Dileptons and Charm at RHIC

Thomas K Hemmick

Strongly Interacting Matter under Extreme Conditions

International Workshop XXXVIII on Gross Properties of Nuclei and Nuclear Excitations

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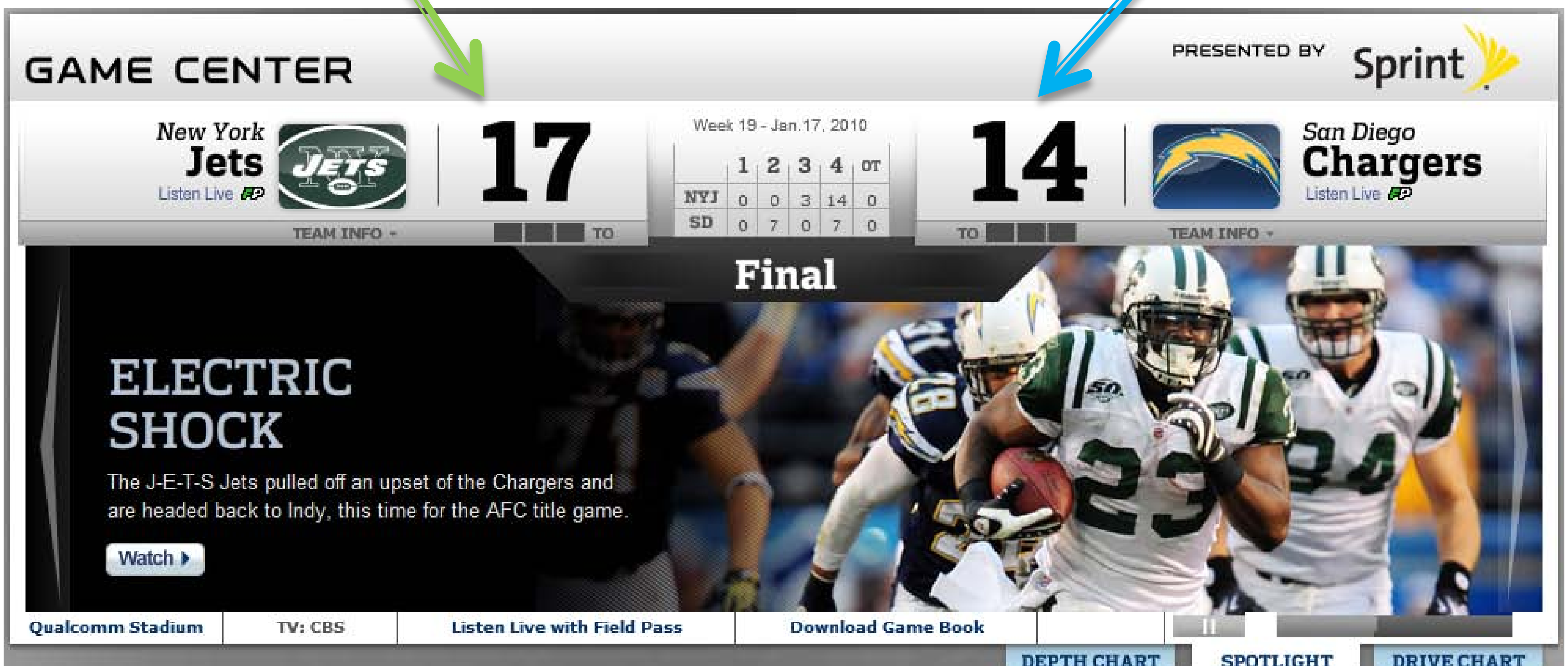
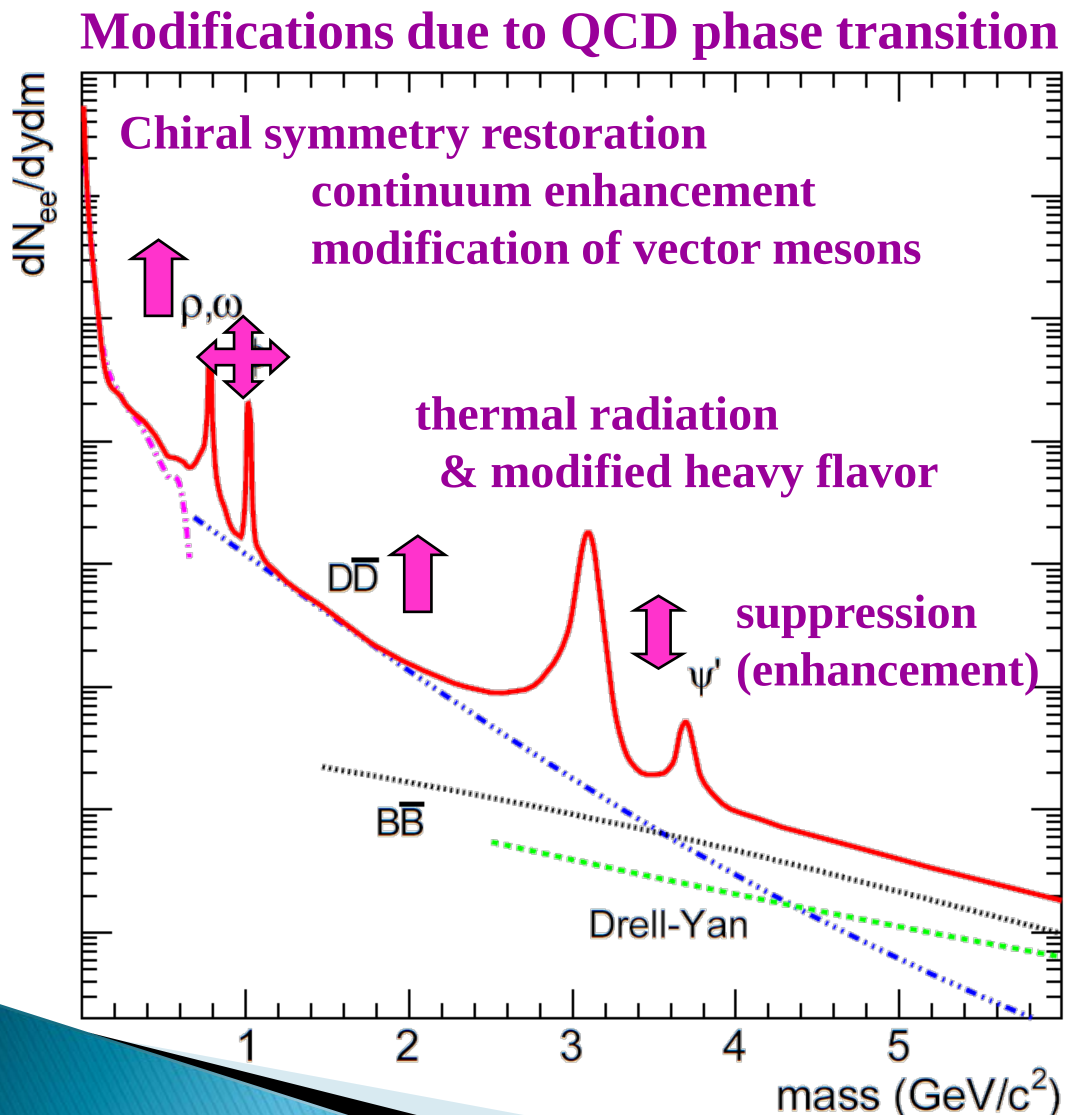
Recent Physics Experiment

Immovable Object

Irresistible Force$_1$



Lepton–Pair Continuum Physics



- **Sources "long" after collision:**
  - **π^0, η, ω Dalitz decays**
  - **(ρ), ω, ϕ, J/ψ, ψ' decays**
- **Early in collision (hard probes):**
  - **Heavy flavor production**
  - **Drell Yan, direct radiation**
- **Baseline from p-p**

- **Thermal (blackbody) radiation**
  - **in dileptons and photons**
  - **temperature evolution**
- **Medium modifications of meson**
  - **$\pi\pi \rightarrow \rho \rightarrow l^+l^-$**
  - **chiral symmetry restoration**
- **Medium effects on hard probes**
  - **Heavy flavor energy loss**

Challenge for PHENIX: Pair Background

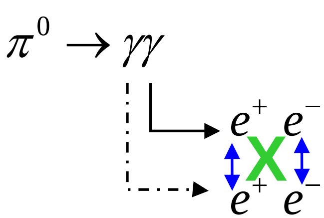
- No background rejection → Signal/Background ≥ 1/100 in Au–Au
- Unphysical correlated background
  - Track overlaps in detectors
  - Not reproducible by mixed events: removed from event sample (pair cut)

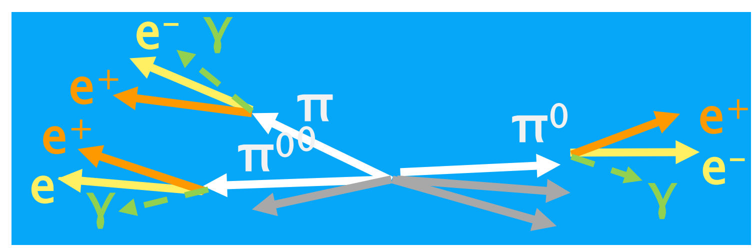
- Combinatorial background: e^+ and e^- from different uncorrelated source

$$\pi^0 \to e^+ e^- \gamma \qquad\qquad \gamma \to e^+ e^-$$

  - Need event mixing because of acceptance differences for e^+ and e^-
  - Use like sign pairs to check event mixing

- Correlated background: e^+ and e^- from same source but not "signal"
  - "Cross" pairs
  - "jet" pairs





  - Use Monte Carlo simulation and like sign data to estimate and subtract background

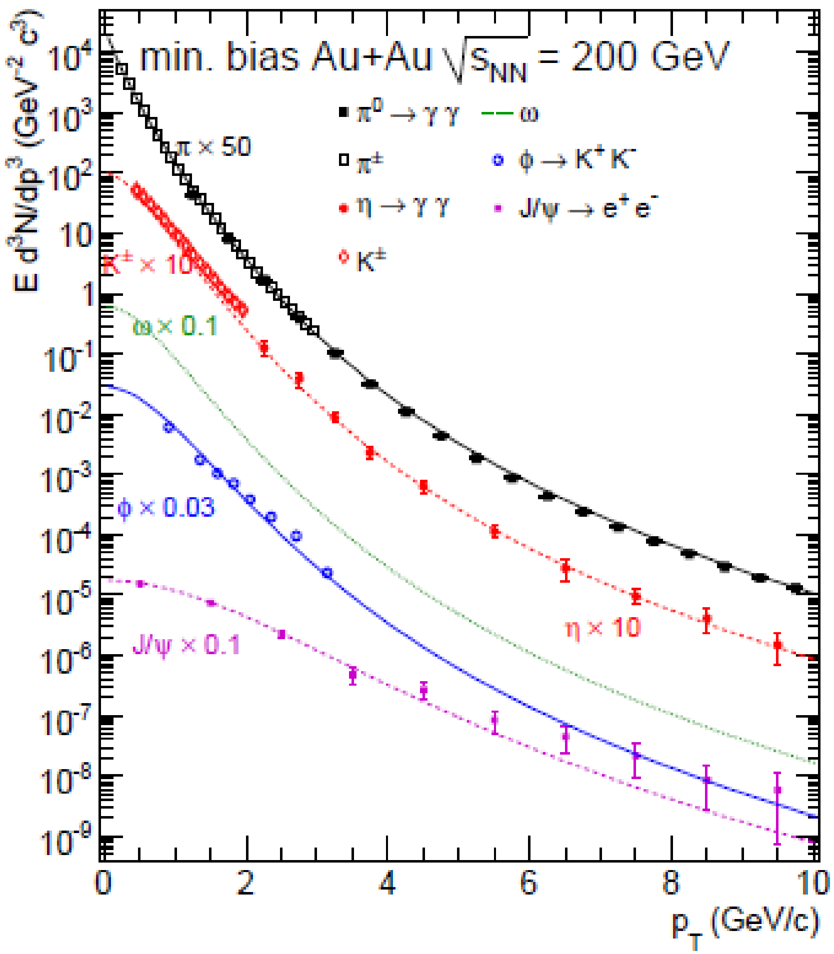
Estimate of Expected Sources

- Hadron decays:
  - Fit π^0 and $\pi^\pm$ data p+p or Au+Au

$$E\frac{d^3\sigma}{d^3p} = \frac{A}{\left(\exp(-ap_T - bp_T^2) + p_T/p_0\right)^n}$$

  - For other mesons η, ω, ρ, ϕ, J/ψ etc. replace $p_T \rightarrow m_T$ and fit normalization to existing data where available

Hadron data follows "m_T scaling"

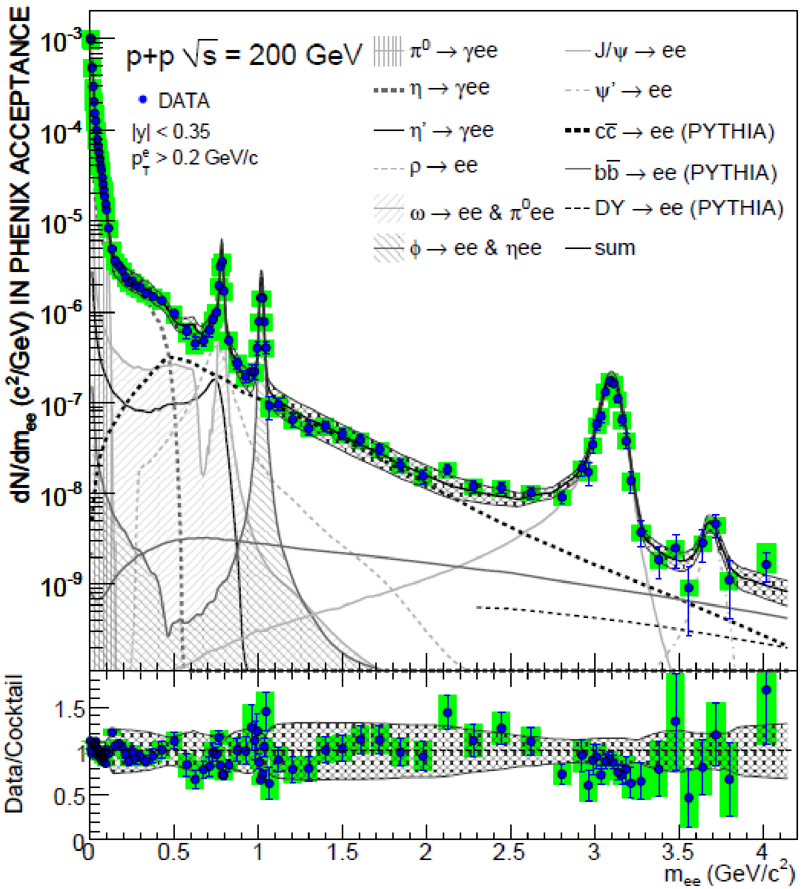


- Heavy flavor production:
  - $\sigma_c = N_{coll}$ x 567±57±193μb from single electron measurement

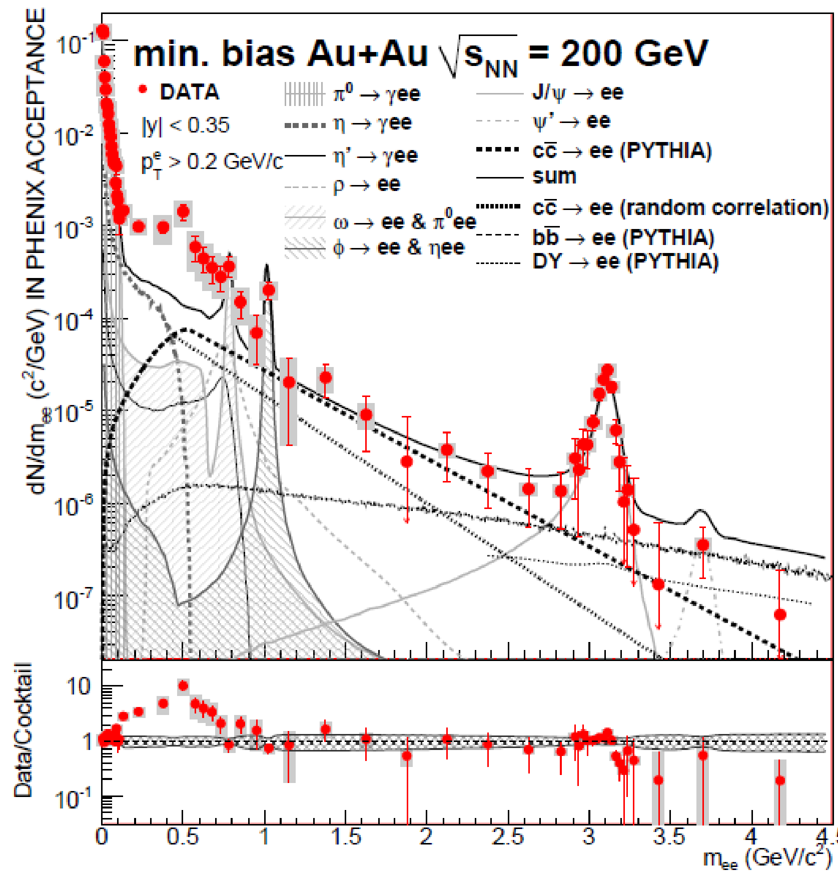
Predict cocktail of known pair sources

Continuum in p+p and AuAu

Phys. Lett. B 670, 313 (2009)



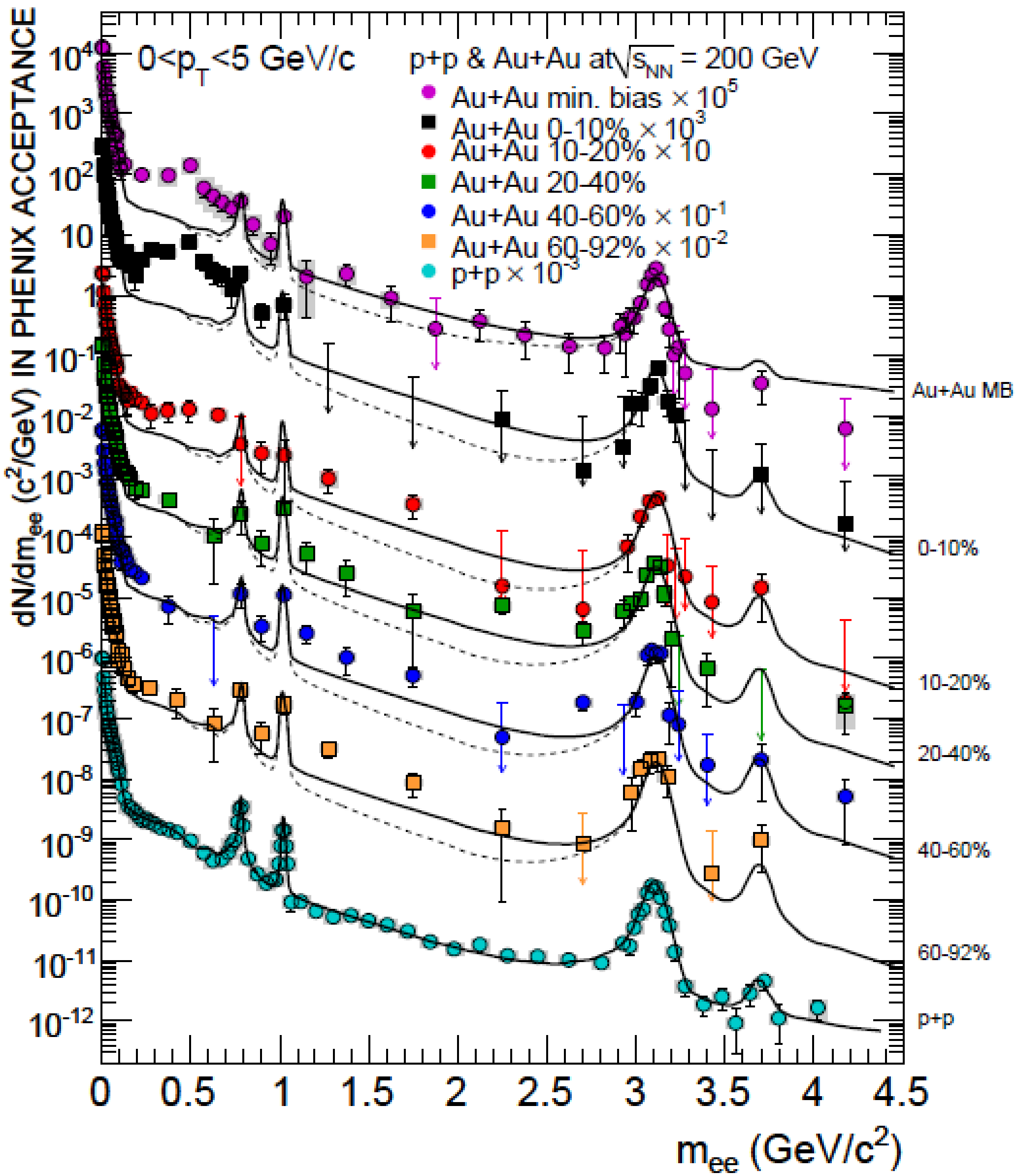
arXiv:0912.0244



- **Data and Cocktail of known sources**
- **Excellent Agreement**

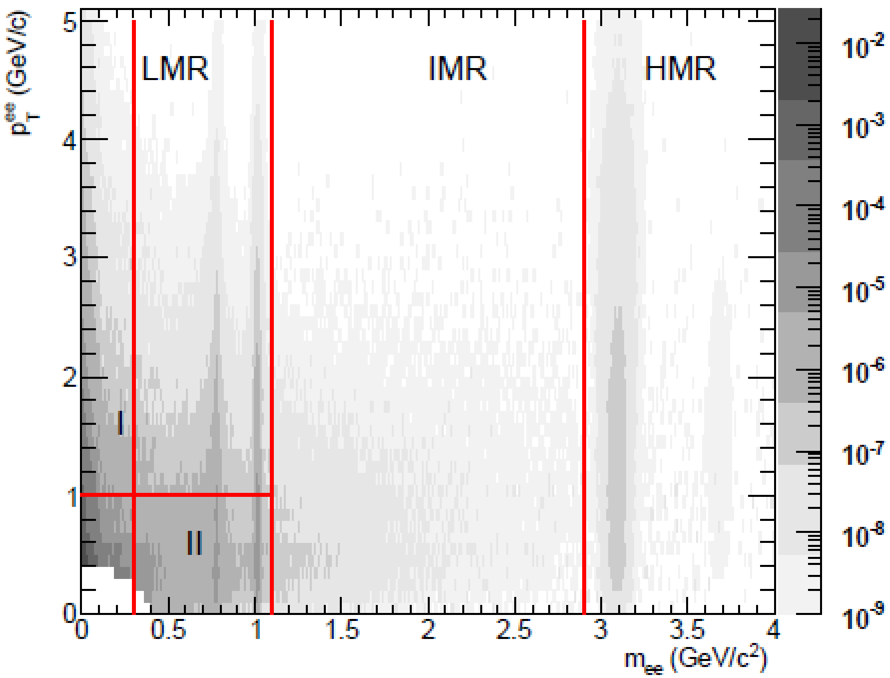
- **Data and Cocktail of known sources**
- **Striking Enhancement at and below the ω mass.**

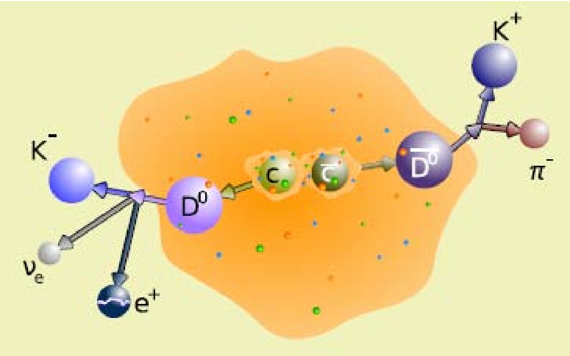
Centrality Dependence



- Enhancement in low mass region is a strong function of centrality.
- Statistics are also sufficient to analyze p_T dependence.
- Need methodical approach to the spectra.

Methodical Spectral Analysis

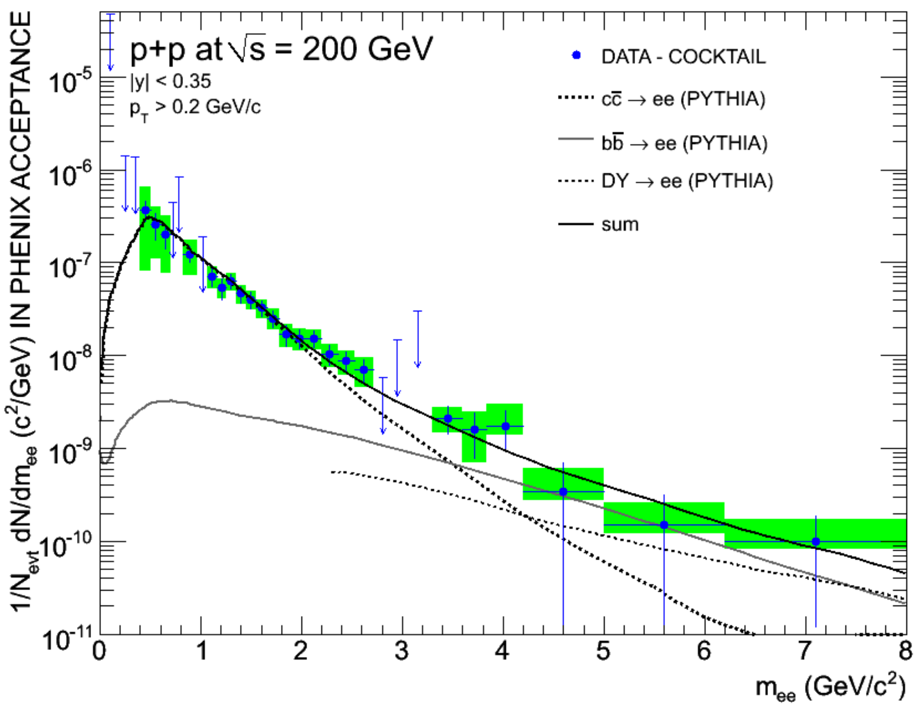




- IMR in cocktail is dominated by correlated open charm.
- LMR-I wherein $m_{ee} << p_T$
- LMR-II where the above condition does not apply.

IMR Region ($\phi \rightarrow J/\psi$)

Subtract hadron decay contribution and fit difference:

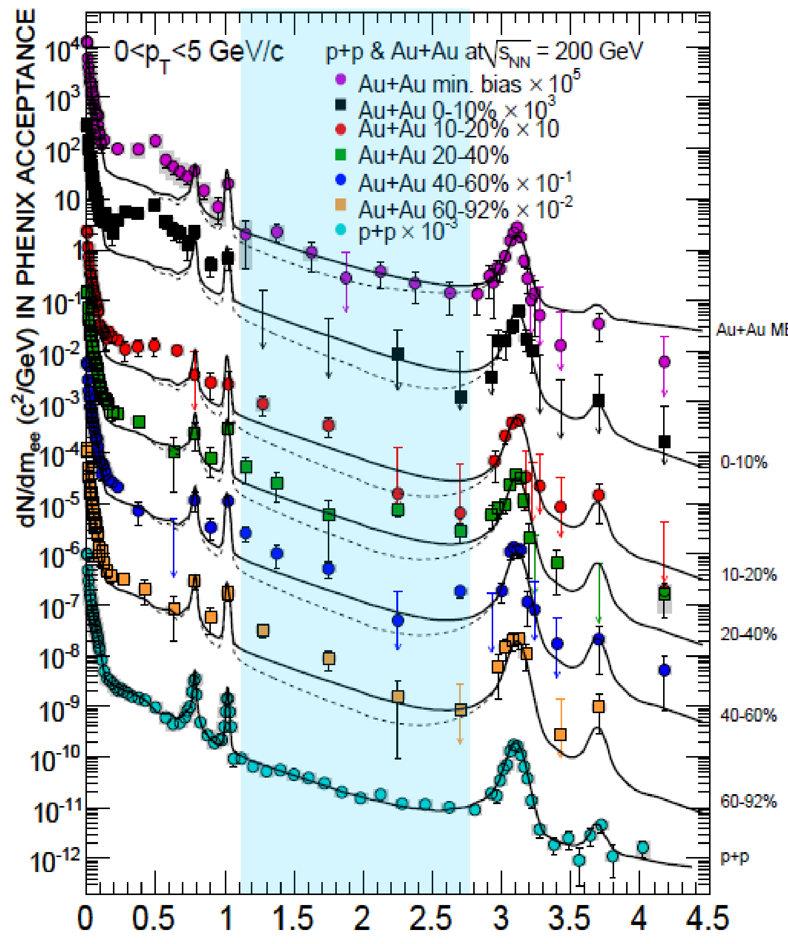


Charm: after cocktail subtraction

- σ_c=544 ± 39 (stat) ± 142 (sys) ± 200 (model) μb

Simultaneous fit of charm and bottom:

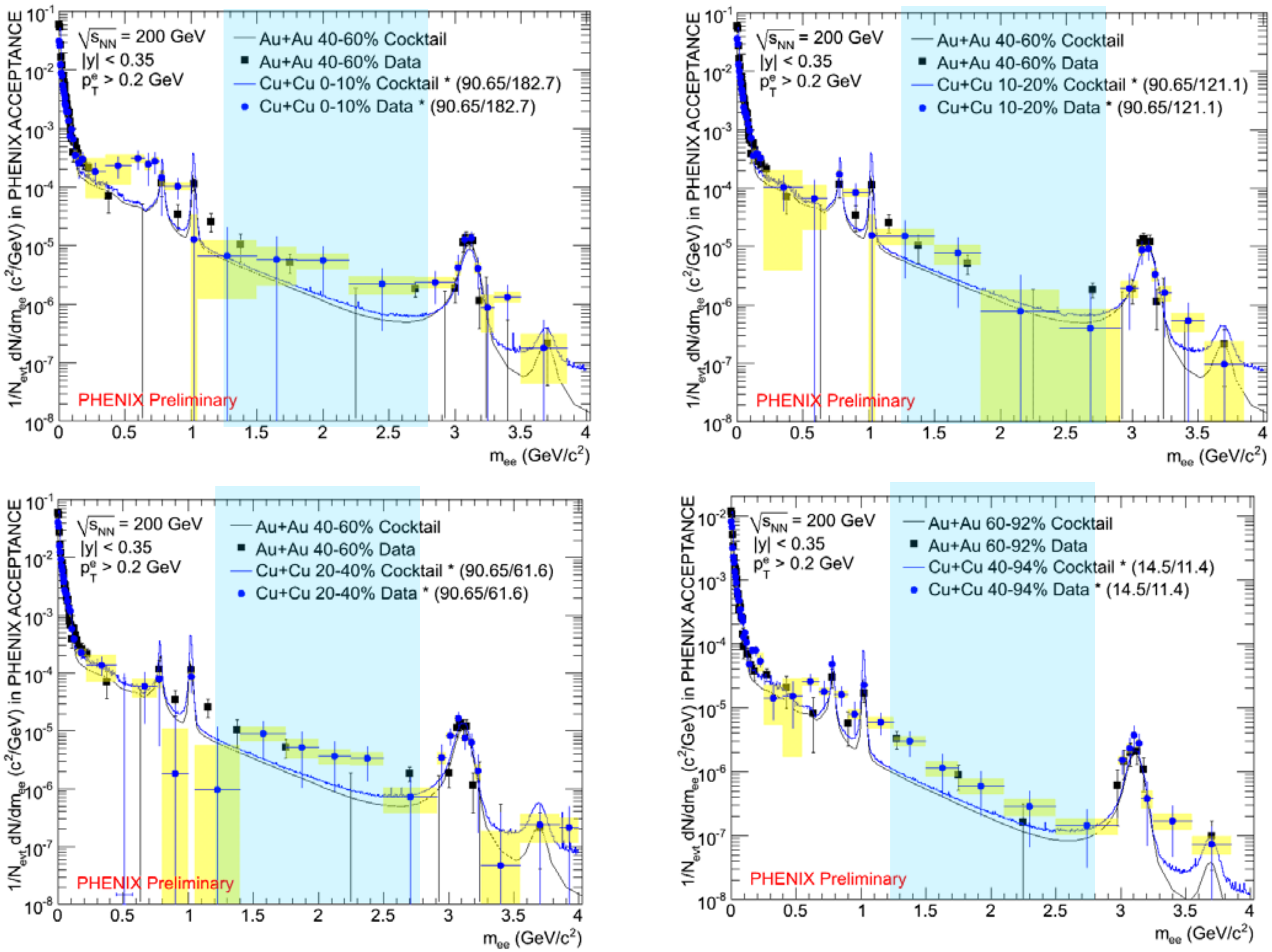
- σ_c=518 ± 47 (stat) ± 135 (sys) ± 190 (model) μb
- σ_b= 3.9 ± 2.4 (stat) +3/-2 (sys) μb



Surprise!

- **AuAu matches cocktail in MB.**
- **Slightly higher in peripheral**
- **Dashed line is result of max. smearing of charm pairs.**

Cu+Cu Au+Au comparison



Spectral modification should lower yield.

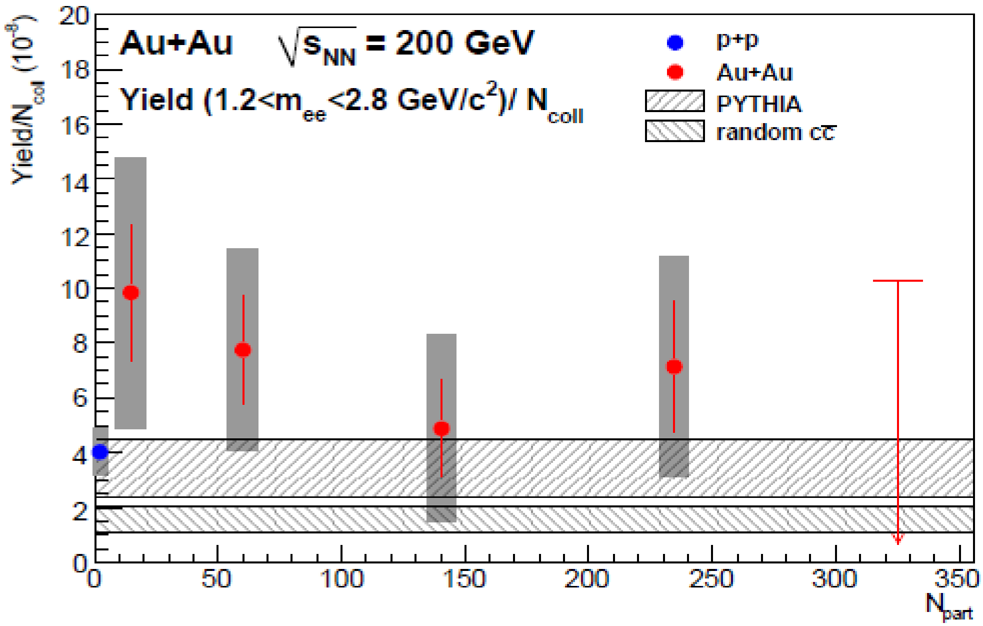
- **Charm singles are well known to be strongly modified by the medium.**
- **These effects should lower the IMR yield most at the most central bin.**

Prompt yields were observed by NA60 in this regime.

- **Prompt yields might rise with centrality.**

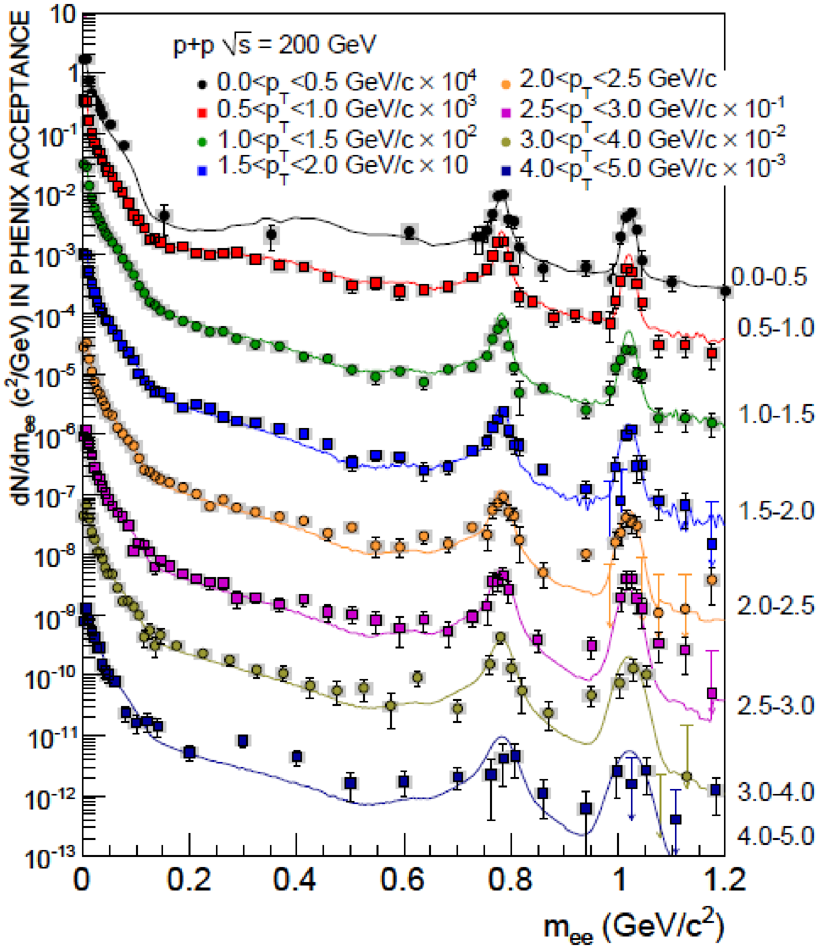
- **Competing or compensating effects?**

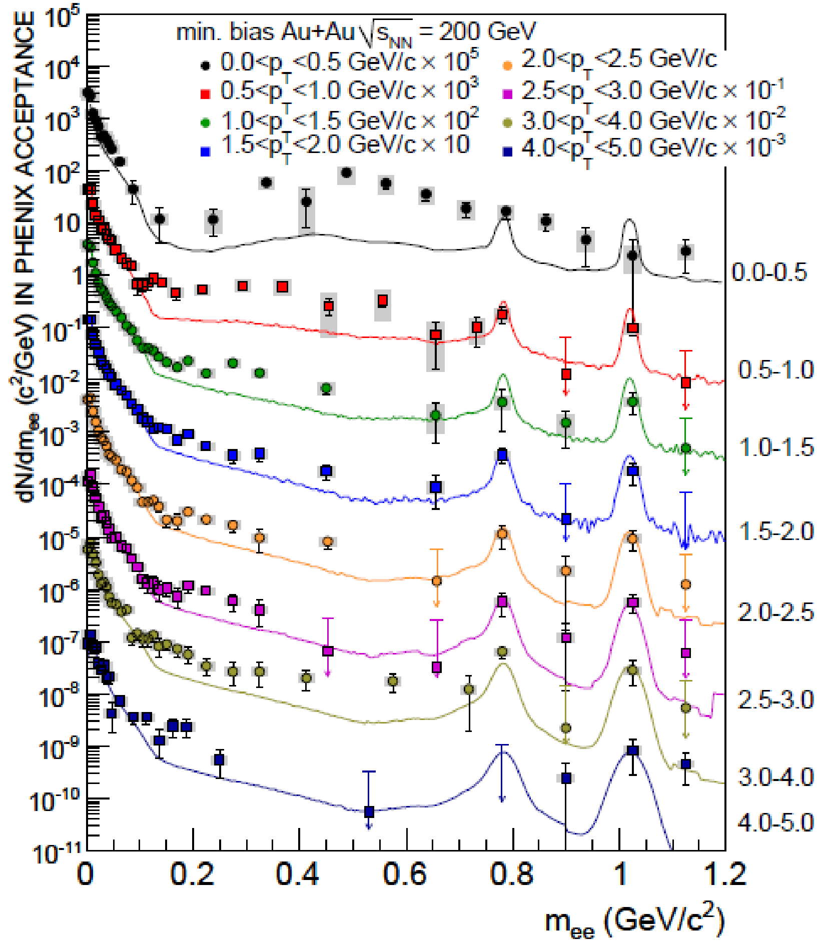
AuAu IMR yield vs Centrality.



- Because of large errors, the IMR of AuAu is still consistent with unmodified scaled pp or Pythia.
- Additional sources may also be present since “suppression” due to charm spectral modification is not observed in the pair data.

LRM divided into p_T Slices





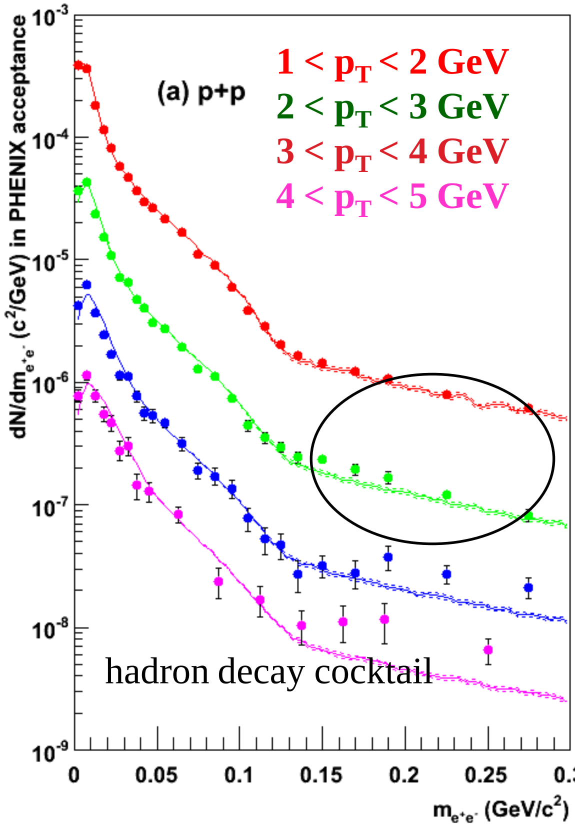
- pp shows excess growing with p_{T}.
- pp excess slopes downward.

- AuAu shows excess at all p_T
- AuAu excess similarly shaped to pp in higher p_T region

Direct (pQCD) Radiation

- **Measuring direct photons via virtual photons:**
  - any process that radiates γ will also radiate $\gamma*$
  - for $m << p_T$ $\gamma*$ is "almost real"
  - extrapolate $\gamma* \rightarrow e+e-$ yield to $m = 0$ → direct γ yield
  - $m > m_\pi$ removes 90% of hadron decay background
  - S/B improves by factor 10: 10% direct γ → 100% direct γ*

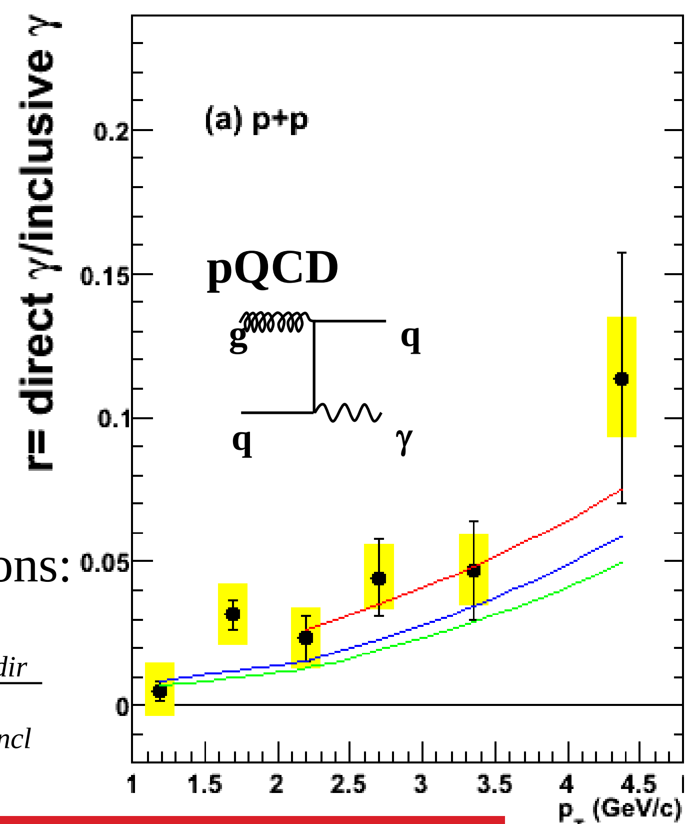
arXiv:0804.4168



access above cocktail

fraction or direct photons:

$$r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$$



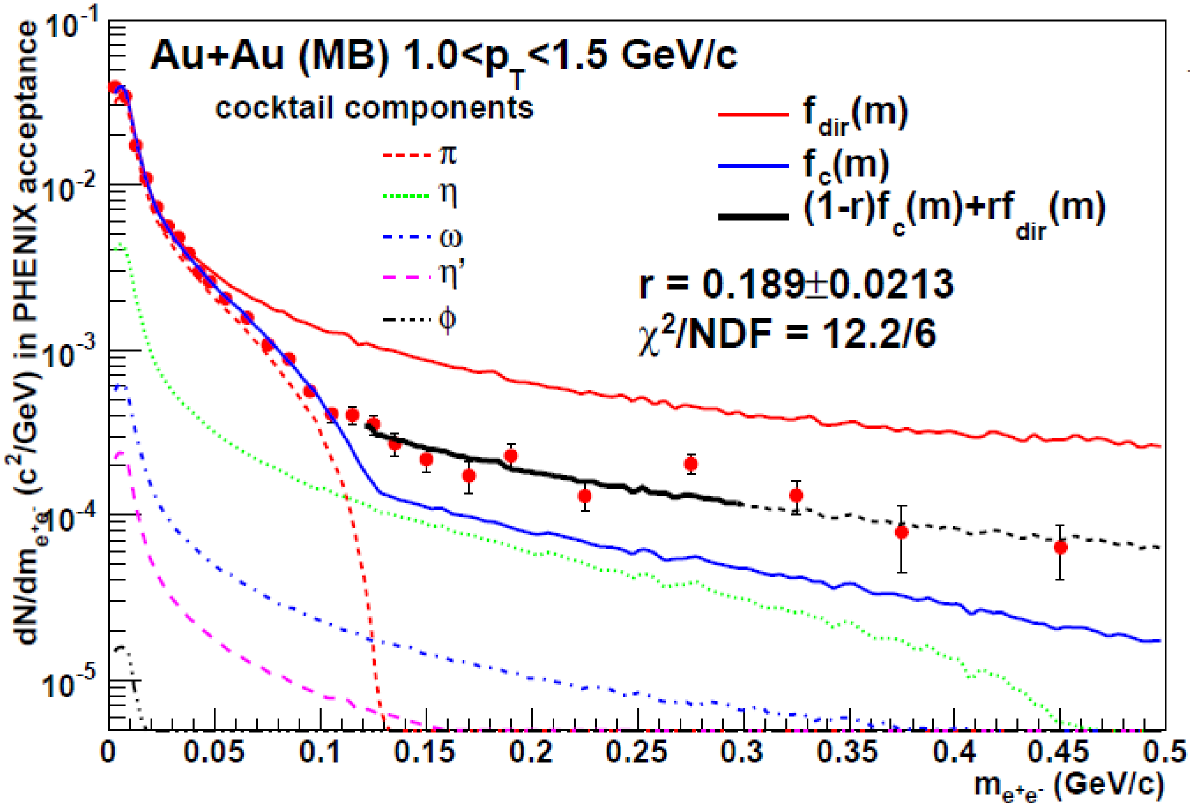
Small excess for m<< p_T consistent with pQCD direct photons

Fit Mass Distribution to Extract the Direct Yield:

- Example: one pT bin for Au+Au collisions

$$\frac{d^2N_{ee}}{dm_{ee}dp_T} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}L(m_{ee})S(m_{ee},p_T)\frac{dN_\gamma}{dp_T},$$

$$L(m_{ee}) = \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right).$$



$f_c(m_{ee})$ and $f_{dir}(m_{ee})$ normalized to data for $m_{ee} < 30\,MeV$

Direct γ* yield fitted in range 120 to 300 MeV
Insensitive to π^0 yield

Interpretation as Direct Photon

Relation between real and virtual photons:

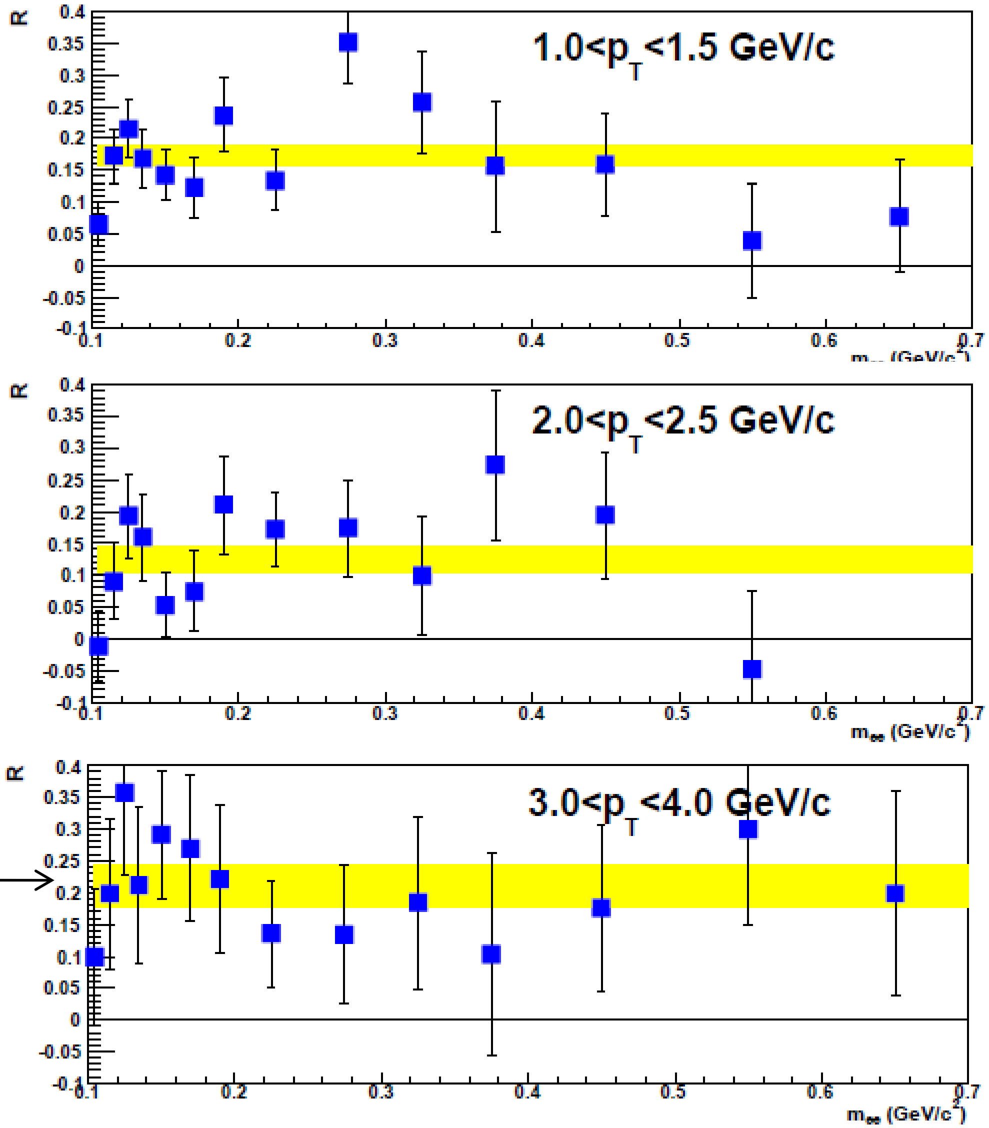
$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

Extrapolate real γ yield from dileptons:

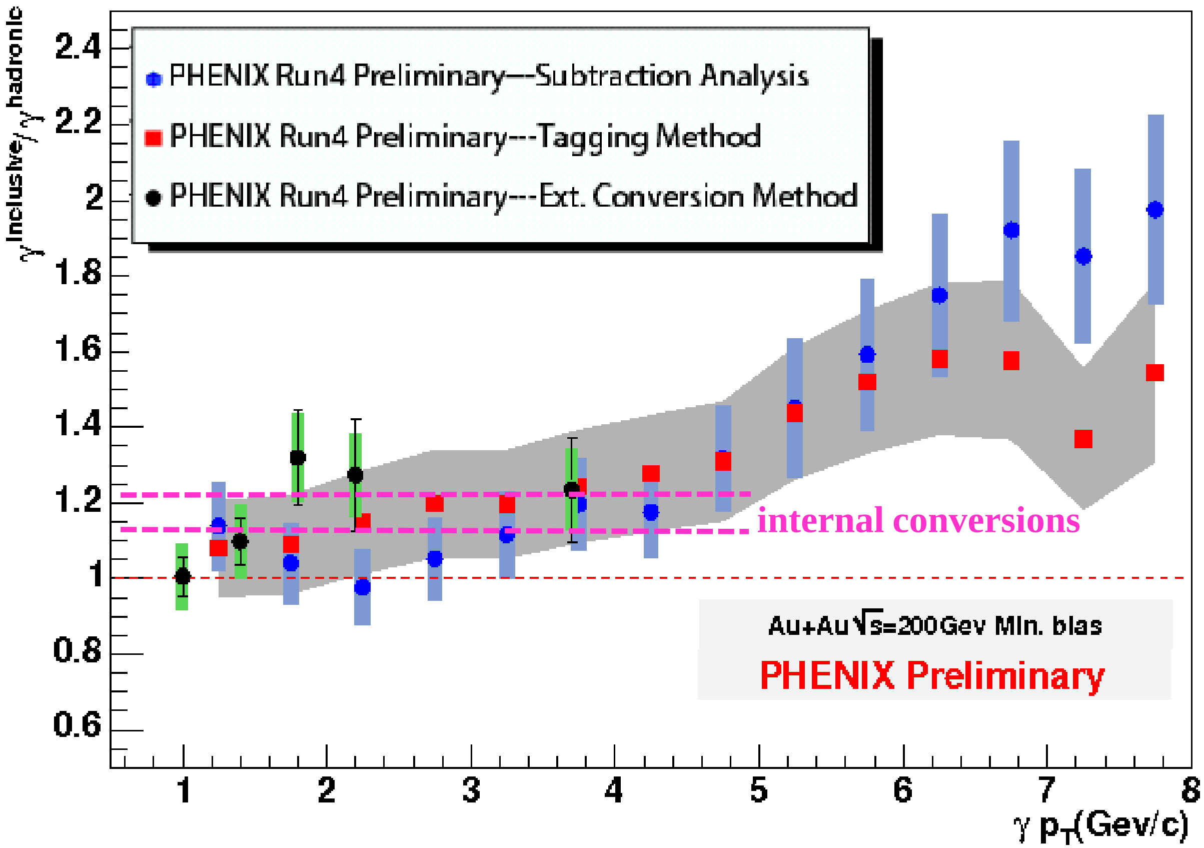
$$M \times \frac{dN_{ee}}{dM} \rightarrow \frac{dN_\gamma}{dM} \quad \text{for} \quad M \rightarrow 0$$

Virtual Photon excess
At small mass and high p_T
Can be interpreted as
real photon excess

no change in shape
can be extrapolated
to m=0

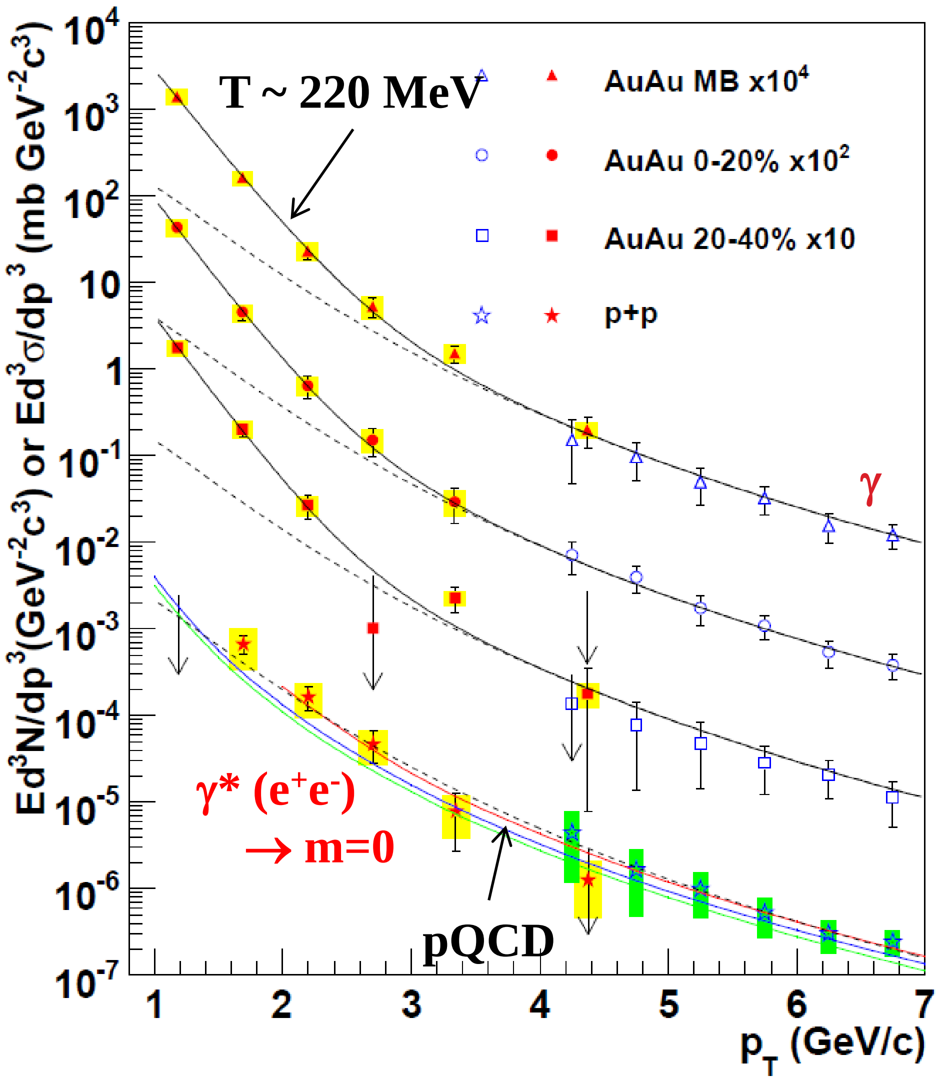


Search for Thermal Photons via Real Photons



- PHENIX has developed different methods:
  - Subtraction or tagging of photons detected by calorimeter
  - Tagging photons detected by conversions, i.e. e^+e^- pairs
- Results consistent with internal conversion method

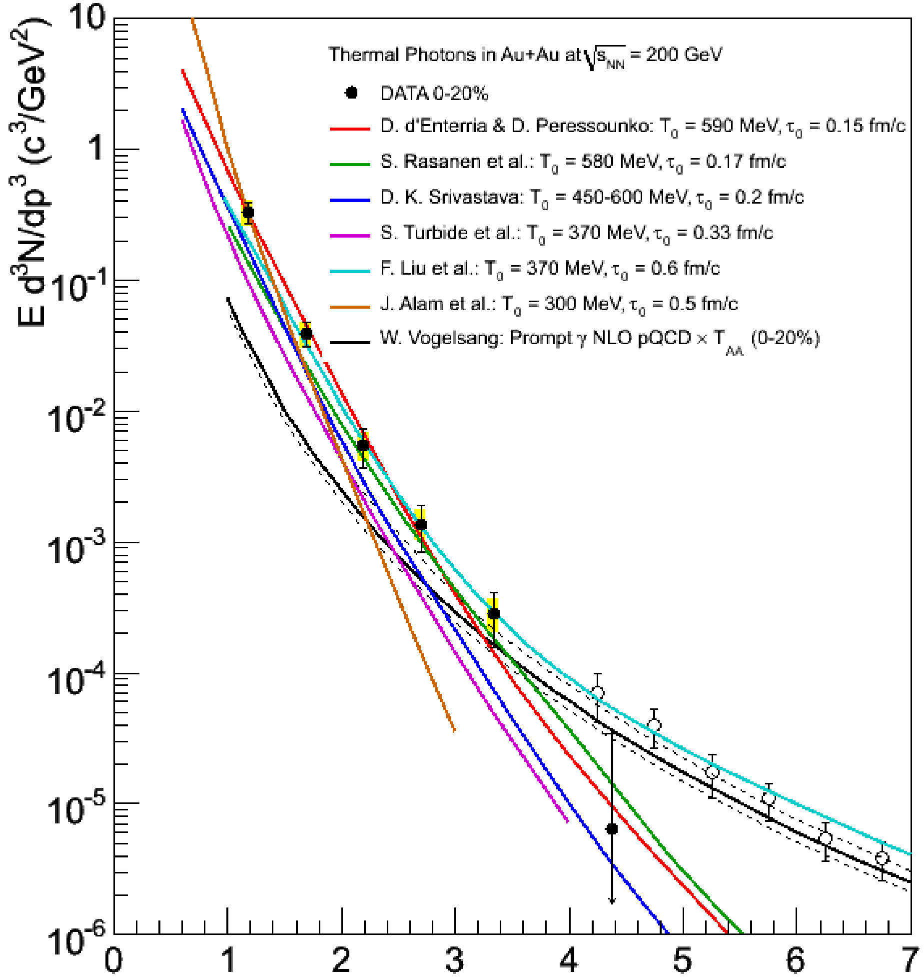
Thermal Radiation at RHIC



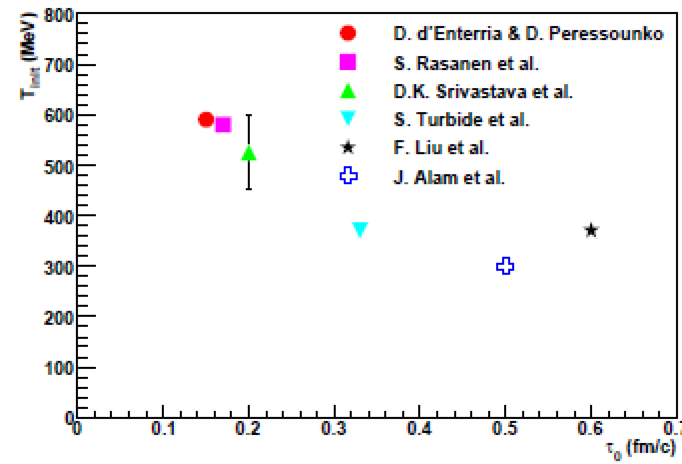
- Direct photons from real photons:
  - Measure inclusive photons
  - Subtract π^0 and η decay photons at S/B < 1:10 for p_T<3 GeV
- Direct photons from virtual photons:
  - Measure e^+e^- pairs at $m_\pi < m << p_T$
  - Subtract η decays at S/B ~ 1:1
  - Extrapolate to mass 0

First thermal photon measurement:
T_{ini} > 220 MeV > T_C

Calculation of Thermal Photons



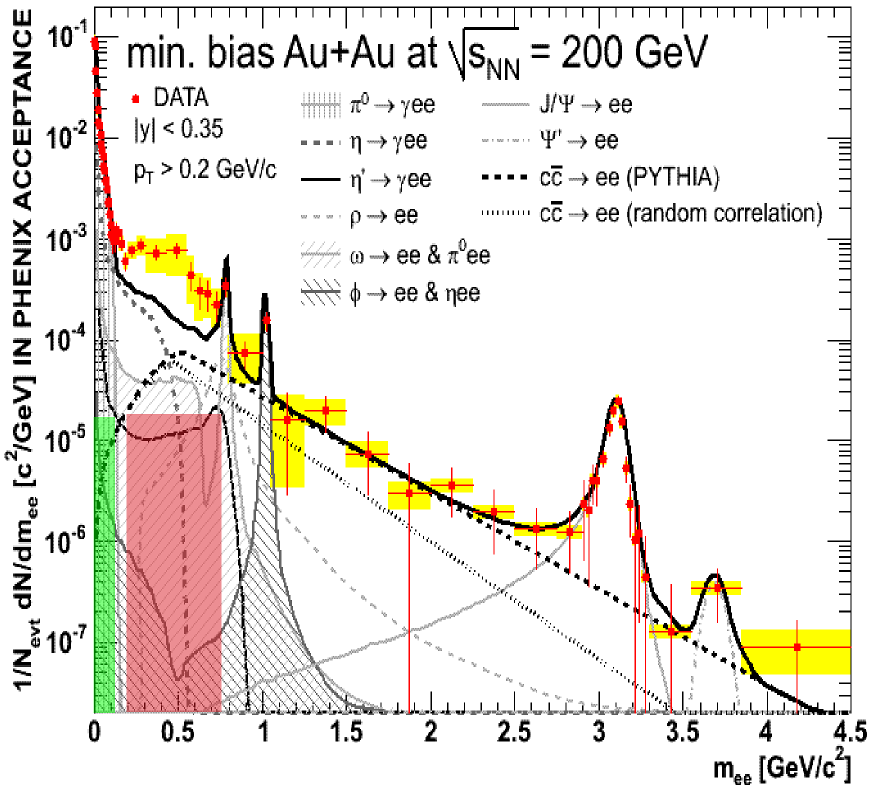
D.d'Enterria, D.Peressounko, Eur.Phys.J.C 46 (2006)



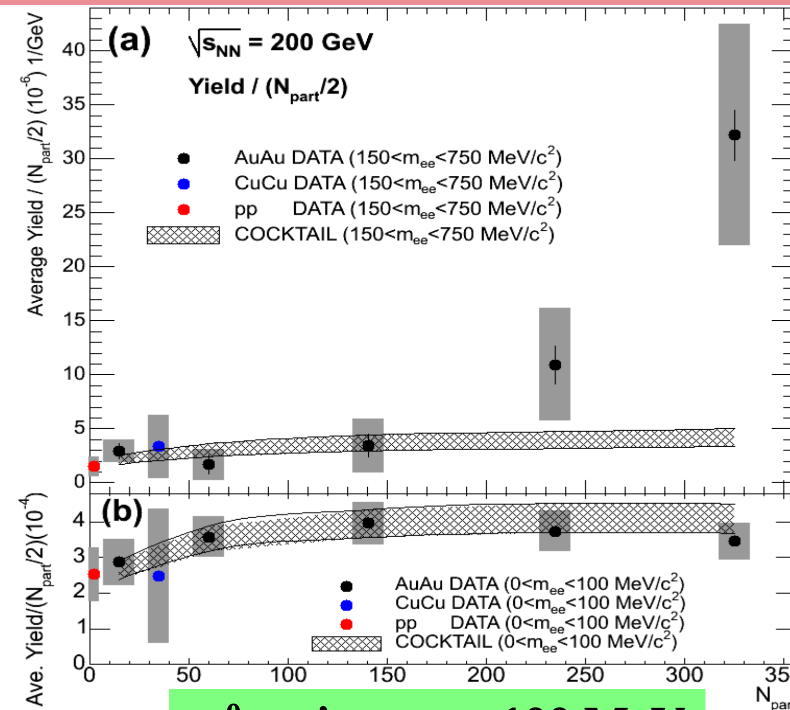
T_{ini} = 300 to 600 MeV
τ_0 = 0.15 to 0.5 fm/c

- Initial temperatures and times from theoretical model fits to data:
  - 0.15 fm/c, 590 MeV (d'Enterria et al.)
  - 0.2 fm/c, 450–660 MeV (Srivastava et al.)
  - 0.5 fm/c, 300 MeV (Alam et al.)
  - 0.17 fm/c, 580 MeV (Rasanen et al.)
  - 0.33 fm/c, 370 MeV (Turbide et al.

Au+Au Dilepton Continuum



Excess region: 150 < m < 750 MeV



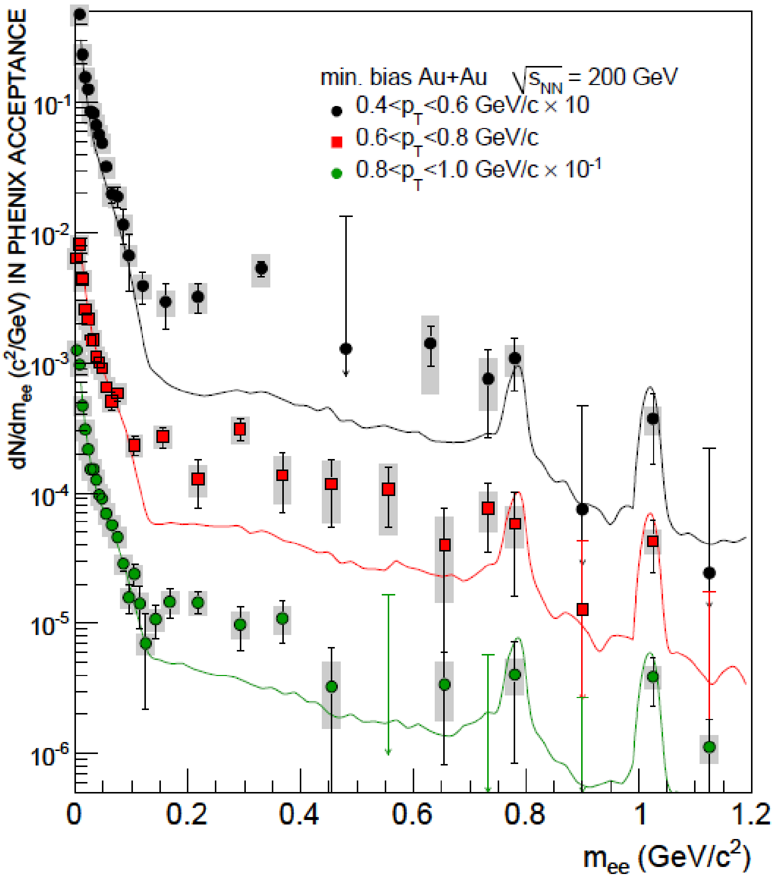
π^0 region: m < 100 MeV

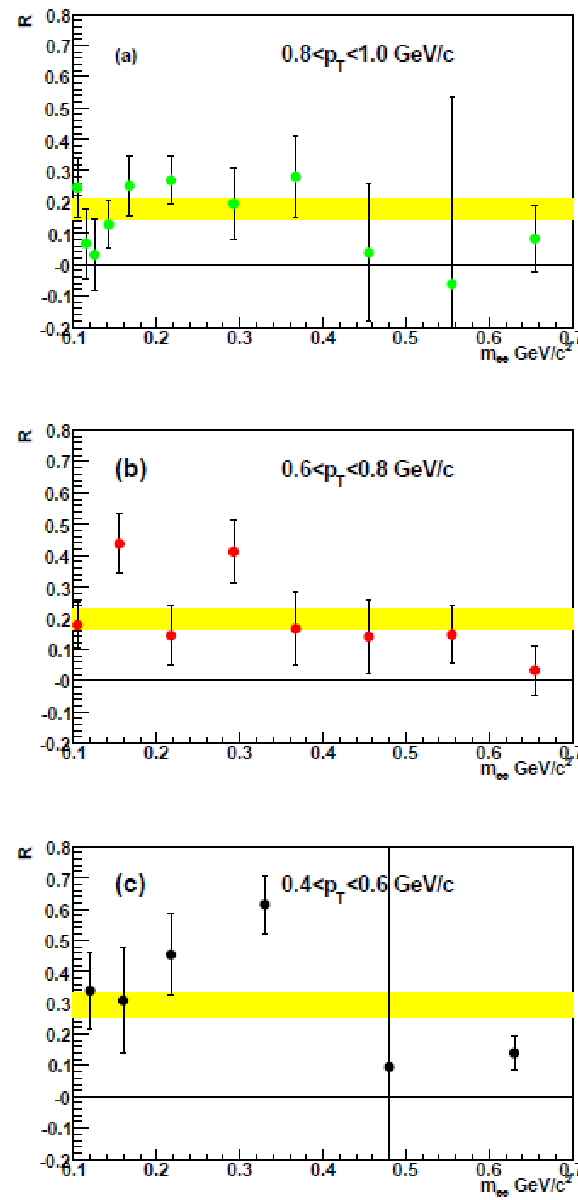
- Excess 150 <mee<750 MeV: 3.4 ± 0.2(stat.) ± 1.3(syst.) ± 0.7(model)
- Intermediate-mass continuum: consistent with PYTHIA if charm is modified room for thermal radiation

- **Yield / (N_{part}/2) in mass windows**
- **π^0 region: production scales approximately with N_{part}**
- **Excess region: expect contribution from hot matter**
  - **in-medium production from ππ or qq annihilation**
  - → **yield should scale faster than N_{part}**

p_T < 1 GeV Enhancement

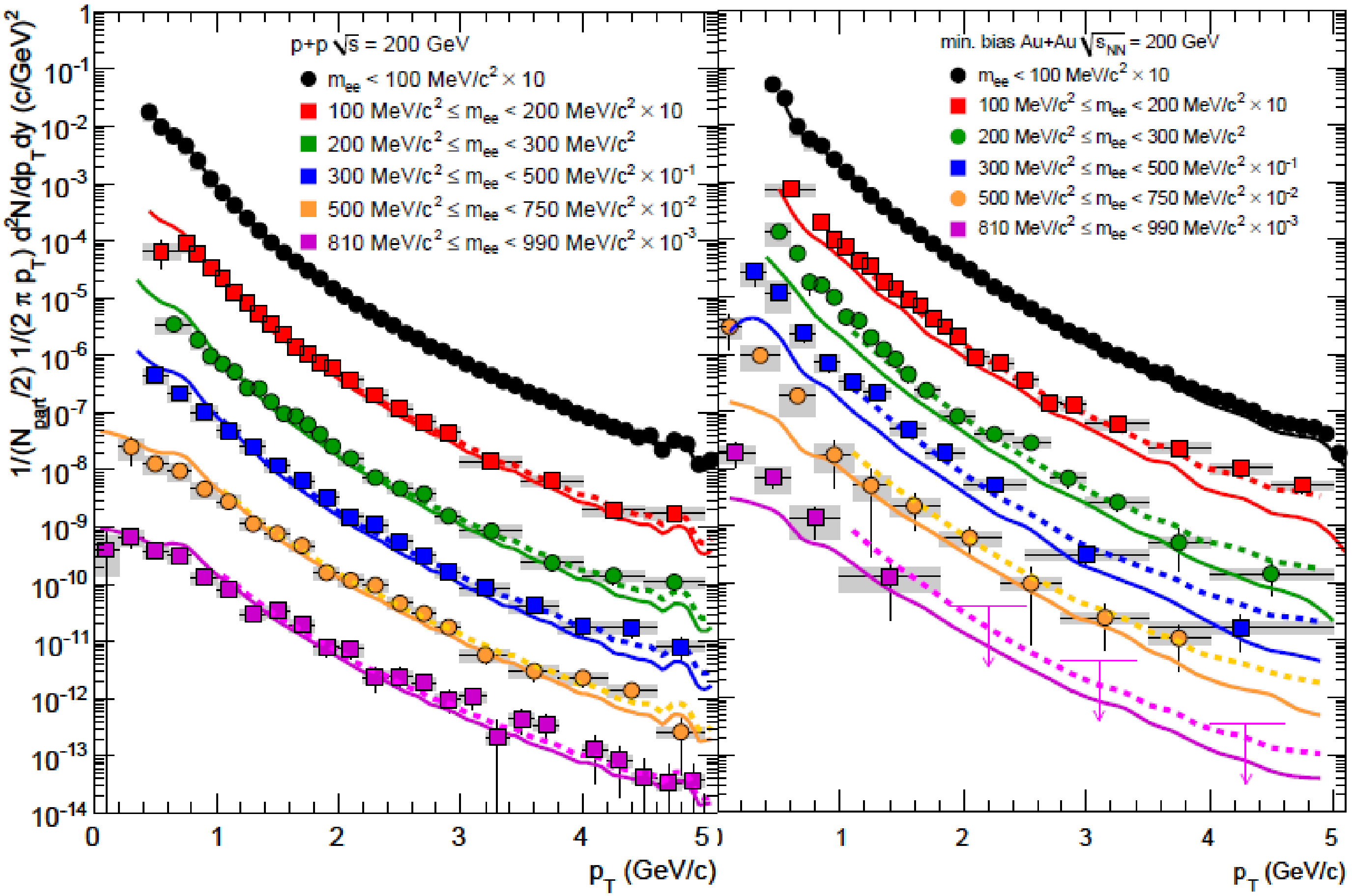
Poorly described as γ^*





Low mass excess in Au-Au concentrated at low p_T!

p_T Spectra

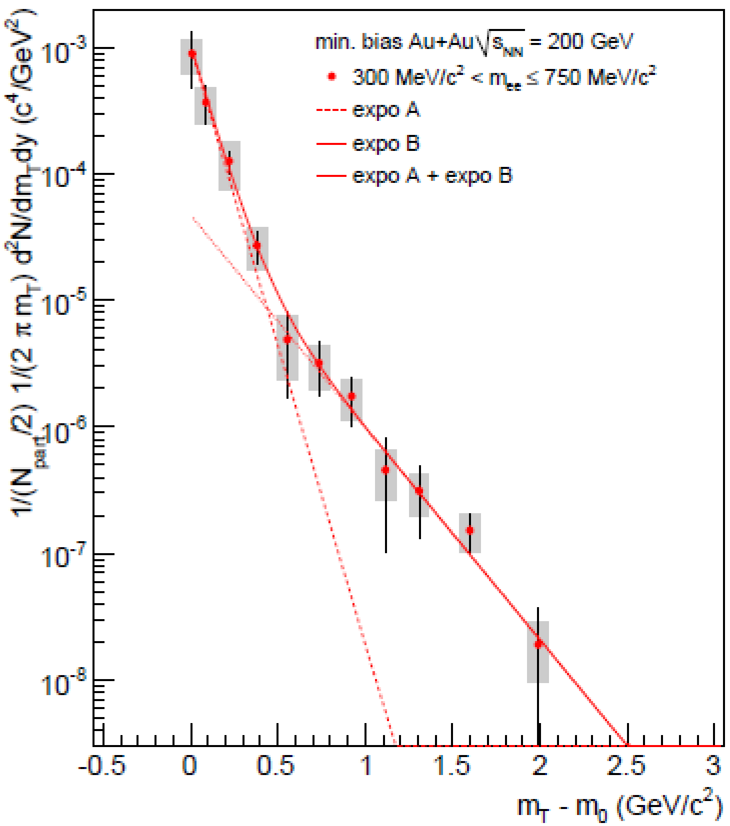


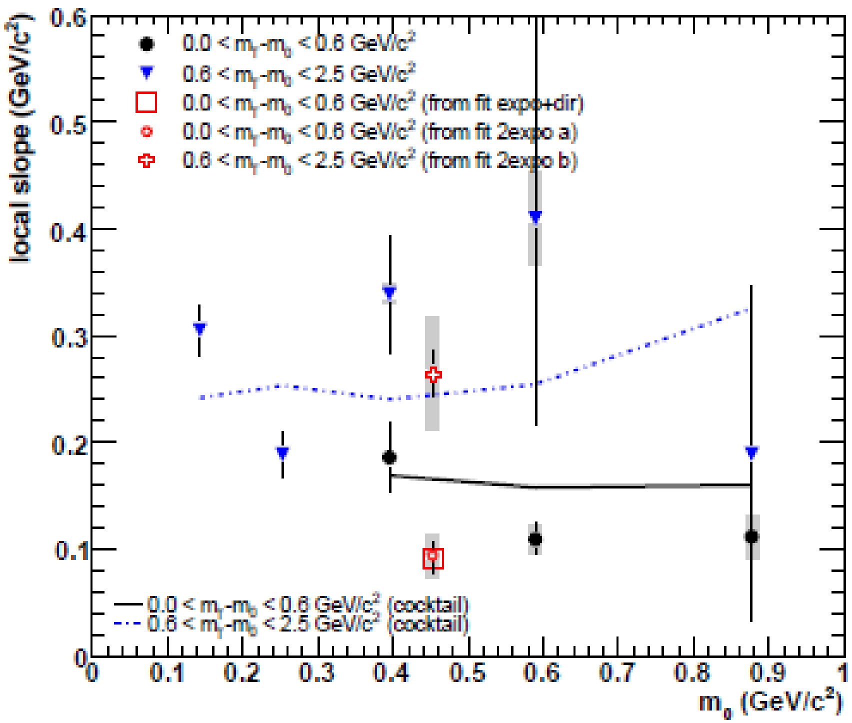
pp well described by Cocktail + gamma.

AuAu not well described:

Additional excess at low p_T

Local Slopes – Cold Component



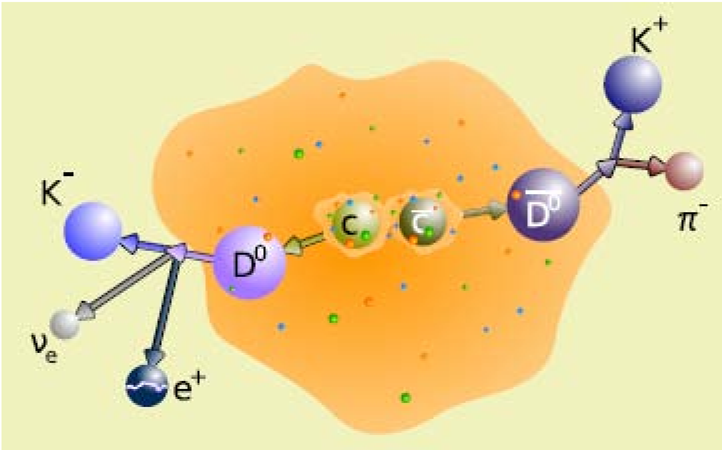


Soft component below m_T ~ 500 MeV:

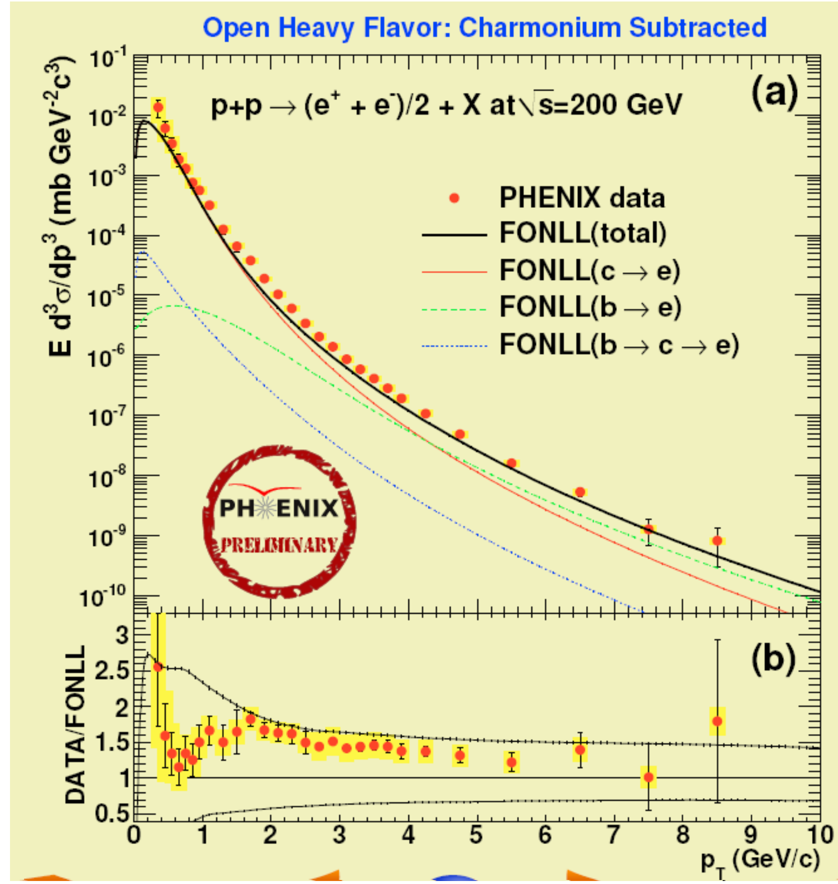
T_{eff} < 120MeV independent of mass

more than 50% of yield

Heavy Flavor from Single Leptons

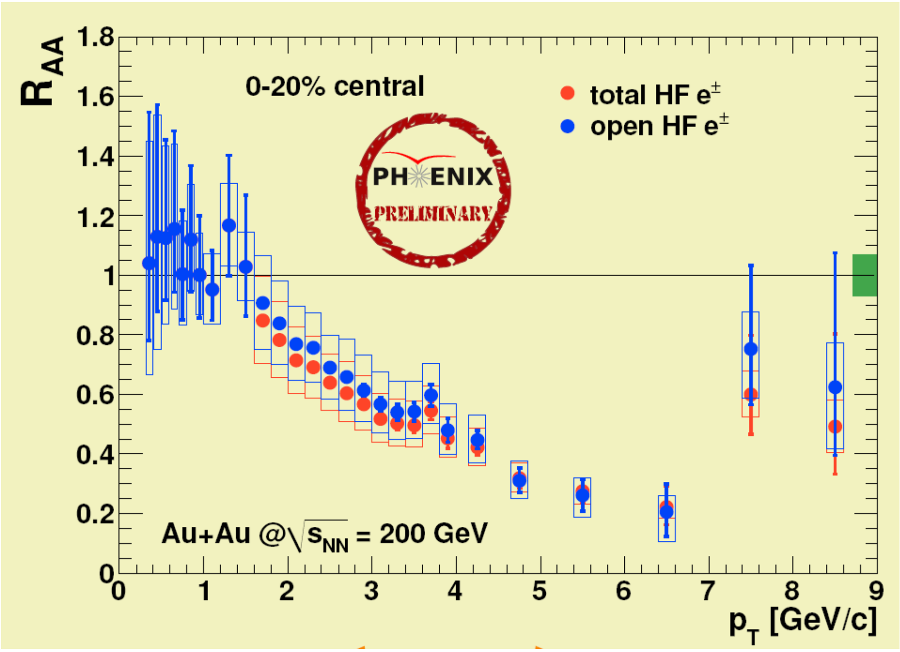


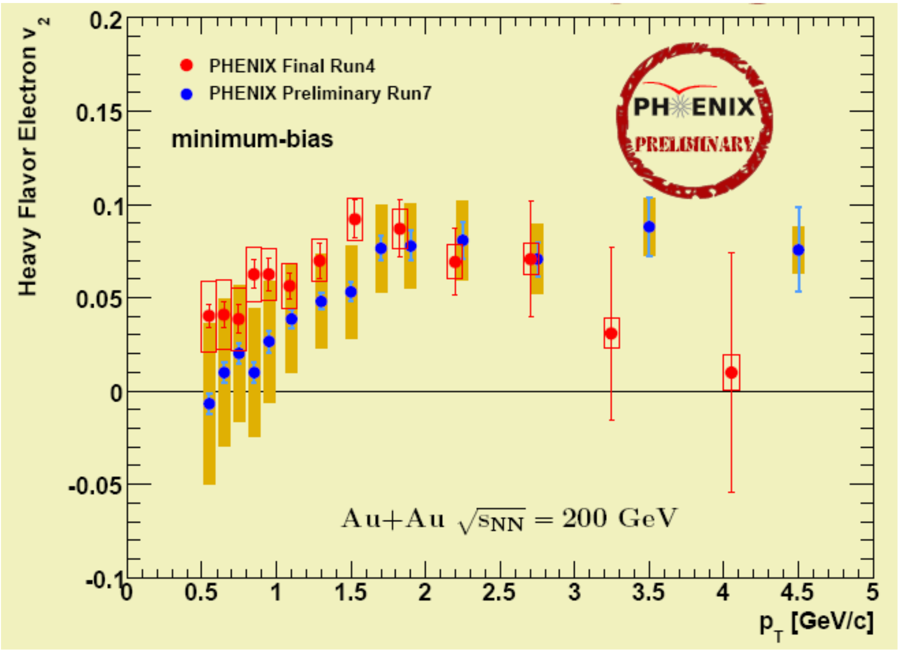
- Open Charm (and bottom) states decay with significant branching ratios (~10%) semi-leptonically.
- Parent quark mass makes these the dominant source at high p_T
- Cocktail (or convertor) subtraction yields spectrum of heavy flavor lepton decays.



- **pp results presented both as inclusive heavy flavor and "open" heavy flavor.**
- **Good agreement with pQCD**

Heavy Flavor Leptons in AuAu

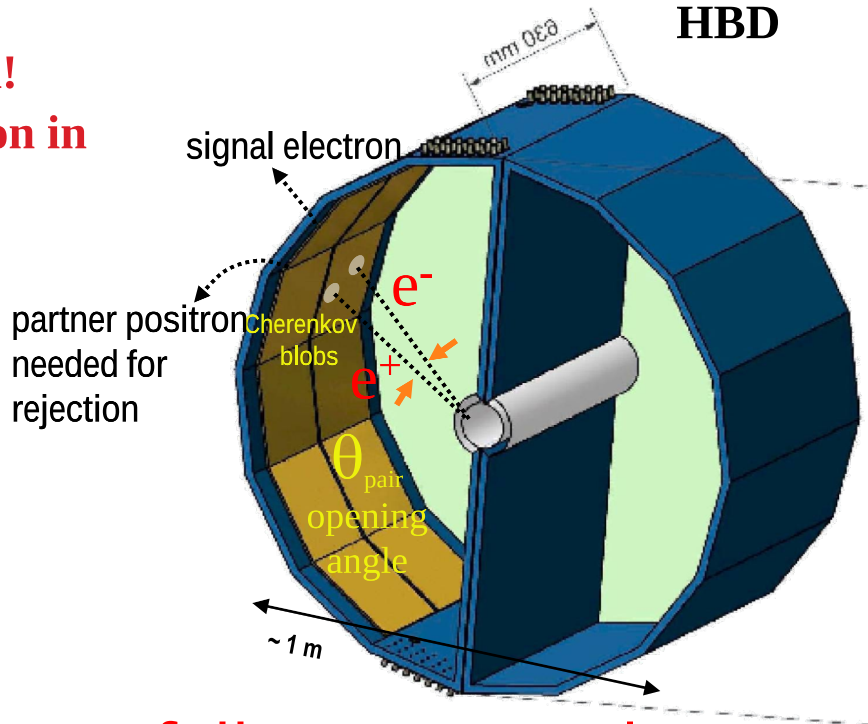




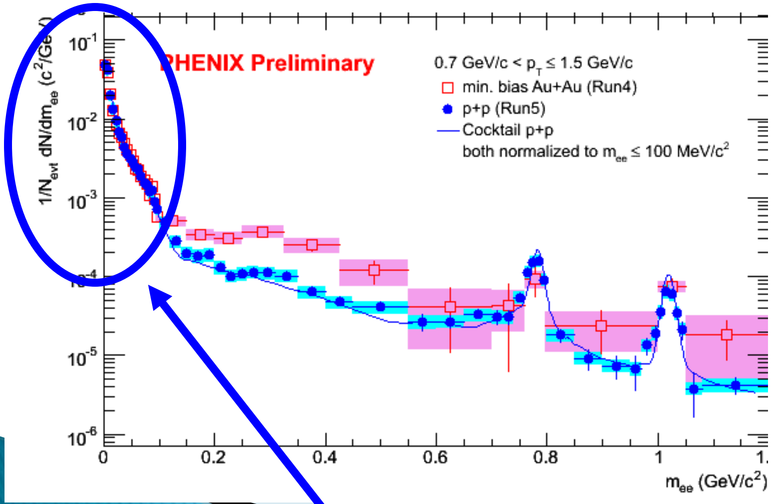
- Heavy Flavor shows suppression similar to π^0 at fill RHIC Energy.
- Heavy Flavor even flows.
- These results are the principal ones that define η/s.
- Similar conclusion for muons from CuCu: suppression similar to π

Future of the Continuum at RHIC

- Open experimental issues
  - **Large combinatorial background prohibits precision measurements in low mass region!**
  - **Disentangle charm and thermal contribution in intermediate mass region!**



Need tools to reject photon conversions and Dalitz decays and to identify open charm

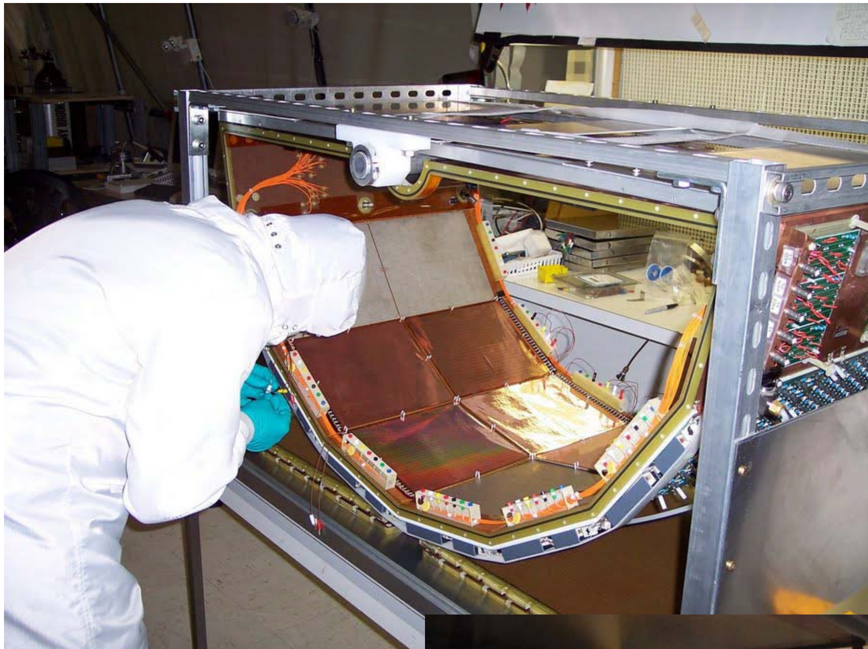


False combinations dominated by region where yield is largest

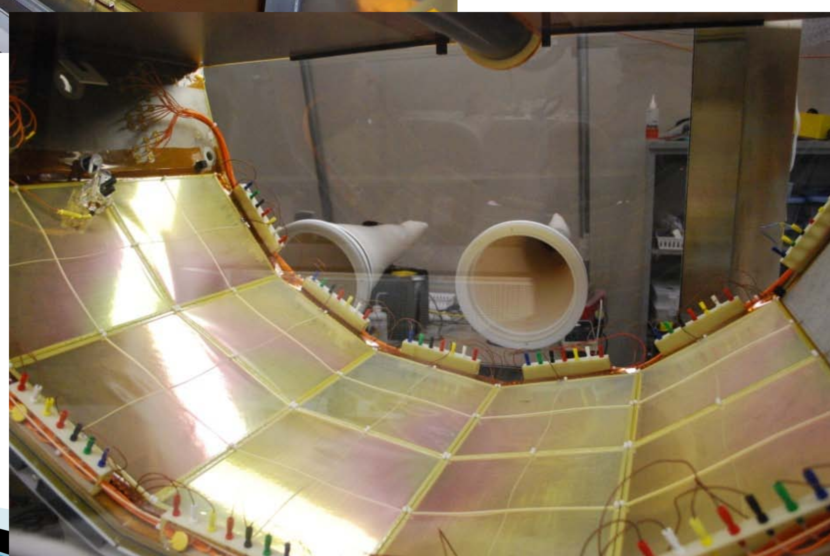
- HBD is fully operational
  - Proof of principle in 2007
  - Taking data right now with p+p
  - Hope for large Au+Au data set in 2010

HBD Construction

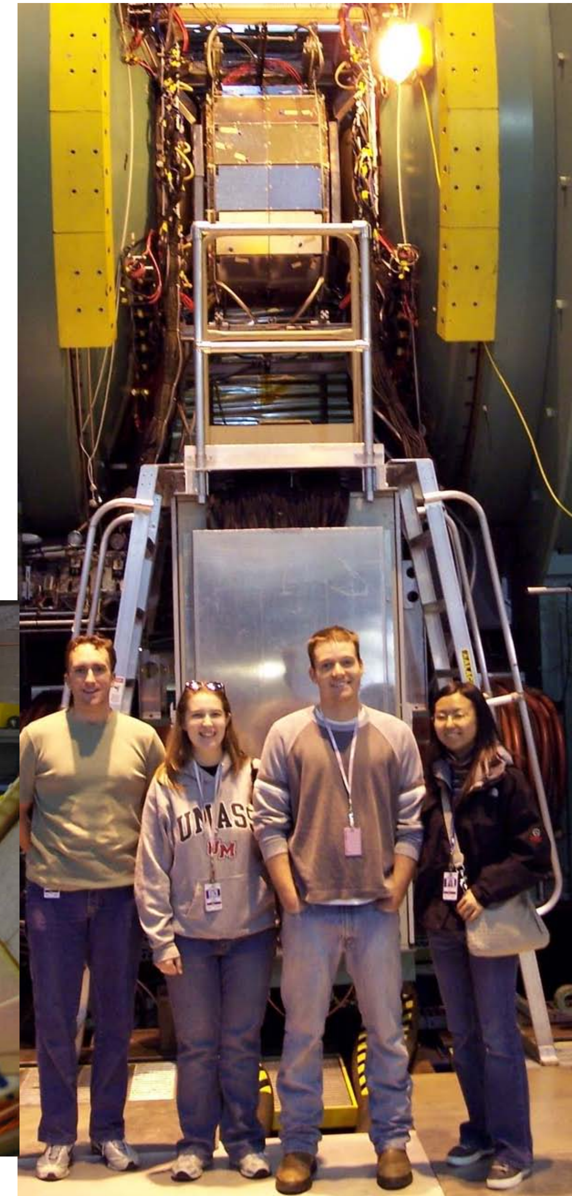
“Standard” CERN Cu GEM foils in HBD



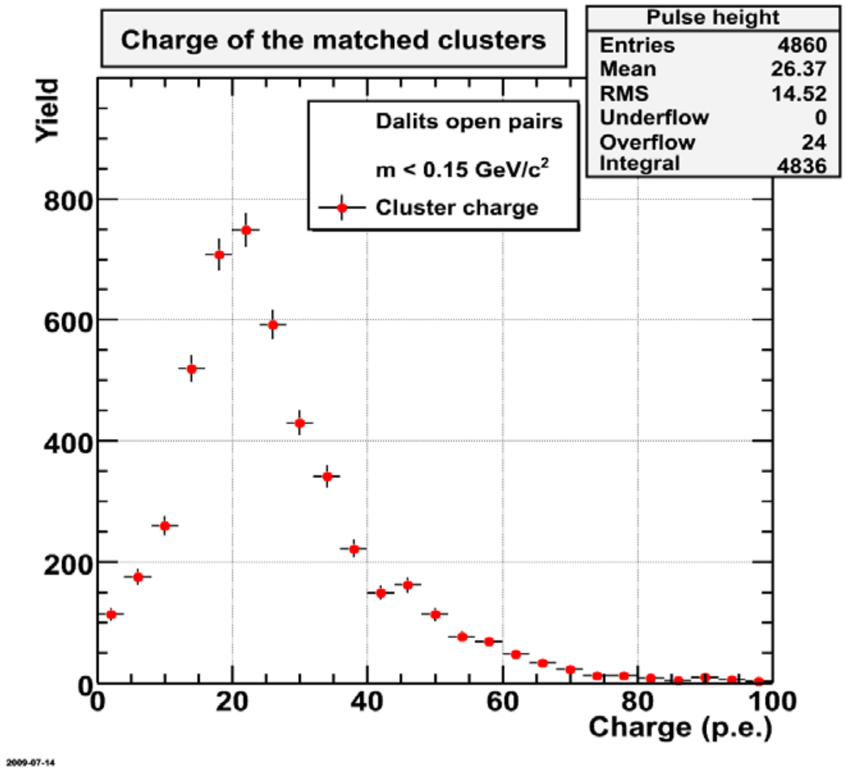
CSI photocathods on GEM foils

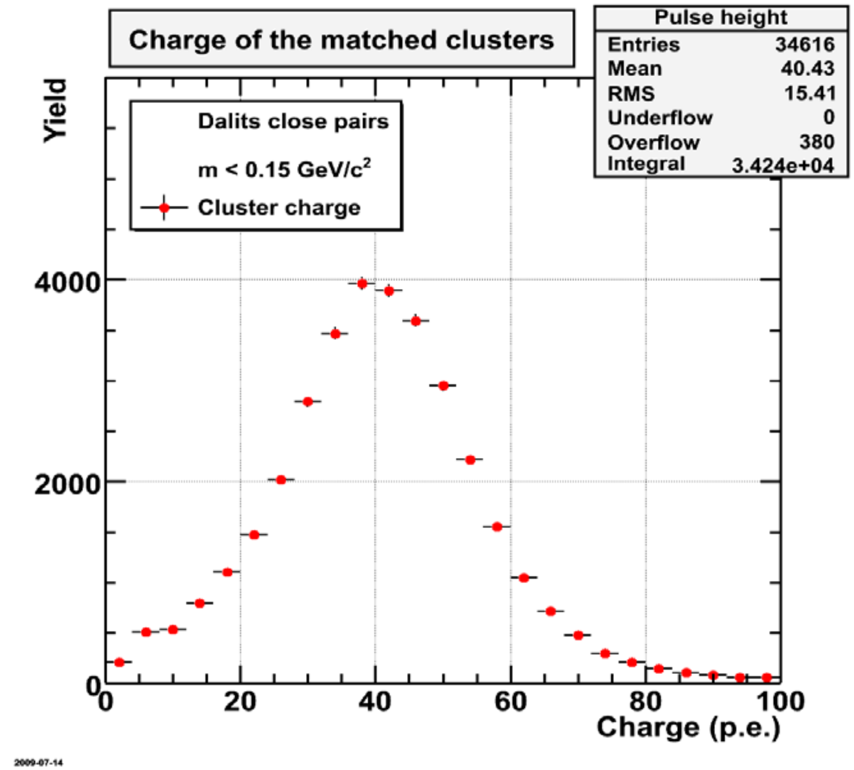


2nd HBD installed in PHENIX



Single and Double Response



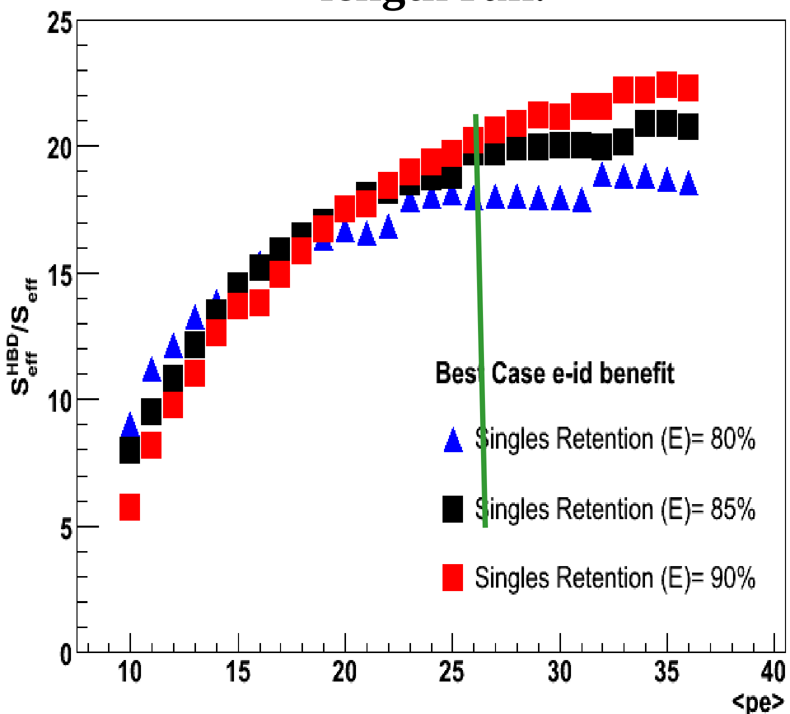


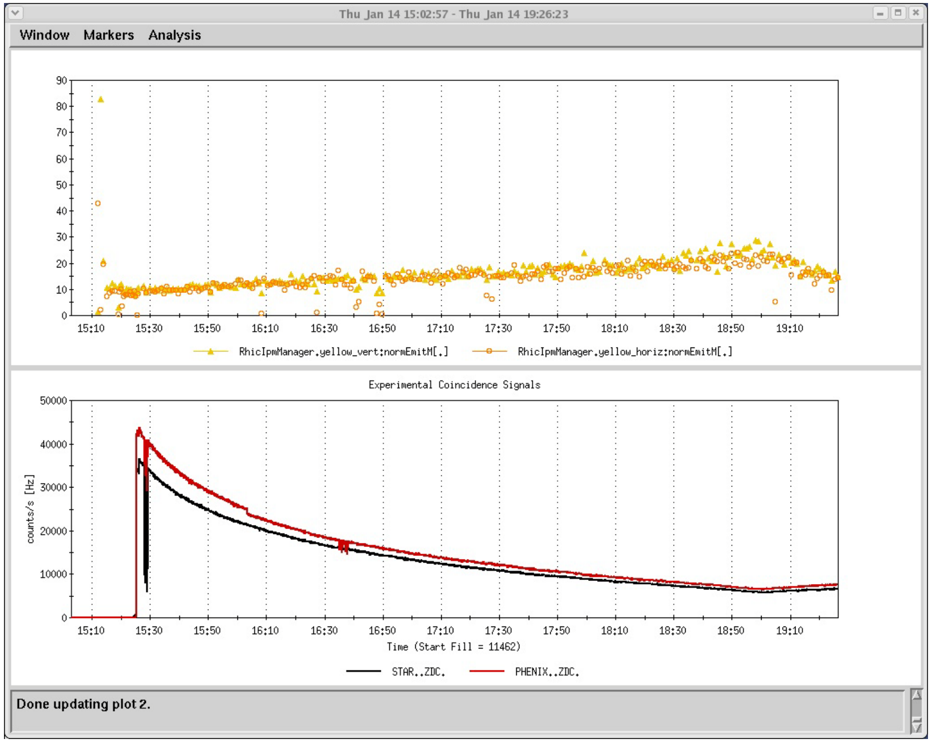
- Using low mass pairs, one can select a sample with large opening angle (isolated) or small opening angle (overlapping)
- The responses are 20 p.e. & 40 p.e. respectively. (WOW!)

Compared to Run 4 Results

$$\frac{1}{\sqrt{S_{eff}}} = \frac{\sqrt{\sigma_{stat}^{1} + \sigma_{sys}^{2}}}{S} = \frac{\sqrt{(\sqrt{S+BG})^2 + (BG \times \sqrt{\sigma_{LikeSign}^{2} + (0.2\%)^2})^2}}{S}$$

Improvement of effective Signal vs <Npe> for same length run.

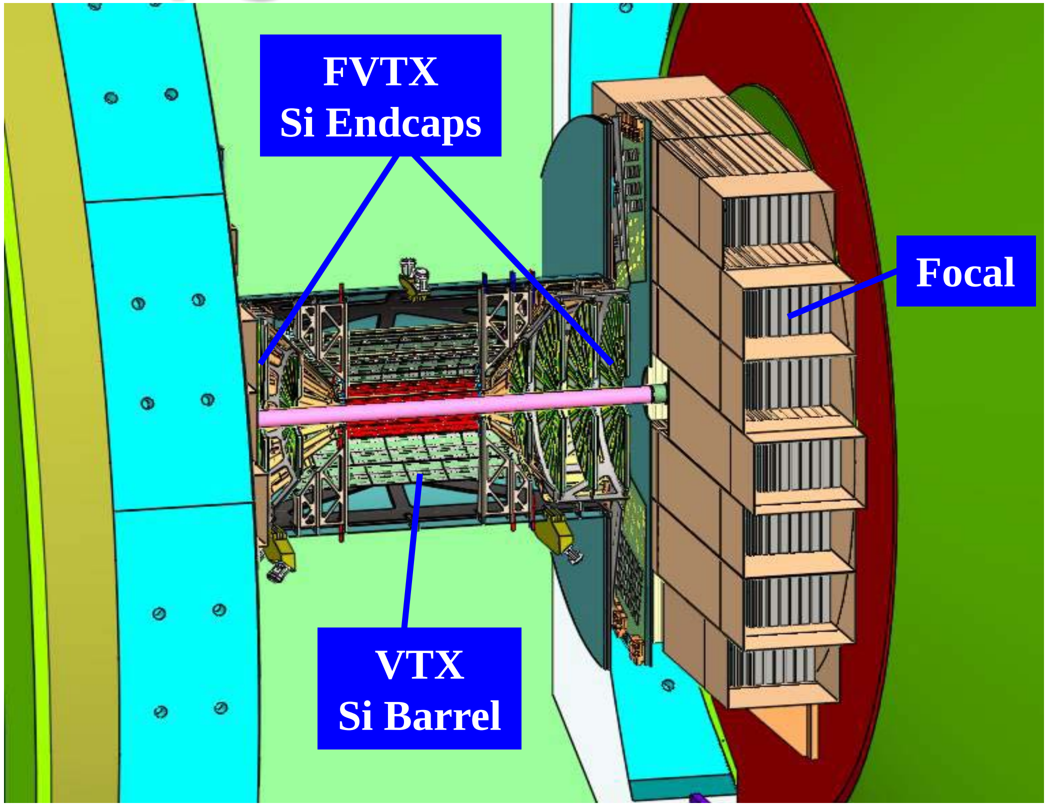




Stochastic Cooling at RHIC

Effective statistics increased at least by factor 32
→ errors reduced by factor 5.6 – 8.5

PHENIX Upgrades @ Vertex



VTX, FVTX and NCC add key measurements to RHIC program:

Heavy quark characteristics in dense medium

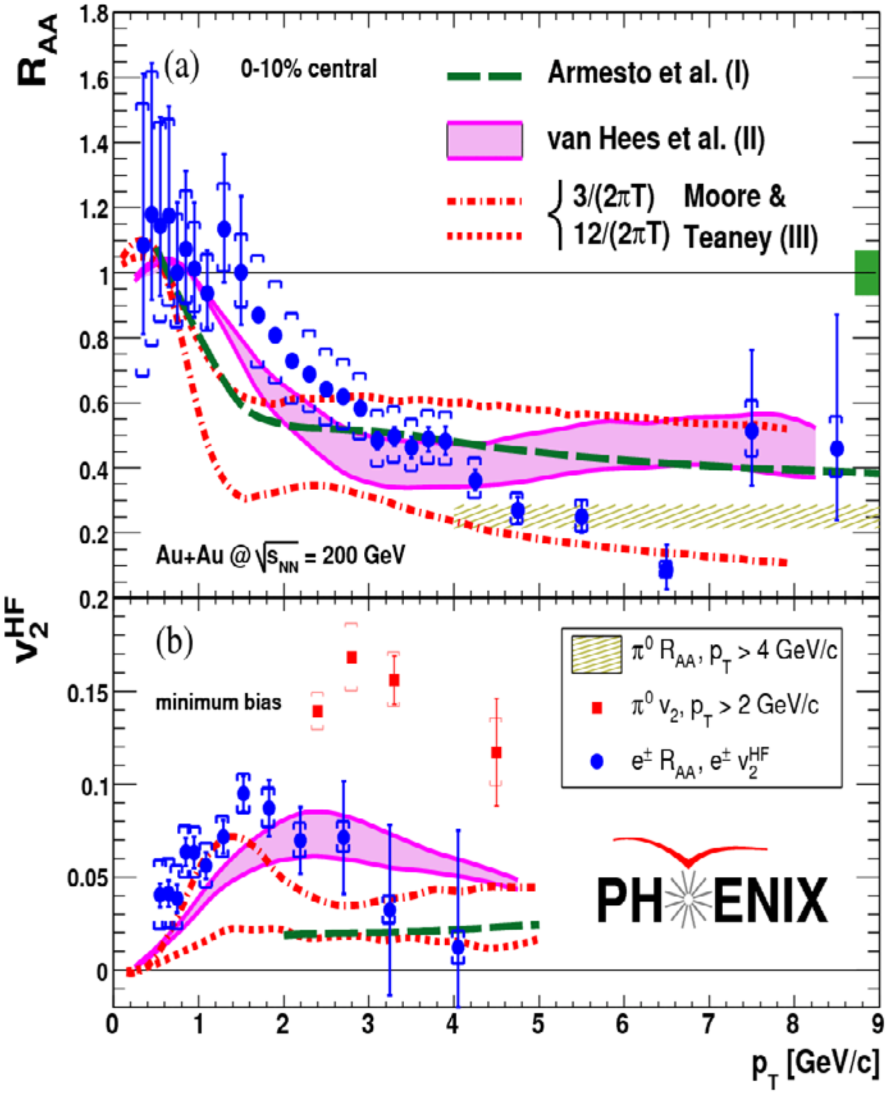
Charmonium spectroscopy (J/ψ, ψ' , χ_c and Υ)

Light qurak/gluon energy loss through γ-jet

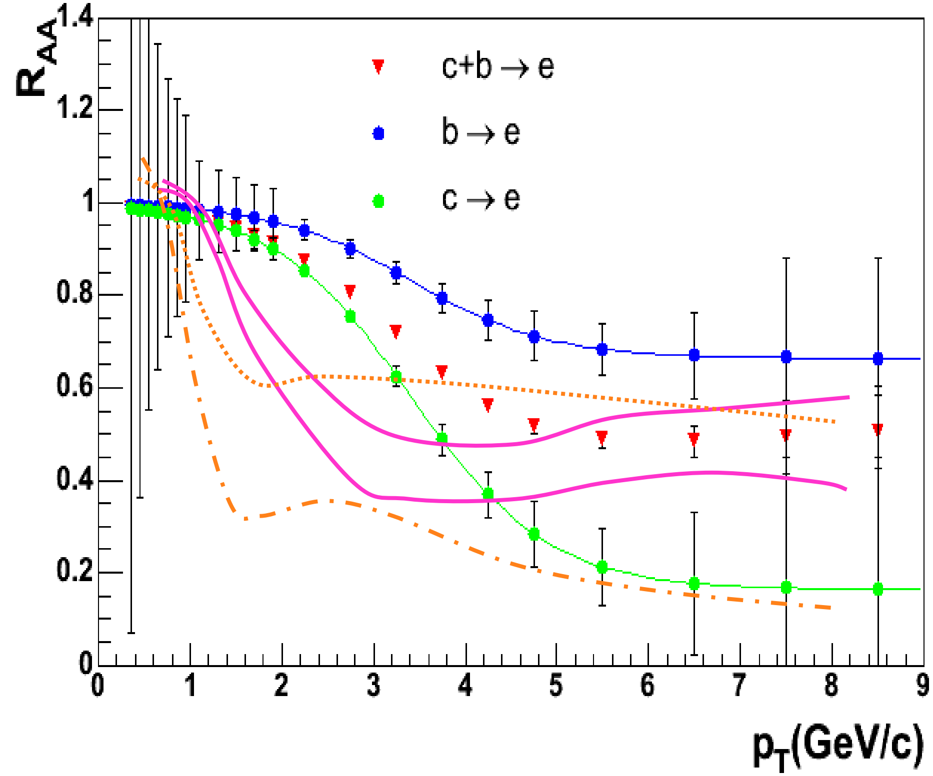
Gluon spin structure ($\Delta G/G$) through γ-jet and c,b quarks

A-, p_T-, x-dependence of the parton structure of nuclei

$R_{AA}(c \to e)$ and $R_{AA}(b \to e)$ with VTX



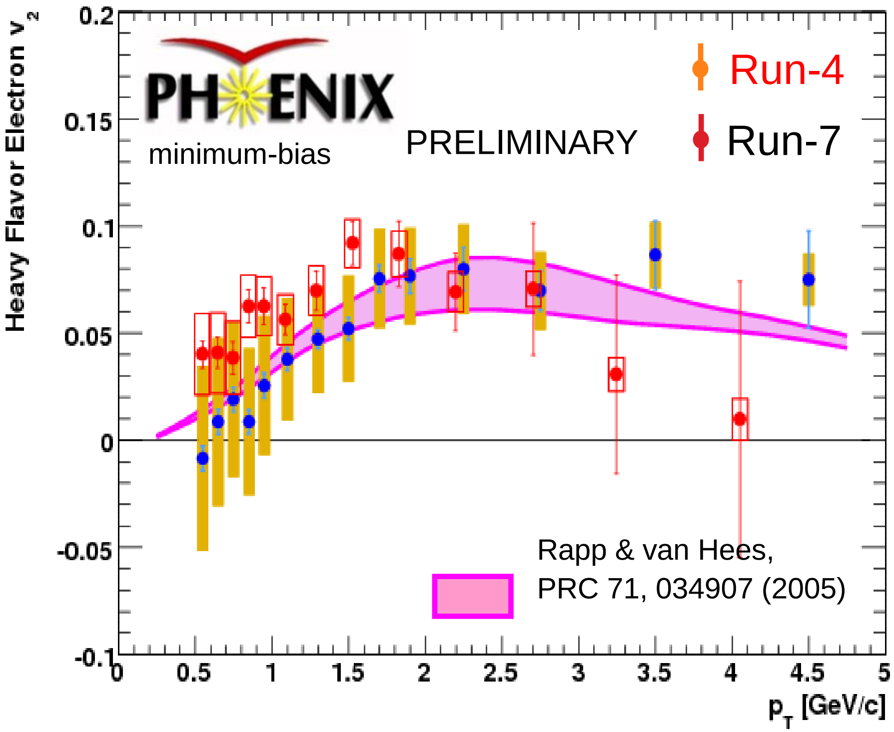
PHENIX VXT ~2 nb^{-1}

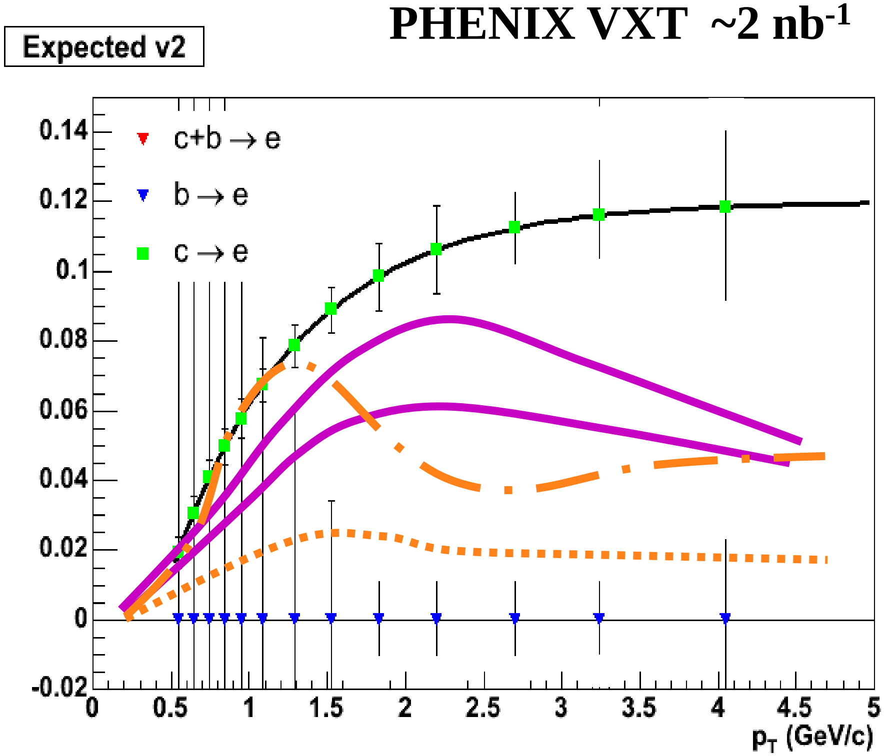


RHIC II increases statistics by factor >10

Decisive measurement of R_{AA} for both c and b

$v_2(b \to e)$ and $v_2(c \to e)$ with VTX

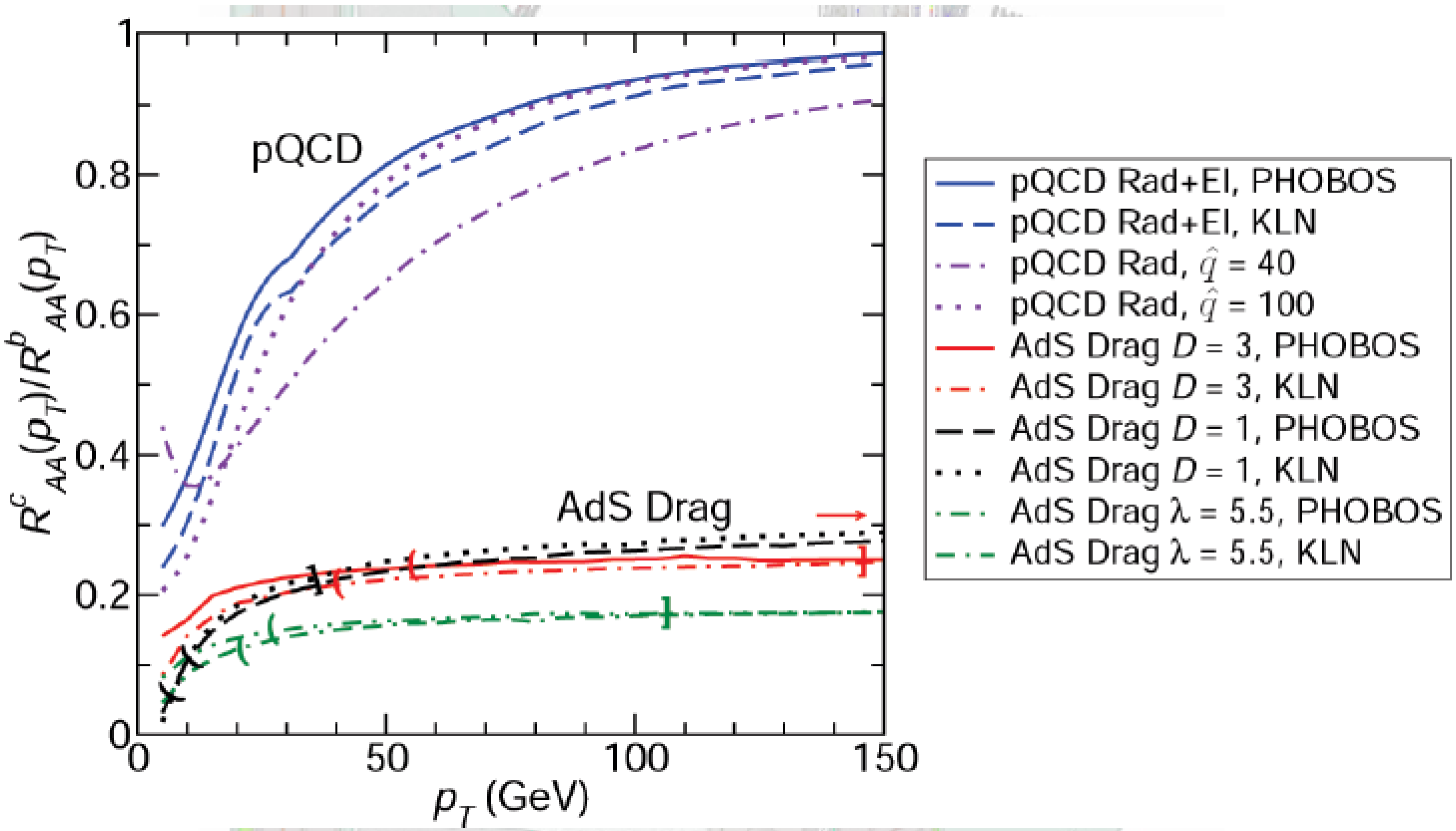




RHIC II increases statistics by factor >10

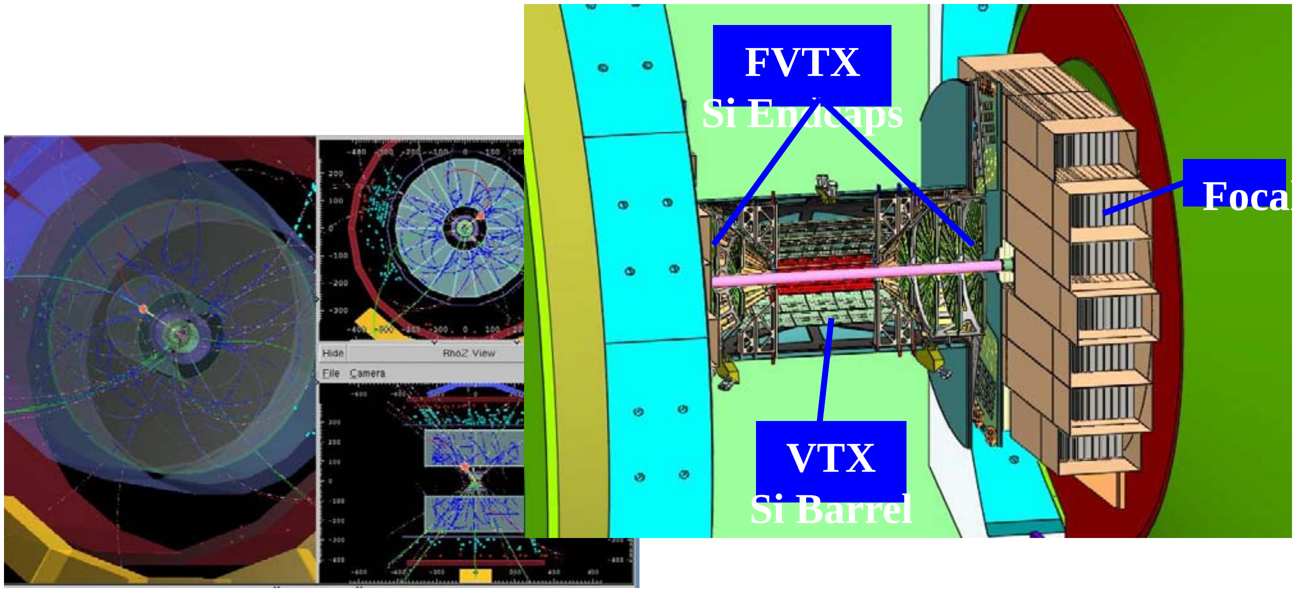
Decisive measurement of v_2 for both c and b

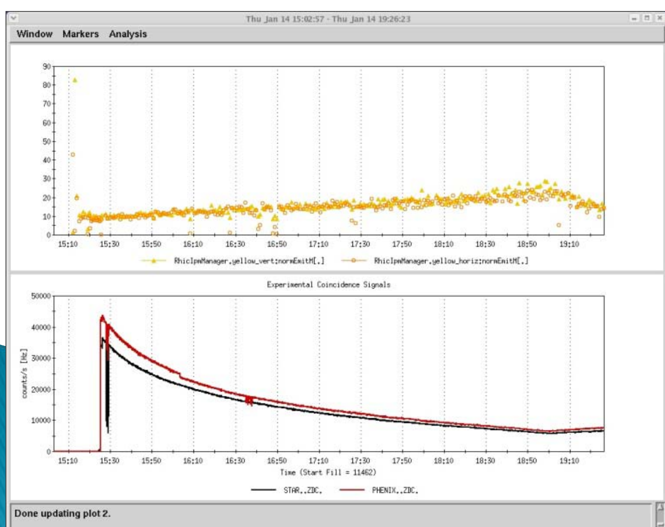
Importance of c/b Separation

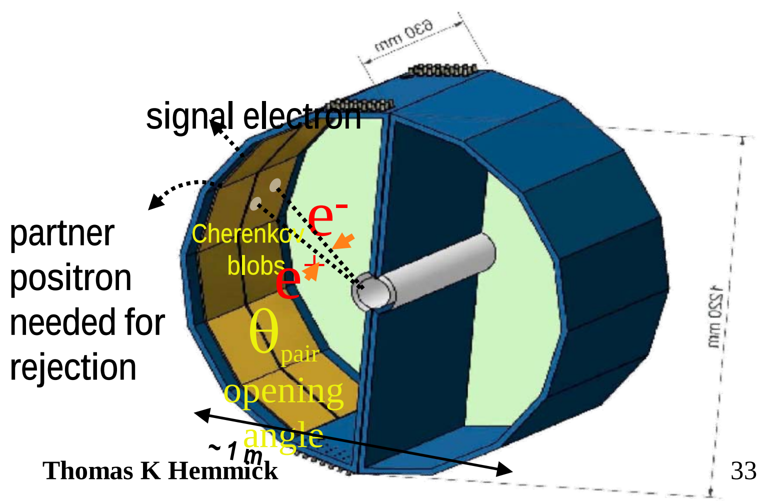


- Immovable Object – Irresistable Force Problem.
- I’m again rooting for the immovable object!

Future Looks Bright!





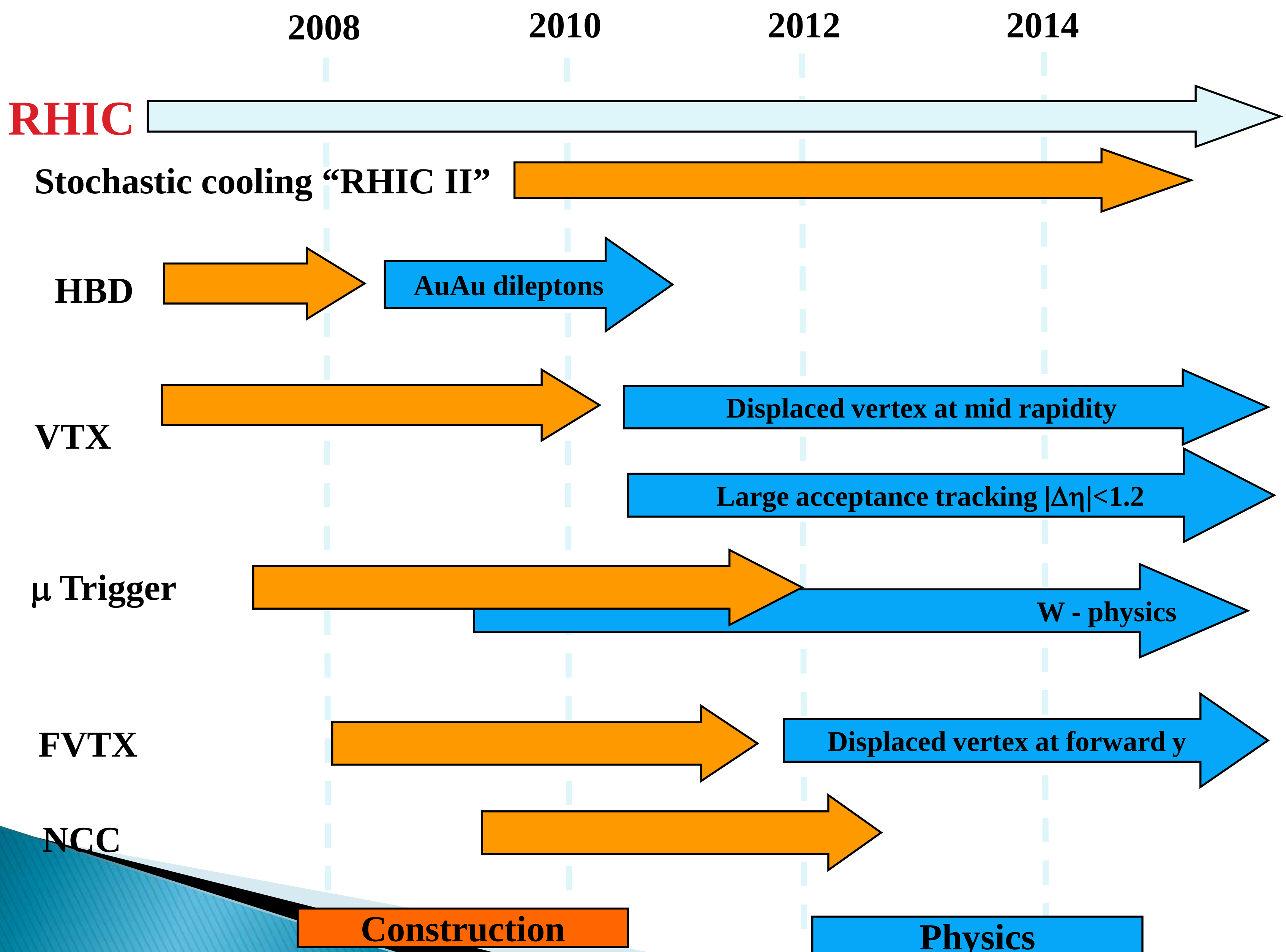


Summary

- PHENIX results on dielectrons reveal a wealth of information:
  - Normalization of cocktail
  - Correlated charm
  - Correlated bottom
  - Low Mass Enhancement (primarily at low p_T)
  - Direct Virtual Photons
- Results will be dramatically improved by use of the HBD during Run-10.
  - Practical for 200, 62.4, ~39, (27) GeV.
  - Impractical below these energies before RHIC II.
  - However, detector will be removed prior to Run-11.
- PHENIX results on single leptons show that:
  - Heavy flavor is modified at high $p_{T.}$
  - Heavy Flavor Flows.
  - Effects may (need more stats) vanish by 62.4 GeV
- VTX & FVTX upgrades will dramatically improve heavy flavor capabilities and allow individual tagging of leptons from heavy flavor decay.

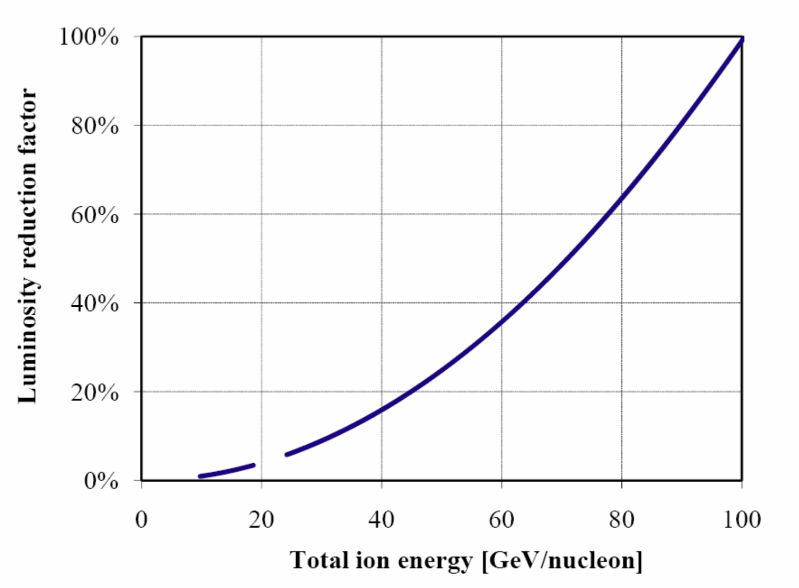
- Backups…

Timeline of PHENIX Upgrades



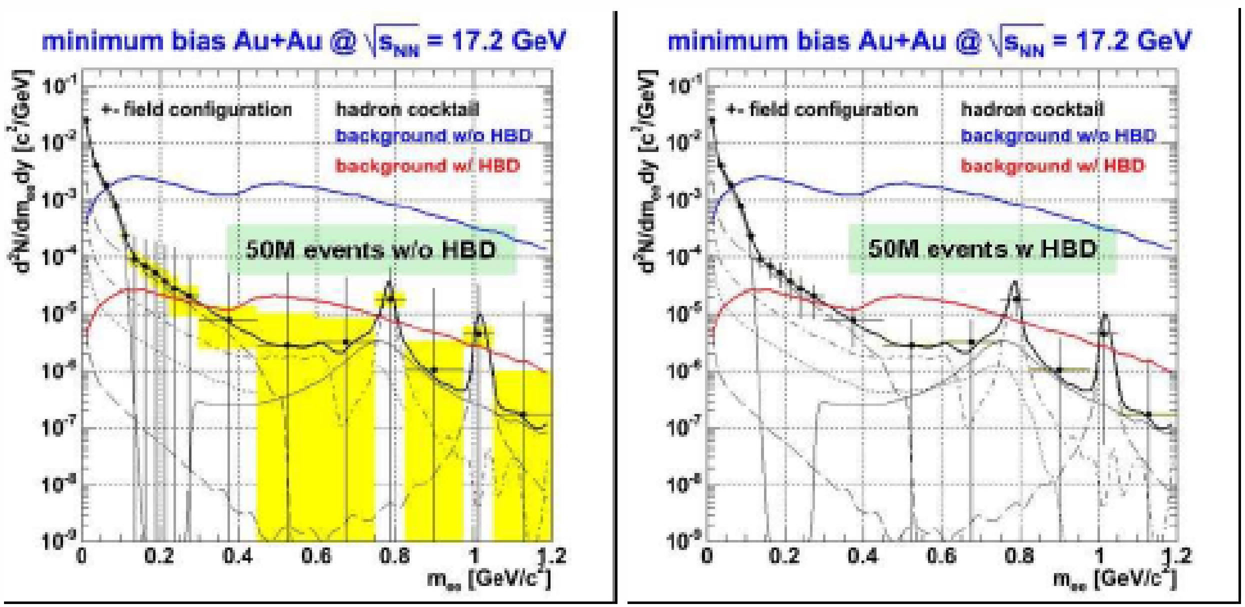
Examining these signatures at finite μ_B

μ_B	$\sqrt{s_{NN}}$
550	5
470	6.3
410	7.6
380	8.8
300	12.3
220	18
150	28
75	60



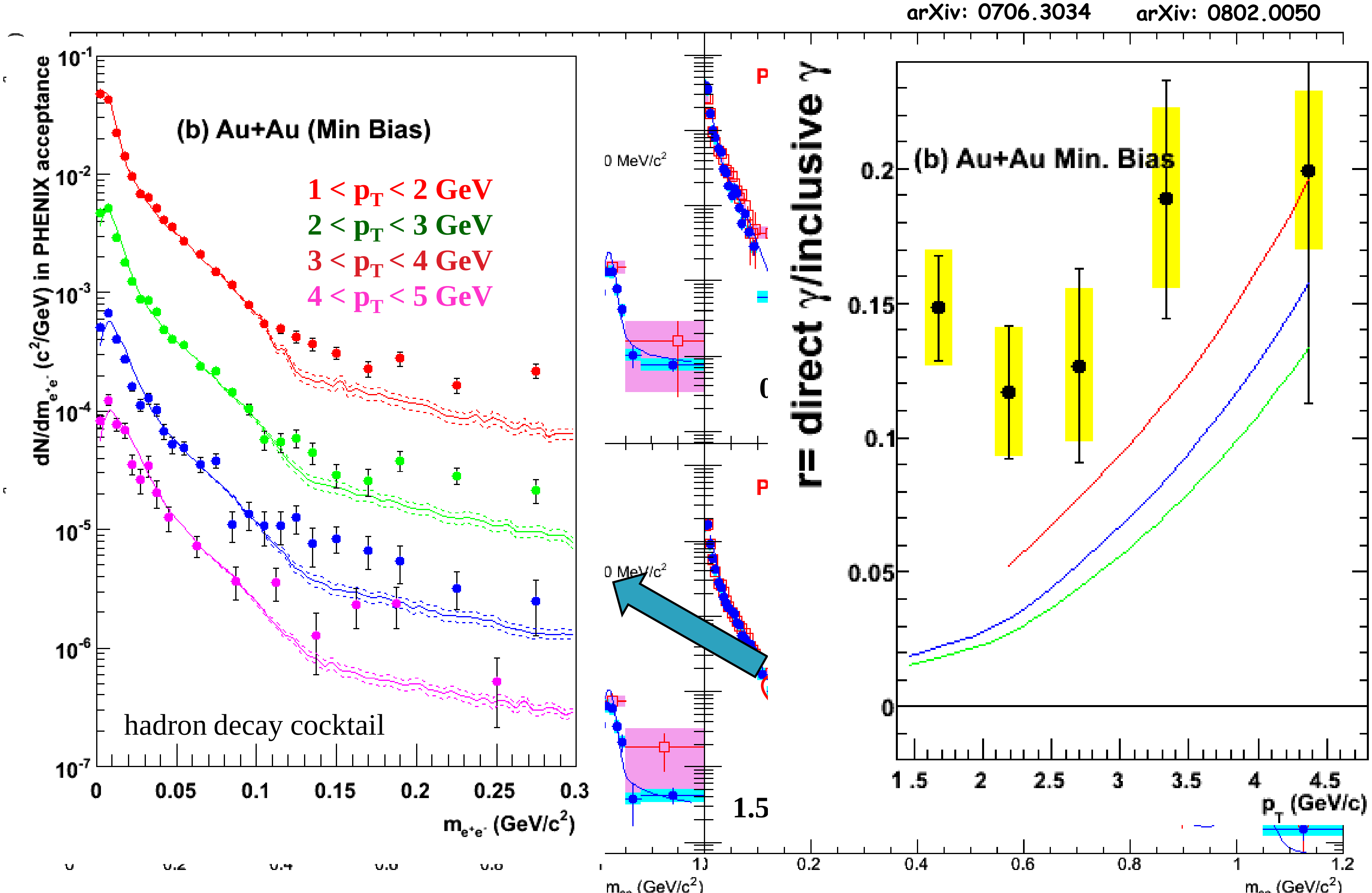
- Critical Point and the Onset of Deconfinement studies necessarily involve lowering the beam energy in the machine.
- Luminosity scales as the square of beam energy.
- Furthermore, heavy quarks suffer in production rate at lower energies.
- The product of these factors limits all present RHIC experiment capabilities, but will be offset by future efforts:
  - Stochastic Cooling for high energy running.
  - E-beam cooling (3-6 X) for below 10.7 GeV running.

Dielectron Capabilities at low Energy



- With the inclusion of the HBD, PHENIX could get a marginal measurement for energies as low as 17.2 GeV w/ 50 M-evts
- However(!!!), the rate of collisions at this low energy makes the collection time for 50 million evts prohibitively long.
  - Practical di-electron measurements are at 62.4 & ~39 GeV.
  - Marginal measurements available at 27 GeV.
  - Impractical due to running time at lower energy.

Dilepton Excess at High p_T – Small Mass



Significant direct photon excess beyond pQCD in Au+Au

Interpretation as Direct Photon

Relation between real and virtual photons:

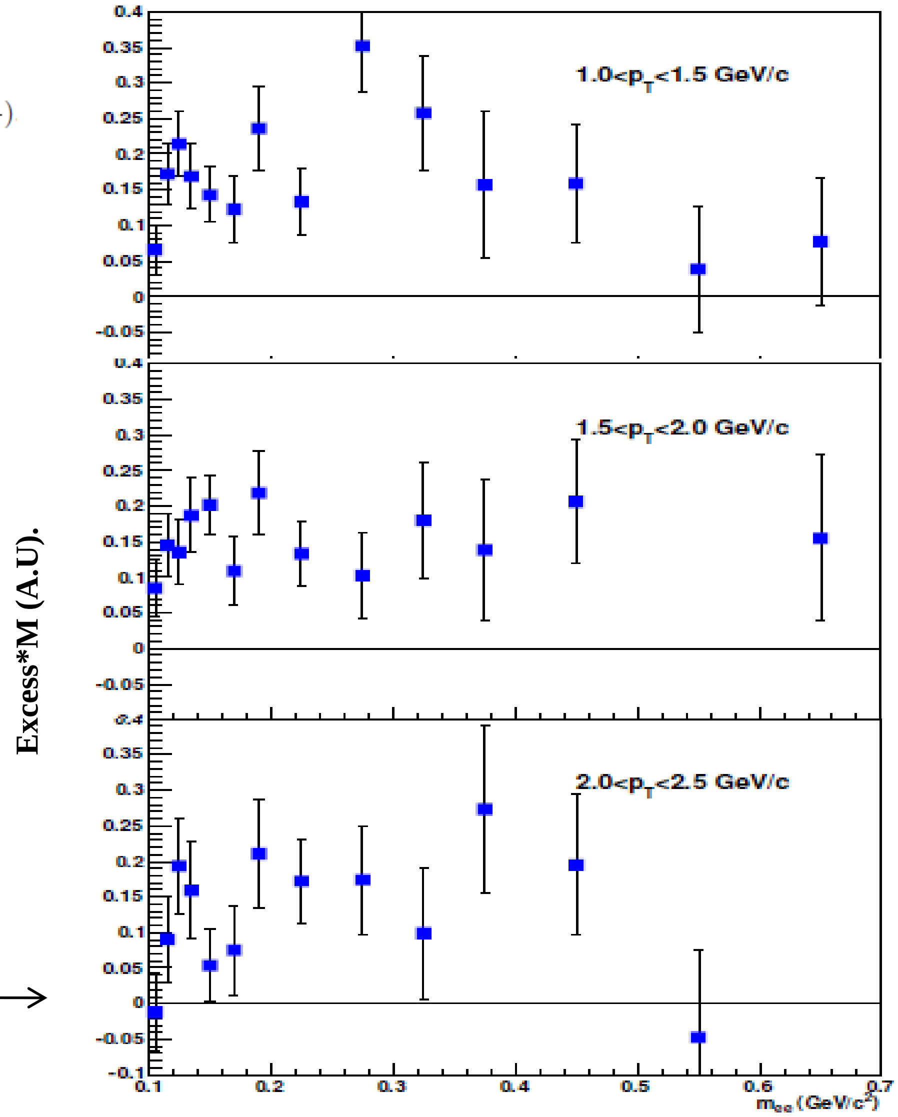
$$L(M) = \sqrt{1 - \frac{4m_l^2}{M^2}}\left(1 + \frac{2m_l^2}{M^2}\right)$$

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

Extrapolate real γ yield from dileptons:

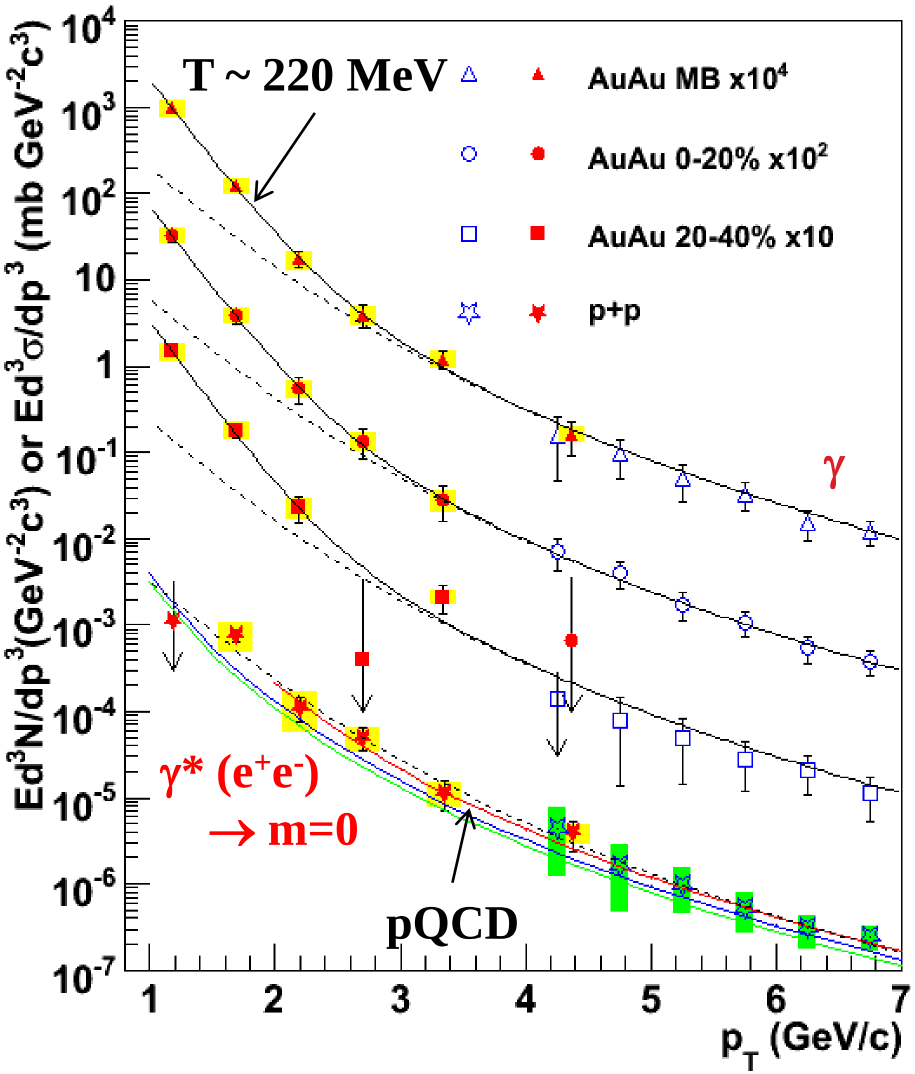
$$M \times \frac{dN_{ee}}{dM} \rightarrow \frac{dN_\gamma}{dM} \quad \text{for} \quad M \rightarrow 0$$

Virtual Photon excess
At small mass and high p_T
Can be interpreted as
real photon excess



no change in shape
can be extrapolated
to m=0

First Measurement of Thermal Radiation at RHIC



Direct photons from real photons:

- Measure inclusive photons
- Subtract π^0 and η decay photons at S/B < 1:10 for p_T<3 GeV

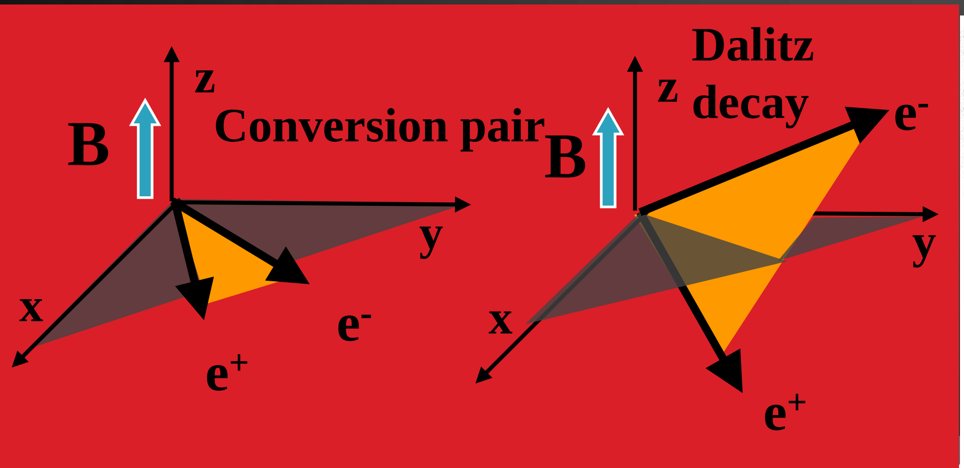
Direct photons from virtual photons:

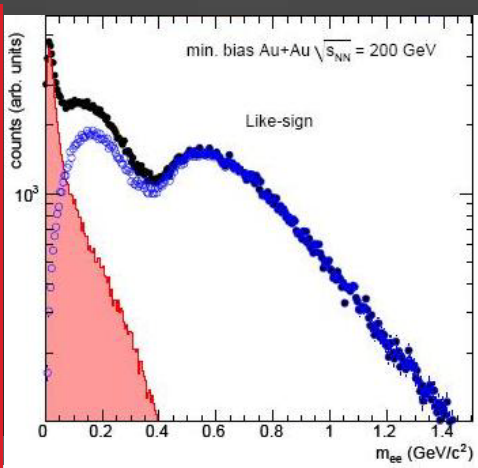
- Measure e^+e^- pairs at $m_\pi < m << p_T$
- Subtract η decays at S/B ~ 1:1
- Extrapolate to mass 0

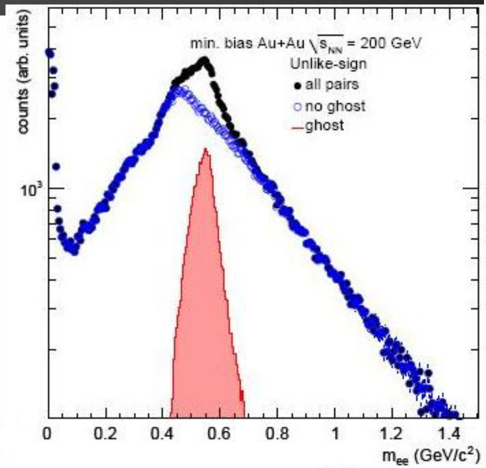
First thermal photon measurement:
T_{ini} > 220 MeV > T_C

False Pair Rejection

- Conversion Pairs
  - Opening angle in the plane perp. to B field
    - Charges ordered by B field
  - Mass of the pair is roughly proportional to the radius of the conversion point
- Overlapping Pairs
  - RICH ring overlap
  - Require pairs are separated by twice the nominal ring size

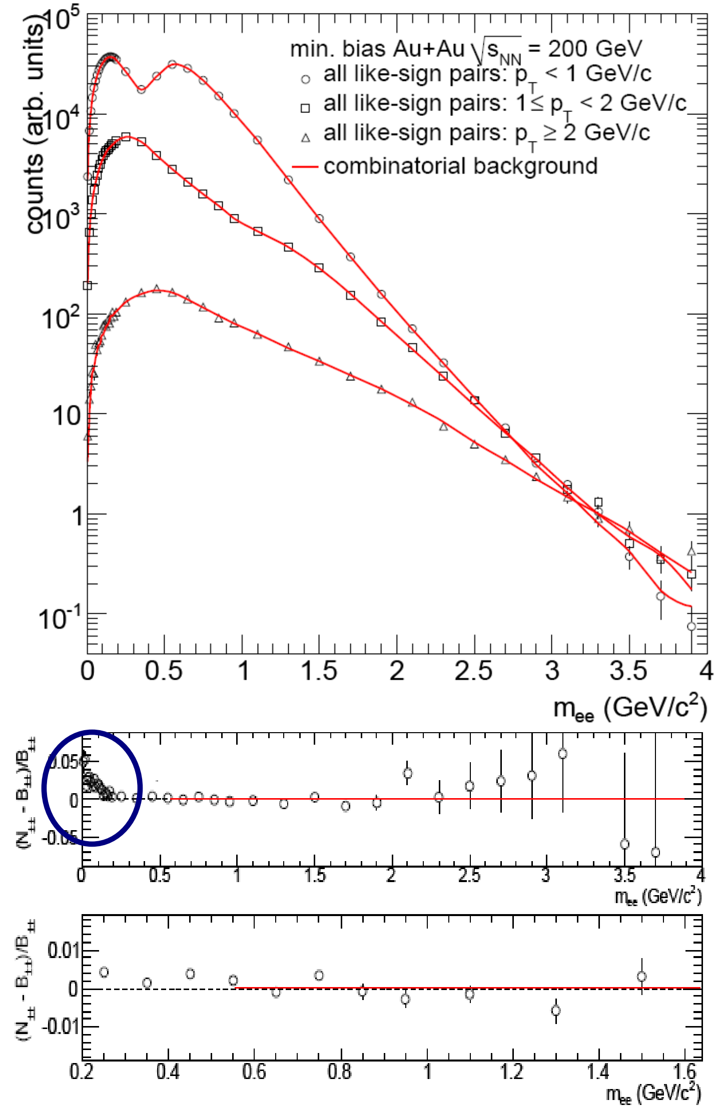






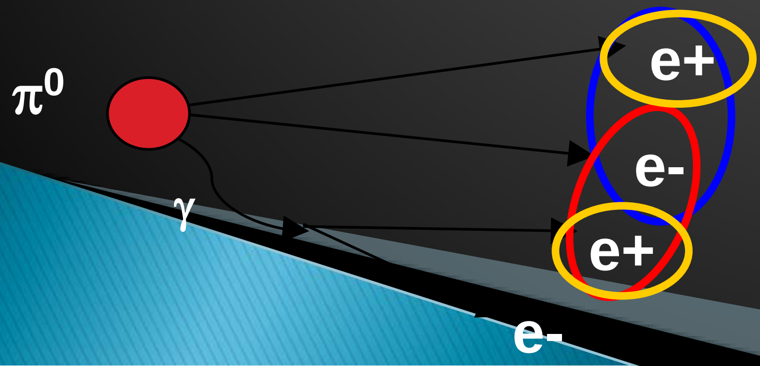
Combinatorial Background

- Largest background in heavy ions
  - Large multiplicities
- Shape determined by event mixing
- Normalization determined using the like-sign pairs in regions where combinatorial dominates

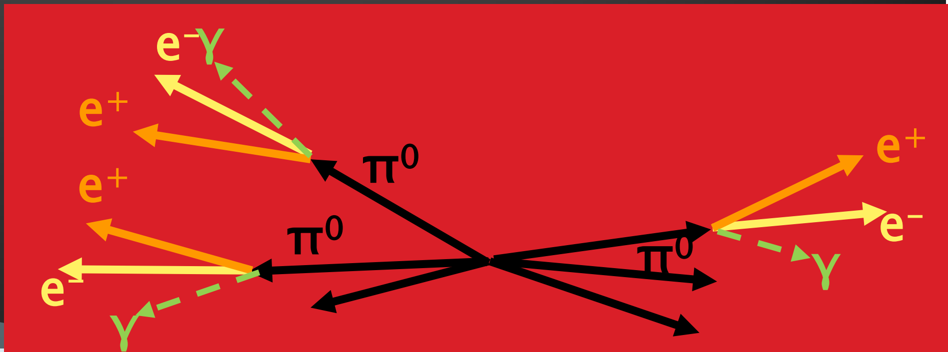


Correlated Background

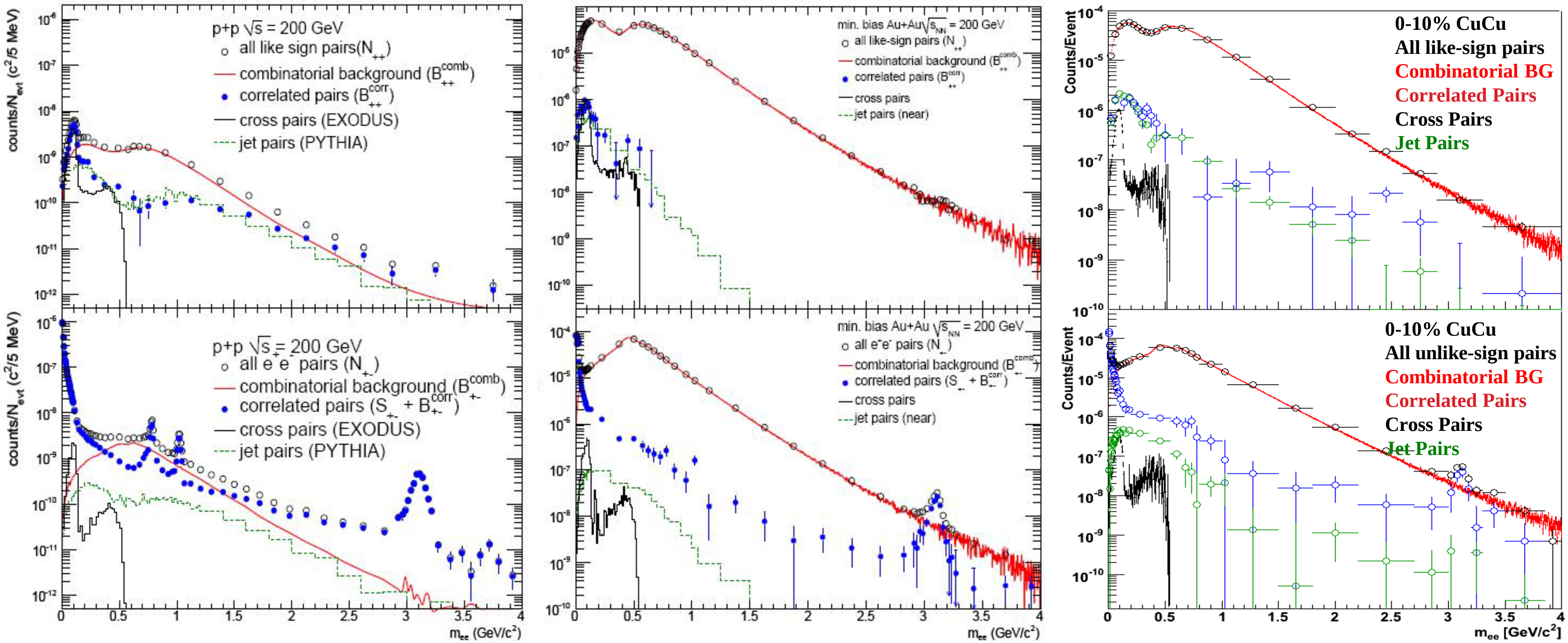
- "Cross" pairs
  - Decays that produce multiple lepton pairs
    - Double dalitz, double conversion, dalitz + conversion
    - Like-sign and unlike-sign pairs produced at same rate
  - Simulated with Exodus
    - Pions, etas only sizable source



- Jet Background
  - Pions in jets dalitz decay into electrons
    - Produced electron pairs are correlated by the jet
    - Like-sign and unlike-sign pairs produced at same rate
  - Simulated with Pythia



Full Background Removal



- In Cu+Cu and Au+Au jet awayside component (dϕ > 90) altered to account for jet modification in HI systems