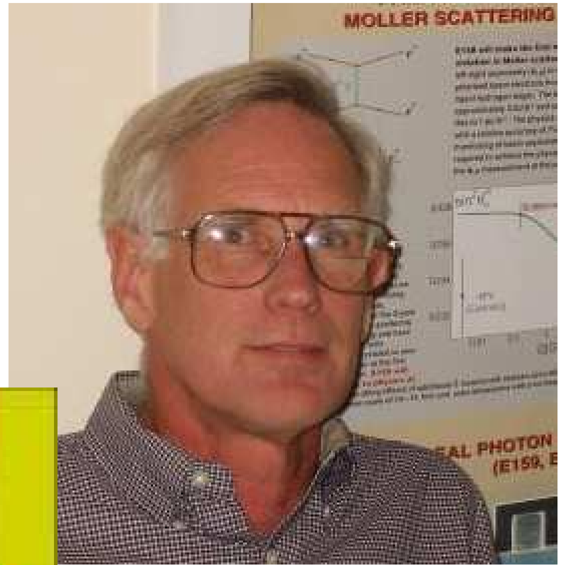
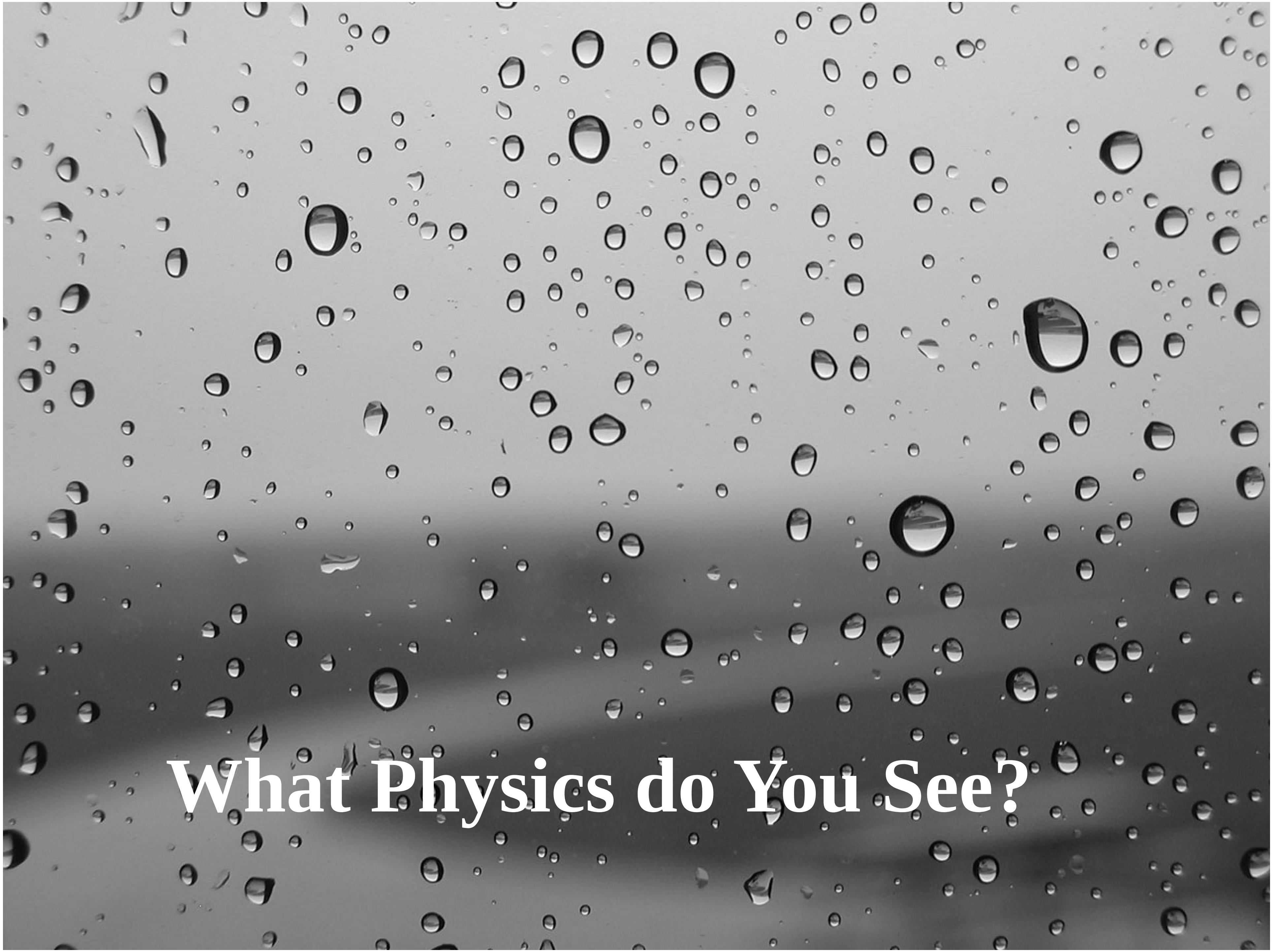
Exploring Early Times in the QGP Evolution through Direct Virtual Photons

Thomas K Hemmick

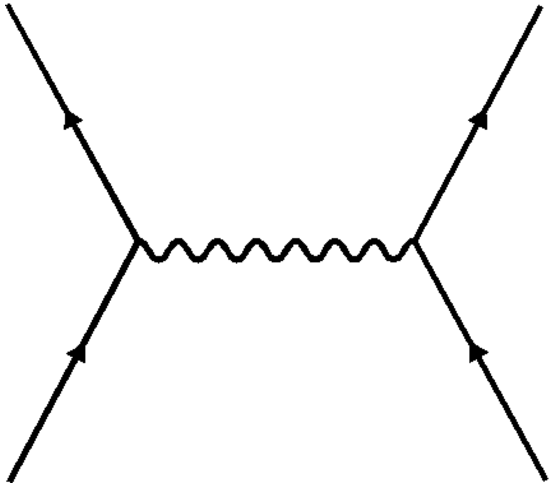


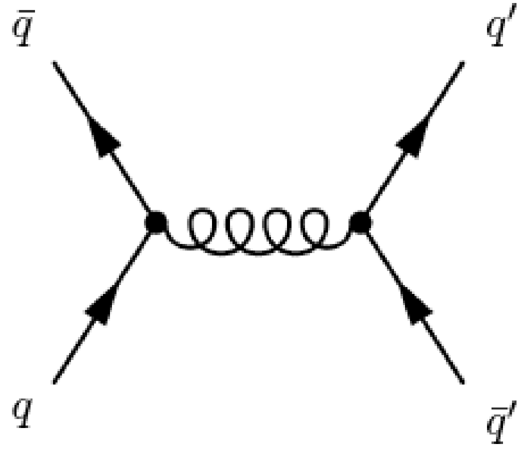
U Va Nuclear Physics Seminar this week.

SBU NP Seminar week before last.


What Physics do You See?

Physics beyond $(N)^n LO$ Diagram!!!

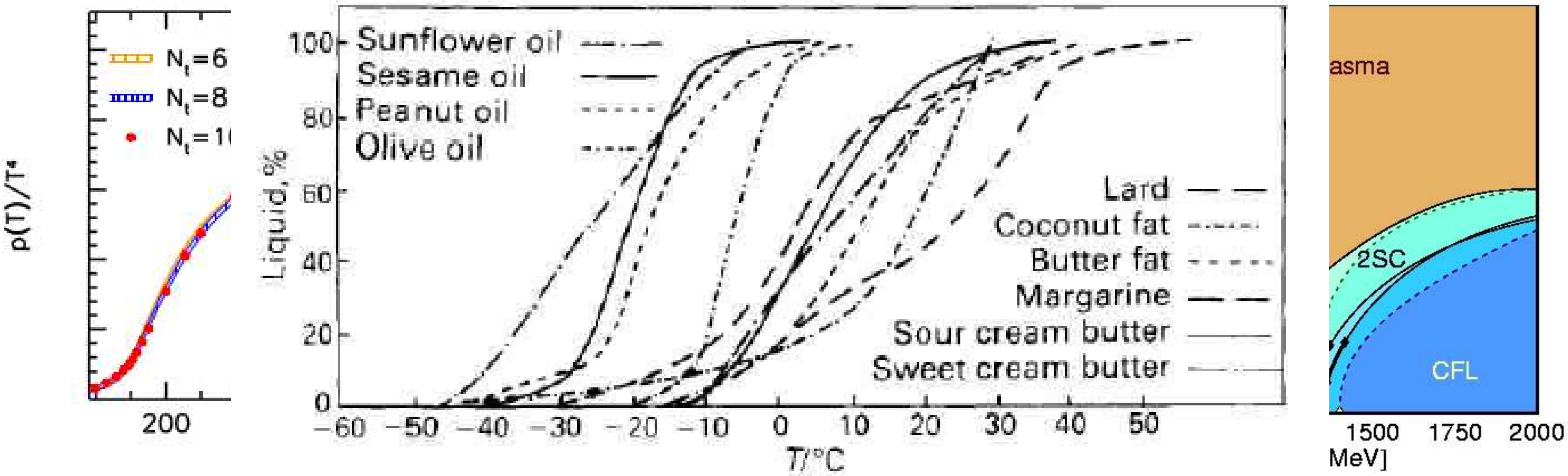




- The water droplets on the window demonstrate a principle.
- Truly beautiful physics is expressed in systems whose underlying physics is QED.
- The diagram is a beginning not an end

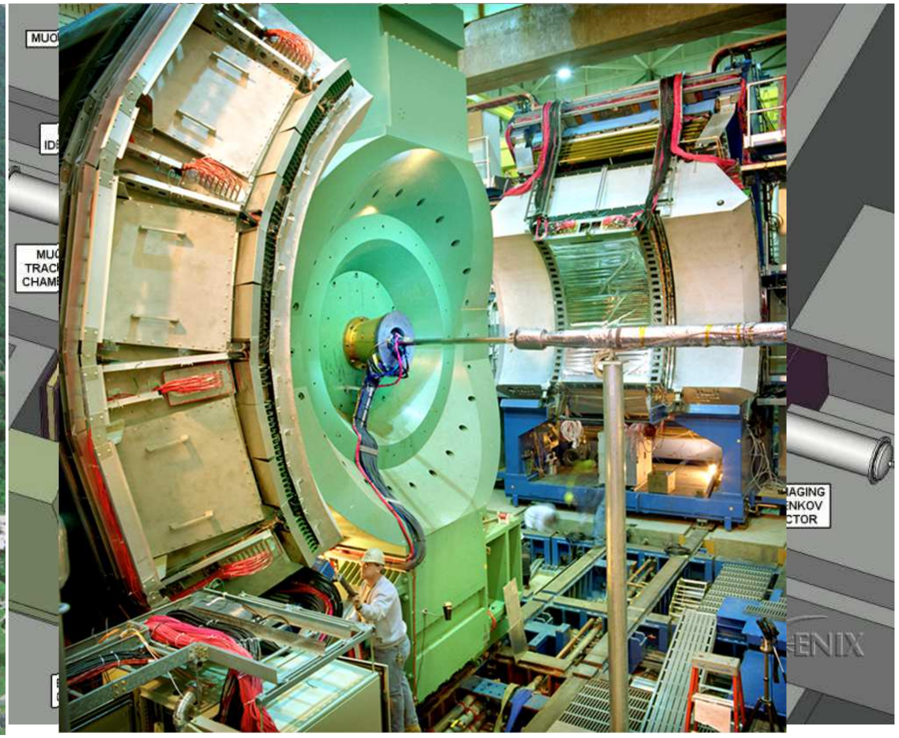
- Does QCD exhibit equally beautiful properties as a bulk medium.
- ANSWER: YES!
  - Nucleon Structure
  - Phase Structure

Lattice QCD Shows Phase Structure



- Lattice QCD results indicate a complex phase structure including multiple features.
- At low baryon chemical potential, transition is 2nd order (cross-over).

Relativistic Heavy Ion Collider (RHIC)
Pioneering High Energy Nuclear Interaction eXperiment (PHENIX)

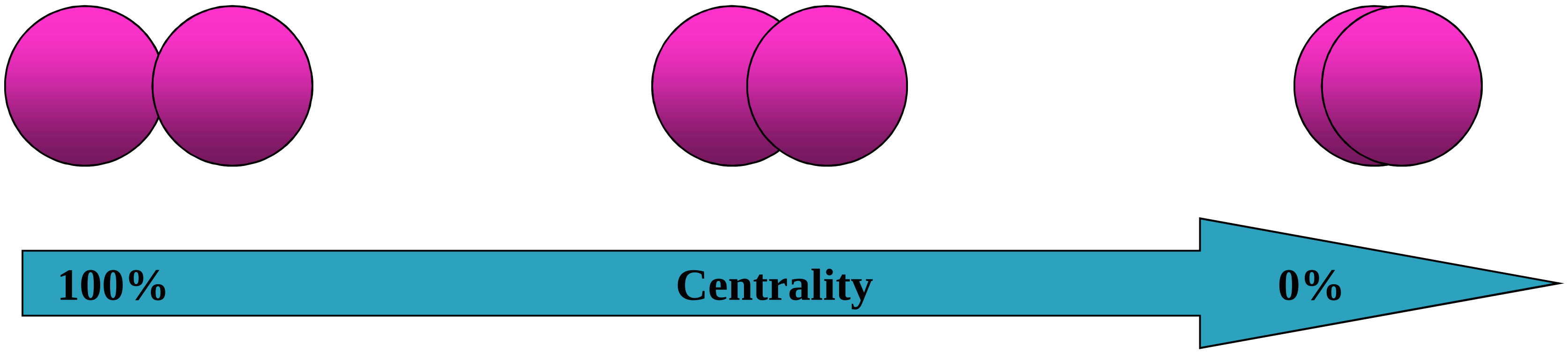


- 2 counter-circulating rings, 3.8 km circumference
- Any nucleus on any other.
- Top energies (each beam):
  - 100 GeV/nucleon Au-Au.
  - 250 GeV polarized p-p.

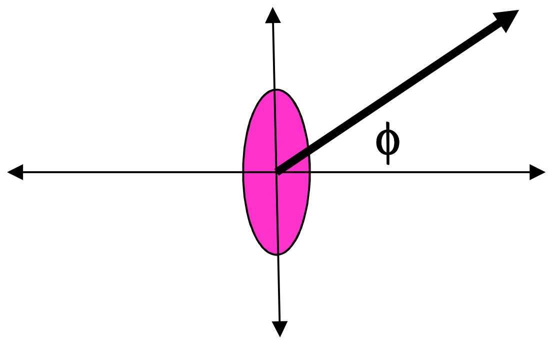
- **Maximal Set of Observables**
  - **Photons, Electrons, Muons, ID-hadrons**
- **Highly Selective Triggering**
  - **High Rate Capability.**
  - **Rare Processes.**

RHI Collision Terminology

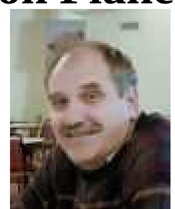
Peripheral Collision **Semi-Central Collision** **Central Collision**



- Centrality and Reaction Plane determined on an Event-by-Event basis.
- N_{part}= # of Participants
  - 2 → 394
- N_{binary}=# of Collisions



Reaction Plane



- **Fourier decompose azimuthal**

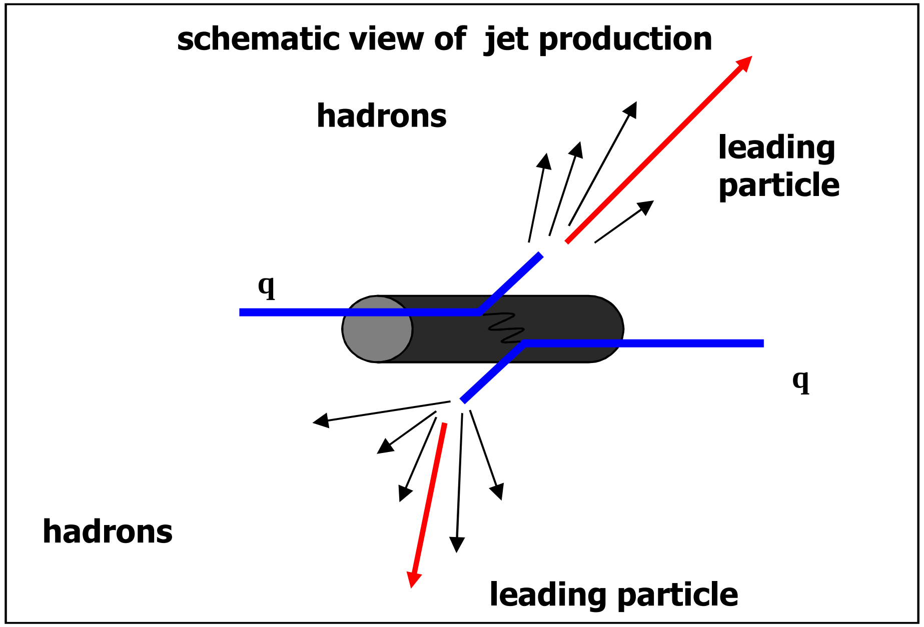
$$\frac{d^3N}{d\phi dp_T dy} \propto \left[1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right]$$

Paradigm #1: Hard Probes

- We accelerate nuclei to high energies with the hope and intent of utilizing the beam energy to drive a phase transition to QGP.
- The created system lasts for only ~10 fm/c
- The collision must not only utilize the energy effectively, but generate the signatures of the new phase for us.
- I will make an artificial distinction as follows:
  - Medium: The bulk of the particles; dominantly soft production and possibly exhibiting some phase.
  - Probe: Particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium.

q/g jets as probe of hot medium

Jets from hard scattered quarks observed via fast leading particles or azimuthal correlations between the leading particles



However, before they create jets, the scattered quarks radiate energy (~ GeV/fm) in the colored medium

Jet Quenching

R_{AA} Normalization

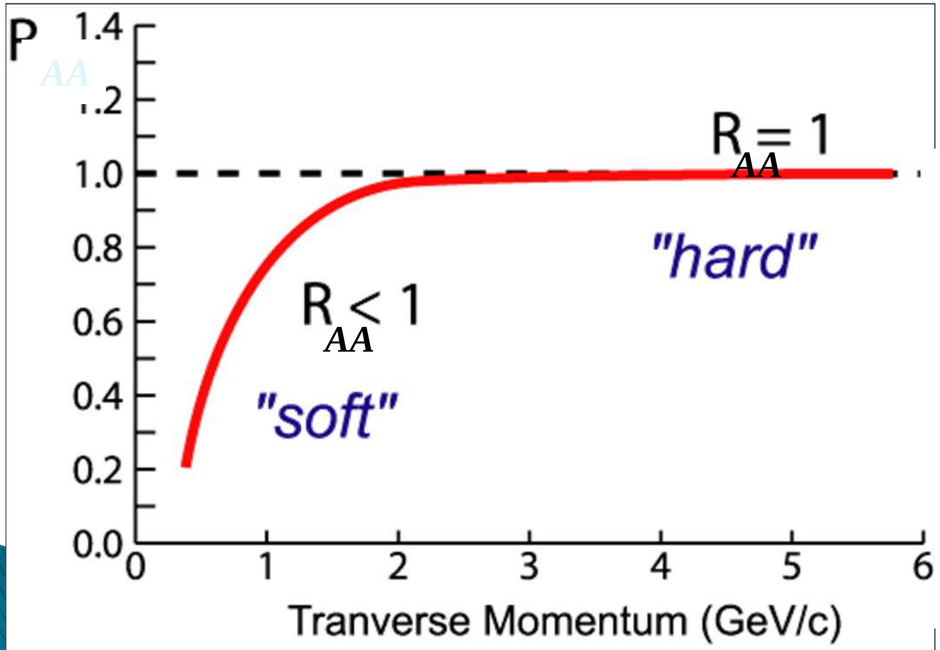
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

nucleon-nucleon cross section

$\langle N_{binary}\rangle/\sigma_{inel}^{p+p}$



If no "effects":

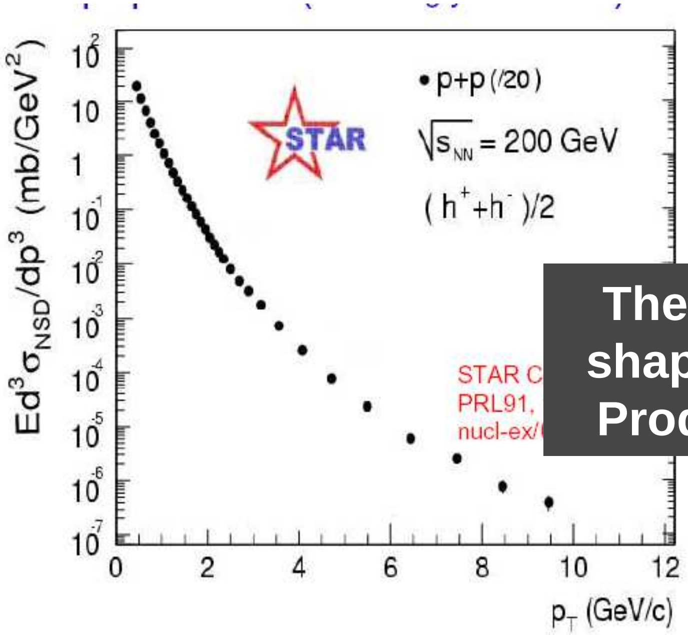
R_{AA} < 1 in regime of soft physics

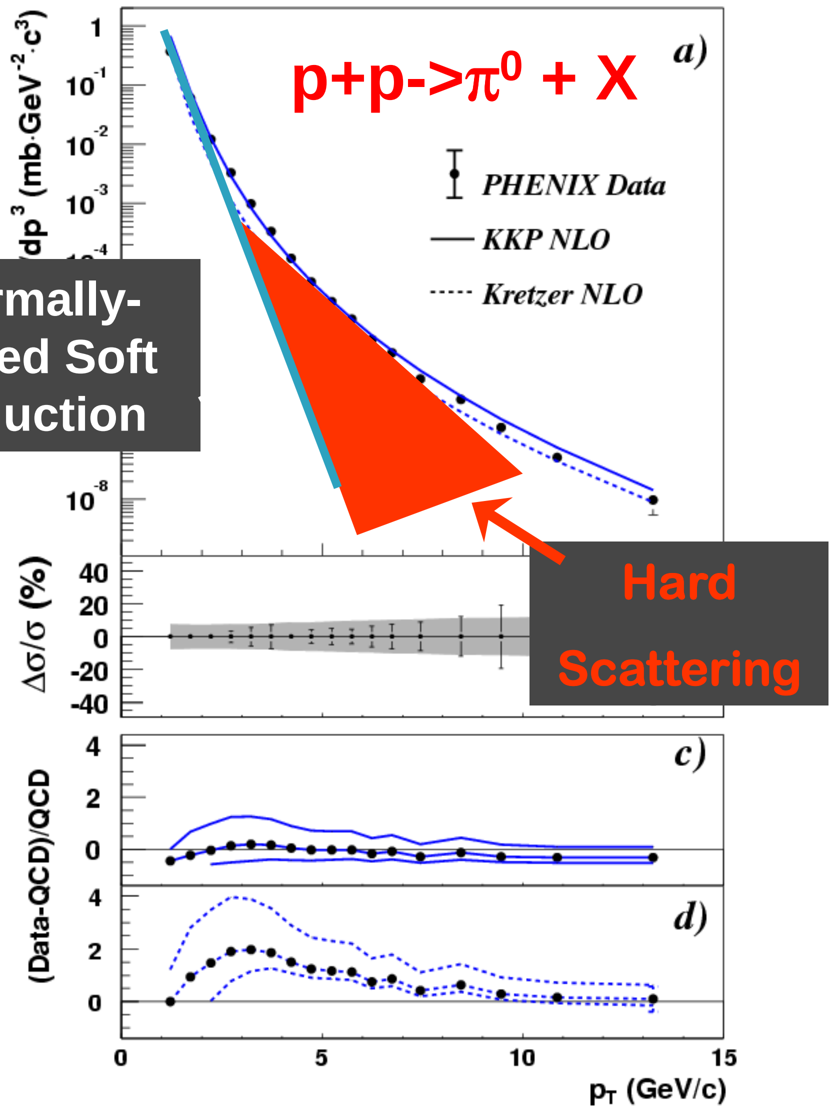
R_{AA} = 1 at high-p_T where hard scattering dominates

Suppression:

R_{AA} < 1 at high-p_T

Calibrating the Probe(s)

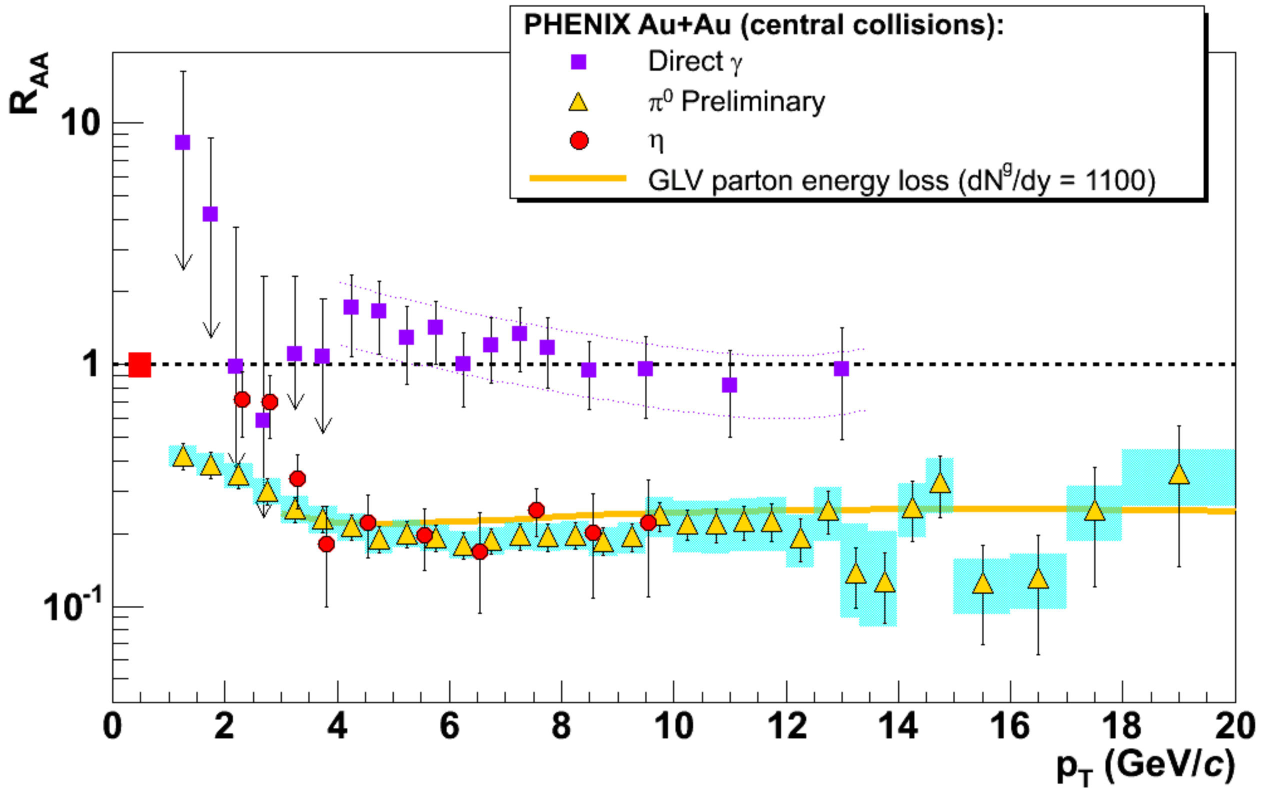


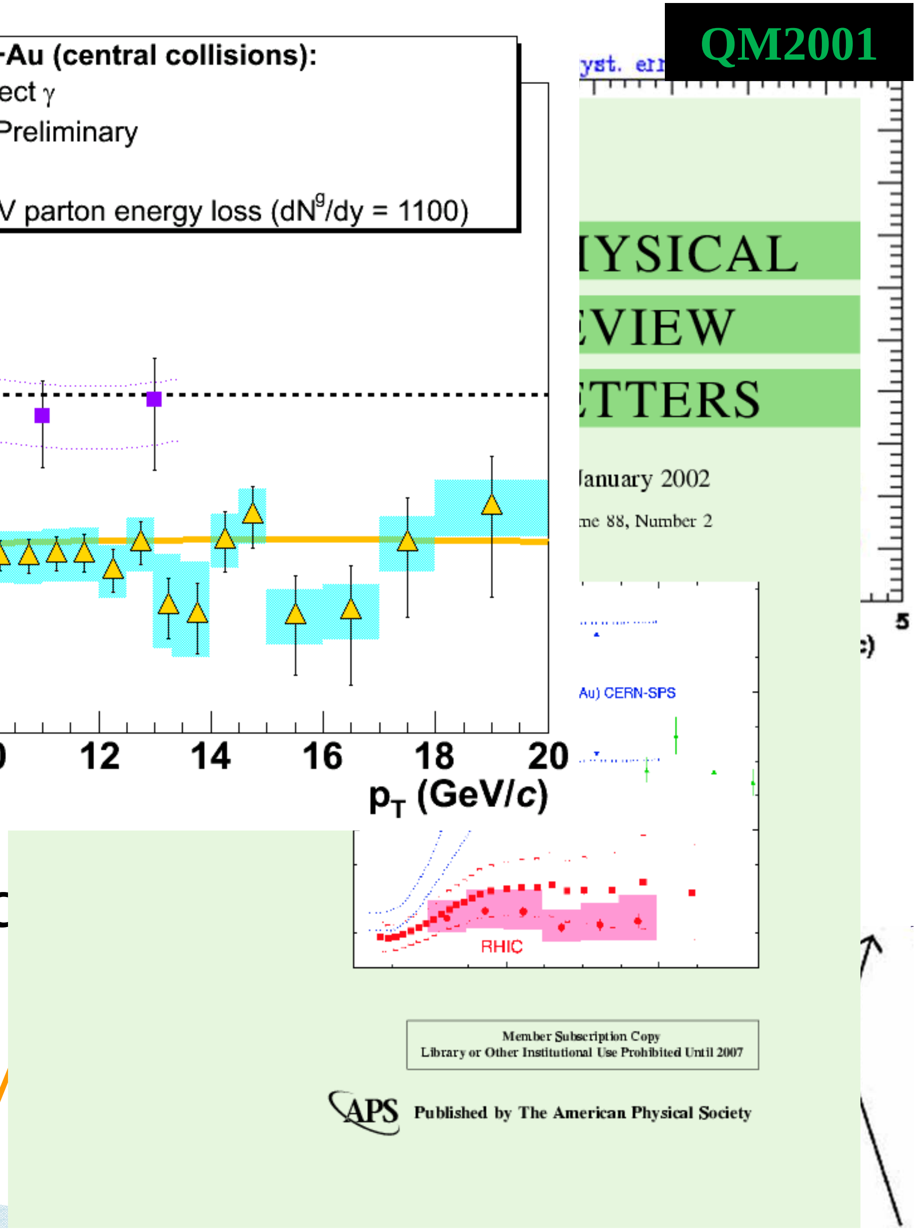


- Measurement from elementary collisions.
- “The tail that wags the dog” (M. Gyulassy)

Suppression Discovered in Year One

$$\frac{\textit{Observed}}{\textit{Expected}}$$



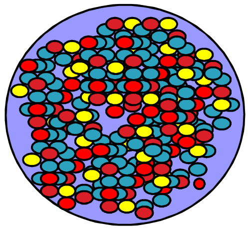


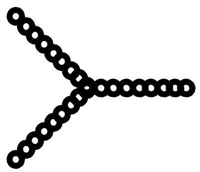
- Quark-containing partic
- Photons Escape!

Gluon Density = dN_g/dy

Could it be Initial Parton Distributions?

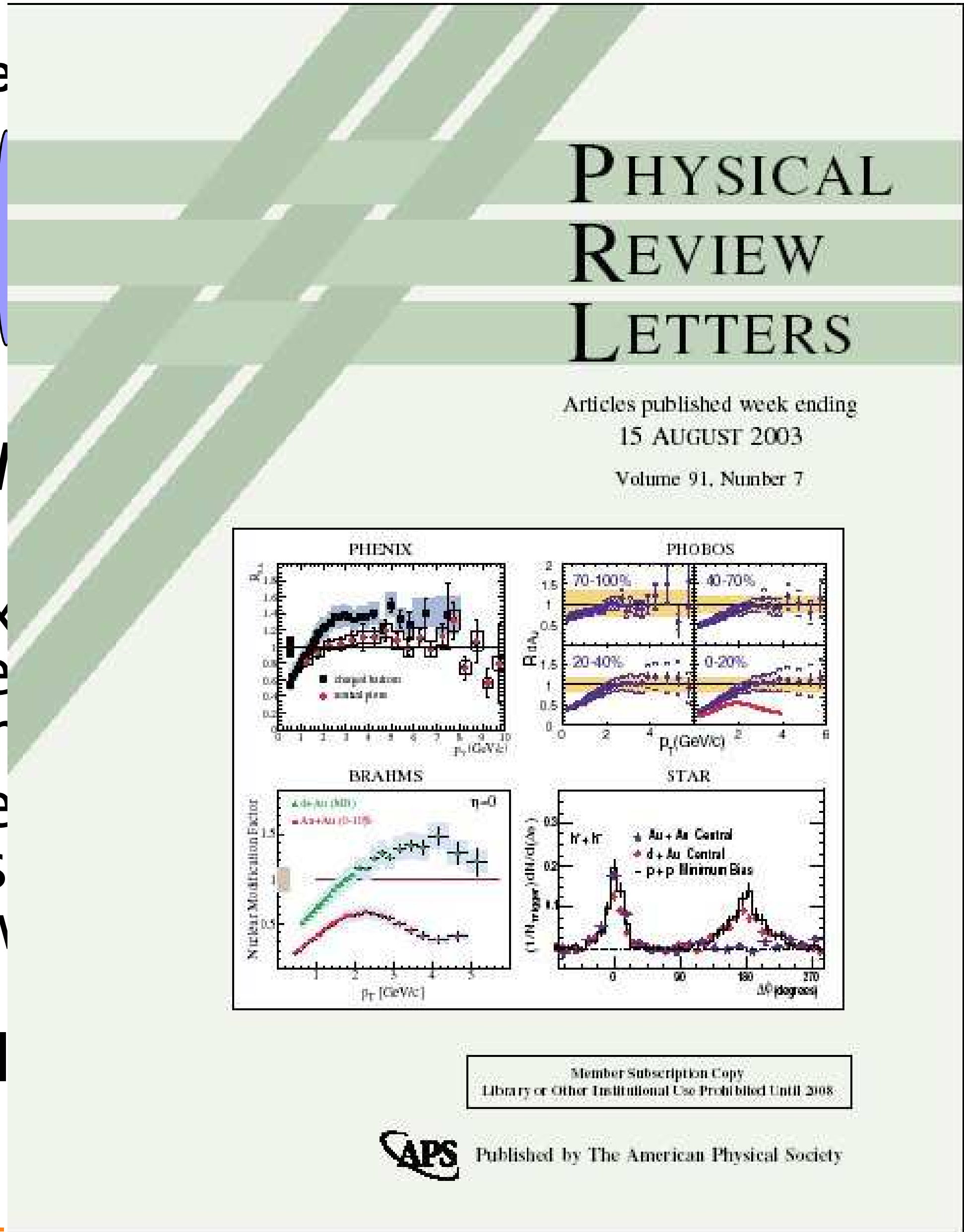
probe rest frame

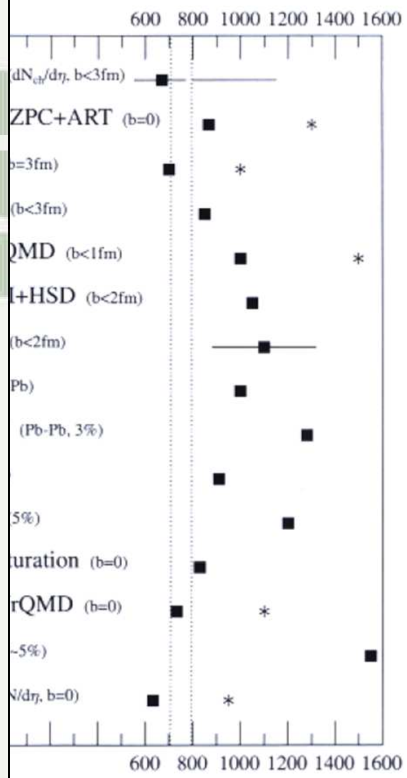


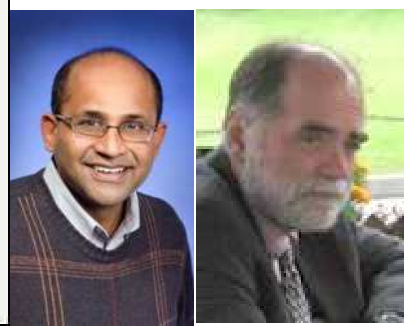


gg→g **r/**

- The lower in x measures, the gluons you fir
- At some low e phase space s and gluons sw another.
- Another novel <u>Color Glass Condensate</u>

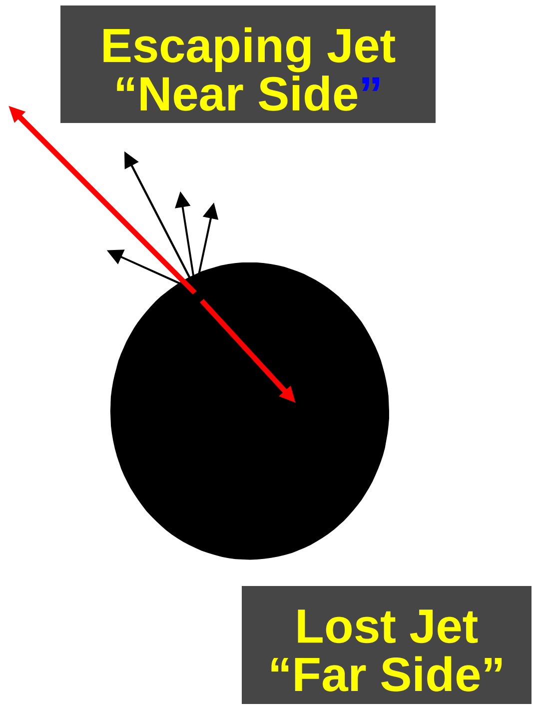


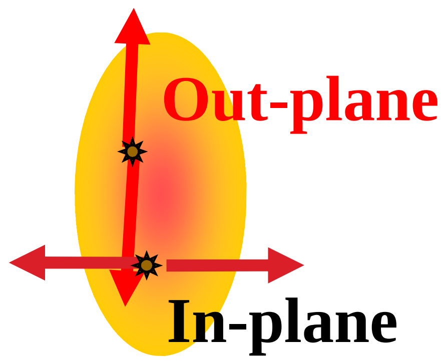




Jet Tomography

- Jets are produced as back-to-back pairs.
- If one jet escapes, is the other shadowed?
- Map the dynamics of Near-Side and Away-Side jets.
  - Vary the reaction plane vs. jet orientation.
  - Study the composition of the jets
  - Reconstruct the WHOLE jet
    - Find "suppressed" momentum & energy.

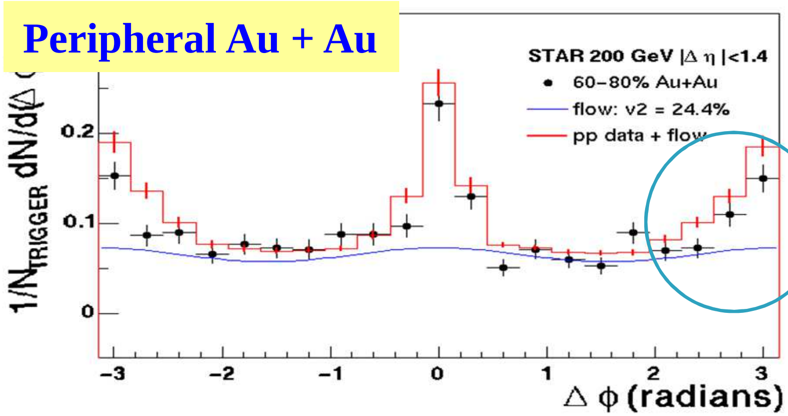


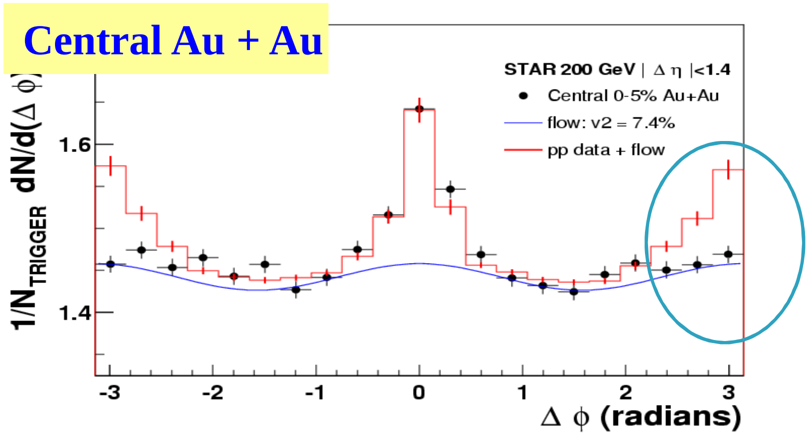


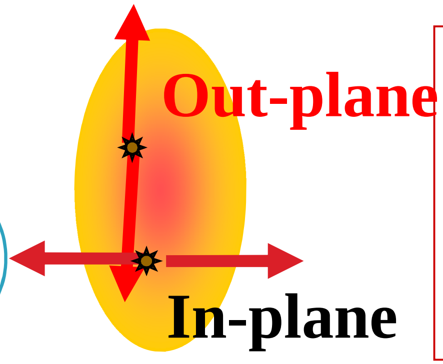
X-ray pictures are shadows of bones

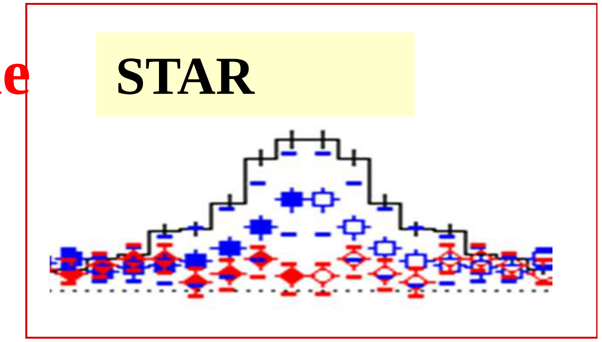
Can Jet Absorption be Used to "Take an X-ray" of our Medium?

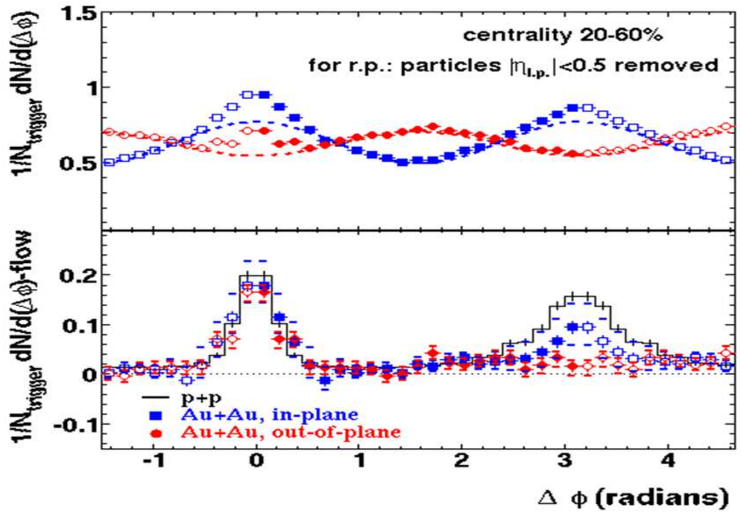
Back-to-back jets





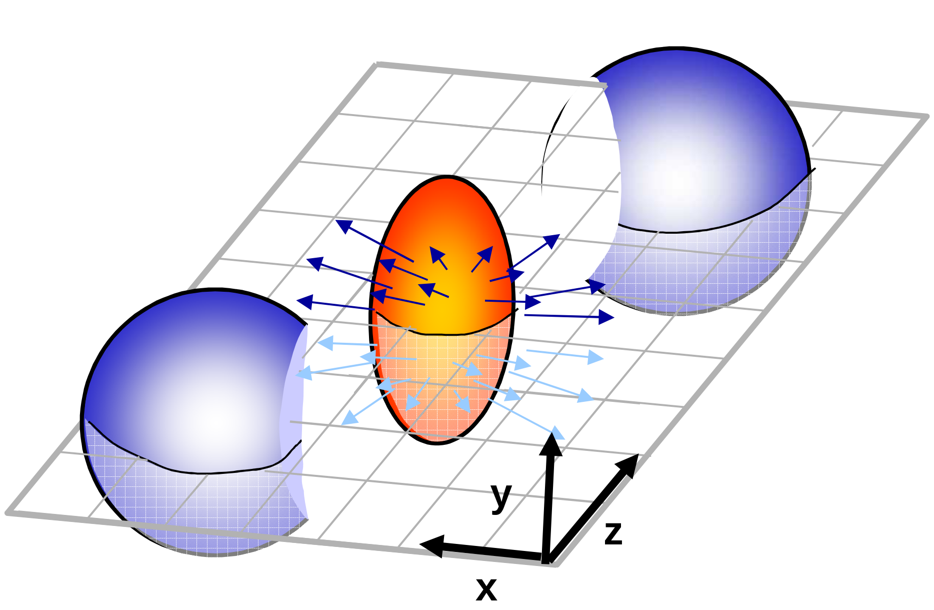


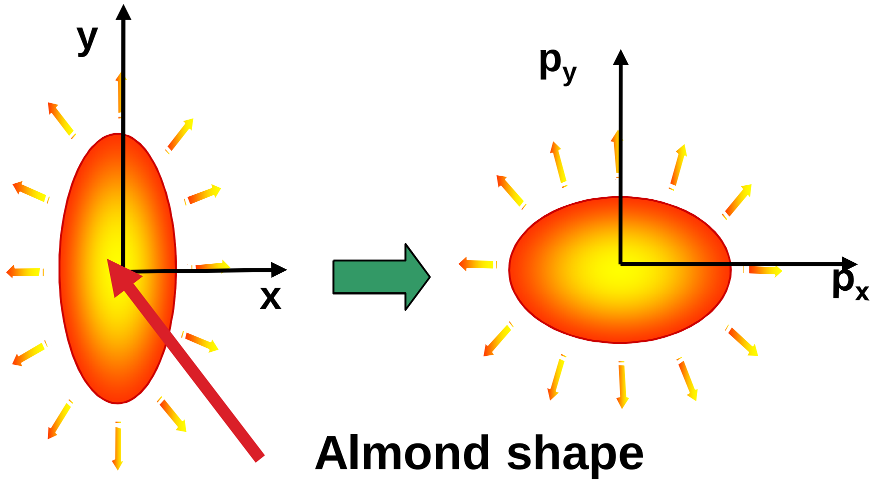




- Given one “jet” particle, where are it’s friends:
  - Members of the “same jet” are in nearly the same direction.
  - Members of the “partner jet” are off by 180°
- Away-side jet “gone”

Paradigm 2: Collective Flow





Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system
spatial anisotropy $\rightarrow$ momentum anisotropy

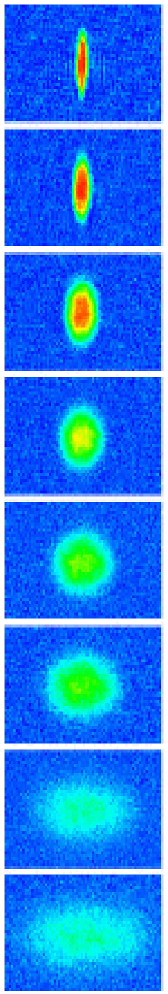
v_2: 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane

$$\frac{d^3N}{d\phi dp_T dy} \propto \left[1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right]$$

$$v_2 = \langle \cos 2\phi \rangle \qquad \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Anisotropic Flow

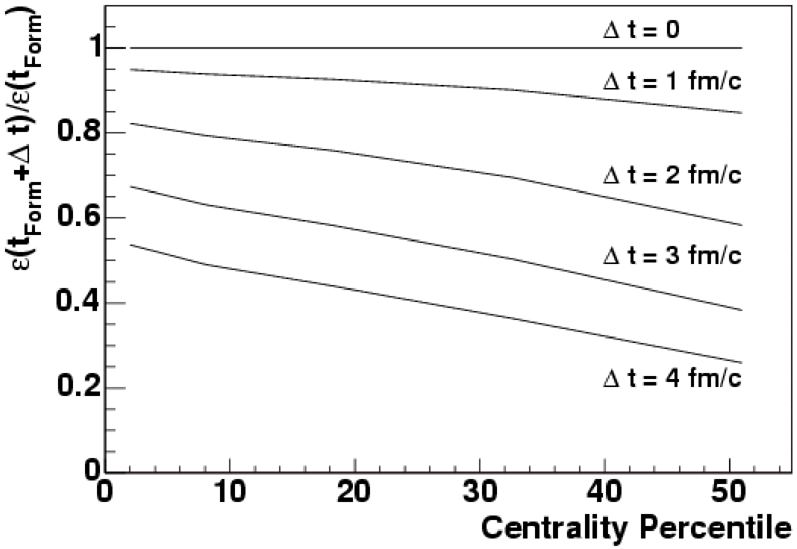
Liquid Li Explodes into Vacuum



Position Space anisotropy (eccentricity) is transferred to a momentum space anisotropy visible to experiment

- **Gases explode into vacuum uniformly in all directions.**
- **Liquids flow violently along the short axis and gently along the long axis.**
- **We can observe the RHIC medium and decide if it is more liquid-like or gas-like**

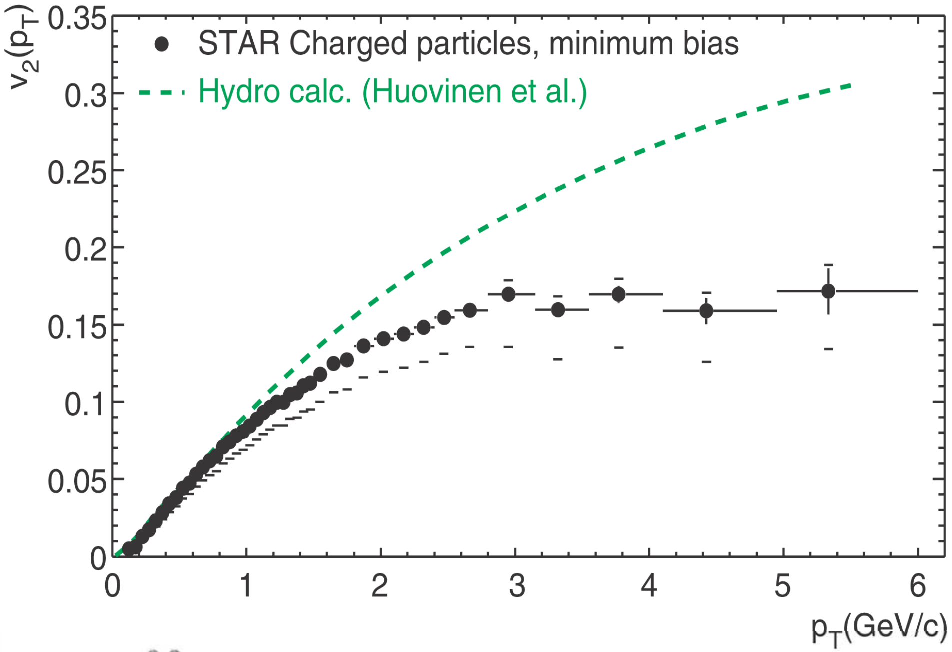
- **Process is SELF-LIMITING**
- **Sensitive to the initial time**

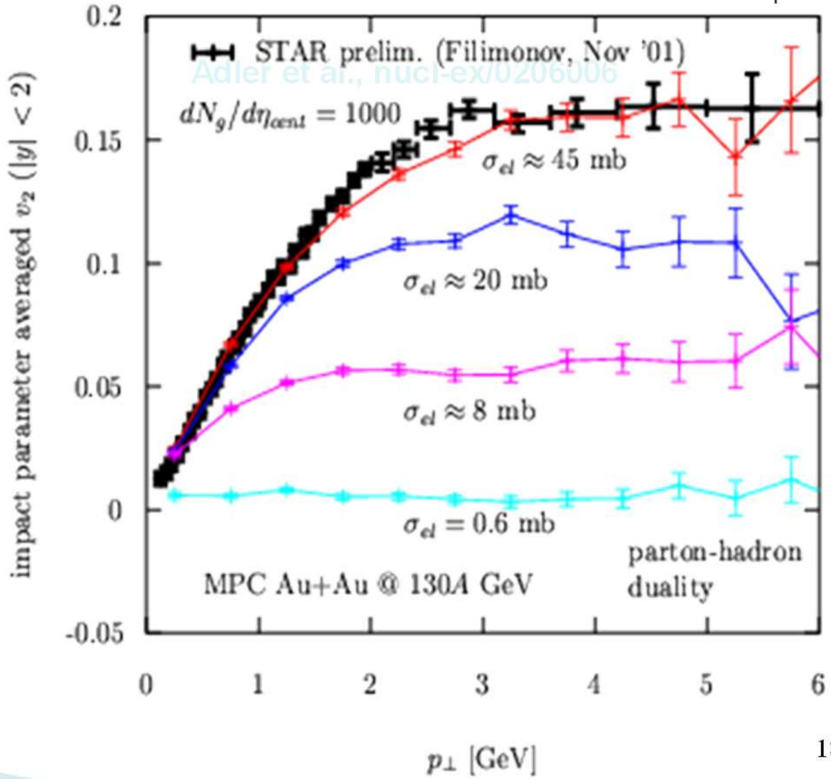


- **Delays in the initiation of anisotropic flow not only change the magnitude of the flow but also the centrality dependence increasing the sensitivity of the results to the initial time.**

Large v_2 !!!

- Hydrodynamic limit exhausted at RHIC for low p_T particles.
- Can microscopic models work as well?
- Flow is sensitive to thermalization time since expanding system loses spatial asymmetry over time.
- Hydro models require thermalization in less than t=1 fm/c

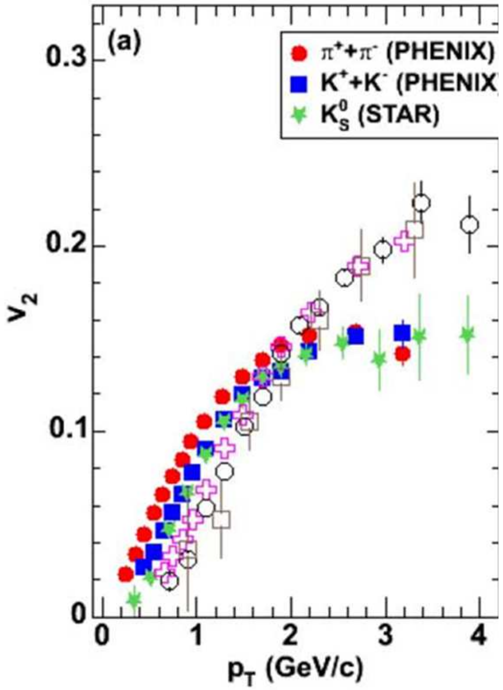




v_2 Scales with valence quarks

$KE_T = m(\gamma_T - 1)$

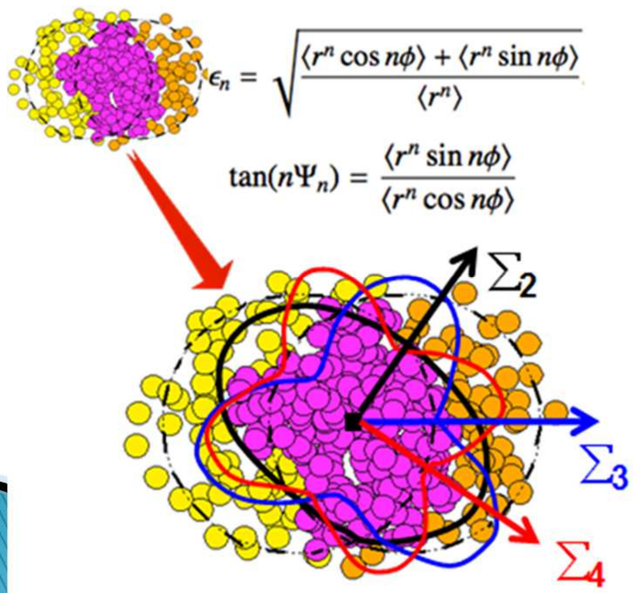
$P \propto$ Kinetic Energy Density



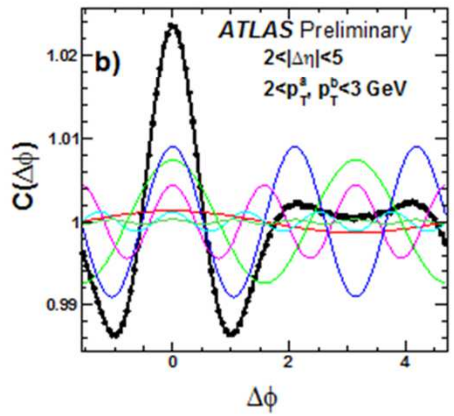
- Valence quark scaling indicates that partons (aka constituent quarks) exhibit collective motion.
- Implies that the final state hadrons may have come from "recombination"

High Order Moments v_n

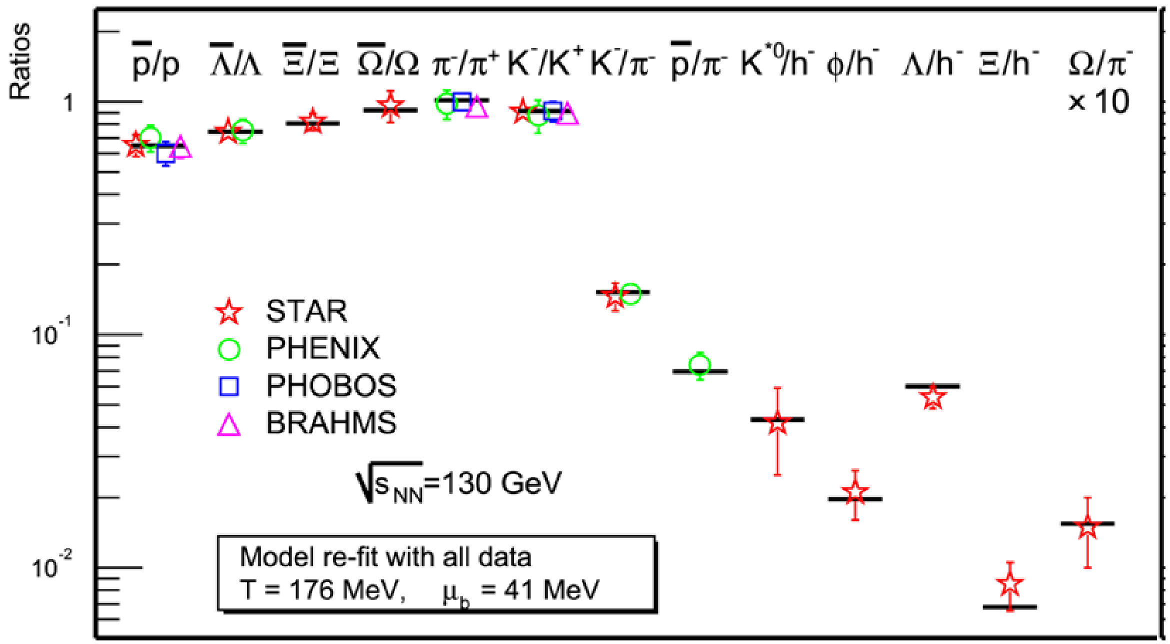
- Event Plane method yields $\langle v_n \rangle$ ($v_{odd}=0$).
- 2-particle yields SQRT($\langle v_n^2 \rangle$) ($v_{odd}>0$).
- How to deal:
  - PHENIX = EP method + factorization.
  - ATLAS = Rapidity OUTSIDE other Jet.
  - Everyone else = Factorization.



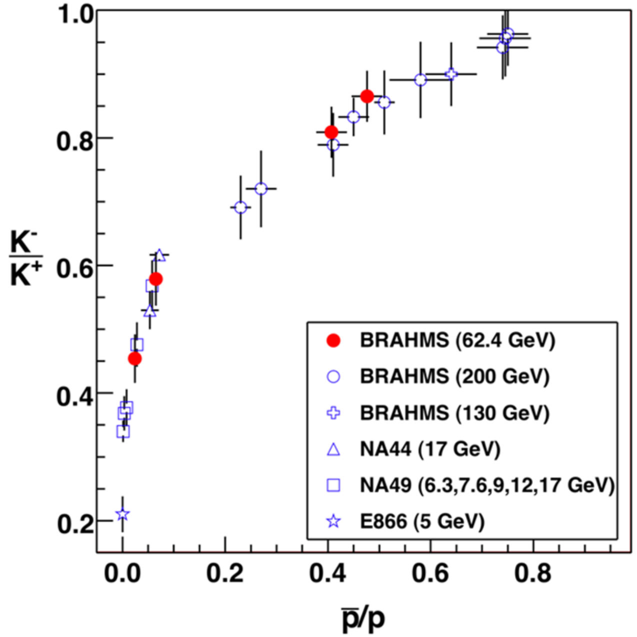
Singles:	$\frac{dN}{d\phi} \propto 1 + \sum_n 2 v_n \cos n(\phi - \Psi_n)$	**EP method**
Pairs:	$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2 v_n^a v_n^b \cos(n\Delta\phi)$	**2PC method**



Paradigm 3: Hadrochemistry



Braun-Munzinger et al., PLB 518 (2001) 41

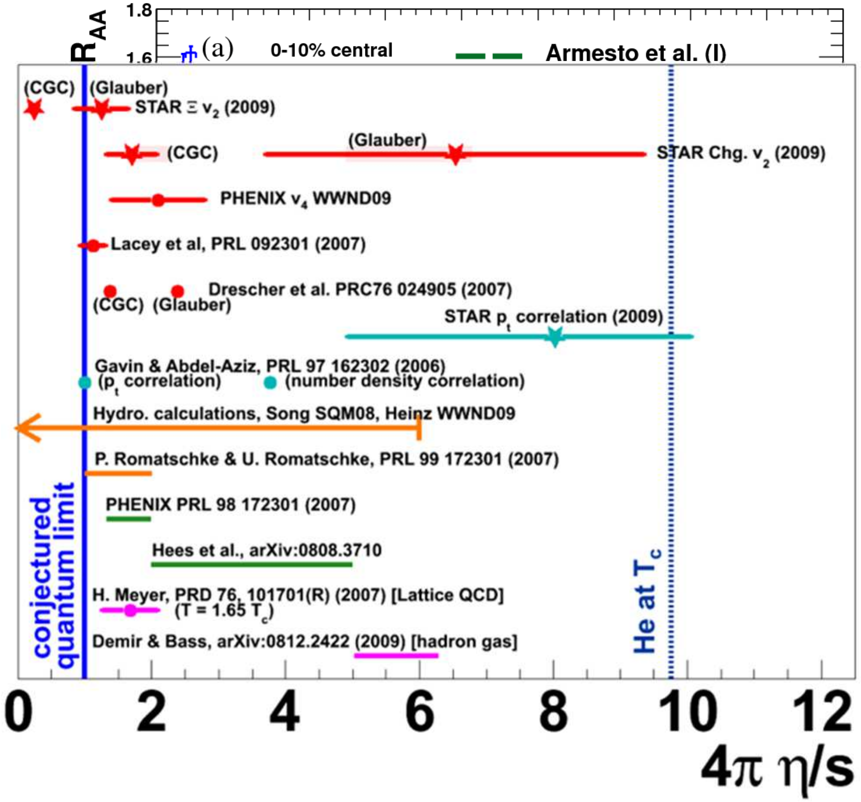


- Hadronization by random choice or recombination will follow simple statistical distributions:

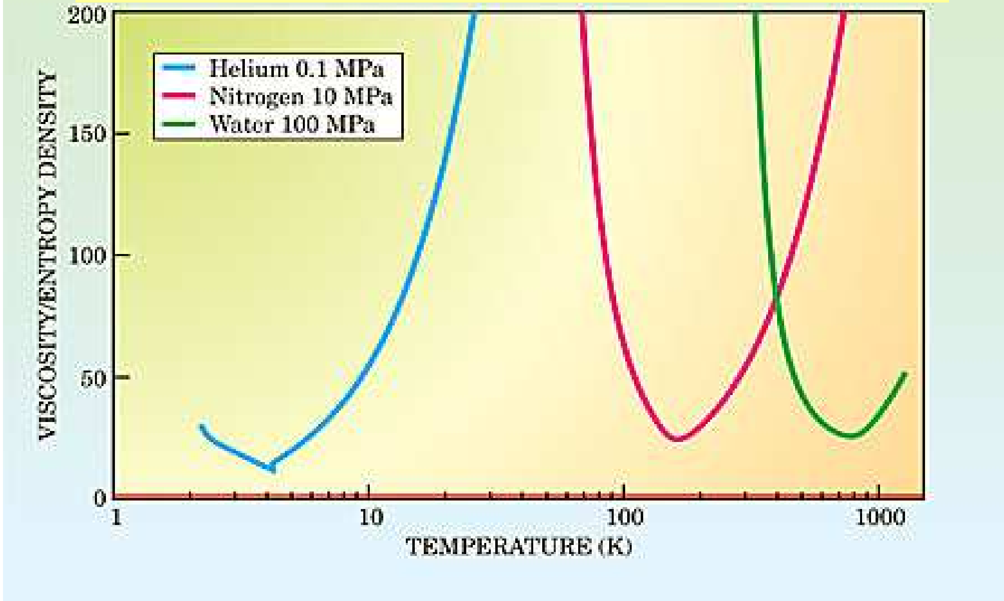
$$n_i^0 = \frac{g_i}{2\pi^2} \int \frac{p^2 dp}{e^{\left(E-\mu_B B_i - \mu_s S_i - \mu_3 I^3\right)/T} \pm 1}$$

- pp collisions exhibit "canonical suppression" of strange quark production (lifted by QGP).

"Perfect" Fluid



$$\eta \geq \frac{\hbar}{4\pi}\left(Entropy\ \ Density\right) \equiv \frac{\hbar}{4\pi} s$$



- RHIC "fluid" is at ~1-3 on this scale (!)
- The Quark-Gluon Plasma is, within preset error, the most perfect fluid possible in nature.

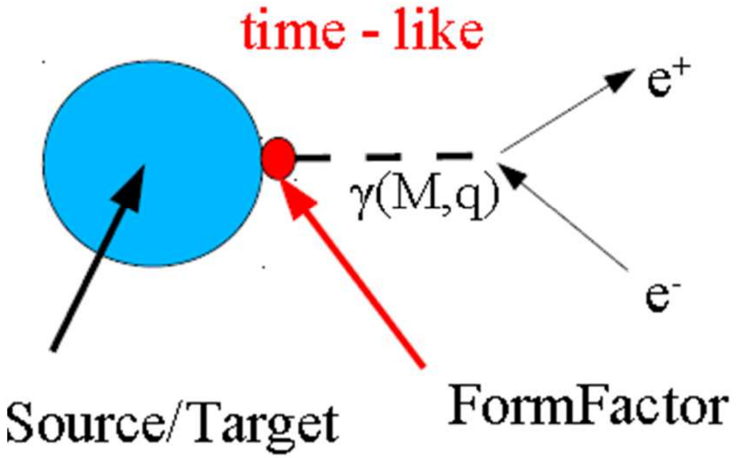
Limitations of these Paradigms

- Hard or Jet Probes provide useful information BECAUSE their initial production is well known.
- Flow is driven by “pre-collision” spatial anisotropy.
- Hadro-chemistry (and HBT) probe the final state at de-coupling time.

PENETRATING (color-less) Probes are Transparent to the QGP medium and directly probe the initial state

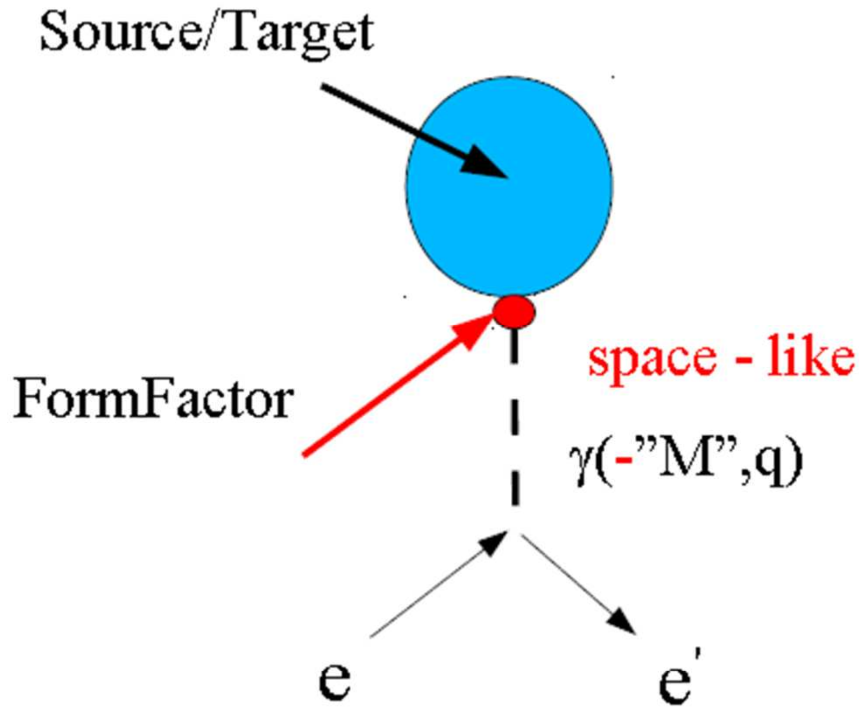
PHOTONS & DILEPTONS!!!

Dileptons vs Electron Scattering



Measures “time structure”

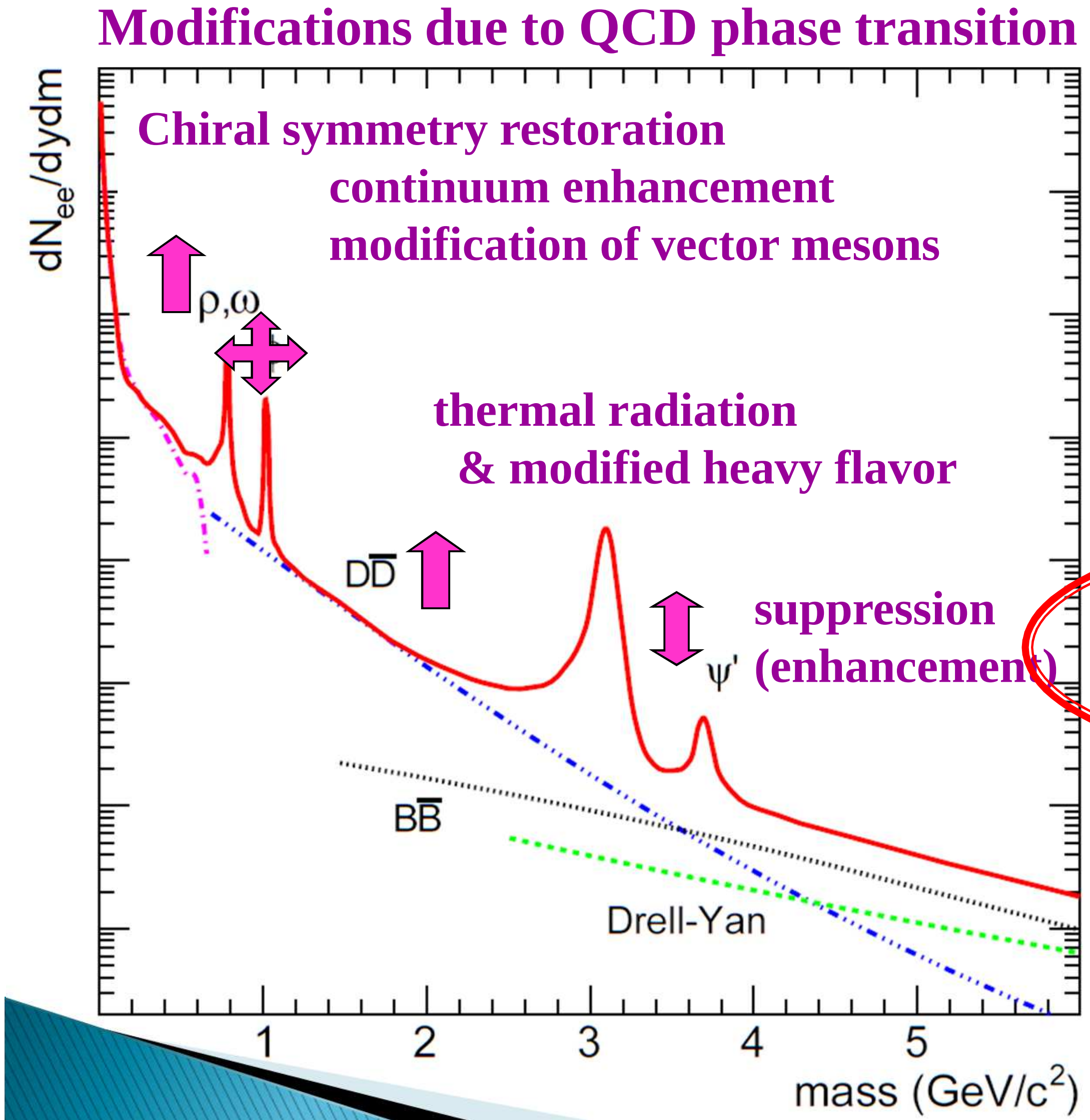
$$S(\omega,0)\rightarrow S(t)$$



Measures “space structure”

$$S(0,q)\rightarrow S(r)$$

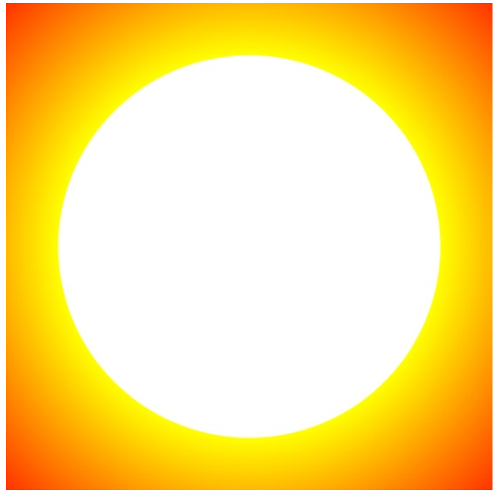
Dilepton Continuum Physics



- 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

Remote Temperature Sensing

Red Hot



White Hot

- Hot Objects produce thermal spectrum of EM radiation.
- Red clothes are NOT red hot, reflected light is not thermal.

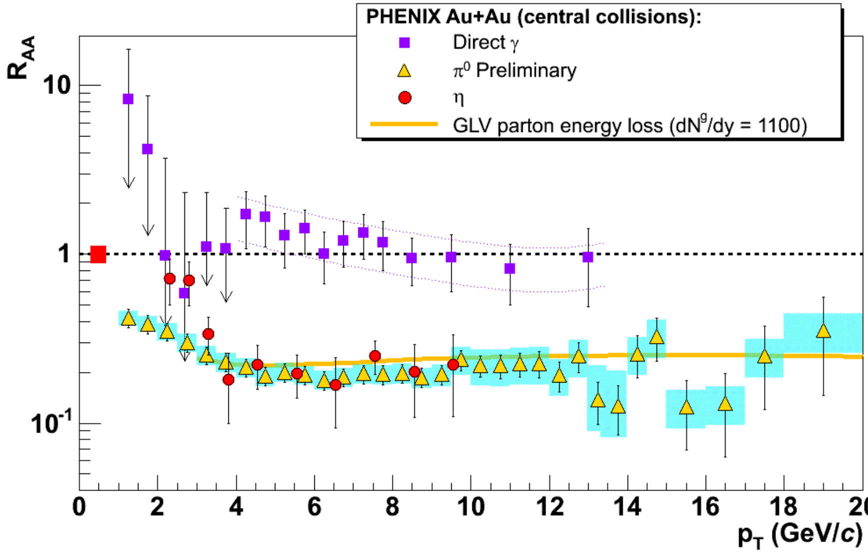
Not Red Hot!

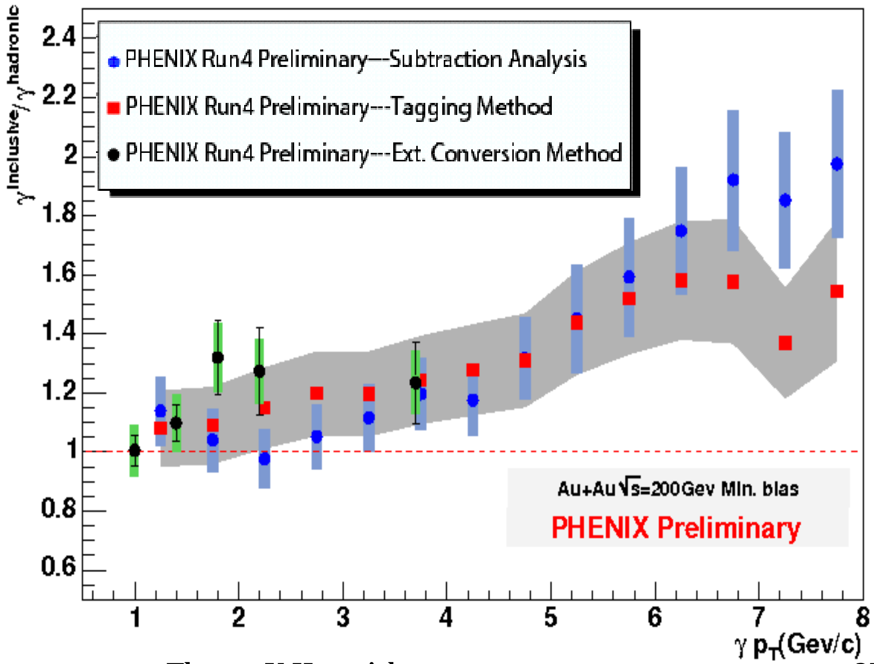
Photon measurements must distinguish thermal radiation from other sources: HADRONS!!!

Non-Thermal Real Photon Sources

- $\gamma^{inclusive}/\gamma^{hadronic}$ (1st plot) exceeds 1 at high p_T indicating presence of non-hadronic photons.
- R_{AA} equals 1 for these same p_T indicating that high p_T yields are similar to pp: initial state hard scattering.
- Measurement difficult at low p_T w/ real photons.

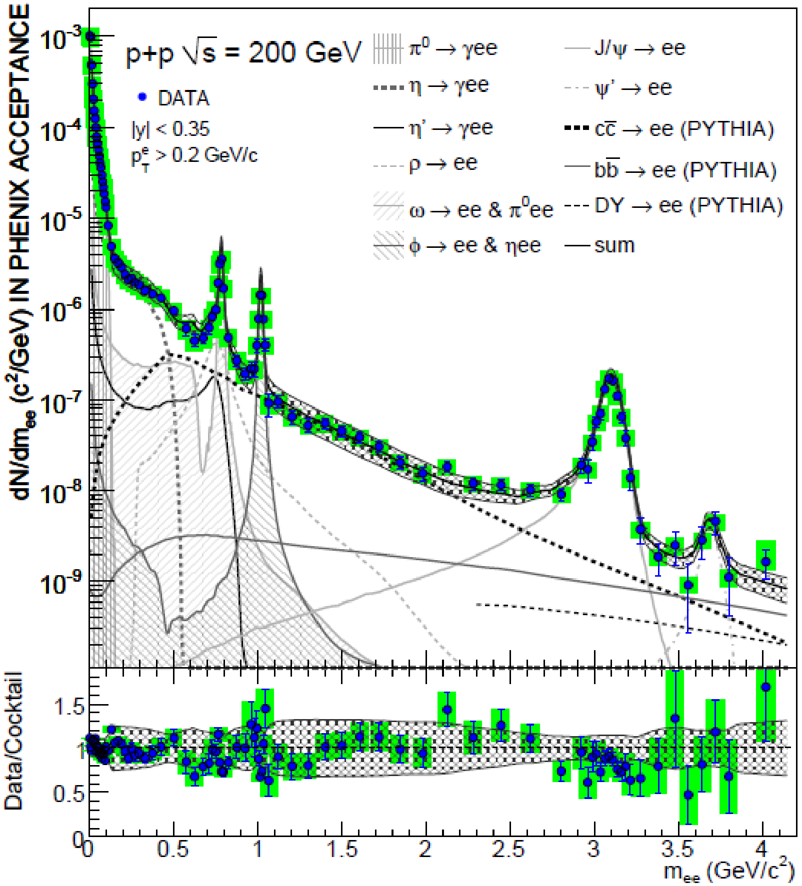
$$R_{AA}(p_T) \equiv \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$



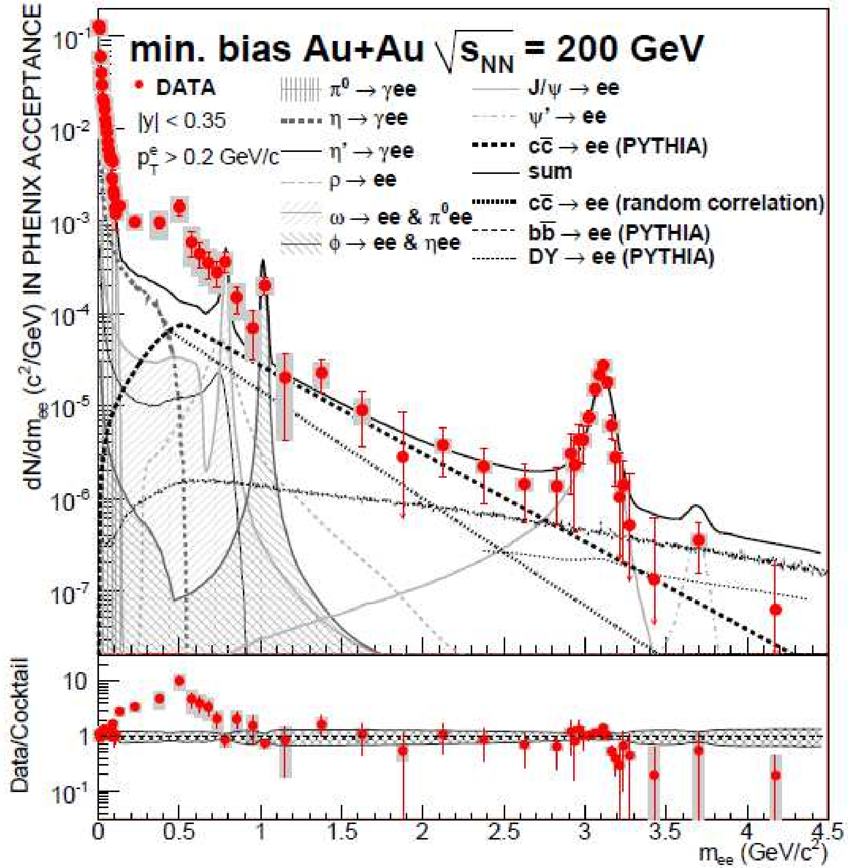


Continuum in p+p and AuAu

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.**

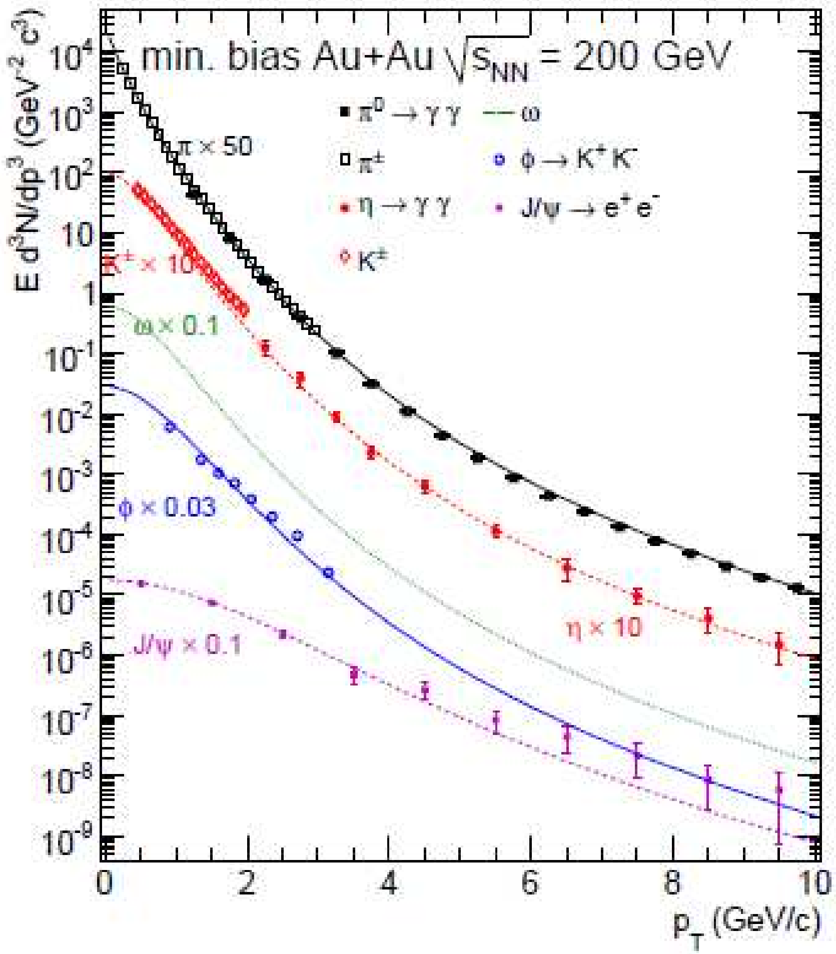
Estimate of Expected Sources

- 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

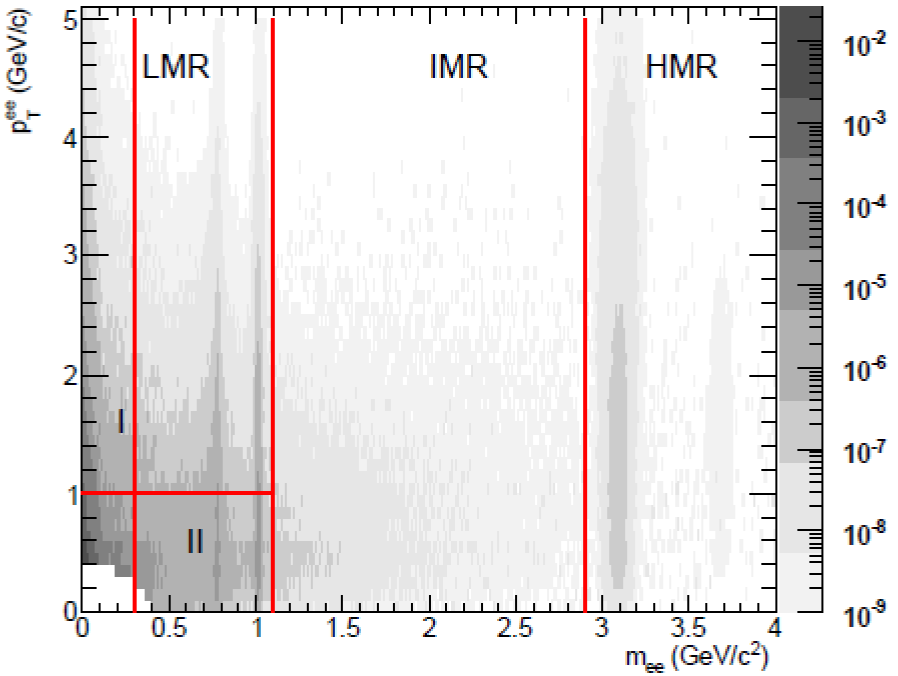
Hadron data follows "m_T scaling"

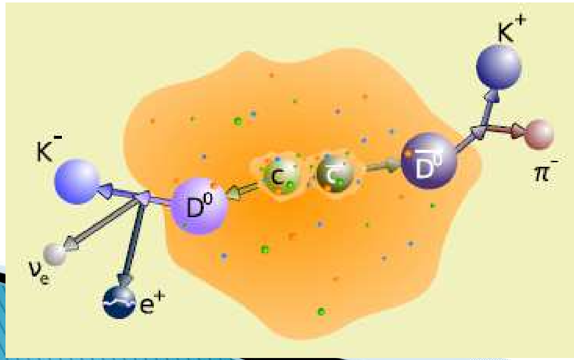


- Heavy flavor production:
  - σ_c = N_{coll} x 567±57±193μb from single electron measurement

Predict cocktail of known pair sources

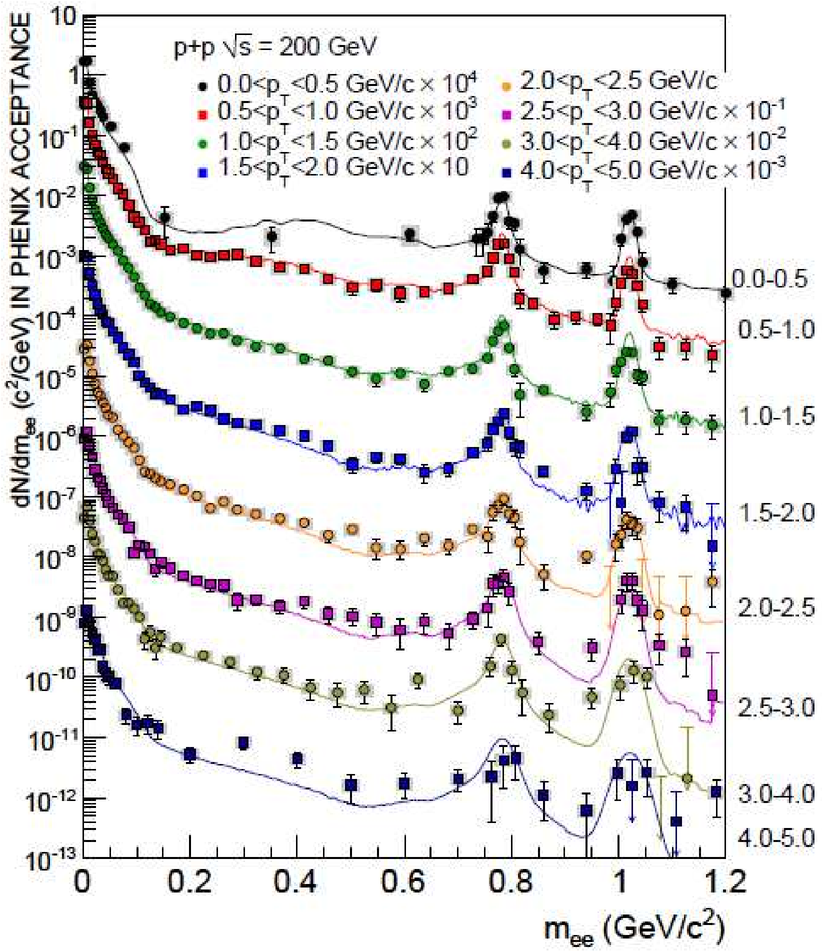
Methodical Spectral Analysis

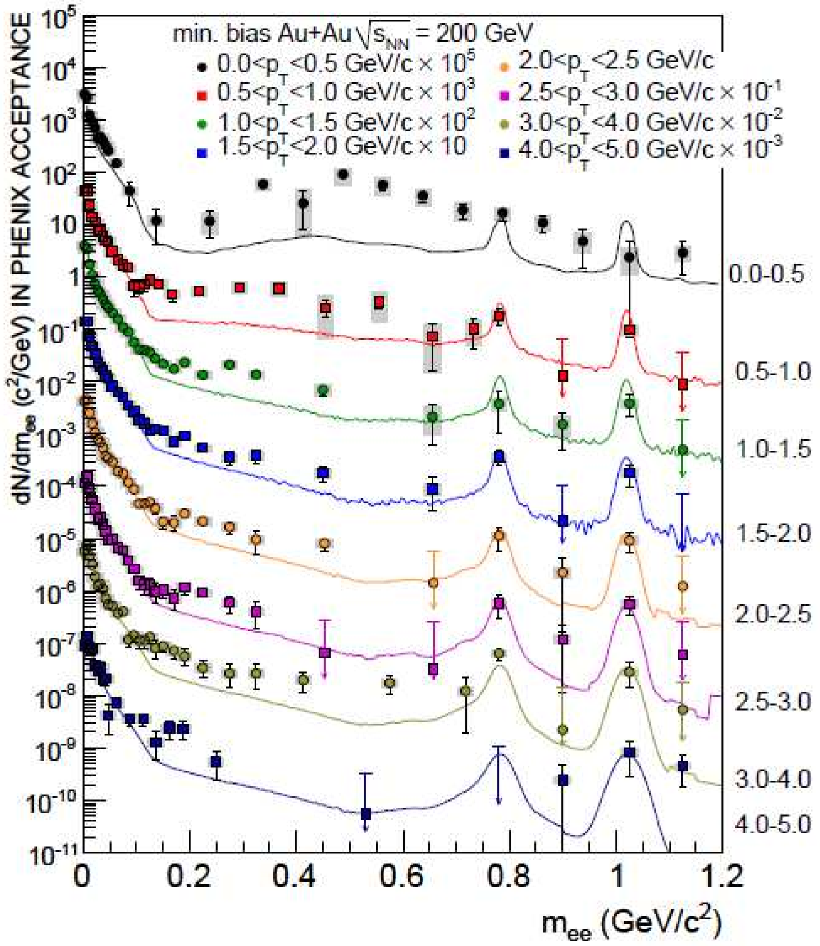




- IMR in cocktail is dominated by correlated open charm.
- LMR-I wherein $m_{ee} << p_T$
- LMR-II where the above condition does not apply.

LRM divided into p_T Slices





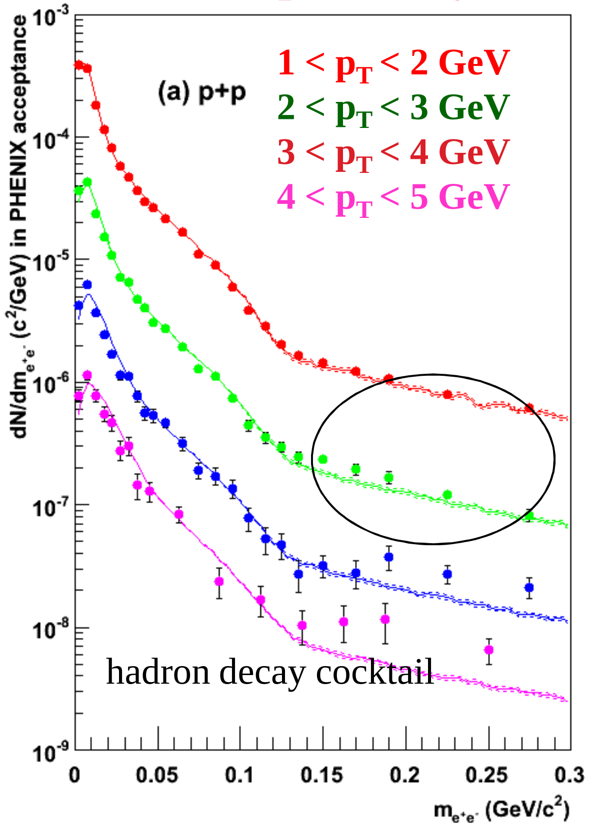
- pp shows excess growing with p_T.
- pp excess slopes downward.

- 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 $m \ll p_T$ γ^* is "almost real"
  - extrapolate $\gamma^* \rightarrow e+e-$ yield to $m = 0 \rightarrow$ direct γ yield
  - $m > m_\pi$ removes 90% of hadron decay background
  - S/B improves by factor 10: 10% direct $\gamma \rightarrow$ 100% direct γ^*

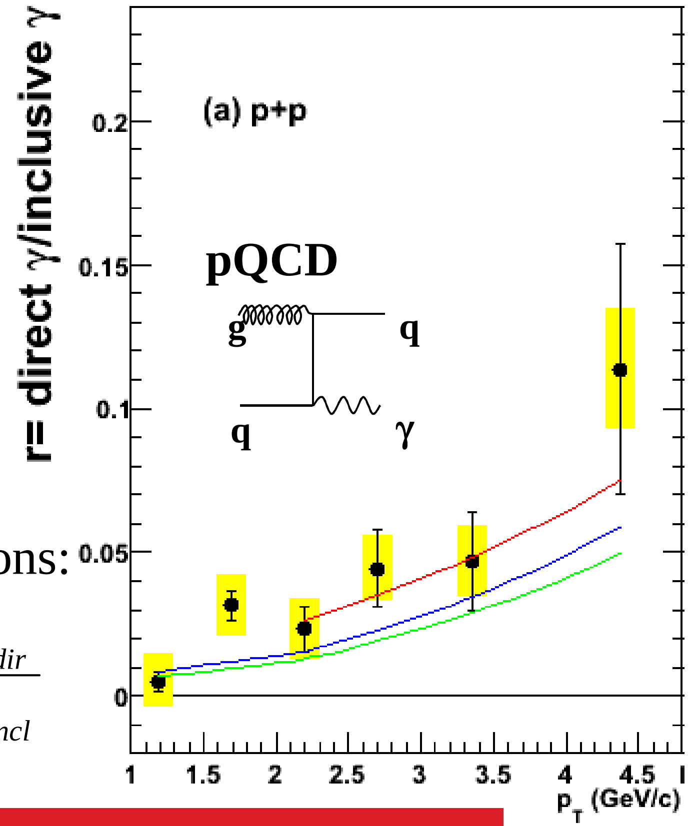
arXiv:0804.4168



access above cocktail

fraction or direct photons:

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



Small excess for $m \ll p_T$ consistent with pQCD direct photons

Fit Mass Distribution to Extract the Direct Yield:

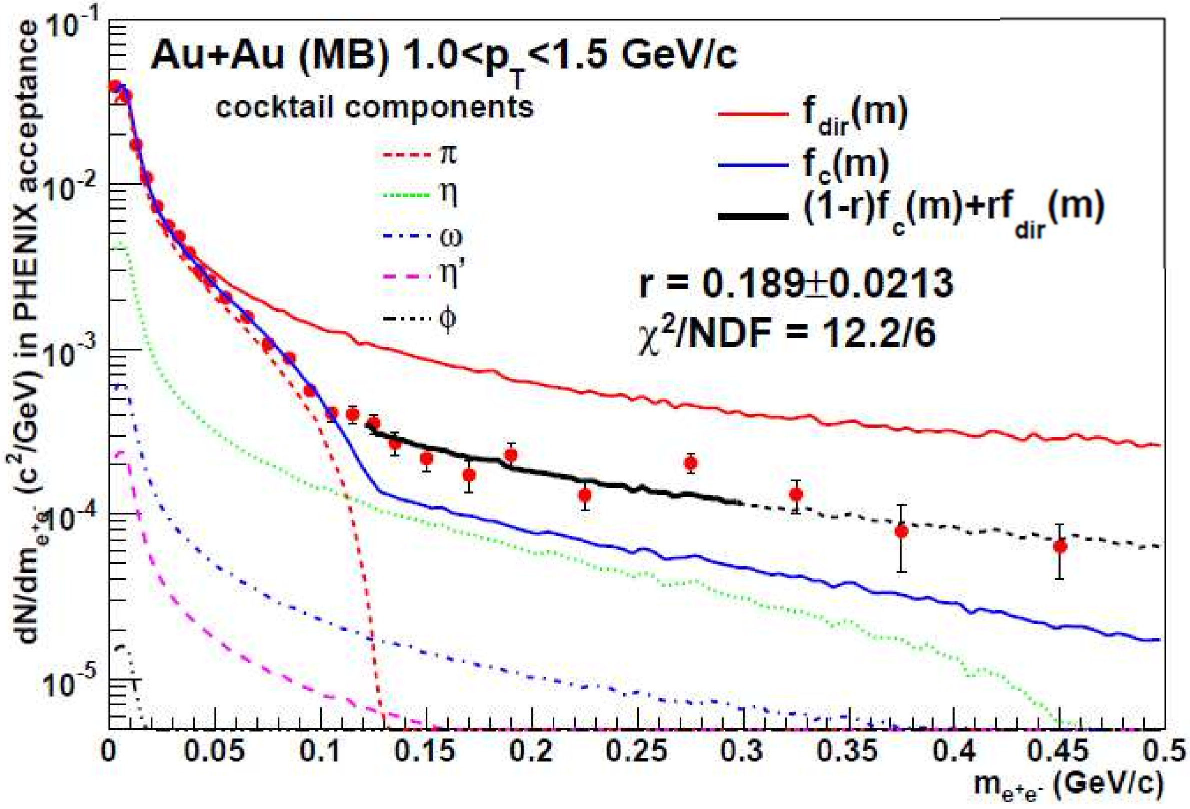
- Example: one pT bin for Au+Au collisions

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

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

$$S_{KW}(M) = |F_P(M^2)|^2\left(1-\frac{M^2}{m_P^2}\right)^3$$

Yield truncated at parent mass



$f_c(m_{ee})$ 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:

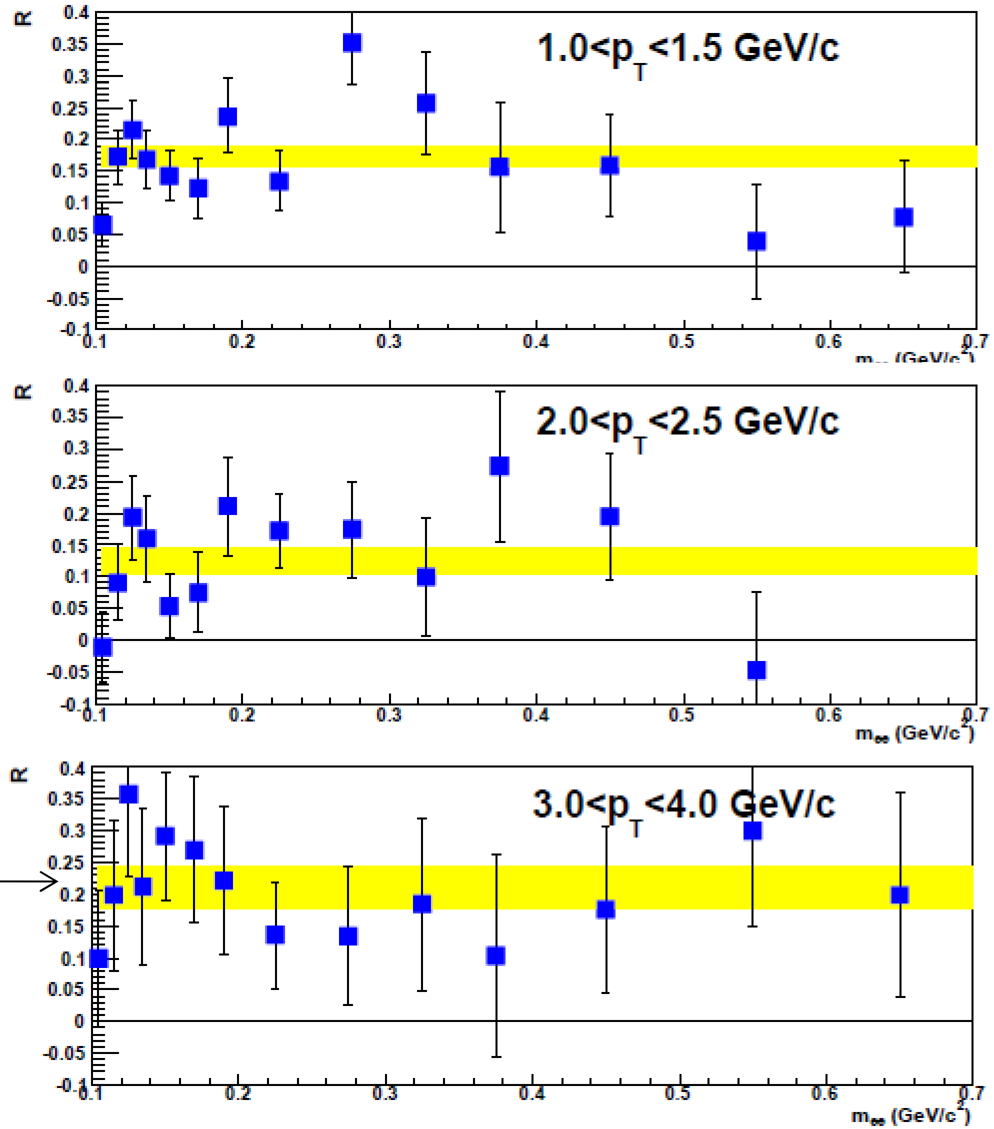
$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

Extrapolate real γ yield from dileptons:

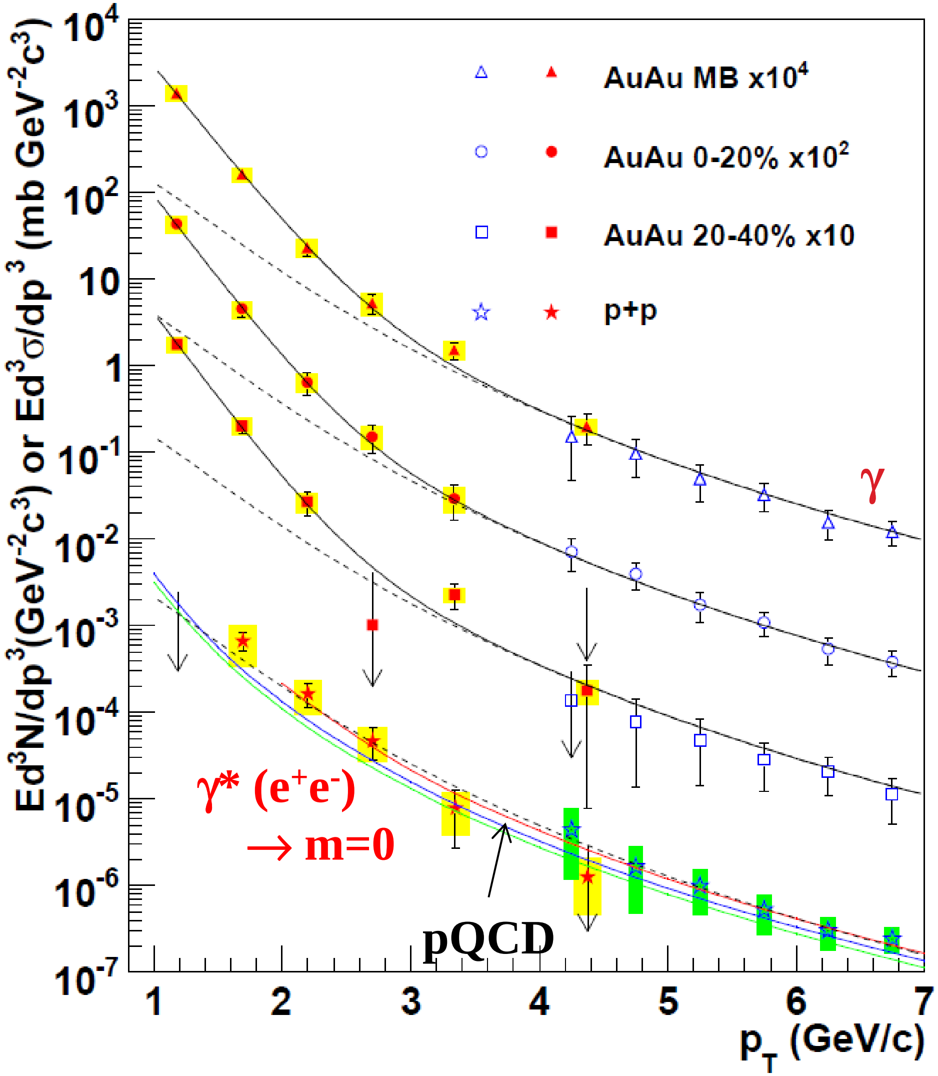
$$M \times \frac{dN_{ee}}{dM} \rightarrow \frac{dN_\gamma}{dM} \quad \text{for} \quad M \rightarrow 0$$

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



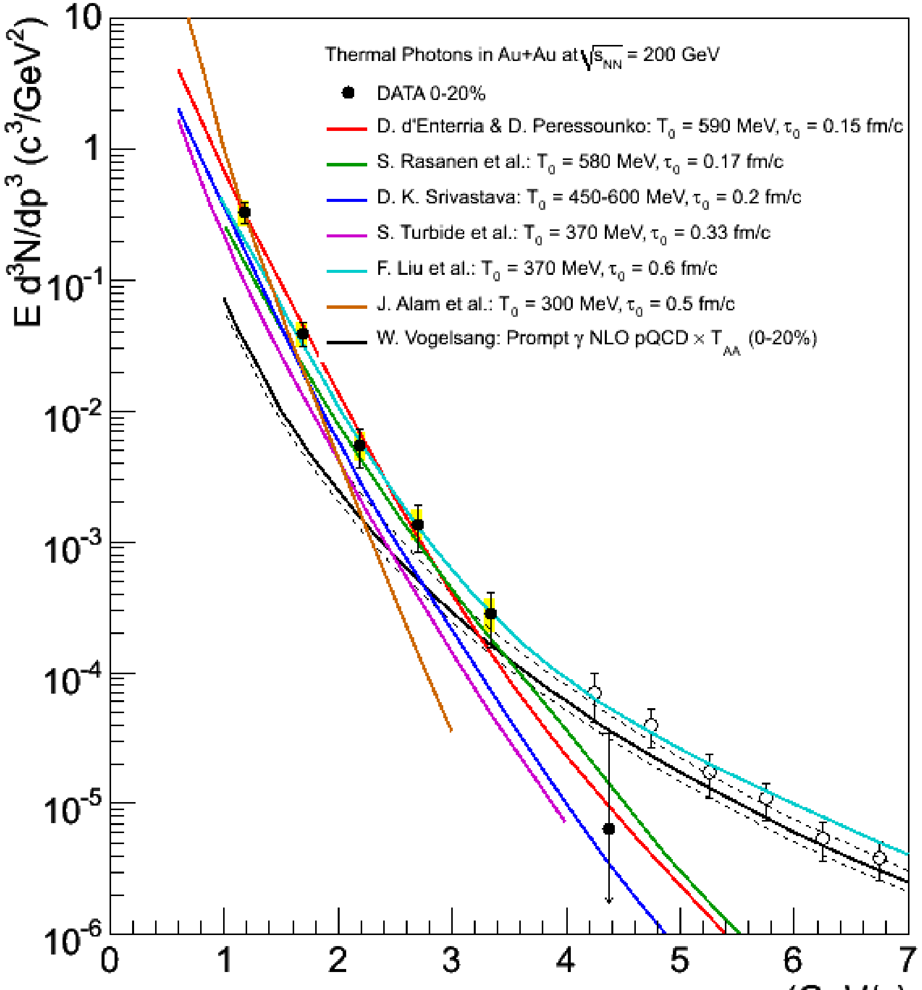
Thermal Radiation at RHIC



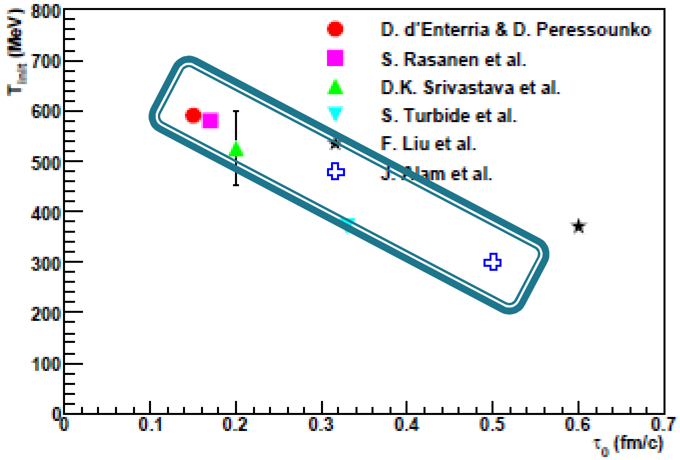
- Direct photons from real photons:
  - Measure inclusive photons
  - Subtract π^0 and η decay photons at $S/B < 1:10$ for $p_T<3$ GeV
- Direct photons from virtual photons:
  - Measure e^+e^- pairs at $m_\pi < m << p_T$
  - Subtract η decays at $S/B \sim 1:1$
  - Extrapolate to mass 0

First thermal photon measurement in RHI Collisions!

Calculation of Thermal Photons



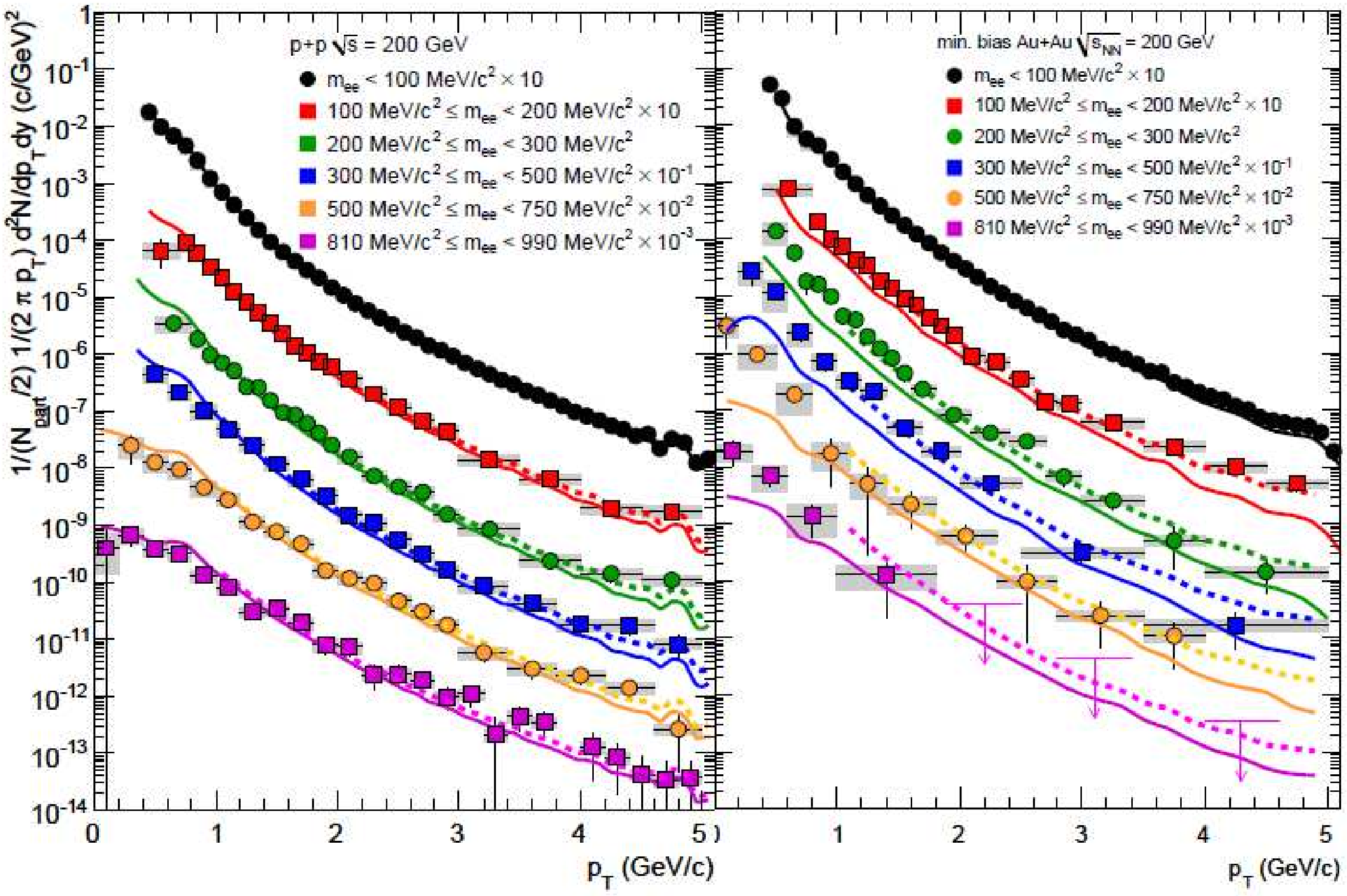
D.d'Enterria, D.Peressounko, Eur.Phys.J.C 46 (2006)



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.

p_T Spectra

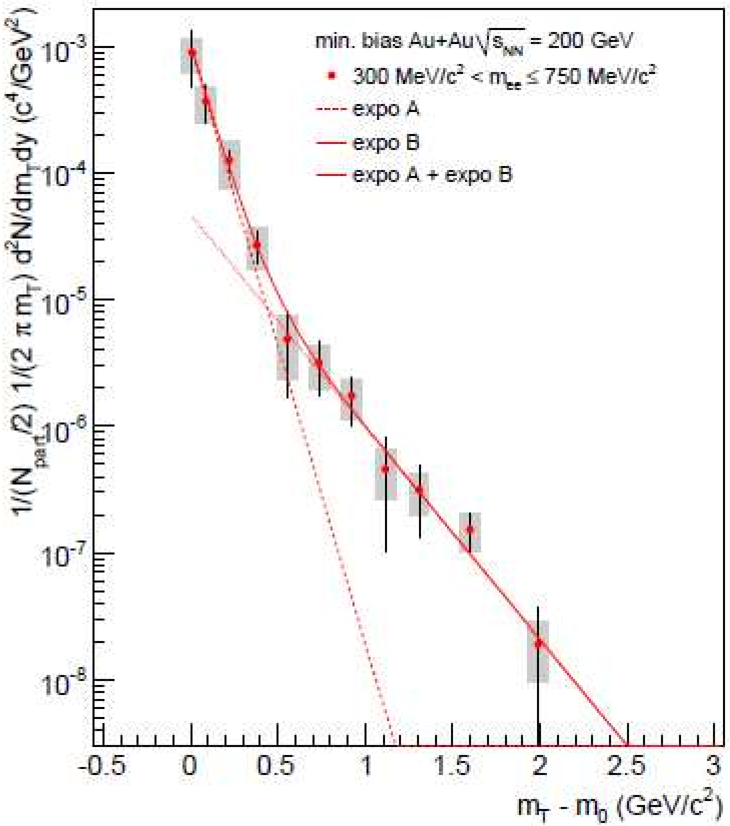


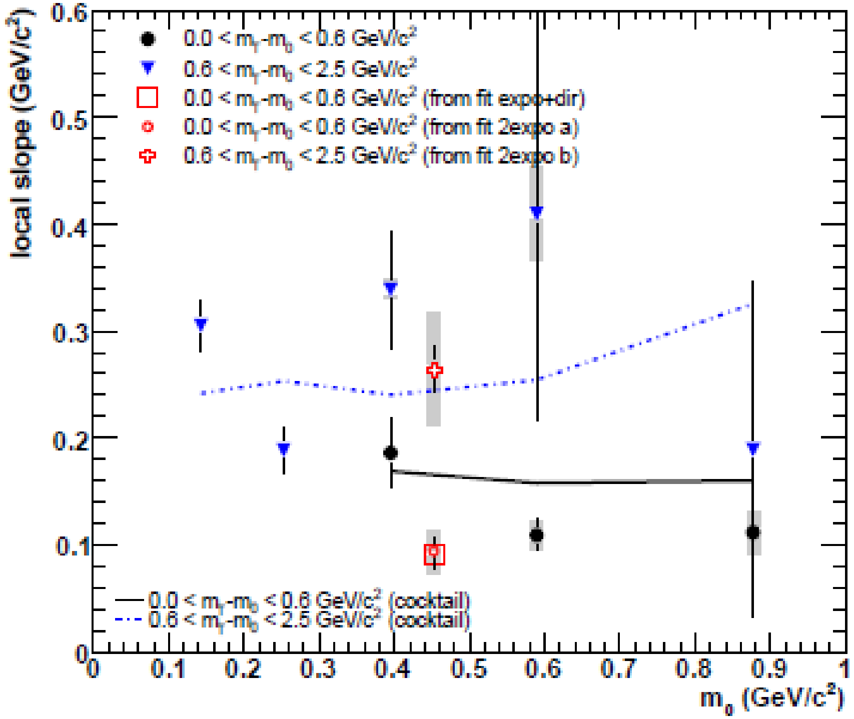
pp well described by Cocktail + gamma.

AuAu not well described:

Additional excess at low p_T

Local Slopes – Cold Component



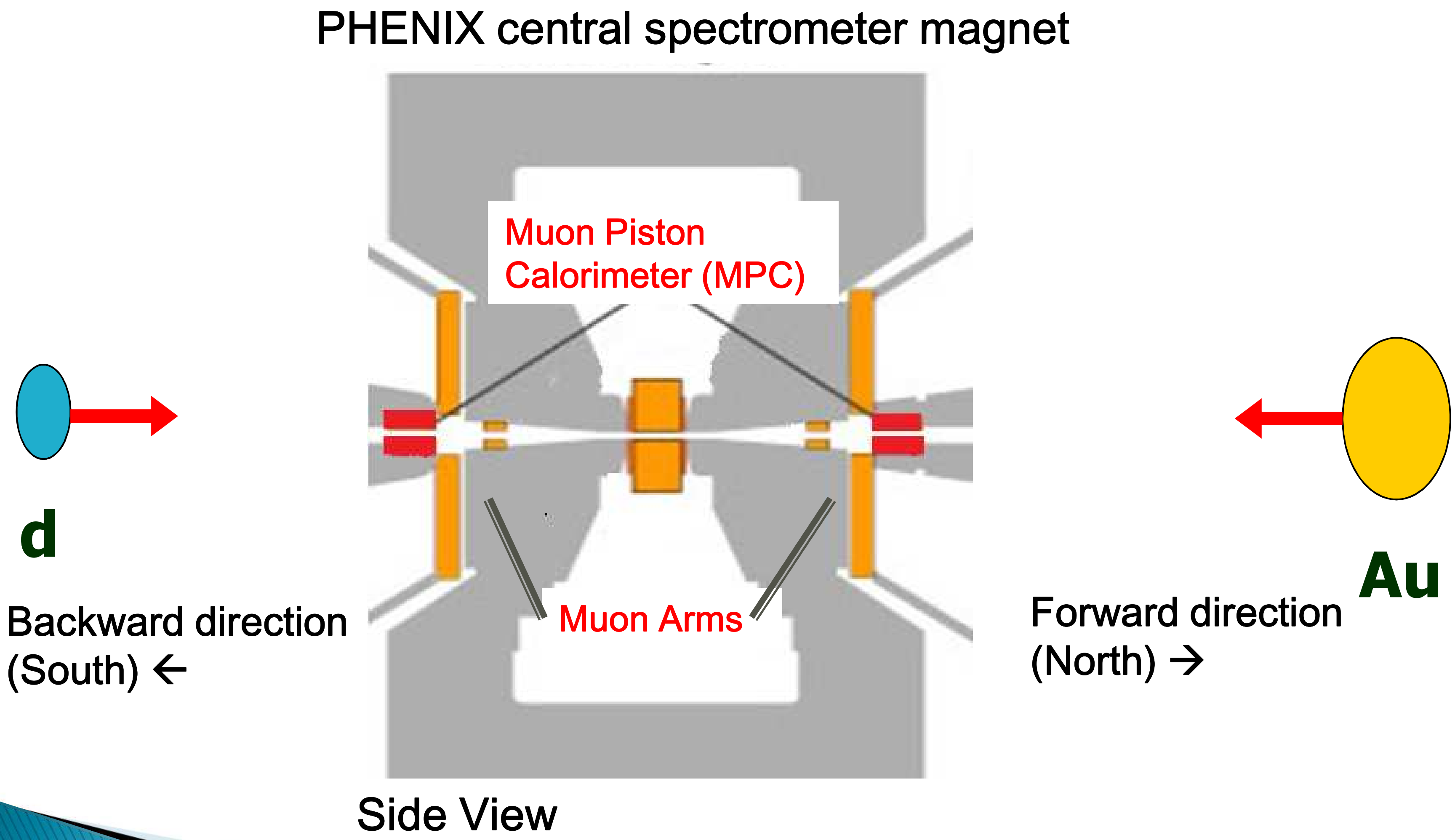


Soft component below m_T ~ 500 MeV:

T_{eff} < 120MeV independent of mass

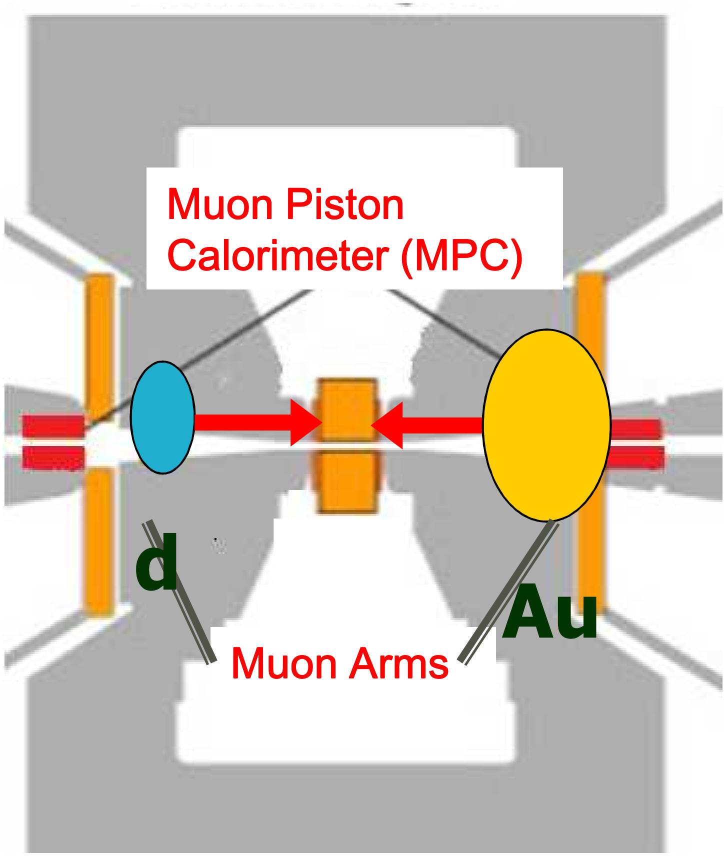
more than 50% of yield

CGC Revisited 200 GeV d+Au



CGC Revisited 200 GeV d+Au

PHENIX central spectrometer magnet

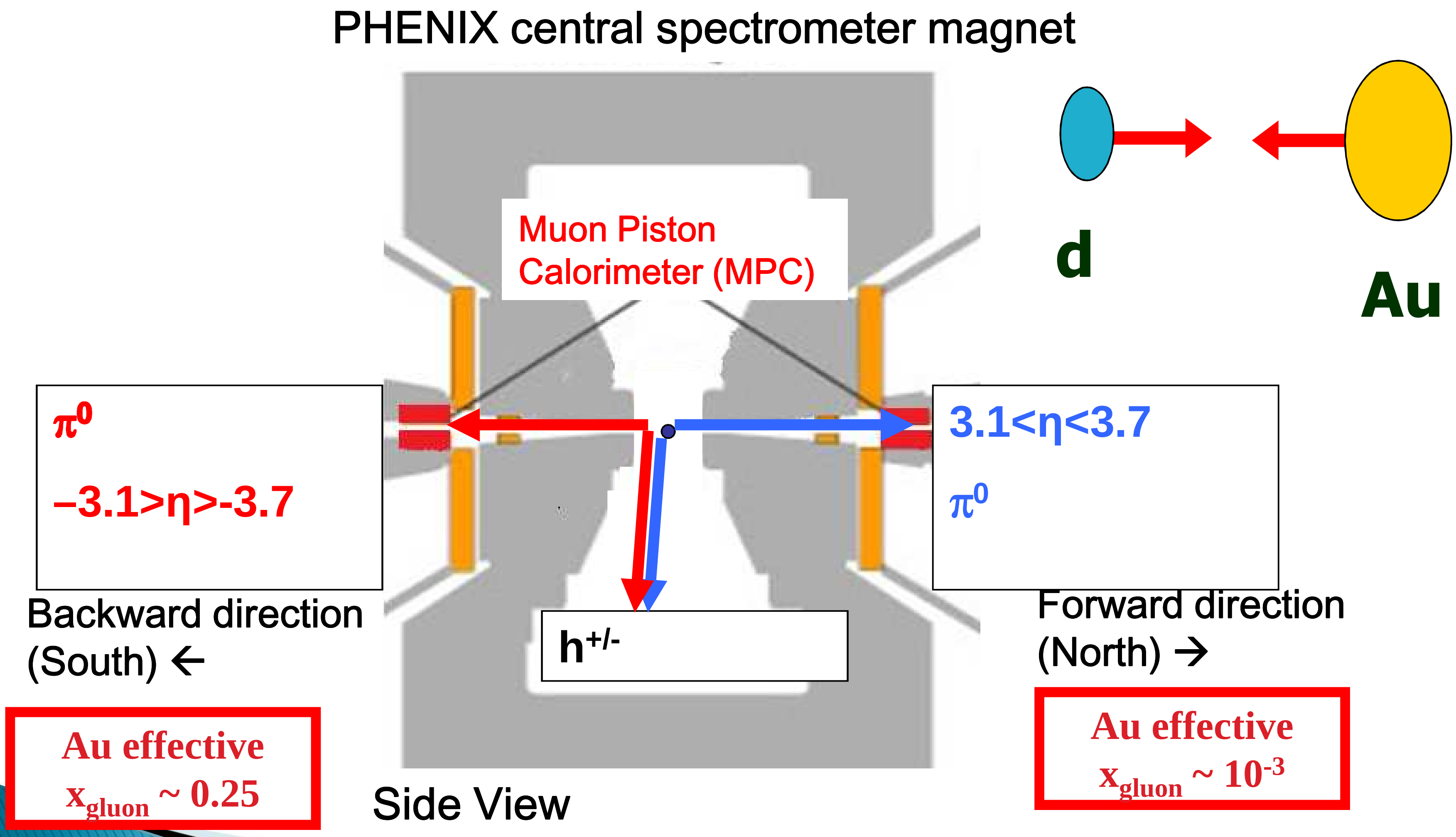


Backward direction (South) ←

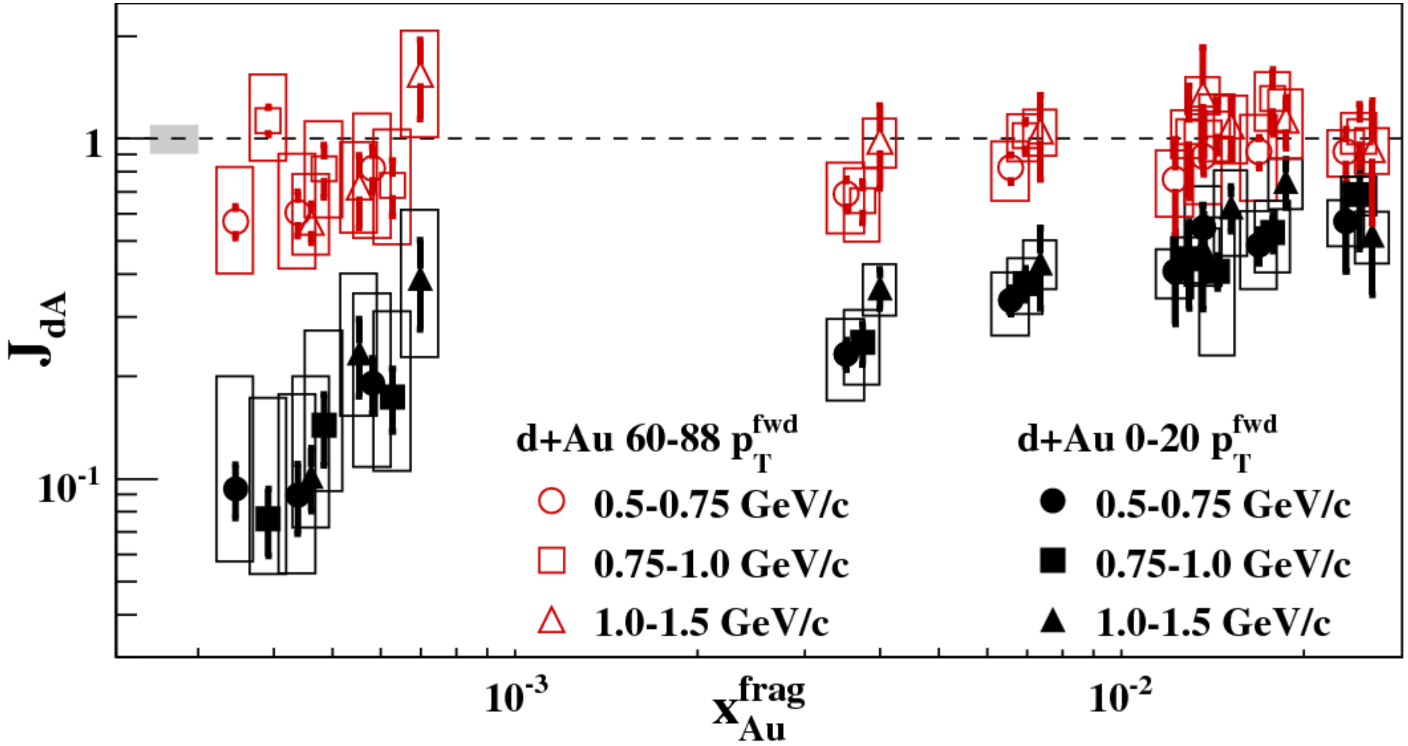
Forward direction (North) →

Side View

Di-Jet Correlations Span η and x

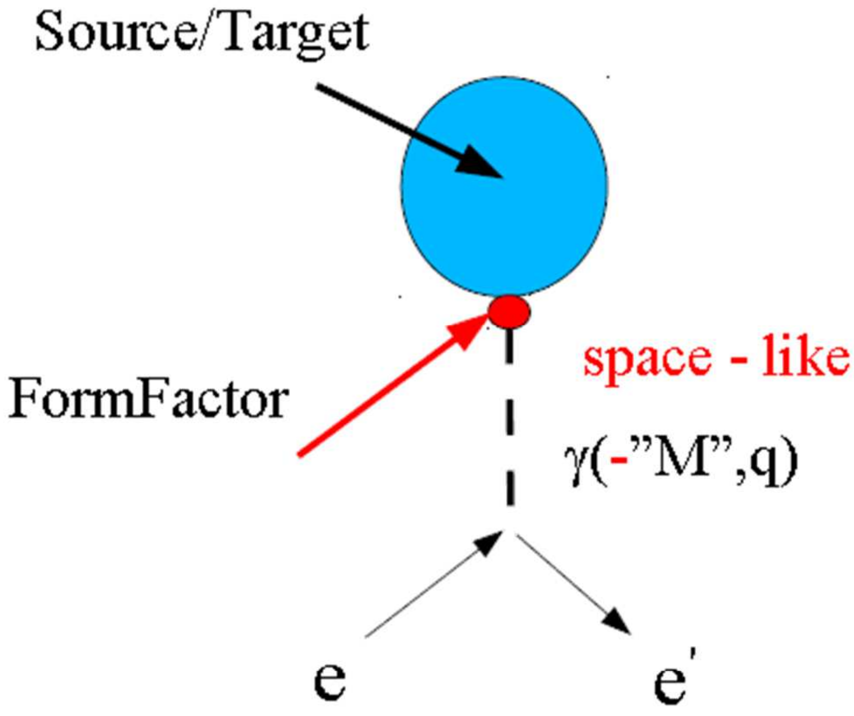


Revisiting Color Glass Condensate



- d_+Au results at mid rapidity show that jet suppression is a final state effect.
- However, at very low x, suppression is seen.
- Hints of CGC?
- What to do next?

Dileptons vs Electron Scattering



Measures "space structure"

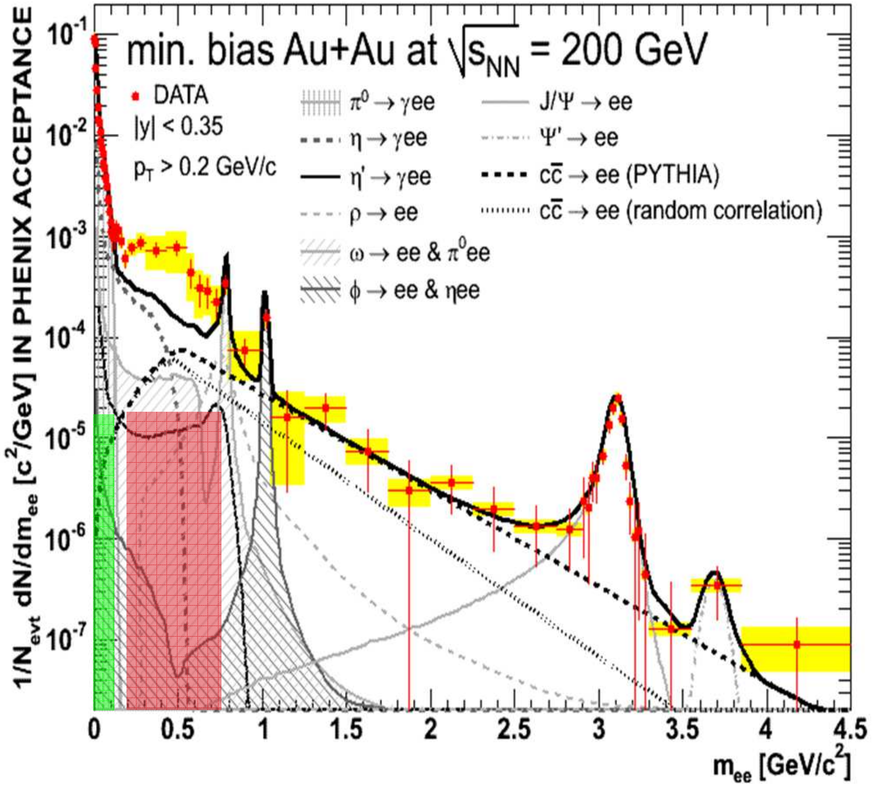
$$S(0,q) \rightarrow S(r)$$

New Friends and Collaborators…

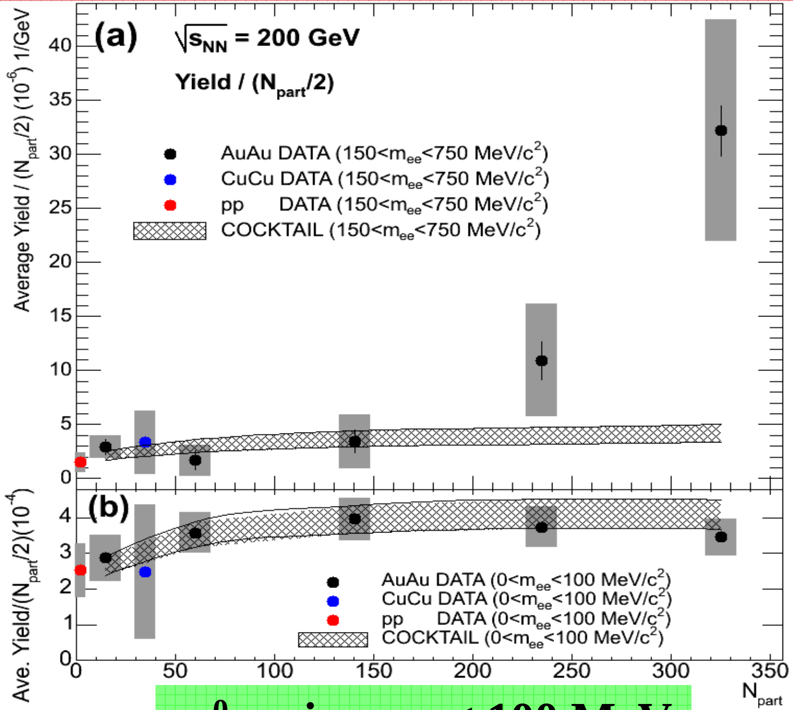
Thank You

Backups…

Au+Au Dilepton Continuum



Excess region: 150 < m < 750 MeV



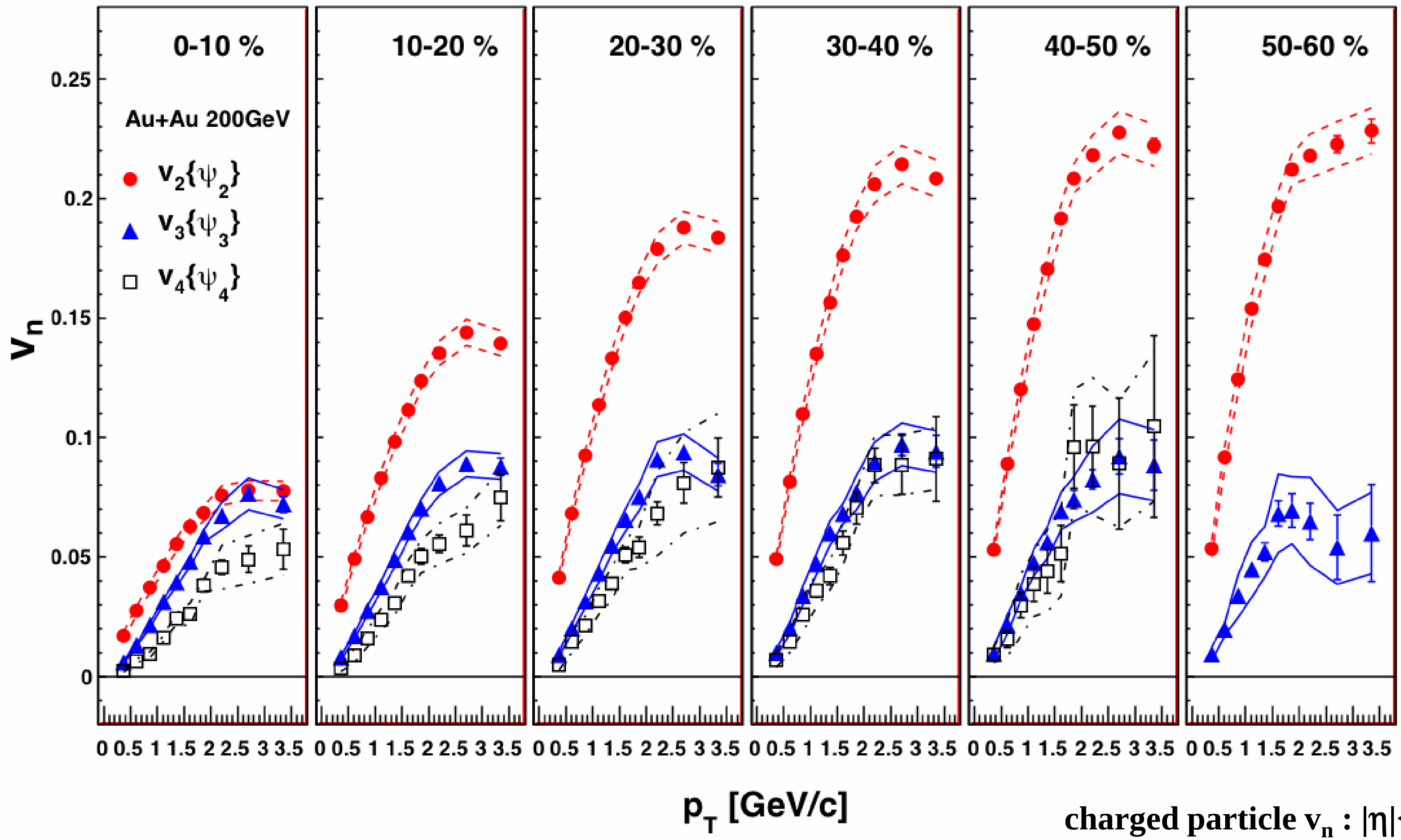
π^0 region: m < 100 MeV

- 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}**

$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 200GeV Au+Au

arXiv:1105.3928



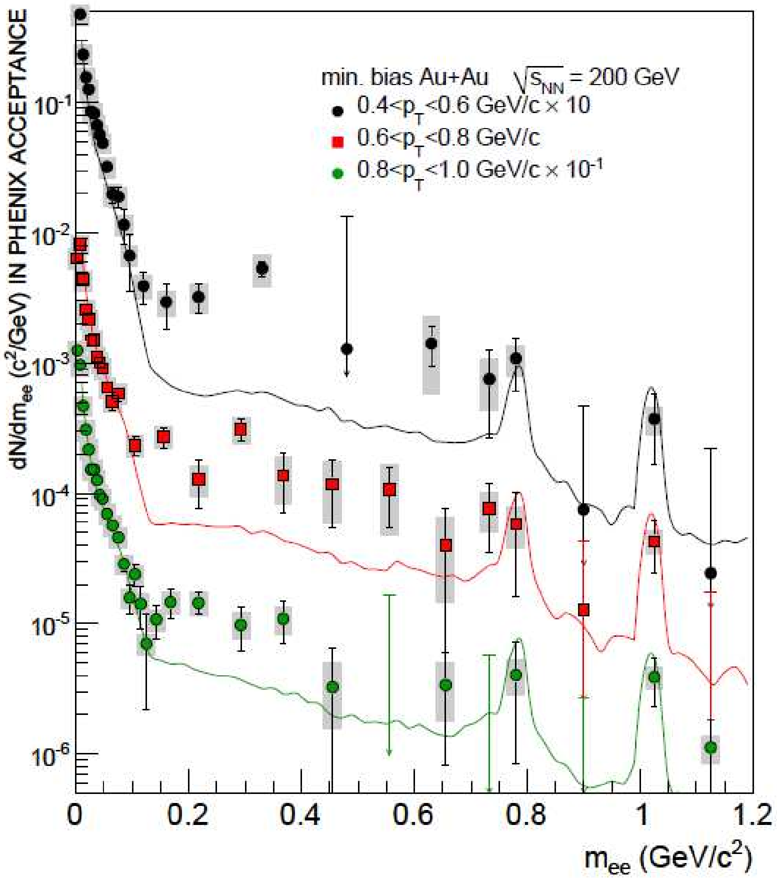
charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

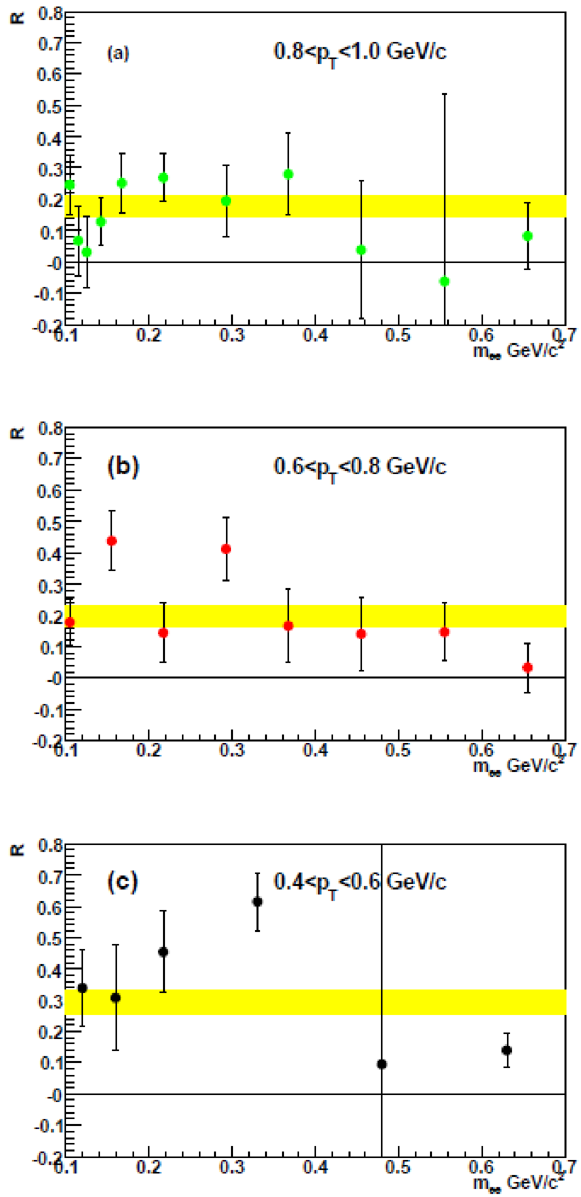
(1) v_3 is comparable to v_2 at 0~10%
(2) weak centrality dependence on v_3
(3) $v_4\{\Phi_4\} \sim 2 \times v_4\{\Phi_2\}$

All of these are consistent with initial fluctuation.

p_T < 1 GeV Enhancement

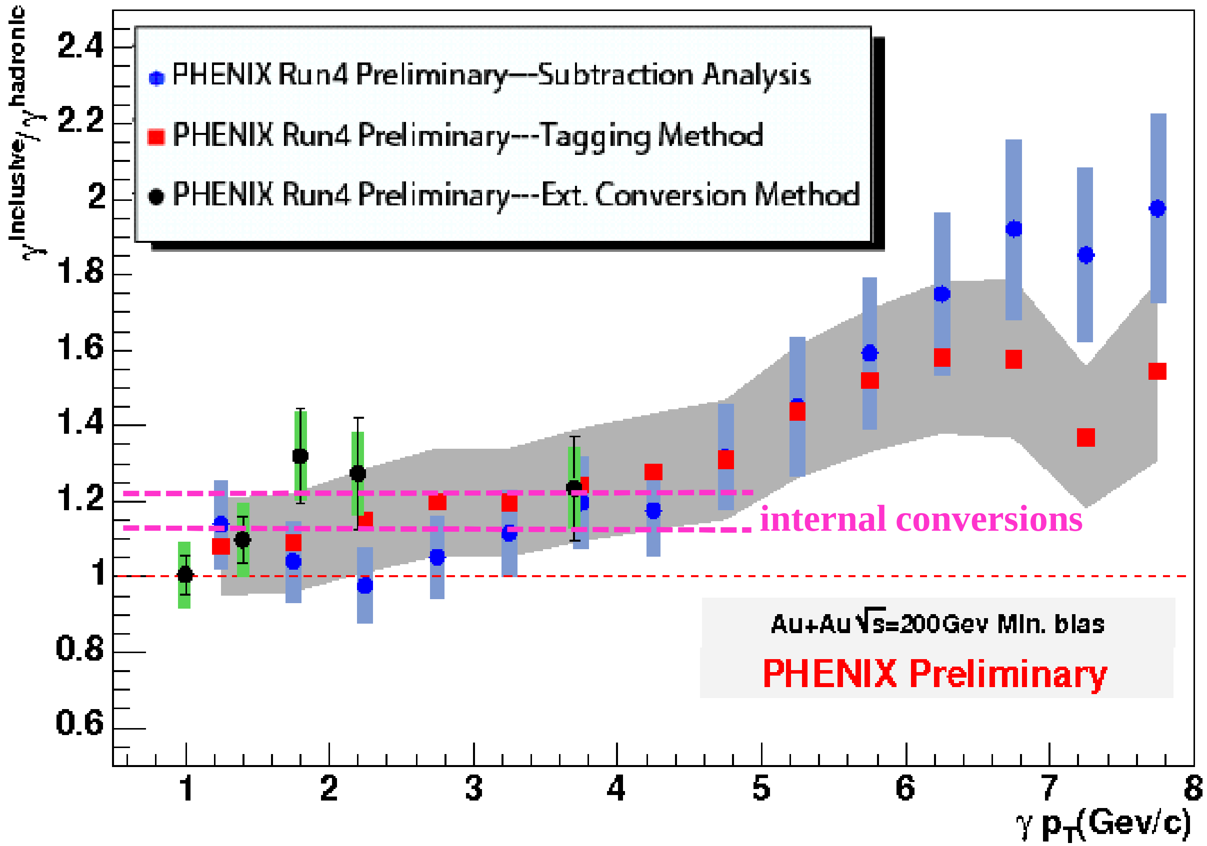
Poorly described as γ^*





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

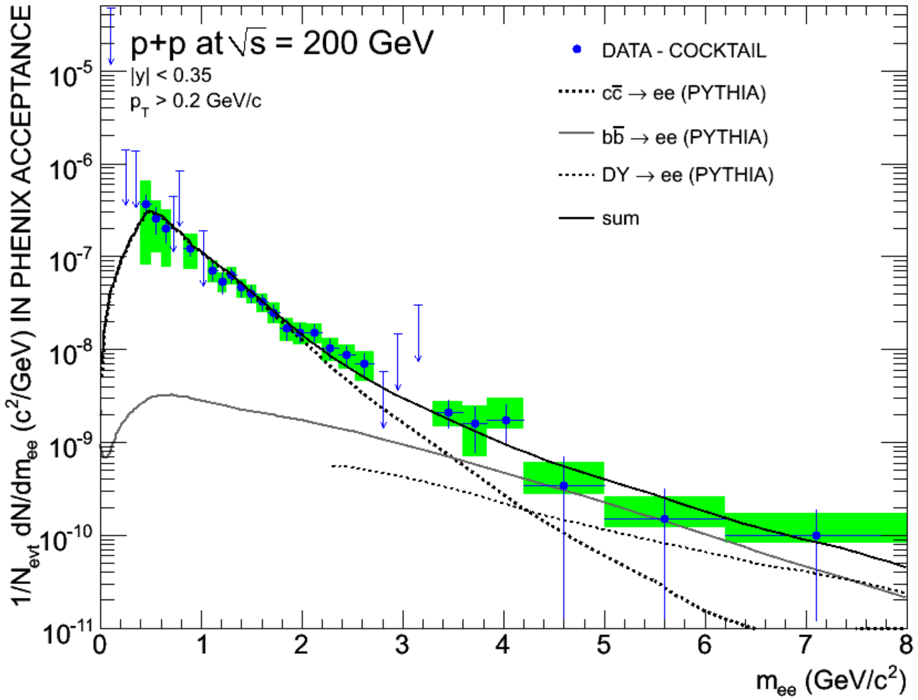
Search for Thermal Photons via Real Photons



- 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

IMR Region (ϕ → J/ψ)

Subtract hadron decay contribution and fit difference:

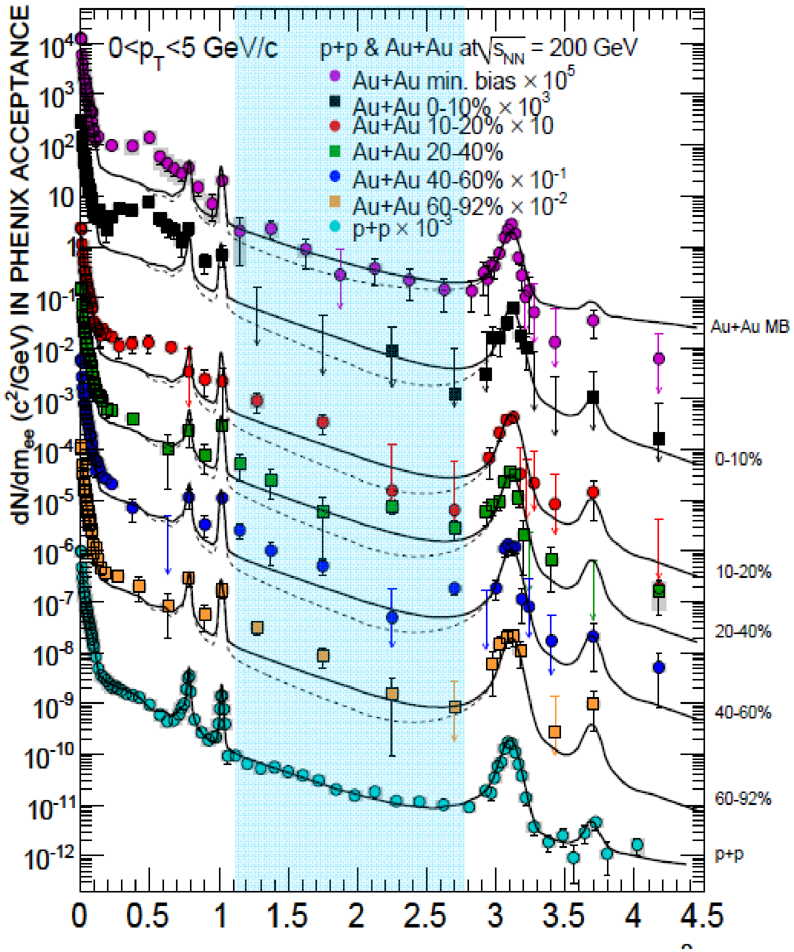


Charm: after cocktail subtraction

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

Simultaneous fit of charm and bottom:

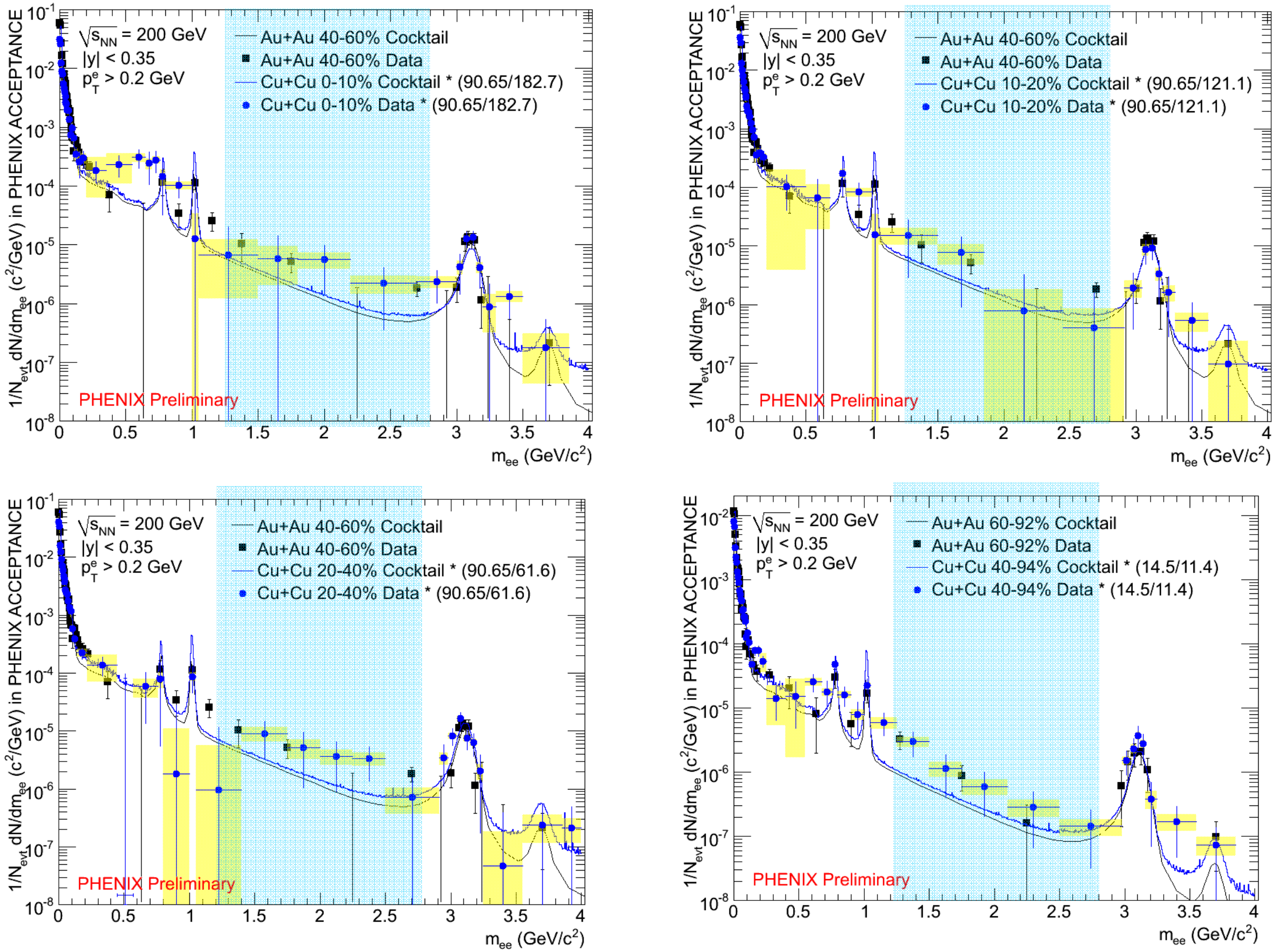
- σ_c=518 ± 47 (stat) ± 135 (sys) ± 190 (model) μb
- σ_b= 3.9 ± 2.4 (stat) +3/-2 (sys) μb



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.

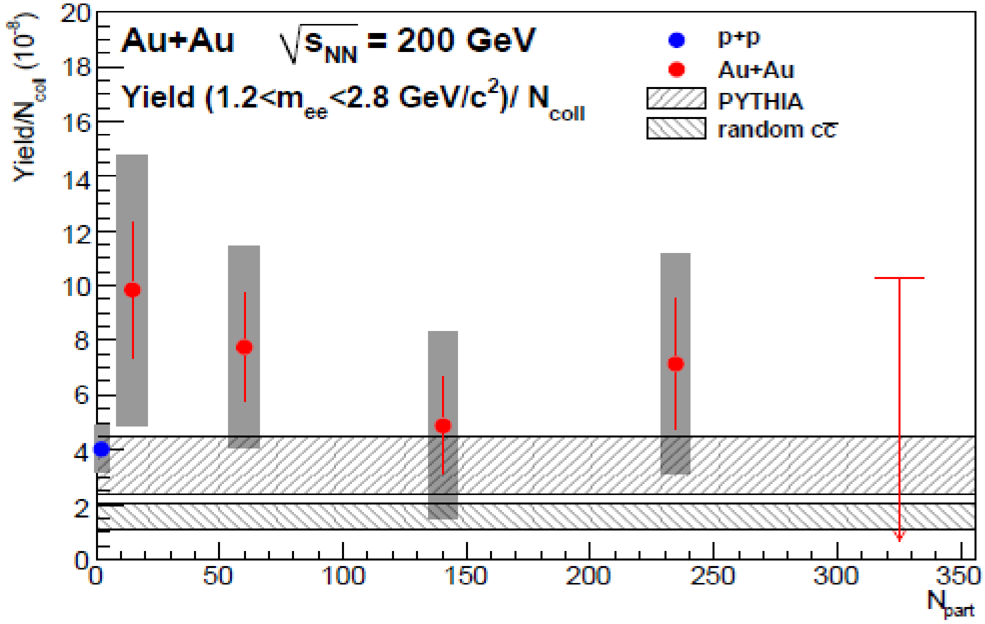
- **Charm singles are well known to be strongly modified by the medium.**
- **These effects should lower the IMR yield most at the most central bin.**

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.

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)

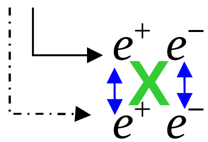
- Combinatorial background: e^+ and e^- from different uncorrelated source

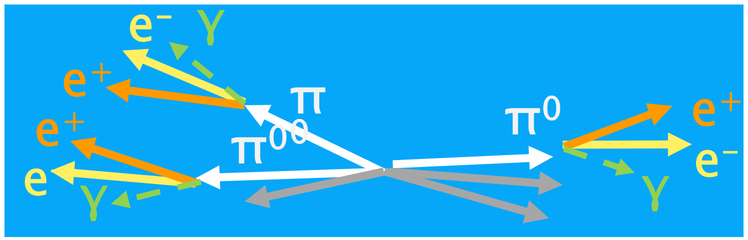
$$\pi^0 \rightarrow e^+ e^- \gamma \qquad\qquad \gamma \rightarrow e^+ e^-$$

  - 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

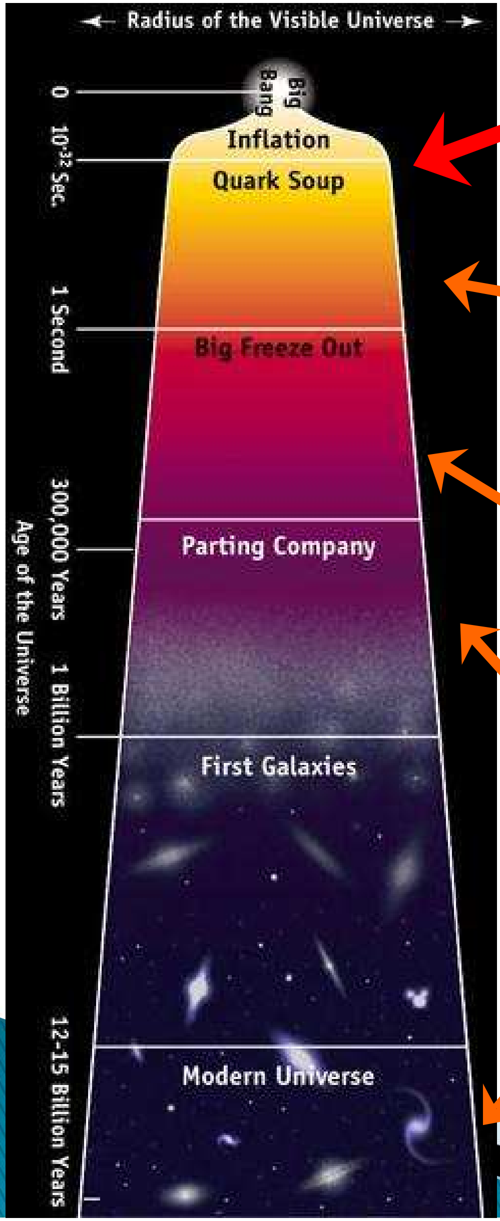
$$\pi^0 \rightarrow \gamma\gamma$$





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

Evolution of the Universe



Reheating Matter

T… !!

Standard Model (N/P) P…

Quark-

Too hot for nuclei to bin…

Nuclear/Particle (N/P)

…synthesis builds

Nucl… Force…Nucle…

…ec…

…) Physics

…e

…/General Relativity

- Collisions of "Large" nuclei convert beam energy to temperatures above 200 MeV or 1,500,000,000,000 K
  - ~100,000 times higher temperature than the center of our sun.
- "Large" as compared to mean-free path of produced particles.

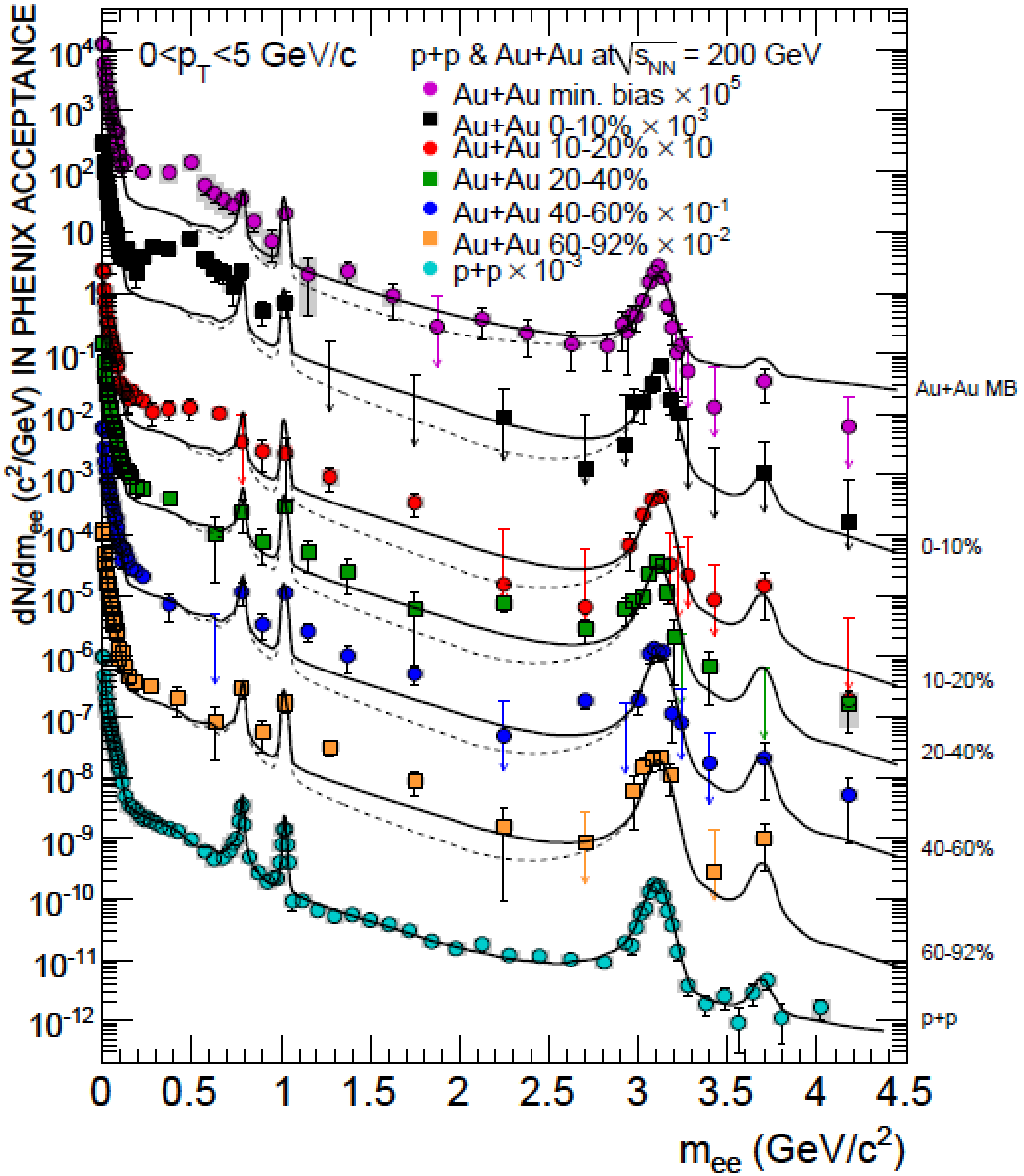
Stars convert gravitational energy to temperature.

They "replay" and finish nucleosynthesis

~15,000,000 K in the center of our sun.

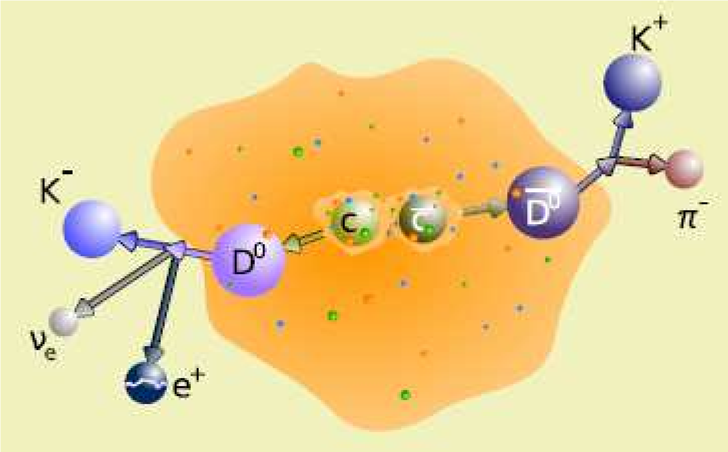
Solid
Liquid
Gas

Centrality Dependence

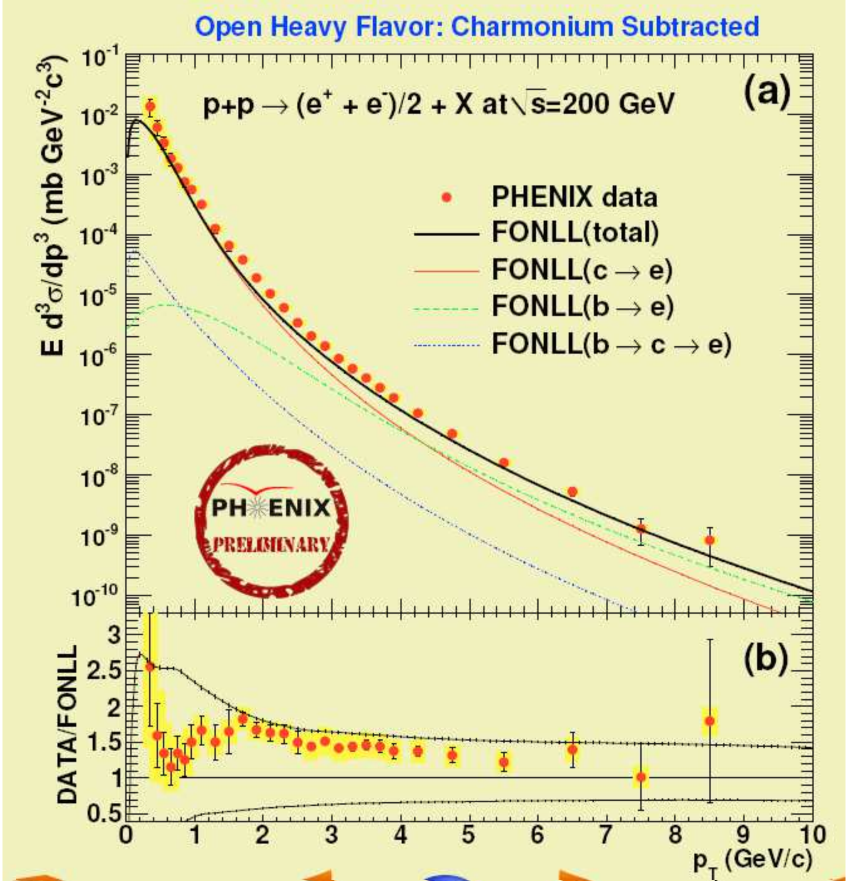


- Enhancement in low mass region is a strong function of centrality.
- Statistics are also sufficient to analyze p_T dependence.
- Need methodical approach to the spectra.

Heavy Flavor from Single Leptons

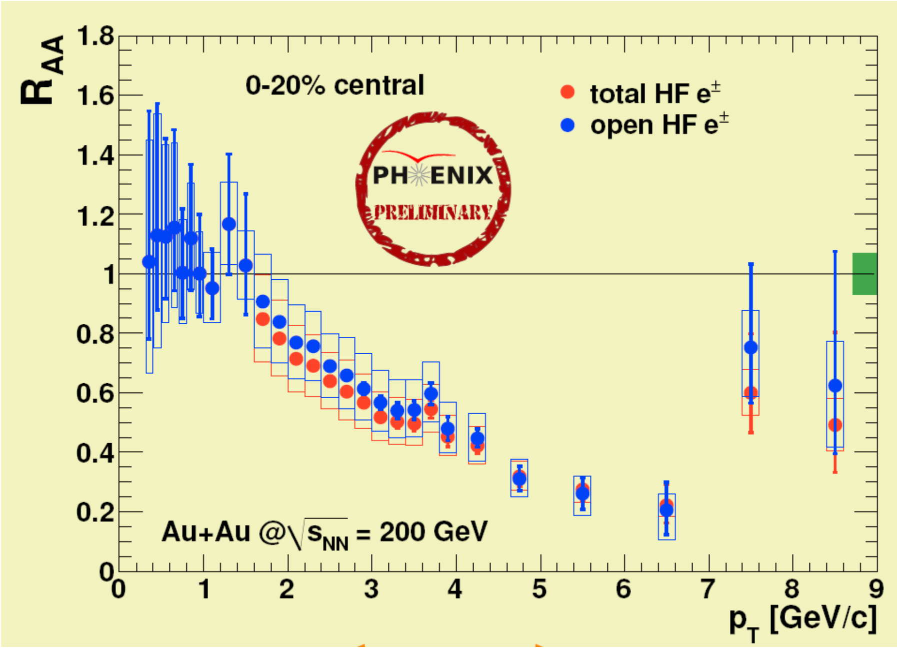


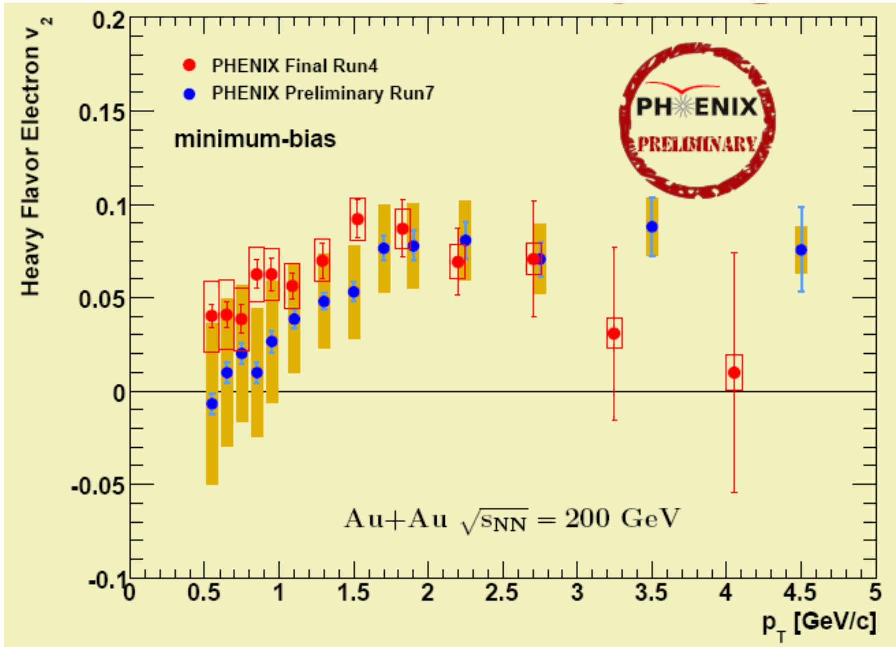
- Open Charm (and bottom) states decay with significant branching ratios (~10%) semi-leptonically.
- Parent quark mass makes these the dominant source at high p_T
- Cocktail (or convertor) subtraction yields spectrum of heavy flavor lepton decays.



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

Heavy Flavor Leptons in AuAu



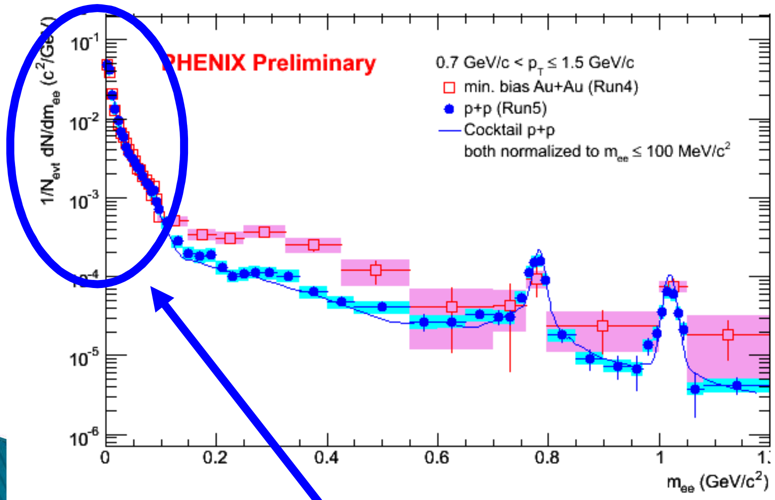


- Heavy Flavor shows suppression similar to π^0 at fill RHIC Energy.
- Heavy Flavor even flows.
- These results are the principal ones that define η/s.
- Similar conclusion for muons from CuCu: suppression similar to π

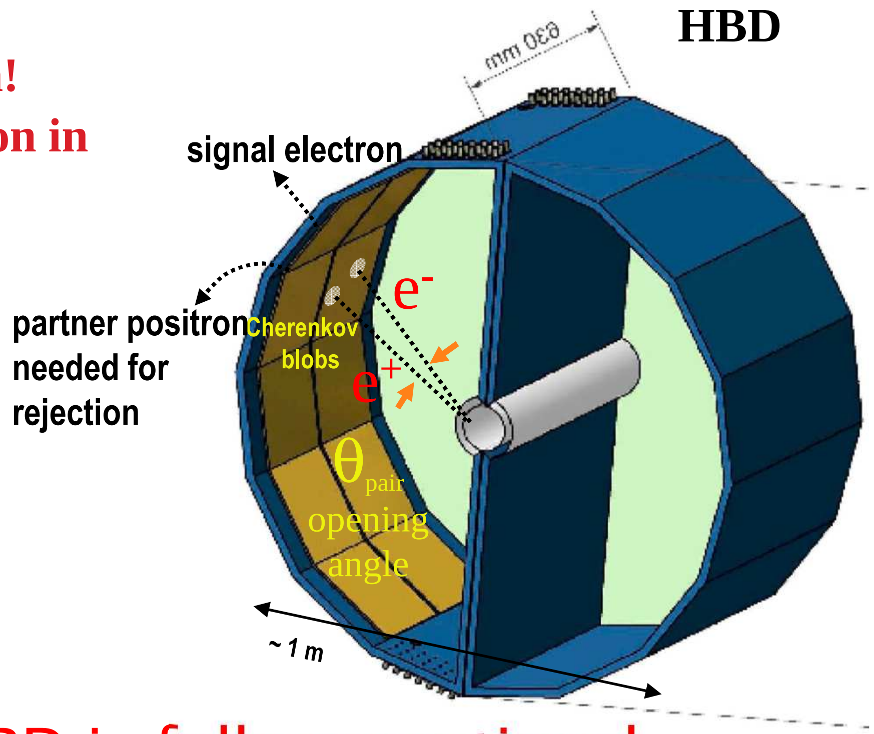
Future of the Continuum at RHIC

- 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



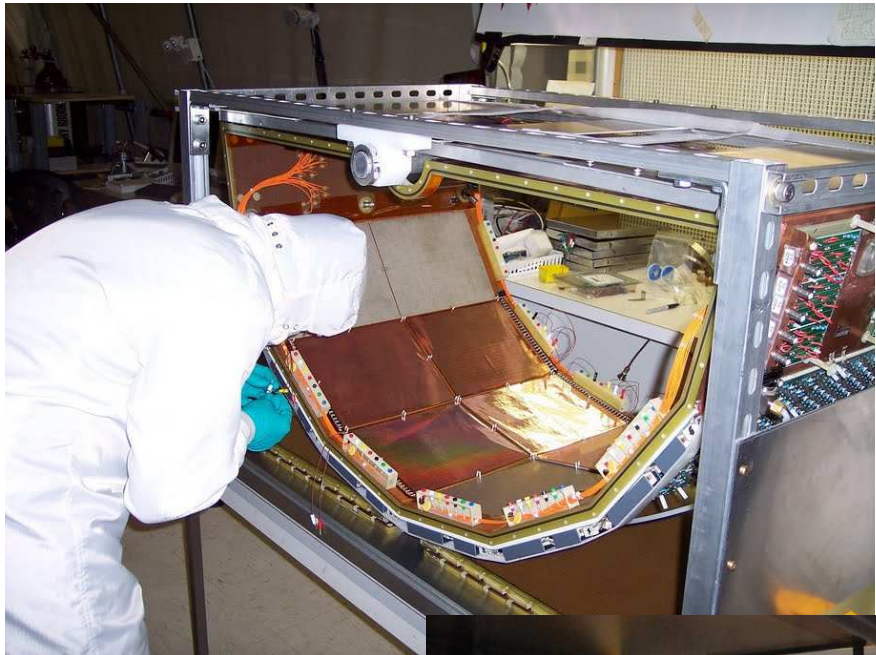
False combinations dominated by region where yield is largest



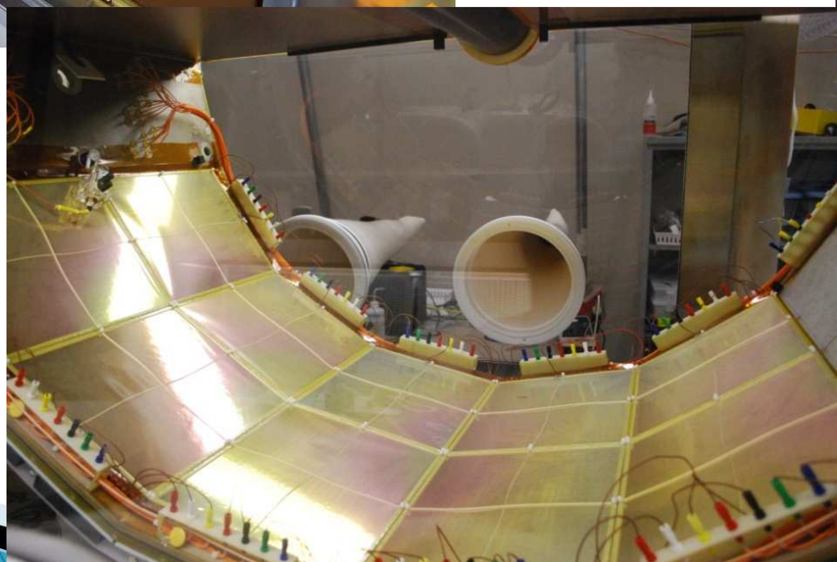
- HBD is fully operational
  - Proof of principle in 2007
  - Taking data right now with p+p
  - Hope for large Au+Au data set in 2010

HBD Construction

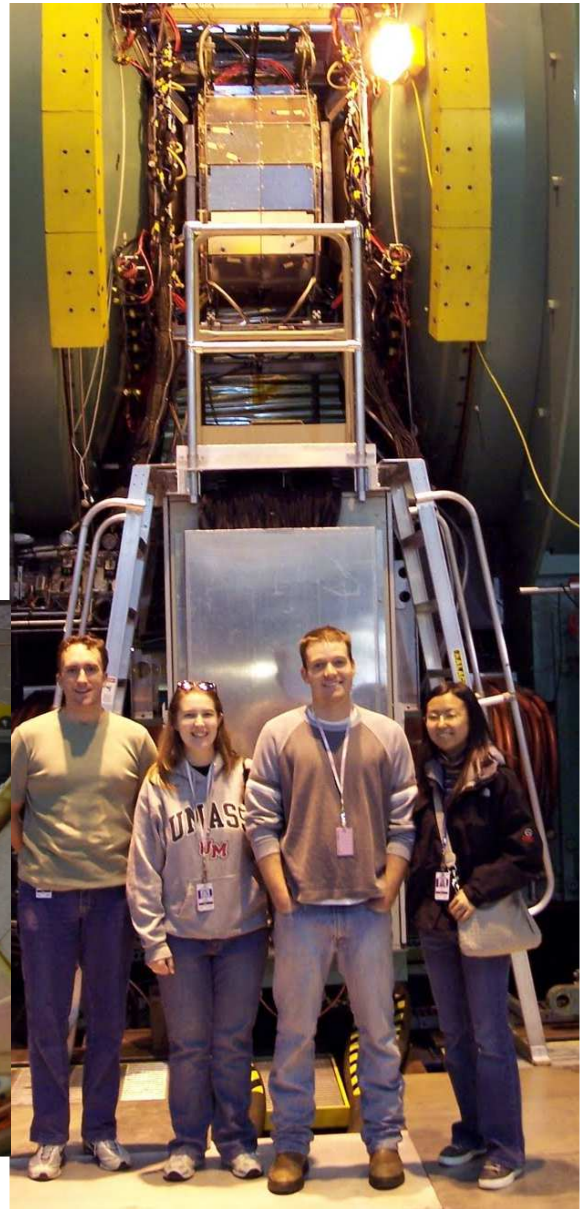
“Standard” CERN Cu GEM foils in HBD



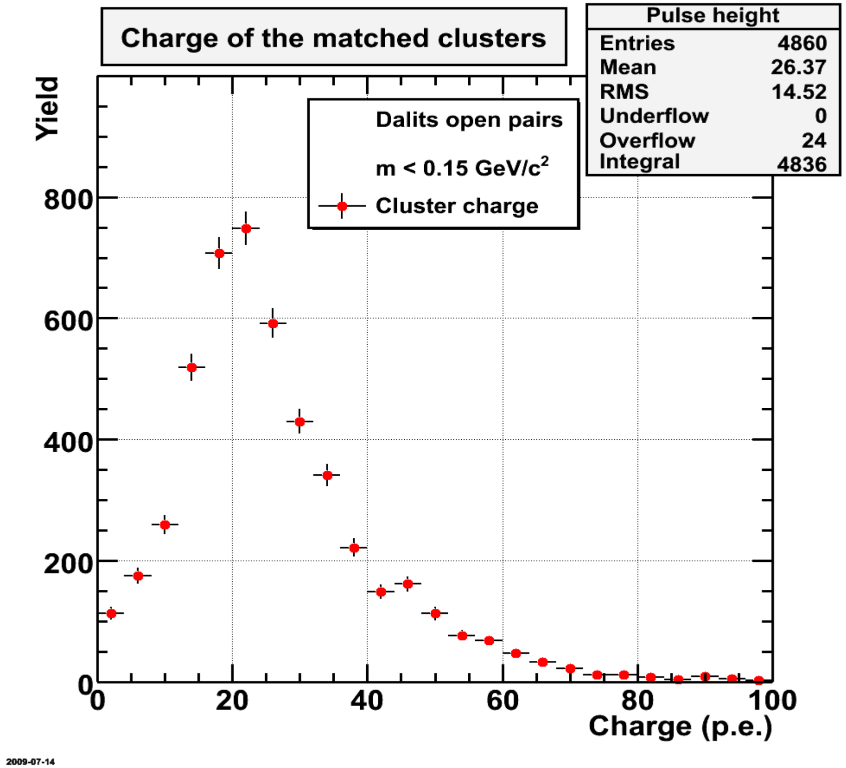
CSI photocathods on GEM foils

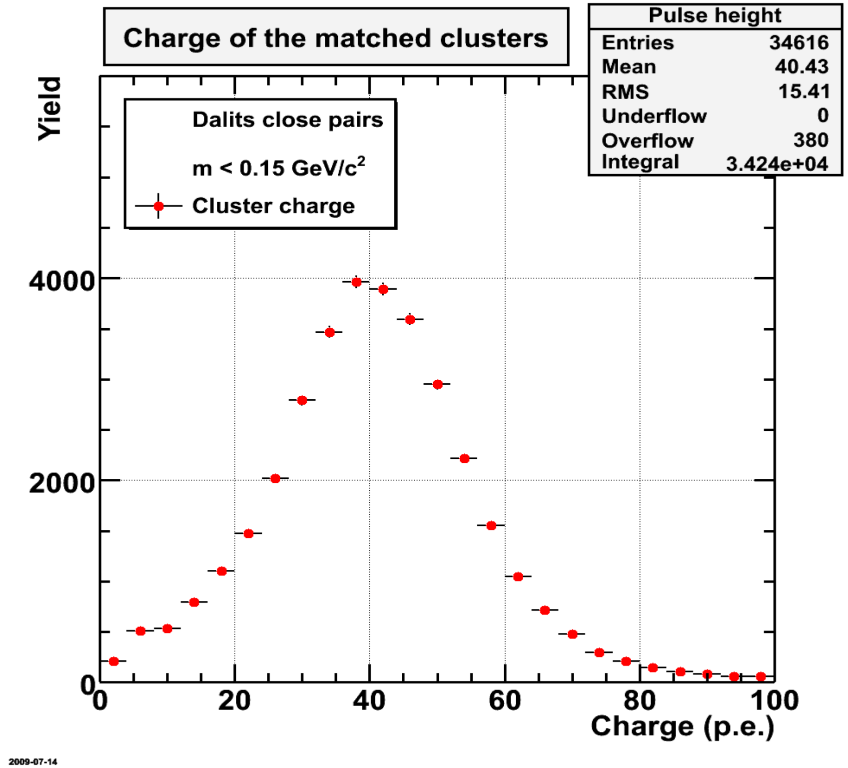


2nd HBD installed in PHENIX



Single and Double Response



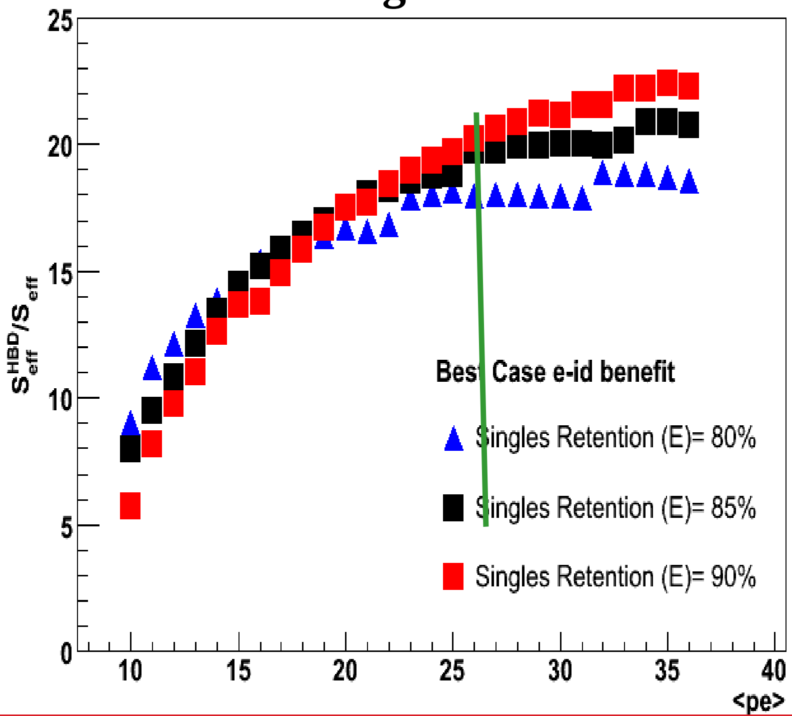


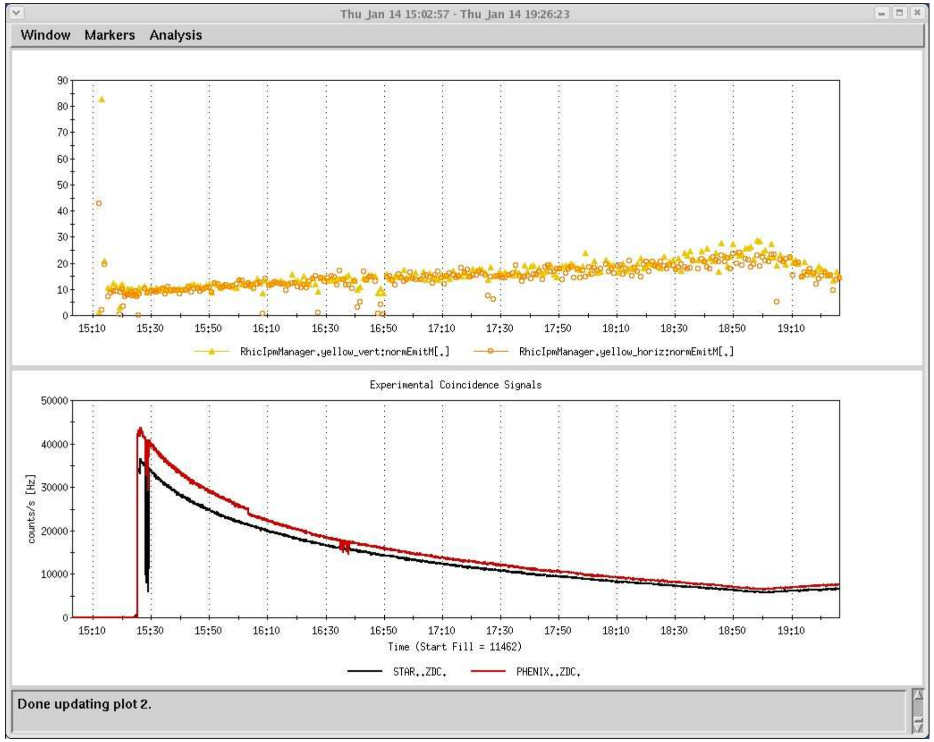
- Using low mass pairs, one can select a sample with large opening angle (isolated) or small opening angle (overlapping)
- The responses are 20 p.e. & 40 p.e. respectively. (WOW!)

Compared to Run 4 Results

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

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

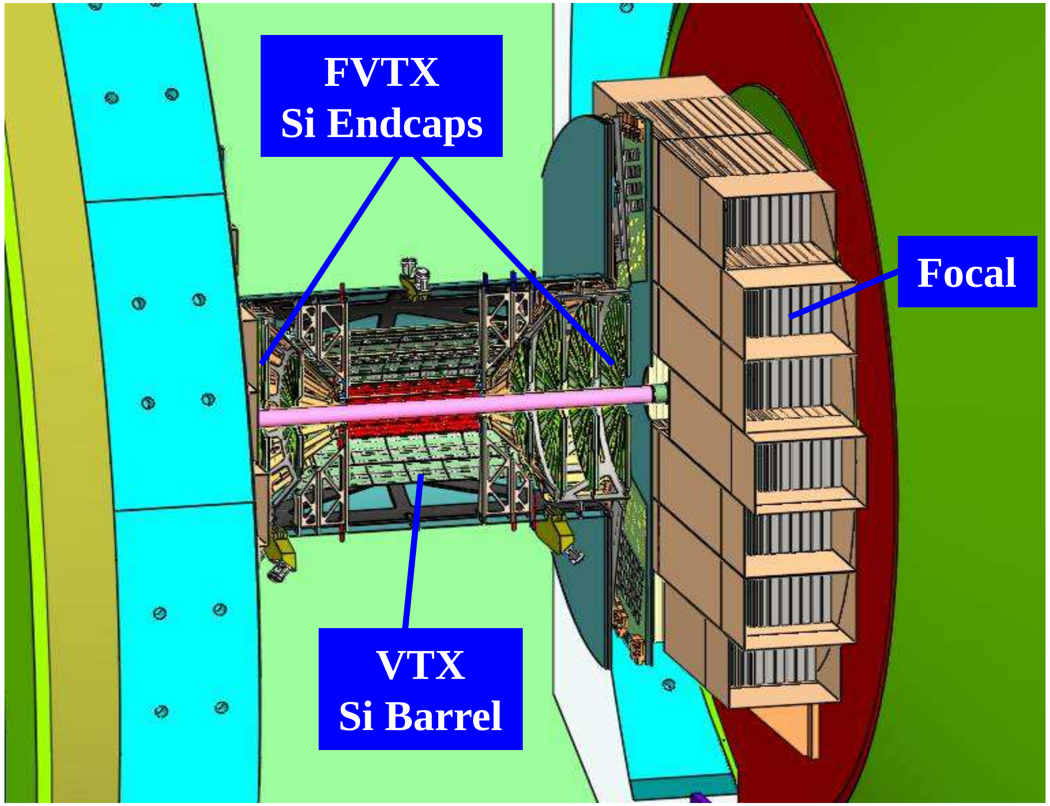




Stochastic Cooling at RHIC

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

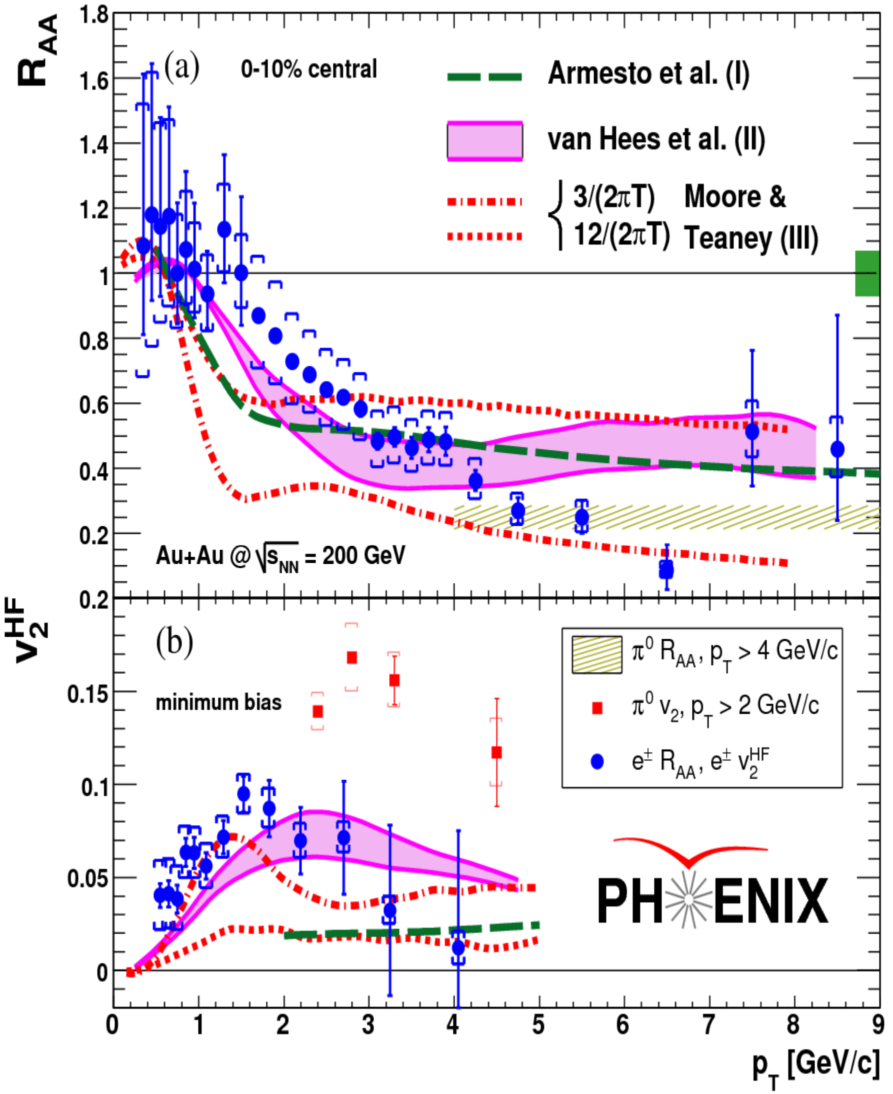
PHENIX Upgrades @ Vertex



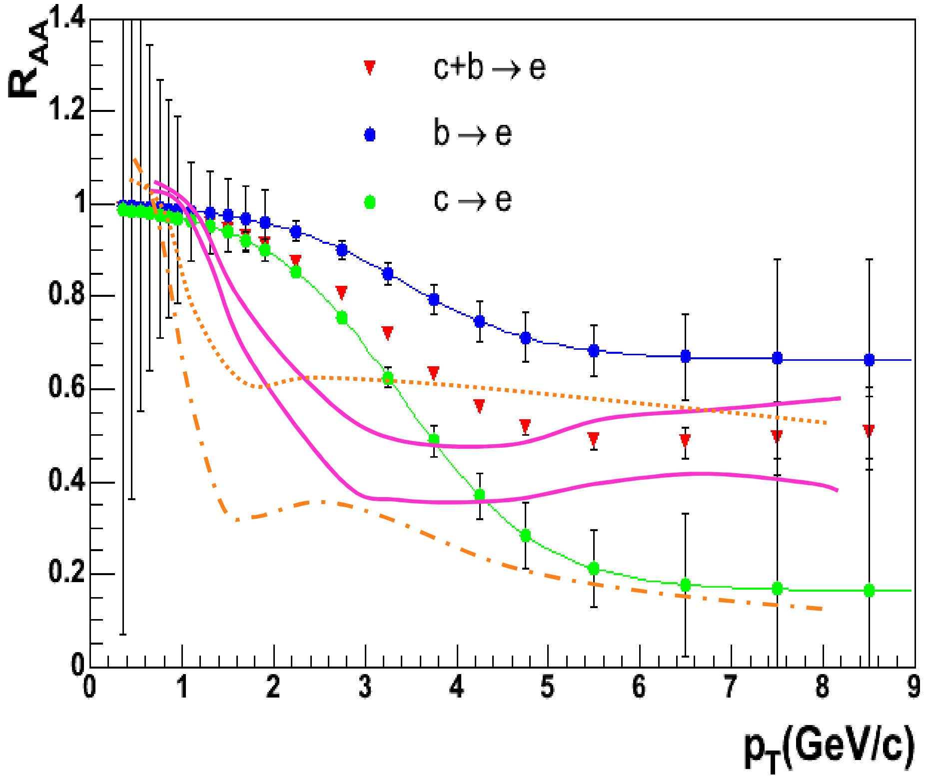
VTX, FVTX and NCC add key measurements to RHIC program:

- 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



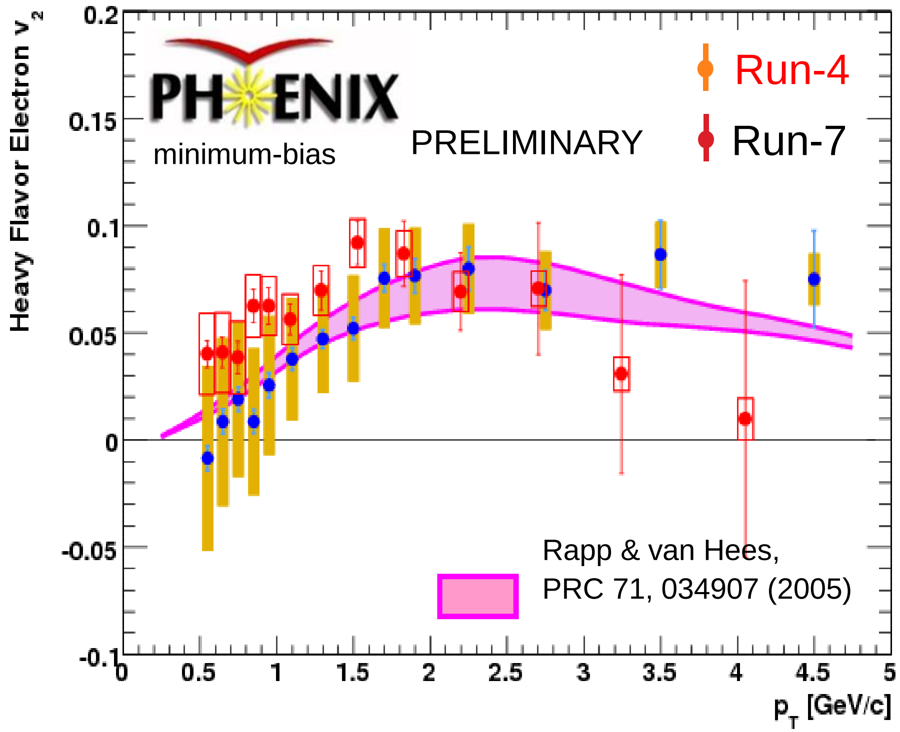
PHENIX VXT ~2 nb^{-1}



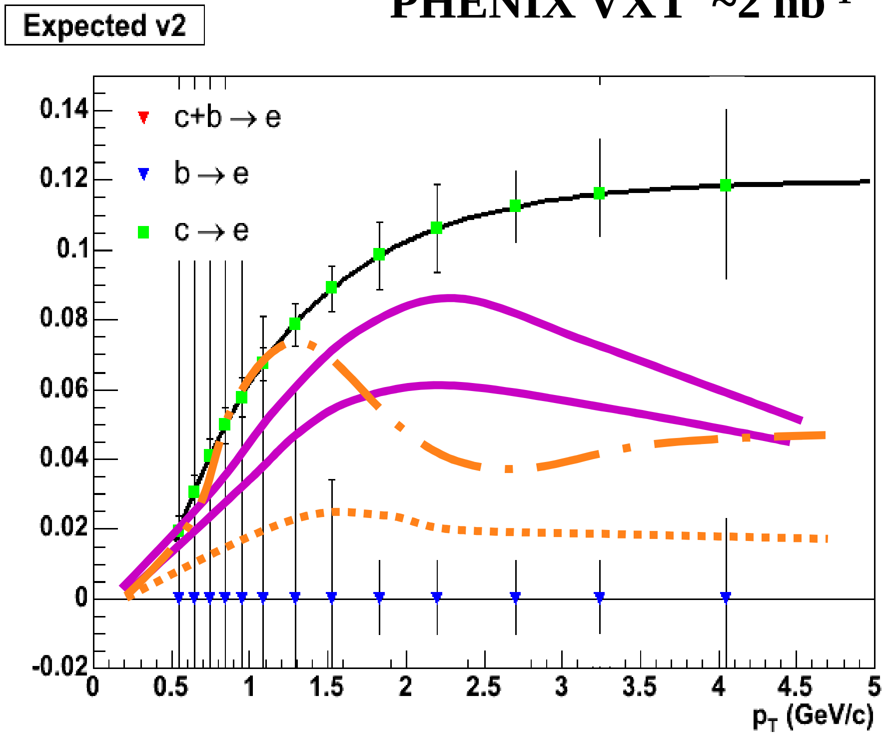
RHIC II increases statistics by factor >10

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

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



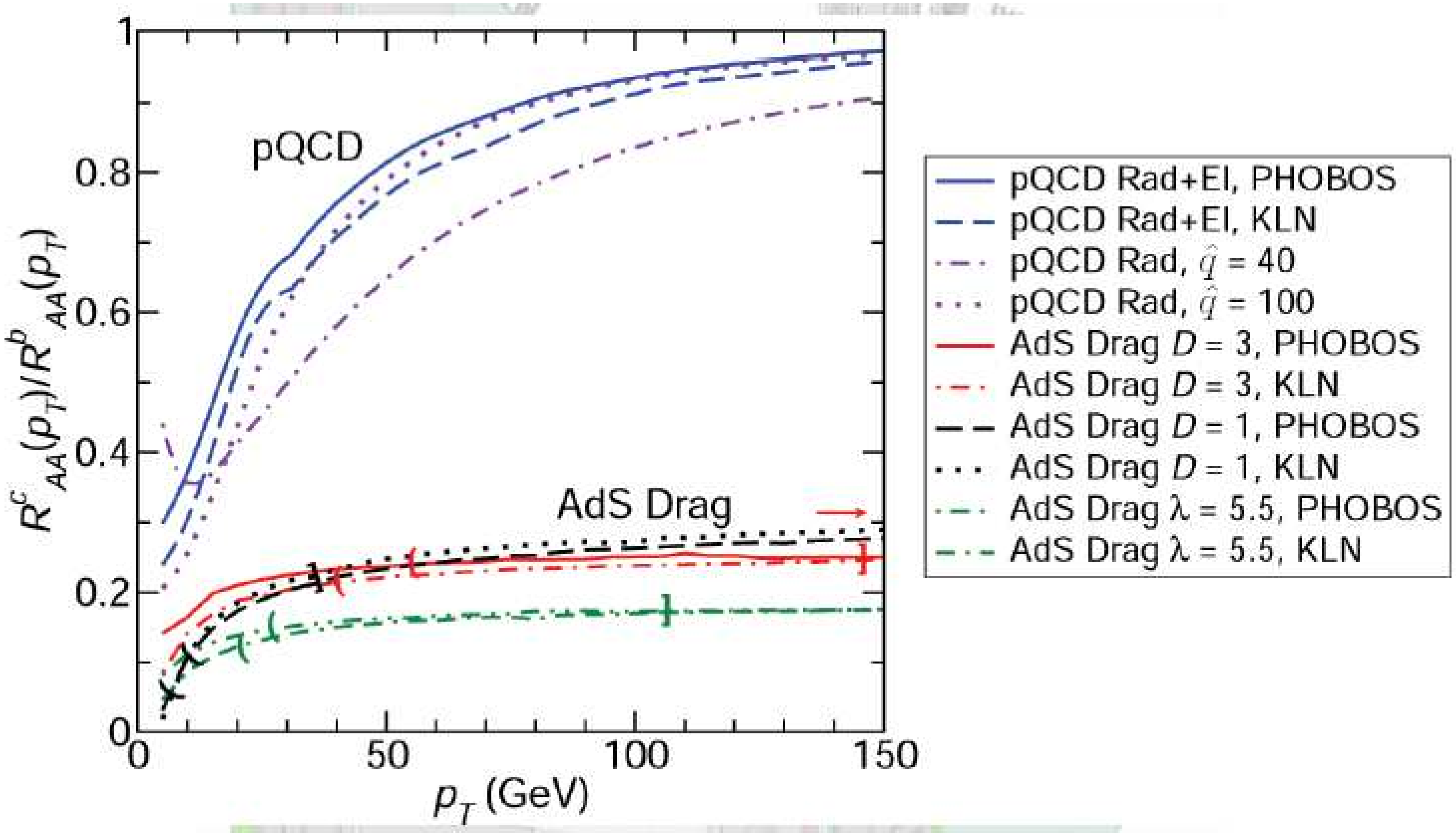
PHENIX VXT ~2 nb^{-1}



RHIC II increases statistics by factor >10

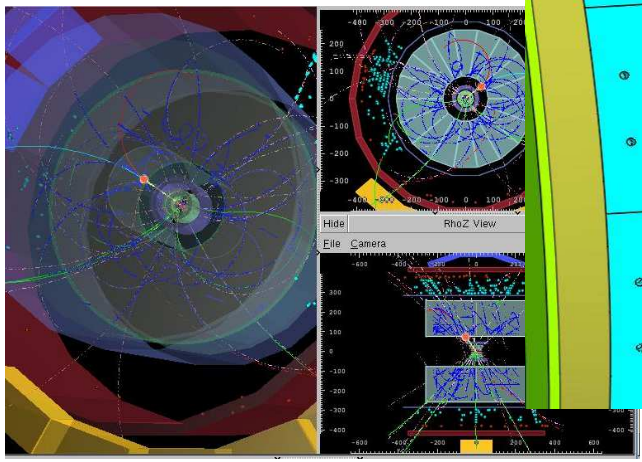
Decisive measurement of v_2 for both c and b

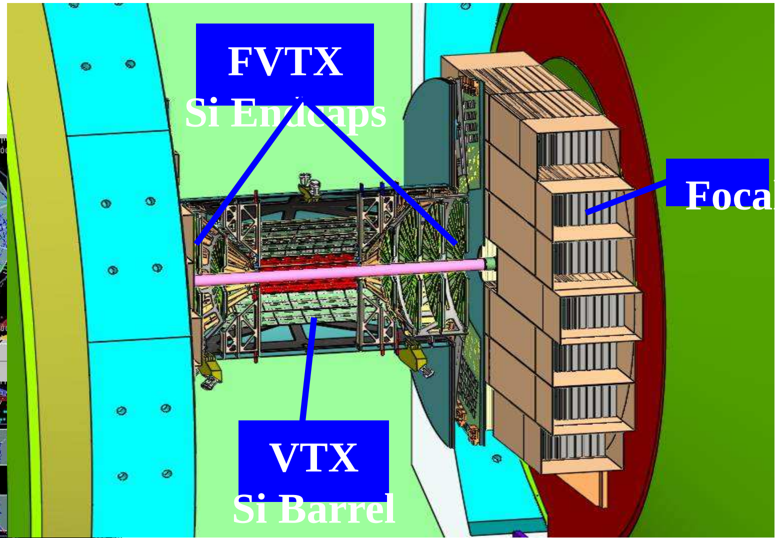
Importance of c/b Separation

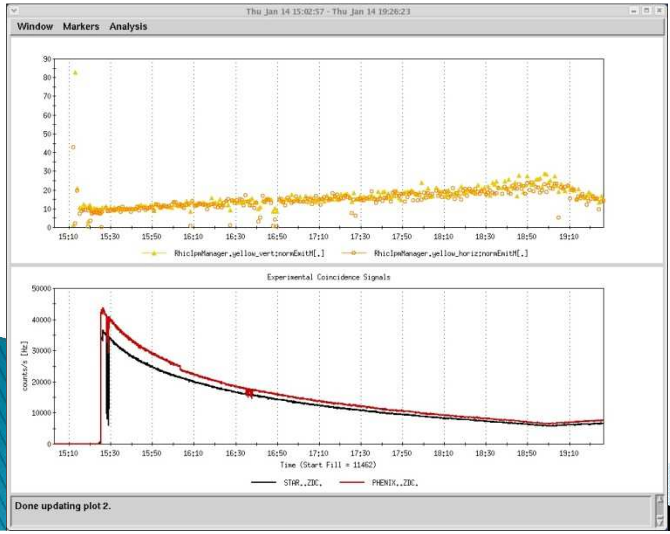


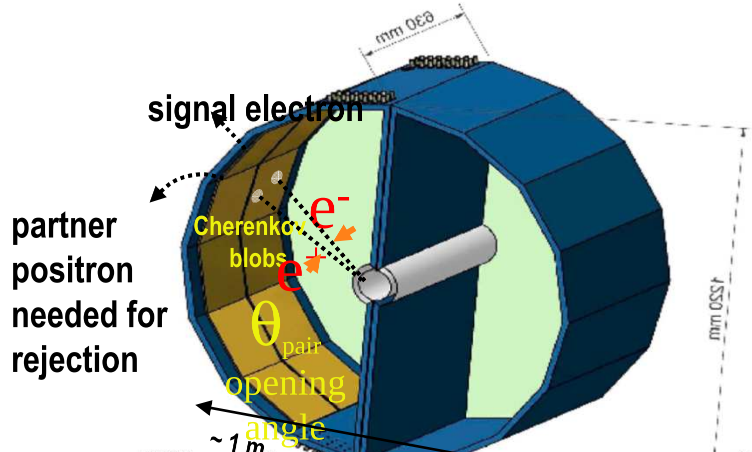
- Immovable Object – Irresistable Force Problem.
- I'm again rooting for the immovable object!

Future Looks Bright!







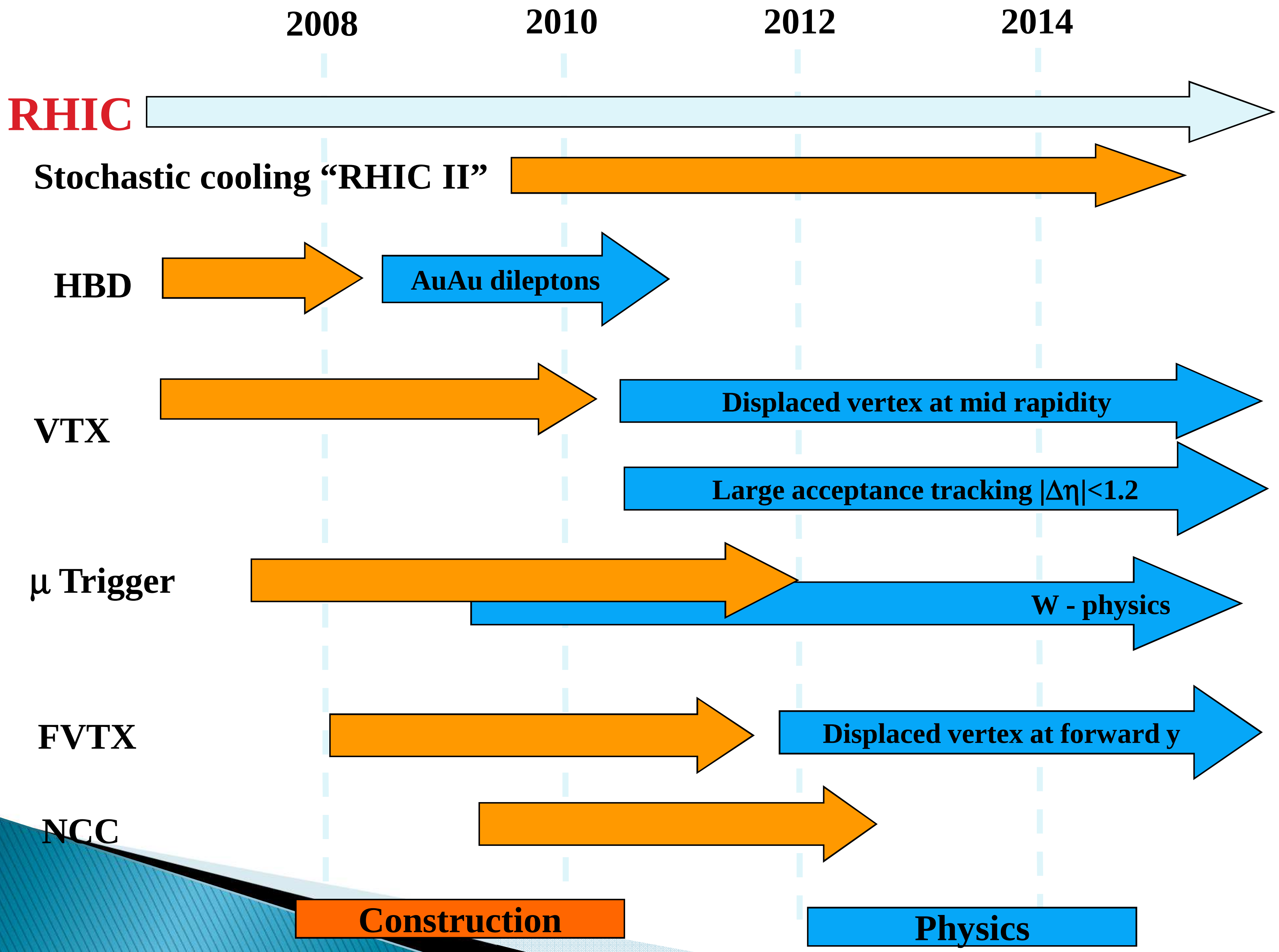


Summary

- 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.

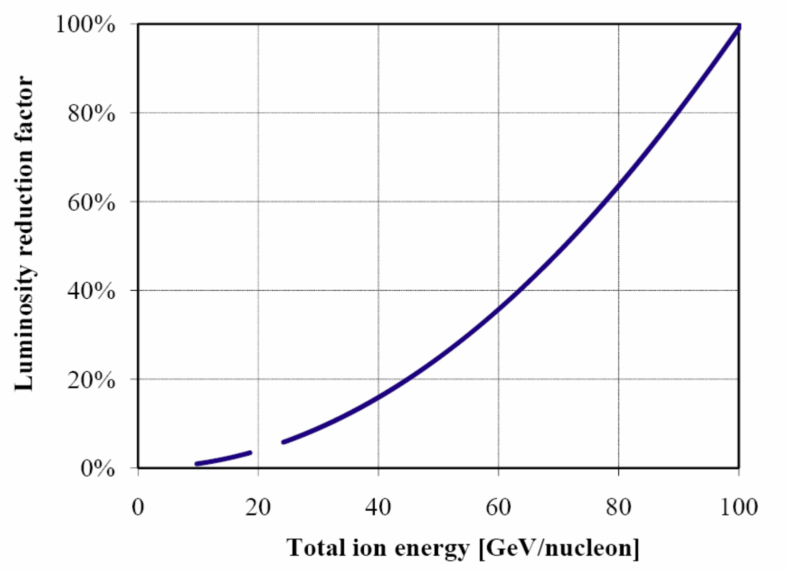
- Backups…

Timeline of PHENIX Upgrades



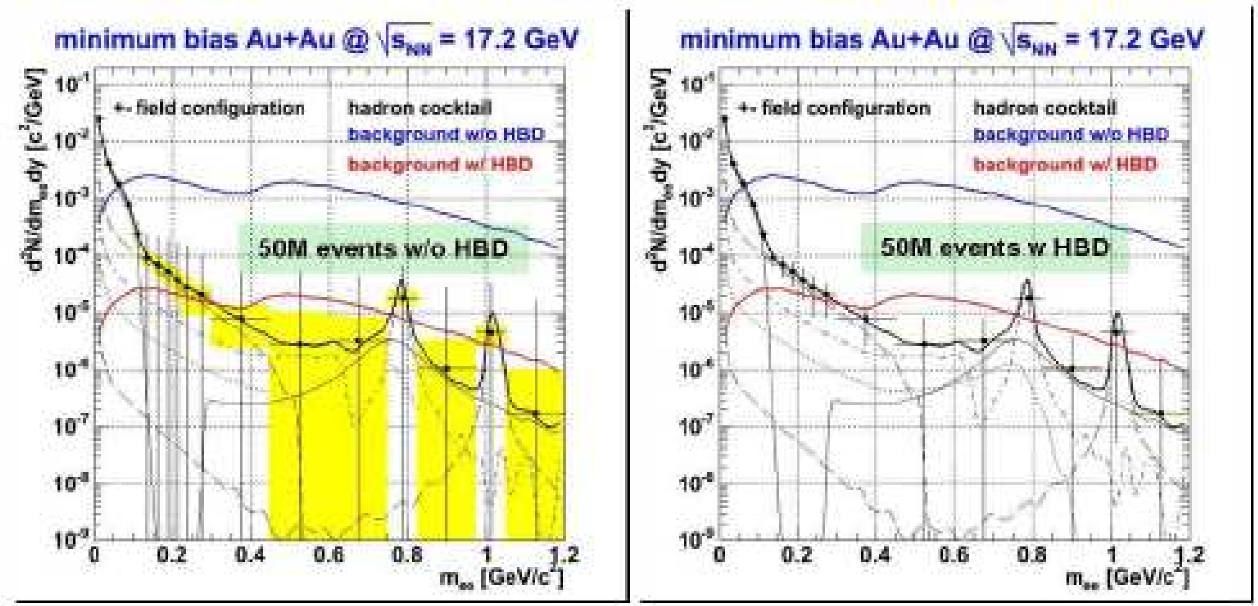
Examining these signatures at finite μ_B

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



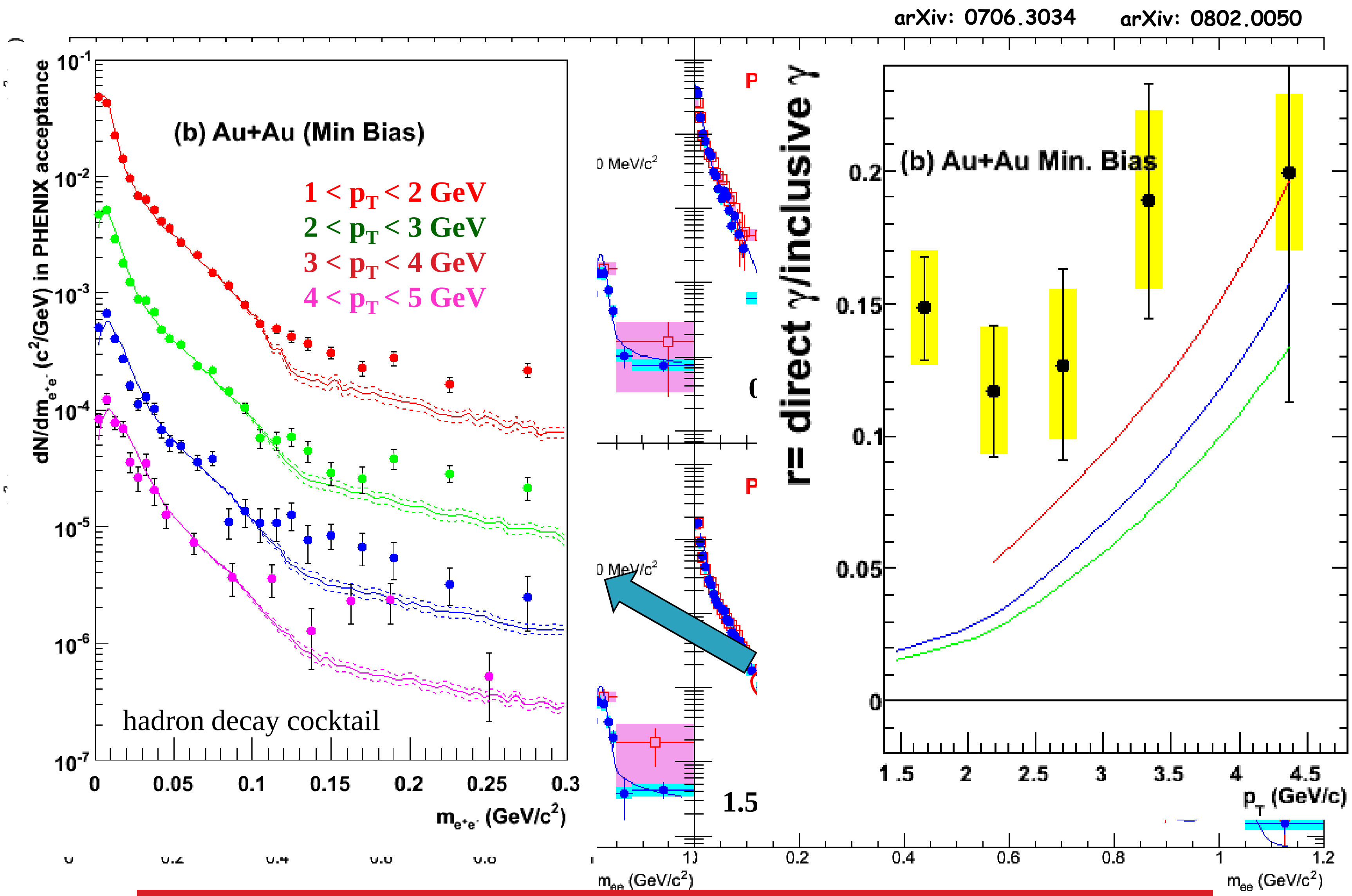
- Critical Point and the Onset of Deconfinement studies necessarily involve lowering the beam energy in the machine.
- Luminosity scales as the square of beam energy.
- Furthermore, heavy quarks suffer in production rate at lower energies.
- The product of these factors limits all present RHIC experiment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

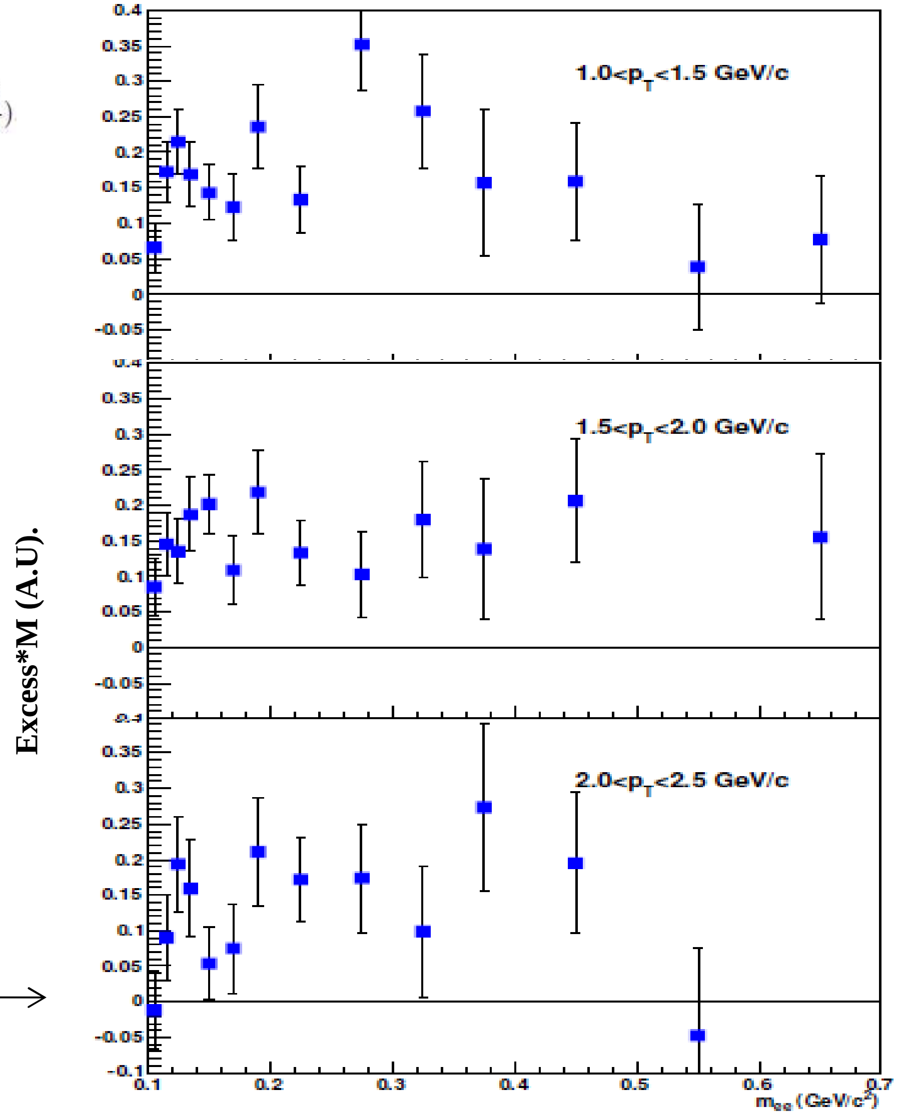
$$L(M) = \sqrt{1 - \frac{4m_l^2}{M^2}}\left(1 + \frac{2m_l^2}{M^2}\right)$$

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

Extrapolate real γ yield from dileptons:

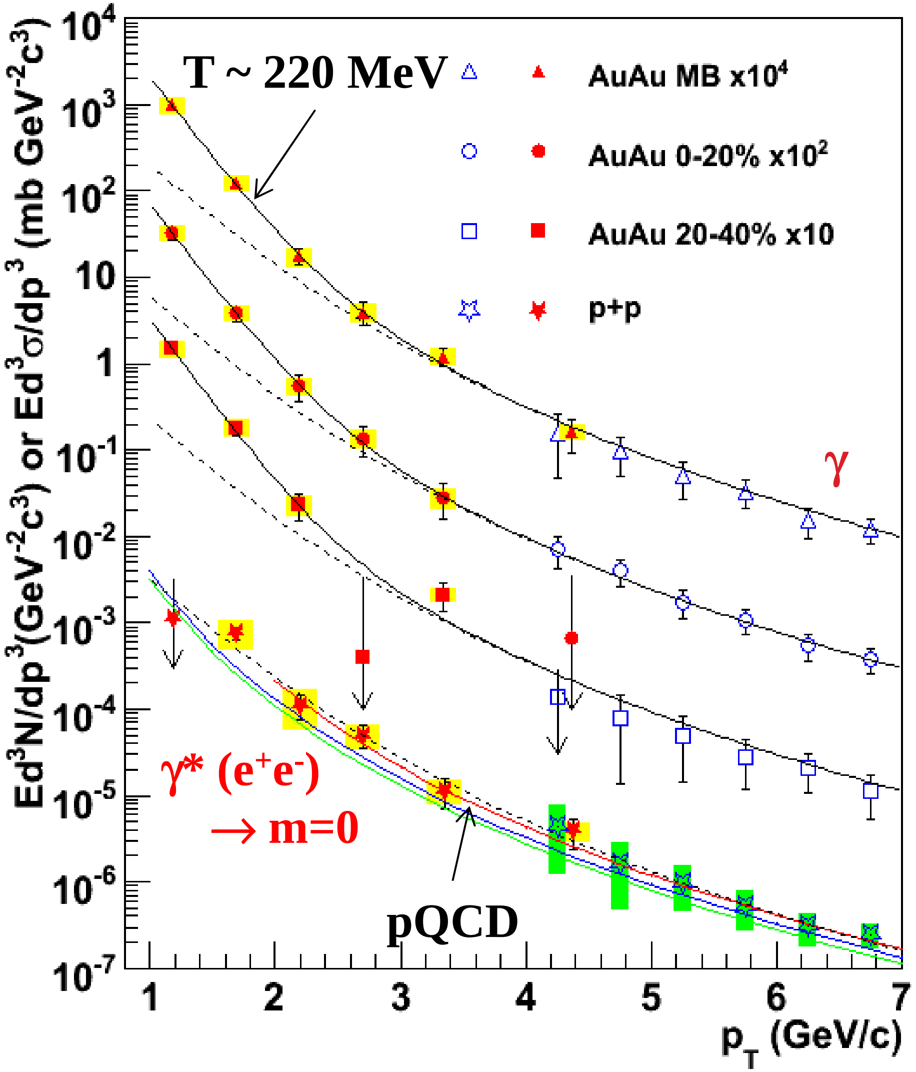
$$M \times \frac{dN_{ee}}{dM} \rightarrow \frac{dN_\gamma}{dM} \quad \text{for} \quad M \rightarrow 0$$

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

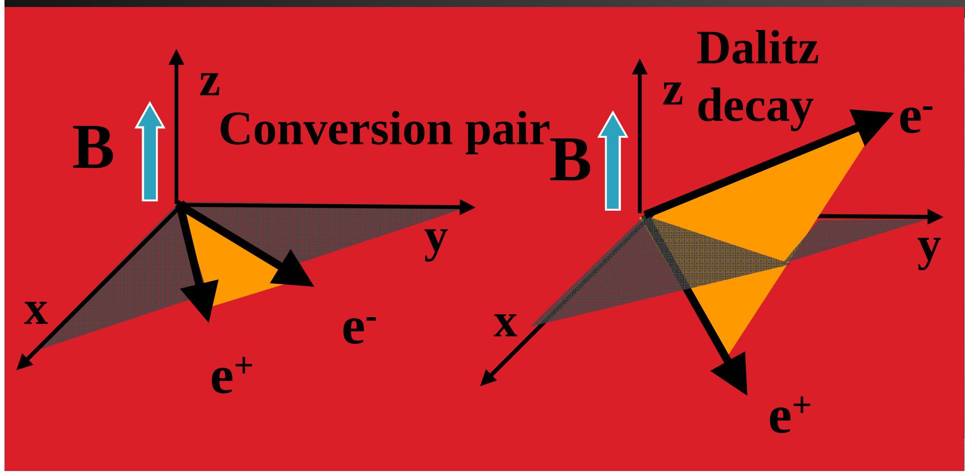
Direct photons from virtual photons:

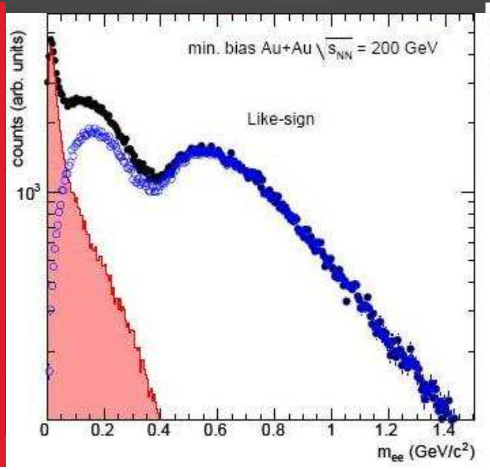
- Measure e^+e^- pairs at $m_\pi < m << p_T$
- Subtract η decays at S/B ~ 1:1
- Extrapolate to mass 0

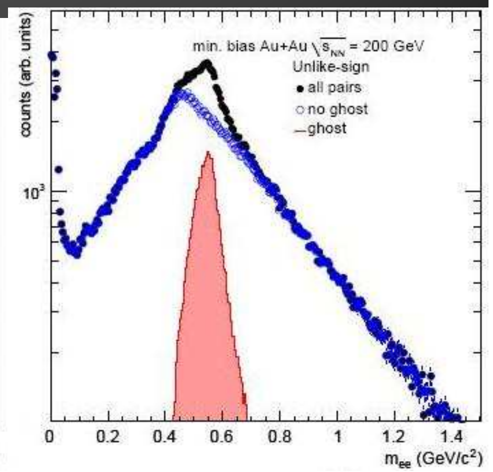
First thermal photon measurement:
T_{ini} > 220 MeV > T_C

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

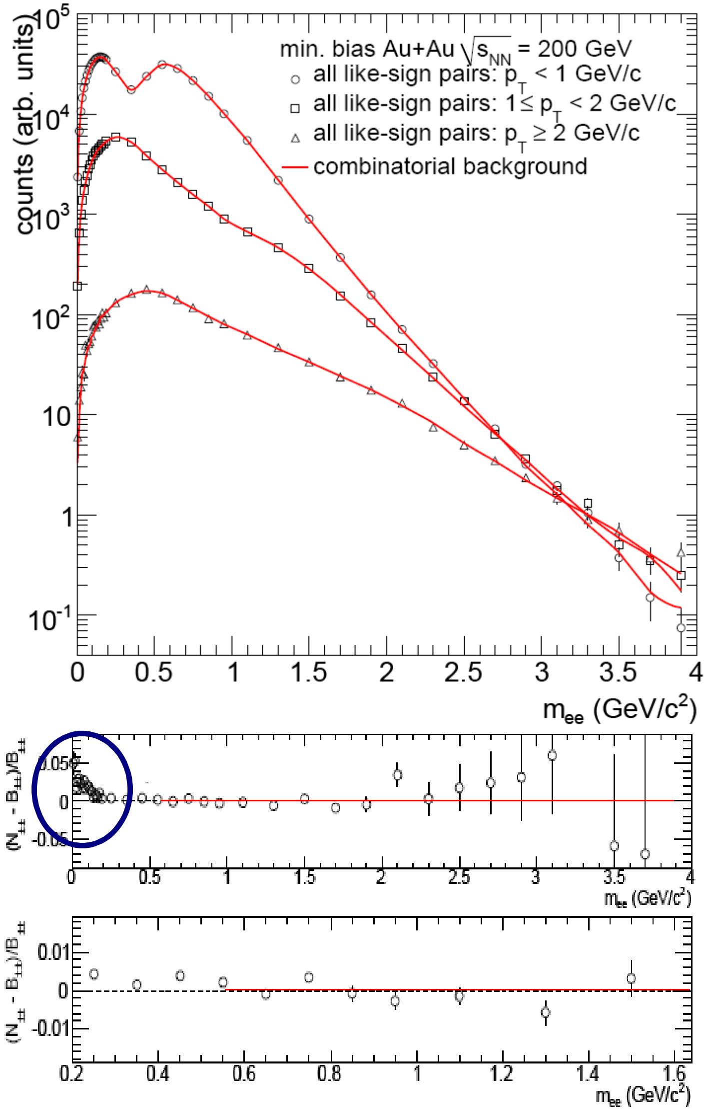






Combinatorial Background

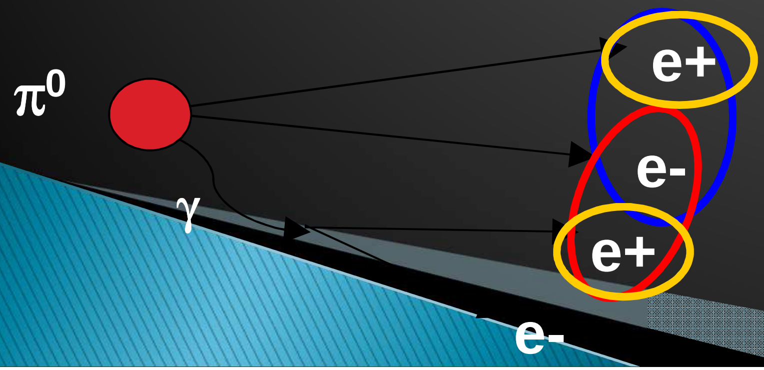
- Largest background in heavy ions
  - Large multiplicities
- Shape determined by event mixing
- Normalization determined using the like-sign pairs in regions where combinatorial dominates

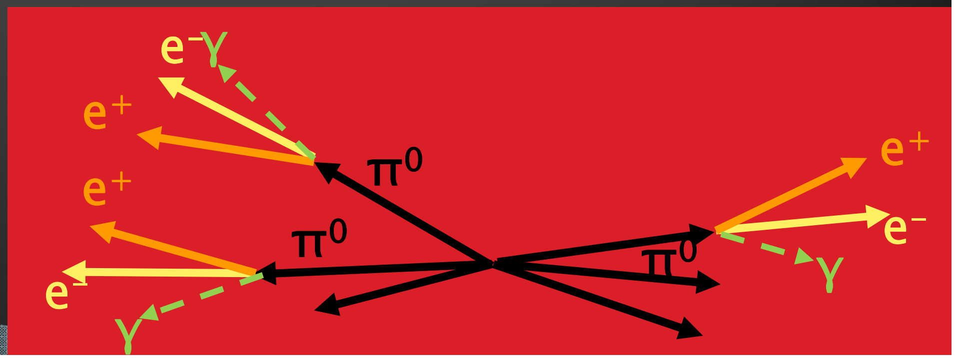


Correlated Background

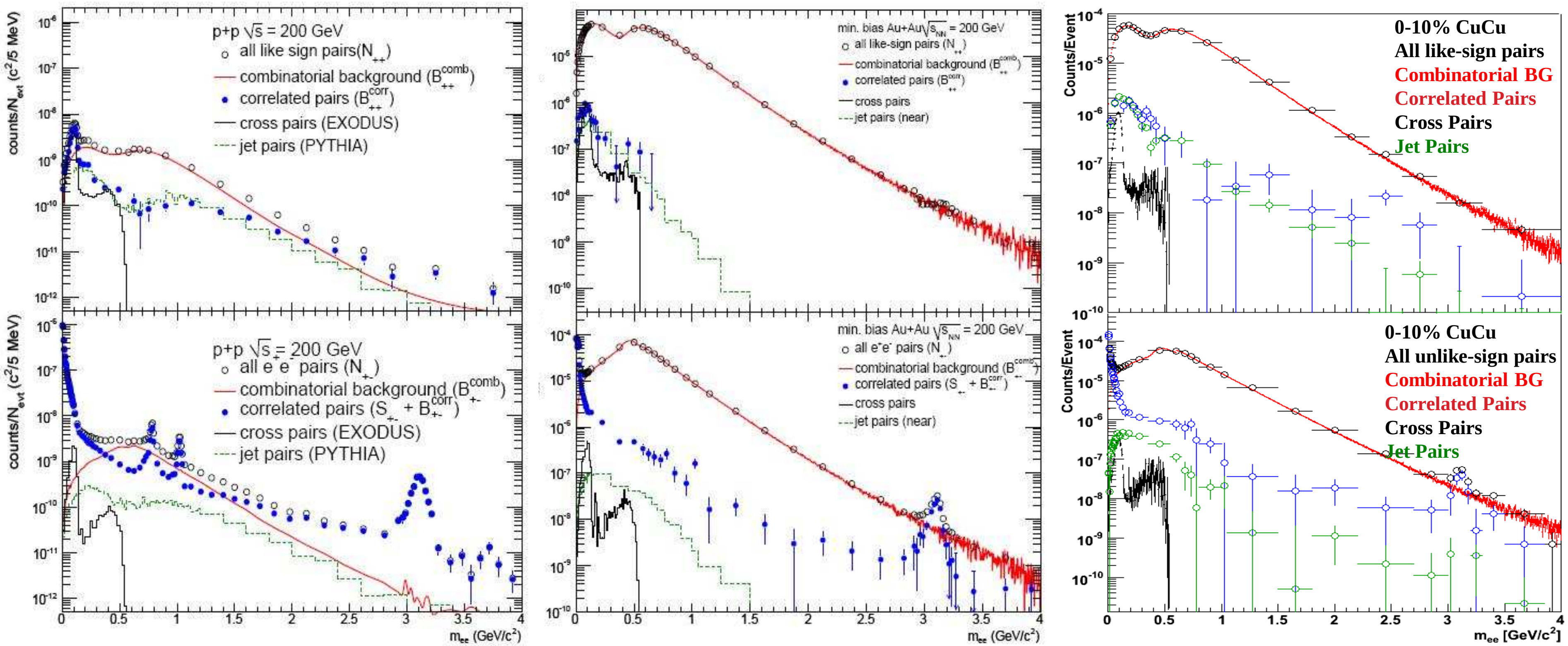
- "Cross" pairs
  - Decays that produce multiple lepton pairs
    - Double dalitz, double conversion, dalitz + conversion
    - Like-sign and unlike-sign pairs produced at same rate
  - Simulated with Exodus
    - Pions, etas only sizable source

- 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