SQM 2016 - Theory Summary

Vincenzo Greco University of Catania

Strangeness in Quark Matter 2016
July 1, 2016
University of Berkeley, California (USA)

Overview

- ✧ TH Plenary Talks: 10
- ✧ TH Parallel Talks: 42 (4 parallel sessions)
- ✧ TH Theory Summary: 1

Time evolution

	Mon-27	Tue-28	Wed-29	Thur -30	Fri - 1
Plenary	3	1	4	2	
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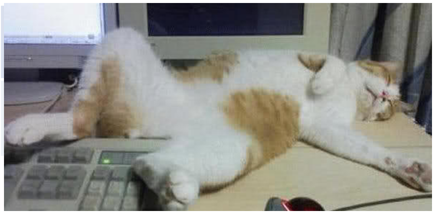


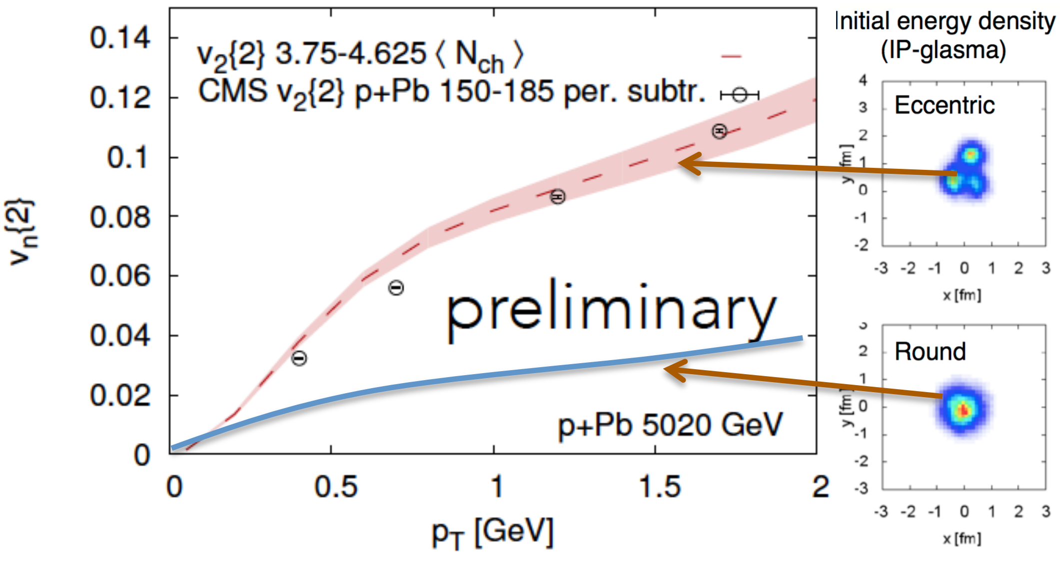
This are just the yields, with the correlations it is much worse !

Outline

- ✧ Small Systems [w/o SHM]
- ✧ Strangeness production [low E]
- ✧ QCD Phase Diagram &Chemical freeze-out
- ✧ Open Heavy Flavor
- ✧ Quarkonia
- ✧ Chiral Magnetic & Polarization

Collectivity in small systems

B. Schenke, Tue 12:00



<u>Viscous Hydrodynamics</u> can!
Evidence for shape fluctuations from J/Ψ diffractive production -> **constrain!**

Knudsen ratio small for hydro?
Yes! Conclusion may be correct
(AdS/CFT check … Kin. Transp.?)

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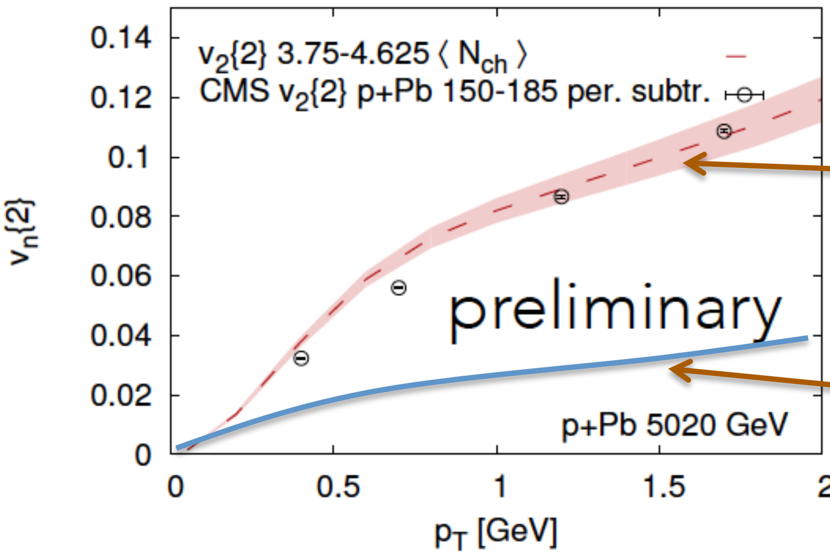

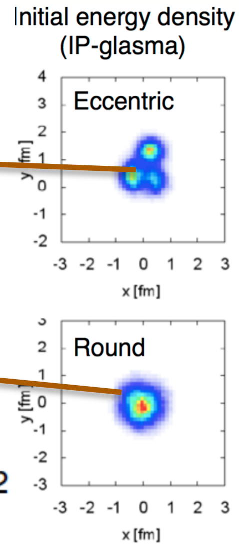

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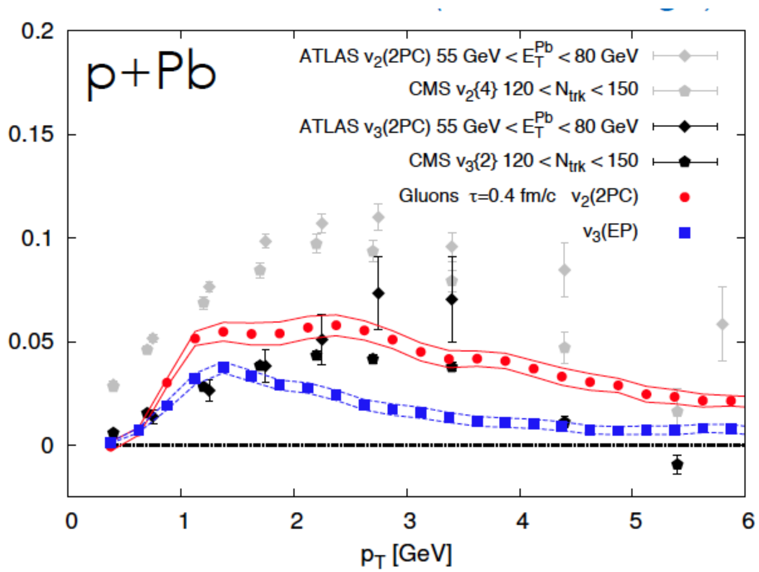
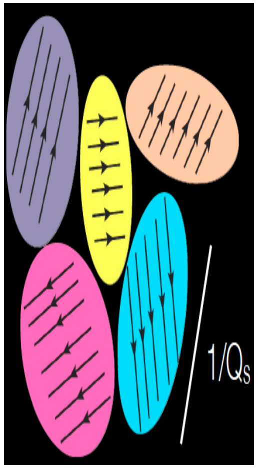
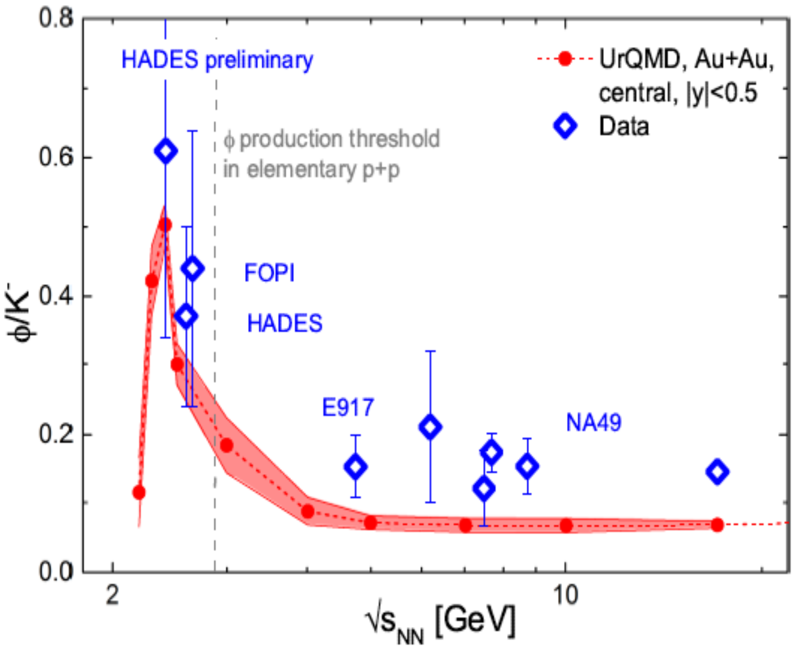




<u>Initial state **local** correlation</u>
in small domains:
- calculation in Yang-Mills frame
- no correlation with initial ε_n
- start with $v_2 \neq 0$

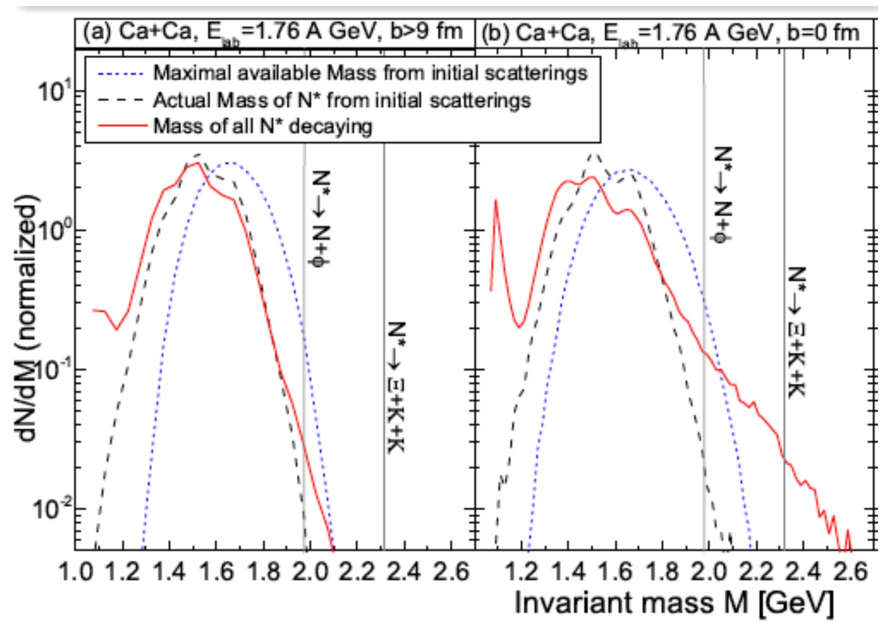
Sub-threshold Strangeness & Charm

J. Steinheimer, Thu 14:00



Explanation of ϕ/K^- enhancement in HADES

- Secondary collision -> strong non-th tail.
- Ξ enhancement ok!
- J/Ψ, Λ_c, D enhancement → measurable also at E_{lab}=6 GeV



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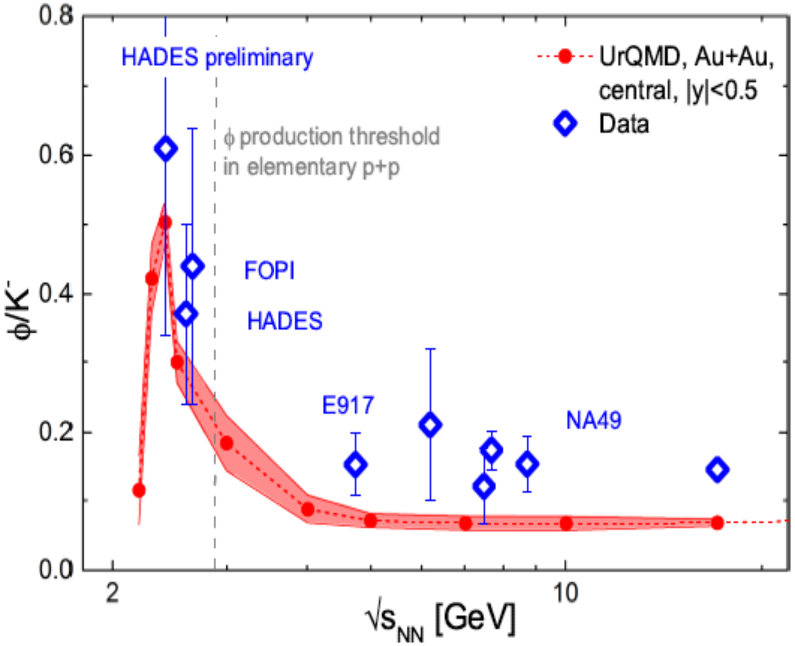

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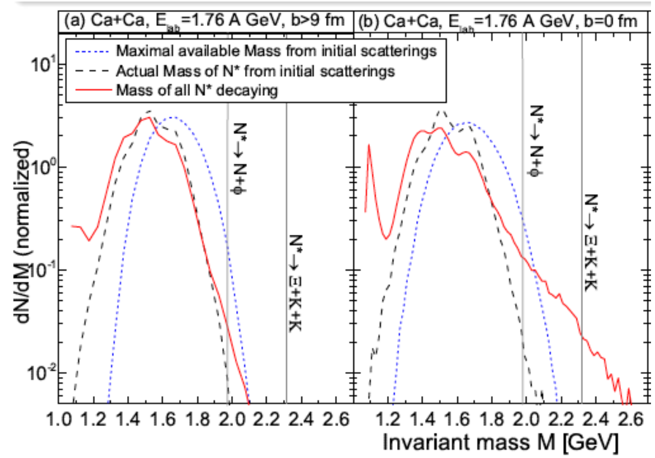
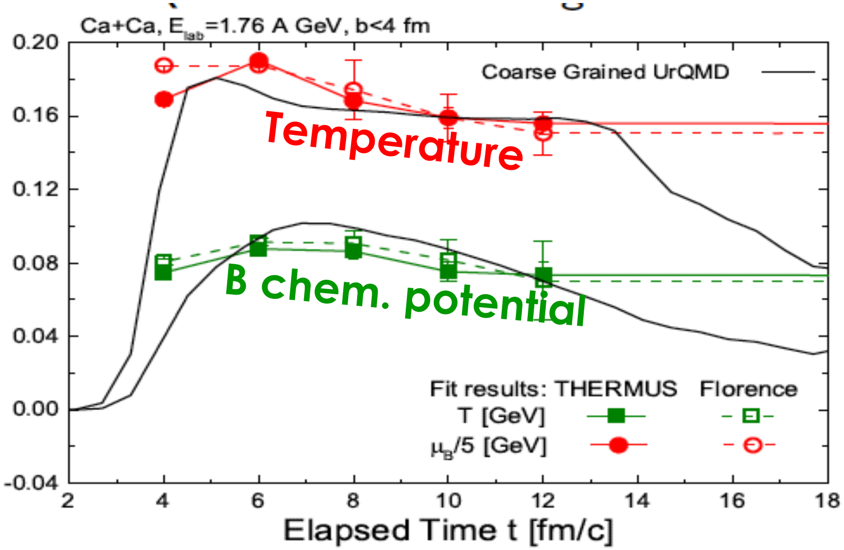


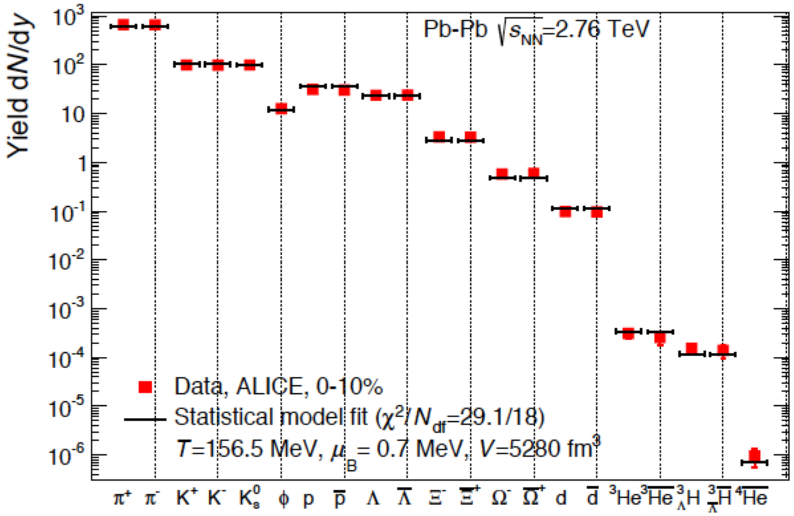


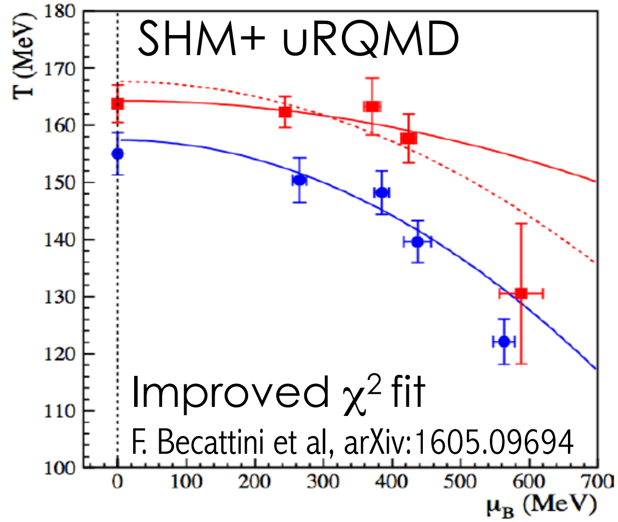
✓ Before passing time the T, μ_B agree with SHM + hadronic yield quite close

✓ It's not the many scatterings but the large # of states populated

Statistical Thermal Model

A. Andronic, Wed 11:00





See R. Stock's Talk. Tue 16:20

Tension p,pbar / strange, but enjoy
9 order of magnitute plot and be impressed!
Be careful with systematic errors!

We miss SHM for pA, dAu ….

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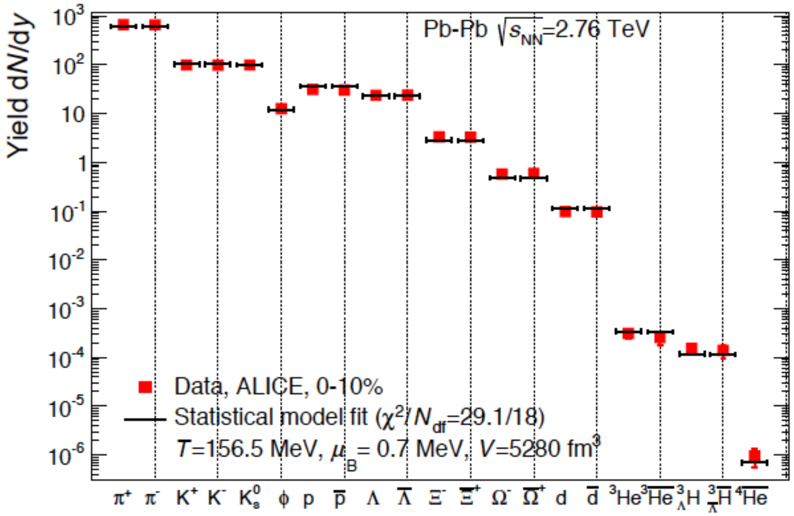

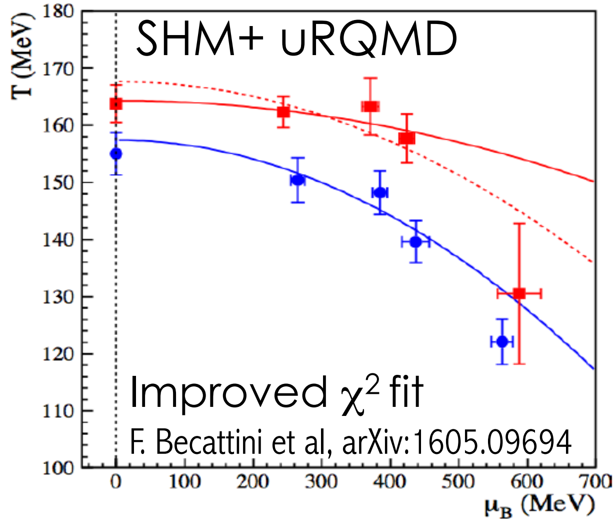

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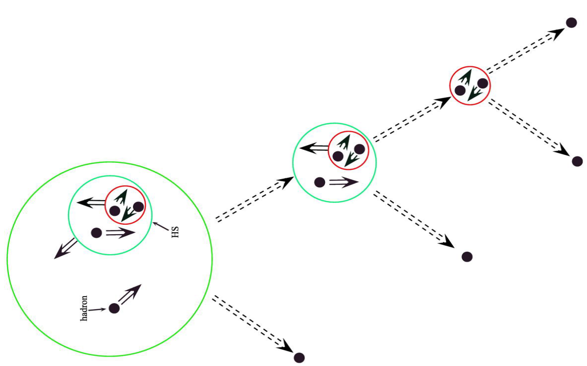
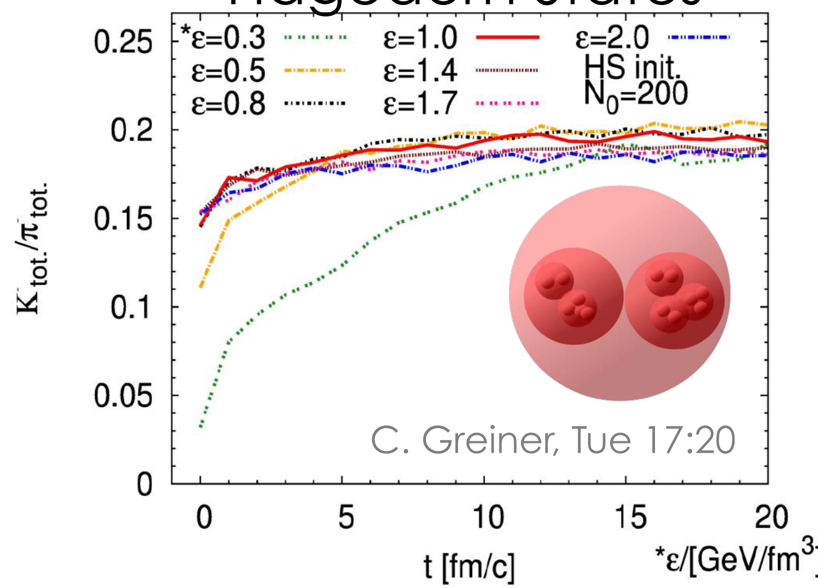


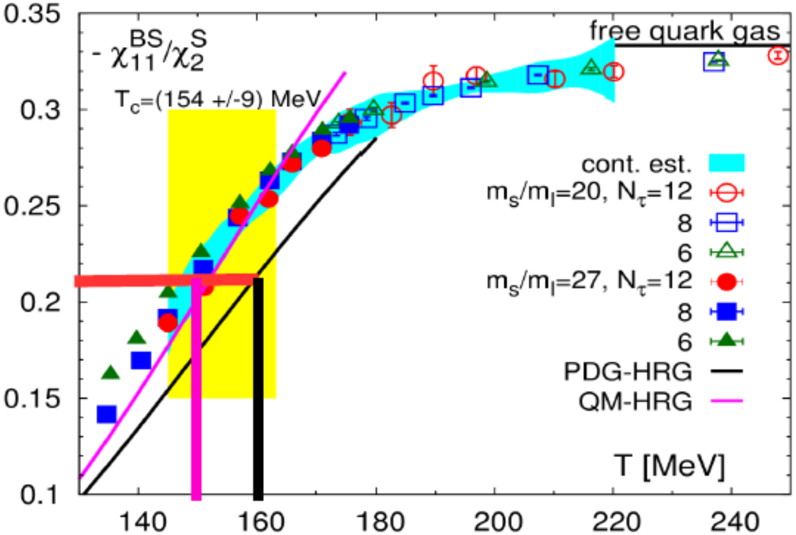
Hagedorn States



Lattice results on freeze-out

F. Karsch, Wed 9:30

Koch ratio



with HRG gives: $T_f = 160\ \mathrm{MeV}$

with QCD gives: $T_f = 150\ \mathrm{MeV}$

$$\chi_{ijk}^{BQS} = \left.\frac{\partial^{i+j+k} P/T^4}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\right|_{\mu_{B,Q,S}=0}$$ Susceptibilities/cumulants

If PDG is not ok→ this is a problem also
For the yields- standard SHM!?
Solution: use QM! But :

- we do not know decays!
- Is anyway QM-HRG nearly perfect?
  C. Ratti's talk, Wed 10:00

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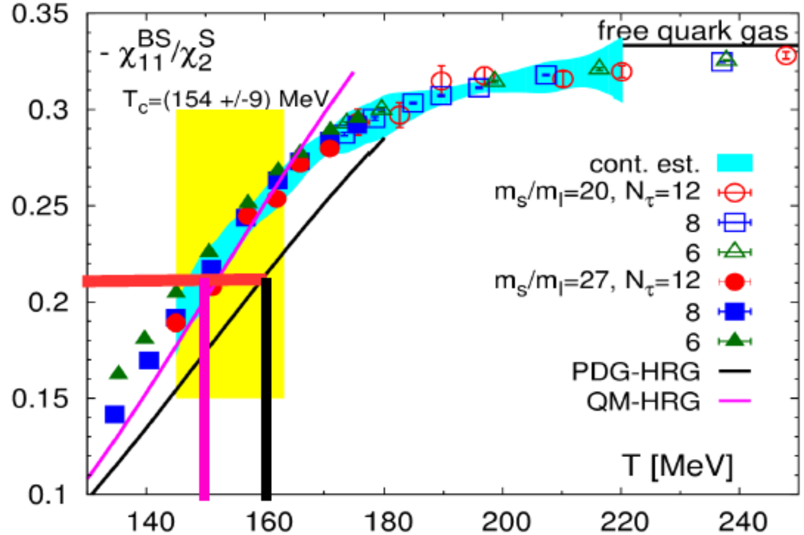

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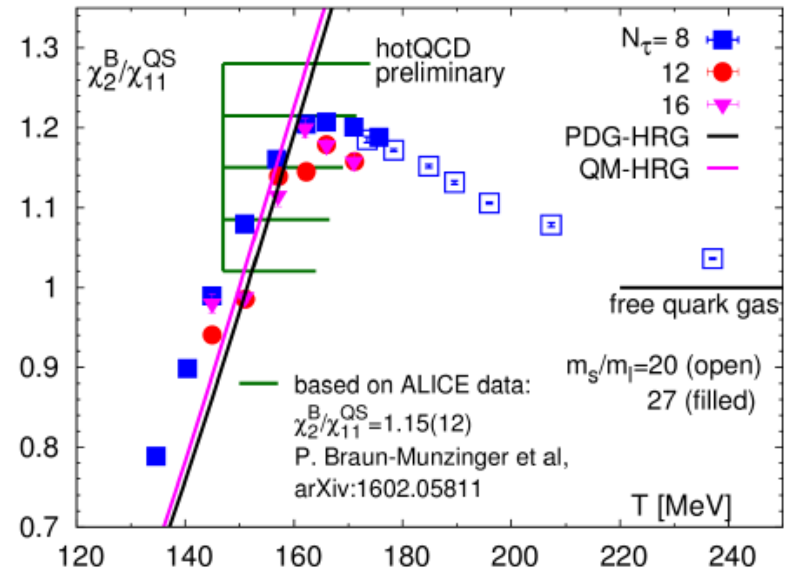
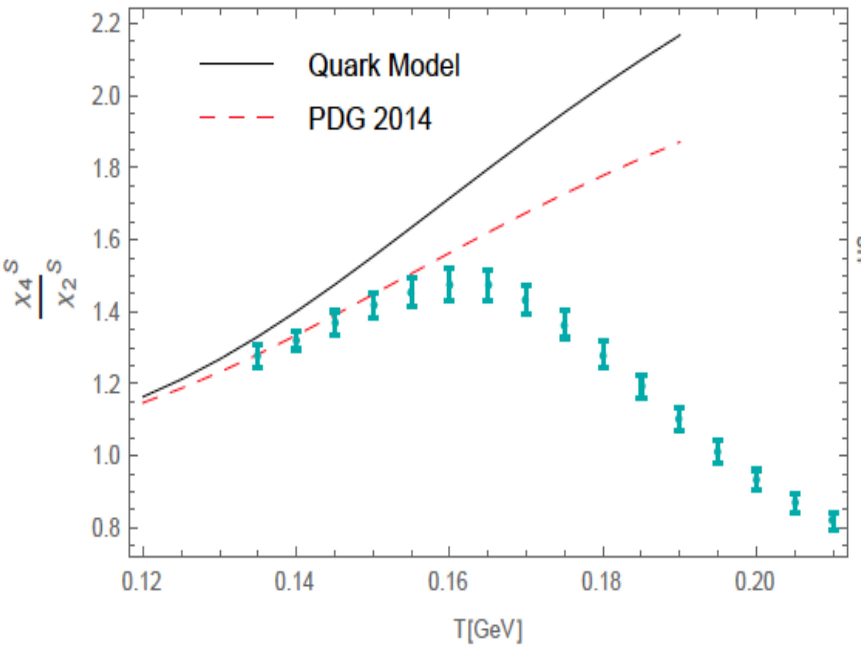
Net baryon/strang. to net-electric fluctuations, safe up to Tc=160 MeV + lQCD bounds



Bulk Properties of QCD Matter

C. Ratti, Wed 10:00 [156]

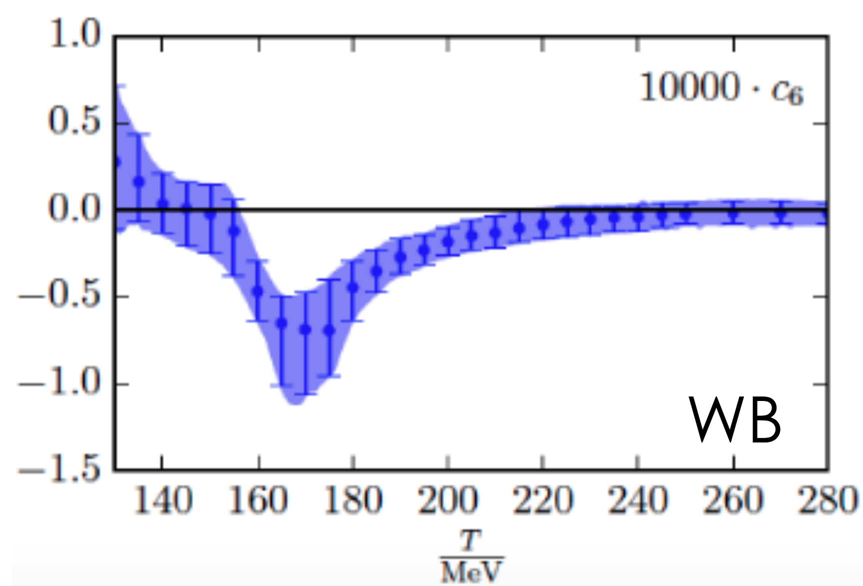


- ✧ For some suscep. ratios PDG better than QM
- ✧ Compare for each quantum number: both HRG-PDG and QM miss meson states with S=1
- ✧ PDG 2014 better than 2012 overall
- ✧ Hagedorn States? (C. Greiner's talk)

See J. Noronha-Hostler's talk
Thu 10:00 for detailed analysis

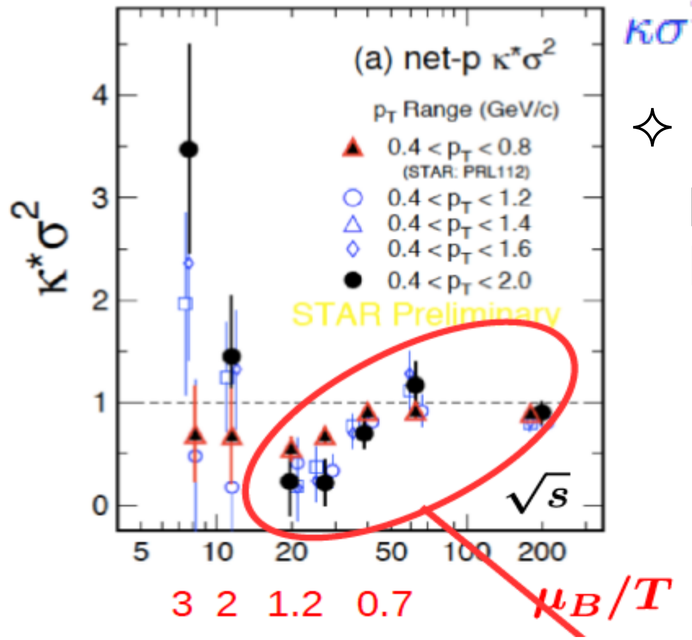
Possible to have EoS from lQCD up to μ_B=2.5 and $(\mu_B/T)^6$

$$\frac{p(\mu_B)}{T^4} = c_0 + c_2\left(\frac{\mu_B}{T}\right)^2 + + c_4\left(\frac{\mu_B}{T}\right)^4 + c_6\left(\frac{\mu_B}{T}\right)^6 + \mathcal{O}(\mu_B^8)$$

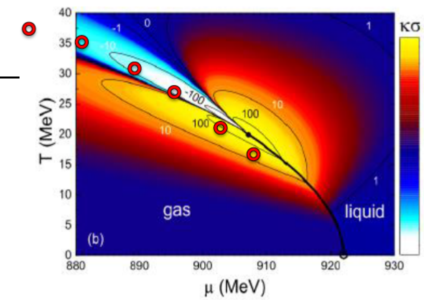


Exploring QCD Phase Diagram

F. Karsch, Wed 9:30

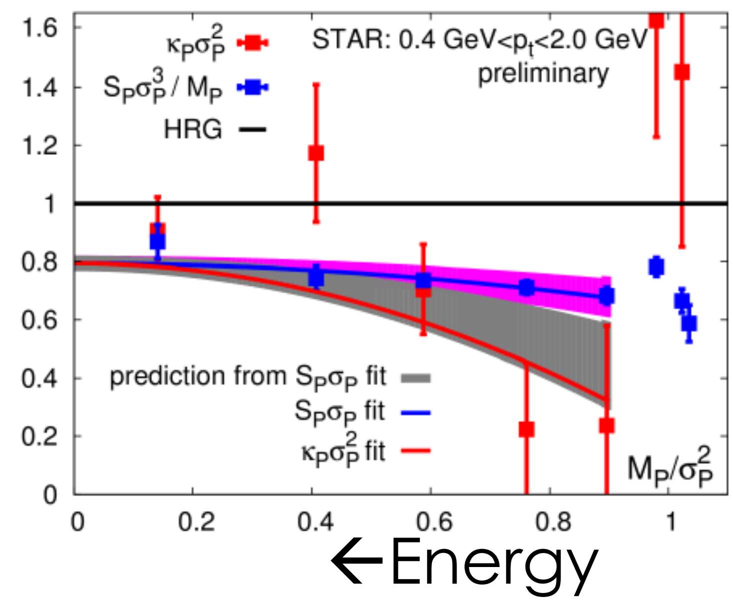


$\kappa\sigma^2 = \chi_4/\chi_2$ kurtosis



✧ lQCD reliable for $\mu_B/T < 2$,
properties of cumulants in BES-I differ from HRG
but are consistent with QCD thermodynamics

$$R_{42}^{B,2} = 3R_{31}^{B,2} = \frac{1}{2}\left(\frac{\chi_6^B}{\chi_2^B} - \left(\frac{\chi_4^B}{\chi_2^B}\right)^2\right)$$



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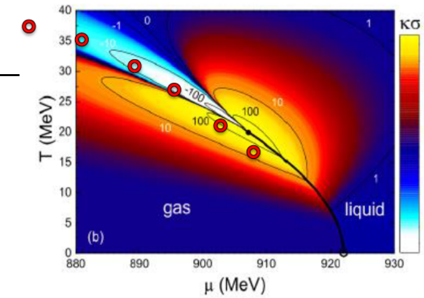

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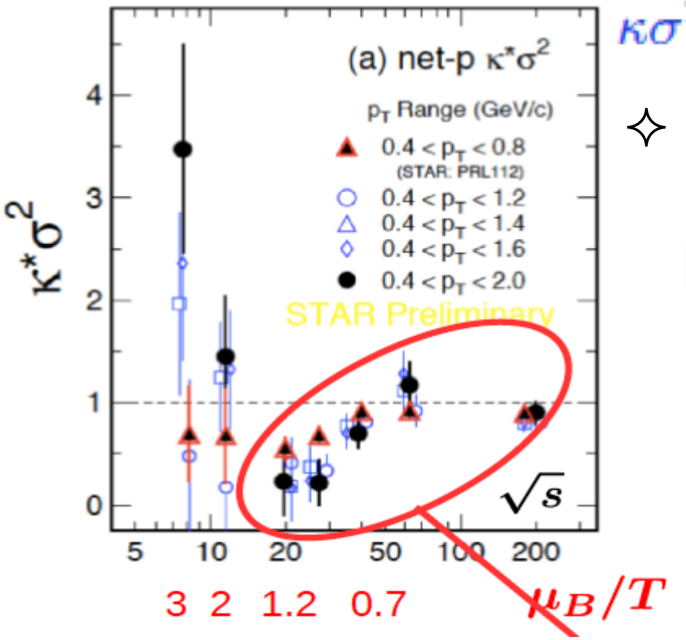

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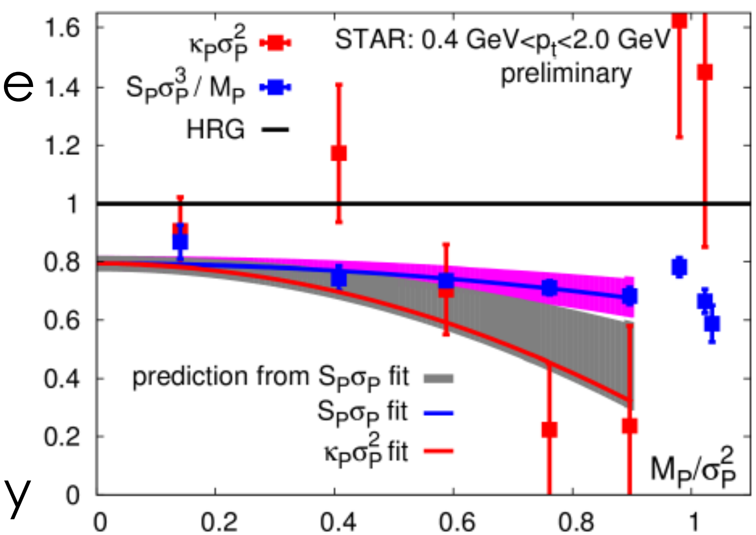
✧ Critical fluctuations survive resonance decays: reduction Sσ & kσ² by 40-50%,
M. Bluhm, Tues 14.40

✧ Signal of kσ² remains also in NFχD,
C. Herold – Tue 15:00

✧ Explore phase diagram for CP looking at large rapidity High-Energy
J. Kapusta – Tue 17.40



←Energy

Open Heavy Flavor

One remark

Differences with bulk dynamics:

- Initial state known (FONLL- pp, pA data)
- Non-equilibrium $\tau \geq \tau_{QGP}$ → Carry info on detailed dynamics

❖ After ≈ 12 years we still struggle with R_{AA} and V_2
Differently w.r.t. to light bulk - hydrodynamics
T dependence of interaction very relevant

Open Heavy Flavor

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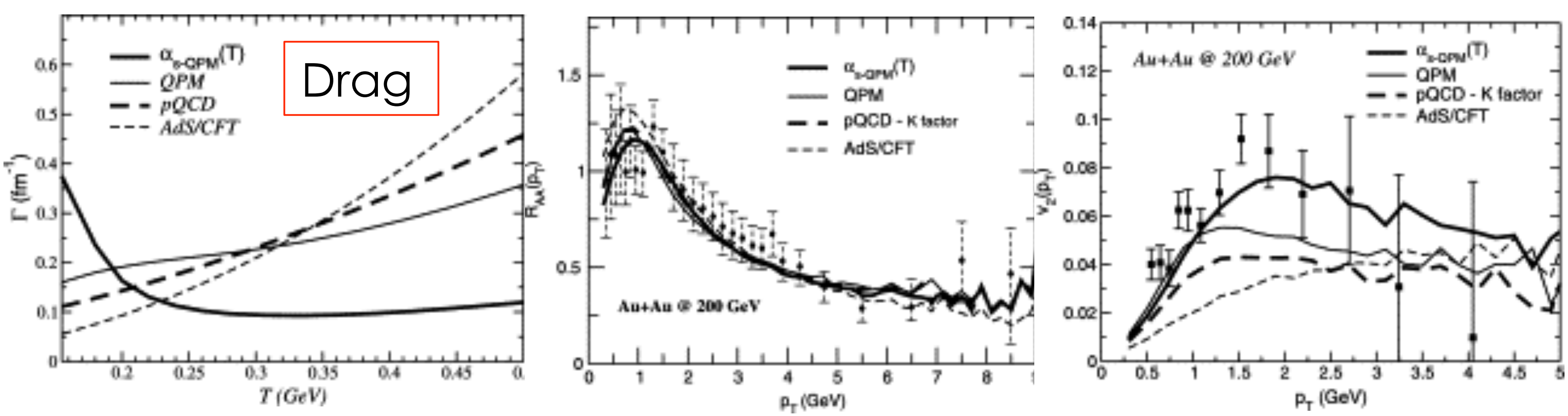
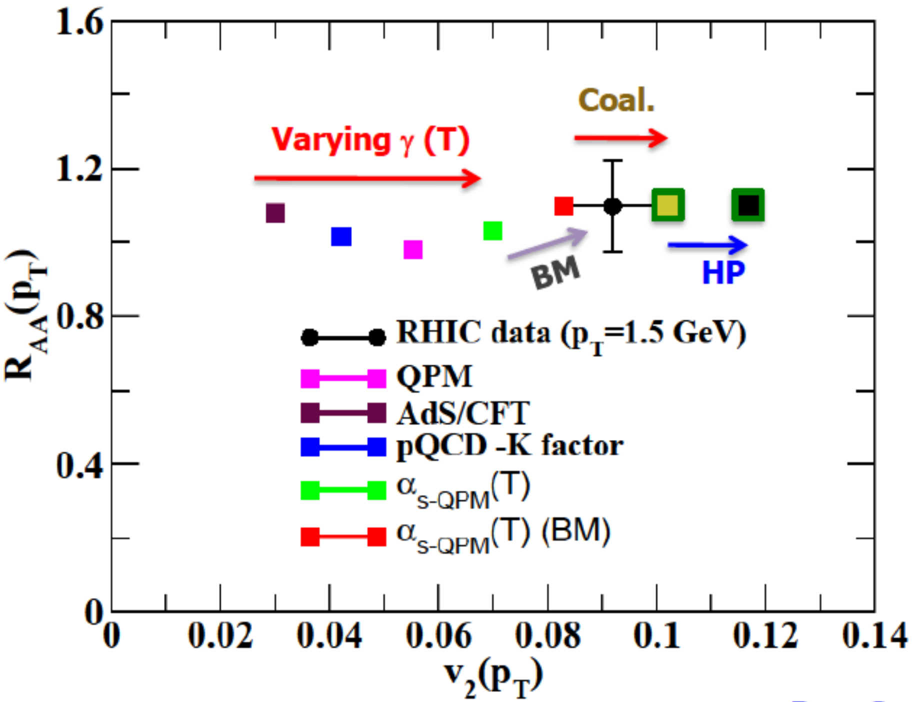


S. Cao, Mon 14:30

S. Das et al., PLB747 (2015) 260

R_{AA} – V_2

S. Das, Thu 16:30



Γ(T) for HQ much more impact than η/s(T) for bulk evol.:

- factor 2.5-3 vs 20%

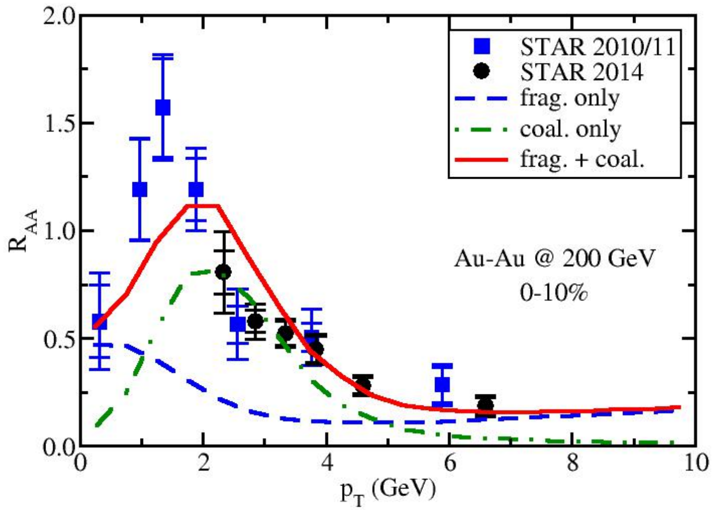
S. Cao's Talk, still several ingredients to be sorted out, we are working on that…

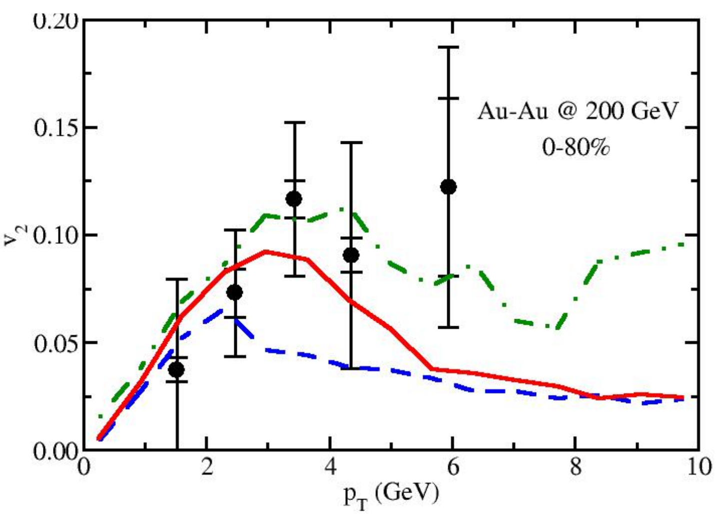
✧ Both pQCD (α_s=cost) & AdS/CFT ruled out $\Gamma \approx T^2$

✧ At RHIC solution for R_{AA}-v_2, not clear is sufficient at LHC (still large error bars)

Medium Energy Loss

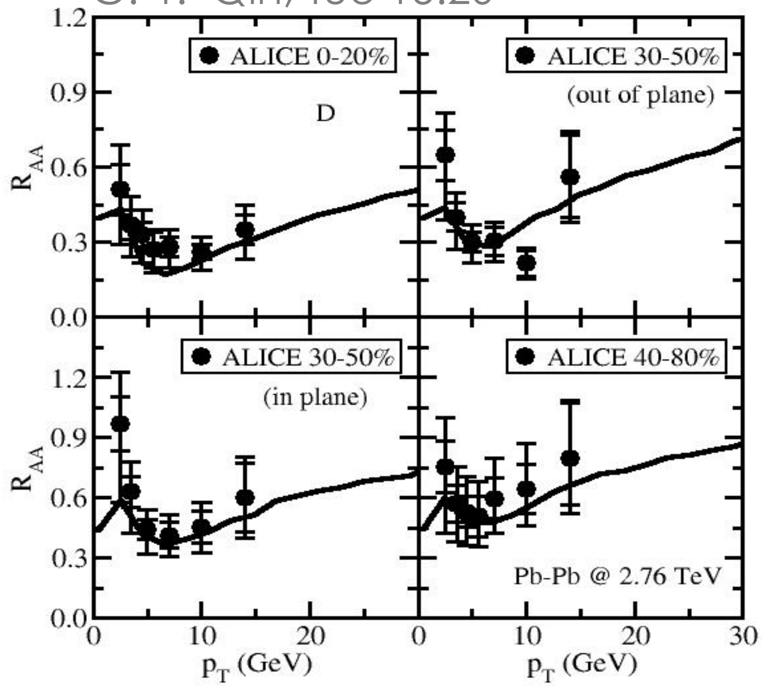
S. Cao, Thu 12:00





[S.Cao, Luo, Qin and Wang, arXiv: 1605.06447]

G.-Y. Qin, Tue 15:20



- ✧ T e p dependent K factor needed starting from pQCD
- ✧ Unique approach from low to high p_t from **heavy to light** (high-p_t) [LBL, Duke, CCNU]
- ✧ Also PHSD – E. Bratkovaskaia talk, Tue 16:20 + Angular correlations between **heavy and light** mesons, M. Rohrmoser's talk, Thu 10:00

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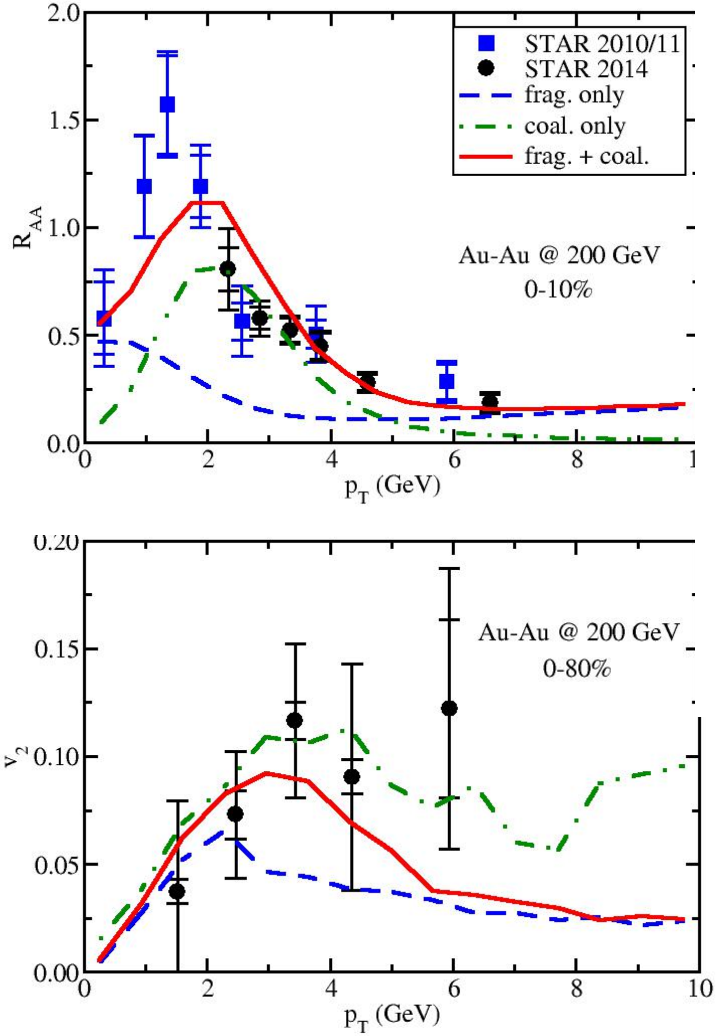

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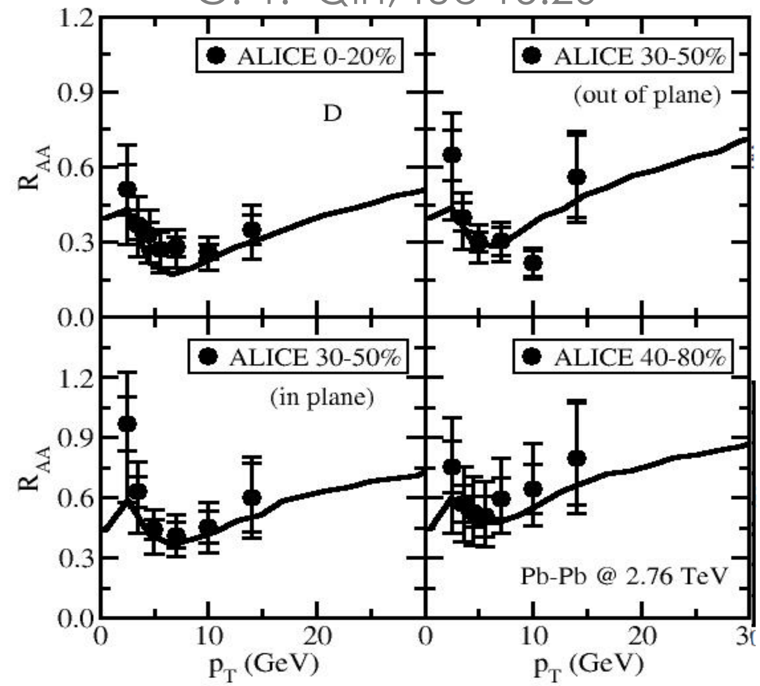

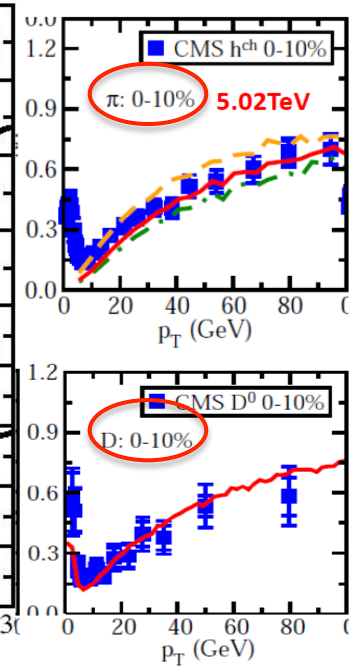

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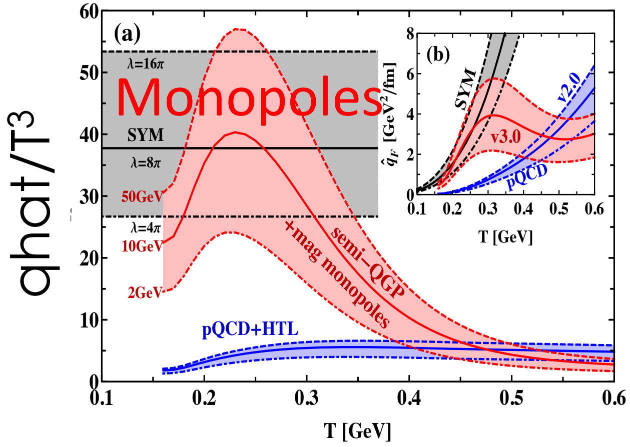
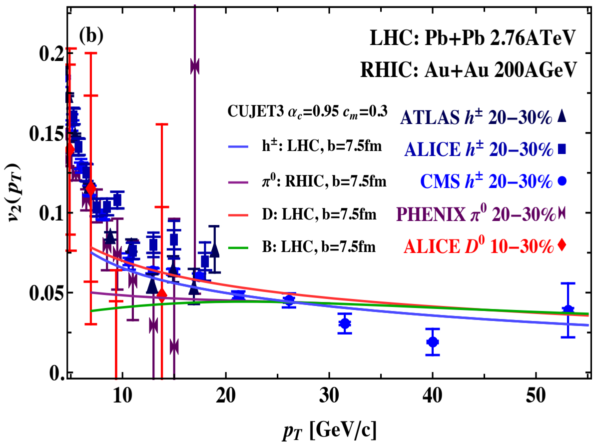
Open HF – High p_T jets

J. Liao, Wed 12:00





[J. Xu et al. arXiv: 1411.3673]
CuJET3.0 explains 7 sets of E_{loss} data at RHIC +LHC

See also Caio Prado's Talk, Thu 11:20 – also prediction v_3

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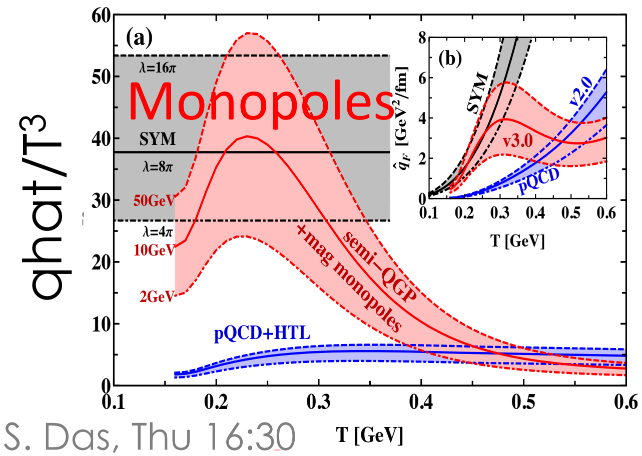

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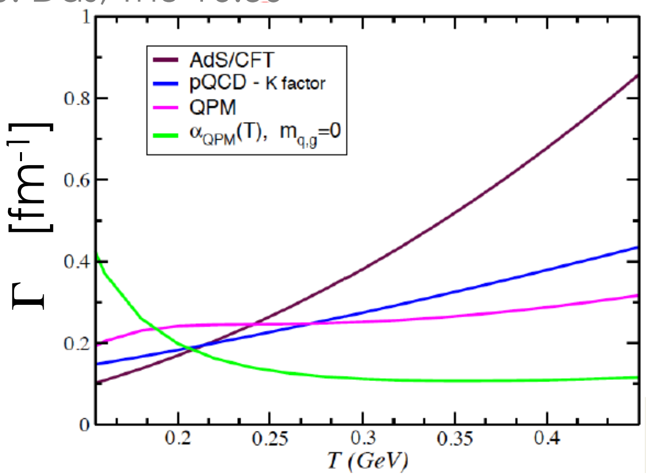
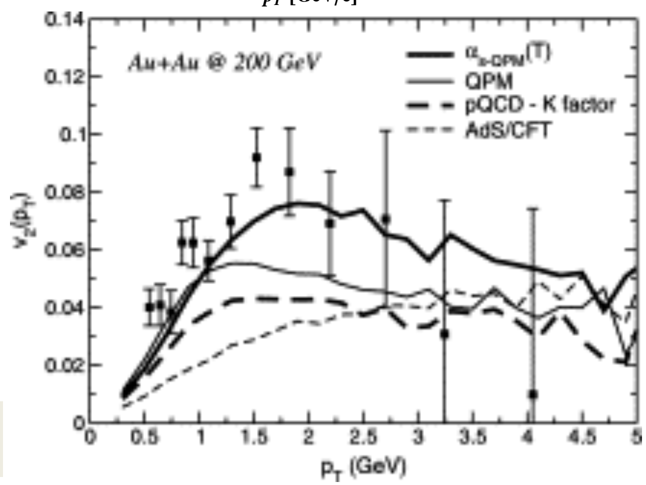




Drag (HQ transp.)

AdS/CFT, pQCD → $\Gamma \approx T^2$

QPM, PHSD, → T-matrix, CuJet3... $\Gamma \approx$ cost

Diff. space (lQCD)

$D_s(2\pi T) \approx$ cost

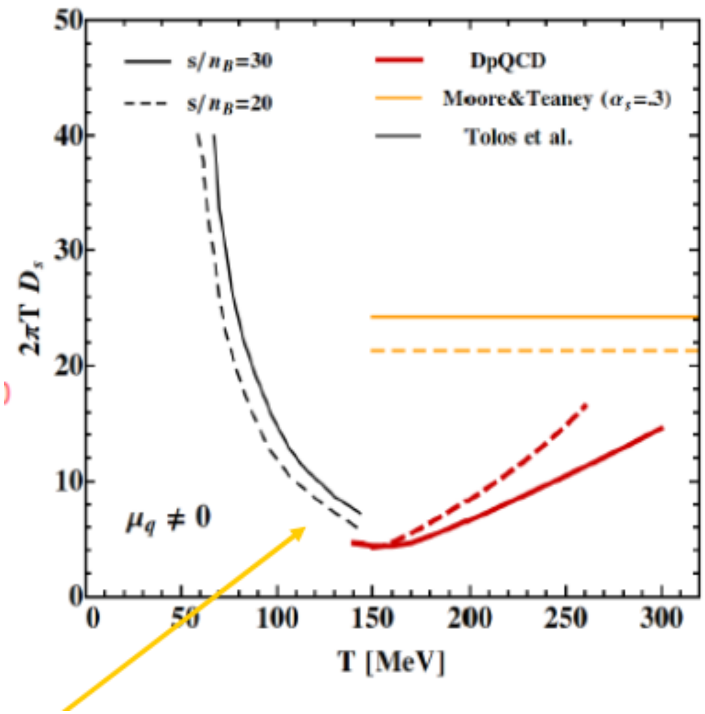
$D_s(2\pi T) \approx T^2$

Jet transp. Coeff.

$q/T^3 \approx$ cost

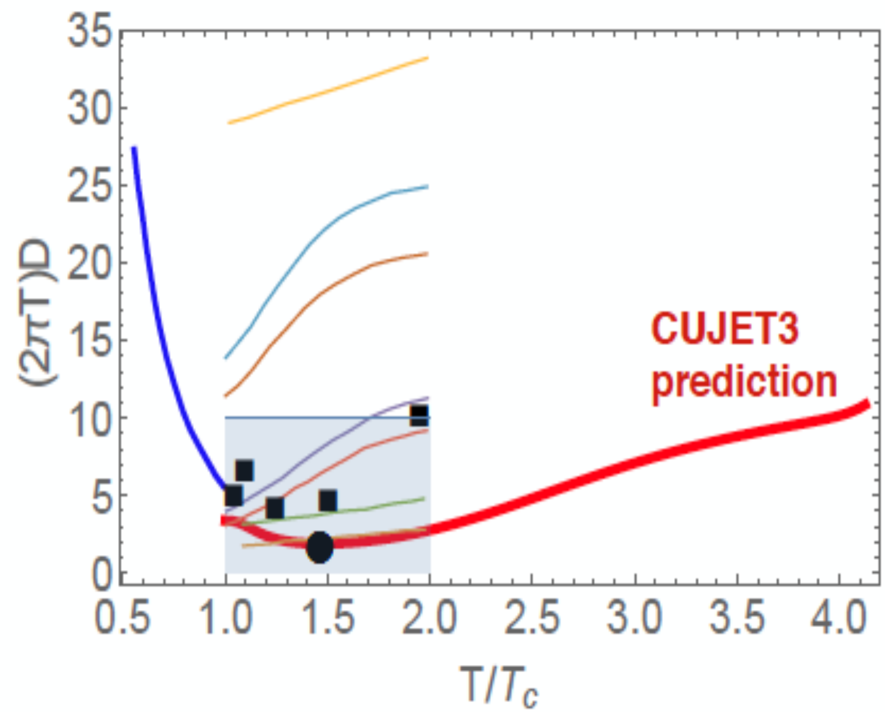
$q/T^3 \approx 1/T^2$

From HQ



E. Bratkovaskaya's talk, Tue 16:20
Similar for TAMU, Nantes, Catania…

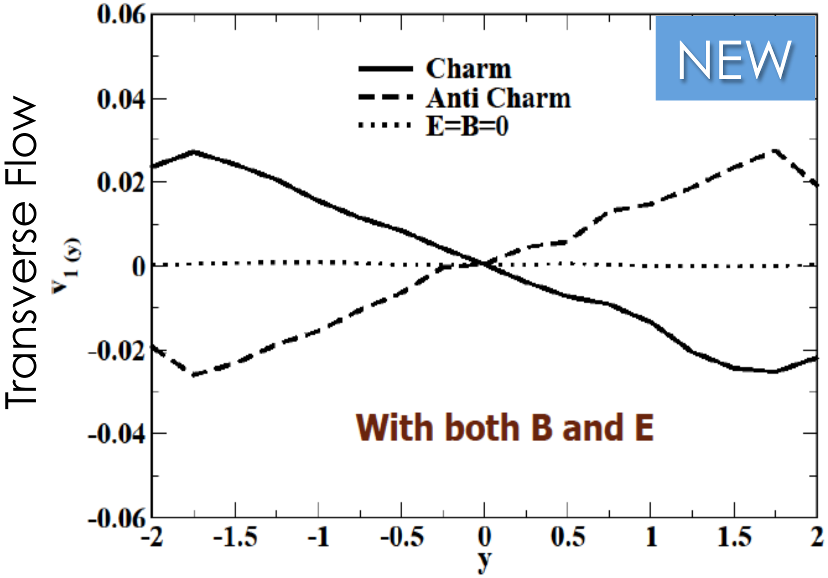
From Jets



J. Liao's talk

Magnetic Field

S. Das, Thu 16:30

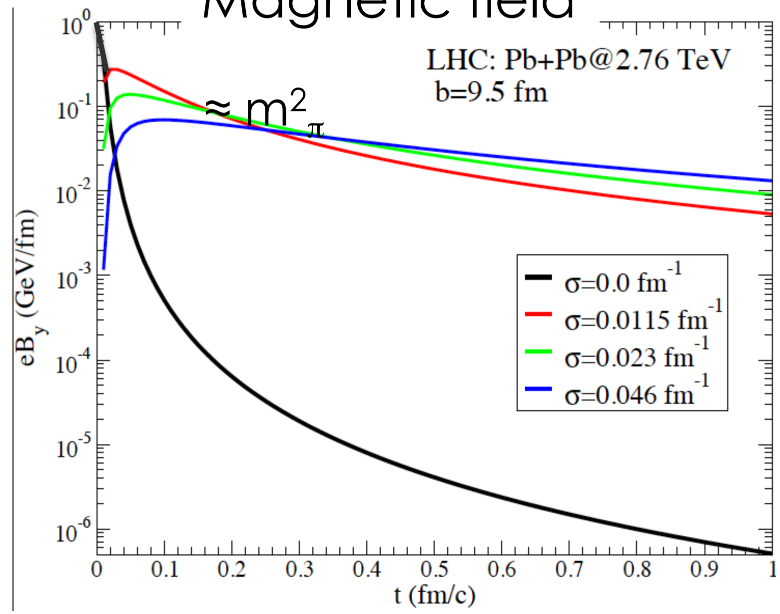


E,B field like Gusoy, Kharzeev, Rajagopal, PRC 89(2014)

HQ best probe for v_1 from B:

- $\tau_{form} \approx 0.1$ fm/c vs q << g at this time
- do not mix with CME [c no chiral]
- do not mix CVE, c opposite $\bar{c}$
- Needed evolution at t>0.1-0.2 fm/c

Magnetic field



Effect of strong magnetic field on heavy quark diffusion $K_T >> K_{||}$ qualitative effect on v_2

H.-U. Yee's talk, Thu 10:20

Charmonia

K. Zhou, Mon 16:00

History?

Static Screening / Potential

Color Screening, Survival of J/Ψ, Ψ(2S), Υ,… up to 1.2 T_c, 1.4 T_c, … 2 T_c

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}$$

Coalescence/Statistical

✧ gluon dissociation+ recombination

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

or

$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi (N_\psi - N_\psi^{eq})$$

Dynamical /Transport Approach

Different Approaches

K. Zhou, Mon 16:00

History?

Static Screening / Potential

Color Screening, Survival of J/Ψ, Ψ(2S), Υ,… up to 1.2 T_c, 1.4 T_c, … 2 T_c

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}$$

Coalescence/Statistical

- ✧ Quantum treatment: Schroedinger- Langevin eq. beyond independent quarkonia decays (see P. Gossiaux's talk- Thu 12:00)

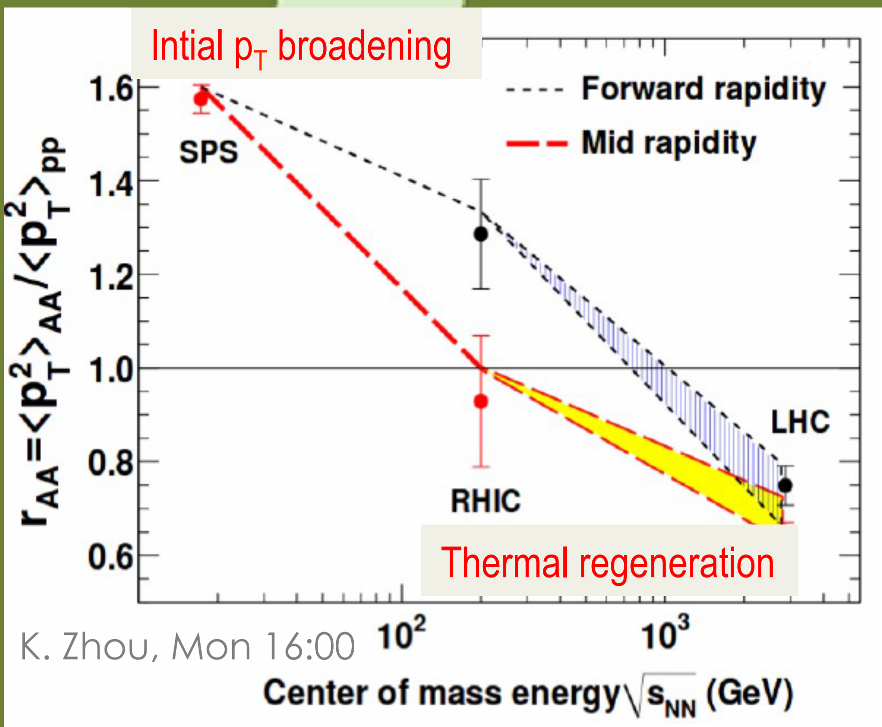
- ✧ Damping + gluon dissociation+ recombination

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

Dynamical /Transport Approach

Success of Regeneration

Static Screening / Potential



Coalescence/Statistical

✧ Damping + gluon dissociation+ recombination

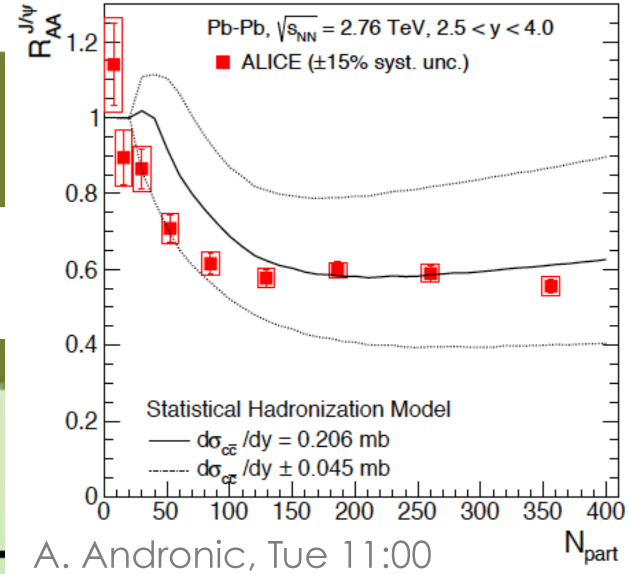
$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

Dynamical /Transport Approach

SHM vs Dynamical

Static Screening / Potential

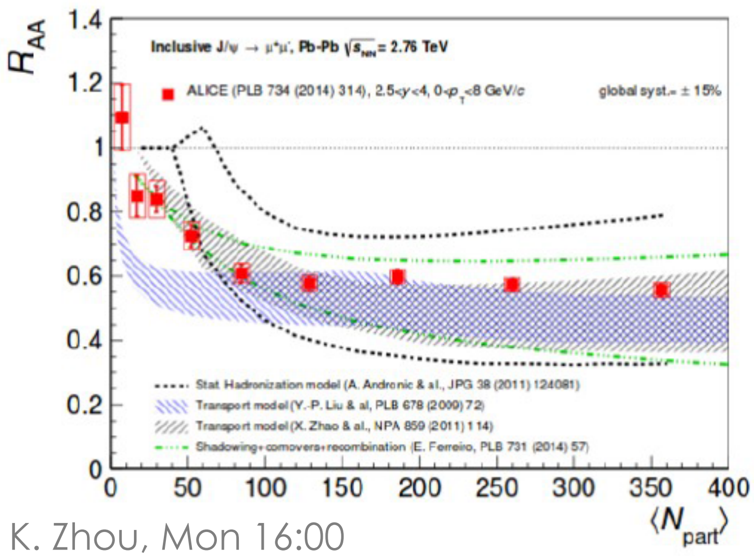
$$N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$$



A. Andronic, Tue 11:00

Coalescence/Statistical

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$



K. Zhou, Mon 16:00

Cross section measurement crucial

- Hope improved precision
- Must employ current exp. constraint

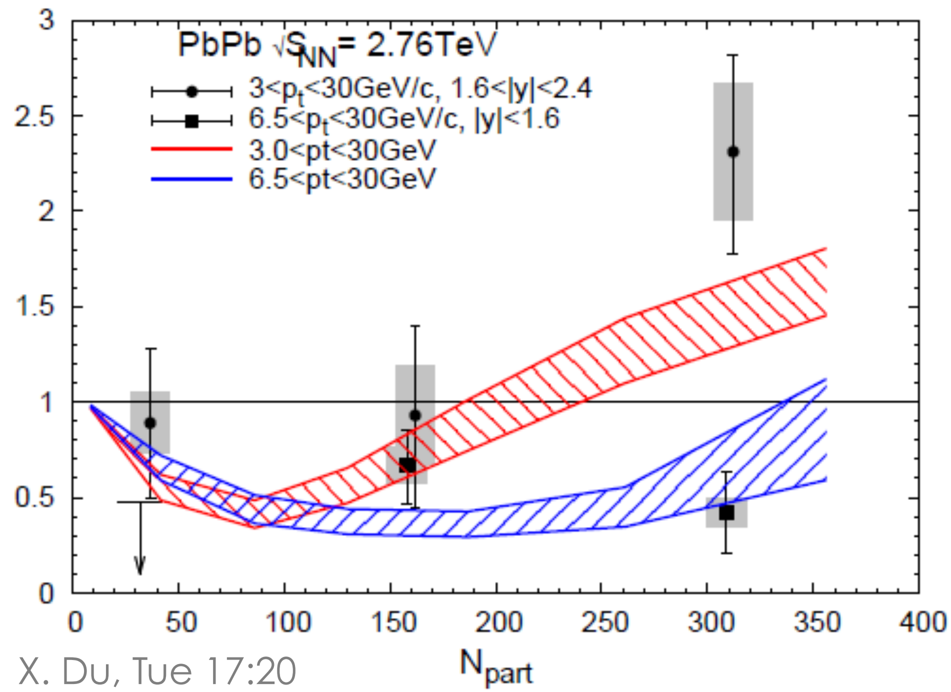
Dynamical /Transport Approach

Quarkonia at Phase boundary?

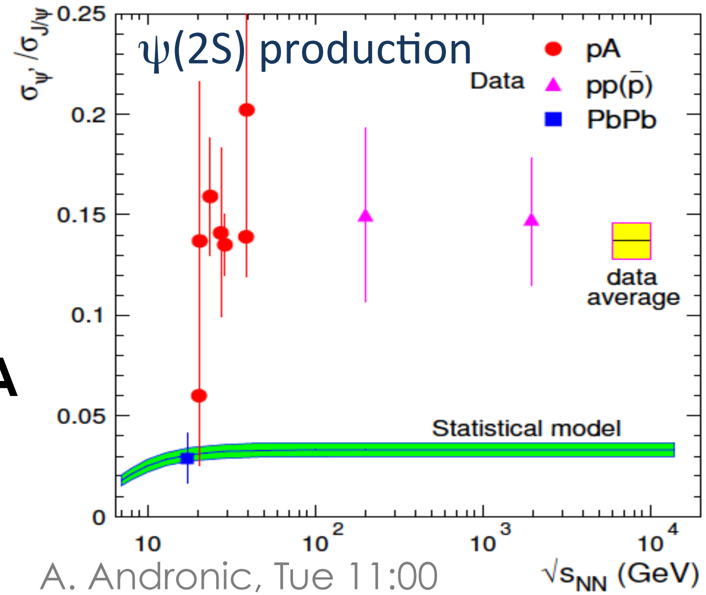
K. Zhou, Mon 16:00

Static Screening / Potential

High-p_T Ψ(2S) less suppression than pA



X. Du, Tue 17:20



A. Andronic, Tue 11:00

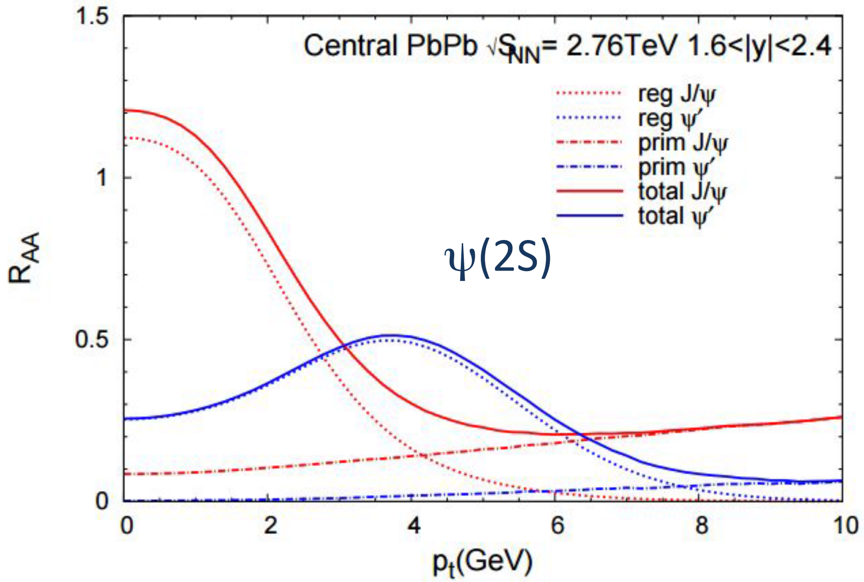
Coalescence/Statistical

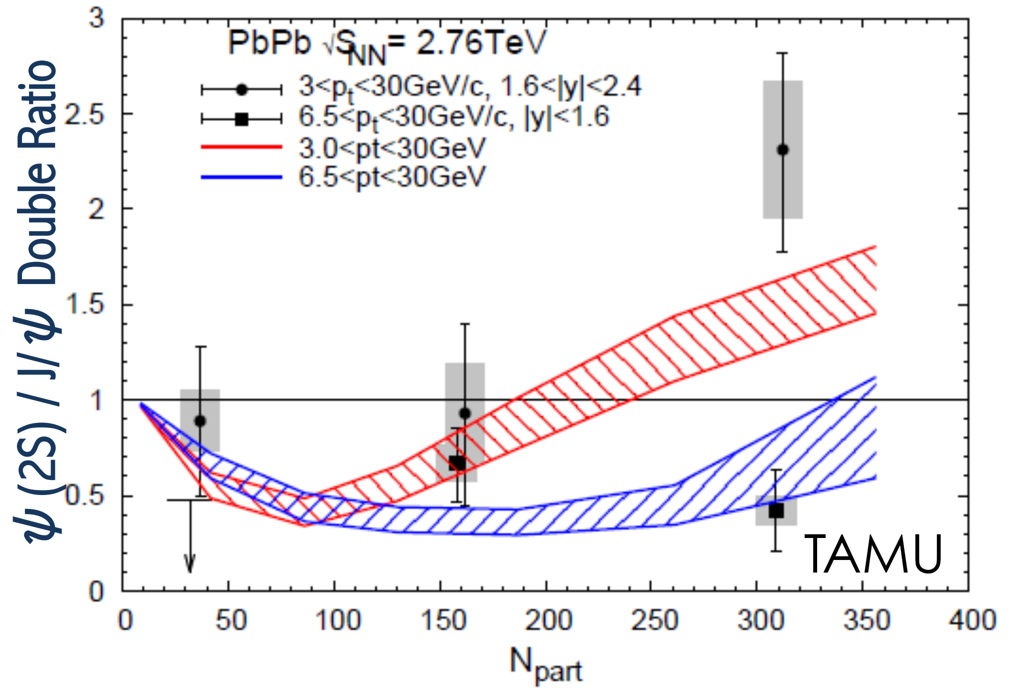
Dynamical /Transport Approach

Sequential Regeneration

X. Du, Tue 17:20

ψ(2S) Suppression in d/p-A

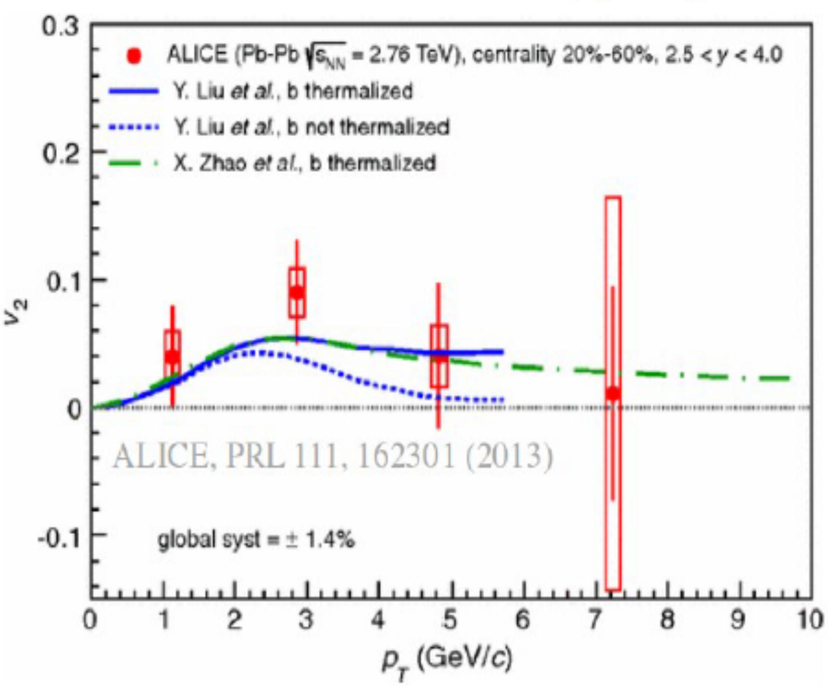




- Hadronic ψ(2S) suppression ⟹
- **ψ(2S)** regenerated in **Pb-Pb** later, with larger flow, than **J/ψ**

SHM/Dynamical regeneration

How to resolve Quarkonia at phase boundary?



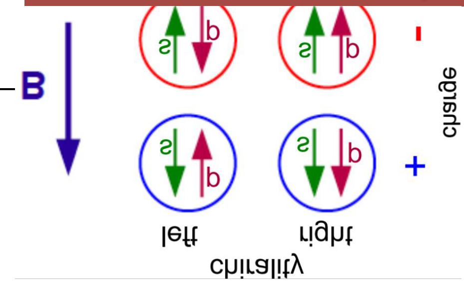
Precise measurement of $v_2(J/\Psi)$ greatly helps, generation at T_C larger v_2
solution entangled with the Open HF

V.G., R. Rapp, C.M. Ko, PLB(2004)

✧ *Observable* $\sigma_{c\bar{c}}$ *Indepedent*

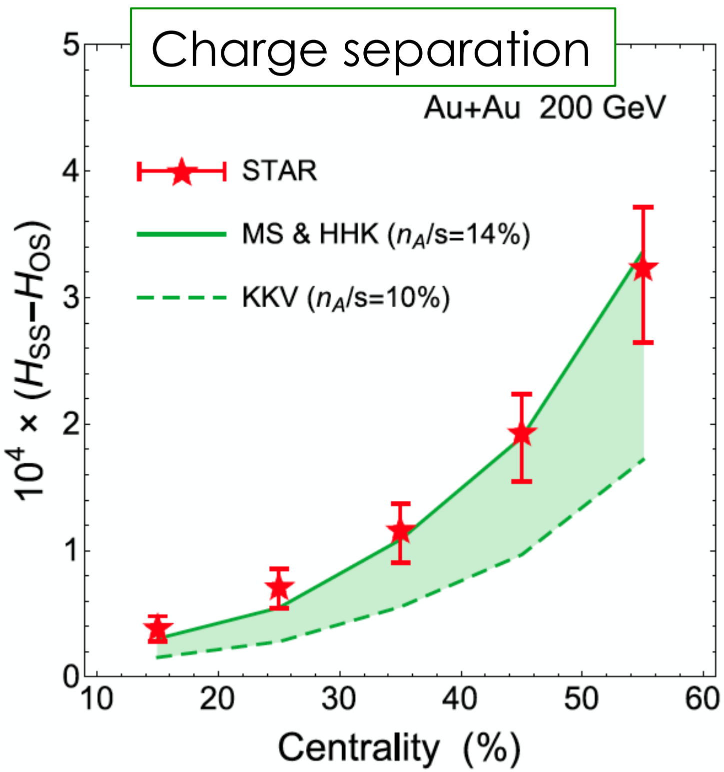
Chiral Magnetic

Chiral Anomaly



J. Liao, Wed 12:00

- ✓ Evidence in Semimetals, Nature Physics 12 (2016)
- ✓ Can we quantitatevely study it in HIC?
- ✓ Chiral Rel. Hydrodynamics – 21st century hydro
  2 currents added (non dissipative, T-even) [Son, Surowka,…,Jiang,Shin]



$$\partial_\mu J^\mu = C E^\mu B_\mu$$

$$D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{\sigma}{2} E^\mu + \frac{N_c q}{4\pi^2} \mu_R B^\mu$$

$$J_L^\mu = n_L u^\mu + \nu_L^\mu + \frac{\sigma}{2} E^\mu - \frac{N_c q}{4\pi^2} \mu_L B^\mu$$

CME

$$d\, \nu_{R,L}^\mu = (\nu_{NS}^\mu - \nu_{R,L}^\mu) / \tau_{rlx}$$

on top of 2+1D VISHNew— OSU Group

$$D_\mu T^{\mu\nu} = 0 \qquad n = 0$$

- **Realistic initial condition:**
  Modelings for μ_5 (chiral imbalance)
- Early stage physics → Chiral Kinetic Theory

[See also: Hirono, Hirano, Kharzeev, arXiv:1412.0311; Yin and JL, arXiv:1504.06906]

Global Polarization

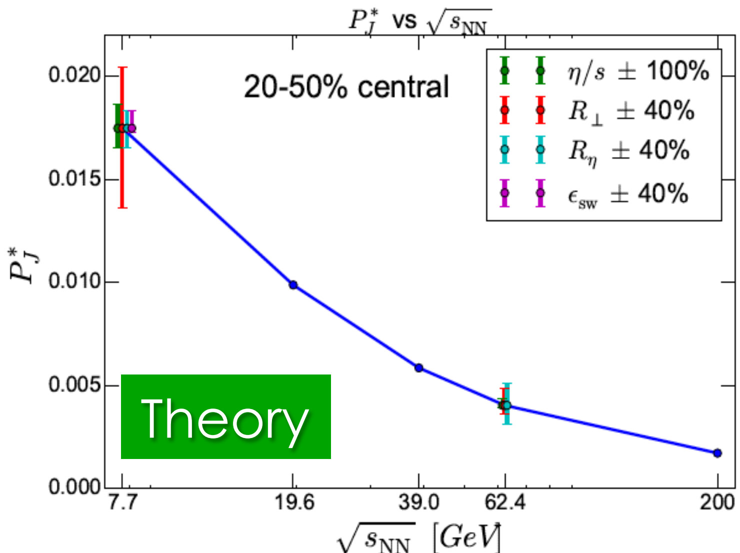
F. Becattini, Mon 16:30

Thermal vorticity= conv.+ accel.+ cond. → polarization

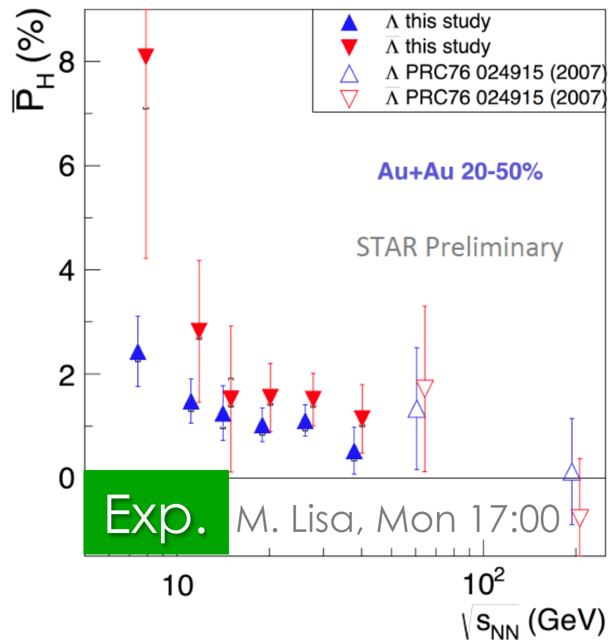
$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{8m} \frac{\int d\Sigma_\lambda p^\lambda n_F (1-n_F) \partial^\rho \beta^\sigma}{\int d\Sigma_\lambda p^\lambda n_F}$$

P=2 Π

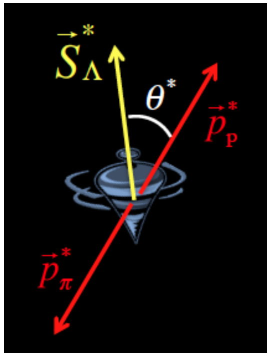
F. Becattini et al.,Ann. Phys. 338 (2013)32



I. Karpenko, Tue 15:00



M. Lisa, Mon 17:00



Global Polarization

F. Becattini, Mon 16:30

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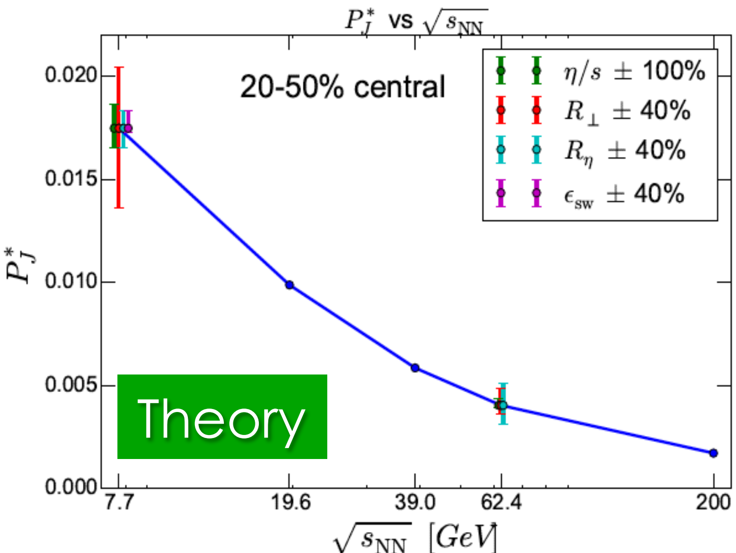

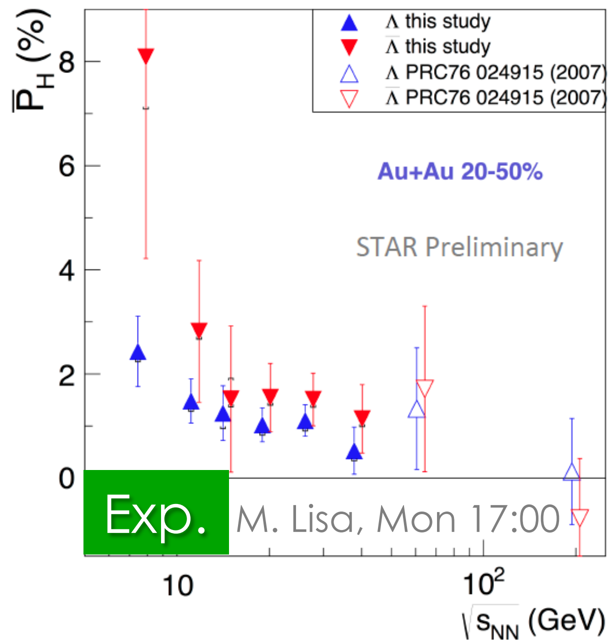

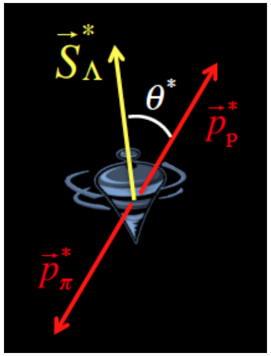

I. Karpenko, Tue 15:00

- ✧ Λ and anti-Λ splitting to be understood (CME,Pauli Blocking…)
- ✧ Feed-down from Σ(1385) J=3/2
- ✧ Hadronic rescattering to be incl.
- ✧ Constrain to initial state vorticity

See L.G. Pang's talk Tue 15:40 for Polarization correlation & X.G. Huang for more details

Conclusions

- There is **a clear progress**, many questions was not even conceivable a decade ago we have already solved or *we are solving getting info on physics that were unexpected* from small systems, heavy quarks and quarkonia, vorticities, lQCD precision in fluctuations….

Conclusions

❖ Please take the time to enjoy this field,
with more control & rich perspectives
now than 10 years ago!