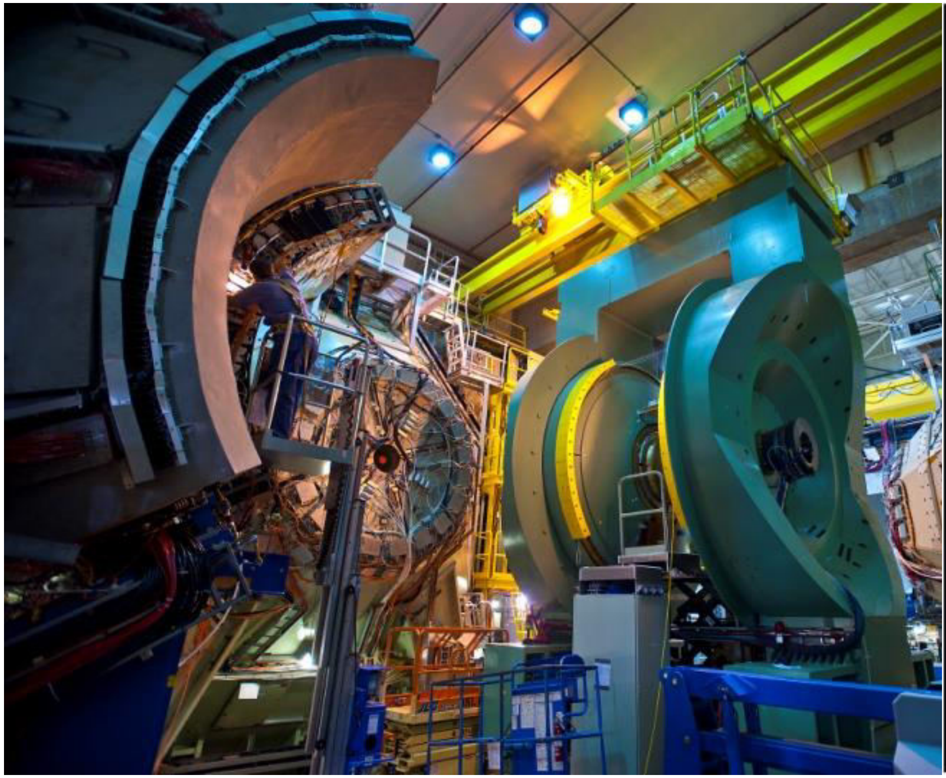
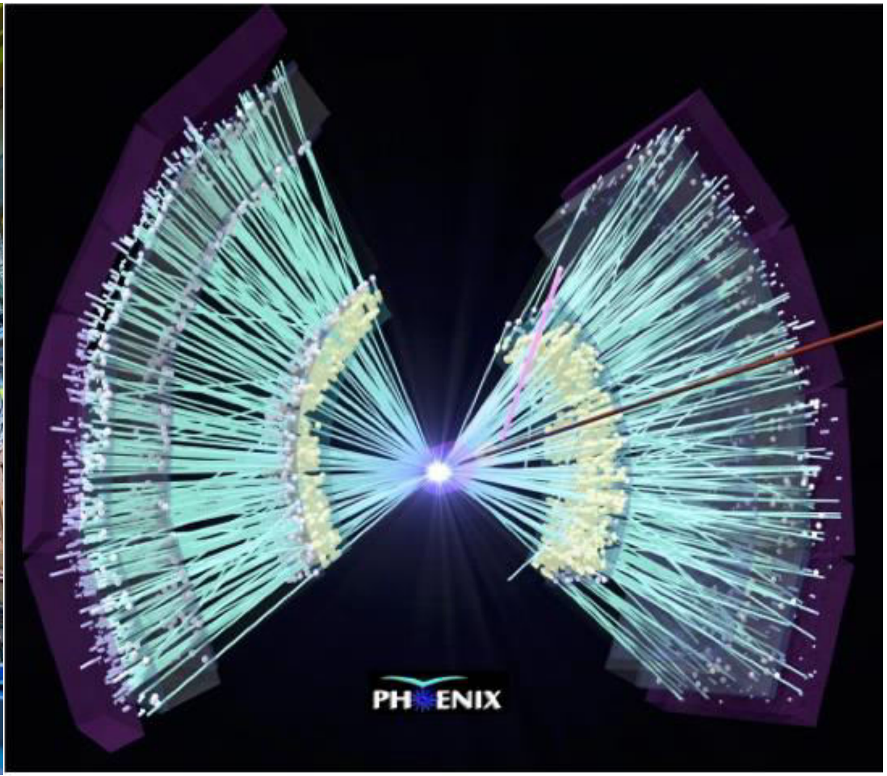
Коллективные эффекты во взаимодействиях малых систем в эксперименте PHENIX на коллайдере RHIC

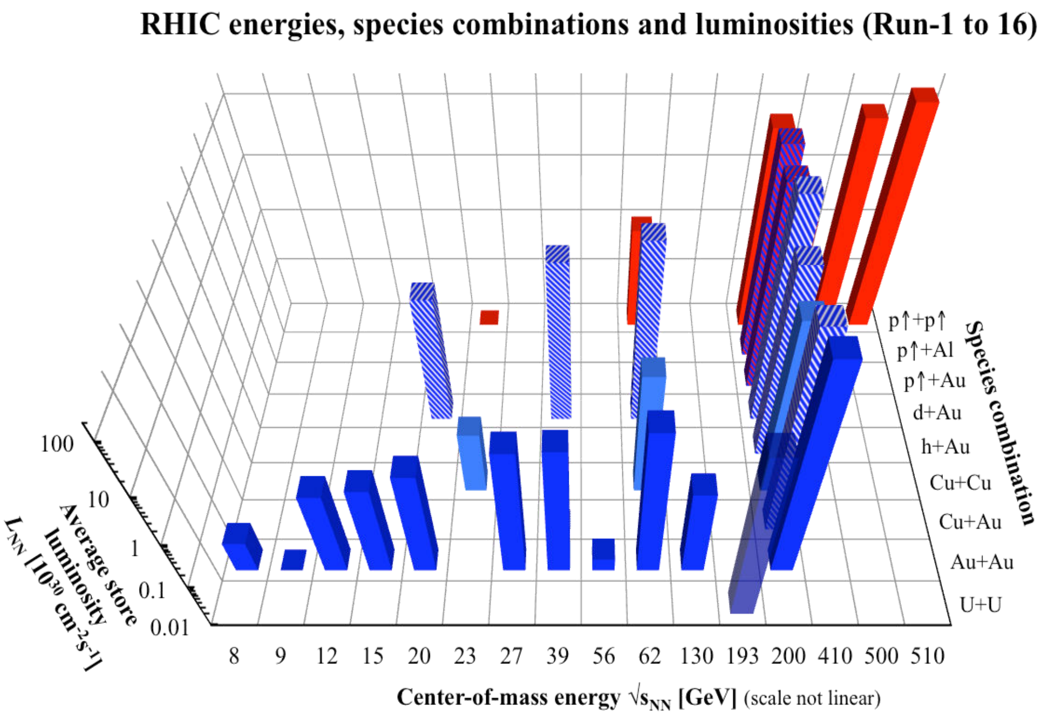
В. Рябов, ЛРЯФ ОФВЭ





PHENIX сегодня

- PHENIX закончил свою работу в 2016 году, но оставил богатое наследие



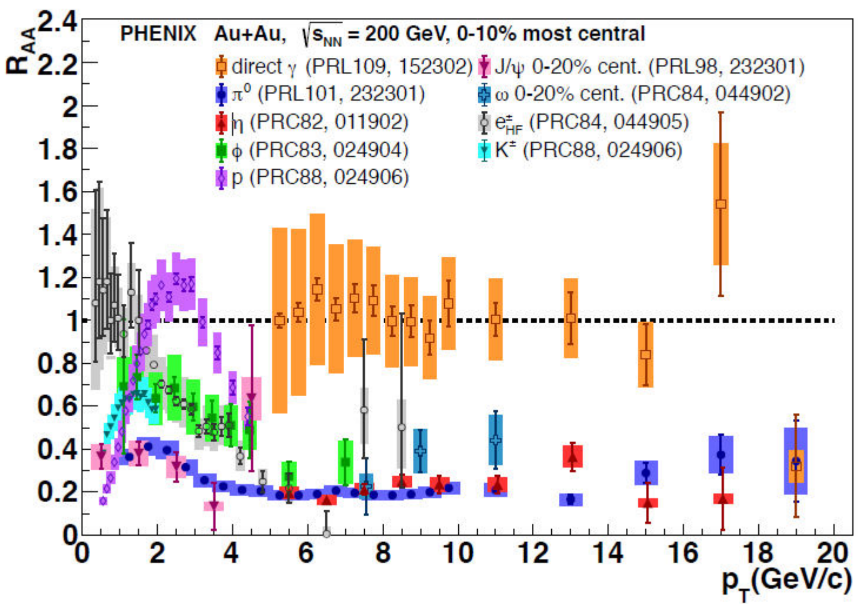
Открытие sQGP

- В 2005 году все коллаборации, работающие на RHIC, сделали заявление об открытии нового состояния – сильновзаимодействующей КГП (sQGP)
  - ✓ быстрая термализация ($\tau_0 << 1$ фм/с)
  - ✓ идеальная жидкость ($\eta/s \sim 1/4\pi$); сильно-связанная, не газ
  - ✓ ε >15 ГэВ/фм^3, $T_0 \sim$ 300-400 MeV; превышены условия для фазового перехода
  - ✓ dN_g/dy > 1100, высокая глюонная плотность, среда не прозрачная

- Заявление ФЕНИКС обусловлено обнаружением и измерением:
  - ✓ эффекта гашения струй
  - ✓ эллиптического потока, его n_q - масштабирования
  - ✓ выхода мягких прямых фотонов
  - ✓ подавление кваркония

- За 10+ лет результаты/заключения не были опровергнуты, в том числе и с запуском коллайдера LHC

Jet quenching



$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{pp}/dp_T d\eta}$$

$R_{AA} > 1$ – enhancement

$R_{AA} = 1$ – no modification

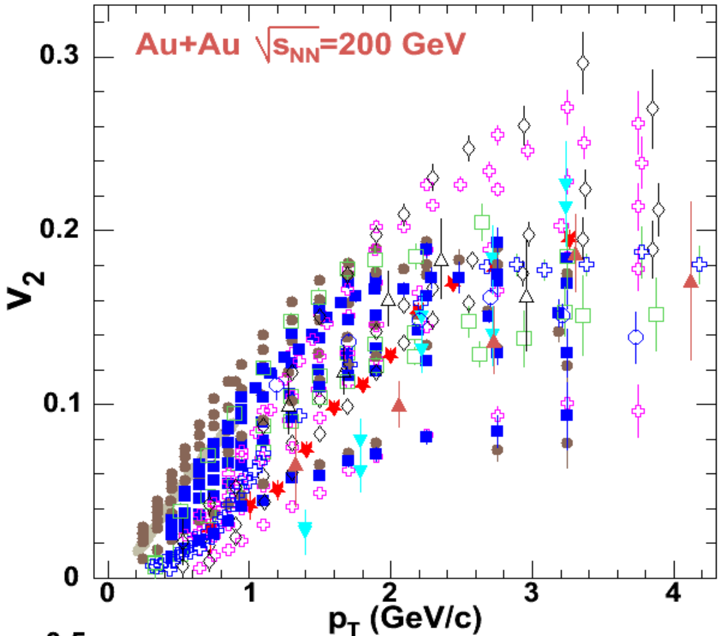
$R_{AA} < 1$ – suppression

- Выход адронов сильно подавлен (R_{AA}=0.2!) до 20 ГэВ/с в центральных A+A
- Отсутствие подавления для γ_{direct} и адронов в p+A → эффект конечного состояния
- Одинаковое подавление для легких адронов → партонный уровень
- Тяжелые c-кварки испытывают существенные энергетические потери
- Сравнение с теорией: ε > 15 ГэВ/фм^3; dN_g/dy > 1100

→ *Образующаяся среда обладает высокой глюонной плотностью*

→ *Начальная плотность энергии >> необходимой для фазового перехода*

Elliptic flow (v_2)

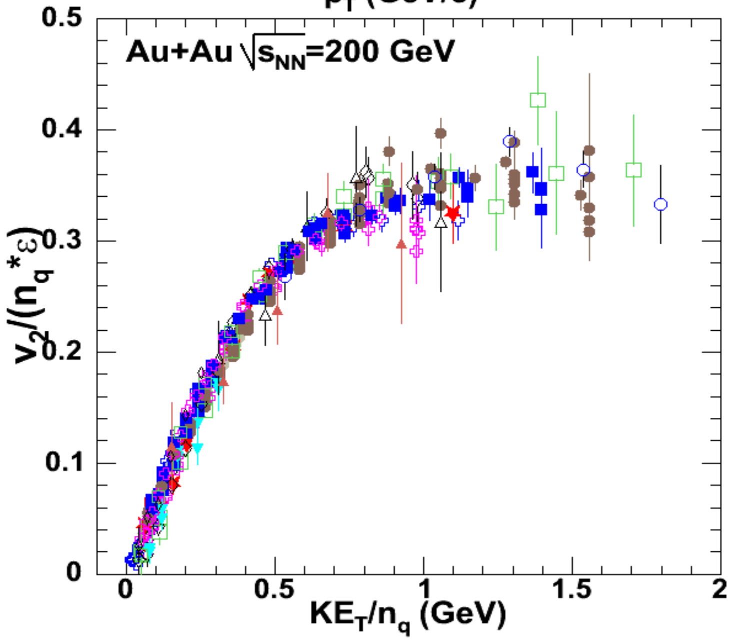


PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, QM06)

- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,20-60%
- π^0 : min.bias
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,20-60%
- $p+\bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005)

- $\pi^+ + \pi^-$: min.bias
- K^0_S : min.bias, 5-30%,30-70%
- $p+\bar{p}$: min.bias
- $\Lambda+\bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi+\bar{\Xi}$: min.bias
- $\Omega+\bar{\Omega}$: min.bias



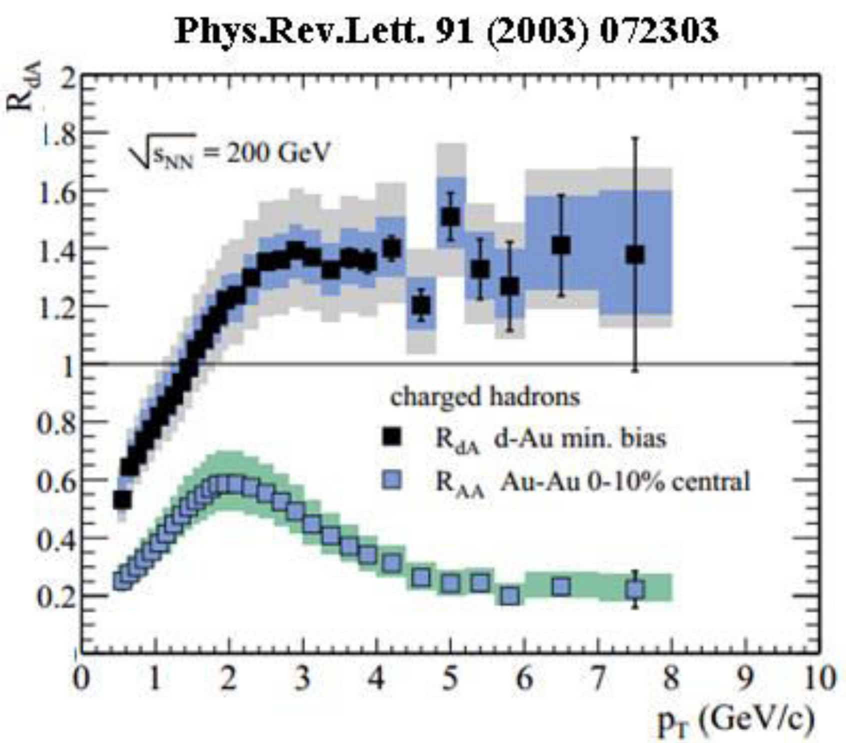
- $v_2(p_T, m)$ описывается гидродинамическими моделями, предполагающими образование среды со свойствами идеальной жидкости с очень малой вязкостью ($\eta/s \sim 1/4\pi$)
- Ранняя термализация (τ < 1 фм/с) и высокая начальная плотность энергии (ε > 15 ГэВ/фм^3).
- Универсальное n_q - масштабирование для легких адронов
- Тяжелые кварки также участвуют в коллективном потоке, но слабее легких

→ *Равновесная среда*

→ *Идеальная жидкость, не газ*

→ *Поток развивается на партонном уровне, партонные степени свободы*

Малые системы (p/d/He+A) – контрольный эксперимент?



- Первоначальная идея для малых систем
  – контрольные эксперименты
- p/d/He+A – суперпозиция N+N столкновений за исключением эффектов начального состояния и эффектов холодной ядерной материи
- Отсутствие подавления для адронов в d+Au эффект гашения струй ответственен за подавление выхода адронов в центральных Au+Au взаимодействиях
- Появление новых экспериментальных данных на RHIC и LHC показало, что малые системы выходят далеко за пределы просто контрольных измерений

Flow

Geometry engineering and energy scan

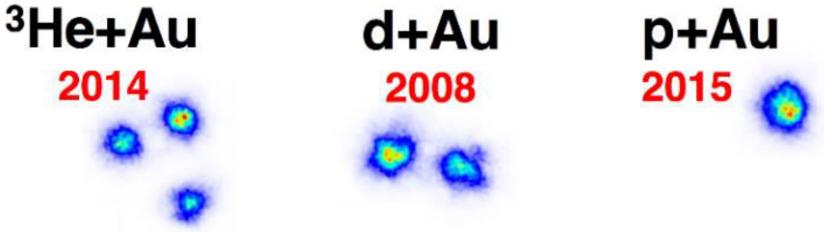
- Поиск коллективных эффектов во взаимодействиях малых систем
- Связь потоков с геометрией области перекрытия ядер → **geometry scan**
- Связь потоков с плотностью энергии → **energy scan (d+Au)**

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

2016 Data

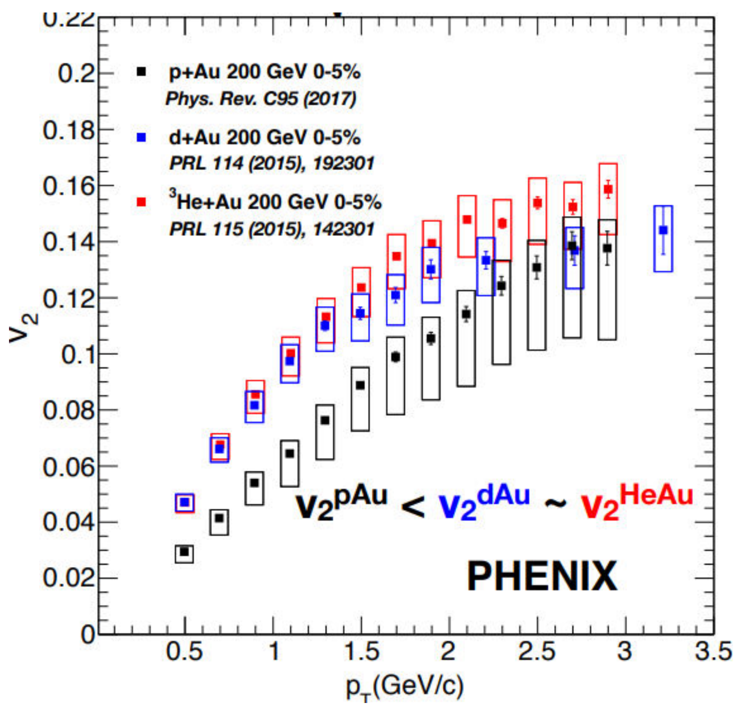
Geometry engineering – charged hadrons

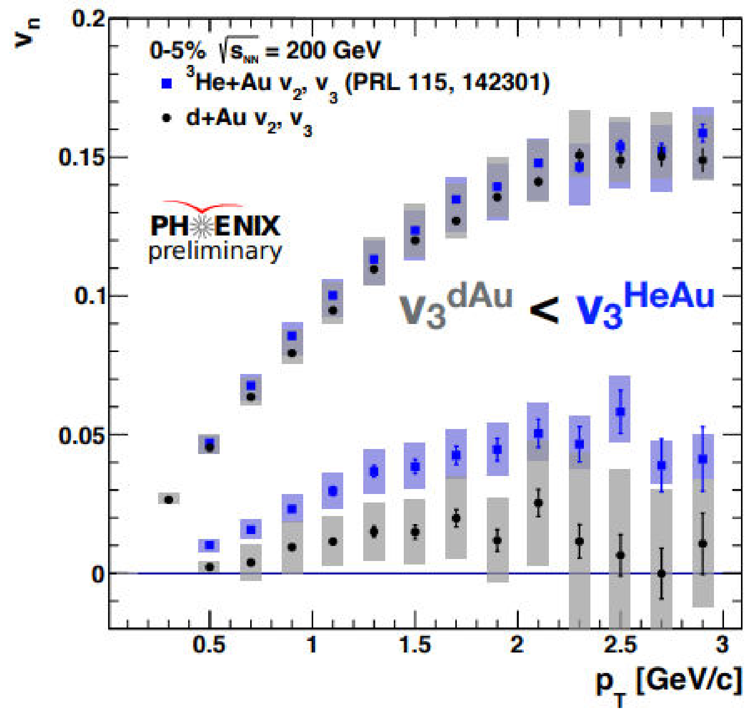
- Geometry engineering is a unique capability of the RHIC



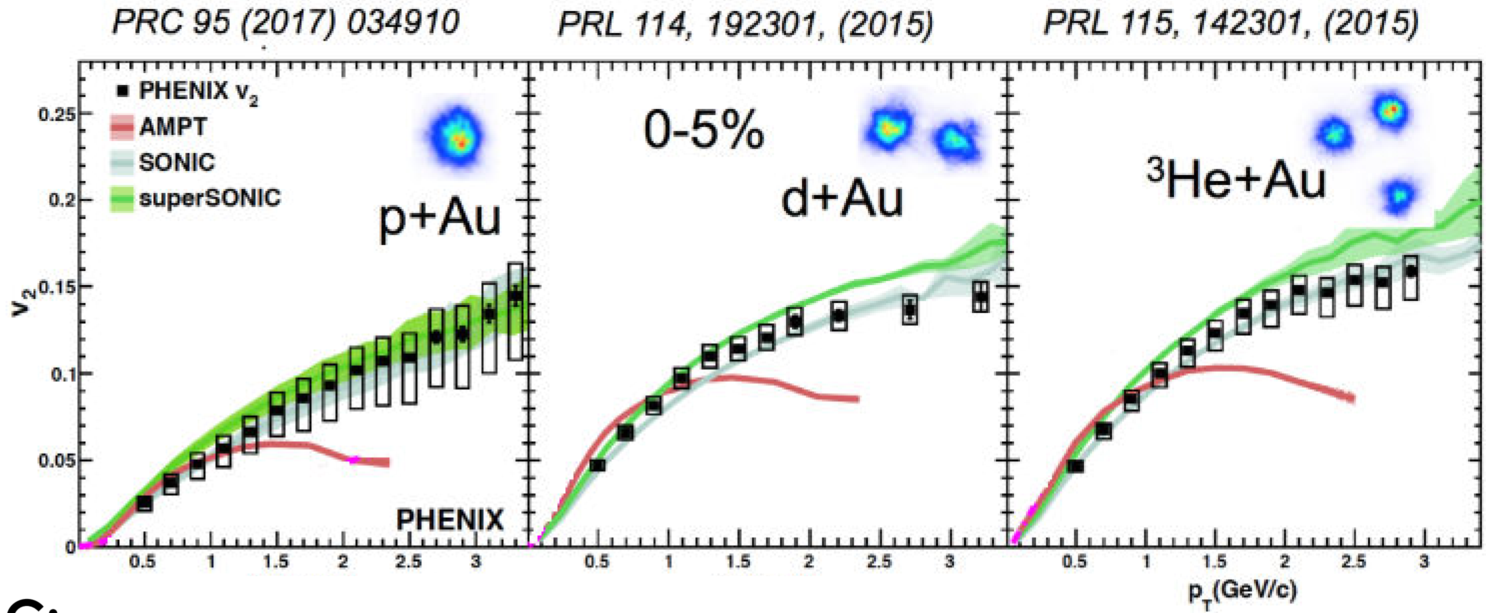
$\varepsilon_2^{pAu} < \varepsilon_2^{dAu} \sim \varepsilon_2^{HeAu}$

- v_2 & v_3 for charged hadrons in central p+Au, d+Au, ³He+Au at $\sqrt{s_{NN}}$ = 200 GeV
- v_2 (³He+Au) ~ v_2 (d+Au) > v_2 (p+Au)
- v_3 (³He+Au) > v_3 (d+Au)



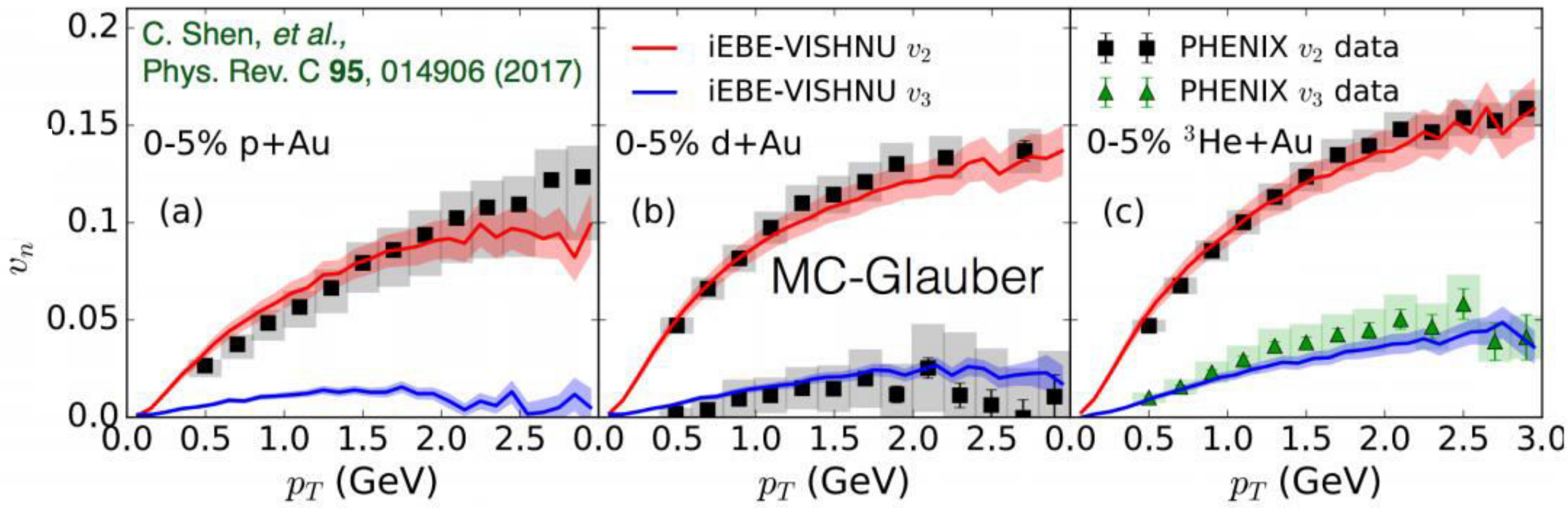


Geometry engineering – v_2 model comparison



- **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
- **AMPT (a-multiphase-transport model):**
  - MC Glauber initial conditions
  - Strings melt to partons
  - Partonic transport (partonic cross section σpart = 1.5 mb)
  - Haronization - parton coalescence
  - Hadronic rescattering (ART package)

Geometry engineering – v_2/v_3 model comparison

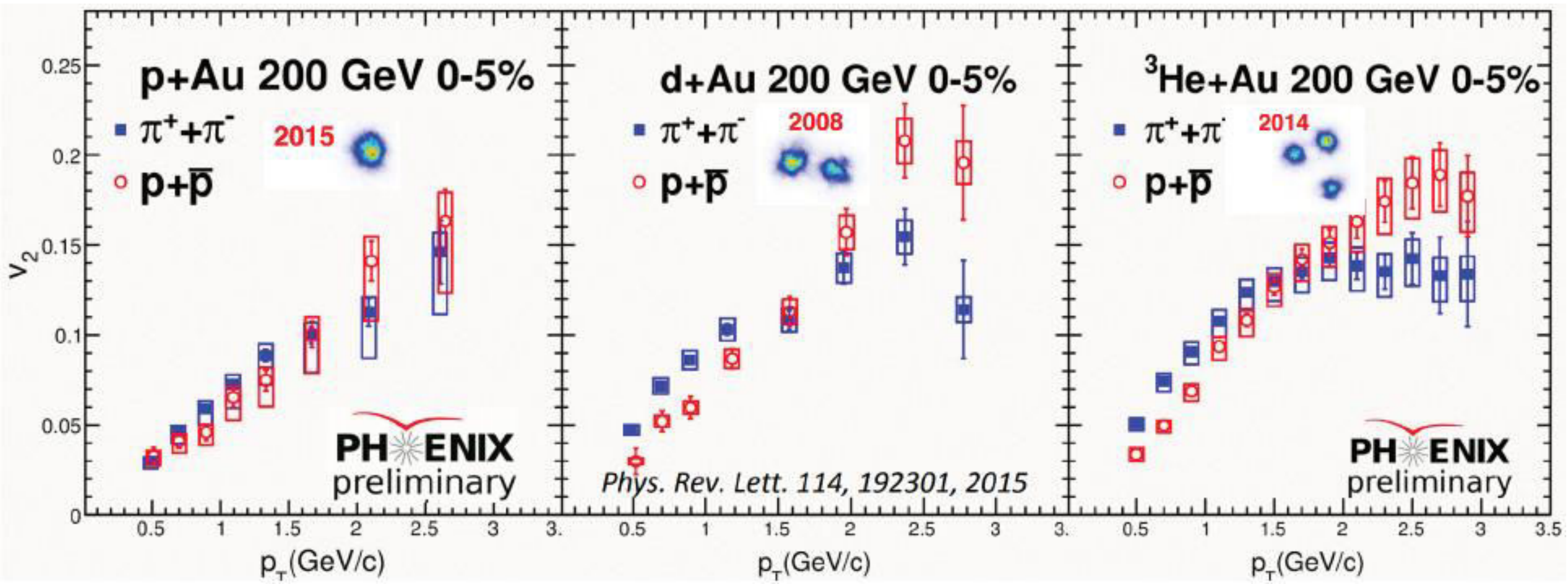


- **iEBE-VISHNU:**
  - MC Glauber initial conditions
  - 2+1d Hydro evolution starting at τ = 0.6 fm/c, η/s = 0.08
  - Hadronization at T = 155 MeV
  - Hadronic rescattering (UrQMD 3.4 package)

❖ v_2 & v_3 well described by hydrodynamics (as well as spectra)

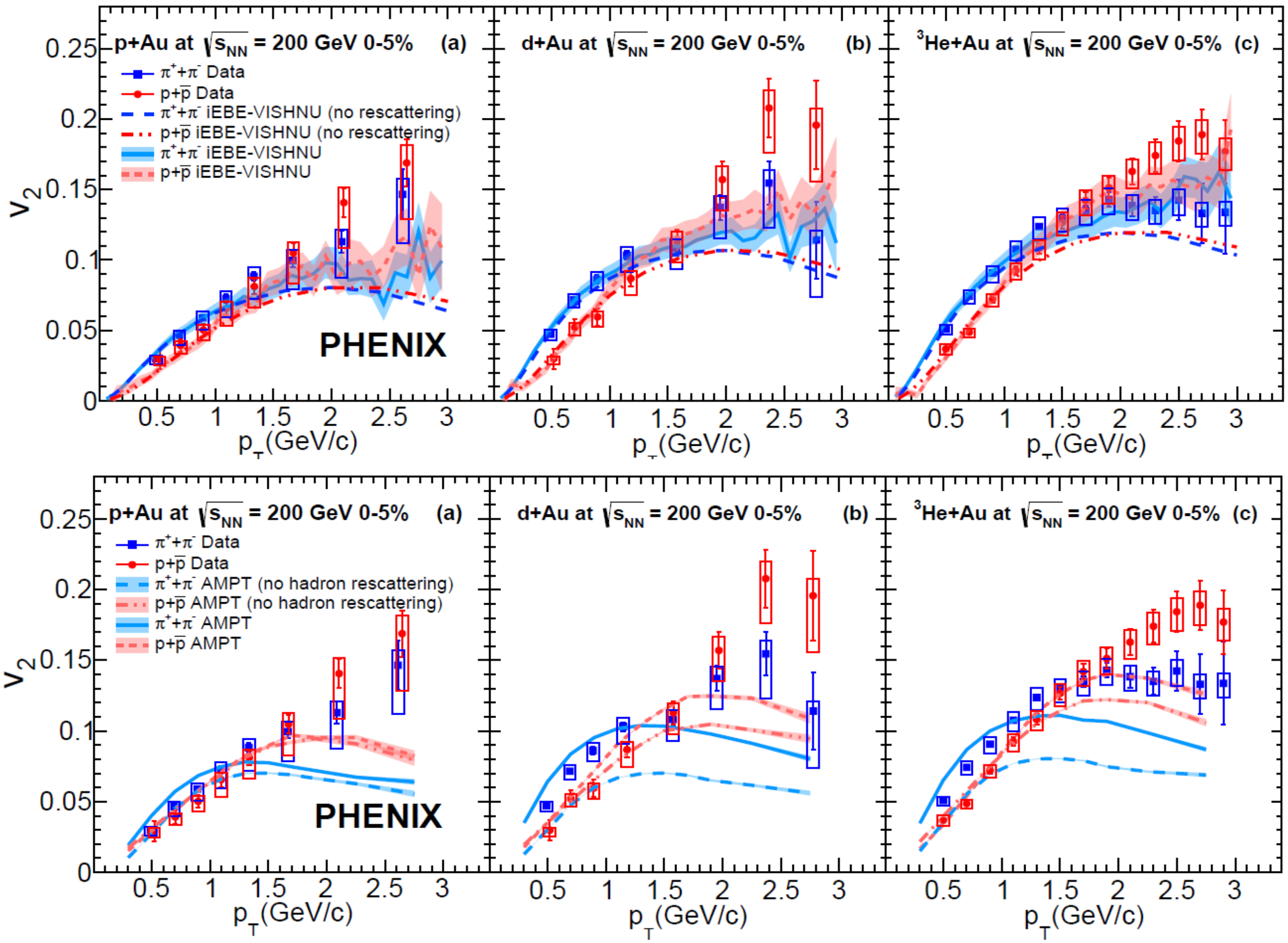
❖ System dependence described by hydro

Geometry engineering – identified hadrons



- Mass ordering for v_2 is observed
- Ordering is more prominent in d/^{3}He+Au

Geometry engineering – v_2 model comparison



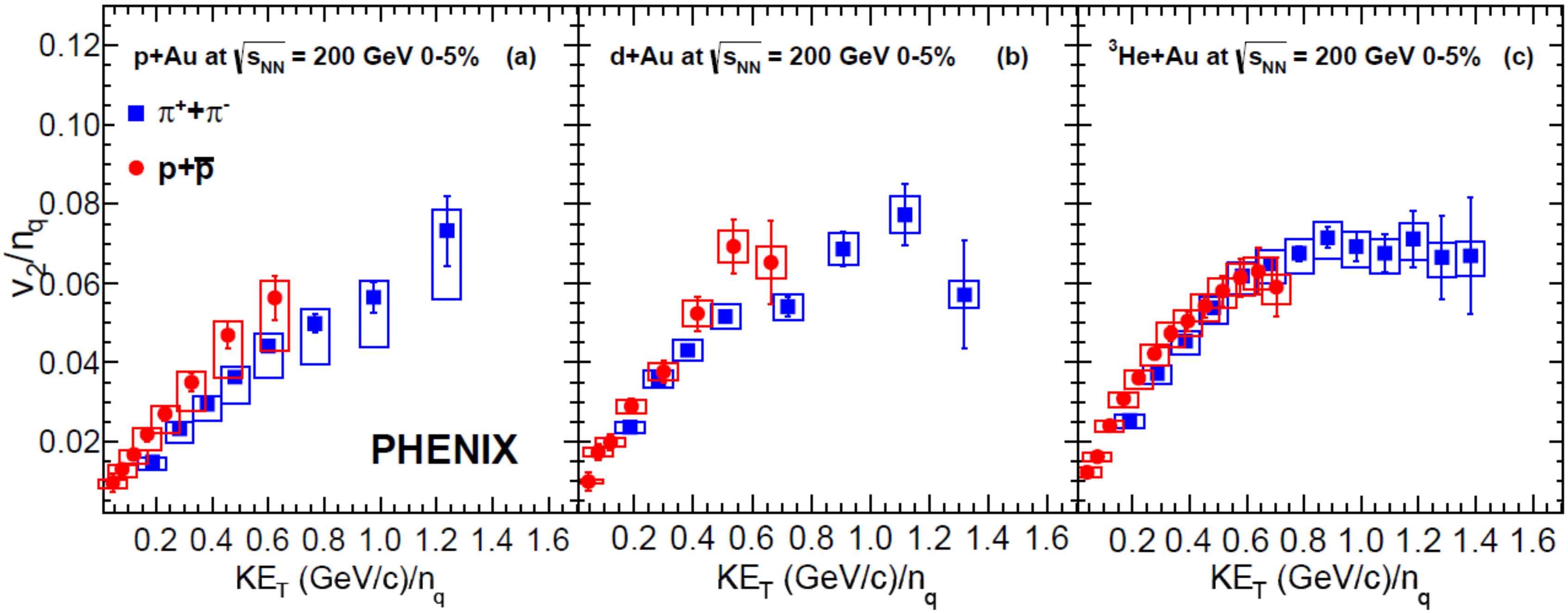
Hadronic rescattering models

iEBE-VISHNU:	**UrQMD**
SONIC:	**B3D**
AMPT:	**ART**

- Mass ordering at low p_T is well described by hydro and AMPT models
- AMPT is not adequate at higher p_T (B/M)

- Mass ordering at low p_T is not sensitive to hadronic rescattering in hydro models and is totally driven by rescattering in AMPT model
- Mass ordering at higher p_T is driven by hadronic rescattering in hydro models and by partonic coalescence in AMPT

Geometry engineering – n_q scaling

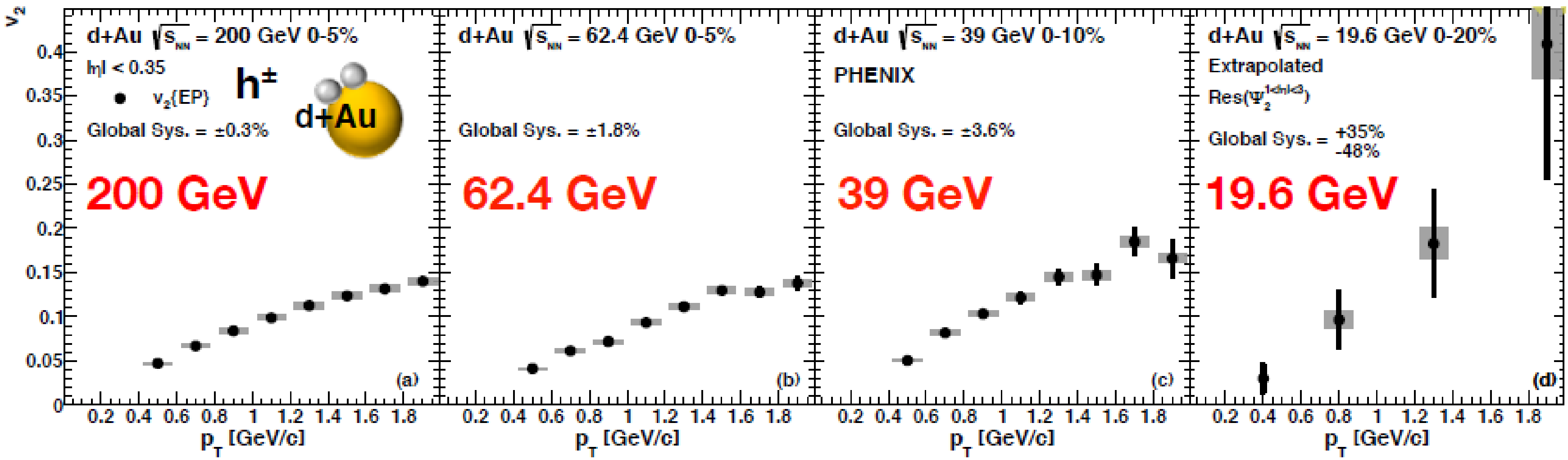


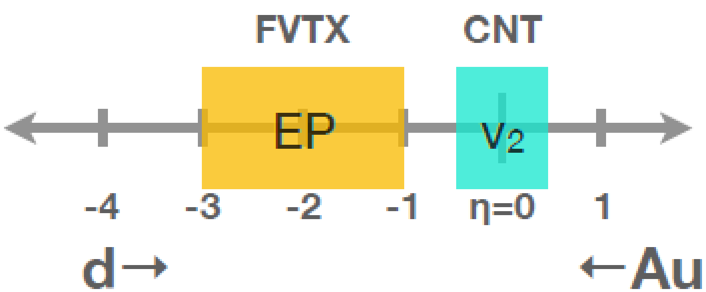
- Measurements for identified hadrons follow the n_q scaling within uncertainties
- Better agreement in d/^{3}He+Au collisions

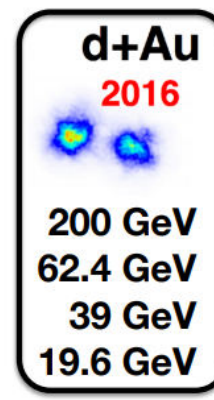
Geometry engineering - summary

1. Final State Anisotropy = Initial Geometry + Final State Interactions
2. Mechanisms of transformation of initial geometry in final state momentum anisotropy is not unique
3. The mass ordering, n_q-scaling show similarity to A+A and indicate a collective behavior in small systems

Energy scan – charged hadrons

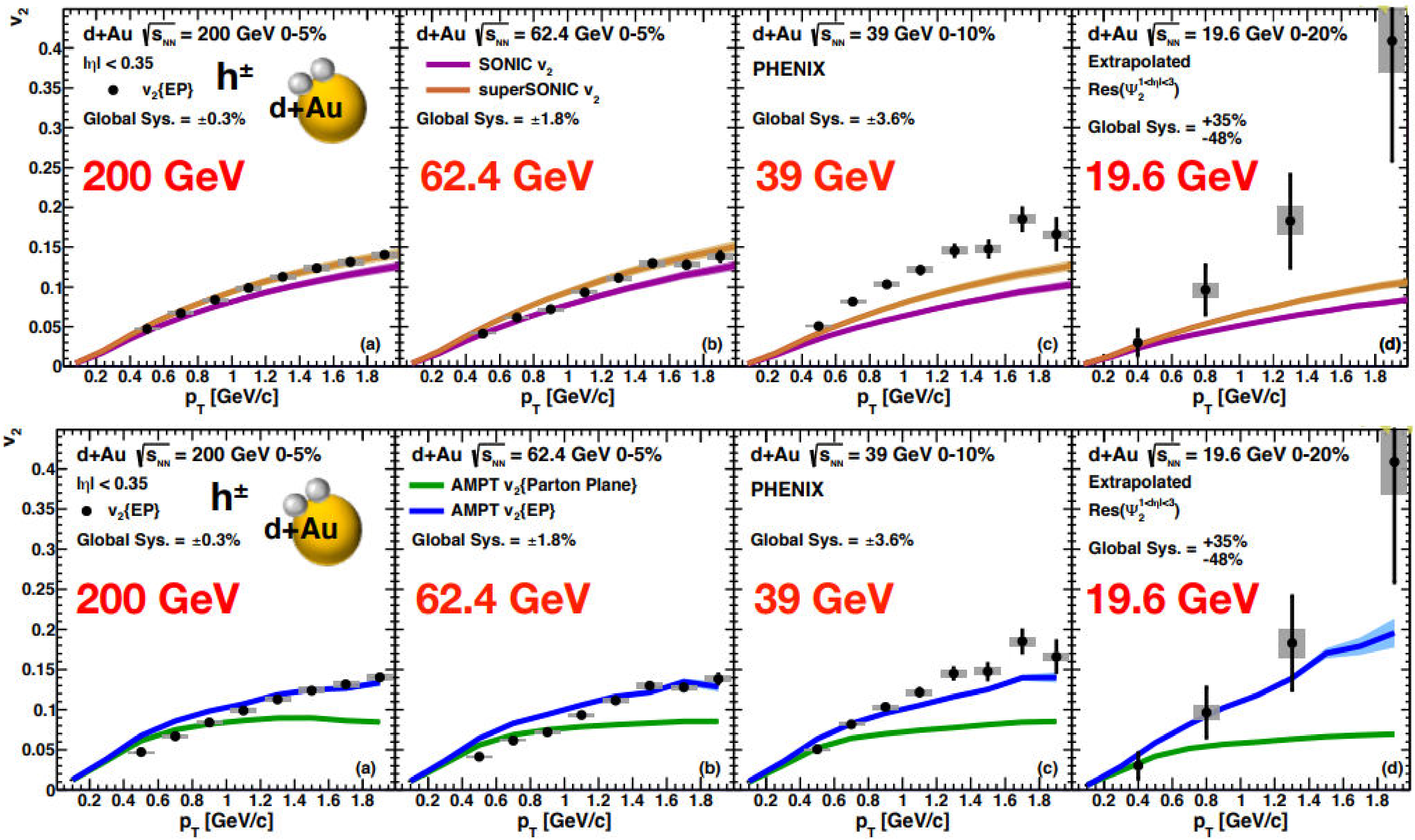






- How does the flow depend on collision energy?
- Significant v_2 signal at all 4 energies (20, 62.4, 39, 19.6 GeV)!
- Results are not corrected for non-flow contributions (neither included in systematic uncertainties)

Energy scan – v_2 model comparison



❖ Hydro in good agreement at 200 & 62.4 GeV; under predicts data at 39 & 19.6 GeV

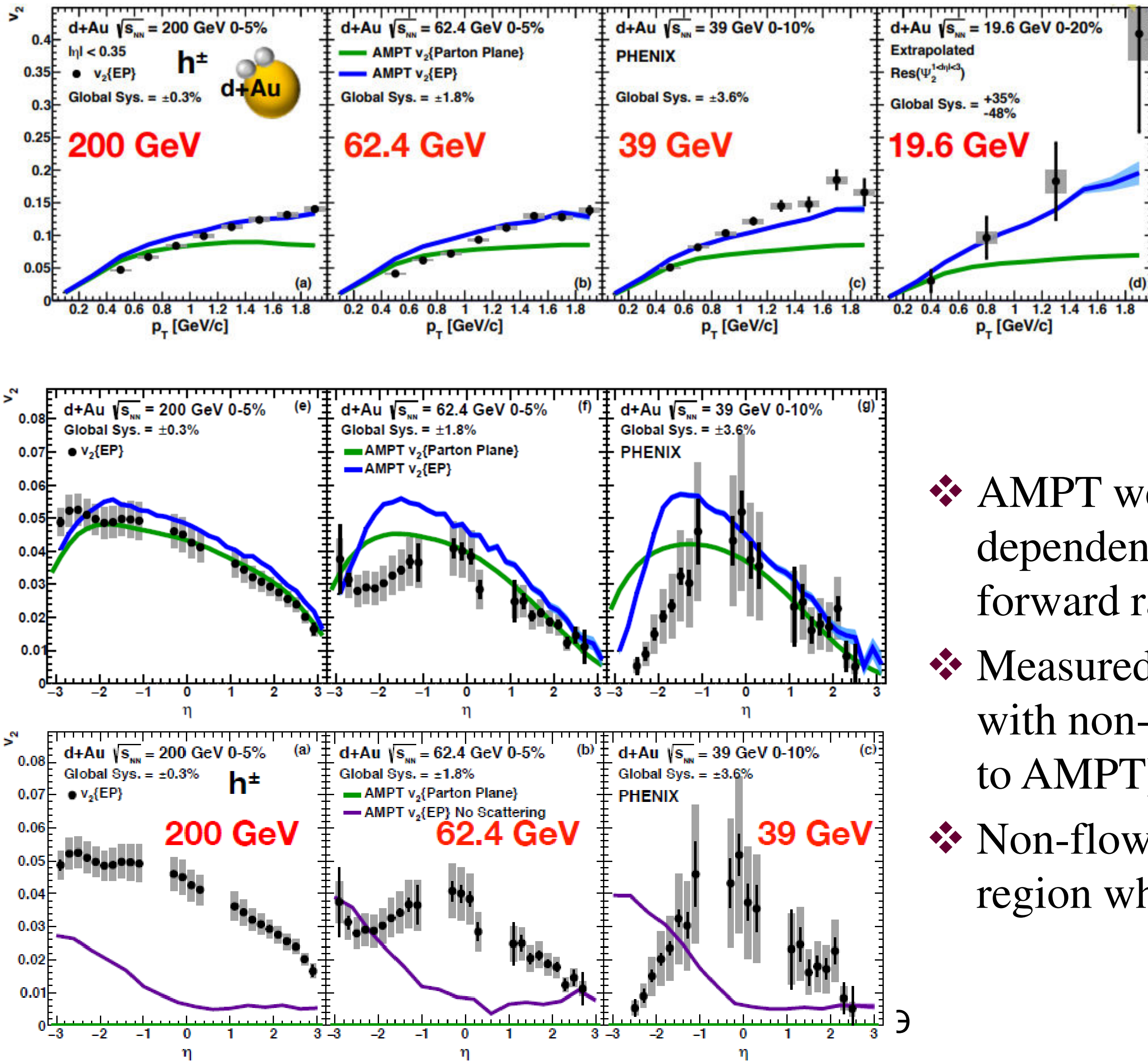
❖ Comparison to AMPT:

AMPT v_2 {Parton Plane}: ← Flow

AMPT v_2 {EP}: ← Flow ⊗ Non-flow

→ Strong v2 signal even at 19.6 GeV … interpretation is complicated by non-flow

Energy scan – v_2 model comparison



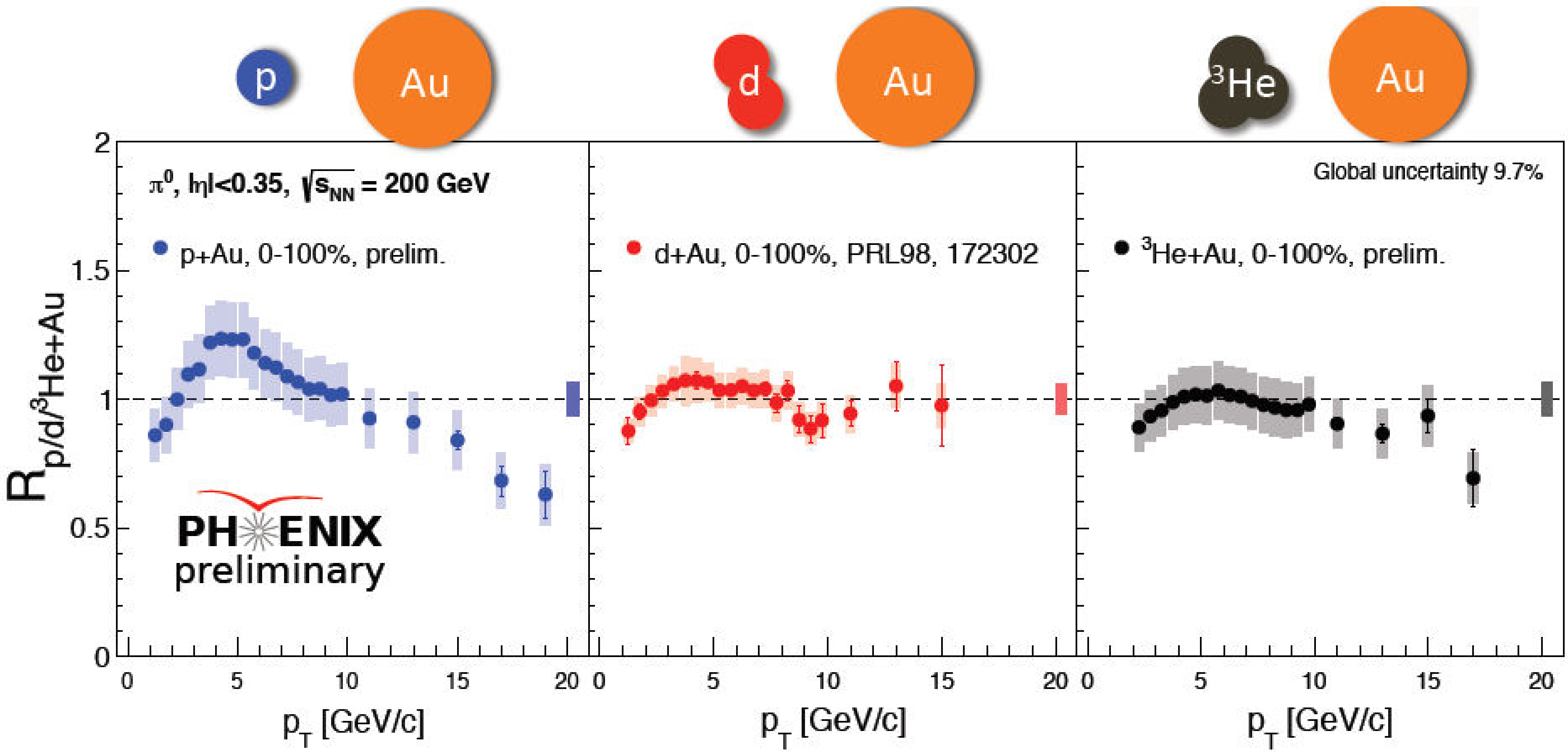
- AMPT well describes rapidity dependence at central and forward rapidity
- Measured signal is inconsistent with non-flow only! (according to AMPT)
- Non-flow is greatest near the region where the

Energy scan – summary

1. Evidence of collectivity even at 19.6 GeV
2. Interpretation of results is complicated by non-flow

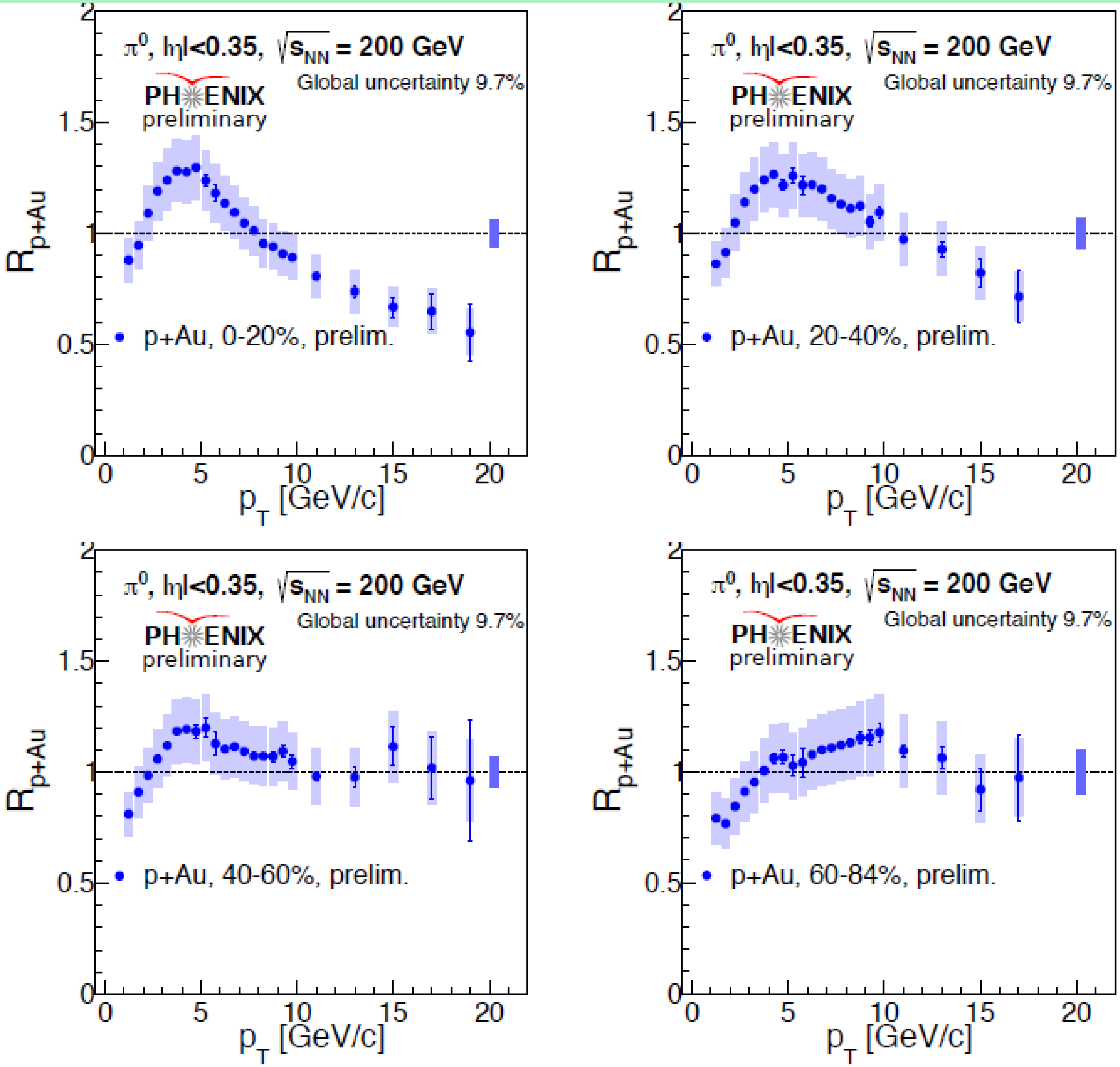
Energy loss

Nuclear modification, R_{AA} in p/d/^{3}He+Au



- Enhancement at p_T ~ 5 GeV/c, system size dependence
- Is there a hint of suppression at high p_T?

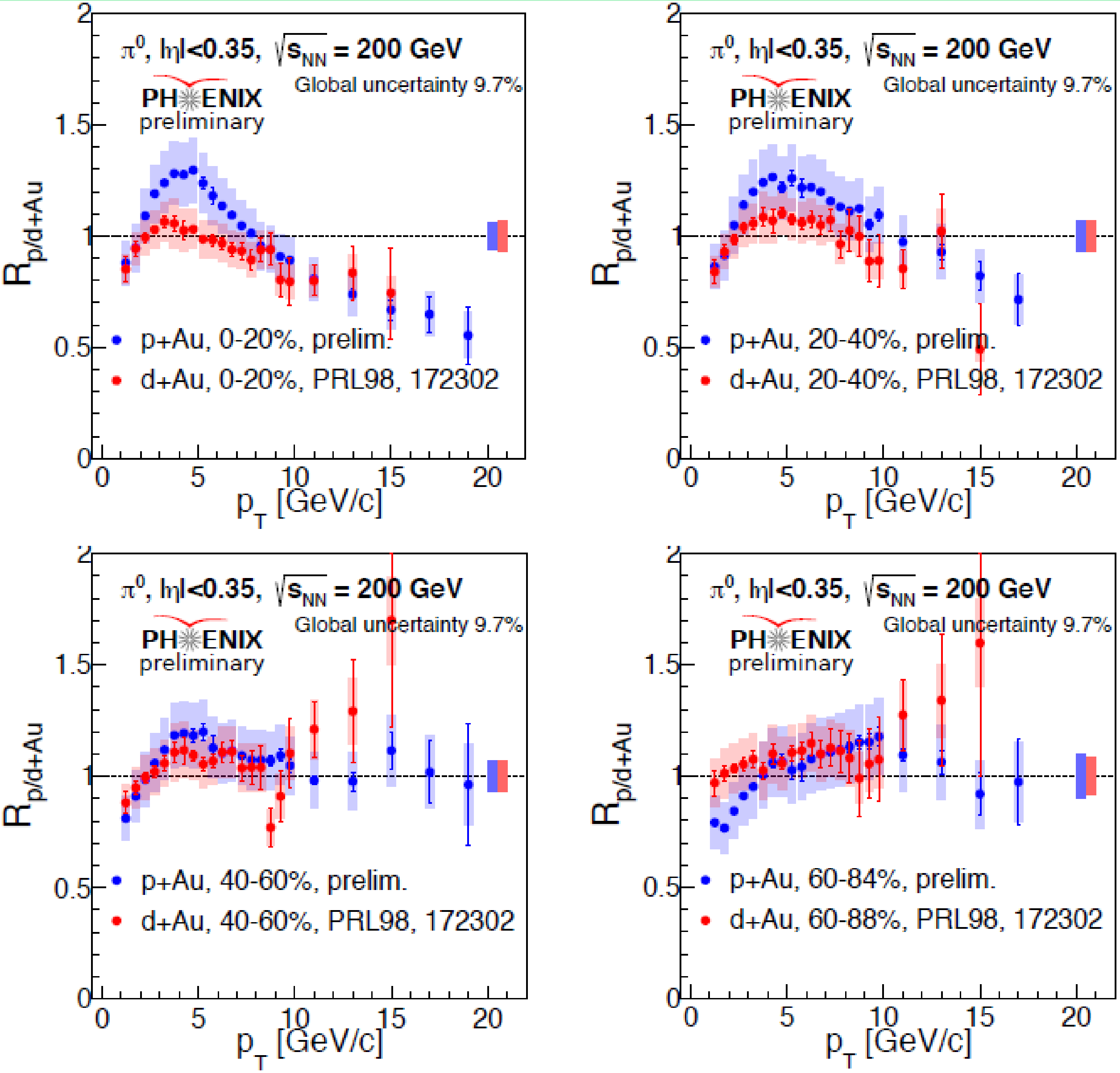
R_{AA} in p/d/^{3}He+Au, centrality dependence



Nuclear modification in centralities:

- Centrality determined similarly as for large systems (PRC90,034902)
- **p+Au results show large centrality dependence**

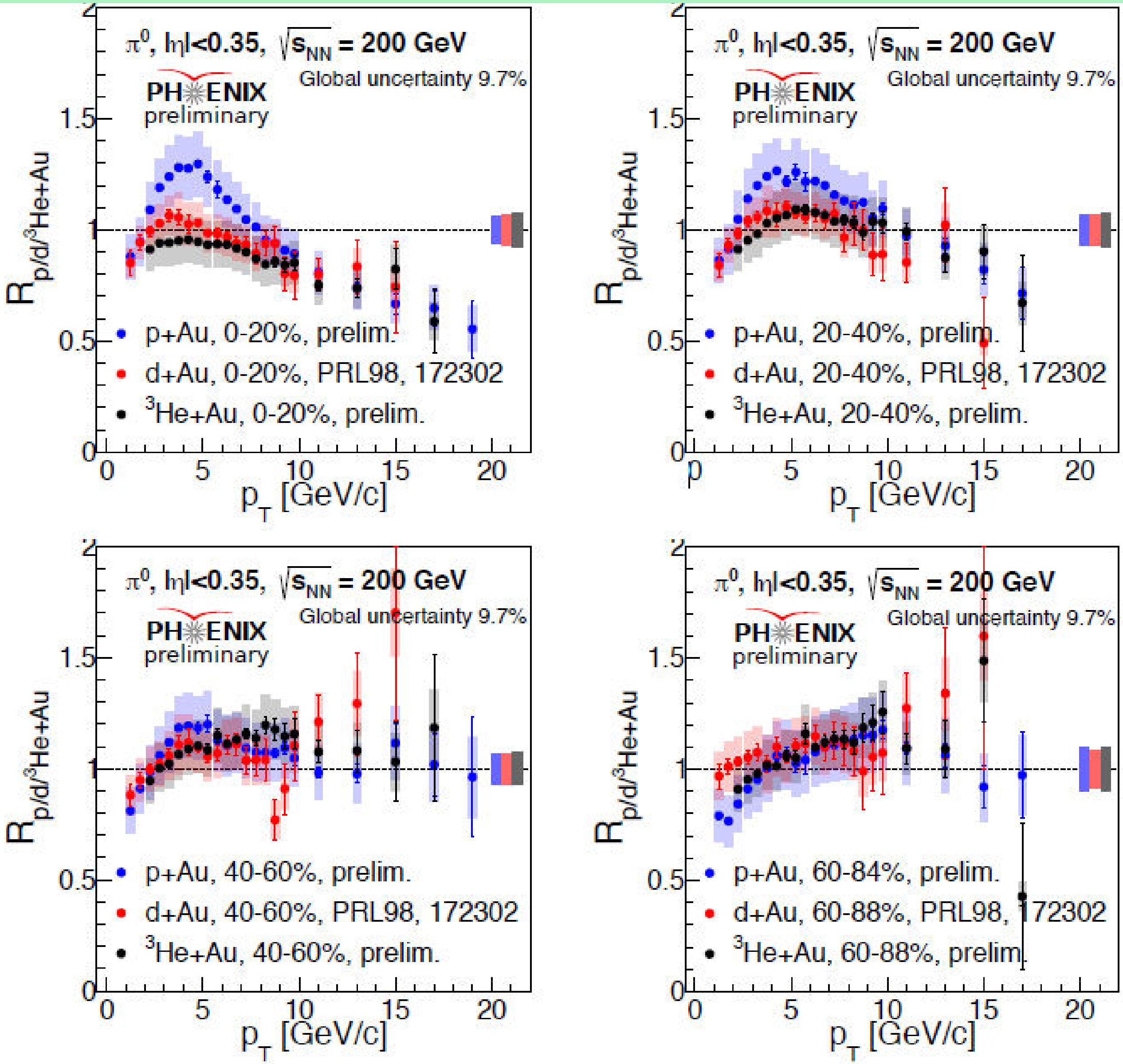
R_{AA} in p/d/^{3}He+Au, centrality dependence



Nuclear modification in centralities:

- Centrality determined similarly as for large systems (PRC90,034902)
- **p+Au results show large centrality dependence**
- **d+Au results agree with p+Au at high-p_T**

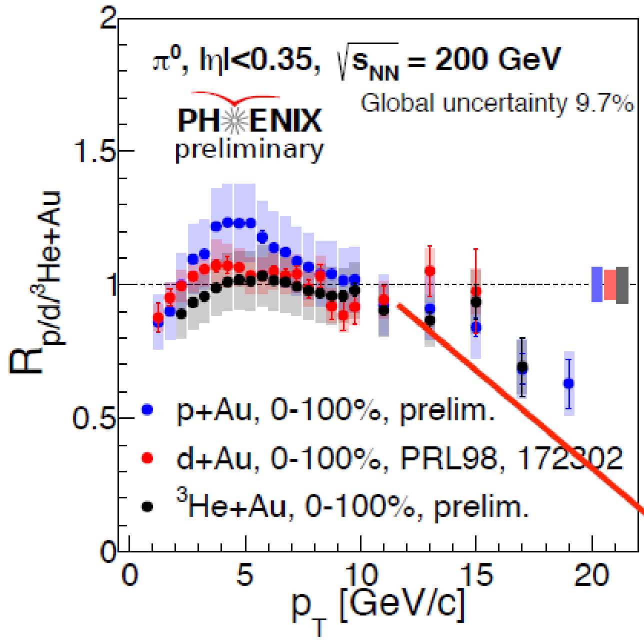
R_{AA} in p/d/^{3}He+Au, centrality dependence



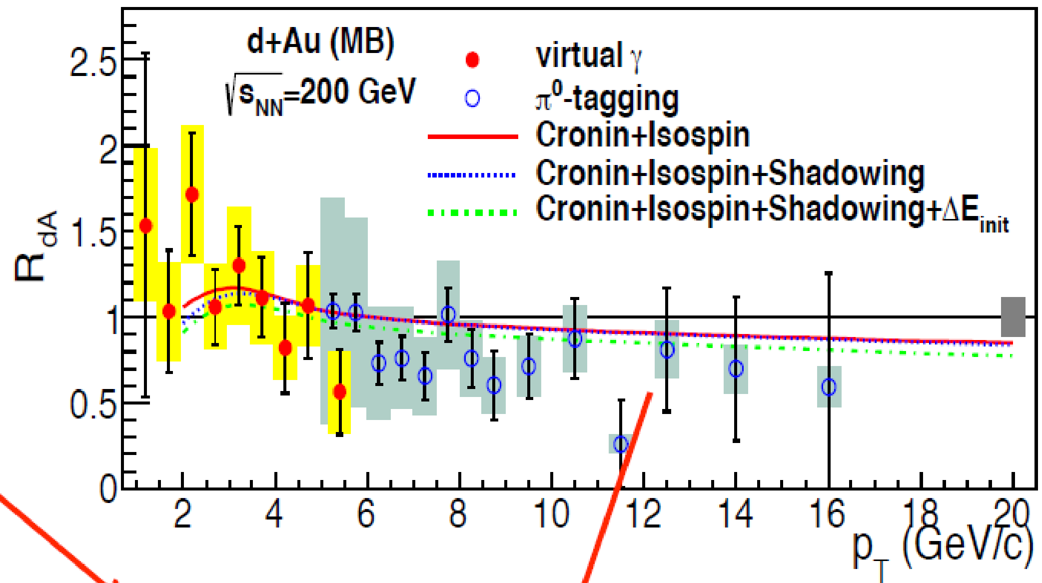
Nuclear modification in centralities:

- Centrality determined similarly as for large systems (PRC90,034902)
- **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**
- **At moderate p_T an ordering is seen in most central collisions**

Nuclear modification, R_{AA} in p/d/^{3}He+Au



Phys. Rev. C **87,** 054907



At high-p_T they are consistent with 0.85

	p+Au	d+Au	^{3}He+Au
N_{Coll}	4.67	7.59	10.4
Bias Factor	0.86	0.89	0.89

- $R_{AA}{}^{h} \sim R_{AA}{}^{\gamma}$

Conclusions

- Strong evidence for initial geometry translating to hadronic momentum anisotropy through final state interactions
- Both hydro and AMPT similarly describe v_2 and mass splitting at low p_T but the origin of the effect is quite different
- Energy loss is not yet conclusive

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)

Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil
China Institute of Atomic Energy (CIAE), Beijing, People's Republic of China
Peking University, Beijing, People's Republic of China
University of Zagreb, Faculty of Science, Horvatovac 102a, HR-10000 Zagreb, Croatia
Charles University, Ovocnytrh 5, Praha 1, 116 36, Prague, Czech Republic
Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland
Dapnia, CEA Saclay, F-91191, Gif-sur-Yvette, France
Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
Laboratoire de Physique Corpusculaire (LPC), Université Blaise Pascal, CNRS-IN2P3,
Clermont-Fd, 63177 Aubiere Cedex, France
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France
Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
ELTE, Eötvös Loránd University, H - 1117 Budapest, Pázmány P. s. 1/A, Hungary
KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences (MTA KFKI RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary
Department of Physics, Banaras Hindu University, Varanasi 221005, India
Bhabha Atomic Research Centre, Bombay 400 085, India
Weizmann Institute, Rehovot 76100, Israel
Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
Advanced Science Research Center, Japan Atomic Energy Agency, 2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
Kyoto University, Kyoto 606-8502, Japan
Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan
RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
INR_RAS, Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
National Research Nuclear University, MEPhI, Moscow Engineering Physics Institute, Moscow, 115409, Russia
Russian Research Center "Kurchatov Institute", Moscow, Russia
PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
Saint Petersburg State Polytechnic University, St. Petersburg, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Vorob'evy Gory, Moscow 119992, Russia
Chonbuk National University, Jeonju, South Korea
Ewha Womans University, Seoul 120-750, South Korea
Hanyang University, Seoul 133-792, South Korea
Korea University, Seoul, 136-701, South Korea
Accelerator and Medical Instrumentation Engineering Lab, SungKyunKwan University, 53 Myeongnyun-dong, 3-ga, Jongno-gu, Seoul, South Korea
Myongji University, Yongin, Kyonggido 449-728, Korea
Department of Physocs and Astronomy, Seoul National University, Seoul, South Korea
Yonsei University, IPAP, Seoul 120-749, South Korea

14 countries, 75 institutions, Jan 2015

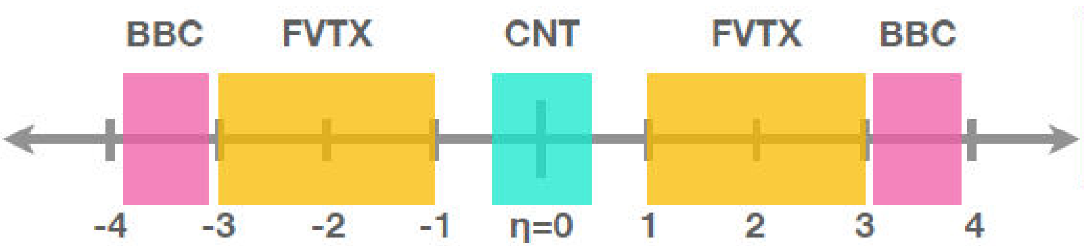
Abilene Christian University, Abilene, TX 79699, U.S.
Department of Physics, Augustana College, Sioux Falls, SD 57197
Baruch College, CUNY, New York City, NY 10010-5518, U.S.
Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
University of California - Riverside, Riverside, CA 92521, U.S.
University of Colorado, Boulder, CO 80309, U.S.
Columbia University, New York, NY 10027 and Nevis Laboratories, Irvington, NY 10533, U.S.
Florida Institute of Technology, Melbourne, FL 32901, U.S.
Florida State University, Tallahassee, FL 32306, U.S.
Georgia State University, Atlanta, GA 30303, U.S.
University of Illinois at Urbana-Champaign, Urbana, IL 61801, U.S.
Iowa State University, Ames, IA 50011, U.S.
Lawrence Livermore National Laboratory, Livermore, CA 94550, U.S.
Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.
University of Maryland, College Park, MD 20742, U.S.
Department of Physics, University of Massachusetts, Amherst, MA 01003-9337, U.S.
Department of Physics, University of Michigan, Ann Arbor, MI 48109-1040
Morgan State University, Baltimore, MD 21251, U.S.
Muhlenberg College, Allentown, PA 18104-5586, U.S.
University of New Mexico, Albuquerque, NM 87131, U.S.
New Mexico State University, Las Cruces, NM 88003, U.S.
Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.
Department of Physics and Astronomy, Ohio University, Athens, OH 45701, U.S.
RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
Chemistry Department, Stony Brook University,SUNY, Stony Brook, NY 11794-3400, U.S.
Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, NY 11794, U.S.
University of Tennessee, Knoxville, TN 37996, U.S.
Vanderbilt University, Nashville, TN 37235, U.S.
Department of Physics and Astronomy, Howard University, 2355 6th St. NW, Washington, DC 20059, U.S.

PHENIX

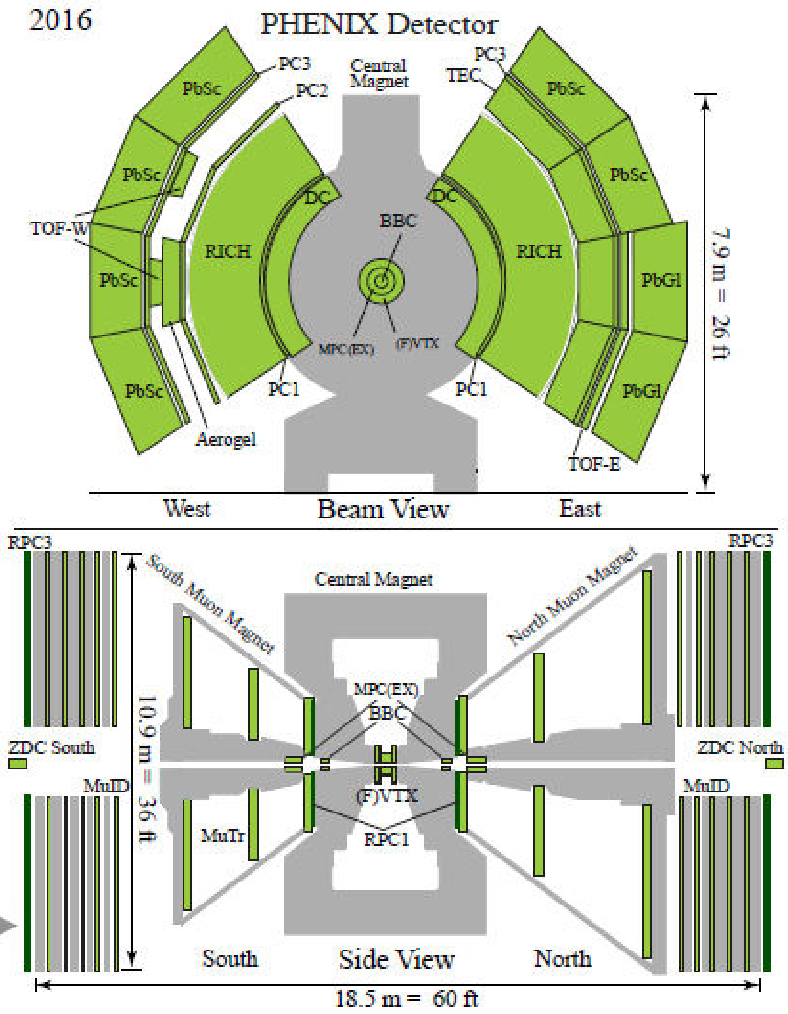
CNT - **Charged particle tracking**

FVTX - **Unidentified particle tracking Cluster (Event Plane)**

BBC - **Clusters (Event Plane) Centrality determination**



$p/d/^{3}He \rightarrow$ **$\leftarrow Au$**



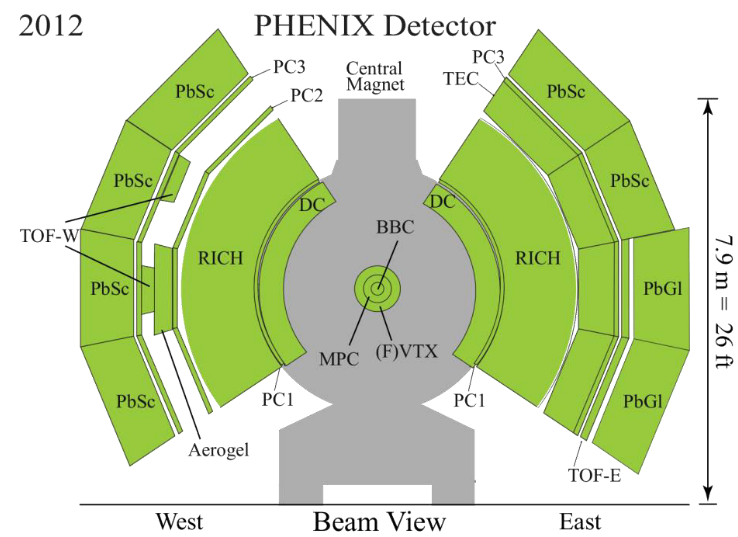
PHENIX setup

❖ Центральные спектрометры:

- ✓ центральный магнит (Ижорский завод)
- ✓ дрейфовые камеры (ПИЯФ, Гатчина)
- ✓ падовые камеры (PC1, PC2, PC3)
- ✓ черенковский детектор (RICH)
- ✓ электромагнитный калориметр (PbSc – ИТЭФ, PbGl - КИ)
- ✓ TRD
- ✓ TOF
- ✓ AGEL (ОИЯФ, Дубна)
- ✓ VTX/FVTX

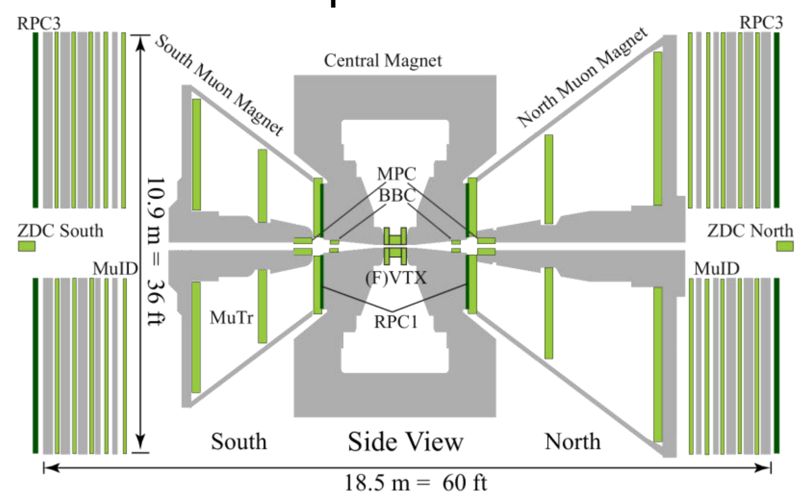
❖ Мюонные спектрометры:

- ✓ MuTr
- ✓ MuID
- ✓ MPC



$-0.35 < \eta < 0.35$

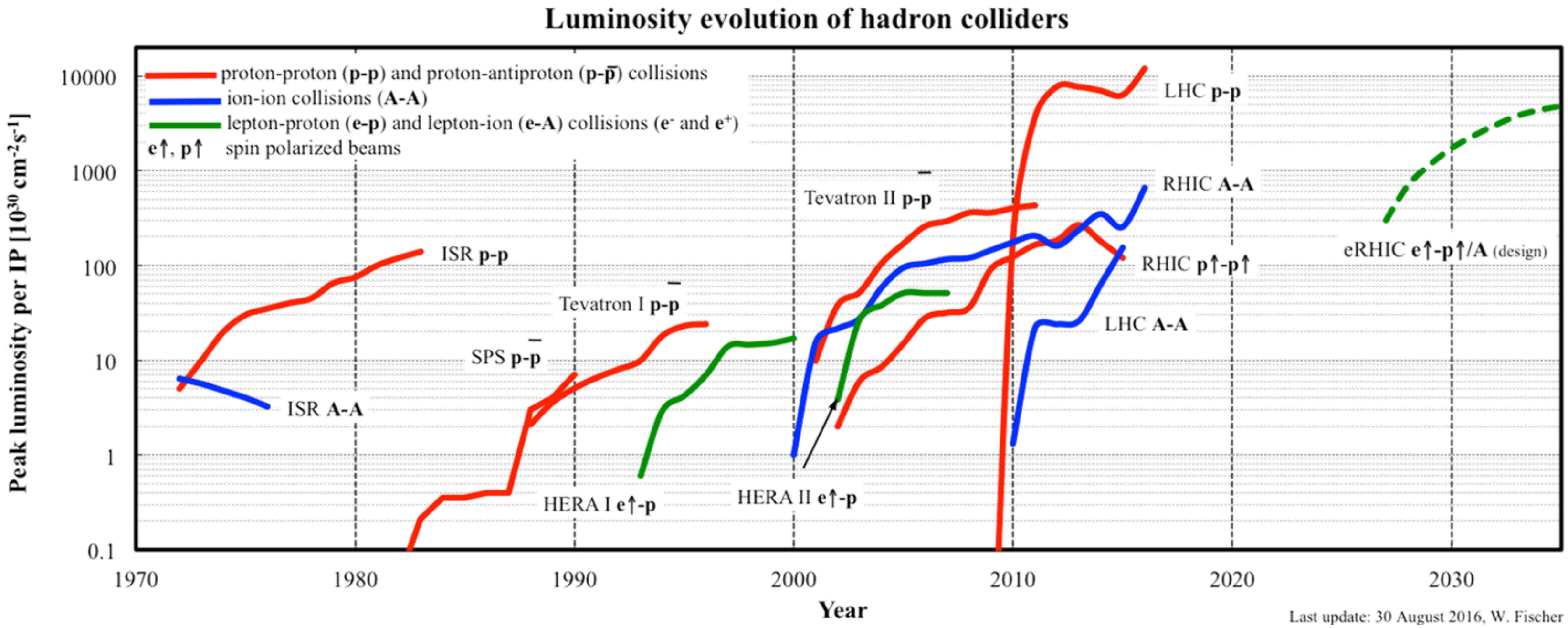
$\Delta\varphi$ - 2 x 90°



$1.2 < \eta < 2.4$

$\Delta\varphi$ - 2 x 360°

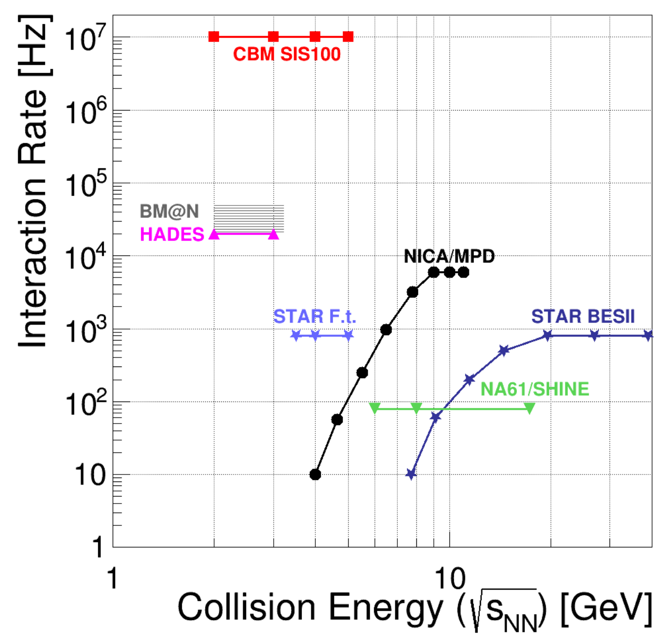
Relativistic Heavy-Ion Collided (RHIC)

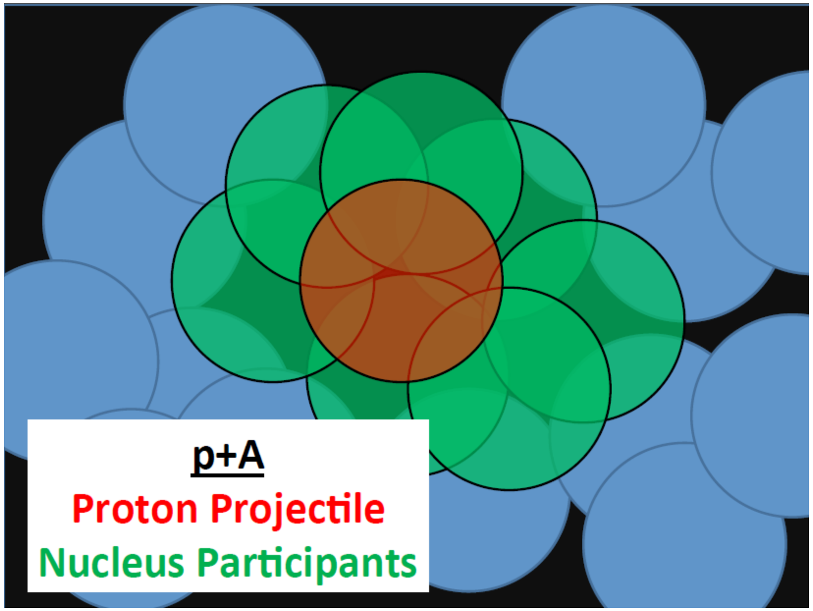


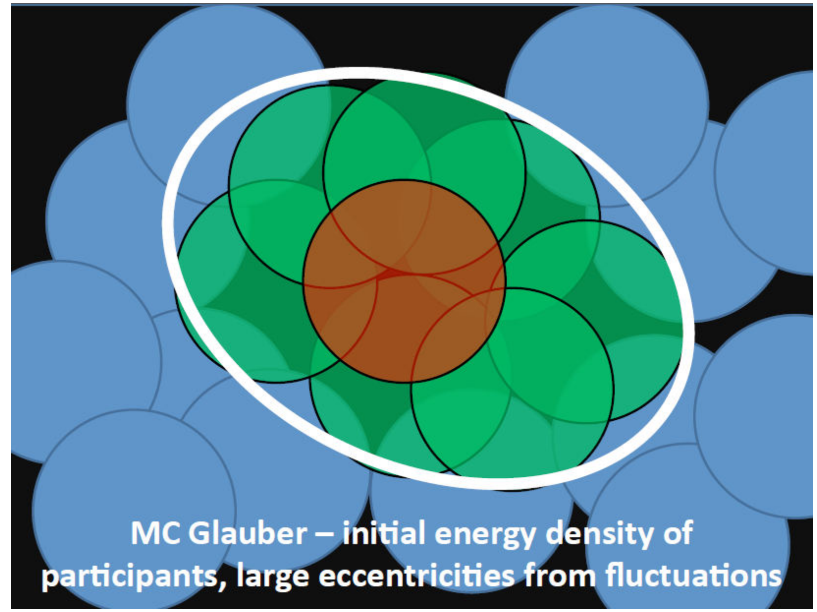
❖ Непрерывное увеличение светимости:

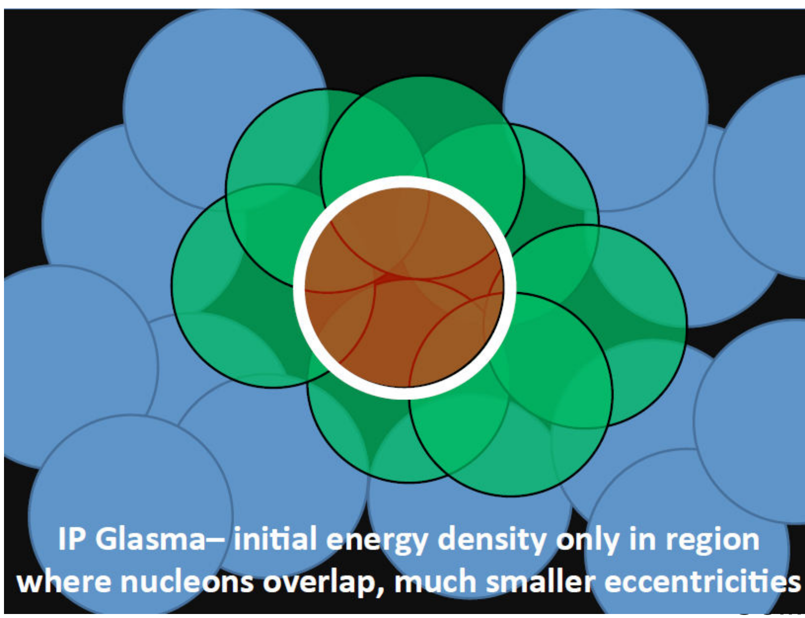
- ✓ p+p ~ 10^{32} $cm^{-2}s^{-1}$
- ✓ A+A ~ 10^{28} $cm^{-2}s^{-1}$

❖ Программа сканирования по энергиям имеет ограничения по накопленной светимости
→ необходимость в специализированных экспериментах (NICA, FAIR)



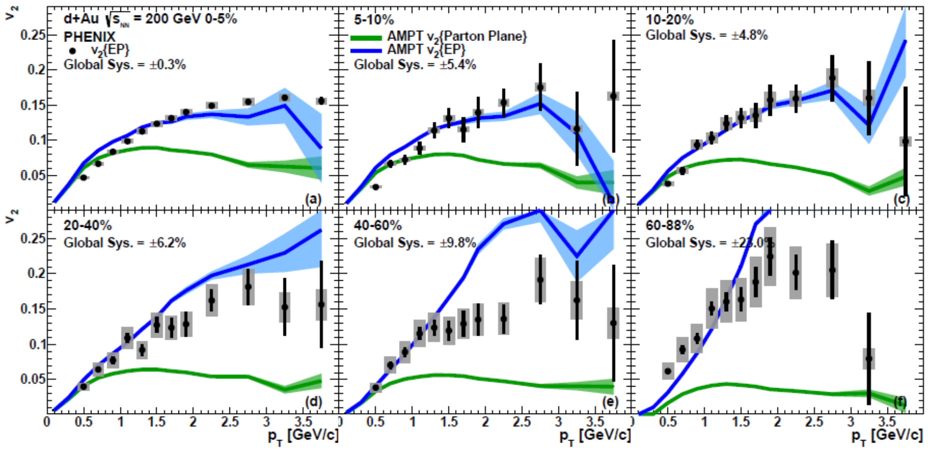

p+A
Proton Projectile
Nucleus Participants


MC Glauber – initial energy density of
participants, large eccentricities from fluctuations

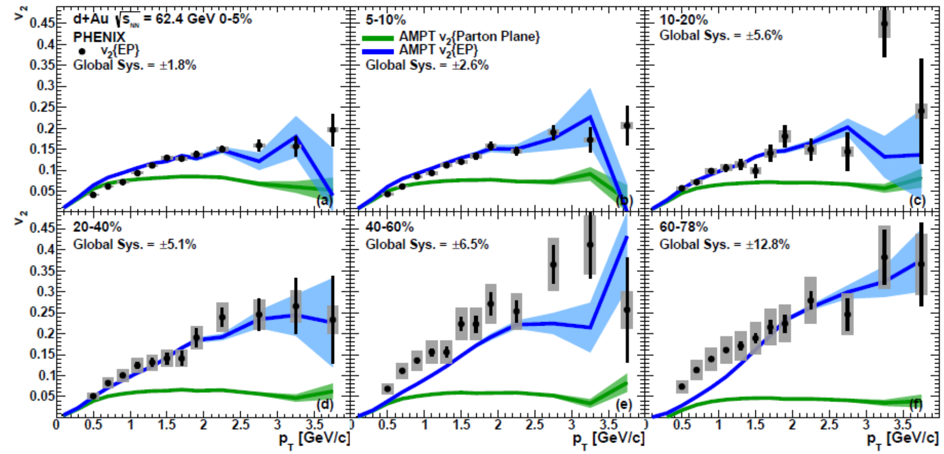

IP Glasma– initial energy density only in region
where nucleons overlap, much smaller eccentricities

Energy scan – v_2 model comparison

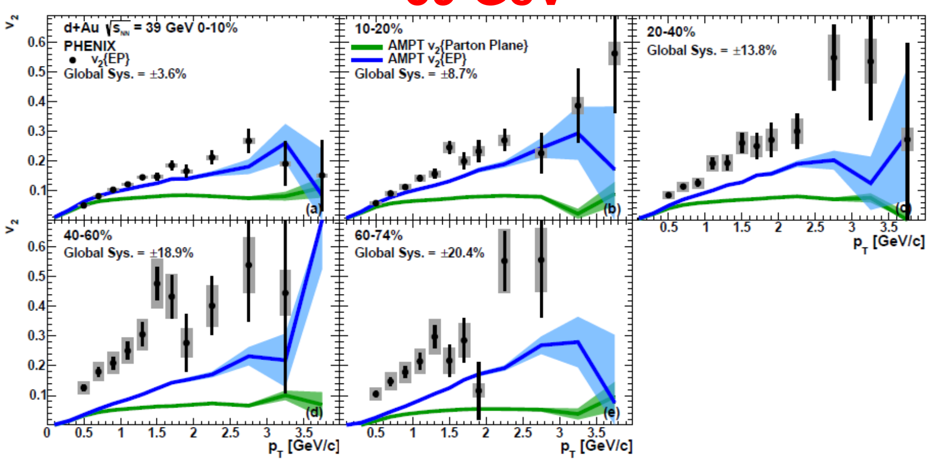
200 GeV



62 GeV



39 GeV



- v_2(EP) in AMPT reproduces general shape of data
- Non-flow contribution becomes significant in peripheral collisions and/or high p_T
- At lower collision energies v_2(EP) in AMPT starts to underestimate v_2, especially at high p_T or peripheral collisions