Highlights from PHENIX

2015 KOBE JAPAN

Axel Drees, Stony Brook University

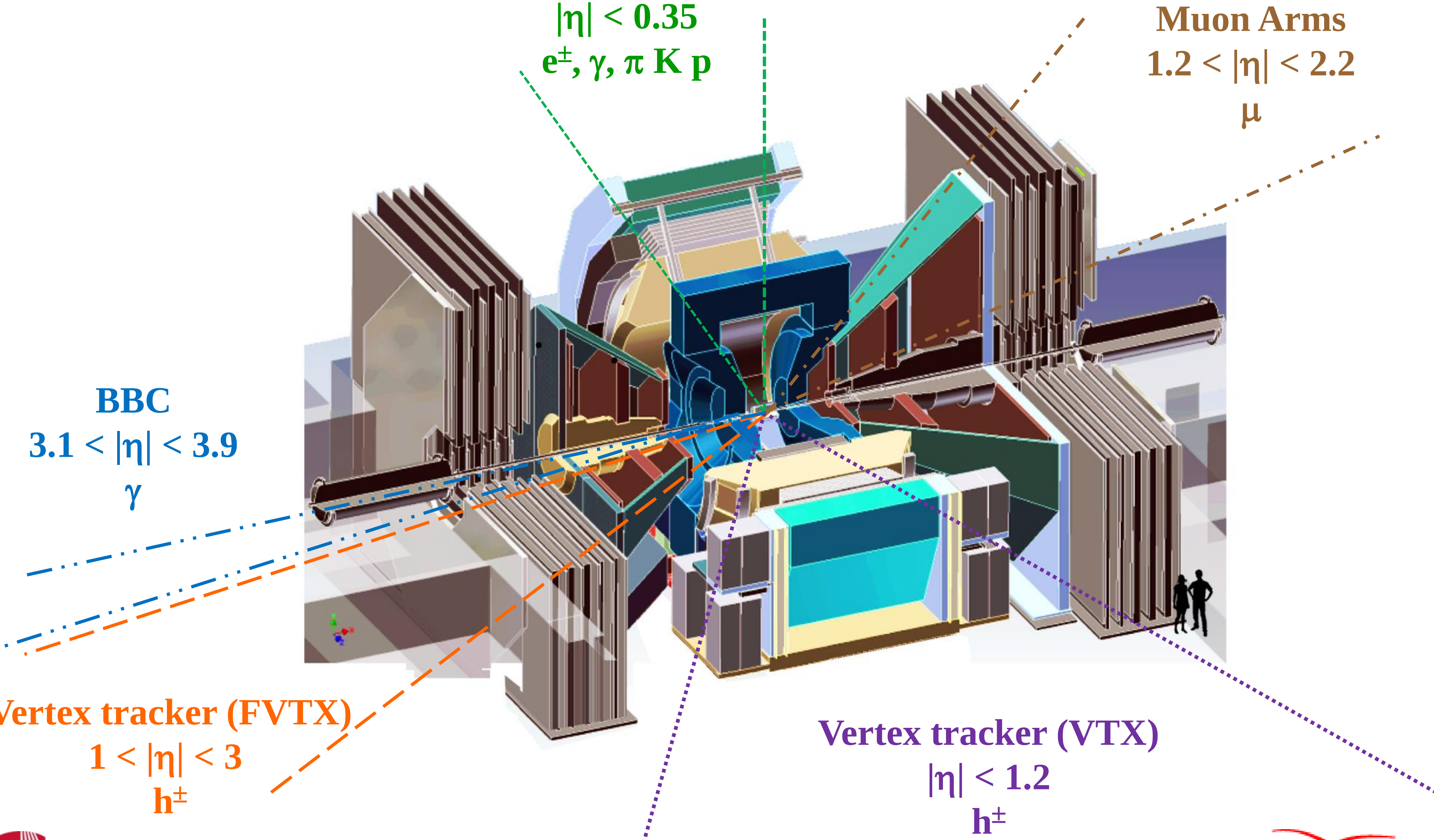
Introduction

Highlights selected from recent PHENIX results

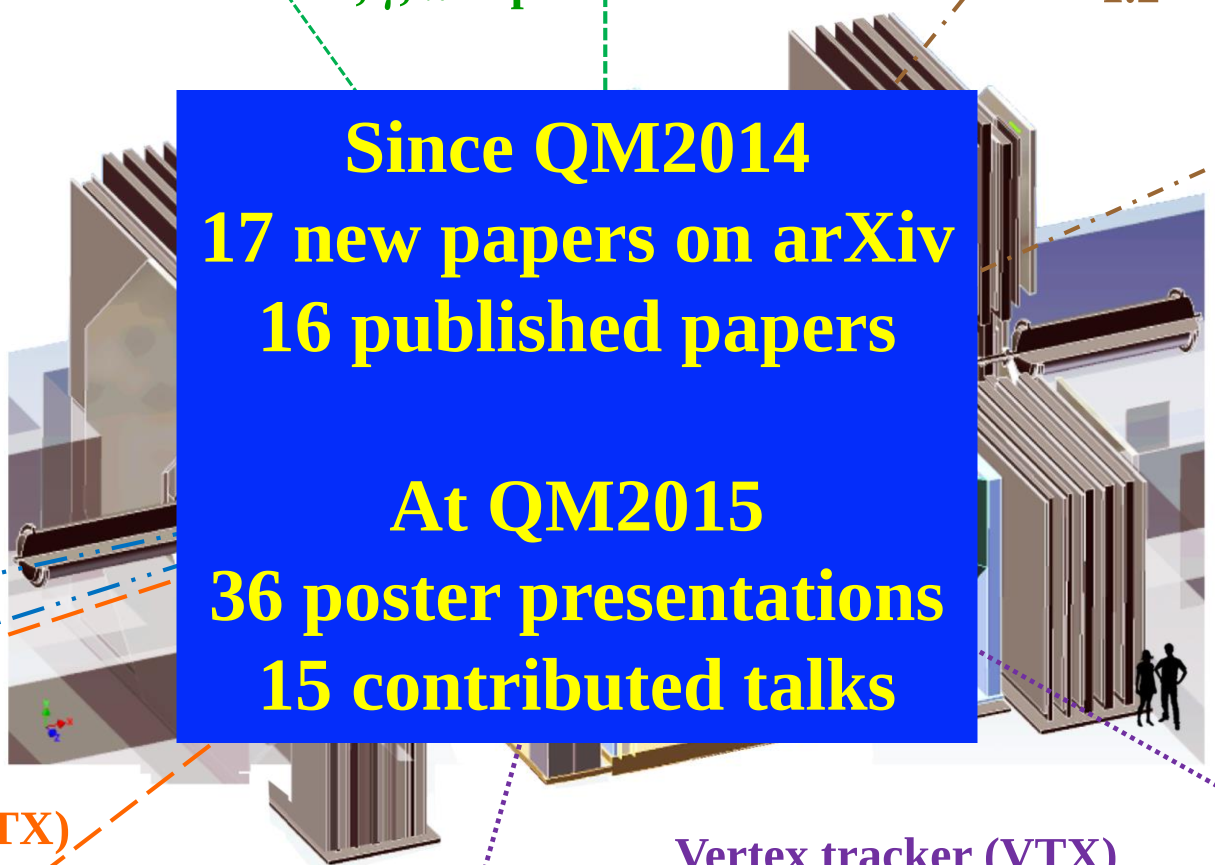
- **Beam Energy scan 7.7 – 200 GeV**
- **Direct photon emission in AuAu**
- **Dilepton continuum in AuAu**
- **Charm and Bottom energy loss in AuAu**
- **Strongly coupled matter in small systems (pA, dA, ^{3}HeA)**

Summary and Outlook

The PHENIX Experiment



The PHENIX Experiment



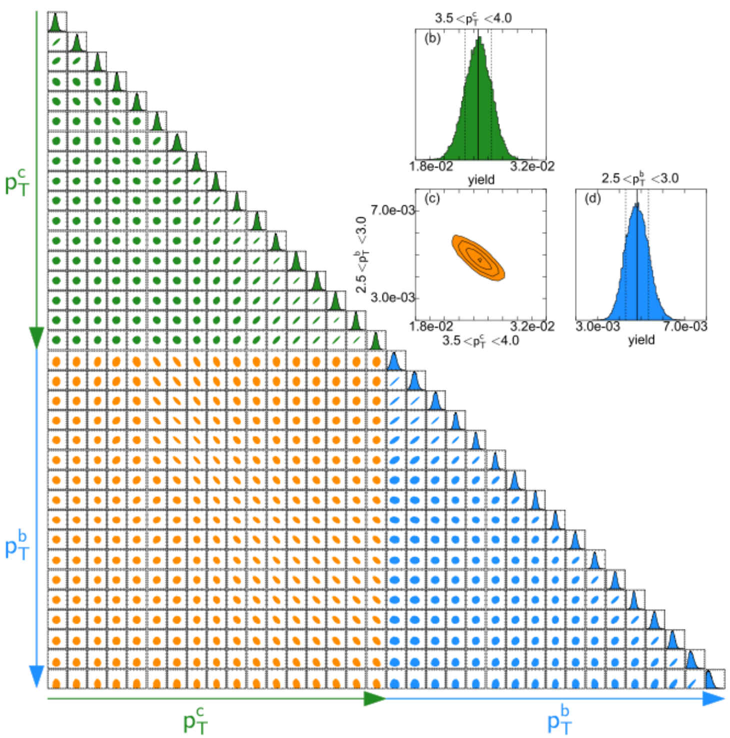
Since QM2014
17 new papers on arXiv
16 published papers

At QM2015
36 poster presentations
15 contributed talks

PHENIX Results after 15 Years of Operation

Highlights based on:

Advanced analysis techniques:
Example b/c separation

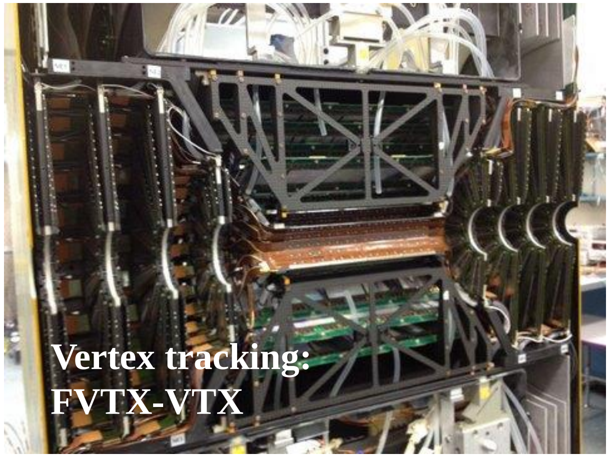


Versatile operation RHIC

energy GeV	U+U	Au+Au	Cu+Au	Cu+Cu	3He+Au	d+Au	p+Au	p+Al	p+p
	Collision System								
500									x
200	x	x	x	x	x	x	x	x	x
130		x							
62.4		x		x					x
39		x							
27		x							
~20		x		x					
14.5		x							
7.7		x							

2015

Results from detector upgrades



Schematic View of Space-Time Evolution

Collision

Initial state?
CGC?

Rapid equilibration

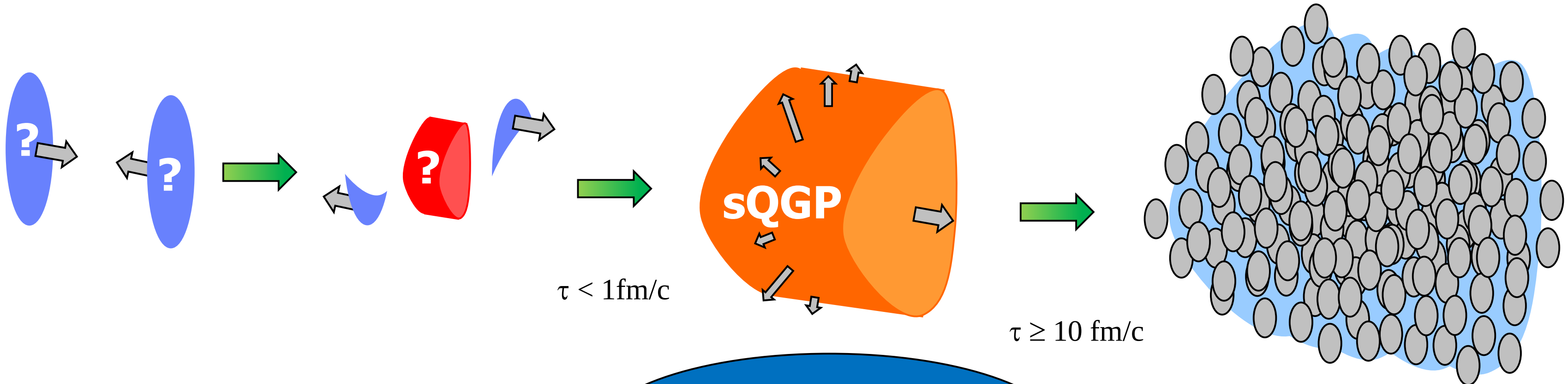
How?
Glasma?
Role of B-field?

Anisotropicaly expanding sQGG

Properties?
T, η/s, $\hat{q}$, D, … ?

Hadronization to freeze-out

Coalescence?
Chiral symmetry?



PHENIX highlights:

- Heavy flavor energy loss
- Dilepton continuum
- Strongly coupled matter in small systems
- Direct photon emission

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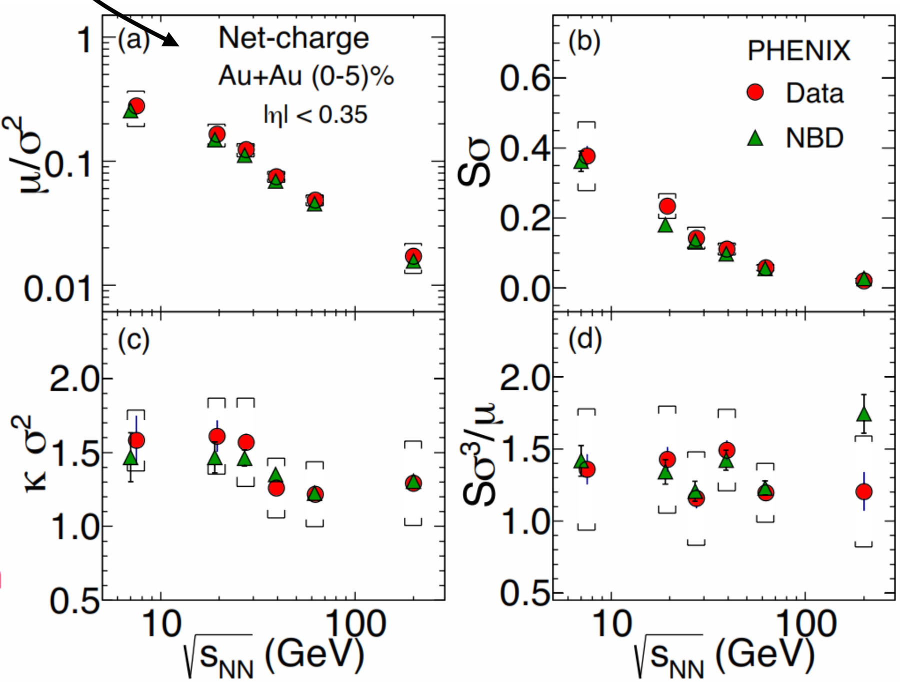
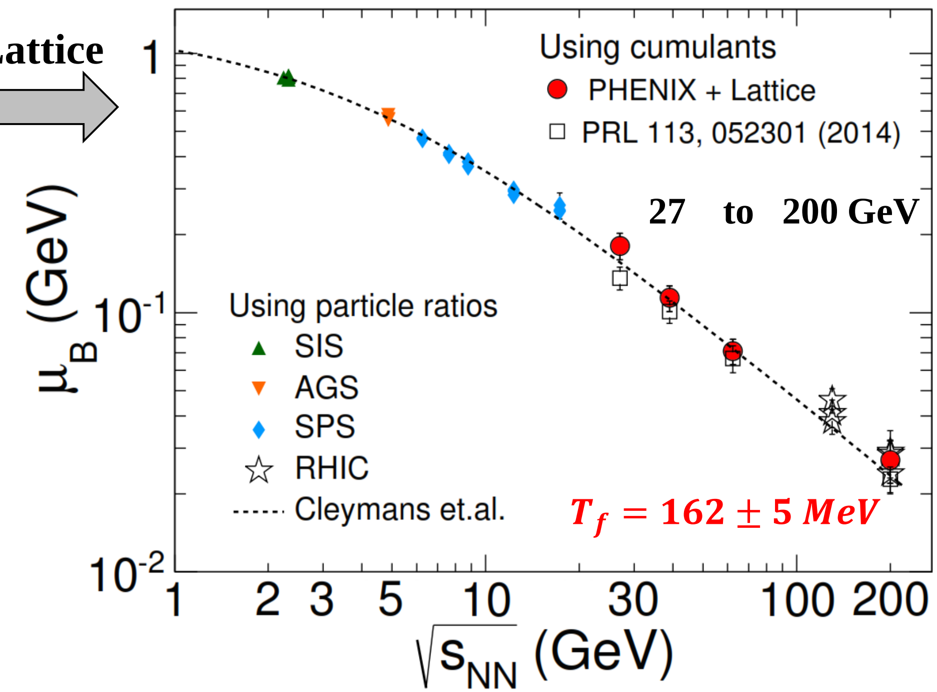
Beam Energy Scan

- **Comprehensive surveys of multiple observables as function of beam energy**
  - **HBT Radii:** *PHENIX: arXiv 1410:2559 (2014)*
  - N_{ch}, E_T: *PHENIX: arXiv 1509:06727 (2015)*
  - *net* N_{ch} **cumulants** *PHENIX: arXiv 1506:07834 (2015)*



Lattice



Monotonic change of baryo-chemical potential at constant freeze-out temperature

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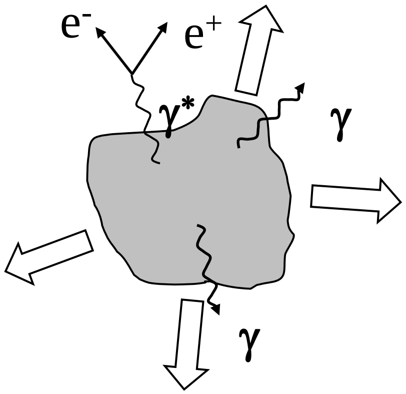
Thermal Radiation from Hot & Dense Matter

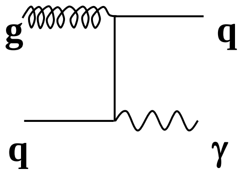
- **Black Body Radiation**
  - **Real or virtual photons**
  - **Spectrum and yield sensitive to temperature**
    Avg. inv. slope ∝ T, Yield ∝ T^3
  - **Space-time evolution of matter**
    collective motion → Doppler shift
    → anisotropy



High yield → high T → early emission
Large Doppler shift → late emission

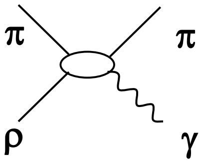
- **Microscopic view of thermal radiation**

QGP:



photons

hadron gas:

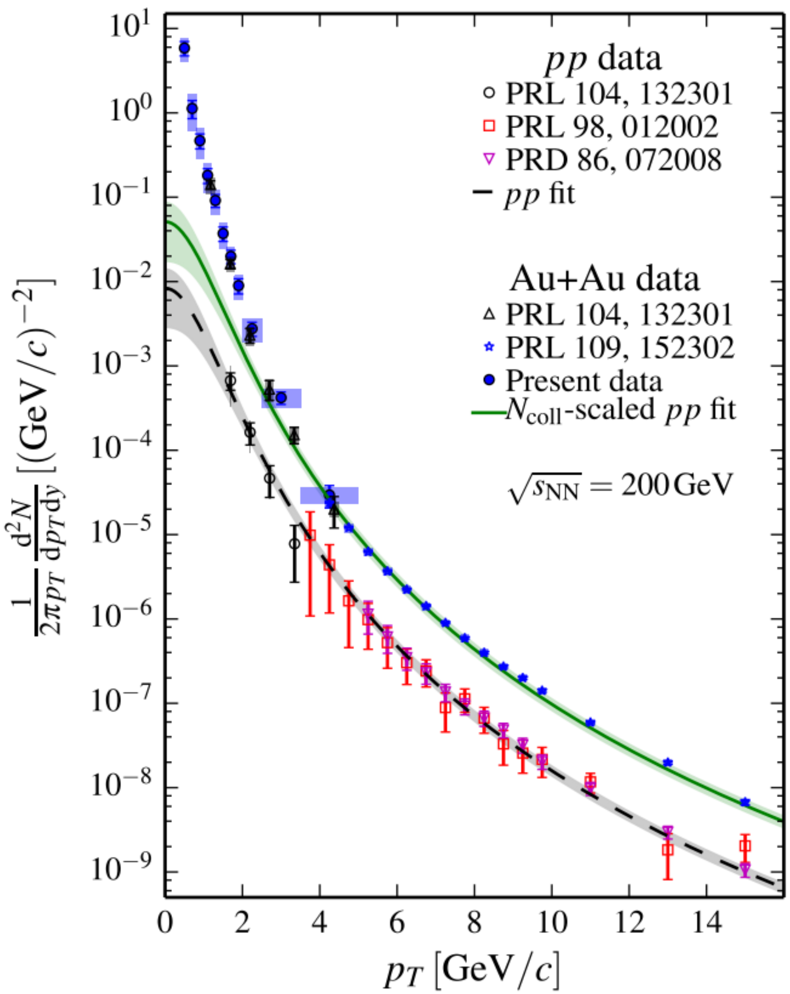


low mass lepton pairs

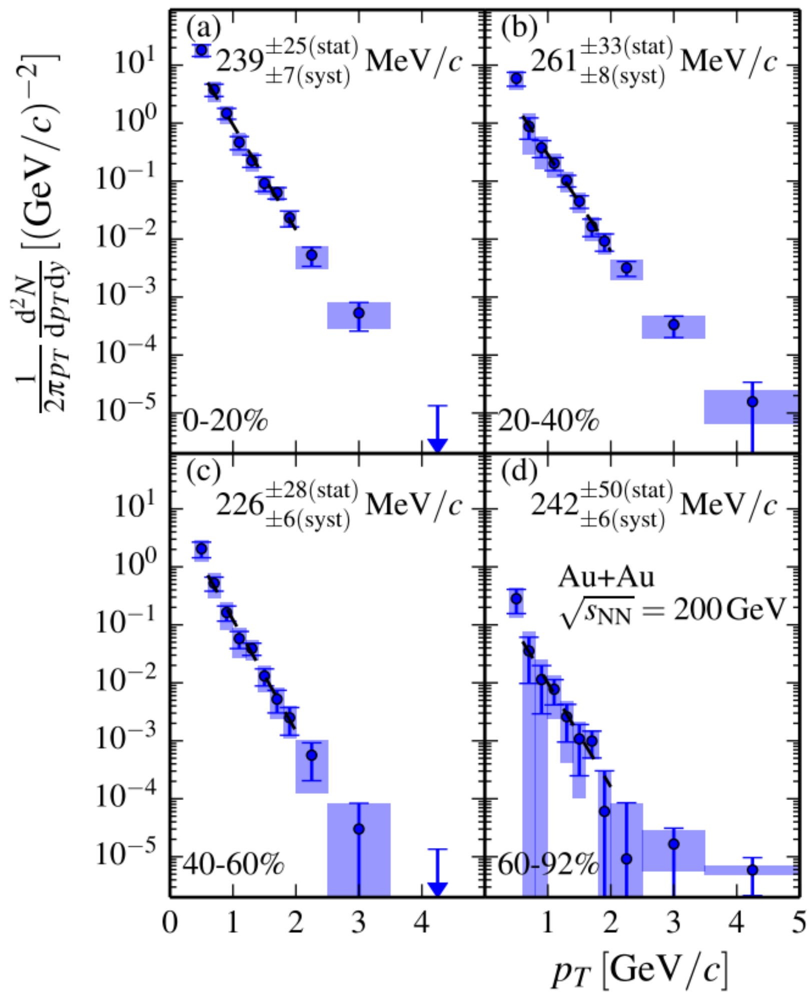
Need realistic model simulation for rates and space-time evolution for quantitative comparison with data

Direct Photon Emission from 200 GeV Au+Au

PHENIX: Phys. Rev. C 91 064904 (2015)



Prompt component subtracted



Large direct photon excess

yield $\propto N_{part}^{1.38\pm0.3\pm0.07}$ with inv. slope T ~ 240 MeV

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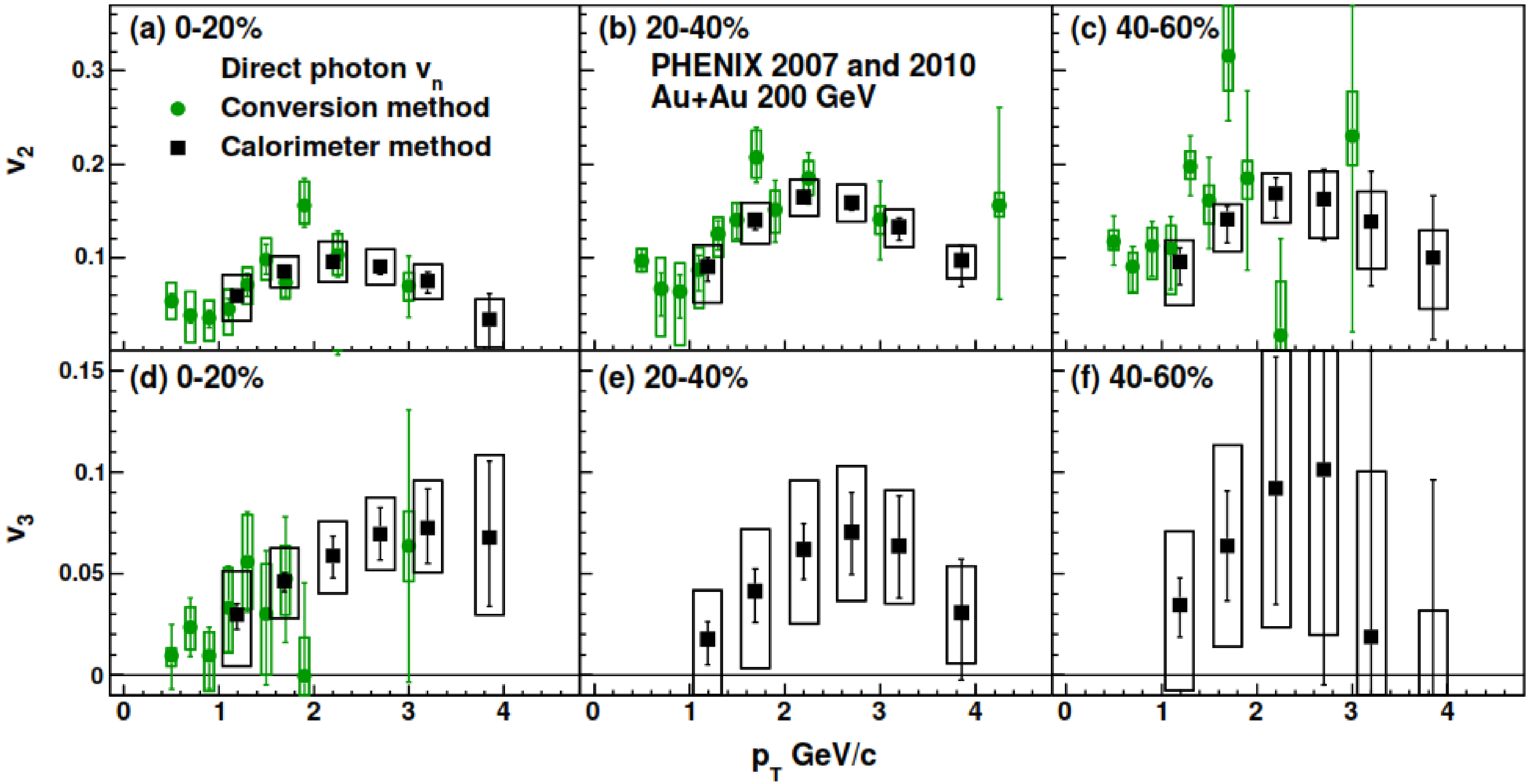
Anisotropic Emission of Direct Photons

PHENIX: arXiv:1509.07758 (2015)



Anisotropic emission of direct photon with large v_2 and v_3

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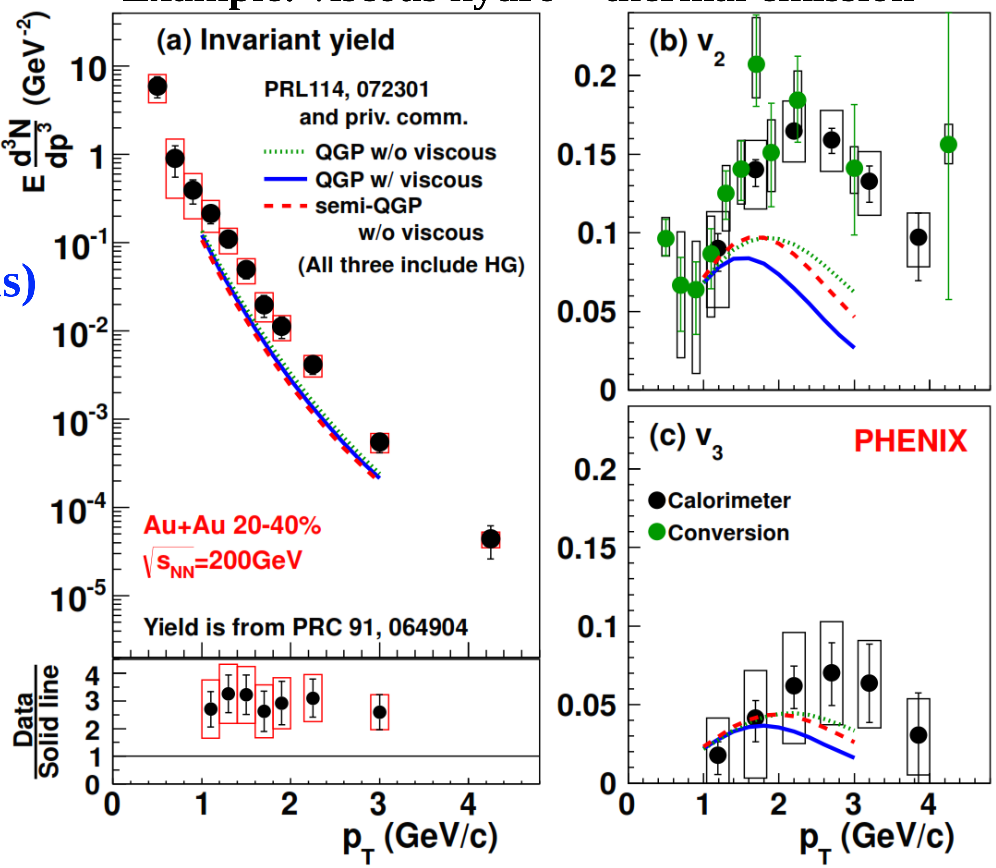
Direct Photon Puzzle

PHENIX: Phys. Rev. C 91 064904 (2015)

Many model calculations and consideration*:

- **More traditional, large contribution from hadron gas**
  - Thermal rate in QGP & HG, with hydro (viscous/non viscous) or blastwave evolution
  - Microscopic transport (PHSD)
- **New early contributions**
  - Non-equilibrium effects (glasma, etc.)
  - Enhanced thermal emission in large B-fields
  - Modified formation time and initial conditions
- **New effects at phase boundary**
  - Extended emission
  - Emission at hadronization

Example: viscous hydro + thermal emission



Large yield and v_n challenge understanding of sources, emission rates and space-time evolution

*list not complete

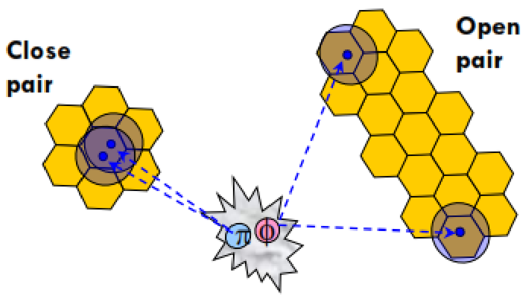
Low Mass e^+e^- Pair Emission

- **PHENIX run 2004 data show large low mass dilepton excess**
  - **factor of ~5 in min.bias collisions** *PHENIX: Phys.Rev.C81 034911 (2010)*
  - **Small signal-to-background (S/B) ratio ~ 1:500**

  - **Much larger than expected from theoretical models**
  - **Recent STAR results shows smaller (factor ~1.8) enhancement**

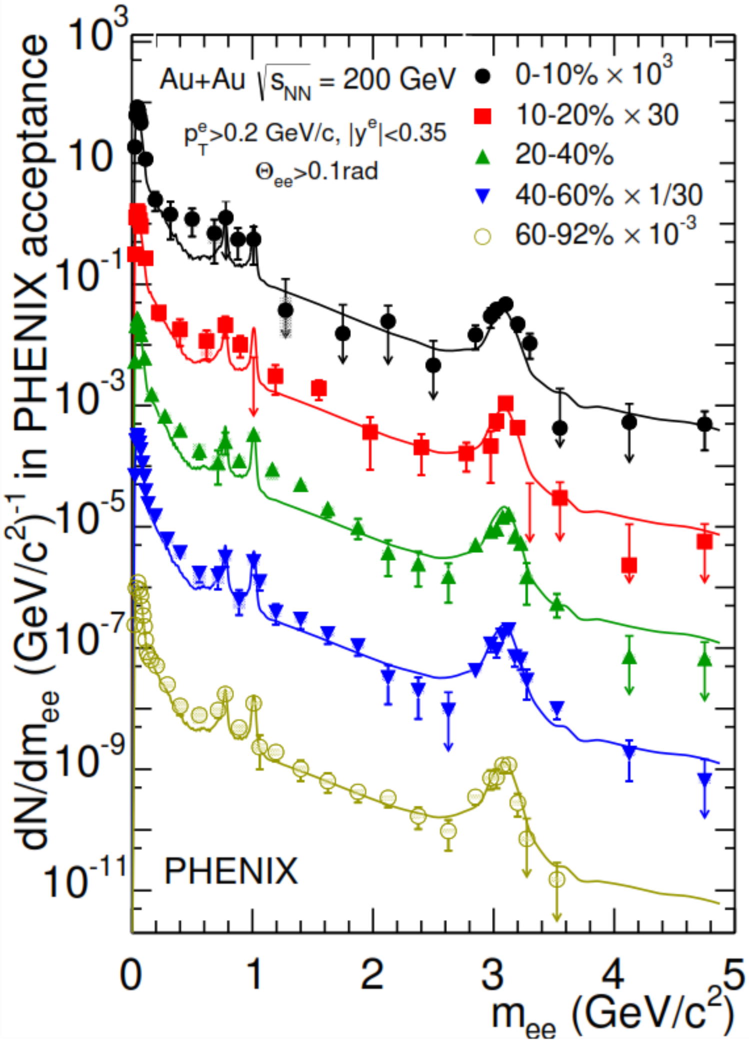
STAR: Phys.Lett. 113 022301 (2014)

- **PHENIX Hadron Blind Detector (HBD) upgrade designed to improve S/B and to study e^+e^- continuum more precisely**
- **HBD data taken in 2010 now fully analyzed:** *PHENIX: arXiv 1509.04667 (2015)*
  - **Active rejection of conversion and Dalitz pairs (close pairs)**
  - **Improved hadron rejection**
  - **Neural networks to optimize cuts**



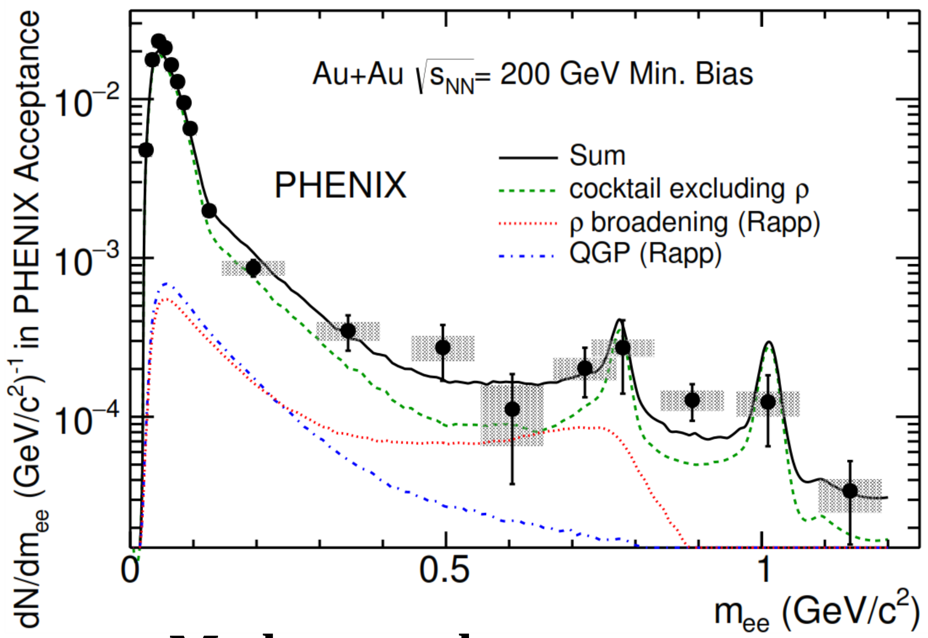
- **Quantitative understanding of background**
- **Results verified by 2nd analysis using different techniques**

Low Mass e^+e^- Enhancement in 200 GeV Au+Au



Moderate enhancement consistent with ρ broadening

PHENIX: arXiv 1509.04667 (2015)



- **Moderate enhancement**
  - **for 300 < m < 750 MeV factor***
    min.bias 2.3 ± 0.4 ± 0.4 ± 0.2
    central 3.2 ± 1.0 ± 0.7 ± 0.2
- **Smaller than previous result**
- **Consistent with STAR data**
- **Consistent with ρ broadening**

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**binary scaled PYTHIA for c/b*

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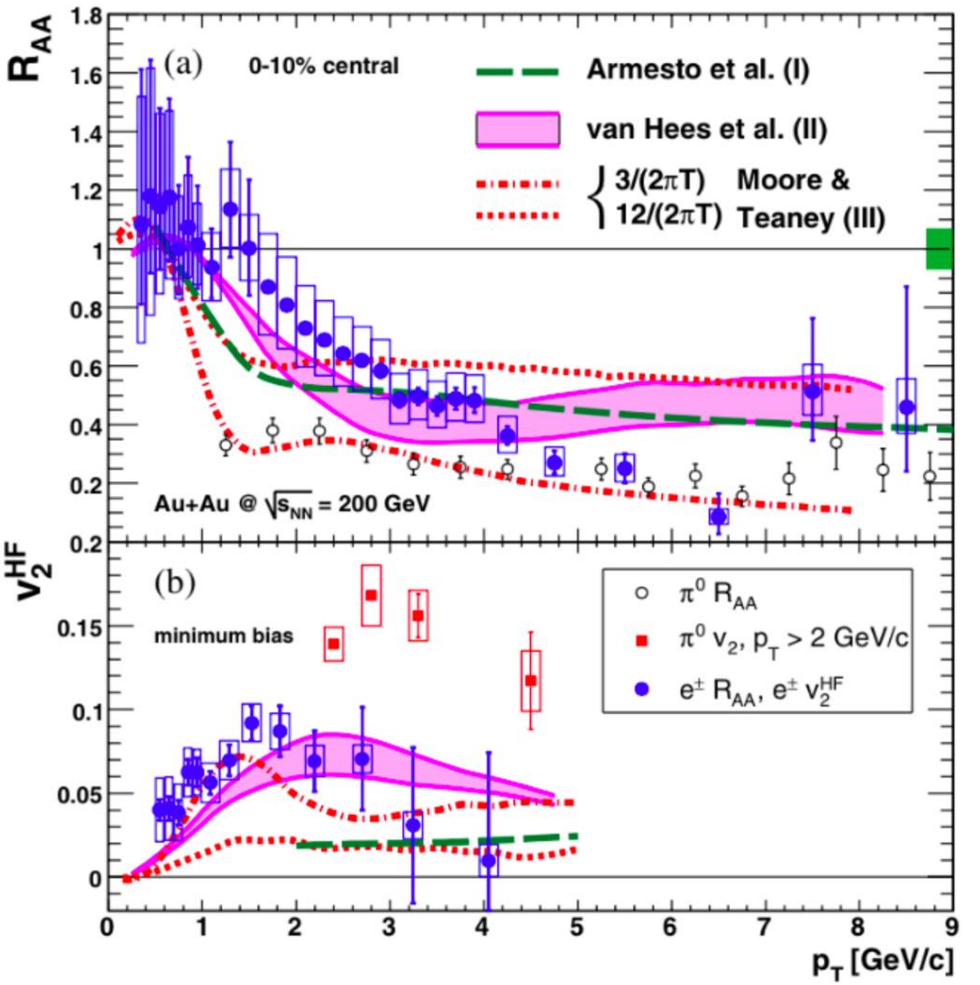
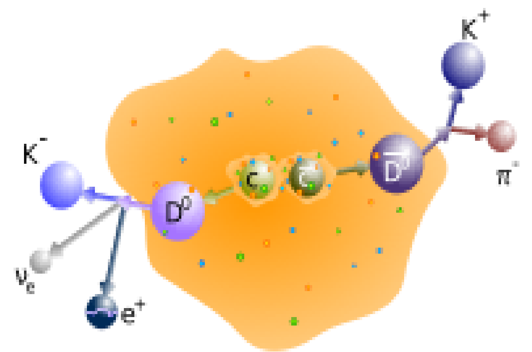
Energy Loss of Open Heavy Flavor

PHENIX: Phys. Rev. C 84, 044905 (2011)



- **Discovery of large suppression and elliptic flow of single electrons from heavy flavor decays**



- **Data implies charm AND bottom lose energy**

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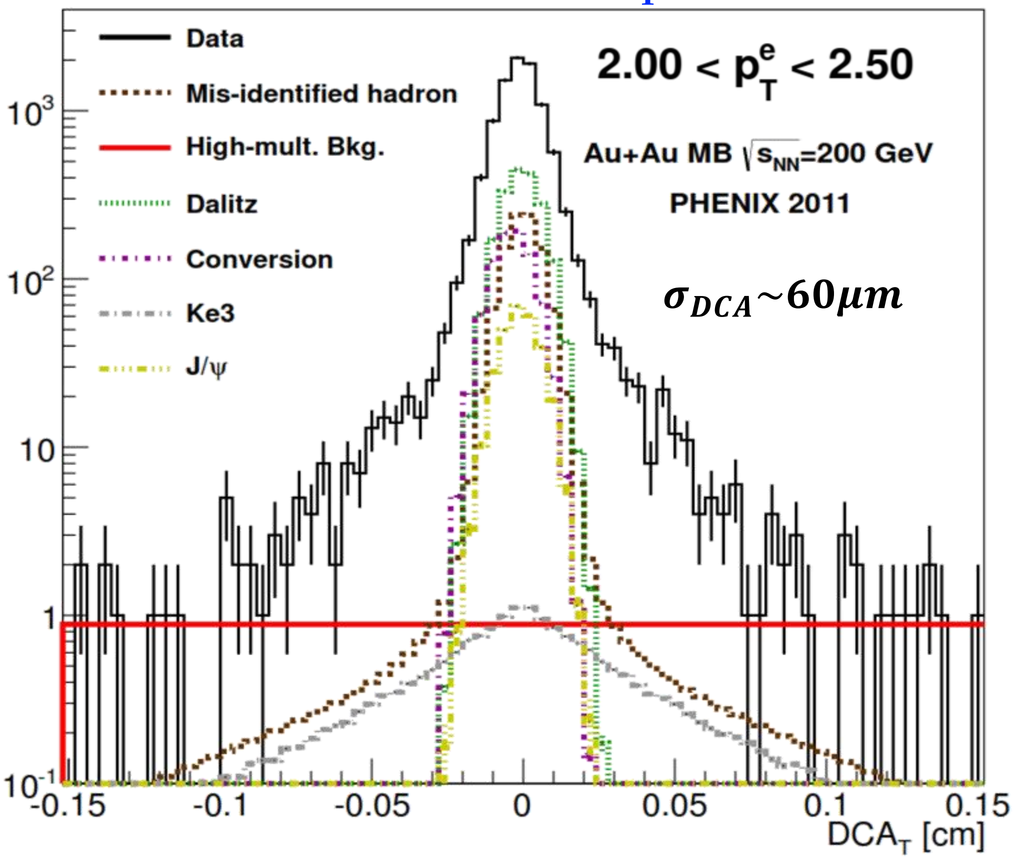
Silicon Vertex Tracker (VTX) since 2011

PHENIX: arXiv:1509.04662 (2015)

Use distance of closest approach (DCA) to unfold charm and bottom contribution

Electron DCA_T



- **Prompt components**
  - Dalitz ($\pi, \eta \rightarrow e^+e^-\gamma$)
  - $J/\psi \rightarrow e^+e^-$
- **Non-prompt components**
  - Conversions $\gamma \rightarrow e^+e$ after ~75% rejected by 2nd hit in VTX
  - $K_s^0, K^\pm \rightarrow e\,\nu\,\pi$
- **Mis-reconstructed component**
  - Hadrons identified as electrons
  - Wrong VTX hit association

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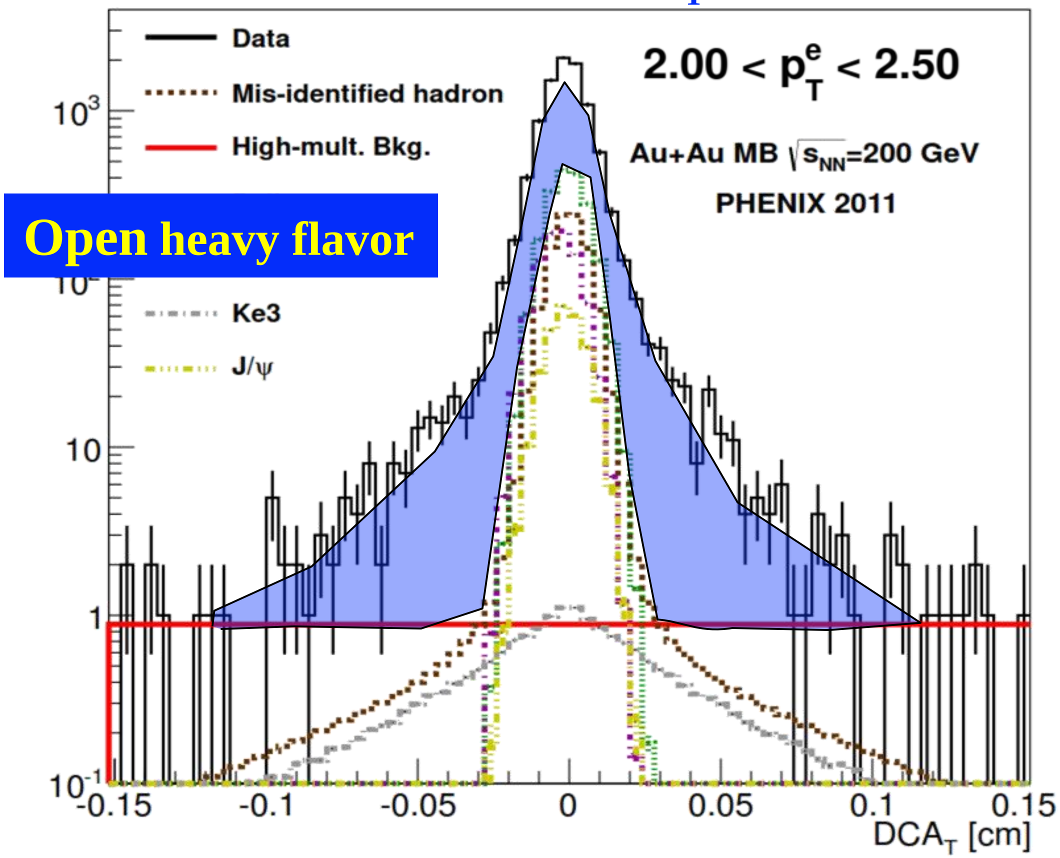

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Unfolding Charm and Bottom Spectra

DCA for B, D decays depends on momentum distribution which is not *a priori* known

PHENIX: arXiv:1509.04662 (2015)

Input:

Heavy flavor electron data x:

$$\frac{1}{N_{evt}}\frac{dN^{ehf}}{dp_T}$$

$$DCA_T(p_T)$$

Variables:

c,b hadron yields θ:

$$\frac{d\theta_c}{dp_T}, \frac{d\theta_b}{dp_T}$$

Likelihood $P(x|\theta)$

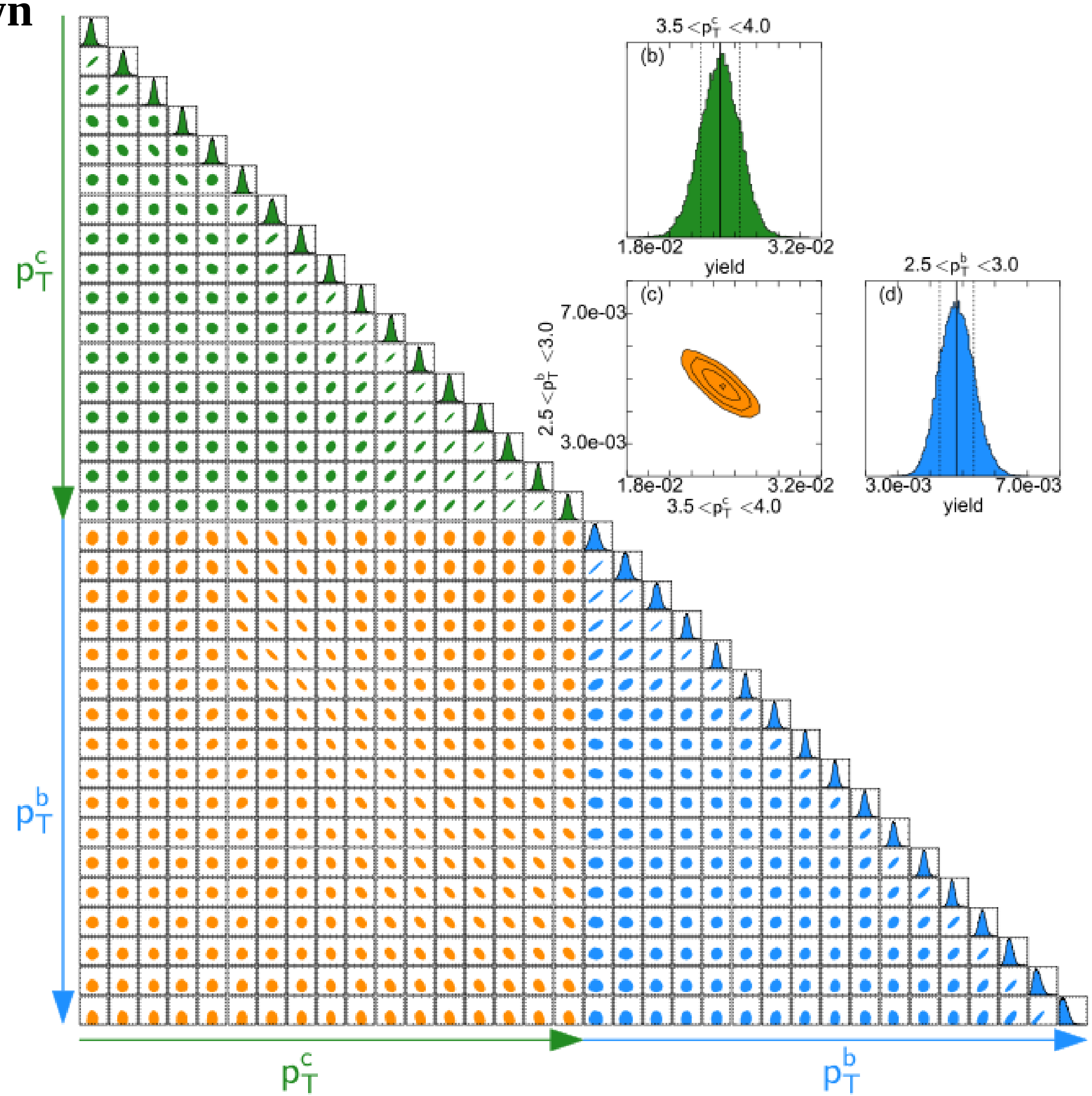
sample θ_c, θ_b Markov Chain MC

$\pi(\theta)$ surpress discontinuities deviations from θ_{prior}

Output:

Probability for θ given x:

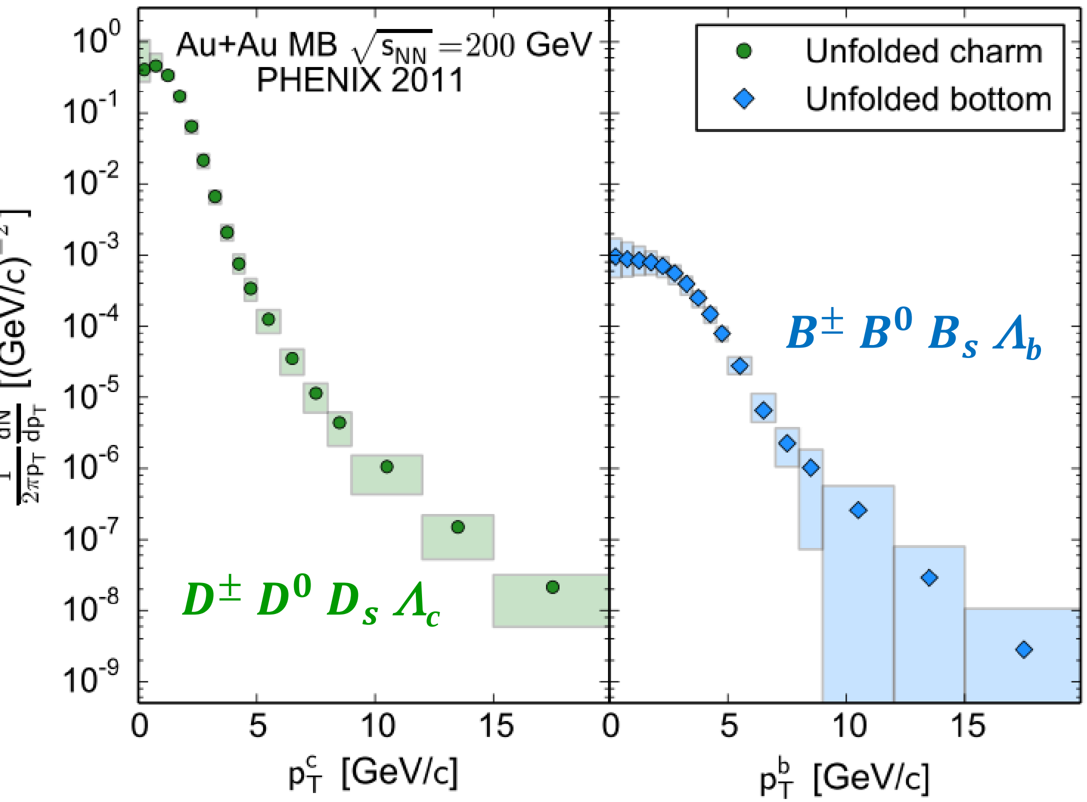
$$p(\theta|x) = \frac{P(x|\theta)\pi(\theta)}{P(x)}$$

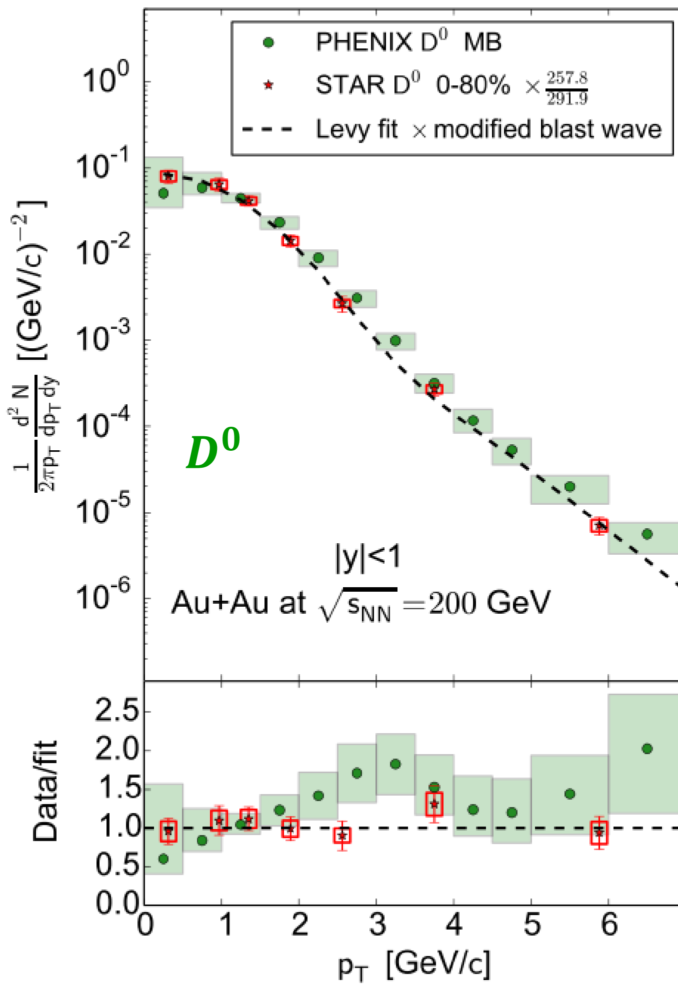


Charm and Bottom Hadrons

PHENIX: arXiv:1509.04662 (2015)

Yields in 4π for min. bias Au+Au at 200 GeV





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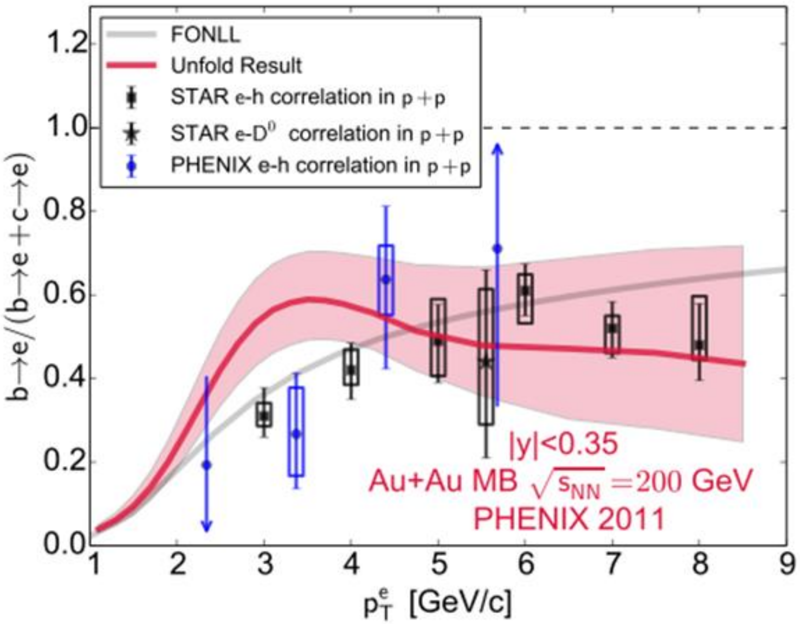
Charm and Bottom R_{AA}

PHENIX: arXiv:1509.04662 (2015)

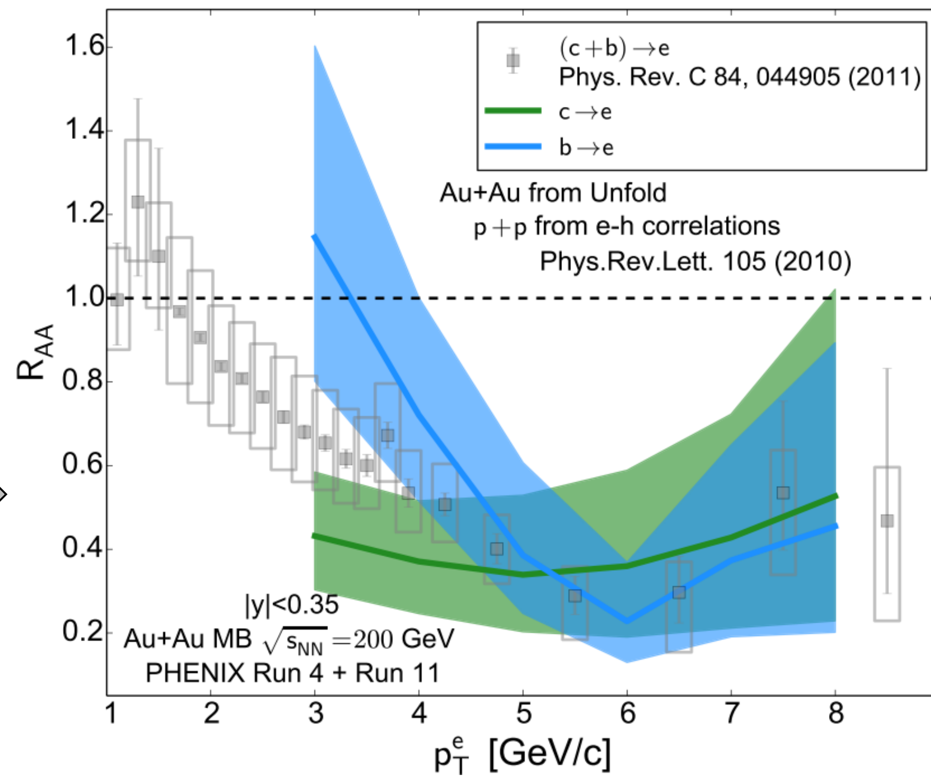
Fraction of electrons from bottom

$$F = \frac{b \to e}{b \to e + c \to e}$$



$F_{AuAu} > F_{pp}$ $F_{AuAu} \sim F_{pp}$

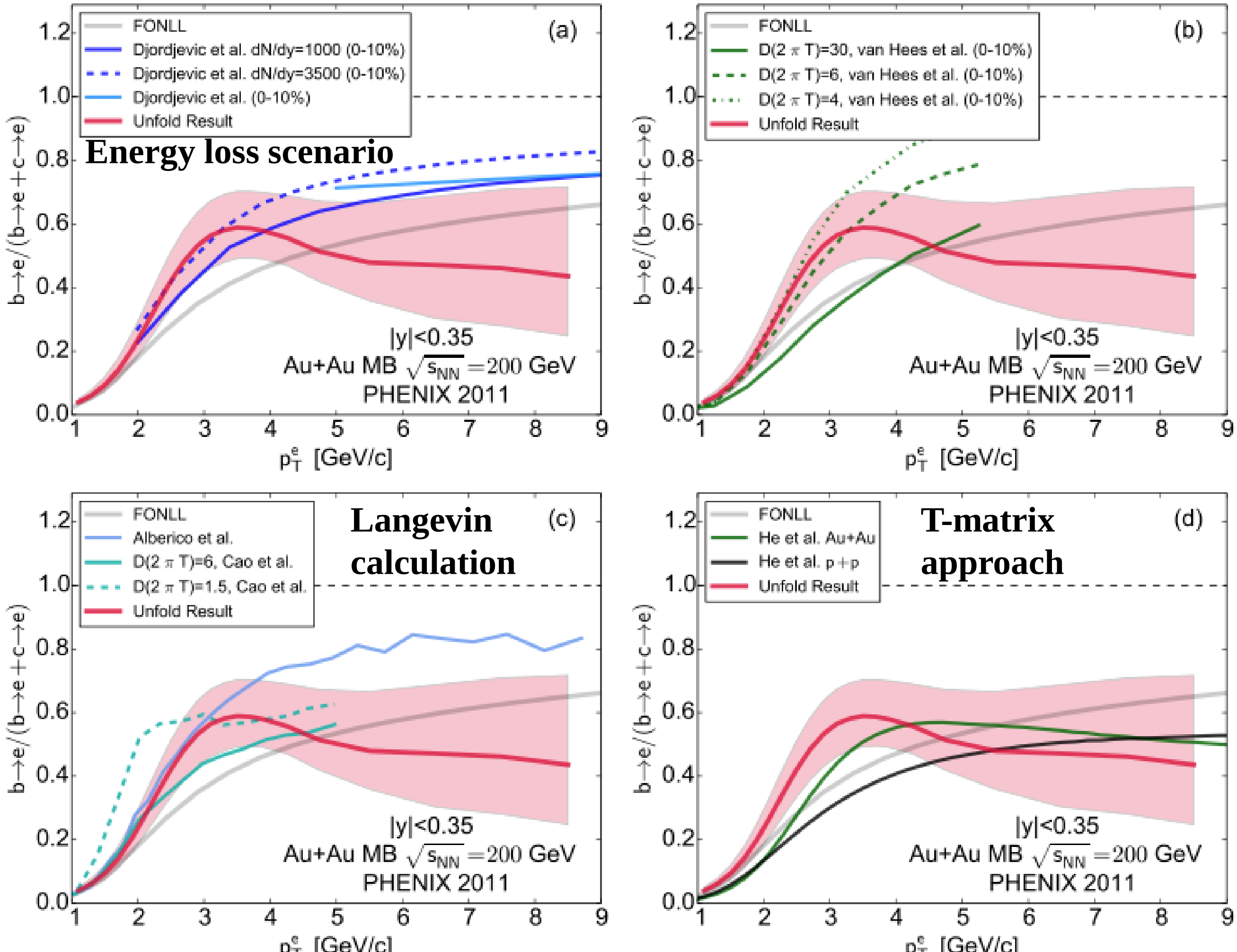
Single electron R_{AA} for bottom and charm



Mapped p_T dependence separately for charm and bottom suppression

Comparison to Theoretical Models

PHENIX: arXiv:1509.04662 (2015)

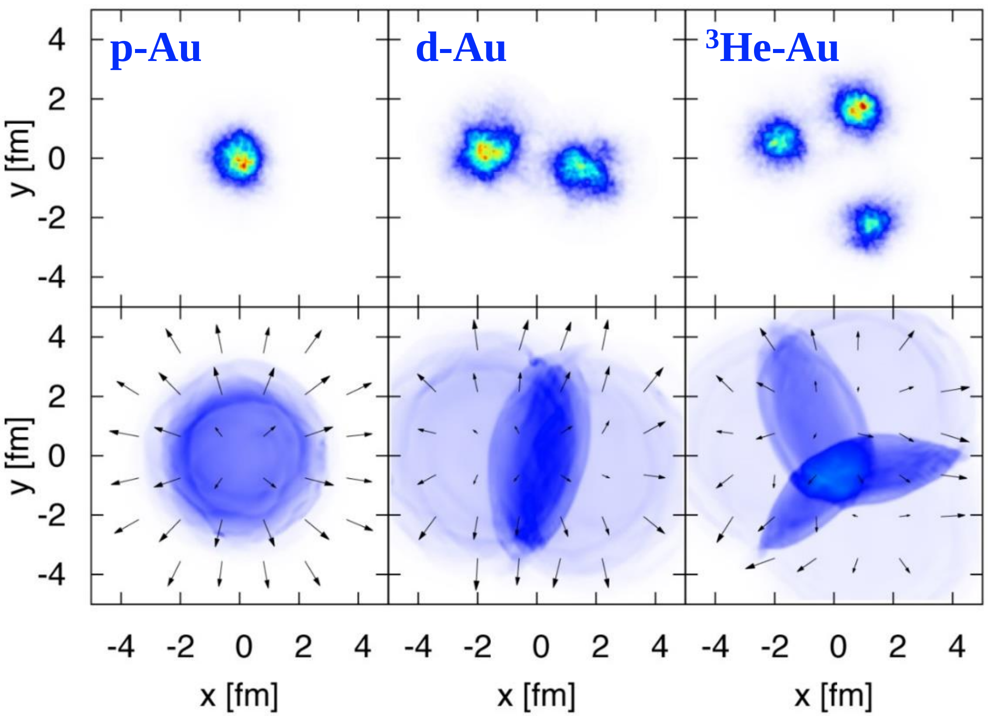


Data provides new constraints on theoretical description of b & c energy loss

QGP in Small Systems

- **CMS discovery of collective phenomena "the ridge" in p+p and p+Pb**
- **Use versatility RHIC for a set of controlled experiment**
  - **Engineer initial state geometry through collision system**

Phys. Rev. Lett. 113, 112301 (2014), figure courtesy of B. Schenke



Initial State Hot Spots
Glauber with nucleons

Hydrodynamics

Collectivity in Final State

p+Au(2015) d+Au(2008) ^{3}He-Au(2014)
PHENIX data with high multiplicity trigger

Sensitivity to initial conditions and early time evolution

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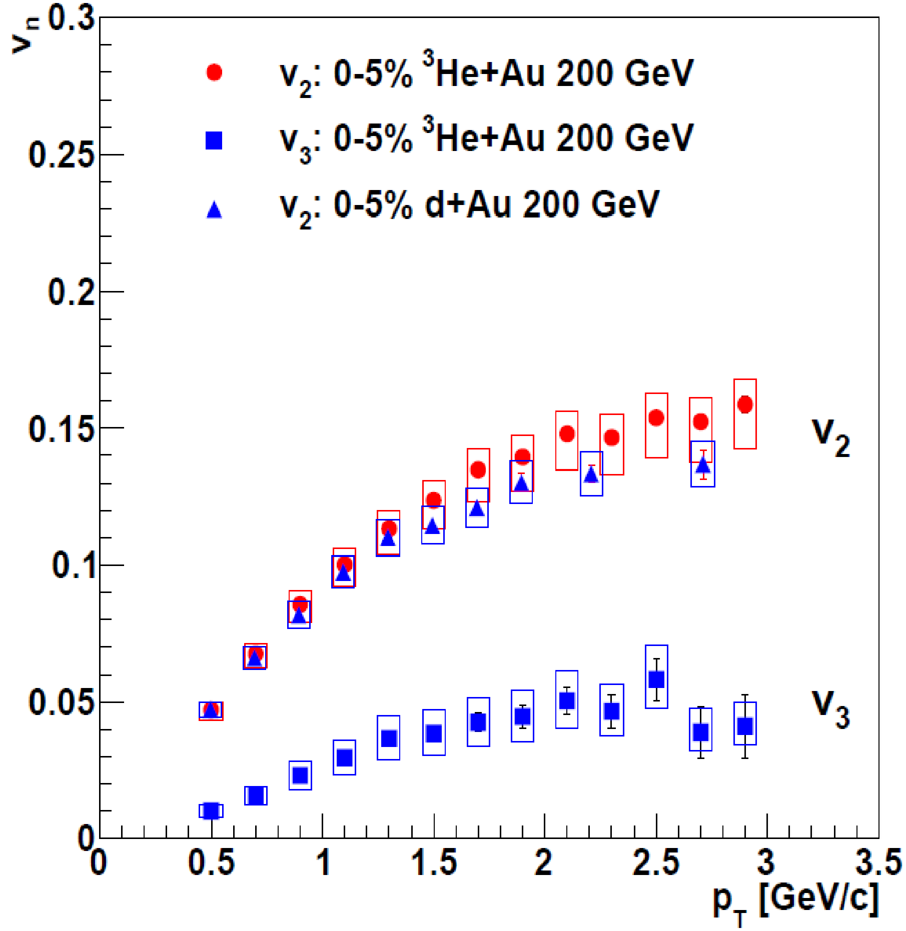
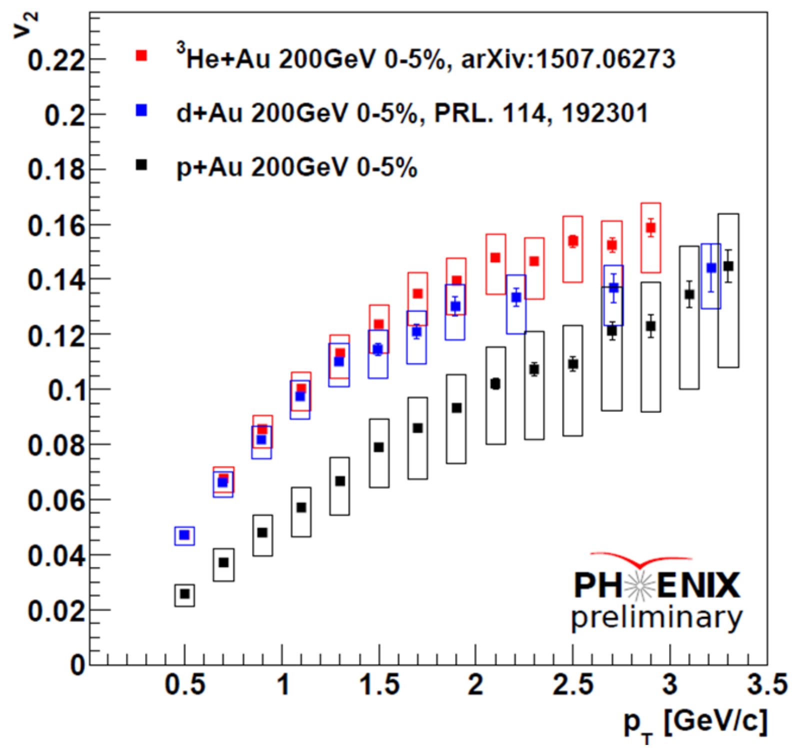
Flow in Small Systems at $\sqrt{s_{NN}}$ = 200 GeV

PHENIX ^{3}HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)



Top 5% in centrality

$$v_2^{^3HeAu} \geq v_2^{dAu} > v_2^{pAu}$$

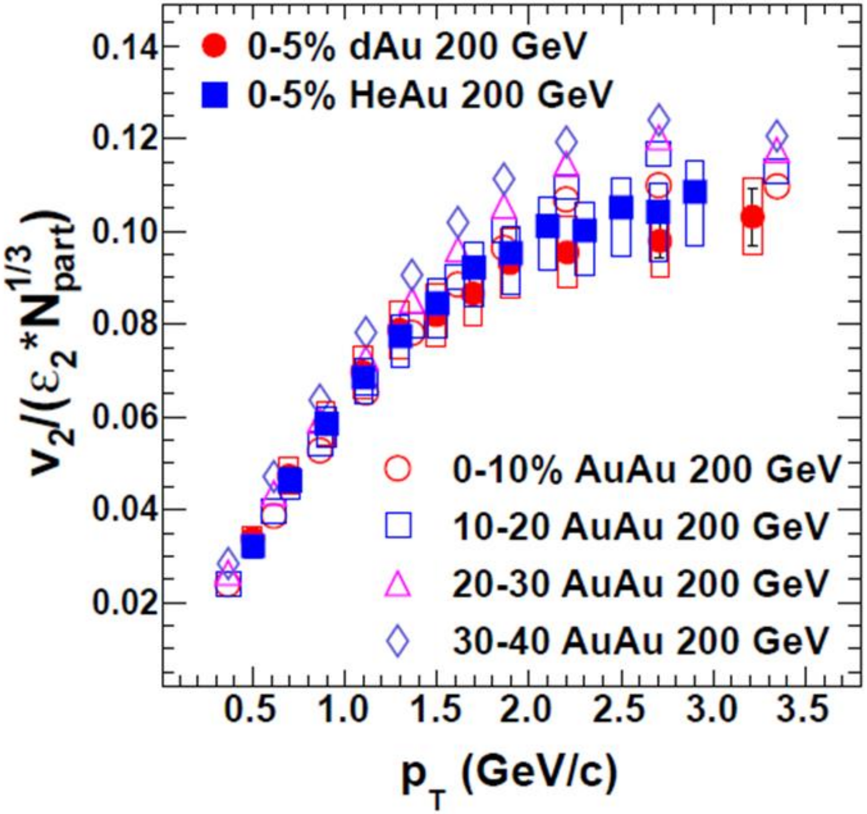


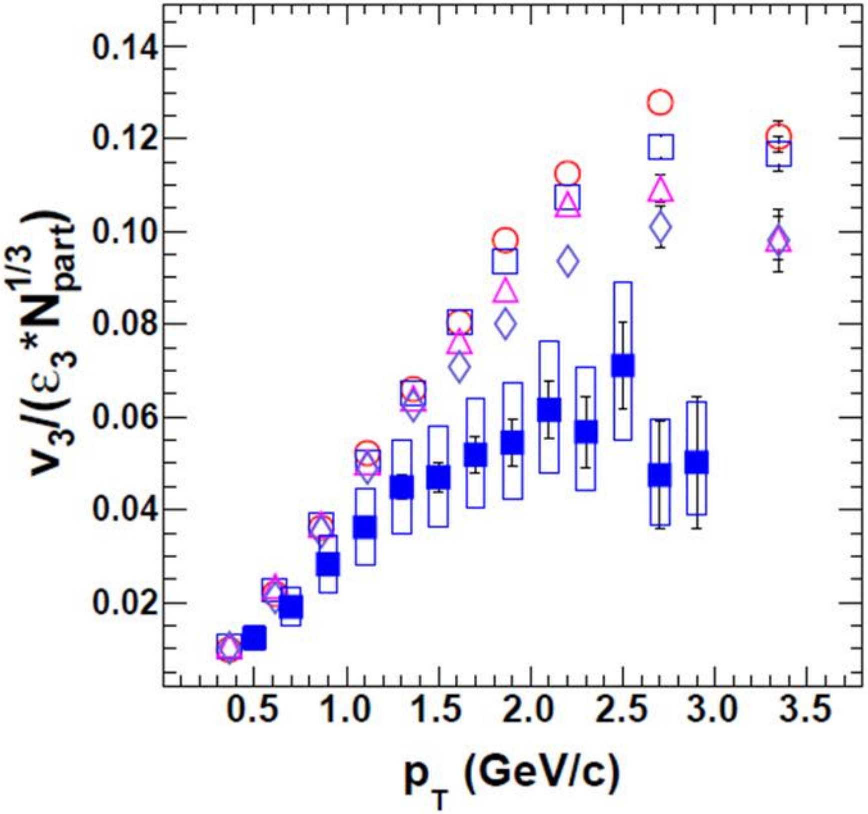
Collective motion: Large anisotropy v_2 in p+Au, d+Au, and v2, v3 ^{3}He-Au

Empirical Scaling Behavior

PHENIX: Phys. Rev. C92, 034913 (2015)

A+A collisions show scaling: $\frac{v_n}{\epsilon_n N_{part}^{1/3}}$





Empirical scaling of v_2 works well for small collision systems

For v_3 scaling does not work for small collision systems

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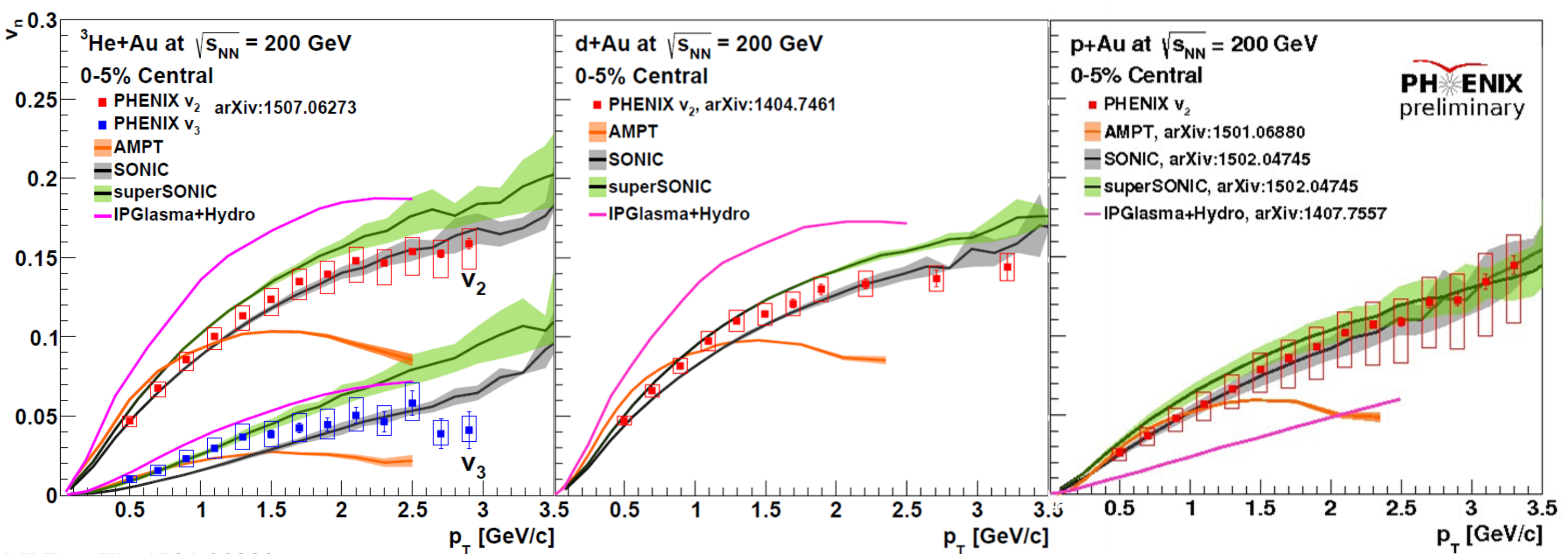
Comparison to Model Predictions

SONIC Glauber + hydro + hadron cascade
super SONIC + pre-equilibrium
} predicts v_n

IPGlasma + hydrodynamic

AMPT parton + hadron cascade

3He(d)+A ↑ v_n , p+A ↓ v_n
under predicts v_n at high p_T



AMPT: arXiv:1501.06880
SONIC: arXiv:1502.04745
IP+Hydro:arXiv:1407:7557

Sensitivity to initial conditions and early time evolution

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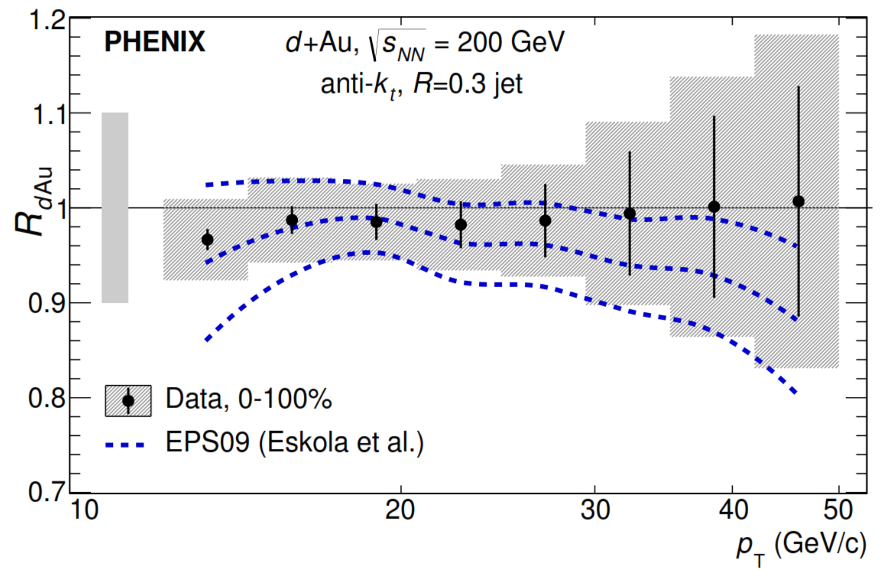
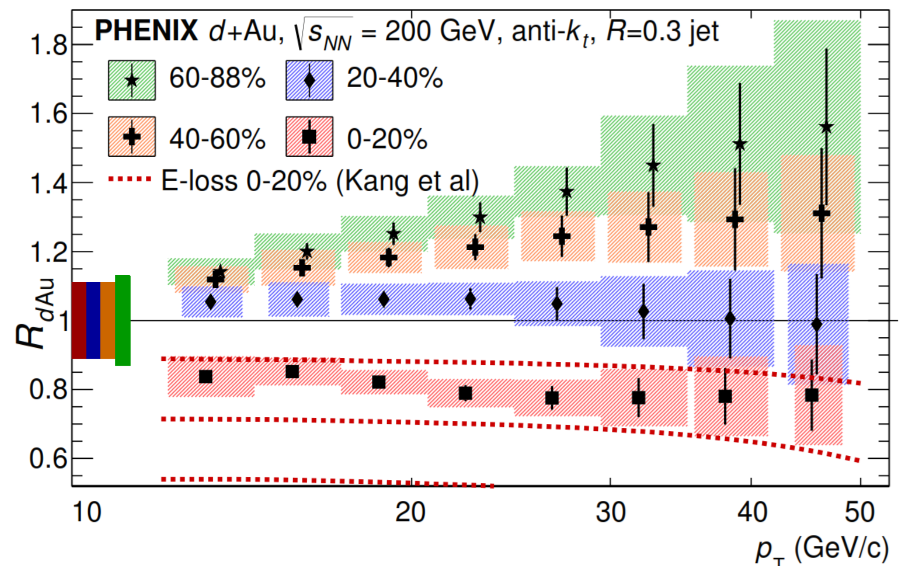
Jet Measurements in d+Au

PHENIX: arXiv 1509.04657 (2015)

- **Jet reconstruction in p+p and d+Au**
  - $12 < p_T < 50$ GeV/s
- **$R_{dA} \sim 1$ for min.bias d+Au**
- **R_{dA} shows strong centrality dependence**
  - For central collisions jets are suppressed
  - For peripheral collisions jets are enhanced

No evidence for final state effects in jet measurements in d+Au





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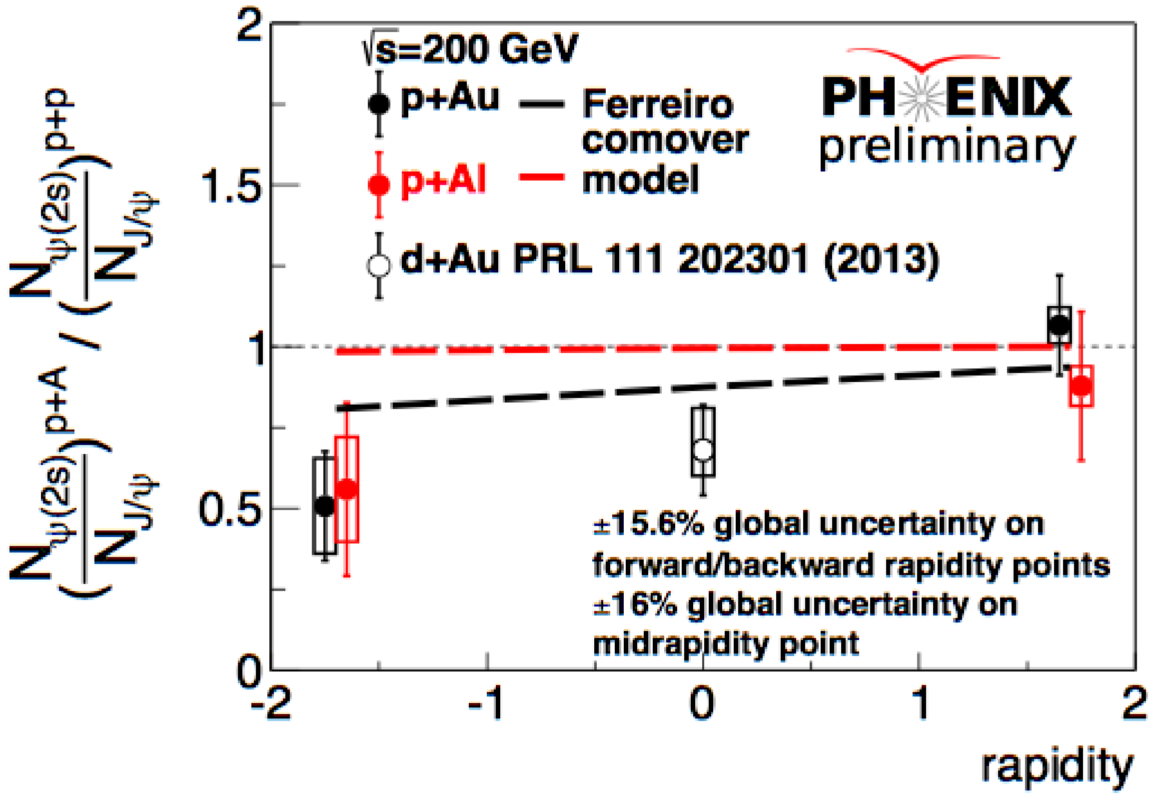
ψ(2S) Suppression in p+A Collisions



- **Strong suppression of ψ(2S) at backward rapidity in p+Au**
  - 50% suppression of double ratio to J/ψ in min.bias collisions

Evidence for final state effect in charmonium production in p+Au

Summary and Outlook

- **Large yield and large anisotropy (v2,v3) of direct photons**
  - **Challenges understanding of sources, rates and space-time evolution**
- **Final results on low mass dielectron continuum**
  - **Moderate enhancement consistent with broadening of ρ in medium**
- **Separate charm and bottom both are suppressed at high p_T**
  - **New constraints for theoretical models**
- **Strongly coupled matter created in central pA, dA, ^{3}HeA**
  - **New sensitive to initial state and early collision dynamics**
  - **No indication for jet energy loss**
  - **Evidence for final state effects in charmonium**
- **Outlook beyond QM2015**
  - **Many ongoing analysis**
  - **High statistics data sets Au+Au 2014, p+p 2015**
  - **Final run in 2016: high statistics Au+Au and d+Au energy scan**

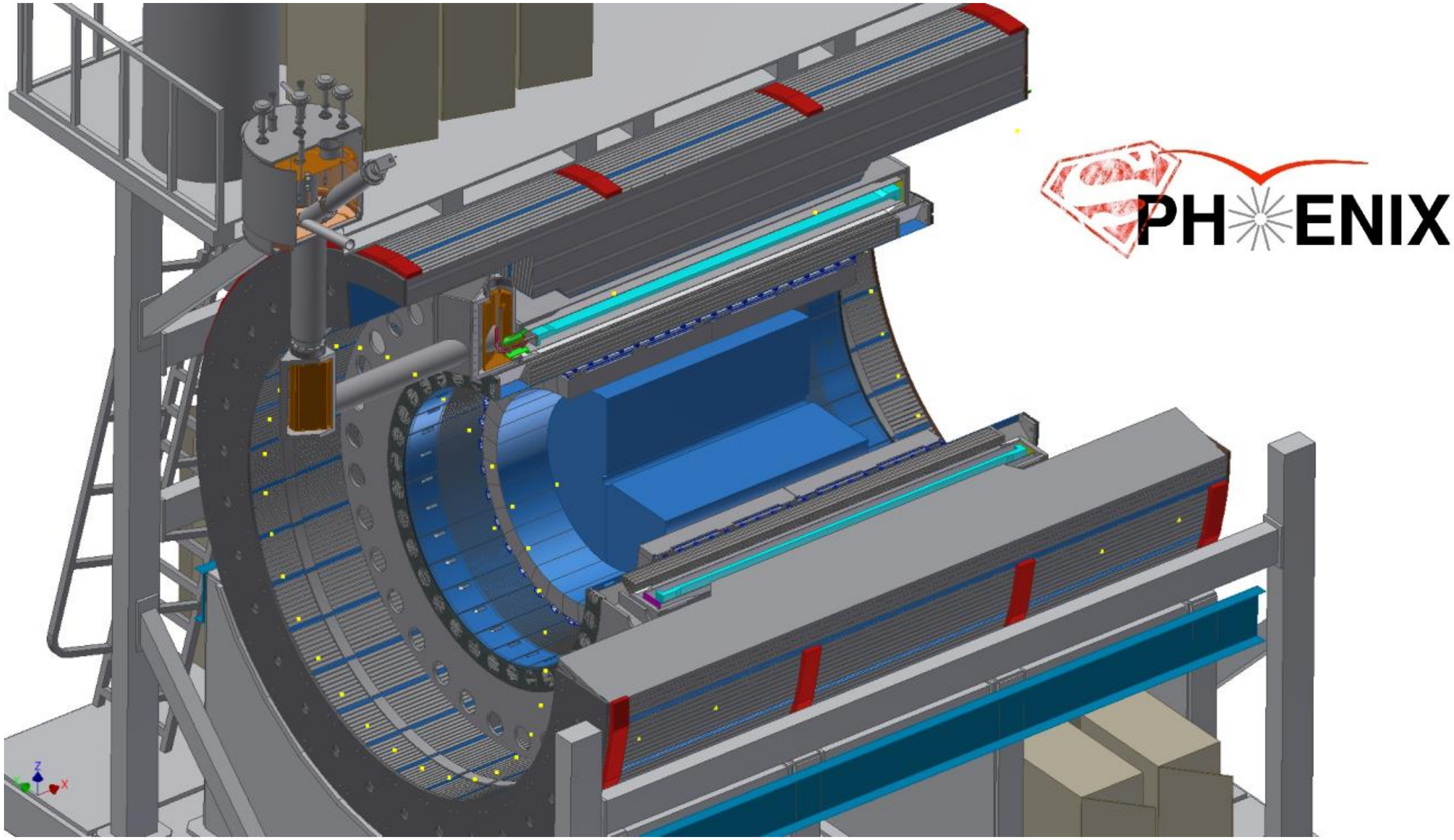
energy	Collision System							
GeV	U+U	Au+Au	Cu+Au	Cu+Cu	3He+Au	d+Au	p+Au	p+Al	p+p
500									x
200	x	x	x	x	x	x	x	x	x
130		x							
62.4		x		x		o			x
39		x				o			
27		x							
~20		x		x		o			
14.5		x							
7.7		x							

2014

2015

2016

A Large-Acceptance Jet and ϒ Detector for RHIC



- **Science case endorsed through Department of Energy review**
- **First constitutional collaboration meeting December 10-12, 2015 at Rutgers University, New Jersey, USA**

Backup

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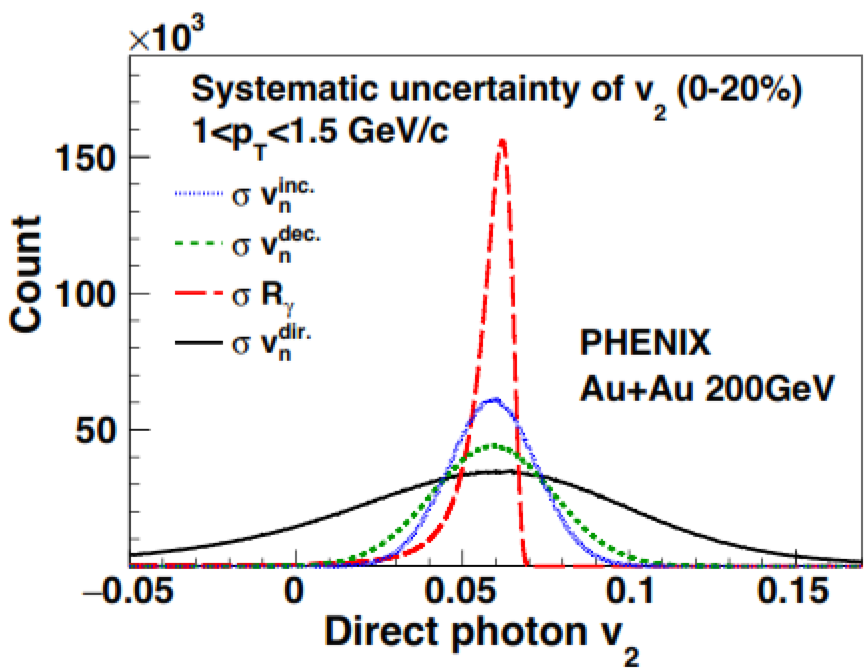
Systematic Uncertainties on v_n

$$\sigma^2_{v_n^{dir}} = \left(\frac{R_\gamma}{R_\gamma - 1}\right)^2 \times \sigma^2_{v_n^{inc}} + \left(\frac{1}{R_\gamma - 1}\right)^2 \times \sigma^2_{v_n^{dec}} + \left(\frac{v_n^{dec} - v_n^{inc}}{R_\gamma - 1}\right)^2 \times \sigma^2_{R_\gamma} + \sigma^2_{EP}$$

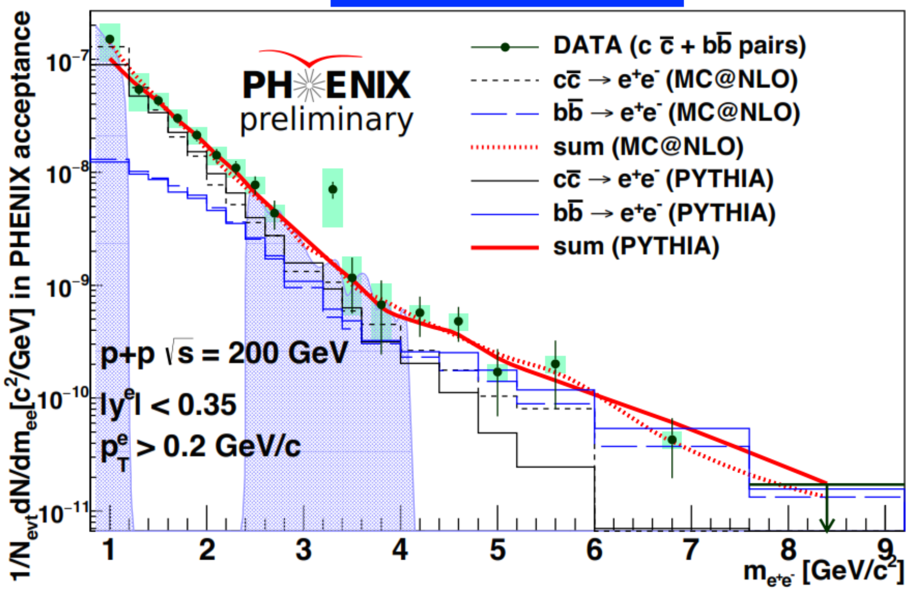
- Revisited systematic uncertainty calculation based on discussions with ALICE
- Non-linear dependence of uncertainty on R_γ
  - Asymmetric uncertainties
- Model probability distributions with MC

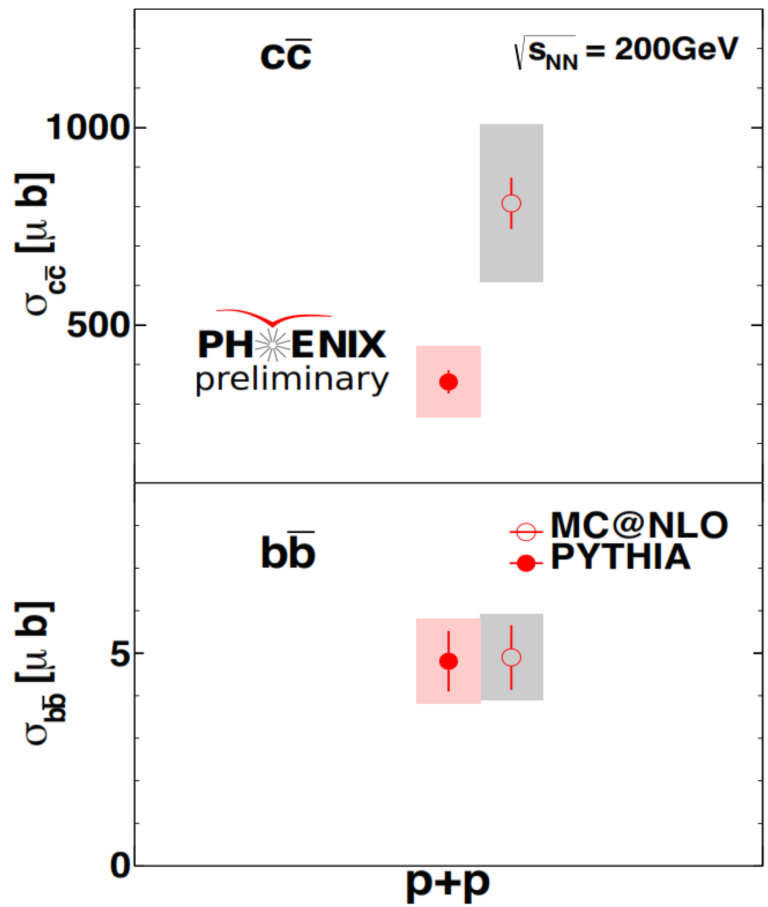


Source	0-20%	20-40%	40-60%	Type
R_γ (from [3])	5.5%	5.5%	5.5%	B
v_2^{inc} inclusive photons				
conversion method	<1%	<1%	<1%	B
calorimeter method	4%	3%	4%	B
v_2^{dec} decay photon				
meson v_2 (stat)	<1%	<1%	<1%	A
π^0 v_2 (sys)	5%	3%	2%	B
η, ω v_2 (sys)	<1%	<1%	<1%	B
Event plane	3%	3%	3%	C
v_3^{inc} inclusive photons				
conversion method	<1%	<1%	<1%	B
calorimeter method	5%	7%	10%	B
v_3^{dec} decay photon				
meson v_3 (stat)	1%	2%	4%	A
π^0 v_3 (sys)	11%	11%	11%	B
η, ω v_3 (sys)	$\sim$ 1%	$\sim$1%	$\sim$1%	B
Event plane	6%	7%	18%	C

Model Dependence of Heavy Flavor

Mass spectra





Comparison to previous PHENIX analysis

- **Hadron contamination:** was 30%, now 5% in MB
- **Signal sensitivity:** a factor of ~3.5 improvement in 0.15-0.75 GeV/c^2
- **Pair cuts:** now stronger pair cuts fully remove detector correlations
- **Flow:** now included in the shape of the mixed BG
- **e-h pairs:** now subtracted
- **Jets:** oposite jets component now explicitly subtracted
- **Background subtraction:** all correlated components calculated and subtracted on absoulte terms

Dilepton Enhancement

TABLE IX: The enhancement factor, defined as the ratio between the measured yield and the expected yield for $0.15 < m_{ee} < 0.75$ GeV/c^2, for different centrality bins. The meaning of the errors is defined in the text.

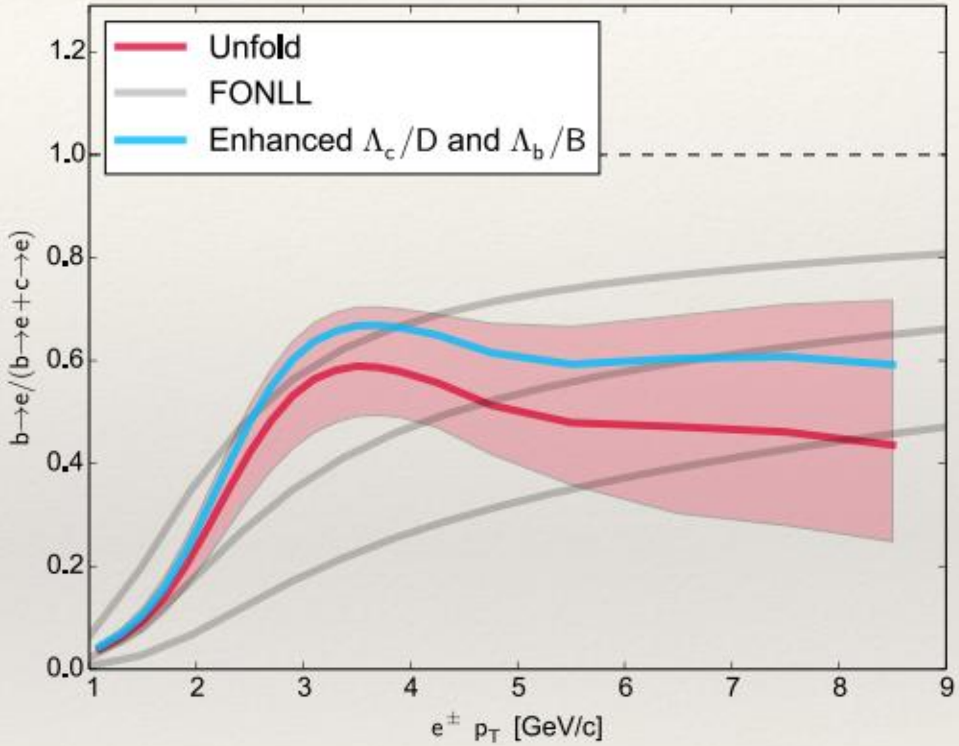
Centrality	Enhancement (±stat ±syst ±model)
00-10 %	7.6 ± 0.5 ± 1.5 ± 1.5
10-20 %	3.2 ± 0.4 ± 0.1 ± 0.6
20-40 %	1.4 ± 1.3 ± 0.02 ± 0.3
40-60 %	0.8 ± 0.3 ± 0.03 ± 0.2
60-92 %	1.5 ± 0.3 ± 0.001 ± 0.3
Min. Bias	4.7 ± 0.4 ± 1.5 ± 0.9

TABLE VIII. Enhancement factors, defined as the ratio of measured over expected dilepton yield in the mass region m_{ee} = 0.30–0.76 GeV/c^2, for the five centrality bins and for MB. The enhancement factors are quoted separately for the two cases where the correlated yield from $c\bar{c}$ decays is calculated with PYTHIA or MC@NLO. The ±model uncertainties represent the cocktail systematic uncertainties.

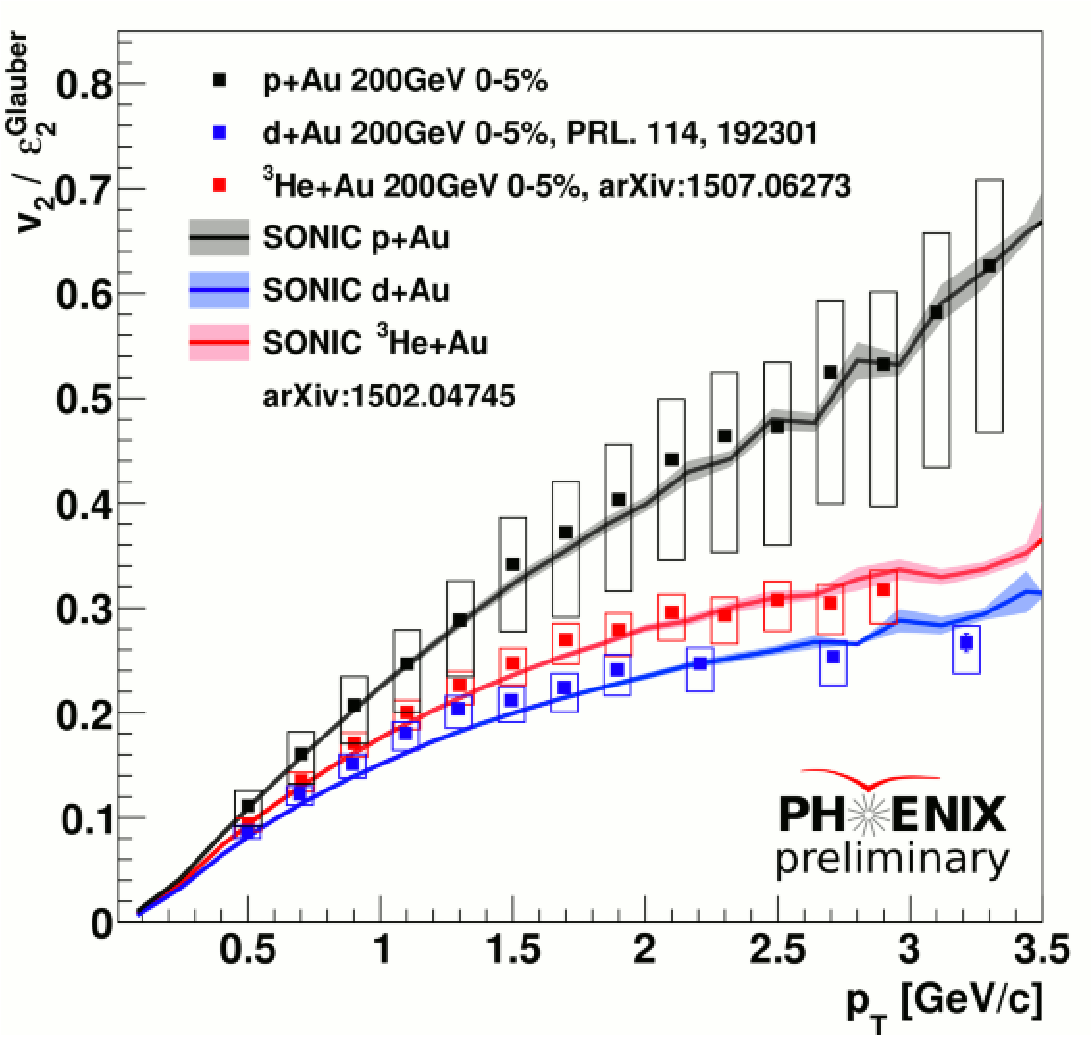
Centrality	Enhancement factor ±stat ±syst ±model	
	MC@NLO $c\bar{c}$	PYTHIA $c\bar{c}$
MB	1.7 ±0.3 ±0.3 ±0.2	2.3 ±0.4 ±0.4 ±0.2
0%–10%	2.3 ±0.7 ±0.5 ±0.2	3.2 ±1.0 ±0.7±0.2
10%–20%	1.3 ±0.4 ±0.5 ±0.2	1.8 ±0.6 ±0.7 ±0.2
20%–40%	1.4 ±0.2 ±0.3 ±0.2	1.8 ±0.3 ±0.4 ±0.2
40%–60%	1.2 ±0.2 ±0.3 ±0.2	1.6 ±0.2 ±0.4 ±0.2
60%–92%	1.0 ±0.1 ±0.2 ±0.2	1.4 ±0.2 ±0.3 ±0.2

Testing Possible Baryon Enhancement II

- Including above enhancement causes an increase in the bottom electron fraction.
- Within systematic uncertainties of the measurement.
- Not included as an additional uncertainty.



Small Systems



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PHENIX