Electromagnetic Probes and Heavy Flavor in PHENIX

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Outline

1. *Motivation*
2. *PHENIX experimental set-up*
3. *Low mass di-electron continuum*
4. *Open heavy flavor*
5. *Quarkonia*

Motivation

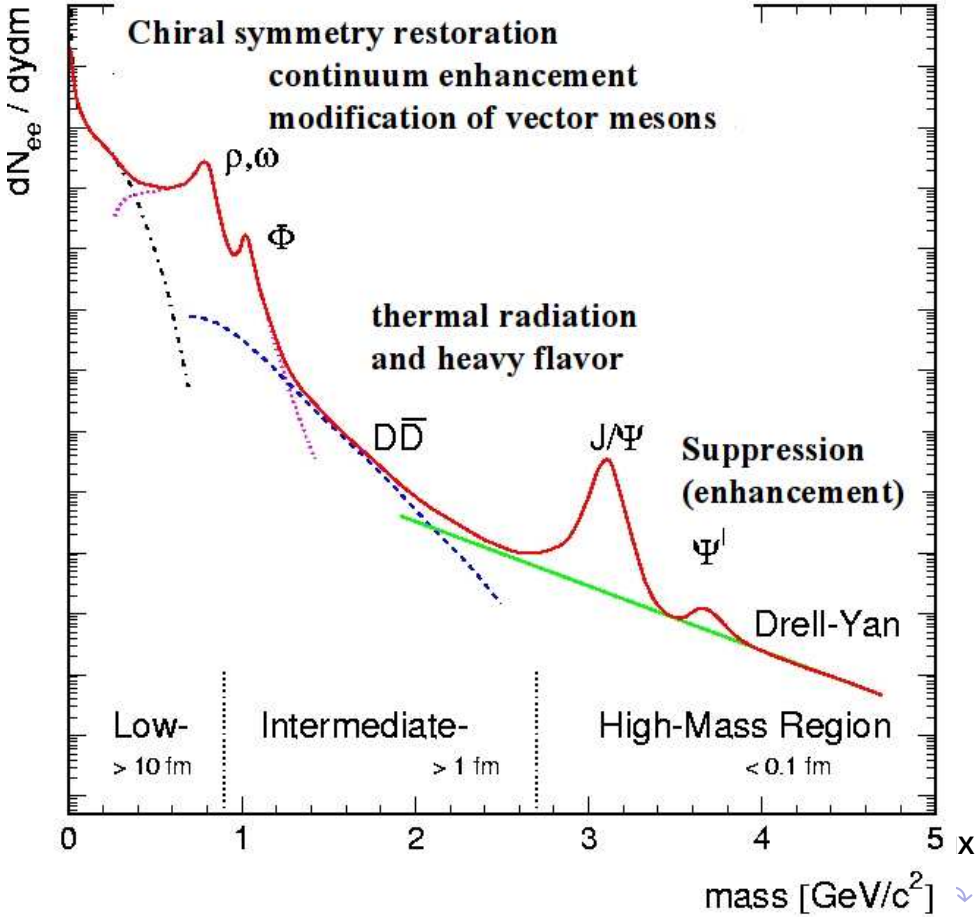
EM probes are an important and powerful tool to diagonse the hot and dense medium created in relativistic heavy ion collisions.

- interact only electromagnetically, once produced leave collision region unscathed.
- carry information about the early times

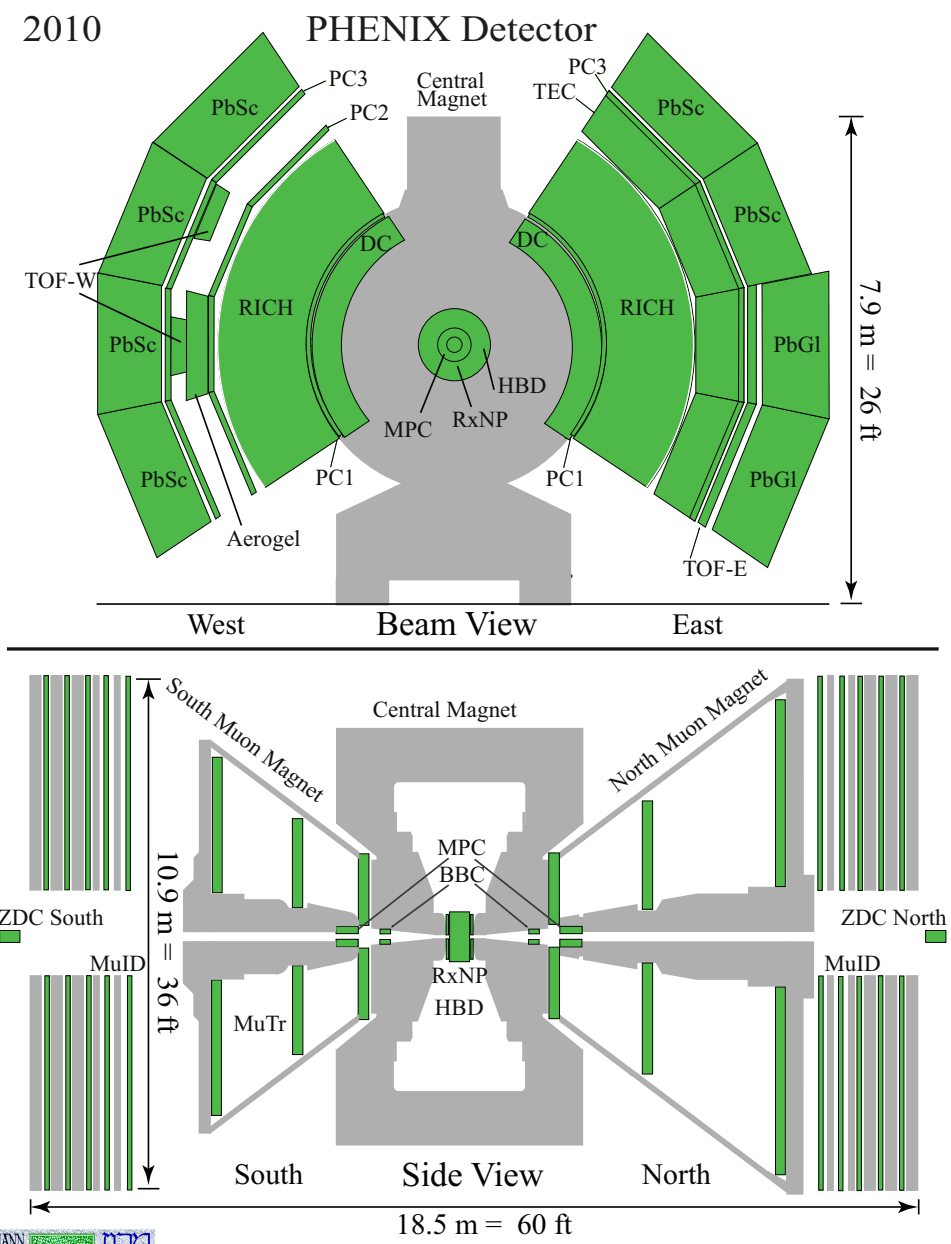
Dilepton mass spectrum

- π^0 and η Dalitz decay: thermal radiation from real and virtual photons
- light vector mesons and low-mass continuum: sensitive to chiral symmetry restoration that will appear as mass shifts, broadening or excess yield.
- open heavy flavor: thermal radiation and medium modification.
- quarkonia: suppression/enhancement of quarkonium production reveals critical features of the medium.

Expected modifications to the dilepton spectrum, due to the QCD phase transition



PHENIX Experimental set-up



Central Arms: hadrons, photons, electrons;

- $-0.35 \leq \eta \leq 0.35$;
- $p_e > 0.2$ GeV/c;
- $\Delta\phi = \pi(2\ arms \times \pi/2)$;
- charged particle tracking analysis using DC and PC.

Electron identification based on:

- Ring Imaging Čerenkov detector (RICH);
- Electromagnetic Calorimeter (EMCal).

Forward rapidity arms: muons;

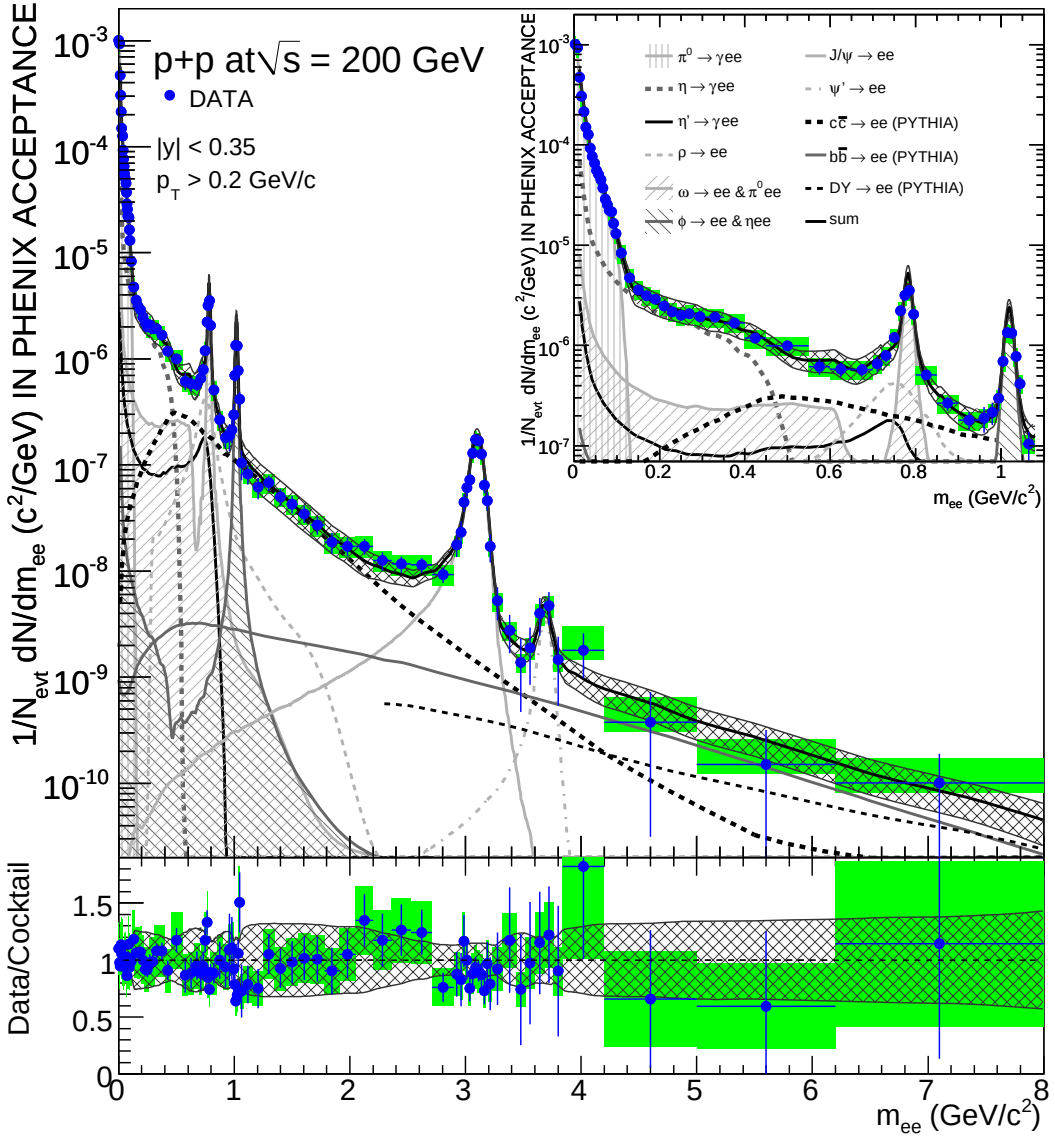
- $1.2 \leq |\eta| \leq 2.4$;
- $p_\mu > 1.0$ GeV/c
- $\Delta\phi = 2\pi$
- μ-Magnets and μ-Identifier steel absorb hadrons, π-rejection $\sim$ 250:1
- μ-Tracker reconstructs trajectories and determines momentum.

Low mass di-electron continuum

Dileptons in PHENIX: $p + p$ collisions

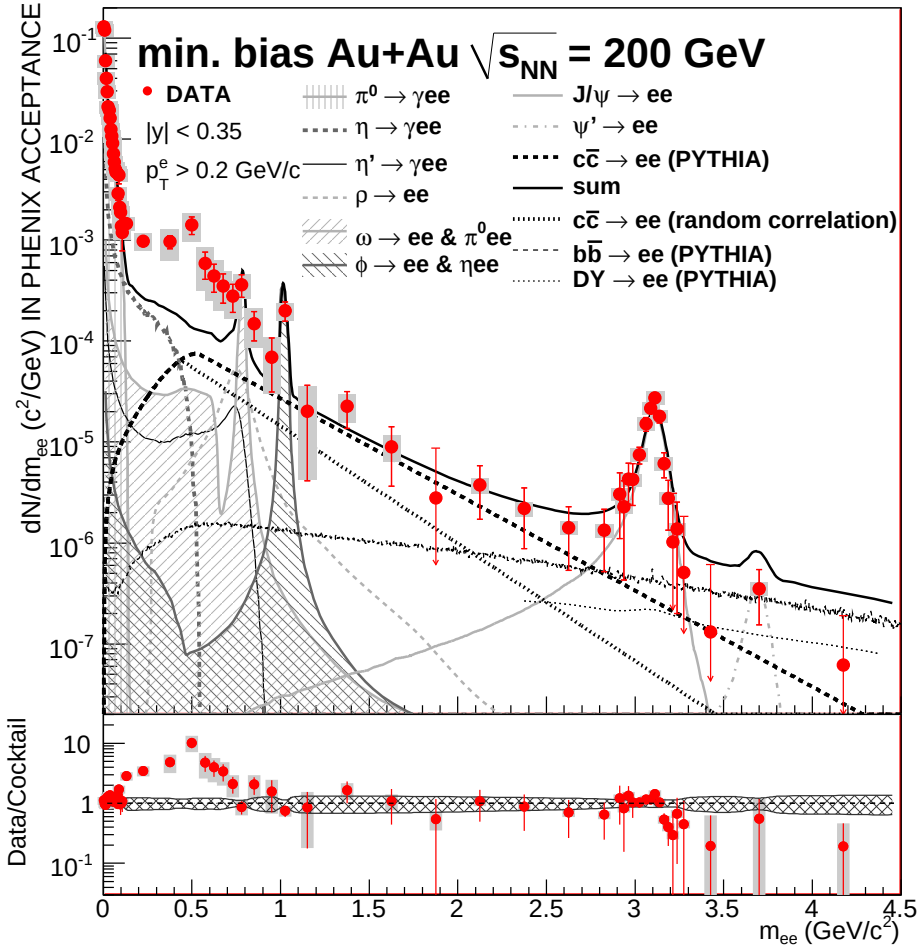
- Inclusive mass spectrum of e^+e^- measured from $m = 0$ to $m = 8$ GeV/c^2.
- Very well understood in terms of
  - hadron cocktail at low masses.
  - heavy Flavor + DY at high masses
- **Charm: integration after cocktail subtraction;** $\sigma_{c\bar{c}} = 544 \pm 39(stat) \pm 142(sys) \pm 200(model)\mu b$
- **Simultaneous fit of charm and bottom;**
  - $\sigma_{c\bar{c}} = 518 \pm 47(stat) \pm 135(sys) \pm 190(model)\mu b$
  - $\sigma_{b\bar{b}} = 3.9 \pm 2.4(stat) \pm^{3}_{-2} (sys)\mu b$

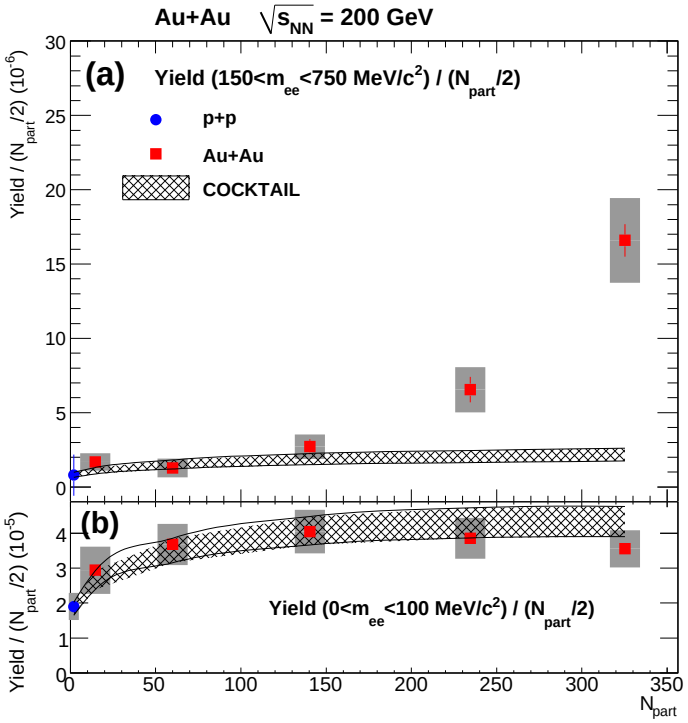
PLB 670, 313 (2009)

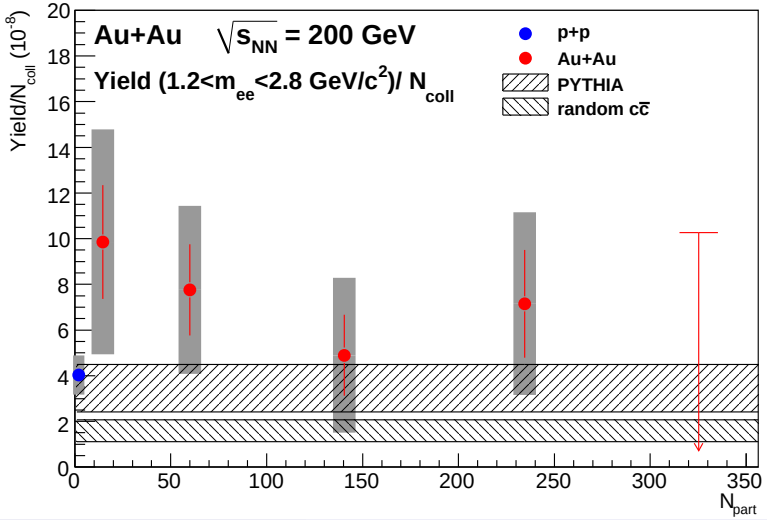


Dileptons in PHENIX: Au + Au collisions

Au + Au **(PRC 79, 81 034911(2010))**







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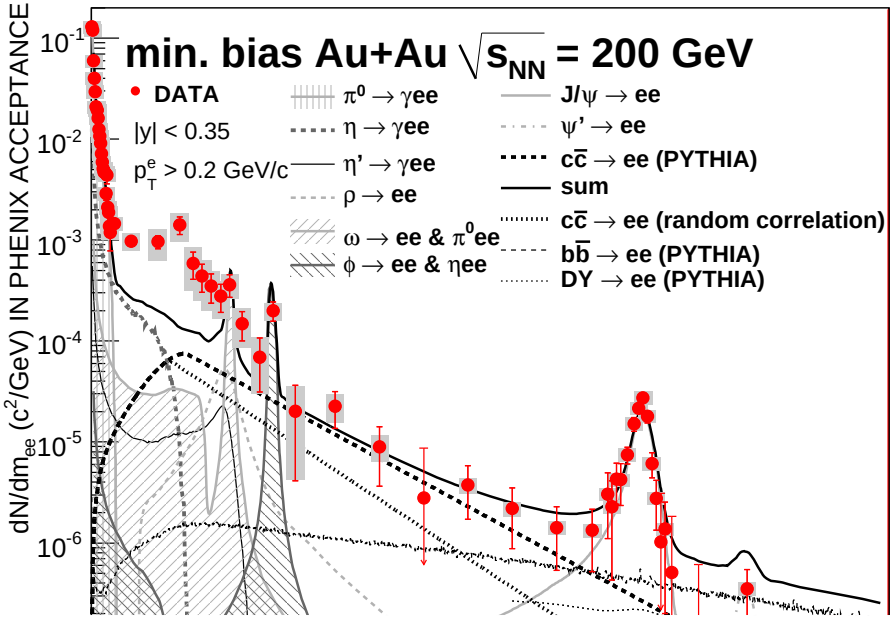
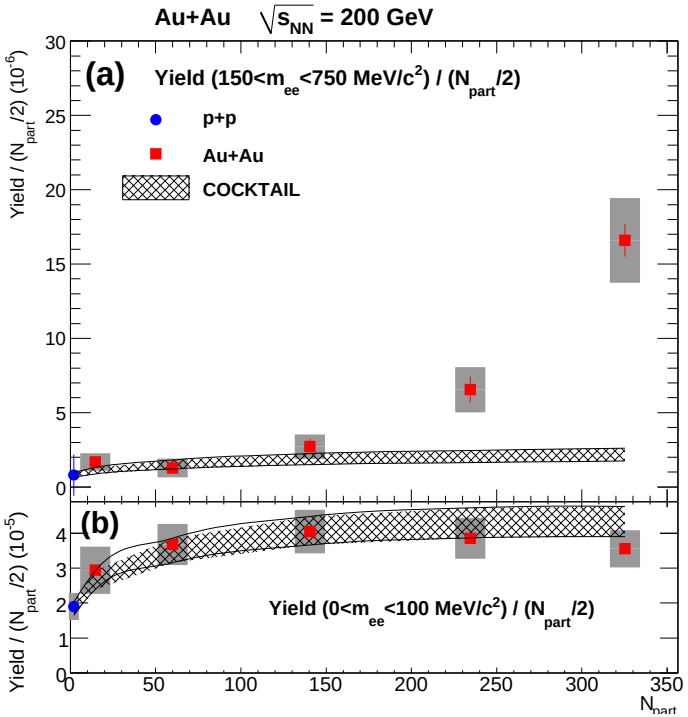
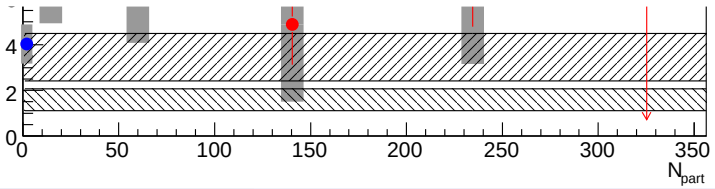


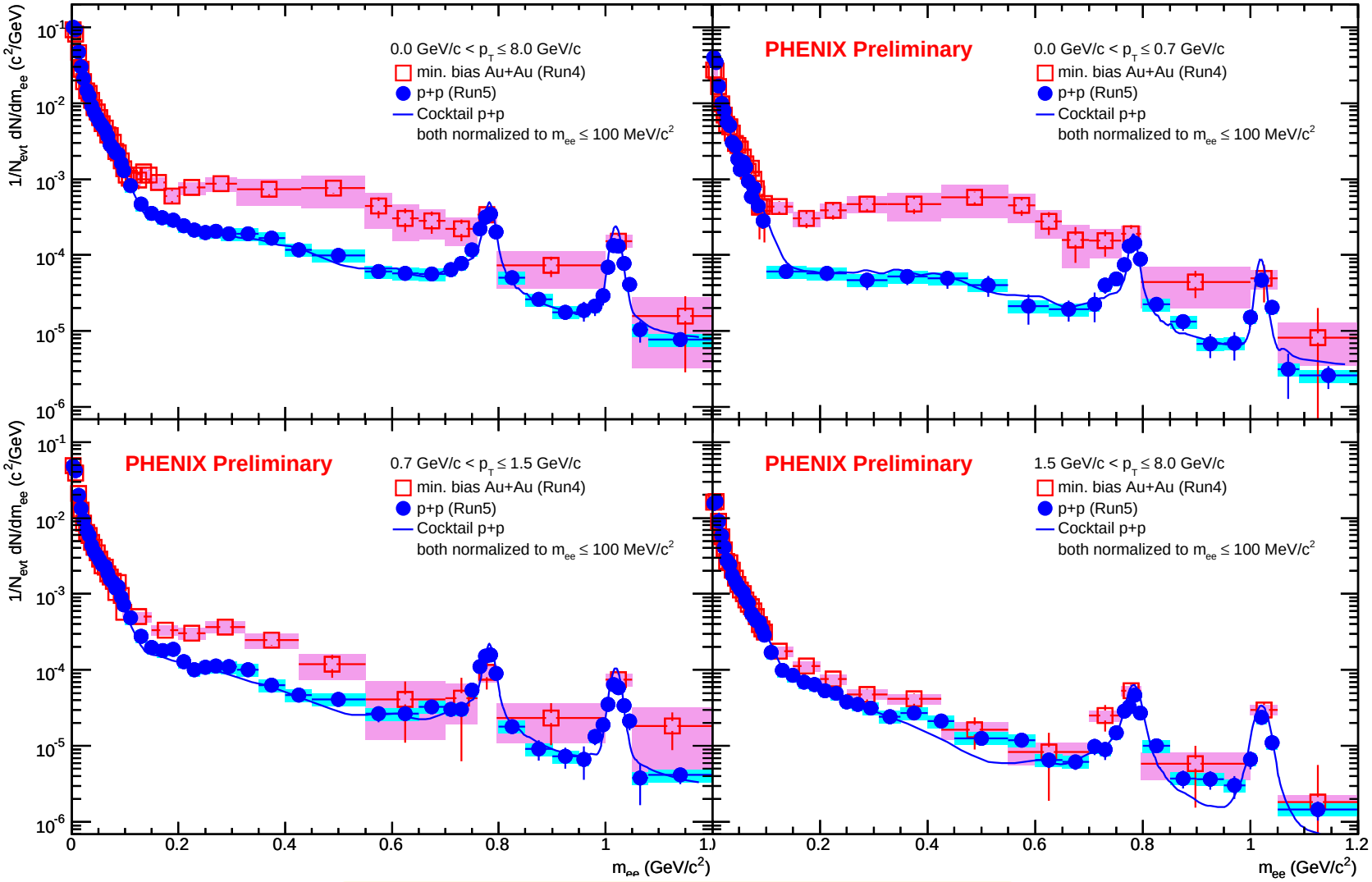


Data/Cocktail

- Strong enhancement of e^+e^- pairs at low masses:
  $(3.4 \pm 0.2(stat) \pm 1.3(sys) \pm 0.7(model)\mu b$ $(0.15 \leq \ m_{e^+e^-} \ \leq 0.75 \mathrm{GeV}c^2)$
- Characteristic properties:
  - Enhancement down to very low masses
  - Enhancement concentrated in central collisions
  - No enhancement in the IMR

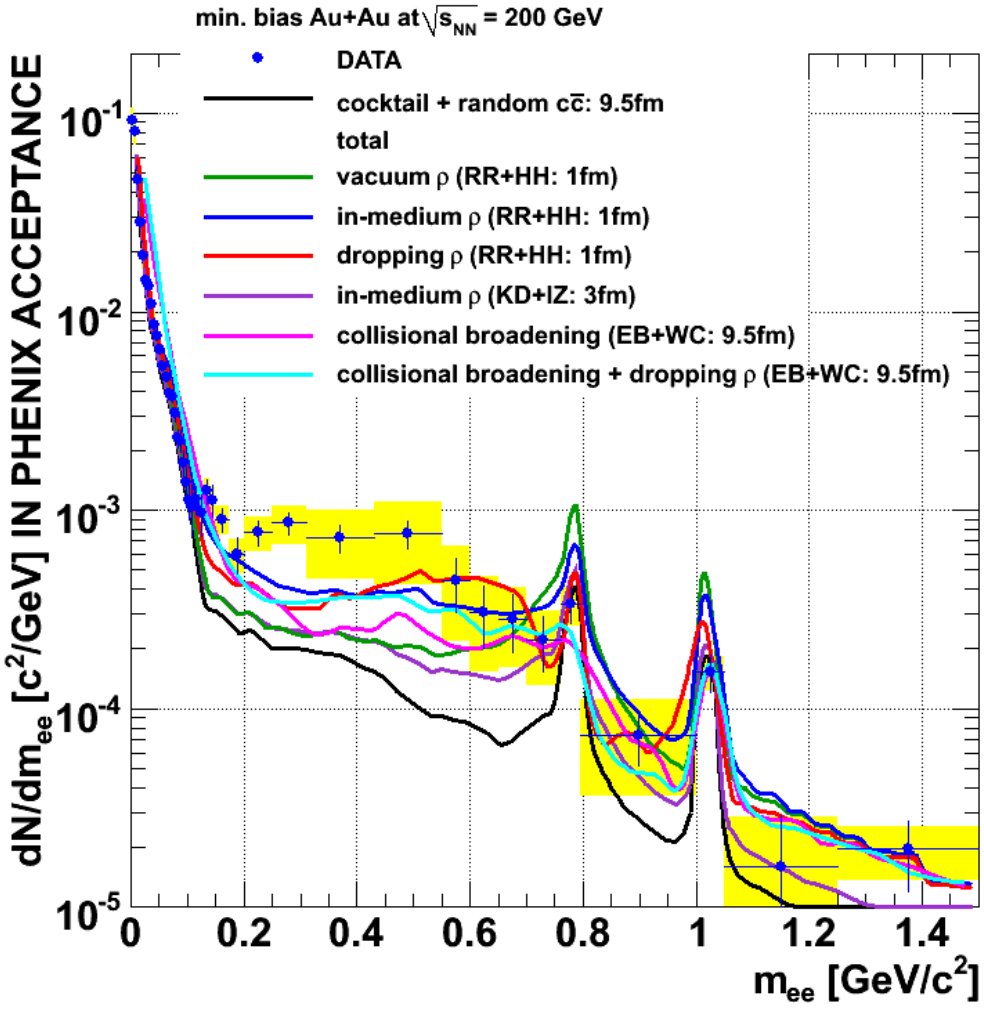


Low mass region: evolution with p_T



Enhancement mostly at low p_T

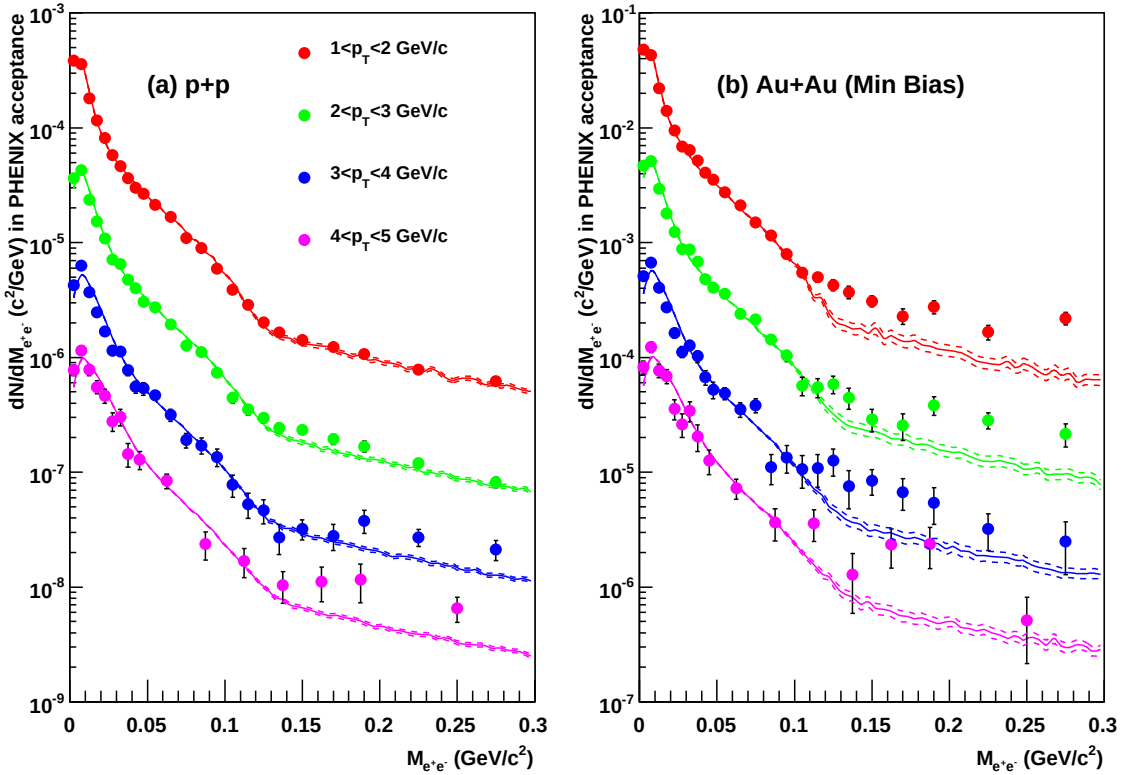
Comparison to theoretical models ($Au + Au$)



All models and groups that successfully described the SPS data fail in describing the PHENIX results

Thermal radiation at RHIC - I

- **Real photon yield can be measured from virtual photon yield, observed as low mass e^+e^- pairs.**
- Enhancement of low mass dileptons → emission of almost real photons.

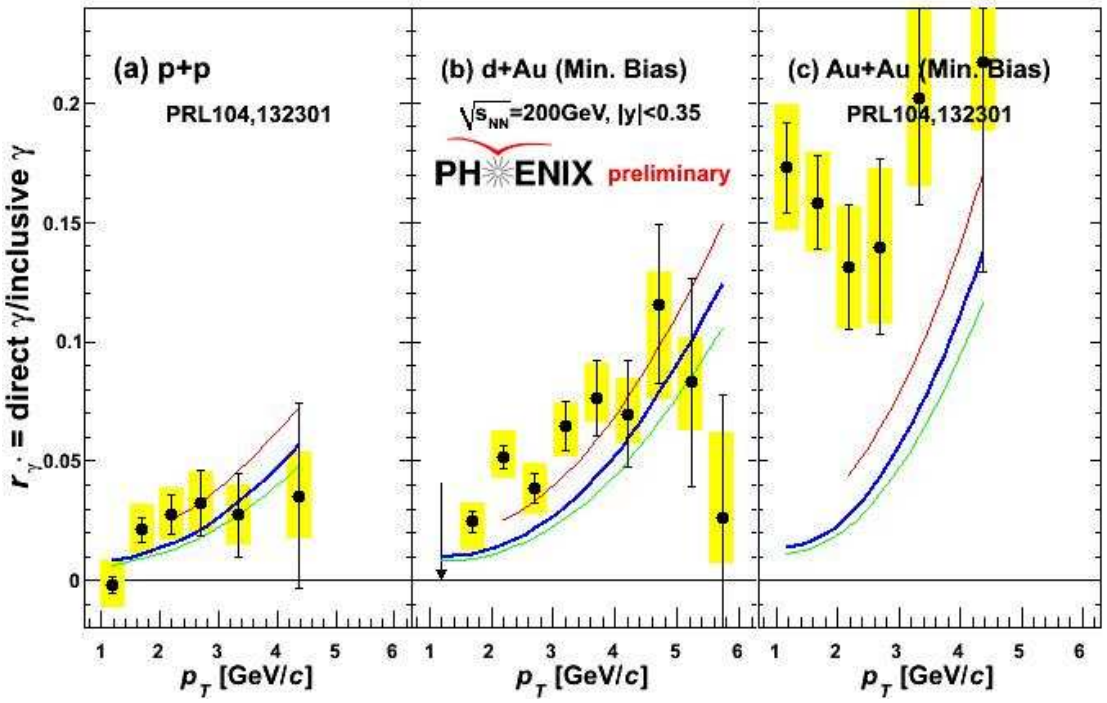


- Restricted kinematic window: low mass e^+e^- pairs ($M < 300\ MeV\ \&\ 1 < p_T < 5\ GeV/c$)
- **p+p**
  - Good agreement of $p+p$ data and hadronic decay cocktail.
- **Au+Au**
  - Clear enhancement visible above $m_\pi = 135$ MeV for all p_T.

Thermal radiation at RHIC - II

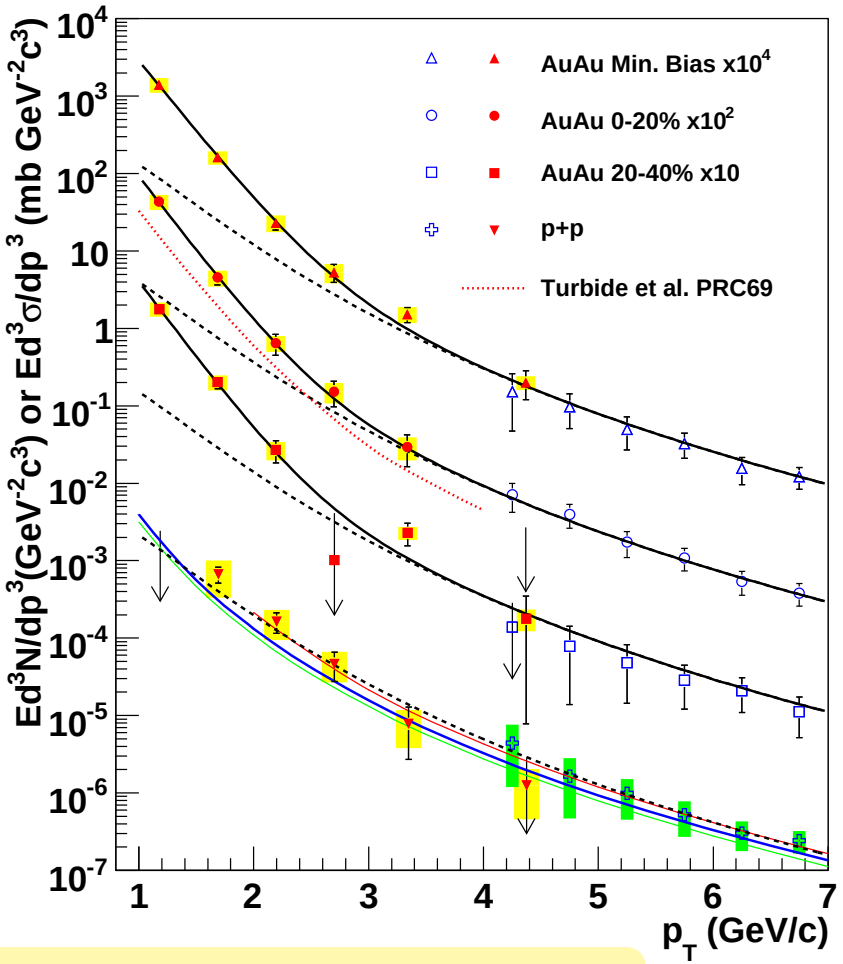
Direct γ^* to inclusive γ^* ratio

- Shown are the results for $p+p$, $d+Au$ and $Au+Au$ collsions at $\sqrt{s_{NN}} = 200$ GeV
- Curves are NLO pQCD calculations with different theoretical scales.
- $p+p$ is consistent with NLO pQCD calculations, excess in minimum bias $Au+Au$ collisions is much higher than that in $d+Au$.



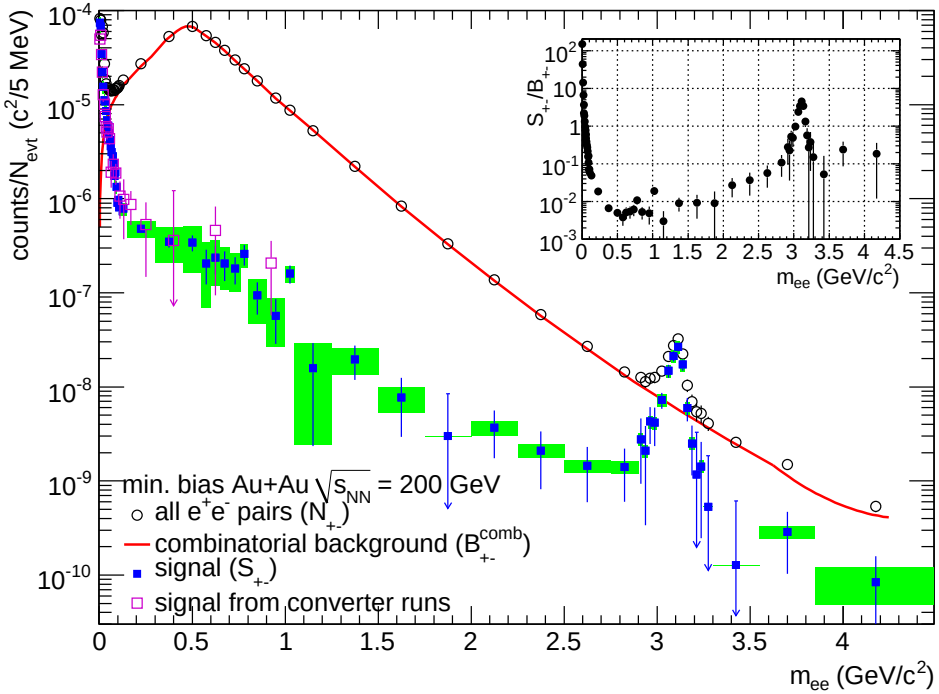
Thermal radiation at RHIC - III

- e^+e^- invariant mass excess
  - transformed into a spectrum of real photons under the assumption that the excess is entirely due to internal conversion of photons.
  - compared to direct (real) photon measurement, $p_T > 4$ GeV (*PRL 98, 012002 (2007)*)
    Good agreement in range of overlap
- pQCD consistent with $p+p$ down to p_T =1GeV/c
- $Au+Au$ data are above N_{coll} scaled $p+p$ for $p_T < 2.5$ GeV/c.
- Fit $Au+Au$ excess with exponential function + N_{coll} scaled $p+p$.



$T_{ave} = 221 \pm 19(stat) \pm 19(sys)$MeV corresponds to T_{ini}= 300 to 600 MeV, $\tau_0 = 0.15$ to 0.6 fm/c

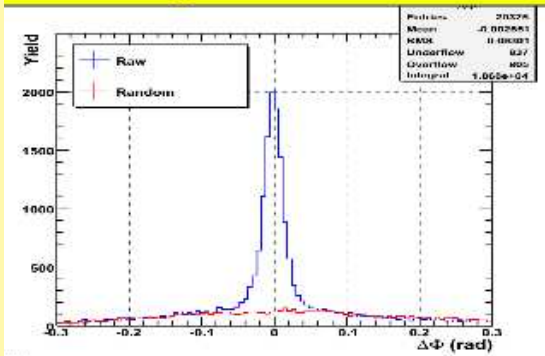
The future: Hadron Blind Detector

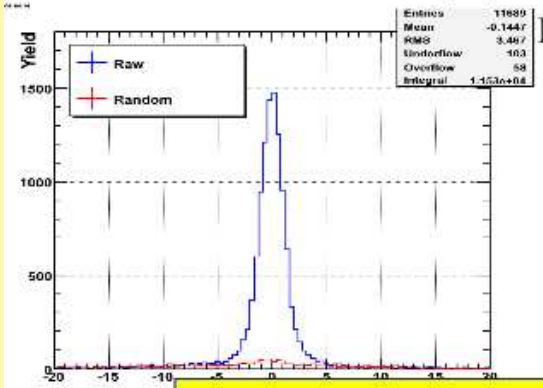


- The present PHENIX results suffer from large systematic uncertainties.
- The S/B ratio in $Au + Au$ (Run4) is $\sim 1/200$ at mass $m_{e^+e^-} \approx 500$ MeV/^{2}.
- A Hadron Blind Detector was installed in 2009 to improve measurements in the LMR by reducing the combinatorial background.
  - use opening angle cut to reject Dalitz decays and conversion pairs

The future: Hadron Blind Detector

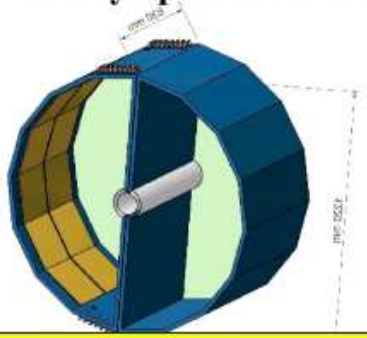
Matching resolution in z and Φ



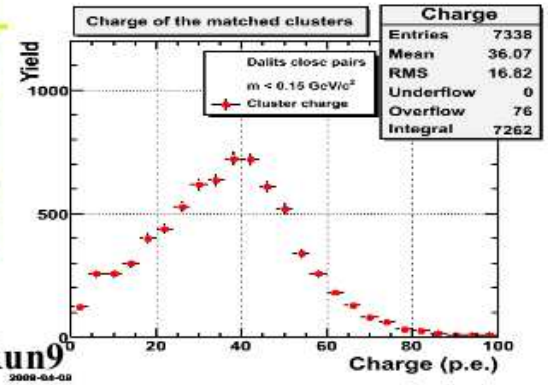


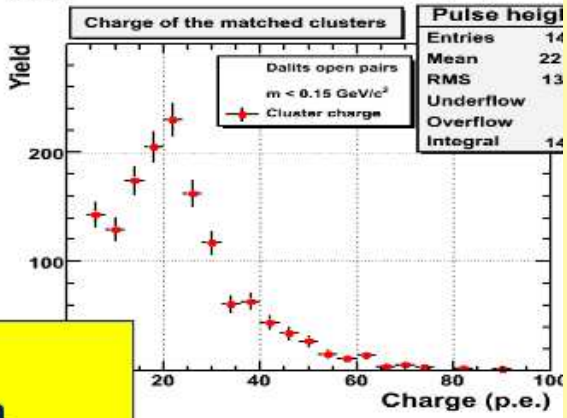
HBD

Installed and fully operational since Run9



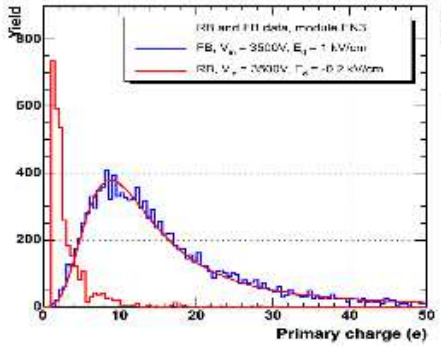
Single vs double e separation

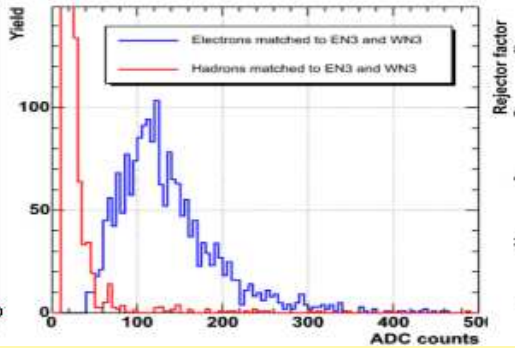


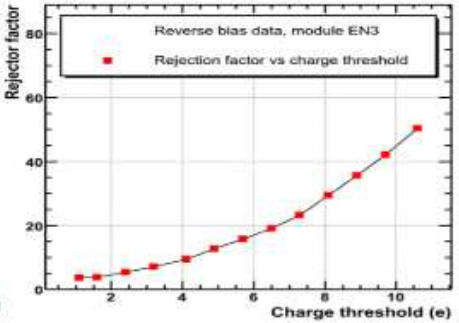


Hadron blindness

h in F and R bias e-h separation h rejection



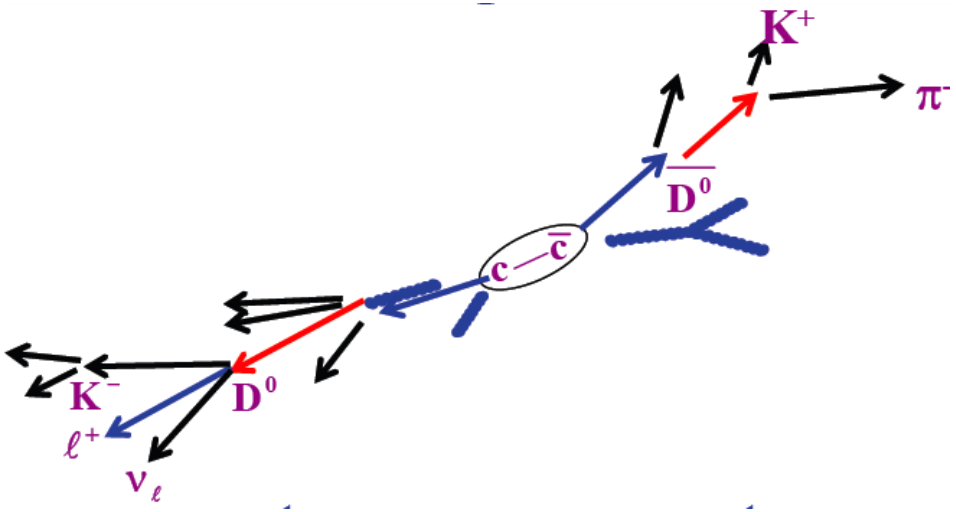




Open heavy flavor

Open heavy flavor measurement in PHENIX

PHENIX measures open heavy flavor indirectly via semi-leptonic decays.



- Measure spectrum of all electrons.
- Subtract photonic electrons using cocktail of known (measured) sources: conversions, Dalitz decays of π^0 and η etc.
- Additional subtraction of quarkonia contribution.
- Cross-check of photonic contribution by inserting converter.

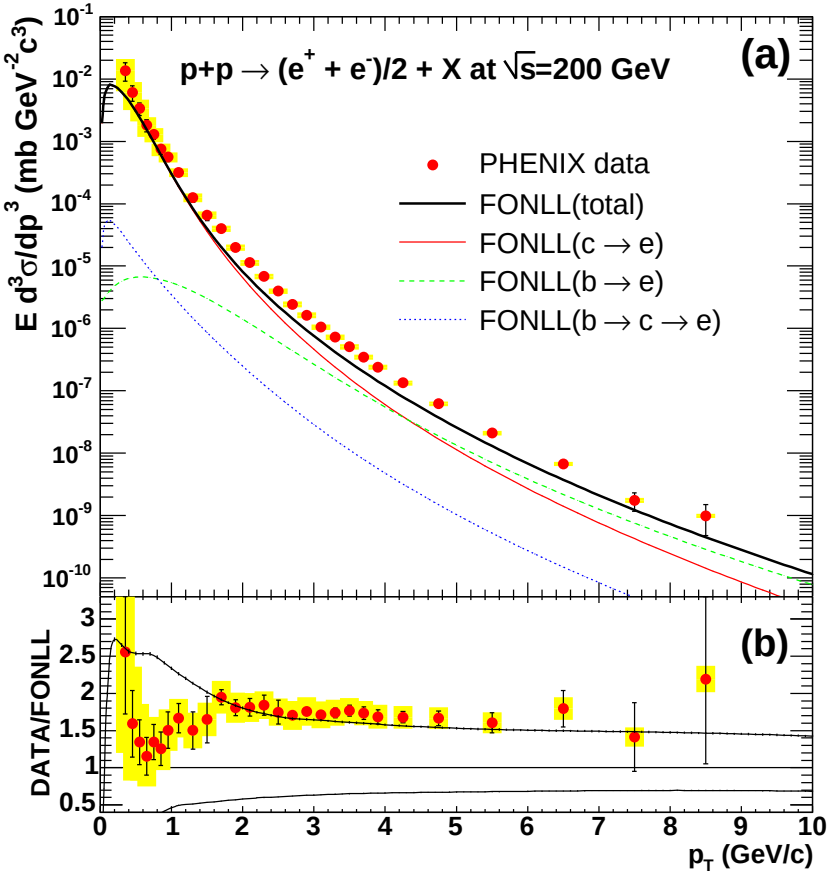
Open heavy flavor measurement in $p + p$ collisions

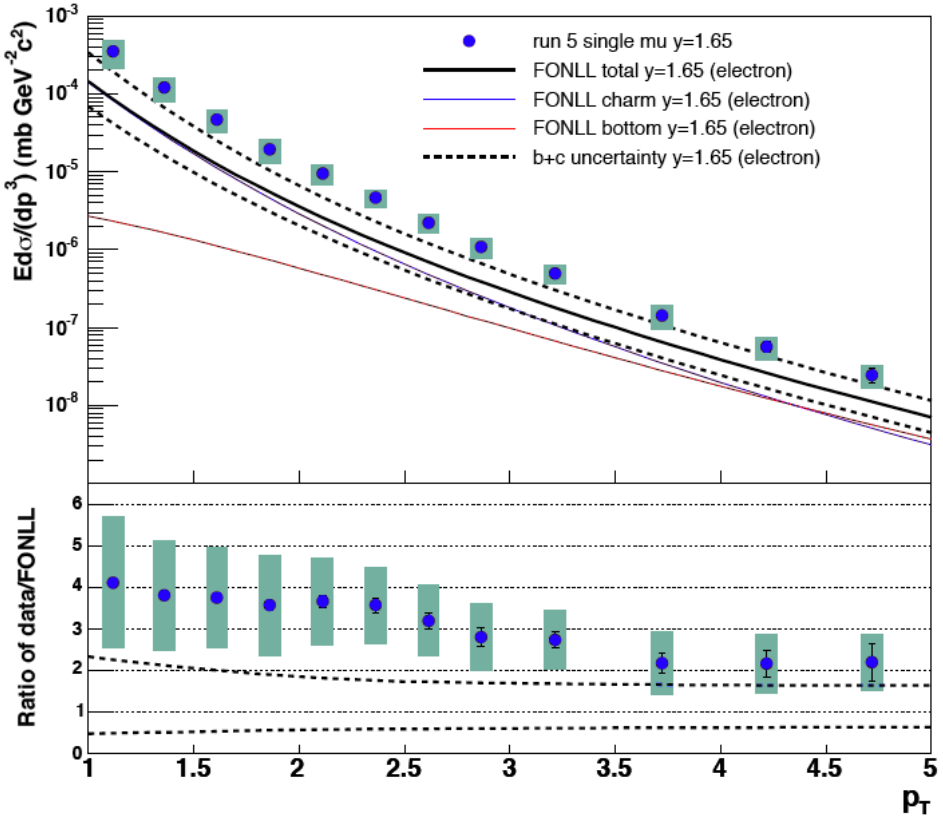
PRL 97, 252002(2006)

Single electrons ($|y| < 0.35$)

In agreement with previous PHENIX publication **PRD 76, 09200**

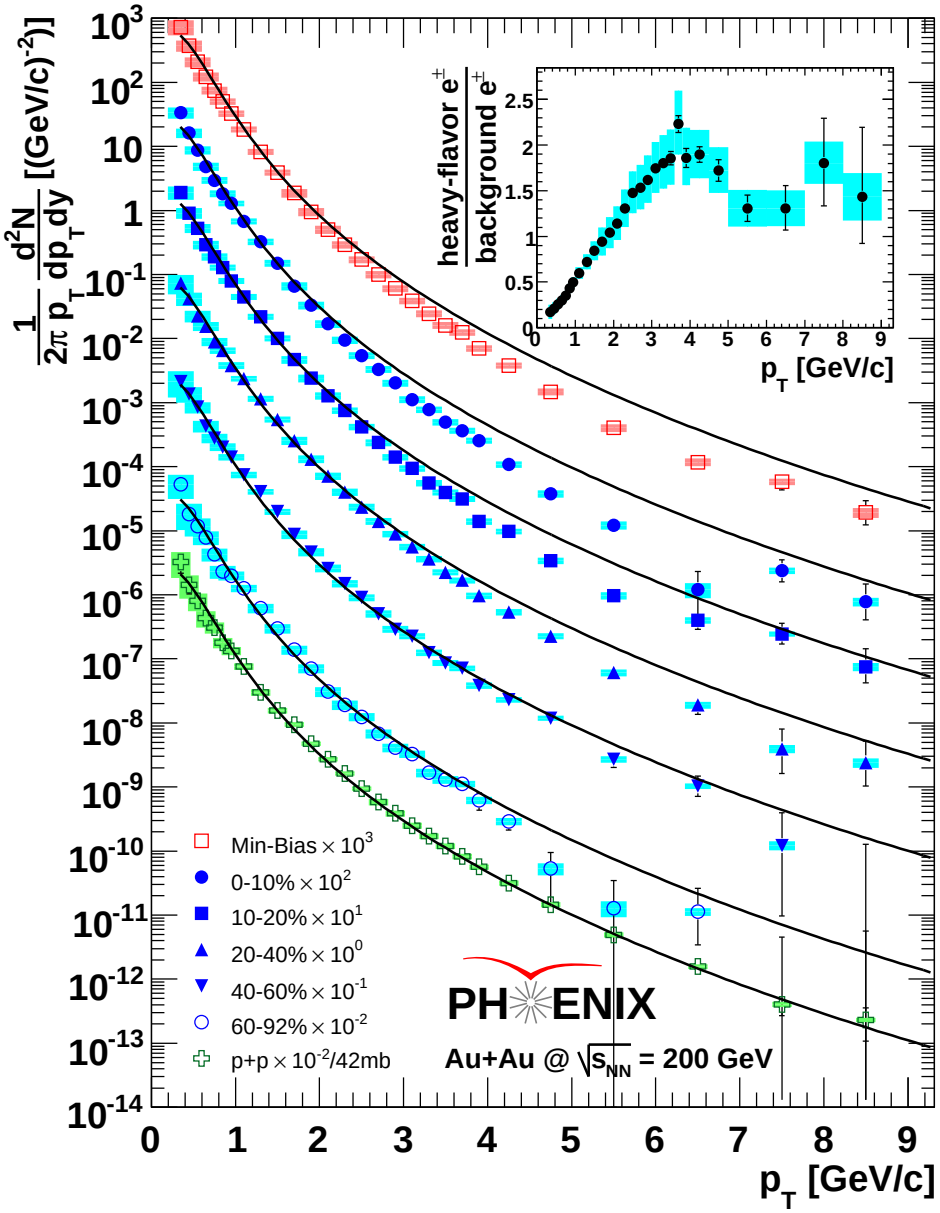
Single muons ($1.4 < y < 1.9$)





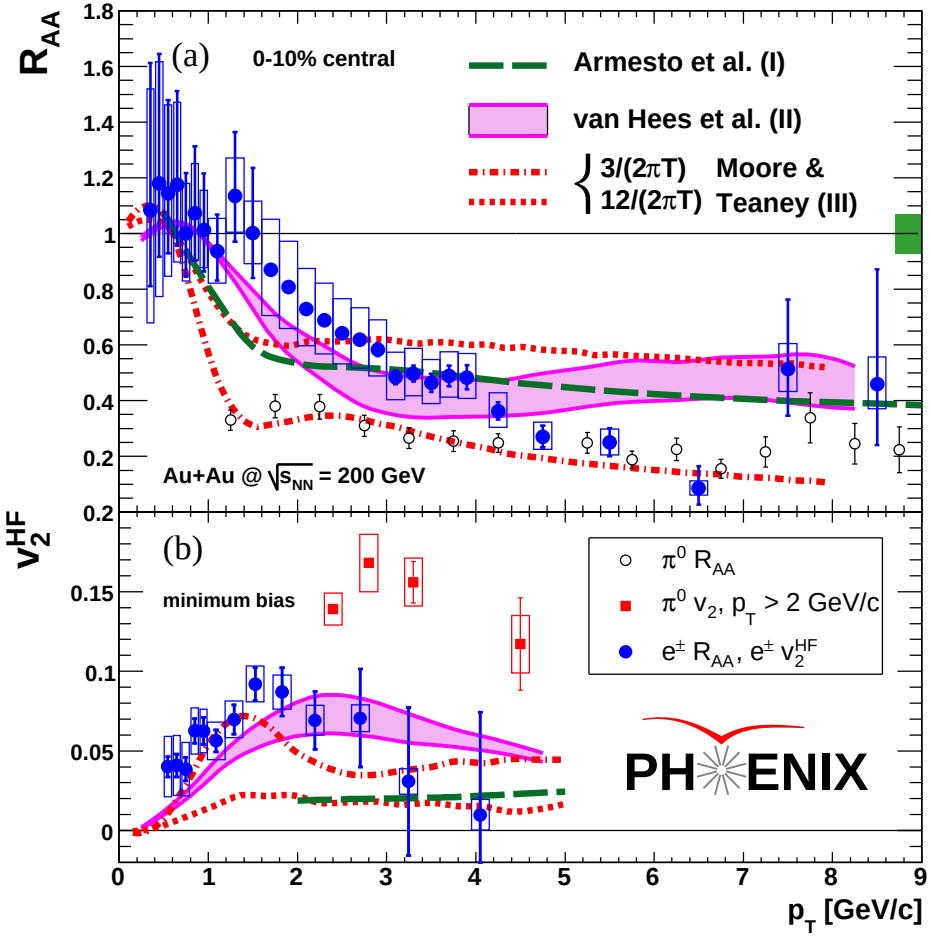
- **Derived charm X-section from single electrons,** $\sigma_{c\bar{c}} = 567 \pm 57(stat) \pm 224(sys)\mu b$
- Mid-rapidity measurement is in agreement with pQCD calculations.
- Measurement at the forward rapidity agrees for $p_T > 3.5$ GeV/c, where S/B is better.

Open heavy flavor in $Au + Au$



PRL 98, 172301 (2007)

- Same method as in $p + p$
- Heavy flavor electrons from $Au + Au$ compared to N_{coll} scaled $p + p$ (FONLL × 1.71)



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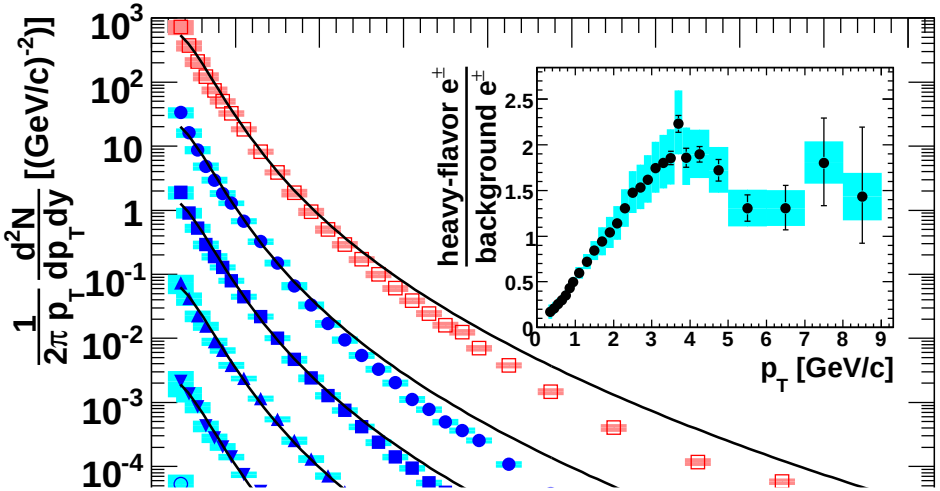

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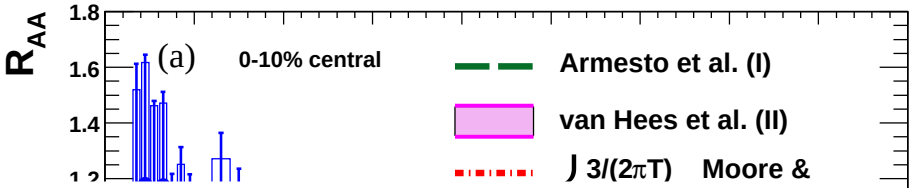
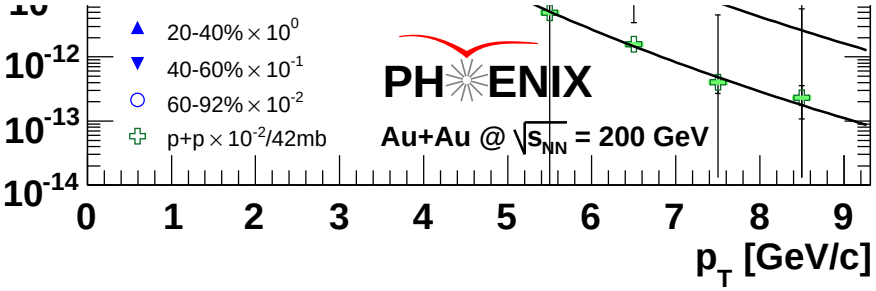
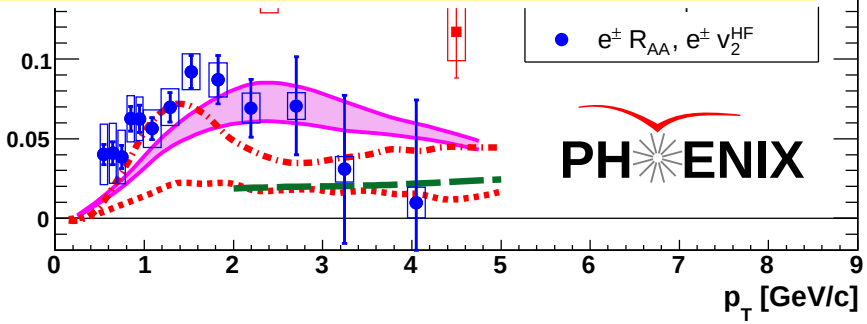


- Suppression level is almost the same as for light quarks at high p_T !
- Intermediate p_T suppression compatible with the scenario, where the radiative energy loss is larger for light mesons.
- Comparison to the Transport models that describe suppression and elliptic flow simultaneously, suggest that $\frac{\eta}{s}$ is close to the conjectured quantum lower bound *i.e.* near a perfect fluid.





Future of open heavy flavor in PHENIX

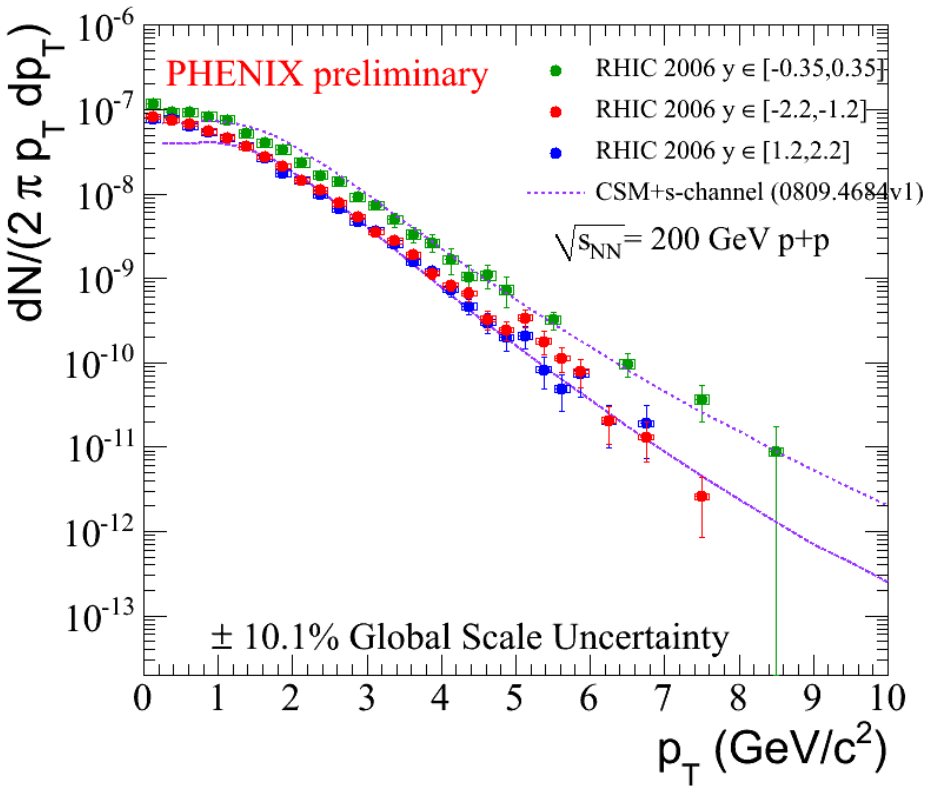
- The $p+p$ and $Au+Au$ data in 2009 and 2010 were taken with the HBD in the central arms - large improvement in e_{HF} signal/background.
- Results of $e_{HF}-$hadron correlations from 2008 $d+Au$ run.
- VTX detector (mid-rapidity) in Run 11 and FVTX (forward rapidity) on Run 12 will allow b/c separation for e_{HF}
- Trigger on $e_{HF}-e_{HF}$ to explicitly select back-to-back heavy flavor using the VTX detector starts in Run 11.

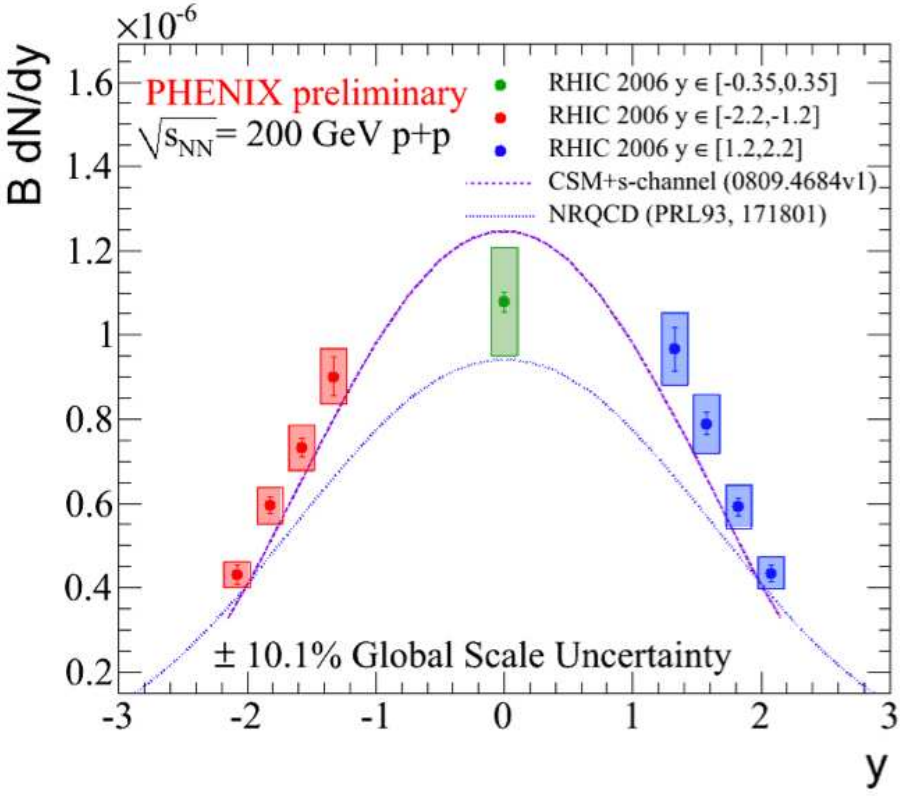
Quarkonia

Invariant yield of J/ψ in $p+p$ collisions

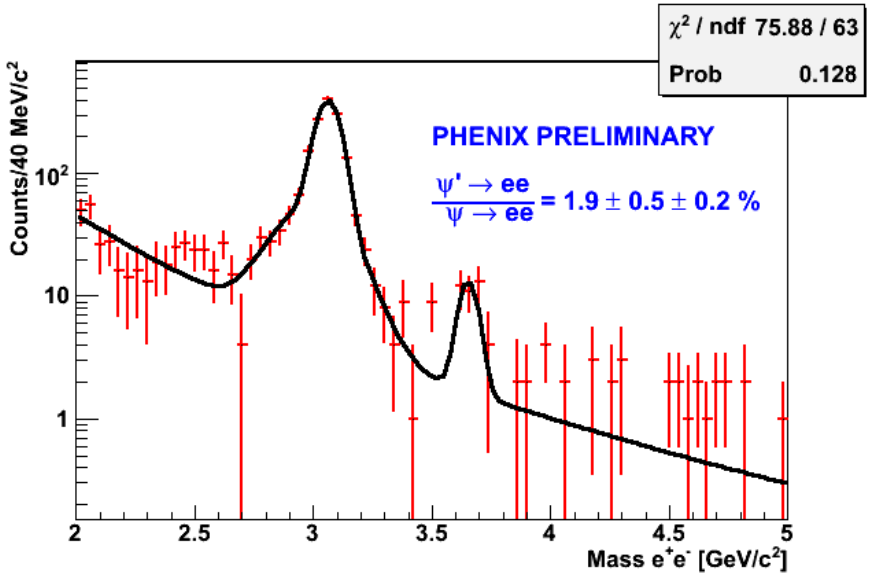
PHENIX has made high luminosity measurements of J/ψ yields from $p+p$ collisions in 2005, 2006 and 2009 runs. Data shown here are from 2005 and 2006.

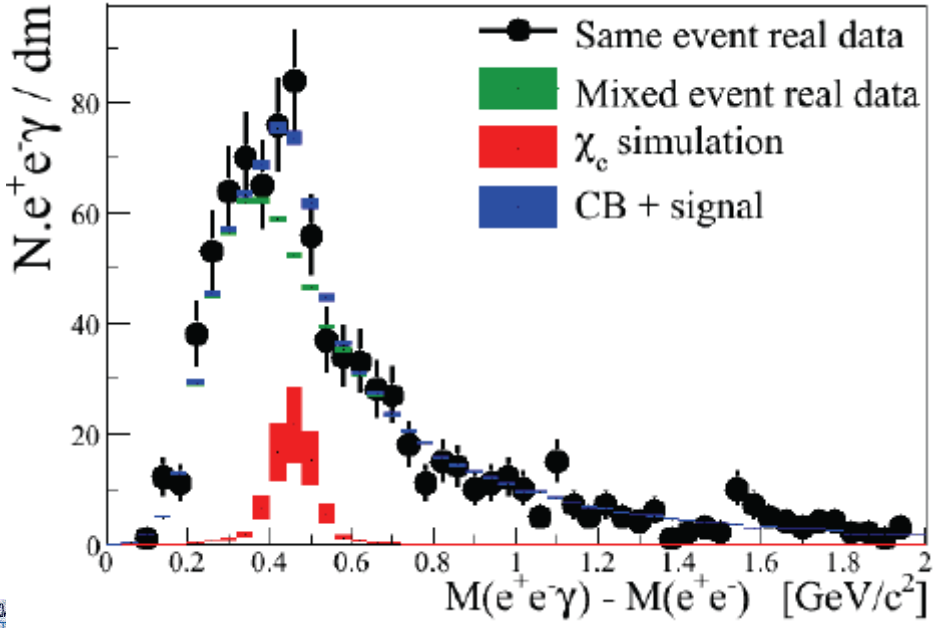
Excellent agreement between the runs

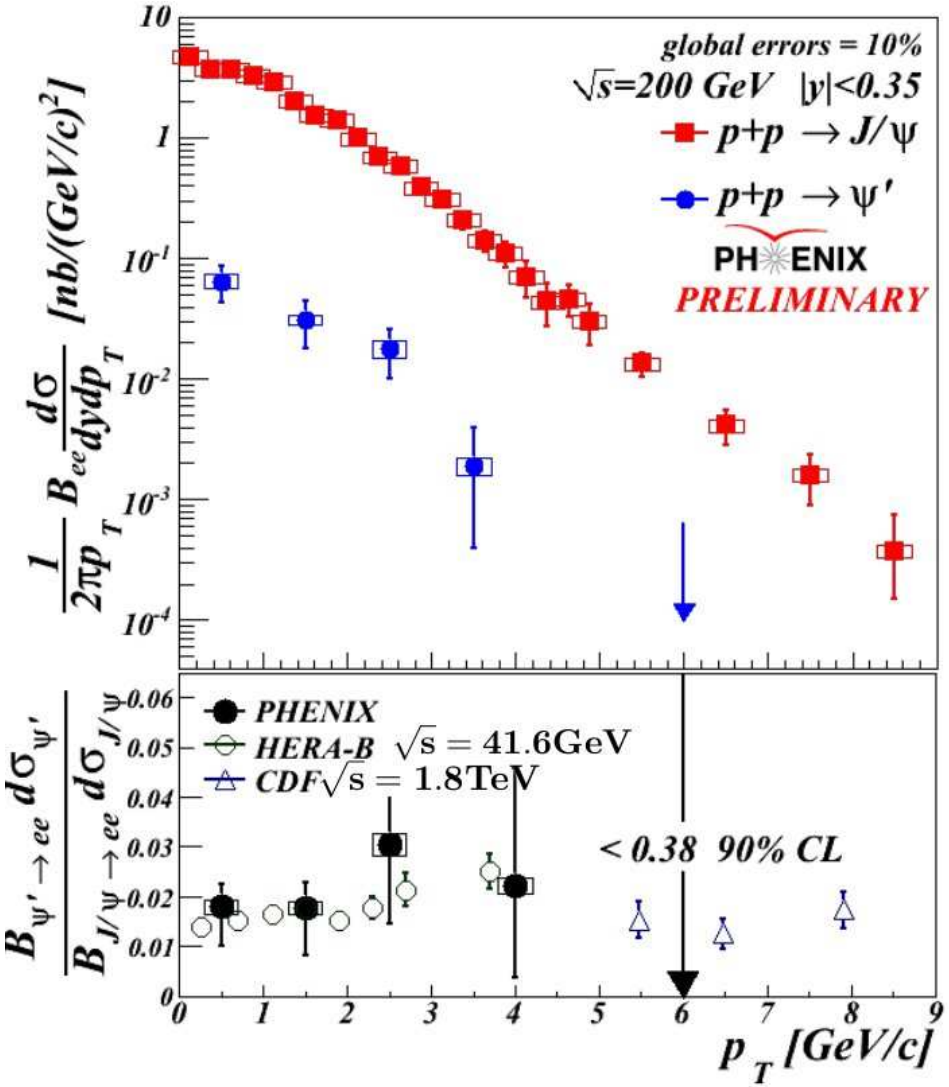




$\psi' \to e^+e^-$ and χ_c via $J/\psi + \gamma$ in $p+p$

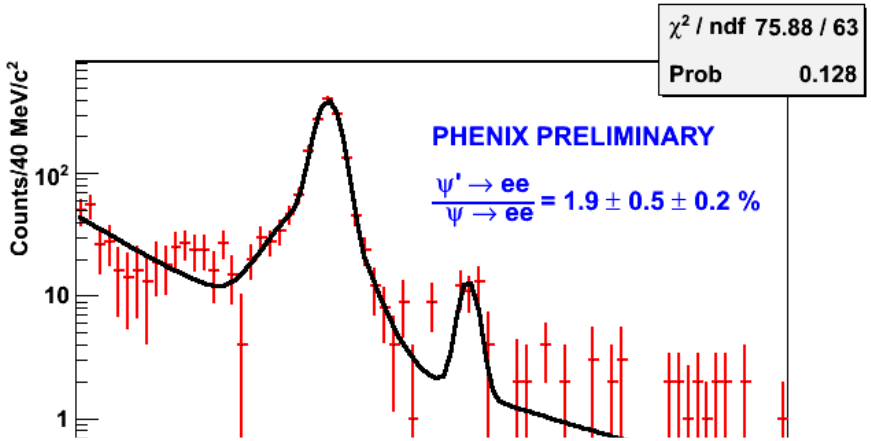


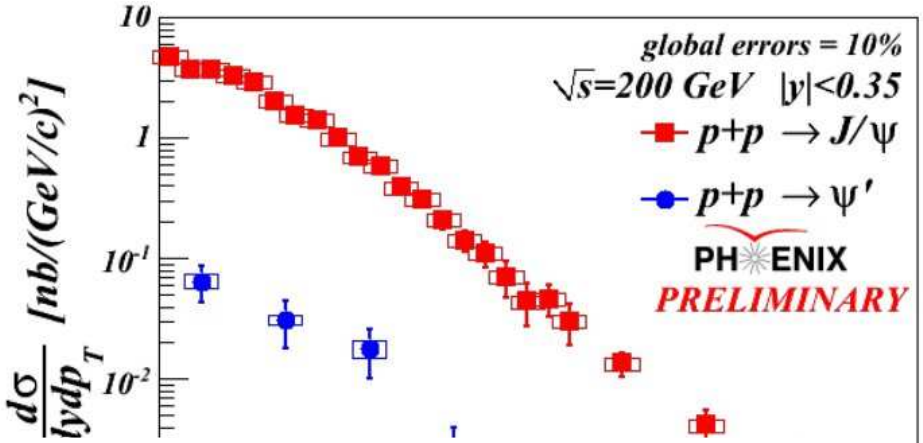




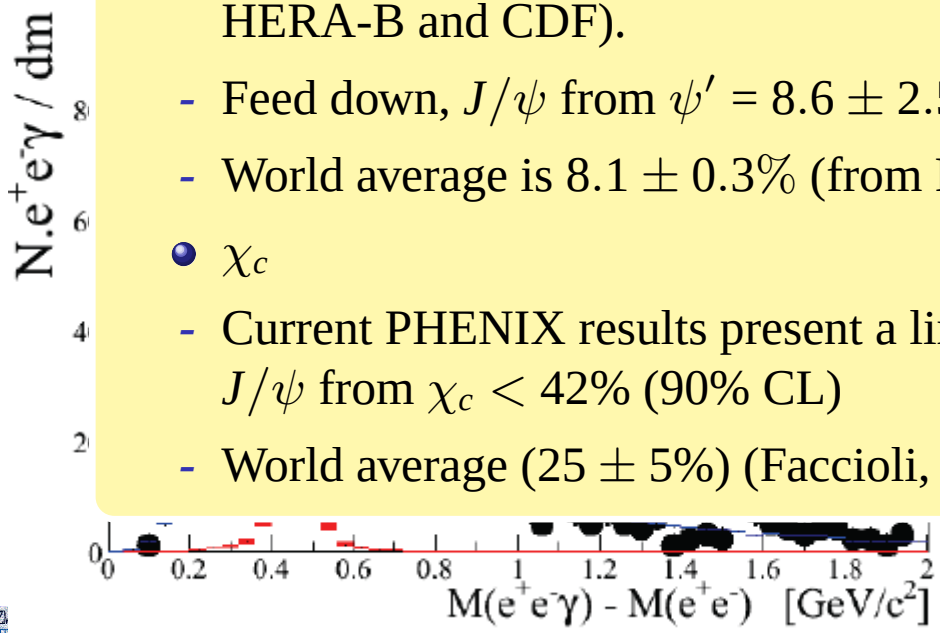
HERA-B: Eur. Phys. J. C49, 545 (2007)
CDF: PRL 79, 572 (1997)

$\psi' \to e^+e^-$ and χ_c via $J/\psi + \gamma$ in $p+p$





- ψ'
  - ψ' to J/ψ ratio in the di-electron channel is of the order of 2% (consistent with HERA-B and CDF).
  - Feed down, J/ψ from ψ' = 8.6 $\pm$ 2.5%
  - World average is 8.1 $\pm$ 0.3% (from Faccoli, JHEP 0810:004, 2008)
- χ_c
  - Current PHENIX results present a limit on χ_c feed-down to J/ψ J/ψ from χ_c < 42% (90% CL)
  - World average (25 $\pm$ 5%) (Faccioli, JHEP 0810:004, 2008)



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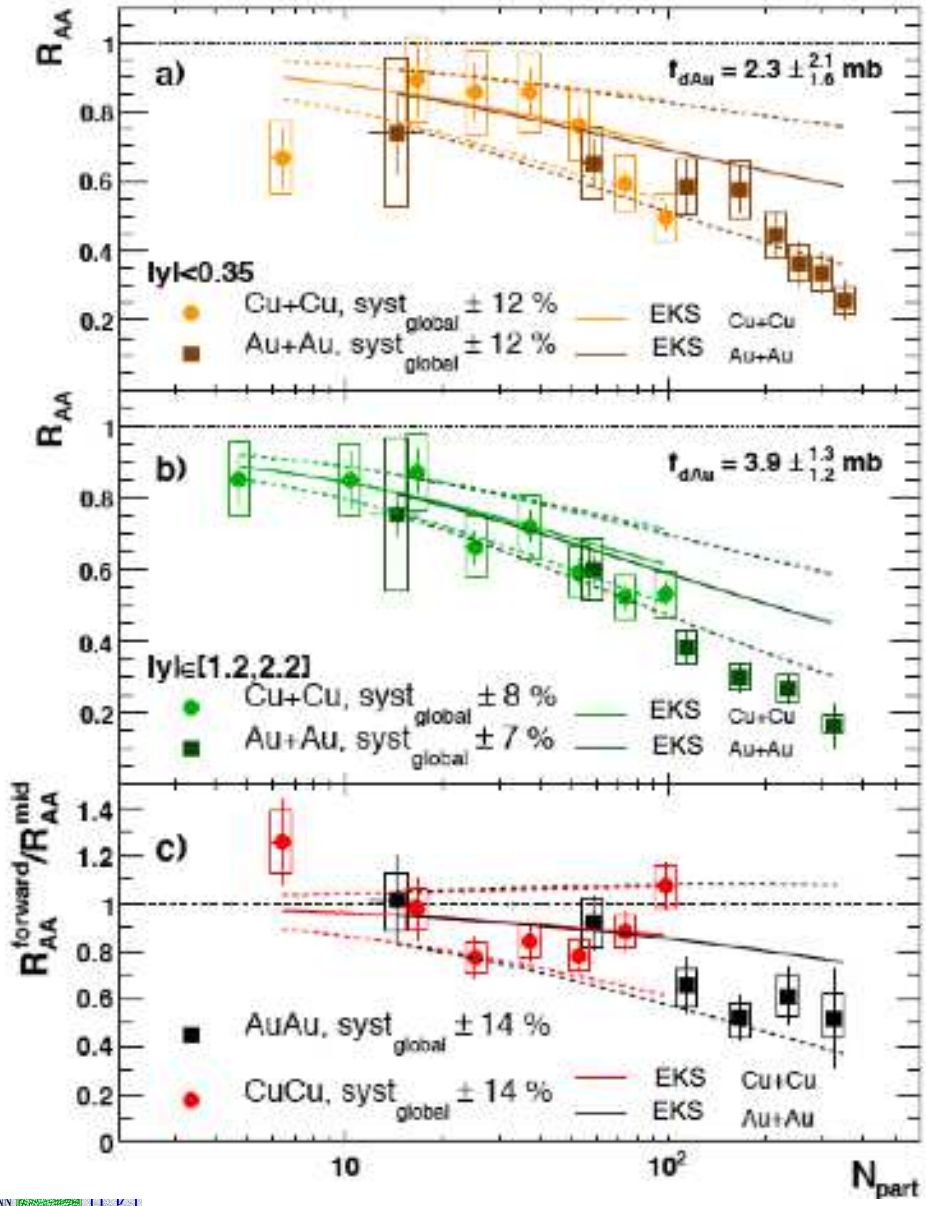
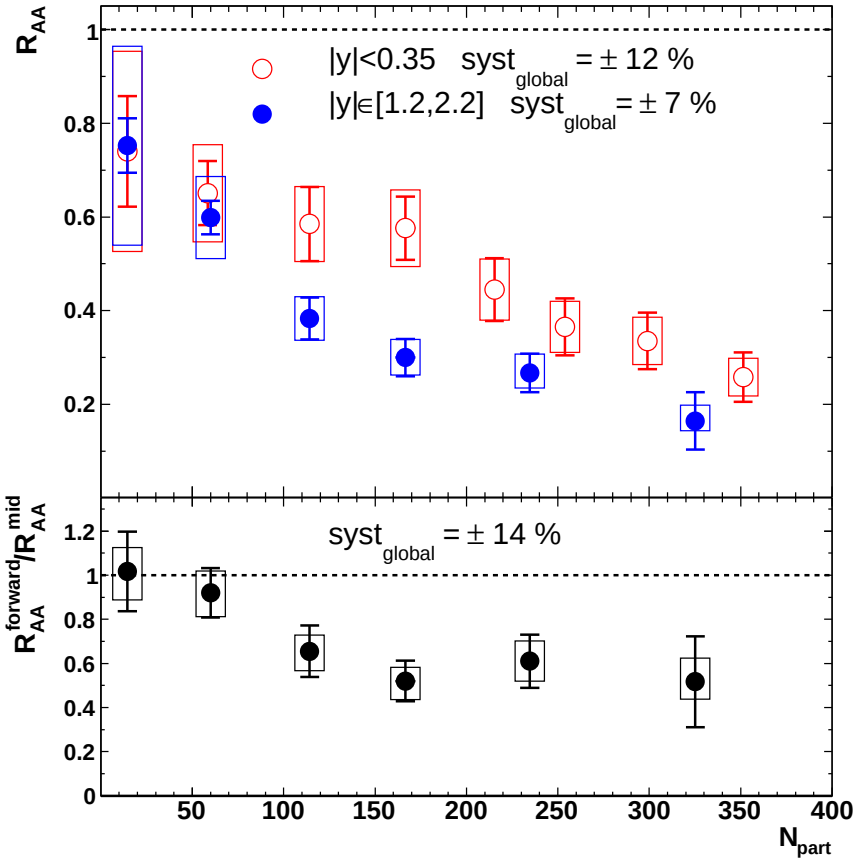
J/ψ - R_{AA} in $Au + Au$ and $Cu + Cu$

PRL 101, 122301 (2008)

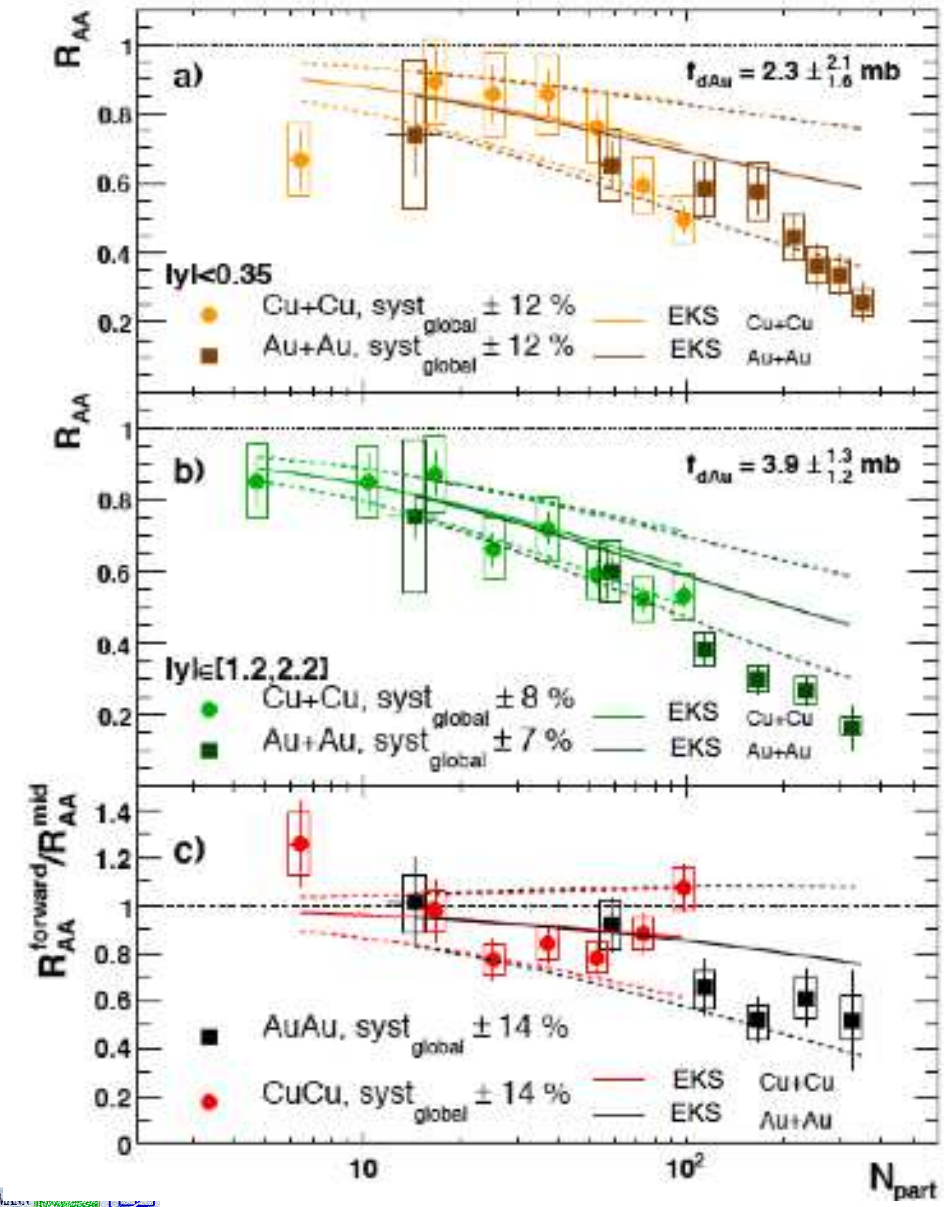


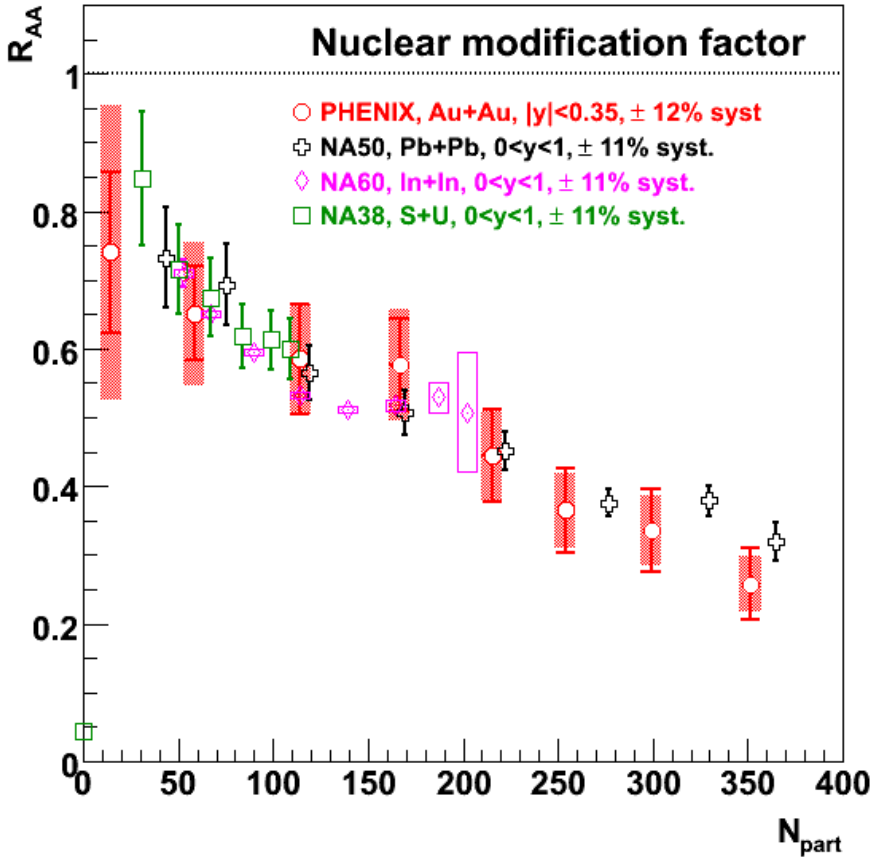


- The two data sets $Cu + Cu$ (2005) and $Au + Au$ (2004) are in good agreement about the dependence of suppression on the number of participants (N_{part}).
- Suppression is substantially stronger at forward rapidity than at mid-rapidity.

J/ψ - R_{AA} in $Au + Au$ and $Cu + Cu$

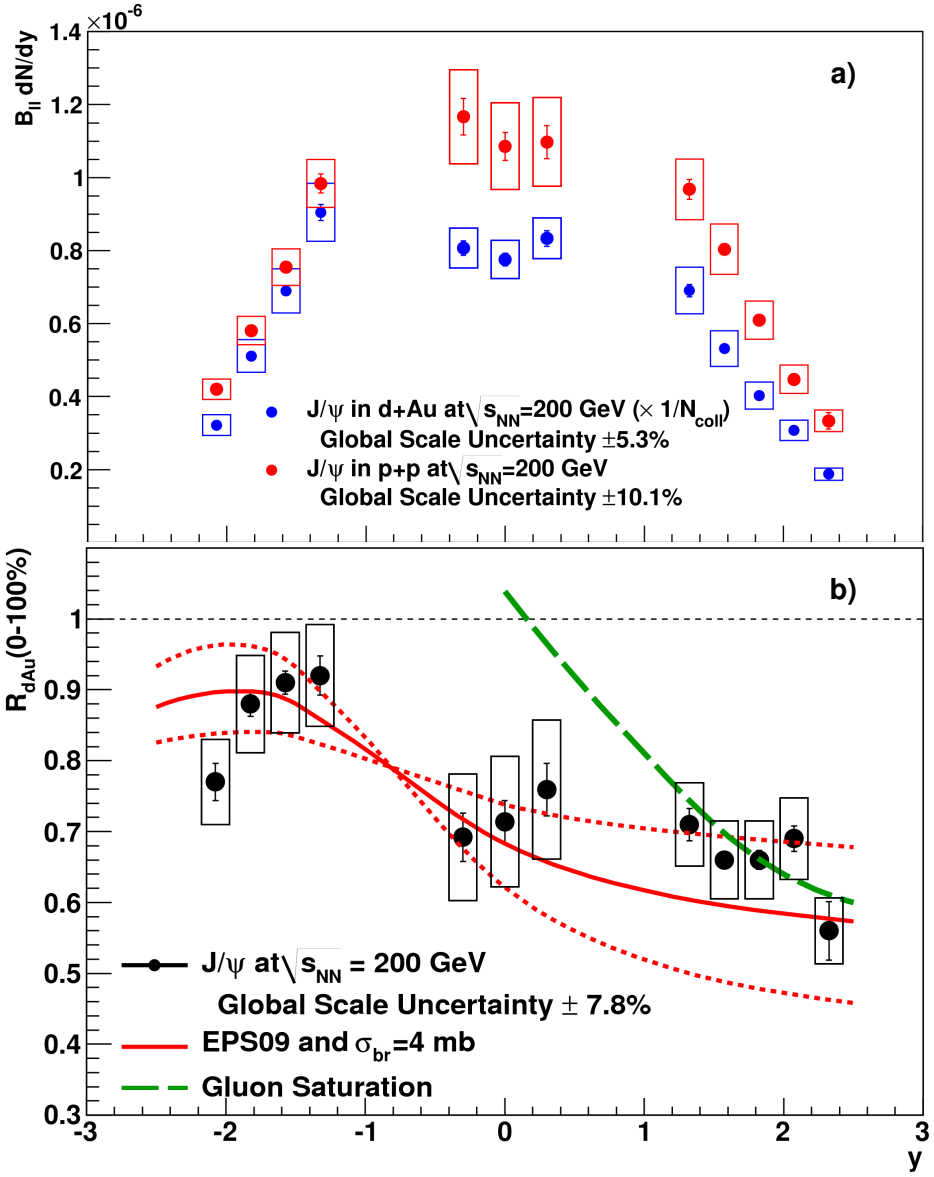
PRL 101, 122301 (2008)





- BUT SPS (17.3 GeV) $Pb + Pb$ J/ψ data show comparable suppression at $y \sim 0.5$ to PHENIX at $y \sim 0$
- Different CNM effects ?

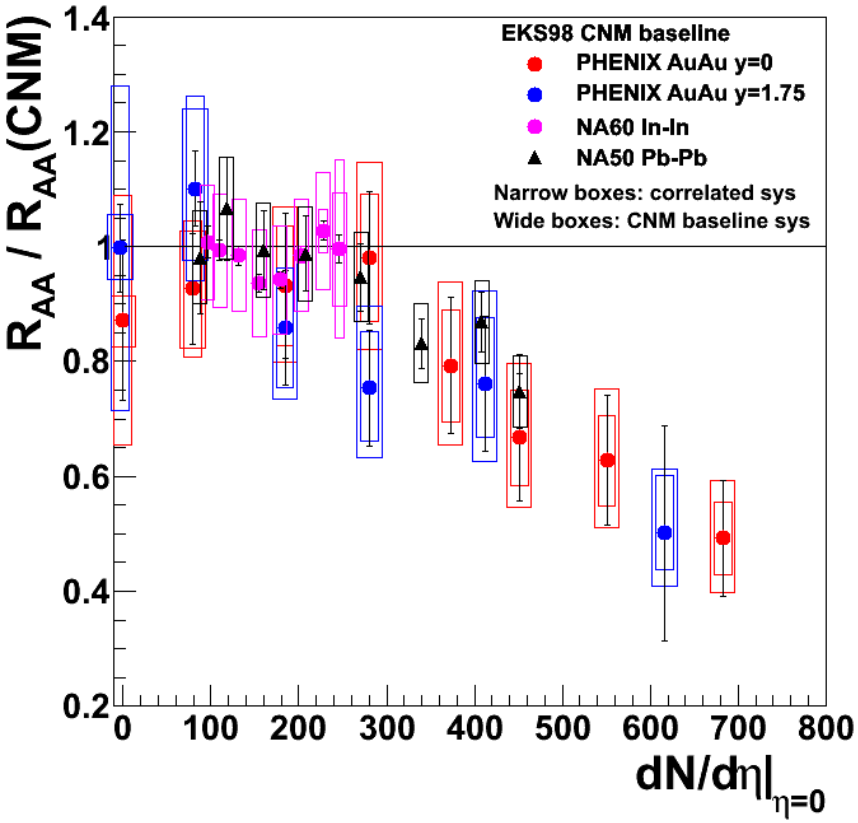
Cold nuclear matter effects: J/ψ in $d + Au$



- PHENIX previously measured the nuclear modification factor R_{dAu} in $d + Au$ collisions at 200 GeV in 2003.
- In 2008, PHENIX collected a much higher dataset - provides a much better constraint on cold nuclear effects on the J/ψ with smaller uncertainties and finer binning (**arXiv:1010.1246, A.Adare et al.**)
- Top panel shown the new results for the rapidity dependence of invariant yield in $p + p$ and $d + Au$.
- Lower panel shows the calculations for the rapidity dependence from different models.

J/ψ suppression over CNM in $Cu + Cu$ and $Au + Au$

Recent work by Tony Frawley and Mike Leitch using rapidity dependent break-up cross-section and errors estimated from 2008 data.

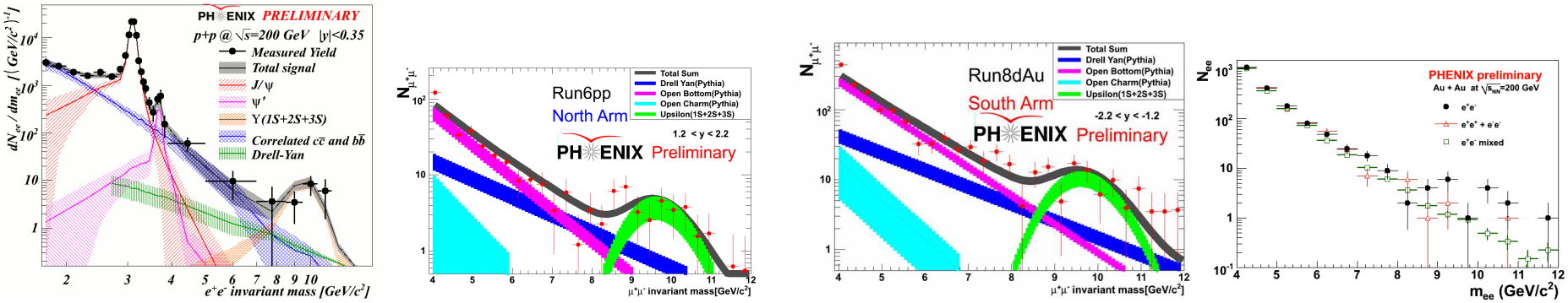


- Difference between mid and forward rapidity measurement is washed out.
- Suppression beyond cold nuclear matter effects is observed.

Future possibilities

Υ (1S+2S+3S) states in p+p, d+Au and Au+Au

$p+p(e^+e^-)$ (|y|<0.35) $\mu^+\mu^-$ (1.2<|y|<2.2) d+Au ($\mu^+\mu^-$) Au+Au (e^+e^-)



- X-section in $p+p$ follows world trend: $BR * \frac{d\sigma}{dy} = 114^{+46}_{-45}\, pb, y\epsilon[-0.35, 0.35]$
- Run6 $p+p$ and Run8 $d+Au$ $\Upsilon \rightarrow \mu^+\mu^-$ measurements have been used to get R_{dAu}
  - $R_{dAu} = 0.84 \pm 0.34(stat) \pm 0.20(sys), y\epsilon[-2.2, -1.2]$
  - $R_{dAu} = 0.53 \pm 0.20(stat) \pm 0.16(sys), y\epsilon[1.2, 2.2]$
- $Au+Au$
  - High mass di-lepton R_{AA} $R_{AA}[0.5, 11.5] < 0.64$ at 90% C.L.

- Vertex detectors will allow better $\Upsilon \rightarrow e^+e^-$ mass resolution and less background at mid-rapidity.
- separation of $\psi\prime$ from J/ψ at forward rapidity ($\mu^+\mu^-$)
- $B \rightarrow J/\psi + X$

Summary

- The low-mass region in $Au + Au$ shows an enhancement above the cocktail expectations: $3.4 \pm 0.2(stat) \pm 1.3(sys) \pm 0.7(model)$
- Theory models fail to describe the data.
- The measured temperature is $T_{ave} = 221 \pm 19(stat) \pm 19(sys)$MeV corresponding to T_{ini}= 300 to 600 MeV, $\tau_0 = 0.15$ to 0.6 fm/c, from the theoretical models.
- Data taken with HBD will provide better precision measurement for the LMR.

- Open charm in $p + p$ is in good agreement with FONL.
- In $Au + Au$, open charm suppression is similar to that of light quarks at high p_T !
- The VTX and FVTX detector in future will allow better b/c separation studies.

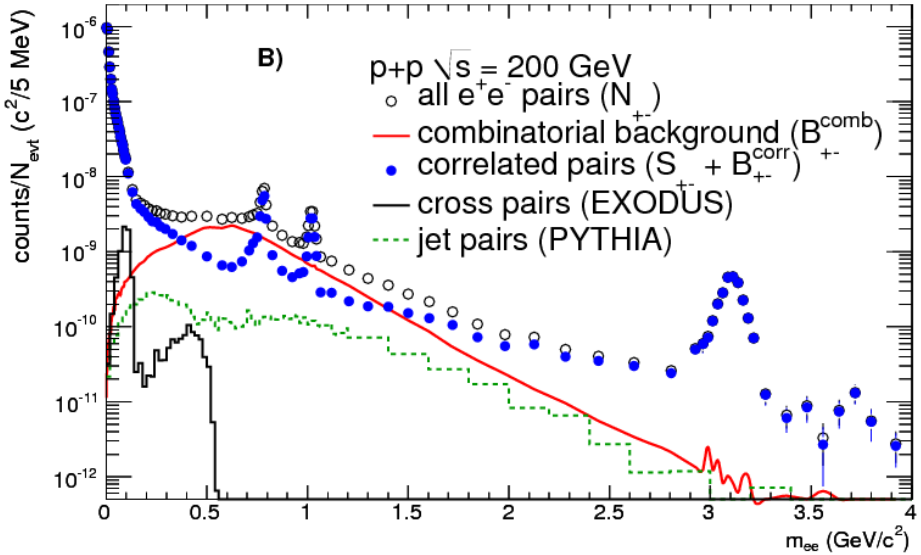
- J/ψ is $p + p$ is well described by the models.
- J/ψ to ψ' ratio and ψ' feed-down to J/ψ are in agreement with the world data.
- Suppression measurements of charmonium excited states can throw a light on production and nuclear modification mechanisms.

Back-ups

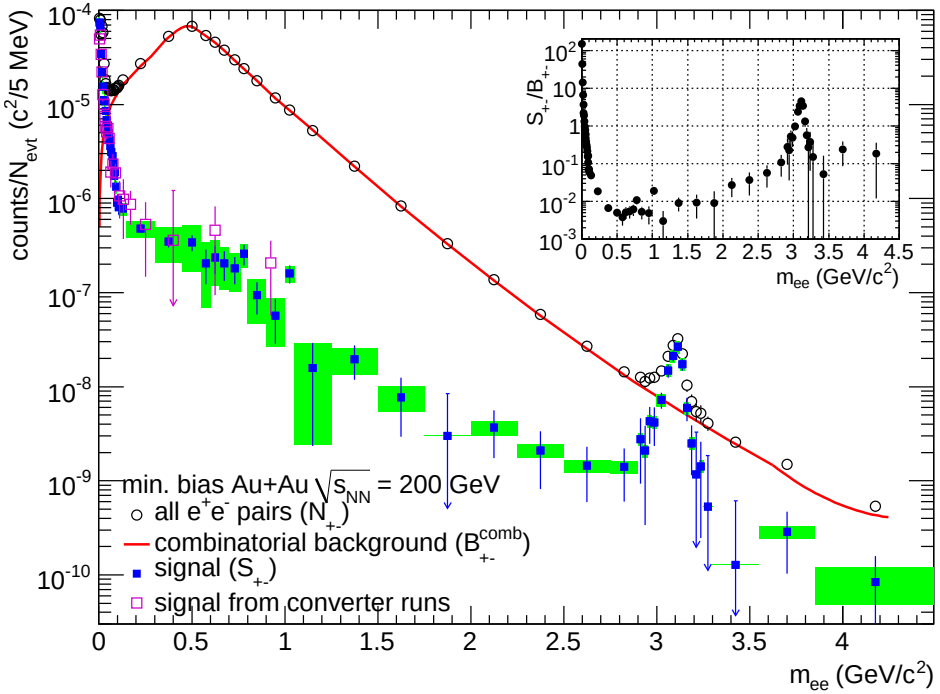
The Raw Subtracted Unlike Mass Spectrum

Uncorrected mass spectra of e^+e^- pairs, mixed event and signal in $p+p$ and minimum bias $Au+Au$ collisions.

$p+p$ **(PLB 670, 313(2009))**



$Au+Au$ **(PRC 79, 81 034911(2010))**

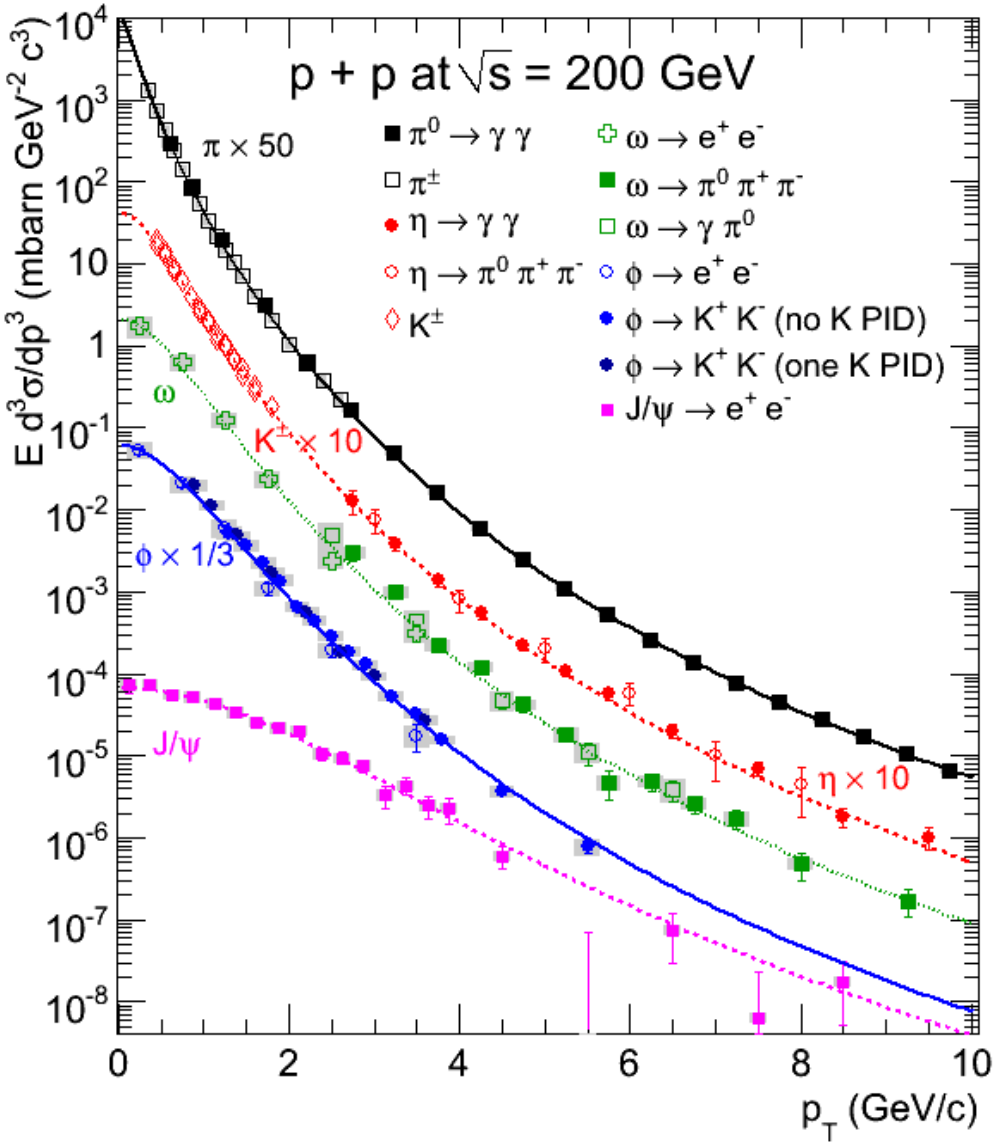


- Mixed unlike sign pairs normalized to $\langle N_{+-}\rangle = 2\sqrt{\langle N_{++}\rangle\langle N_{--}\rangle}$
- $Au+Au$ has analysis on a data sample with additional conversion material, which increased the combinatorial background by 2.5. *Good agreement within statistical errors*
- Systematic errors from background subtraction: $\frac{\sigma_{signal}}{signal} = \frac{\sigma_{BG}}{BG}(0.25\%) * \frac{BG}{signal}$ $\rightarrow$ upto 50% near 500 MeV.

Cocktail Tuning in $p + p$

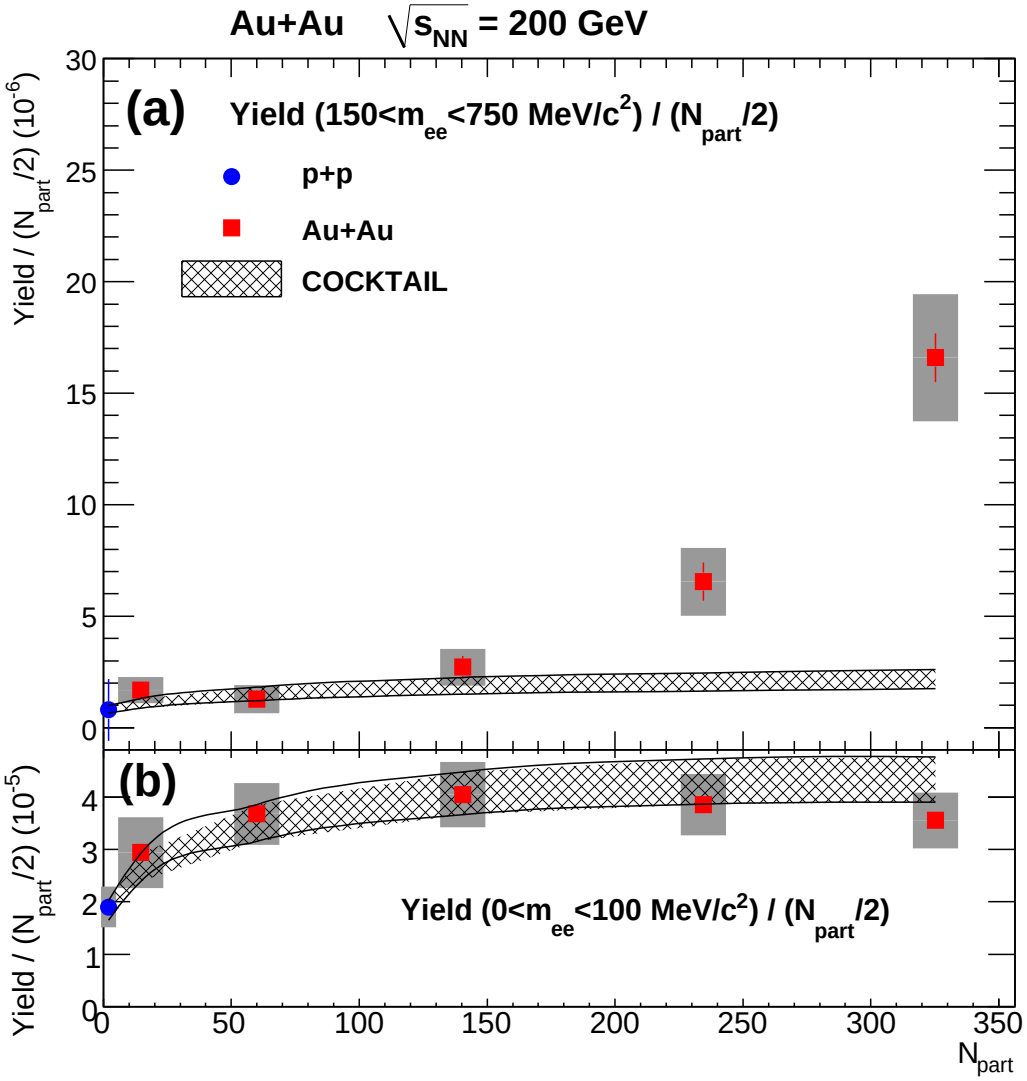
The cocktail of hadronic decay contributions was estimated using PHENIX data for meson production.

- The key input is the rapidity density $\frac{dN}{dy}$ of π^0, determined from a fit to the PHENIX data on charged and neutral pions. The function used is modified Hagedorn function; $E \cdot \frac{d^3\sigma}{dp^3} = A(e^{-(ap_T+bp_T^2)} + p_T/p_0)^{-n}$
- For η, ω, ϕ and J/ψ, the measured yield and spectra are used.
- For all other mesons, assume m_T scaling of π^0 parameterization; replace $p_T \rightarrow \sqrt{p_T^2 + m_{meson}^2 - m_\pi^2}$



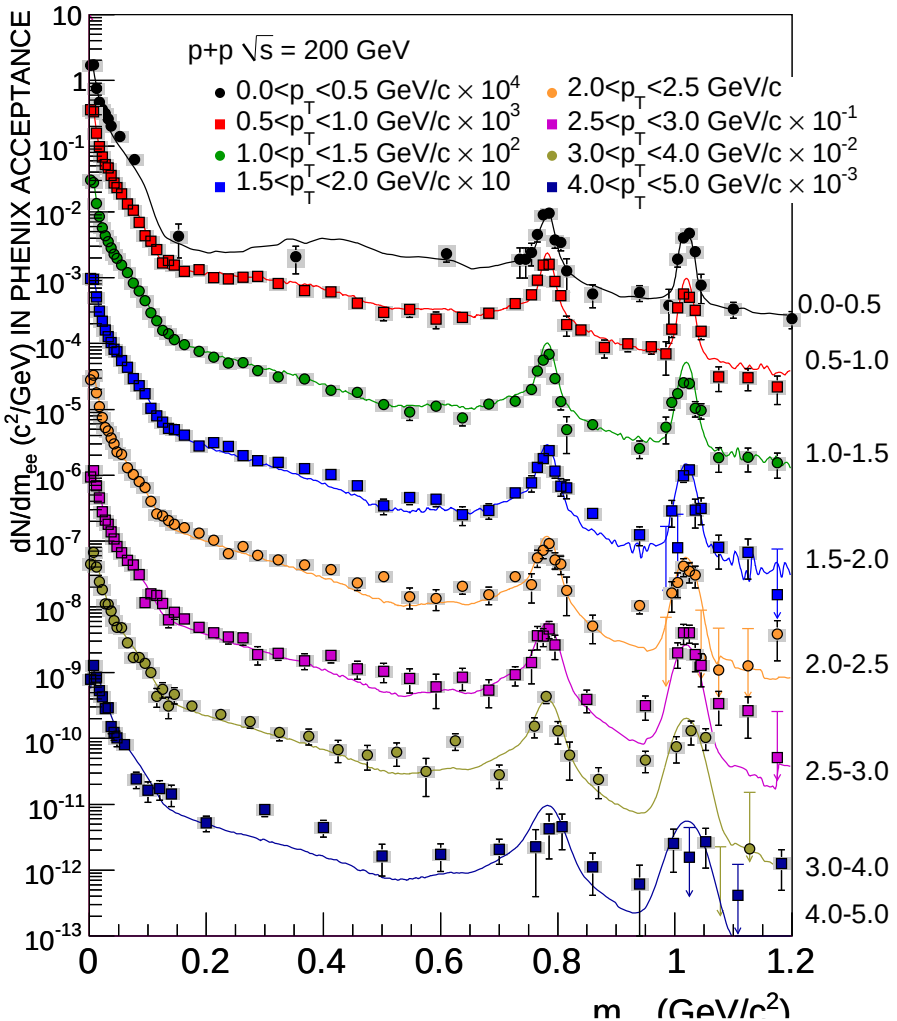
Centrality Dependence of Low Mass Continuum

- Plotted are the yield per number of participating nucleon pairs ($N_{part}/2$), in the two mass windows.
- π^0 region ($m_{e^+e^-} \leq$) 0.1 GeV: the production scales approximately with N_{part}
- Low mass ($0.15 < m_{e^+e^-} < 0.75$ GeV): yield increases faster than proportional to N_{part}
  - qualitatively consistent with the conjecture of in-medium production from $\pi\pi$ or qq annihilation.

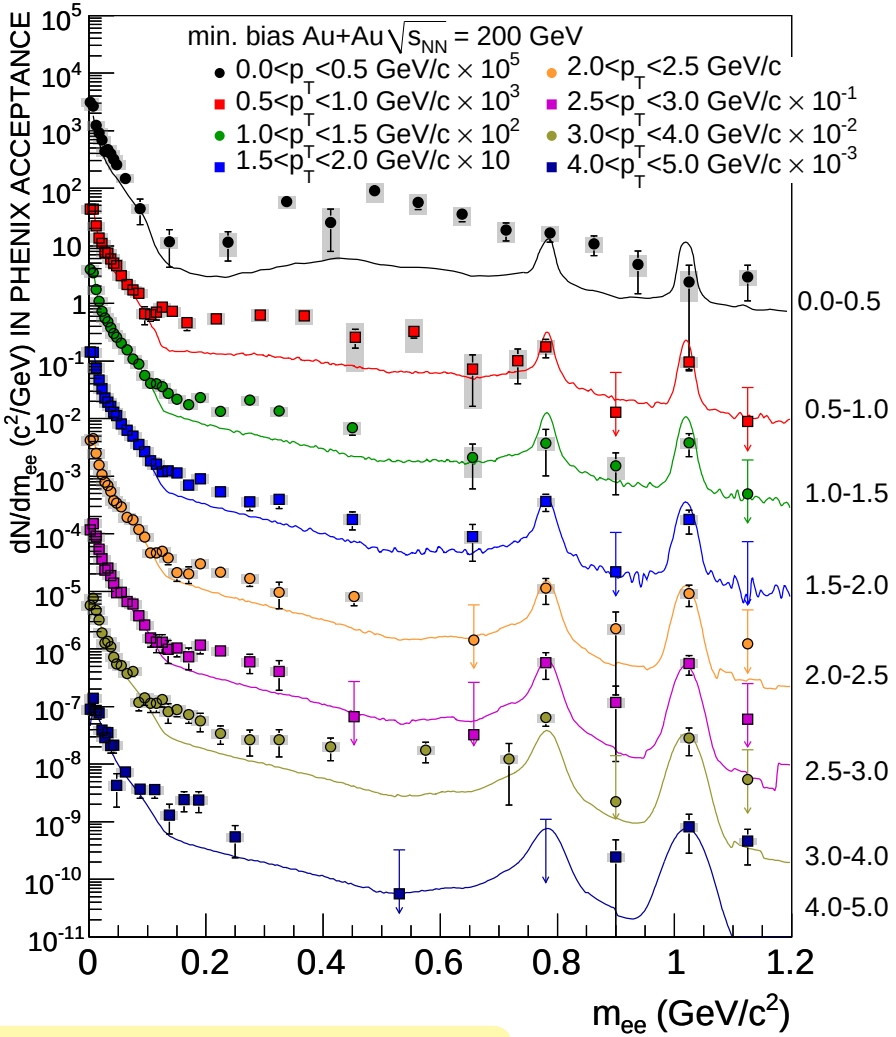


Low Mass Region Mass Spectra in p_T Slices

$p + p$



$Au + Au$



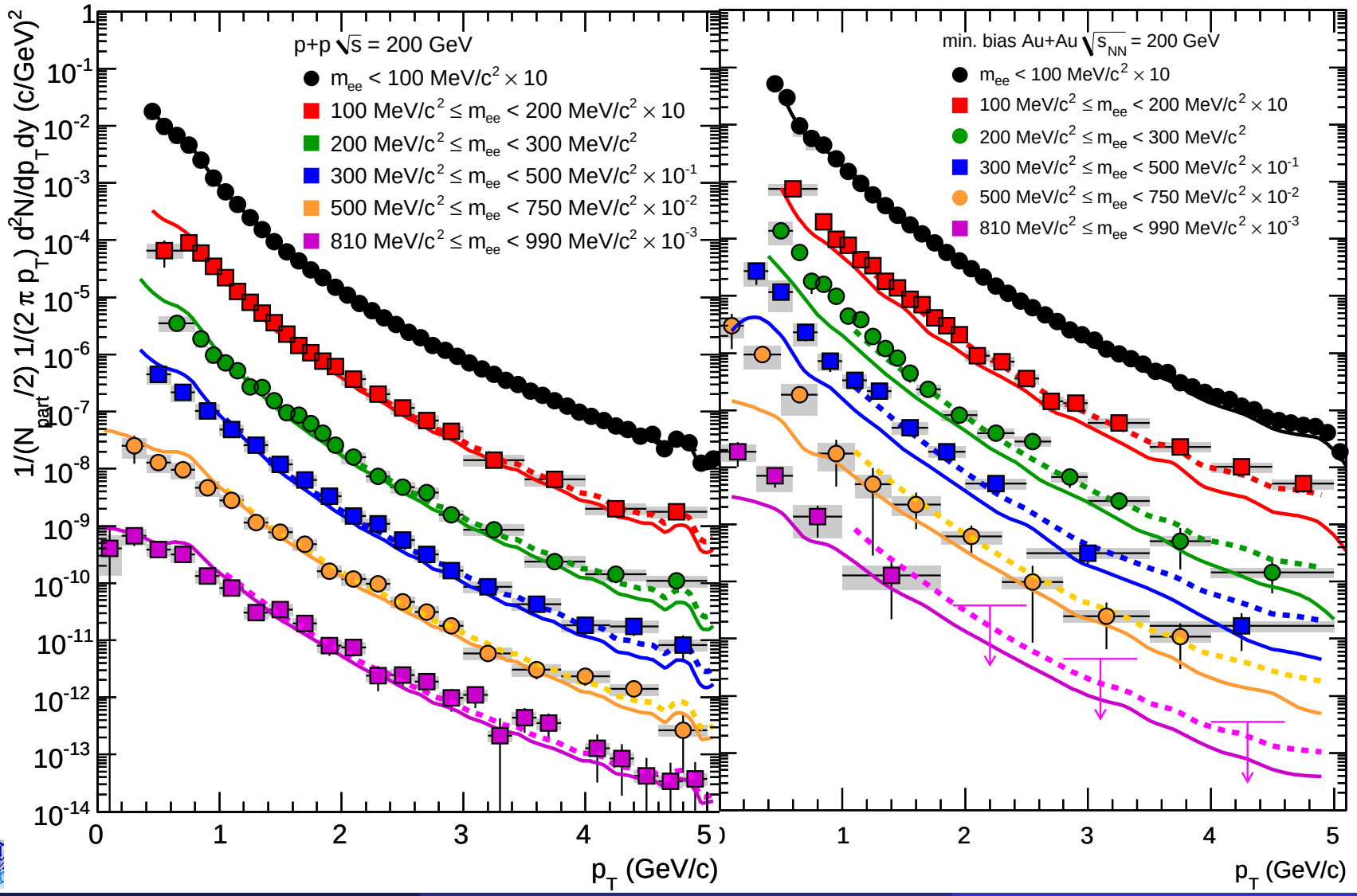
- $p + p$ matches the cocktail fairly well.
- There exists LMR excess in $Au + Au$ at all p_Ts.
- LMR excess is largest at low pair p_T

p_T Spectra of Low Mass Region

Acceptance corrected

Solid lines (cocktail); Dashed lines (cocktail + virtual photon)

$p + p$ $\qquad$ $Au + Au$



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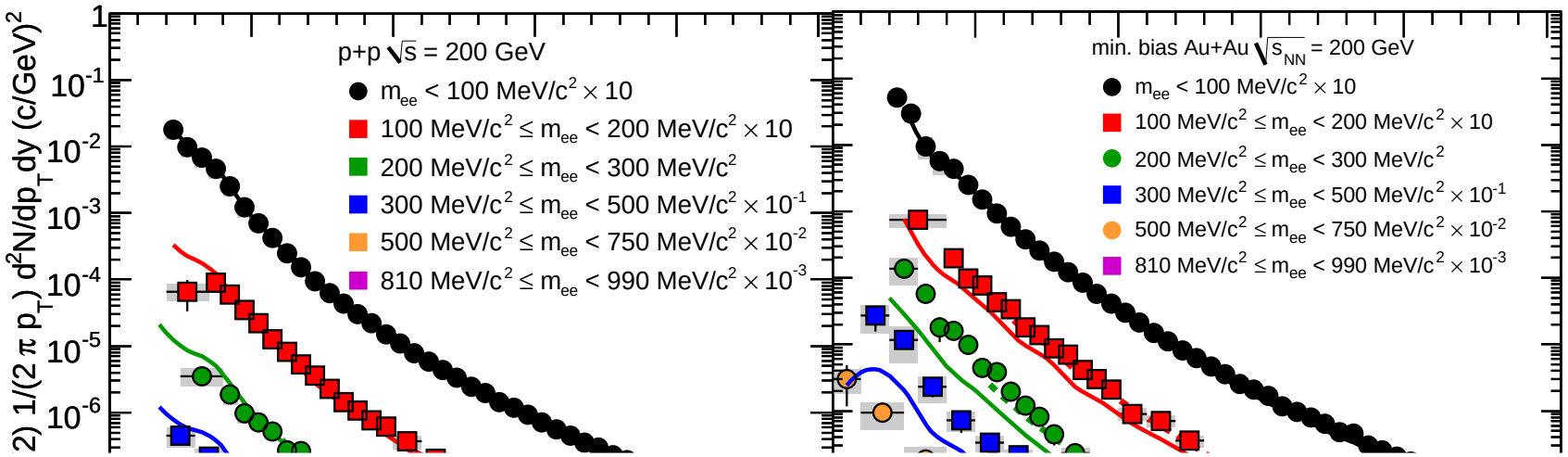
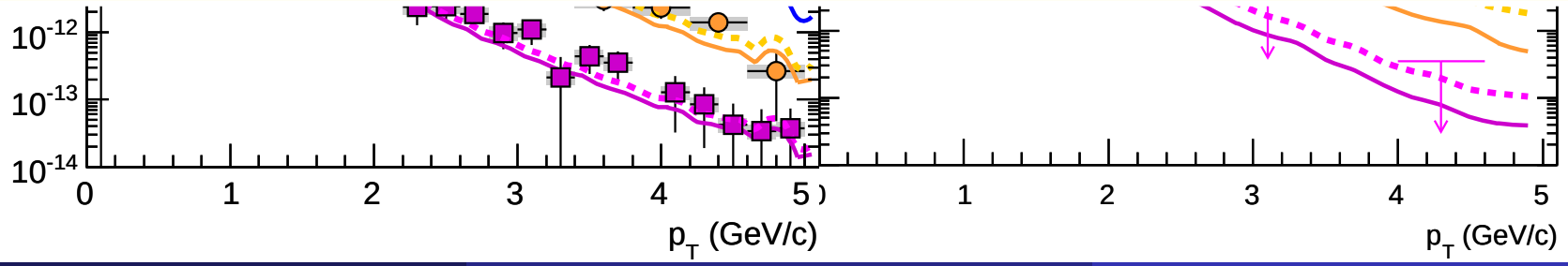
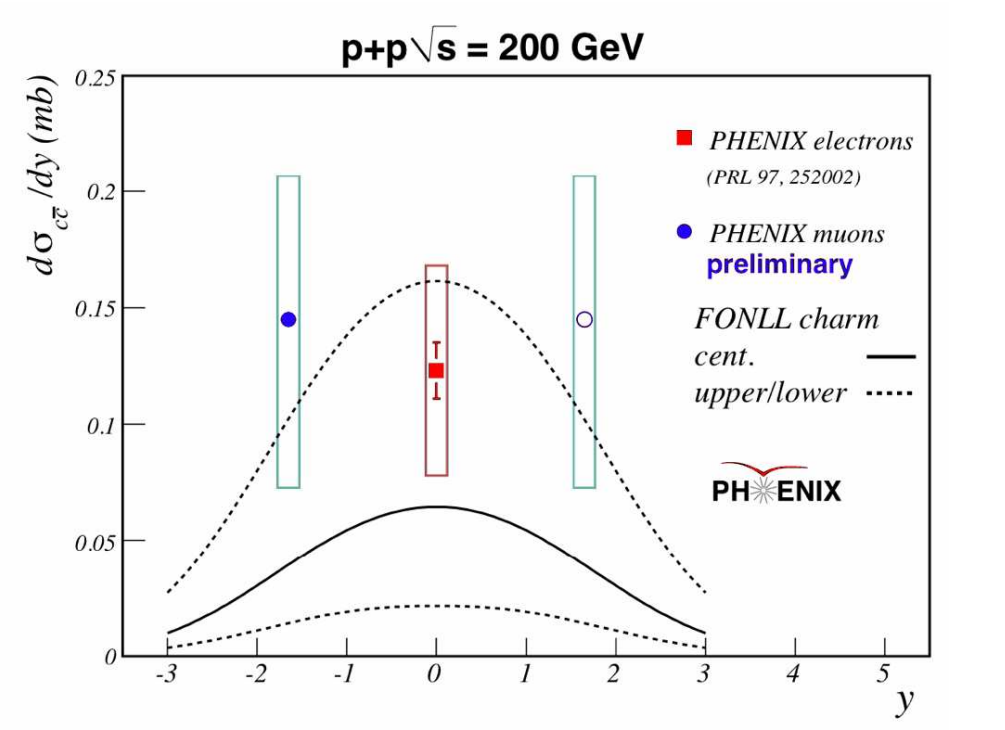


- $p + p$
  Agreement with cocktail + internal conversions of direct photons.
- $Au + Au$
  For $p_T > 1$ GeV/c, small excess $\rightarrow$ internal conversion of direct photons.
  For $p_T < 1$ GeV/c, large excess for $0.3 < m_{e^+e^-} < 1$ GeV



Rapidity Dependence of Integrated X-section in $p + p$

Integrate the single electron/muon spectra, extrapolates to p_T =0 and convert to $d\sigma_{c\bar{c}}/dy$ using FONLL.

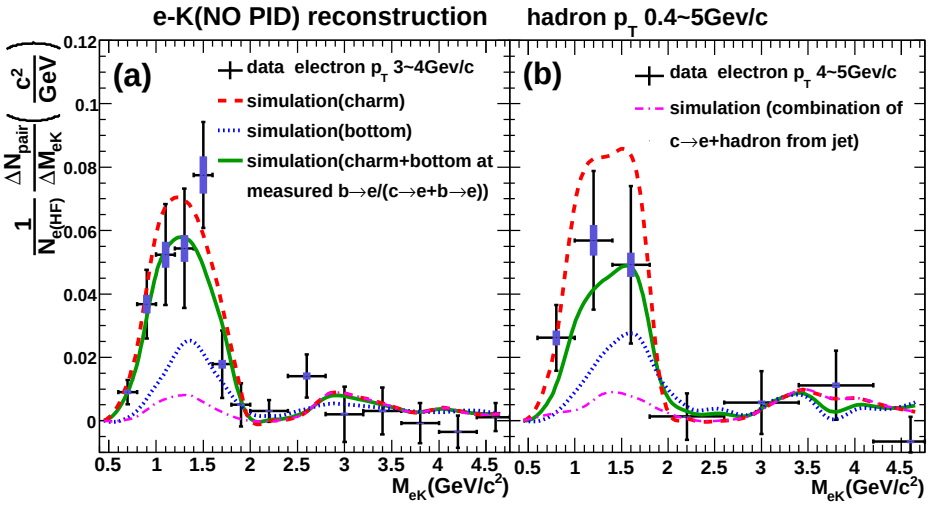


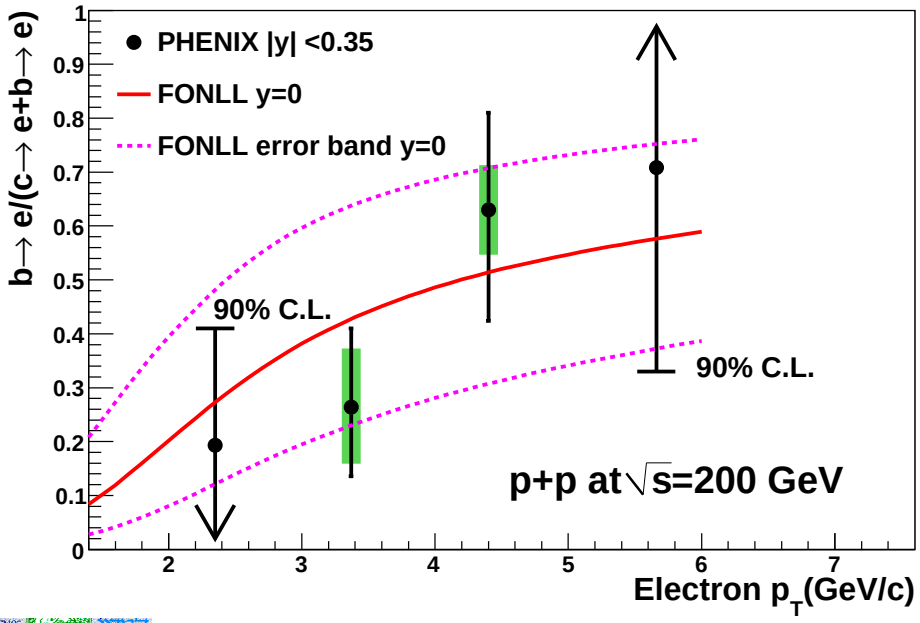
Uncertainties dominated by background systematic errors.

Charm and Beauty Separation from $e - h$ Correlations at Mid-rapidity

Electron hadron invariant mass is different for B and D meson decays.

PRL 103, 082002 (2002)

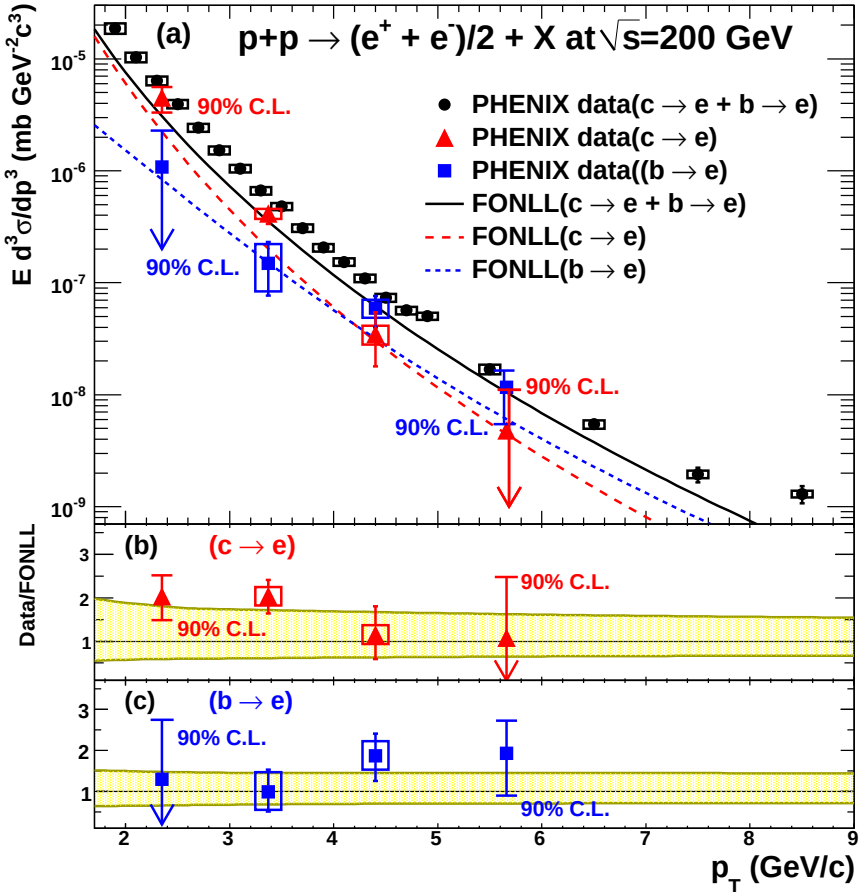




Combining with single electron spectra, extract the charm and beauty distributions.

Derived beauty X-section,

$$\sigma_{b\bar{b}} = 3.2^{+1.2}_{-1.1}(stat)\ ^{+1.4}_{-1.3}(sys)\mu b$$



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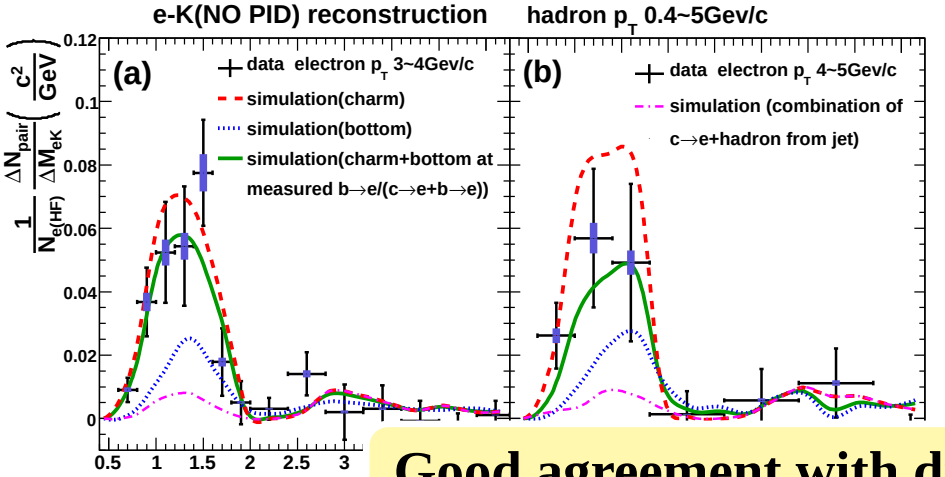

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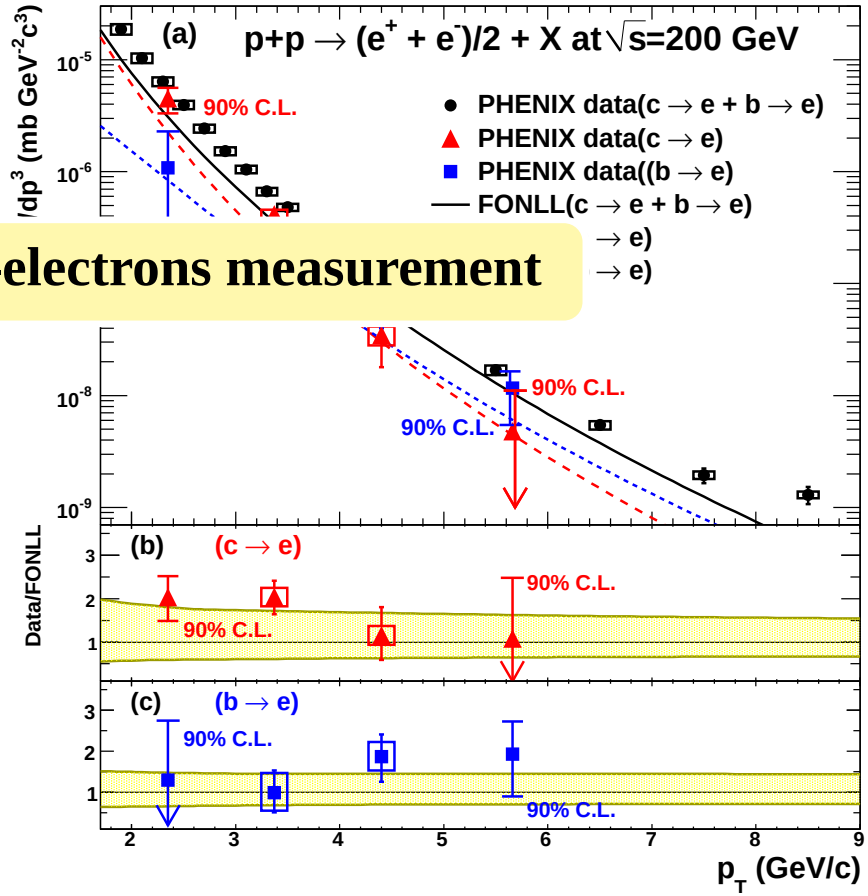
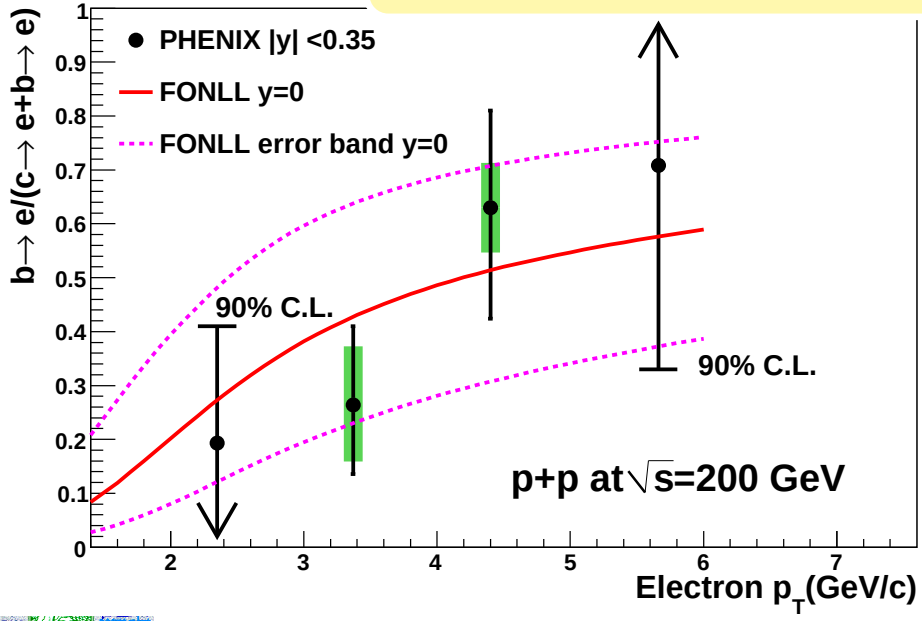
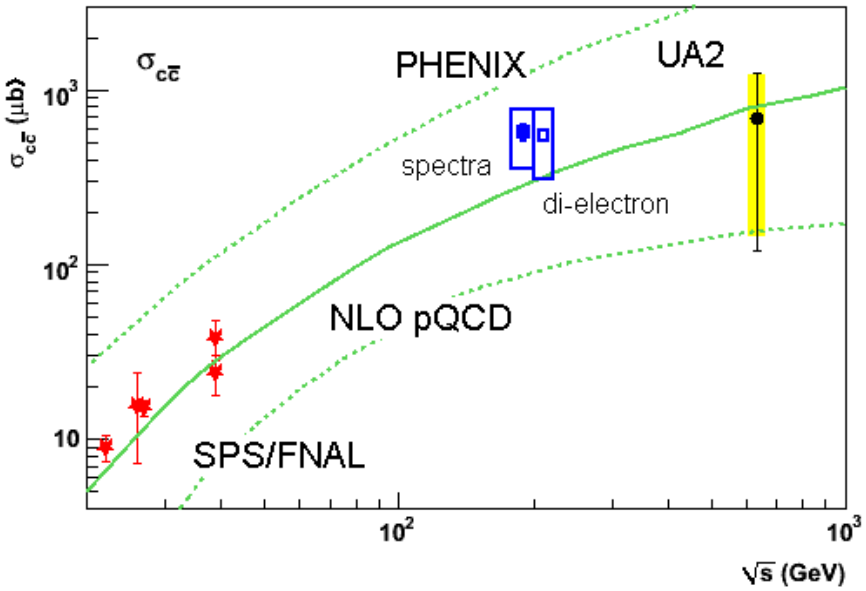


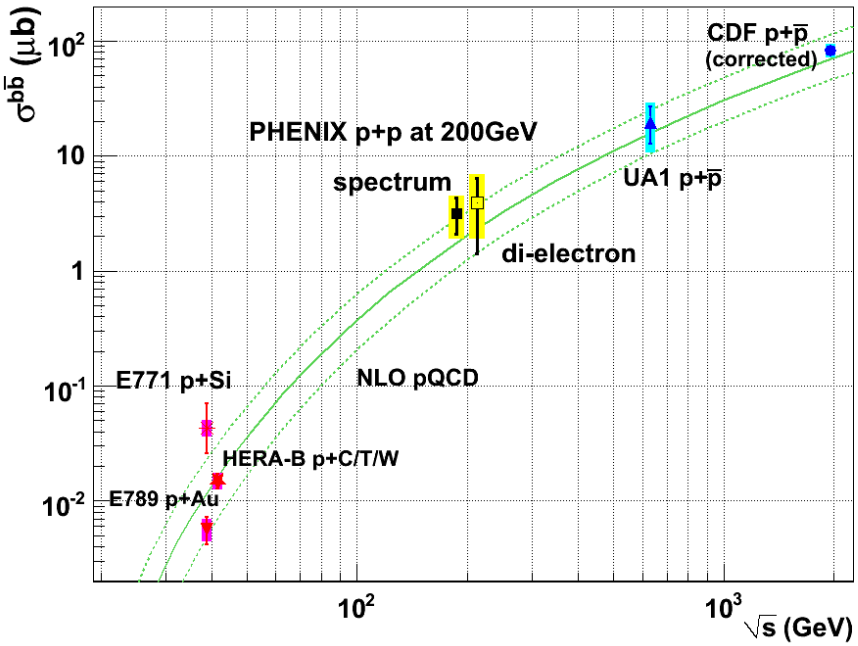
Good agreement with di-electrons measurement



Charm and Bottom X-section Summary

Looking at other center-of-mass energy measurements.





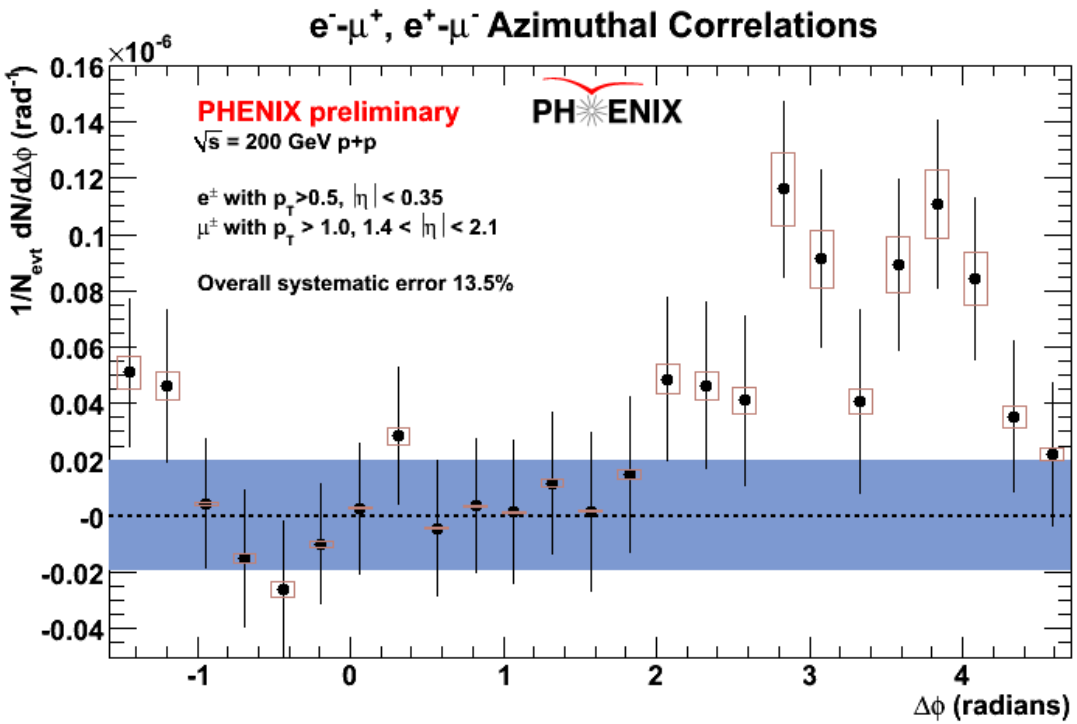
PHENIX results at the same energy, shifted for clarity

$\sigma_{c\bar{c}}$ and $\sigma_{b\bar{b}}$ from single electrons and di-electrons agree with each other and NLO pQCD calculation.

Electron-Muon Correlations

Golden channel for open heavy flavor - almost no background

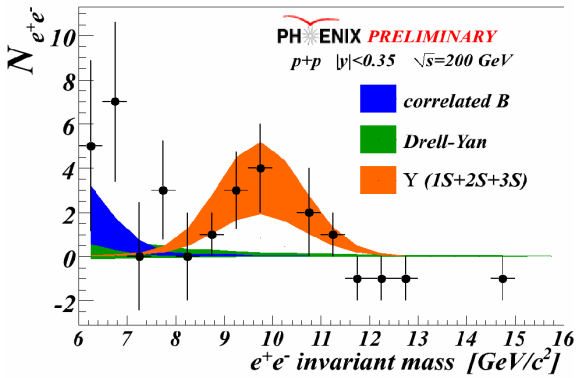
- Heavy flavor signal consists of opposite sign mid-rapidity electron and forward rapidity muon.
- No backgrounds from other physical processes, majority of the background from combinatorics, light meson decays and photonic electrons removed by like-sign subtraction.
- Proof of principle - new method to measure charm X-section.

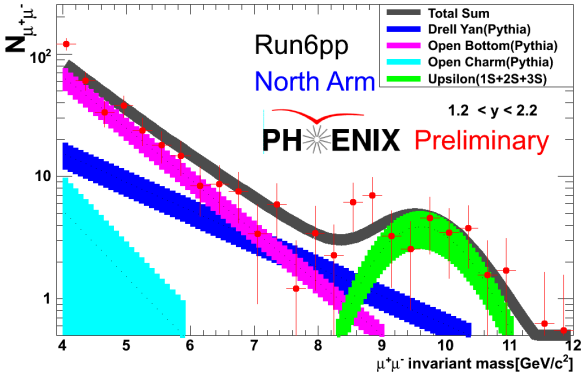


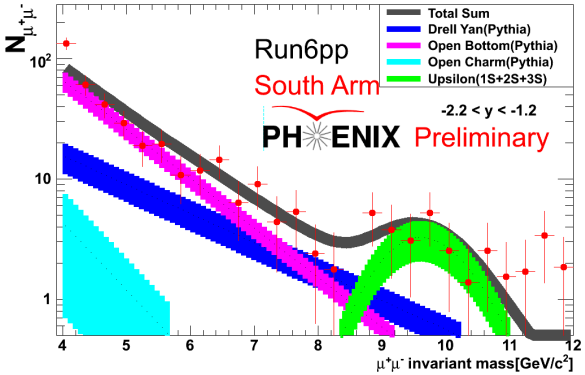
Upsilon $\Upsilon(1S + 2S + 3S)$

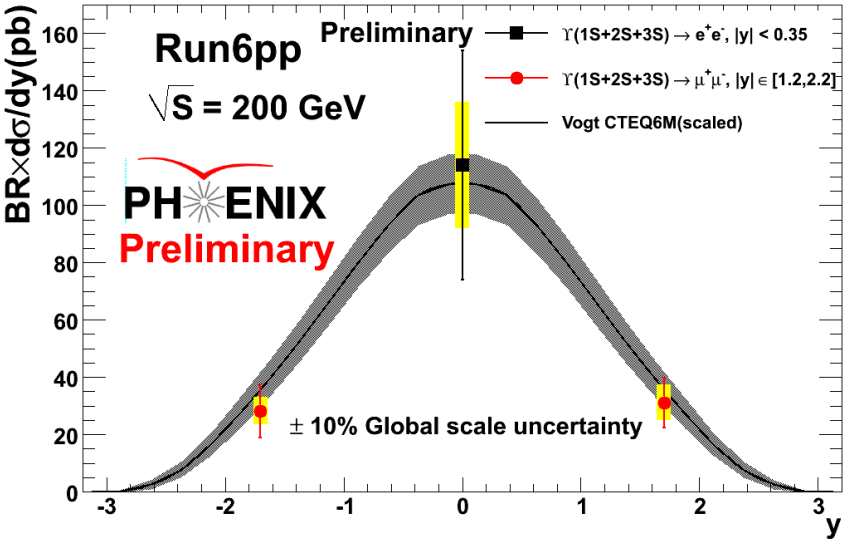
Upsilons in $p + p$

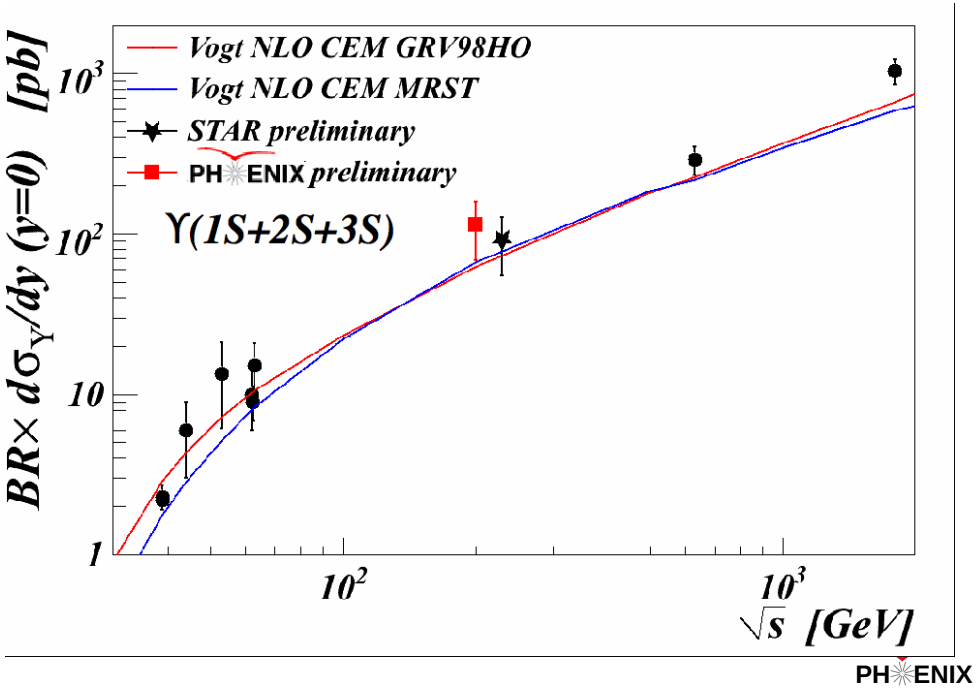
$\Upsilon(1S + 2S + 3S) \rightarrow e^+e^-$ **(|y|<0.35)** $\Upsilon(1S + 2S + 3S) \rightarrow \mu^+\mu^-$ **(1.2<|y|<2.2)**











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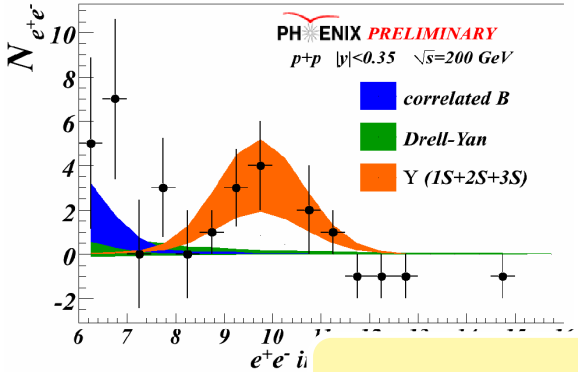
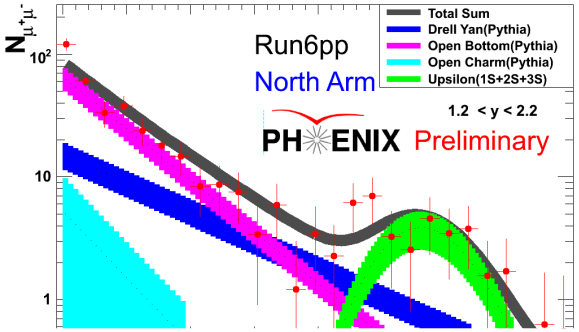
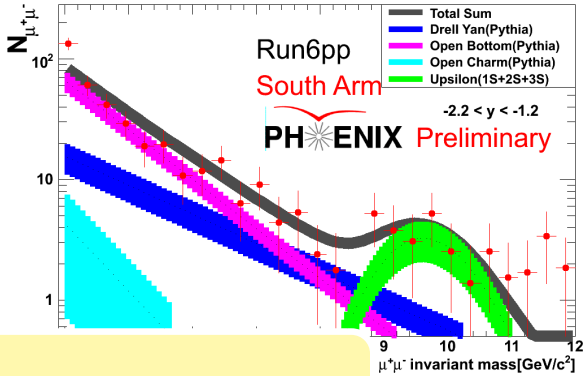
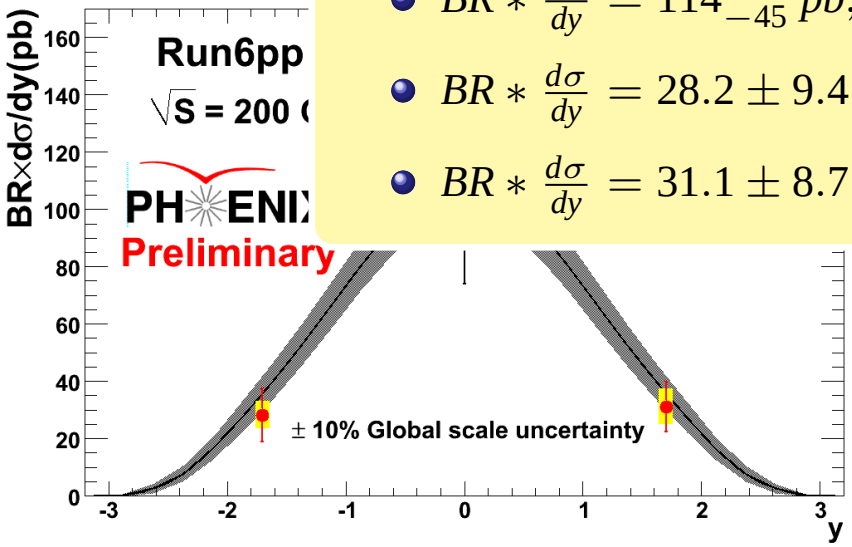
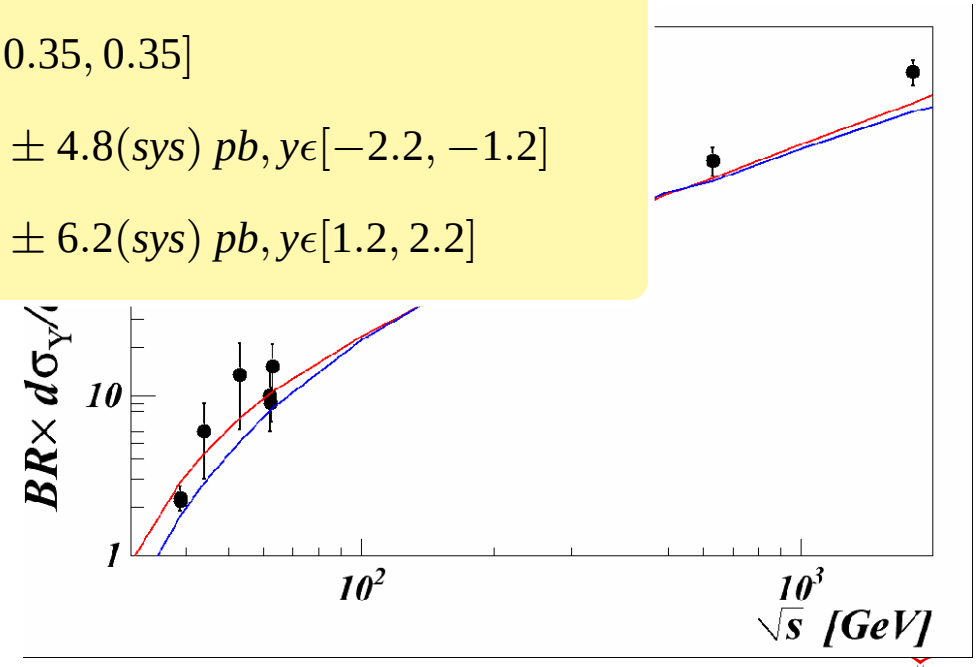




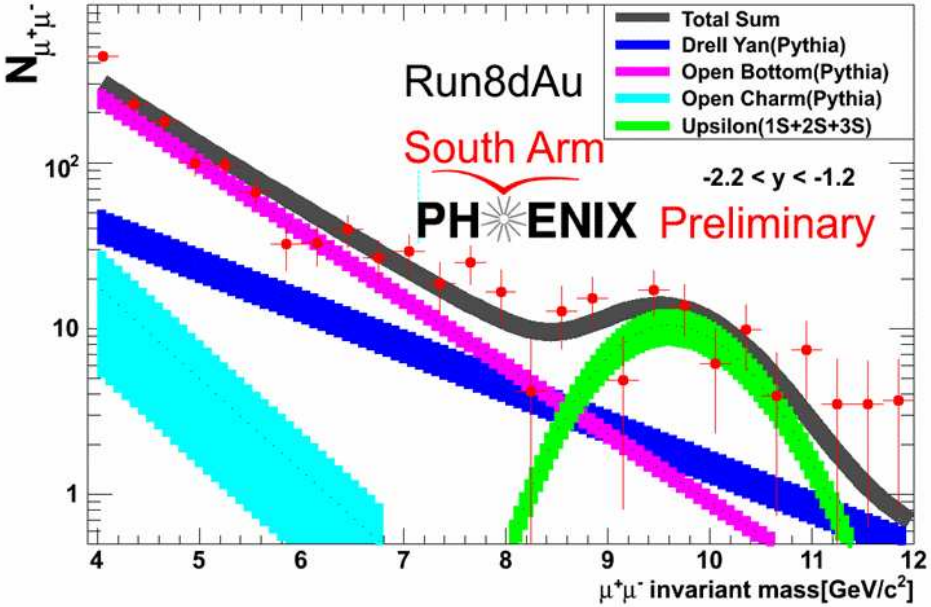


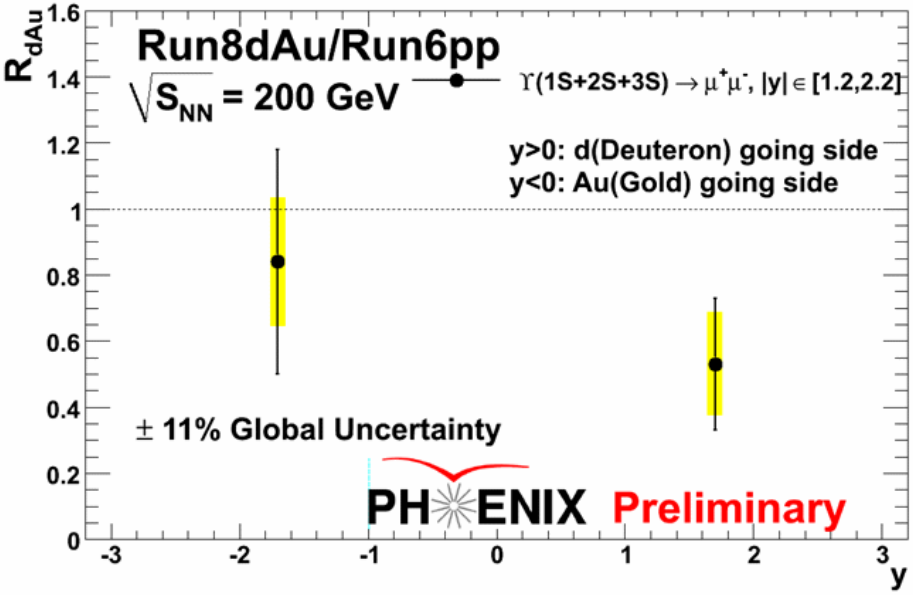
- X-section follows world trend.
- $BR * \frac{d\sigma}{dy} = 114^{+46}_{-45}\ pb, y\epsilon[-0.35, 0.35]$
- $BR * \frac{d\sigma}{dy} = 28.2 \pm 9.4(stat) \pm 4.8(sys)\ pb, y\epsilon[-2.2, -1.2]$
- $BR * \frac{d\sigma}{dy} = 31.1 \pm 8.7(stat) \pm 6.2(sys)\ pb, y\epsilon[1.2, 2.2]$





Upsilon in $d + Au$

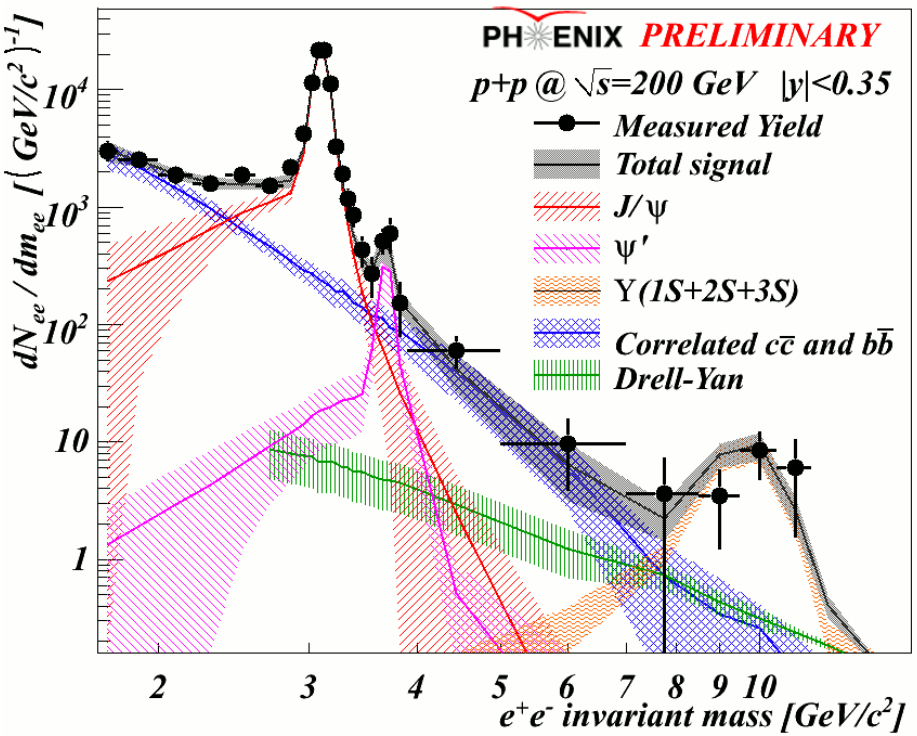




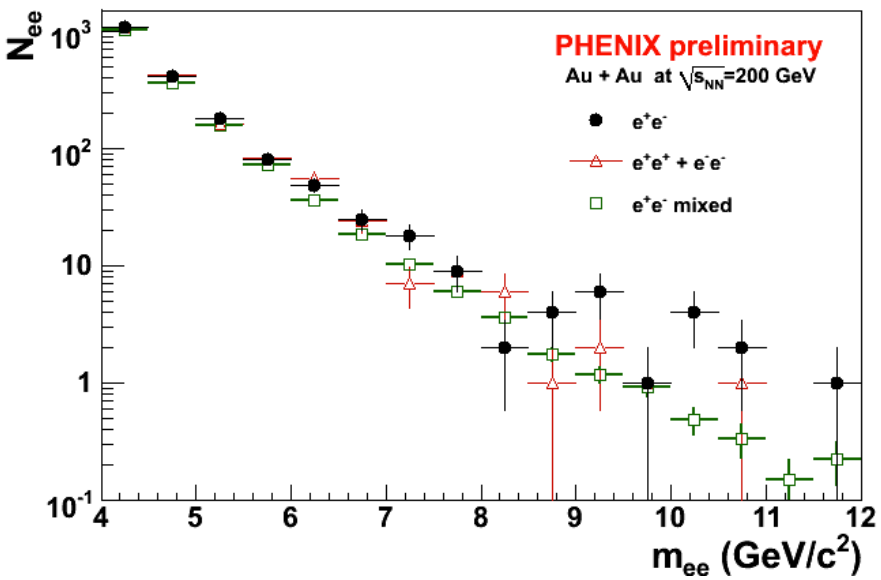
- Run6 $p + p$ and Run8 $d + Au$ $\Upsilon \rightarrow \mu^+\mu^-$ measurements have been used to get R_{dAu}
- $R_{dAu} = 0.84 \pm 0.34(stat) \pm 0.20(sys), y\epsilon[-2.2, -1.2]$
- $R_{dAu} = 0.53 \pm 0.20(stat) \pm 0.16(sys), y\epsilon[1.2, 2.2]$
- No measurements available (yet) at mid-rapidity.

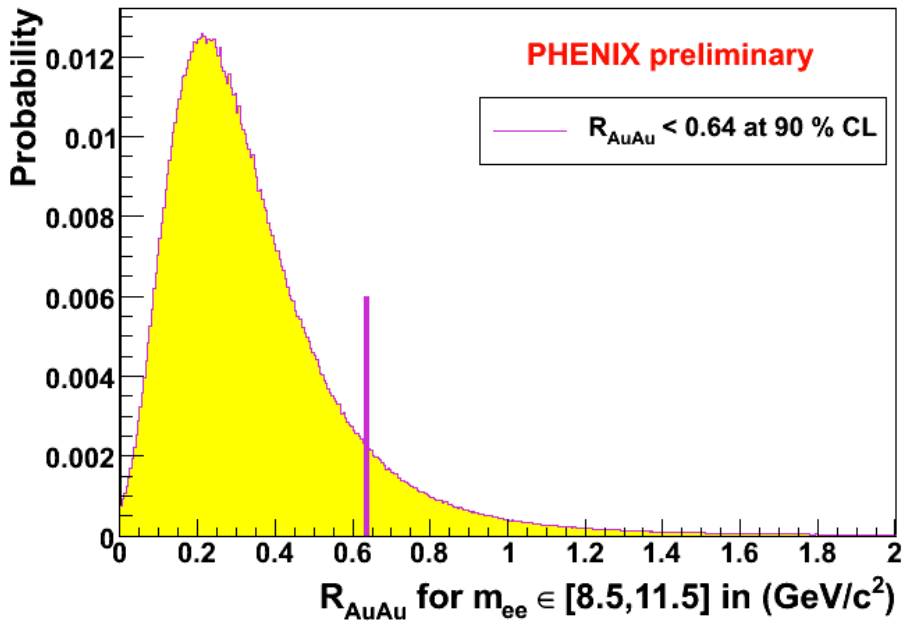
Upsilon in $d + Au$

p+p



Au+Au



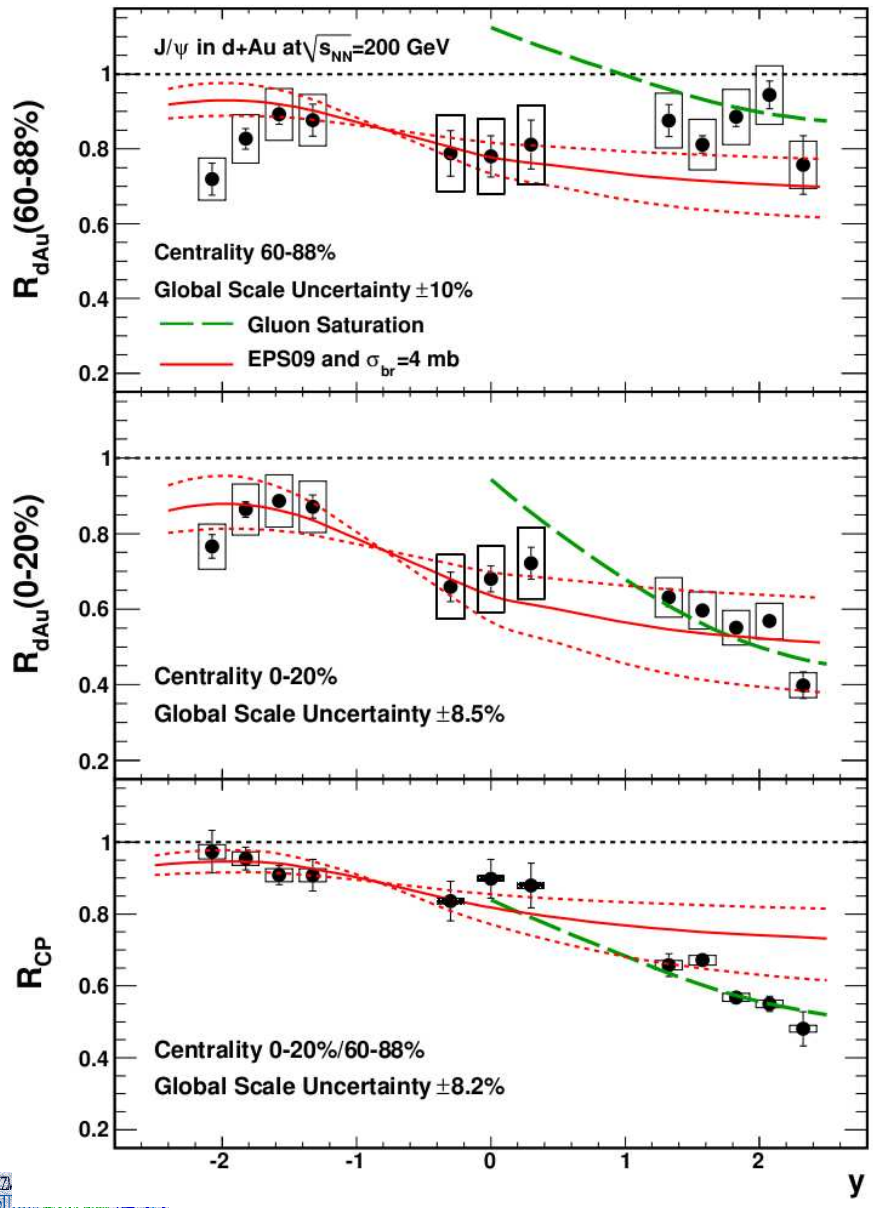


Excess over combinatorial background at high mass ($M > 8GeV/c^2$ attributed to:

- Upsilons
- Open beauty
- Drell-Yan

High mad di-lepton R_{AA} $R_{AA}[0.5, 11.5] < 0.64$ at 90% C.L.

J/ψ-R_{dAu} and R_{cp} vs. rapidity



- Peripheral R_{dAu} shows, some suppression at all rapidities, though the systematics is $\approx 15\%$. Central R_{dAu} indicates a much larger suppression for J/ψ at forward rapidity.
- R_{cp} (cancels out many systematic uncertainties) shows a dramatic suppression of forward rapidity yields for central $d + Au$ events compared to peripheral events.
- As can be seen, models including a nuclear-modified PDF and a (fixed) break-up X-section are unable to reproduce the rapidity dependence of R_{dAu} in central and peripheral events with the same $\sigma_{breakup}$.
- Gluon saturation matches the forward rapidity points relatively well, but not mid-rapidity.