Heavy Flavor Results from PHENIX

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Yonsei University for PHENIX collaboration

Outline

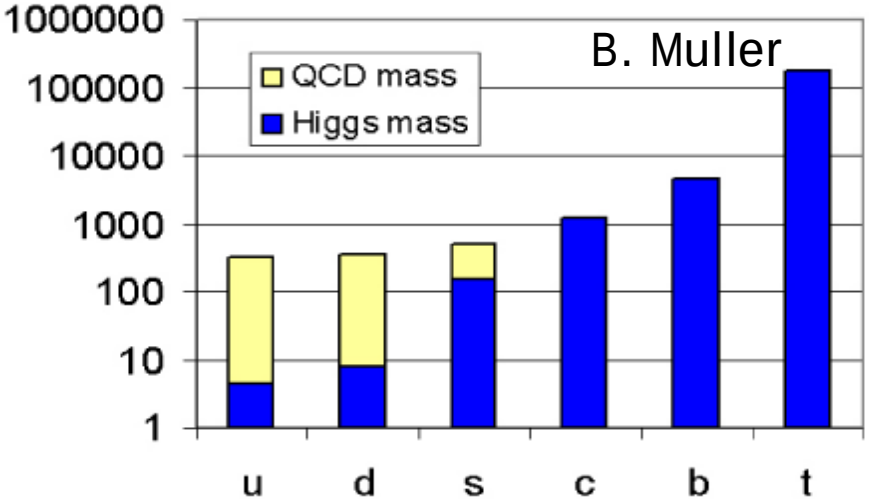
- Why Heavy Flavor ?
- What PHENIX Measured?

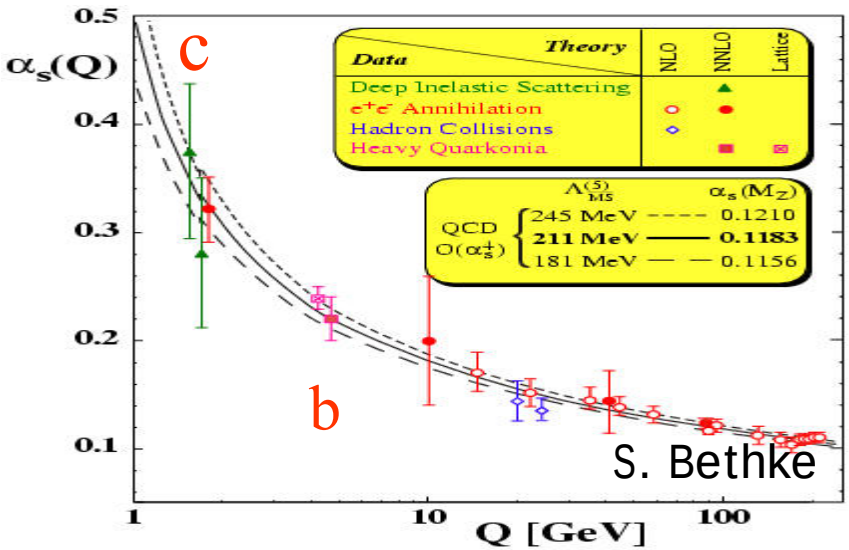
→Open Charm (p-p, d-Au, AuAu)

→ J/Ψ (p-p, d-Au, AuAu)

- Precision measurements →Upgrade
- Summary

Why Heavy Quarks ?



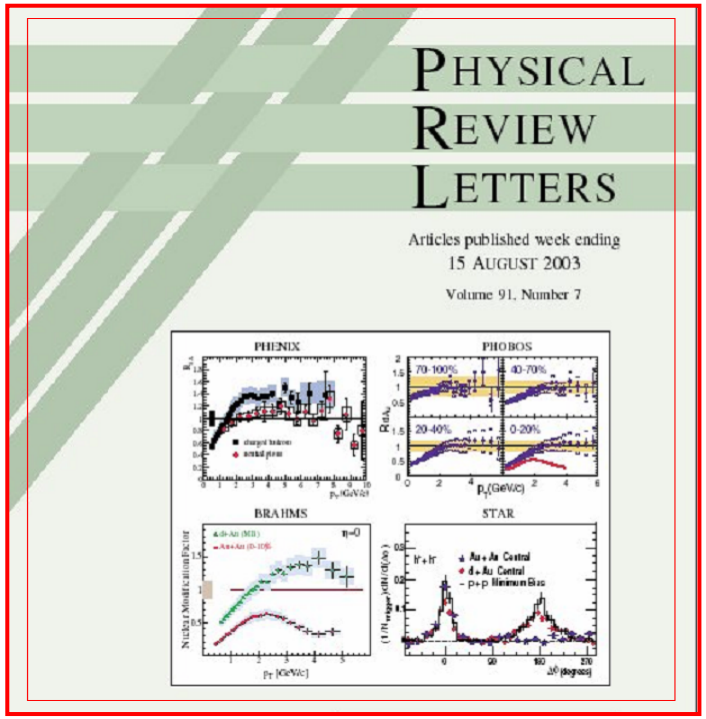


- Heavy quarks (charm and beauty) - produced early in the collision. Live long enough to sample the plasma
- Intrinsic large mass scale allows precise calculations
- Mass dependence of diffusion of heavy quarks determines plasma properties, e.g. viscosity and conductivity
- Yields of charm and beauty pairs compared to first principle lattice simulations determine the energy density and temperature
- Comparison between light and heavy quark suppression distinguishes between theoretical models of energy loss in the QGP

PHENIX

One of the central questions in high energy heavy ion physics is whether a quark-gluon Plasma (QGP) has been discovered at RHIC.

(M.Gyulassy and L. McLerran, nucl-th/0405013, M.Gyulassy, nucl-th/0403032)



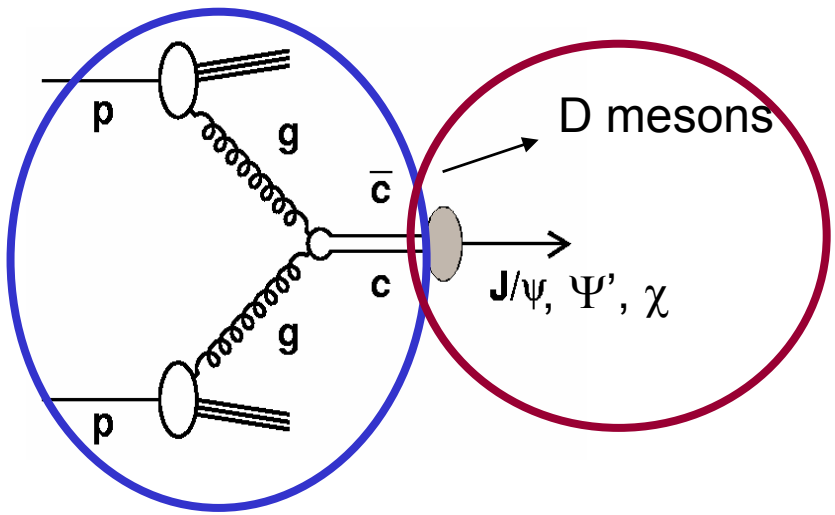
- Collective Flow and Jet Quenching of light partons strongly suggest that QGP is discovered.
- Further detailed tests of jet tomography using heavy quarks could be decisive as a complementary test of the theory.

⌘Open charm suppression, which can now be measured at RHIC by comparing pt distributions of D-mesons in *d-Au* and *Au-Au* collisions, is a novel probe of QGP dynamics.

⌘J/psi suppression or enhancement mechanism should be nailed down with high statistical and systematical precision.

Heavy flavor production

- a (very) complex playground
  - cc production in hard scattering
    - sensitive to PDF
  - propagation
  - hadronization
- medium modifications
  - modification of PDF in nuclei (shadowing, antishadowing)
  - multiple scattering $\Rightarrow p_T$ broadening
  - initial state parton energy loss
  - charmonia:
    - "normal" nuclear absorption
    - "anomalous" suppression ("Debye" screening)
    - enhancement via "coalescence"?
  - additional "thermal" production?
  - energy loss by induced gluon radiation? "Dead-cone effect"?



- **how to disentangle this?**
- **measure charmonium states and open charm**
  - **in pp, pA, AA collisions**
  - **in various kinematic regions**
  - **at various energies**

What can we measure?

- Open heavy flavor (HF)
  - y, p_T dependence
  - Centrality dependence
  - Reaction plane dependence
  - Tagged HF jets
- J/Ψ
  - y, p_T dependence
  - Centrality dependence
  - Reaction plane dependence
  - J/Ψ - hadron correlations
  - Polarization
  - Ψ', χ_c and B contributions
  - Compare to Ψ', ϒ
- Everything should be studied vs √s, collision species.

What have we measured

- Open heavy flavor (HF)
  - y, p_T dependence ✓ABe(y=0,pp,pA,AA, y=0)
  - Centrality dependence ✓ABe(y=0,pA,AA)
  - Reaction plane dependence ✓ABe(y=0)
  - Tagged HF jets ✓C

✓A - ✓B - ✓C - ✓D

Very Good , Good, started, will start

✓e ➔ statistics !!!

- J/Ψ
  - y, p_T dependence ✓ABe(pp,pA,AA)
  - Centrality dependence ✓ABe(pA,AA(y=0))
  - Reaction plane dependence ✓Ce(y=0?,y>0)
  - J/Ψ - hadron correlations ✓Ce
  - Polarization ✓Ce(y=0,pA)
  - Ψ', χ_c and B contributions ✓D
  - Compare to Ψ', ϒ ✓D
- Everything should be studied vs. √s, collision species.

c : $0.8 < p_T$ (GeV/c) < 2.5
$c+b$: p_T(GeV/c) < 4.5
Species : pp, dAu, CuCu, AuAu
√s : 200 GeV, 62.4GeV, 130GeV

Statistics : More is always better (allows reduction in statistical and systematic errors)

Open Heavy Flavor Measurement

- How to measure open heavy flavor?
- Results from Electron channel

  p-p, dAU, AuAu 200GeV

  AuAu 62.4GeV
- Results from Muon Channel

  p-p 200GeV

How to measure Heavy Flavor ?

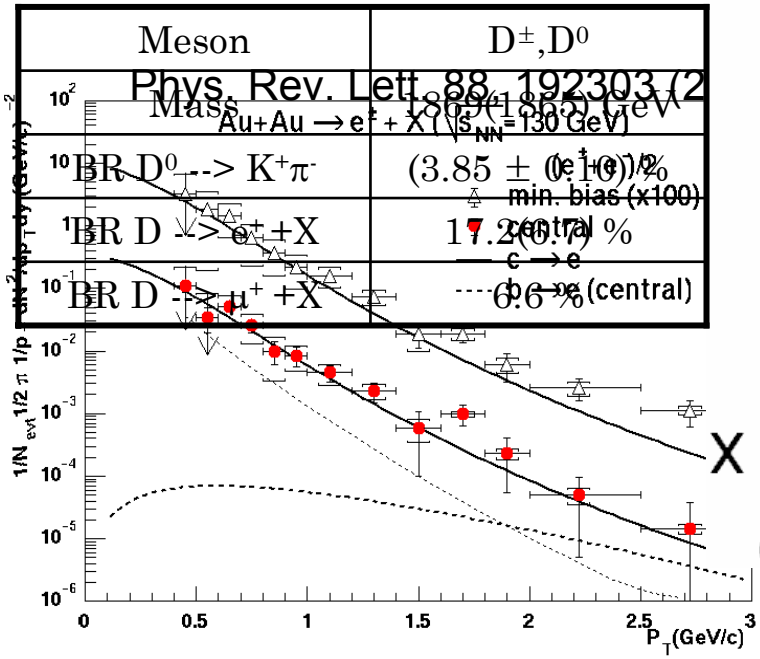
➢ Experimentally observe the decay products of Heavy Flavor particles (e.g. D-mesons)

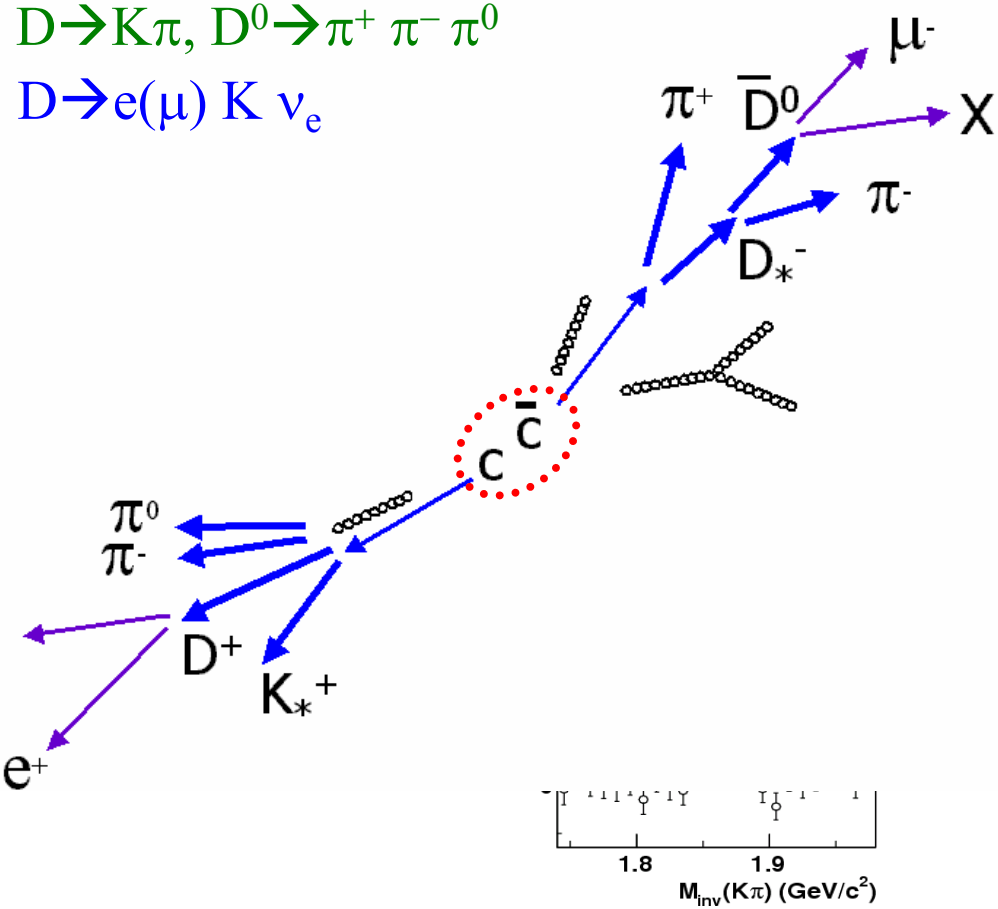
- PHENIX
  - Single electron measurements in p+p, d+Au, Au+Au $\sqrt{s_{NN}}$ = 130,200,62.4 GeV
  - Semi-leptonic decays $D \rightarrow e(\mu)\, K\, \nu_e$
- STAR
  - Direct D mesons hadronic decay channels in d+Au

Hadronic decay channels $D \rightarrow K\pi$, $D^0 \rightarrow \pi^+ \pi^- \pi^0$

Meson	$D^{\pm}, D^0$
Mass	1869(1865) GeV
BR D^0 --> $K^+\pi^-$	(3.85 ± 0.16) %
BR D -> $e^{\pm}$+X	17.2(6.7) %
BR D -> μ^+ +X	6.6 %

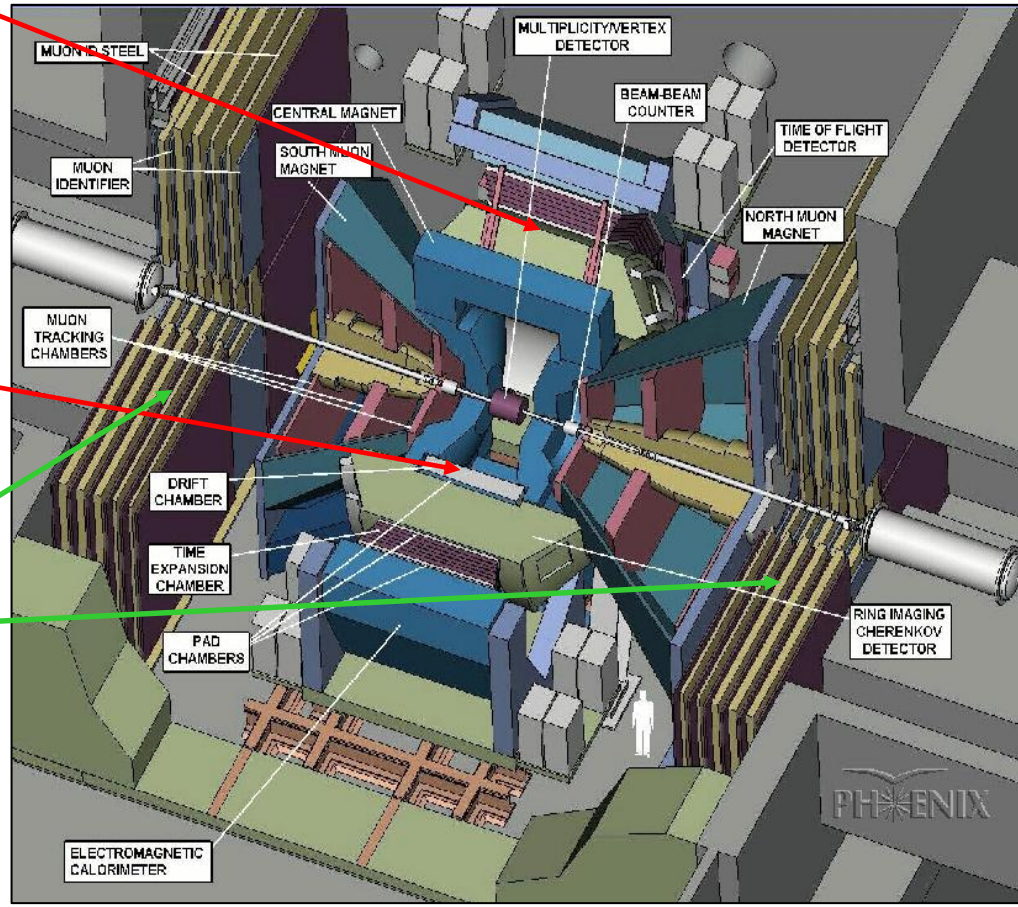
Phys. Rev. Lett. 88, 192303 (2





PHENIX detector at RHIC

- Electron measurements
  - $|\eta|<0.35$
  - Two separate arms $2x\Delta\phi = 90^0$
  - $\delta p/p \sim 1\%\ p$
- Electron ID
  - RICH (γ_{thr}=35)
  - e/π separation up to $p_T \sim 4.8$ GeV/c
- Muon measurements
  - $1.2 < |\eta| < 2.4$
  - Two separate arms in forward and backward rapidity



Cocktail Subtraction Analysis

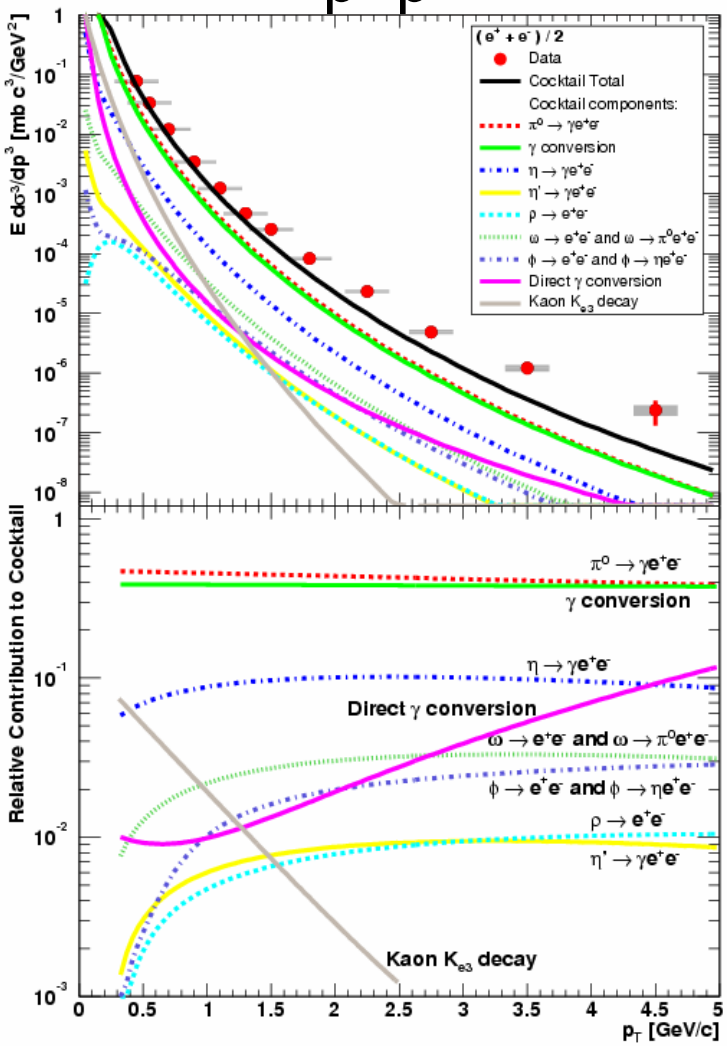
- Calculate inclusive single electron spectrum from all known electron sources:
  - π^0 Dalitz decay (dominant contributor at low pt)
  - Photon conversions in PHENIX material
  - Other light meson's (η, η', ρ, ω, ϕ) leptonic decays
  - Direct radiation contribution
  - Weak kaon decays electrons (K_{e3})

- Input to the Cocktail
  - π^0 & $\pi^{\pm}$ invariant p_T distributions as published by PHENIX
  - Yield ratios of other light mesons to pions as measured at RHIC (where available)
  - Use m_T scaling of pion momentum distribution for light mesons
  - Photon conversions from full simulation of PHENIX apparatus
  - Direct γ and K_{e3} from PHENIX measurements

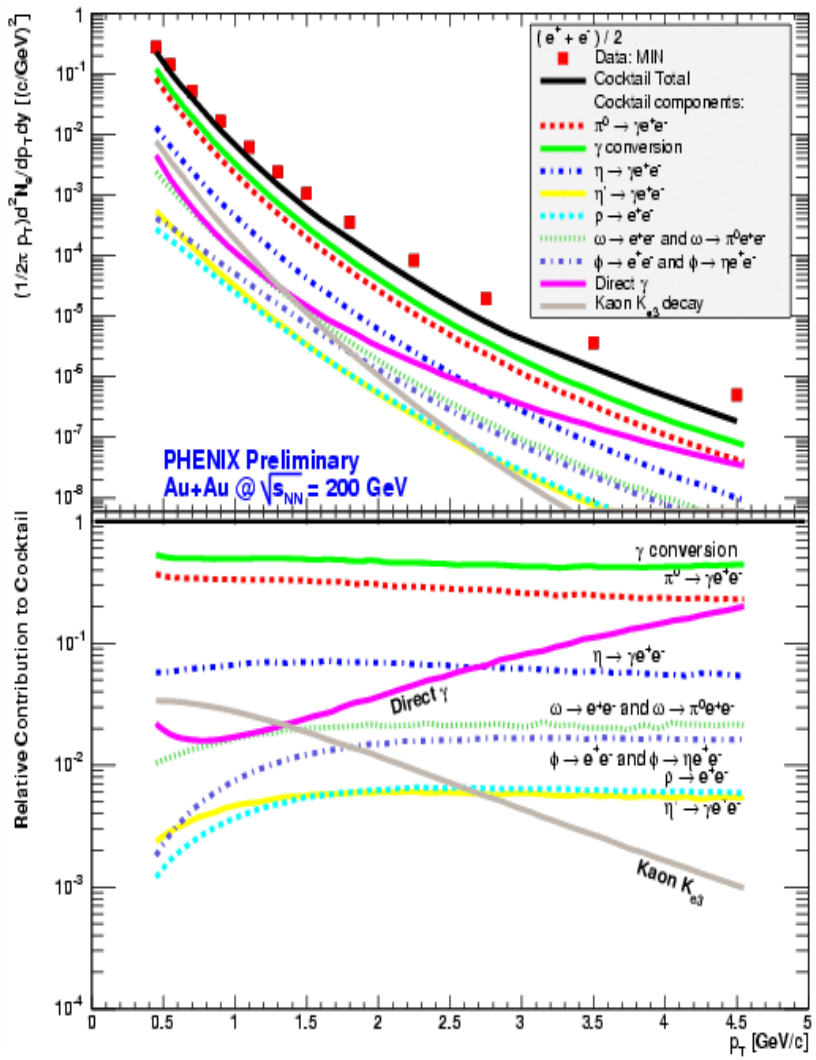
- Excess of the data over the Cocktail prediction can be interpreted as heavy flavor particle semi-leptonic decays contribution

Cocktail vs. Data

p+p



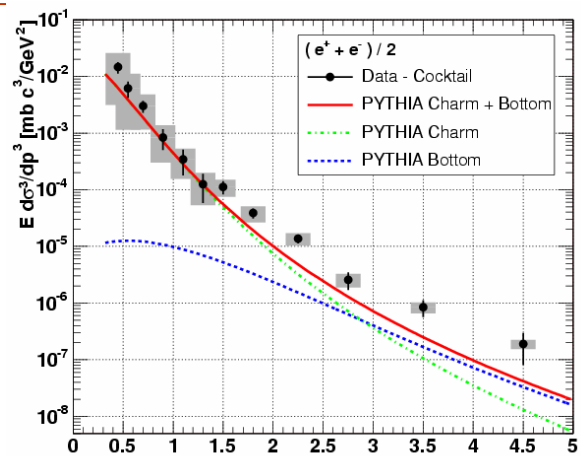
Au+Au Min. Bias



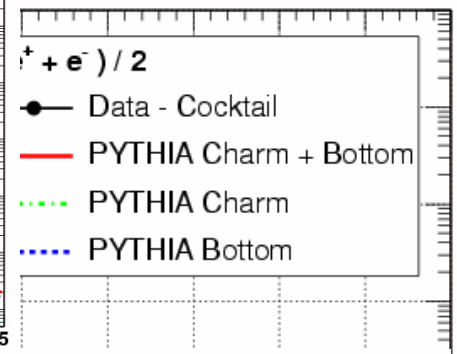
Non-Photonic Single Electron Spectra

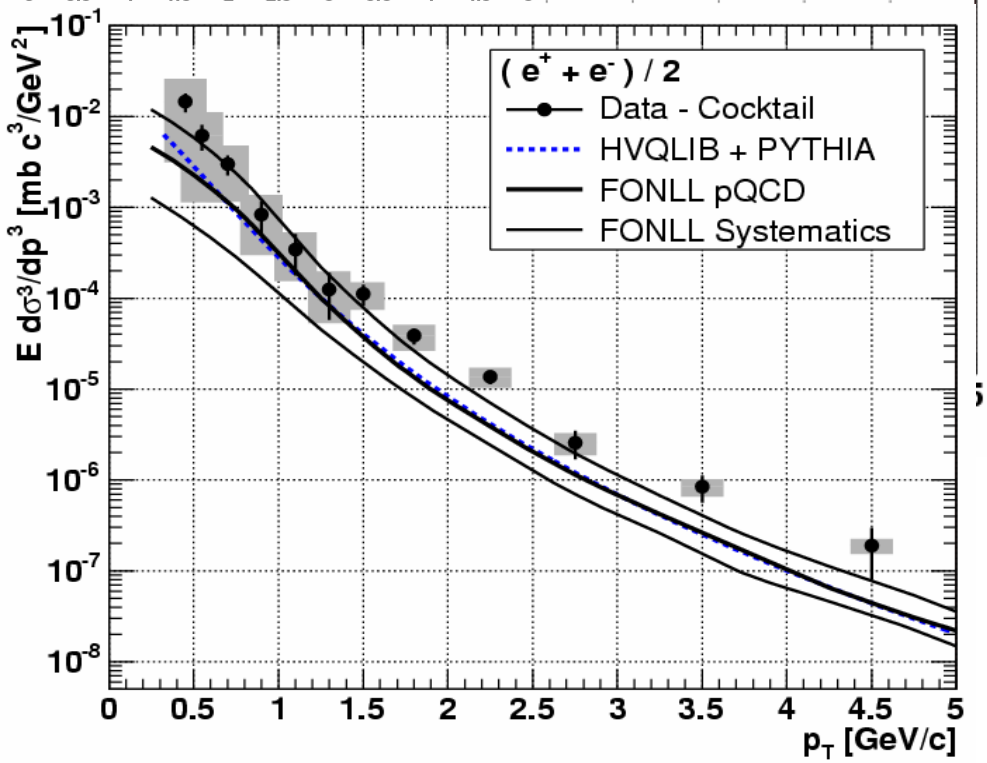
pp @ √s = 200 GeV

- Comparison with PYTHIA (tuned to available data)
  - p_T < 1.5 GeV/c: reasonable
  - p_T > 1.5 GeV/c: spectra "harder" than PYTHIA LO
    - hard fragmentation?
    - bottom enhancement?
    - higher order contributions?
- Comparison with FONLL
  - Fixed Order Next-to-Leading Log pQCD calculation (M. Cacciari, P. Nason, R. Vogt hep-ph/0502203)
  - better description of spectral shape
  - still room for further contributions
    - from jet fragmentation?



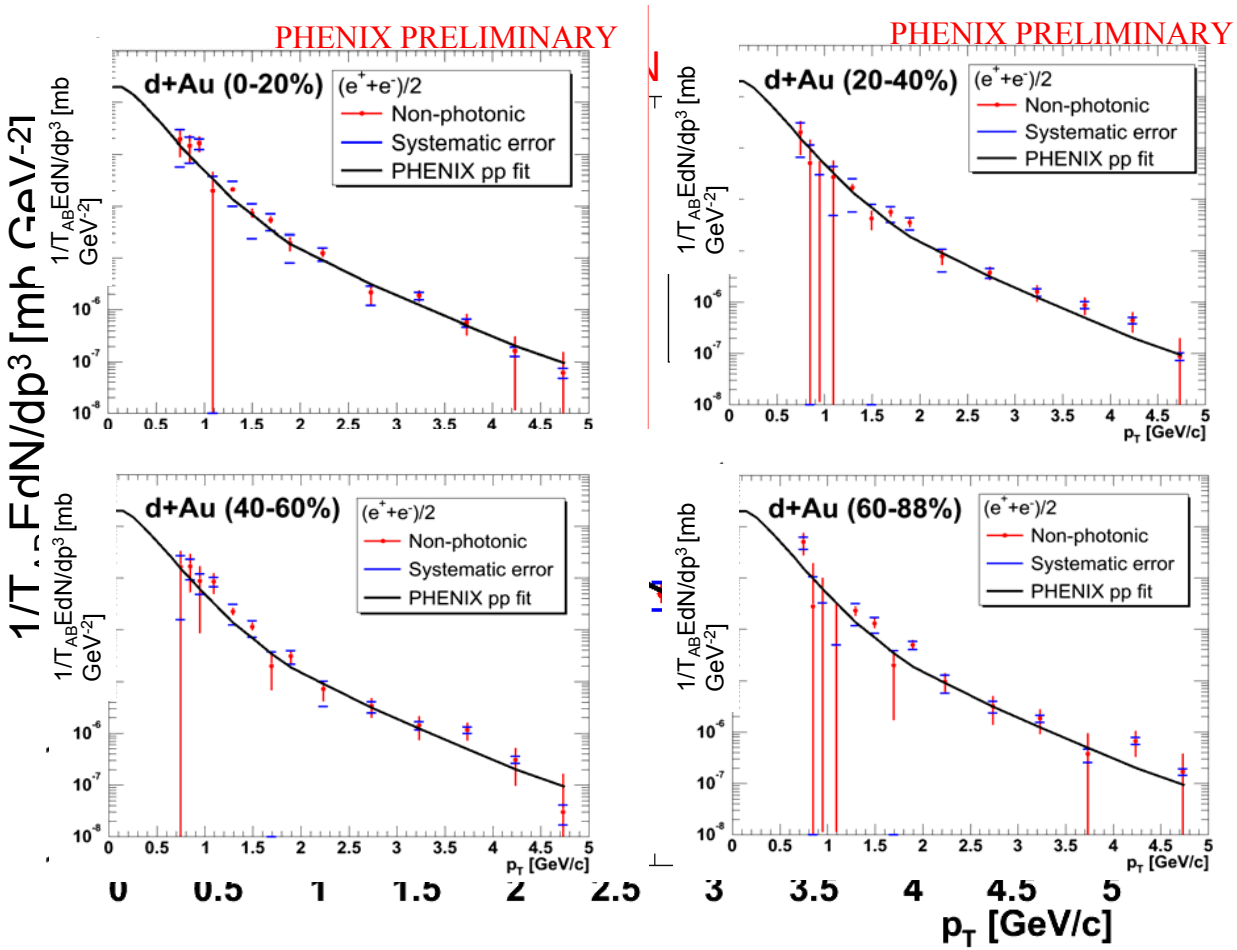
PHENIX data





Non-Photonic Single Electron Spectra

d-Au √s = 200 GeV

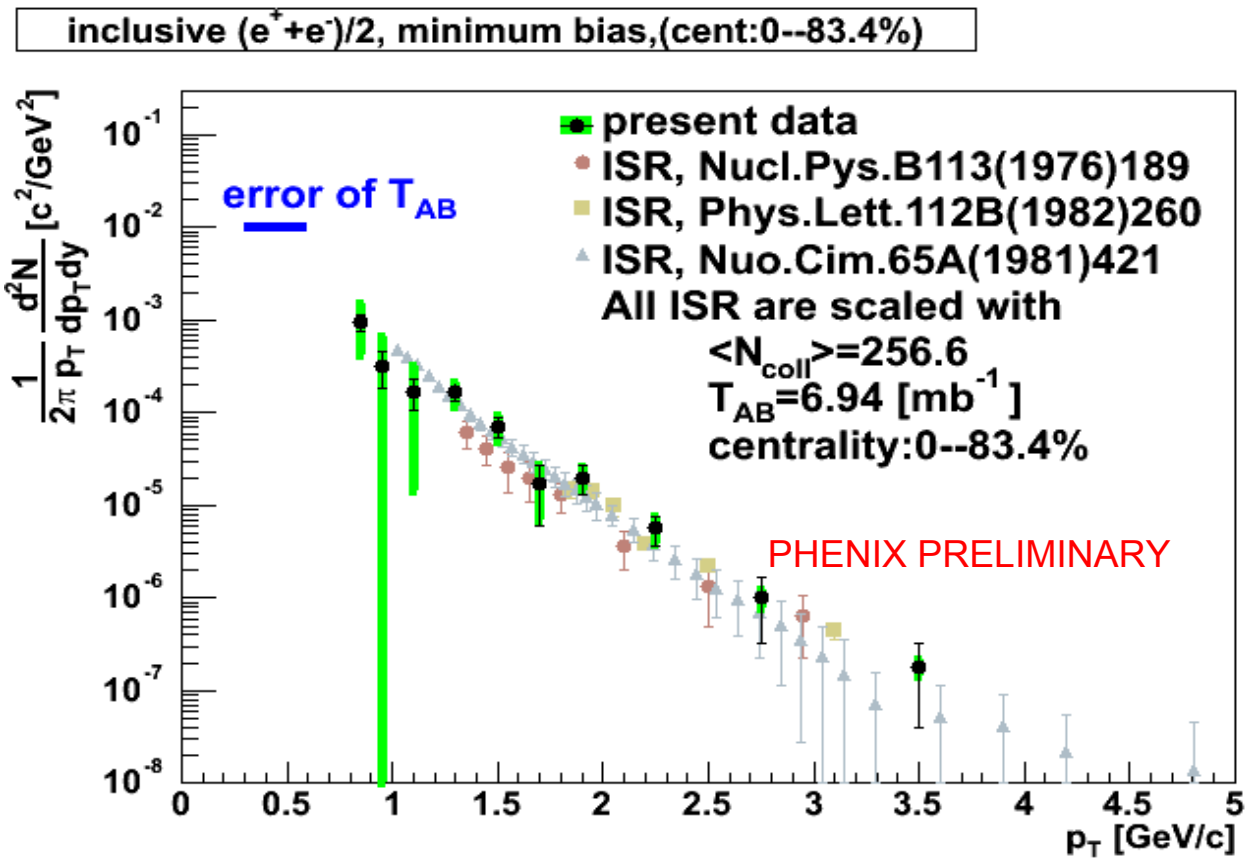


- Scale with number of collision in d-Au collision
- no indication of shadowing effect at mid-rapidity.

PHENIX Non-Photonic Single Electron Spectra

Au-Au @ √s = 62.4 GeV

- Spectra agree with the ISR *p-p* data scaled by T_{AB} i.e. with the number of binary collisions Ncoll with uncertainty.



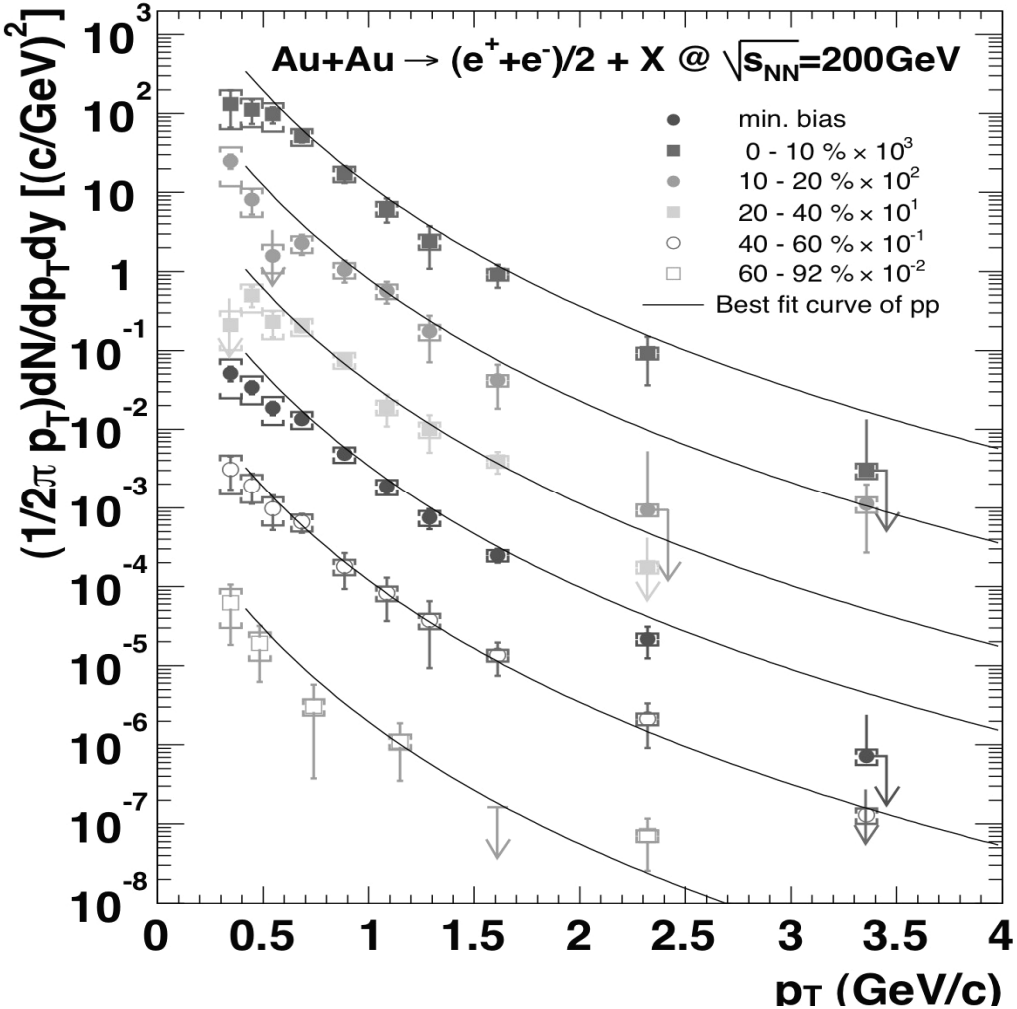
$$T_{AB} = \frac{\langle N_{binary} \rangle}{\sigma_{pp\ \text{inel.}}}$$

PHENIX Non-Photonic Single Electron Spectra

Au-Au @ √s = 200 GeV

- "Converter subtraction" method used
- Limiting factor - statistics of Converter run period (Insufficient statistics at p_T > 1.5 GeV/c to study modification of spectral shape)
- Statistics is too low to make a definitive statement about spectral shape or centrality dependence

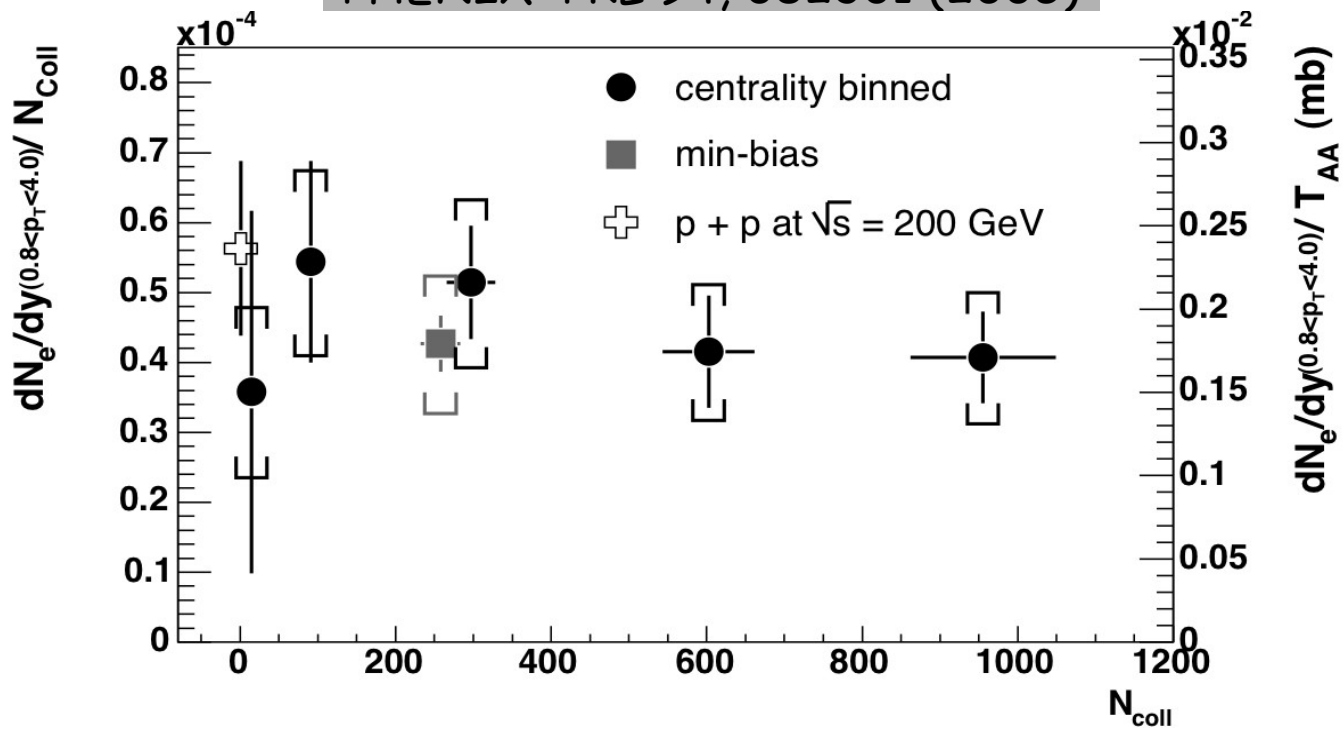
PHENIX: PRL 94, 082301 (2005)



Binary Scaling of Electron Yield

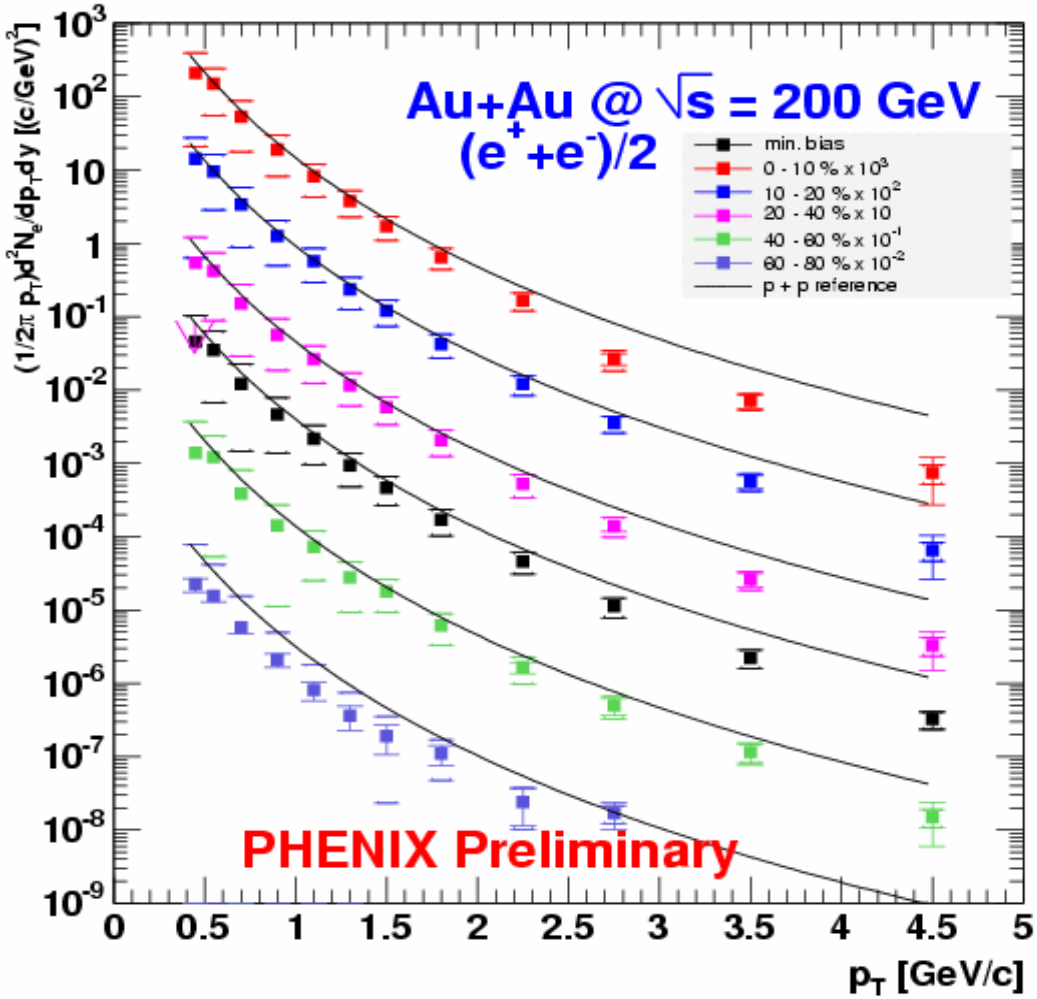
- dN/dy of "Non-photonic" electrons for $p_T > 0.8$ GeV/c indicates scaling with N_{coll}
- $dN/dy \sim Nc_{oll}^{a}$ where $0.906 < a < 1.042$ within 90% C.L.

PHENIX: PRL 94, 082301 (2005)

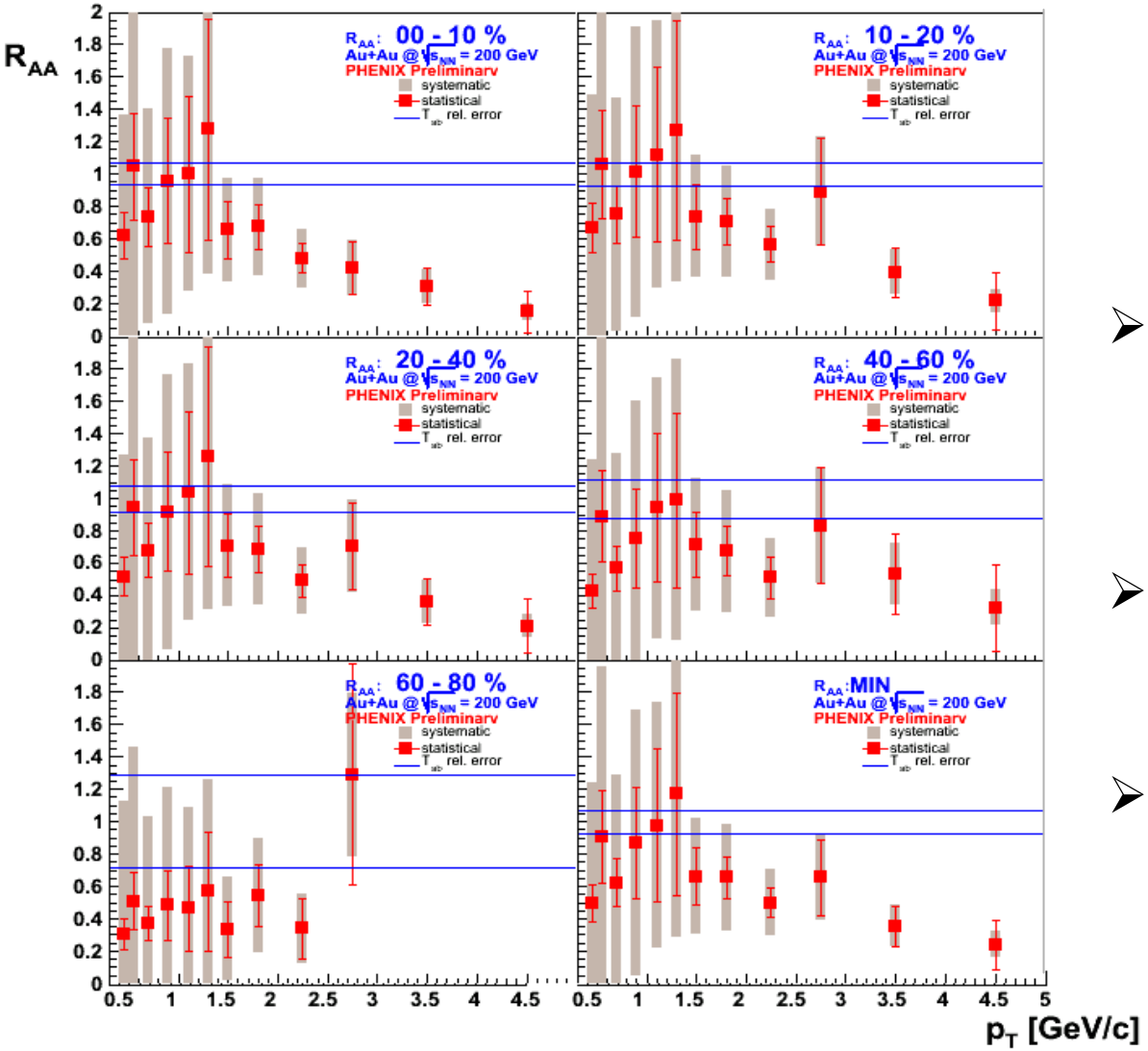


Cocktail Subtraction analysis in Au+Au

- Cocktail analysis has ~ 4.5 higher statistics
- Systematic error is higher at low p_T due to small S/B
- Clear suppression of electron yield at high p_T is observed at most central bins



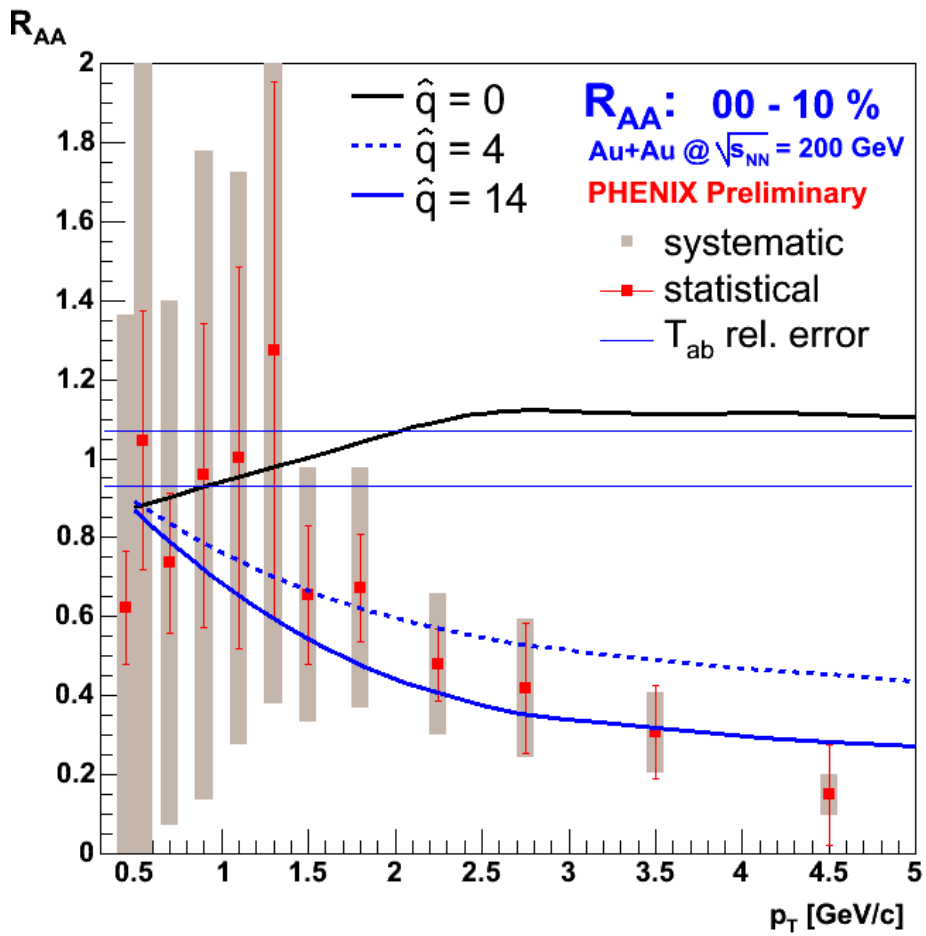
Nuclear Modification Factor R_{AA}



$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

- Strong modification of the spectral shape in Au+Au is observed at high p_T
- Systematic error on T_{AA} is large for 60-80% centrality bin
- Statistics insufficient to quantify centrality dependence

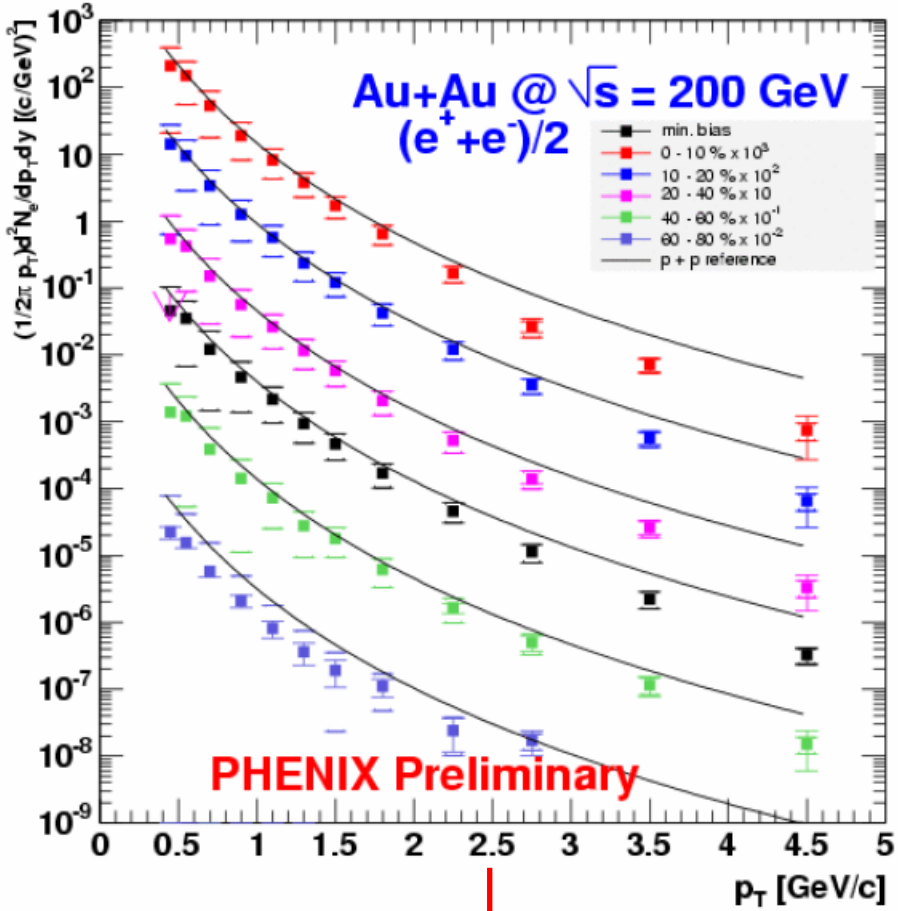
Theory Comparison

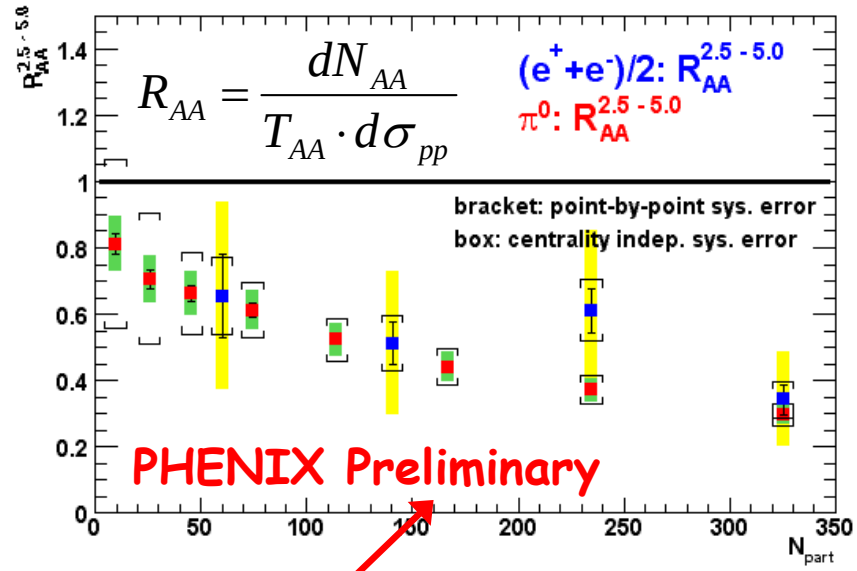


- Observed suppression is in good agreement with theoretical predictions for the final state energy loss of heavy flavor
- Charm only component is used for comparison, Bottom electron contribution need to be taken into account at $p_T > 4$ GeV/c

Theory curves from N. Armesto, *et al.*, hep-ph/0501225

Charm $R_{AA}(p_T) \neq 1$



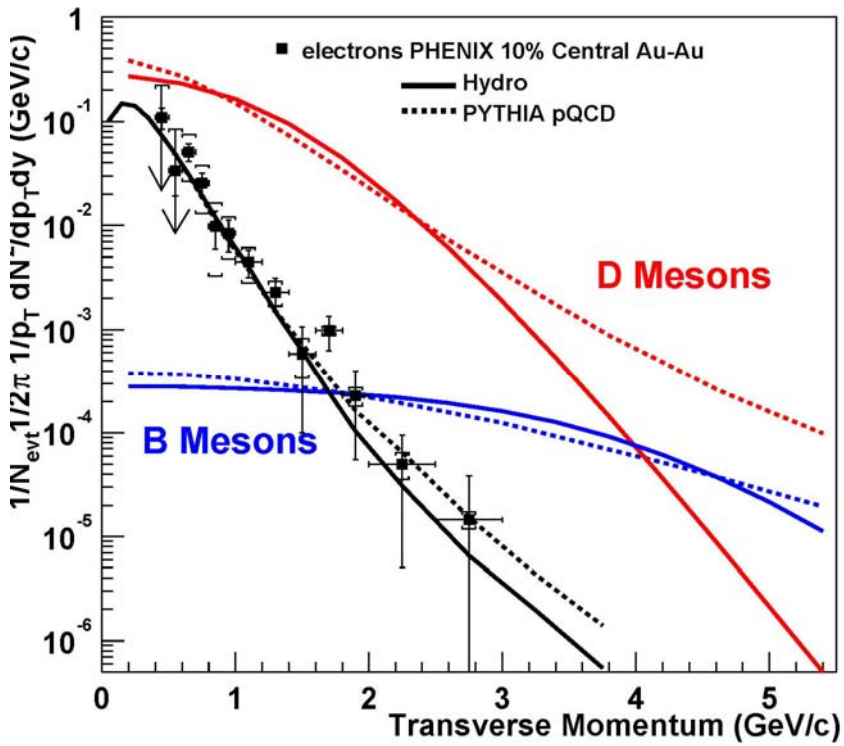


R_{AA} with yield above 2.5 GeV/c

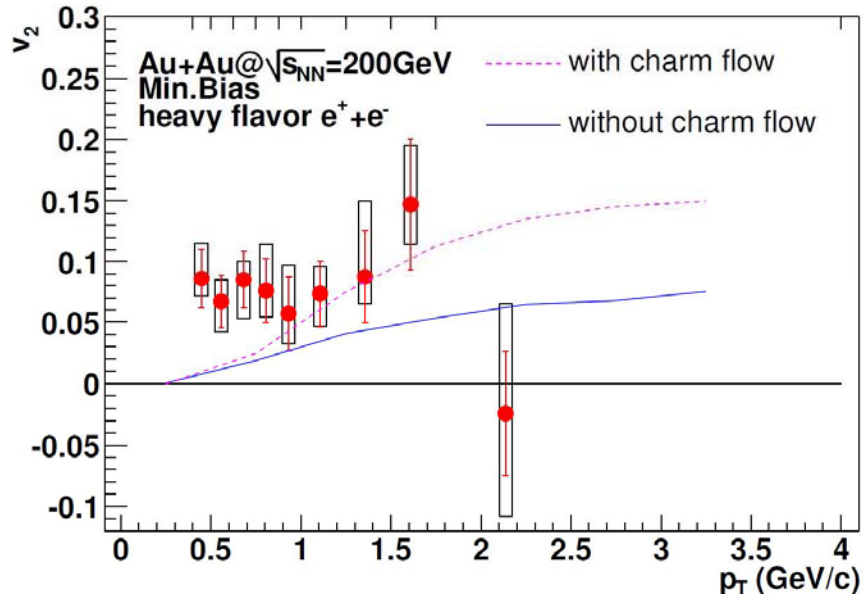
- Need to go to cocktail analysis to obtain sufficient statistics at high-p_T.
- Will lower systematics at low-p_T by combining with converter method.

Charm May Flow ?

- PHENIX HF electron spectra @ 130 GeV/c are compatible w/ no interactions and also with hydrodynamics. ???
- Measure flow, go to higher p_T



Batsouli *et al.*, Phys. Lett. **B557**, 26



S.S. Adler *et al.*, nucl-ex/0502009

Theoretical predictions from Greco *et al.*, Phys. Lett. **B595**, 202

Single muon spectra in backward rapidity

Candidate Muon Tracks in the Muon Spectrometer

The muon arms covered rapidities $1.2 < |\eta| < 2.4$

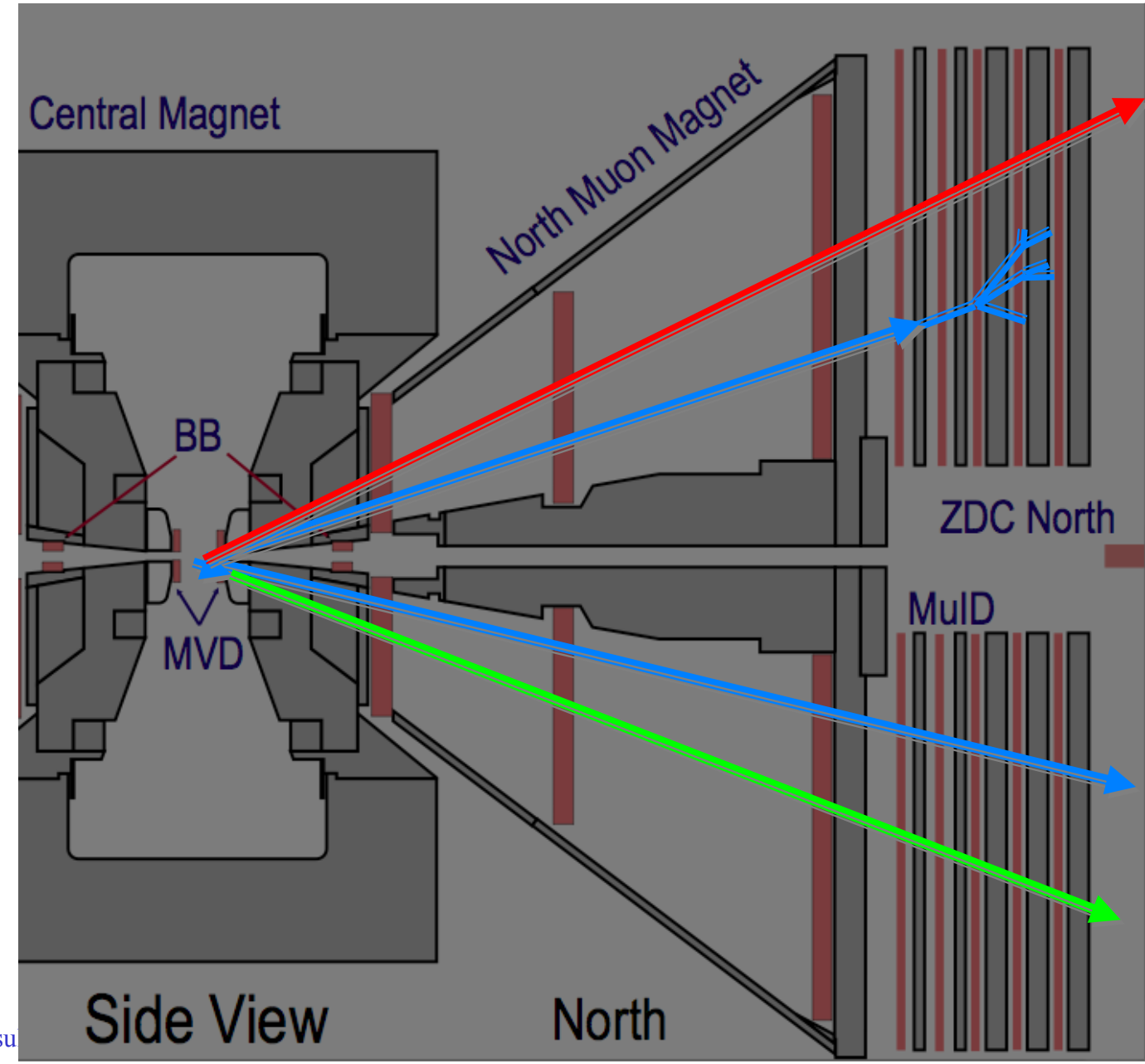
Candidate Tracks:

Prompt Muons

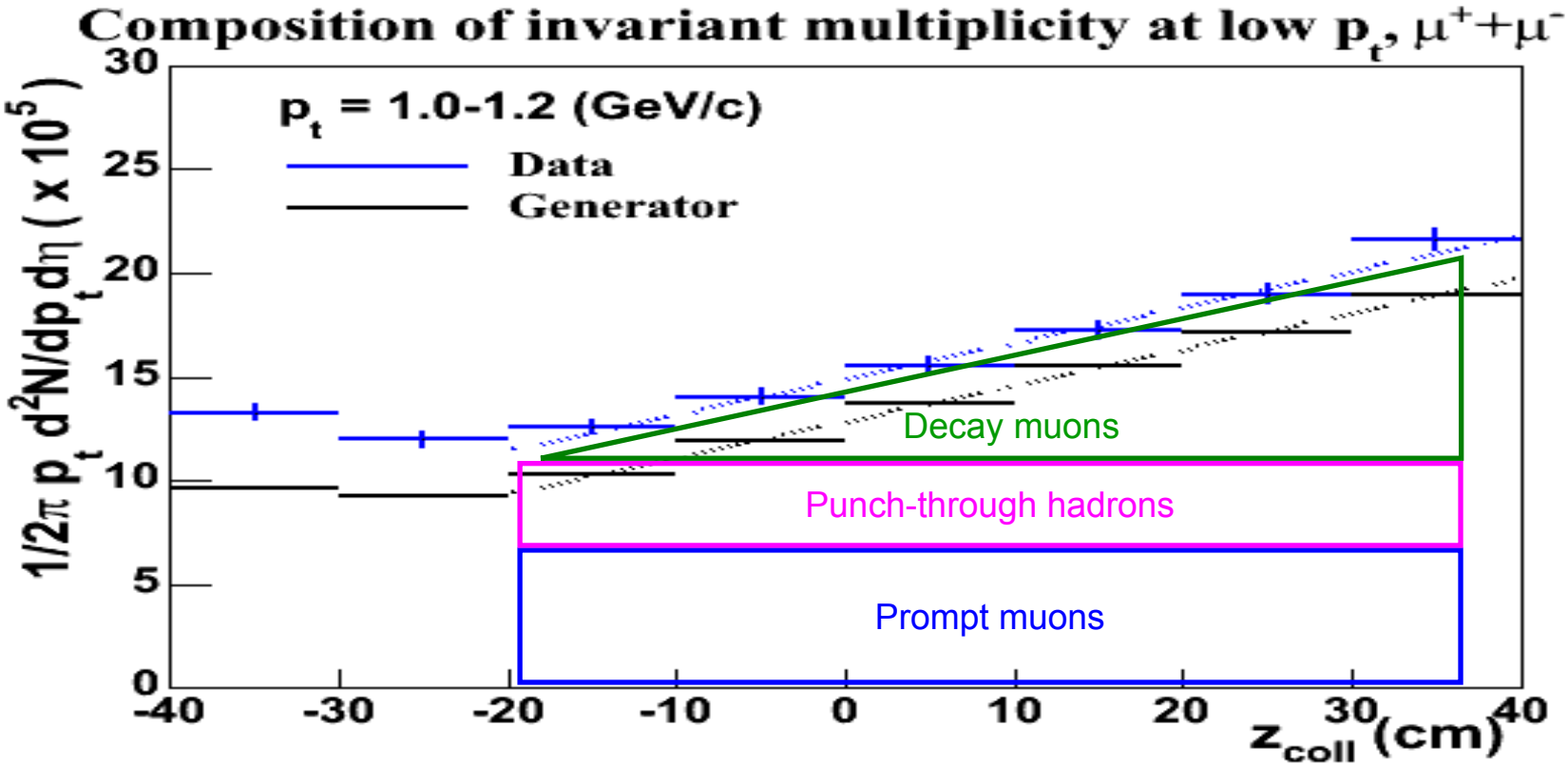
Punch-through hadrons

Stopped hadrons

Decay muons



Measuring Heavy Flavor at Forward Rapidity in the PHENIX Muon Arms



Z

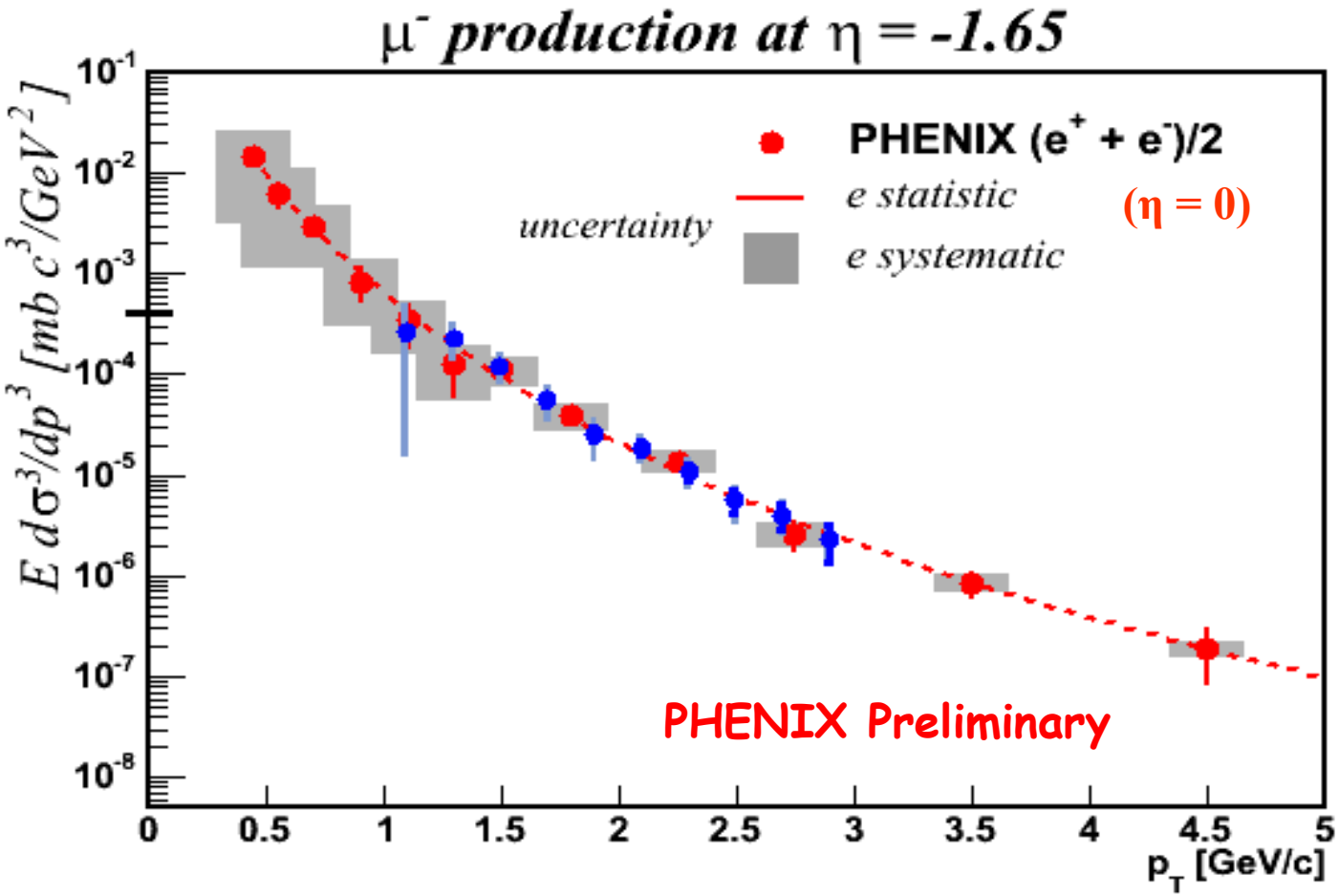
- Extract decay component from *z*-vertex slope of normalized muon yield.
- Calculate punch-through component with simplified absorption model:

$$I2_{inclusive} = I2_{exclusive} + I3_{exclusive} + \text{punchthrough} = I_0 e^{-\frac{L_2}{\lambda}}$$

$$I3_{inclusive} = I3_{exclusive} + \text{punchthrough} = I_0 e^{-\frac{L_3}{\lambda}}$$

$$I4_{inclusive} = I_0 e^{-\frac{L_4}{\lambda}} \longleftarrow \text{Hadron Punch-through}$$

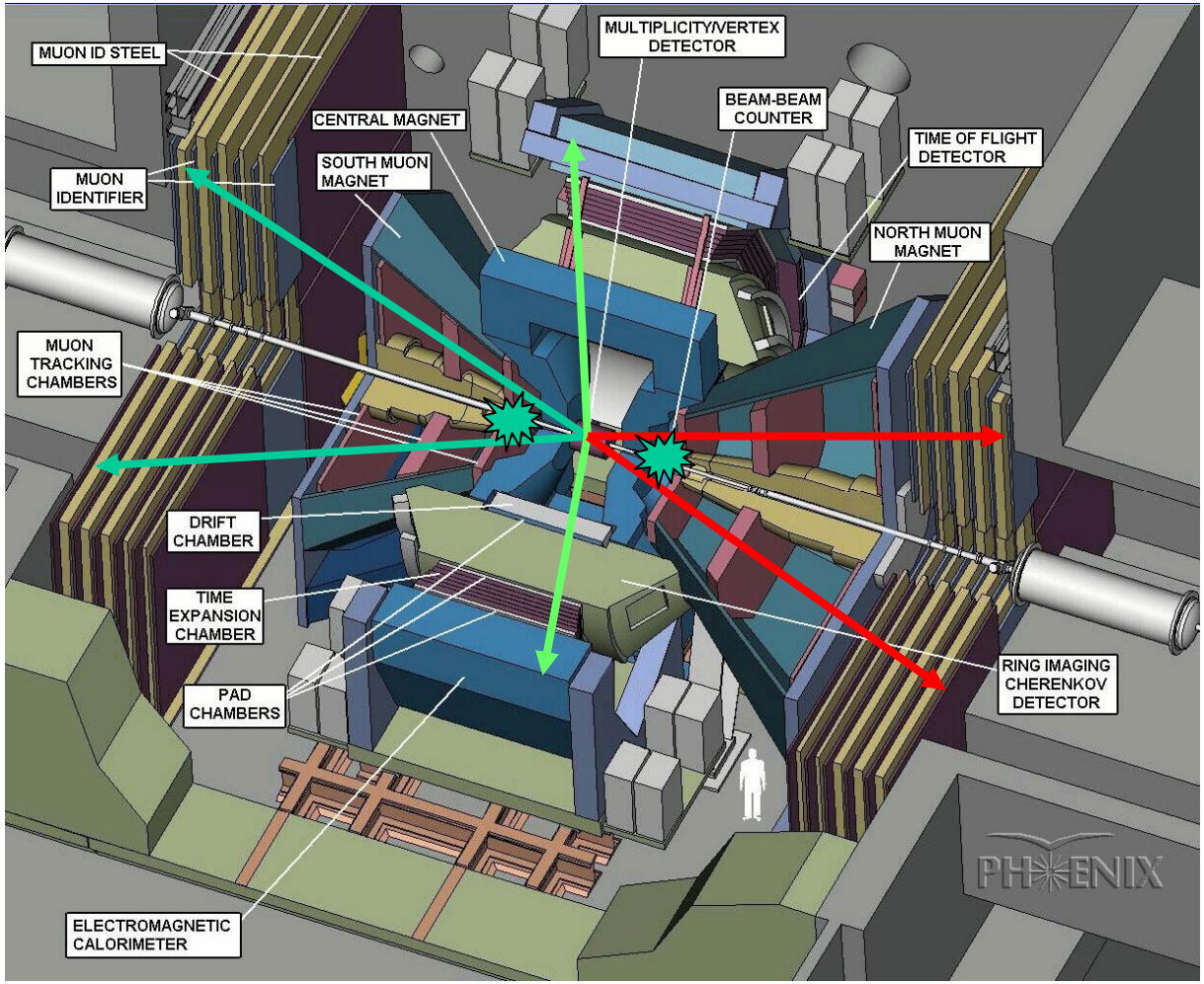
Measuring Heavy Flavor at Forward Rapidity in the PHENIX Muon Arms,p-p 200GeV



J/ Ψ measurements

- How to measure ?
- Results : p-p 200GeV, d-Au 20GeV, Au-Au 200GeV
- Future aspects

How does PHENIX see the J/Ψ ?



$J/\Psi \rightarrow e^+e^-$

identified in RICH and EMCal

- $|\eta| < 0.35$
- $p > 0.2$ GeV

$J/\Psi \rightarrow \mu^+\mu^-$

identified in 2 fwd spectrometers

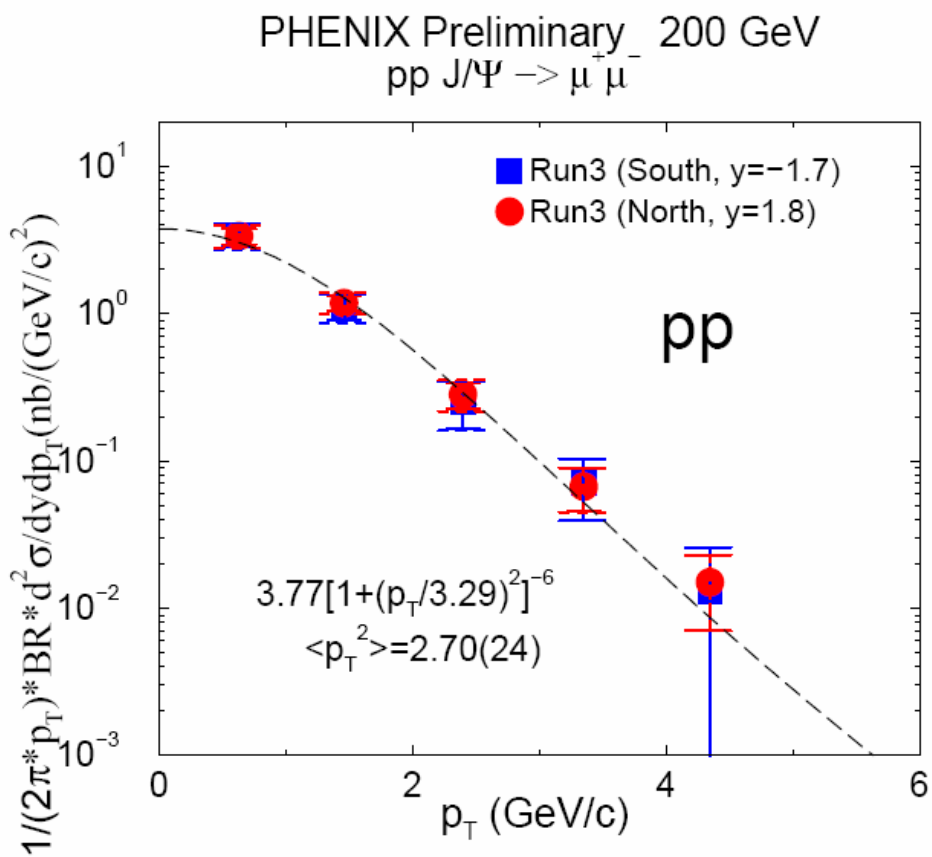
- $1.2 < |\eta| < 2.4$
- $p > 2$ GeV

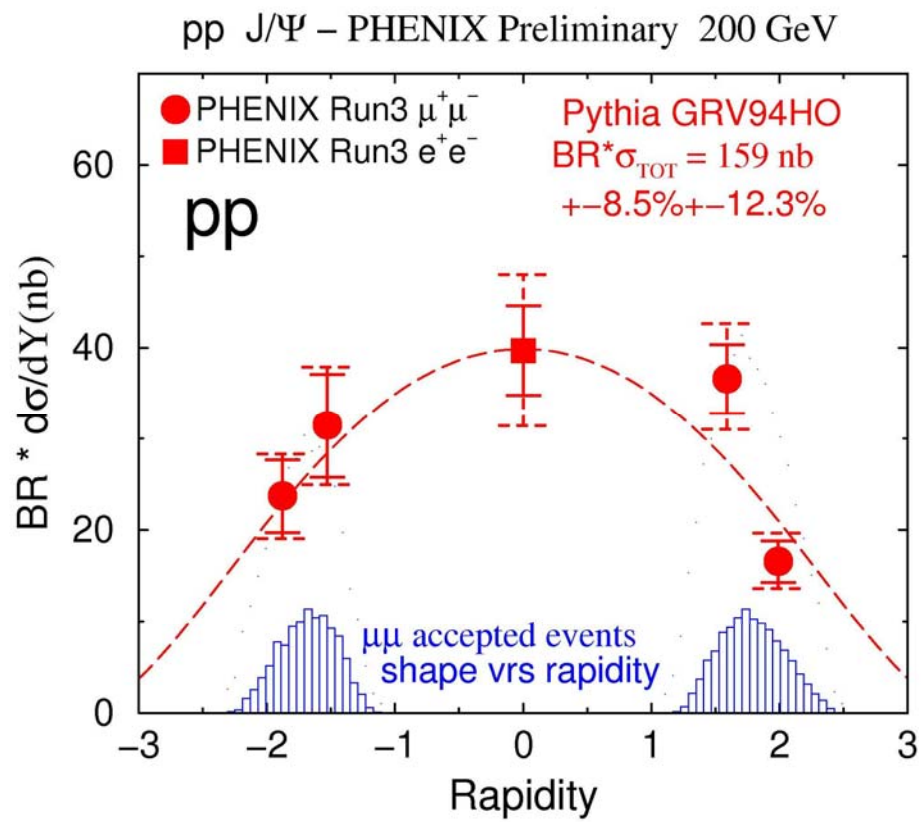
Centrality and vertex given by

BBC in $3<|\eta|<3.9$

J/Ψ in *p-p* $\sqrt{s_{nn}}$=200GeV

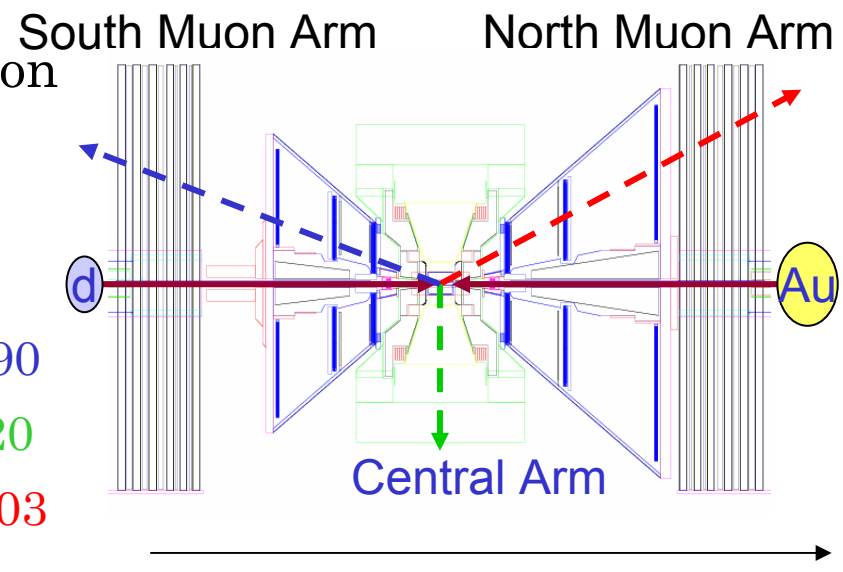
In *pp* we've measured the J/Ψ close to $p_T = 0$ and over much of the rapidity range.



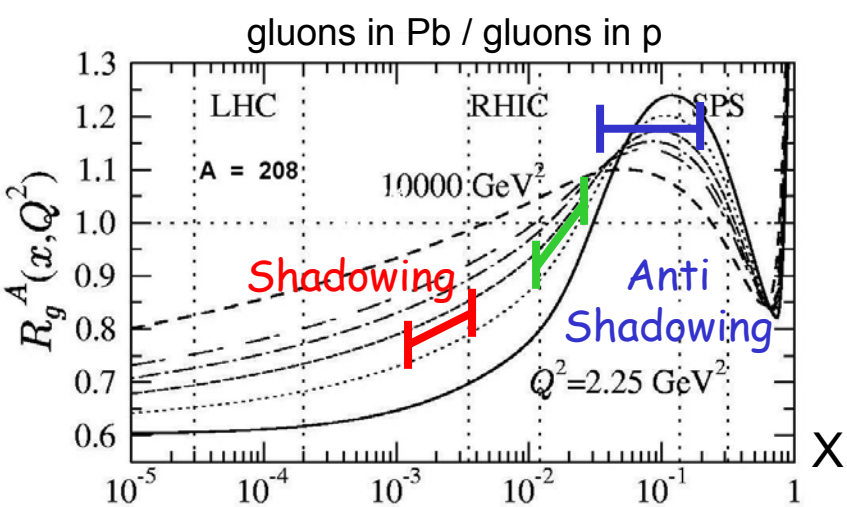


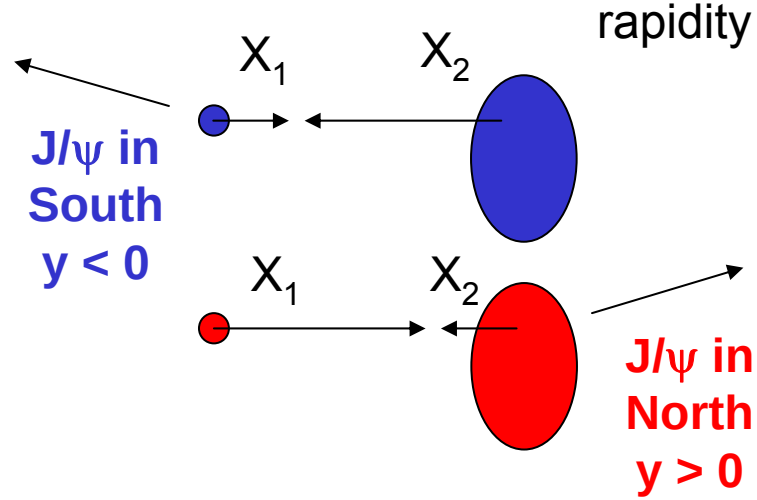
Deuteron → ← Gold

- ☑In PHENIX, J/ψ mostly produced by gluon fusion, and thus sensitive to gluon pdf
- ☑Three rapidity ranges probe different momentum fraction of Au partons
  - ☑South ($y < -1.2$) : large X_2 (in gold) ~ 0.090
  - ☑Central ($y \sim 0$) : intermediate X_2 ~ 0.020
  - ☑North ($y > 1.2$) : small X_2 (in gold) ~ 0.003



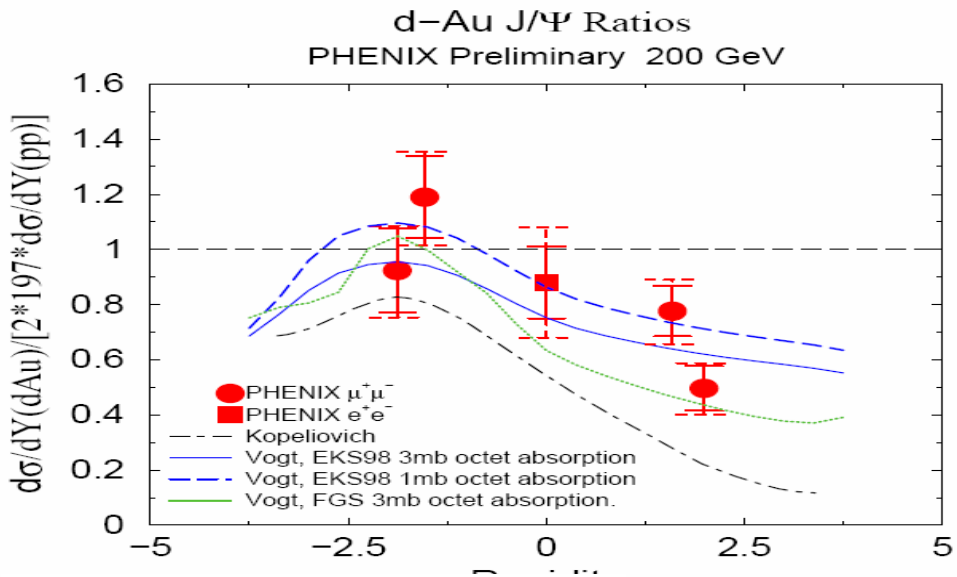
Example of predicted gluon shadowing in d+Au



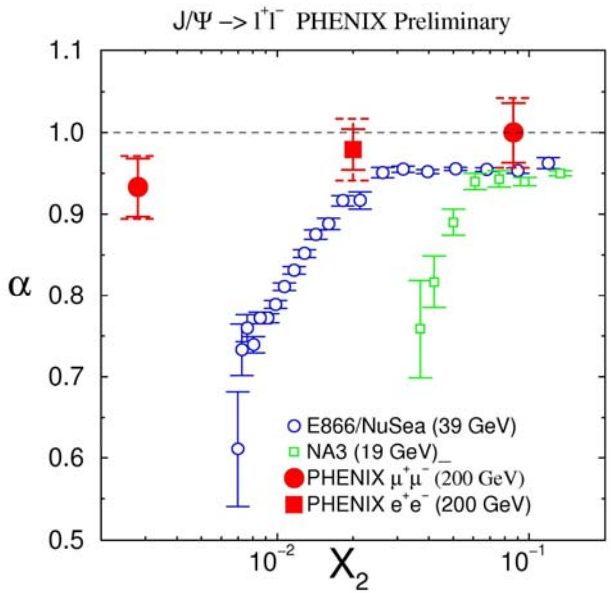


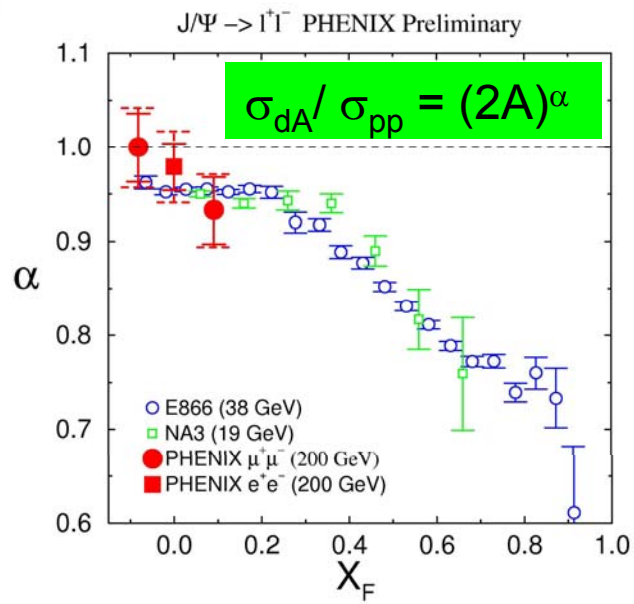
From Eskola, Kolhinen, Vogt
Nucl. Phys. A696 (2001) 729-746.

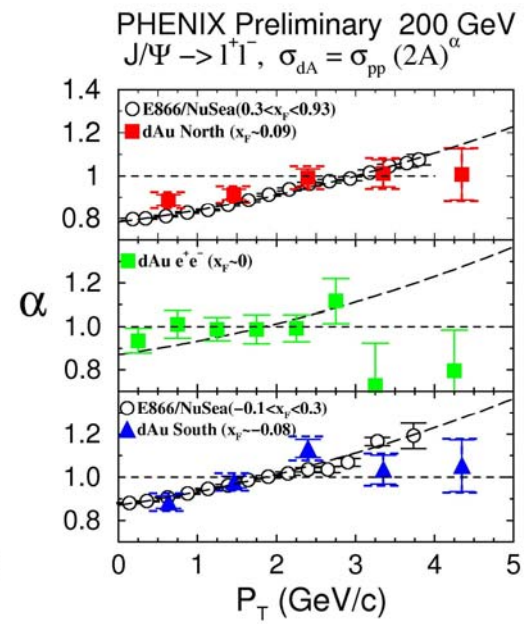
Nuclear modifications in d-Au collisions



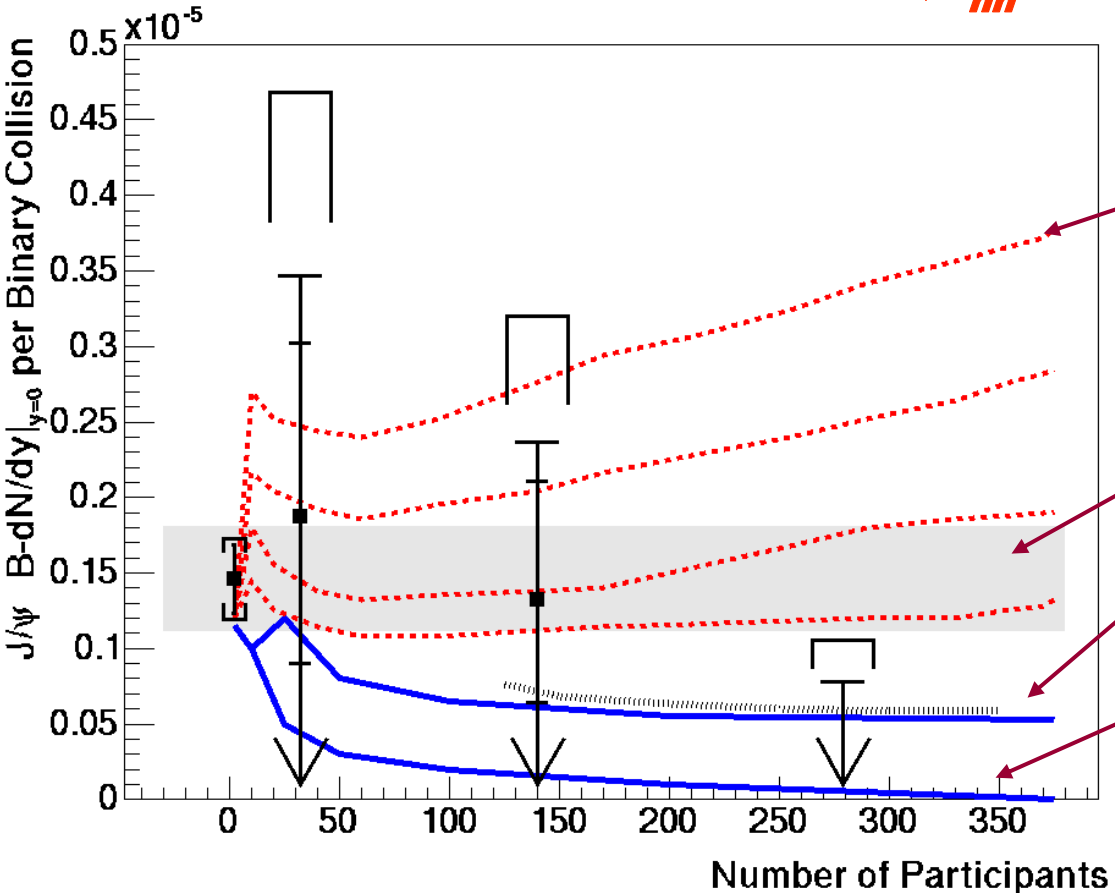
Modest cold nuclear effects seen, but data are not sufficient to completely understand those effects.







J/ Ψ Measurement in Au-Au Collisions at $\sqrt{s_{nn}}$=200GeV –run2



R. L. Thews, M. Schroedter, J. Rafelski, Phys Rev C 63, 054905
Plasma Coalescence Model

Binary Scaling

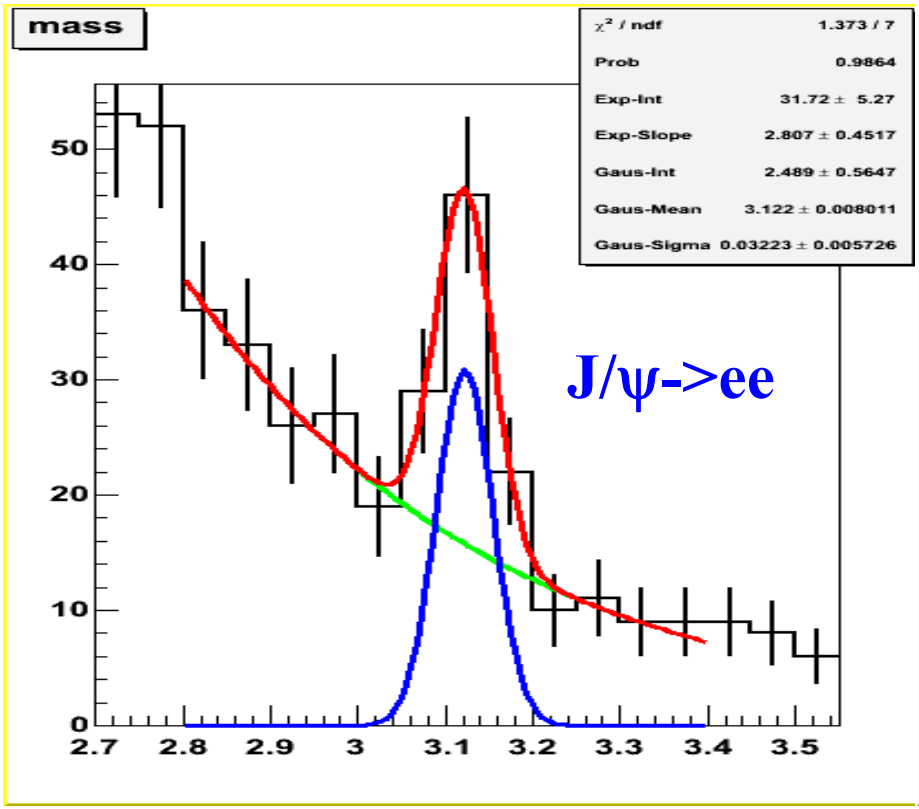
Absorption (Nuclear + QGP) + final-state coalescence

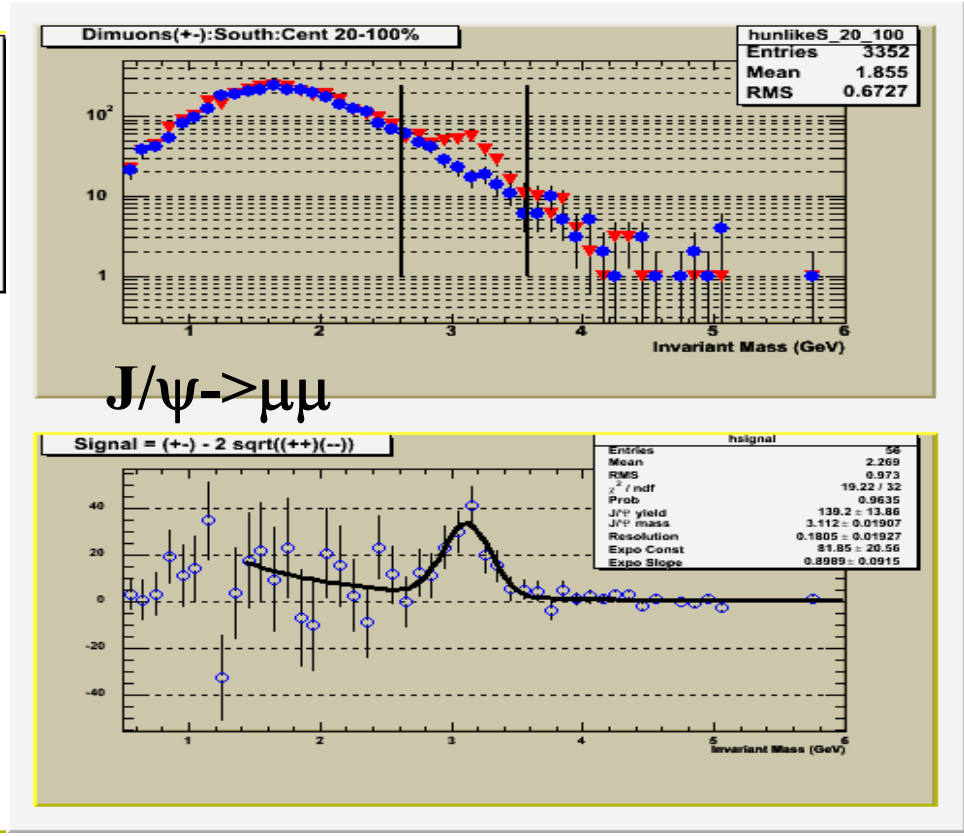
Absorption (Nuclear + QGP)
L. Grandchamp, R. Rapp, Nucl Phys A709, 415; Phys Lett B 523, 60

- 49.3 million minimum bias events analyzed in Central Arm, Run 2
- 8, 5, 0 "most likely signal" for 3 centrality bins
- Not enough statistical significance to distinguish various models but strong enhancement seems to be disfavored.

J/ Ψ Signal in Au-Au Collisions

- RUN2 Au-Au data disfavor enhancement
- RUN4 has accumulated 50 times(~240mb-1) more data and already see clear J/Ψ signal from a small portion of AuAu *(data less than 10%).*





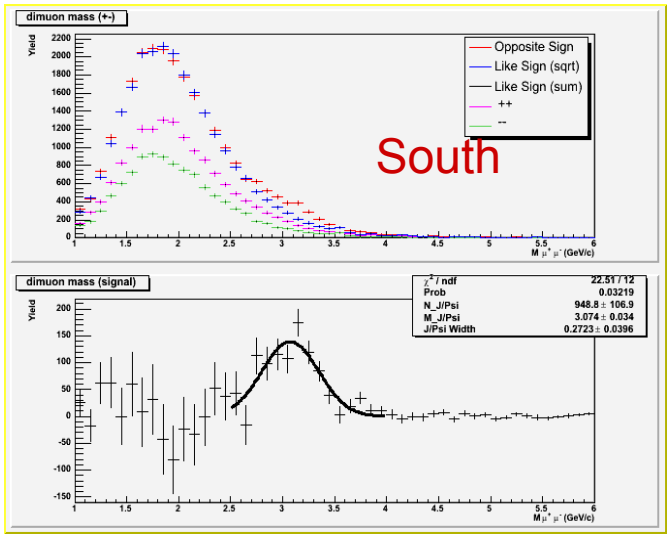
~ 600 J/psi's mid-rapidity, ~2k forward-rapidity

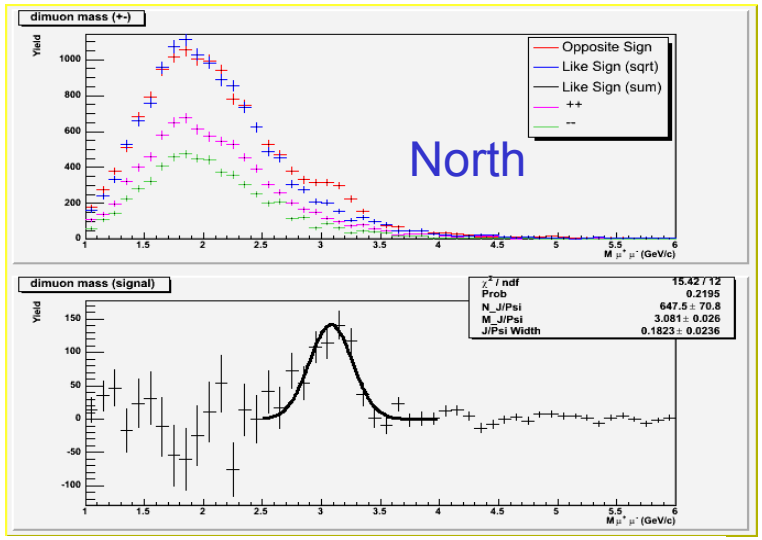
Cu-Cu 200GeV : Forward rapidity

Central

J/ψ->μμ

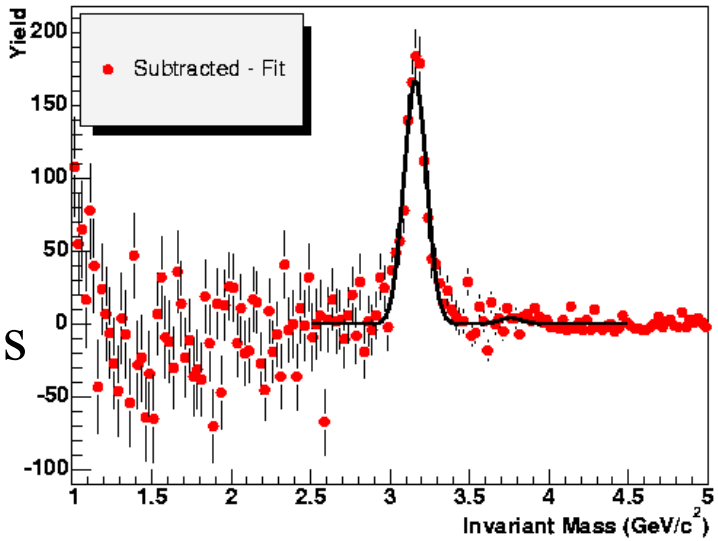
~13k J/psi's





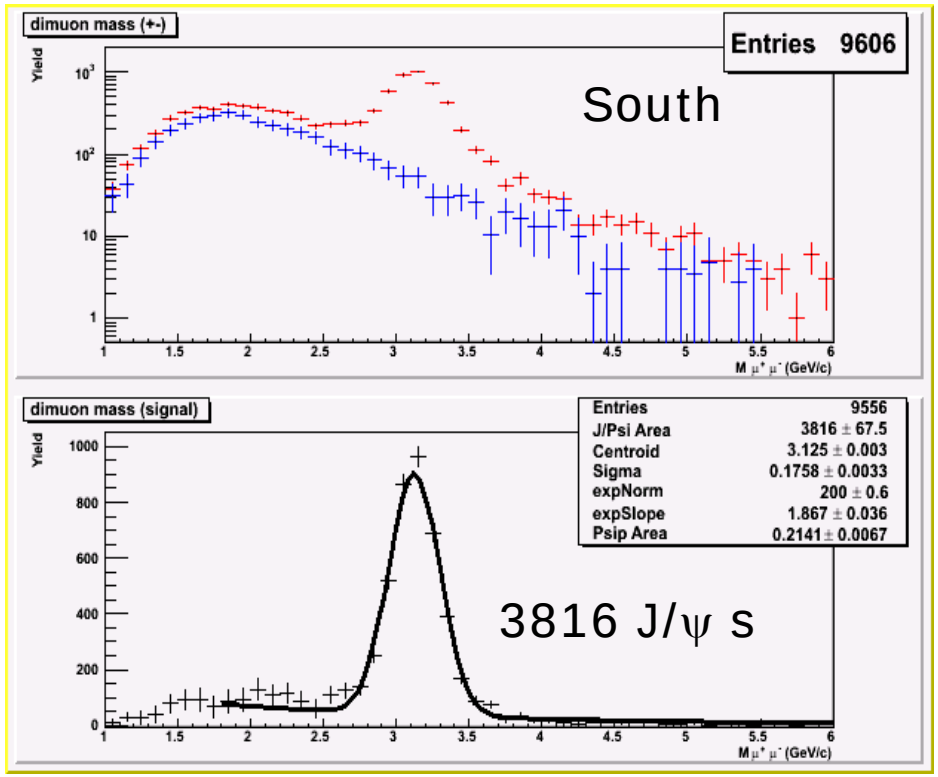
J/ψ->ee

~1.2k J/psi's



Better reference Run 5 pp 200GeV

- Clean J/psi signal in both Muon Arms and central arm ; ongoing Online production.
- June 12th (~2.17 pb^{-1})

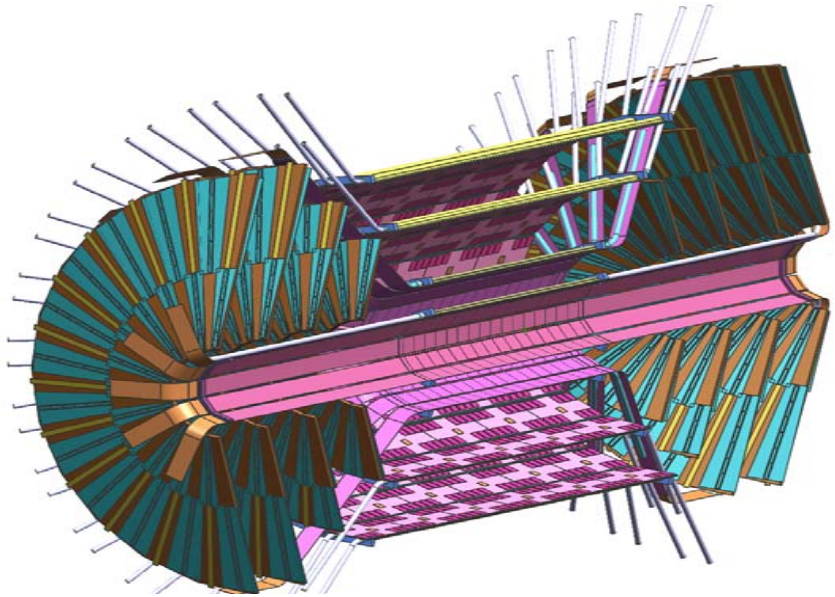


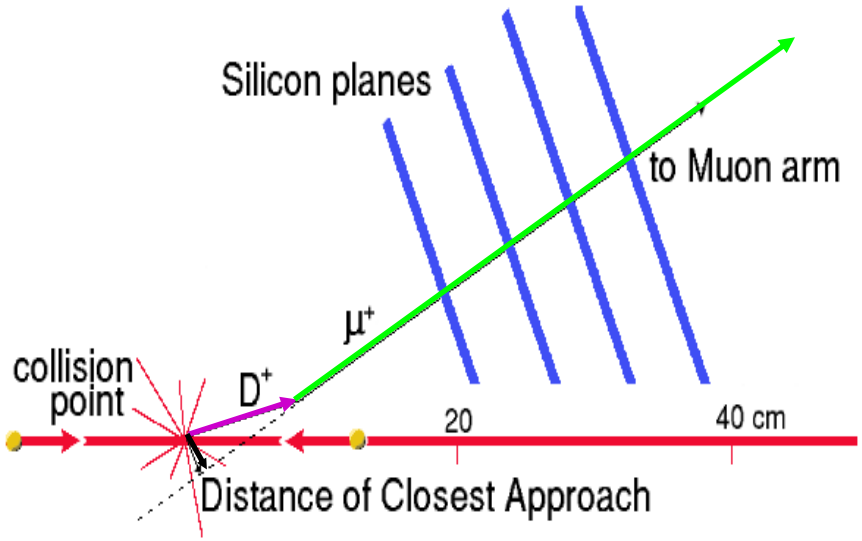
The precision Measurements

- Detector upgrade
  - Precise measurement of Displaced vertex
  - Onium measurements
  - Trigger
- RHIC II Luminosity

Silicon Vertex Detector

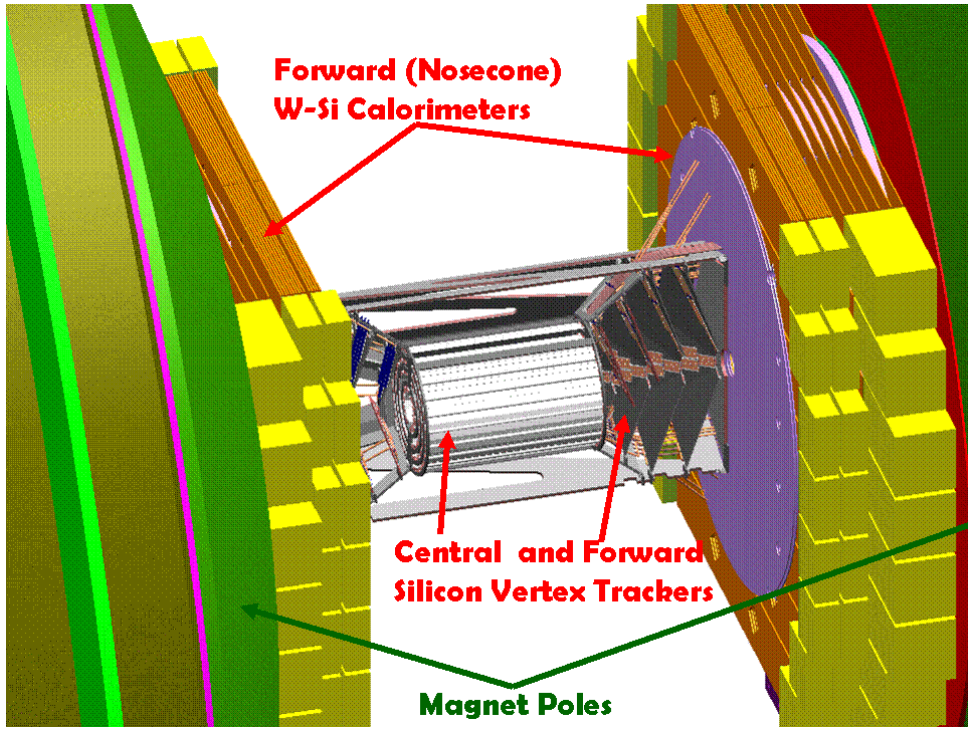
- Four barrel layers
  - Two ALICE pixel bus layers
  - Two strip-pixel layers
- Four end-cap pixel layers
- Displaced vertex (σ ~50 μm)
- Full azimuthal inner tracking $|\eta| <$ ~2.4
  - Improve acceptance for γ-jet correlations, $D \rightarrow K\pi$
- Connect to tracks in central and muon arms
  - Tag heavy flavor decays
    - $c,b \rightarrow e,\mu$
    - $B \rightarrow J/\Psi$
  - Improve onium resolution
  - Eliminate decay hadrons
  - Reduce high-p_T background





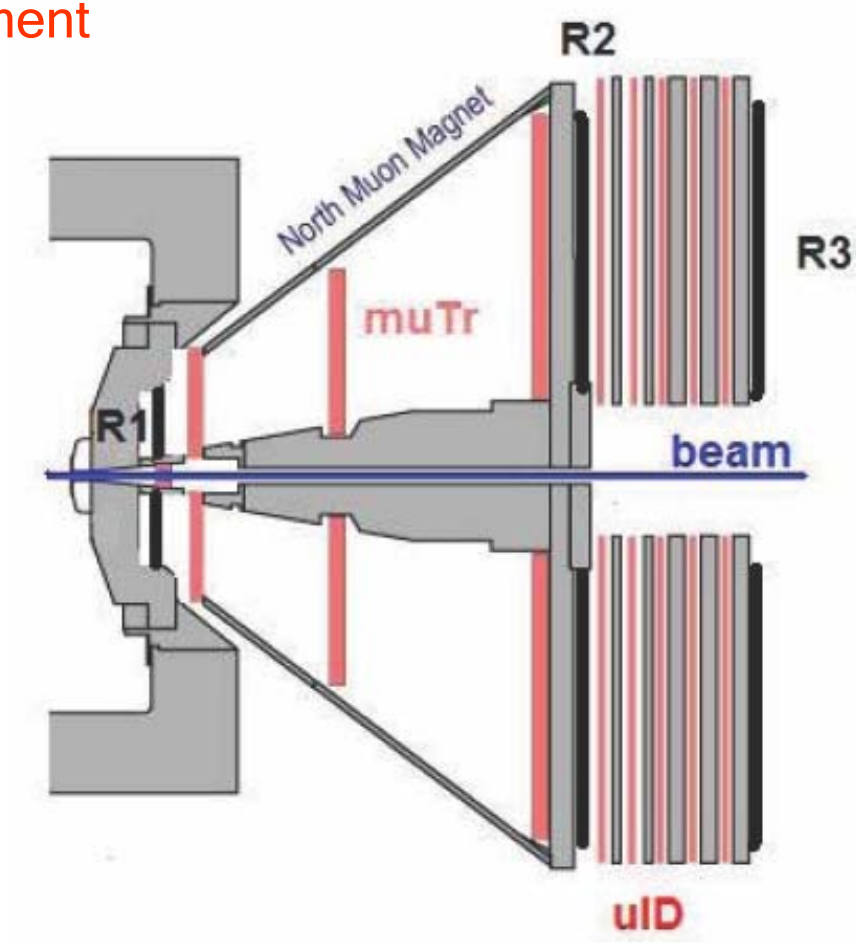
Nose Cone Calorimeter

- Replace central arm magnet nosecones (Cu) w/ tungsten-silicon calorimeters
- Coverage at forward/backward rapidity: $0.9 < |\eta| < 3.5$
  - γ/π^0 separation for $p_T < 30$ GeV/c
  - Jet identification
- γ identification gives good acceptance for $\chi_c \rightarrow J/\Psi + \gamma$



Muon Trigger Upgrade

- Three layers of RPCs with 2D (θ,φ) pad readout
- Provides online momentum measurement to improve Level-1 trigger rejection
  - Single-particle
    - p_T cut
    - W spin-measurements in pp
  - Two-particle
    - M_{inv} cut
    - onium measurements in AA
  - Necessary to take complete advantage of luminosity upgrades
- Provides improved high-multiplicity background rejection



RHIC II Luminosity – CAD Guidance

W. Fischer, T. Roser, I. Ben-Zvi, A. Fedotov, BNL C-AD, 16-Mar-2005

Classical proton radius [m] 1.53E-18

http://rhicii-heavy.bnl.gov/doc/RHIC_II_Luminosity_Roser.xls

Maximum Luminosity Estimates for RHIC II

Beams	unit	p	p	unit	Si	Cu	d	p	Au	unit	Au
Charge number Z	…	1	1	…	14	29	1	1	79	…	79
Mass number A	…	1	1	…	28	63	2	1	197	…	197
Relativistic γ	…	108	271	…	108	108	107	108	107	…	107
Revolution frequency	kHz	78.2	78.2	kHz	78.2	78.2	78.2	78	78.2	kHz	78.2
Normalised emittance, 95%, min	mm mrad	12	12	mm mrad	12	12	12	12	12	mm mrad	10
Ions/bunch, initial	10^9	200	200	10^9	10.7	5.2	150	200	1.0	10^9	1.0
Charges per bunch	10^9e	200	200	10^9e	150	150	150	200	80	10^9e	80
No of bunches	…	110	110	…	110	110	110	110	110	…	110
Average beam current/ring	mA	275	275	mA	206	206	206	275	110	mA	110
Luminosity at one IP	**unit**	**p-p**	**p-p**	**unit**	**Si-Si**	**Cu-Cu**	**d-Au**	**p-Au**	**Au-Au**	**unit**	**Au-Au**
Beam-beam parameter per IP	…	0.0123	0.0123	…	0.0046	0.0043	0.0024 0.0036	0.0048 0.0048		…	0.0024
β*	m	1.0	0.5	m	1.0	1.0	2.0	2.0		m	0.5
Peak luminosity	10^{30} $cm^{-2}s^{-1}$	150	750	10^{28} $cm^{-2}s^{-1}$	42	10	28	37		10^{26} $cm^{-2}s^{-1}$	90
Peak / average luminosity	…	1.5	1.5	…	1.3	1.3	1.5	1.5		…	1.3
Average store luminosity	10^{30} $cm^{-2}s^{-1}$	100	500	10^{28} $cm^{-2}s^{-1}$	32	8	19	25		10^{26} $cm^{-2}s^{-1}$	70
Time in store	%	55	55	%	55	55	55	55		%	60
Luminosity/week	pb^{-1}	33	166	nb^{-1}	108	25	62	83		nb^{-1}	2.5
Luminosity/week, achieved	pb^{-1}	0.9		nb^{-1}		2.4	4.5			nb^{-1}	0.16

x 35 increase for pp

x 15 increase for dAu

x 10 increase for CuCu

x 15 increase for AuAu

RHIC II Yields – ADF, MJL Guidance

Machine	RHIC II	PHENIX
sqroot(s)	200 GeV	

Species 1 mass	1	p	RHIC II pp luminosity (average) 1 x 10^32	PHENIX Jpsi and psi' acceptances from PPG038
Species 2 mass	1	p		PHENIX Upsilon acceptance from Axel Drees
luminosity/week	33 /pb/wk		PHENIX chi_c acceptances from AN229	Branch factors from PDG
number of weeks	12		(muon arm acceptance is for south arm only, hence factor of 2)	Collision vertex sig SVTX covers +/- 10 cm
PHENIX uptime	0.6			RF efficiency 80% (in central peak)
Integrated luminosity	237.6 /pb			

Signal	p+p dσ/dy	units	ref. dy	process / source	branch factor	nuclear scaling	collision vert cut	minbias trig eff	Level 1 trig eff	acceptance	reconstr efficiency	yield
Jpsi->ee	673000	pb	1	Jpsi ds/dy / PHENIX AN258	0.059	1	0.55	0.75	0.76	2.27E-002	0.82	55054
psi(2S)->ee	94220	pb	1	Psi/Jpsi ratio from hep-ph/9502270	7.60E-003	1	0.55	0.75	0.76	2.27E-002	0.82	993
chi_c0->gamma Jpsi->ee	6510000	pb	1	sigma(chi->gamma Jpsi->ee) AN229	3.90E-004	1	0.55	0.75	0.76	6.45E-004	0.82	100
chi_c1->gamma Jpsi->ee	2100000	pb	1	sigma(chi->gamma Jpsi->ee) AN229	1.62E-002	1	0.55	0.75	0.76	6.45E-004	0.82	1340
chi_c2->gamma Jpsi->ee	6950000	pb	1	sigma(chi->gamma Jpsi->ee) AN229	8.00E-003	1	0.55	0.75	0.76	6.45E-004	0.82	2190
Y(0,1,2)->ee	86	pb	1	Ups B*ds/dy / hep-ph/9502270	1	1	0.55	0.75	0.76	4.00E-002	0.82	210
Jpsi->mumu	451542	pb	2.2	Jpsi ds/dy / PHENIX AN255	0.059	1	0.55	0.75	0.8	1.28E-001	0.8	468741
psi(2S)->mm	63215.88	pb	2.2	Psi/Jpsi ratio from hep-ph/9502270	7.60E-003	1	0.55	0.75	0.8	1.28E-001	0.8	8453
chi_c0->gamma Jpsi->mn	6510000	pb	2	sigma(chi->gamma Jpsi->mm) AN22	3.90E-004	1	0.55	0.75	0.8	1.20E-002	0.8	3822
chi_c1->gamma Jpsi->mn	2100000	pb	2	sigma(chi->gamma Jpsi->mm) AN22	1.62E-002	1	0.55	0.75	0.8	1.20E-002	0.8	51215
chi_c2->gamma Jpsi->mn	6950000	pb	2	sigma(chi->gamma Jpsi->mm) AN22	8.00E-003	1	0.55	0.75	0.8	1.20E-002	0.8	83702
Y(0,1,2)->mm	43	pb	2.2	Ups B*ds/dy / hep-ph/9502270	1	1	0.55	0.75	0.8	8.90E-002	0.8	528

- Assume CAD "Maximum Average" Luminosity Projection, 12 week runs, known PHENIX uptime (60%) to get Live Delivered Luminosity.
- Use measured values when possible to calculate *pp* σ's, B.R.'s.
- Assume nuclear scaling - $(AB)^{\alpha}$, w/α=1 for Υ, α=0.92 for others.
- Use stated RF efficiency, diamond size to get vertex cut efficiency.
- Use measured PHENIX performance, assume PHENIX SiVTX, Nosecone Calorimeter, Muon Trigger upgrades to get acceptances, efficiencies.

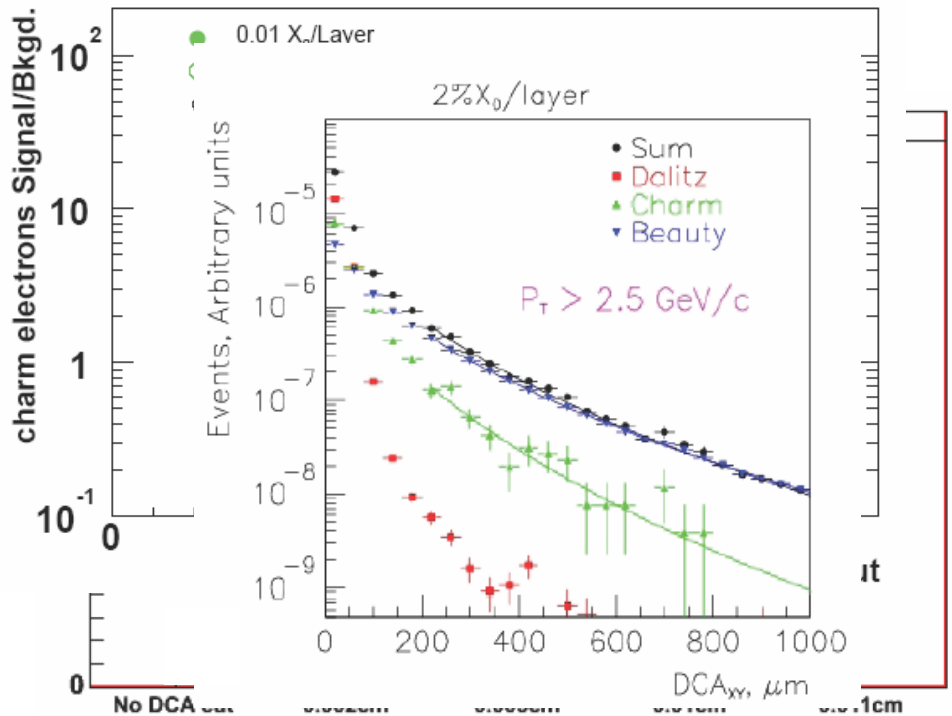
Onium Yields

Signal/System	pp (200 GeV)	pp (500 GeV)	CuCu (200 GeV)	AuAu (200 GeV)	dAu (200 GeV)
$J/\Psi \to ee$	55,054	609,128	73,921	44,614	29,919
$\Psi'(2S) \to ee$	993	10,985	1,333	805	540
$\chi_{c0} \to \gamma + J/\Psi \to ee$	100	2,578	134	81	54
$\chi_{c1} \to \gamma + J/\Psi \to ee$	1,340	40,870	1,800	1,086	728
$\chi_{c2} \to \gamma + J/\Psi \to ee$	2,190	59,296	2,941	1,775	1,190
$\Upsilon(0,1,2) \to ee$	210	3,032	547	397	184
$B \to J/\Psi \to ee$	1,237	41,480	4,567	3,572	1,085
$J/\Psi \to \mu\mu$	468,741	5,483,006	653,715	394,535	258,136
$\Psi'(2S) \to \mu\mu$	8,453	98,880	11,789	7,115	4,655
$\chi_{c0} \to \gamma + J/\Psi \to \mu\mu$	3,822	99,824	5,330	3,217	2,105
$\chi_{c1} \to \gamma + J/\Psi \to \mu\mu$	51,215	1,582,561	71,425	43,107	28,204
$\chi_{c2} \to \gamma + J/\Psi \to \mu\mu$	83,702	2,296,069	116,732	70,451	46,095
$\Upsilon(0,1,2) \to \mu\mu$	528	7,723	1,429	1,035	469
$B \to J/\Psi \to \mu\mu$	2079	76466	5756	3752	1824

- Precision measurements of the J/Ψ
- Exploratory measurements of the other onium states.
- Steep increase at $\sqrt{s}$ = 500 GeV illustrates the significant difficulties for measurements at lower energies.

Synergistic Benefits of Detector/Luminosity Upgrades for Open Heavy Flavor Measurement

- Detector upgrades assist by determining decay vertex.
  - Allows direct measurement of charm via $D \rightarrow K\pi$
  - Reduces backgrounds at low-p_T
  - Allows statistical separation of *c/b* at high-p_T
  - Allows direct elimination of hadron decay muons.



- Luminosity upgrades extend p_T reach and allow reduction of systematic errors.
  - Additional special runs (*e.g.*, w/ different converter thicknesses and locations, different field configurations, etc.)
  - Finer binning of DCA dependence for *c/b* separation.
  - Better determination of punchthrough absorption.

Summary and Future Perspective(I)

Open Charm

1. Spectral shape of "Non-photonic" electron cross section in p+p is "harder" then PYTHIA predicts.
2. No significant cold matter effect is seen in d-Au collisions within the uncertainty (mid-rapidity)
3. Low energy AuAu single electron spectra agrees with the ISR *p-p* data scaled with Ncoll within uncertainty.
4. The integrated charm yield in the mid-rapidity(pT>0.8) at Au-Au collisions is consistent with binary collision scaling.
5. Cocktail subtraction results from Au+Au improved the statistical significance of the previous "Converter subtraction" analysis for high pt (>1.5GeV)
6. R_{AA}(pT) for non-photonic single electrons in Au+Au which shows significant reduction at high pT suggests sizable energy loss.
7. In high *p*T region (>2.5 GeV), the charm yield in Au-Au is small compared to *p-p*, seems to be suppressed in central collisions .Ongoing high luminosity data might give better understanding of charm production.
8. Single muon spectra at forward-rapidity in p-p collision was measured.
9. The charm flow ($v2$) measurement is on going with high statistic Au-Au run.

Summary and Future Perspective(II)

J/ψ

- dAu J/ψ data suggests that gluon shadowing is weak and pT broadening is very similar to that seen at lower energies.
- RUN4 has accumulated 50 times more data than RUN2, already see clear J/ψ signals, being analyzed at both mid-rapidity and forward-rapidity.
- Light nuclear collision(CuCu) at $\sqrt{s_{nn}}$=200GeV to study the system size dependence of J/ψ production is being studied (clear signals are seen).
- Much higher statistics in run5 -> better reference

With PHENIX upgrade(SiVTX,NCC, RPC) and RHIC II luminosities, we will be able to open a much broader new territory for PHENIX charm physics.

LINKS

Understanding J/Ψ Production Mechanisms

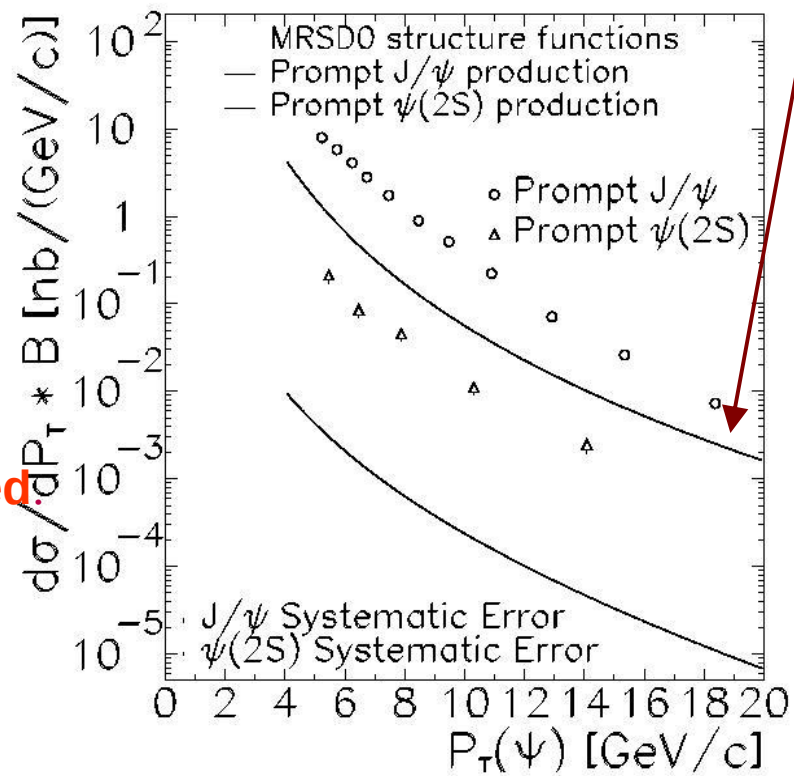
☑ Fixed target data have provided J/ψ σ_{TOTAL} and $\langle p_T \rangle$ for $\sqrt{s}$ = 7-38.8 GeV

☑ Results from collider energies have raised interest in various models:

- Color Singlet Model
- Color Octet Model (NRQCD)
- Color Evaporation Model (phenomenological)

★ ***Systematic studies at RHIC energies with wide η and p_T coverage are needed***

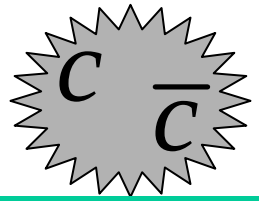
CDF J/ψ cross section is greater than Color Singlet Model prediction PRL **79** 572 (1997)



How do you make a J/ψ ?

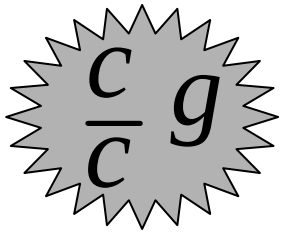
Active subject of research: world of NRQCD

Color singlet model: J/Psi formed by coalescence of c-cbar



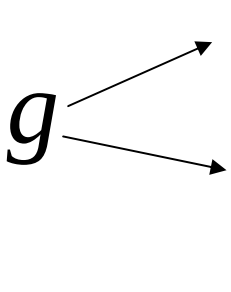
J/ψ

Color octet: Octet c-cbar precursor picks up a gluon

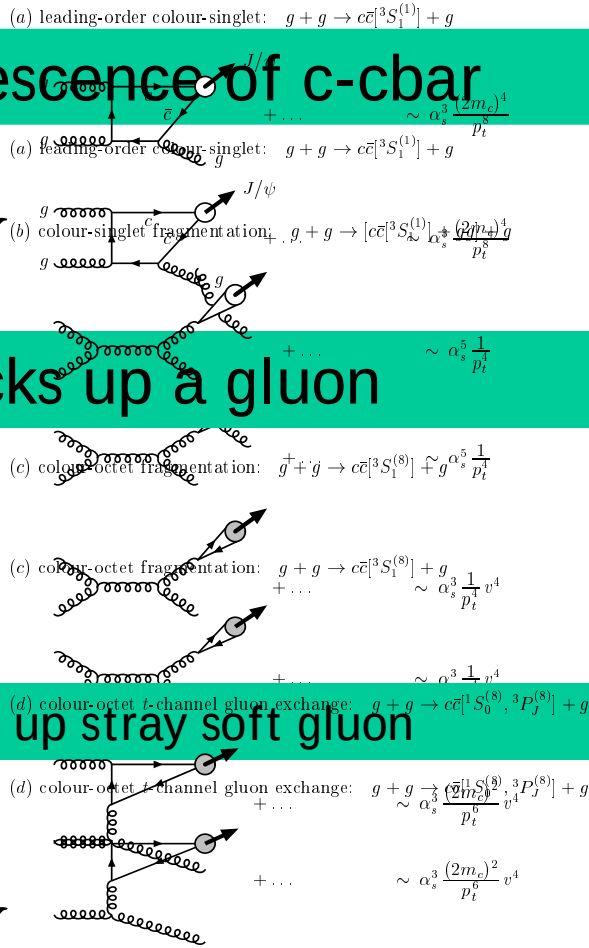


J/ψ

Color Evaporation: gluon fragments into c-cbar, picks up stray soft gluon



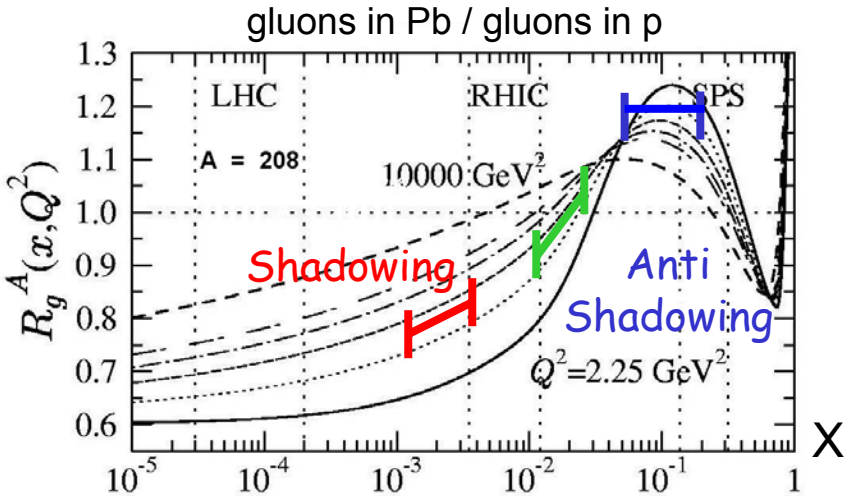
J/ψ



What is the Cold Nuclear Effect

There's also suppression or enhancement due to normal nuclear effect:

- Gluon(anti)shadowing
- Nuclear absorption.
- Initial state energy loss.
- Cronin effect



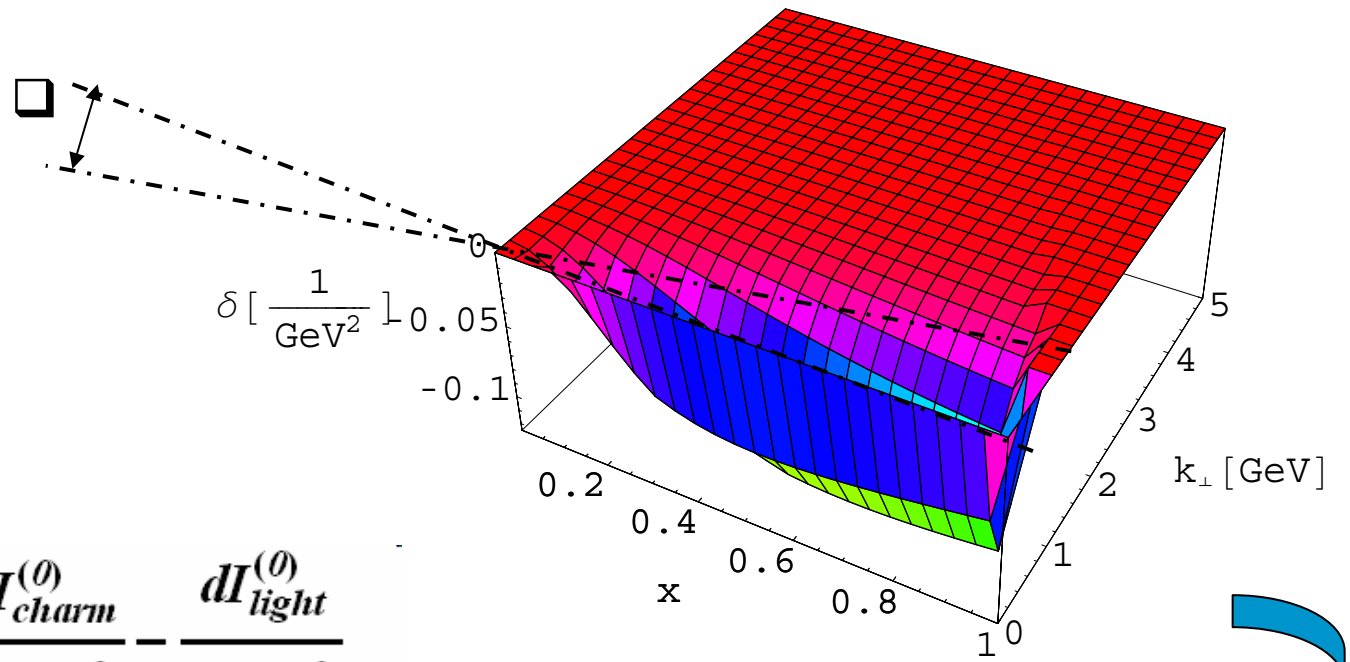
Eskola, et al., Nucl. Phys. A696 (2001) 729-746.

Nuclear effect expected to be understood through p-p and p(d)-A collisions. PHENIX has measured J/ψ production and open charm in p-p, d-Au and AuAu Collisions

What value of heavy quark suppression we can expect at RHIC?

1997 Shuryak proposed that charm quarks will have large energy loss in QGP => large suppression of D mesons.

2001 Dokshitzer and Kharzeev proposed "dead cone" effect => charm quark small energy loss

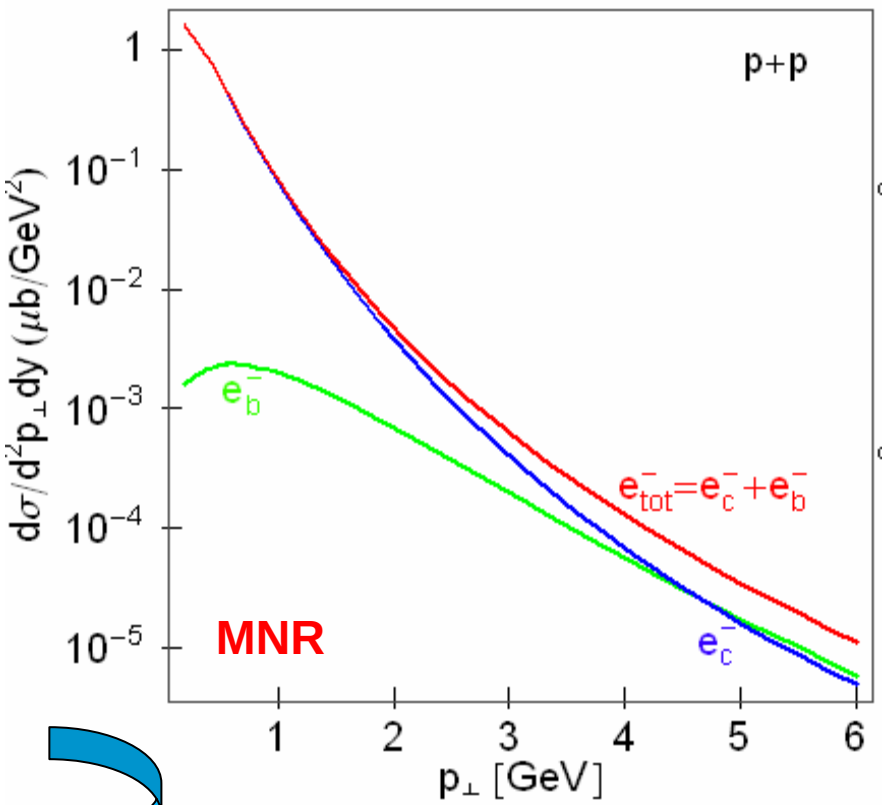


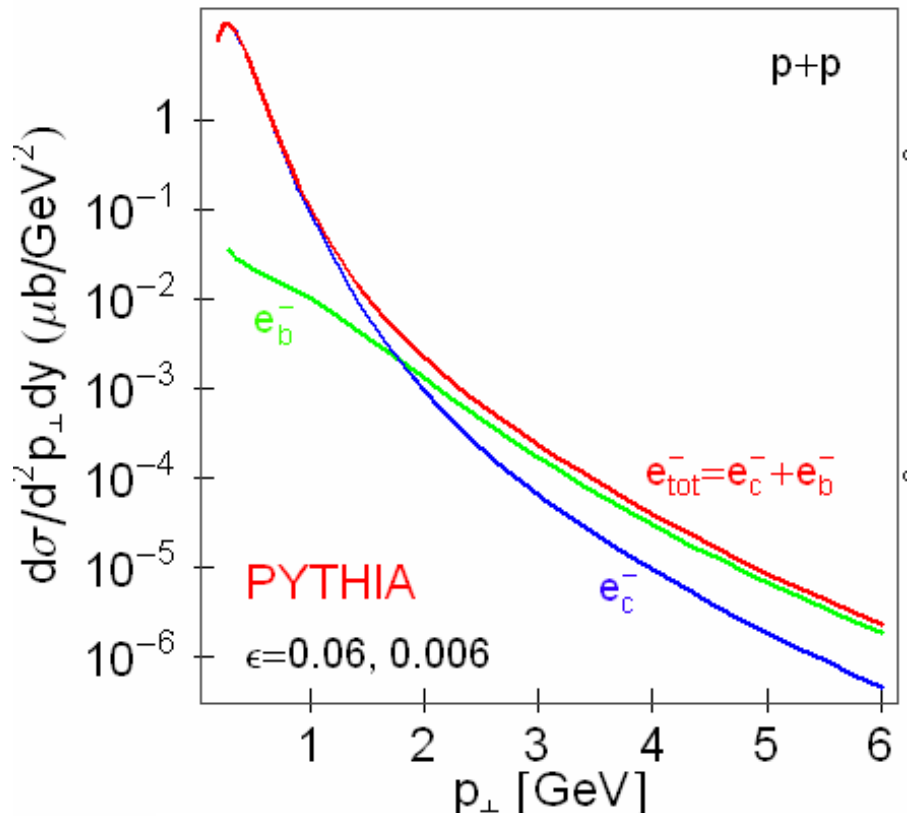
$$\delta = \frac{dI^{(0)}_{charm}}{dx\, dk_\perp^2} - \frac{dI^{(0)}_{light}}{dx\, dk_\perp^2}$$

From Magdalena Djordjevic

Charm and beauty content in the single electrons is very sensitive to their fragmentation functions

Single electrons suppression is strongly dependent on (unknown) charm and beauty fragmentation functions





Simon Wicks (Columbia U.)

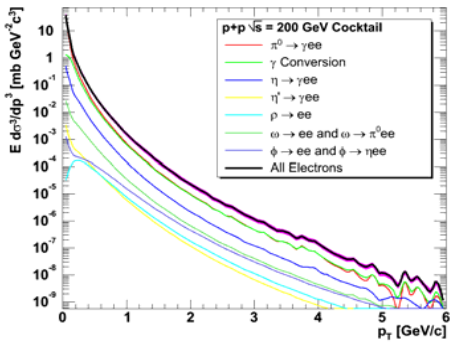
Backup

Subtracting Photonic Electrons

Cocktail subtraction method

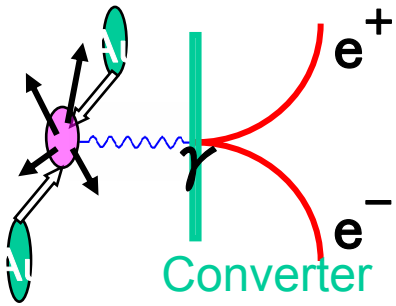
Includes conversion of photons from hadron decays in material, Dalitz decays of light mesons (π^0, η, ω, η, ϕ)

cocktail



Converter method

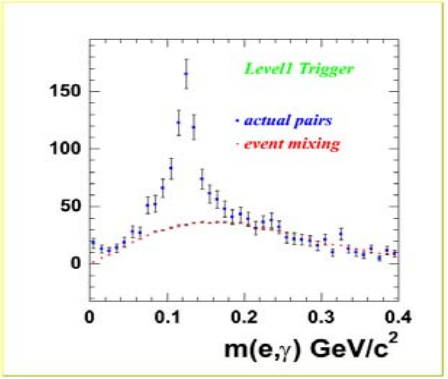
Comparison of $e^{+/-}$ spectra with and without converter allows separation of photonic and non-photonic sources of single electrons.



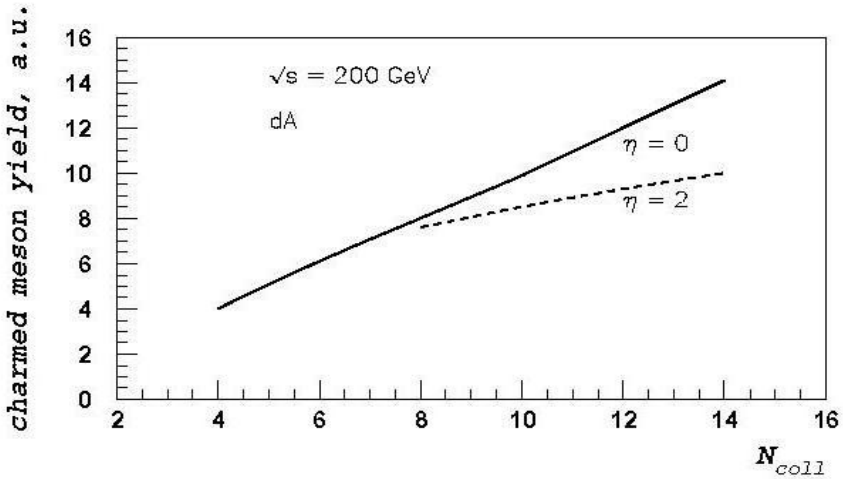
Direct measurement via γ-e coincidences

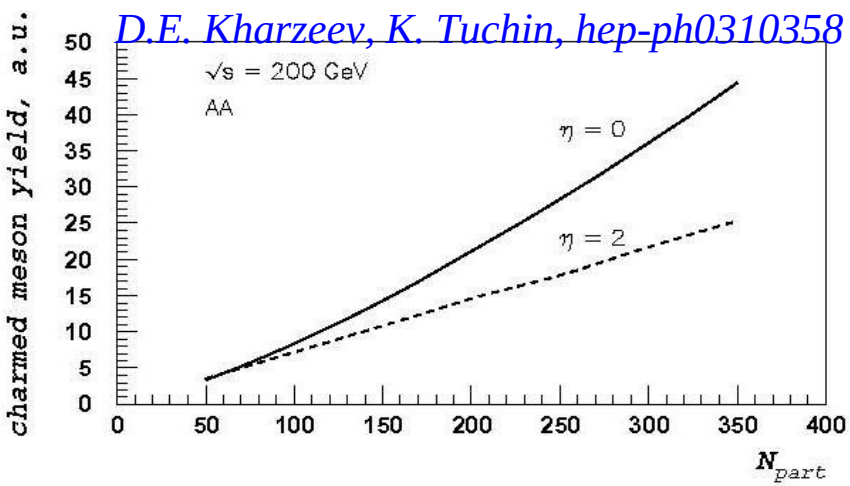
Yield of γ-e in vicinity of π η mass with mixed event subtraction.

γ-e invariant mass



Open Charm Measurement in forward region and CGC





D.E. Kharzeev, K. Tuchin, hep-ph0310358

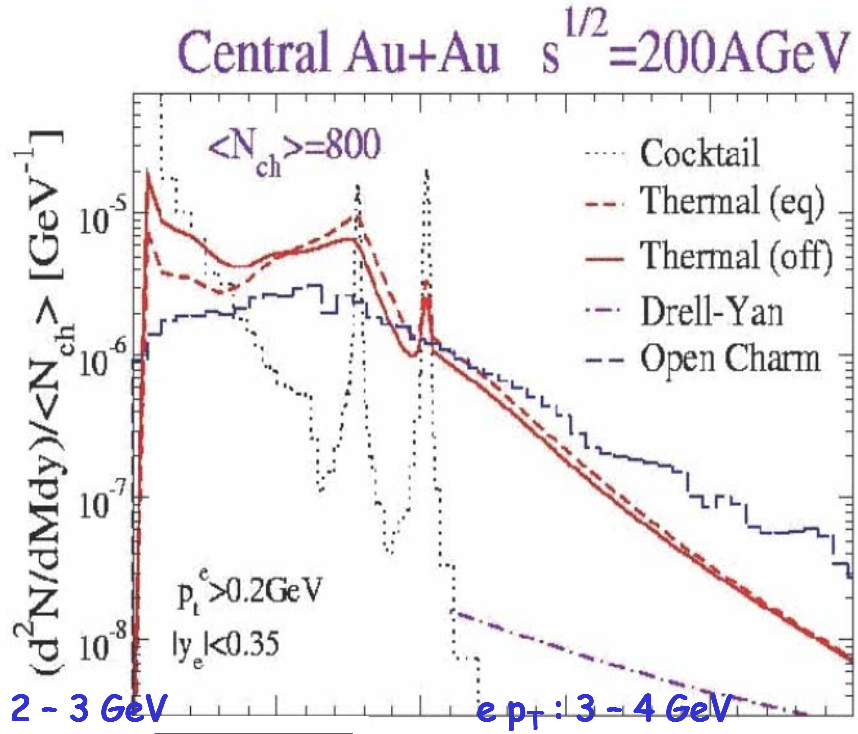
In Central region: Q_s<m(cc) open charm production is expected to scale with N_{coll}

In forward region: Q_s>m(cc). Open charm production is expected to scale with N_{part} *(AA)* and $\sqrt{N_{part}^{A}}$ *(pA)* in forward rapidity region.

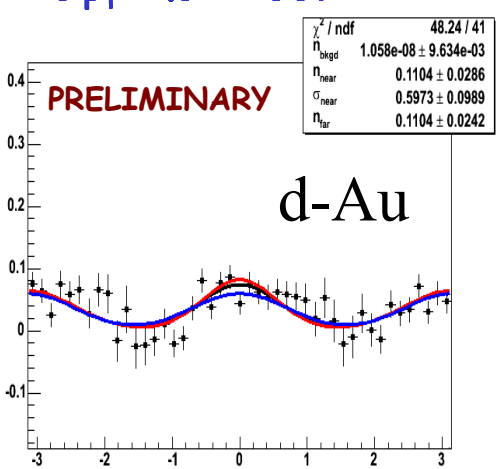
Ongoing PHENIX open charm analysis on muon channel is expected to give the answer

Other HF Topics

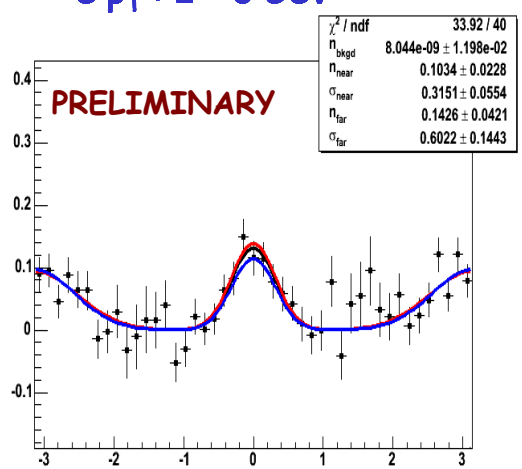
- $c\bar{c} \rightarrow e^+e^-$
  - Drell-Yan
  - IM di-leptons
- Charm-jet tomography
  - Tag charm jet w/ electrons
  - Measure J/Ψ near- and far-side correlations



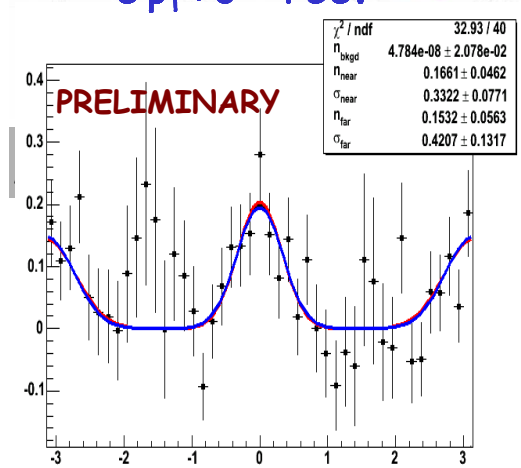
e p_T : 1.5 – 2 GeV



e p_T : 2 – 3 GeV



e p_T : 3 – 4 GeV

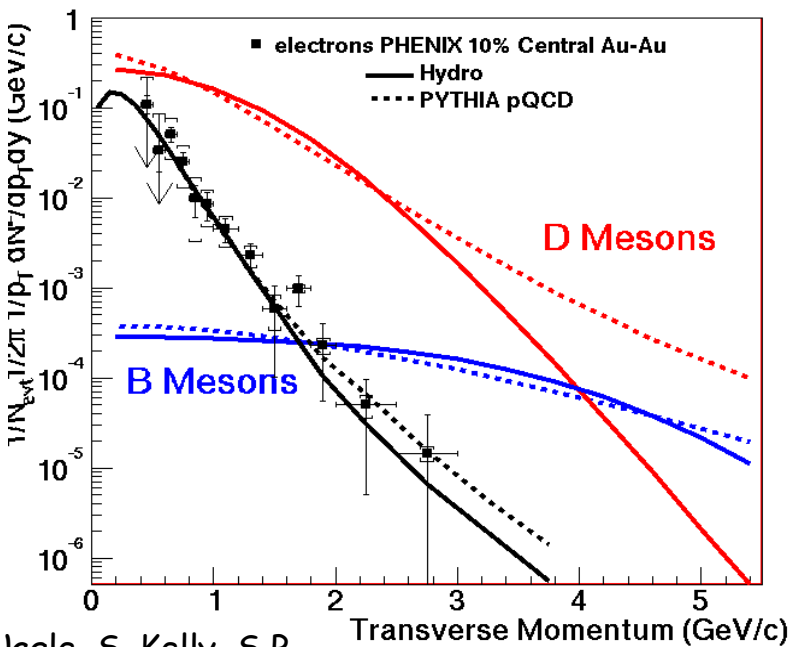


Charm questions – motivation for analysis

- **Do heavy quark suffer energy loss, as light flavors do ?**
  - Higher quark mass -> less gluon radiation ("dead cone effect")
  - Effective gluon mass in plasma

M. Djordjevic and M. Gyulassy nucl-th:0302069

- **Do heavy quark participate in collective flow ?**
  - Scattering in partonic medium and participate in hydrodynamic type expansion and fragment or coalesce with spectators to form D mesons



Electron data consistent with

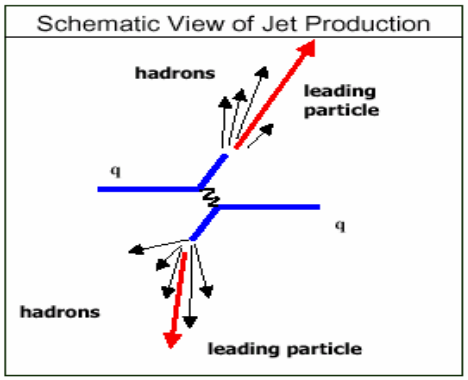
1. Medium transparent to heavy quarks which then fragment into D/B mesons outside the system
2. Highly opaque medium with charm boosted via rescattering and hadronizing in the system

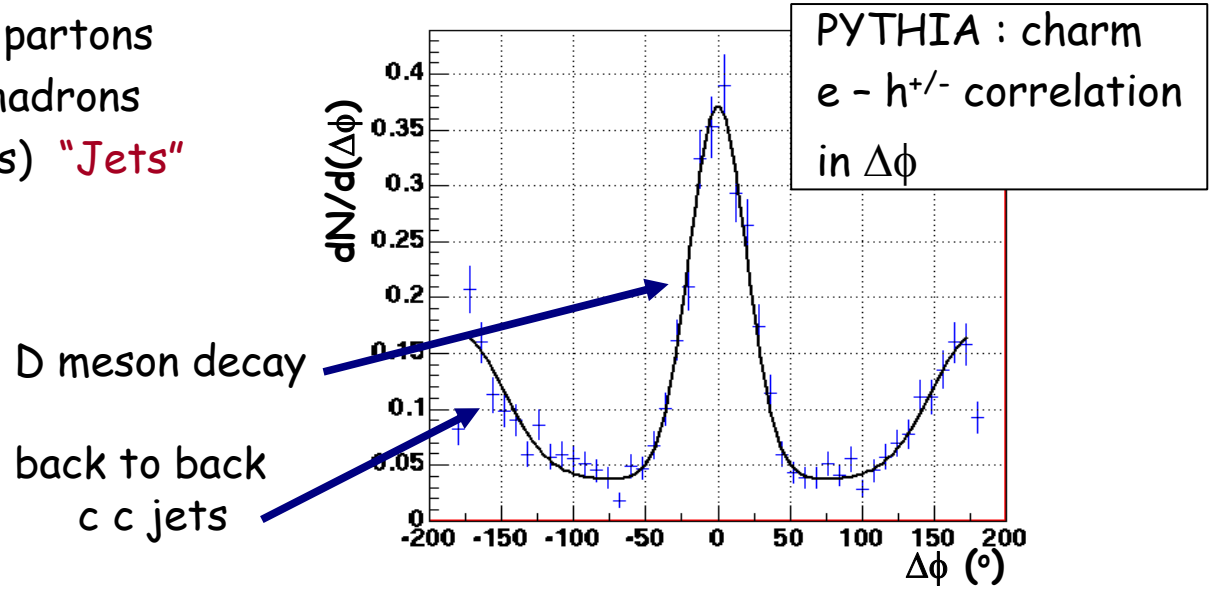
Initial c, b quarks from pQCD may be produced going with the flow!

J. Nagle, S. Kelly, S.B.

electron – charged particle azimuthal correlations to study charm production

In hard process the scattered partons
→ fragment into showers of hadrons
(concentrated in angular cones) "Jets"





What can we learn from e – $h^{+/-}$ Δϕ correlations ?

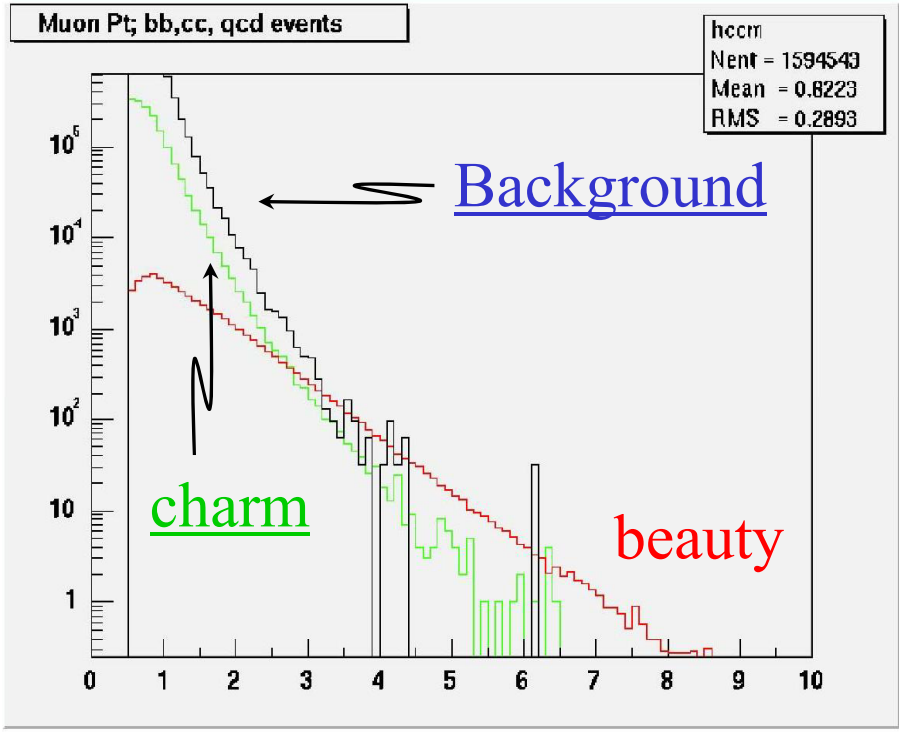
- Objervation of c c jets
- If medium **transparent** to heavy quarks which then fragment to D/B mesons outside the system

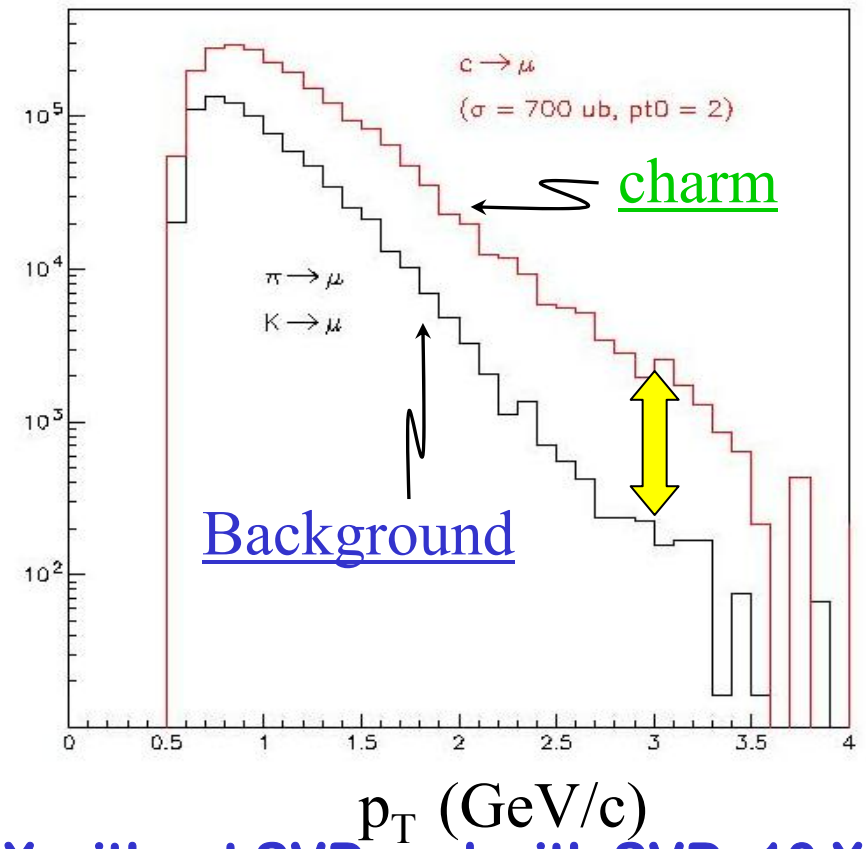
  ⇒ **Au –Au Away side: similar magnitude as p-p, d-Au**
- If medium **opaque** with heavy quarks rescattering and hadronizing in the system

  ⇒ **Au – Au Away side: disappear**

Dramatic Signal / Background Improvement for Heavy Quarks with SVD

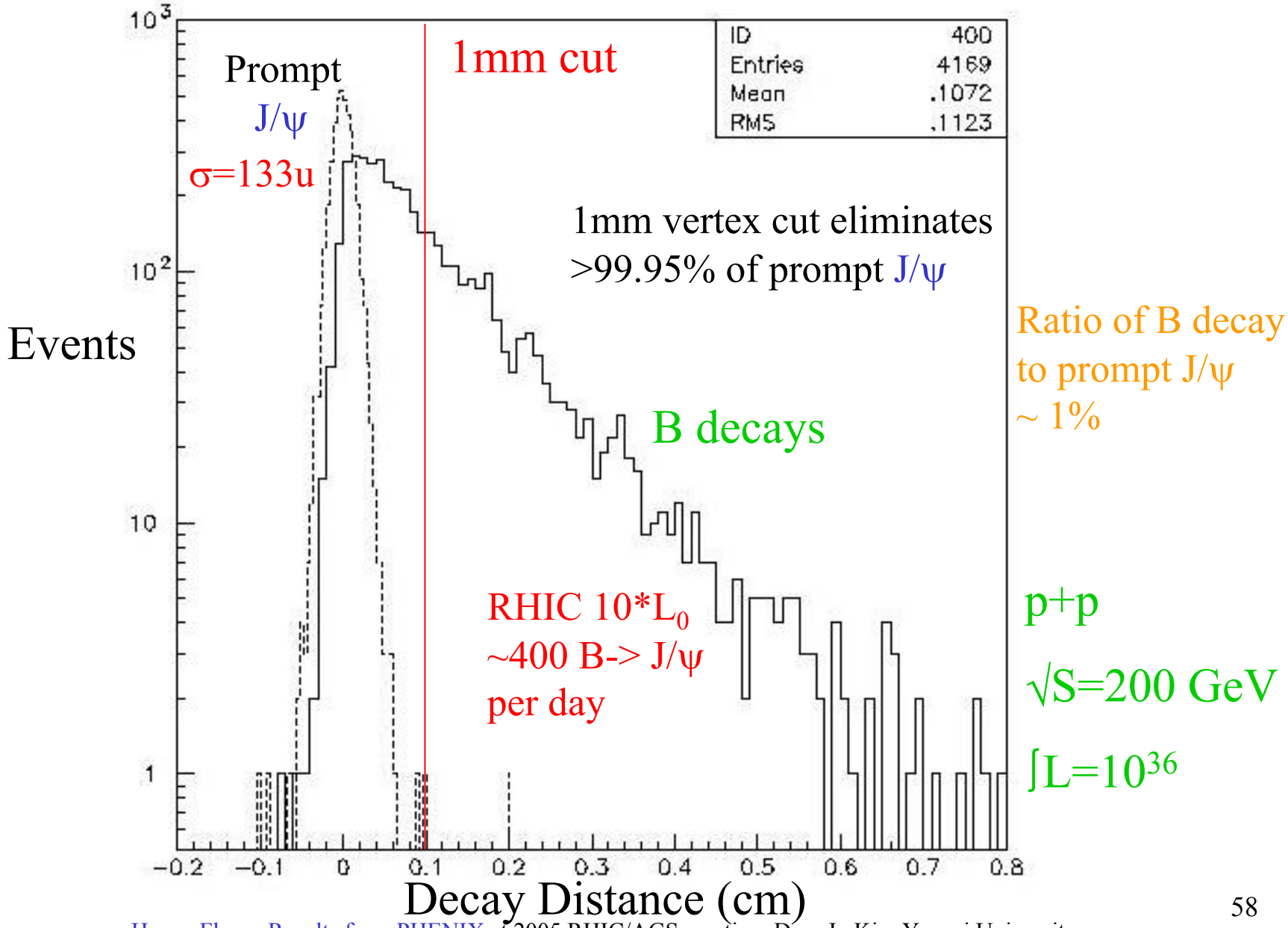
Before vertex cuts Muon Events **After vertex cuts**





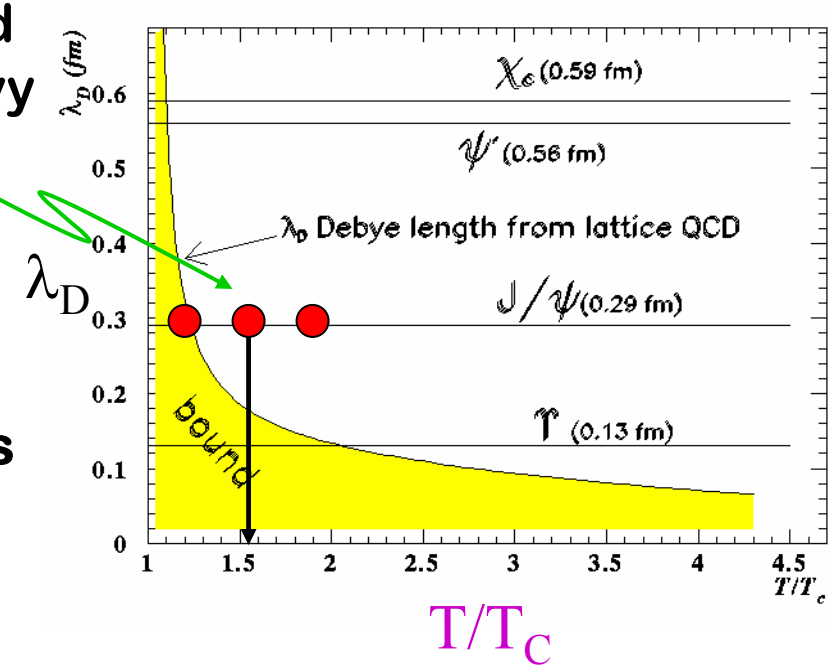
Simulated Signal to Noise for D→ μ+X without SVD and with SVD, 10 X improvement is signal / background → accurate yield, slope of charm

Simulation of B → J/ψ → $\mu^+\mu^-$ with Endcap VTX



Taking the Plasma Temperature

Currently large theoretical spread of "melting" temperatures of heavy quark bound states

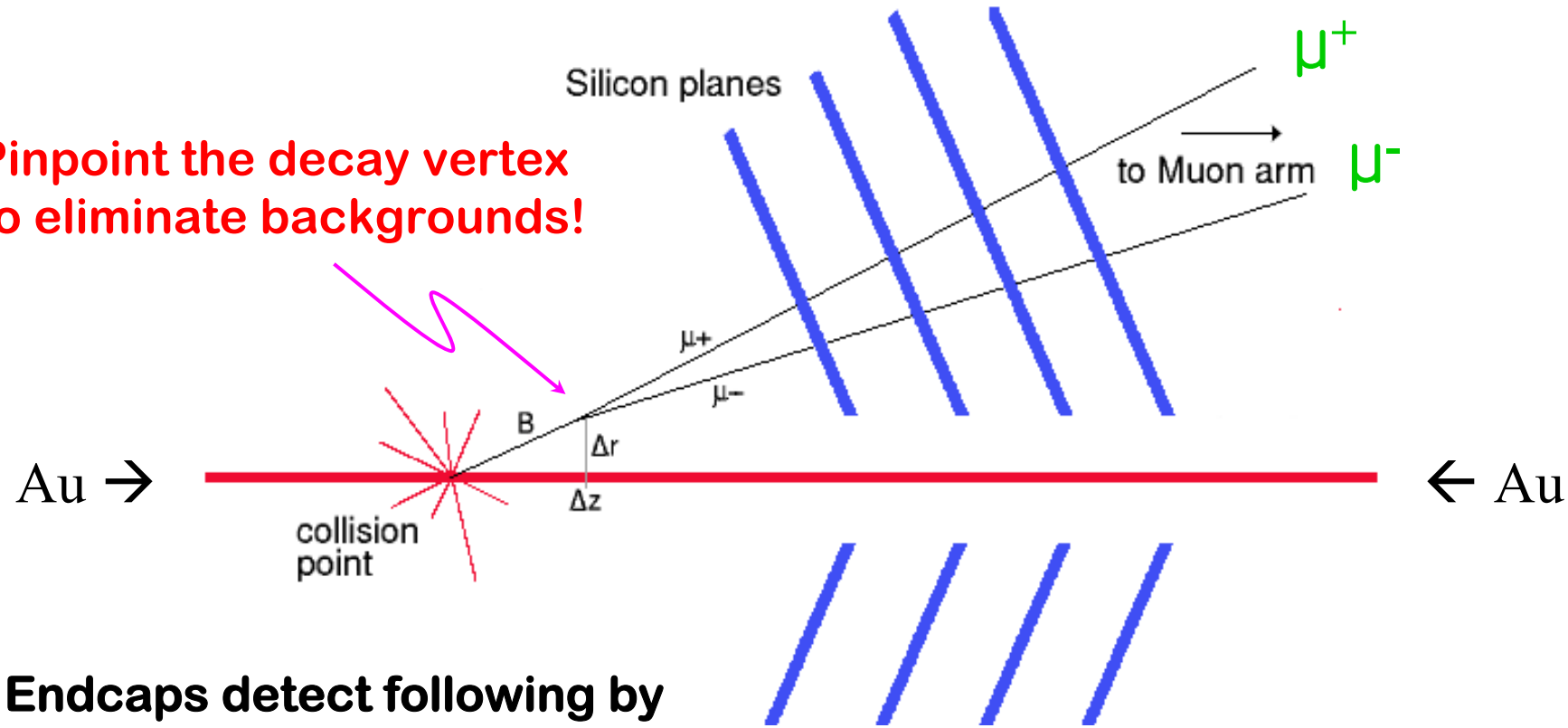


- **Improved** lattice QCD calculations of charmonium dissociation

To **pinpoint** the plasma temperature
Calculate equation of state

Silicon Vertex Detector Upgrade

Pinpoint the decay vertex to eliminate backgrounds!



Endcaps detect following by displaced vertex (Δr, Δz) of muons:

- D (charm) → μ + X
- B (beauty) → μ + X
- B → J/ψ + X → $\mu^+\mu^-$

Si planes constructed of strips 50 λm by few mm long