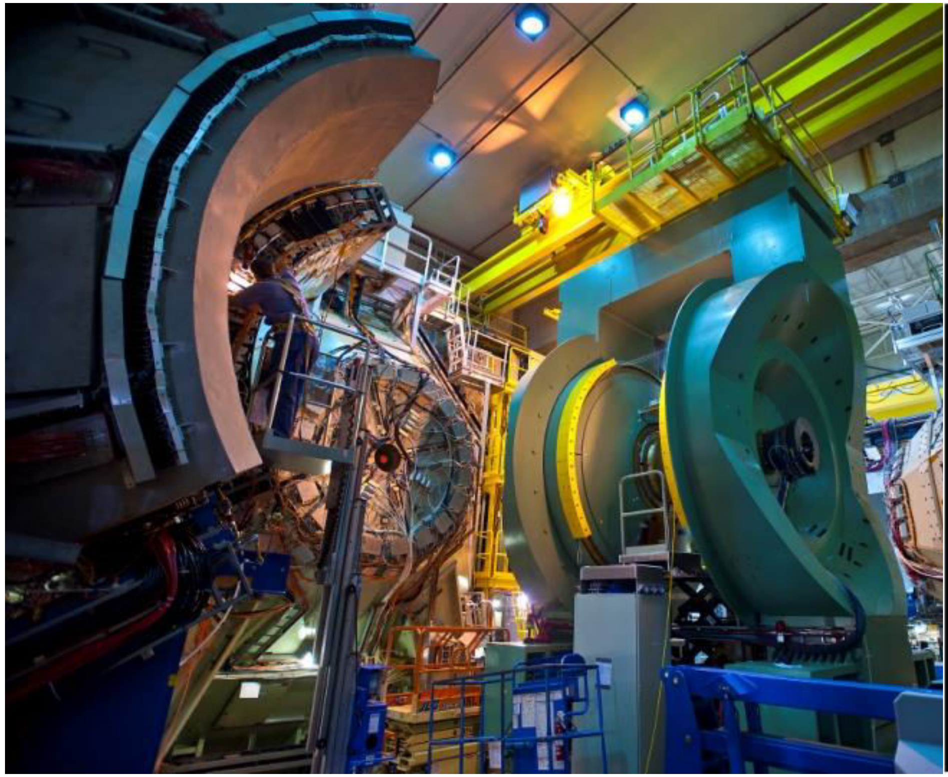
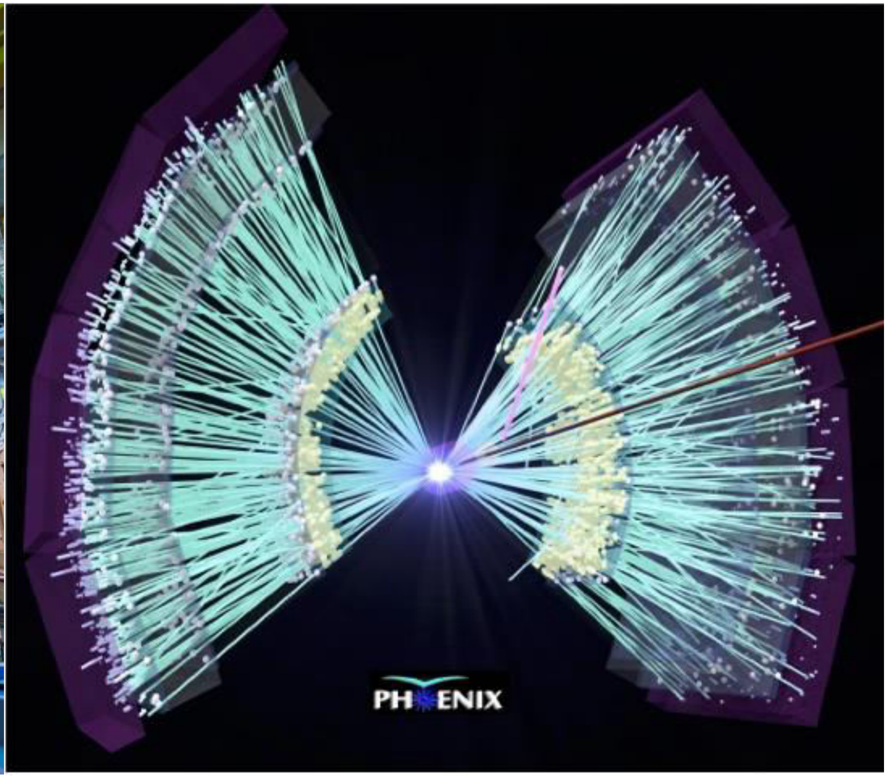
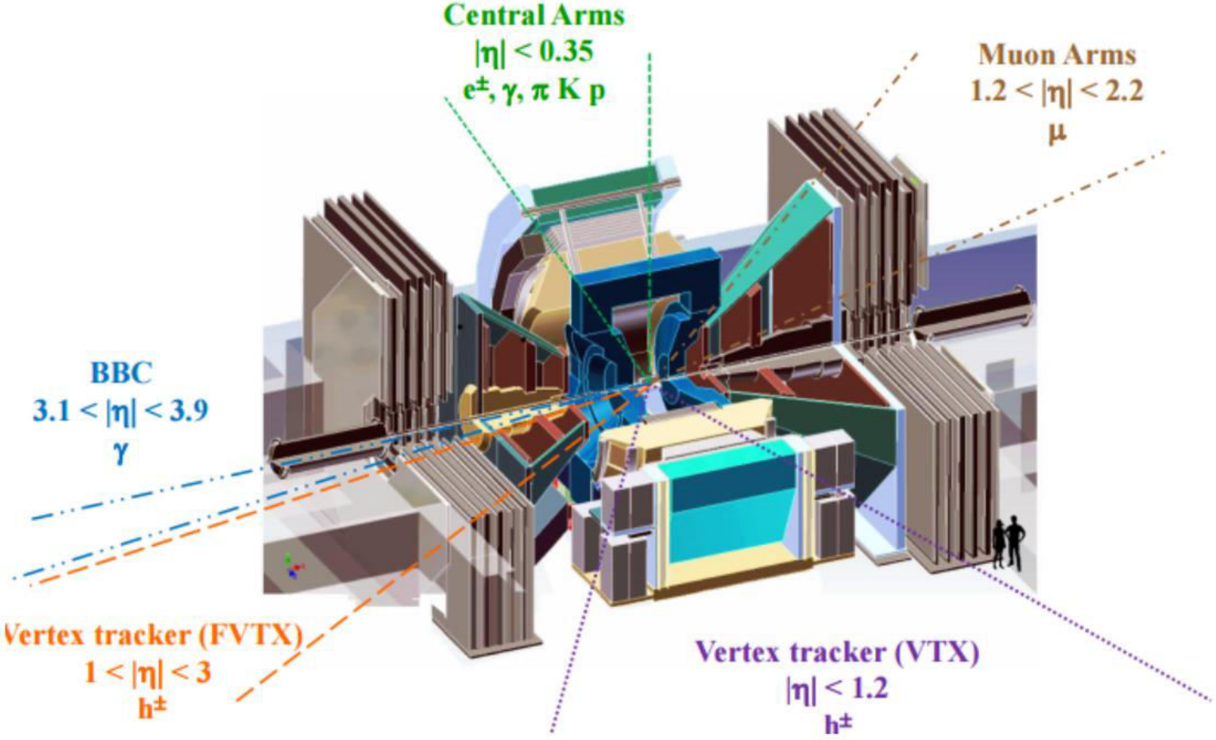
Recent results from PHENIX at RHIC

V. Riabov for the PHENIX Collaboration





PHENIX at RHIC



√s [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

- Detectors:
  - ✓ Central spectrometers (|η| < 0.35, 2x90^0): DC, PC, TOF, RICH, EMC, VTX
  - ✓ Muon spectrometers (1.2 < |η| < 2.2, 360^0): MuTr, MuID, RPC
  - ✓ Forward detectors (1 < |η| < 4, 360^0): FVTX, BBC, ZDC → triggering, event plane
- PHENIX finished data taking in 2016 (Run-16)
- Data samples (p+p, p+A and A+A) taken at different collision energies in the last years of the detector operation are actively analyzed and bring a wealth of new experimental results

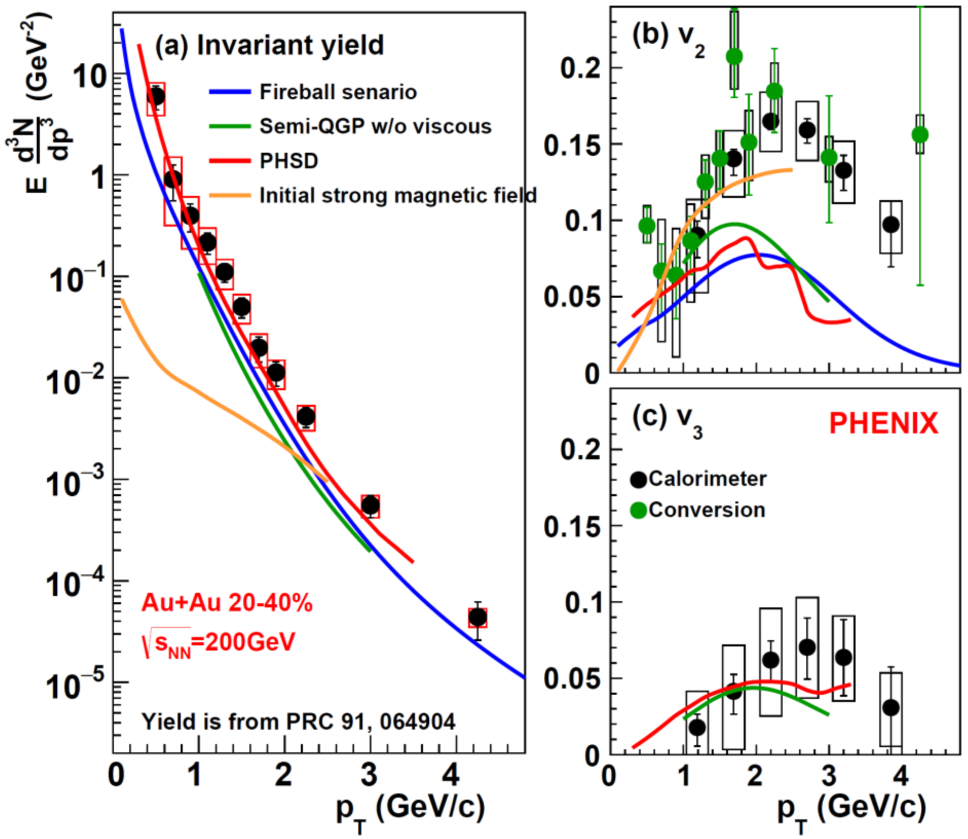
Outline

- Low-p_T direct photon production in small and large systems:
  - photon enhancement in pAu@200
  - new measurements of photons in CuCu@200, AuAu@39, and AuAu@62
  - scaling of photon production in A+A collisions at RHIC-LHC energies
- Flow in small systems:
  - correlations between initial geometry and momentum anisotropy in p/d/3He+Au
  - energy dependence of flow in d+Au
- Heavy flavor production:
  - J/ψ production in small and large systems
  - measurement of separated charm and bottom

Direct photon production

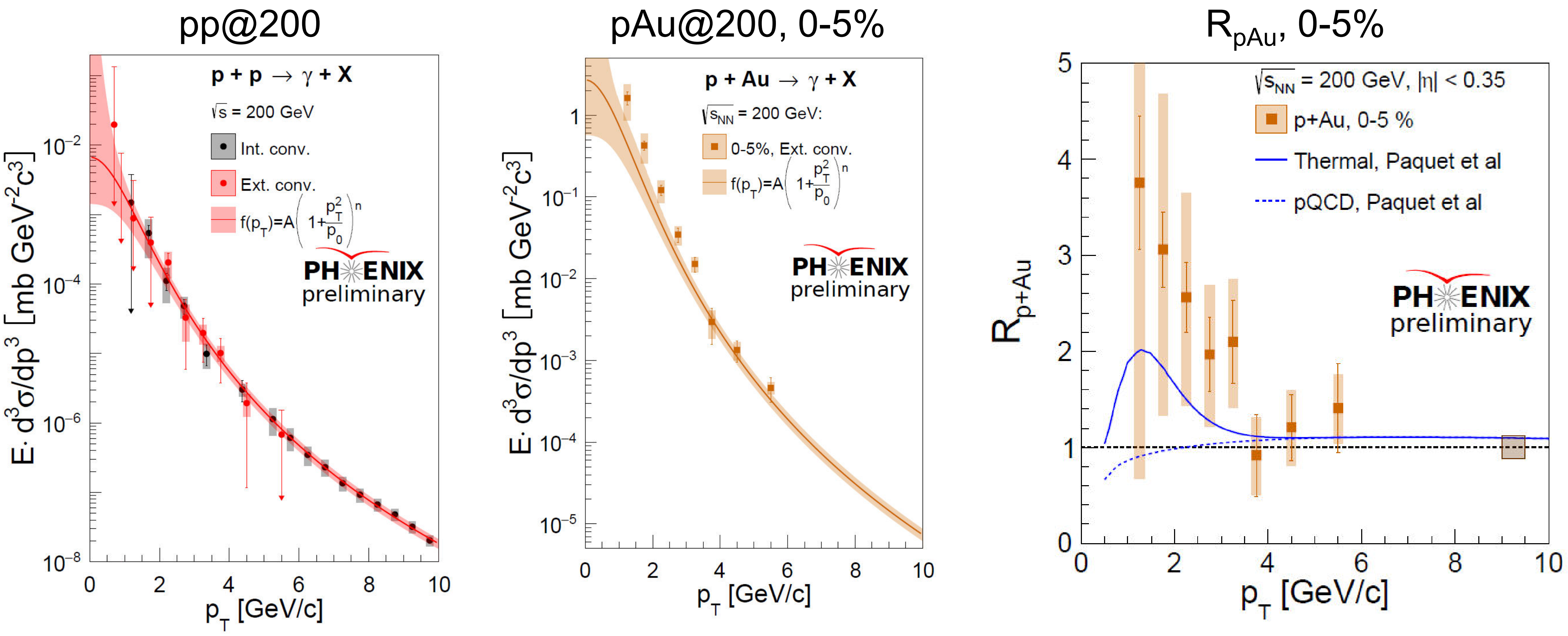
Direct photon puzzle

Phys.Rev. C94 (2016) no.6, 064901



- Simultaneous description of the large photon yields and flow is a challenge for theoretical models
- Similar situation at the LHC
- Systematic studies vs. collision system and energy are required

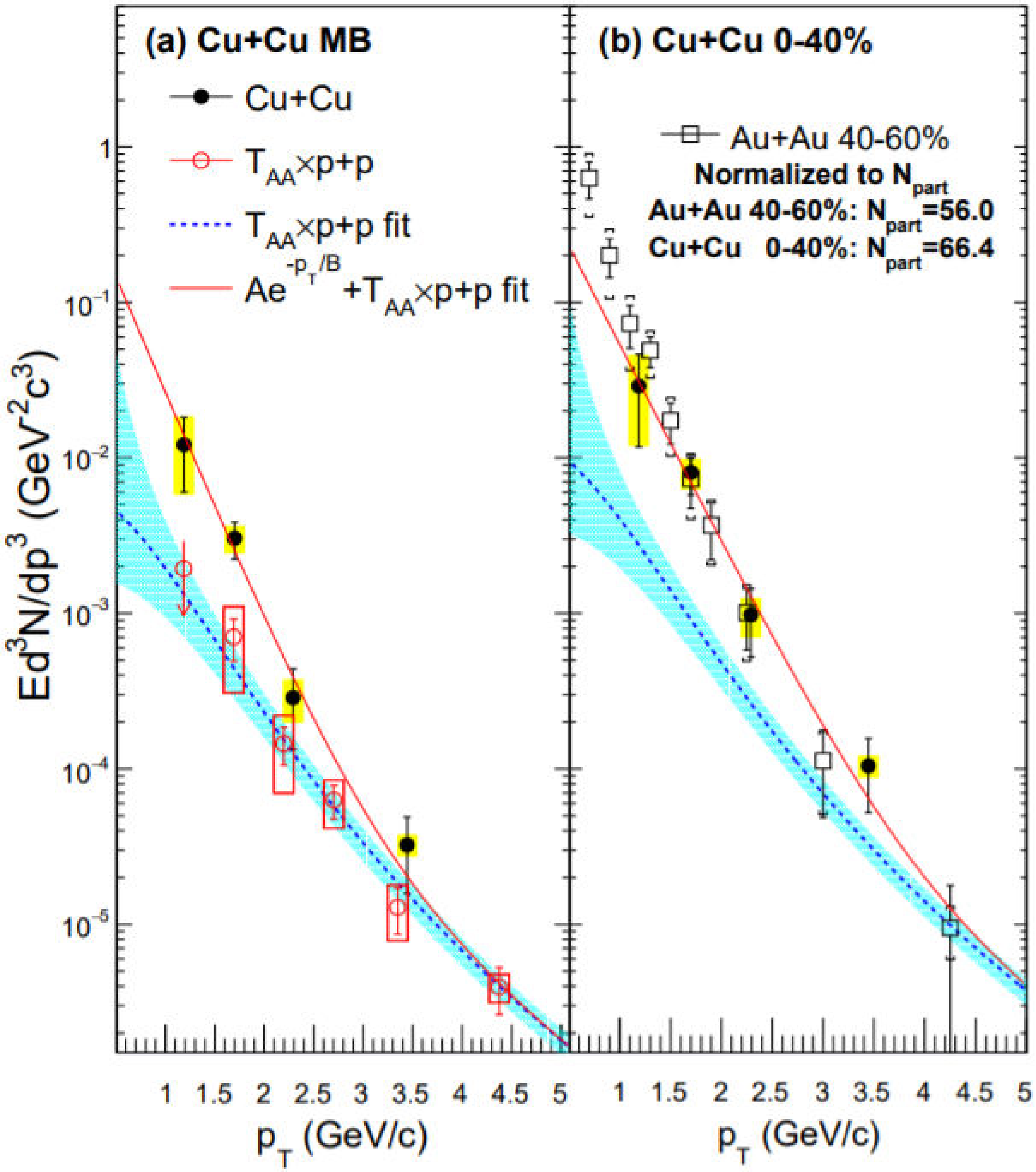
New results, pp@200 & pAu@200



- New pp@200 reference & fit
- Clear enhancement of the photon yield in central pAu@200 with respect to N_{coll}-scaled pp@200
- R_{pA} > 0 at low momentum, described by models assuming formation of the QGP droplets in pAu@200

New results, CuCu@200

arXiv:1805.04066



- ❖ Improve our knowledge of the direct photon production in dependence on the system size in the region of small N_{part}
- ❖ Clear excess yield of direct photons over the binary scaled p+p in two centrality bins
- ❖ p_T spectra and dN/dy are consistent with Au+Au data at similar N_{part}
- ❖ Exponential fits:

  T = 285 ± 53(stat) ± 57(syst) MeV (MB)

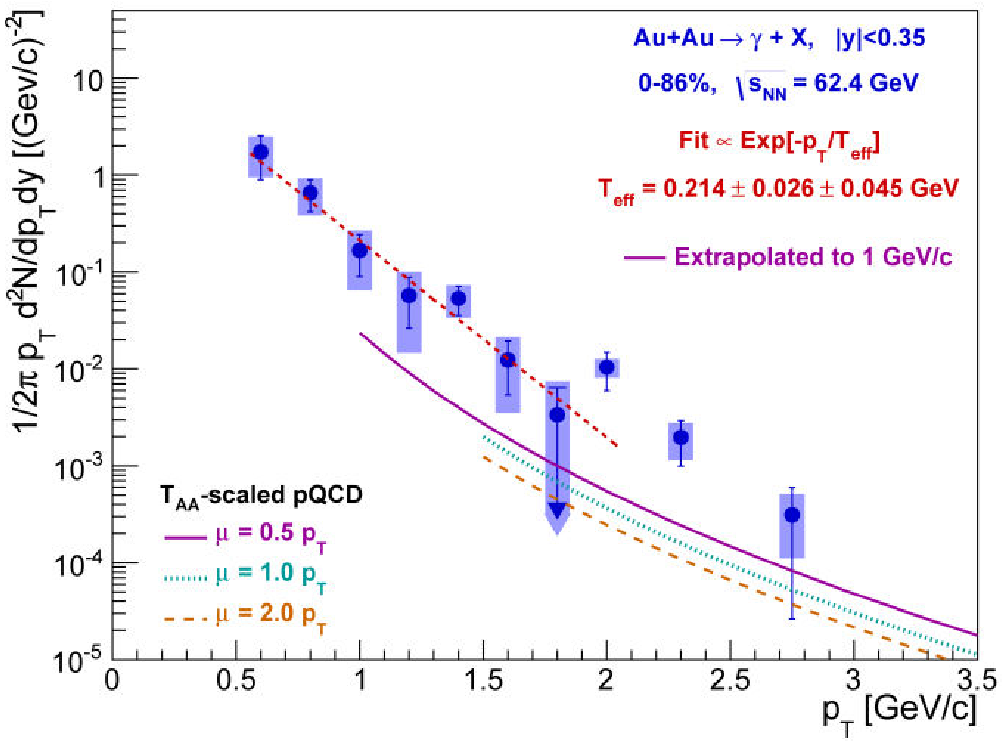
  T = 333 ± 72(stat) ± 45(syst) MeV (0-40%)

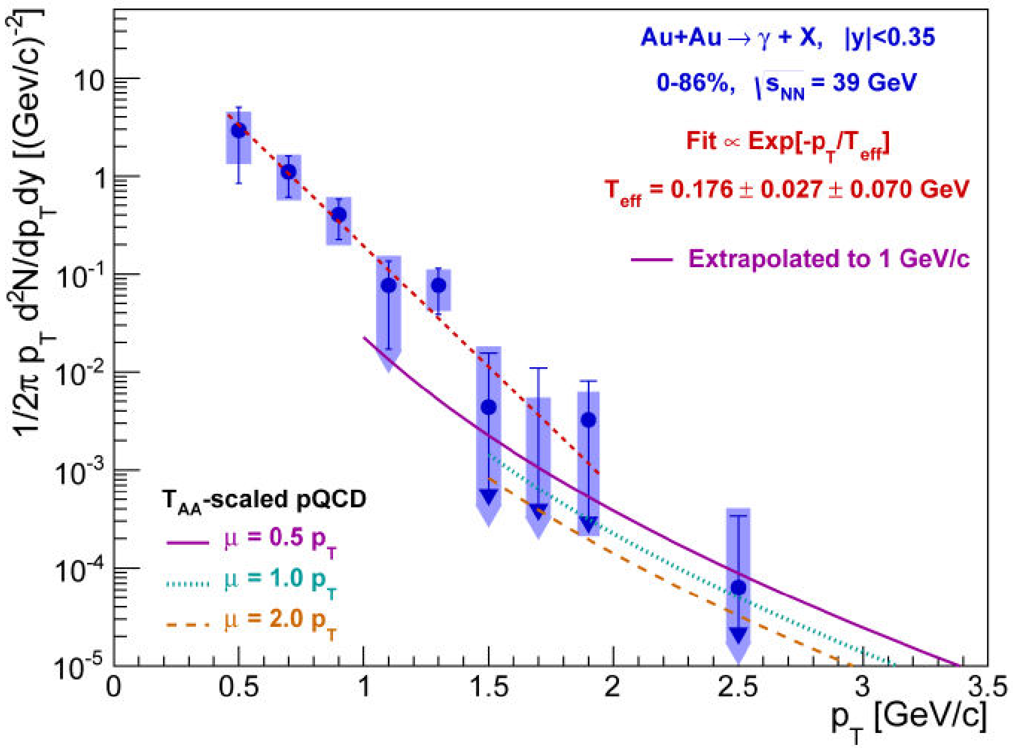
New results, AuAu@62 & AuAu@39

AuAu@62, 0-86%

AuAu@39, 0-86%

arXiv:1805.04084

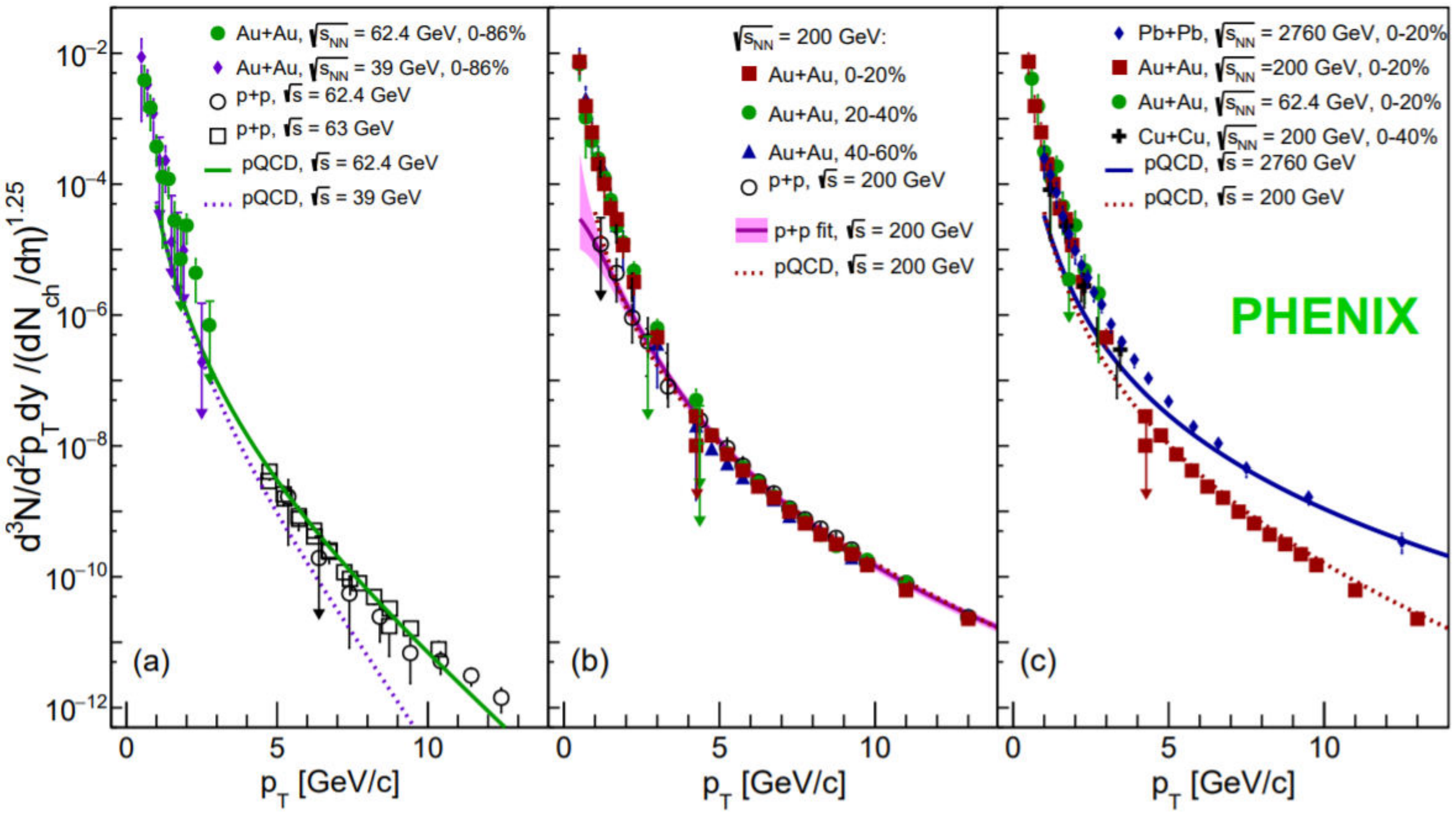




- ❖ Improve our knowledge of the direct photon production in dependence on collision energy
- ❖ Substantial direct photon yield at p_T < 3 GeV/c at both energies
- ❖ In AuAu@62 observe increase of the photon yields with centrality
- ❖ Exponential fits: T = 214±26(stat)±45(syst) MeV (62 GeV); T = 176±27(stat)±70(syst) MeV/c (39 GeV)

Spectra normalized by $(dN_{ch}/d\eta)^{1.25}$

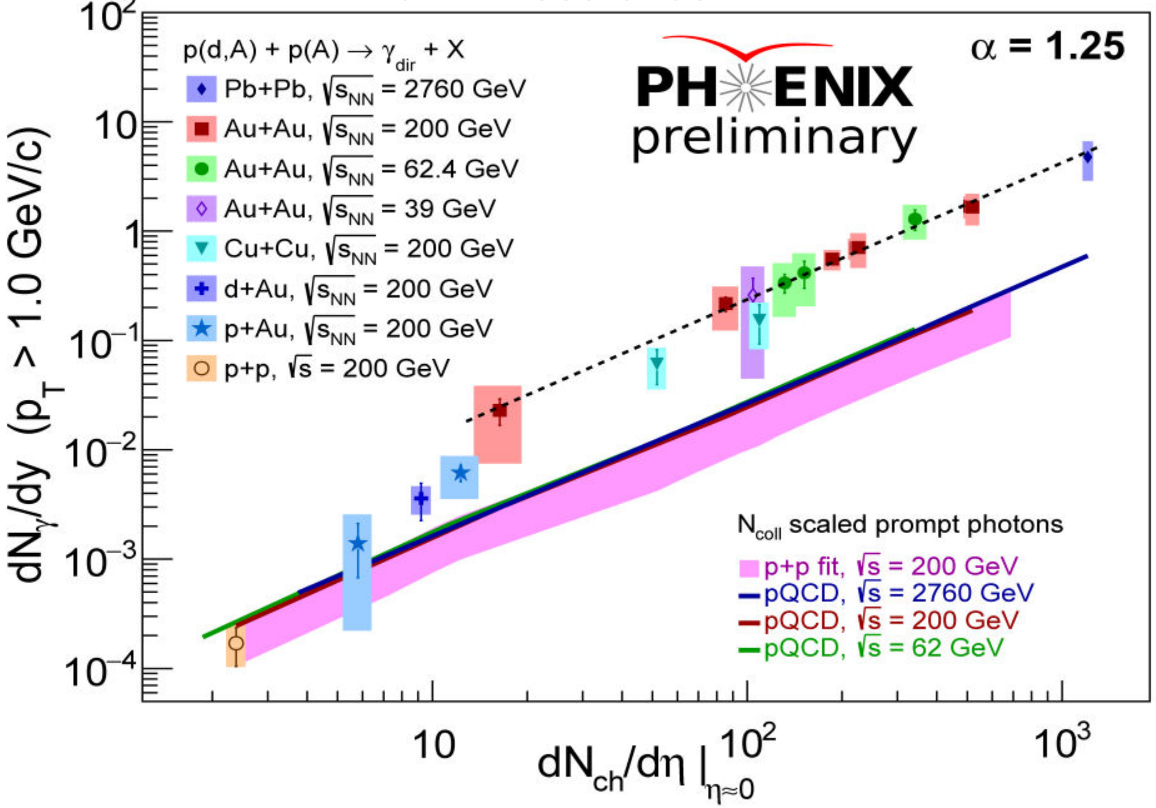
arXiv:1805.04084



❖ Spectra in A+A collisions at different energies and centralities as well as pQCD curves are normalized by $(dN_{ch}/d\eta)^{1.25}$:

- ✓ separation by energy at high momentum
- ✓ nearly perfect scaling at low momentum

Scaling of low-p_T photon yields



- Photon yields are integrated at p_T > 1 GeV/c → dominated by thermal photons
- A+A:
  - ✓ common trend for integrated yields with $dN_{ch}/d\eta$ at different centralities and energies
  - ✓ integrated photon yields grow faster than multiplicity, α = 1.25
- p+p:
  - ✓ integrated pQCD curves have similar slope
- p/d+Au:
  - ✓ another trend for small systems, suggests the possible turn on of thermal radiation

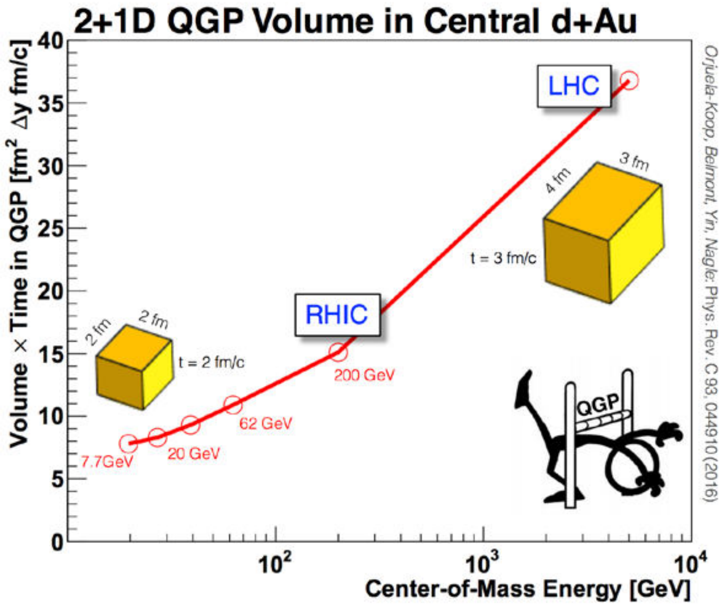
Direct photons: summary

- Observation of universal scaling for photon yields in A+A collisions at RHIC-LHC
  → large photon production near the phase transition to hadronic phase?
- Observation of low-p_T photon enhancement in central p+Au collisions
  → consistent with formation of the QGP droplets in hydro evolution

Flow in small systems

Geometry engineering and energy scan

Phys.Rev. C93 (2016) no.4, 044910



√s [GeV]	p+p	p+Al	p+Au	d+Au	³He+Au
200	✓	✓	✓	✓	✓
62.4	✓			✓	
39				✓	
20				✓	

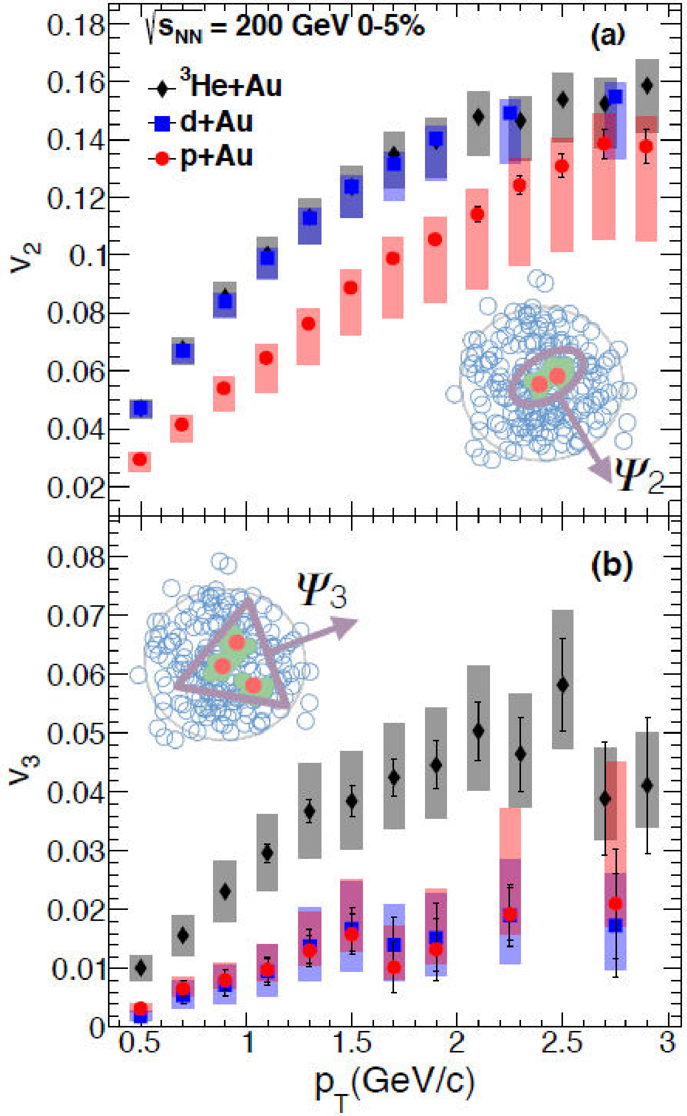
2016 Data

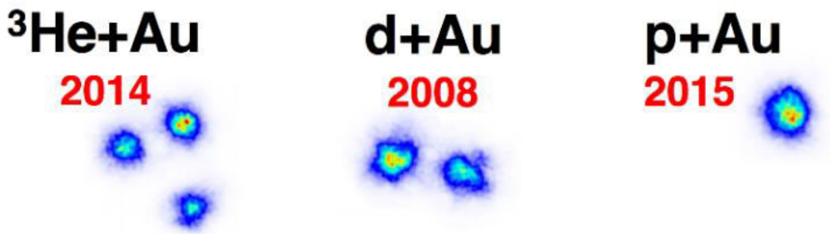
- Observation of large particle flow in A+A collisions at RHIC and LHC energies has been interpreted to indicate formation of a strongly-coupled QGP with properties of the nearly perfect fluid
- Similar flow signatures have also been observed in high-multiplicity p+p and p+A collisions, first at the LHC and later at RHIC → formation of sQGP?
- Systematic study of various observables in p+p and p+A collisions is needed to understand the system evolution
- **Geometry scan** → relation between initial geometry / system size and final state momentum anisotropies
- **Energy scan (d+Au)** → relation between initial temperature / lifetime of the medium and the collectivity

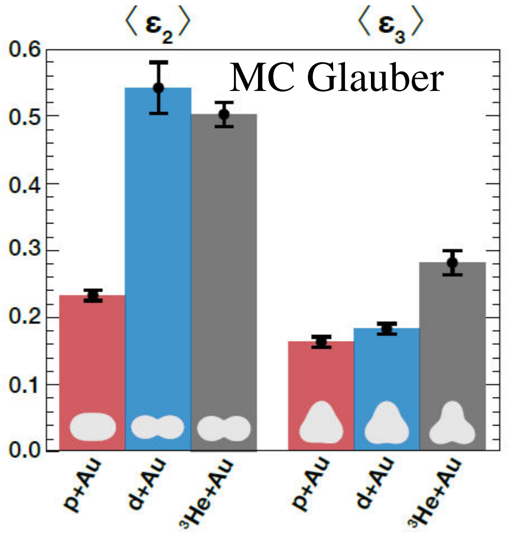
Geometry engineering – v_2, v_3 of charged hadrons

❖ Geometry engineering is a unique capability of RHIC

arXiv:1805.02973







$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

❖ v_2 (^{3}He+Au) ~ v_2 (d+Au) > v_2 (p+Au)

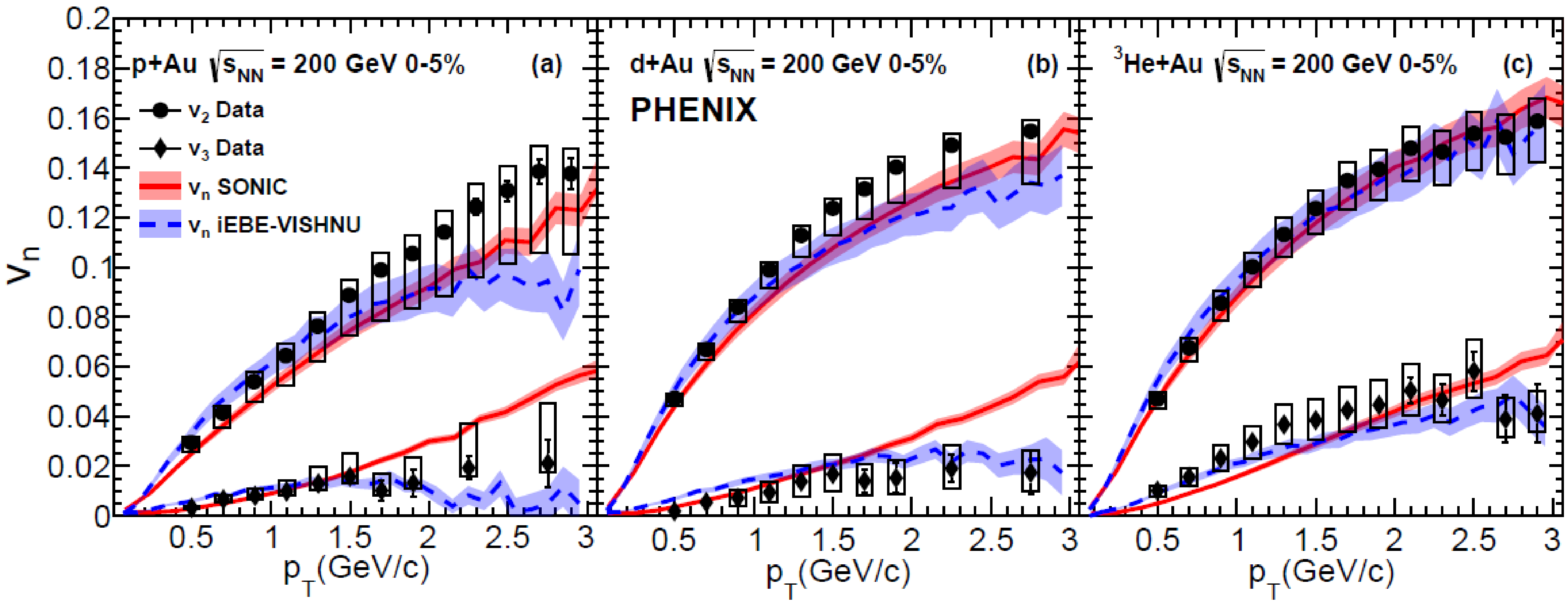
❖ v_3 (^{3}He+Au) > v_3 (d+Au)

→ initial geometry transforms in the final state momentum anisotropy

→ what is the mechanism of the transformation?

v_2, v_3 of charged hadrons – model comparison (hydro)

arXiv:1805.02973

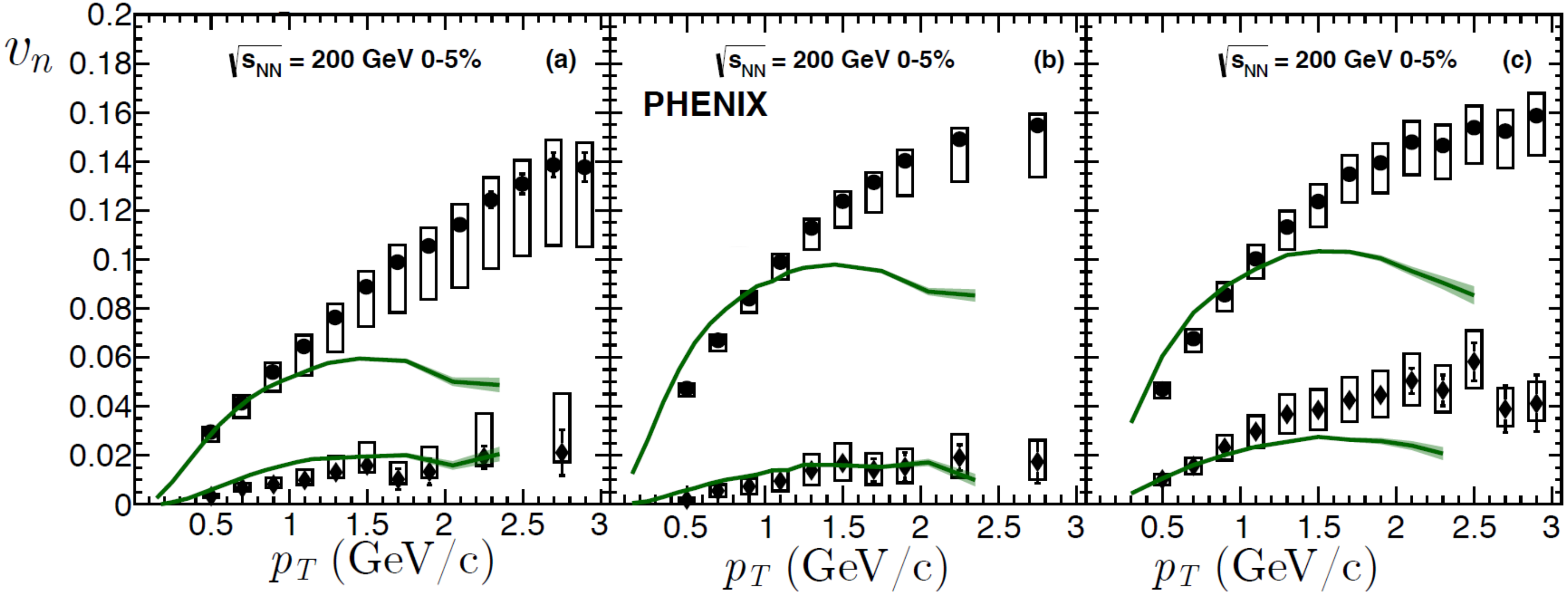


- v_2 and v_3 in three systems are simultaneously described by hydrodynamic models:
  - ✓ both models use η/s=0.08, MC Glauber initial conditions, 2+1D viscous hydrodynamic evolution
  - ✓ different hadronic rescattering packages: B3D(SONIC), UrQMD(iEBE-VISHNU)
- Same models describe the production spectra

→ strong evidence for quark-gluon plasma droplets in high-multiplicity collisions of small systems

v_2, v_3 of charged hadrons – model comparison (AMPT)

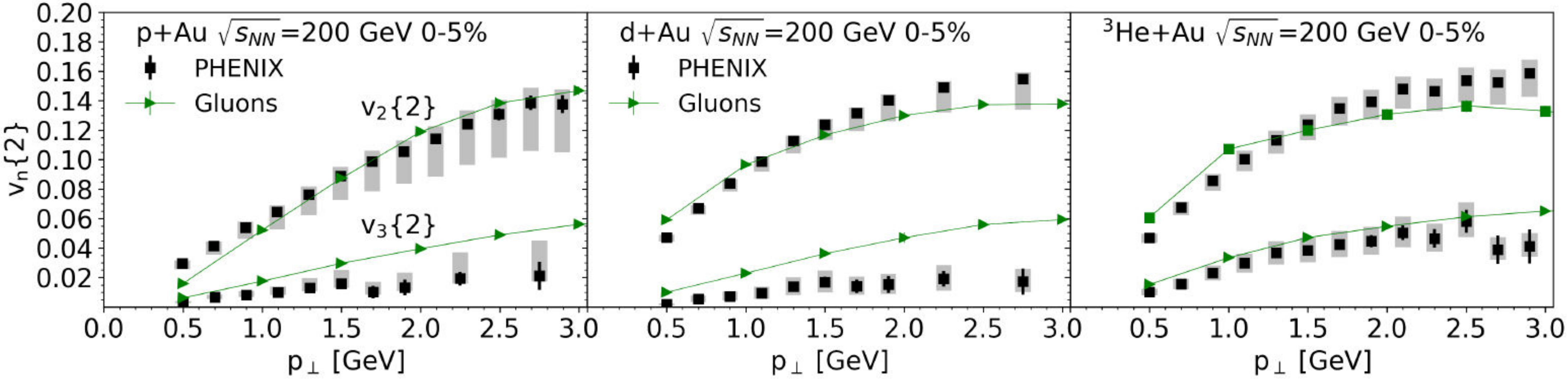
arXiv:1805.02973



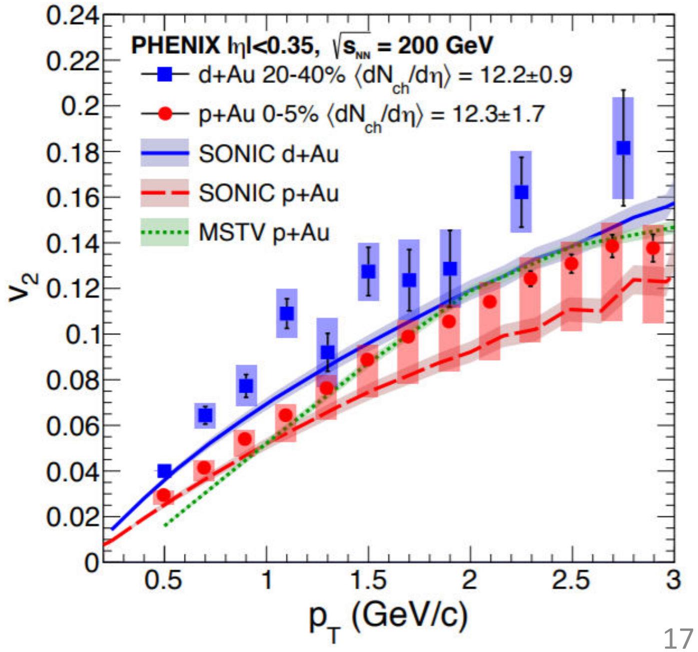
- ❖ AMPT:
  - ✓ MC Glauber initial conditions
  - ✓ Strings melt to partons
  - ✓ Partonic transport (partonic cross section σpart = 1.5 mb)
  - ✓ Haronization - parton coalescence
  - ✓ Hadronic rescattering (ART package)
- ❖ Decent consistency with v_2 and v_3 in three systems, but only at low momentum
- ❖ AMPT calculations do not describe large and small systems with a consistent set of parameters

v_2, v_3 of charged hadrons – model comparison (CGC)

arXiv:1805.09342

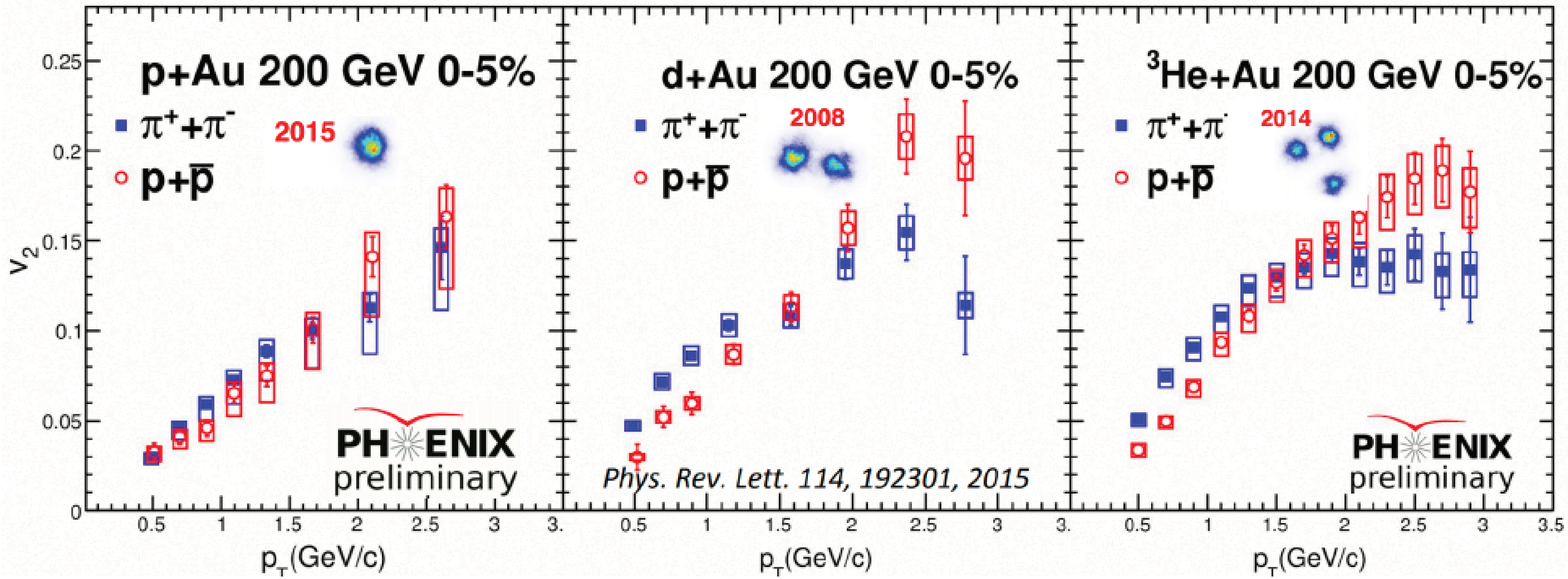


- ❖ Model explains data via initial state color correlations computed in the Color Glass Condensate effective field theory (CGC EFT)
- ❖ Provides a competitive explanation for the v_2 data
- ❖ Describes v_3 in ^{3}He+Au, but overestimates that in d+Au and p+Au
- ❖ Predicts that v_2 will be identical between systems when selecting on the same event multiplicity → not supported by data



Geometry engineering – v_2 of identified hadrons

Phys.Rev. C97 (2018) 064904



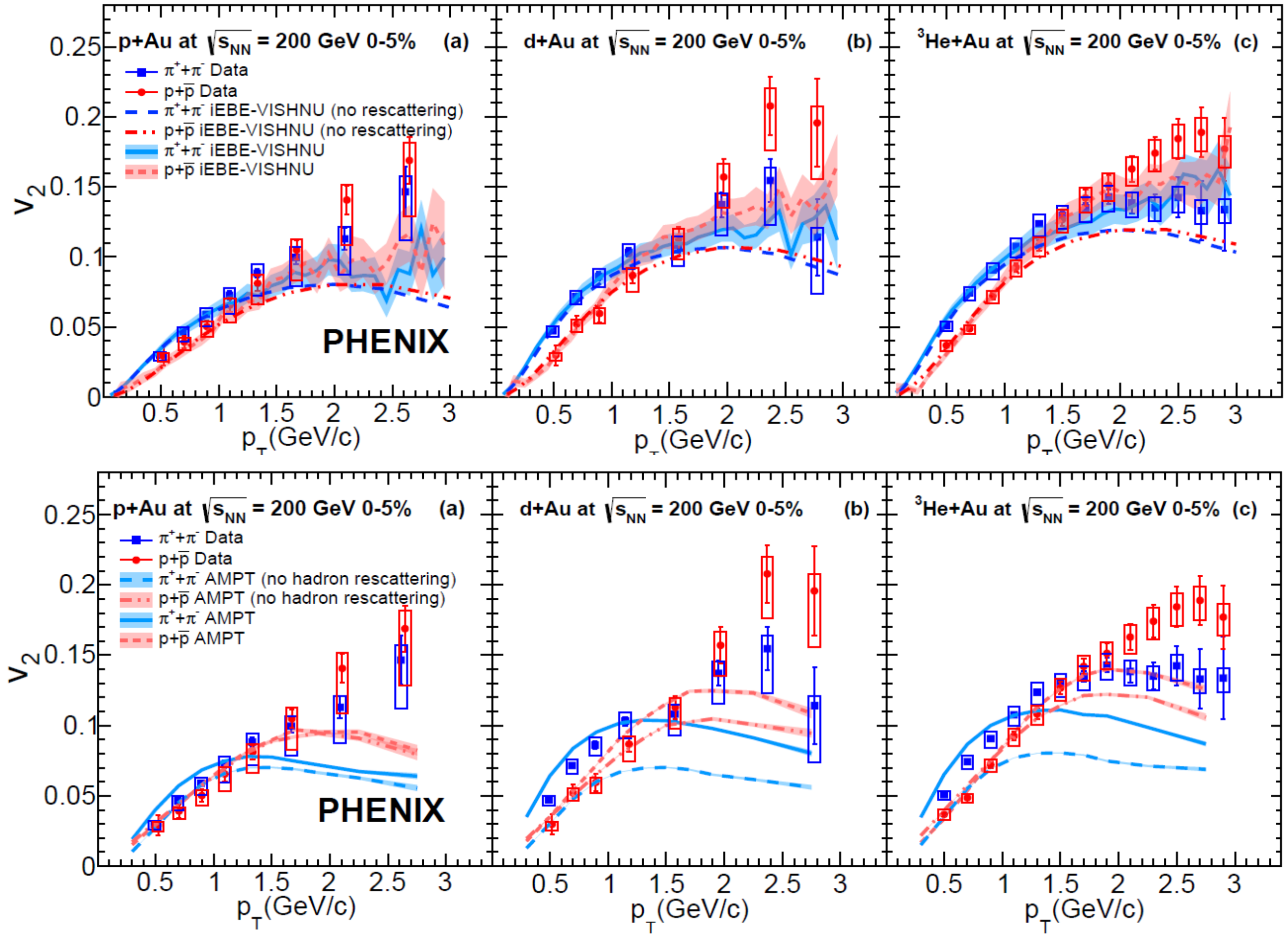
❖ Mass ordering for v_2 is observed in central p/d/^{3}He + Au collisions

p_T	< 1.5	$\simeq 1.5$	> 1.5
v_2	$\pi > p$	$\pi = p$	$\pi < p$

❖ Ordering is more prominent in d/^{3}He+Au collisions

v_2 of identified hadrons – model comparison (hydro & AMPT)

Phys.Rev. C97 (2018) 064904



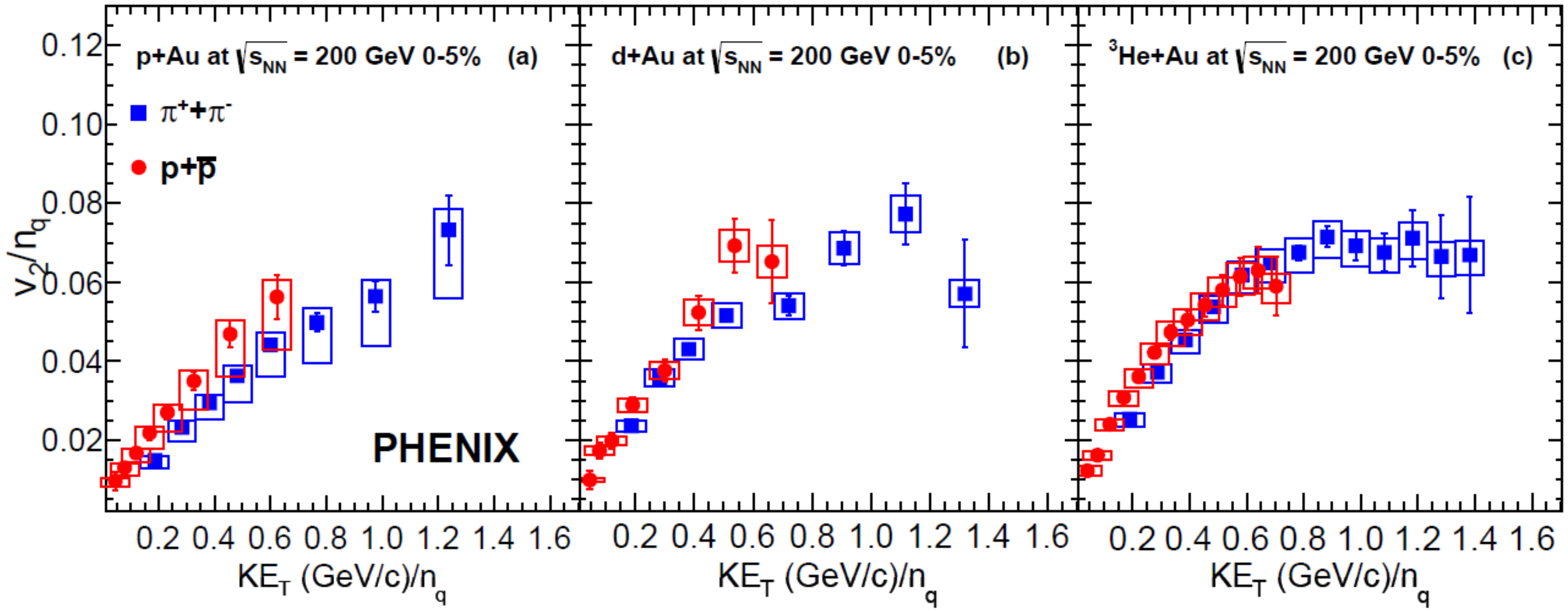
- ❖ Low p_T:
  - ✓ mass ordering is reproduced by hydro and AMPT models
  - ✓ Mass ordering is not sensitive to hadronic rescattering in hydro models and is totally driven by rescattering in AMPT
- ❖ Higher p_T:
  - ✓ AMPT does not describe data, but reproduces the mass splitting
  - ✓ Mass ordering is driven by hadronic rescattering in hydro models and by partonic coalescence in AMPT

→ mass dependence of v_2 is best described by hydrodynamic models

→ alternative explanations exist

v_2 of identified hadrons – n_q scaling

Phys.Rev. C97 (2018) 064904



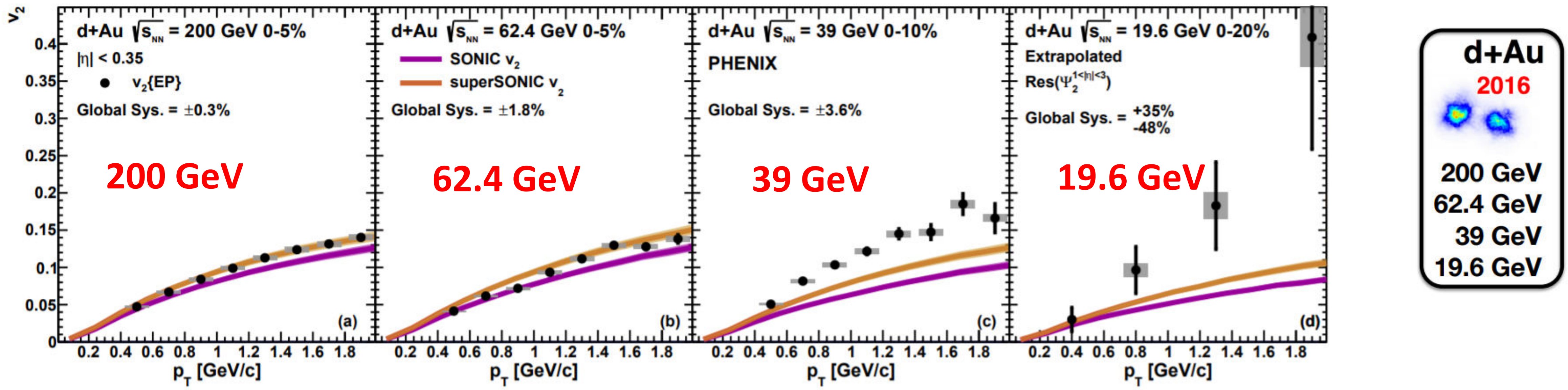
❖ Measurements for identified hadrons follow the n_q scaling within uncertainties → similar to A+A

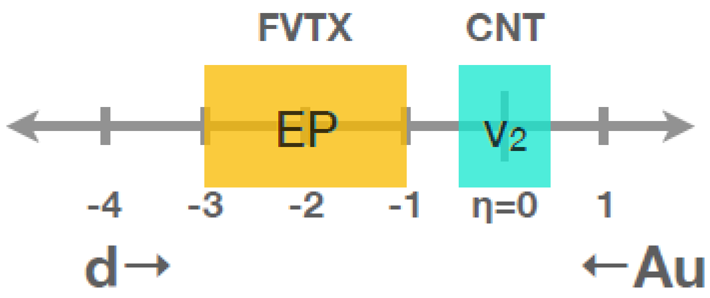
❖ Better agreement in d/^{3}He+Au collisions

→ strengthens the case for QGP droplets

Energy scan – charged hadrons

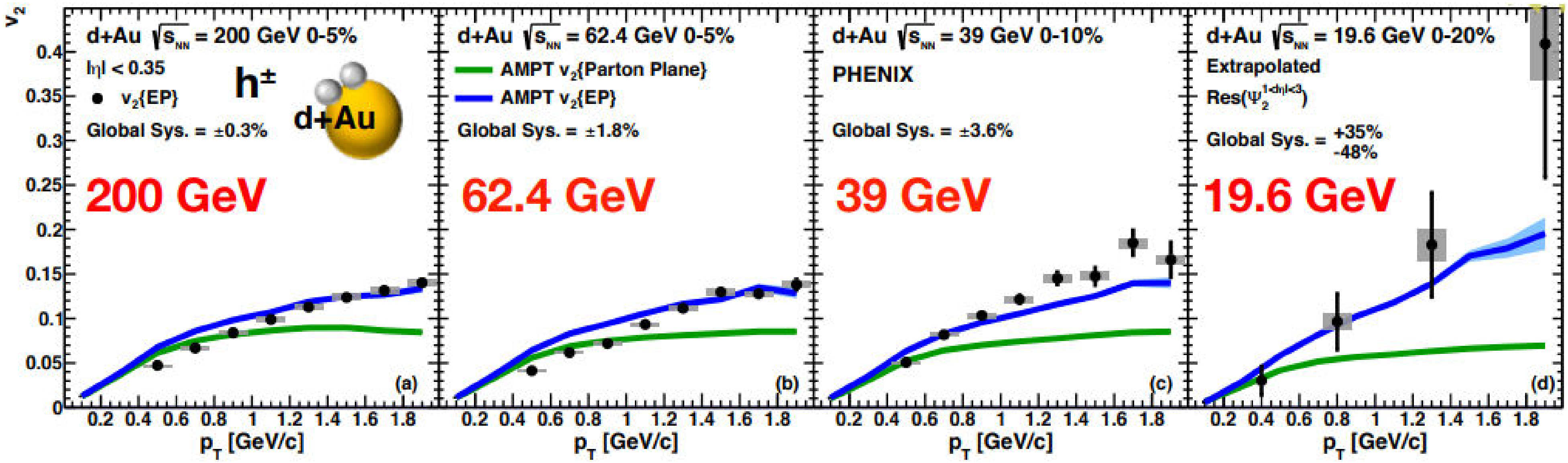
Phys.Rev. C96 (2017) no.6, 064905





- ❖ How does the flow depend on collision energy?
- ❖ Significant v_2 signal at all four energies (200, 62.4, 39, 19.6 GeV)!
- ❖ Results are not corrected for non-flow contributions (neither included in systematic uncertainties)
- ❖ Hydro reproduces data at 200 & 62.4 GeV and under predicts data at 39 & 19.6 GeV

Charged hadrons – comparison to AMPT



❖ Comparison to AMPT:

AMPT v_2 {Parton Plane}: ← Flow

AMPT v_2 {EP}: ← Flow ⊗ Non-flow

❖ Strong v_2 signal even at 19.6 GeV … interpretation is complicated by non-flow

❖ Measured signal is inconsistent with non-flow only! (according to AMPT)

Flow in small systems - summary

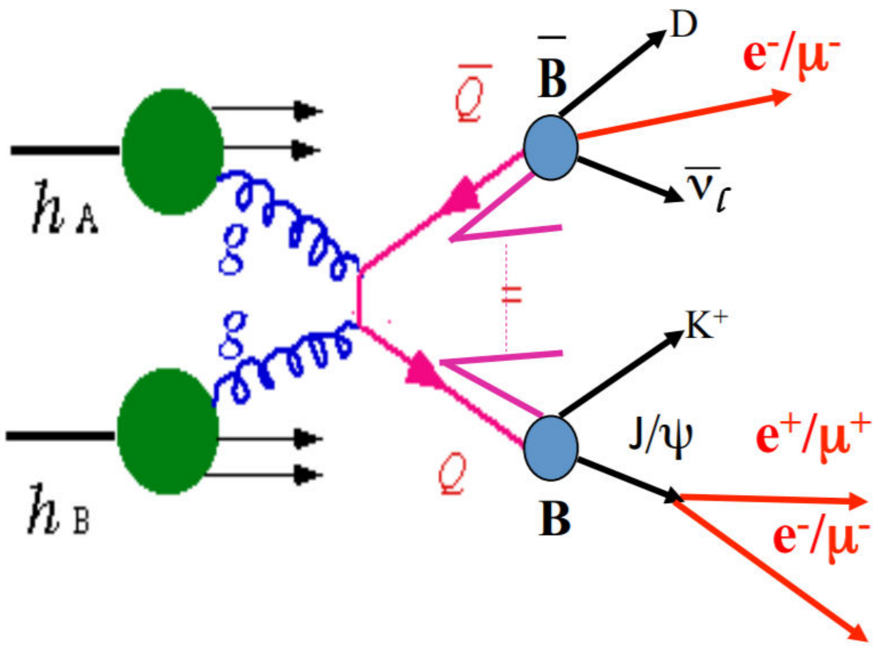
- Geometry scan:
  - ✓ initial state momentum correlations are disfavored by data (v_3)
  - ✓ final state anisotropy = initial geometry + final state Interactions
  - ✓ mechanisms of transformation is not fully constrained
  - ✓ the whole variety of results is well (and uniquely) described by hydrodynamic model calculations, which suggests formation of the QGP droplets

- Energy scan:
  - ✓ observe evidence of the collective flow even at the lowest energy of $\sqrt{s_{NN}}$ = 19 GeV
  - ✓ interpretation of results, especially at lower energies and higher momenta, is complicated by significant non-flow contributions

Heavy flavor production

Probing nuclear matter with heavy flavor

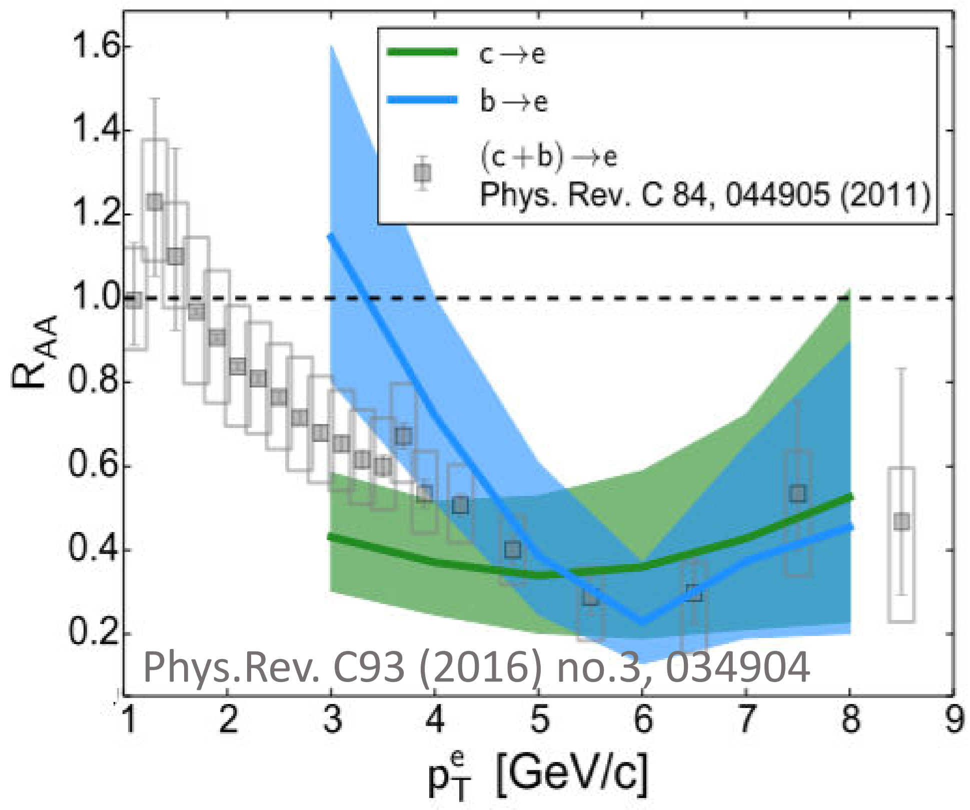
- Produced at early stage of the collision (m_c ~ 1.3 GeV, m_b ~ 4.5 GeV)
- Can be described by pQCD calculations
- Experimental observables:
  - ✓ leptons and di-leptons from semileptonic decays of heavy flavor hadrons
  - ✓ bound states of heavy flavor quarks (J/ψ, ϒ etc.)



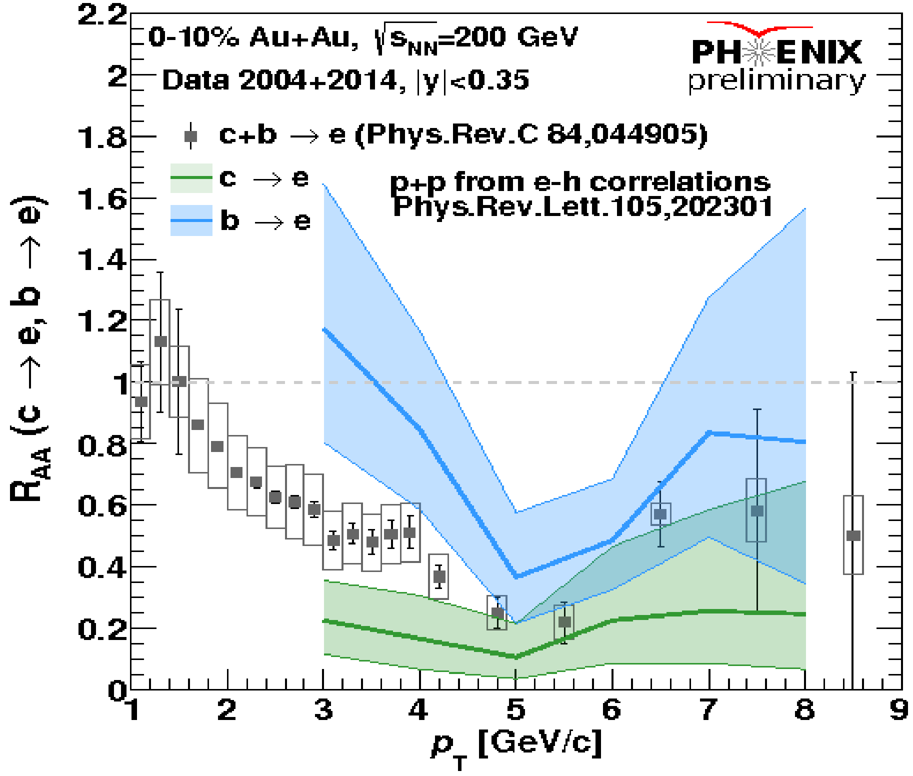
- pp:
  - ✓ no nuclear matter
  - ✓ test pQCD model calculations
  - ✓ baseline reference for heavier collision systems
- p+A:
  - ✓ understanding initial (nPDF, Cronin, CGC, parton energy loss) and final state effects (breakup, co-movers)
- A+A:
  - ✓ hot (parton energy loss in plasma, flow) & cold nuclear matter effects

Nuclear modification, R_{AA}(c→e) & R_{AA} (b→e) in AuAu@200

AuAu@200, MinBias

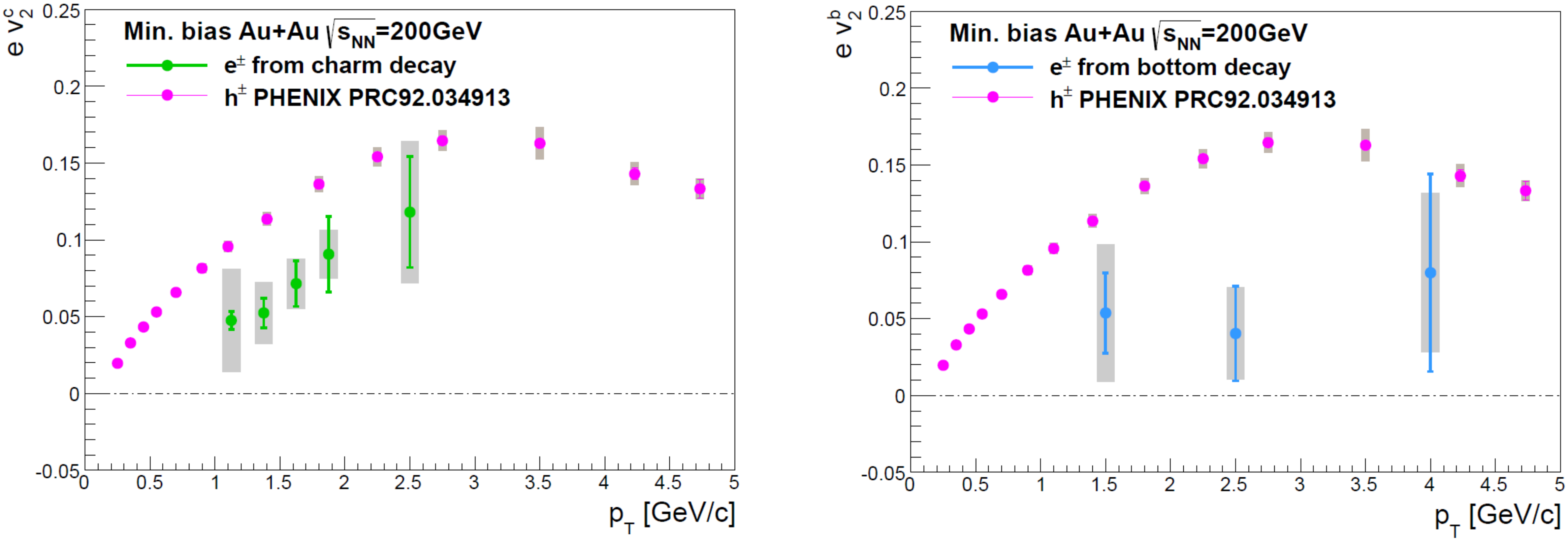


AuAu@200, 0-10%



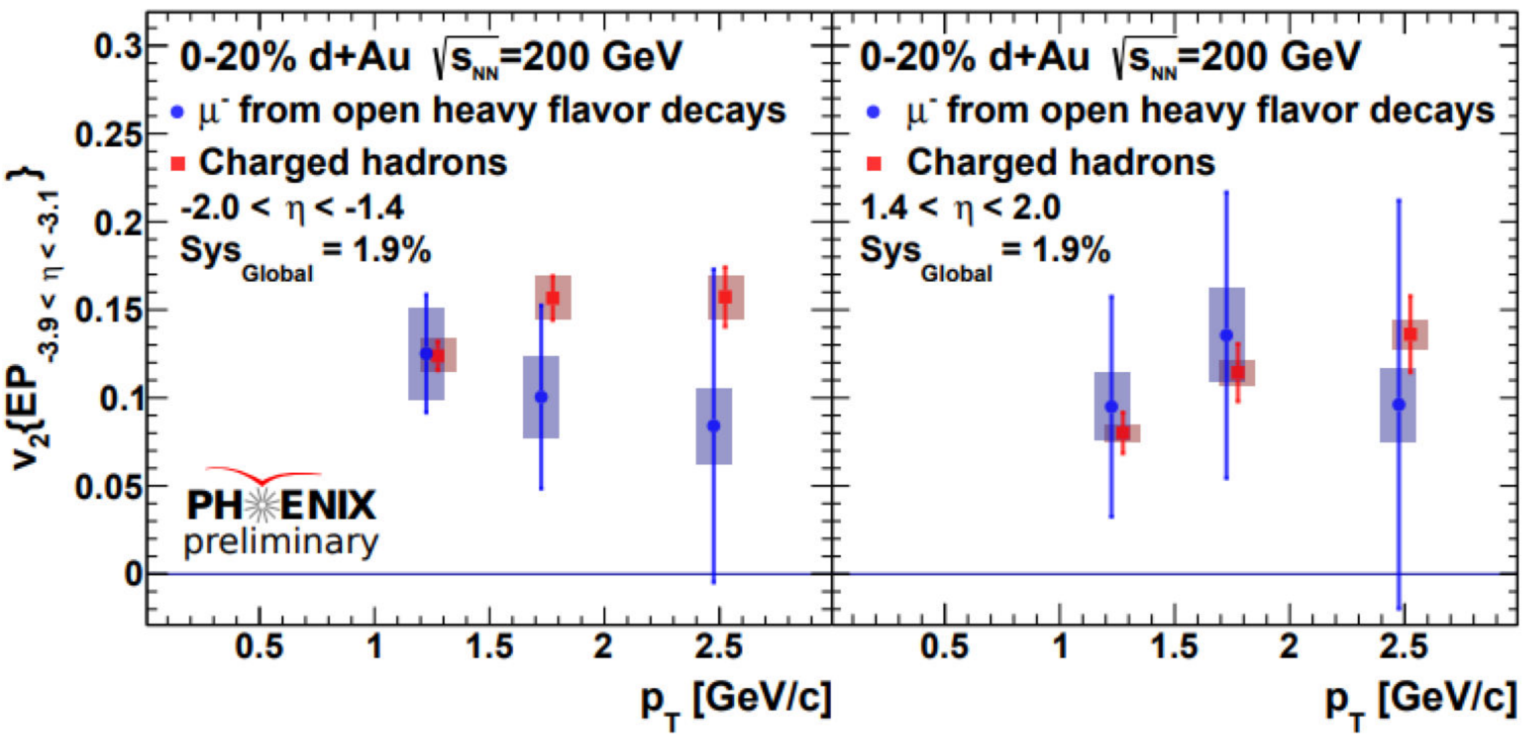
- Suppression of charm and bottom is separated, better seen in 0-10%
- Consistent with expectations from flavor dependent energy loss in the sQGP:
  - ✓ $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Flow, v_2(c→e) & v_2 (b→e) in AuAu@200



- Charm flows, $v_2^c > 0$, flow is smaller than for charged hadrons, mind decay kinematics!
- Indication of bottom flow, $v_2^b \geq 0$, although consistent with ‘0’ within large experimental uncertainties
- $v_2^b < v_2^c$
- Consistent with the LHC results in PbPb@2.76

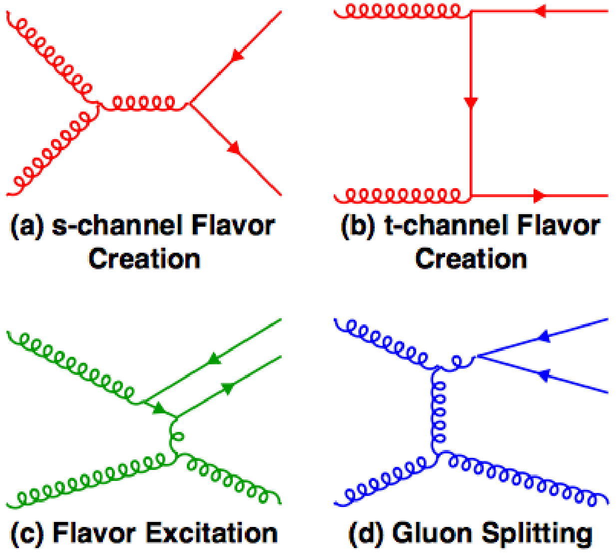
Flow, v_2(c/b→μ) in dAu@200, 0-20%



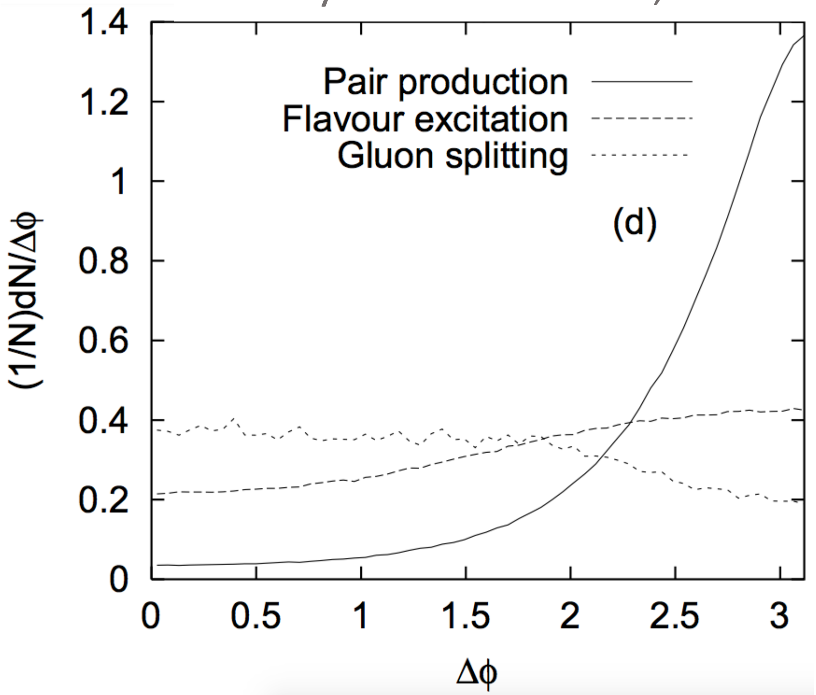
- First measurement of flow for HF-leptons in p+A collisions at RHIC
- Heavy flavor flows in central dAu@200 collisions:
  - 3.22σ (2.16σ) or 99.93% (98.61%) confidence level for positive v_2 at backward (forward) rapidity

Heavy flavor correlations

- Angular correlations of heavy flavor leptons probe the heavy flavor production mechanisms:
  - ✓ LO – flavor creation (FC) – strong back-to-back peak
  - ✓ NLO – flavor excitation (FE) and gluon splitting (GS) – broader azimuthal angle distributions



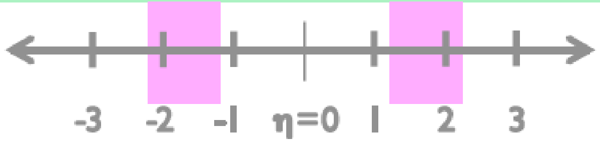
Eur.Phys.J.C17: 137-161,2000



- Relative contribution of different production mechanisms depends on collision energy:
  - ✓ role of NLO processes increases with energy

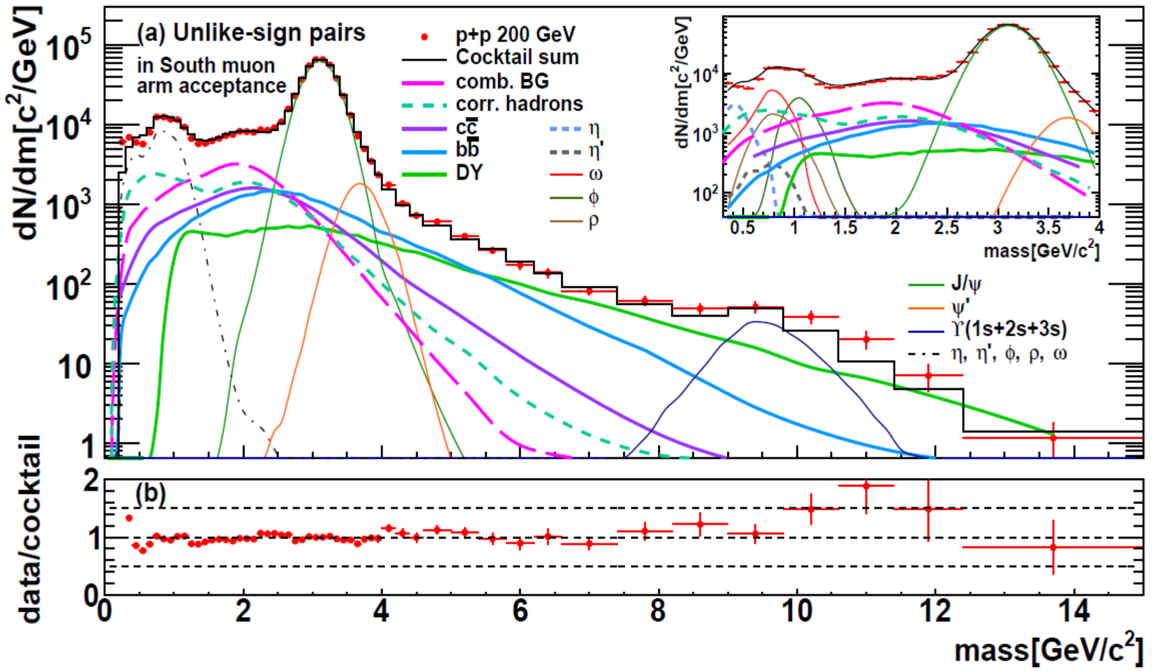
HF di-muon (1.2 < |y| < 2.2) correlations in pp@200

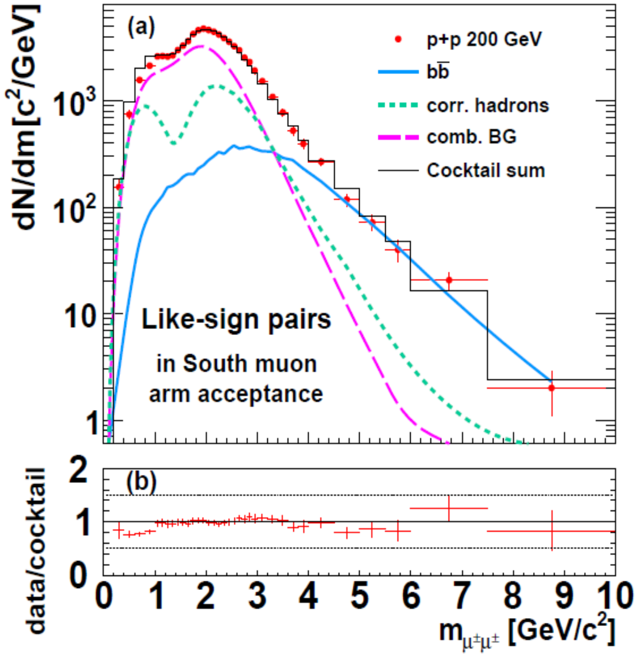
- Di-muon pairs from two muon spectrometers



- Use template (from PYTHIA6 and POWHEGv1) fits to unlike-sign and like-sign di-muon distributions:
  - ✓ high mass region (3.5-10.0 GeV/c^2) of like-sign pairs is dominated by bottom
  - ✓ high mass region (4.8-15.0 GeV/c^2) of unlike-sign pairs is dominated by Drell-Yan
  - ✓ intermediate mass region (1.5-2.5 GeV/c^2) of unlike-sign pairs is dominated by charm
- Simultaneous fitting of like-sign and unlike-sign spectra in mass & p_T
- Cocktails describe data quite well

arXiv:1805.02448

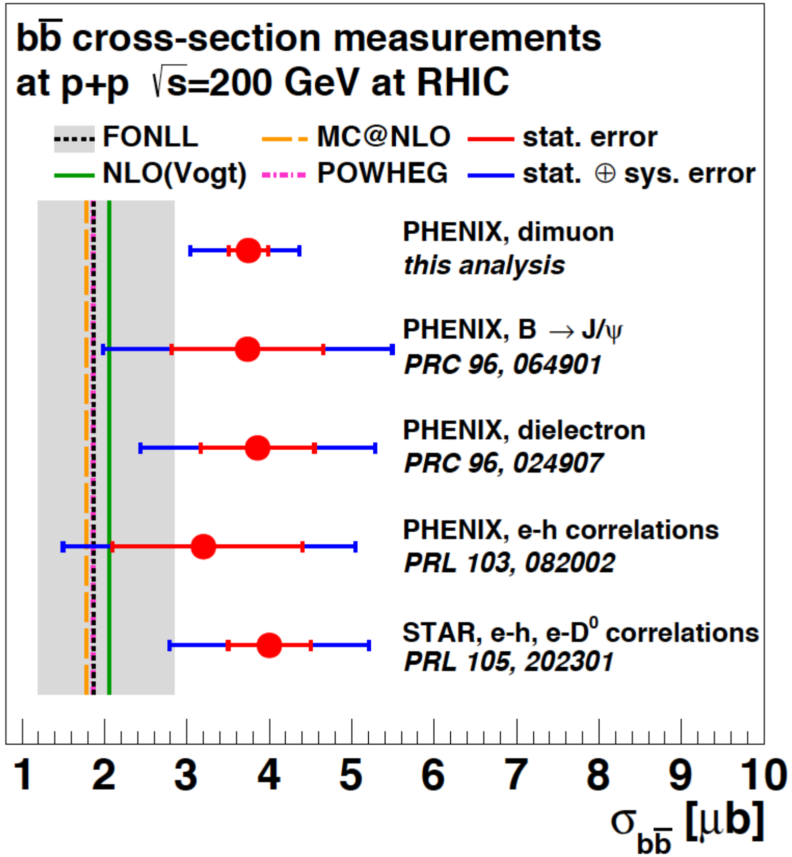


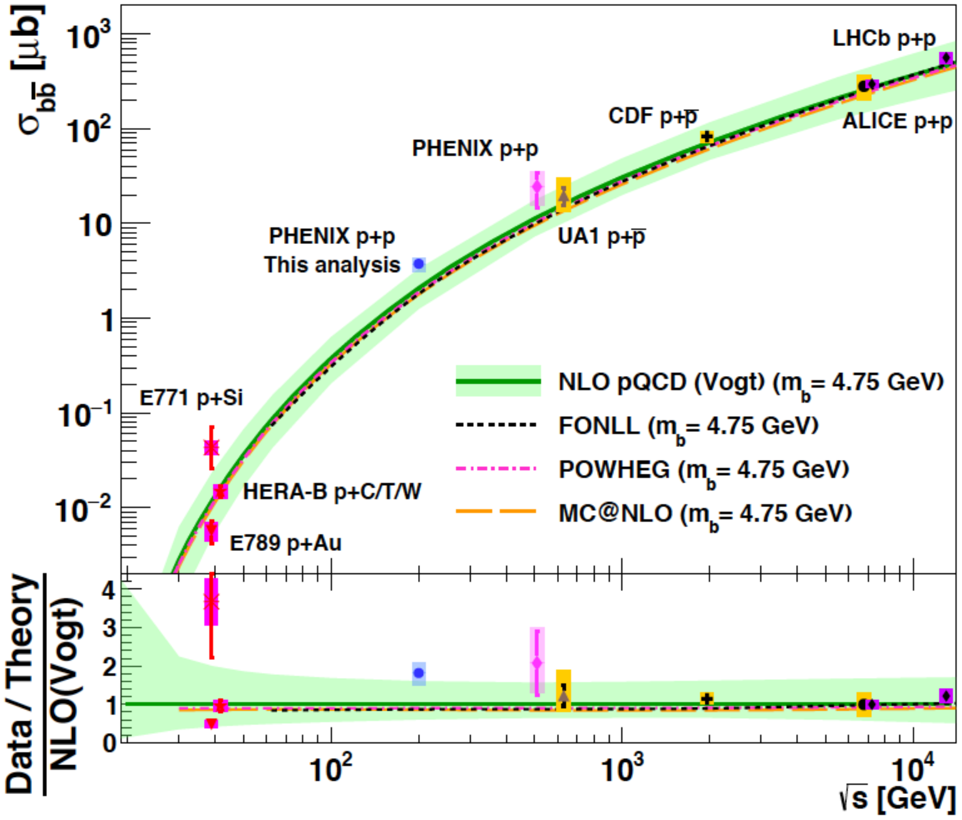


Bottom cross section from angular correlations in pp@200

- Consistent with previous results, smaller uncertainty
- Consistent with FONLL within large uncertainties, x2 the central FONLL value

arXiv:1805.04075
arXiv:1805.02448

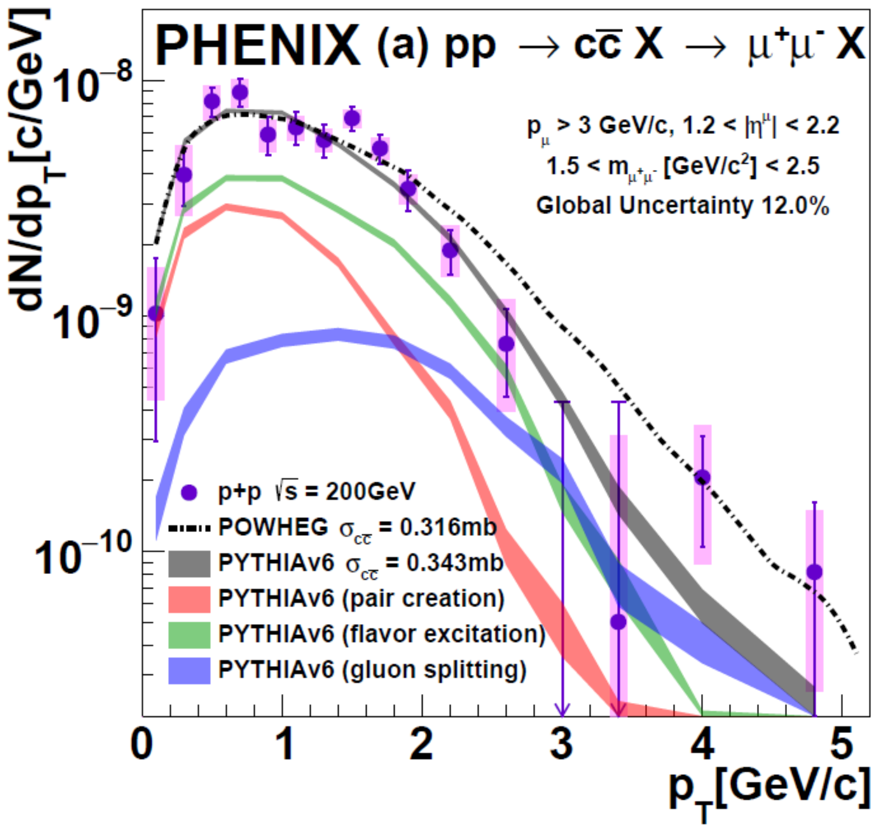


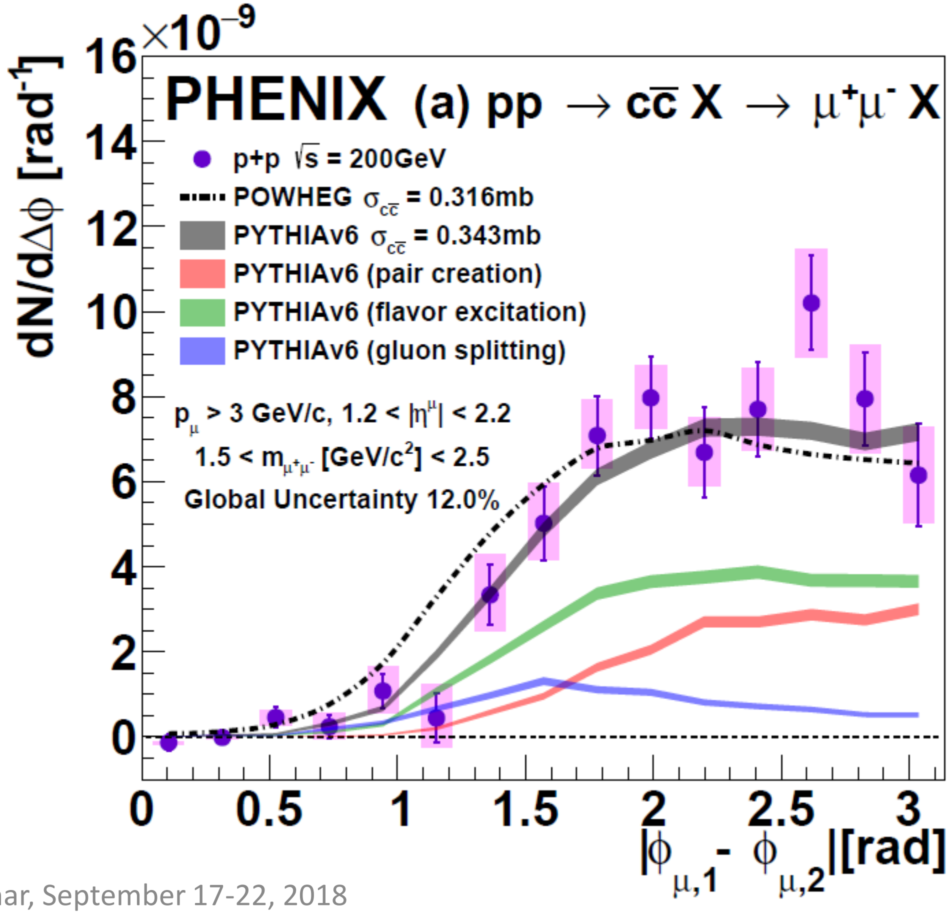


HF di-muon (1.2 < |y| < 2.2) correlations in pp@200 - charm

- Comparison with PYTHIA6 (Tune A) and POWHEG, data favors PYTHIA6
- Theoretical curves normalized with cross-sections from fitting technique
- Suggests that the charm production is dominated by flavor excitation

arXiv:1805.02448

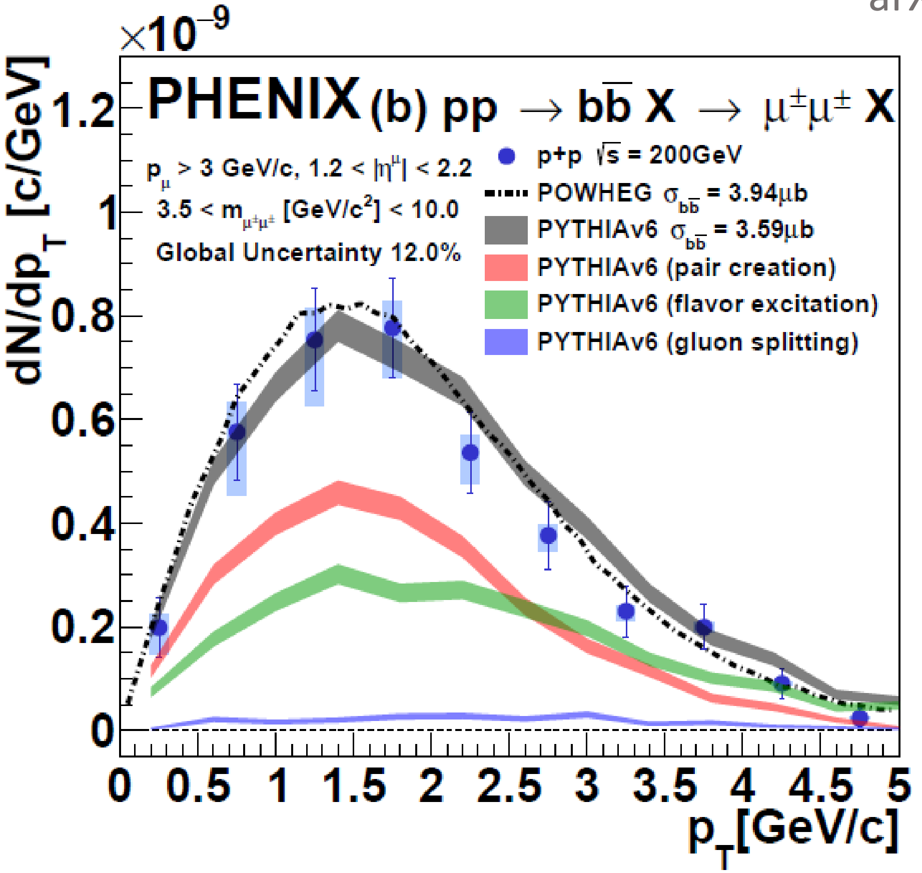


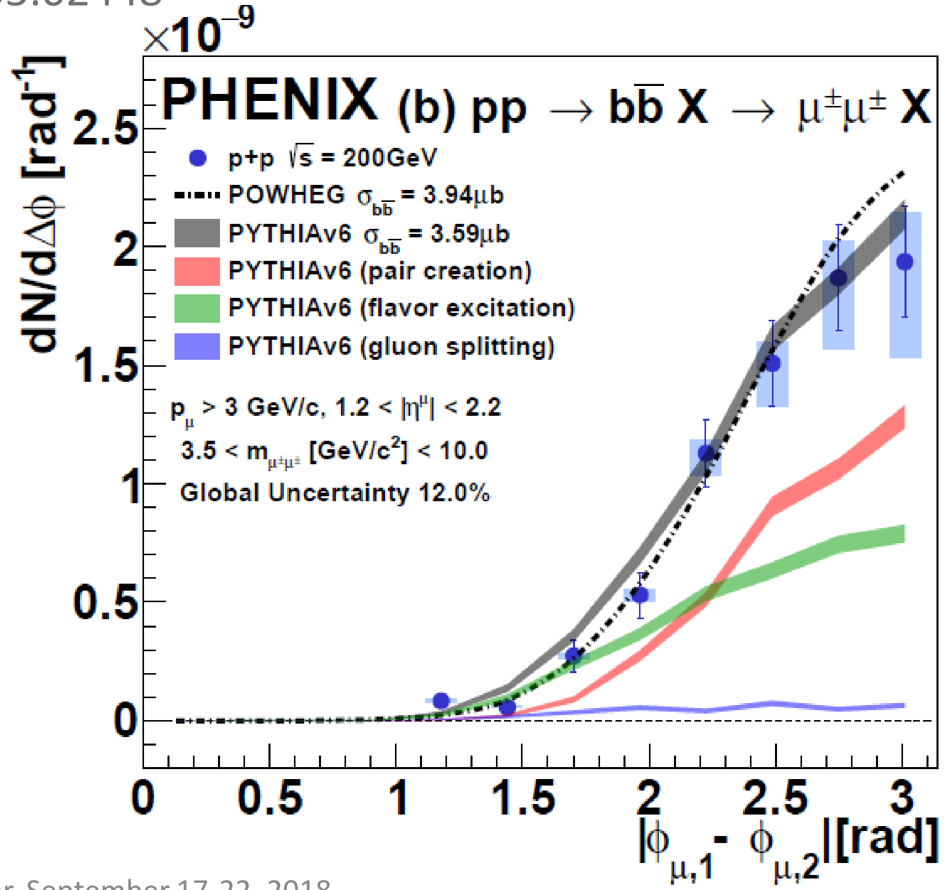


HF di-muon (1.2 < |y| < 2.2) correlations in pp@200 – bottom

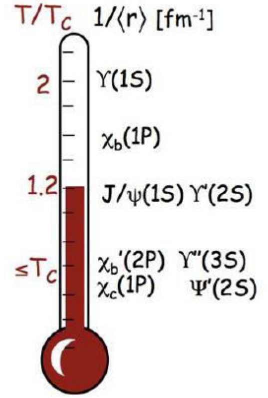
- Comparison with PYTHIA6 (Tune A) and POWHEG, good agreement with data
- Theoretical curves normalized with cross-sections from fitting technique
- Suggests that the bottom production is dominated by leading order flavor (pair) creation

arXiv:1805.02448

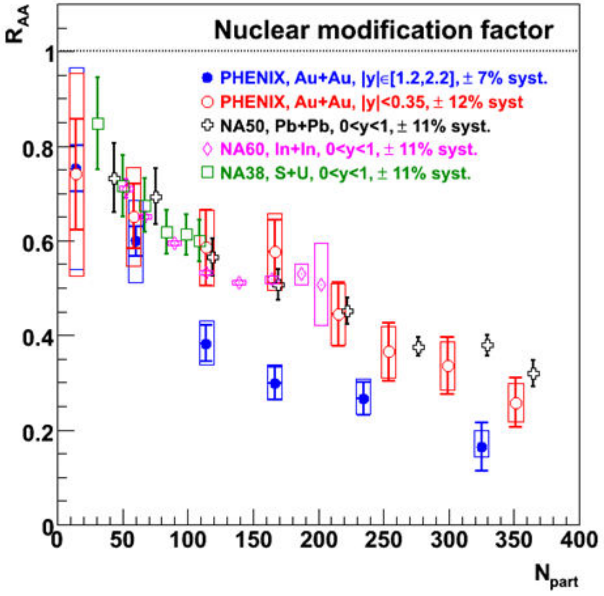


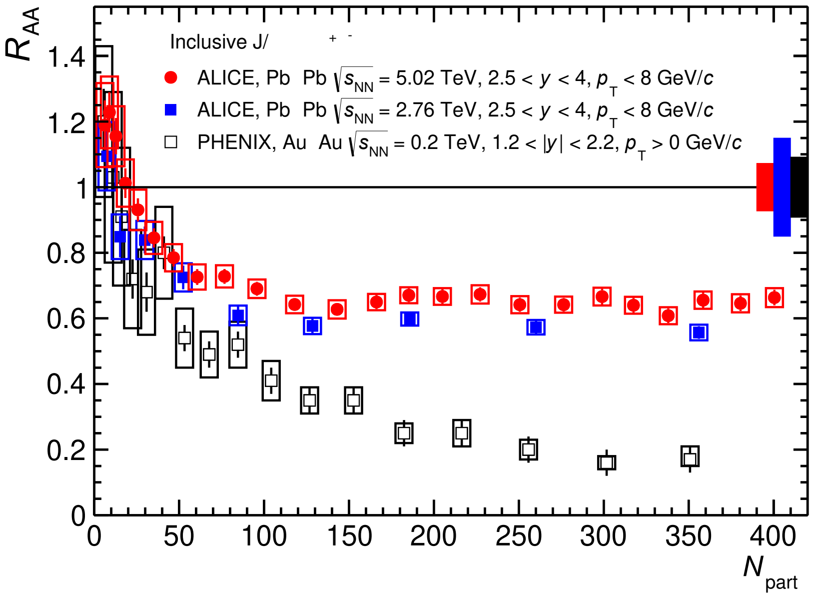


Quarkonia



- Original idea of color screening by Matsui and Satz, 1986:
  - ✓ sequential melting of quarkonia states
  - ✓ relative yield measurements can be used as QGP thermometer
- Real life turned out to be more complicated:
  - ✓ J/ψ suppression does not increase with collision energy SPS → RHIC → LHC

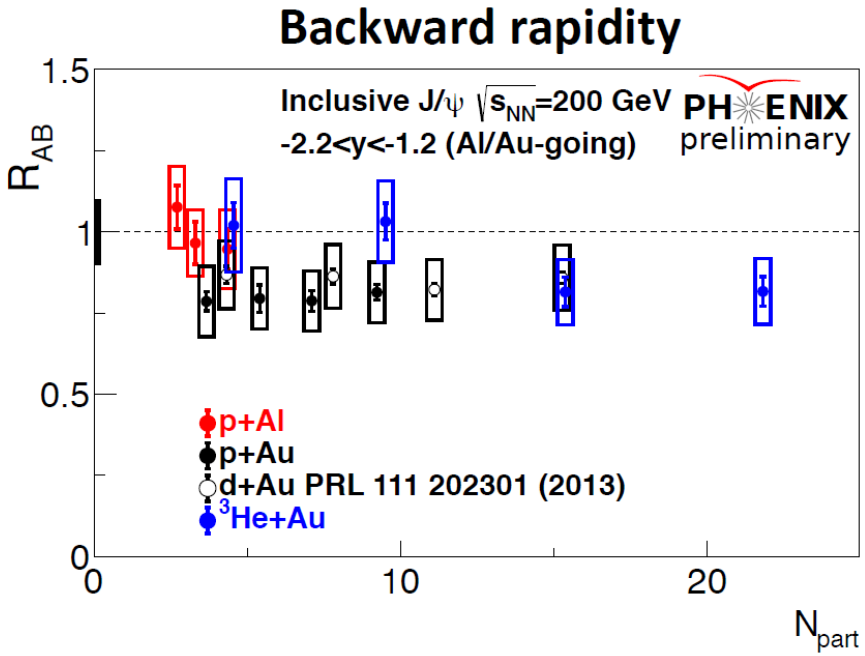


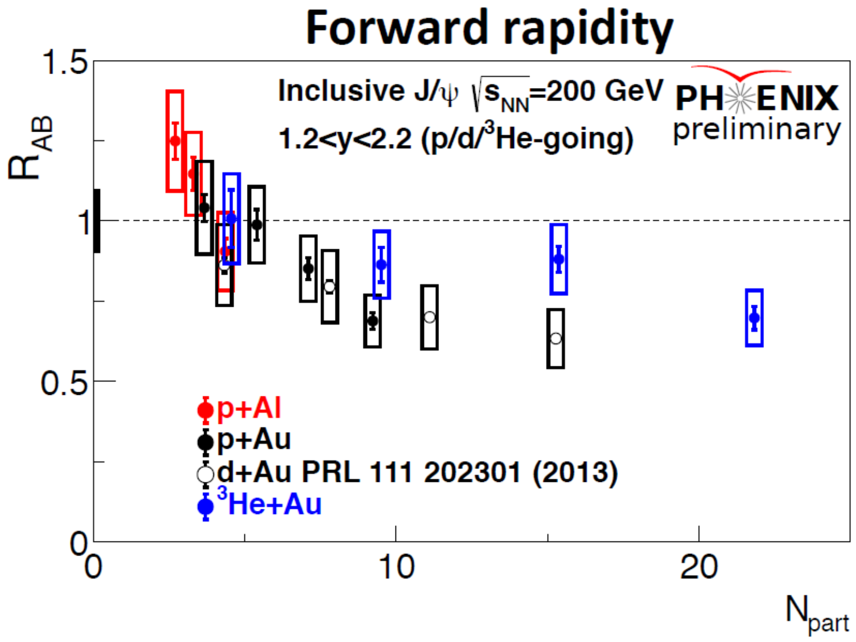


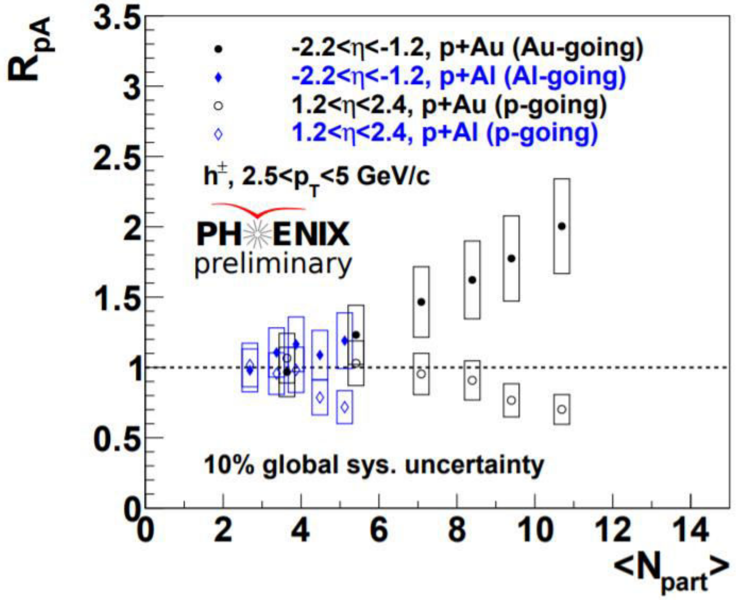
- Need to account for many initial and final state effects:
  - ✓ nPDF, CGC, energy loss
  - ✓ nuclear absorption, co-mover dissociation, recombination of open charm

J/ψ in p/d/³He + Al/Au collisions @ 200 GeV

- Forward rapidity:
  - ✓ low hadron density
  - ✓ suppression of charged hadrons and J/ψ suggests dominant effect of shadowing ($x \sim 5\cdot10^{-3}$)
- Backward rapidity:
  - ✓ high hadron density
  - ✓ production of charged hadrons is enhanced ($x \sim 8\cdot10^{-2}$)
  - ✓ suppression of J/ψ suggests breakup or co-mover effects







Ψ' in small systems at $\sqrt{s}$ = 200 GeV

- Double ratio, $[\Psi' / J/\Psi]_{p+A}$ to $[\Psi' / J/\Psi]_{p+p}$ cancels out systematic uncertainties
- Ψ' / J/Ψ ratio is unchanged in p(^{3}He)-going direction
- Ψ' / J/Ψ ratio is suppressed by a factor of ~2 in Au/Al-going direction
- Ψ' and J/Ψ are c-cbar pairs with different binding energies of ~ 50 MeV and ~ 640 MeV
- Plotting against co-moving particle density shows common behavior at RHIC and the LHC
- Note suppression in p-going direction in p+Pb

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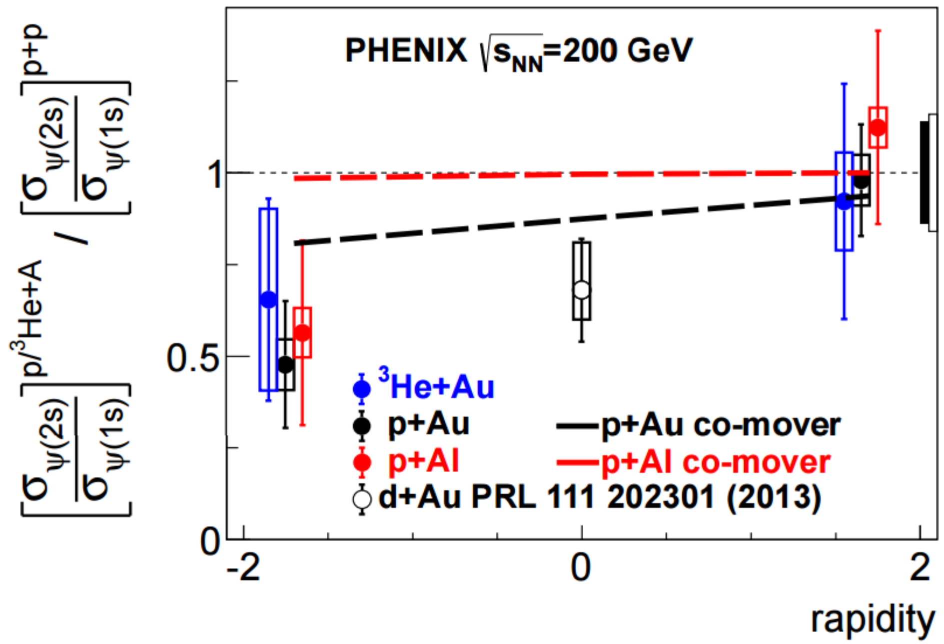

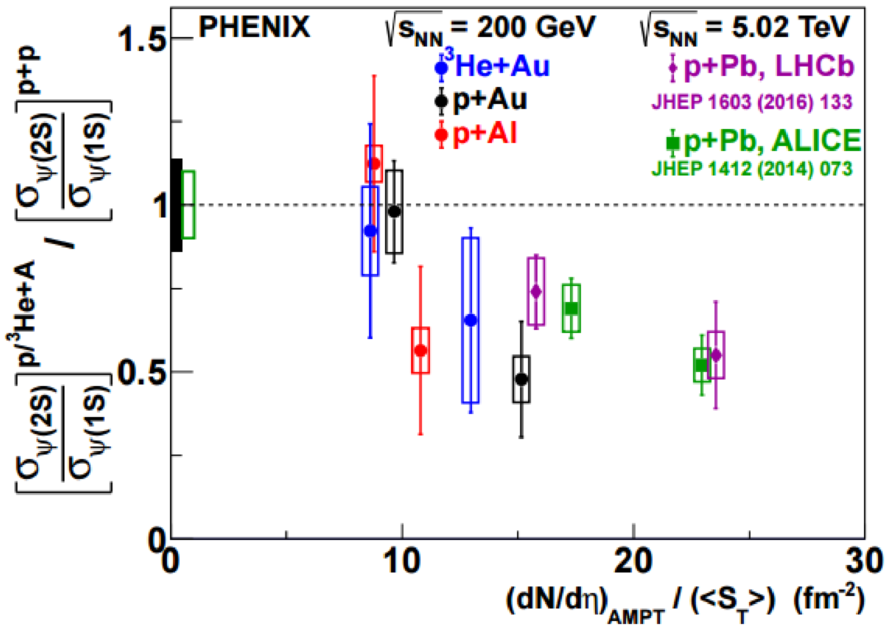

Heavy flavor - summary

- First measurement of charm and bottom separated R_{AA} and v_2 in AuAu@200:
  - clear charm flow
  - flavor dependent energy loss and thermalization in the QGP
- First measurement of non-zero heavy flavor flow in small system at RHIC, central dAu@200
- New measurements of c-cbar and b-bar production:
  - b-bbar production is dominated by flavor (pair) creation, x2 FONLL prediction
- J/ψ and ψ' measurements in small systems:
  - final state effects are important for interpretation of charmonia results, especially for weakly bound states

Summary

- PHENIX continues to deliver new and unique results on light hadron, direct photon and heavy flavor production in different collision systems → some of them were presented today
- Not all data has been analyzed → new results will emerge shortly, stay tuned
- Many of the obtained/presented results still do not have unambiguous and exhaustive theoretical interpretation → consistent picture of small system and heavy-ion collisions is yet to be refined, new subjects of interest are not excluded

Thank you

BACKUP

Model Comparison

- **SONIC:**
  - MC Glauber initial conditions
  - 2+1d Hydro evolution, $\eta/s = 0.08$
  - Cooper-Frye hadronization at T = 170 MeV
  - Hadronic rescattering (B3D package)
- **Super SONIC:** SONIC + pre-equilibrium flow
- **iEBE-VISHNU:**
  - MC Glauber initial conditions
  - 2+1d Hydro evolution starting at $\tau = 0.6$ fm/c, $\eta/s = 0.08$
  - Hadronization at T = 155 MeV
  - Hadronic rescattering (UrQMD 3.4 package)
- **Bozek – Broniowski:**
  - MC Glauber initial conditions
  - 3+1d Hydro evolution
- **AMPT**
  - MC Glauber initial conditions
  - Strings melt to partons
  - Partonic transport (partonic cross section σpart = 1.5 mb)
  - Haronization - parton coalescence
  - Hadronic rescattering (ART package)

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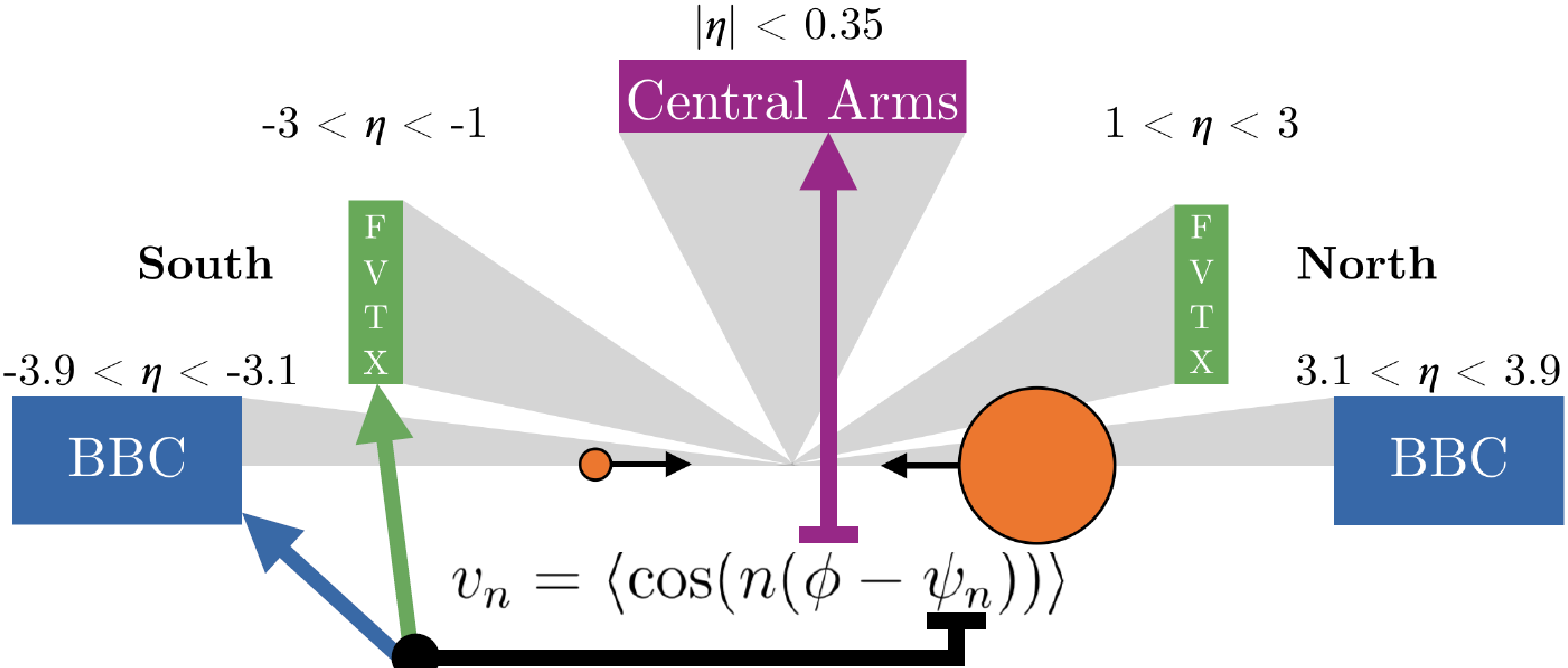


$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle$$

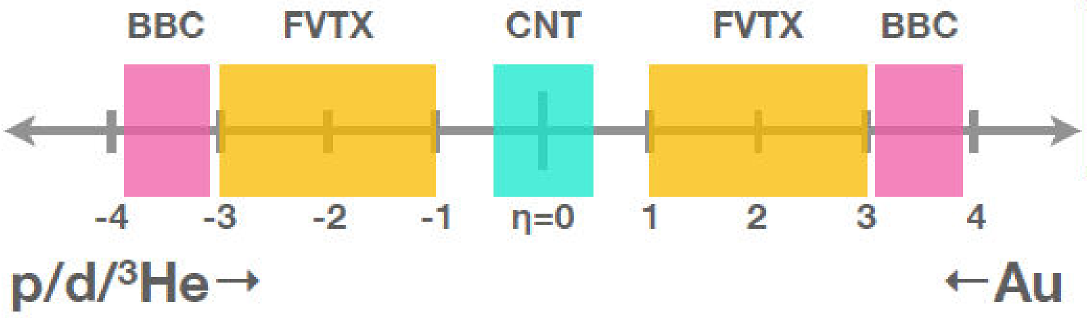
$$\mathrm{Res}(\psi_n)^2 = \frac{\langle \cos(n(\psi_n^a - \psi_n^b)) \rangle \langle \cos(n(\psi_n^a - \psi_n^c)) \rangle}{\langle \cos(n(\psi_n^b - \psi_n^c)) \rangle}$$

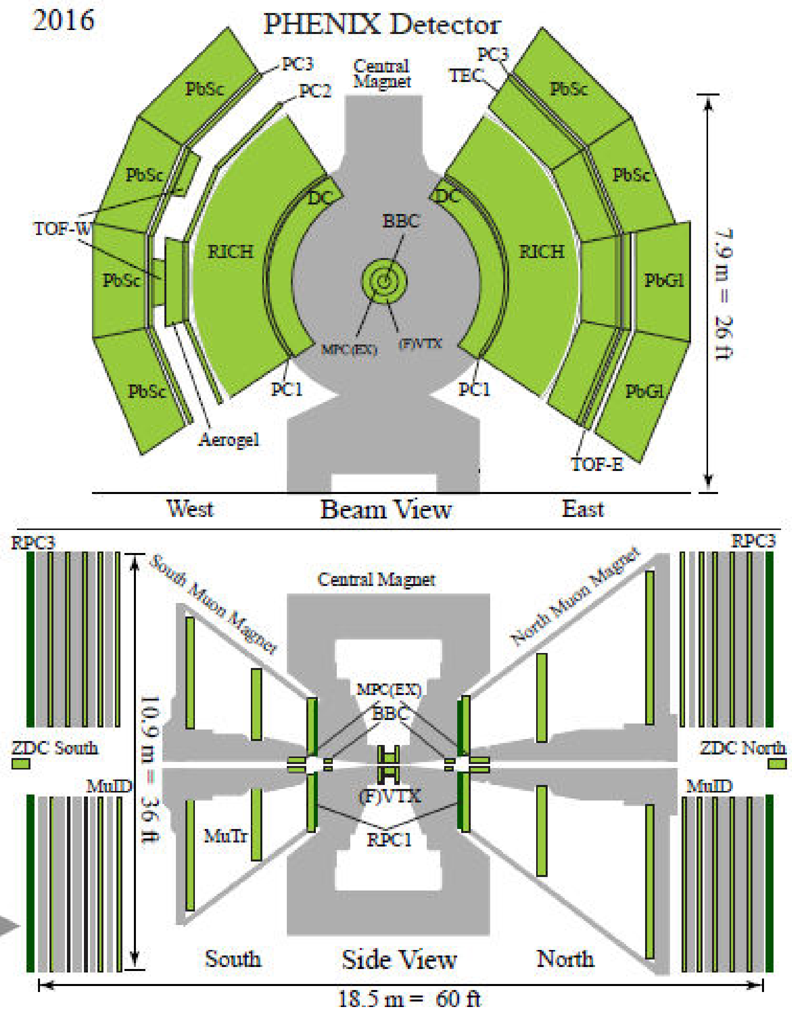
PHENIX

CNT - Charged particle tracking

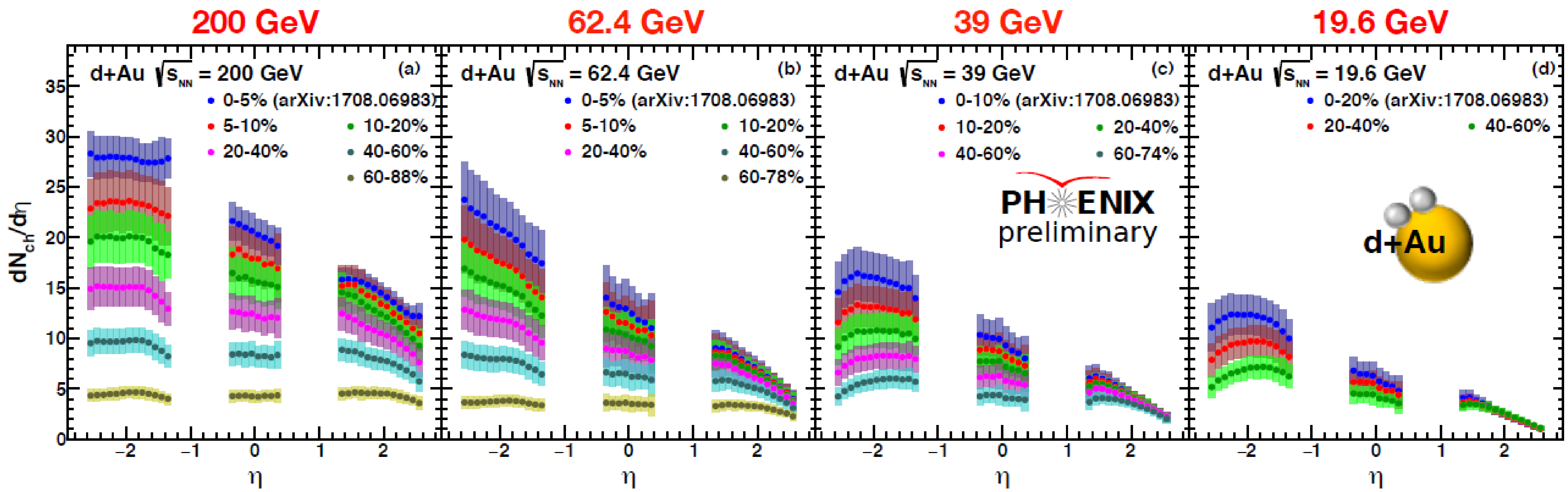
FVTX - Unidentified particle tracking
Cluster (Event Plane)

BBC - Clusters (Event Plane)
Centrality determination



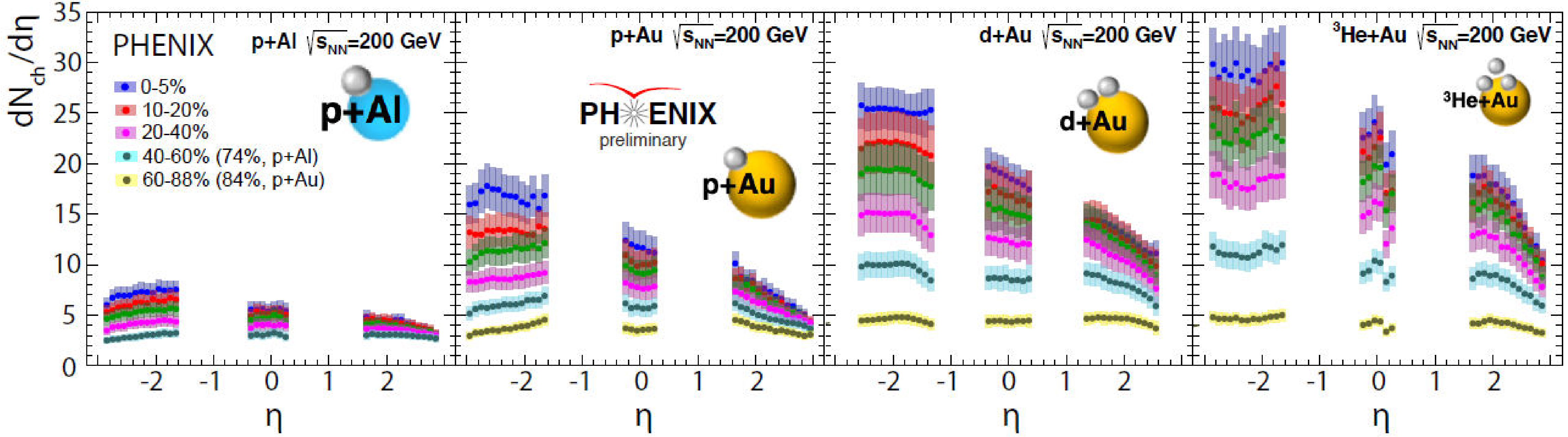


d+Au Energy Dependence



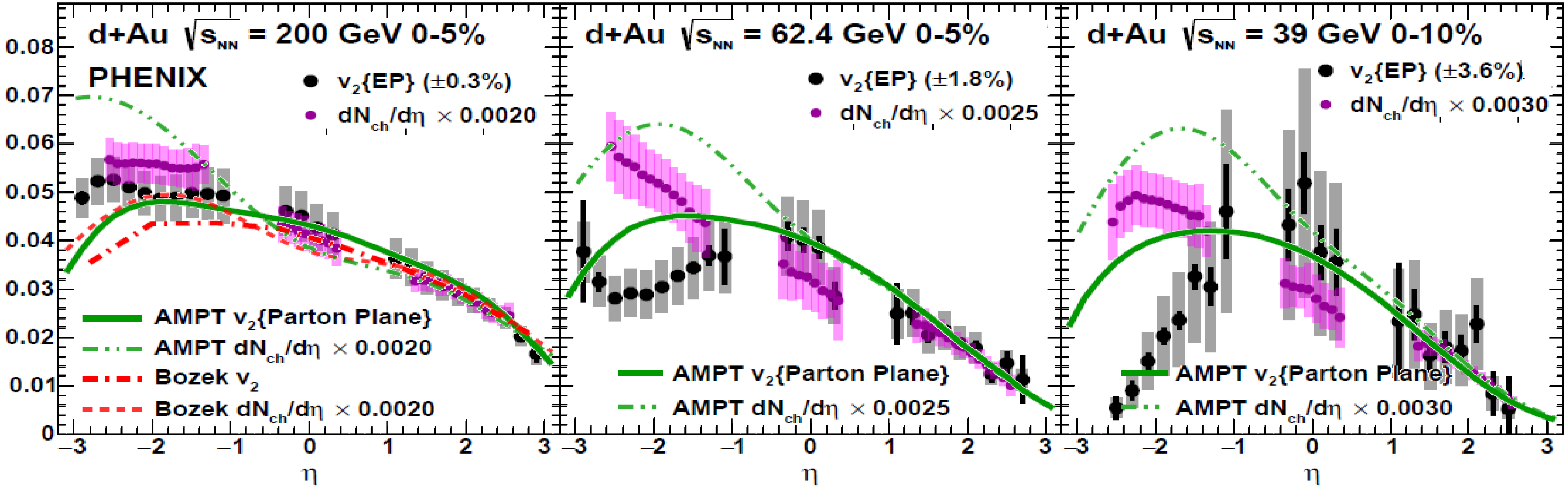
Factor of ~3 decrease in $dN_{ch}/d\eta$ from 200 to 20 GeV

Geometry Scan



$dN_{ch}/d\eta$ increases with system size

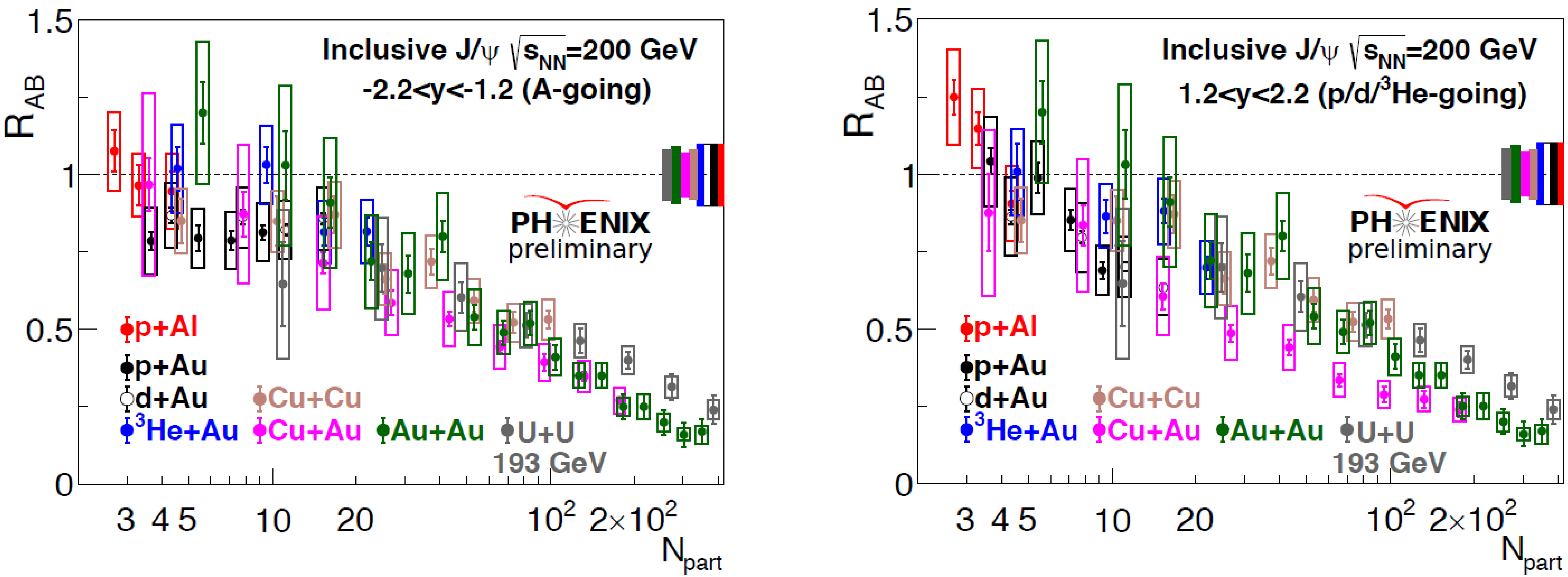
Charged hadrons – comparison to $dN_{ch}/d\eta$



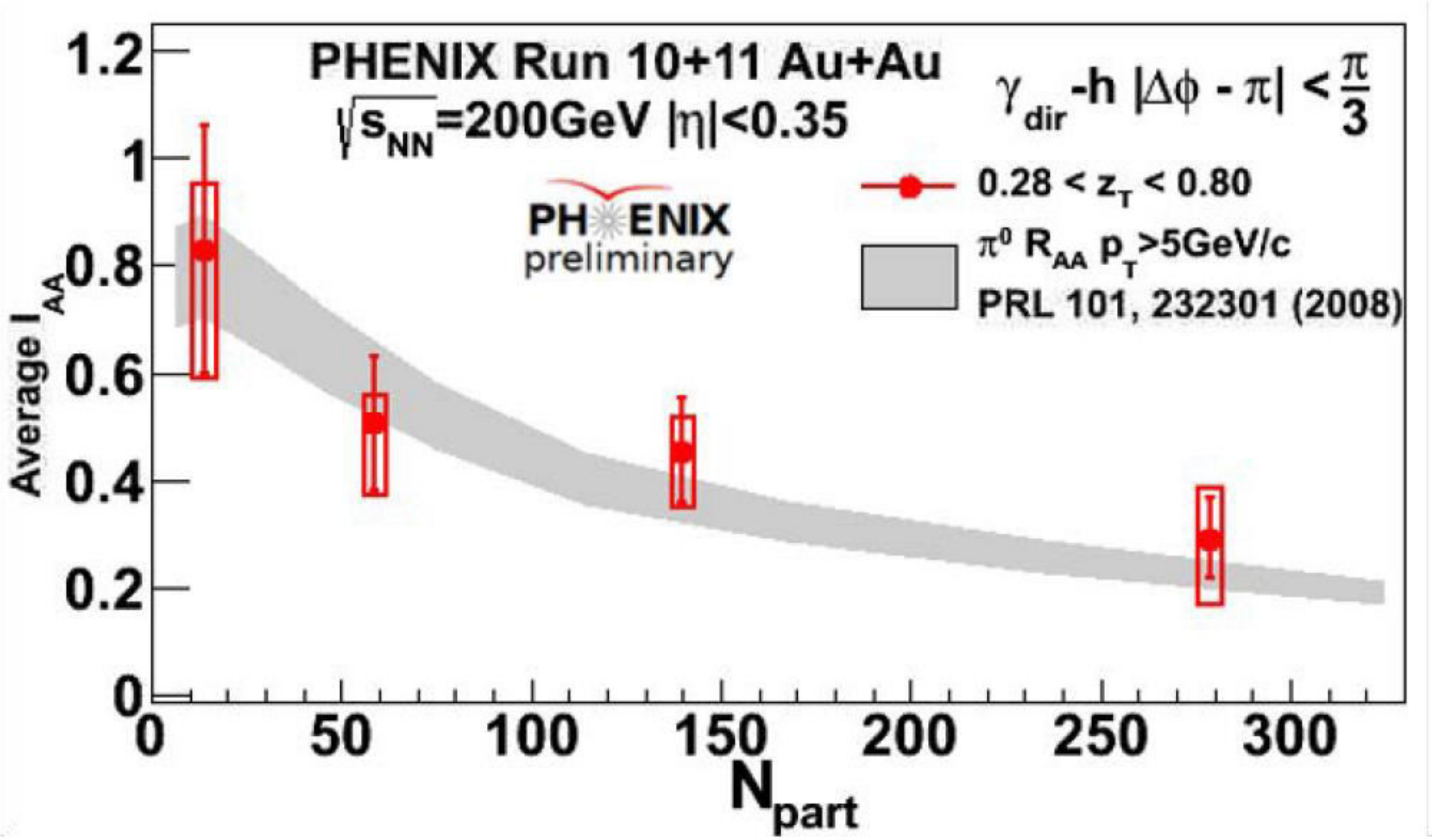
- ❖ $dN_{ch}/d\eta$ is scaled to match v_2 at forward rapidity, $1 < \eta < 3$
- ❖ At 200 GeV, the scaled $dN_{ch}/d\eta$ matches the v_2 in the whole rapidity range
- ❖ At 62 and 39 GeV, the scaled $dN_{ch}/d\eta$ matches the v_2 at $\eta > 0$ and overestimates it at $\eta < 0$
- ❖ Hydro (only at 200 GeV): reproduces the trends for $dN_{ch}/d\eta$ and v_2
- ❖ AMPT: reproduces data at $\eta > 0$; $dN_{ch}/d\eta$ always overestimates v_2 at $\eta < 0$
- ❖ Can underestimate true v_2 at $\eta < 0$ with the EP method because of anti-correlation with a small $\Delta\eta$ gap

Modification of J/ψ vs. N_{part} @ 200 GeV

❖ R_{AB} shows consistent dependence on N_{part} in small and large collision systems at forward and backward rapidity



γ-h correlations, AuAu@200



❖ Isolation cut + larger statistics greatly improved the measurement precision

❖ Better constraints on jet quenching parameters