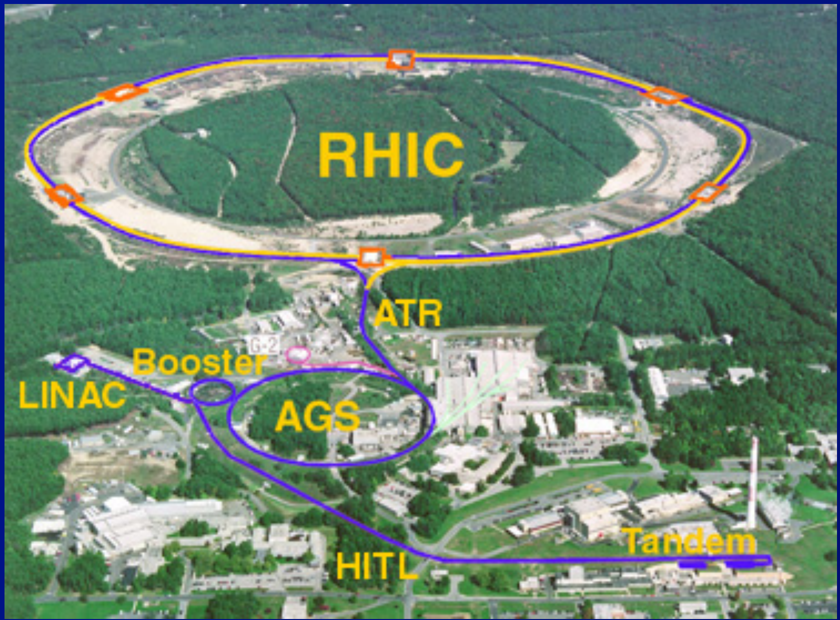
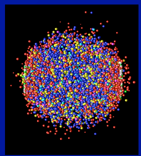
Heavy Ion Physics After Nine Years of RHIC Operation

Prof. Brian A. Cole
Columbia University

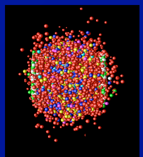


Looming on the heavy ion horizon

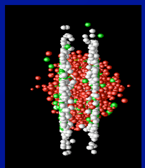
Ultra-relativistic A+A, Canonically



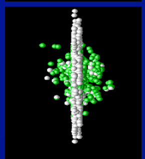
Recombination,
Hadronic cascade



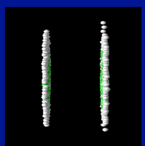
Hydro evolution



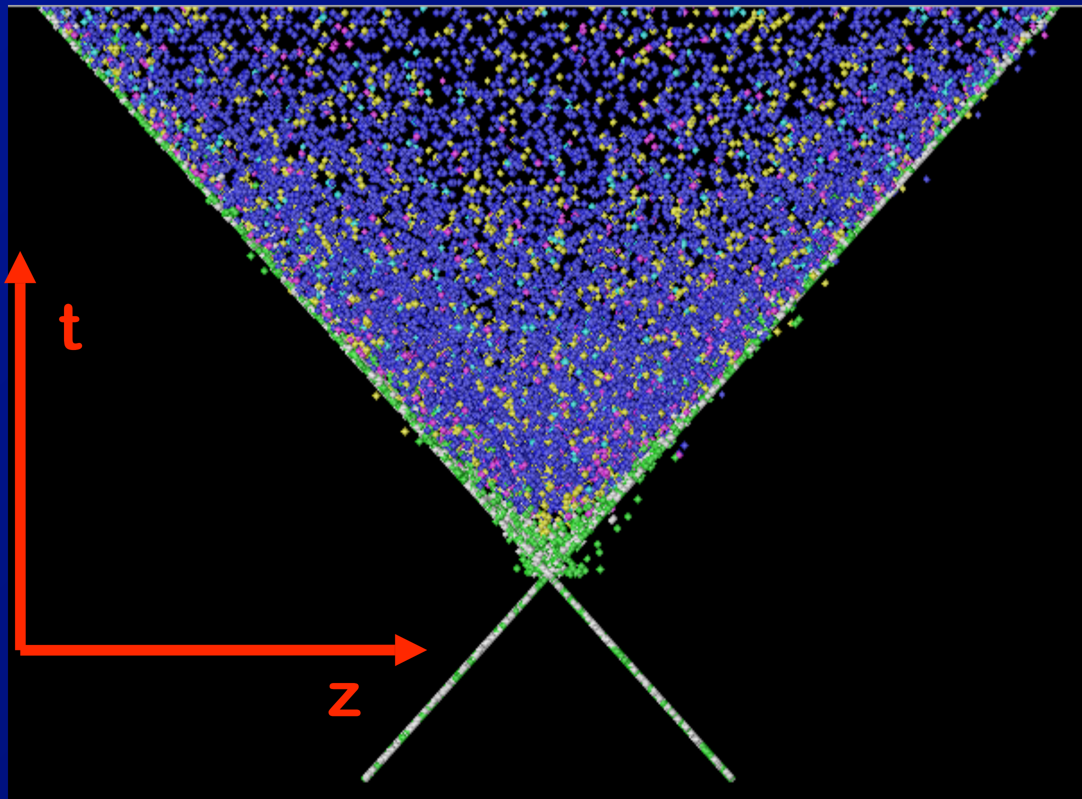
Fast thermalization



Hard processes,
CGC → Glasma



Saturated nuclei

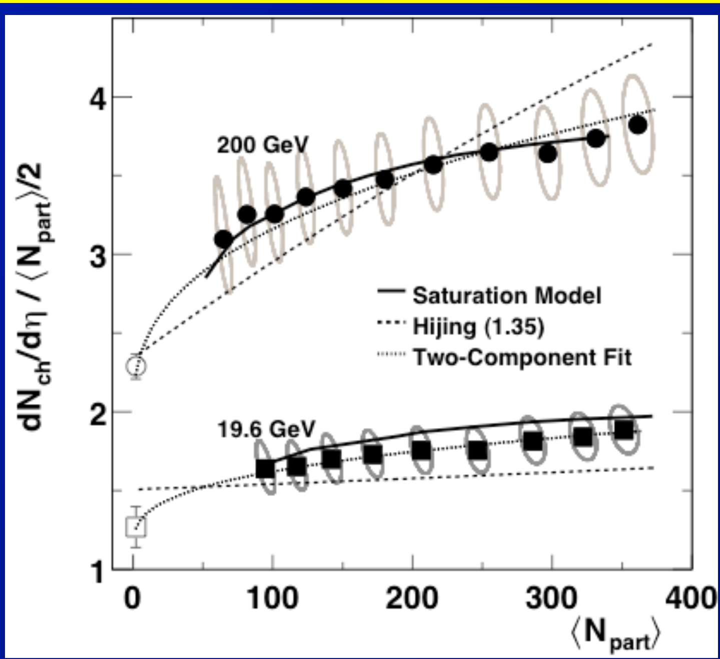


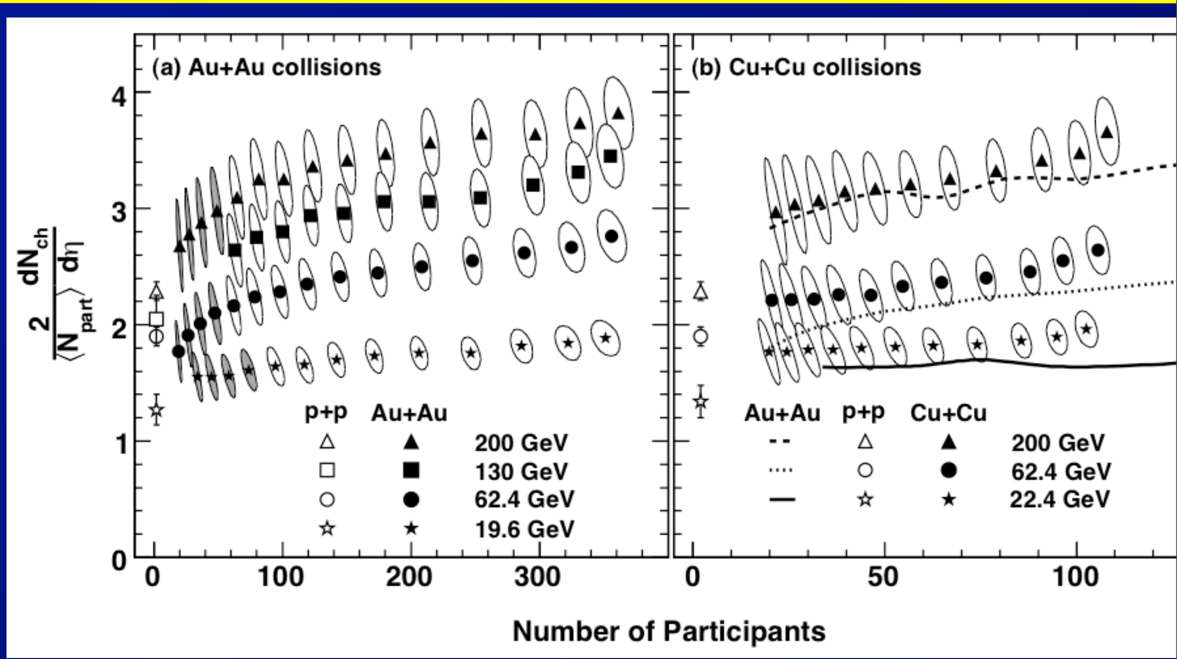
- How well do we understand each stage?
  - How certain are we that the canonical interpretation is indeed the correct one?
  - What if one of these is wrong, does it all fall apart?

Physics Issues that I will touch on

- **Saturation & Glasma**
  - Do we really understand A+A multiplicities?
  - Is CGC responsible for d+Au forward suppression of "high" p_T production?
- **Thermalization/strong coupling**
  - Clearly there is strong collective motion
  - But is our application of hydrodynamics really consistent with the data
- **Jet quenching**
  - Strong or weak coupling, how to tell?
  - Issues for full jet measurements (RHIC & LHC)
- **Measurements w/ prompt photons**

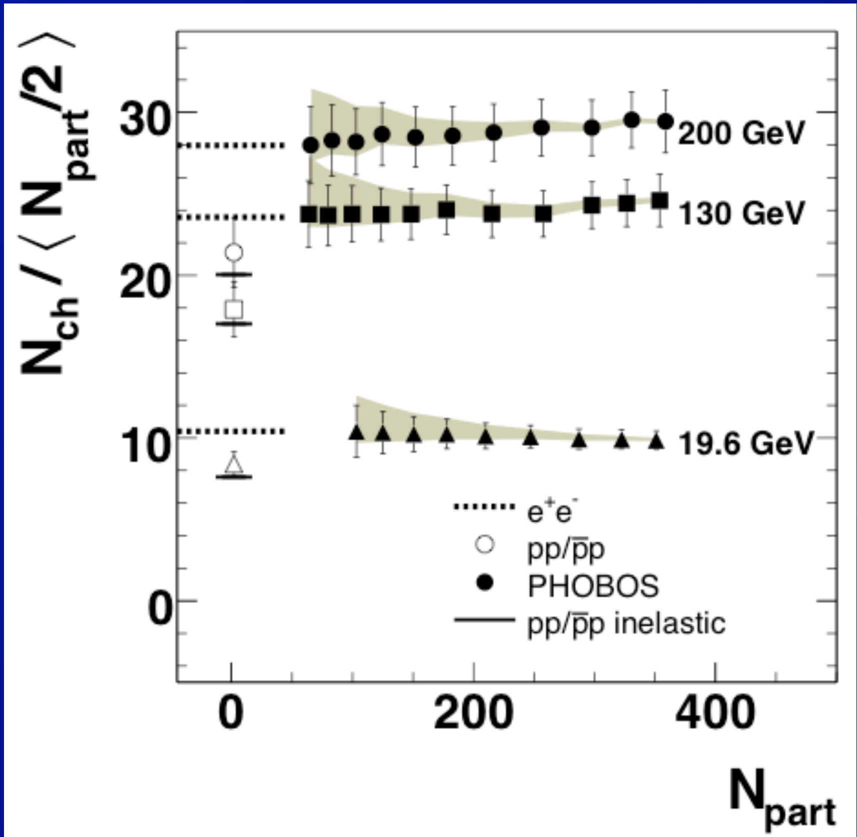
Charged Particle Multiplicity

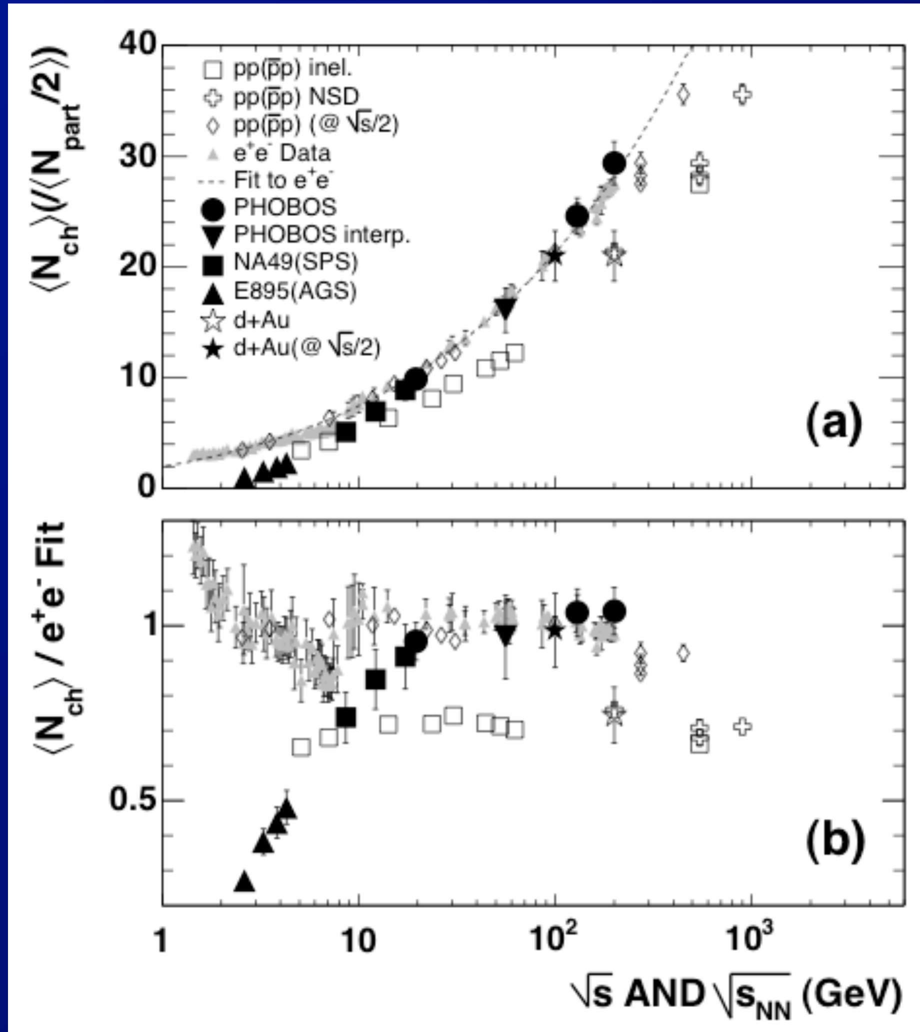




- Evidence for saturation(?)
  - Slow growth of multiplicity with energy
  - Slow growth of multiplicity with N_{part}
    - ⇒Same multiplicity at same N_{part} in Cu+Cu and Au+Au
    - ⇒For (≈ 20), 62.4, 200 GeV.
- But, could this behavior result from (leading twist) shadowing of nuclear PDFs (e.g. EPS08/9)

Charged Particle Multiplicity (2)

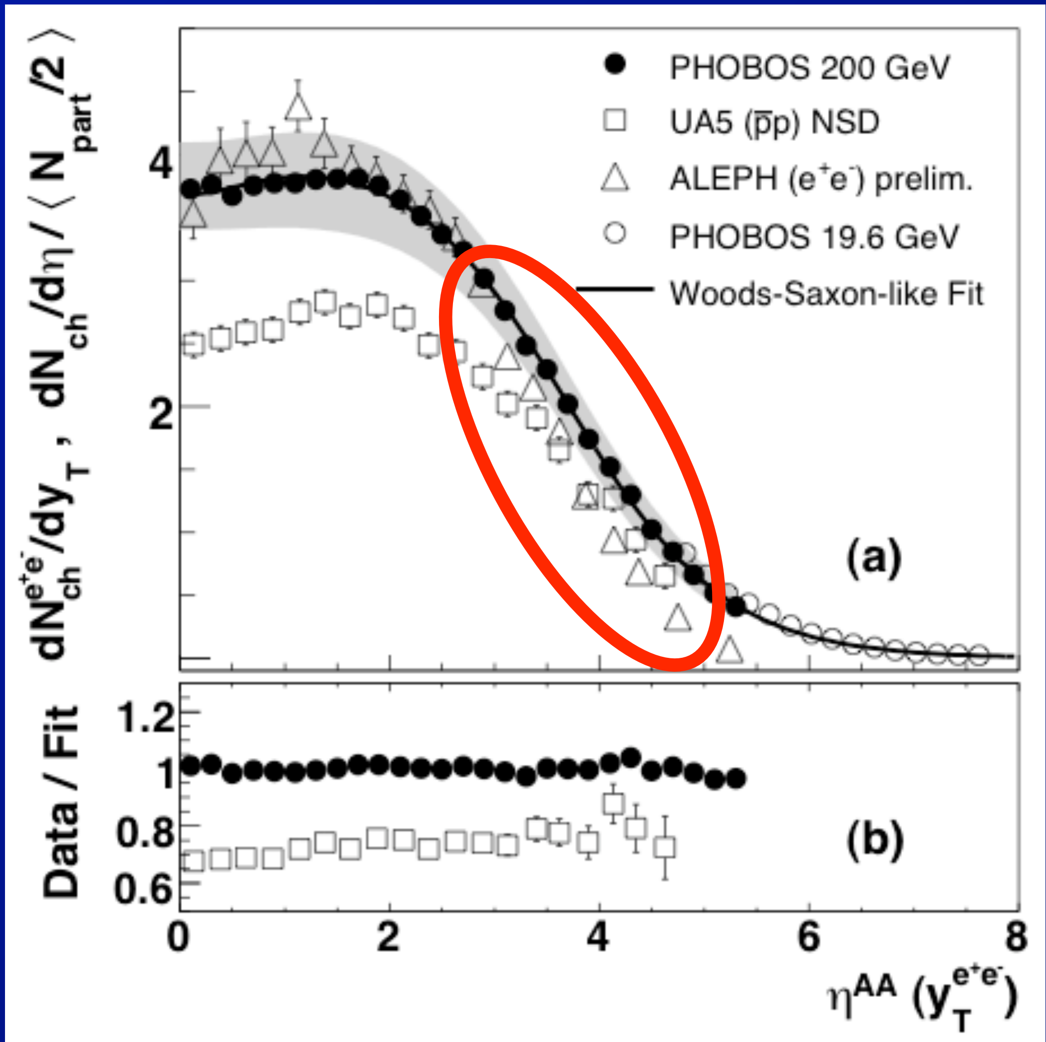




- Remarkable agreement between e^+e^- multiplicity and A+A multiplicity per participant pair.
  - Sets in at $\sqrt{s_{NN}}$ ~ 20 GeV

Charged Particle Multiplicity (3)

← Increasing angle



- See difference btw A+A $dN/d\eta$. e^+e^- dN/dy_T at large η
  - Completely natural due to nucleon frag. products
  - But at large angles with respect to beam (A+A) or thrust (e^+e^-)

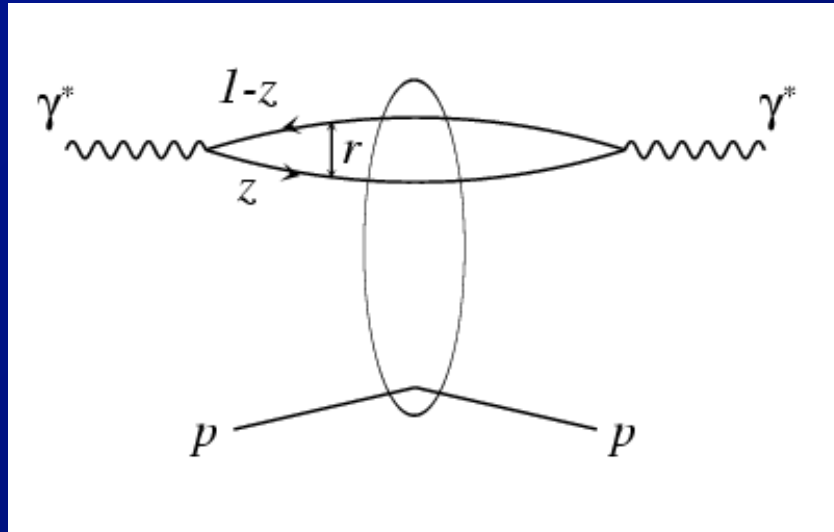
⇒Identical shape, normalization

Naive question:

Could this agreement result from angular ordering in QCD, evolution to large angles independent of “sources”

DIS: Target Rest Frame & Dipole Picture

- Suppose we view DIS in rest frame of target
  - γ^* fluctuation into quark, anti-quark (dipole) frozen
  - w/ radial separation r
  - Dipole interacts with proton



Unitarity diagram: $\gamma^* p$ $A^* A$

- Then DIS cross-section

$$\sigma(x,Q^2) = \int dz \int d^2r \left|\psi(r,z,Q^2)\right|^2 \hat{\sigma}(r,x)$$

- Interesting physics in $\hat{\sigma}(r,x)$
- What happens @ large r ? $r \sim h/\sqrt{Q^2}$

"Saturation" @ low x

- In dipole picture suppose $\hat{\sigma}(r,x)$ saturates for $r > R_0 = 1/Q_s$
- And assume

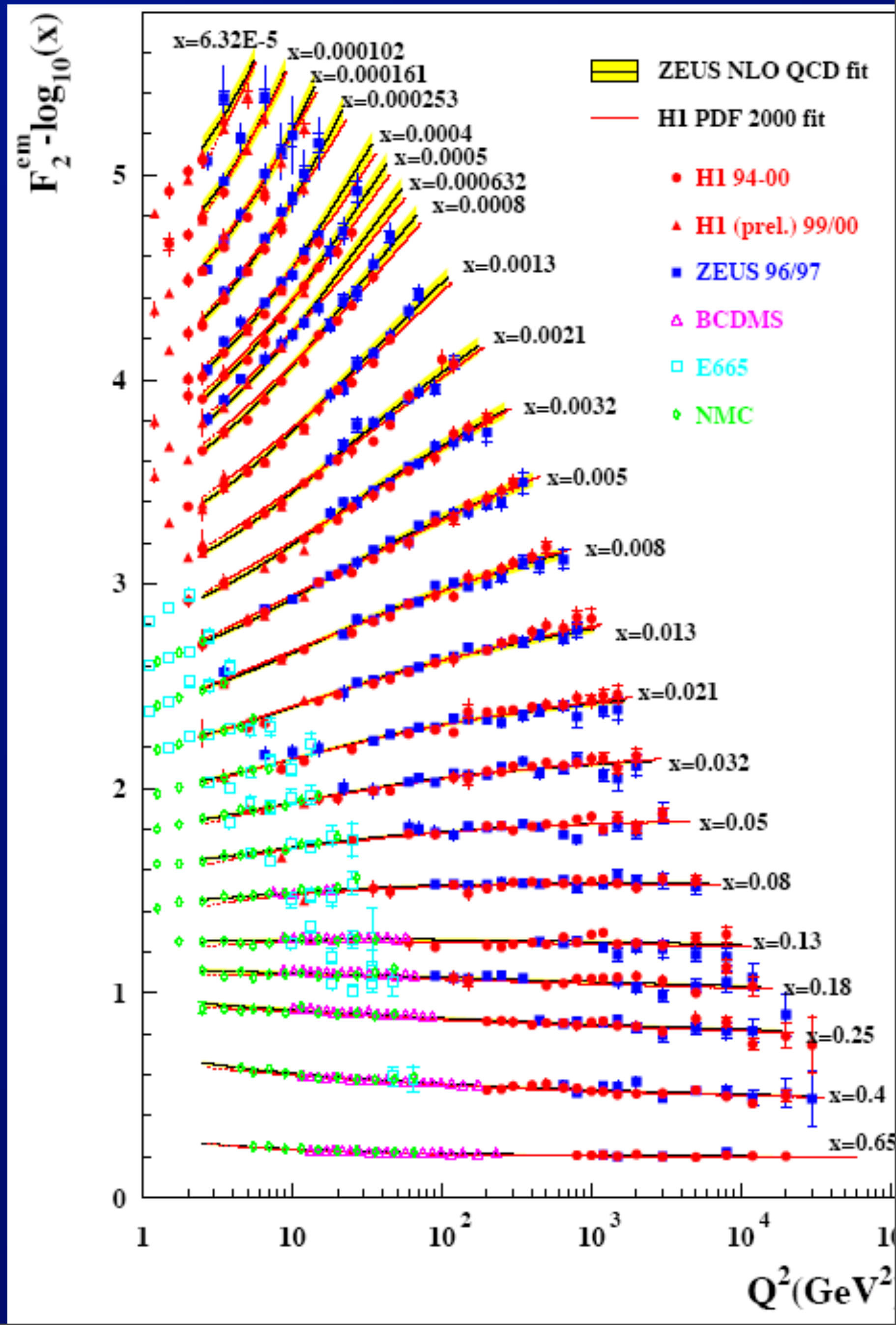
$$\hat{\sigma}(r,x) = g(r\,Q_s)$$

- Use BFKL for x dependence of Q_s

$$Q_s(x) = Q_0\left(\frac{x_0}{x}\right)^{\lambda/2}$$

- Plot

$$\sigma_{tot}^{\gamma^* p}(\tau),\ \tau = \left(Q/Q_s(x)\right)^2$$



Saturation: Empirical evidence?

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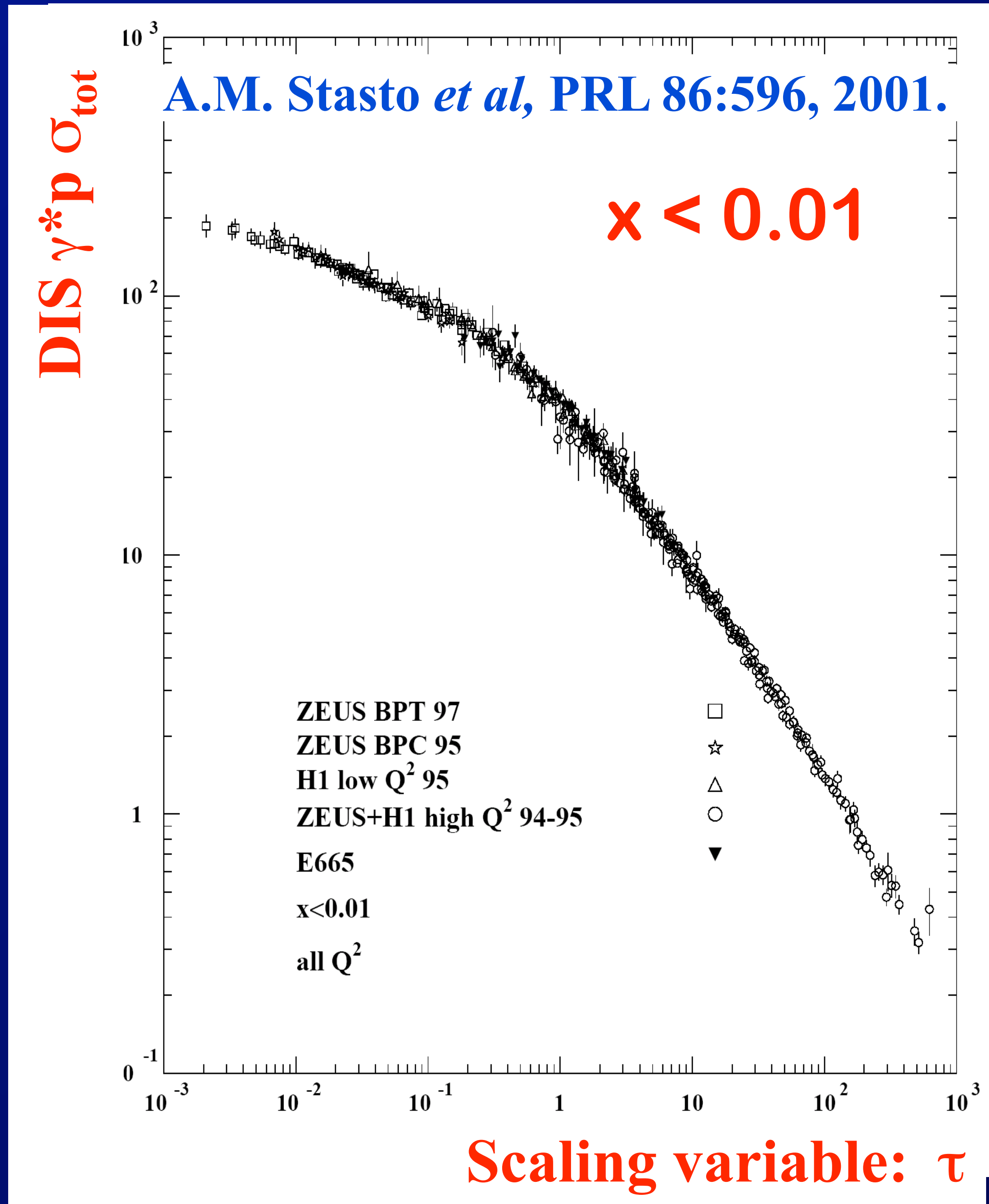
"Geometric Scaling"



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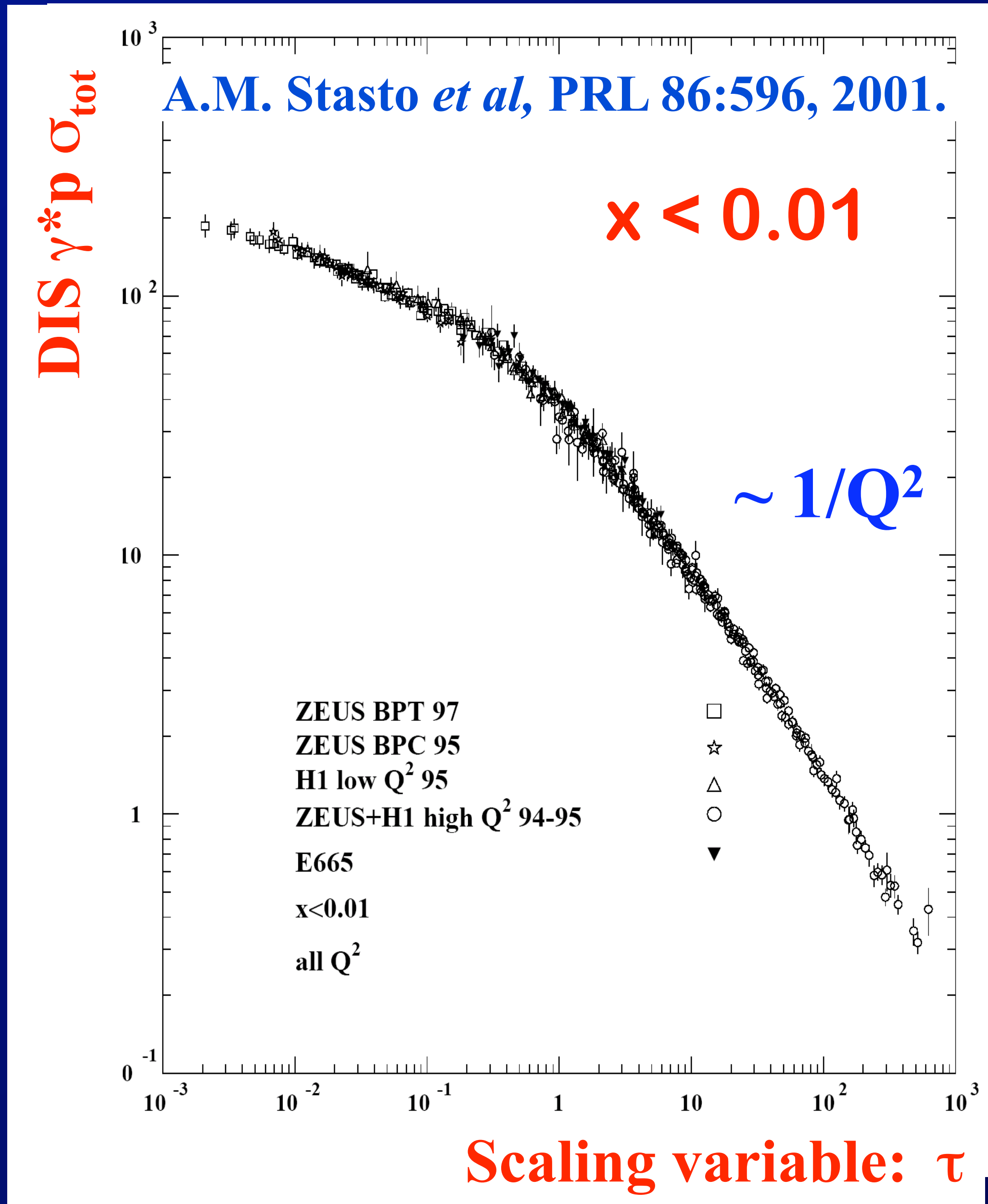

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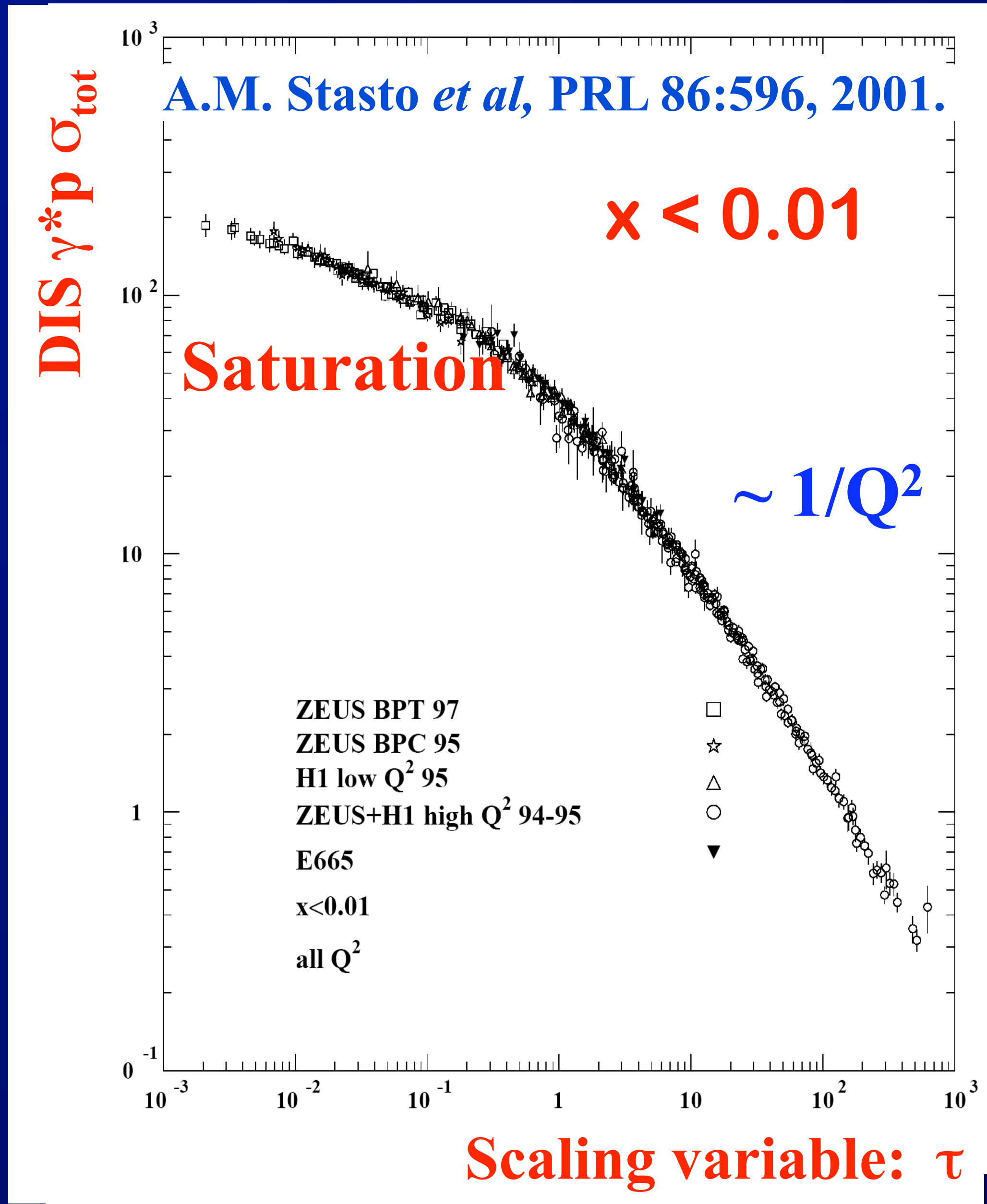
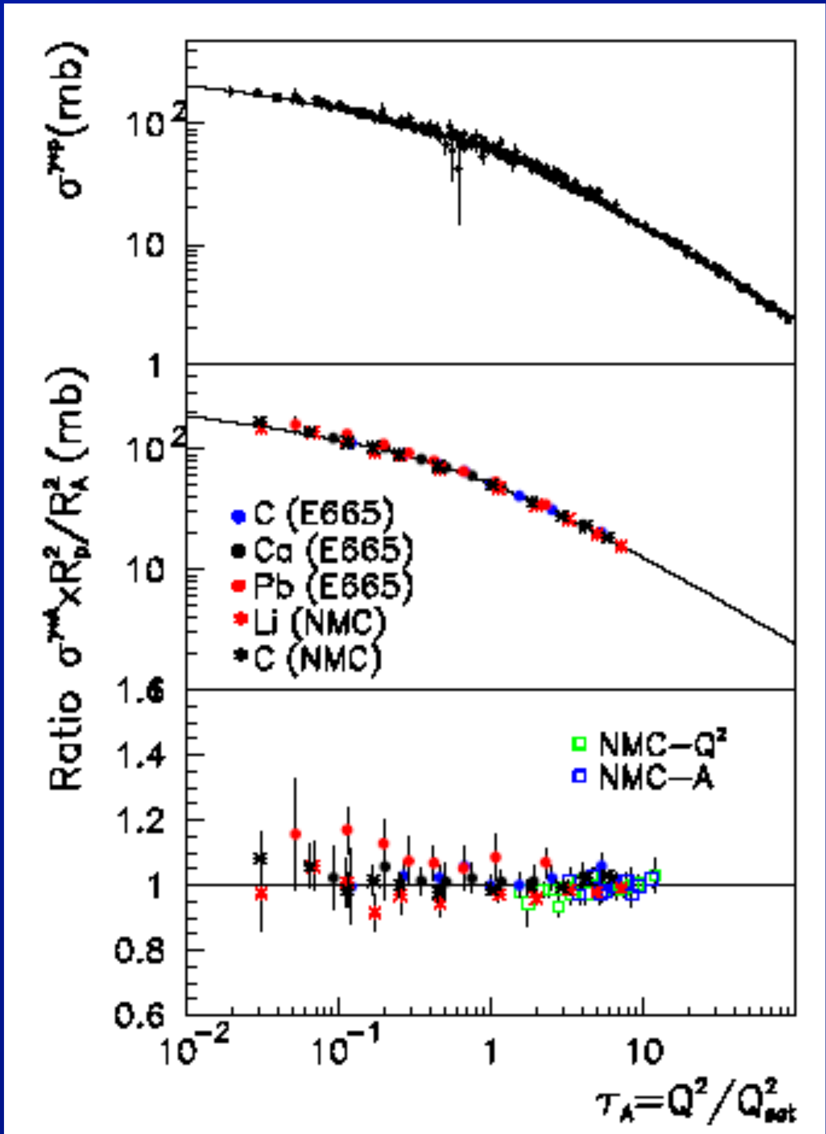


Charged multiplicity: saturation(?)

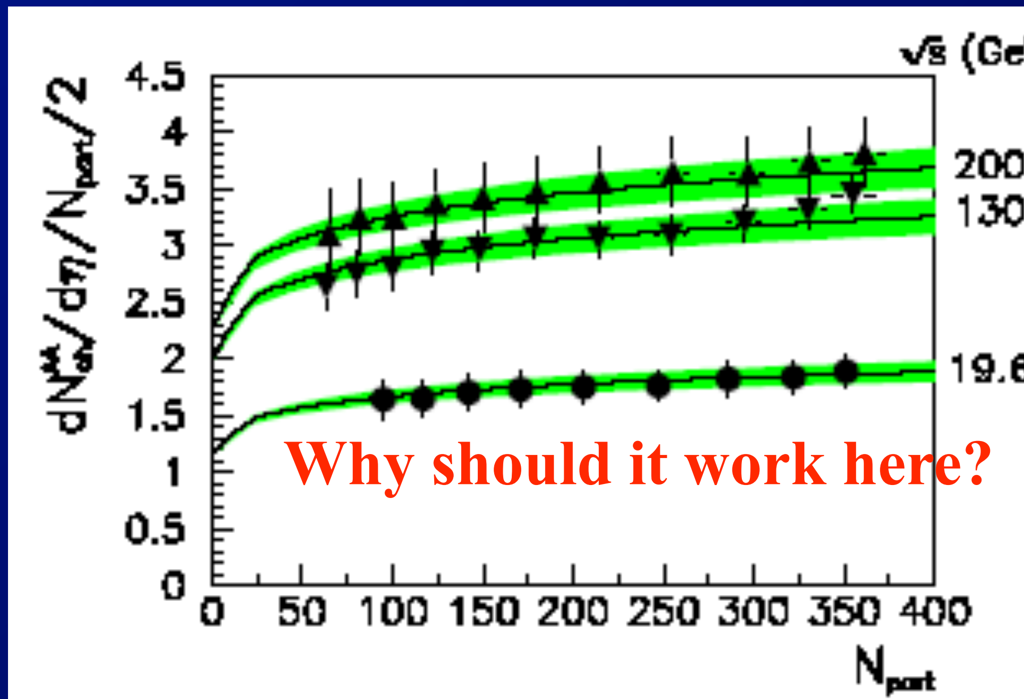


$$Q^2_{\mathrm{sat,A}} = Q^2_{\mathrm{sat,p}} \left(\frac{A \pi R_p^2}{\pi R_A^2} \right)^{\frac{1}{\delta}}$$

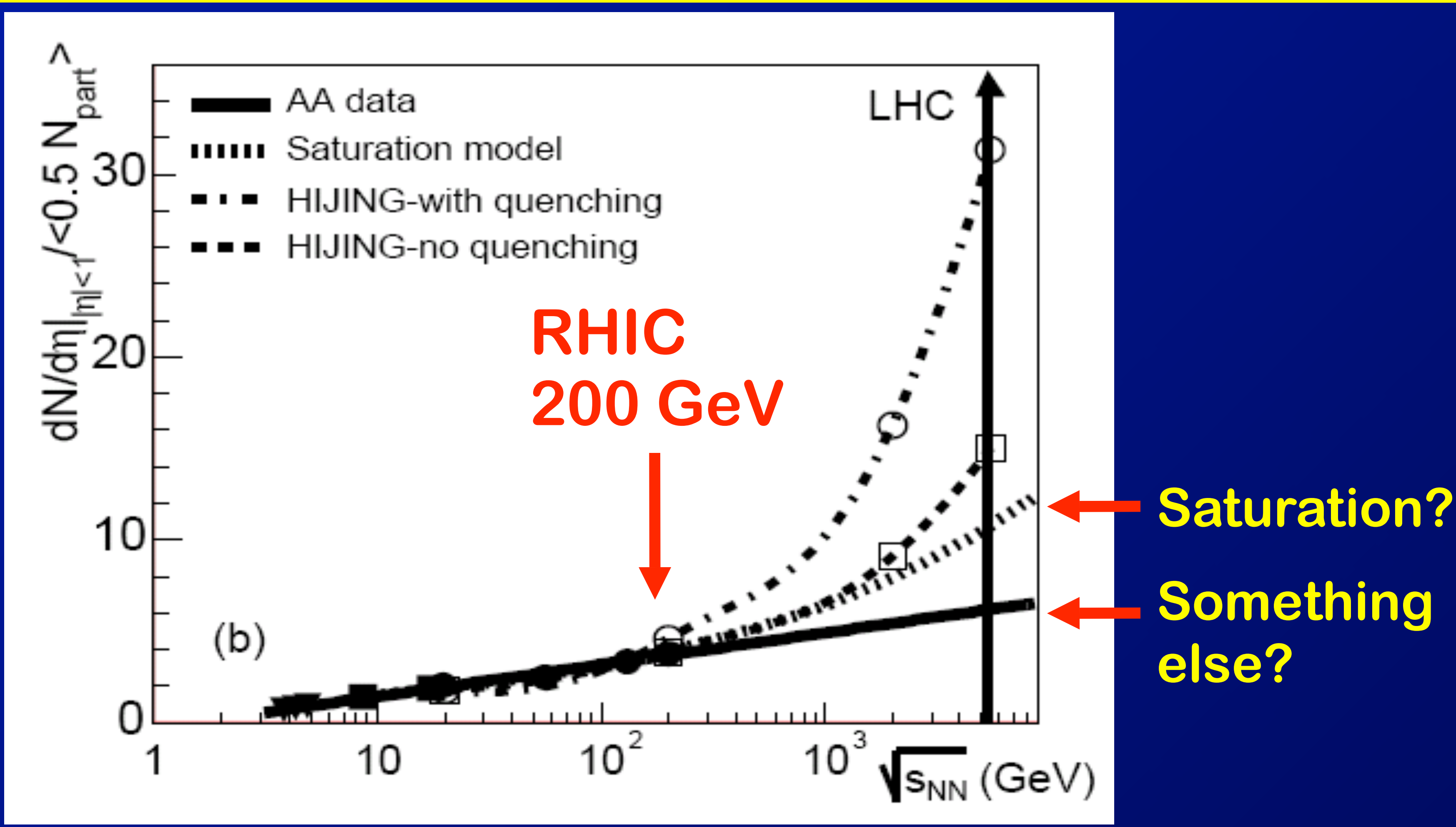
Armesto, Salgado, Wiedemann

Phys. Rev. Lett. 94 :022002,2005

- Extension of geometric scaling analysis to nuclear targets
- Using k_T factorization calculate mult. (parton-hadron duality)
- Compare to PHOBOS data

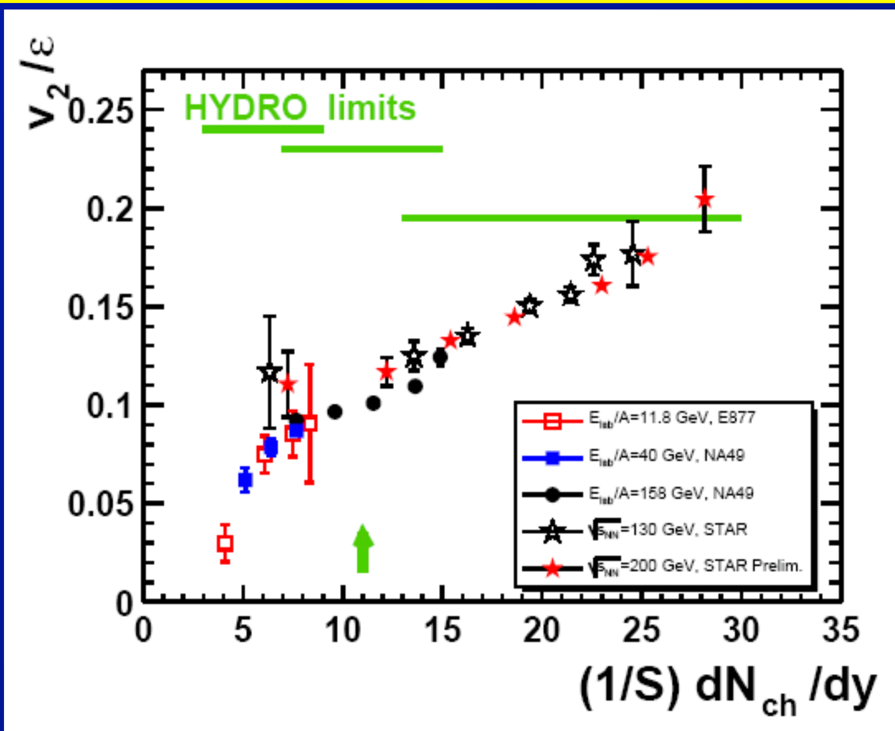


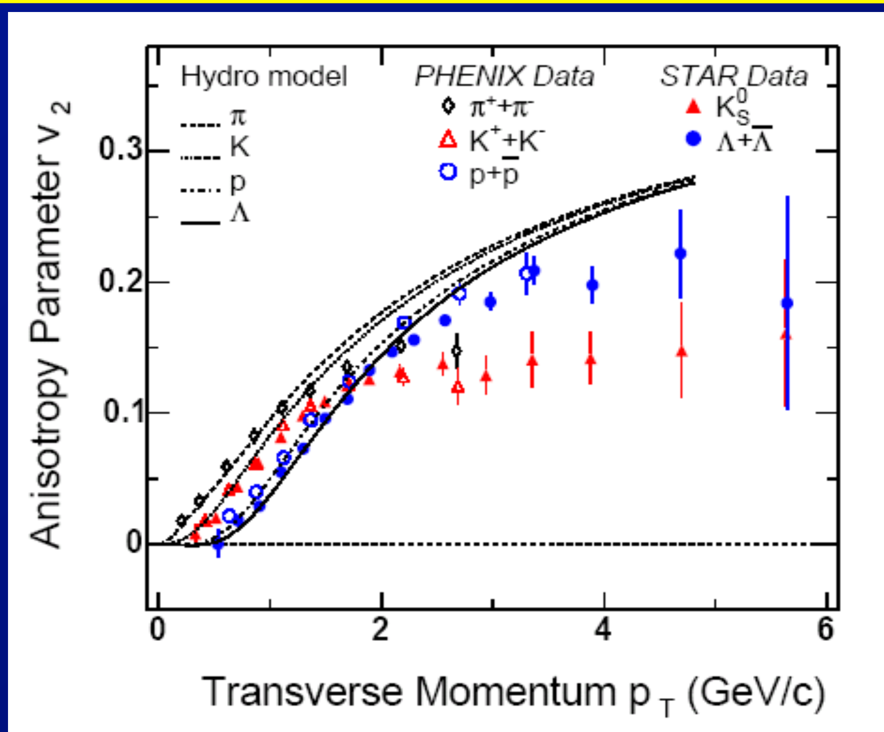
A+A Multiplicity: Extrapolation to LHC



- Day-1 measurements @ LHC will test our understanding of bulk particle production.
  - What if it's "something else ?"

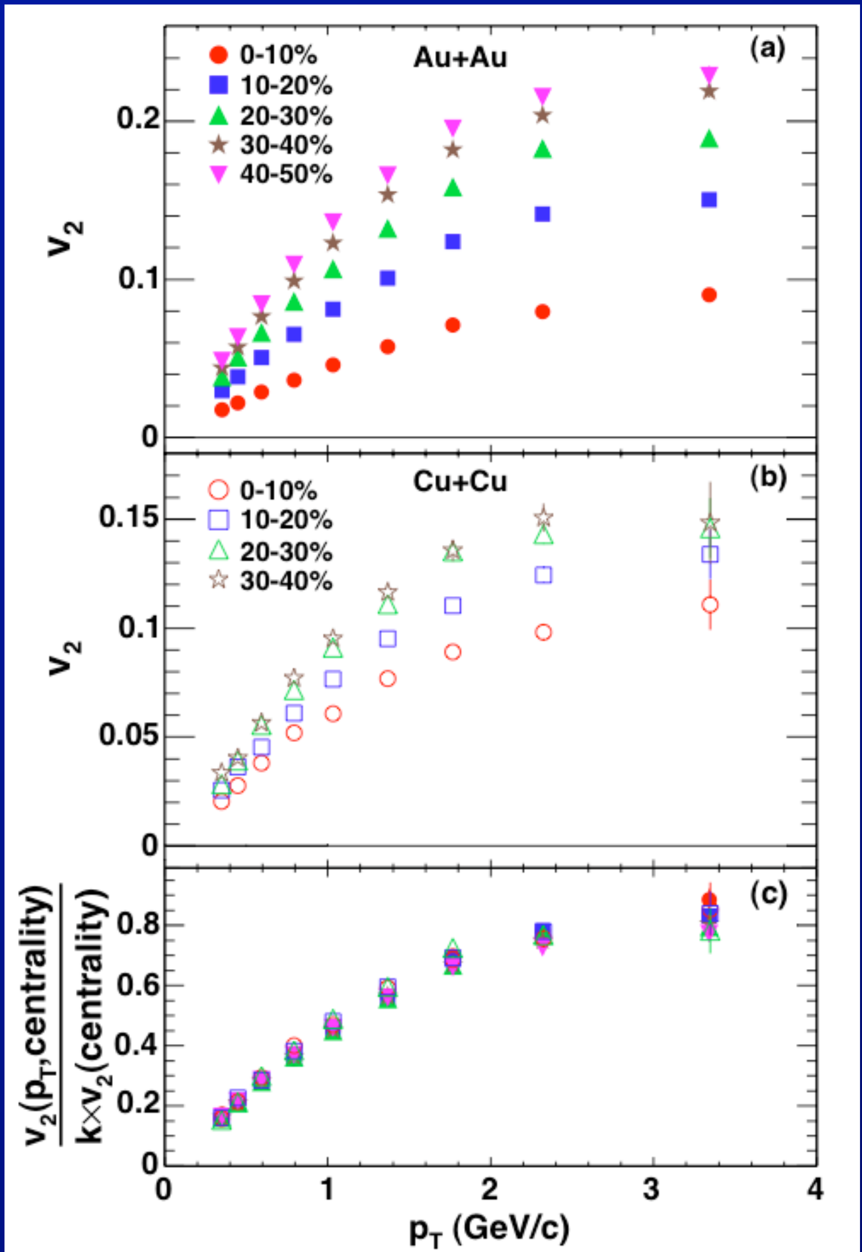
Elliptic Flow: Once upon a time …





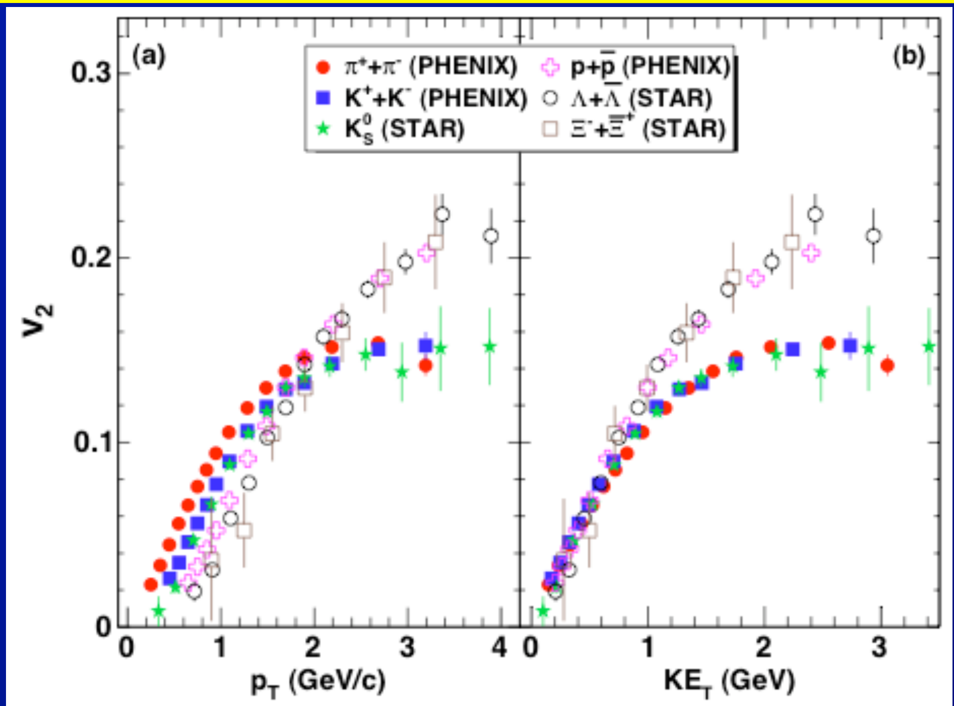
- **We once a simple picture of elliptic flow results**
  - v_2 scaled with eccentricity
  - Increased with (transverse) density of hadrons
  - Showed mass splitting consistent with hydro
- **Experimentally, v_2 now much more complicated**
  - Though the conclusions are qualitatively the same

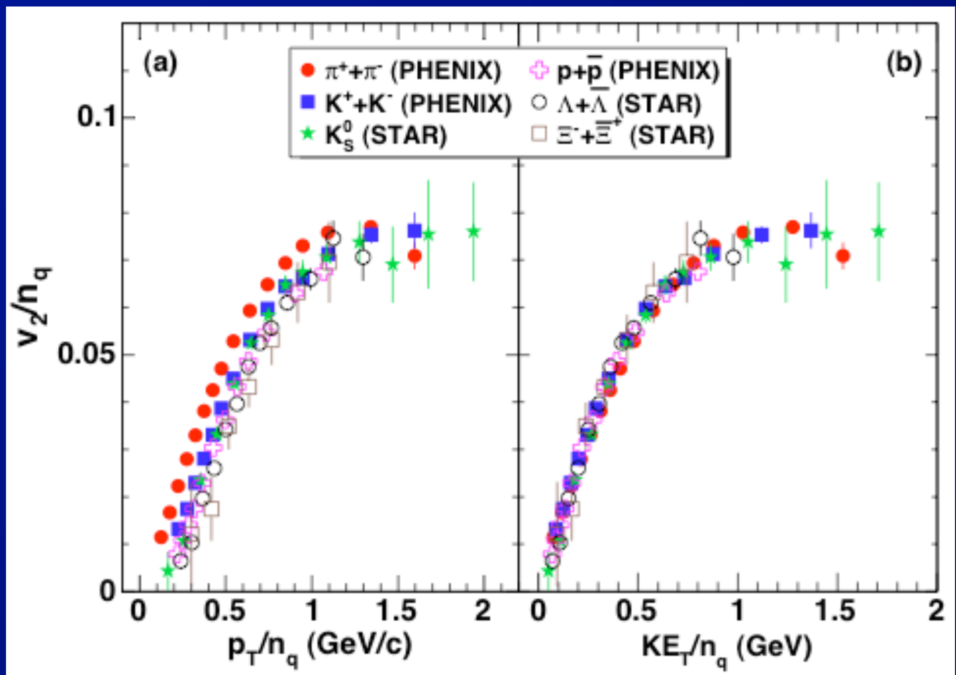
v_2 scaling (*a la* PHENIX)



- Charged $v_2(p_T)$ for different centrality bins
  - Measured using event reaction plane
  - With detectors at $3<|\eta|<4$
  - RP resolution corrected
- Au+Au and Cu+Cu
- All $v_2(p_T)$ sets divided by p_T-integrated v_2.
  - And scaling factor k=3.1 (estimated ε/v_2)
- Obtain universal result for $v_2(p_T)/v_2$ (why?!)

v_2 scaling (*a la* PHENIX)





Au+Au minimum-bias
@ η=0 (important)

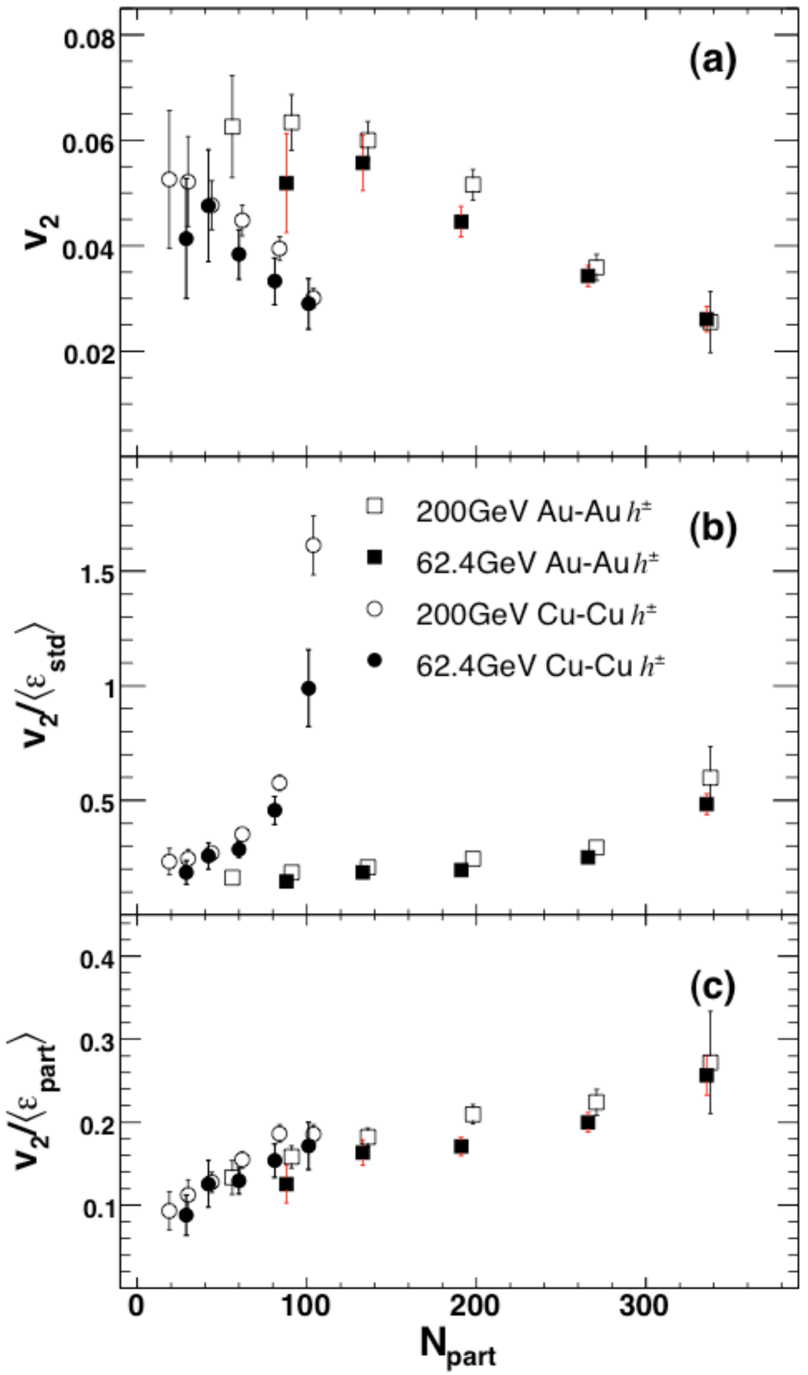
- Departure from mass independent $v_2(KE_T)$ due to incomplete thermalization at "high" p_T (?)
- Recombination:
  - $v_2 \propto n_q$ (?)
  - $KE_T \propto n_q$ (?)
- So plot $\frac{v_2}{n_q}$ vs $\frac{KE_T}{n_q}$

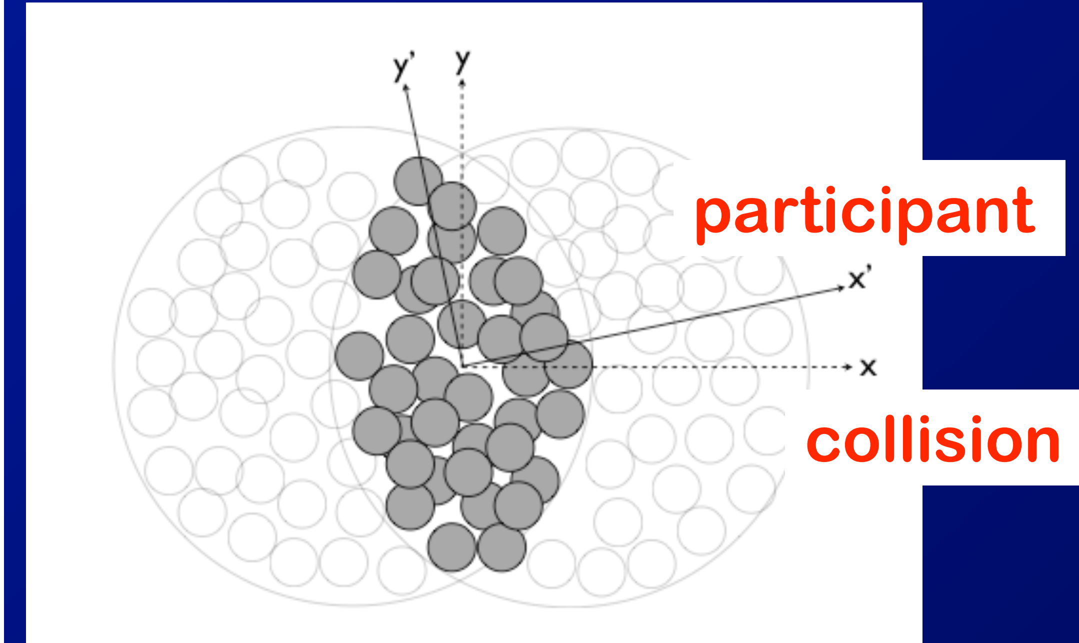
⇒Universal curve

Some comments

- Previous plots carefully chosen to avoid some non-trivial experimental difficulties.
  - Notice that the collision zone eccentricity (ε) never explicitly appeared (except implicitly in k = 3.1)
    - ⇒No need to address collision vs participant ε.
  - What about expected deviations from hydrodynamics due to hadronic cascade?
- And PHENIX, STAR have different systematics
  - Where/how reaction plane is measured
    - ⇒Different non-flow effects
    - ⇒Potentially different sensitivity to fluctuations in participant vs collision reaction plane.
- To better understand details of elliptic flow, need better control of experimental effects.

Participant Eccentricity (PHOBOS)

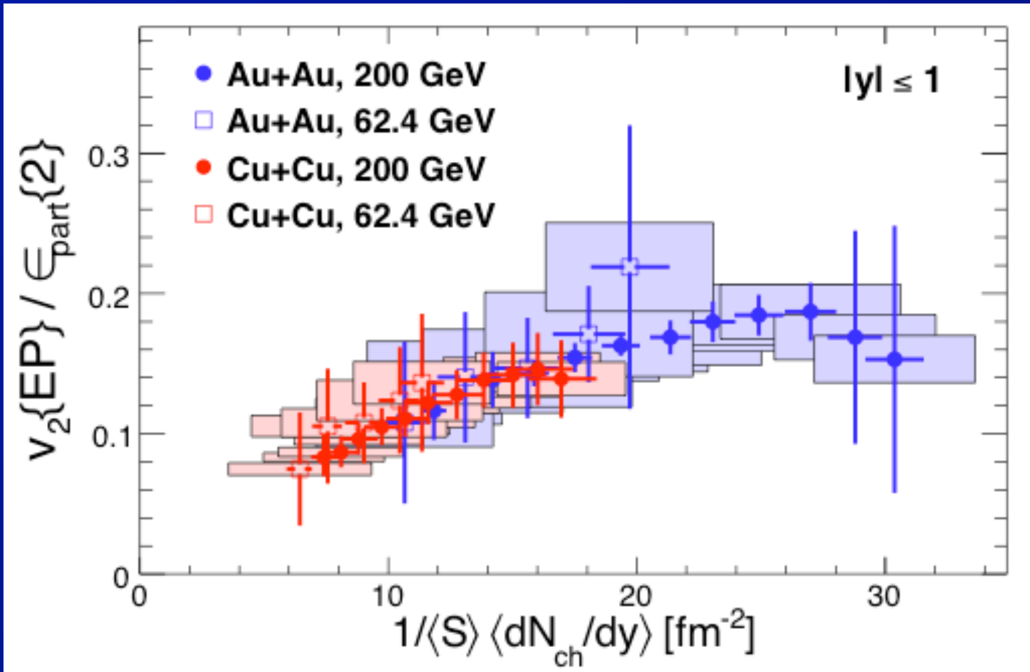


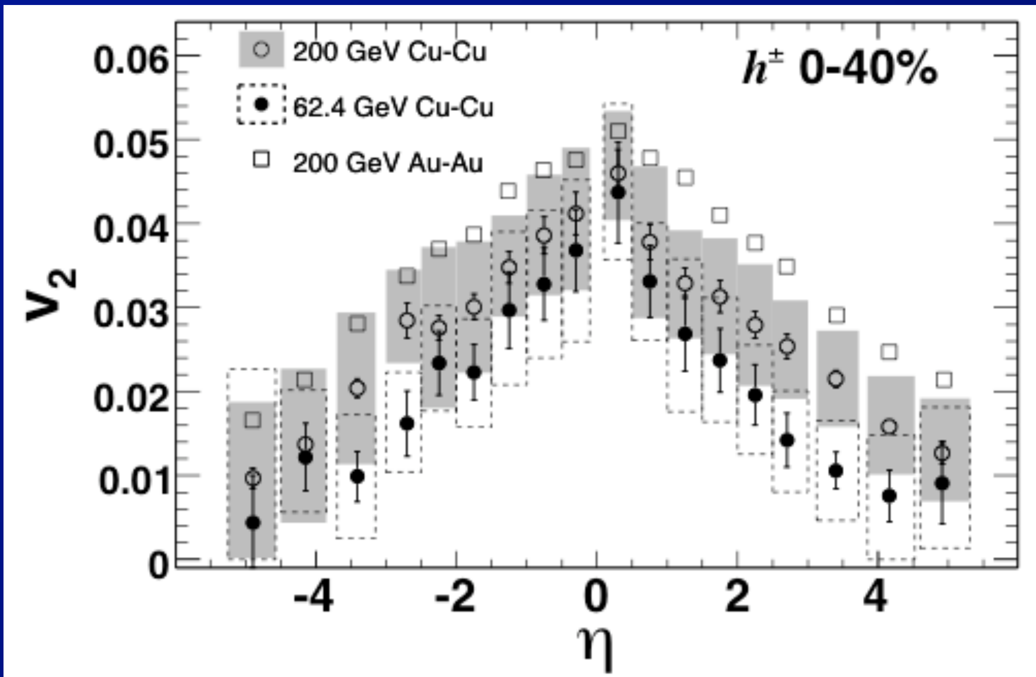


- 1st results from PHOBOS on Cu+Cu v_2 yielded v_2/ε values > v_2/ε in Au+Au
- PHOBOS first to realize impact of fluctuations in participant locations

$$\Rightarrow \Phi_{\mathrm{part}} \neq \Phi_{\vec{b}}$$

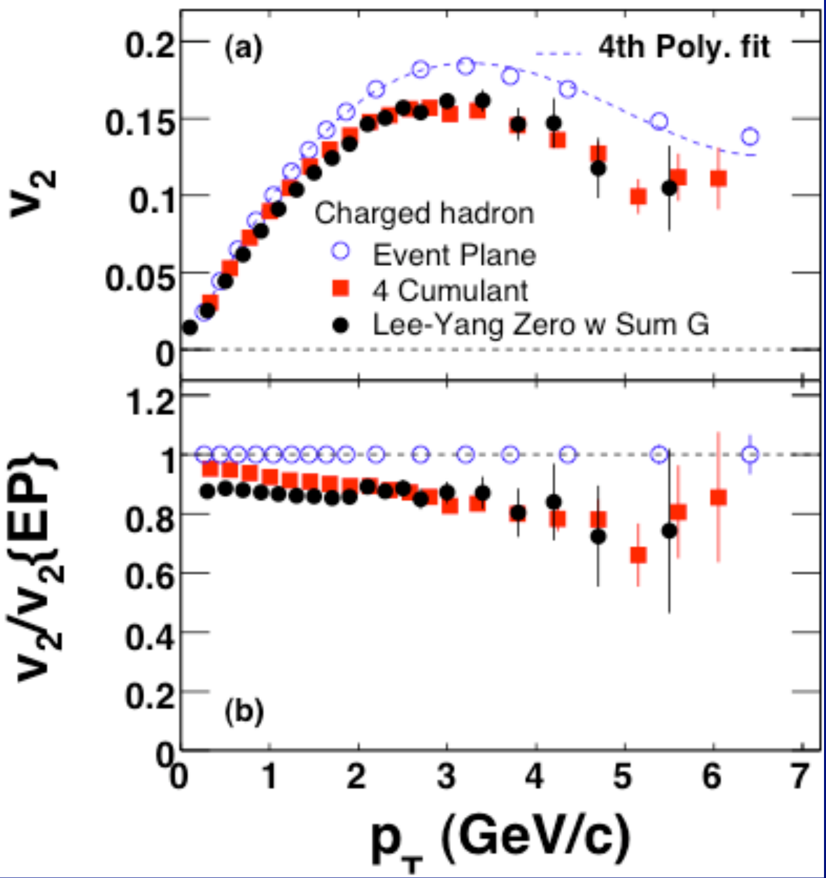
Integrated v_2, Cu+Cu, Au+Au (PHOBOS)

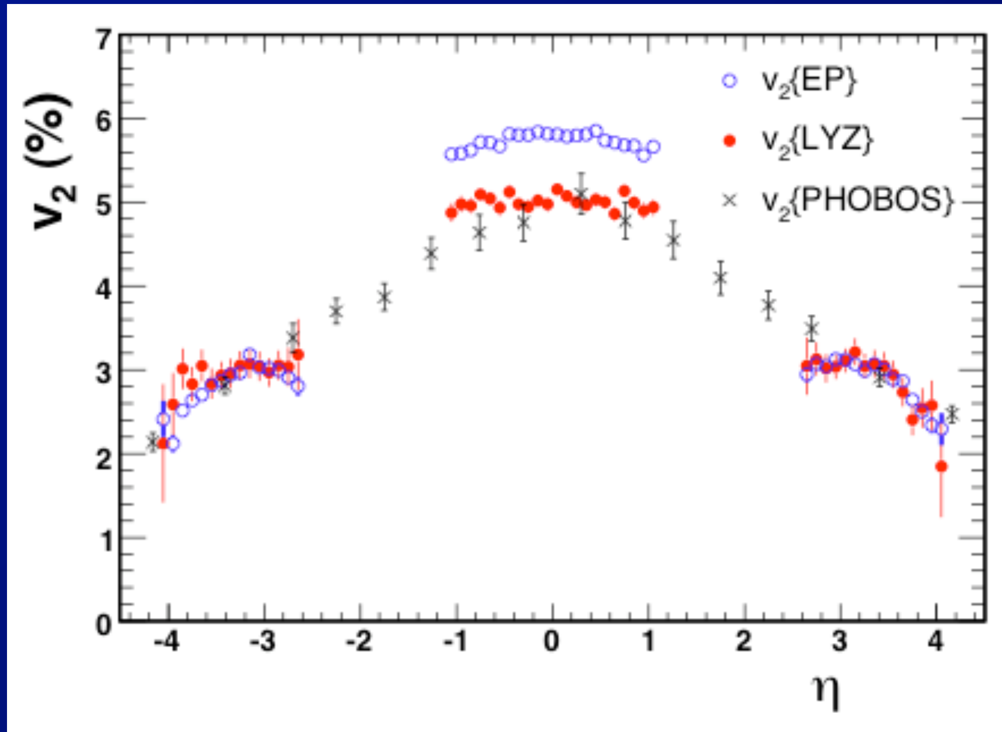




- Consistent results for v_2/ε_{part} vs chgd particle transverse density
  - Cu+Cu and Au+Au
  - 62.4 and 200 GeV
  - Why?
- Similar shapes for $v_2(\varepsilon)$ over full range
  - Cu+Cu and Au+Au
  - 62.4 and 200 GeV
  - Why?

Non-flow effects (STAR)

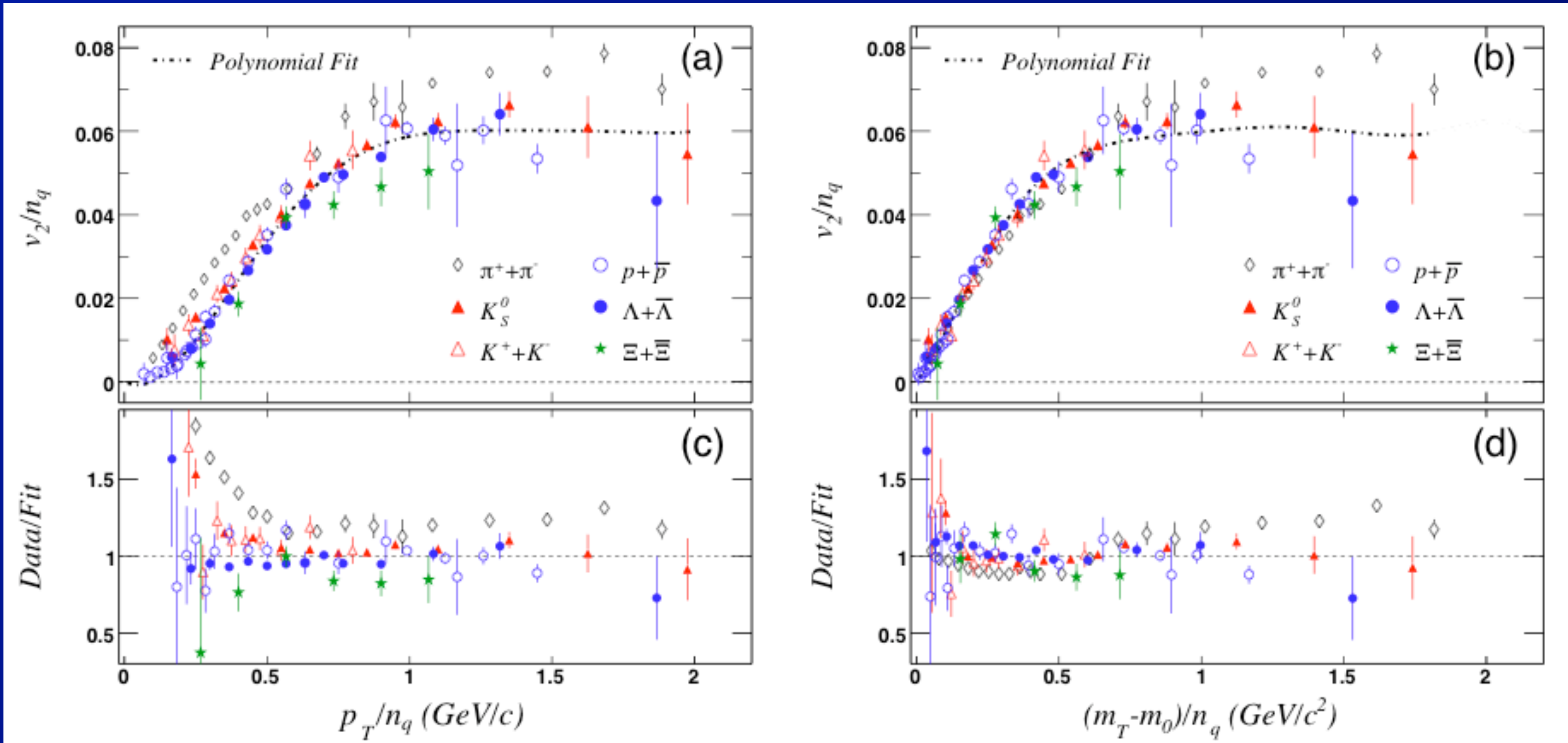




- Event plane determination potentially sensitive to non-flow effects in dn/dφ distribution.
  - Particularly when Φ measured at/near mid-rapidity
  - Lee-Yang Zeros method less sensitive to "non-flow"

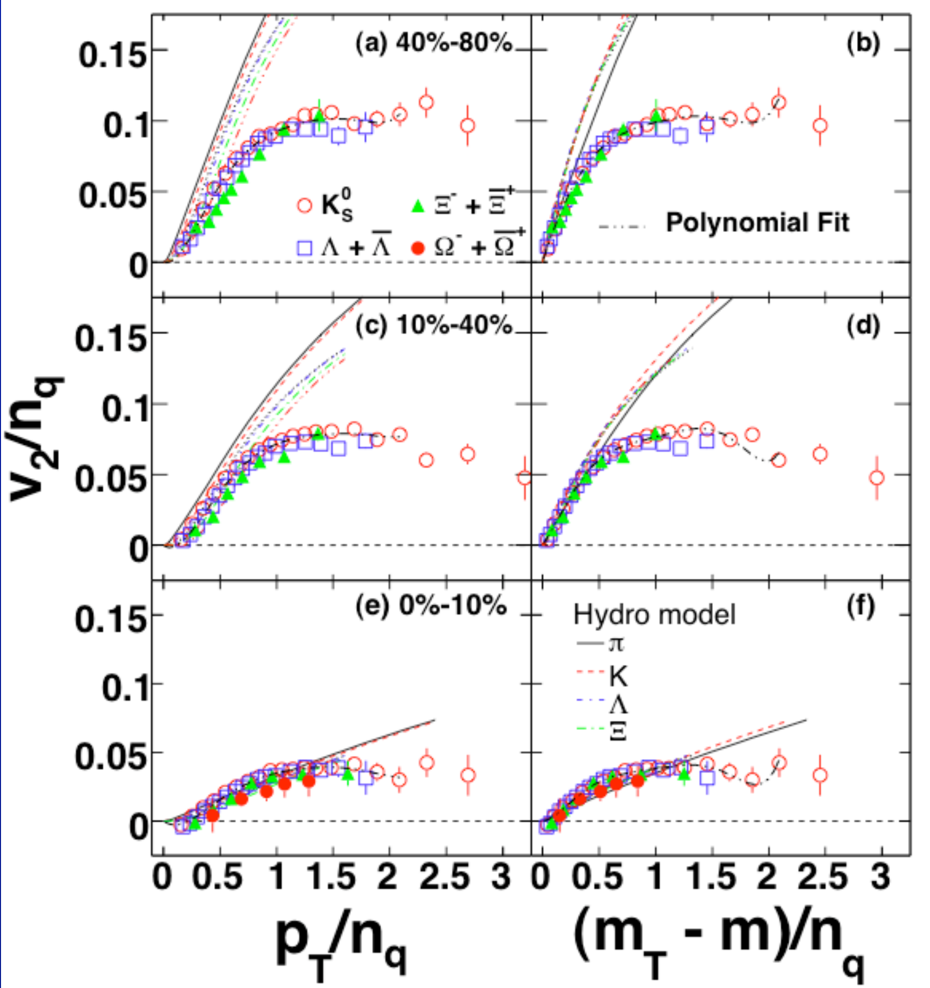
    ⇒Clearly seen in STAR comparison to event-plane v_2

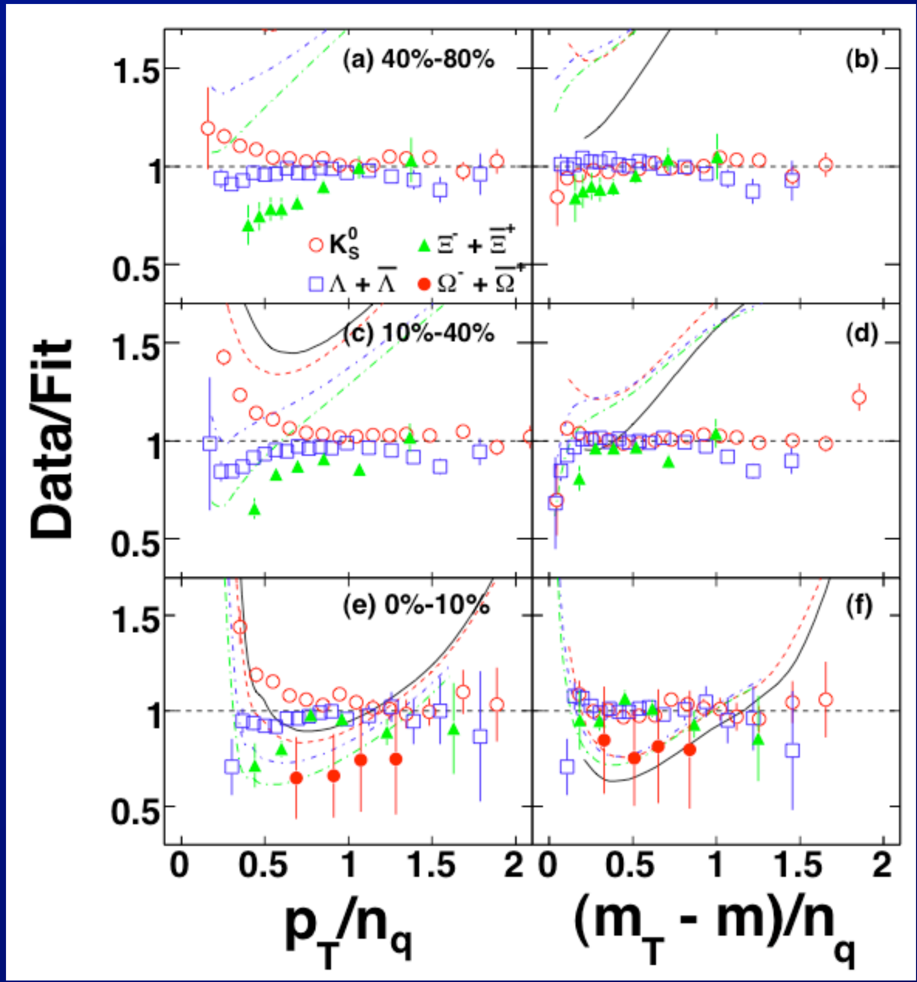
v_2 scaling (STAR)



- v_2 scaling with n_q, Au+Au minimum-bias
  - Appears to work well at low p_T
  - Maybe not so well for baryons at intermediate p_T
  - But, beware species-dependent non-flow effects.

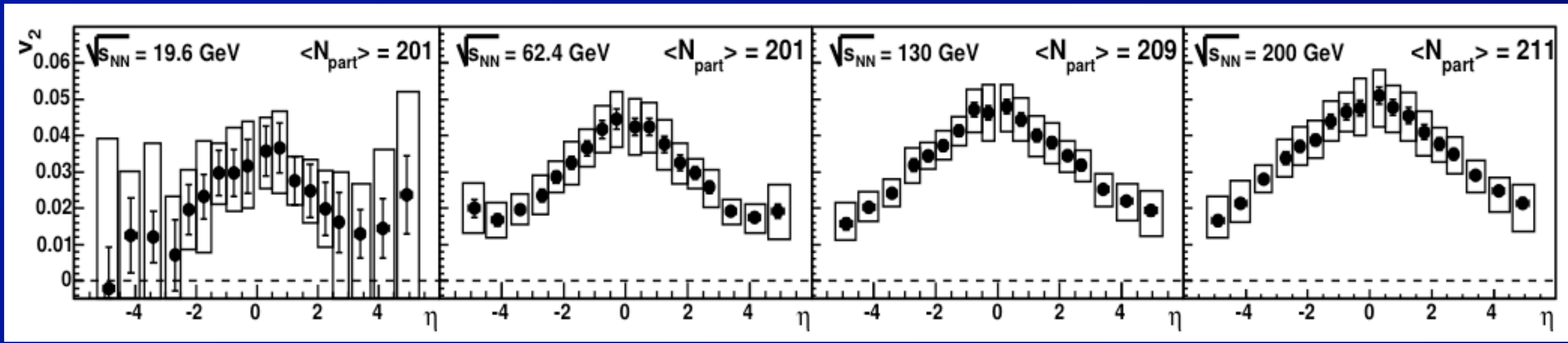
STAR v_2 systematics (vs centrality)



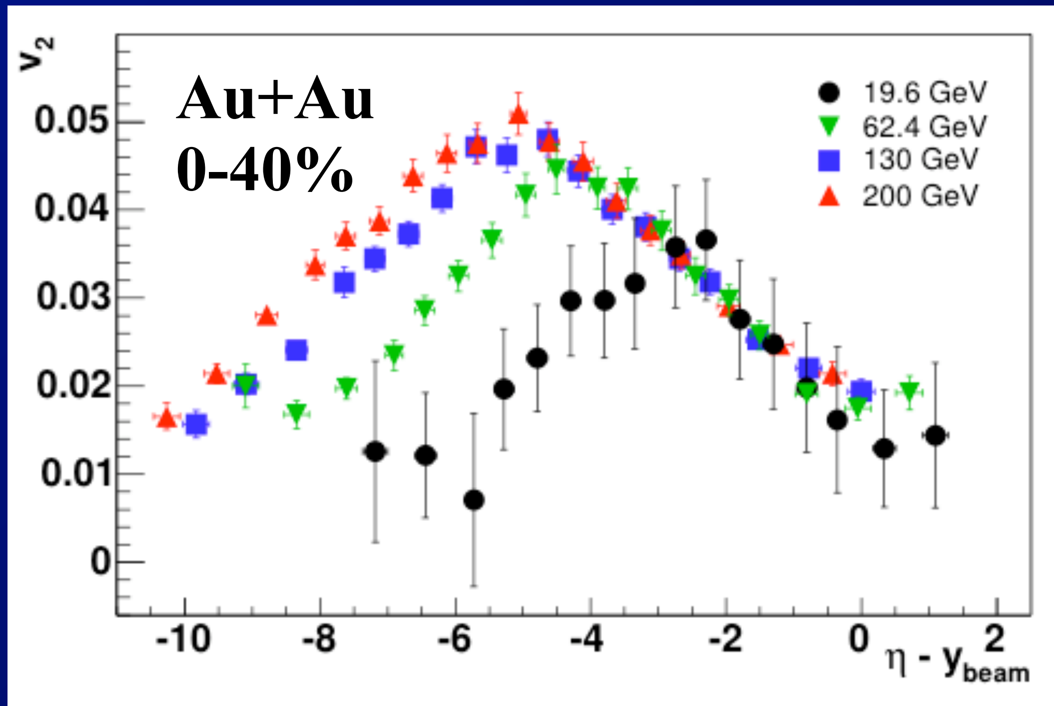


- Scaling persists in restricted centrality bins
- Ideal hydrodynamics (Huovinen) does not match low-KE_T/n_q scaling in data for non-central Au+Au

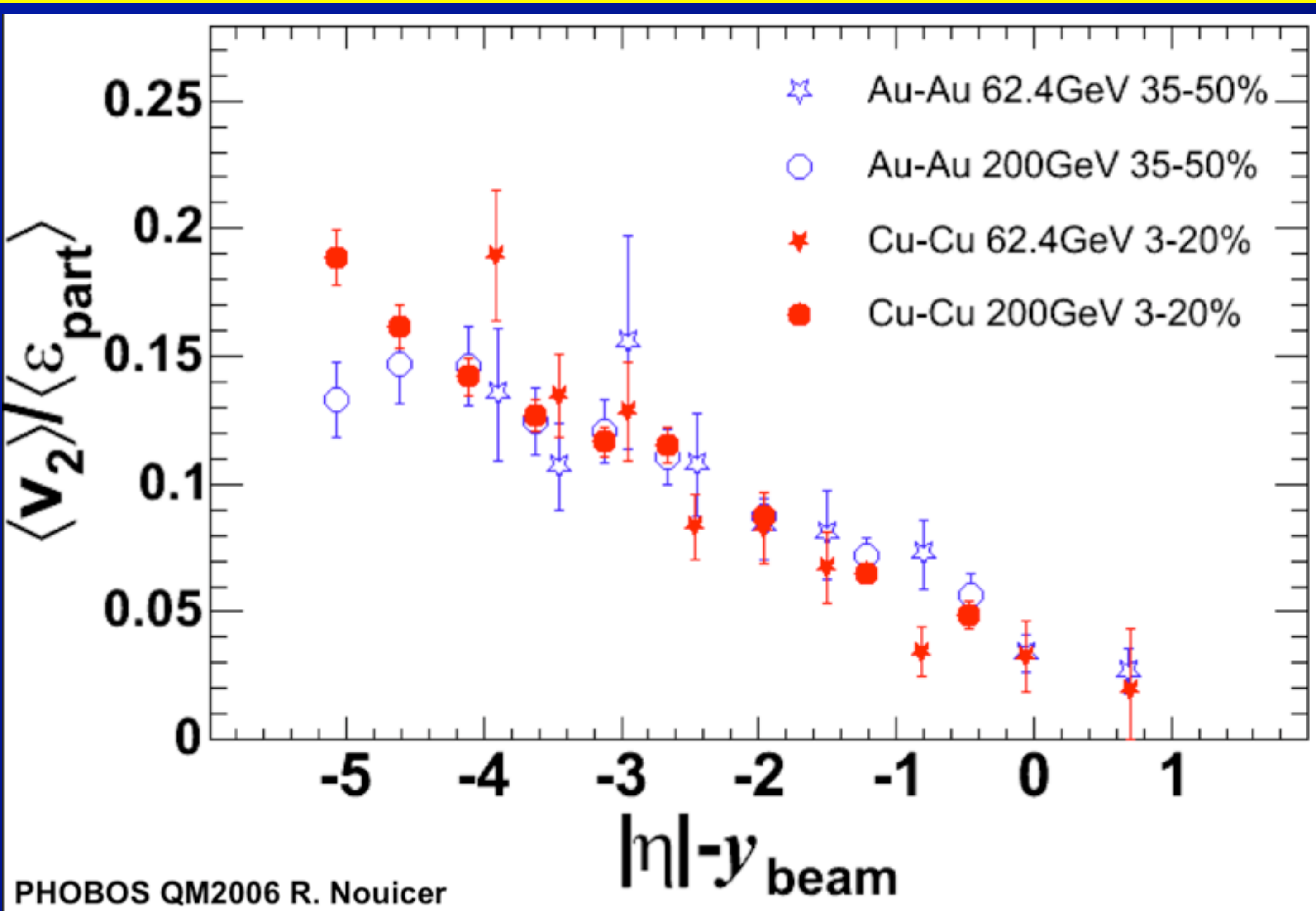
PHOBOS: v_2 Limiting Frag.



- Non-trivial evolution of $v_2(\eta)$ vs collision energy
  - Maximum v_2
  - Width
- Scales!
  - p_T integrated
    - ⇒Sensitive to hydro
  - Scaling hydro?
    - ⇒If so, not Bjorken



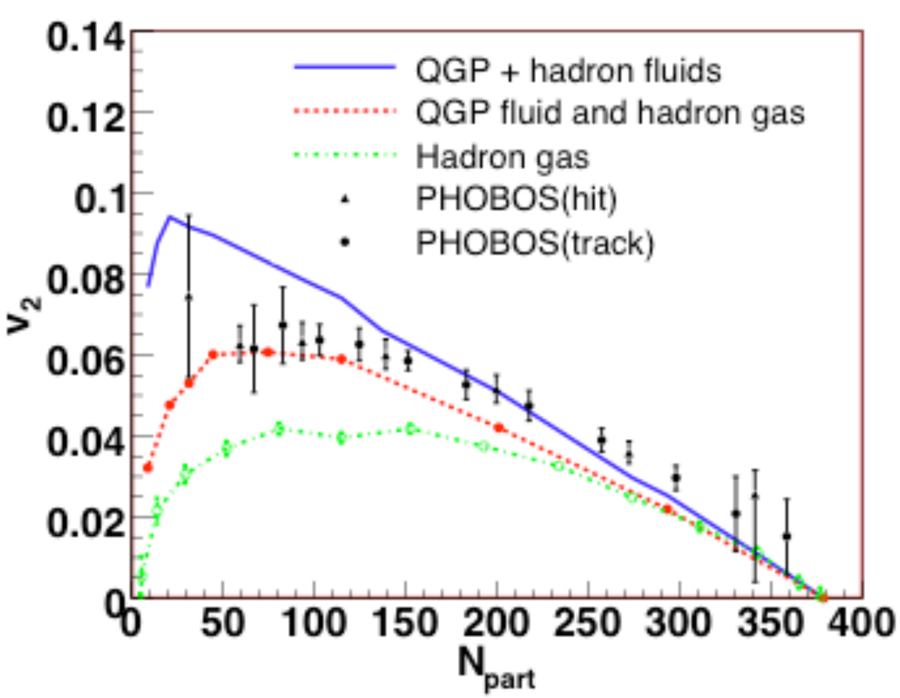
PHOBOS: v_2 Limiting Frag. (2)

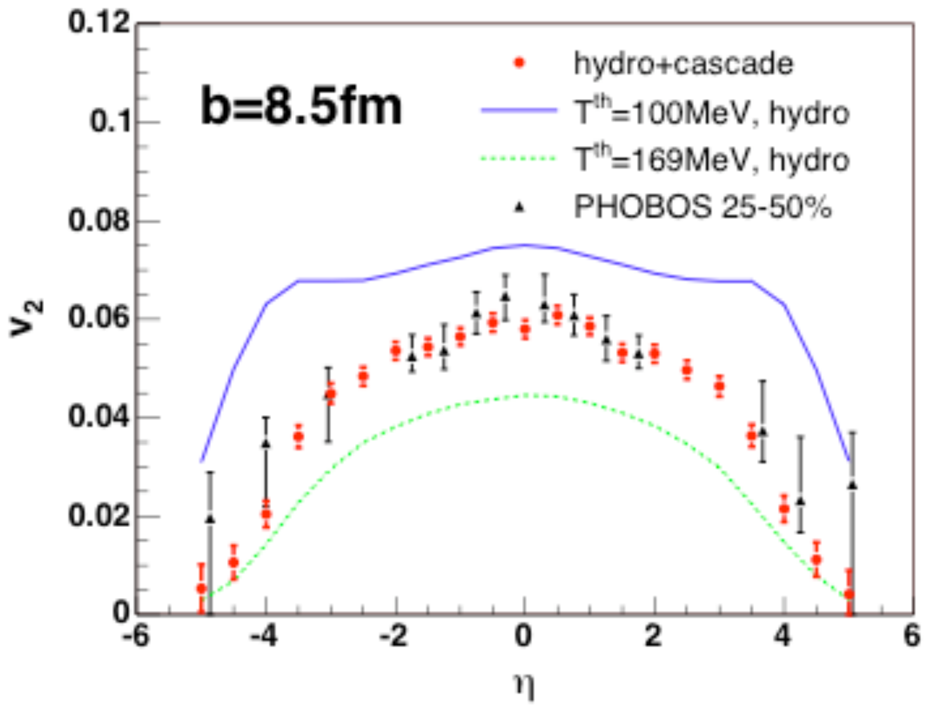


Au+Au and Cu+Cu at same # of participants

- This result really bothers me
  - And I think it should bother you too
    - ⇒In the context of "canonical" explanation for $v_2(\eta)$

Success of hydro+cascade (Hirano)

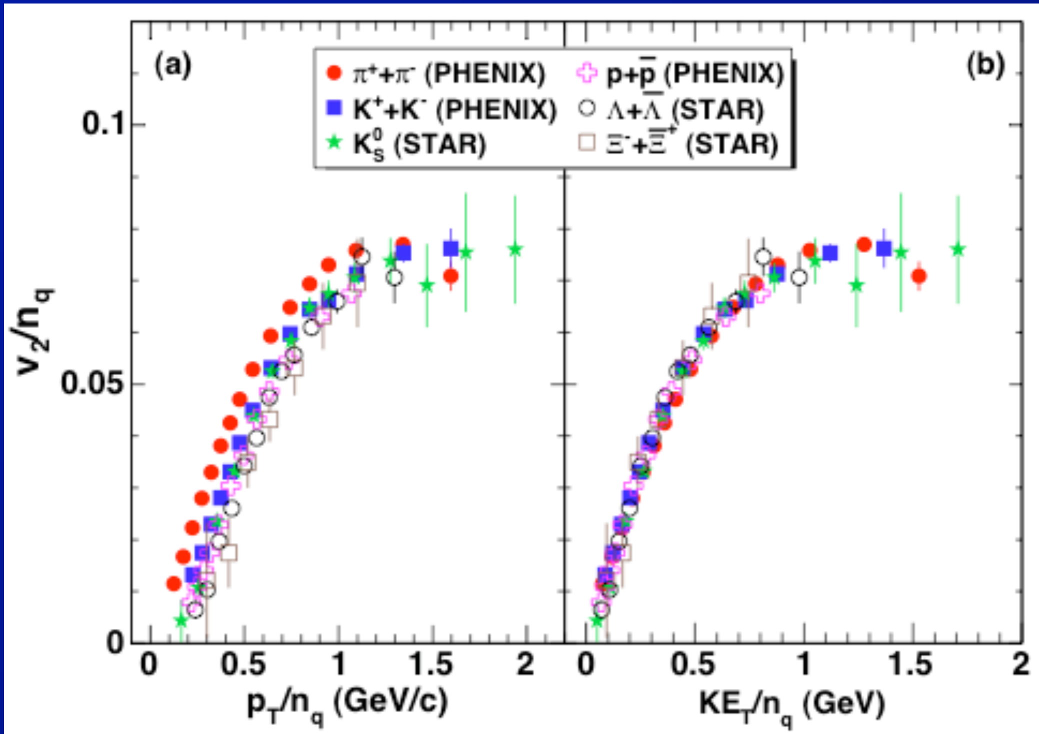


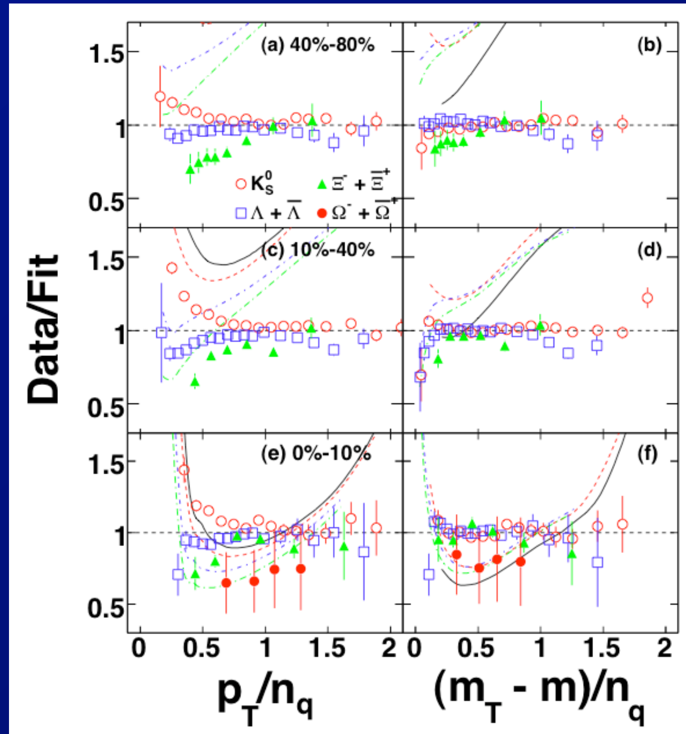


- Hirano (et al):
  - Hadronic dissipative effects important for non-central collisions (Cu+Cu ?!) and for $\eta \neq 0$.
  - (presumably) depends on full 3D hydro evolution
  - Non-trivial dependence on energy, system, η, …

$\Rightarrow$ So why the (_____) does v_2 exhibit long. scaling???

Something else that bothers me ...



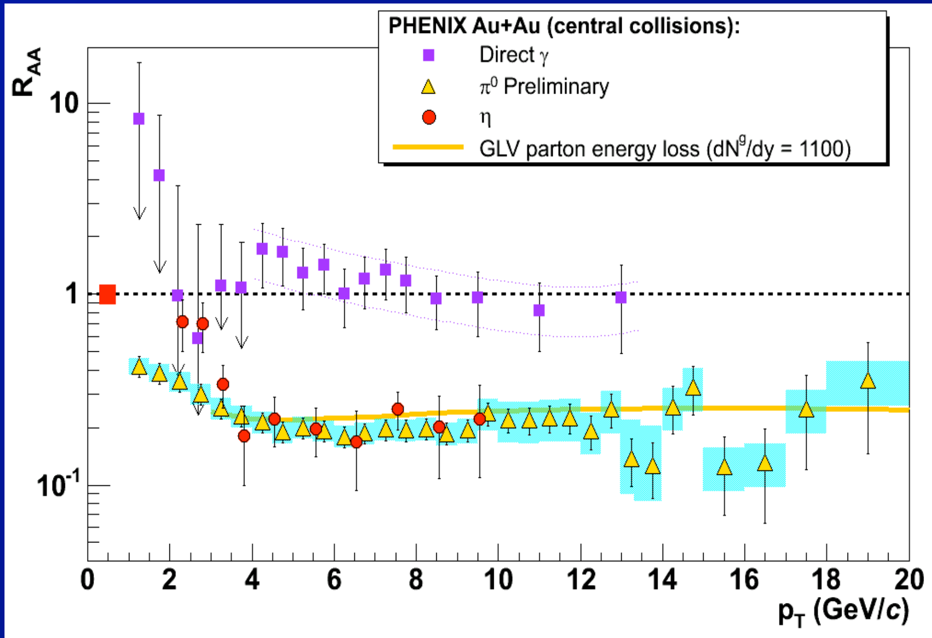


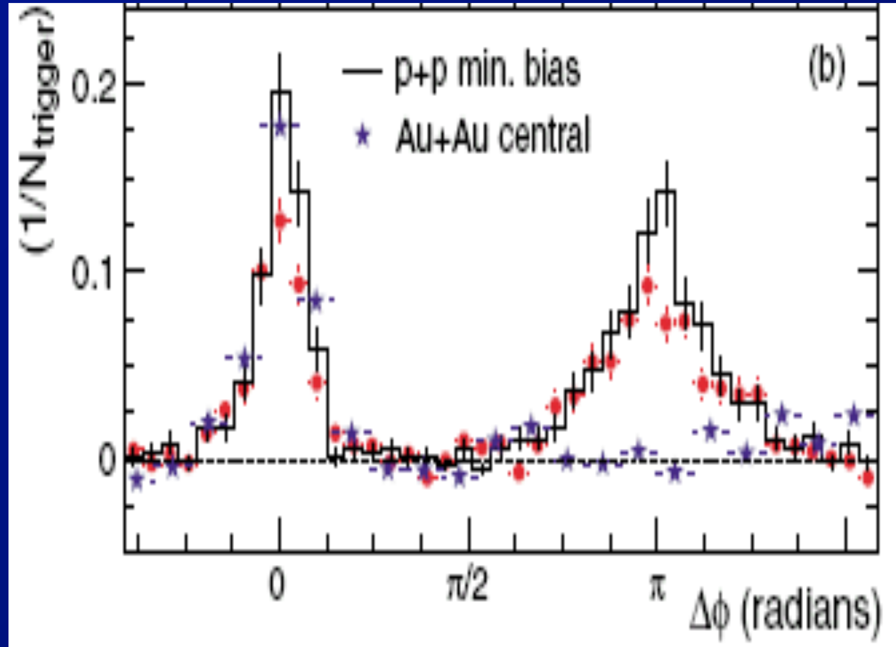
- For that matter, why does the n_q scaling work better at low KE_T than it has any right to?
  - Hirano *et al*: mass splitting affected by late evolution

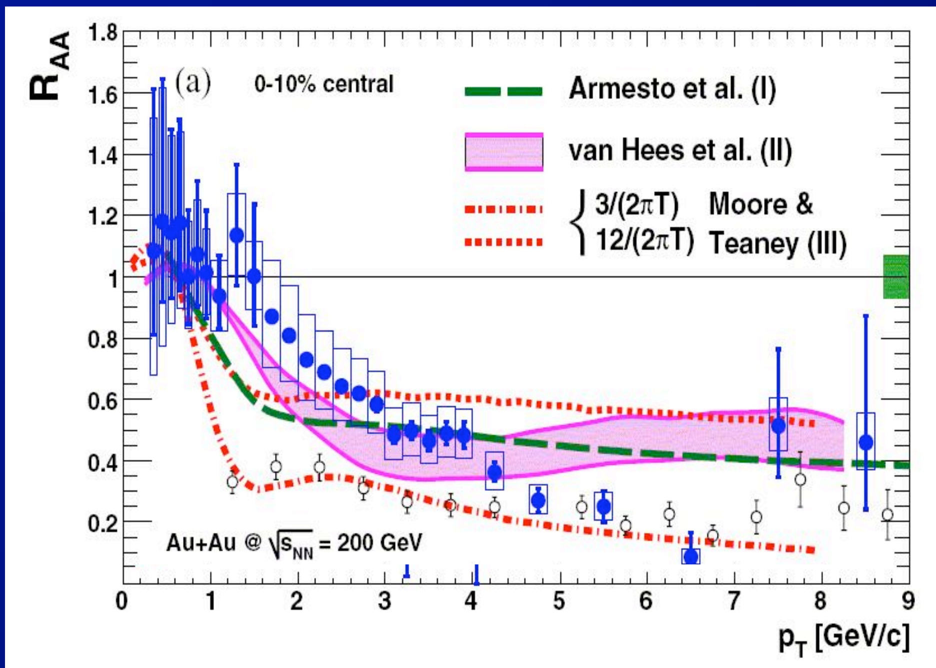
    ⇒Does hadron gas naturally produce n_q scaling?
- Maybe the n_q and long. scaling are accidents

  ⇒But maybe nature is trying to tell us something ...

Jet Quenching





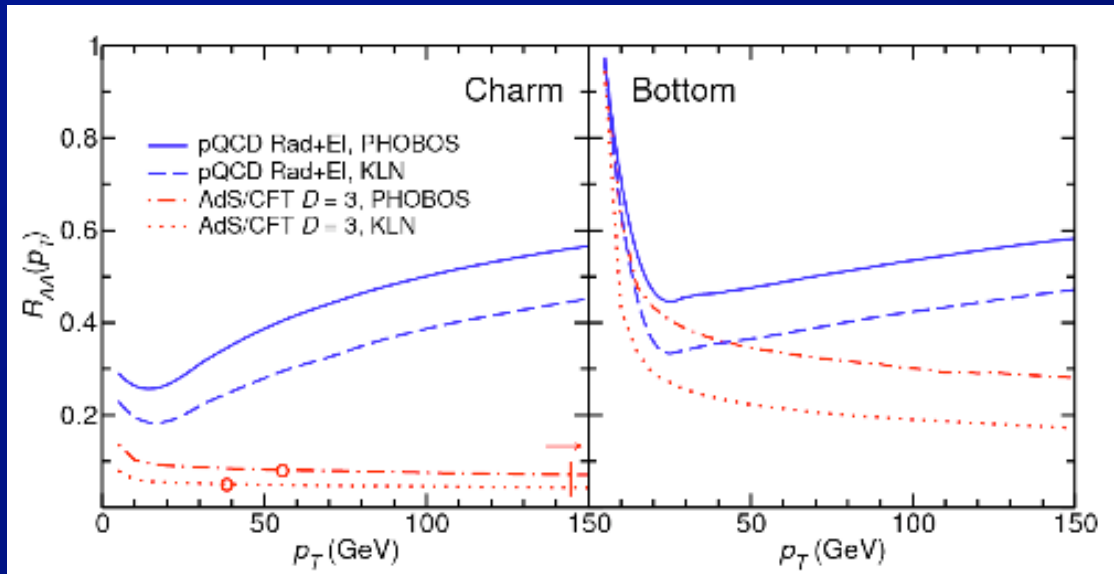


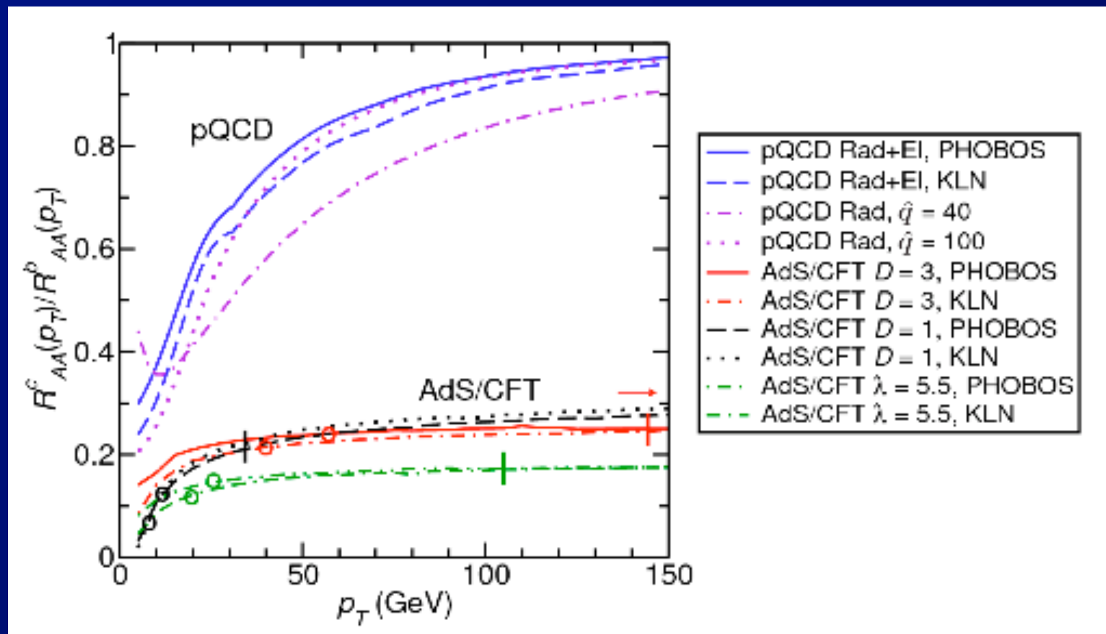
- In spite of the wealth of single hadron, di-hadron results
  - It's the heavy flavor quenching that poses the biggest problem for perturbative/weak coupling quenching.

Heavy Quark Quenching: AdS/CFT

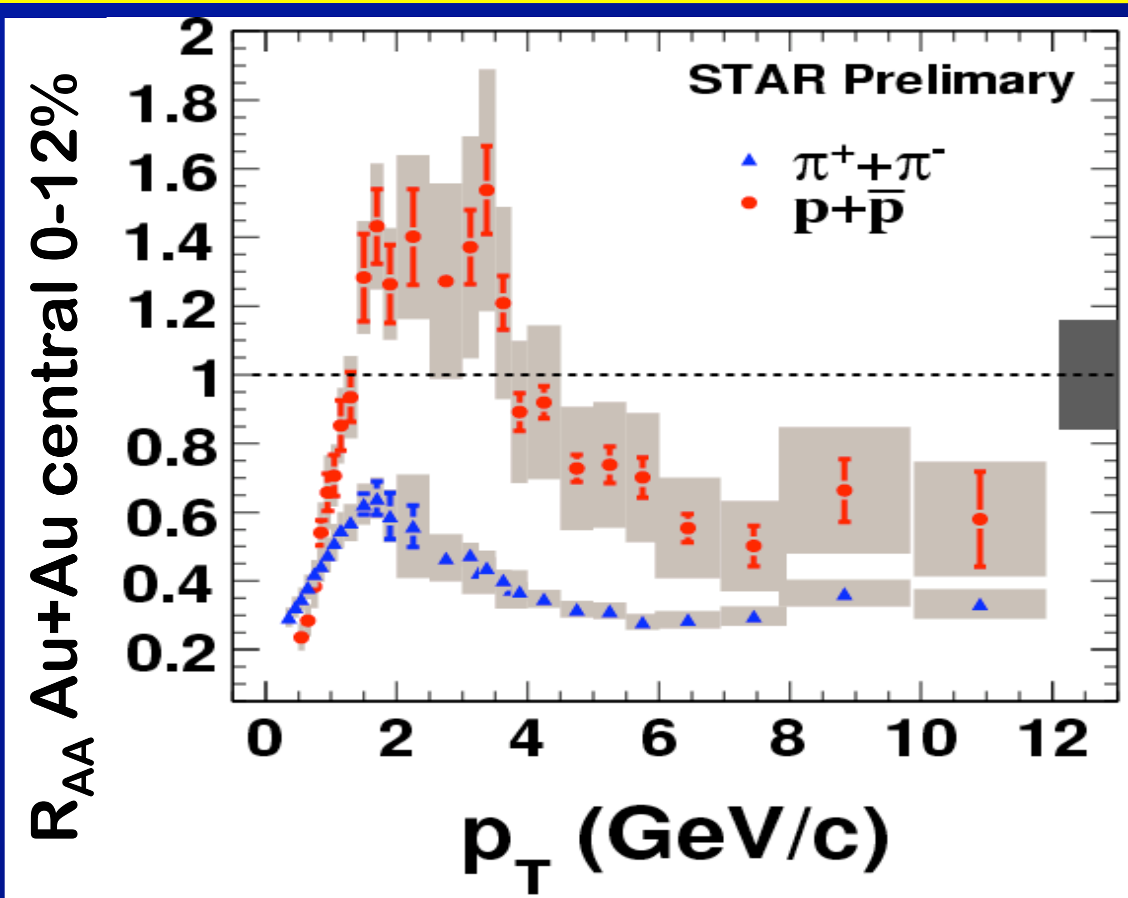
Horowitz and Gyulassy, Phys.Lett.B666:320-323,2008

- Heavy flavor measurements:
  - robust test for weakly (pQCD) or strongly coupled quenching.
  - Due to explicit dependent of AdS/CFT dp/dt on quark mass.
- But need to wait for LHC and/or RHIC vertex upgrades





Where is the color factor?



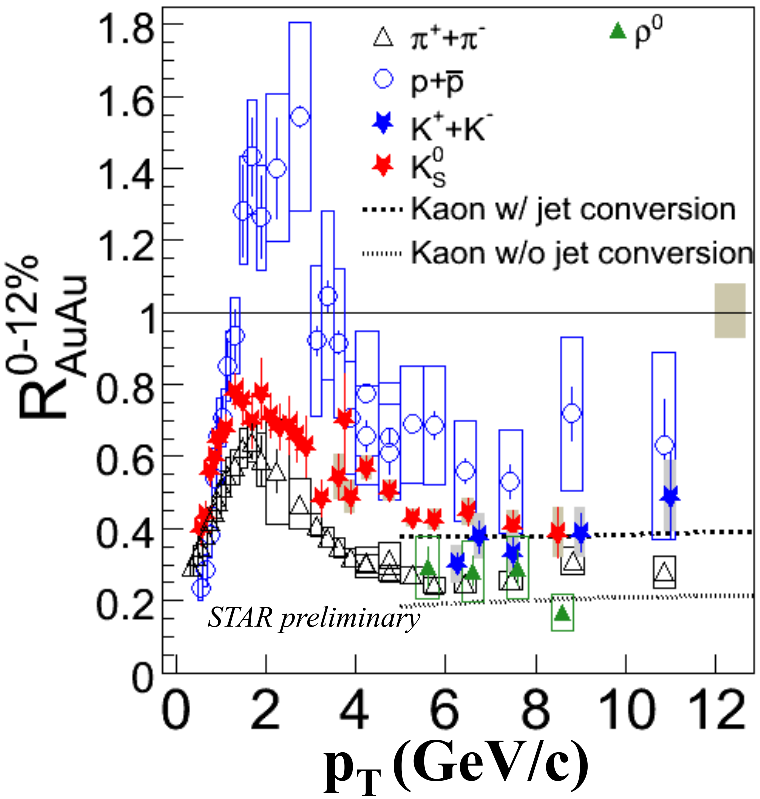
A slide I showed at Quark Matter 2008

Now out of date (?) ...

- p(bar) has larger gluon contribution than π
- color factors: gluon energy loss > quark
  - ⇒Expect p(bar) $R_{AA} < \pi\ R_{AA}$
  - ⇒Opposite observed

Flavor-dependent R_{AA}

R_{AA} for π, K and p



R_{AA}(proton)>R_{AA}(pion) at high p_T

➔Which is in contrast to the prediction of color charge dependence of **Energy Loss.**

➔how the **gluon** jet/**quark** jet interact with the medium created in Au+Au collisions.

R_{AA}(K) ~ 0.4 at high p_T > 5.0 GeV/c

➔consistent with the prediction of jet conversion by interaction with the medium in Au+Au.

$R_{AA}(\pi)$ ~ $R_{AA}(\rho^0)$ at high p_T

See more R_{AA} Vs N_{part} in ***Anthony*** 's talk in **6C** session.

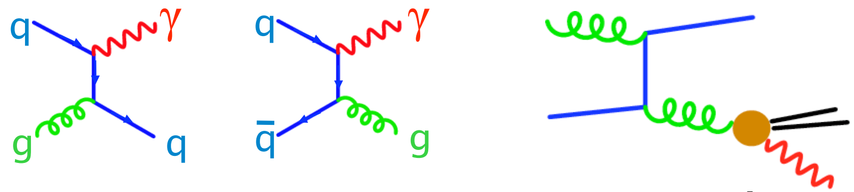
Candidate explanation for unexpected flavor-dependent R_{AA}: jet flavor conversion

Photons: Beyond gamma-jet

Direct photon sources in hadronic

(*) Direct = not from decays of hadrons (π^0, η, K^0_s, ...)

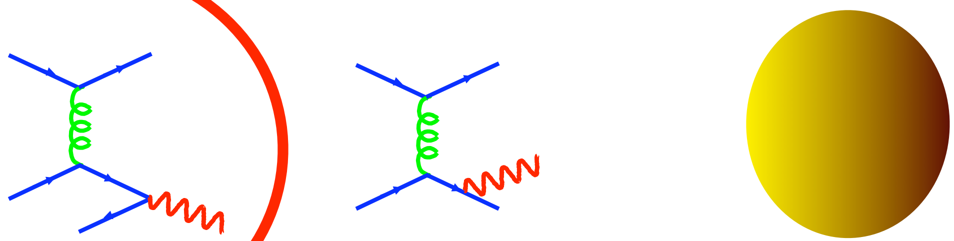
Direct photons in p+p



Compton **Annihilation** **Fragmentation,** see poster Ali Hanks

At high p_T and lowest order: Compton dominates.

A+A adds medium

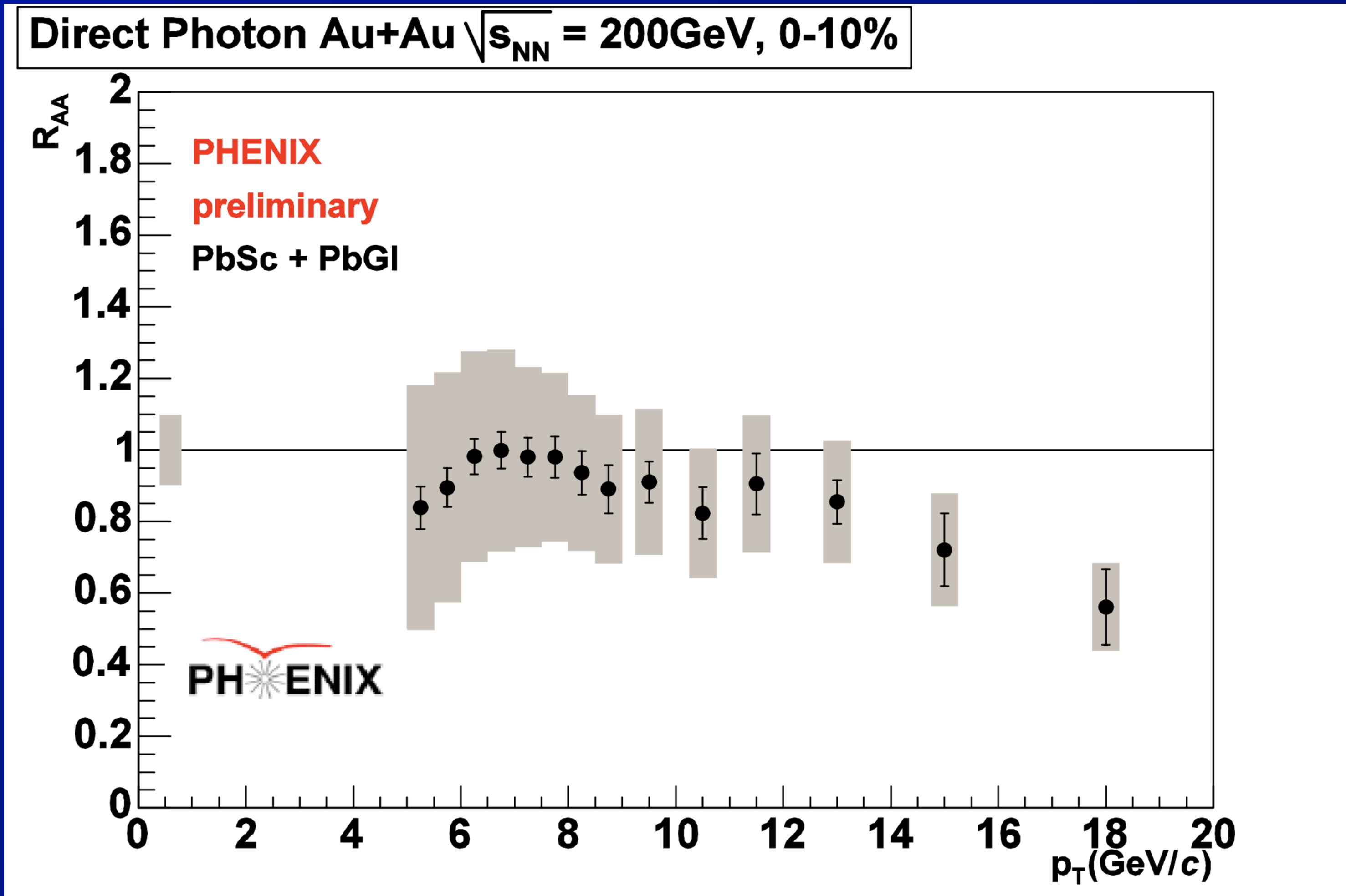


Jet conversion (Annihilation) **Medium induced bremsstrahlung** **Thermal radiation?**

Created in all phases of the collision
Once created, they survive ($\alpha_e << \alpha_s$) → time, temperature … history
But this also makes measurements hard to interpret

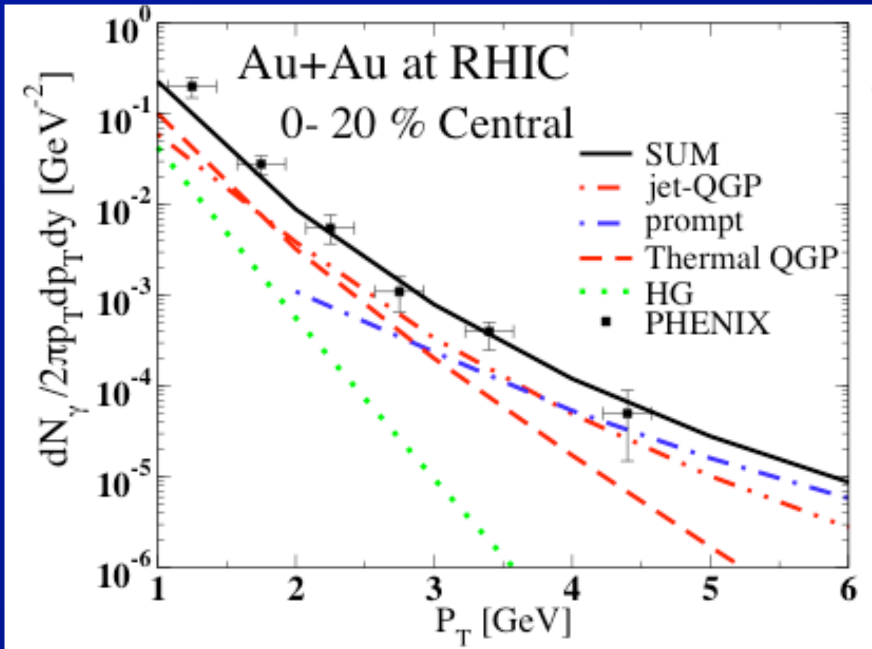
- From nice RHIC User's Mtg talk by Ondrej

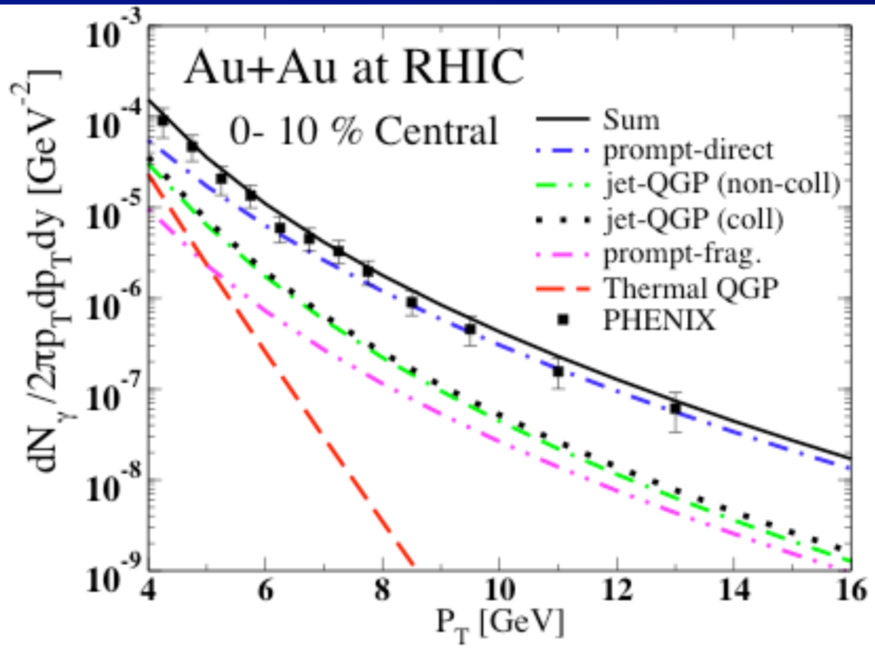
Single Prompt Photons in Au+Au



- Much speculation re: drop at high p_T
  - Should always beware of drawing conclusions from the last data point, but taking the data at face value …

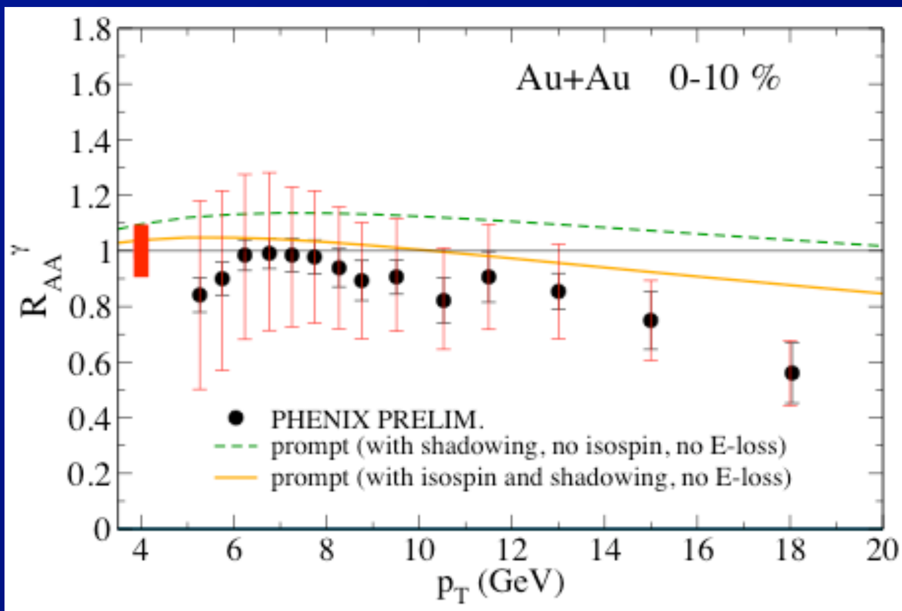
Au+Au: Single Prompt Photons

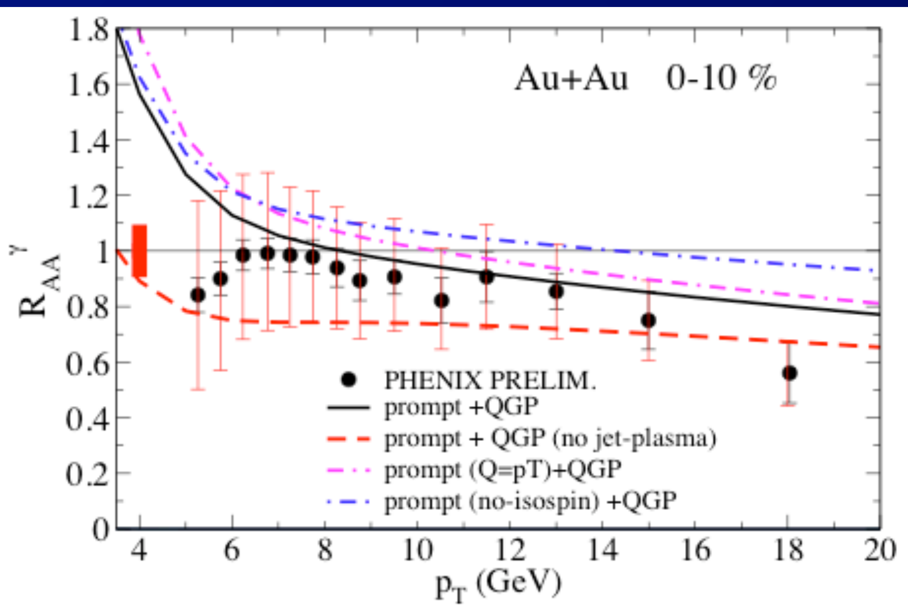




Non-medium effects

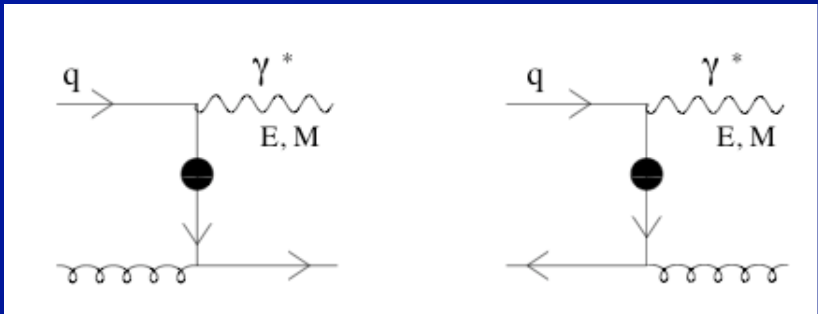
Medium effects



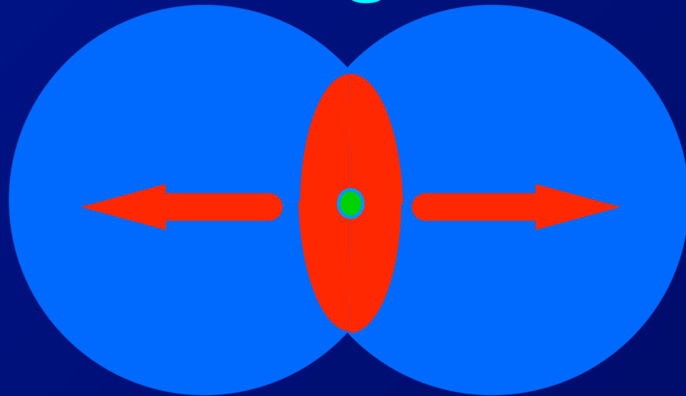


Au+Au: Single Prompt Photons: v_2!

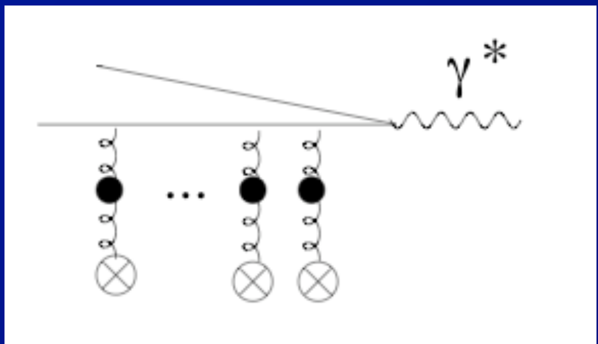
Jet conversion



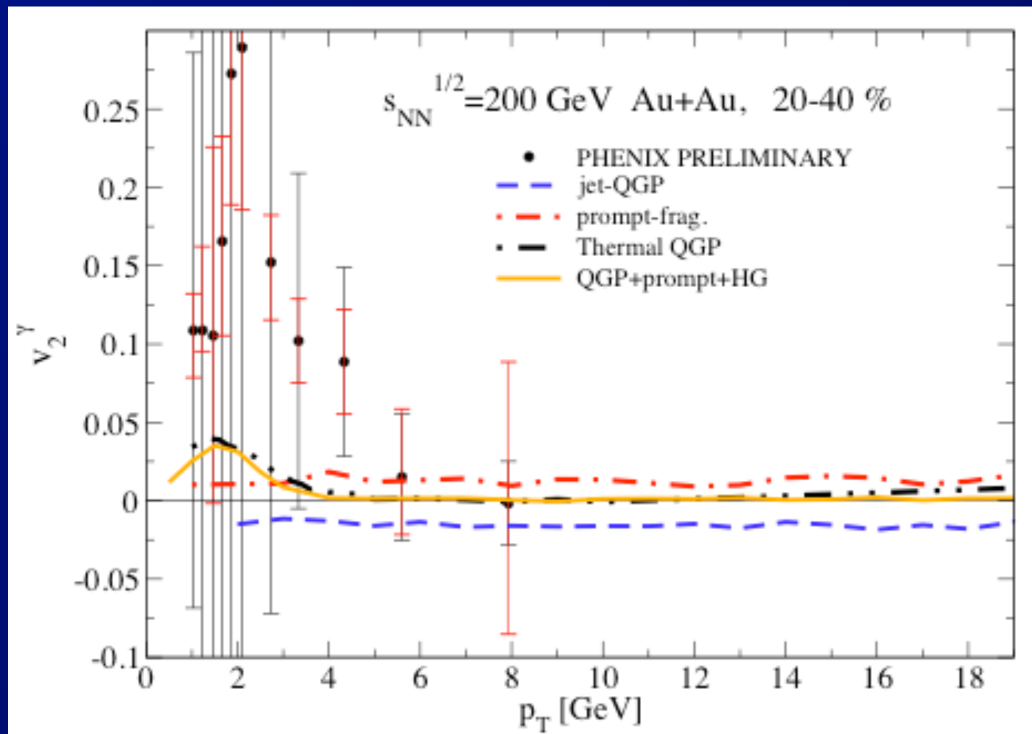
More of both in long direction -- negative v_2



Annihilation



- Existing data not good enough
  - Crucial measurement

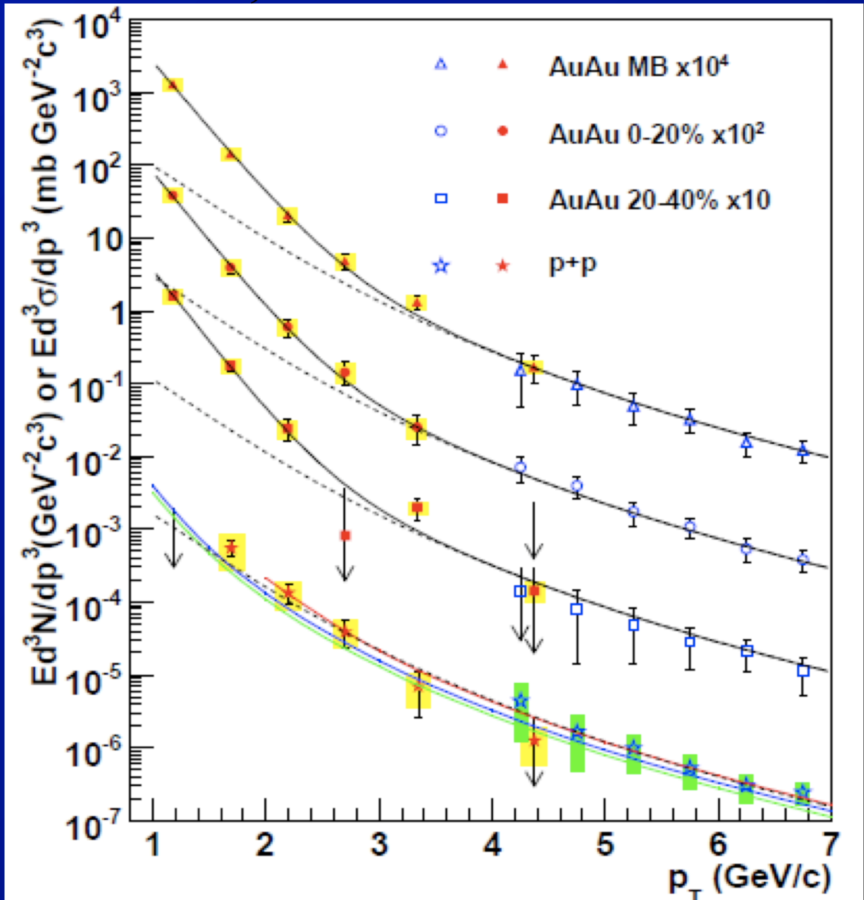


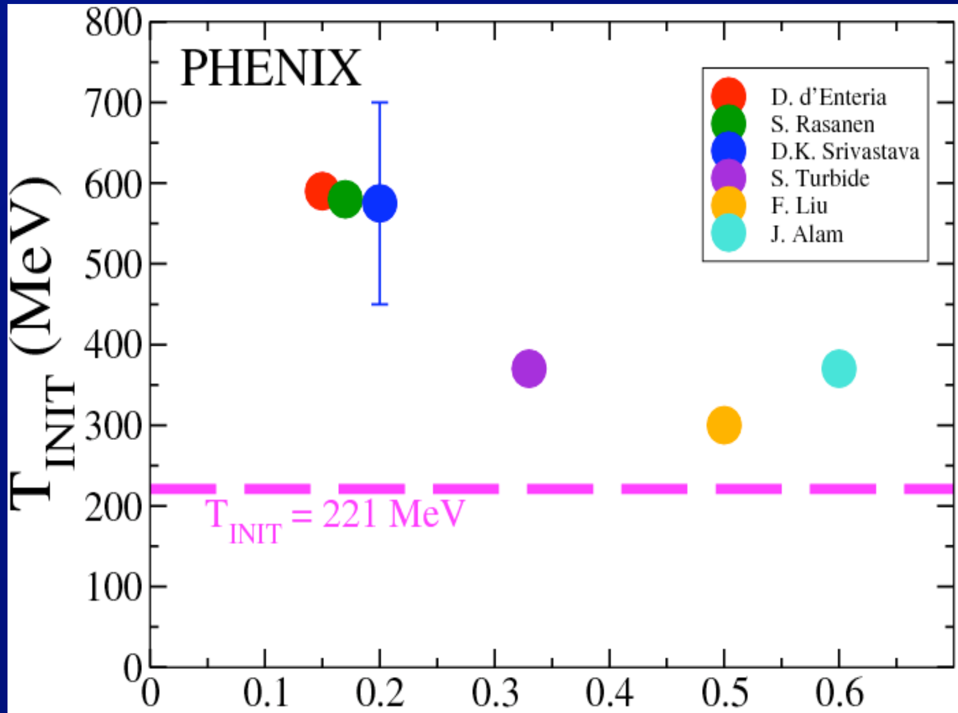
Photons & Jet Conversion

- In my opinion, this is one of the most important outstanding physics issues @ RHIC
- Why?
  - We have a scenario of strongly coupled QGP.
    - ⇒'Normal" QCD scattering processes like jet conversion either don't happen, or happen with very different rates.
    - ⇒Is there AdS analog of jet conversion?
      - » More generally, jet conversions provide a test of our understanding of scattering in medium.
  - Jet conversion diagrams are nearly identical to jet flavor change diagrams
    - ⇒Insight on jet conversion provides insight on jet flavor change processes.

Thermal Photons

PHENIX, arXiv:0804.4168v1

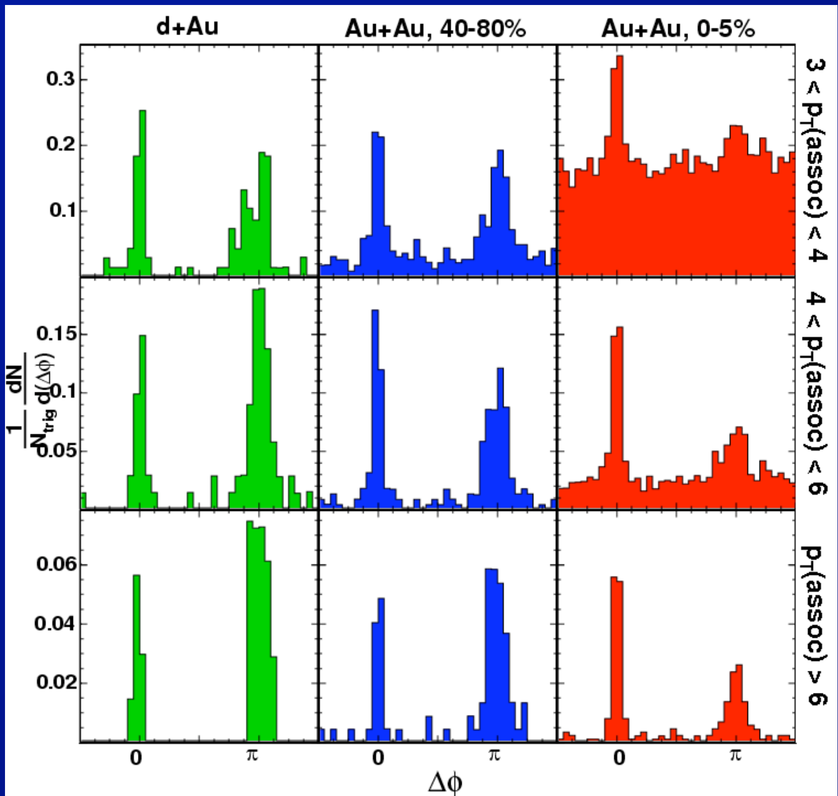


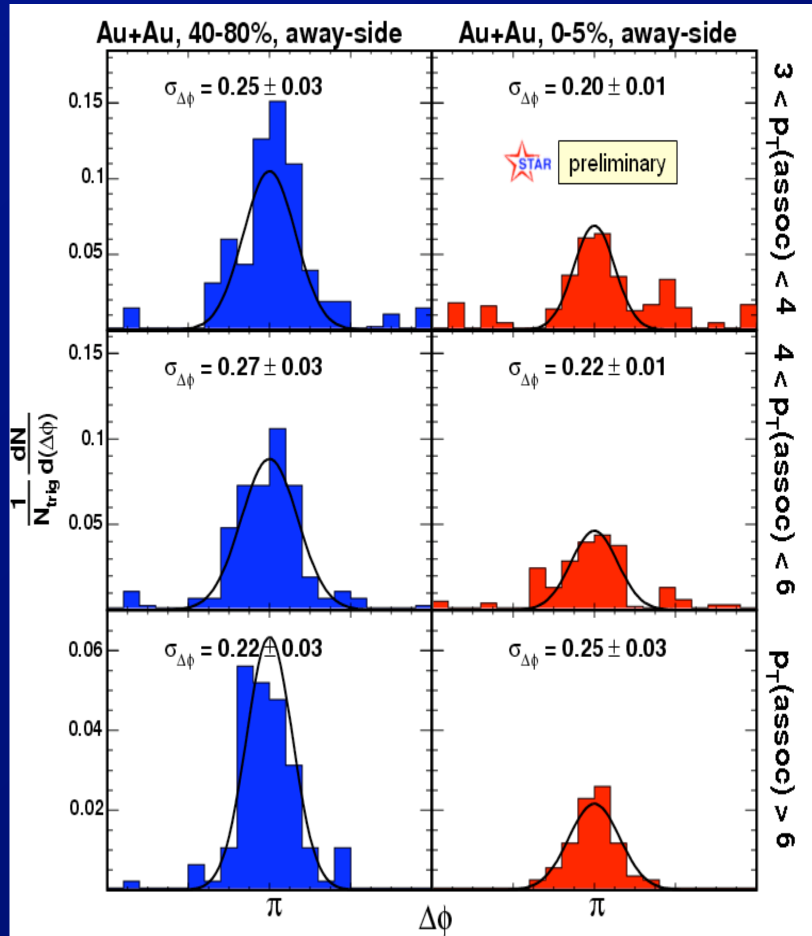


- PHENIX measurement of low-pT prompt photons
  - ⇒Very important constraint on initial T.
- Even better would be thermal photon v2(pT)!
  - – Ultimate test of/constraint on collective motion.

Where are the modified di-jets?

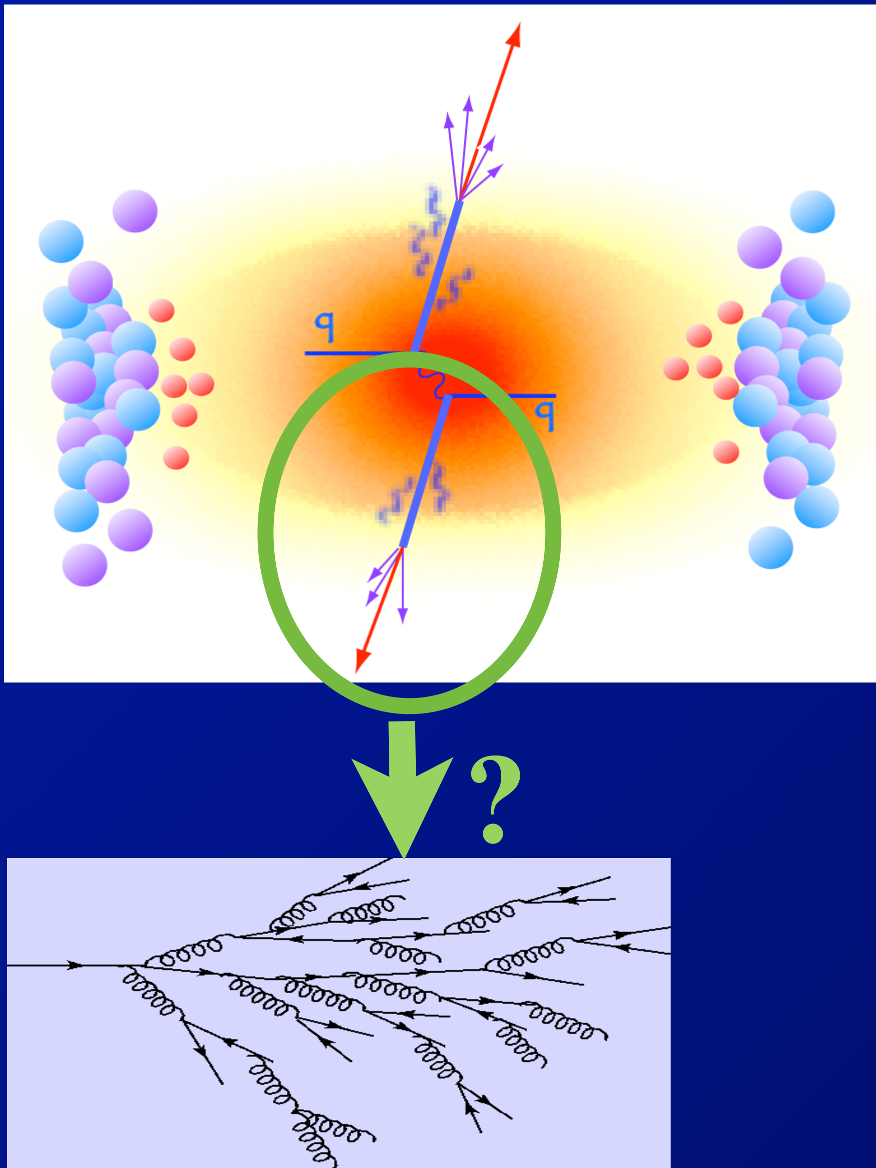
STAR 8<p_T(trig)<15 GeV/c





- STAR di-jet signal in di-hadron correlations at high p_T (Gaussian shows d-Au shape)
  - Detected di-hadrons show no broadening

Physics of jet quenching



- **Crucial question:**
  - Does parton evolution in medium behave similar to "normal" parton shower?
  - Or is the evolution completely different
- **In other words**
  - Weakly coupled radiative + collisional energy loss
  - Or strongly coupled/non-perturbative quenching
- **We don't really know!**

A Particular Quenching Scenario

Universal upper bound on the energy of a parton escaping from the strongly coupled quark-gluon matter

Dmitri E. Kharzeev

Nuclear Theory Group,

Department of Physics,

Brookhaven National Laboratory,

Upton, New York 11973-5000, USA

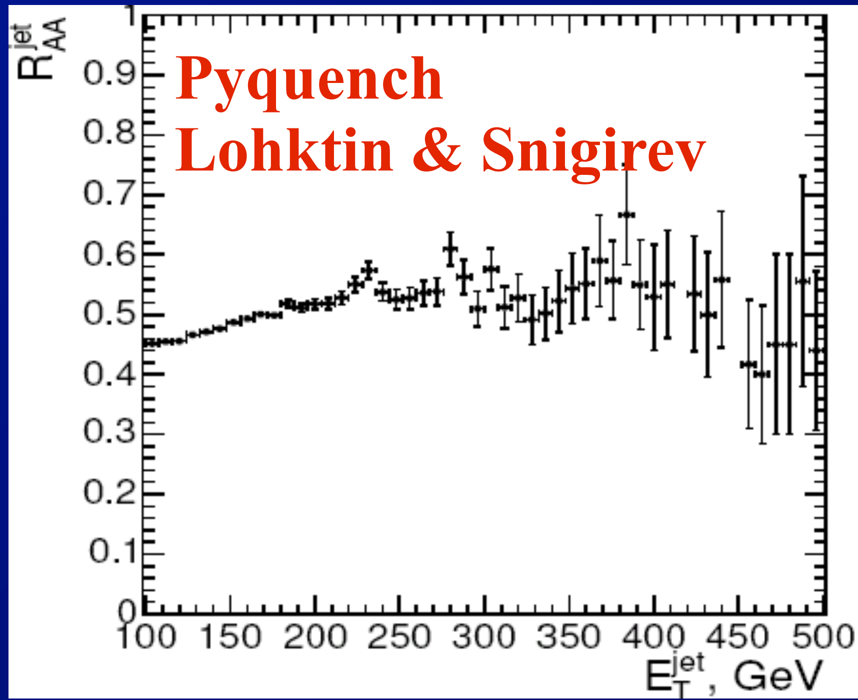
(Dated: June 3, 2008)

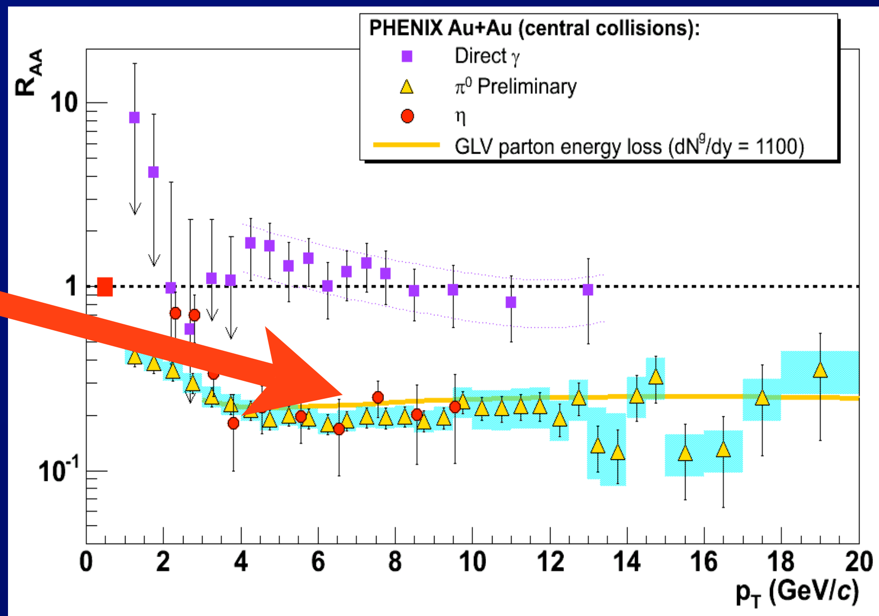
- What would we expect to see?
  - Jets produced near the edge survive (unmodified?)
  - Jets in the interior “disappear”
    - ⇒The ultimate surface emission scenario
  - No modified jets, di-jet pairs
  - And no color factors
  - Significant charm & beauty quenching too.

How to tell if Dima is right?

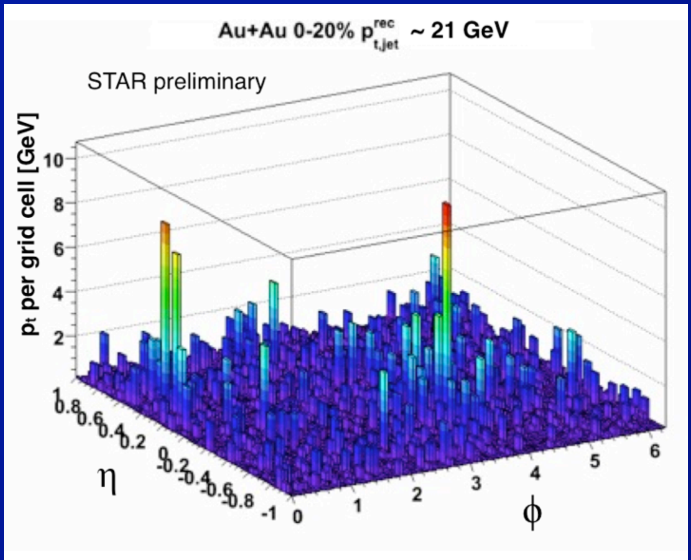
- First step
  - Measure Jet R_{AA}
- From Pyquench code of Lohktin, Snigirev
  - x2 suppression purely from collisional dE/dx
  - plus radiation outside the jet cone
- But if Dima is right,
  - Jet $R_{AA} \sim \pi^0 R_{AA}$
  - Easy to distinguish from $R_{AA} \sim 0.5$

    ⇒If we can measure jets in A+A collisions



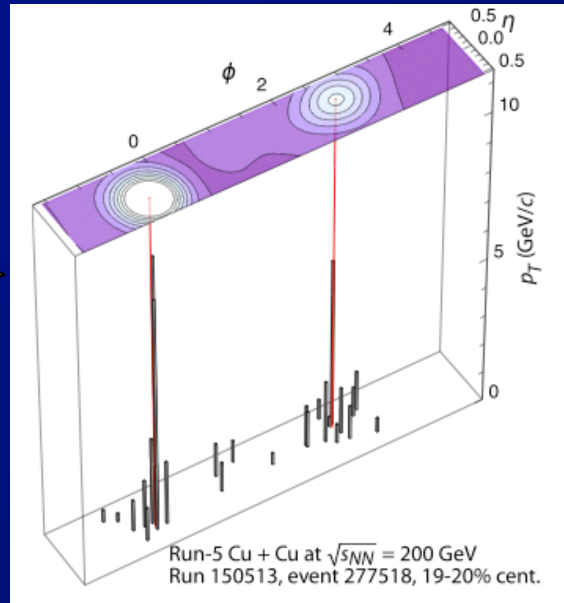


True Jet measurements in progress

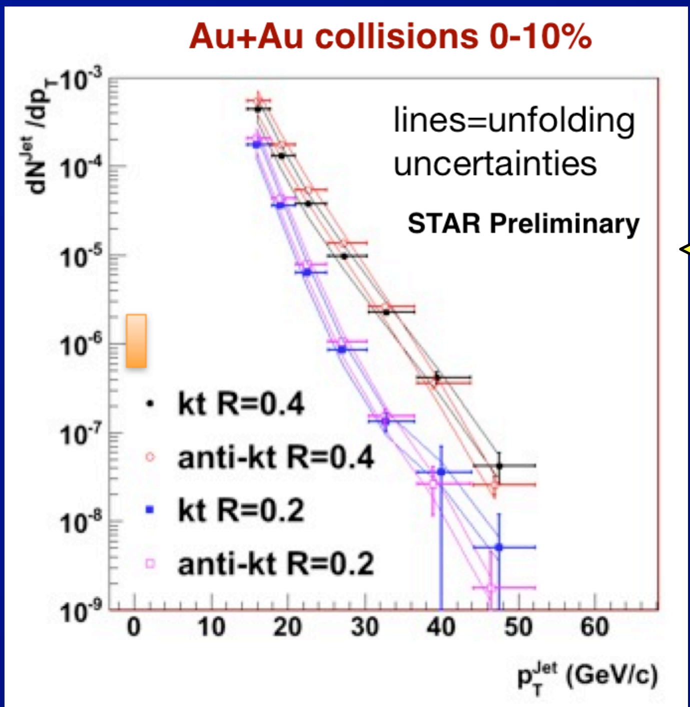


STAR (Au-Au)

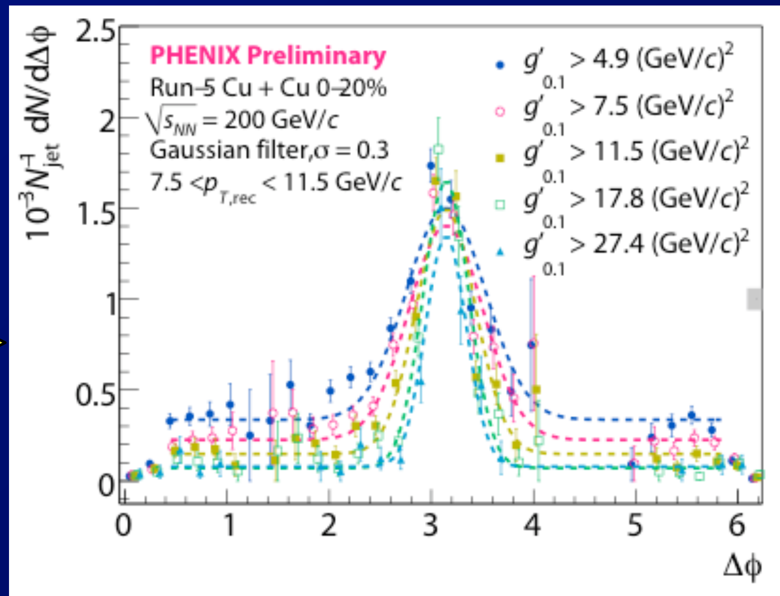
PHENIX (Cu+Cu) jet events



STAR Au+Au spectrum



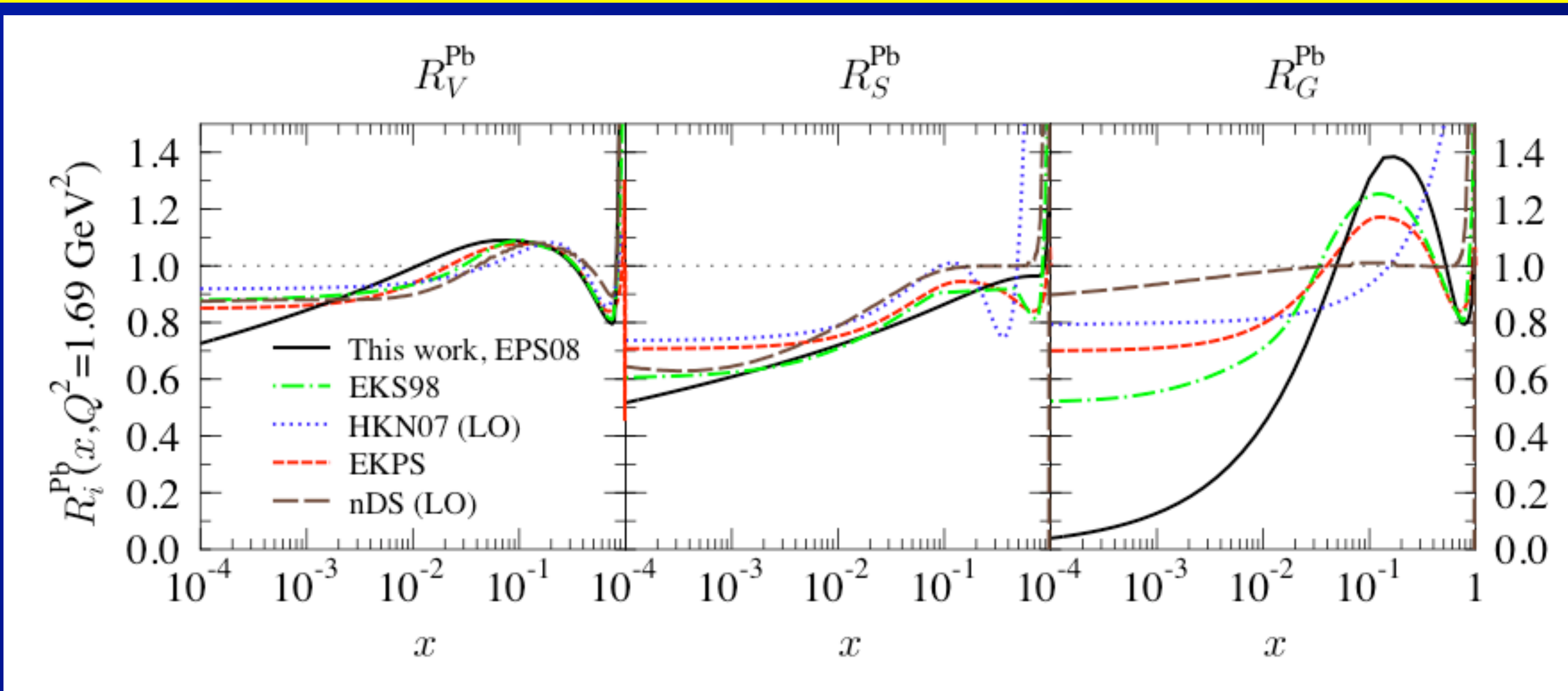
PHENIX Cu+Cu di-jet Δϕ



RHIC Jet Analyses

- This topic is very important to me
  - Because I belive that full jet measurements are crucial to resolving many of the difficulties in interpreting jet quenching data
- But, this is also a topic for which (now) more is less.
  - One or two results that are fully worked out with experimental effects understood is far better than many different results each of which provides a different "cut" on the physics.
    - ⇒It would be a big mistake to "muddy the waters" with RHIC jet measurements.
    - ⇒We have a chance to beat LHC experiments to some of the insights from jet measurements.
      - » We shouldn't end up with LHC cleaning up a mess

Jets and nuclear PDFs



- **Effects of nuclear modifications of partons distributions will be more significant for jet R_{AA} than for (e.g.) π^0 R_{AA}.**
  - Especially for new EPS08 PDFs with strong shadowing and anti-shadowing.

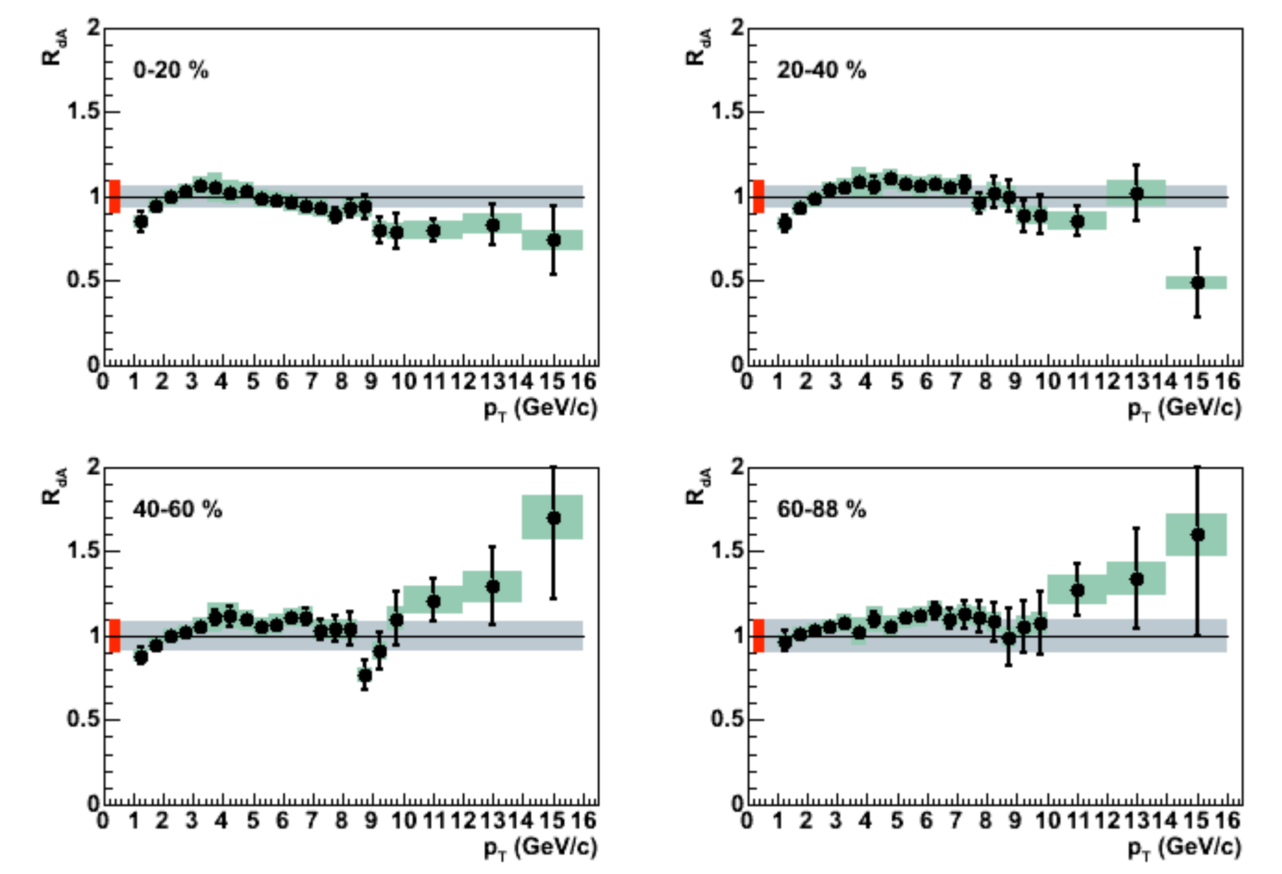
  ⇒Large anti-shadowing up to ~ 30 GeV (d+Au!!!) ?

But, b dependence of PDFs!

PHENIX
d+Au π^0
R_{dA} vs
centrality

- Suppression @ high p_T in central d+Au
  - Suggests b dependence of PDF's
  - Not surprising (for shadowing, but for EMC?)
    - ⇒Essential for understanding Au+Au
    - ⇒MUST try to measure with run 8 data

But, b dependence of PDFs!



PHENIX
d+Au π^0
R_{dA} vs
centrality

- Suppression @ high p_T in central d+Au
  - Suggests b dependence of PDF's
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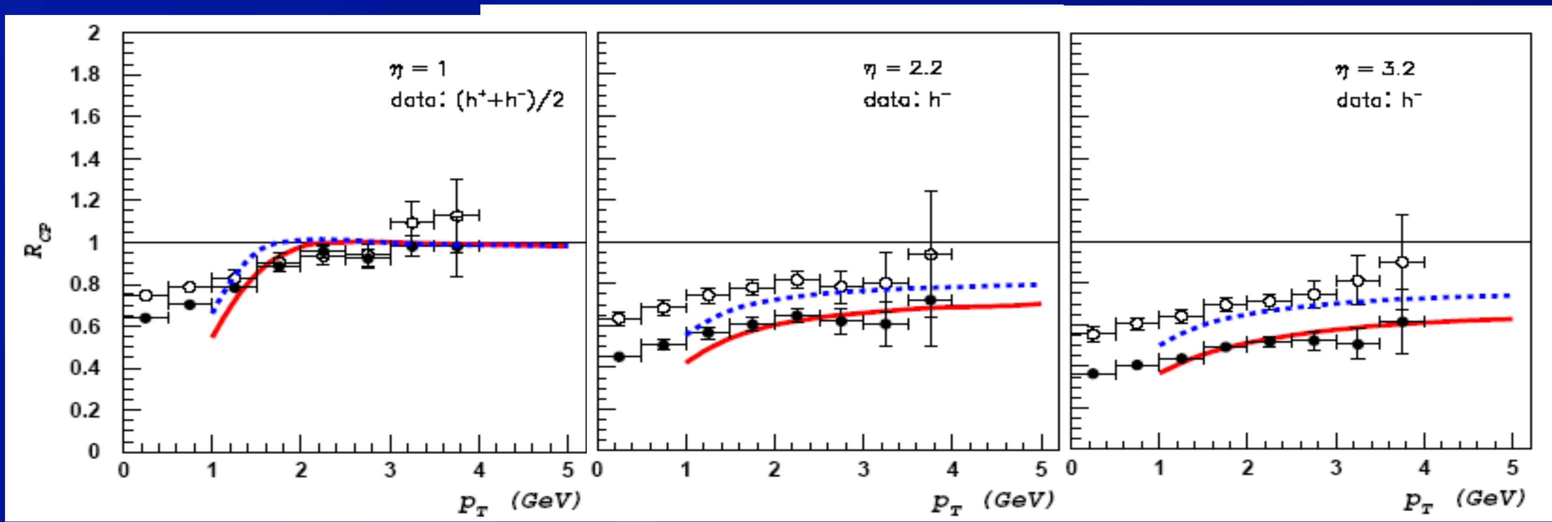
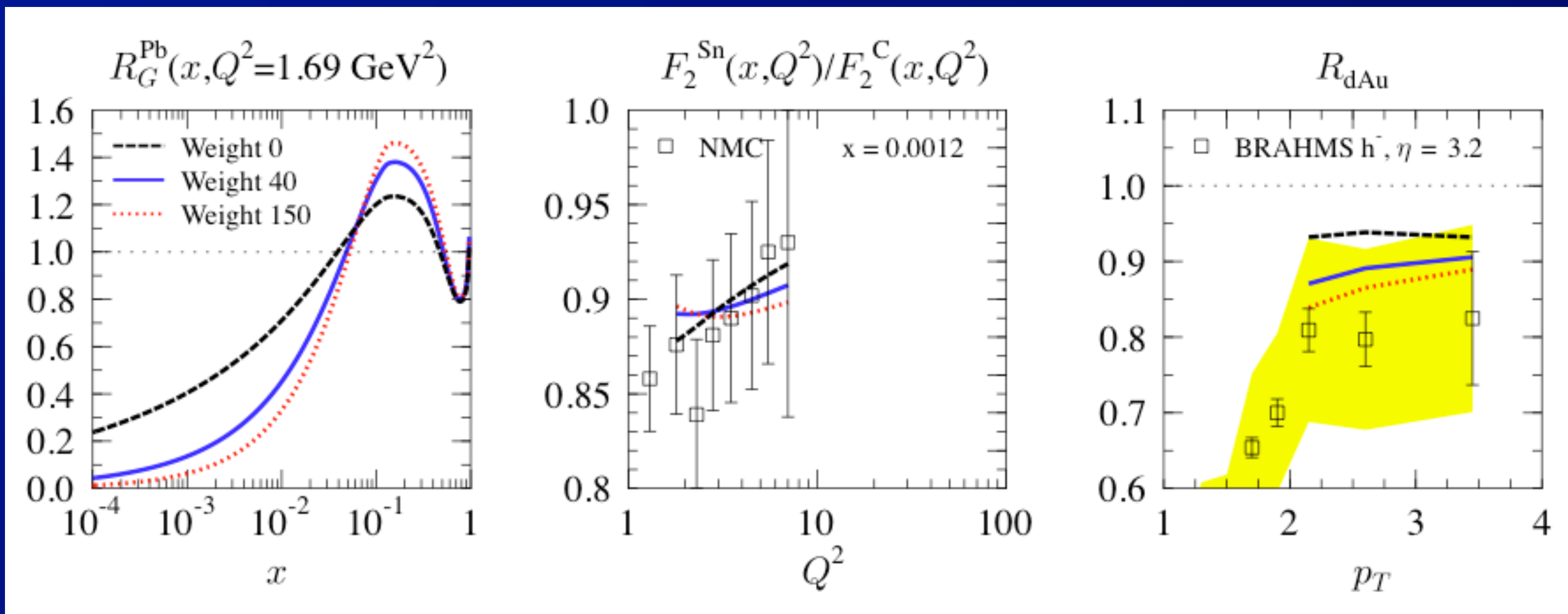
    - ⇒Essential for understanding Au+Au
    - ⇒MUST try to measure with run 8 data

Coming full circle …

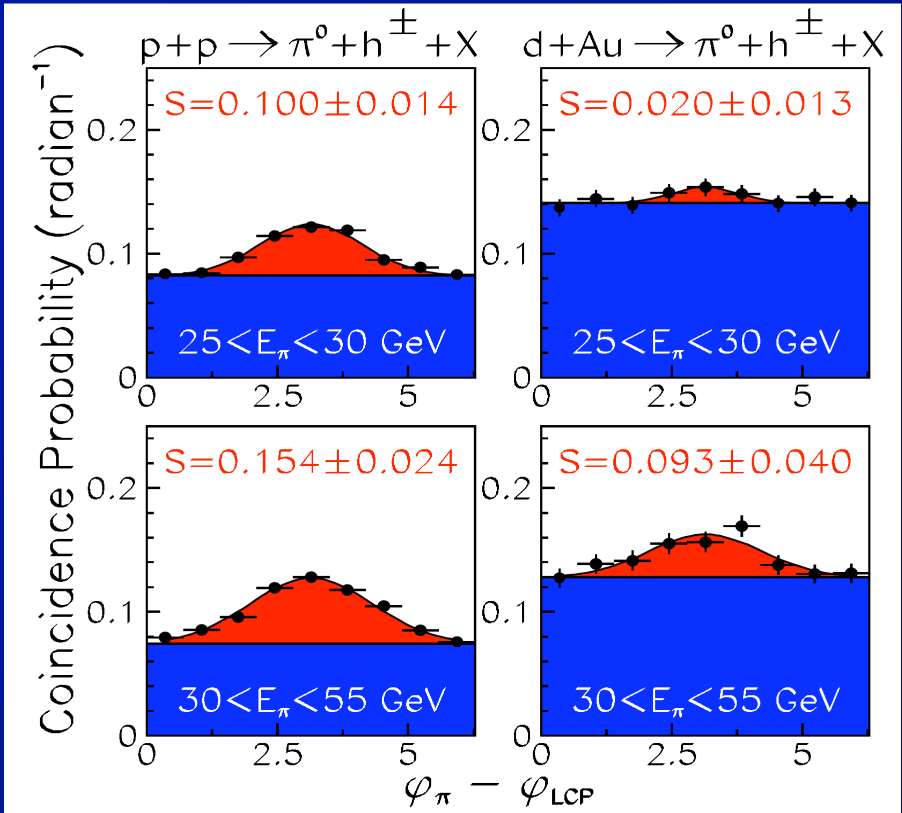
Forward d+Au suppression, saturation/CGC?



Or (leading twist) shadowing?

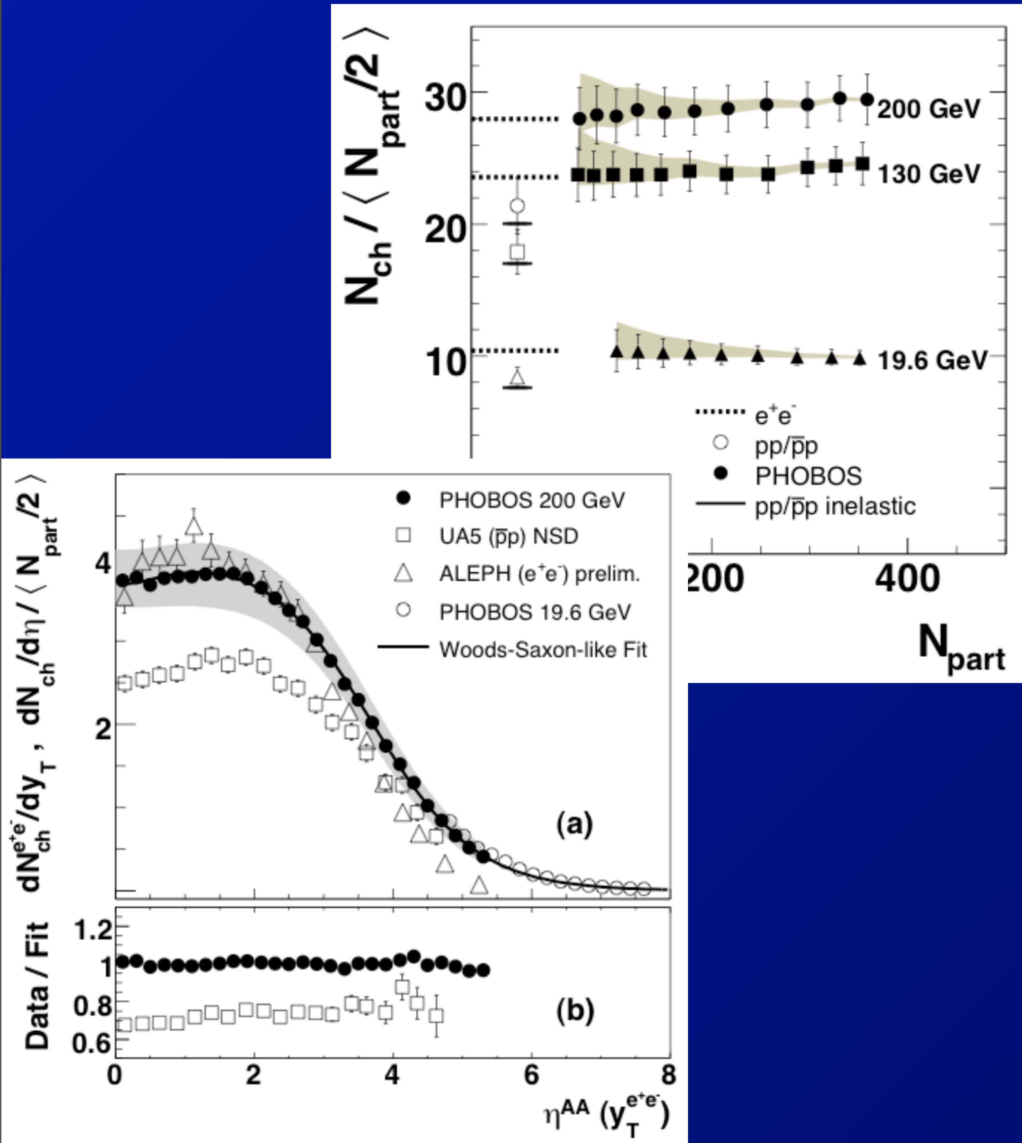


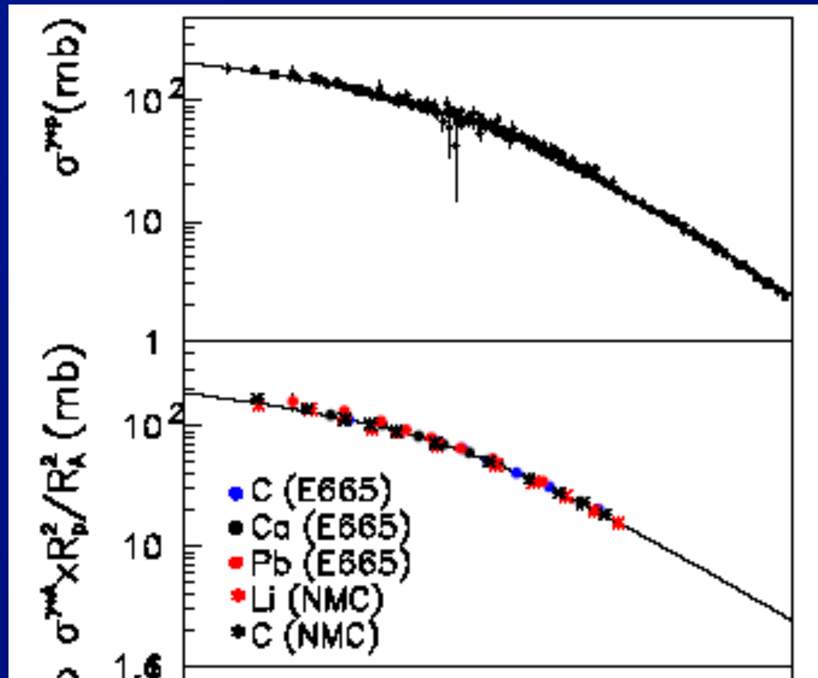
Di-jet azimuthal (de)correlation

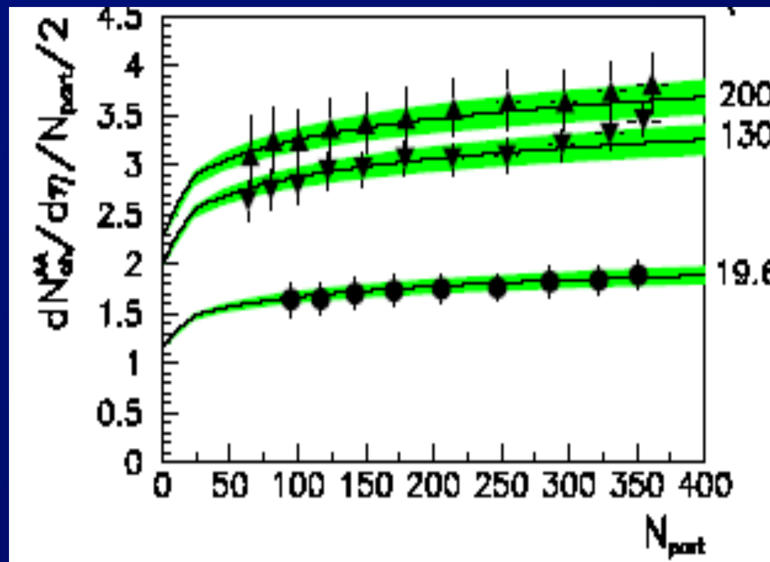


- How to test CGC vs LT shadowing?
  - Azimuthal correlation of forward jet pairs or widely separated jets
  - Results from STAR
  - By no means definitive
    - ⇒New, better data from Run 8 STAR & PHENIX
- Shadowing should reduce total number of di-jet pairs and the strength of correlation
  - Relative to random/non-perturbative background
  - I worry about controlling that background when comparing p+p to d+Au (e.g. isospin effects)
  - ⇒Is this a definitive measurement for CGC?

Multiplicities (Initial Conditions)

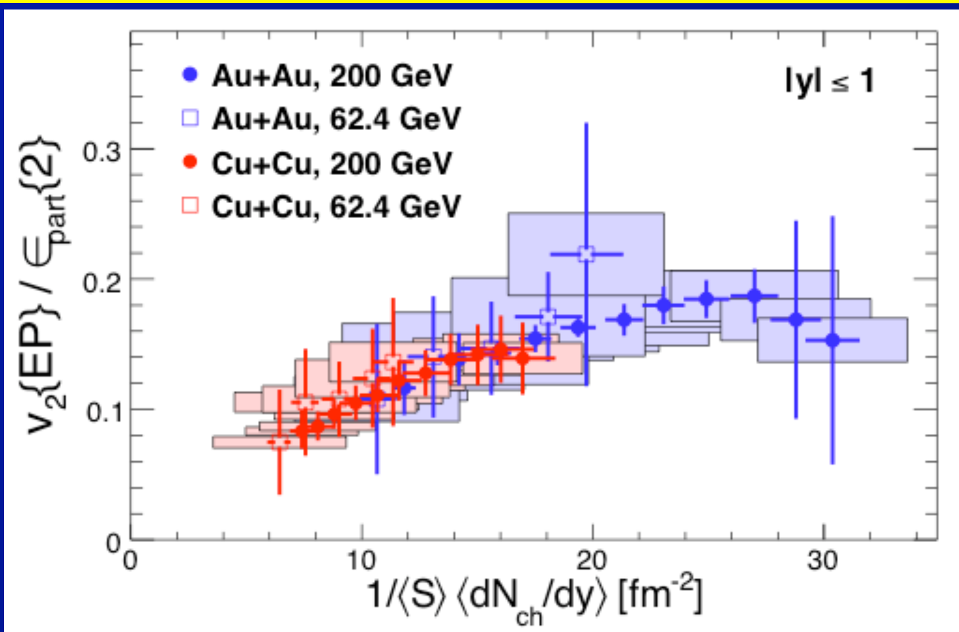


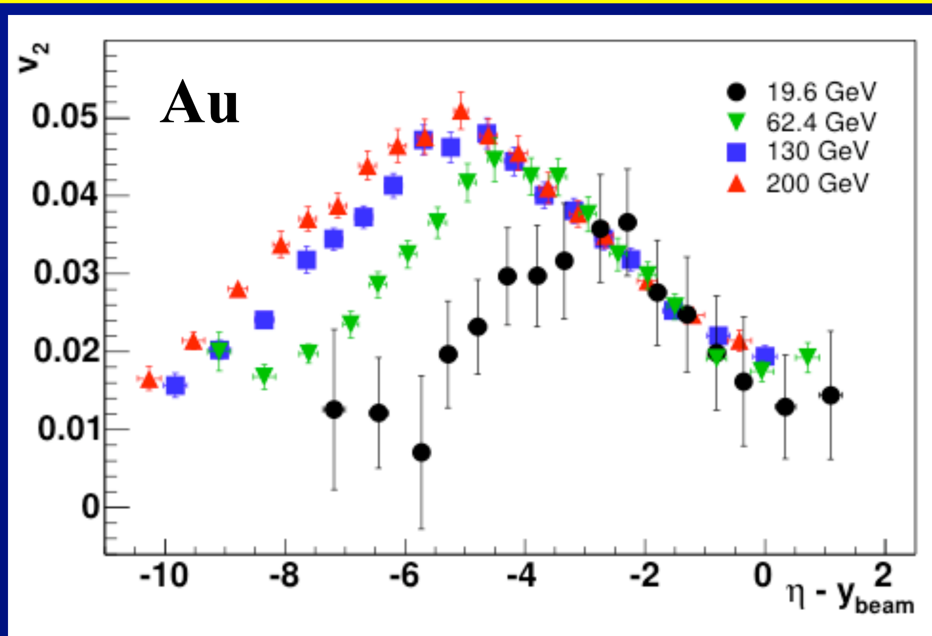


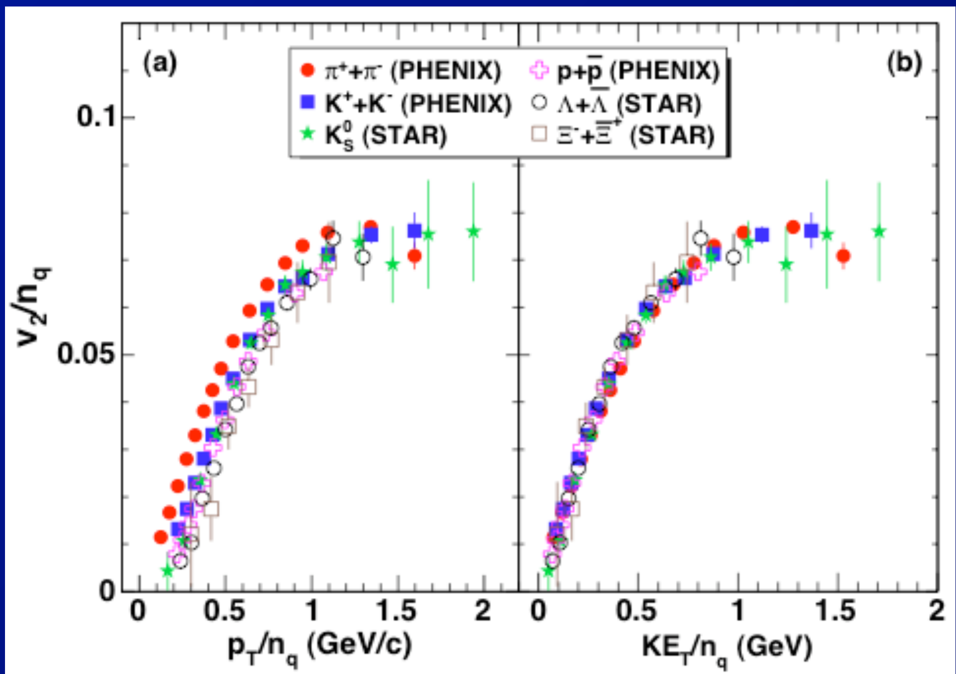


- Is nature trying to tell us something? Are we listening?

Elliptic Flow







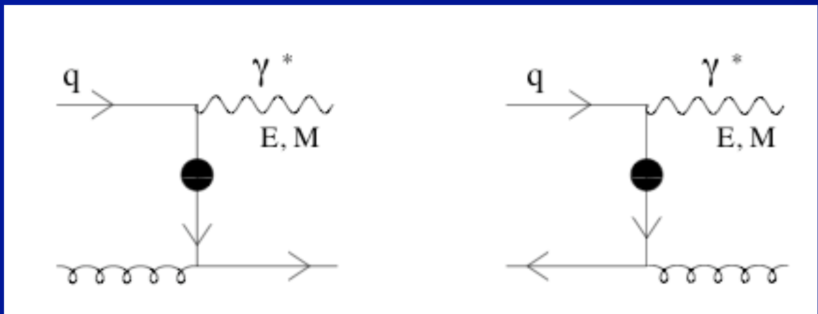
- Data
  - v_2/ε set by entropy/area
    - ⇒Explains limit. frag.
  - perfect scaling of v_2/n_q vs KE_T/n_q
- Why? (don't our hydro codes do this?)

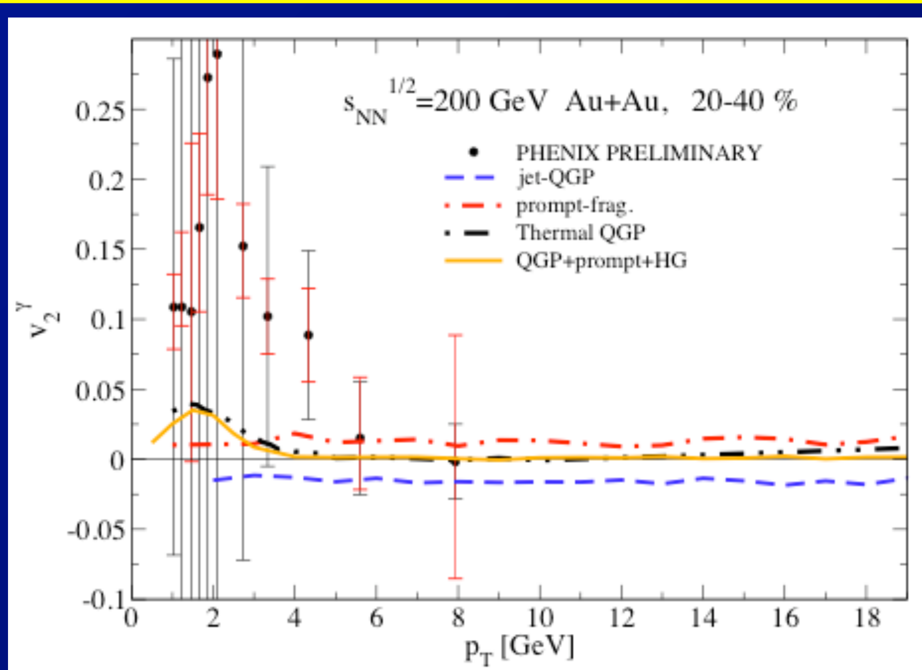
Jet Quenching: Weak/Strongly Coupled?

- We claim sQGP?
  - Yet we use weak-coupling for jet quenching?
    - ⇒Large jet energies do not (necessarily) make the interaction with the medium perturbative!
  - Because that's what we know how to calculate.
- In my opinion, all detailed analysis of jet quenching, extraction of $\hat{q}$, eta useless until we know that the quenching is weakly coupled
  - And best test is jet R_{AA}
    - ⇒Coming soon @ RHIC and LHC
- But we need to be ready
  - PDFs with b-dependent nuclear modifications
  - More weak-coupling jet R_{AA} calculations

Photons: Interactions in the Medium

Jet conversion





- In my opinion, in all the discussion re: strong coupling and viscosity, we've lost track of what I consider one of the essential physics questions
  - How do quarks and gluons interact in the medium?
    - ⇒Jet Conversion photons provide direct test
    - ⇒And provide insight on flavor conversion too.
- This measurement needs $\int \mathcal{L} dt$!!!