HEAVY ION PHYSICS WITH FLOW IN LARGE AND SMALL SYSTEMS

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UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA 1635

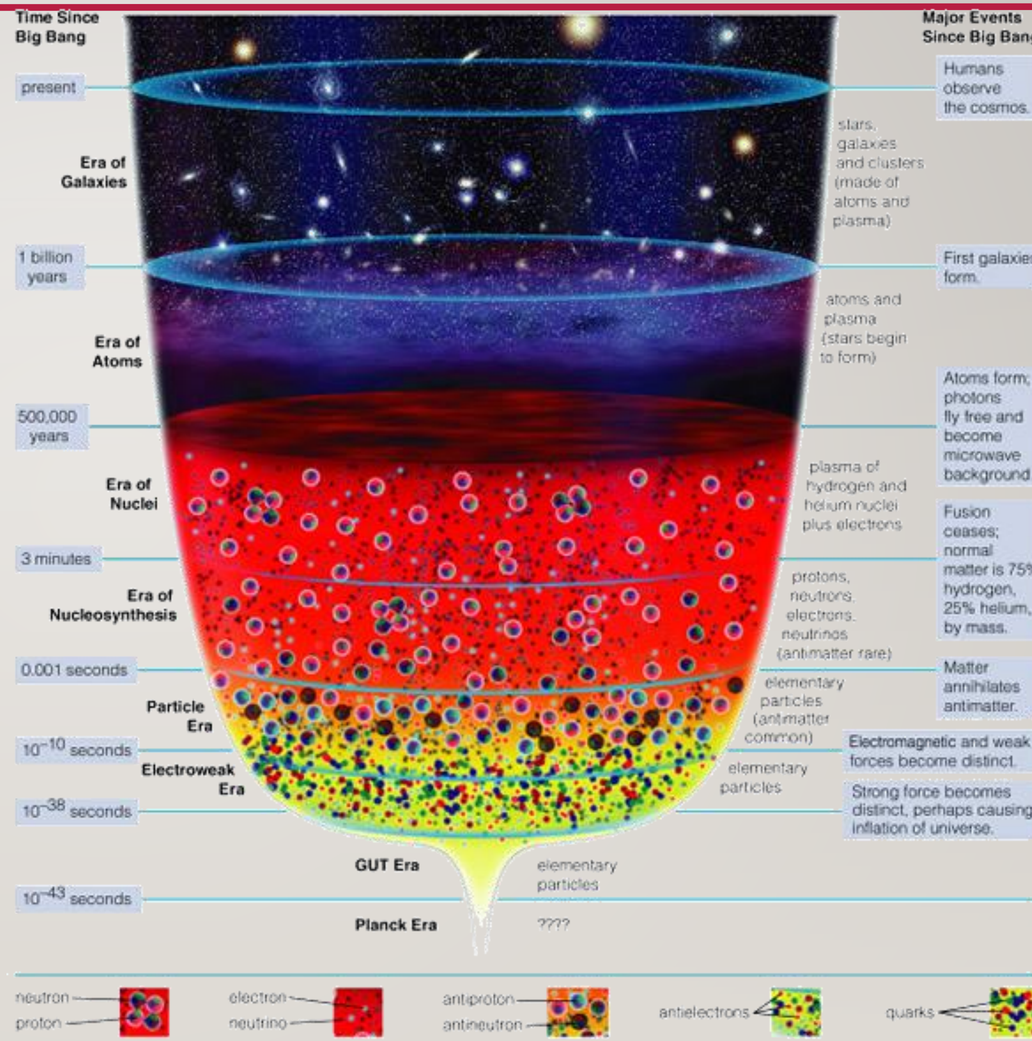
PHENIX

CONTENT OF THIS TALK

- INTRODUCTION
  - The Big Bang and the Little Bangs in the lab
  - Experimental control parameters
  - RHIC and PHENIX
- BASIC OBSERVATIONS
  - Nuclear modification, flow, thermal photons, heavy flavor, HBT, fluctuations
- FLOW IN SMALL SYSTEMS
  - d+Au energy scan, p+Pb and p+p at the LHC
  - p/d/^{3}He geometry scan
  - Smallest droplets of QGP

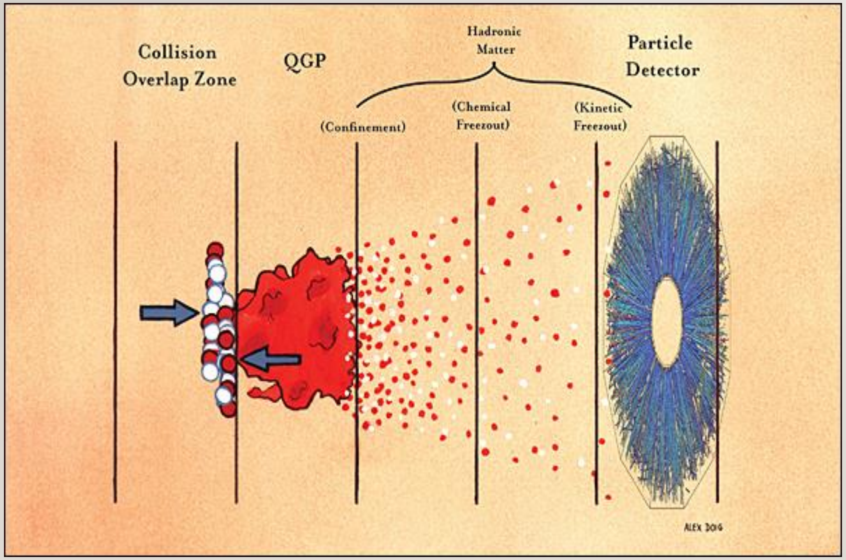
3/29 BIG BANG IN THE LAB

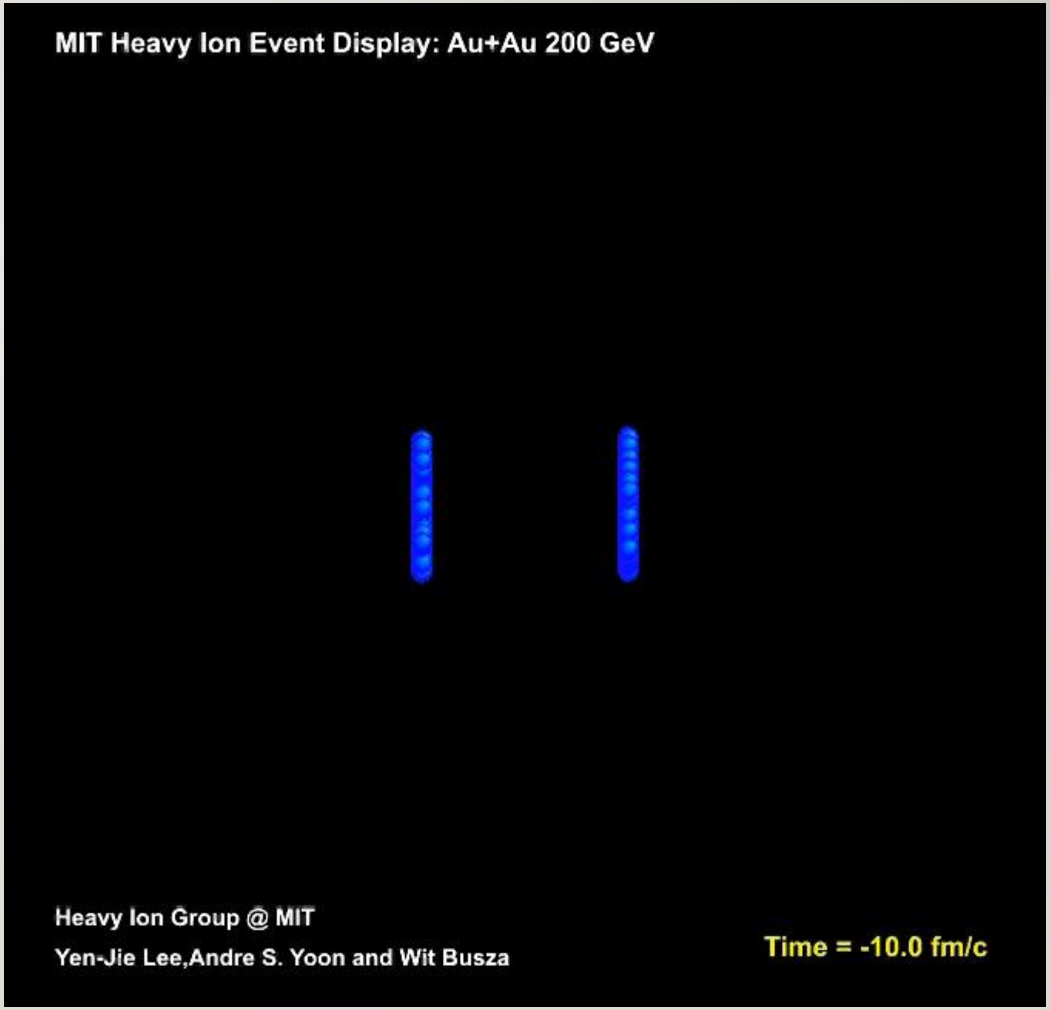
- Ages of the Universe:
  - Stars & Galaxies
  - Atoms
  - Nuclei
  - Nucleosynthesis
  - Elementary particles
  - … ?
- How to investigate?
- Create little bangs
- Collisions of heavy ions
- Record outcoming particles



TIMELINE OF A HEAVY ION COLLISION

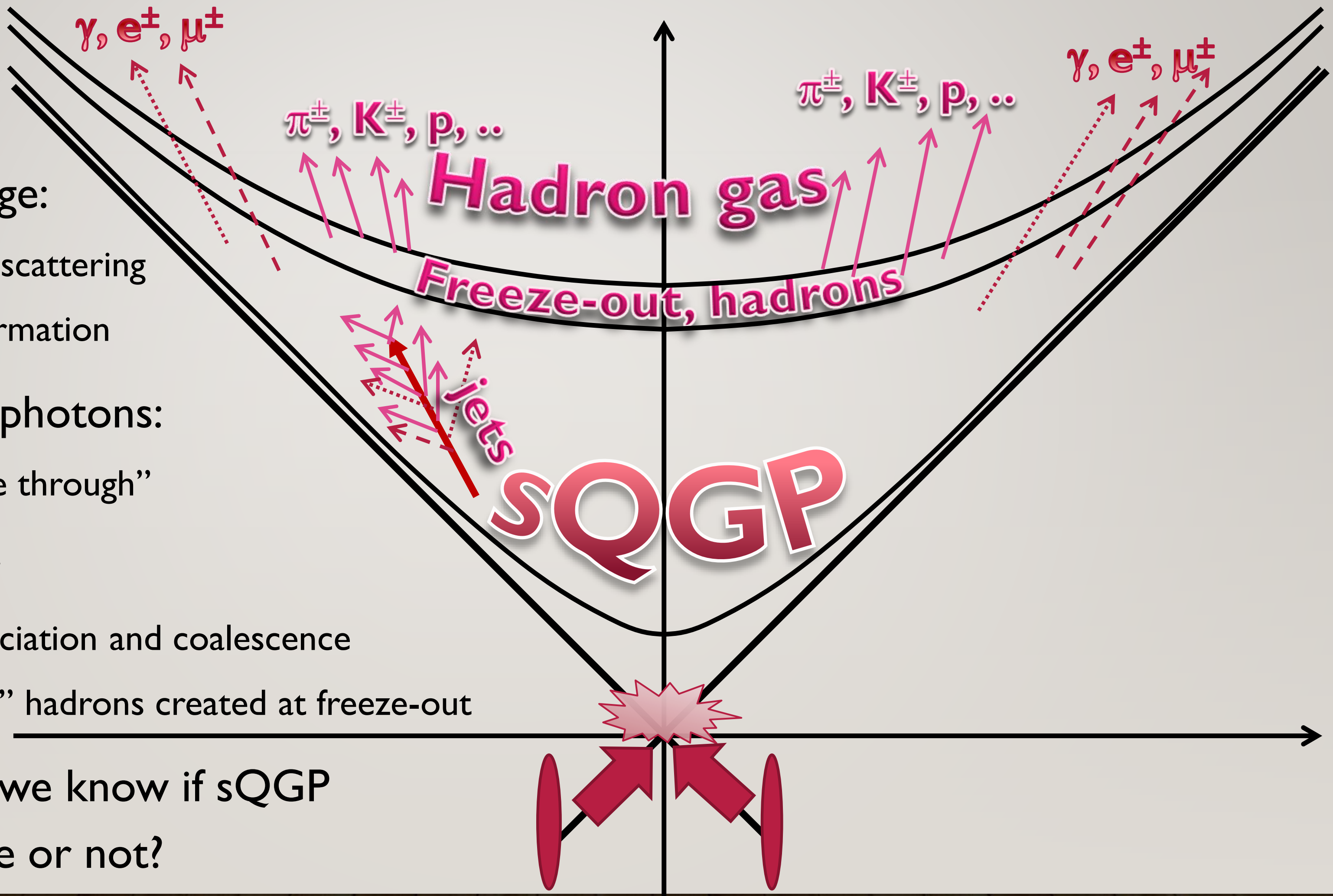
- Pre-thermalization stage: ~1 fm/c
- Quark-hadron transition: ~7-10 fm/c
- Chemical + kinetic freeze-out





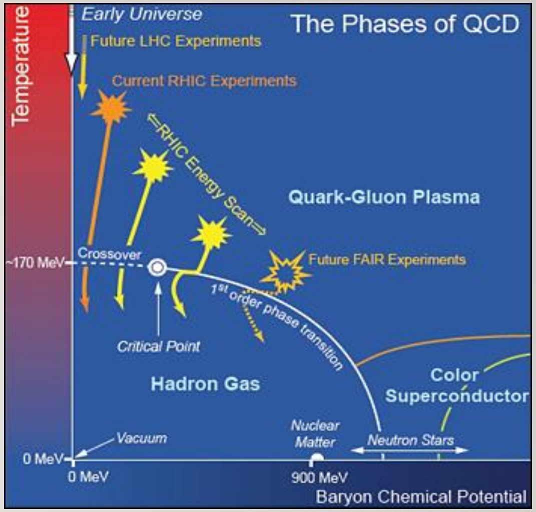
5/29 TIME EVOLUTION OF A HEAVY ION COLLISION

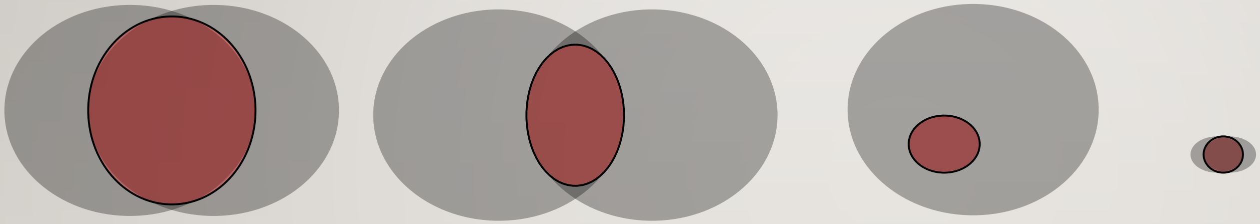
- Initial stage:
  - Hard scattering
  - Jet formation
- Leptons, photons:
  - ”shine through”
- Hadrons:
  - Dissociation and coalescence
  - ”Final” hadrons created at freeze-out
- How do we know if sQGP was there or not?



EXPERIMENTAL CONTROL PARAMETERS

- Collision energy: controls initial temperature, initial μ_B
- Collision system & centrality: controls available volume
- Event geometry: reaction plane, event plane, fluctuations
- Important parameters: N_{part} (system size), N_{coll} (x-sect)



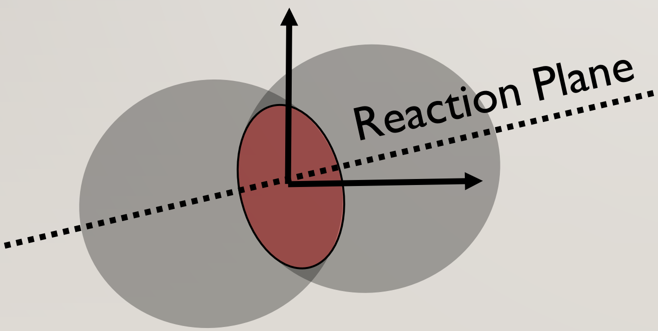


Central Au+Au
N_{part}~300

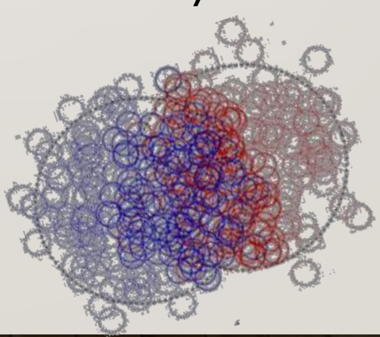
Peripheral Au+Au
N_{part}~50

d+Au

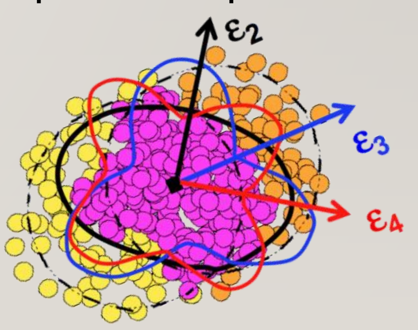
p+p



Reality

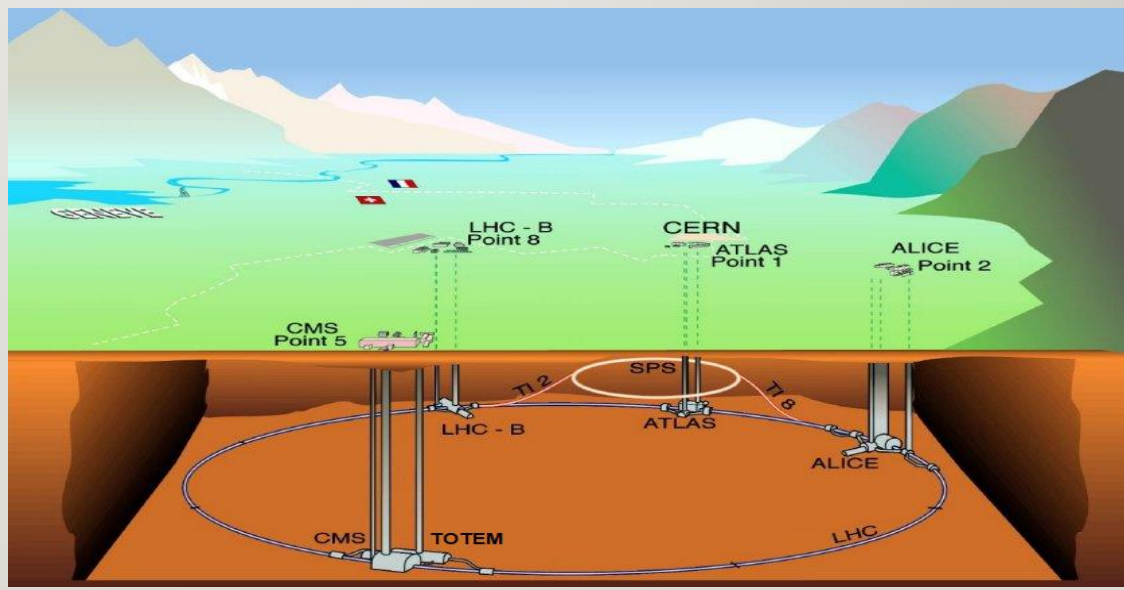


Multipole event planes



FACILITIES: LARGE HADRON COLLIDER (+SPS)

- LHC collisions: p+p, p+Pb and Pb+Pb
- Energies: from 2.76 TeV/nucleon to 13 TeV (p+p only)
- Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL, TOTEM
- Phase diagram related studies: SPS (NA61/SHINE, previously NA49)

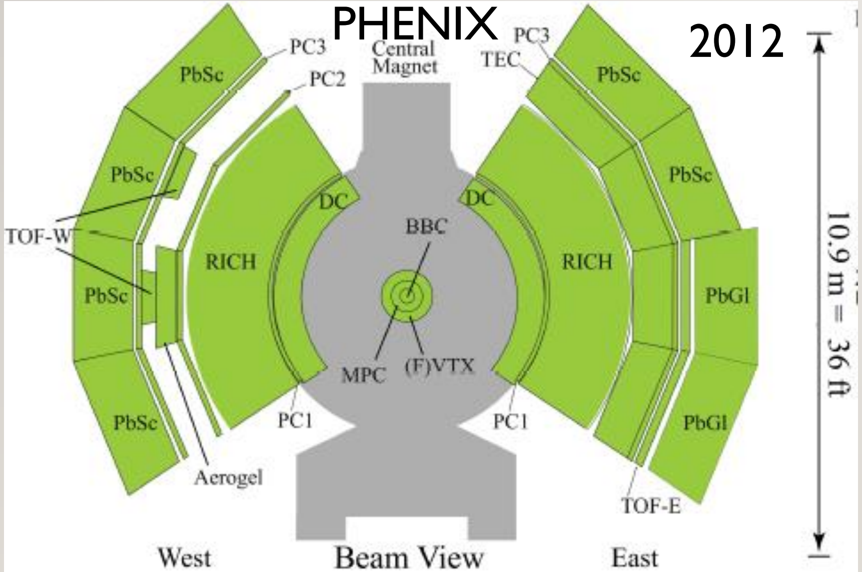


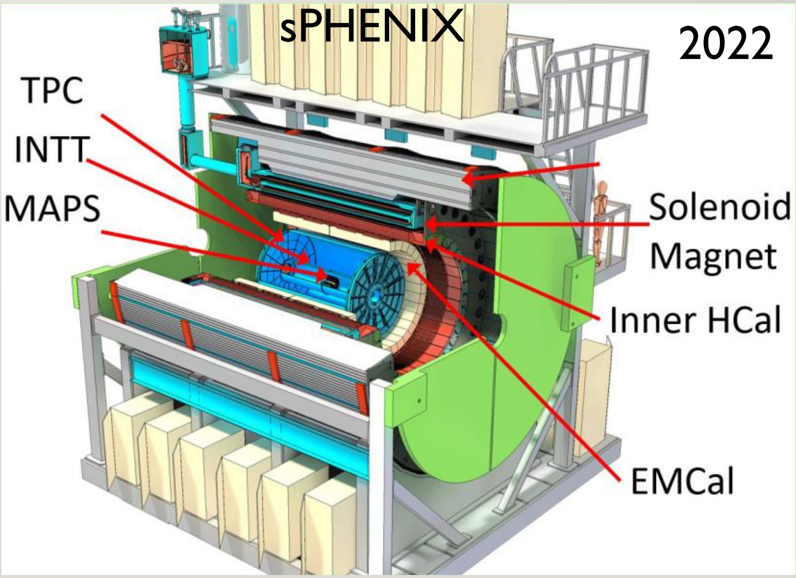
THE RELATIVISTIC HEAVY ION COLLIDER

- At the Brookhaven National Laboratory, Long Island, New York, USA
- Collisions of: $\vec{p}$, d, ^{3}He, Al, Cu, Au, U
- Accelerator energies: 7.7-200 GeV/nucleon, even 0.51 TeV for $\vec{p}$
- Experiments: STAR; future: sPHENIX; past: BRAHMS & PHOBOS & PHENIX

PHENIX AND sPHENIX

- PHENIX: versatile detector identifying many different particles, recording large amount of collisions. Dismantled in 2016, to give way to sPHENIX
- sPHENIX: to take data in ~2023
  - Jets, jet correlations, Upsilon states
  - EM+Hadronic calorimetry, high resolution tracking, fast (~100 kHz) data aquisition





THE RHIC BEAM ENERGY/SPECIES SCAN

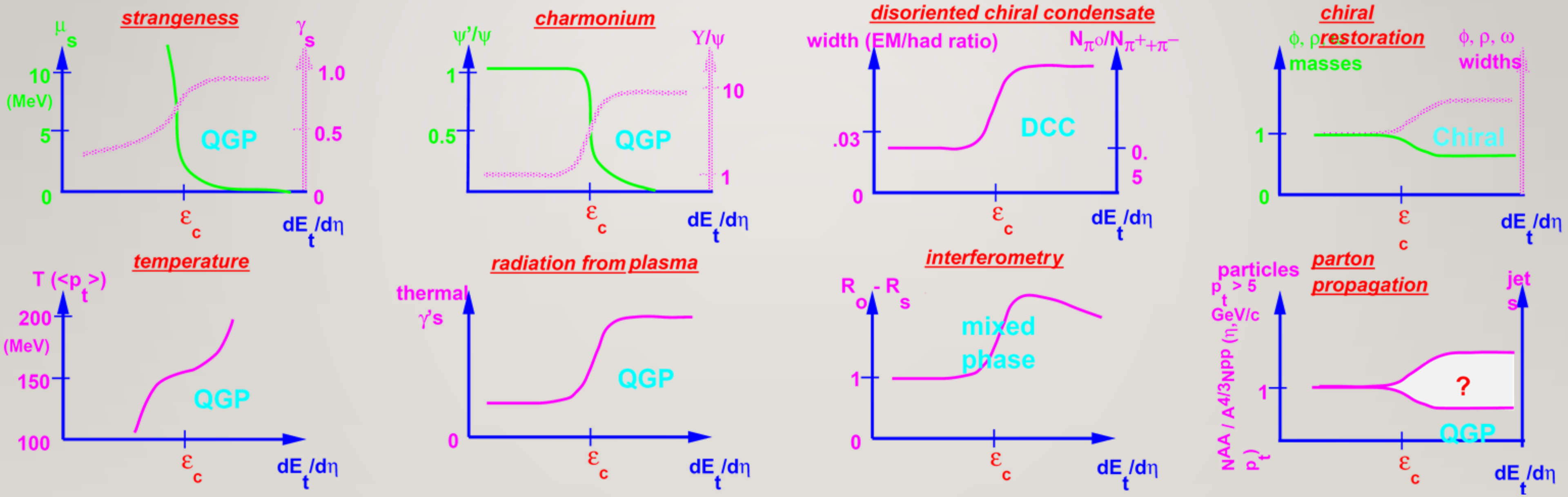
- Collision experiments: acceptance independent of energy
- BES-I: 7.7-200 GeV; BES-II: 7.7-19.9 GeV, increased luminosity
- Small system scan: x+Au, 19.6-200 GeV
- STAR fixed target mode: down to 3 GeV

$\sqrt{s_{NN}}$ [GeV]	STAR Au+Au events [10^6]	PHENIX Au+Au events [10^6]	Year
200.0	2000	7000	2010
62.4	67	830	2010
54.4	1300	-	2017
39.0	130	385	2010
27.0	70	220	2011
19.6	36	88	2011
14.5	20	247	2014
11.5	12	-	2010
7.7	4	1.4	2010

$\sqrt{s_{NN}}$ [GeV]	PHENIX events [10^6]	Species
200.0	2.2	p+Au
200.0	1600	^{3}He+Au
200.0	2057	d+Au
62.4	1655	d+Au
39.0	2000	d+Au
19.6	1040	d+Au

QGP SIGNATURES EXPECTATIONS, 1996

- Critical energy density: $\epsilon_c \approx 1\ \mathrm{GeV/fm^3}$, temperature $T_c \approx 170\ \mathrm{MeV}$
- Some observed, some not…

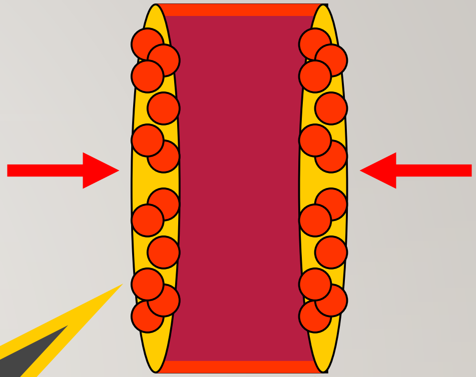


J. Harris & B. Mueller, „The Search for the QGP", Ann.Rev.Nucl.Part.Sci. 46 (1996) 71 [hep-ph/9602235]

NUCLEAR MODIFICATION: TOMOGRAPHY!

proton+proton

nucleus+nucleus



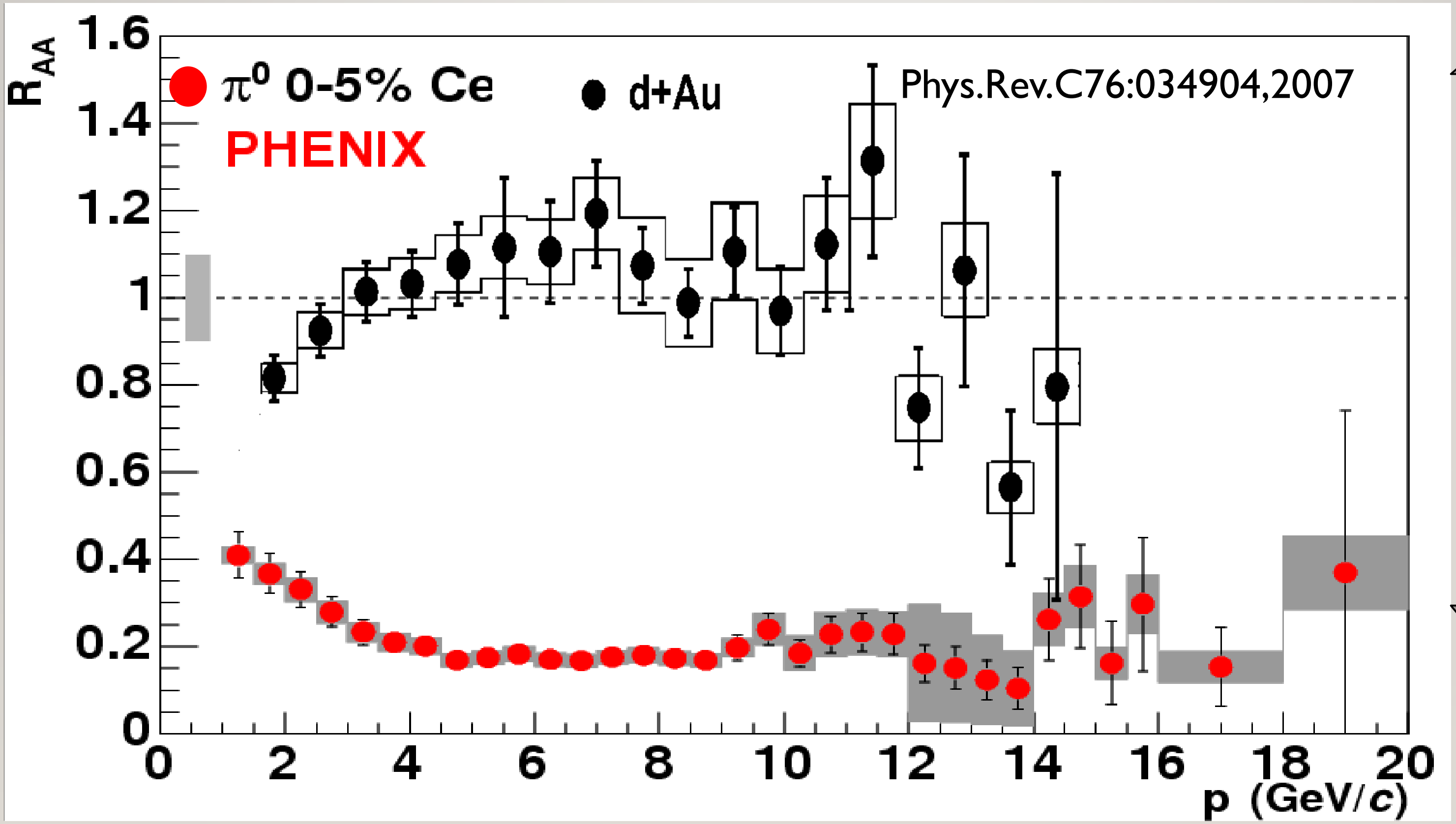
Simply just more?

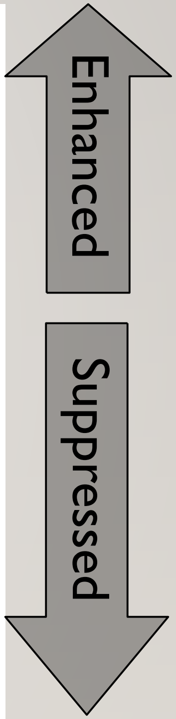
A+A = many p+p?

$$R_{AA} = \frac{\text{High } p_T \text{ particle yield in A+A}}{\text{High } p_T \text{ particle yield in p+p} \times \text{Number of p+p collisions}}$$

SUPPRESSION AS A FUNCTION OF CENTRALITY

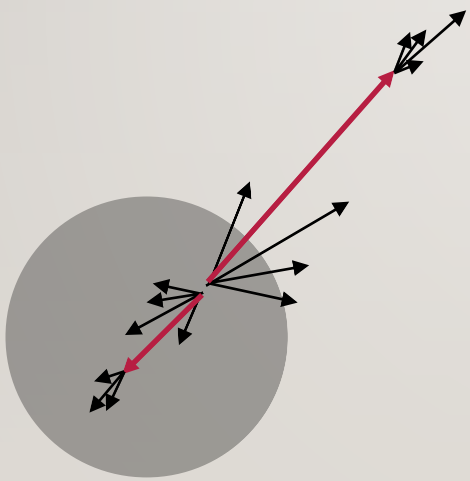
- No suppression in d+Au or peripheral Au+Au; strong suppression in central!

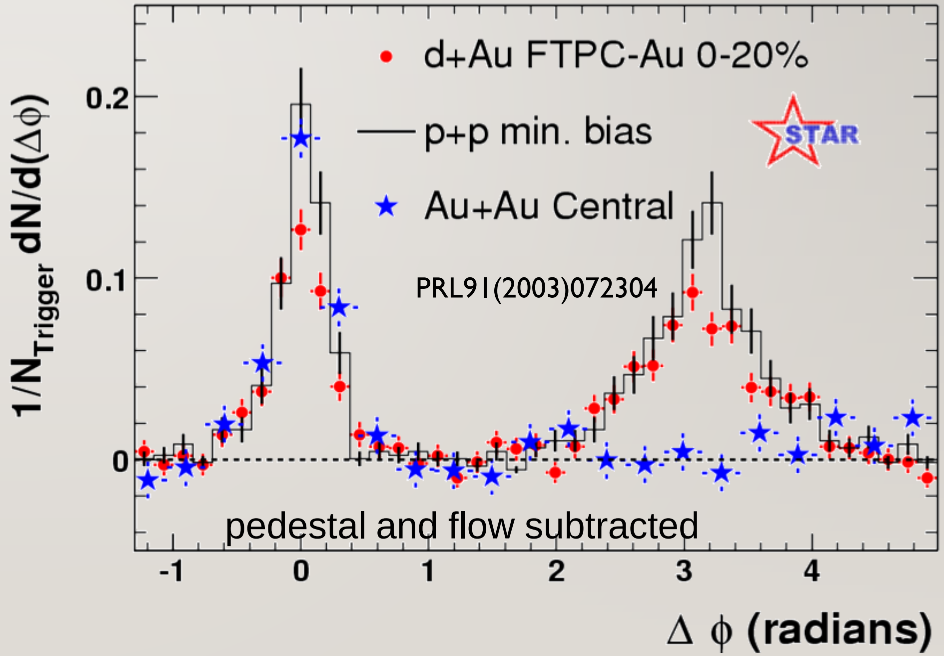




SUPPRESSION OF THE AWAY SIDE JET

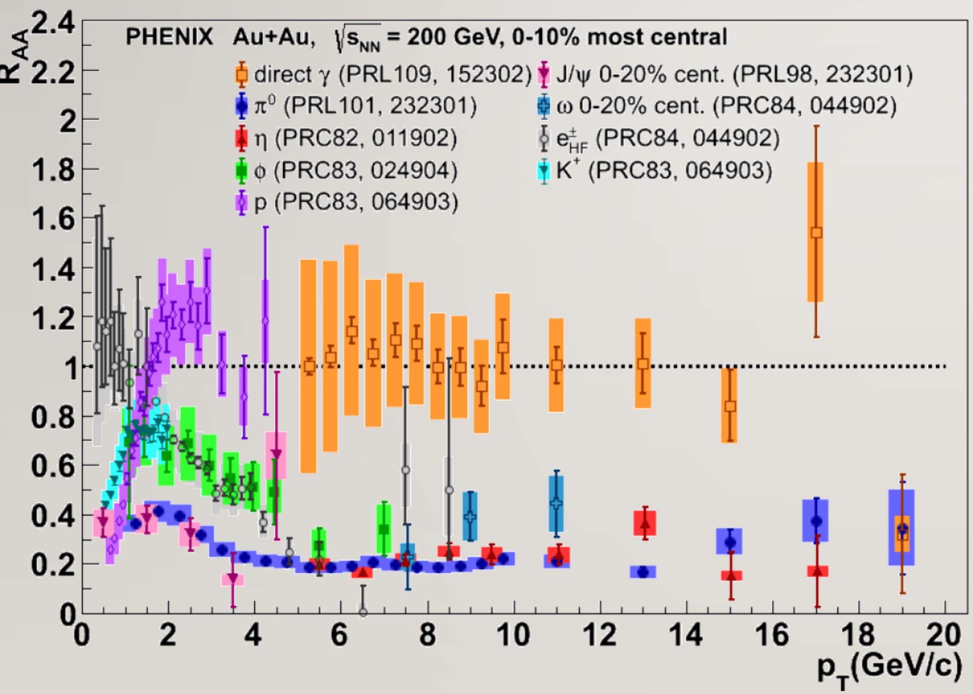
- Angular correlation of high energy hadrons
- Outgoing jet: similar in p+p, d+Au, Au+Au
- Inward going (away side) jet: missing in central Au+Au

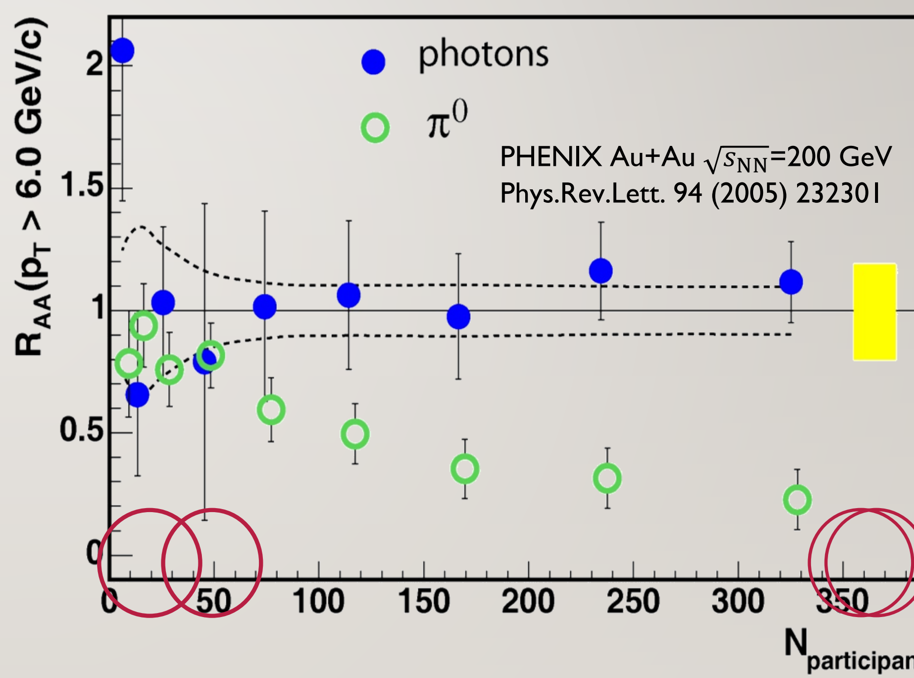




HOW DO OTHER PARTICLES BEHAVE?

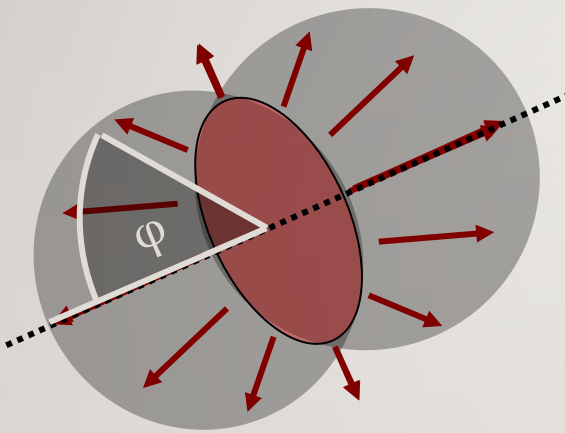
- All hadrons suppressed, direct photons „shine through"
- Suppression dependent of system size (controlled by centrality or N_{part})

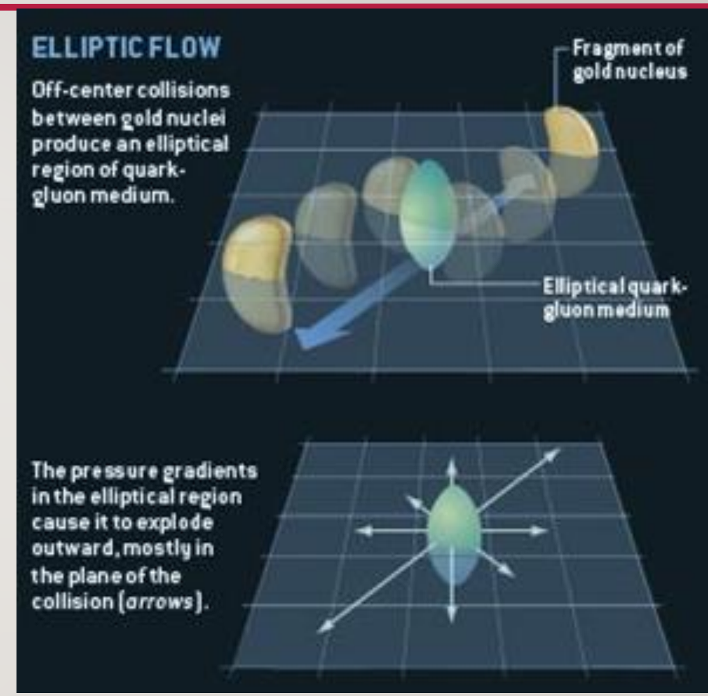




OBSERVATION OF THE ELLIPTIC FLOW

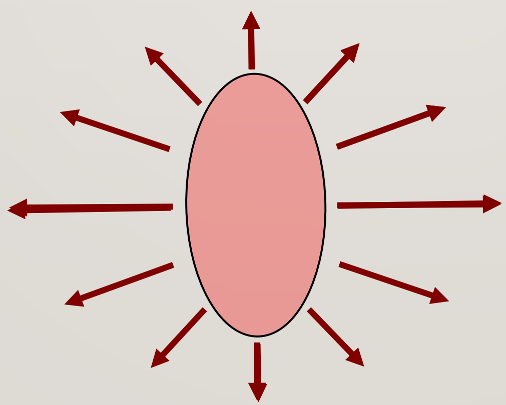
- Spatial anisotropy creates momentum-space anisotropy!

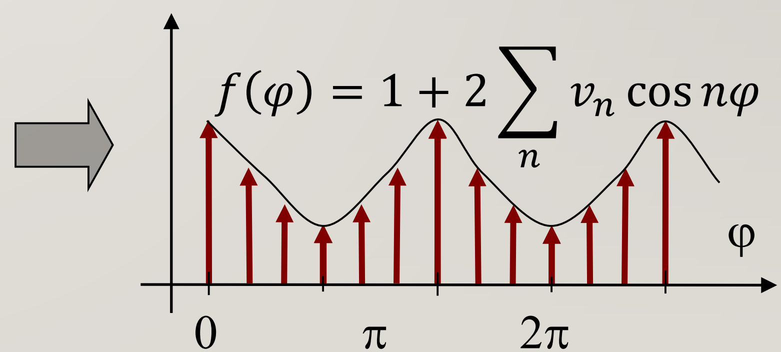




Zajc, Riordan, Scientific American

- Quantified via anisotropy parameters





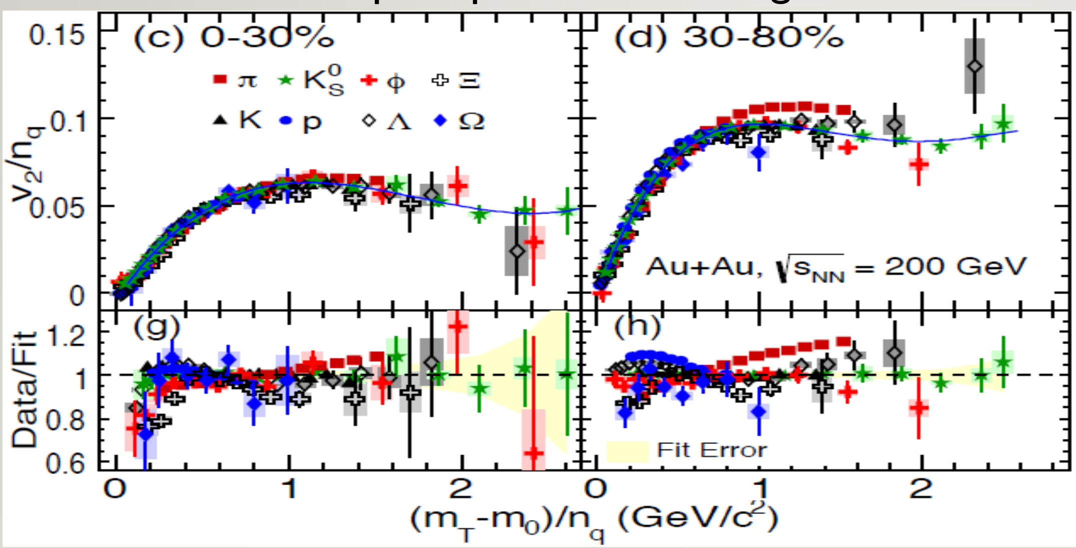
ELLIPTIC FLOW SCALING

- Hydro predicts scaling (v_2 versus $w \sim E_K / T_{\text{eff}}$)
- Coalescence predicts quark number scaling

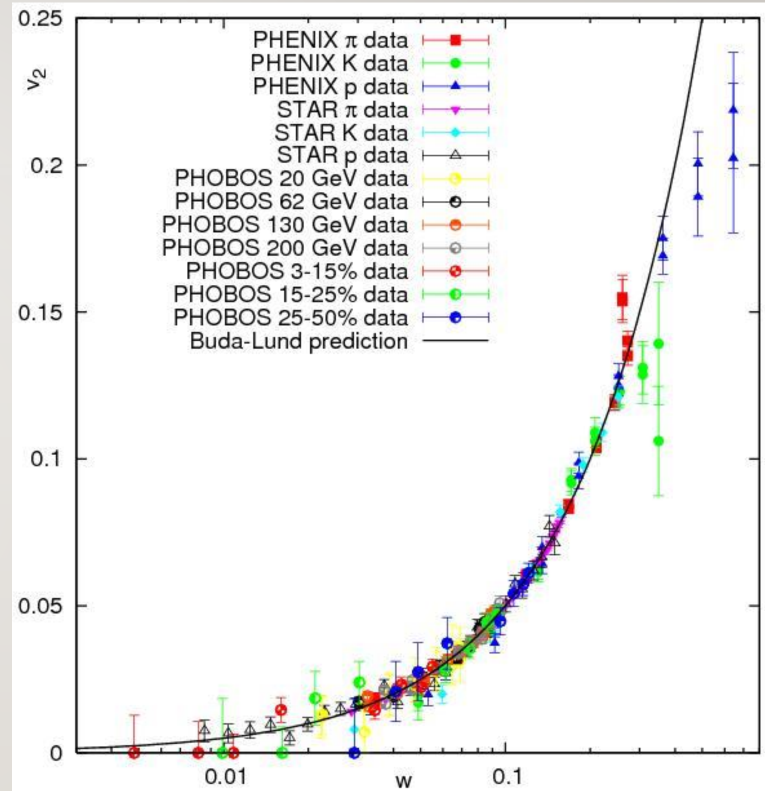
$$E_K^{\text{hadron}} = n_q E_K^{\text{quark}}$$

$$v_n^{\text{hadron}}\left(E_K^{\text{hadron}}\right) \cong \mathrm{n_q} v_n^{\text{quark}}\left(E_K^{\text{quark}}\right)$$

- Flow develops in pre-hadronic stage!



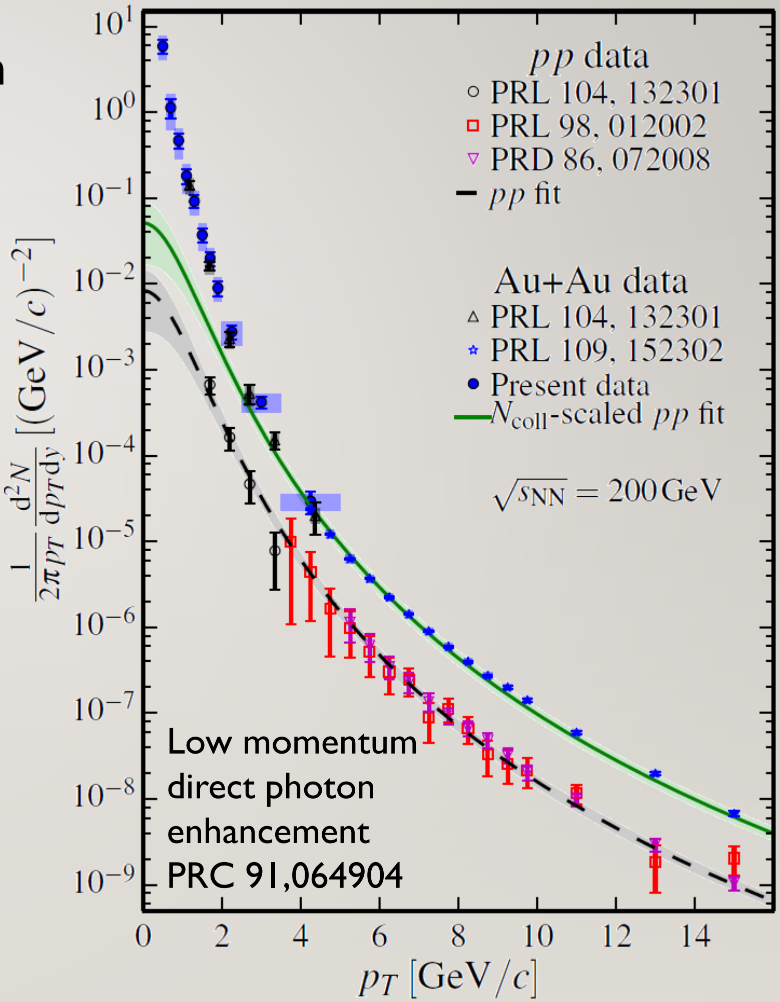
PHENIX, PRL98(2007)162301; STAR, PRL116(2016)62301



Csanád, Csörgő, Lörstad, Ster (NPA742:80-94,2004)
Csanád, Csörgő, Lörstad, Ster et al. (EPJA38:363-368,2008)

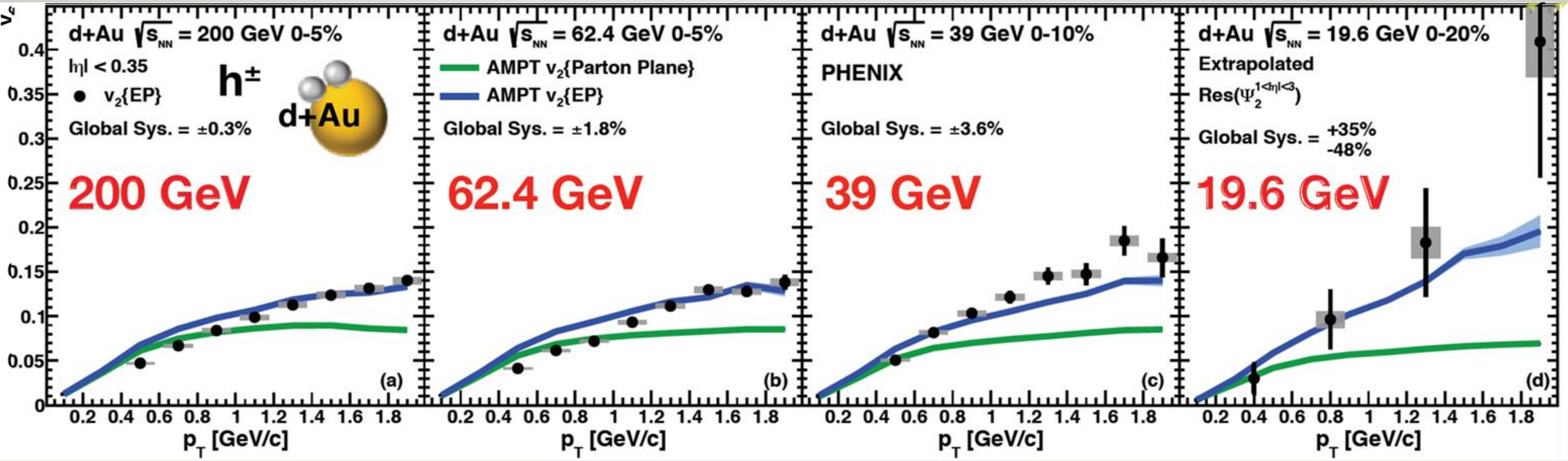
THERMAL PHOTONS

- Soft component in direct photon spectrum compared to p+p extrapolation
- These are thermal photons!
- Large initial temperature, 3-600 MeV!



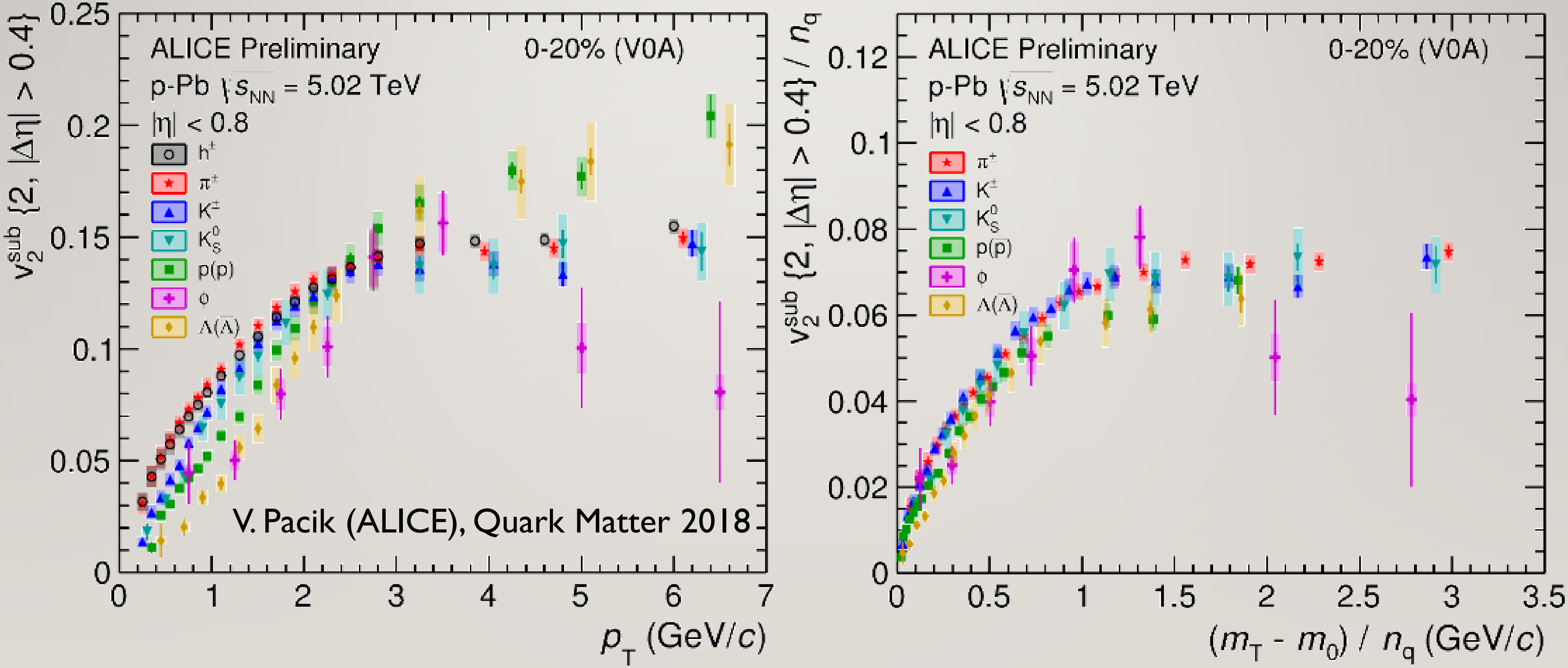
ELLIPTIC FLOW IN D+AU AT RHIC

- Deuteron-gold energy scan (19.6-200 GeV), PHENIX, PRC96, 064905 (2017)
- superSONIC in good agreement at 62.4 GeV and 200 GeV
- Underpredicts data at 19.6 GeV and 39 GeV
- Data still contains nonflow effects: AMPT(EventPlane) w/ nonflow matches



ELLIPTIC FLOW IN P+PB AT THE LHC

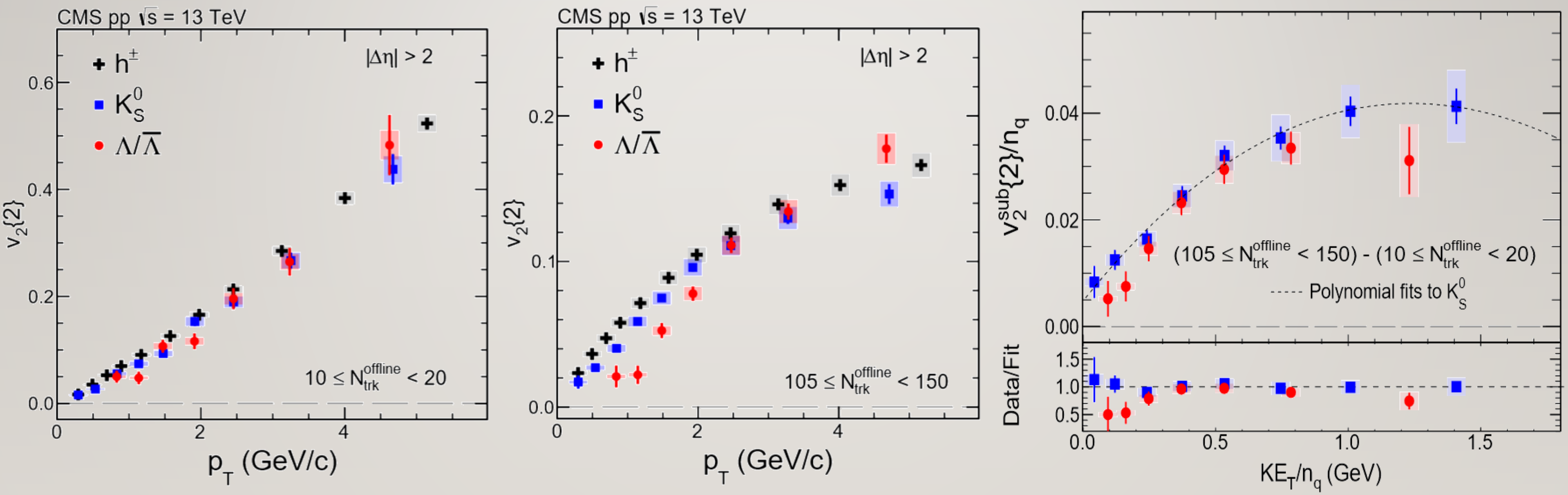
- Identified particle elliptic flow, ALICE pPb @ 5.02 TeV, from pions to Λ's
- Quark number scaling works well; LHC pPb not so small system though…



FLOW IN 13 TEV P+P AT CMS

- No mass ordering in low multiplicity p+p (v_2 due to jets)
- Mass ordering, quark number scaling in high multiplicity pp

CMS, Phys. Lett. B 765 (2017) 193

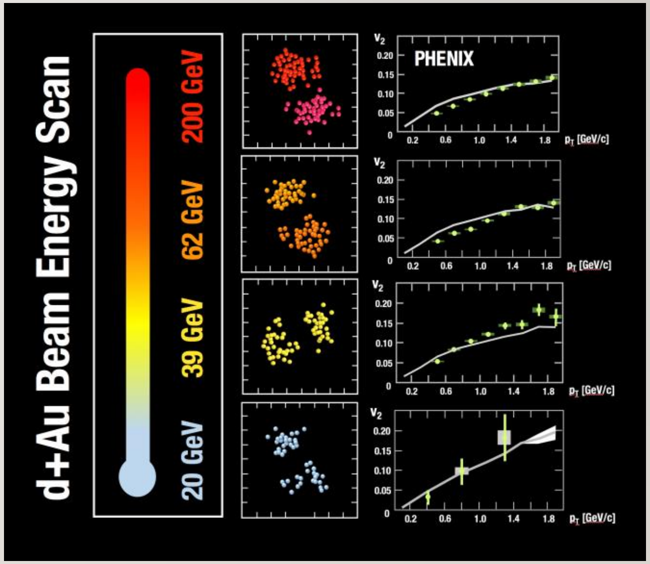


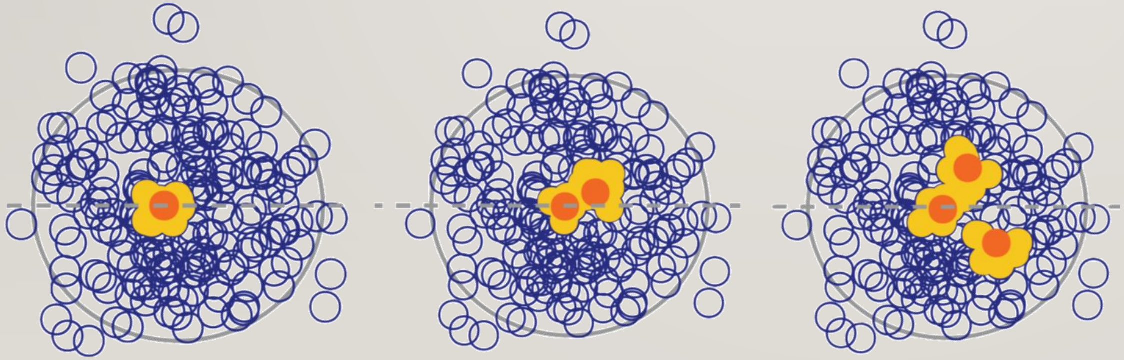
- Note: initial energy density may reach 1 GeV/fm^3 already around N_{ch}=10

Csanád et al., Universe 3 (2017) no.1, 9

ORIGIN OF FINAL STATE COLLECTIVITY?

- Is it due to the appearance of the sQGP (i.e. a strongly coupled fluid)?
  - If yes, how much time is needed to spend in QGP phase?
  - Test: d+Au collisions from 20 to 200 GeV
- Is it due to initial geometry and hydro?
  - Hydrodynamics: initial spatial correlations
  - Alternative: initial momentum correlations
  - Test: p+Au, d+Au, ^{3}He+Au
  - How do v_2 and v_3 evolve with initial state geom.?



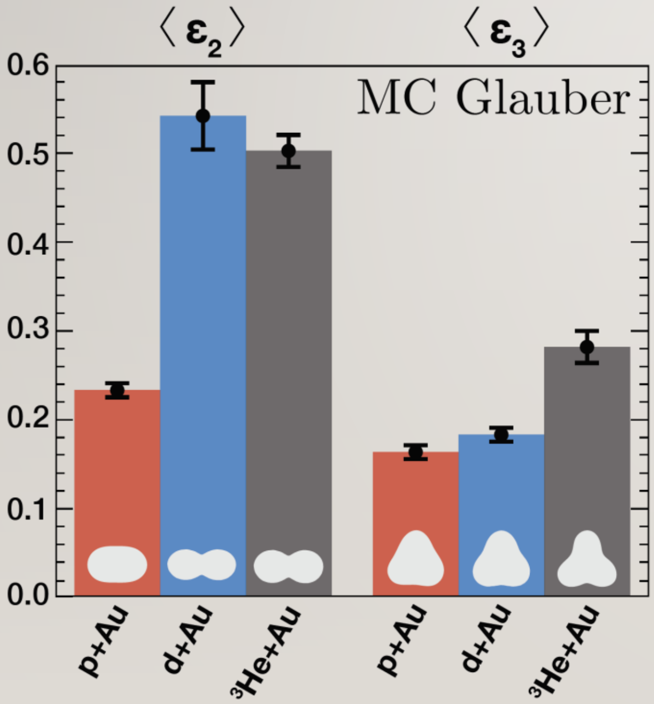


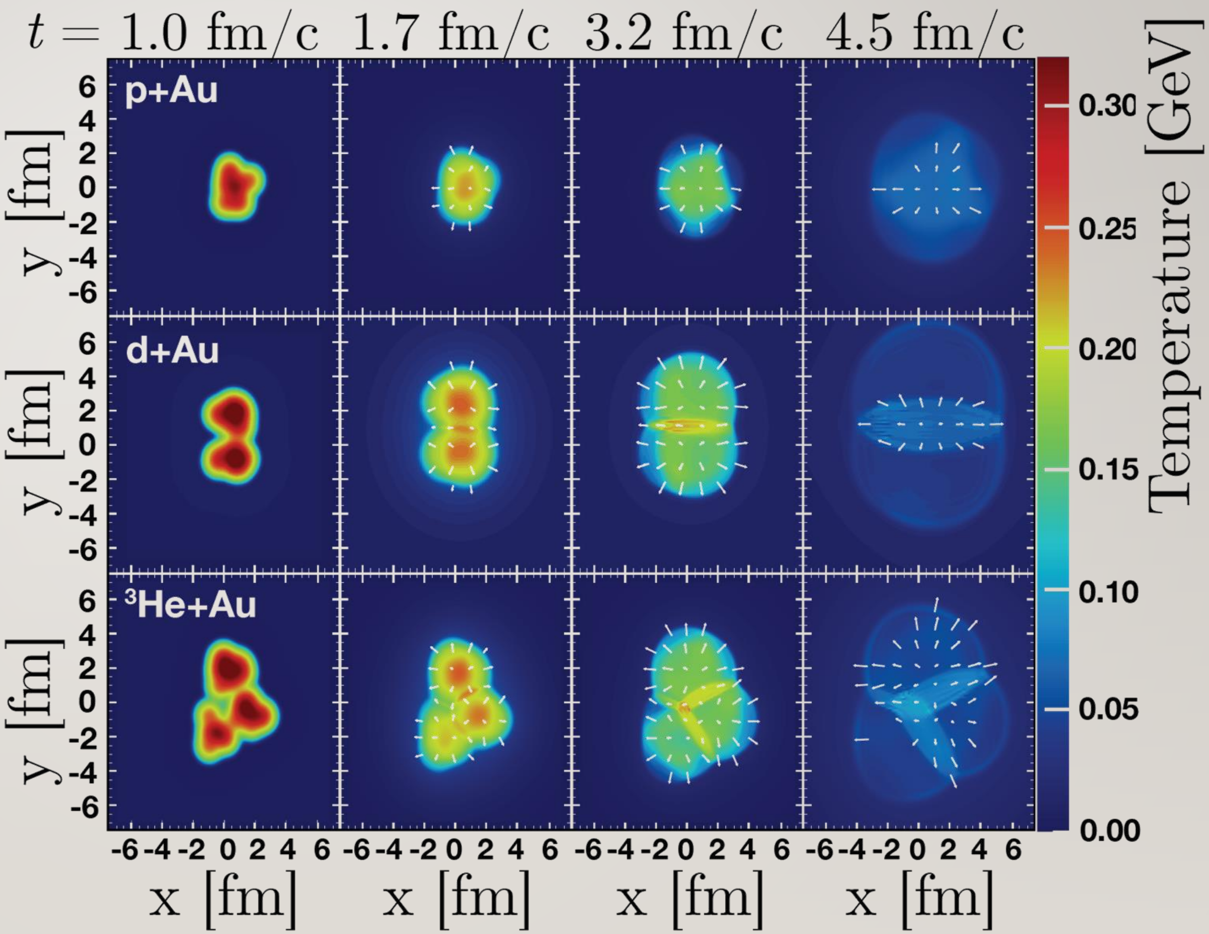
INITIAL STATE AND HYDRO EVOLUTION

- Evolution from SONIC
- Initial stage:

$$\epsilon_2^{p+\mathrm{Au}} < \epsilon_2^{d+\mathrm{Au}} \approx \epsilon_2^{^3\mathrm{He+Au}}$$

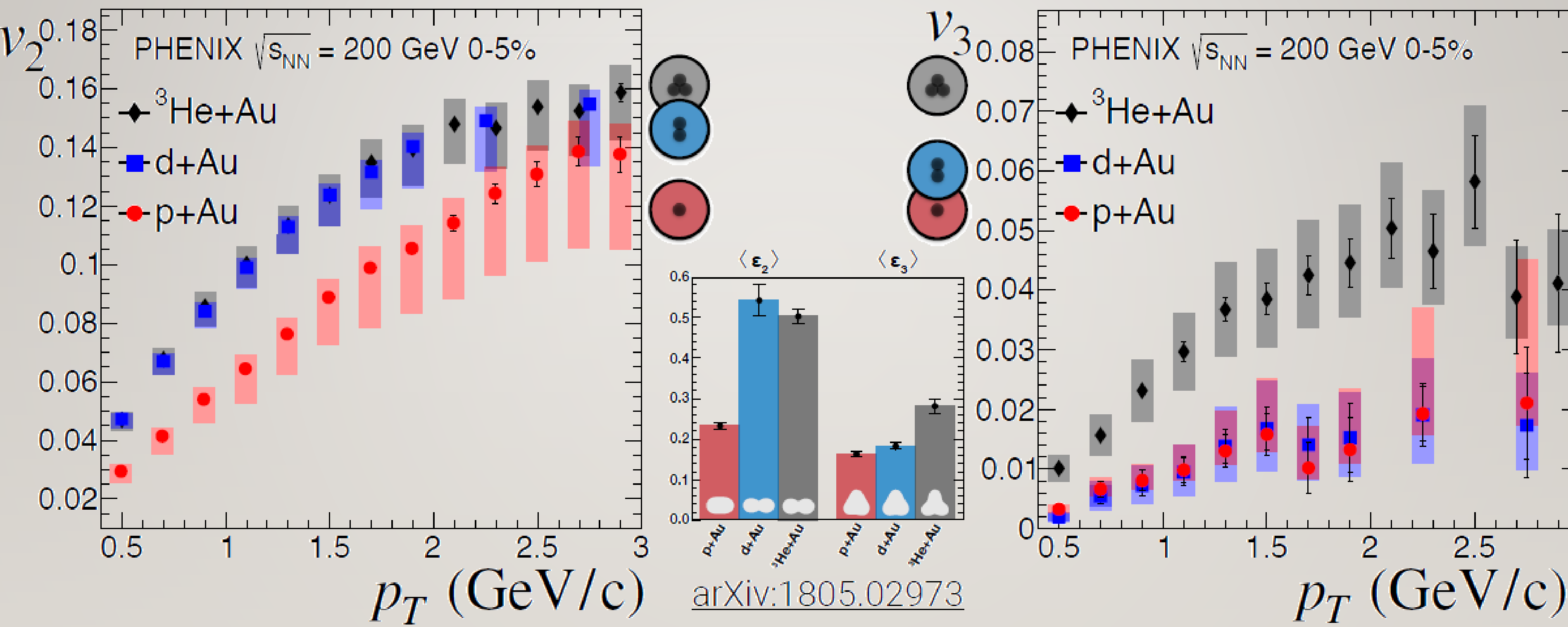
$$\epsilon_3^{p+\mathrm{Au}} \approx \epsilon_3^{d+\mathrm{Au}} < \epsilon_3^{^3\mathrm{He+Au}}$$





FLOW IN SMALL SYSTEMS: GEOMETRIC ORDERING

- Flow ordered similarly as initial state:



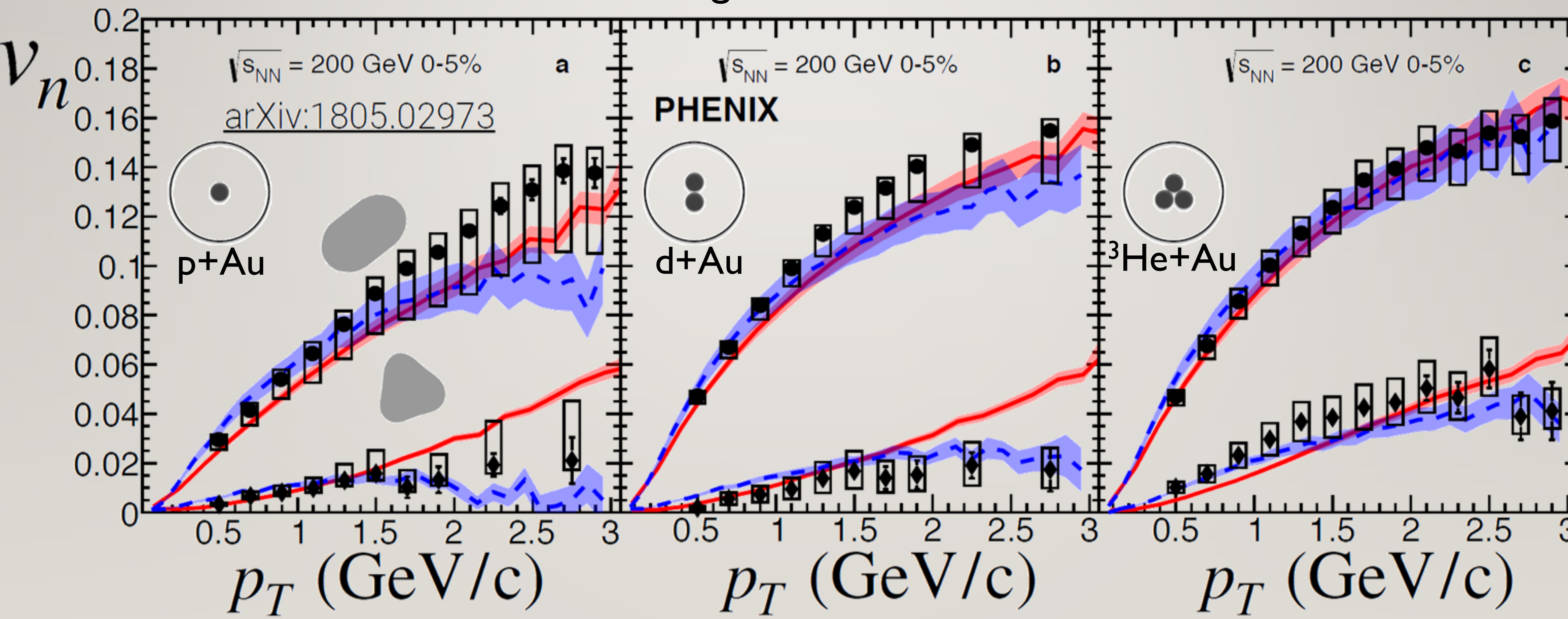
$$v_2^{p+\text{Au}} < v_2^{d+\text{Au}} \approx v_2^{^3\text{He+Au}}$$

$$v_3^{p+\text{Au}} \approx v_3^{d+\text{Au}} < v_3^{^3\text{He+Au}}$$

COMPARISON TO HYDRO CALCULATIONS

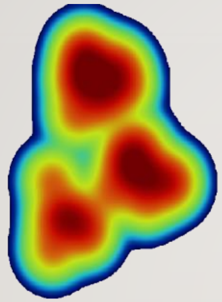
- Hydro calculations
- Both 2+1D, η/s = 0.08, MCGlauber initial cond.
- Different hadronic rescattering

v_2 Data
v_3 Data
v_n SONIC Eur. Phys. J. C 75, 15 (2015)
v_n iEBE-VISHNU PRC 95, 014906 (2017)

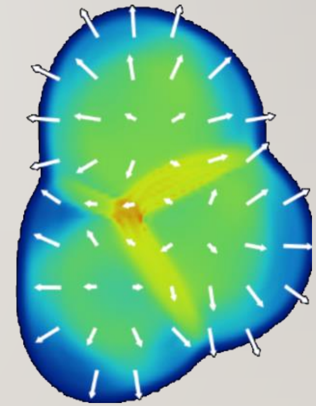


IS THERE AN ALTERNATIVE EXPLANATION?

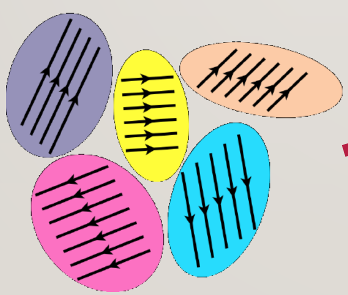
- Hydro: initial state spatial correlations a.k.a. geometry



Final state momentum correlations

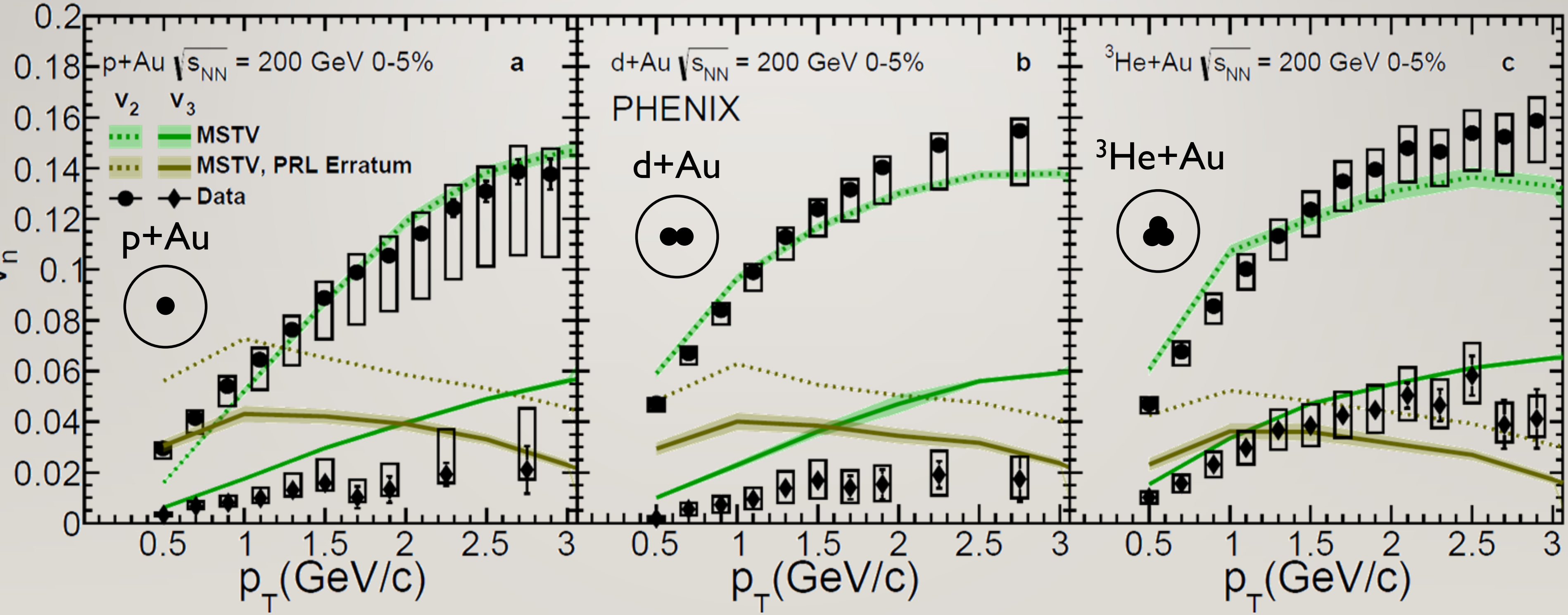


- Alternative: initial state momentum correlations
  Mace et al. Phys. Rev. Lett. 121, 052301 (2018)



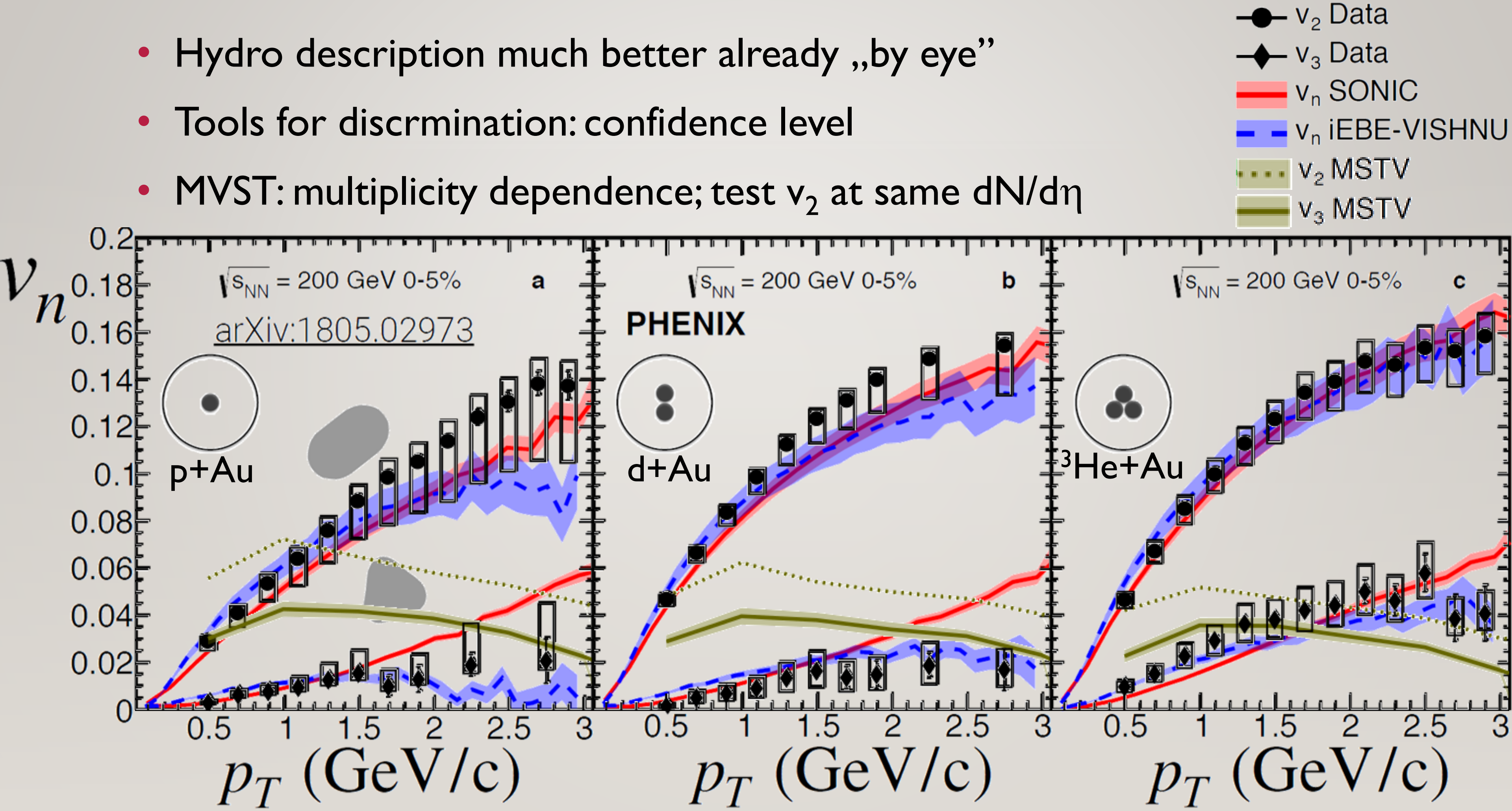
27/29 ALTERNATIVE MODEL VS DATA

- MVST postdiction (Mace, Skokov, Tribedy, Venugopalan, PRL121, 052301)
  - Official PRL Erratum: Phys. Rev. Lett. 123,039901(E) (2019)
- Before erratum: reasonable v_2 description, misses v_3 ordering



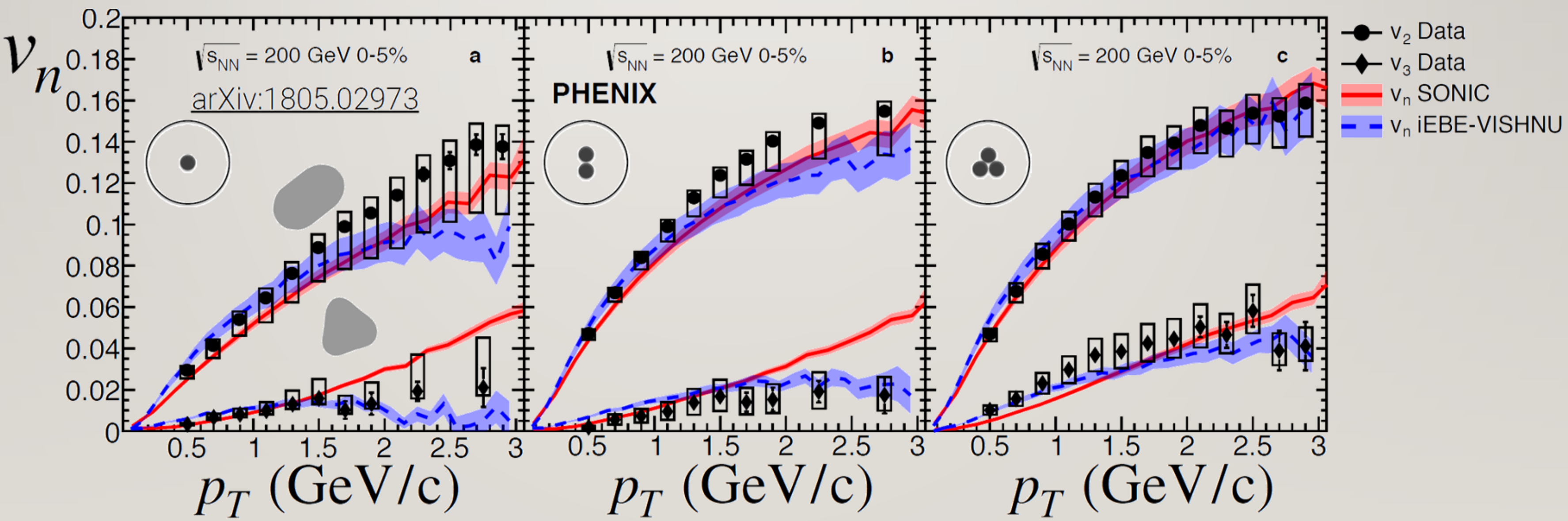
ALL MODELS VS DATA

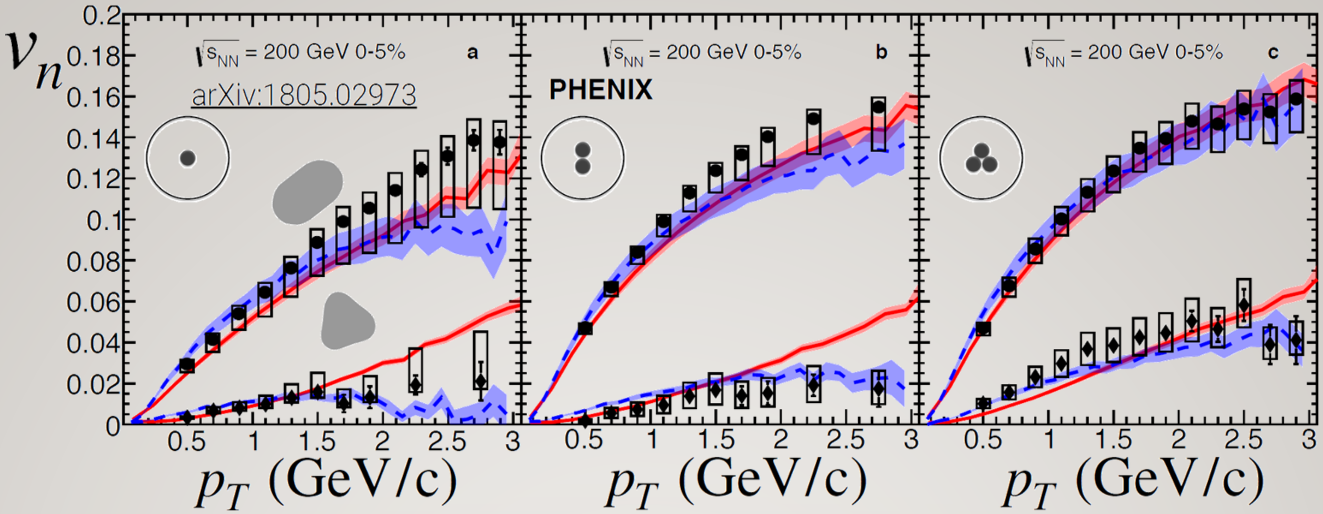
- Hydro description much better already „by eye"
- Tools for discrmination: confidence level
- MVST: multiplicity dependence; test v_2 at same dN/dη



SUMMARY

- Clear consensus on a list of QGP signs found in nucleus-nucleus collisions
  - Suppression, flow, thermal photons
- Strong evidence for QGP droplets in small systems
  - Quark number scaling works in p+Pb, mass ordering already in pp
  - Hydro works well in p/d/^{3}He+Au





THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, come to our
Zimányi School 2019
December 2-6., Budapest, Hungary

http://zimanyischool.kfki.hu/19

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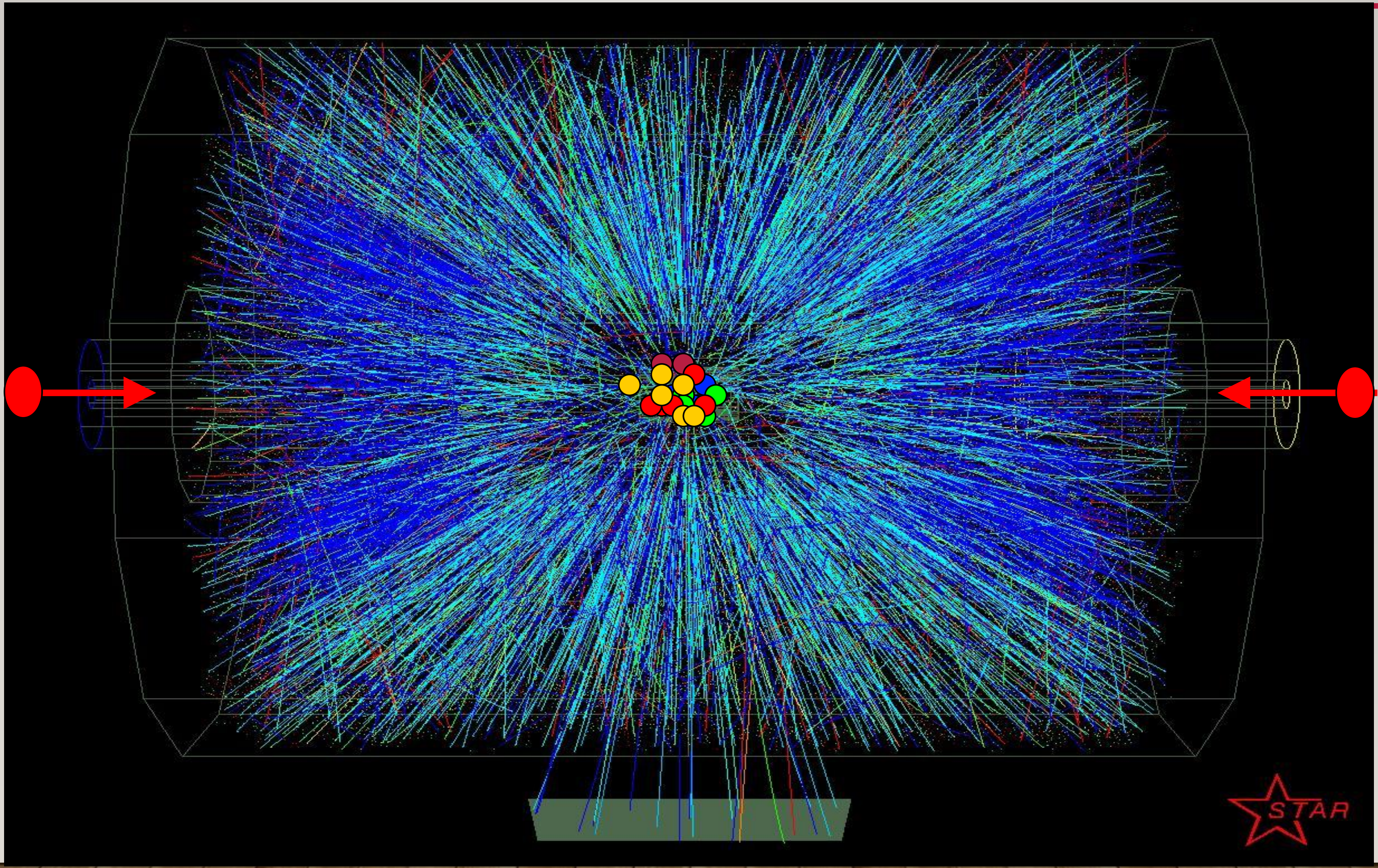
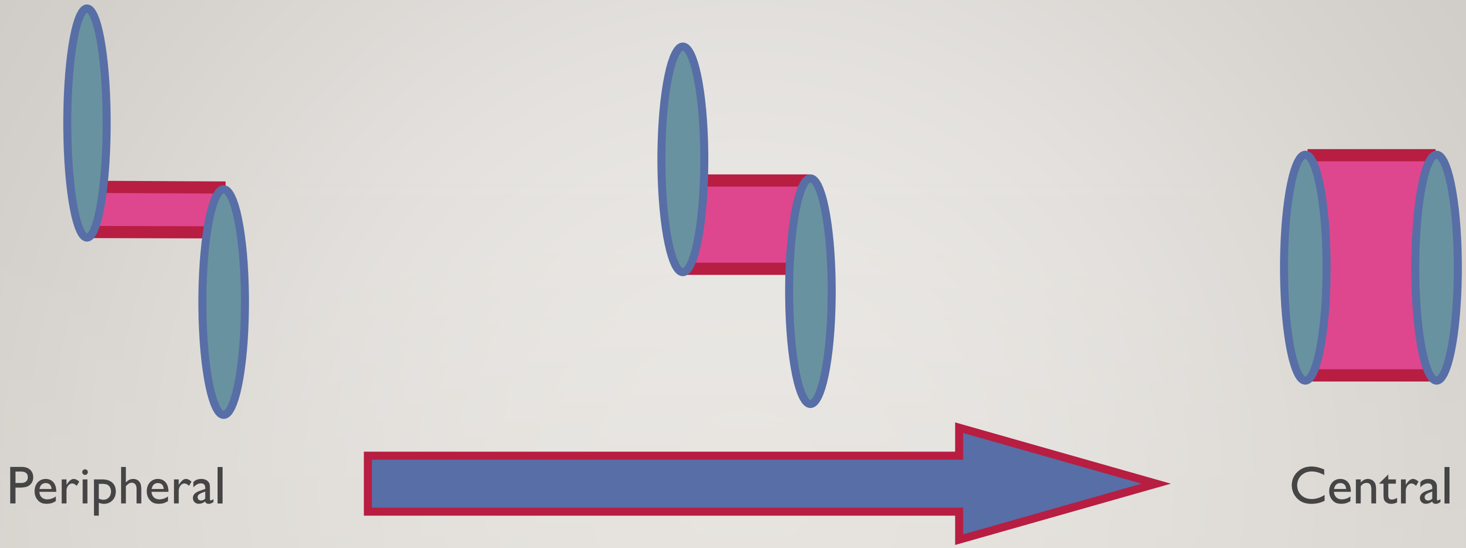
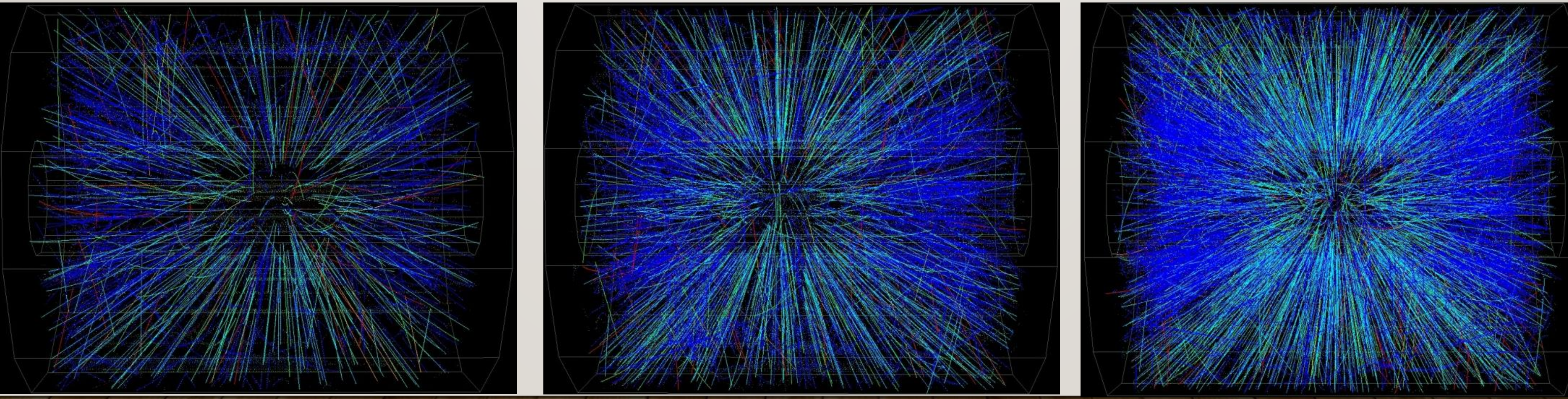
BACKUP SLIDES

HOW TO INVESTIGATE THESE LITTLE BANGS?



COLLISIONS OF DIFFERENT CENTRALITY





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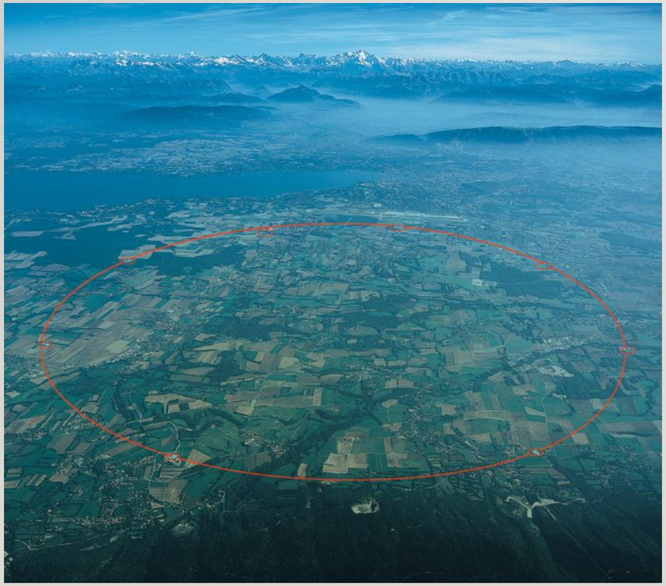
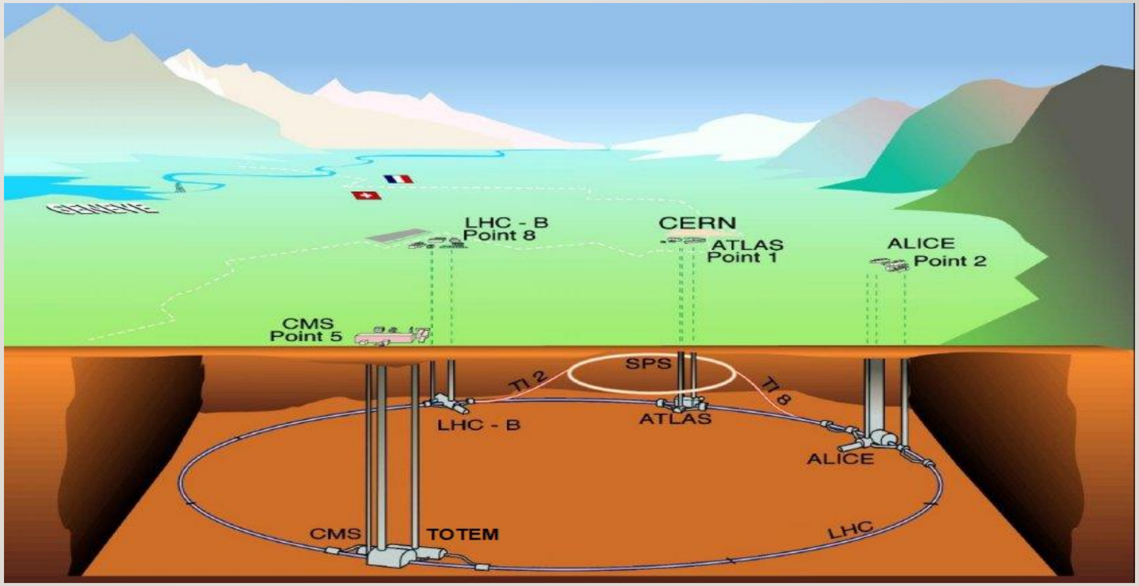
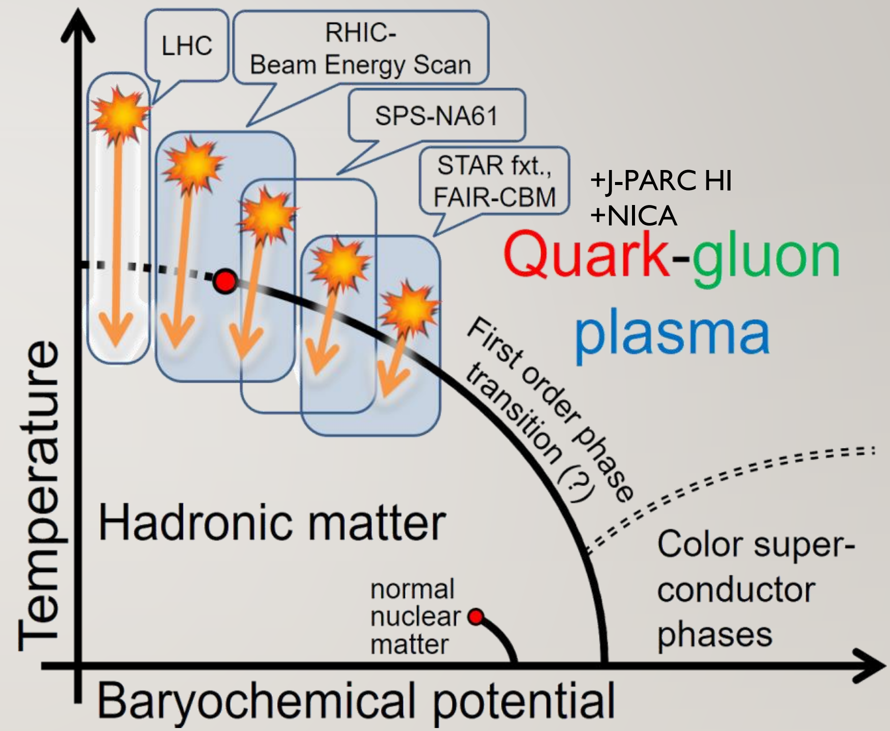
- LHC collisions: p+p, p+Pb and Pb+Pb
- Energies: from 2.76 TeV/nucleon to 13 TeV (p+p only)
- Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL, TOTEM
- Phase diagram related studies: SPS (NA61/SHINE, previously NA49)





EXPLORING THE PHASE MAP OF QCD

- Phase map: temperature versus matter excess (baryochem. pot. μ_B)
- Control parameters:
  - Collision energy, system
  - Collision geometry
- Crossover at low μ_B and $T \cong 170$ MeV
- Probably 1st order quark-hadron p.t. at high μ_B (NJL, bag model, etc)
- Critical End Point (CEP) in between?

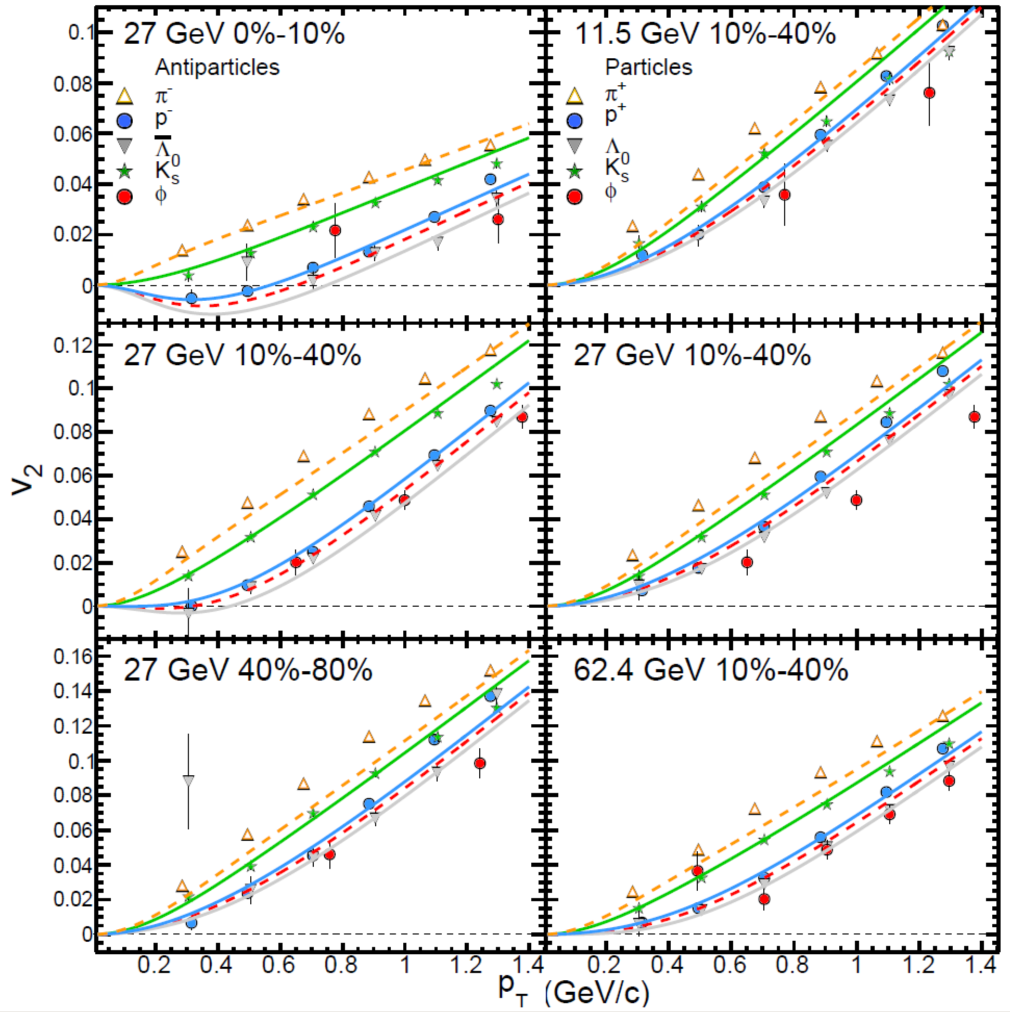


- High μ_B: nuclear matter, neutron stars, color superconductors…
- Phase transition importance: even in core-collapse supernovae!

ELLIPTIC FLOW IN THE BEAM ENERGY SCAN

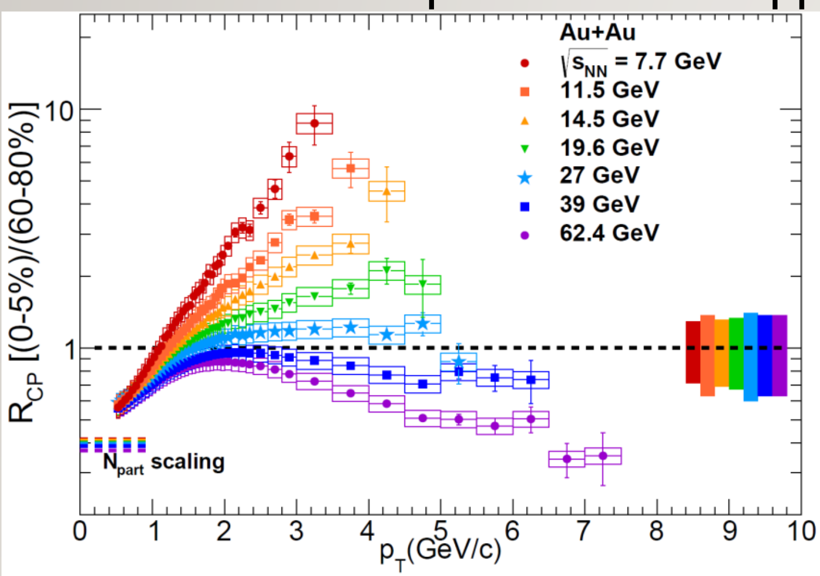
- With Blast-Wave fits
- Predictions for not fitted particles agree well
- Flow in all systems!

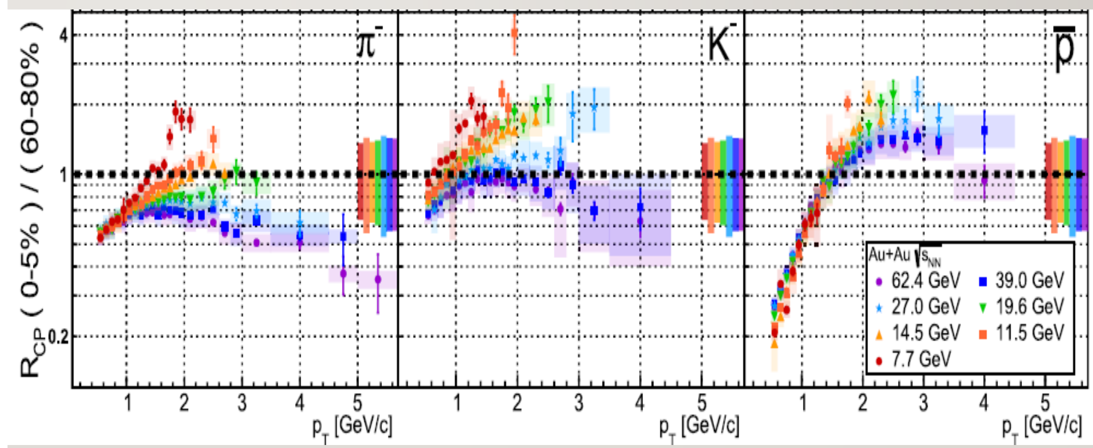
STAR Collaboration, PRC93, 014907 (2016)



SUPPRESSION IN THE BEAM ENERGY SCAN

- R_{CP} analyzed here instead of R_{AA}, transition to above one with coll. energy
- Hadron enhancement: Cronin-effect, radial flow, coalescence domination
- Competing effects, HIJING reproduces enhancement w/o jet quenching
- Identified particles: less suppression for kaons, enhancement for protons

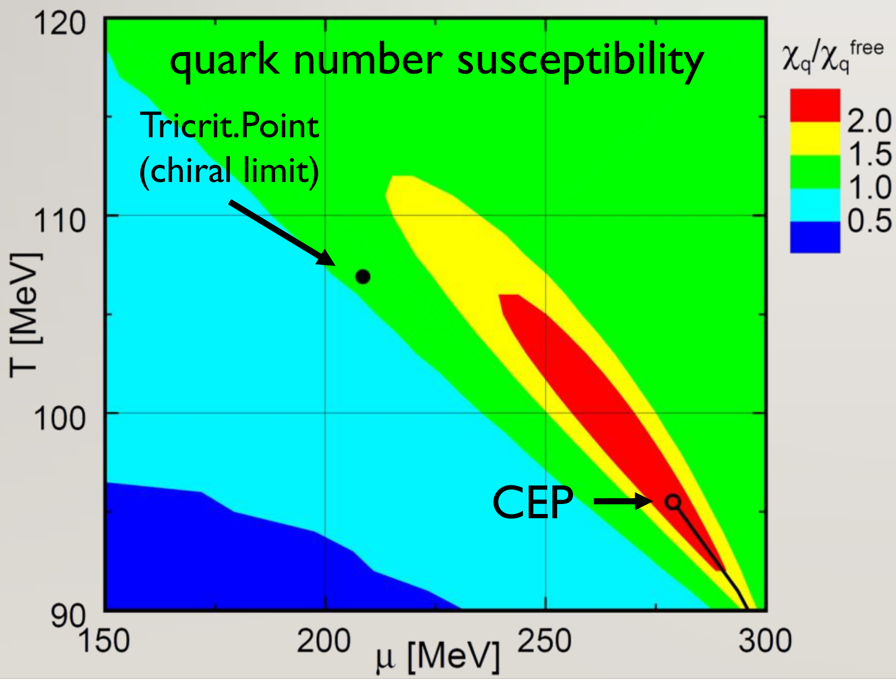


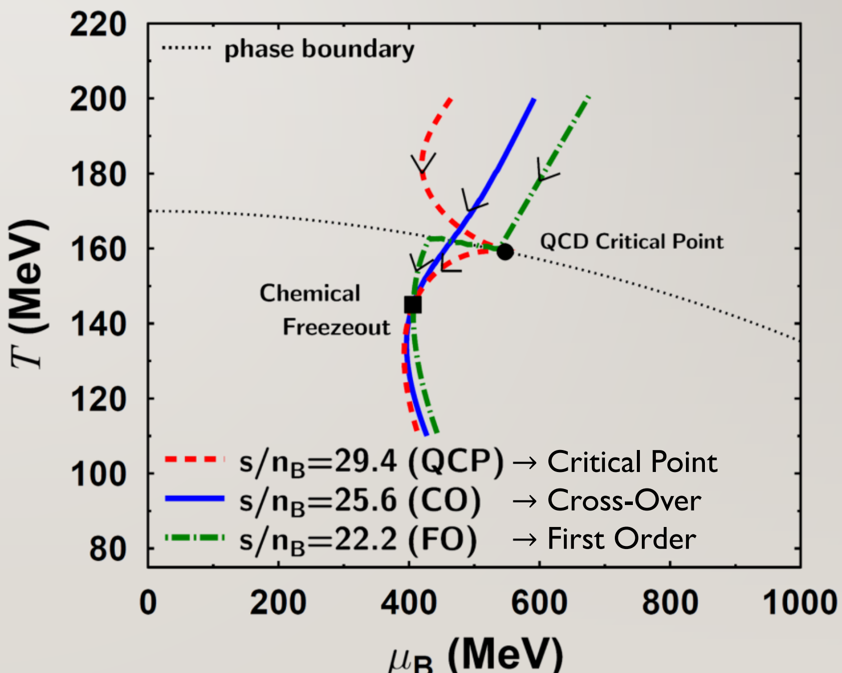


STAR collaboration, Phys. Rev. Lett. 121, 032301 (2018) [arXiv:1707.01988]

SEARCH FOR THE CRITICAL POINT POSSIBLE?

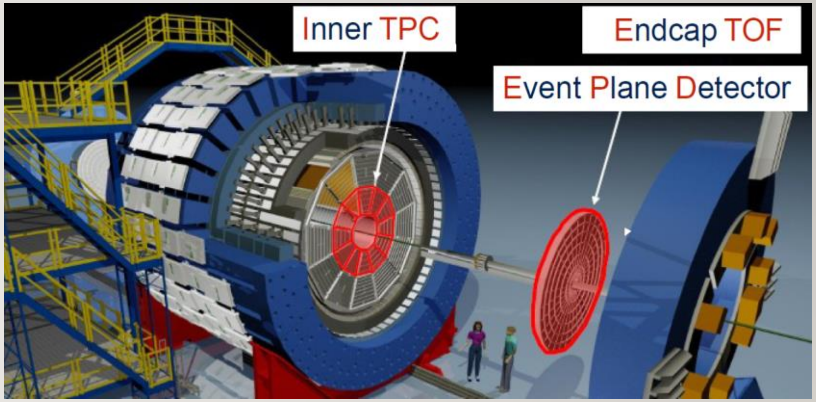
- Effects of the CEP in a broad region (via an effective potential ~ N_f=2 QCD)
  - Y. Hatta and T. Ikeda, PRD67,014028(2003) [hep-ph/0210284]
- Hydro evolution attracted to the critical point
  - M. Asakawa et al., PRL101,122302(2008) [arXiv:0803.2449]



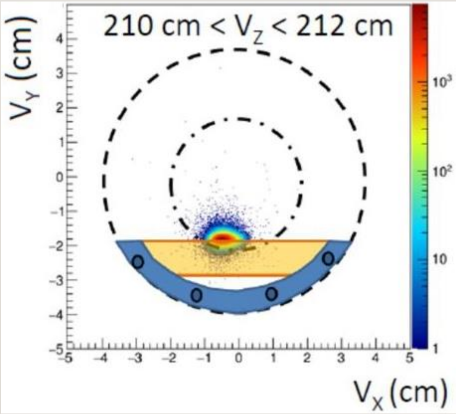


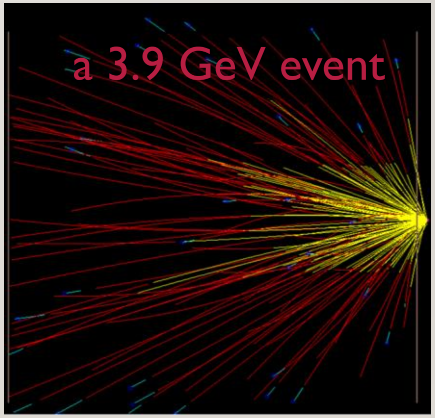
STAR: UPGRADES AND FIXED TARGET PROGRAM

- Large acceptance, great PID capabilities: great for identified hadrons
- Upgrades for BES-II
  - innerTPC: better dE/dx (PID) and momentum resolution, by 2019
  - Event Plane Detector: replace BBC, better triggering & EP resolution, by 2018
  - Endcap TOF: extended fwd PID, by 2019



- Fixed target program: 1 cm wide, 1mm thick target at 2.1 m
- At the lowest energies: out to $\mu_B > 700$ MeV





FIXED TARGET BARYOCHEMICAL POTENTIALS

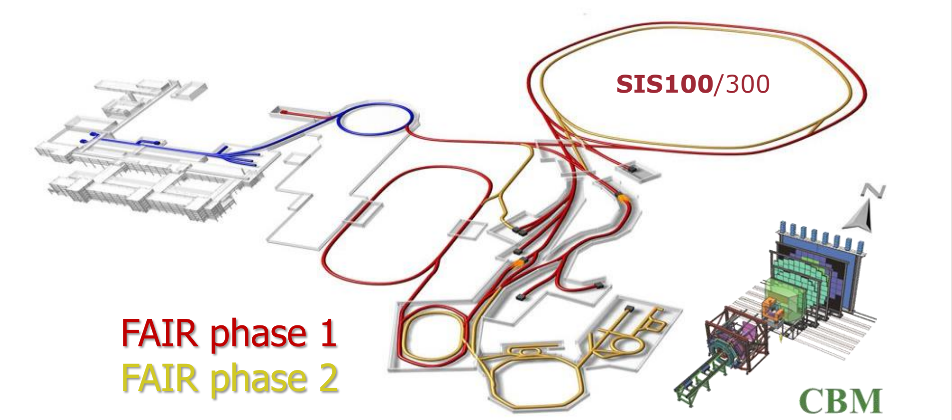
- Reach down to 3 GeV in center of mass energy!

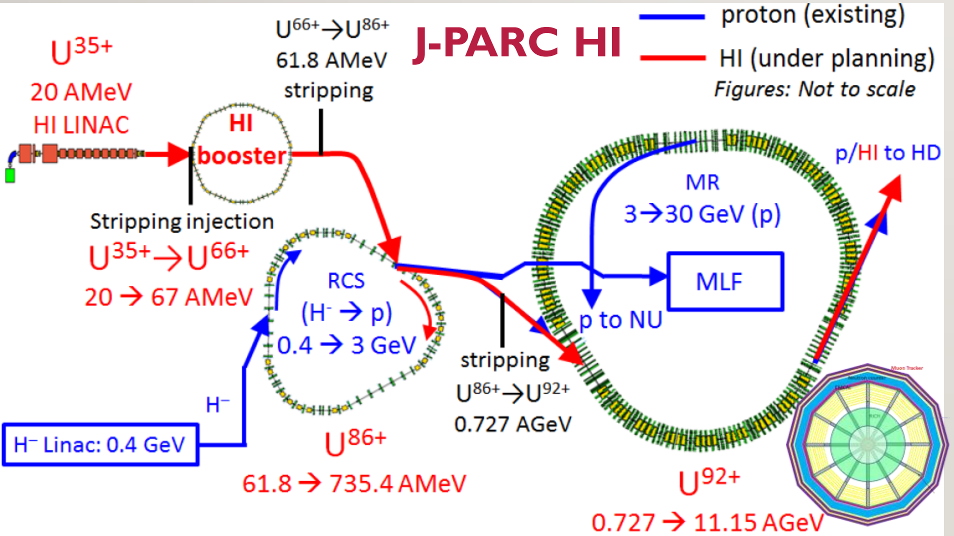
Collider Energy	Fixed Target Coll. Energy	Single Beam C.M. Energy	Rapidity	μ_B(MeV)
62.4	7.7	30.3	2.10	420
39.0	6.2	18.6	1.87	487
27.0	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721

Energies unreachable in collider mode

FUTURE FACILITIES: NICA, FAIR, J-PARC HI

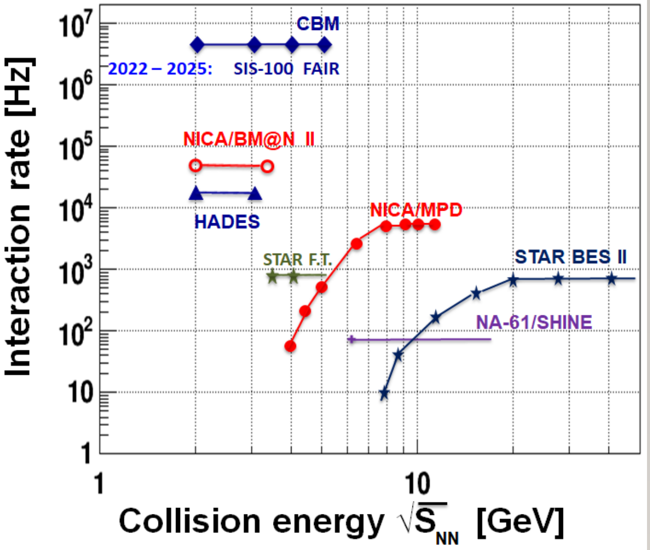
- New facilities planned/built
- NICA: 2020, MPD&BM@N
- FAIR: 2022, CBM
- J-PARC HI: 2025, JHITS





(FUTURE) FACILITIES COMPARISON

- Many future facilities and experiments, SPS and RHIC already running
- RHIC, NICA: Collider and fixed target
- SPS, FAIR, J-PARC: fixed target
- Energy ranges from 2 to 20 GeV in $\sqrt{s_{NN}}$

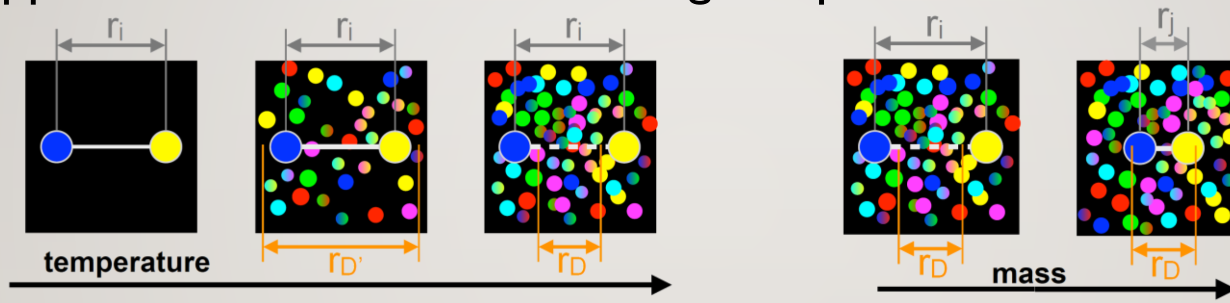


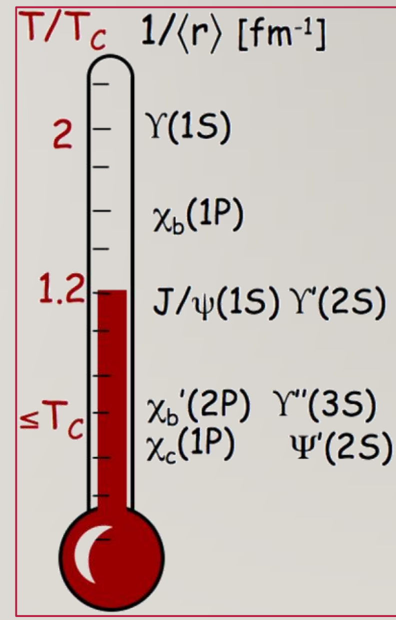
Compilation from Daniel Cebra and Olga Evkidomiv:

Facility	RHIC BES-II & Fixed Target	SPS	NICA	FAIR	J-PARC HI
Experiment	STAR	NA61	MPD & BM@N	CBM	JHITS
Start	2019	2009	2020-23	2025	2025
Energy ($\sqrt{s_{NN}}$, GeV)	2.9-19.6 GeV	4.9-17.3	2.0-11	2.7-8.2	2.0-6.2
Rate	100-1000 Hz	100 Hz	10 kHz	10 MHz	10-100 MHz
Physics	Critical Point Onset of Deconf.	Critical Point Onset of Deconf.	Onset of Deconfinement Compr. Hadronic Matter	Onset of Deconfinement Compr. Hadronic Matter	Onset of Deconfinement Compr. Hadronic Matter

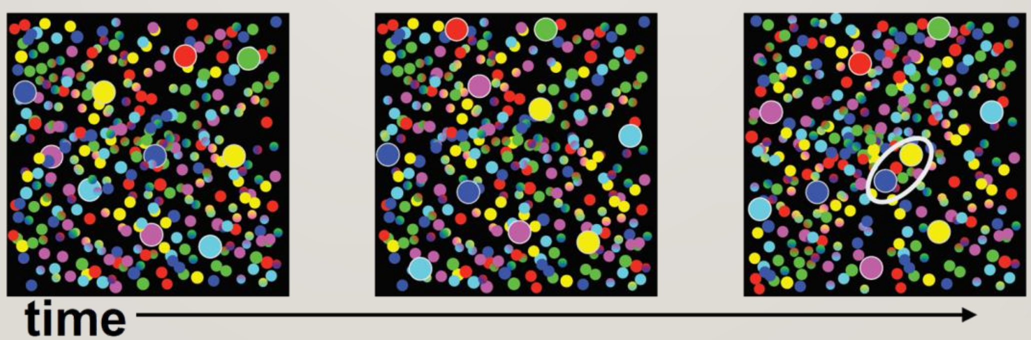
HEAVY FLAVOR SUPPRESSION & REGENERATION

- Timeline: quarkonium ($q\bar{q}$) formation → QGP evolution → $q\bar{q}$ decay
- Quarkonia experience the whole QGP evolution, competing processes
- Suppression due to color-screening: temperature and size/mass dependence





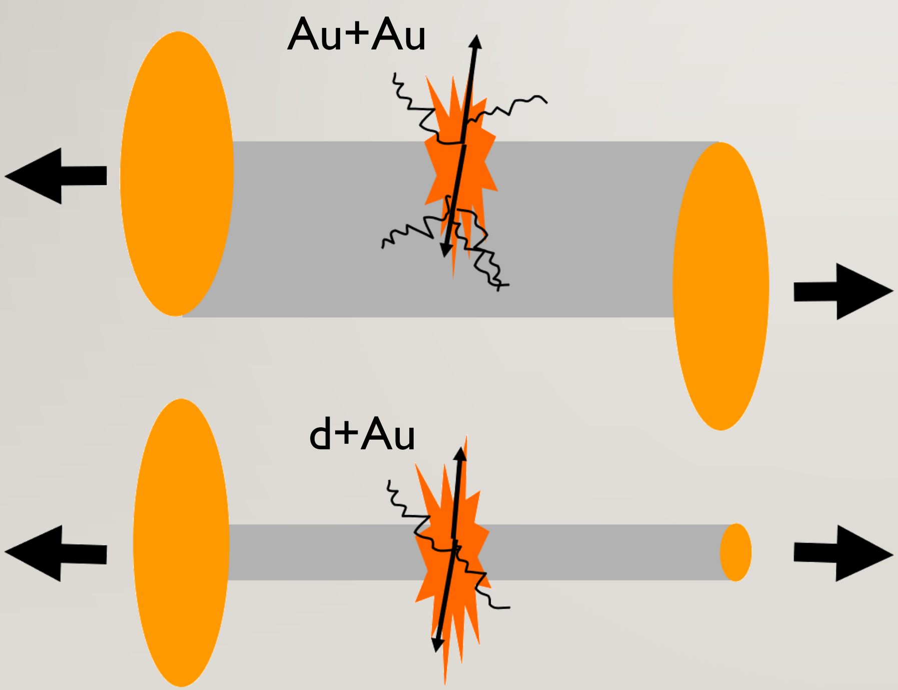
- Statistical regeneration in time:

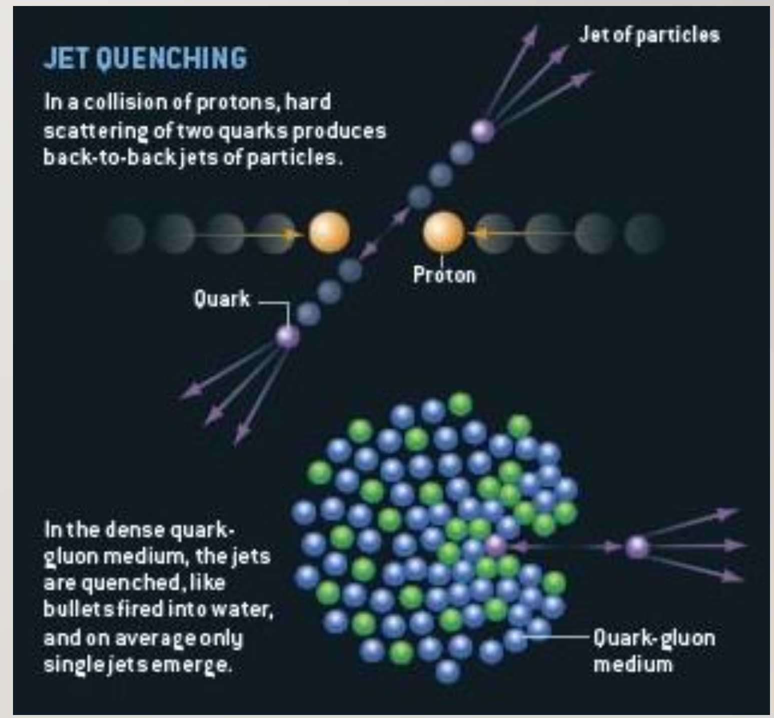


Images from J Castillo, SQM17 and A Mócsy, HardProbes2009

CONTROL EXPERIMENT: D+AU COLLISIONS

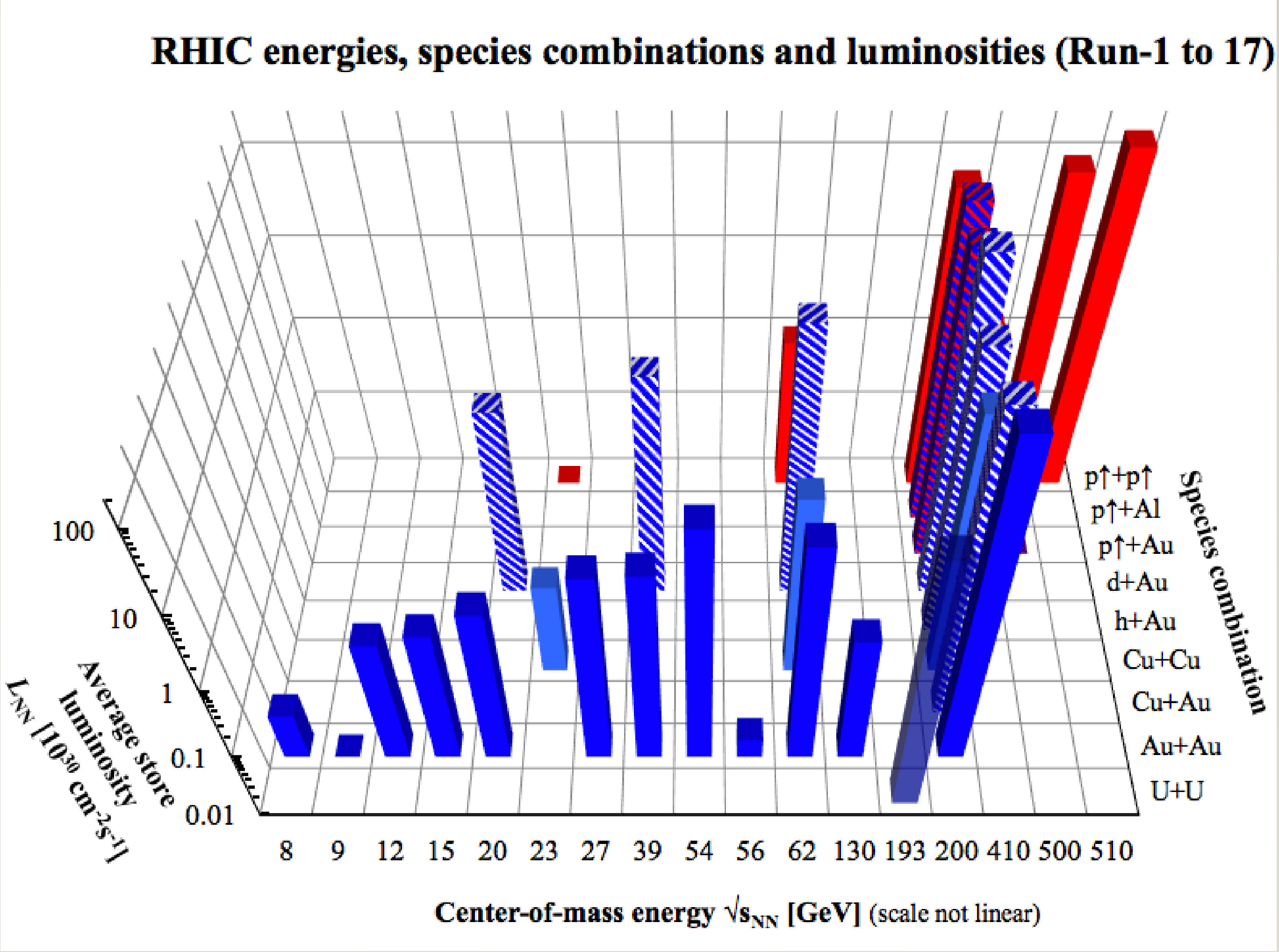
- Suppression in Au+Au collisions: 1st milestone
- Lack of suppression in d+Au: 2nd milestone
- Two PRL covers





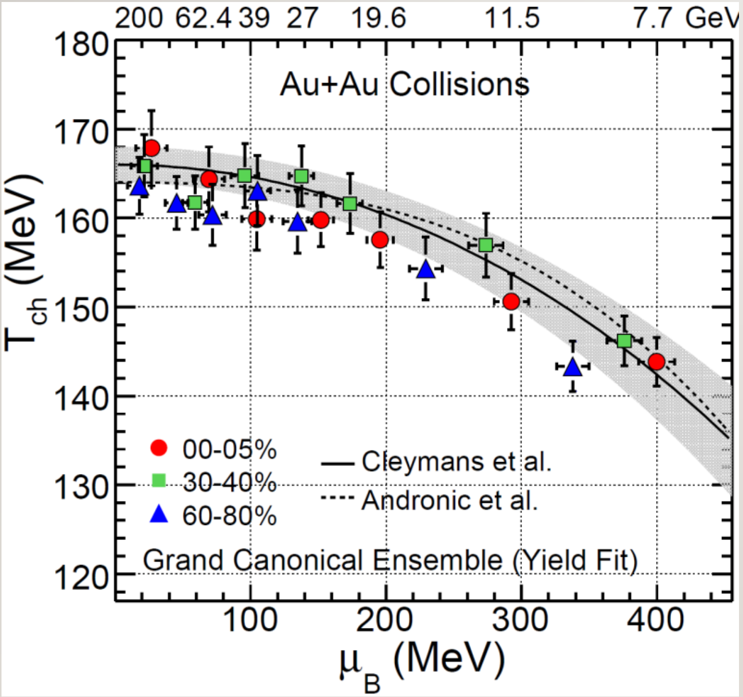
Zajc, Riordan, Scientific American

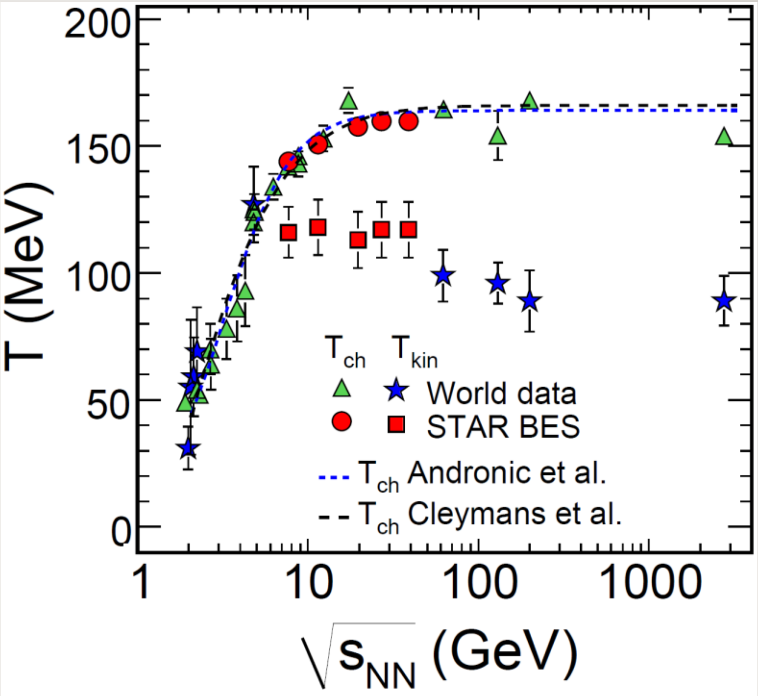
RHIC RECORDED RUNS AND LUMINOSITY



FREEZE-OUT FROM PARTICLE YIELDS

- Chemical and kinetic freeze-out parameters via THERMUS and BlastWave
- Thermal multiplicity assumption valid
- Systematics investigated (parameter constraints, included species)
- Separation of T_{ch} and T_{kin} around $\sqrt{s_{NN}}$ = 4-5 GeV, T_{ch} flattens at ~10 GeV

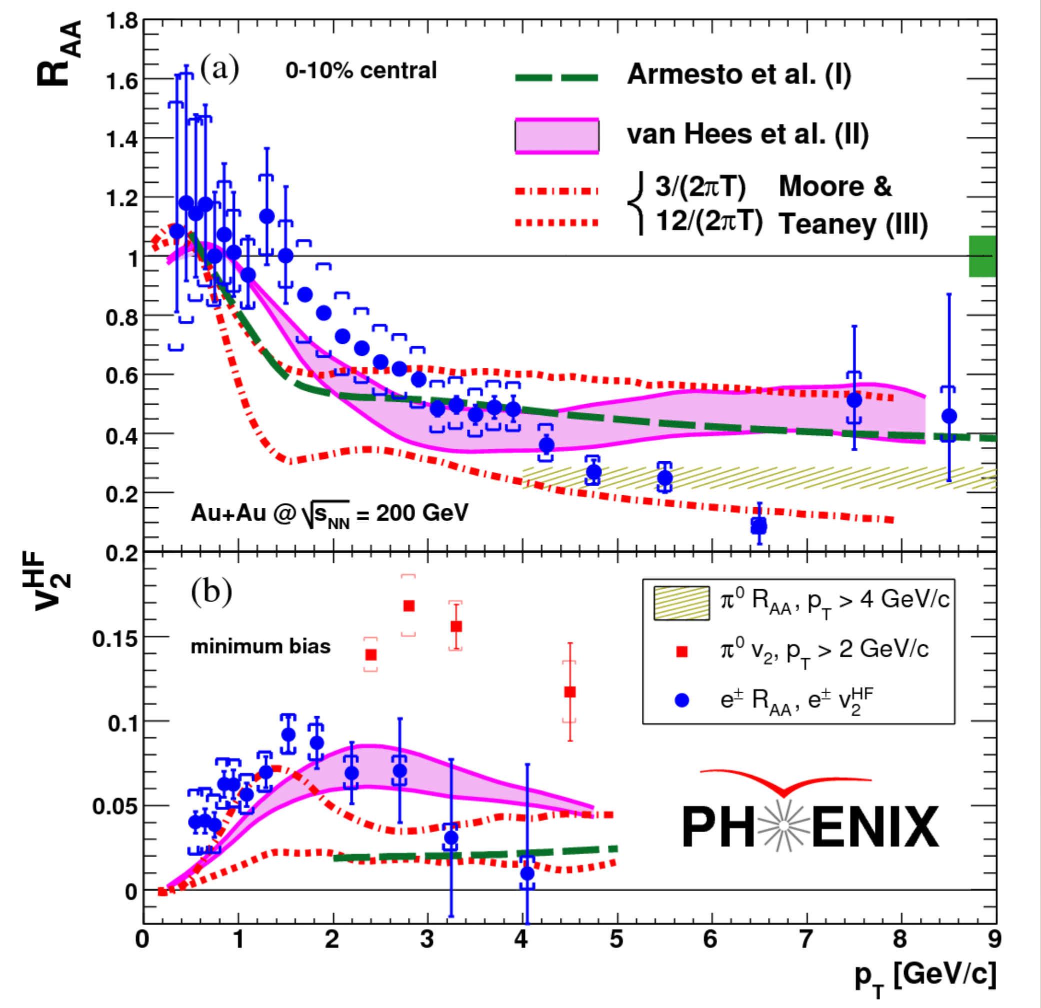




STAR Collaboration, Phys. Rev. C 96, 044904 (2017) [arXiv:1701.07065]

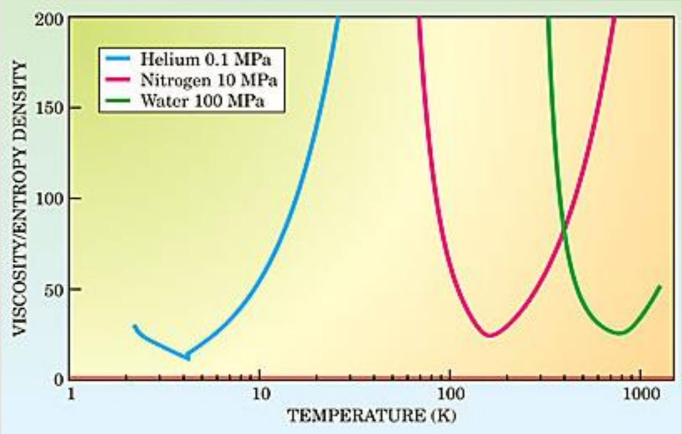
EVEN HEAVY FLAVOR FLOWS!

- Electrons from heavy flavor measured
- Even heavy flavor is suppressed
- Even heavy flavor flows
- Strong coupling of charm&bottom to the medium
- Small charm&bottom relaxation time in medium and *small viscosity*

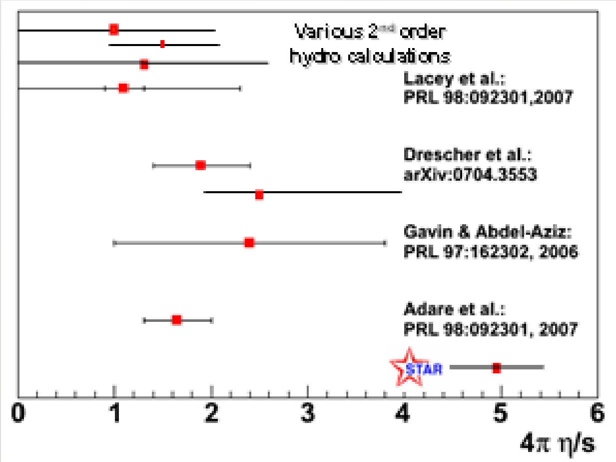


VISCOSITY

- Viscosity/entropy density: proportional to mean free path
- Strong coupling: small η/s
- AdS_{D+1}/CFT_D lower bound: $\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$
  - Malcadena et al.: Adv.Theor.Math.Phys.2:231-252
  - Kovtun et al.: Phys.Rev.Lett. 94 (2005) 111601

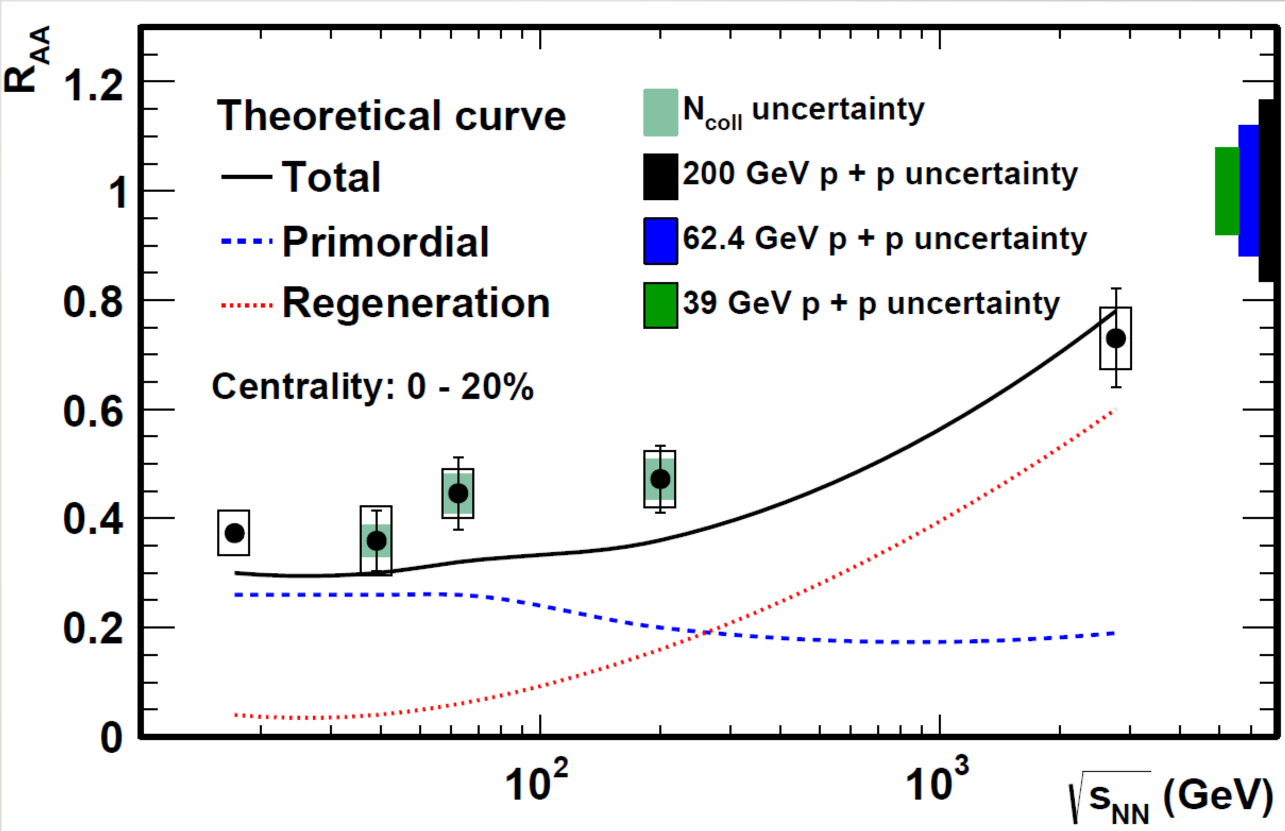


- Measurement and calculation results:
  - R. Lacey et al., Phys.Rev.Lett.98:092301,2007
  - H.-J. Drescher et al., Phys.Rev.C76:024905,2007
  - S. Gavin, M. Abdel-Aziz, Phys.Rev.Lett.97(2006)162302
  - A. Adare et al. (PHENIX), PRL98:172301,2007



J/Ψ IN THE BEAM ENERGY SCAN

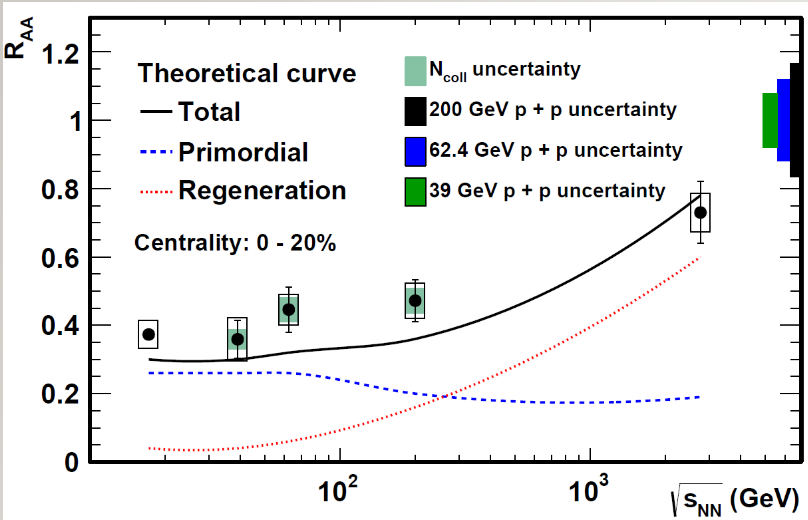
- Regeneration from cc̄ and feed-down from χ_c and ψ', increases with $\sqrt{s_{NN}}$
- Screening and cold nucl. matt.: less primordial charmonium with increasing $\sqrt{s_{NN}}$
- Two effects seem to compensate for $\sqrt{s_{NN}} < 200$ GeV

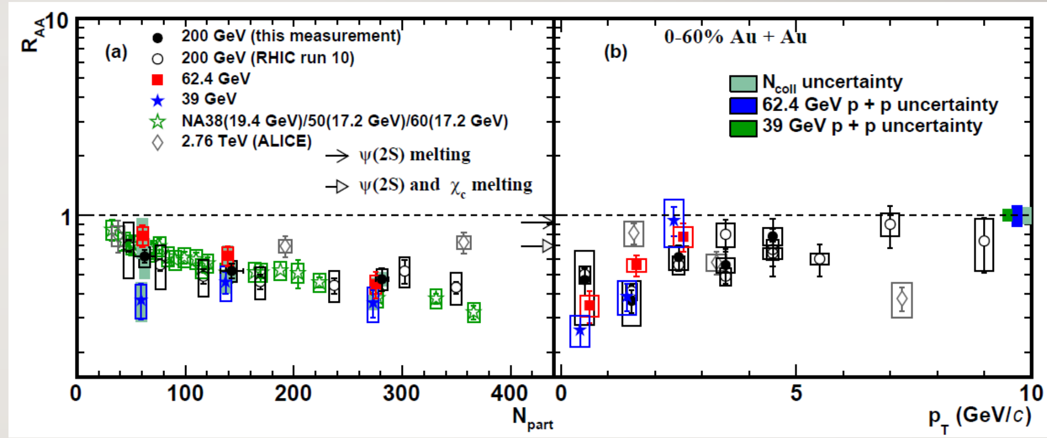


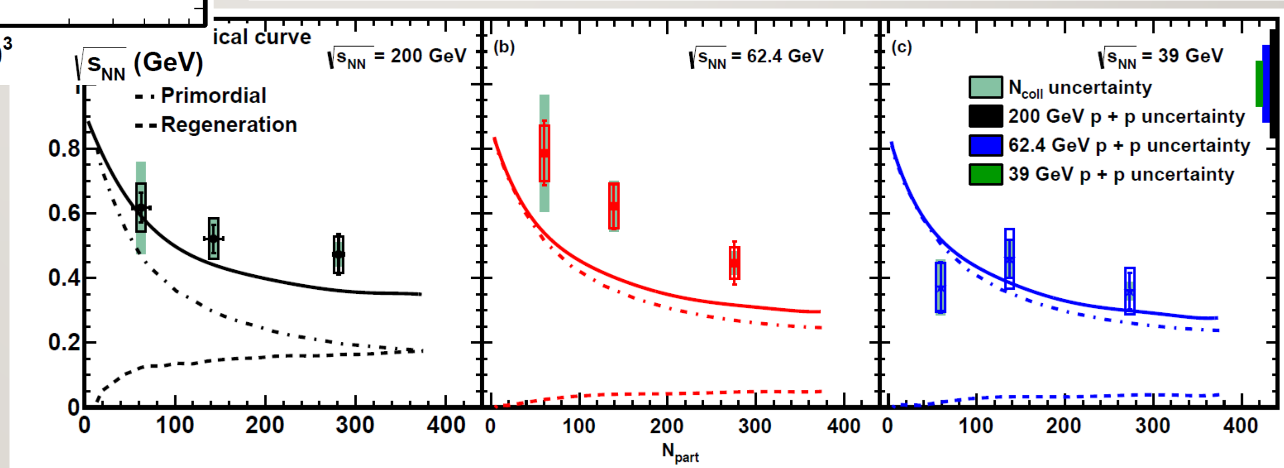
STAR Collaboration, Phys.Lett. B771 (2017) 13-20

J/PSI IN THE BEAM ENERGY SCAN

- STAR Collaboration, Phys.Lett. B771 (2017) 13-20

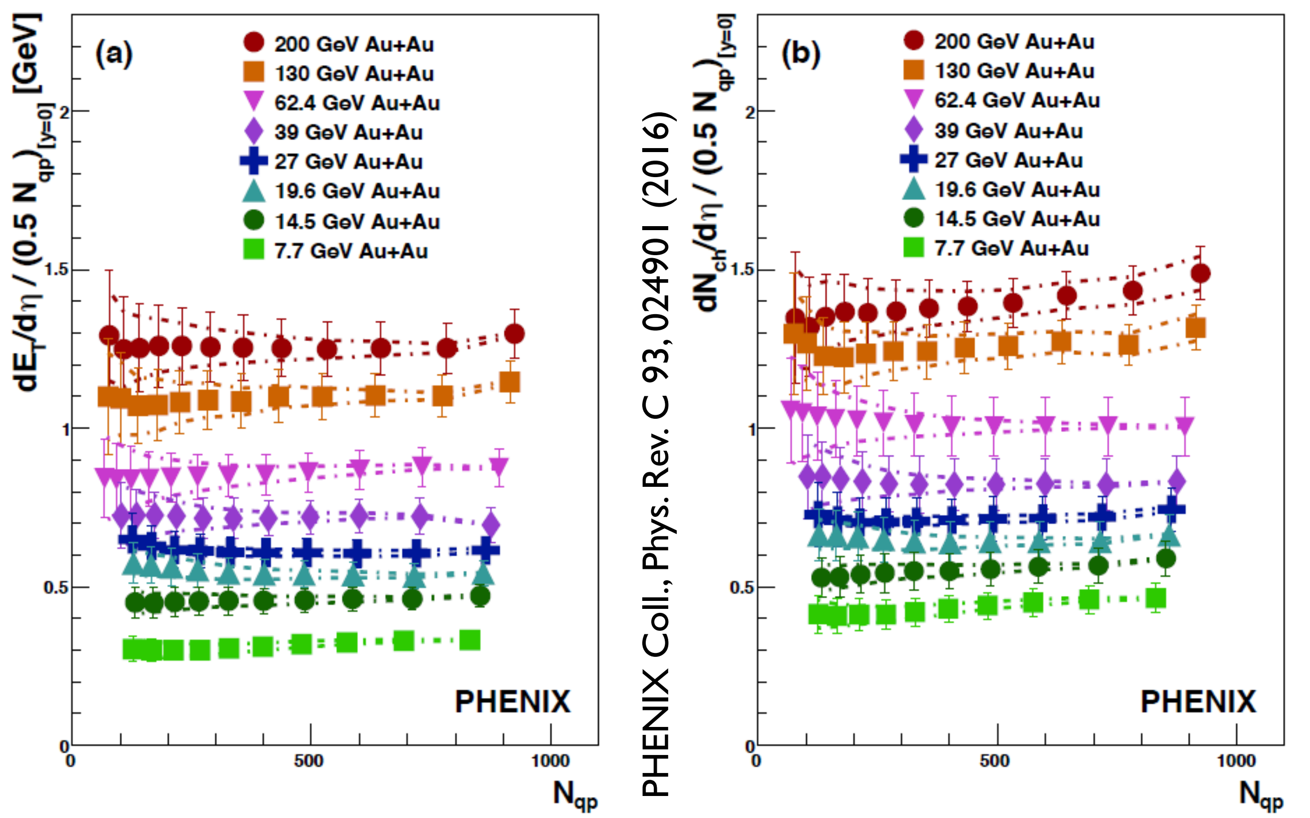






QUARK PARTICIPANT SCALING

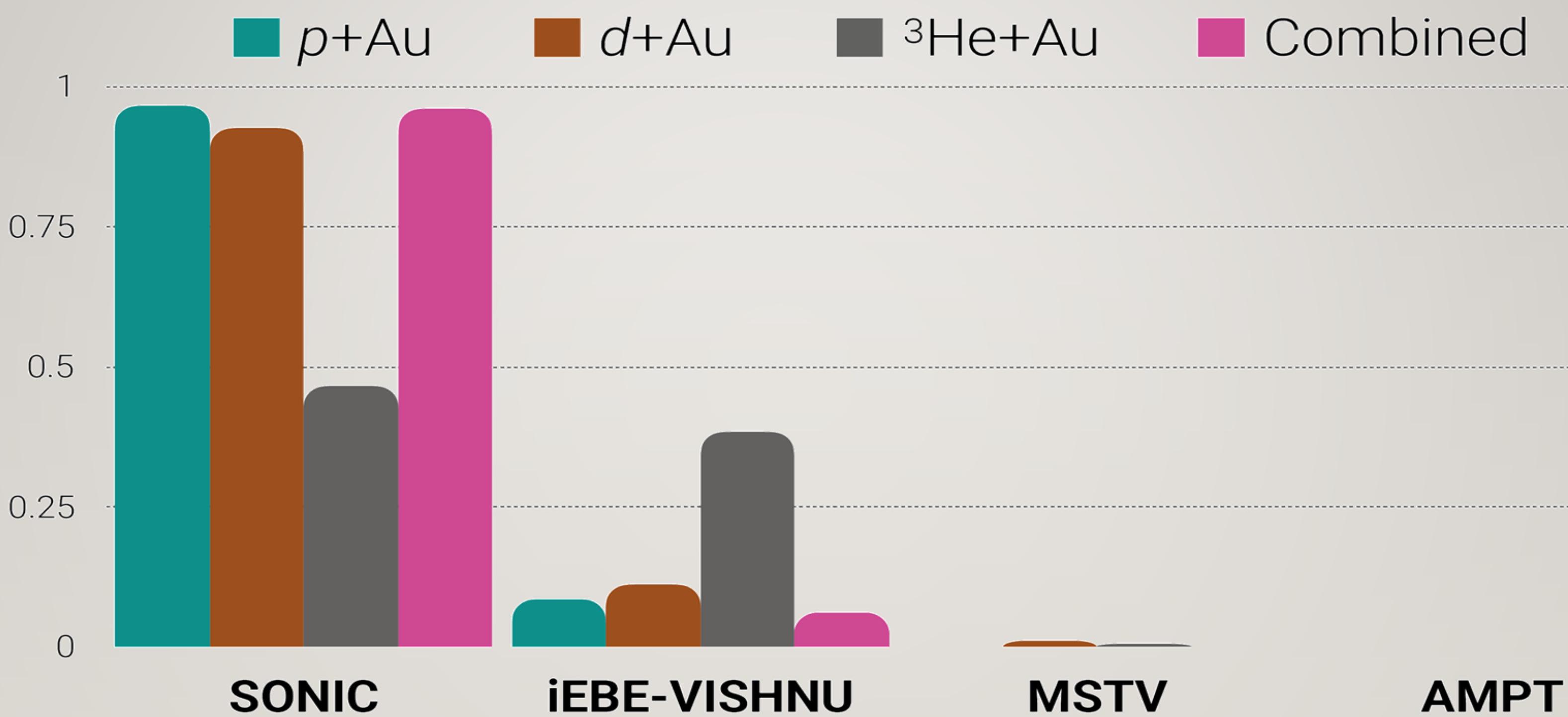
- Transverse energy and particle number: not constant vs Npart!
- Number of quark participants: a better estimator, quark degrees of freedom?



PHENIX Coll., Phys. Rev. C 93, 024901 (2016)

STATISTICAL TEST OF ALL MODELS

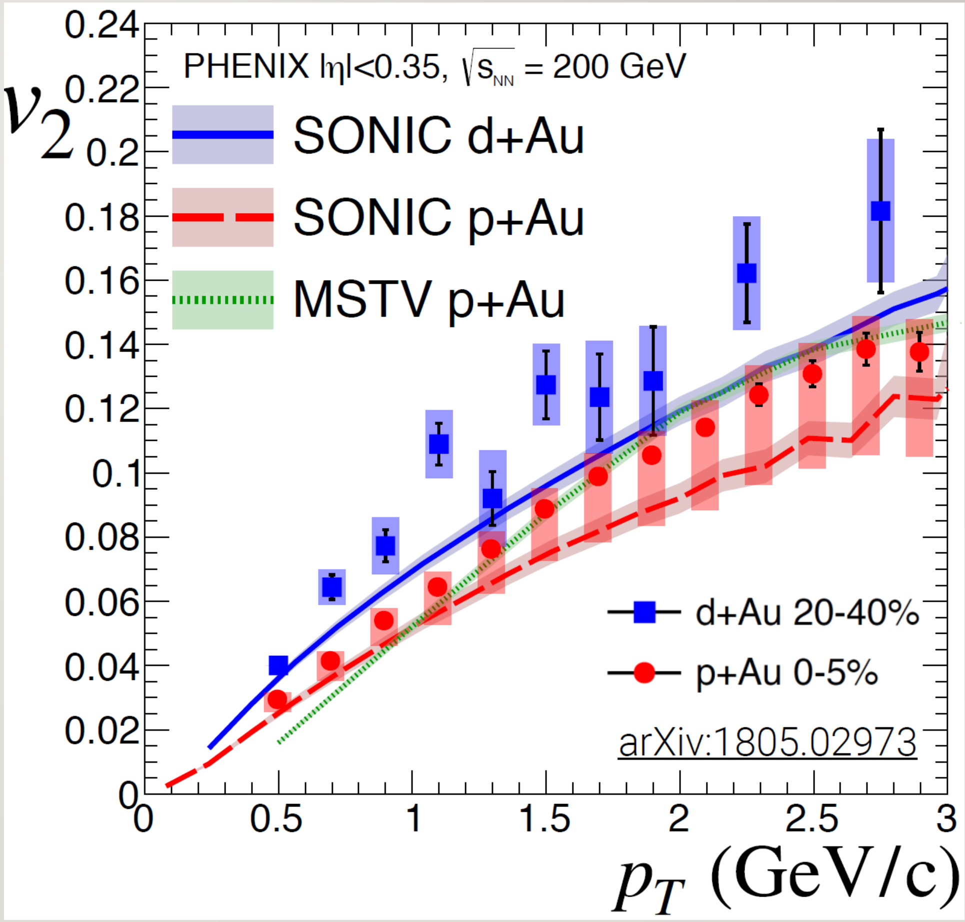
- QGP droplet and hydro describes data the best; MSVT close to marginal



	SONIC	iEBE-VISHNU	MSTV	AMPT
p+Au	0.966	0.086	7.07×10^{-17}	2.09×10^{-7}
d+Au	0.689	0.313	0.011	1.58×10^{-18}
3He+Au	0.465	0.432	0.007	2.17×10^{-22}
Combined	0.896	0.139	9.8×10^{-17}	2.67×10^{-43}

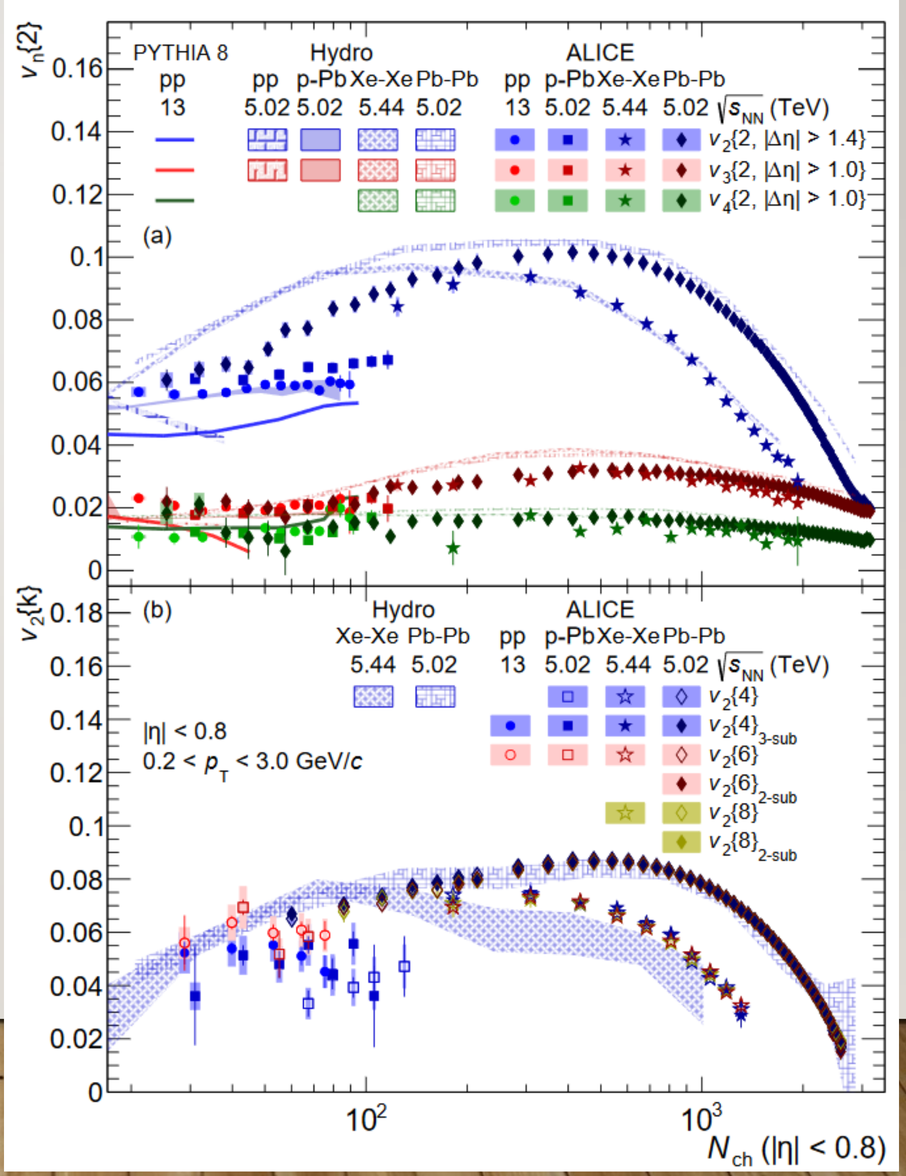
MVST PREDICTION FOR FIXED MULTIPLICITY

- Compare similar collision systems
  - d+Au 20-40% ($dN/d\eta = 12.2 \pm 0.9$) PRC 96, 064905 (2017)
  - p+Au 0-5% ($dN/d\eta = 12.3 \pm 1.7$) PRC 95, 034910 (2017)
- Fixed multiplicity: same MVST prediction for v_2
- Hydro description: better qualitative agreement (same multiplicity scales with eccentricity)
- Note: no nonflow systematics estimate in d+Au (≤ than in p+Au)



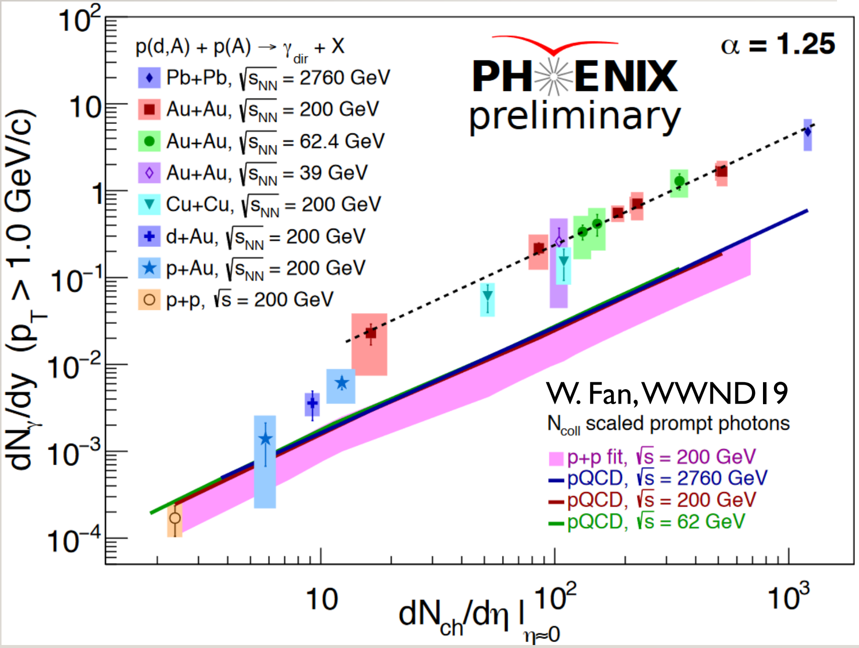
54/29 FROM PP THROUGH PPB TO PBPB

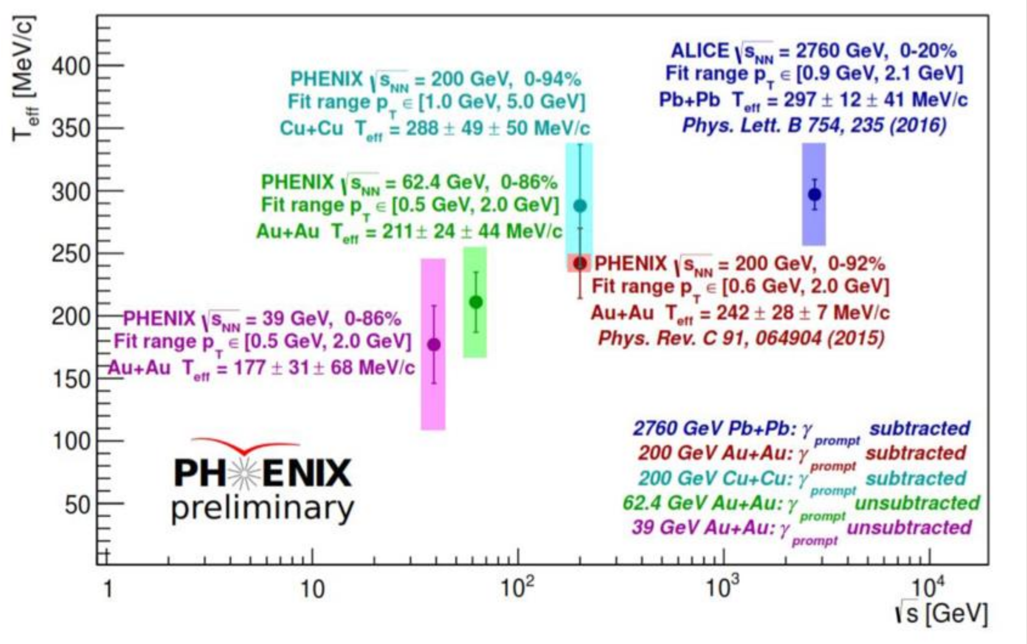
- ALICE, arXiv:1903.01790
- A given hydro does not describe pp very well, still better than Pythia
- Unified description from pp to PbPb in Weller, Romatschke Phys.Lett. B774 (2017) 351-356 arXiv:1701.07145



DIRECT PHOTONS

- Clear direct γ signal at lower energies
- Yield scaling from RHIC to LHC, transition from p+p, to A+A: p+Au, d+Au
- Effective photon temperature similar from 39 to 2760 GeV
- Note overlapping mechanisms: hadron gas, sQGP, jets, bremsstrahlung, hard scatt.





SUPPRESSION IN HIGHLY ASYMMETRIC SYSYTEMS

- p+Au, d+Au, ^{3}He+Au compared
- Centralities determined as for large systems
- New p+Au results show large centrality dependence
- System sizes agree at high pT
- At moderate pT, ordering seen
- Model comparision:
  - Vitev, HIJING++ investigated
  - No full match of ordering, peak location, etc