Recent results from PHENIX on jet suppression and direct photon production

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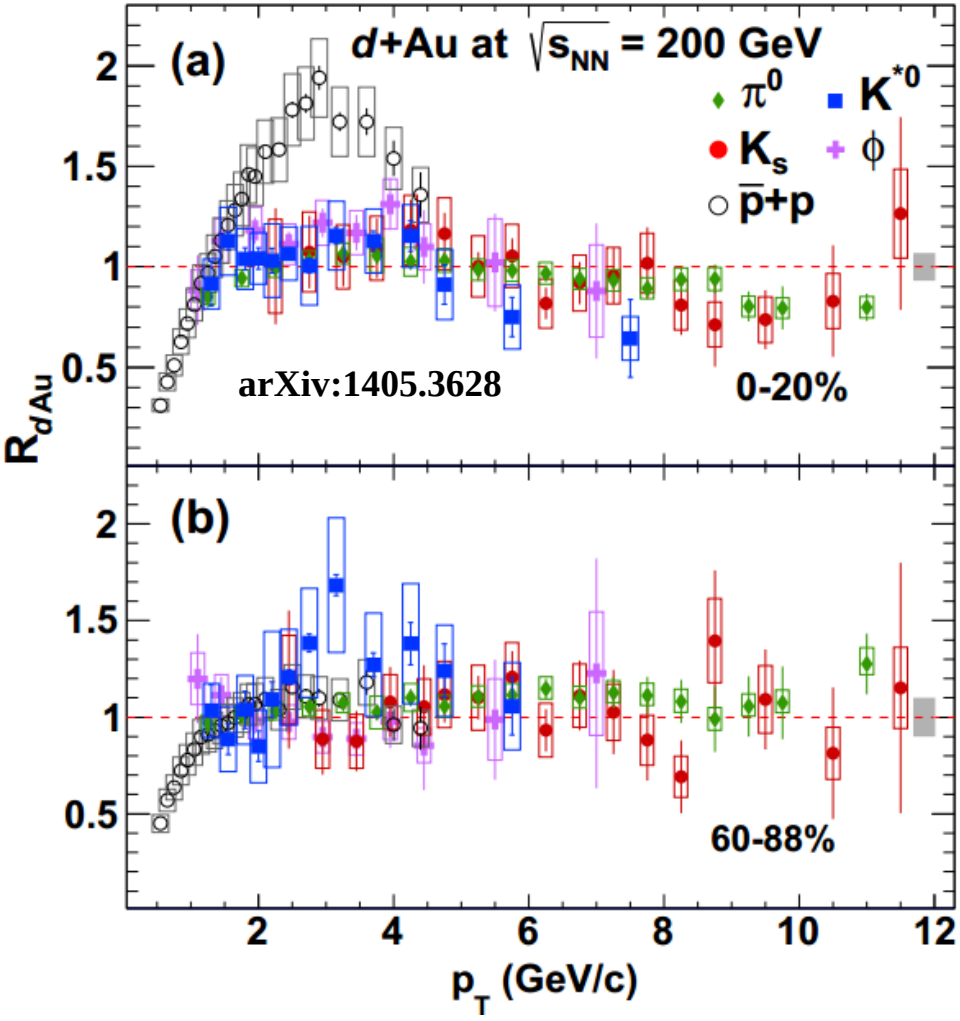
PHENIX data

RHIC Run	Year	Species	Energy	Ldt
Run-1	2000	Au+Au	130 GeV	1 μb-1
Run-2	2001-2	Au+Au	200 GeV	24 μb-1
Run-2		Au+Au	19 GeV	0.4 μb-1
		p+p	200 Gev	150 nb-1
Run-3	2002/3	d+Au	200 GeV	2.74 nb-1
		p+p	200 GeV	0.35 nb-1
Run-4	2003/4	Au+Au	200 GeV	241 μb-1
		Au+Au	62.4 GeV	9 μb-1
Run-5	2005	Cu+Cu	200 GeV	3 nb-1
		Cu+Cu	62.4 GeV	0.19 nb-1
		Cu+Cu	22.4 GeV	2.7 μb-1
Run-6	2006	p+p	200 GeV	10.7 pb-1
		p+p	62.4 GeV	100 nb-1
Run-7	2007	Au+Au	200 GeV	813 μb-1
Run-8	2007/2008	d+Au	200 GeV	80 nb-1
		p+p	200 GeV	5.2 pb-1
		Au+Au	9.2 GeV	
Run-9	2009	p+p	200 GeV	16 pb-1
		p+p	500 GeV	14 pb-1
Run-10	2010	Au+Au	200 GeV	1.3 nb-1
		Au+Au	62.4 GeV	100 μb-1
		Au+Au	39 GeV	40 μb-1
		Au+Au	7.7 GeV	260 mb-1
Run-11	2011	p+p	500 GeV	27 pb-1
		Au+Au	200 GeV	915 μb-1
		Au+Au	27 GeV	5.2 μb-1
		Au+Au	19.6 GeV	13.7 M events
Run-12	2012	p+p	200 GeV	9.2 pb-1
		p+p	510 GeV	30 pb-1
		U+U	193 GeV	171 μb-1
		Cu+Au	200 GeV	4.96 nb-1
Run-13	2013	p+p	510 GeV	156 pb-1
Run-14	2014	Au+Au	15 GeV	44.2 μb-1
		Au+Au	200 GeV	2.56 nb-1

Hadrons

Hadrons in d+Au at $\sqrt{s_{NN}}$ = 200 GeV

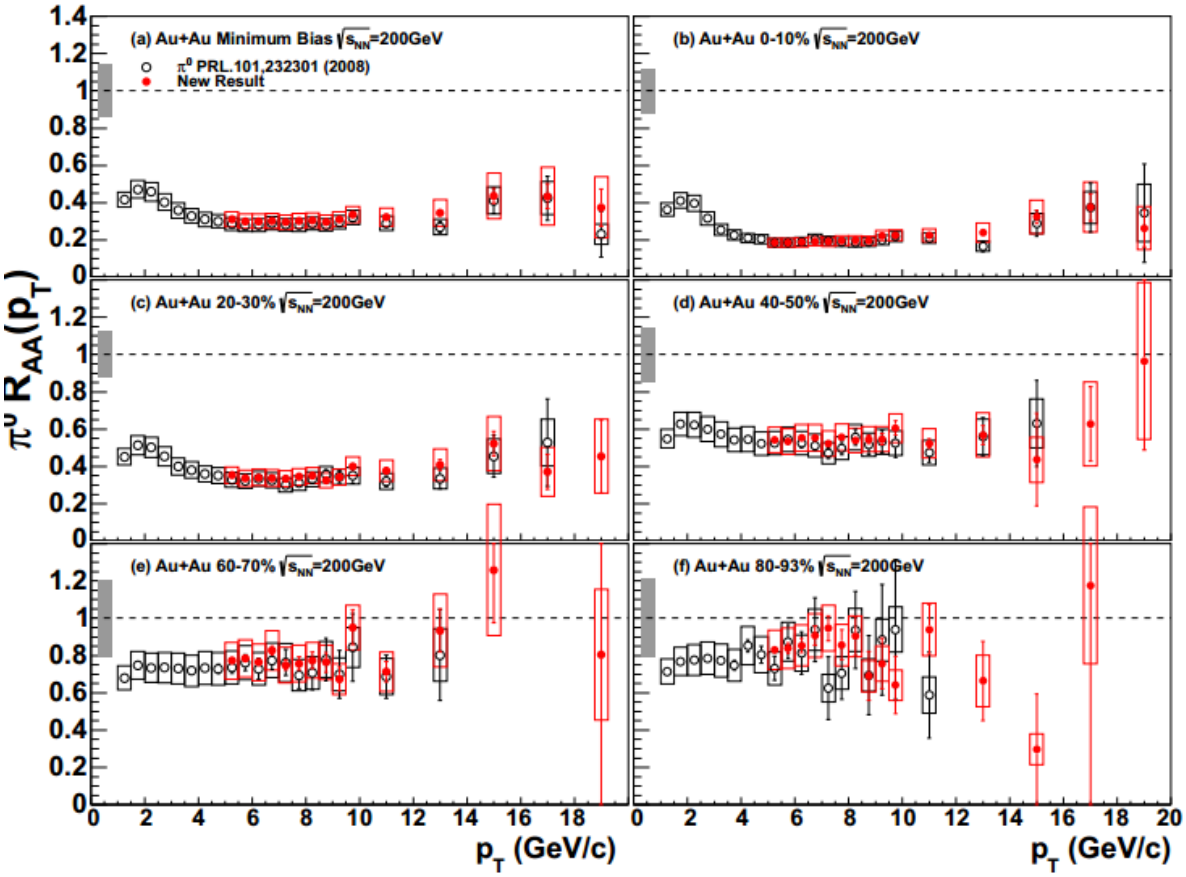
- Nuclear modification factor: $R_{AA} = \dfrac{dN_{AA}/dy}{\langle N_{coll} \rangle \cdot dN_{pp}/dy}$



- In peripheral collisions R_{dA} is consistent with unity for all hadrons at $p_T > 2$ GeV/c
- In central collisions:
  - ✓ R_{dA} for all mesons is the same with a hint of modest Cronin-like enhancement at intermediate p_T and suppression at high p_T
  - ✓ Production of baryons (protons) is strongly enhanced
  - ✓ Cronin enhancement for hadrons is weaker at RHIC than at SPS

Hadrons at high p_T, Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

- Production of hadrons is suppressed in (semi)central heavy ion collisions ↔ jet quenching; **Phys.Rev.Lett. 88 (2002) 022301**



Phys.Rev.C87 (2013) 3, 034911

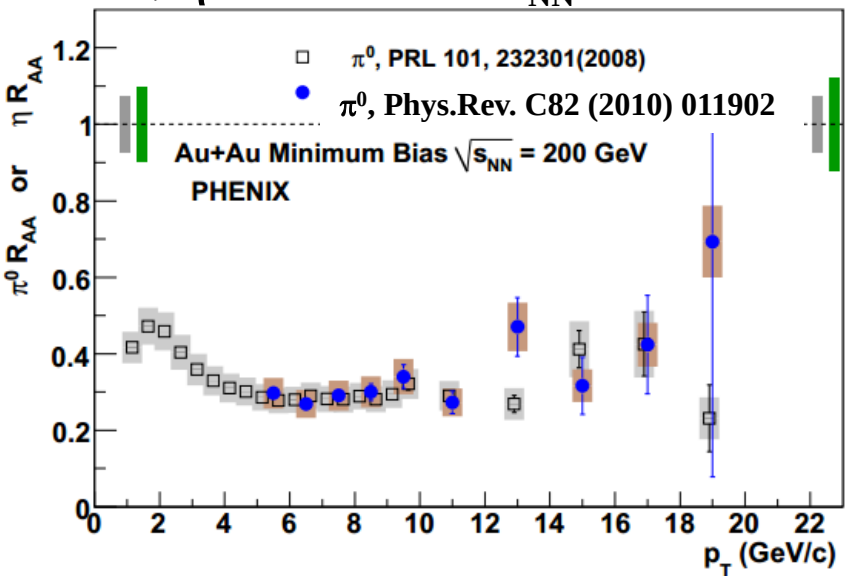
π^0, 2004 data
π^0, 2007 data

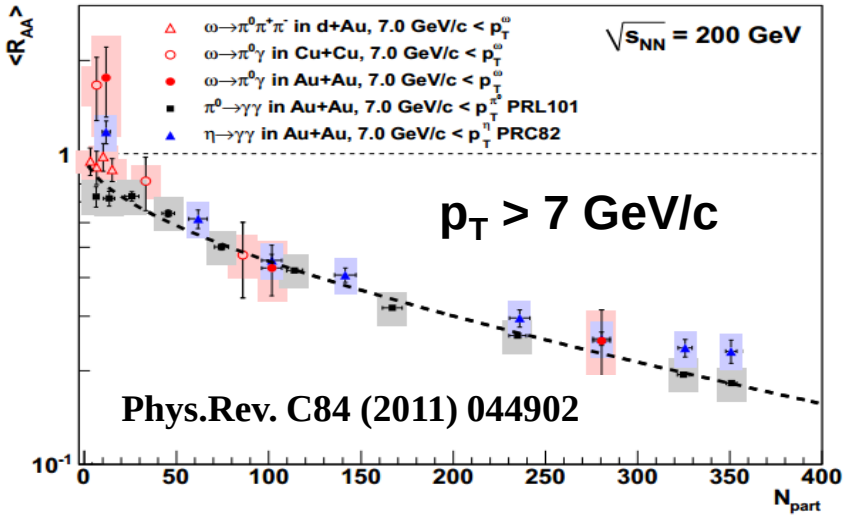
- System size dependence of R_{AA}
- New measurements confirm previous observations
- In central collisions suppression is strongest (~ 0.2) at 6-8 GeV/c and decreases at higher/lower momenta
- In peripheral collisions R_{AA} ~ 0.8

Species dependence, A+A at $\sqrt{s_{NN}}$ = 200 GeV

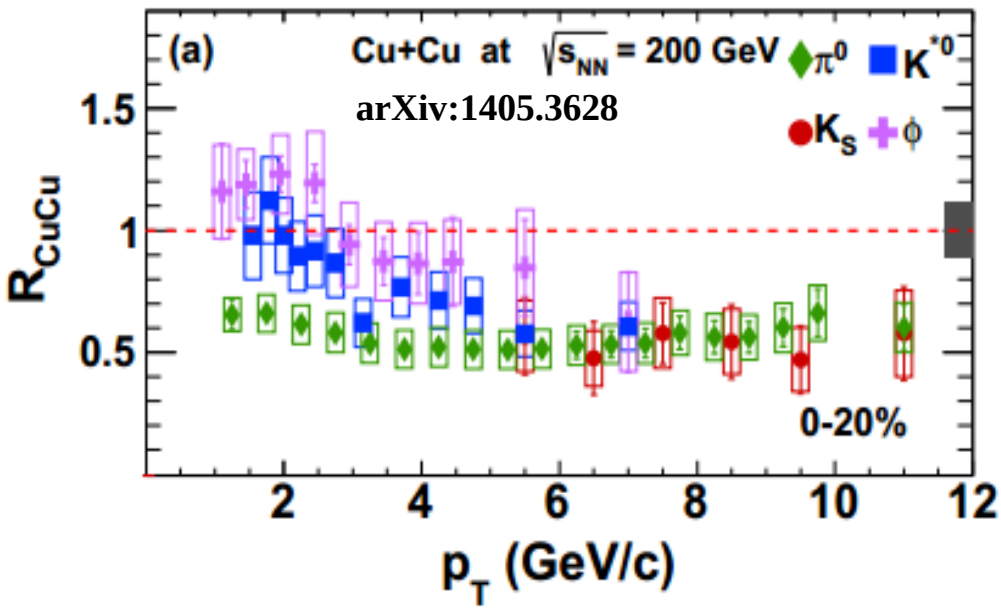
- Hadrons (π^0, η, K_s, K^*, ϕ) are similarly suppressed at high $p_T > 6$ GeV/c

π^0, η in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



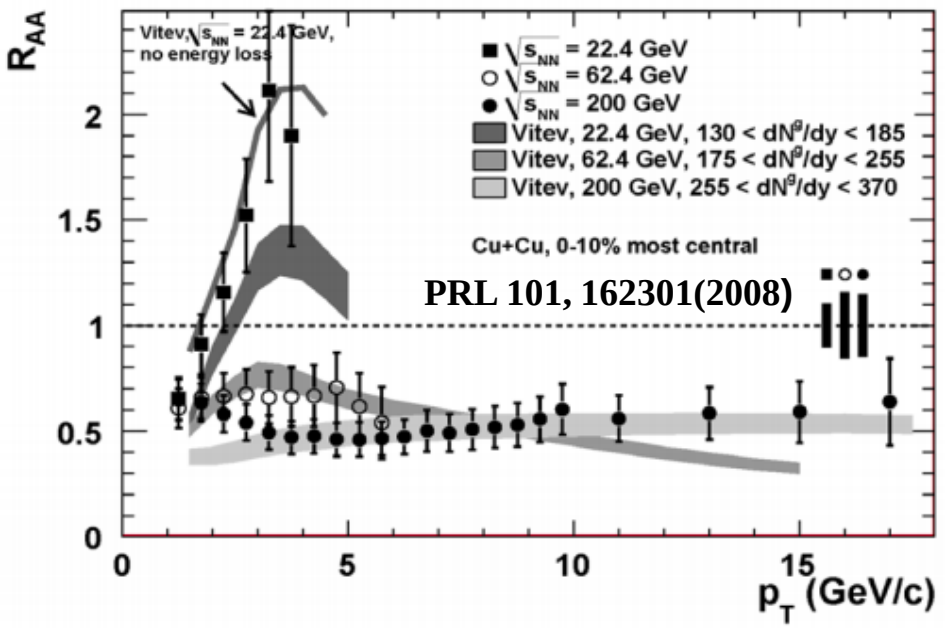


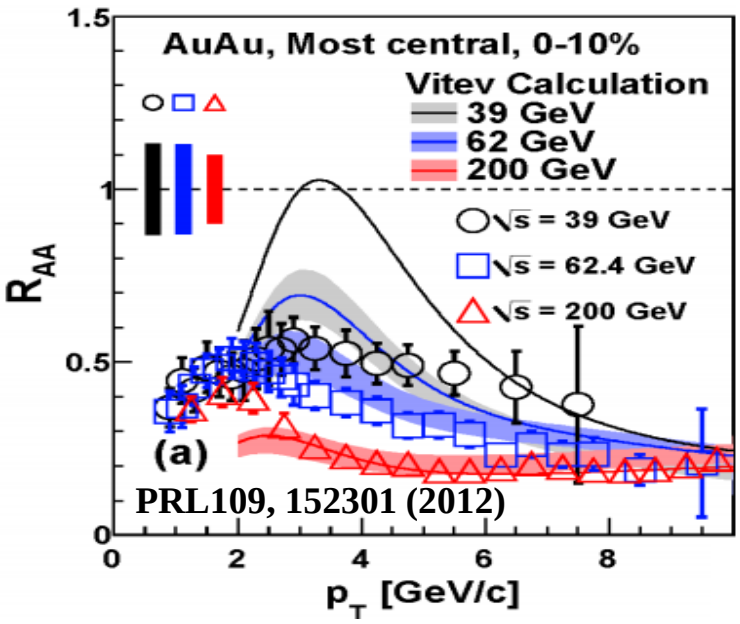
π^0, K_s, K^*, ϕ in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV

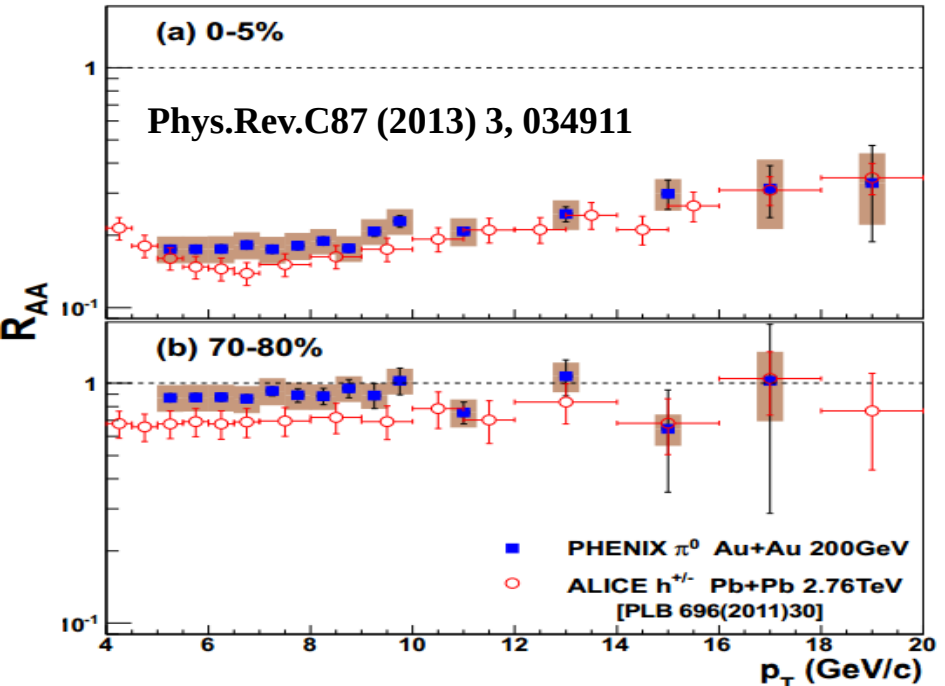


- R_{AA} (integrated at $p_T > 7$ GeV/c) vs N_{part}:
  - ✓ similar for π^0, η, ω
  - ✓ follows the same trend for Au+Au and Cu+Cu

Energy dependence, A+A at $\sqrt{s_{NN}}$= 22-2760 GeV







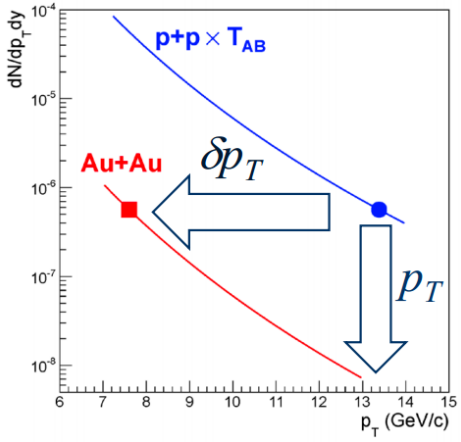
- Production of π^0 is suppressed in central Pb+Pb at $\sqrt{s_{NN}}$ =2760 GeV, Au+Au at $\sqrt{s_{NN}}$ =39, 62, 200 GeV and Cu+Cu at $\sqrt{s_{NN}}$ =62, 200 GeV
- Enhancement takes over suppression in a range of $\sqrt{s_{NN}}$ from 22 to 39 GeV
- Similar suppression:

✓Au+Au @ 62 and 200 GeV

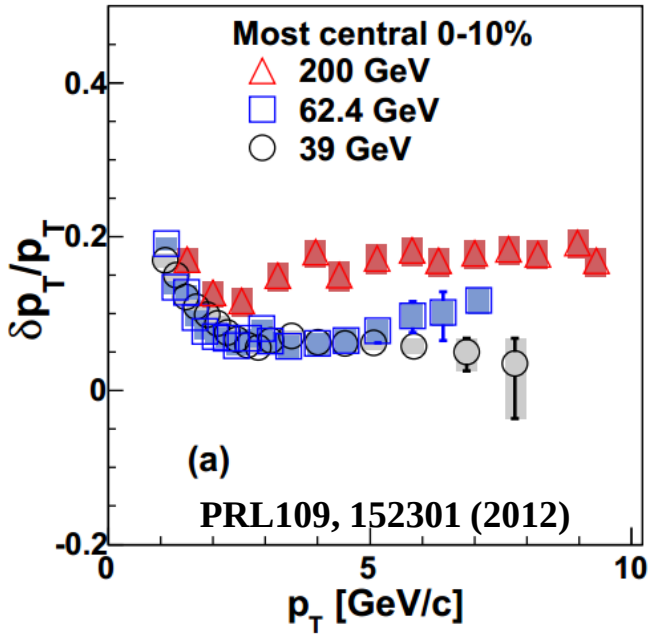
✓ Au+Au @ 200 GeV and Pb+Pb @ 2760 GeV

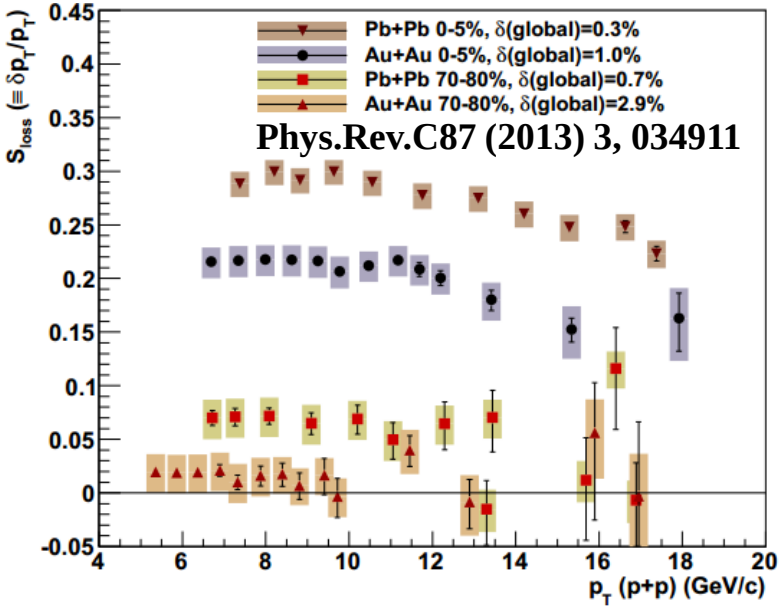
Fractional momentum loss, A+A at $\sqrt{s_{NN}}$=22-2760 GeV

- Estimate energy loss by $\delta p_T/p_T$ for high-p_T hadrons

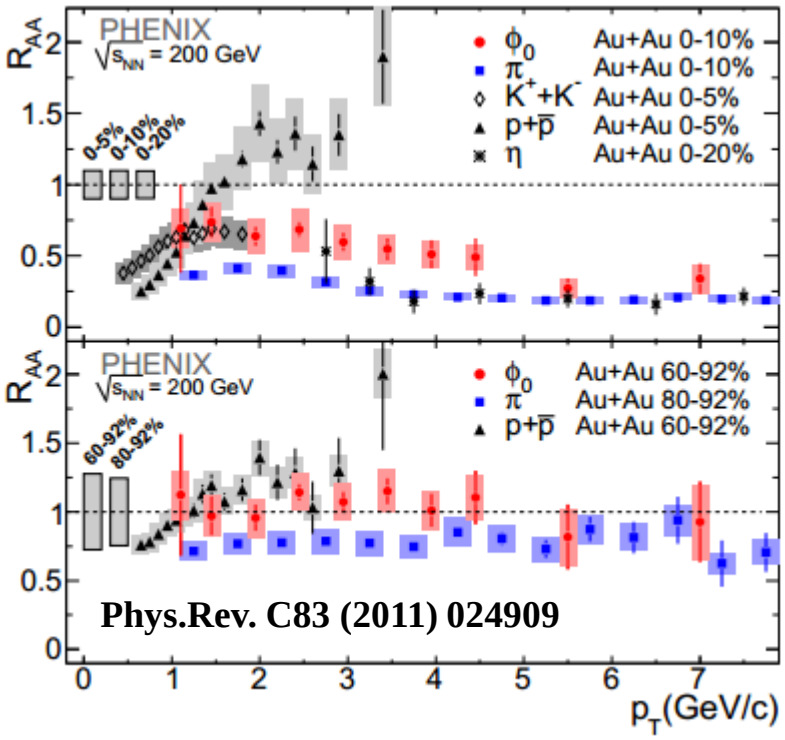


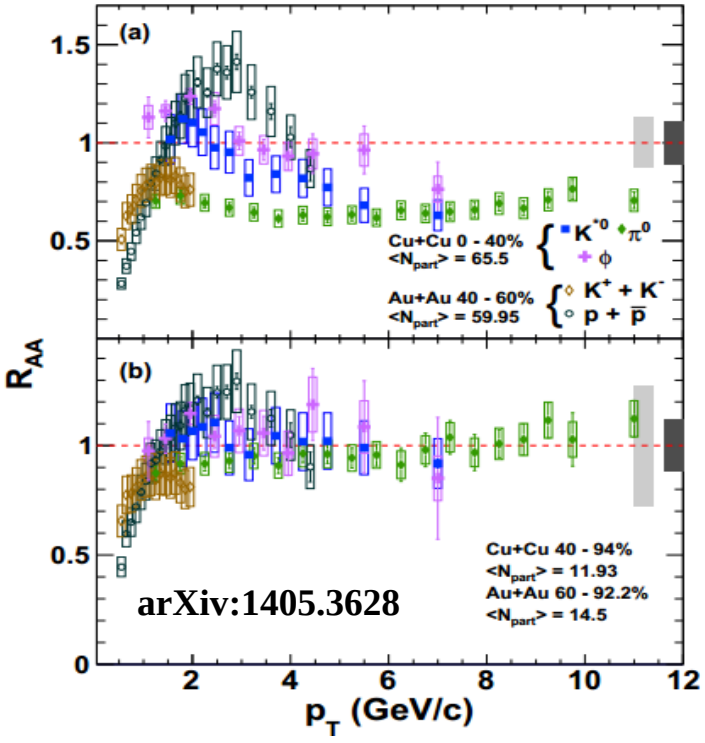
- Similar R_{AA} ↔ different energy losses due to steeper production spectra at lower $\sqrt{s_{NN}}$
- $\delta p_T/p_T$ changes by a factor of 1.5 (6) from AuAu@200 (62) to PbPb@2760





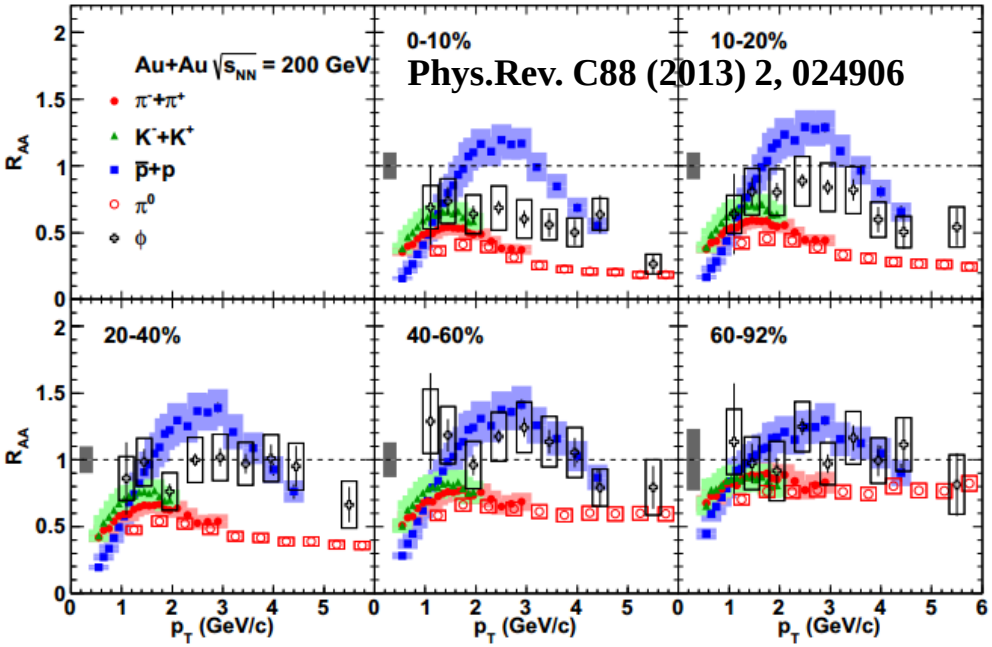
Hadrons at intermediate p_T, A+A at $\sqrt{s_{NN}}$ = 200 GeV



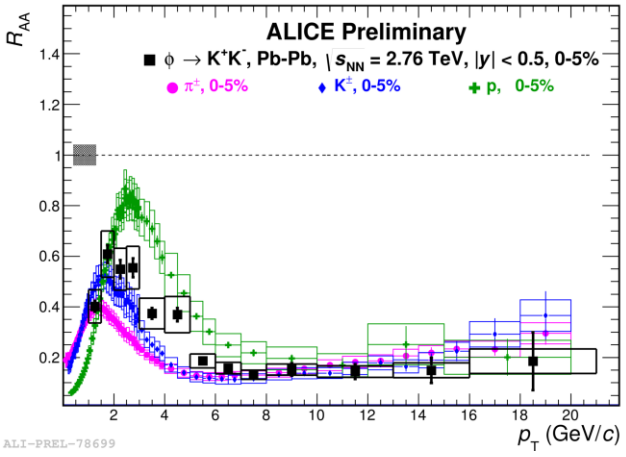


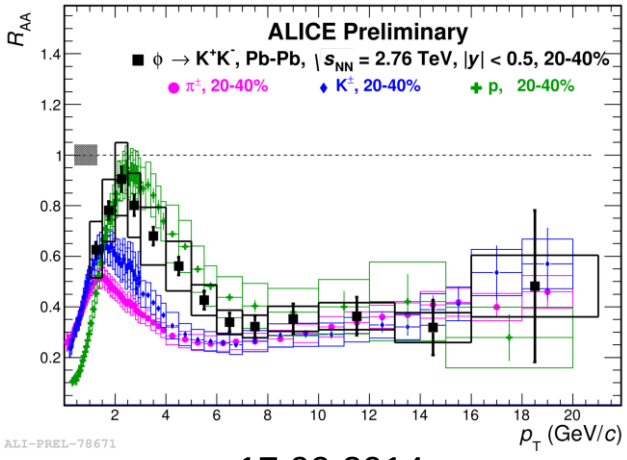
- Species dependence of R_{AA} in central Au+Au/Cu+Cu collisions at intermediate p_T:
  - ✓ bayons (protons) are enhanced
  - ✓ mesons are suppressed
  - ✓ no apparent mass dependence of suppression
  - ✓ mesons containing strange quarks (K*, ϕ) show an intermediate suppression

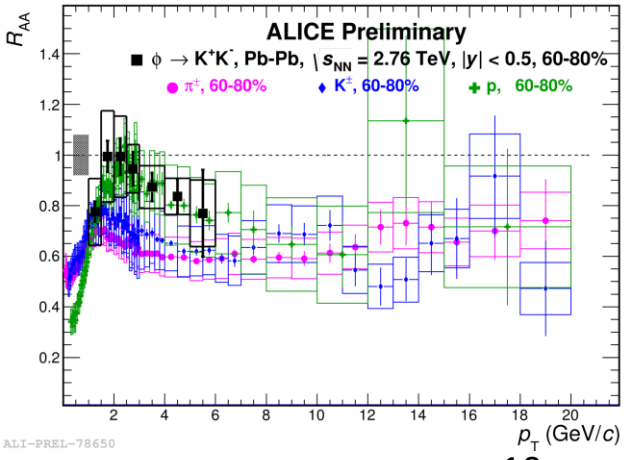
Centrality dependence, A+A at $\sqrt{s_{NN}}$ = 200-2760 GeV



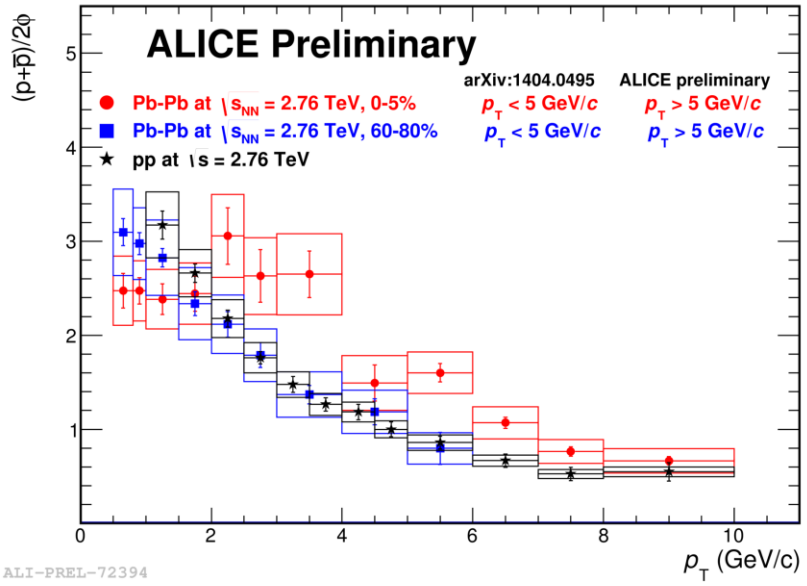
- Similar evolution of R_{AA} for ϕ with respect to that for $\pi^{\pm}$, $K^{\pm}$, p and anti-p in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and Pb+Pb at $\sqrt{s_{NN}}$ = 2760 GeV $\leftrightarrow$ ϕ is closer to mesons in most central collisions and is consistent with protons in peripheral
- ϕ is a meson that has a mass very similar to that of a proton

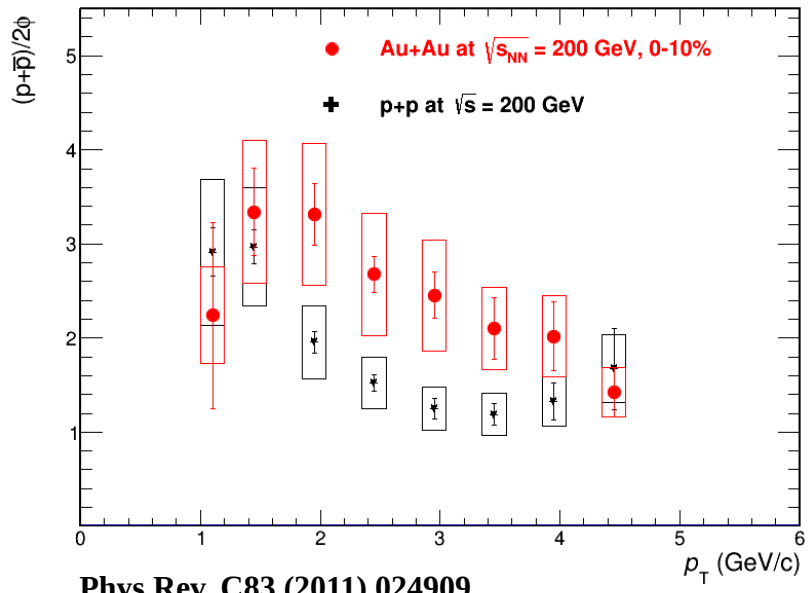






p/ϕ vs p_T, A+A at $\sqrt{s_{NN}}$ = 200-2760 GeV





• In central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 200 GeV the p/ϕ ratio is a flat function of p_T at intermediate p_T ↔ shape of production spectra is defined by particle masses, not by baryon/meson or quark content differences ↔ consistent with hydrodynamics ↔ difference in R_{AA} between p and ϕ is driven by difference in p+p references

• Observe a similar evolution of p/ϕ ratio from p+p to central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, although full flattening of the ratio vs p_T is not achieved ↔ interpretation is incomplete

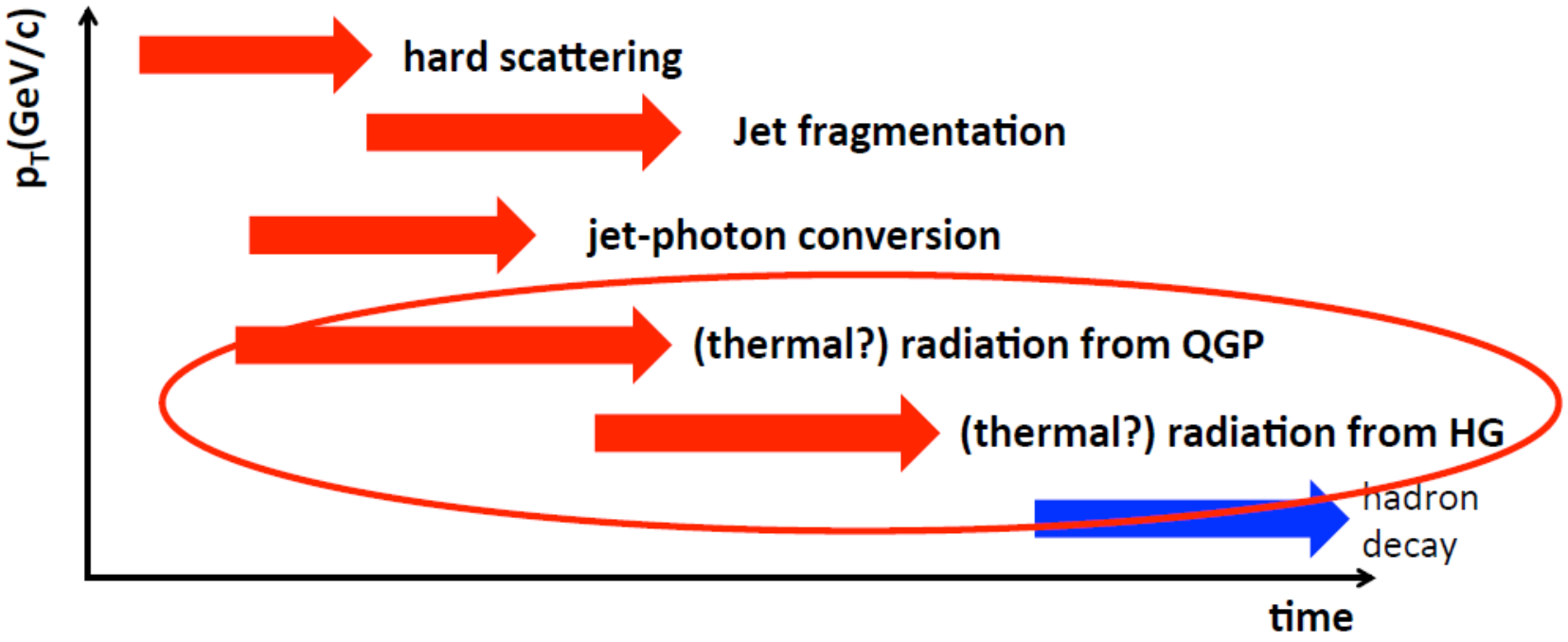
• Similar ratios for particles of similar mass could shed some light

Phys.Rev. C83 (2011) 024909
Phys.Rev. C83 (2011) 064903
Phys.Rev. C88 (2013) 2, 024906

Direct photons

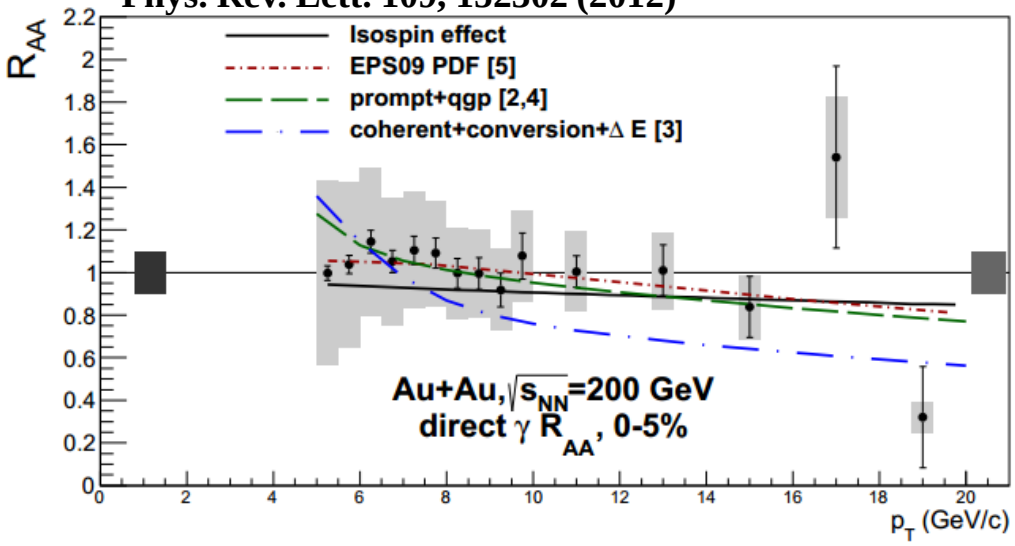
Direct photons

- Direct photons are all photons except for those coming from hadron decays:
  - ✓ produced during all stages of the collision
  - ✓ strongly interacting matter is transparent for photons → a good probe

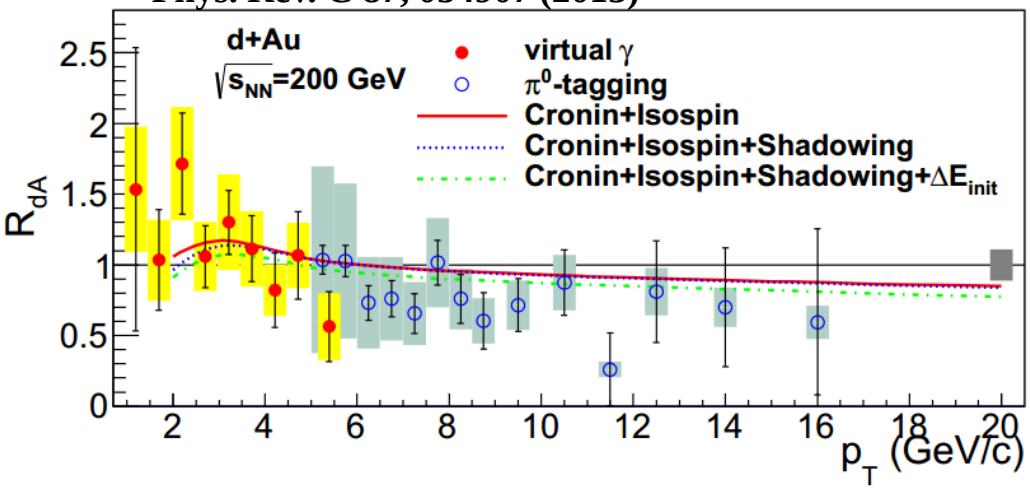


High-p_T direct photons , A+A at $\sqrt{s_{NN}}$ = 200 GeV

Phys. Rev. Lett. 109, 152302 (2012)

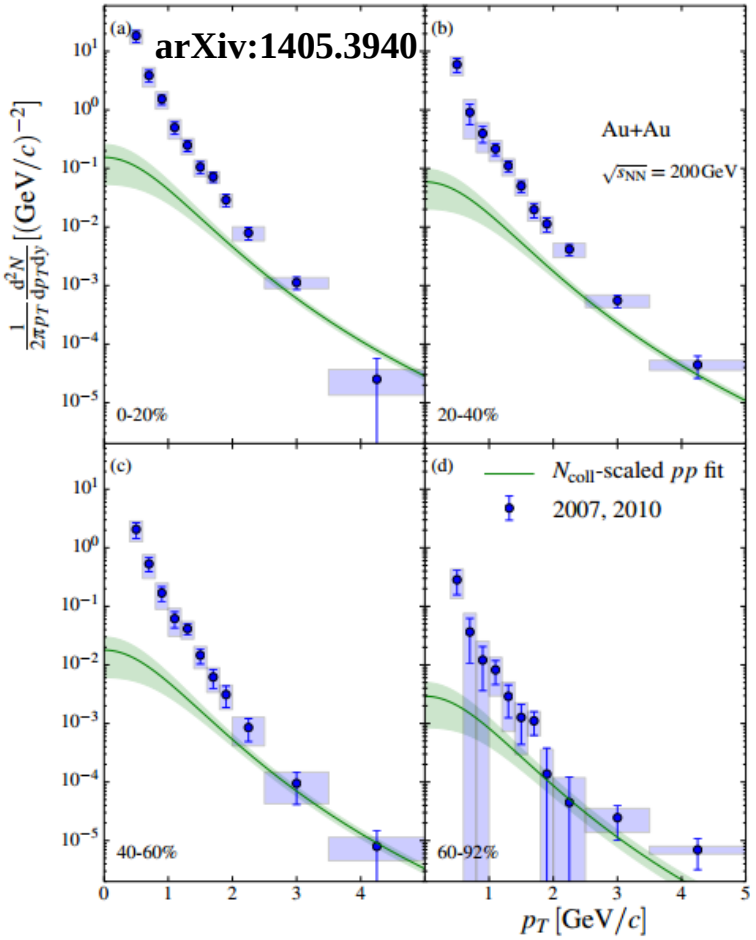


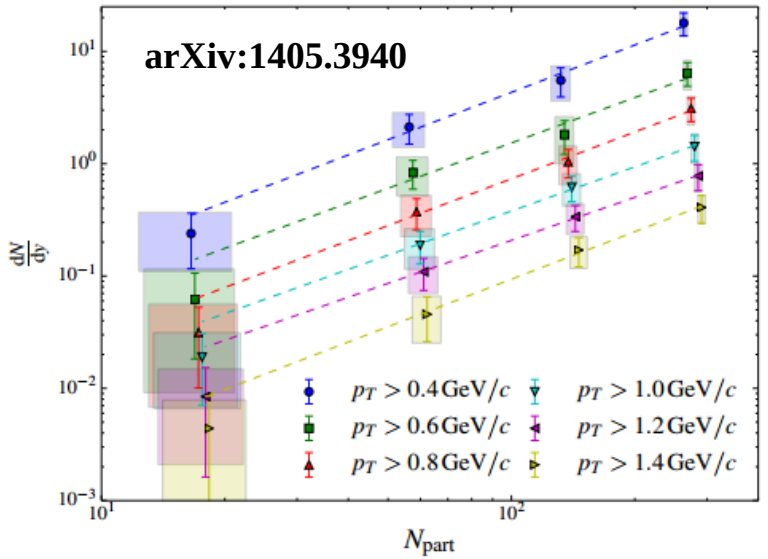
Phys. Rev. C 87, 054907 (2013)



- R_{dA} and R_{AA} are consistent with unity in d+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at all centralities
- In quantitative agreement with model calculations
- There is a place for Cronin-like enhancement in d+Au collisions at $\sqrt{s}$NN = 200 GeV $\rightarrow$ initial state effect

Excess of photon yields , Au+Au at $\sqrt{s_{NN}}$ = 200 GeV





• Exponential slopes (**~exp(-p_T/T)**) of photon excess are centrality independent within uncertainties:

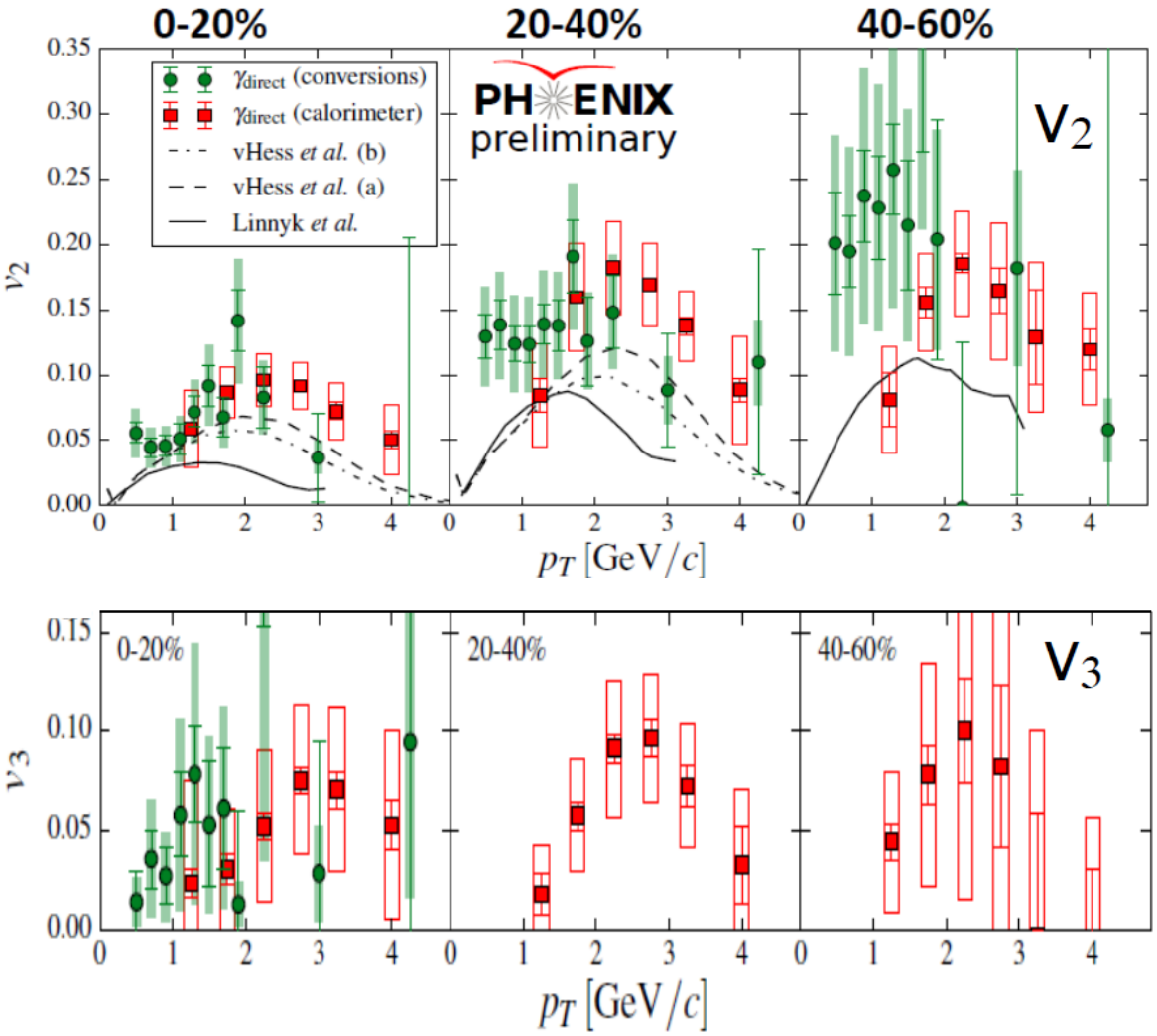
T (0-20%) = 239 ± 25 ± 7 MeV
T (20-40%) = 260 ± 33 ± 8 MeV
T (40-60%) = 225 ± 28 ± 6 MeV
T (60-92%) = 238 ± 50 ± 6 MeV

• Excess of photon yields increases as AN_{part}^{α}, where **α=1.48±0.08(stat.)±0.04(sys.)**

• Centrality dependence is not an artifact of the lowest p_T points, same slope is observed as we increase the lower limit of integration

• Suggests early emission when temperature is still very high

Photon anisotropy , Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



- Two new methods to measure direct photon v_2 and v_3 produce consistent results
- No strong centrality dependence for v_3
- Magnitudes of v_2 and v_3 are similar that of π^0
- Challenge for dynamical models
- Large flow suggests late emission when temperature is low and collective motion is large

Conclusion

- Hadrons and direct photons at high p_T:
  - ✓ R_{dA} for all measured hadrons is consistent with unity with a hint of modest suppression
  - ✓ similar suppression of all measured hadrons in central heavy ion collisions, R_{AA}~ 0.2
  - ✓ δpT/pT changes by a factor of 1.5 (6) from AuAu@200 (62) to PbPb@2760
  - ✓ direct photons R_{dA} and R_{AA} are consistent with unity, quantitative agreement with models

Measurements are consistent jet quenching from parton energy loss in hot and dense matter

- Hadrons at intermediate p_T:
  - R_{dA} splits between mesons and baryons; modest Cronin for mesns and ~ 2 enhancement for protons
  - R_{AA} hierarchy for different hadrons with no apparent mass and quark content dependence
  - similar evolution at RHIC and LHC
  - p/ϕ ratio flattens vs p_T indicating larger importance of flow

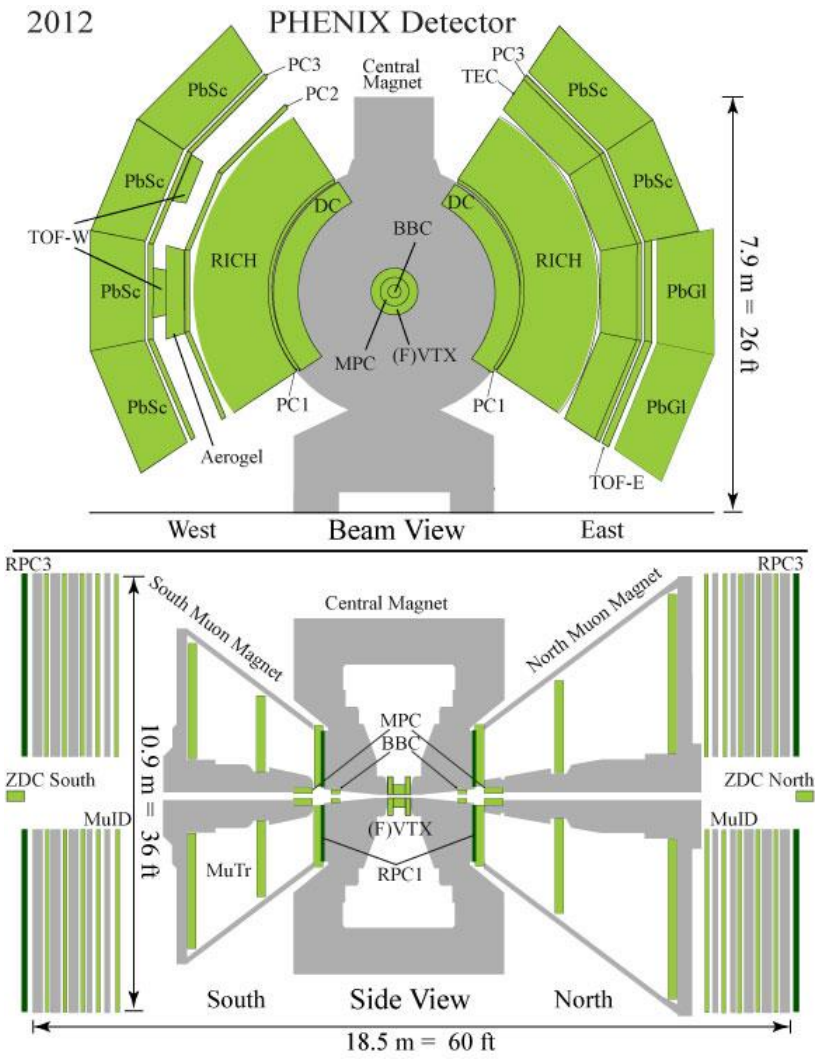
Understanding of dominating hadron production mechanisms (coalescence, flow, fragmentation etc.) is still incomplete

- Soft direct photons:
  - ✓ large excessive yield of photons with respect to N_{coll} scaled pp results
  - ✓ shape of pT spectra doesn't depend on centrality within uncertainties
  - ✓ photon excess increases with centrality as N_{part}^{α}, $\alpha \approx 1.48$l
  - ✓ large v2 and v3 comparable to that of hadrons

New measurements for direct photons put new constraints on hydrodynamic time evolution and modeling of radiative emission

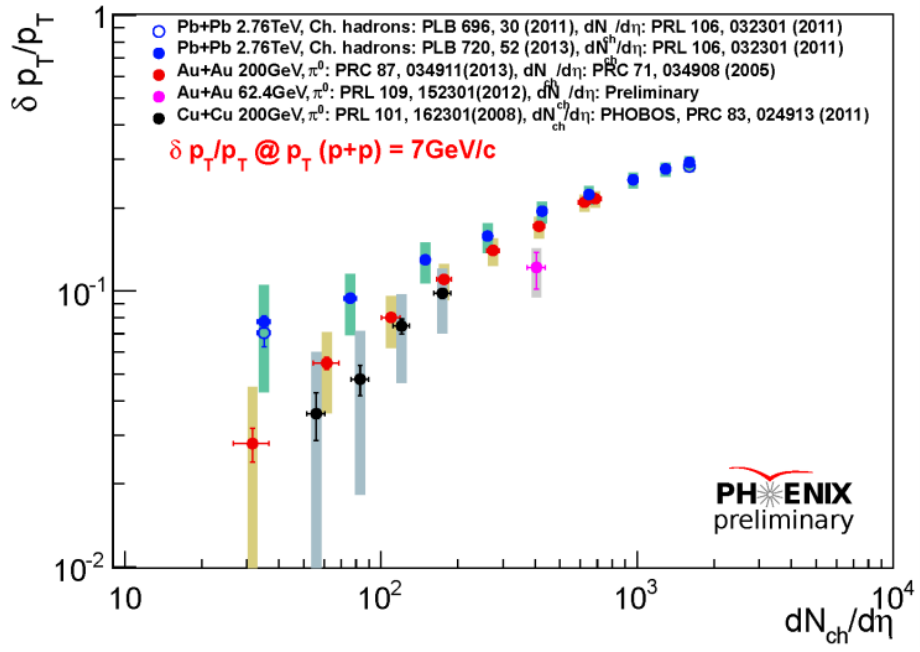
Backup

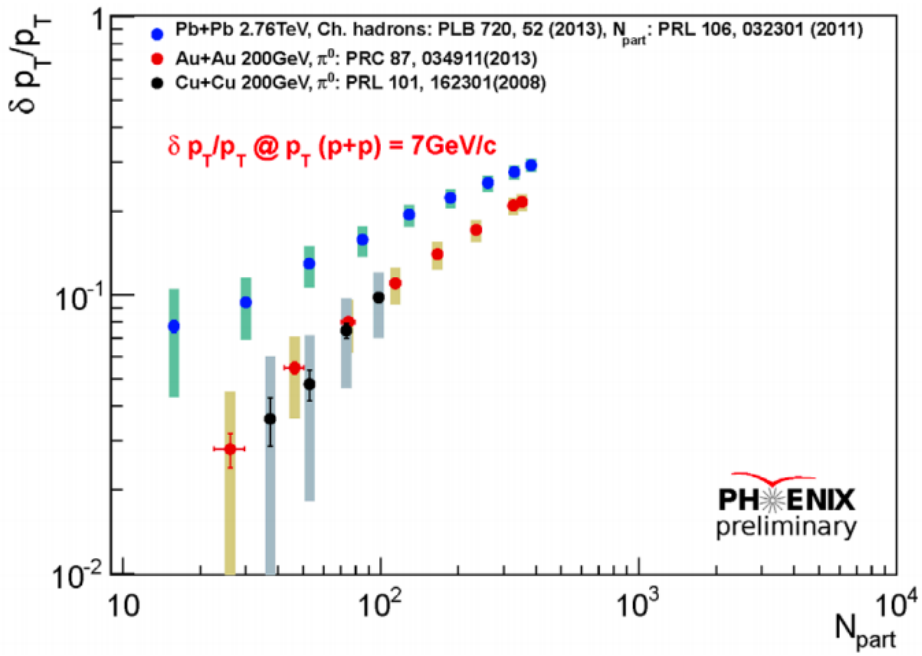
PHENIX detector



- PHENIX has been designed to measure rare processes involving leptons and photons at the highest RHIC luminosities
- Central arms, each $|\eta| < 0.35$ and $\Delta\varphi = \pi$:
  - ✓ tracking, $\delta p/p \sim 0.7\% \oplus 1.1\% p[GeV/c]$
  - ✓ calorimetry, $\sigma(E)/E = \frac{8.1(5.9)\%}{\sqrt{E[GeV]}} \oplus 2.1(0.8)\%$ for PbSc(PbGl): γ, $e^{\pm}$, π^0, η, ω, ϕ etc.
  - ✓ EMC (~400 ps), TOF-E (~ 120 ps), TOF-W (~ 100 ps): $h^{\pm}$ ID:
  - ✓ EMC & RICH: $e^{\pm}$ ID and Lvl-1 trigger
- Two forward arms, $1.1 < |\eta| < 2.3$, $\Delta\varphi = 2\pi$
- BBC, ZDC provide the minbias trigger, determine z-coordinate of the collision vertex, centrality of events in p(A)+A
- MPC, (F)VTX

$\delta p_T/p_T$ over collision systems

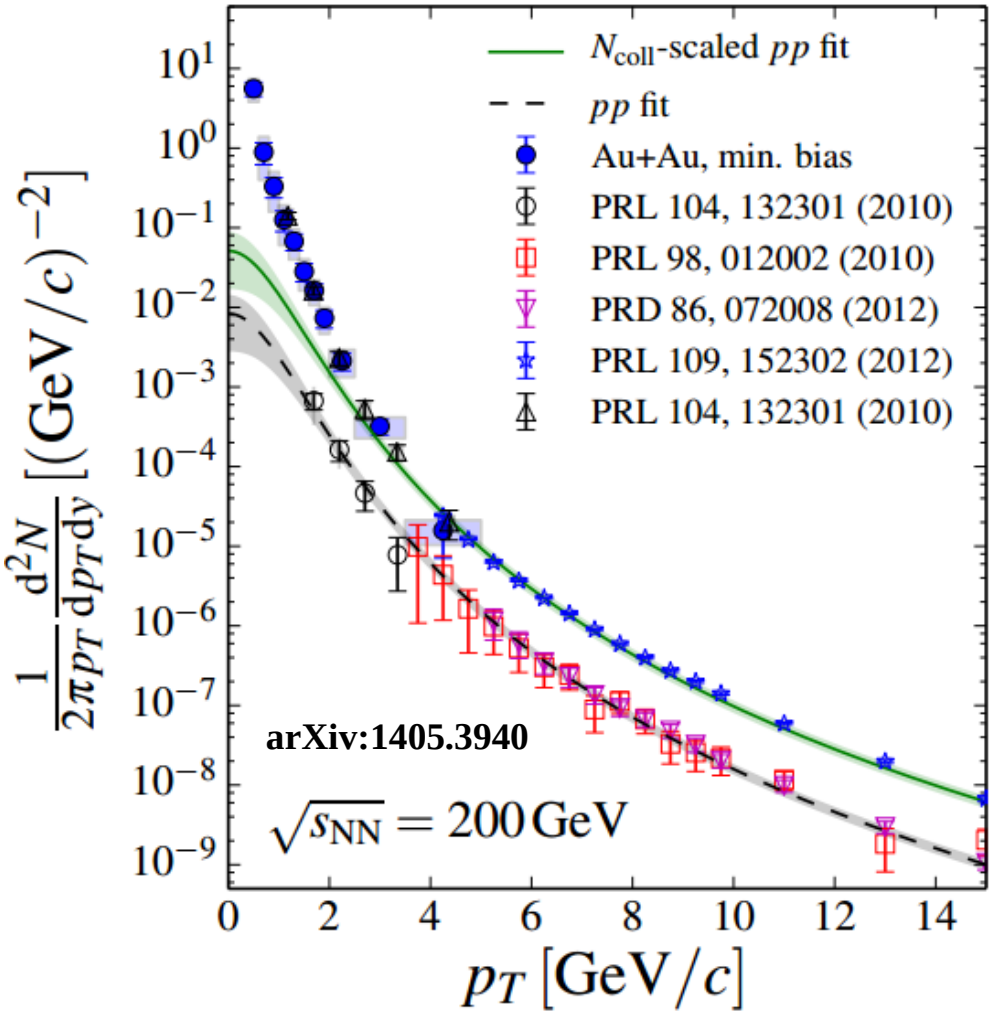




- $\delta p_T/p_T$ vs $dN_{ch}/d\eta$ dependences for all collision systems merge to one curve at large values of dNch/dη independent of $\sqrt{s_{NN}}$

- At the same $\sqrt{s_{NN}}$ experimental points follow the same scaling for different collision systems

Real and virtual photons



- New analysis using external conversion of real photons on detector materials (HBD backplane)

- Agreement with earlier virtual photon results

- Extended p_T range, more centrality selections, higher precision