BROOKHAVEN NATIONAL LABORATORY

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Highlights from PHENIX at RHIC

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PHENIX has several recent findings. Few (relevant) selected results:

1. Energy and System Size Dependence of Strangeness (ϕ meson) Production
2. Open Heavy Flavor: Charm and Bottom Separation
3. Collective Dynamics in Small Systems
4. Summary

PHENIX Collected Large Data Sets: 2000 to 2016

Run	Species	Total particle energy [GeV/nucleon]	total delivered Luminosity [μb^{-1}]
I (2000)	Au+Au	56	< 0.001
	Au+Au	130	20
II (2001/2002)	Au+Au	200	25.8
	Au+Au	19.6	0.4
	p+p	200	1.4x10^{-6}
III (2003)	d+Au	200	73x10^{-3}
	p+p	200	5.5x10^{-6}
IV(2004)	Au+Au	200	3.53x10^{-3}
	Au+Au	62.4	67
	p+p	200	7.1x10^{-6}
V (2005)	Cu+Cu	200	42.1x10^{-3}
	Cu+Cu	62.4	1.5x10^{-3}
	Cu+Cu	22.4	0.02x10^{-3}
	p+p	200	29.5x10^{-6}
	p+p	410	0.1x10^{-6}
VI (2006)	p+p	200	88.6x10^{-6}
	p+p	62.4	1.05x10^{-6}
VII (2007)	Au+Au	200	7.25x10^{-3}
	Au+Au	9.2	Small
VIII (2008)	d+Au	200	437x10^{-3}
	p+p	200	38.4x10^{-6}
	Au+Au	9.6	Small

Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity [μb^{-1}]
IX (2009)	p+p	500	110x10^{-6}
	+p	200	114x10^{-6}
X (2010)	Au+Au	200	10.3x10^{-3}
	Au+Au	62.4	544
	Au+Au	39	206
	Au+Au	7.7	4.23
	Au+Au	11.5	7.8
XI (2011)	p+p	500	166x10^{-6}
	Au+Au	19.6	33.2
	Au+Au	200	9.79x10^{-3}
	Au+Au	27	63.1
XII (2012)	p+p	200	74x10^{-6}
	p+p	510	283x10^{-6}
	U+U	193	736
	Cu+Au	200	27x10^{-3}
XIII (2013)	p+p	510	1.04x10^{-9}
XIV (2014)	Au+Au	14.6	44.2
	Au+Au	200	43.9x10^{-3}
	^{3}He+Au	200	134x10^{-3}
XV (2015)	p+p	200	282x10^{-6}
	p+Au	200	1.27x10^{-6}
	p+Al	200	3.97x10^{-6}
XVI (2016)	Au+Au	200	46.1x10^{-3}
	d+Au	200	46.1x10^{-3}
	d+Au	62.4	44.0x10^{-3}
	d+Au	19.6	7.2x10^{-3}
	d+Au	39	---
	Au+Au	200	7:50 AM 06/27/2016

PHENIX Collected Large Data Sets: 2000 to 2016

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I (2000)	Au+Au Au+Au	56 130	< 0.001 20
II (2001/2002)	Au+Au Au+Au p+p	200 19.6 200	25.8 0.4 1.4×10^{-6}
VI (2006)	p+p p+p	200 62.4	88.6×10^{-6} 1.05×10^{-6}
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VIII (2008)	d+Au p+p Au+Au	200 200 9.6	437×10^{-3} 38.4×10^{-6} Small

Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity [μb^{-1}]
IX (2009)	p+p +p	500 200	110×10^{-6} 114×10^{-6}
X (2010)	Au+Au Au+Au Au+Au Au+Au [illegible]	200 62.4 39 7.7 [illegible]	10.3×10^{-3} 544 206 4.23 [illegible]
[illegible]	^{3}He+Au	200	134x10[illegible]
XV (2015)	p+p p+Au p+Al	200 200 200	282×10^{-6} 1.27×10^{-6} 3.97×10^{-6}
XVI (2016)	Au+Au d+Au d+Au d+Au d+Au Au+Au	200 200 62.4 19.6 39 200	46.1×10^{-3} 46.1×10^{-3} 44.0×10^{-3} 7.2×10^{-3} --- 7:50 AM 06/27/2016

Major Upgrades to PHENIX = sPHENIX

New sPHENIX Collaboration

PHENIX Detector

- PHENIX: optimized to measure leptons: rapidity coverage: 1.2<|y|<2.2 and |y|<0.35

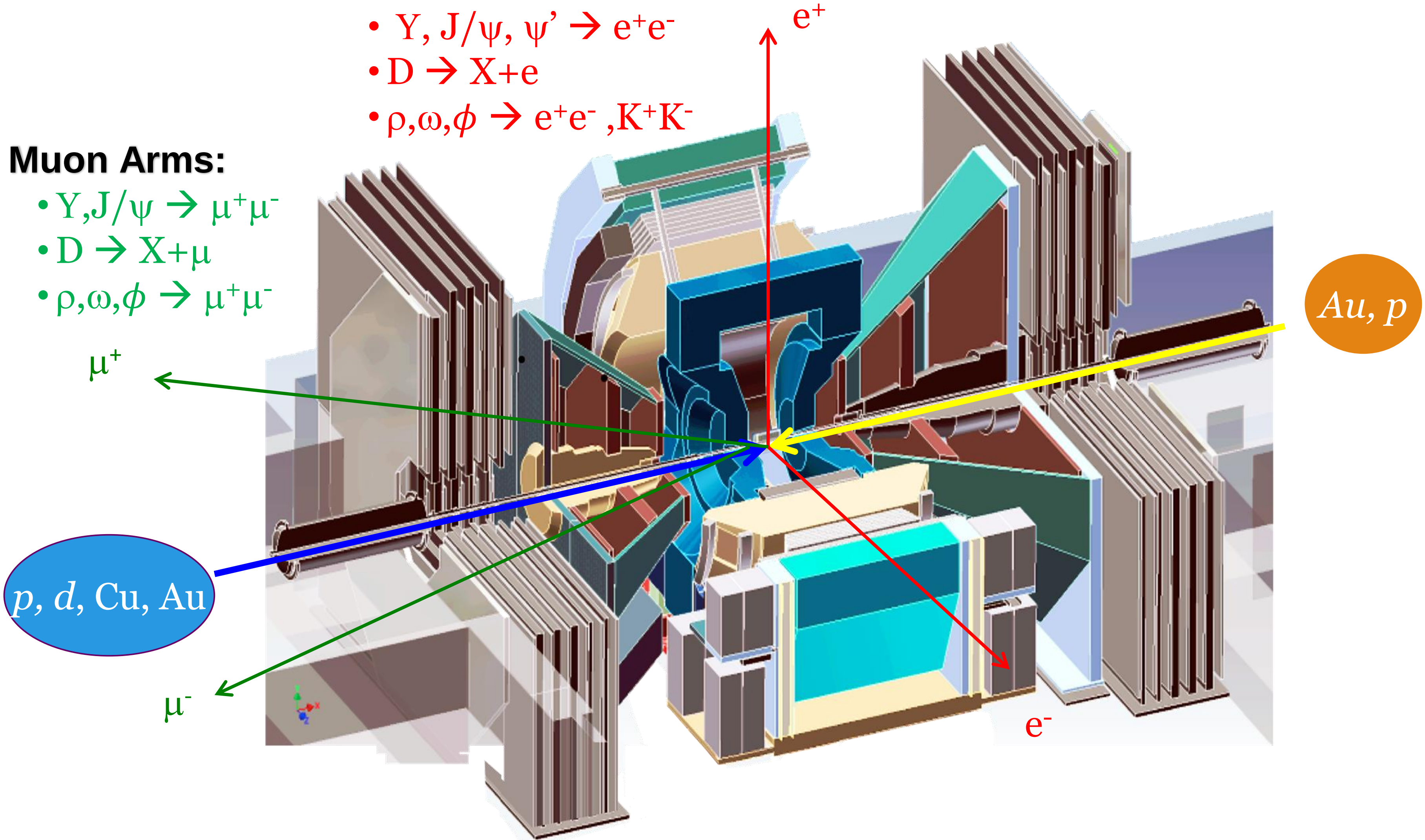
1) high rate capability 2) emphasis on mass resolution & particle ID 3) first level e&μ triggers

Central Arms:

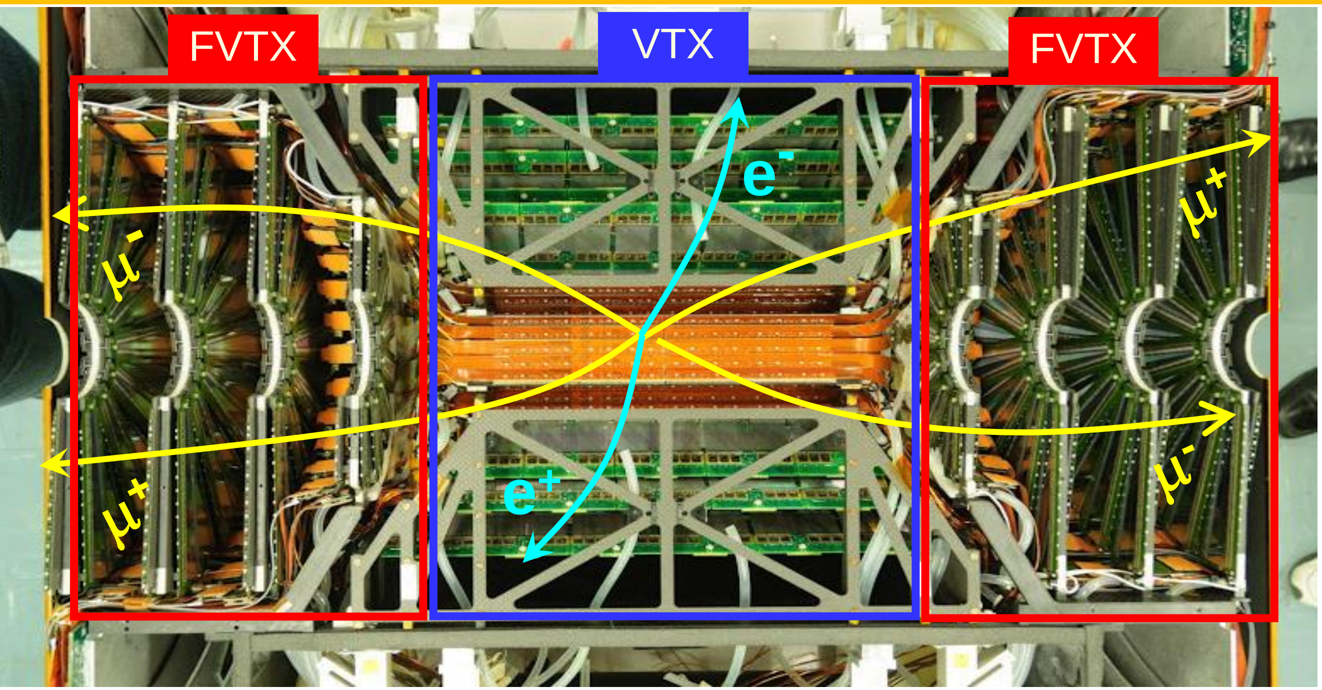
- Υ, J/ψ, ψ' → e^+e^-
- D → X+e
- ρ,ω,ϕ → e^+e^- ,K^+K^-

Muon Arms:

- Υ,J/ψ → $\mu^+\mu^-$
- D → X+μ
- ρ,ω,ϕ → $\mu^+\mu^-$

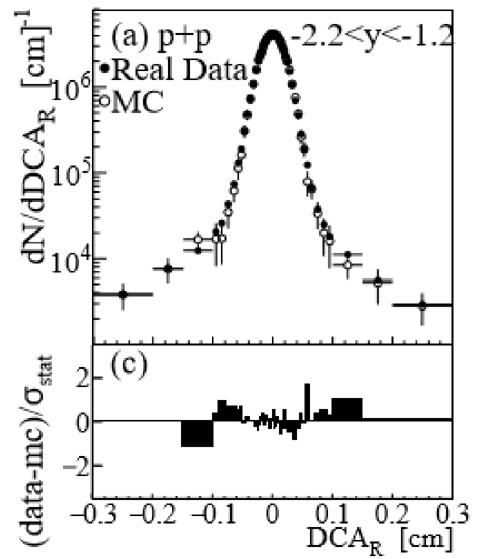


Recent Measurements Use Silicon Trackers



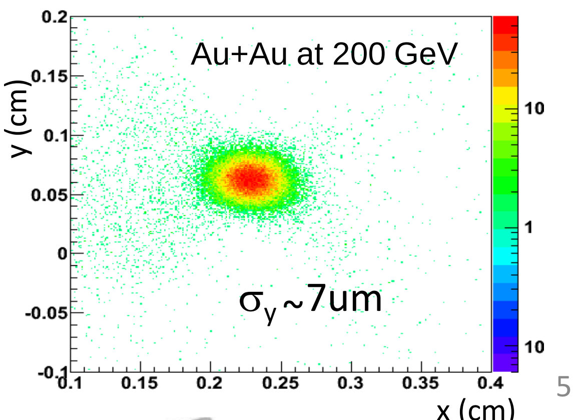
FVTX

DCA$_R$ Distribution

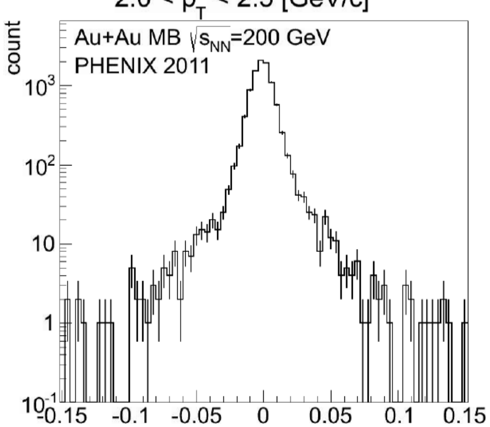


VTX

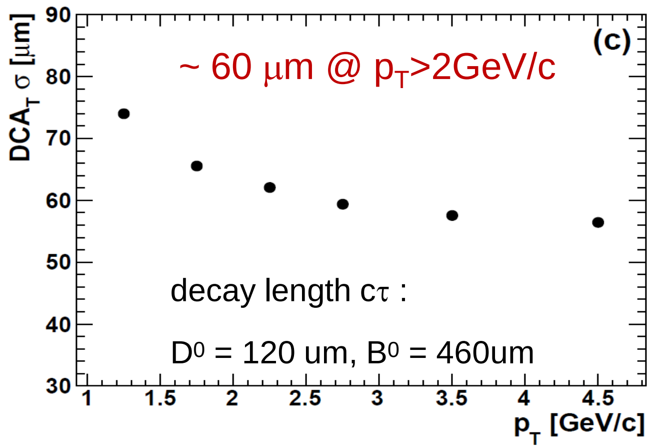
Vertex Distribution



DCA$_T$ Distribution



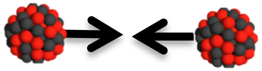
DCA$_T$ Resolution

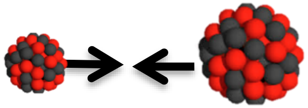


What NEW on ϕ Production?

What have we learned from ϕ production in colliding small systems?

p+*p*, *p*+Al, *p*+Au, d+Au, and ^{3}He+Au



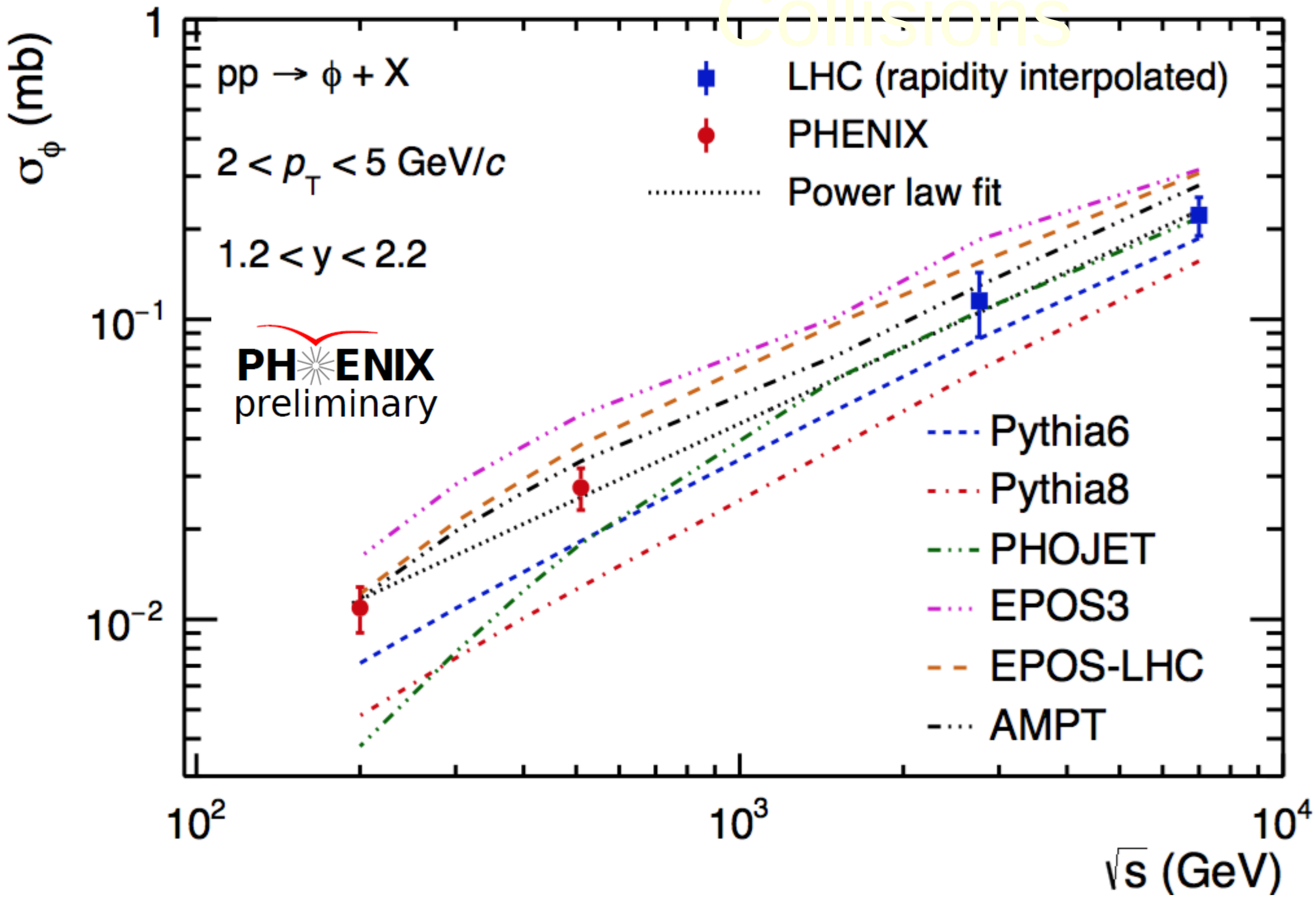


Energy and System Size Dependence

Remarks on ϕ production:

- In the early state of high-energy collisions, strangeness is produced in flavor creation (gg→ss, qq→ss) and flavor excitation (gs→gs, qs→qs). Strangeness is also created during the subsequent partonic evolution via gluon splittings (g→ss). These processes tend to dominate the production of high-p_T strange hadrons.
- At low-p_T, nonperturbative processes dominate the production of strange hadrons. The detailed production mechanism is still an open issue.

Energy Dependence of ϕ Production in $p+p$ Collisions



See also talk by Murad Sarsour PSS Thur. 10:00

RHIC/PHENIX
p+p 200 GeV:
- PRD90, 052002 (2014)

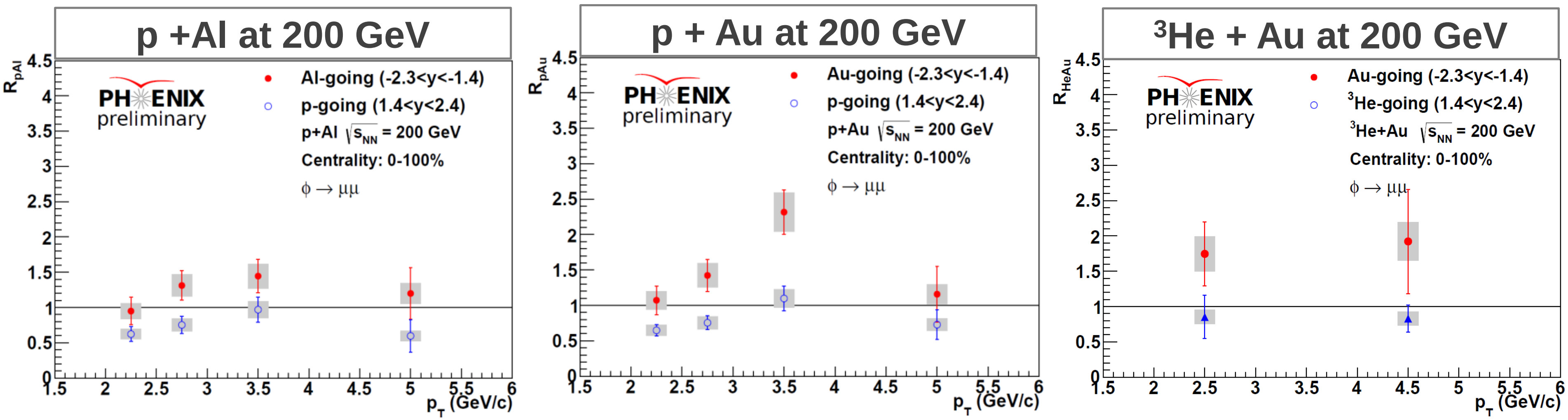
LHC:
- PLB703, 267 (2011)
- PLB710, 557 (2012)
- Eur. Phys. J. C 72, 2183 (2012)
- PLB 768, 203 (2017)

- Strangeness (ϕ meson) production cross section increases as a function of energy: from RHIC(PHENIX) to LHC(ALICE).
- Model calculations of strangeness (ϕ meson) production exhibit the same trends as data from RHIC to LHC energies.

Strangeness (ϕ Meson) Production in Small System

Variety of small systems: *p*+Al, *p*+Au, and ^{3}He+Au

- Nuclear Modification Factor versus Momentum
  - Wide Range in p_T



- Allow systematic study of cold nuclear matter effects involved in ϕ meson production using models like AMPT and EPOS.

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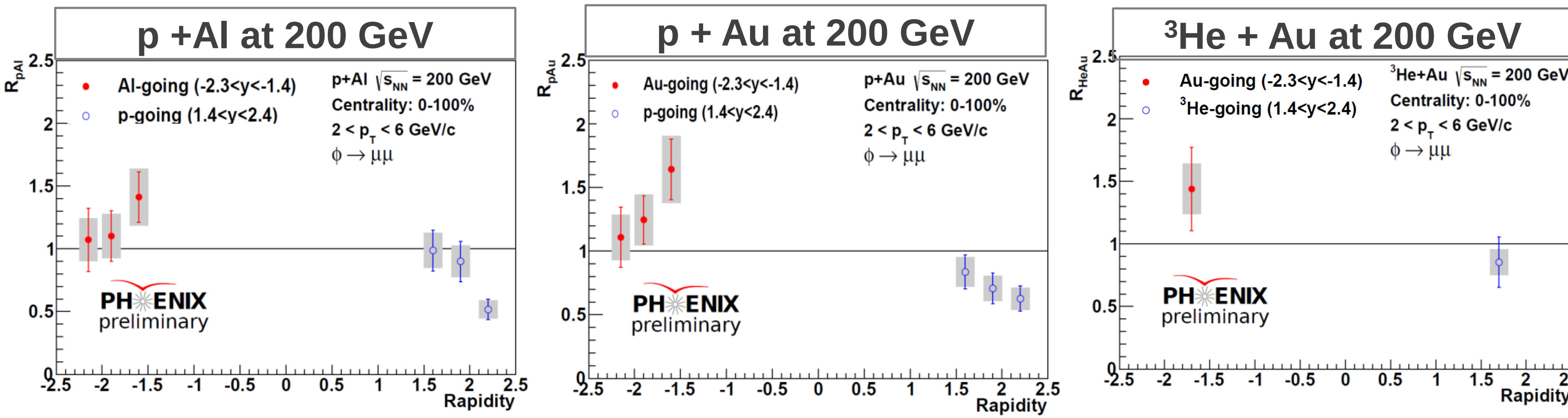
Strangeness (ϕ Meson) Production in Small System

Variety of small systems: *p*+Al, *p*+Au, *d*+Au, and ^{3}He+Au

- ➢ Nuclear Modification Factor versus Rapidity
  - → Backward Rapidity: no suppression
  - → Forward Rapidity: observe suppression



- ➢ Allow systematic study of cold nuclear matter effects involved in ϕ meson production using models like AMPT and EPOS.

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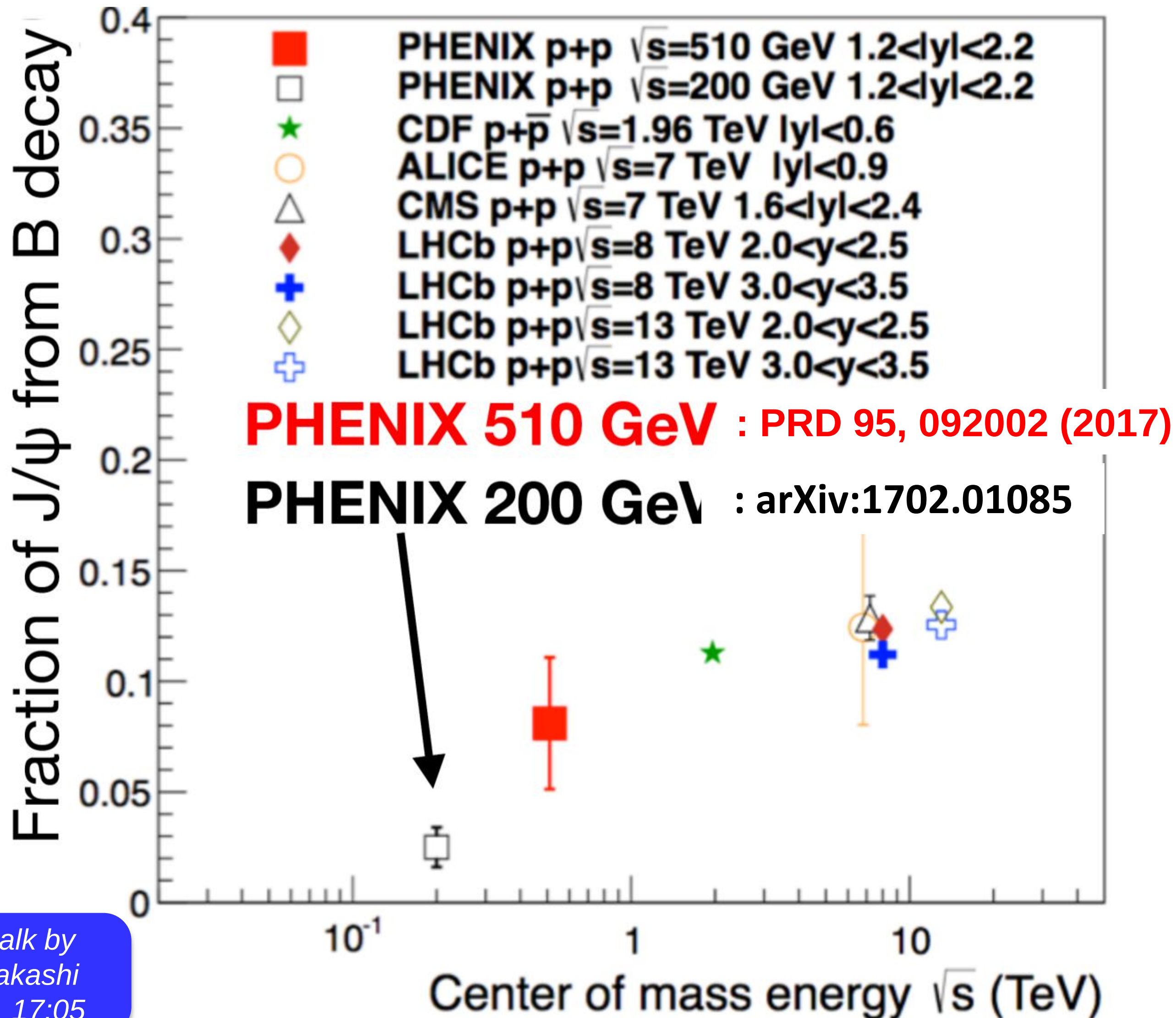
Fraction of J/ψ from B decays in p+p Collisions

Forward Silicon Vertex detector (FVTX): Measure B→ J/ψ → $\mu^{\pm}$

- **B's measured down to $p_T = 0$!**
- **New results: measured in p+p at 200 GeV**
- **Clear energy dependence**

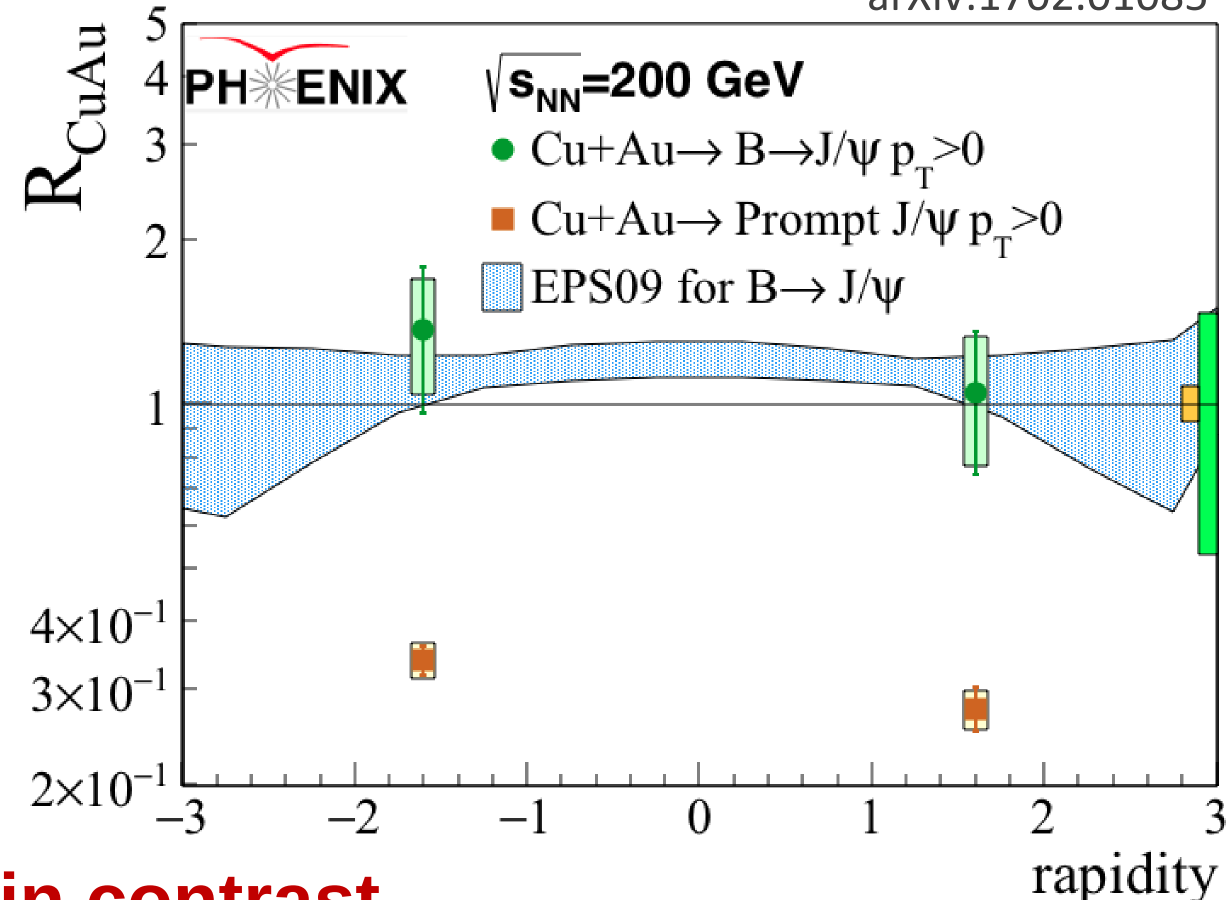


See also talk by Hachiya Takashi PSHF4 Fri. 17:05

Fraction of J/ψ from B decays (Cu+Au)

- Now using the measured B→J/ψ fraction in p+p @ 200 as the baseline (see previous slide)

arXiv:1702.01085



- **Non-prompt J/ψ R_{CuAu} consistent with binary scaling**

- **Non-prompt *J/ψ* R_{CuAu} consistent with nPDF EPS09 initial state effets**

- **Non-prompt J/ψ in contrast to highly suppressed prompt J/ψ**

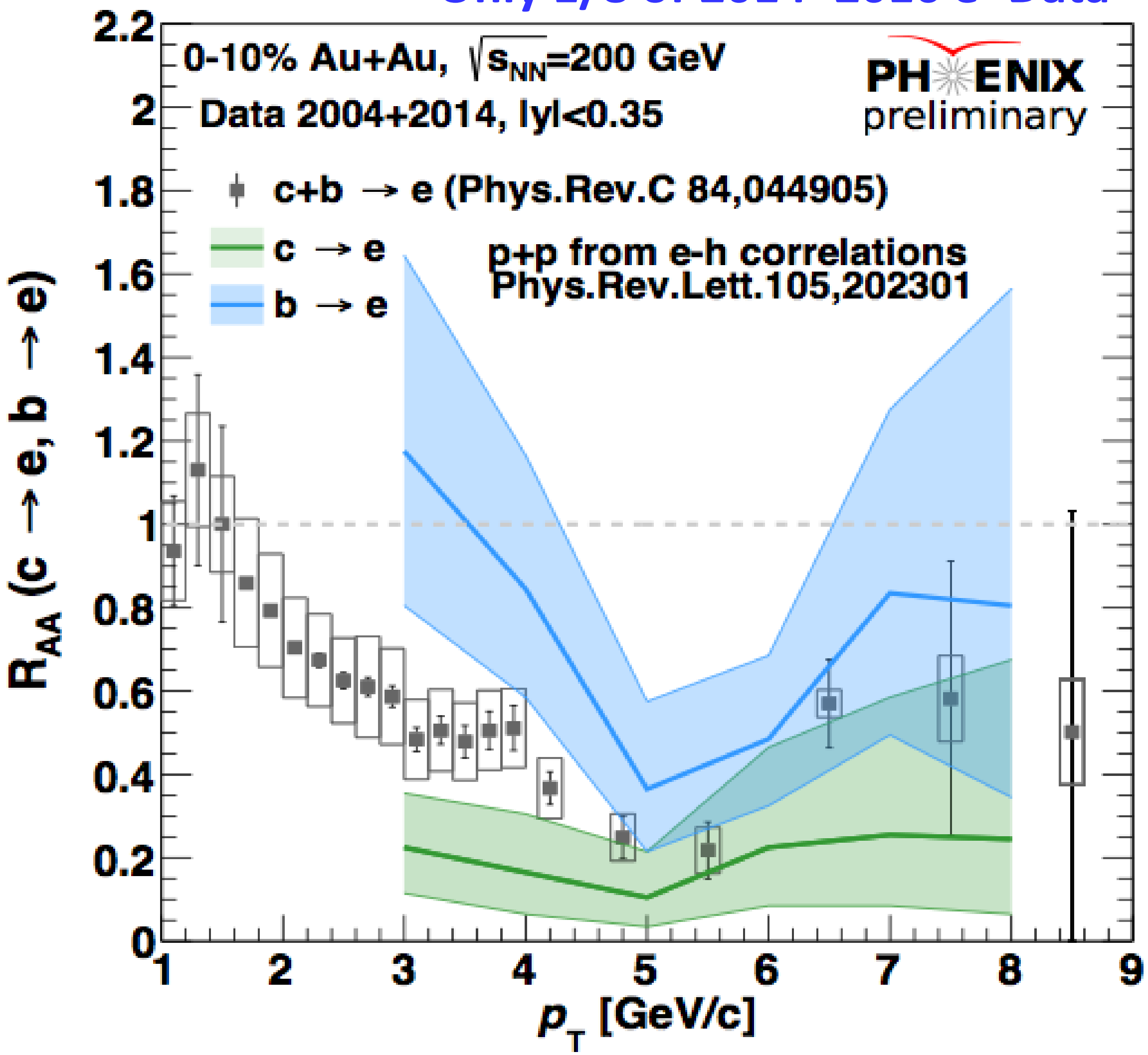
See also talk by Hachiya Takashi PSHF4 Fri. 17:05

Separation of Charm and Bottom in AuAu Collisions

Silicon Vertex Detector (VTX): Measure D,B mesons → $e^{\pm}$

- Using "unfolding" method PRC 93, 3, 034904 (2016)
- **New results: 0-10% AuAu at 200 GeV**
- **Clear separation of charm/bottom for $p_T < 5$ GeV/c $R_{AA}(c \rightarrow e) < R_{AA}(b \rightarrow e)$**

Only 1/8 of 2014+2016 $e^{\pm}$ Data



Separation of Charm and Bottom in AuAu

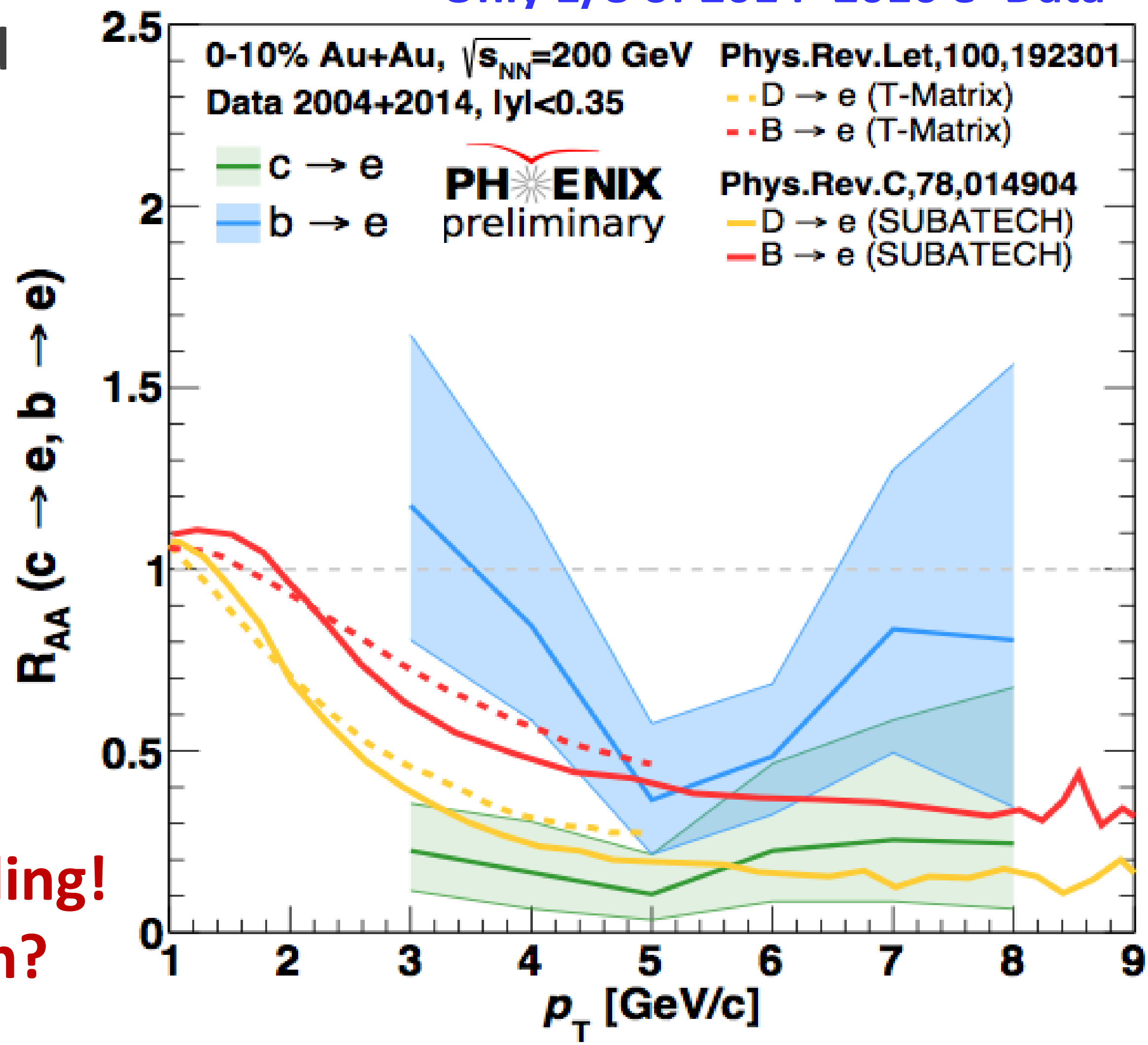
Silicon Vertex Detector (VTX): Measure D,B mesons → $e^{\pm}$

- Using "unfolding" method PRC 93, 3, 034904 (2016)

- **New results: 0-10% AuAu at 200 GeV**

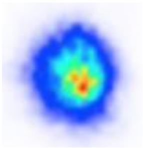
- Transport (Langevin): Reasonable agreement at low-p_T
- Theory needs large coupling! More extreme separation?

Only 1/8 of 2014+2016 $e^{\pm}$ Data

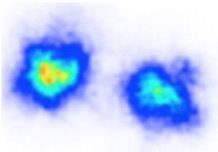


Collective Dynamics in Small Systems

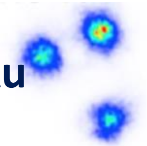
***p* + Au**



d+ Au



^{3}He + Au

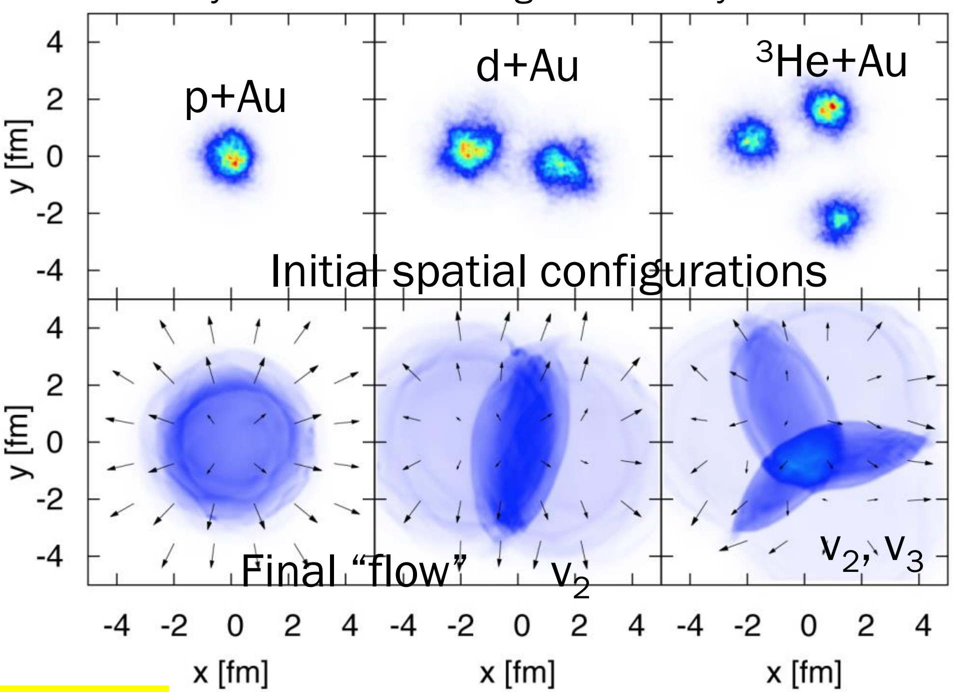


$$\varepsilon = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$$

Courtesy of Richard Seto, Lake Louise 2017

System (0-5%)	$N_{participants}$	$N_{collisions}$	ε_2	ε_3
Au+Au	347	946		
^{3}He+Au	25	26	0.50	0.28
d+Au	17	18	0.54	0.19
p+Au	10	11	0.23	

Hydro simulations: Figure Courtesy of B Shenke

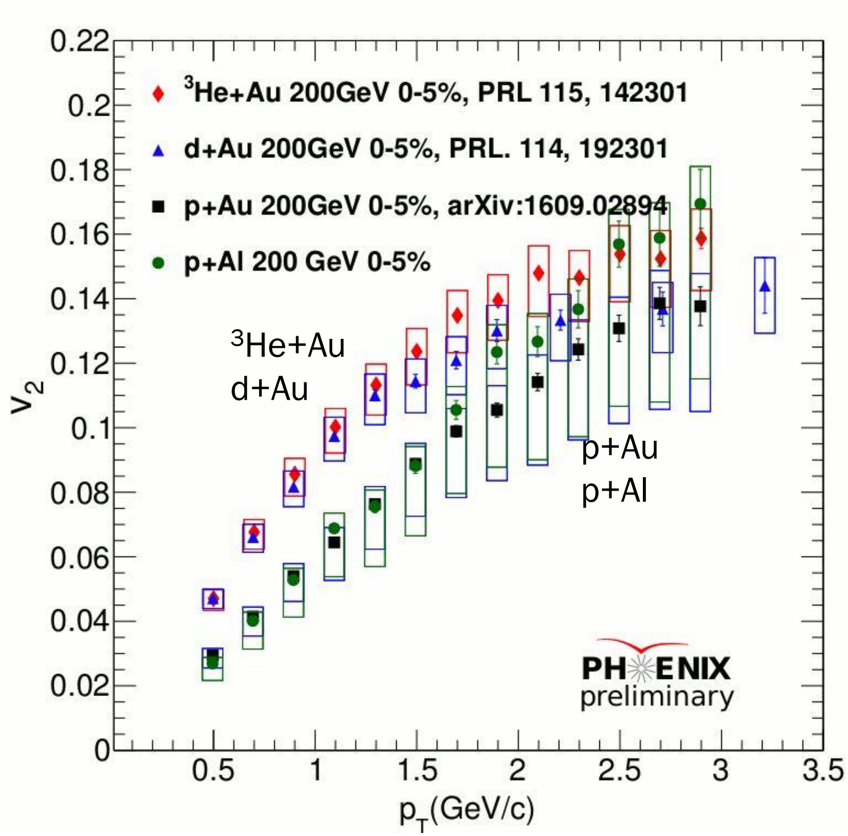


EXPECT for v_2 (elliptic flow) : ^{3}He+Au ~ d+Au > p+Au

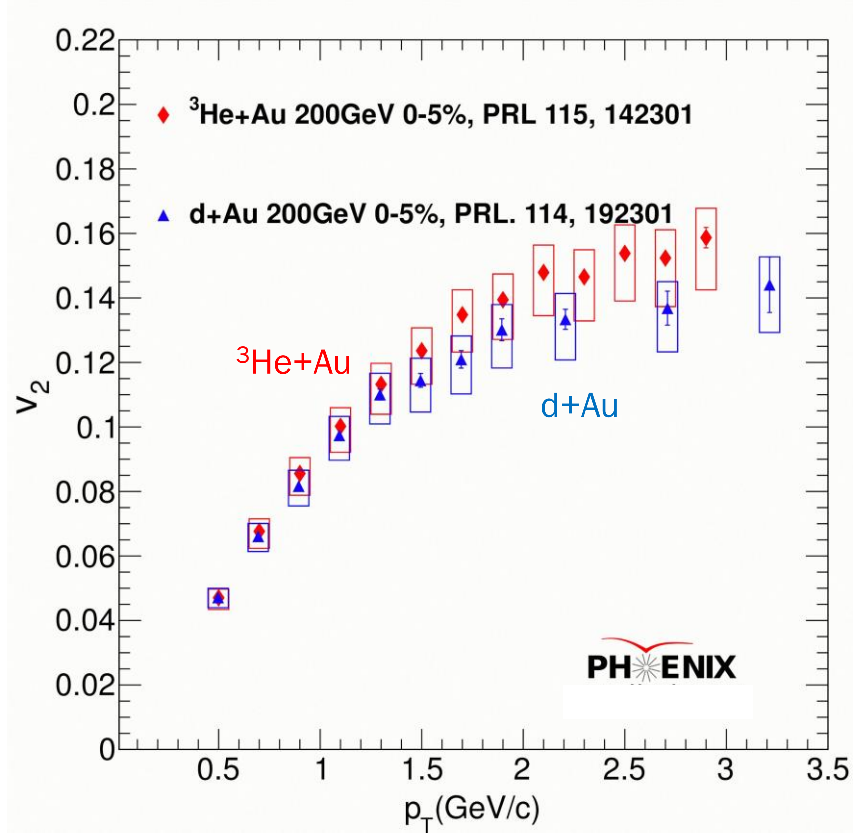
EXPECT for v_3 (triangular) : ^{3}He+Au > d+Au

v_2 (Elliptic Flow) : ^{3}He+Au, d+Au, p+Au and p+Al

v_2 (elliptic flow) charged hadrons



Estimate of "non-flow" included systematic error)



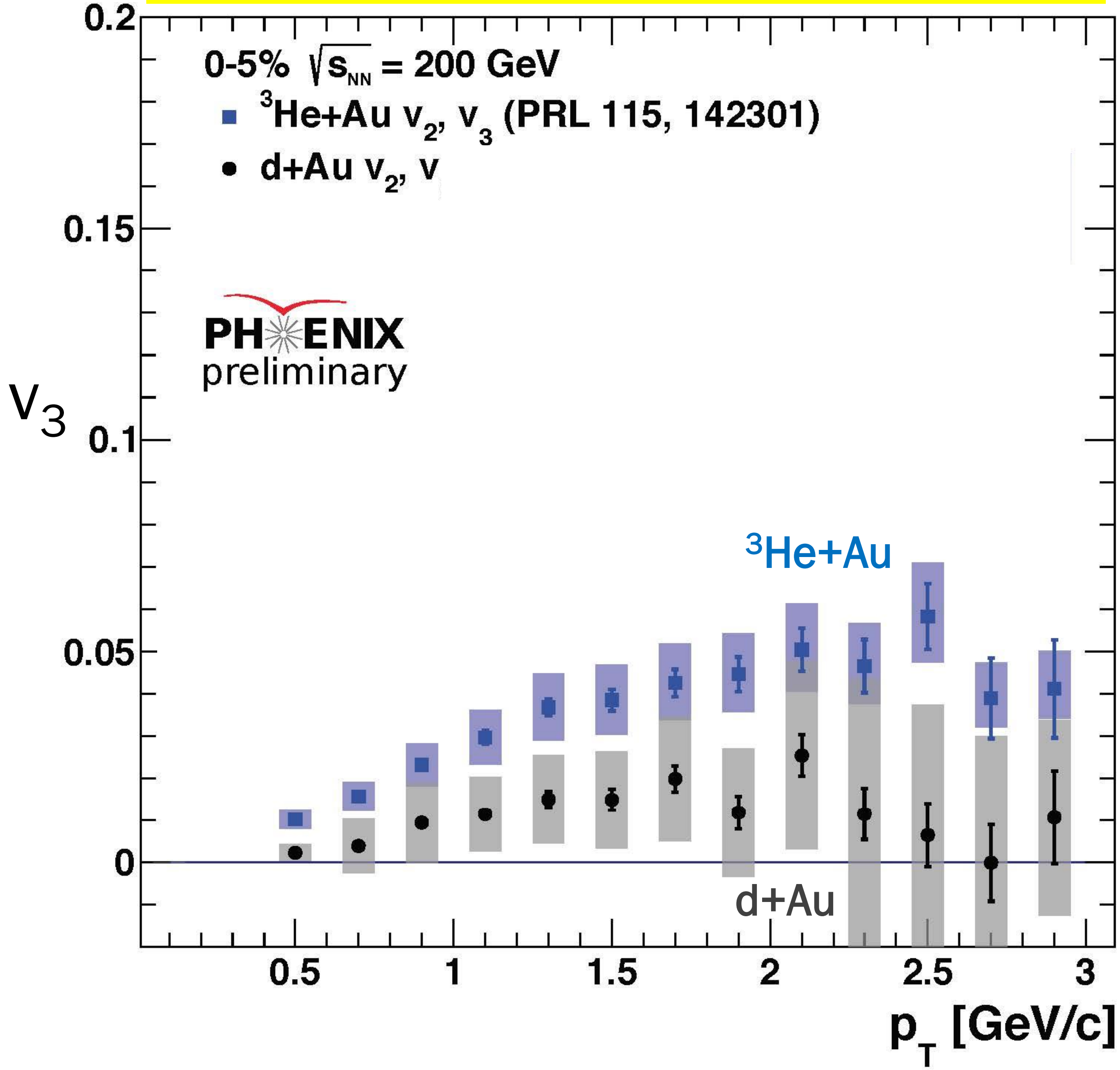
Estimate of "non-flow" included systematic error)

Expct.: v_2 (elliptic flow) : ^{3}He+Au ~ d+A> p+Au

v_2 (elliptic flow) is developed for even for p+Al Collisions ($N_{participants}$ ~ 6)

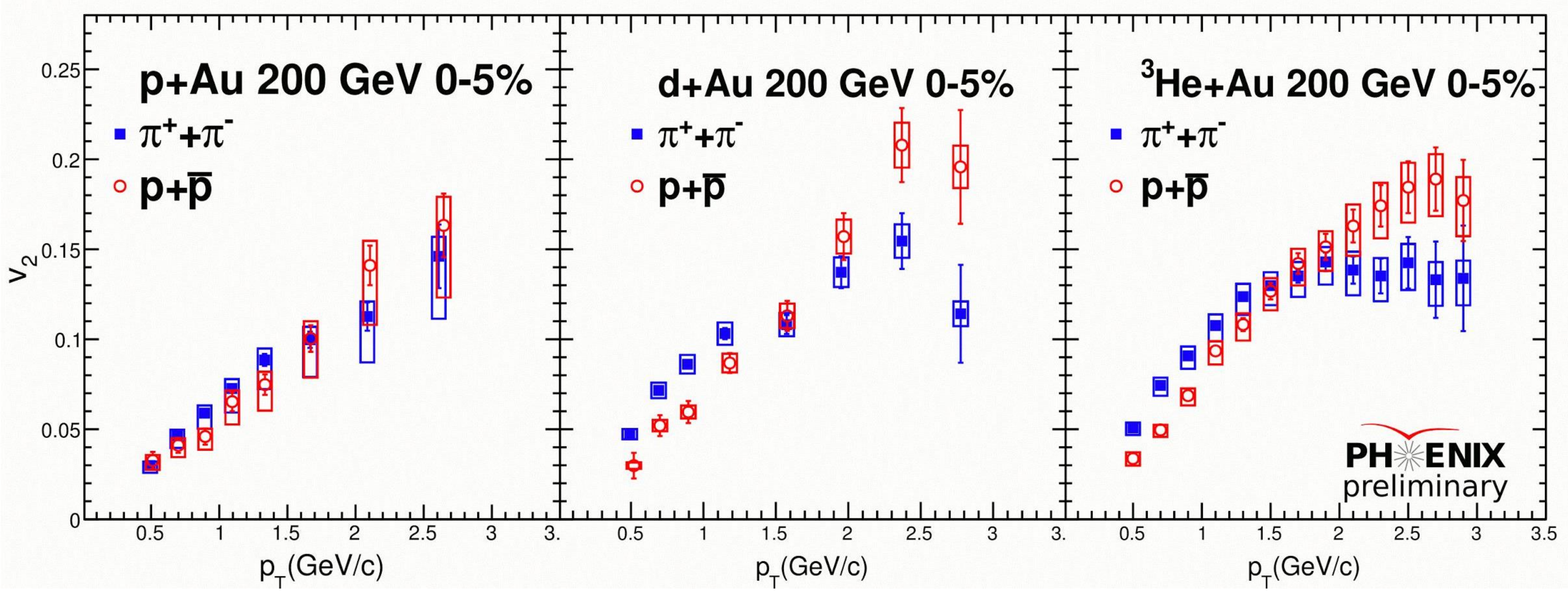
What about v_3 (Triangular Flow) ?

EXPECT for v_3 (triangular) : ^{3}He+Au > d+Au



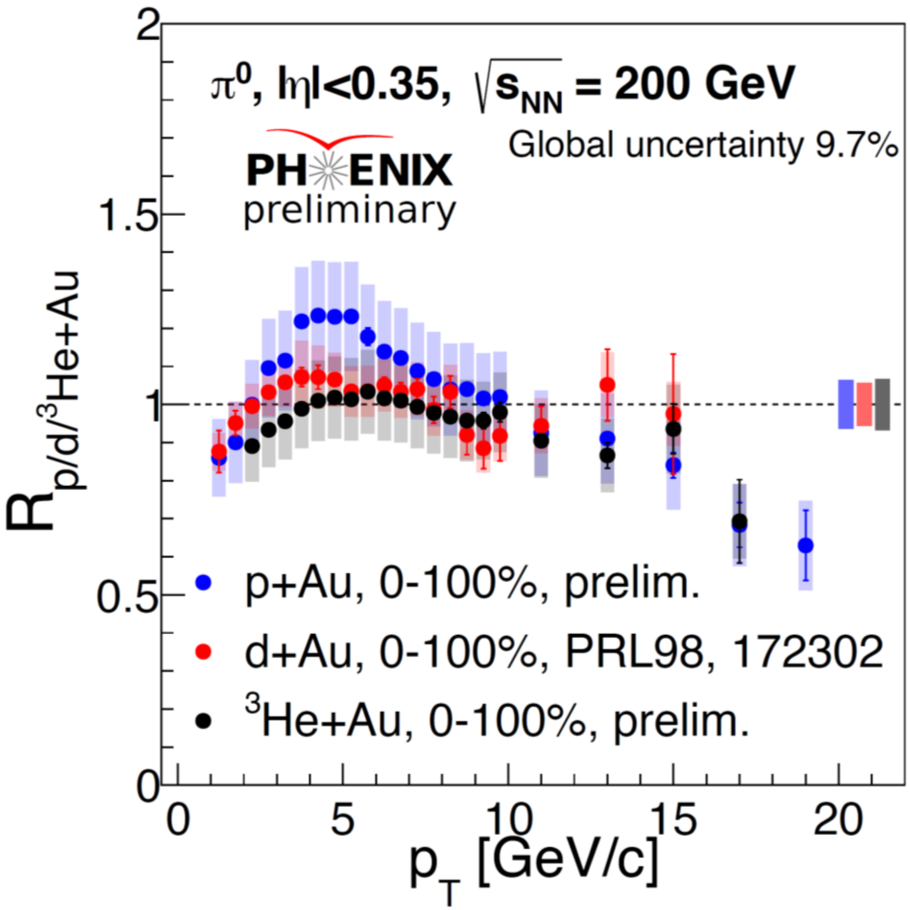
v_2 (Elliptic Flow) : ^{3}He+Au, d+Au, p+Au and p+Al

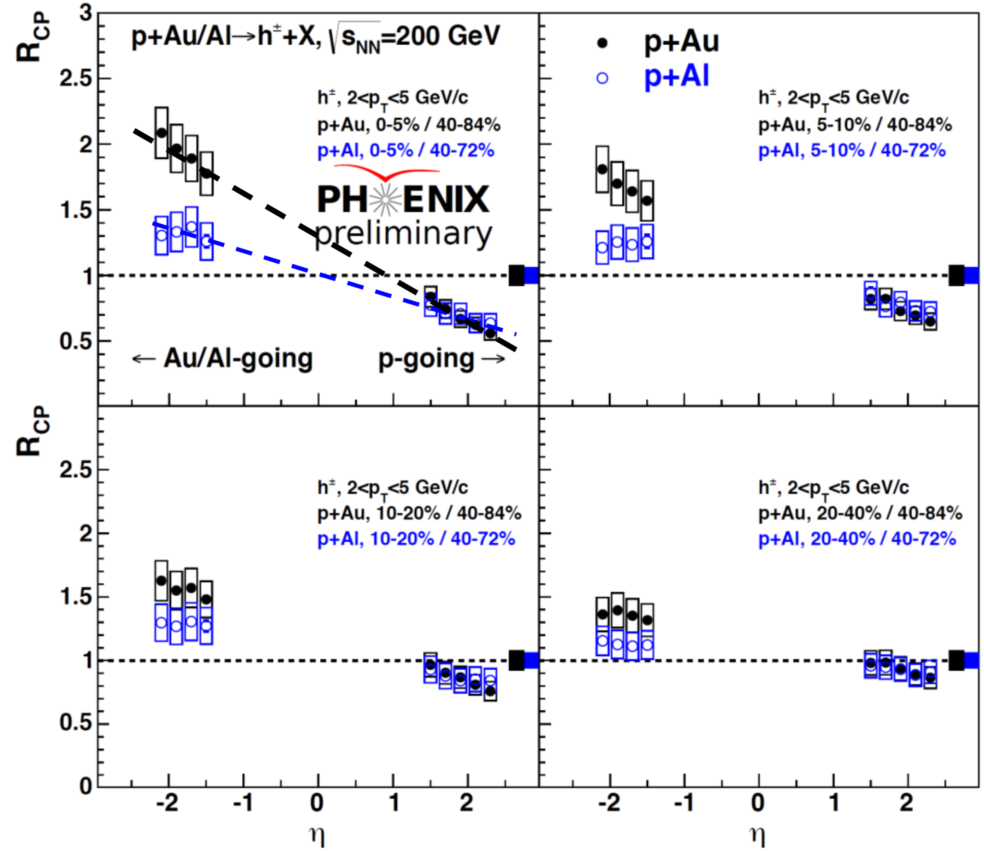
Mass ordering π, p?



Mass ordering characteristic of hydrodynamic behavior

What about Quenching in Small Systems?





Note: centrality detector $-4<\eta<-3$

- System size dependent enhancement at $p_T \sim$ 5GeV/c:

$R_{p+Au} > R_{d+Au} > R_{^3He+Au}$

Linear pseudorapidity dependence:

→ Backward enhancement – p+Au > p+Al

→ Forward suppression – p+Au ≈ p+Al

Summary

- **Without Doubt RHIC is Amazing QCD Machine**
  - Many Species, Many Energies, and High Luminosity and Stability.

- **Strangeness in Small Systems**
  - The PHENIX experiment measured ϕ meson production in p+p, p+Al, p+Au, d+Au, Cu+Cu, Cu+Au and Au+Au collisions with a wide range in p_T and rapidity to study cold and hot nuclear matters' effects. The ϕ meson cross section exhibits increase from RHIC to LHC energies.

- **Open Heavy Flavor Nuclear Modification Factor**
  - New measurements 0-10% AuAu at 200 GeV show clear separation of charm and bottom for $p_T < 5$ GeV. Analyzing full data set and reduce systematic errors for the high-p_T range are crucial for clear separation of charm and bottom.

- **Collective Dynamics in Small Systems**
  - PHENIX has measured Flow, v_2 (elliptic) v_3(triangularity) in a variety of small systems at $\sqrt{s}$ = 200 GeV. v_2 (elliptic flow) is developed for even for p+Al Collisions ($N_{participants} \sim 6$). Without doubt, these results became a challenge to many models and final physics interpretation still work in progress.

PHENIX has lots of data left to analyze, and more surprises are expected.