Lattice QCD + Hydro/Cascade Model of Heavy Ion Collisions

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Outline

- Calculation of T_c via lattice QCD – domain wall fermion method
- Parameterization of LQCD EoS
- Model of heavy ion collision including:
  - Initial, non-equilibrium flow (Pratt)
  - 2D viscuous hydrodynamics (Romatschke's vh2)
  - Parton cascade (URQMD)

Lattice QCD with Domain Wall Fermions

Staggered

- Many recent high-precision calculations are performed with some variant of staggered fermion discretization (stout-link, asqtad, p4, HISQ)
- Single quark flavor for staggered fermions correspond to 4 flavors of continuum quark flavor.
- Spontaneous breakdown of SU(4) chiral symmetry -> 15 Goldstone bosons.
- However, lattice effects explicitly break SU(4) chiral symmetry -> U(1). Only one GB. Other pions have non-zero mass of $O(a^2)$
- To recover a one flavor theory on the lattice, take ¼ root.

Domain Wall Fermions

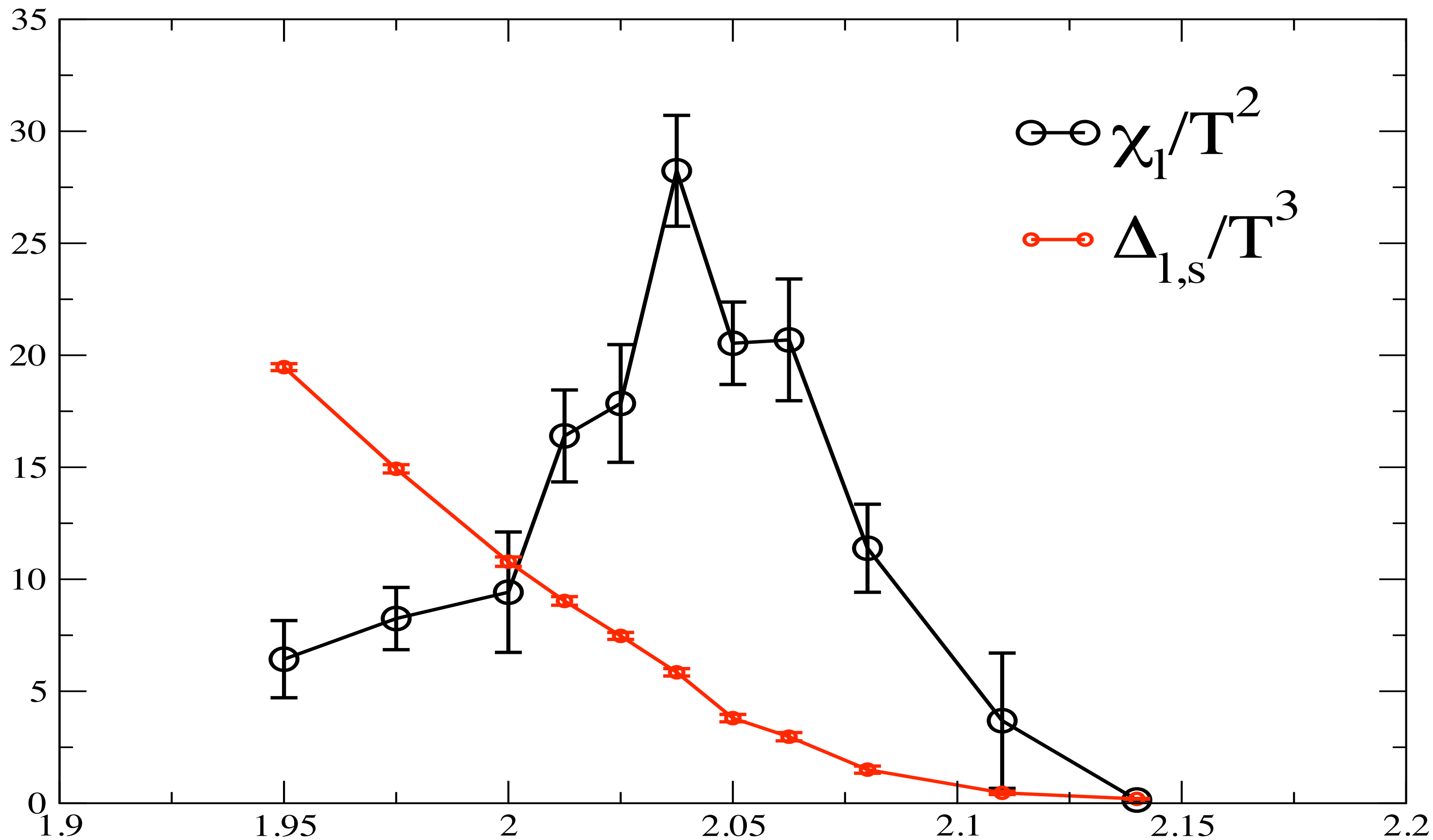
- Domain Wall Fermions (DWF) faithfully preserve $SU(N_f)$ chiral symmetry to arbitrary accuracy even at finite lattice spacing.
- Therefore, meson spectrum, *e.g.* 3 light pions, is more correctly reproduced by DWF method.
- Penalty: QCD with DWF is recovered as a 4-d space-time slice of a 5-d theory.

Staggered v. DWF

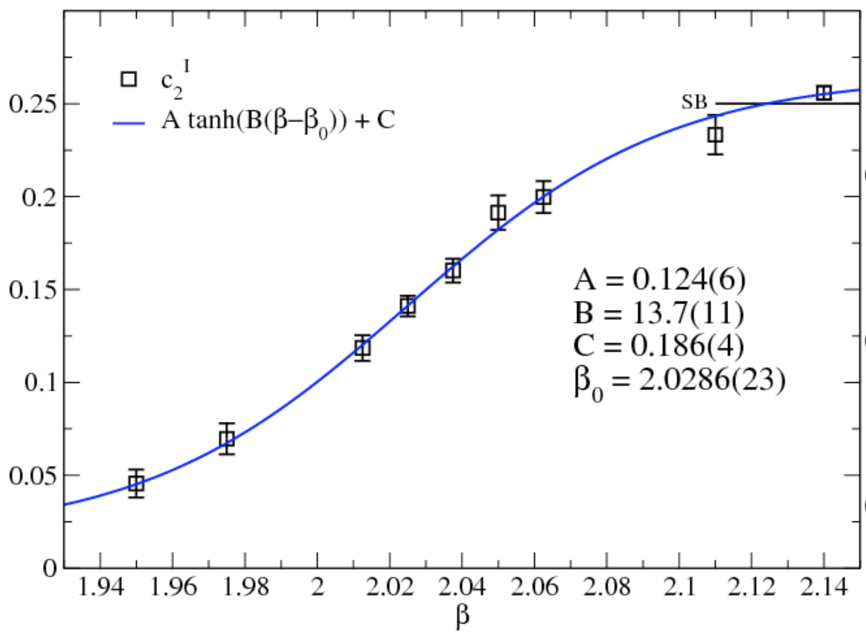
- Primary reason to use staggered fermions: cost.
- Size of fifth dimension in DWF calculations: 8-32.
- Staggered fermions approach smaller lattice spacing at high precision faster than DWF.
- Since $T = 1/(N_t a)$, lattice calculations are done at fixed N_t and varying lattice spacing.
- Until recently, only large lattice spacings feasible for exploration of finite T QCD (N_t=4, 6). In this regime, DWF formulation does not work so well

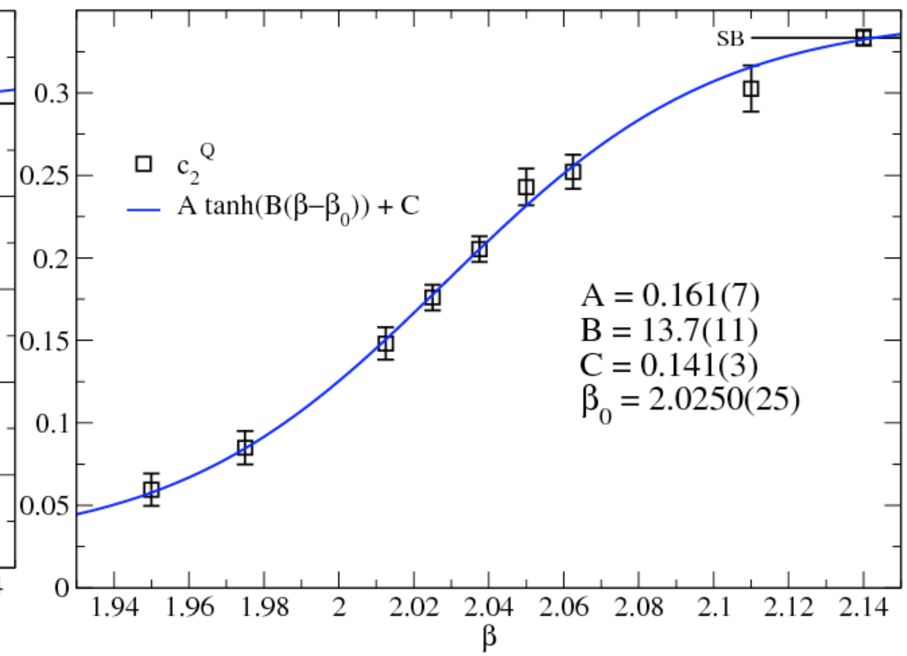
DWF at $N_t = 8$

- Well-known disagreement for T_c among staggered fermion calculations. Cannot agree on whether chiral, deconfining transitions are distinct. T_c = 150-200 MeV
- Calculations at N_t=8 for DWF are feasible. Useful check on the staggered calculations.
- Work done in collaboration with RBC Collaboration (arXiv:0911.3450)
- Vary lattice coupling ($\beta=6/g^2$) to change temperature.
- Calculate chiral, deconfinement observables.



- χ_l/T^2 -> Chiral susceptibility. Peaks in transition region
- $\Delta_{l,s}/T^3$ -> Chiral condensate. Non-zero at low temperature, zero at high temperature.



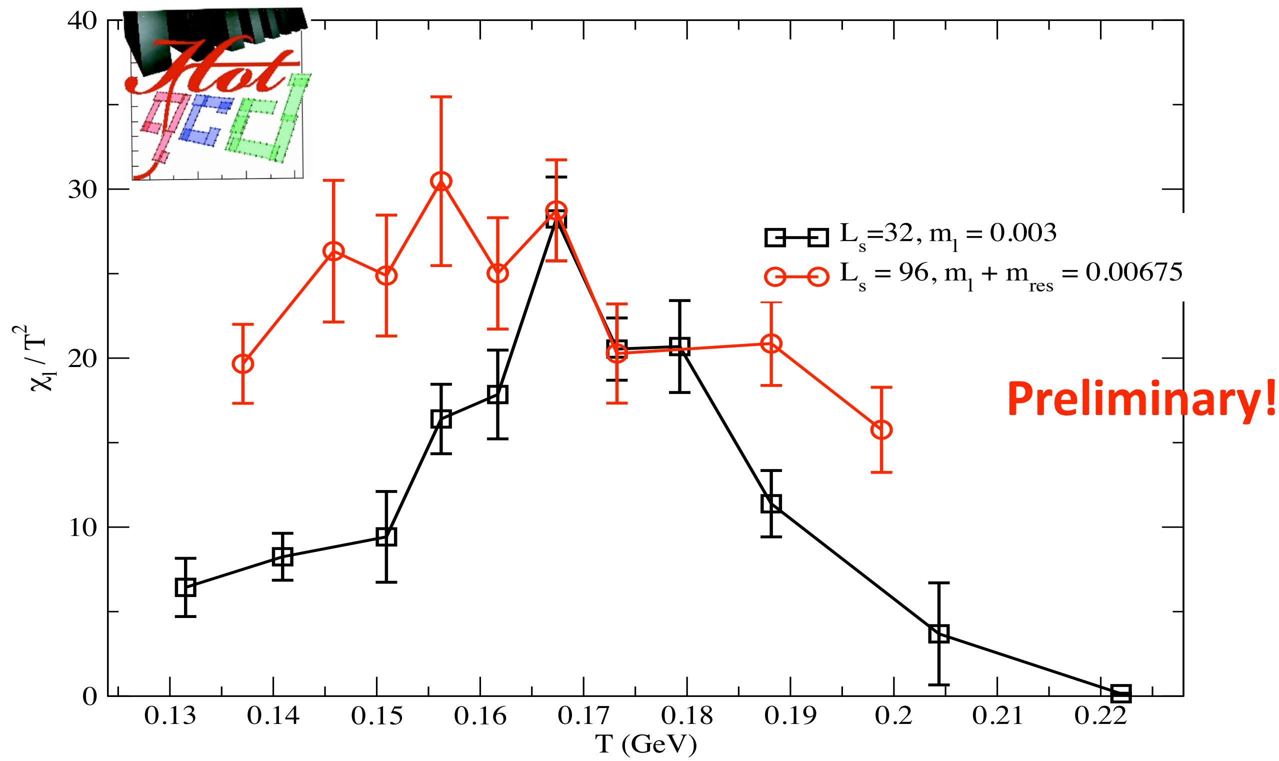


- Deconfinement observables: isospin and charge susceptibilities.
- Inflection point determined by fitting data to ansatz.
- Consistent with peak in chiral susceptibility.
- However, SB limit already saturated at low temperature, as expected as DWF formulation is unimproved at high temperature.

Caveats

- Limitations in this calculation:
  - Small volume (Finite volume effects not controlled)
  - Lacks precision of staggered studies.
  - Quark mass not held constant in this calculation -> $m_\pi \approx$ 300 MeV at T = 170 MeV, but larger at low temperature, smaller at high temperature.
  - Single lattice spacing – cannot make continuum extrapolation (4-7% error suggested by other calculations)
  - Single set of masses – guess at extrapolation to physical quark masses.

Comparison with L_s = 96 calculation



T_c = 171(17)(10) MeV

Hydro/Cascade Model

Description of Model

- Hybrid model includes:
  - Pre-thermalization flow (Pratt arXiv:0810.4325)
  - 2D viscuous hydrodynamic evolution (Romatshke's vh2)
  - Hadron cascade, after Cooper-Frye freezeout (URQMD)
- Examine the effect of varying:
  - Equation of state (LQCD EoS vs. 1st order transition)
  - Viscosity
  - Pre-thermalization flow.
  - Initial conditions/freezeout temperature
- Collaborators:
  - Ron Soltz, Andrew Glenn, Jason Newby (LLNL and ORNL)
  - Scott Pratt
- Talk by R. Soltz at CATHIE/TECHQM

Parameterizing LQCD EoS

- Already saw a more detailed study in talk by Petreczky, but also many others.
- Let f(T) be parameterization of EoS
- Suggestion by K. Rajagopal:
- $1/f(T) = 1/g(T) + 1/h(T)$
- g(T) -> low temperature
- h(T) -> high temperature

- $h(T) = d_2/T^2 + d_4/T^4$
- $g(T) = (a + (T/T_0)^b)*HRG(T)$

- Fix low T to HRG by setting a = 1.0

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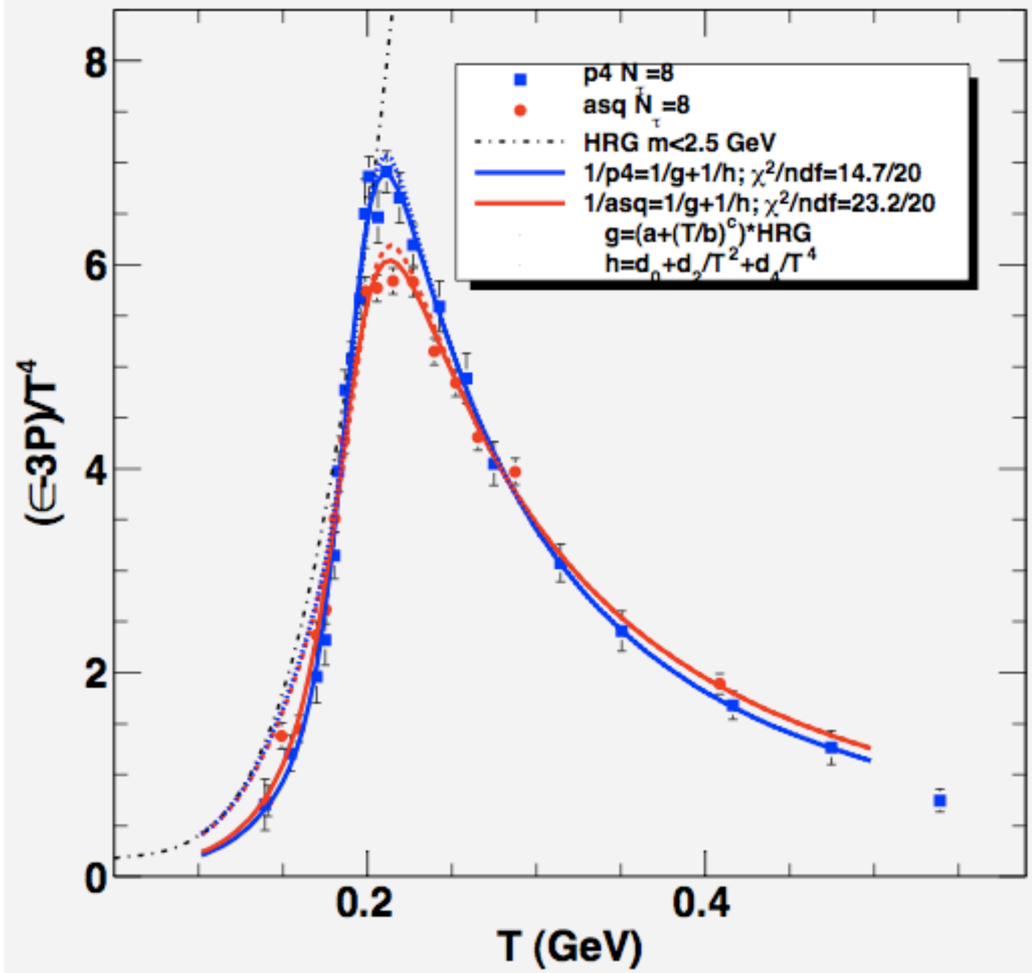
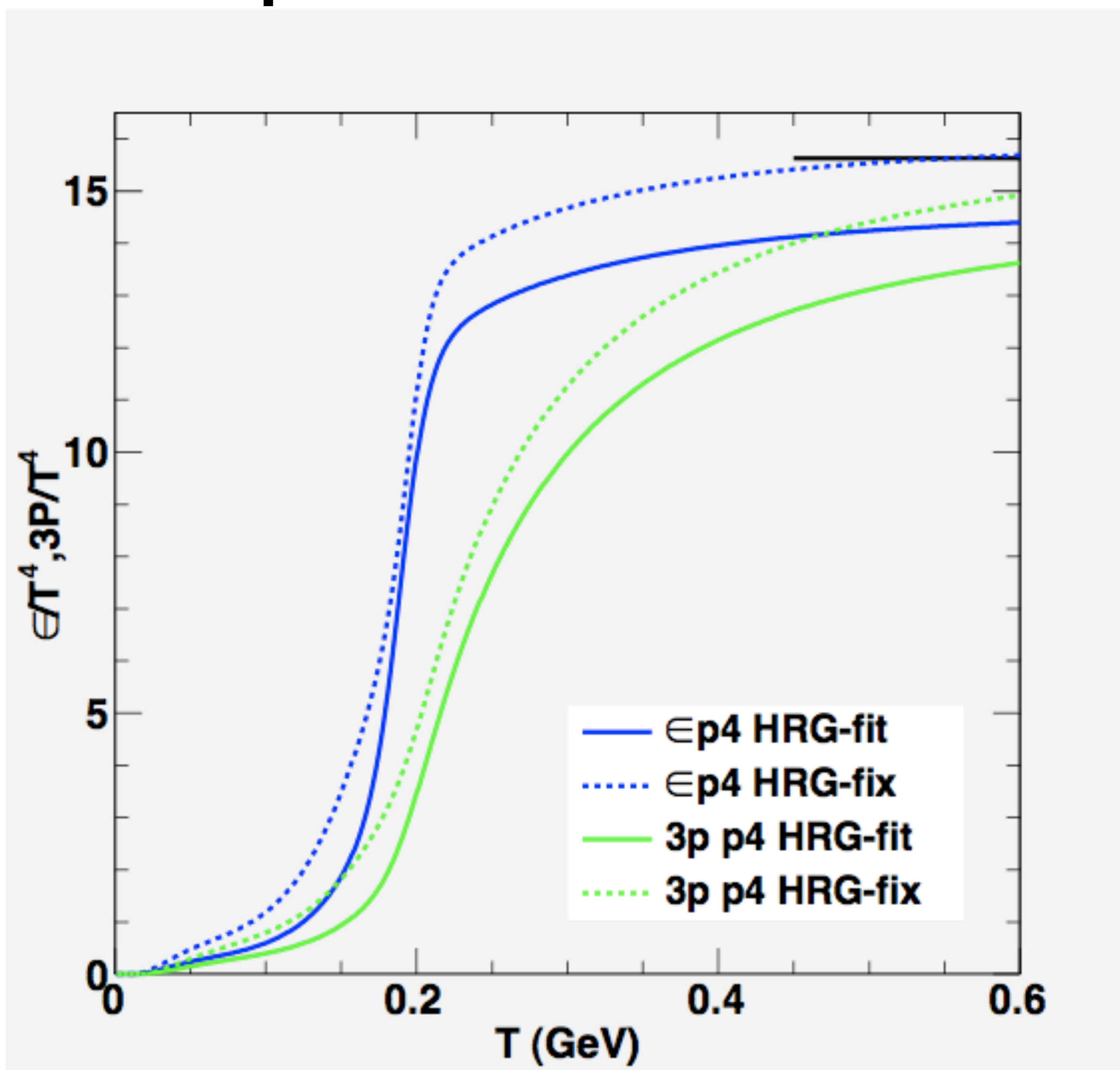
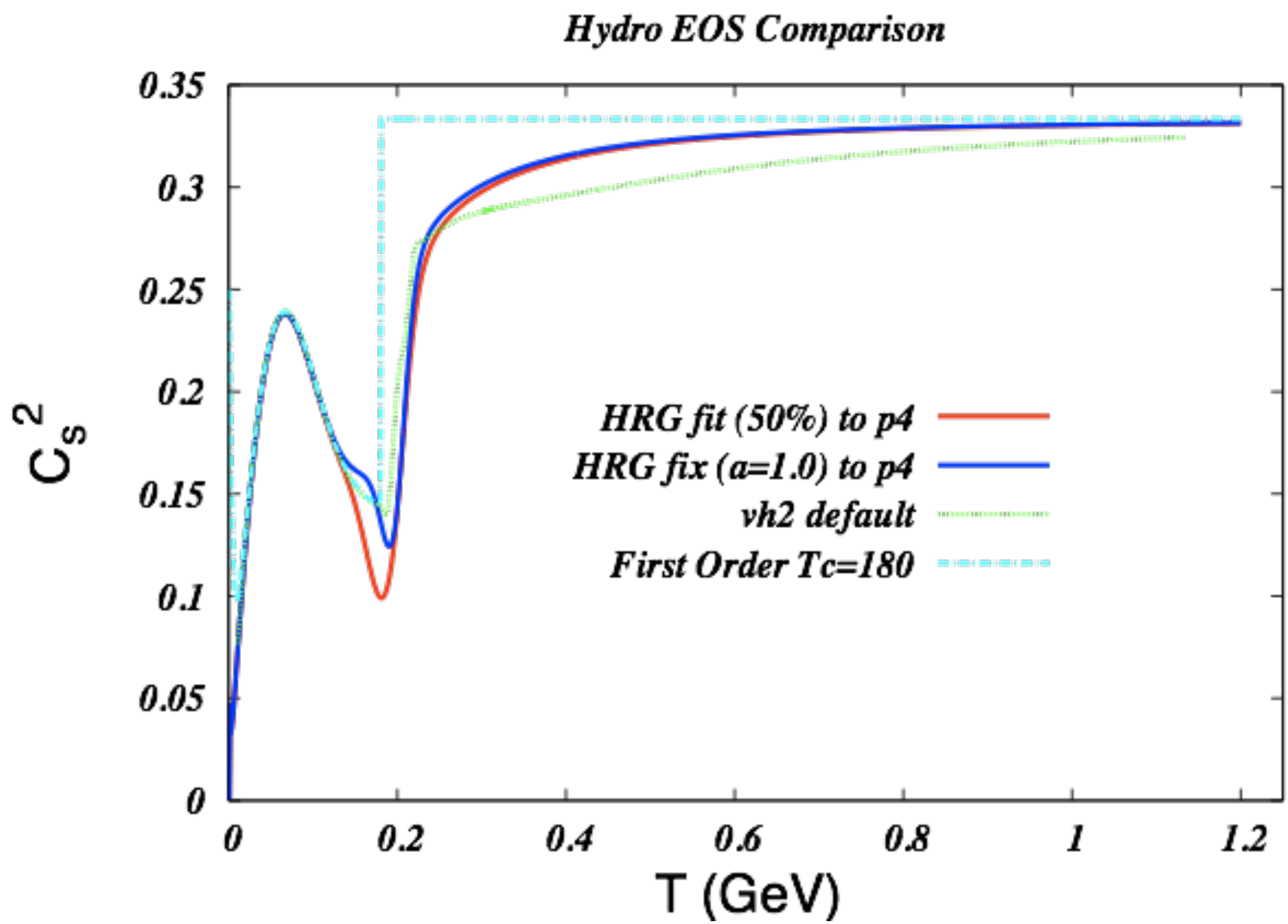


Re-parmeterized EoS



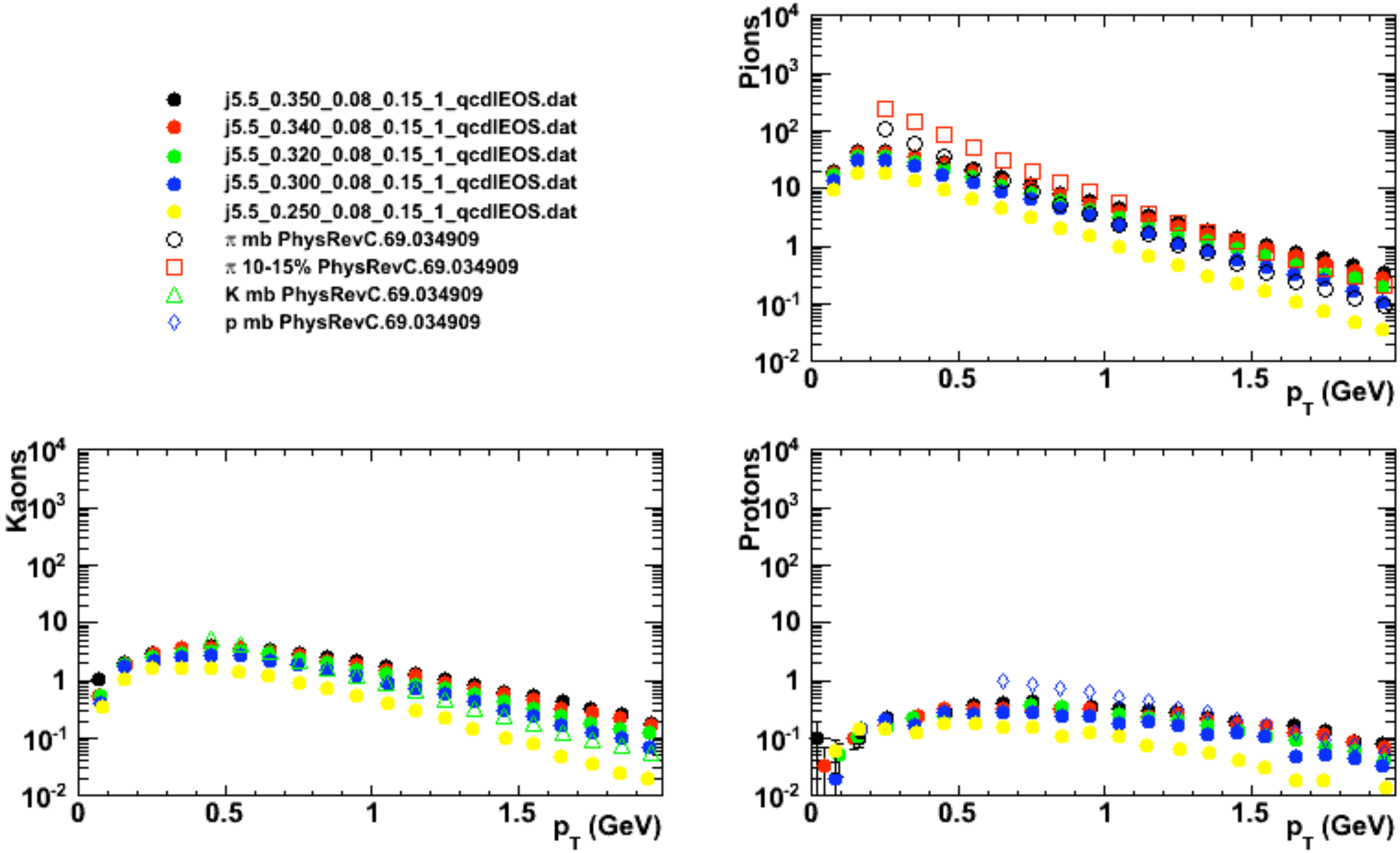
Speed of Sound



Description of existing runs

- Initial Flow
  - From Glauber profile.
  - b = 3.4, 5.5 fm., $T_{initial}$ = 250-350 MeV
- Vh2 2-D hydro:
  - η/s = 0.08 – 0.40
  - EoS = Romatchske EoS, LQCD, LQCD+HRG
- Cooper-Frye freezeout
  - $T_{freezeout}$= 120 – 170 MeV
- URQMD for hadronic cascade
- Match spectra to tune parameters

Spectra



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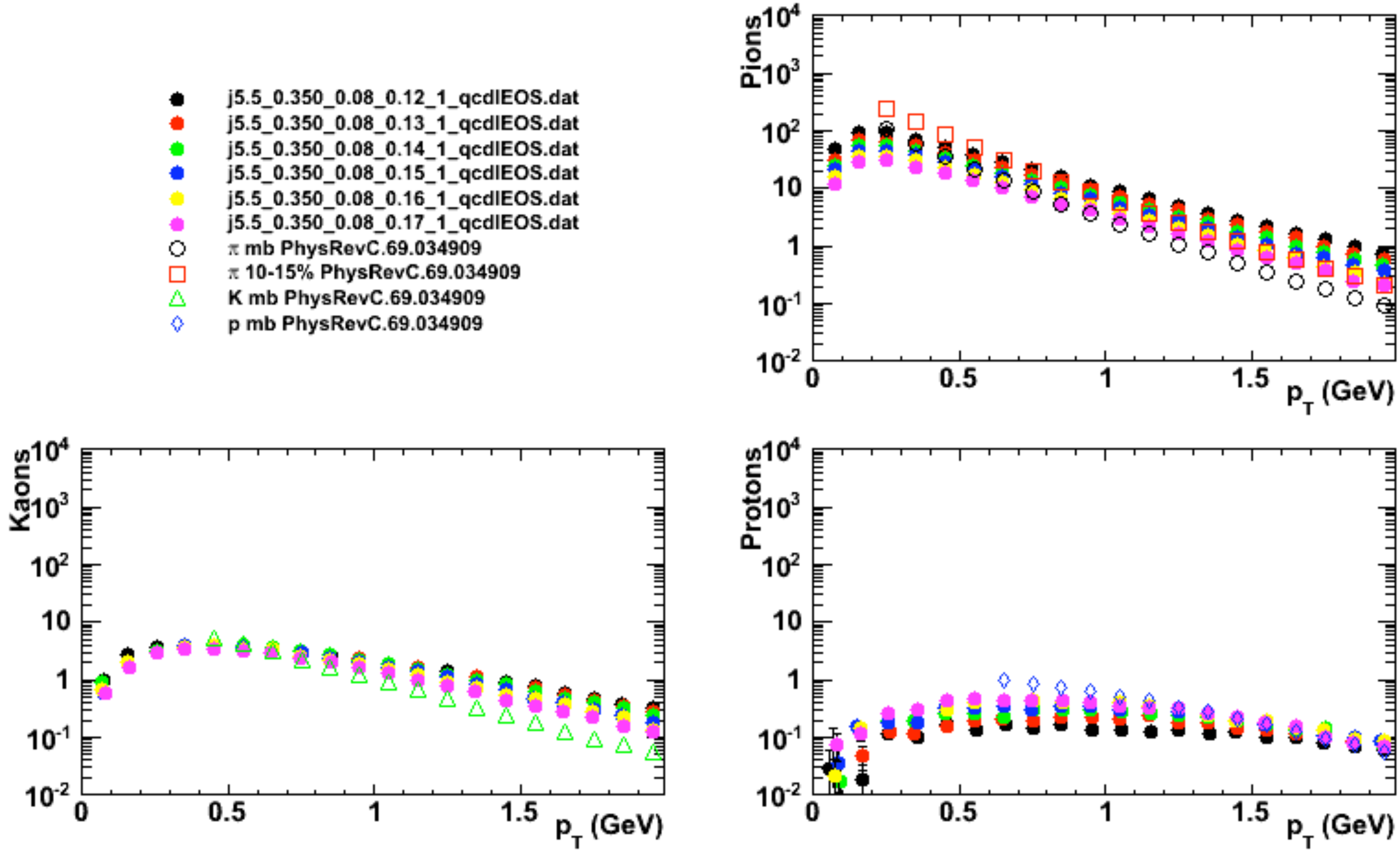
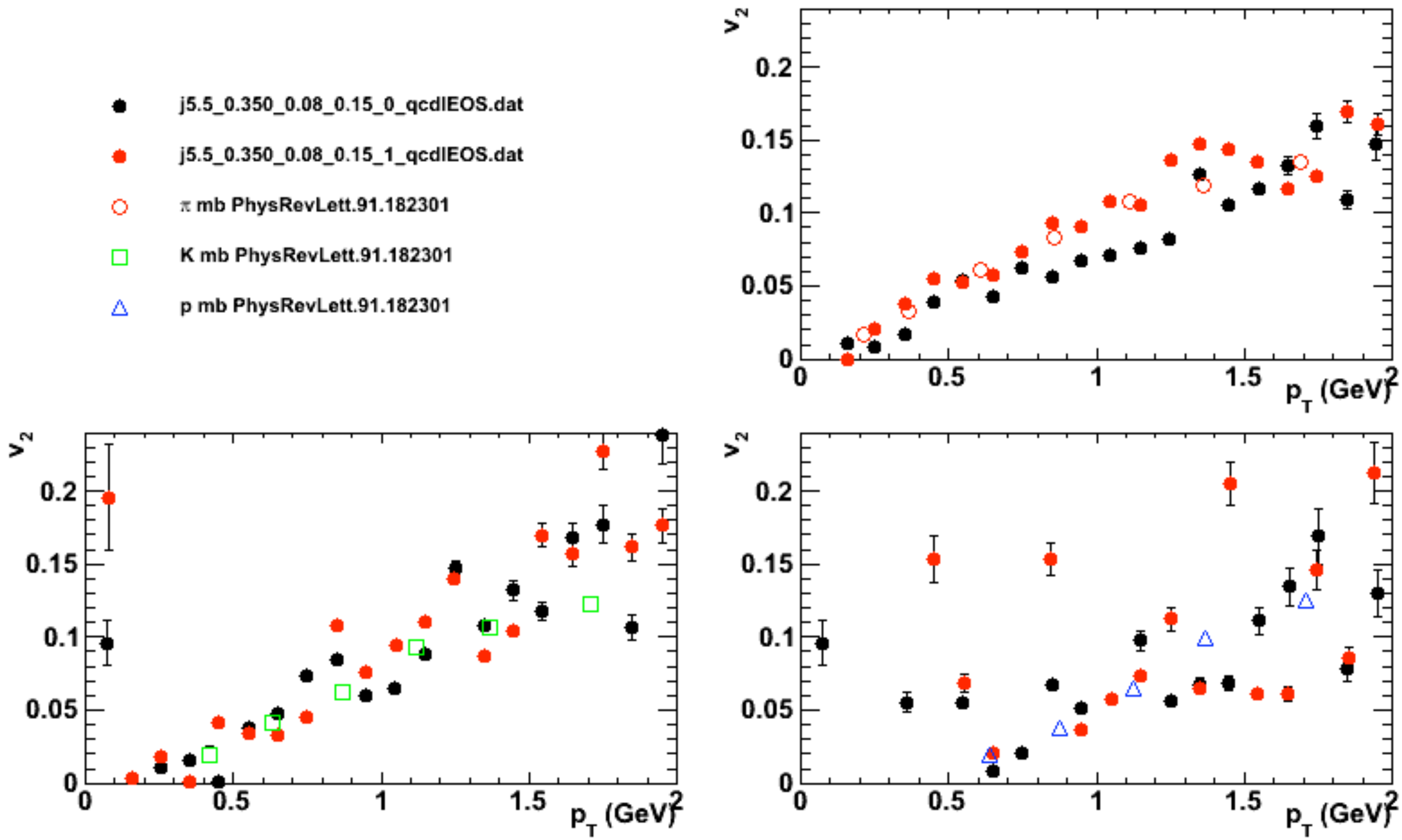
π mb PhysRevC.69.034909
π 10-15% PhysRevC.69.034909
K mb PhysRevC.69.034909
p mb PhysRevC.69.034909
Pions
Kaons
Protons
p_T (GeV)

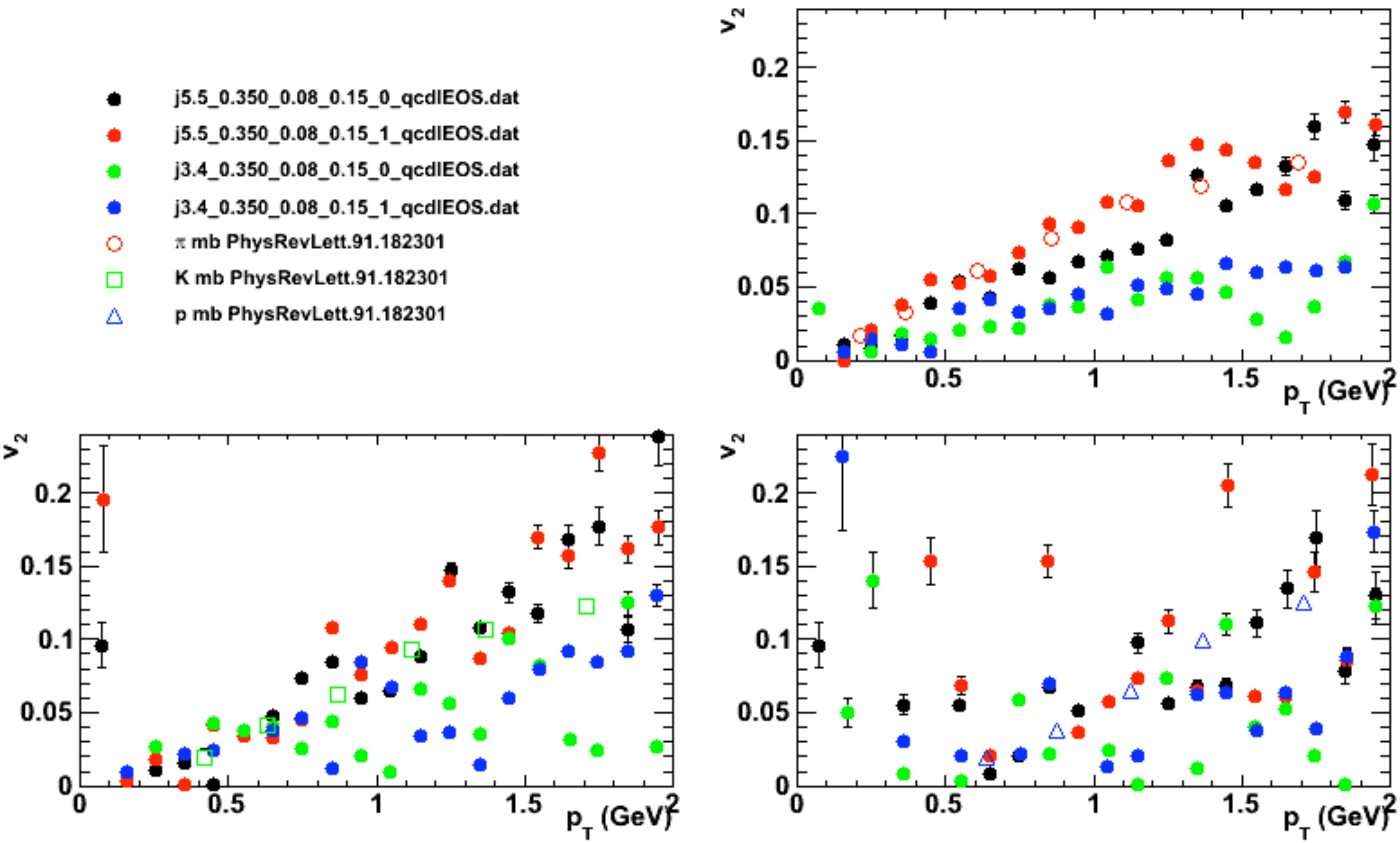
Spectra, T_f=120-170 MeV



V2 – with/without initial flow



V2, b = 3.4, 5.5 fm.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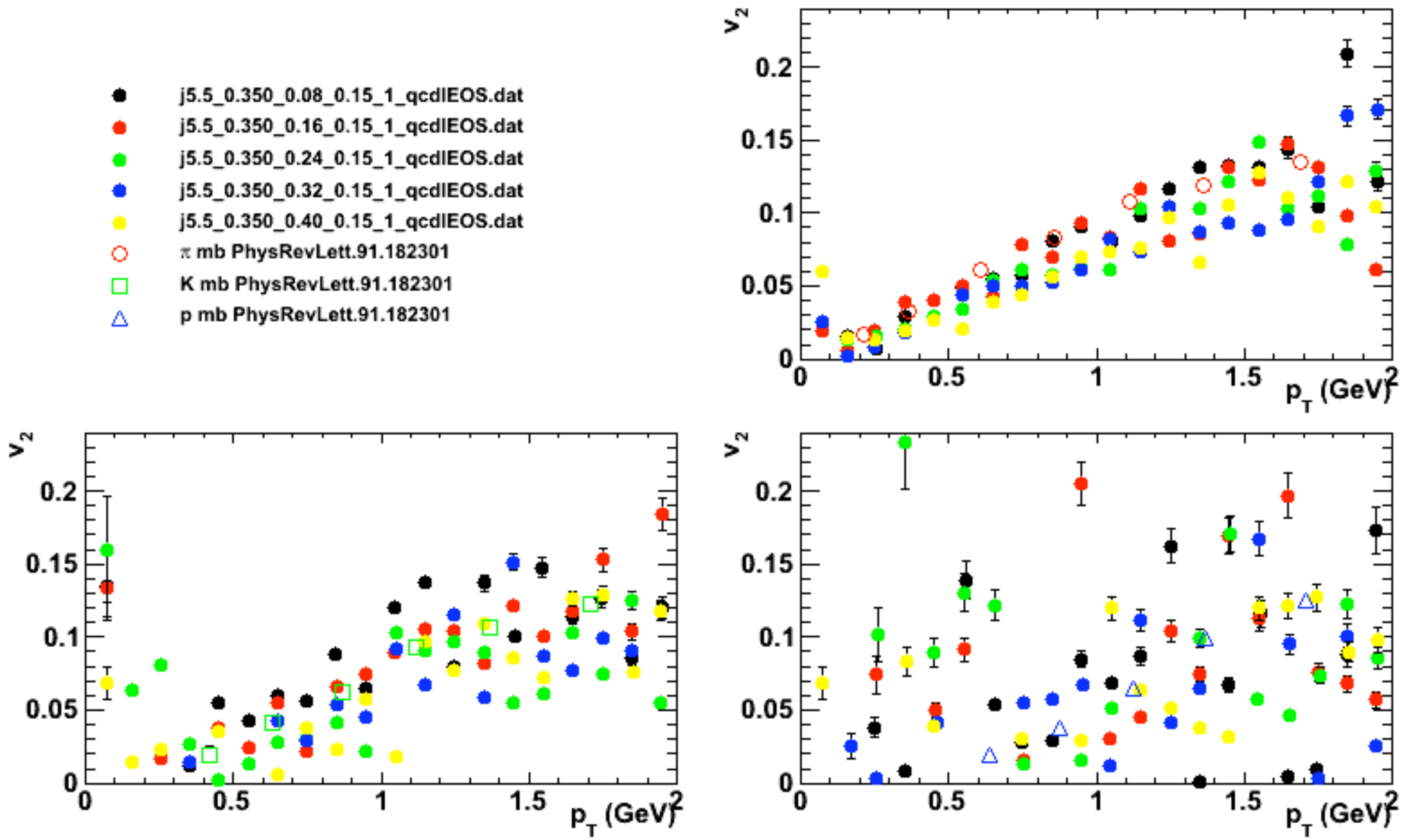
π mb PhysRevLett.91.182301
K mb PhysRevLett.91.182301
p mb PhysRevLett.91.182301
v2
p_T (GeV)
0
0.05
0.1
0.15
0.2
0.5
1
1.5
2

V2, η/s=0.08-0.40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π mb PhysRevLett.91.182301
K mb PhysRevLett.91.182301
p mb PhysRevLett.91.182301
v2
pT (GeV)

Conclusions

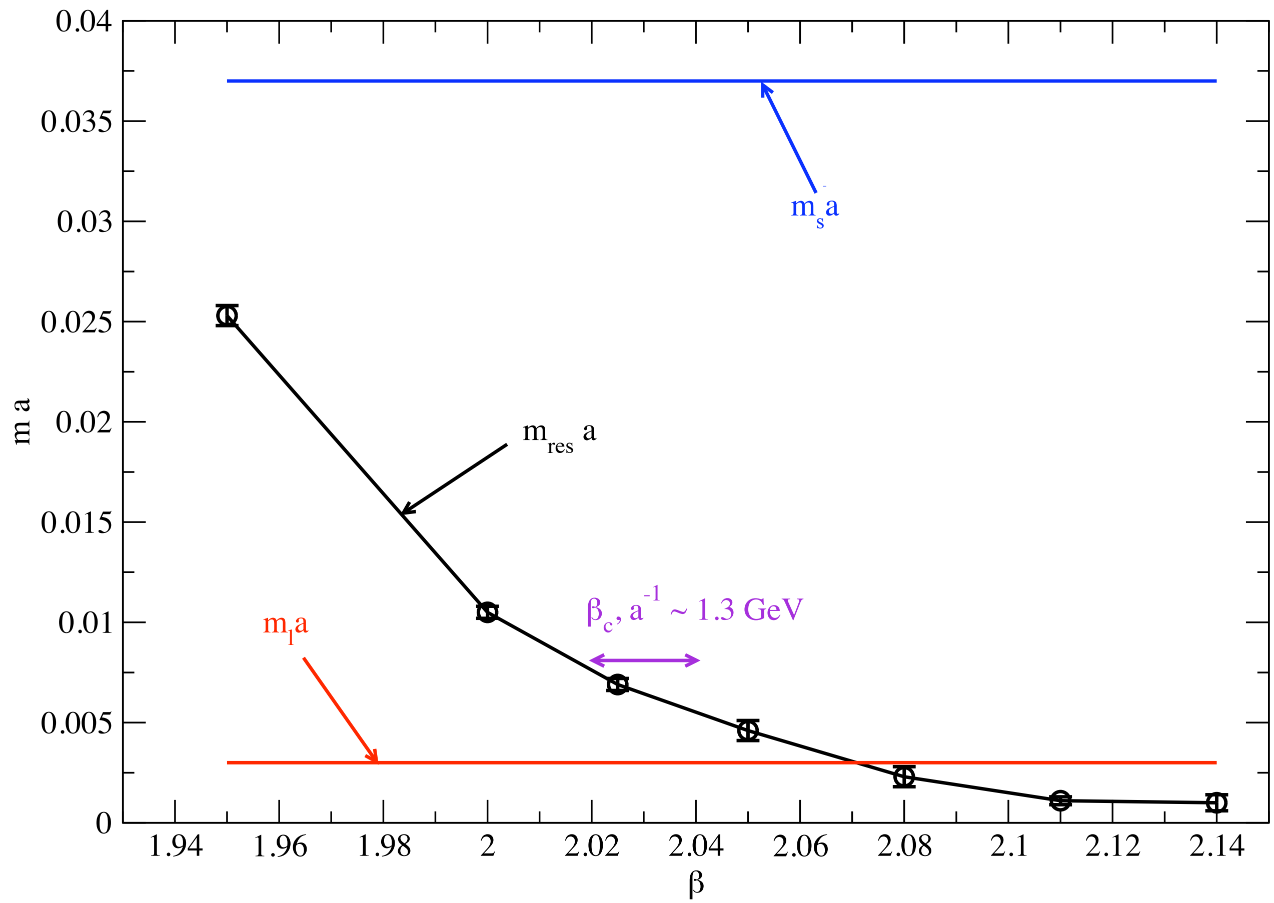
- Calculation of crossover temperature with DWF to compare with staggered-type calculations.
- T_c~ 170 MeV, but with large error because of statistics and several systematic uncertainties.
- No splitting evident for deconfinement, chiral observables
- Not really in disagreement with either of conflicting staggered calculations.
- Exploratory calculation – need to do a calculation that corrects many of the flaws of current calculation.
- One is underway, thinking about other methods, but still computationally too expensive…

Conclusions (cont.)

- Hybrid model including pre-thermalization flow + 2D viscuous hydrodynamics + URQMD (almost) working.
- Still work in progress.
- Goals:
  - Study collective flow, femtoscopy.
  - Effects of varying η/s, initial conditions, $T_{freezeout}$
  - Does pre-thermal flow help explain HBT puzzle?
  - Quantify effects of varying EoS
  - Systematic comparison to experimental data.

Backup

Residual Mass at Ls = 32



HBT Radii, varying viscosity