PHENIX measurements of nuclear modification factor of hadrons in *d*+Au and A+A collisions

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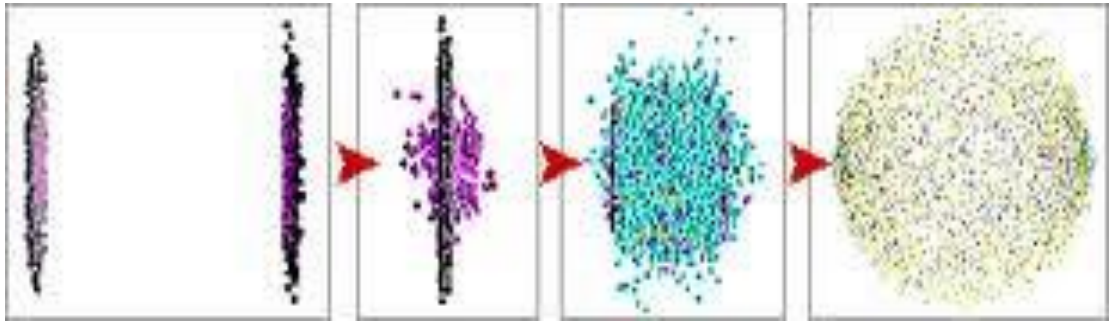
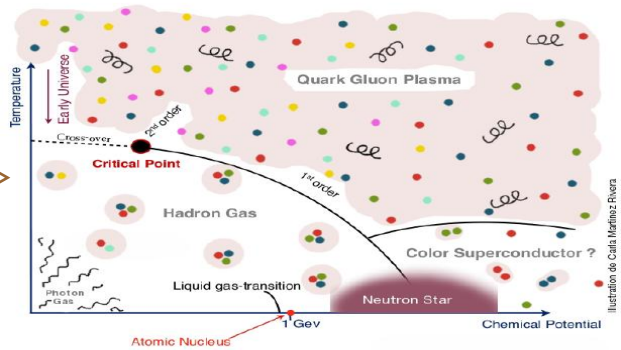
Outline

- ✓ Introduction
- ✓ Brief overview of PHENIX detector systems.
- ✓ Recent R_{dAu} and R_{AB} measurements from PHENIX.
- ✓ Summary and Conclusions.

Introduction





G. Martinez

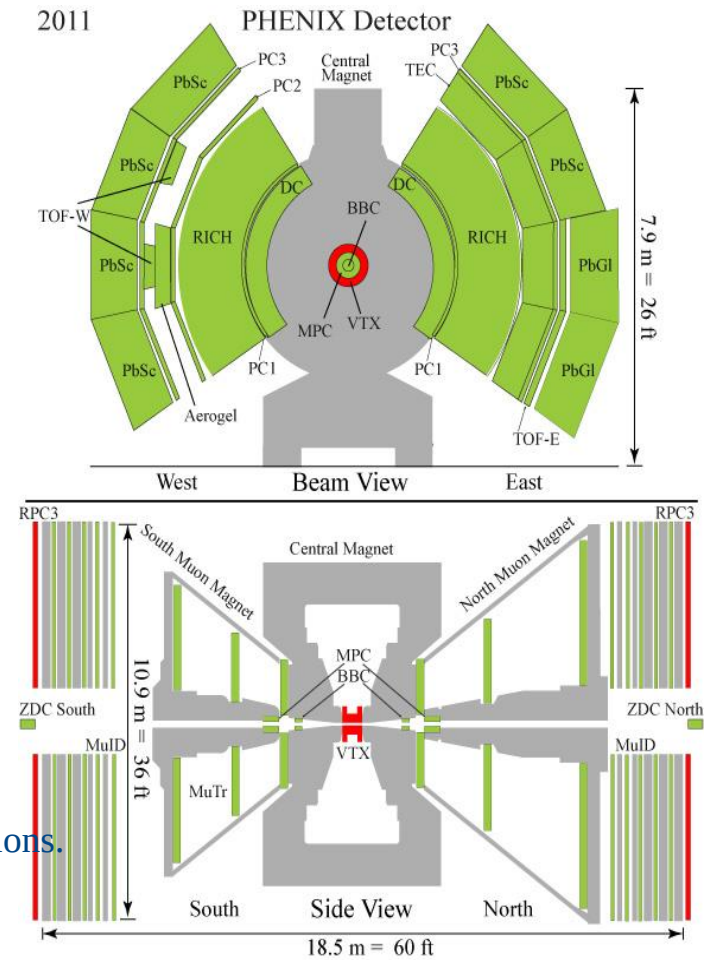
- High energy heavy ion collisions result in phase transition of hadrons to QGP.
- RHIC and LHC are the biggest facilities for high energy experiments.
- High p_T particle suppression due to energy loss of partons inside the medium, is one of the most important QGP signals.
- Modification of the spectrum due to energy loss can be quantified by, nuclear modification factor.

$$R_{AB}(p_T) = \frac{d^2N^{AB}/dp_T dy}{(\langle N_{coll}\rangle/d^2N^{pp})/dp_T dy}$$

$R_{AB} = 1 \rightarrow$ No medium effects present
$R_{AB} \neq 1 \rightarrow$ Medium effects present
$R_{AB} < 1 \rightarrow$ Energy loss occurred due to medium

Brief overview of PHENIX detector systems

Information used	Detector
i) Event Triggering ii) Collision time and z_{vertex} & iii) Centrality determination	Beam – Beam Counter (BBC)
Track reconstruction and momentum determination	Drift Chamber (DC) and 1st Layer of Pad Chamber (PC1)
Rejection of secondary tracks	2nd and 3rd layer of Pad Chambers
Charged Hadron ID	Time of Flight (TOF)
Photon position and energy measurement	Electro – Magnetic Calorimeter (EMCal)
Electron ID	Ring Imaging Cherenkov (RICH)



System Specifications :

- BBC zvertex position resolution: ~ 1.1 cm in *p+p* to 3 mm in Au+Au collisions.
- Momentum resolution for charged particles with $p_T > 0.2$ GeV/c, $\delta p/p = 0.7 \oplus 1.1\ \%\ p$ (GeV/c).
- ToF(E) timing resolution ~ 130 ps. π/K separation up to $p_T \sim 2.5$ GeV/c and K/p separation up to $p_T \sim 4.5$ GeV/c.
- EMCal energy and spatial resolution for PbSc (PbGl) $\delta E/E = 2.1\ (0.8)\ \% \oplus 8.1\ (5.9)\ \% / \sqrt{E}$ (GeV) % . $\sigma(E) = 1.55\ (0.2) \oplus 5.74\ (8.4)\ \% / \sqrt{E}$ (GeV) mm.

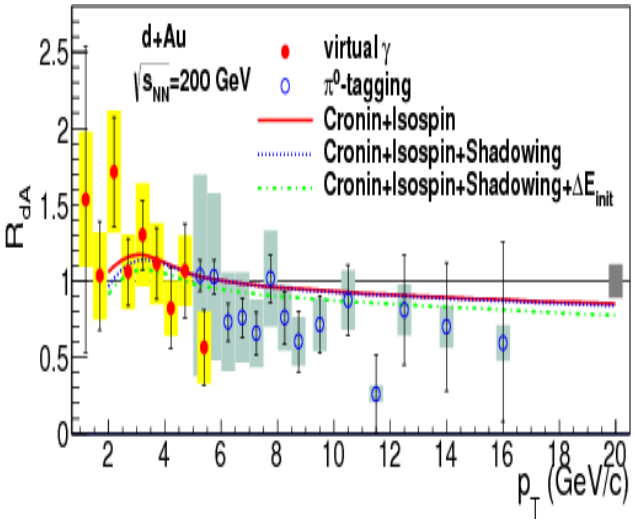
Results

R_{dAu} and R_{AB} results for :

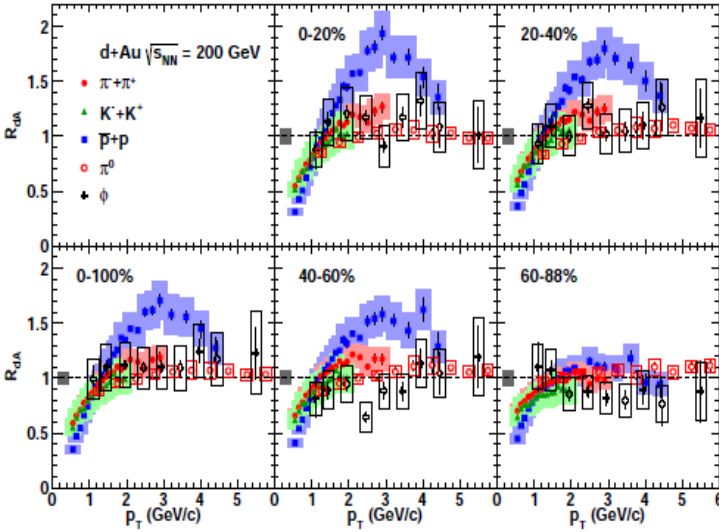
- π^0
- $\pi^{\pm}$, $K^{\pm}$, p
- Direct γ
- e_{HF}^{-}
- φ
- K_S^0 and K^{*0}

R_{AB} in d+Au collisions

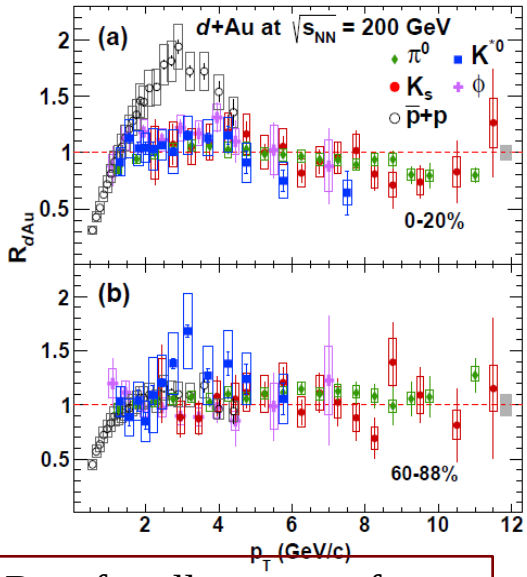
PRC**87**, 054907 (2013)



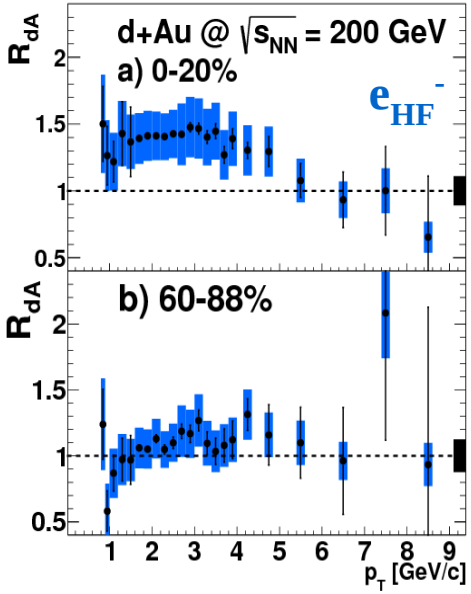
PRC**88**, 024906 (2013)



PRC**90**, 054905 (2014)



PRL**109**, 242301 (2012)



- For p_T > 2 GeV/c, R_{dAu} ~ 1 within uncertainties for π^0, $\pi^\pm$, $K^\pm$, K_S^0, K^{*0} and φ for all measured centralities.
- Protons:
  - In central collisions – R_{dAu} > 1 for p_T = 2-5 GeV/c.
  - For peripheral collisions – R_{dAu} ~ 1 within uncertainties in the measured p_T range.
- At high p_T, photon R_{dAu} ~ 1 within uncertainties and is in agreement with model calculations.
- For p_T > 5 GeV/c, e_{HF}^- R_{dAu} ~ 1 within uncertainties in both central and peripheral collisions.

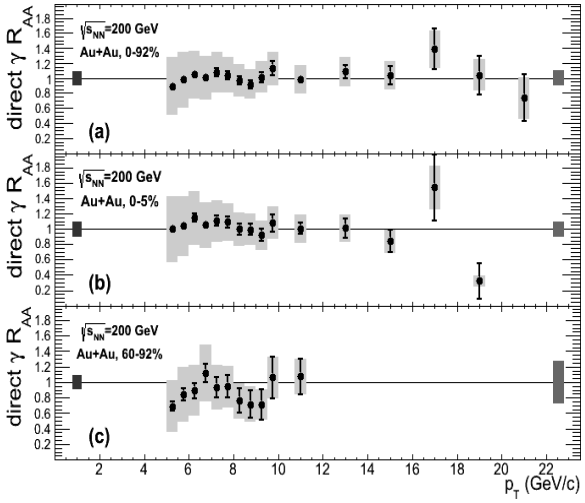
R_{dAu} for all mesons of different masses are consistent with each other.

Enhancement can be explained from recombination model

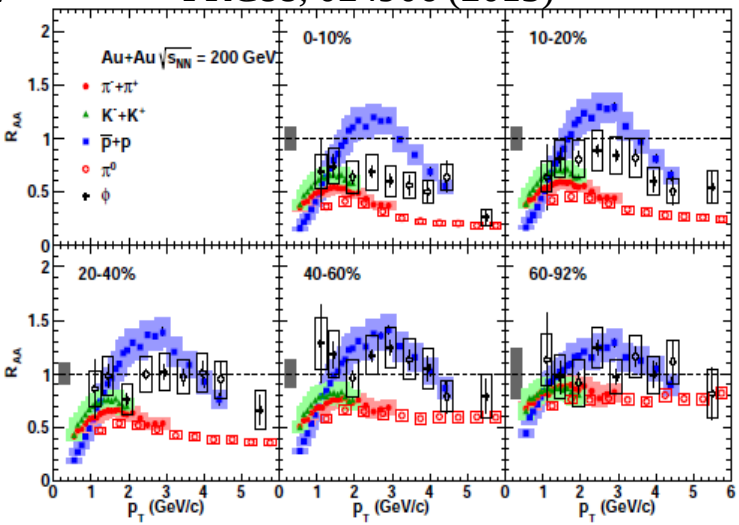
At high p_T, no significant CNM effects observed for the mesons, e_{HF}^- and photons.

R_{AB} in Au+Au and Cu+Cu collisions

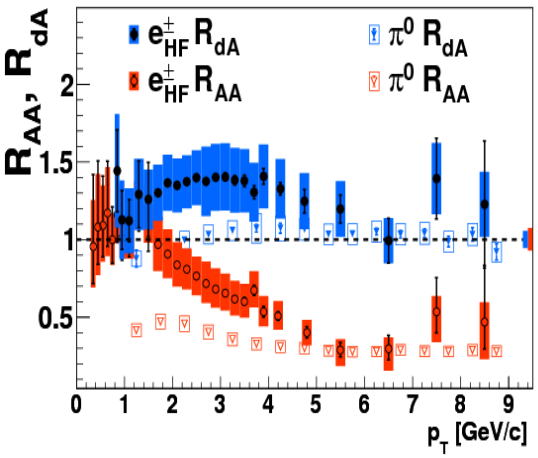
PRL**109**, 152302 (2012)

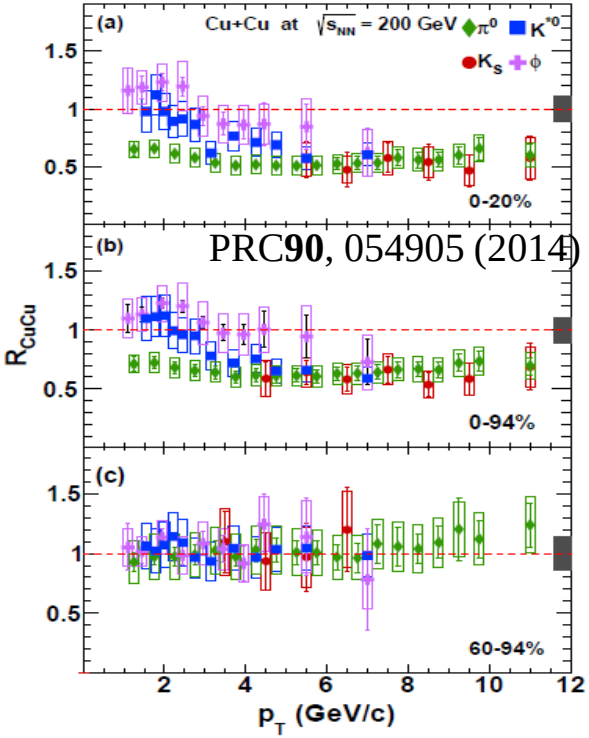


PRC**88**, 024906 (2013)



PRL**109**, 242301 (2012)





PRC**90**, 054905 (2014)

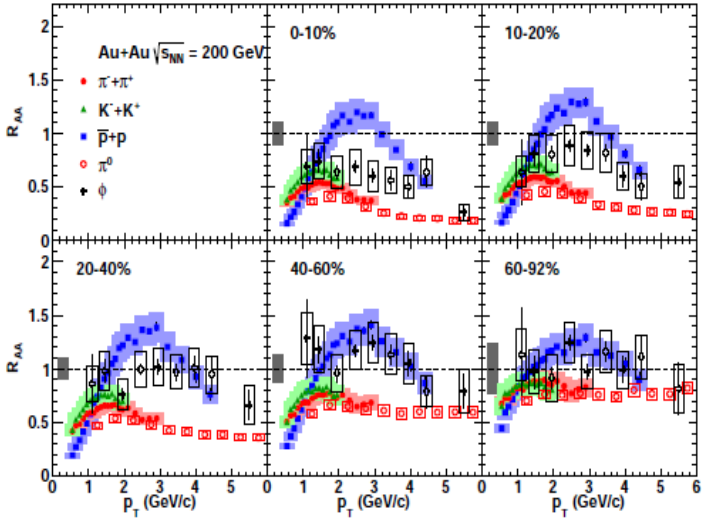
High p_T : p_T > 5 GeV/c

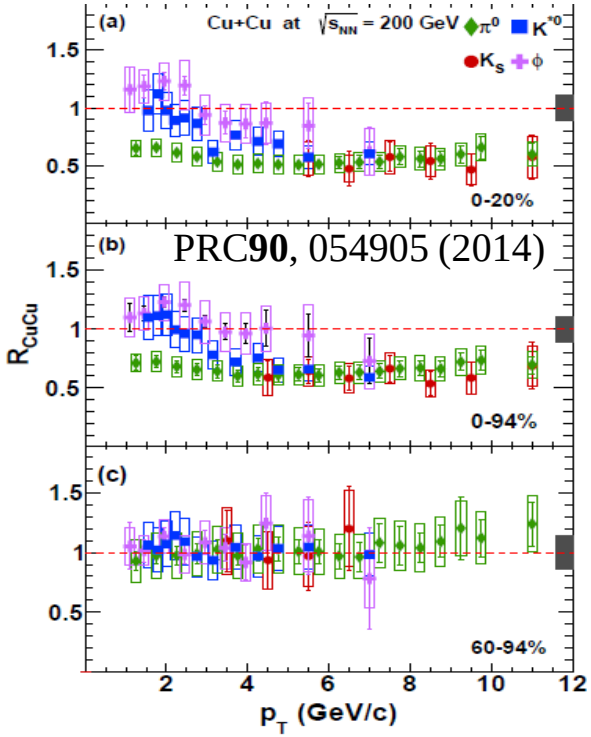
- Photon R_{AA} ~ 1 for all centrality bins.
- R_{AB} shows a system size dependence for all other particles.
- π^0 are the most suppressed species.
- R_{AB} for the mesons and e_{HF}^- are similar in the most central collisions, R_{AB} ~ 0.2 in Au+Au and ~ 0.5 in Cu+Cu systems.

Parton energy loss is similar for all particles for p_T > 5 GeV/c

R_{AB} in Au+Au and Cu+Cu collisions

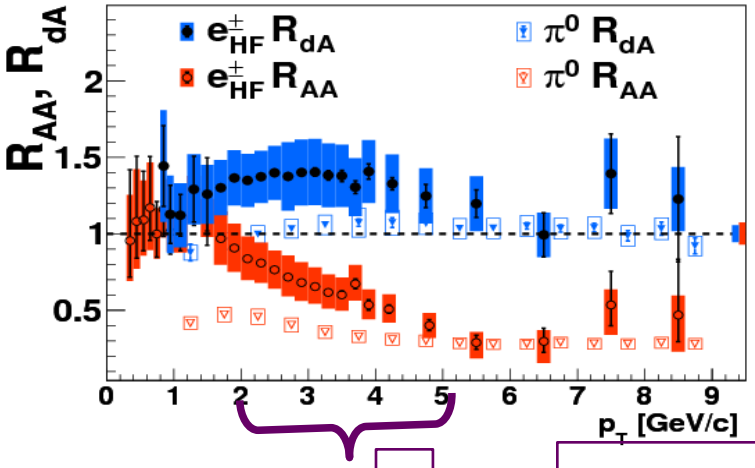
PRC**88**, 024906 (2013)





PRC**90**, 054905 (2014)

PRL**109**, 242301 (2012)



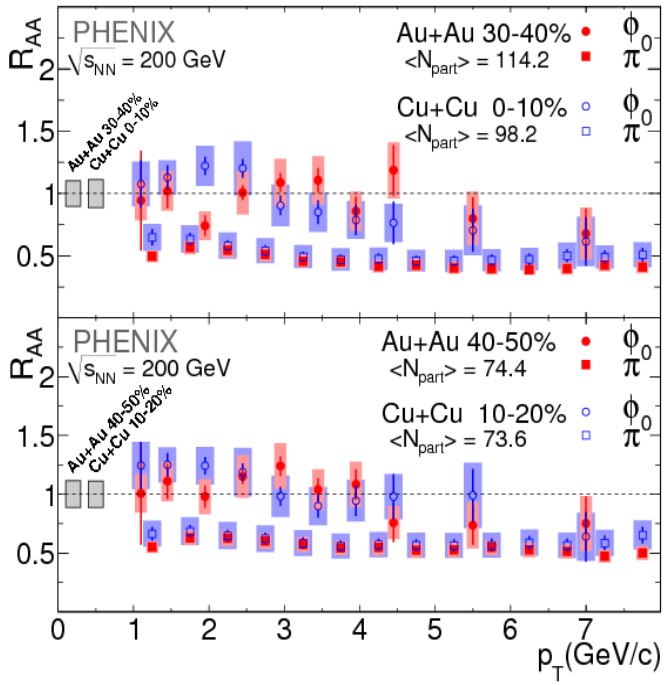
e_{HF}^{-} suppression is due to the final state effects only.

Intermediate p_T : $2 < p_T$ (GeV/c)< 5

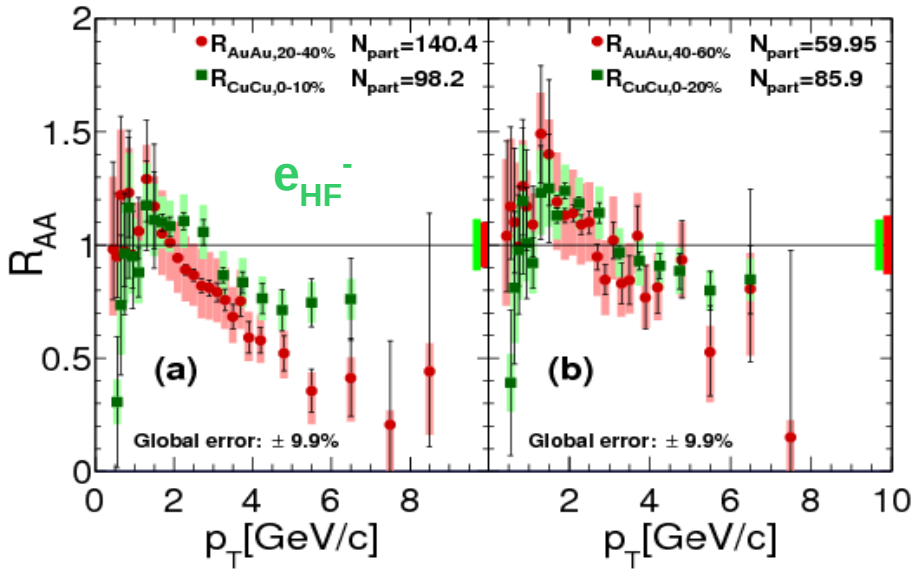
- Proton shows enhancement.
- π^0 are the most suppressed species.
- R_{AB} for strange meson lies in between of π^0 and protons.

R_{AB} in Au+Au and Cu+Cu collisions

PRC**83**, 024909 (2011)



PRC**90**, 034903 (2014)

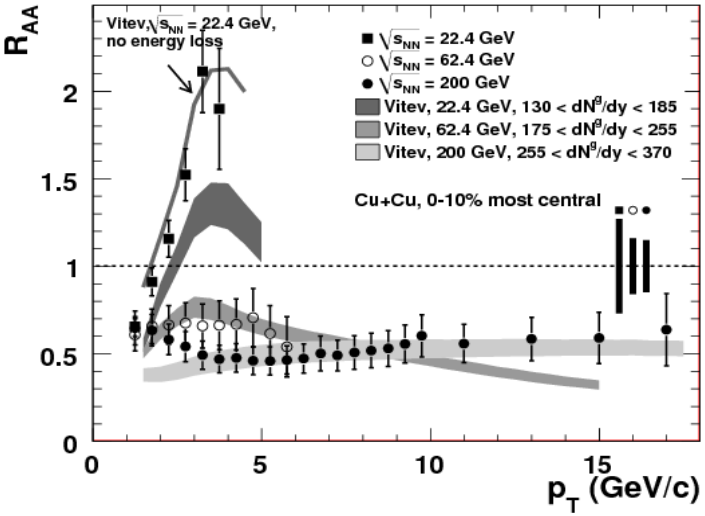


R_{AB} results for similar $\langle N_{part} \rangle$

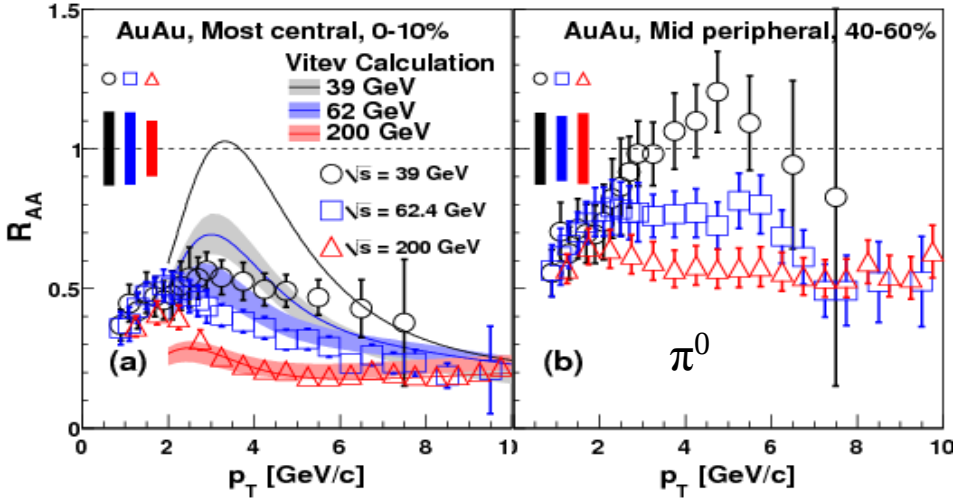
- For similar $\langle N_{part} \rangle$, particles suffer similar suppression both in peripheral and central collsions.

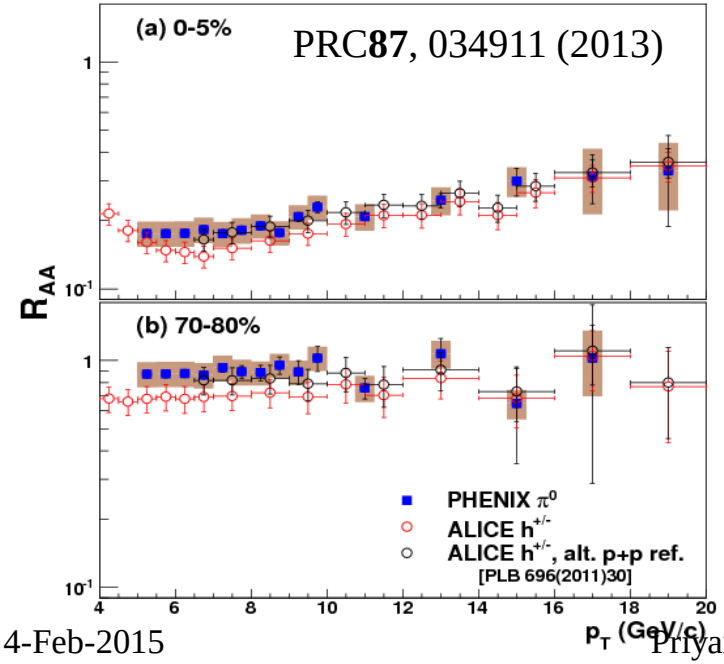
R_{AA} as a func. of $\sqrt{s_{NN}}$

PRL**101**, 162301 (2008)



PRL**109**, 152301 (2012)





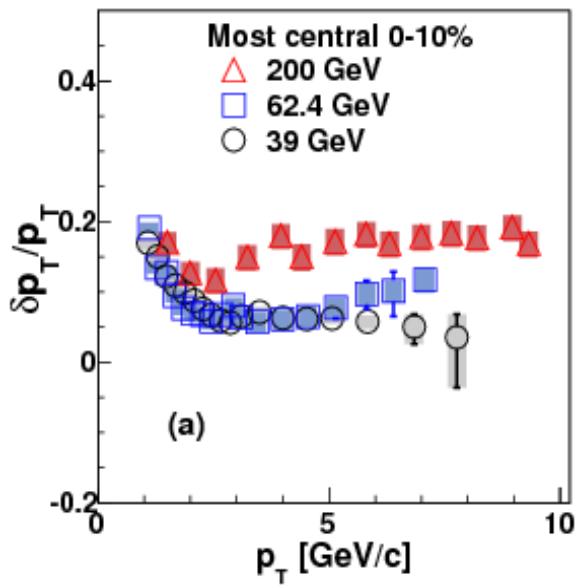
PRC**87**, 034911 (2013)

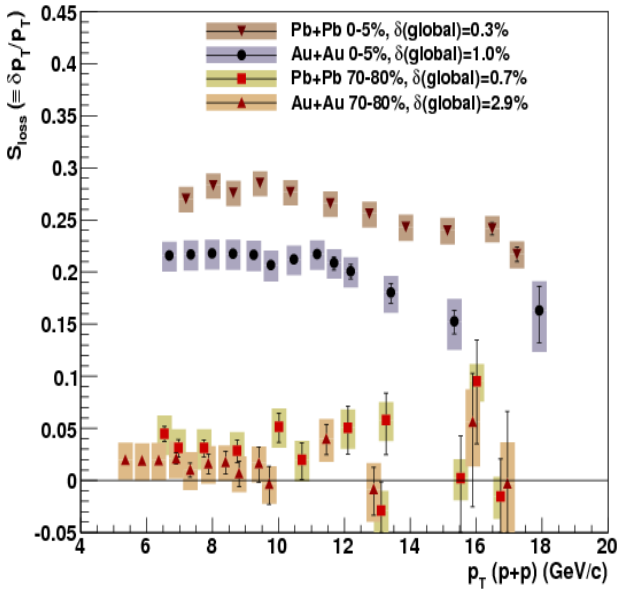
- Central Cu+Cu collisions - $(R_{CuCu})_{200} < (R_{CuCu})_{62.4} < (R_{cuCu})_{22.4}$.
- $R_{CuCu} > 1$ for $\sqrt{s_{NN}} = 22.4$ GeV.
- Central Au+Au collisions - $(R_{AA})_{200} < (R_{AA})_{62.4} < (R_{AA})_{39}$.
- Peripheral Collisions - $(R_{AA})_{39} \sim 1$ for $p_T > 3$ GeV/c.
- Model calculations agree with 200 GeV data both for Au+Au and Cu+Cu collisions.
- R_{AA} is similar for Au+Au 200 GeV and Pb+Pb 2.76 TeV.

This behavior needs investigation

Fractional energy loss as a func. $\sqrt{s_{NN}}$

PRC**87**, 034911 (2013)

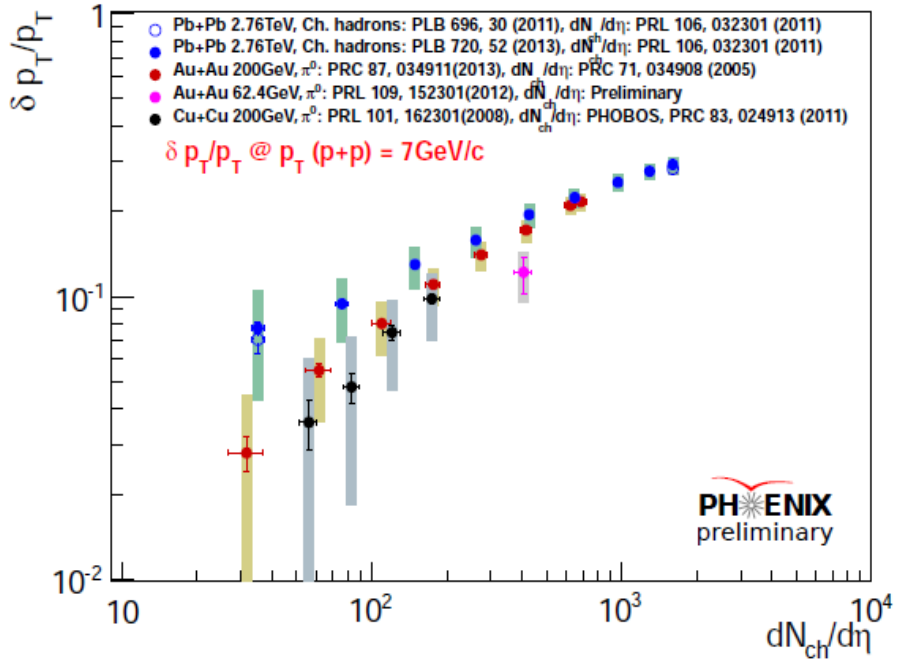


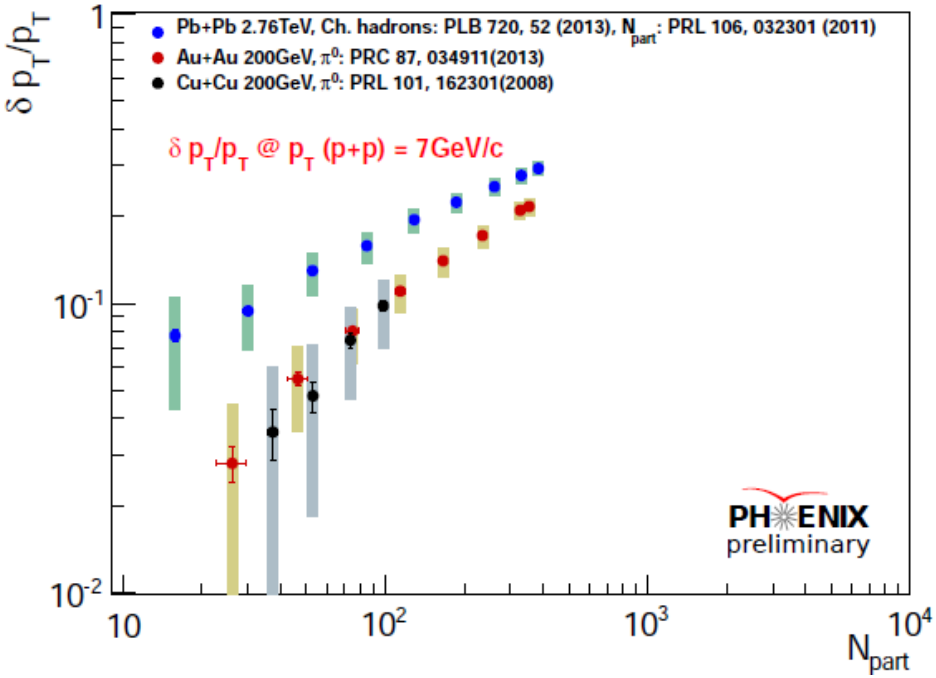


- The similar R_{AA} values at 200 GeV and 2.76 TeV can be understood from the fractional energy loss calculations.
- $(\delta p_T/p_T)_{200} > (\delta p_T/p_T)_{62.4}$ and $(\delta p_T/p_T)_{39}$
- In the most central collisions, energy loss in LHC is 30% higher than that at RHIC.
- This can be understood from the different energy losses due to steeper production spectra. The power (n) of power-law fit of the p_T spectra : $n_{LHC(2.76\ TeV)} = 6$, $n_{RHIC(200\ GeV)} = 8$.

Fractional energy loss is more for higher collisional energies.

Fractional energy loss as a func. collision systems





- For large enough $dN_{ch}/d\eta$, $\delta p_T/p_T$ is independent of collision energy and collision systems.
- For same collision energy, fractional energy loss is same for similar N_{part} and independent of collision species.
- As a function of N_{part}, $\delta p_T/p_T$ is more for higher collision energy.

Summary and Conclusions

- **High p_T :**
  - High p_T photon R_{dAu} and R_{AA} are consistent with unity and are in agreement with model calculations. As photon is an e.m. probe, one can expect this.
  - R_{dAu} for e_{HF}^- is consistent with unity for central and peripheral collisions.
  - R_{dAu} for all mesons are consistent with unity. R_{dAu} is independent of meson mass.
  - Light mesons, strange mesons and e_{HF}^- suffer similar suppression in the most central A+A collisions. $R_{AA} \sim 0.2$ and $R_{CuCu} \sim 0.5$. Energy loss takes place at partonic level.
  - Fractional energy loss increases with increasing collision energy. Harder collision and large system size leads to larger energy loss of partons.

- **Intermediate p_T :**
  - Except peripheral collisions proton show enhancement both in d+Au and Au+Au collisions.
  - e_{HF}^- suffers less suppression than neutral pions.
  - Strange meson suppression lies in between baryons and neutral pions.

Different processes (eg. recombination, flow etc.) play important role in this p_T region.

Back-up

Direct photon analysis

p+p data – 2005
Au+Au data – 2004
d+Au data - 2008

Direct γ analysis

Low p_T photon : $p_T < 5$ GeV/c

- m_{e+e-} is obtained using track $p_T > 0.2$ GeV/c.
- $m_{e+e-} < 0.3$ GeV/c^2 and $p_{T(pair)} > 1$ GeV/c

- Background Removal :
  - → Uncorrelated background is estimated using event-mixing.
  - → Correlated bkg is estimated by the like-sign technique and also corrected for acceptance.
  - → External conversions are estimated using 'cocktail' method and subtracted.

- Direct photon yield:

$$d^2n_{ee}/dm_{ee} = 2\alpha/3\pi \,.\, 1/m_{ee} \,.\, dn_\gamma$$

High p_T photon : $p_T > 5$ GeV/c

- Photon ID is done with EMCal by putting proper shower profile cut.
- The cut rejects 50% of hadrons depositing E > 3 GeV in EMCal and accepts 98% of real photons.
- Background removal :
  - → π^0 tagging.
  - → Cocktail subtraction.

- Direct photon Yield :

$$\gamma_{direct} = \gamma_{incl} - (1 + \delta_{hadrons/\pi0}) \times (1 + R_{\pi0}^{miss})\ \gamma_{\pi0}.$$

Contributions from hadrons/π^0

Total contributions from π^0 decays

Correction for missing photon partners to π^0

Neutral pion analysis

- π^0 is reconstructed from $\gamma\gamma$ + Asymmetry cut: $|E_1 - E_2|/|E_1 - E_2| < 0.7$
- γ energy and position is obtained from EMCal.
- Measurement in p+p collisions at 62.4, 200 GeV. -- MB + ERT data
- Measurement in Cu+Cu collisions at 22.4, 62.4 and 200 GeV. -- MB + ERT data
- The p+p data for 22.4 GeV is obtained from a parameterization of the world's data on π^0 data. Ref: Phys.Rev. D78 (2008) 094004
- Measurement in Au+Au collisions at 39, 62.4, 200 GeV. (39 GeV is from Run10 data) -- MB data
- For pp ref at 39 GeV, FermiLab E706 data has been used. This data is corrected for the detector acceptance and efficiency.
- The pp data at 62.4 GeV is fitted with power law for $4.5 < p_T$ (GeV/c) < 7 GeV and extrapolated to 10 GeV in order to obtain R_{AA} at 62.4 GeV.

Electron analysis

Data → **Tracking** → **e ID** → **$e_{HF} = e_{Inc} - (e_{ph} + e_{nPh})$**

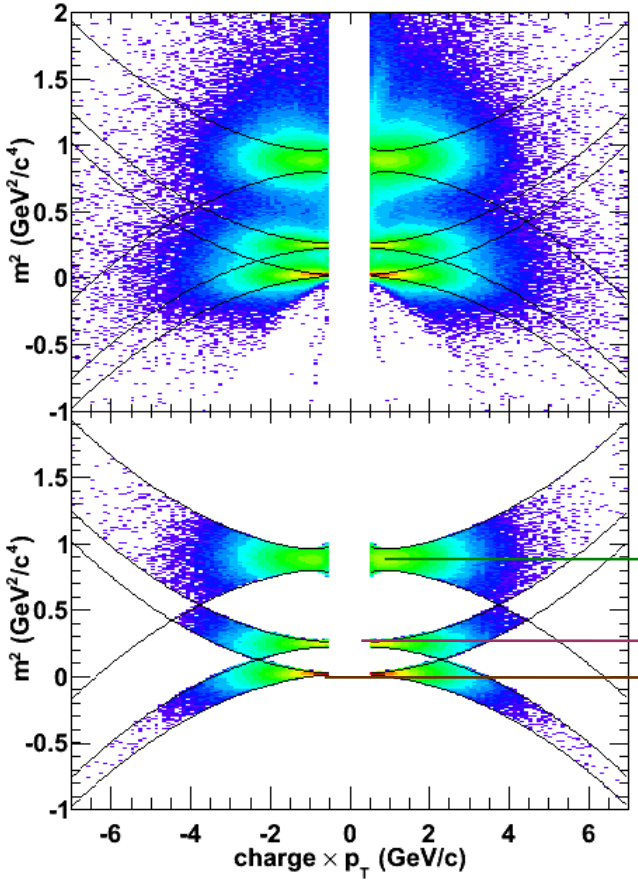
- **p+p**
  - 2005 data
  - MB (45 nb^{-1})
  - Photon triggered (1.57 pb^{-1})
- **Au+Au**
  - 2004 data
  - MB
- **d+Au**
  - 2008 data
  - MB (80 nb^{-1})

- **p+p**
  - $Z_{vertex} < 20$ cm
  - DC + PC1 + EMCal (4 σ)
- **Au+Au**
  - $z_{vertex} < 20$ cm
  - DC + PC1 + EMCal (2 σ)

- **p+p**
  - $0.8 < p_T < 5$ GeV/c
    2 hits in RICH + $0.7 < E/p < 1.3$
  - $5 < p_T < 9$ GeV/c
    5 hits in RICH + $0.8 < E/p < 1.3$
- **Au+Au**
  - 3 hits in RICH
  - $E/p - 1 > -2\ \sigma$
- **d+Au**
  - $MB+E_{RICH}$ = 600-800 MeV

- **p+p**
  - $e_{ph} + e_{nPh}$ is removed by 'cocktail' + 'convertor' subtraction method.
- **Au+Au**
  - Similar approach used in p+p.
- **d+Au**
  - Similar approach used in p+p

Charged Hadon analysis



Before ID cuts

After ID cuts

Proton

Kaon

Pion

- MB Data – 2005 p+p, 2008 d+Au, 2007 Au+Au.
- $|z_{vertex}| < 30$ cm.
- Charged hadrons are identified in TOF.

$$m^2 = \frac{p^2}{c^2}\left(\frac{t^2c^2}{L^2} - 1\right)$$

$$\sigma^2_{m^2} = \frac{\sigma^2_\alpha}{K_1^2}(4m^4p^2) + \frac{\sigma^2_{m\alpha}}{K_1^2}\left(4m^4\left(1+\frac{m^2}{p^2}\right)\right) + \frac{\sigma_t^2c^2}{L^2}(4p^2(m^2+p^2))$$

Parameter		2007 Au+Au	2008 d+Au
σ_α	(mrad)	0.896	1.050
$\sigma_{m\alpha}$	(mrad·GeV/c)	0.992	1.000
σ_t	(ps)	0.084	0.095
K_1	(mrad·GeV/c)	75.0	104.0

φ, K_S^0 and K^{*0}analysis

- $\varphi \rightarrow K^+K^-$
- MB Data – 2005 p+p, 2008 d+Au, 2005 Cu+Cu, 2003 Au+Au.
- Charged kaons are identified in TOF.
- 3 techniques used to reconstruct invariant mass.
  - ➔ One kaon PID.
  - ➔ No PID.
  - ➔ Two kaons PID
- Uncorrelated background is estimated by event-mixing technique.

Data	Int. Lum.
p+p	3.78 pb^{-1}
d+Au	81 nb^{-1}
Cu+Cu	3.06 nb^{-1}

- $K_S^0 \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma$
- Data – 2005 p+p, 2008 d+Au, 2005 Cu+Cu. - MB & ERT
- π^0 reconstruction from $\gamma\gamma$:
  - ➔ d+Au – $E_\gamma > 0.2$ GeV
  - ➔ Cu+Cu – $E_\gamma > 0.2$ (peripheral)
    $E_\gamma > 0.4$ (central)
  - ➔ Both γ forming π^0, are in the same EMCal sector.
  - ➔ Asymmetry cut:

$|E_1 - E_2|/|E_1 - E_2| < 0.8$

- K_S^0 reconst. from $\pi^0\pi^0$:
  - ➔ d+Au – π^0 $p_T > 1.0$ GeV/c
  - ➔ Cu+Cu – π^0 $p_T > 1.5$ GeV/c (> 20%)
    π^0 $p_T > 2$ GeV/c (< 20%)
  - ➔ Corrections due to inflight decay are included.

- $K^{*0} \rightarrow K^+\pi^-$
- MB Data – 2005 p+p, 2008 d+Au, 2005 Cu+Cu.
- $K^{+/-}$ and $\pi^{-/+}$ identified in TOF.
- Track $p_T > 0.3$ GeV/c.
- 3 techniques used to reconstruct invariant mass.
  - ➔ Fully idenified.
  - ➔ Unidentified.
  - ➔ Kaon identified.
- Uncorrelated background are removed by event-mixing technique.
- Contributions from the mis-identified tracks ($K_S^0 \rightarrow \pi^+\pi^-$ and $\varphi \rightarrow K^+K^-$) are also removed.

PHENIX detector specifications

SubSystem	$\Delta\eta$	$\Delta\phi$	Special Features
Central (CM)	$\pm$ 0.35	2π	Upto 1.15 Tm
Muon Magnet South	-1.1 - -2.2	2π	0.72 Tm for $\eta = 2$
Muon Magnet South	1.1 - 2.4	2π	0.72 Tm for $\eta = 2$
Beam Beam Counters (BBC)	$\pm$ 3.1 - 3.9	2π	Start timing for TOF collision vertex, Minimum Bias Trigger and Centrality
Zero Degree Calorimeter (ZDC)	3 mrad	2π	Minimum Bias Trigger and Centrality
Drift Chambers (DC)	$\pm$ 0.35	$2\times\pi/2$	Good Momentum and mass resolution Δm = 1% at m = 1 GeV
Pad Chambers (PC)	$\pm$ 0.35	$2\times\pi/2$	Pattern recognition of tracks and tracking for non-bend non-bend direction
Ring Imaging Čerenkov (RICH)	$\pm$ 0.35	$2\times\pi/2$	Identifies electron
Time of Flight (ToF)	$\pm$ 0.35	$2\times\pi/2$	Identifies charged hadrons, resolution<100 ps
Electromagnetic Calorimeter (EMCal)			
EMCal (PbSc)	$\pm$ 0.35	$\pi/2 + \pi/4$	Identifies electron and photon
EMCal (PbGl)	$\pm$ 0.35	$\pi/4$	Identifies electron and photon Good $e^{\pm}/\pi^{\pm}$ separation at $p_T > 1$ GeV/c by EM shower and $p < 0.35$ GeV/c