Physics from the HBD

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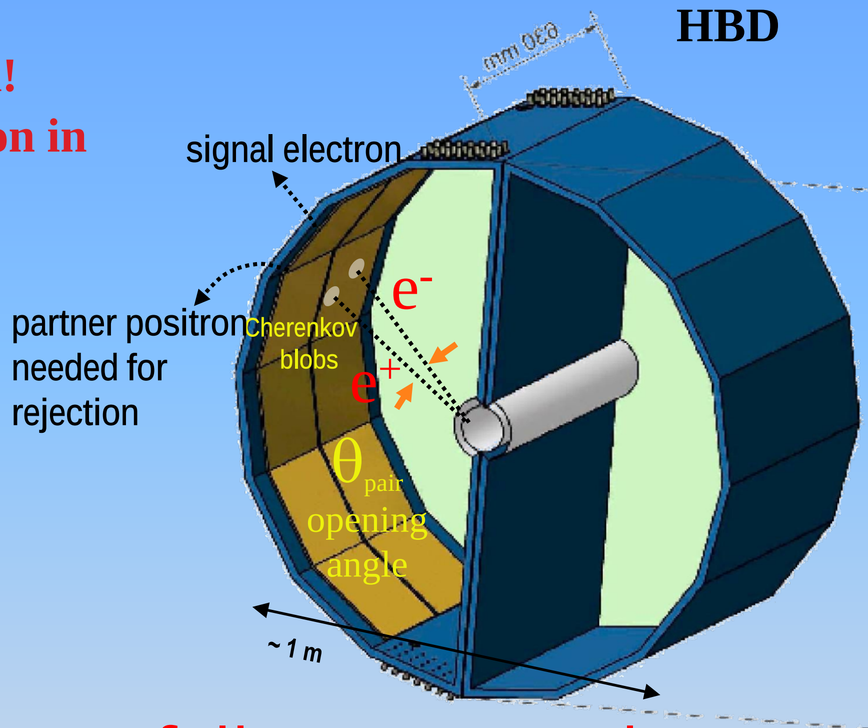
PHENIX Focus

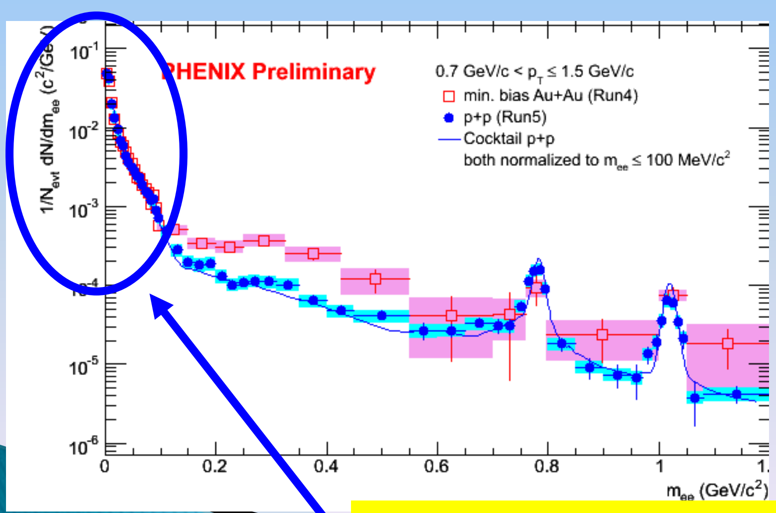
February 16 , 2010

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





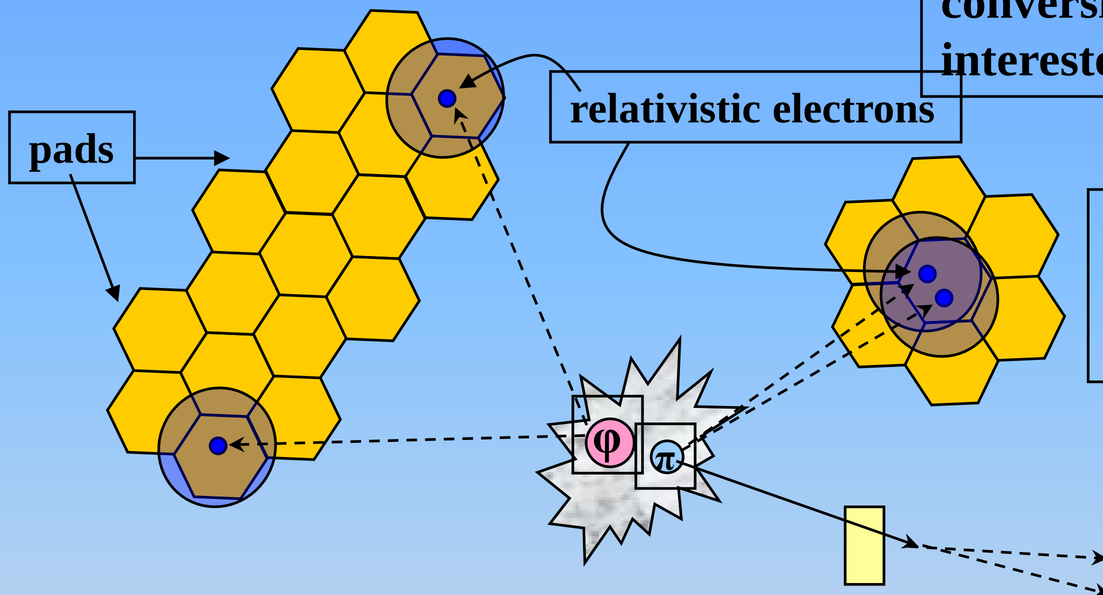
False combinations dominated by region where yield is largest

- 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

Is it a π or a ϕ?

Back to the basics (briefly)…

A lot of particles have e^+e^- decay channels. How can we tell the Dalitz decays and photon conversions apart from the decays that we're interested in??



Dalitz decay electrons have apparent mass from $2m_e \rightarrow m_\pi$ with highest probability near $2m_e$

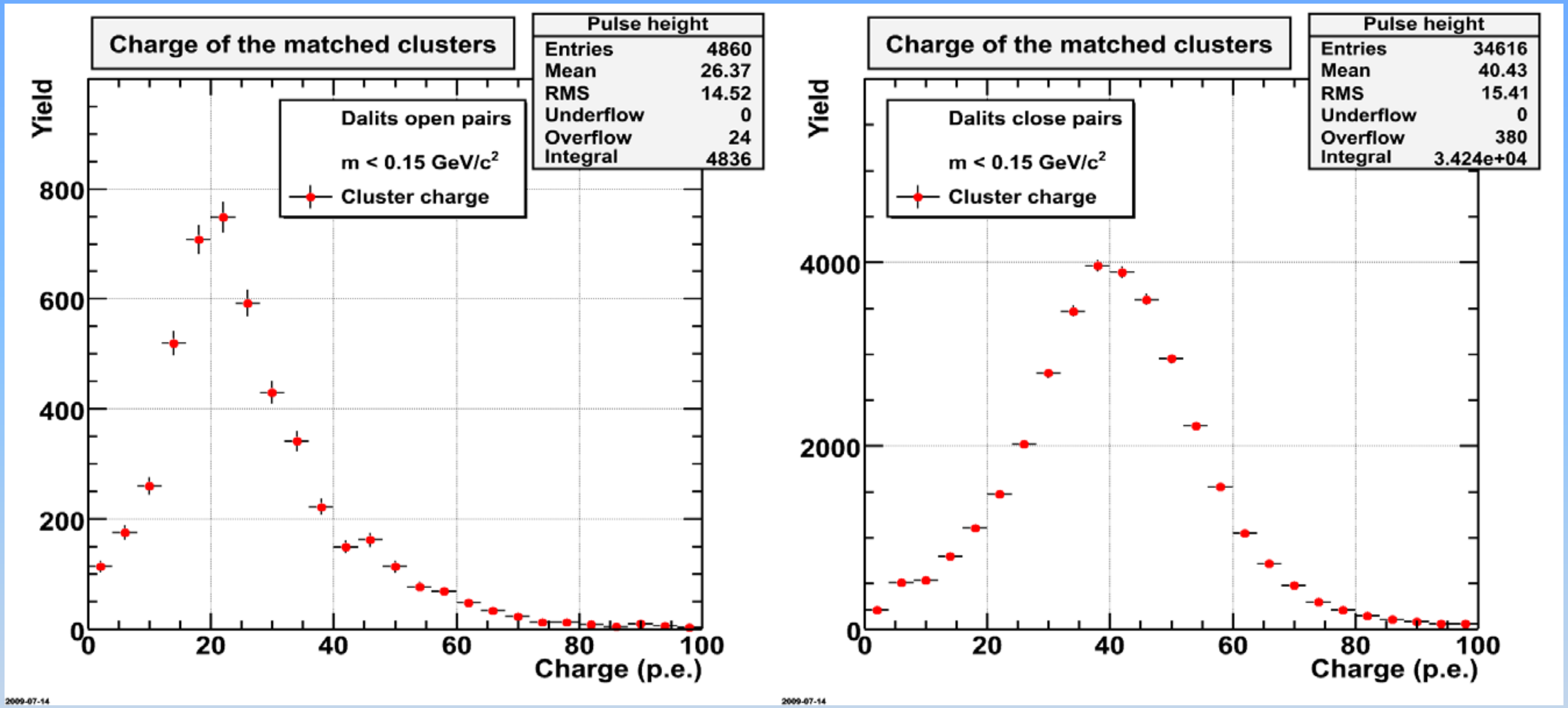
Photon conversions EVEN MORE tightly peaked around $2m_e$

Dalitz and Photon conversions have smaller opening angles!!

How about a Cherenkov Detector???

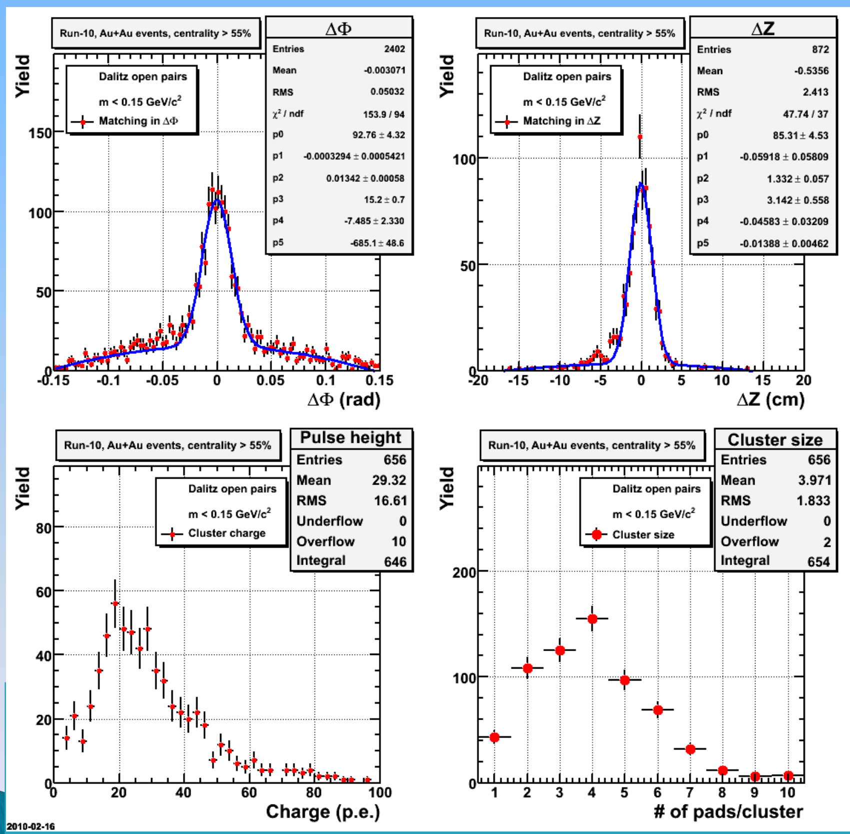
- ID electrons
- give directional information.

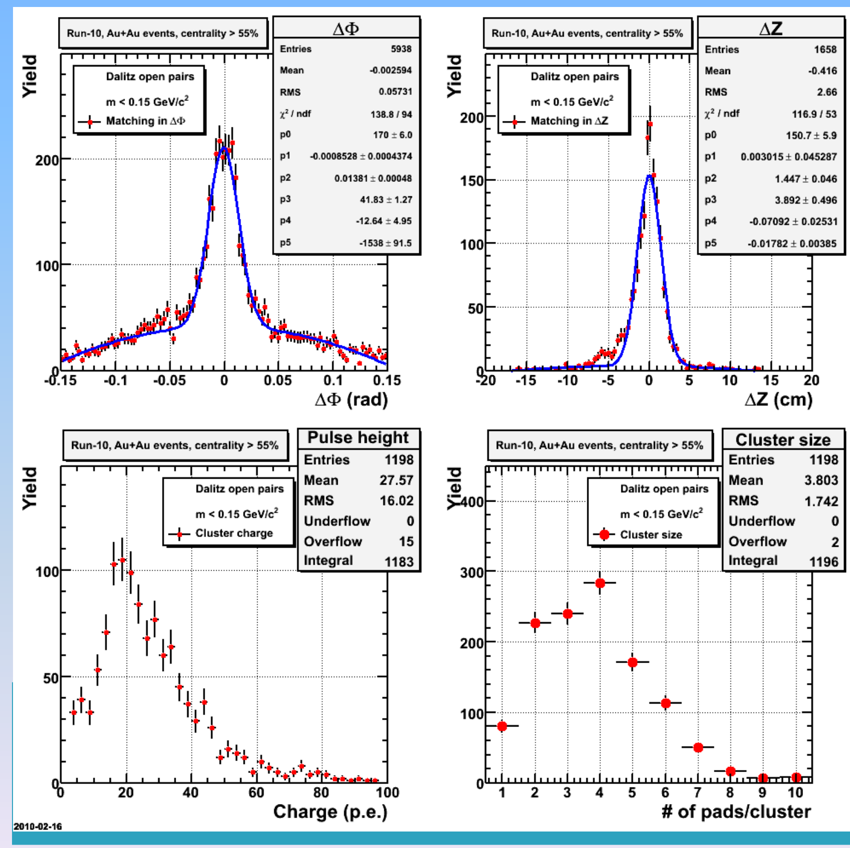
Run9 Single and Double Response



- 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!)

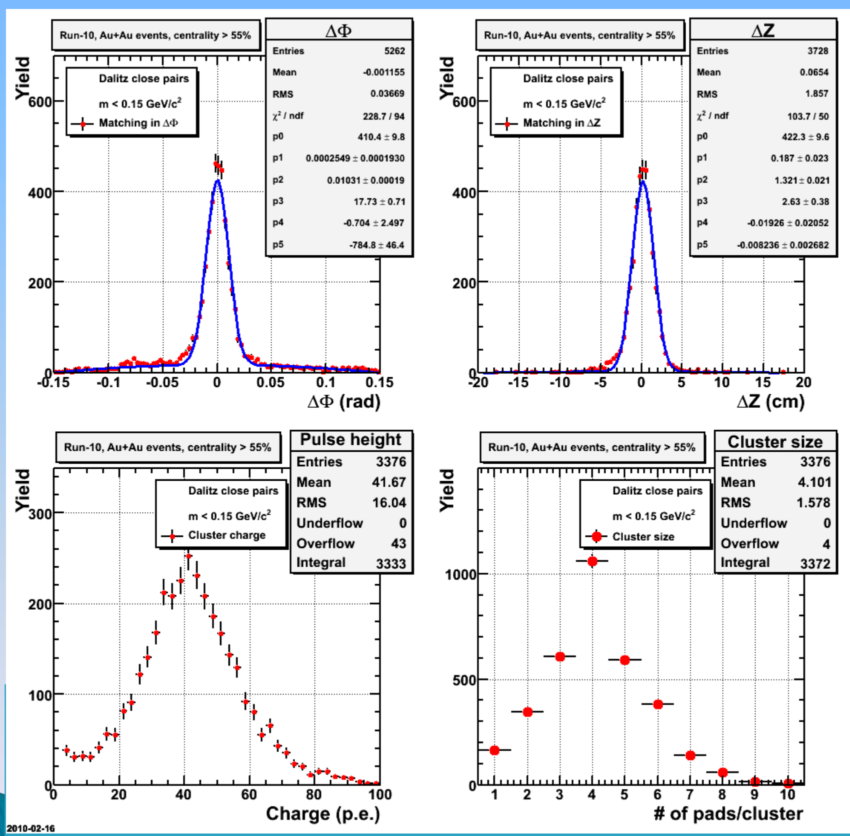
Run10 HBD performance using Dalitz pairs: response from singles

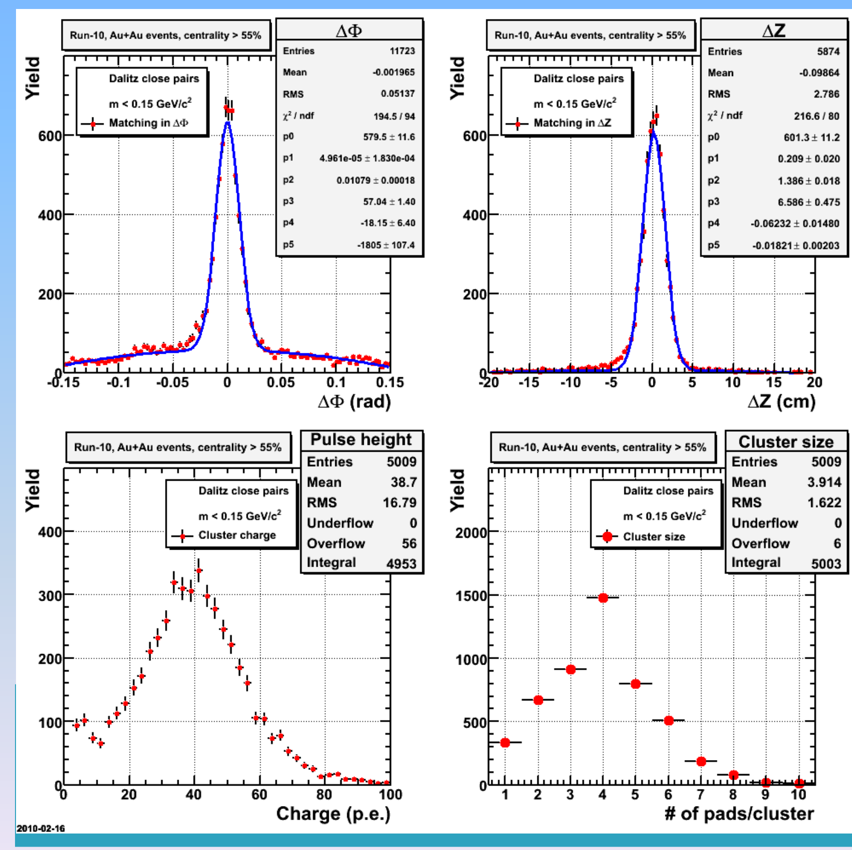




I. Ravinovich

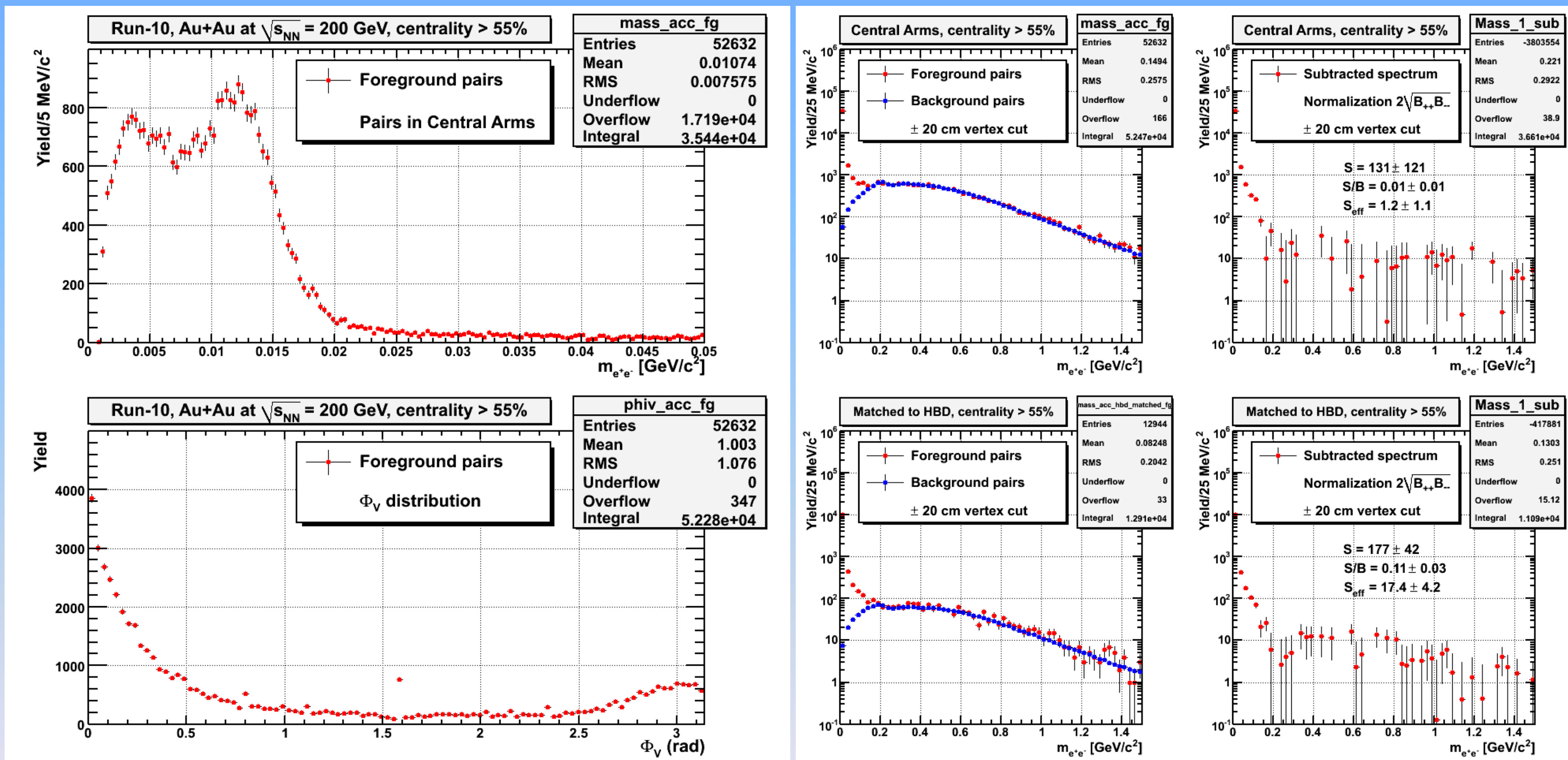
Run10 HBD performance using Dalitz pairs: response from doubles





I. Ravinovich

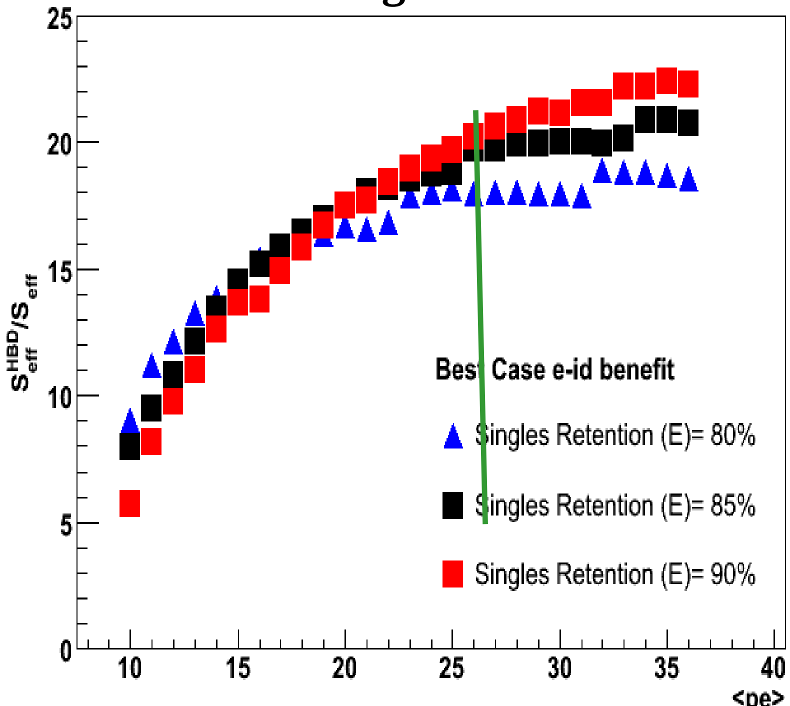
Mass spectra from this sample

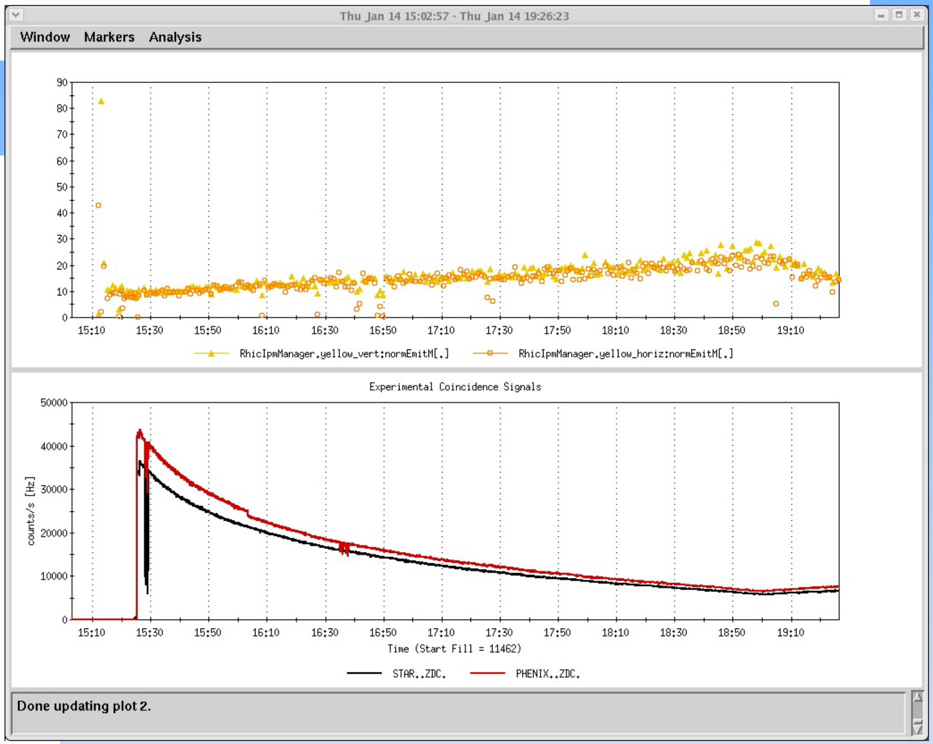


Compared to Run 4 Results

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

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

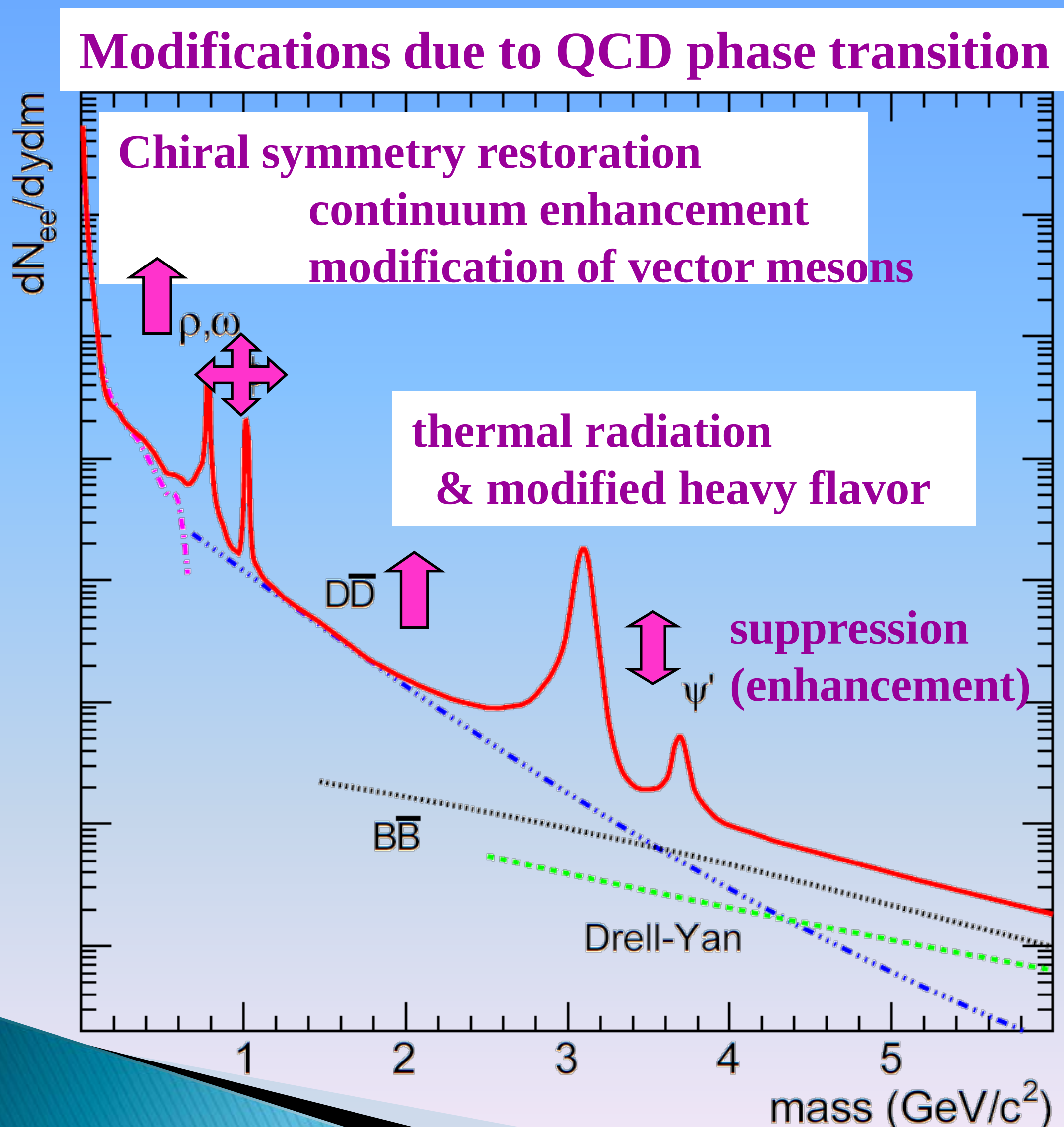




Stochastic Cooling at RHIC

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

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

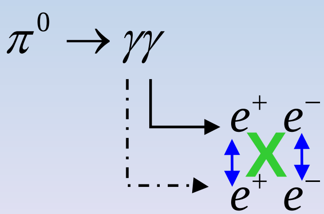
- No background rejection → Signal/Background ≥ 1/100 in Au-Au
- Unphysical correlated background
  - Track overlaps in detectors
  - Not reproducible by mixed events: removed from event sample (pair cut)

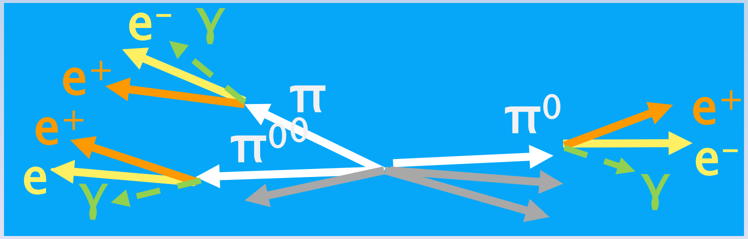
- Combinatorial background: e^+ and e^- from different uncorrelated source

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

  - 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

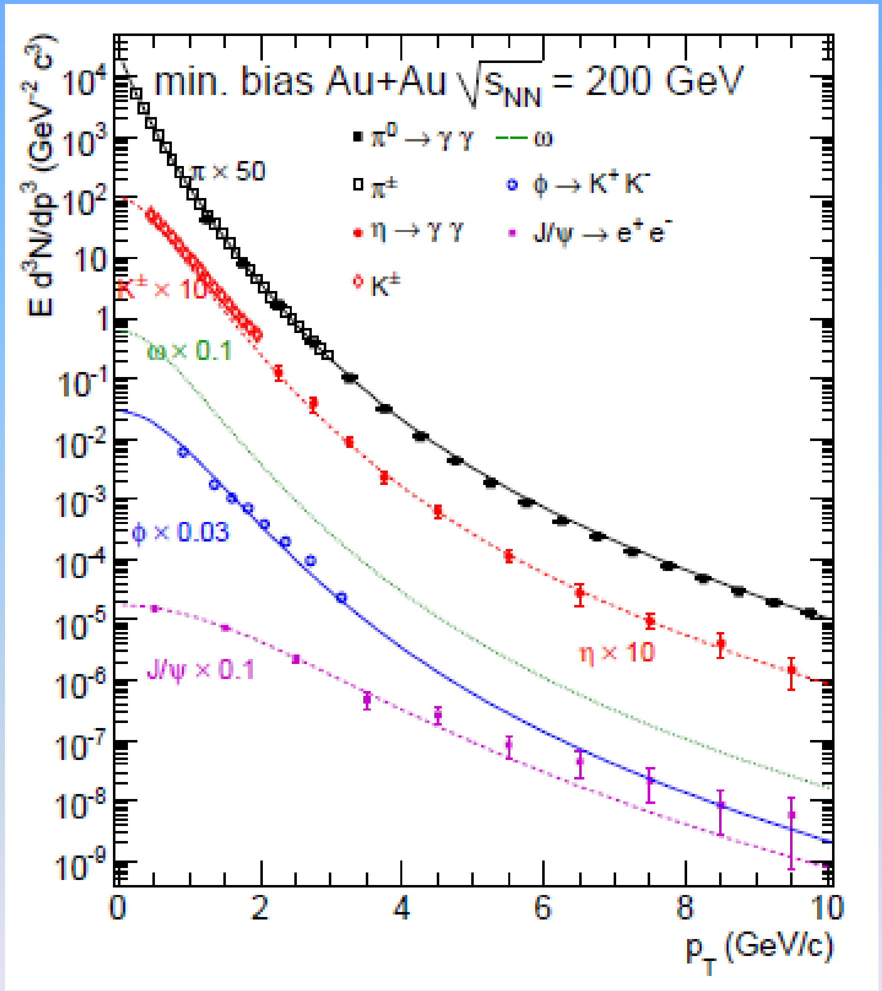
Estimate of Expected Sources

- 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"

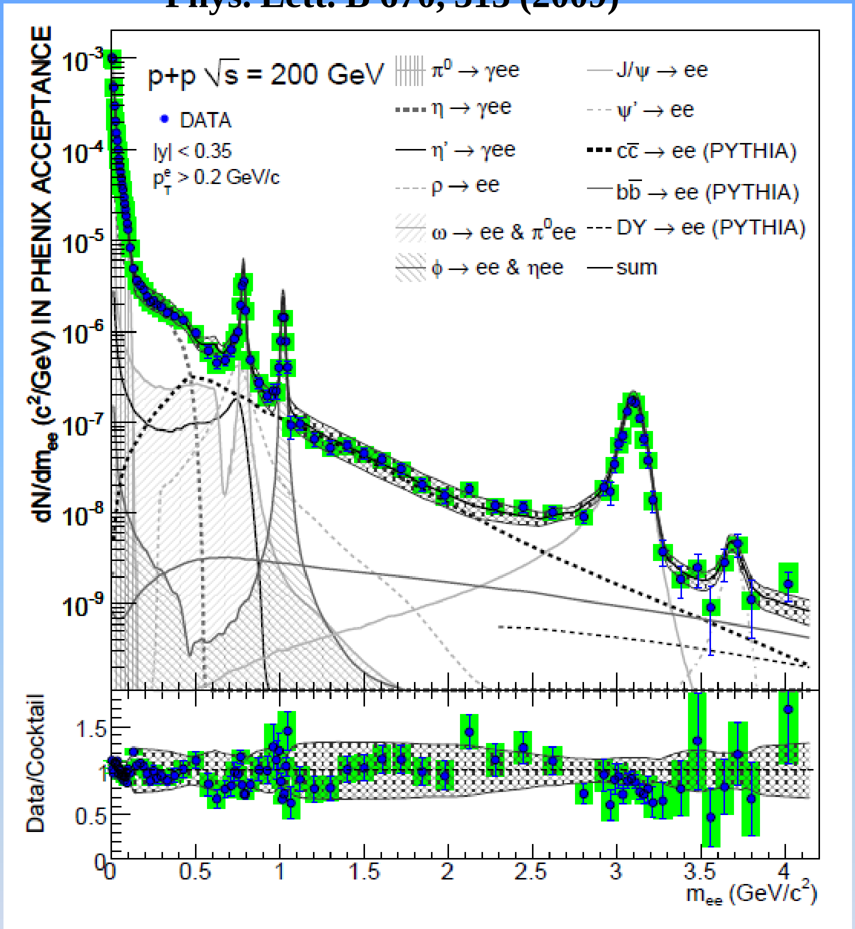


- Heavy flavor production:
  - $\sigma_c = N_{coll}$ x 567±57±193μb from single electron measurement

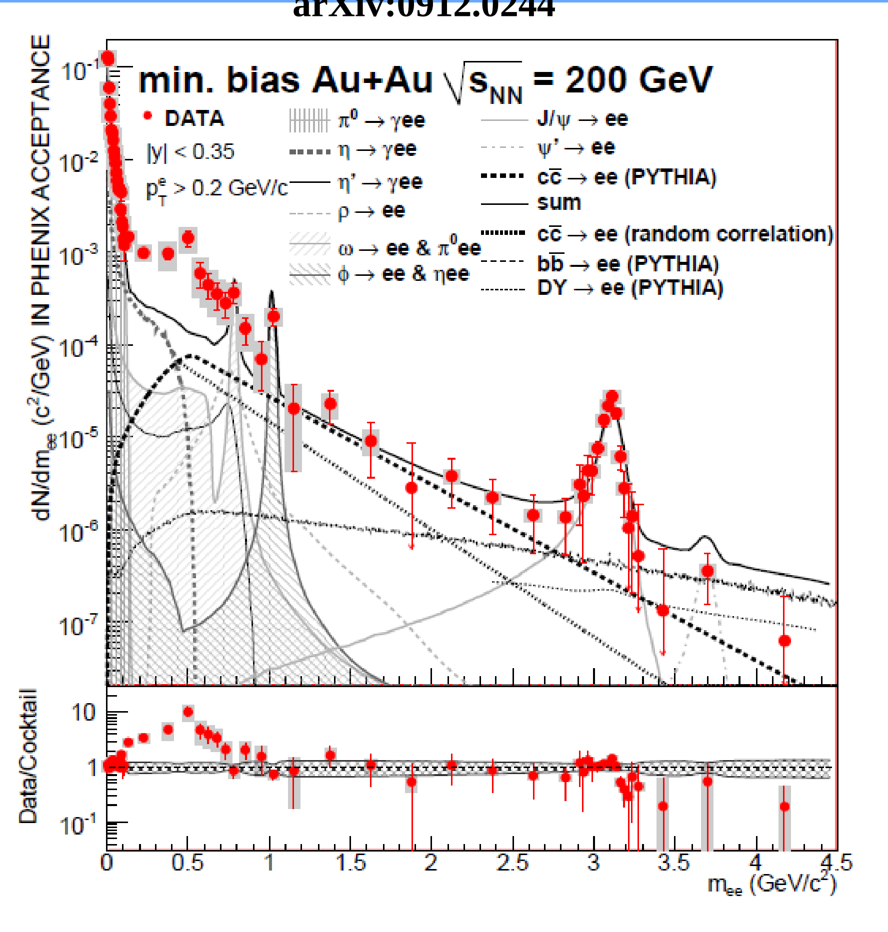
Predict cocktail of known pair sources

Continuum in p+p and AuAu

Phys. Lett. B 670, 313 (2009)



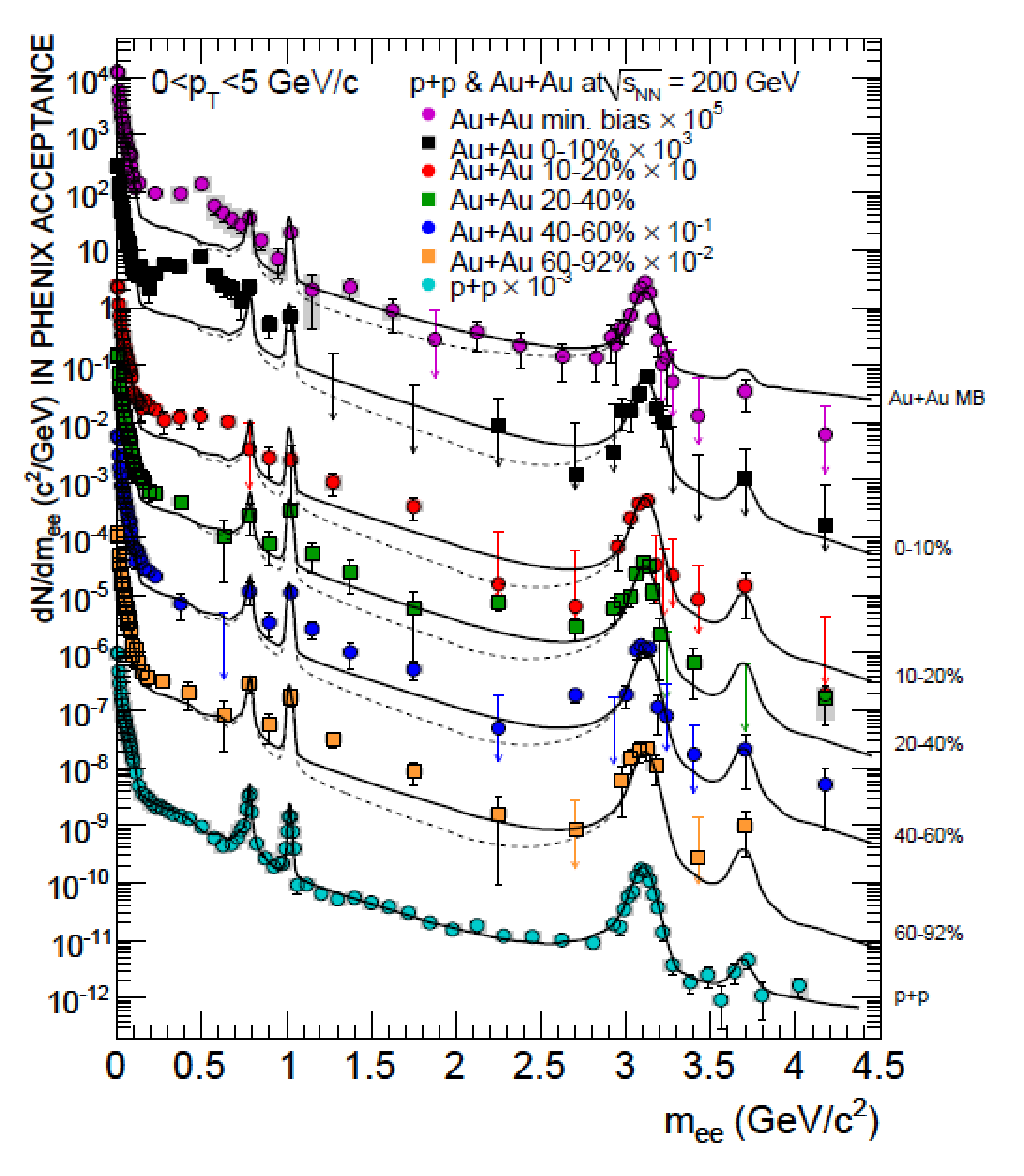
arXiv:0912.0244



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

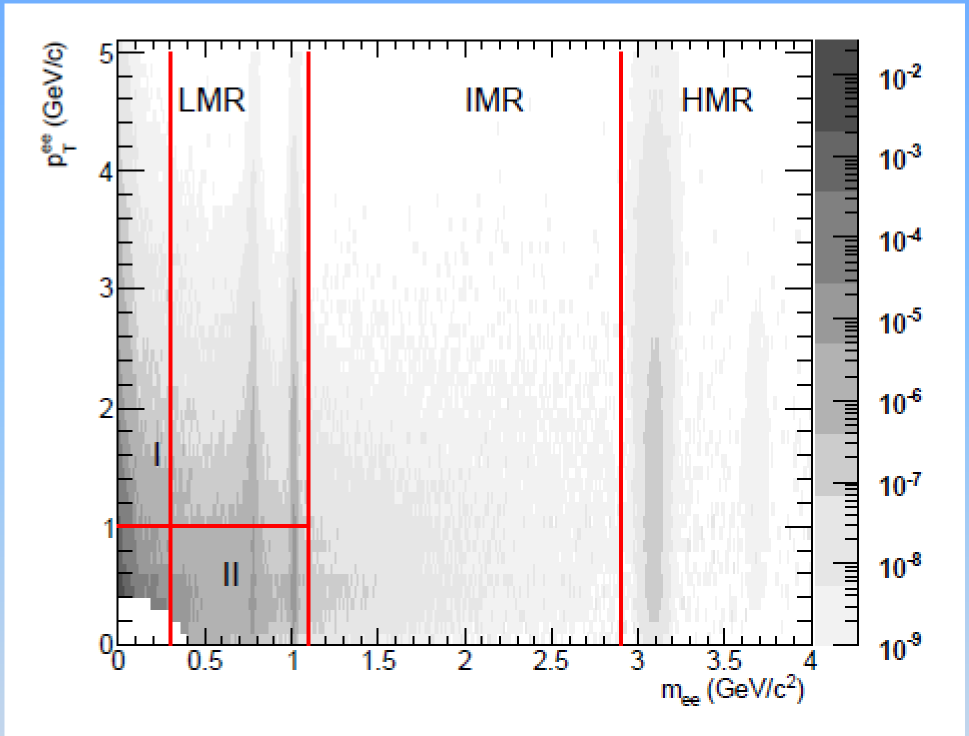
- **Data and Cocktail of known sources**
- **Striking Enhancement at and below the ω mass.**

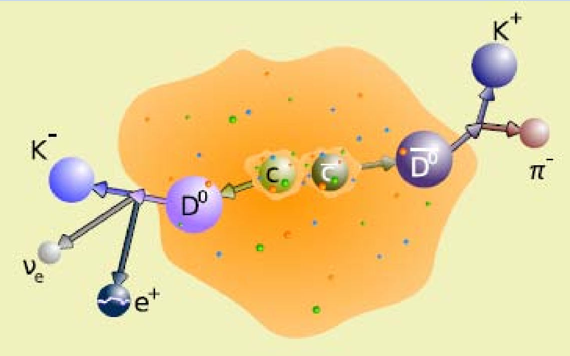
Centrality Dependence



- 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

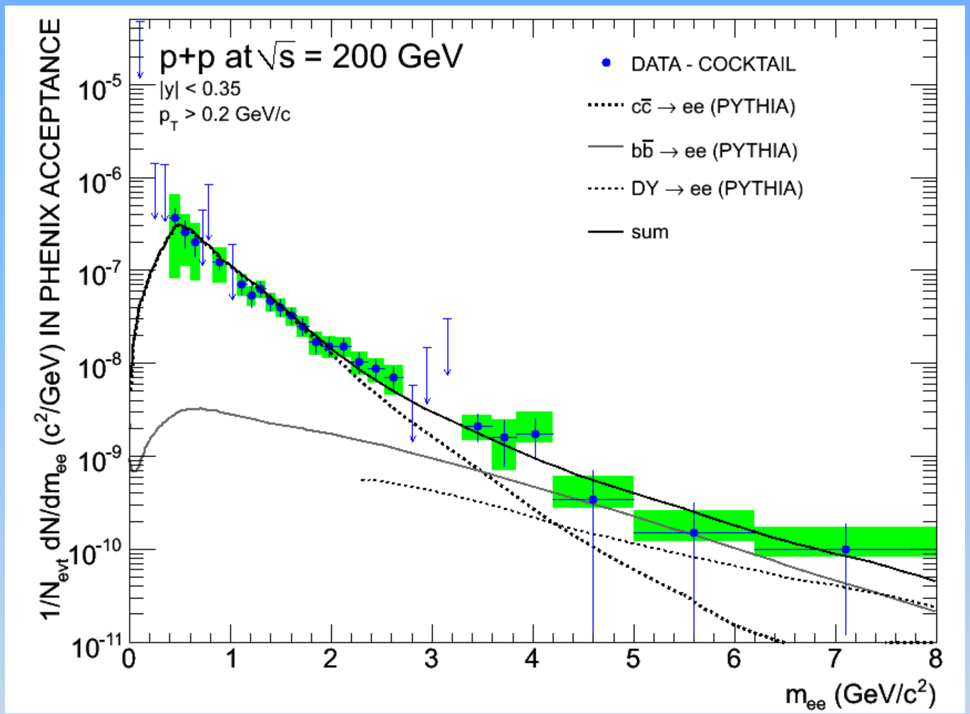


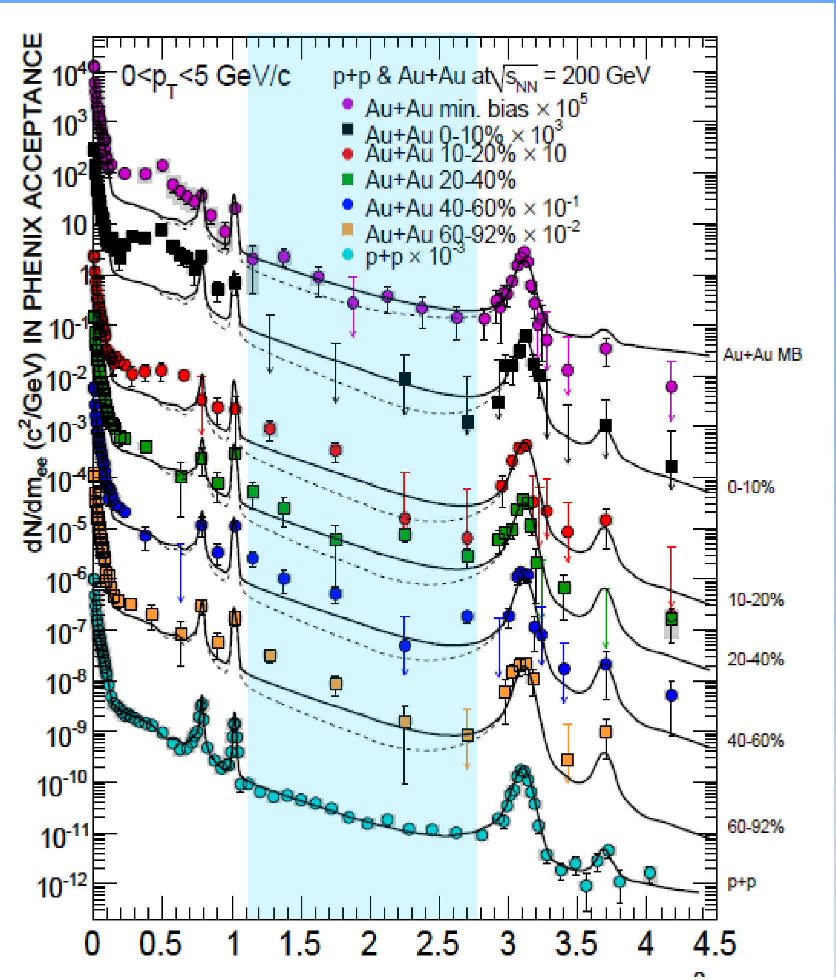


- IMR in cocktail is dominated by correlated open charm.
- LMR-I wherein $m_{ee} << p_T$
- LMR-II where the above condition does not apply.

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

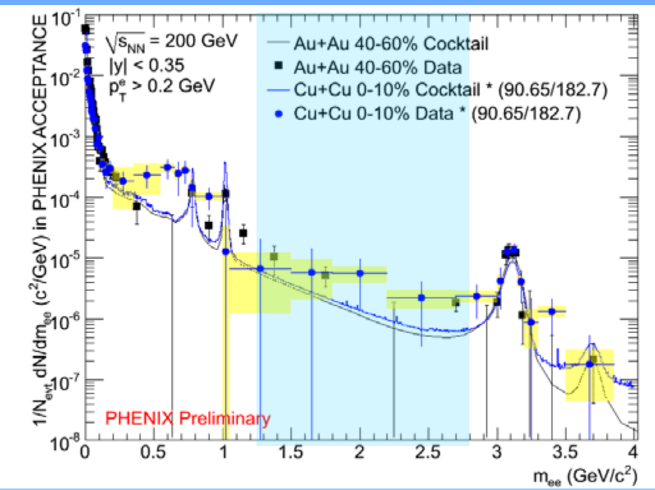
Simultaneous fit of charm and bottom:

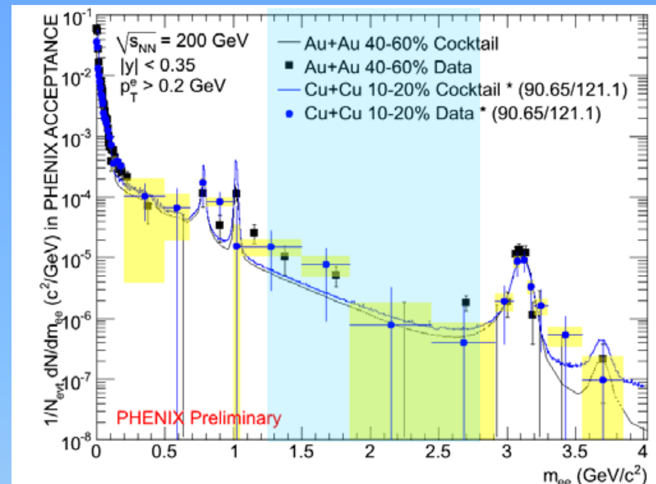
- σ_c=518 ± 47 (stat) ± 135 (sys) ± 190 (model) μb
- σ_b= 3.9 ± 2.4 (stat) +3/-2 (sys) μb

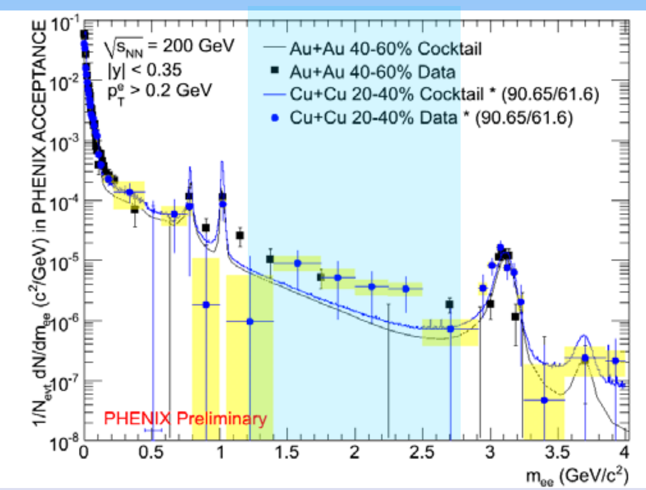
Surprise!

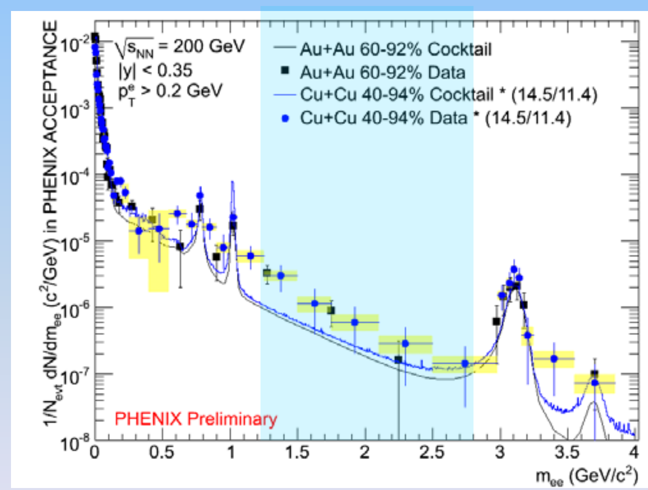
- AuAu matches cocktail in MB.
- Slightly higher in peripheral
- Dashed line is result of max. smearing of charm pairs.

Cu+Cu Au+Au comparison









Spectral modification should lower yield.

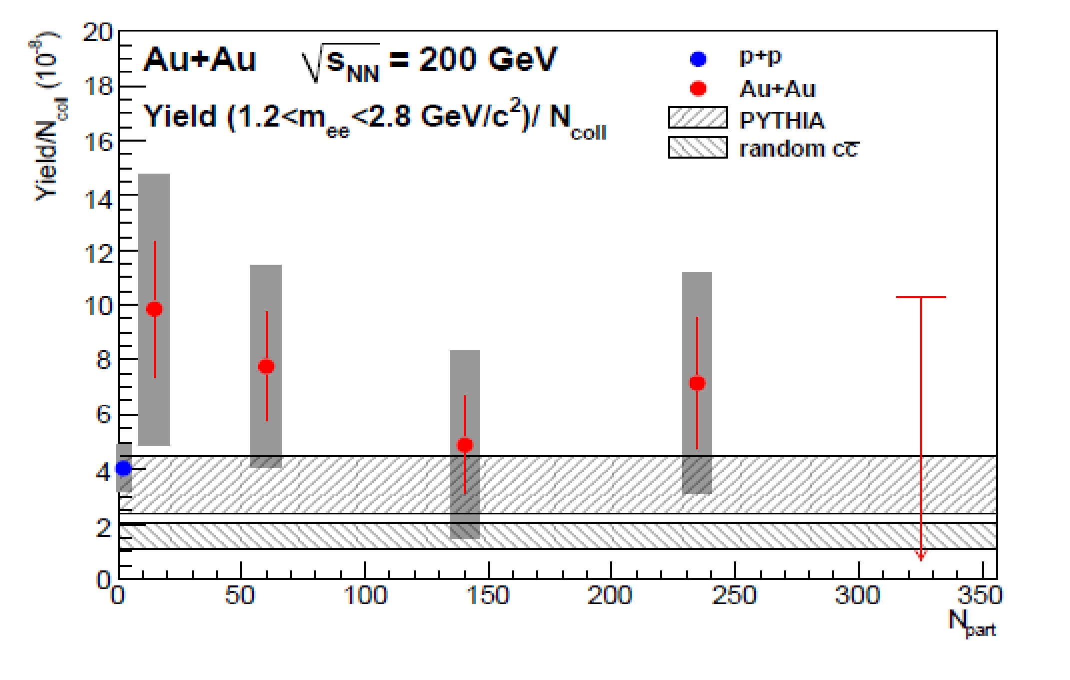
- **Charm singles are well known to be strongly modified by the medium.**
- **These effects should lower the IMR yield most at the most central bin.**

Prompt yields were observed by NA60 in this regime.

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

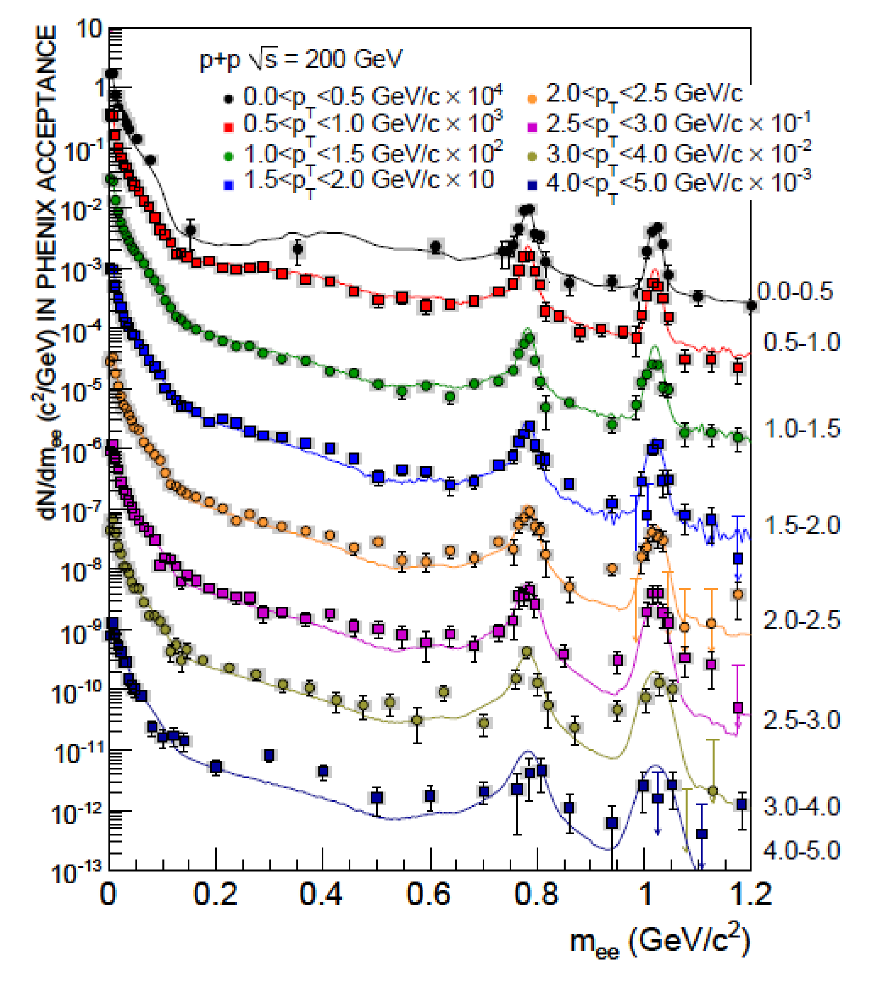
- **Competing or compensating effects?**

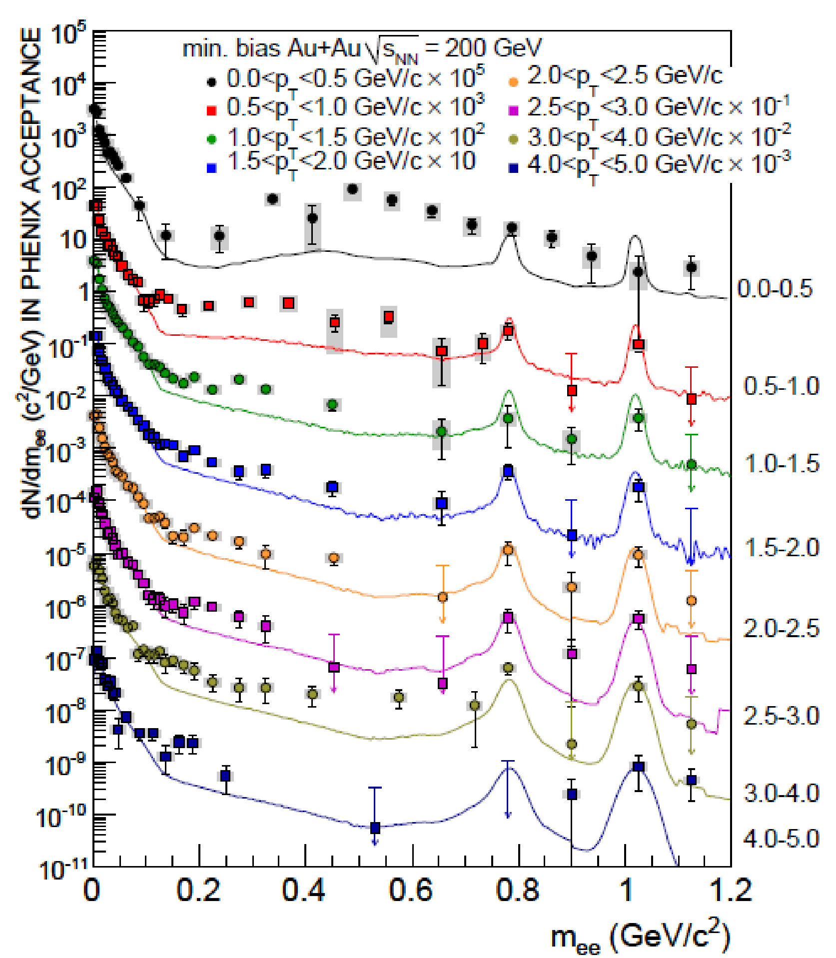
AuAu IMR yield vs Centrality.



- 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





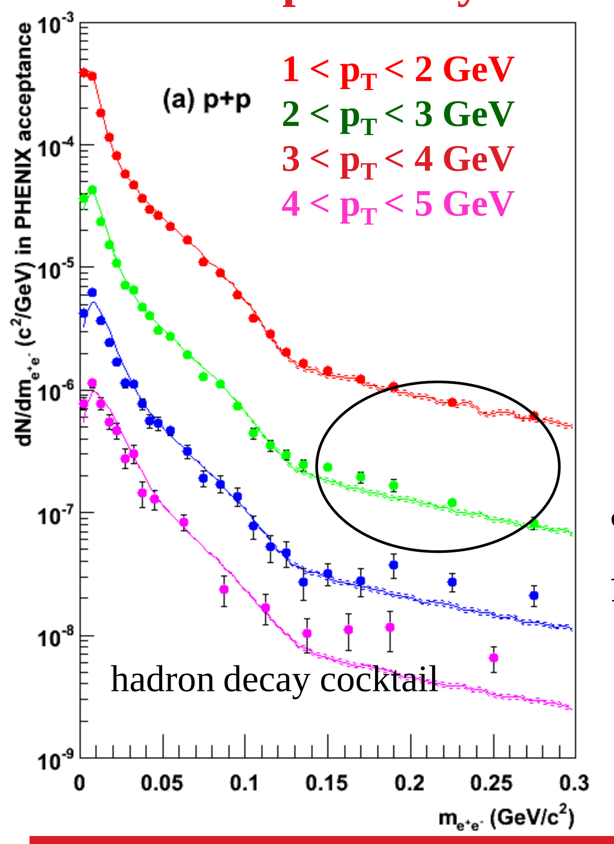
- pp shows excess growing with p_T.
- pp excess slopes downward.

- 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 γ*
  - for m<<p_T γ* is "almost real"
  - extrapolate γ* → e+e− yield to m = 0 → direct γ yield
  - m > m_π removes 90% of hadron decay background
  - S/B improves by factor 10: 10% direct γ → 100% direct γ*

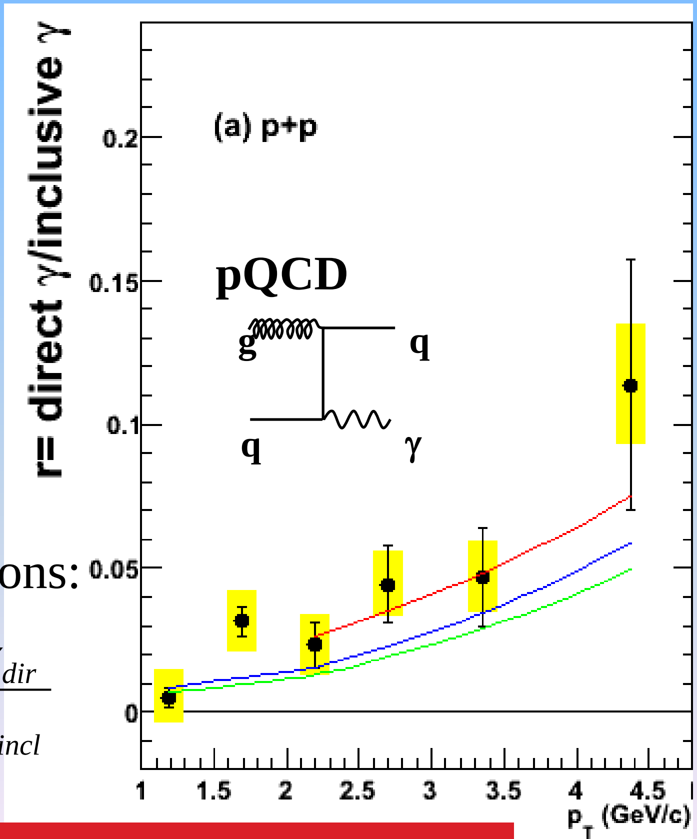
arXiv:0804.4168



access above cocktail

fraction or direct photons:

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



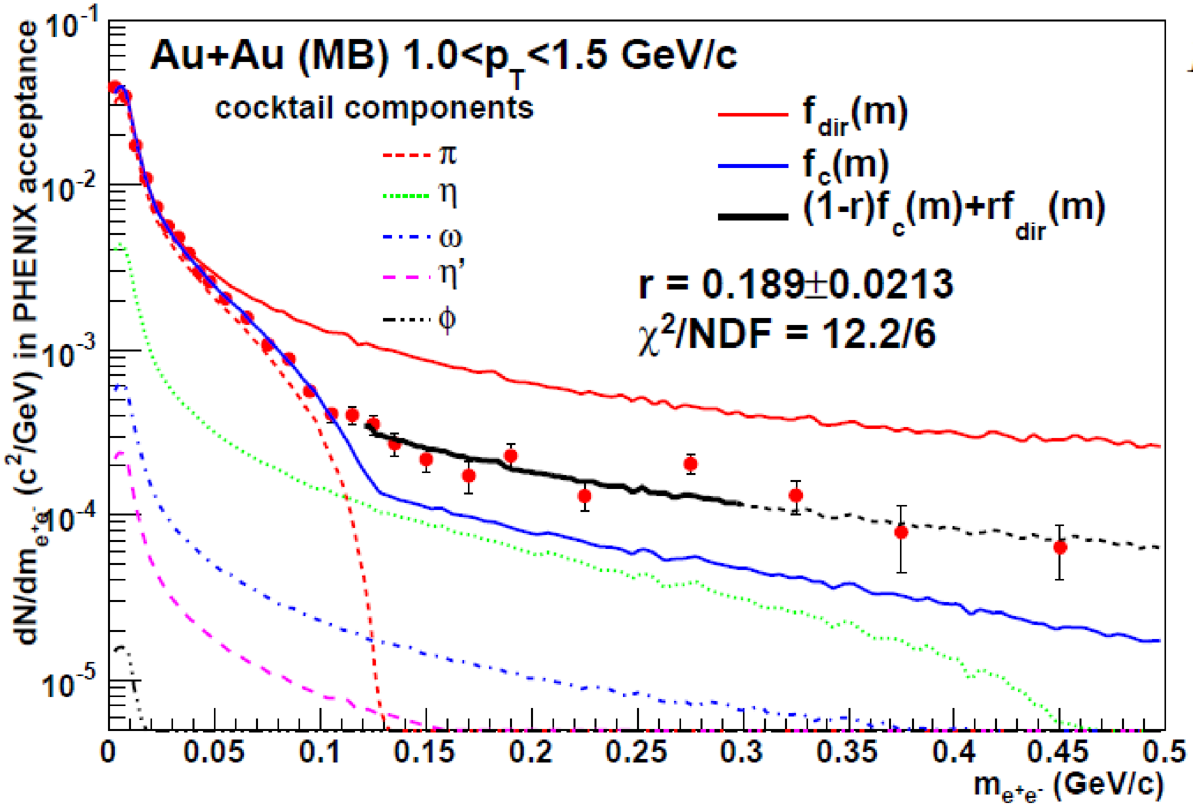
Small excess for m<< p_T consistent with pQCD direct photons

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:

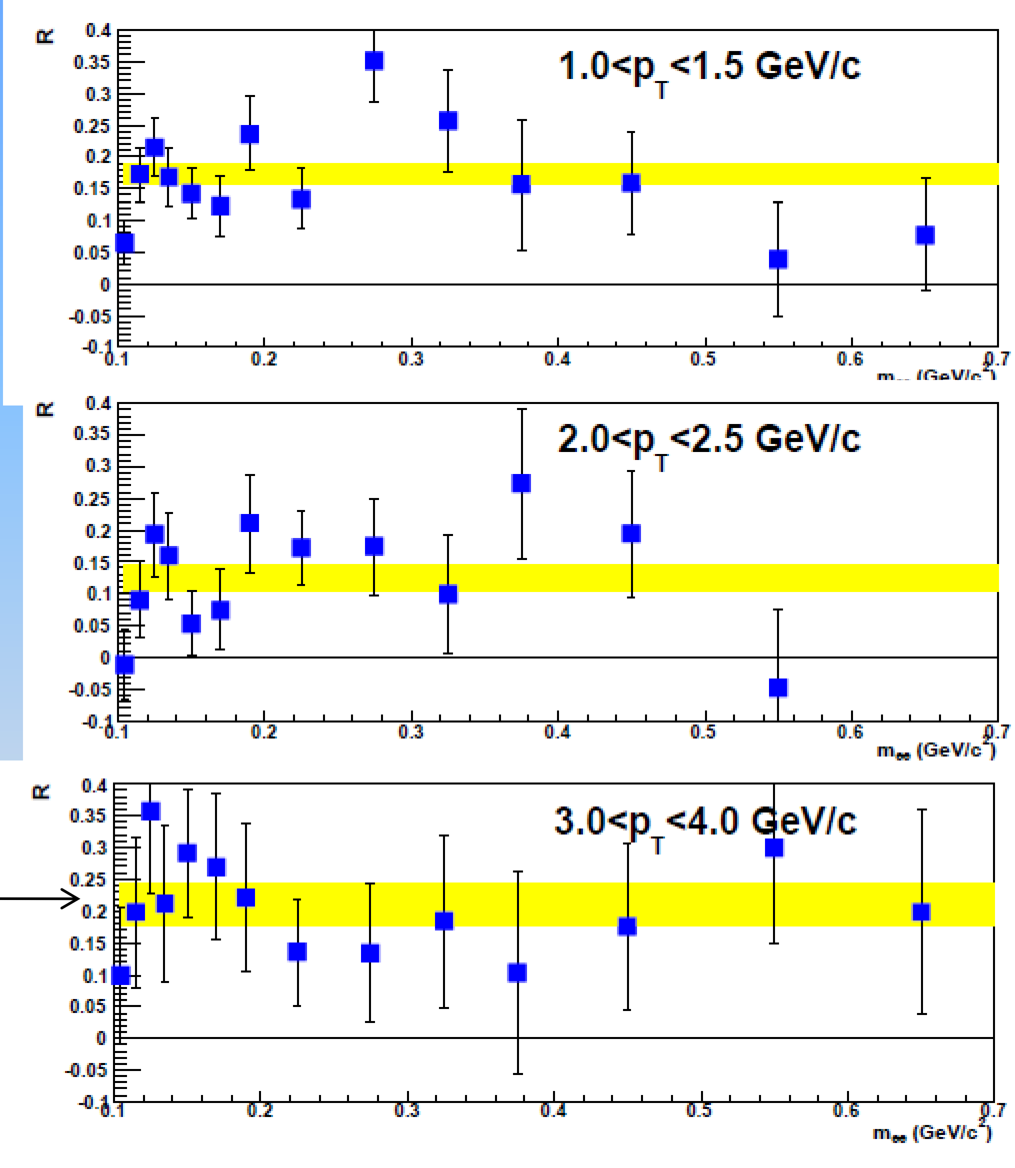
$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

Extrapolate real γ yield from dileptons:

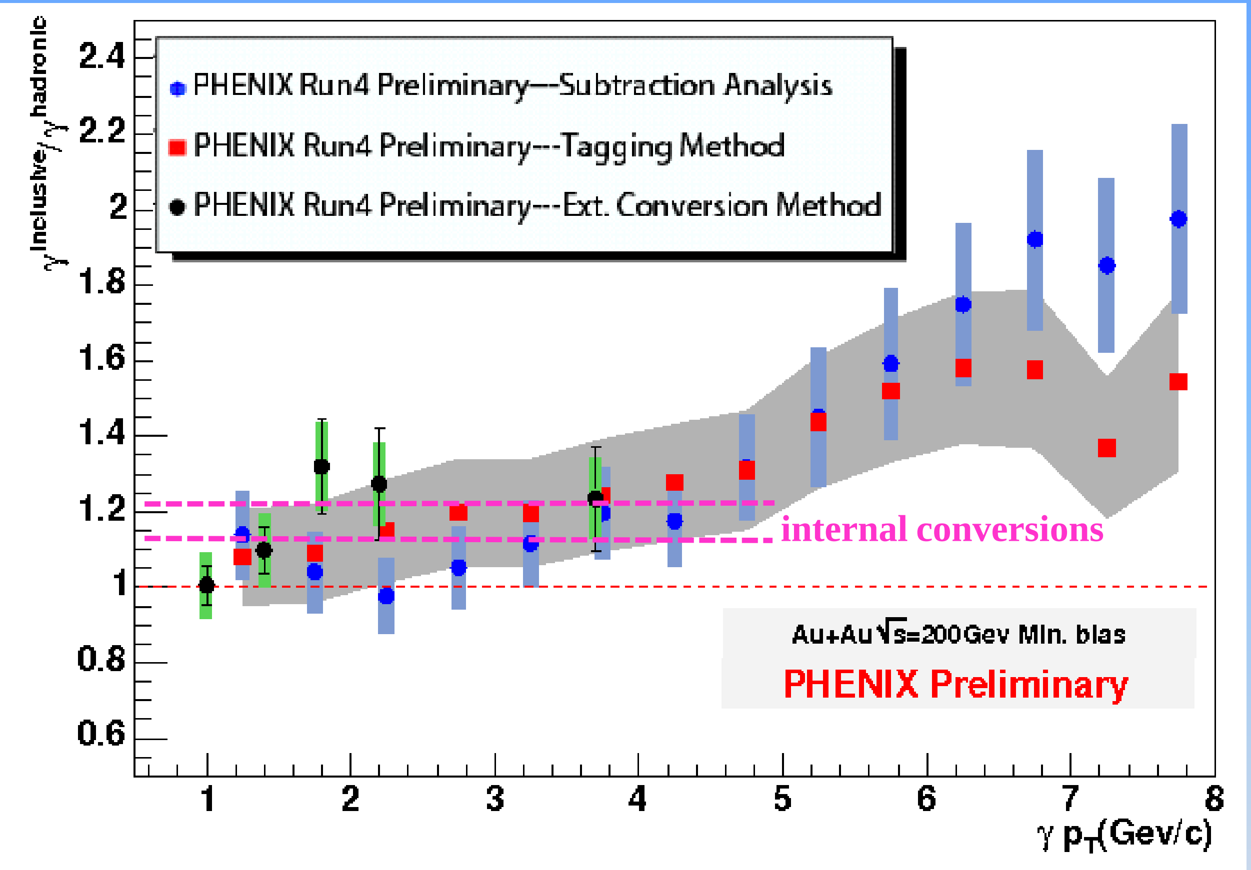
$$M \times \frac{dN_{ee}}{dM} \to \frac{dN_\gamma}{dM} \quad \text{for} \quad M \to 0$$

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

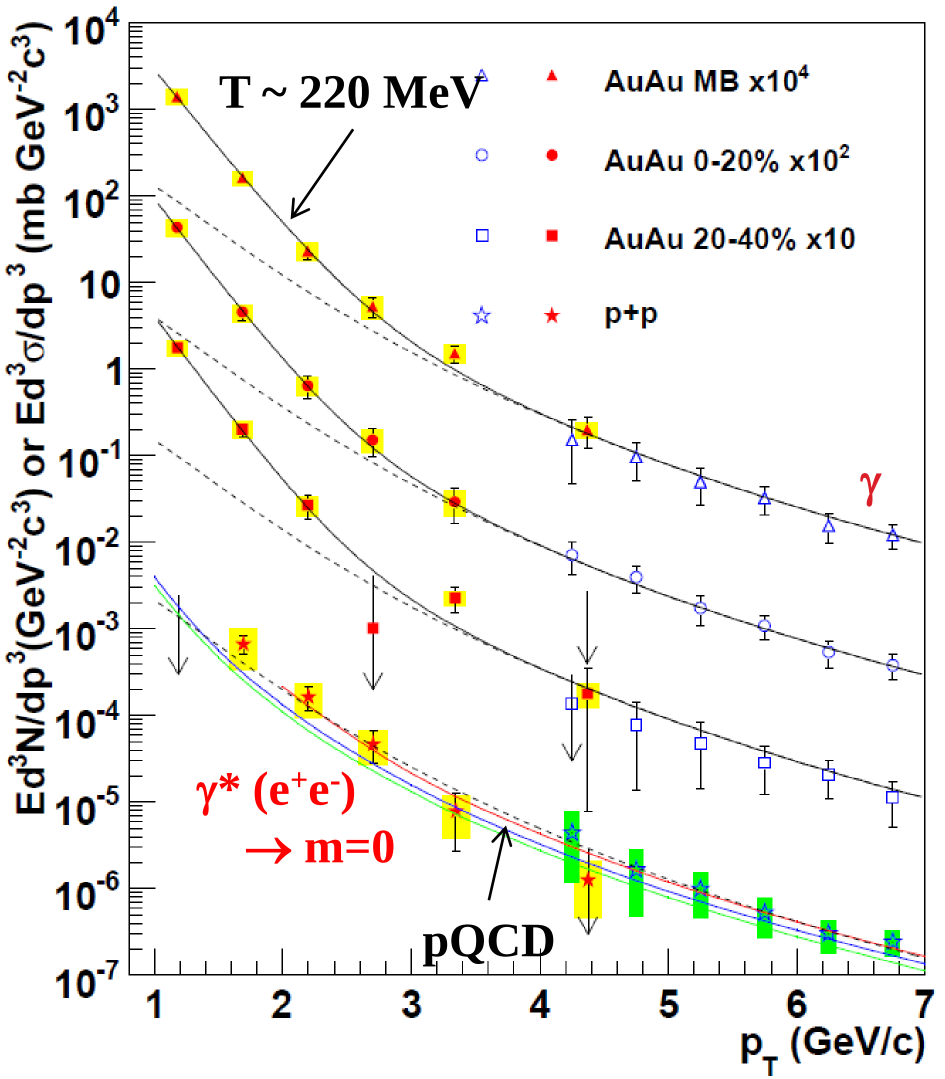


Search for Thermal Photons via Real Photons



- 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

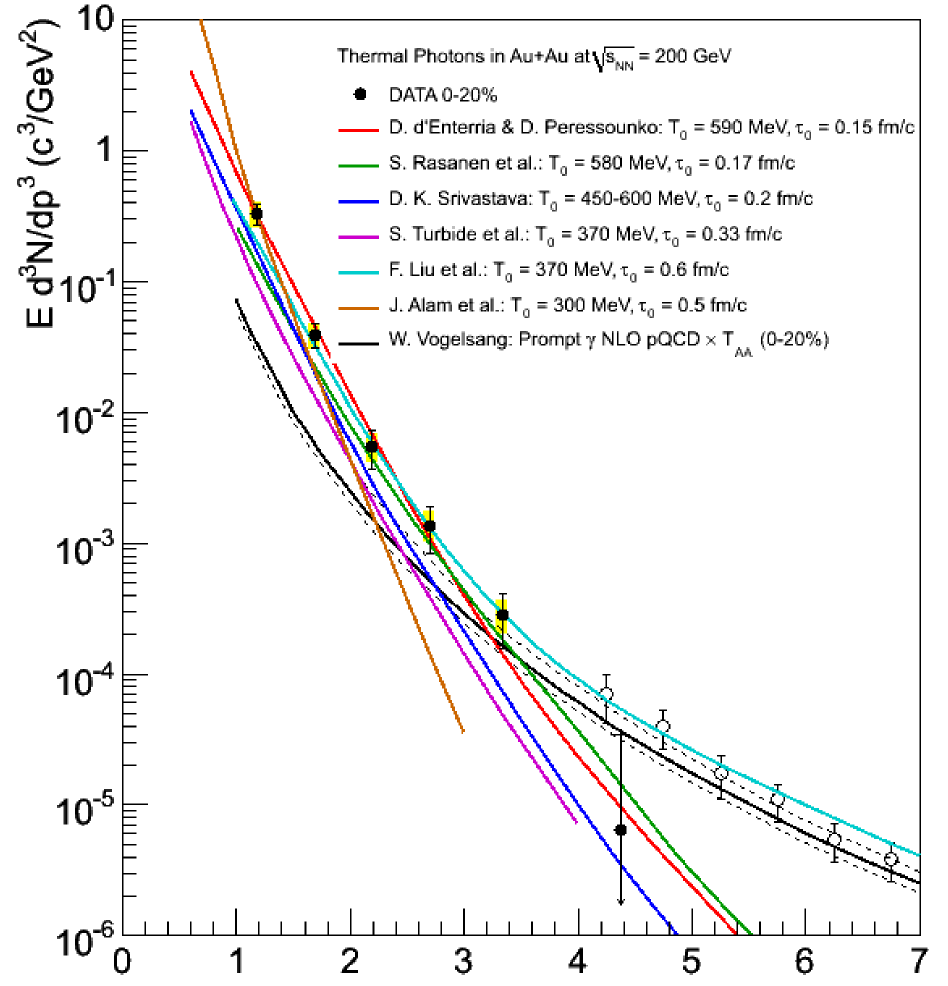
Thermal Radiation at RHIC



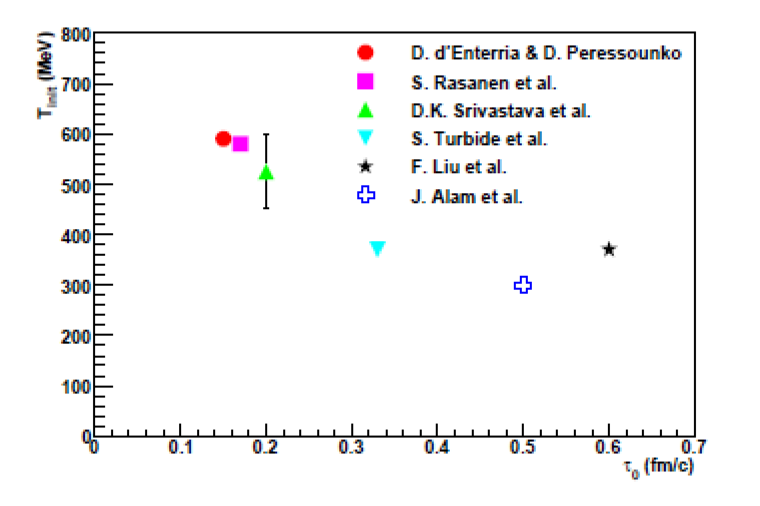
- Direct photons from real photons:
  - Measure inclusive photons
  - Subtract π^0 and η decay photons at S/B < 1:10 for p_T<3 GeV
- Direct photons from virtual photons:
  - Measure e^+e^- pairs at $m_\pi < m << p_T$
  - Subtract η decays at S/B ~ 1:1
  - Extrapolate to mass 0

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.)

Real Photons through Conversions

$$\frac{\gamma^{\mathrm{incl}}(p_T)}{\gamma^{\mathrm{hadr}}(p_T)} = \frac{\epsilon_\gamma(p_T)\cdot\left(\frac{N_\gamma^{\mathrm{incl}}(p_T)}{N_\gamma^{\pi^0\mathrm{tag}}(p_T)}\right)_{\mathrm{Data}}}{\left(\frac{N_\gamma^{\mathrm{hadr}}(p_T)}{f\ N_\gamma^{\pi^0}(p_T)}\right)_{\mathrm{Sim}}}$$

DATA

$$N_\gamma^{\mathrm{incl}}(p_T) = \varepsilon_{\mathrm{pair}} a_{\mathrm{pair}} \gamma^{\mathrm{incl}}(p_T)$$

$$N_\gamma^{\pi^0\ \mathrm{tag}}(p_T) = \varepsilon_{\mathrm{pair}} a_{\mathrm{pair}} \varepsilon_\gamma\, f\, \gamma^{\pi^0}(p_T)$$

SIMULATION

$$N_\gamma^{\mathrm{hadron}}(p_T) = a_{\mathrm{pair}} \gamma^{\mathrm{hadr}}(p_T)$$

$$N_\gamma^{\pi^0\ \mathrm{tag}}(p_T) = f\ N_\gamma^{\pi^0} = a_{\mathrm{pair}}\, f\, \gamma^{\pi^0}(p_T)$$

e+/e− Pair efficiency

e+/e− Pair acceptance

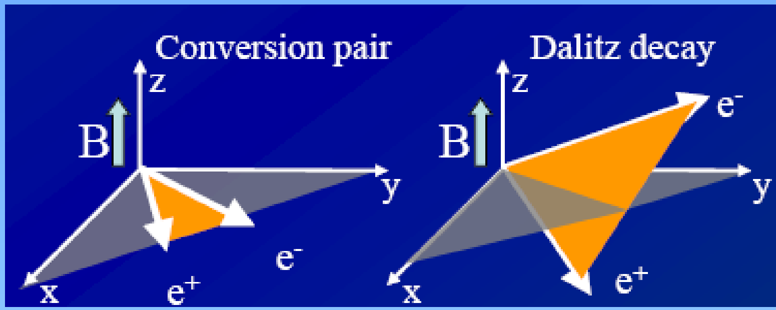
Photon efficiency

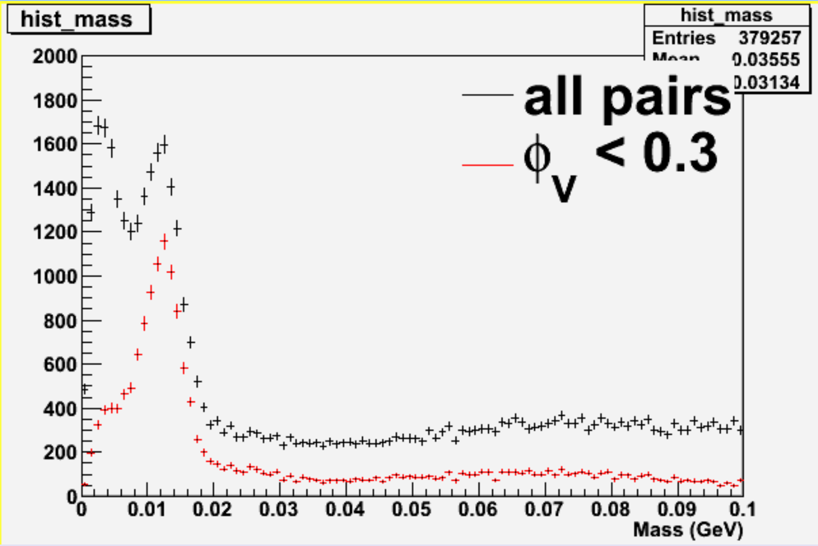
Conditional probability of having the photon in acceptance, given that the pair is already in the acceptance

- This method has the advantage of the pair acceptance canceling out in the ratio
- We do not need to know the conversion length of the HBD because of this pi0 tagging method

Conversion Pairs

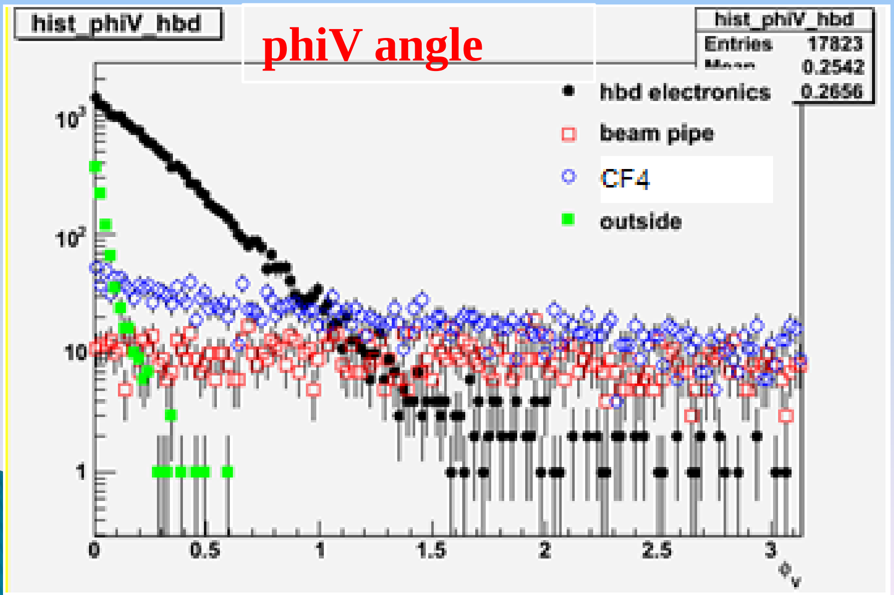
- The PHENIX reconstruction software assumes that all particles come from the event vertex
  - This is not true for the electrons that come from a photon conversion in the HBD (r ≈ 60cm)
  - This gives the pair an apparent opening angle, and hence an artificial mass proportional to the radius that the conversion occurs at
  - In addition, the pair will open up in a plane relative to the magnetic field and this can be measured and called the phiV angle
  - Conversion pairs will open up perpendicular to the field
  - Dalitz decays will open randomly to the field

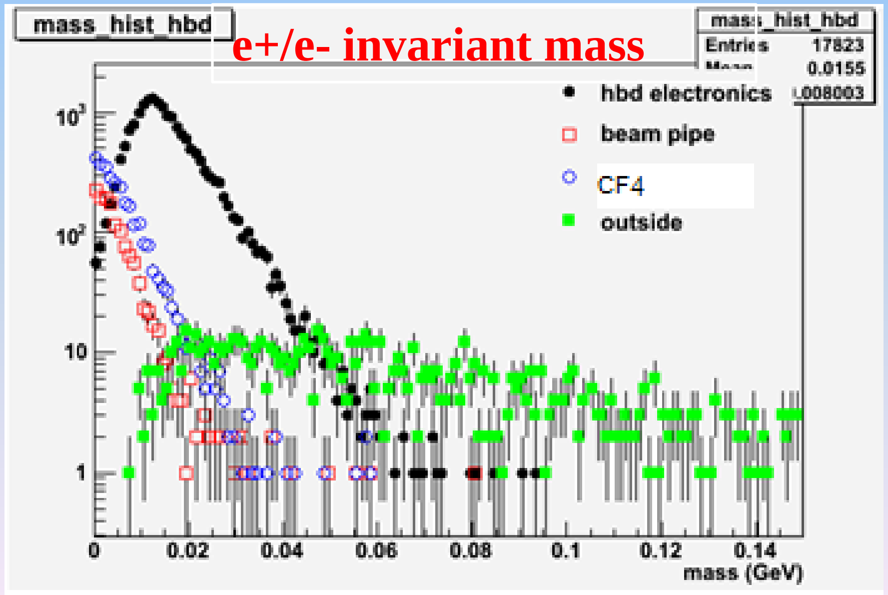




Simulation Studies

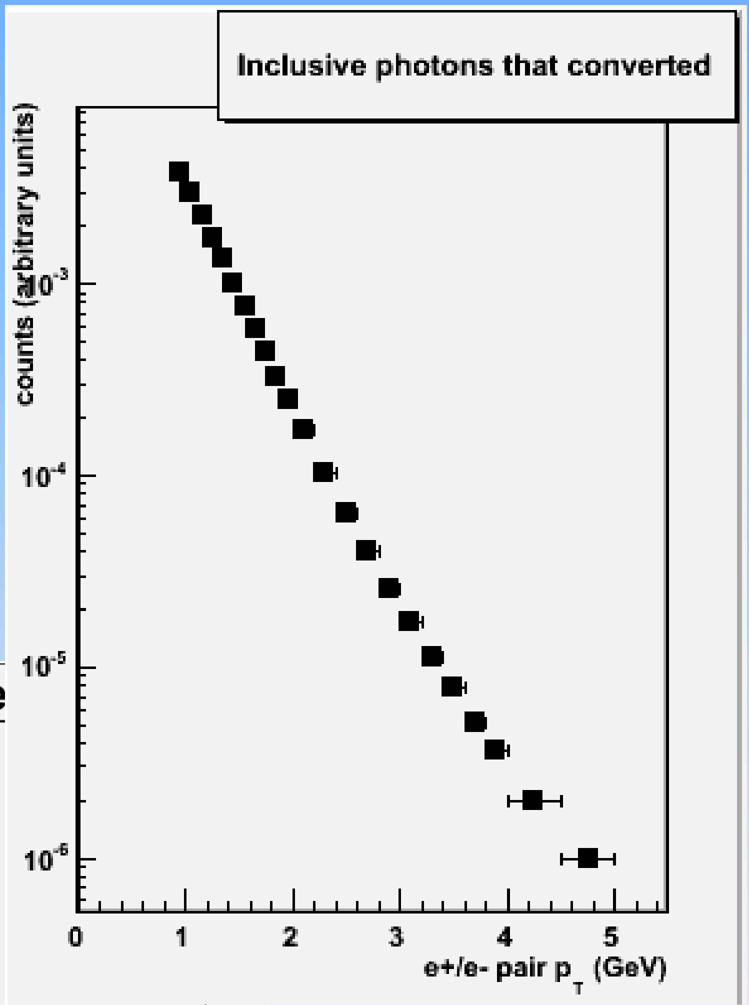
- Simulations show that we can isolate photons that convert in the electronics of the HBD through the apparent mass observed and the phiV angle even in the weaker magnetic field of the +- configuration for Run 7
- Shown are full Monte Carlo simulations of photons, modeling detector response (GEANT) and doing the full PHENIX reconstruction on the simulated data

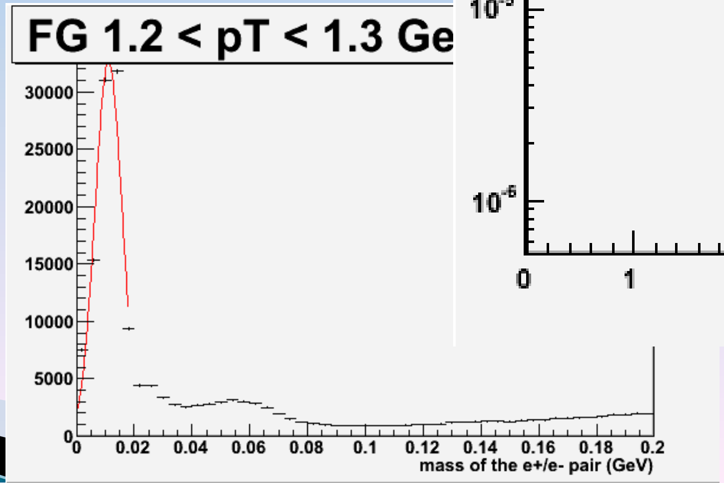




Measuring the Raw Uncorrected Inclusive Photon Sample

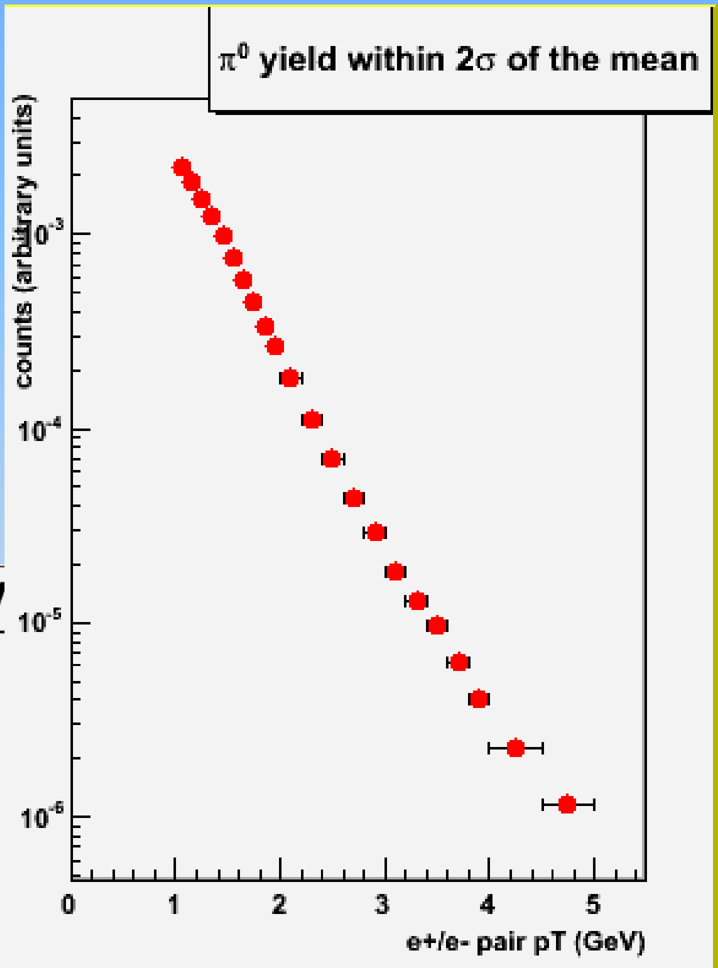
- Electrons and positrons are identified using standard PHENIX eid cuts
  - Number of RICH phototubes fired
  - Shower shape in the emcal
  - Energy/momentum ratio
- Then all electrons and positrons within an event are paired
  - Keep pairs with phiV < 0.3
  - Pairs with mass < 18MeV are the converted photons

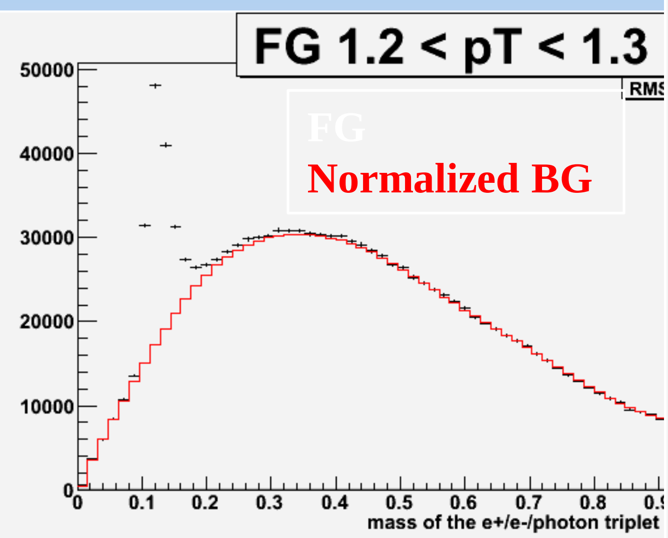


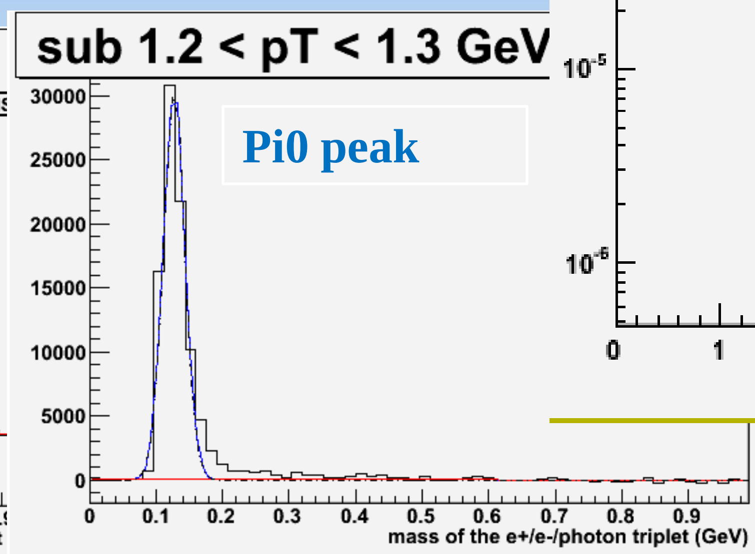


Measuring the Raw Uncorrected pi0 Tagged Sample

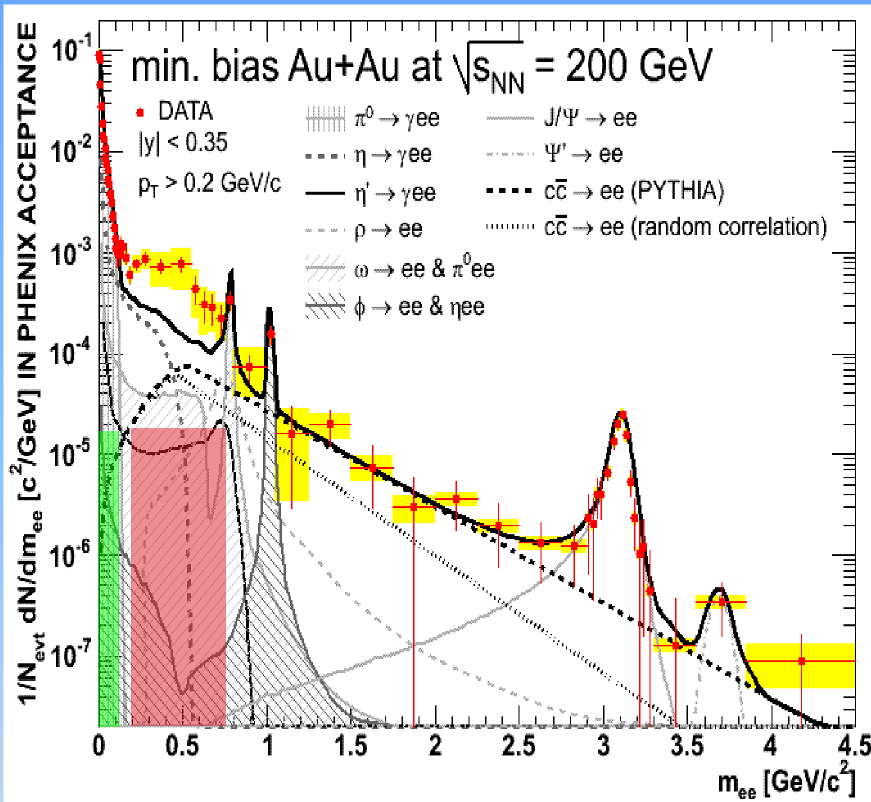
- Many of the photons are coming from pi0 decays
- To get a pi0 tagged sample, photons in the emcal are paired with the converted photons found in the inclusive sample
- Combinatorial background is estimated using a mixed event technique
  - Pairs are formed with particles from different (but similar) events to get the uncorrelated combinatorial background



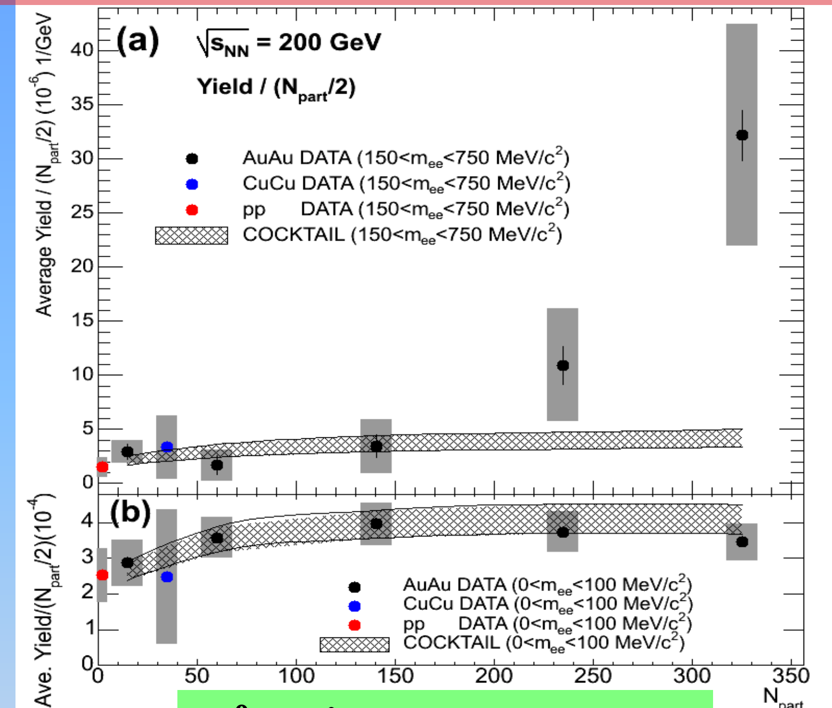




Au+Au Dilepton Continuum



Excess region: 150 < m < 750 MeV



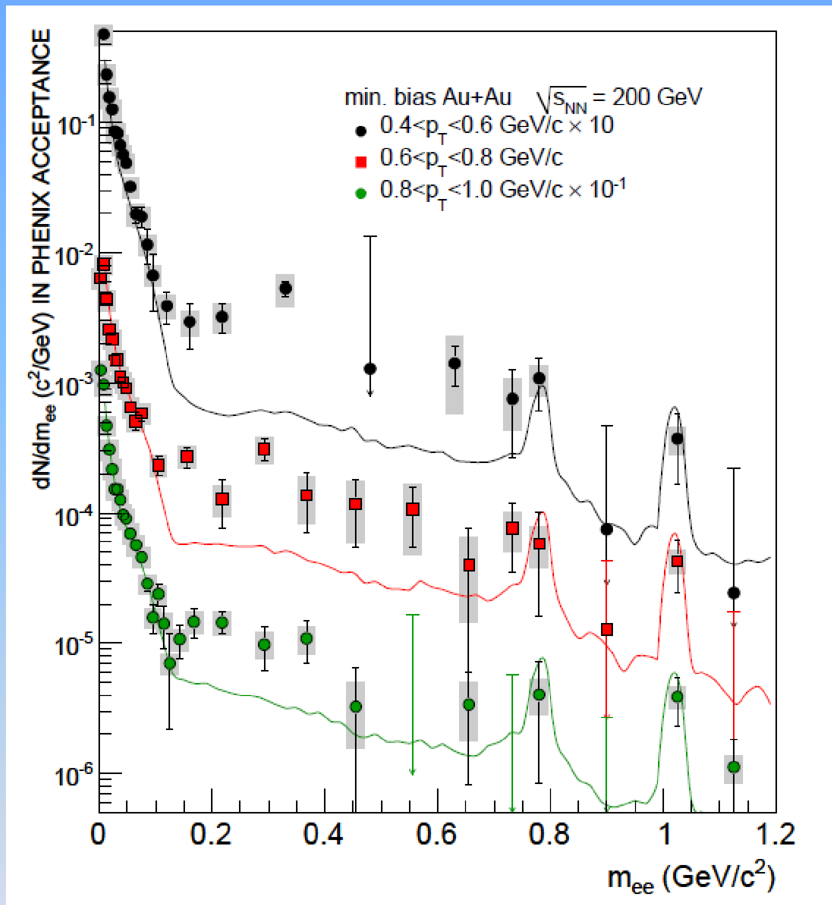
π^0 region: m < 100 MeV

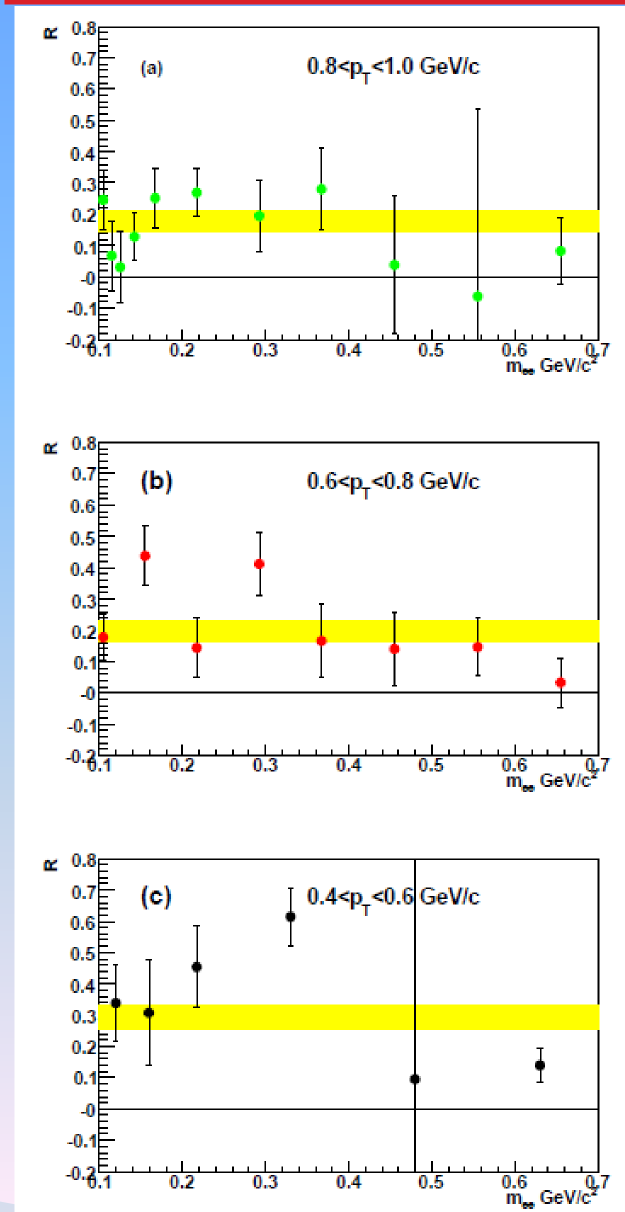
- Excess 150 <mee<750 MeV: 3.4 ± 0.2(stat.) ± 1.3(syst.) ± 0.7(model)
- Intermediate-mass continuum: consistent with PYTHIA if charm is modified room for thermal radiation

- **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

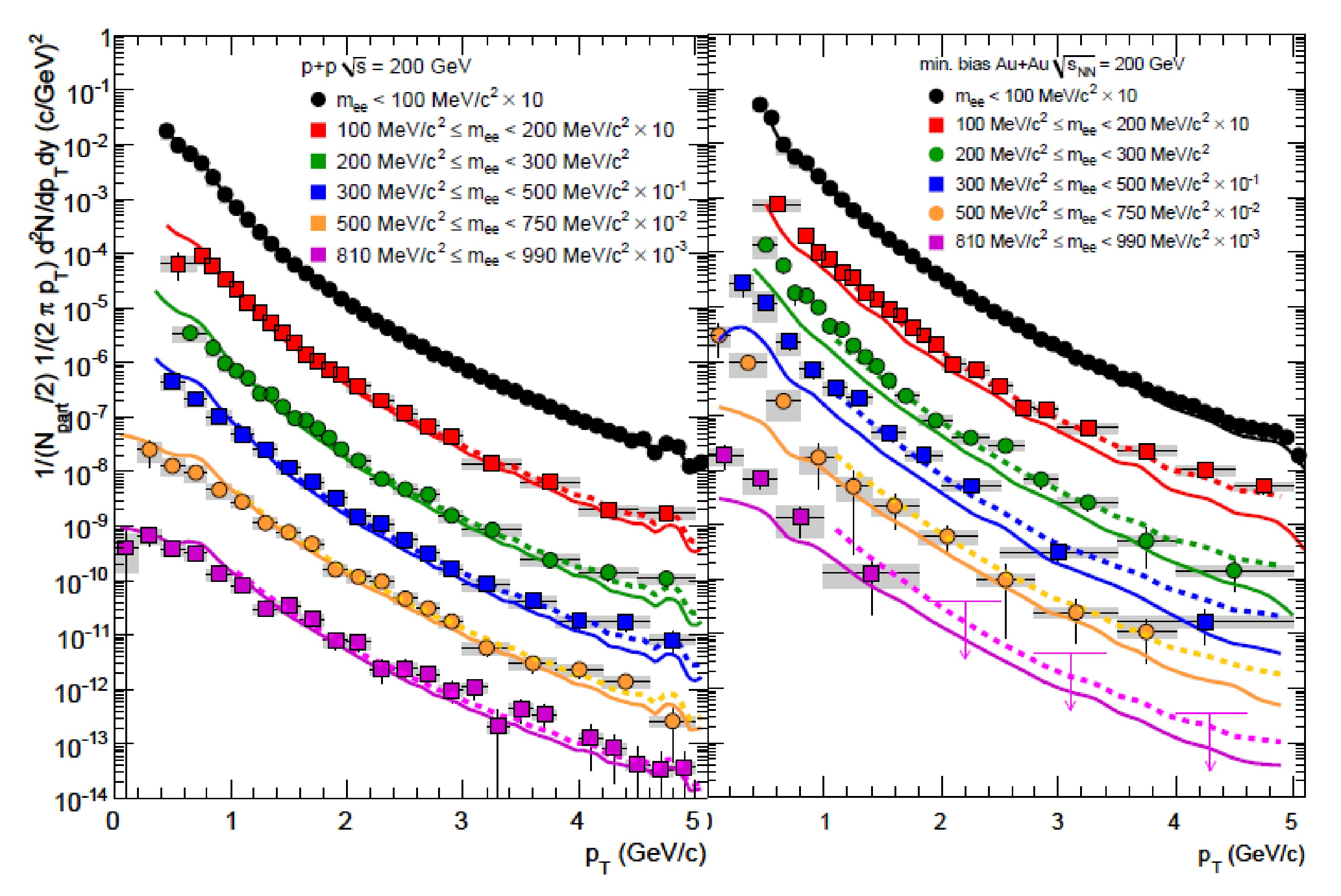
Poorly described as γ^*





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

p_T Spectra

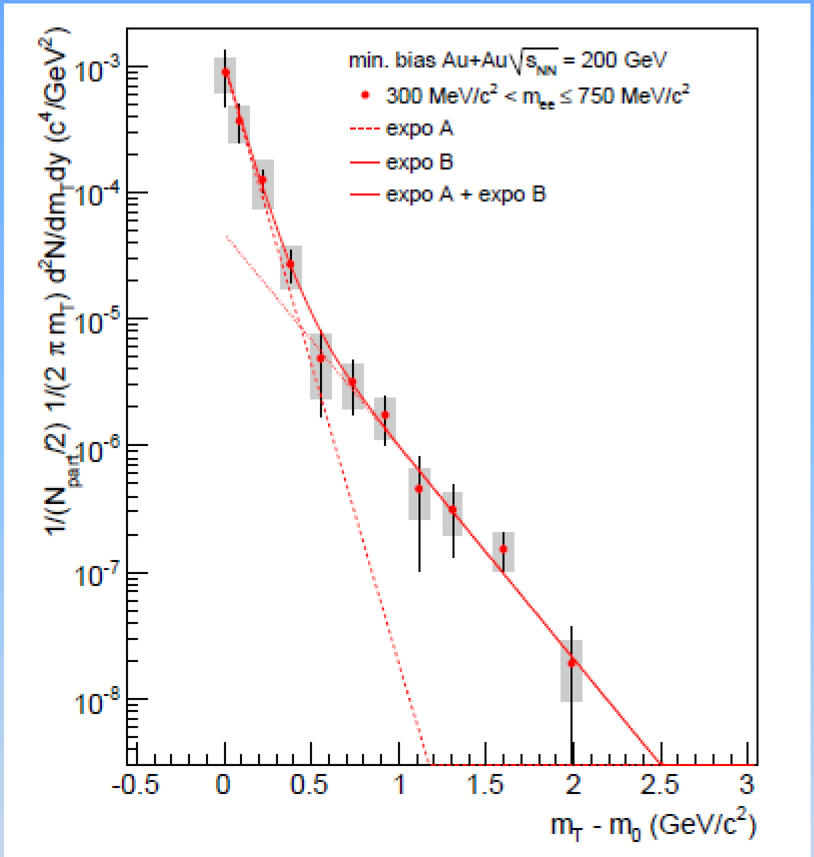


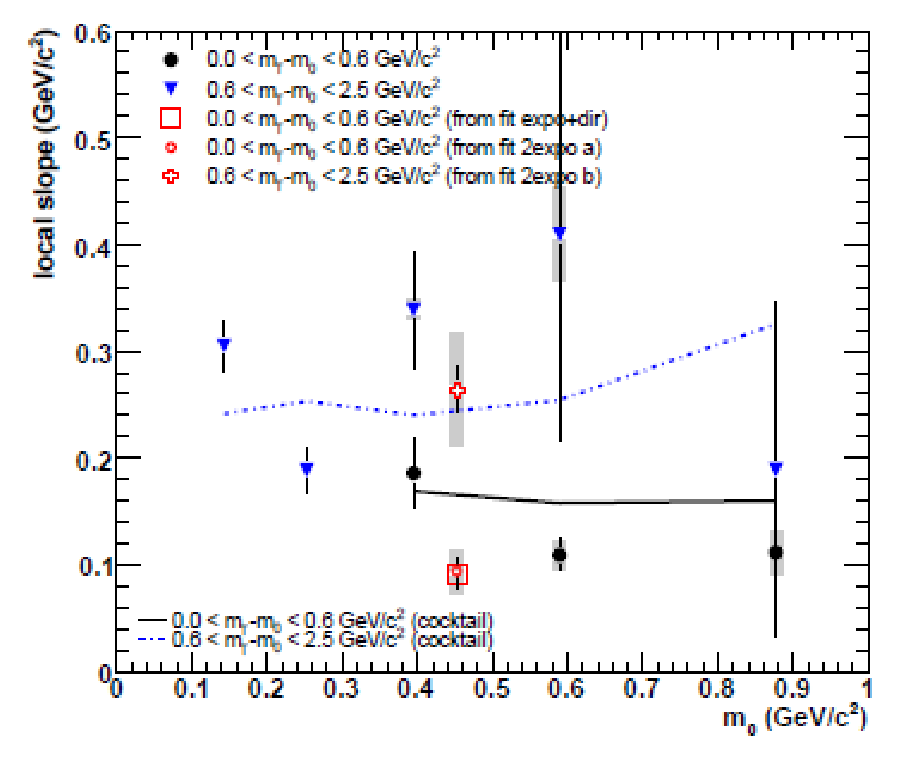
pp well described by Cocktail + gamma.

AuAu not well described:

Additional excess at low p_T

Local Slopes – Cold Component



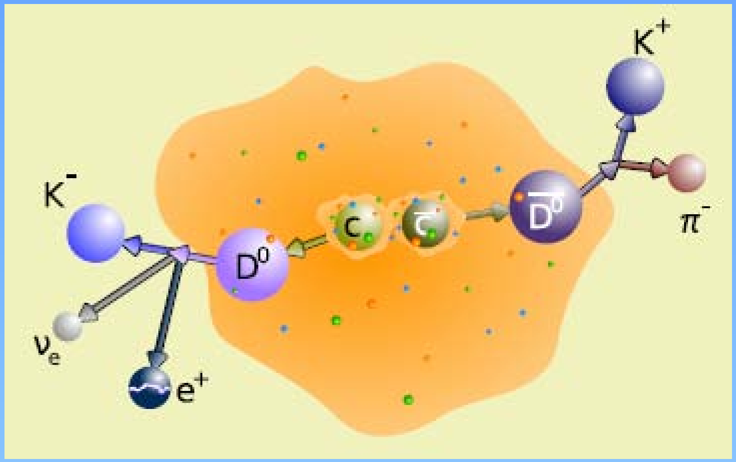


Soft component below m_T ~ 500 MeV:

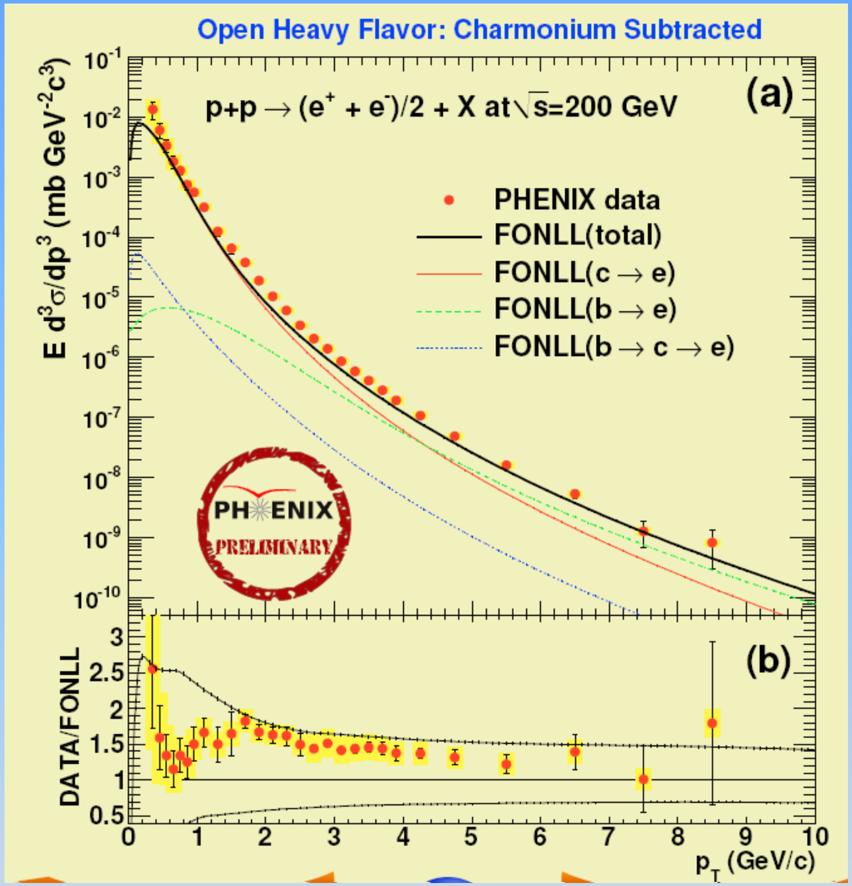
T_{eff} < 120MeV independent of mass

more than 50% of yield

Heavy Flavor from Single Leptons

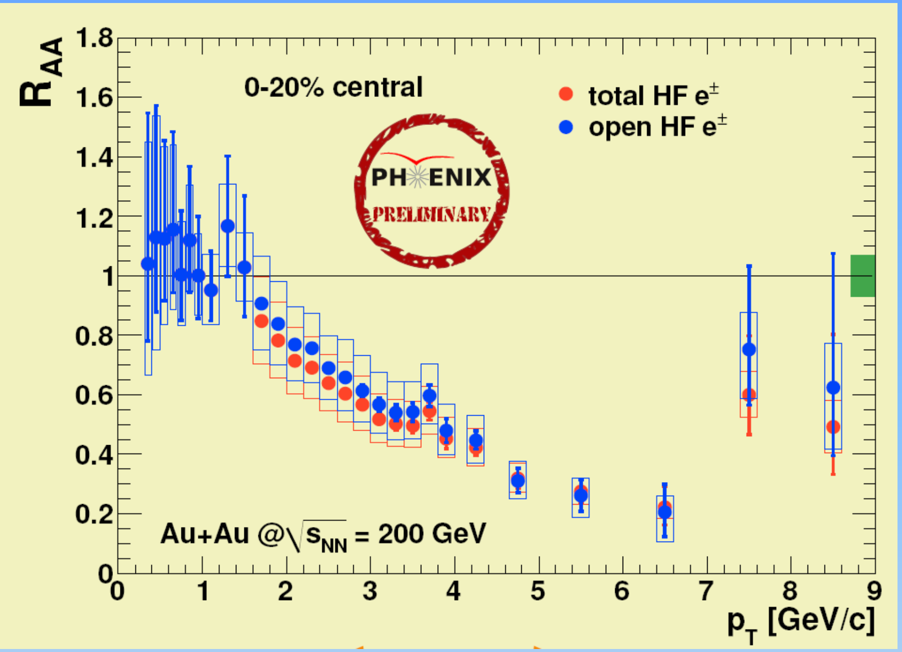


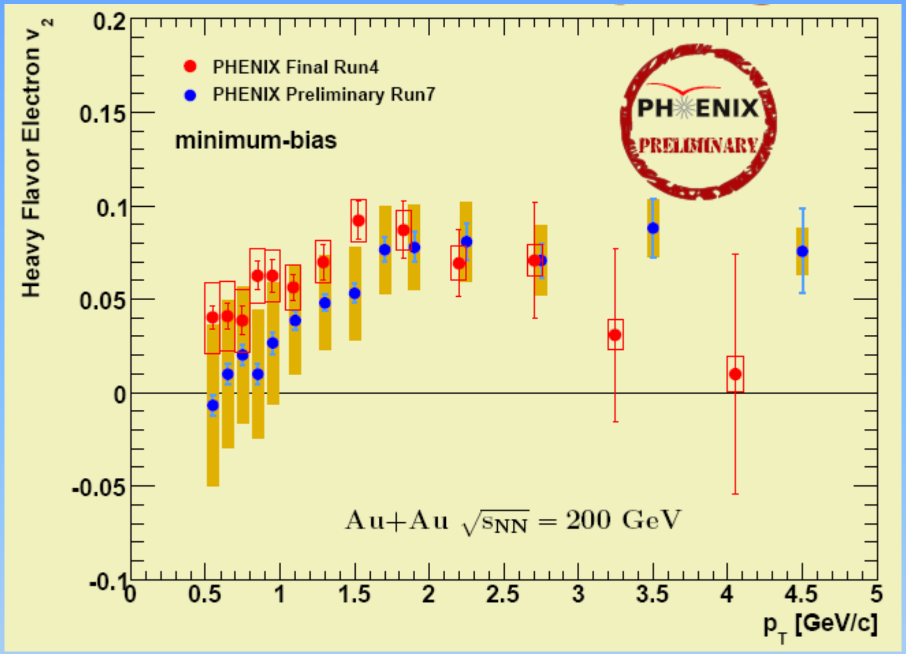
- Open Charm (and bottom) states decay with significant branching ratios (~10%) semi-leptonically.
- Parent quark mass makes these the dominant source at high p_T
- Cocktail (or convertor) subtraction yields spectrum of heavy flavor lepton decays.



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

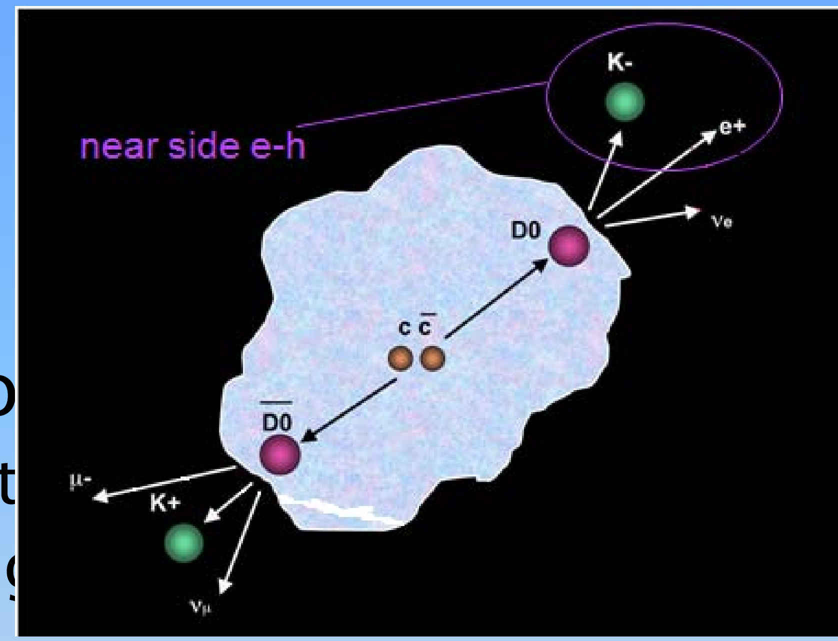
Heavy Flavor Leptons in AuAu



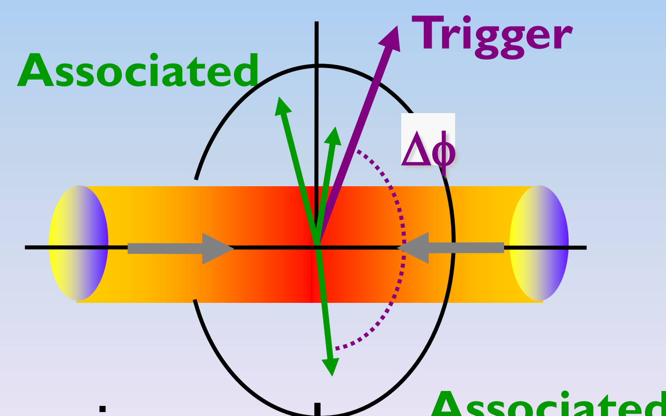


- Heavy Flavor shows suppression similar to π^0 at fill RHIC Energy.
- Heavy Flavor even flows.
- These results are the principal ones that define η/s.
- Similar conclusion for muons from CuCu: suppression similar to π

Heavy Flavor Decay e–h Correlations



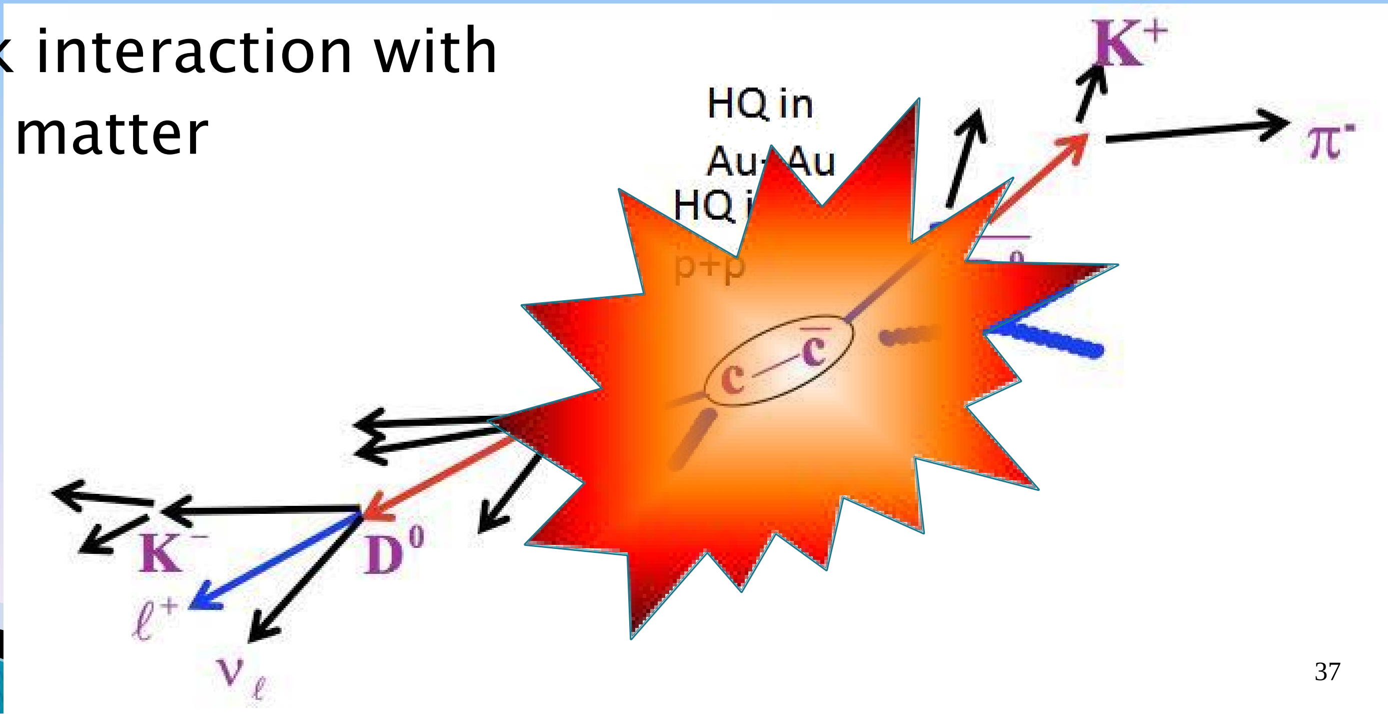
- Charm → D → e + X
- Bottom → B → e + X
- Trigger: $e^{+/-}$
- Associated: charged hadro
  - Near side: decay, fragmentat
  - Away side: from the balancin
  heavy quark
- Azimuthal distribution ($\Delta\phi$)



- Sensitive to geometry
- Sensitive to HQ energy loss
- Addressing the problem of HQ suppression and more

p+p vs. Au+Au

- p+p collisions @ √s = 200GeV
  - Data taken from 2005, 2006
  - control measurements
- Au+Au collisions @ √s = 200GeV
  - Data taken from 2007
  - Heavy quark interaction with hot nuclear matter



Method

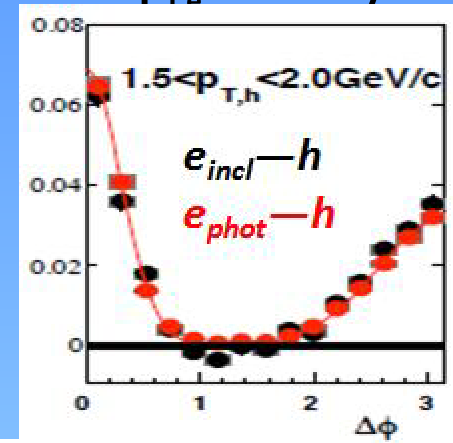
- $e_{incl} = e_{HF} + e_{phot}$
- $e_{HF} - h$:

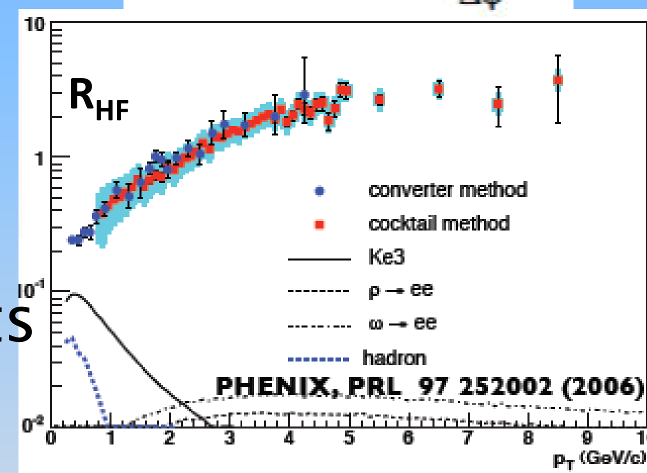
$$Y_{e_{HF}-h} = \frac{(R_{HF}+1)Y_{e_{incl}-h} - Y_{e_{phot}-h}}{R_{HF}}$$

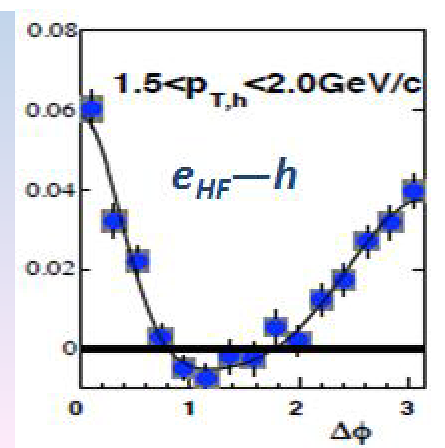
$$Y_{A-B} = \frac{1}{N^A}\frac{dN^{AB}_{(di)\,jet}}{d(\Delta\phi)} \qquad R_{HF} = \frac{N_{e_{HF}}}{N_{e_{phot}}}$$

- $e_{incl} - h$: from direct measurements
- $e_{phot} - h$:
  - e_{phot} from meson decay (mainly π^0)
  - Can be constructed from inclusive $\gamma - h$
- R_{HF} measured from data

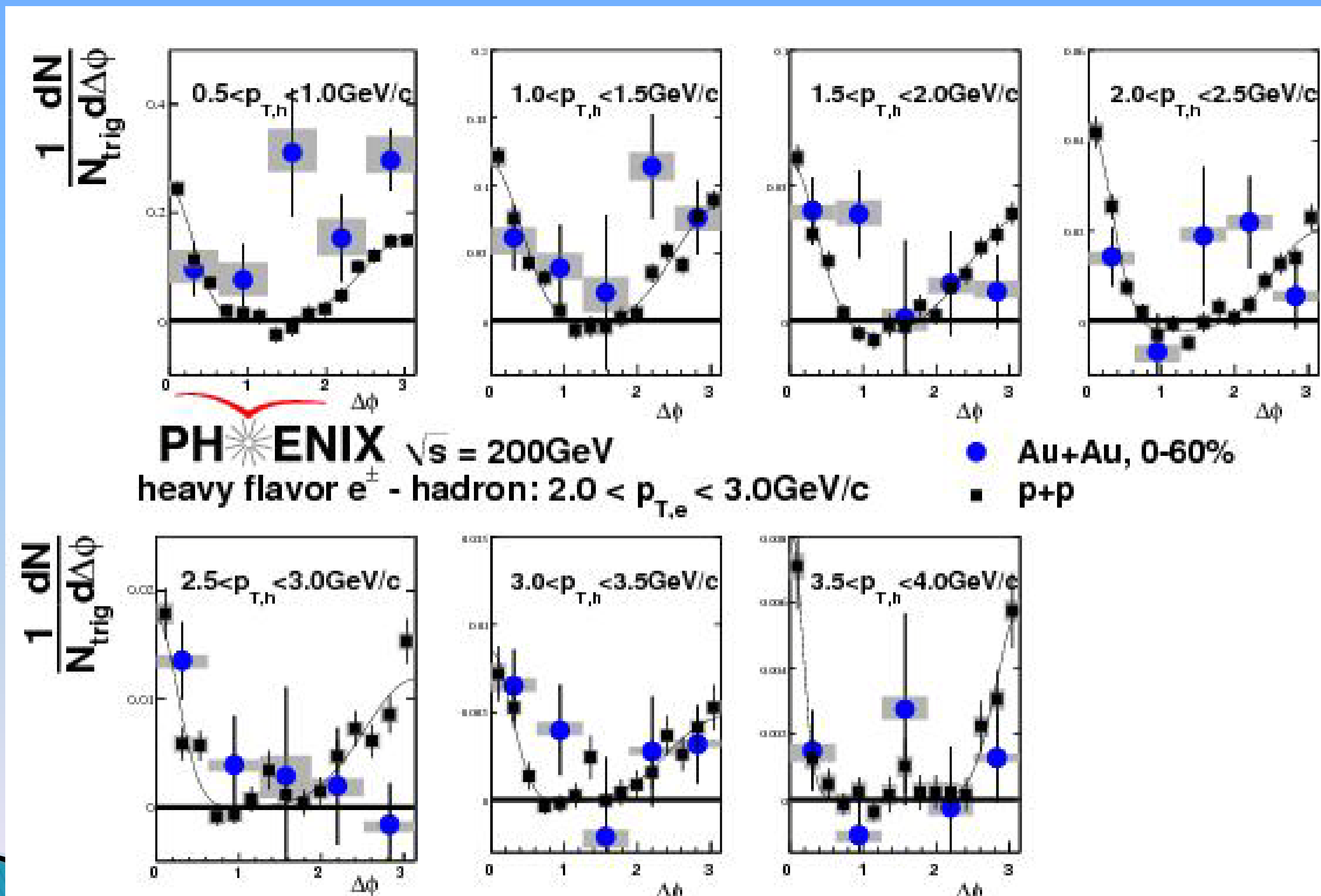
2.0<p$_{T,e}$<3.0GeV/c





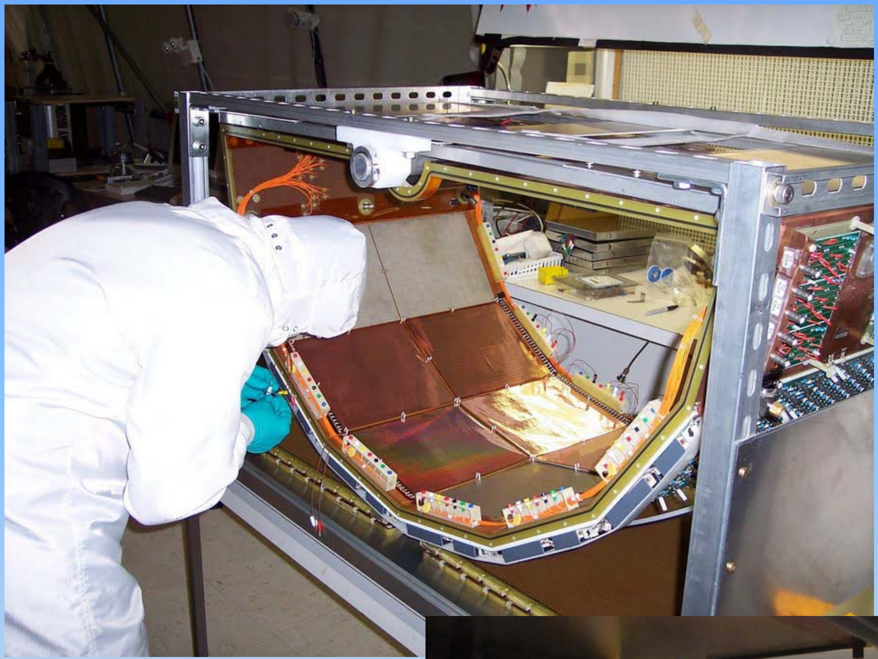


e_{HF} – h correlations p+p & Au+Au

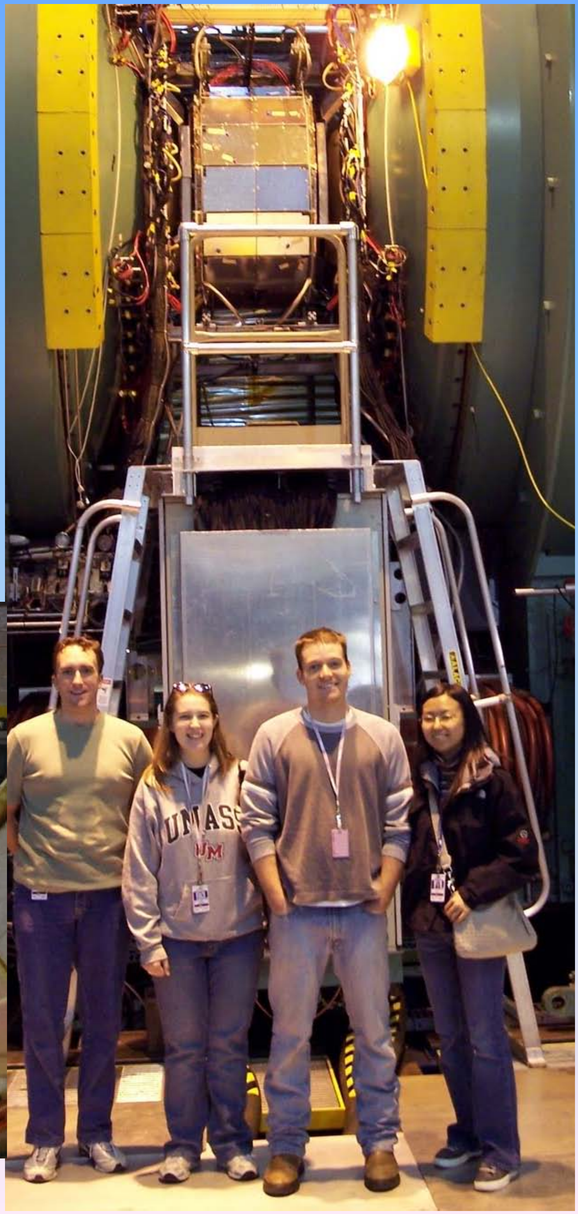


HBD Construction

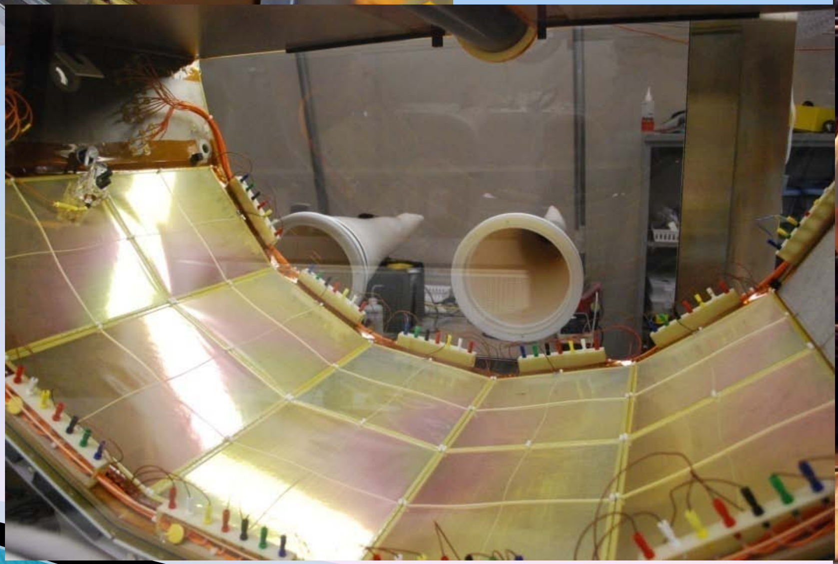
"Standard" CERN Cu GEM foils in HBD



2nd HBD installed in PHENIX



CSI photocathods on GEM foils

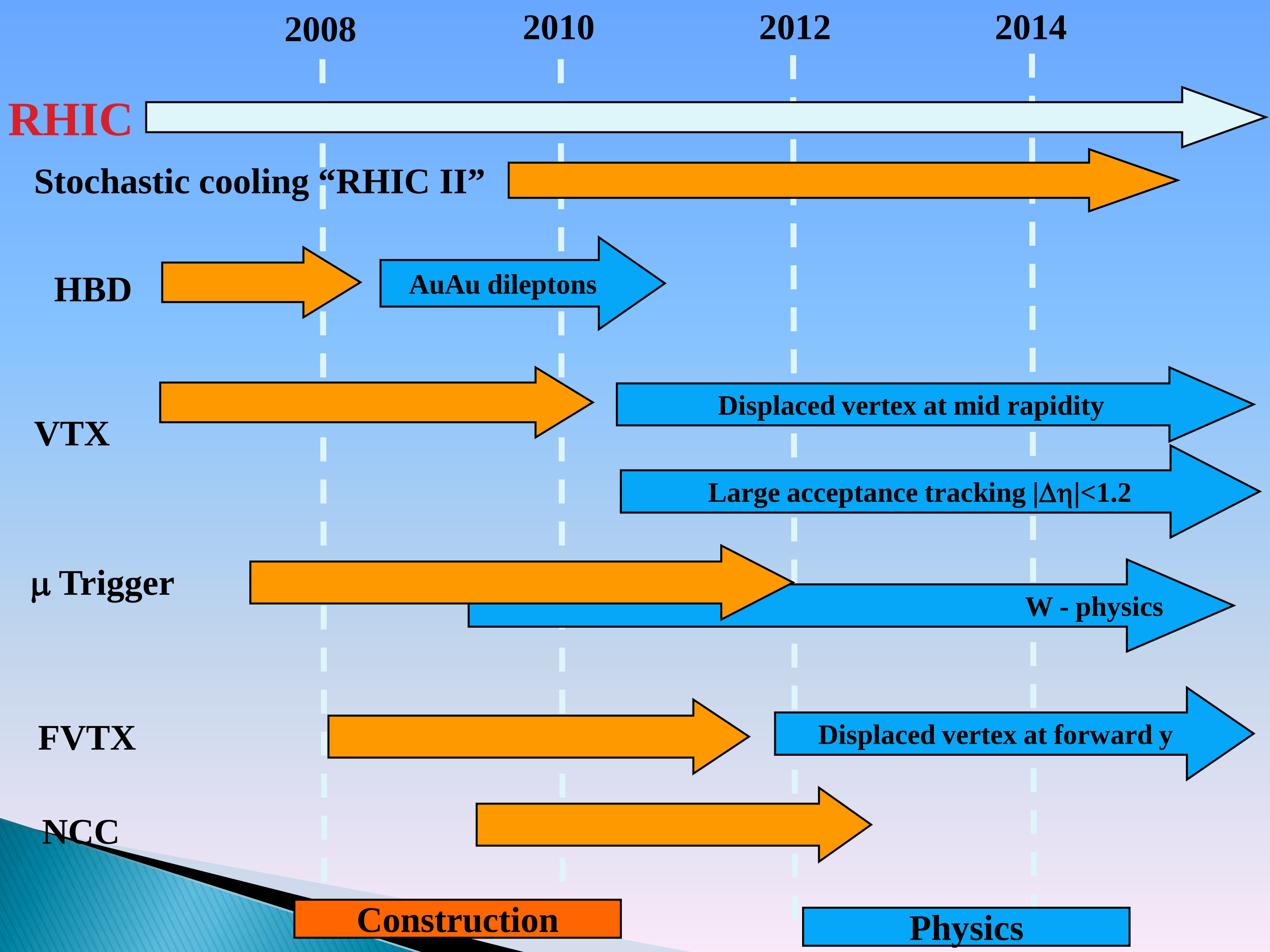


Summary

- 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.
  - Identify source of very low pT pairs in LMR
  - Precision on initial temperature.
  - Real photons through conversions.
  - Charm fate through IMR and Df correlations
  - Photon HBT????
- Future looks bright!

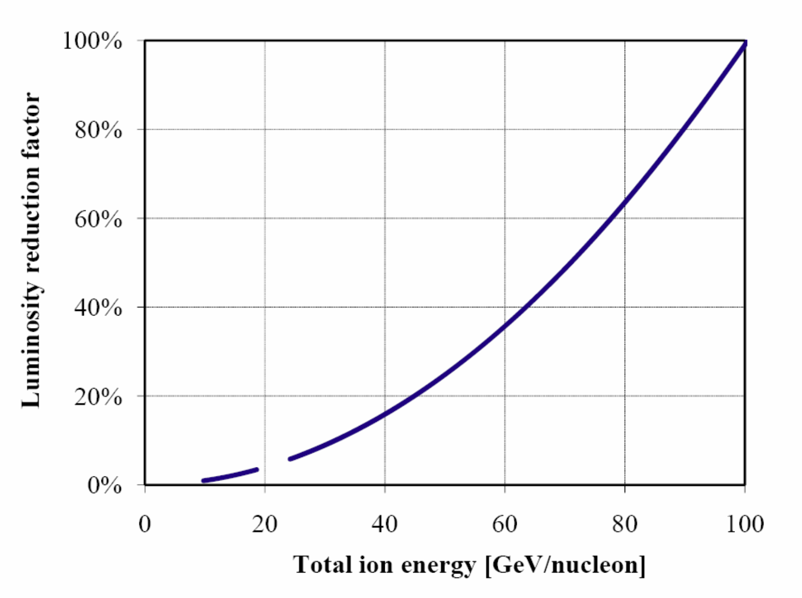
- Backups…

Timeline of PHENIX Upgrades



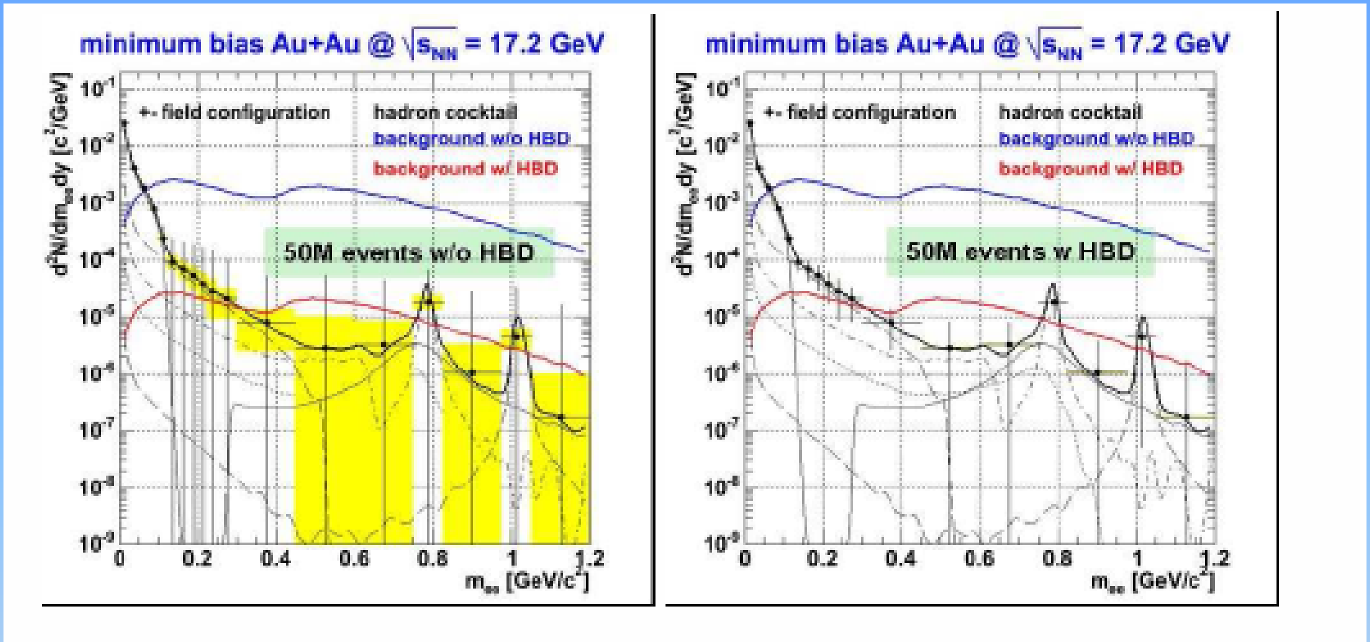
Examining these signatures at finite μ_B

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



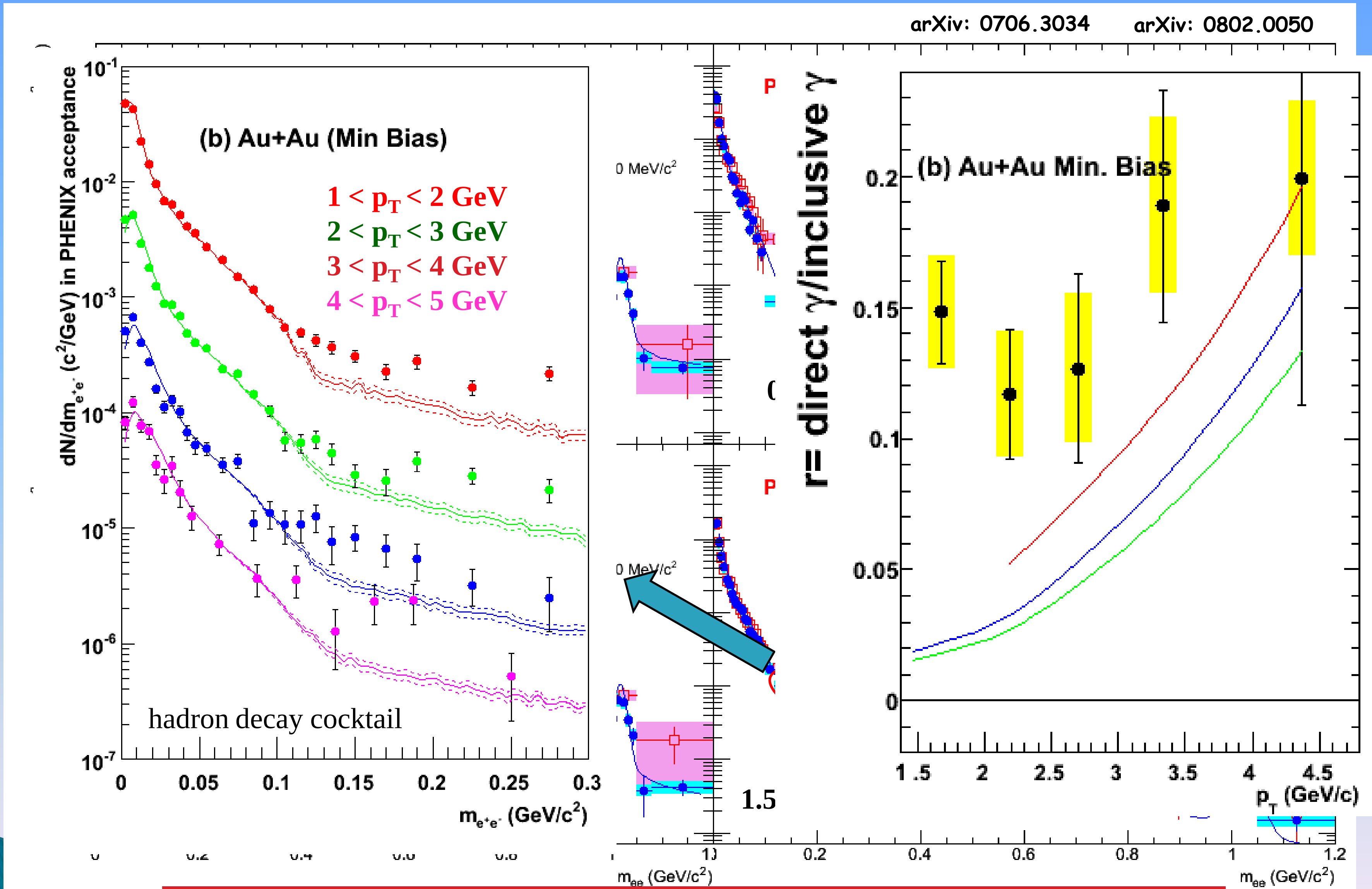
- Critical Point and the Onset of Deconfinement studies necessarily involve lowering the beam energy in the machine.
- Luminosity scales as the square of beam energy.
- Furthermore, heavy quarks suffer in production rate at lower energies.
- The product of these factors limits all present RHIC experiment 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:

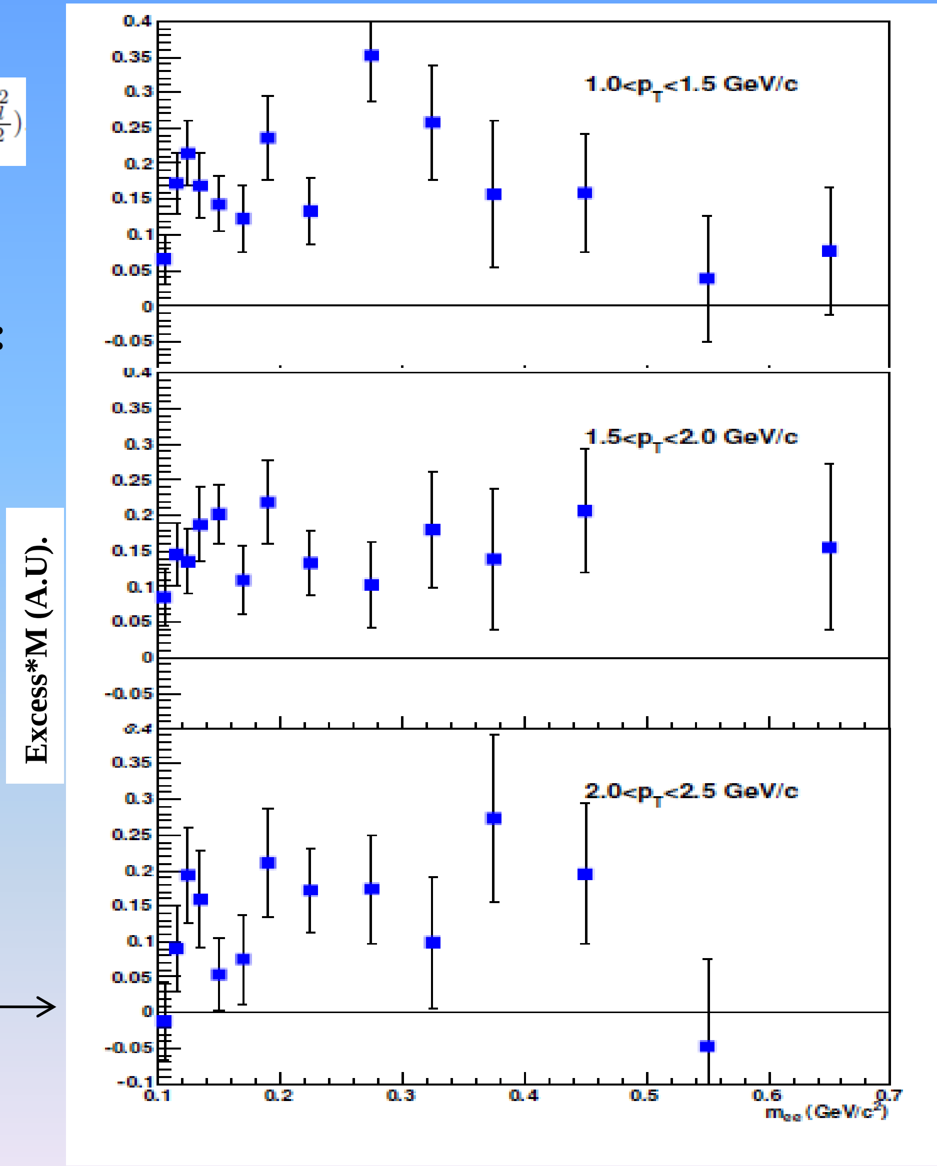
$$L(M) = \sqrt{1 - \frac{4m_l^2}{M^2}}\left(1 + \frac{2m_l^2}{M^2}\right)$$

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

Extrapolate real γ yield from dileptons:

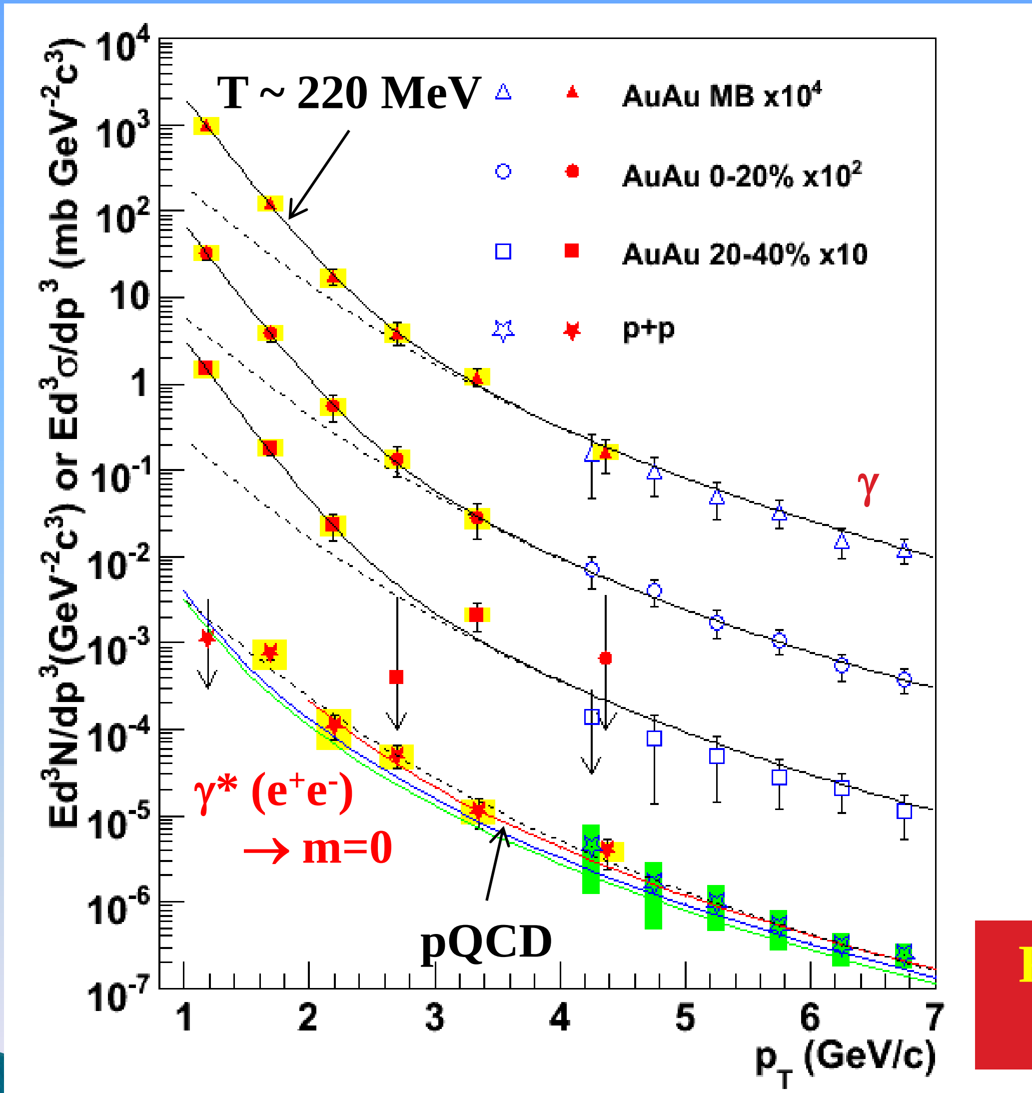
$$M \times \frac{dN_{ee}}{dM} \rightarrow \frac{dN_\gamma}{dM} \quad \text{for} \quad M \rightarrow 0$$

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

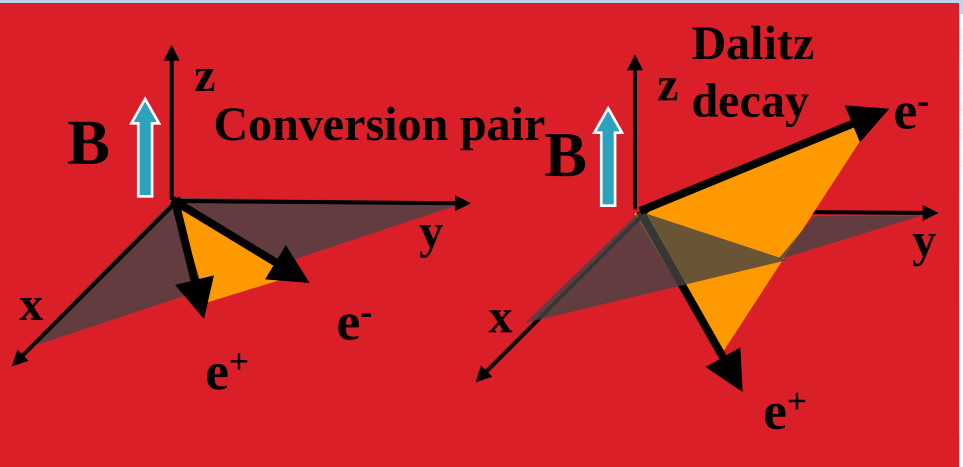
Direct photons from virtual photons:

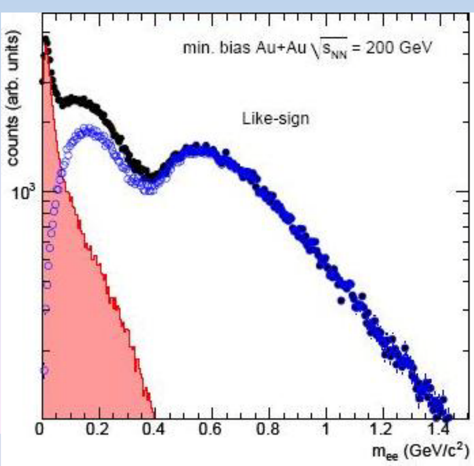
- Measure e^+e^- pairs at $m_\pi < m << p_T$
- Subtract η decays at S/B ~ 1:1
- Extrapolate to mass 0

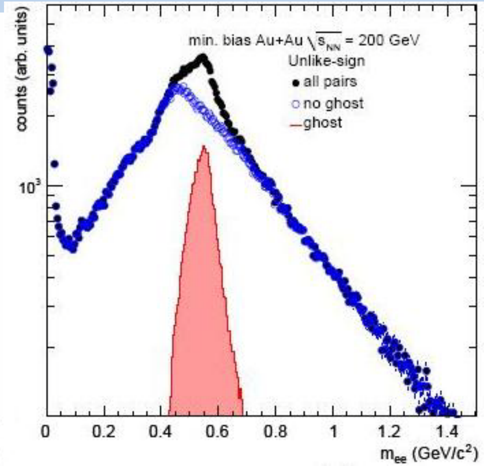
First thermal photon measurement:
T_{ini} > 220 MeV > T_C

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

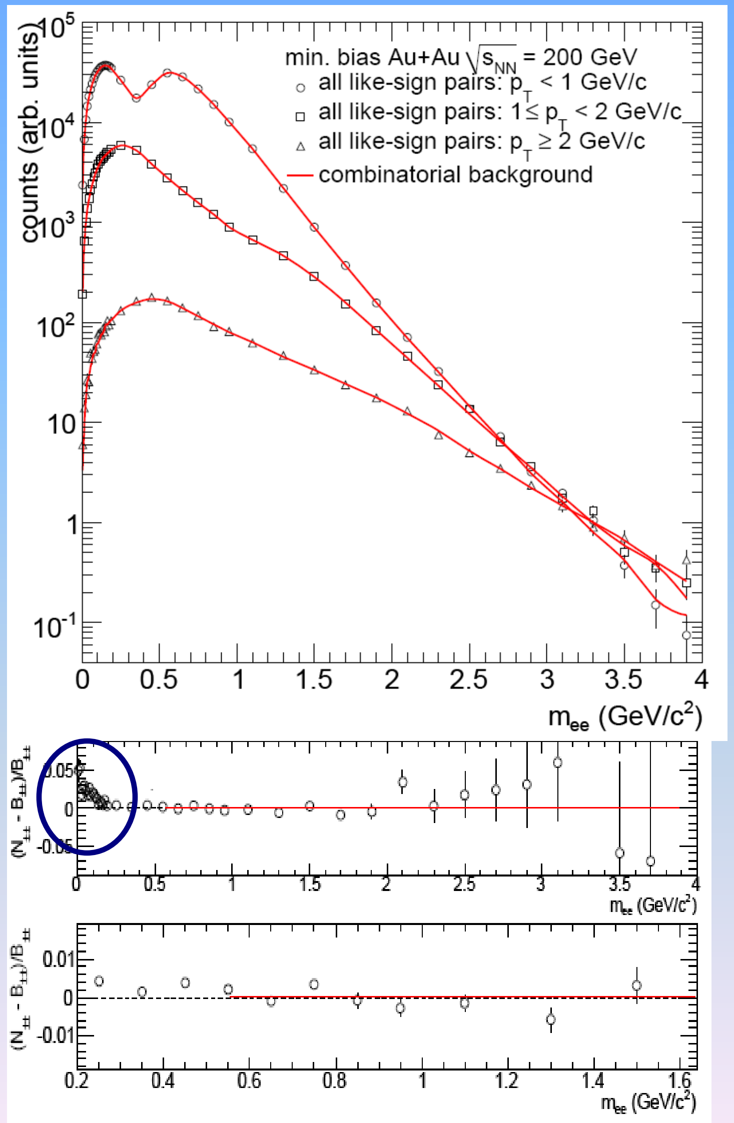






Combinatorial Background

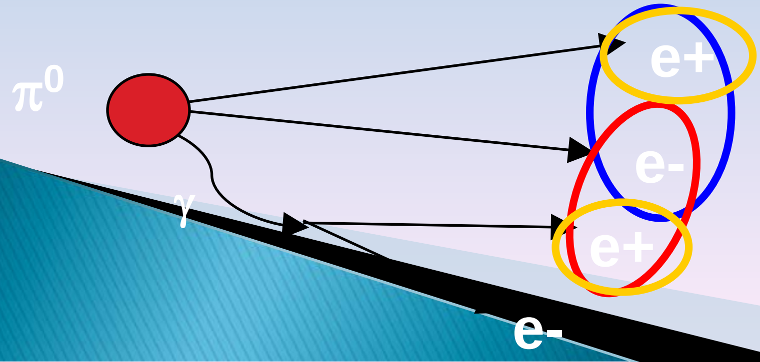
- Largest background in heavy ions
  - Large multiplicities
- Shape determined by event mixing
- Normalization determined using the like-sign pairs in regions where combinatorial dominates

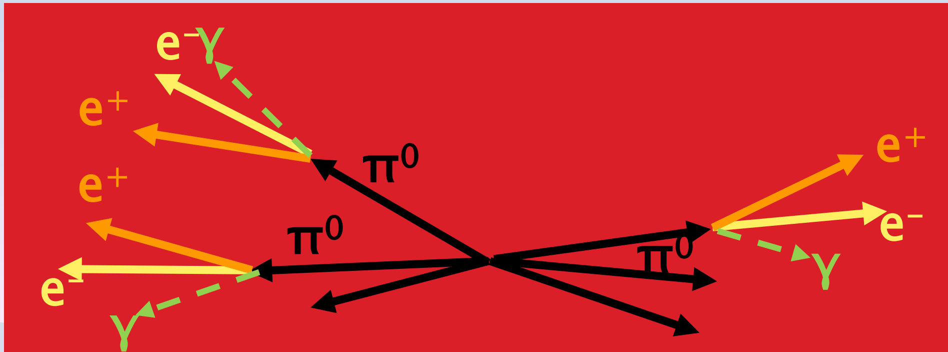


Correlated Background

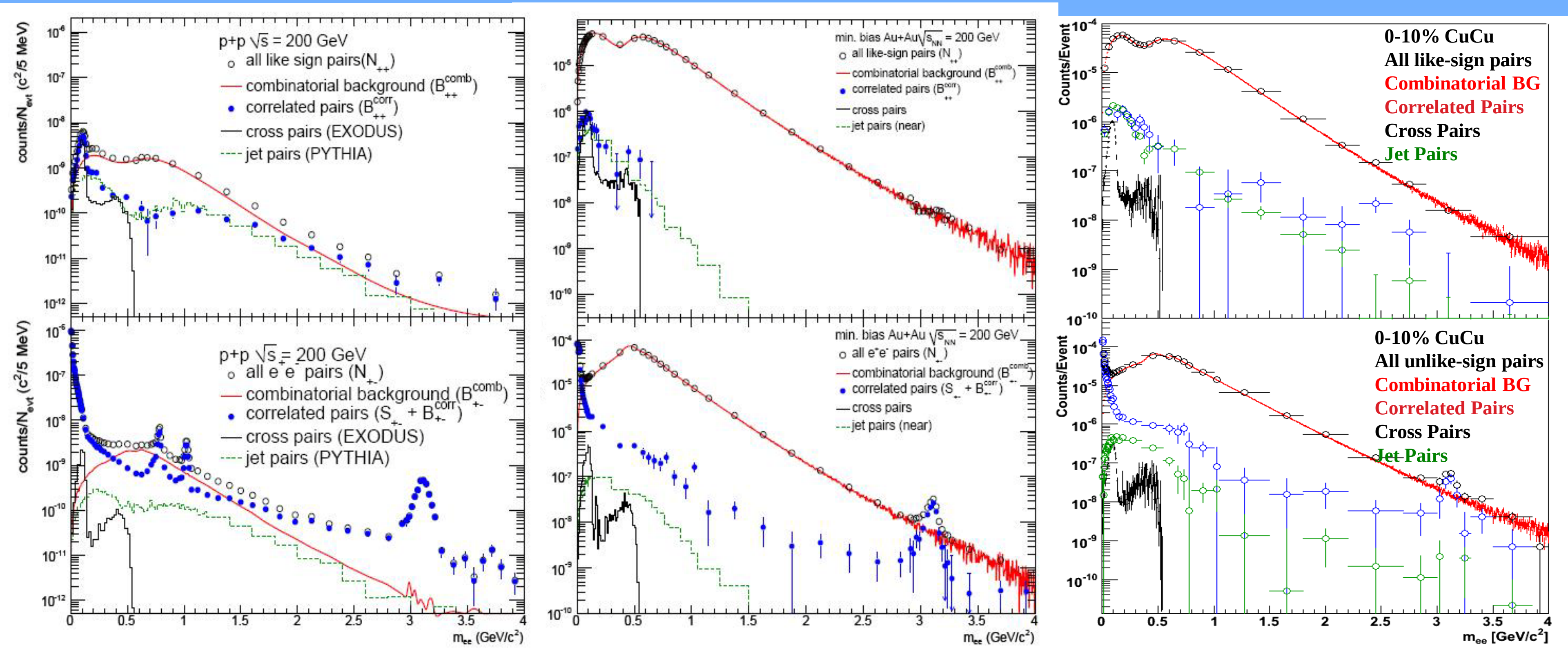
- "Cross" pairs
  - Decays that produce multiple lepton pairs
    - Double dalitz, double conversion, dalitz + conversion
    - Like-sign and unlike-sign pairs produced at same rate
  - Simulated with Exodus
    - Pions, etas only sizable source

- 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