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Interplay of repulsive interactions and extra strange resonances

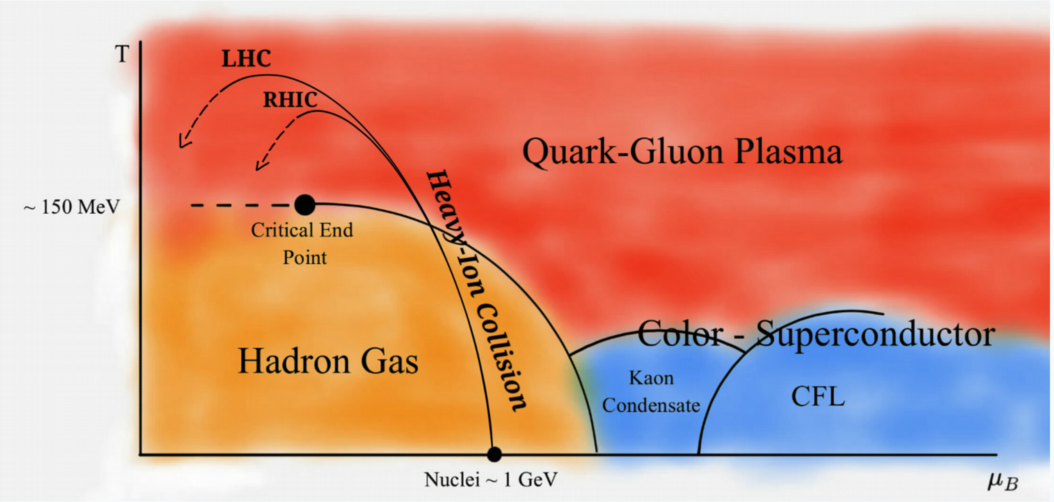
Jefferson Lab, Virginia, 17th November 2016

in collaboration with: R. Bellwied, M.I. Gorenstein, V. Mantovani-Sarti, A. Nada, J. Norohona-Hostler, M. Panero, P. Parotto, C. Ratti, H. Stoecker, V. Vovchenko

The QCD phase diagram

The QCD phase diagram summarizes the most of our achivements in understanding strong interactions.

For high temperatures/densities is predicted a phase with “free” quarks and gluons, the Quark-Gluon plasma.

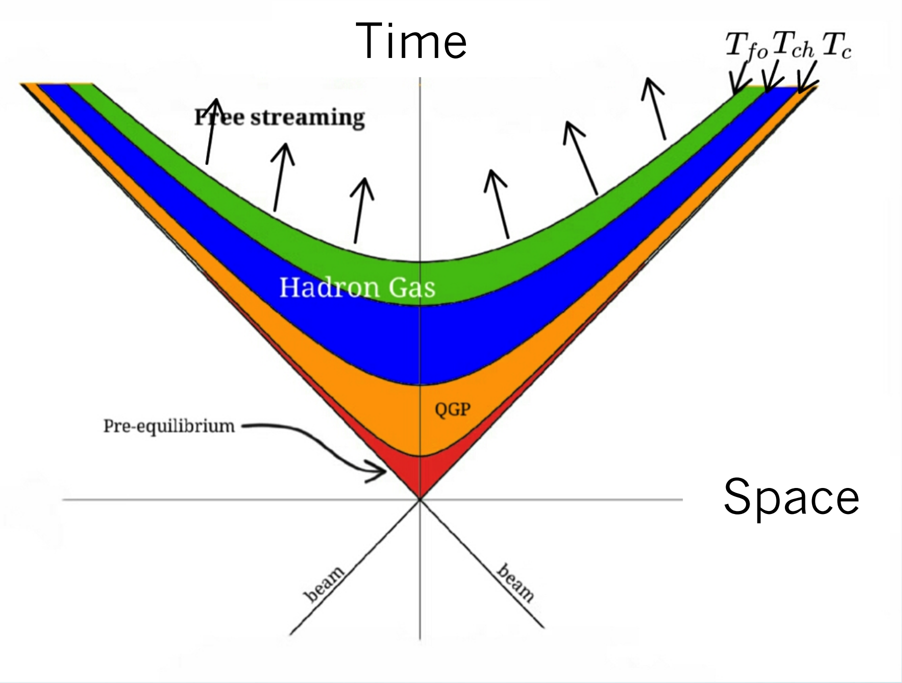


In order to identify the properties of the QGP we analyze data from Heavy-Ion collisions at relativistic energies.

Evolution of the fireball

After the collision the evolution of the fireball could be the following:

- A pre-equilibrium stage in which there is a lot of interaction driving quickly the system toward the QGP phase.



- The QGP phase in which quarks and gluons are thermalized.

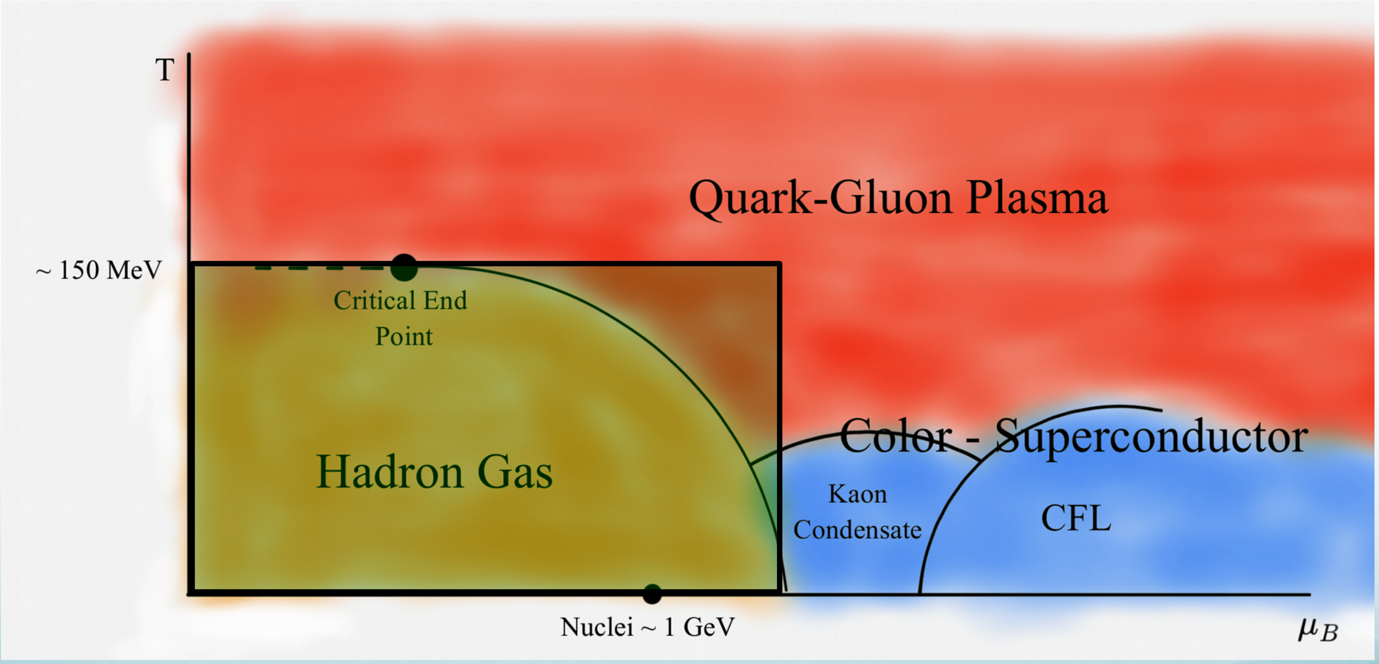
- Then the particles bind into hadrons (Hadronization), $T=T_c$.

- Chemical freeze-out: the inelastic scatterings between hadrons stop, only the long-lived hadrons propagate, anything else decays, $T=T_{ch}$.

- Kinetic freeze-out: the elastic scatterings stop, and the hadrons reach the detector, $T=T_{fo}$.

Confined phase

Through the experiment we can access directly the confined/hadronic phase, which is well described by mean of the Hadron-Resonance gas model.



Hadron-Resonance Gas model

The Hadron-Resonance Gas (HRG) model assumes that resonance formation, and subsequent decay, mediates the attractive interactions among hadrons in the ground state.

$$p(T,\{\mu_k\}) = \sum_k (-1)^{B_k+1} \frac{d_k T}{(2\pi)^3} \int d^3\vec{p}\ \ln\left[1+(-1)^{B_k+1} e^{-(\sqrt{\vec{p}^{\,2}+m_k{}^2}-\mu_k)/T}\right]$$

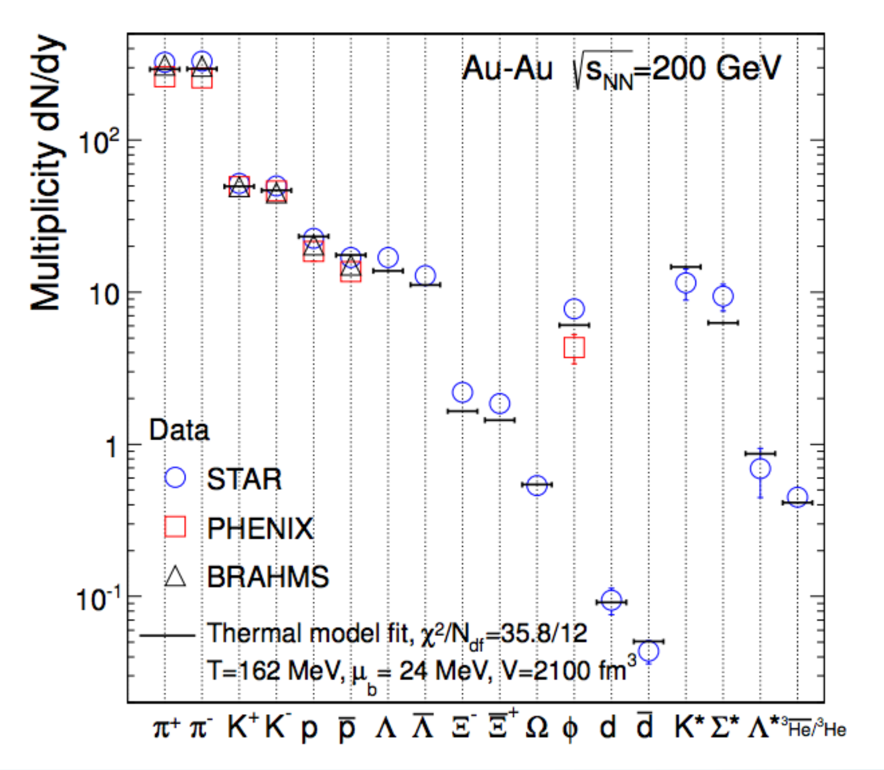
B_k = baryon number　　d_k= spin degeneracy　　m_k= mass

$$\mu_k = B_k\mu_B + Q_k\mu_Q + S_k\mu_S$$

Particle properties are listed by the Particle Data Group (PDG), which updates the list every year with the latest measured spectrum.

Freeze-Out parameters from HRG

Andronic et al., Nucl.Phys. A904-905 (2013) 535c-538c



The abundancies of stable hadrons are fixed at the chemical FO.
Through a thermal fit of these observables it is possible to extract T and μ_B.

$$n_k = \frac{d_k}{(2\pi)^3} \int d^3p \, \frac{1}{e^{(\omega_k - \mu_k)/T} \pm 1}$$

More recently, fluctuations of conserved charges have been proposed for the same purpose. The main reason is that these observables can be simulated on the lattice.

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A. Andronic, Int. J. Mod. Phys. A 29 (2014) 1430047

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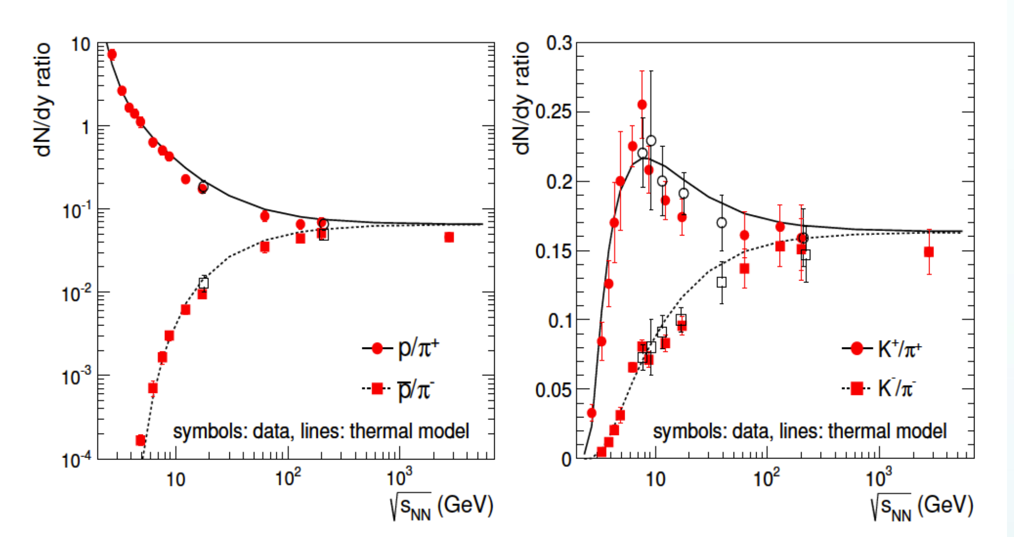

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Fluctuations ⟺ Moments

Starting from a given partition function we define the fluctuations of a set of conserved charges as:

$$\frac{p}{T^4} = \frac{\ln \mathcal{Z}}{VT^3}$$

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}\left(p/T^4\right)}{\partial\left(\mu_B/T\right)^l \partial\left(\mu_S/T\right)^m \partial\left(\mu_Q/T\right)^n}$$

The fluctuations of conserved charges are related to the moments of the multiplicity distributions of the same charge measured in HICs.

$$\delta N = N - \langle N \rangle$$

mean: $M = \langle N \rangle = VT^3\chi_1,$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = VT^3\chi_2,$

skewness: $S = \frac{\langle (\delta N)^3 \rangle}{\sigma^3} = \frac{VT^3\chi_3}{(VT^3\chi_2)^{3/2}},$

kurtosis: $k = \frac{\langle (\delta N)^4 \rangle}{\sigma^4} - 3 = \frac{VT^3\chi_4}{(VT^3\chi_2)^2};$

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Taking ratios of these fluctuations we can obtain quantities related to the moments of the distributions with any volume dependence.

$$\sigma^2/M = \chi_2/\chi_1$$

$$k\sigma^2 = \chi_4/\chi_2$$

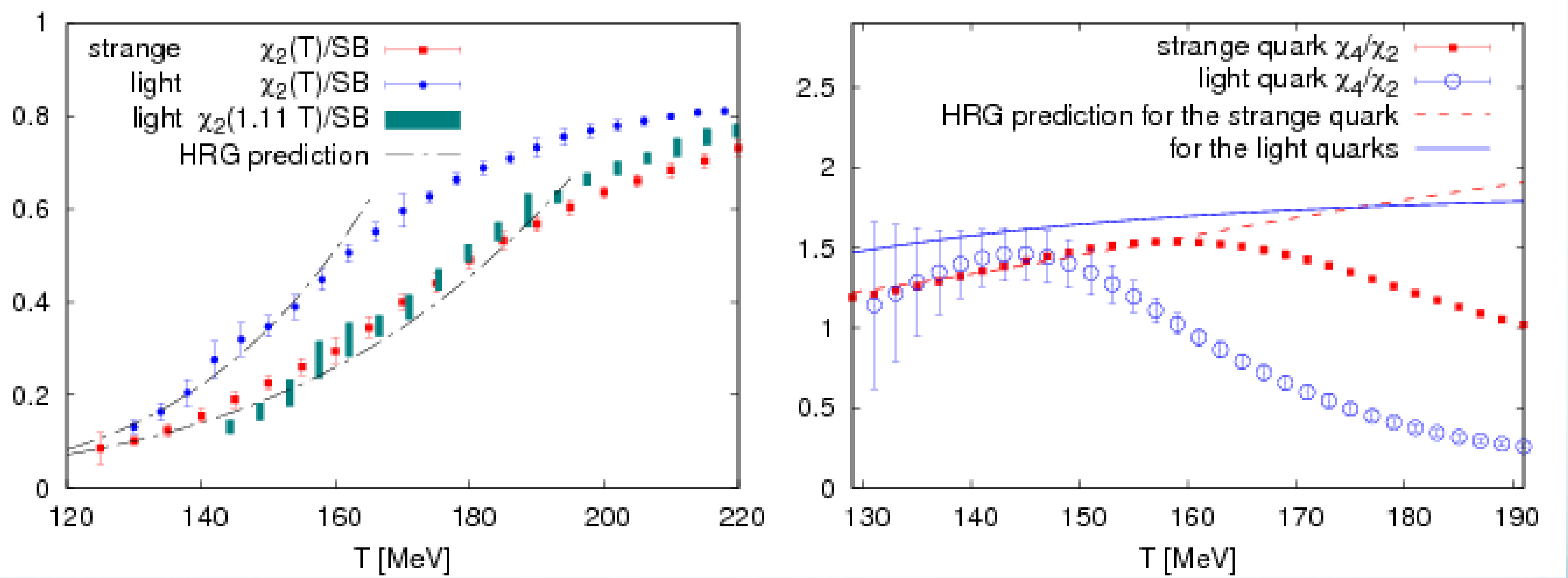
$$S\sigma = \chi_3/\chi_2$$

$$S\sigma^3/M = \chi_3/\chi_1$$

Karsch, Central Eur.J.Phys.10 (2012) 1234-1237

Fluctuations from Lattice

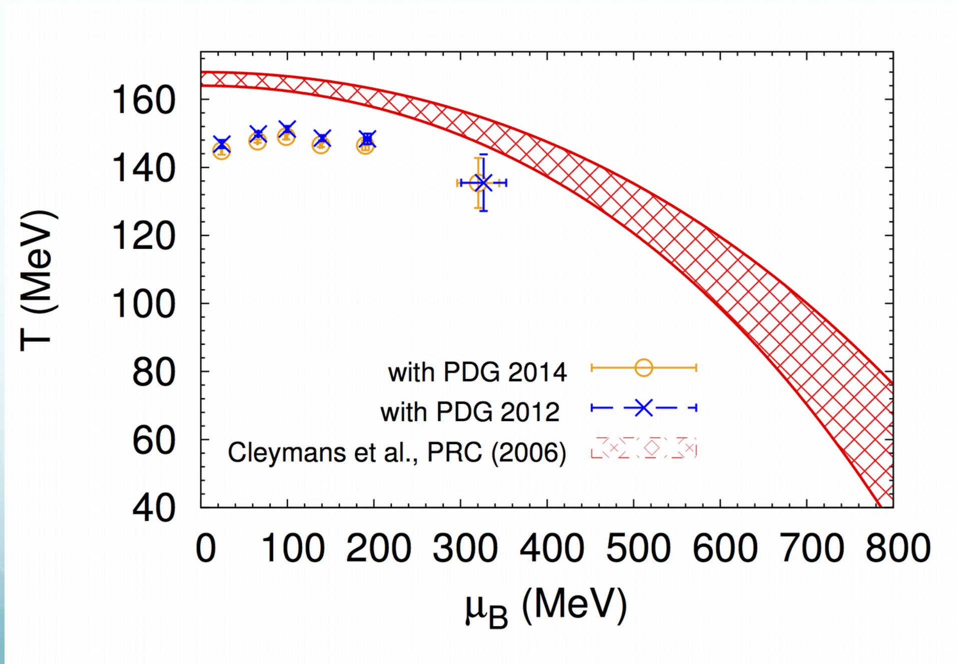
These quantities can be calculated by means of first principles simulations on the lattice, showing a remarkable agreement with HRG model predictions.

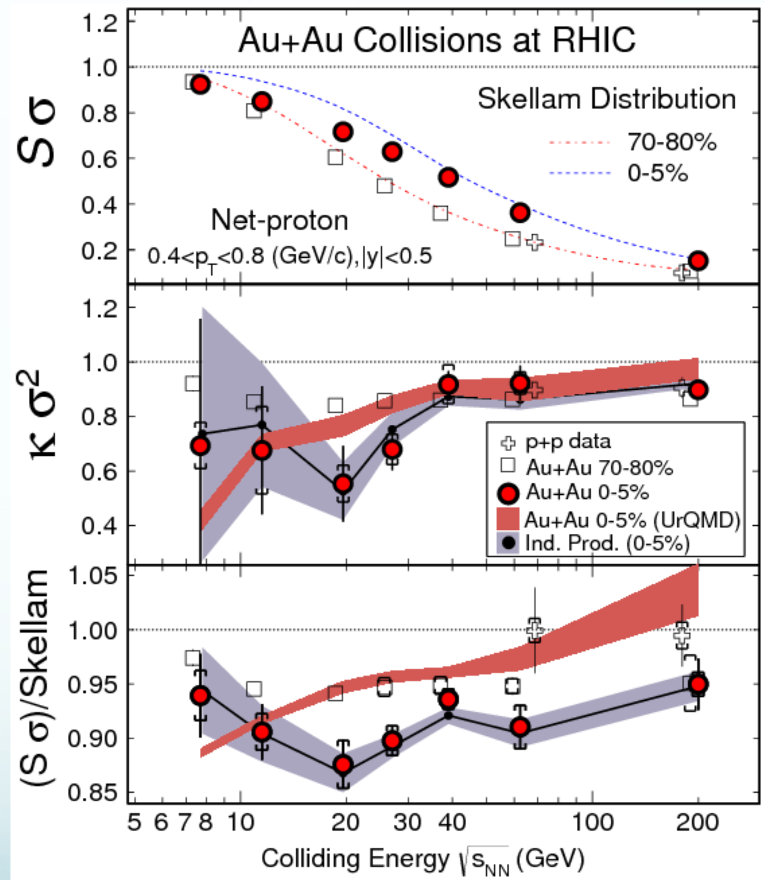


R.Bellwied et al., Phys.Rev.Lett. 111 (2013) 202302

Moments from HICs

Higher moments, for different quantum number distributions, have been measured at RHIC and analyzed within the HRG framework.





STAR Coll., Phys.Rev.Lett. 112 (2014) 032302
P.A. et al., Phys.Lett. B738 (2014) 305-310

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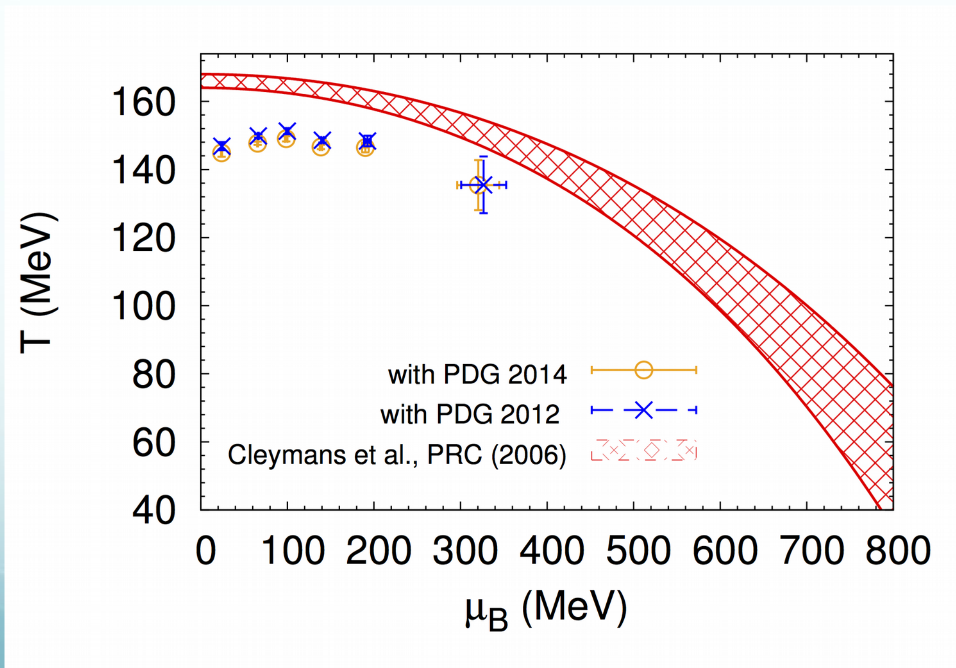
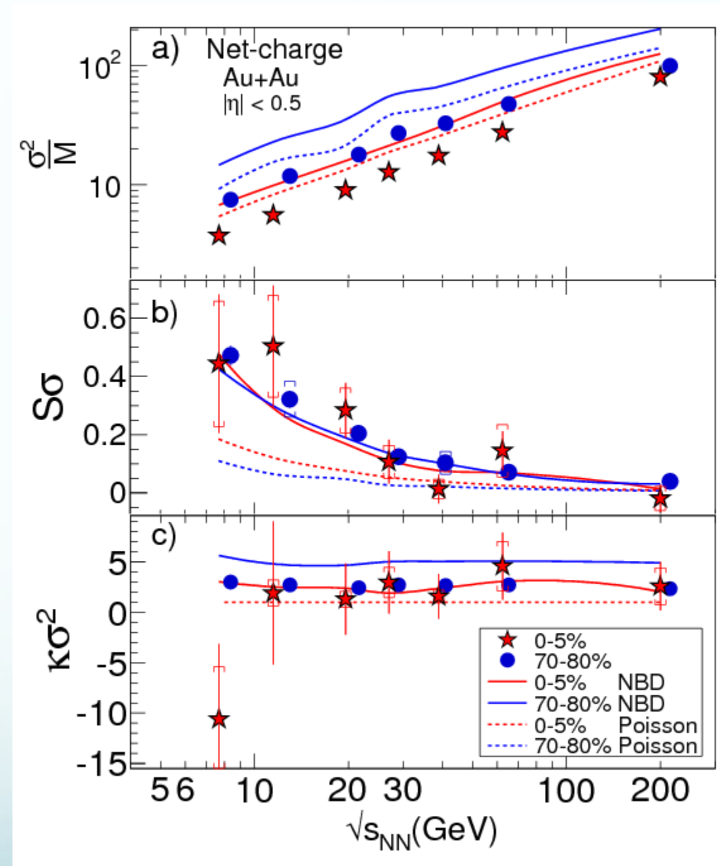
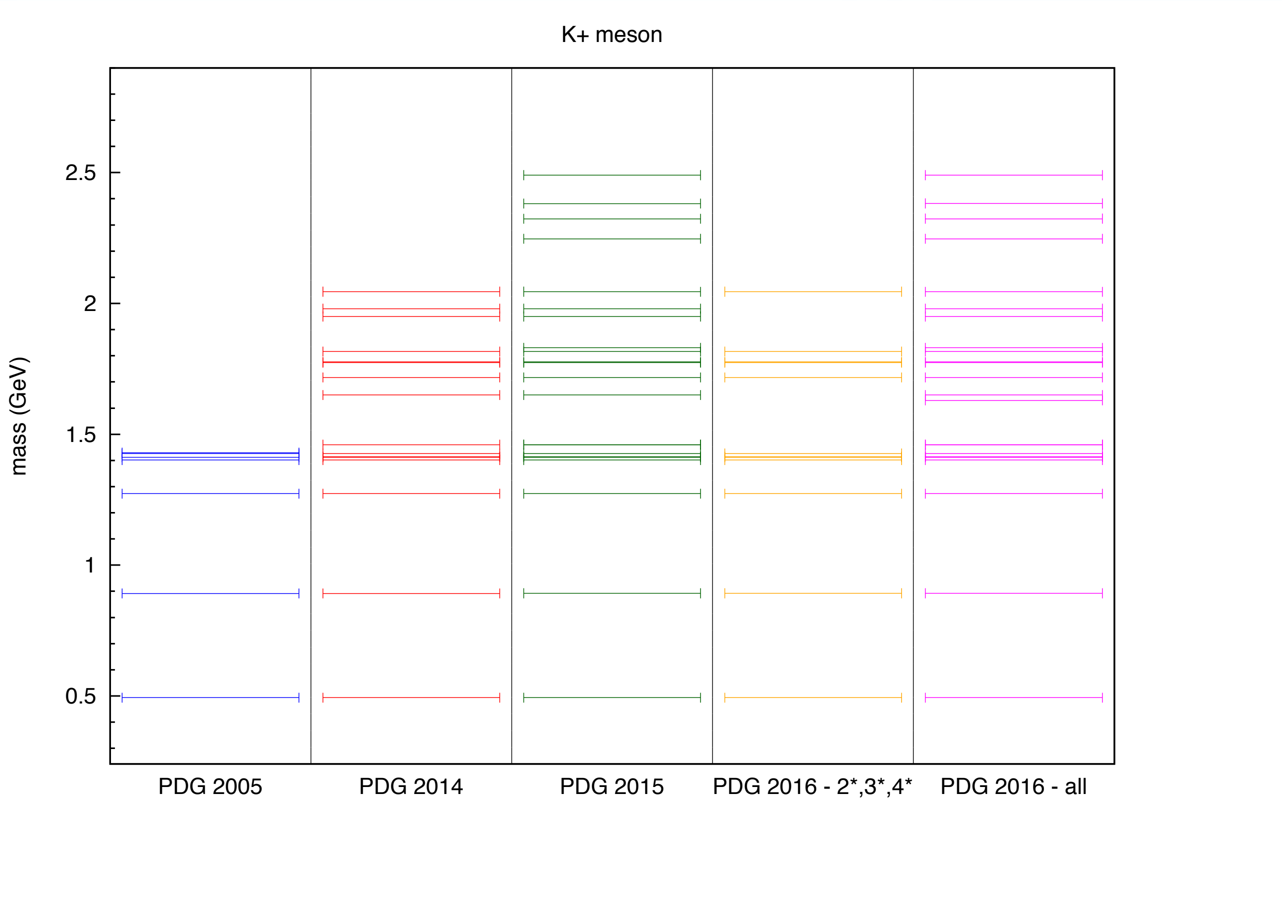




STAR Coll., Phys.Rev.Lett. 113 (2014) 092301
P.A. et al., Phys.Lett. B738 (2014) 305-310

Influence of the particle list

One of the biggest sources of uncertainty in the HRG model is the particle list.
The PDG lists are strongly dependent on the criteria used in the selection



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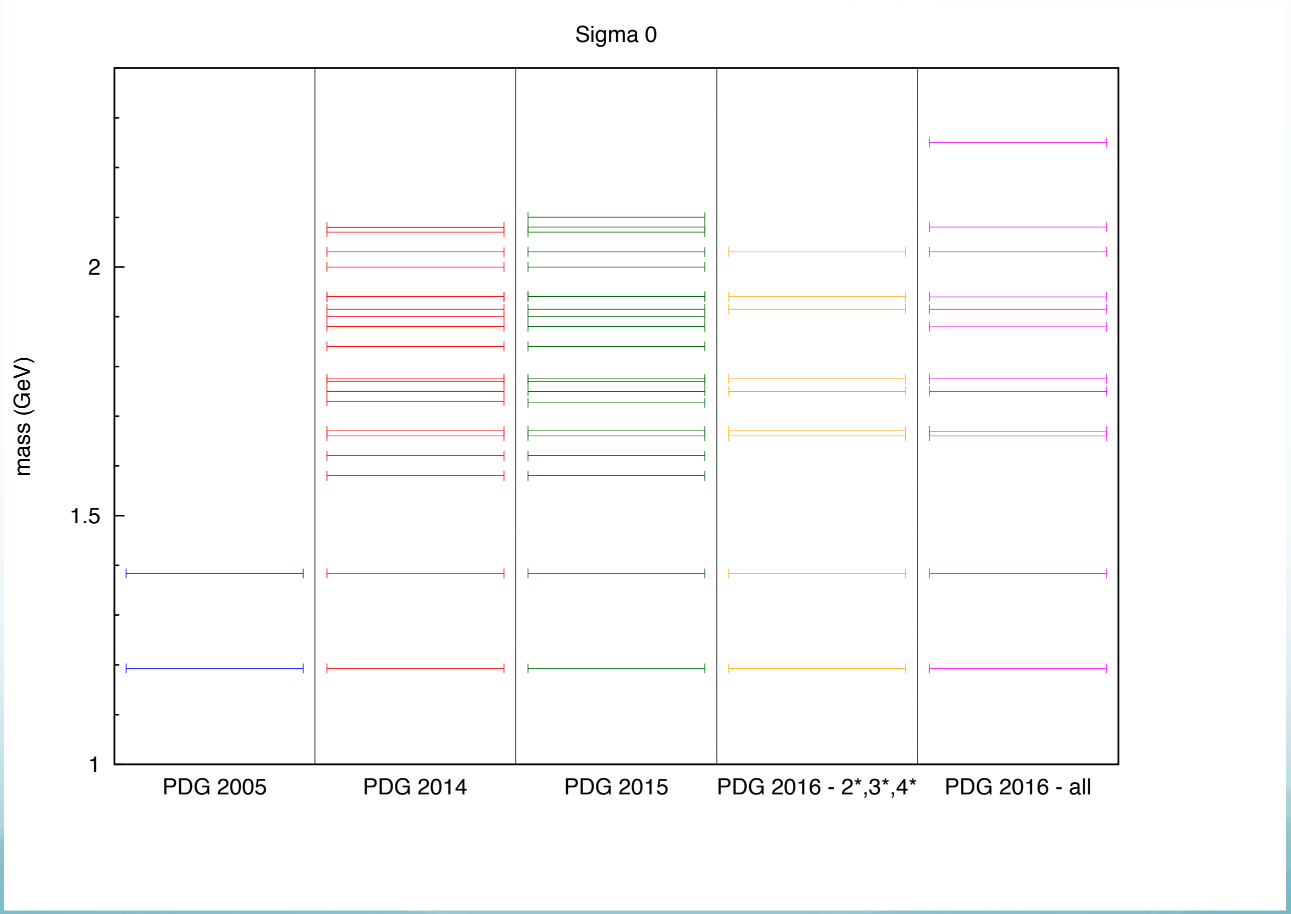

Influence of the particle list

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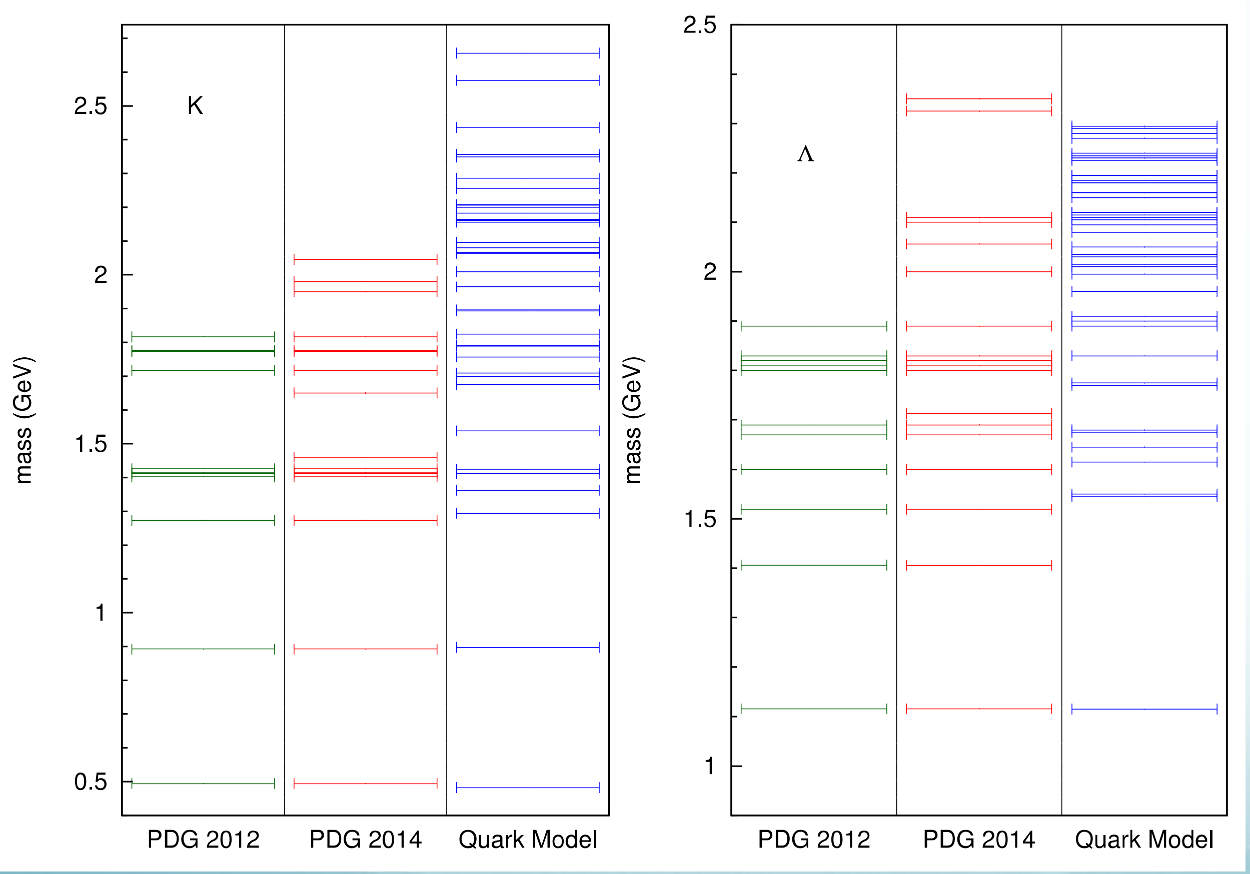
Hadronic states can be directly calculated within the Quark-Model.



$$\mathrm{PDG} \simeq 600$$

$$\mathrm{QM} \simeq 1500$$

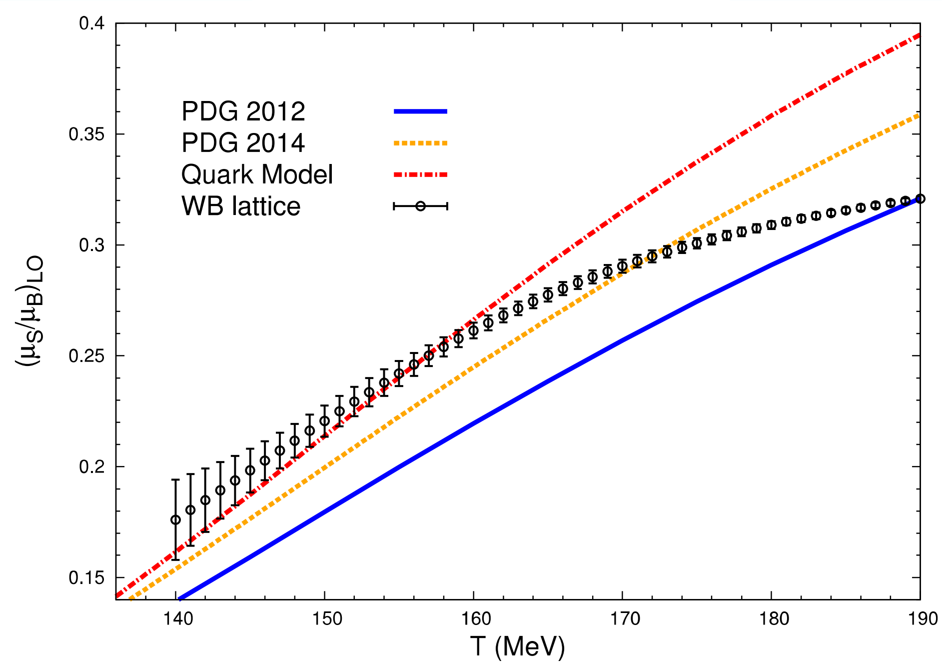
D. Ebert et al., Phys.Rev. D79 (2009) 114029
S. Capstick et al., Phys.Rev. D34 (1986) 2809

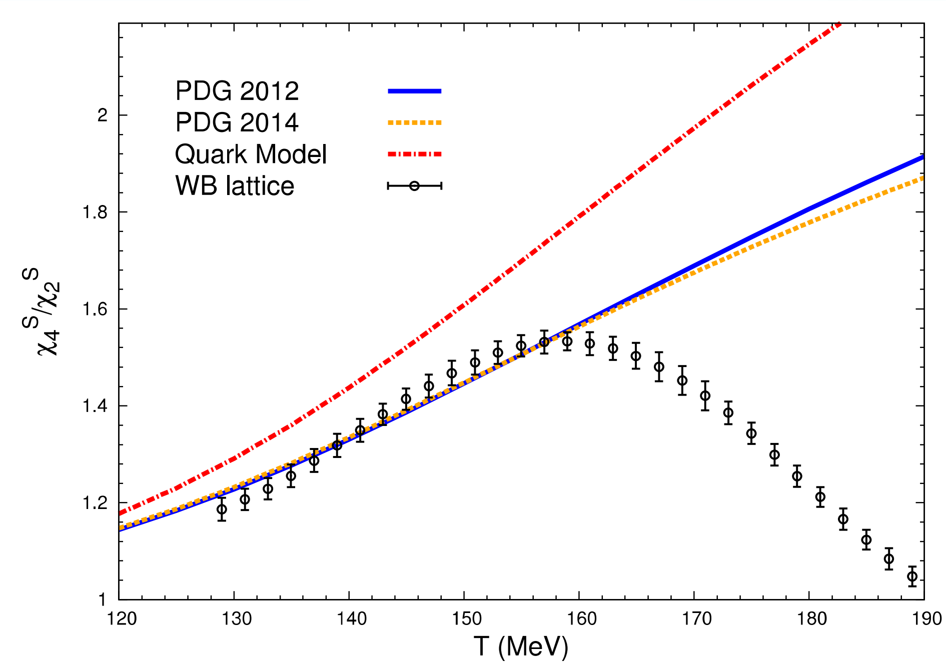
QM: lattice observables

The QM predictions in the strange sector can be relevant in the description of key observables.

$$\left.\frac{\mu_S}{\mu_B}\right|_{LO} \simeq -\frac{\chi^{11}_{BS}}{\chi^2_S}$$

$$\frac{\chi^4_S}{\chi^2_S} \simeq \langle S^2 \rangle$$

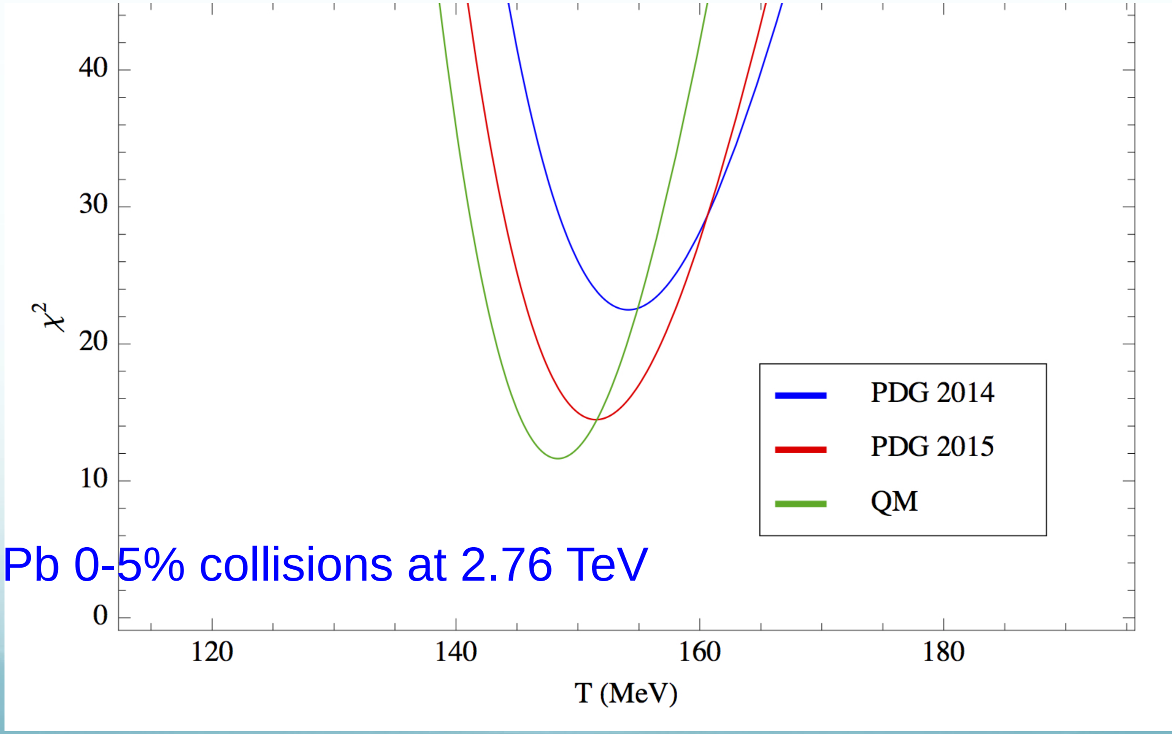




QM: particle yields

Guessing on the decay branches for this undetected states we can estimate their influence in the fit of particle yields.

	T (MeV)	V (fm^{-3})	χ^2
PDG2014	154.12 ± 2.29	5020.9 ± 663	$22.49/8 \simeq 2.81$
PDG2015	151.47 ± 2.12	5594 ± 705	$14.47/8 \simeq 1.8$
QM	148.34 ± 1.83	6202 ± 772	$11.62/8 \simeq 1.45$

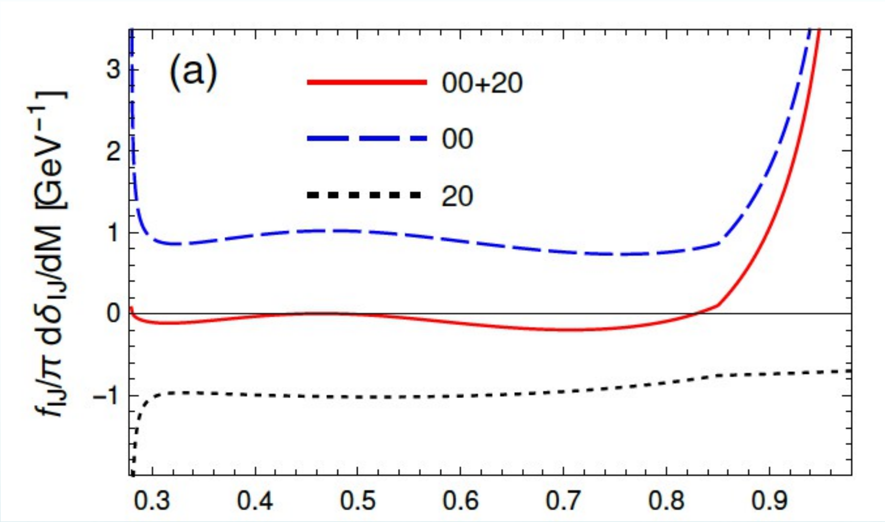


Fit to ALICE PbPb 0-5% collisions at 2.76 TeV

Repulsive interactions

The influence of resonance formation can be understood in terms of the measured phase shifts.
This formalism takes into account also repulsive channels, which can be crucial.

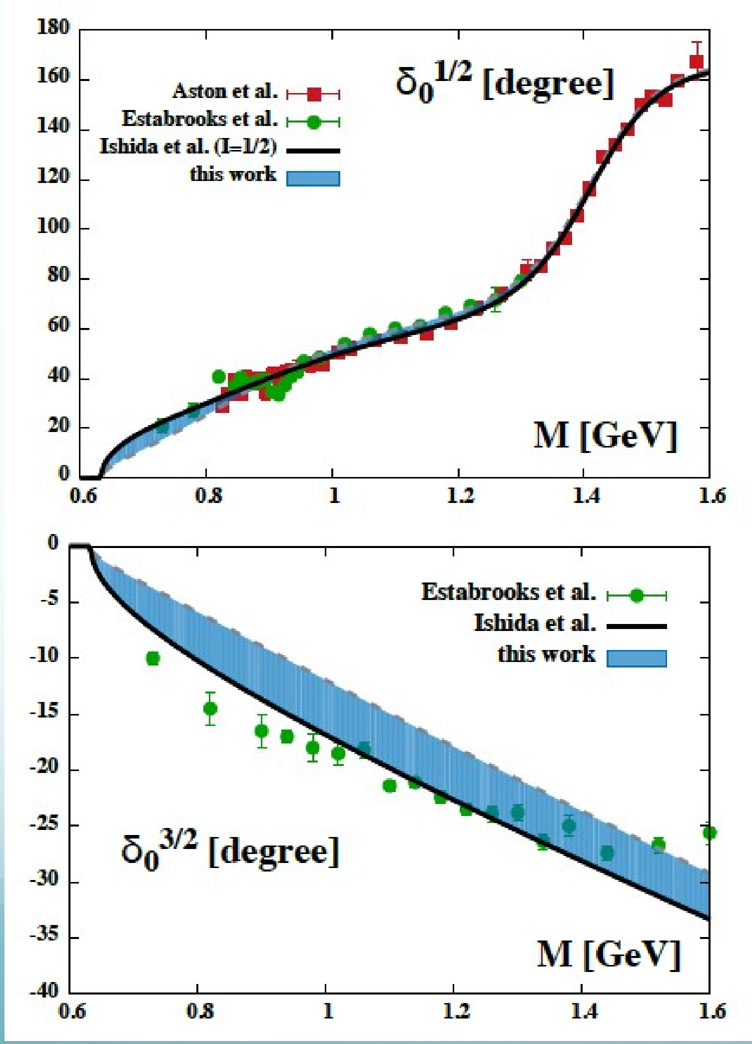
$$\ln Z = \ln Z_\pi + f_{IJ} \int_0^\infty dM \frac{d\delta_{IJ}}{\pi dM} \int \frac{d^3p}{(2\pi)^3} \ln \left[1 - e^{-E_p/T}\right]^{-1}$$

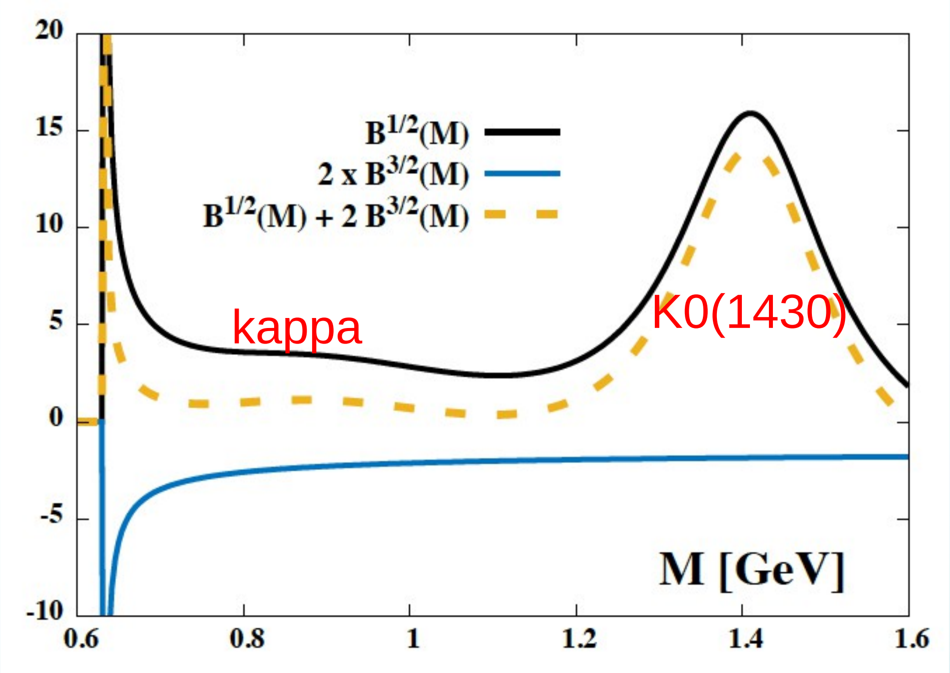


Broniowski et al., Phys.Rev. C92 (2015) no.3, 034905

Repulsive interactions

The same happens for other channels, but with partial cancellations.





Pok Man Lo et al., Phys.Rev. D92 (2015) no.7, 074003

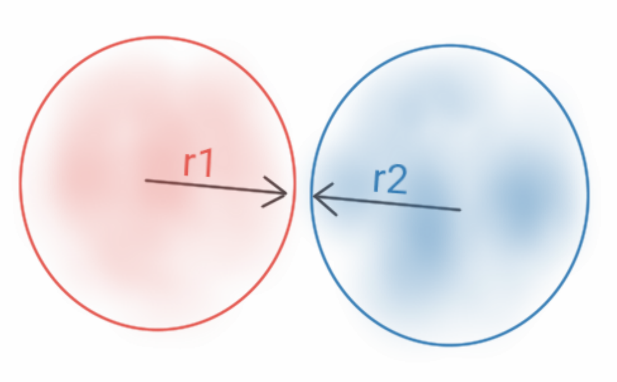
Excluded Volume

Repulsive interactions can be modeled in the HRG model with the introduction of an effective radius.
With this assumption particles have a finite size, and occupy a portion of space which must be Excluded from the Volume of the system.

$$p_{\mathrm{I}}(T,\vec{\mu}) = \sum_j p_j^{\mathrm{id}}(T,\mu_j)$$

Trascendental equation

$$p(T,\vec{\mu}) = \sum_j p_j^{\mathrm{id}}\left(T,\mu_j^*\right)$$



$$\mu_j^* = \mu_j - v_j p(T,\vec{\mu})$$

$$v_j = 16\pi\, r_j^3/3$$

D.H. Rischke et al., Z.Phys. C51 (1991) 485-490
M. Albright et al., Phys.Rev. C90 (2014) no.2, 024915

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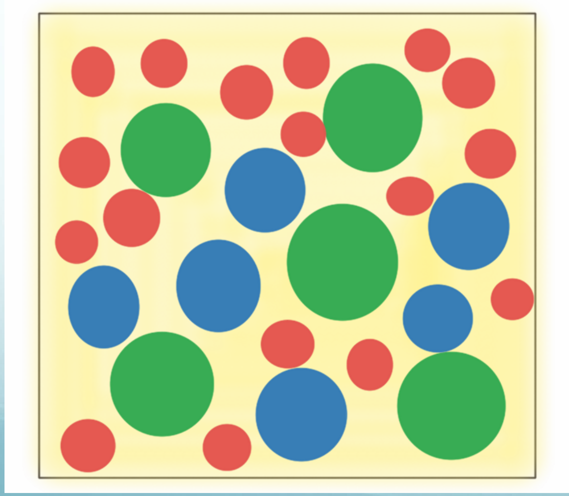

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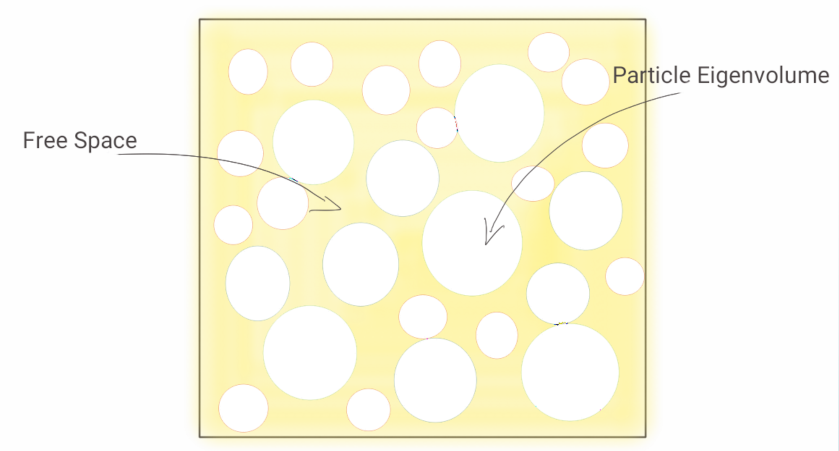

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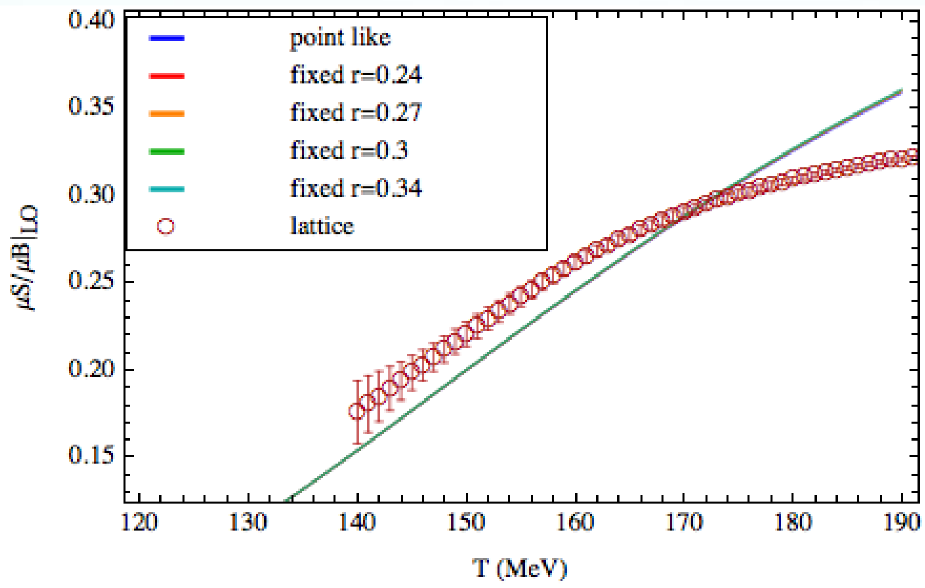
$$p_{\mathrm{I}}(T,\vec{\mu}) \;=\; \sum_j p_j^{\mathrm{id}}(T,\mu_j) \;\Rightarrow\; p(T,\vec{\mu}) = \sum_j p_j^{\mathrm{id}}\left(T,\mu_j^*\right)$$

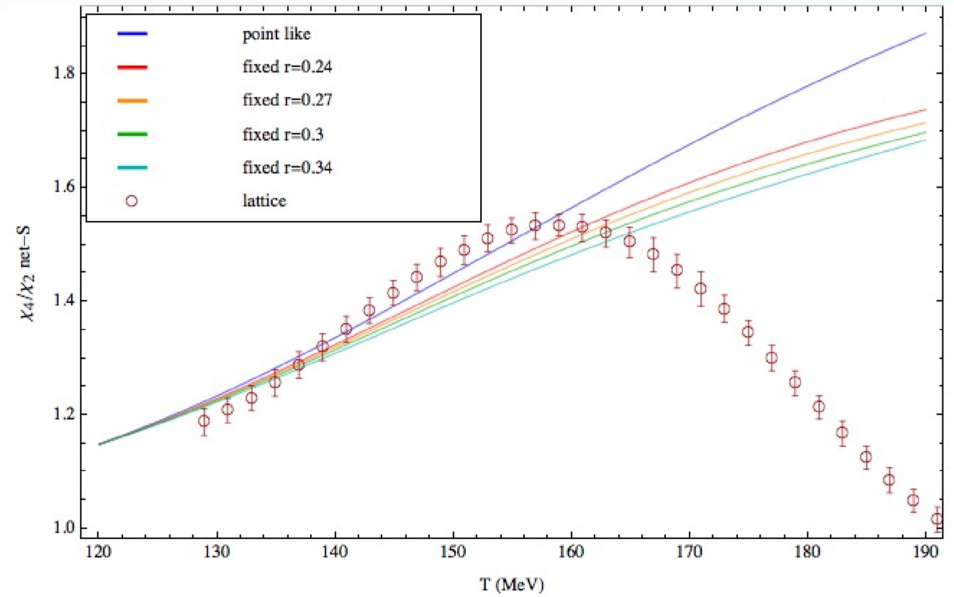
$$n_B(T,\vec{\mu}) = \left(\frac{\partial p}{\partial \mu_B}\right)_T = \frac{\sum_i b_i\, n_i^{id}(T,\mu_i^*)}{1+\sum_j v_j n_j^{id}(T,\mu_j^*)}$$

D.H. Rischke et al., Z.Phys. C51 (1991) 485-490
M. Albright et al., Phys.Rev. C90 (2014) no.2, 024915

EV: lattice observables

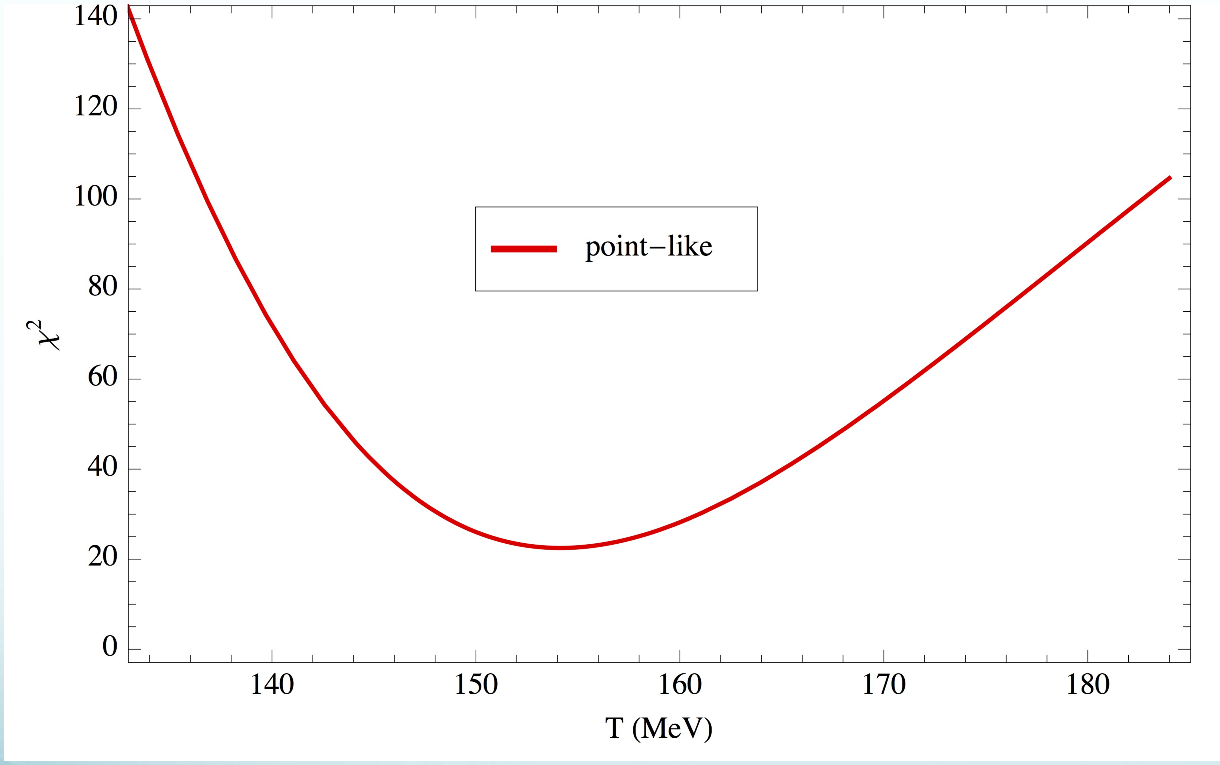
The hard-core suppression can easily influence some observables.





EV: particle yields

It is not clear how to parametrize the repulsive channels, and this could have various effect.



Fit to ALICE PbPb 0-5% collisions at 2.76 TeV

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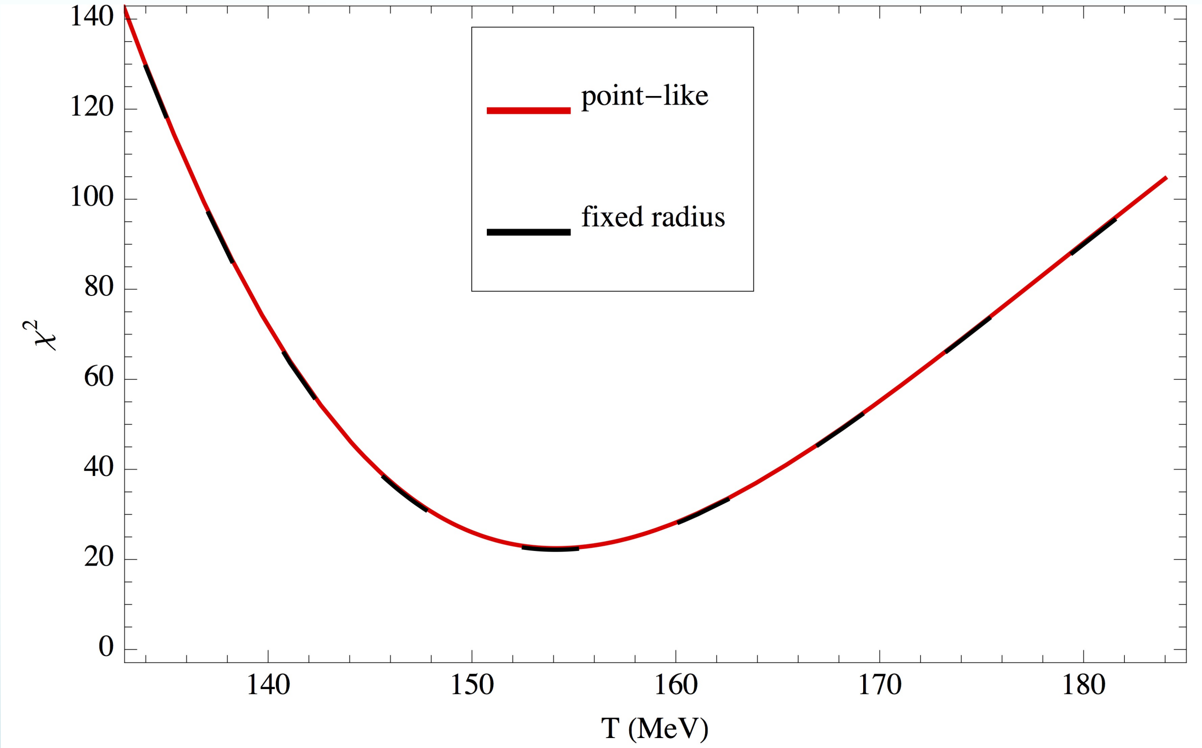

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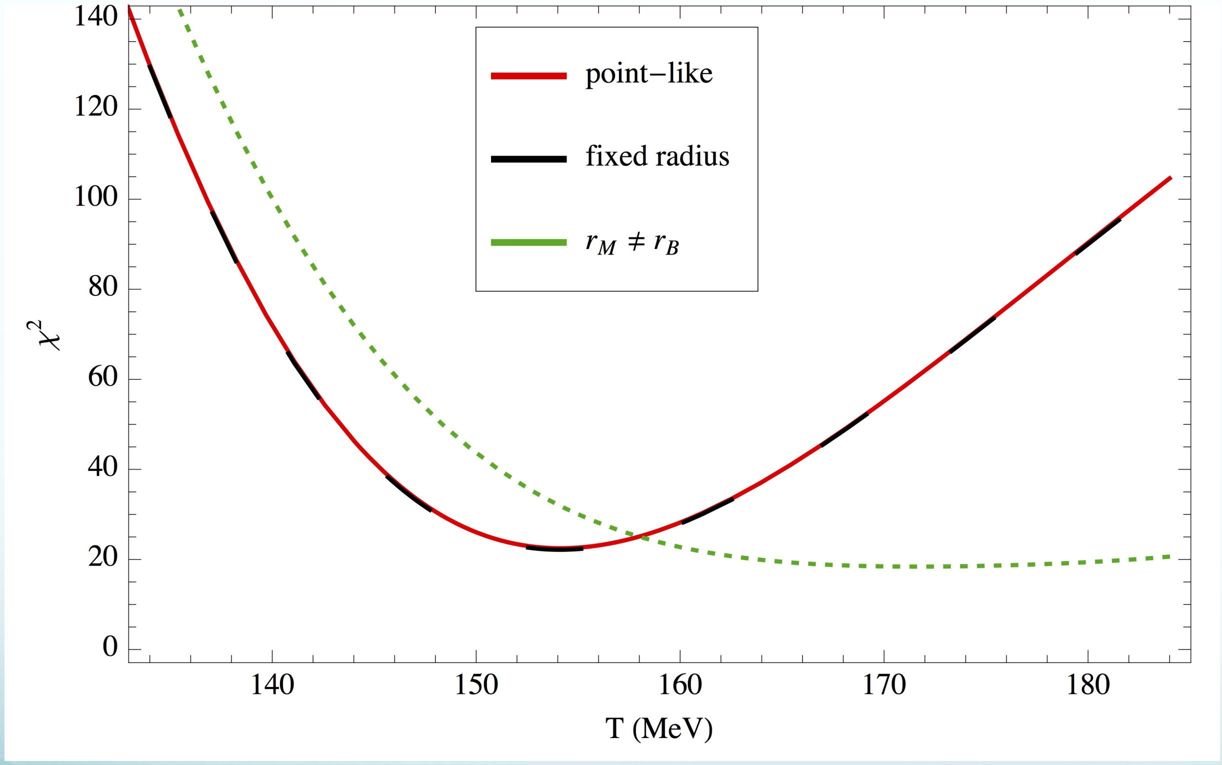

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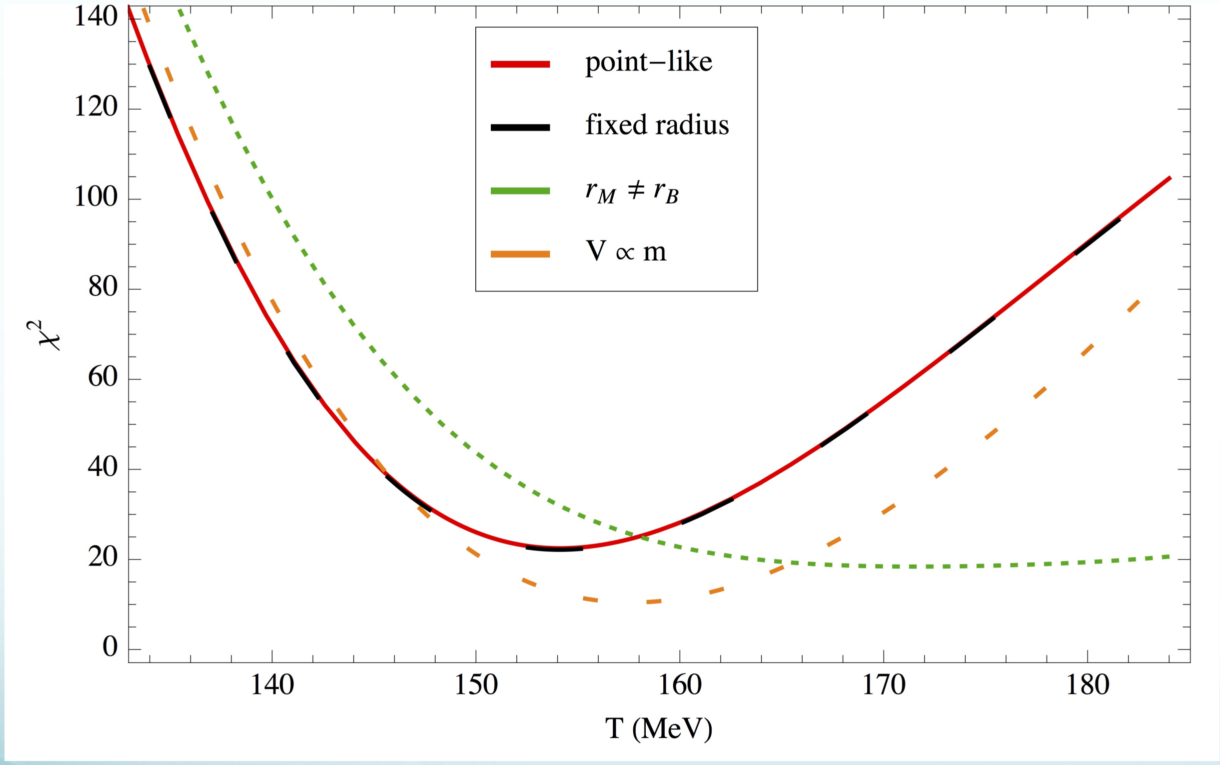

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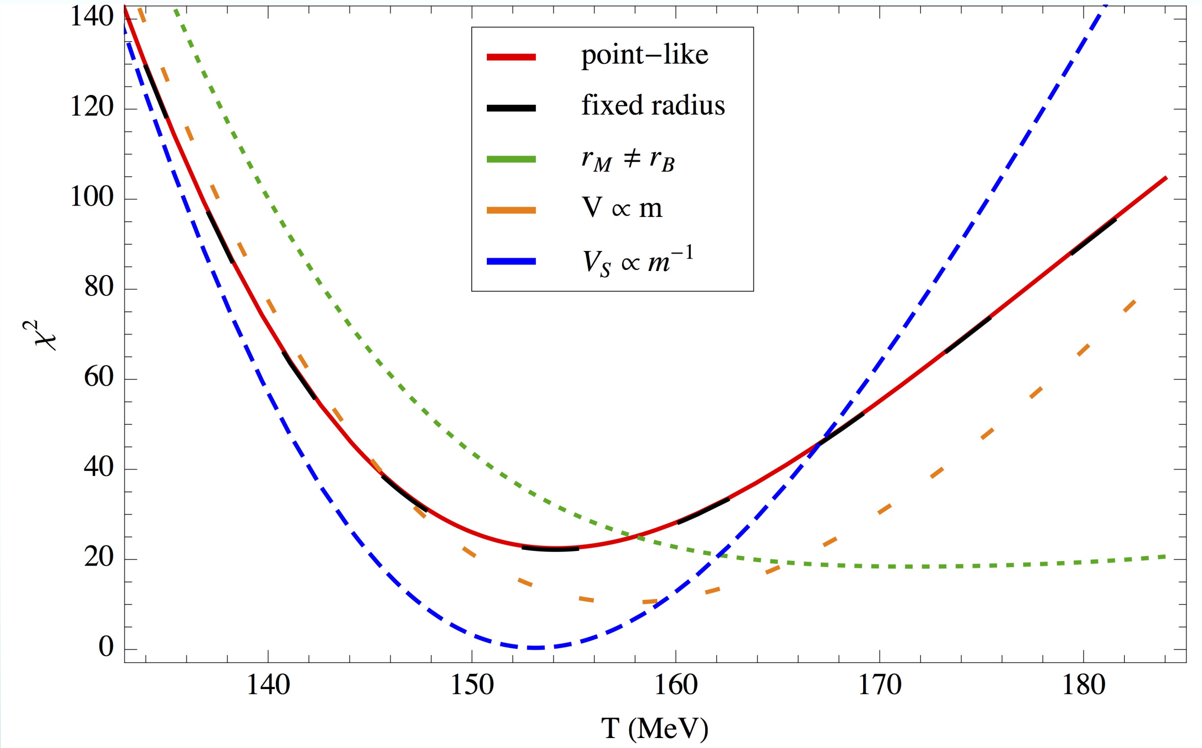
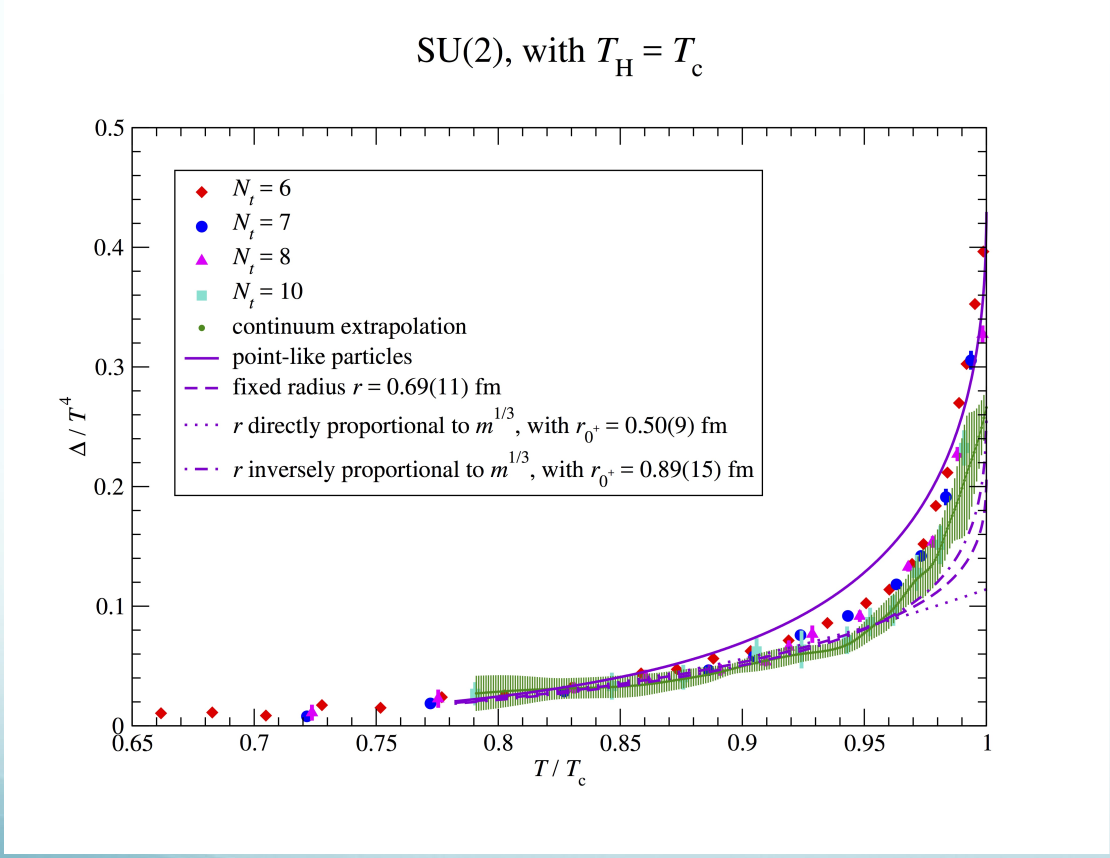


	T (MeV)	χ^2
point-like	154.12	2.81
fixed	154.10	3.16
$r_M \neq r_B$	171.62	3.06
$V \propto m$	157.62	1.74
$V_S \propto m^{-1}$	153.11	0.062

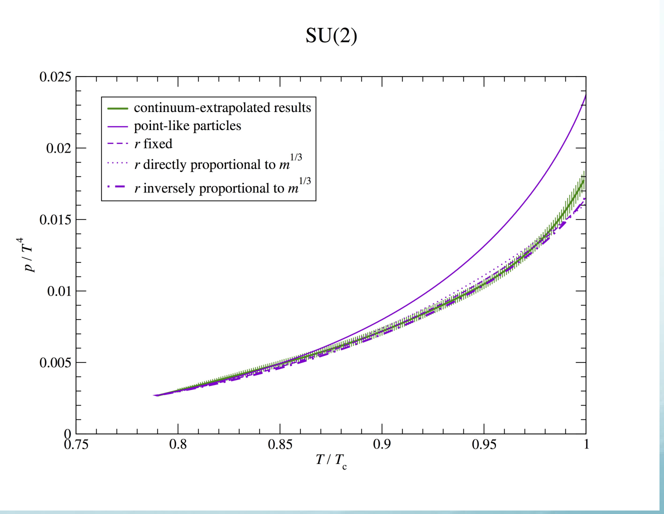
Fit to ALICE PbPb 0-5% collisions at 2.76 TeV

EV: Pure gauge - lattice

The different parameterizations can be tested against lattice simulations in the pure gauge sector for different theories.



	r_{0+} (fm)	Δr_{0+} (fm)	χ^2_Δ
point-like	0	0	11.25
fixed	0.69	0.114	0.52
direct	0.49	0.092	1.27
inverse	0.89	0.152	0.35



P.A. et al., in preparation

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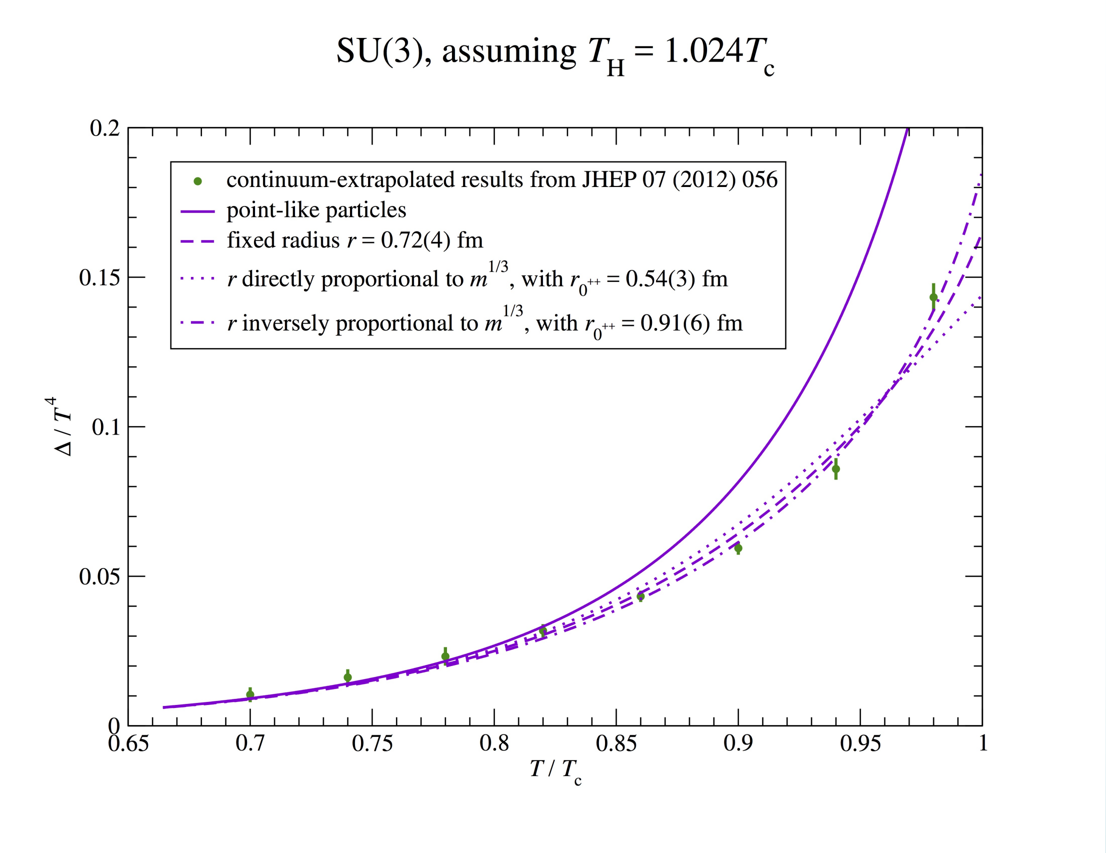
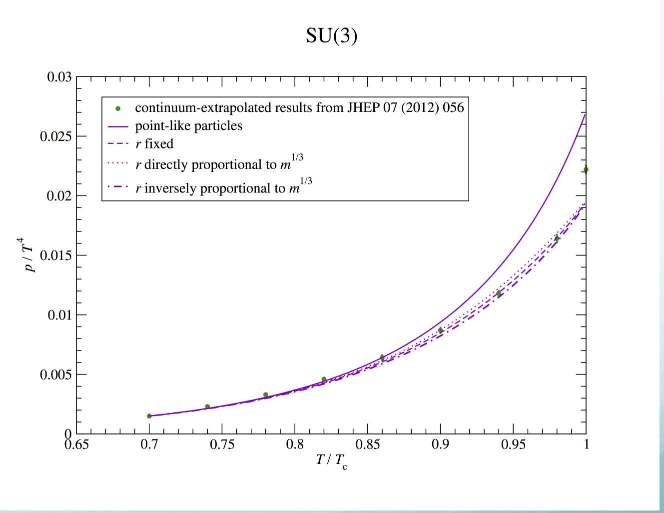


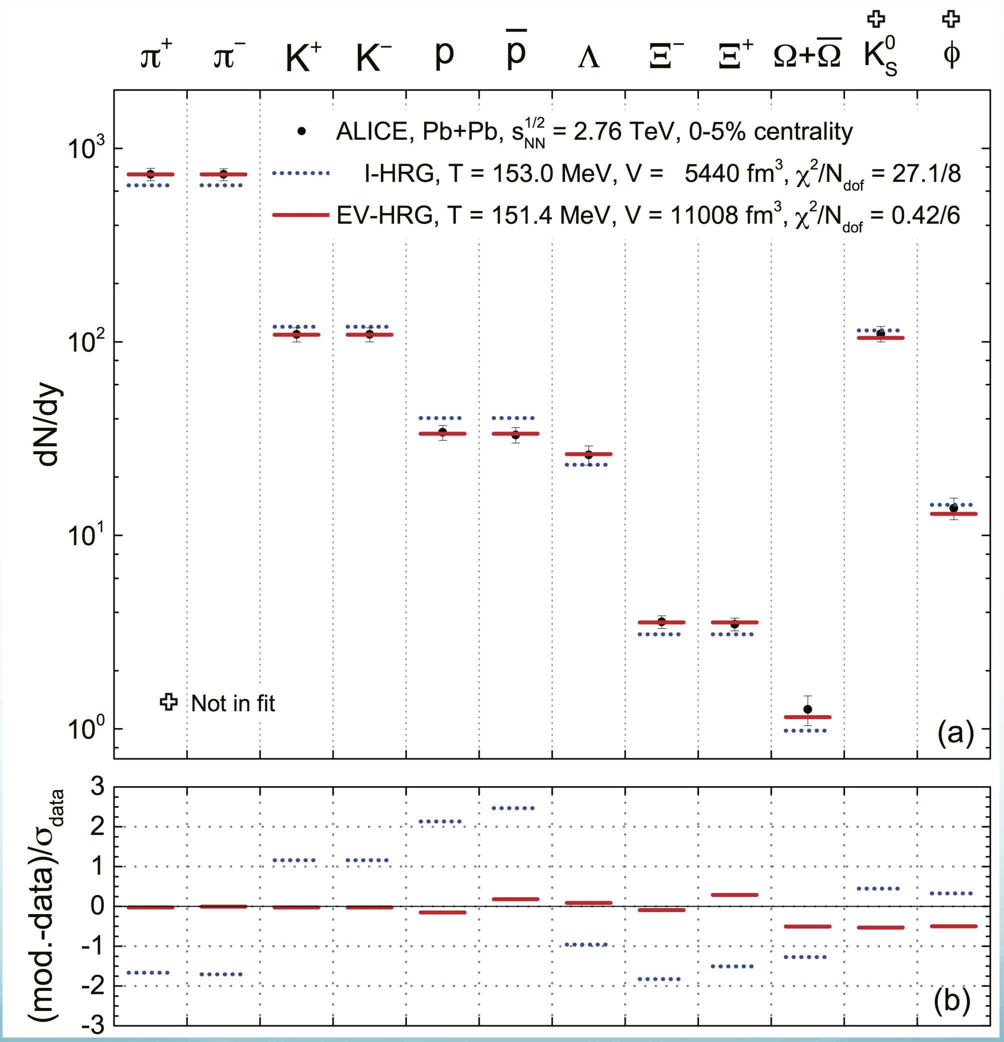
	r_{0++} (fm)	Δr_{0++} (fm)	χ^2_Δ
point-like	0	0	84.3
fixed	0.72	0.0428	1.95
direct	0.54	0.033	4.41
inverse	0.91	0.0558	0.869



Borsanyi et al., JHEP 1207 (2012) 056
Meyer, Phys.Rev. D80 (2009) 051502

EV: test on particle yields

No more "proton anomaly"; consistency with resonance formation.



P.A. et al.,arxiv: hep-ph 1606.06542

EV: test on particle yields

The improvement holds for different centralities and energies.

	χ^2/Ndf p.l.	χ^2/Ndf	T (MeV) p.l.	T (MeV)
ALICE 0-5%	2.642537	0.0985746	152.576606	150.270412
ALICE 5-10%	4.038844	0.082681	153.855798	151.702161
ALICE 10-20%	4.831962	0.187238	156.912643	153.761281
ALICE 20-30%	5.779079	0.505264	156.269898	155.342295
ALICE 30-40%	5.290277	0.479082	156.606086	155.778665
ALICE 40-50%	4.320371	0.225175	156.901153	155.046625
ALICE 50-60%	2.528466	0.431904	153.374355	152.640780
ALICE 60-70%	2.522801	0.896884	148.338287	150.736294
ALICE 70-80%	2.480648	0.516741	150.701703	158.829787

EV: test on particle yields

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	χ^2/Ndf p.l.	χ^2/Ndf	T (MeV) p.l.	T (MeV)
NA49 20GeV	5.868216	3.668726	106.448226	122.919464
NA49 30GeV	7.222598	1.269705	141.555846	136.454728
NA49 40GeV	8.077212	2.292649	139.293714	136.775614
NA49 80GeV	13.783130	4.812104	138.121797	141.917805
NA49 158GeV	5.329034	1.590537	146.535995	142.932057

EV and QM: do we need both?

The presence of resonances balances the effect of repulsion, and generally improves the description of the lattice data.

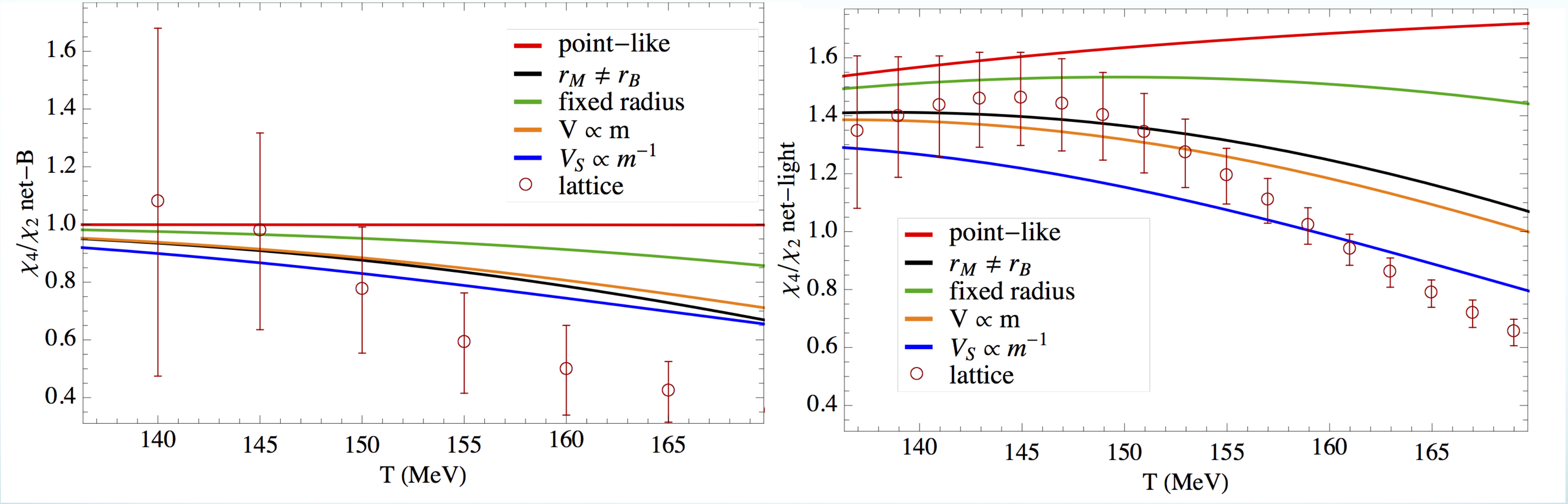
list	EV	χ^2
PDG2014	point-like	9.49
PDG2014	$V \propto m$	11.772
QM	$V \propto m$	1.72

observables involved in the calculation of χ^2:

- pressure, interaction measure
- χ^{11}_{ud}, χ^4_B/χ^2_B, χ^4_l/χ^2_l
- χ^{11}_{us}, χ^2_s, $\mu_S/\mu_B|_{LO}$, χ^4_S/χ^2_S

Light observables

Light observables are mainly influenced by EV effects, and not by QM states (light sector is known to a good accuracy).



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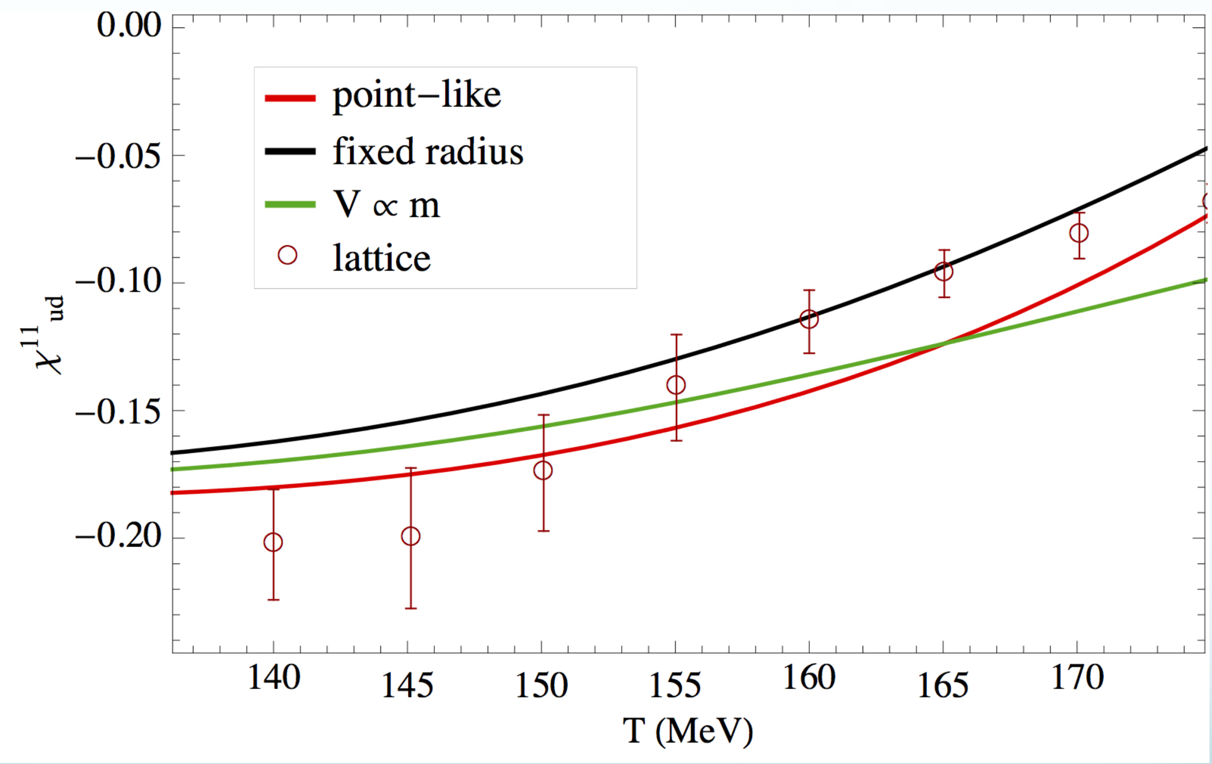
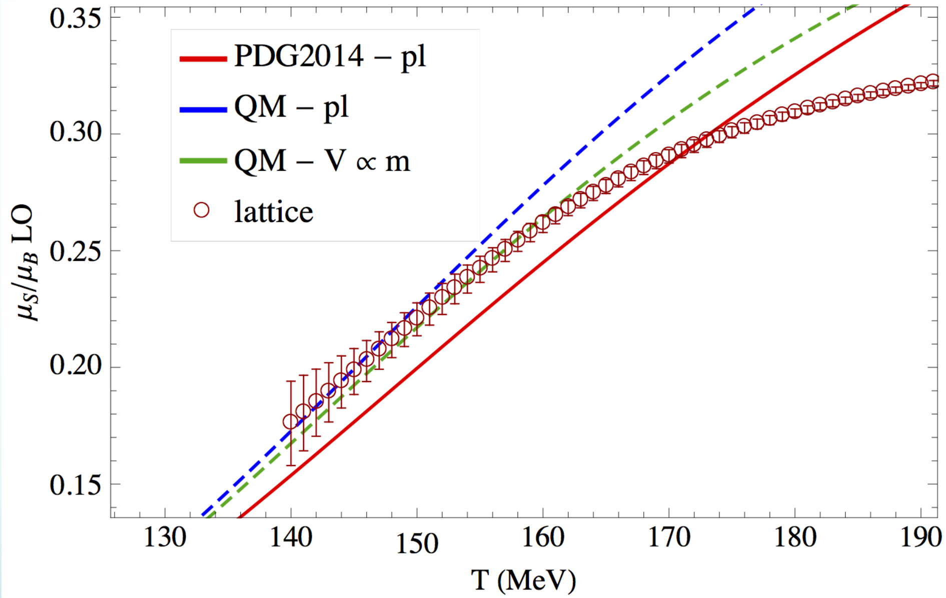
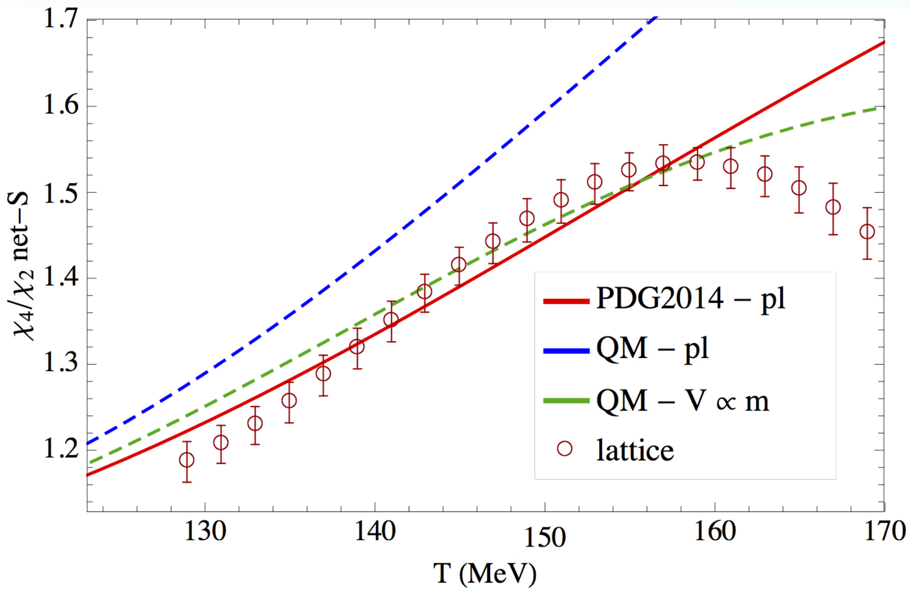


Strange observables

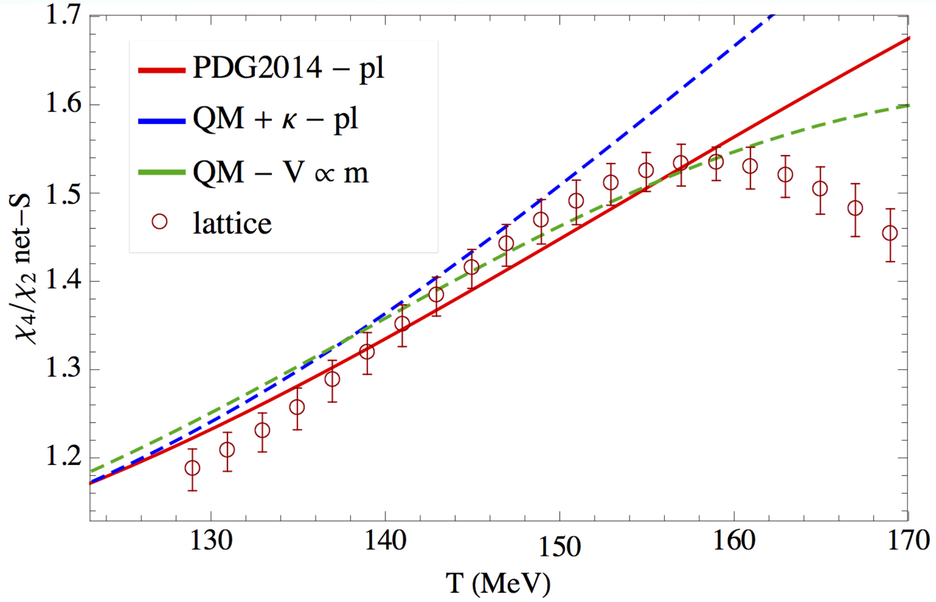
With the same EV parameters obtained from particle yields I correct the behavior for key strange observables.

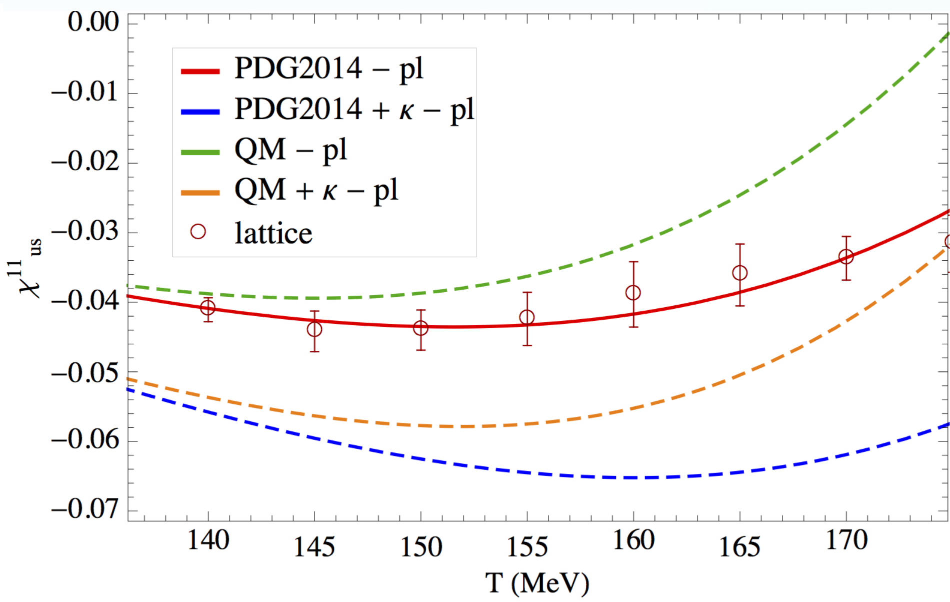




Strange observables

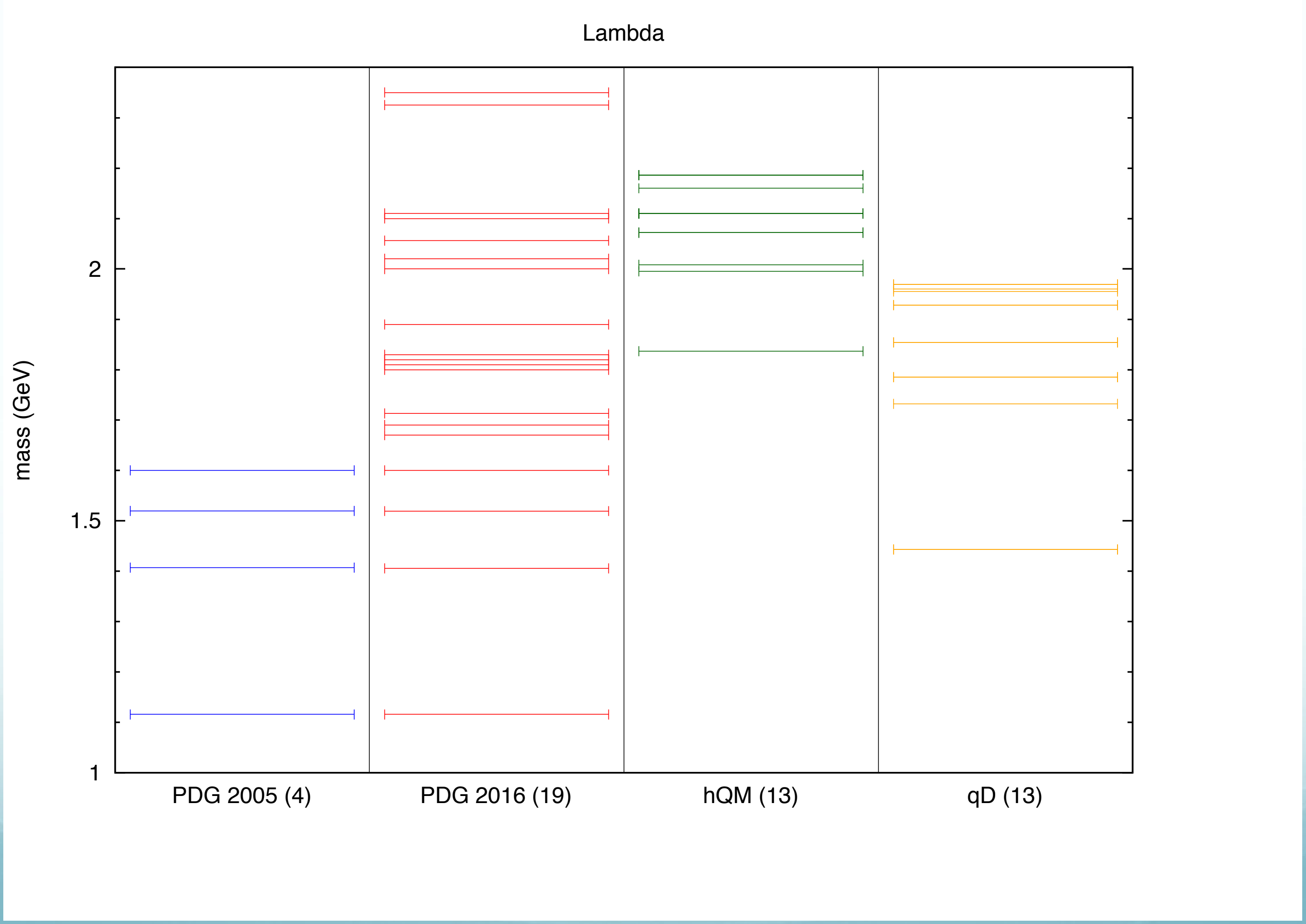
One should pay attention to the influence of the kappa resonance on the strange observables, and its influence on the fit of particle yields should be investigated.





Quark-Models selection

Different Quark Models give different predictions; a comparison of these against lattice results could distinguish among them, but repulsive forces should be considered.



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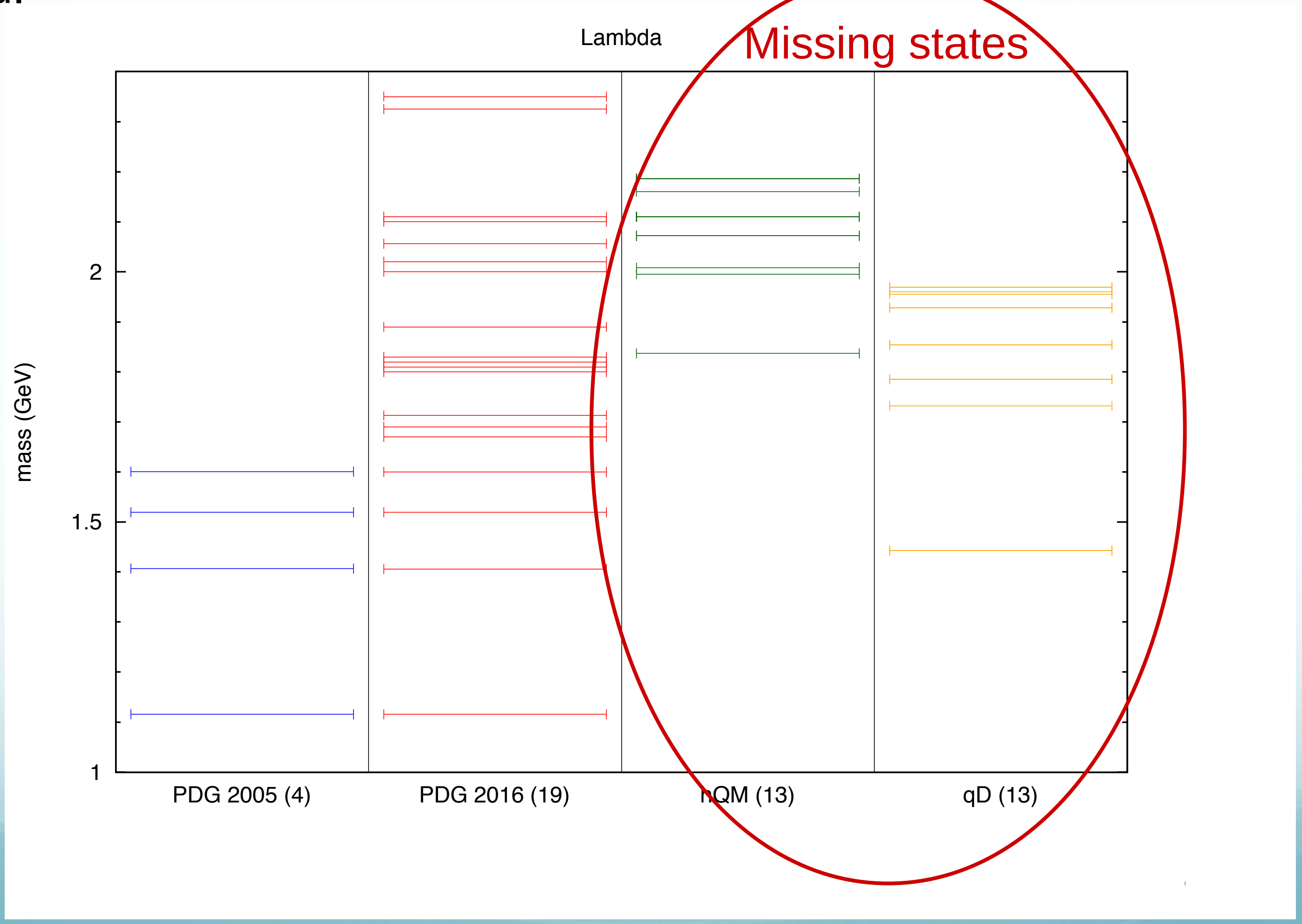

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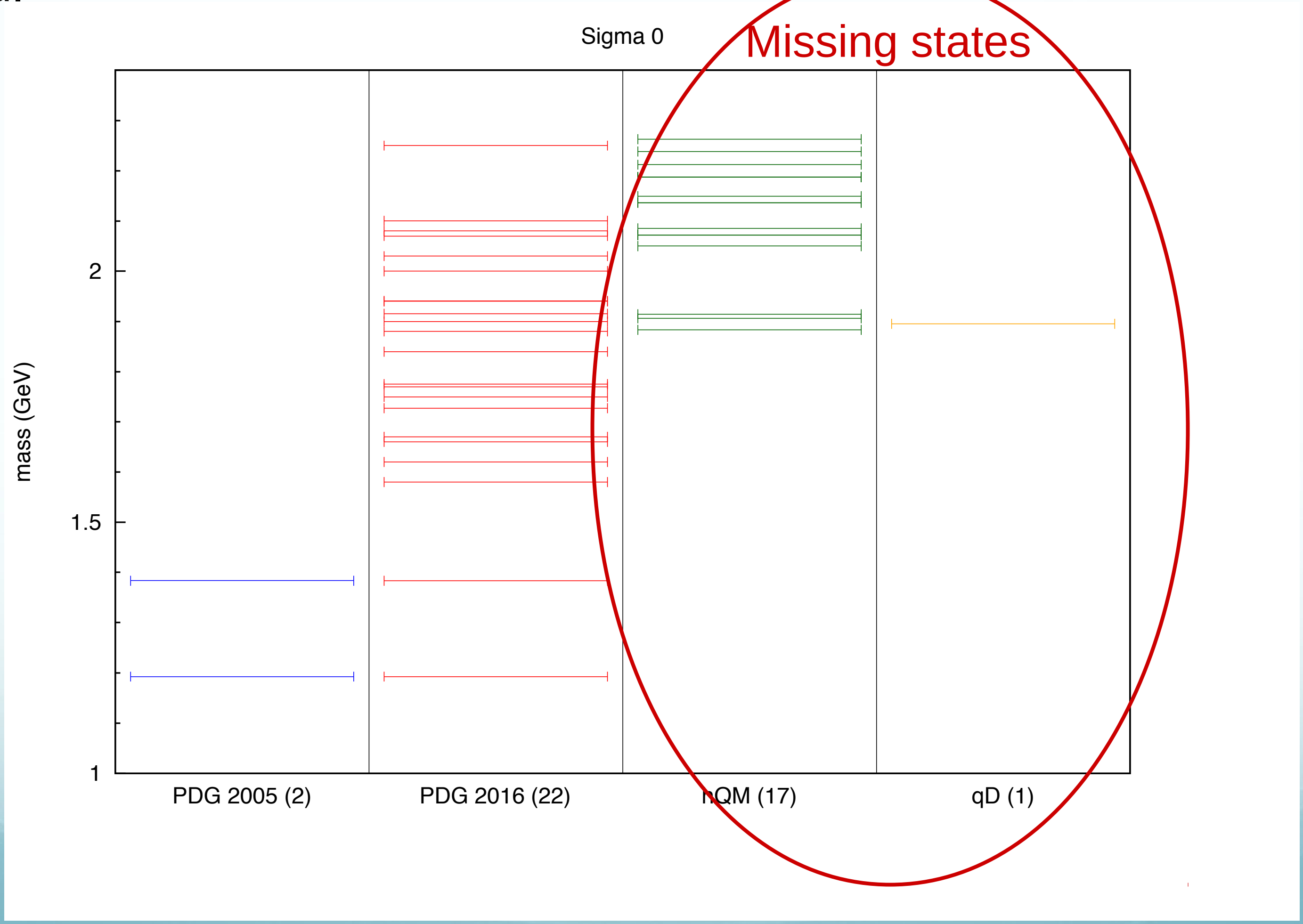


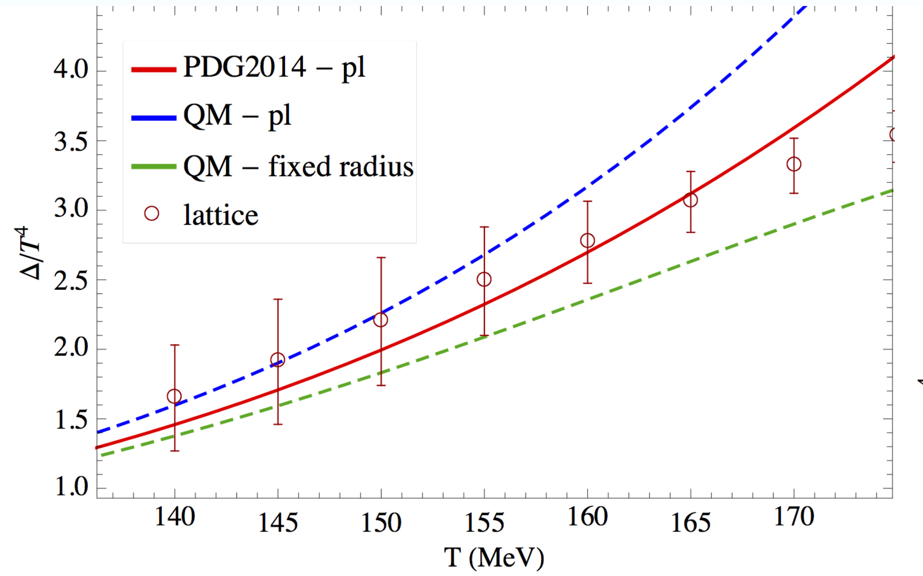
Summary

- The usual HRG model is not enough to describe all the available results from lattice QCD and experimental measurements.
- A comparison to lattice QCD simulations hints for the presence of extra resonances in the strange sector.
- Repulsive interactions play an important role in the interplay with these resonances for a coherent description of all the available observables.
- There is an agreement between lattice and experimental results in the relevance of repulsive interaction channels
- The role of exotic resonances should be clarified
- It is needed an experimental confirmation for the “good” QM predictions

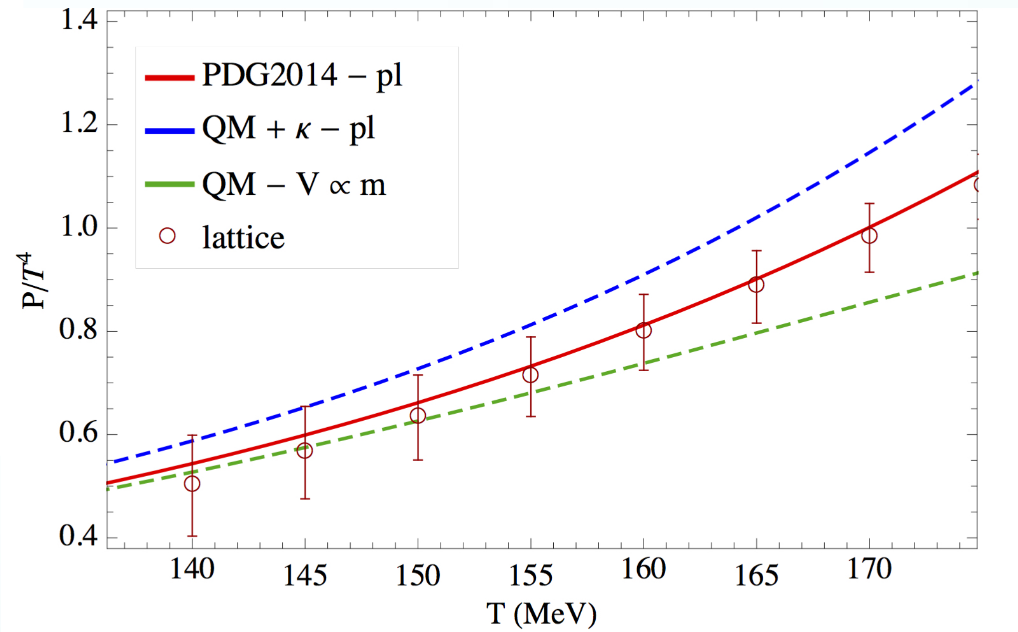
Thanks for your attention

Backup slides

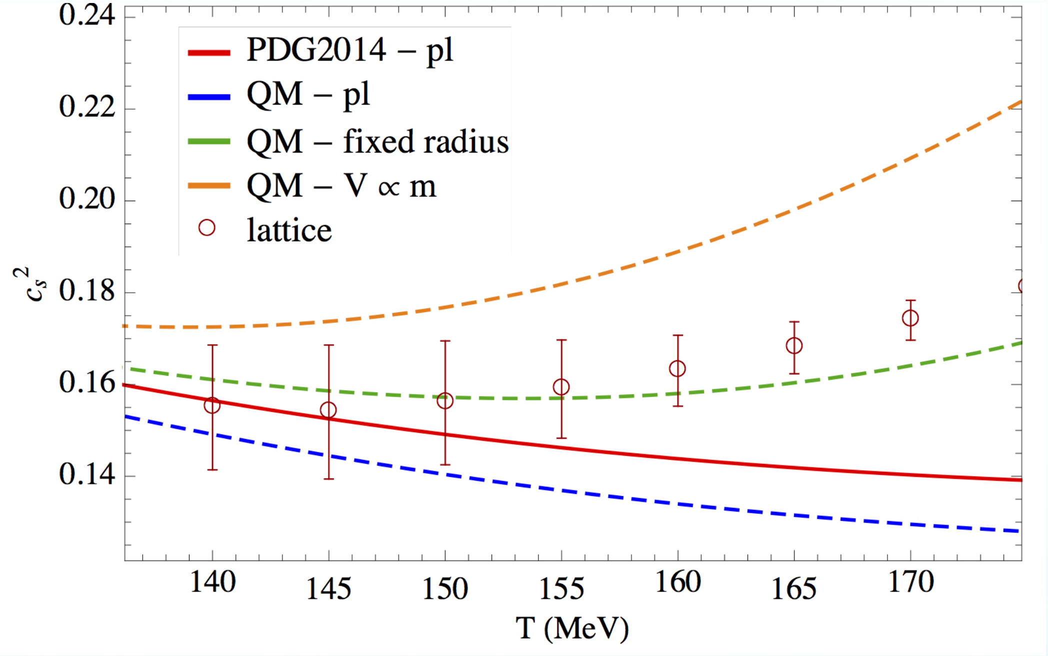
and Outlook



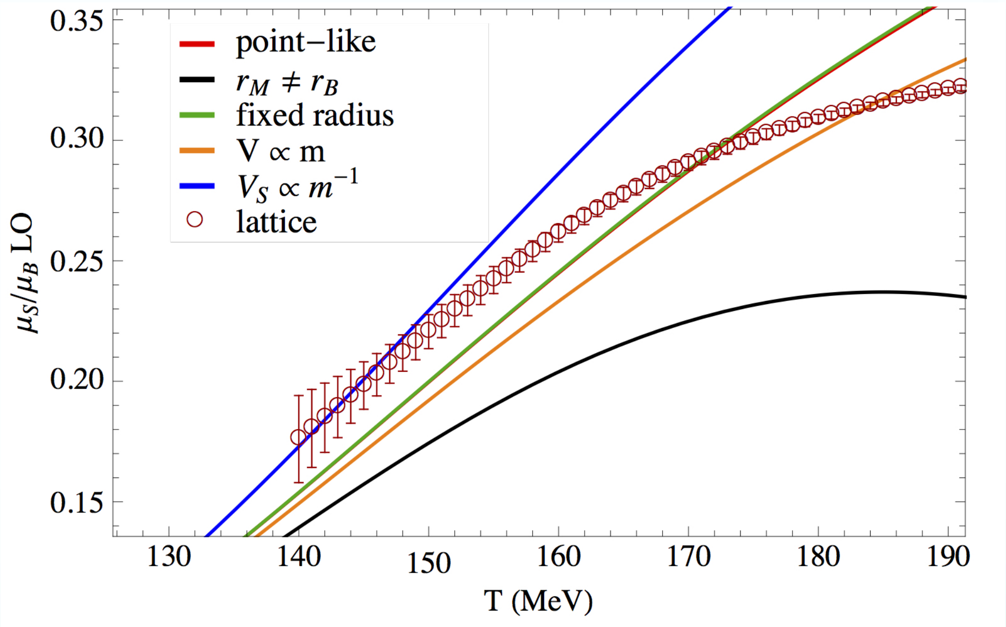
PDG2014 − pl
QM − pl
QM − fixed radius
lattice
Δ/T⁴
T (MeV)



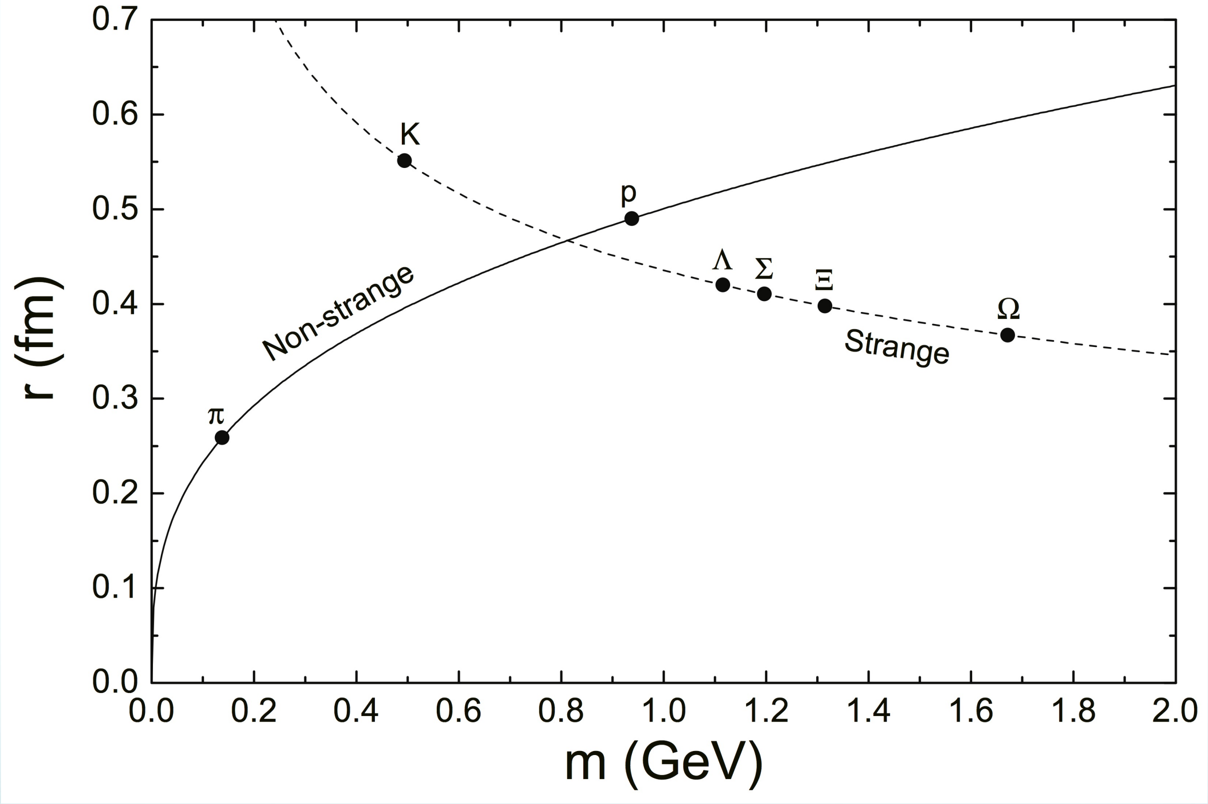
PDG2014 − pl
QM + κ − pl
QM − V ∝ m
lattice
P/T⁴
T (MeV)



PDG2014 – pl
QM – pl
QM – fixed radius
QM – V ∝ m
lattice
c_s^2
0.24
0.22
0.20
0.18
0.16
0.14
140
145
150
155
160
165
170
T (MeV)



point−like
$r_M \neq r_B$
fixed radius
V ∝ m
$V_S \propto m^{-1}$
lattice
μ_S/μ_B LO
T (MeV)
0.35
0.30
0.25
0.20
0.15
130
140
150
160
170
180
190



r (fm)
m (GeV)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
K
p
π
Λ
Σ
Ξ
Ω
Non-strange
Strange