Heavy Flavor and Quarkonia

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on behalf of the PHENIX Collaboration

Quark Matter Houston 2023

September 5, 2023

Brief Introduction

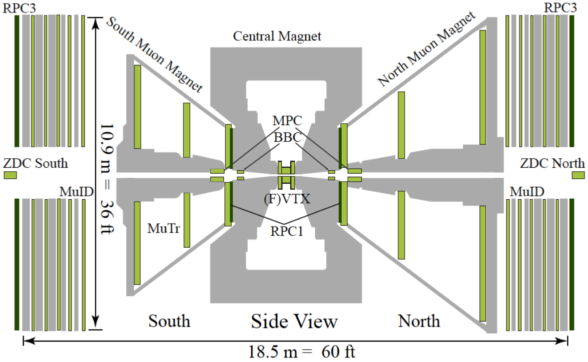
Quarkonia & Heavy Flavor Overview

Three recent PHENIX analyses focus on the following collision systems and investigate the following:

- 2013 $p+p$ at $\sqrt{s} = 510$ GeV
- 2014 ^{3}**He+Au**, **Au+Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2015 $p+p$, $p+$**Al**, $p+$**Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2016 $d+$**Au**, **Au+Au** at $\sqrt{s_{NN}} = 200$ GeV

1. Do we see evidence for multi-parton interactions at RHIC energies?
2. Are there final state effects on charmonium production in $p+p$ collisions?
3. Is there evidence of mass ordering for charged hadron vs. open heavy flavor v_2?

PHENIX Muon Arms



South arm: -2.2 < η < -1.2

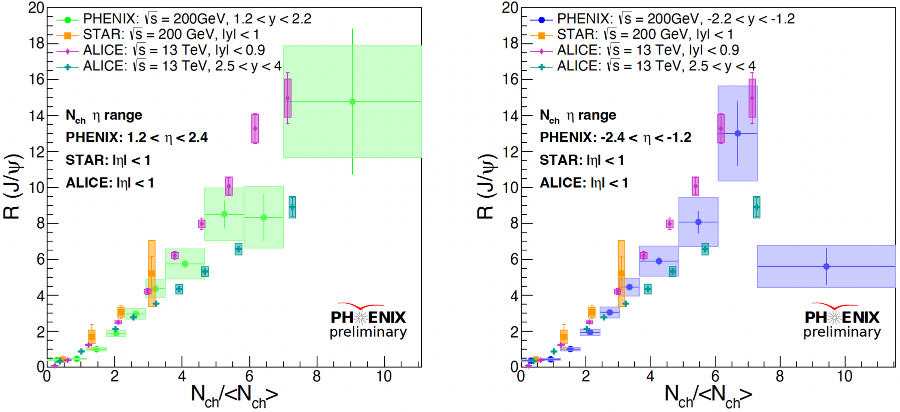
North arm: 1.2 < η < 2.4

- **Forward Silicon Vertex Detector (FVTX)**
  - 4 layers of silicon strip stations for precision measurement of track trajectory
  - Charged particle multiplicity
- **Muon Tracker (MuTr)**
  - 3 cathode strip chambers measure momentum of charged tracks
- **Muon Identifier (MuID)**
  - 5 layers of steel absorbers for hadron and muon separation

Quarkonia & Heavy Flavor Results

Multiplicity Dependent J/ψ Production

PHENIX NEW RESULT



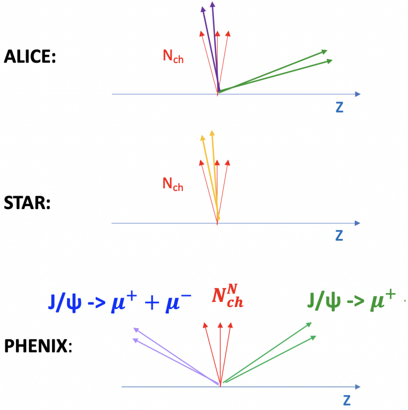
Universe 2023, 9(7), 322

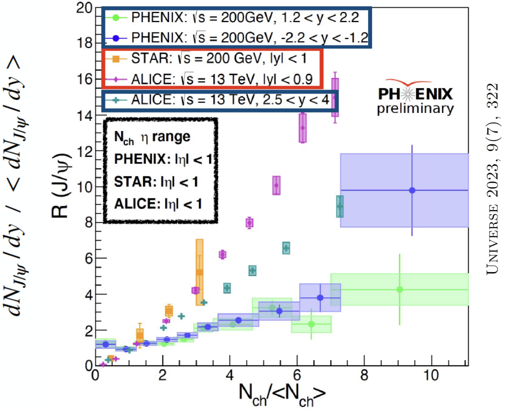
- First PHENIX measurement of relative J/ψ yields R vs. normalized event charged particle multiplicity $N_{ch}/\langle N_{ch}\rangle$ in p+p collisions at $\sqrt{s}$=200 GeV

Los Alamos NATIONAL LABORATORY

Multiplicity Dependent J/ψ Production

PHENIX NEW RESULT

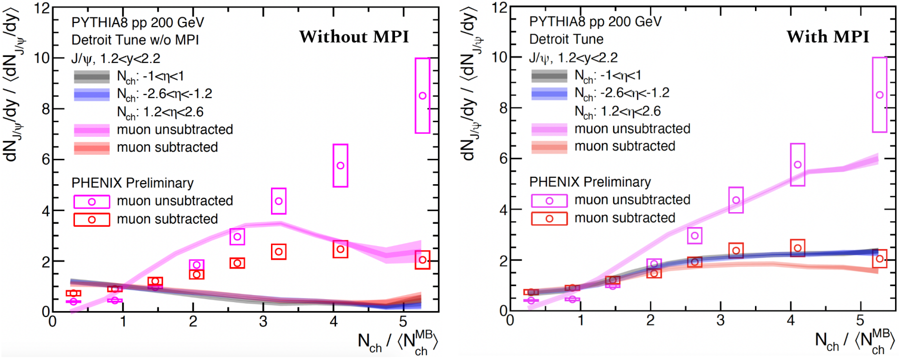




- Multiplicity dependent measurements vary based on rapidity of N_{ch}
- After J/ψ tracks subtracted, PHENIX multiplicity dependence similar at fwd, bkwd rapidity

Multiplicity Dependent J/ψ Production

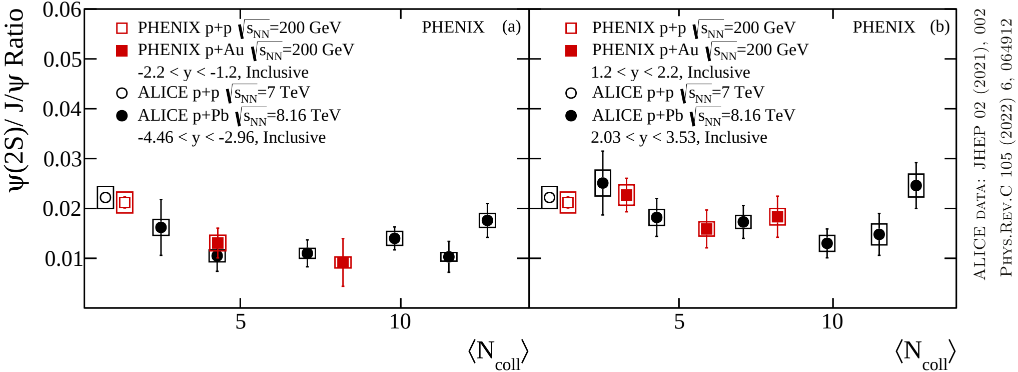
PHENIX NEW RESULT



Eur.Phys.J.C 74 (2014) 8, 3024
Phys.Rev.D 105 (2022) 1, 016011

- J/ψ relative yields compared with PYTHIA8 Detroit tune for RHIC energies
- Data is shown for J/ψ multiplicity both before and after J/ψ tracks subtracted
  - **Multi-parton interactions are required to reproduce PHENIX data**

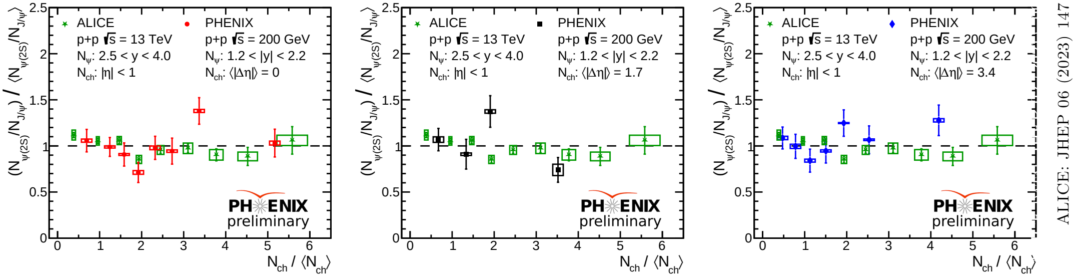
ψ(2S) to J/ψ Ratio at RHIC and LHC



- The ψ(2S) to J/ψ ratio in p+p collisions at RHIC, LHC show no clear energy dependence
- **Comparison of the p+A to p+p ratio strongly suggests final state effects** in p+A collisions at backward rapidity, as initial state effects expected to largely cancel

Multiplicity Dependent $\psi(2S)$ to J/ψ

PHENIX NEW RESULT

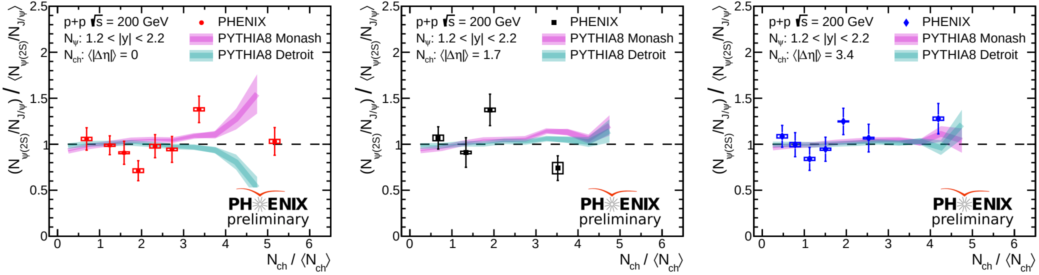


- Multiplicity-dependent studies in small systems provide a testing ground for examining the onset of QGP-like effects
- PHENIX ($\sqrt{s_{NN}}$=200 GeV) and ALICE ($\sqrt{s_{NN}}$=13 TeV) results consistent, with **weak multiplicity dependence more or less consistent with unity**
  - Note that ALICE results have charged particle multiplicity measured at mid-rapidity

See poster by JongHo Oh

Multiplicity Dependent $\psi(2S)$ to J/ψ

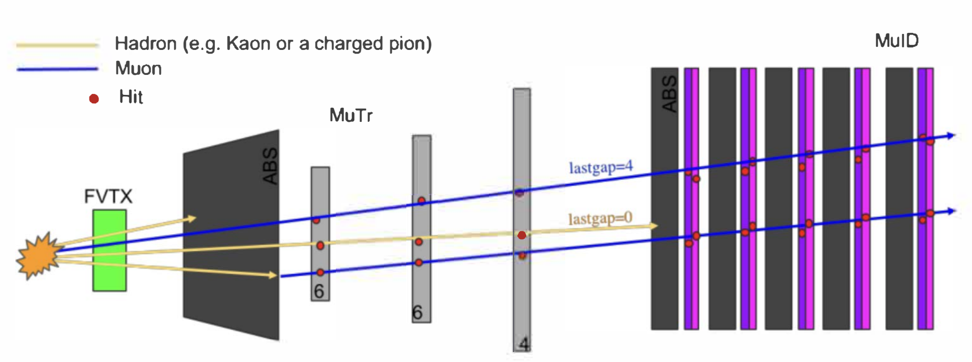
PHENIX NEW RESULT



- $\psi(2S)$ to J/ψ ratios shown with particle multiplicity measured in different $|\Delta\eta|$ ranges
- **Co-moving particle or QGP related final state effects appear to be small** in RHIC p+p collisions, with minimal change in ratio with increasing particle multiplicity
  - Overall, both PYTHIA tunes with MPI describe measurements well at lower multiplicity

Open Heavy Flavor v_2 at RHIC

PHENIX NEW RESULT

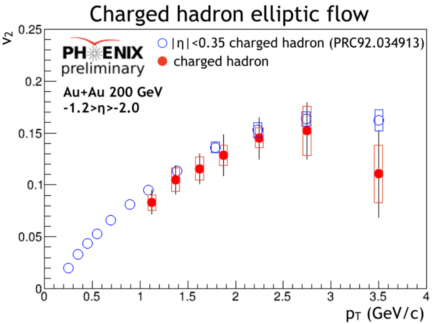


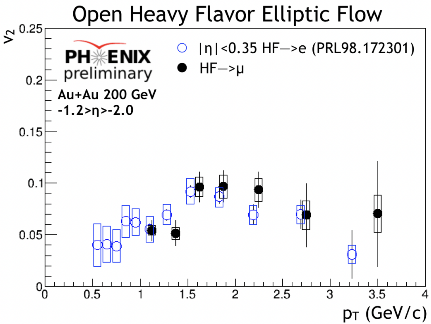
- Charged hadron tracks shown stopping in Muon Arm absorber, last gap 0 of MuID
- Heavy flavor muon tracks shown penetrating the full length of Muon Identifier

See poster by Bran Blankenship

Open Heavy Flavor v_2 at RHIC

PHENIX NEW RESULT





- First-ever RHIC measurement of open heavy flavor elliptic flow at forward rapidity
  - **Open heavy flavor v_2 consistent with PHENIX mid-rapidity results**
- Mass ordering apparent where lighter charged hadrons (left) show stronger elliptic flow
  - Only 2014 data shown (2016 data will increase statistics $\sim$ 4 times)

Conclusion

Small System Collisions — p+p

- Multiplicity dependent J/ψ varies based on η of charged particle tracks
  - PHENIX data well described by PYTHIA Detroit tune with MPI

  $\Longrightarrow$ Evidence for MPI at RHIC energies
- $\psi(2S)$ to J/ψ ratio in p+p collisions shows weak dependence on multiplicity

  $\Longrightarrow$ No evidence for $\psi(2S)$ final state effects in p+p collisions at RHIC

Large System Collisions — A+A

- First RHIC measurement of open heavy flavor v_2 at forward rapidity
  - Results consistent with PHENIX mid-rapidity measurements, suggesting similar QGP effects (temperature/pressure gradients) at both rapidities

  $\Longrightarrow$ Mass ordering observed at forward rapidity

Back-Up

PHENIX, Past & Present

PHENIX Overview

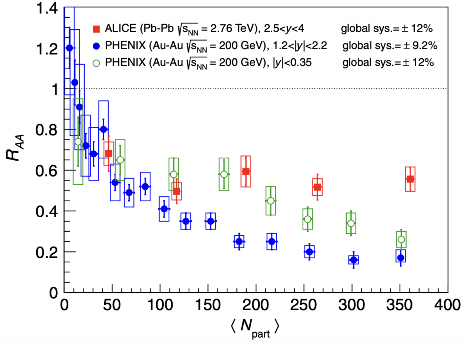
- **2000–2016**
  PHENIX recorded heavy-ion data at RHIC for 16 years
- **Publications**
  PHENIX has 215 physics papers published (75 in *Phys. Rev. Lett.*)
- **Presentations/Theses**
  Zenodo contains ∼400 materials
- **Recent Highlights**
  2023 direct photon measurement **BNL News Release**

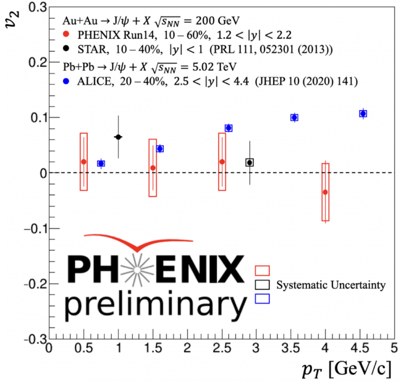
Data Preservation

- **2021–Present**
  Efforts led by Gabor David, Maxim Potekhin, Christine Nattrass and team of undergraduates at UT Knoxville
- **Publications**
  PHENIX data from ∼200 PHENIX publications uploaded to HEPData
- **Present**
  Still have PHENIX data from ∼30 publications to upload

See poster by Luis Bichon

J/ψ in A+A Collisions at RHIC (LHC)

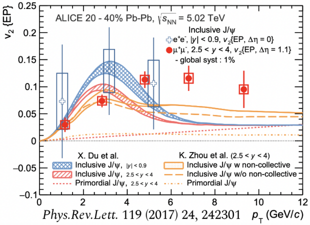


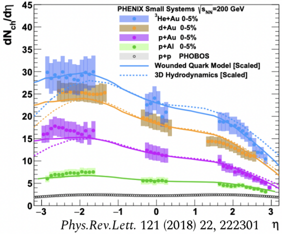


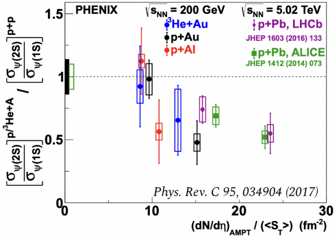
ALICE: Phys.Rev.Lett. 109 (2012) 072301
Phys.Rev.Lett. 98 (2007) 232301

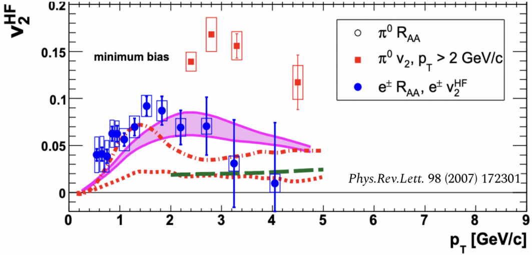
- PHENIX J/ψ R_{AA} shows stronger suppression than ALICE at both forward and mid-rapidity
  - Regeneration effects modify charmonia measurements at LHC energies
- At RHIC energies, regeneration not as significant → J/ψ flow consistent with zero

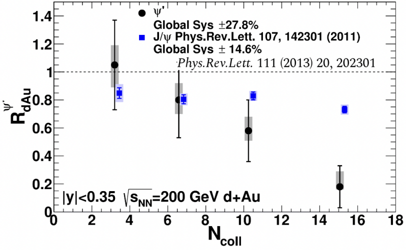
Motivation for Current Work











Recent PHENIX Heavy Ion Talks

QM 2022, WWND 2023, DIS 2023, and HP 2023 (all talks hyperlinked)

Charm and bottom quark energy loss and flow measurements in Au+Au collisions by PHENIX

J/ψ forward rapidity azimuthal anisotropy in Au+Au collisions at 200 GeV measured by PHENIX

Nuclear modification of hard scattering processes in small systems at PHENIX

J/ψ and ψ(2S) production in small systems with PHENIX

Low p_T direct photon production at RHIC measured with PHENIX

Exploring jet modification via γ-hadron and π^0-hadron correlations in Au+Au collisions at PHENIX

Study of multiplicity-dependent charmonia production in p+p collisions at PHENIX

Systematic study of the energy loss in QGP at RHIC-PHENIX

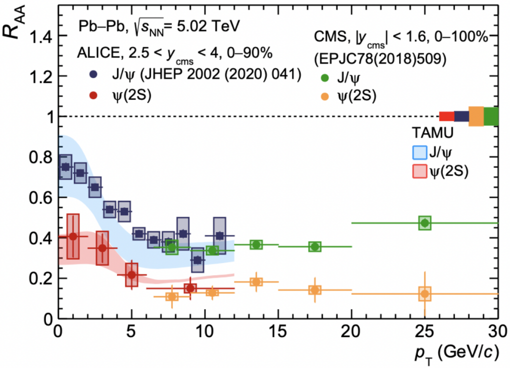
Transverse single spin asymmetries of charged hadrons from p+p, p+Al, and p+Au collisions in PHENIX

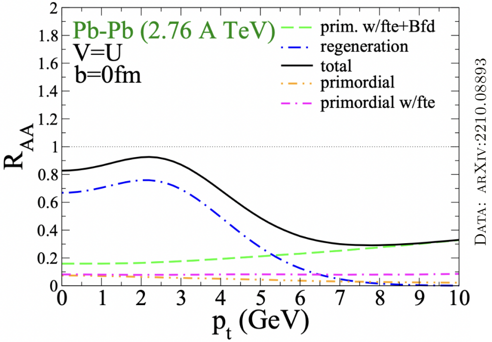
Recent longitudinal spin asymmetry and cross section results at PHENIX

Transverse single-spin asymmetry of midrapidity π^0 and η mesons in p+Al and p+Au collisions at PHENIX

PHENIX measurements of azimuthal anisotropy of heavy flavor hadrons and J/ψ in Au+Au collisions

Charmonia in PbPb Collisions





- J/ψ and $\psi(2S)$ R_{AA} strongly suppressed at high p_T - consistent with CMS results
- Transport Model predictions expect sizeable regeneration at LHC energies
  - $q\bar{q}$ pairs close in phase space can recombine to form a quarkonium state

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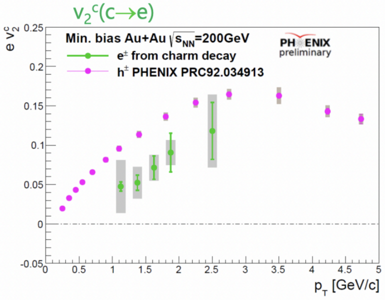
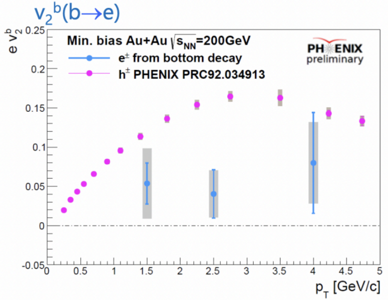
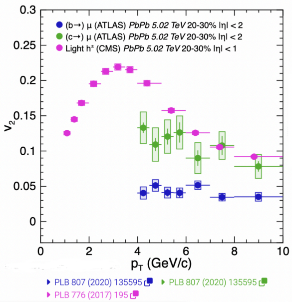
Los Alamos National Laboratory

Charm & Bottom v_2 in A+A Collisions

PHENIX







- PHENIX v_2 at central rapidity show mass ordering consistent with R_{AA} results
- Elliptic flow results for charm and bottom differ at RHIC and LHC energies
- PHENIX is currently working to extend these measurements to forward rapidity
  - Necessary for a more complete understanding of heavy flavor interactions with QGP

Charged Particle Multiplicity

PRL 110, 032301 (2013)

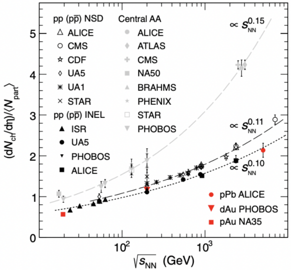


FIG. 2 (color online). Charged-particle pseudorapidity density at midrapidity normalized to the number of participants, calculated with the Glauber model, for $p + $Pb, $p + $Au, and $d + $Au [8,9] collisions as a function of $\sqrt{s_{NN}}$, compared to NSD [10–16] and inelastic [12,17–19] pp ($p\bar{p}$) collisions as well as central heavy-ion [19–30] collisions. The curves $\propto s_{NN}^{0.11}$ and $s_{NN}^{0.15}$ (from Ref. [28]) are superimposed on the NSD pp ($p\bar{p}$) and central heavy-ion data, respectively, while $\propto s_{NN}^{0.10}$ (from Ref. [18]) is superimposed on the inelastic pp ($p\bar{p}$) data.

PRL 121, 222301 (2018)

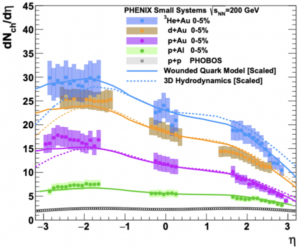


FIG. 1. Charged hadron $dN_{ch}/d\eta$ as a function of pseudorapidity in high-multiplicity 0%–5% central ^{3}He+Au, d+Au, p+Au, and p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV. Also shown are results in inelastic p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV as measured by the PHOBOS Collaboration [27]. Predictions from the wounded-quark [3] and hydrodynamical [4] models are shown. The calculations have an overall normalization factor (S) to best match the data. These factors are S=0.88, 0.93, 0.85, 0.77 for the wound quark model for p+Al, p+Au, d+Au, ^{3}He+Au respectively, and S=0.81, 0.96, 0.75 for the hydrodynamical model for p+Au, d+Au, ^{3}He+Au respectively.

Radial and Elliptic Flow at RHIC: Further Predictions

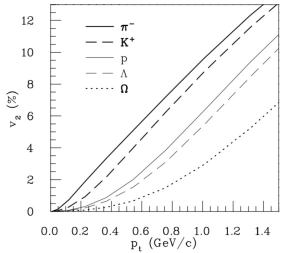
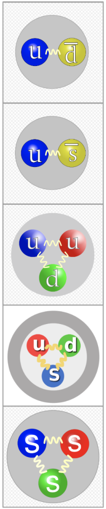


FIG. 3. p_t-differential elliptic flow at midrapidity for various hadrons from minimum bias Au+Au collisions at $\sqrt{s} = 130\,A\,$GeV for EOS Q(120).

3. Analytical results.– In the remainder we try to understand the hydrodynamic behaviour of $v_2(p_t)$ and its dependence on the hadron mass and freeze-out temperature, using a simple analytical model. Before going into the technical details we give a simple intuitive argument why, at small p_t, the elliptic flow of heavier particles is smaller than for lighter ones. It is well-known that radial flow shifts the p_t-distributions to larger values of p_t, and that for nonrelativistic $p_t < m$ this effect increases with the particle mass m and the radial flow velocity $\langle v_\perp \rangle$. In the extreme case of a thin shell expanding at high velocity, the spectrum actually develops a relative minimum at $p_t = 0$ and a peak at nonzero p_t ("blast wave peak" [19]), and with increasing mass and $\langle v_\perp \rangle$ the peak shifts to larger p_t. Relative to the case without radial flow, the spectrum is thus depleted at small p_t, and the depletion as well as the p_t range over which it occurs increase with m and $\langle v_\perp \rangle$.

Figure 3 shows the differential momentum anisotropy $v_2(p_t)$ for different hadron species for EOS Q and $T_f \approx 120\,$MeV. At a given value of p_t, the elliptic flow is seen to decrease with increasing particle mass. This is a consequence of rest-mass-dependent radial flow effects on the shape of the single-particle p_t-spectrum, as will be analytically discussed in the following section.

Phys.Lett.B 503 (2001)



π^- ~ 140 MeV

K^+ ~ 495 MeV

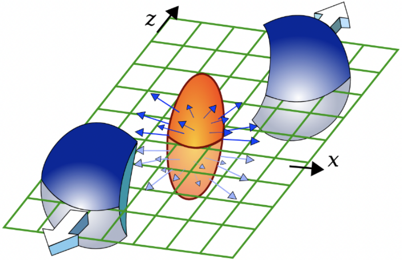
p ~ 940 MeV

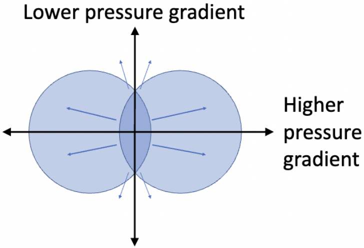
Λ ~ 1115 MeV

Ω ~ 1675 MeV

PHENIX

Azimuthal anisotropy measurements



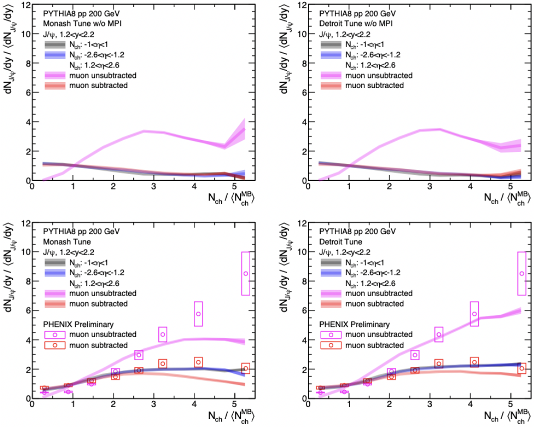


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

- Hydrodynamics translates initial shape (including fluctuations) into final state distribution

Credit: Ron Belmont, Initial Stages 2021

3. PHENIX Results - Comparison with PYTHIA8



Turn off the MPI effect

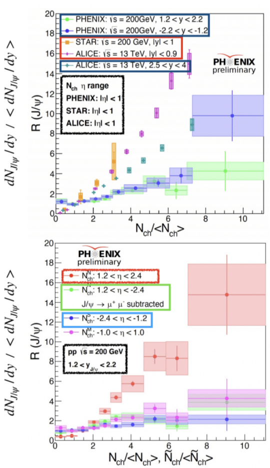
- Multiplicity at different acceptances and the same acceptance with subtraction (red): show a decreasing trend
- PYTHIA with MPI can better describe the data
  MPI effect is important at 200 GeV

- Monash Tune for the LHC energies
  Detroit Tune for the RHIC energies
  (*Phys.Rev.D 105 (2022) 1, 016011)
- J/ψ at forward rapidity (1.2<y<2.2)
  Multiplicity at different (other) acceptance: similar multiplicity dependence between two tunes

  Multiplicity at same acceptance: slightly stronger dependence in Detroit Tune at high multiplicity
- Detroit Tune shows a better agreement with the PHENIX results

11

Credit: Jongho Oh, ICNFP 2023



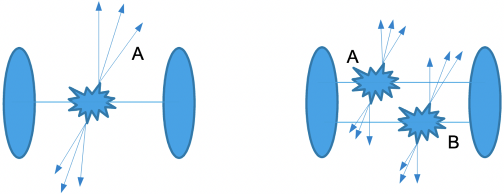
- J/ψ at mid-rapidity:
  Similar dependence between STAR* (200 GeV) and ALICE (13 TeV)
  *Tracks from J/ψ are **included** in multiplicity calculation
- J/ψ at forward rapidity:
  Stronger dependence in ALICE (13 TeV) than PHENIX** (200 GeV)
  Tracks from J/ψ are **excluded in multiplicity calculation

→**Different trends at different rapidity**
rapidity-dependent MPI?
or contribution from J/ψ to multiplicity calculation?

- Measuring J/ψ and multiplicity in the same direction:
  When including tracks from J/ψ,
  the multiplicity dependence becomes stronger
  and comparable with the ALICE results
- Measuring multiplicity in different directions:
  Similar multiplicity dependence

Credit: JongHo Oh, 2022 RHIC/AGS Annual User's Meeting

Multiparton Interactions (MPI)



- Hadronic collider at higher energy enables the phase space for MPI
  - Allow several semi-hard scatterings near the charmonium mass
- Traditional single hard scattering picture is insufficient
  - Typically 4 – 10 scatterings at LHC pp collisions
- MPI: influence charmonium production at high energy hadronic colliders
- Enhance of J/ψ production along with color reconnection model

Credit: Zhaozhong Shi, 2023 Initial Stages

Multiparton Interactions (MPI)

Hard Partonic Scattering: Energetic partons scatter off each other with large momentum transfers. In the traditional pQCD picture, it is simply described as a single hard scattering between two partons in each collision. They can be calculated analytically by pQCD with Feynman diagrams to a very high precision [20]. At RHIC, the $c\bar{c}$ pair production is dominated by gluon–gluon fusion: $gg \to c\bar{c}$.

Multiple Parton Interaction (MPI): MPI is an elaborate paradigm to describe the partonic interaction stage at high-energy colliders at RHIC, Tevatron, and the LHC [21]. According to MPI, one hard scattering, accompanied by several semi-hard interactions, takes place in each collision. All of them need to be included in the partonic scattering amplitudes. At present, high-energy hadronic colliders create more phase space for MPI to occur. Many studies at the LHC suggest MPI should be included to better describe the data [22].

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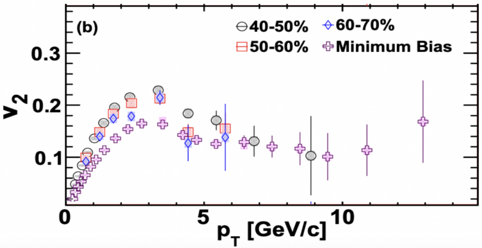
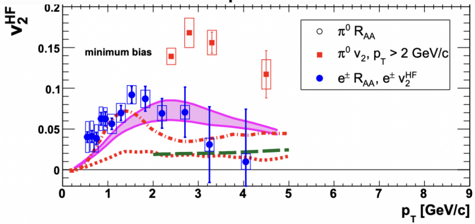
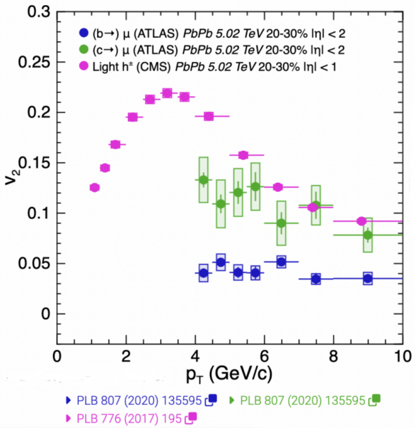
The evidence for MPI comes from high p_T events observed in hadron collisions at the ISR at CERN [1] and later at the Fermilab Tevatron collider[2,3,4]. At lower p_T, underlying event (UE) observables have been measured in $p\bar{p}$ collisions in dijet and Drell-Yan events at CDF in Run I [5] and Run II [6] at center-of-mass energies of $\sqrt{s} = 1.8$ TeV and 1.96 TeV respectively, and in pp collisions at $\sqrt{s} = 900$ GeV in a detector-specific study by CMS [7].

At small transverse momentum MPI have been shown to be necessary for the successful description of the UE in Monte Carlo generators such as Pythia [8,9,10] or Herwig [11,12]. Additionally, MPI are currently invoked to account for observations at hadron colliders that would not be explained otherwise: the cross sections of multi-jet production, the survival probability of large rapidity gaps in hard diffraction, etc. [13]. The wide range of phenomena in which MPI are involved highlights the urgency of a more thorough understanding of these reactions both experimentally and from a theoretical point of view.

arXiv:1111.0469v2







Top left: PHENIX, Phys.Rev.C 92 (2015) 3, 034913. Bottom left: PHENIX, Phys.Rev.Lett. 98 (2007) 172301. Right: ATLAS and CMS.