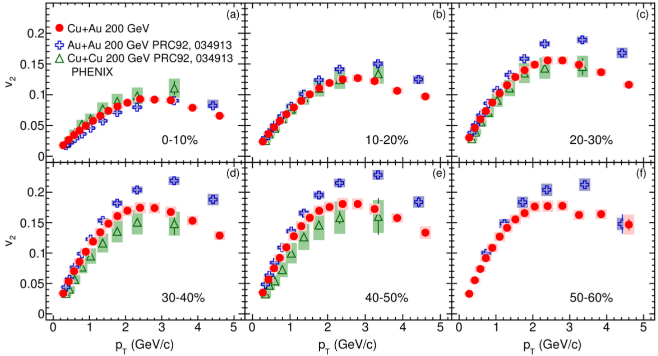
Flow harmonics in Cu+Au collisions

- v_1 for asymmetric collision like Cu+Au is significantly different from zero for both positive and negative particles. In symmetric Au+Au collisions $v_1 \approx 0$.
- The p_T dependence of the difference Δv_1 is qualitatively described by a model taking into account strong, initial, electric field. However, the magnitude of Δv_1 is smaller by a factor of 10 than the model predictions. This may suggest that not all quarks are created within the lifetime of the electric field (< 0.25 fm/c).
- v_2 for Cu+Au lies between v_2 for Au+Au and Cu+Cu collisions.

PRL 118 (2017) 0123901

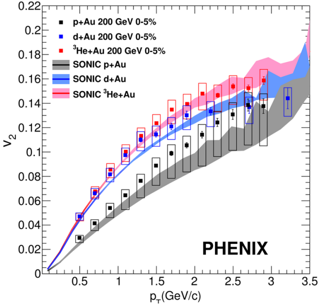


PRC 94 (2016) 054910



Flow in small systems

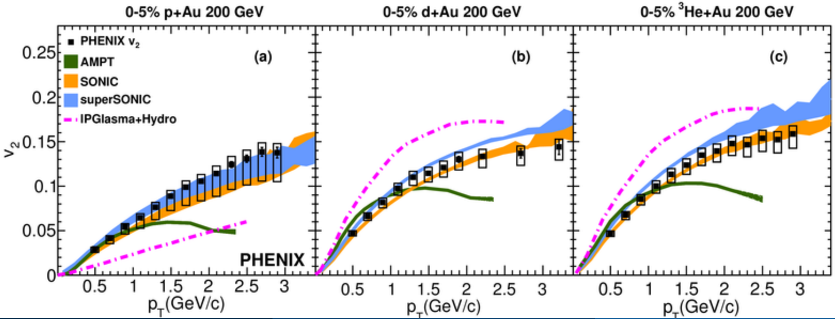
PRC 95 (2017) 034910



- In all cases there is a substantial v_2 risig with p_T.
- Geometry control works:

$$\mathrm{v}_2(\mathrm{d+Au}) \sim \mathrm{v}_2(^3\mathrm{He+Au}) > \mathrm{v}_2(p\mathrm{+Au})$$

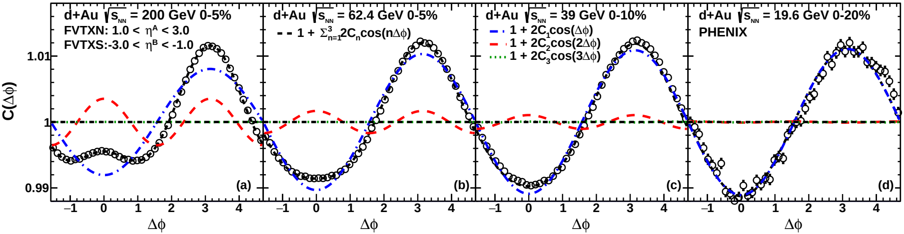
  similarily as their eccentricities ϵ_2.
- SONIC model (initial conditions, hydrodynamics, hadronic cascades) describes well p_T dependence.
- AMPT - weakly coupled partonic cascade, quark coalescence, hadronic cascade - works at low p_T.



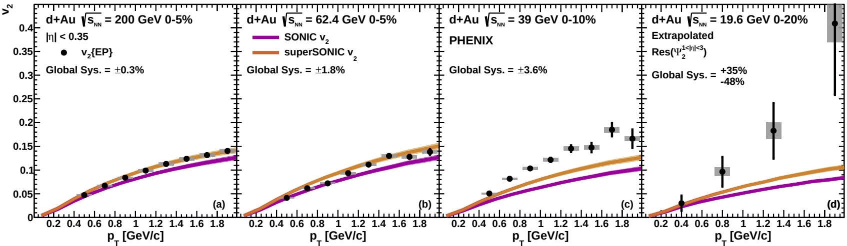
Energy scan of d+Au system

- In two particle correlation function $C(\Delta\phi)$, a clear peak at $\Delta\phi = 0$ (ridge) is present down to $\sqrt{s_{\rm NN}} = 39$ GeV, but not at $\sqrt{s_{\rm NN}} = 19.6$ GeV.

arXiv:1708.06983 [nucl-ex]



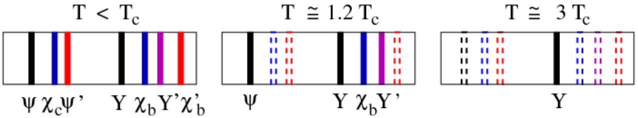
- SONIC model does not fit the v_2 data at $\sqrt{s_{\rm NN}} = 19.6$ and 39 GeV.

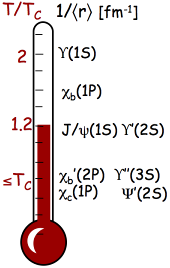


Quarkonium production in QGP

Quarkonium is a bound state of heavy $Q\bar{Q}$ pair ($c\bar{c}$ - charmonia, $b\bar{b}$ - bottomonia).

- Mainly produced in early stage of the collision via $g + g \to Q + \bar{Q}$
$m_c \approx 1.3$ GeV, $m_b \approx 4.5$ GeV $\Rightarrow$ can be calculated using pQCD.
- In deconfined medium (QGP), color screening prevents $Q\bar{Q}$ binding
- Different quarkonium states are melted in different temperatures:





- Conversely, by investigating which states survive and which have been melted, one can pin down the temperature reached by the medium created in HI collision.
- However, measuring temperature takes time - the thermometer has to reach thermodynamical equilibrium. Bottomonium, Υ, may not reach thermodynamical equlibrium in the lifetime of QGP (< 10 fm/c):

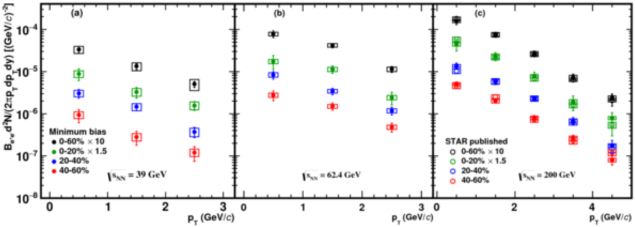
$\langle r\rangle_\Upsilon \approx 0.25 - 0.5$ fm, $v_{b/\bar{b}} \approx 0.3$c, duration of an "orbit" $\approx 5 - 10$ fm/c

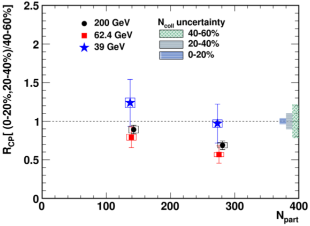
- Suppresion due to CNM effects (nPDF, energy loss of partons in nucleus before hard scattering, absorption of the quarkonium state as it passes through nucleus)
- Also possible enhancement through random recombination of Q and $\bar{Q}$ in QGP.

Quarkonium production in Au+Au collisions

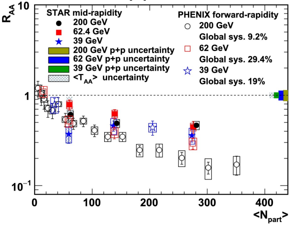
- J/Ψ invariant yields and $R_{\rm CP}$ for different cms energies.
- Suppresion in $\sqrt{s_{\rm NN}} = 62.4$ GeV and $\sqrt{s_{\rm NN}} = 200$ GeV data is similar.

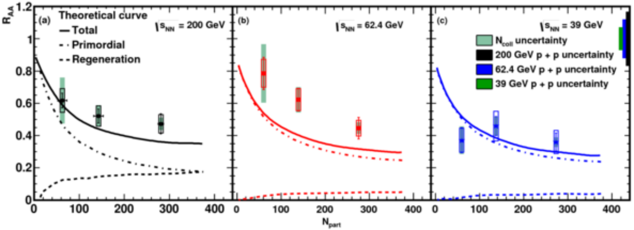
PLB 771 (2017) 13





- $R_{\rm AA}$ in function of centrality is described by theoretical calculations including both suppresion due to CNM and color screening and regeneration from $c\bar{c}$ pairs.

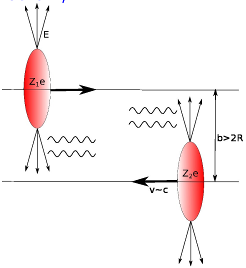




Ultra-peripheral collisions and Diffraction at RHIC

Ultra-peripheral heavy-ion collisions

Heavy ions are intense sources of photons: in ultra-peripheral collisions one can study two photon interactions, photonuclear production, diffraction, ...

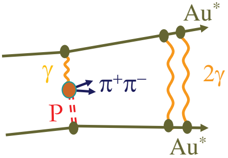


- Ultra-peripheral collisions (UPC): $\boldsymbol{b > 2R}$
  - hadronic interactions strongly suppressed,
  - intense source of photons ($\sim Z^2$), well described by Weizsäcker-Williams (EPA).
  - virtualities $Q^2 < (\hbar/R_A)^2 < 10^{-3}$ GeV^2 ($R_A = 7$ fm).
  - maximum energy of coherent photons ($\sqrt{s_{\mathrm{NN}}} = 200$ GeV):

    $E = \gamma\hbar c/R_A = \{\gamma \approx 106.5\} \approx 3$ GeV

- Coherent diffractive photoproduction of ρ^0 mesons:

$$\mathrm{Au} + \mathrm{Au} \to \mathrm{Au}^\star + \mathrm{Au}^\star + \rho^0$$

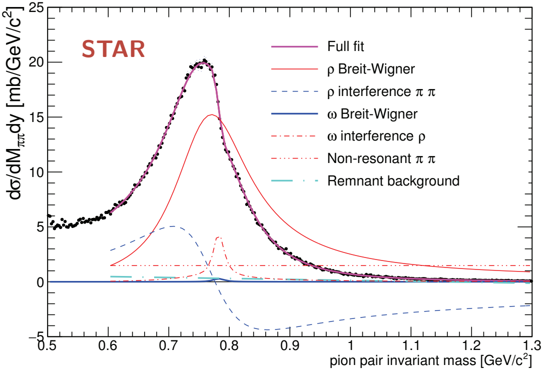


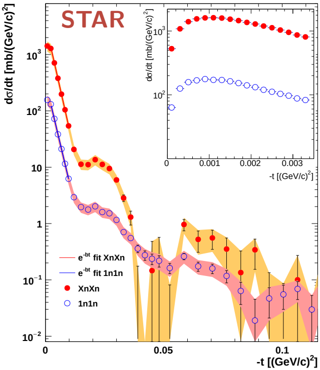
Obtain cross section integrating over impact parameter:

$$\sigma(A_1 A_2 \to A_1^\star A_2^\star \rho^0) = \iint \mathrm{d}^2 b\, P_1(b, A^\star) P_2(b, A^\star) P(b, \rho^0)[1 - P_{\mathrm{Had}}(b)]$$

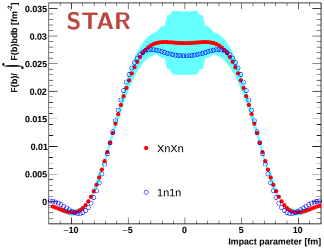
- $\pi^+\pi^-$ invariant mass spectrum can be well fitted by the sum of B$-$W shapes for ρ^0 and ω, direct $\pi\pi$ production and their interference terms.

Coherent diffractive production of ρ^0 mesons on gold nuclei





- Obtain coherent spectrum of $d\sigma/dt$ by subtracting incoherent part (estimated from fit of a dipole form factor $F(t) = A/(Q_0^2 + |t|)^2$ to the full spectrum for $-t > 0.2$ GeV^2) from the full spectrum.
- Clear diffractive minima can be seen - gold nuclei appear to be acting like black discs.
- 2D Fourier transform can be used to obtain transverse density distribution of the gold nuclei.



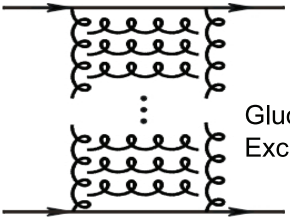
Processes with tagged forward protons

Processes mediated by Pomeron exchange in proton-proton scattering:

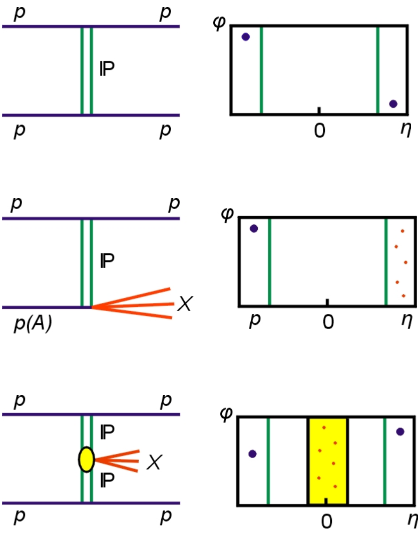
- elastic scattering: $p + p \to p + p$
- single diffraction: $p + p \to p + X$
- double diffraction: $p + p \to p + X + p$

In terms of QCD, Pomeron exchange consists of the exchange of a color singlet combination of gluons.

Hence, triggering on forward protons at high energies predominantly selects exchanges mediated by gluonic matter.



Gluon Exchanges

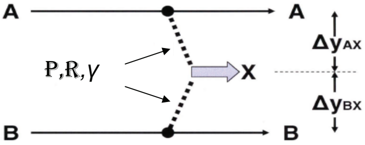


X - final state particles, glueballs?

Central Exclusive Production and DPE

Central Exclusive Production

- $A + B \to A + X + B$
- colliding particles emerge intact,
- produced state X is fully measured,
- X couples to colour neutral objects: Regge trajectories, photons



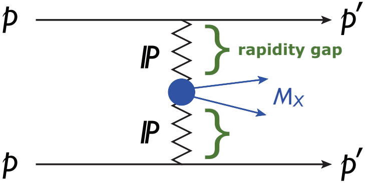
For hadronic processes at high energies CEP is dominated by Double Pomeron Exchange (DPE), photon-Pomeron or photon-photon fusion.

In DPE process each proton 'emits' a Pomeron and the two Pomerons interact producing a final masive state M_X.

Kinematics:

- t – four momentum transfer
- $\xi = \Delta p/p$ - momentum loss of the proton
- Invariant mass: $M_X = \sqrt{\xi_1 \xi_2 s}$

$M_X = \pi^+\pi^-, \chi_c(\chi_b), qq(\text{jets}), gg(\text{gluballs}), \ldots$

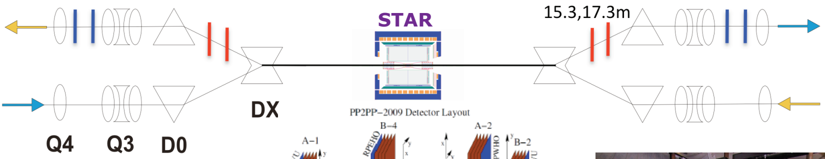


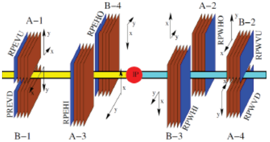
DPE is a spin-parity-isospin filter $\mathrm{I}^G\mathrm{J}^{PC}$ for system X: 0^+0^{++}, 0^+2^{++}

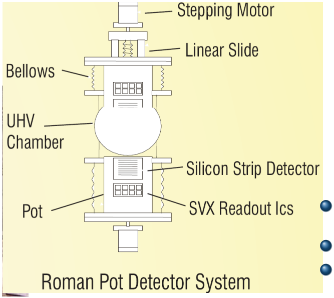
Diffractive photoproduction (γ+Pomeron) of vector particles ($J/\Psi, \rho, \ldots$)

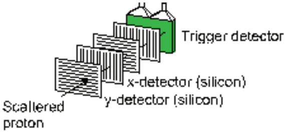
Forward Proton Taggers

Need detectors (Roman Pots) to measure forward protons (small t and ξ):









- Each RP vessel contains Si strip detector package made of 4 planes.
- $\sim$ 30 μm position resolution of a single plane.
- Scintilation counter is used for triggering.

Summary

- All four experiments at RHIC confirmed unambiguuosly creation of deconfined hot dense medium - the Quark Gluon Plasma.
- PHENIX and STAR have provided many new results on detailed study of the properties of QGP, using both hard and soft probes.
- Beam Energy Scan programs (BESI and BESII) aim at pin down of the critical point and phase transition boundary in the QCD phase diagram.
- New program of diffraction with tagging of final state protons is ongoing in STAR - be prepared for new results soon.
- There is ongoing program on the study of the proton spin puzzle - what is the contribution to the proton spin from quarks, gluons and their orbital motion?

Thank you for your attention!

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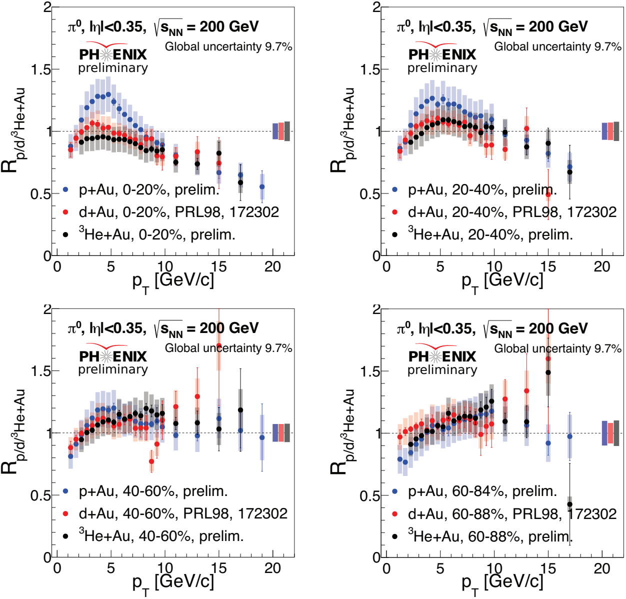
Backup slides

π^0 suppression in small systems



- p+Au results show large centrality dependence,
- d+Au results agree with p+Au at high p_{T},
- ^{3}He+Au results agree with p+Au and d+Au at high p_{T},
- An ordering of $R_{\mathrm{pAu}} > R_{\mathrm{dAu}} > R_{\mathrm{HeAu}}$ is observed in central events at moderate p_{T}.

Suppression of identified hadrons in d+Au collisions

- All the mesons are more or less binary scaled at higher p_T.
- Protons show large and strongly centrality dependent Cronin enhancement, reaching a factor of 2 in the most central collisions at intermediate p_T.

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