Effect of the QCD equation of state and strange hadronic resonances on multiparticle correlations in heavy ion collisions
(nucl-th:1711.05207)

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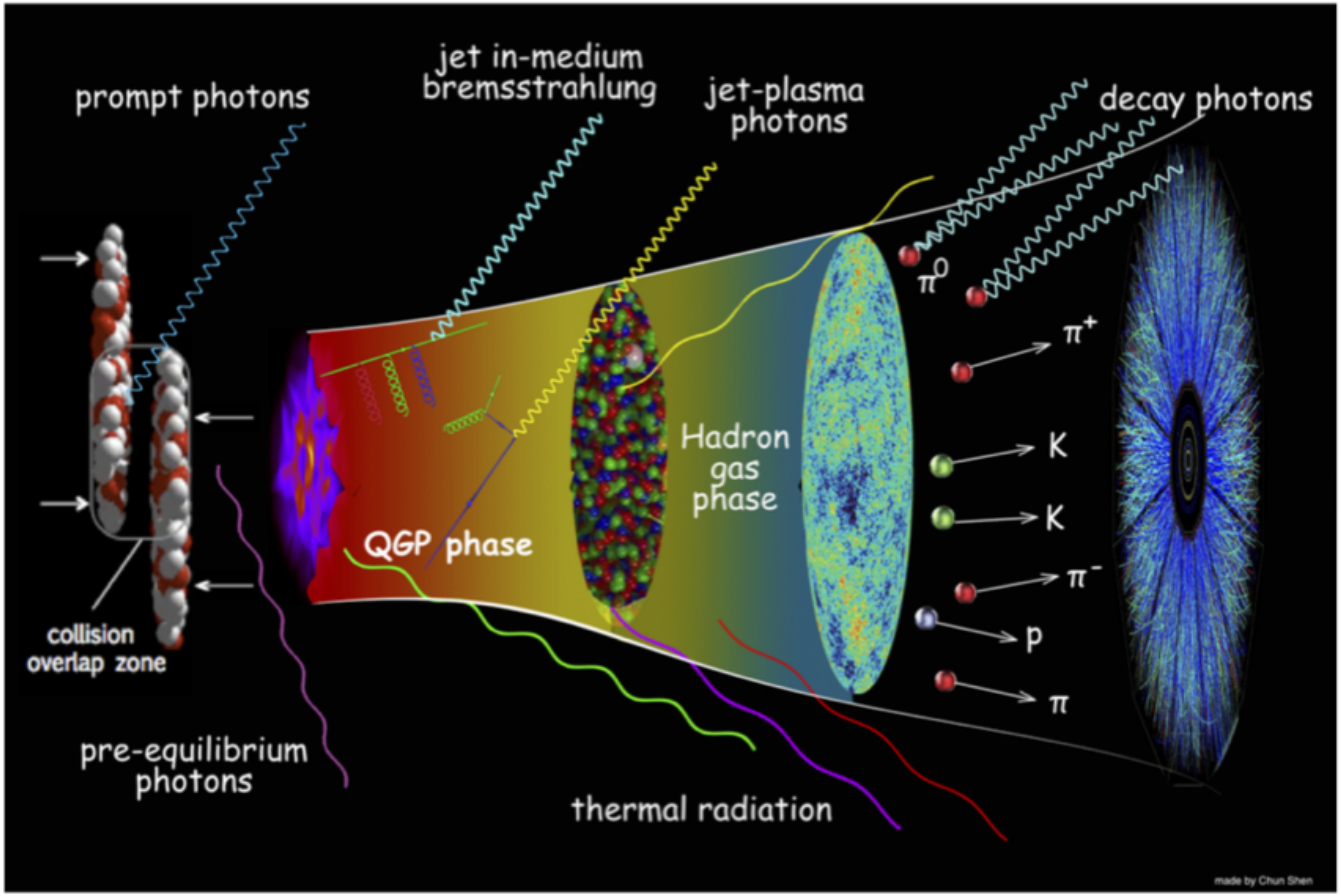
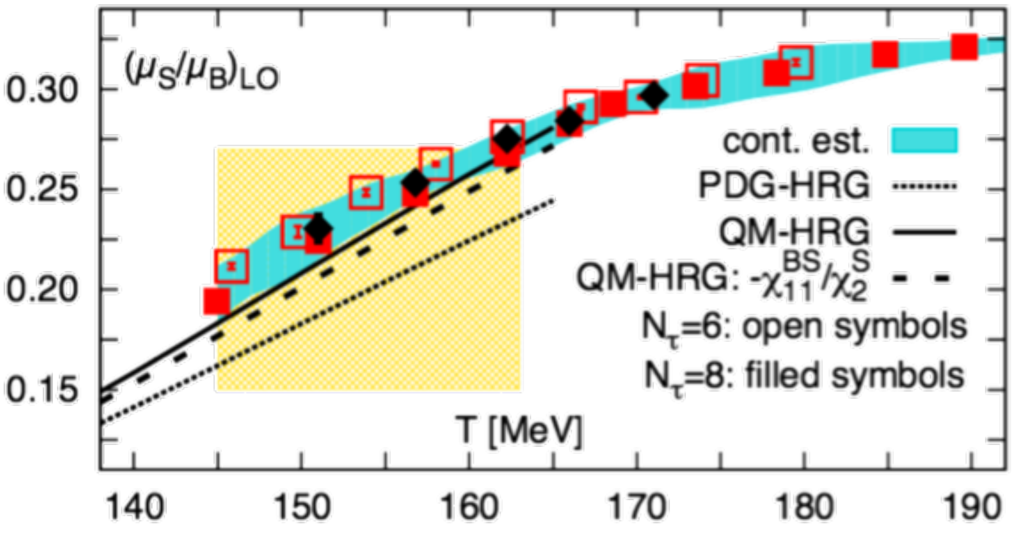
Outline

- Why do we need additional resonances
- Inclusion of additional states in the hadronic spectrum
- Lattice QCD based Equation of State (EoS)
- Results:
  - Particle spectra and mean p_t
  - η/s and flow harmonics: comparison with STAR results in QM18
- Conclusions

Heavy-ion collisions evolution



Why do we need additional states?



Bazazov et al. PRL 113(2014)
QM: Capstick,Isgur PRD (1986

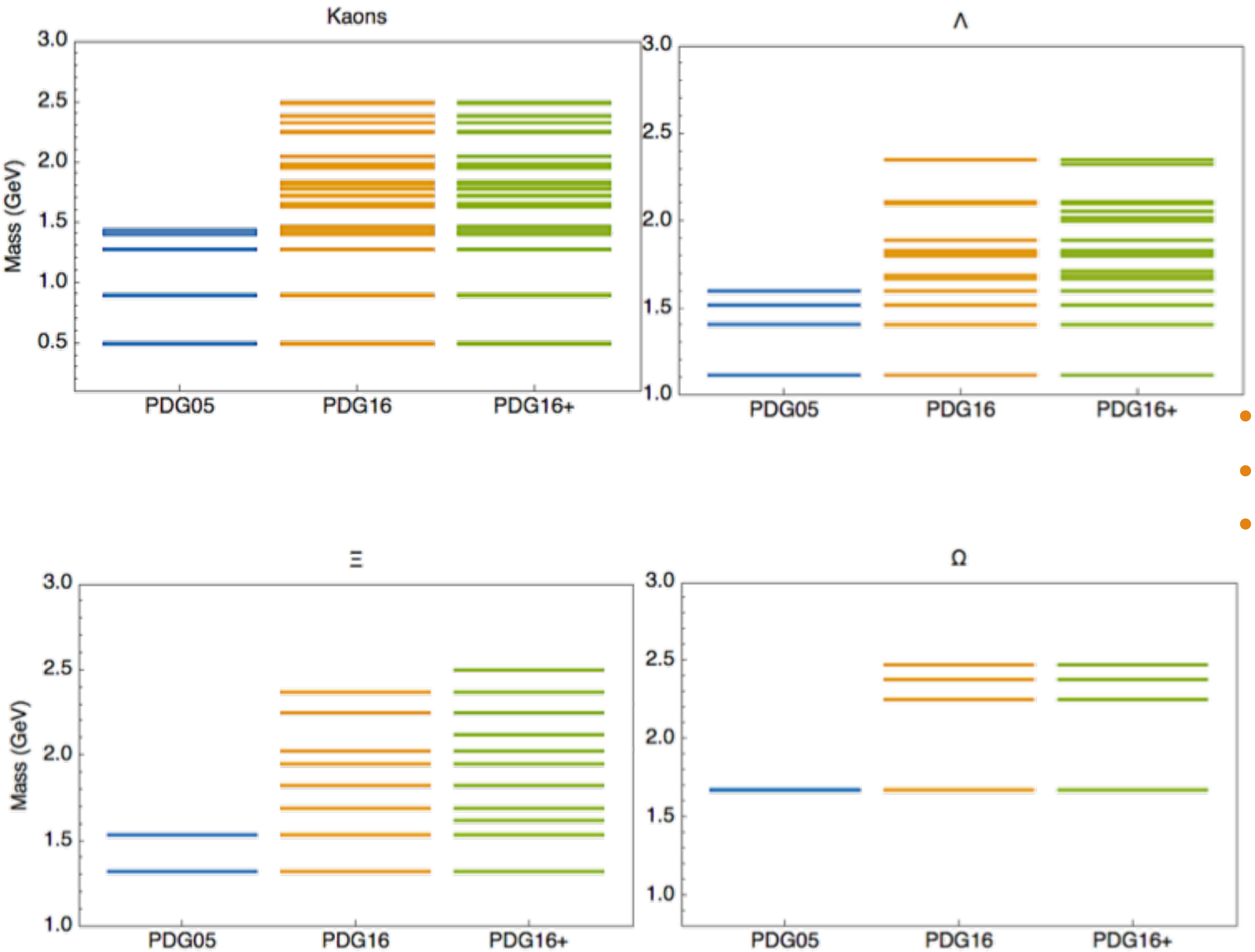
Baryon-Strangeness correlator

$$\left(\frac{\mu_S}{\mu_B}\right)_{LO} = -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B}.$$

- **QM-HRG** improves the agreement with LQCD data
- QM predicts not-yet-detected strange states $\Longrightarrow$ overestimate other strangeness related observables as X_4/X_2

ADDING *-** STATES FROM UP-TO-DATE PDG LIST?

Additional states from up-to-date PDG list

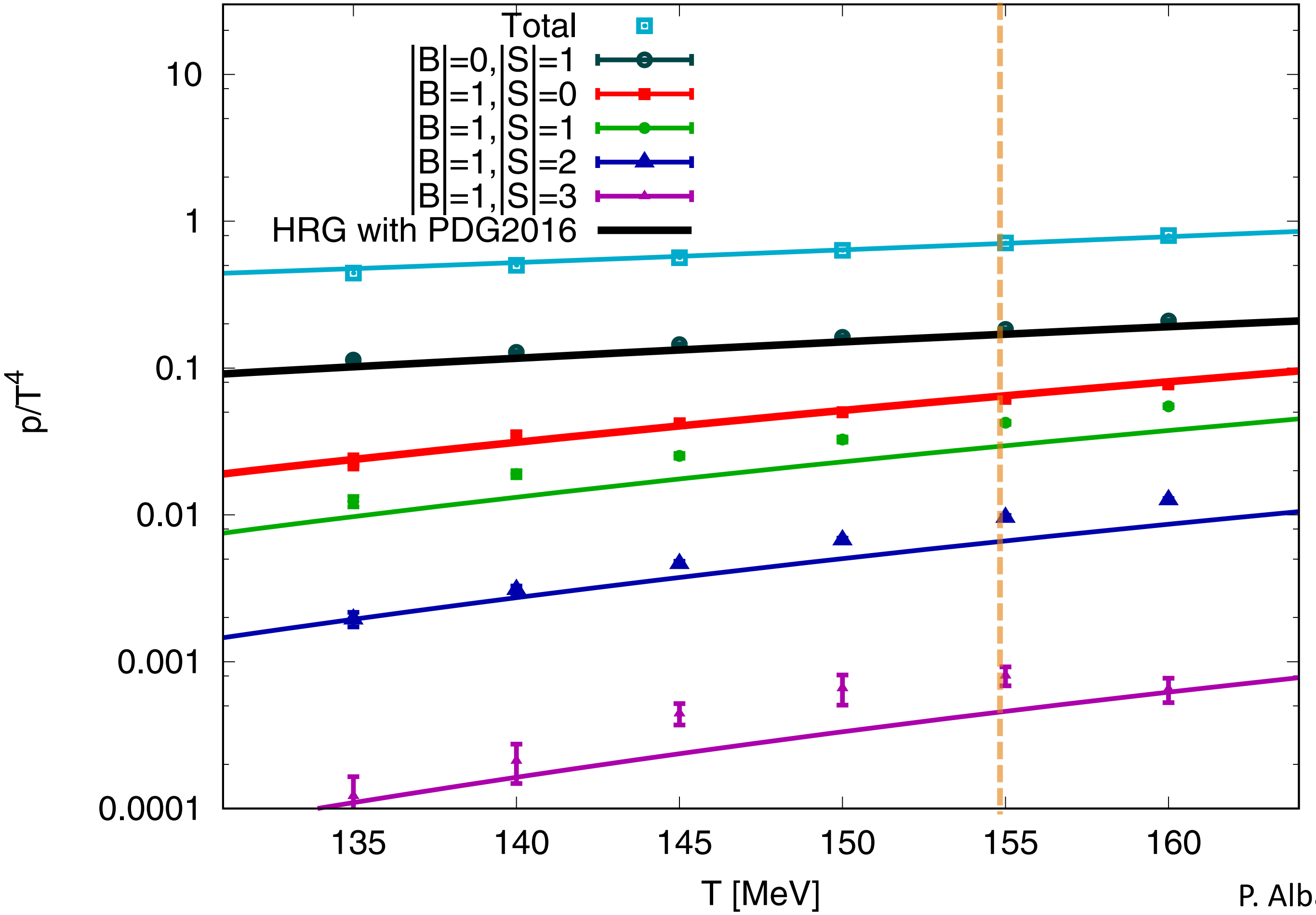


- PDG 2005: 144
- PDG 2016: 608
- PDG 2016+: **738** (including also * states)

P. Alba PRD96 (2017)

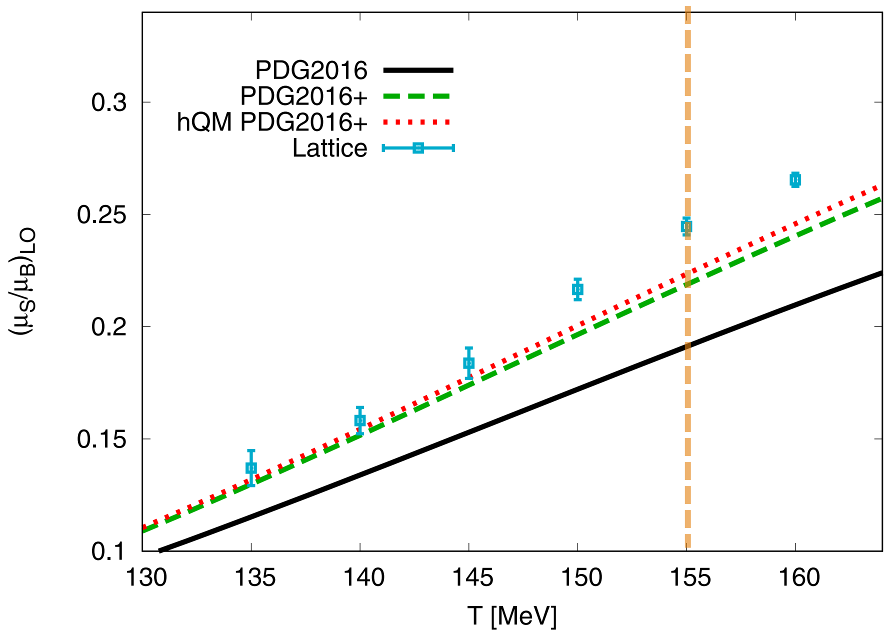
Partial pressures from LQCD

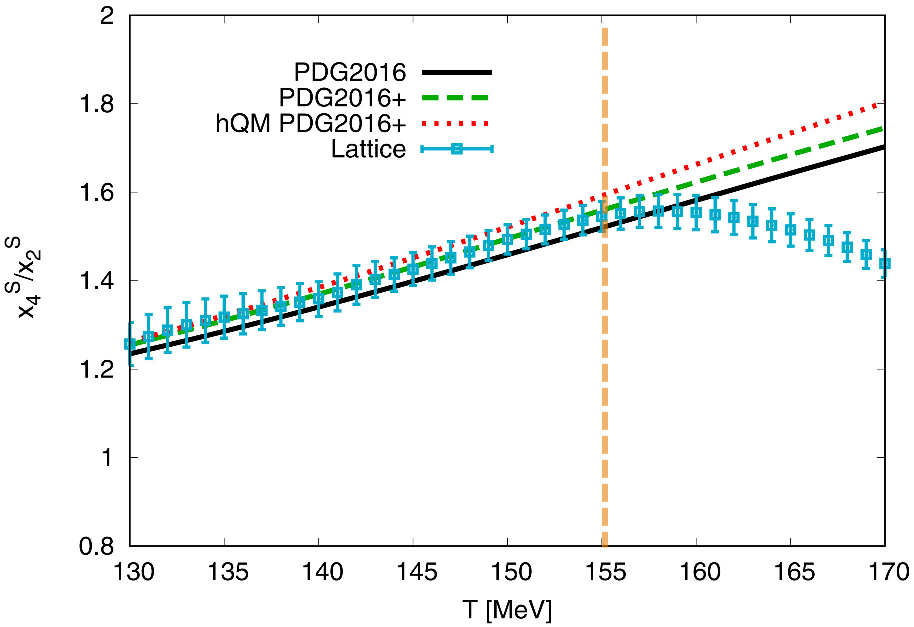
- Sensitive to the strangeness content



P. Alba PRD96 (2017)

Baryon-strangeness fluctuations from LQCD





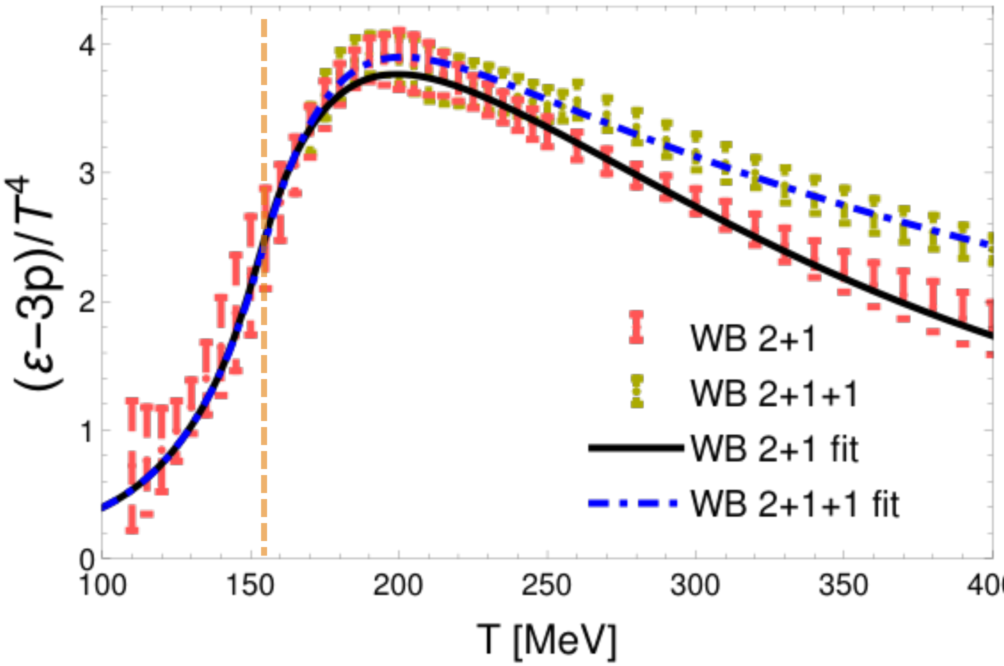
$$\left(\frac{\mu_S}{\mu_B}\right)_{LO} = -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B}.$$

$$\frac{\chi_4^S}{\chi_2^S} \propto |S|^2$$

P. Alba PRD96 (2017)

Lattice QCD based Equation of State

$$\left(\frac{\varepsilon-3p}{T^4}\right)_{all}=\left(\frac{\varepsilon-3p}{T^4}\right)_{\pi}-\frac{1+\tanh\left[b(T-T_{HRG+Latt/\pi})\right]}{2}\left[\left(\frac{\varepsilon-3p}{T^4}\right)_{HRG+Latt}-\left(\frac{\varepsilon-3p}{T^4}\right)_{\pi}\right]$$

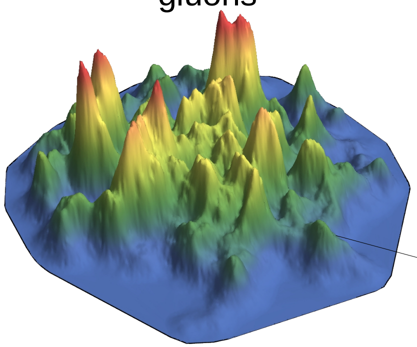


- **T < 153 MeV** ⇒HRG with PDG16+
- **T > 153 MeV** ⇒ state-of-the art LQCD fitted EoS for 2+1 (PLB730,2014) /2+1+1(Nature 539,2016) with thermalized quark charm, from WB collaboration

PDG16+: Chin. Phys. C40 (2016)

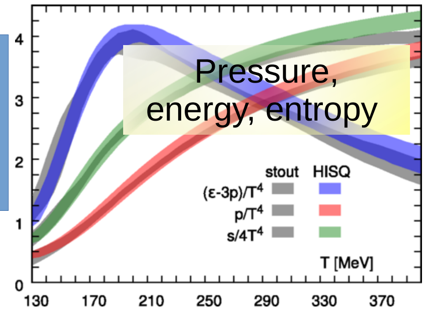
Hydrodynamical evolution in a nutshell

Initial Conditions
Quantum fluctuations in the position of protons, neutrons, quarks, and gluons

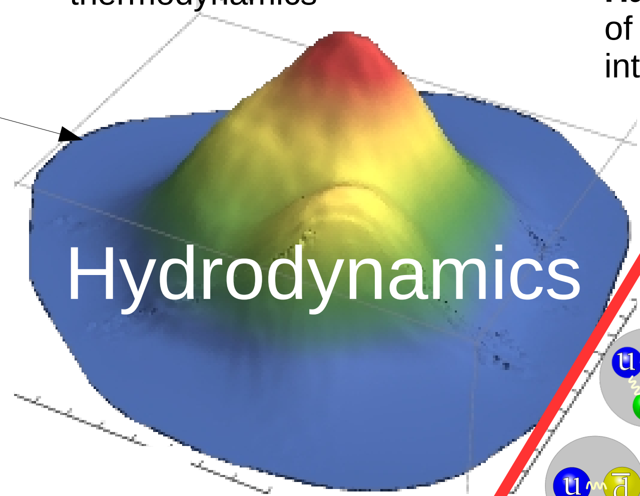


τ_0 initial time to switch on hydro

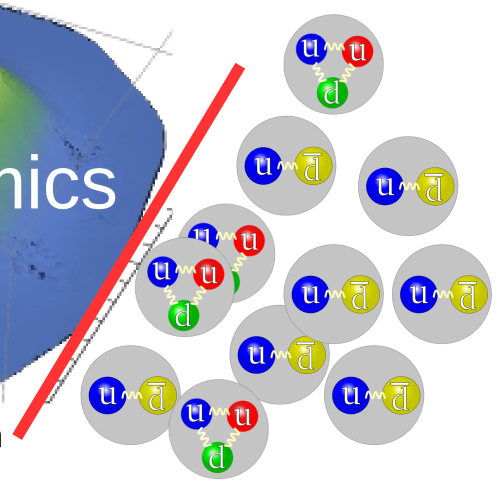
Hydrodynamics
(for heavy-ions collisions)
in a nutshell



Hydrodynamics viscosity and thermodynamics



Hadron Gas: number of hadrons,decays, interactions etc

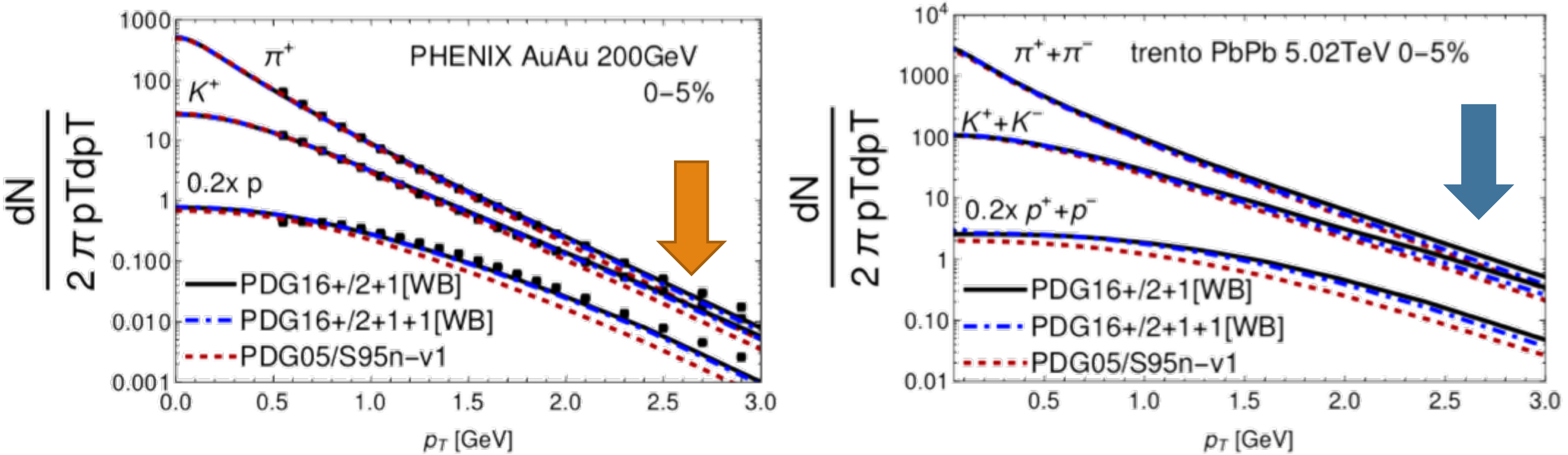


Tsw temperature at which the Quark Gluon Plasma switches to hadrons

(J.Norohna-Hostler slides)

Results

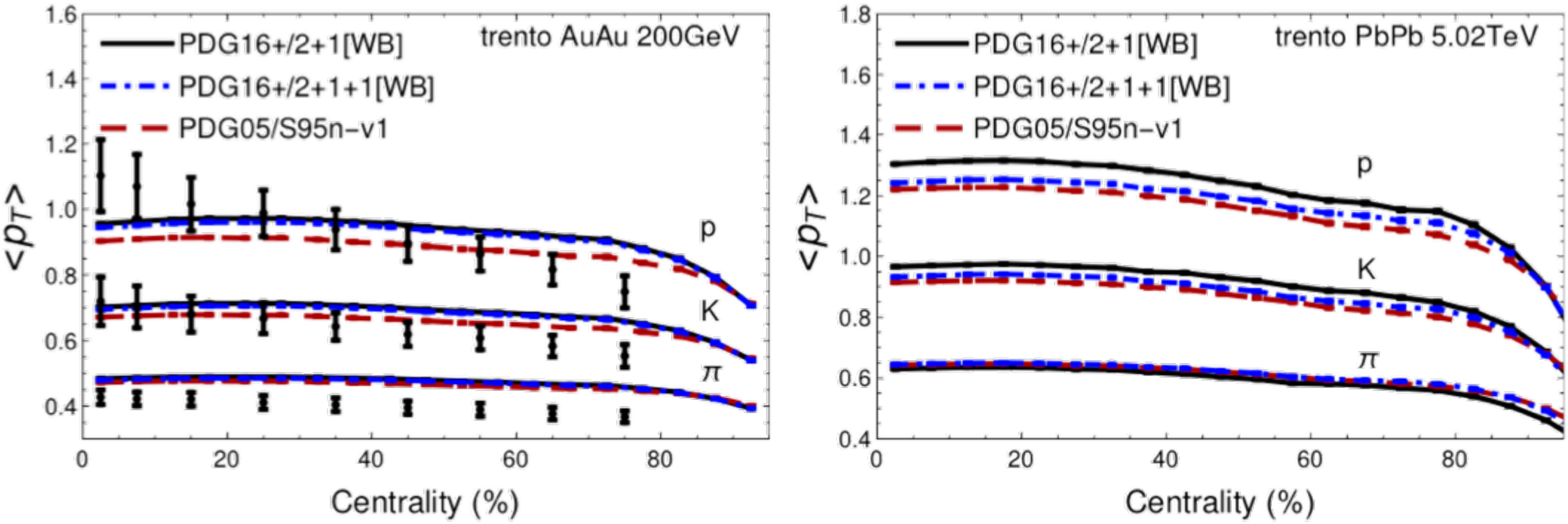
Particle spectra: additional states & charm quarks



- Inclusion of **additional states** ⇒ better agreement for **p** and **K** at **high p_t**
- Inclusion of **charm quarks** ⇒ **less high p_t particles**

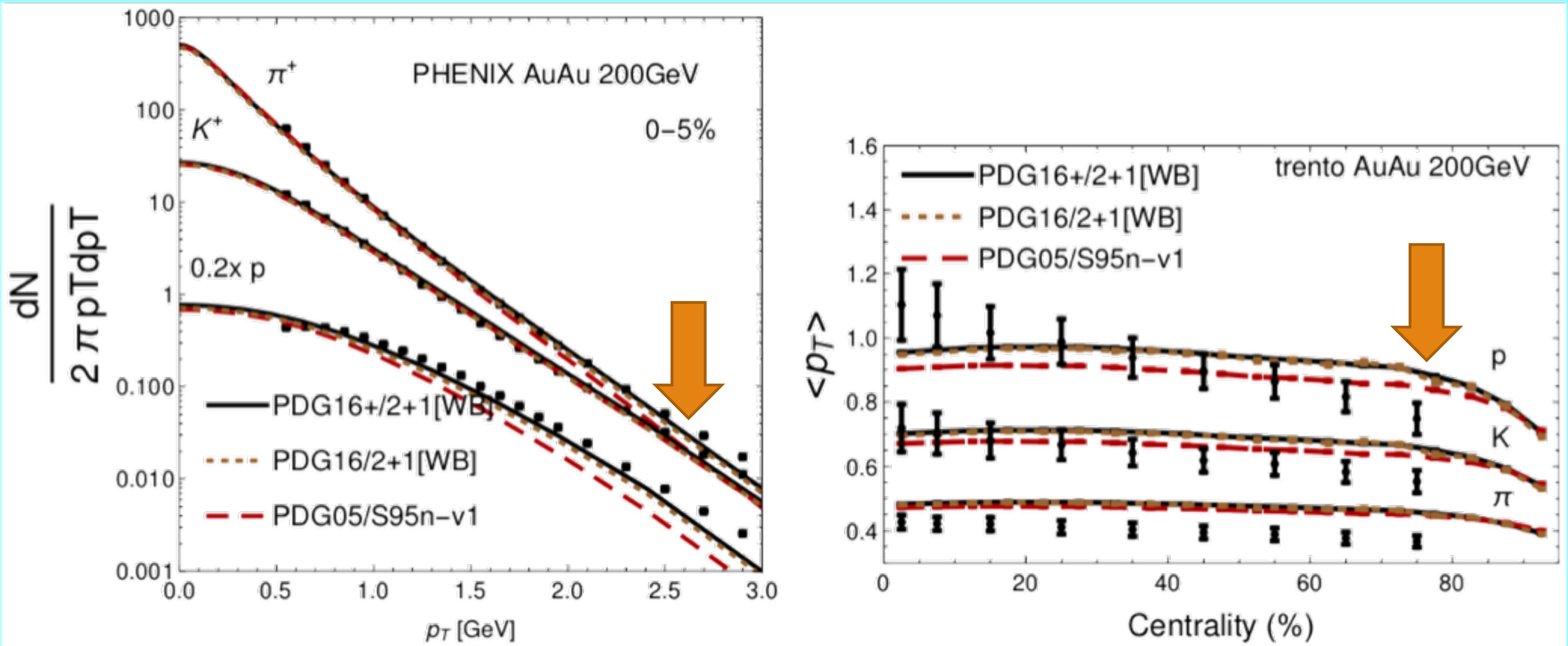
PDG05/S95n-v1:Huovinen et al.
Nucl. Phys., A837:26–53, 2010

$\langle p_t \rangle$: additional states & charm quarks



- Inclusion of **extra resonances** $\Rightarrow$ **larger $\langle p_t \rangle$**
- Inclusion of **charm quarks** $\Rightarrow$ **smaller $\langle p_t \rangle$ up to intermediate centralities**

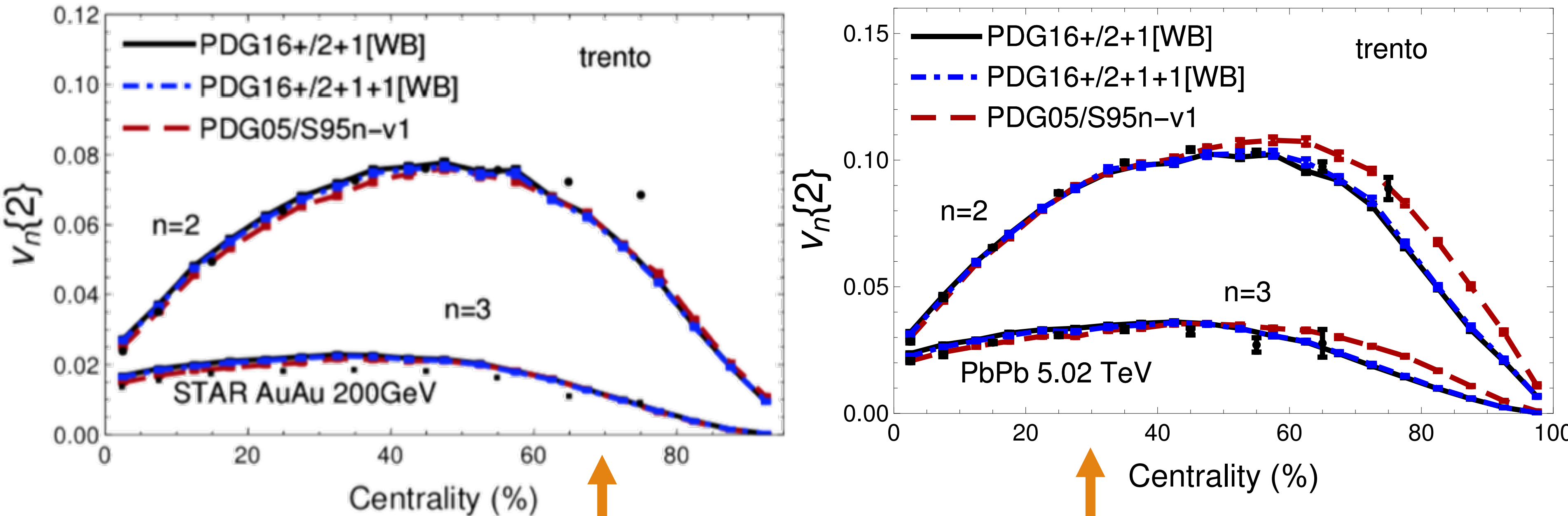
Particle spectra and $<p_t>$: *-** states effect



- increase of $\simeq$**5-15%** in p_t spectra
- up to $\simeq$ **7%** in $<p_t>$

PHENIX Collaboration, PRC69 (2004)

How is η/s affected by the new EoS?



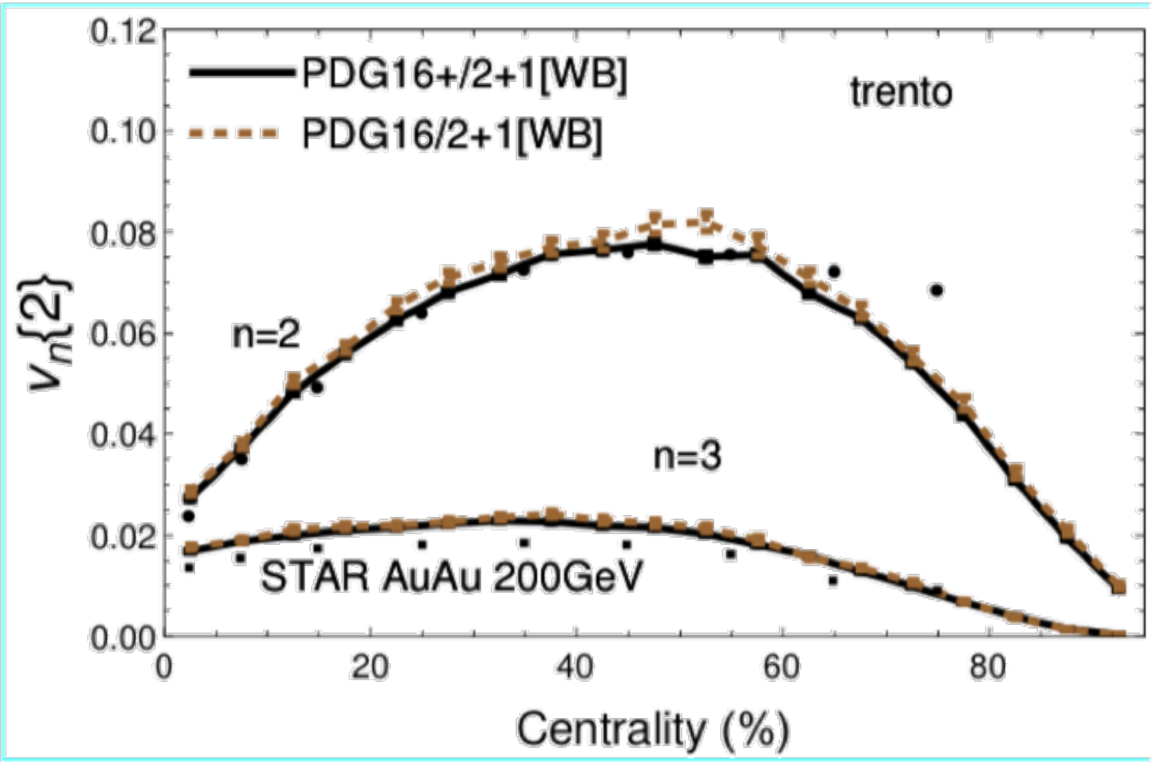
- η/s from fit to **STAR 200 GeV** (nucl-ex: 1701.06496) and **ALICE RUN2 5.02 TeV** (PRL116,2016)
- LHC energies more sensitive to different EoS

How is η/s affected by the new EoS?

EoS	Au-Au 200 GeV	Pb-Pb 5.02TGeV
PDG05/S95n − v1 [11]	0.05	0.025
PDG16 + /2 + 1 [WB]	0.05	0.047
PDG16 + /2 + 1 + 1 [WB]	0.05	0.04

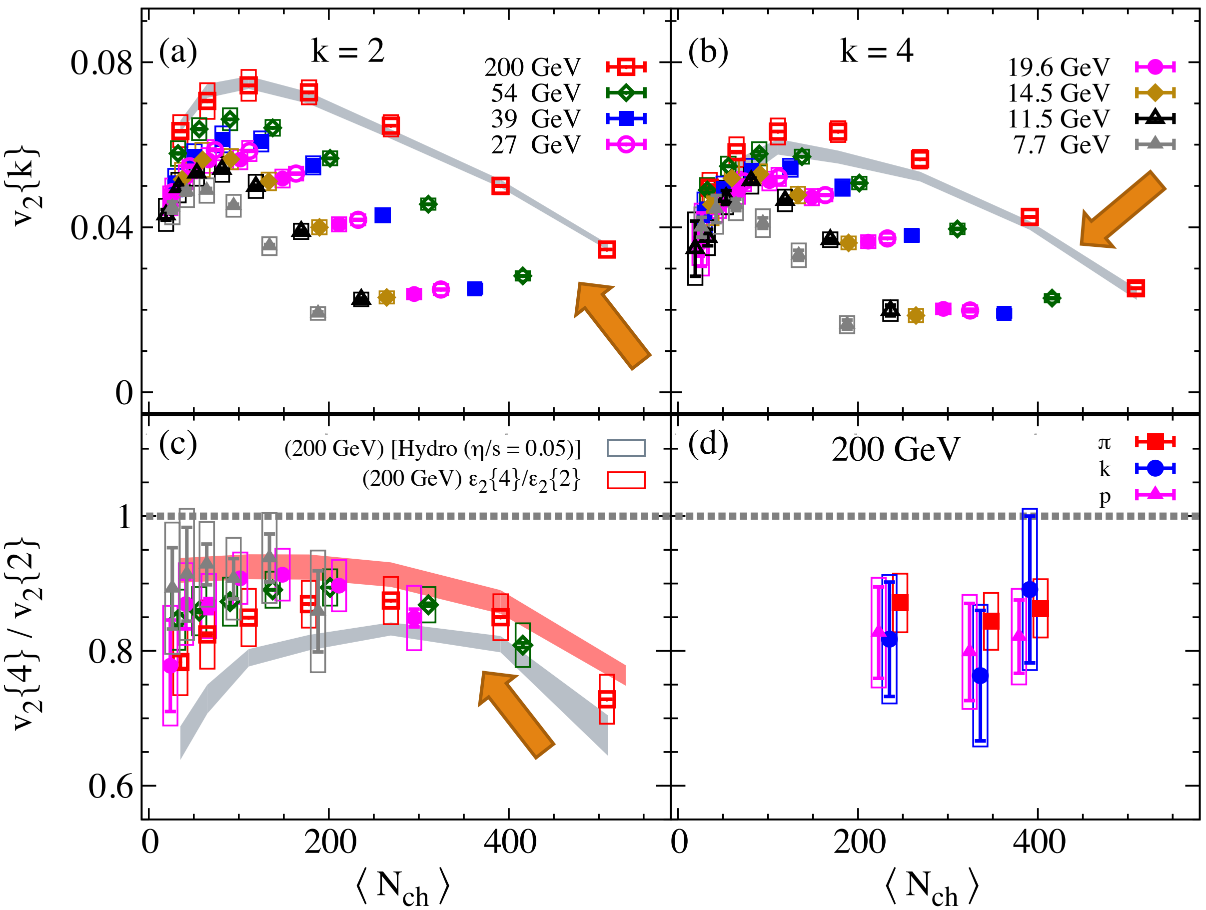
- No EoS dependence at RHIC⇒agreement with Bayesian analysis (PRC94, 2016)
- LHC energies ⇒decrease of 50% for old EoS
  ⇒ charm contribution leads to a smaller η/s
- higher temperatures probed at LHC run 2 (up to **T≃600** MeV)
  ⇒ **splitting between the 2+1 and 2+1+1 EoS**

Shear viscosity and flow harmonics: *-** states



- *-** states act as «viscosity»
- ~2-10% decrease in $v_2\{2\}$
- ~1-8% decrease in $v_3\{2\}$

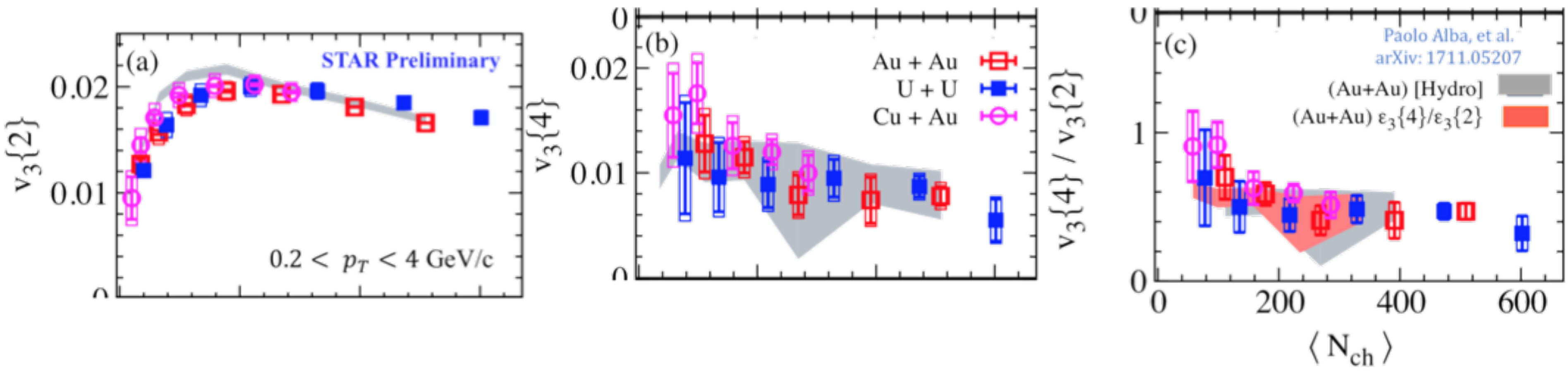
Flow harmonics: comparison to STAR results



- Agreement with $v_2\{2\}$,$v_2\{4\}$ at 200 GeV
- Slightly underestimating the ratio $v_2\{4\}/v_2\{2\} \Rightarrow$ non-linear effects? (BES)

QM18 talk by Niseem Magdy-STAR Coll.

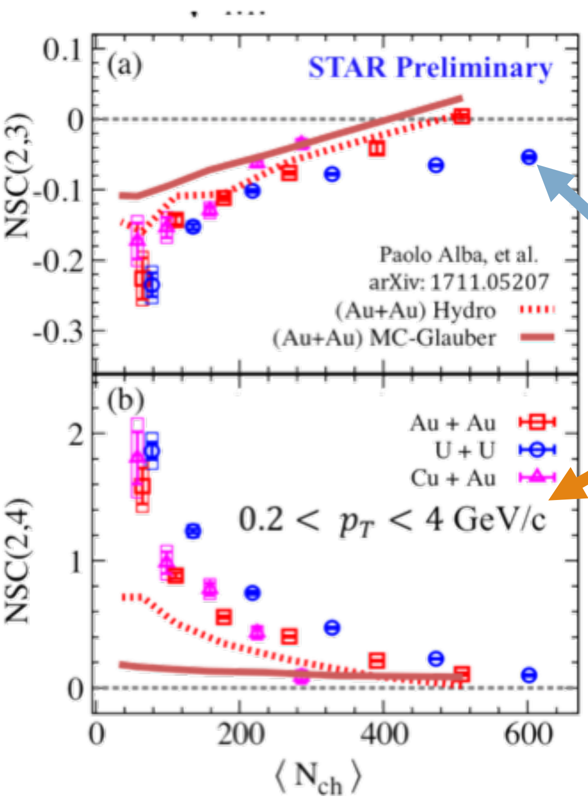
Flow harmonics: comparison to STAR results



- Ratio $v_3\{2\}/v_3\{4\}$ mildly affected by medium and does not depend on the colliding system ⇒ **probe to investigate properties of initial state**

QM18 talk by Niseem Magdy-STAR Coll.

NS cumulants: comparison to STAR results



$$NSC(m,n) = \frac{\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

- NSC ⇒ insight into medium and initial state
- **NSC(2,3)** independent of viscous effects
- **NSC(4,2)** sensitive to viscosity

QM18 talk by Niseem Magdy-STAR Coll.

Conclusions & Outlooks (for more details: [nucl-th]:1711.05207)

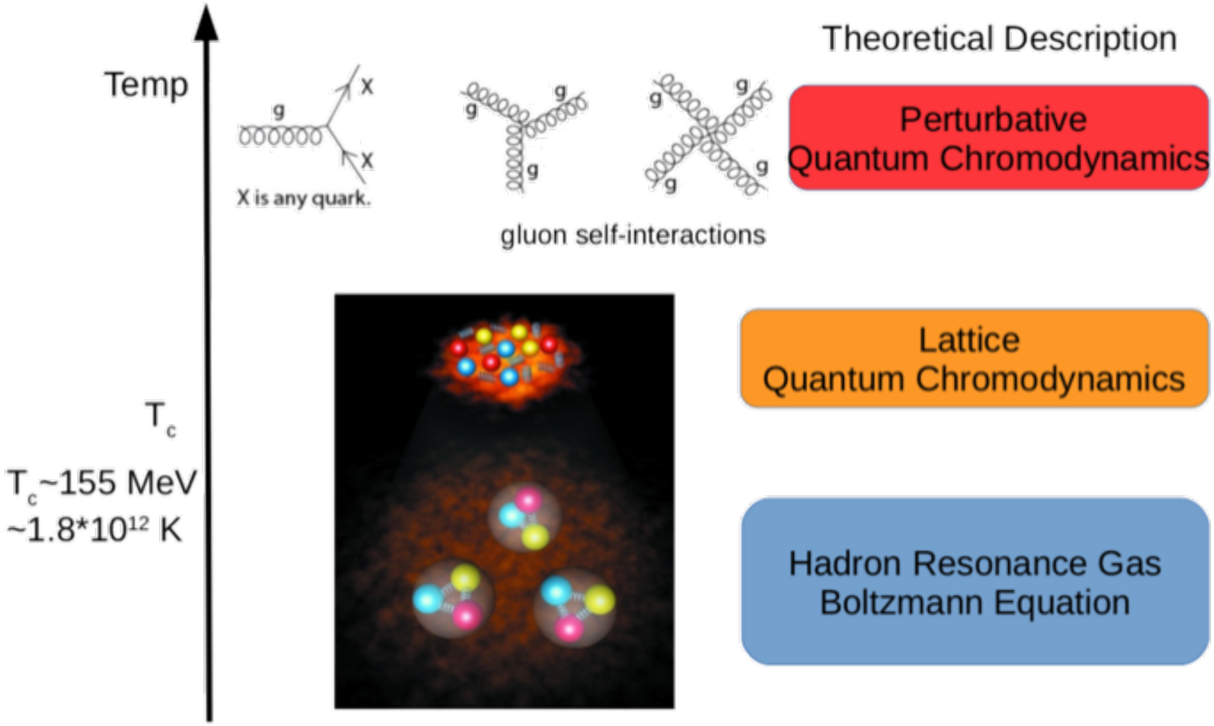
- EoS based on **additional strange hadronic states** (PDG2016+) and **state-of-the-art LQCD** calculations for **2+1/2+1+1** quark flavors ⇒ **partial pressures analysis**
- inclusion of **additional *-** states**:
  - increase the agreement with LQCD data up **T≃145 MeV**, close to the crossover region
  - enhance the production of **particles at higher p_t** and leads to a **higher $\langle p_t \rangle$**
- **Shear viscosity and new EoS**:
  - **50% increase** wrt to old EoS at LHC energies
  - **at LHC run2 energies sensitive to EoS**⇒ 15% difference in 2+1 and 2+1+1 EoS results which should increase at higher temperatures
- **Flow harmonics and NSC at STAR 200 GeV**:
  - Nice **agreement** with recent results presented at **QM18** by **STAR collaboration**
- **Outlooks:** thermal fit analysis on STAR and LHC yields and ratios to study QCD flavour hierarchy and transport coefficients near phase transition (in preparation)

Outlooks:

- Thermal fit analysis based on this new-up-to-date spectrum for particle yields at RHIC and LHC data (in preparation)

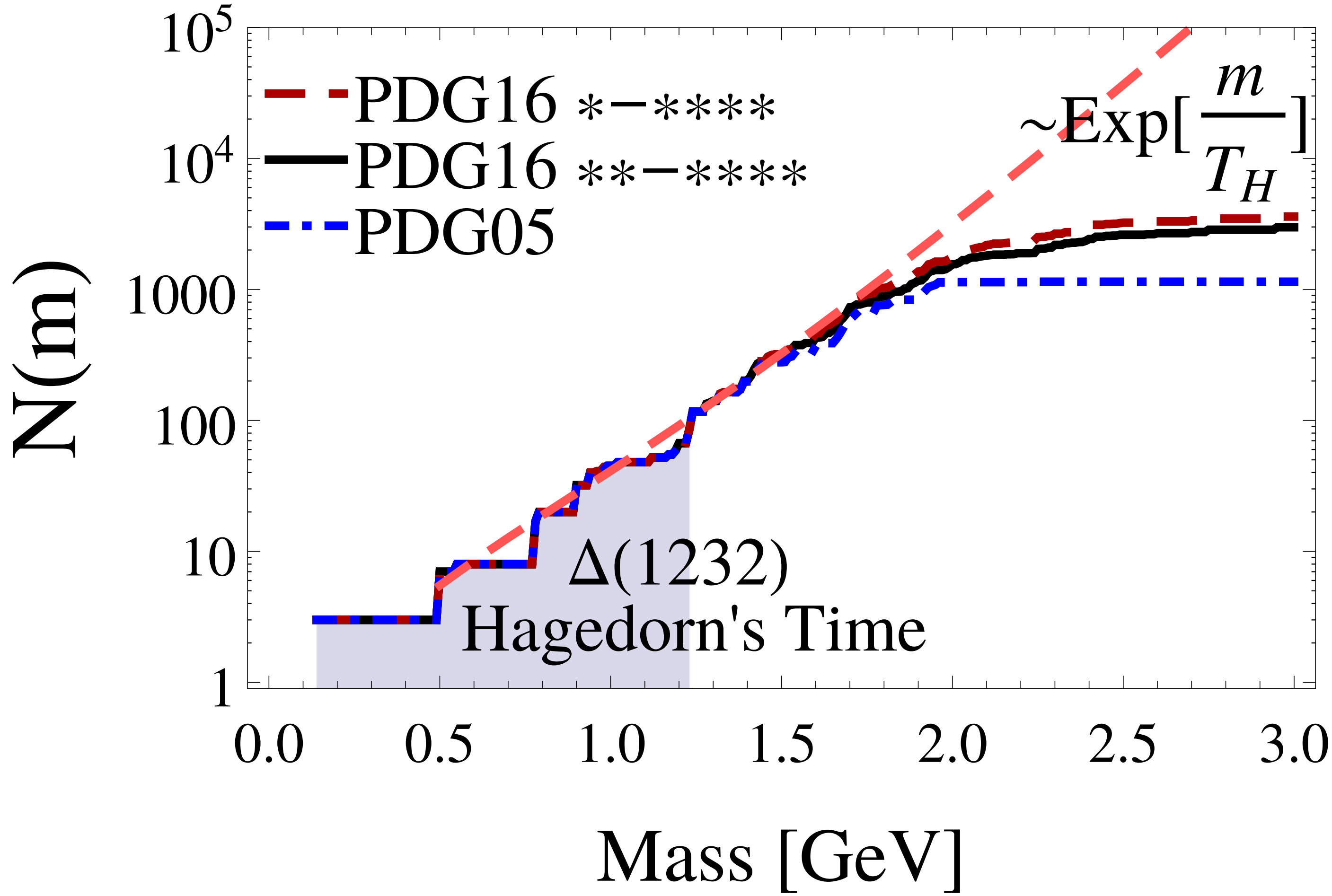
BACKUP SLIDES

Building the EoS: HRG model at low T



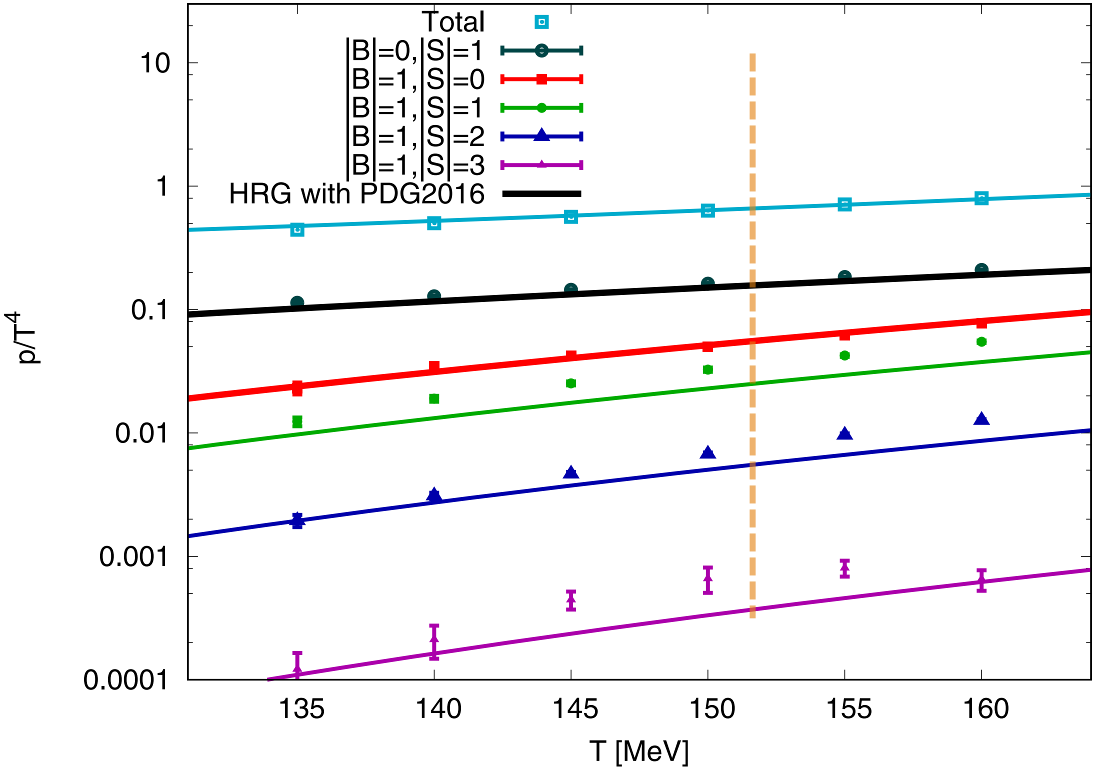
(J.Norohna-Hostler slides)

Building the EoS: HRG model at low T



(J.Norohna-Hostler slides)

Partial pressures from LQCD



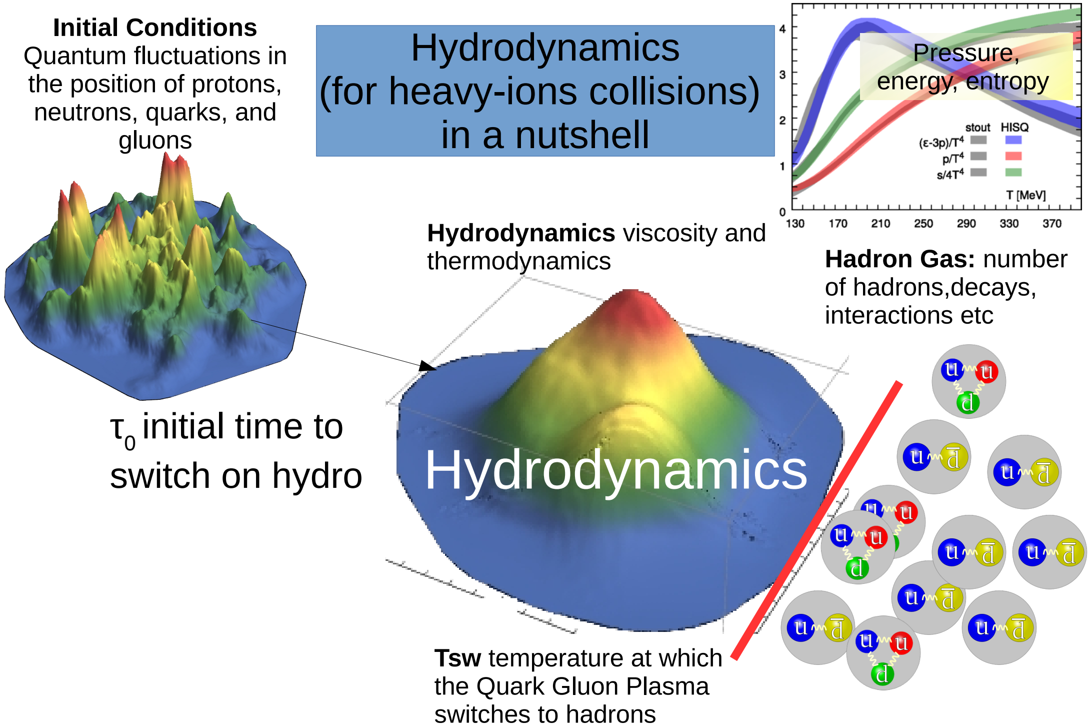
- Sensitive to the strangeness content

$$
\begin{aligned}
P_S(\hat{\mu}_B, \hat{\mu}_S) &= P_{0|1|}\cosh(\hat{\mu}_S) \\
&+ P_{1|1|}\cosh(\hat{\mu}_B - \hat{\mu}_S) \\
&+ P_{1|2|}\cosh(\hat{\mu}_B - 2\hat{\mu}_S) \\
&+ P_{1|3|}\cosh(\hat{\mu}_B - 3\hat{\mu}_S)
\end{aligned}
$$

$$
\begin{aligned}
P_{0|1|} &= \chi_2^S - \chi_{22}^{BS} \\
P_{1|1|} &= \frac{1}{2}\left(\chi_4^S - \chi_2^S + 5\chi_{13}^{BS} + 7\chi_{22}^{BS}\right) \\
P_{1|2|} &= -\frac{1}{4}\left(\chi_4^S - \chi_2^S + 4\chi_{13}^{BS} + 4\chi_{22}^{BS}\right) \\
P_{1|3|} &= \frac{1}{18}\left(\chi_4^S - \chi_2^S + 3\chi_{13}^{BS} + 3\chi_{22}^{BS}\right)
\end{aligned}
$$

P. Alba PRD96 (2017)

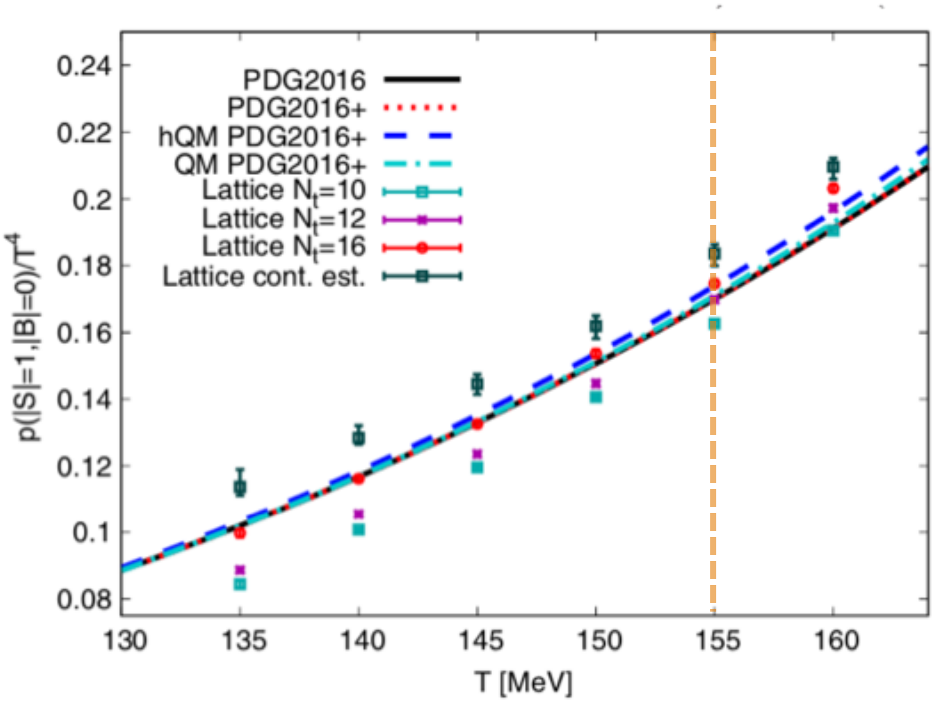
Hydrodynamical evolution



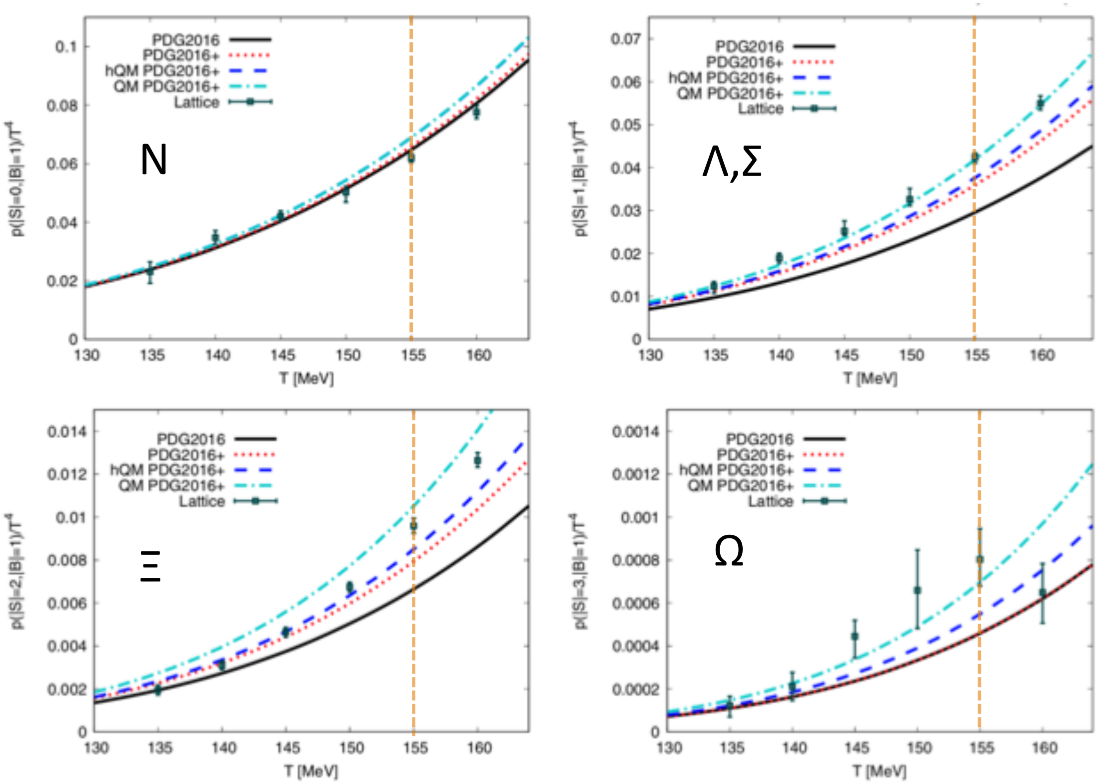
- E-b-E **v-USPHydro** + **TRENTO I.C.** $+T_{kin}=T_{chem}$
- On/off hydro chosen to be consistent as possible with LQCD
- $\boldsymbol{\tau_0 = 0.6}$ **fm,** $\boldsymbol{T_{SW} = 150}$ **MeV**

(J.Norohna-Hostler slides)

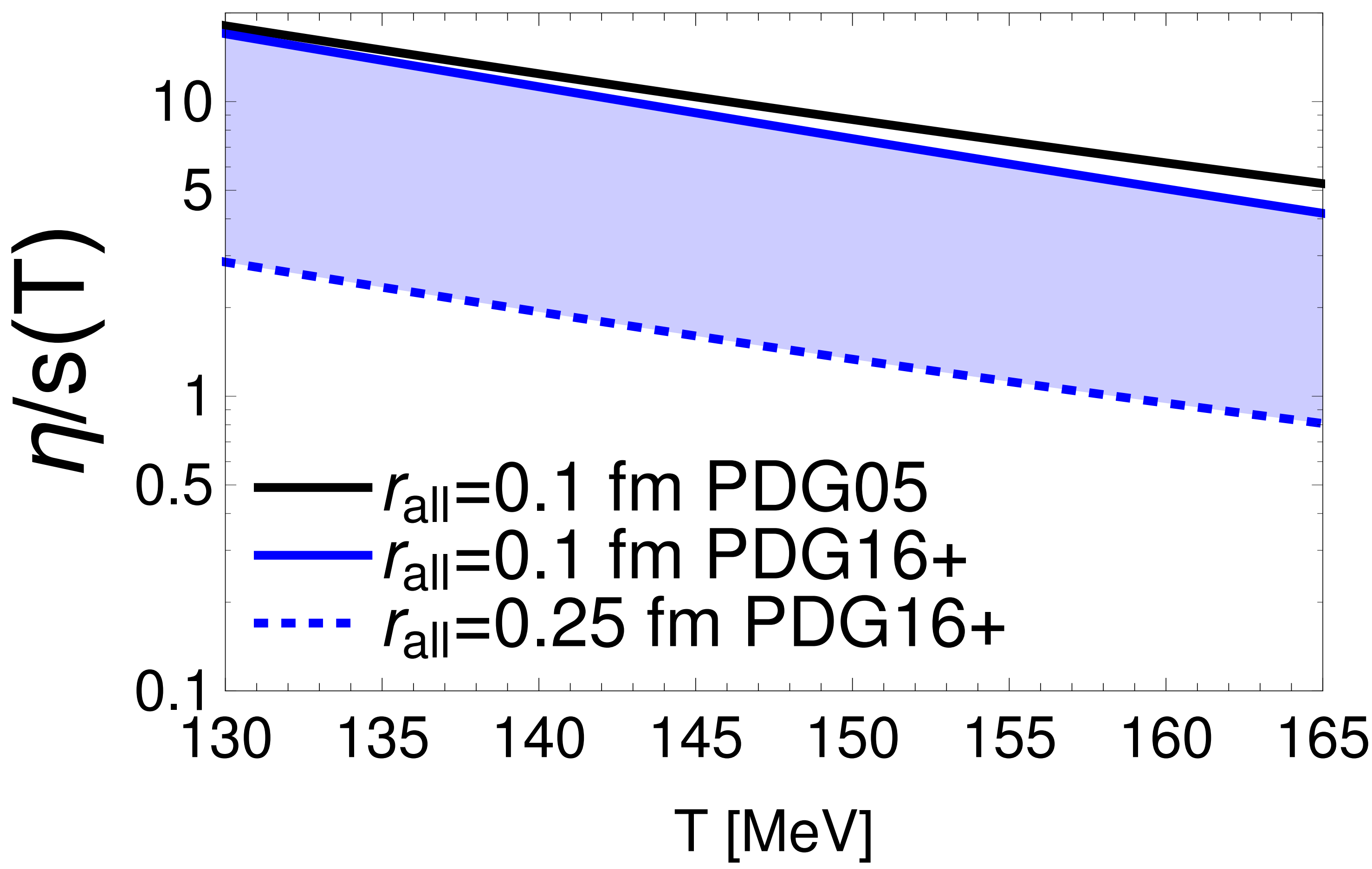
Partial pressures from LQCD: Kaons



Partial pressures from LQCD: N states and Hyperons



Shear viscosity and hadronic spectrum



Master Stud. J.Rose (Houston Univ.)