Preface

- arXiv:arXiv:0706.3034 (50+ citations)
- PLB 670, 313 (2009) (31 citations)
- arXiv:0804.4168, accepted by PRL (50+ citations)
- arXiv:0912.0244, accepted by PRC

Viewpoint expected today!

- DiscoverMagazine *The Hottest Science Experiment on the Planet*
- NY Times *Scientists Briefly Break a Law of Nature*
- Newsday *Brookhaven Lab findings eye birth of the universe*
- Reuters UK *Hottest temperature ever heads science to Big Bang*
- Fox News *Measuring the Hottest Temperatures in the Universe*
- DailyMail *Scientists create hottest temperature since Big Bang*
- ABCNews *Hottest Temperature Ever Heads Science to Big Bang*
- ... And many more

Measuring the hottest Temperature in the Universe

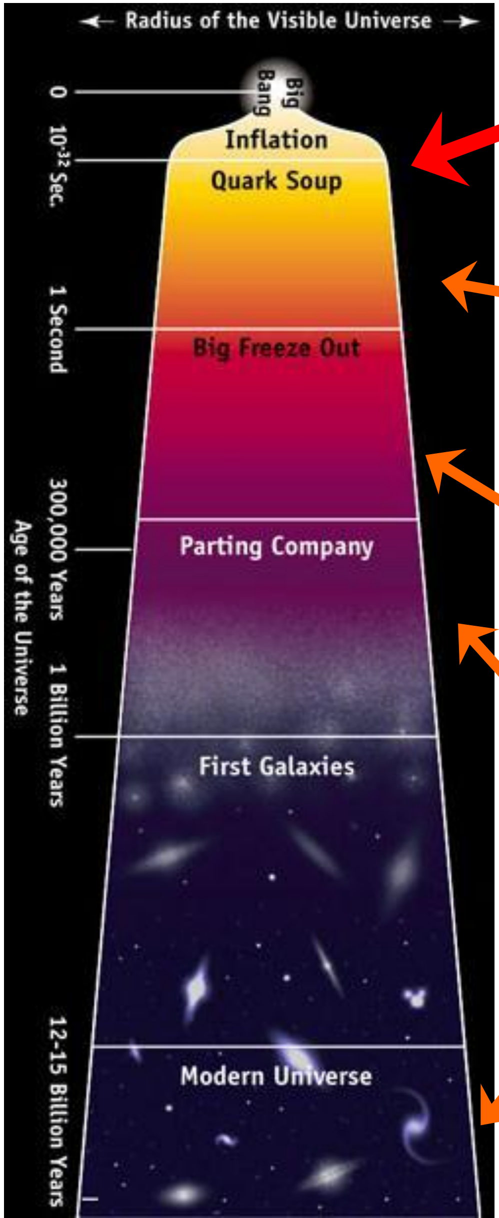
Electromagnetic Radiation from a Quark Gluon Plasma

Alberica Toia
CERN

Outline
- Understanding and Modelling **QCD** and its properties
- The experimental methods: **Relativistic Heavy Ion Collisions**
- The **golden probe** of Quark Gluon Plasma: **Electromagnetic Radiation**
  - Temperature of the matter
  - Medium modifications of EM spectral functions

ExtreMe Matter Institute EMMI Symposium on
Perspectives in Quark-Gluon Plasma Physics
March 29-30, 2010 GSI, Seminar Room Theory

Evolution of the Universe



Too hot for quarks to bind!!!

Standard Model (N/P) Physics

Quark-Gluon Plasma

Too hot for nuclei to bind

Nuclear/Particle (N/P) Physics

Hadron Gas

Nucleosynthesis builds nuclei up to He

Nuclear Force…Nuclear Physics

Universe too hot for electrons to bind

E-M…Atomic (Plasma) Physics

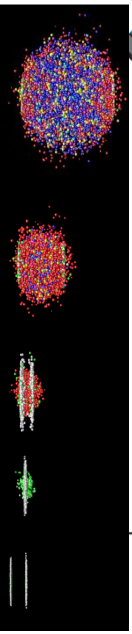
E/M Plasma

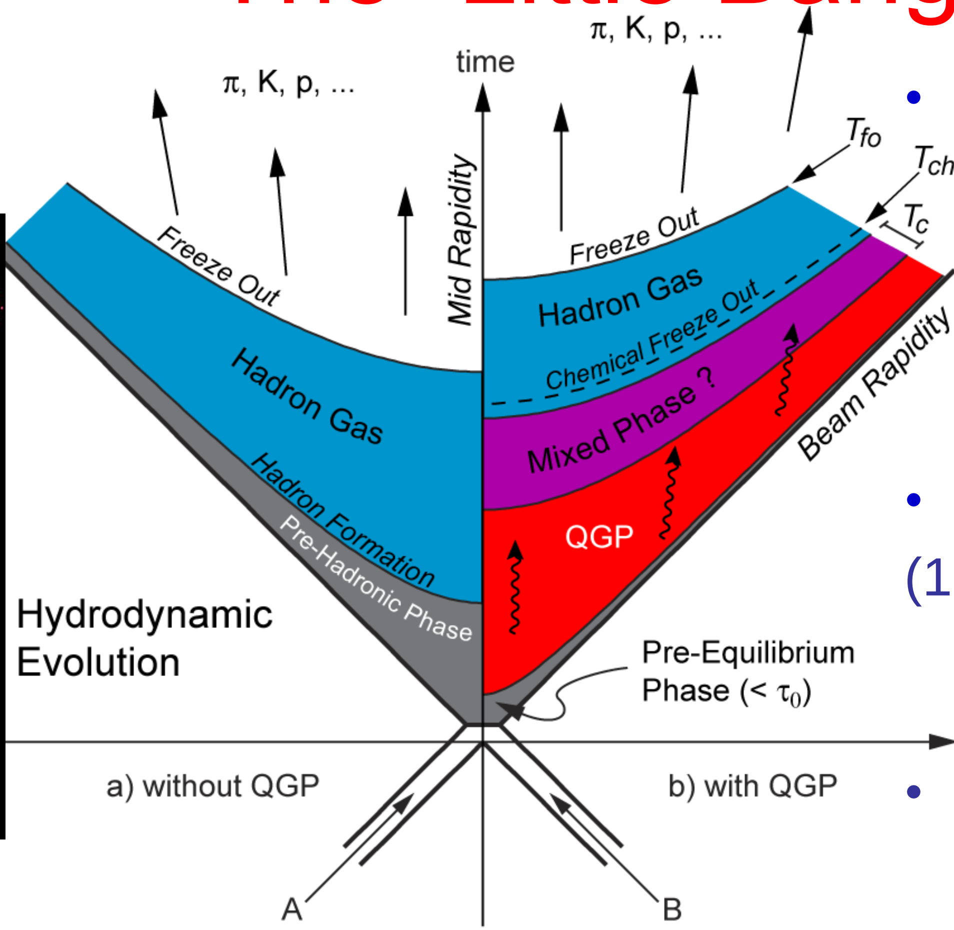
Today's Cold Universe

Gravity…Newtonian/General Relativity

Solid Liquid Gas

The "Little Bang" in the lab

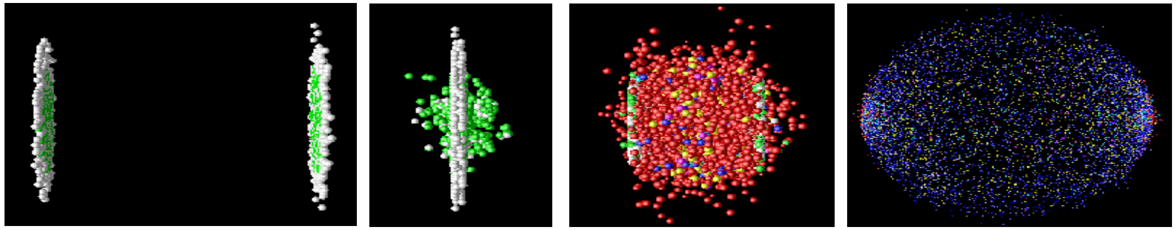




- High energy nucleus-nucleus collisions:
  - fixed target (SPS: √s=20GeV)
  - colliders
    - RHIC: √s=200GeV
    - LHC: √s=5.5TeV
- QGP formed in a tiny region (10^{-14}m) for very short time (10^{-23}s)
  - Existence of a mixed phase?
  - Later freeze-out
- Collision dynamics: different observables sensitive to different reaction stages

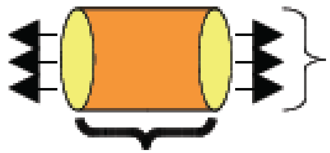
- **2 counter-circulating rings, 3.8 km circumference**
- **Top energies (each beam):**
  - **100 GeV/nucleon Au+Au.**
  - **250 GeV polarized p+p.**
  - **Mixed Species (e.g. d+Au)**

Energy density in heavy ion collisions



Energy density: "Bjorken estimate" (for a longitudinally expanding plasma):

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

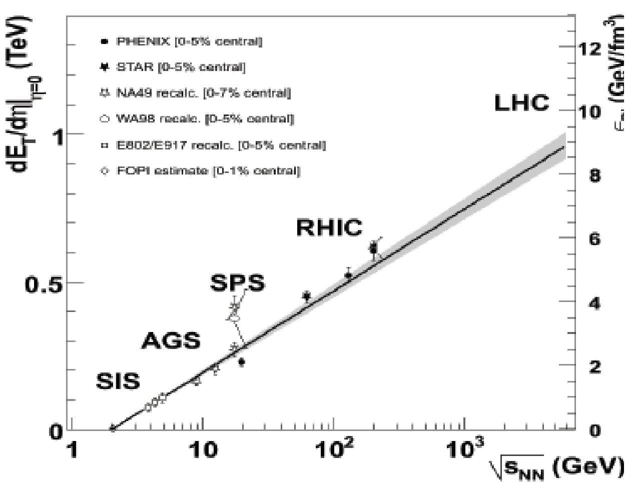


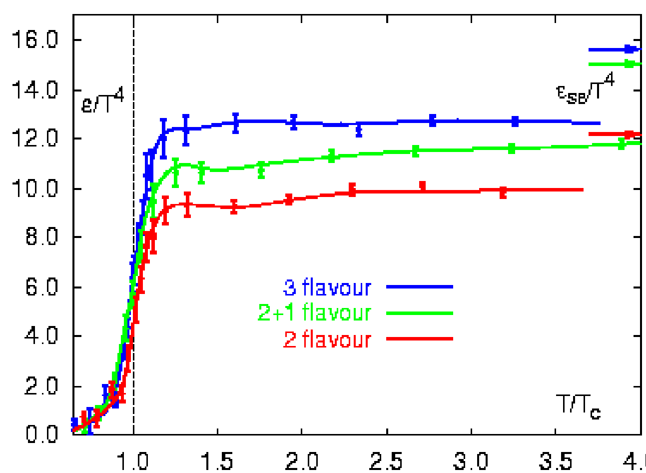
$\pi R^2 \sim 150\ \mathrm{fm}^2$

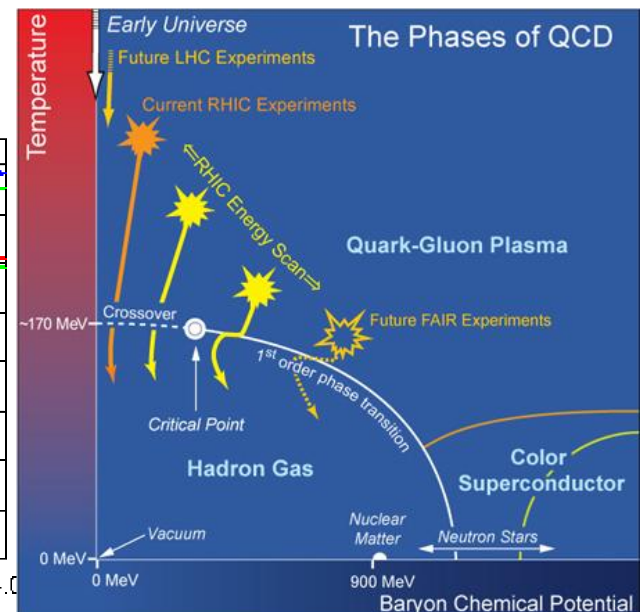
$\tau_0 \sim 1$ fm/c $> \tau_{cross} = 2R/\gamma \sim 0.15$ fm/c

- Large Transverse Energy
- Parton Energy Loss
- Parton Elliptic Flow

$\boxed{\varepsilon_{init} \sim 15\ \mathrm{GeV/fm^3} > \varepsilon_c}$

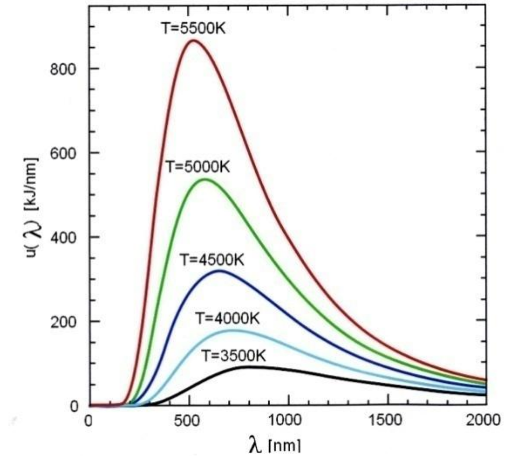


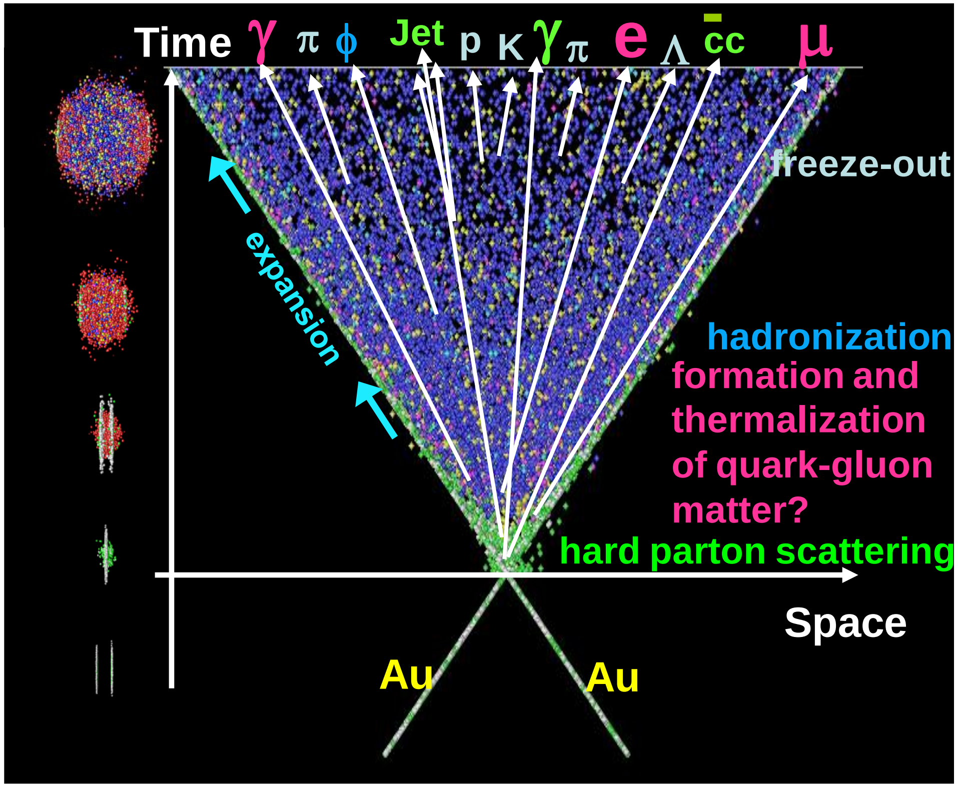


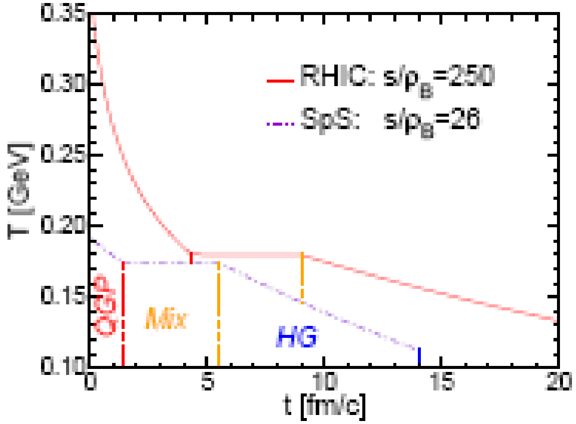


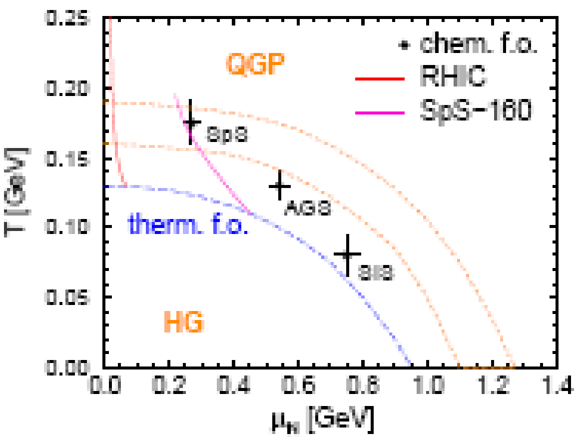
Electromagnetic Radiation

- Thermal black body radiation (γ, $\gamma^* \rightarrow e+e-$)
  - Hot matter emits thermal radiation
  - Temperature can be measured from emission spectrum
- No strong final state interaction
  - Leave reaction volume undisturbed and reach detector
- Emitted at **all stages** of the space time development
  - Information must be deconvoluted

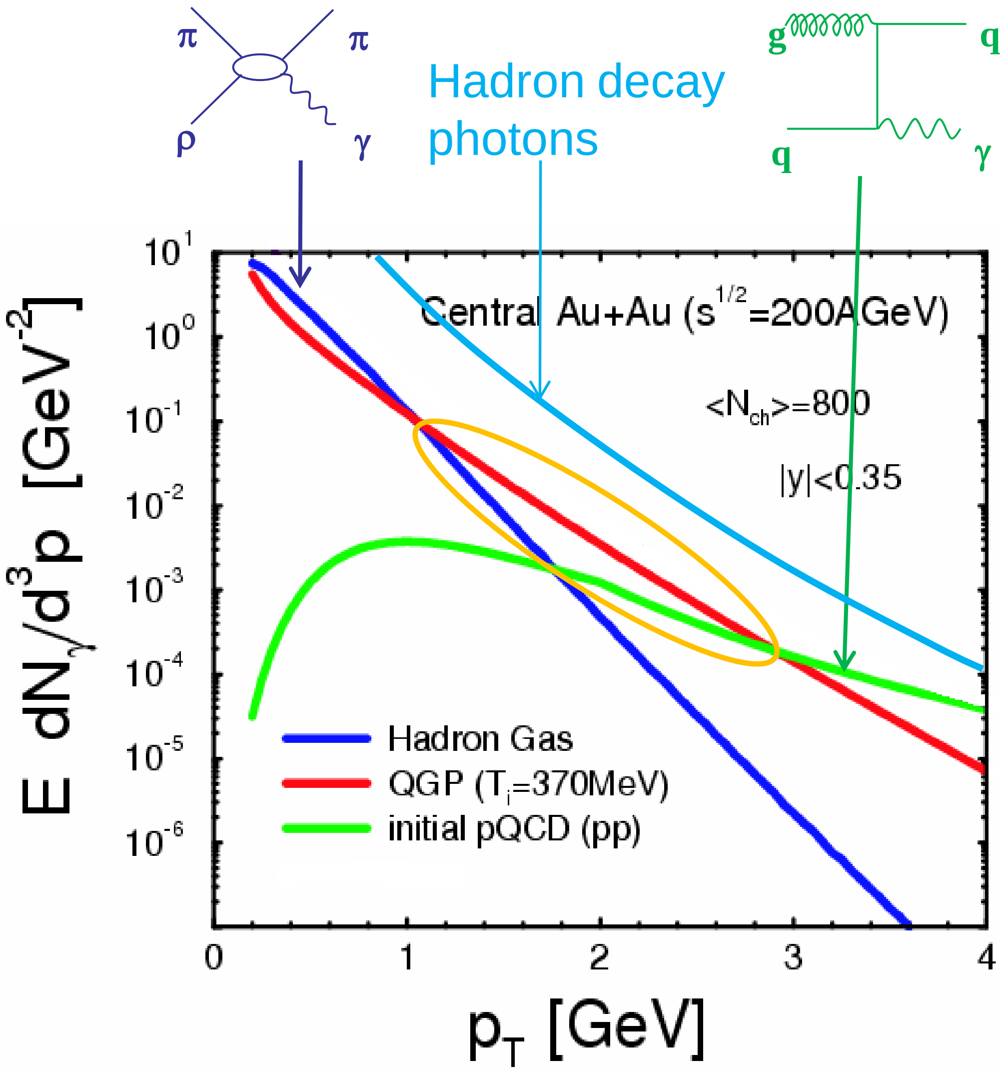








Thermal photons (theory prediction)

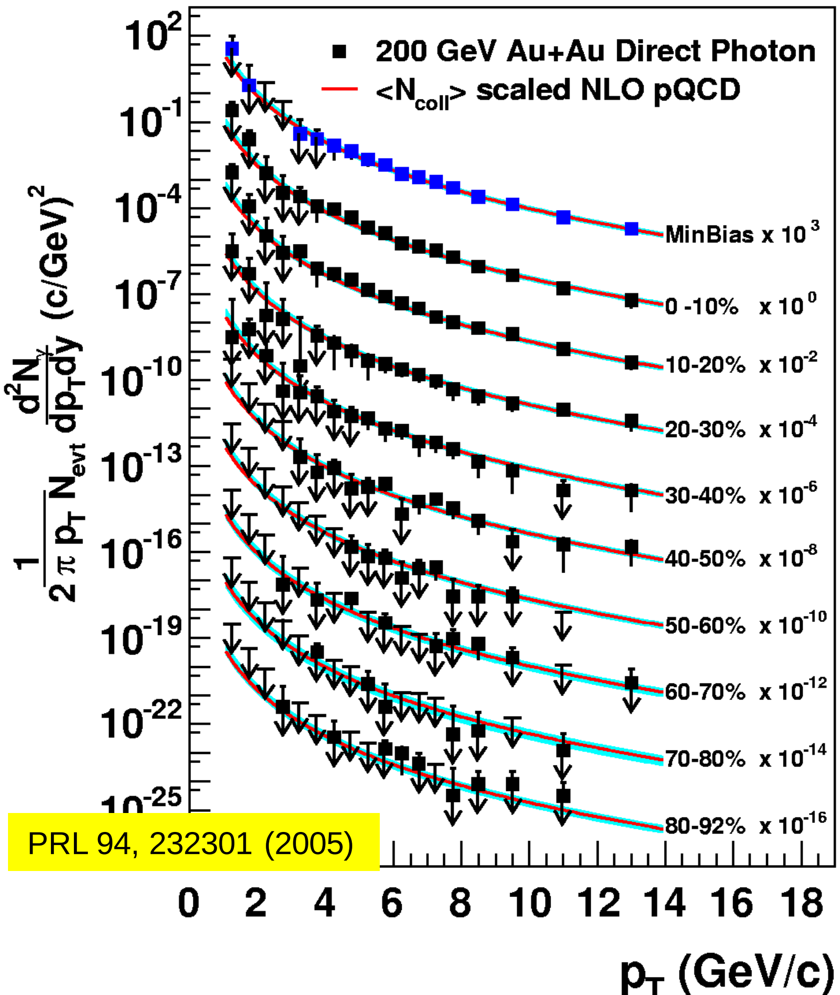


S.Turbide *et al* PRC 69 014903

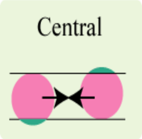
- High p_T (p_T>3 GeV/c) pQCD photon
- Low p_T (p_T<1 GeV/c) photons from hadronic Gas
- Themal photons from QGP is the dominant source of direct photons for 1<p_T<3 GeV/c
- Recently, other sources, such as jet-medium interaction are discussed
- Measurement is difficult since the expected signal is only 1/10 of photons from hadron decays

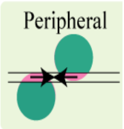
Direct Photons in Au+Au

Blue line: N_{coll} scaled p+p cross-section



PRL 94, 232301 (2005)

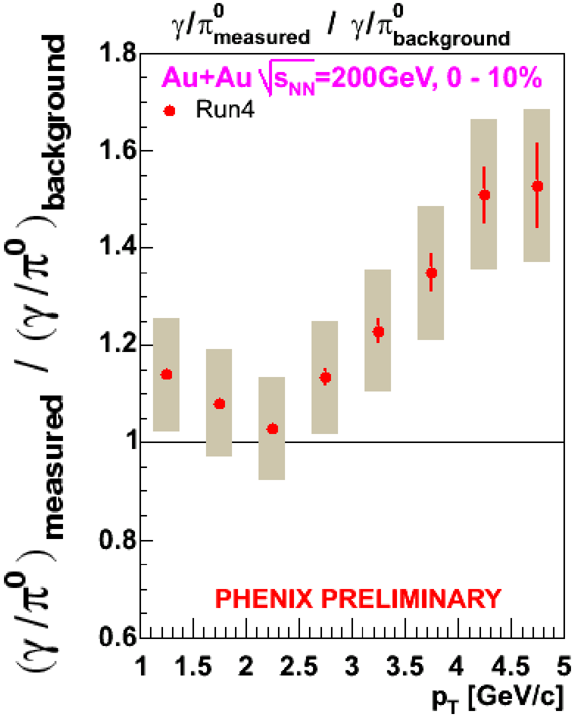


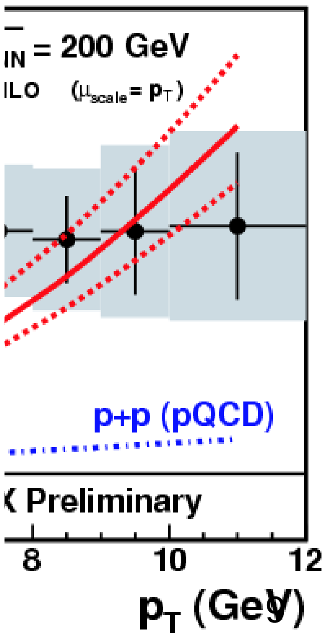


Au+Au data consistent with pQCD calculation scaled by N_{coll}

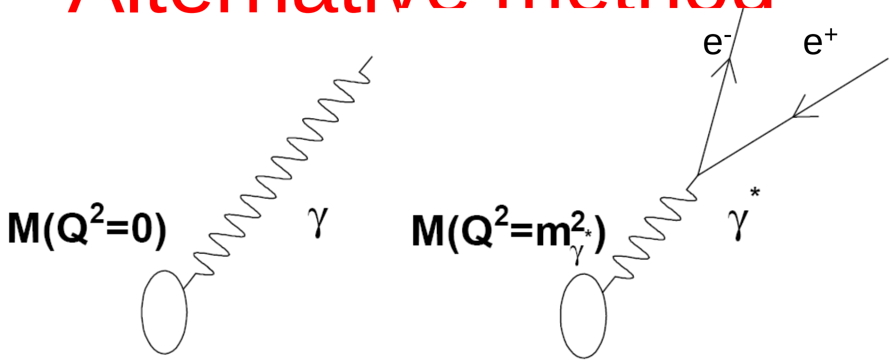
Direct photon is measured as "excess" above hadron decay photons

Measurement below p_T<3 GeV/c is difficult since the yield of thermal photons is only 1/10 of that of hadron decay photons





Alternative method --- measure virtual photons

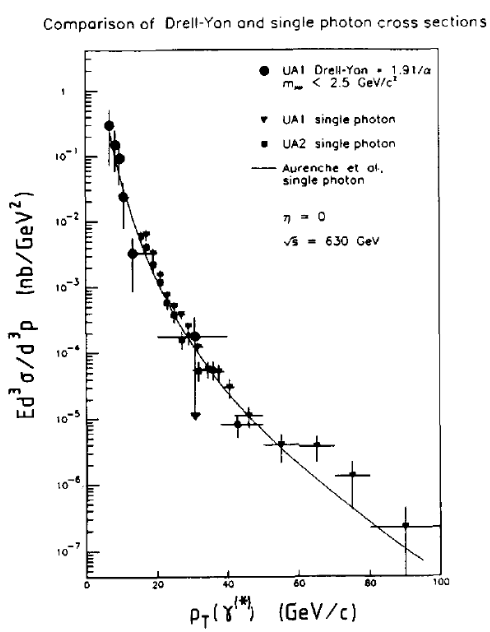


- Source of real photon should also be able to emit virtual photon
- At m→0, the yield of virtual photons is the same as real photon

→ Real photon yield can be measured from virtual photon yield, which is observed as low mass e^+e^- pairs

- Advantage:
  - Reduce hadron decay background For $m>m_\pi$, ~80% of background removed
  - photon ID, energy resolution, etc
- Disadvantage
  - Reduce the yield (~ $\alpha/3\pi$ ~ 1/1000)

- This method is first tried at CERN ISR in search for direct photon in p+p at $s^{1/2}$=55GeV. They measure e^+e^- pairs for 200<m<500 MeV, and set one of the most stringent limit on direct photon production at low p_T
- Later, UA1 measured low mass muon pairs and deduced the direct photon cross section.



What we can learn from lepton pair emission

arXiv:0912.0244

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

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

$\gamma^* \rightarrow ee$ decay

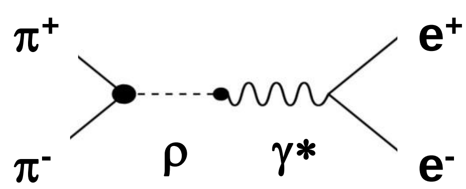
EM correlator
Medium property

Boltzmann factor
temperature

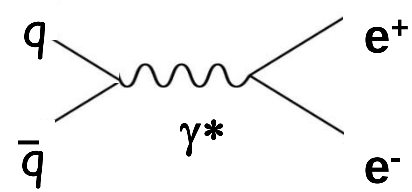
Hadronic contribution
Vector Meson Dominance

Medium modification of meson
Chiral restoration

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V(M) \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right)N_c\sum_{q=u,d,s}(e_q)^2 \end{cases}$$



qq annihilation



Thermal radiation from partonic phase (QGP)

From emission rate of dilepton, the medium effect on the EM correlator as well as temperature of the medium can be decoded.

Relation between dilepton and virtual photon

arXiv:0912.0244

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

Emission rate of (virtual) photon per volume

$$q_0\frac{dR_{\gamma^*}}{d^3q} = -\frac{\alpha}{2\pi^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T).$$

Relation between them

Prob. $\gamma^* \rightarrow l^+l^-$

$$\underbrace{q_0\frac{dR_{ll}}{dM^2d^3q}}_{\text{Dilepton}} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}\underbrace{q_0\frac{dR_{\gamma^*}}{d^3q}}_{\text{virtual photon}}$$

This relation holds for the yield after space-time integral

Virtual photon emission rate can be determined from dilepton emission rate

$$q_0\frac{dn_{\gamma^*}}{d^3q} \simeq \frac{3\pi}{\alpha}M^2 q_0\frac{dn_{ll}}{d^3q\,dM^2} = \frac{3\pi}{2\alpha}M q_0\frac{dn_{ll}}{d^3q\,dM}.$$

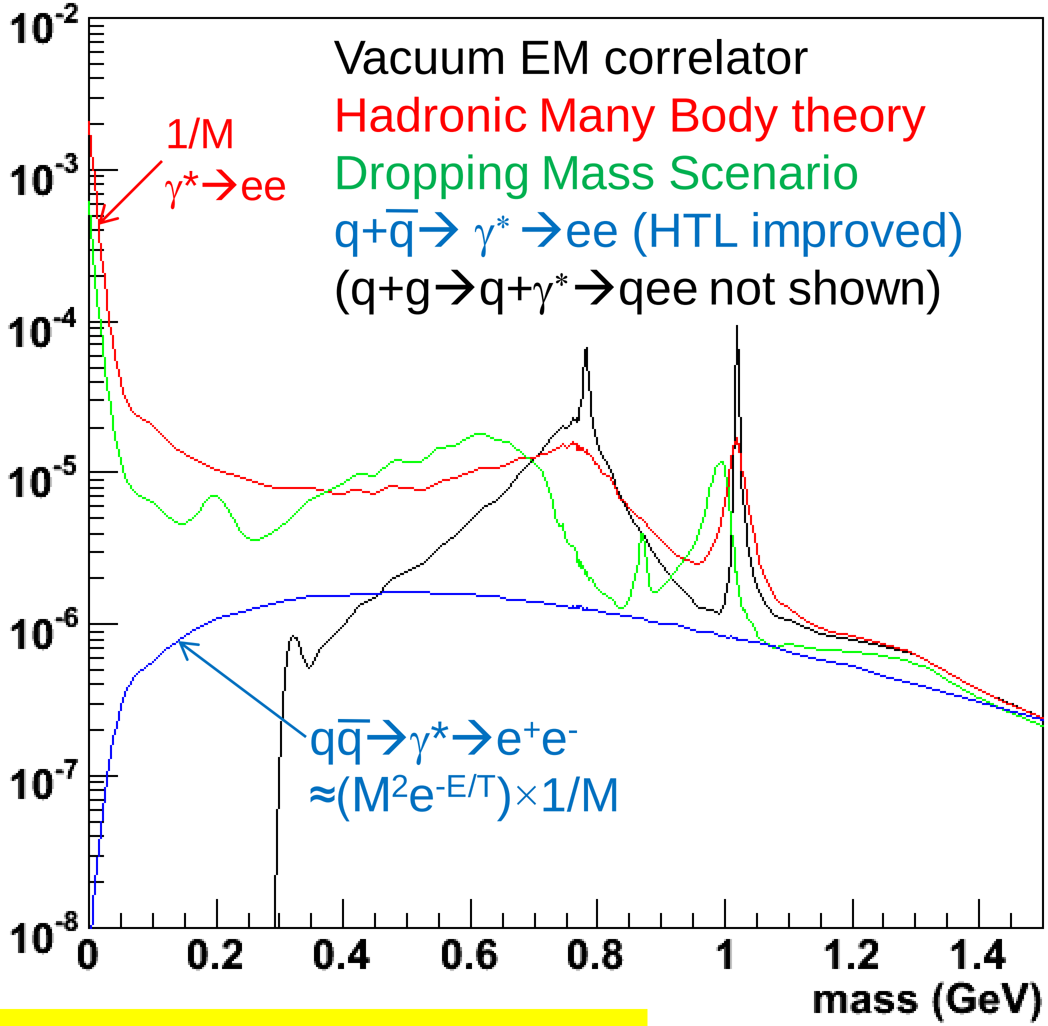
M $\times dN_{ee}/dM$ gives virtual photon yield

For M→0, n_{γ}* → n_{γ}(real); real photon emission rate can also be determined

Theory prediction of dilepton emission

arXiv:0912.0244

$\frac{dN_{ee}}{p_t dp_t dM dy}$ at y=0, p_T=1.025 GeV/c



Usually the dilepton emission is measured and compared as $dN/dp_T dM$

The mass spectrum at low p_T is distorted by the virtual photon→ee decay factor 1/M, which causes a steep rise near M=0

qq annihilaiton contribution is negligible in the low mass region due to the M^2 factor of the EM correlator

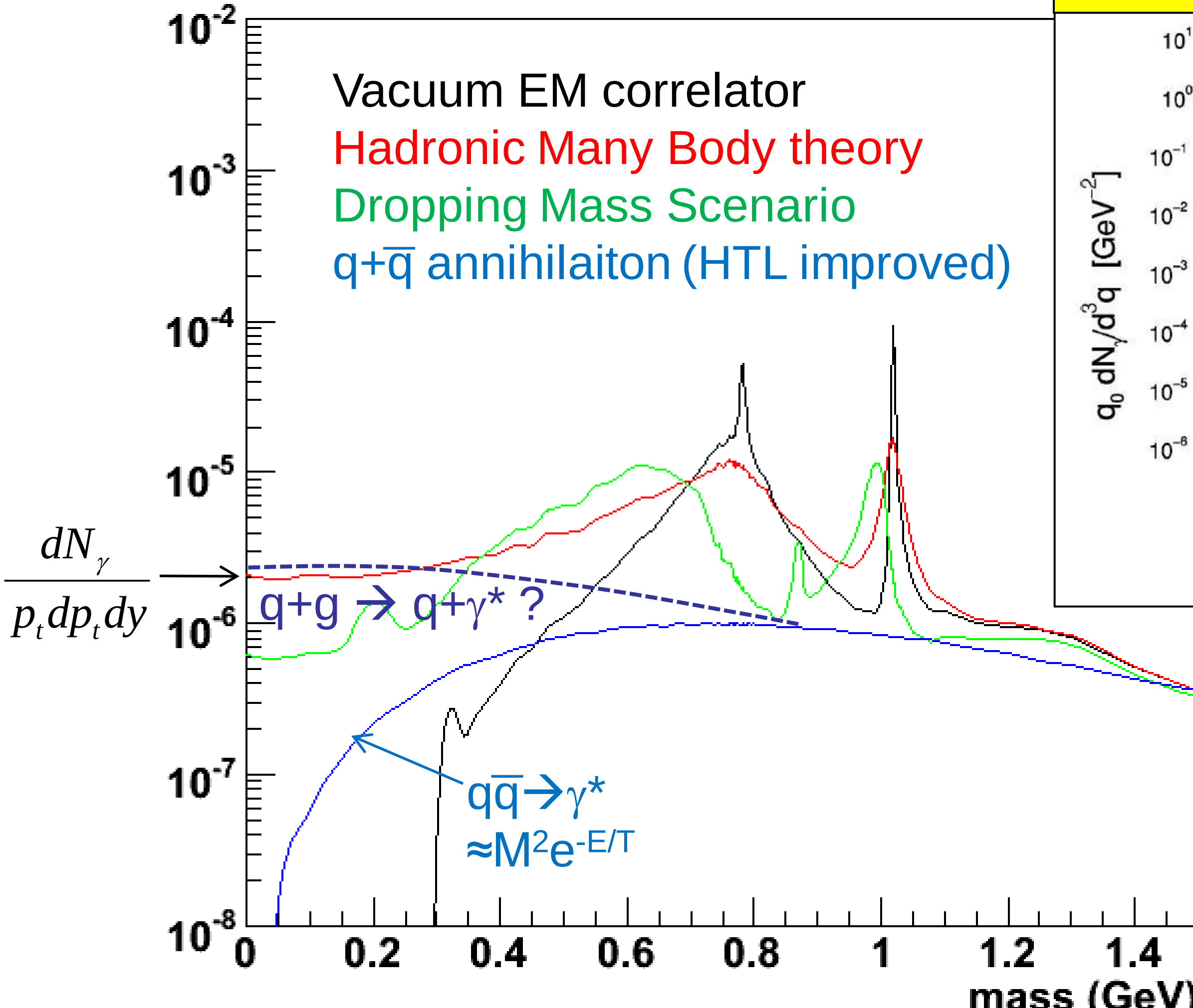
In the caluculation, partonic photon emission process $q+g \rightarrow q+\gamma^* \rightarrow qe^+e^-$ is not included

Theory calculation by Ralf Rapp

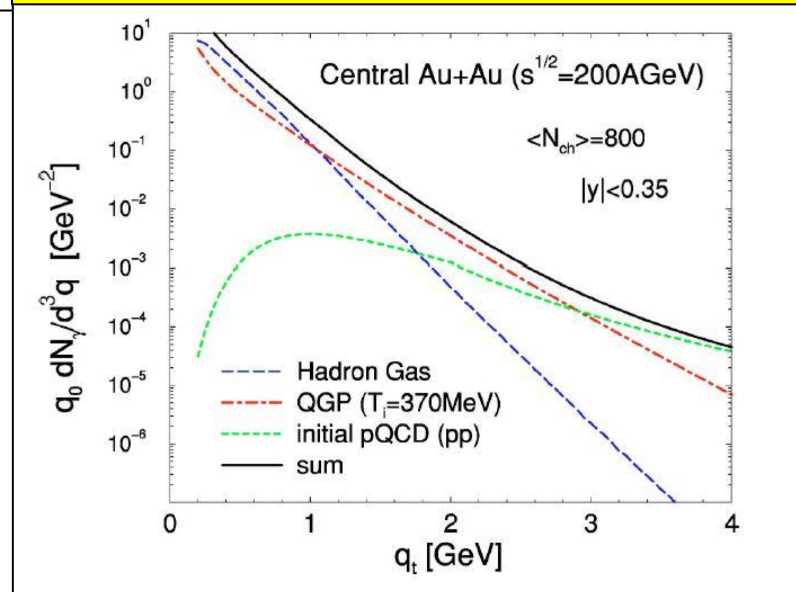
Virtual photon emission rate

arXiv:0912.0244

$$M \times \frac{dN_{ee}}{p_t dp_t dM dy} \propto \frac{dN_{\gamma^*}}{p_t dp_t dy}$$ at y=0, p_T=1.025 GeV/c



Real photon yield
Turbide, Rapp, Gale PRC69,014903(2004)



When extrapolated to M=0, the real photon emission rate is determined.

q+g→q+γ* is not shown; it should be similar size as HMBT at this p_T

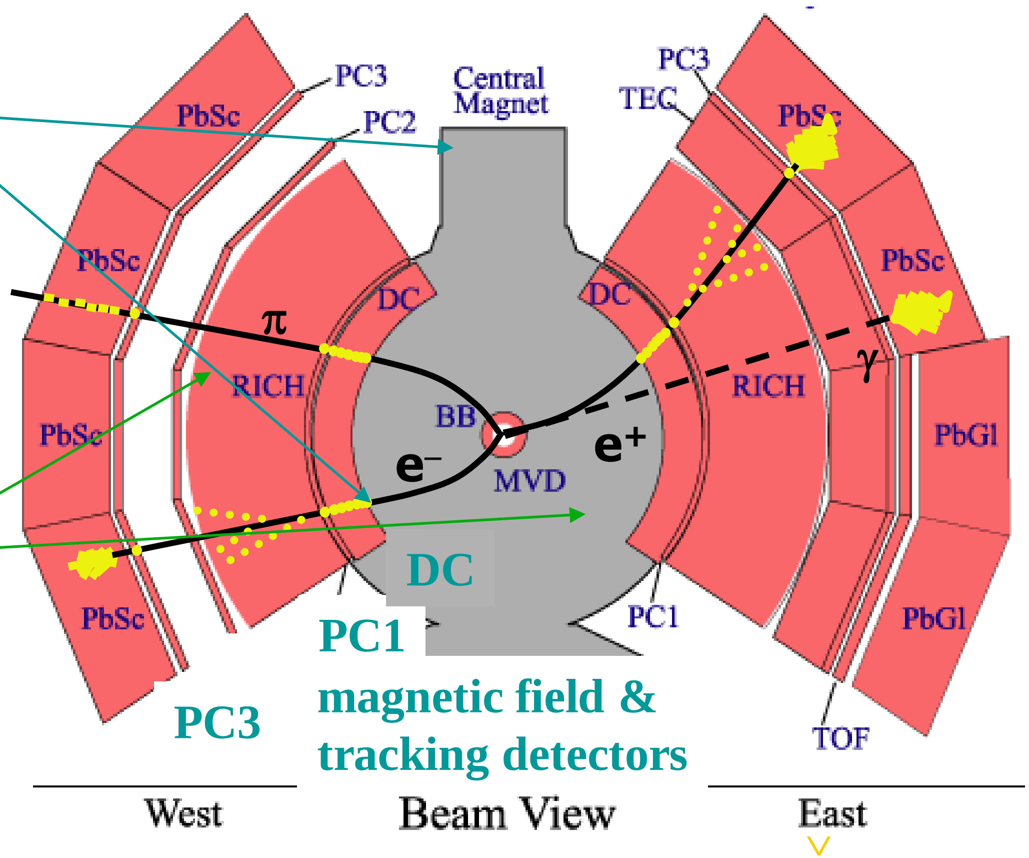
PHENIX Physics Capabilities

designed to measure rare probes:

Au+Au & p+p spin

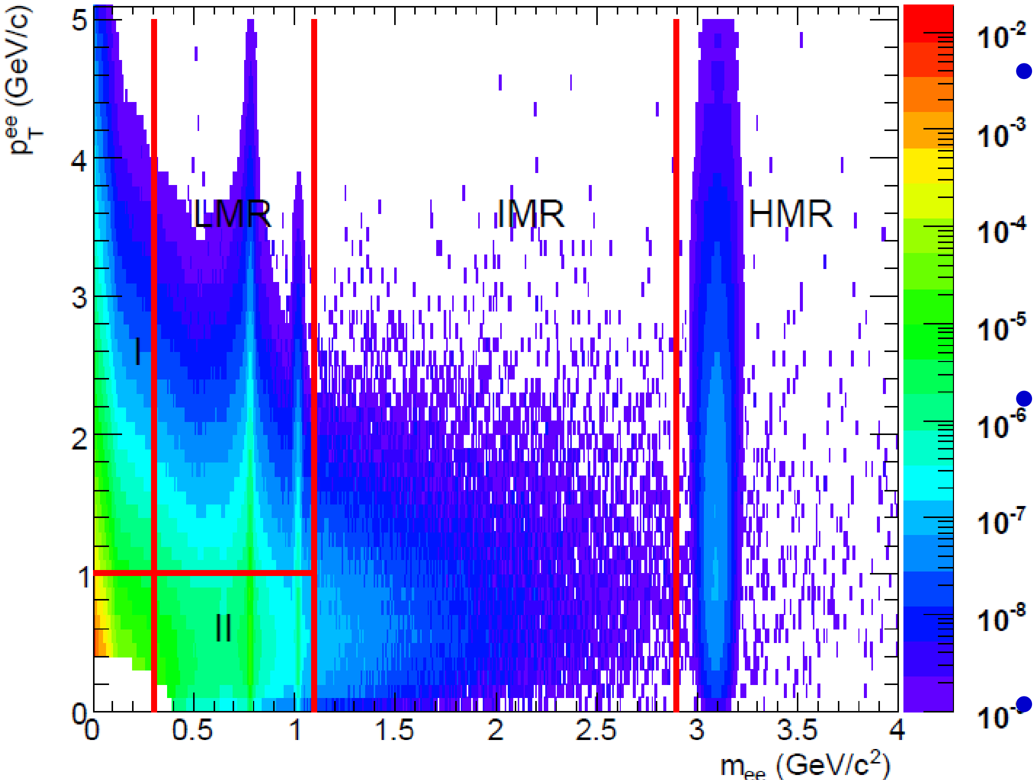
+ high rate capability & granularity
+ good mass resolution and particle ID
- limited acceptance

- 2 central arms:
  electrons, photons, hadrons
  - charmonium $J/\psi, \psi' \rightarrow e^+e^-$
  - vector meson $\rho, \omega, \phi \rightarrow e^+e^-$
  - high p_T π^o, π^+, π^-
  - direct photons
  - open charm
  - hadron physics
- 2 muon arms: muons
  - "onium" $J/\psi, \psi', \Upsilon \rightarrow \mu^+\mu^-$
  - vector meson $\phi \rightarrow \mu^+\mu^-$
  - open charm
- combined central and muon arms:
  charm production $DD \rightarrow e\mu$



- global detectors
  forward energy and multiplicity
  - event characterization

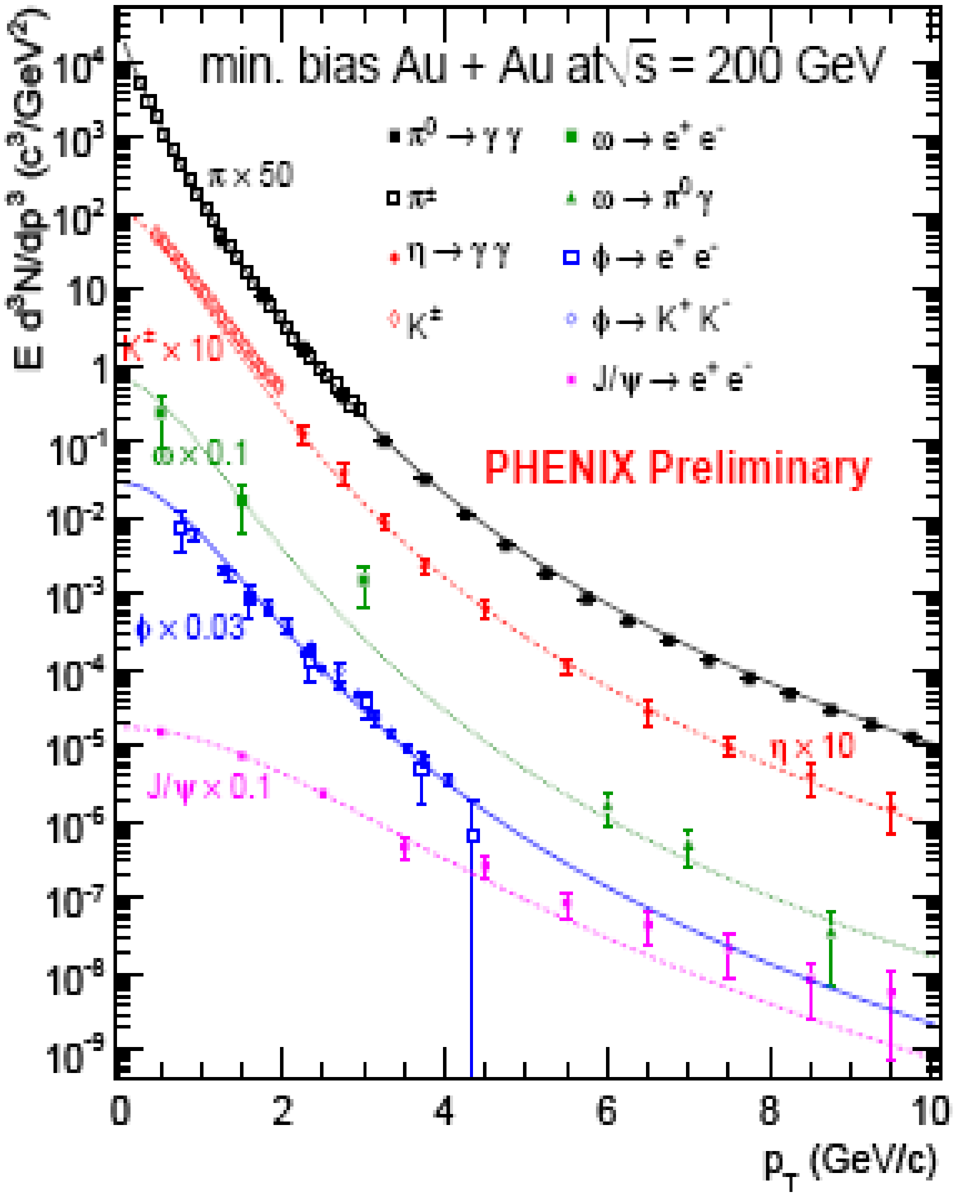
Dilepton Signal



- LMR: $m_{ee} < 1.2$ GeV/c^2
  - **LMR I** ($p_T >> m_{ee}$)
    quasi-real virtual photon region. Low mass pairs produced by higher order QED correction to the real photon emission
  - **LMR II** (p_T<1GeV)
    Enhancement of dilepton discovered at SPS (CERES, NA60)

- Low Mass Region: $m_{ee} < 1.2$ GeV/c^2
  - –Dalitz decays of pseudo-scalar mesons
  - –Direct decays of vector mesons
  - –In-medium decay of ρ mesons in the hadronic gas phase
- Intermediate Mass Region:
  $1.2 < m_{ee} < 2.9$ GeV/c^2
  - –correlated semi-leptonic decays of charm quark pairs
  - –Dileptons from the QGP
- High Mass Region: $m_{ee} > 2.9$ GeV/c^2
  - –Dileptons from hard processes
    - Drell-Yan process
    - correlated semi-leptonic decays of heavy quark pairs
    - Charmonia
    - Upsilons
  - →HMR probe the initial stage
  - –Little contribution from thermal radiation

Hadronic Cocktail Measurement



- Parameterization of PHENIX $\pi^{\pm}$,π^0 data
  $\pi^0 = (\pi^+ + \pi^-)/2$

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

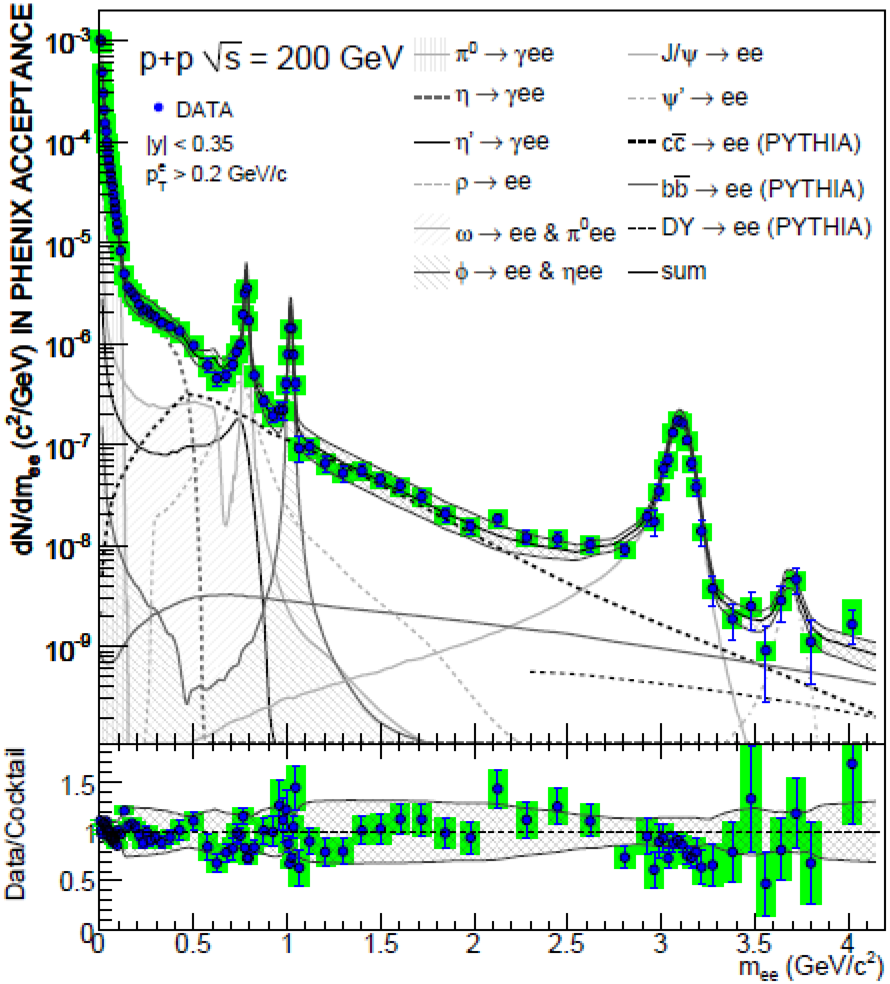
- Other mesons:fit with m_T scaling of π^0
  $p_T \to \sqrt{(p_T^2 + m_{meson}^2 - m_\pi^2)}$
  fit the normalization constant

→All mesons m_T scale!!!

- Hadronic cocktail was well tuned to individually measured yield of mesons in PHENIX for both p+p and Au+Au collisions.
- Mass distributions from hadron decays are simulated by Monte Carlo.
- π^0, η, η', ω, ϕ, ρ, J/ψ, ψ'
- Effects on real data are implemented….

PLB 670,313(2009)
arXiv:0912.0244

Cocktail Comparison p+p



- 2.25pb^{-1} of triggered p+p data
- Data absolutely normalized

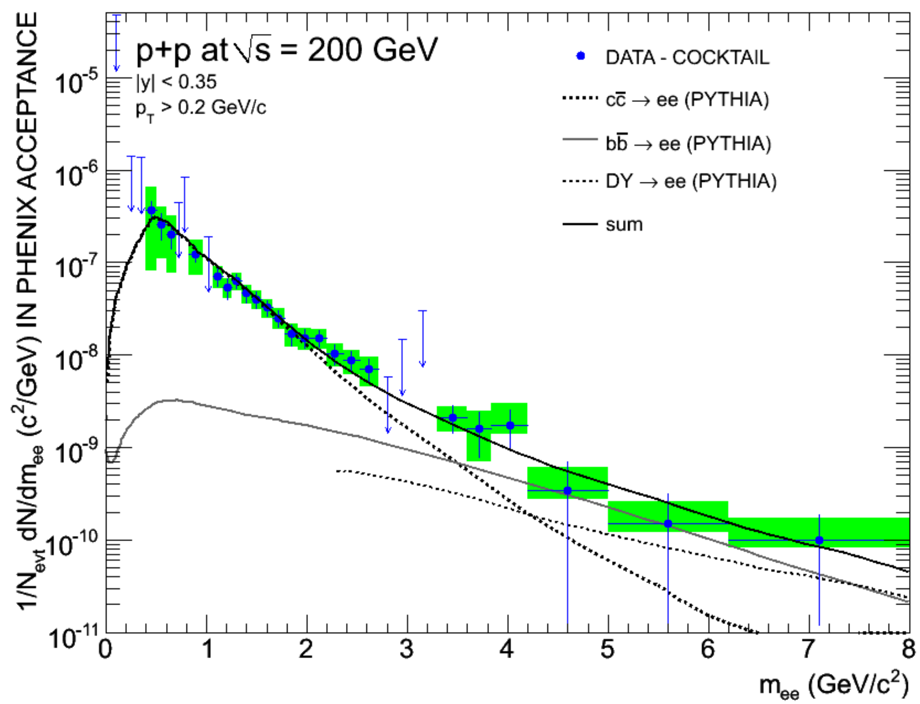
- Excellent agreement with Cocktail
- Filtered in PHENIX acceptance

Light hadron contributions subtracted

Heavy Quark Cross Sections:

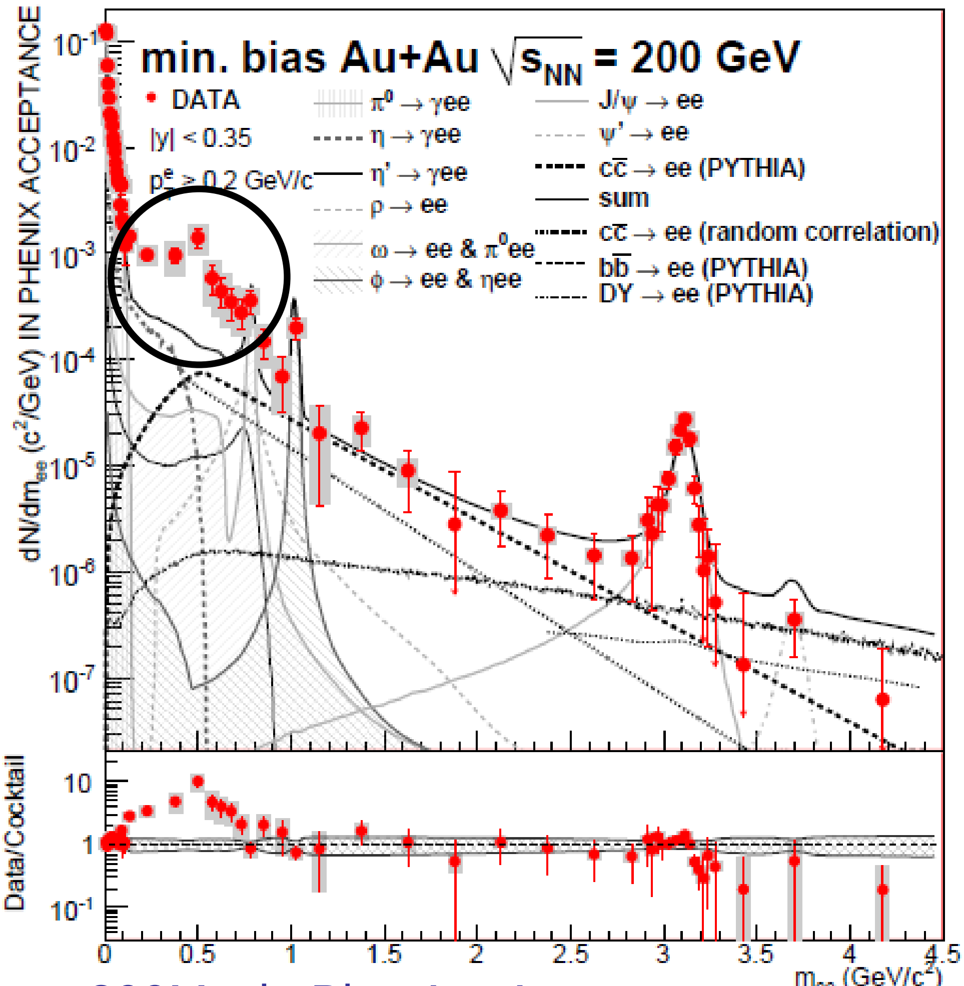
- Charm: integration after cocktail subtraction
  σ_{cc} = 544 ± 39^{stat} ±142^{syst} ± 200^{model} μb
- Simultaneous fit of charm and bottom:
  - σ_{cc} = 518 ± 47^{stat} ± 135 ^{syst}± 190^{model} μb
  - σ_{bb} = 3.9 ± 2.4^{stat} +3/-2^{syst} μb
- Charm cross section from single electron measurement [PRL97, 252002 (2006)]:
  - σ_{cc} = 567 ± 57 ± 193 μb

PLB 670,313(2009)



Cocktail Comparison Au+Au

arXiv:0912.0244



- 800M min.Bias Au+Au events
- Data absolutely normalized

- Light hadrons cocktail
- Charm normalized N_{coll} x σ_{pp}

Filtered in PHENIX acceptance

- Low Mass Region:

large enhancement 150 <m_{ee}<750 MeV

$4.7 \pm 0.4^{stat} \pm 1.5^{syst} \pm 0.9^{model}$

- Intermediate Mass Region:

dominated by charm (N_{coll} x σ_{cc})

  - PYTHIA
  - Random cc correlation

- Single electron measurement
  - High p_T suppression
  - Flow

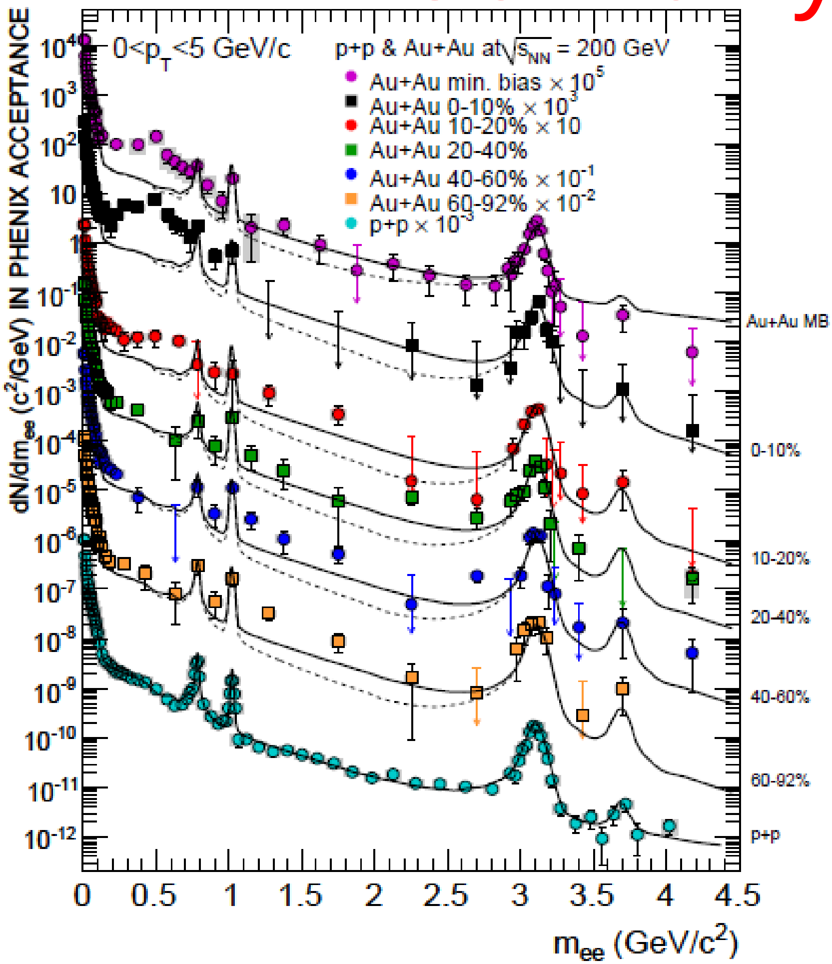
  → Expected modifications in the pair invariant mass

  → random cc correlation?

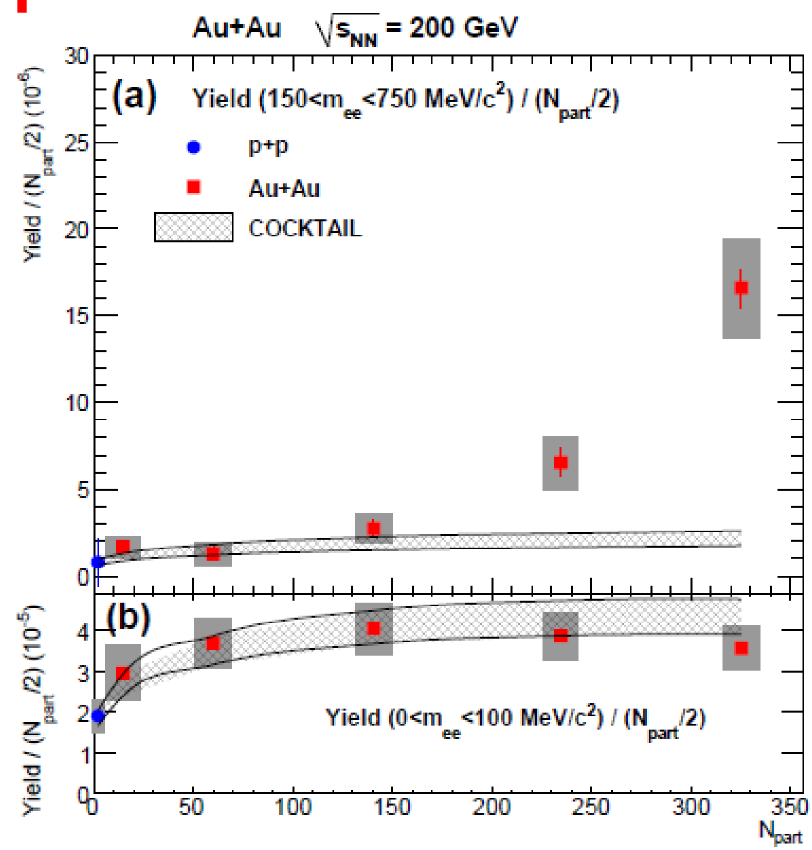
  → Room for thermal contribution?

Centrality Dependence

arXiv:0912.0244



Centrality	Enhancement (±stat ±syst ±model)
00–10%	7.6 ± 0.5 ± 1.3 ± 1.5
10–20%	3.2 ± 0.4 ± 0.7 ± 0.6
20–40%	1.4 ± 0.3 ± 0.4 ± 0.3
40–60%	0.8 ± 0.3 ± 0.4 ± 0.2
60–92%	1.5 ± 0.3 ± 0.5 ± 0.3
Min.Bias	4.7 ± 0.4 ± 1.5 ± 0.9



arXiv:0912.0244

- **π^0 region:**

consistent with cocktail

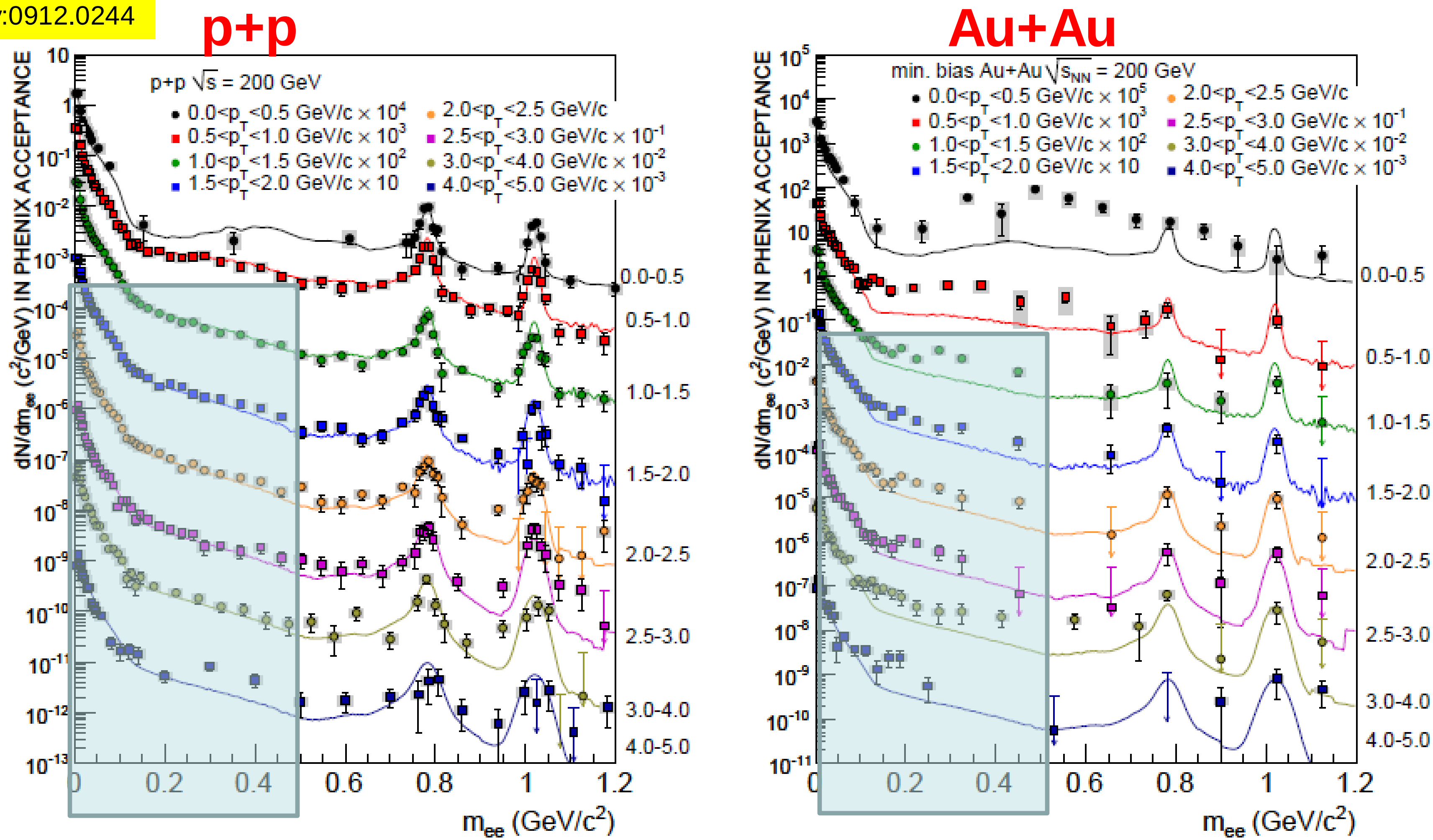
- **Low Mass Region:**

yield increases faster than proportional to N_{part}

→ enhancement from binary annihilation ($\pi\pi$ or qq) ?

Momentum Dependence

arXiv:0912.0244



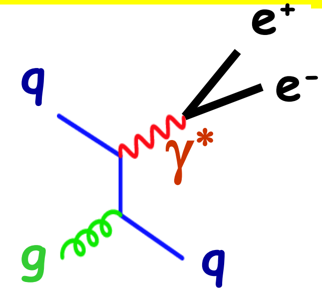
- p+p in agreement with cocktail
- Au+Au low mass enhancement concentrated at low p_T

LMR I: Virtual Photons

- Any source of real γ can emit γ^* with very low mass.
- If the Q^2 (=m^2) of virtual photon is sufficiently small, the source strength should be the same
- The ratio of real photon and quasi-real photon can be calculated by QED

→ Real photon yield can be measured from virtual photon yield, which is observed as low mass e^+e^- pairs

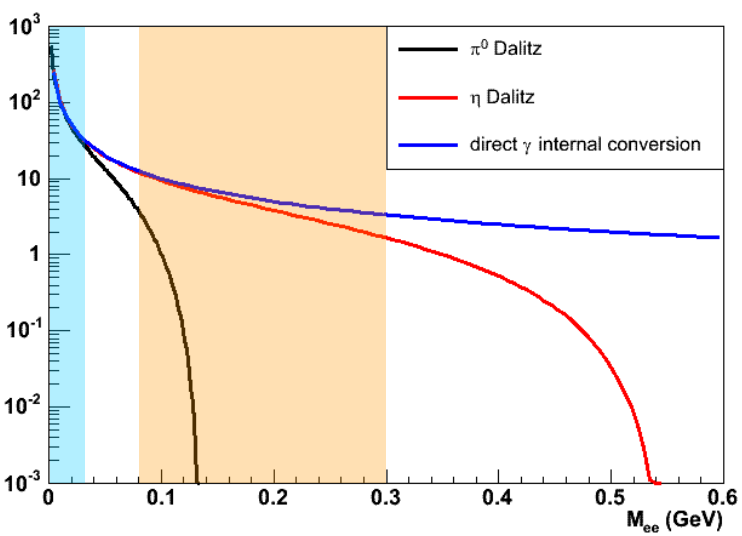
$$\frac{\gamma_{direct}}{\gamma_{inclusive}} = \frac{\gamma^*_{direct}}{\gamma^*_{inclusive}}$$



Kroll-Wada formula

$$\frac{d^2N}{dM_{ee}dN_\gamma} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}S$$

S **: Process dependent factor**



- Case of Hadrons
  - $S = \left|F\left(M_{ee}^2\right)\right|^2\left(1-\frac{M_{ee}^2}{M_{hadron}^2}\right)^3$
  - Obviously S = 0 at $M_{ee} > M_{hadron}$
- Case of γ^*
  - If $p_T^2 >> M_{ee}^2$

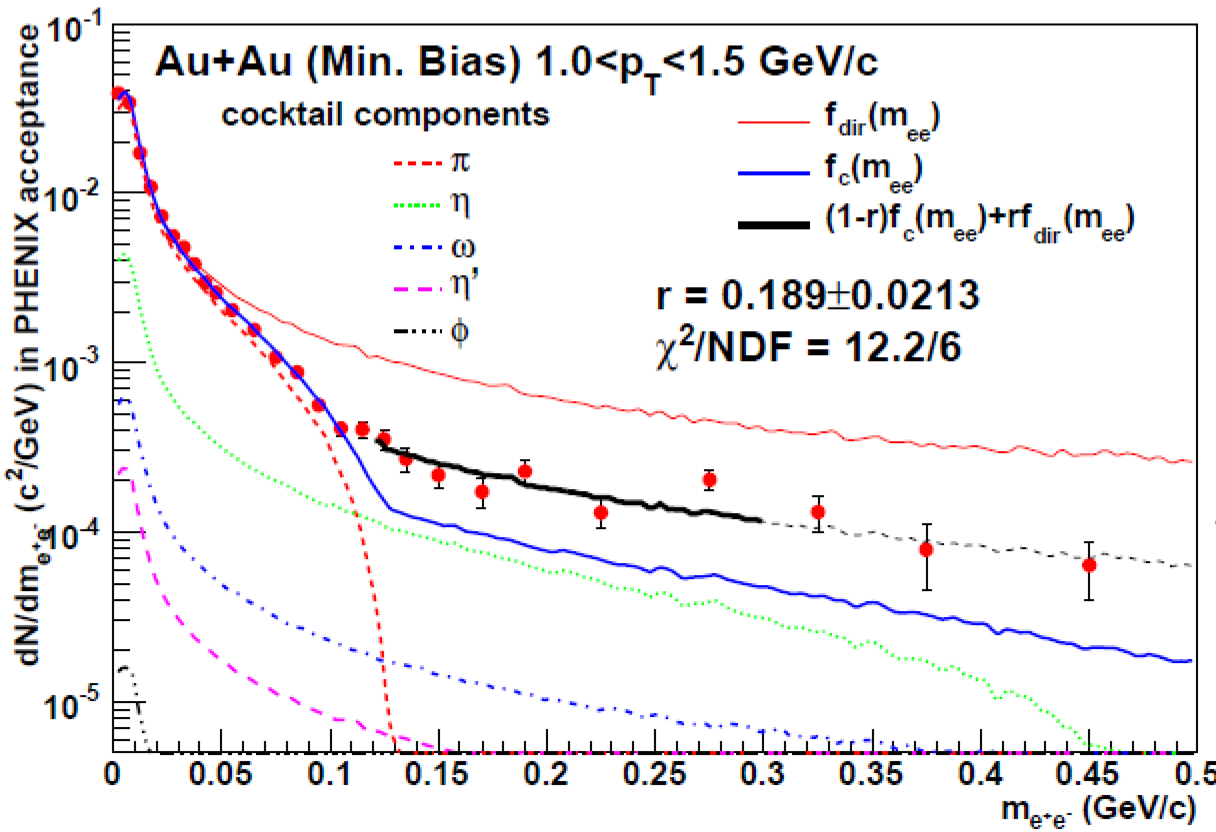
    $S = 1$
- Possible to separate hadron decay components from real signal in the proper mass window.

Determination of γ^* fraction, *r*

r = direct γ^*/inclusive γ^*

determined by fitting the following function for each p_T bin.

$$f_{data}(M_{ee}) = (1-r)\cdot f_{cocktail}(M_{ee}) + r\cdot f_{direct}(M_{ee})$$



- f_{direct} is given by Kroll-Wada formula with *S* = 1.
- $f_{cocktail}$ is given by cocktail components
- Normalized to the data for m<30 MeV/c^2

- Fit in 120-300MeV/c^2 (insensitive to π^0 yield)
- – Assuming direct γ^* mass shape
- χ^2/NDF=12.2/6

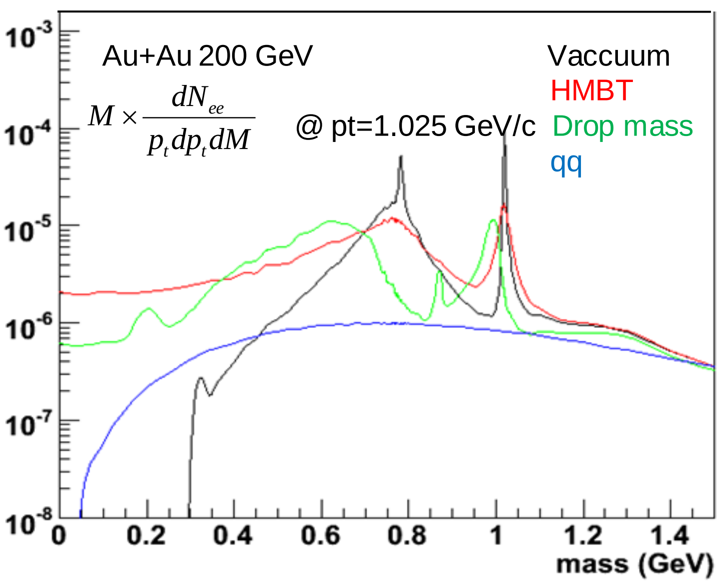
arXiv:0804.4168
arXiv:0912.0244

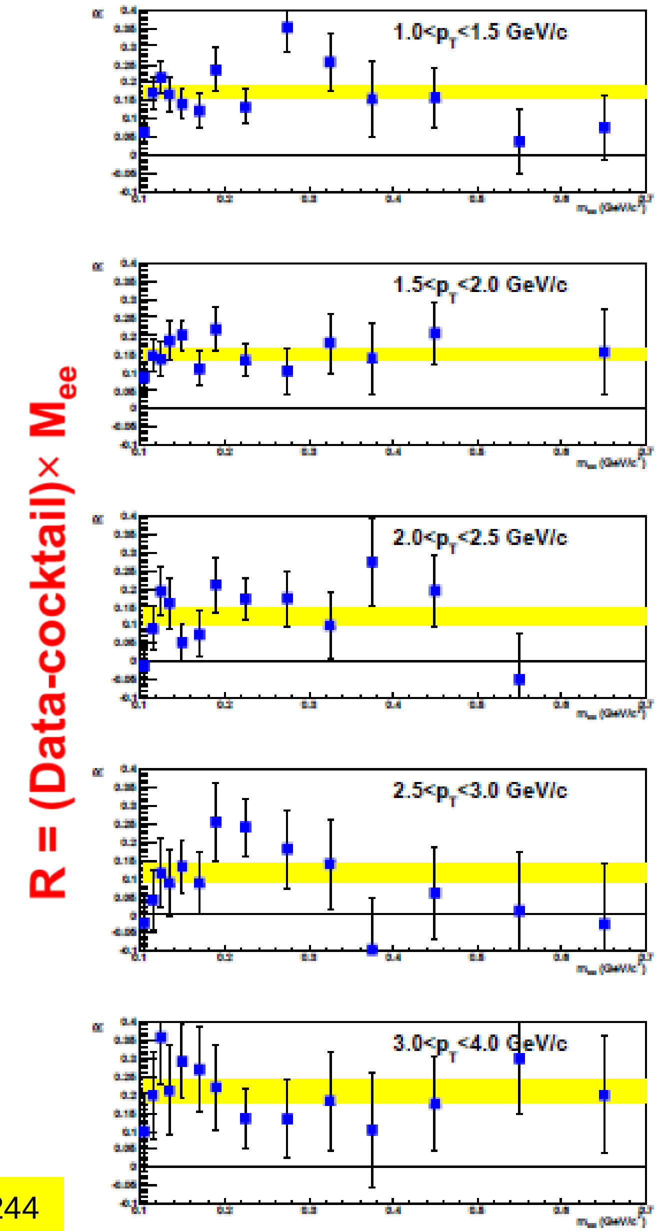
Direct measurement of $S(m_{ee}, p_T)$

$$R(m,p_T) \simeq \frac{dN_{\gamma^*}^{\rm excess}(m,p_T)}{dp_T} \Big/ \frac{dN_{\gamma}^{\rm incl}(p_T)}{dp_T}$$
$$= S(m,p_T) dN_{\gamma}^{direct}(p_T)/dN_{\gamma}^{\rm incl}(p_T)$$

No indication of strong modification of EM correlator at this high p_T region (presumably the virtual photon emission is dominated by hadronic scattering process like $\pi+\rho \rightarrow \pi+\gamma^*$ or $q+g \rightarrow q+\gamma^*$)

Extrapolation to M=0 should give the real photon emission rate



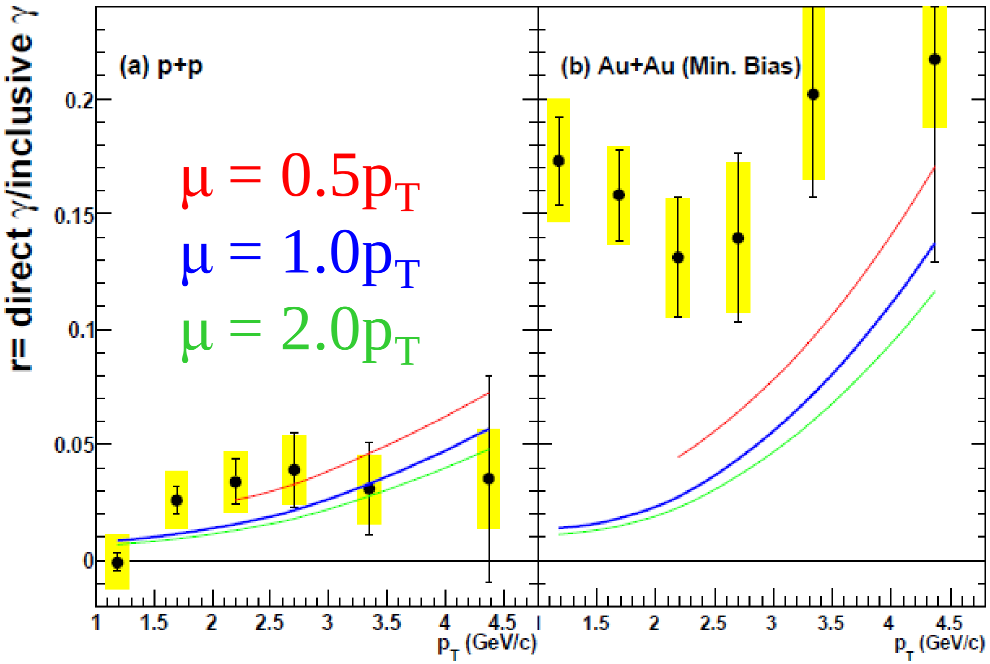


arXiv:0912.0244

Fraction of direct photons

arXiv:0804.4168
arXiv:0912.0244

p+p **Au+Au**



Base line

Curves : NLO pQCD calculations with different theoretical scales done by W. Vogelsang.

$$\left(d\sigma_{\gamma}^{NLO} / dp_T\right) / \left(d\sigma_{\gamma}^{NLO} / dp_T + d\sigma_{\gamma}^{hadron} / dp_T\right)$$

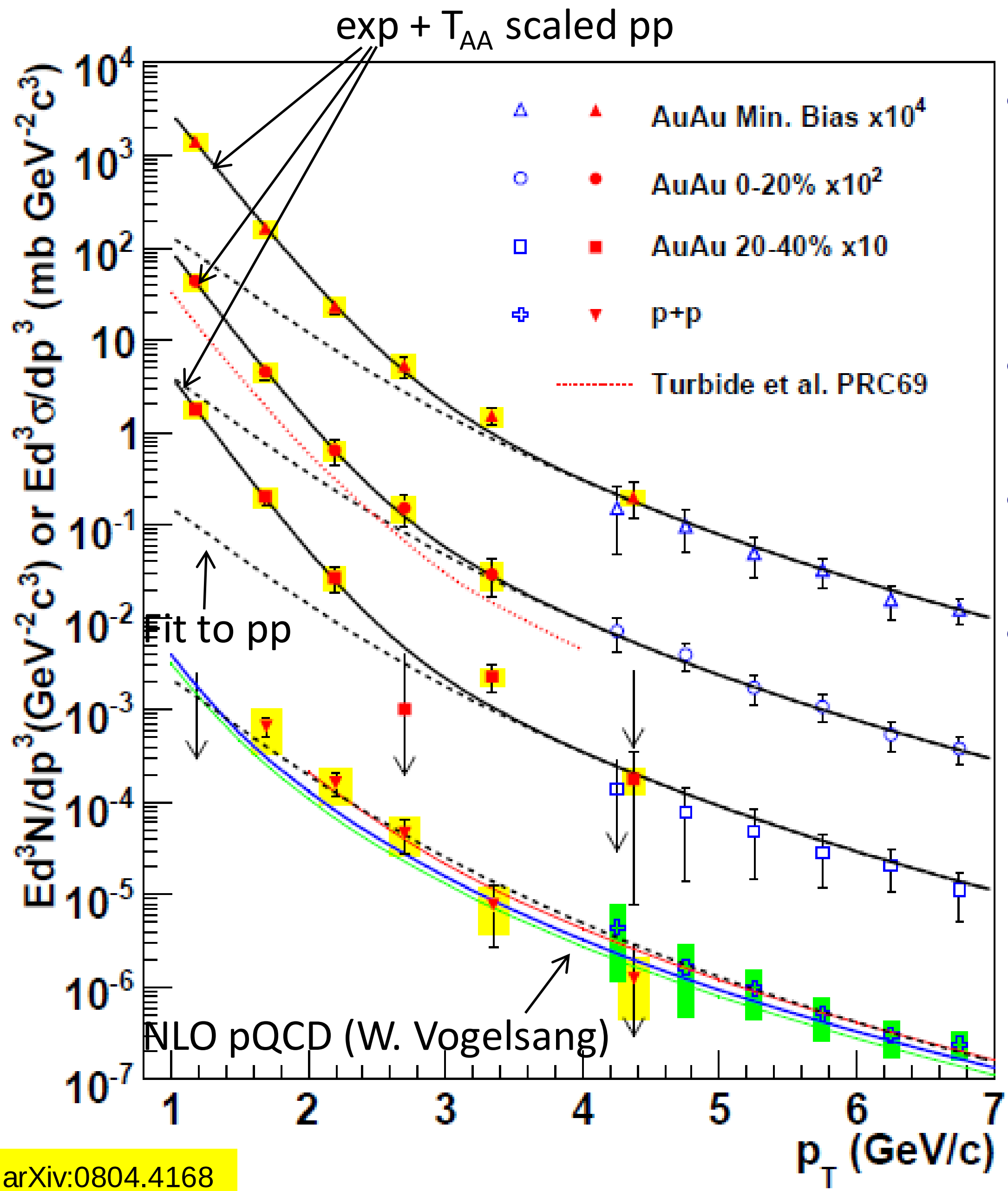
p+p

- Consistent with NLO pQCD
  - better agreement with small μ

Au+Au

- Clear enhancement above NLO pQCD

Direct Photon Spectra

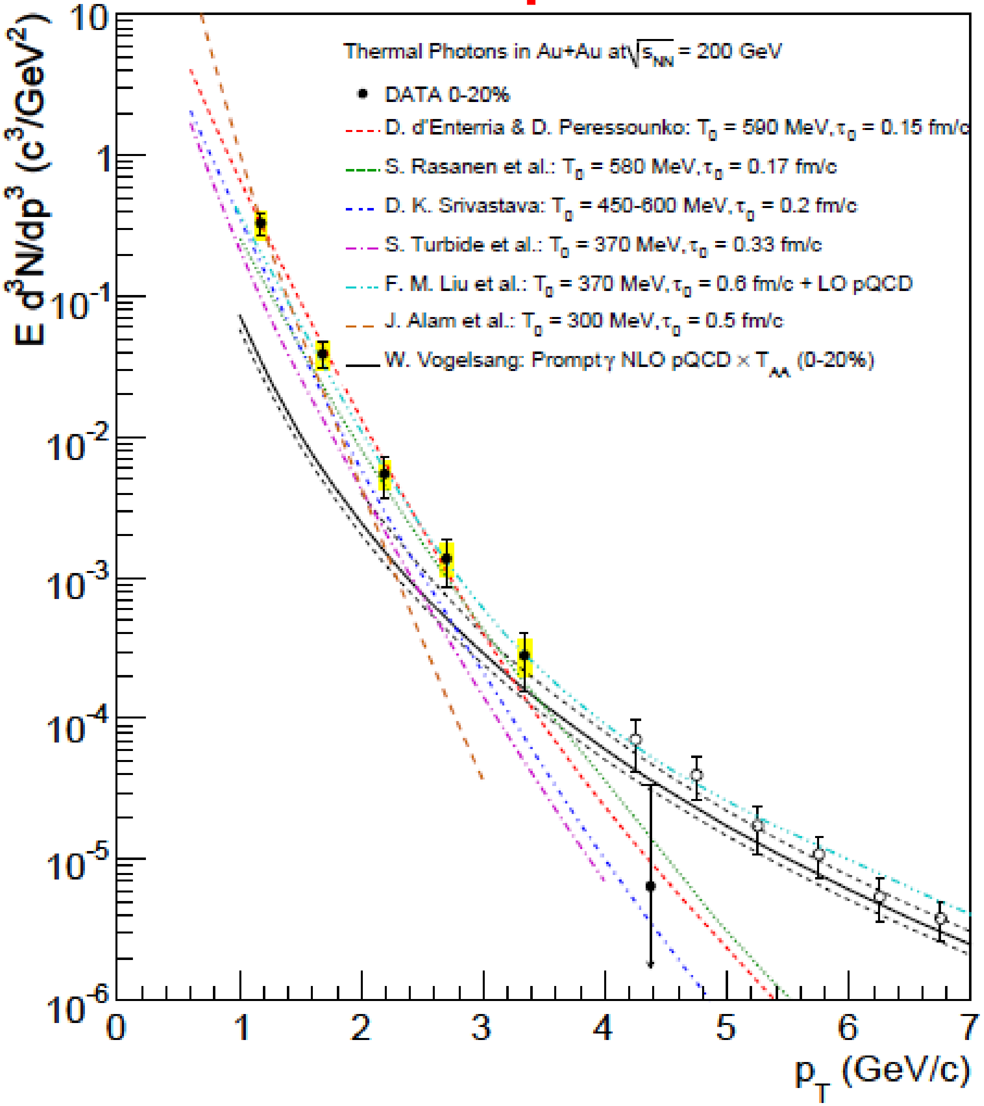


- Direct photon
  - real (p_T>4GeV)
  - virtual (1<p_T<4GeV & m_{ee}<300MeV)
- pQCD consistent with p+p down to p_T=1GeV/c
- Au+Au above N_{coll} x p+p for p_T < 2.5 GeV/c
- Au+Au = pQCD + exp:
  $T_{ave} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV

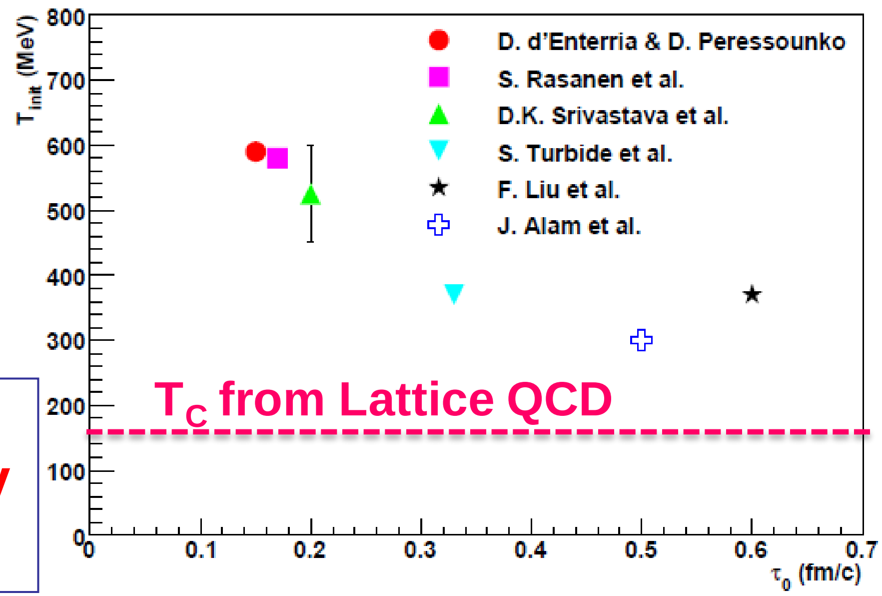
arXiv:0804.4168
arXiv:0912.0244

arXiv:0912.0244

Comparison to Hydro models



- From data: Au+Au = pQCD + exp: $T_{ave} = 221 \pm 19^{stat} \pm 19^{syst}$
- Comparison to hydrodynamical models:
  - p_T<3 GeV/c thermal contribution dominates over pQCD.
  - Assume formation of a hot QGP with 300 MeV < T_{init} < 600 MeV 0.6 fm/c < τ_0< 0.15 fm/c
  - Models reproduce the data within a factor of two.



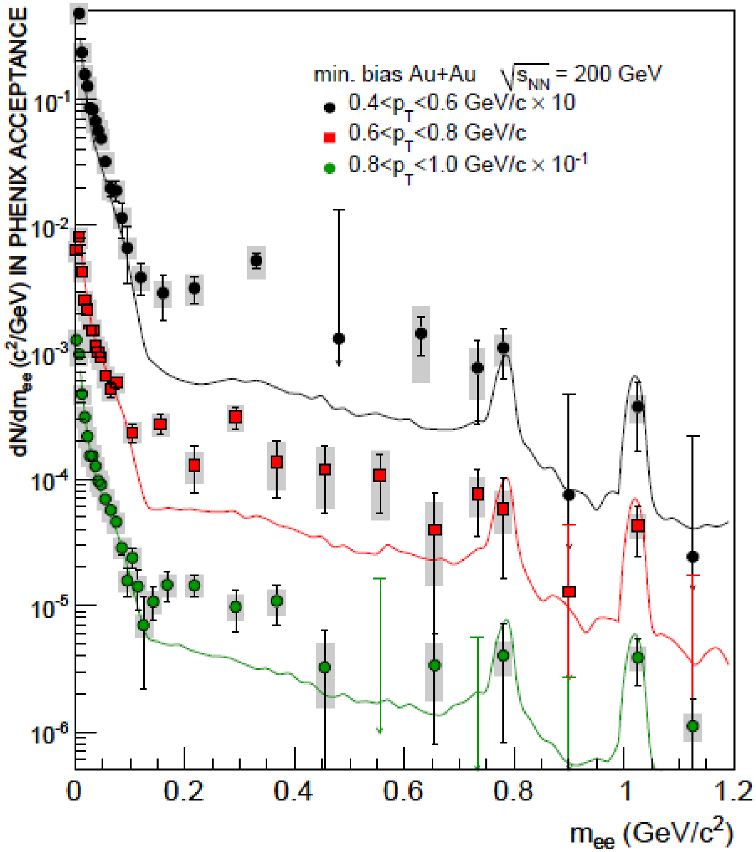
From data: T_{ini} > 220 MeV > T_C

From models: T_{ini} = 300 to 600 MeV

τ_0 = 0.15 to 0.5 fm/c

LMR II

arXiv:0912.0244

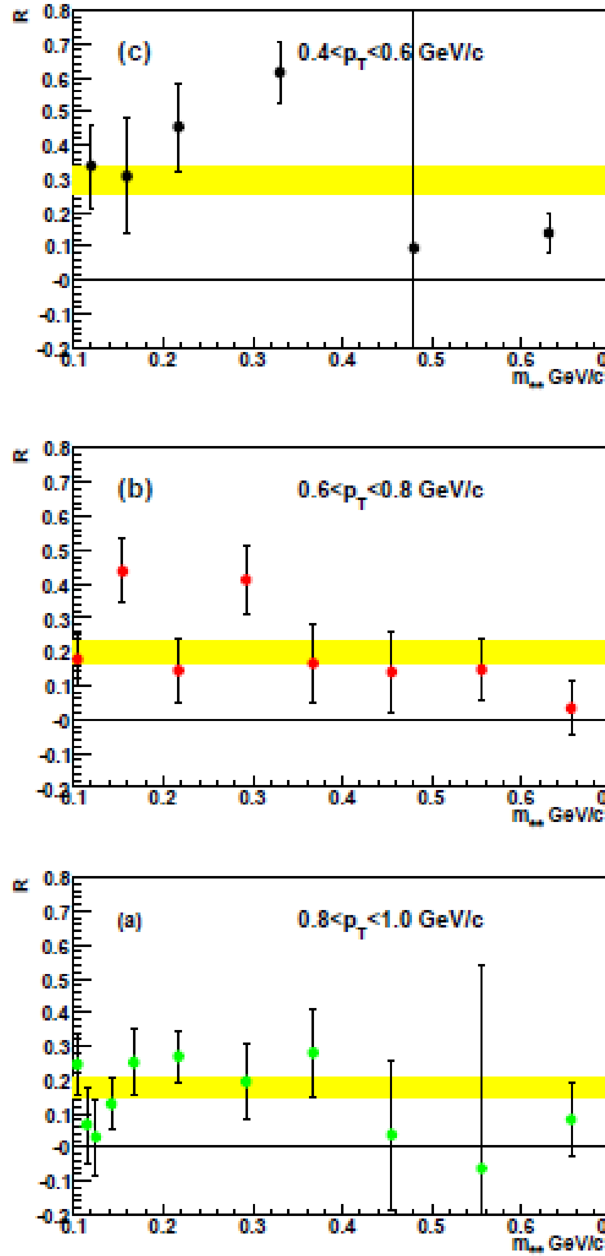


Large and broad enhancement
→ $S(m_{ee})$ no longer const

Towards lower p_T

- Consistent with flat →$S(m_{ee})$ const
- <R>=0.177±0.032
- Consistent with higher p_T values

arXiv:0912.0244

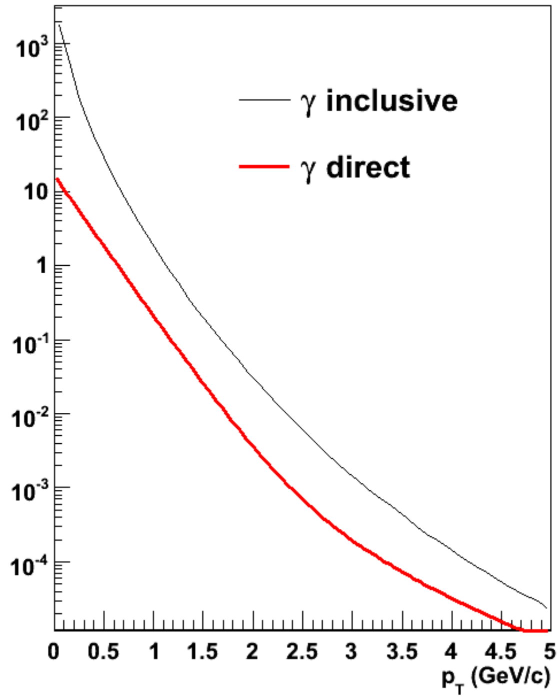


R = (Data-cocktail)× M_{ee}

Extrapolate the spectrum of direct photons

- For $0.8 < p_T < 1.0$ GeV/c
  $\langle R \rangle = 0.177 \pm 0.032$
  consistent with higher p_T
- Decay photons spectrum
  steeper than direct γ spectrum

→At lower p_T,
the expected direct photon fraction
r = direct γ / inclusive γ = direct γ / (direct + decay) $\gamma \leq 0.17$

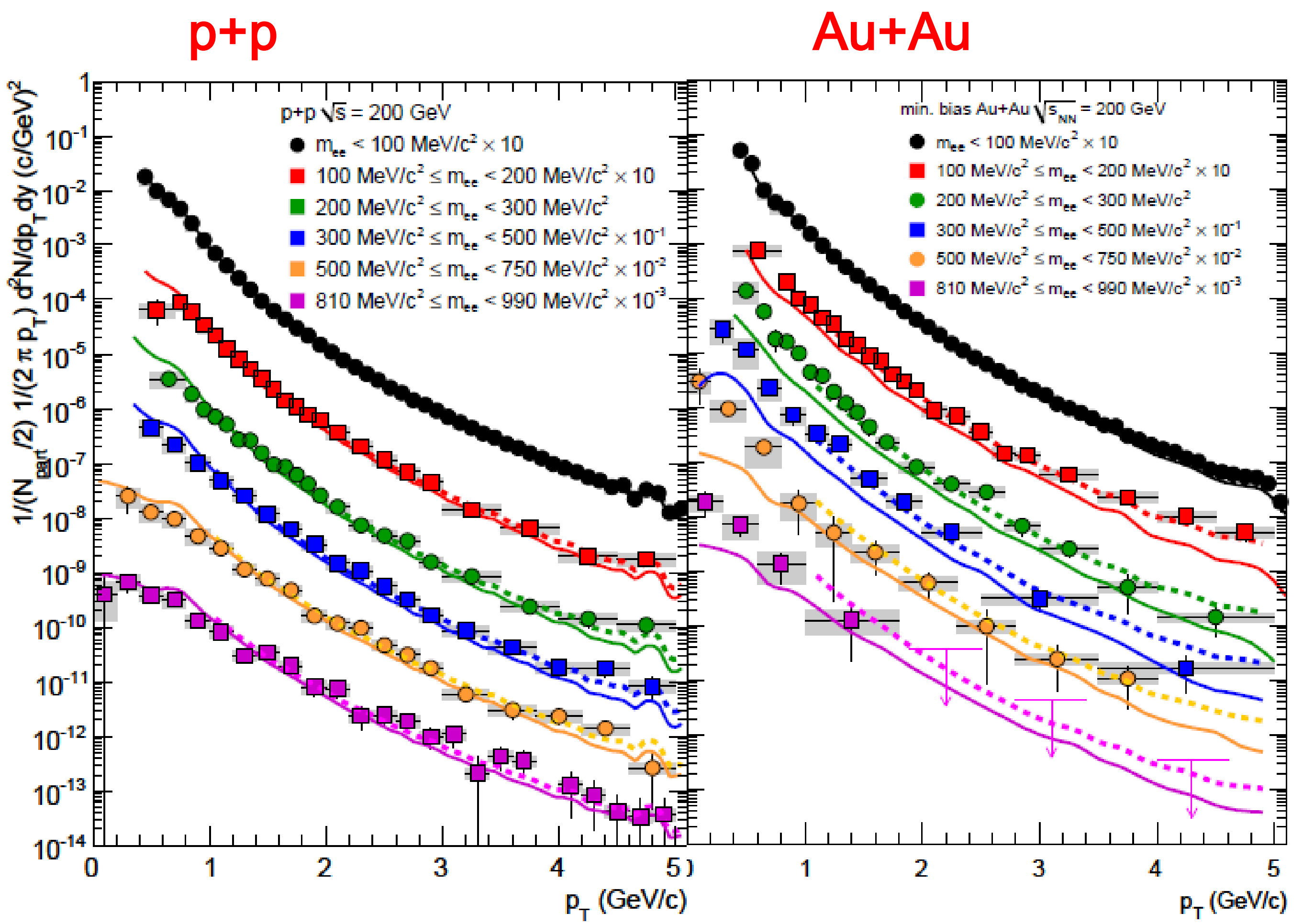


- For $0.4 < p_T < 0.6$ GeV/c
  $R(m) > 0.17$

→The enhancement in the low p_T region is larger than that expected from internal conversion of direct photons.

arXiv:0912.0244

Dilepton Spectra



Acceptance-corrected

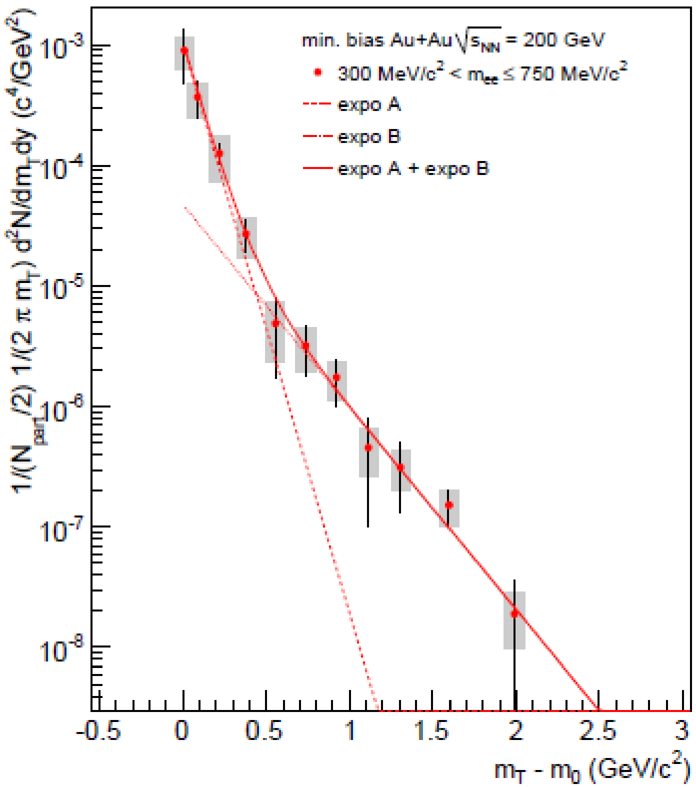
- p+p
  - Agreement with cocktail + internal conversion of direct photons
- Au+Au
  - p_T>1GeV/c: small excess → internal conversion of direct photons
  - p_T<1GeV/c: large excess for 0.3<m_{ee}<1 GeV

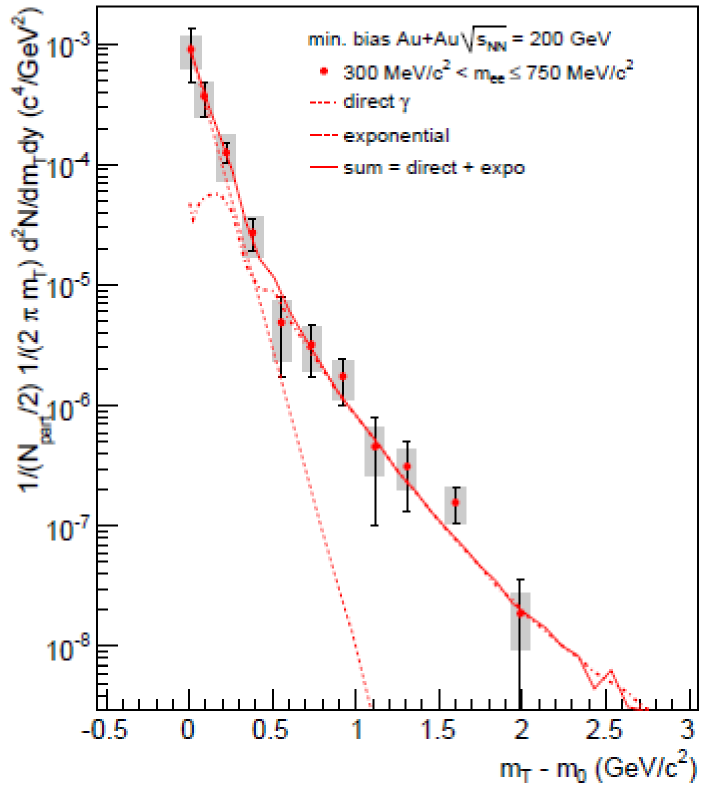
→Low temperature component with strong modification of EM correlator?

Average Temperature of the sources

arXiv:0912.0244

- $m_T - m_0$ spectrum of Excess = Data – (cocktail+charm)
- Fit: $\frac{d^2N}{2\pi m_T dm_T dy} = A_1 \cdot \exp - \frac{m_T}{T_1} + A_2 \cdot \exp - \frac{m_T}{T_2}$ or $\frac{d^2N}{2\pi m_T dm_T dy} = A_1 \cdot \exp - \frac{m_T}{T_1} +$ Direct γ





T_2 consistent with $T\gamma$

$T_1 = 92.0 \pm 11.4^{stat} \pm 8.4^{syst}$ MeV
$T_2 = 258.4 \pm 37.3^{stat} \pm 9.6^{syst}$ MeV
χ^2/NDF= 4.00/9

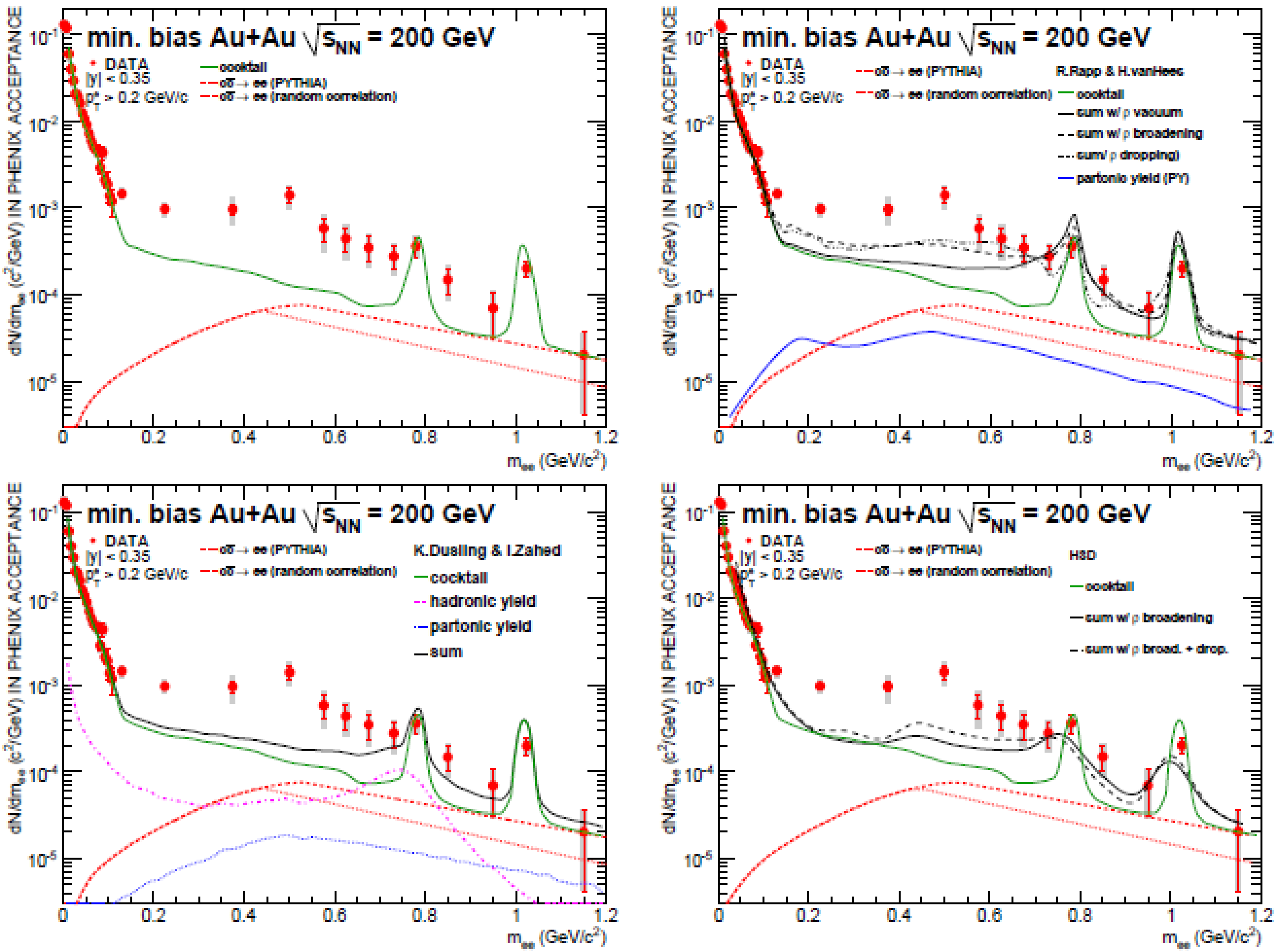
$T_1 = 86.5 \pm 12.7^{stat}\ {}^{+11.0}_{-28.4}{}^{syst}$ MeV
$T_\gamma = 221 \pm 19^{stat} \pm 19^{syst}$ MeV
χ^2/NDF= 16.6/11

low mass enhancement has inverse slope of ~100 MeV.

Theory comparison

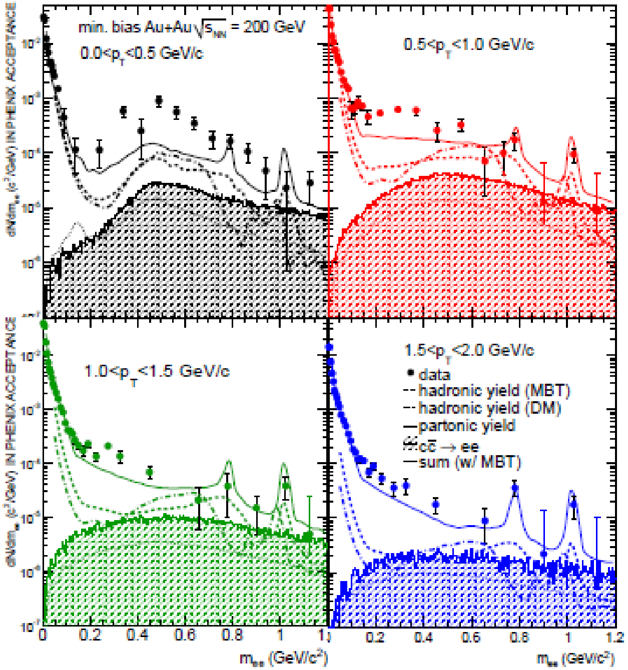
- $\pi\pi$ annihilation + modified ρ spectral function
  - Broadening
  - Mass shifting
  - Both
- Insufficient to explain data

arXiv:0912.0244

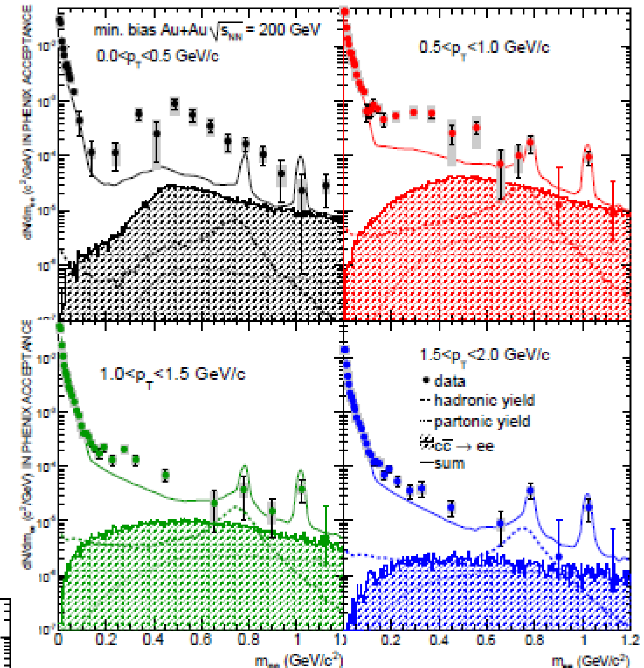


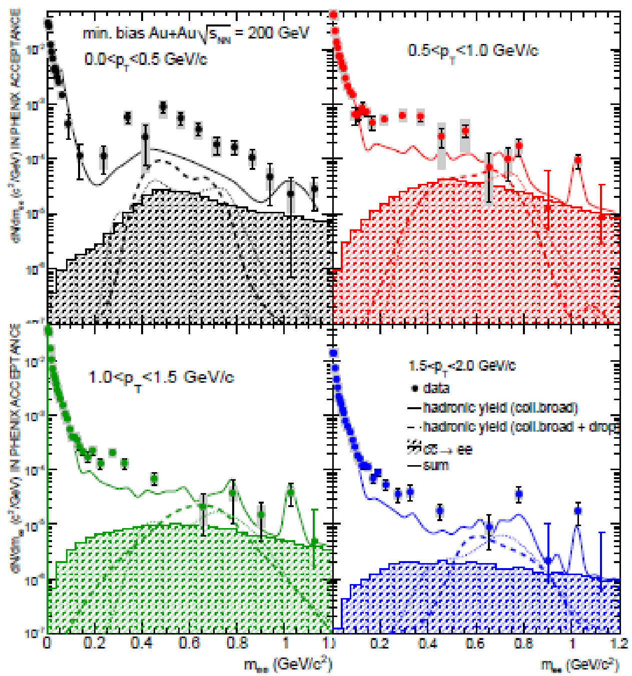
arXiv:0912.0244

Theory comparison II



High p_T region:
here we isolated a contribution arising from
- $\pi+\rho \rightarrow \pi+\gamma^*$
(typically included)
or
- $q+g \rightarrow q+\gamma^*$
(not included so far)



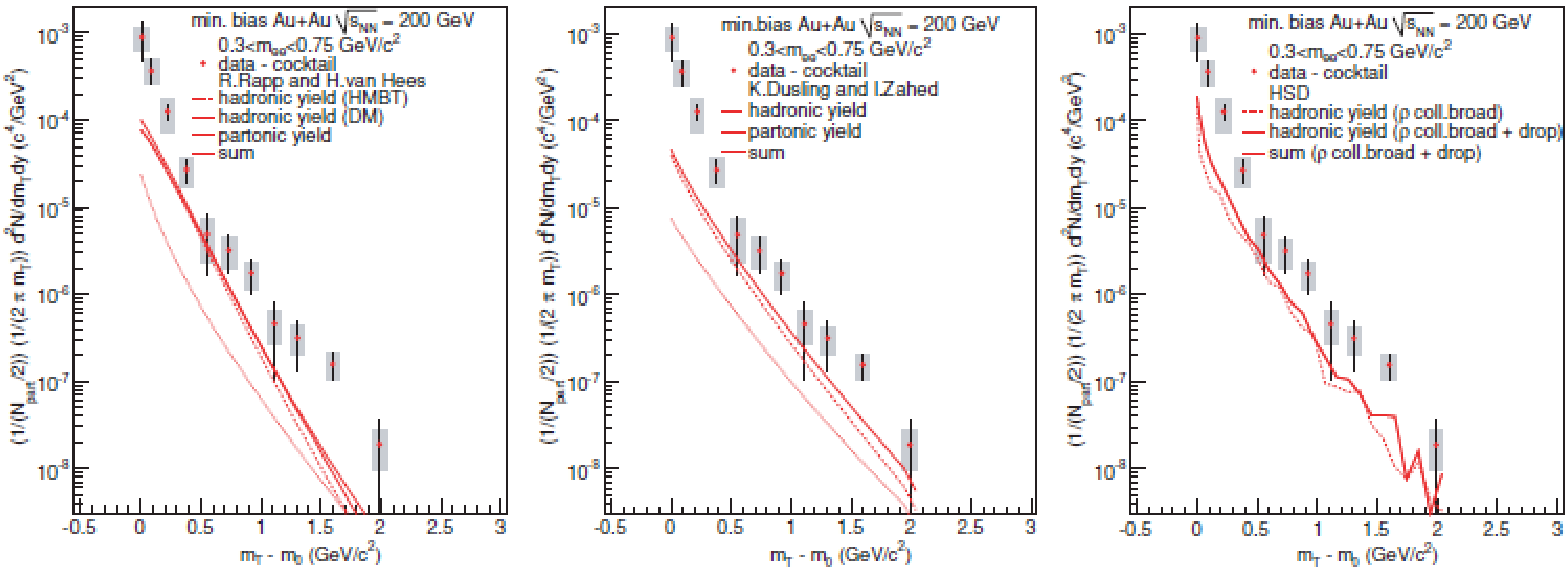


Even when looking differentially in various p_T bins the theoretical calculations are insufficient to explain the data

Low p_T region:
where the enhancement becomes large and its shape seems incompatible with unmodified $q+g \rightarrow q+\gamma^*$

arXiv:0912.0244

Theory comparison III



- The theoretical calculations are insufficient to explain the data
- High p_T: they are too soft (except for HSD which does not include partonic contribution)
- Low p_T: they are too hard to explain the enhancement (T~100 MeV)
  what is missing ?

Summary

- EM probes ideal “penetrating probes” of dense partonic matter created at RHIC
- Double differential measurement of dilepton emission rates can provide
  - Temperature of the matter
  - Medium modification of EM spectral function
- PHENIX measured dilepton continuum in p+p and Au+Au

p+p

Low Mass Region

- Excellent agreement with cocktail

- LMR I
deduce photon emission in agreement with pQCD

- LMR II
Excellent agreement with cocktail

Intermediate Mass Region

- Extract charm and bottom cross section

Au+Au

Low Mass Region

- Enhancement above the cocktail
$4.7 \pm 0.4^{stat} \pm 1.5^{syst} \pm 0.9^{model}$

- LMR I
deduce photon emission exponential above pQCD, T>200 MeV

- LMR II
  - Centrality dependency: increase faster than N_{part}
  - p_T dependency: enhancement concentrated at low p_T, T ~ 100 MeV

Intermediate Mass Region

- Agreement with PYTHIA: coincidence?

The new frontier …

“It's still the last frontier you might say. We're still out here dancing on the edge of the world.“ (Lawrence Ferlinghetti)

Central collisions	SPS	RHIC	LHC
$\sqrt{s}$ (GeV)	17	200	5500
dN_{ch}/dy	430	700	$1\text{-}3\times10^3$
ε (GeV/fm^3)	3	5-10	15- 60
V_f(fm^3)	10^3	7×10^3	2×10^4
T / T_c	> 1	2	3-4

- RHIC upgrades (STAR/PHENIX)

Quantitative analysis of **sQGP**
New regions in the phase-space

- e-RHIC: electron – ion collider
  - Momentum distribution of **gluons G(x,Q^2)**
  - Space-time distributions of gluons in matter
  - Interaction of fast probes with gluonic medium?
  - Role of color neutral excitations

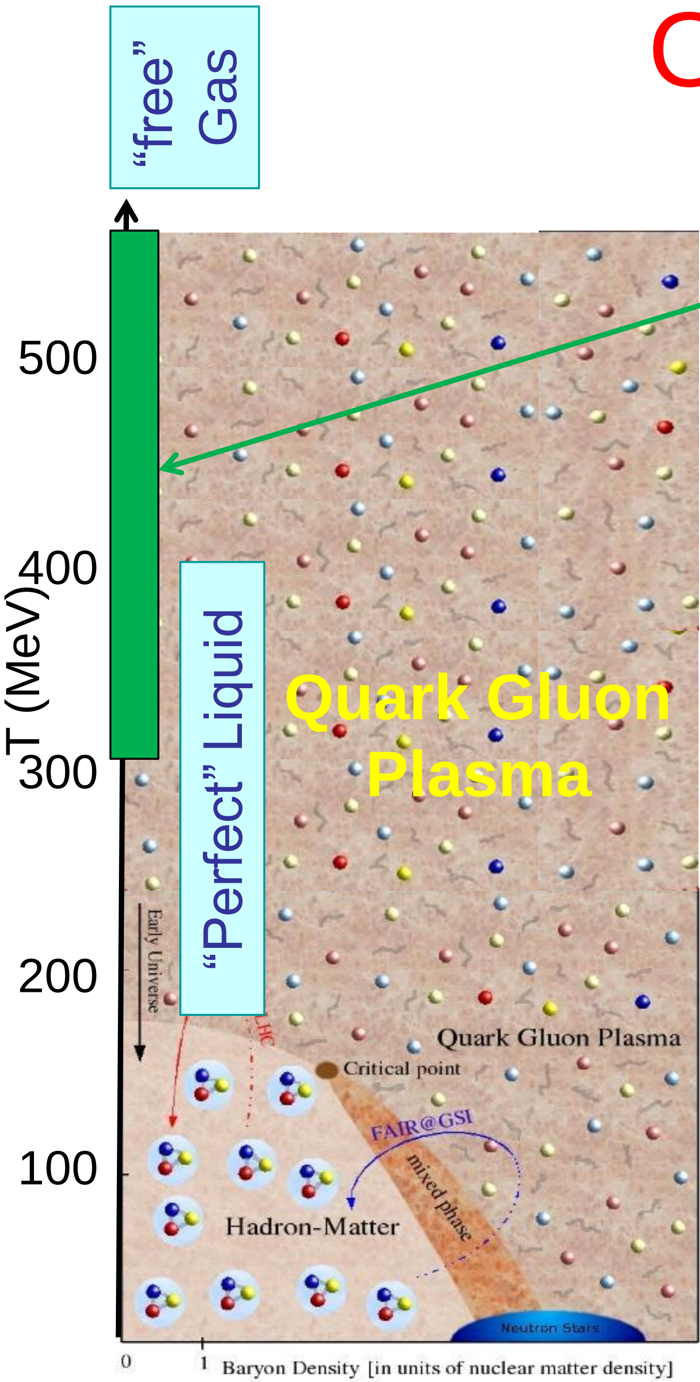
- LHC

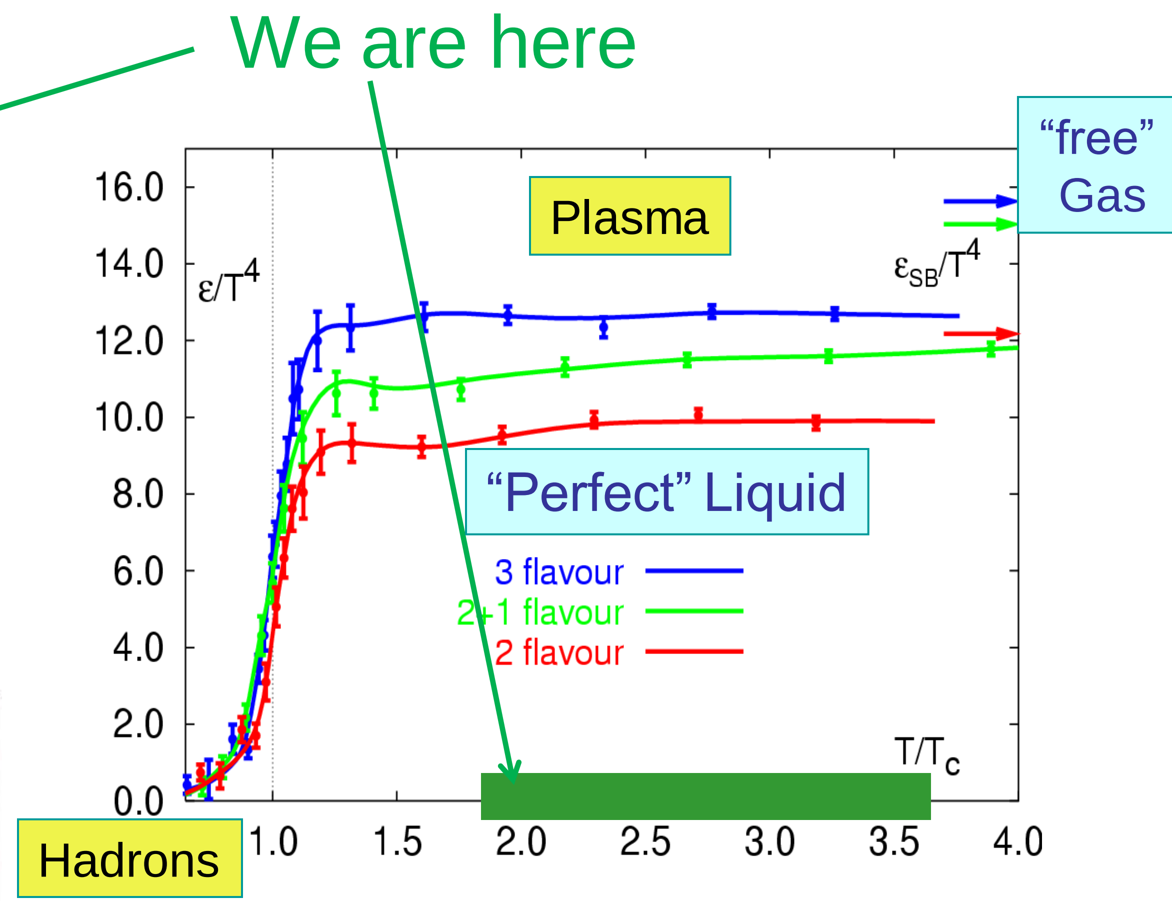
- hotter, larger, longer-lived QGP → wQGP?
- Hard Probes
  - Hard parton quenching → ε
  - Quarkonia and photons → T
  - jet fragmentation function → γ / Z^0 + jet
- Probe unexplored small-*x* region with heavy quarks at low p_T and/or forward y
- $dN_{ch}/d\eta$ (p+p @ LHC) ~ $dN_{ch}/d\eta$ (Cu+Cu @ RHIC) → pp-QGP?

- FAIR

Search for the **critical point**

On the Map





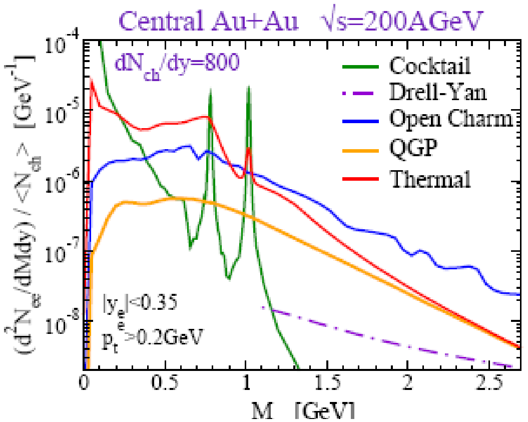
T_c ~ 170 MeV; ε ~ 1 GeV/fm^3

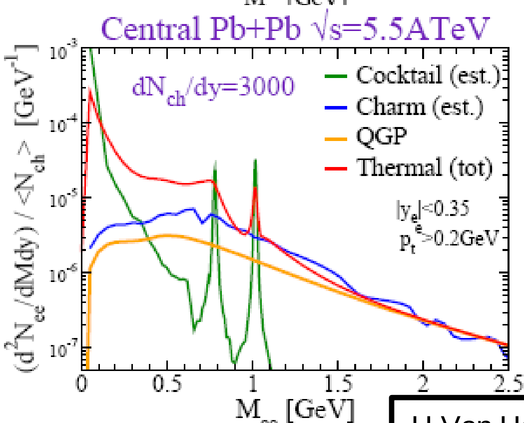
At these temperature, QGP is *"perfect" liquid.*

At higher temperature, it can become *"gas"*

EM Probes at LHC

DILEPTONS





H.Van Hees and R.Rapp

PHOTONS

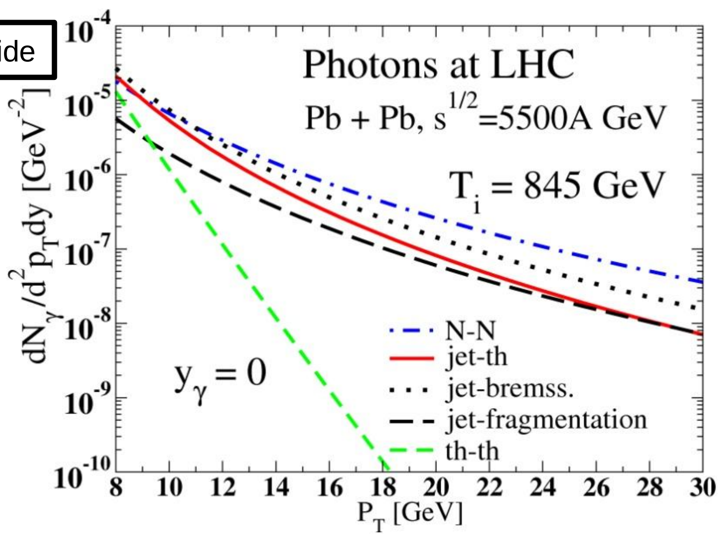
Low p_T

- Thermal/bulk photons (QGP + hadronic phase)
- Photons from jet-medium interactions
  - Jet-photon conversion, Induced photon bremsstrahlung
  - Cross sections forward/backward peaked
  - Yields approximately proportional to the jet distributions → Sensitivity to *early* time jet distributions
  - Longer path lads to increased production → Negative v2

High p_T

- Prompt photons from initial hard processes
  - No final state effects at all.
- Fragmentation/vacuum bremsstrahlung
  - Sensitivity to medium effects in the final state

S.Turbide



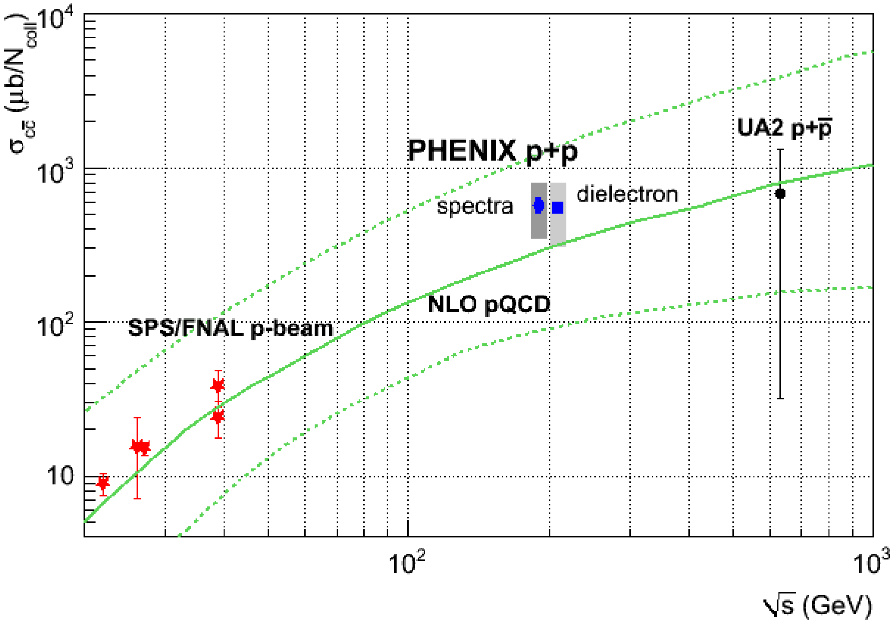
- At higher dN/dy thermal radiation from hadron gas dominant for m<1GeV
- For m>1GeV relatively stronger QGP radiation:
comparable to DD but energy loss???

The End

Charm and bottom cross sections

CHARM

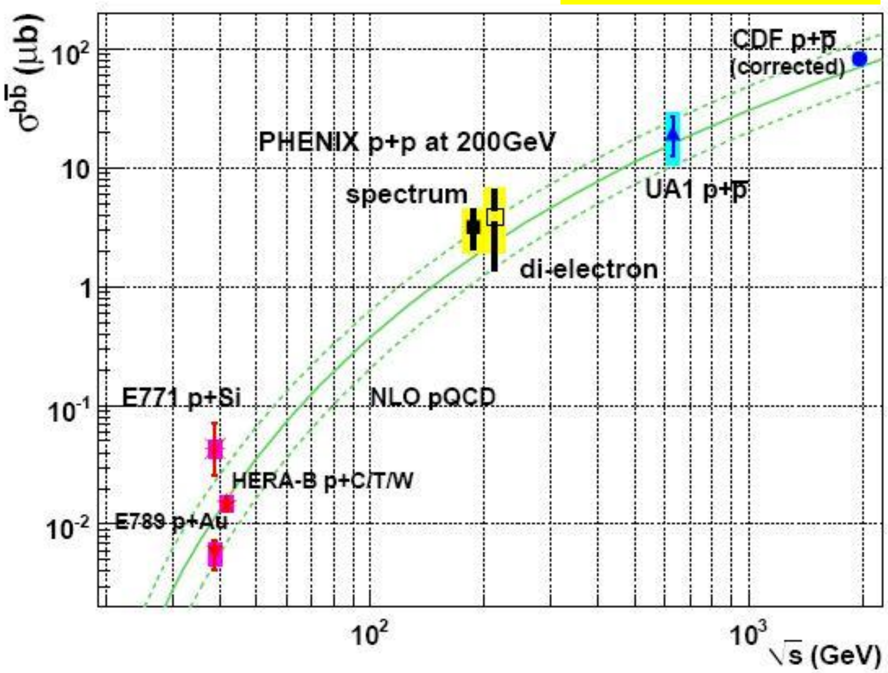
Dilepton measurement in agreement with single electron, single muon, and with FONLL (upper end)



BOTTOM

Dilepton measurement in agreement with measurement from e-h correlation and with FONLL (upper end)

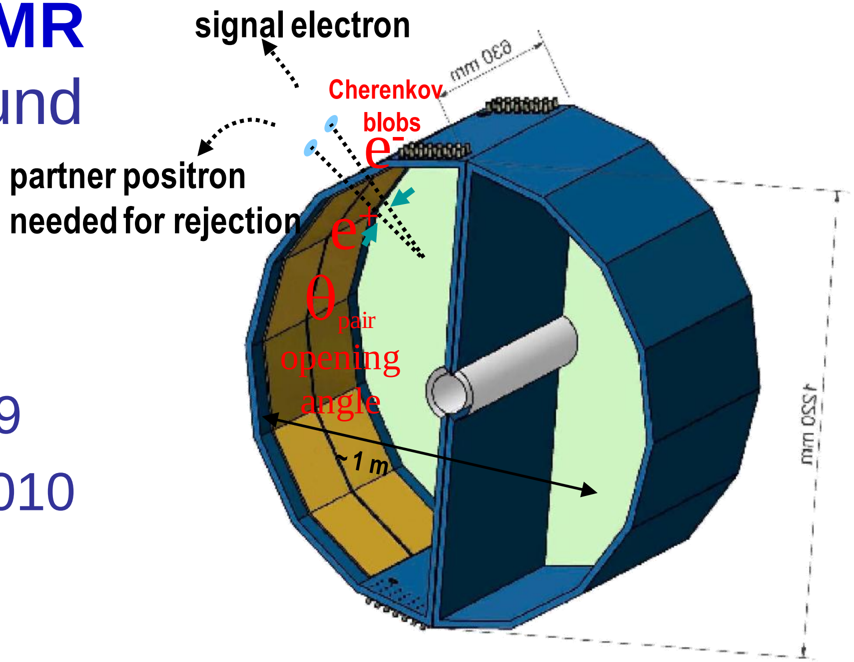
PLB670,313(2009)
PRL103,082002



First measurements of bottom cross section at RHIC energies!

Future EM Measurements at RHIC

- **Improve measurement in the LMR**
  → reduce combinatorial background
  → Hadron Blind Detector
  - HBD is fully operational
  - Proof of principle in 2007
  - Successful data taking with p+p 2009
  - Ready for large Au+Au data set in 2010 (which is starting right now)

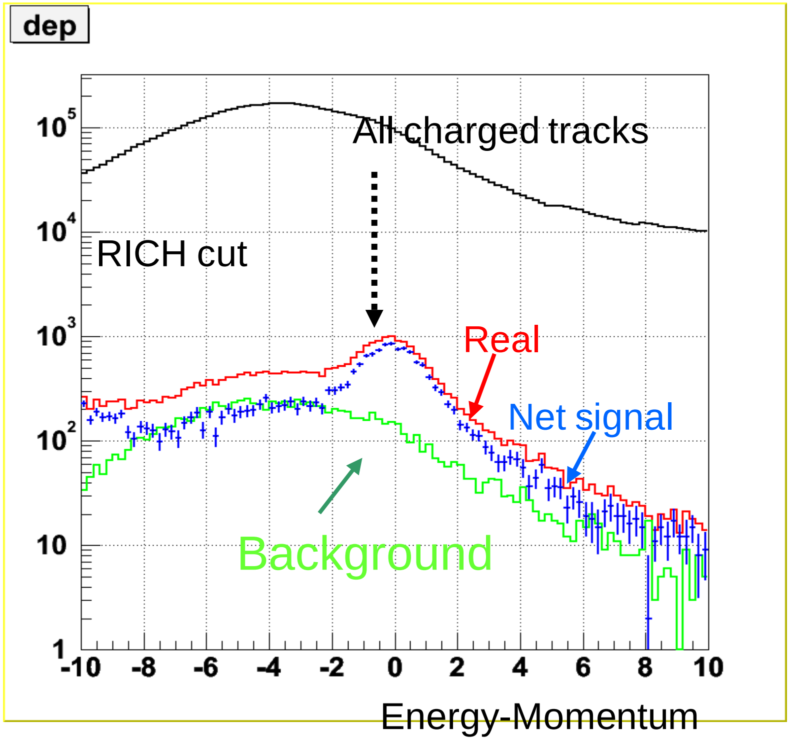


- **Improve measurement in the IMR**
  → disentangle charm and thermal contribution
  → Silicon Vertex Detector
  - Coming soon...

The Analysis

Electron Identification

– emission and measurement of Cherenkov light in the Ring Imaging Cherenkov detector
→ measure of min. velocity
– production and of EM shower in the Electro- Magnetic Calorimeters (PbSc, PbGl)
→ measure of energy E

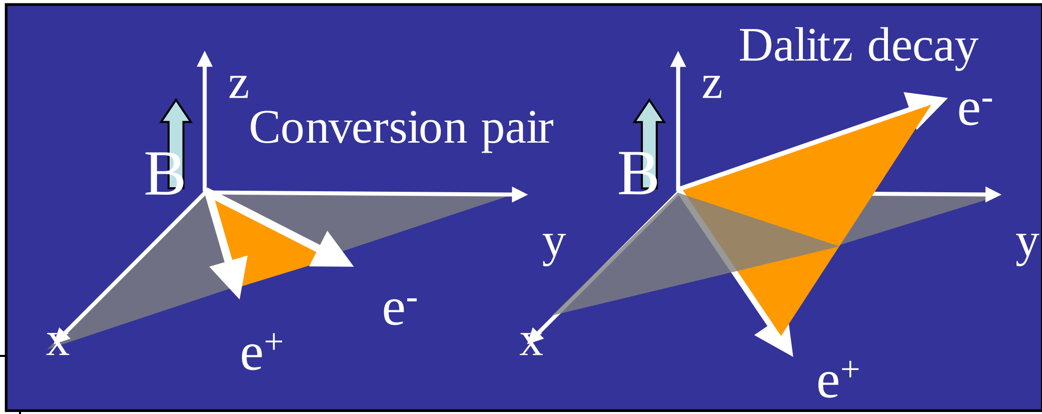


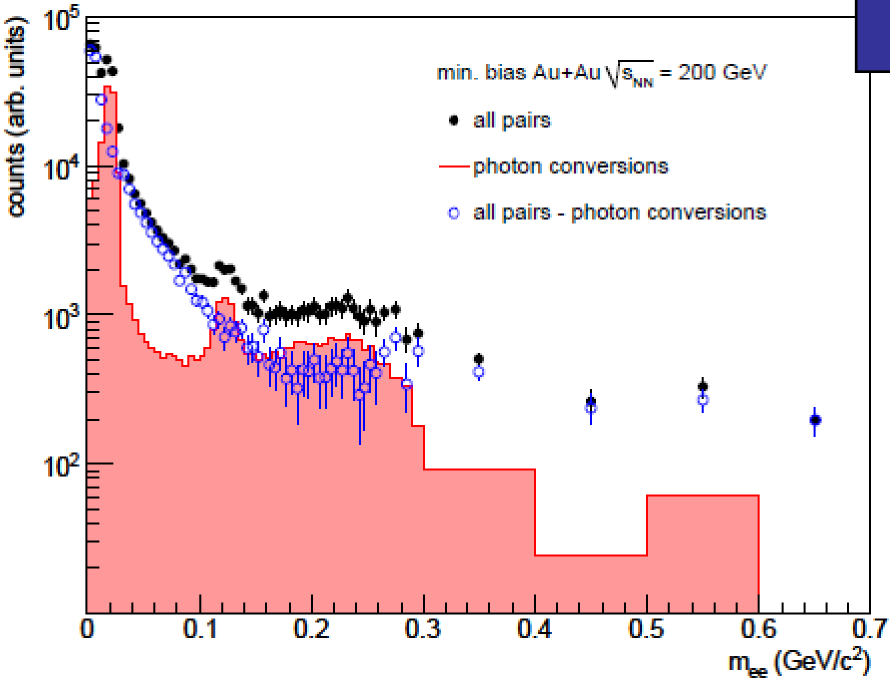
- electron: E ≈ p
- hadron: E < p
- after RICH cuts, clear electron signal
- cut on E/p cleans electron sample!
- background
  - photon conversions
  - random associations (next slide)
- main background source: random combination of hadron track/shower with uncorrelated RICH ring
- "standard" subtraction technique: flip-and-slide of RICH
- swapped background agrees in shape with E/p distribution of identified hadrons
- background increases with detector occupancy (can reach ~30 % in central Au+Au collisions)

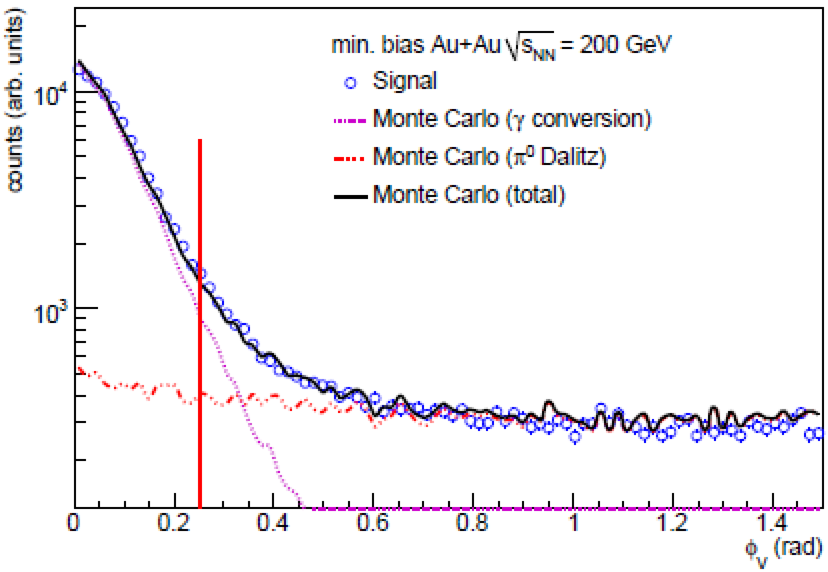
Photon conversion rejection

γ→e+e- at r≠0 have m≠0
(artifact of PHENIX tracking:
no tracking before the field)
• effect low mass region
• have to be removed

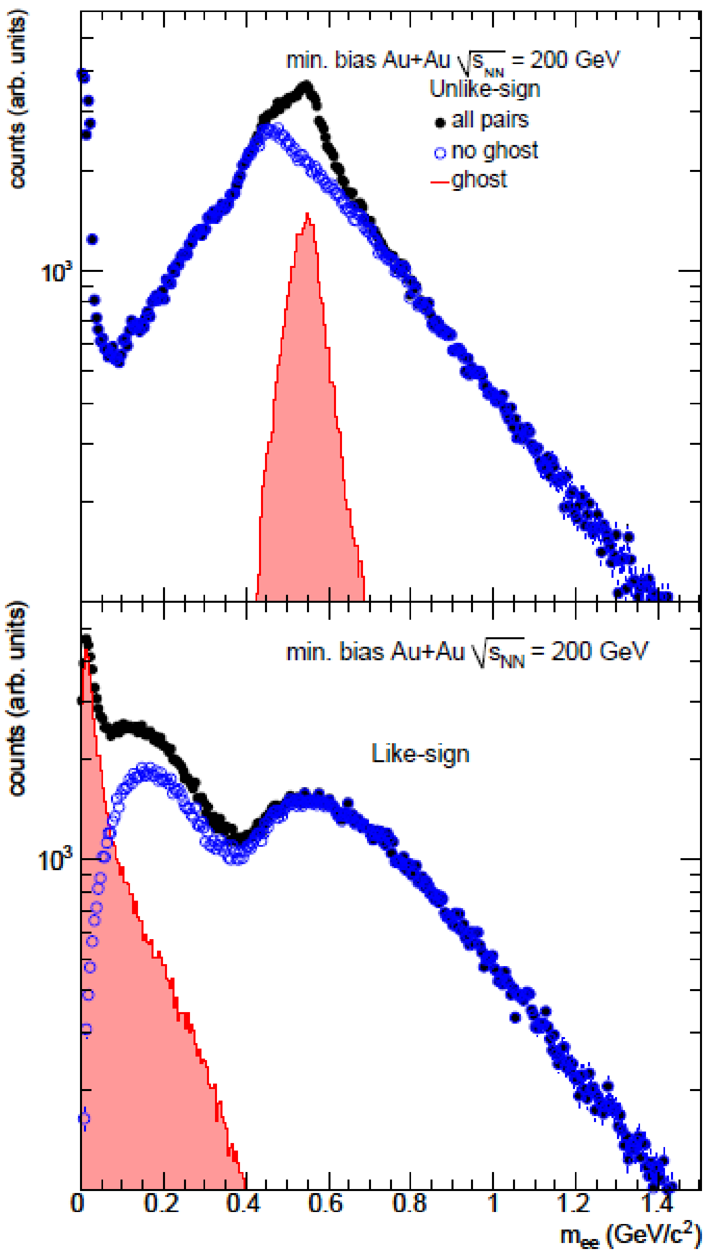
Conversion removed with orientation angle of the pair in the magnetic field





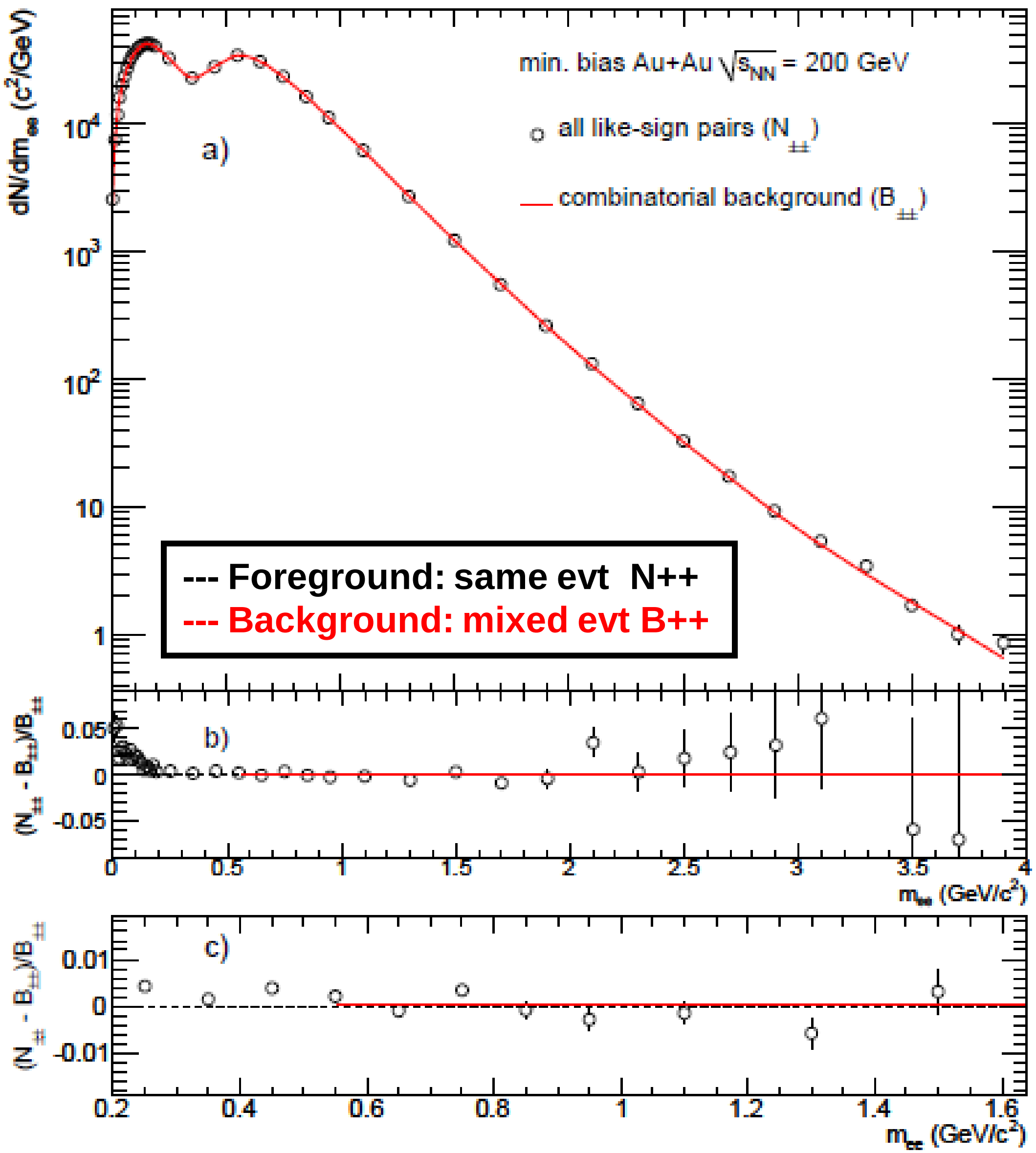


Overlapping pairs



- when a pion points to the same ring as an electron, it is associated to the same ring, therefore considered an electron
  This happens for a typical values of opening angle (different for like and unlike) which folded with the average momentum of the electron corresponds to a particular invariant mass (different for like and unlike)
  → cut: requested minimum distance between the rings (~1 ring diameter)
- Cut applied as event cut
  - Real events: discarded and never reused
  - Mixed events: regenerated to avoid topology dependence

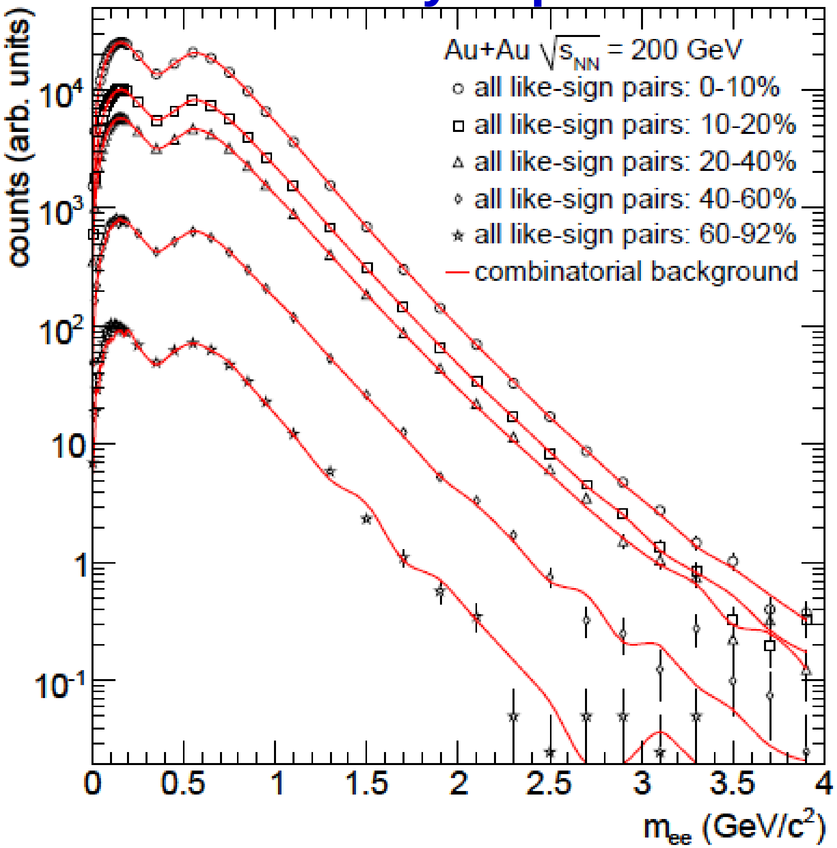
Background shape: like sign



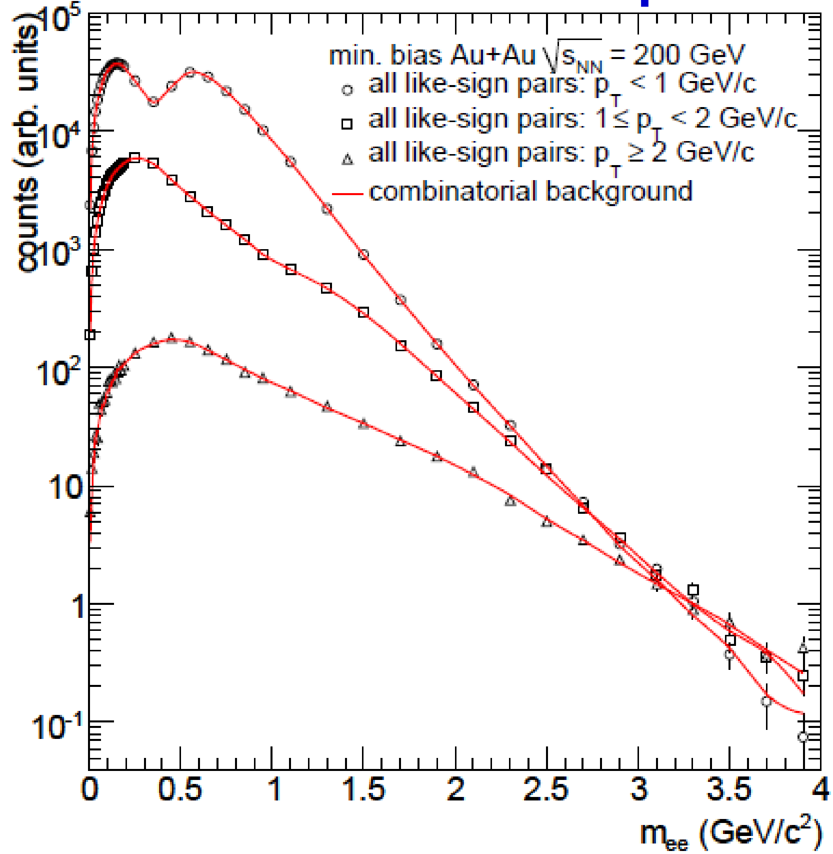
- Shape determined with event mixing
  - Excellent agreements for like-sign pairs
- Normalization of mixed pairs
  - Small correlated background at low masses
  - normalize B_{++} and B_{--} to N_{++} and N_{--} for $m_{ee} > 0.7$ GeV/c^2
  - Normalize mixed B_{+-} pairs to $N_{+-} = 2\sqrt{N_{++}N_{--}}$
  - Subtract correlated background
- Systematic uncertainties
  - statistics of N_{++} and N_{--} : 0.12%
  - different pair cuts in like and unlike sign: 0.2 %

Differential Background studies

Centrality Dependence



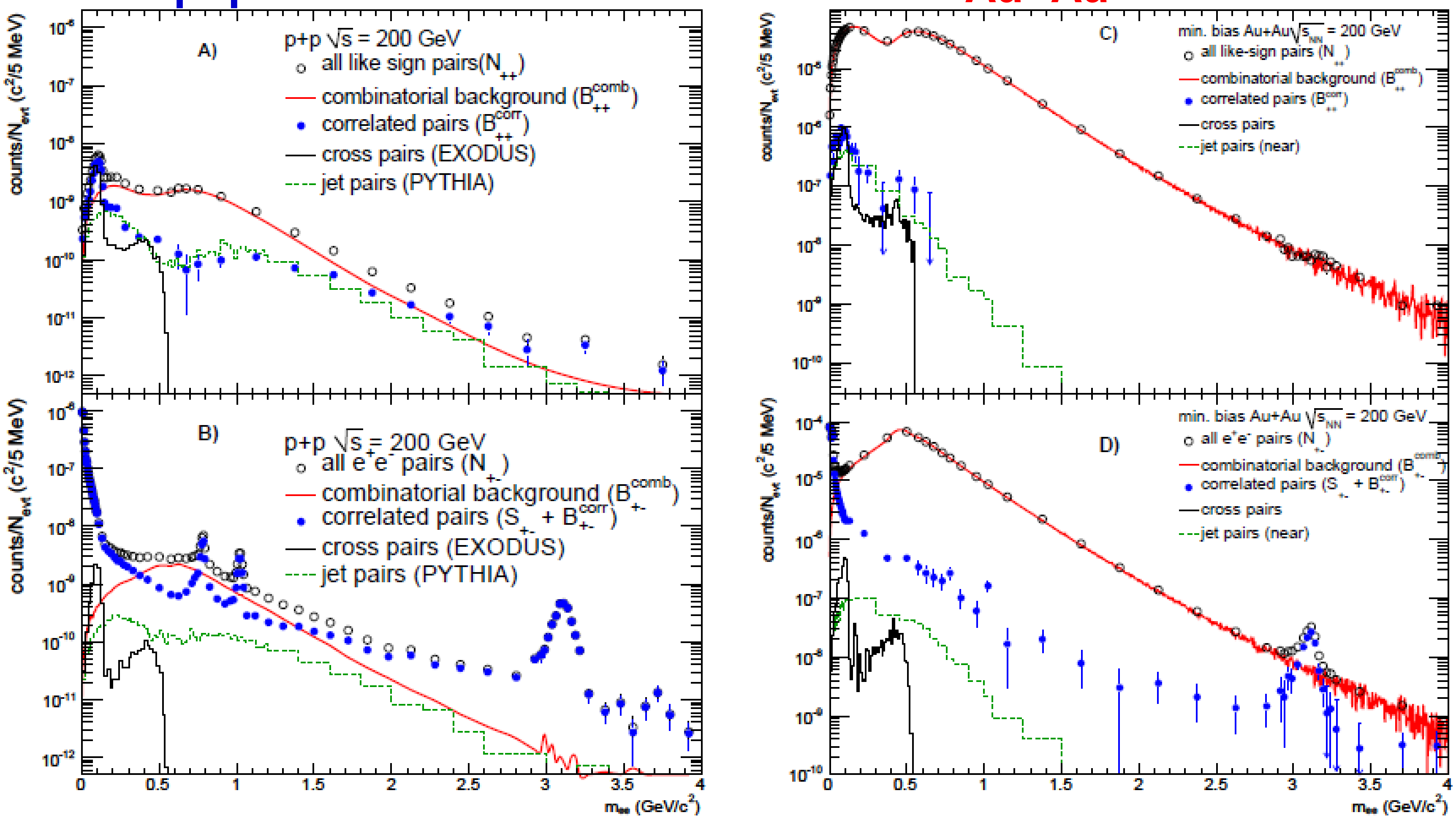
Transverse Momentum Dependence



Centrality	p_0	χ^2/NDF	χ^2 test	p-value	max dev.
0-10%	$6.3 \pm 8.8 \times 10^{-4}$	30.2/19	1.05	0.25	0.0014
10-20%	$-9.4 \pm 1.4 \times 10^{-4}$	18.6/19	0.97	0.61	0.0018
20-40%	$-2.4 \pm 1.8 \times 10^{-3}$	18.7/19	1.02	0.40	0.0034
40-60%	$-8.5 \pm 4.9 \times 10^{-3}$	21.9/19	1.65	0.02	0.0071
60-92%	$-1.8 \pm 1.6 \times 10^{-2}$	21.5/14	1.51	0.04	0.0321
00-92%	$2.6 \pm 6.3 \times 10^{-4}$	27.6/19	0.92	0.83	0.0010
$p_T < 1$ GeV/c	$9.2 \pm 5.1 \times 10^{-4}$	18.9/18	0.95	0.73	0.0011
1< $p_T < 2$ GeV/c	$-3.4 \pm 1.6 \times 10^{-3}$	27.9/18	0.91	0.84	0.0029
$p_T > 2$ GeV/c	$-9.6 \pm 5.4 \times 10^{-3}$	15.2/18	0.97	0.63	0.0038

Correlated Background

p+p **Au+Au**



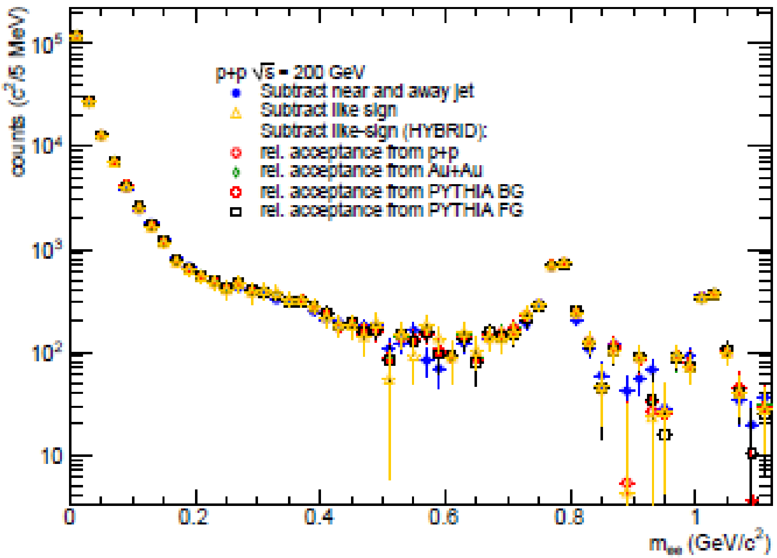
Cross pairs simulated with decay generator
Jet pairs simulated with PYTHIA
normalized to like sign data
same normalization for unlike-sign

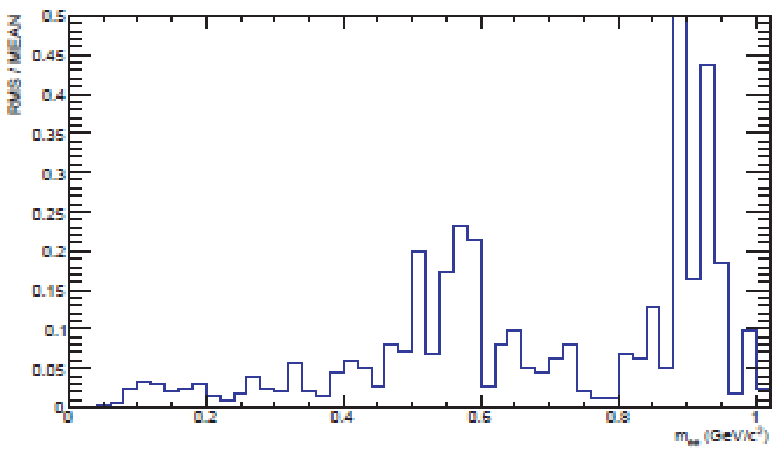
Alternative method
Correct and subtract like sign data

$$S_{+-} = N_{+-} - 2\sqrt{N_{++}N_{--}} \cdot \frac{B_{+-}^{\mathrm{comb}}}{2\sqrt{B_{++}^{\mathrm{comb}} \cdot B_{--}^{\mathrm{comb}}}}$$

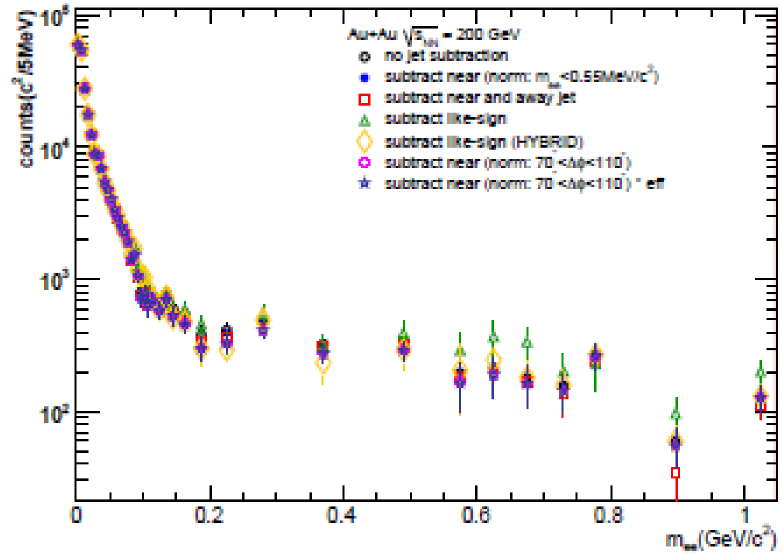
Uncertainty of Background Subtraction

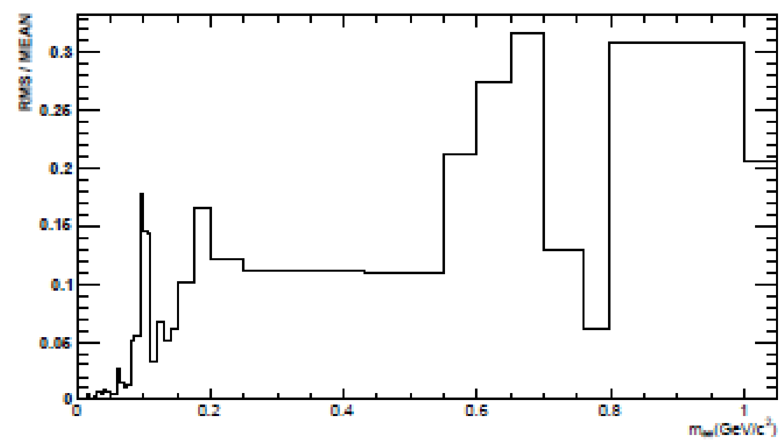
p+p





Au+Au





Cross check Converter Method

We know precise radiation length (X_0) of each detector material

The photonic electron yield can be measured by increase of additional material (photon converter was installed)

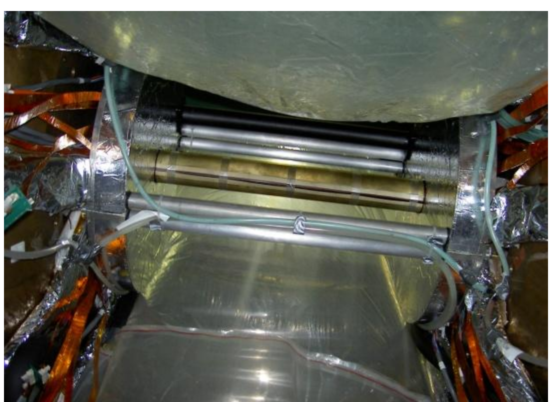
The non-photonic electron yield
does not increase

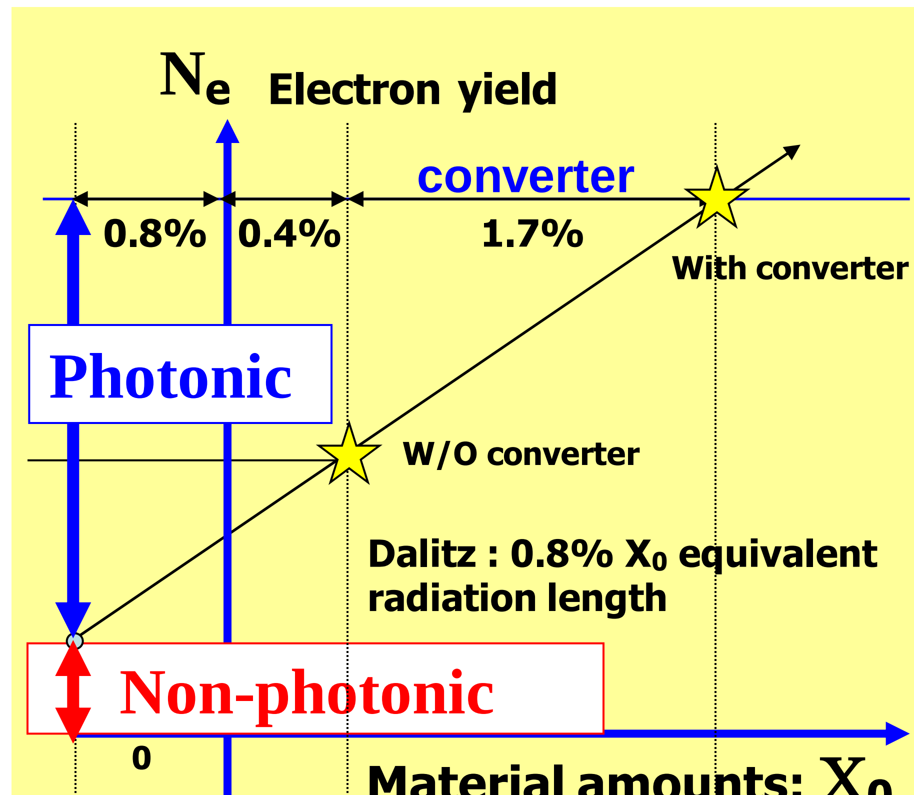
Photonic single electron: x 2.3

Inclusive single electron :x 1.6

Combinatorial pairs :x 2.5

Photon Converter (Brass: 1.7% X_0)



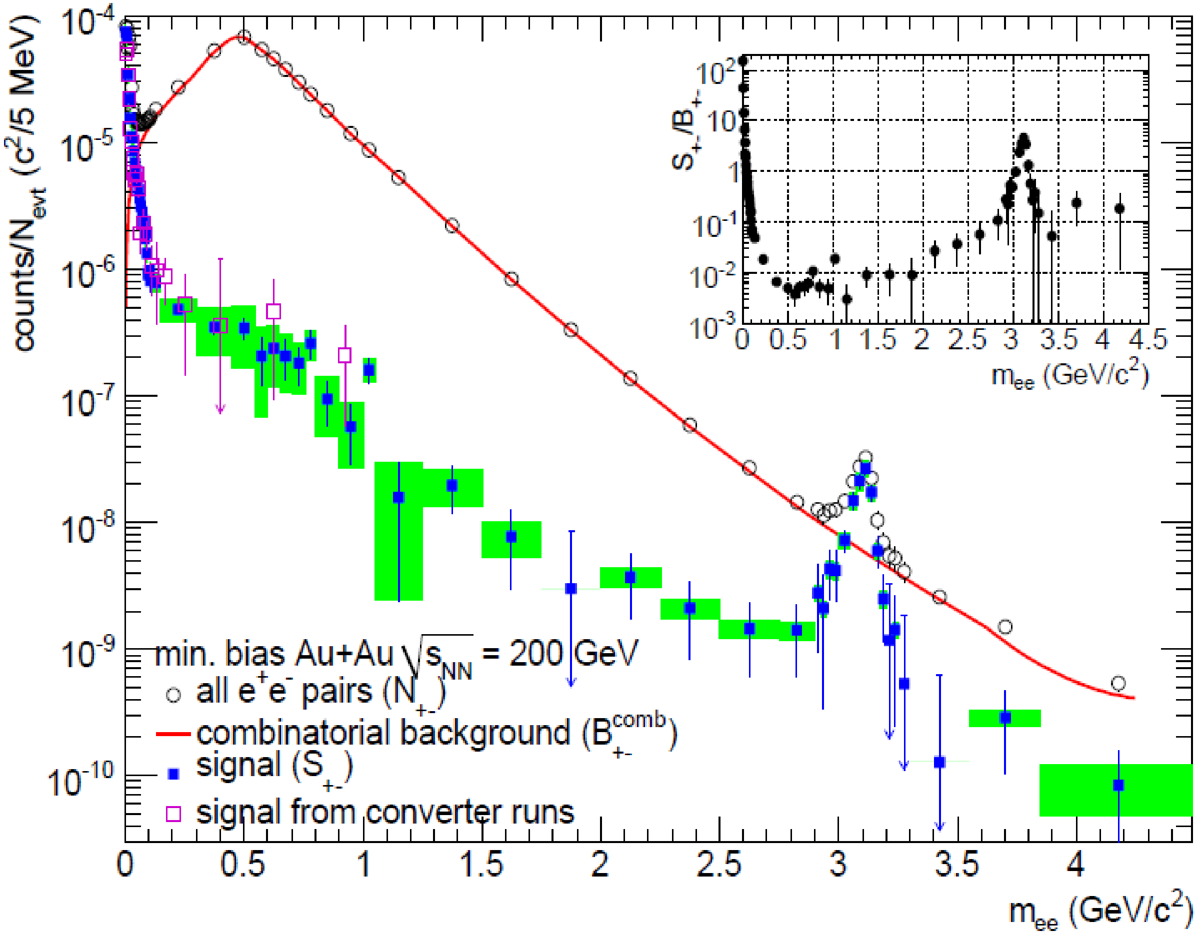


The raw subtracted spectrum

Same analysis on data sample with additional conversion material
→Combinatorial background increased by 2.5
Good agreement within statistical error

σ_{signal}/signal = $\boxed{\sigma_{BG}/BG}$ * $\boxed{\text{BG/signal}}$

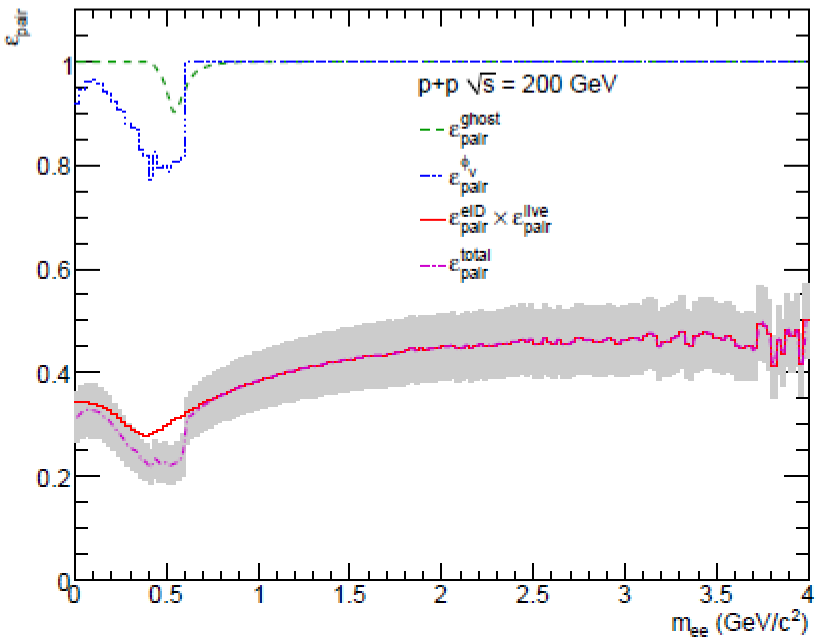
0.25% large!!!



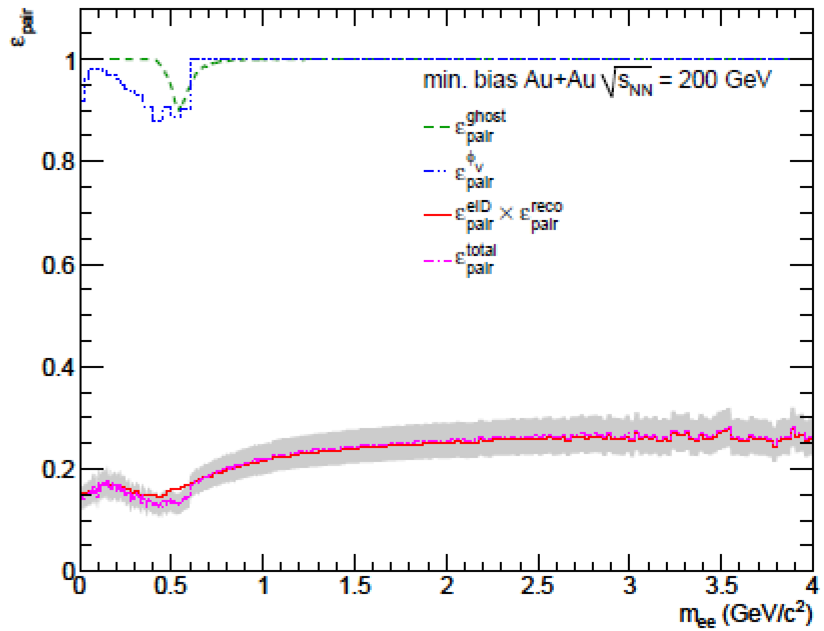
From the agreement converter/non-converter and the decreased S/B ratio
scale error = 0.15±0.51%
(consistent with the 0.25% error we assigned)

Efficiency Correction

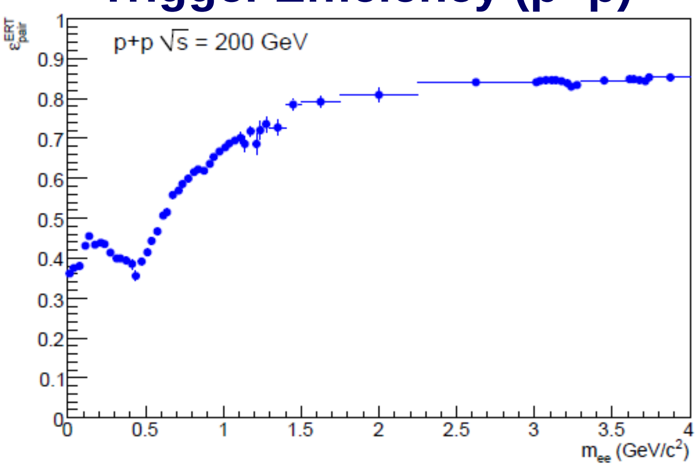
p+p



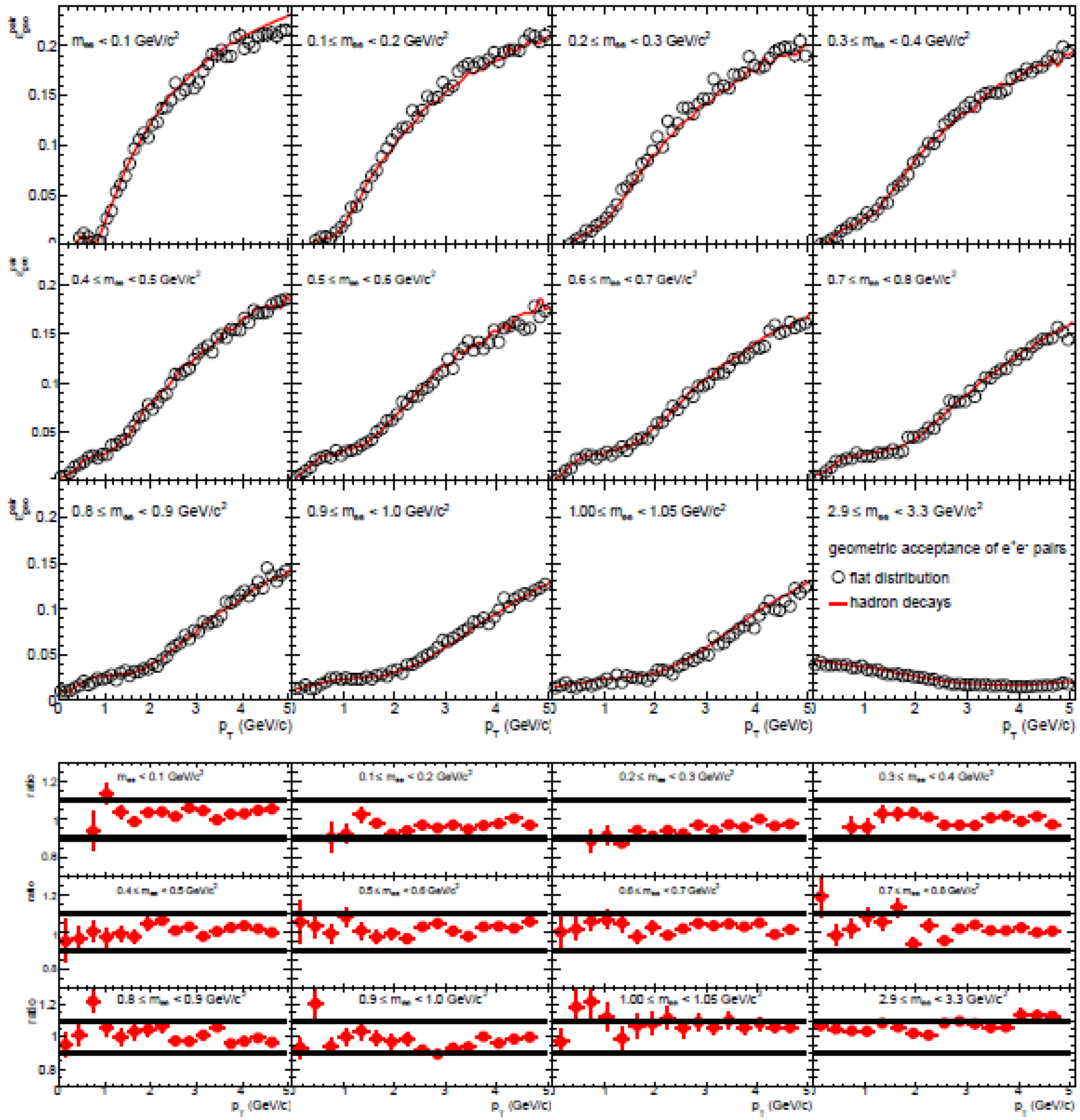
Au+Au



Trigger Efficiency (p+p)



Acceptance Correction

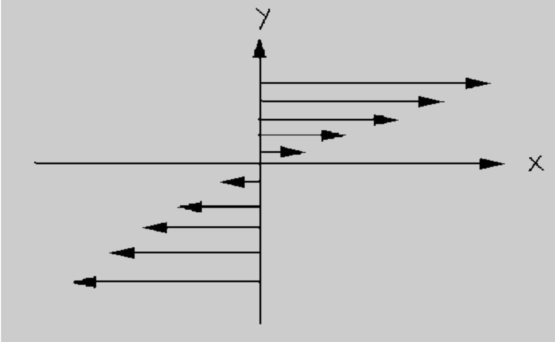


Other measurements

Viscosity of "near perfect" fluid

- viscous fluid
  - supports a shear stress
  - viscosity η defined as
  - dimensional estimate

$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



$$\eta \approx (\boldsymbol{momentum\ \ density}) \times (\boldsymbol{mean\ \ free\ \ path})$$

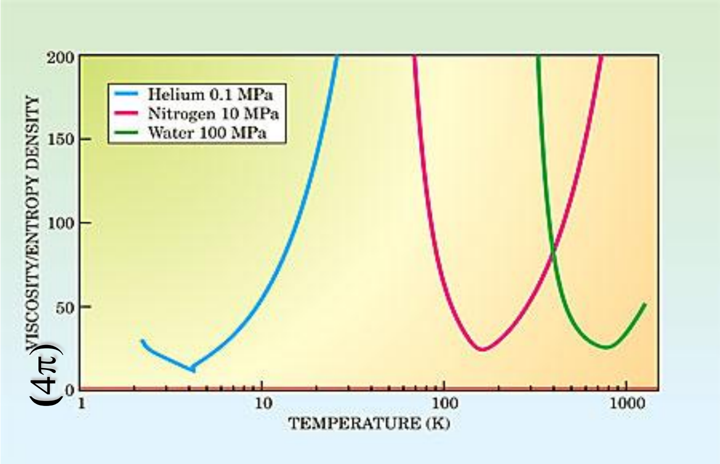
$$\approx \boldsymbol{n\ \bar{p}\ mfp = n\ \bar{p}\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma}}$$

- Large cross sections → small viscosity
- early hydrodynamic calculations of the medium at RHIC have assumed zero viscosity: η = 0, i.e. a "perfect fluid"
- conjectured lower quantum limit $\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$
  - derived first in (P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005)
  - motivated by AdS/CFT (Anti de Sitter space / Conformal Field Theory) correspondence (J. Maldacena: Adv. Theor. Math. Phys. 2, 231, 1998)

H_2O (at normal conditions): η/s ~ 380ħ/4π
He (at λ point): η/s ~ 9 ħ/4π

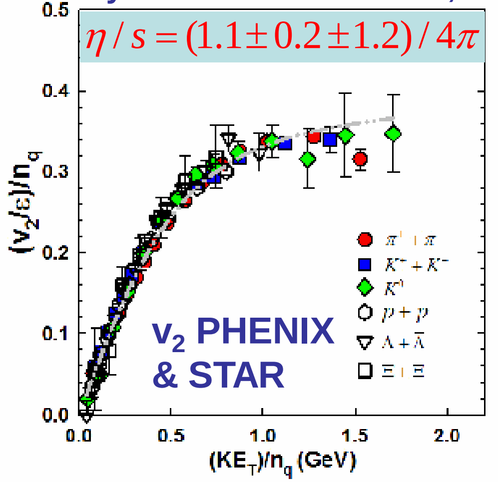
- "ordinary" fluids
  - Gas: η/s↑ for T↑ (because <p> ↑) divergent viscosity of ideal gas
  - Liquid: η/s↓ for T↑ (lower T easier to transport p)

  → η/s has a minimum at the critical point?
- "RHIC fluid"?

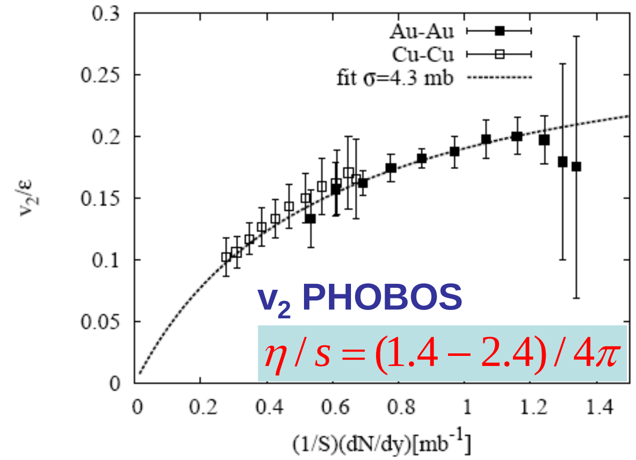


Measuring viscosity

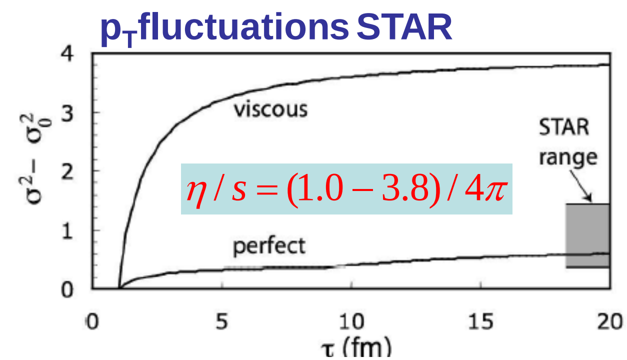
R. Lacey et al.: PRL 98:092301, 2007



H.-J. Drescher et al.: arXiv:0704.3553

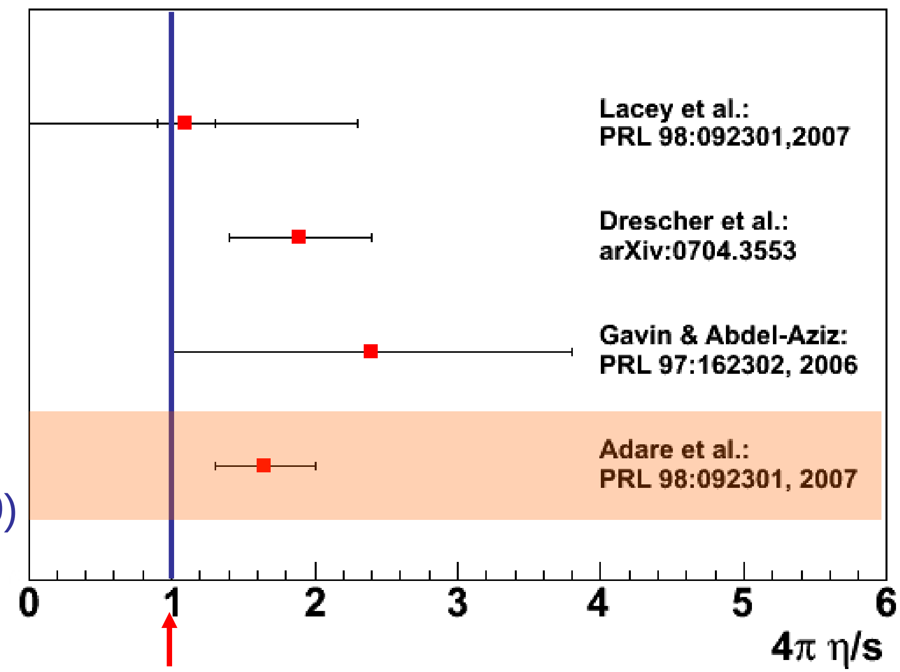


S. Gavin and M. Abdel-Aziz: PRL 97:162302, 2006



- need observables that are sensitive to shear stress
- damping (flow, fluctuations, heavy quark motion) ~ η/s
- estimates of η/s based on flow and fluctuation data
  - indicate small value as well
  - close to conjectured limit
  - significantly below η/s of helium (4πη/s ~ 9)
- In chiral limit: $\eta/s = 15/16\pi * f_4/T^4$
  - $T \to 0$: $\eta/s \to \infty$
  - $T \to \infty$: $\eta/s \sim 1/g^4$ where $g^2 \sim 1/\ln(T/\Lambda_T)$

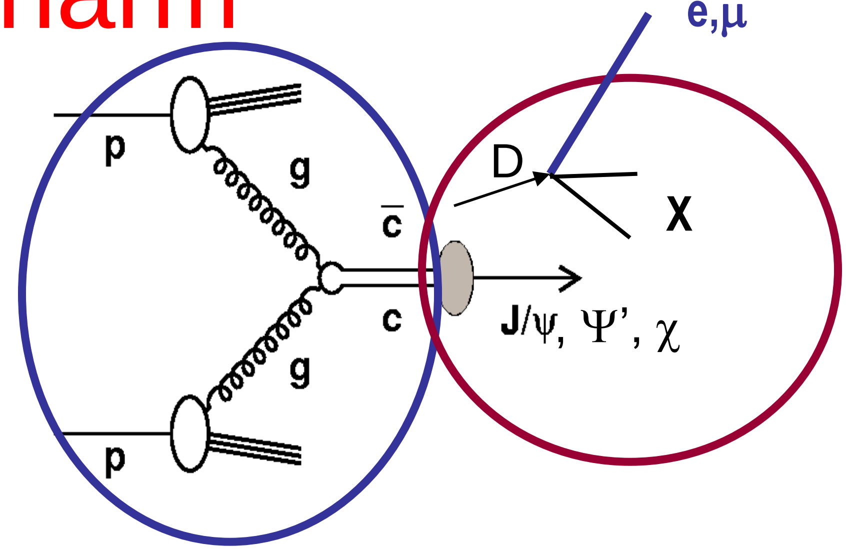
  → Minimum at T_c?



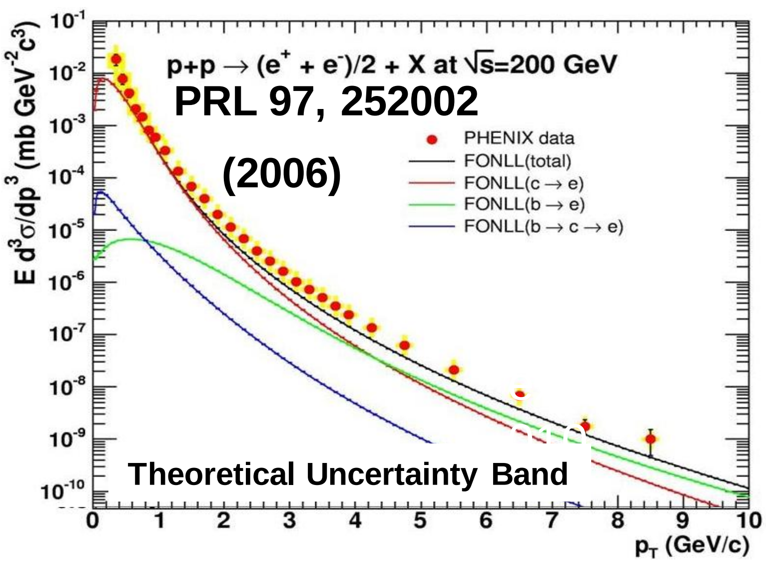
conjectured quantum limit

Open Charm

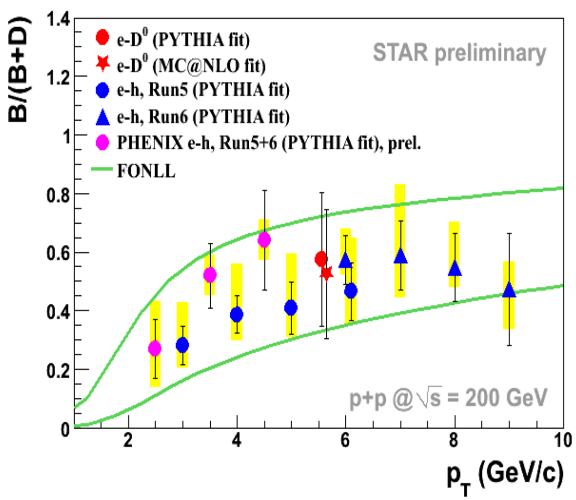
– hard process ($m_q \gg \Lambda_{QCD}$)
- at leading order (LO):
  – quark-antiquark annihilation
  – gluon fusion
- higher order processes important at large $\sqrt{s}$



p+p: BASELINE



BOTTOM CONTRIBUTION

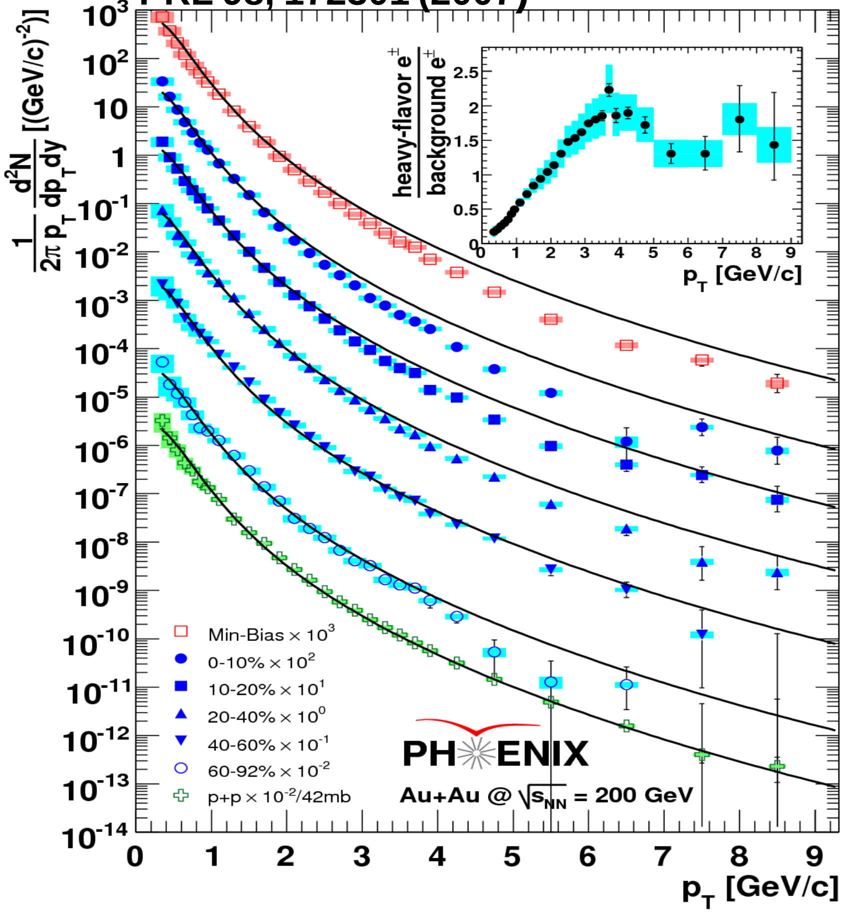


- comparison with FONLL calculation:
  – Fixed Order Next-to-Leading Log pQCD
  (Cacciari, P. Nason, R. Vogt PRL95,122001 (2005))
- bottom is important at high p_T!

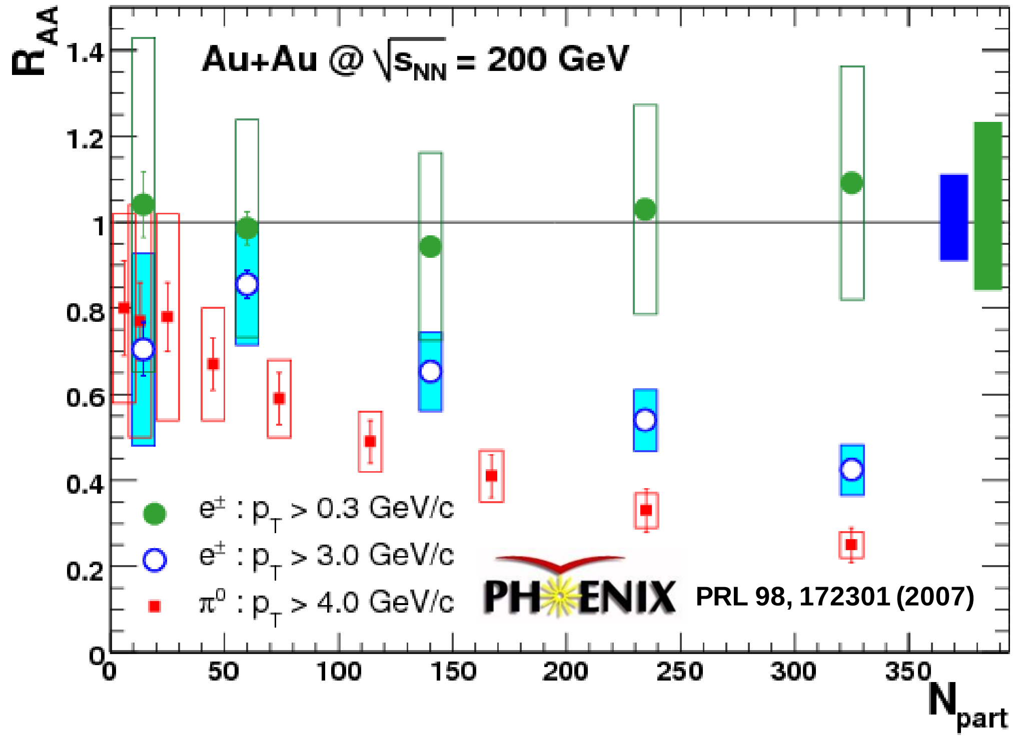
- electron-hadron correlations
  – sensitive to bottom vs. charm due to the different masses of D and B mesons

Probing the medium in Au+Au

PRL 98, 172301 (2007)

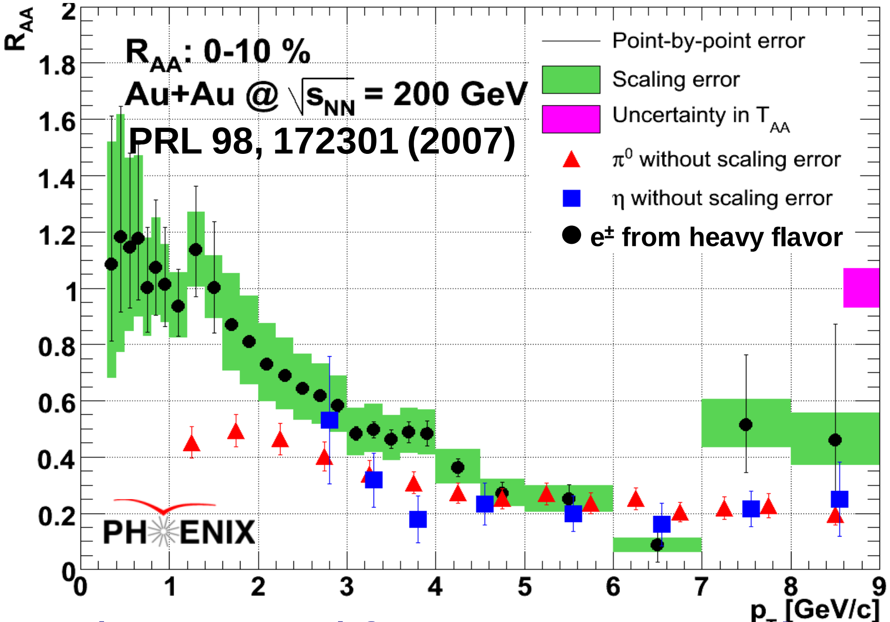


$$R_{AA} = \frac{Yield\ \ in\ \ Au+Au}{N_{binary} \times Yield\ \ in\ \ p+p}$$



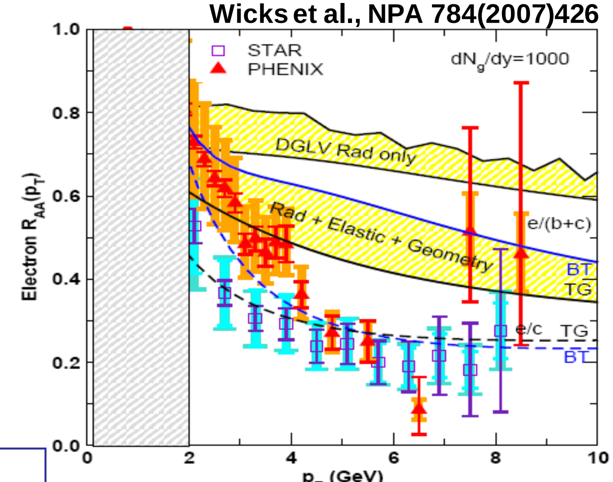
- binary scaling of total e± yield from heavy-flavor decays
  → hard process production and no destruction (as expected)
- high p_T e± suppression increasing with centrality
  – similar to π^0 suppression (a big surprise)

Nuclear modification factor R_{AA}



- similar to light hadrons
  !!! kinematics: $p_T(e^{\pm}) < p_T(D)$
  - intermediate p_T: quark mass hierarchy
  - high p_T: $R_{AA}(e^{\pm}) \sim R_{AA}(\pi^0) \sim R_{AA}(\eta)$
- bottom contribution at high p_T ???

Wicks et al., NPA 784(2007)426



- testing ground for parton energy loss (ΔE) models
  - radiative ΔE only
    would need a very large colour opacity with static scattering centers (odd for b)

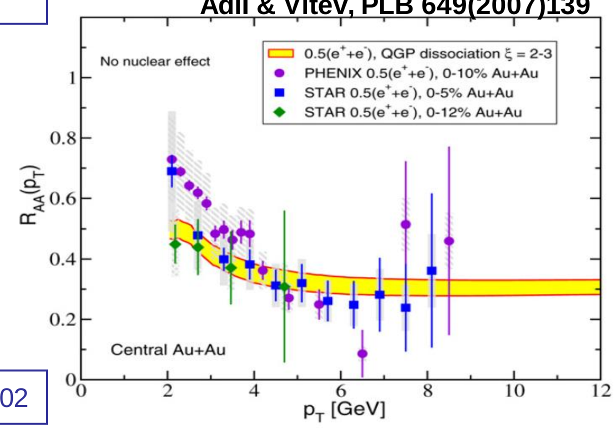
    Djordjevic et al., PLB 632(2006)81
    Armesto et al., PLB 637(2006)362)
  - collisional ΔE included
    reduces R_{AA} significantly, but the challenge persists (also for light quarks)

    Wicks et al., NPA 784(2007)426
    van Hees & Rapp, PRC 73(2006)034913)
- alternative approaches

  Adil & Vitev, PLB 649(2007)139
  - collisional dissociation of heavy mesons
  - contribution from baryon enhancement

  Sorensen & Dong, PRC 74(2006)024902

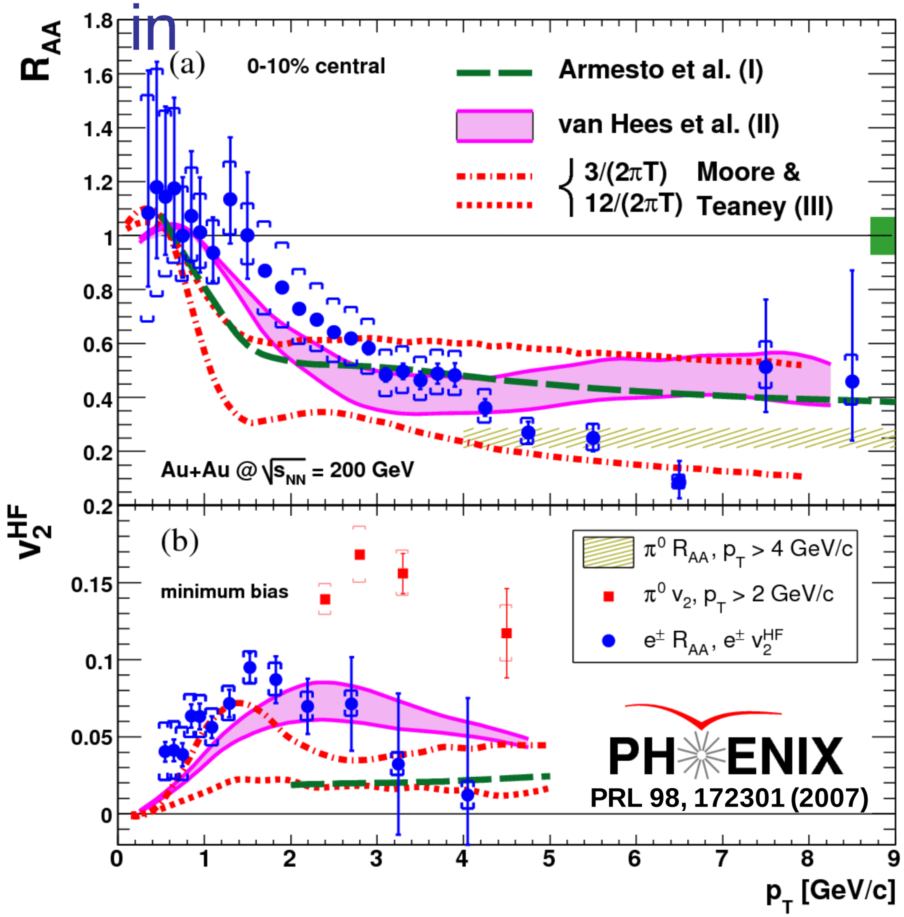
Adil & Vitev, PLB 649(2007)139



Does charm thermalize?

- transport of heavy quarks in the medium
  - Rapp & van Hees (PRC 71, 034907 (2005))
    - small relaxation time required for simultaneous fit of R_{AA} and v_2

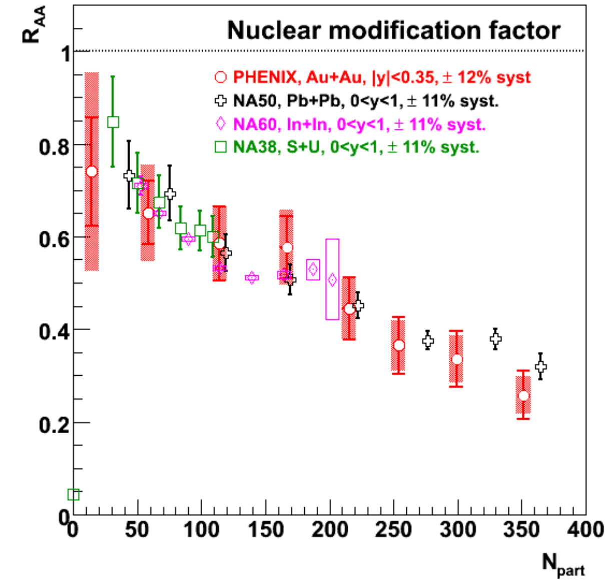
    → diffusion coefficient D_{HQ}
  - Moore & Teaney (PRC 71, 064904 (2005))
    - difficulties to describe R_{AA} and v_2 simultaneously
    - relate D_{HQ} with viscosity density of the medium



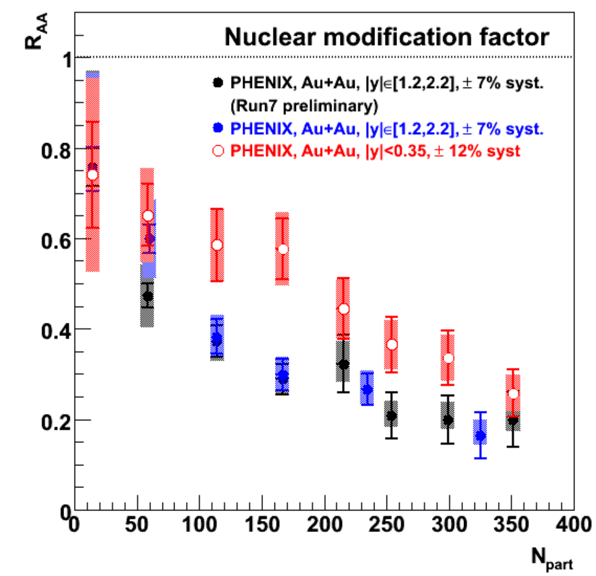
- suggests
  - $\eta/s = (1.3\text{-}2.0)/4\pi$
  - close to a conjectured lower bound ($\eta/s = 1/4\pi$)
- consistent with other estimates of η/s based on flow and fluctuation measurements for light hadrons

Heavy quarkonia at RHIC

- Same suppression observed at RHIC (T~400 MeV) and SPS (T~200MeV) !?!
- At RHIC: forward rapidity (where energy density should be smaller) suppressed more than mid-rapidity !?!

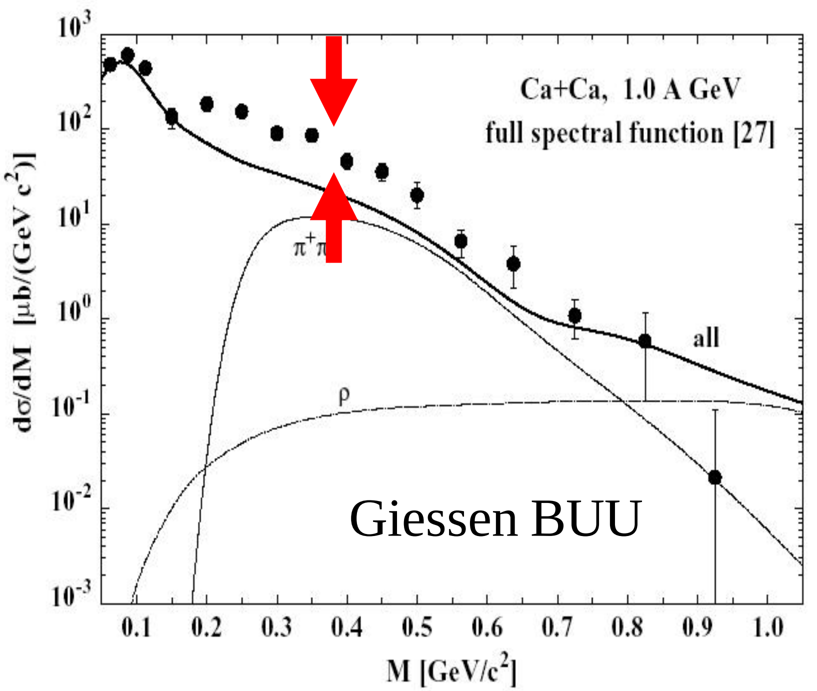


- Coalescence:
  cc regeneration compensates screening (there are more cc pairs at mid-rapidity)
  → J/ψ produced by statistical hadronization at the phase boundary as all other hadrons?
- Sequential dissociation:
  only ψ' and χ_c (~40% feed-down to J/ψ) melt
  Direct J/ψ survives at RHIC → $T_0<2T_c$
- Saturation could suppress forward J/ψ in AuAu



Other dilepton measurements

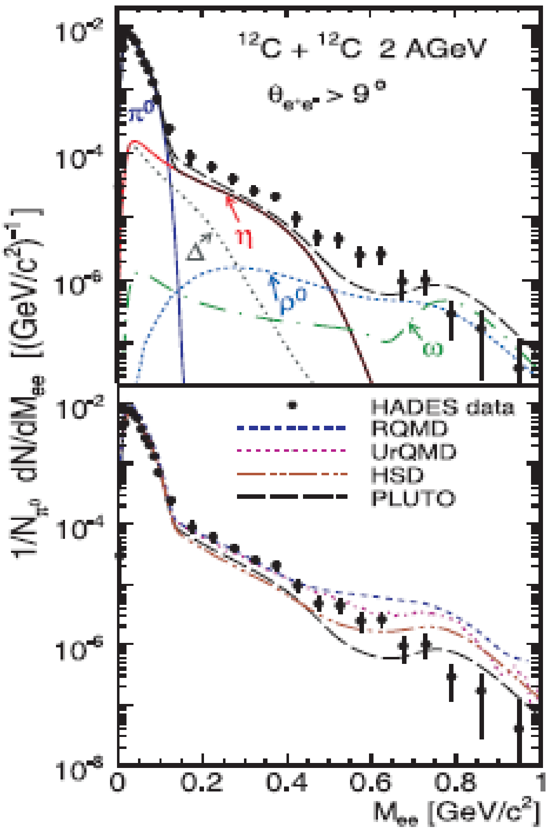
Dielectron pairs –the history I
low energy



Data: **R.J. Porter et al.:** PRL 79 (1997) 1229
BUU model: **E.L. Bratkovskaya et al.:** NP A634 (1998) 168
transport + in-medium spectral functions

DLS measured an excess of dielectron pairs over the expected yield
Never fully explained

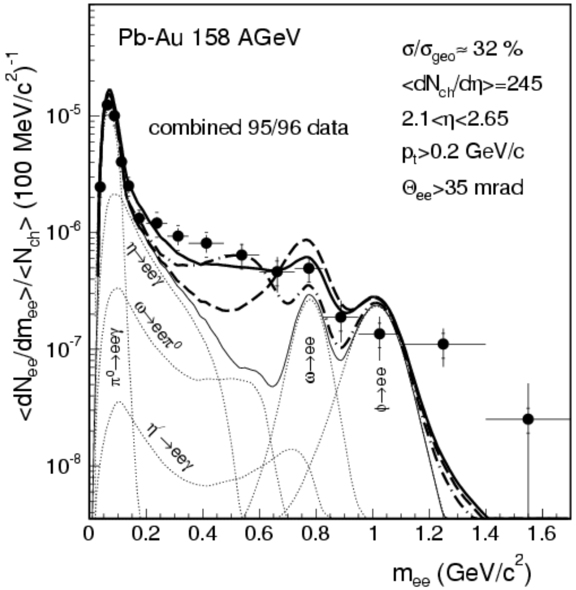
HADES (high acceptance, resolution, rate capability): first measurements



excess over standard known sources compared with theory calculations
Agreement with DLS
Excess possibly explained with bremsstrahlung

Dielectron pairs –the history II

high energy



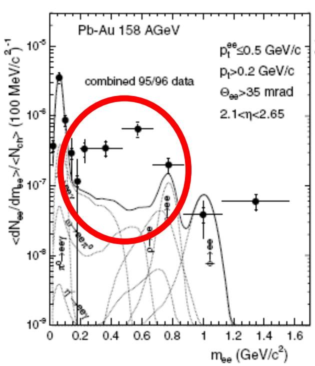
CERES measured an excess of dielectron pairs over the expected yield, rising faster than linear with centrality

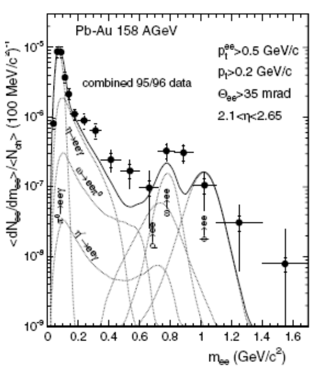
Attributed to in-medium modification of ρ spectral function from $\pi\pi$ annihilation

Thermal radiation: window 0.5 to 2.5 GeV

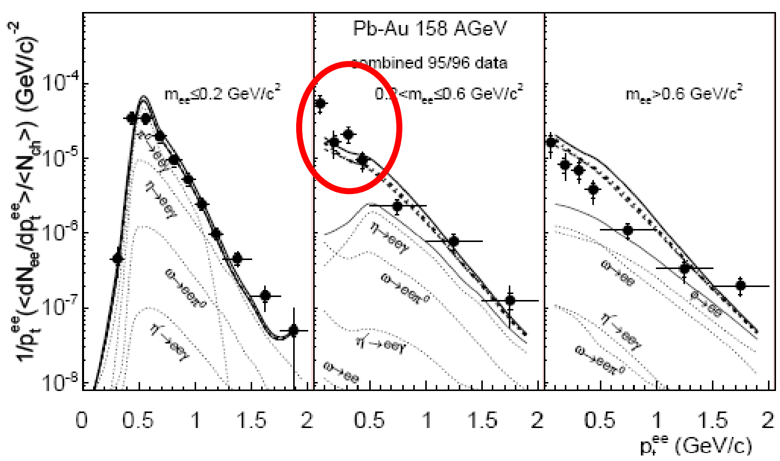
- direct photons (HELIOS, WA80/98)
- di-lepton pairs (NA38/50)

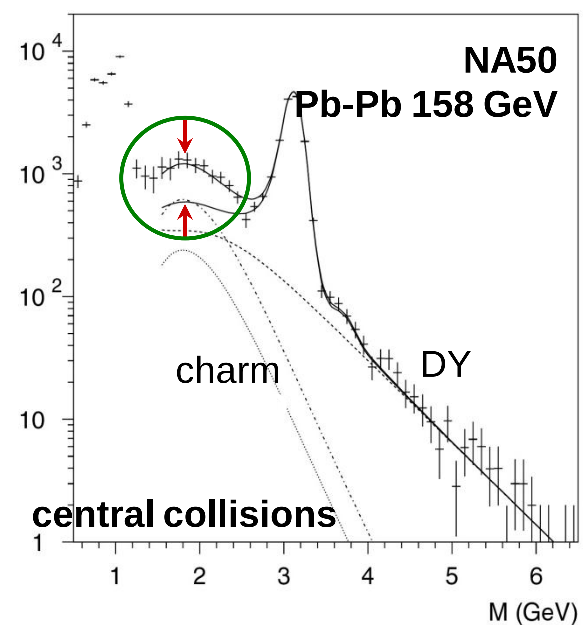
Excess of dilepton yield measured above charm pairs



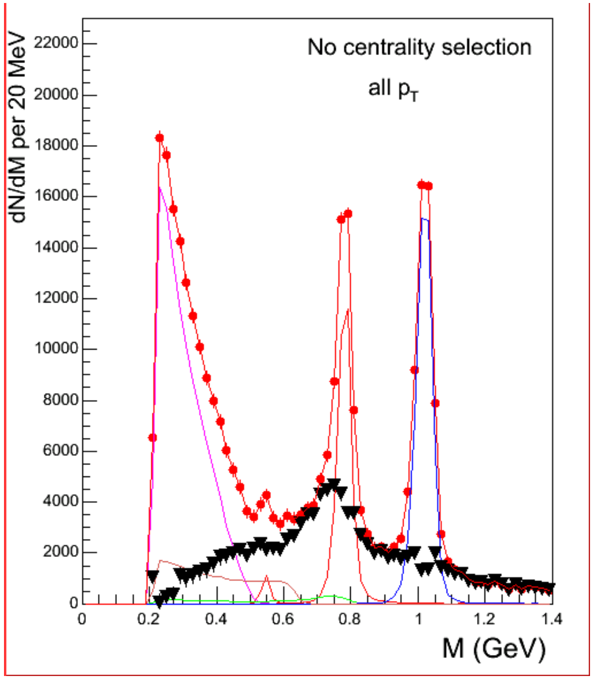


The enhancement is concentrated at low p_T





Dielectron pairs –the history II



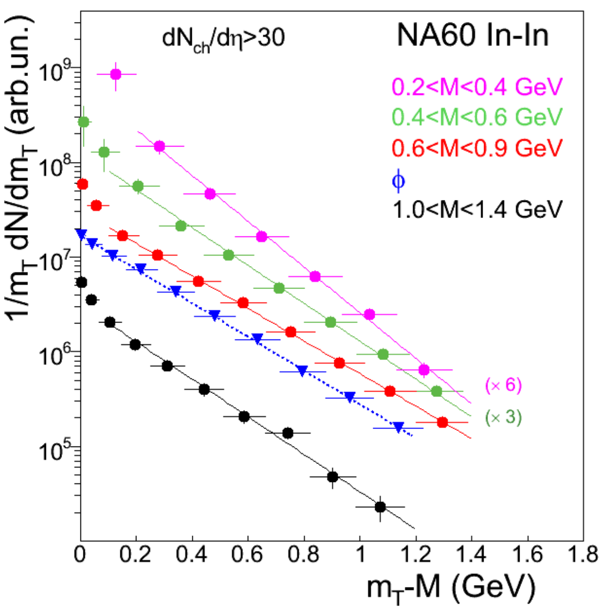
III generation

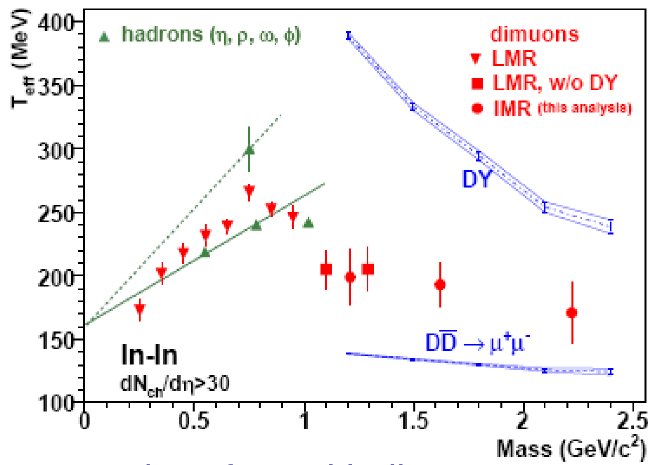
NA60 First measurement of the ρ spectral function

Clear excess above the cocktail ρ, centered at the nominal ρ pole and rising with centrality

p_T spectra: Steepening at low m_T contrary to expectation for radial flow; relation to pion spectra?

Monotonic flattening of spectra with mass up to M=1 GeV





Strong rise of T_{eff} with dimuon mass, followed by a sudden drop for M>1 GeV

Rise reminiscent of radial flow of a hadronic source

Drop signals sudden transition to low-flow source, i.e. source of partonic origin (here qq→$\mu\mu$)

IMR: measurement of muon offsets $\Delta\mu$ attributes the IMR excess to prompt dimuon