Electromagnetic Particle Production at PHENIX

~Study of QGP with photon probes at RHIC-PHENIX~

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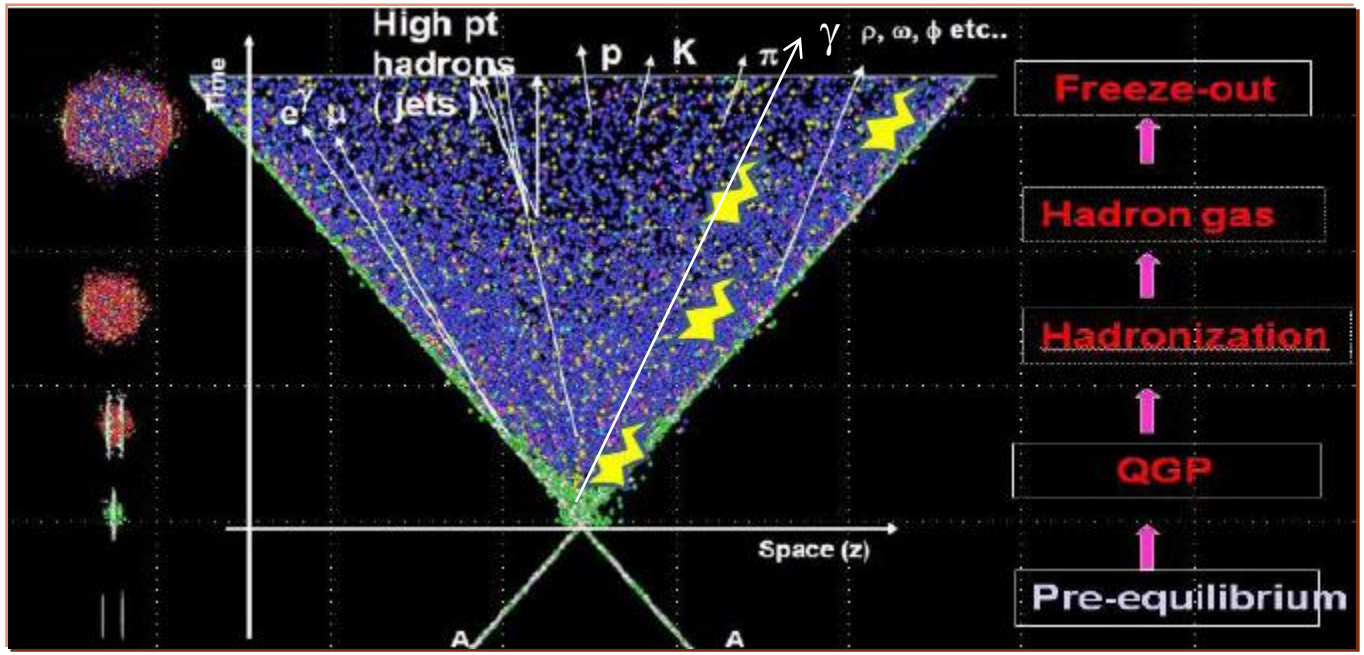
PHENIX

Picture of heavy ion collisions



- High pT hadrons (Leading jets)
  Partons pass through the medium and lose their energy.
  Sensitive to the **density** of the medium.
- Low p_T direct photons (Not from hadron decay)
  No strong interaction
  Sensitive to the **initial temperature** of the medium

High pT hadron (Leading jet)

- Recent experimetal results
- Comparison with theoretical calculations

Parton energy loss mechanism

- **Jet Quenching**
  - Suppression of π^0 yields in central collision
  - **Energy loss** has been considered totally due to gluon radiation in the medium
- **Parton Energy Loss vs. Path length (L)**

Collisional Process

$$E_{loss} \propto L$$

Relation by GLV method (Radiative E-loss)

$$\Delta E = \frac{9\pi C_R \alpha_s^3}{4} \int_0^L d\tau \, \rho_{eff}(\tau, x(\tau)) \, \tau \ln\left(\frac{1}{x_c}\right), \quad x_c = \frac{\mu^2 L}{2E}$$

If ρ_{eff} **is constant** (independent of time),

Radiative Process

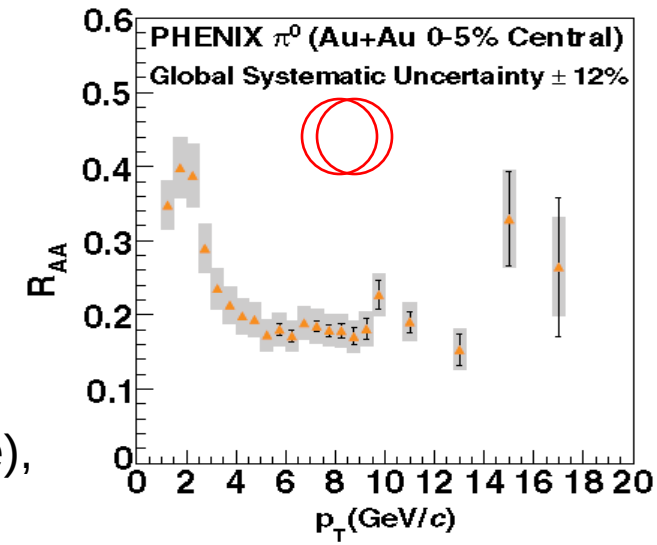
$$E_{loss} \propto L^2$$

Nuclear Modification Factor

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

Average number of nucleon-nucleon collisions

$$\langle N_{coll} \rangle = \sigma_{pp}^{inel} \langle T_{AA} \rangle$$



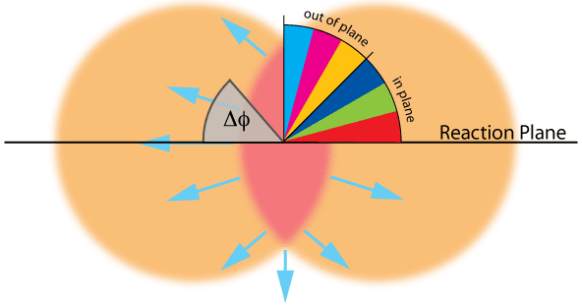
PRC **77**, 064907 (2008)

- Path length dependence of energy loss

First step : Measurement of R_{AA} for each **azimuthal angle**

Measurement of $R_{AA}(p_T, L)$

- **Relation between path length (L) and azimuthal angle ($\Delta\phi$)**



$$R_{AA}(p_T, L) \leftrightarrow R_{AA}(p_T, \text{centrality}, \Delta\phi)$$

- **Extraction of $R_{AA}(p_T,\Delta\phi)$**

$$R_{AA}(p_T,\Delta\phi) \cong R_{AA}(p_T) \times \frac{N(p_T,\Delta\phi_i)}{\sum_{\phi_i} N(p_T,\Delta\phi_i)}$$

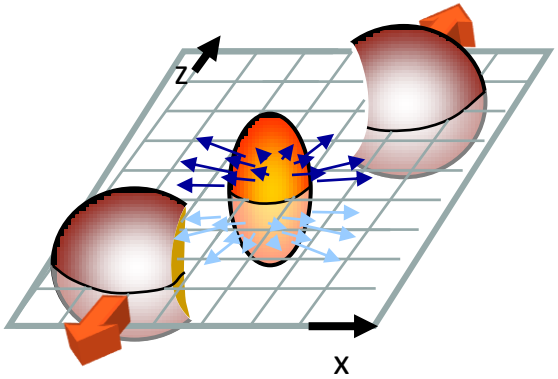
$$N(p_T,\Delta\phi_i) \cong N(1+2v_2\cos(2\Delta\phi_i))$$

- **Anisotropy v_2 at high p_T**

Spatial anisotropy in non-central collisions should make effect on R_{AA} at each azimuthal angle from the reaction plane.

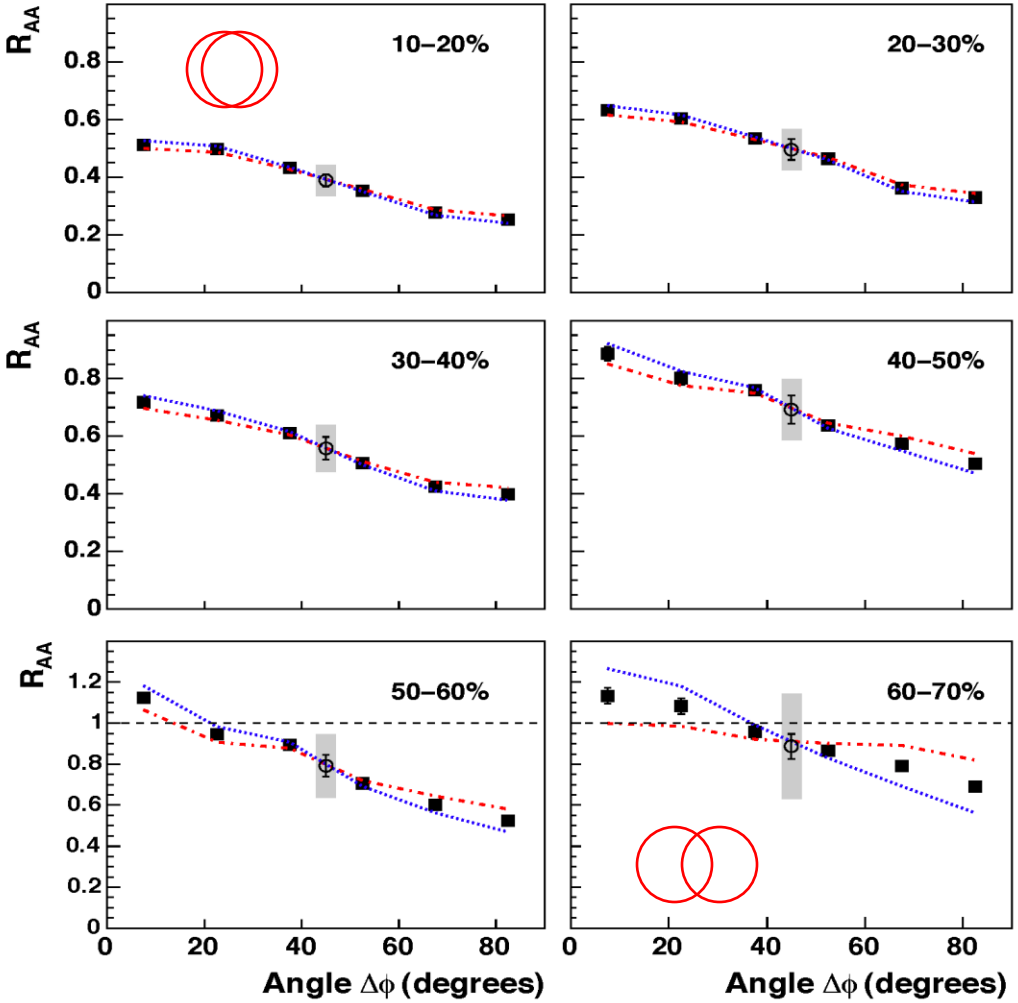
$$\frac{dN}{d(\phi-\Psi)} = N[1+\Sigma 2v_n\cos(n(\phi-\Psi))]$$

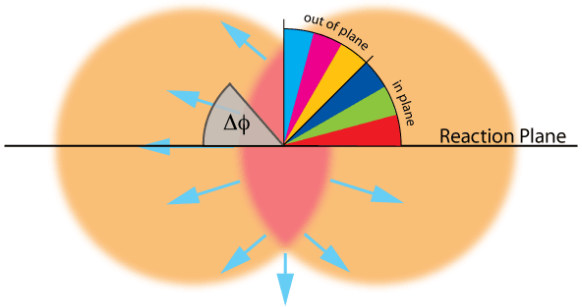
ϕ : Azimuthal angle of emitted particles
Ψ : Azimuthal angle from reaction plane



Azimuthal angle dependence of $R_{AA}(\pi^0)$

Phys. Rev. C 76, 034904 (2007)





For peripheral collisions
- Energy loss : Small
- Difference of path length : Large

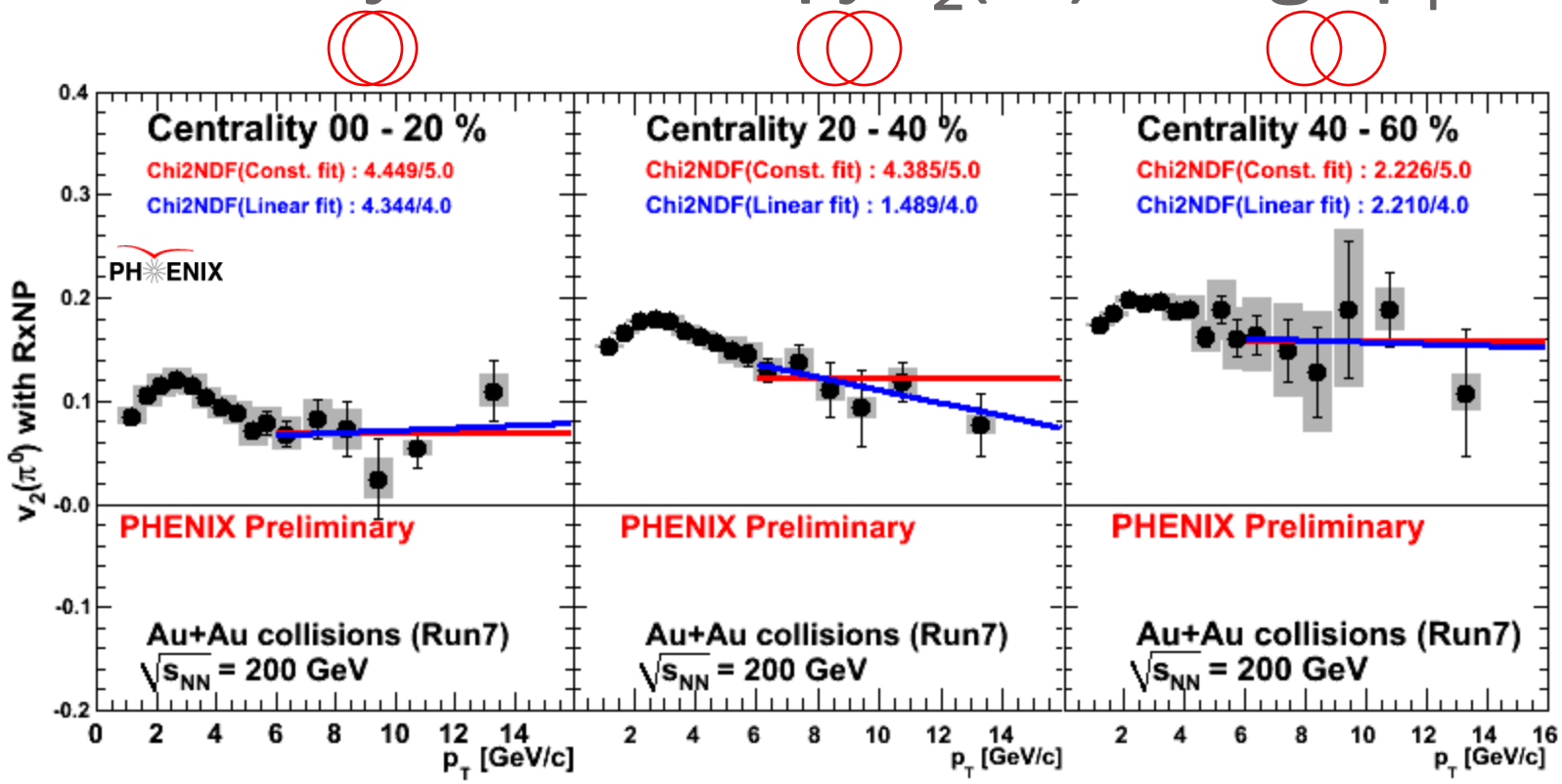
For **all centrality**,

$$\frac{R_{AA}(\Delta\phi = 0)}{R_{AA}(\Delta\phi = \pi/2)} \sim 2$$

Collective flow effect?
→ v_2 at high p_T should be small
→ Measure v_2 for possible higher p_T
→ Measure $R_{AA}(p_T, \Delta\phi)$ at higher p_T

$3 < p_T < 5$ GeV/*c*

Tendency of anisotropy $v_2(\pi^0)$ at high p_T



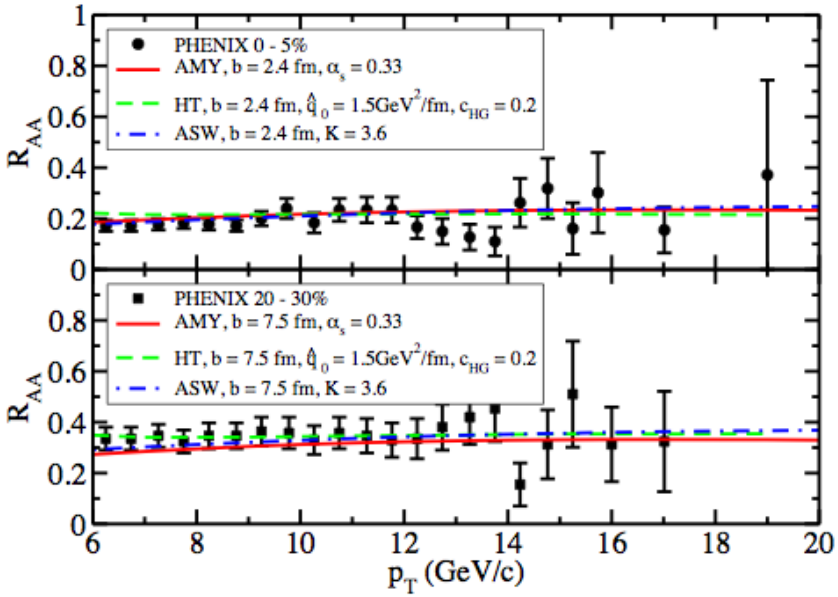
$v_2(\pi^0)$ at pT > 10 GeV/c (All the data)
$v_2(\pi^0)$ at pT < 10 GeV/c (A part of all the data)

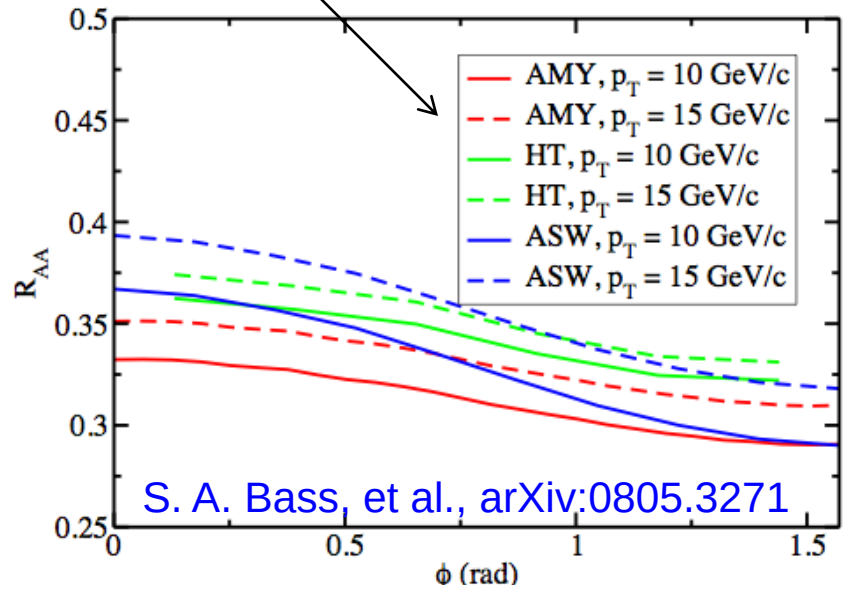
Blue : Liner function ($f(v_2) = ax + b$)
Red : Constant ($f(v_2) = c$)

v_2 (Most central and Peripheral)	Non-zero and constant
v_2 (Mid-central)	Non-zero, but decrease at high pT

Theorist's approach to $R_{AA}(p_T, \Delta\phi)$

ASW, HT and AMY set same condition (ex. Initial state, Fragmentation function).
Difference : transport coefficient $\hat{q}_0$(GeV^2/*c*), ASW(20), HT(3.4) and AMY(5.5)

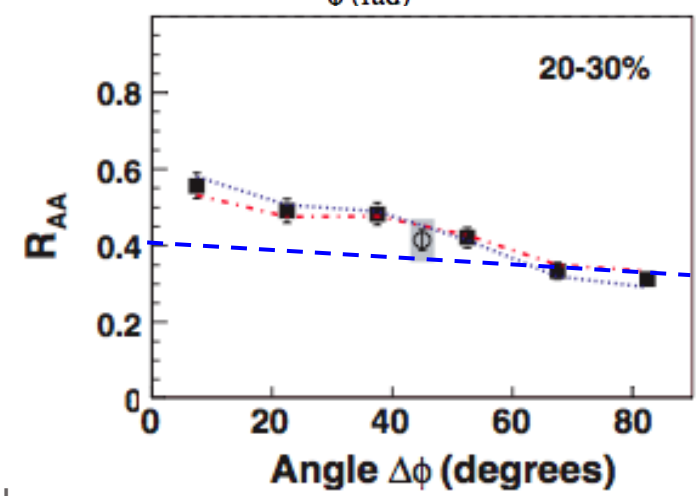




S. A. Bass, et al., arXiv:0805.3271

$R_{AA}(p_T)$ vs. p_T is **GOOD AGREEMENT !**

- ASW model has largest variation in the above models due to set large q-hat.
- **The data has much larger variation** than ASW(p_T=15 GeV/*c*).

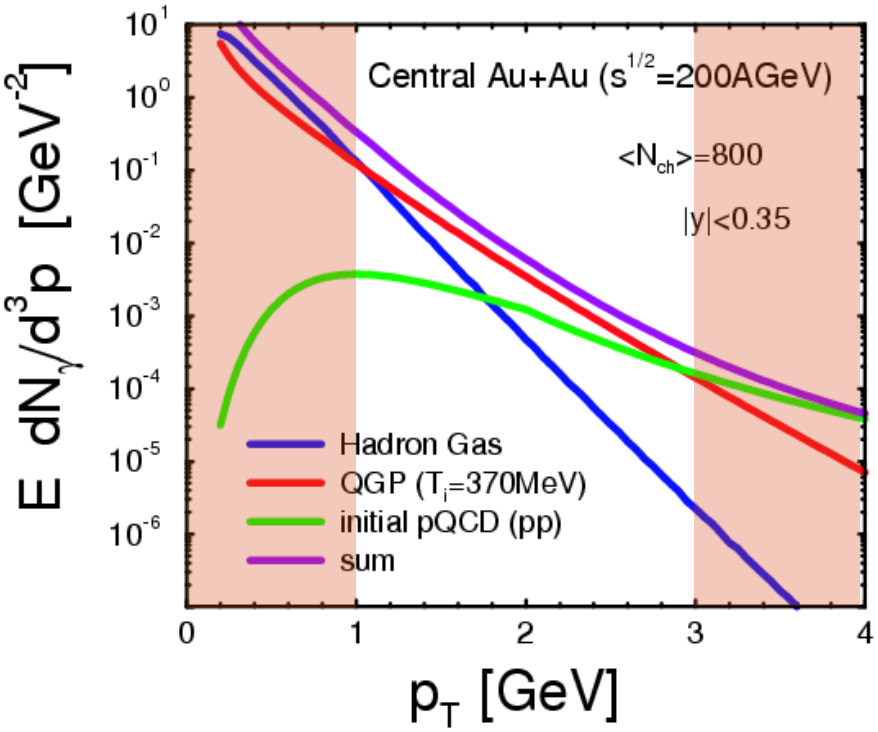


Low p_T direct photon

M_{e+e-}<300 MeV/c^2 && 1<p_T<5 GeV/c
in p+p and Au+Au collisions

Photons from thermally-equilibrated medium

Turbide, Rapp, Gale, Phys. Rev. C 69 (014903), 2004

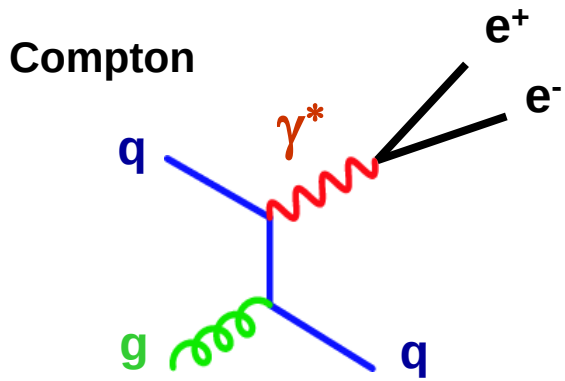


- Thermally-equilibrated medium at RHIC is expected to radiate photons.
  - Direct photon (Thermal photons) from partonic phase
- Predicted to be dominant source of direct photons for $1<p_T<3$ GeV/*c* in Au+Au
- Huge background of photons from hadron decay for $1<p_T<3$ GeV/*c*

Alternative photon measurement : $\gamma^* \rightarrow e^+e^-$

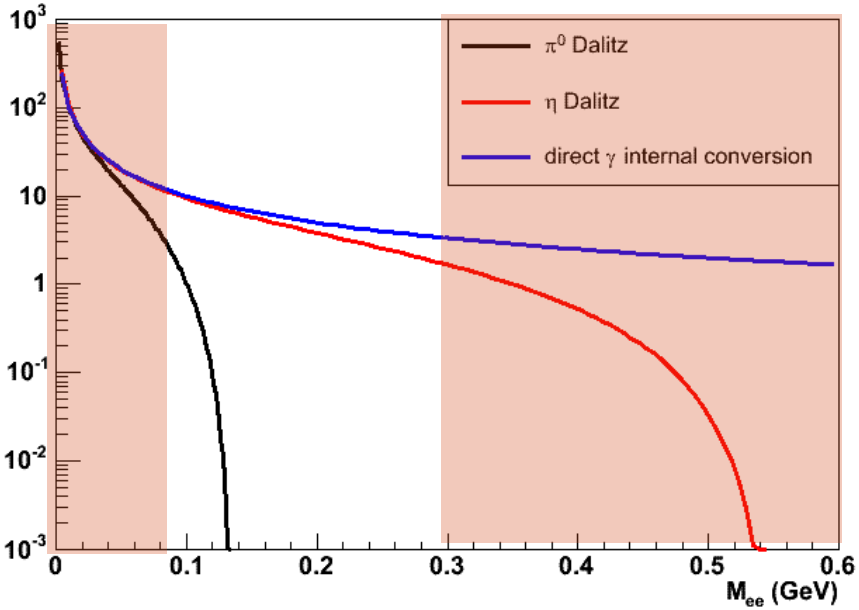
- Target p_T range : $1<p_T<3$ GeV/*c*
- Measure direct photons via internal conversion

Internal Conversion Method



- Any sources of high-E photons emits virtual photons (γ^*)
- γ^* convert to low-mass e^+e^-
- e^+e^- yields convert to real γ yields
  - Knoll-Wada fomula is supported

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



Property of process independent factor (S)

- Di-electron via hadron decay

$$S = \left|F\left(M_{ee}^2\right)\right|^2\left(1-\frac{M_{ee}^2}{M_{hadron}^2}\right)^3$$

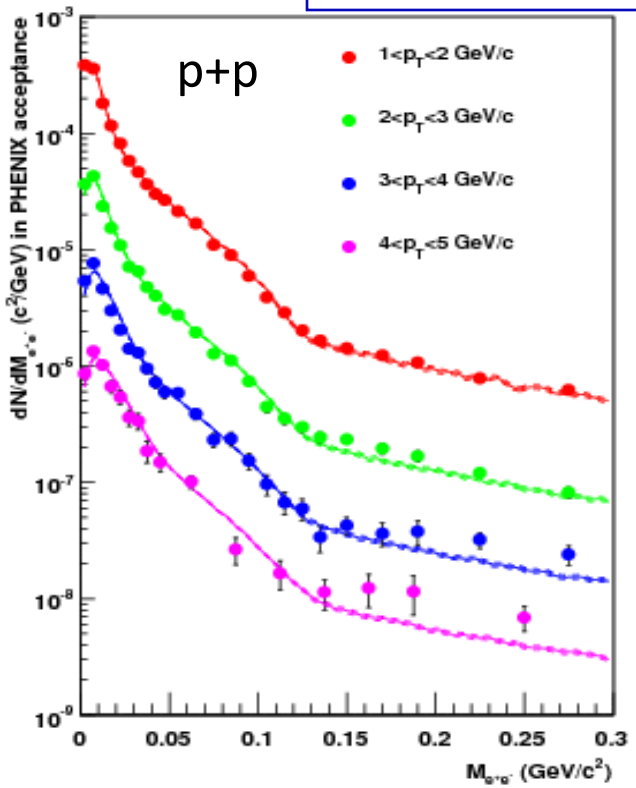
If $M_{ee} > M_{hadron}$, S = 0

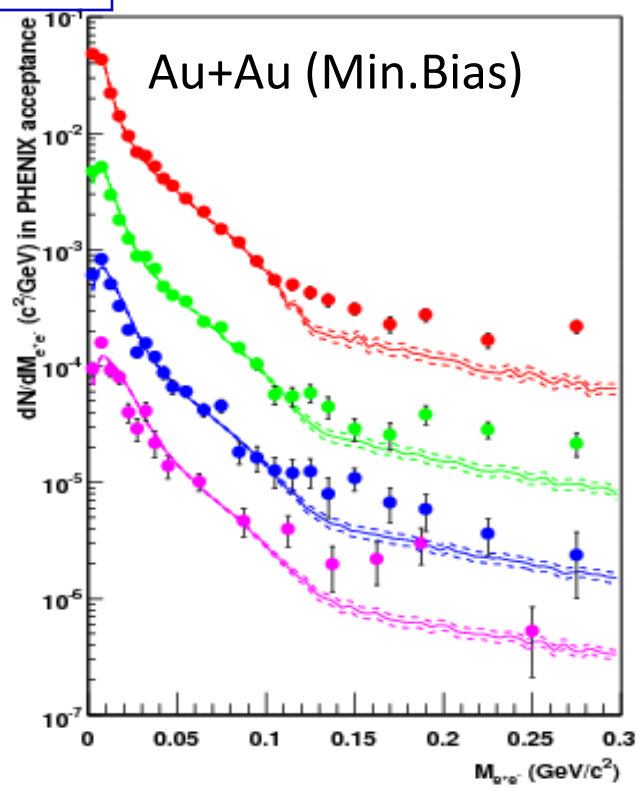
- Di-electron via internal conversion

If $p_T > M_{ee}$, S = 1

Low mass di-electron spectra

PHENIX, arXiv: 0804.4168





$1 < p_T < 2$ GeV/c

$2 < p_T < 3$ GeV/c

$3 < p_T < 4$ GeV/c

$4 < p_T < 5$ GeV/c

Normalization

$M_{e+e-} < 30$ MeV

p+p

- Good agreement between real and cocktail
- Small excess at higher p_T

Au+Au

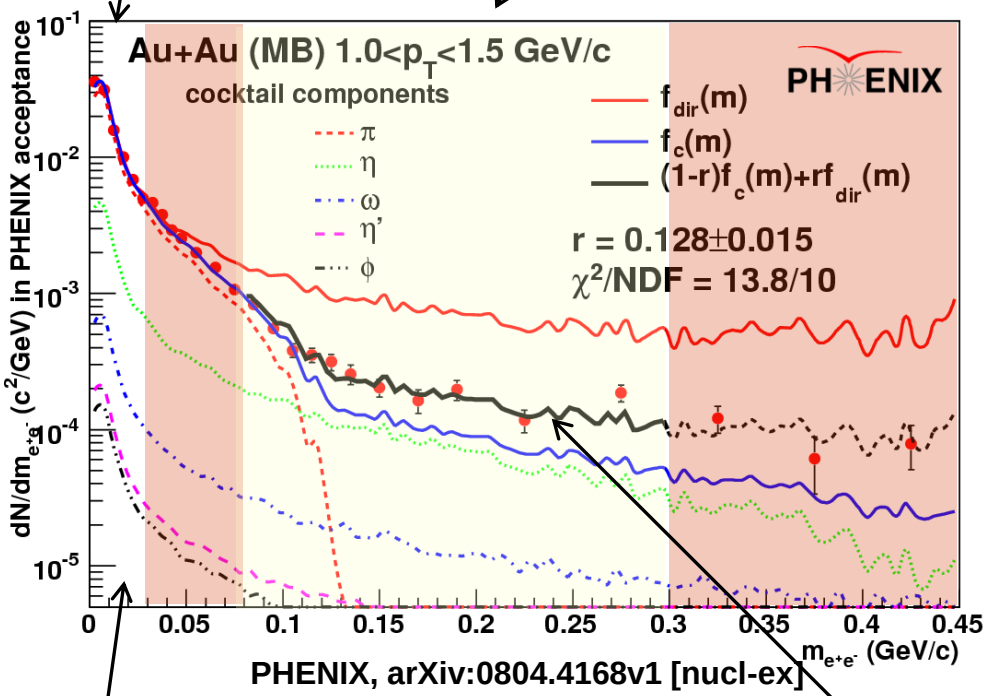
- Good agreement in $M_{ee} < 50$MeV
- **Yield excess** in $M_{ee} > 100$MeV.

Cocktail : Mixture of assumed hadron decay components from Monte Carlo calc.

Extracting Direct γ Signal

Normalization range
m<30 MeV

Fit range
80<m<300 MeV



- Two-component fit

$$f(m) = (1-r)\, f_c(m) + r f_{dir}(m)$$

f_c : shape of cocktail

f_{dir} : shape of direct photon(γ*)

r : fit parameter

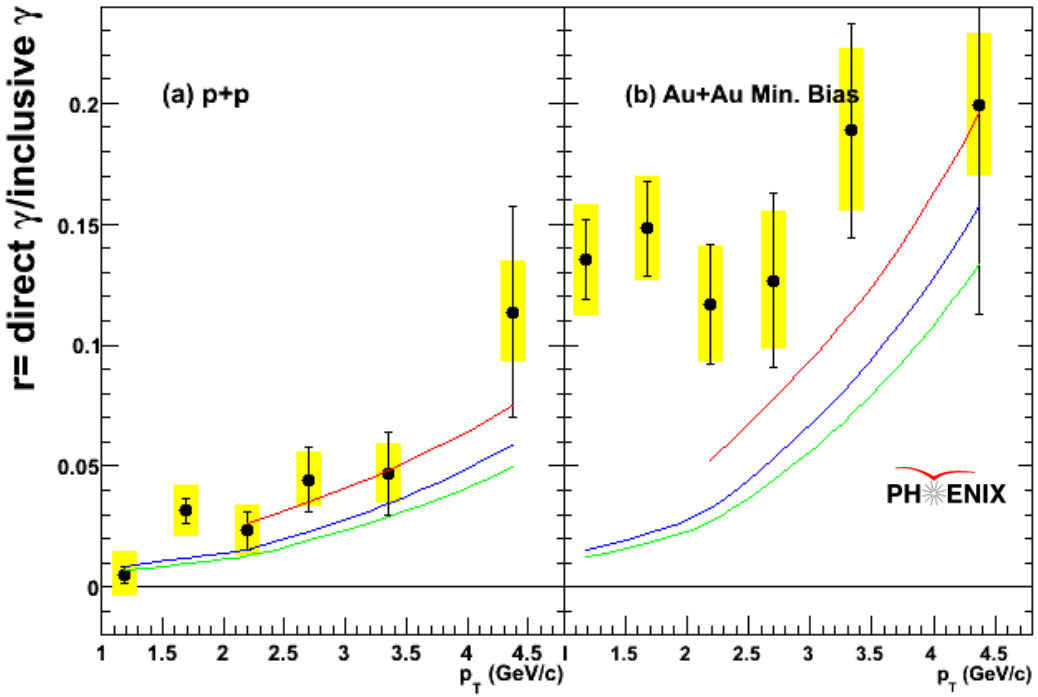
f_c, f_{dir} : separately normalized to data for m<30 MeV

normalization preserves meaning of *r* as real direct photon fraction

r is determined in fit region

Fraction (r) of direct γ^*/inclusive γ^*

PHENIX, arXiv: 0804.4168



Au+Au

Clear enhancement above NLO pQCD at low p_T

p+p

Consistent with NLO pQCD

Base line

Curves : NLO pQCD calculations with different theoretical scale (μ).

(μ = 0.5pT, pT, 2pT)

$$r = \frac{\left(d\sigma_\gamma^{NLO} / dp_T\right)}{\left(d\sigma_\gamma^{NLO} / dp_T + d\sigma_\gamma^{had} / dp_T\right)}$$

$$dN_\gamma^{incl} = N_{ee}^{data} \times (dN_\gamma^c / N_{ee}^c)$$

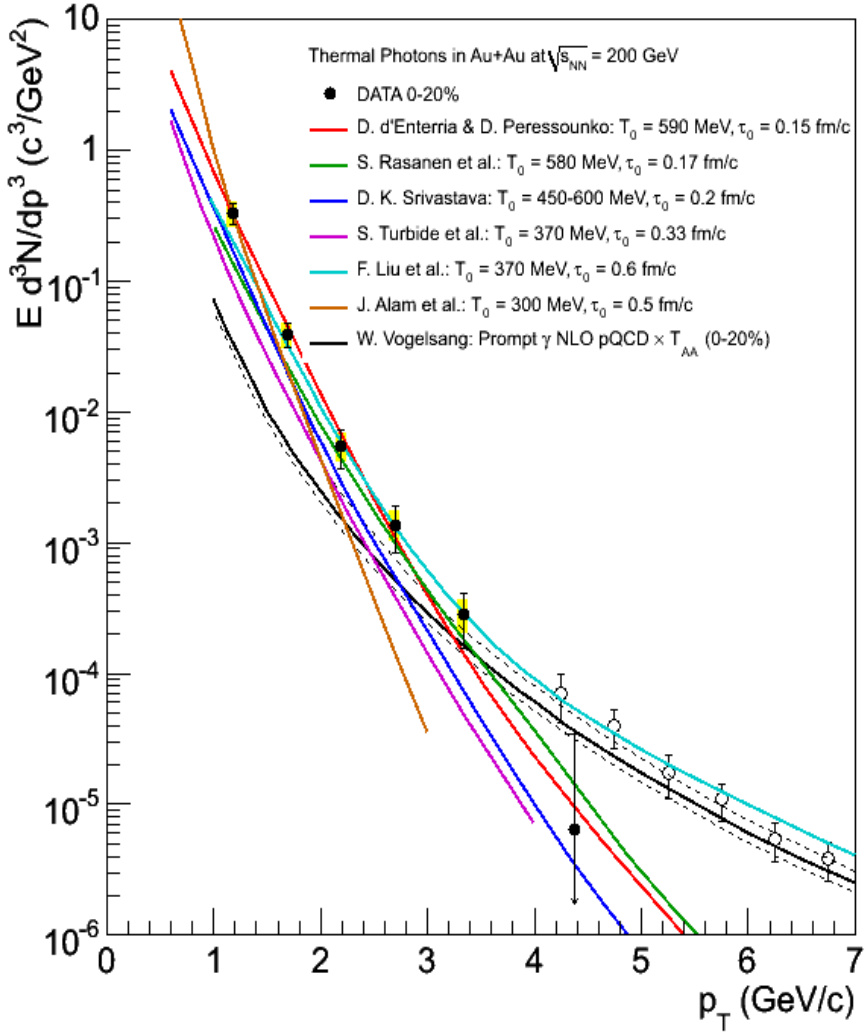
$$dN_{\gamma_{direct}}(p_T) = r \times dN_{\gamma_{inclusive}}(p_T)$$

First observation at RHIC!

Invariant cross section and models

Centrality 0 – 20 %

D. d'Enterria and D. Peressounko, EPJ C46, 451 (2006)



- Initial temperatures and thermalization time from theoretical models
  - T=590MeV, τ_0=0.15fm/c (D.d'Enterria et al.)
  - T=580MeV, τ_0=0.17fm/c (S.Rasanen et al.)
  - T=450-600MeV, τ_0=0.2fm/c (D.K.Srivastava)
  - T=370MeV, τ_0=0.33fm/c (S.Turbide et al.)
  - T=300MeV, τ_0=0.5fm/c (J.Alam et al.)
  - T=370MeV, τ_0=0.6fm/c (F.Liu et al.)
- All of the available hydro calculations reproduce the data within a factor of 2 in spite of their wide-ranging conditions.

Theory

$T_{init} \approx$ 300~600 MeV

$\tau_0 \approx$ 0.6~0.15 fm/*c*

Experiment (centrality 0-20 %)

T_{init} ~ 221±20(stat.)±15(sys.) MeV

$$(Ae^{-p_T/T} + T_{AA} \times A_{pp}(1 + p_T^2/b)^{-n})$$

Summary

- *Study of parton energy loss mechanism with high p_T hadrons*

Azimuthal angle ($\Delta\phi$) vs. $R_{AA}(p_T, \Delta\phi)$ at high p_T

- Theoretical model
  - Centrality dependence of R_{AA} : Can reproduce
  - **Azimuthal angle dependence of R_{AA} : Not yet**
- Experiment
  - $v_2(\pi^0)$ vs. p_T (centrality 20% bin) : p_T~14 GeV/*c*
  - **$\Delta\phi$ vs. R_{AA} at higher p_T : Ongoing**

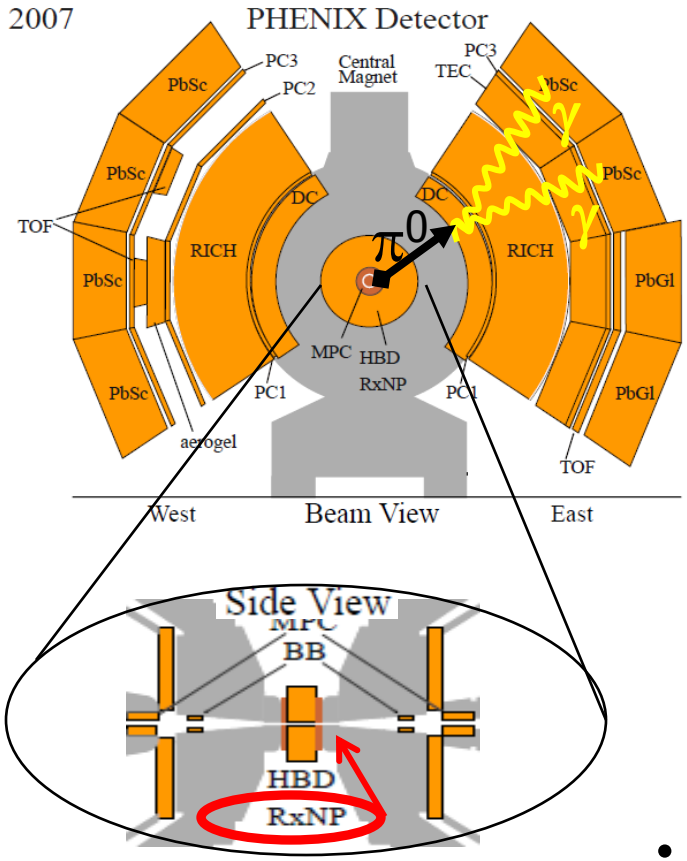
- *Thermal photon measurement ($1<p_T<5$ GeV/c @ cent 0-20%)*

Internal conversion method ($\gamma^* \rightarrow e^+e^-$)

- Theoretical model
  - Direct g p_T spectrum with a factor of two : Not bad
  - Initial temperature : $T_{init} \approx$ 300~600 MeV
  - Thermalization time : $\tau_0 \approx$ 0.06~0.15 fm/*c*
- Experiment
  - Enhancement of di-electron (Au+Au) : First observation at RHIC
  - Initial temperature : T_{init} ~ 221±20(stat)±15(sys.) MeV

Backups

Measurement of $R_{AA}(\pi^0, \Delta\phi)$ in PHENIX



EMCal (PbSc and PbGl)

- π^0 ($\rightarrow 2\gamma$) measurement

Beam Beam Counter (BBC)

- Trigger and determination of centralities
- Determination of reaction plane (until 2006)
  $3.0 < |\eta| < 3.9$

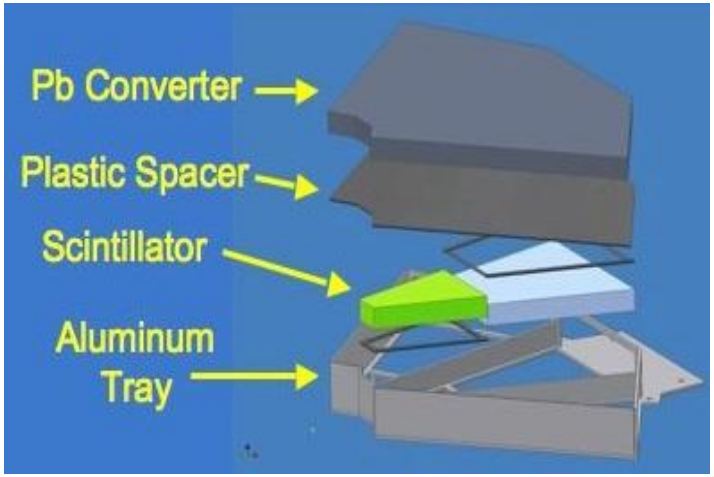
Reaction plane Detector (RxNP)

- Determination of reaction plane (from 2007)
  $1.0 < |\eta| < 1.5$ && $1.5 < |\eta| < 2.8$

Advantage for Run7 (2007)

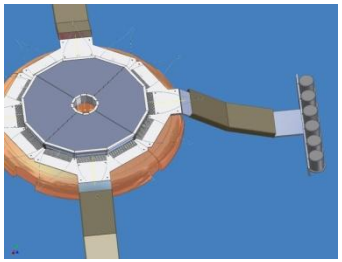
- **Higher Statistics than that in Run4 (2004)**
  4 times higher → ½ of statistical error (Run4)
- **Improve the determination of reaction plane**

Structure and performance of RxNP



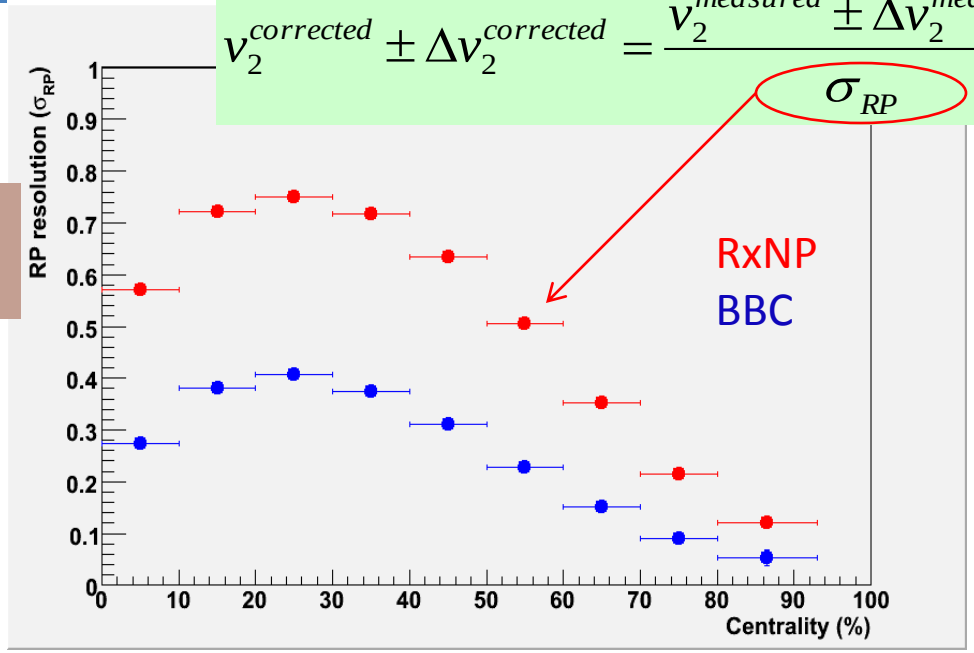
Beam Side View

- **Each quadrant contains**
  - 1 Pb convertor
  - 3 inner & 3 outer scintillation
  - 6 fine mesh PMT's



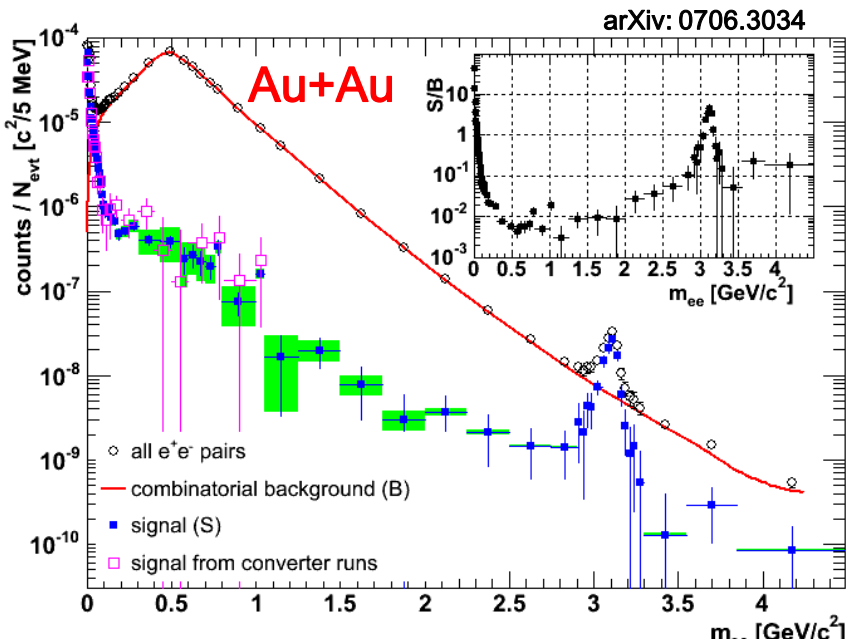
- **Determination of reaction plane**
  - Direction where many particles are emitted.

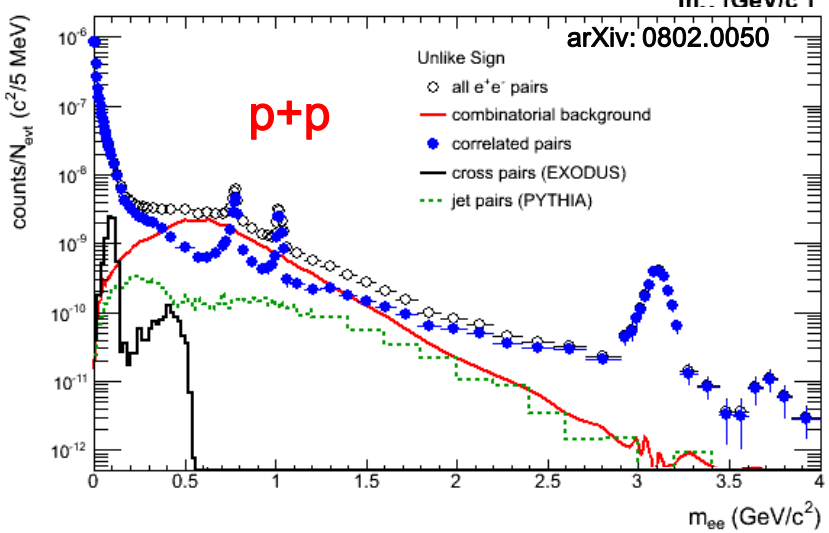
$$v_2^{corrected} \pm \Delta v_2^{corrected} = \frac{v_2^{measured} \pm \Delta v_2^{measured}}{\sigma_{RP}}$$



2 times better →
½ of statistical error of v_2(Run4)

Signal Extraction





- Real signal
  - di-electron continuum
- Background sources
  1. Combinatorial background
  2. Material conversion pairs
  3. Additional correlated background
     - Visible in p+p collisions
     - Cross pairs from decays with 4 electrons in the final state
     - Pairs in same jet or back-to-back jet

After subtraction

- Remaining pairs
  - Real signal + Hadron decay components
    - Estimate hadron components using hadronic cocktail
    - Tuned to individually measured yields of mesons at PHENIX