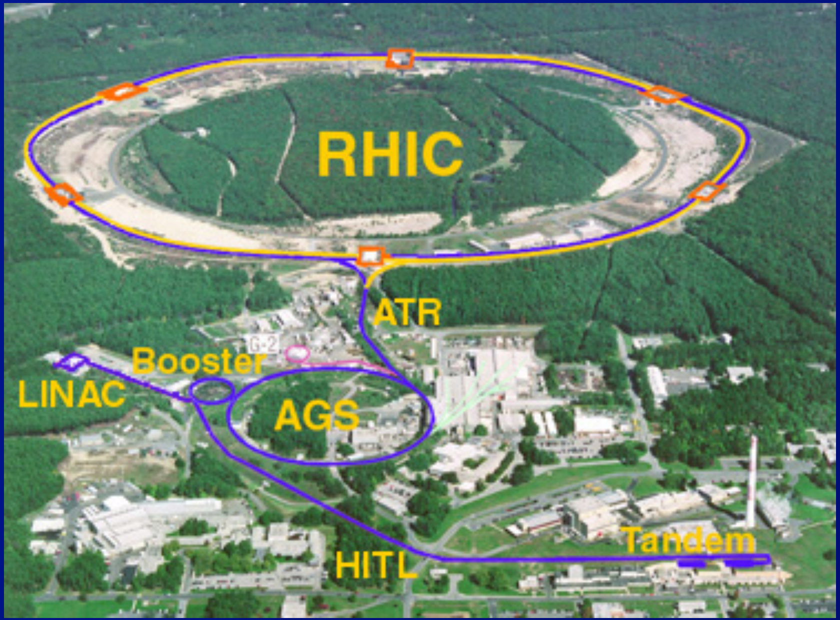
Ultra-relativistic Heavy Ion Collisions at RHIC and (soon) the LHC

Prof. Brian A. Cole
Columbia University



Looming on the heavy ion horizon

The Big Picture

- We know that strong interactions are well described by the QCD Lagrangian:

$$L_{QCD} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a} - \sum_n \bar{\psi}_n \left(\not{\partial} - ig\gamma^{\mu}A^{a}_{\mu}t_a - m_n \right) \psi_n$$

  ⇒Perturbative limit well studied

- Nuclear collisions provide a laboratory for studying QCD outside the large Q^2 regime:
  - Deconfined matter (quark gluon plasma)

    ⇒“Emergent” physics not manifest in L_{QCD}

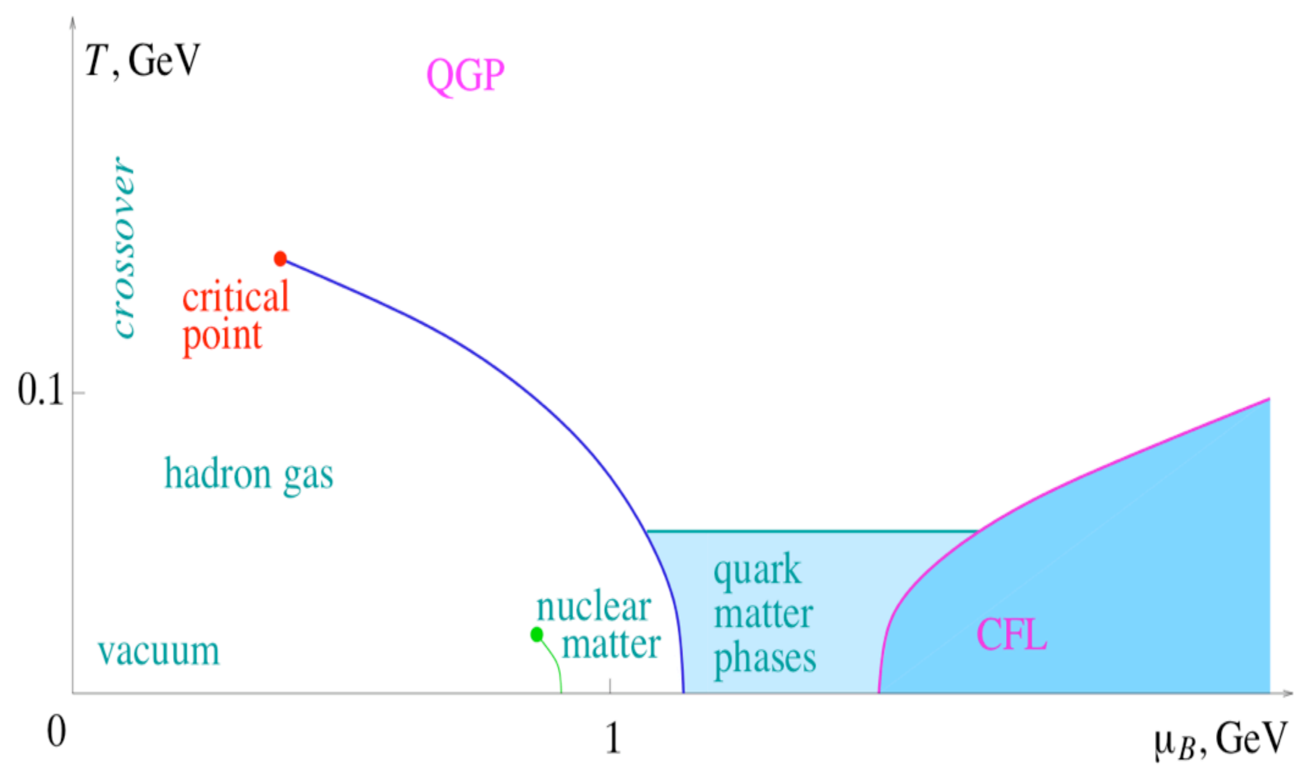
    ⇒ Strong coupling ⇒ AdS/QCD (?)

  - High gluon field strength, saturation

    ⇒ Unitarity in fundamental field theory

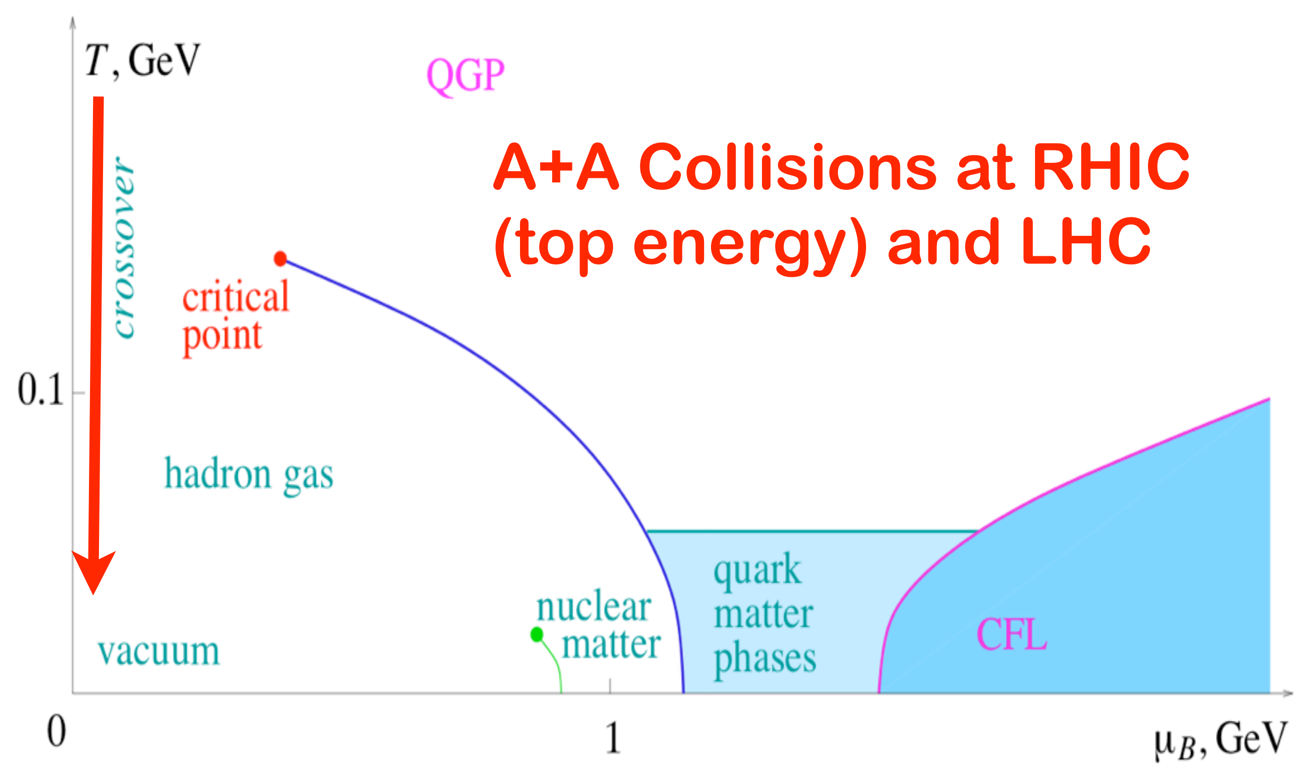
- Only non-Abelian FT whose phase transition & multi-particle behavior we can study in lab.

Phase Diagram of QCD "Matter"



- Strongly interacting matter has complex phase diagram.
  - 1st order transition @ high temperature and finite μ_B ending in critical point (?)
  - Continuous crossover for $\mu_B \sim 0$

Phase Diagram of QCD "Matter"



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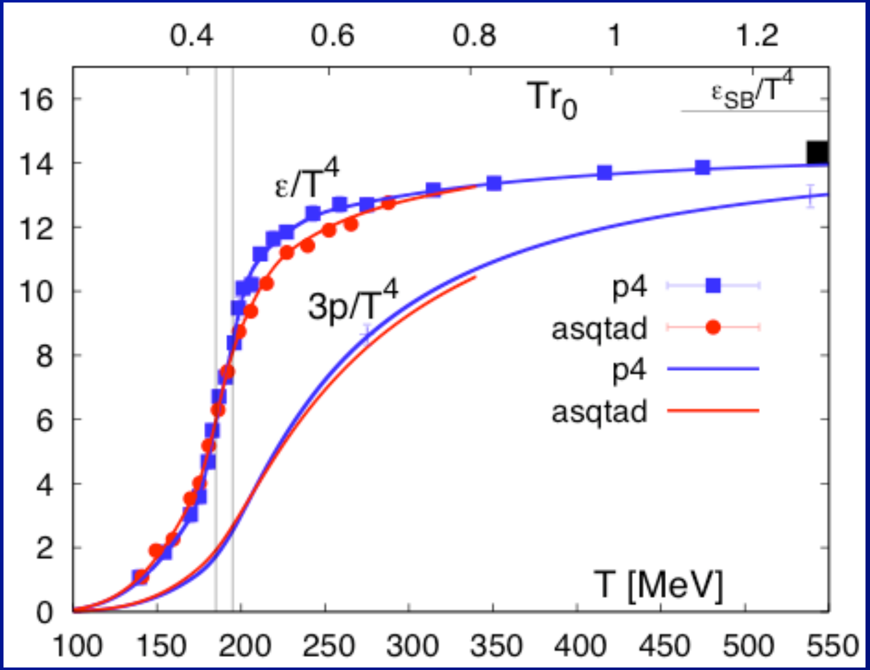
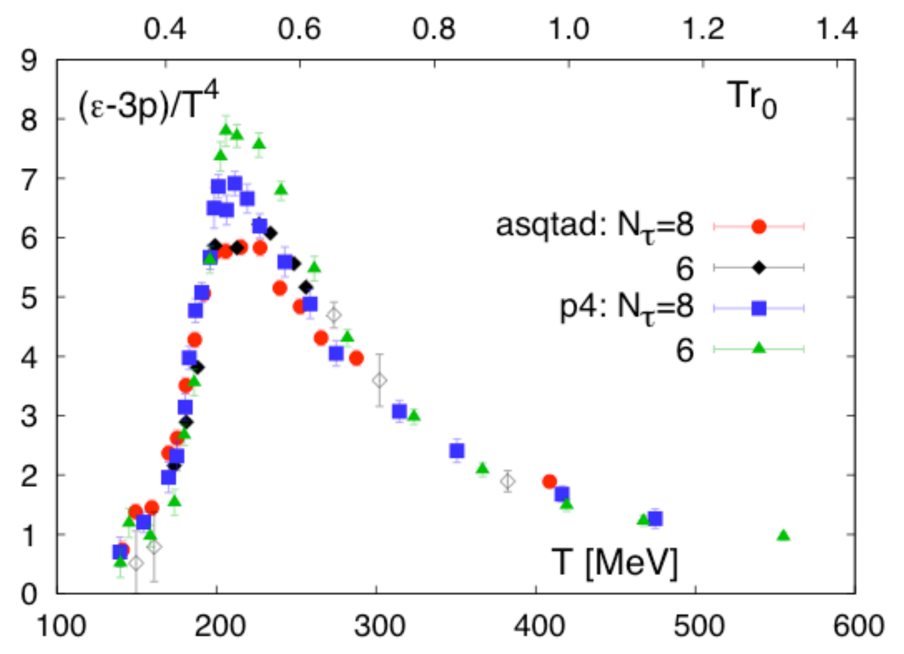
QCD Thermodynamics on Lattice

Energy Density or pressure



QCD trace anomaly

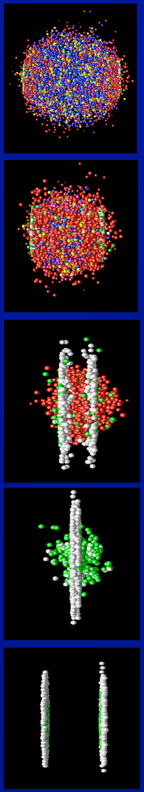


- Lattice thermodynamics from hotQCD group
  - Sudden change in NDoF at Tc ~ 190 MeV.
    - ⇒Continuous cross-over transition from hadrons to deconfined “quark gluon plasma”
- $(\varepsilon\text{-}3p)/T^4$, an “interaction measure”
    - ⇒Strong coupling already evident near T_C (?)

Relativistic Heavy Ion Collider

- Ten years of operation colliding protons, deuterons, Au, Cu at a variety of energies

Ultra-relativistic A+A, Canonically



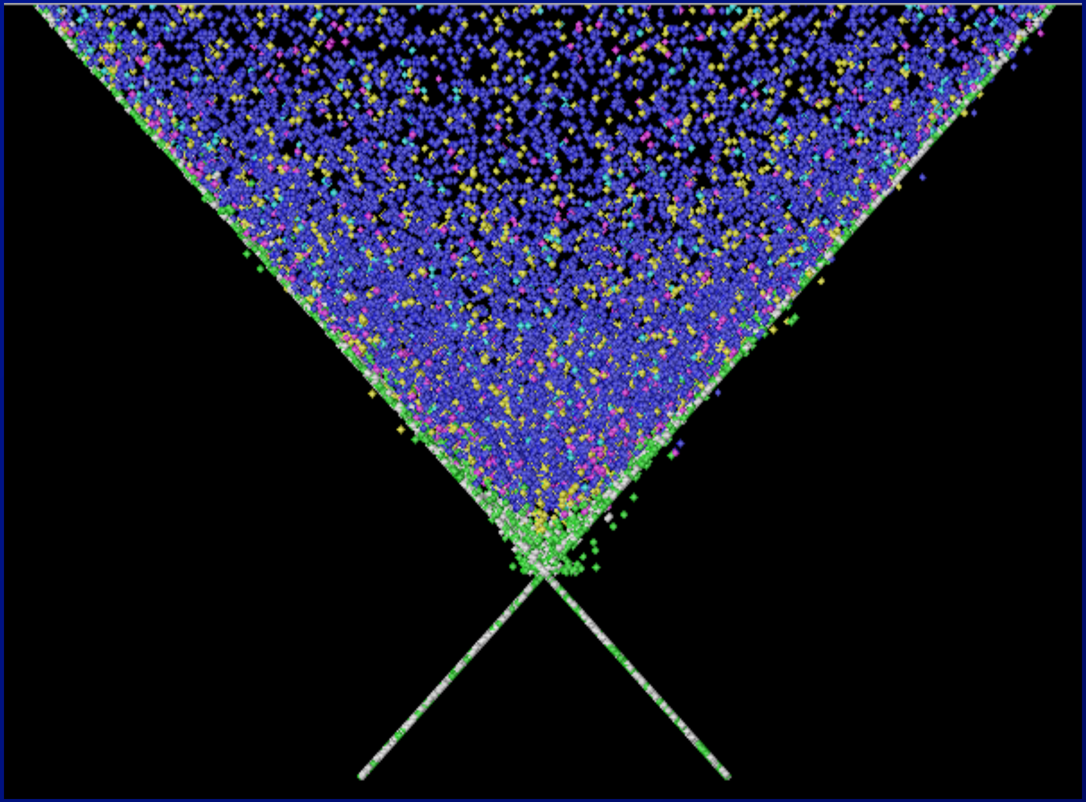
Recombination, Hadronic cascade

“Hydro” evolution

Fast thermalization

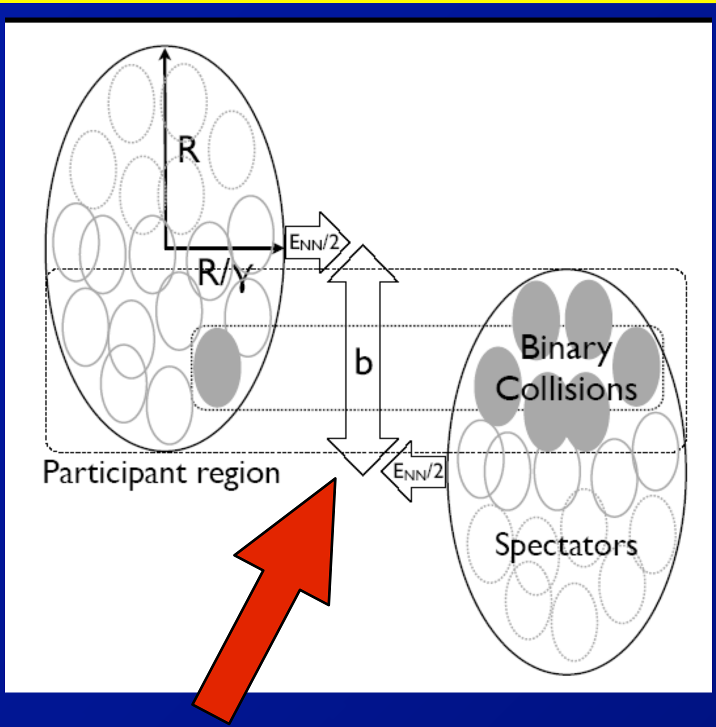
Hard processes, CGC → Glasma

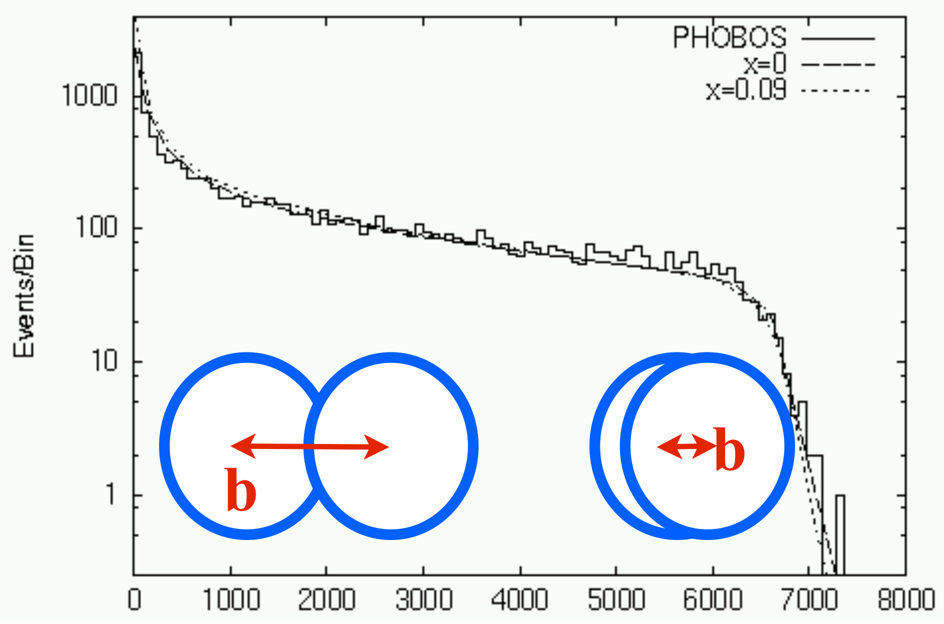
Saturated nuclei



- In this talk focus on three problems for which first Pb+Pb run(s) at LHC will provide insight
  - – Initial conditions
  - – Collective evolution
  - – Jet quenching

Nuclear Collision Geometry

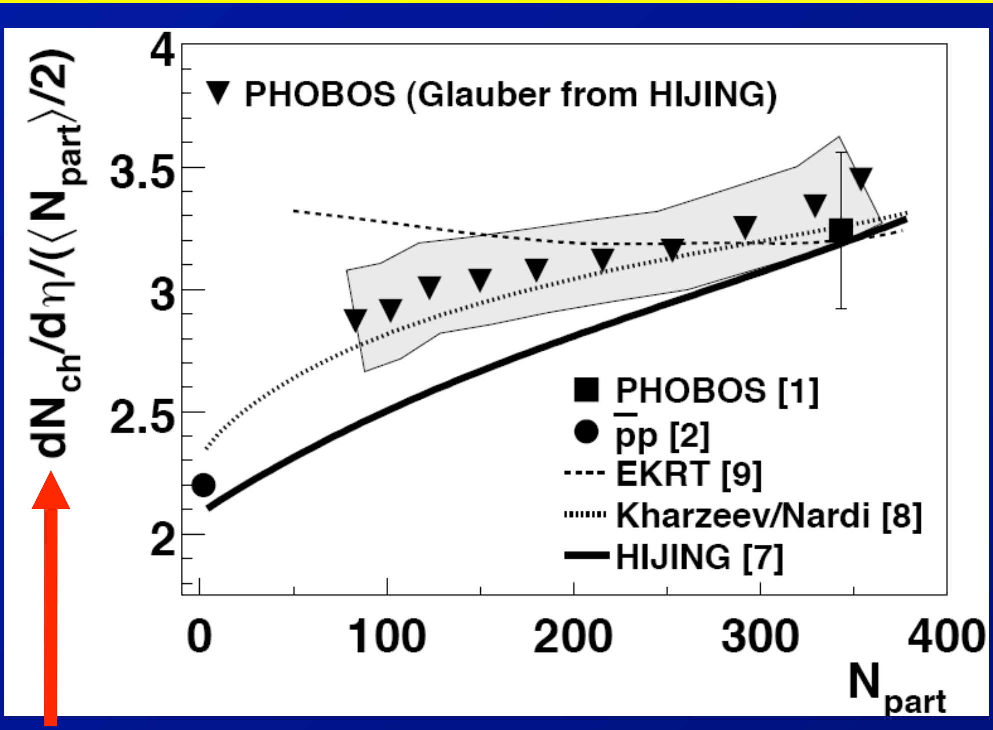


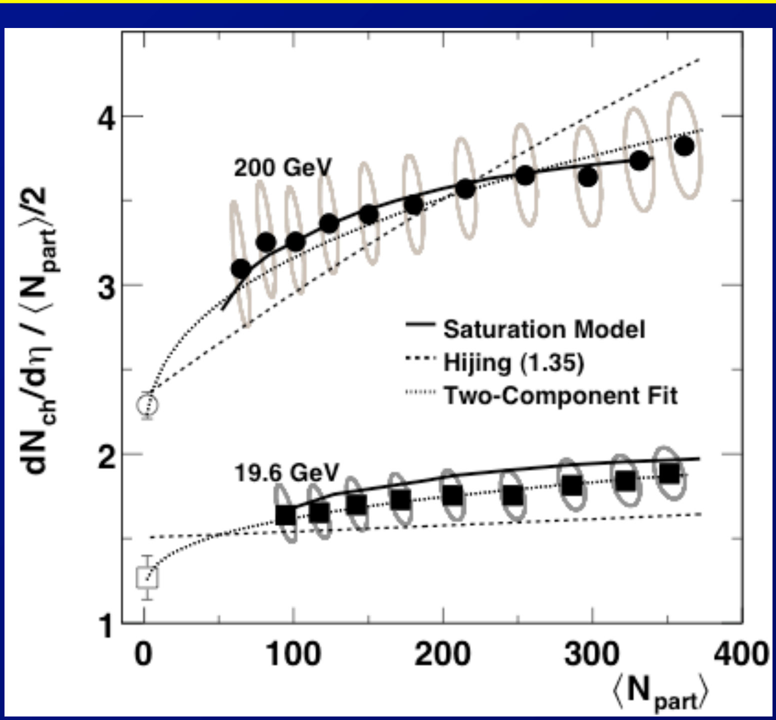


Charged particle multiplicity

- **Dynamics of ultra-relativistic collision controlled by (classical) impact parameter (b)**
  - How many nucleons scatter hadronically
    - ⇒ “# of participants”, N_{part}
  - # of nucleon-nucleon scatterings (semi-classically)
    - ⇒ # of collisions, N_{coll}
- **Surprise: $dN/d\eta \approx$ determined by N_{part}**

RHIC Particle Multiplicities





Multiplicity per colliding nucleon pair

- Two different interpretations of results
  - Phenomenological:
    - ⇒dn/dη determined by geometry ≈ participant nucleons
  - Saturation:
    - ⇒dn/dη determined by nuclear gluon fields, gluon production from those fields.

“Saturation” @ low x

- @ High energy nuclei are highly Lorentz contracted

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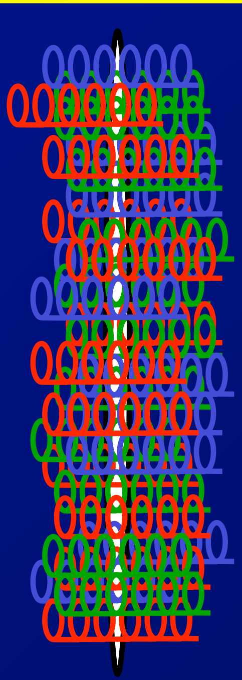
  - Except for soft gluons
  - Which overlap longitudinally



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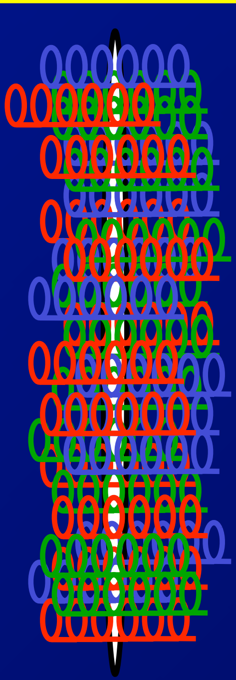

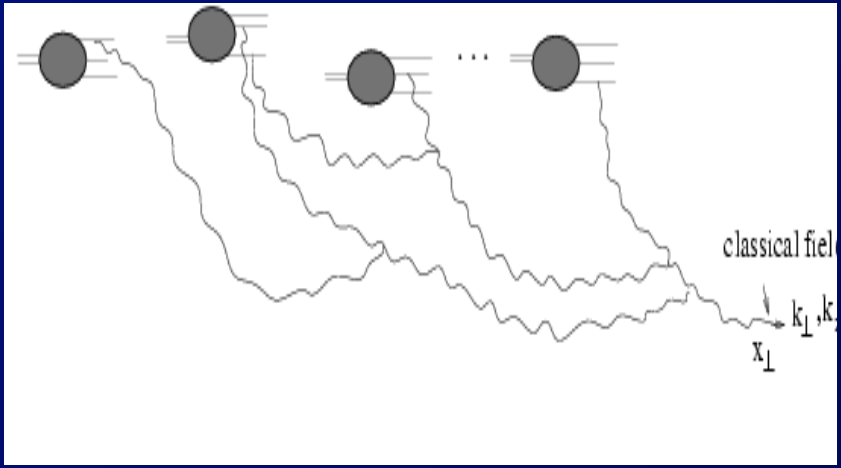

“Saturation” @ low x

- @ High energy nuclei are highly Lorentz contracted
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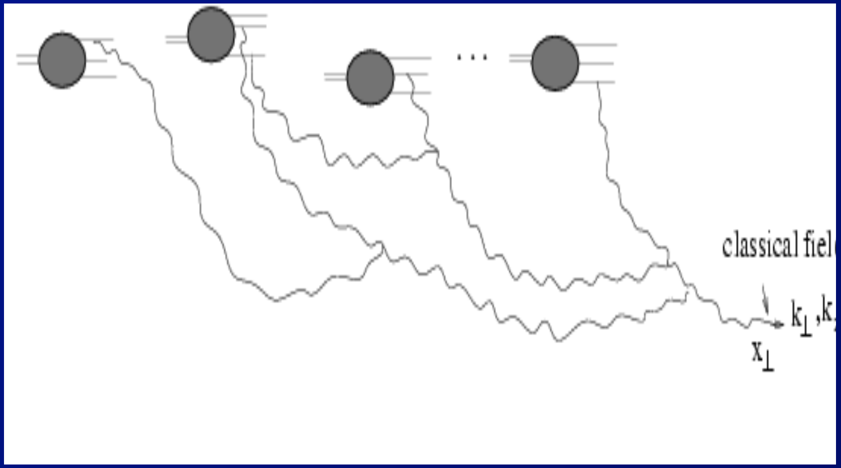
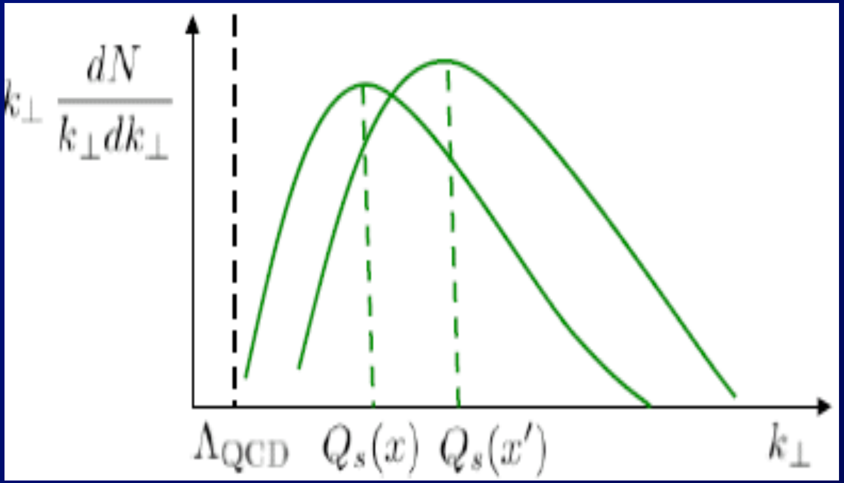
  - – Which overlap longitudinally
  - – And recombine
  - – Broadening k_T distribution
    - ⇒Generates a new scale: Q_s





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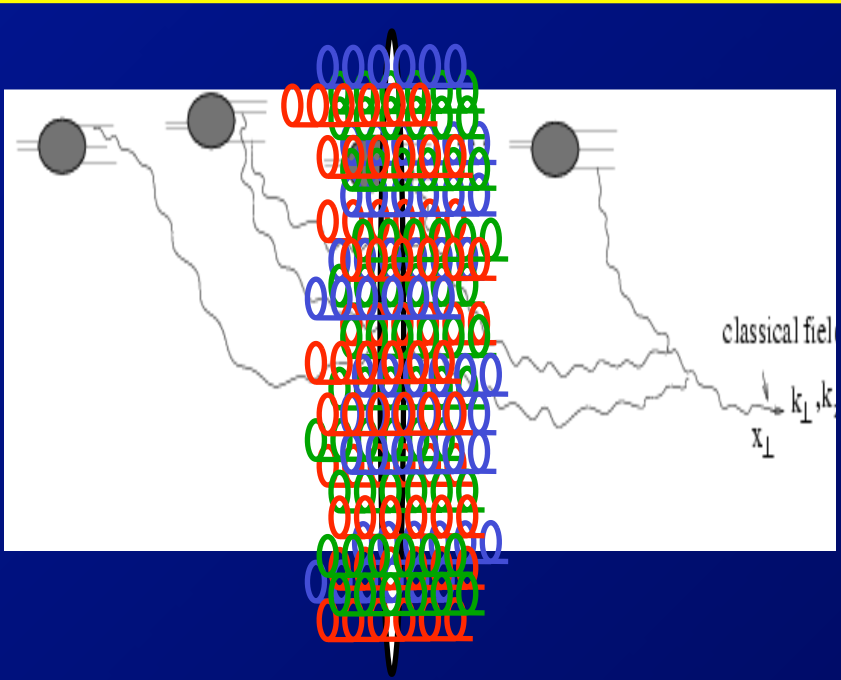
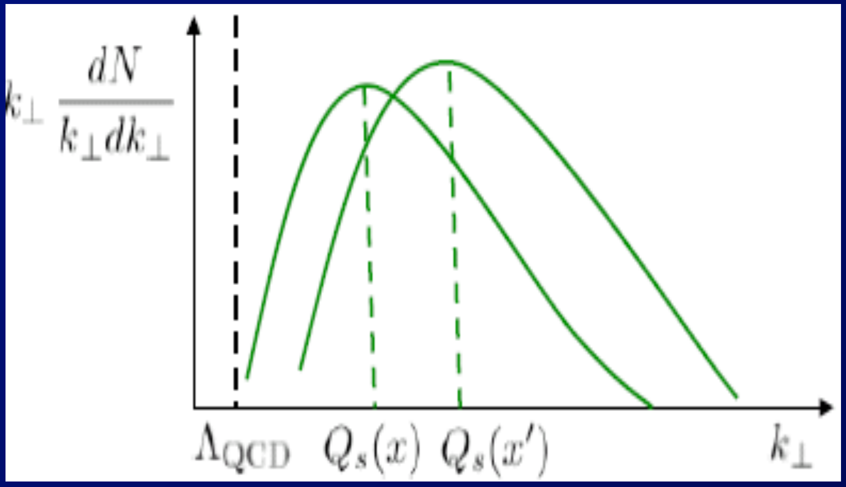


- Naively, for $Q_s \gg \Lambda_{QCD}$, perturbative calculations

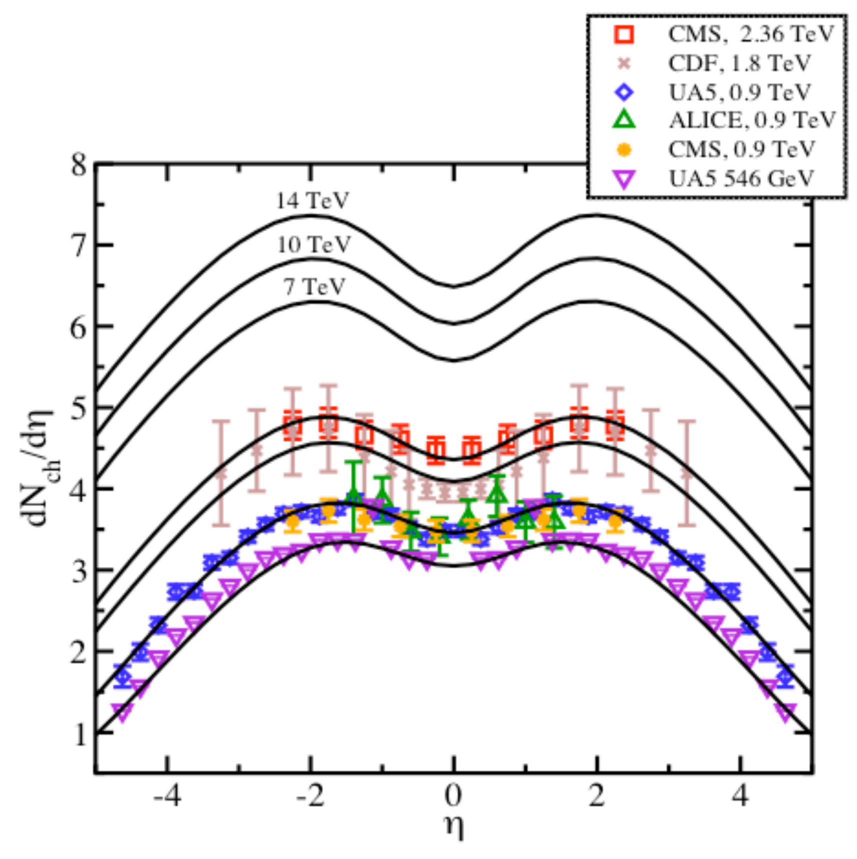
    ⇒Large occupation #s for $k_T < Q_s$ ⇒ classical fields

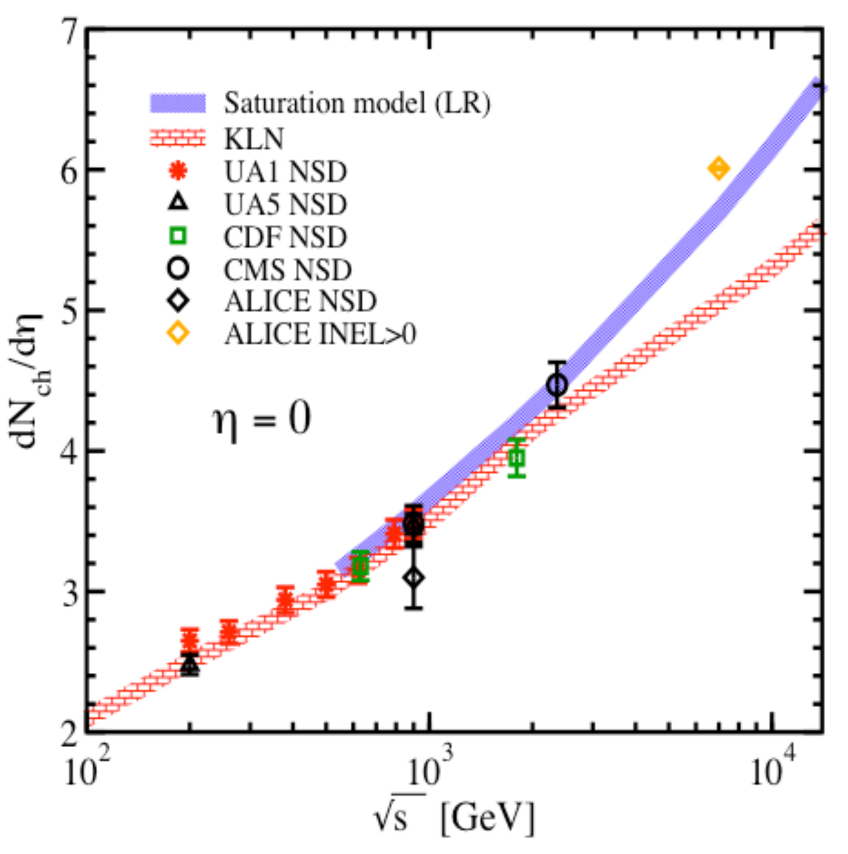
- Saturation a result of unitarity in QCD



Saturation and p-p dn/dη

Levin and Rezaeian, arXiv:1005.0631v2

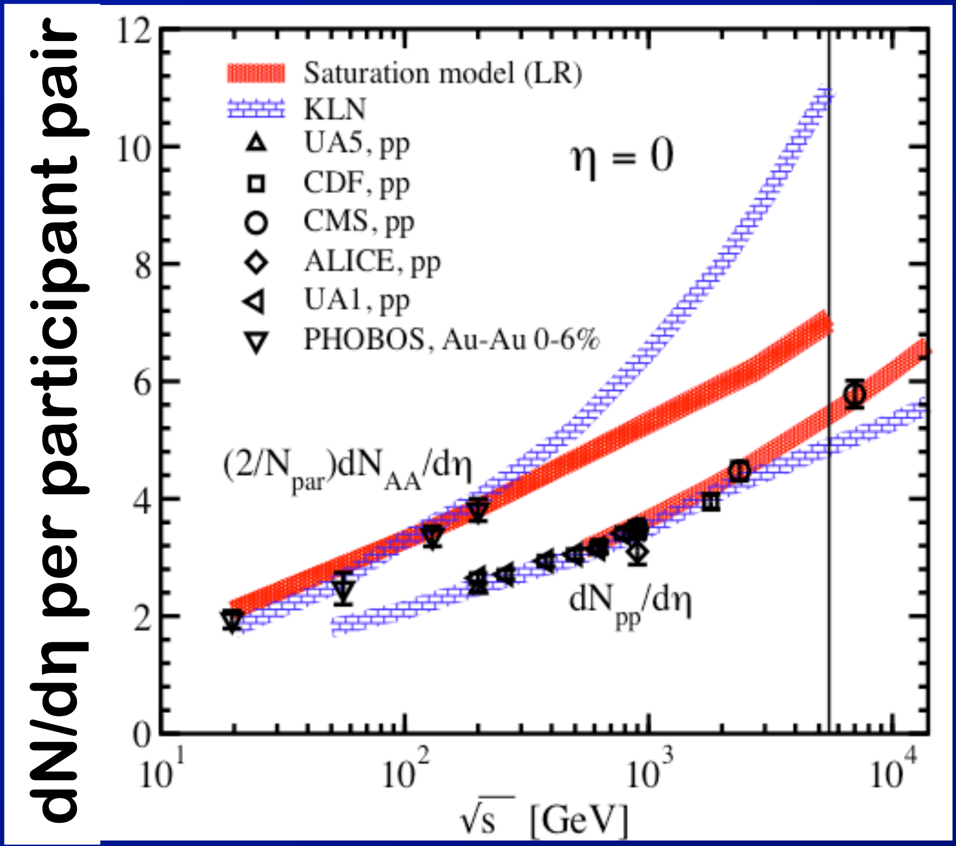


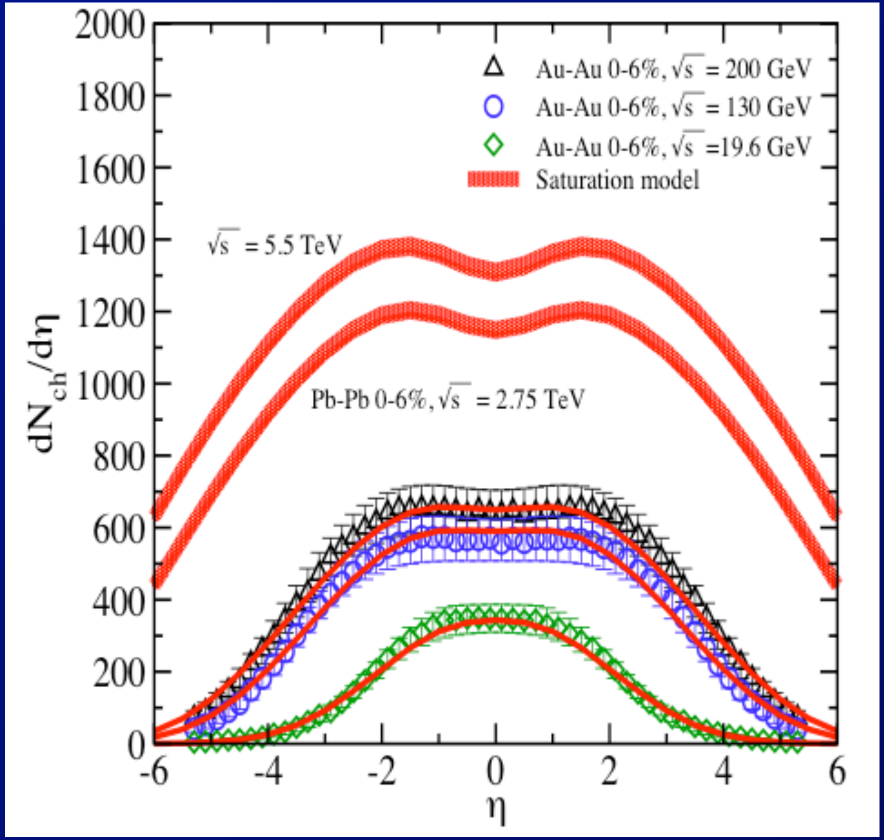


- Saturation w/ non-linear (BK) evolution ← **HERA**
  + k_T factorization
  + local parton-hadron duality ← **UA5 p+p @546 GeV**

“Hot off the Press”

Levin and Rezaeian, arXiv:1007.2430v2





- p-p prediction at 7 TeV confirmed by CMS
- p-p → A+A evolution of Q_s fixed using RHIC Au+Au 0-6% central @ 200 GeV
  - No other free parameters

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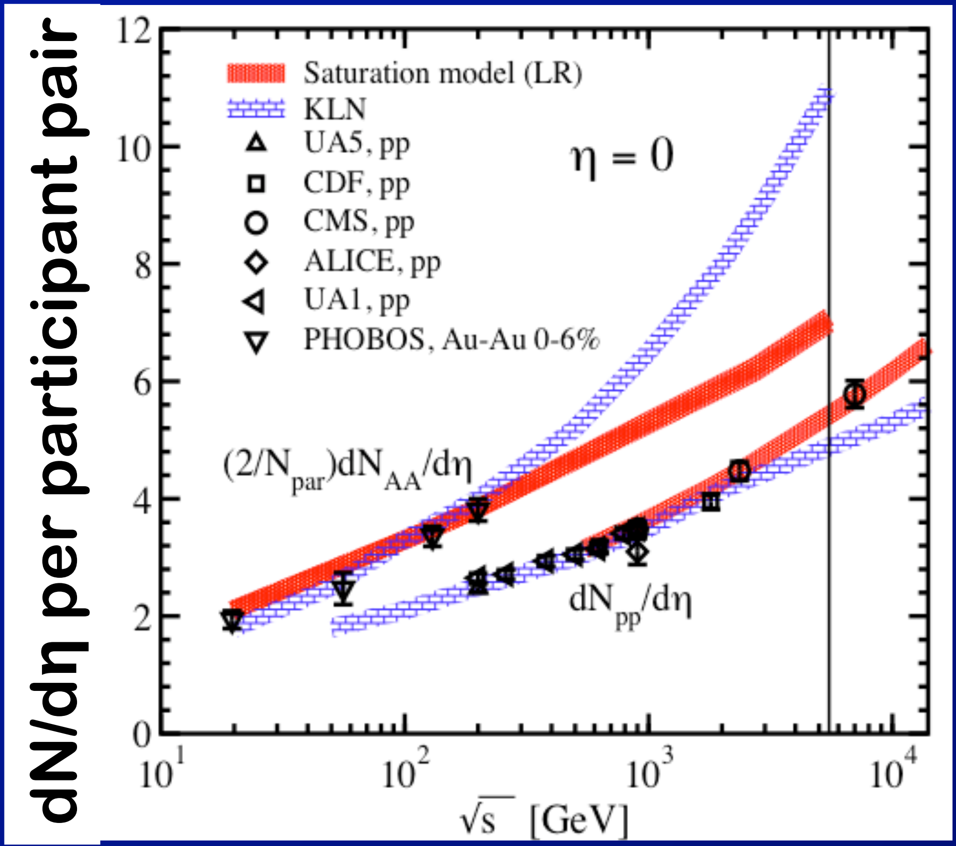

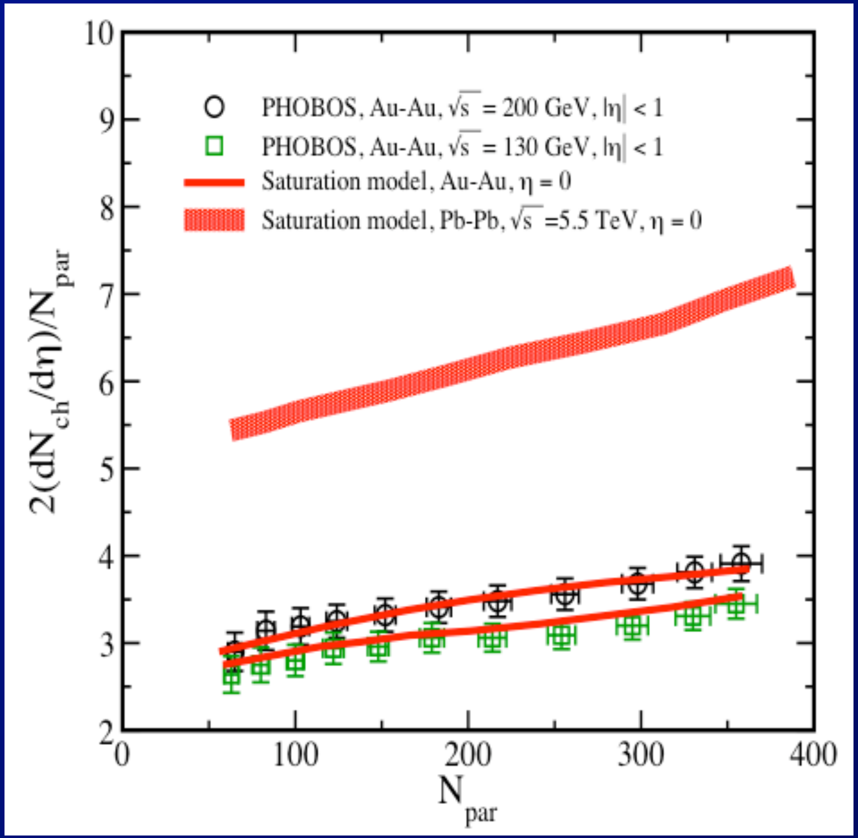

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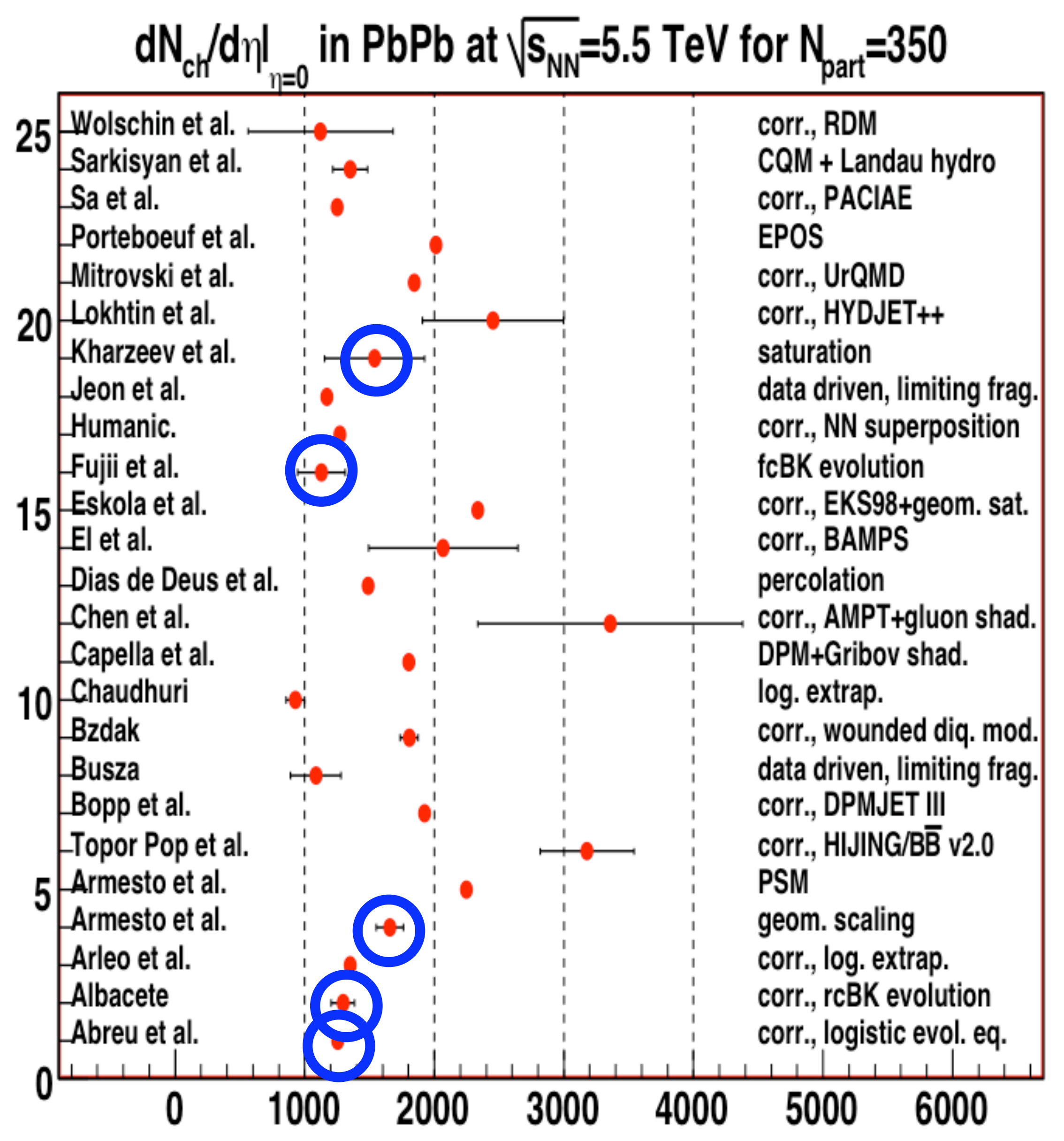
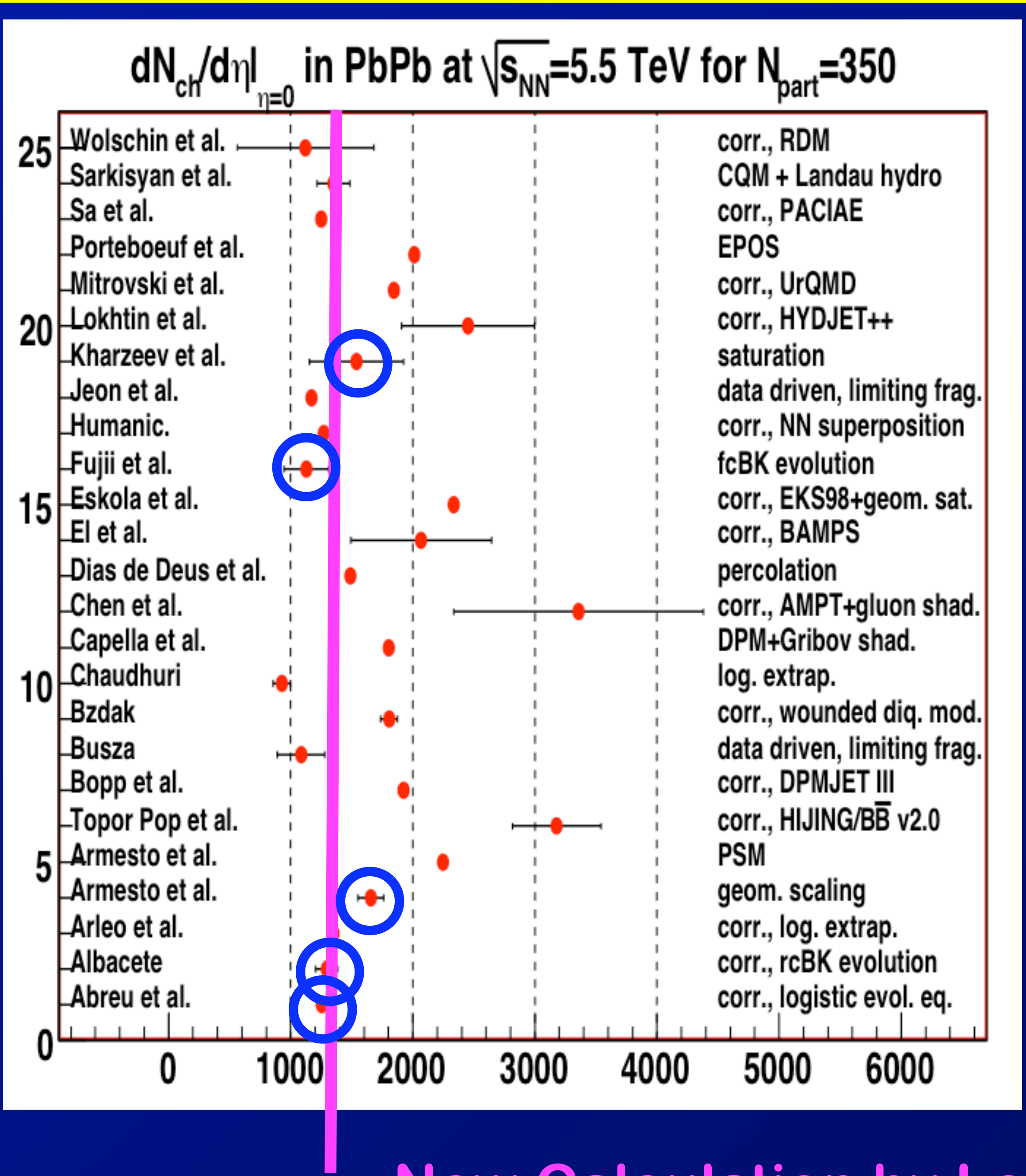
LHC dN/dη Predictions



- Many different predictions for LHC Pb+Pb central dN/dη
  - @ 5.5 TeV
- Saturation (motivated) predictions at low end of range
  - 1200-1600

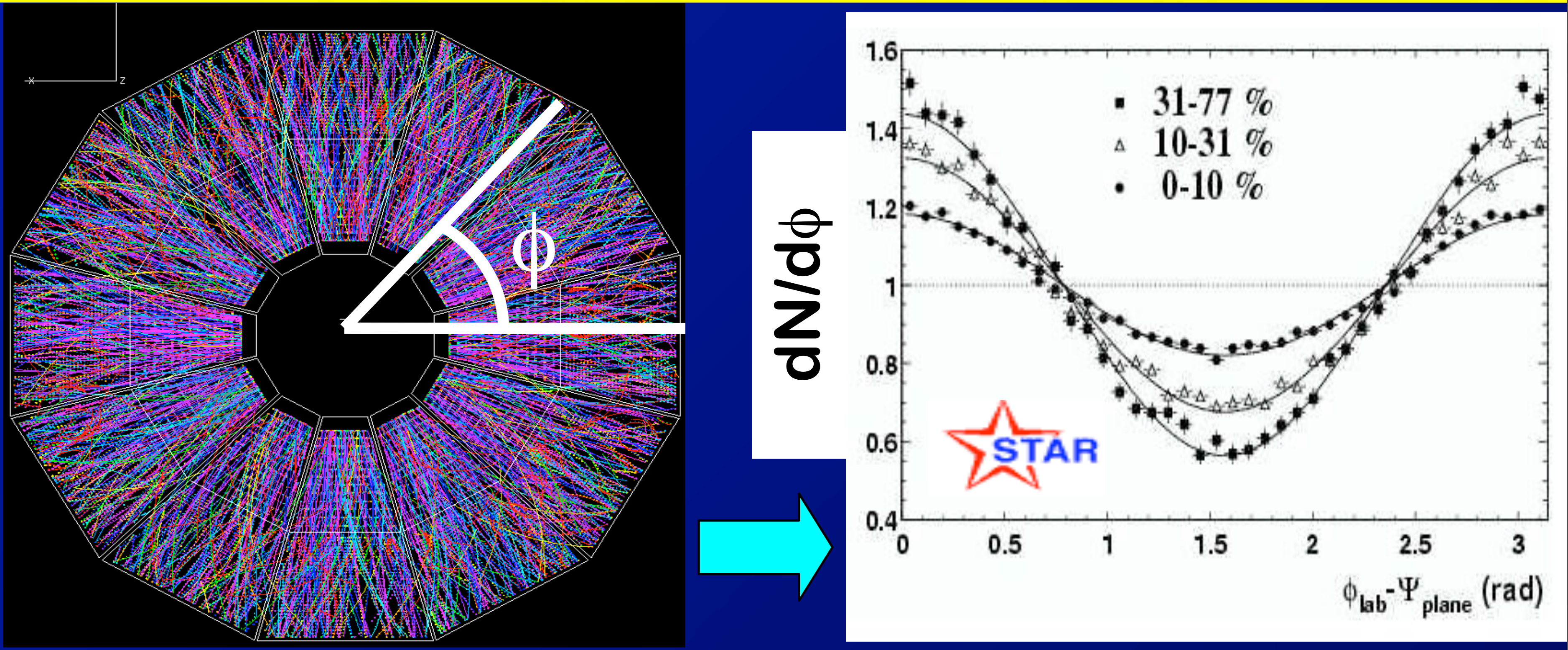
LHC dN/dη Predictions



New Calculation by Levin

- “Day-1” measurements @ LHC will provide crucial insight on mechanism for initial particle production in A+A collisions
  - Applicable to both RHIC and the LHC

Collective Motion: Elliptic Flow



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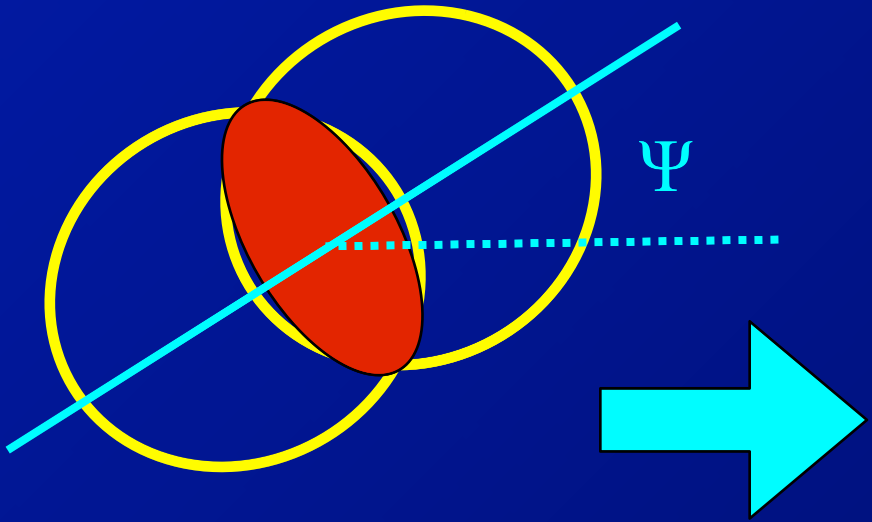
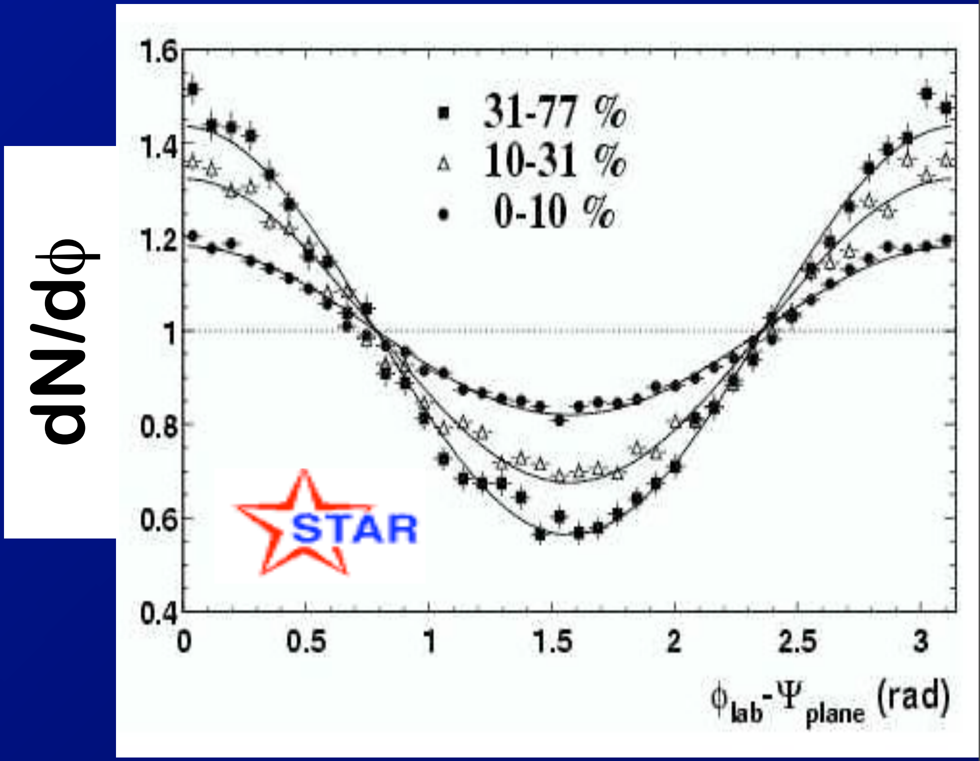
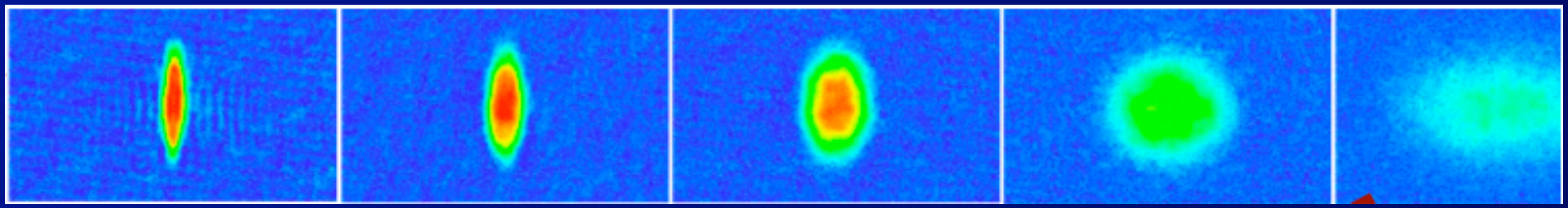


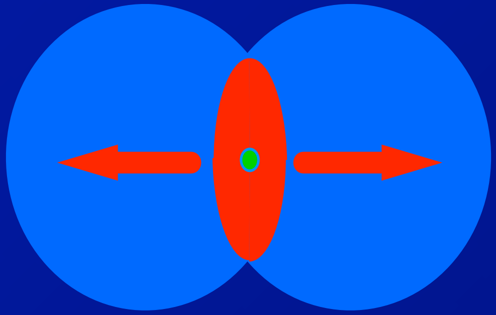




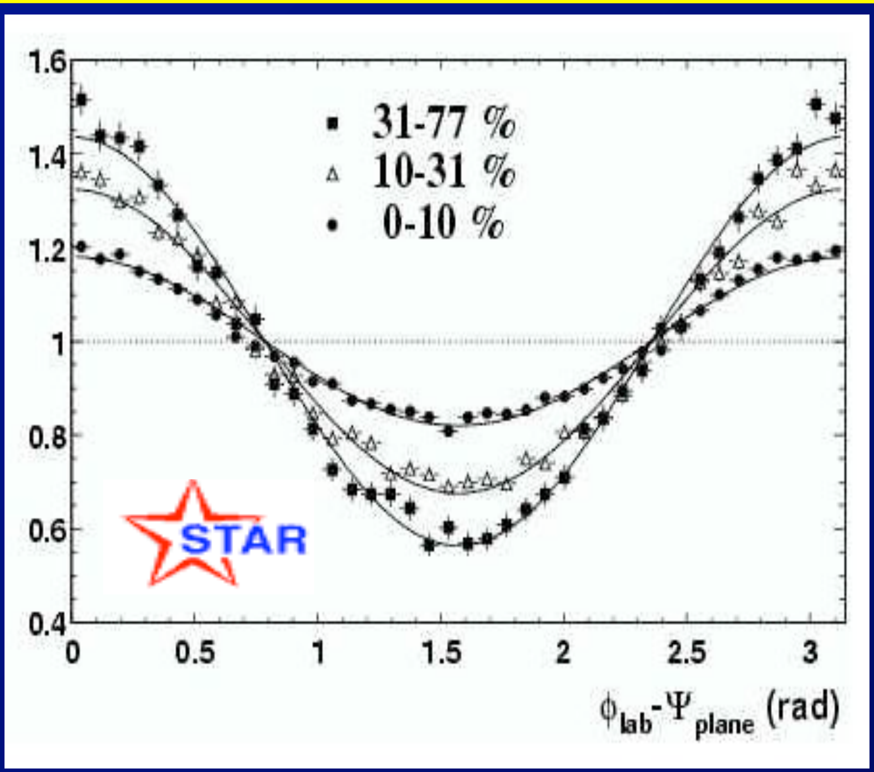
- Pressure converts spatial anisotropy to momentum anisotropy.

  ⇒Picture above not cartoon! From measurements of strongly coupled cold atoms

Elliptic Flow Systematics: ~ 8 years old



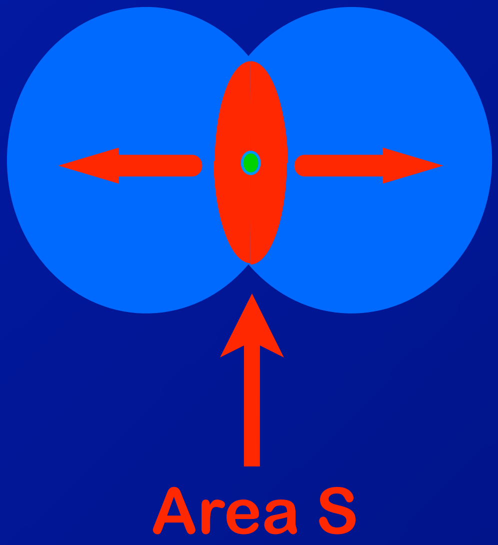
$$\varepsilon = \frac{\left\langle y^2 - x^2 \right\rangle}{\left\langle y^2 + x^2 \right\rangle}$$

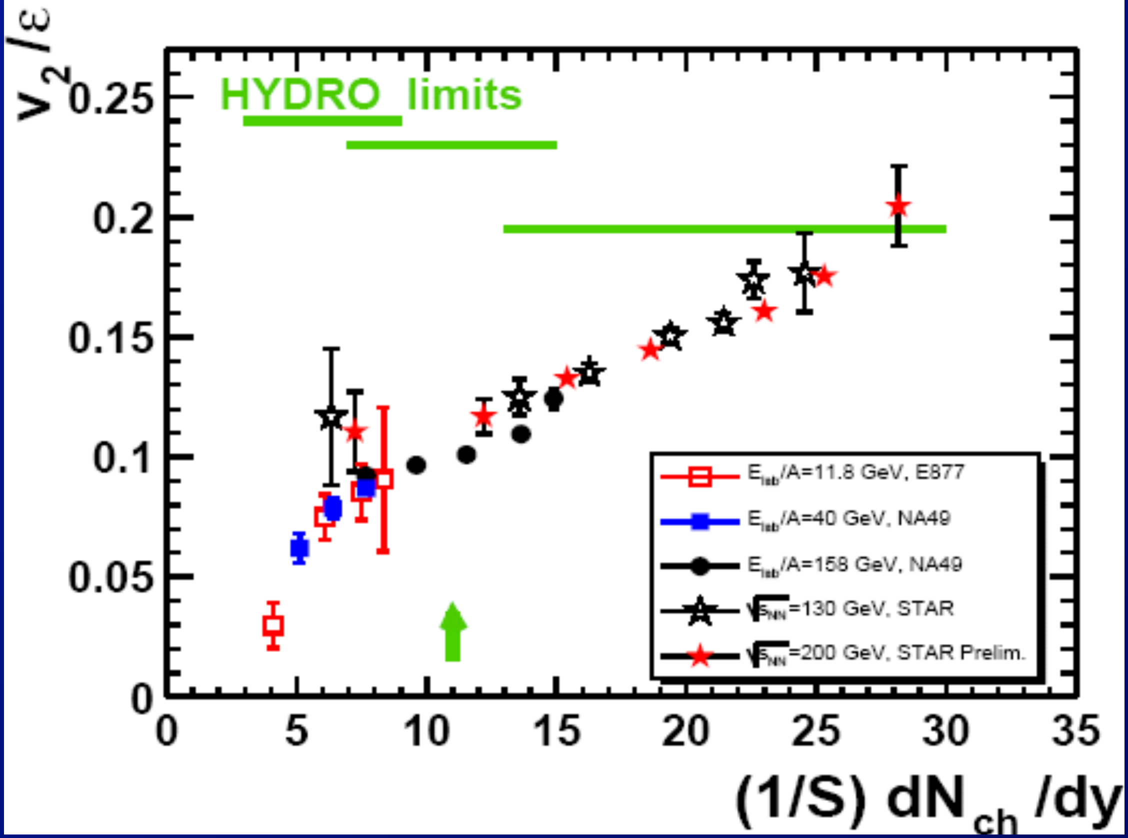


- Quantify azimuthal anisotropy by "v_2"
  - $$\frac{dN}{d\phi} \propto 1 + 2\underline{v_2}\cos(2\phi)$$

$\Rightarrow$2nd coefficient of Fourier decomposition of dN/dφ

Elliptic Flow Systematics: ~ 8 years old



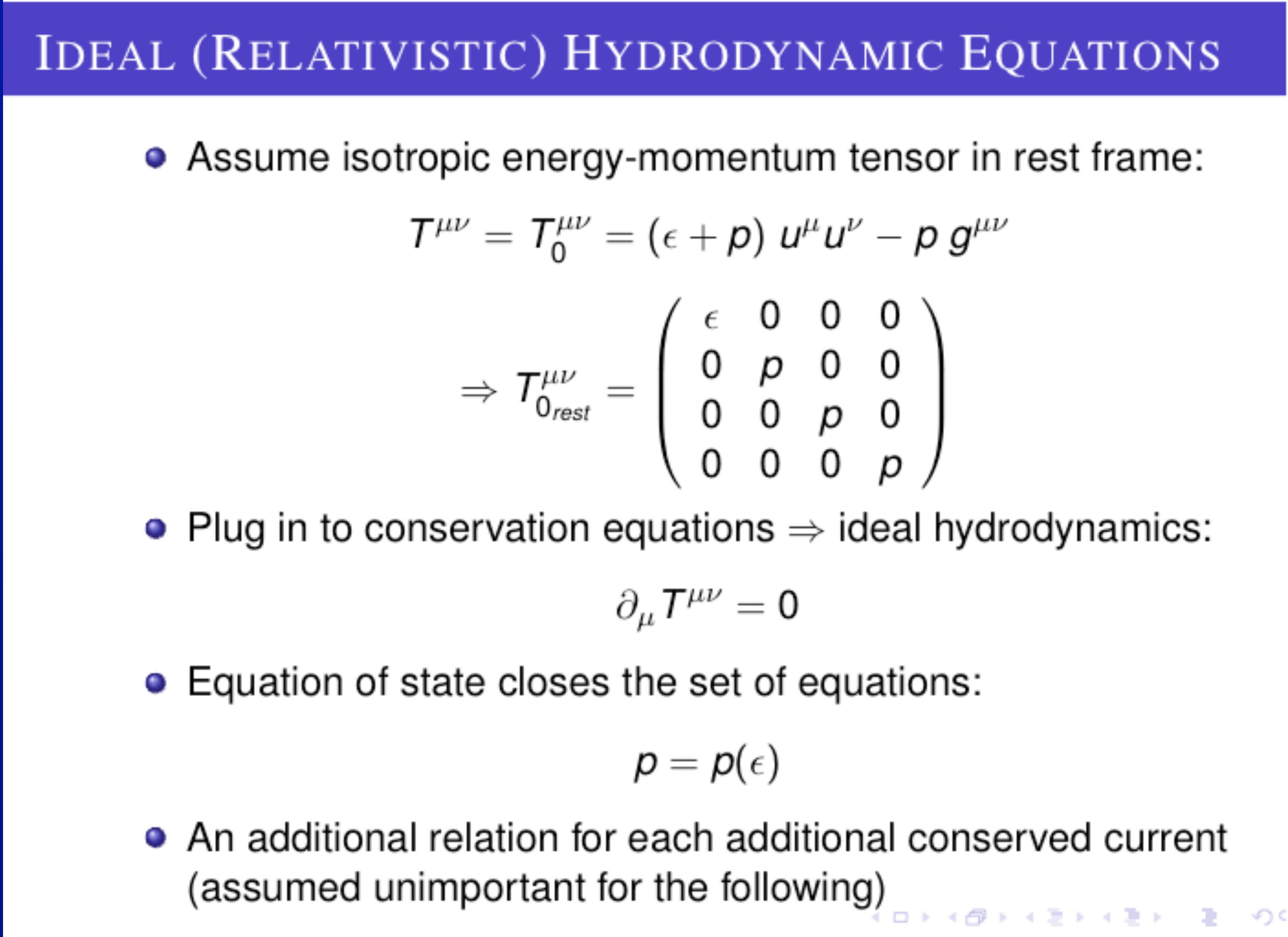


- Plot v_2/ε vs particle density / overlap area
  - Higher density ⇒ more collectivity
- Result for central collisions consistent with ideal (zero viscosity) hydrodynamics.

⇒Quark gluon plasma @ RHIC “perfect fluid”? NO!

Ideal Hydrodynamics in 1 slide

Shamelessly borrowed from nice talk by Matt Luzum



Ideal (Relativistic) Hydrodynamic Equations

- Assume isotropic energy-momentum tensor in rest frame:

$$T^{\mu\nu} = T_0^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$$

$$\Rightarrow T_{0_{rest}}^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

- Plug in to conservation equations $\Rightarrow$ ideal hydrodynamics:

$$\partial_\mu T^{\mu\nu} = 0$$

- Equation of state closes the set of equations:

$$p = p(\epsilon)$$

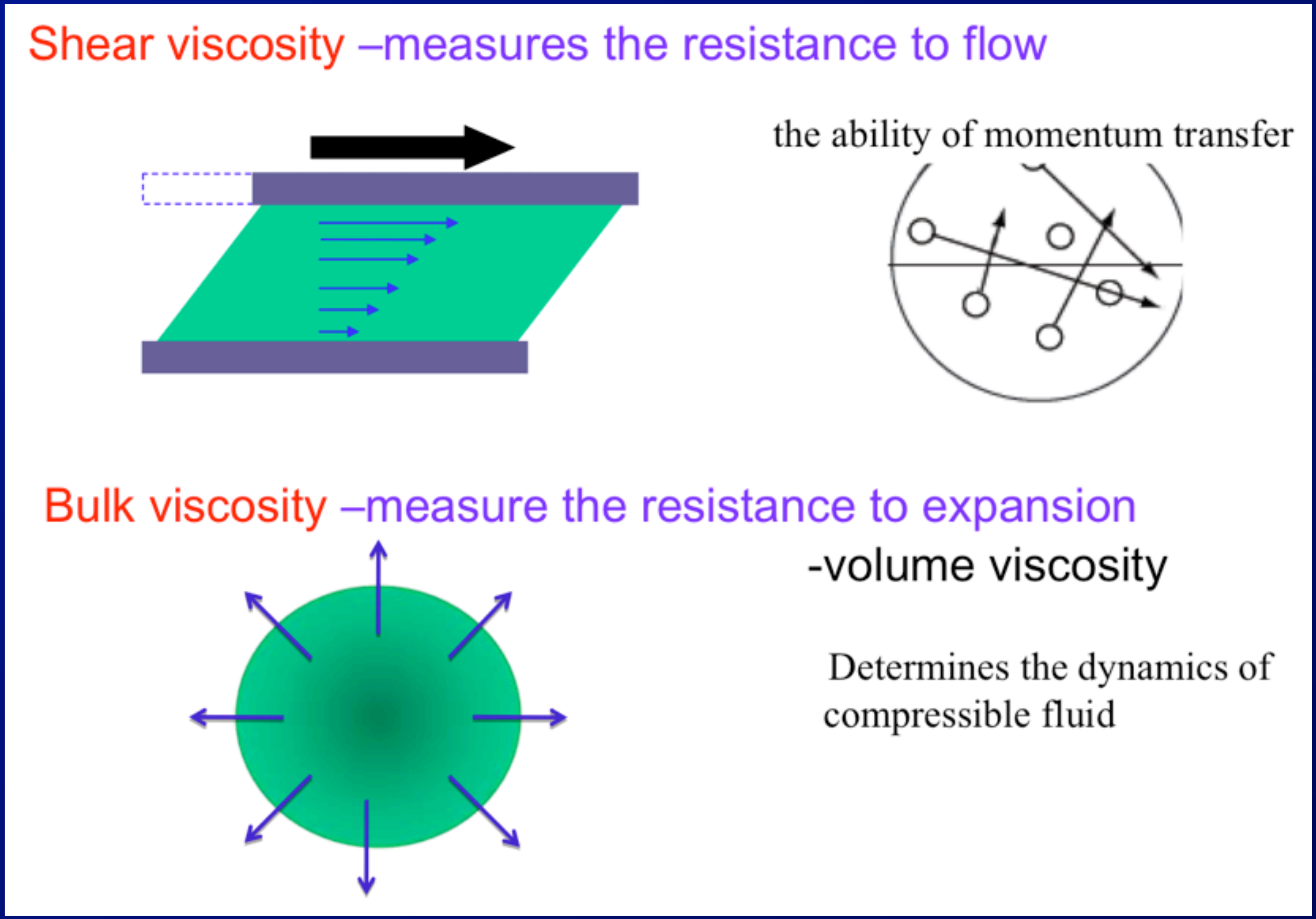
- An additional relation for each additional conserved current (assumed unimportant for the following)

Relativistic hydrodynamics w/ viscosity

- A fundamental problem in physics
  - How to solve relativistic fluid dynamics at finite viscosity.

Much progress in last two years due to RHIC application

Important insights from AdS/CFT



Shear viscosity –measures the resistance to flow

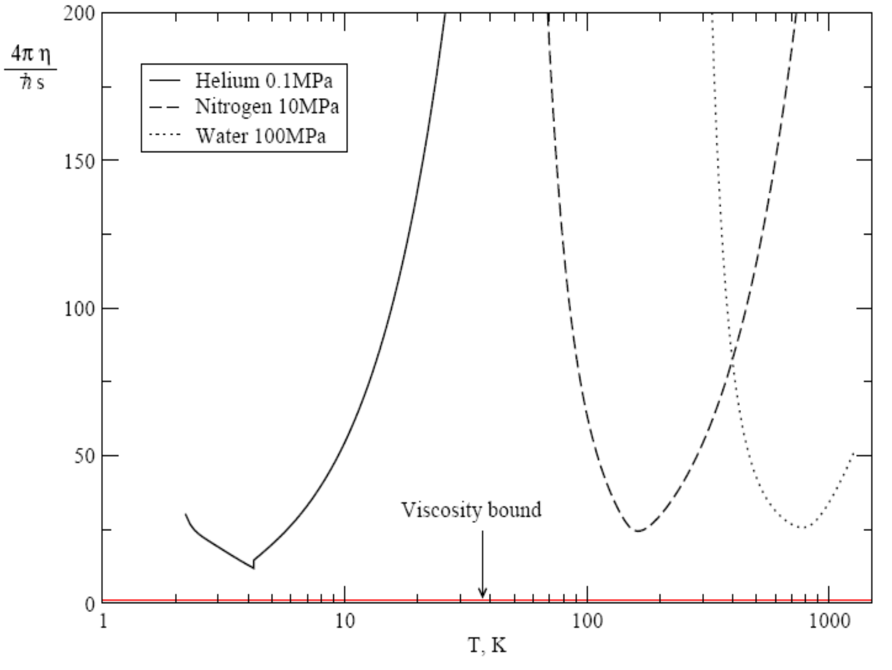
the ability of momentum transfer

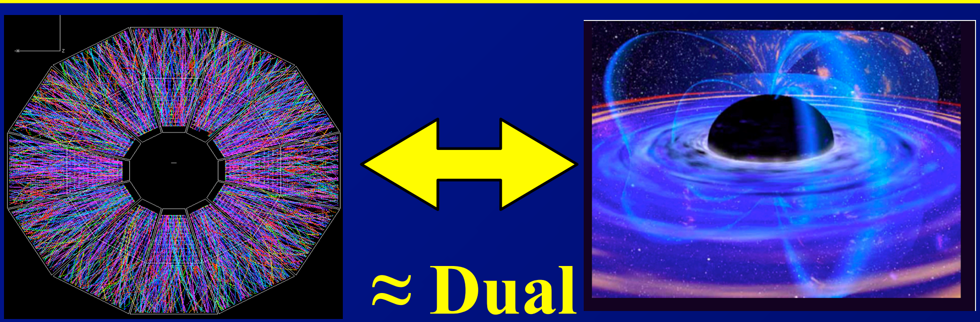
Bulk viscosity –measure the resistance to expansion

-volume viscosity

Determines the dynamics of compressible fluid

Shear Viscosity and AdS/CFT





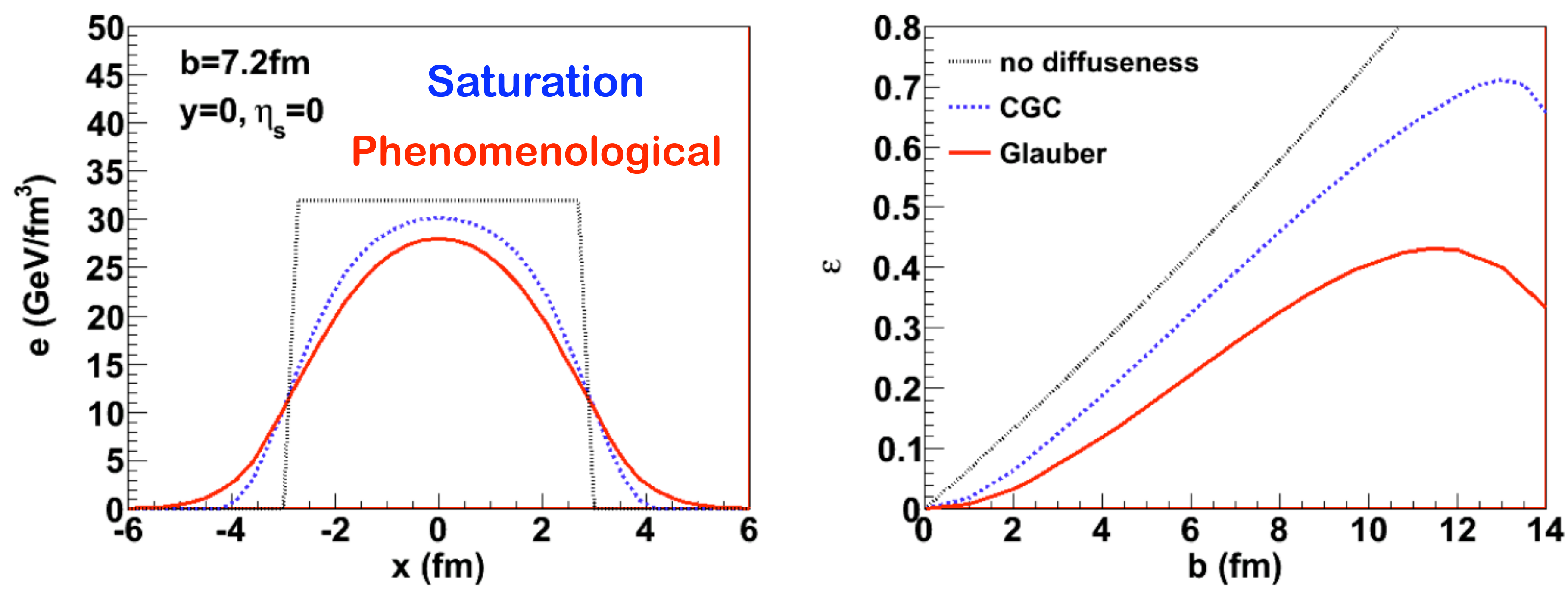
≈ Dual
???

$$\longleftarrow \quad \frac{\eta}{s} = \frac{1}{4\pi}$$

- **KSS argued that η/s has a lower bound, 1/4π.**
  - Applies for large class of conformal FT / AdS duals.
- **In strong-coupling limit, can AdS/CFT provide approximate description of some QGP physics?**
  - e.g. 5-dimensional gravity in background of black hole dual to N = 4 Super-symmetric Yang-Mills @ T >0.

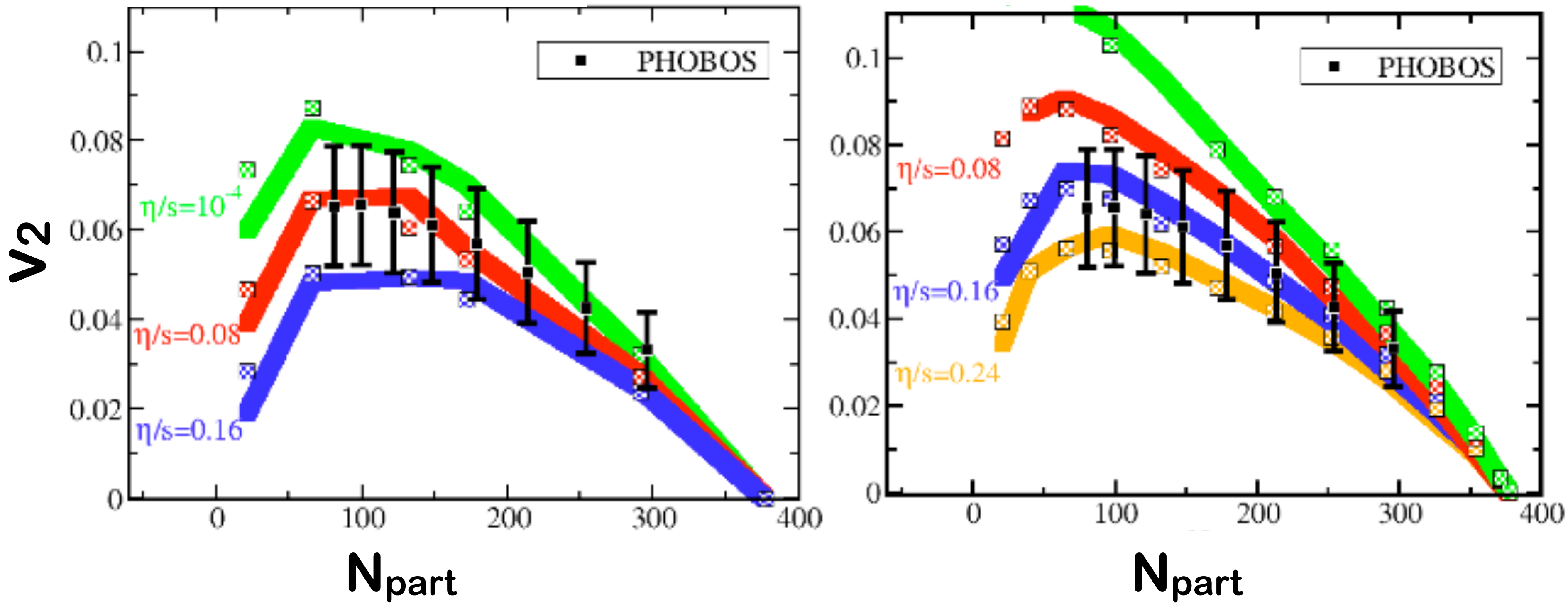
  ⇒ not QCD but close enough?

Caveat: Theoretical Uncertainty in ε



- Problem:
  - Energy density profile depends on assumption re: particle production mechanism
    - ⇒i.e. (e.g.) phenomenological vs saturation
  - Different profiles give different eccentricities
    - ⇒Irreducible uncertainty until initial-state particle production mechanism is under control

Romatschke: Quantitative evaluation of η/s

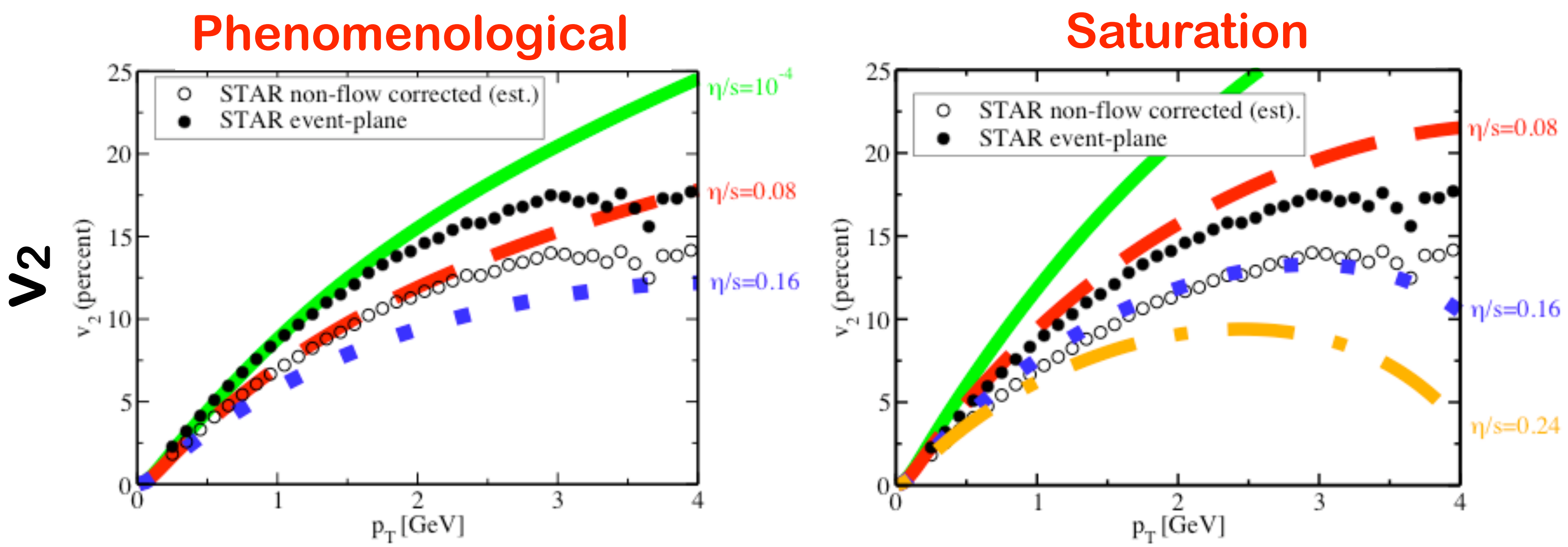


Phenomenological

Saturation

- Compare viscous hydro calculations to PHOBOS $v_2(N_{part})$
  - Phenomenological (Glauber) geometry prefers
    $\Rightarrow$ η/s ~ 0.08 ≈ 1/4π
  - Saturation (CGC) geometry prefers
    $\Rightarrow$η/s ~ 0.16 ≈ 2/4π

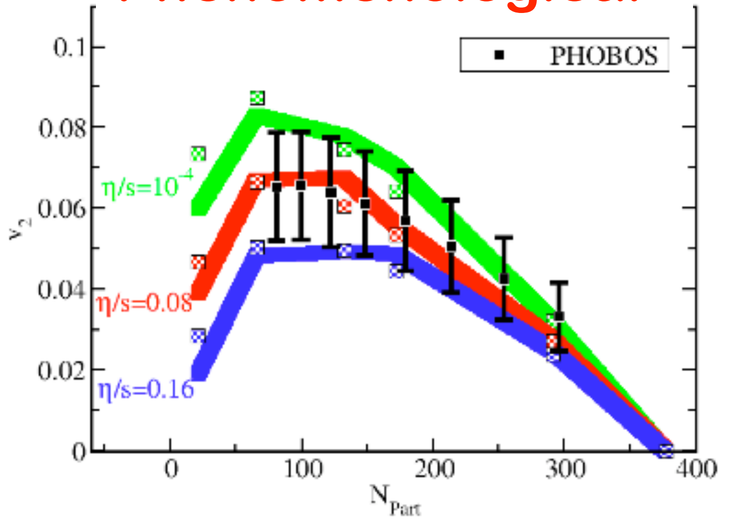
Romatschke: Quantitative evaluation of η/s



- Compare viscous hydro calculations to STAR $v_2(p_T)$ non-flow corrected
  - Phenomenological (Glauber) geometry prefers
    $\Rightarrow \eta/s \sim 0.08 \approx 1/4\pi$
  - Saturation (CGC) geometry prefers
    $\Rightarrow \eta/s \sim 0.16 \approx 2/4\pi$

Romatschke: Quantitative evaluation of η/s

Phenomenological



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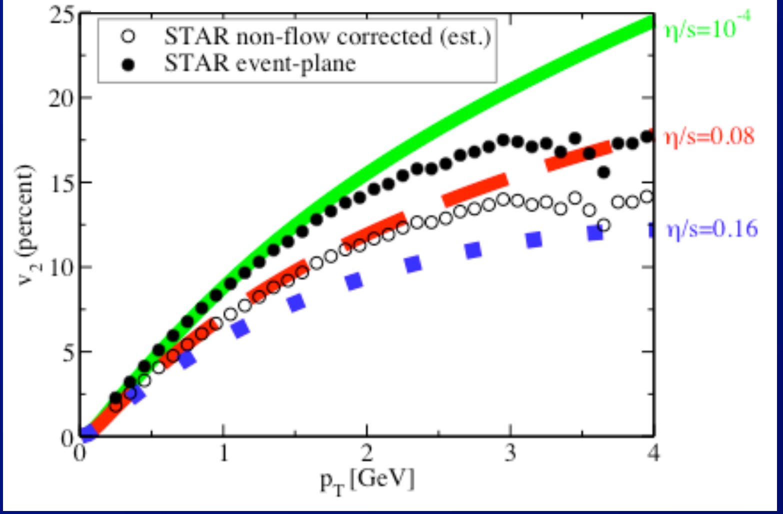
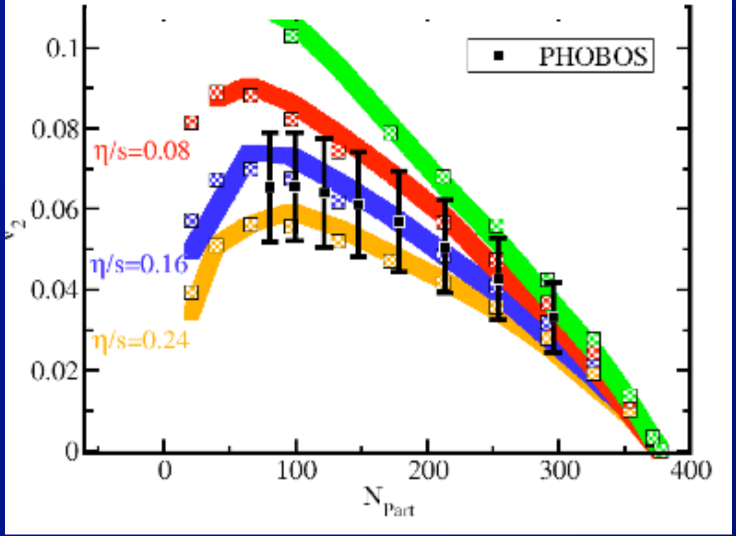
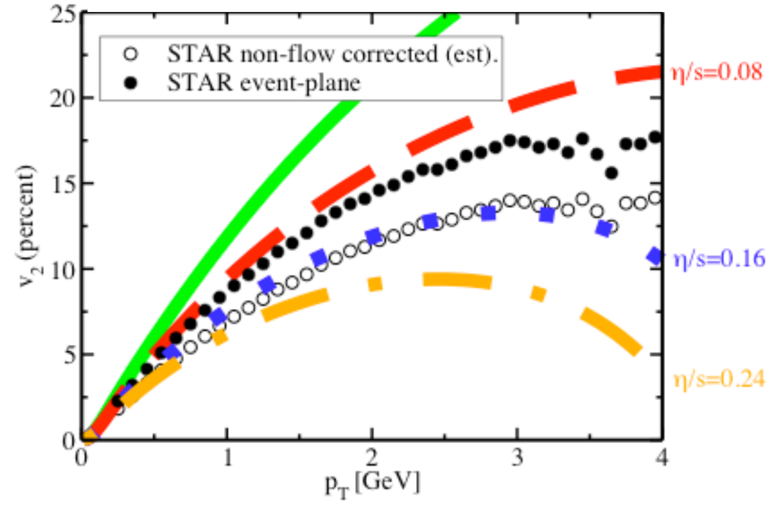


PHOBOS vs N_{part}

Saturation



Saturation

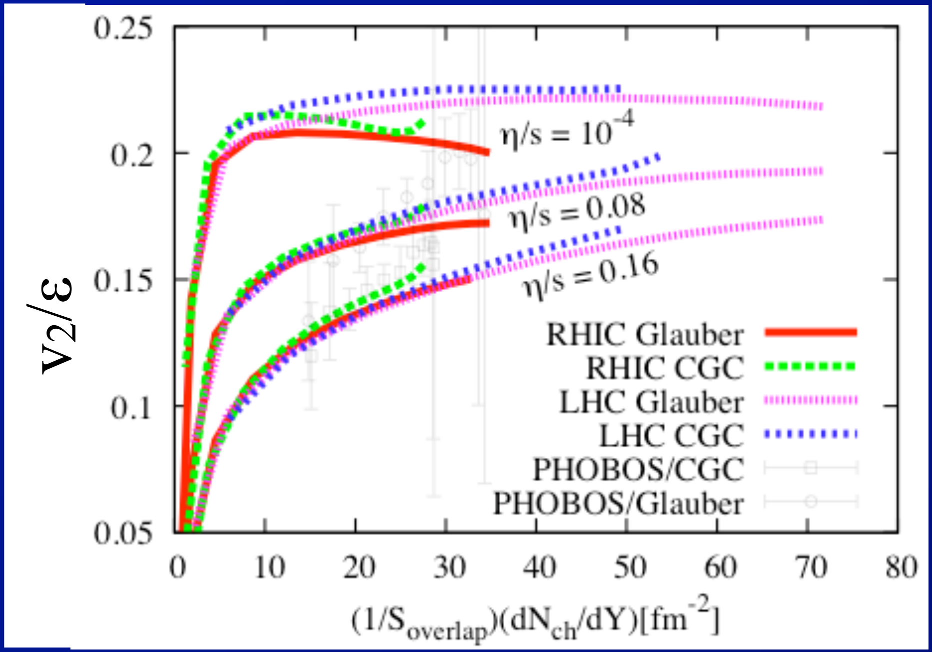


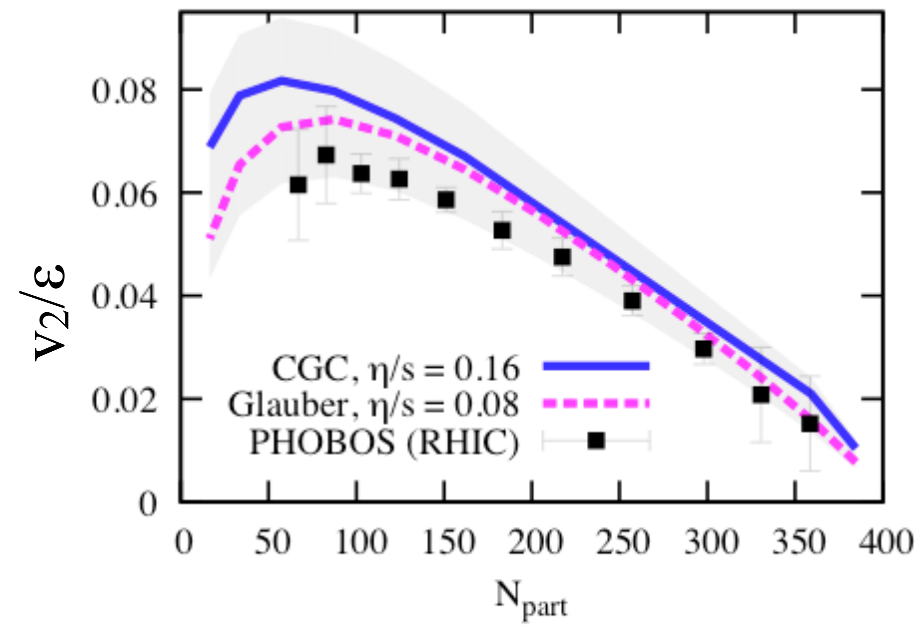
STAR vs p_T

- **Conclusion** $\frac{1}{4\pi} \leqslant \frac{\eta}{s} < 2 - 3\left(\frac{1}{4\pi}\right)$

Viscous Hydro RHIC → LHC

Luzum and Romatschke,
Phys. Rev. Lett. 103:262302, 2009





- Prediction: only modest increase in v_2/ε from RHIC to LHC due to longer evolution

  ⇒For fixed η/s!

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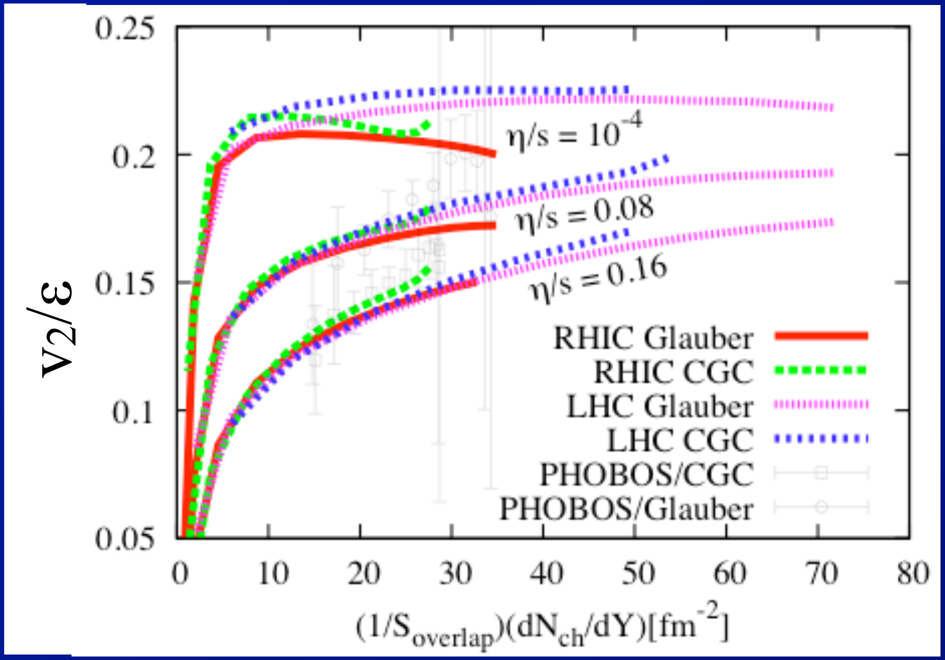
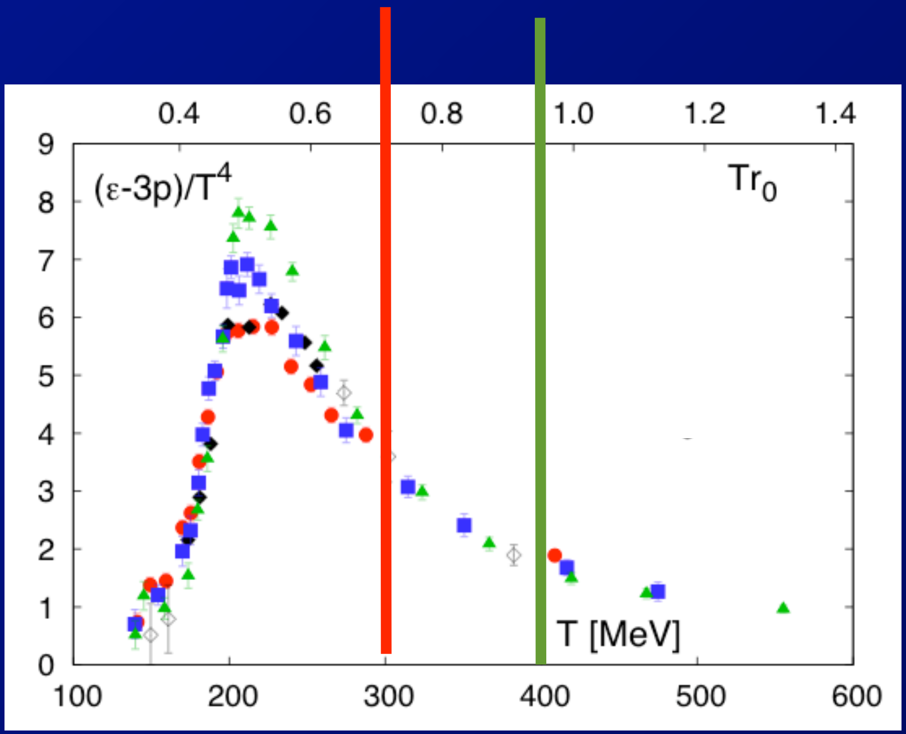


T_{RHIC} (τ =1fm) T_{LHC} (τ =1fm)



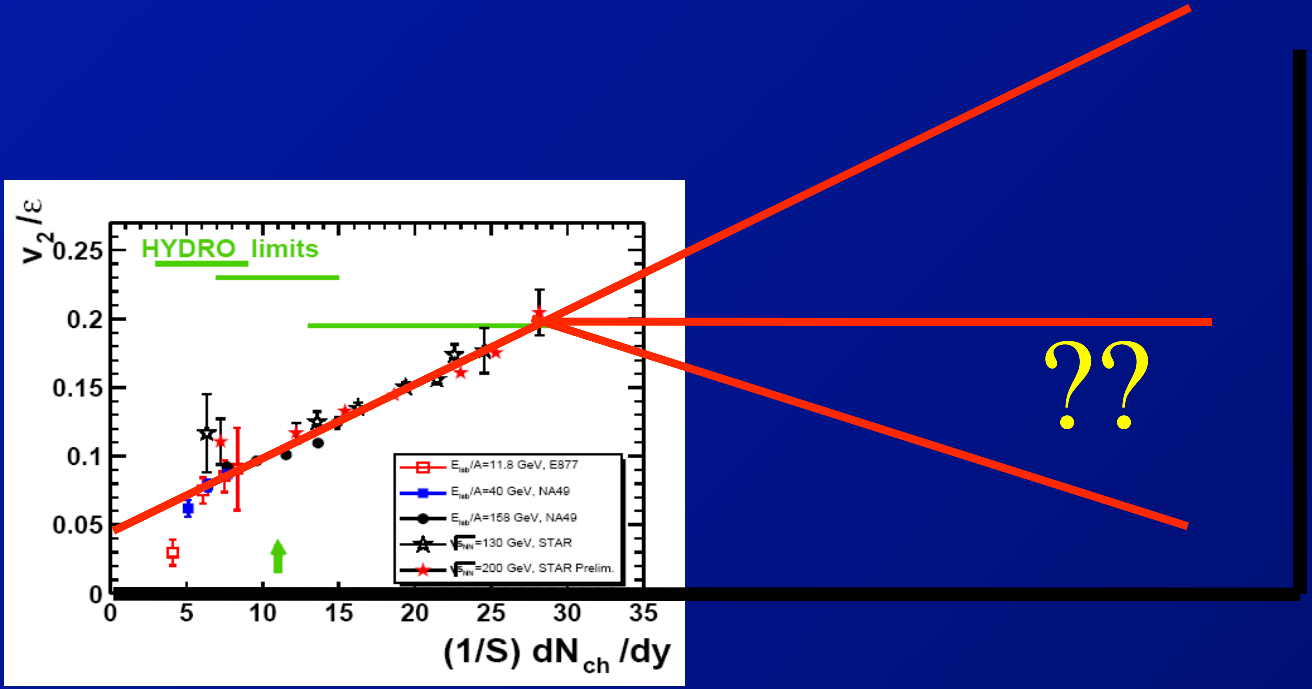
- Prediction: only modest increase in v_2/ε from RHIC to LHC due to longer evolution

    ⇒For fixed η/s!

    - But, η/s expected to decrease @ larger T

        ⇒T dependence poorly known, not in any hydrodynamic calculation (must be solved!)

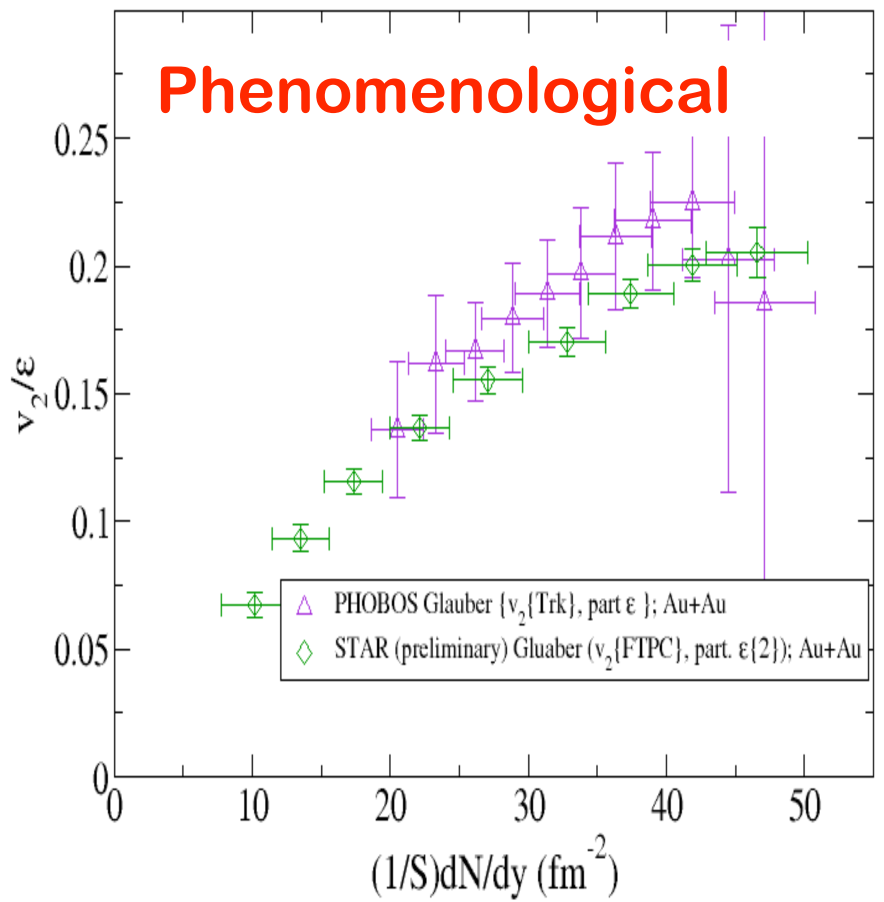
Elliptic Flow @ LHC

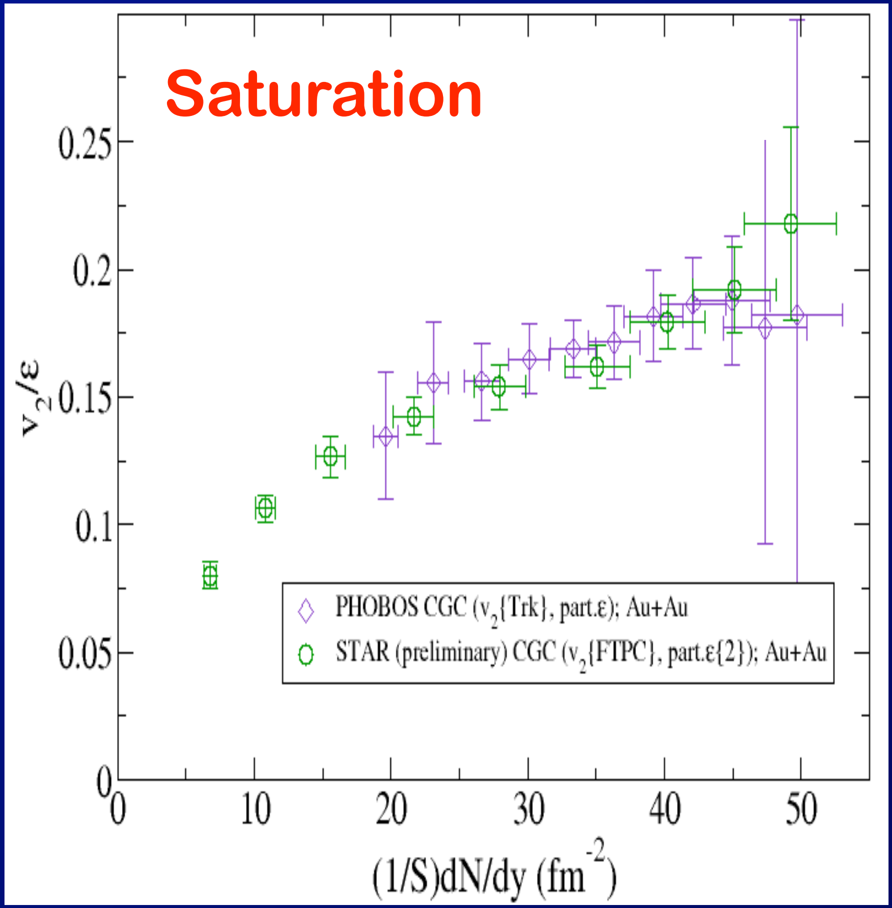


Can change horizontal scale by x2 @ LHC

- LHC data will provide an essential test of our understanding of elliptic flow data @ RHIC
  - And test whether QGP is still strongly coupled
- But RHIC measurements will continue to provide new tests
  - e.g. do thermal photons/di-leptons have flow imprint?

“Modern” V_2/ε : STAR, PHOBOS

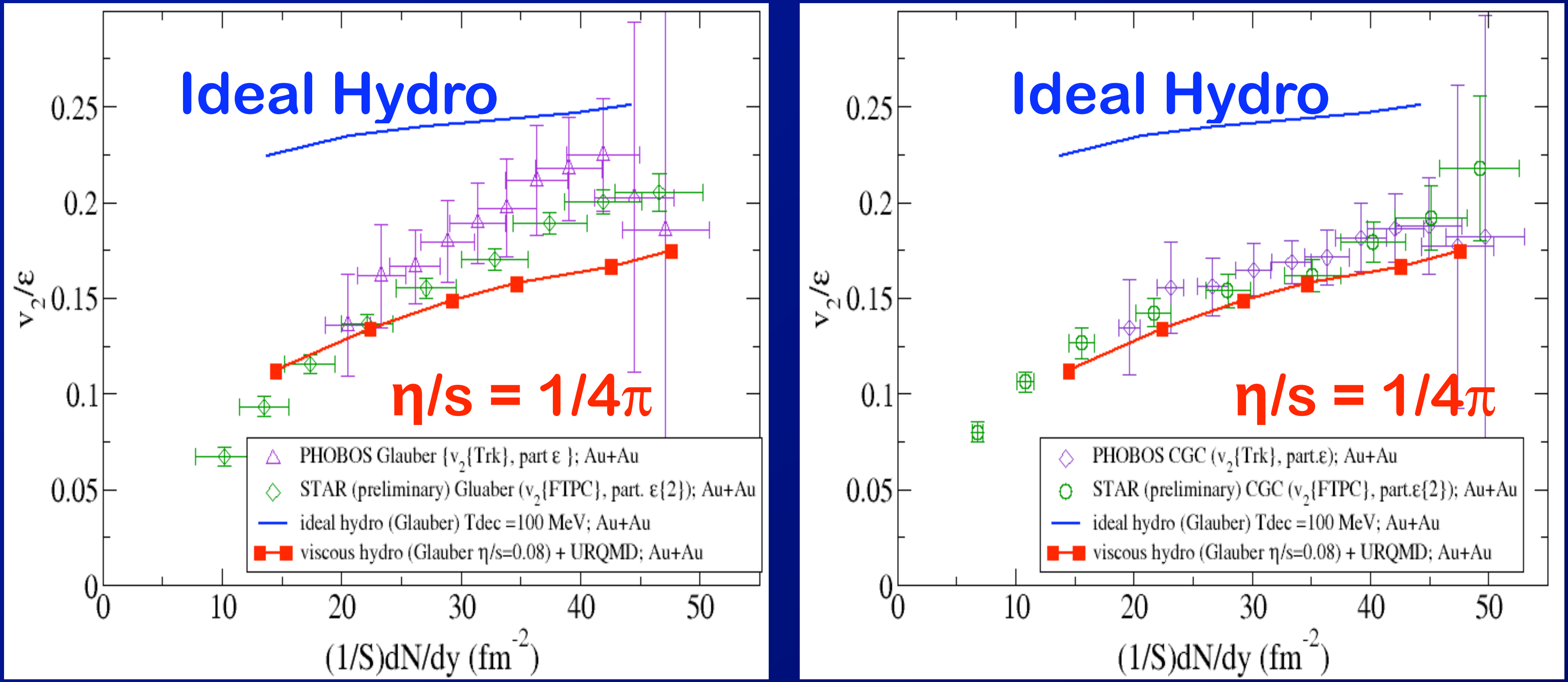




- v_2, dN/dη experimentally measured
- ε, S (transverse area) from collision geometry
  - Glauber - “phenomenological” particle production
  - CGC - Saturation (KLN)

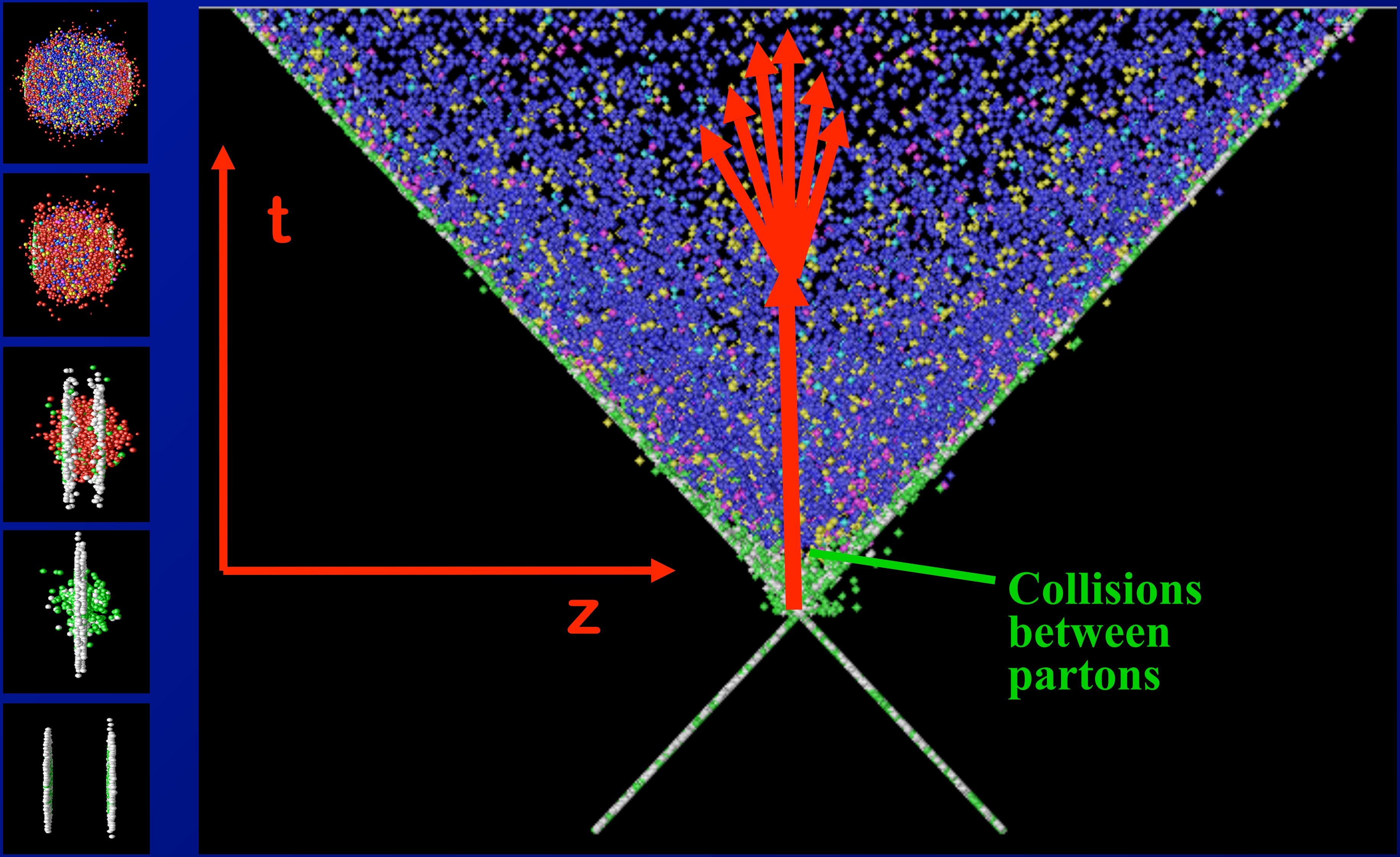
Viscous Hydro + Hadronic Transport

Heinz and Song, INT Workshop “Quantifying the Properties of Hot QCD Matter” http://www.int.washington.edu/PROGRAMS/10-2a/



- Most complete hydrodynamic calculation yet
  - – Viscous hydrodynamics + hadronic transport
  - – With Lattice QCD + hadron resonance gas EOS
    - ⇒“minimum” viscosity
    - ⇒ Preference for saturation initial conditions (?)

Penetrating Probes of Created Matter

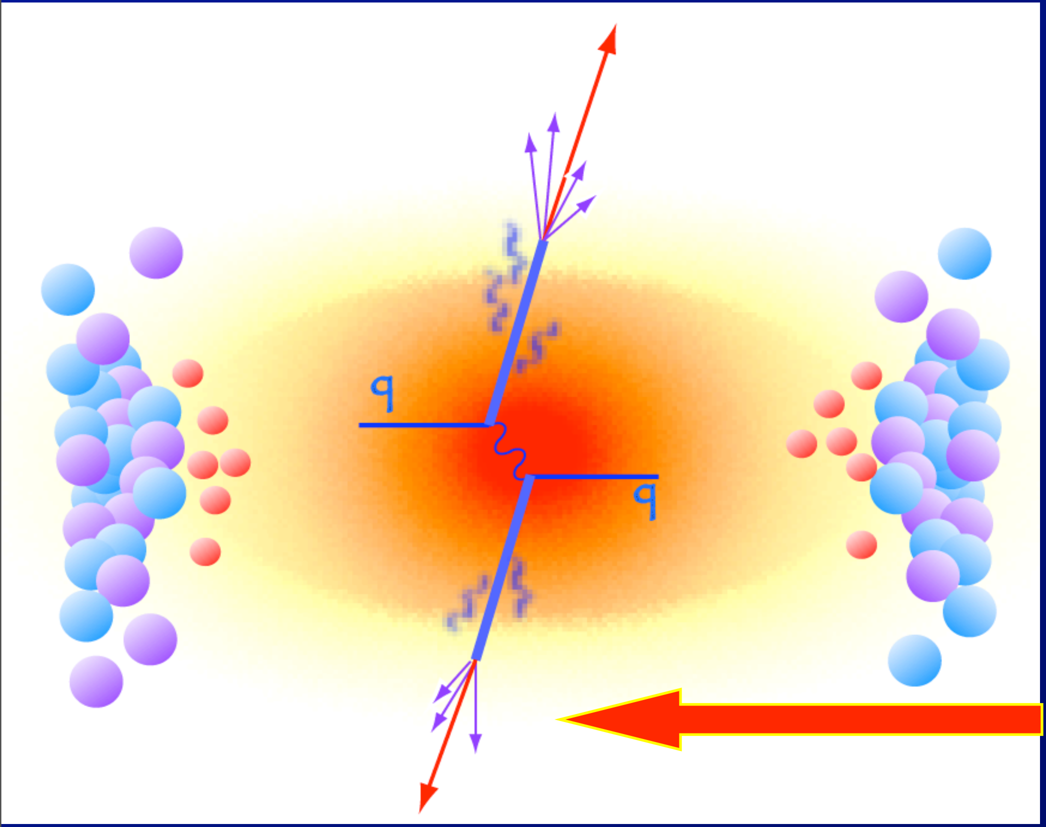


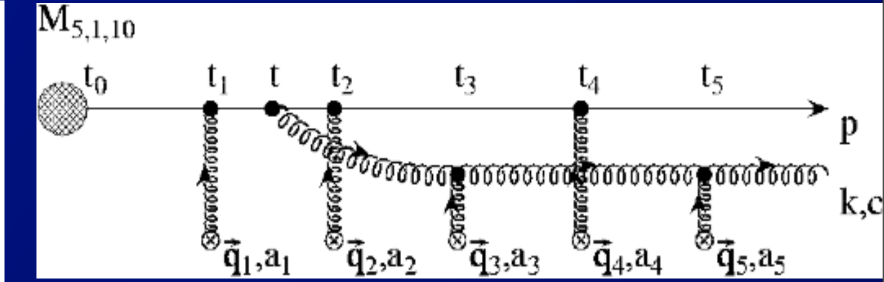
- Use self-generated hard quarks/gluons/photons as probes of initial (early) medium properties

“Jet Quenching” @ RHIC

- (QCD) Energy loss of (color) charged particle
  - Dominated by medium-induced gluon radiation (?)
  - Strong coherence effects for high-p_T jets

⇒Virtual gluons of high-p_T parton multiple scatter in the medium and are emitted as real radiation





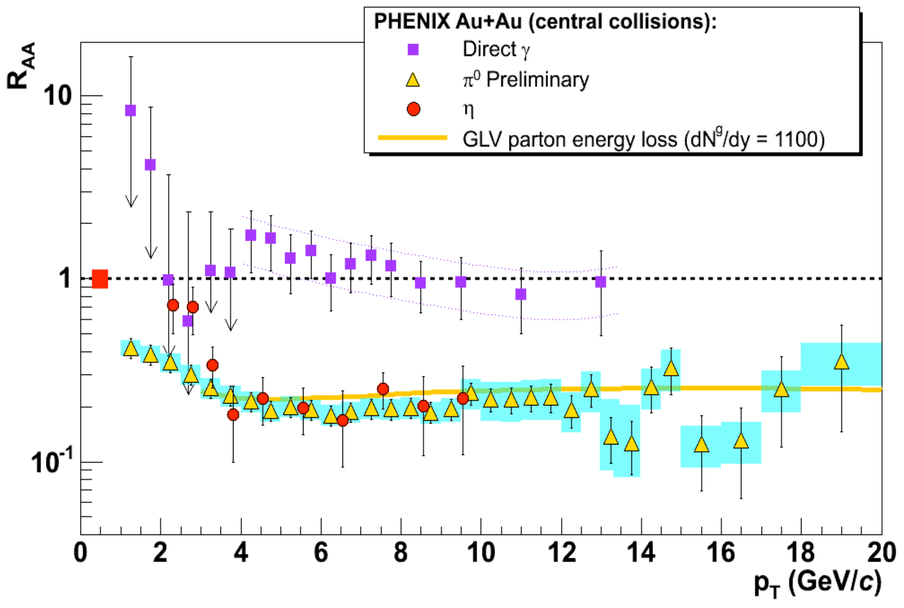
$$\hat{q} = \langle k_T^2 \rangle / L$$

@RHIC measure using:

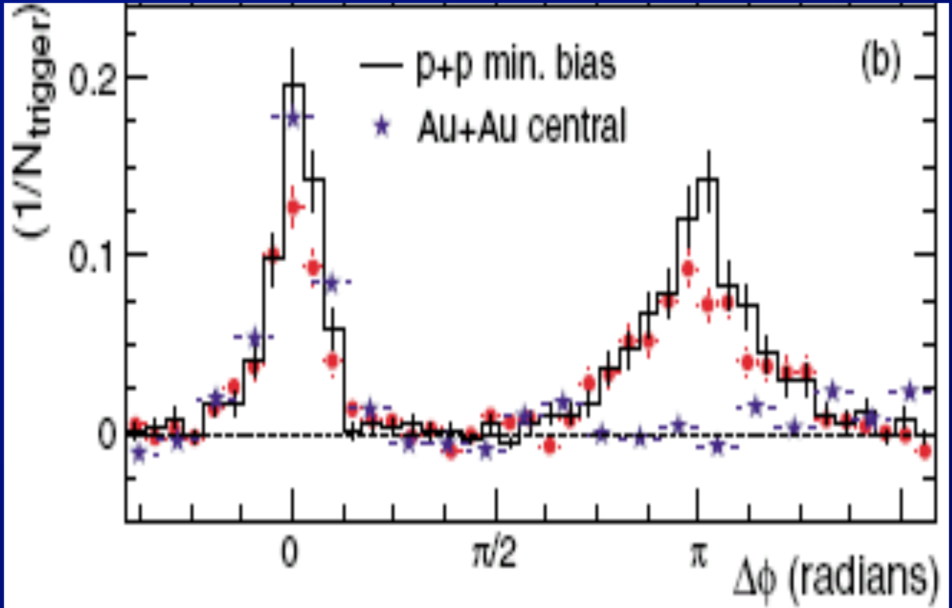
- ➢High-$p_\perp$ single hadrons
- ➢Di-hadron correlations

“Jet” Quenching at RHIC

Single hadron but not γ suppression



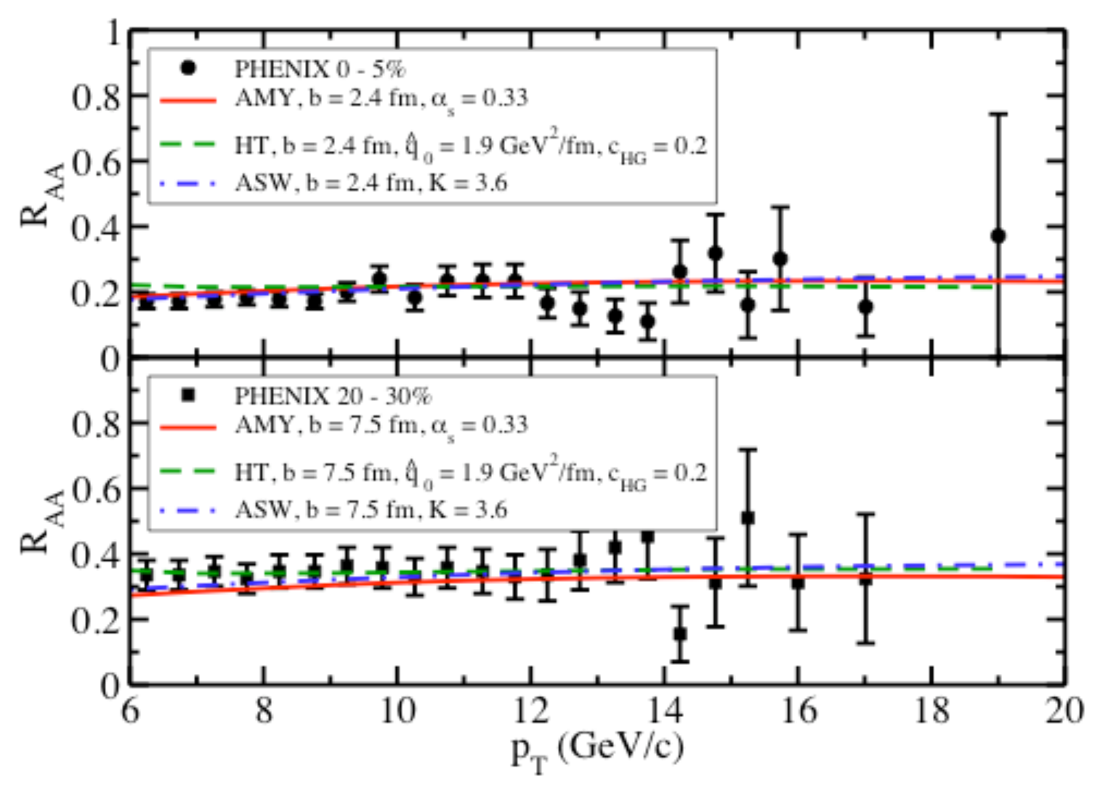
di-jet disappearance via di-hadron Δϕ correlations



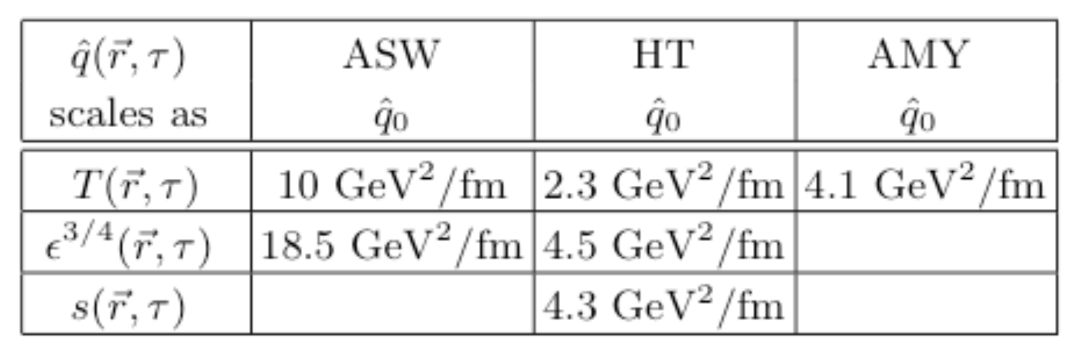
- RHIC results have clearly established “jet quenching” as an experimental fact
  - By using single hadrons or di-hadrons (?)
  - Where are the jets?
    - ⇒Hard @ RHIC due to soft background.

Quenching: Quantitative Difficulties

- Compare different dE/dx calculations to PHENIX π^0 data.
  - Different approximation schemes
- Result: factor of 4 variation in $\hat{q}$
  - Approximations clearly not yet under control
    - ⇒Data currently cannot not help discriminate



Extracted transport parameter $\hat{q} = \langle k_T^2 \rangle / L$

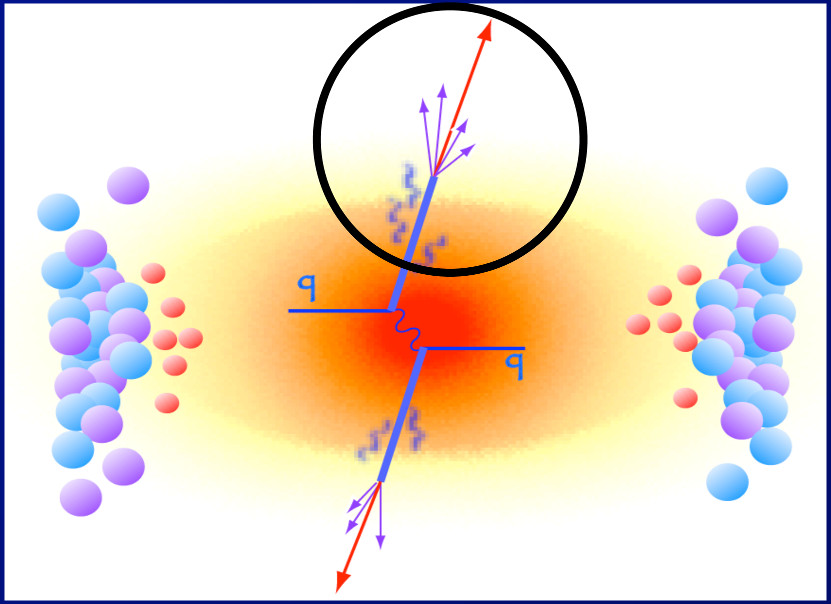


$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 GeV^2/fm	2.3 GeV^2/fm	4.1 GeV^2/fm
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 GeV^2/fm	4.5 GeV^2/fm	
$s(\vec{r},\tau)$		4.3 GeV^2/fm	

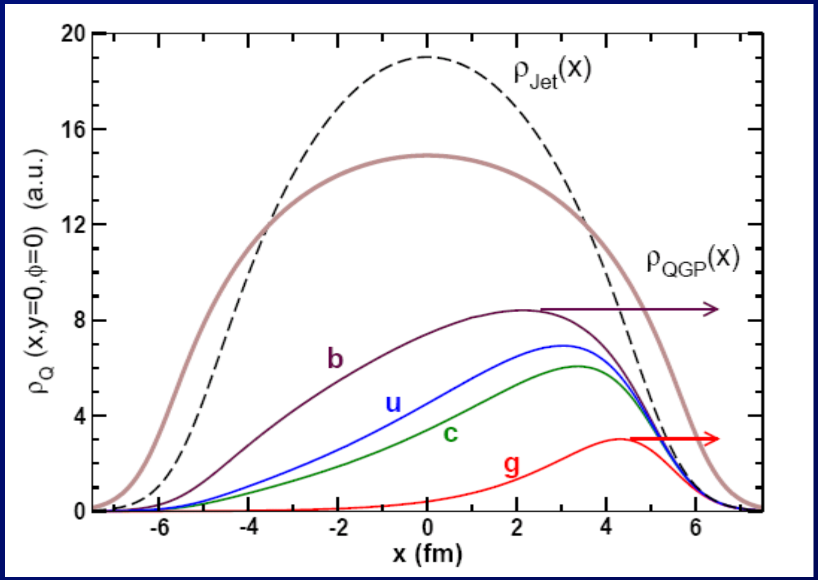
Problem with relying on hadrons

- Energy loss bias
  - Hadrons biased to jets that lose the least energy
    - ⇒ geometry
    - ⇒ radiation fluctuations
- Averaging
  - Hadron measurements average over jet energies
    - ⇒ Indirect measurement of jet quenching
- Rates
  - Suffer from steep fragmentation function

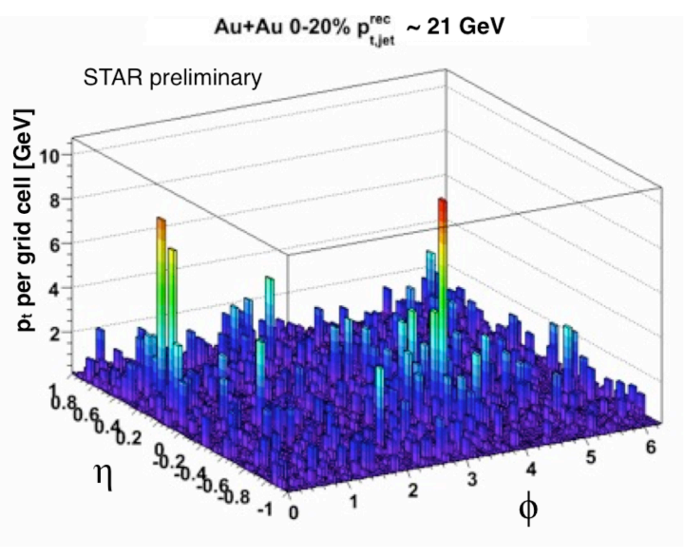
⇒ Use full jets



Wicks et al (GLV + collisional

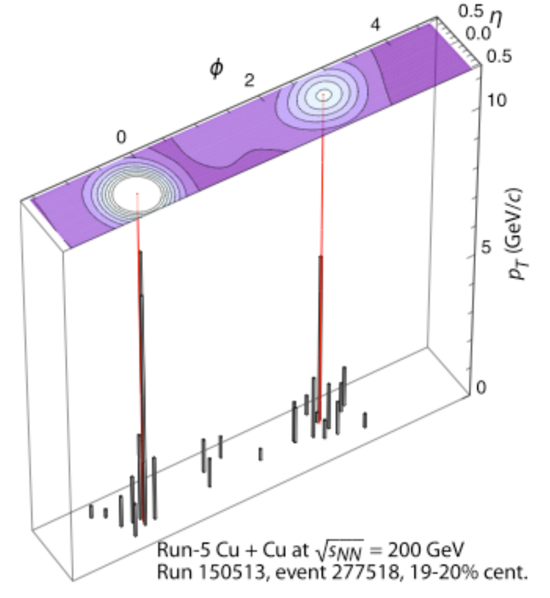


True Jet measurements in progress

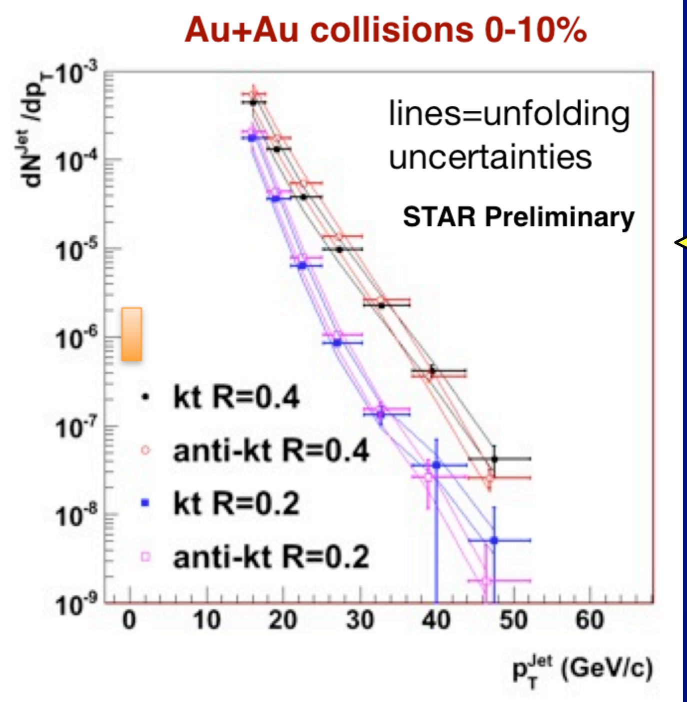


STAR
(Au-Au)

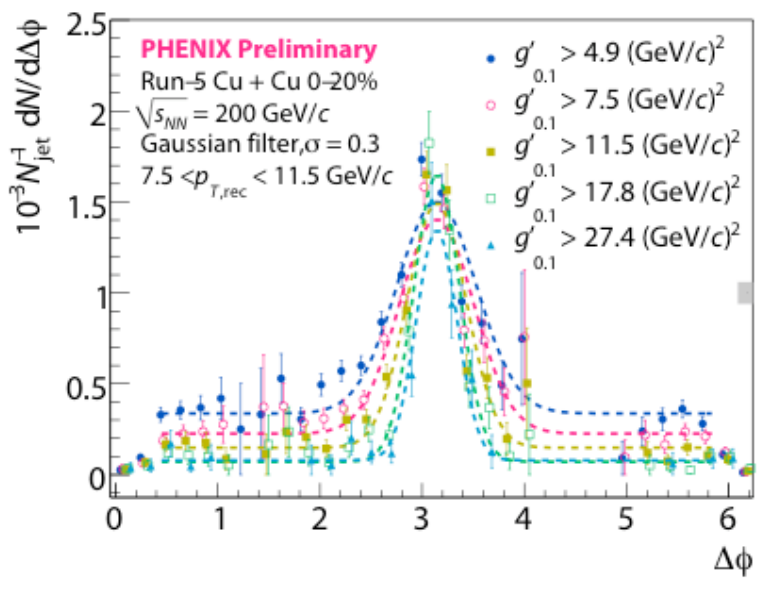
PHENIX
(Cu+Cu)
jet events



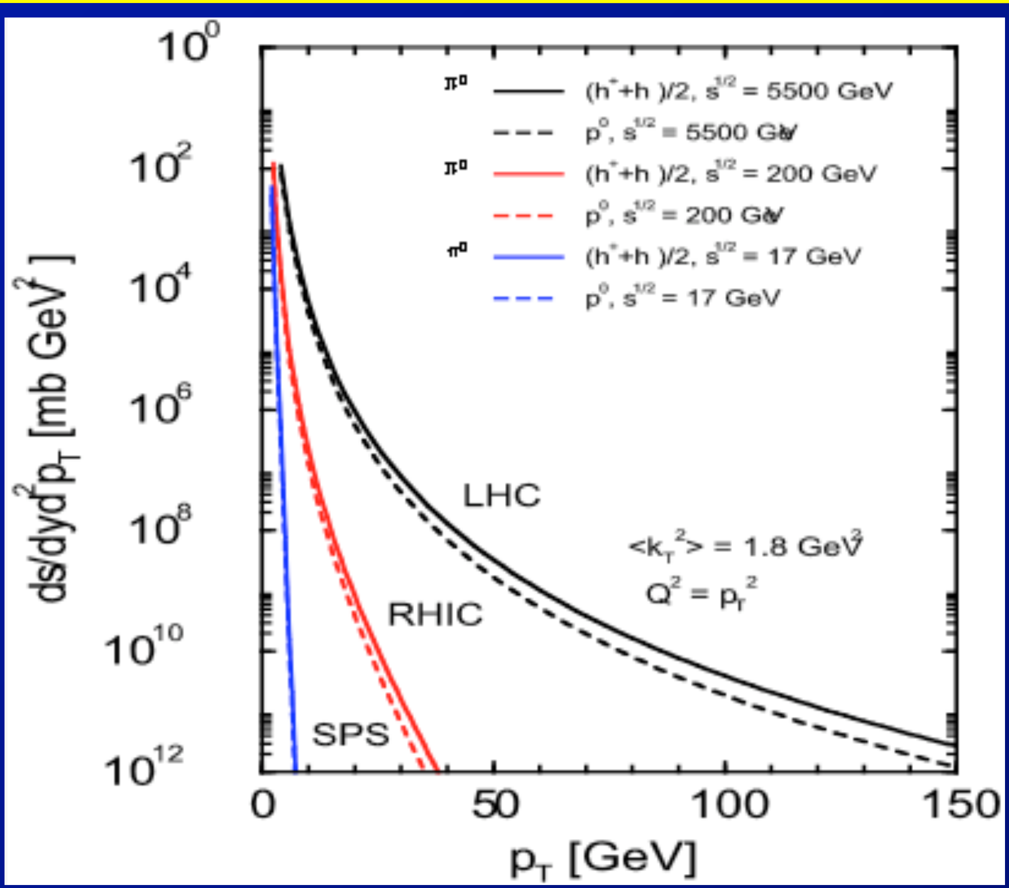
STAR
Au+Au
spectrum



PHENIX
Cu+Cu
di-jet Δϕ



Jet Measurements @ LHC



Comparison of single high-p_T hadron cross-sections at different energies

Jet spectra change similarly

- Large increase in hard cross-sections from RHIC to LHC, range extended by > x10
  - Soft background expected to increase by ~ x3.
- And large-acceptance detectors with electro-magnetic + hadron calorimeters.

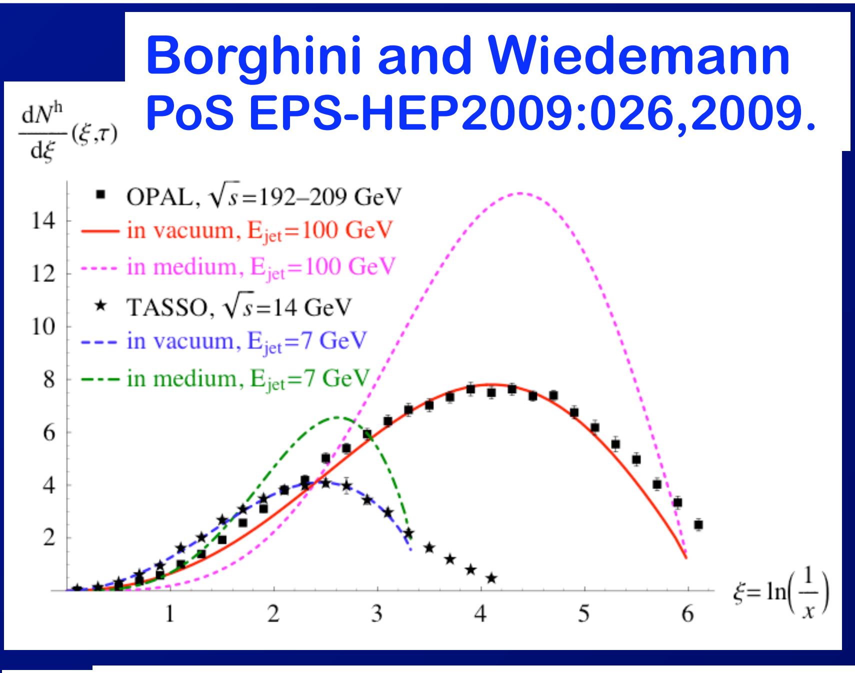
Quenching as Modified Parton Shower

- One way to describe medium-induced energy loss
  - Enhancement of splitting functions

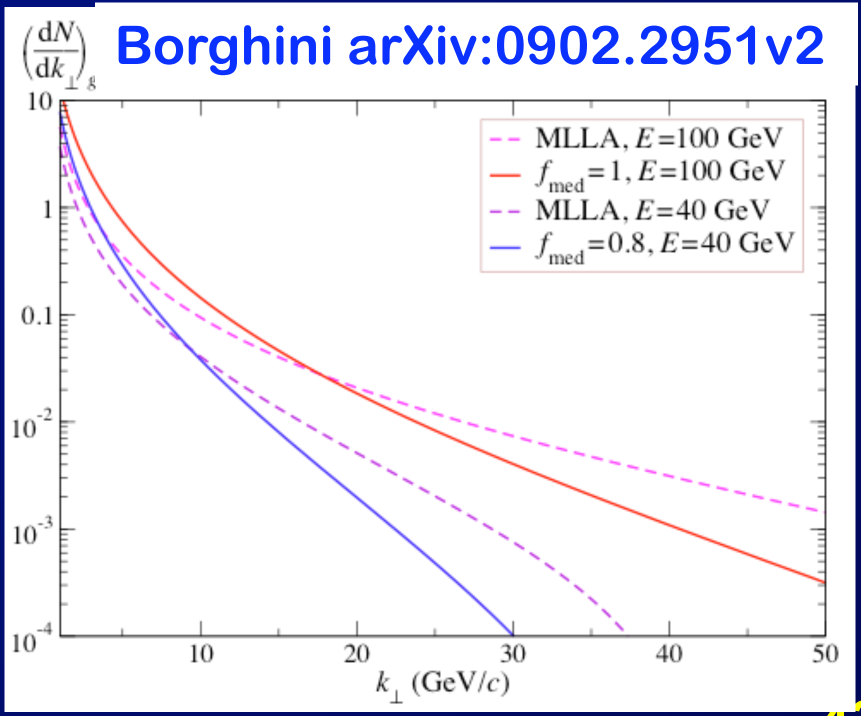
$$P_{gq}(z) = C_F\left[\frac{2(1+f_{\mathrm{med}})}{z} - 2 + z\right],$$

$$P_{gg}(z) = 2C_A\left[\frac{1}{1-z} + \frac{1+f_{\mathrm{med}}}{z} - 2 + z(1-z)\right]$$

- Softens the hadron x distribution in jet
  - Strongly enhanced production at small x
- Broadens k_T spectrum at low k_T, softens at large k_T



Borghini and Wiedemann PoS EPS-HEP2009:026,2009.

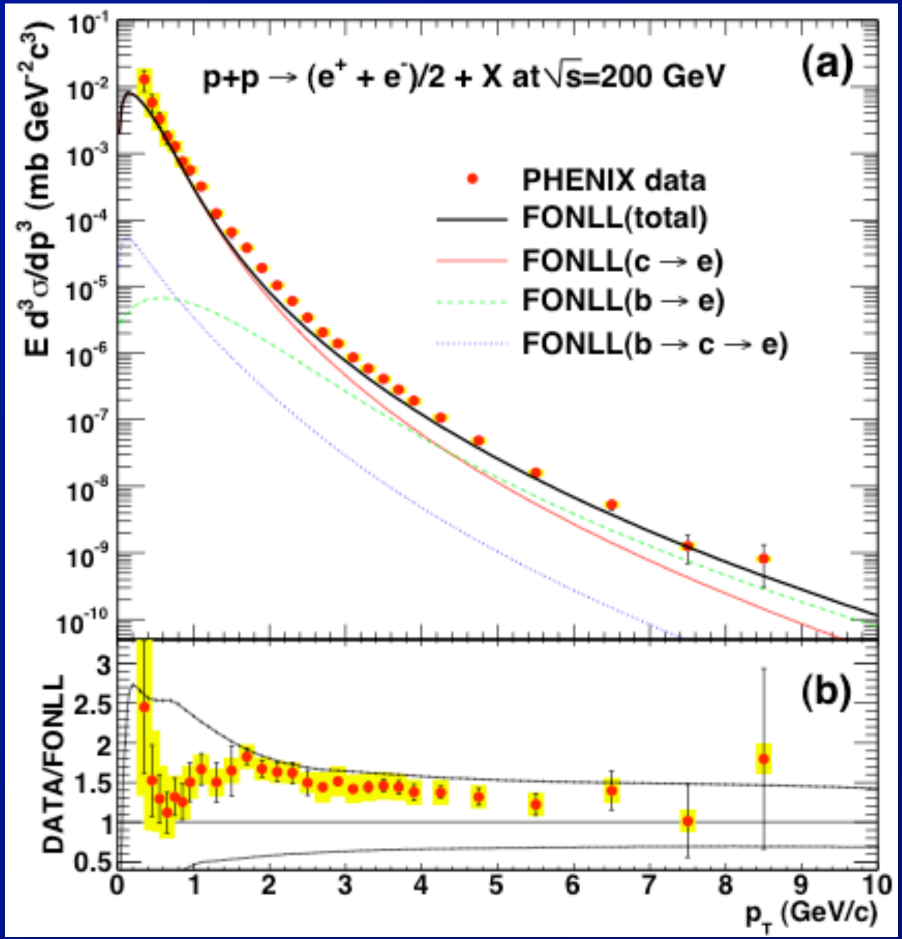


Borghini arXiv:0902.2951v2

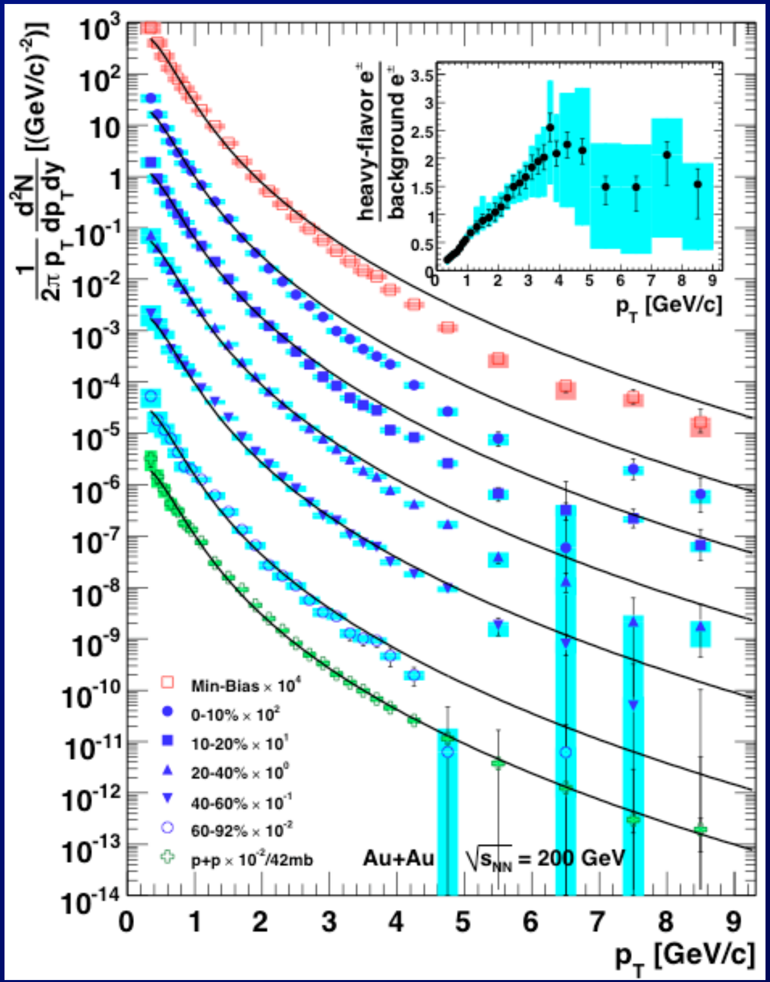
PHENIX: Heavy Quark Quenching

- Currently, best measurements of heavy quarks via semi-leptonic decays: single $e^+ + e^-$ spectrum
  - – Details re: background & subtraction not presented

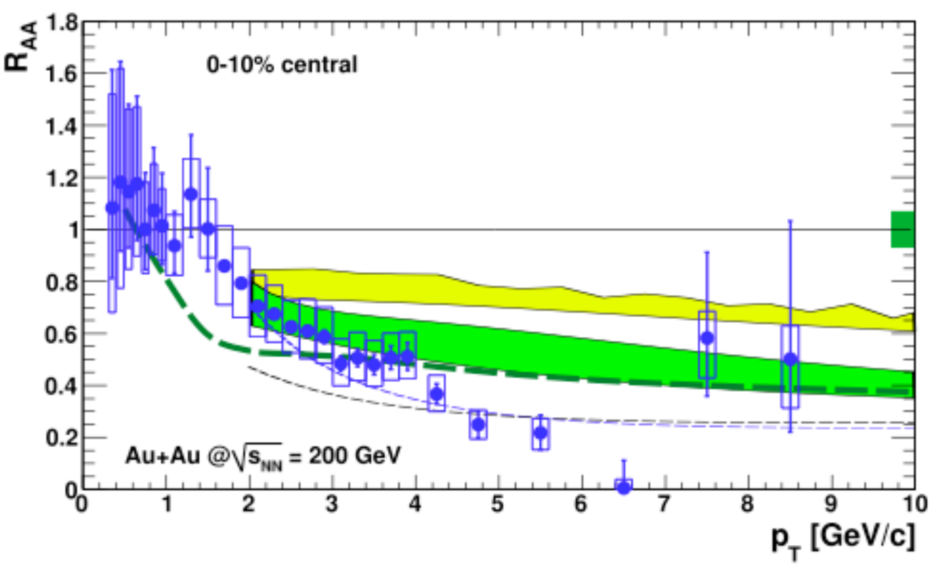
p-p compared w/ FONLL



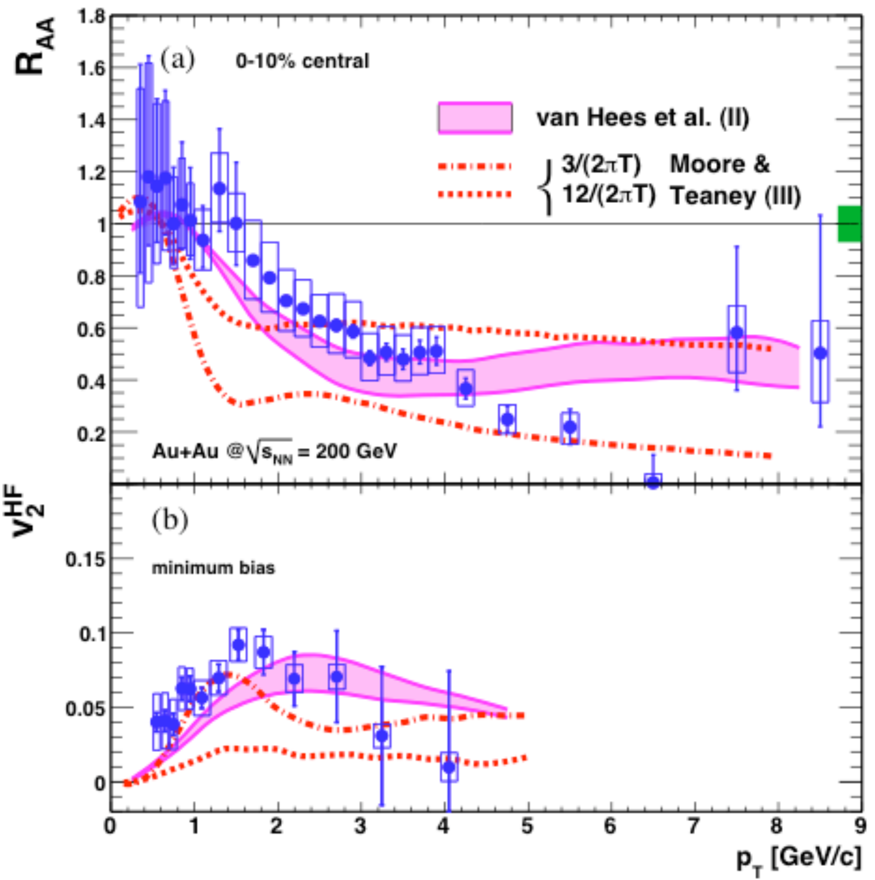
Au+Au compared w/ p-p



Heavy Flavor Quenching, Theory



- "Standard" radiative + collisional energy loss calculations that reproduce π^0 data cannot reproduce single electron suppression

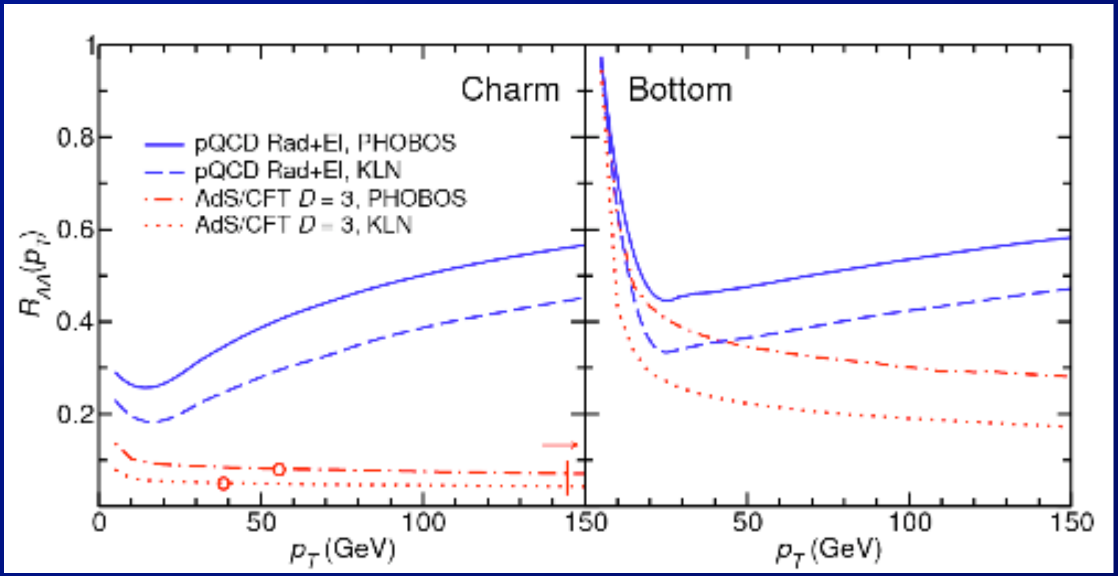


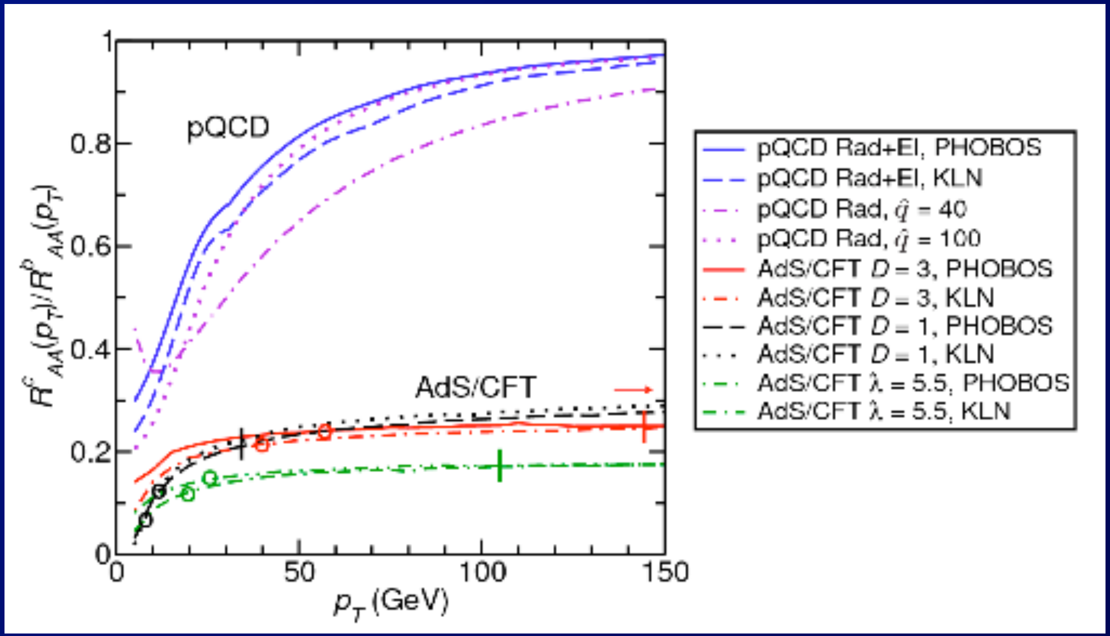
- Calculations with heavy flavor diffusion & "drag" can describe single electron suppression and single electron v_2

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.
- Measurements will be made at RHIC (luminosity upgrades) & LHC

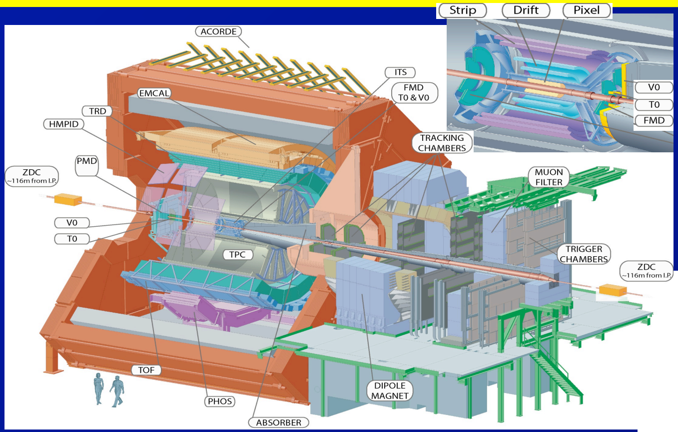




Summary

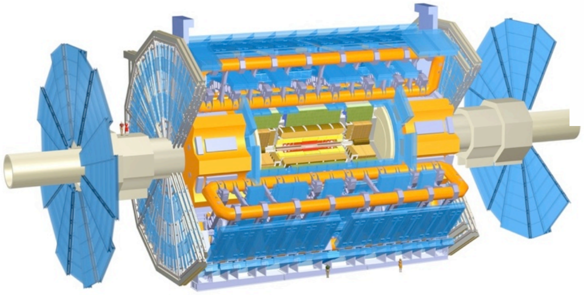
- Three open problems in understanding initial conditions for and properties of Quark Gluon Plasma on which LHC will provide critical insight
  - Initial conditions
    - ⇒Can A+A initial conditions @ RHIC and/or LHC be described within the framework of saturation
      - » Technical issue: validity of k_T factorization (Raju)
  - Collective evolution of QGP, hydrodynamics and QGP viscosity
    - ⇒Essential test of paradigm developed @ RHIC at higher temperatures / particle densities
    - ⇒Continued dominance of strong coupling?
  - Jet quenching: direct probe of QGP
    - ⇒ Full jet measurements crucial for realization of “jet tomography”

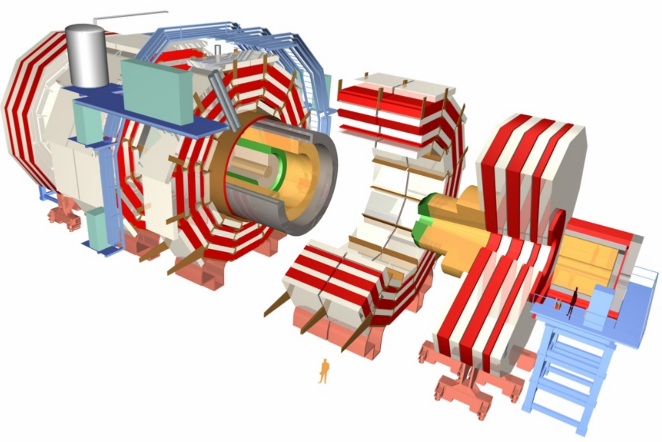
Heavy Ion Experiments @ LHC



ALICE

ATLAS





CMS

- You will have to take my word that these three experiments can perform the measurements required to address above physics
  - ⇒And much, much, much more.
- Extraordinary complement of experiments that broadens the scientific reach of LHC

The Big Picture

- We know that strong interactions are well described by the QCD Lagrangian:

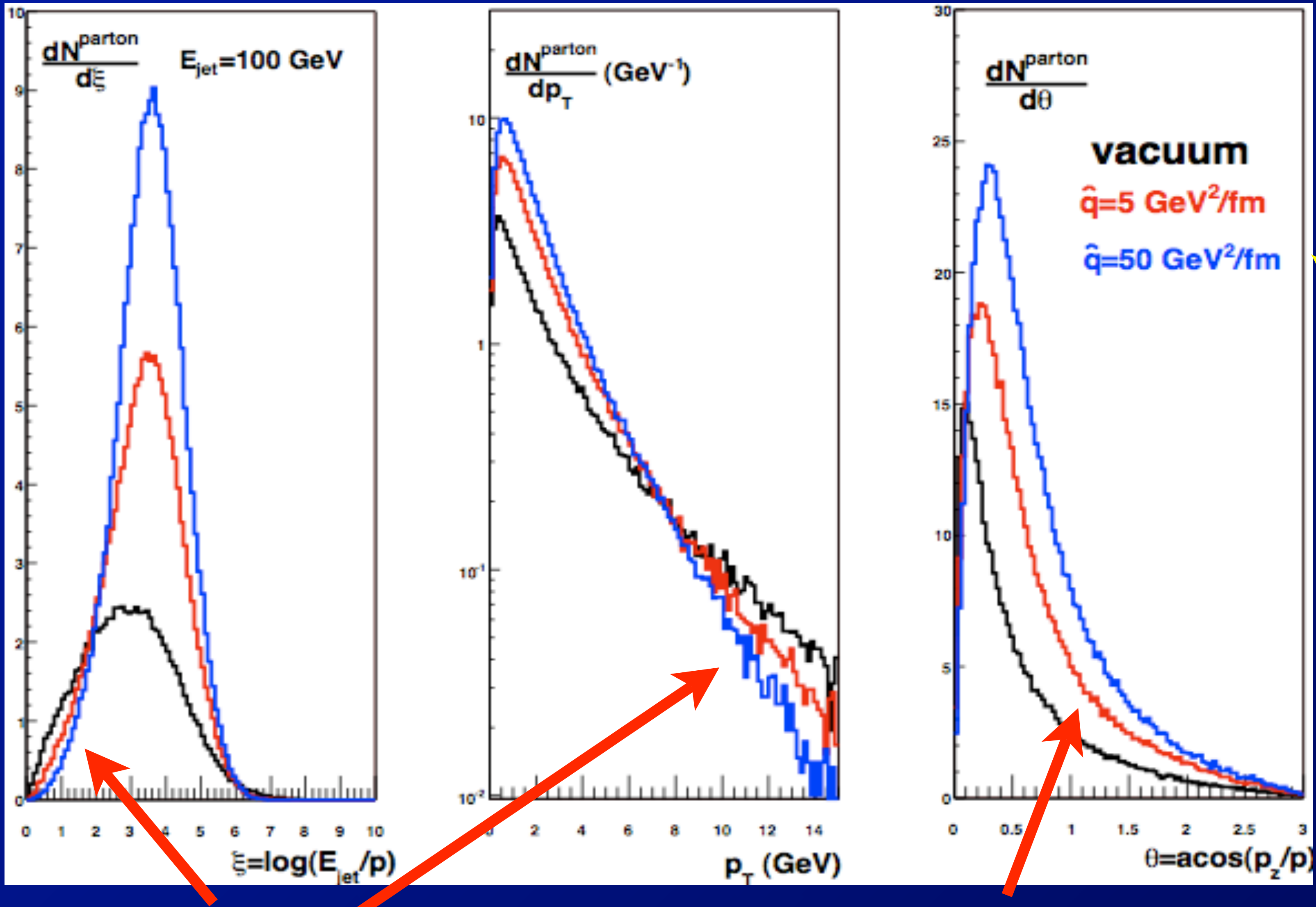
$$L_{QCD} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a} - \sum_n \bar{\psi}_n \left(\partial\!\!\!/ - ig\gamma^{\mu}A^{a}_{\mu}t_a - m_n\right)\psi_n$$

  ⇒Perturbative limit well studied

- Nuclear collisions provide a laboratory for studying QCD outside the large Q^2 regime:
  - Deconfined matter (quark gluon plasma)
    - ⇒“Emergent” physics not manifest in L_{QCD}
    - ⇒ Strong coupling ⇒ AdS/QCD (?)
  - High gluon field strength, saturation
    - ⇒ Unitarity in fundamental field theory
- Only non-Abelian FT whose phase transition & multi-particle behavior we can study in lab.

Jet Modifications: Expectations

Wiedemann: Quark Matter 2009

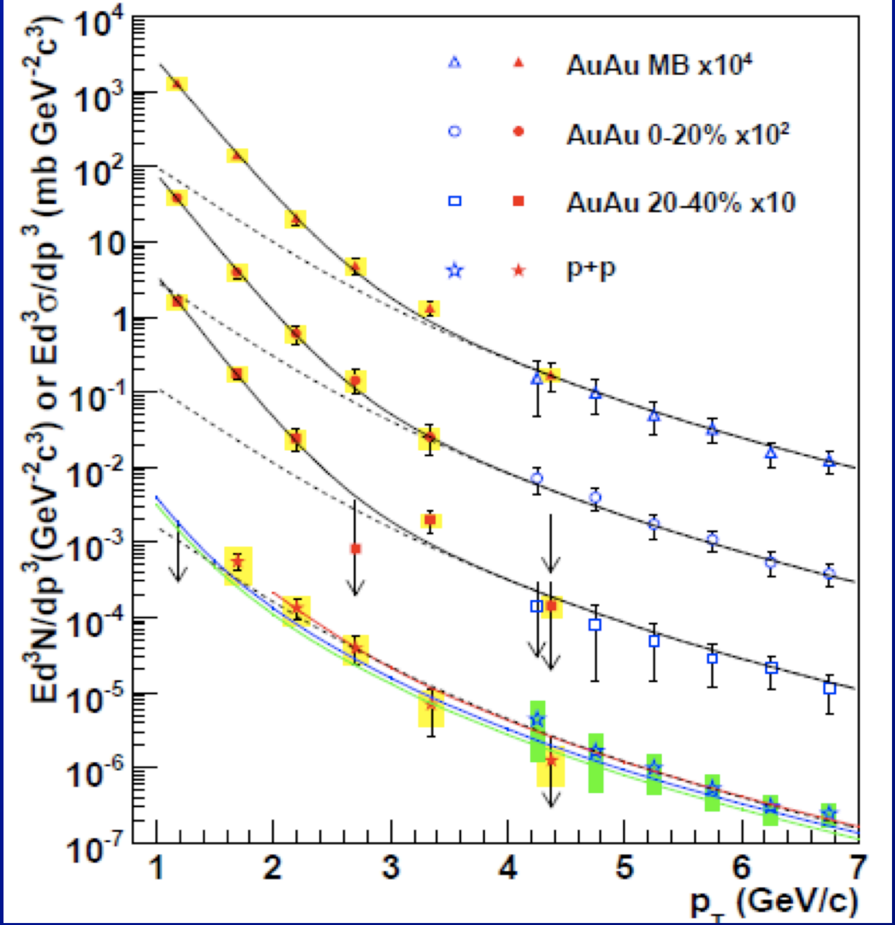


More dense medium

- Softening and angular broadening of fragmentation due to medium.

Thermal Photons

PHENIX, arXiv:0804.4168v1 [nucl-



- **PHENIX measurement of prompt photons**
  - Clear “thermal” excess at low p_T $T_{avg} \sim 200$ MeV
  - But T is time dependent
- **Hydrodynamics:**
  - $\Rightarrow T_{init} > 300$ MeV

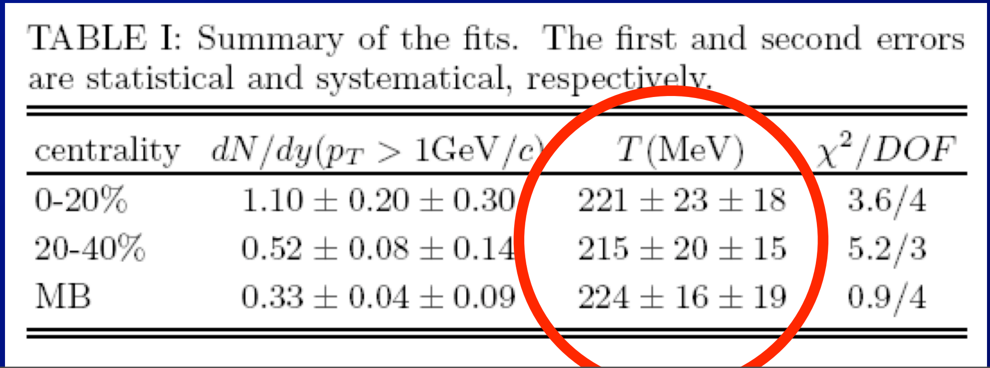
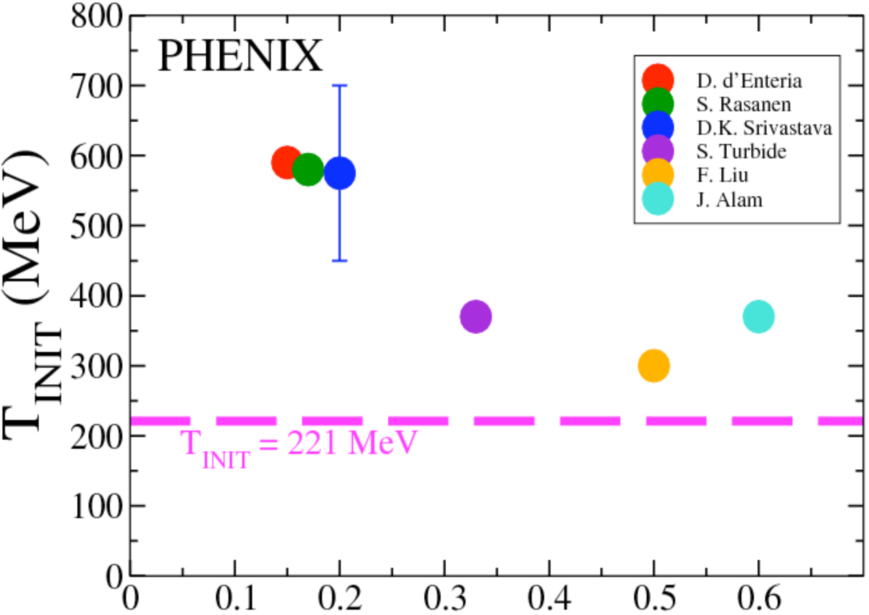


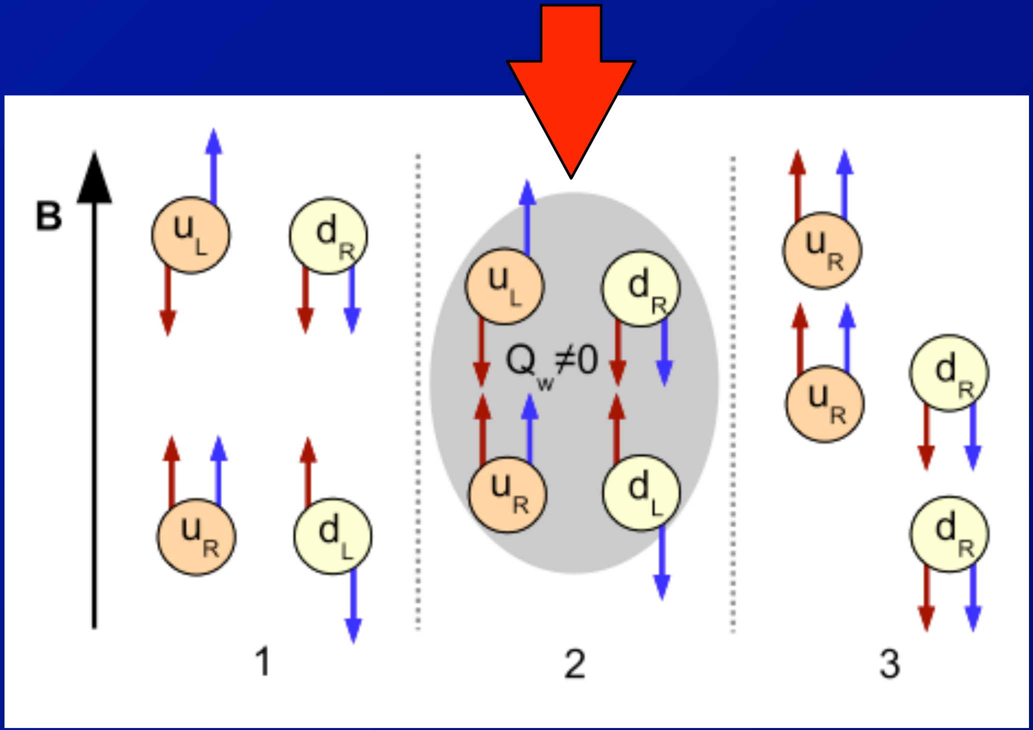
TABLE I: Summary of the fits. The first and second errors are statistical and systematical, respectively.

centrality	$dN/dy(p_T > 1GeV/c)$	T(MeV)	χ^2/DOF
0-20%	1.10 ± 0.20 ± 0.30	221 ± 23 ± 18	3.6/4
20-40%	0.52 ± 0.08 ± 0.14	215 ± 20 ± 15	5.2/3
MB	0.33 ± 0.04 ± 0.09	224 ± 16 ± 19	0.9/4

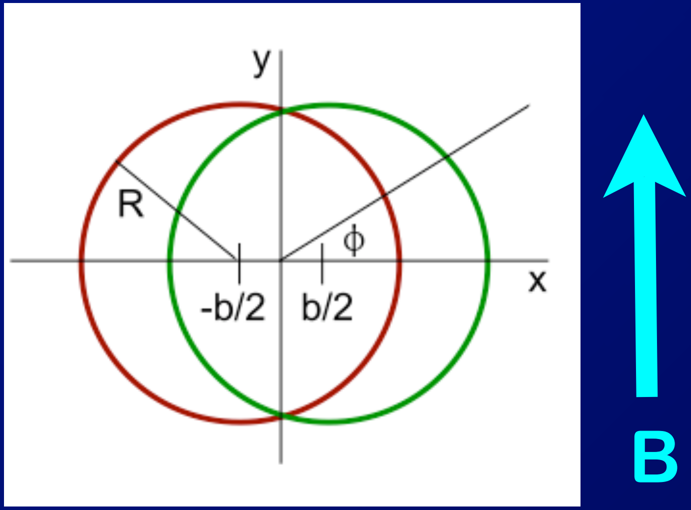


Chiral Magnetic Effect @ RHIC?

Region of non-zero winding #

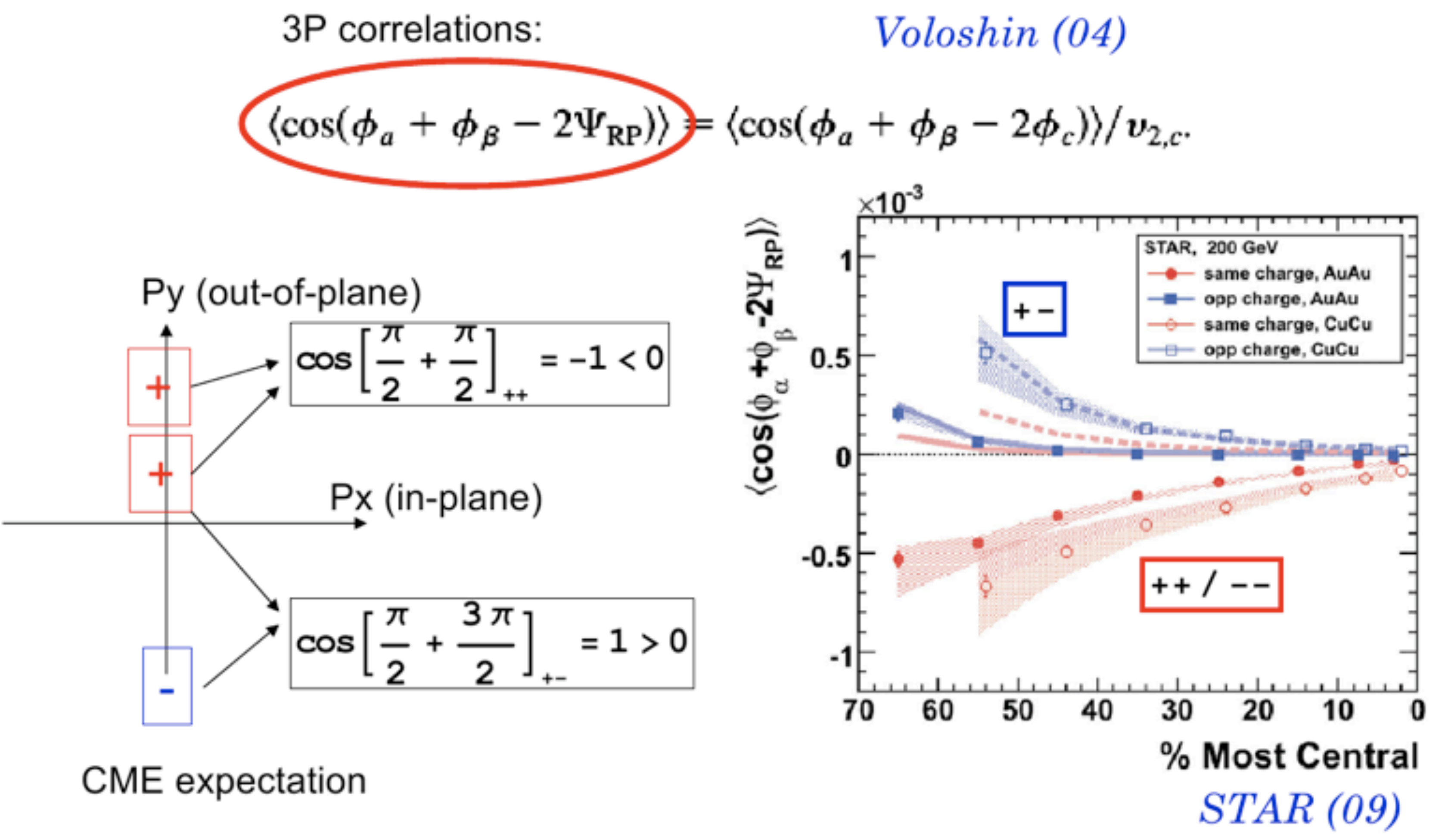


$$Q_{\mathrm{w}} = \frac{g^2}{32\pi^2} \int \mathrm{d}^4x\, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$



- Chiral magnetic effect:
  - Generates charge separation ⊥ to event plane
  - Requires magnetic field generated by incident nuclei in non-central collisions

From INT Workshop Talk by V. Kock



3P correlations:

Voloshin (04)

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle = \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle / v_{2,c}.$$

$$\cos\left[\frac{\pi}{2} + \frac{\pi}{2}\right]_{++} = -1 < 0$$

$$\cos\left[\frac{\pi}{2} + \frac{3\pi}{2}\right]_{+-} = 1 > 0$$

CME expectation

STAR (09)

- **Data suggest a charge separation consistent with the proposed chiral magnetic effect**
  - But, Koch: separation may in fact be in plane not ⊥
  - Many other critiques … too early to conclude!

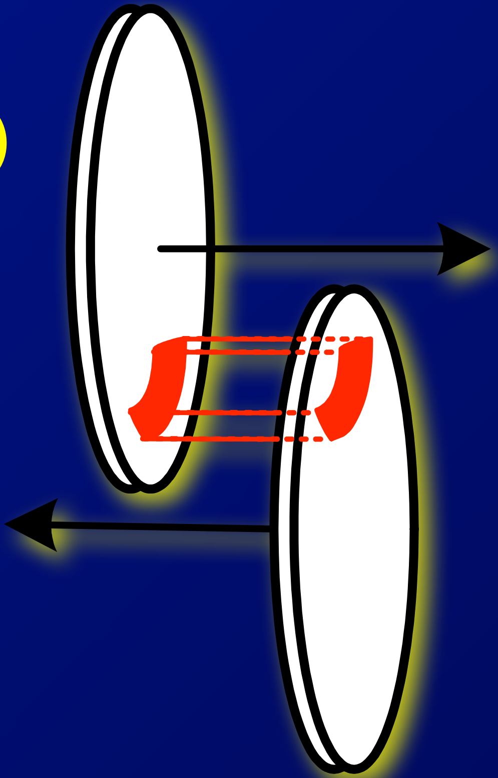
A-A Hard Scattering Rates

- For "partonic" scattering or production processes, rates are determined by T_{AB}

$$T(r_t) = \int_{-\infty}^{\infty} dz\, \rho_A^{nucleon}(z, r_t)$$

$$T_{AB} = \int d\vec{r}_\perp T_A(|\vec{r}_\perp|) T_B(|\vec{b} - \vec{r}_\perp|)$$

  - integrated A-A parton luminosity normalized relative to p-p



- If factorization holds, then

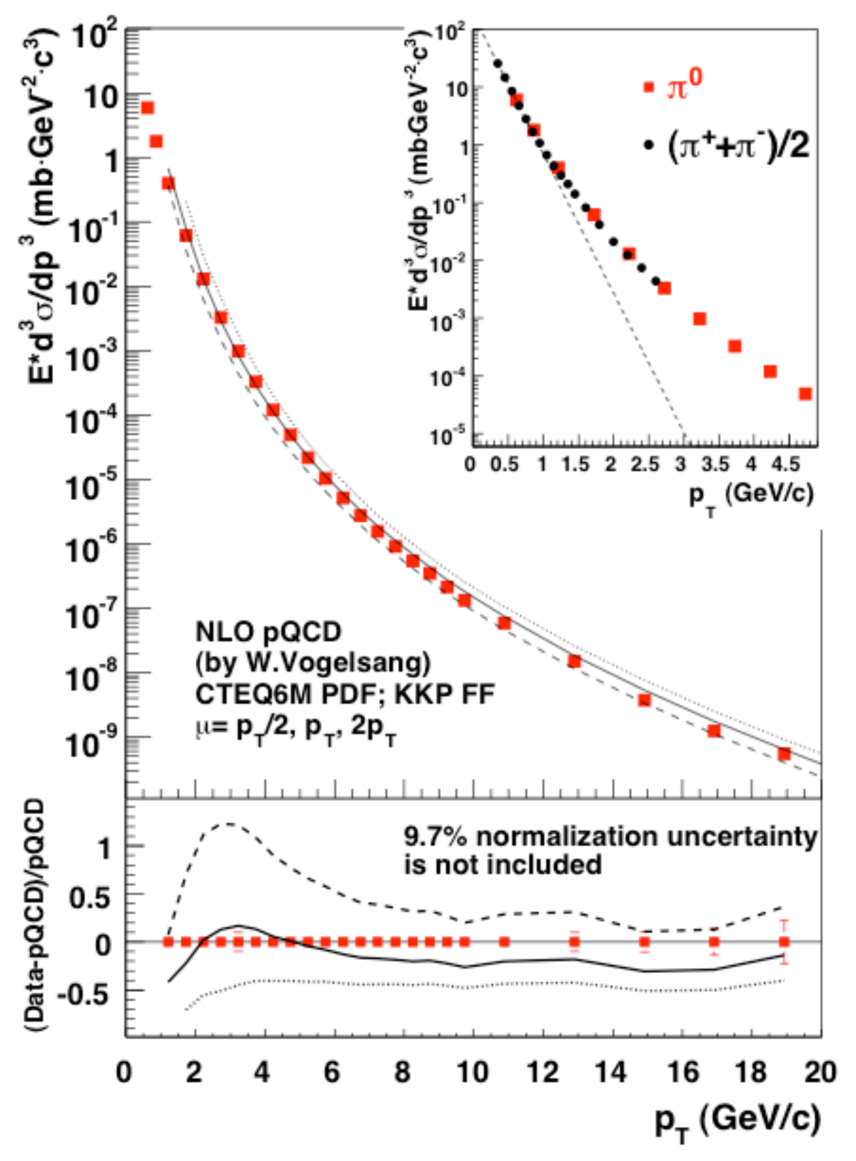
$$dN_{hard}^{A-B} = d\sigma_{hard}^{p-p}\, T_{AB}(b)$$

- Define R_{AB} or R_{AA}
  - Degree to which factorization is violated

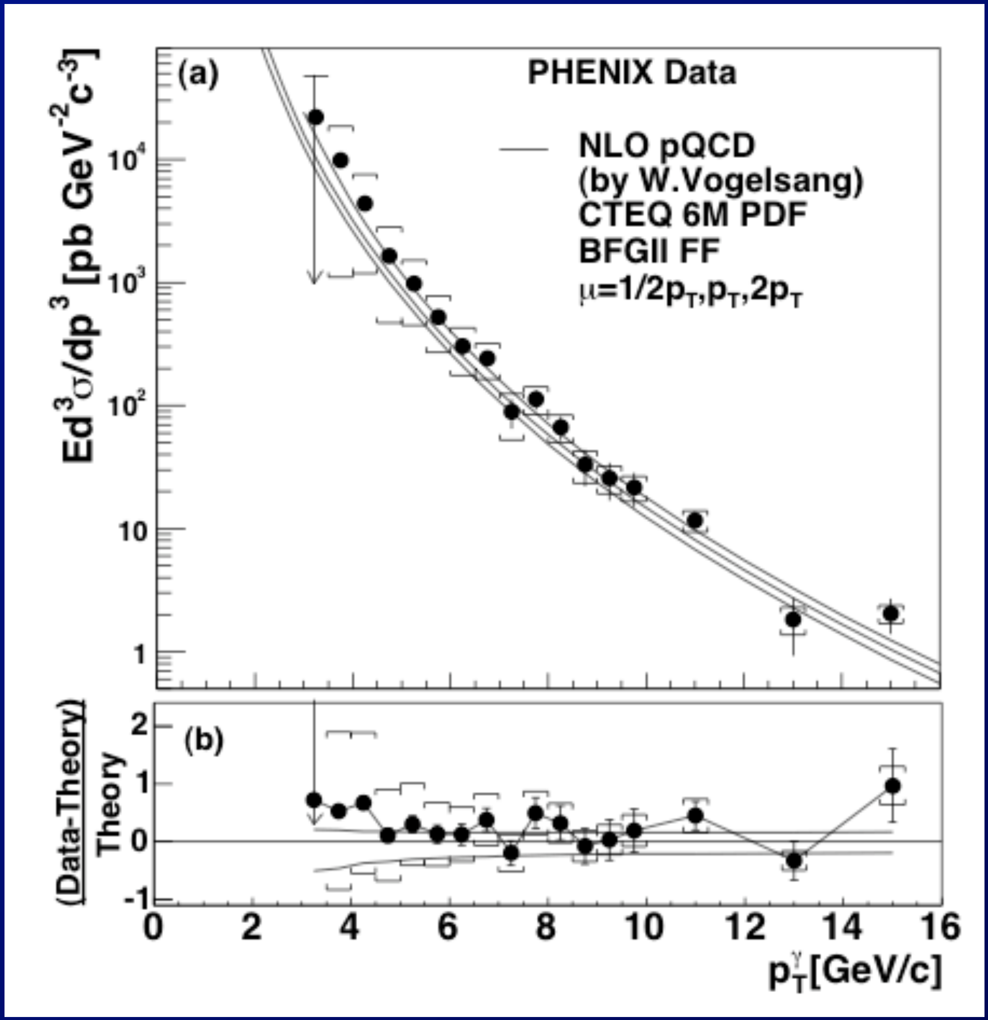
$$R_{AB} = \frac{dN_{hard}^{A-B}}{d\sigma_{hard}^{p-p}\, T_{AB}(b)}$$

PHENIX: p-p Baseline

PHENIX, p-p π^0
Phys. Rev. D76:051106, 2007

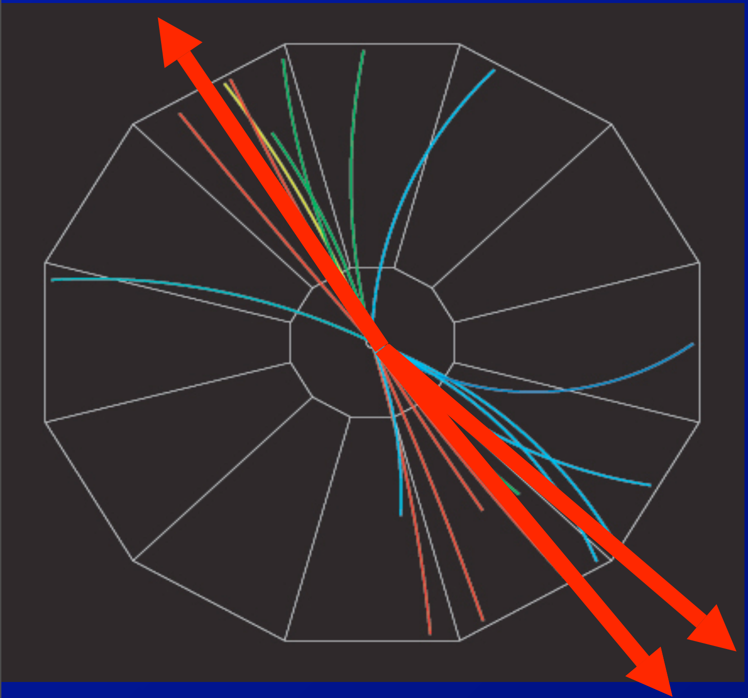


PHENIX, p-p prompt γ
Phys. Rev. Lett
98:012002,2007

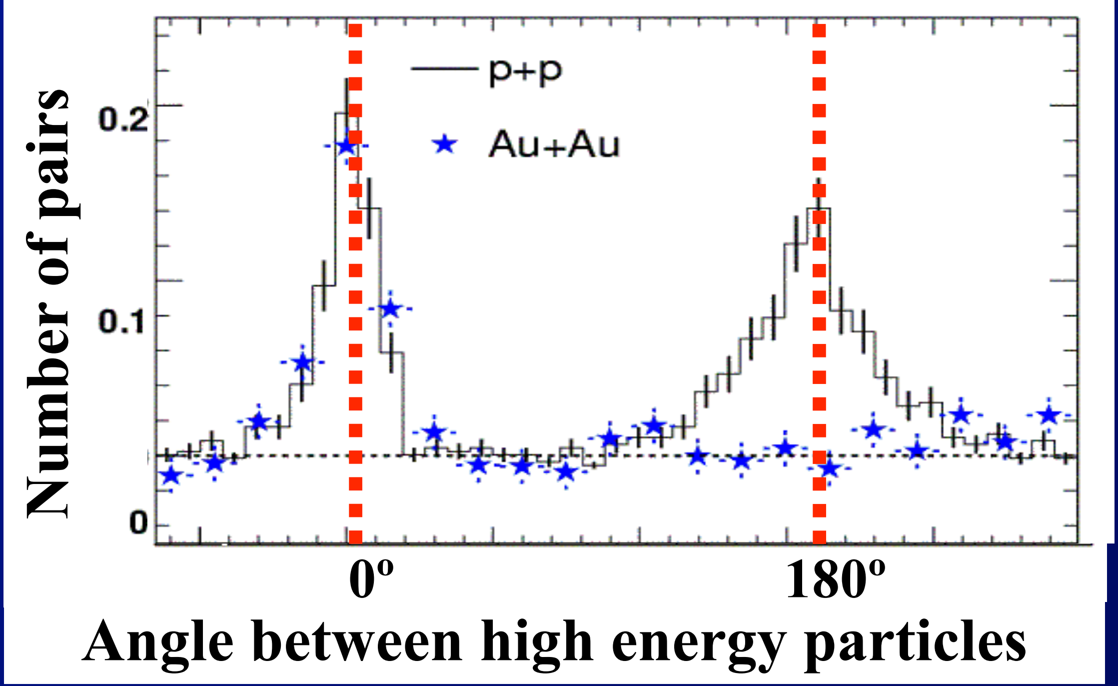


STAR Experiment: "Jet" Observations

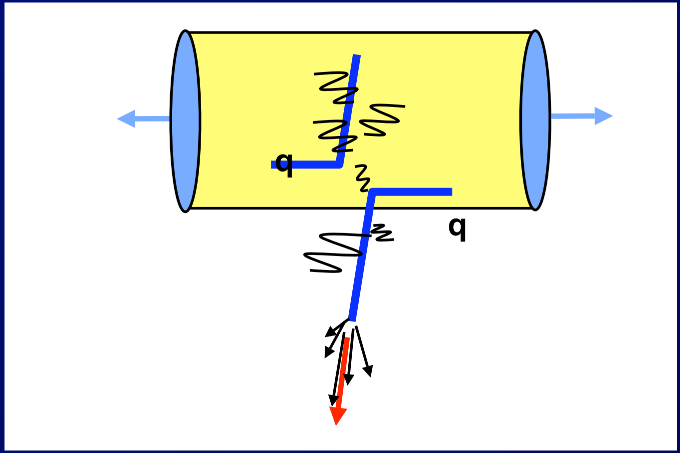
proton-proton jet event



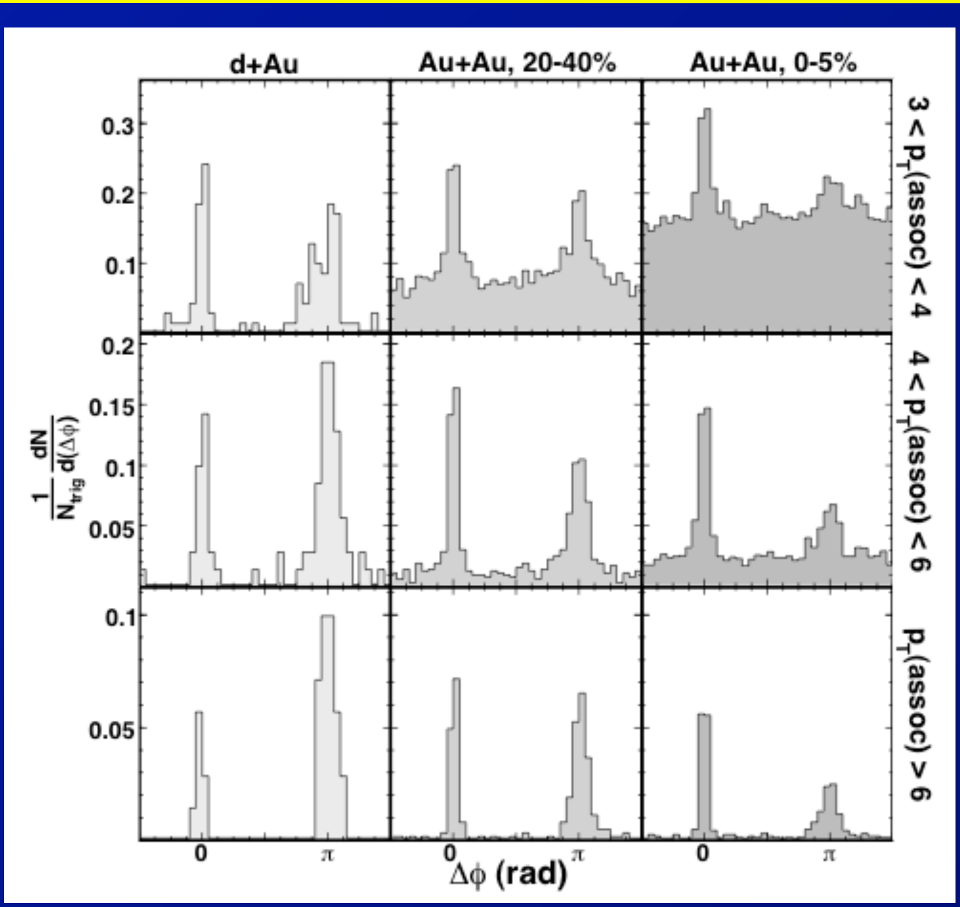
Analyze by measuring (azimuthal) angle between pairs of particles

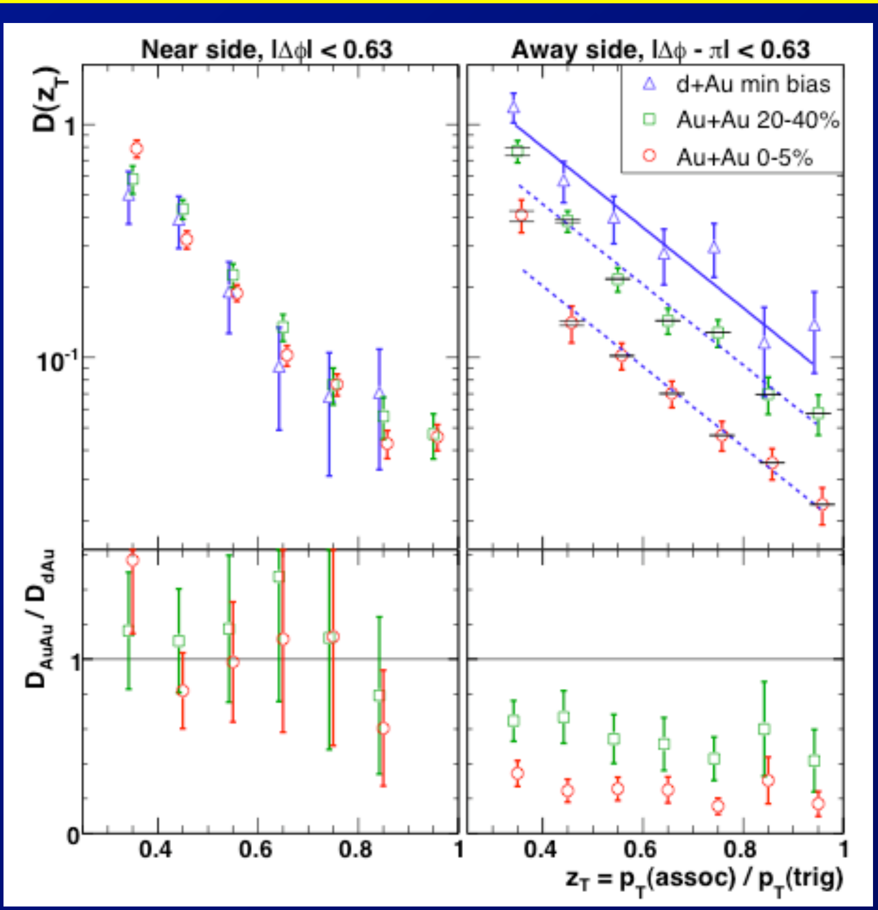


- In Au-Au collisions we see one "jet" at a time
- Strong jet quenching
- Enhanced by surface bias



di-hadron probes of quenching



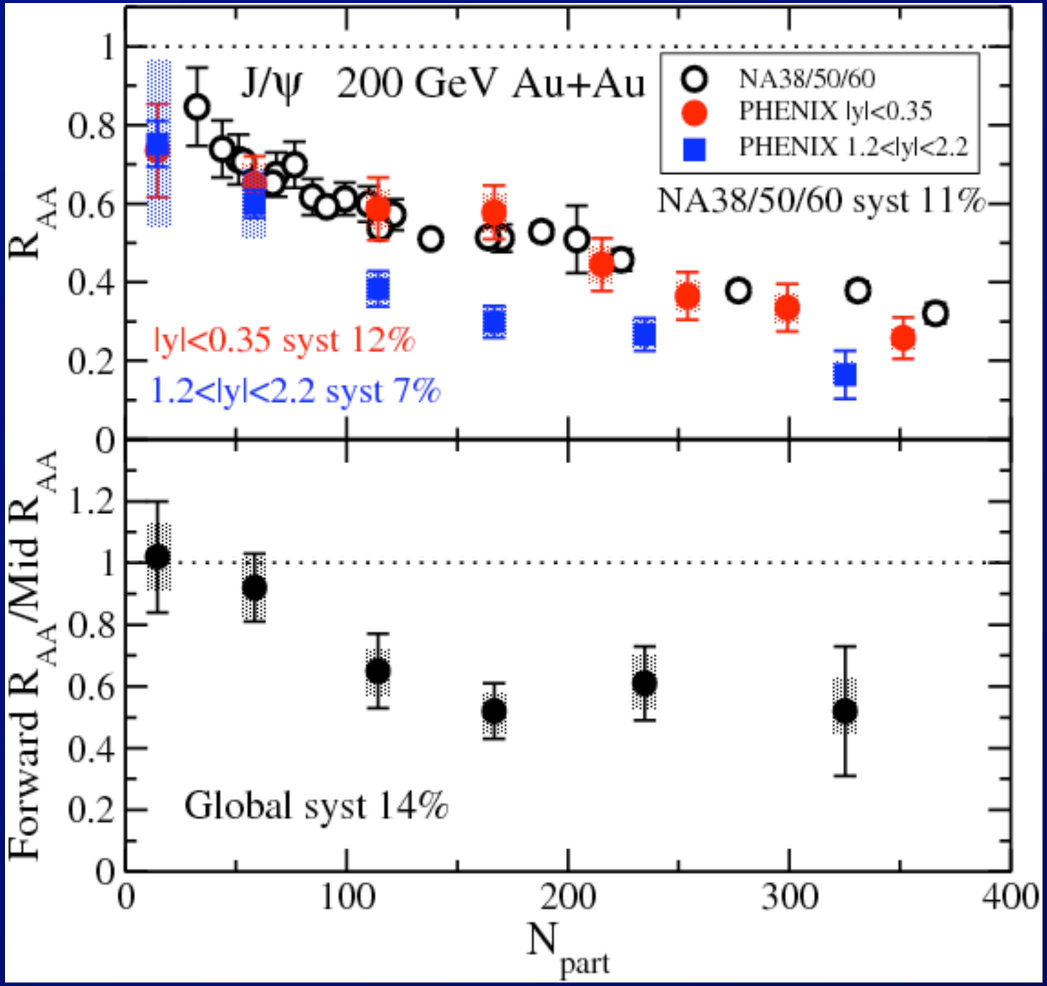


- **STAR:**
  - With increasing hadron pT di-jet signal re-appears
  - But, strength is still suppressed relative to baseline
    - ⇒In this case d+Au ≈ p+p
  - And similar results from PHENIX

J/ψ Production / Dissociation

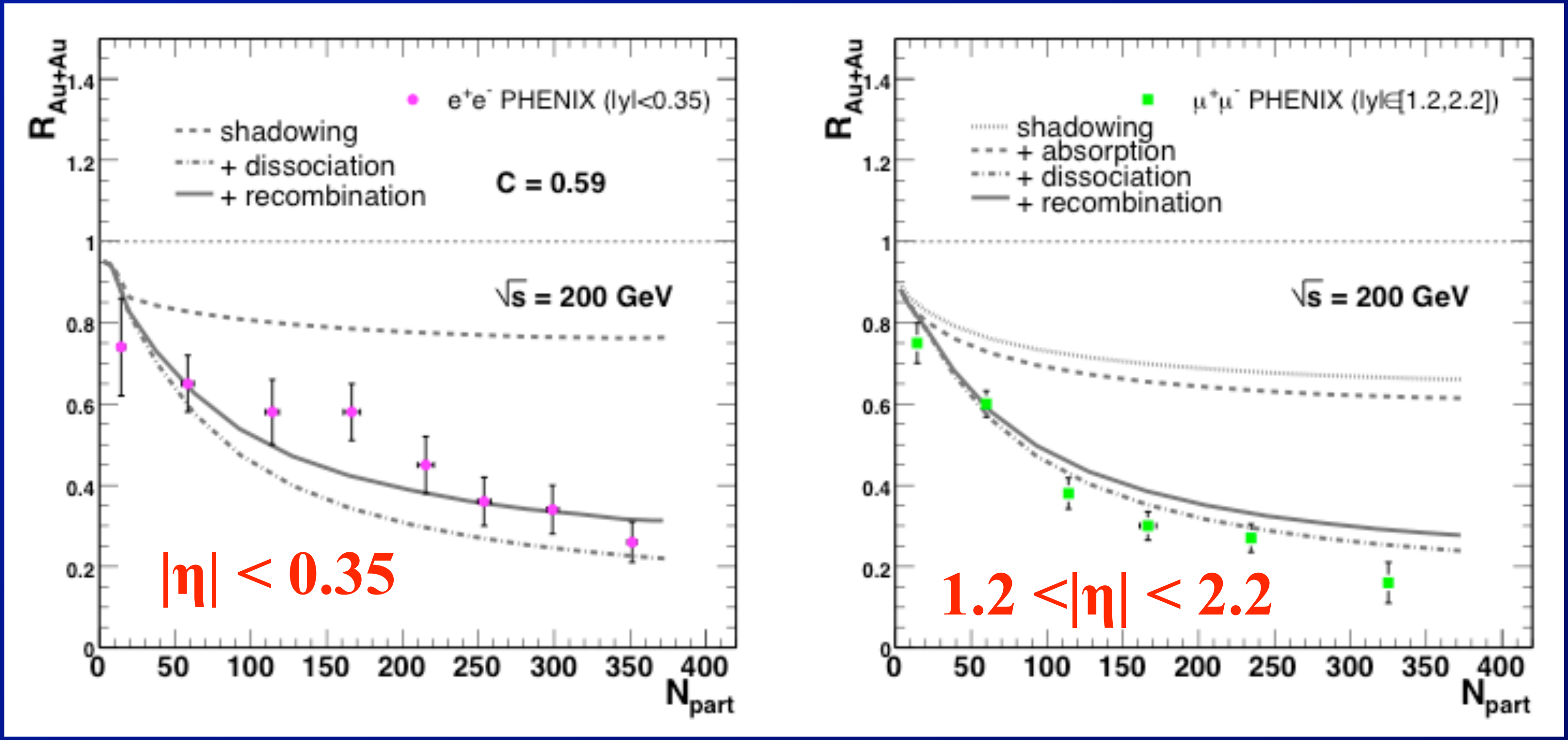
state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$< T_c$	$\leq T_c$	$1.2\, T_c$	$1.2\, T_c$	$1.3\, T_c$	$2\, T_c$

- J/ψ has long been considered good probe for deconfinement
  - Debye screening of c-cbar state
- Glossy over many important details:
  - Suppression at RHIC ~ consistent with SPS data ($\sqrt{s}$ = 17 GeV) at mid-rapidity.



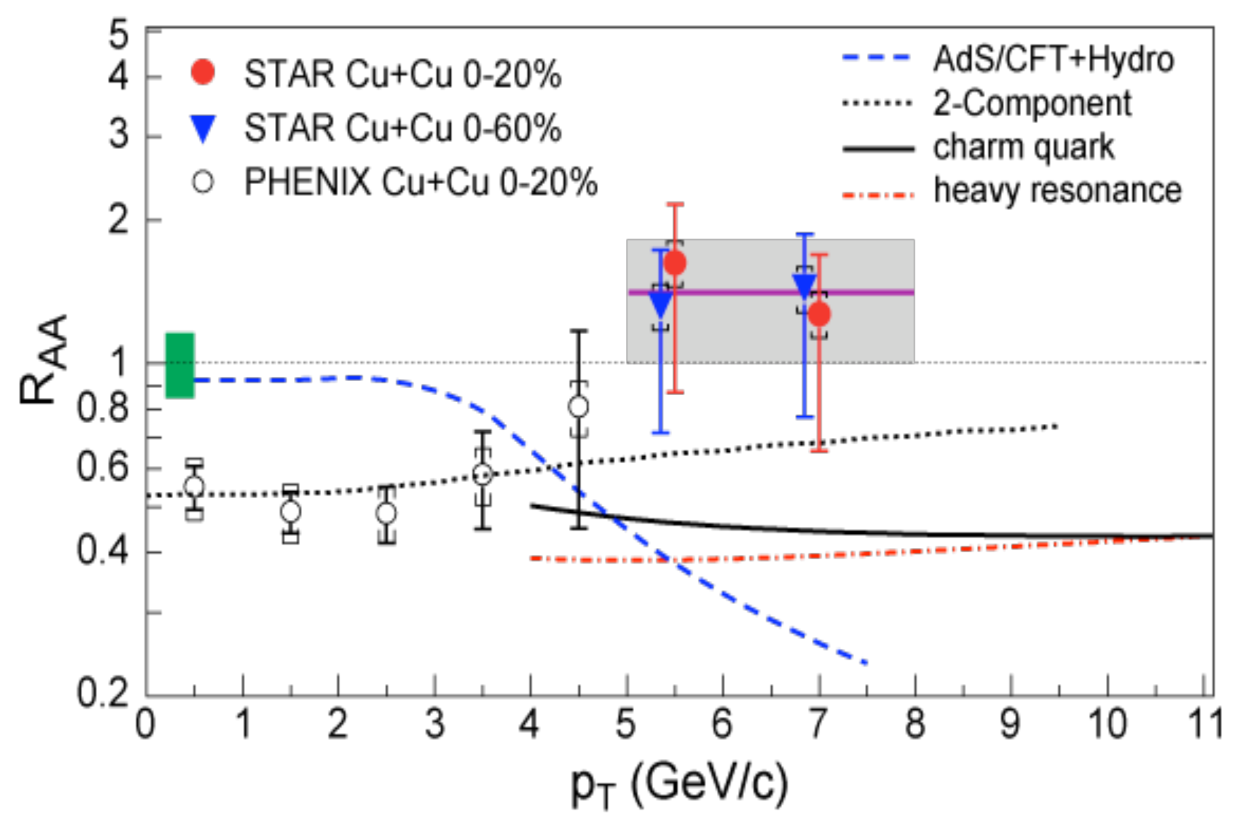
J/ψ Production / Dissociation (2)

Capella, Kaidalov, ArXiv 0902.4662



- Multiple effects: (but not feed-down)
  - shadowing, “cold” nuclear break-up, “co-mover” dissociation, recombination
    - ⇒Can (approximately) describe suppression at mid-rapidity and forward rapidity.
    - ⇒Recombination of c-cbar →J/ψ non-negligible

J/ψ Production / Dissociation (3)

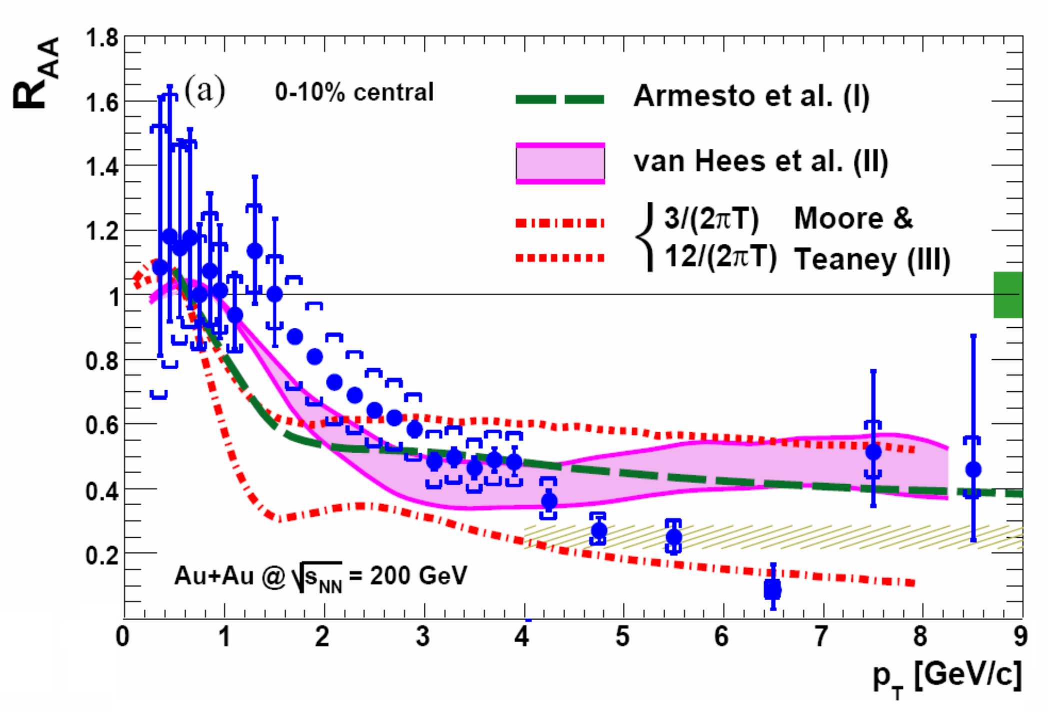


- p_T dependence provides valuable discrimination
  - Currently best description is calculation accounting for B feed-down, leakage from periphery
  - But, sensitive to initial J/ψ production mechanism

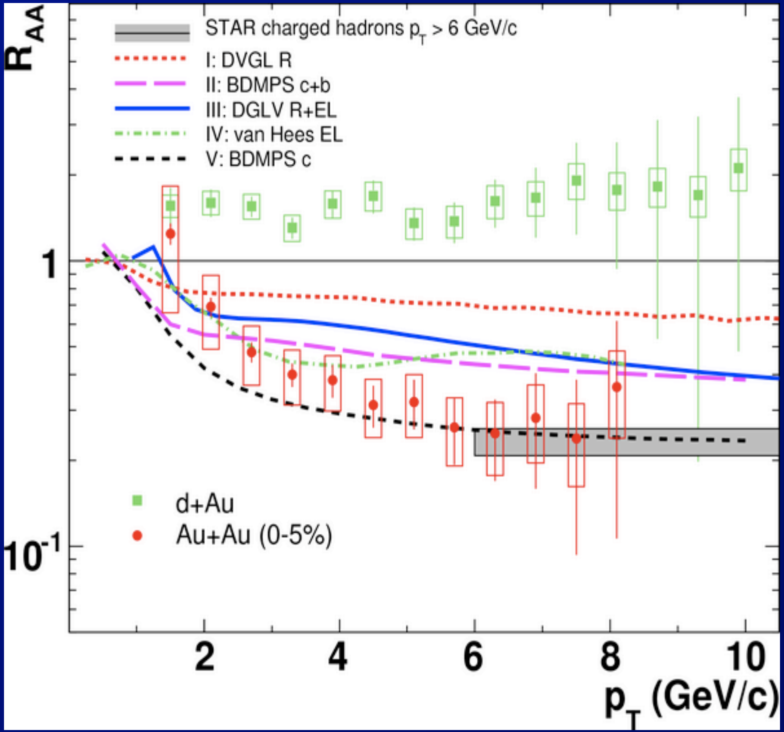
    ⇒p-p data (especially polarization)

Strong Heavy Flavor Suppression

PHENIX: *PRL98(2007)172301*

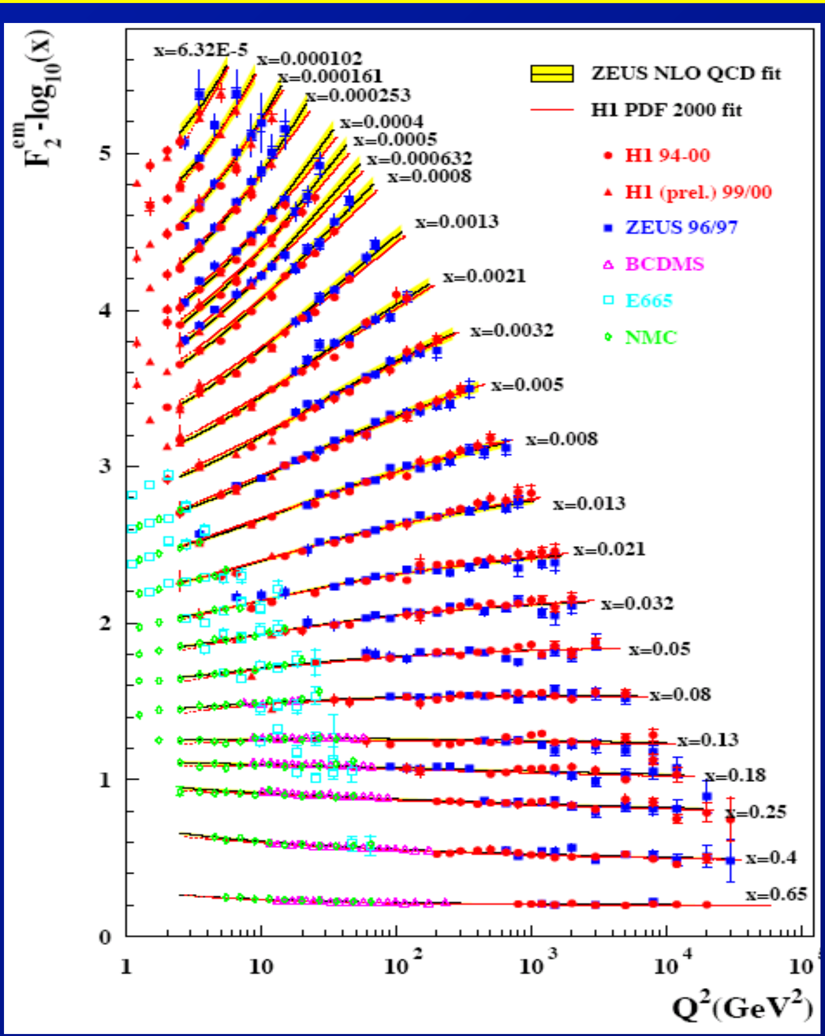


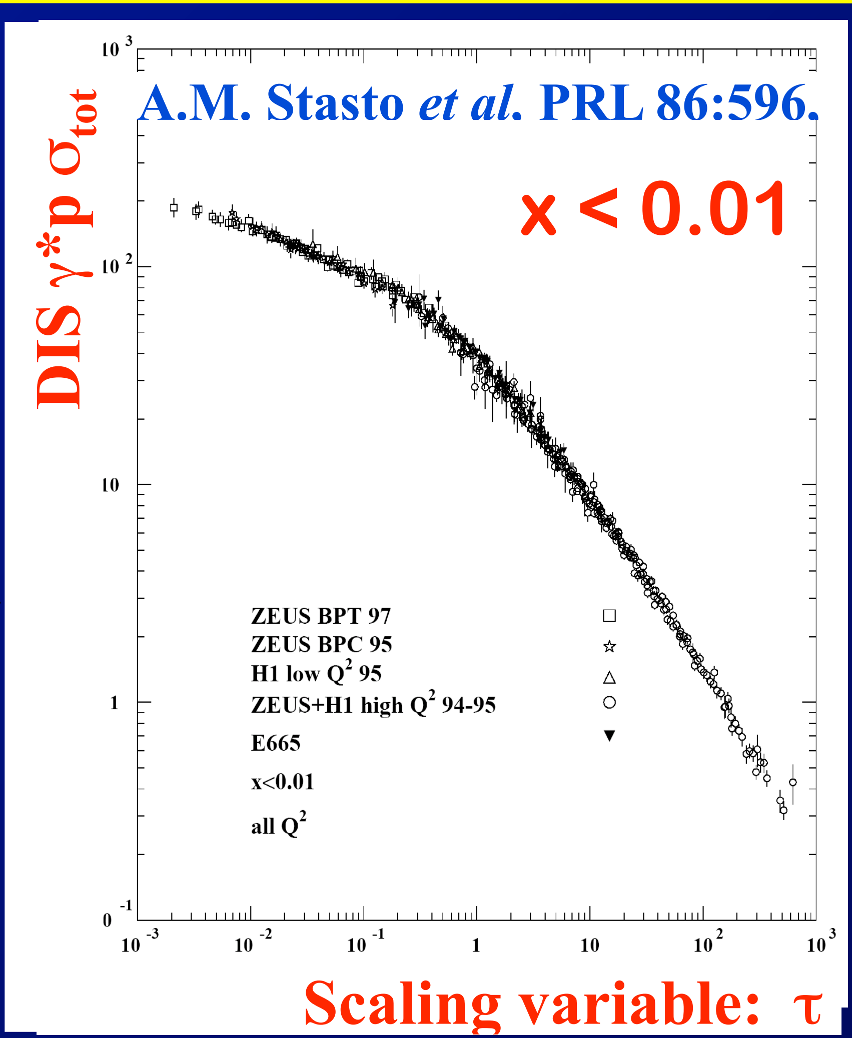
STAR: *PRL98(2007) 192301*



- Radiative energy loss calculations cannot reproduce heavy flavor measurements
  - Unless B contribution is neglected (reject!)
- Best description of data using collisional energy loss + diffusion
  - ⇒ With large diffusion constant (strong coupling!)

HERA: Geometric Scaling (saturation?)





A.M. Stasto *et al.* PRL 86:596.

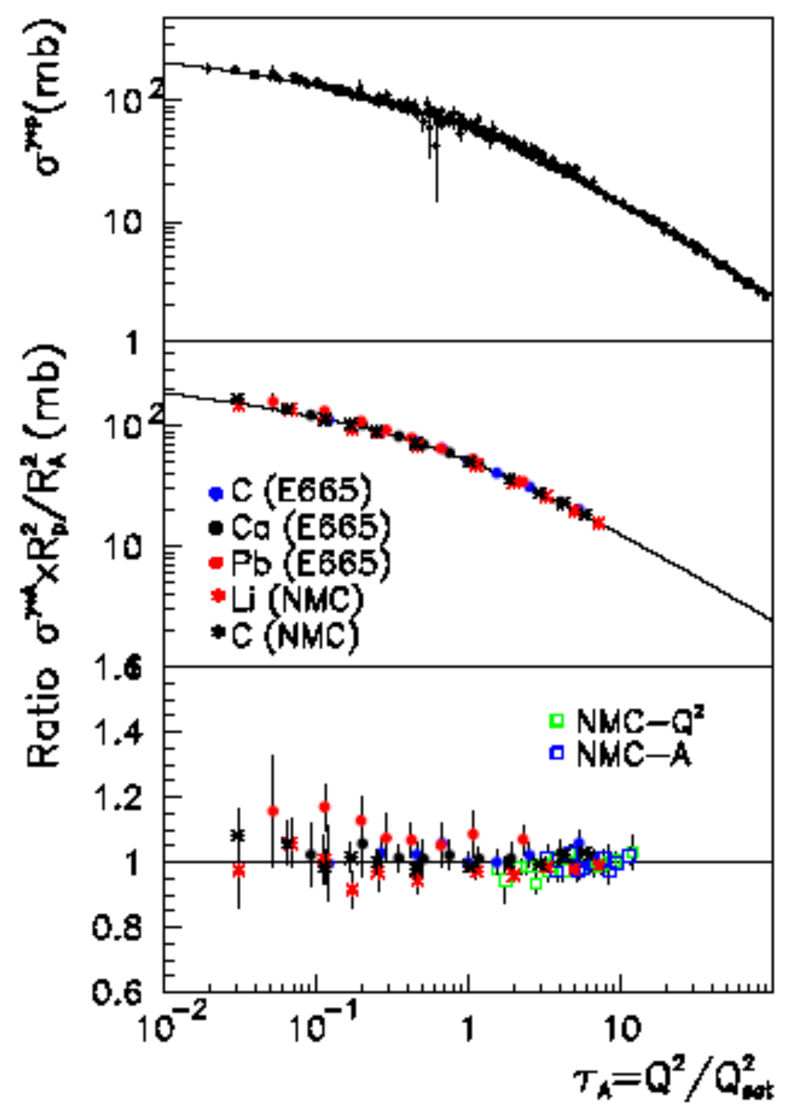
x < 0.01

Scaling variable: τ

- Phenomenological "saturation" (?)
  - Introduce an x-dependent Q_s

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

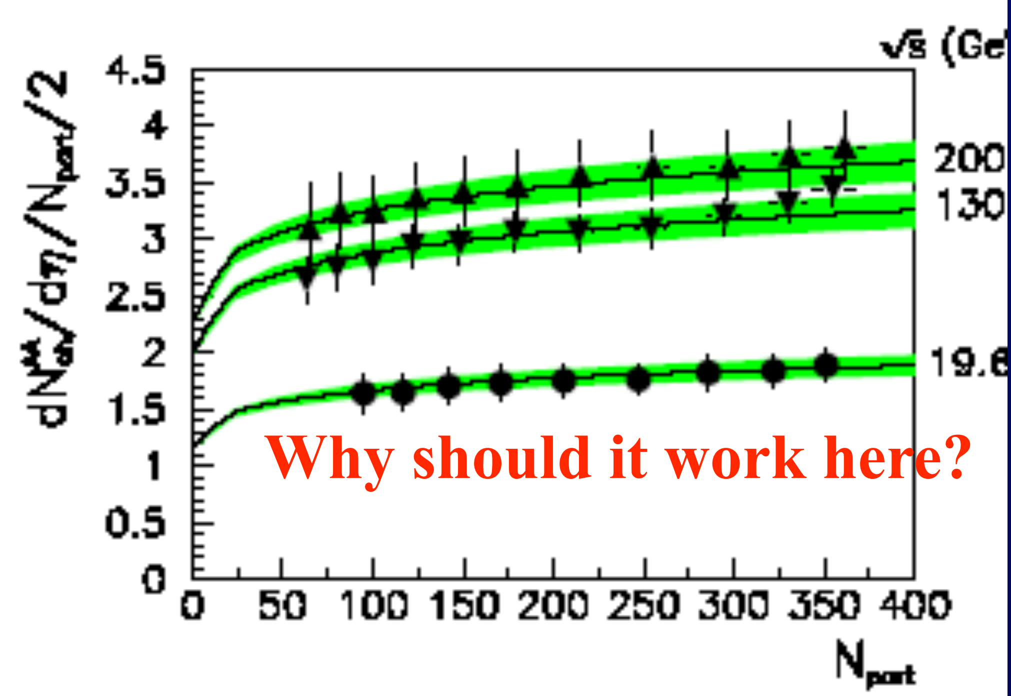
A+A Charged multiplicity: saturation(?)



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

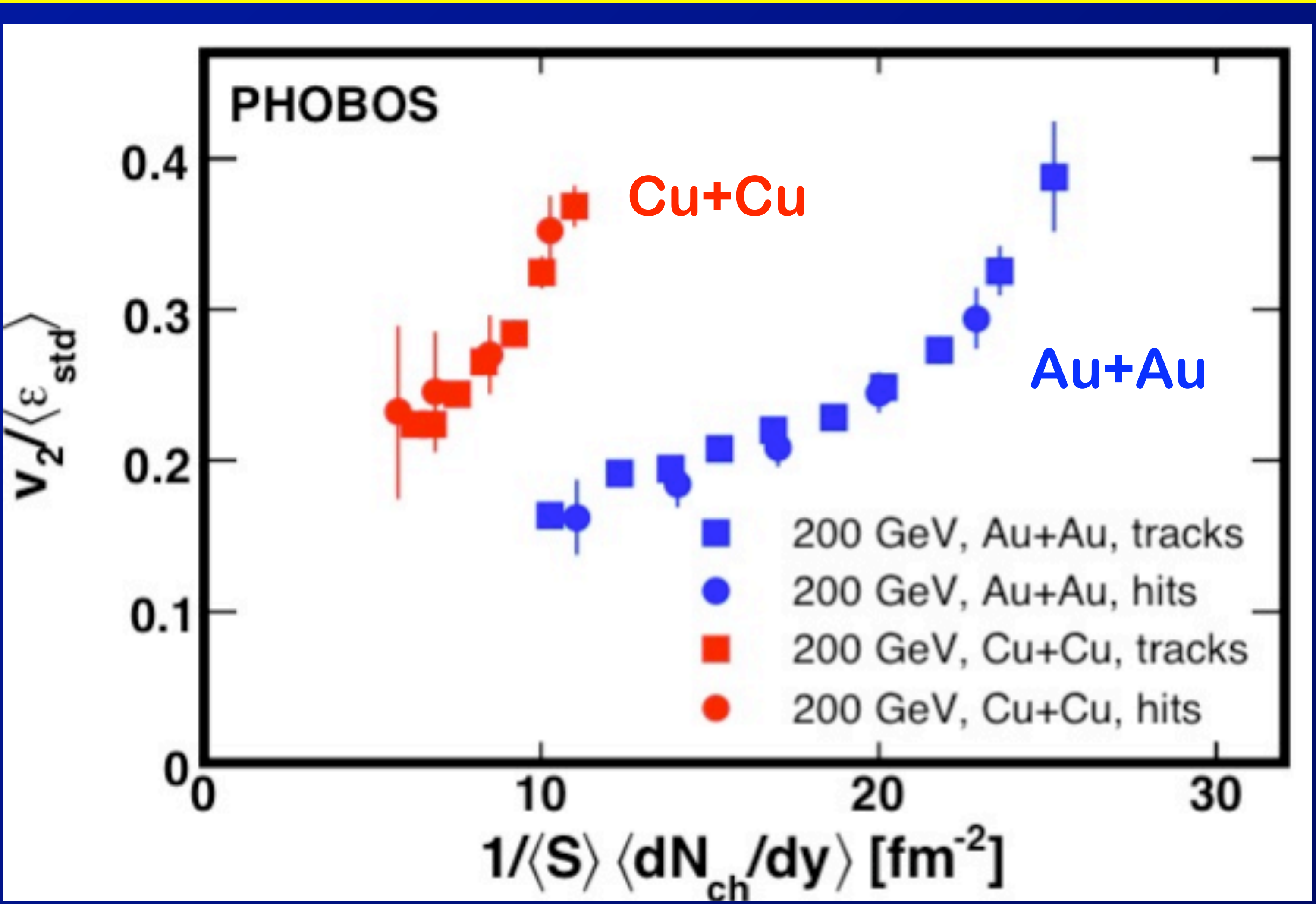
Armesto, Salgado, Wiedemann
Phys. Rev. Lett. 94 :022002,2005

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



Why should it work here?

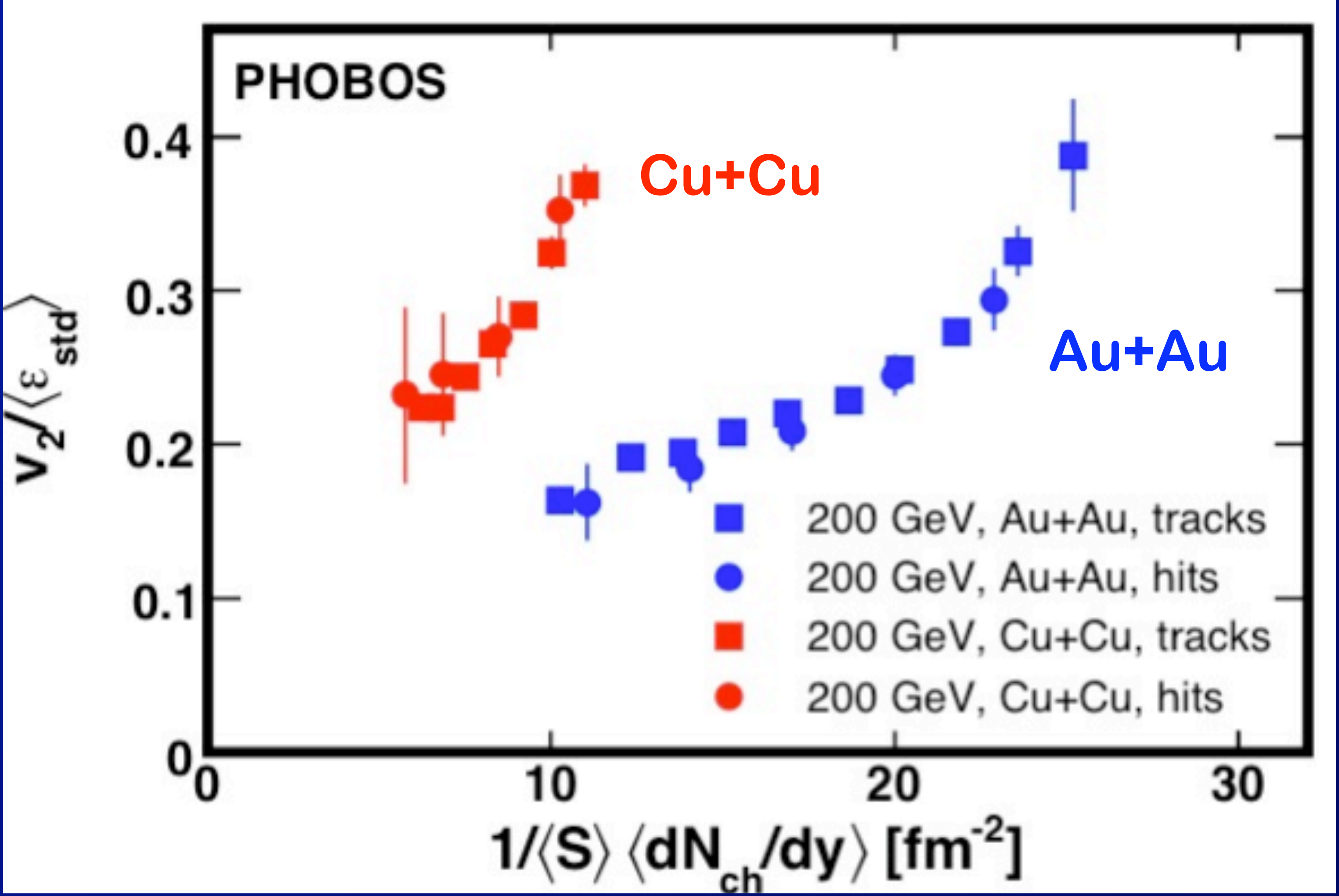
Elliptic Flow and System Size



- Totally unexpected (unphysical) result:

  ⇒ More collectivity in smaller system ??

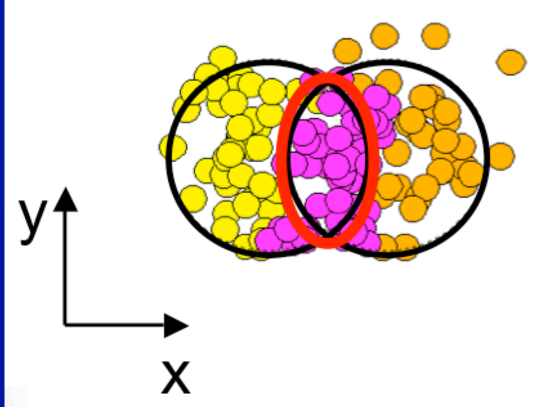
Elliptic Flow and System Size



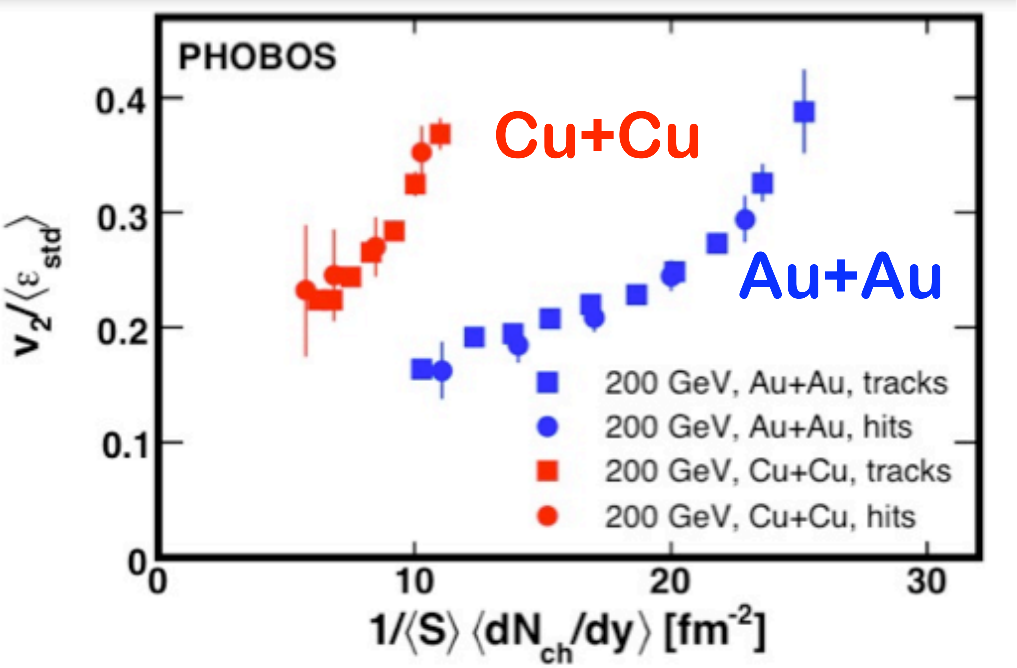
- Totally unexpected (unphysical) result:

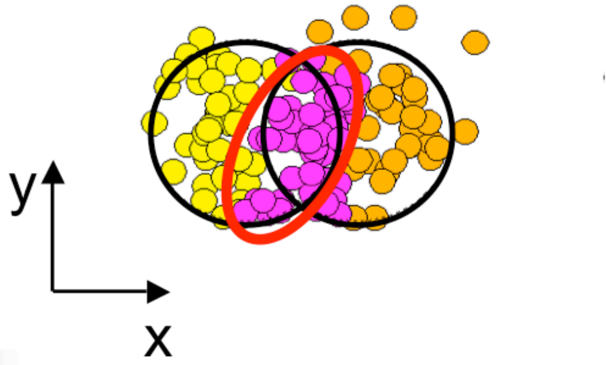
  ⇒ ~~More collectivity in smaller system ??~~

The Problem: Initial State Fluctuations

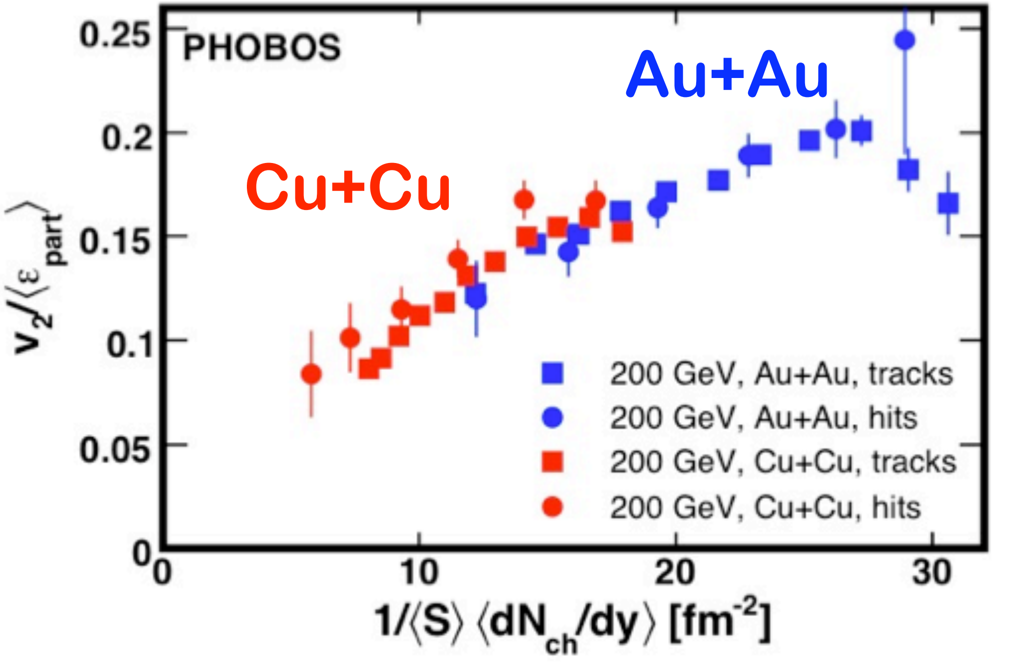


$$\varepsilon_{\mathrm{RP}} = \frac{\left\langle y^2 \right\rangle - \left\langle x^2 \right\rangle}{\left\langle y^2 \right\rangle + \left\langle x^2 \right\rangle}$$

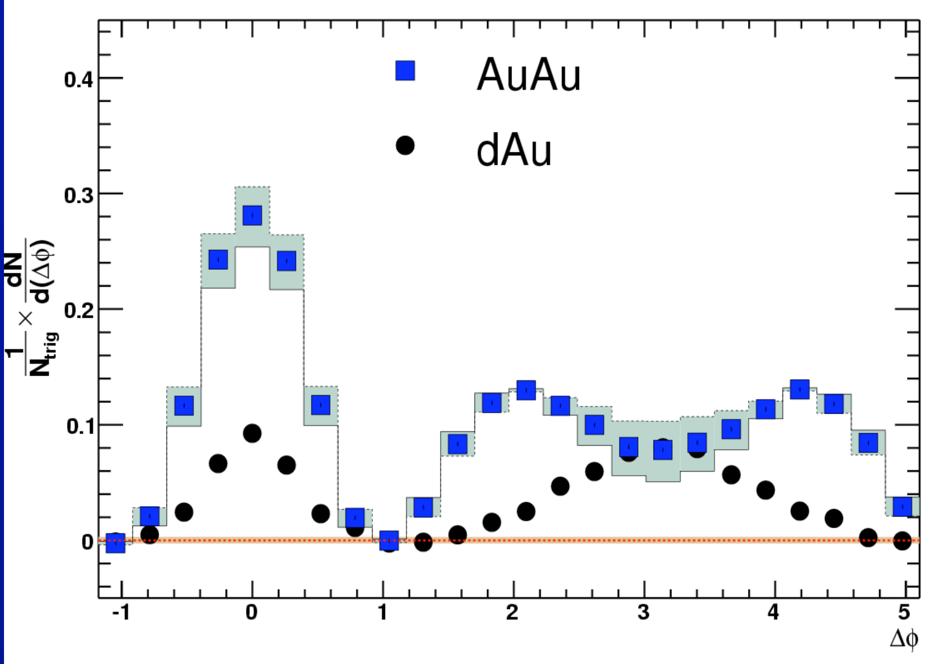


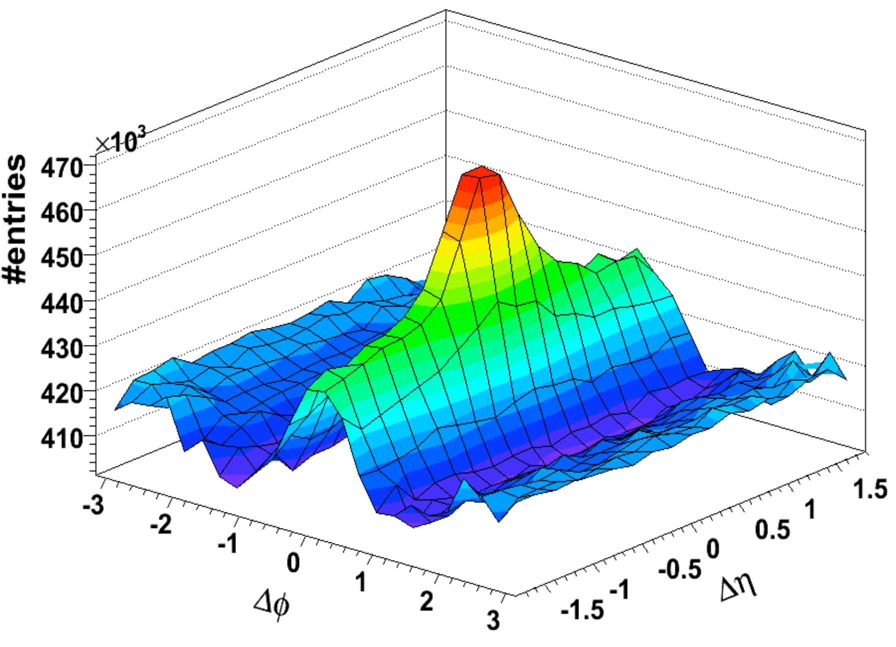


$$\varepsilon_{\mathrm{part}} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



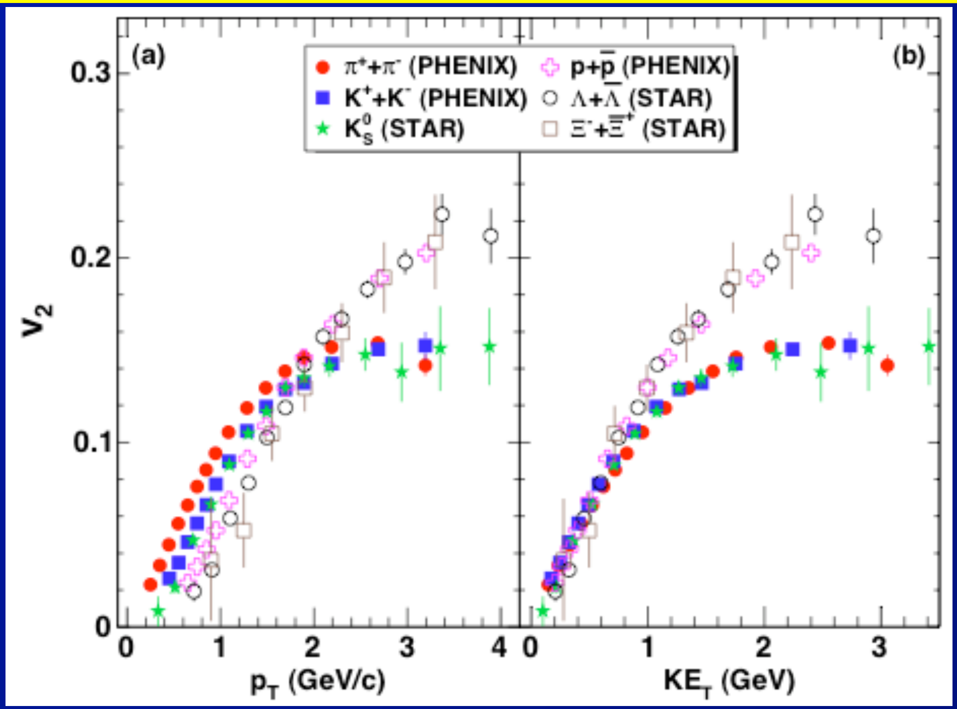
Jet Quenching, Medium Response(?)

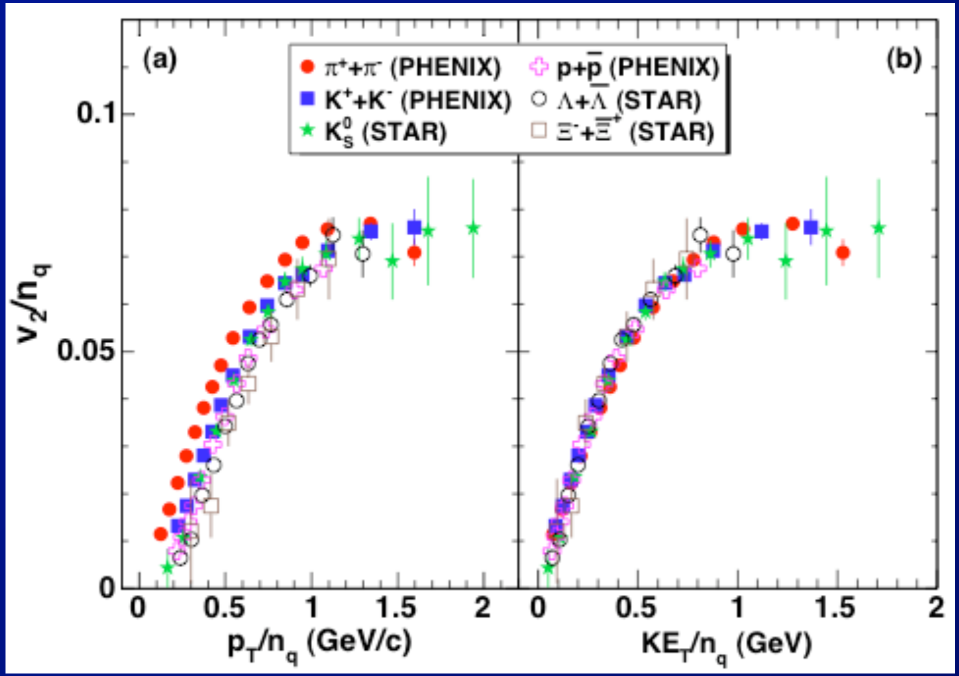




- We see two strong modifications of jet shape in Au+Au collisions
  - Extra peaks in azimuthal angle distribution
  - Broadening of jet in η (longitudinally)
    - ⇒ Neither of these effects is yet understood
    - ⇒ Strong coupling effects? we don't know yet.

v_2 scaling



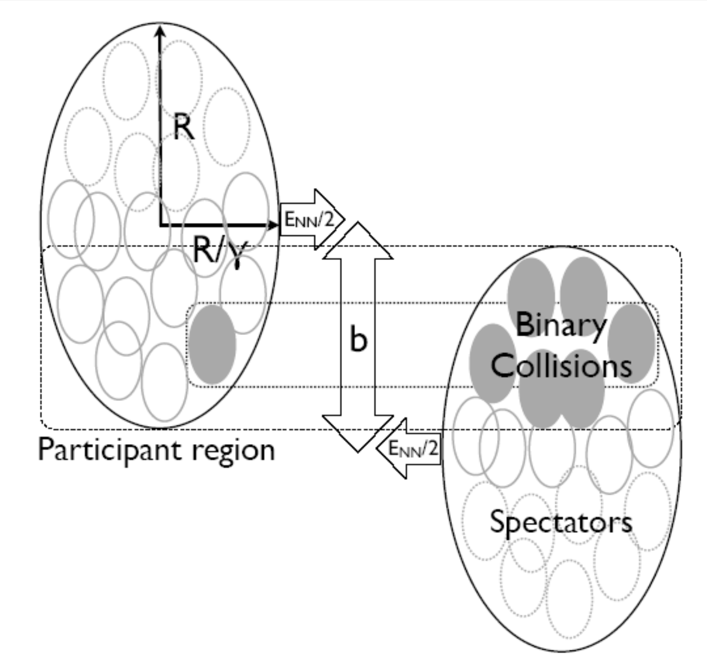


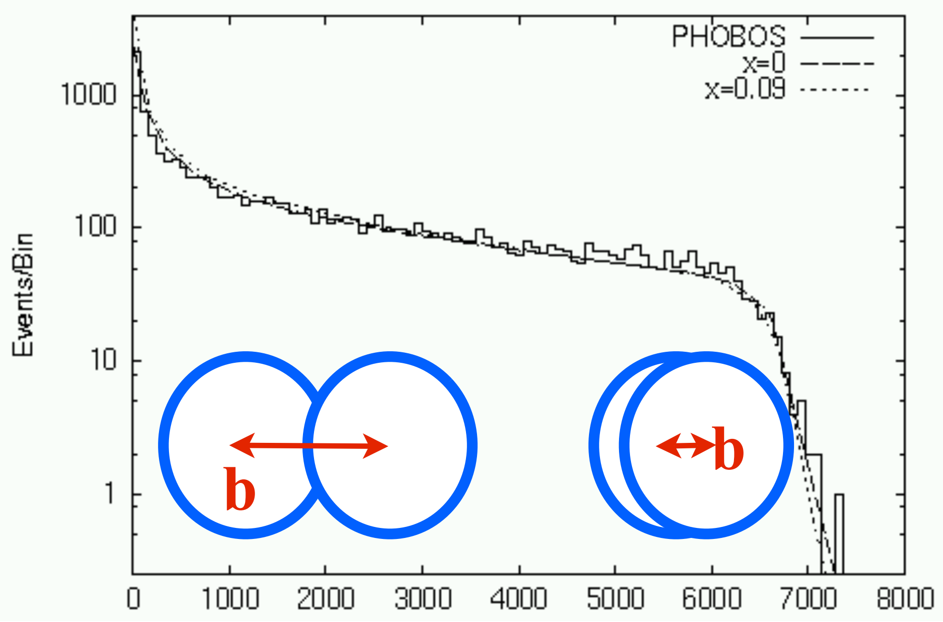
Au+Au minimum-bias @ η=0 (important)

- 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

Geometry and (Charged) Multiplicity





Charged particle multiplicity

- Due to strong coherence in soft processes
  - Soft production ∝ N_{part} (no factorization)
- Factorization in hard processes
  - Hard production ∝ N_{coll}
- Try $N_{chg}^{A-B} = N_{chg}^{p-p}\left(\frac{1-x}{2}N_{part} + xN_{coll}\right)$

⇒Small hard contribution (x < ~ 0.1)