Direct photons in PHENIX

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for the PHENIX Collaboration
Heavy Ion Collisions in the LHC era 2012
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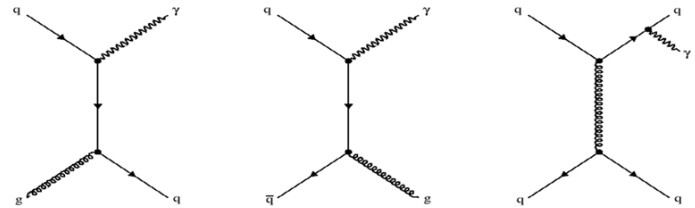
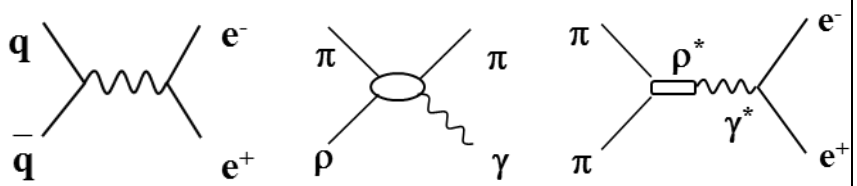
Outline

- Detector
- Measurements
  - High p_T photons in p+p and Au+Au
  - Low p_T thermal photons
    - Virtual photon method
    - External conversion method
- Direct photon flow in Au+Au
- Conclusions

Photon sources

- Hadron decays
  - π^0 ~ 80%, η ~15% background in p+p
- High p_T
  - Initial hard scattering → $v_2 = 0$
  - Fragmentation → $v_2 > 0$
  - Jet conversion and bremsstralung → $v_2 < 0$
- Low p_T
  - Thermal → $v_2 > 0$
  - $q\bar{q}$ annihilation in QGP
  - Hadron annihilation

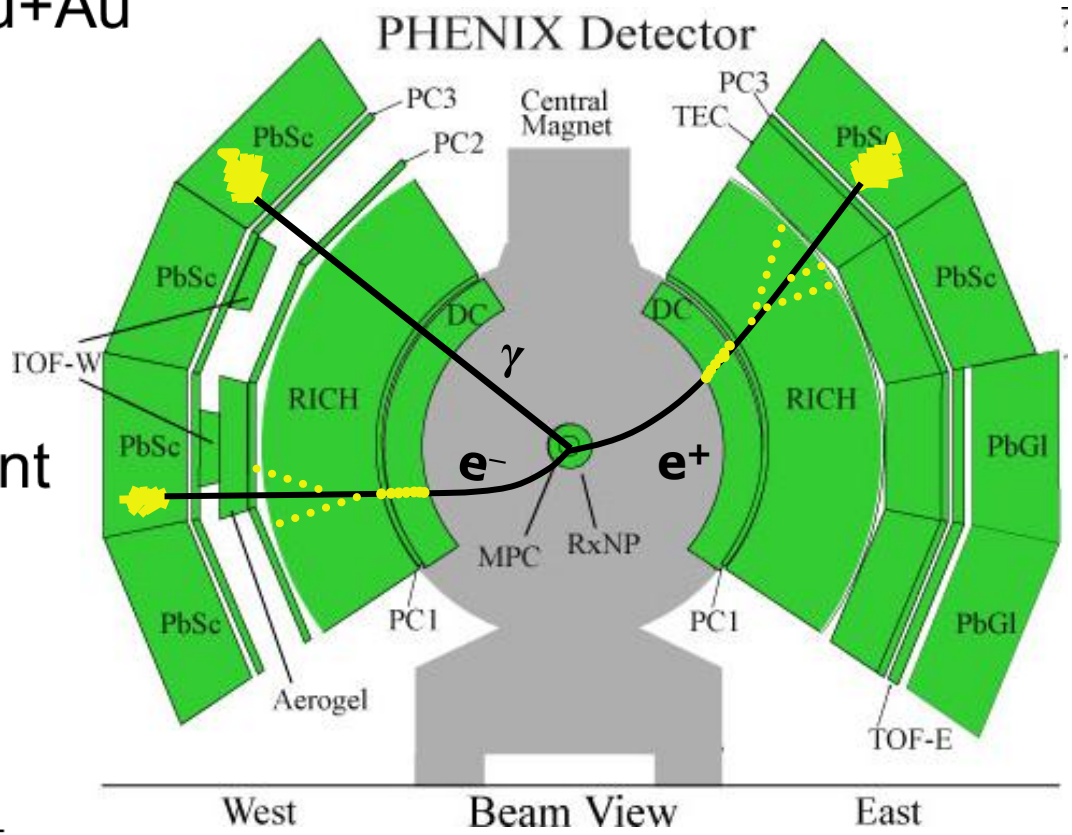




- Possible modifications
  - Isospin
  - nPDFs
    - Shadowing, anti-shadowing
  - Energy loss
    → suppress frag. photons
  - Radiation from jet-medium interactions
  - Modified ρ

PHENIX

- At RHIC
  - p+p, d+Au, Cu+Cu, Au+Au
- For EMCal photons:
  - Shower in the EMCal
    - PbSc $2.1\% \oplus 8.1/\sqrt{E}$
    - PbGl $0.8\% \oplus 5.9/\sqrt{E}$
  - No charged tracks point to the cluster
- For virtual photons:
  - Tracking in DC & PC1
    - $\sigma_{pT}/p_T = 0.7\% \oplus 1\%\ p_T$
  - Electron ID with RICH ring and EMC shower



p+p high p_T photon measurement

- π^0 Tagging method
  - Reconstruct $\pi^0 \rightarrow \gamma\gamma$ to measure $N_{\pi 0}$
    - E^{γ}_{min} cut to remove cluster merged photons

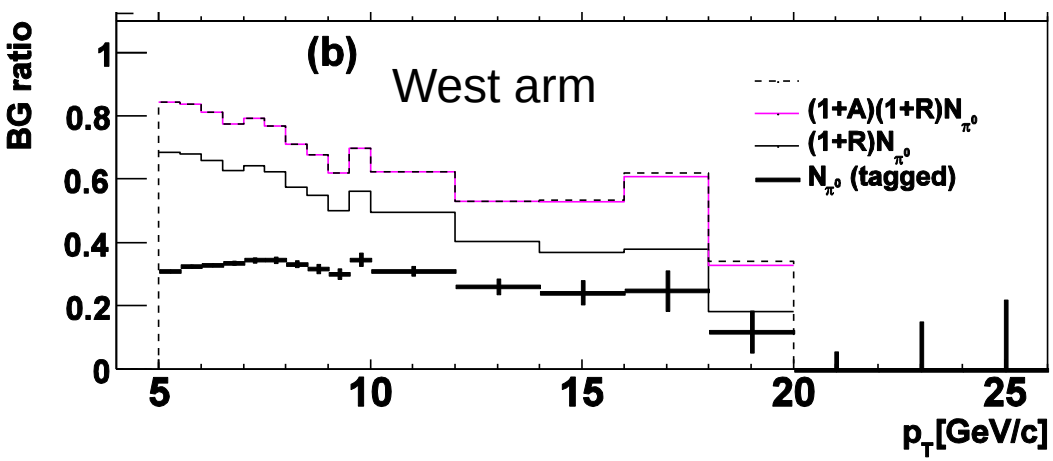
unmerged π^0's

$$N_{Dir} = N_{Incl} - (1+A)(1+R)N_{\pi^0}$$

π^0, η, ω and η' backgrounds

A calculated with m_T scaling, meson-to-π ratios

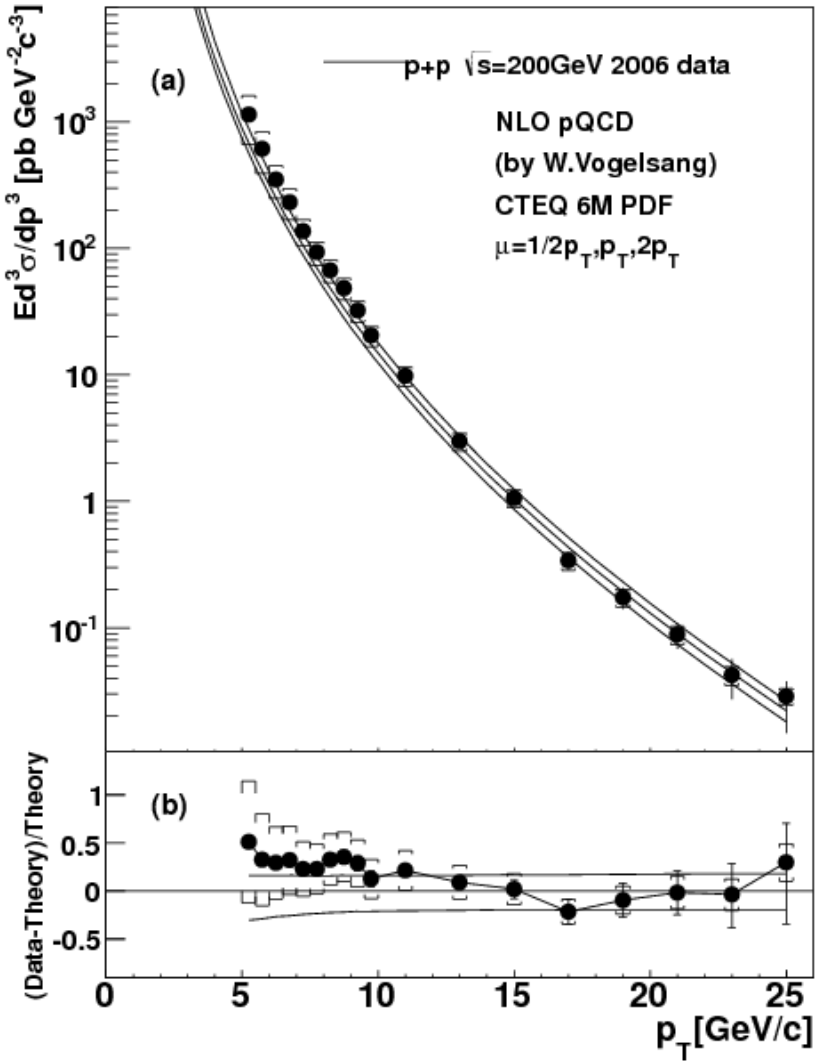
R calculated by Monte Carlo using the known π^0 shape, detector dead areas, acceptance and resolution



High p_T photons in p+p

- 2006 PHENIX p+p data
  - p_T 5-25 GeV/c
- Agrees with NLO pQCD
  - BFGII Frag. Function
- Power law fit
  - p_T 8-25 GeV/c
  - χ^2/NDF = 8.3/10

$$n = 7.08 \pm 0.09\ (\text{stat}) \pm 0.1\ (\text{sys})$$



arXiv:1205.5533

High p_T photon measurement in Au+Au

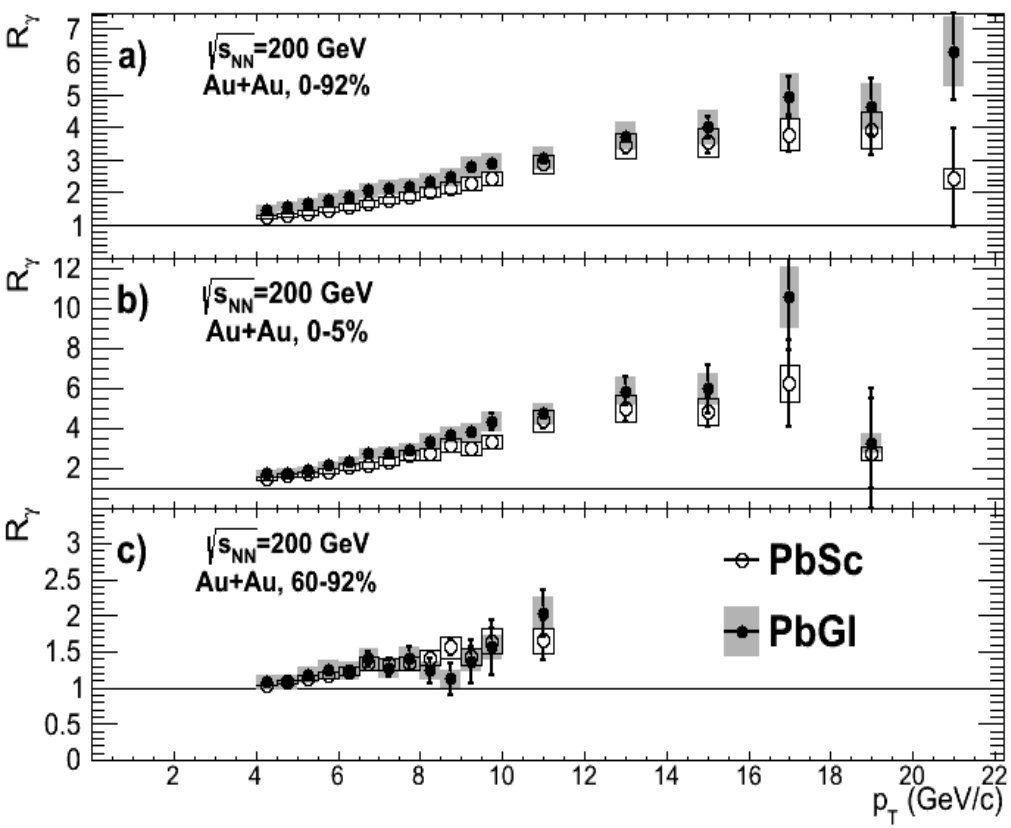
- Double ratio method
  - Systematic errors cancel

$$\gamma_{Direct} = \gamma_{Incl} * (1 - 1/R_\gamma)$$

$$R_\gamma = \frac{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Meas}}{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Sim}}$$

Photons from hadron decays

Simulation calculated with detector resolution, dead areas, and meson-to-pion ratios



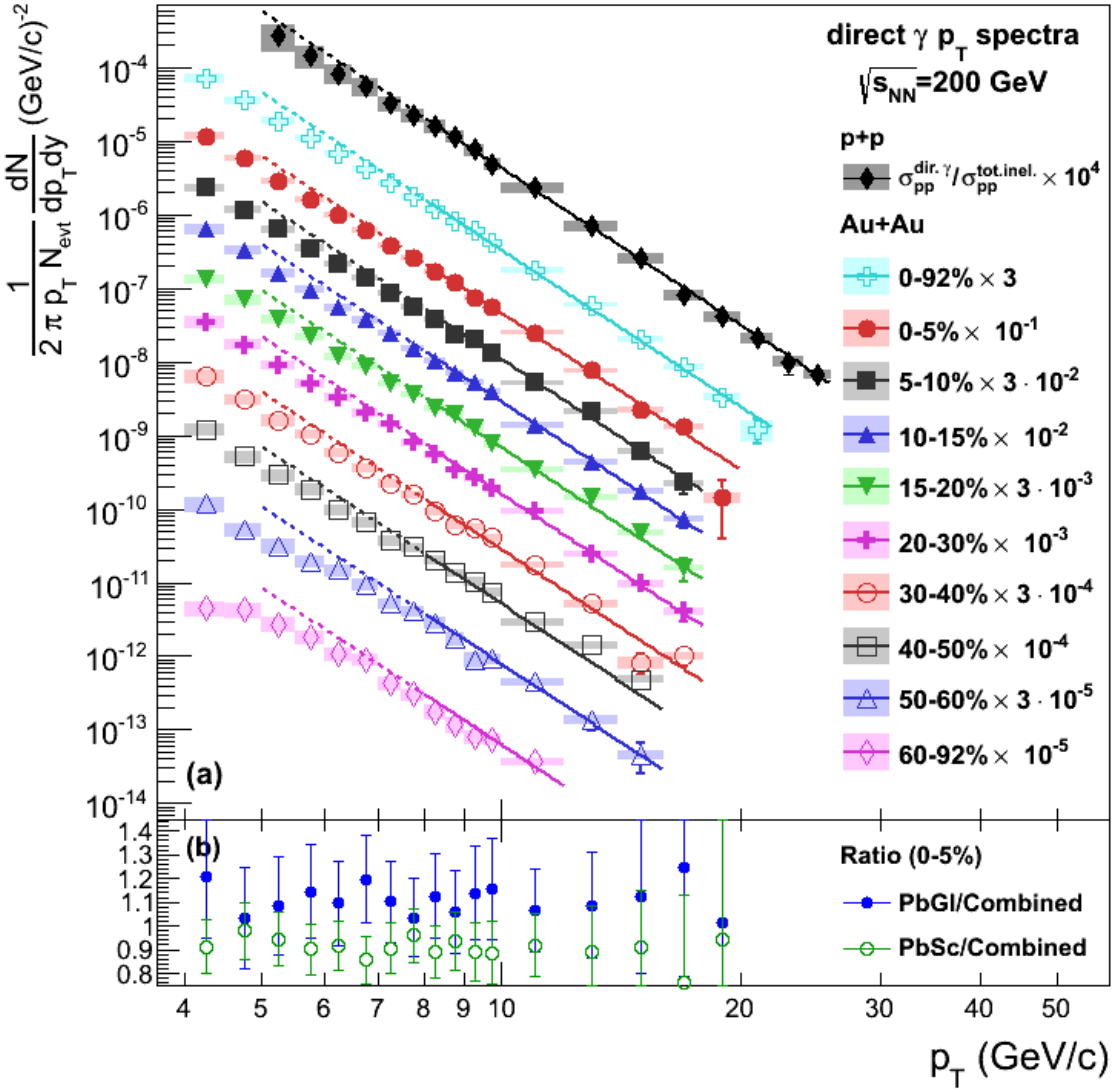
- R_γ increases with centrality because π^0 suppressed

arXiv:1205.5759

High p_T photons in Au+Au

- 2004 Au+Au data
  - p_T 4-22 GeV/c
- T_{AA} scaled fit of p+p data
  - No apparent modification

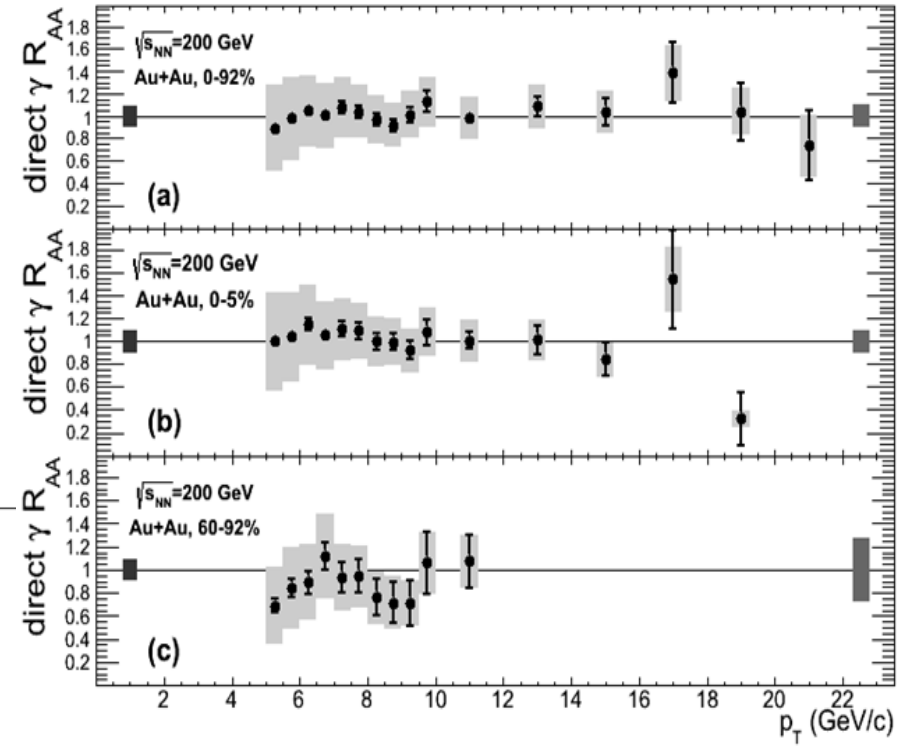
$$T_{AA} = {N_{Coll}}/{\sigma_{pp}{}^{inel}}$$

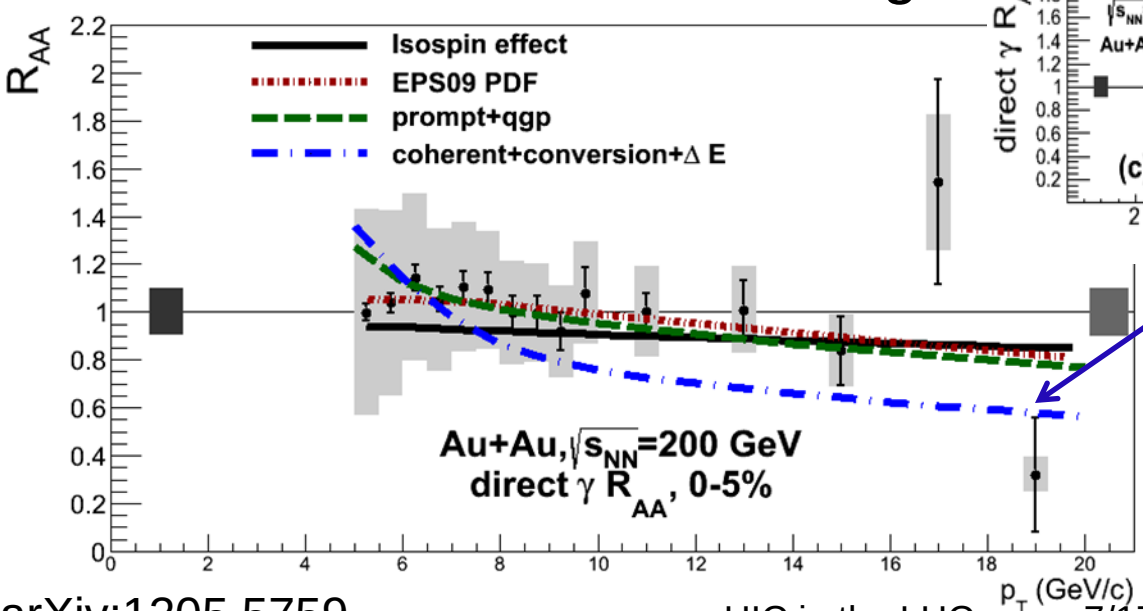


arXiv:1205.5759

R_{AA} direct photons

- First time using p+p reference data NOT a fit
- Consistent with 1
  - No modification OR balancing of terms
    - energy loss, medium-induced bremsstralung





Does not agree with the data

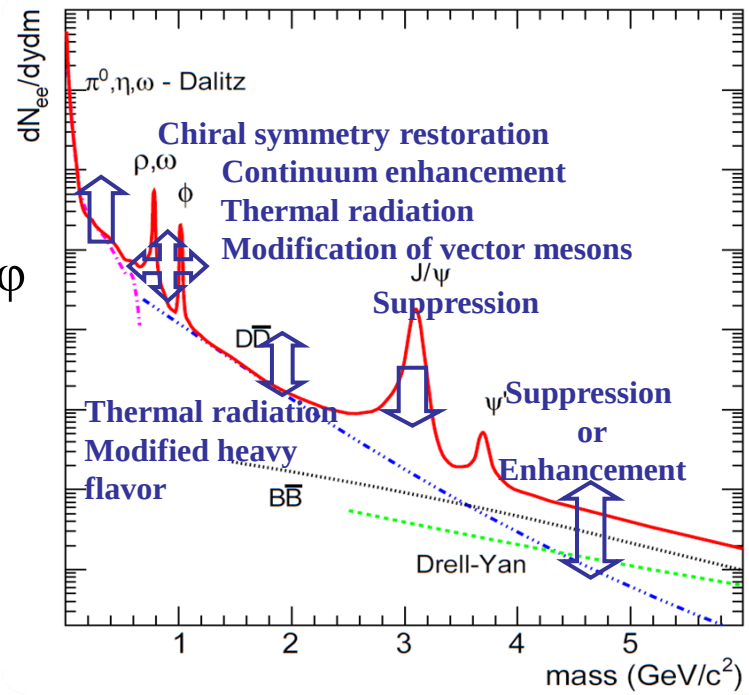
Most of high pT direct photons are from hard scattering

arXiv:1205.5759

Thermal photons from dielectrons

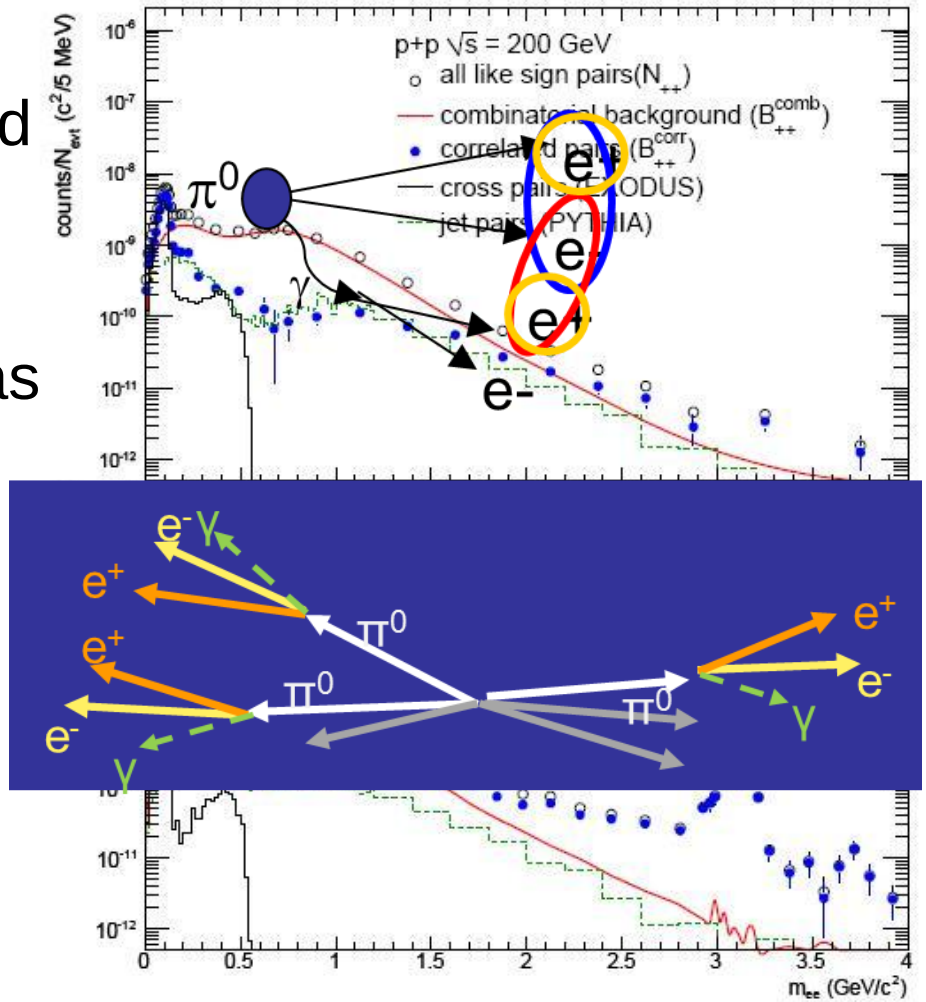
- Virtual photons access low p_T thermal photons
  - $m_{ee} << p_T \rightarrow m_{ee} < 0.3$, $p_T > 1$

- Cocktail background signals
  - Hadron → e+e- ω, ρ, φ
  - Hadron Dalitz decays π^0, η, η', ω, φ
  - Correlated open charm decays
- Possible QGP modifications
  - Mass-modified ρ
  - Correlated charm modification
  - Additional thermal photon yield



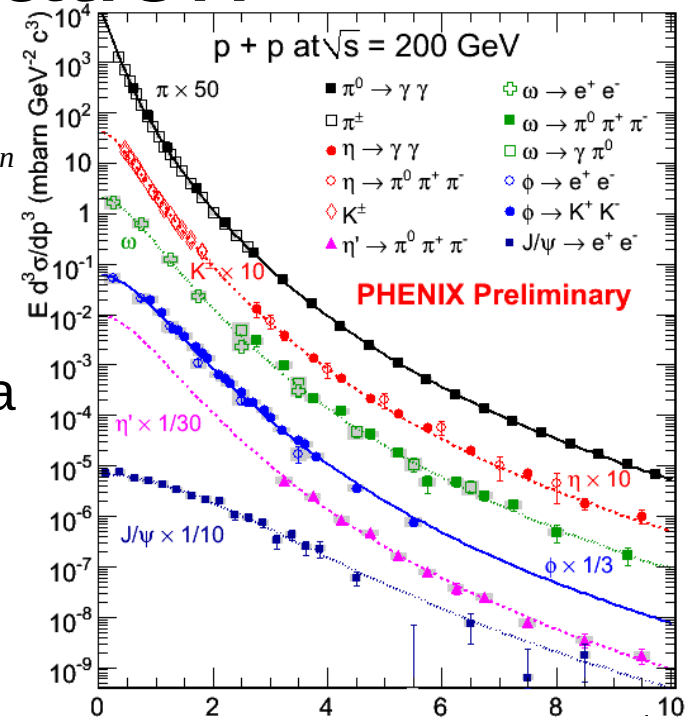
Background removal

- Remove with pair cut
  - Conversions, RICH ring overlap
- Simulate backgrounds
  - Combinatorial → event mixed
  - Jets → Pythia
  - Cross pairs → Exodus
  - Include efficiency, dead areas
- Statistical subtraction
  - in m_{ee} and p_T
- Use like-sign pairs to normalize backgrounds
  - No like-sign signal yield
- Correct for efficiency, dead areas in m_{ee} and p_T



Cocktail Generation

- Hadrons from Exodus using data
  - π p_T spectra fit: $E\frac{d^3\sigma}{dp^3} = A(e^{-(ap_T+bp_T^2)} + p_T / p_0)^{-n}$
  - m_T scaling: $p_T \rightarrow \sqrt{p_T^2 + m_{meson}^2 - m_\pi^2}$
  - When able use measured mesons p_T spectra
    - J/ψ suppression, J/ψ and ψ' rad. tails



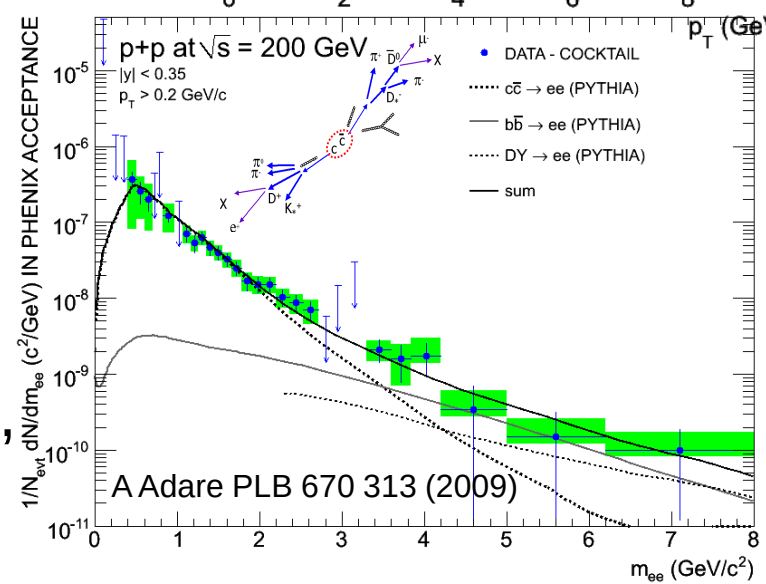
- Charm, Bottom, Drell Yan from Pythia
  - In p+p, measure the σ_{cc}

σ_{cc} = 544 ± 39(stat) ± 142(sys) ± 200 (model) μb

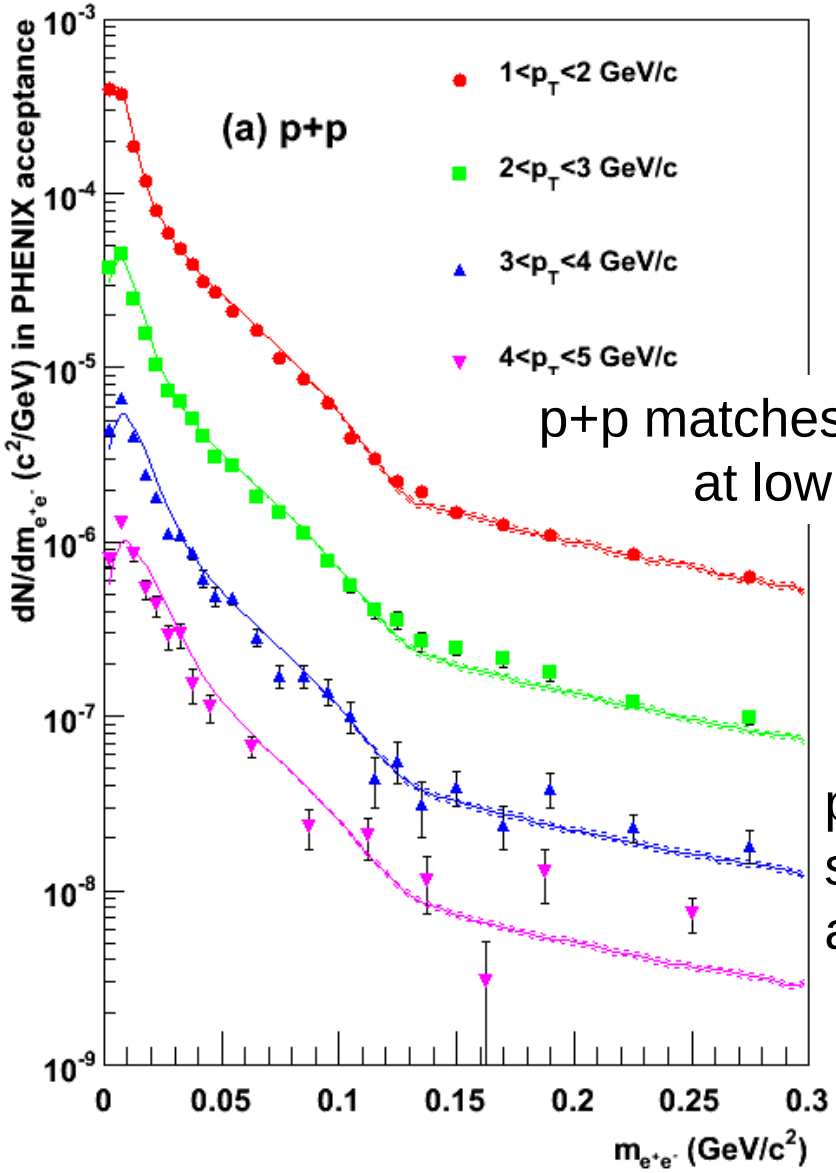
    - agrees with non-photonic single e-

σ_{cc} = 567 ± 57(stat) ± 193 (sys) μb

  - d+Au, Cu+Cu, Au+Au N_{Coll} scale
- Filter into PHENIX ideal acceptance, smear by detector resolution

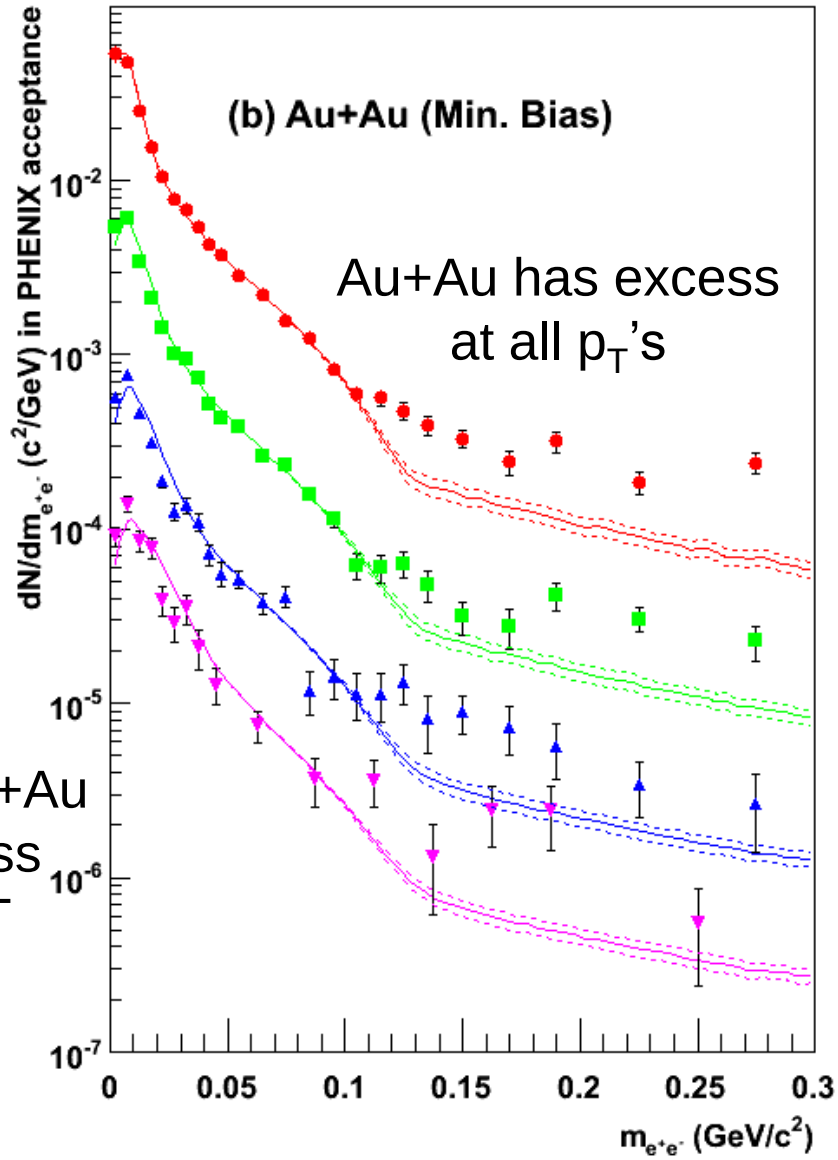


Dielectron mass spectra in p_T slices



p+p matches cocktail at low p_T

p+p & Au+Au see excess at high pT



Au+Au has excess at all p_T's

PRC 81 02391 (2010)

Photons from dielectrons

- Virtual photons produce e+e- pairs
  - $m_{ee} << p_T \rightarrow p_T > 1$, $m_{ee} < 0.3$
  - $m_{ee} > 0.15 \rightarrow$ avoid large π^0 backgrounds
- Thermal photon production

$$\frac{d^2N_{ee}}{dM^2} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}S(M,q)dN_\gamma$$

  - As $m_{ee}/p_T \rightarrow 0$, then $L(m_{ee}) \rightarrow 1$, $S(m_{ee}) \rightarrow 1$

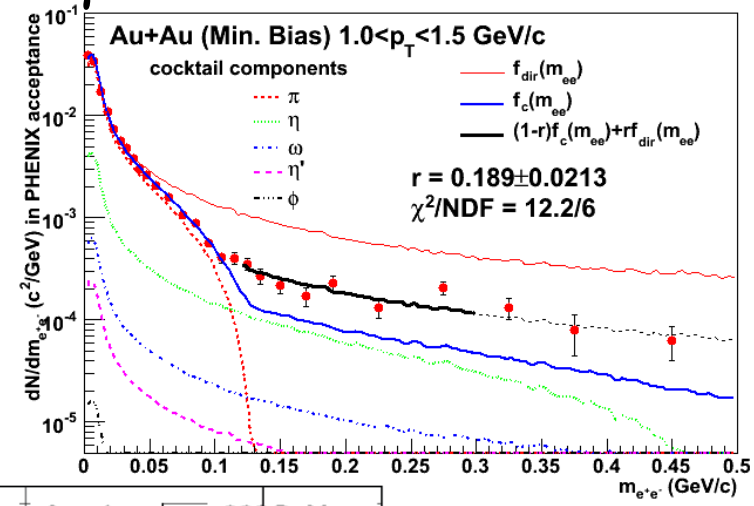
$$\frac{d^2N_{ee}}{dm_{ee}dp_T} \simeq \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\frac{dN_\gamma}{dp_T}$$

- Thermal photon component, $f_{dir}\ \alpha\ 1/m_{ee}$
  - Filter by acceptance, smear by resolution

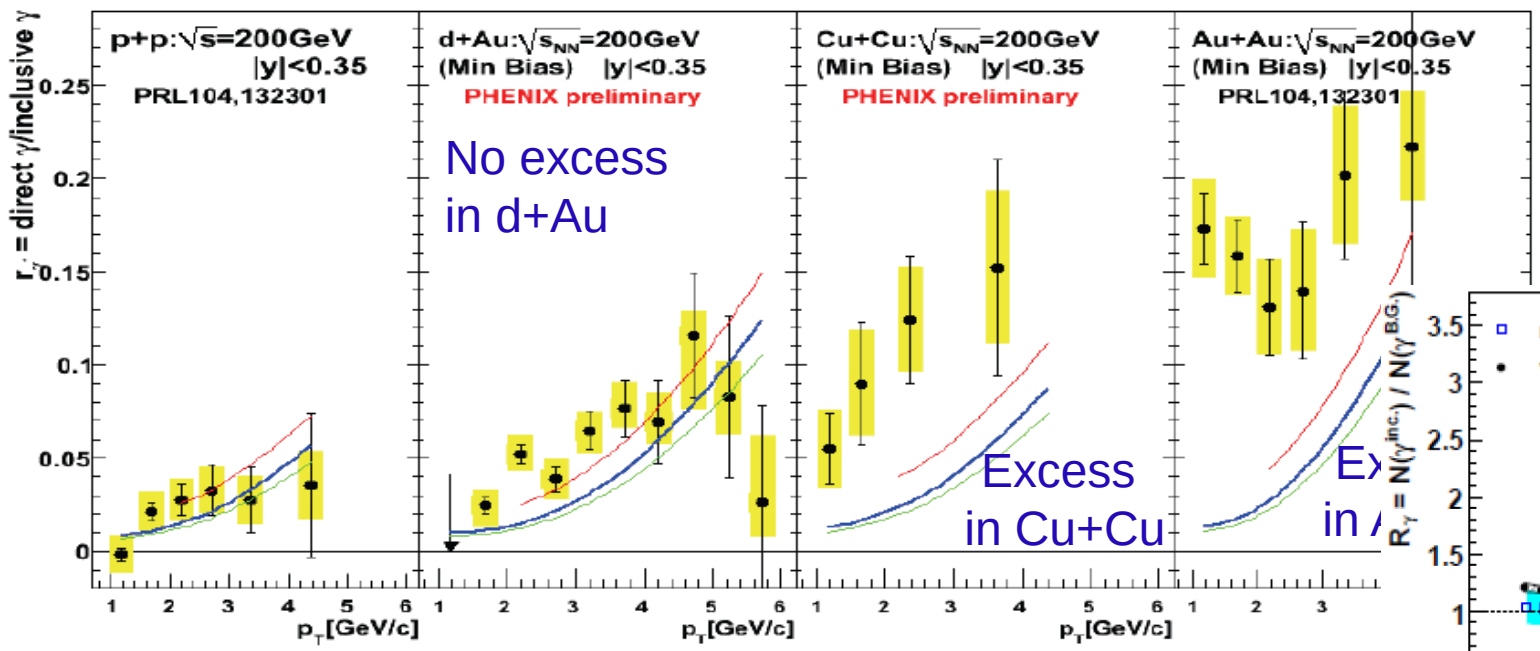
Fit to find r_γ

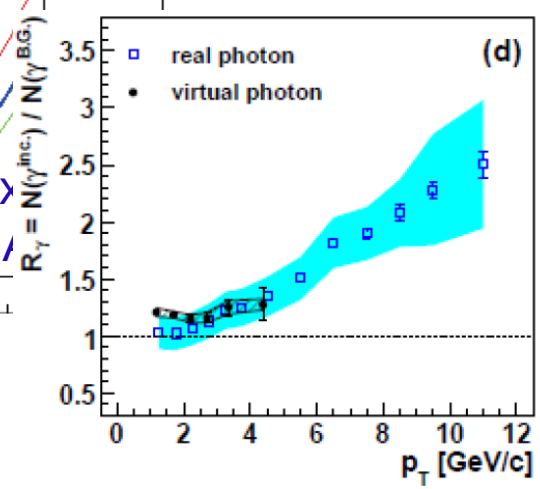
$$f(m_{ee}) = (1 - r_\gamma) f_c(m_{ee}) + r_\gamma f_{dir}(m_{ee})$$

$$r_\gamma = R_\gamma$$



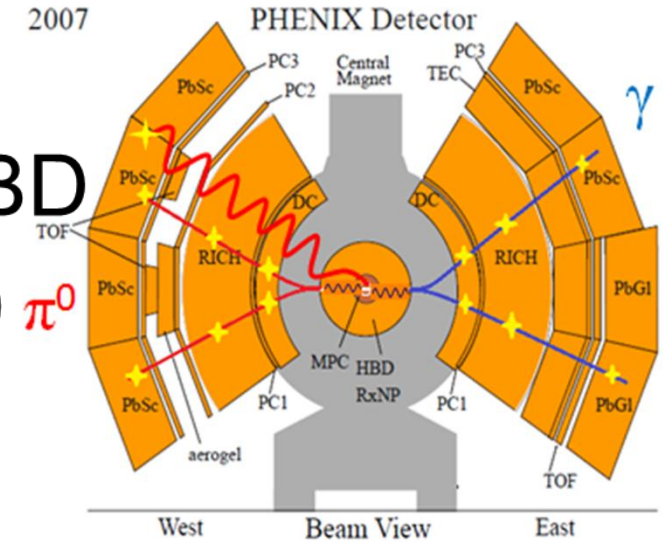
- Fit for m_{ee} in 0.15-0.3 GeV/c^2 in each p_T slice

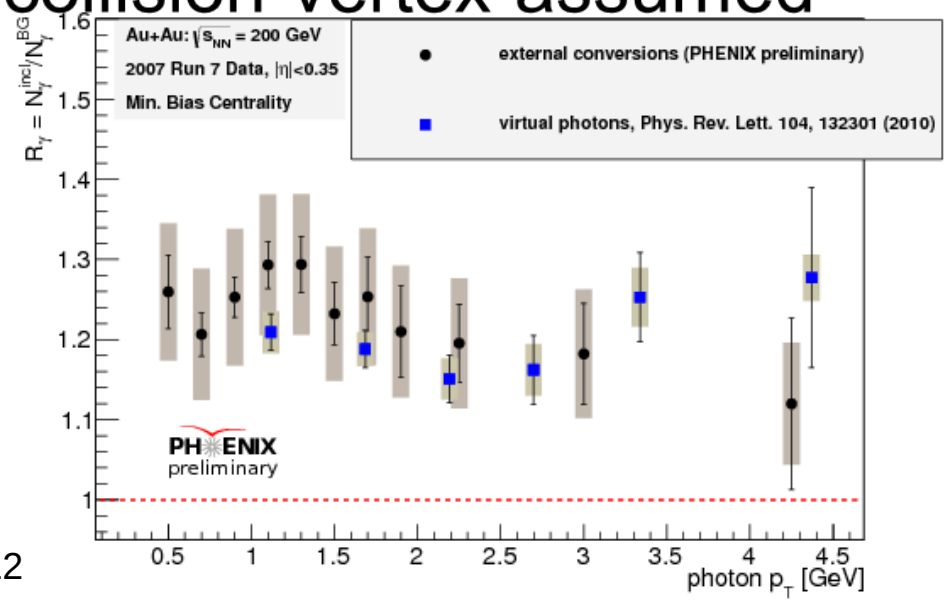




Au+Au low p_T photons

- External conversion method
- Photons convert in back of HBD
  - Off-vertex decay (r_{conv} ~ 60 cm)
- Apparent mass from mis-reconstructed momentum
  - In PHENIX 2007 data, collision vertex assumed
  - $m_{ee} \propto r_{conv}$
- R_γ method
  - Measure π^0 by tagging inclusive π^0 photons

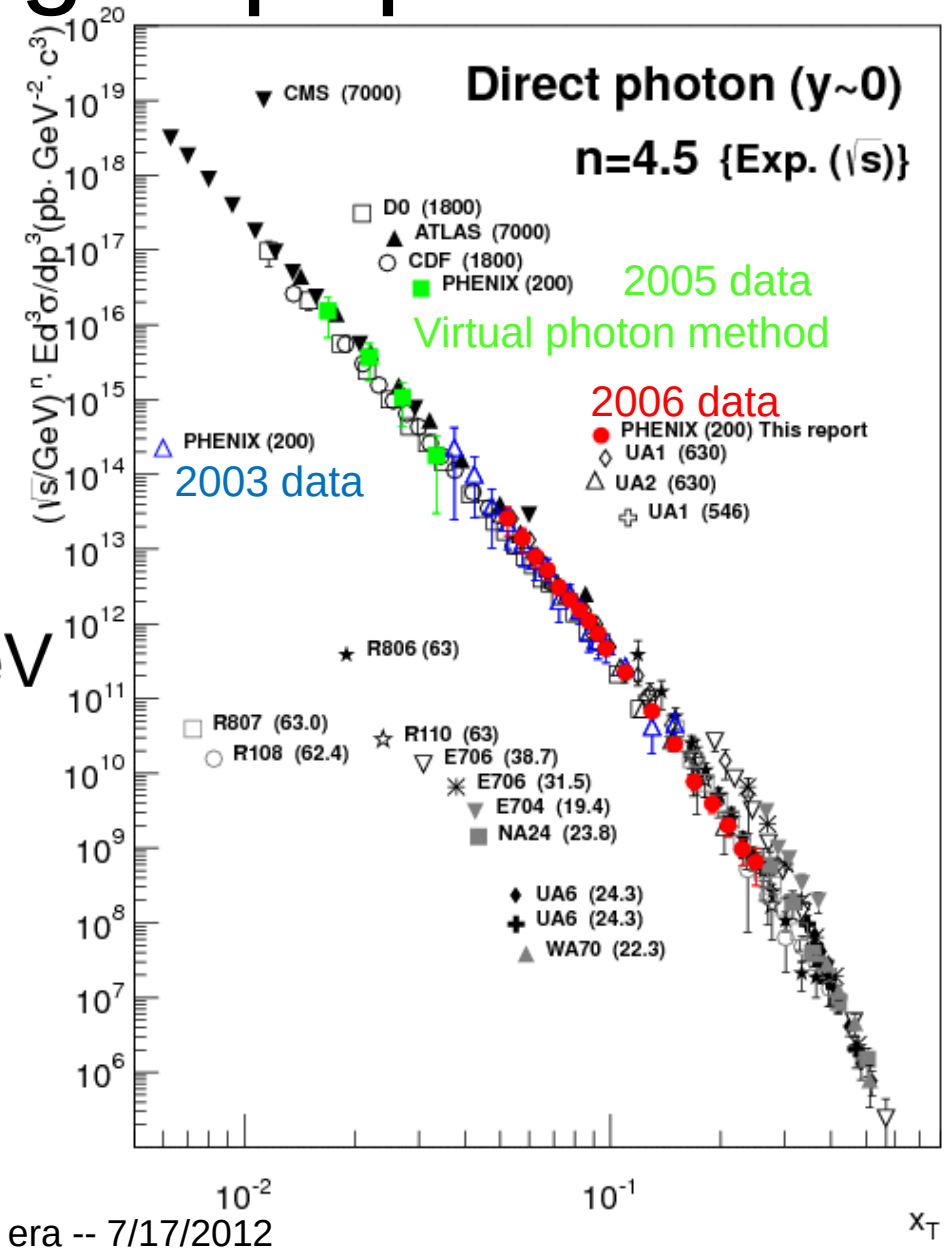




x_T scaling in p+p

- PHENIX p+p $\sqrt{s_{NN}} = 200$ GeV data with other p+p experiments
  - Collider & fixed target
  - $\sqrt{s_{NN}} = 19.4$ - 7000 GeV
- Cross sections scaled by $\sqrt{s}^{n_{eff}}$, $n_{eff} = 4.5$

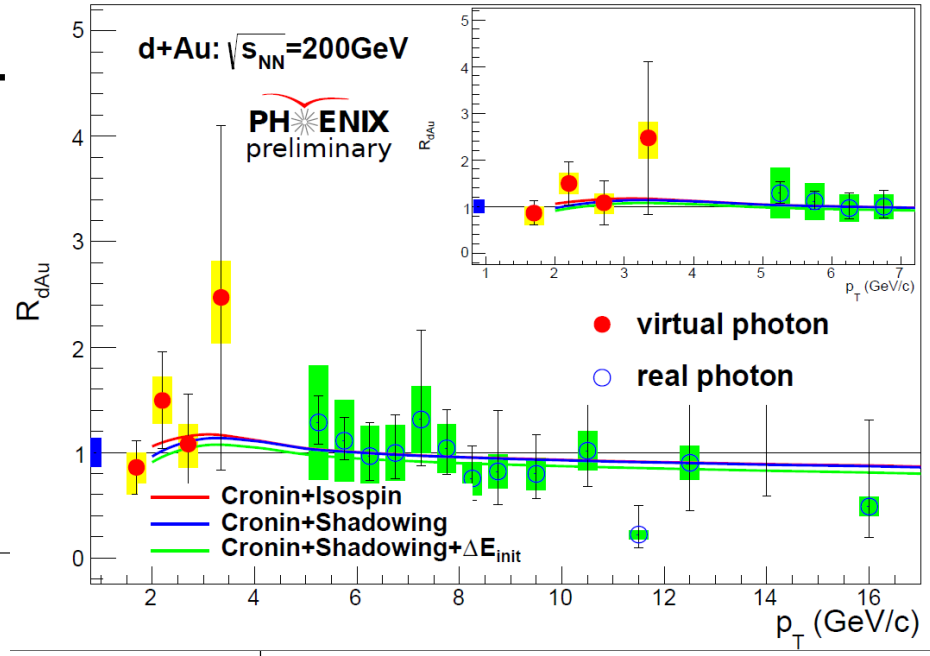
$$x_T = {2\,p_T}/{\sqrt{s}}$$

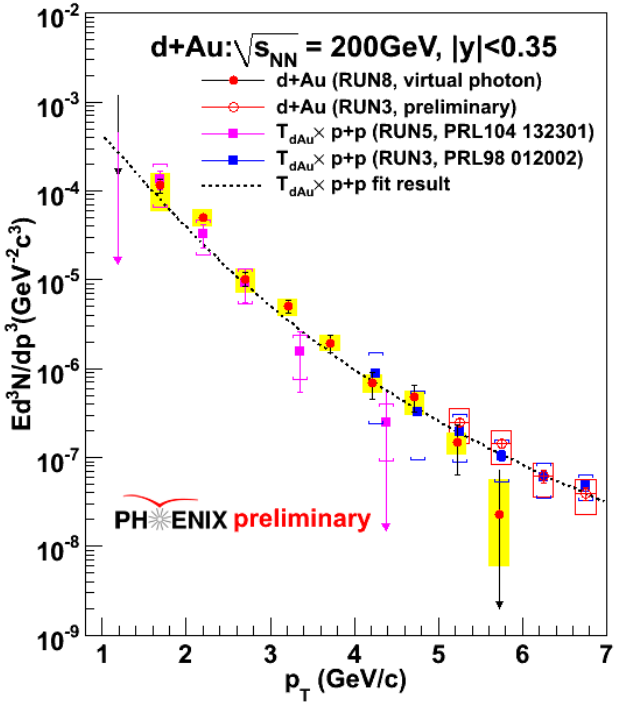


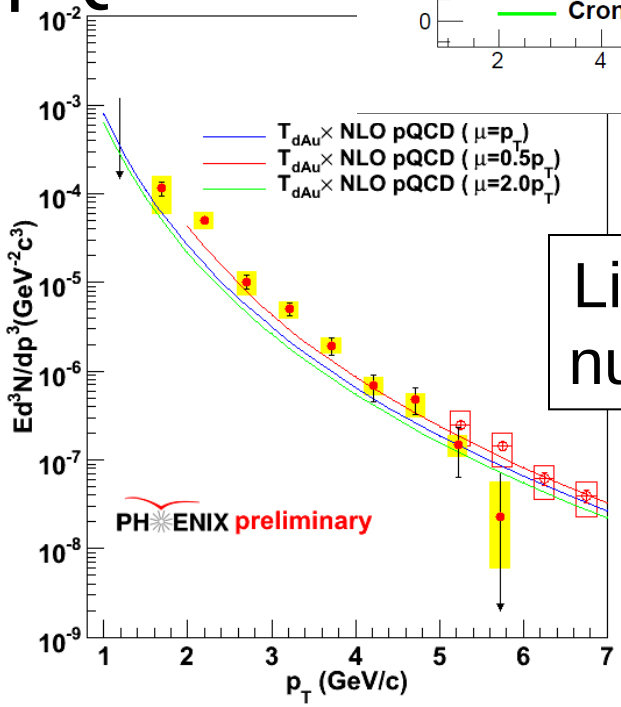
arXiv:1205.5533

d+Au photons

- RdA consistent with 1
- dAu agrees with T_{AA}-scaled p+p data
- dAu agrees with T_{AA}-scaled NLO pQCD



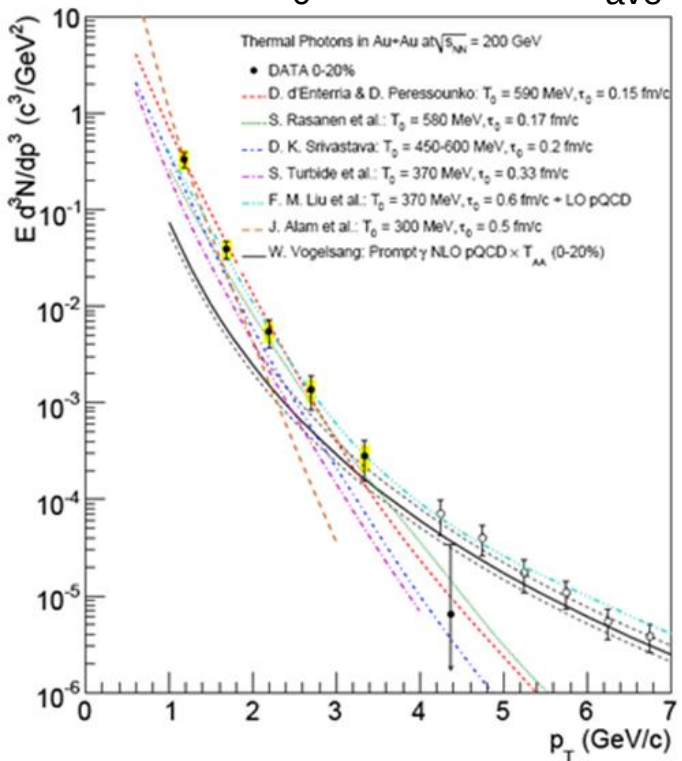


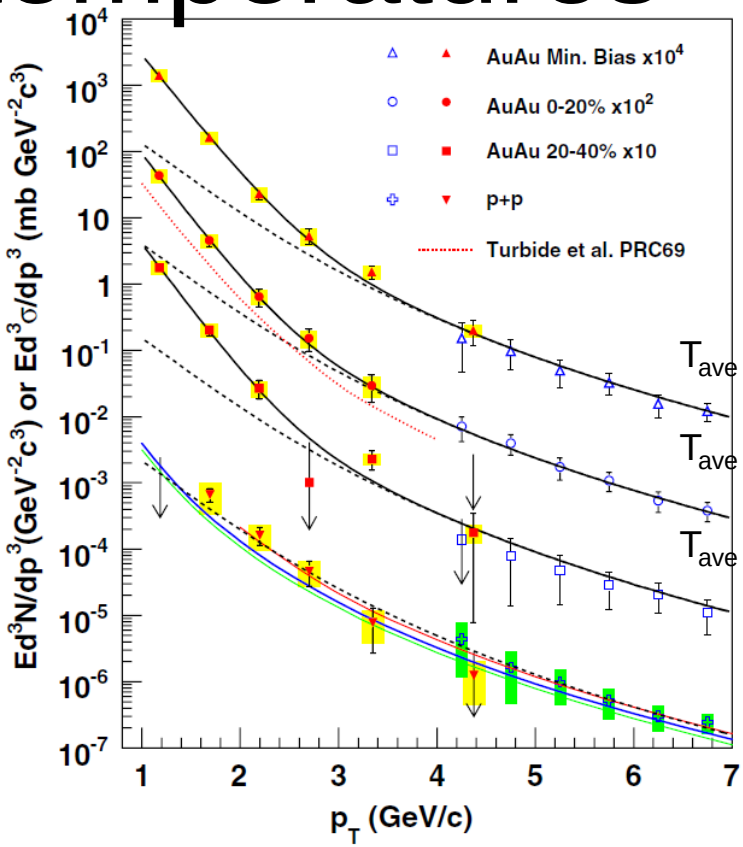


Little to no visible cold nuclear matter effects

Thermal temperatures

- Additional thermal yield
  - Average temperature → inverse slope of expo.
  - Initial temperatures from theoretical calculations
    - $T_0 \sim 1.5 - 3 * T_{ave}$





Dashed lines T_{AA}-scaled p+p

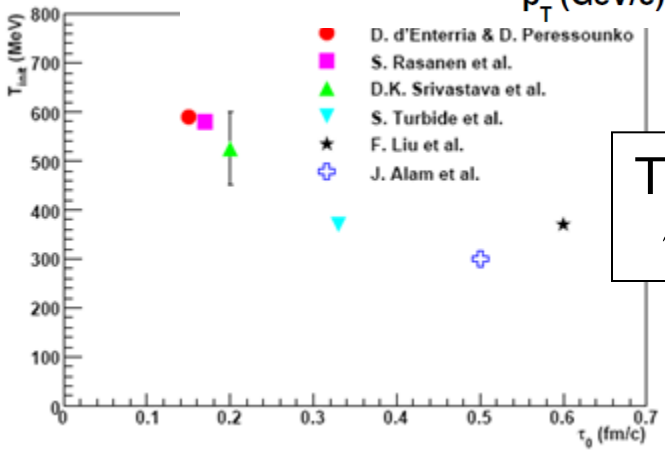
Solid lines T_{AA}-scaled p+p + expo

T_{ave} = 233 ± 14 ± 19 MeV

T_{ave} = 221 ± 19 ± 19 MeV

T_{ave} = 217 ± 18 ± 16 MeV

NLO pQCD

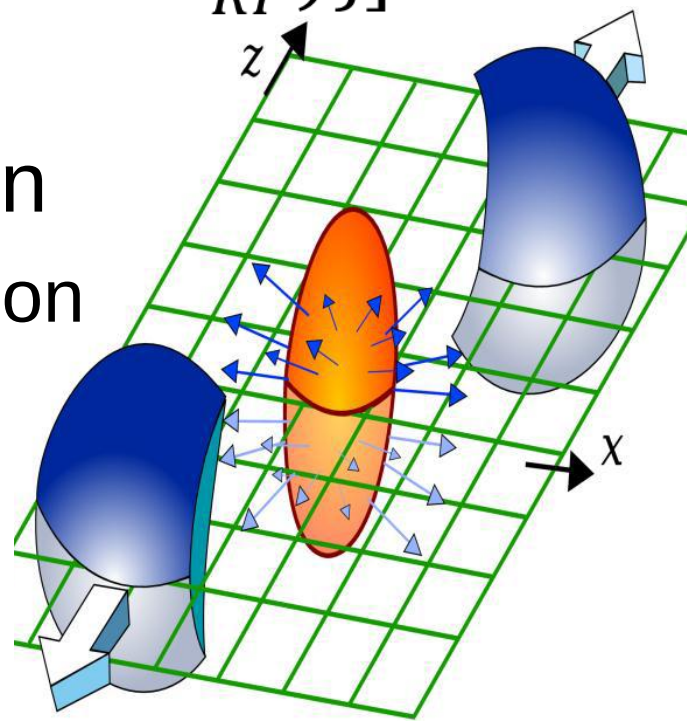


$T_{init} \sim 300$ to 600 MeV

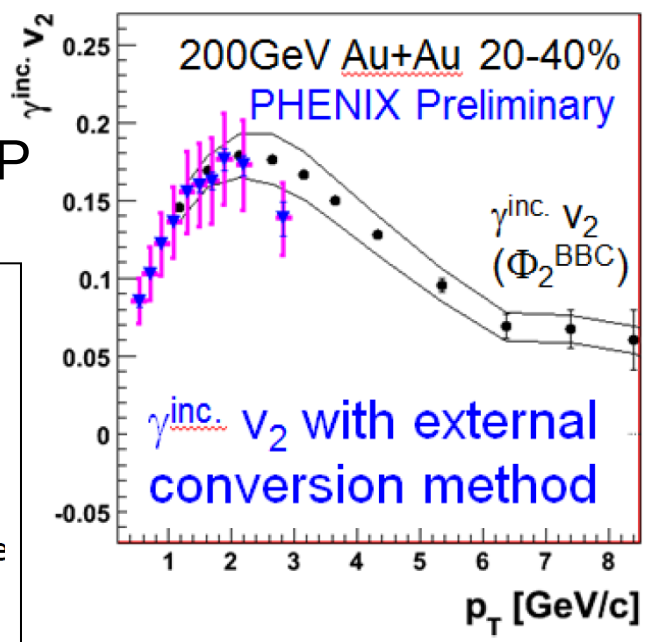
$\tau_0 \sim 0.15 - 0.5$ fm/c

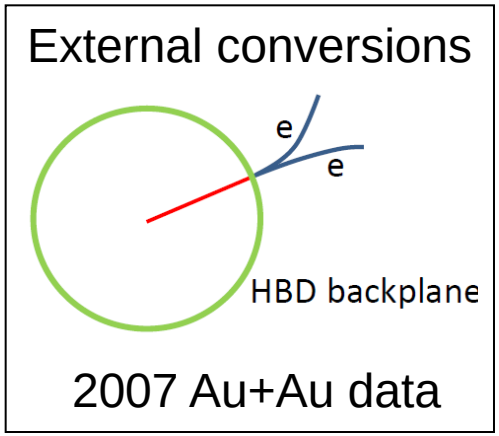
Inclusive photon v_2

$$\frac{dN}{d(\Phi-\Psi_{RP})} \propto N_0[1+2v_2\cos\{2(\Phi-\Psi_{RP})\}]$$



- Remove hadron contamination
  - Confirmed by external conversion method
- Divide by σ_{RP}



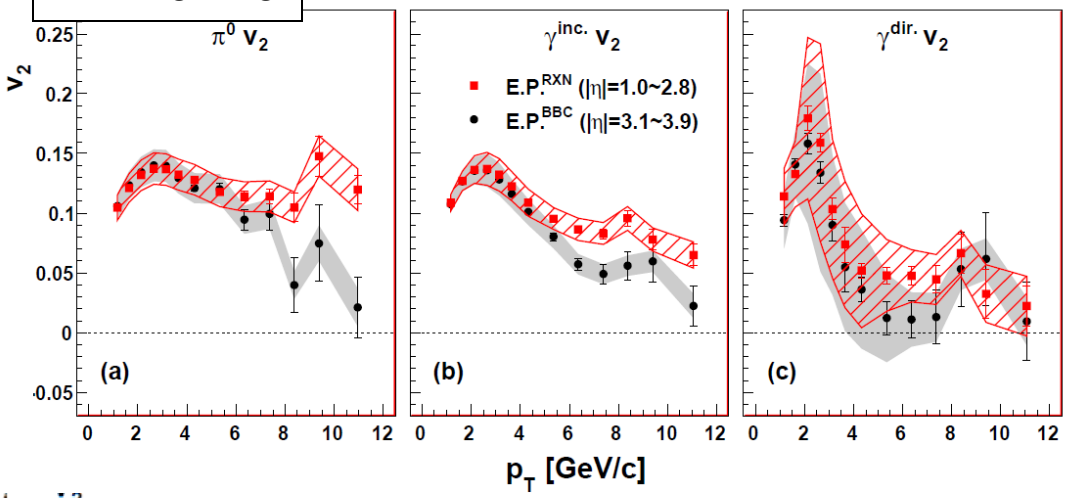


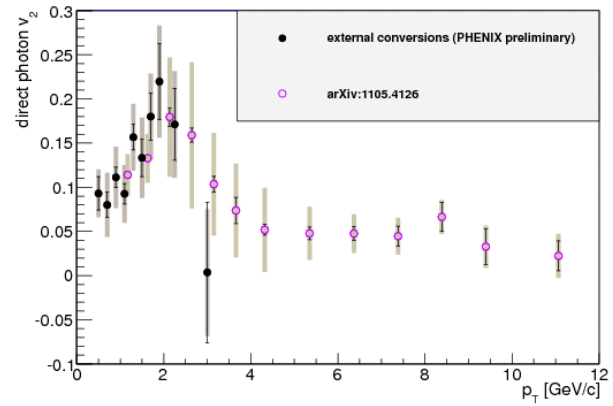
Measuring v_2^{dir}

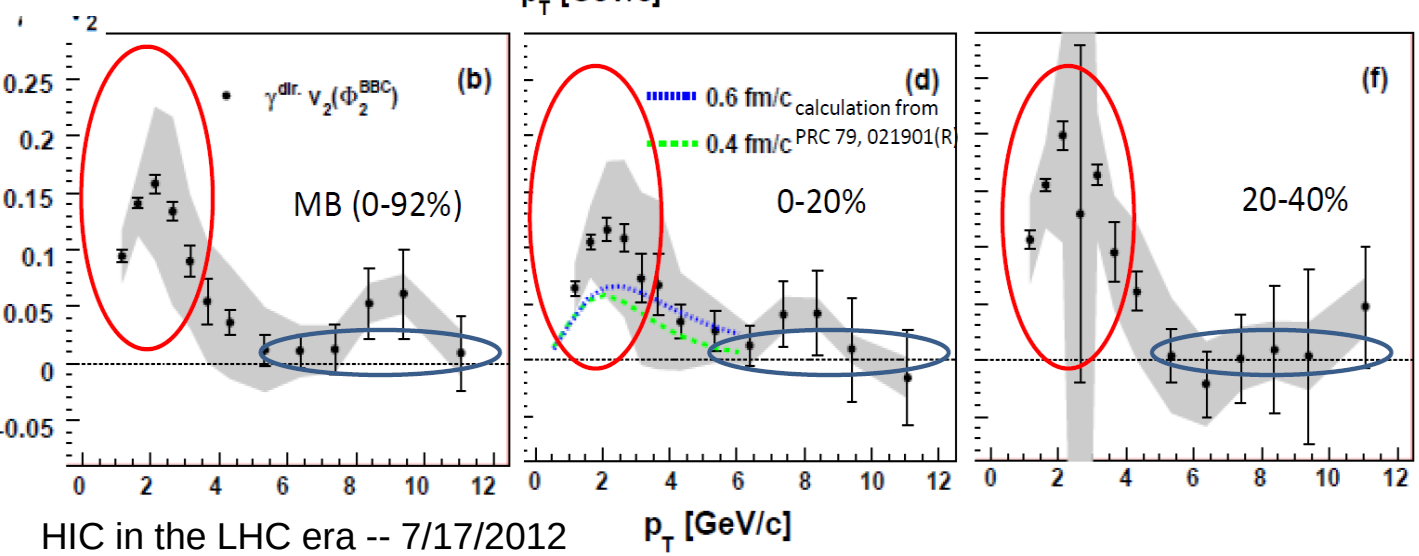
$$v_2^{\gamma,dir} = \frac{R_\gamma(p_T) v_2^{\gamma,incl} - v_2^{\gamma,BG}}{R_\gamma(p_T) - 1}$$

Calculated with a cocktail assuming KE_T and m_T scaling and measured $v_2^{\pi 0}$

MB Au+Au







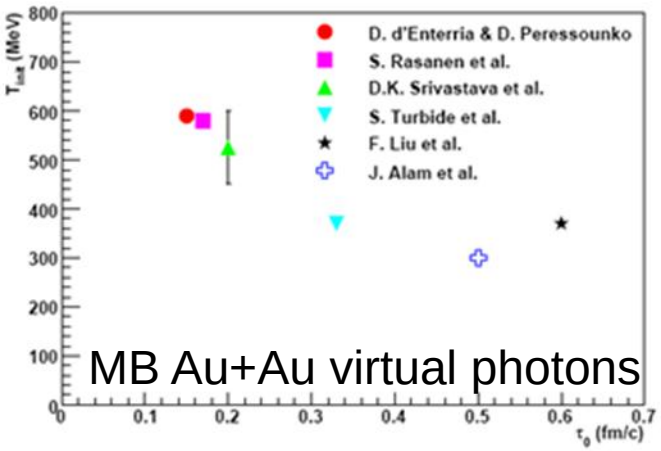
High p_T, $v_2 \sim 0$

- Consistent with hard scattering

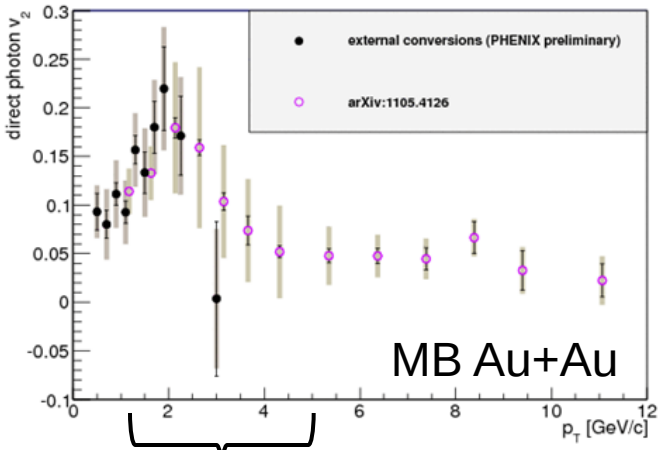
Low p_T, v_2 large

- Larger than theoretical expectations

Thermal photon emission



Looks like partonic emission
T_{init} ~ 300 to 600 MeV
τ_0 ~ 0.15 - 0.5 fm/c



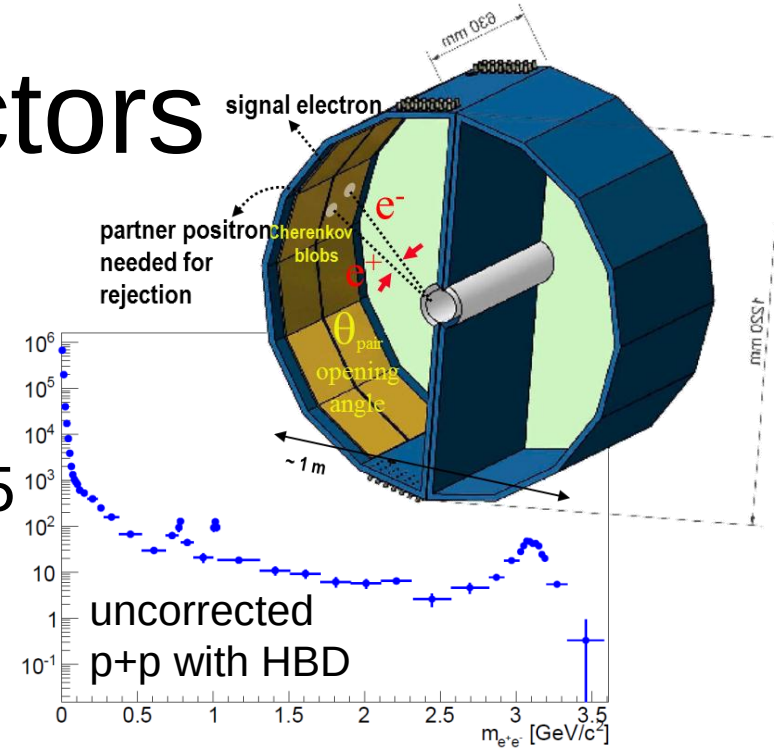
p_T range of virtual photon analysis

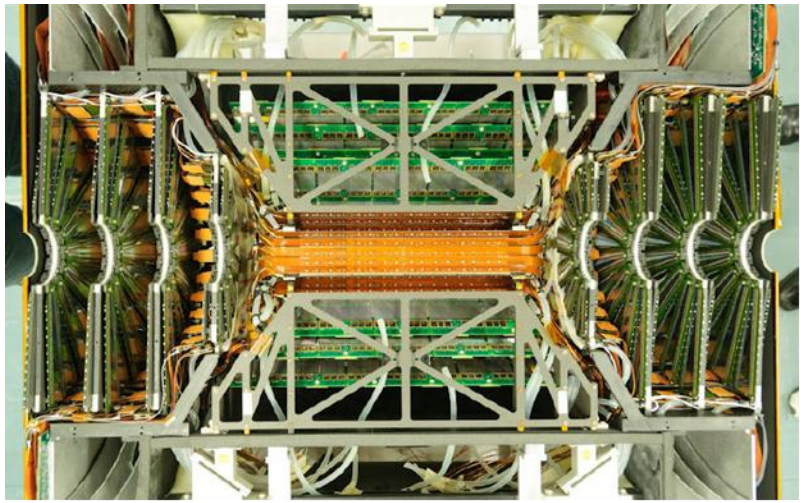
Looks like hadronic emission
Large v_2

- Inconsistent with standard hydro-space time evolution
  - After impact but before τ_0?

New detectors

- Hadron blind detector (HBD)
  - 2009 p+p, 2010 Au+Au
  - Improve dielectron spectrum signal-to-background by factor of 5
    - Reject combinatorial background
  - Results will be shown at QM

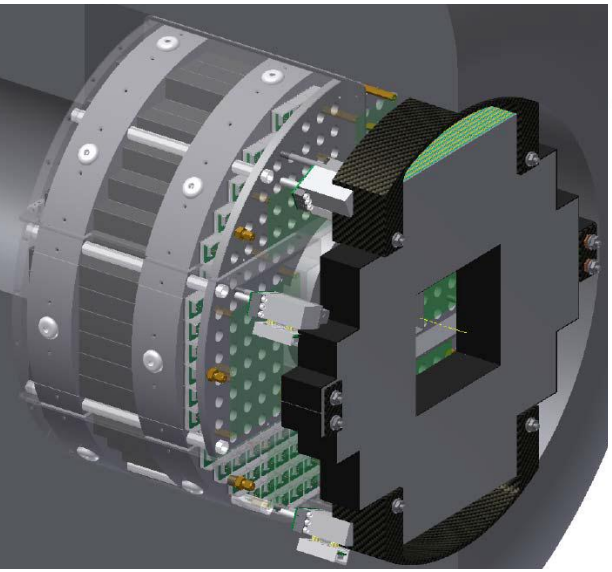


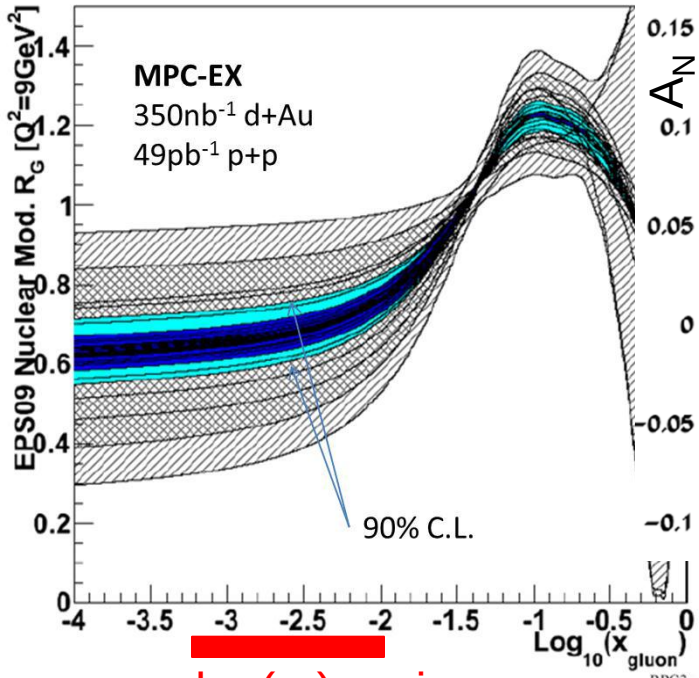


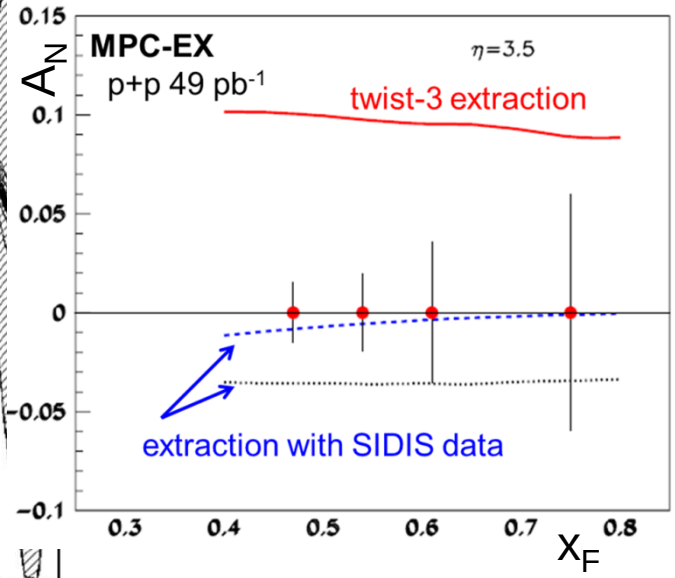
FVTX Si VTX FVTX

- Vertex detectors (VTX)
  - Si VTX: 2011 Au+Au, 2012 p+p
    - Virtual photons at $m_{ee} > 1$ GeV/c^2
    - Measure correlated charm distribution
  - Forward VTX: 2012 Cu+Au
    - Electrons at $1.2 < |\eta| < 2.4$
  - Measure reaction plane

MPC-EX

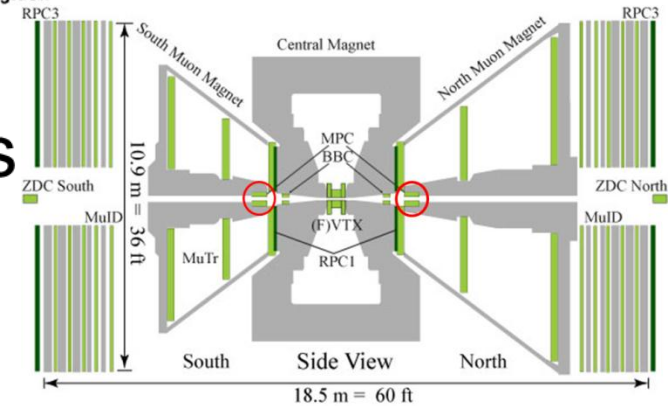






log(x_2) region
for p_T > 3 GeV γ^{dir}

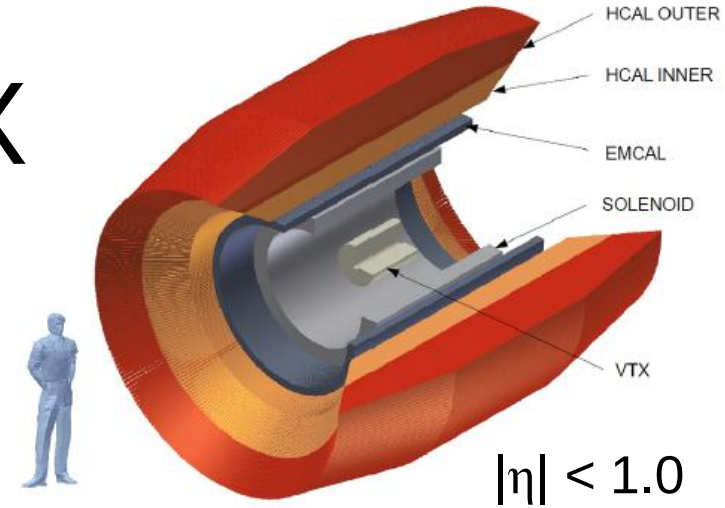
- Si+W preshower
  - 1.8mm x 15mm minipad sensors
- Measure forward prompt γ
  - pT > 3 GeV, 3.1 < |η| < 3.8
  - Separate π^0 and γ out to 80 GeV



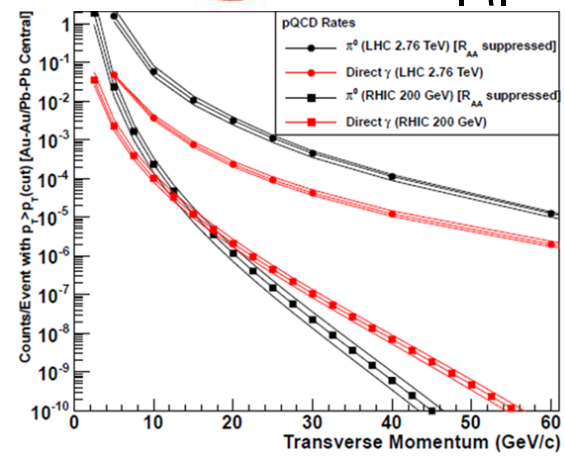
Planned for 2014

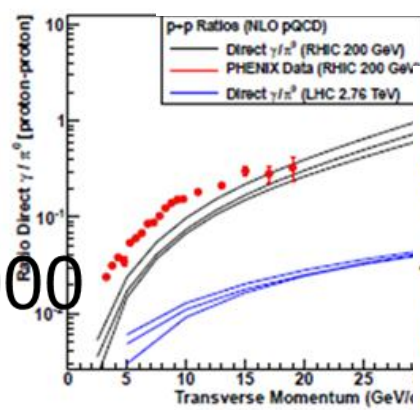
sPHENIX

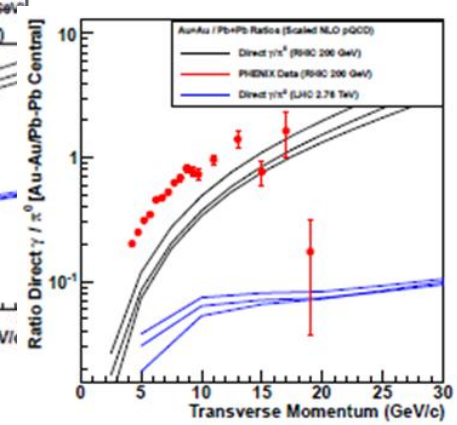
- EMCal compact W-Si
  - $\sigma/E = 15\%/\sqrt{E}$
  - $\Delta\eta \times \Delta\phi \sim 0.03 \times 0.03$
- Will be able to measure direct photons with EMCal before isolation cuts
- Internal and external photon conversions
  - $\Delta p/p \sim 1\%$
  - e/π rejection ~ 1/500 - 1/1000
  - Study on going



$|\eta| < 1.0$







Conclusions

- x_T scaling at wide range of energies
- High p_T of direct photons extended
  - $R_{AA} \sim 1$, v2 ~ 0
- Low p_T Au+Au, Cu+Cu enhanced thermal yield
  - Little to no cold nuclear matter effects
  - Au+Au v_2 VERY large

Confirmed by two separate analyses in Au+Au data

- Future:
  - Virtual photon v_2
  - HBD virtual photons
  - $m_{ee} > 1$ virtual photons VTX
  - Forward prompt photons MPC-EX
  - p+Au collisions
  - sPHENIX

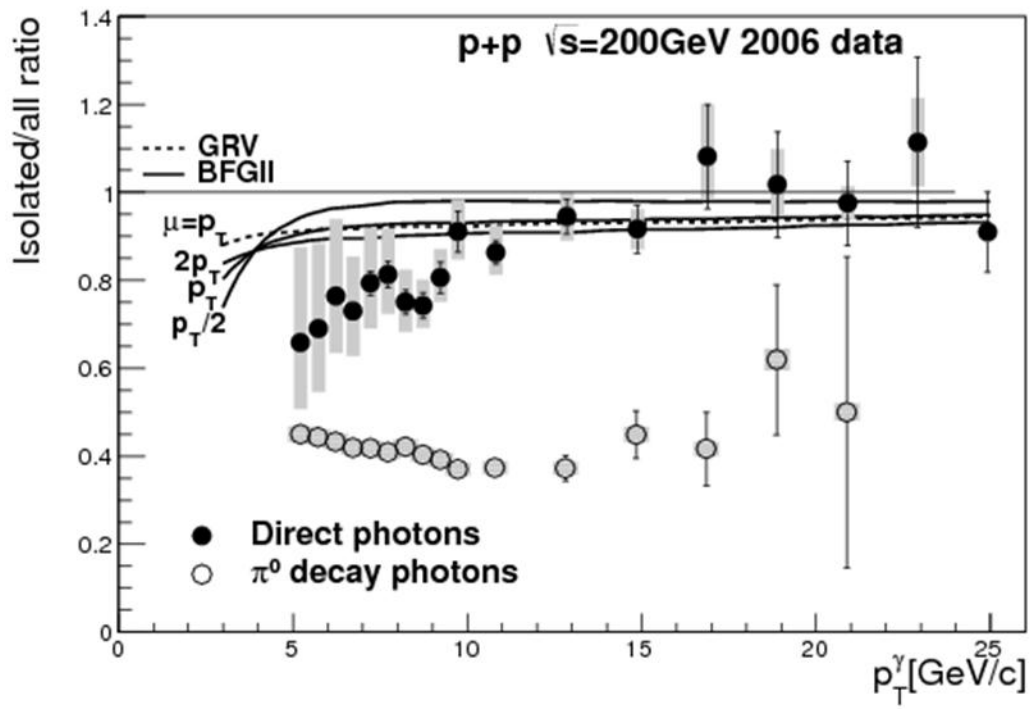
Backup

Isolation cuts in p+p

$$N_{Dir}{}^{Iso} = N_{Incl}{}^{Iso} - \left(n_{\pi^0}{}^{Iso} + N_{\pi^0}{}^{Iso} R\right) - A^{Iso}(1+R)N_{\pi^0}{}^{Iso}$$

$n_{\pi^0}{}^{Iso}$ -- a subset of $N_{\pi^0}{}^{Iso}$ when γ passes the isolation cut without the partner's energy

- Remove direct photon backgrounds from fragmentation photons
- Cone in dφ-dη space
  - radius 0.5
- $E_{InCone} < 0.9 * E_{\gamma}$
  - E_{InCone} is total cluster energy and charged track momenta



arXiv:1205.5533

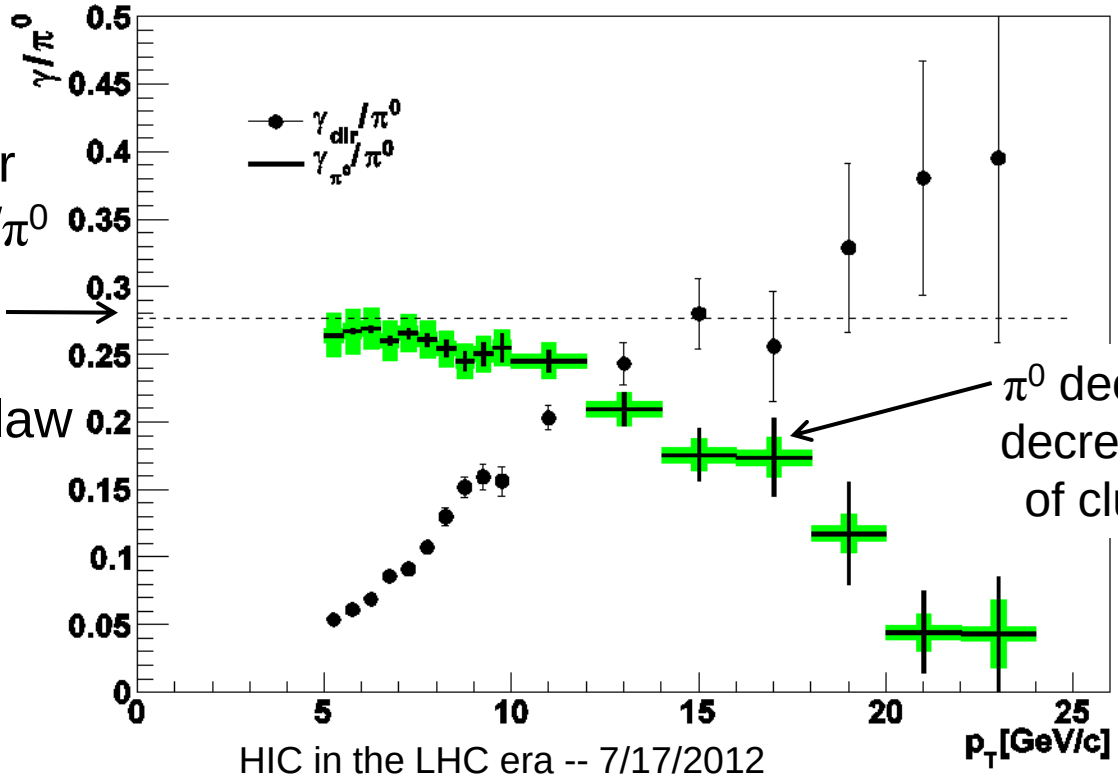
π^0 Photon concentration

- Using π^0 cross section $E\,\frac{d^3\sigma}{dp^3} = 1.777 \times 10^{10}\, p_T{}^{-8.22}$
- Ratio of direct photons/π^0
- Ratio of π^0 decay photons/π^0

Expected ratio for π^0 decay photons/π^0

$$\frac{2}{8.22-1} = 0.277$$

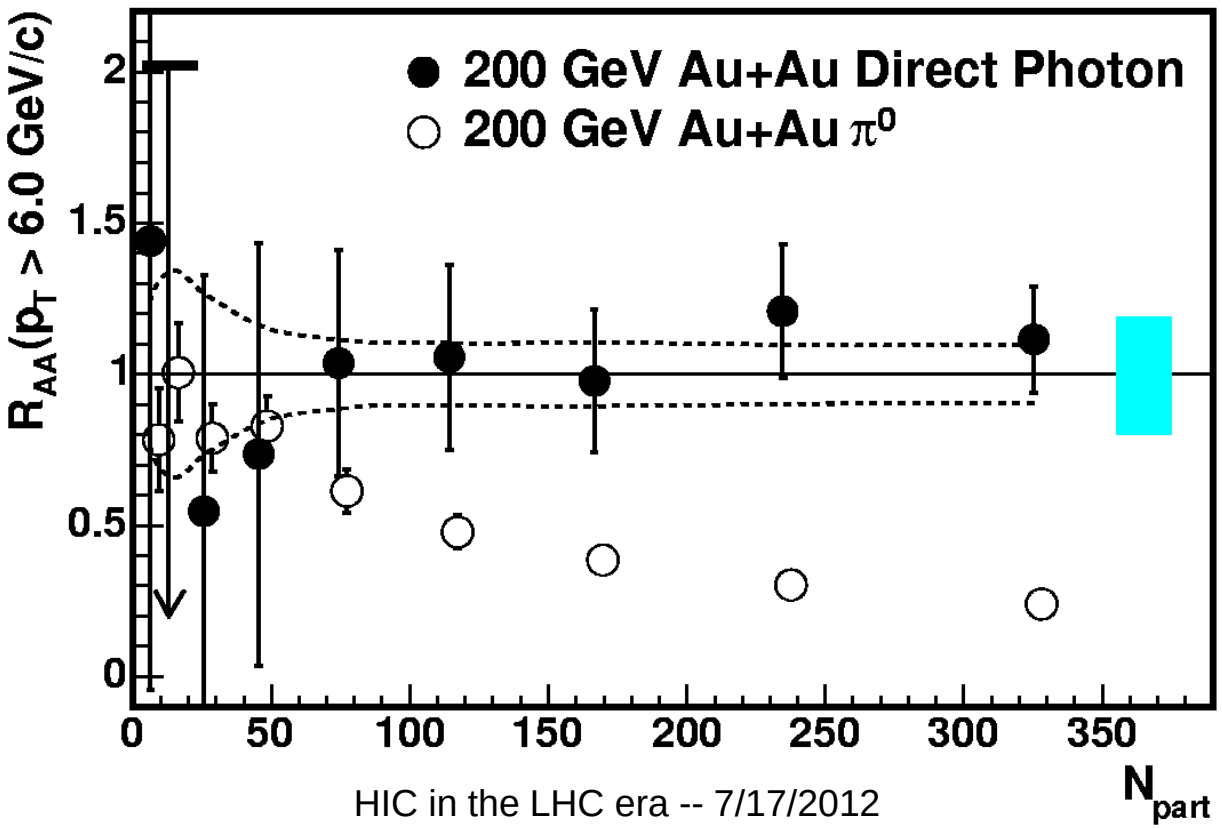
if π^0 is pure power law



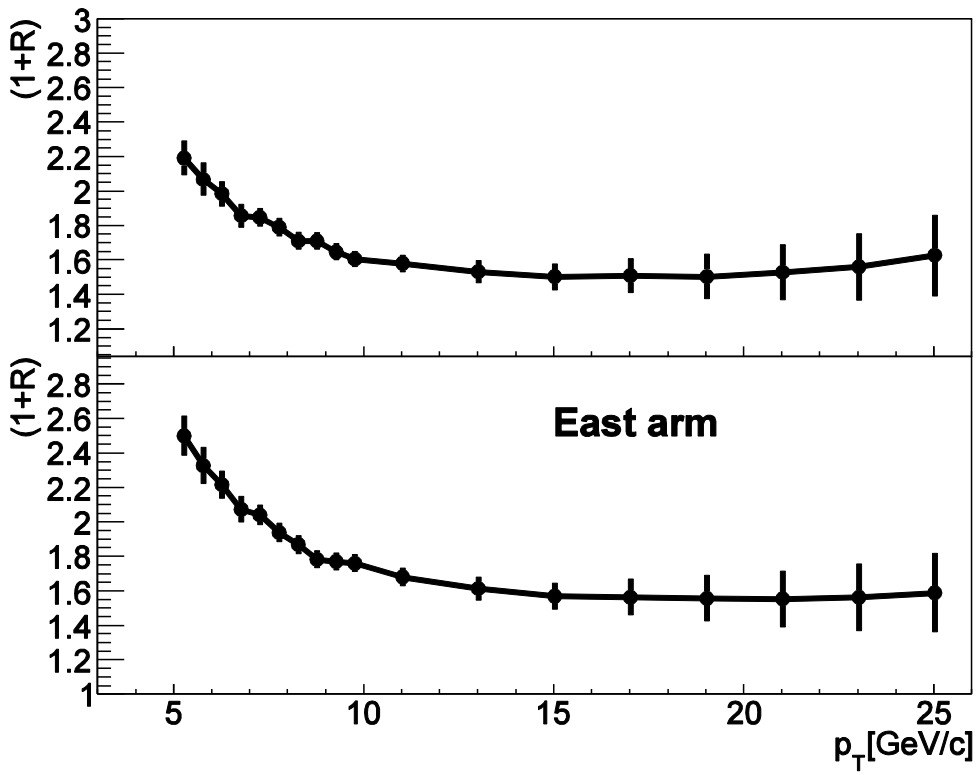
π^0 decay photons/π^0 decreases because of cluster merging

RAA vs Npart

- Photons from 2001 data with a fit of p+p data

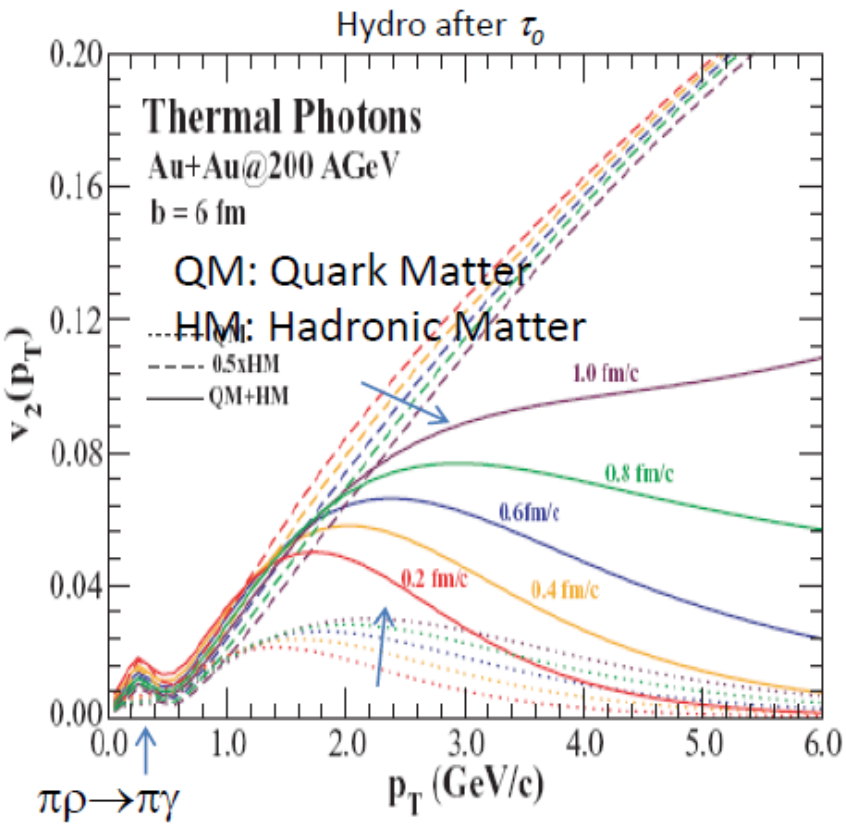


1+R

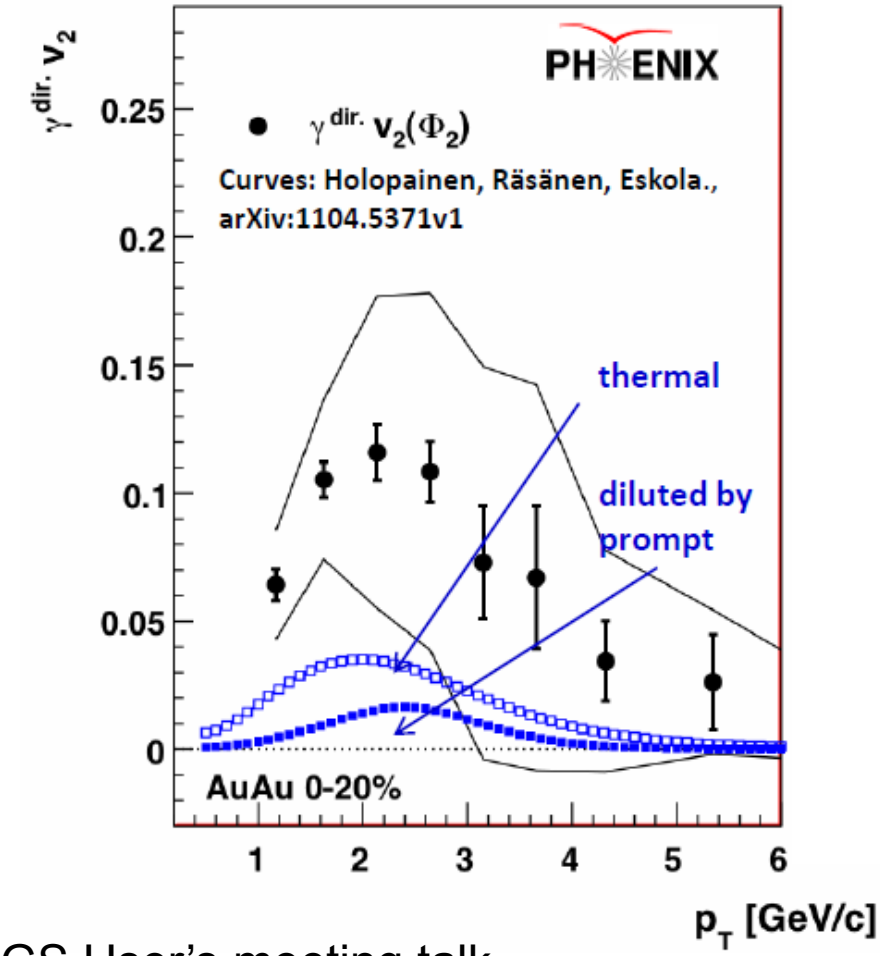

(1+R)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
(1+R)
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
East arm
5
10
15
20
25
p_T[GeV/c]

Comparison with models. No success..

- Later thermalization gives larger v_2 (QGP photons)
- Large photon flow is not explained by models for QGP



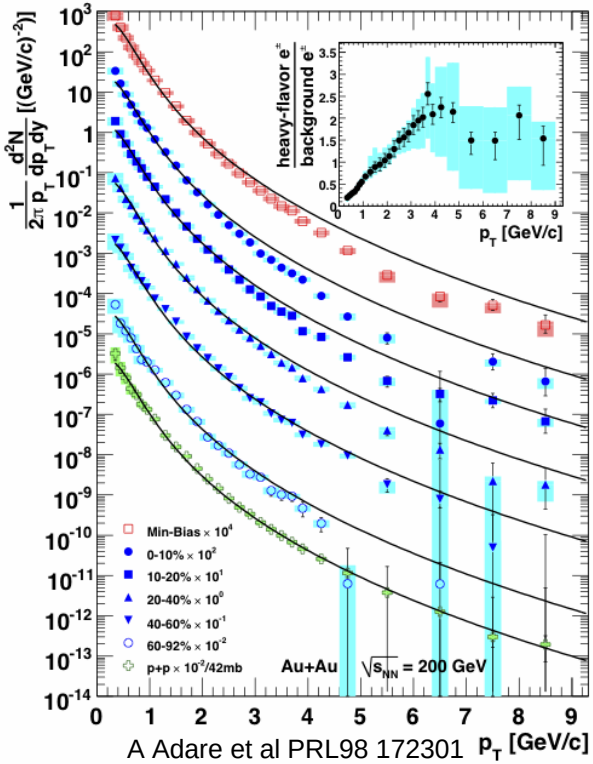
Chatterjee, Srivastava PRC79, 021901 (2009)



From Kensuke Okada's RHIC/AGS User's meeting talk

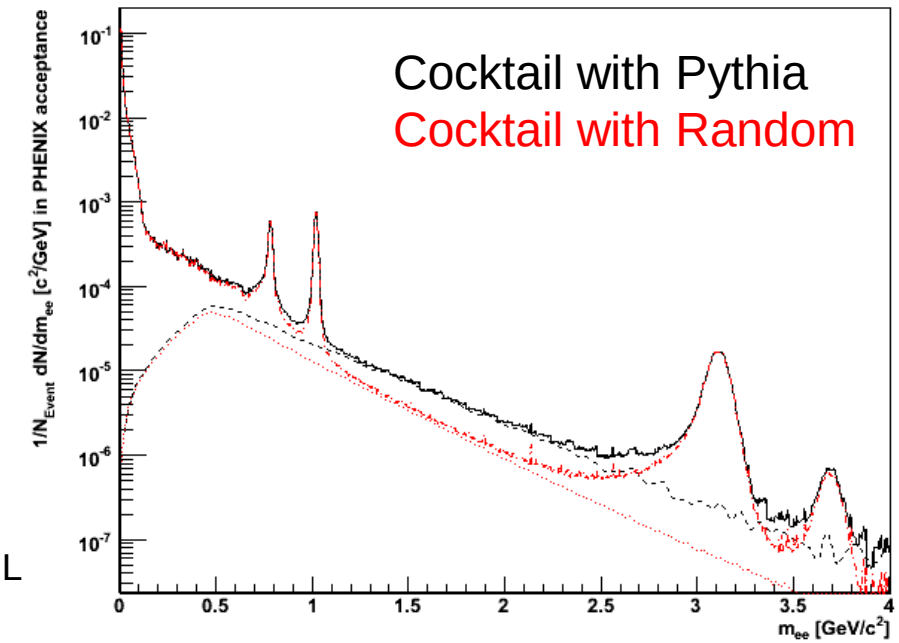
Is Pythia the right way to model the heavy quark components?

- p+p non-photonic electron p_T not well described by PYTHIA
- Au+Au suppression of high p_T non-photonic electrons
- Model a random heavy quark component, using Au+Au non-photonic p_T spectra with random angular orientation
  - Contains charm and bottom correlations

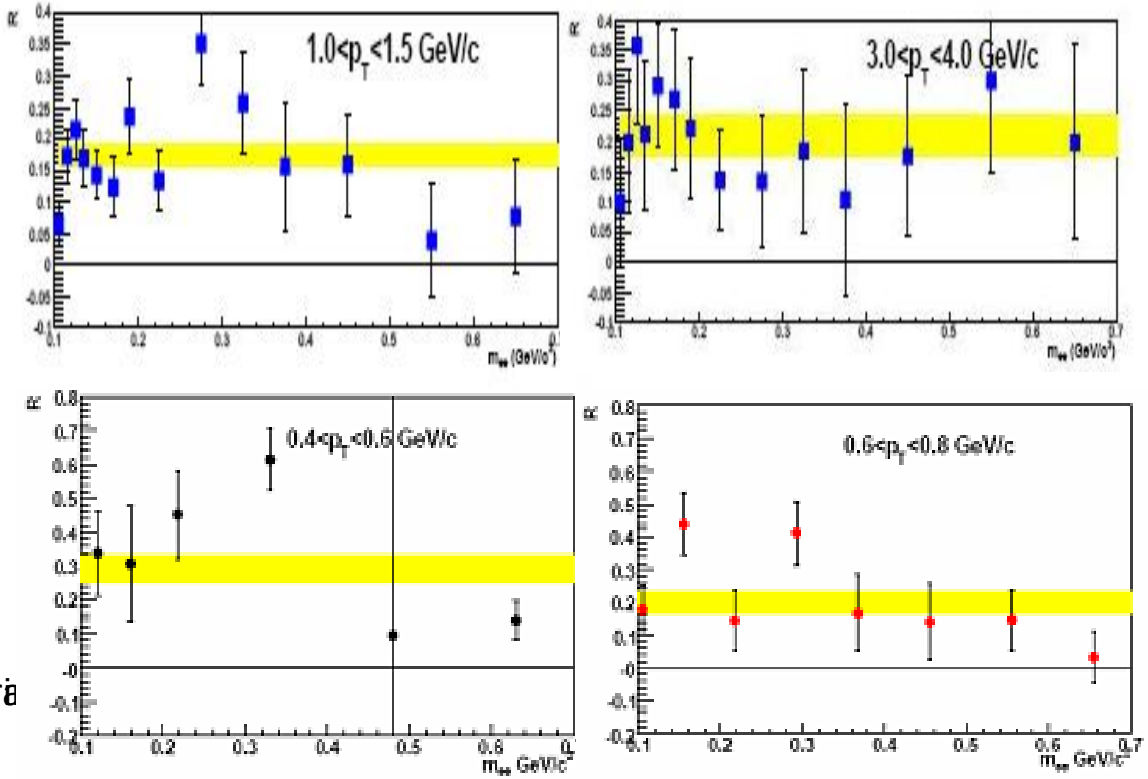


A Adare et al PRL98 172301

C in the L

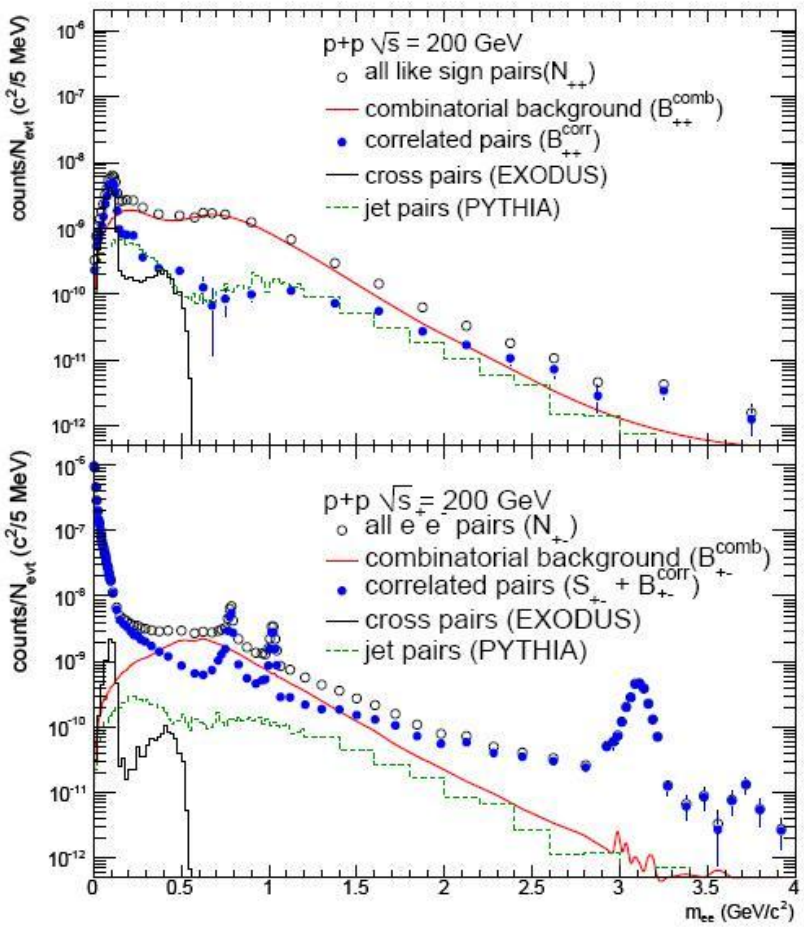


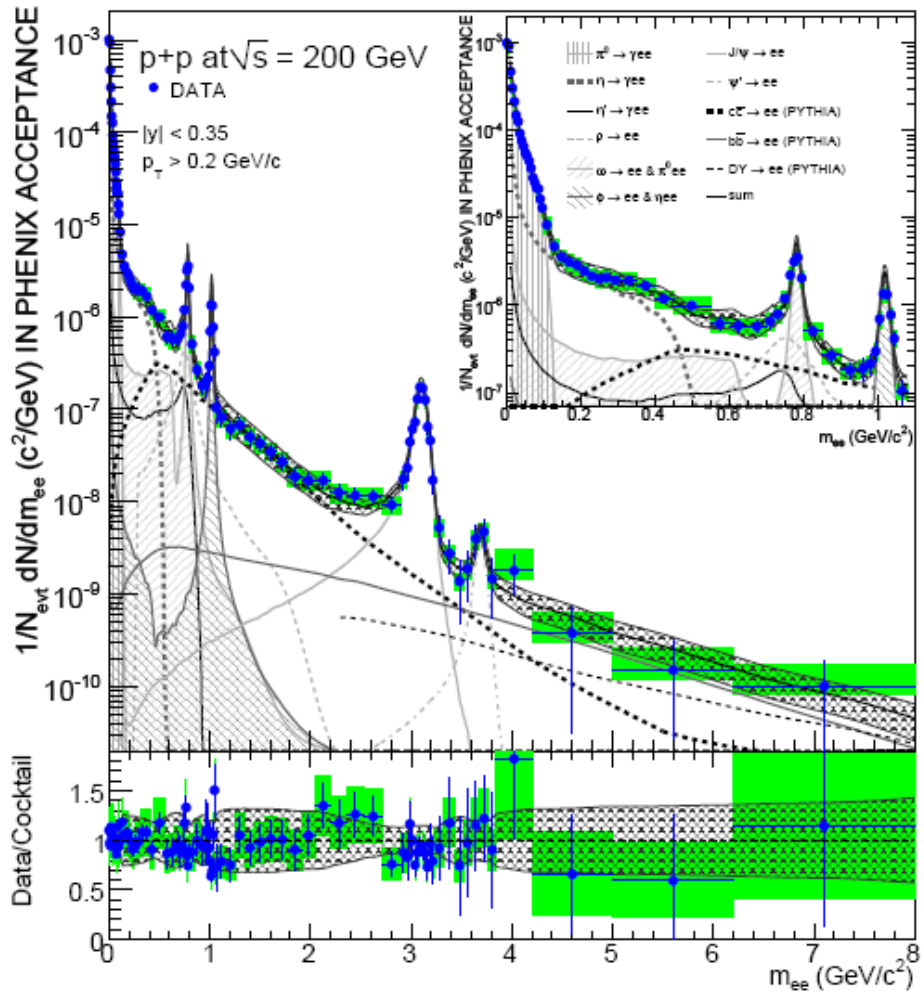
Type equation here.



Hsu

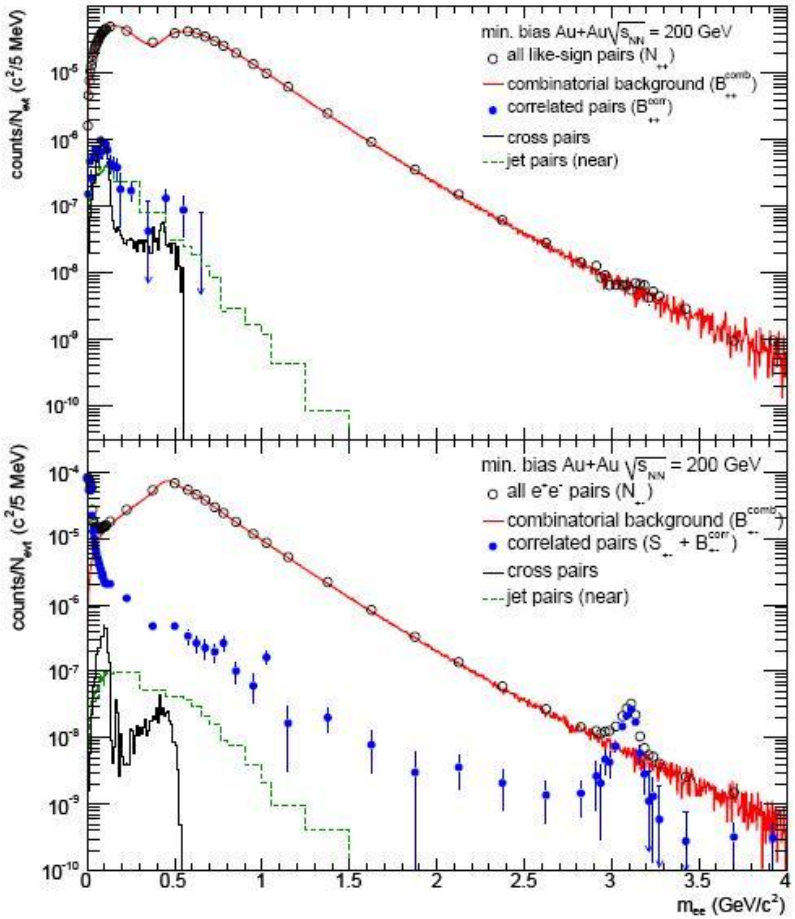
p+p Measurement

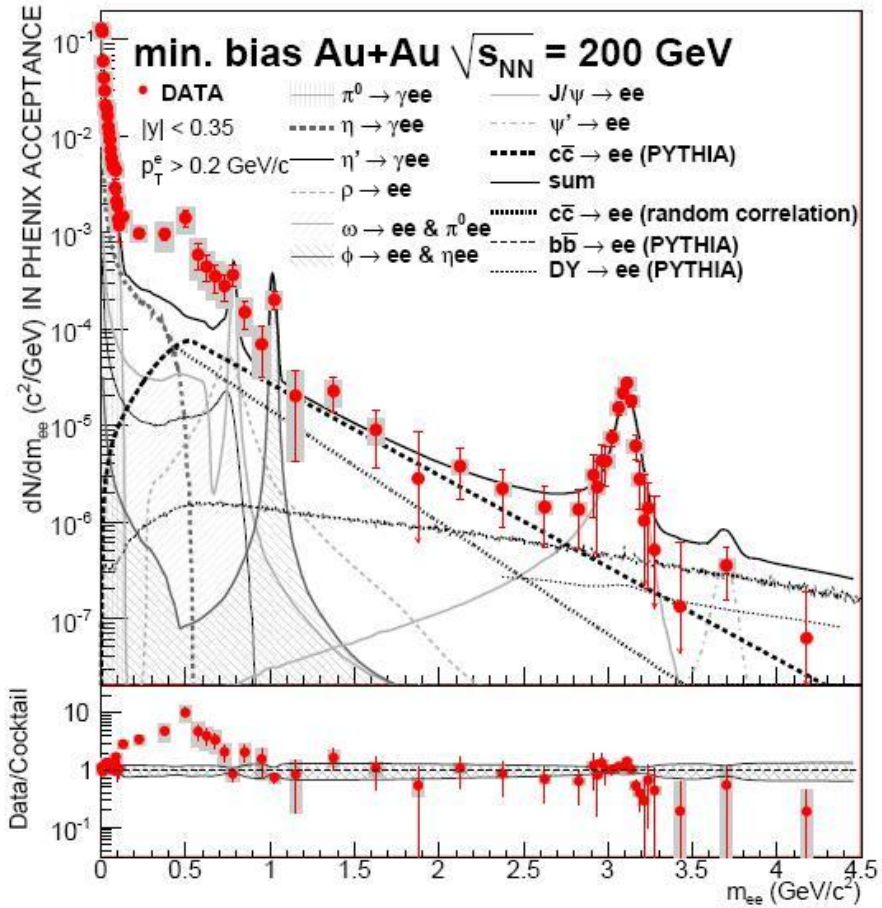




PRC 81 02391 (2010)

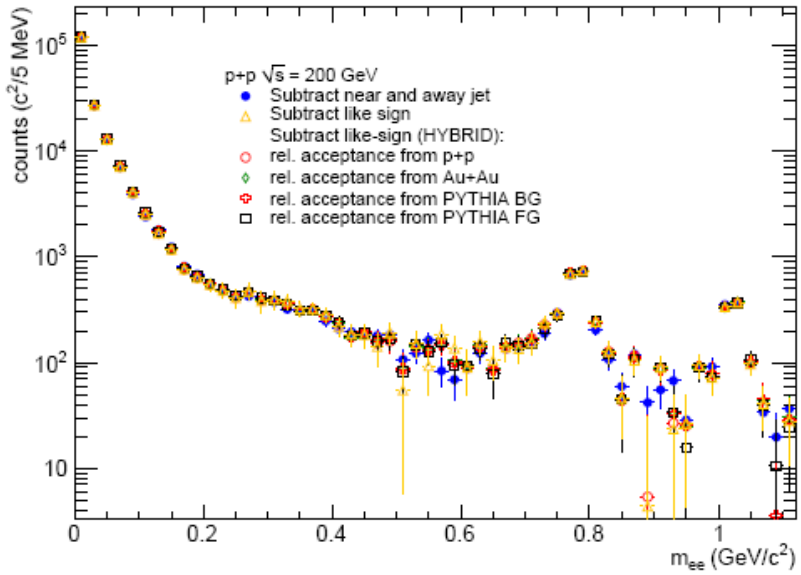
Au+Au measurement

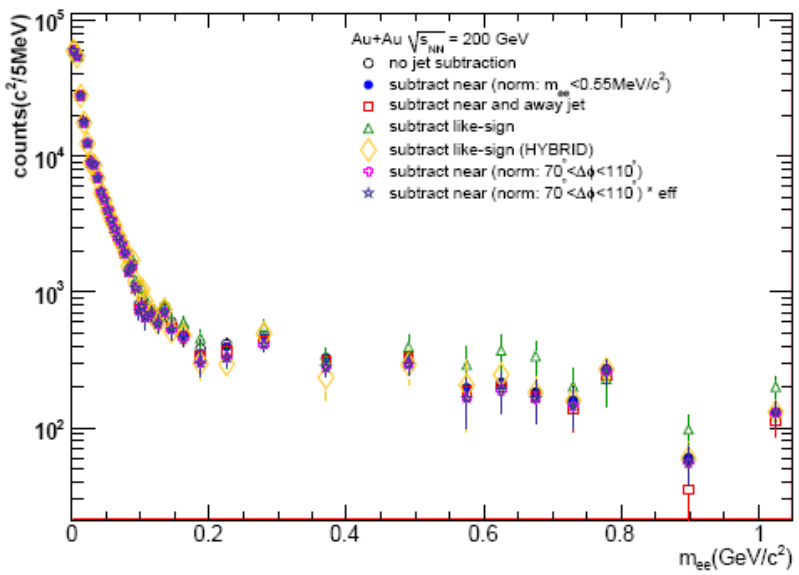




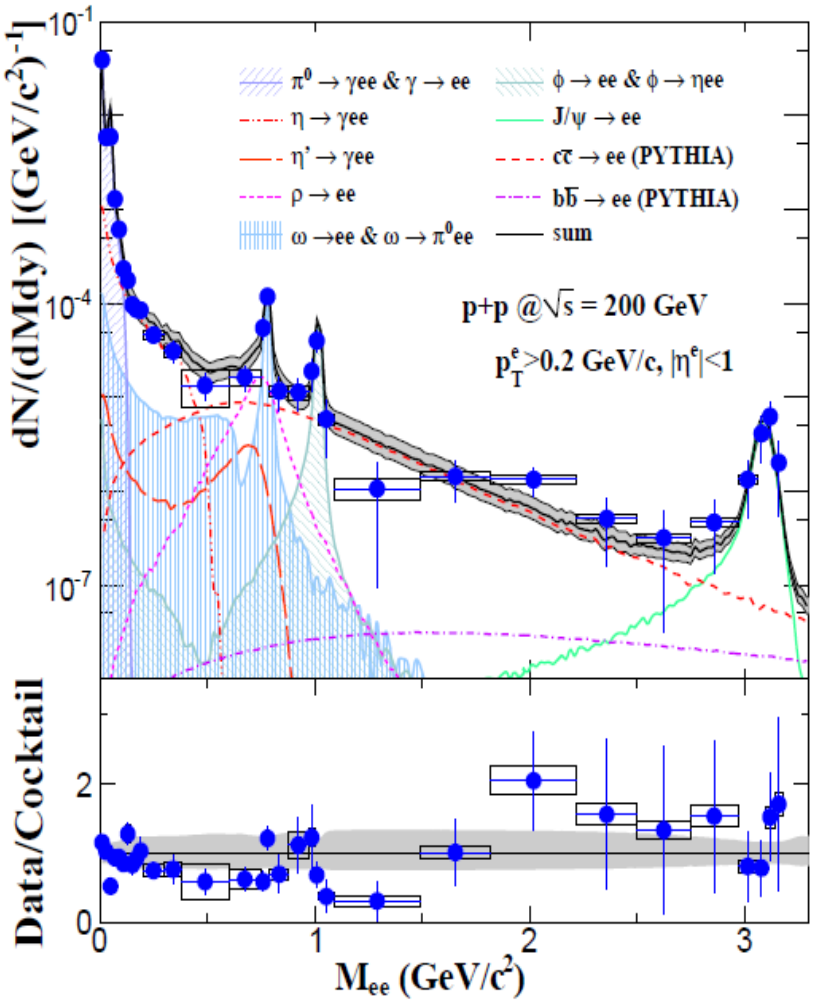
PRC 81 02391 (2010)

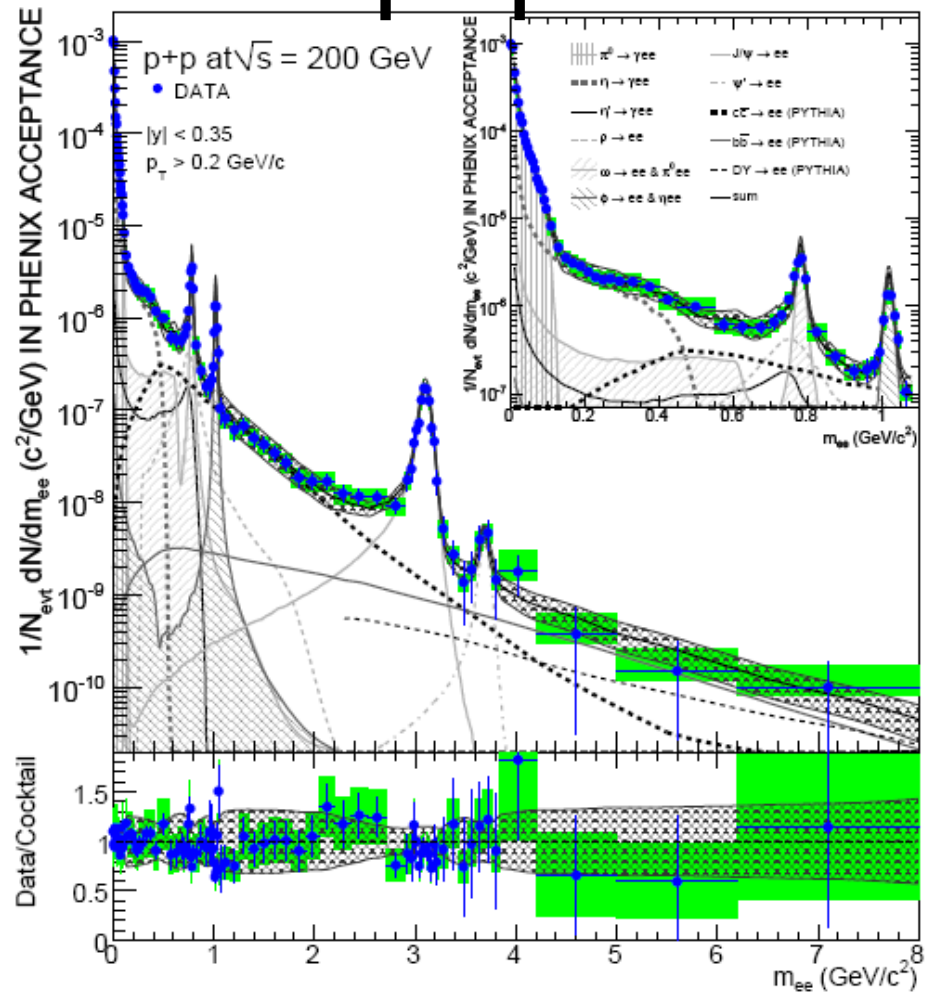
Like Sign subtraction – p+p A+A





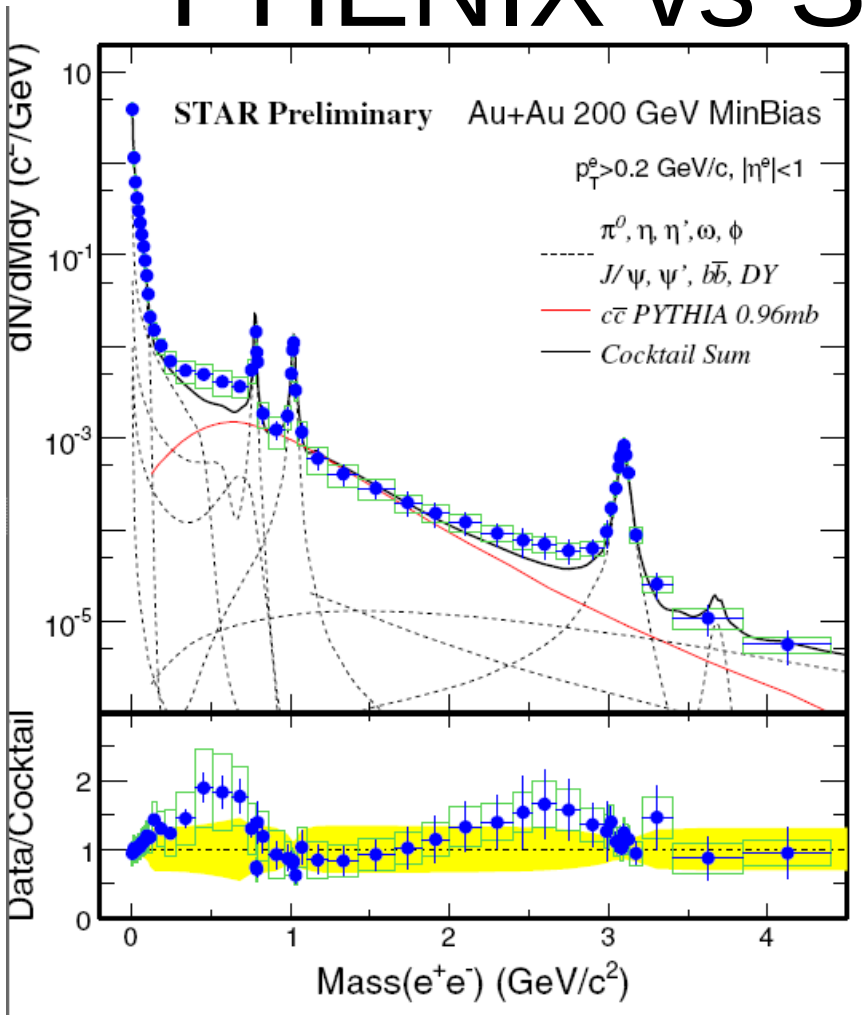
PHENIX vs STAR p+p

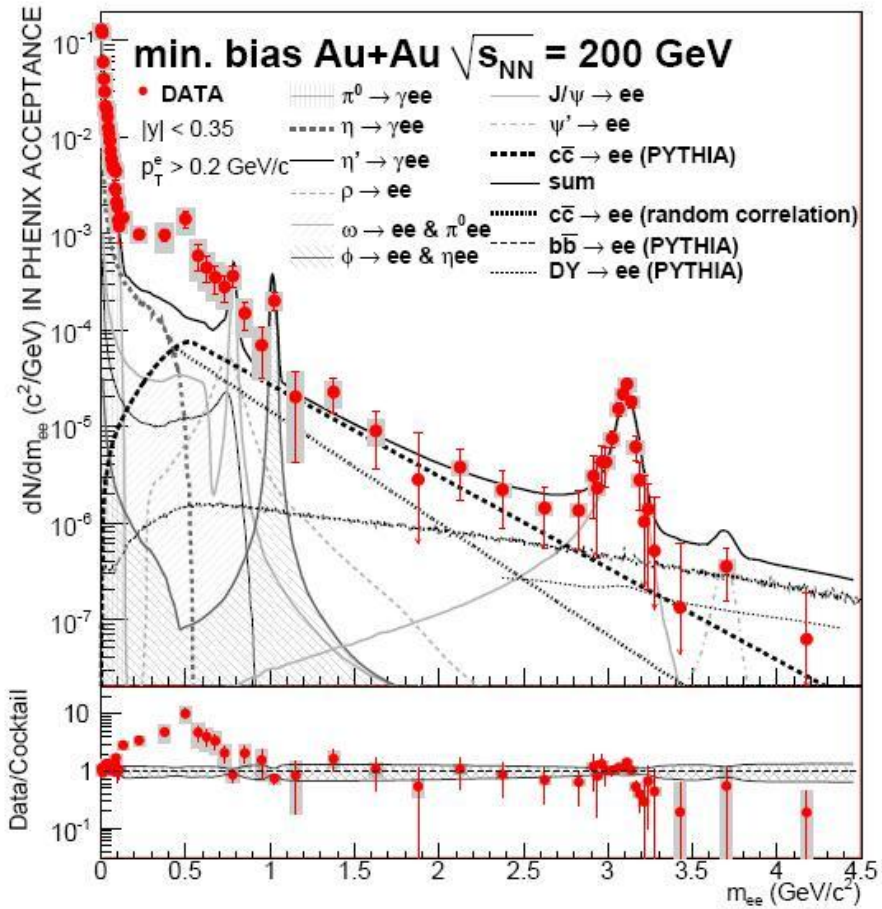




- Different acceptance: 2π, $|\eta_{STAR}| < 1.0$; not 2π, $|\eta_{PHENIX}| < 0.35$
- Different σ_{cc}: STAR 1.4 ± 0.2(stat) ± 0.4 (sys) mb;
  PHENIX 0.57 ± 0.06(stat) ± 0.19 (sys) mb

PHENIX vs STAR Au+Au MB





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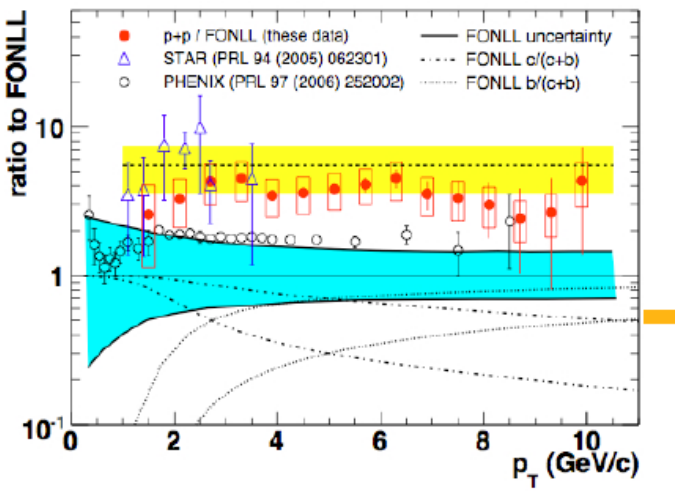
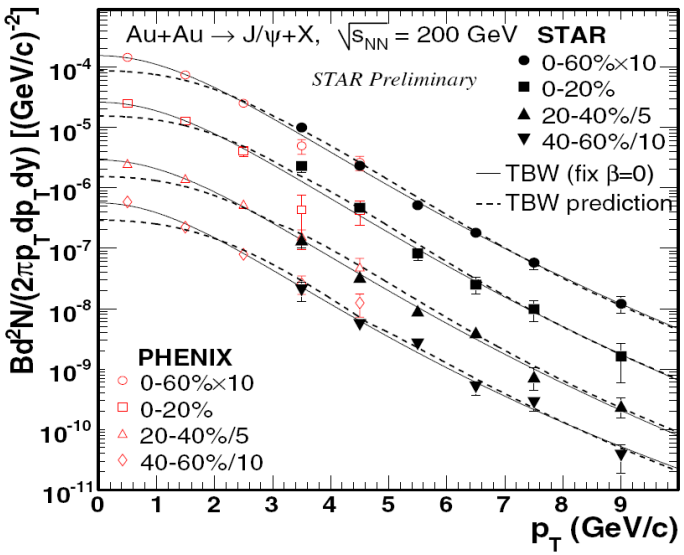
- Different σ_{cc}: STAR 1.4 ± 0.2(stat) ± 0.4 (sys) mb;
  PHENIX 0.57 ± 0.06(stat) ± 0.19 (sys) mb

PHENIX vs STAR: Acceptance: low pt

- PHENIX
  - +/- 0.5 rapidity
  - Single electrons p_T >0.2 GeV
  - Pairs m_T > 0.4 GeV
- STAR efficiency at low p_T?



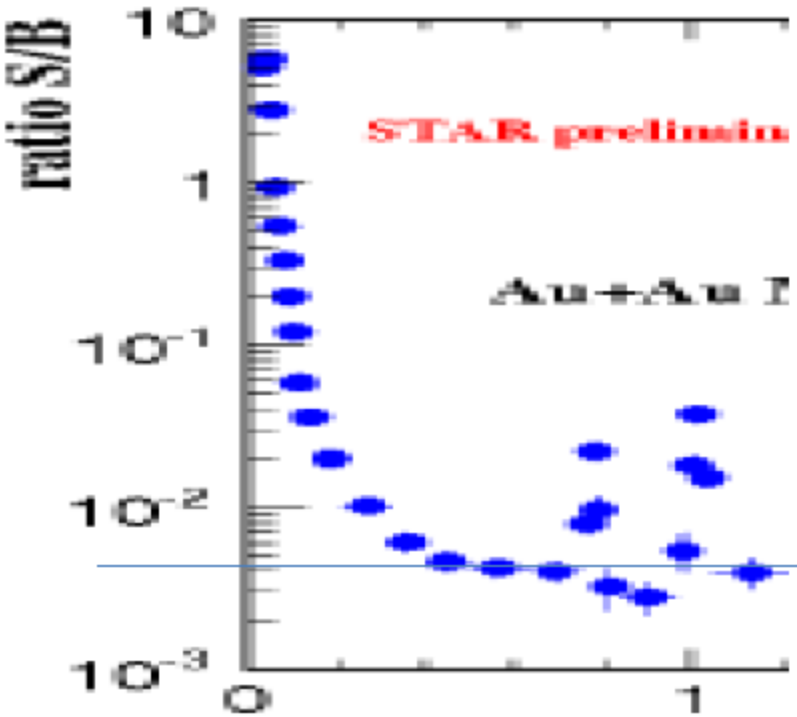


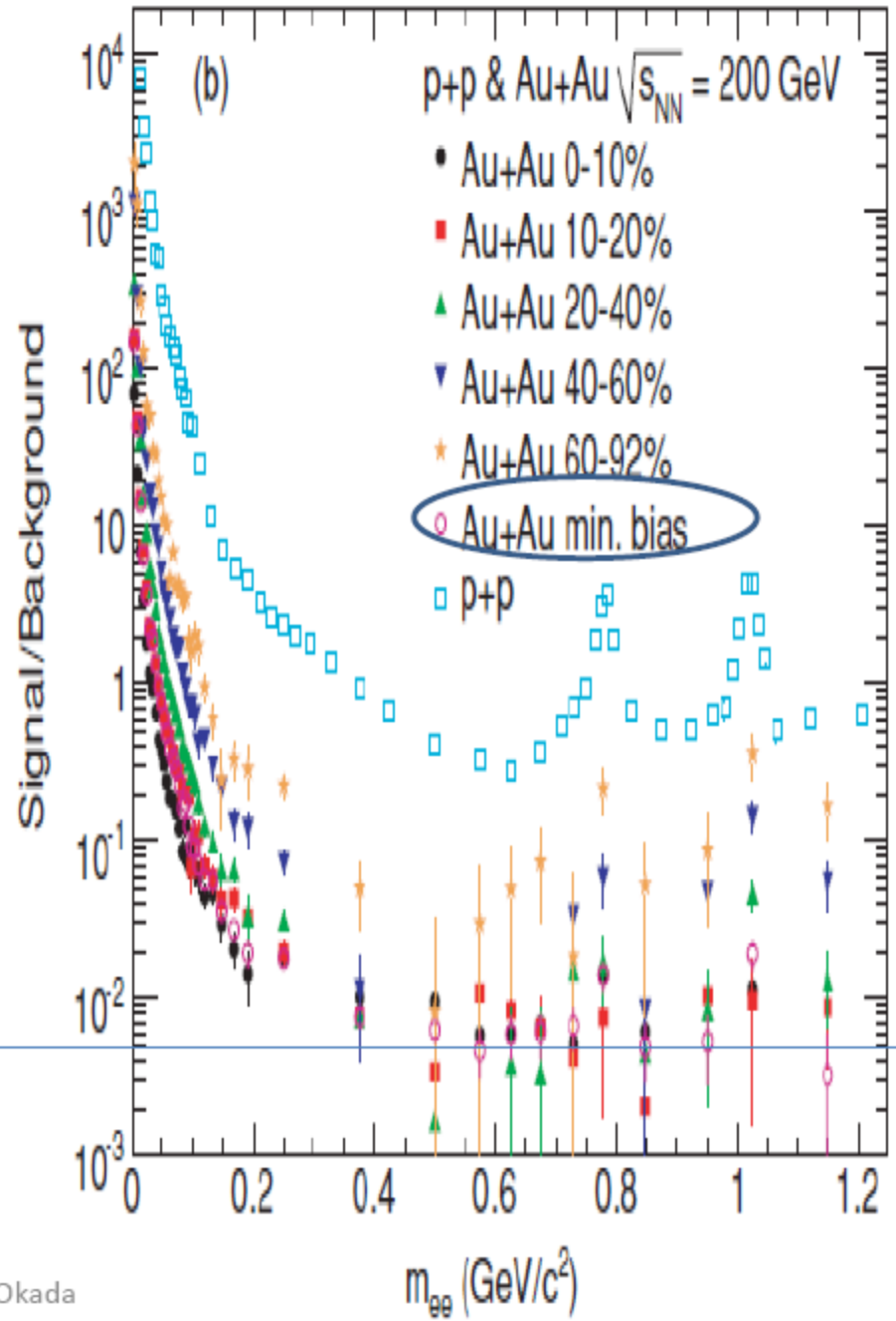
*** STAR and PHENIX NPE results in 200 GeV p+p collisions are consistent within errors at pt > 2.5 GeV/c**

-- 7/17/2012

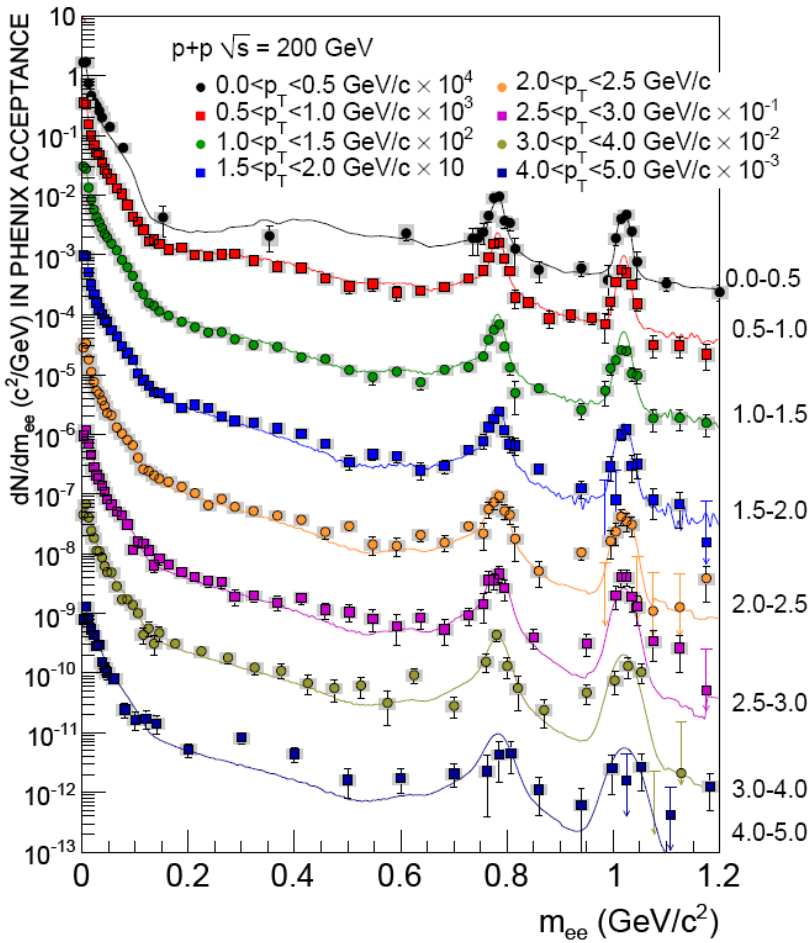
STAR vs PHENIX

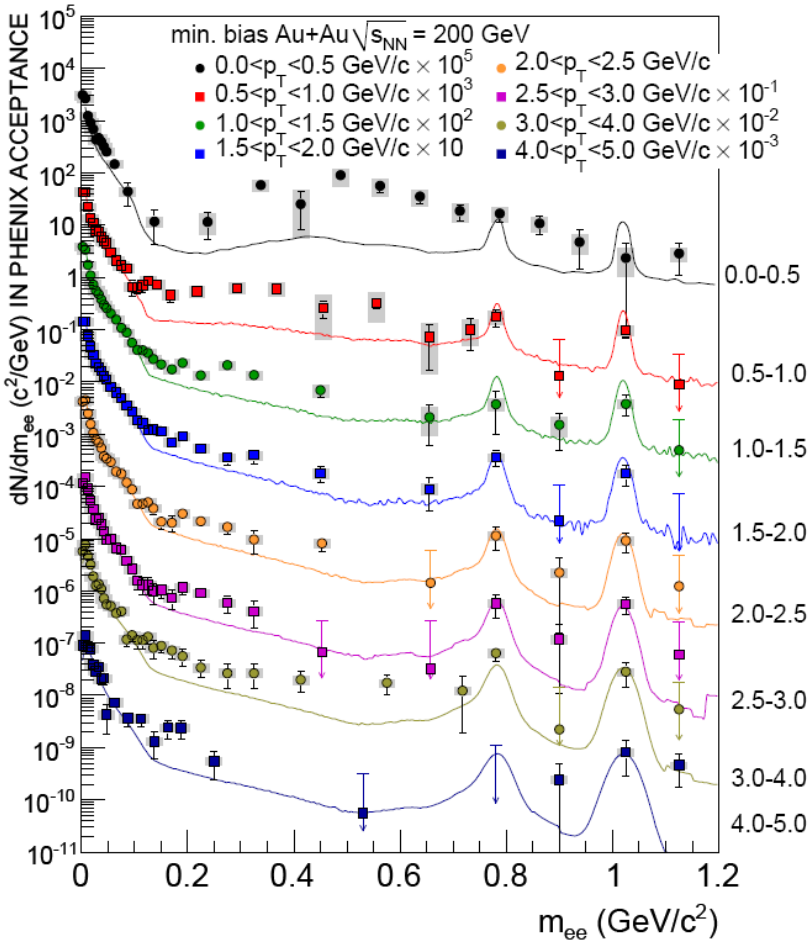
They are not so different.
Doesn't STAR have more combinatorial from conversions? They can be eliminated so well?





LMR m Spectra in p_T Slices



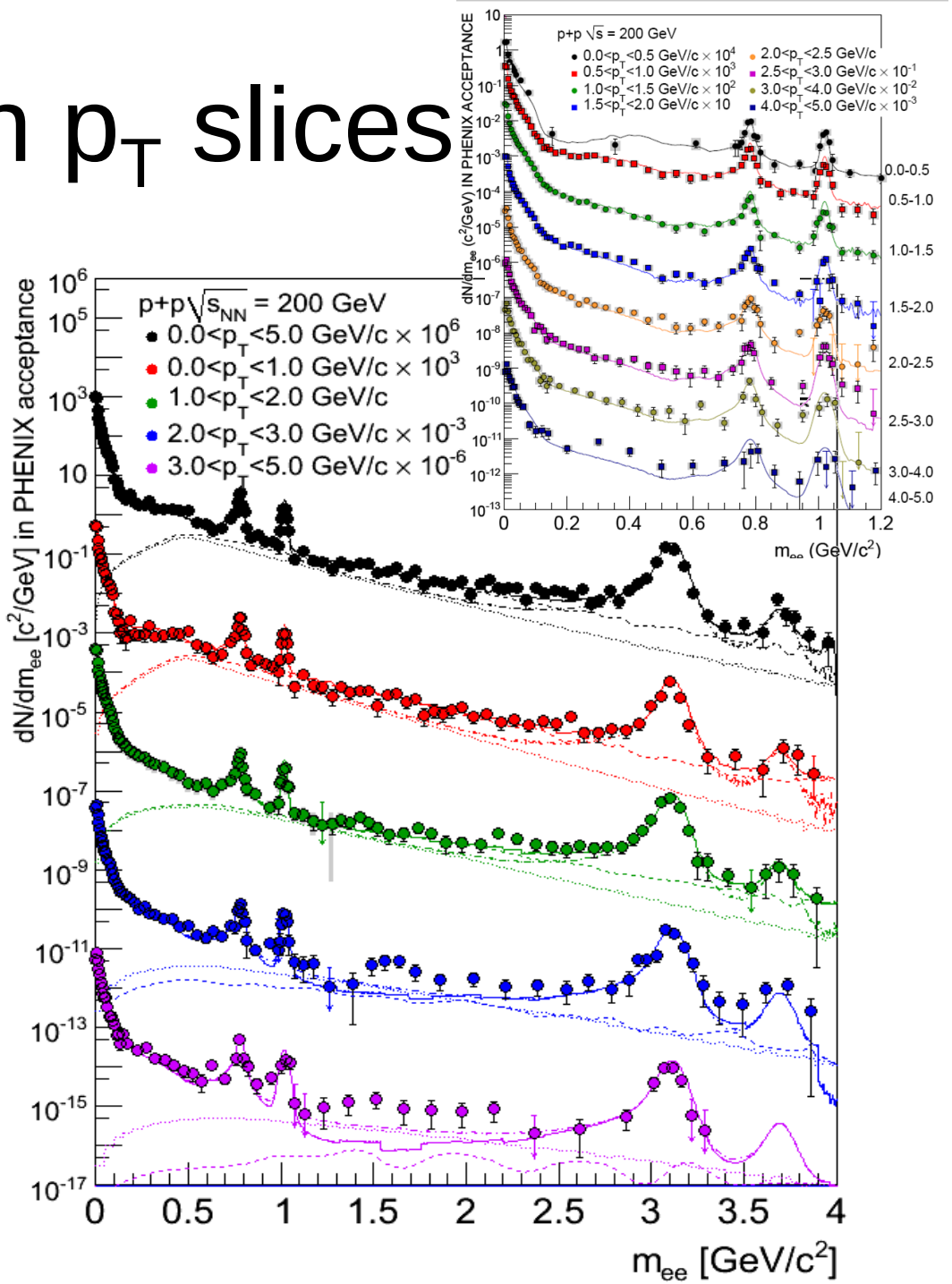


- p+p matches the cocktail fairly well, high p_T excess
- There exists LMR excess in Au+Au at all p_Ts
- Au+Au LMR excess is largest low pair p_T

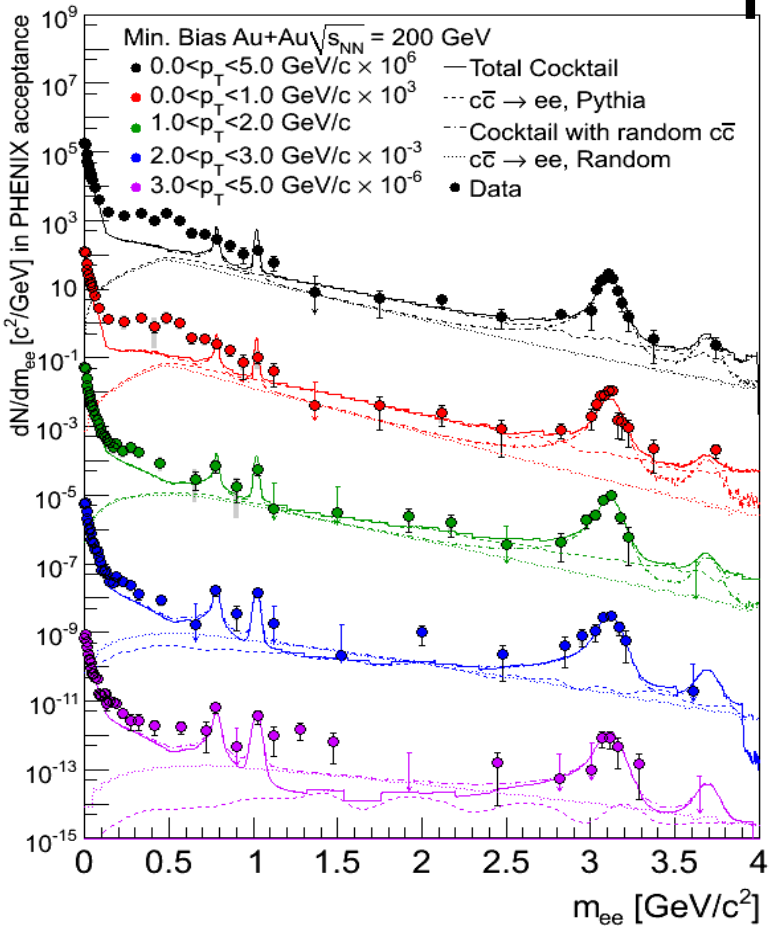
PRC 81 02391 (2010)

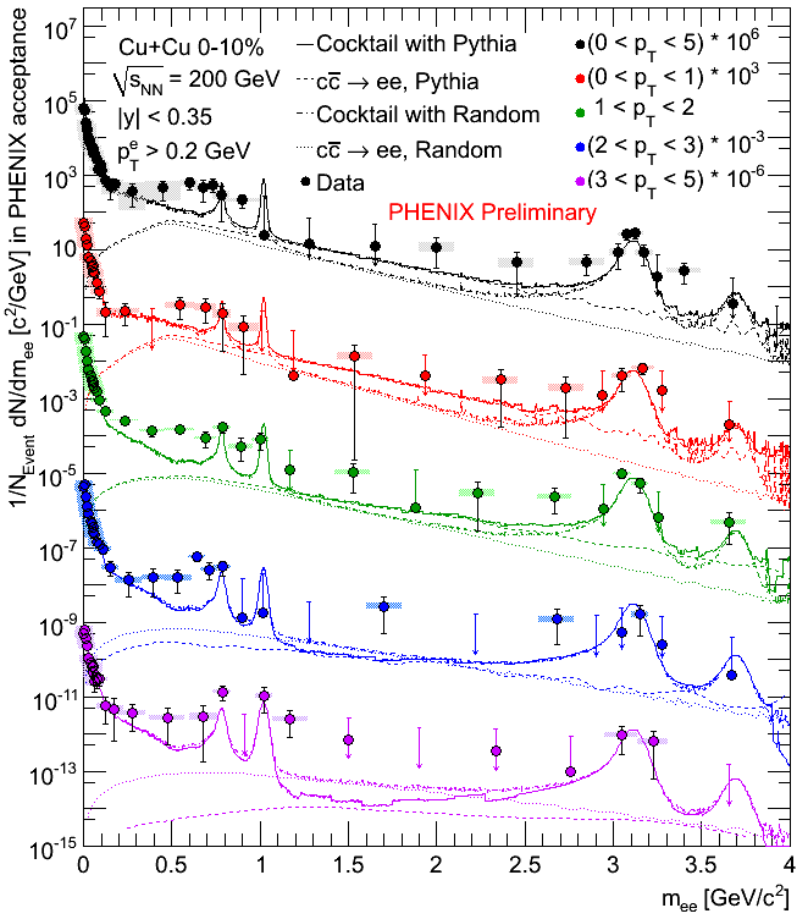
p+p in p_T slices

- Matches at low pT
- High pT IMR excess
  - No bottom in cocktail
  - p+p non-photonic single electron p_T not well described by PYTHIA
- High pT LMR excess from thermal photons



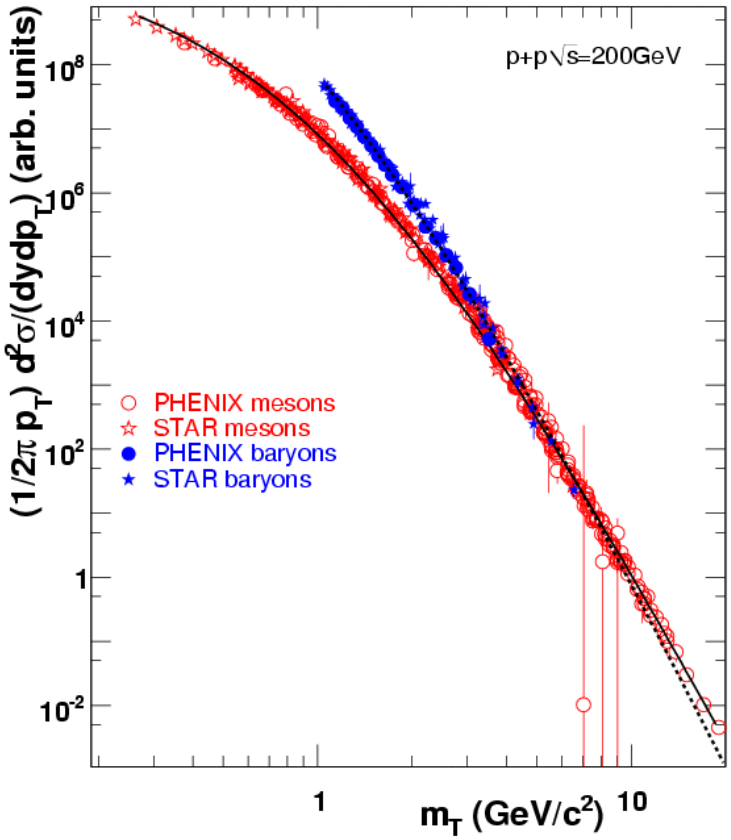
Au+Au MB and Cu+Cu 0-10% in p_T slices

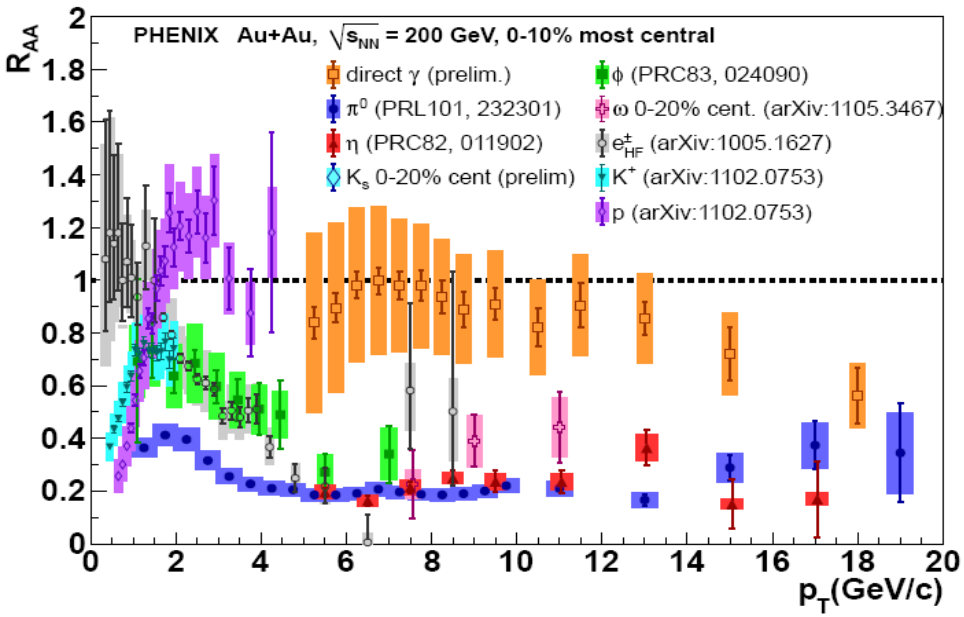




- LMR excess at low pT
- High pT LMR excess from thermal photons

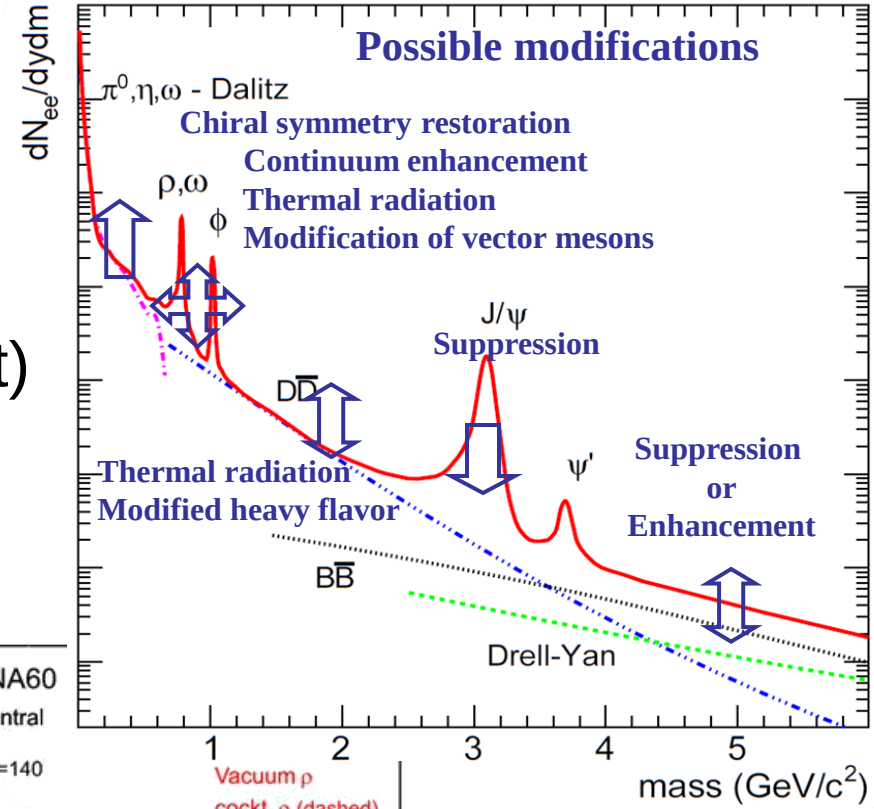
Baryon Meson differences

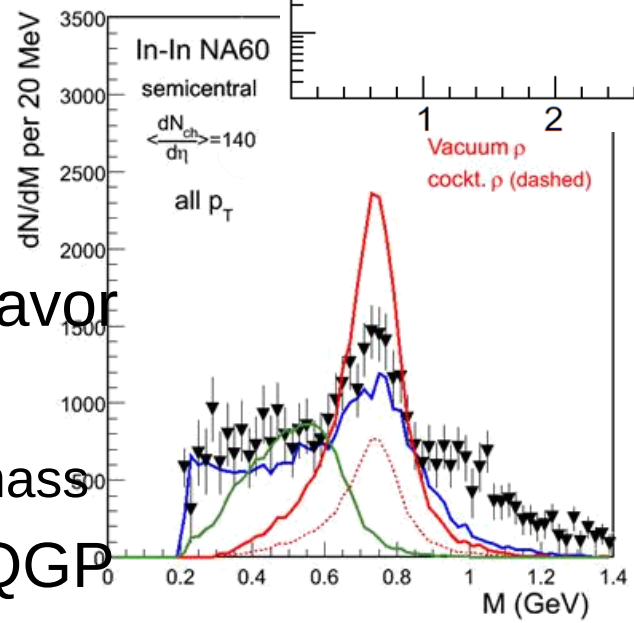




Dielectron Continuum: Motivation

- $\rho \rightarrow$ e+ e-
  - Broad mass distribution
  - Short lifetime
  - Broadening (and/or mass shift)
  - EM probe, no color charge
- Diverse Physics Signals
  - Direct virtual photons
  - Dalitz decays
  - Hadronic decays
  - Semi-leptonic heavy flavor
  - Vector mesons
    - Broadening/dropping mass
  - Full time evolution of QGP





Hadronic Cocktail Generation

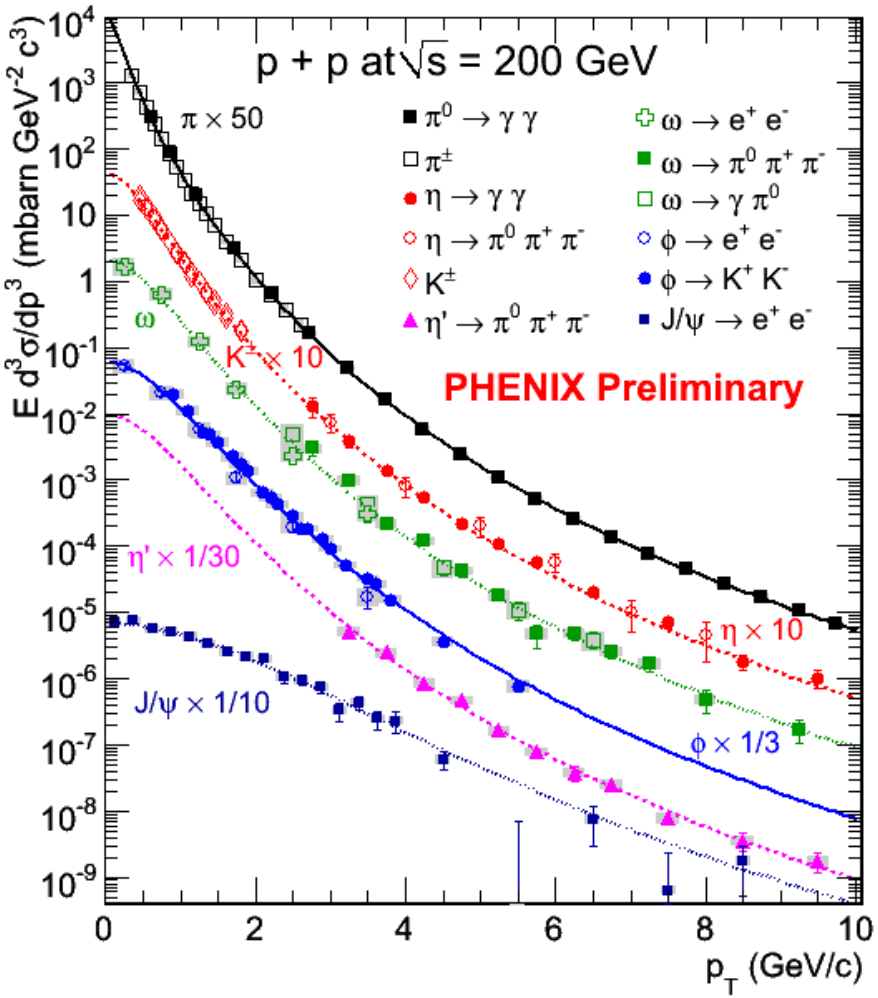
- Calculate known pair sources
- Pion p_T spectra fit to a modified Hagedorn function

$$E\frac{d^3\sigma}{dp^3} = A(e^{-(ap_T + bp_T^2)} + p_T / p_0)^{-n}$$

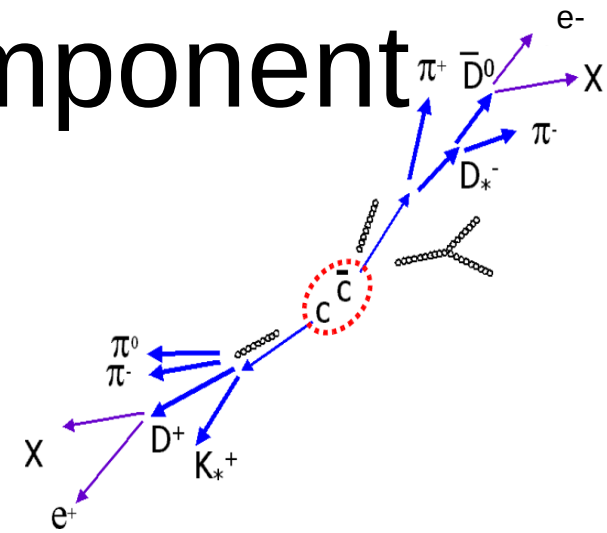
- m_T scaling

$$p_T \rightarrow \sqrt{p_T^2 + m_{meson}^2 - m_\pi^2}$$

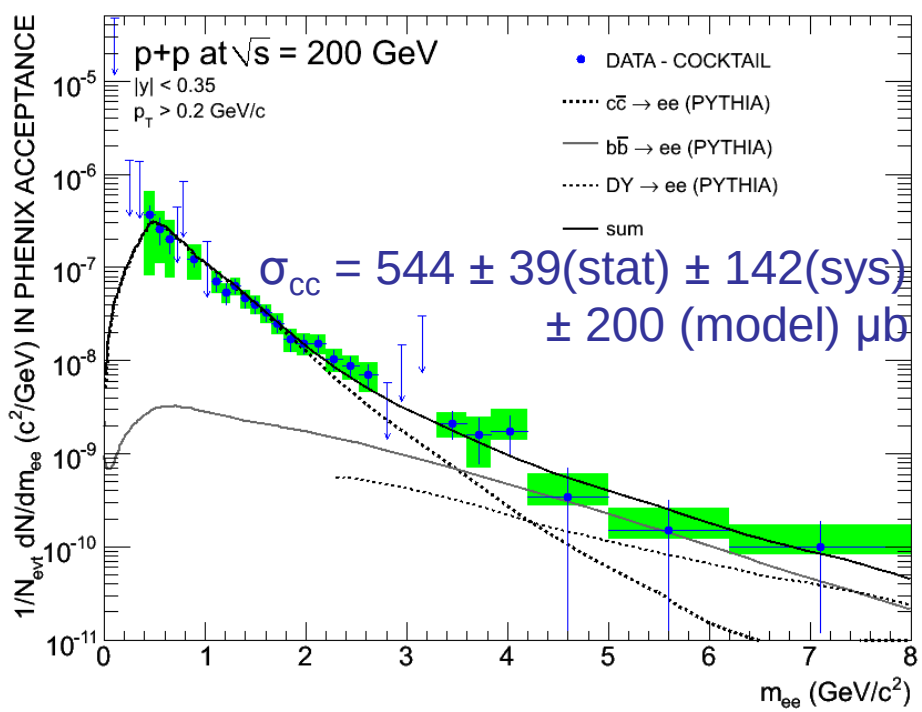
- When possible normalized to measured mesons p_T distributions



Open Charm Component

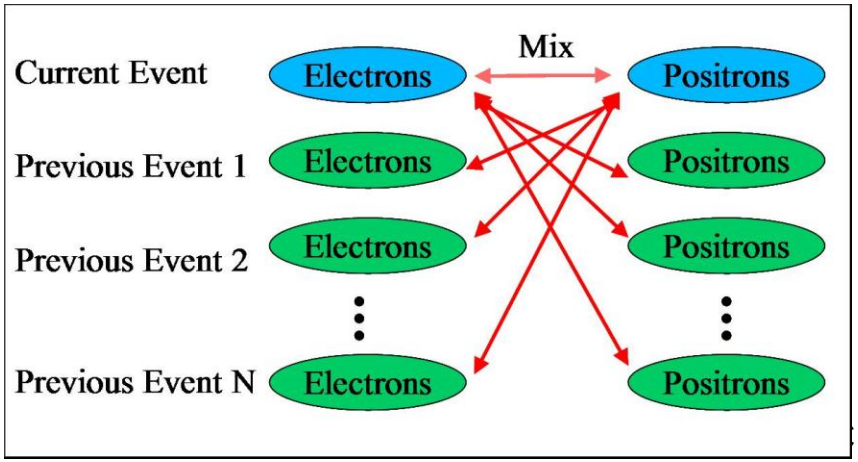


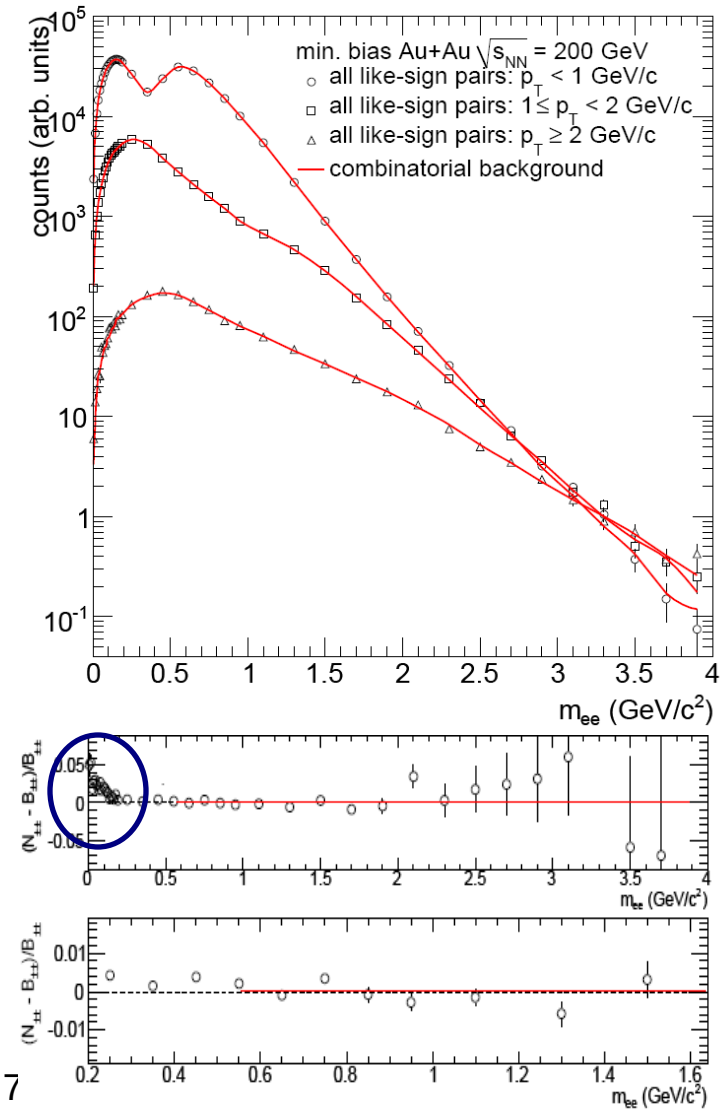
- D mesons semi-leptonically decay
  - e-e+ correlated by the ccbar
- Simulated with Pythia
- In p+p, measure the charm cross section
  - agrees with the non-photonic single electron measurement, σ_{cc} = 567 ± 57(stat) ± 193 (sys)
  - Phys. Lett. B 670, 313 (2009)
- Au+Au and Cu+Cu use N_{Coll} scaling of the p+p



Combinatorial Background

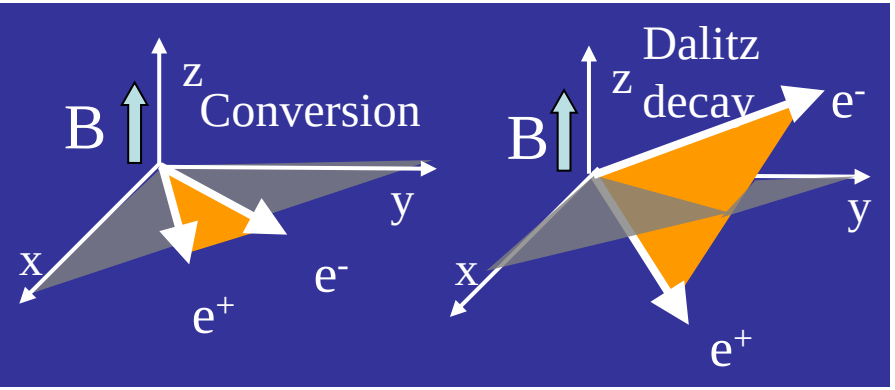
- Largest background in HI
  - Large multiplicities, combinatorial goes as multiplicity squared
- Shape determined by event mixing



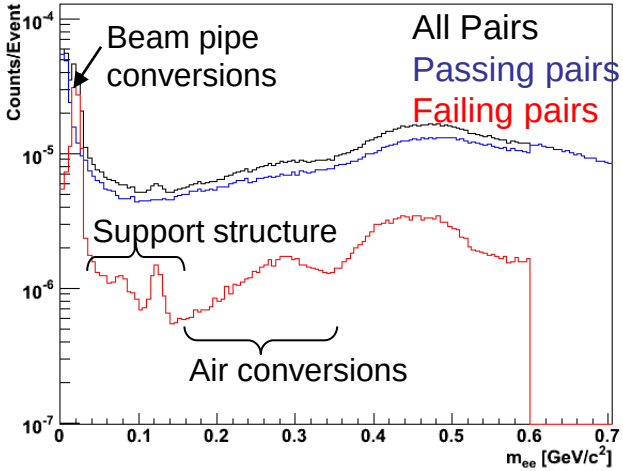


Backgrounds

Conversions

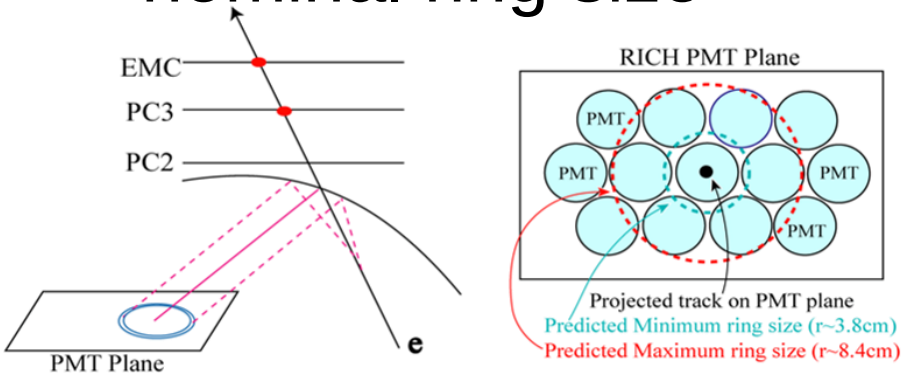


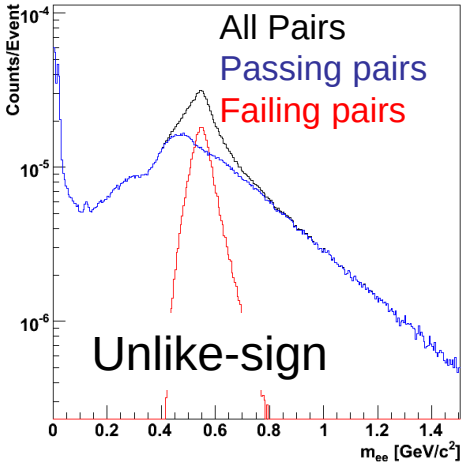
- Cut pairs with opening angle ⊥ to B, low mass and charge ordered

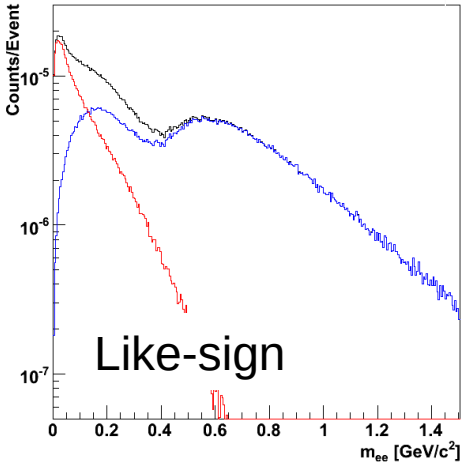


Ring Overlap

- Require pairs are separated by twice the nominal ring size





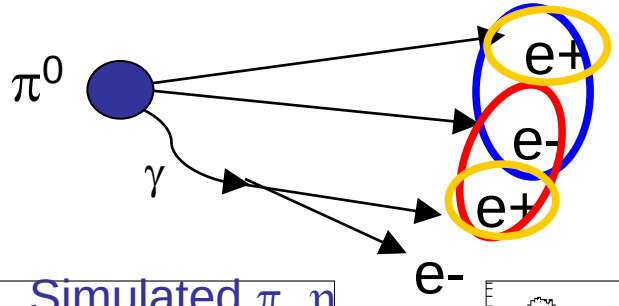


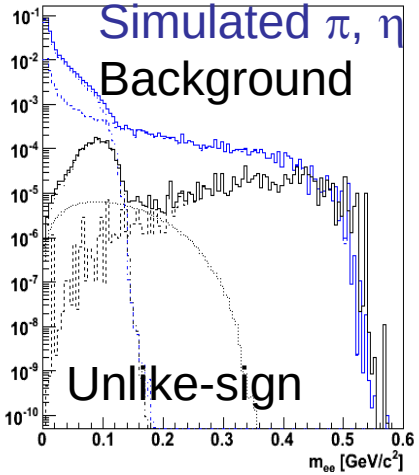
Backgrounds

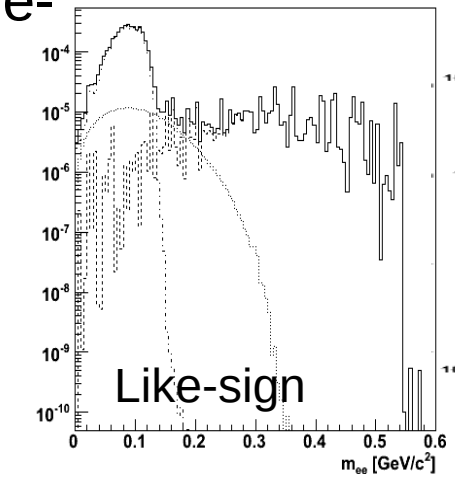
Double Dalitz

- Decays with multiple e+e-
  - Like-, unlike-sign at same rate
  - Exodus-like simulation

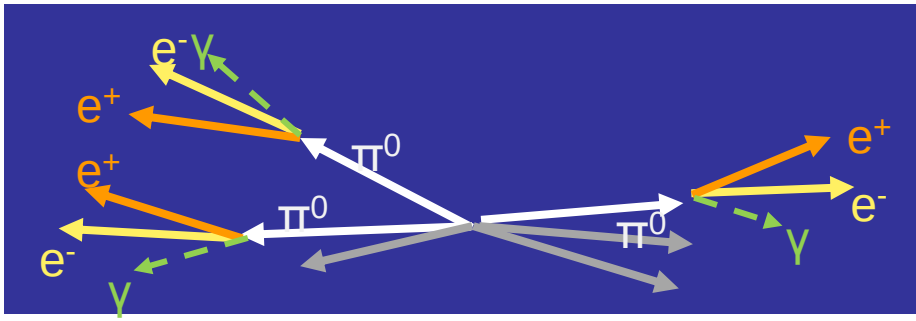
$\pi^0 \rightarrow$ e+e-e+e-, $\eta \rightarrow \pi^0\ \pi^0\ \pi^0$



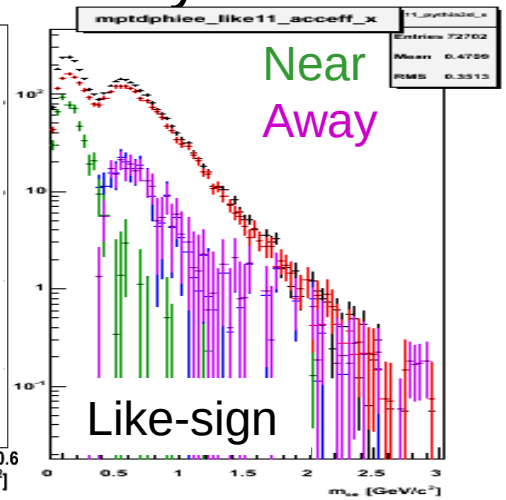


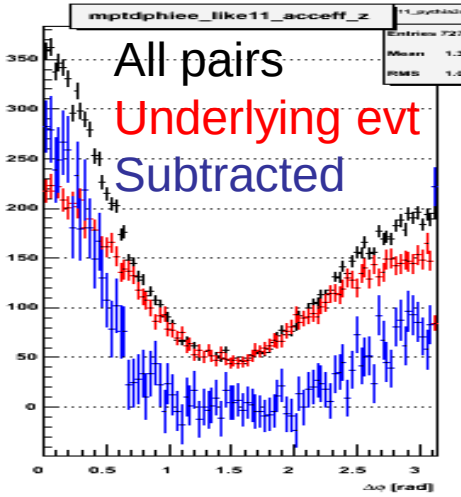


Jets

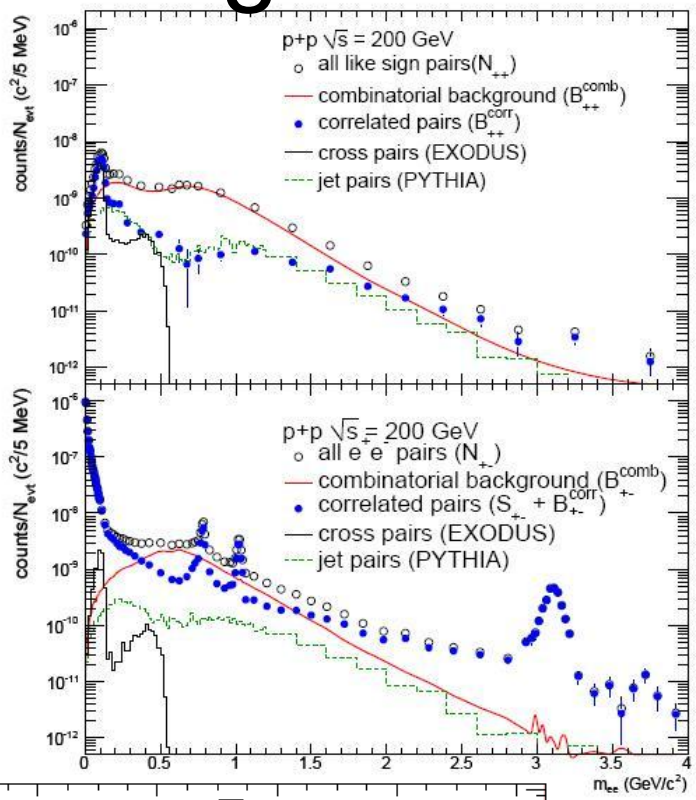


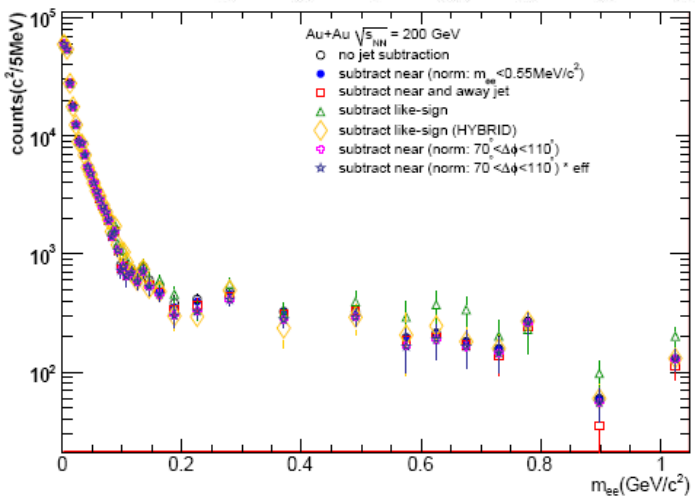
- Pairs from π^0 in jet correlated by jet
  - Like-, unlike-sign at same rate
  - Pythia simulation





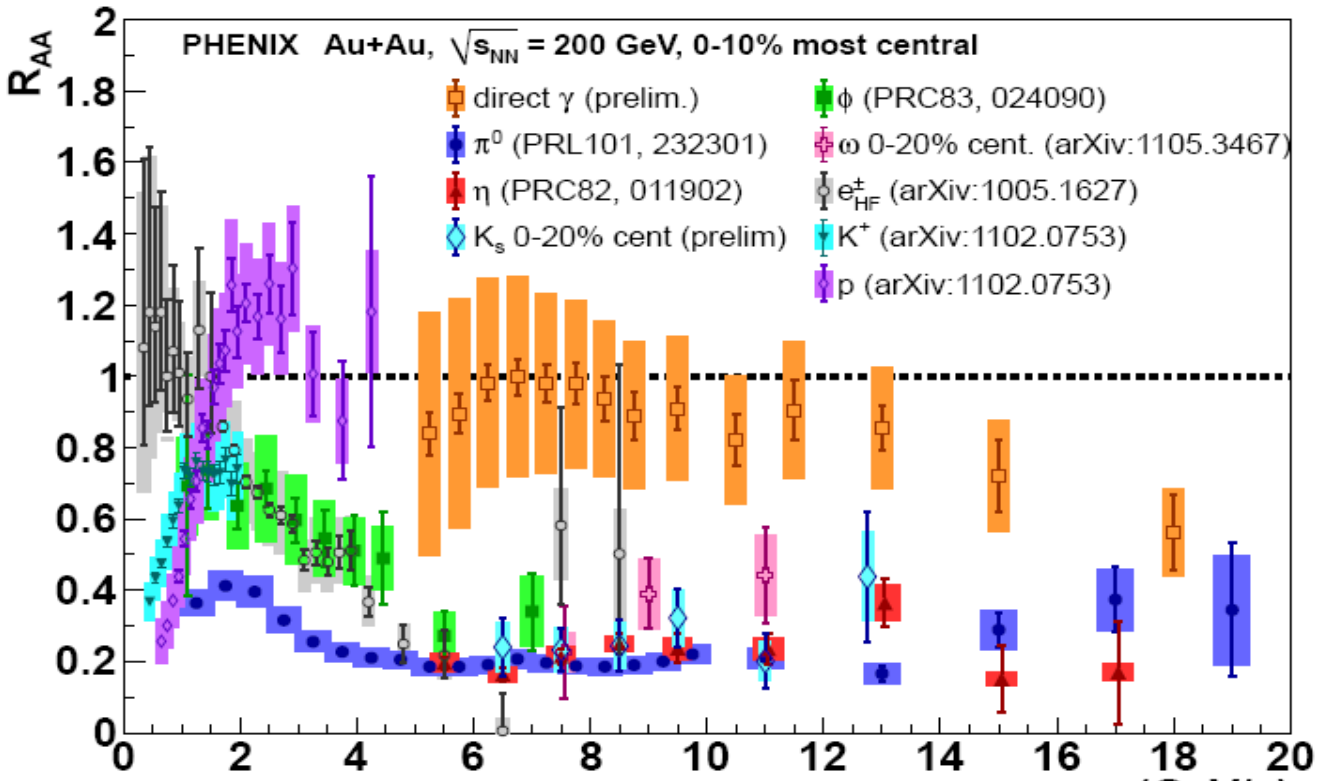
Background Removal – 2 Methods





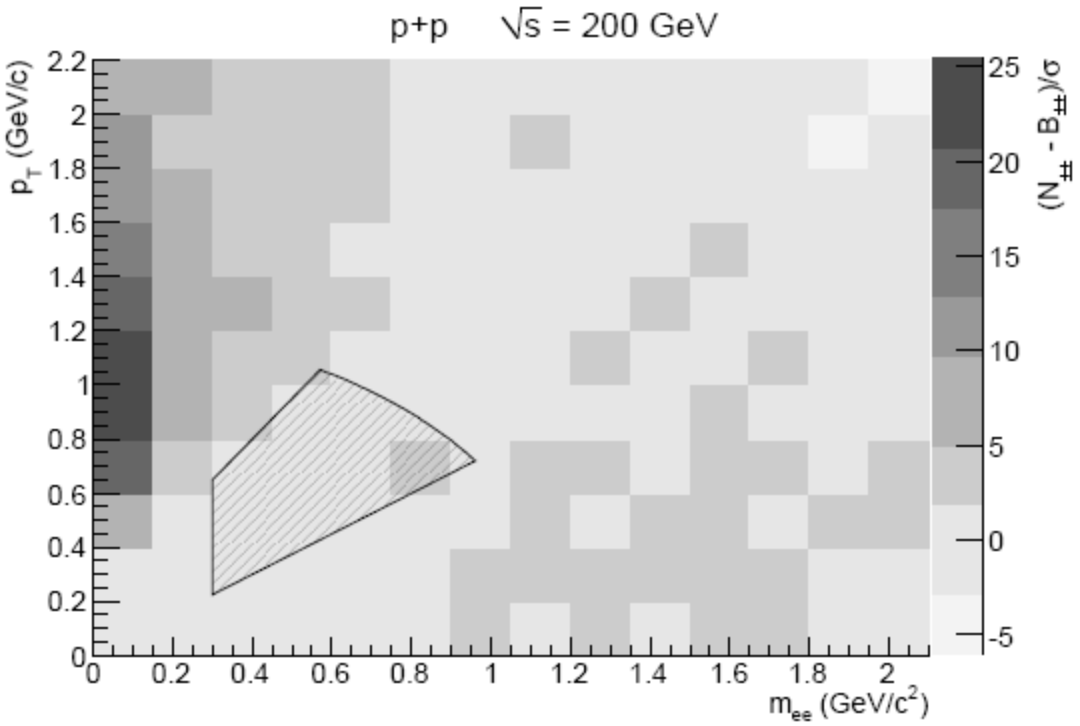
- Component subtraction
  - Use like-sign pairs to normalize BGs
  - Subtract each of the BG components
- Like-sign acceptance corrected subtraction
  - Correct the like-sign pairs to have the unlike-sign pair acceptance
  - Subtract like-sign pairs from unlike-sign pairs
- In p+p, Au+Au, Cu+Cu both methods are consistent

HI Modifications -- R_{AA}

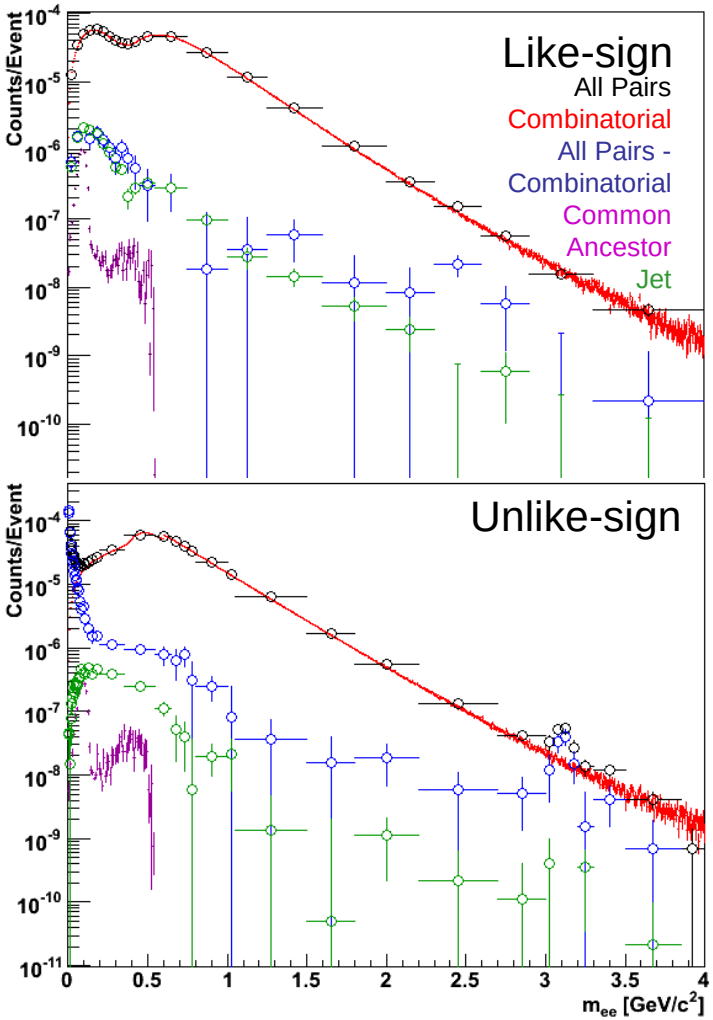


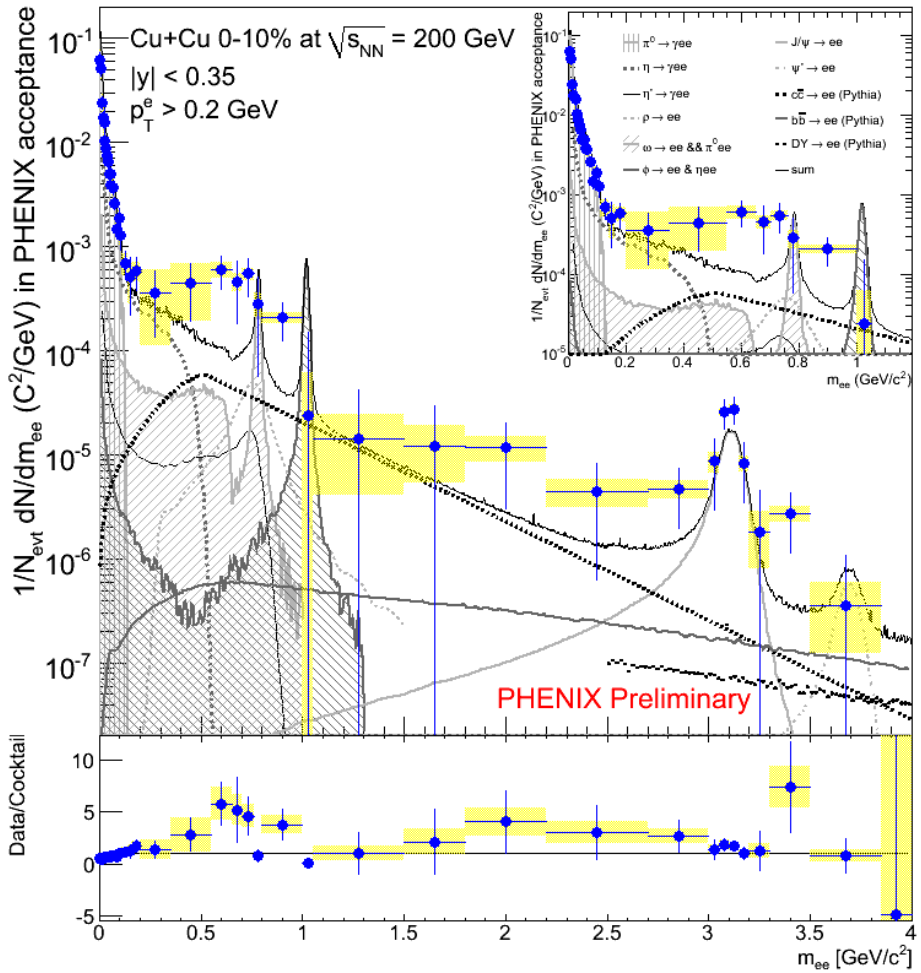
- ω, ϕ are suppressed
  - ϕ, ω, K_S at high pt like π, η
  - ϕ like K+, e_{HF} at low pt; ϕ not like π, η at mid. pt
- Baryon Meson difference in R_{AA}

p+p Normalization region

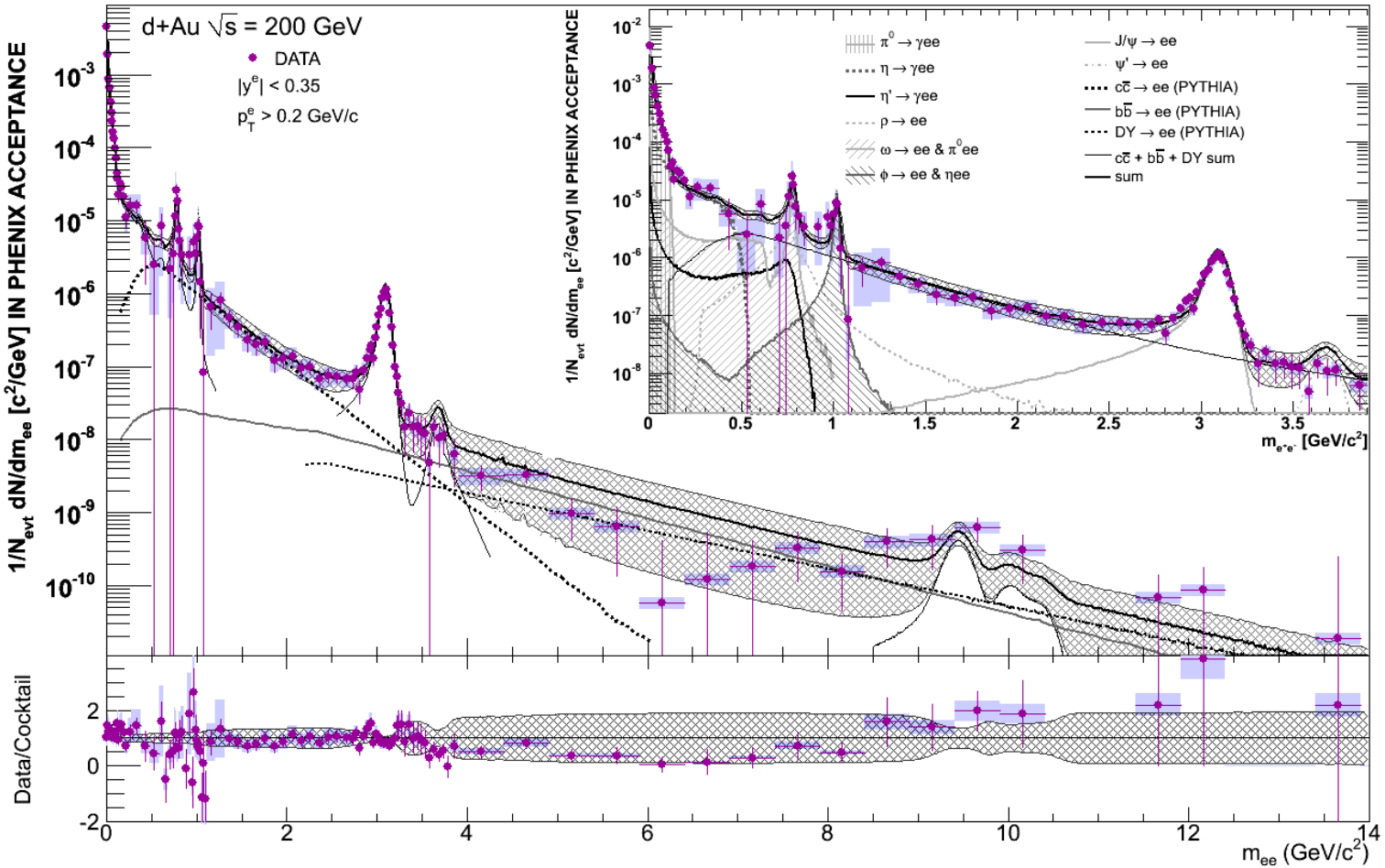


Cu+Cu 0-10% measurement

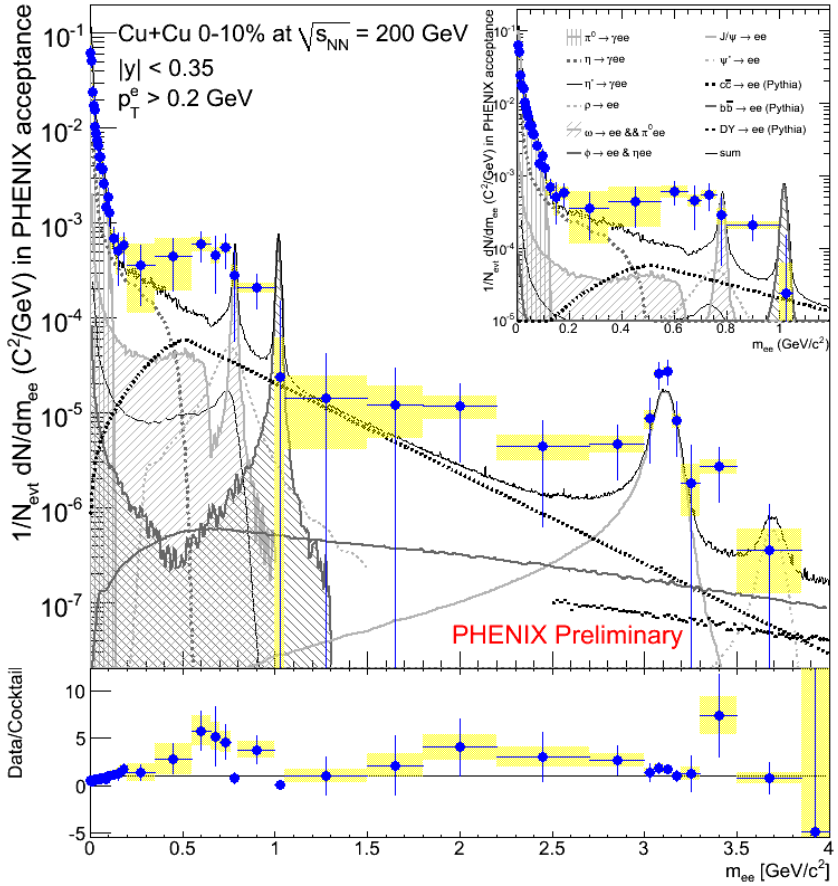


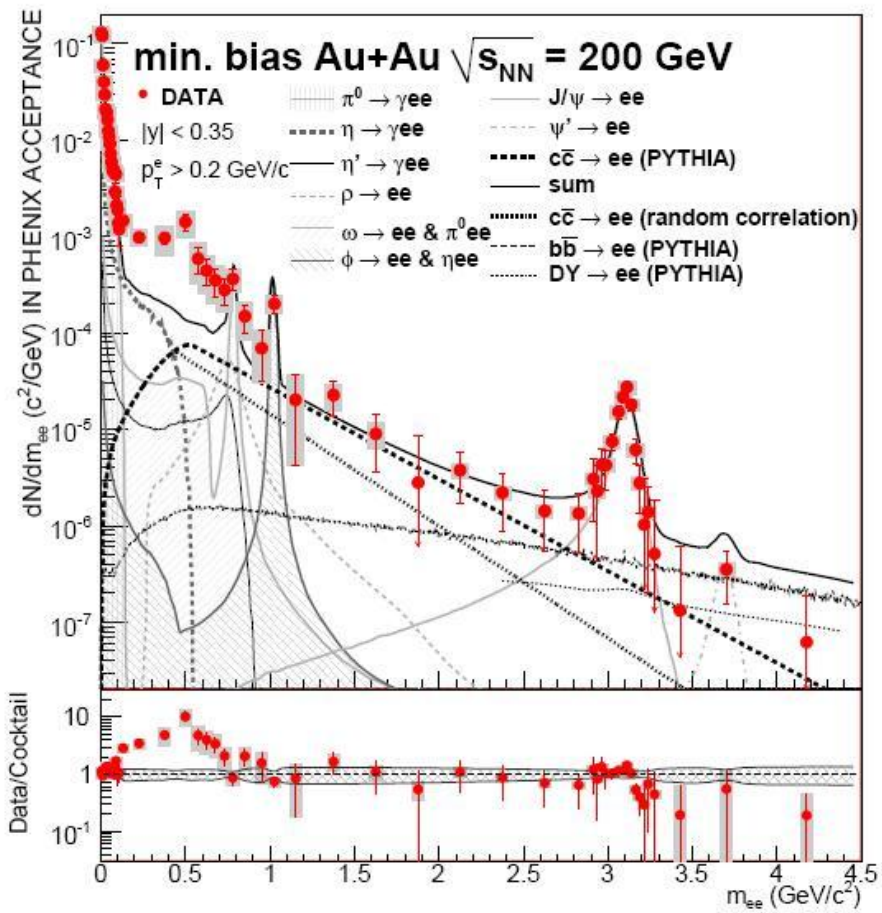


d+Au Min Bias at high mass



Au+Au Min Bias & Cu+Cu 0-10% measurement





HIC in the LHC era -- 7/17/2012

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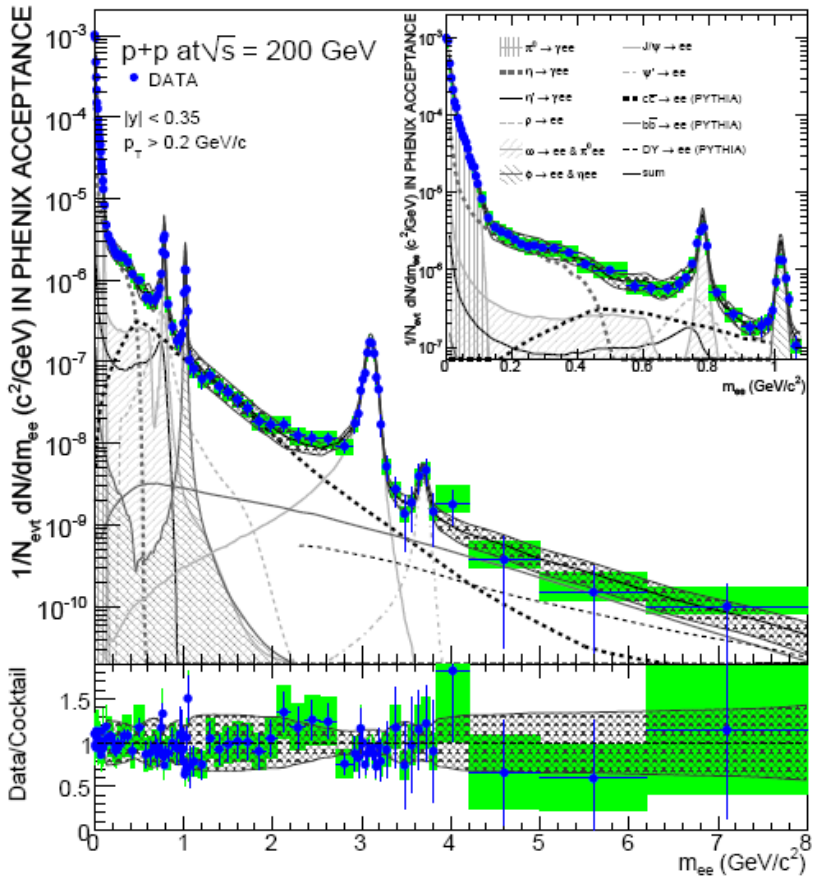
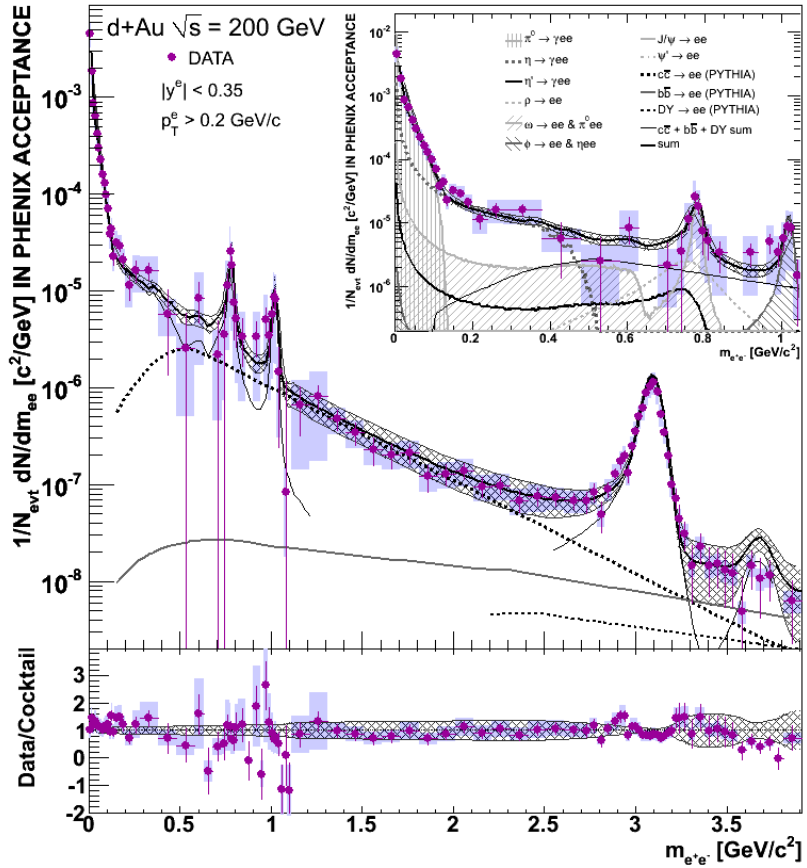
p+p and d+Au Min Bias measurement





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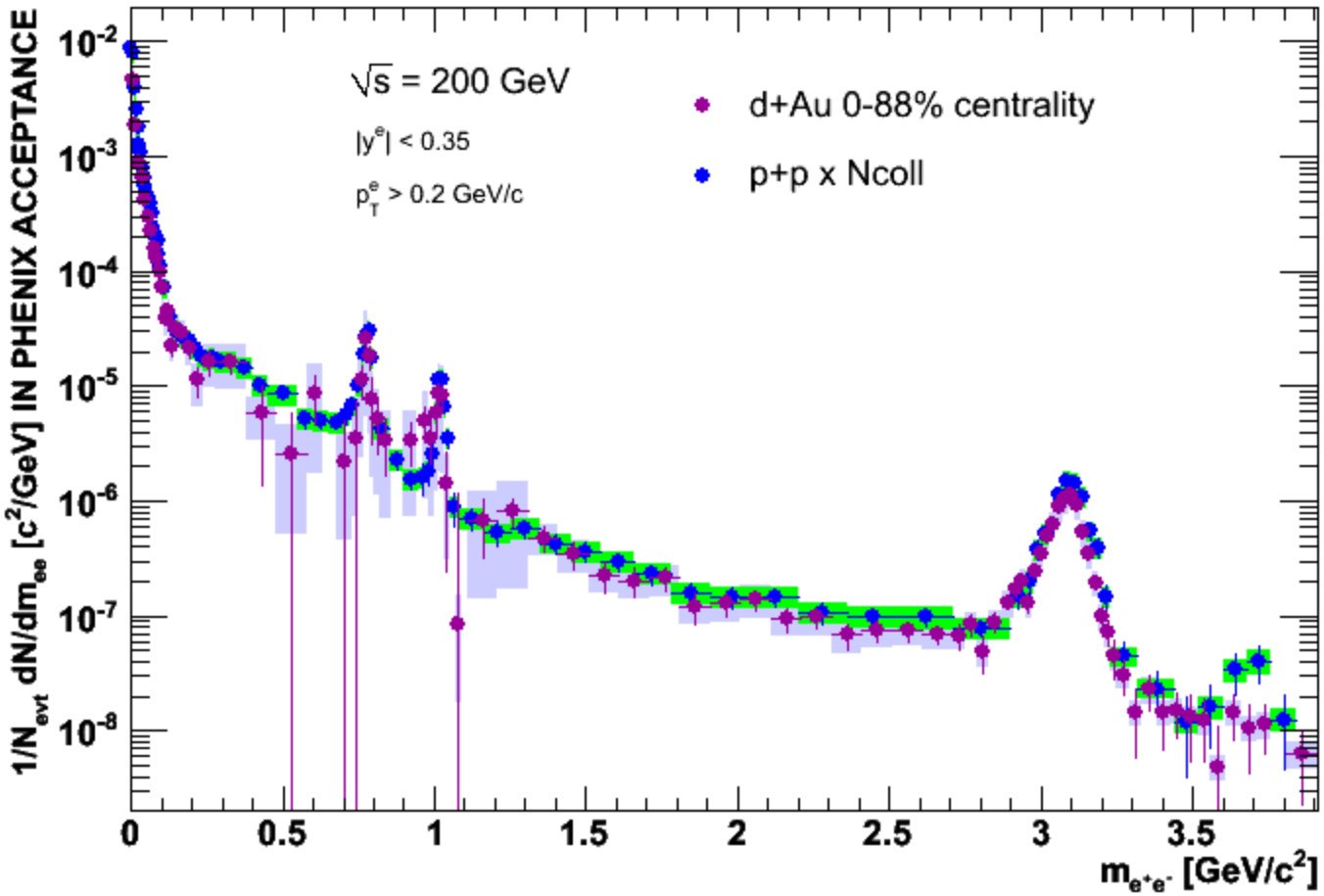
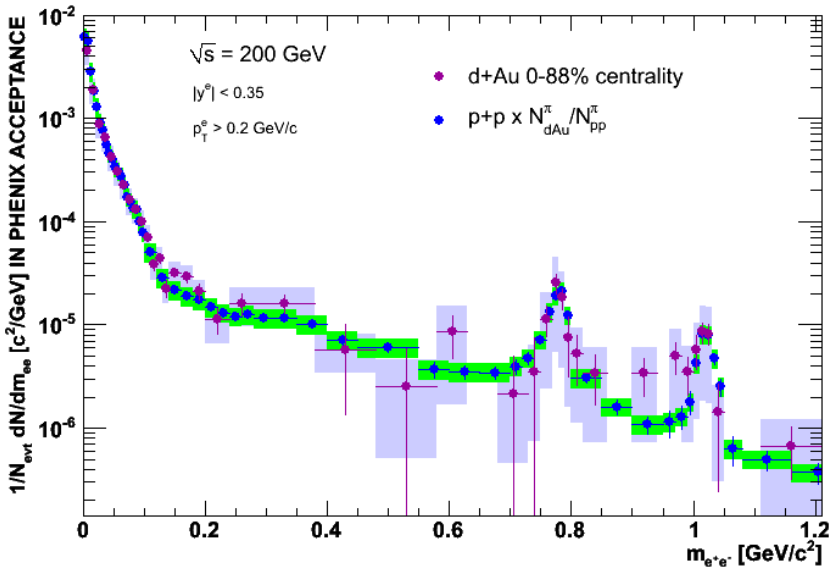
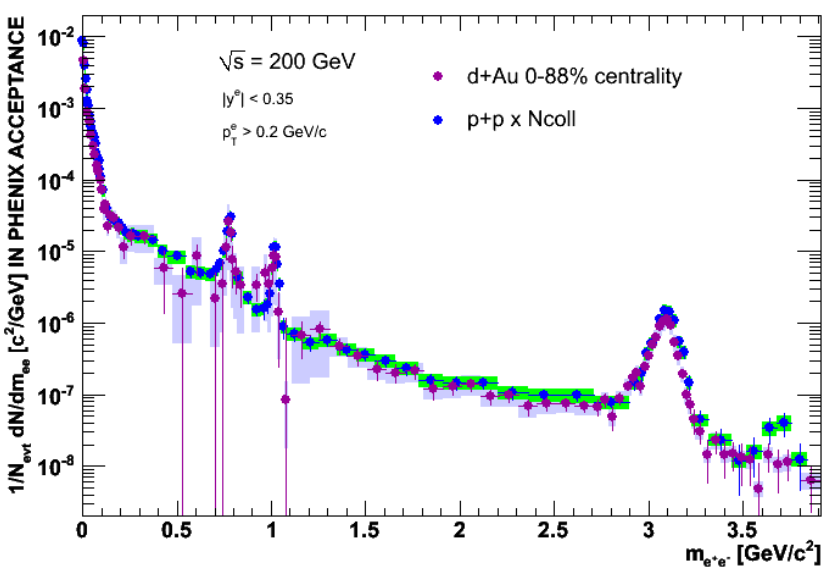
Compare p+p and d+Au



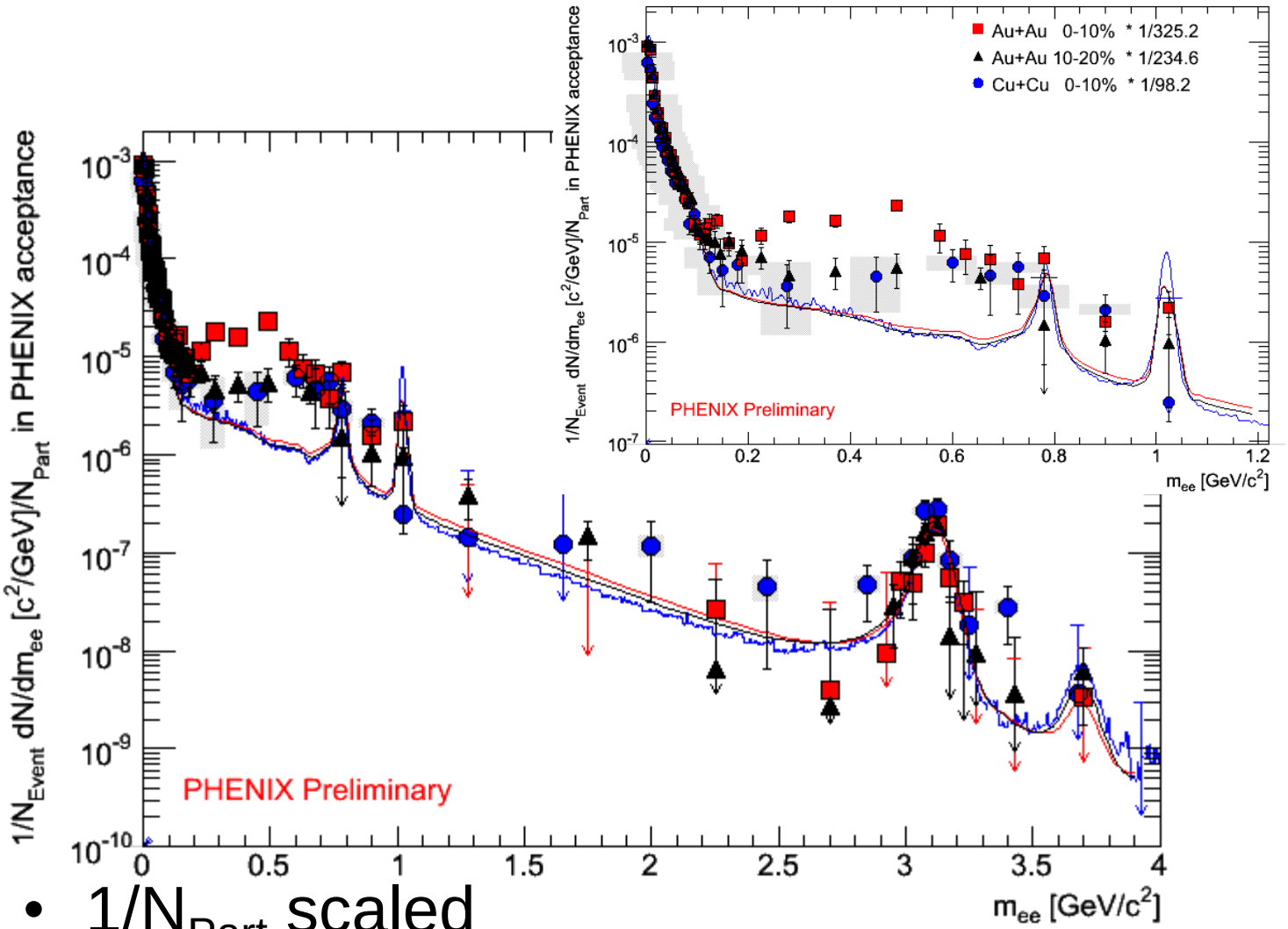
- No cold nuclear matter effects

p+p d+Au comparison



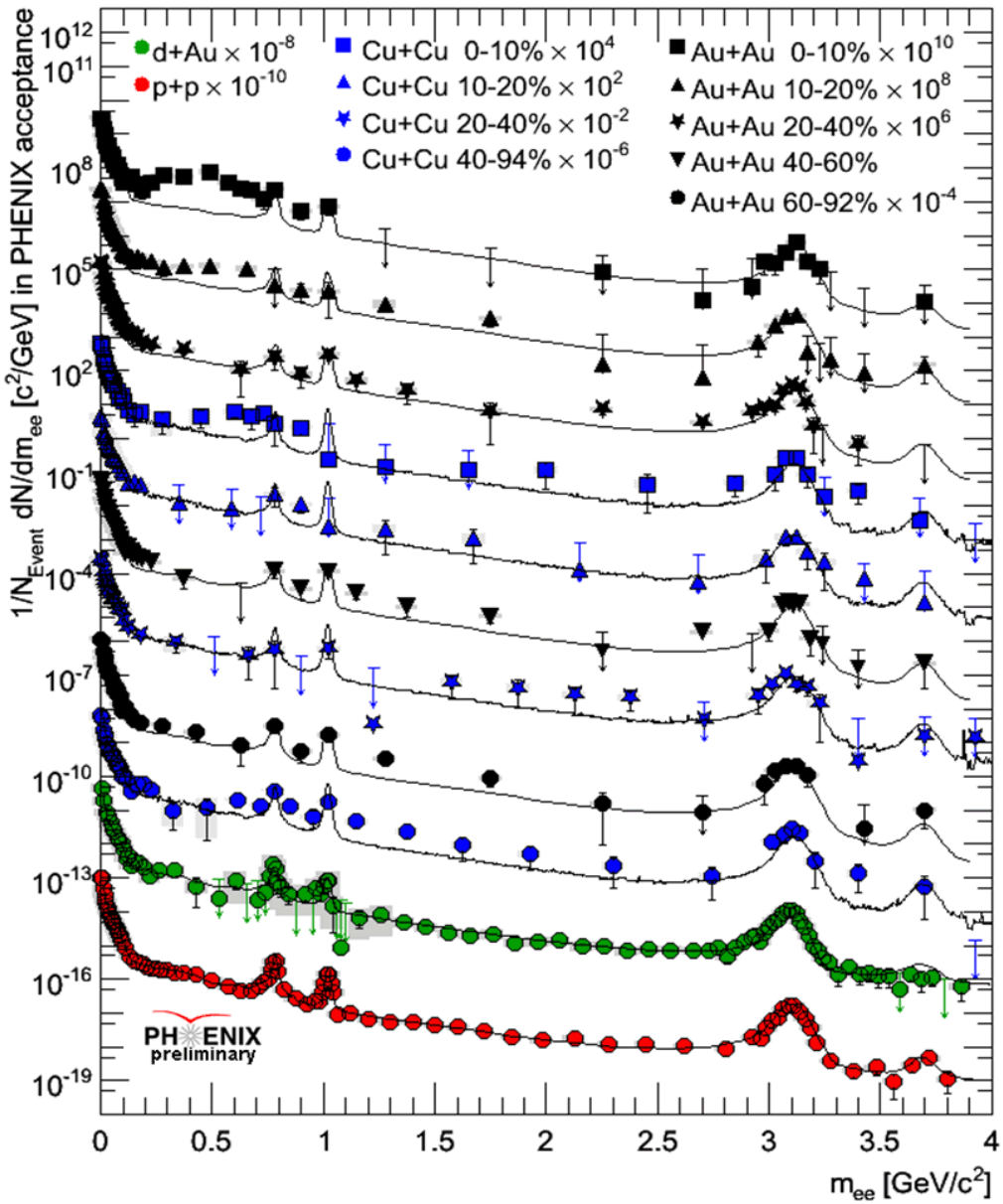


Most Central HI Spectra



- $1/N_{Part}$ scaled
- Onset of LMR excess

Centrality Dependence



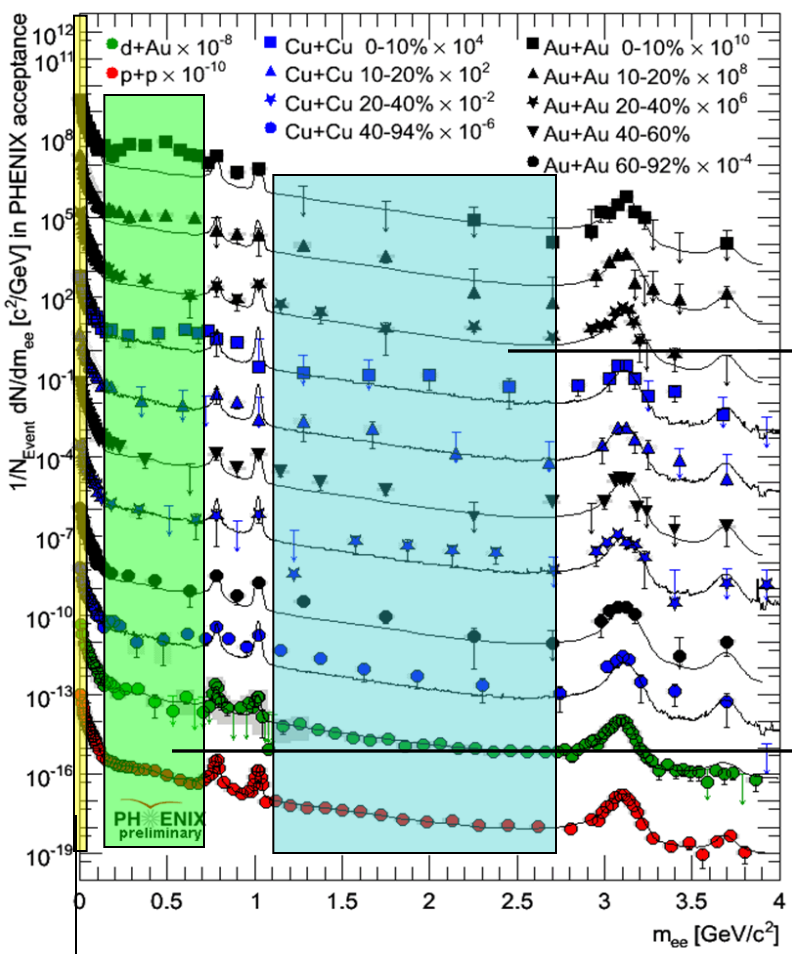
N_{Coll} ordered

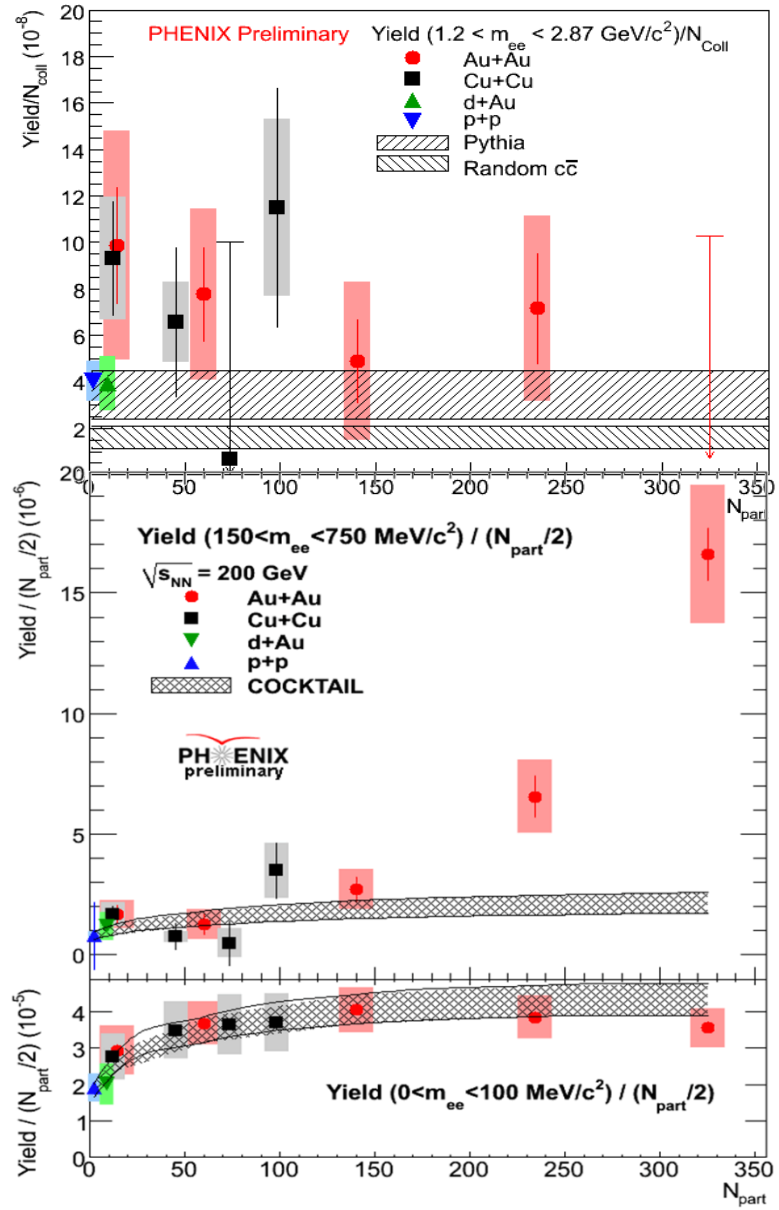
Central

Peripheral d+Au

p+p

Yields vs N_{Part}



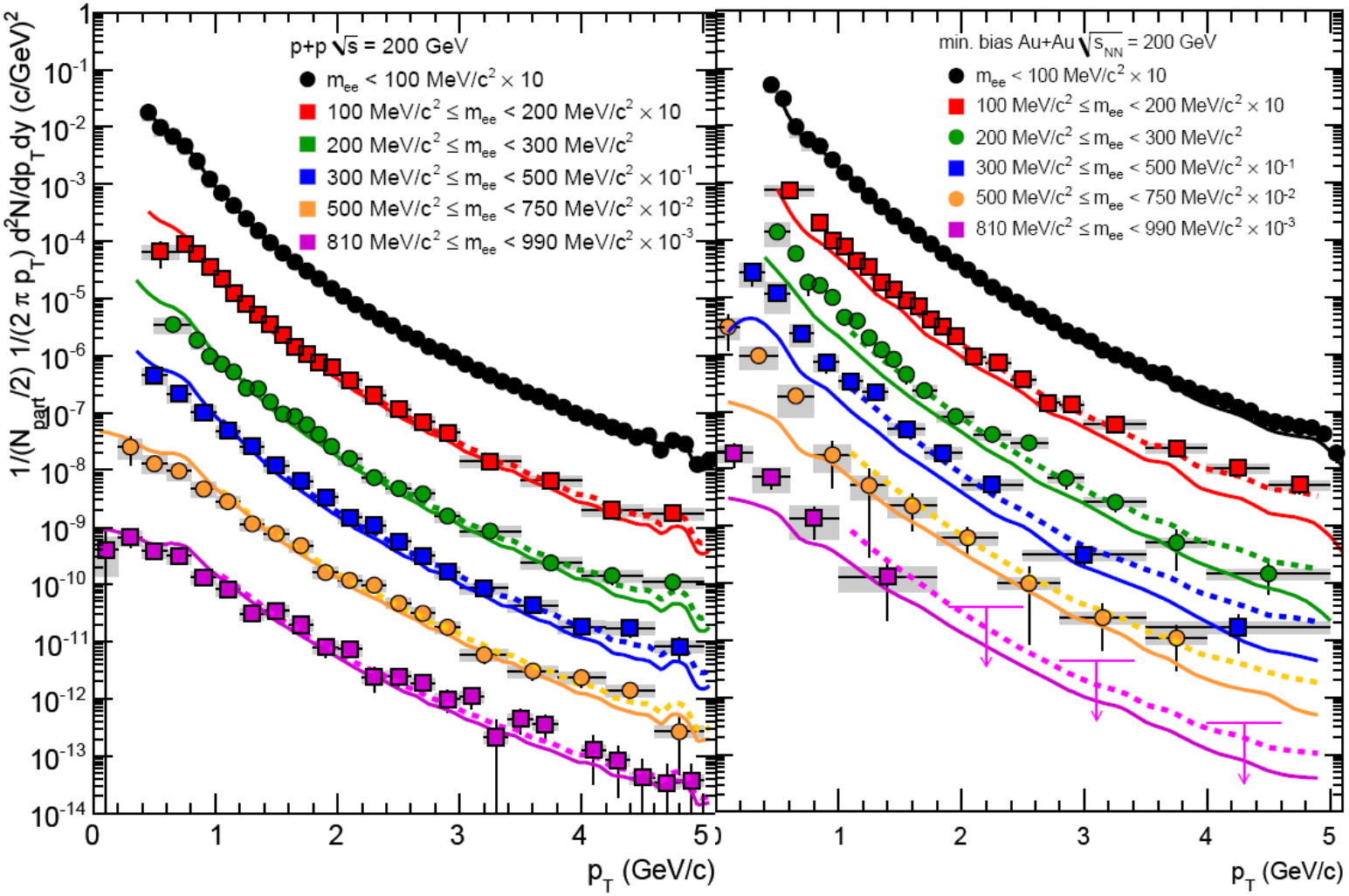


EMC cuts

- p+p
  - No charged tracks point to cluster
    - Remove charged tracks
  - Time-of-flight cut +/- 5 ns
    - Remove cosmics
  - Shower shape cuts
    - Remove conversions after DC
  - Isolation cuts (optional)
    - Remove frag. photons
- Au+Au
  - No charged tracks
  - PID cuts
    - Remove merged clusters mainly from pi0, eta
  - GEANT simulation
    - Remove neutrons

p_T Spectra of LMR

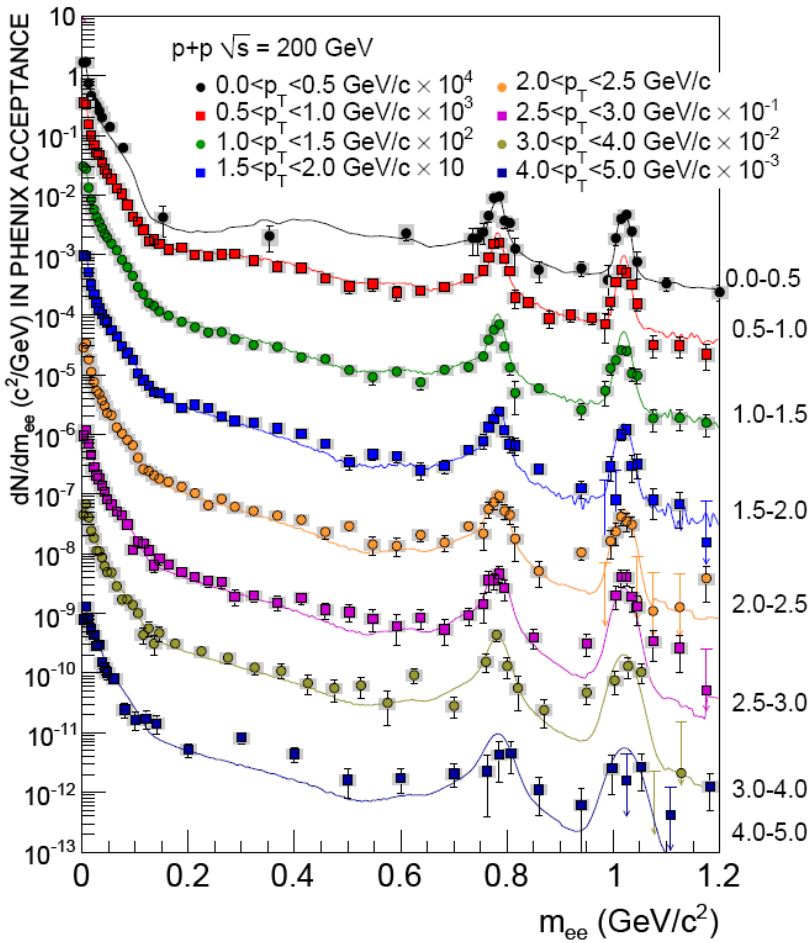
- Corrected to the full 2π acceptance

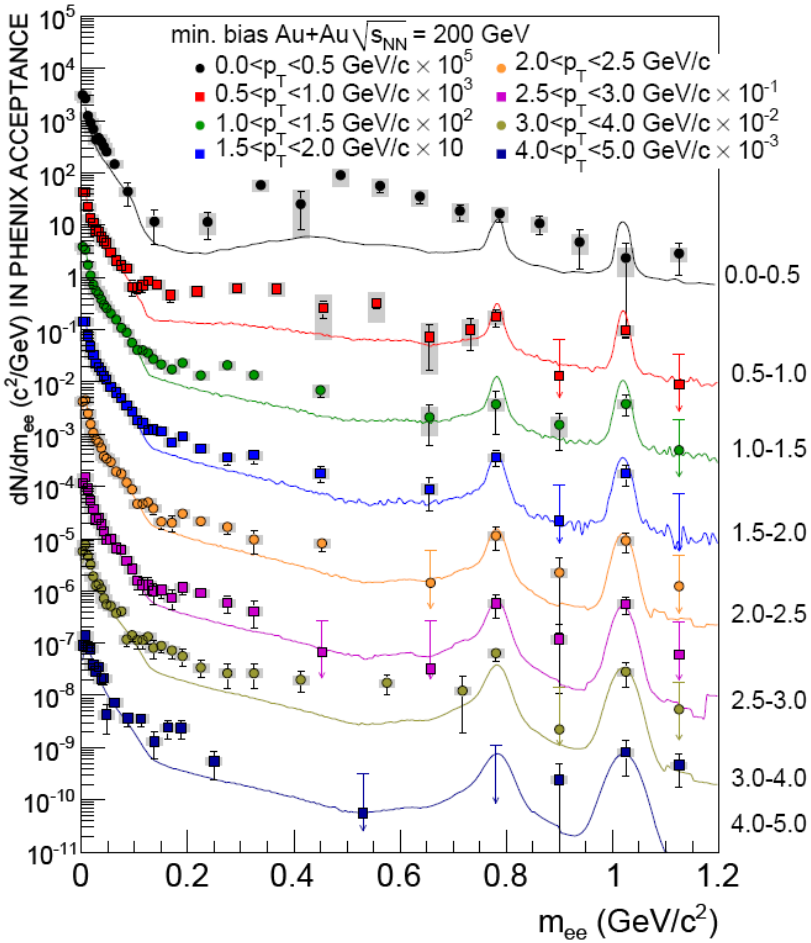


Solid lines cocktail

Dashed lines cocktail + virtual photon

LMR m Spectra in p_T Slices





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

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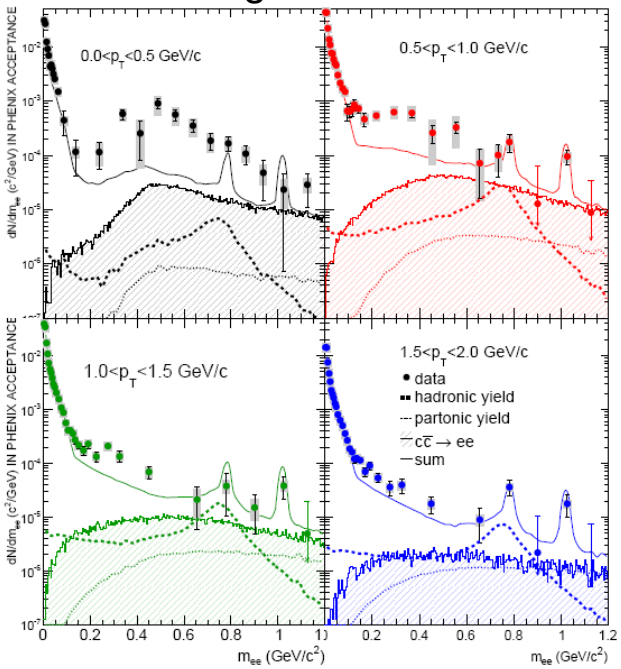
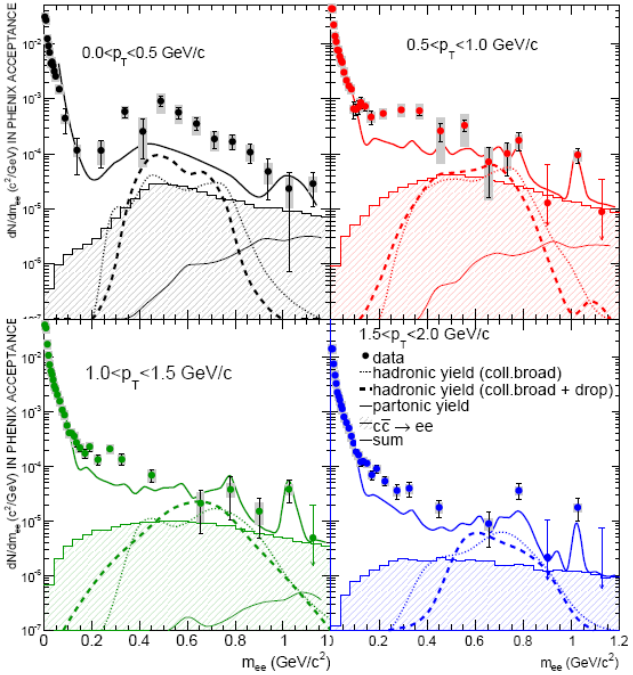
LMR Theory in p_T Slices

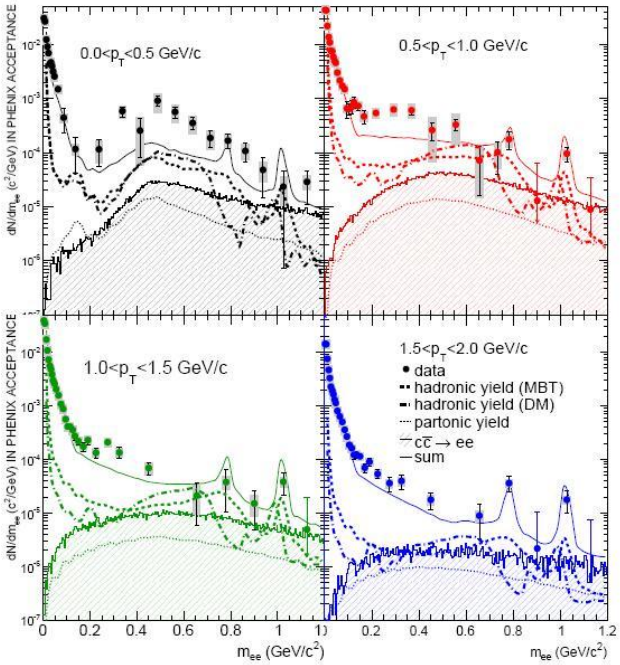
K. Dusling and I. Zahed



W. Cassing and E. Bratkovskaya



R. Rapp and H. van Hees

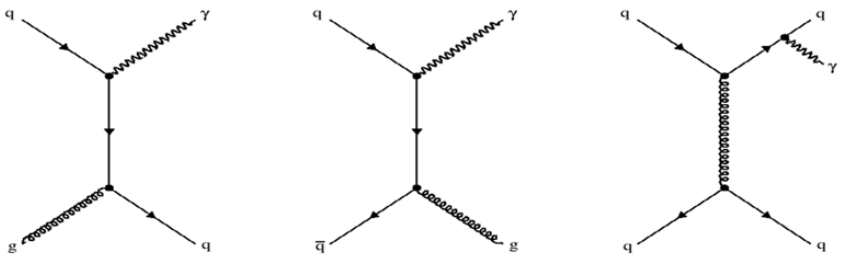


- In the high p_T ranges, the theories are close but still low
  - Should including virtual photon processes, q + g ->q e+ e-
- At low p_T, none describe the Au+Au MB data

PRC 81 02391 (2010)

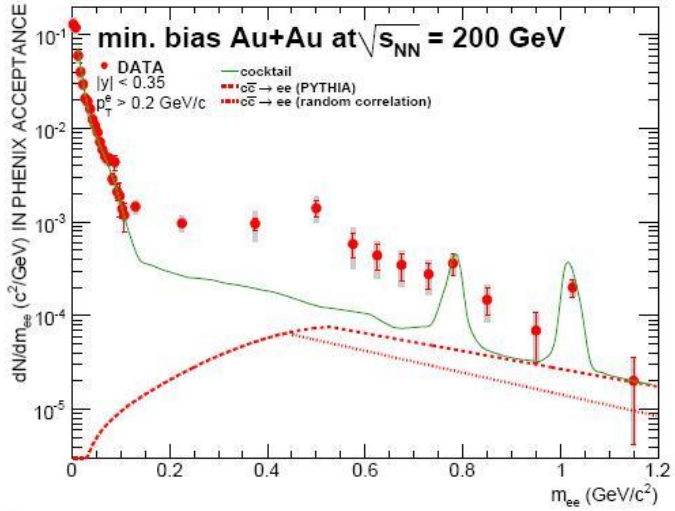
Photon sources

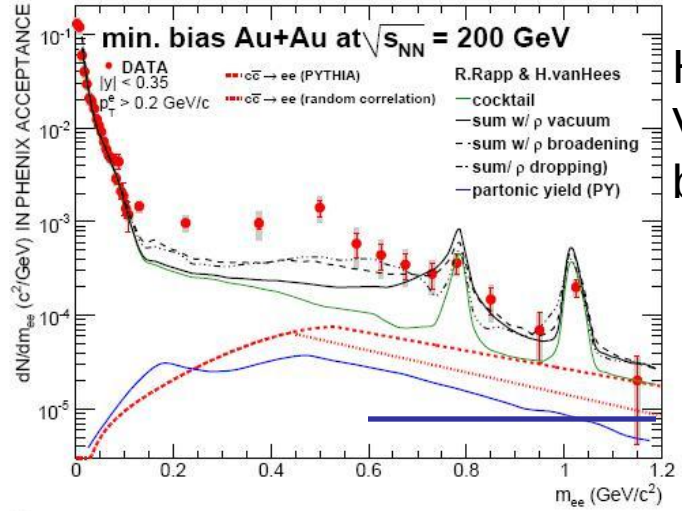
- Hadron decays
  - π^0 ~ 80%, η ~15% background in p+p
- Initial hard scattering
  - High p_T, $v_2 = 0$
- Fragmentation
  - High p_T, $v_2 > 0$
- Jet conversion and Bremsstralung
  - High p_T, $v_2 < 0$
- Thermal
  - Low p_T, $v_2 > 0$



- Possible modifications
  - Isospin
  - nPDFs
    - Shadowing, anti-shadowing
  - Energy loss → suppress frags.
  - Radiation from jet-medium interactions

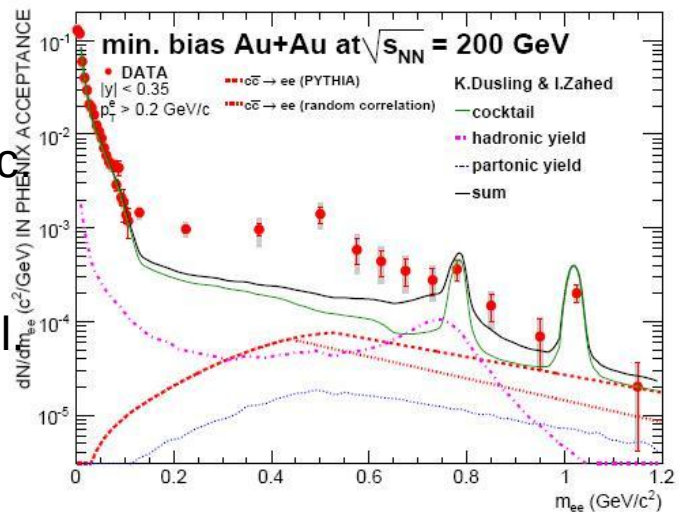
Theory Comparison

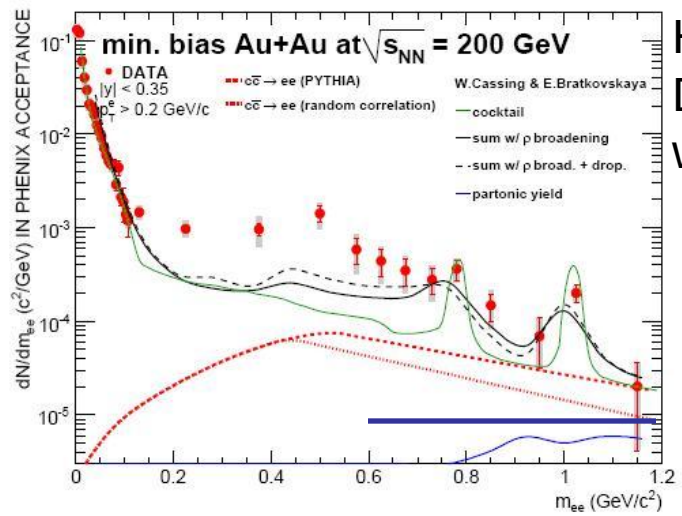




Hadronic gas
VDM
broadening

Current-current correl. func
Hadronic gas
Hydro evol.

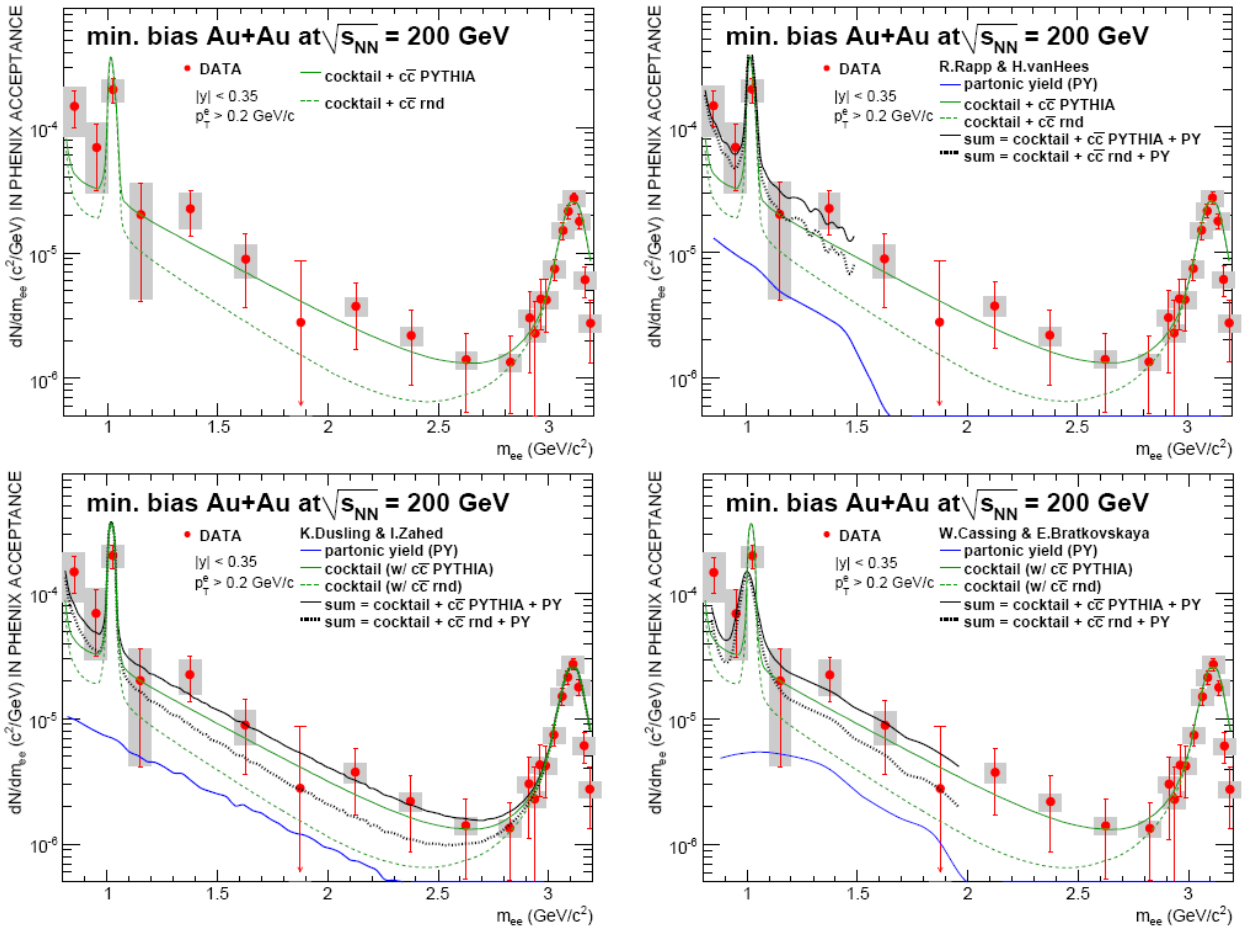




HSD
Dropping rho
w/ broadening

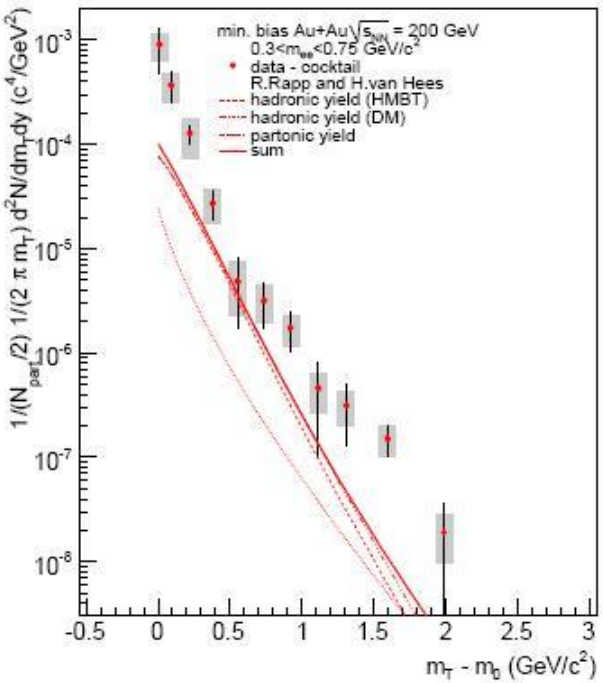
- Fail to describe the excess

IMR Theory

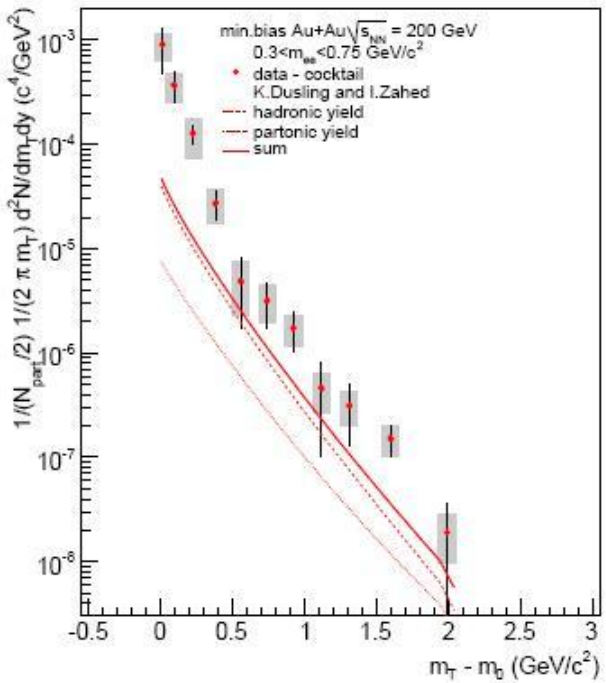

min. bias Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
DATA
|y| < 0.35
p_T^e > 0.2 GeV/c
cocktail + $c\bar{c}$ PYTHIA
cocktail + $c\bar{c}$ rnd
R.Rapp & H.vanHees
partonic yield (PY)
sum = cocktail + $c\bar{c}$ PYTHIA + PY
sum = cocktail + $c\bar{c}$ rnd + PY
K.Dusling & I.Zahed
cocktail (w/ $c\bar{c}$ PYTHIA)
cocktail (w/ $c\bar{c}$ rnd)
W.Cassing & E.Bratkovskaya
dN/dm$_{ee}$ (c^2/GeV) IN PHENIX ACCEPTANCE
m$_{ee}$ (GeV/c^2)

LMR Theory p_T Spectra

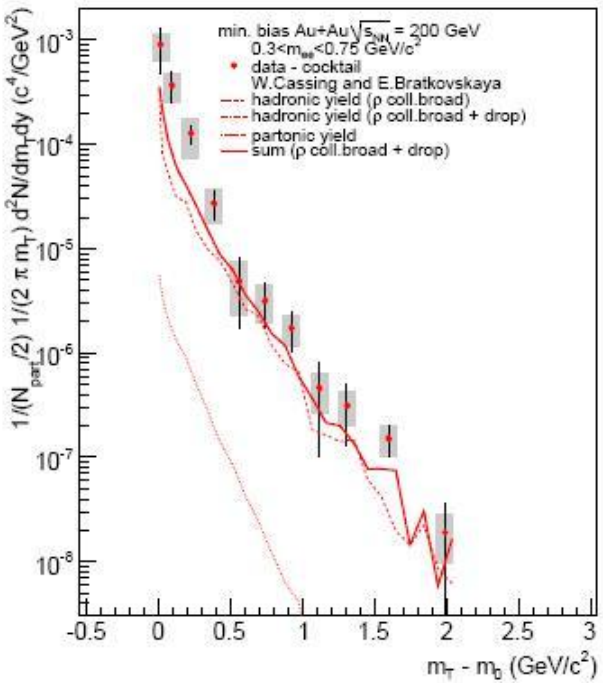
R. Rapp and H. van Hees



K. Dusling and I. Zahed

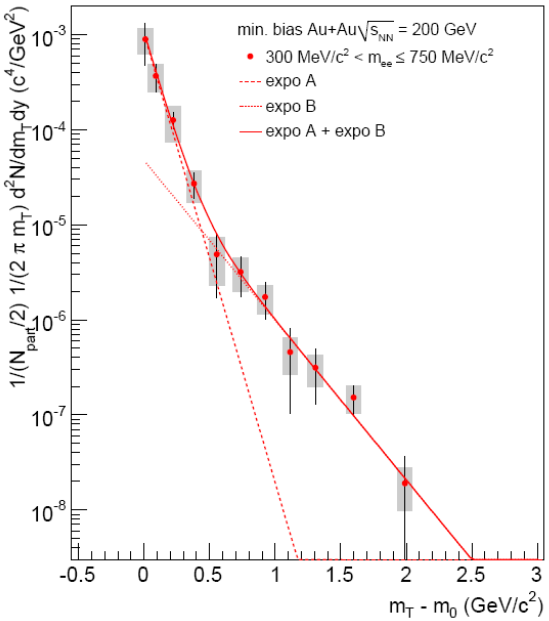


W. Cassing and E. Bratkovskaya

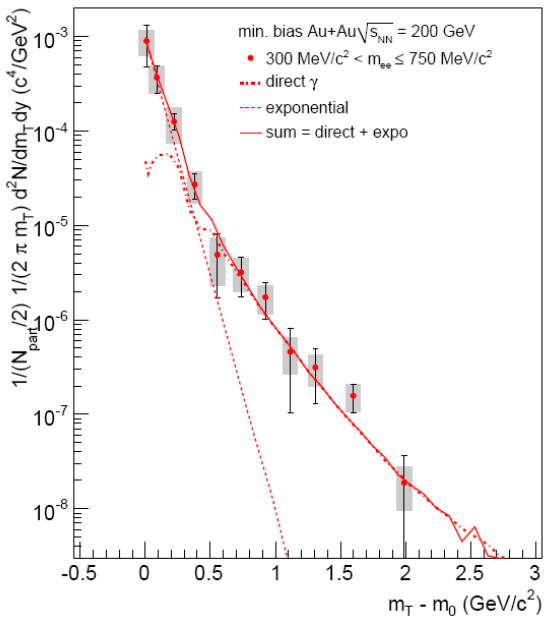


- None really describe the data
  - Cassing and Bratkovskaya closest
  - Benefit from including the virtual photon
    - q + g -> q + e+e-

LMR p_T Spectra → T_{Eff}

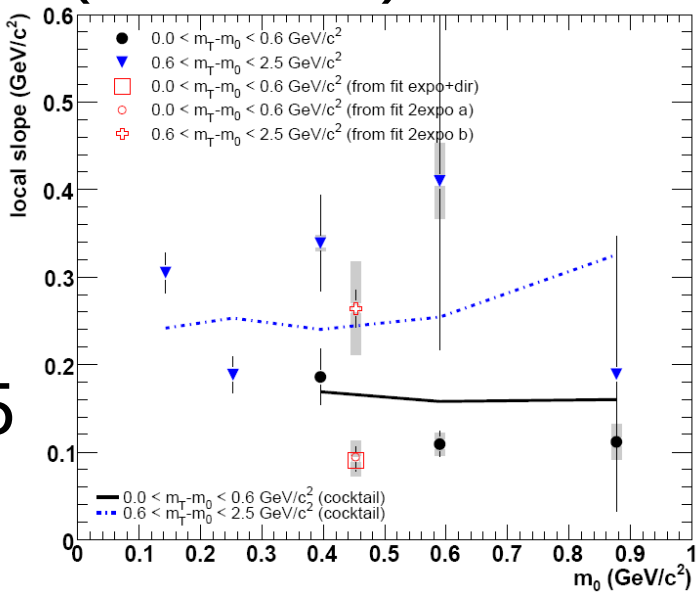


$$T_A = 258.4 \pm 37.7 \pm 9.6 MeV$$
$$T_B = 92.0 \pm 11.4 \pm 8.4 MeV$$



$$T_{direct\gamma} = 221 \pm 19 \pm 19 MeV$$
$$T_B = 86.5 \pm 12.7^{+11.0}_{-28.4} MeV$$

- Calculate local inverse slopes in m ranges (0 - 0.6), (0.6 – 2.5)



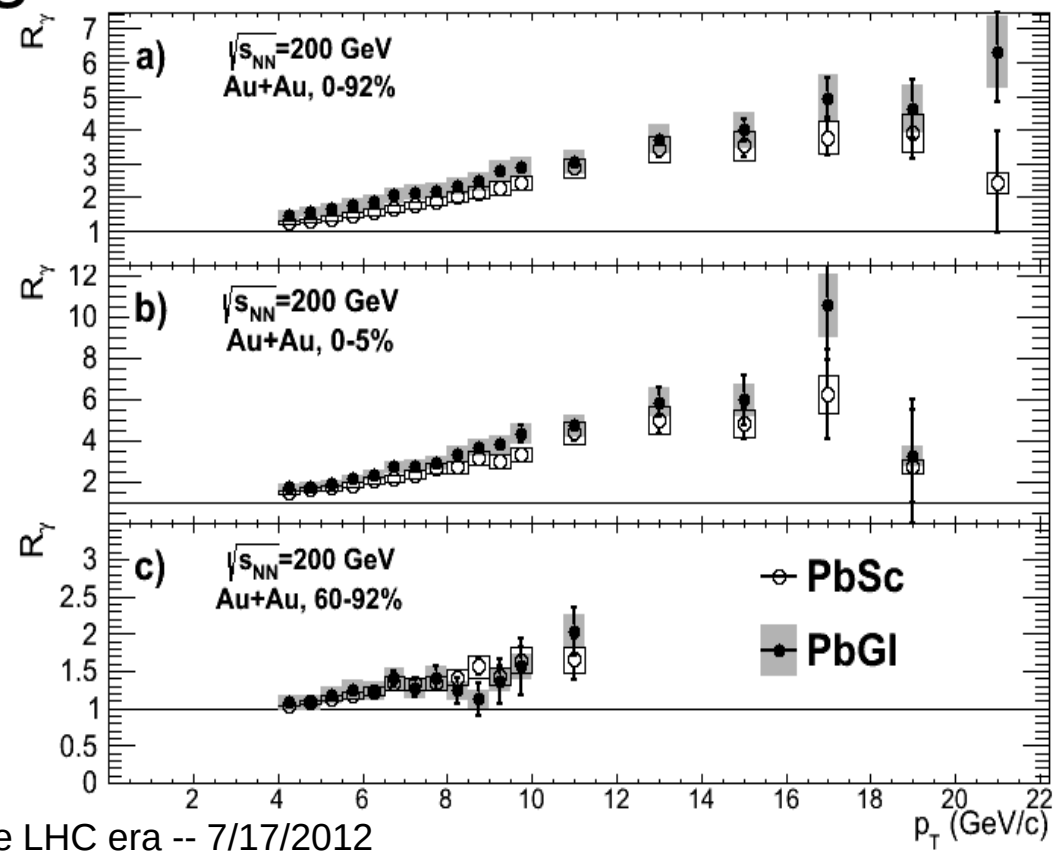
- Soft component at m ~ 0.5
  - T_{Eff} ~ 100 MeV
  - Over 50% of the excess

Au+Au – Double Ratio Method

$$\gamma_{Direct} = \gamma_{Incl} * (1 - 1/R_\gamma)$$

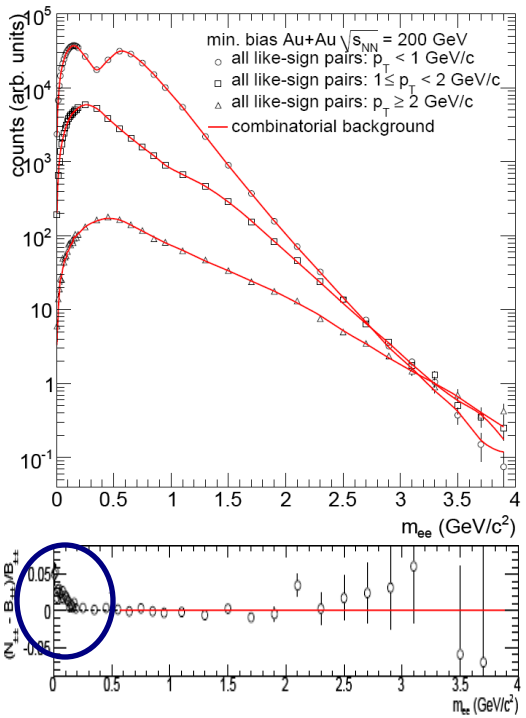
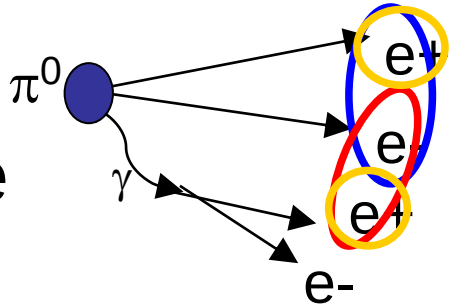
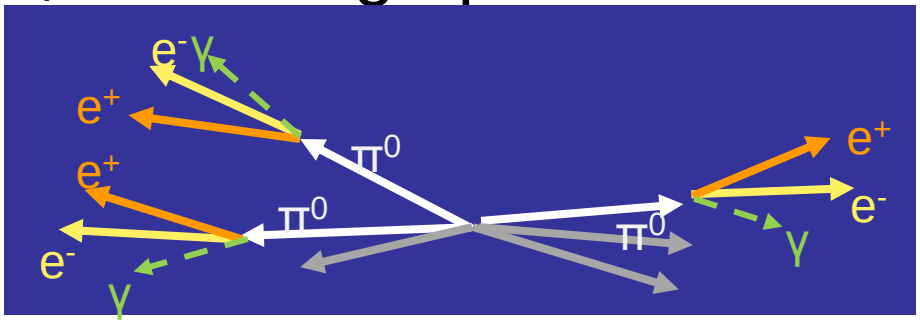
$$R_\gamma = \frac{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Meas}}{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Sim}}$$

- Simulation photons from π^0 and other decays
  - Calculate with
    - detector resolution
    - detector dead areas
    - meson-to-π^0 ratios
  - Assume m_T scaling
- Systematics cancel



arXiv:1205.5759

More Backgrounds

- Combinatorial ← Generate with event mixing
- Conversions
- RICH Ring overlap

  } Remove with cuts
- Double dalitz ← Simulate with Exodus-like code
  - Primarily π, $\eta \rightarrow \pi\pi\pi$
  - Like- and unlike-sign at same rate
- Jets ← Simulate with Pythia
  - Like-, unlike-sign pairs at same rate