
The Nuclear Equation of State

A View from STAR

Richard Witt

University of Bern



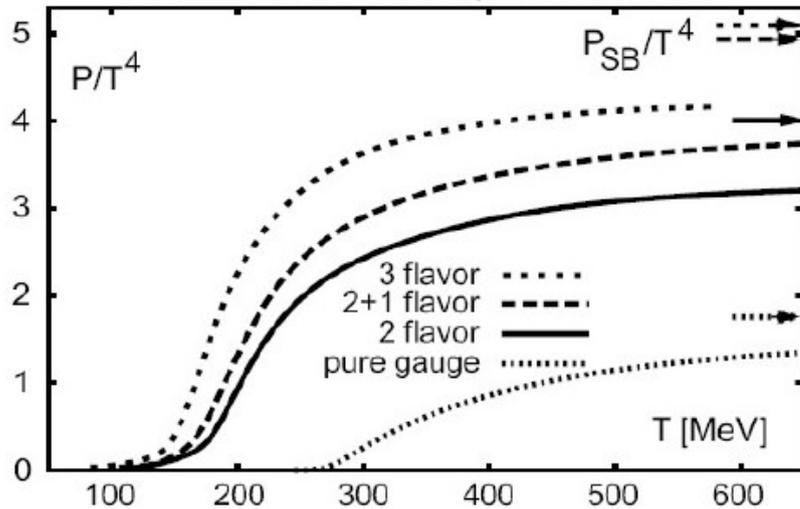
Outline

- Models
 - LQCD
 - Hydro
 - Recombination
 - Statistical
- Data and Comparisons
- Summary and Outlook



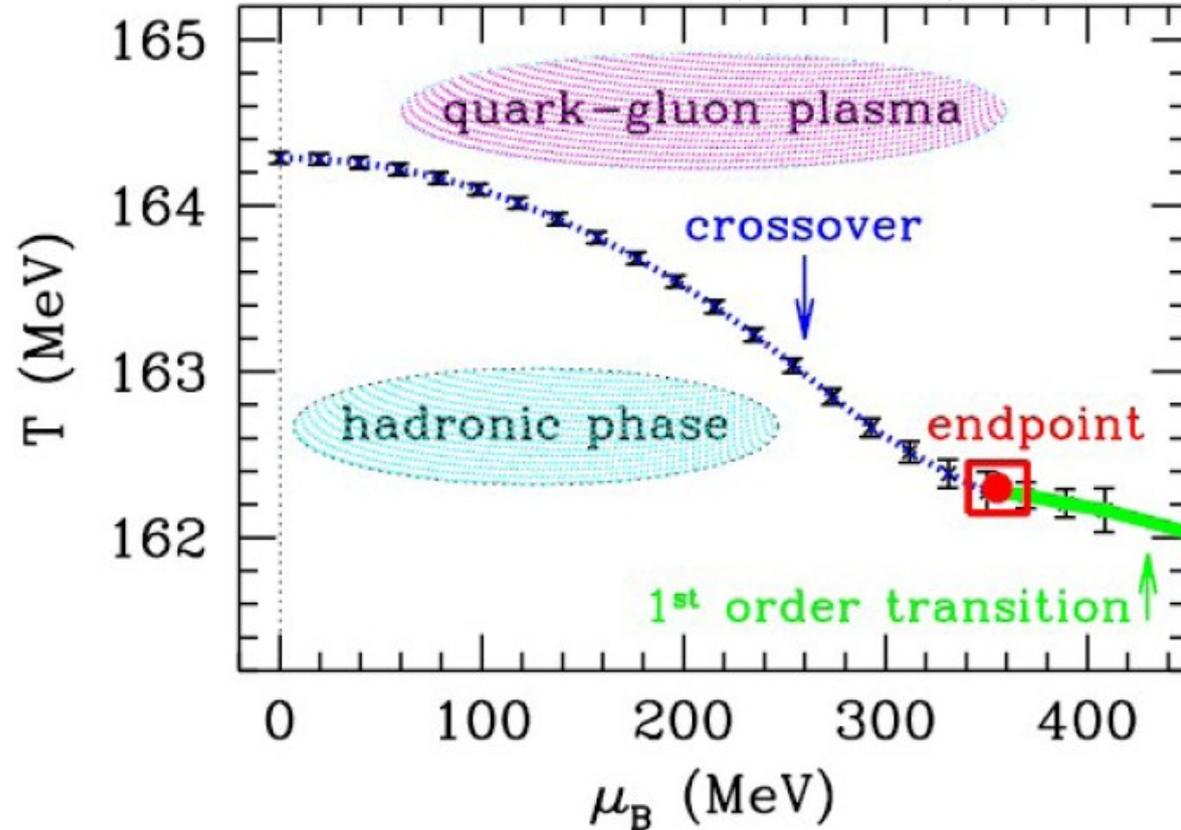
Lattice QCD

F. Karsch, Lecture Notes in Physics 583 (2002) 209



- Phase transition around $T \sim 160$ MeV
- Do not reach SB limit

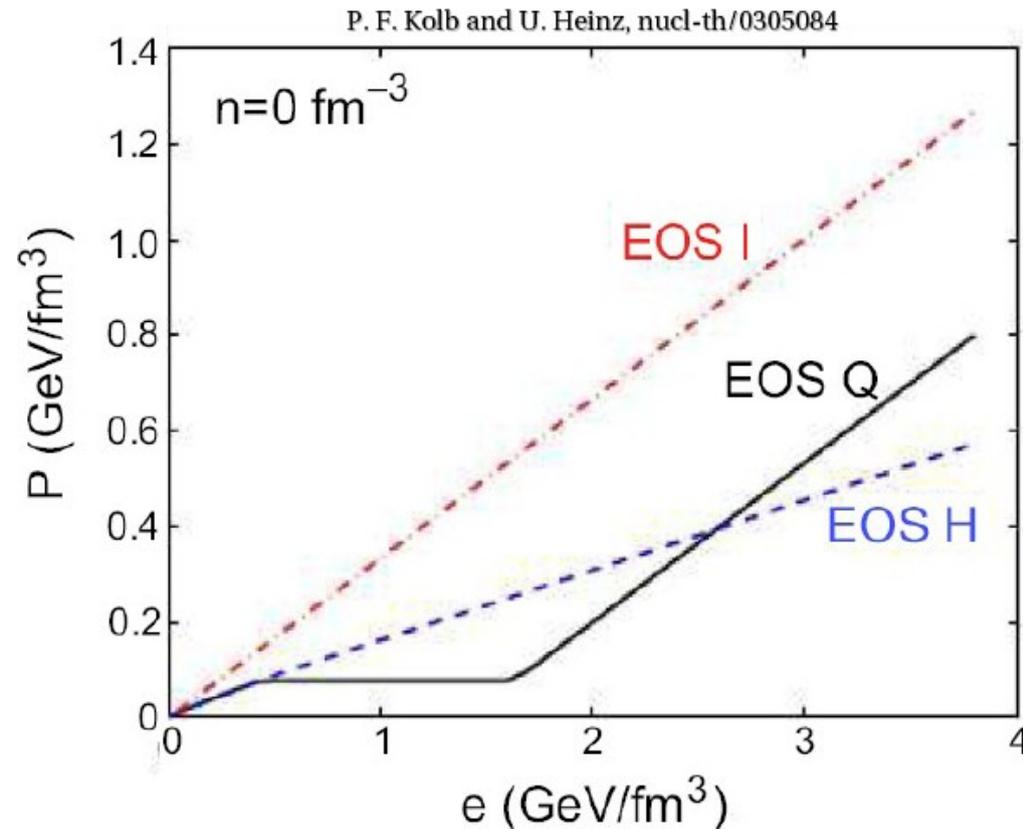
Z. Fodor and S.D. Katz, JHEP 0404 (2004) 050



- Critical point? (above RHIC)
- Crossover transition



Hydrodynamical Models



Assumptions:

- local thermal equilibrium
- boost invariance

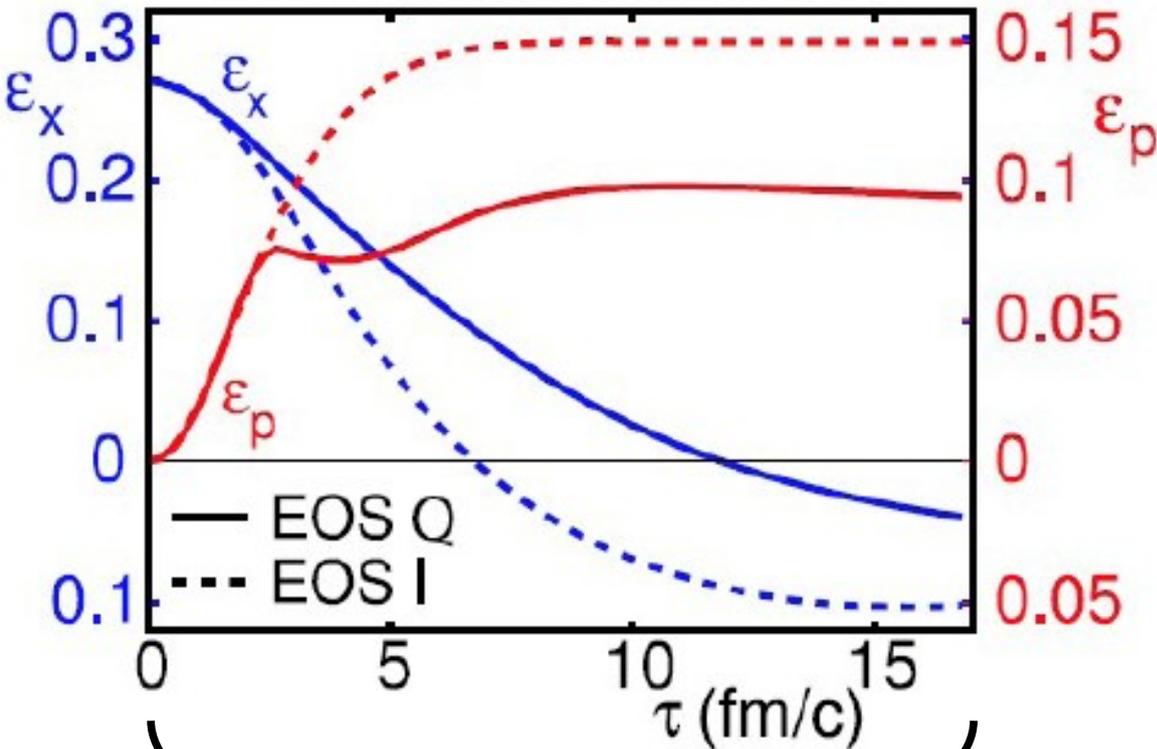
Early and late stages

- parameterized
- EOS Q
 - early Hagedorn resonance gas (EOS H)
 - late ideal gas (EOS I)
 - 1st order phase transition



Hydrodynamical Models

P. F. Kolb and U. Heinz, nucl-th/0305084



- Captures “self-quenching” feature of v_2
- initial high-pressure driven expansion
- reduces anisotropy
- relieves pressure
- Soft point in EOS Q
- stifles pressure buildup

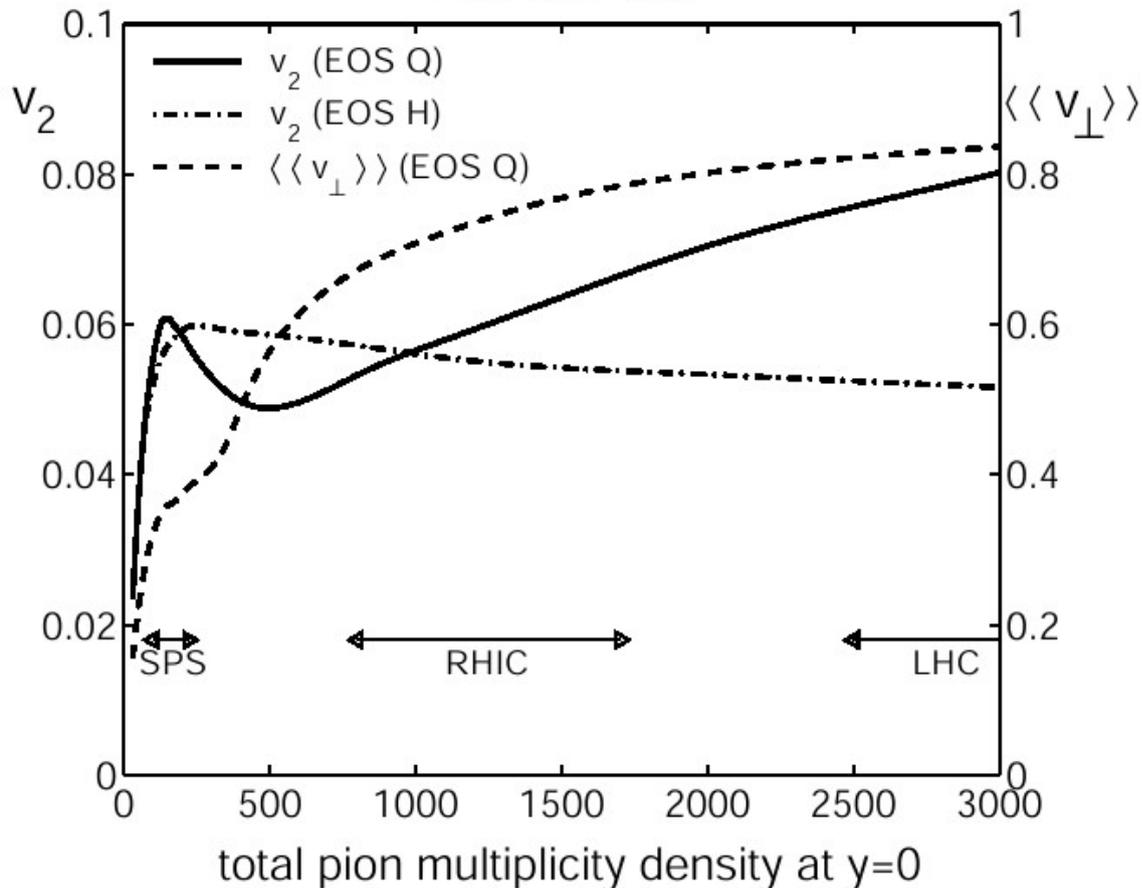
Mid-central 200GeV AuAu ($b=7$ fm)



Hydrodynamical Models

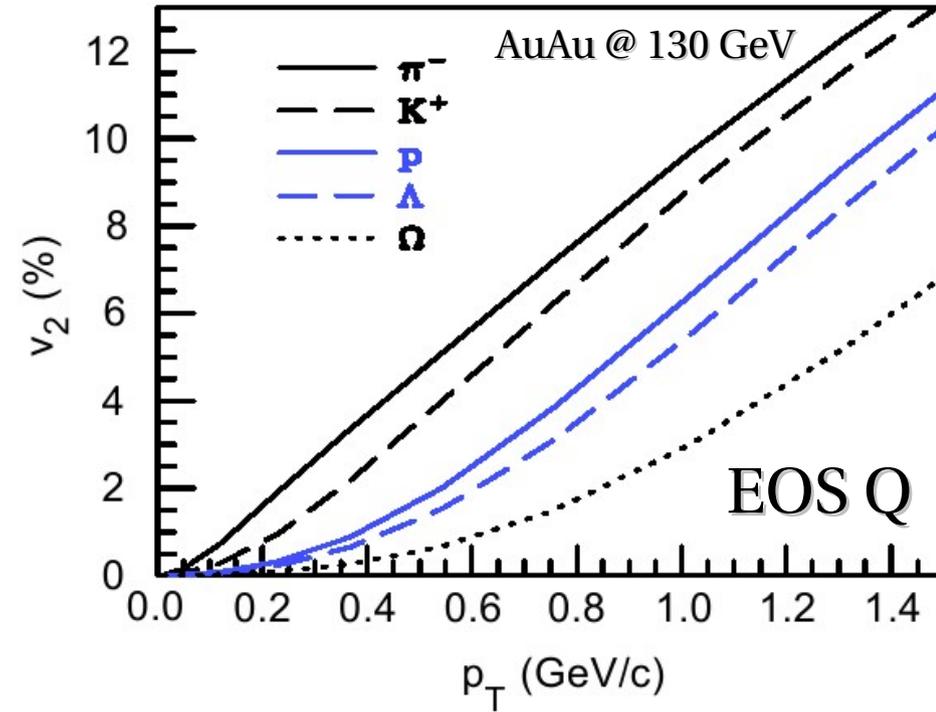
P.F. Kolb, J. Sollfrank and U. Heinz, Phys. Rev. C62 (2000) 054909

Pb+Pb, b=7fm



- Actual multiplicities differ from early predictions

P. Huovinen *et al.* Phys. Lett. B503 (2001)



- Could also use p_T and mass dependence
- FSI affect v_2
 - may need hydro + ...



Recombination Models

- Originally for forward production in $p+p$
 - V.N. Gribov and L.N. Lipatov, Sov. J. Nucl. Phys. 15 (1972) 438 and 675; L.N. Lipatov, Sov. J. Nucl. Phys. 20 (1975) 94; G. Altarelli and G. Parisi, Nucl. Phys. B126 (1977) 298; Yu. L. Dokshitzer, Sov. Phys. JETP 46 (1977) 641.
- Another mechanism in RHI
 - coalescence of thermal partons
- Central assumption at RHIC
 - coalesce thermal *constituent* quarks
- How to relate coalescing constituents with LQCD partons?



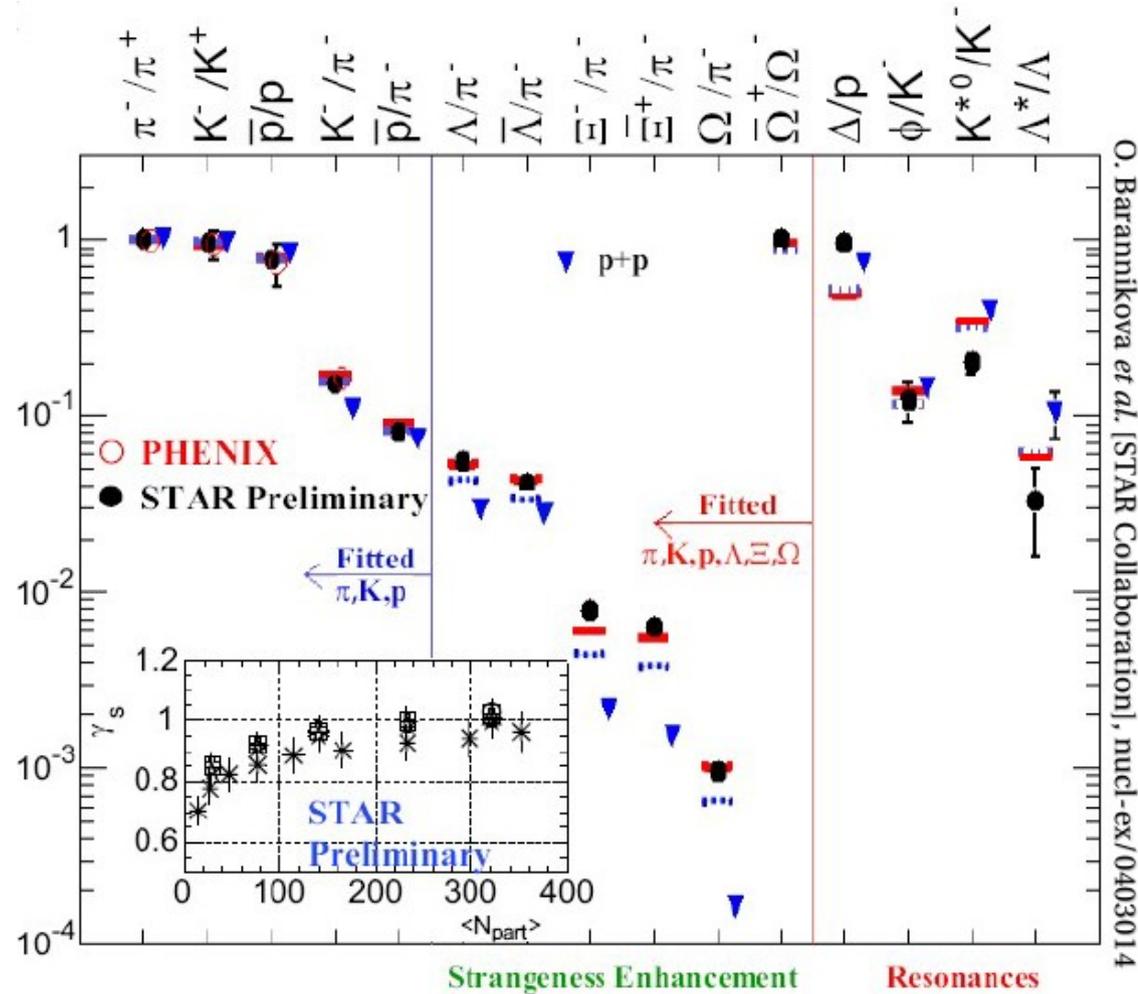
Statistical (Thermal) Models

- Model of hadronization
- Relies on two fundamental assumptions
 - spatially extended massive objects (clusters)
 - all hadronic states equally probable
 - compatible with cluster quantum numbers
- No knowledge of how equilibrium is reached
- Very successful in describing yield ratios
 - even in e^+e^- , $p+p$, $p+A(?)$
- Alone is not enough to verify thermal and chemical equilibrium

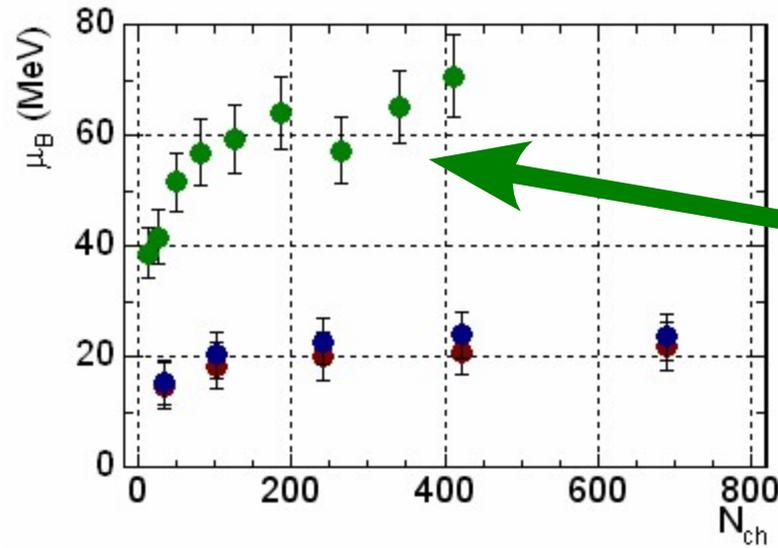
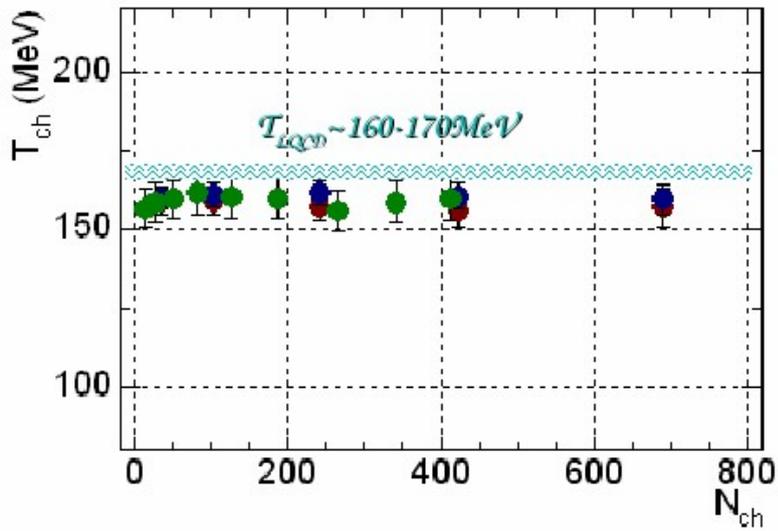


Yield Ratios

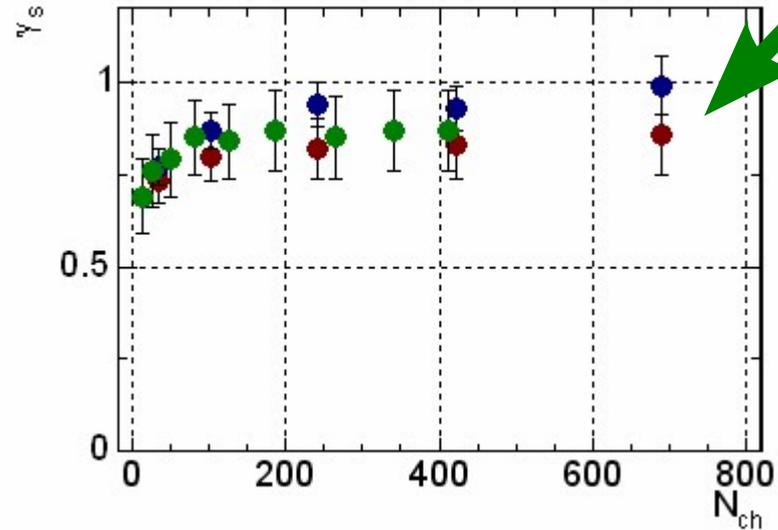
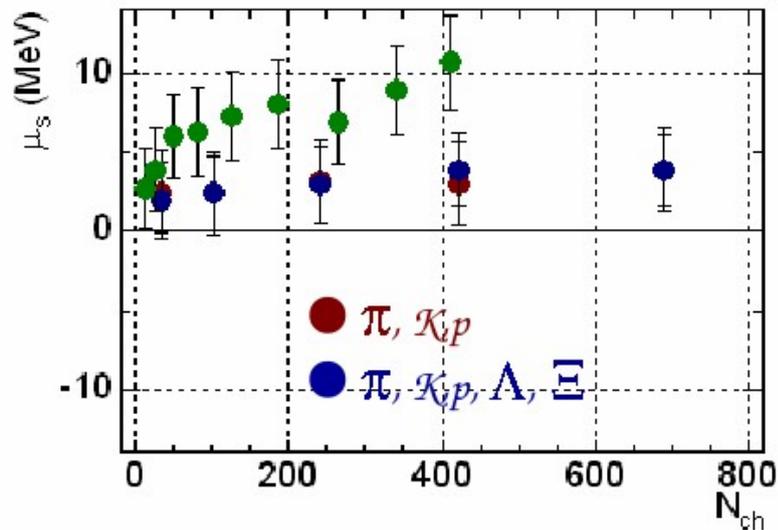
- Relatively large enhancement
 - Ξ and Ω
- Excellent agreement
 - chemical equilibrium?
 - $T_{ch} = 160 \pm 10$ MeV
- Resonance deviations
 - rescattering after chem. FO
- Strangeness saturation?
 - γ_s consistent with unity



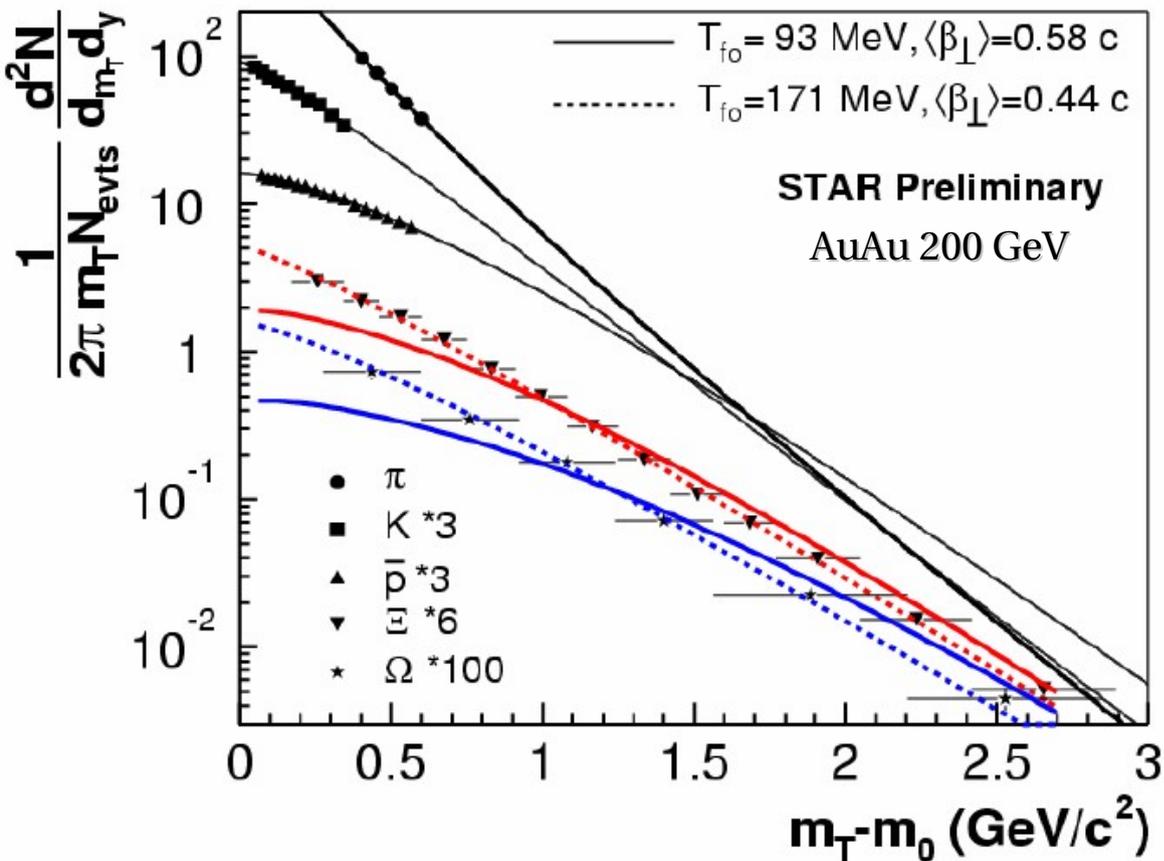
AuAu 200 GeV and 62 GeV



62 GeV in green



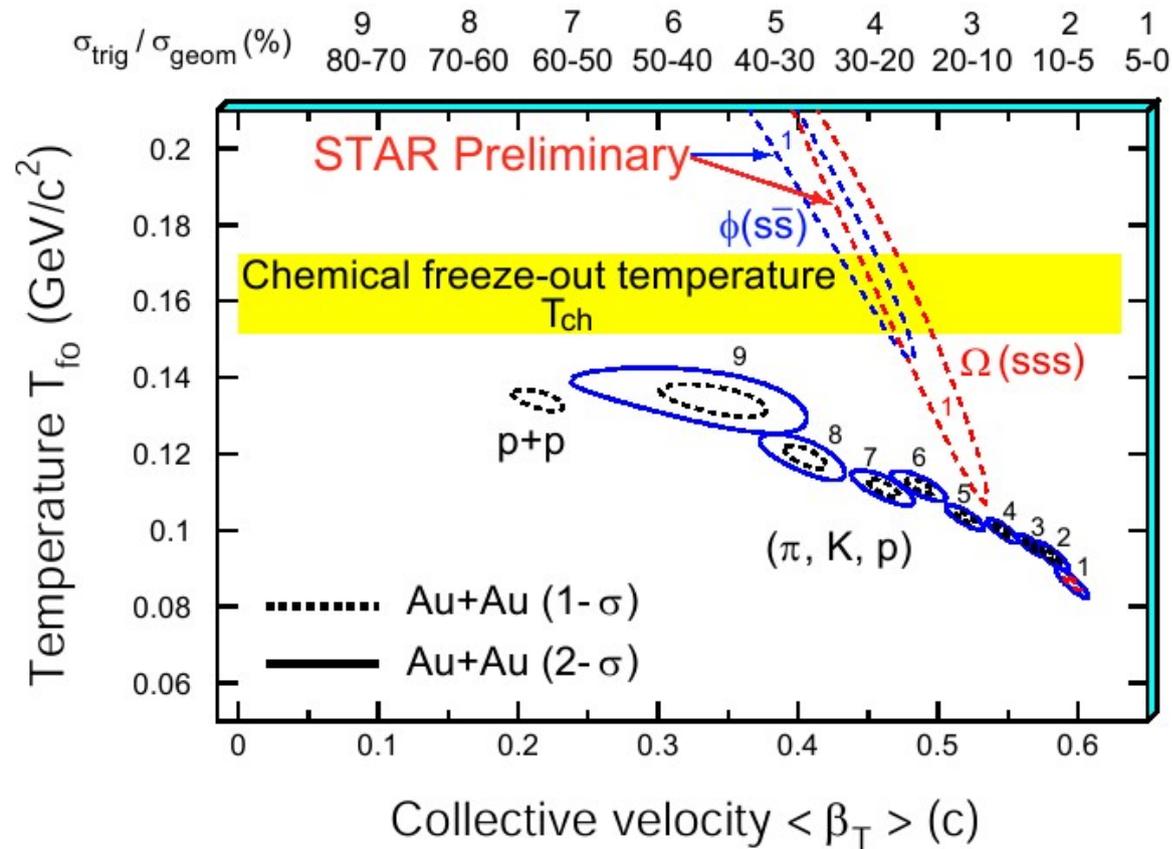
Blastwave Fits and Spectra



- Simultaneous fits
 - Extract T_{kin} and $\langle \beta_T \rangle$
- Careful about feeddown
 - only small effect over STAR p_T range



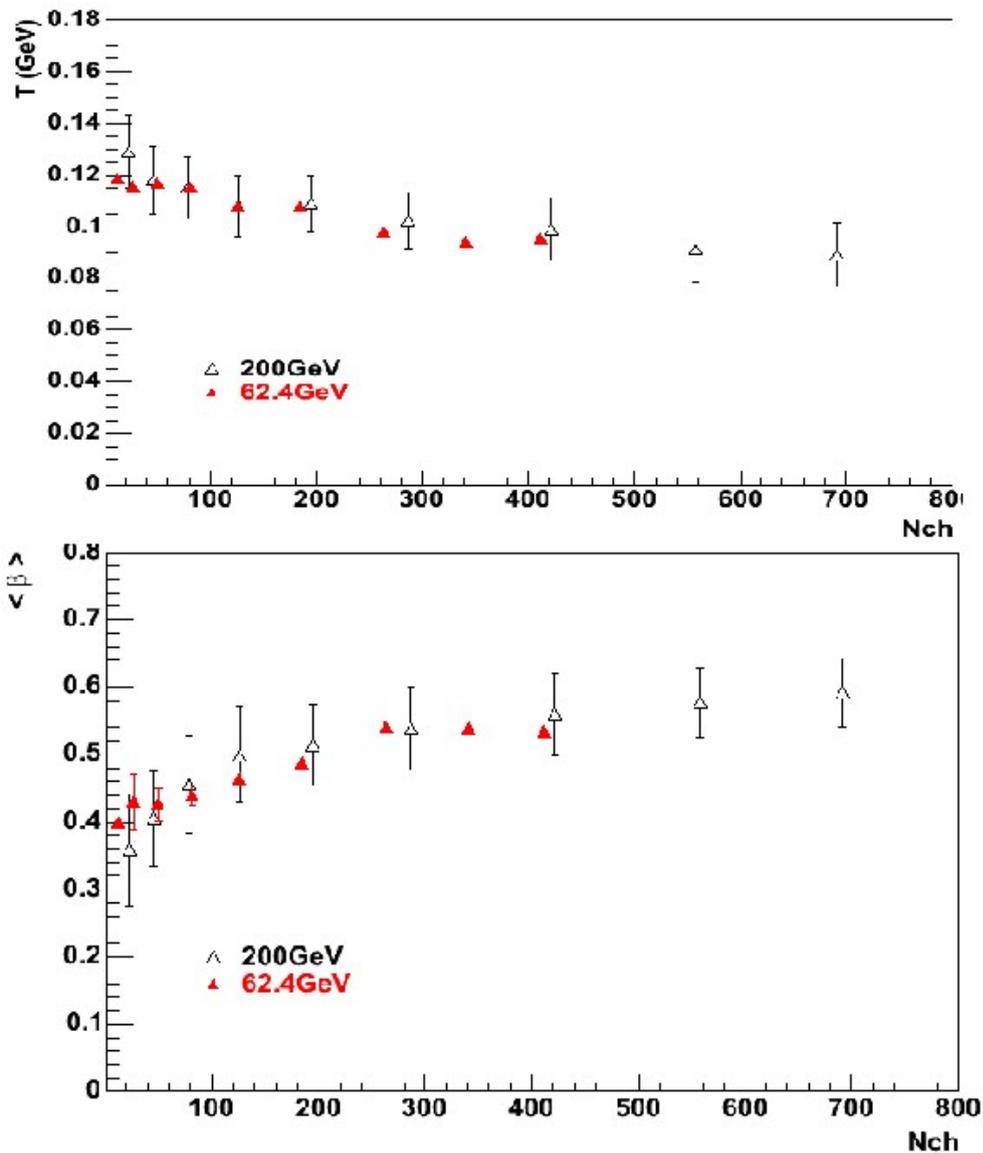
Blastwave Fits



- Bulk *cooler* with centrality
 - Rapid expansion?
- Hotter ϕ and Ω
 - Early decoupling?
 - Partonic collectivity?



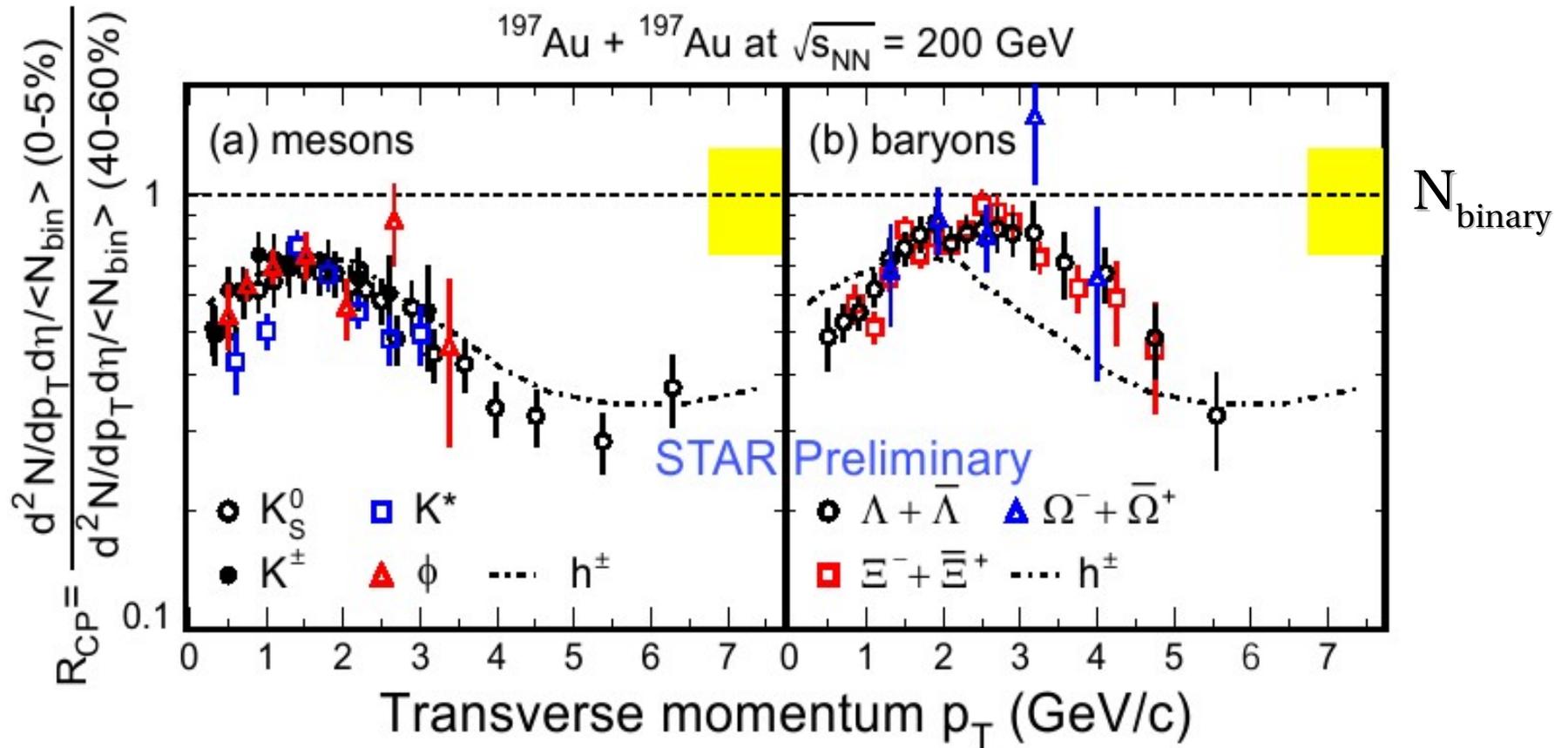
Blastwave in 200 GeV and 62 GeV



- Consistent parameters
 - at both energies
 - across centrality
- Hydro?



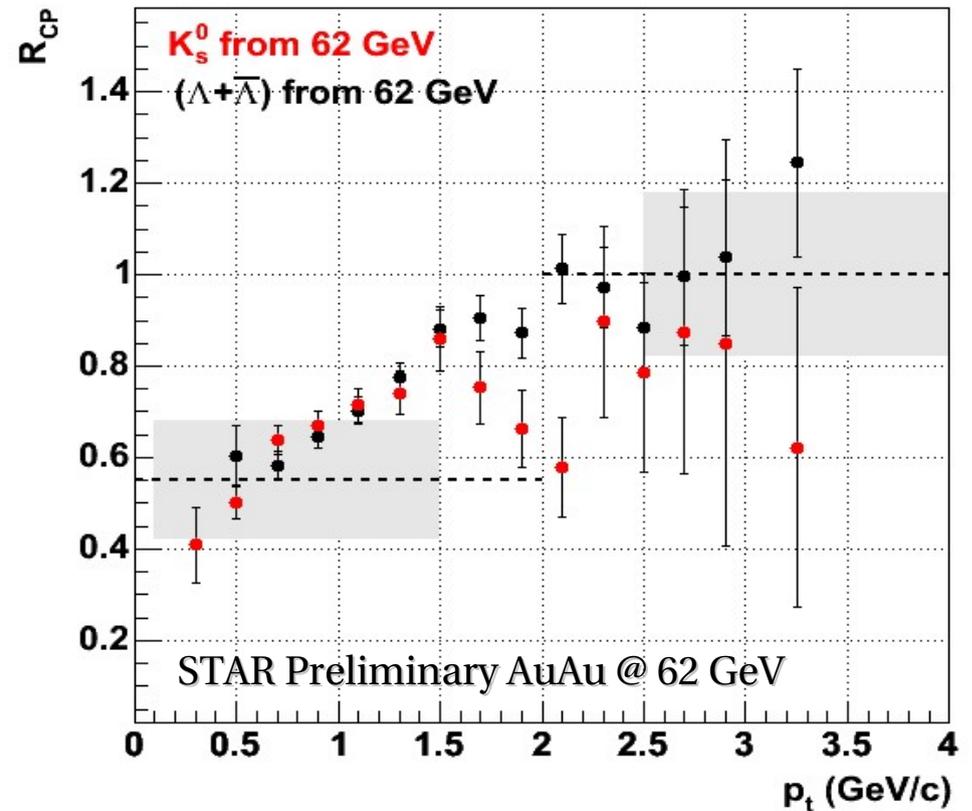
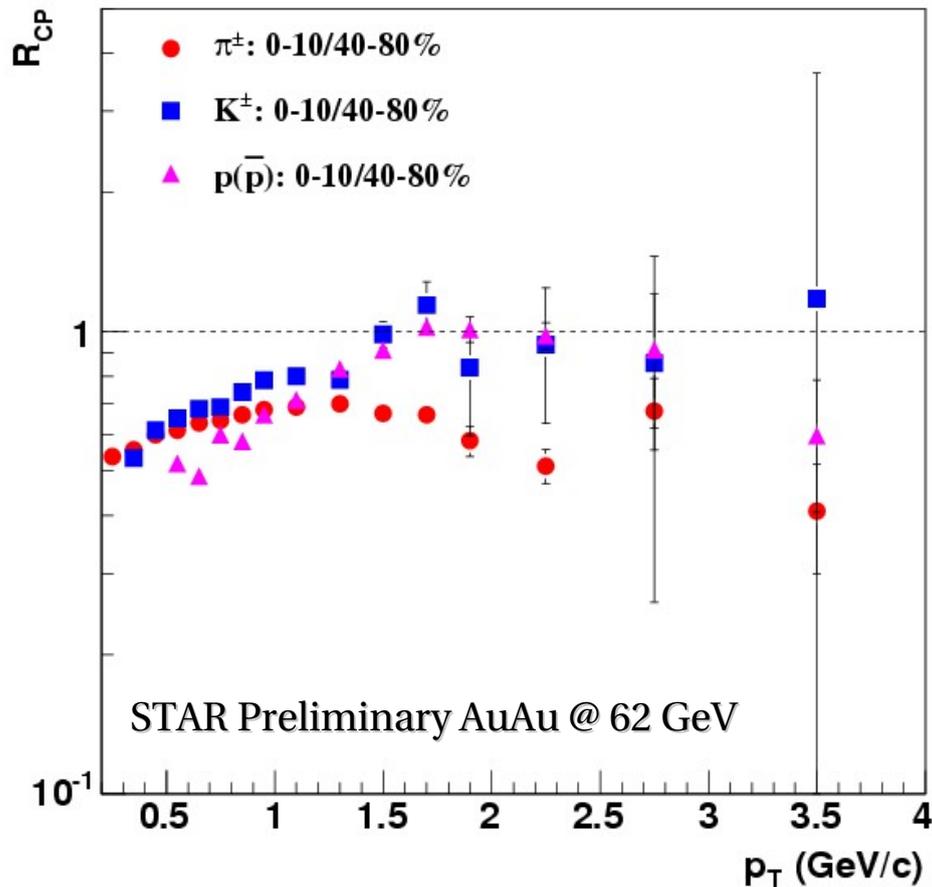
R_{cp}



- Ratio of central to peripheral
- Depends on number of valence quarks



R_{CP} for 62 GeV

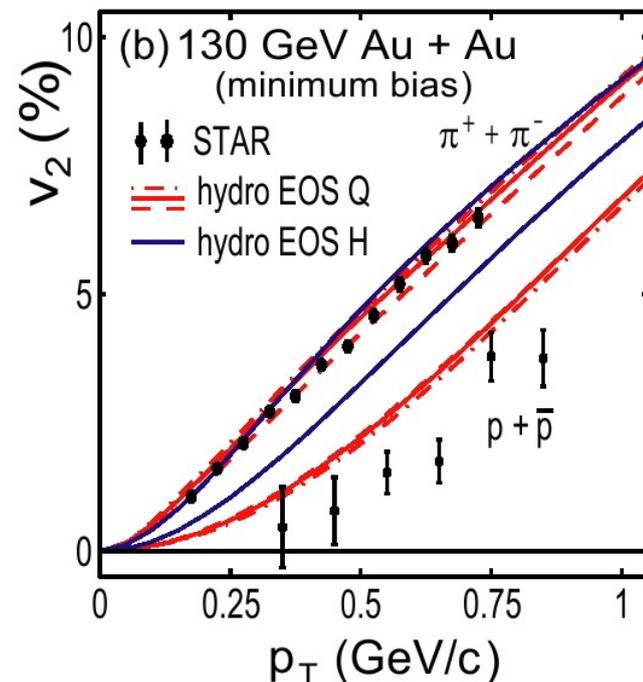
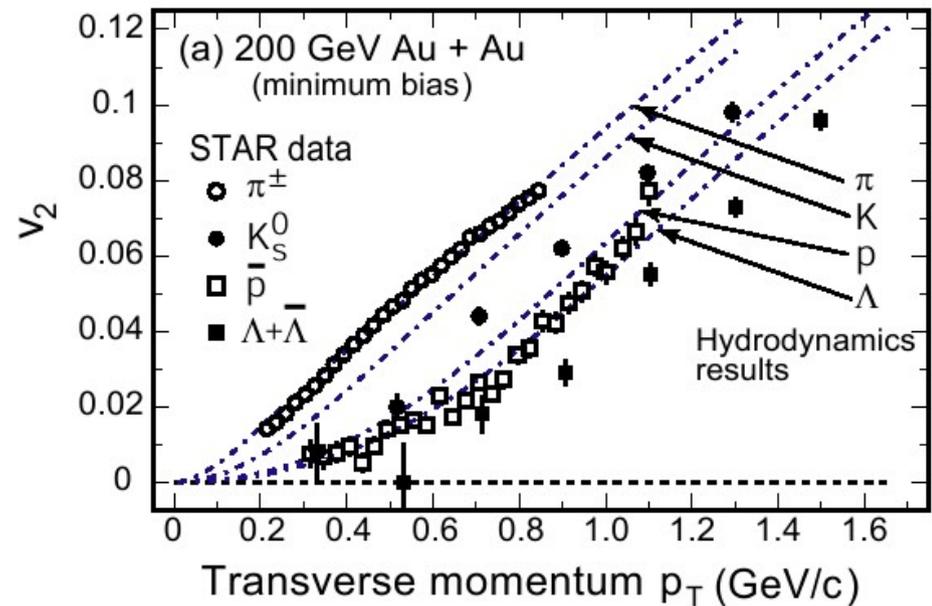


- Same baryon-meson difference in intermediate p_T
- Still statistics limited



Elliptic Flow and Hydro

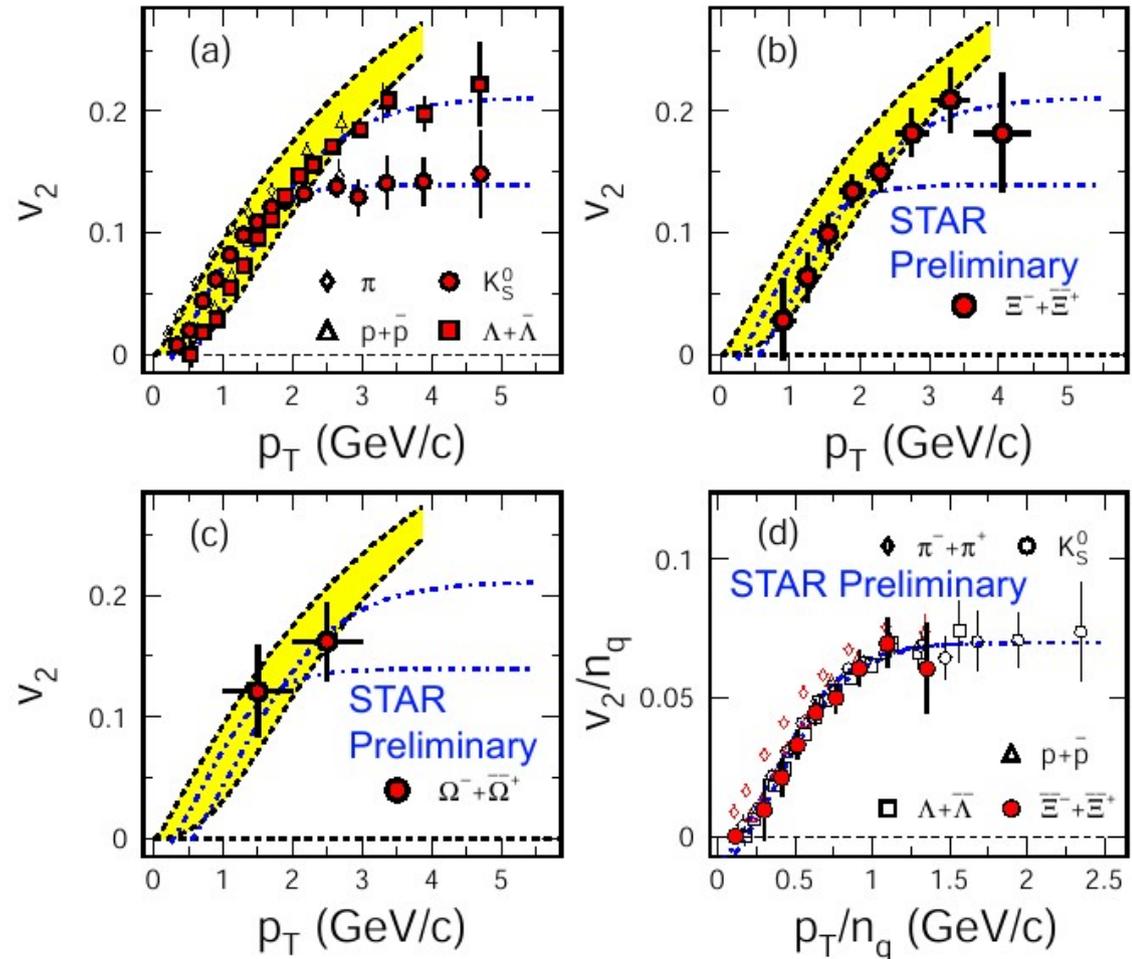
- Clear mass dependence
 - Strong transverse velocity boost
- Hydro shows good agreement
 - Tuned to particle spectra ($b=0$)
- Best agreement:
 - early ($\tau < 1$ fm/c) thermal equilibrium
 - EOS with soft point at LQCD prediction
- Consistent with thermalized sQGP



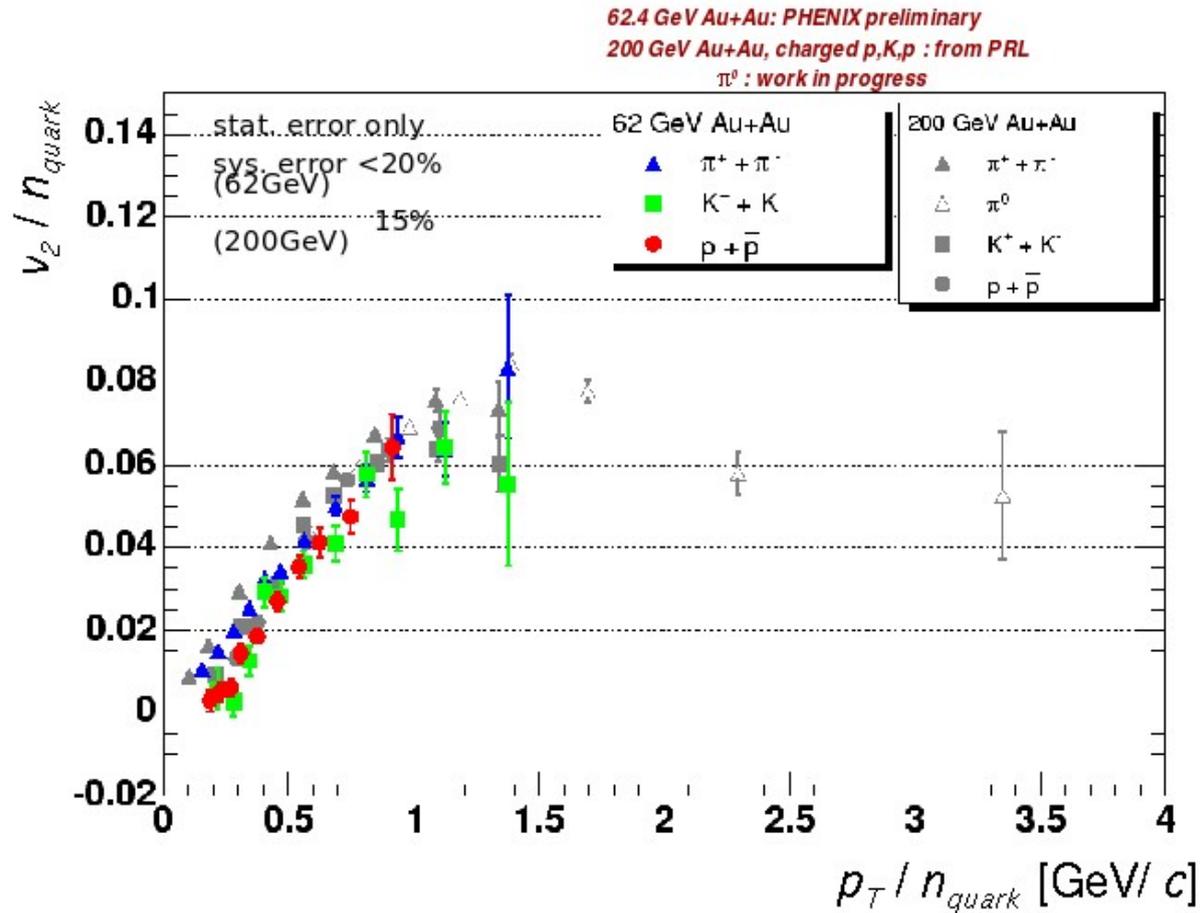
Elliptic Flow and Reco

X. Dong, S. Esumi, P. Sorensen, N. Xu, and Z. Xu, Phys. Lett. B597 (2004) 328

- v_2 saturates above 1.5-2 GeV/c
- meson-baryon difference
- Constituent quark scaling seems to hold
- What about low- p_T ?
 - hydro \rightarrow mass dependence



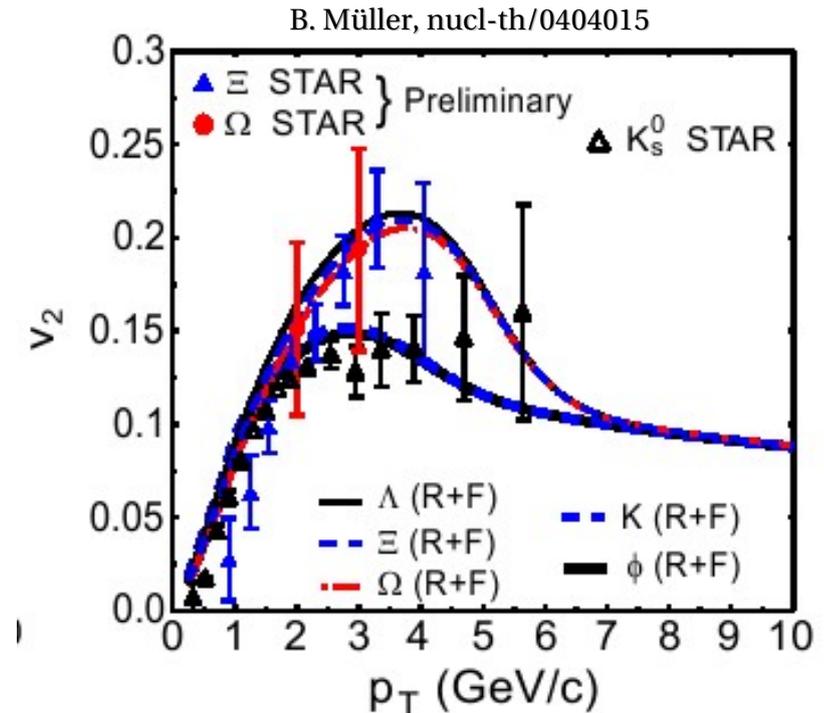
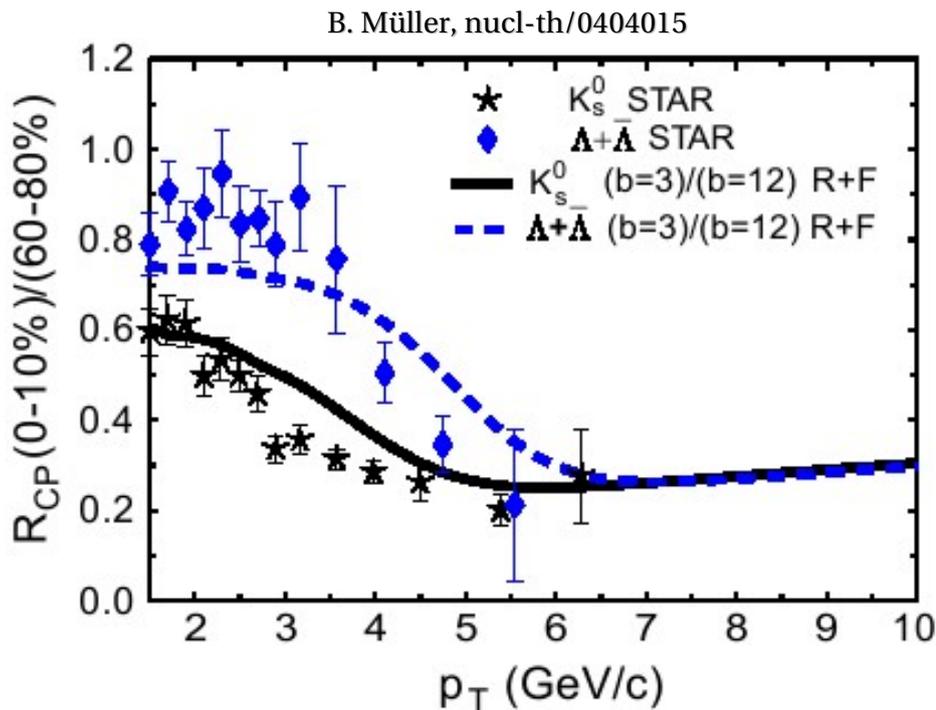
PHENIX and Reco



- Same scaling
 - in 62 GeV and 200 GeV



v_2 , R_{CP} , and Reco



- More statistics needed
- Both R_{CP} meson-baryon difference and v_2 scaling
 - coalesce thermal constituent quarks at p_T/n_q
 - fragmentation of hard-scattered partons



Summary and Outlook

- STAR 200 GeV AuAu results well described by Thermal Model
 - $T \sim 160\text{-}170$ MeV, $\mu_B \sim 23\text{-}25$ MeV, $\mu_S \sim 3\text{-}5$ MeV, $\gamma_S \sim 0.9\text{-}1.0$
 - Similar T and γ_S for 62 GeV
- Blastwave fits may indicate rapid expansion after FO_{chem}
 - Hotter ϕ and Ω may indicate collective partonic motion
 - Similar results from 62 GeV
- R_{cp} shows meson-baryon splitting at intermediate p_T
 - Similar for 62 GeV, need more statistics
- Hydro describes v_2 in RHI for the first time
 - Best agreement with early thermalization and EOS with soft point

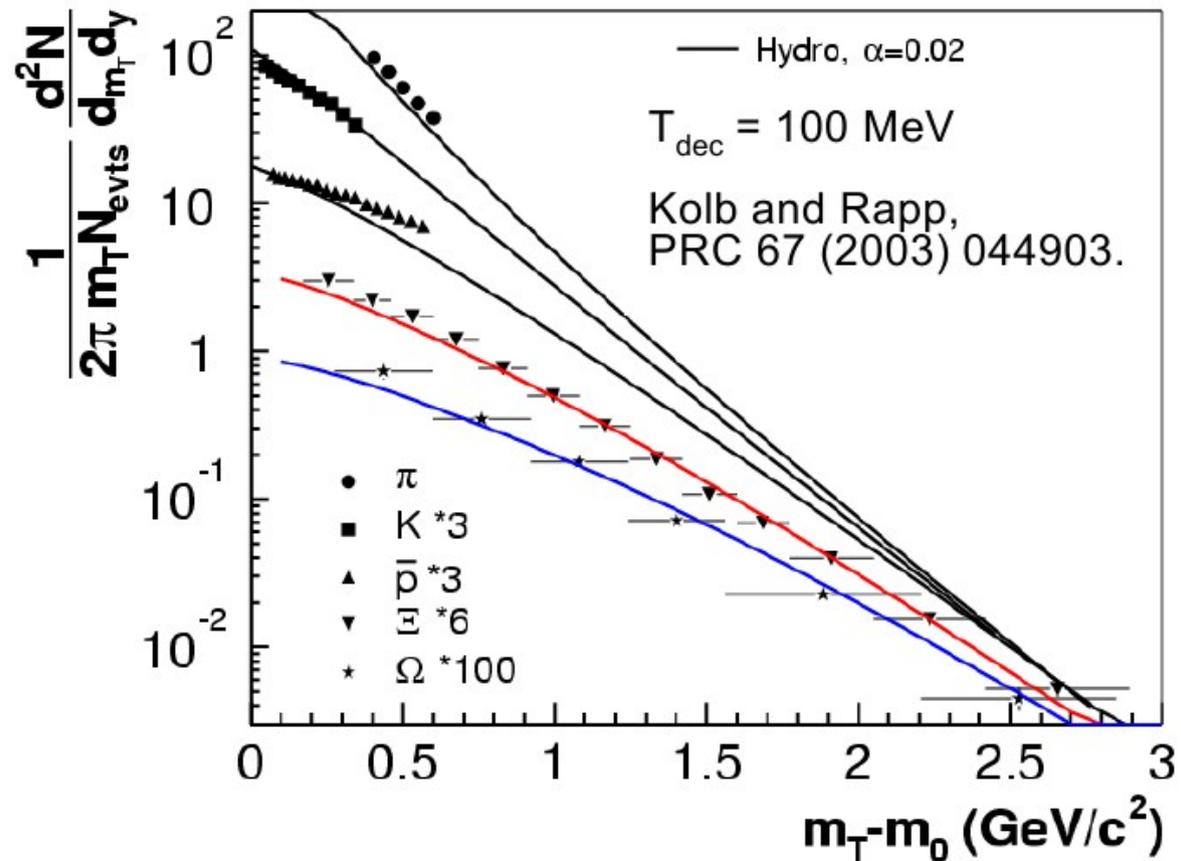


Summary and Outlook

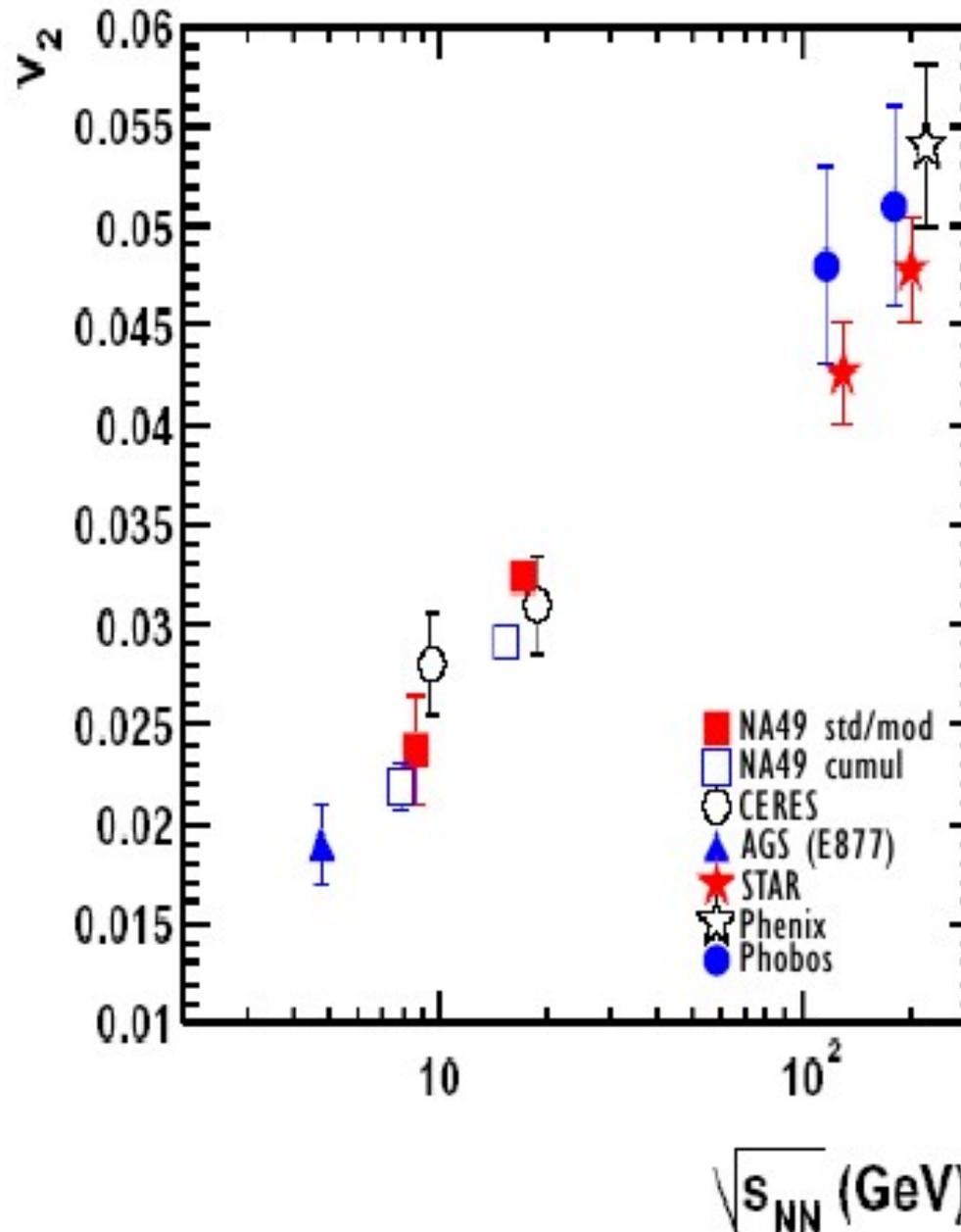
- Constituent quark coalescence
 - explain the baryon-meson splitting in R_{cp} and v_2
 - coupled with fragmentation can be extended to higher p_T
- What next?
 - Extend p_T in *both* directions
 - Improve statistics
 - Better resonance measurements



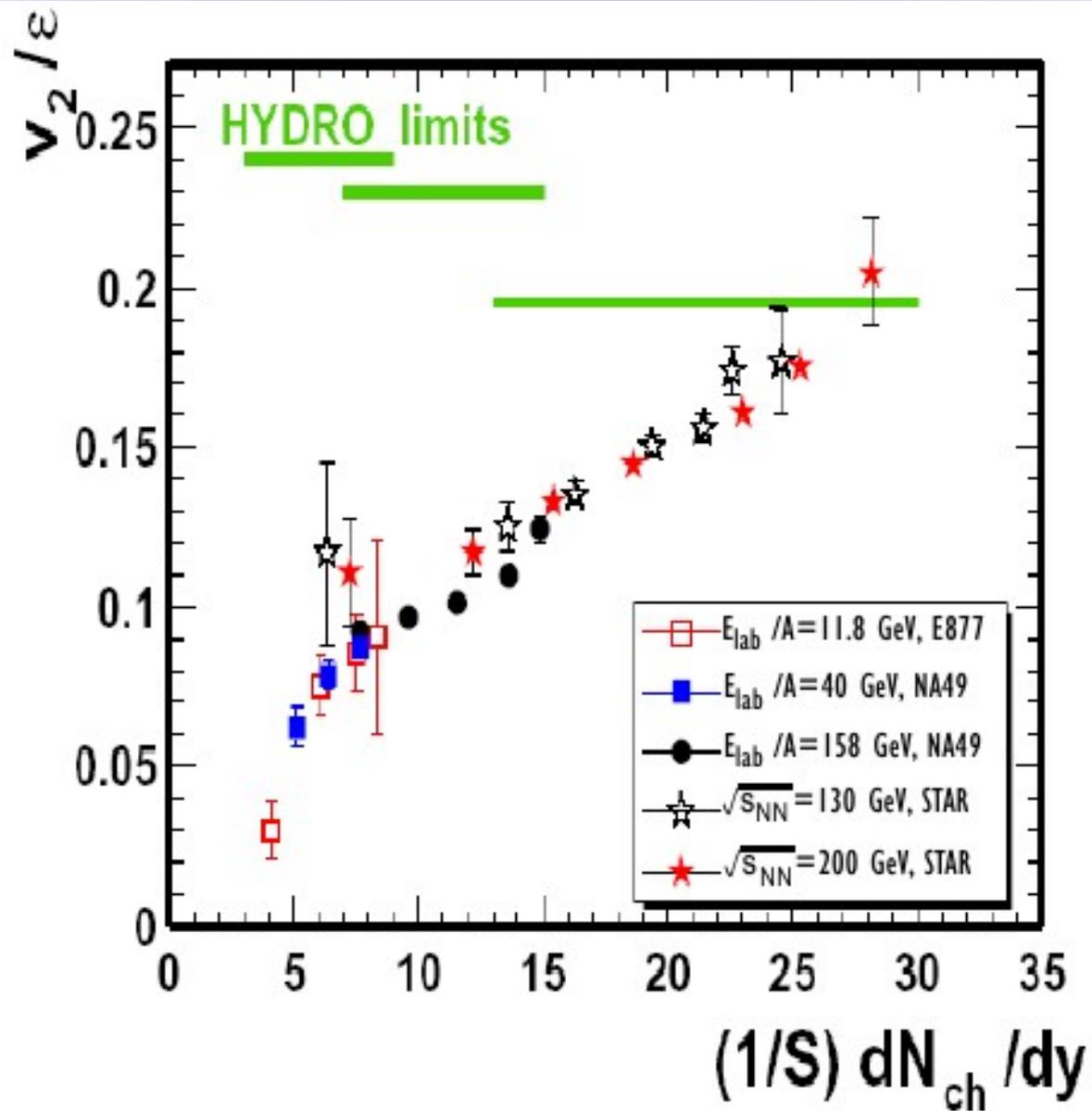
STAR Spectra and Hydro



v_2 vs. Collision Energy



v_2 and Hydro Limit



Transverse Mass Spectra

