# Summary: Theory

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**Strangeness in Quark Matter (SQM) 2015**
JINR, Dubna, Russian Federation
6-11 July 2015

# Outline

# Overview

Plenary Theory Talks : 14
Parallel Talks : 60 in five parallel sessions
Summary: thirty minutes
Focus on summary of plenary talks.

# Equilibrium SHM Fits in Central Pb-Pb

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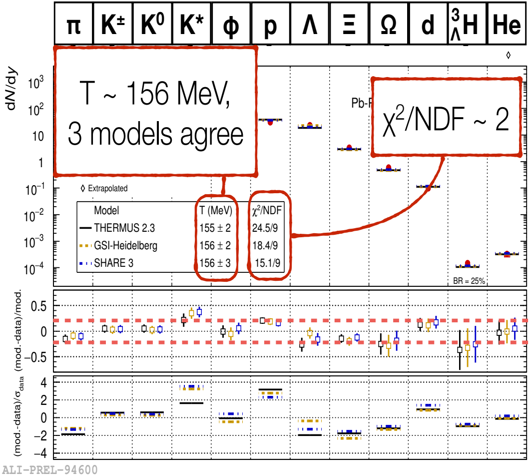



N.B.

RHIC (STAR)

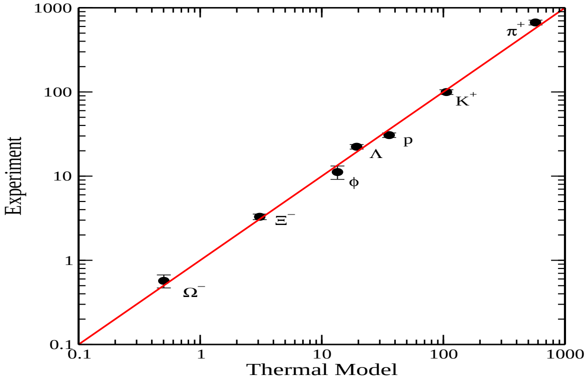
$\sqrt{s}$ = 200 GeV

$\chi^2$/NDF~1

Better fit in 60-80%,

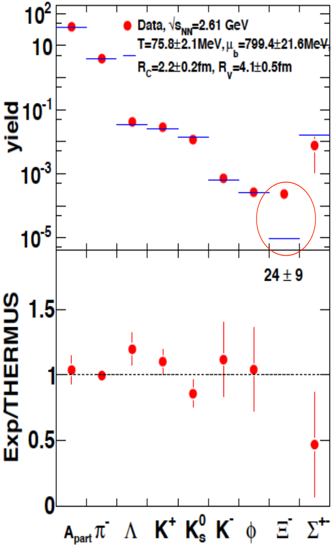
Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

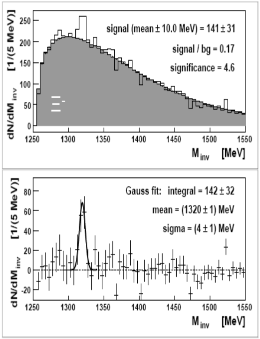
# ALICE Pb-Pb.




Chemical equilibrium is a very good approximation in heavy-ion collisions. Only one volume! Only one temperature!

# Hadrons in Ar+KCl@1.76A GeV




Strong excess of the $\Xi^-$

NN-threshold:

$E_{beam}$= 3.74GeV $\rightarrow \sqrt{s}-\sqrt{s_{th}}$=-630MeV!

THERMUS: S. Wheaton, J.Cleymans: Comput.Phys.Commun.180:84-106,2009

Marcus Bleicher: Transport Models and Strangeness Production

- Introduce a new mechanism for $\phi$ and $\Xi$ production (resonance decay)
- This allows to describe the $\phi$ and $\Xi$ production in elementary and nuclear collisions
- The used branching ratios are small and consistent with OZI

# Introduce a branching ratio to $\phi$ for heavy N* states

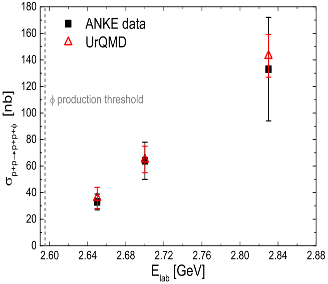
In UrQMD these are the states:
N* (1990), N*(2080), N*(2190), N*(2220), N*(2250)

Assumption: Branching ratio to $\phi$ is equal for all resonances (typical branching ratio into $\omega$ is 5-20%)

# Fixing the branching ratio

- $\phi$ production yields from ANKE can be consistently described with $\Gamma^{N^* \to N\phi}/\Gamma^{total} = 0.2\%$
- Branching ratio is consistent with extracted OZI suppression ($\omega/\phi$)

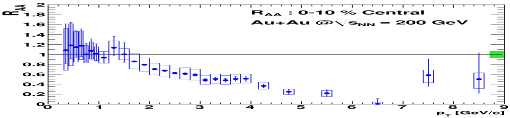
Y. Maeda et al. [ANKE Collaboration], Phys. Rev. C 77, 015204 (2008)




A. Sibirtsev, J. Haidenbauer and U. G. Meissner, Eur. Phys. J. A 27, 263 (2006)

## What to expect from heavy-quark observables?

PHENIX, PRC84 (2011)



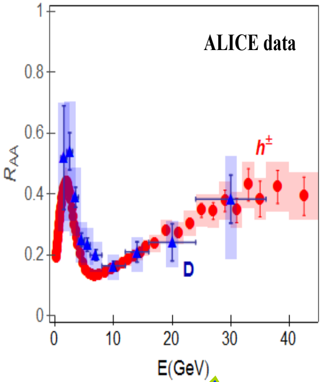

at low $p_T \sim m_Q$

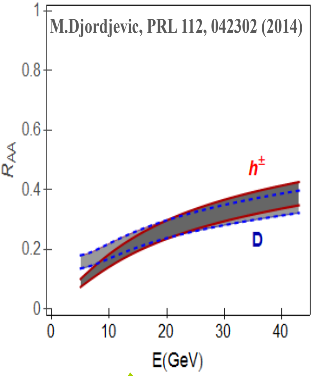
- Very different from light partons.
- Nonperturbative!
- Partial thermalization with the light partons in the QGP?
- Diffusion $D$ mainly via collisional processes?
- Hadronization via coalescence/recombination?
- Initial shadowing and cold nuclear matter effects?

at high $p_T >> m_Q$

- Similar to light partons.
- Perturbative regime...
- Rare processes, probe the opacity of the matter.
- Energy loss $dE/dx$ via collisional and radiative processes?
- Coherent energy loss $\rightarrow$ jet-quenching parameter $\hat{q}$?
- Hadronization via (medium-modified) fragmentation?

# Heavy flavor puzzle at LHC




$$R_{AA}(h^{\pm}) = R_{AA}(D)$$

**No suppression hierarchy!**

# Jet energy loss

Initially, most of the energy loss calculations assumed only *radiative* energy loss, and a QCD medium composed of static scattering centers. (e.g. GW, DGLV, ASW,BDMPS...)

⬇

However, these calculations lead to an obvious disagreement with the experimental data.

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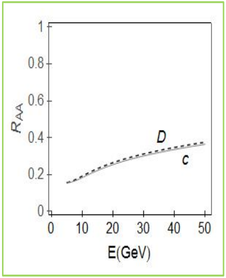
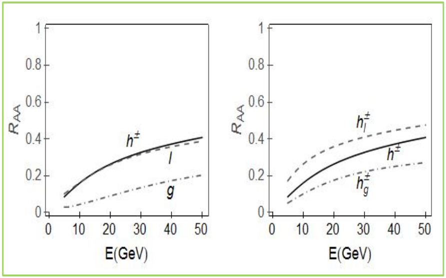
**Is collisional energy loss also important?**

⬇

**Yes, collisional and radiative energy losses are comparable!**

# The reason is distortion by fragmentation functions




$R_{AA}\,(D) = R_{AA}\,(\text{charm})$

$R_{AA}\,(h^{\pm}) = R_{AA}\,(\text{light quarks})$

$R_{AA}\,(\text{light}) = R_{AA}\,(\text{charm})$

$R_{AA}\,(h^{\pm}) = R_{AA}\,(D)$

M. Djordjevic 2

# Magdalena Djordjevic: Radiative and Collisional Energy Loss

- The ALICE experimental results show a similar $R_{AA}$ for charged hadrons and D mesons, i.e., no suppression hierarchy is observed
- The reason behind the disappearance in the suppression hierarchy is an interplay between energy loss and fragmentation effects.
- Modifications to the fragmentation functions, and energy loss effects, combine in such a way that charged hadron suppression becomes almost the same as the bare light quark suppression.
- Charged hadrons and D mesons indeed have the same suppression.

# Andrea Beraudo: Heavy Flavor Transport

- Transport approaches based on Boltzmann and Langevin equations.
- Importance of future beauty measurements.
- Heavy flavor studies in small systems p-Pb ...
- Correlations would be helpful.

# J.P. Lansberg: Status of quarkonium production in pA collisions

- After 30+ years of quarkonium studies in *pA* collisions, the mechanism for their suppression is not clear
- The relative suppression of $\psi(2S)$ w.r.t. $J/\psi$ at $y \simeq 0$ found by E866 at Fermilab could easily be explained by its larger size

  E866 PRL 84 (2000) 3256
- Yet, the excited states were expected not to be more suppressed at RHIC and LHC energies because of the formation-time effect
  [See Ch. 2 of arXiv:1506.03981]
- Such an hypothesis lead CMS (and others) to intepret their observation of the sequential $\Upsilon(nS)$ suppression in PbPb collisions at 2.76 TeV as coming *only* from hot nuclear matter effects
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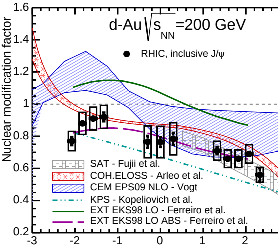
Plot from arXiv:1506.03981

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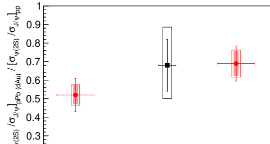

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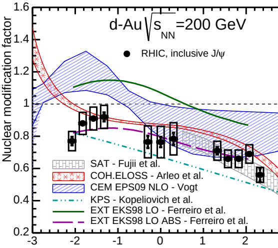


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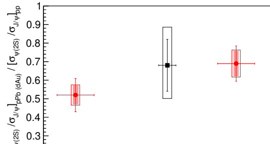

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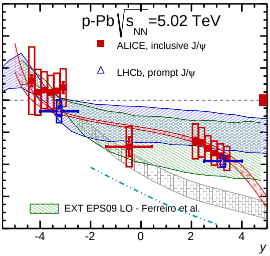


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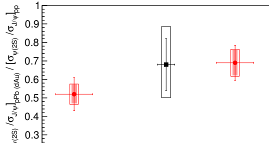

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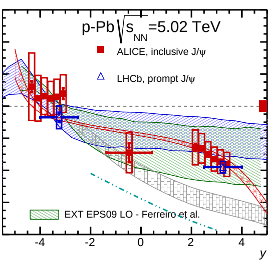


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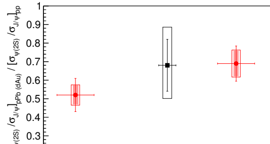

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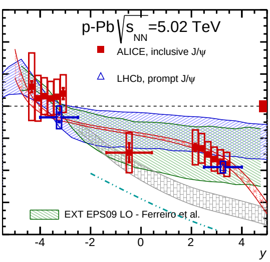


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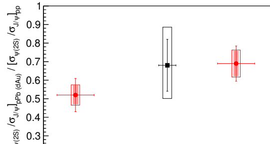

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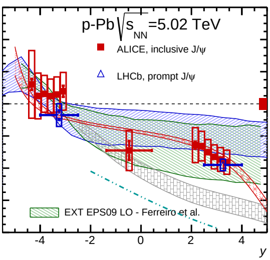


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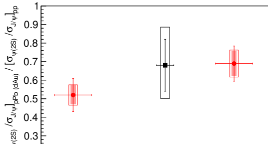

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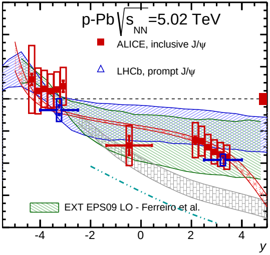


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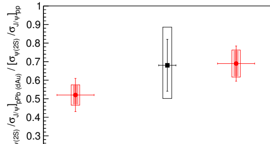

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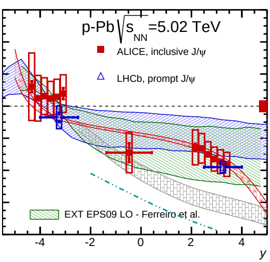


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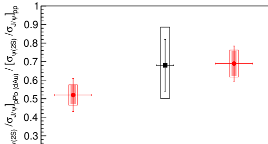

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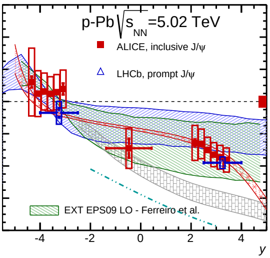


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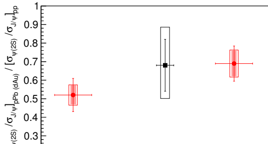

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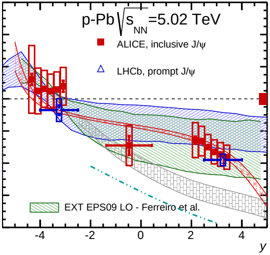


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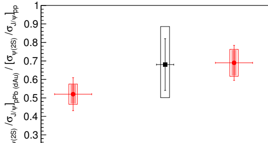
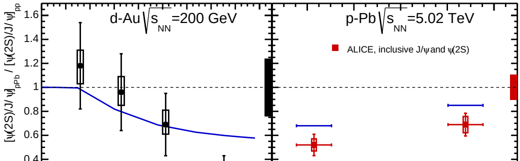


- The most natural explanation would be a final-state effect acting over sufficiently long time in order to impact different states with a different magnitude ! $\rightarrow$ comover interaction model ?
- In a comover model, suppression from scatterings of the nascent $\psi$ with comoving particles **S. Gavin, R. Vogt PRL 78 (1997) 1006; A. Capella *et al.* PLB 393 (1997) 431**
- Stronger suppression for larger comover densities. For asymmetric *pA* collisions, stronger in the nucleus-going direction
- Survival probability:

$$S_{\psi}^{co}(b,s,y) = \exp\left\{-\sigma^{co-\psi}\,\rho^{co}(b,s,y)\,\ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

- $\rho^{co}(b,s,y)$ from multiplicity data & $\sigma^{co-\psi}$ from fits to low-energy *AA* data

[ $\sigma^{co-J/\psi} = 0.65$ mb for the $J/\psi$ and $\sigma^{co-\psi(2S)} = 6$ mb for the $\psi(2S)$] **N. Armesto, A. Capella, PLB 430 (1998) 23**



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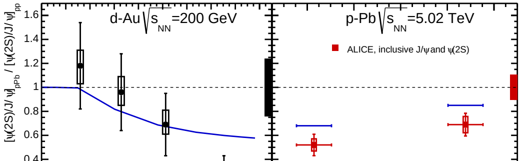

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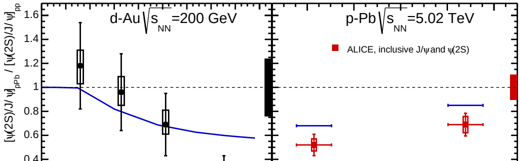

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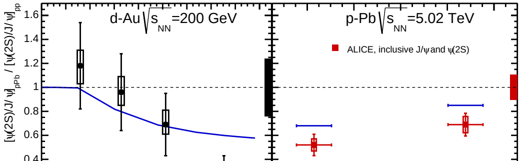

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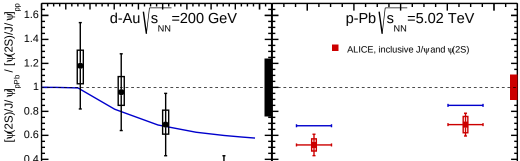

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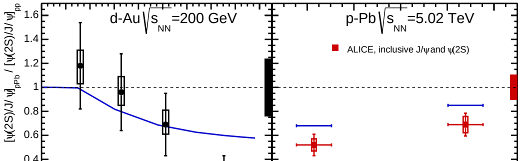

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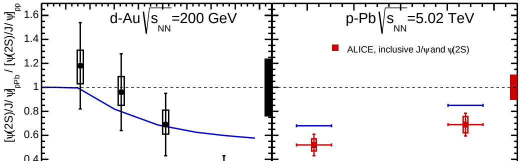
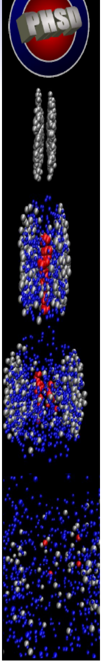





# Parton-Hadron-String-Dynamics (PHSD)

**PHSD** is a **non-equilibrium transport model** with
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **lQCD EoS** for the partonic phase ('crossover' at $\mu_q$=0)
- explicit **parton-parton interactions** - between quarks and gluons
- dynamical **hadronization**

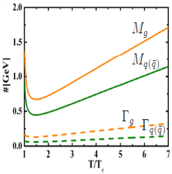
❑ **QGP phase is** described by the **Dynamical QuasiParticle Model (DQPM)** matched to reproduce lattice QCD

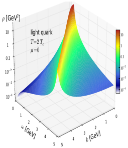
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

- **strongly interacting quasi-particles:** massive quarks and gluons (g,q,$q_{bar}$) with sizeable collisional widths in self-generated **mean-field potential**

- **Spectral functions:**

$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2-\vec{p}^2-M_i^2(T)\right)^2+4\omega^2\Gamma_i^2(T)} \quad (i=q,\bar{q},g)$$

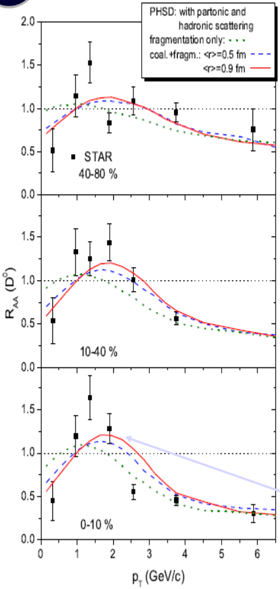


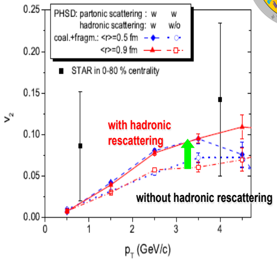




❑ **Transport theory**: **generalized off-shell transport equations** based on the 1st order gradient expansion of Kadanoff-Baym equations (**applicable for strongly interacting system!**)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

# PHSD: charm $R_{AA}$ and $v_2$ at RHIC




- **PHSD** provides a **microscopic description** of **non-equilibrium charm dynamics** in the partonic and hadronic phases
- **Partonic rescattering** suppresses the high $p_T$ part of $R_{AA}$, increases $v_2$
- **Hadronic rescattering** moves $R_{AA}$ peak to higher $p_T$, increases $v_2$
- The structure of $R_{AA}$ at low $p_T$ is sensitive to the **hadronization scenario**, i.e. to the balance between **coalescence and fragmentation**

T. Song et al., PRC (2015), arXiv:1503.03039

# Lattice QCD

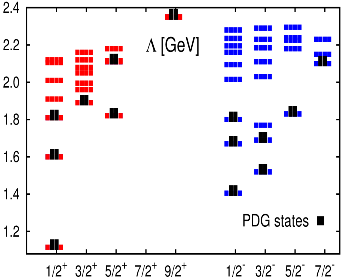
# H. Wittig: H-dibaryon using lattice QCD

- Very demanding calculations
- Bound H-dibaryon found for unphysically large pion masses
- Need more and better lattice data

# What do we know of the hadron spectrum?

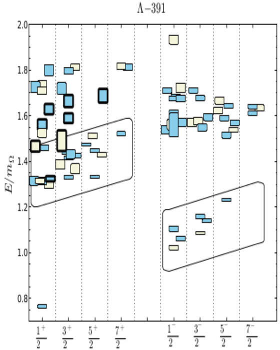
**strange baryons**

**Quark Model**




[Capstick-Isgur, Phys.Rev.D34 (1986) 2809]

**Lattice QCD**




[Edwards et al., Phys.Rev.D87 (2013) 054506]

in the following
PDG will denote results using states listed in the particle data tables
QM will denote results using states calculated in the quark model

# O. Kaczmarek: Additional Strange Hadrons

- Also need non-strange baryons and mesons
- Decay channels unknown
- Need experimental confirmation!

# H. Rothkopf: Heavy Quarkonia from Lattice QCD

- Use QCD spectral functions
- Bottomonium: S-wave and P-wave survive up to at least T = 249 MeV
- Effective field theory based potential for static quarks from $T > 0$ QCD

# The Future: NICA, ALICE, BES, SHINE, FAIR, ...

- Maximum in $K^+/\pi^+$ ratio is in the NICA energy region,
- Maximum in $\Lambda/\pi$ ratio is in the NICA energy region,
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# Good Luck NICA

Thanks JINR

See you in Berkeley for SQM2016