Future of heavy flavor Measurements in PHENIX

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For the PHENIX Collaboration

RBRC Heavy Flavor Workshop
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This talk

I have been asked to describe the future heavy flavor program of PHENIX.

I will discuss the heavy flavor program using the **upgraded PHENIX detector** at **RHIC** luminosity and at **RHIC II** luminosity.

Near the end, I will try to provide quantitative estimates. Please keep in mind that these quantitative estimates are not to be taken more seriously than **a factor of two or so** (or, in the case of unexpected physics effects, worse than that) for signals that have not been seen yet at RHIC.

From the RHIC II Workshop November 12, 2005

Deconfinement

Charmonium spectra

J/ψ R_{AA} vs p_T and y, $\langle p_T^2 \rangle$ and v_2	**(evidence of coalescence)**
J/ψ, ψ' and χ_c	**(deconfinement, temperature)**
Υ, Υ',Υ''	**(deconfinement, temperature)**

Energy density, temperature

Open heavy flavor R_{AA} and v_2	**(energy loss)**
Gamma-jet correlations (vs RP)	(energy loss)
Charm tagged jets (inc. J/ψ)	**(energy loss)**
Quark jets at high p_T at RHIC	
Three particle correlations	(energy loss, speed of sound)
Direct real and virtual gammas	(temperature, gamma HBT)
Intermediate mass dileptons	(temperature, quasi-particles)

Thermalization

Open heavy flavor R_{AA} and v_2	**(thermalization)**
(p_T, ϕ, RP, flavor dependence)	
Gamma-jet correlations (vs RP)	(thermalization)
Direct thermal photons	(chemical equilibration)

(Heavy flavor topics are highlighted in red)

Where does PHENIX Stand Now?

Quarkonium (pp, dAu, CuCu and AuAu)

$J/\psi \rightarrow ee$ and $\mu\mu$ → R_{AA}: y, p_T dependence to < 5 GeV/c

$\Upsilon \rightarrow ee$ and $\mu\mu$ → Observed in pp

Open heavy flavor (pp, dAu, CuCu and AuAu)

$B+D \rightarrow eX$ → R_{AA} : p_T dependence to ~ 9 GeV/c
→ v_2 to a few GeV/c

$B+D \rightarrow \mu X$ → y dependence (large systematics at present)

ie., we have just started!

Detector upgrades in the next 5 years

PHENIX has extensive upgrade plans that will be completed in the mid near term - **about 5 years**.

These detector upgrades are crucial to the RHIC program both before and after the luminosity upgrade.

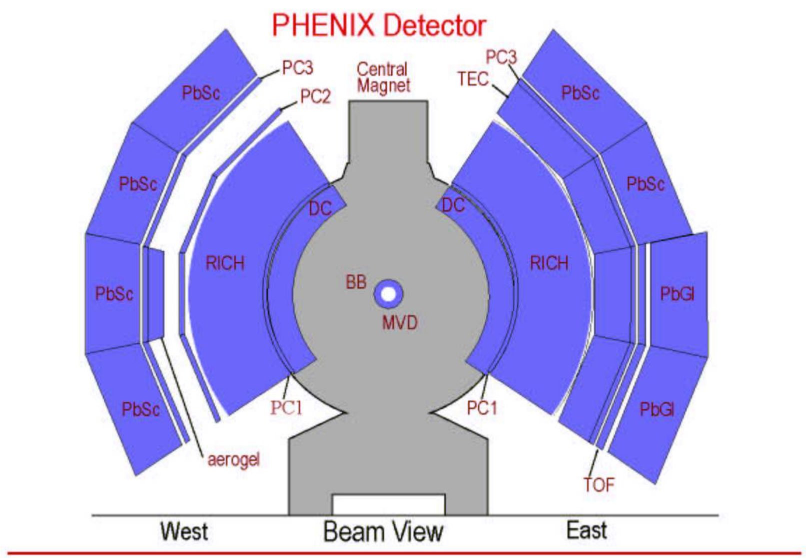
Summary of upgrades:

- **Silicon tracker for heavy flavor, jet physics, spin physics.**
- Forward muon trigger for high rate pp & improved pattern recognition.
- **Nose cone calorimeter for heavy flavor measurements.**
- Aerogel + new MRP TOF detectors for hadron PID.
- Hadron-blind detector for light vector meson e^+e^- measurements.

I will start by discussing the **silicon tracker** and **Nose Cone Calorimeter** first, since these are very important to the heavy flavor program.

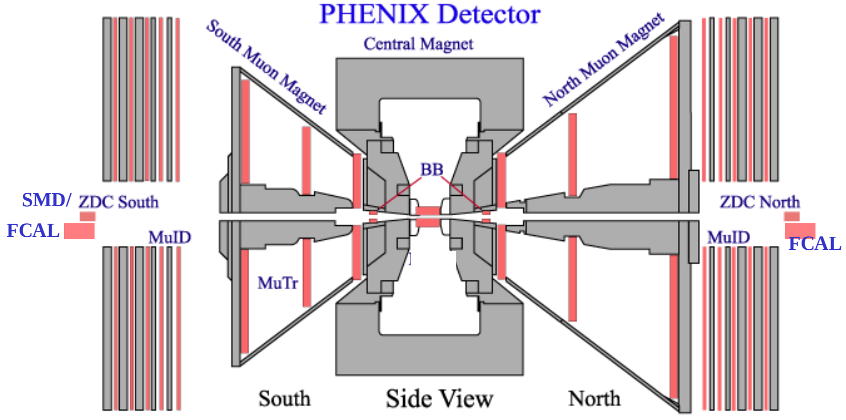
The Upgraded PHENIX Detector

Charged Particle Tracking:
- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)



Particle ID:
- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)

Calorimetry:
- Pb Scintillator
- Pb Glass



Event Characterization:
- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter

Data Acquisition:

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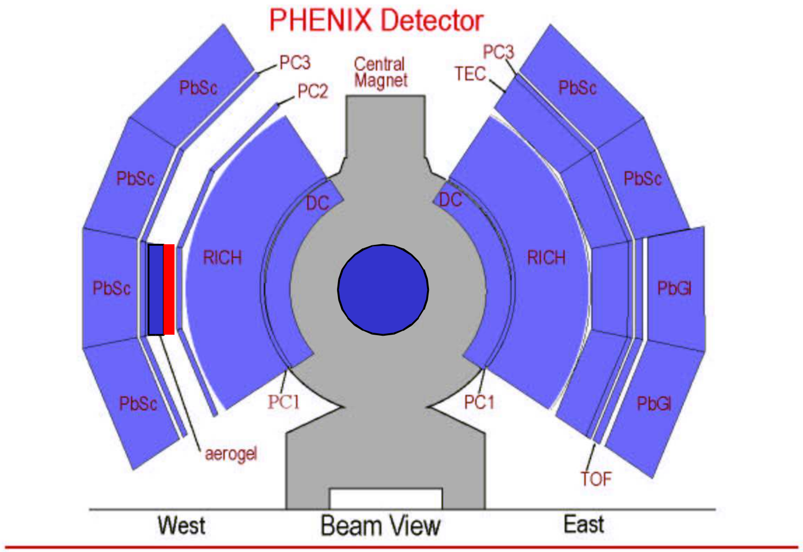
- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)
- Forward Muon Trigger Detector
- Si Vertex Tracking Detector- Barrel (Pixel + Strips)
- Si Vertex Endcap (mini-strips)

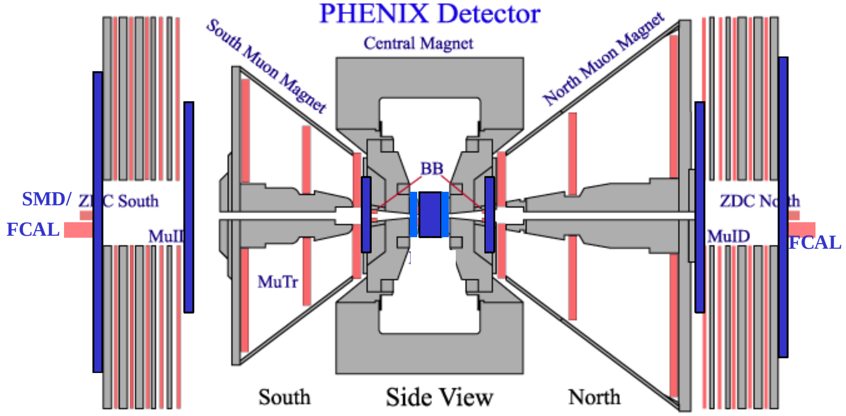
Particle ID:
- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Resistive Plate Chamber Time of Flight
- Hadron Blind Detector

Calorimetry:
- Pb Scintillator
- Pb Glass
- Nose Cone Calorimeter

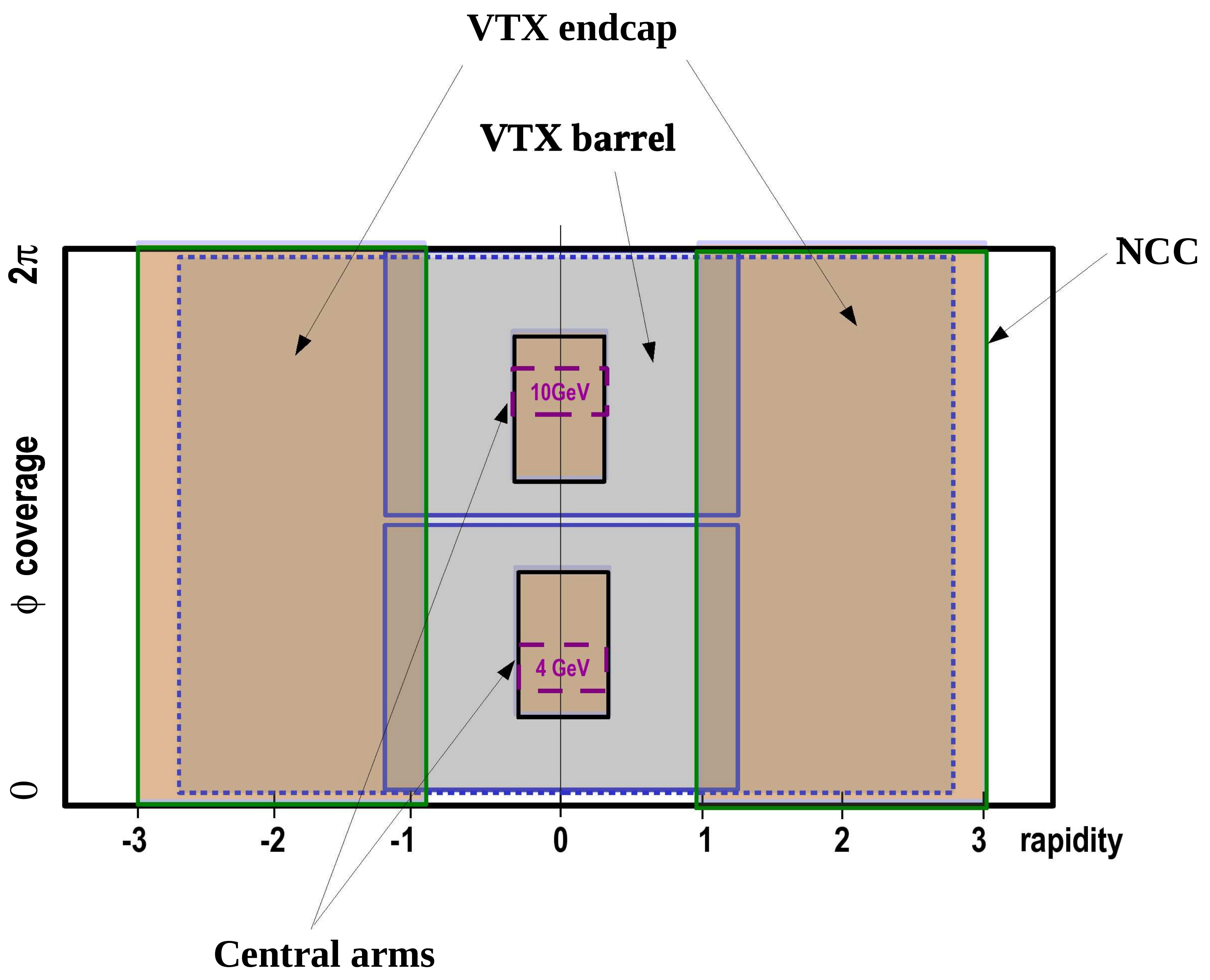
Event Characterization:
- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter

Data Acquisition:
- DAQ Upgrade

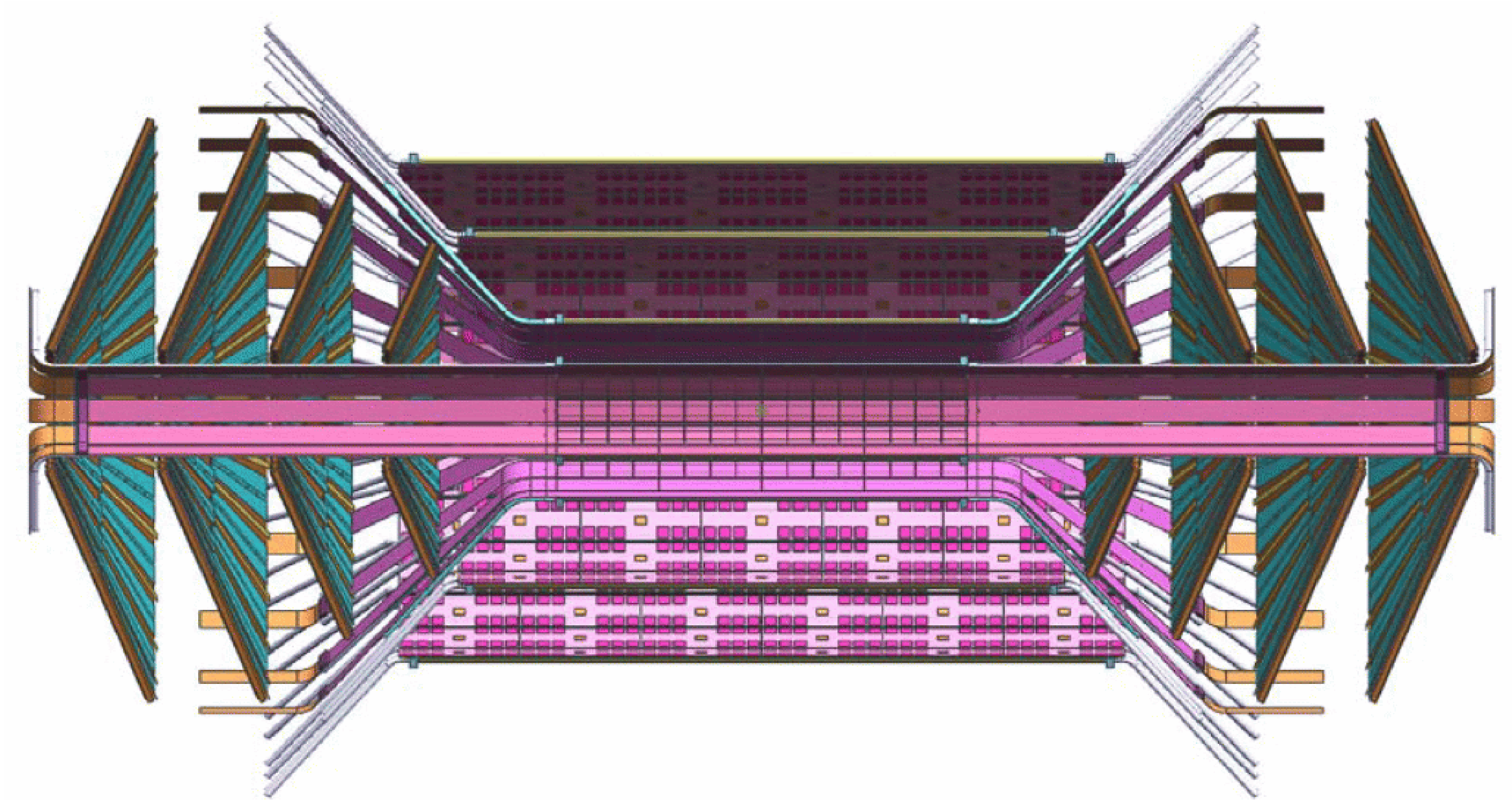




Coverage of PHENIX Detector Upgrades



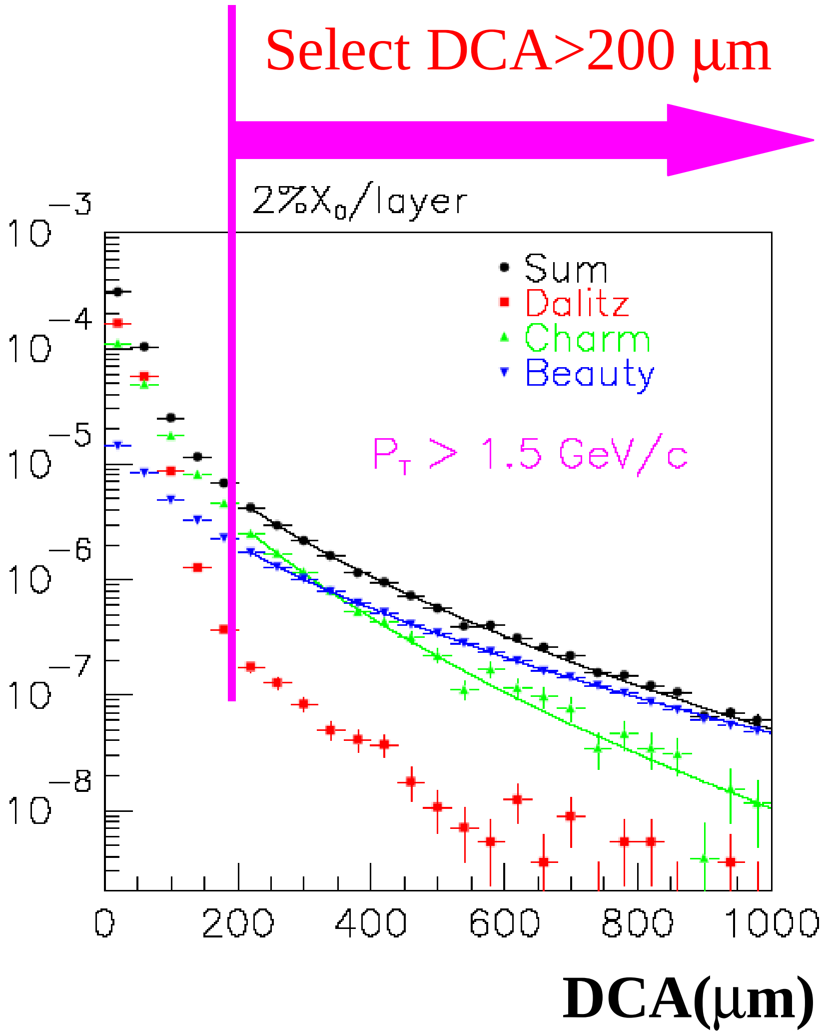
Silicon VTX detectors



Barrel covers η = -1.2 - 1.2, stand alone momentum resolution ~ 10%.
Measures displaced vertex with ~ 50 μm resolution.

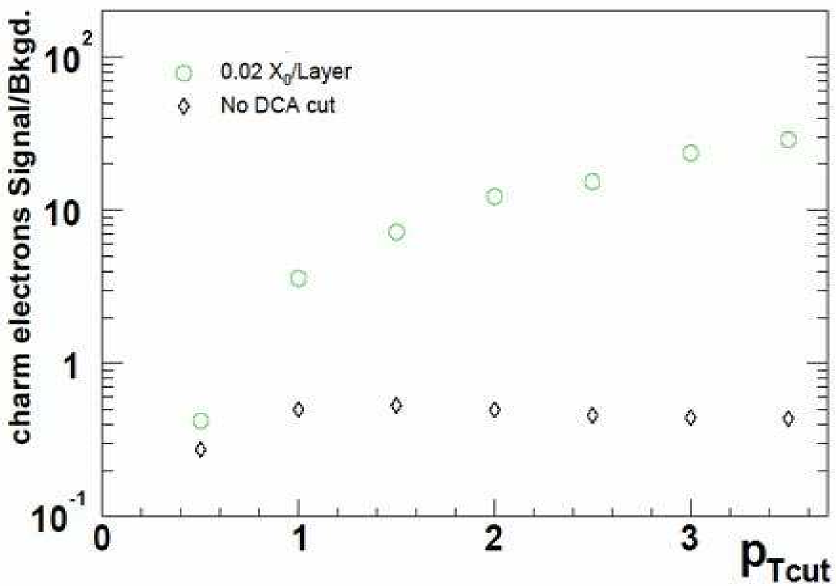
End cap covers 1.2 < $|\eta|$ < 2.2
Measures displaced vertex with < 200 μm resolution.

Identifying Open Heavy Flavor in Central Arm Electron Measurement



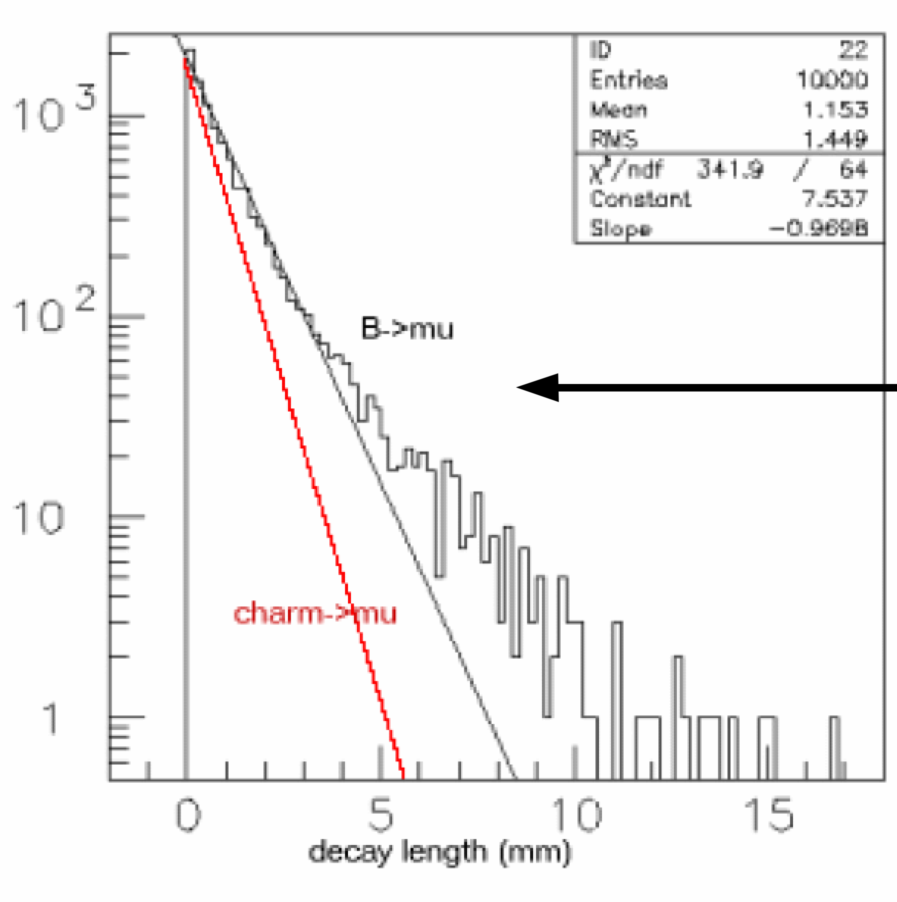
Electron DCA distribution from charm, beauty and π^0 Dalitz decay

meson	Life-time(μm)
$D^{\pm}$	312
D^0	123
$B^{\pm}$	501
B^0	460

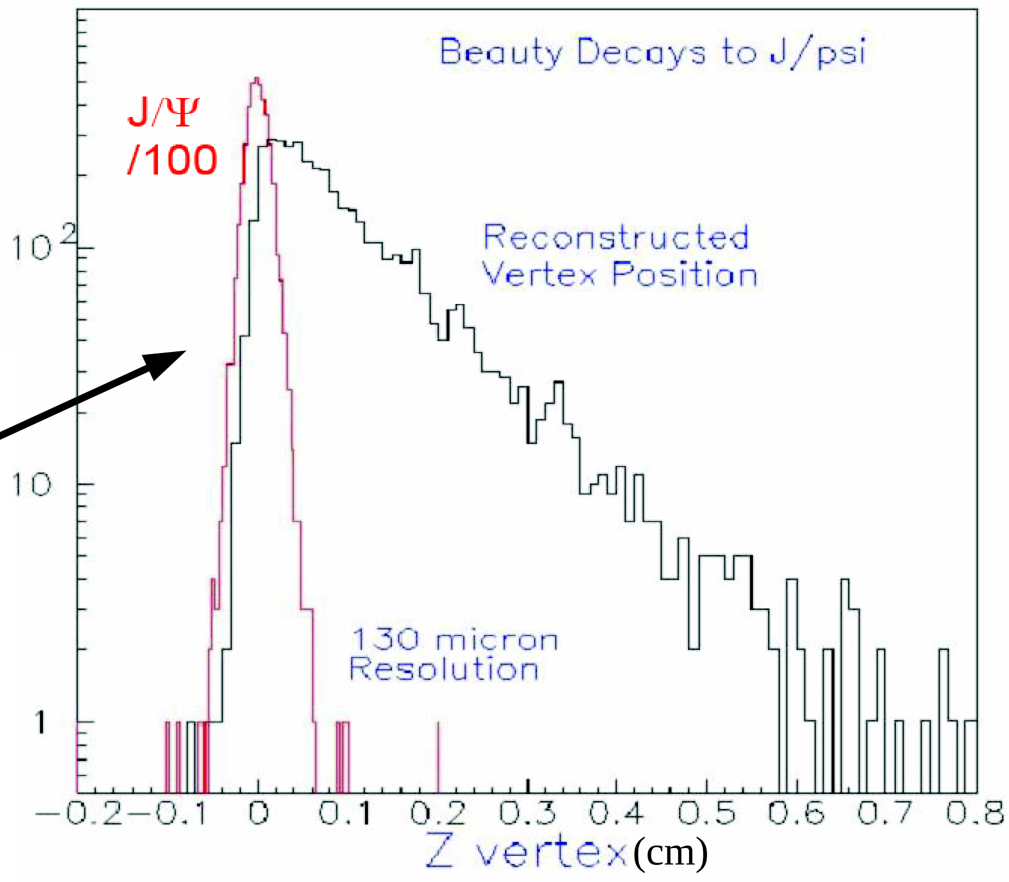


Charm electron **Signal/Background** as a function of p_T cut Factor 20 improvement with DCA cut than without cut at 2 GeV

Identifying Open Heavy Flavor in Muon Measurement



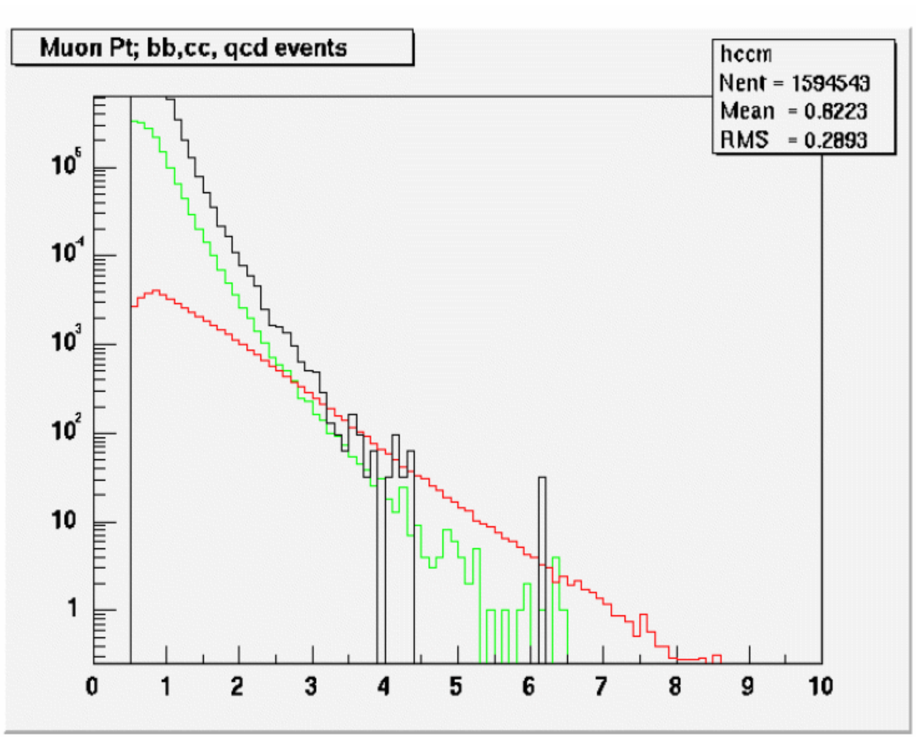
Given enough yield, we can discriminate c and b **statistically** by using different secondary vertex cuts.



Tight vertex cuts (**~ 1mm**) can discriminate between open heavy flavor and prompt tracks

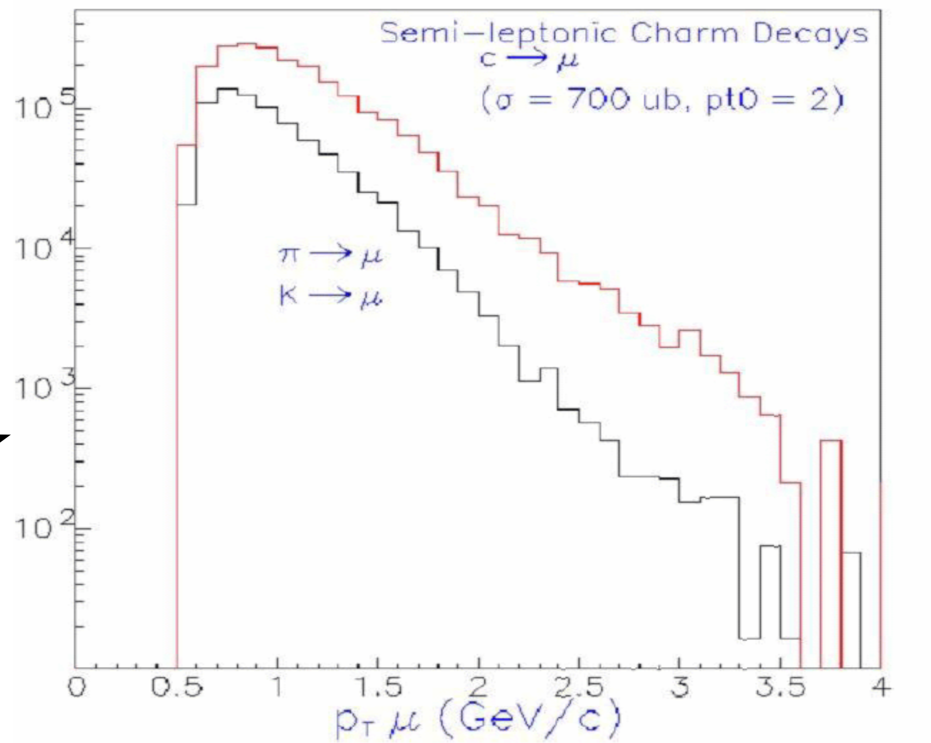
Light Meson Decay Background Reduction in Muon Measurements

Loose vertex cuts (**~ 1 cm**) can discriminate between open heavy flavor and light meson decays.



Without loose vertex cut

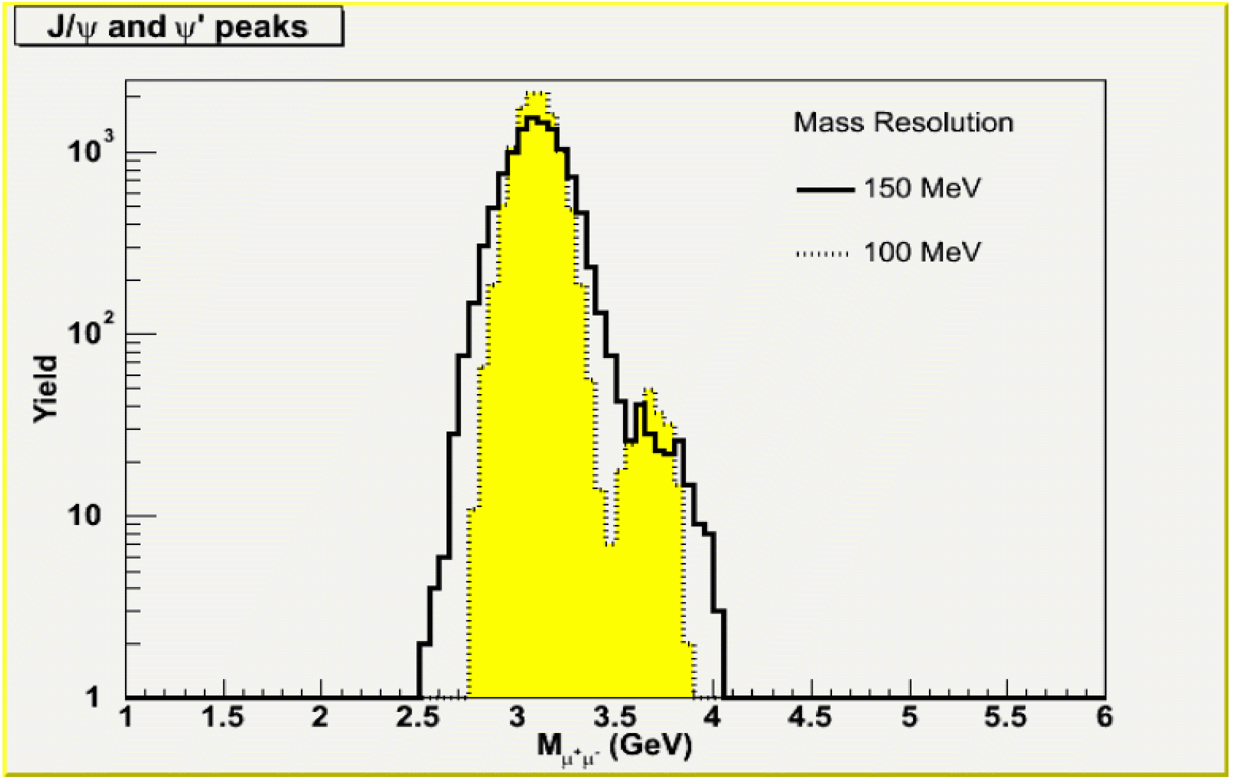
With loose vertex cut



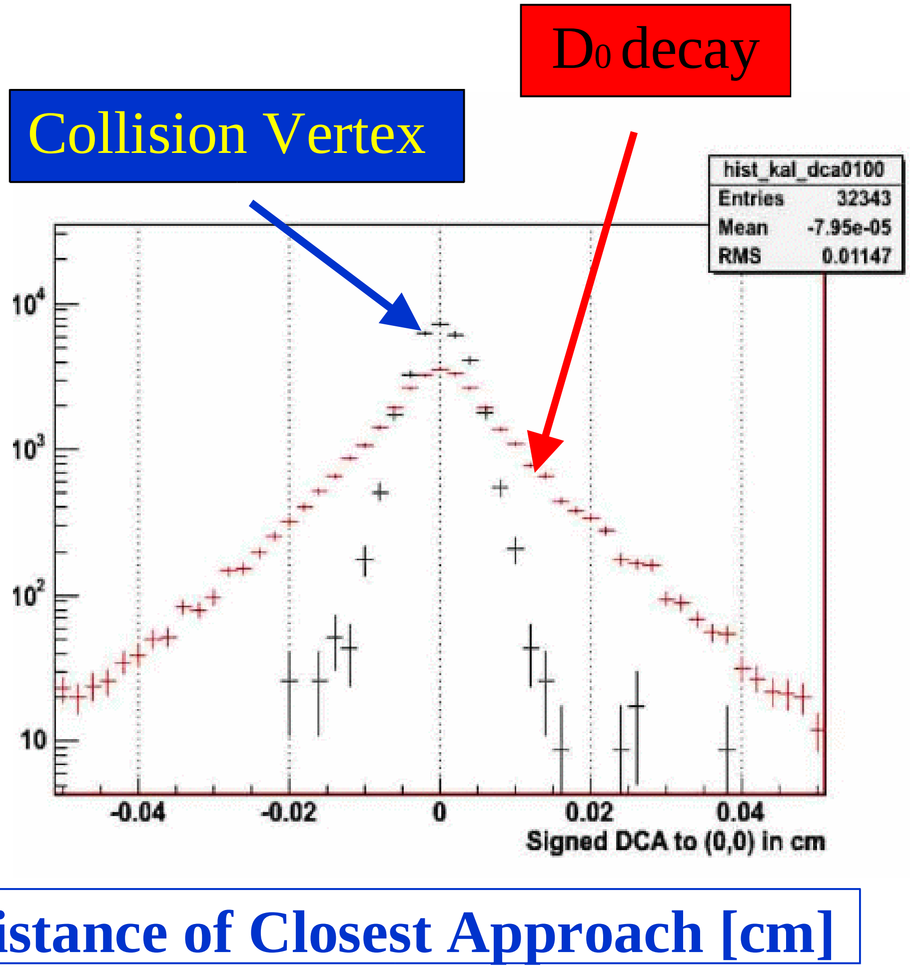
Improved Quarkonium Mass Resolution

Improvement in track momentum measurement leads to better quarkonium mass resolution.

Example shown is for J/ψ and ψ' to dimuons, improvement also in central arms.



The VTX barrel adds the ability to make the **$D^0 \rightarrow K\pi$** measurement in the PHENIX central arms because of the large reduction in background combinatoric yield produced by a displaced vertex cut of 200 μm.

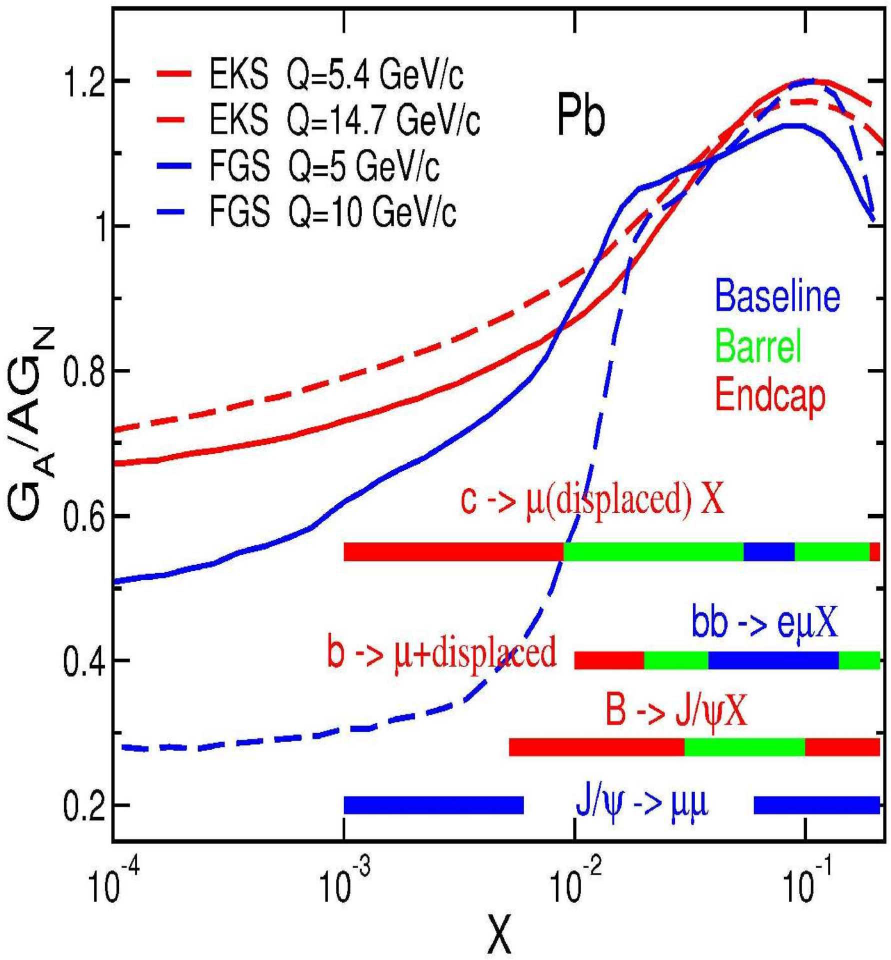


Improved Understanding of the Baseline Physics

Precise comparison of open charm & beauty with quarkonia

• Isolate common effects (e.g. gluon saturation at small-x & initial-state dE/dx).

• From those that are different (e.g. J/ψ absorption)



Summary for VTX detector

Open heavy flavor from tight displaced vertex cuts.

- Much cleaner c+b $\rightarrow$e measurement.
- Separate c$\rightarrow$e and b$\rightarrow$e statistically.
- Separate B$\rightarrow$J/$\psi$$\rightarrow$ee from prompt J/$\psi$.

Background reduction from loose vertex cuts to reduce light meson decays.

- Reduces background in open charm measurements
- Reduces combinatorial background in quarkonium measurements.

Improved momentum resolution $\rightarrow$improved invariant mass resolution.

- J/ψ and ψ' separation
- Upsilon states separation

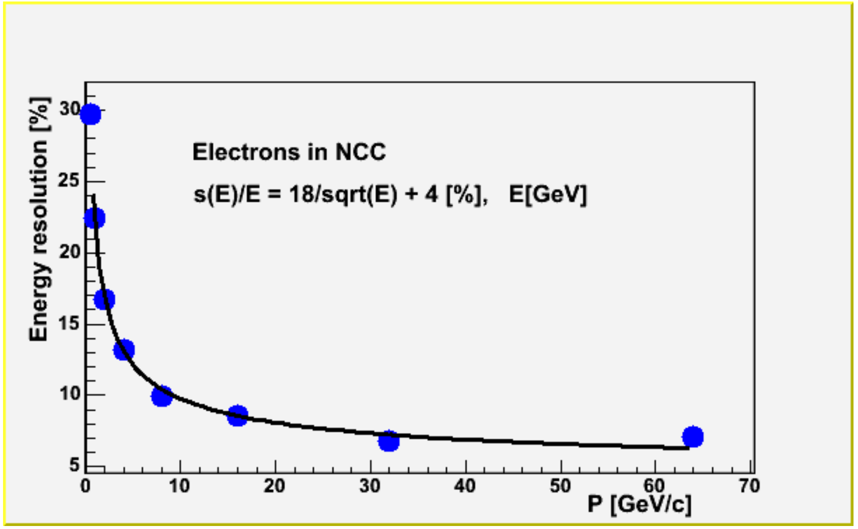
pA program improvements

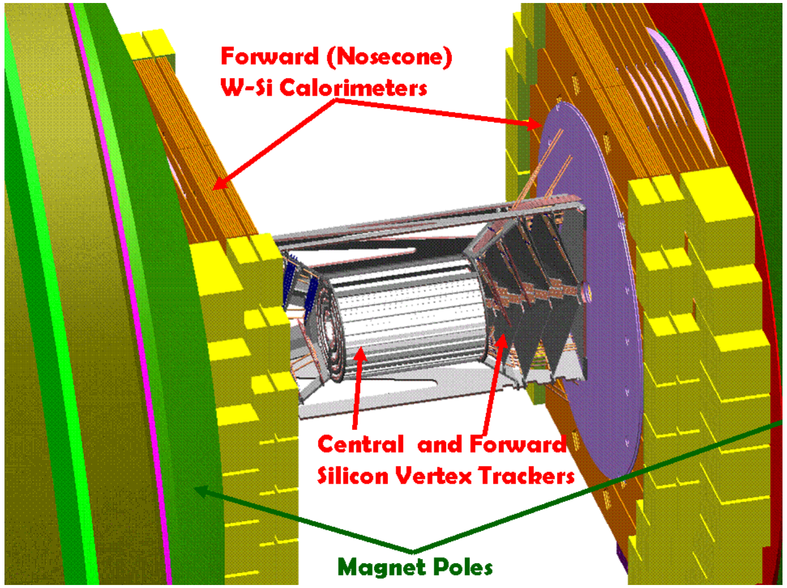
Jet reconstruction in central barrel?

PHENIX Nose Cone Calorimeter

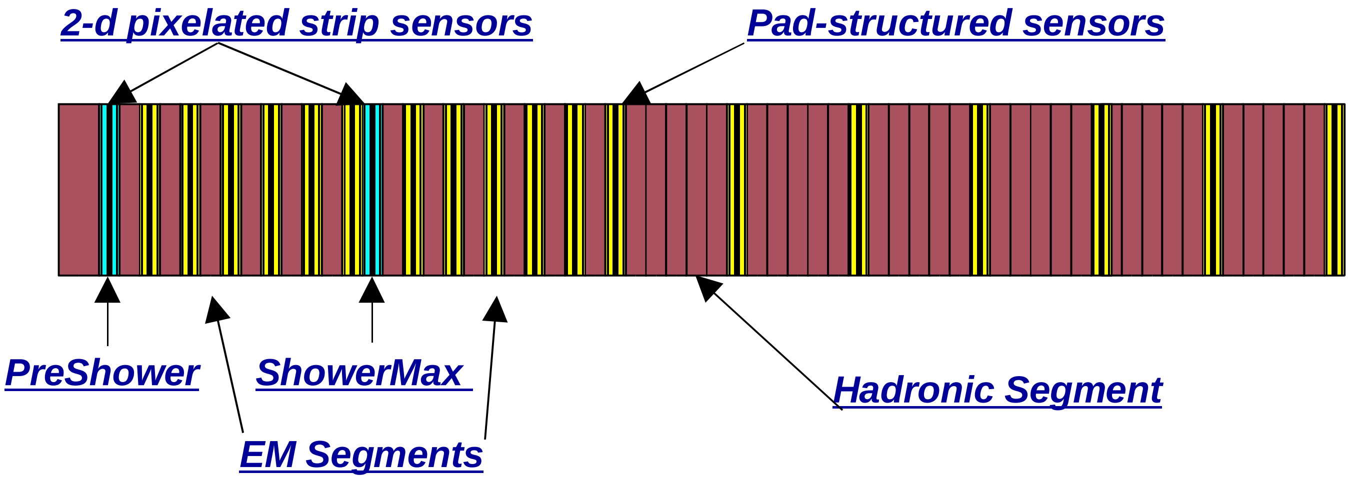
Si-W **EM** and **hadronic** calorimeter

1 < |η| < **3**





Each tower contains a **preshower** and **showermax** detector to separate **single γ** and overlapping γ pairs from **π^0 decays**



$\chi_c \rightarrow J/\psi\, \gamma \rightarrow \mu^+\mu^-\, \gamma$

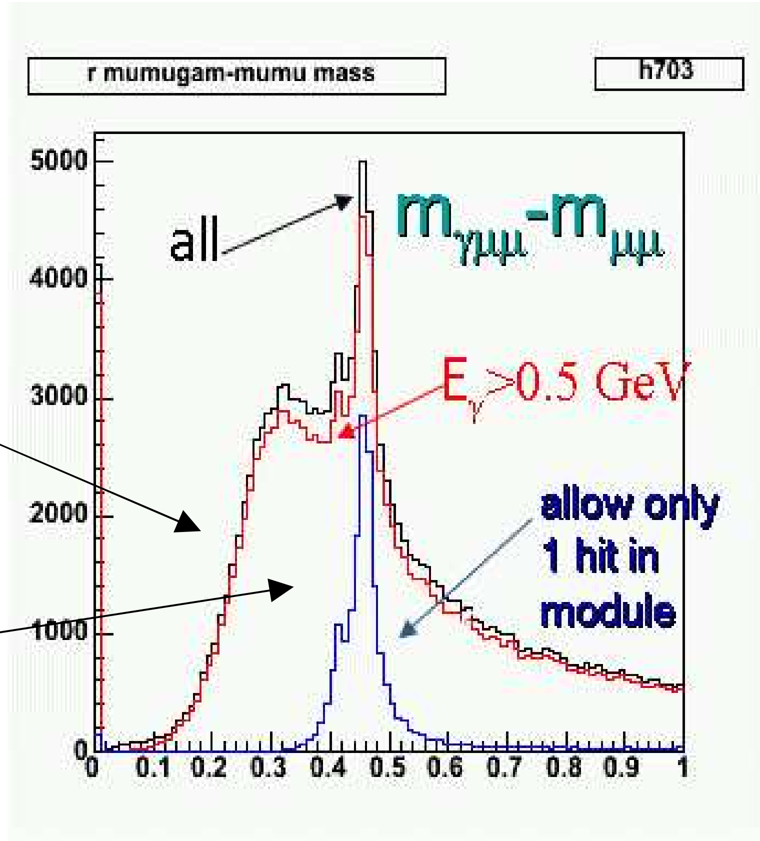
If J/ψ detected in muon arm, 60% of γ are detected in NCC. Plot:

$m(\gamma\mu\mu) - m(\mu\mu) = m(\chi_C) - m(J/\psi)$

for a simulated χ_c embedded in a central AuAu event.

Reject events if preshower+showermax show more than 1 hit in a module.

But we still need to show that the combinatorial background does not kill our signal/background in AuAu



Simulated χ_c embedded in a real AuAu event

Improved Reaction Plane measurement

Because of the limited BBC η range, the PHENIX BBC detector reaction plane resolution results in a correction factor of ~ 3 to measured v_2 values **and their error bars**.

The NCC reaction plane resolution is predicted to be much better due to the much larger η range. The correction factor drops to ~ 1.2, and the error bars **decrease in size by a factor ~ 2.5**.

Summary for NCC

π^0 separation from γ and electrons to 30 GeV/c allows χ_c measurement via $\chi_c \rightarrow J/\psi \rightarrow \mu\mu\ \gamma$.

This measurement will be hard in central AuAu because of the combinatorial background. We are presently trying to quantify the expected signal/background and signal significance.

Even a measurement at Npart ~ 100 would be very useful, since J/ψ suppression is almost fully turned on by then.

The improvement in reaction plane resolution provided by the NCC enhances the J/ψ v_2 precision by ~ 2.5.

What is RHIC II?

RHIC II is a **luminosity upgrade** to RHIC that will produce the following improvements in performance:

		---- Luminosity Delivered / week ---		
Species	**units**	**Obtained**	**RHIC 2008**	**RHIC II**
p+p	pb^{-1}	0.9	26	33
d+Au	nb^{-1}	4.5	--	62
Cu+Cu	nb^{-1}	2.4	--	25
Au+Au	μb^{-1}	160	327	2500

Note: Because the collision diamond has σ = 20 cm at RHIC and σ = 10 cm at RHIC II, the gain in **usable luminosity** is larger than the ratio of delivered luminosity when going to RHIC II.

In the remaining slides I will outline the measurements that we believe we will be able to do with the detector upgrades and luminosity upgrade.

Open Charm and beauty

With PHENIX detector upgrades:

- Dramatically reduce backgrounds for all open charm, open beauty signals using displaced vertex measurements:
  - Eliminate prompt tracks with close vertex cut (~ 1 mm).
  - Eliminate light meson decays with loose vertex cut (~ 1 cm).
- Separate open charm and beauty statistically using displaced vertex.
- Separate B → J/ψ from prompt J/ψ using 1 mm displaced vertex cut.

And with the luminosity upgrade:

- Extend **open charm and beauty R_{AA}** measurements to high p_T. What is the energy loss well above the thermalization region?
- Measure semileptonic charm and beauty decay **v_2 to high p_T**. See the transition from thermalization to jet energy loss for charm.
- Measure **open charm correlations** with open charm or hadrons.

Charmonium and Bottomonium

With detector upgrades:

- J/ψ from B decays with displaced vertex measurement.
- Reduce J/ψ →μμ background with forward μ trigger in PHENIX.
- Improve mass resolution for charmonium and **resolve** Υ family.
- See γ in forward calorimeter in front of muon arms.

And with the luminosity upgrade:

- **J/ψ R_{AA} to high p_T**. Does J/ψ suppression go away at high p_T?
- **J/ψ v_2 measurements versus p_T**. See evidence of charm recombination?
- Υ **R_{AA}**. Which Upsilons are suppressed at RHIC?
- Measure χ_c → **J/ψ**+γ **R_{AA}**. Ratio to J/ψ?
- Measure ψ' **R_{AA}**. Ratio to J/ψ?
- Measure **B** → **J/ψ** using displaced vertex - independent B yield measurement, also get background to prompt J/ψ measurement.

Jet Tagging

With detector upgrades and the luminosity upgrade:

- **b and c tagged jets**. Study heavy quark jet energy loss.
- **Gluon jets** (J/ψ-jet or cc/bb-jet correlations). High p_T J/ψ are from gluon splitting, as are high p_T cc and bb pairs.

Quantitative estimates

In the next few slides I will show some quantitative estimates of the **heavy flavor signal yields** that we can expect at RHIC and at RHIC II. I will focus mostly on quarkonium measurements - these are generally the most statistics starved.

Assumptions for Au+Au at RHIC II:

- J/ψ cross sections from PHENIX data.
- Y and open bottom cross sections from hep-ph/9502270 (agrees with PHENIX preliminary Y measurement)
- Pair reconstruction efficiency 40%
- Trigger efficiency ~ 80%
- PHENIX collision vertex cut 80% (central bucket)*70% in ± 10 cm.
- 1 mm displaced vertex cut (open charm, bottom) 40% efficient.

But first - p_T reach for open and closed charm and beauty

PHENIX has heavy flavor semileptonic decay spectra from Run 4 Au+Au data that extend to ~ 8 GeV/c with good statistics. PHENIX has J/ψ spectra that extend beyond 5 GeV/c with good statistics.

RHIC II will produce about 2 orders of magnitude (x75) more integrated luminosity.

- According to FONLL calculations of p_T distributions for **D** → **e** and **B** → **e** by Ramona Vogt, this will extend the p_T reach by ~ 5 GeV/c to **~ 13 GeV/c**.
- A simple extrapolation of the existing Run 4 PHENIX **J/ψ data** suggests that the p_T reach will increase by ~ 3 GeV/c to **~ 8 GeV/c.**

Heavy flavor yields for PHENIX

200 GeV Au+Au for a 12 week physics run. Other species comparable.

Signal	$\|\eta\|$	**Obtained**	**RHIC I (> 2008)**	**RHIC II**
$J/\psi \rightarrow e^+e^-$	< 0.35	~ 800	3,300	45,000
$J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4	~ 7000	29,000	395,000
$\psi' \rightarrow e^+e^-$	< 0.35		60	800
$\psi' \rightarrow \mu^+\mu^-$	1.2-2.4		520	7,100
$\chi_c \rightarrow e^+e^- \gamma$	< 0.35		220	2,900*
$\chi_c \rightarrow \mu^+\mu^- \gamma$	1.2-2.4		8,600	117,000*
$\Upsilon \rightarrow e^+e^-$	< 0.35		30	400
$\Upsilon \rightarrow \mu^+\mu^-$	1.2-2.4		80	1,040
$B \rightarrow J/\psi \rightarrow e^+e^-$	< 0.35		40	570
$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4		420	5,700

* Large backgrounds, quality uncertain as yet.

Conclusions

RHIC II and the detector upgrades bring us dramatically expanded capabilities in heavy ion collisions, including:

- Separated **open charm and beauty**, R_{AA} and v_2 measurements to high p_T. Clean measurements of heavy quark energy loss.
- **J/ψ R_{AA}** to high p_T. **J/ψ v_2** versus p_T. **J/ψ $\langle p_T^2 \rangle$** vs centrality. Precise J/ψ rapidity dependence. All are strong tests of production models.
- Excited charmonium: $\chi_c \rightarrow$ **J/ψ+γ** and **ψ' R_{AA}**.
- **Υ R_{AA}**. Which Upsilons are suppressed at RHIC?
- **B → J/ψ**. Independent B yield measurement, background to prompt J/ψ.
- **Jets tagged** with J/ψ, b, c, bb, cc - many clean handles on jet properties.

A few comments on RHIC II and LHC

RHIC II

Beams: **p to U**
All combinations $\sqrt{s}$ = **22-200 GeV**

Central Au+Au: $T \sim 2\ T_c$

Detectors:
PHENIX STAR eRHIC detector?

12 weeks / year physics (split runs)
Average luminosity 7 * 10^{27} $cm^{-2}\ s^{-1}$
Au+Au lum/year 18,000 μb^{-1}

$Lint_{RHIC}/Lint_{LHC}$ = **36**

$N_{cc} \sim 10$ $N_{bb} \sim 0.05$ (central)

LHC

Beams: **p to Pb**
p+p $\sqrt{s}$ = **14 TeV**
p+Pb $\sqrt{s}$ = **8.8 TeV**
Pb+Pb $\sqrt{s}$ = **5.5 TeV**

Central Pb+Pb: $T \sim 3.5\ T_c$

Detectors:
ALICE ATLAS CMS

4 weeks / year physics
Average luminosity 5 * 10^{26} $cm^{-2}\ s^{-1}$
Pb+Pb luminosity/year 500 μb^{-1}
$\sigma(J/\psi)_{LHC} = \sigma(J/\psi)_{RHIC}$ * **13**
$\sigma(Y)_{LHC} = \sigma(Y)_{RHIC}$ * **55**

$N_{cc} \sim 115$ $N_{bb} \sim 5$ (central)

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RHIC II

Beams: **p to U**

All combinations $\sqrt{s}$ = **22-200 GeV**

Central Au+Au: **T ~ 2 T_c**

Detectors:

PHENIX STAR eRHIC detector?

12 weeks / year physics (split runs)

Average luminosity 7 * 10^{27} cm^{-2} s^{-1}

Au+Au lum/year **18,000 μb^{-1}**

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N_{cc} ~ 10 N_{bb} ~ 0.05 (central)

LHC

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Pb+Pb luminosity/year **500 μb^{-1}**

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$\sigma(\Upsilon)_{LHC} = \sigma(\Upsilon)_{RHIC}$ * **55**

N_{cc} ~ 115 N_{bb} ~ 5 (central)

RHIC II / LHC Complementarity

RHIC II and LHC, because of their large difference in initial energy density and temperature, explore deconfined matter under substantially different conditions. **To be considered successful, models will have to describe data from both facilities.**

Although the heavy quark cross sections at LHC are much larger than those at RHIC, the much greater RHIC II integrated luminosities cause the heavy flavor yields **per year** to be similar at the two facilities.

The same is **not** true for jet yields. The LHC has far higher jet cross sections, and several times the p_T reach of RHIC II. But conditions are different, and that gives different handles on the physics. And some measurements are expected to be easier at RHIC II.

Backup slides

Heavy flavor yields at LHC - from the LHC experiments

200 GeV Pb+Pb for 1M seconds data taking (ie. 1 month), 500 μb^{-1}.

Signal	ALICE[1]	$\|\eta\|$	CMS[2]	$\|\eta\|$	ATLAS[3]	$\|\eta\|$
$J/\psi \to \mu^+\mu^-$	740,000	2.5-4	24,000	< 2.4	8K-100K	< 2.5
$J/\psi \to e^+e^-$	9,500[4]	< 0.9				
$\psi' \to \mu^+\mu^-$	14,000	2.5-4	440	< 2.4	140-1800	< 2.5
$\psi' \to e^+e^-$	190[4]	< 0.9				
$\Upsilon \to \mu^+\mu^-$	8,400	2.5-4	26,000	< 2.4	15,000	< 2.0
$\Upsilon \to e^+e^-$	2,600	< 0.9				
$D \to K\pi$	8,000	< 0.9				

Prompt J/ψ only

1. Philippe Crochet, EPJdirect A1, 1 (2005), and private comm.
2. Bolek Wyslouch, PANIC LHC satellite workshop
3. Helio Takai, PANIC LHC satellite workshop
4. Minbias + central untriggered events - Philippe Crochet

The yields on the previous slide are from estimates by the LHC experiments. I made some estimates of my own for some signals using published acceptances for ALICE and CMS, with the **same trigger and reconstruction efficiencies** that I used for the RHIC II estimates (80% and 40% respectively).

The p+p cross sections used in my estimates are from **hep-ph/0311048**.

The cold matter corrections (**shadowing+"normal" absorption**) at 5.5 TeV are from recent calculations from R. Vogt (LHC satellite meeting talk).

- J/ψ: 40% at $\eta \sim 0$ 50% at $\eta \sim 2$-4
- Υ : 60% at $\eta \sim 0$ 65% at $\eta \sim 2$-4

My estimates are generally within a factor of 2 of those from the LHC experiments.

Heavy flavor yields at LHC - my numbers in bold black using conservative reconstruction efficiencies

200 GeV Pb+Pb for 1M seconds data taking (ie. 1 month), 500 μb^{-1}.

Signal	ALICE	$\lvert\eta\rvert$	CMS	$\lvert\eta\rvert$	ATLAS[3]	$\lvert\eta\rvert$
$J/\psi \to \mu^+\mu^-$	**380,000**	2.5-4	**40,000**	< 2.4	8K-100K	< 2.5
$J/\psi \to e^+e^-$	9,500[4]	< 0.9				
$\psi' \to \mu^+\mu^-$	**6850**		**731**	< 2.4	140-1800	< 2.5
$\psi' \to e^+e^-$	190[4]					
$\Upsilon \to \mu^+\mu^-$	**4,150**	2.5-4	**8,200**	< 2.4	15,000	< 2.0
$\Upsilon \to e^+e^-$	**1,940**	< 0.9				
$D \to K\pi$	8,000[1]	< 0.9				

Prompt J/ψ only

1. Philippe Crochet, EPJdirect A1, 1 (2005), and private comm.
3. Helio Takai, PANIC LHC satellite workshop
4. Minbias + central untriggered events - Philippe Crochet