Recent Heavy Flavor Measurements from PHENIX at RHIC

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Outline

- **Introduction & Motivation**
- RHIC & The PHENIX Detectors
- Featured Results
  - Charm and bottom production via single electrons from semi-leptonic D and B meson decays produced in *Au+Au* collisions at $\sqrt{s_{NN}}$ = 200 GeV - **Phys. Rev. C 93, 034904 (2016)**
  - Studying heavy flavor production ($\sigma_{b\bar{b}}$ & $\sigma_{c\bar{c}}$) via e^+e^- in *p+p* & *d+Au* collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - Study of $\sigma_{b\bar{b}}$ via $\mu^\pm\mu^\pm$ in *p+p* collisions at $\sqrt{s}$ = 500 GeV utilizing B^0 oscillation

Preliminary Results

- Summary & Outlook

Motivation: The Quark Gluon Plasma!

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- Believed to exist at the beginning of the universe micro-seconds after the Big Bang
- Hot, dense and strongly interacting medium that consists of "free" quarks and gluons
- Matter created in heavy ion collisions that is short lived (~7 fm/c) at T ~ 4 x 10^{12} K

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- Matter created in heavy ion collisions that is short lived (~7 fm/c) at $T \sim 4 \times 10^{12}$ K

It is important to quantify QGP properties!

How do we quantify QGP properties?

- Observables/Probes
  - Particle Flow → Study bulk properties
  - Jets → Study energy loss
  - Quarkonia → Study medium temperature
  - Low Mass Vector Mesons
  - **Open Heavy Flavor** → Study medium density

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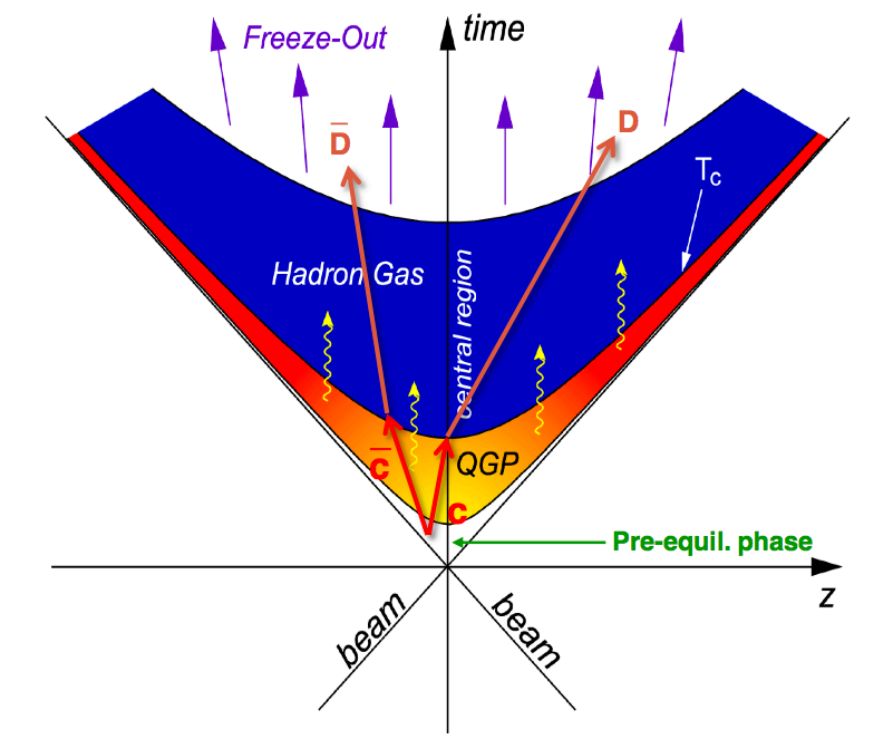
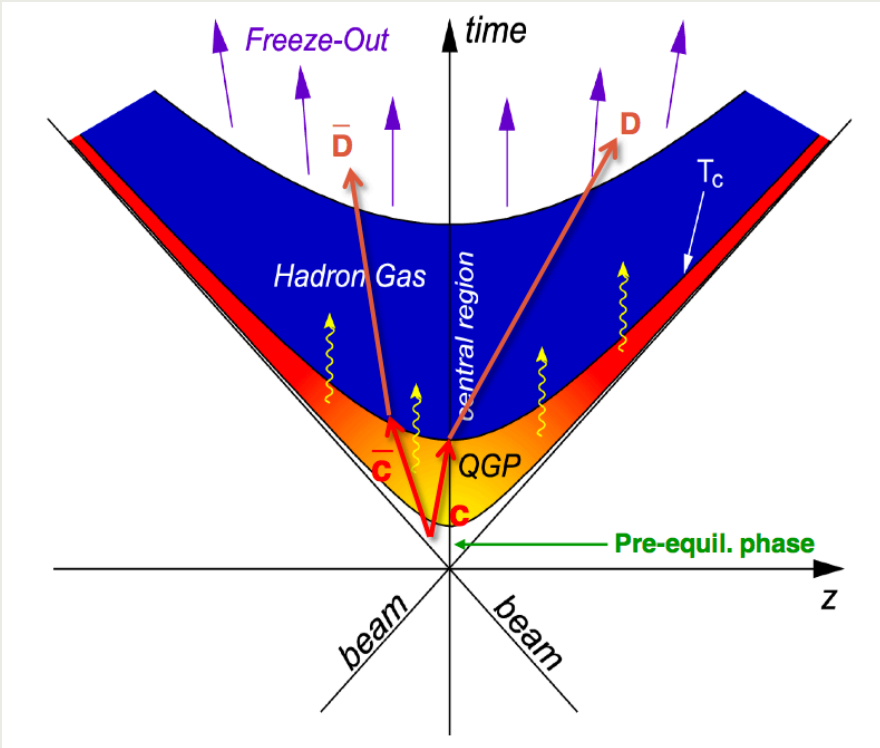
  - **Open Heavy Flavor** → Study medium density
    - Produced in the early stage of nuclear collisions due to large mass, $\Lambda_b << m_{c,b}$
    - Hard scattering dominates production mechanism
    - Test pQCD

Heavy Flavor in Heavy Ion Collisions



- Heavy flavor quarks are a good probe because they transverse the medium
- They interact with medium via scattering leading to energy loss, aka "suppression"
- No thermal production in QGP

Heavy Flavor in Heavy Ion Collisions



- Complications
  - Baseline measurements
    - Need to understand basic collision processes in which no QGP is formed
  - Cold Nuclear Matter Effects
    - Effects due to the presence of normal nuclear matter
  - **p+p collisions serve as baseline measurements to both Hot and Cold Nuclear Matter**

Nuclear Matter Effects

Cold Nuclear Matter

- Nuclear Modification in Parton Distribution Functions
- Energy loss of particles traversing nucleus
- Cronin effect – p_T enhancement due to multiple scattering in initial state

Hot Nuclear Matter

- Energy loss of partons traversing the medium
- Color screening
- Coalescence of quarkonia

Nuclear Modification Factor

- Quantifying medium effects:

$$R_{AA} = \frac{dN^{AuAu}/dp_T}{\langle N_{coll} \rangle \times dN^{pp}/dp_T}$$

Au+Au measurement

p+p measurement

Average number of nucleon-nucleon collisions In Au+Au measurements

- Any modification due to the medium?
  - $R_{AA} > 1$ → Enhancement
  - $R_{AA} = 1$ → No medium effects
  - $R_{AA} < 1$ → Suppression

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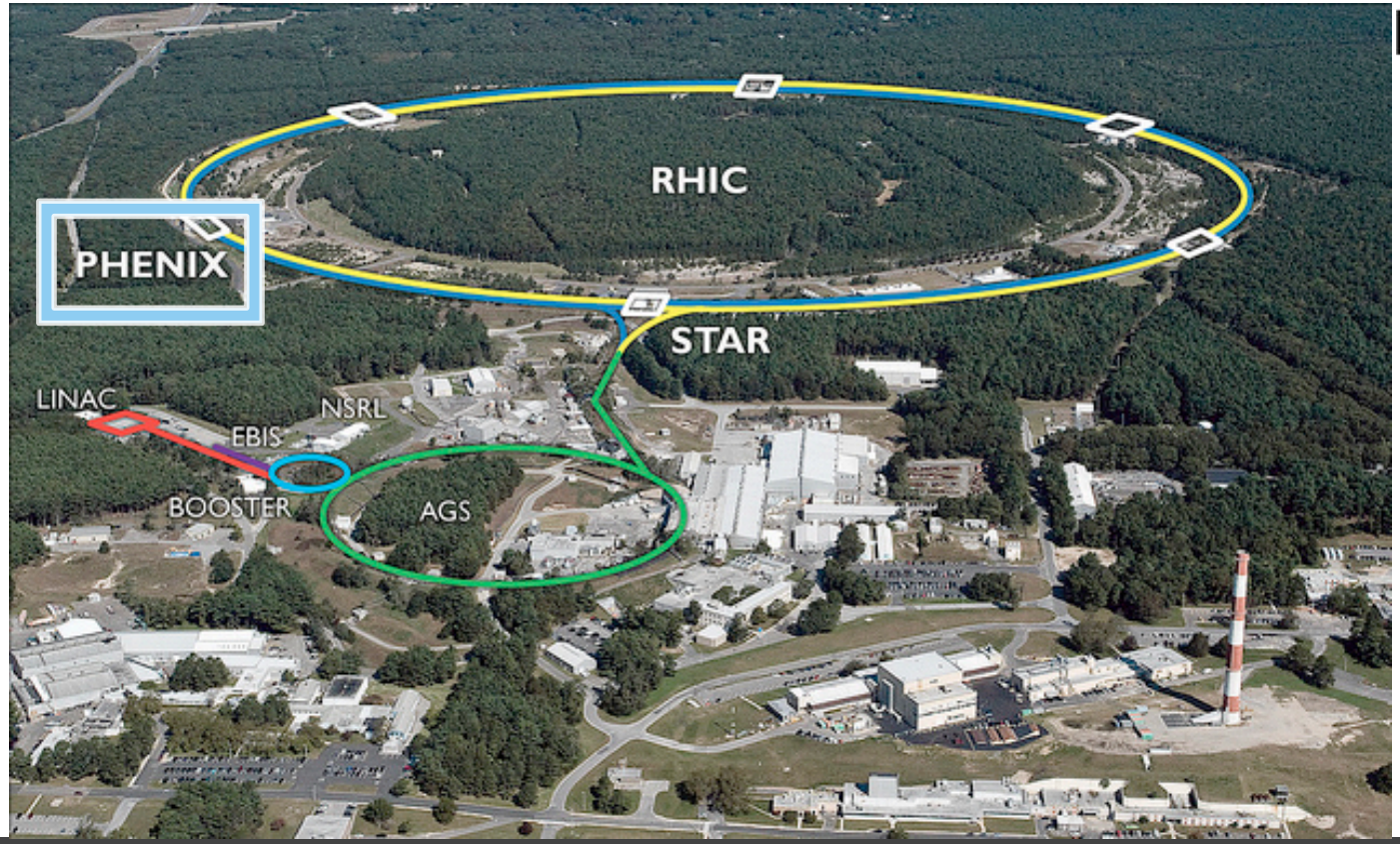
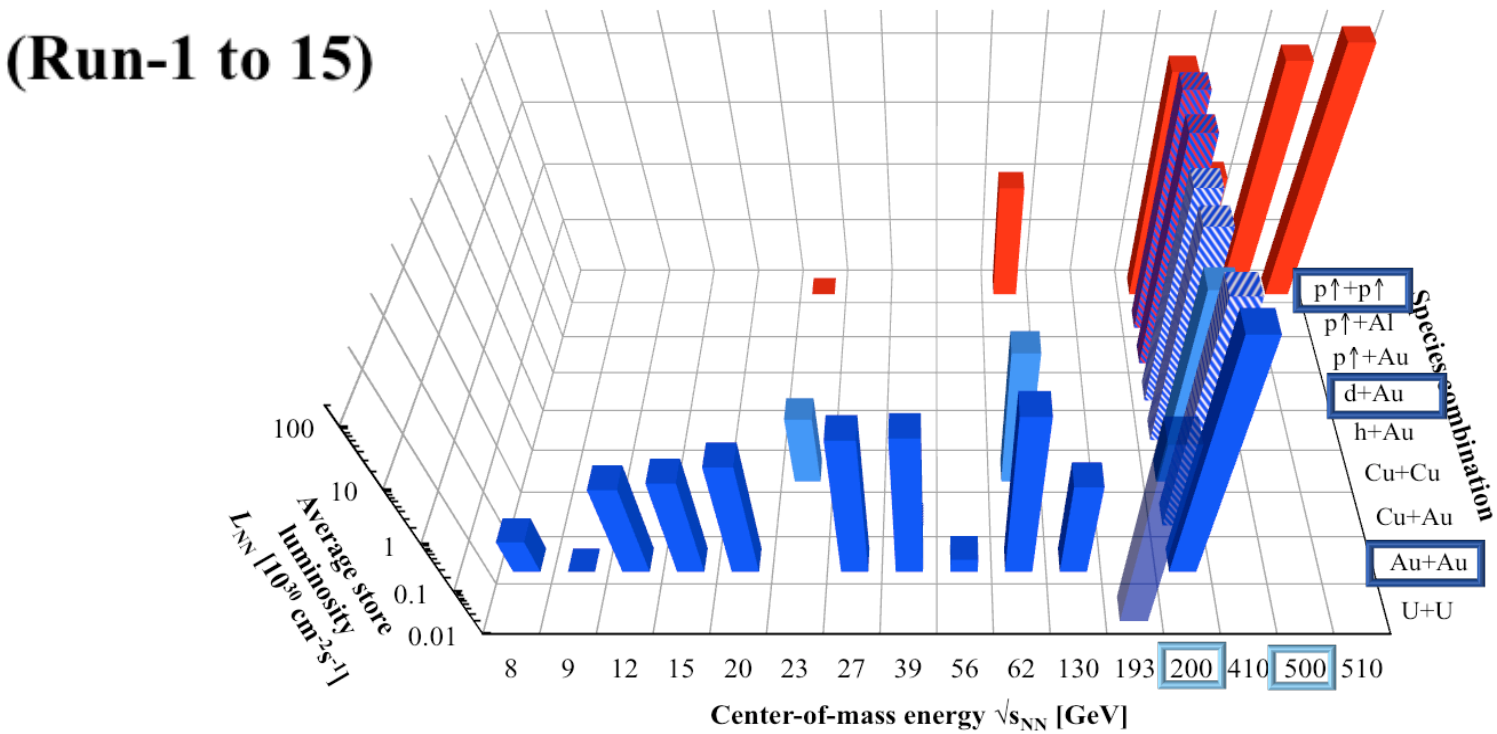


Relativistic Heavy Ion Collider (RHIC)

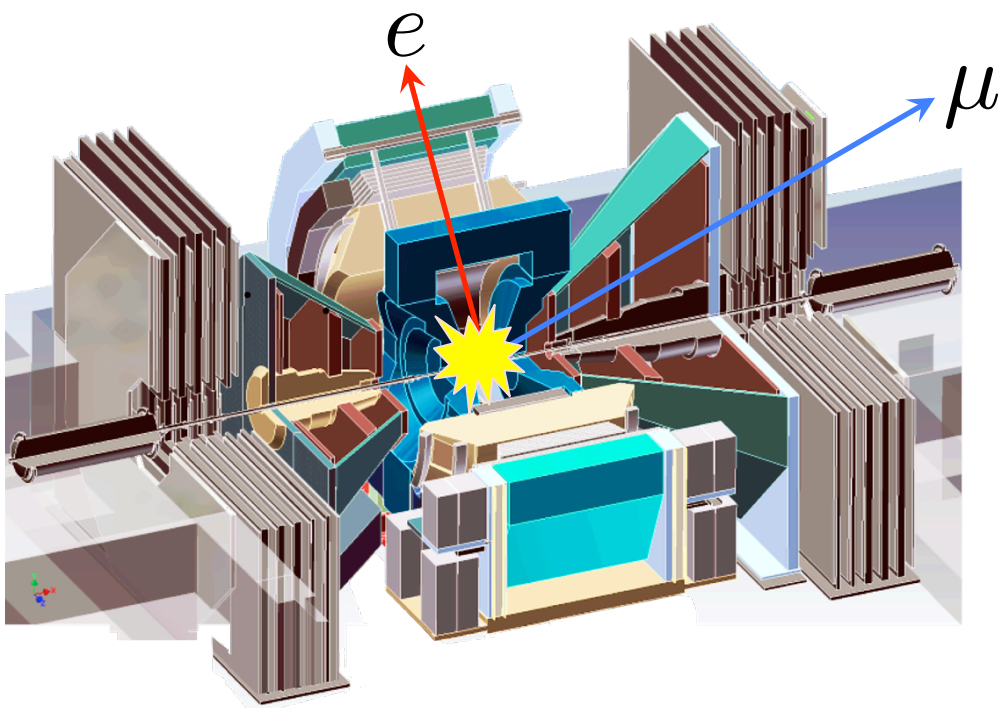
- RHIC is an extremely versatile machine, located at Brookhaven National Lab (BNL), that has collided a variety of collision species at various energies
- Two currently operating experiments at RHIC are PHENIX and STAR

RHIC energies, species combinations and luminosities



- RHIC is an extremely versatile machine, located at Brookhaven National Lab (BNL), that has collided a variety of collision species at various energies
- Two currently operating experiments at RHIC are PHENIX and STAR
- Can systematically study QGP with beam energies and system size

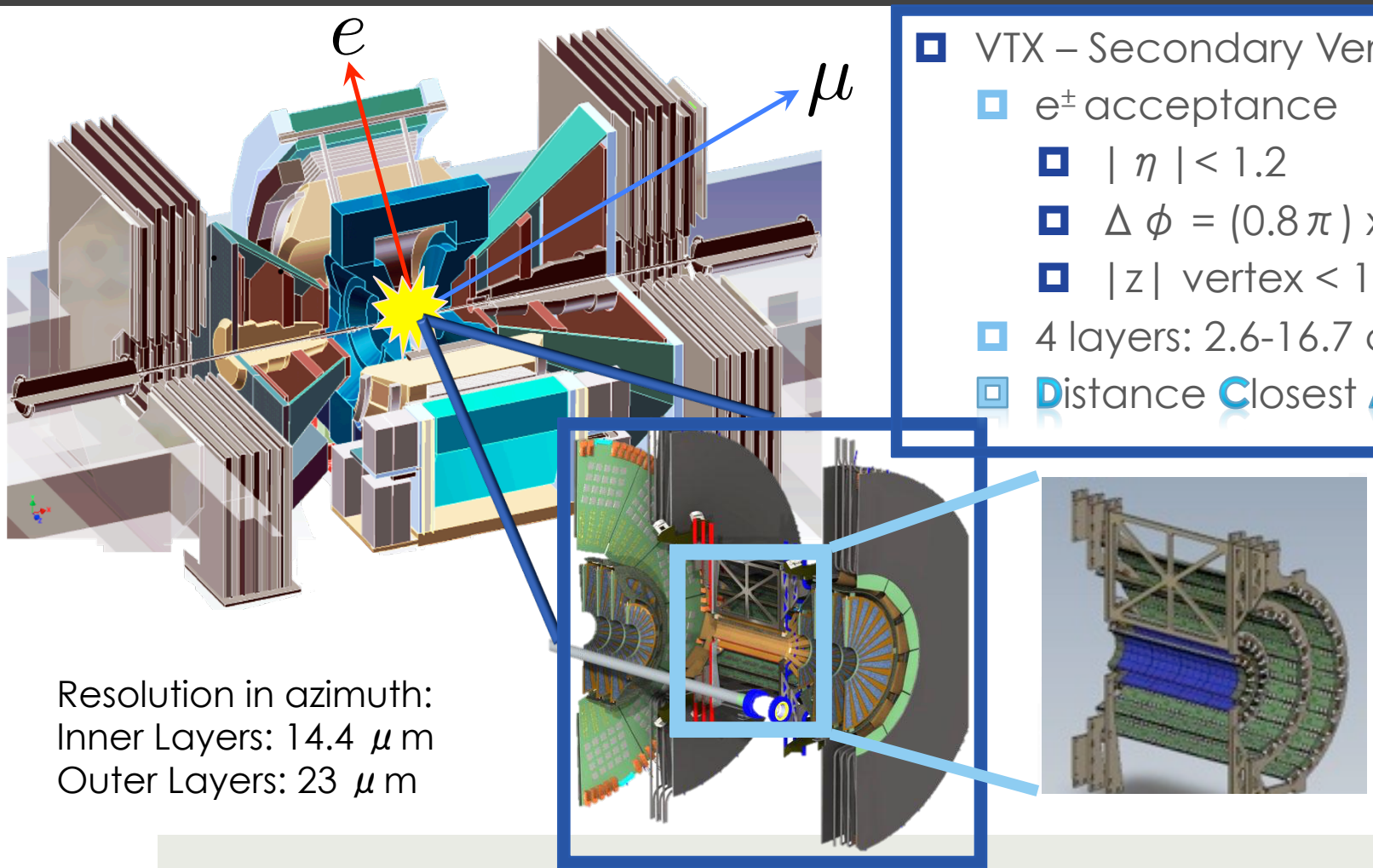
PHENIX Detectors



- Utilize both "central arms" & "muon arms"
  - $e^{\pm}$ acceptance
    - $|\eta| < 0.35$
    - $\Delta\phi = (\pi/2) \times 2$
  - $\mu^{\pm}$ acceptance
    - $1.2 < |\eta| < 2.2$
    - $\Delta\phi = 2\pi$
    - $p_{\mu} > 1$ GeV
- Two silicon vertex detectors, VTX (2011) and FVTX (2012)

- Measurements done both with and without silicon vertex detectors

VTX – Silicon Vertex Detector



- VTX – Secondary Vertex Finder
  - $e^{\pm}$ acceptance
    - $|\eta| < 1.2$
    - $\Delta\phi = (0.8\pi) \times 2$
    - $|z|$ vertex < 10 cm
  - 4 layers: 2.6-16.7 cm
  - Distance Closest Approach

Resolution in azimuth:
Inner Layers: 14.4 μm
Outer Layers: 23 μm

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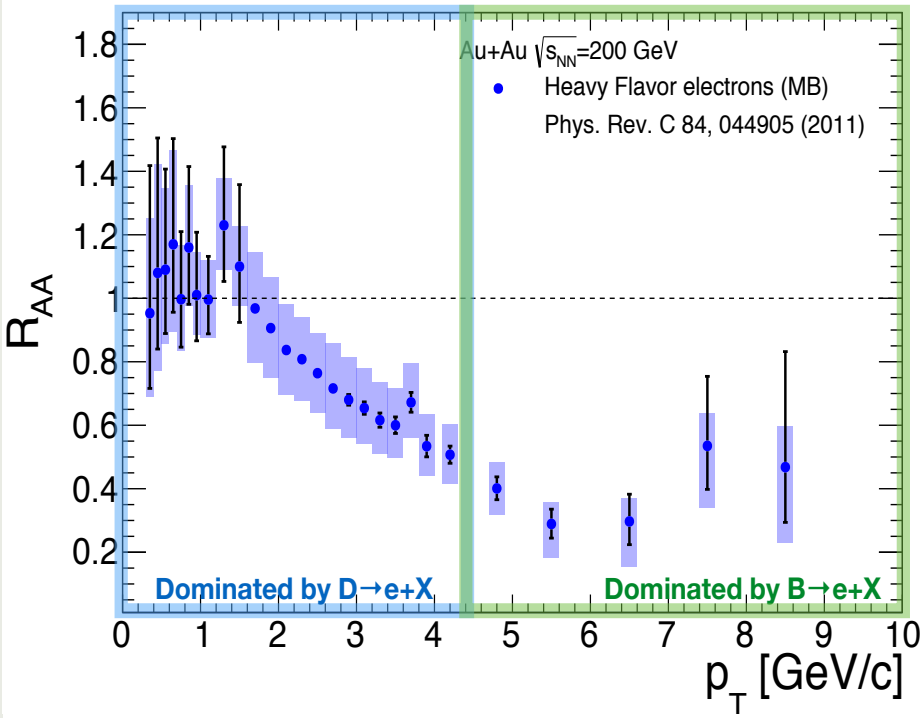
Charm and bottom production via single electrons from semi-leptonic D and B meson decays produced in *Au+Au* collisions at $\sqrt{s_{NN}}$ = 200 GeV

- Motivated by suppression in previous single electron measurement, **from inclusive heavy flavor**, in Au+Au collisions
- Want to separate c & b signals to consider individual modifications
- Decay length, $c\tau$, is used to separate B and D mesons using their decay kinematics:

DCA measurement → Decay Lengths

Charm: D^0 = 123 μm, $D^{\pm}$ = 312 μm

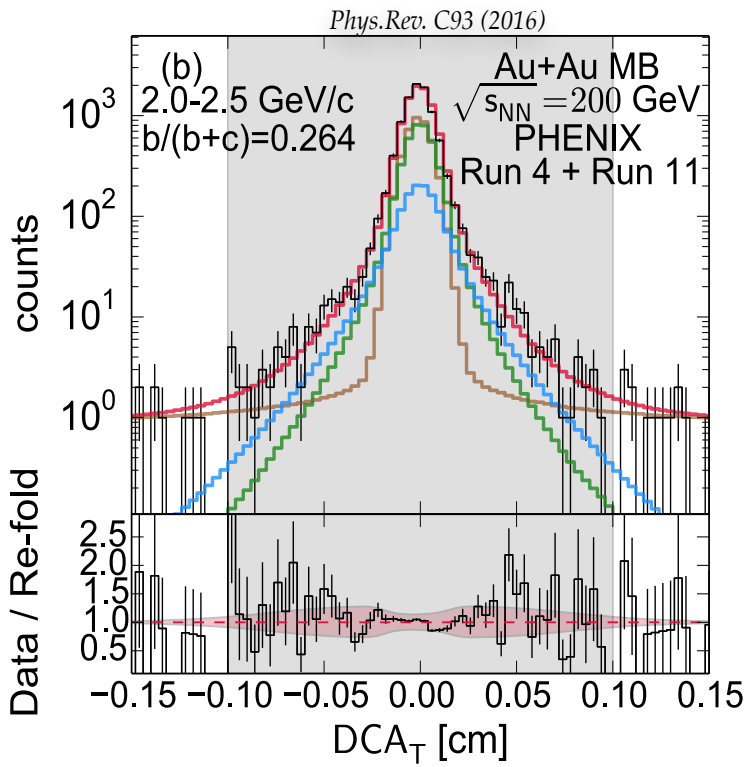
Bottom: B^0 = 455 μm, $B^{\pm}$ = 491 μm



$$R_{AA} = \frac{dN^{AuAu}/dp_T}{\langle N_{coll}\rangle \times dN^{pp}/dp_T}$$

DCA_T Separated Signal

- Unfolded DCA_T distribution



Data

c→e

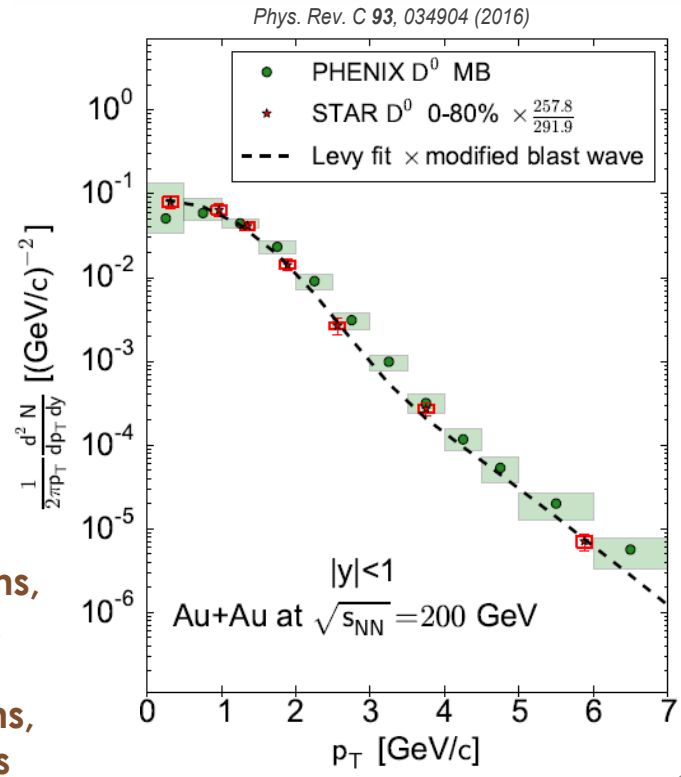
b→e

Total

Background Components

Misidentified Hadrons, High Multiplicity BG, Dalitz Decay, Gamma Conversions, J/Psi & Kaon decays

- Invariant yield cross-check

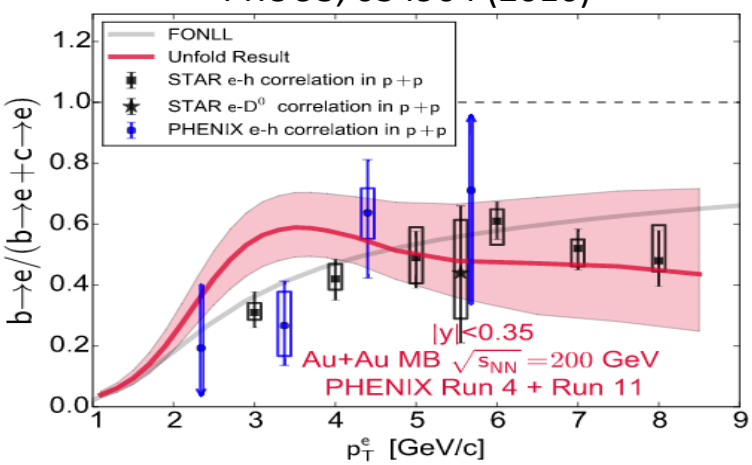


- Separation done with Bayesian Inference Method
- Method provides consistent results between "Total" and "Data"

Bottom Fraction & R_{AA}

- Bottom fraction shown with p_T dependence in Au+Au and p+p collisions

PRC 93, 034904 (2016)



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- Bottom fraction shown with p_T dependence in Au+Au and p+p collisions

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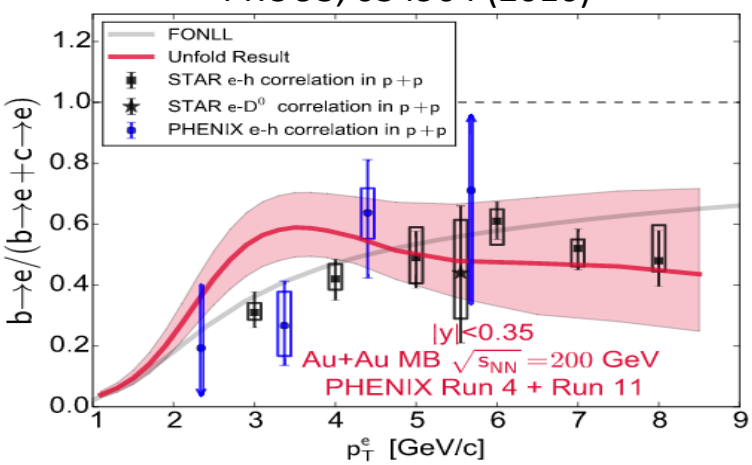
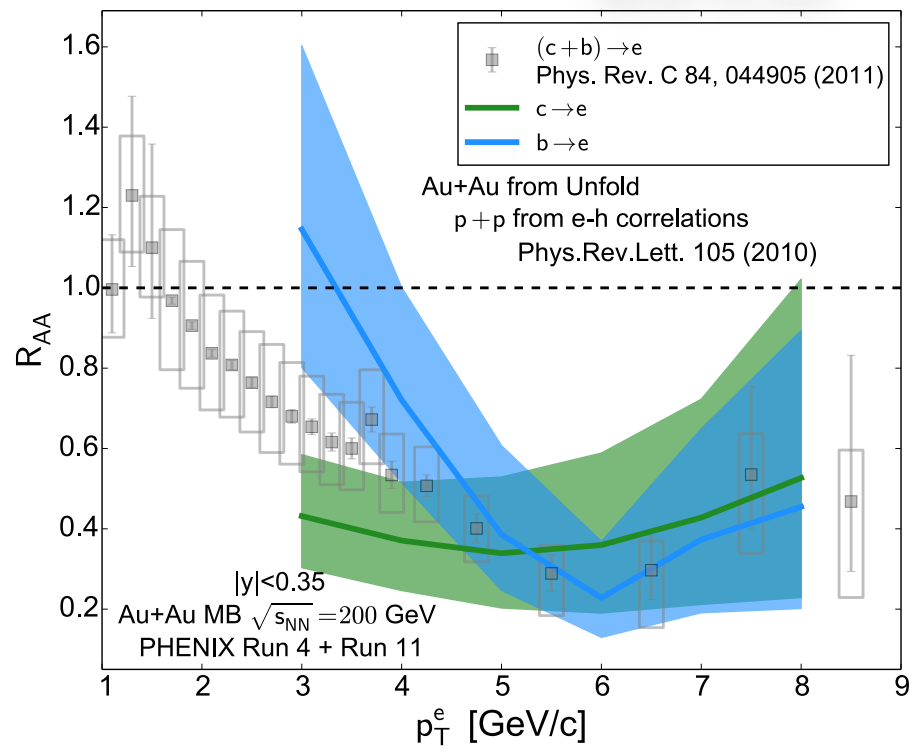


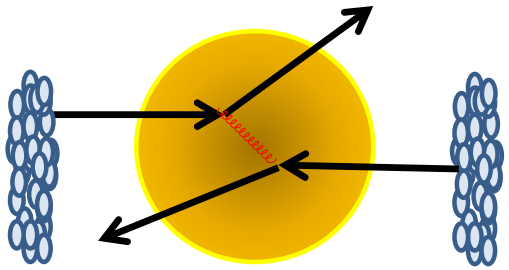
Phys.Rev. C93 (2016)



- Differences in suppressions between contributing components
  - c suppressed much more then b in lower mass region
  - Similar suppression in higher mass region

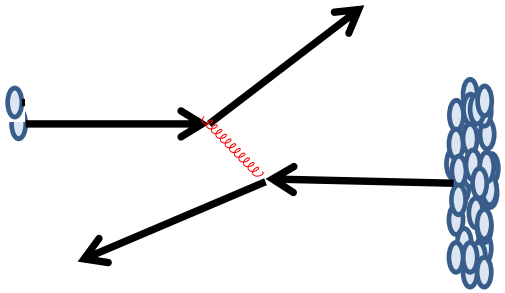
Baseline Measurements & Disentangling Cold Nuclear Matter Effects

Au+Au



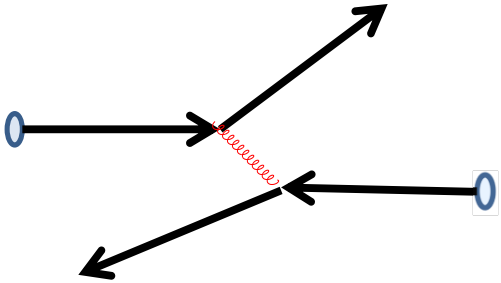
Medium created → Hot Nuclear Effects (Suppression)

d+Au



No Medium → Cold Nuclear Matter Effects

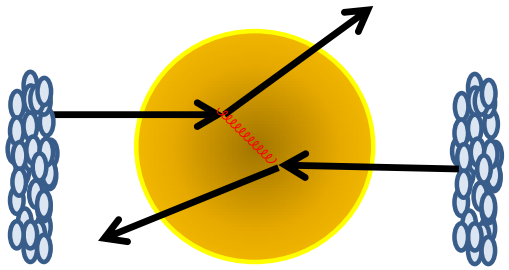
p+p



No Medium → Baseline measurements (R_{AA} Measurements)

Baseline Measurements & Disentangling Cold Nuclear Matter Effects

Au+Au



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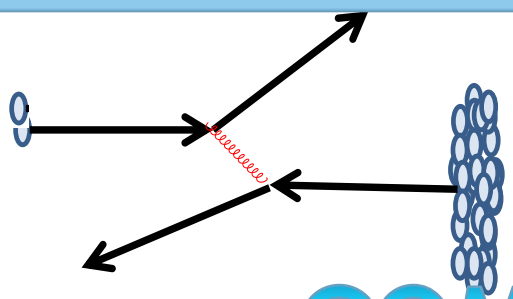
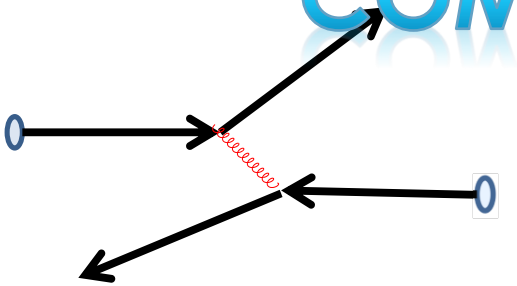


No Medium → Cold Nuclear Matter Effects

COMING UP NEXT

p+p



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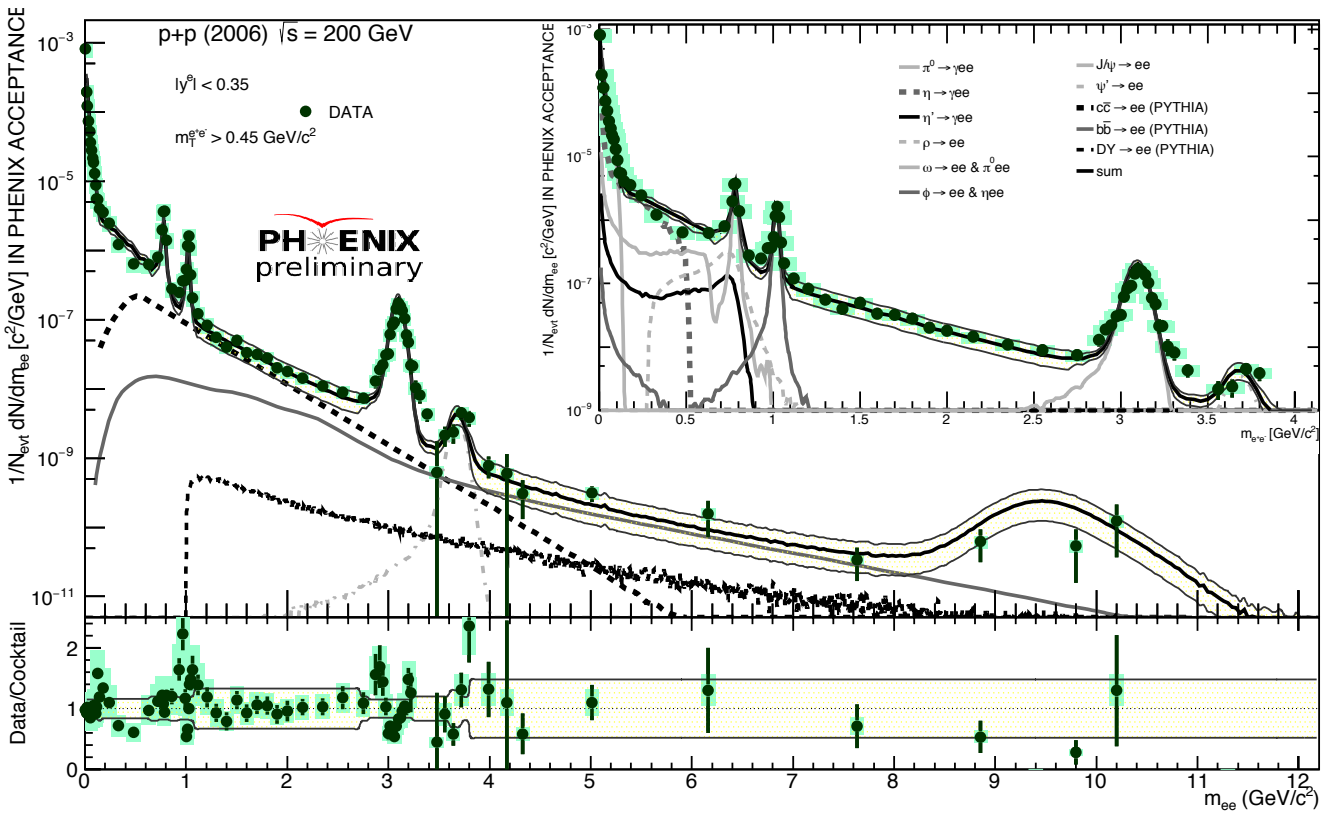
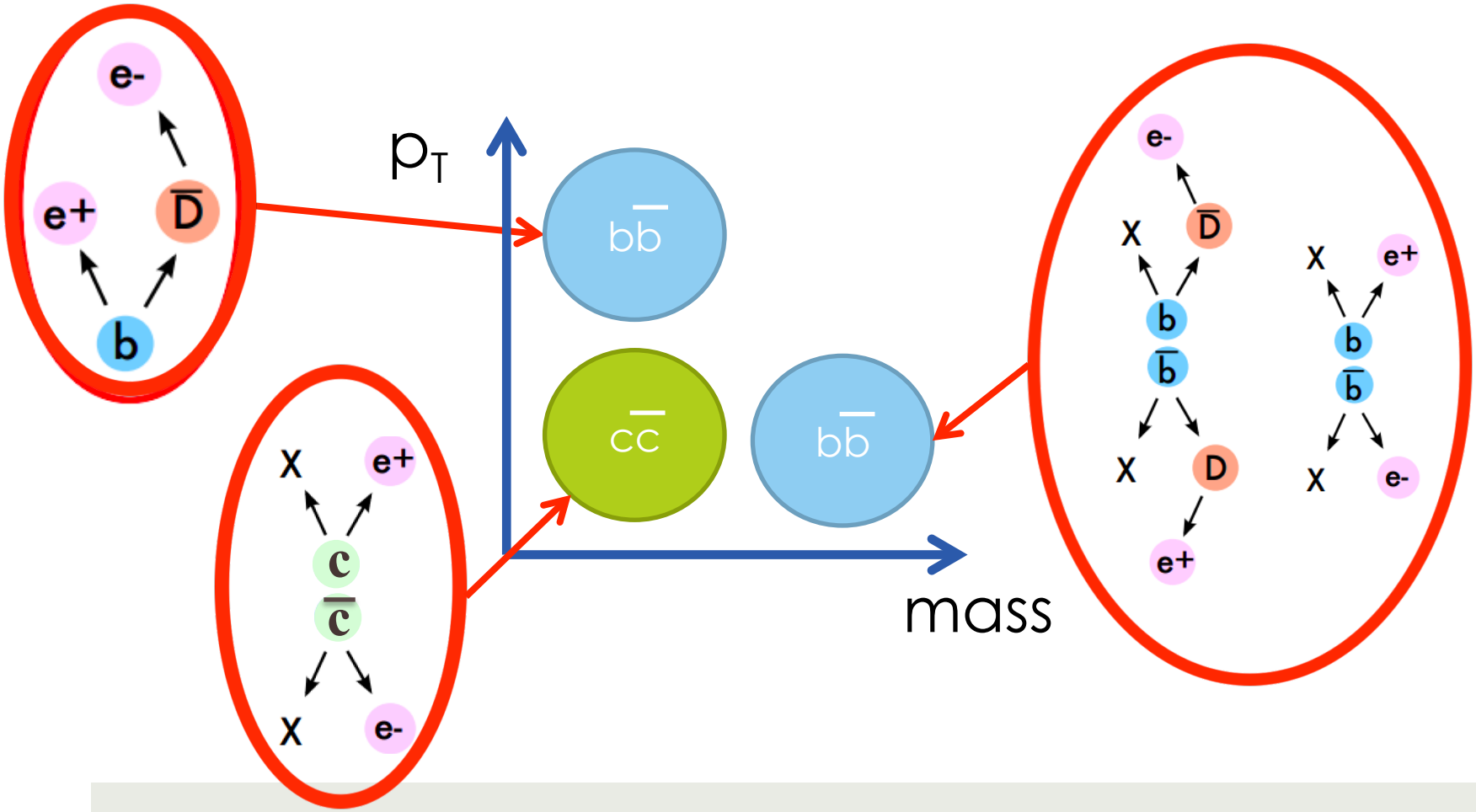


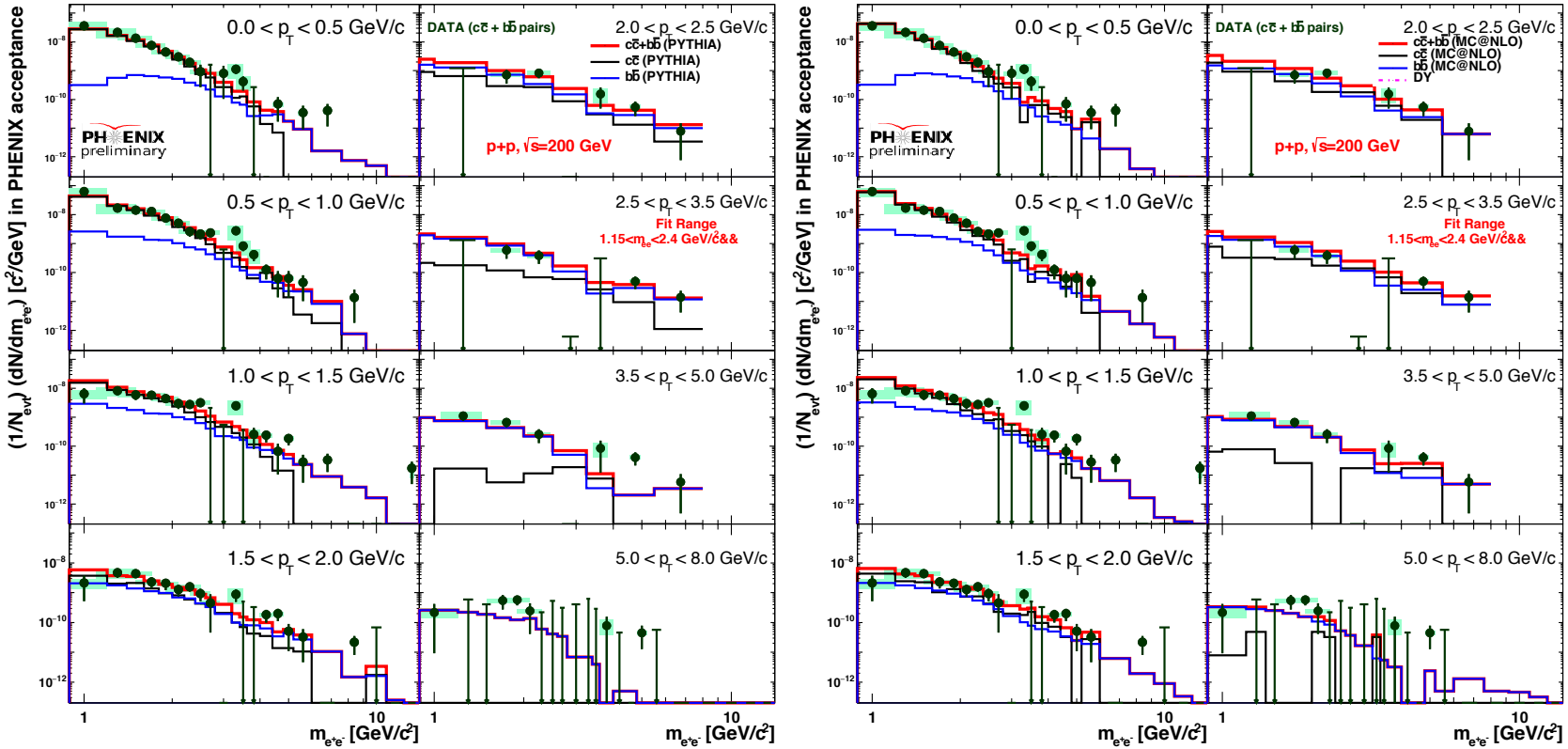
Heavy flavor cross section measurement from e^+e^- pairs in p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV

- Like sign pair background subtraction and further subtract vector mesons, pseudo-scalar mesons and Drell-Yan pairs.
- Separate c and b contributions by fitting to mass and p_T simultaneously.

Heavy Flavor Separation via Phase Space Analysis



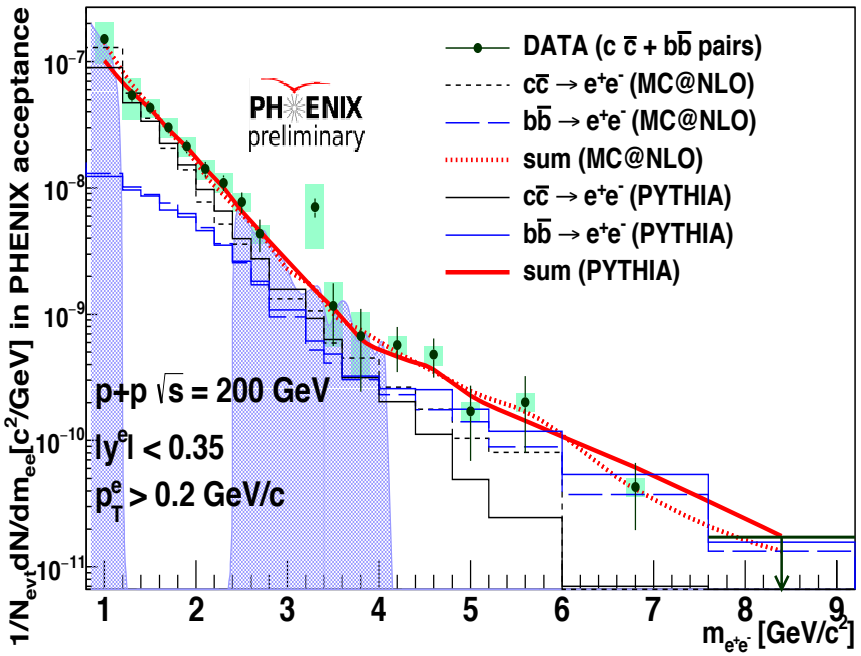
Double Differential Fits to Simulations



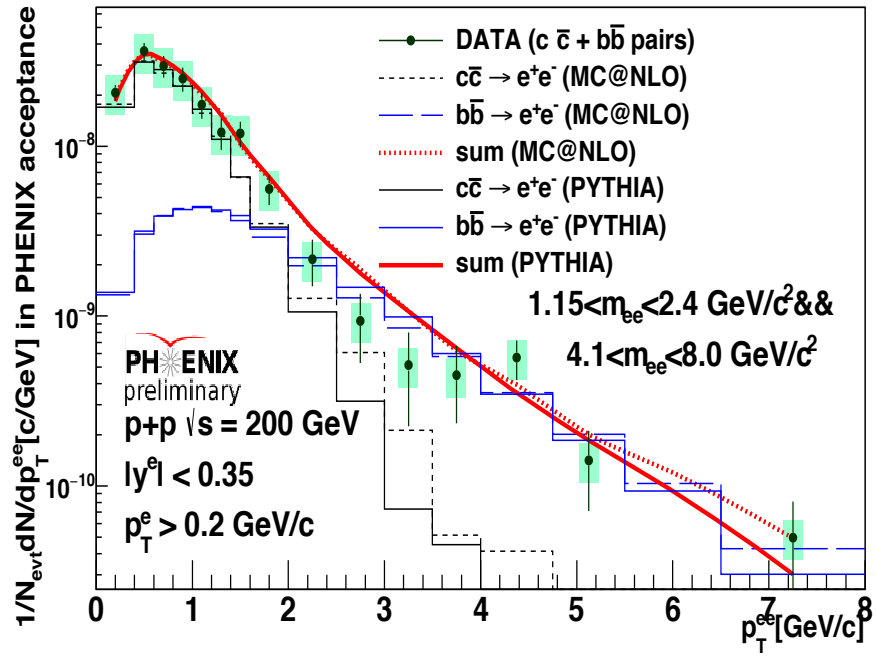
PYTHIA 6 $c\bar{c}$, $c\bar{c}+b\bar{b}$, $b\bar{b}$ & • Data MC@NLO

Method described Phys. Rev. C 91, 014907 (2015)

Mass Distribution



p_T Distribution

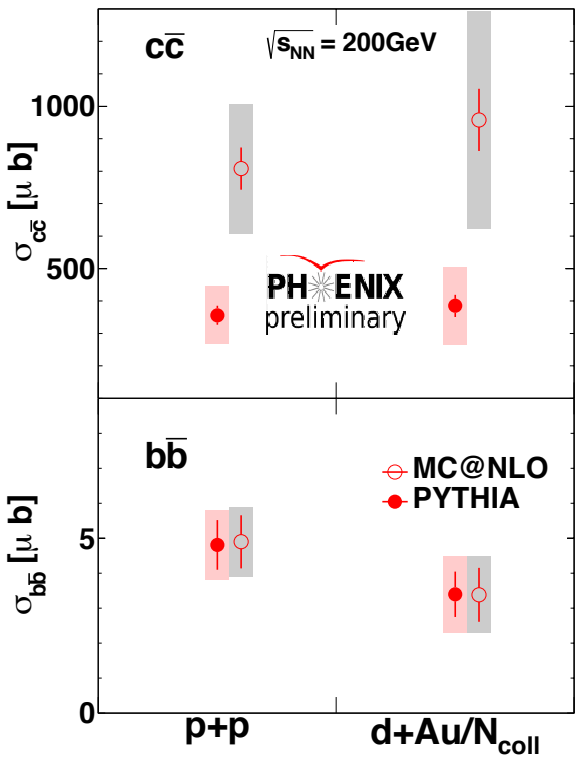


Integrated Mass and p_T Spectrums

- Both simulations match the data well
- Blue regions not included in fits

$$\frac{1}{N_{\rm evt}^{\rm MB}}\frac{dN_{ee}^{hf}}{dmdp_T}\Big|_{PHENIX} = N_{c\bar{c}}\frac{dn_{ee}^{c\bar{c}}}{dmdp_T} + N_{b\bar{b}}\frac{dn_{ee}^{b\bar{b}}}{dmdp_T}$$

Total Cross Section & "R_{dAu}"



Charm Cross Section

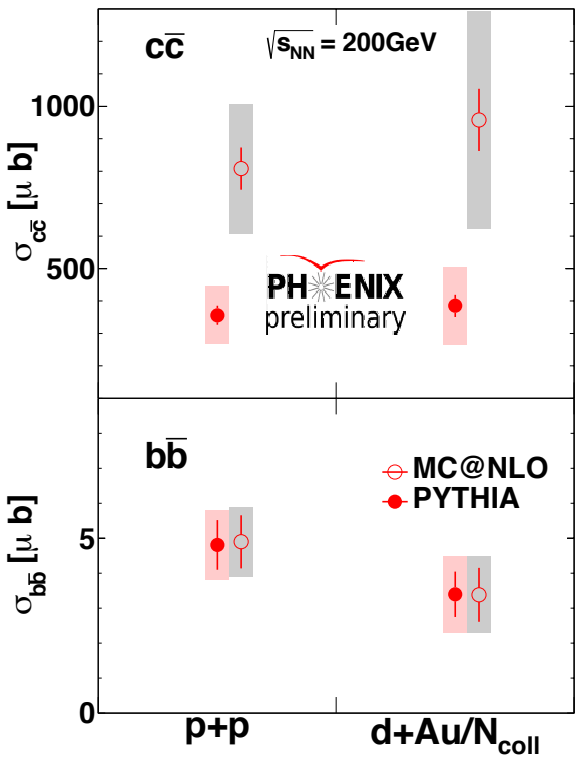
System	PYTHIA	MC@NLO
d+Au/N_{coll} (PRC 91, 014907)	385 ± 34 (stat) ± 119 (syst) μb	795 ± 80 (stat) ± 275 (syst) μb
p+p	356 ± 29 (stat) ± 89(syst) μb	708 ± 56 (stat) ± 175 (syst) μb

Bottom Cross Section

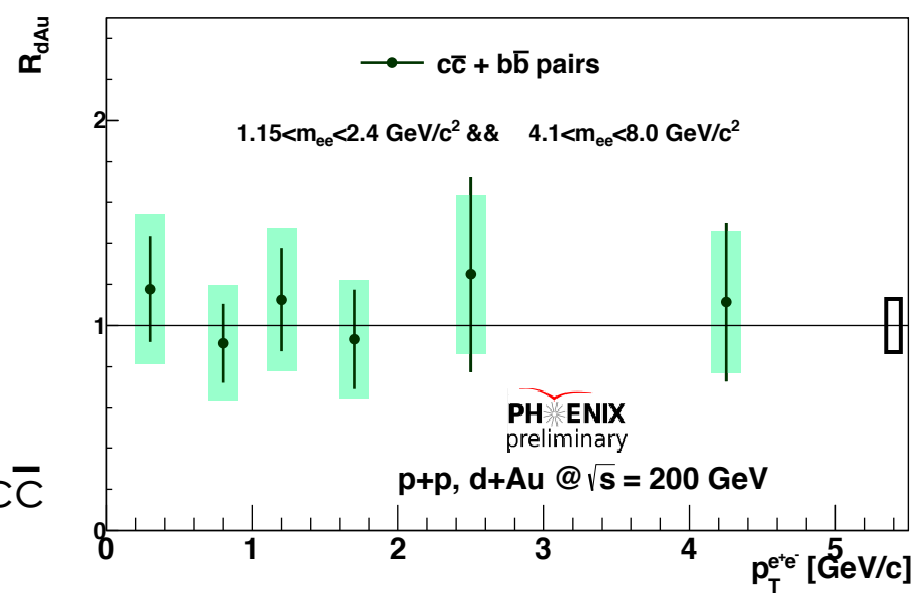
System	PYTHIA	MC@NLO
d+Au/N_{coll} (PRC 91, 014907)	3.40 ± 0.65 (stat)± 1.10 (syst) μb	2.95 ± 0.67 (stat)± 0.95 (syst) μb
p+p	4.81 ± 0.71 (stat)± 1.00 (syst) μb	4.90 ± 0.76 (stat)± 1.00 (syst) μb

- Large model dependence between $c\bar{c}$
- $b\bar{b}$ is model independent

Total Cross Section & "R_{dAu}"



- "R_{dAu}" from e^+e^- pairs
- No substantial modification seen
- d+Au results from **Phys. Rev. C 91, 014907**

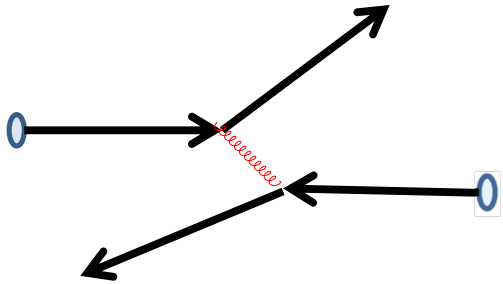


- Large model dependence between $c\bar{c}$
- $b\bar{b}$ is model independent

Study of $\sigma_{b\bar{b}}$ via $\mu^{\pm}\mu^{\pm}$ in p+p collisions at $\sqrt{s}$ = 500 GeV utilizing B^0 oscillation

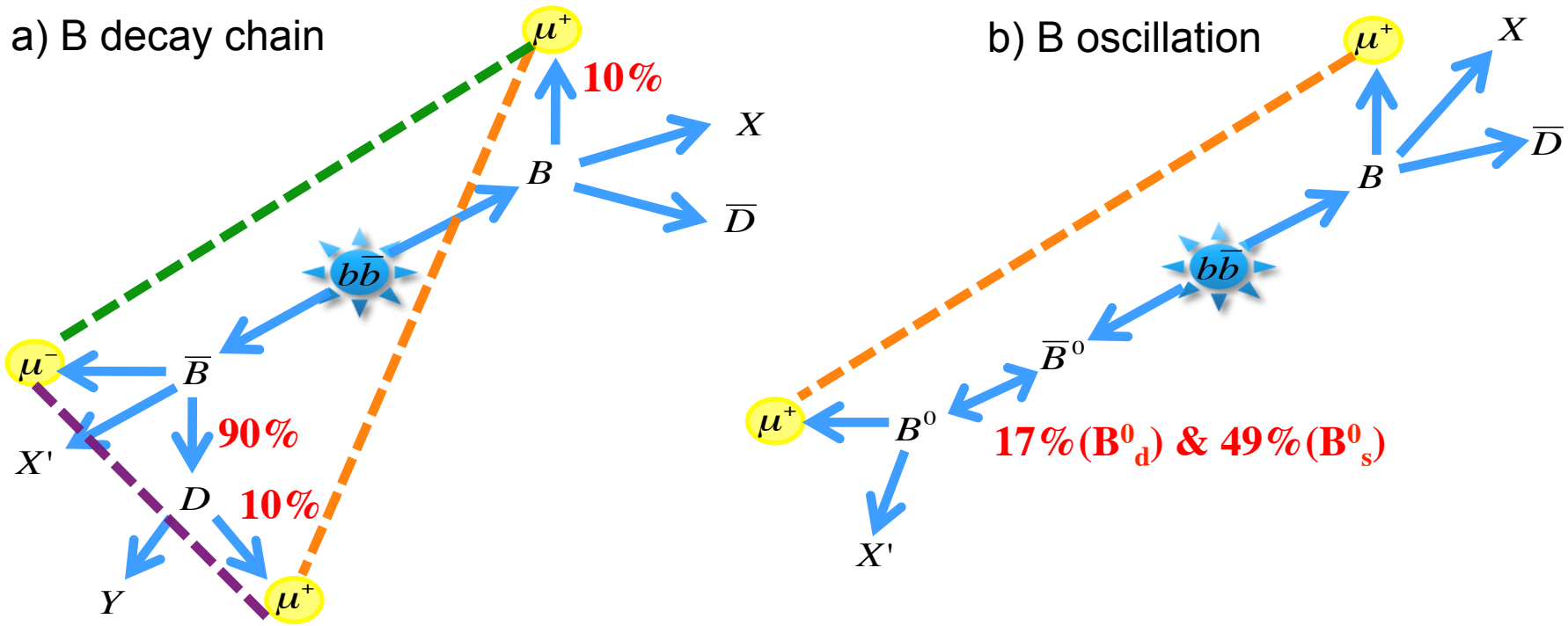
- Developed new technique to isolate b signal without using secondary vertex information
- Like sign pairs → Don't have to worry about Drell-Yan or Quarkonia pairs
- Working in high mass region

p+p



No Medium → Baseline measurements (Production)

Like Sign Muon Pairs From B Decay in the High Mass Region



- a) shows example decay process which includes a feed down process
- b) shows B^0 oscillation which occurs through a weak interaction and decays directly to a lepton

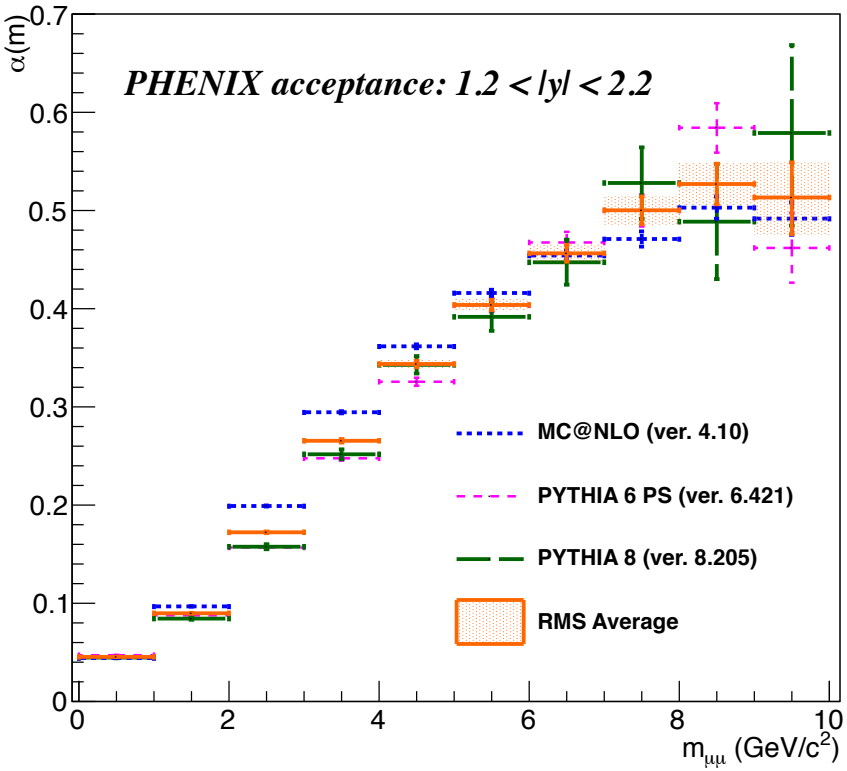
PRC 91, 014907 (2015)

B^0 Oscillation properties

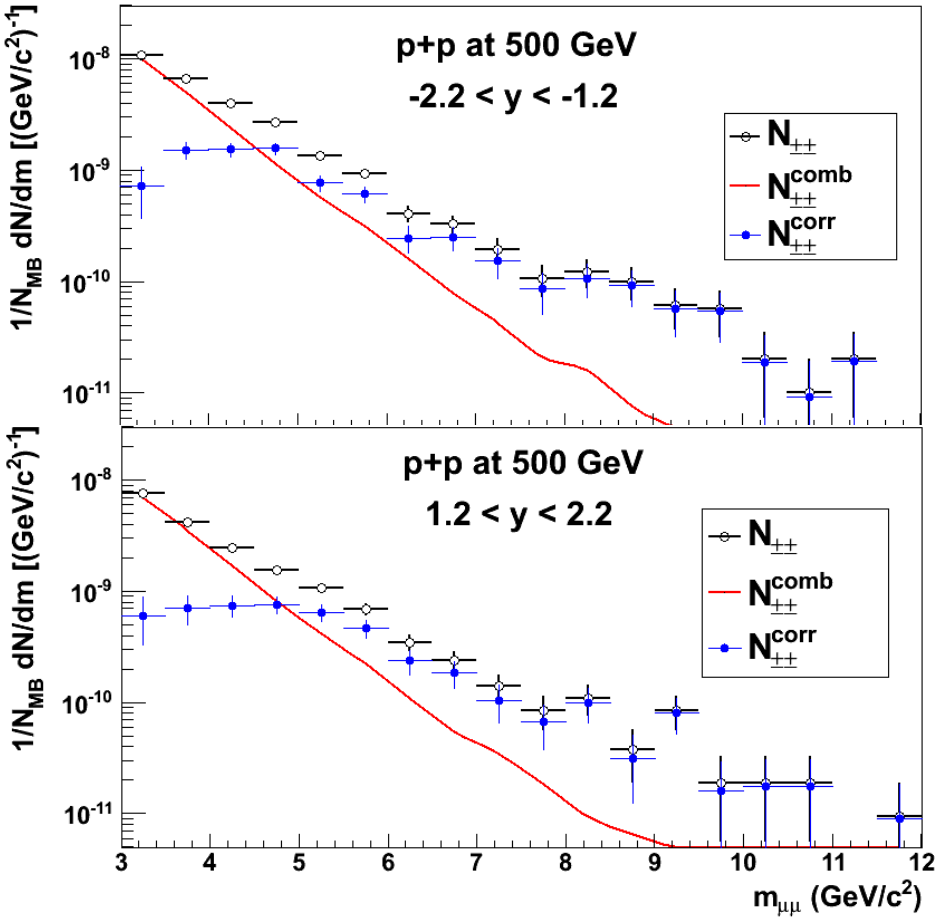
- Fraction of like sign pairs from oscillation to all like sign B pairs

$$\alpha(m) = \frac{b\bar{b} \to B\bar{B} \to \mu^{\pm}\mu^{\pm}\ (\mathrm{osc})}{b\bar{b} \to B\bar{B} \to \mu^{\pm}\mu^{\pm}}.$$

- Pairs from oscillation contribute a large portion to the total like sign pairs in the 5-10 GeV range



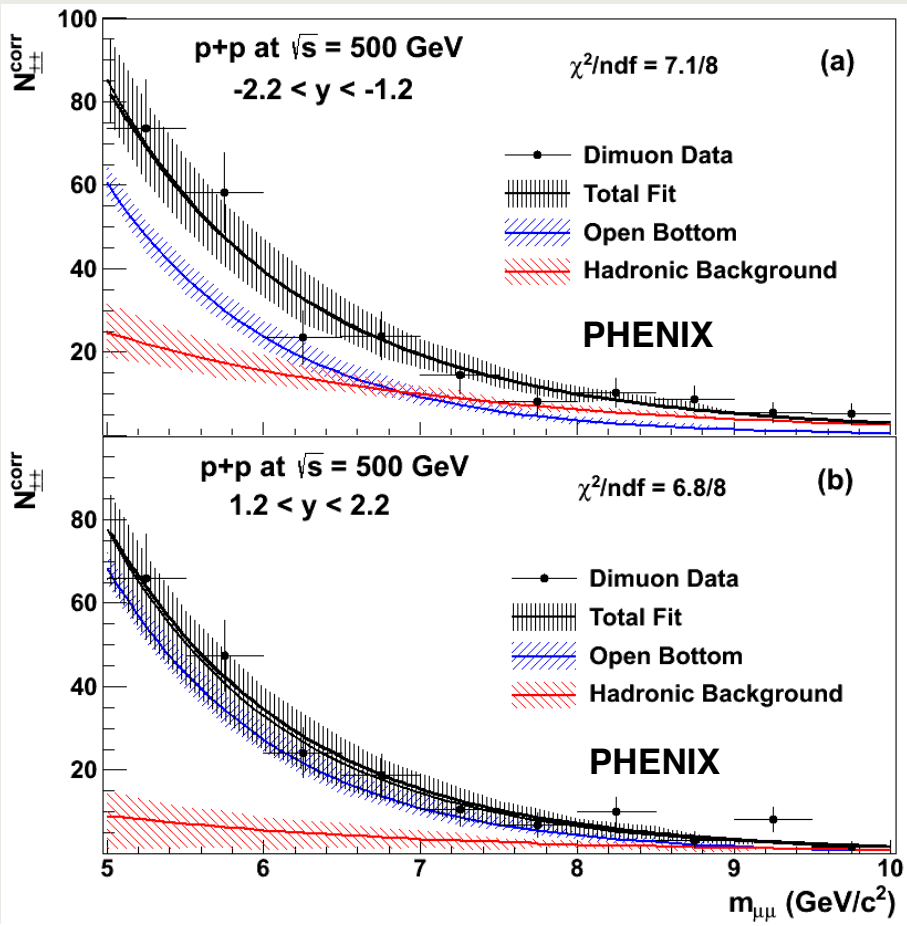
Like Sign Dimuon Distribution: Removing Combinatorial Background



- First of two backgrounds that need to be removed
- Separate correlated like sign signal from mixed event (combinatorial) background
- Remaining signal in $m_{\mu\mu} > 4$ GeV is dominated by B decay **with correlated hadronic background**

$$N_{\pm\pm}^{corr} = N_{\pm\pm}^{like} - N_{\pm\pm}^{mixed}$$

Extracting Open Bottom Signal



- Hadronic (Correlated) background is from jets (K & π)
- Remaining like sign signal is dominated by B mesons
- Differences in background in different rapidity regions due to differences in the PHENIX muon arms (absorber material)

$$N^{BB}_{\pm\pm} = N^{Corr}_{\pm\pm} - N^{HadronicBG}_{\pm\pm}$$

Global Measurements of Total $b\bar{b}$ Cross Section

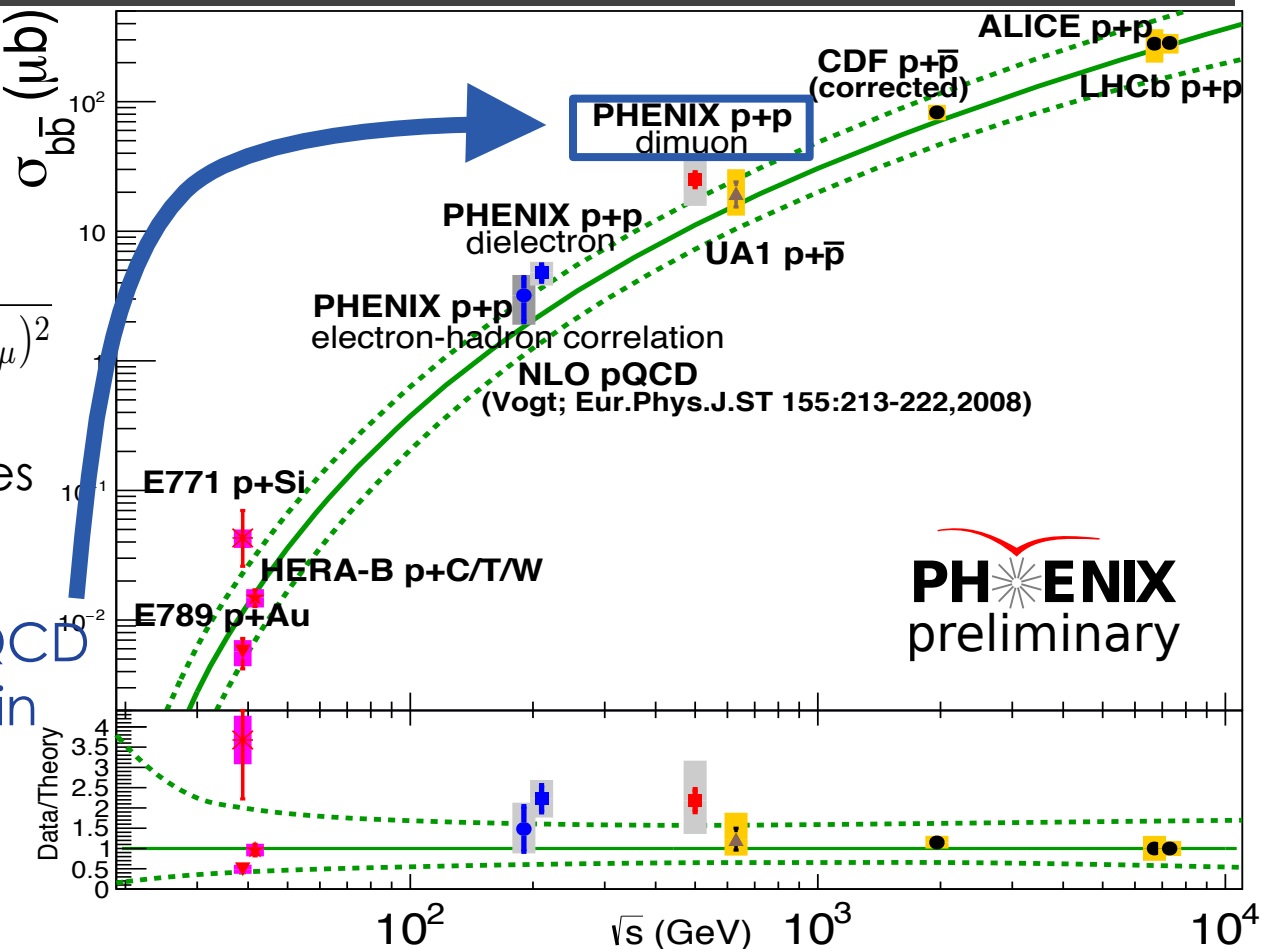
$$\frac{d\sigma_{b\bar{b}\to\mu\mu}}{dy} = \frac{dN_{B\bar{B}\to\mu\mu}}{dy}\sigma^{pp}_{total}$$

$$\sigma_{b\bar{b}} = \frac{d\sigma_{b\bar{b}\to\mu\mu}}{dy} * \frac{1}{scale} * \frac{1}{(BR_{B\to\mu})^2}$$

*Scale factor extrapolates to full phase space

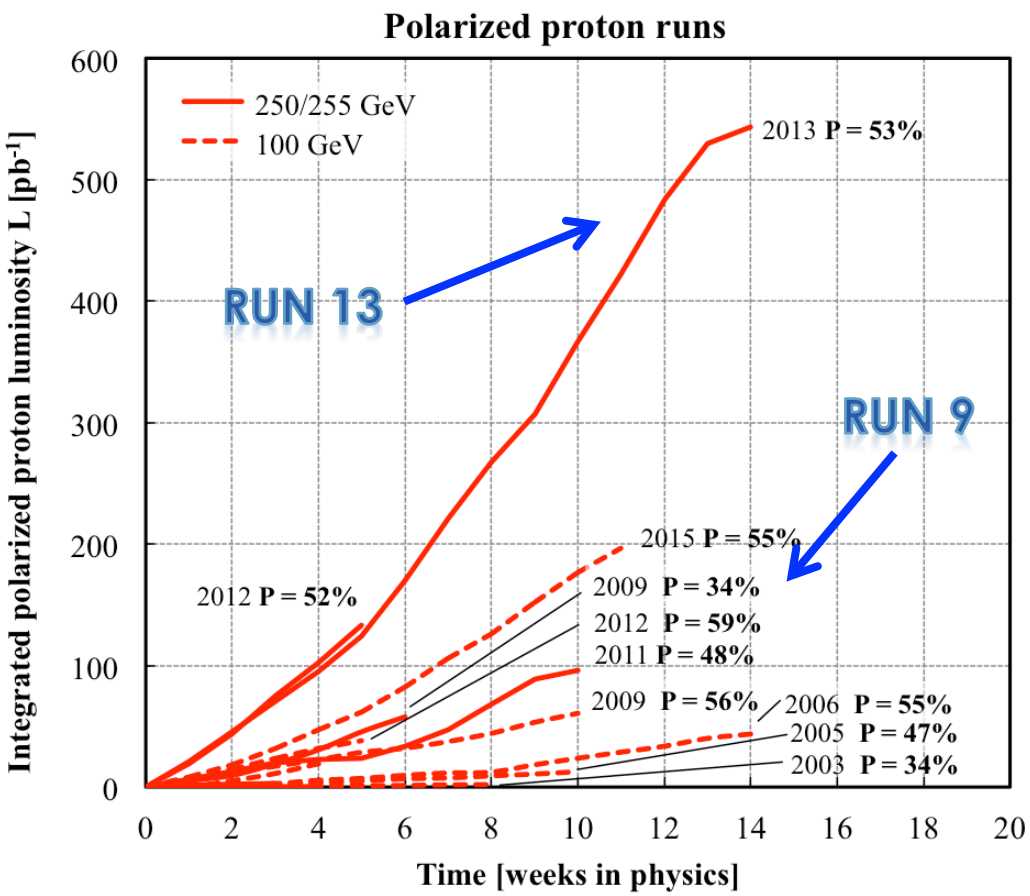
σ_{bb} ~ 26 μb → NLO pQCD calculation agrees within uncertainties

Uncertainties?



Outlook for PHENIX *p+p* 2013 Data Set

- *p+p* at $\sqrt{s}$ = 510 GeV
- $\mathcal{L}$ = 1.04 fb^{-1}
- High Statistics Run!
- Added Absorber in Muon Arms
- Developed iterative background subtraction technique to account for signal in the low mass region



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Preliminary Results

- **Summary & Outlook**

Summary

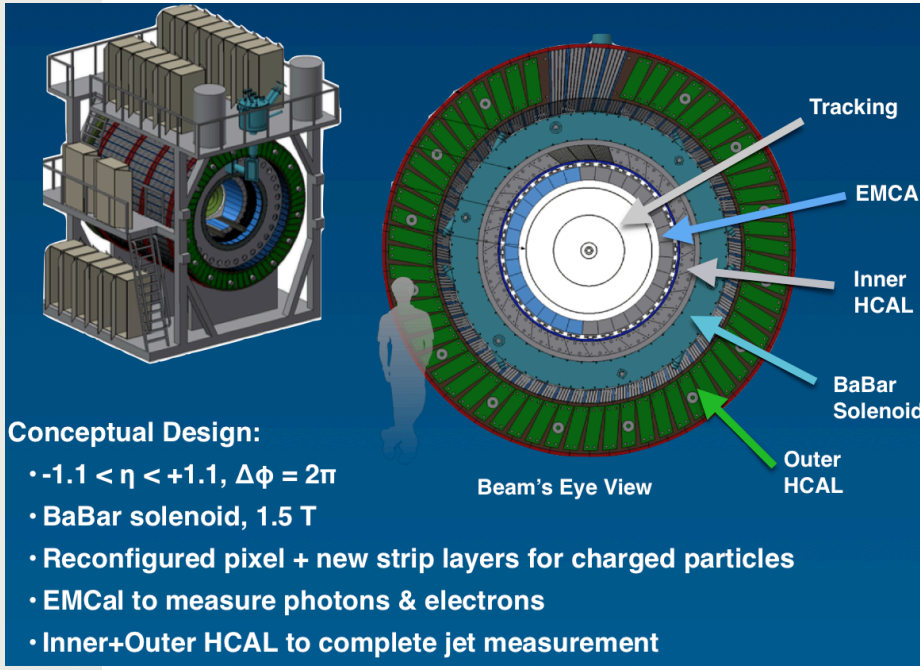
- Study of QGP medium
- Use heavy flavor as one of the many probes of QGP
  - D/B separated signal from single electron
    - Using DCA distribution via secondary vertex measurement
    - Heavy flavor electrons suppressed implying loss while in the medium → c quarks suppressed more then b quarks
- p+p baseline measurements → collisions where no medium is formed
  - Reference for R_{AA} calculations
  - Separate heavy flavor signals in phase space
  - From dielectrons
    - Measure cross sections and no nuclear modification in d+Au vs p+p
  - From dimuons
    - b signal in high mass region using B^0 oscillation properties
    - Measure cross section

Outlook & Other Recent Work

- Phys. Rev. C 93, 034903 (2016) - Forward J/ψ production in U+U collisions at $\sqrt{S_{NN}}$ = 193 GeV
  - Hot Nuclear Matter versus Energy density
- J/ψ & ψ' Ratio in a variety of asymmetric collisions at $\sqrt{S_{NN}}$ = 200 GeV
  - Will be able to further study CNM
- B→J/ψ ratio in p+p collisions at $\sqrt{S_{NN}}$ = 510 GeV & in Cu+Au at $\sqrt{S_{NN}}$ = 200
- Charm and bottom production via single electrons from semi-leptonic D and B meson decays produced in *Au+Au* collisions at $\sqrt{s_{NN}}$ = 200 GeV (With improved statistics from 2014 run)
- …

The future…

- PHENIX is not the end of the story
- Second generation experiment
  - Study jets and jet correlations
  - Upsilon spectroscopy

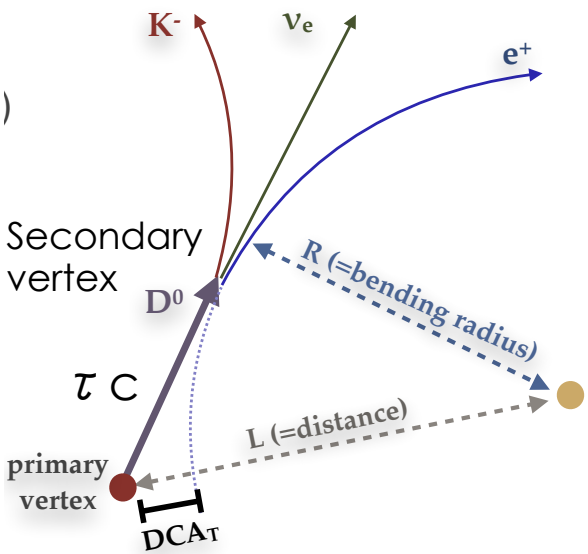


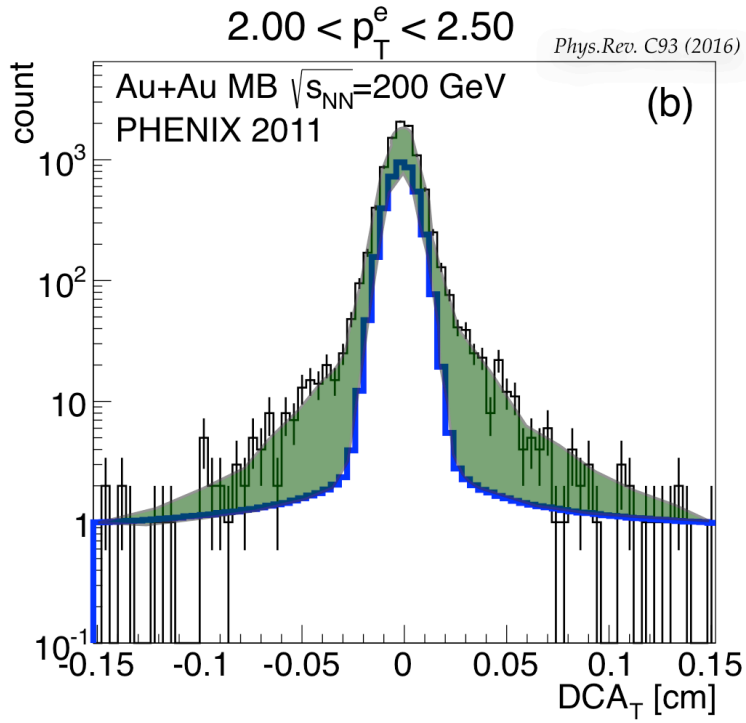
THANK YOU!

Back - up

DCA Measurement

DCA_T Distribution Components





Backgrounds:
Misidentified Hadrons
High Multiplicity BG
Dalitz Decay
Conversions
J/Psi
Kaon decay

c & b signal

data

- Need to separate c and b contributions →Done with Bayesian Inference Method

Lepton Pairs

Source of Di-lepton Signal

	Unlike Sign	Like Sign
$m_{\mu} < 4$ GeV	Quarkonia (J/ψ, ψ') b-decay chain (same b) Drell-Yan $(q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-)$ c pairs	c pairs b-decay chain
$m_{\mu} > 4$ GeV	Drell-Yan Quarkonia (Υ family) b-decay chain (diff b) $b\bar{b} \rightarrow l^+l^-$ (prompt) $c\bar{c} \rightarrow l^+l^-$ (prompt)	$b\bar{b} \rightarrow l^{\pm}l^{\pm}$ (prompt with B osc.) b-decay chain (diff b)

Hadronic background possible in all four cases

BR ~ 10% for open leptonic decay

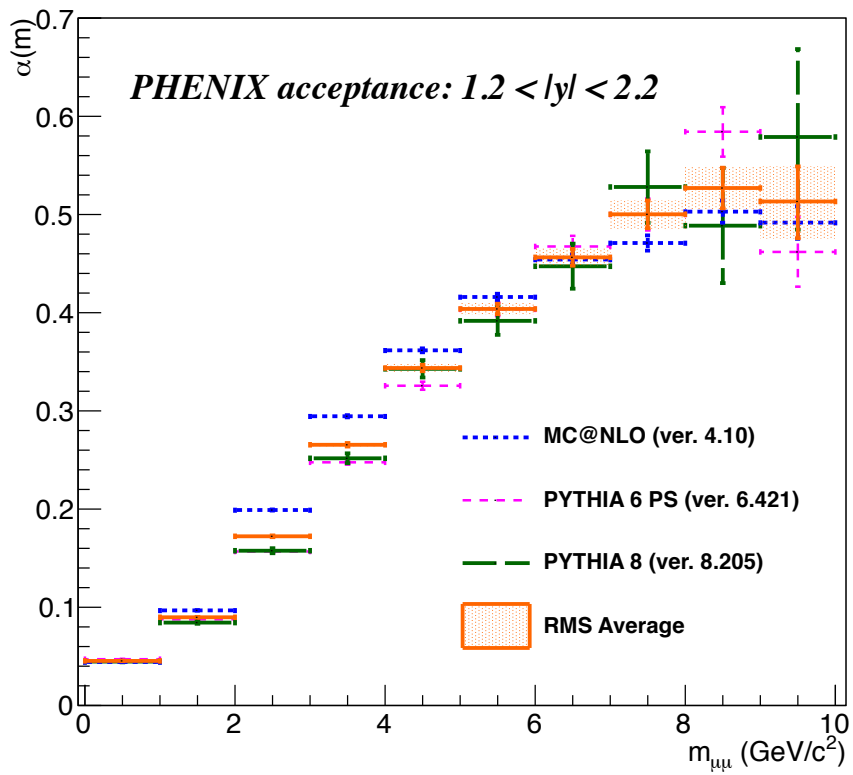
Dominant signal in high mass region is from B meson decay

B^0 Oscillation properties

Fraction of like sign pairs from oscillation to all like sign B pairs

$$\alpha(m) = \frac{b\bar{b} \to B\bar{B} \to \mu^{\pm}\mu^{\pm}\ (\mathrm{osc})}{b\bar{b} \to B\bar{B} \to \mu^{\pm}\mu^{\pm}}.$$

$$N_{B\bar{B}\to\mu\mu} = \frac{N^{osc}_{\pm\pm}}{\beta} = \frac{\alpha(m)}{\beta} * \frac{N^{B\bar{B},corr}_{\pm\pm}}{A\epsilon}$$

β is fraction of primary-primary B decay to all B decays, a flat mass distribution

A ε is an acceptance and efficiency correction