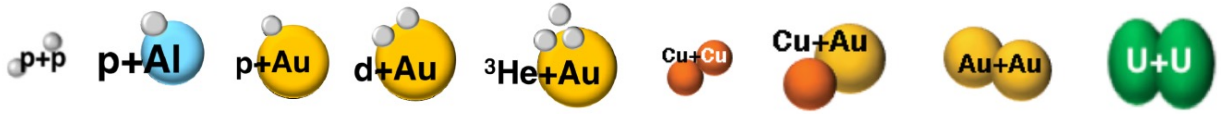
Latest heavy ion results from PHENIX at RHIC

Takao Sakaguchi

Brookhaven National Laboratory

PHENIX experiment

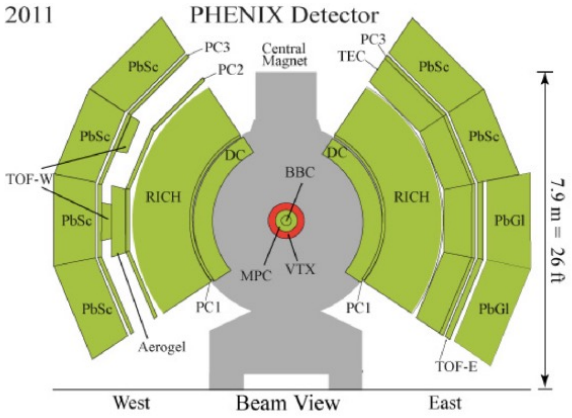
- Accomplished 16 years of operation with 9 collision species and 9 collision energies
  - Results from the recorded data are still coming out.



Hadrons, electron, photons

$|\eta|<0.35$ $\Delta\Phi= 2 \times \pi/2$

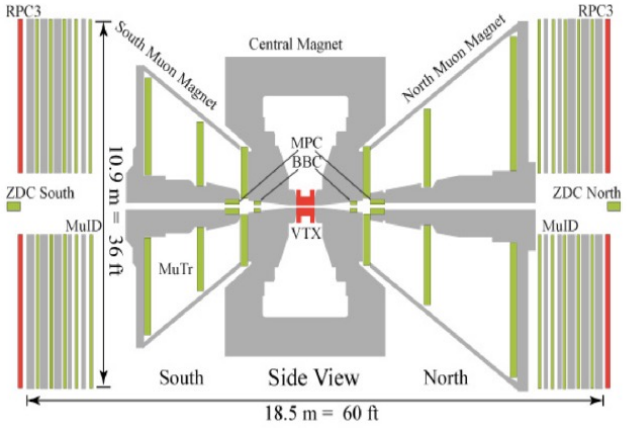
CENTRAL ARMS



Muons

$-2.2<\eta<-1.2$ $1.2<\eta<2.2$ $\Delta\Phi=2\pi$

MUON ARMS

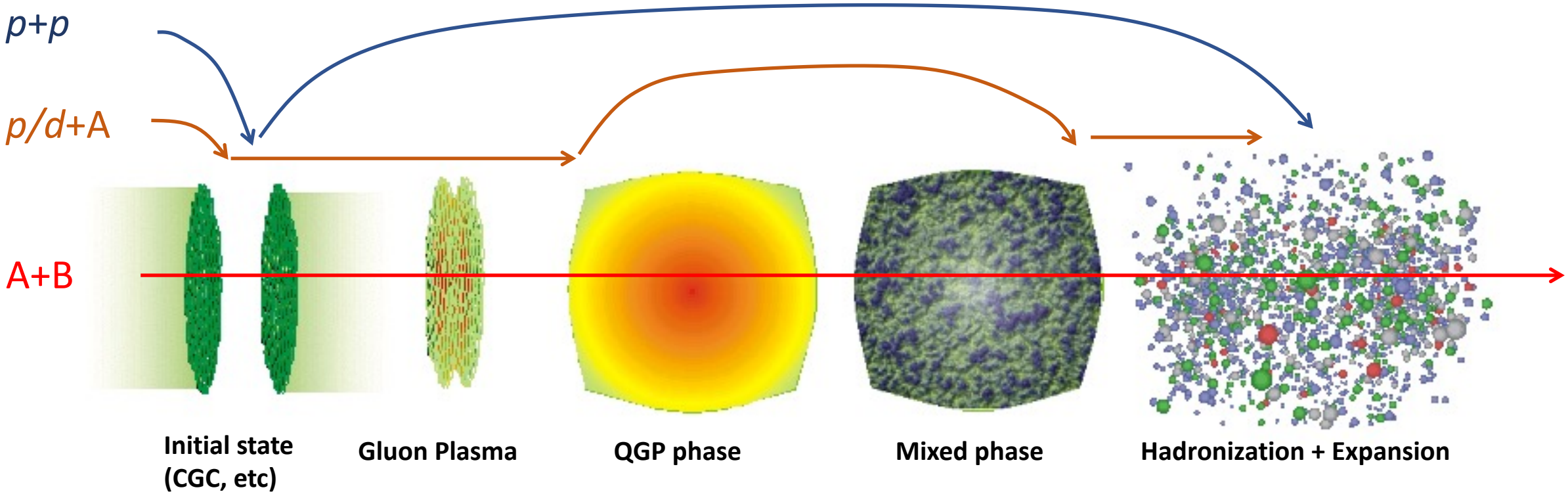


Run	Species	Energy $\sqrt{s_{NN}}$ (GeV)	Integrated Luminosity (mb^{-1})
1 (2000)	Au+Au	56	1.0E-6
2 (2001/2002)	Au+Au	200	2.4E-5
	p+p	200	1.5E+5
3 (2003)	d+Au	200	2.7E+3
	p+p	200	3.5E+5
4 (2004)	Au+Au	200	2.4E+2
	Au+Au	62.4	9.0E+0
5 (2005)	Cu+Cu	200	3.0E+3
	Cu+Cu	62.4	1.9E+2
	Cu+Cu	22.4	2.7E+3
	p+p	200	3.4E+6
6 (2006)	p+p	200	7.5E+6
	p+p	62.4	8.0E+4
7 (2007)	Au+Au	200	8.1E+2
8 (2008)	d+Au	200	8.0E+4
	p+p	200	5.2E+6
9 (2009)	p+p	500	1.4E+7
	p+p	200	1.6E+7
10 (2010)	Au+Au	200	1.5E+3
	Au+Au	62.4	1.1E+2
	Au+Au	39	4.0E+4
	Au+Au	7.7	3.0E+2
11 (2011)	p+p	500	1.8E+7
	Au+Au	19.6	2.0E+0
	Au+Au	200	1.7E+3
	Au+Au	27	7.0E+0
12 (2012)	p+p	200	1.0E+7
	p+p	510	3.2E+7
	U+U	193	2.0E+2
	Cu+Au	200	5.0E+3
13 (2013)	p+p	510	1.6E+8
14 (2014)	Au+Au	14.6	4.0E+0
	Au+Au	200	7.5E+3
	^{3}He+Au	200	2.4E+4
15 (2015)	p+p	200	6.0E+7
	p+Au	200	2.0E+5
	p+Al	200	5.0E+5
16 (2016)	Au+Au	200	7.0E+3
	d+Au	200	5.0E+4
	d+Au	62.4	5.0E+3
	d+Au	19.6	8.0E+1
	d+Au	39	2.0E+3

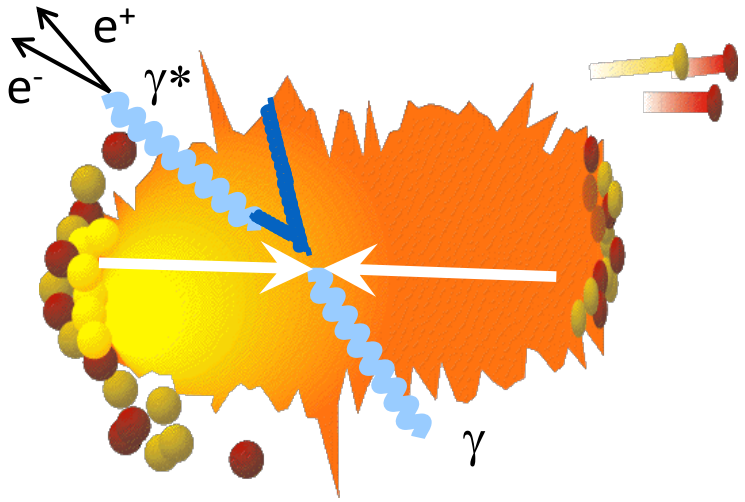
Tuning final/initial state effect by collisions

- Different collision systems go through different states.
- Contributions from final/initial states can be tuned.

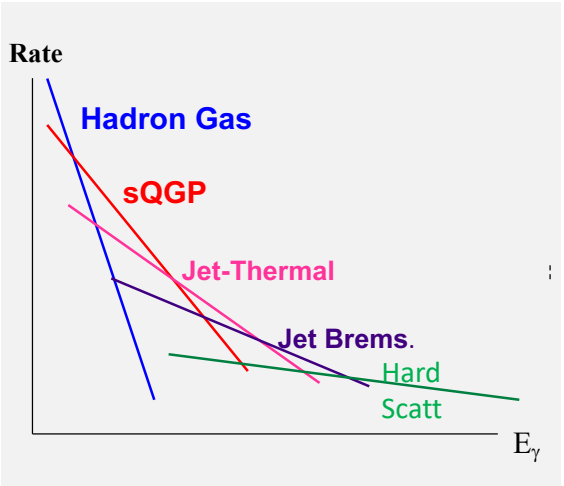
We show highlights by:
- Temperature (EM Probe)
- Density (Quarkonium)
- Viscosity (hadrons)



Temperature (EM probes)



Slopes tell the temperature of the emission source



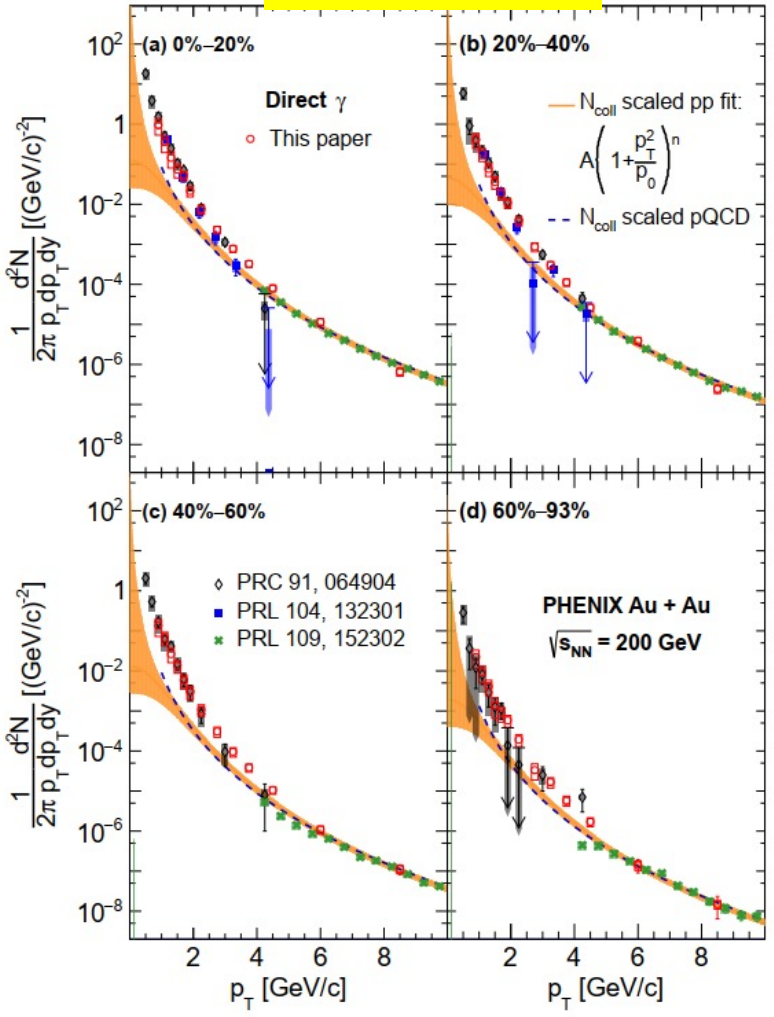
Direct photon spectra in A+A

- Direct photons:
  (all photons) – (hadron-decay photons)

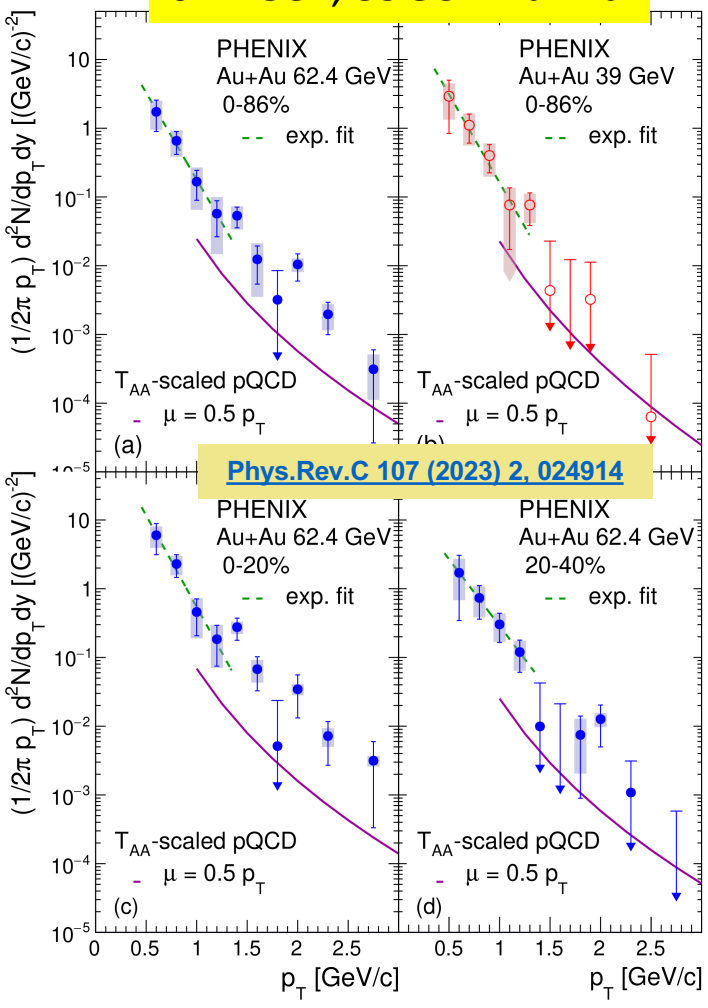
- ~10× higher statistics for 200GeV Au+Au is in progress for publication
  - Agreement with previous results
  - Significant reduction in stat. & sys. Uncertainties

- Result from 62.4GeV, 39GeV Au+Au has been published.

200GeV Au+Au



62.4GeV, 39GeV Au+Au



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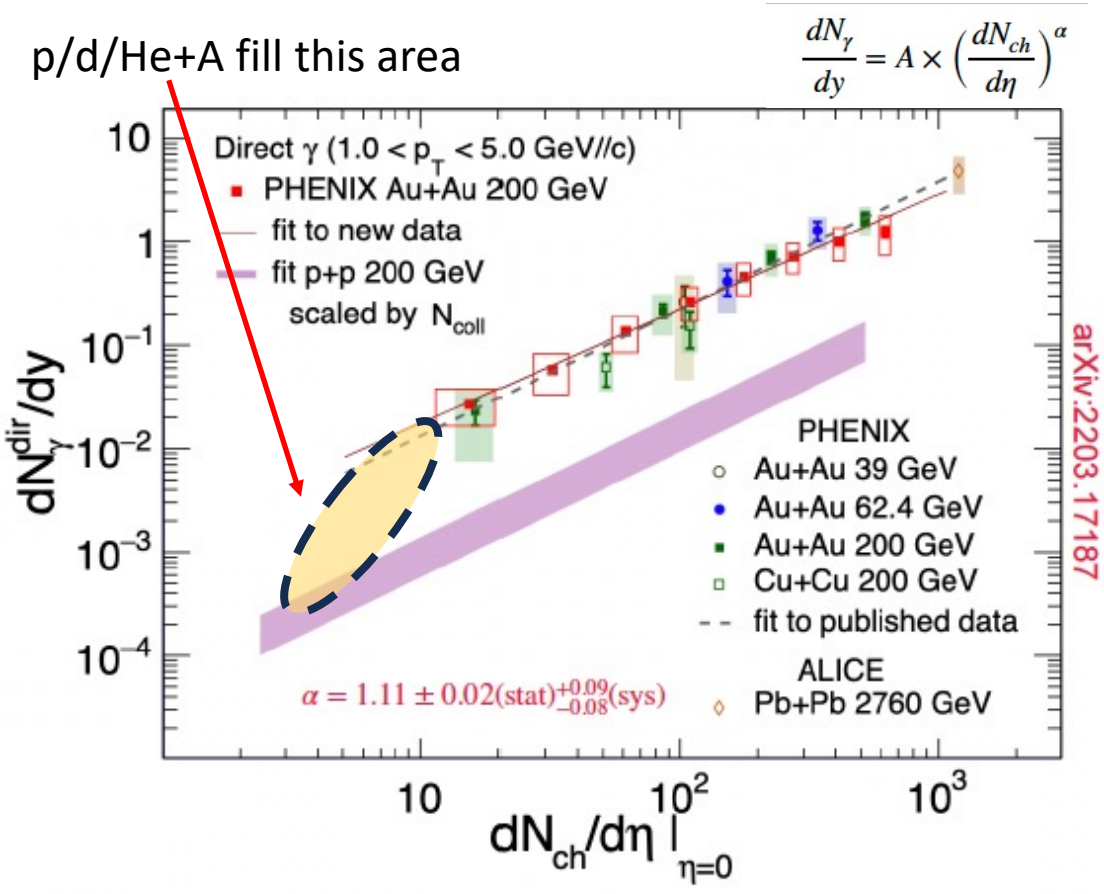
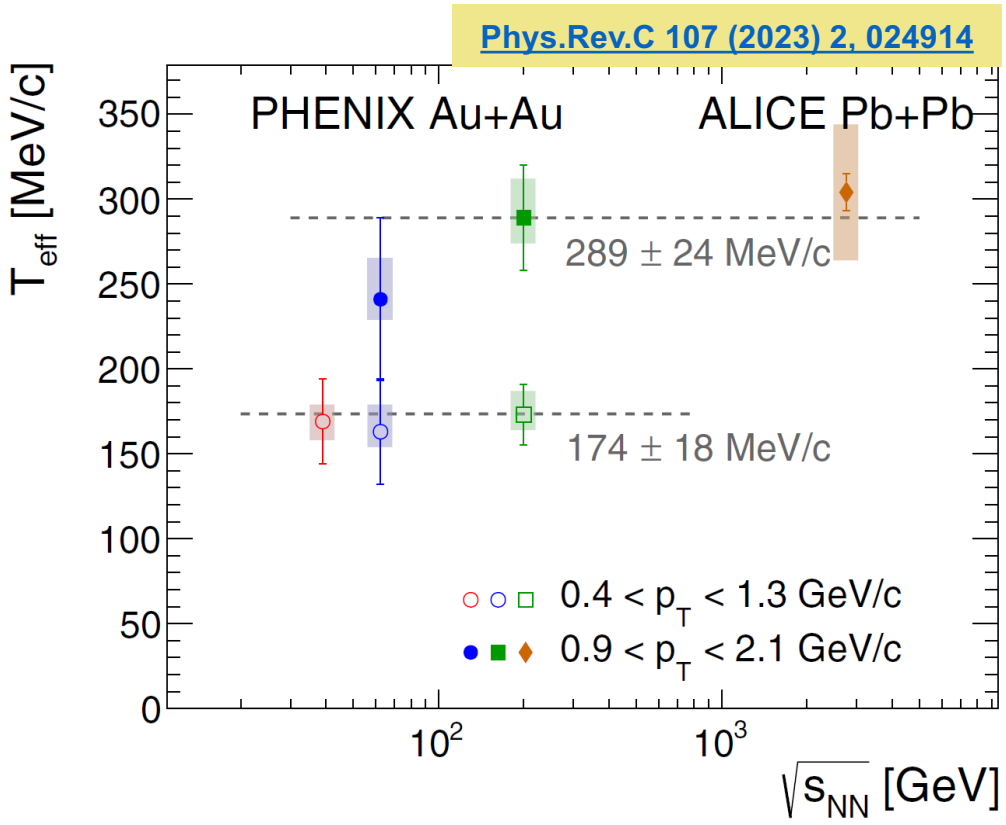
System-dependent direct photons

- Yields show a systematic trend against particle multiplicity.
- Temp. depends on p_T-ranges → manifestation of different emission sources?

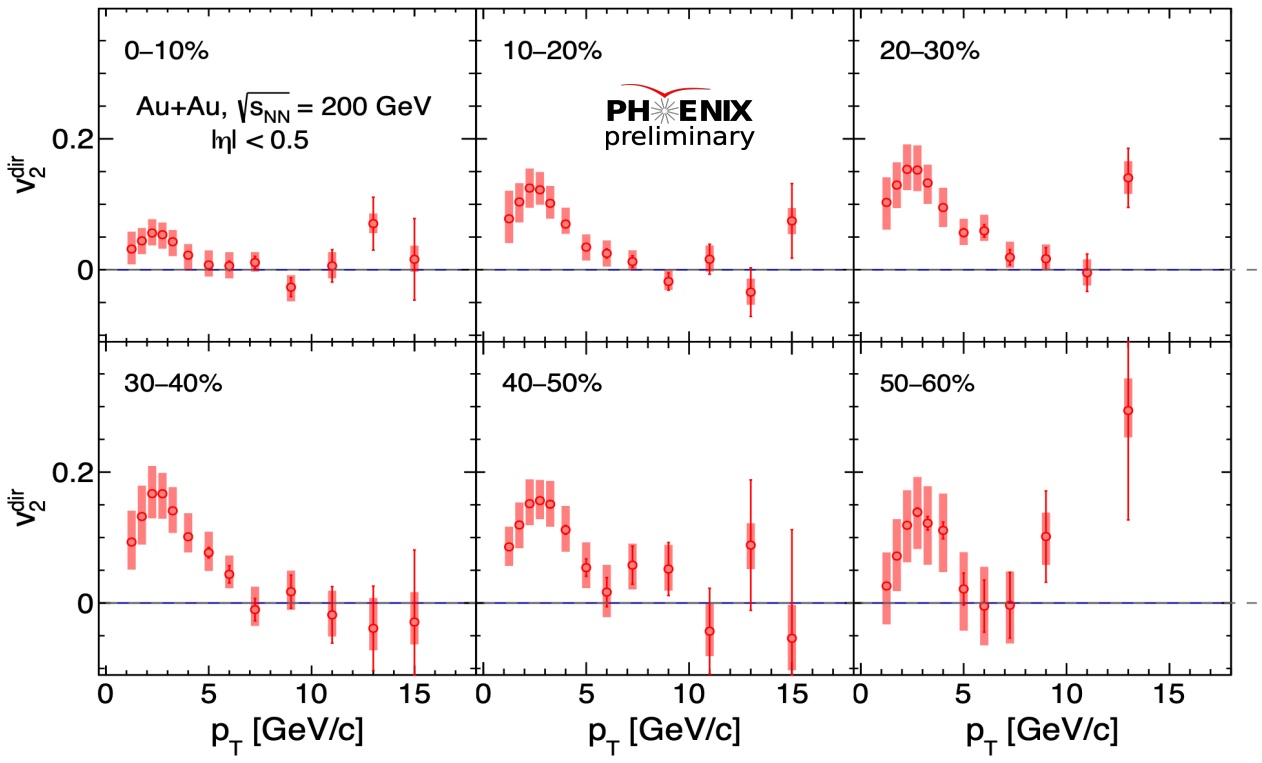




Distinguishing photon emission sources in A+A

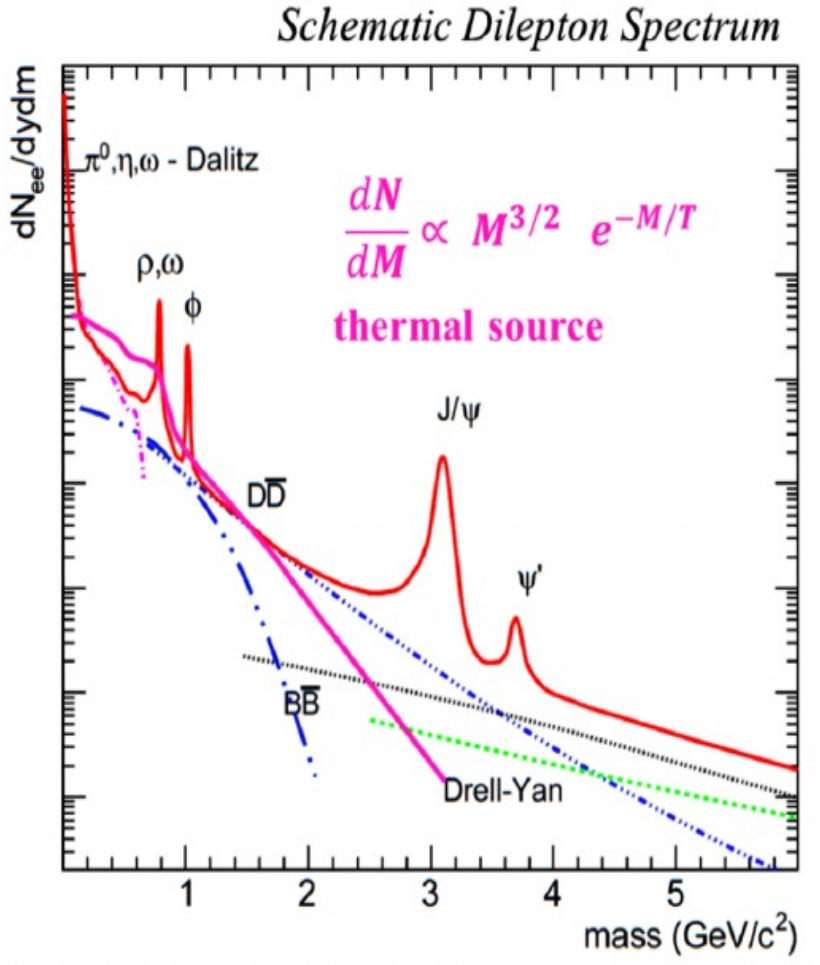
- Photon flow helps distinguish photon emission sources
- With highest statistics available at RHIC, the centrality binning are fined.
- v_2 at high p_T is consistent with 0
  - Consistent with prompt photon contribution

Talk: Michael Giles

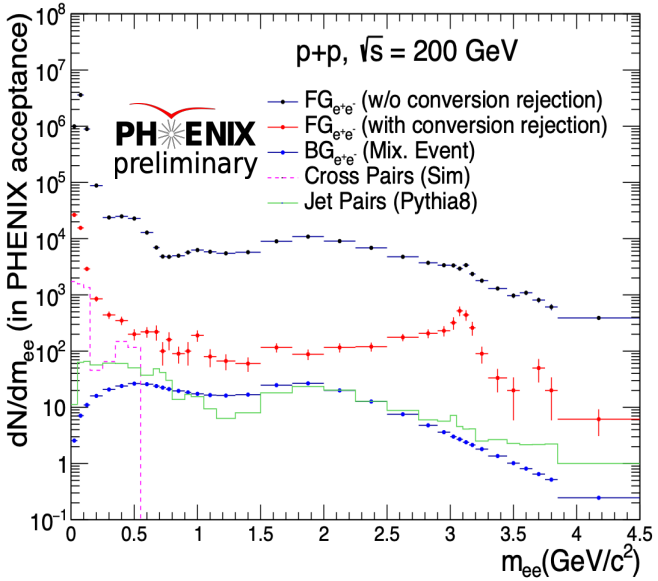


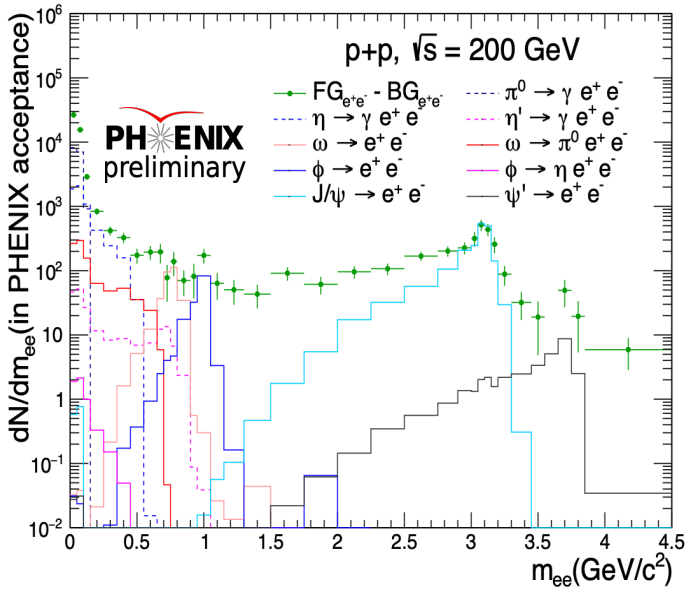
Sources	p_T	v_2	v_3	v_n t-dep.
Hadron-gas	Low p_T	Positive and sizable	Positive and sizable	→
QGP	Mid p_T	Positive and small	Positive and small	↗
Primordial (jets)	High p_T	~zero	~zero	→
Jet-Brems.	Mid p_T	Positive	?	↘
Jet-photon conversion	Mid p_T	Negative	?	↘
Magnetic field	All p_T	Positive down to p_T=0	Zero	→

Another region to look for photons

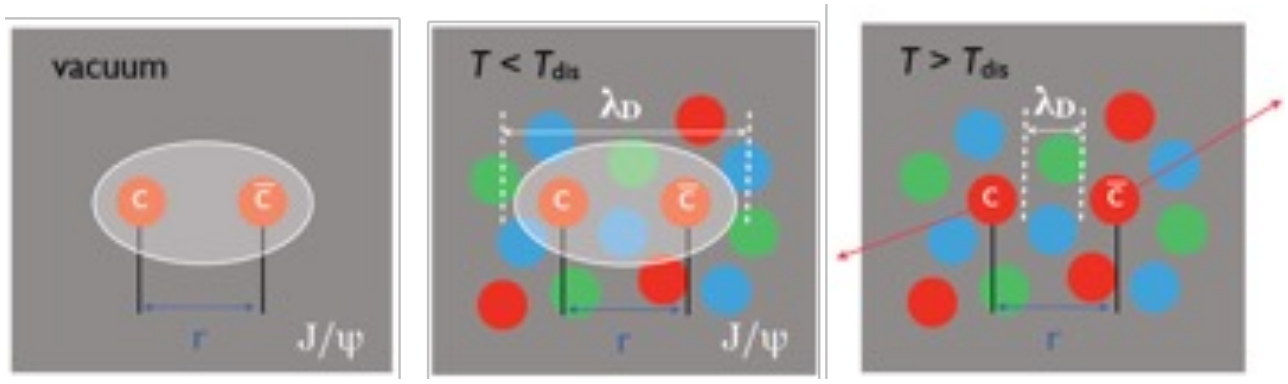


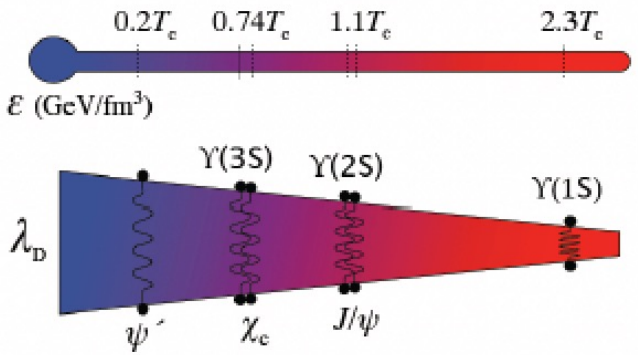
- "direct photons" is from high p_T, low virtuality (Q^2)
- Photonic contribution is also in high Q^2 (M=1-2GeV/c^2), low p_T region (dileptons):
  - Look for Mass slope, instead of p_T slope
- Baseline for high mass dileptons (p+p) was obtained.
  - Determining DDbar->ee and prompt pairs is a key.





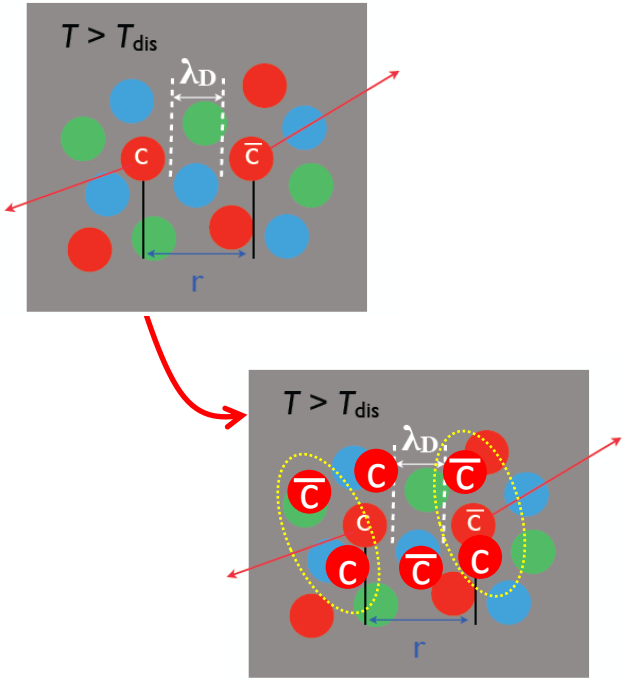
Density (Quarkonia)

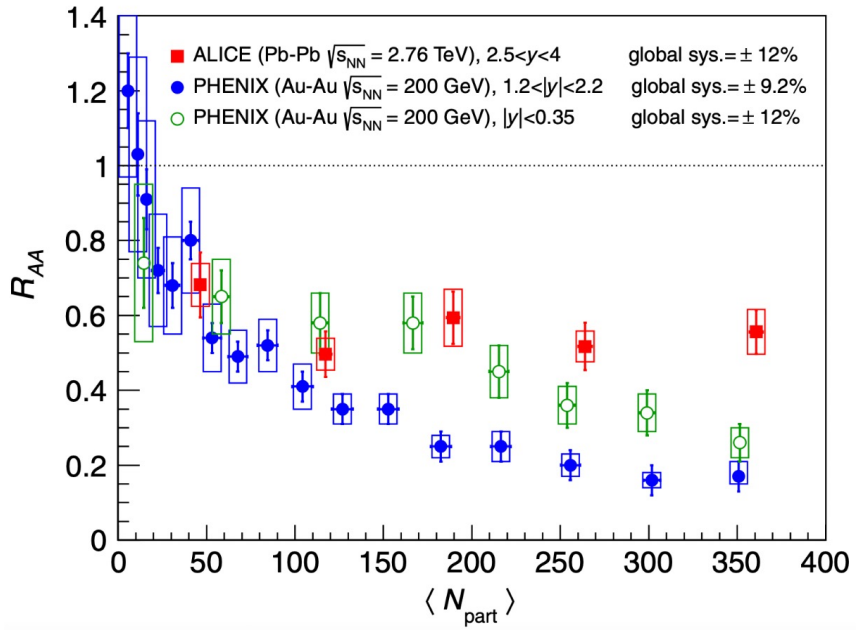


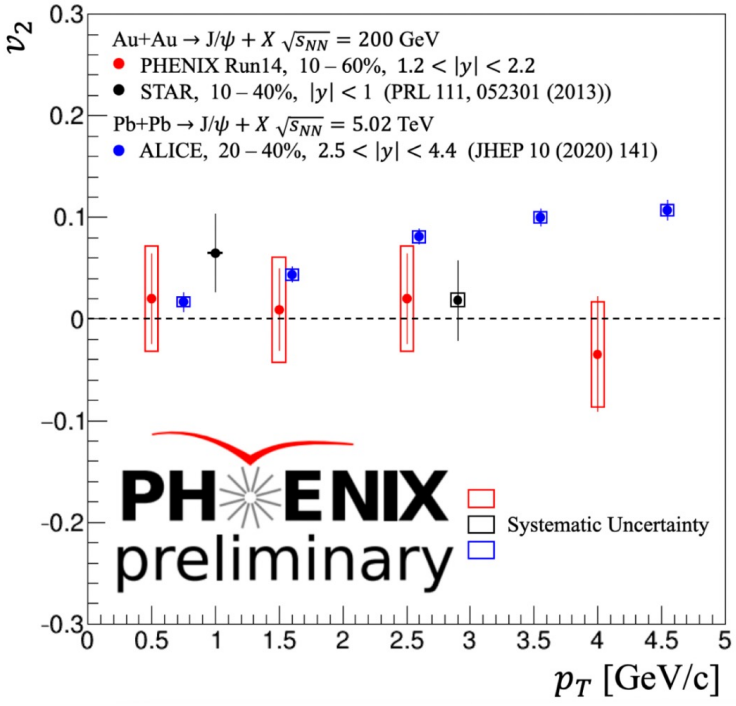


Charmonia chemistry in A+A

- Charmonia was believed to be produced only in the initial state.
  - At high production rate of charms (like LHC), regeneration of J/ψ was proposed.
- PHENIX J/ψ shows the regeneration is not as significant at RHIC energies
  - Stronger suppression at high-*y*, flow consistent with zero. → mostly from prompt



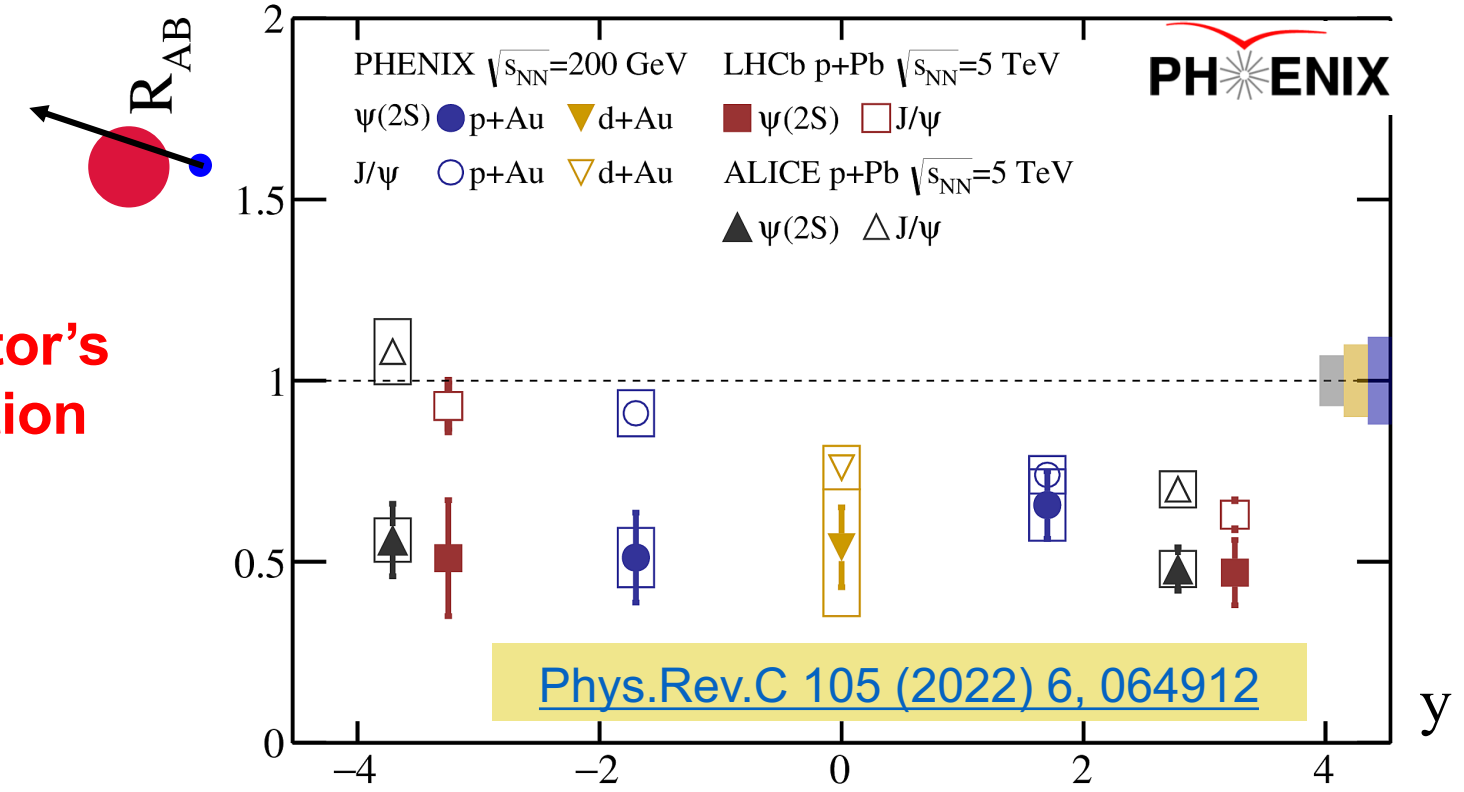


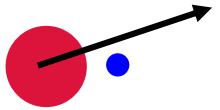


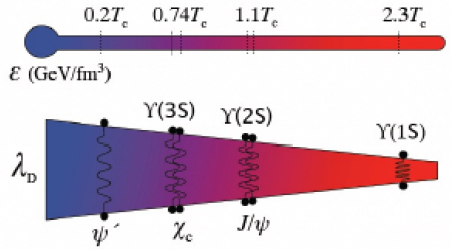
Charmonia in small systems

- Charms are mostly produced at the initial state.
  - Different radius for J/ψ and ψ(2S) → suppression is sensitive to the parton density.
- Similar patterns for J/ψ and ψ(2S) found at RHIC and LHC.
  - Result is consistent with final state effects at backward rapidity.

PRC Editor's suggestion

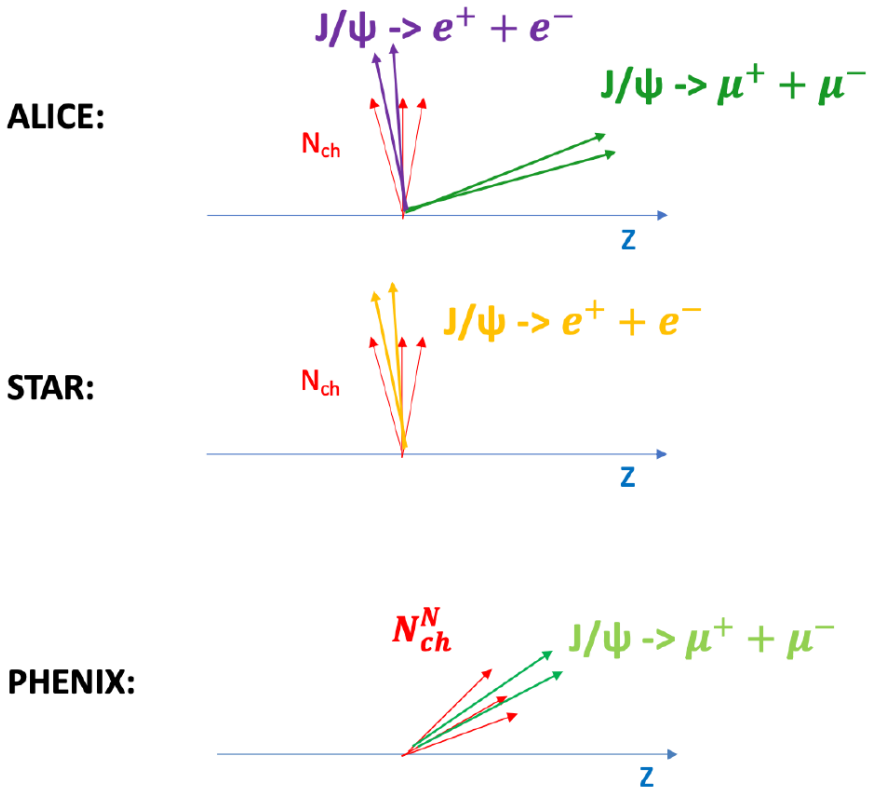




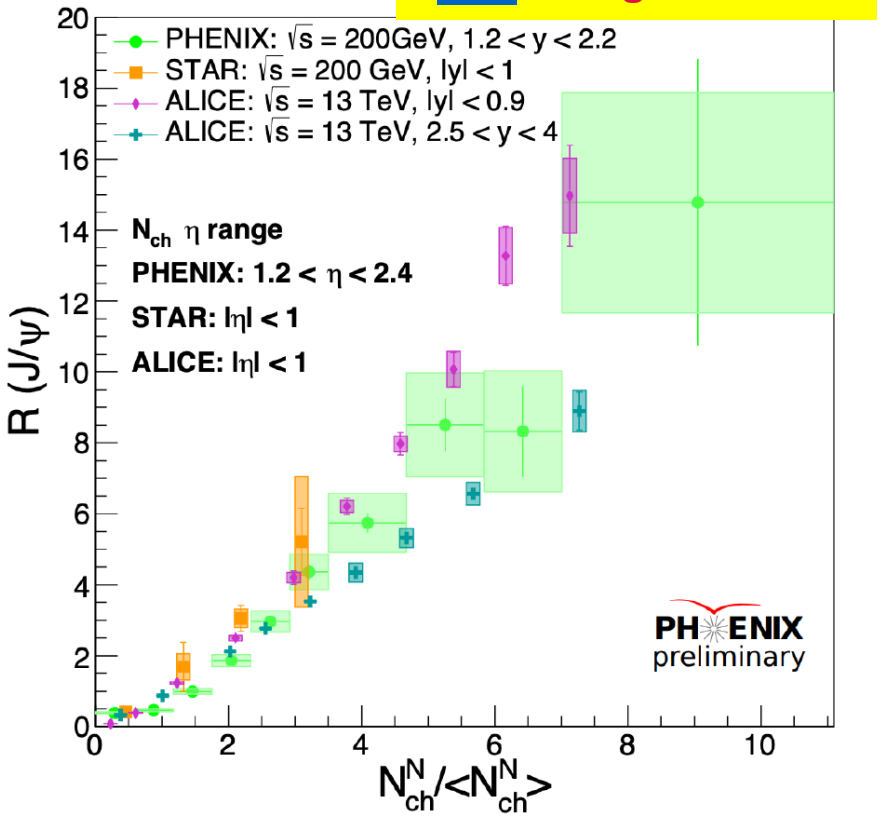


Even smaller system (p+p)

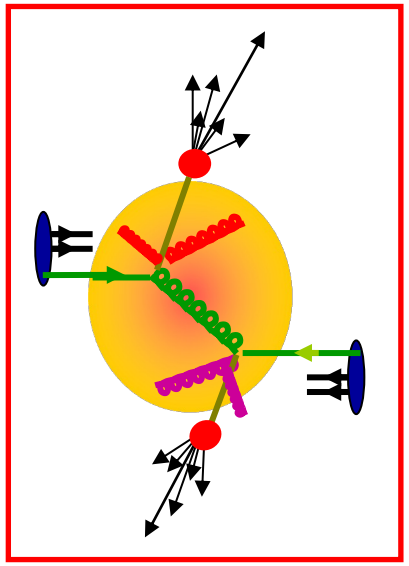
- J/ψ yield exhibits large dependence on local track multiplicity.
  - Often attributed to multi-parton interactions

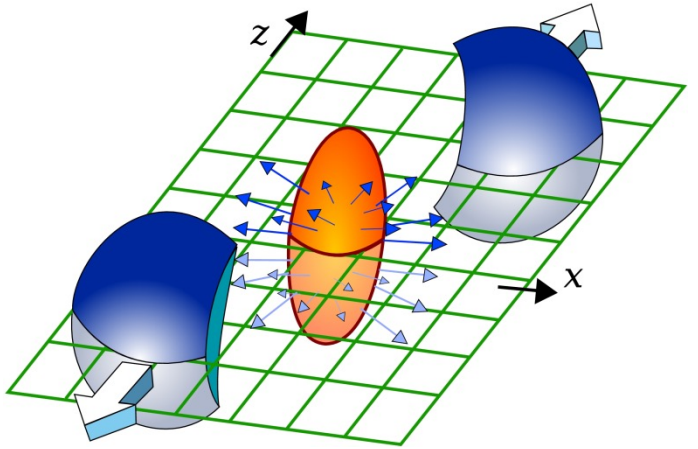


Talk: Sanghoon Lim



Viscosity

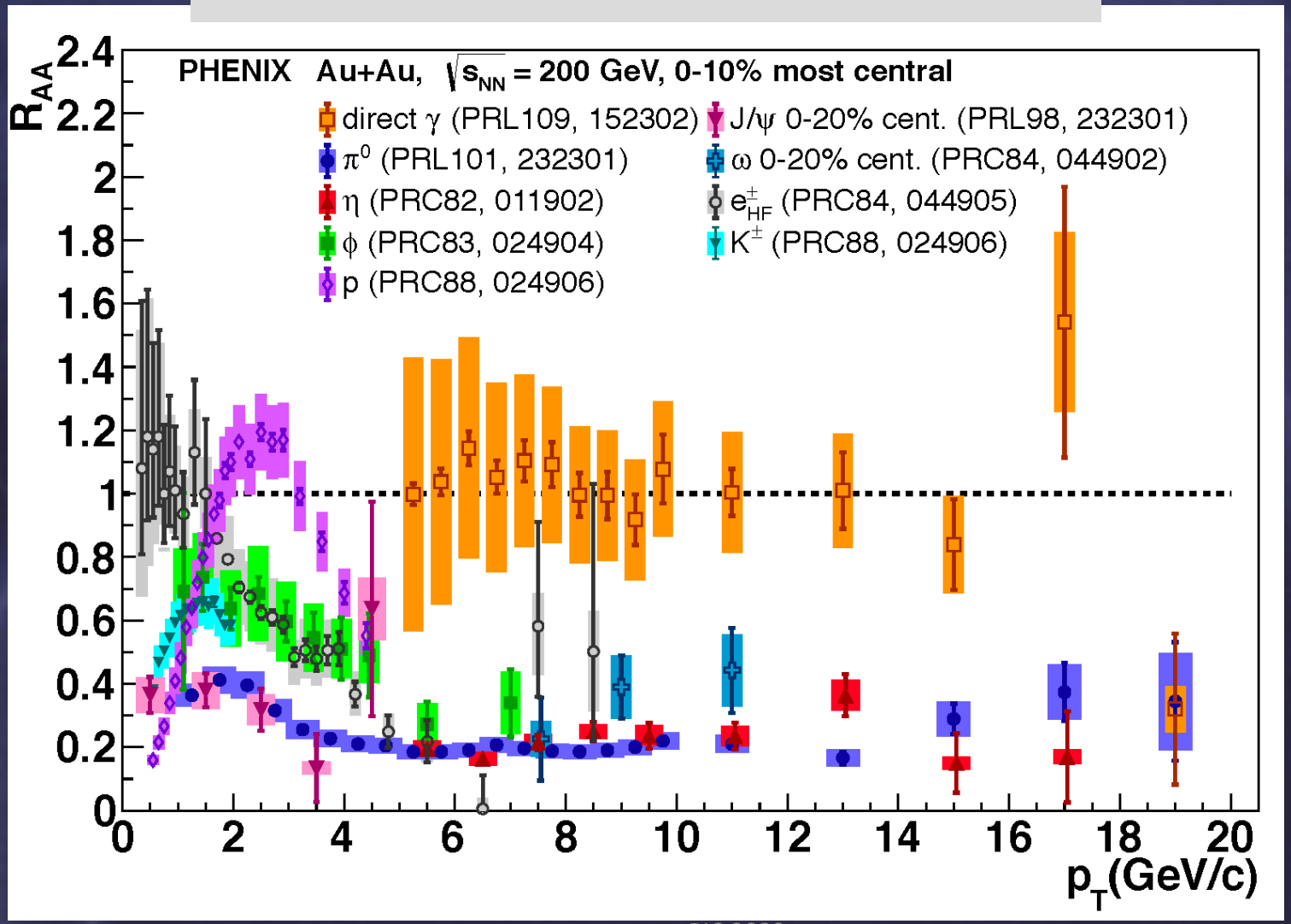




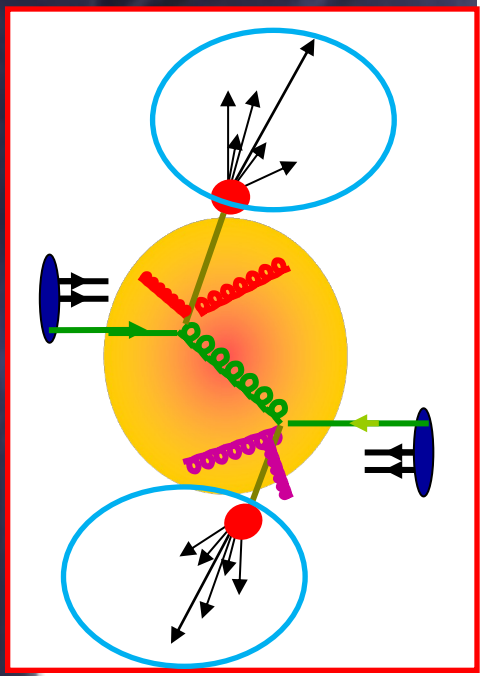
The PHENIX T-shirt R_{AA} plot

Au+Au

Inclusive measurement of hadrons

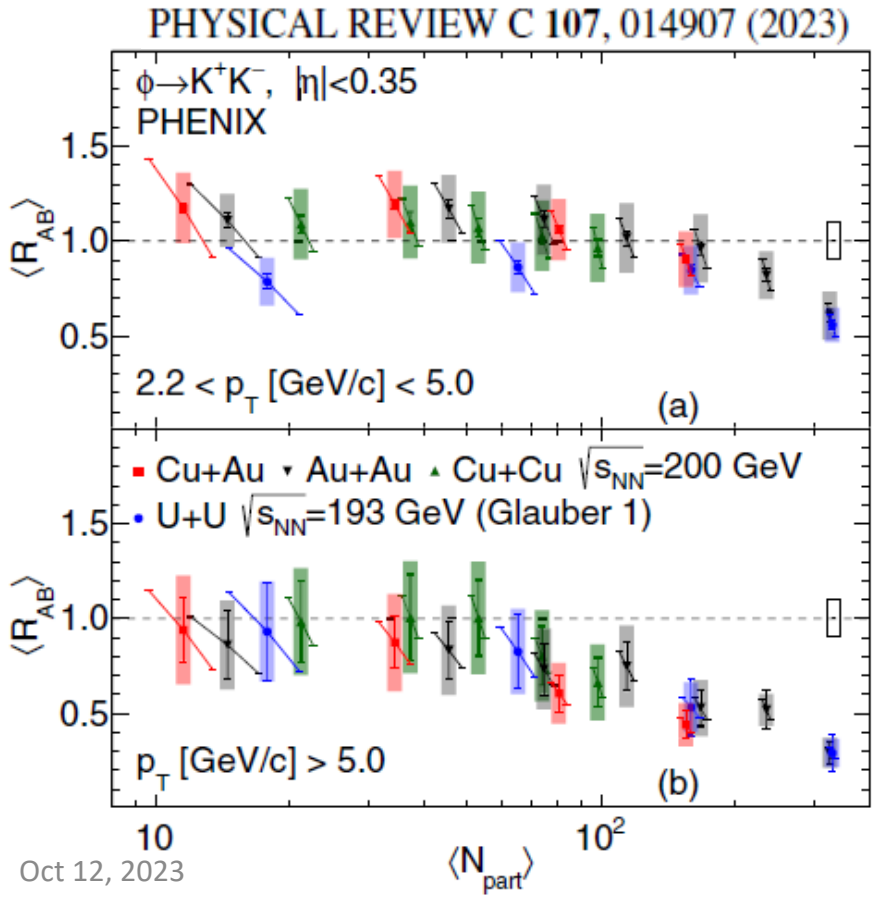


$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{\frac{Ncoll}{\sigma_{inel}} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

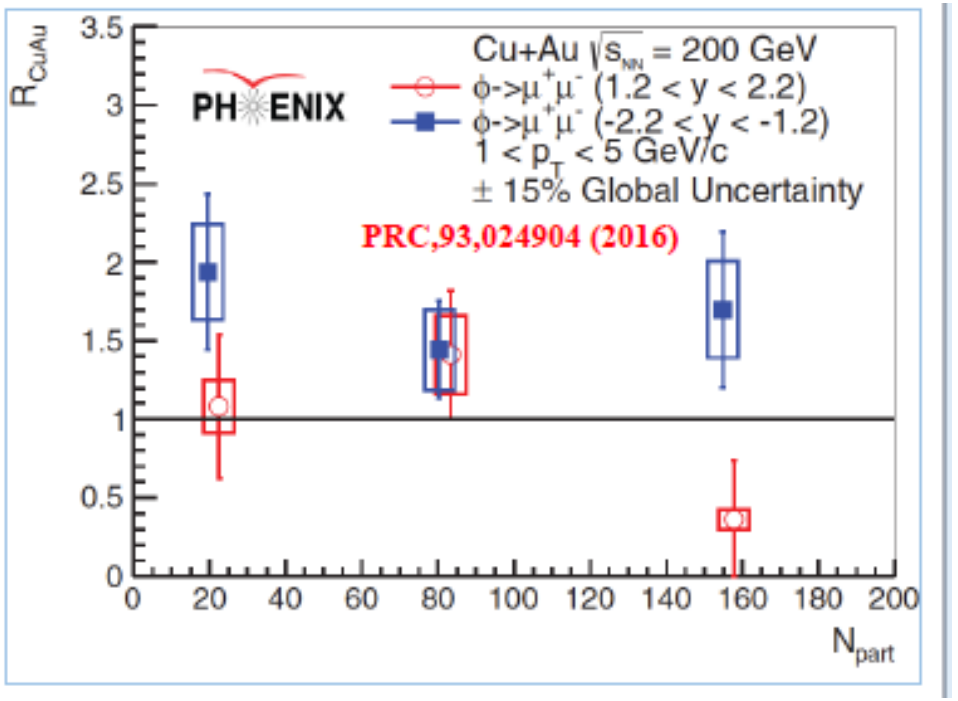


Mass or baryon/meson matters? (ϕ)

- System size dependence of ϕ yields is seen in Au+Au, Cu+Au, and U+U collisions
- Rapidity dependence may shed light on the final effect to ϕ.

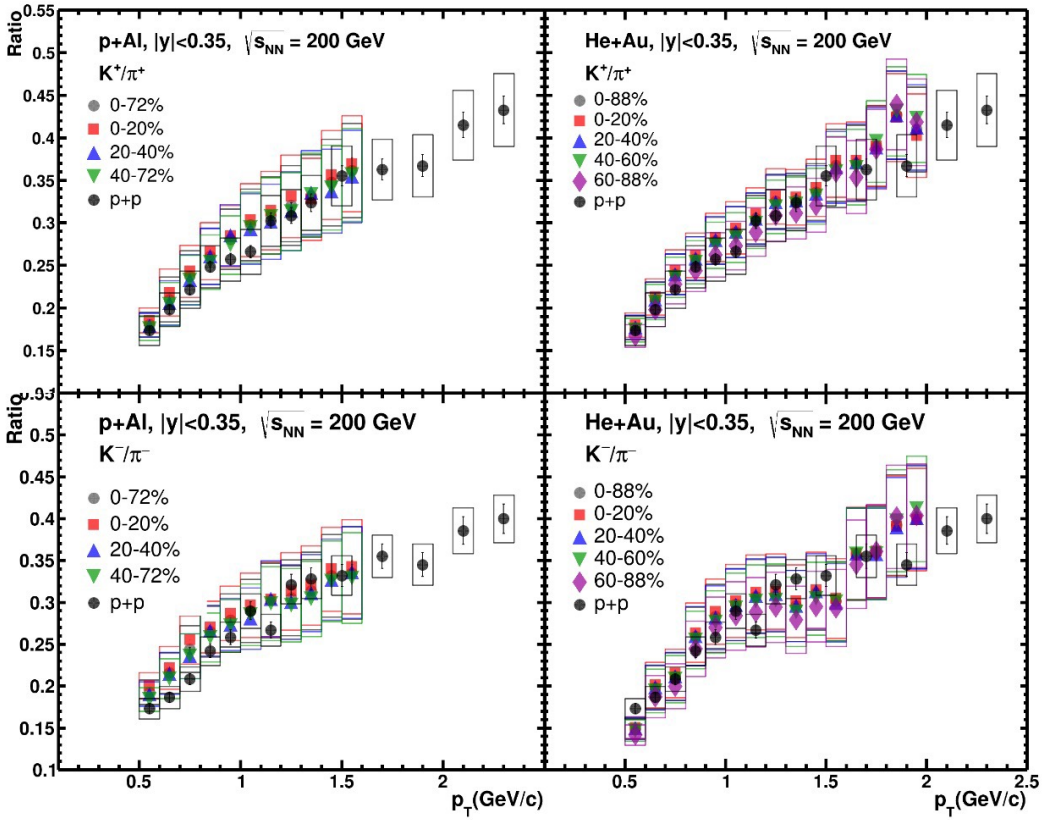


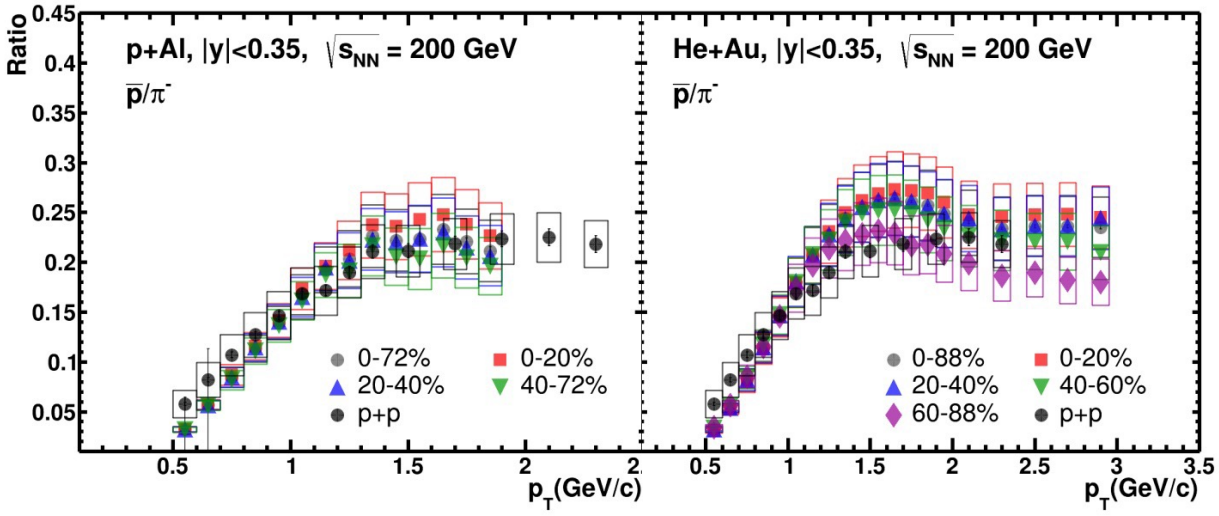
Talk: Uttam Acharya



Identified hadrons in small systems

- π yield as a proxy of charged multiplicity
- Both K/π and pbar/π ratios are consistent over centralities in low p_T.
  - Small centrality dependence: Gradual hot medium production?



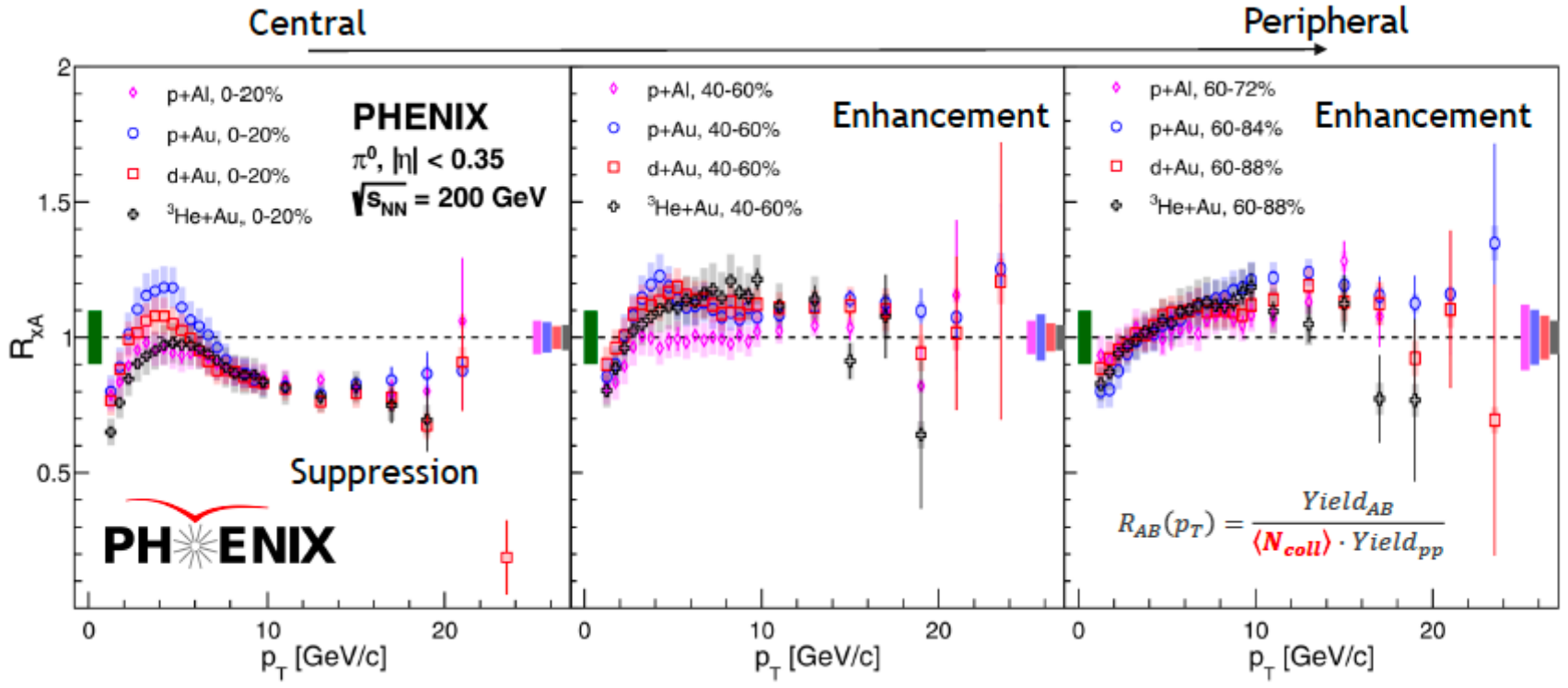


High p_T π^0 in small systems (R_{xA})

Talk: Uttam Acharya

- Same suppression at high p_T in centrals. Some enhancement in peripherals
- Ordering with system size NOT seen at high p_T
  - Potential bias in centrality determination? Final state effect?

Bias in N_{coll} at high p_T ?



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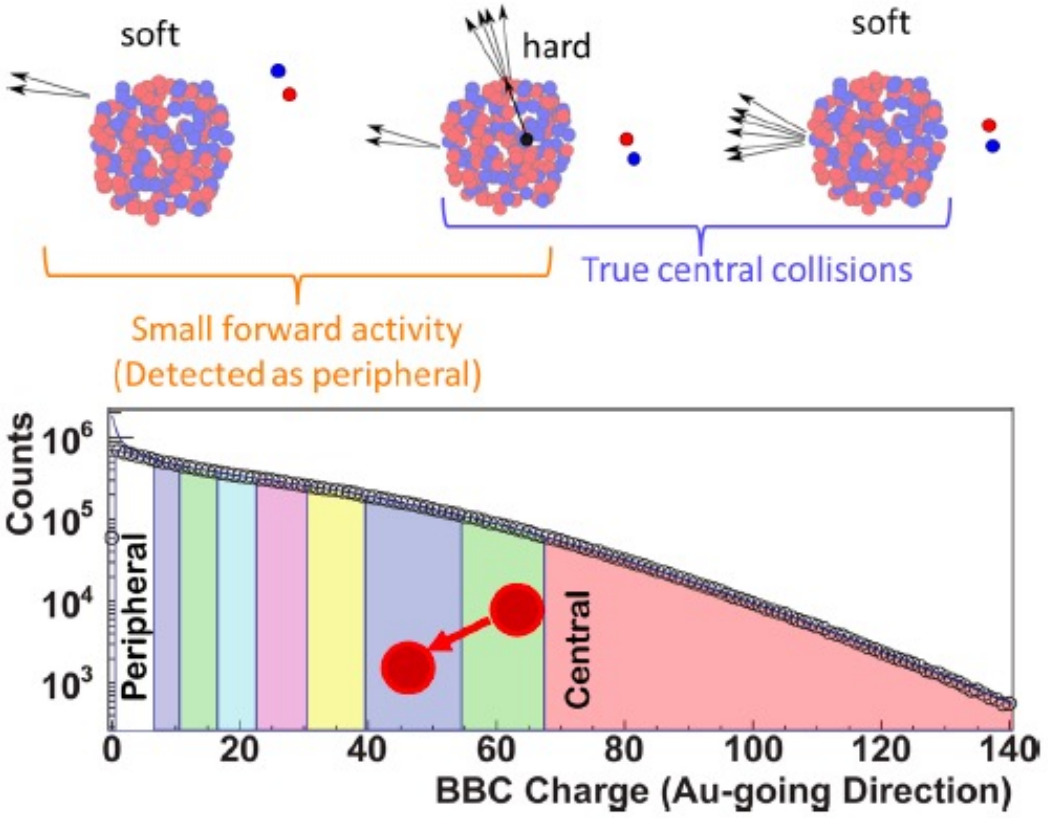
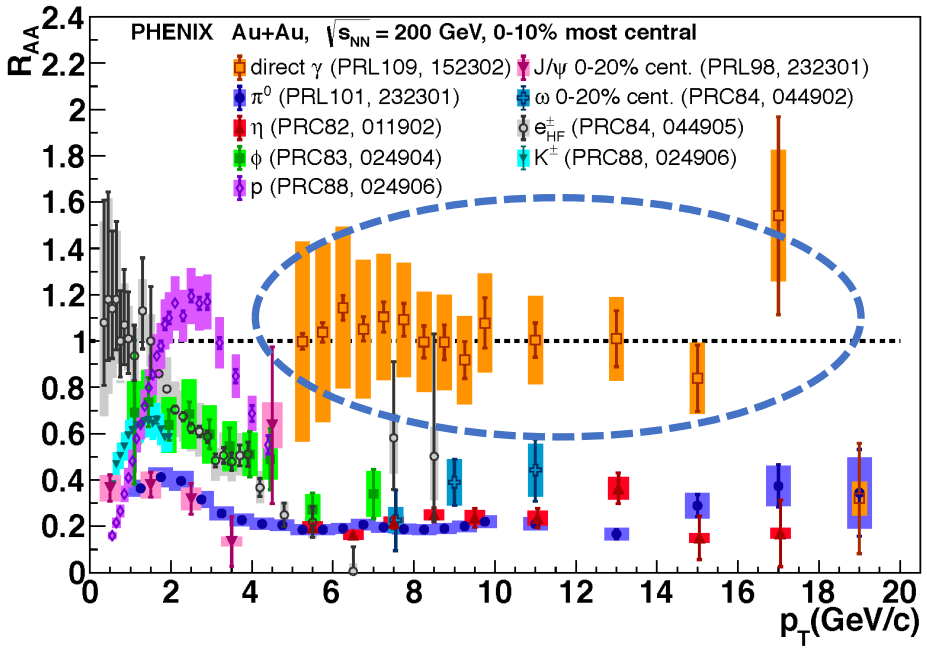
Note different physics in high and low pT!

We trigger events by particle mutiplicities

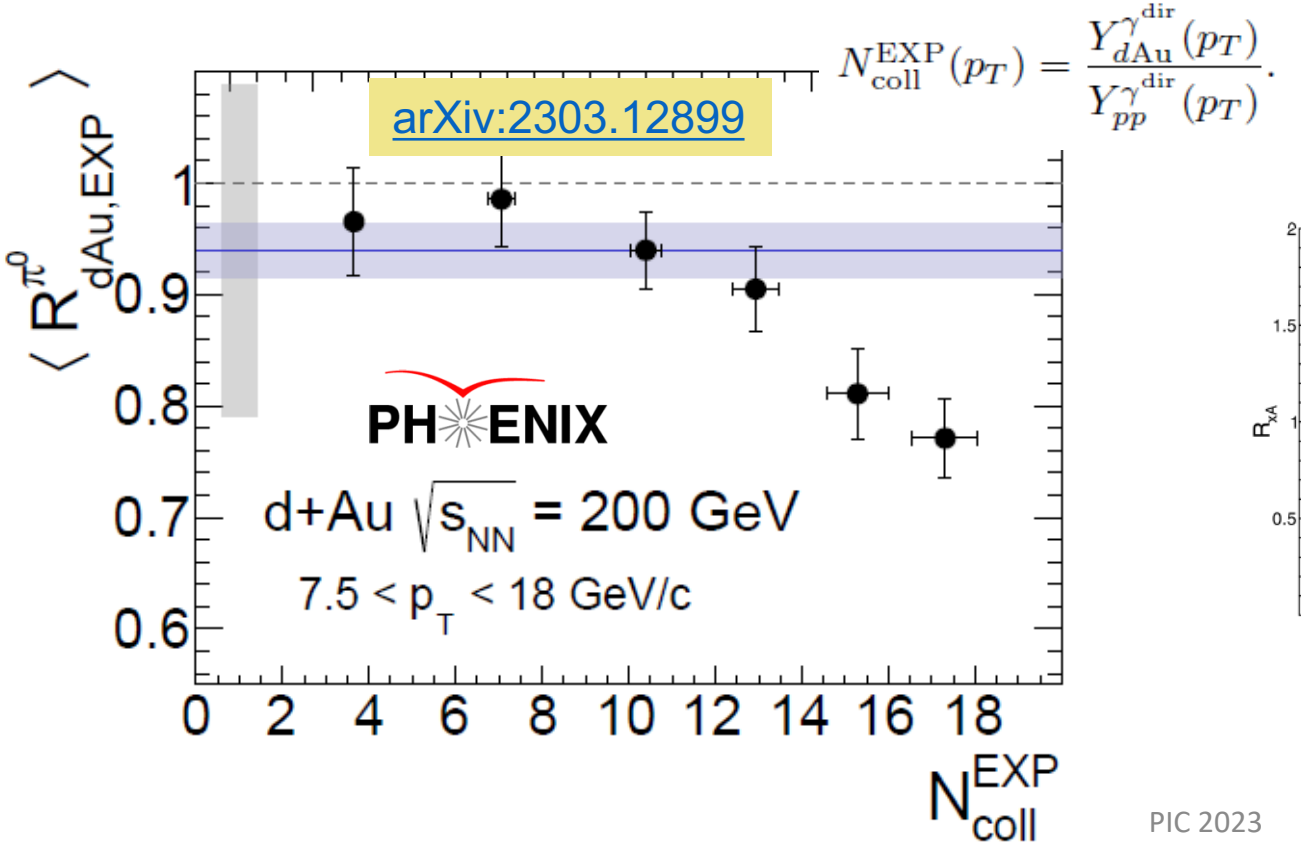
- Note the energy conservation is a universal law and must exist in this small system
- Use of direct photons as an unbiased direct measure of the event activity



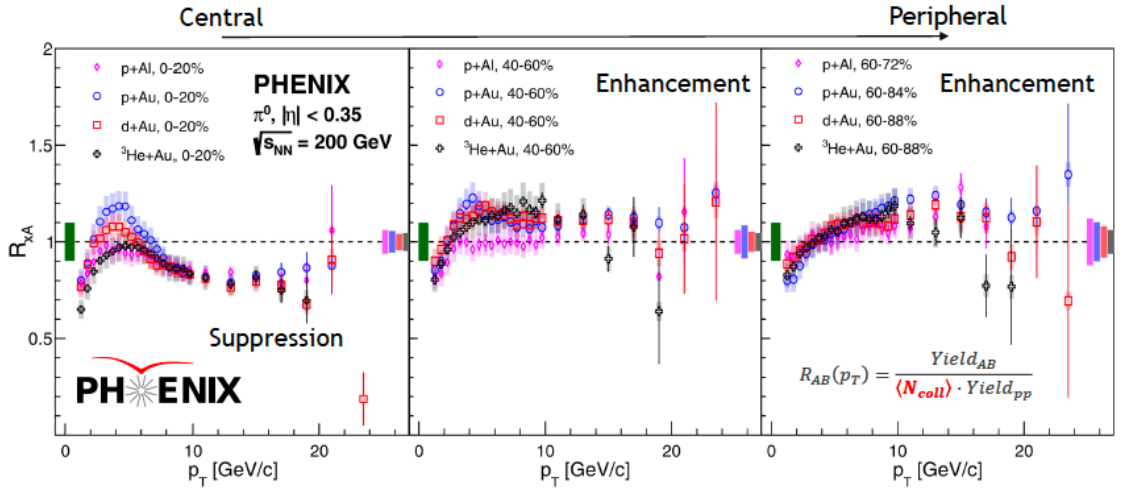


Experimental measure of N_{coll}

- Use electroweak probes (in our case photons) to directly measure N_{coll}
- No enhancement in peripheral. Suppression in most central collisions
- Energy loss of partons in QGP droplets? Or something else?



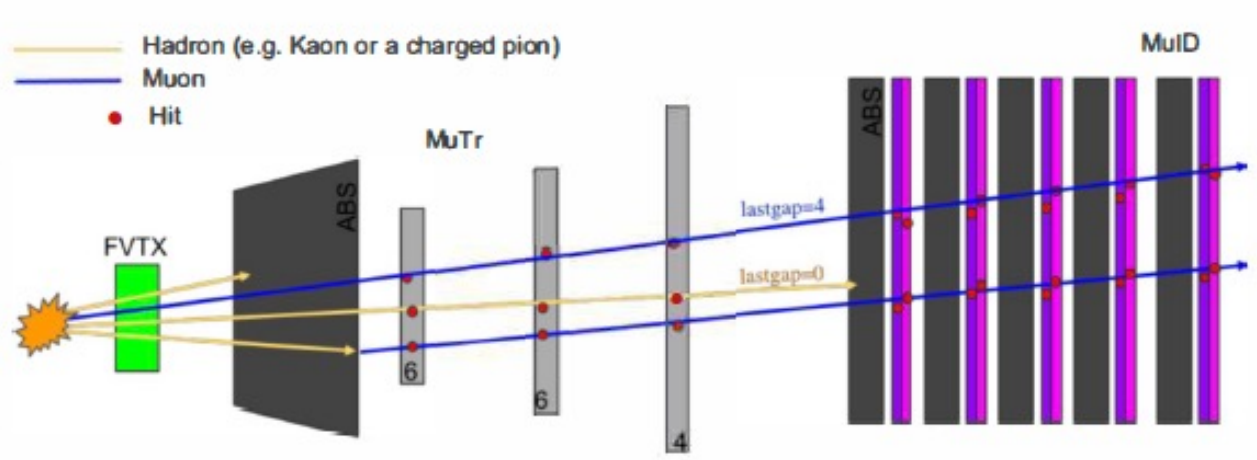
With Glauber N_{coll}



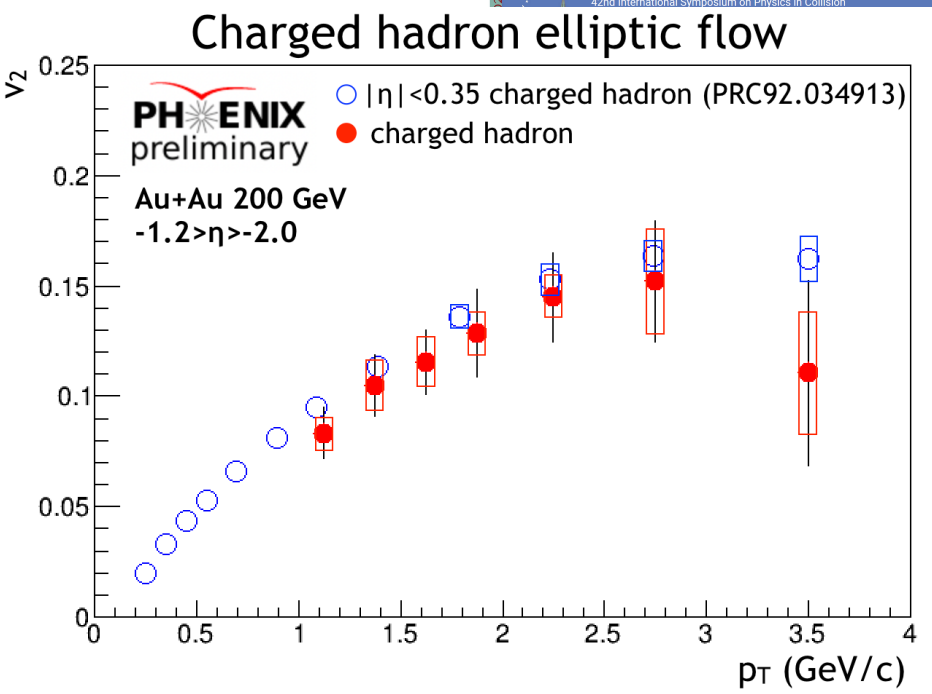
PHENIX: PRC105 (2022) 064902

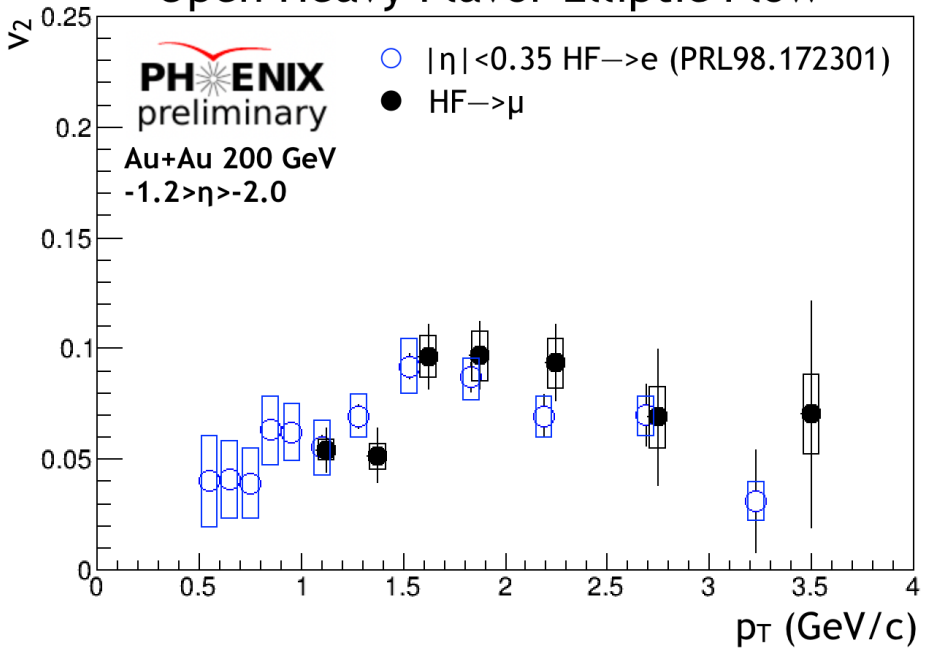
Heavy flavor into medium

- Heavy quarks are produced in the initial state.
- First-ever RHIC measurement of open heavy flavor elliptic flow at forward rapidity
- Mass ordering is apparent

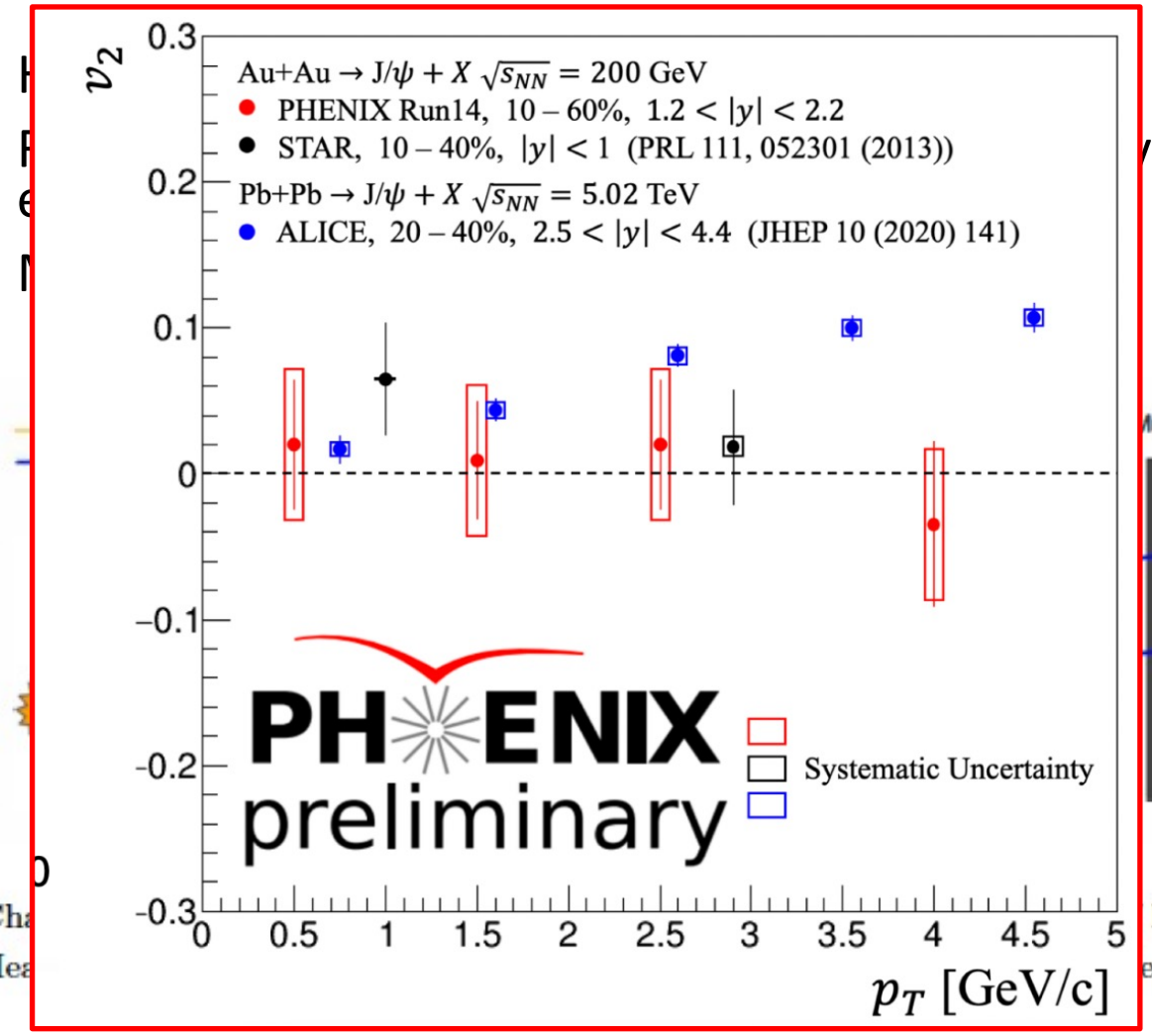


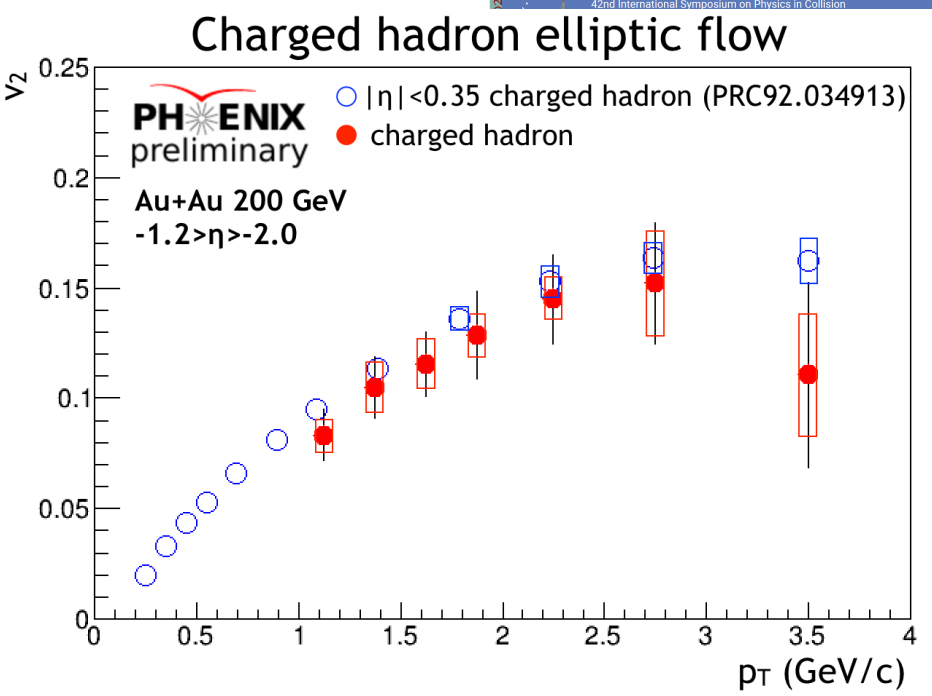
- Charged hadron tracks shown stopping in Muon Arm absorber, last gap 0 of MuID
- Heavy flavor muon tracks shown penetrating the full length of Muon Identifier

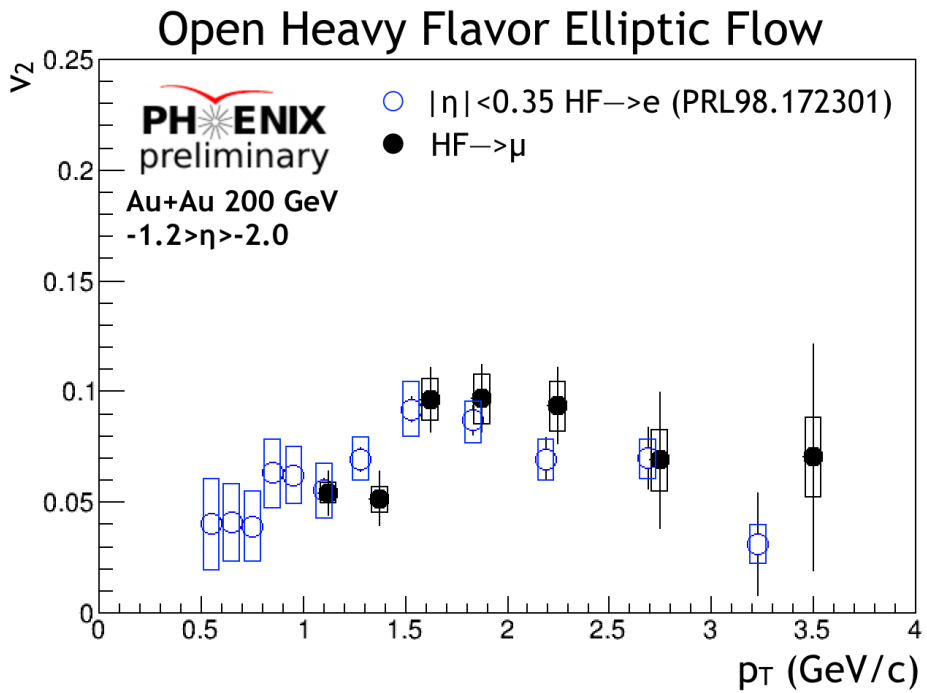




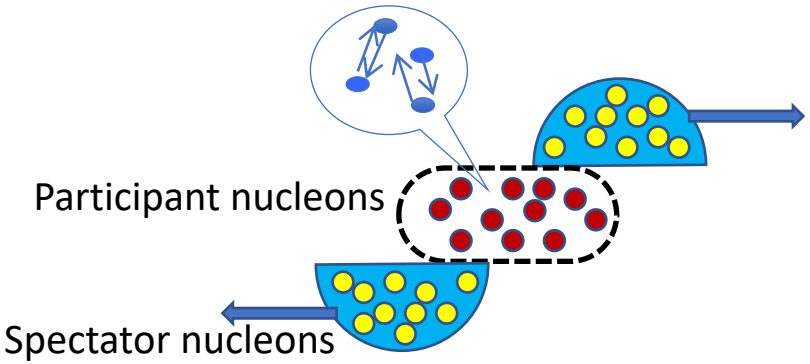
Heavy flavor into medium

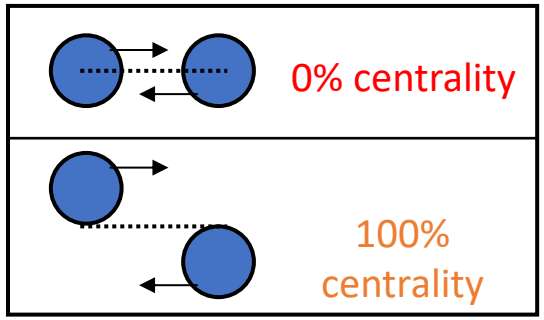






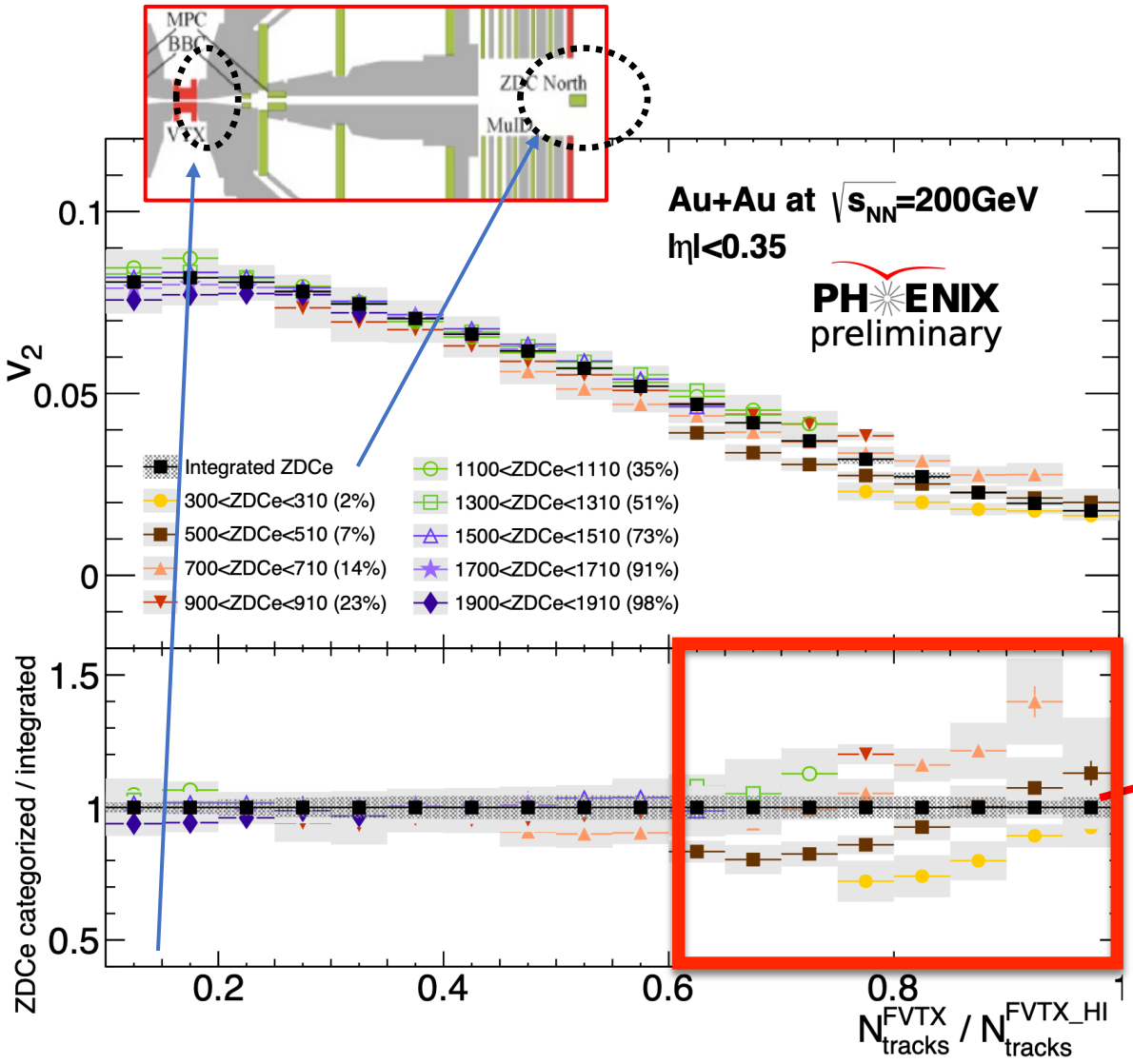
Events


Participant nucleons
Spectator nucleons


0% centrality
100%
centrality

v_2 at different ZDCe event categorization

Talk: Maya Shimomura



- With fixed ZDC bins, measure v_2 as a function of multiplicity.
  - These v_2 seem to reflect different initial geometry with same multiplicity.
  - N_{part} is different but multiplicity is the same.

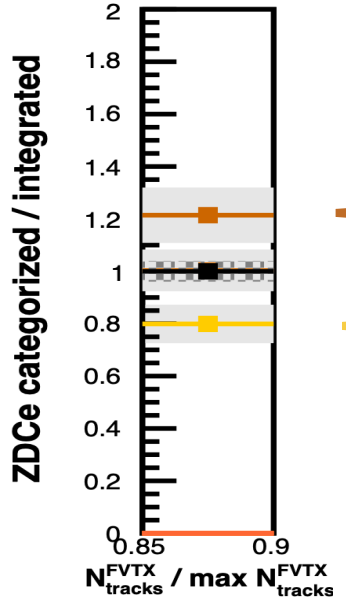
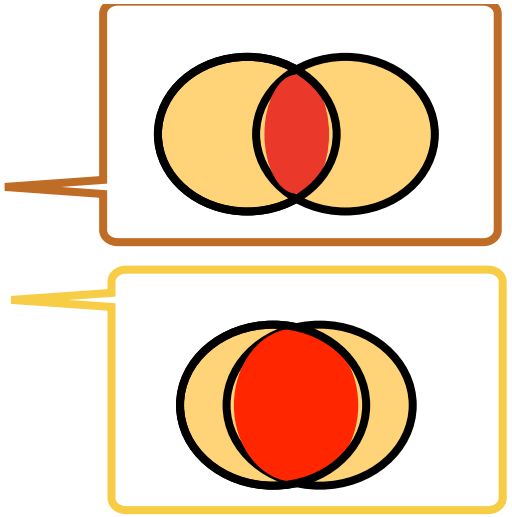
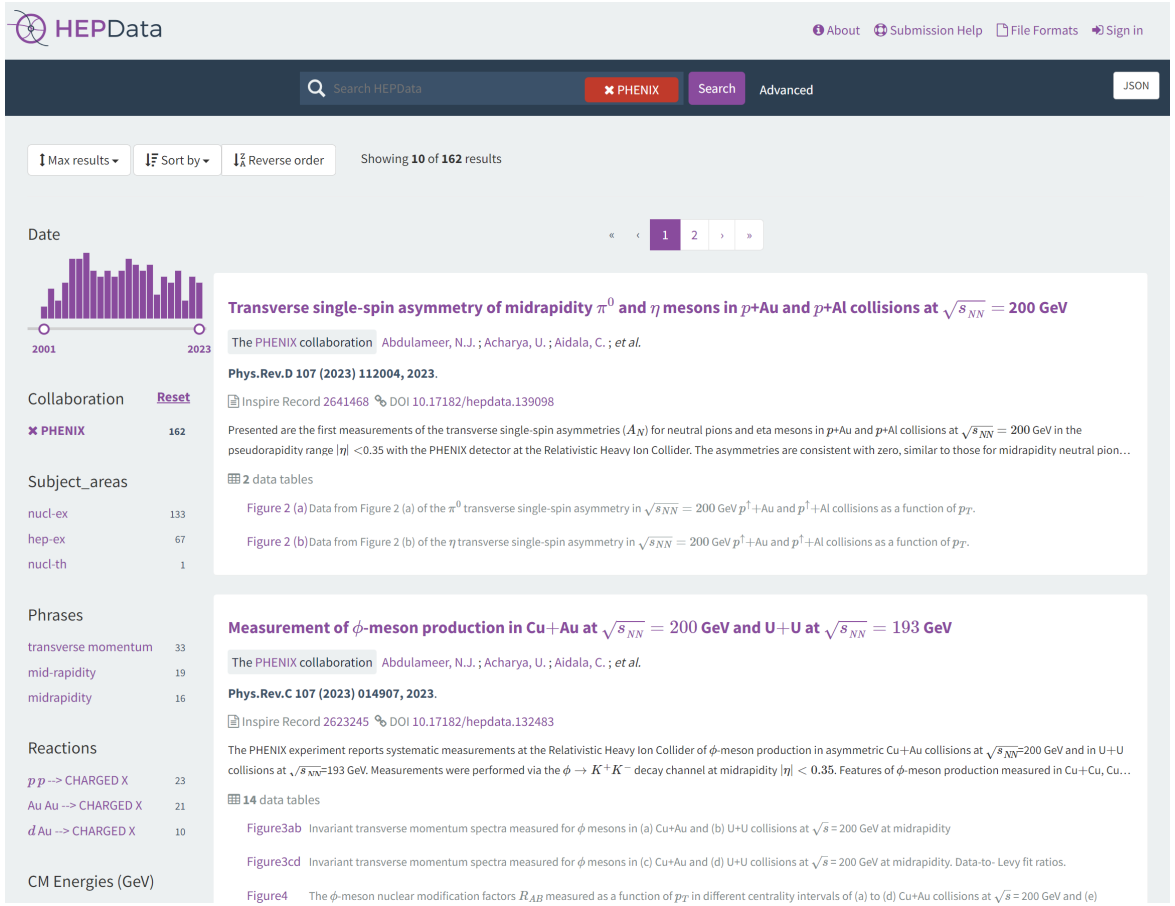


Image of the initial geometry



Data and analysis preservation

- 198/218 PHENIX papers on HEPData
  - As of Oct 10.
- REANA is a framework of analysis preservation
  - Analysis environment (libraries, etc) are in container (Docker)
- Workflow in YAML
  - π^0 and direct γ d+Au analyses implemented
- Welcome to play with PHENIX data!

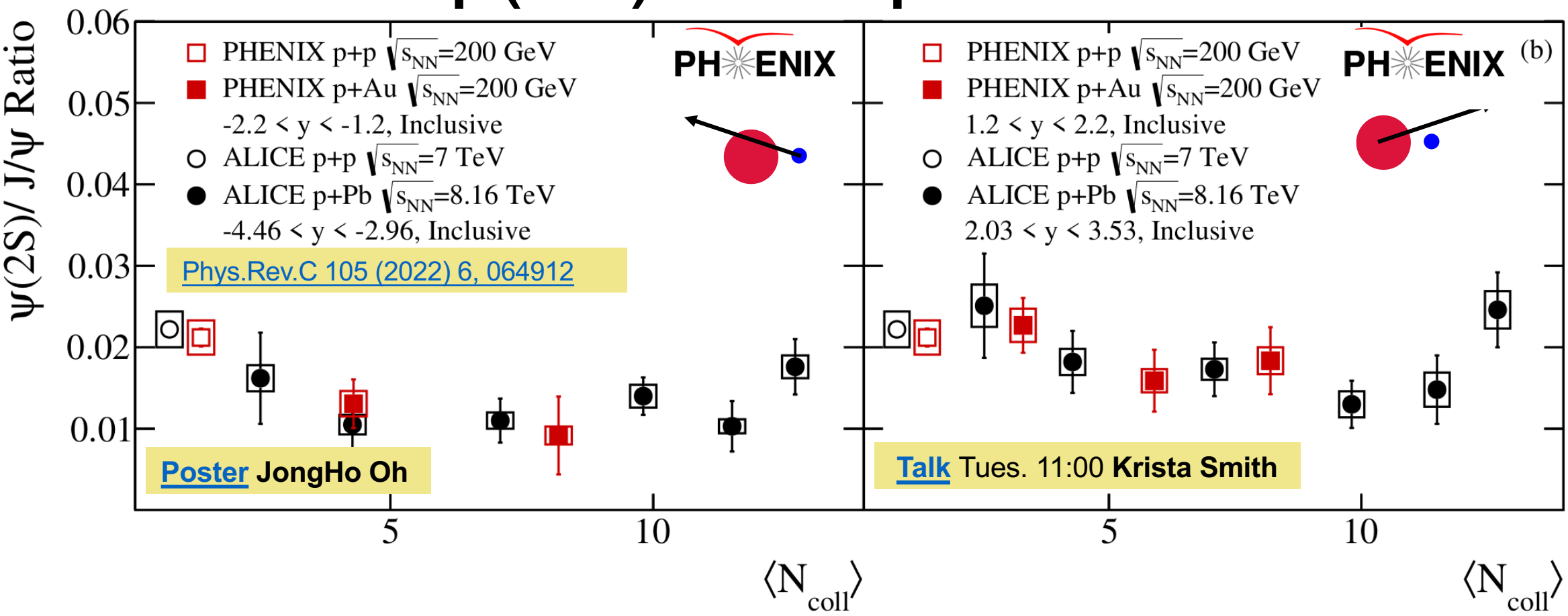


Conclusions

- PHENIX continues many high impact analyses
- Direct photon measurements are even more refined
  - Systematic trend in yields and temperature were found
  - Exploration is extended to high virtuality (Q^2) region.
- Charmonium production at RHIC is mostly at initial state
  - Regeneration in A+A is not significant.
  - Increase of charmonium in high multiplicity p+p events
- Partons are dragged into medium both in A+A and central d+A collisions
  - Suppression of high p_T π^0 is visible in central d+Au collisions with "corrected" N_{coll}.
- New event characterization is being pursued.
- PHENIX data are available in various analysis frameworks

Backup

ψ(2s) to J/ψ ratio



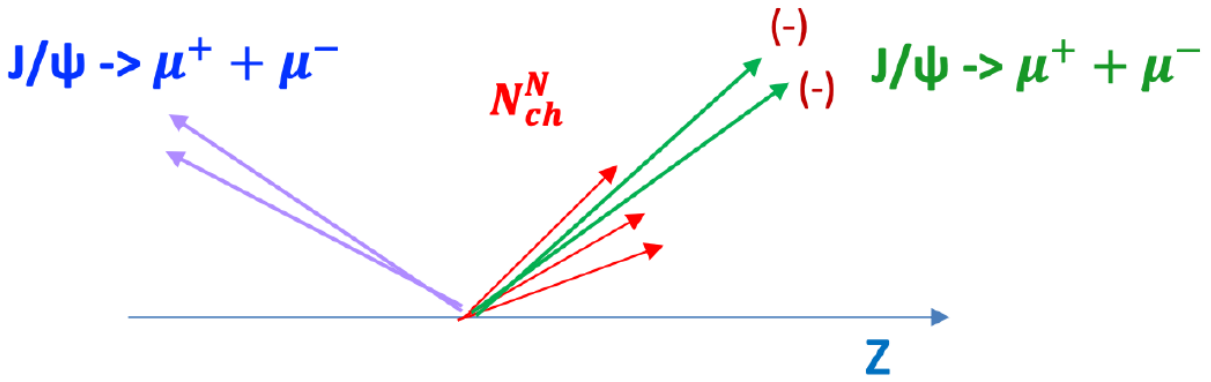
- ψ(2s) to J/ψ ratios p+p at RHIC, LHC show no clear energy dependence
- Suggests final state effects at backward rapidity

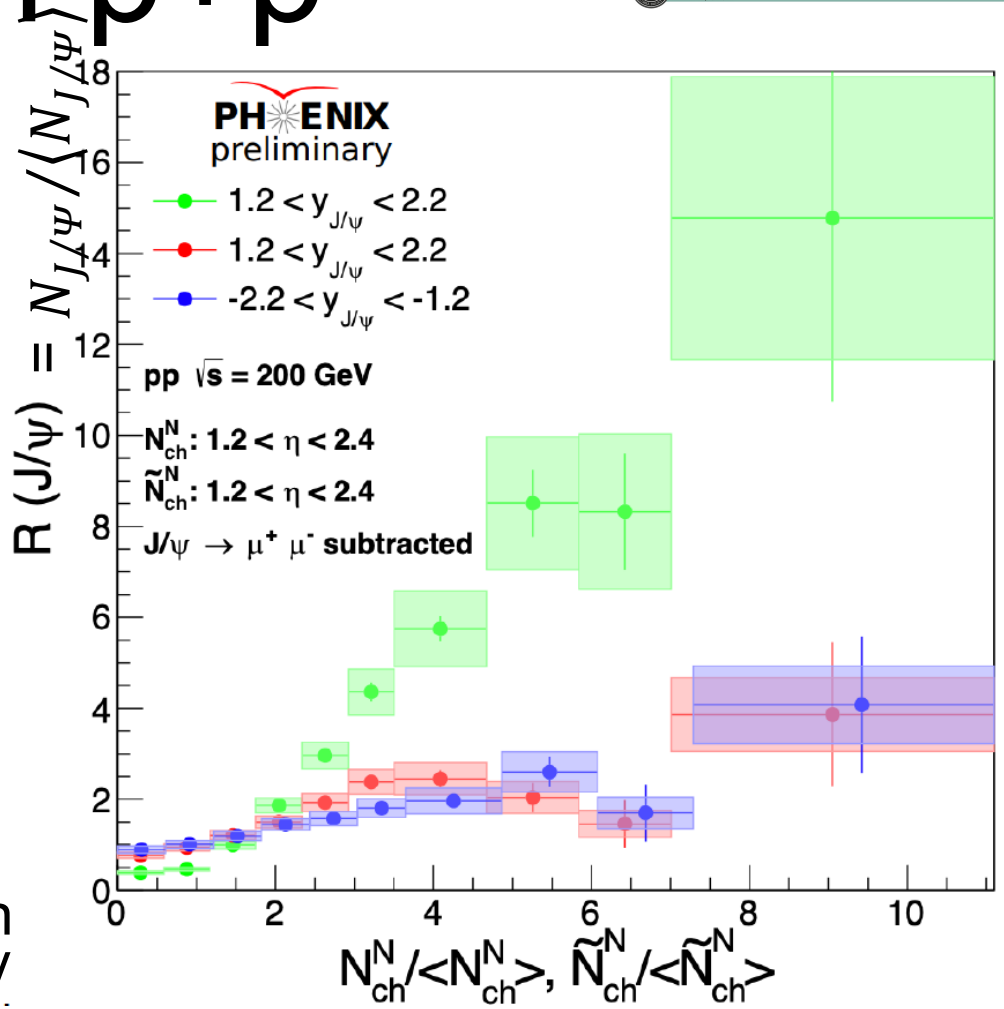
J/ψ yield in p+p

Red = Tracklets N_{ch}^{N} (1.2<η<2.4)

Green = J/ψ (1.2<y<2.2)

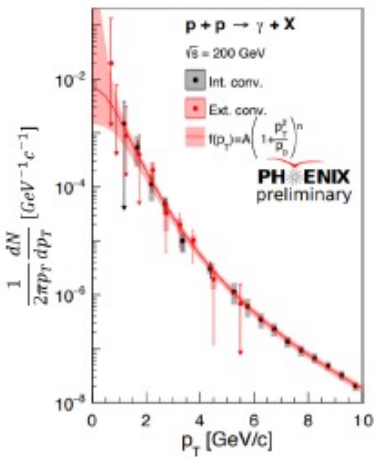
Green = J/ψ (-2.2<y<-1.2)

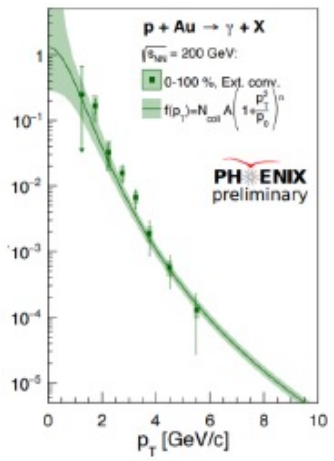


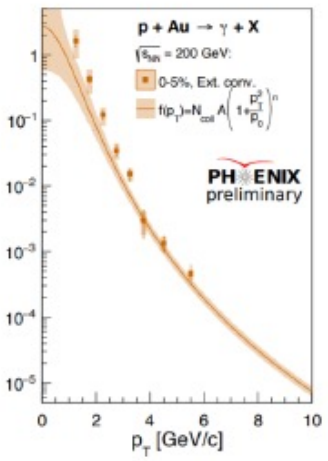


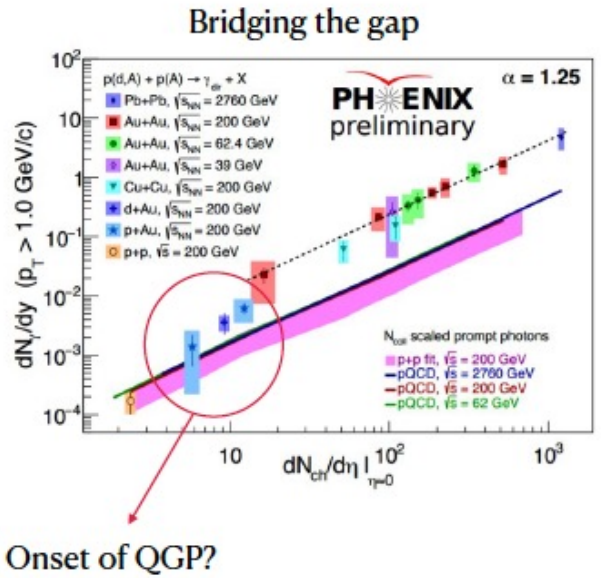
- J/ψ yield vs multiplicity significantly reduced when Looking at J/ψ and multiplicity in separate rapidity windows
  - Looking at J/ψ and multiplicity in the same rapidity window but removing the μ+ μ− from the multiplicity
- Implications for MPI picture

Direct γ in small systems









Direct photons to the rescue

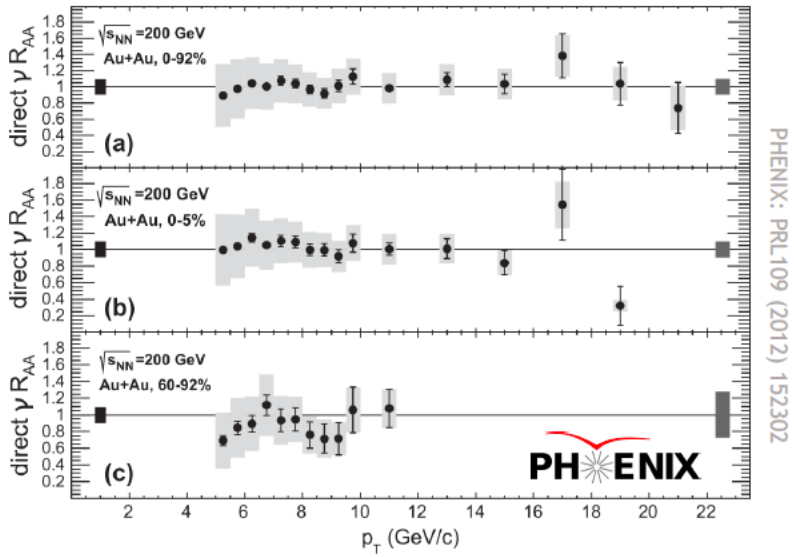
- Unbiased probe

Direct measurement of the N_{coll}

$$R_{AB}^{\gamma^{dir}}(p_T) = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{N_{coll} \cdot Y_{pp}^{\gamma^{dir}}(p_T)} \approx 1$$

- The ratio of direct photon yields can be used as a measure of N_{coll}:

$$N_{Coll}^{EXP} = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$$



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