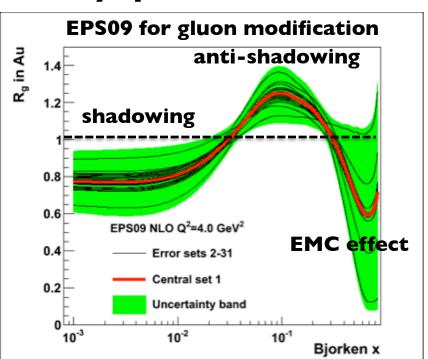**PHENIX measurements of open and hidden heavy-flavor in p+p, p+Al, and p/d/³He+Au collisions across a wide range of rapidity**

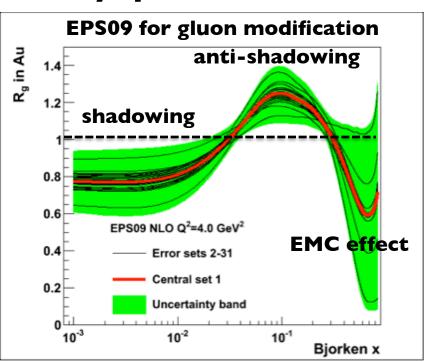**Sanghoon Lim**

for the PHENIX collaboration

Los Alamos National Lab

Heavy quarks can be sensitive to various effects:

EPS09 for gluon modification

anti-shadowing

shadowing

EMC effect

EPS09 NLO $Q^2=4.0$ GeV^2

— Error sets 2-31

— Central set 1

Uncertainty band

Parton distribution functions in nuclei are modified compared to those in nucleon

Heavy quarks can be sensitive to various effects:

EPS09 for gluon modification

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EMC effect

EPS09 NLO Q^2=4.0 GeV^2
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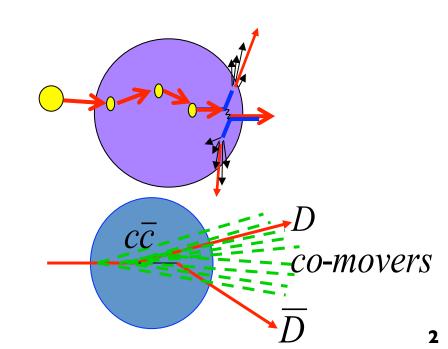
R_g in Au

Bjorken x

Parton distribution functions in nuclei are modified compared to those in nucleon
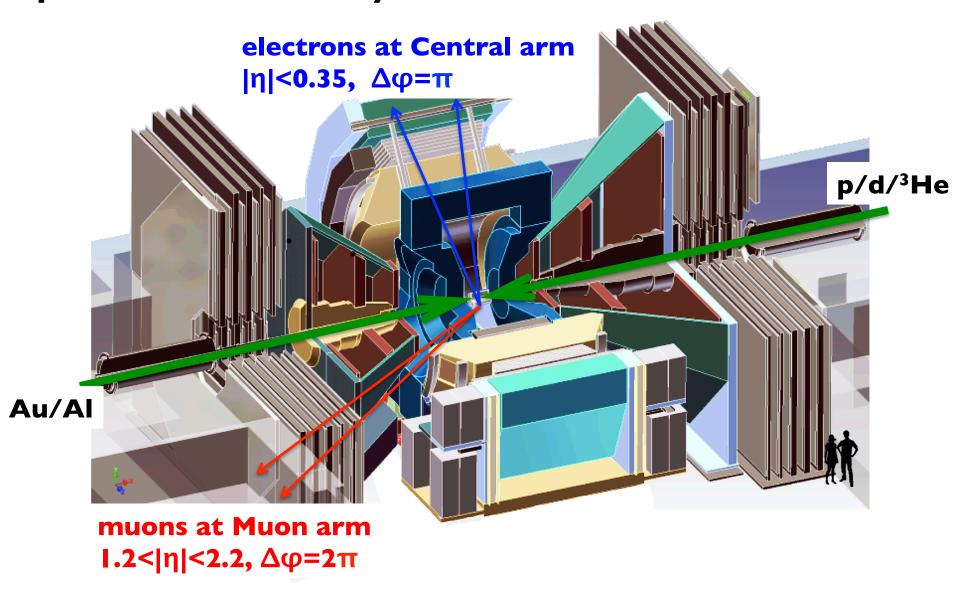
Scattering with nuclear matter:
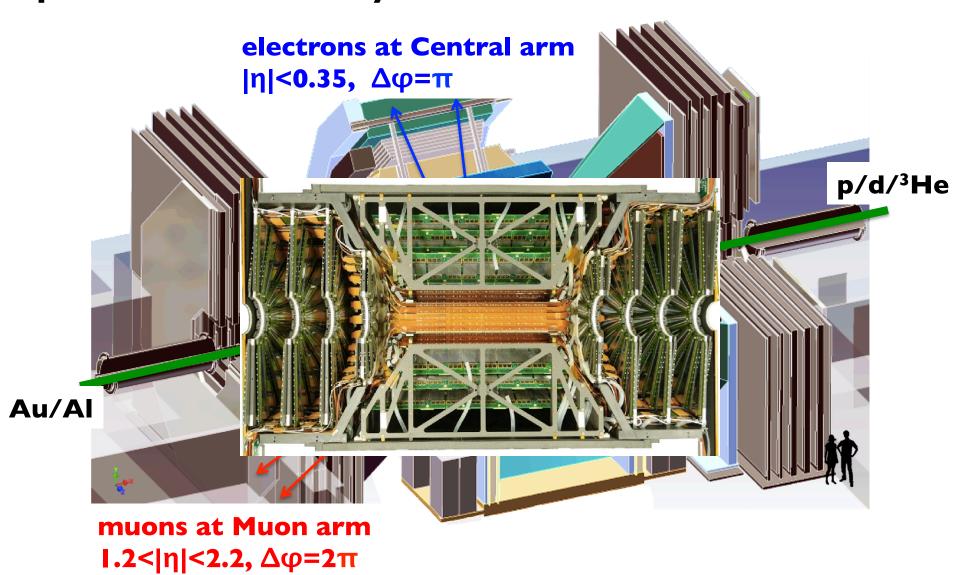(Initial-state and/or final-state interaction)
- **transverse momentum broadening**
- **energy loss**
- **break-up of bound states**

$c\bar{c}$

D

co-movers

$\overline{D}$

Open and hidden heavy-flavor measurements at PHENIX

electrons at Central arm
|η|<0.35, Δφ=π

p/d/³He

Au/Al

muons at Muon arm
1.2<|η|<2.2, Δφ=2π

Open and hidden heavy-flavor measurements at PHENIX

electrons at Central arm
$|\eta|<0.35$, $\Delta\varphi=\pi$

p/d/^{3}He

Au/Al

muons at Muon arm
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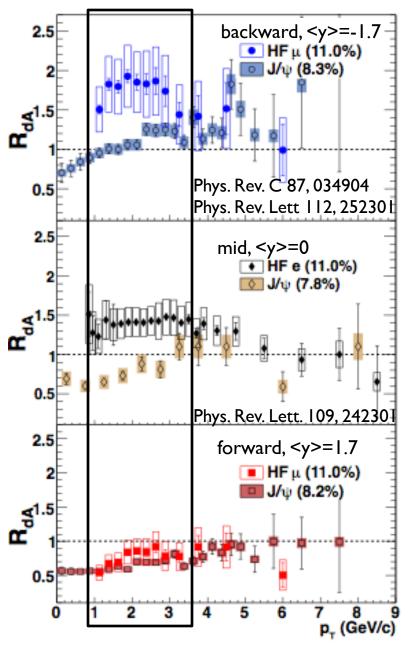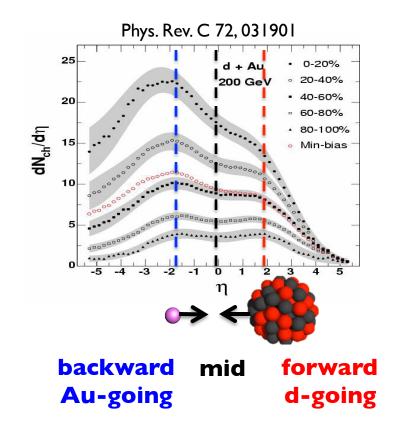
VTX and FVTX provide precise tracking/vertex

Previous results: J/ψ and open heavy-flavor in d+Au

Phys. Rev. C 87, 034904
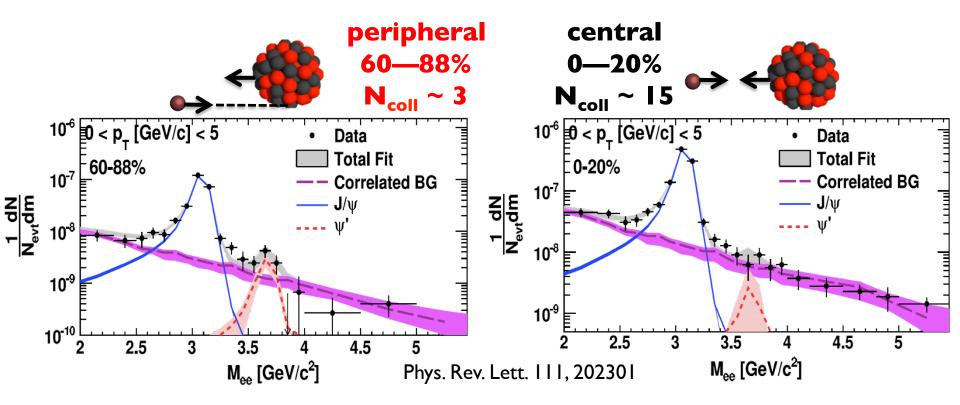Phys. Rev. Lett 112, 25230

Phys. Rev. Lett. 109, 242301

- In **0-20% central** d+Au collisions
  - R_{dA} of HF muon and J/ψ are similar at forward rapidity
  - **charm production is enhanced but J/ψ production is significantly suppressed** at mid- and backward rapidity
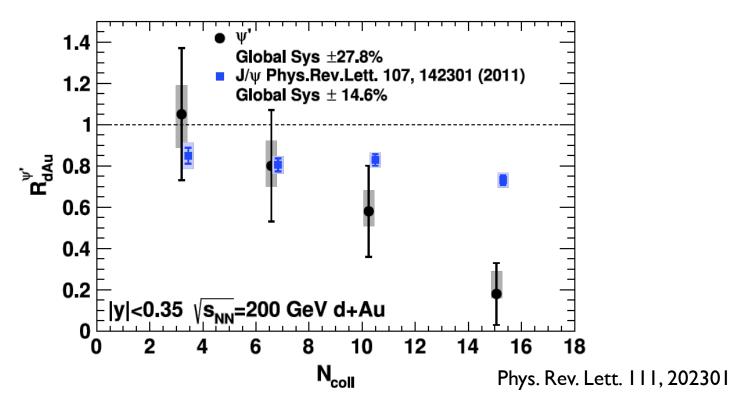

Phys. Rev. C 72, 031901

backward **mid** **forward**
Au-going   **d-going**

Open & hidden heavy-flavor in PHENIX

Previous results: ψ(2S) in d+Au at mid-rapidity

peripheral
60—88%
$N_{coll} \sim 3$

central
0—20%
$N_{coll} \sim 15$

Phys. Rev. Lett. 111, 202301

Previous results: ψ(2S) in d+Au at mid-rapidity
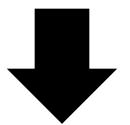

Phys. Rev. Lett. 111, 202301
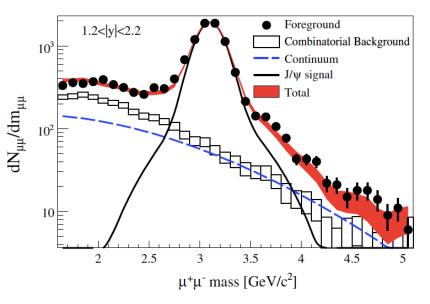
- **Breakup of quarkonia due to interaction with nuclear matter**
  - **Larger suppression of the weakly bound state ψ(2S)**
  - **Interaction with
    co-movers? (model: Phys. Lett. B 749 (2015))
    medium? (model: Nucl. Phys. A 943 (2015))**
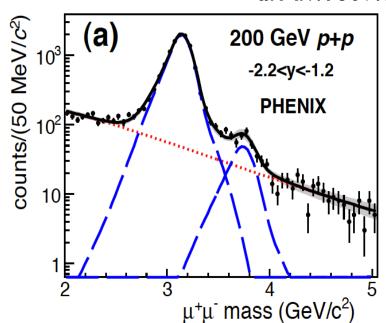
ψ(2S) extraction with FVTX
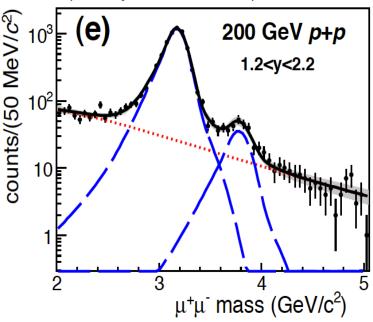

MuTr only
Phys. Rev. D 85, 092004

**Resolve ψ(2S)
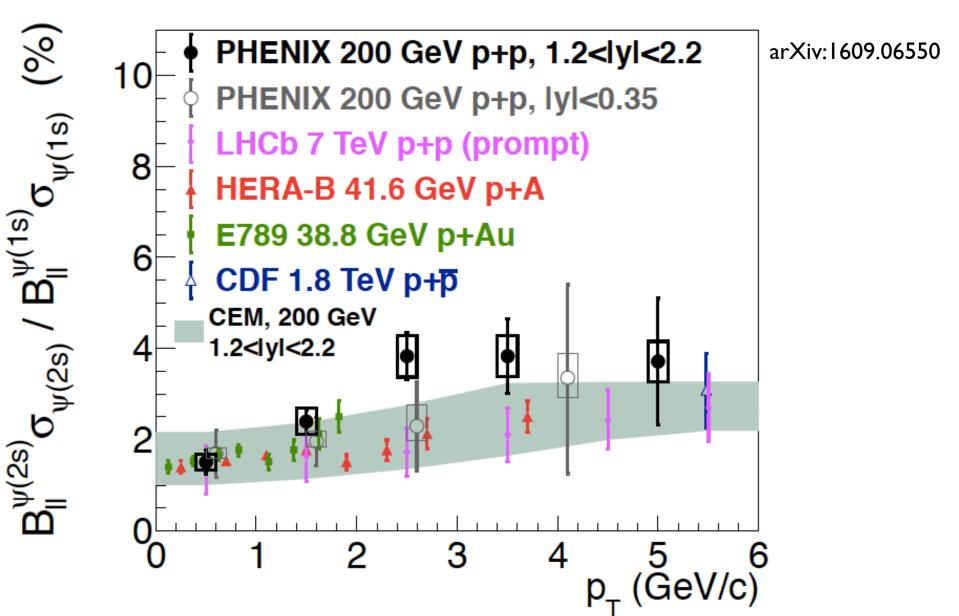by measuring opening angle
in front of absorber**
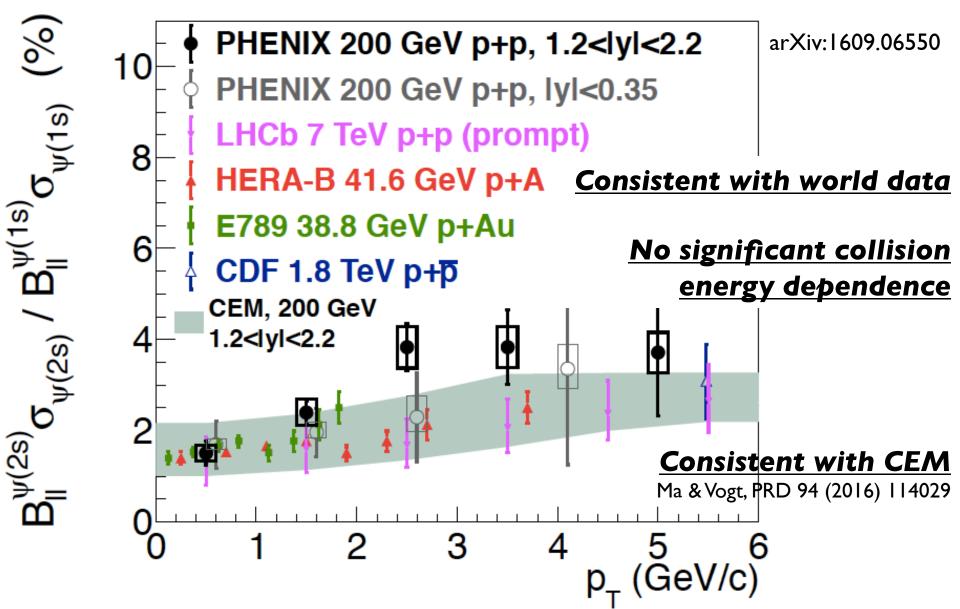
FVTX+MuTr
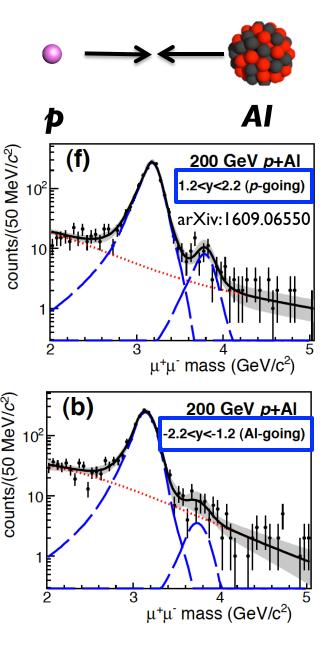arXiv:1609.06550 (accepted in PRC)

ψ(2S)/ψ(1S) in p+p
compared with model and other results

arXiv:1609.06550

ψ(2S)/ψ(1S) in p+p
compared with model and other results

arXiv:1609.06550

Consistent with world data

No significant collision energy dependence

Consistent with CEM
Ma & Vogt, PRD 94 (2016) 114029

ψ(2S) at forward/backward in small systems

p   Al

(f) 200 GeV p+Al
1.2<y<2.2 (p-going)
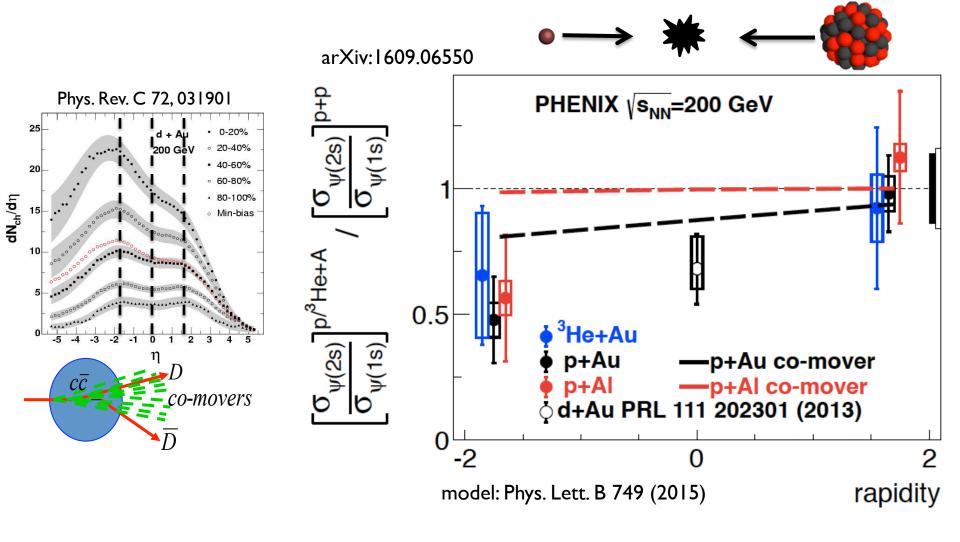arXiv:1609.06550

(b) 200 GeV p+Al
-2.2<y<-1.2 (Al-going)

ψ(2S) at forward/backward in small systems
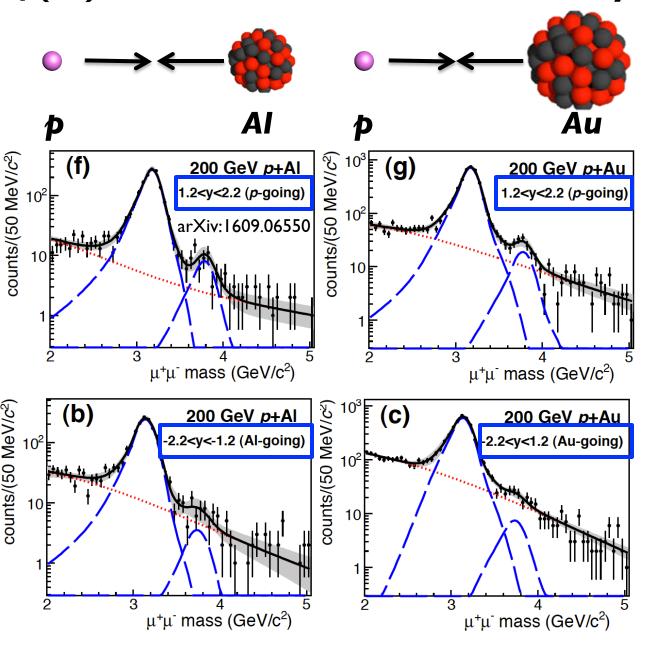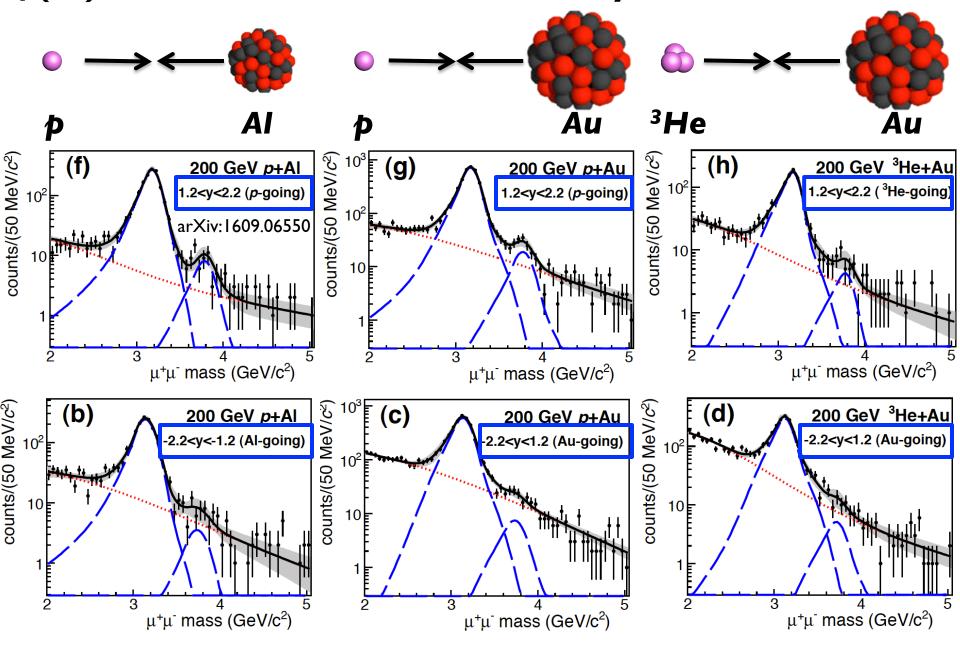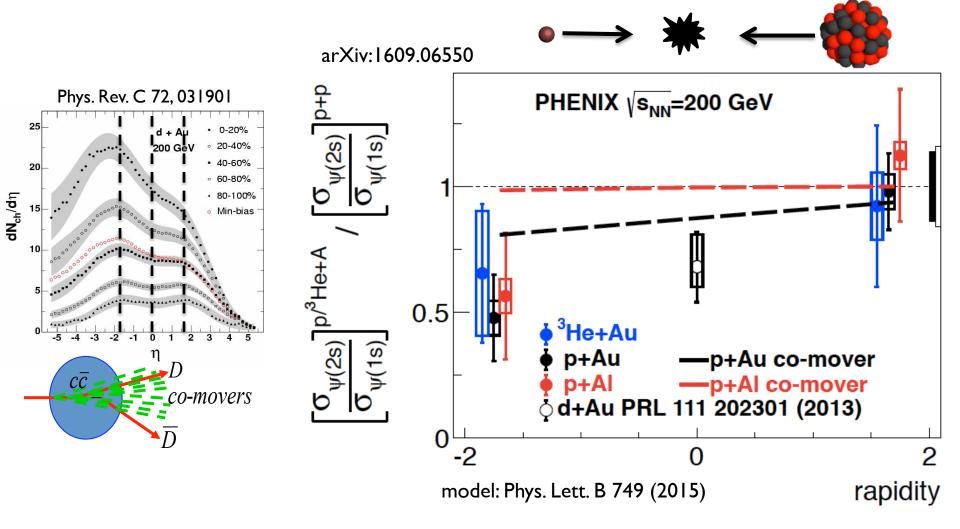
ψ(2S) at forward/backward in small systems

ψ(2S), more easily broken up

Phys. Rev. C 72, 031901

arXiv:1609.06550

model: Phys. Lett. B 749 (2015)

ψ(2S), more easily broken up

Phys. Rev. C 72, 031901

arXiv:1609.06550

$$\left[\frac{\sigma_{\psi(2s)}}{\sigma_{\psi(1s)}}\right]^{p/^3\text{He}+A} \Bigg/ \left[\frac{\sigma_{\psi(2s)}}{\sigma_{\psi(1s)}}\right]^{p+p}$$

PHENIX $\sqrt{s_{NN}}$=200 GeV

^{3}He+Au
p+Au
p+Al
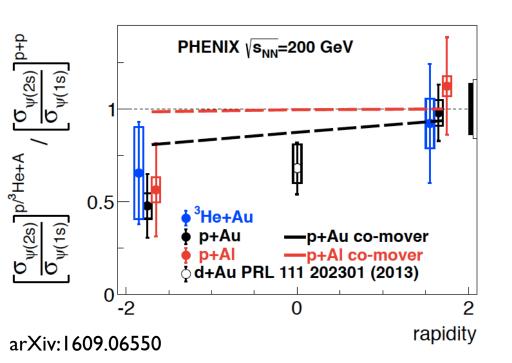d+Au PRL 111 202301 (2013)

p+Au co-mover
p+Al co-mover

model: Phys. Lett. B 749 (2015)
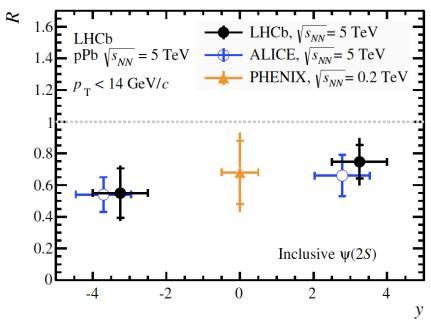
rapidity

**The co-mover dissociation model predicts
a larger suppression of ψ(2S) at nucleus-going direction,
but underestimate the magnitude.**

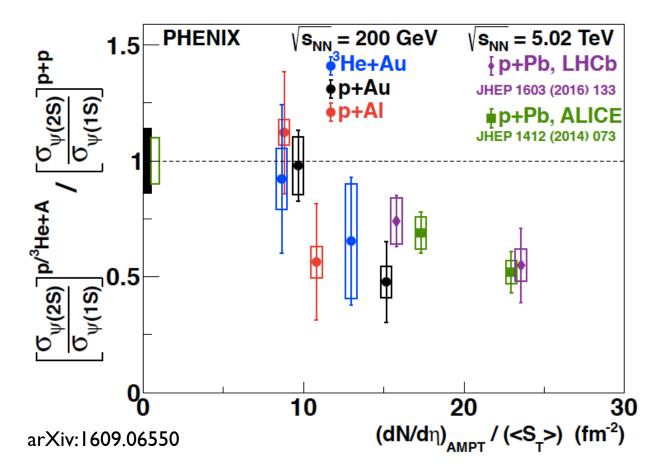# Comparison to LHC

PHENIX $\sqrt{s_{NN}}$=200 GeV

- ^{3}He+Au
- p+Au
- p+Al
- p+Au co-mover
- p+Al co-mover
- d+Au PRL 111 202301 (2013)

arXiv:1609.06550

LHCb pPb $\sqrt{s_{NN}}$ = 5 TeV
$p_T < 14$ GeV/c

- LHCb, $\sqrt{s_{NN}}$= 5 TeV
- ALICE, $\sqrt{s_{NN}}$= 5 TeV
- PHENIX, $\sqrt{s_{NN}}$= 0.2 TeV

Inclusive $\psi(2S)$

Similar relative suppression of ψ(2S) at backward rapidity, but larger relative suppression of ψ(2S) at forward rapidity at LHC
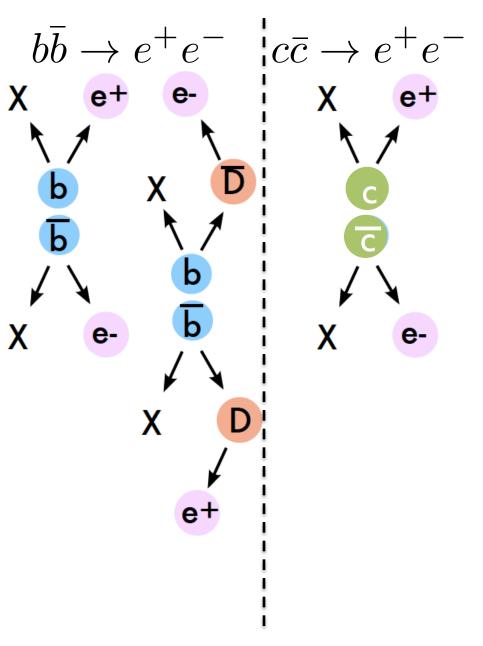
Comparison to LHC

arXiv:1609.06550

Similar relative suppression of ψ(2S) at backward rapidity, but larger relative suppression of ψ(2S) at forward rapidity at LHC
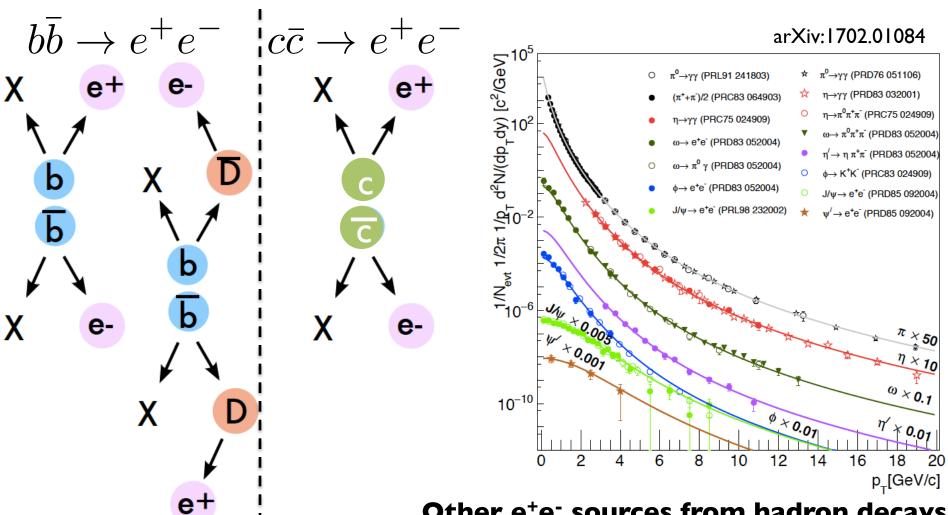
Relative suppression of ψ(2S) increases as the co-moving particle density increases

Open heavy-flavor via **di-electrons** at mid-rapidity
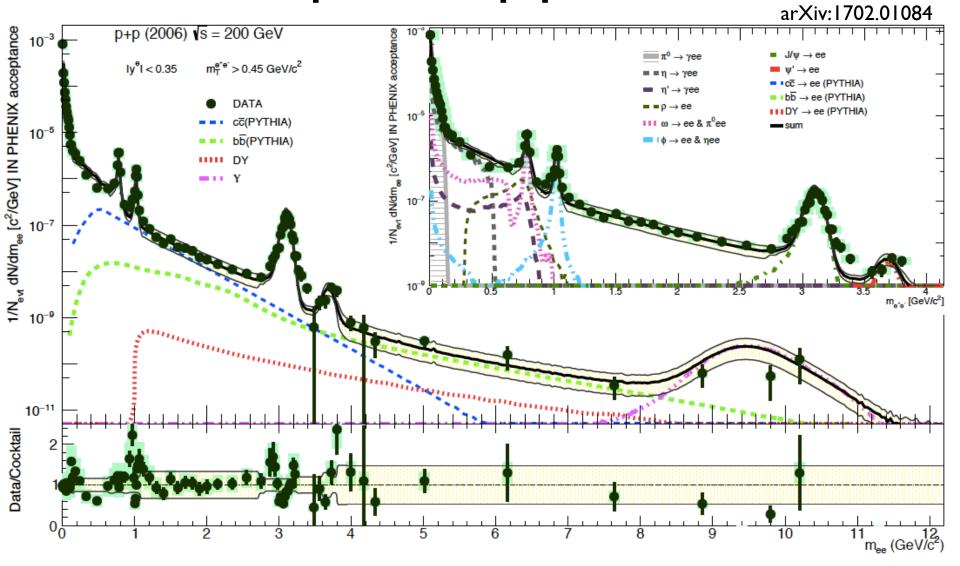
Open heavy-flavor via di-electrons at mid-rapidity

$$b\bar{b} \rightarrow e^+ e^- \quad c\bar{c} \rightarrow e^+ e^-$$

Open heavy-flavor via di-electrons at mid-rapidity

$$b\bar{b} \rightarrow e^+ e^- \quad | \quad c\bar{c} \rightarrow e^+ e^-$$
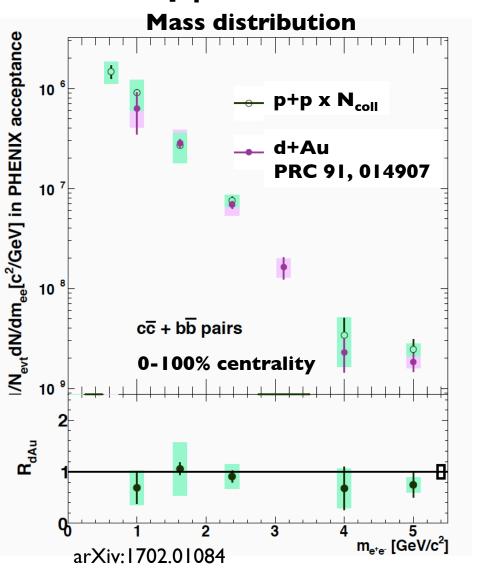

arXiv:1702.01084

Other e⁺e⁻ sources from hadron decays (vector meson and pseudoscalar meson) deduced from hadron measurements, and Drell-Yan from PYTHIA
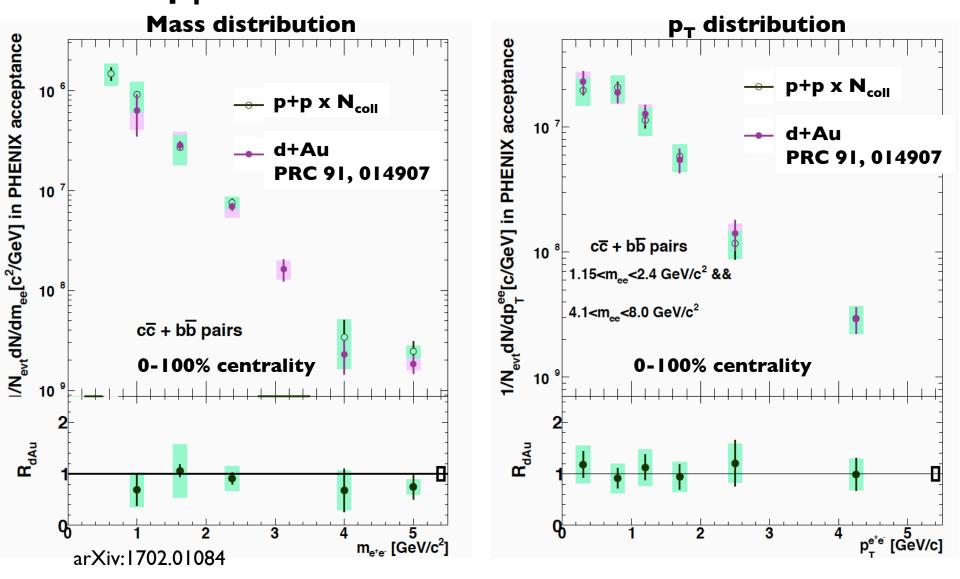
Di-electron mass spectrum in p+p

The cocktail including heavy-flavor contribution describes the data well
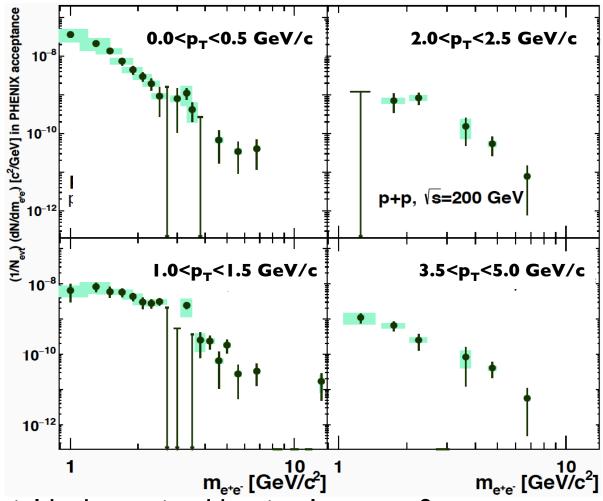
Mass and p_T distribution of di-electrons from HF

Mass distribution

arXiv:1702.01084

Mass and p_T distribution of di-electrons from HF

Mass distribution   **p_T distribution**

arXiv:1702.01084

No significant modification of di-electrons from heavy-flavor in d+Au collisions compared to p+p

Separation of charm and bottom components in mass and p_T

Fit Range
$1.15 < m_{ee} < 2.4$ GeV/c^2
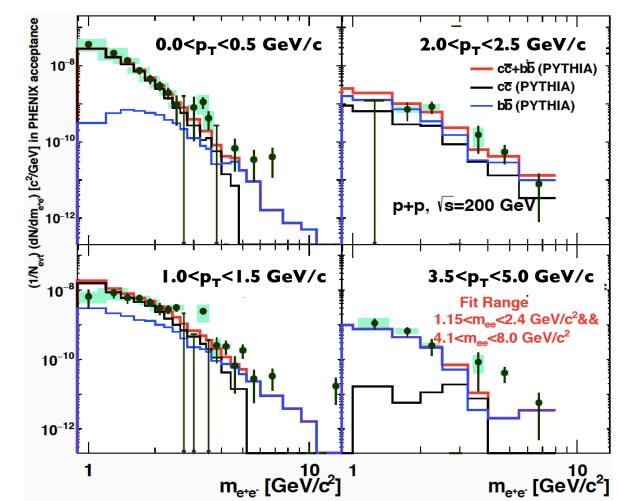**$4.1 < m_{ee} < 8.0$ GeV/c^2**

- Open charm and bottom yields determined by simultaneous fit in mass and p_T distributions

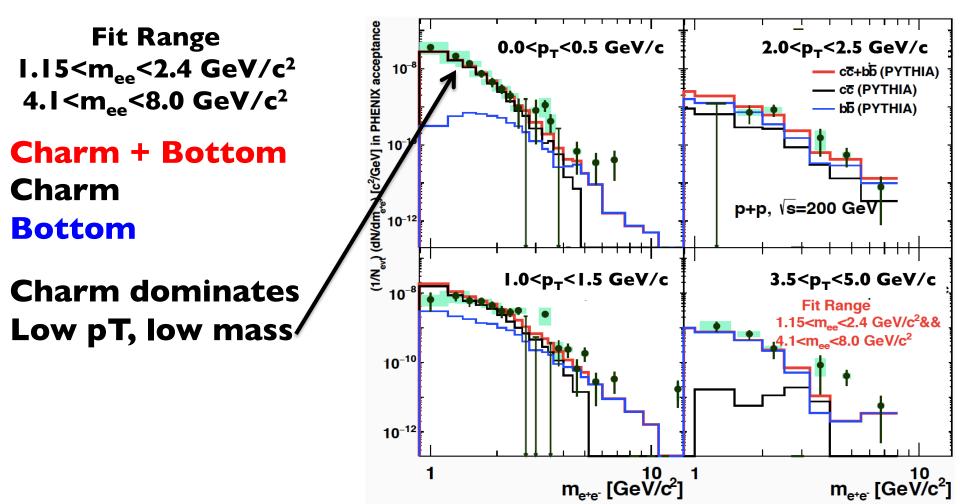# Separation of charm and bottom components in mass and p_T

Fit Range
$1.15 < m_{ee} < 2.4$ GeV/c^2
$4.1 < m_{ee} < 8.0$ GeV/c^2

Charm + Bottom
Charm
Bottom

- Open charm and bottom yields determined by simultaneous fit in mass and p_T distributions

- Three independent extractions based on different models: PYTHIA / MC@NLO / POWHEG

Open & hidden heavy-flavor in PHENIX

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Separation of charm and bottom components in mass and p_T

Fit Range
$1.15 < m_{ee} < 2.4$ GeV/c^2
$4.1 < m_{ee} < 8.0$ GeV/c^2

Charm + Bottom
Charm
Bottom

**Charm dominates
Low pT, low mass**

- Open charm and bottom yields determined by simultaneous fit in mass and p_T distributions

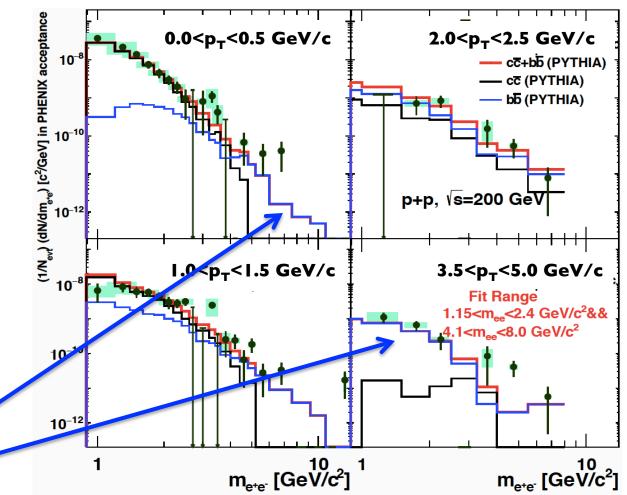- Three independent extractions based on different models: PYTHIA / MC@NLO / POWHEG

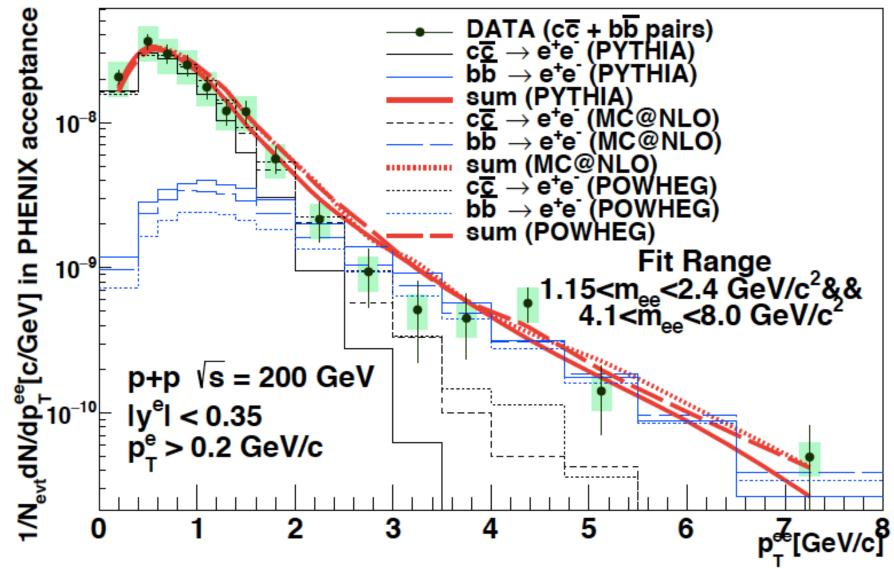# Separation of charm and bottom components in mass and p_T

Fit Range
$1.15 < m_{ee} < 2.4$ GeV/c²
$4.1 < m_{ee} < 8.0$ GeV/c²

Charm + Bottom
Charm
Bottom

Charm dominates
Low pT, low mass

Bottom dominates
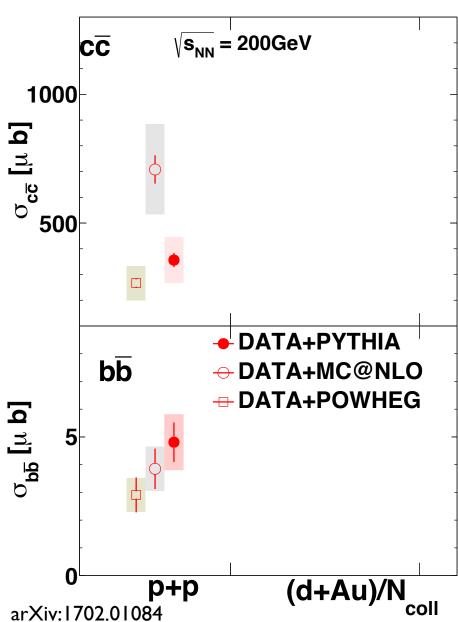**Low p_T, high mass**
High p_T

- Open charm and bottom yields determined by simultaneous fit in mass and p_T distributions

- Three independent extractions based on different models: PYTHIA / MC@NLO / POWHEG

arXiv:1702.01084
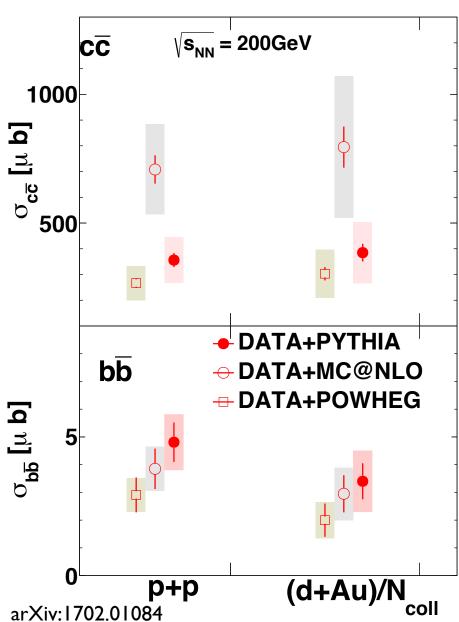
Spectra are well reproduced by fit with all models

Model based extrapolation of charm and bottom cross section and R_dA

Extrapolated charm cross section depends more strongly on model than bottom

→decay kinematics randomize the opening angle for bottom ($m_q >> p$)
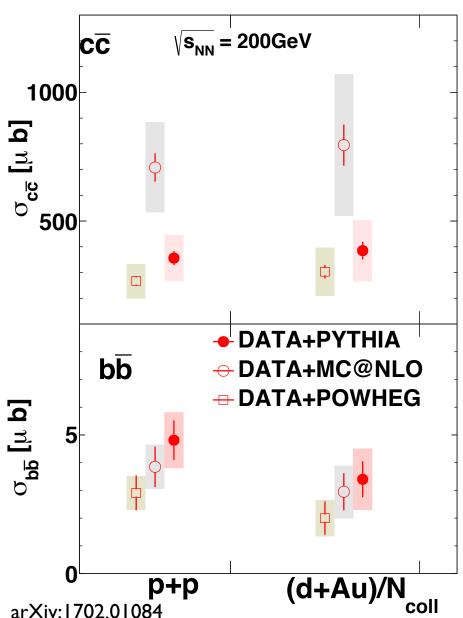
arXiv:1702.01084

Model based extrapolation of charm and bottom cross section and R$_{dA}$

Extrapolated charm cross section depends more strongly on model than bottom

→decay kinematics randomize the opening angle for bottom (m$_q$>>p)

arXiv:1702.01084

Open & hidden heavy-flavor in PHENIX

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Model based extrapolation of charm and bottom cross section and R_{dA}

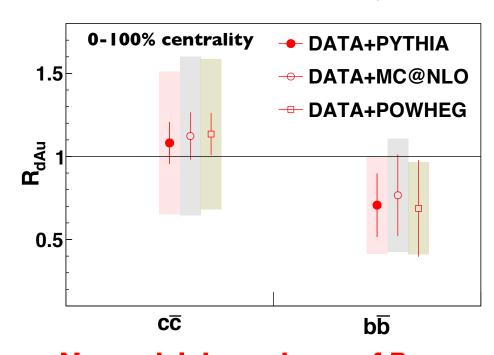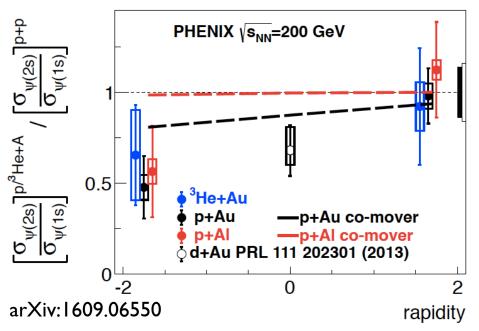**Extrapolated charm cross section depends more strongly on model than bottom**

→decay kinematics randomize the opening angle for bottom ($m_q >> p$)

No model dependence of R_{dA}
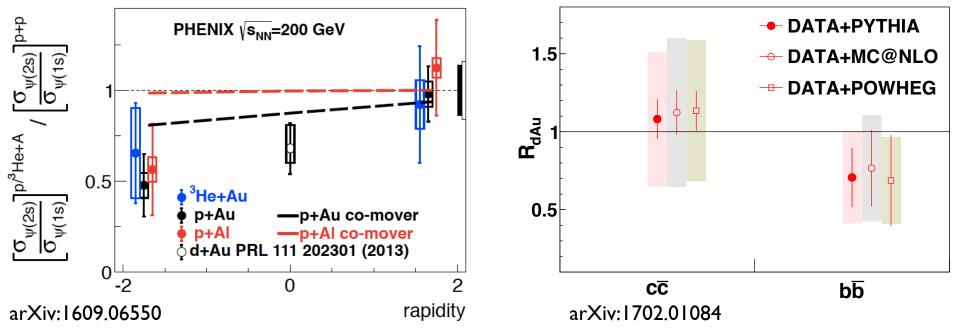**No significant modification in d+Au within uncertainties**

arXiv:1702.01084

Summary & outlook

- **Open and hidden heavy-flavor measurements in small systems**

arXiv:1609.06550

- **Preferential suppression of ψ(2S) at backward rapidity (Nucleus-going direction)**
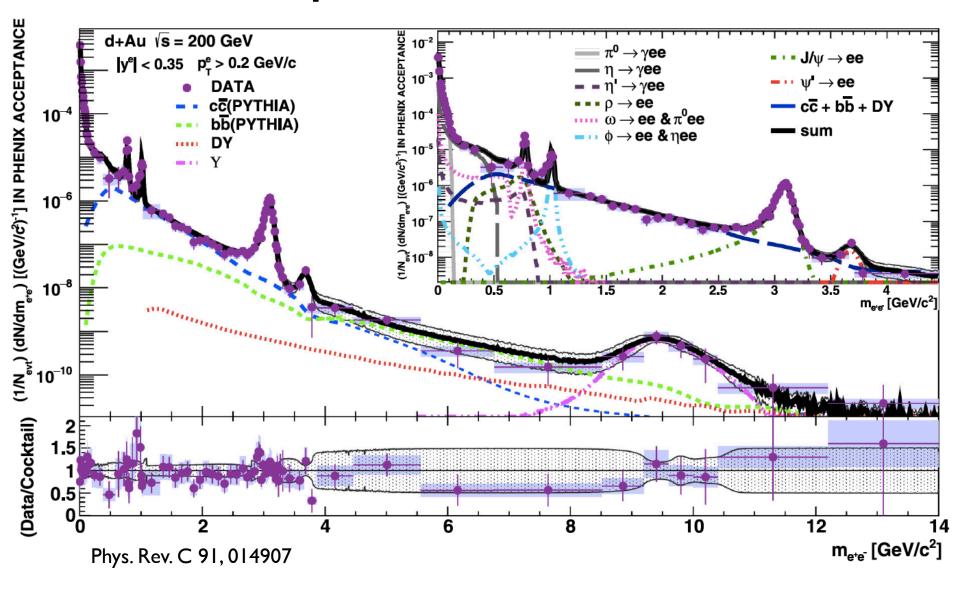 - Inclusive J/ψ, Upsilon, and single lepton results in future

Summary & outlook

- **Open and hidden heavy-flavor measurements in small systems**
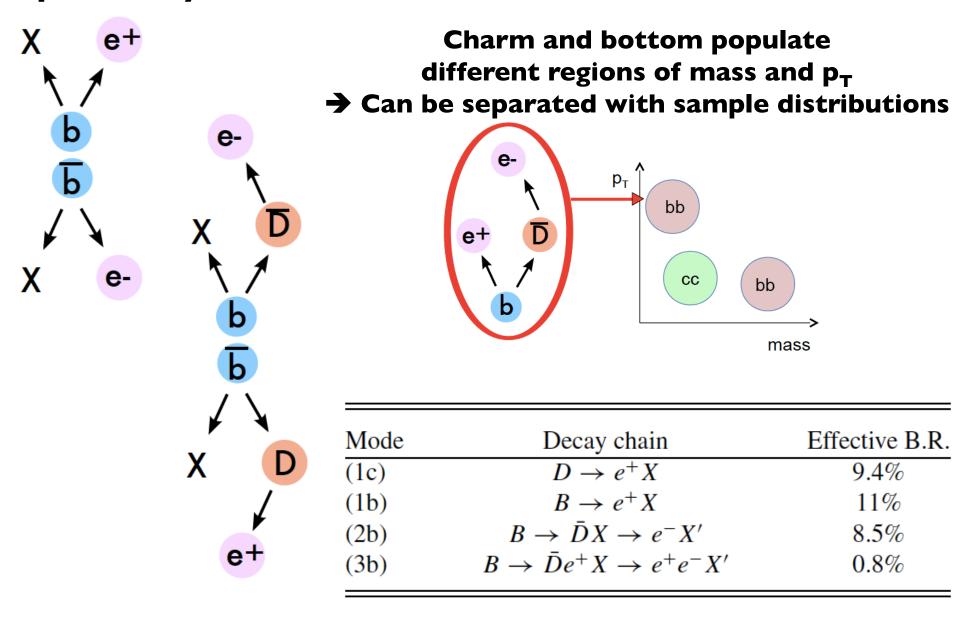

arXiv:1609.06550

arXiv:1702.01084

- **Preferential suppression of ψ(2S) at backward rapidity (Nucleus-going direction)**
  - Inclusive J/ψ, Upsilon, and single lepton results in future

- **Within uncertainties, no evidence of modification of charm and bottom production via di-electrons at mid-rapidity in d+Au**
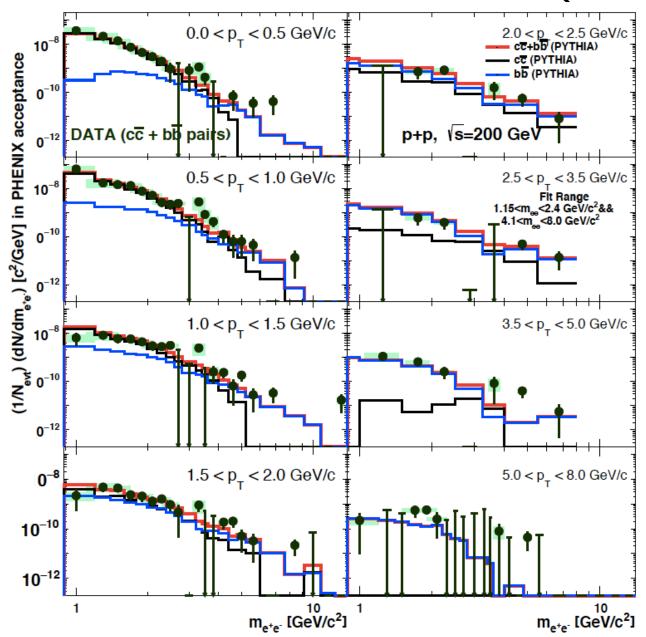 - Di-muon results at forward/backward rapidity in future

BACK UP
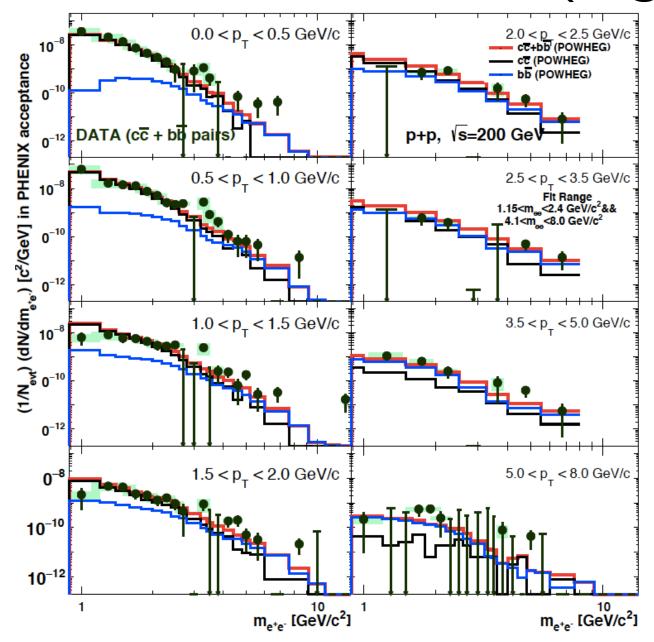
Di-electron mass spectrum in d+Au

Phys. Rev. C 91, 014907

Open heavy-flavor via di-electron

Charm and bottom populate different regions of mass and p_T
➔ Can be separated with sample distributions

Mode	Decay chain	Effective B.R.
(1c)	$D \rightarrow e^+ X$	9.4%
(1b)	$B \rightarrow e^+ X$	11%
(2b)	$B \rightarrow \bar{D} X \rightarrow e^- X'$	8.5%
(3b)	$B \rightarrow \bar{D} e^+ X \rightarrow e^+ e^- X'$	0.8%

Separation of e⁺e⁻ from charm and bottom (PYTHIA)

Separation of e⁺e⁻ from charm and bottom (MC@NLO)

Separation of e⁺e⁻ from charm and bottom (POWHEG)