Magnetic properties of Hadron Resonance Gas with physical magnetic moment

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in collaboration with Wojciech Broniowski

[based on arXiv:2505.14484]

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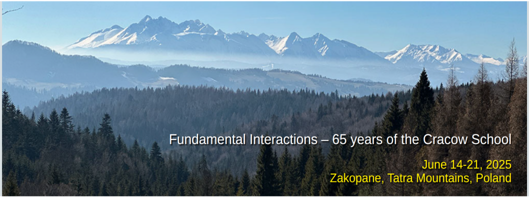

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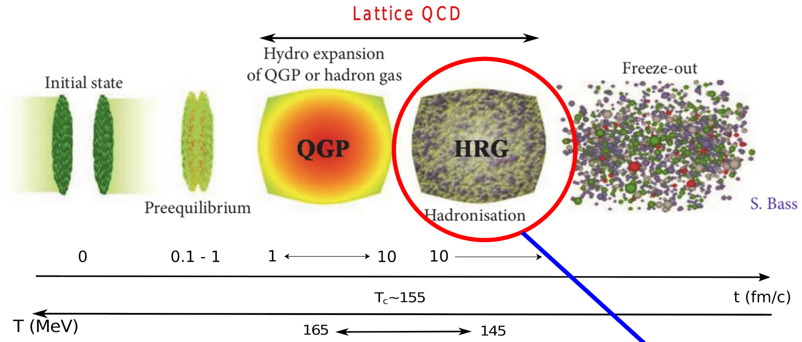
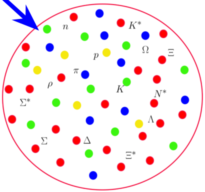
Hadron Resonance Gas (HRG) (heavy-ion collision)





- System of stable and resonance hadron states formed at **later stage of HI collision** $\longrightarrow$ below critical temperature $T_c \sim 155$ MeV at the LHC.[Braun-Munzinger, Phys. Lett. B (1995), Aoki, Nature (2006); Andronic, Nature (2018)]
- also found in cold neutron star matter, early-universe etc.

Lattice QCD and magnetic field

- Strong magnetic field in non-central HI collision, but it's time-dependent and transient. [Kharzeev, Nucl.Phys.A (2008) ; Skokov, Int.J.Mod.Phys.A (2009); Deng, Phys. Rev. C(2012); Huang, Phys. Rev. C (2023)]

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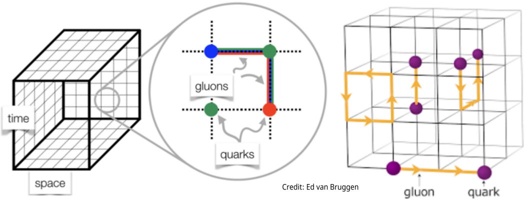
- Lattice QCD : first principle description of QCD matter under extreme condition $\longrightarrow$ **data in the presence of uniform** $\mathcal{B}$ [Bazavov, Phys. Rev. D(2012); Bollweg, Phys. Rev. D(2021); Ding, Phys. Rev. Lett.(2024); Ding, arXiv:2503.18467]



Credit: Ed van Bruggen

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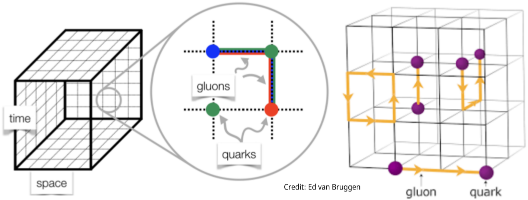
- Fiducial range for comparison with HRG: 0.145 MeV $< T <$ 0.165 MeV



The HRG model in magnetic field

- In the assumption of non-interacting gas, thermal partial pressure of individual hadrons:

$$P = -\eta T(2s+1)\int \frac{d^3p}{(2\pi)^3}\log[1-\eta f(E,T,\mu)]$$

where, $f(E,T,\mu) = \frac{1}{\exp(\frac{E-\mu}{T})+\eta}$ with $\mu = \mu_B B + \mu_S S + \mu_Q Q$ and $\eta = \pm 1$

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- In presence of magnetic field: $(2s+1)\int \frac{d^3p}{(2\pi)^3} \longrightarrow \frac{\mathcal{B}|Q|}{2\pi^2}\sum_{l,s_z}\int_0^\infty dp_z$

$$P_{ch} = -\eta T\frac{\mathcal{B}|Q|}{2\pi^2}\sum_{l=0}^{\infty}\sum_{s_z=-s}^{s}\int_0^\infty dp_z \log[1-\eta f]\ ,\ \ E = E(\mathcal{B})$$

and $$P_{neu} = -\eta T\frac{1}{2\pi^2}\sum_{s_z=-s}^{s}\int_0^\infty p^2 dp \log[1-\eta f]$$

Structureless particle in a uniform magnetic field

- $\mathcal{B}$-field interaction modifies the energy spectra of hadrons. In the non-relativistic limit, energy of a particle :

$$E = M + \frac{p_z^2}{2M} + \underbrace{\frac{\mathcal{B}|Q|}{2M}(2l+1)}_{\text{Landau diamagnetism}} - \underbrace{\mu\,\mathcal{B}}_{\text{Pauli paramagnetism}}$$

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$$E = \sqrt{M^2 + p_z^2 + 2\mathcal{B}|Q|\left(l + \frac{1}{2} - s_z\right)}$$

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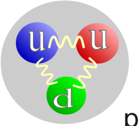
- **This is correct for structureless Dirac particles but not for hadrons with internal structures (quarks)** e.g. for neutron, $\mu_{\text{exp}} = -1.9\mu_N$ (Nuclear magneton) and $g \neq 0 \longrightarrow$ need to include **anomalous magnetic moment** in energy spectrum.

The physical magnetic moment of hadrons

- Due to internal quark structures, **hadrons (both charged and neutral) possess anomalous magnetic moments**:

$$\mu = \underbrace{\mu_D}_{\text{Dirac particle}} + \underbrace{\kappa}_{\text{anomalous part}}$$

and $g = 2(Q+\kappa) \implies \kappa = \dfrac{g-2Q}{2}$



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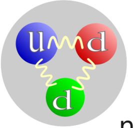

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Quark Model

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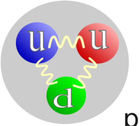

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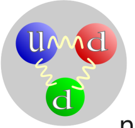

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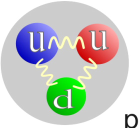
- For example for p, n (in μ_N) :
$\mu^p_{exp} = 2.793 \implies \mu^p_D = 1, g = 5.586, \kappa^p = 1.793$
$\mu^n_{exp} = -1.913 \implies \mu^n_D = 0, g = -3.831, \kappa^n = -1.913$
We include κ systematically inside E of hadrons !



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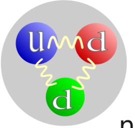

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Quark Model

Energy spectra of hadrons in uniform B with κ

- For **spin-0** states ($\mu = 0$ $\kappa = 0$): Exact

$$E_{ch} = \sqrt{M^2 + p_z^2 + \mathcal{B}|Q|(2l+1)} \qquad E_{neu} = \sqrt{M^2 + p^2}$$

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- For **spin** $>$ **3/2** ($g = 2Q + 2\kappa$): Approximation

$$E_{ch} = \sqrt{M^2 + \mathcal{B}|Q|(2l+1)} - \mu_M \mathcal{B} g s_z \ , \ E_{neu} = \sqrt{M^2 + p^2} - \mu_M \mathcal{B} g s_z$$

Observables: conserved charge susceptibilities

- Then the leading order conserved charge susceptibilities are found as:

$$\chi_{Q_1Q_2} = \frac{\partial^2(P/T^4)}{\partial(\mu_{Q_1}/T)\partial(\mu_{Q_2}/T)}\bigg|_T$$

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- Plugging the expression of P for non-zero $\mathcal{B}$ one finds :

$$\chi^{ch}_{Q_1Q_2} = \frac{Q_1Q_2\mathcal{B}|Q|}{2\pi^2T^3}\sum_{l=0}^{\infty}\sum_{s_z=-s}^{s}\int_0^{\infty} dp_z f(1-\eta f)$$

and $$\chi^{neu}_{Q_1Q_2} = \frac{Q_1Q_2}{2\pi^2T^3}\sum_{s_z=-s}^{s}\int_0^{\infty} p^2 dp f(1-\eta f)$$

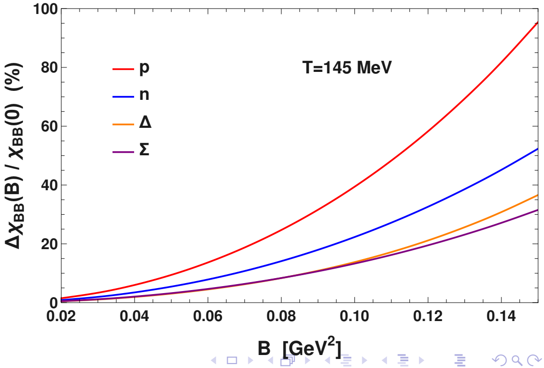
Effects of anomalous magnetic moment on χ_{BB}

- Let us define :

$$\Delta\chi_{BB}(\mathcal{B}) = \chi_{BB}(\mathcal{B},\kappa) - \chi_{BB}(\mathcal{B},\kappa=0)$$

- Then $\frac{\Delta\chi_{BB}(\mathcal{B})}{\chi_{BB}(0)} \longrightarrow$ the relative increase due to κ in presence of $\mathcal{B}$

- Effect of κ is substantial and must be taken into account



Physical μ and g of hadrons

Hadron species	μ/μ_N	g (Eq. 5)	Reference
$\rho^+(775)$	**1.94**(1)	1.60(1)	LQCD [42]
	2.21	1.82	χPT [43]
	2.37	1.96	QM [44]
$K^{*+}(892)$	**2.4**(2)	2.3(2)	LQCD [45]
	2.19	2.08	QM [44]
$K^{*0}(896)$	-0.183	-0.175	QM [44]
$p(938)$	2.793	5.586	PDG [46]
$n(939)$	-1.913	-3.831	PDG [46]
$\Lambda^0(1115)$	-0.613(4)	-1.458(9)	PDG [46]
$\Sigma^+(1189)$	2.458 (10)	6.232(25)	PDG [46]
$\Sigma^0(1192)$	**0.65**	1.65	χPT [47]
	0.791	2.011	QM [48]
$\Sigma^-(1197)$	-1.160(25)	-2.96(63)	PDG [46]
$a_1^+(1230)$	**1.7**(2)	2.2(2)	LQCD [49]
	1.44	1.89	QM [44]
$\Delta^{++}(1232)$	**3.7-7.5**	3.23-6.56	PDG [46]
	6.14(51)	5.37(45)	Lopez et.al [50]
	5.24(18)	4.58(16)	LQCD [51]
	4.97(89)	4.34(78)	χPT [52]
$\Delta^+(1232)$	$2.7^{+1.0}_{-1.3}\pm1.5\pm3$	$2.36^{+0.87}_{-1.14}$	PDG [46]
	2.6(5)	2.27(4)	χPT [52]
$\Delta^0(1232)$	0.02(12)	0.017(100)	χPT [52]
$\Delta^-(1232)$	-2.48(32)	-2.17(28)	χPT [52]
$\Xi^-(1321)$	-0.651(3)	-1.834(8)	PDG [46]
$\Xi^0(1321)$	-1.250(14)	-3.503(39)	PDG [46]
$\Sigma^{*+}(1383)$	**2.55**(26)	2.50(25)	LQCD [53]
	1.76(38)	1.73(37)	χPT [52]

Results: Model vs Lattice data for χ_{BB}

- Lattice data for χ_{BB} **shows increase with** $\mathcal{B}$, we focus on $\mathcal{B} < 0.2$ GeV^2.

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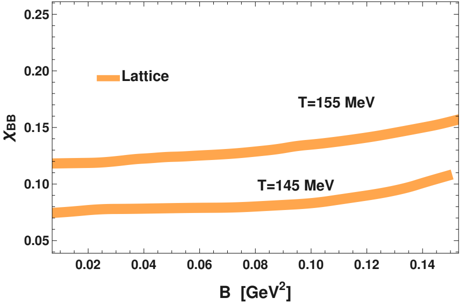

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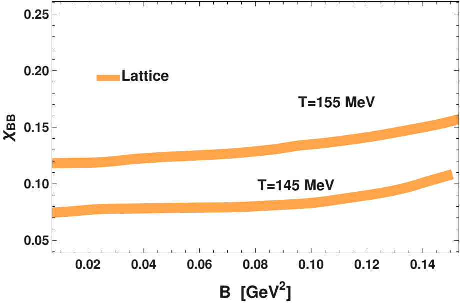

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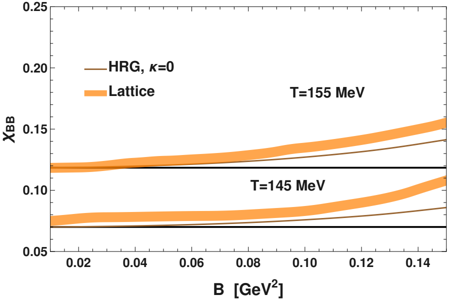

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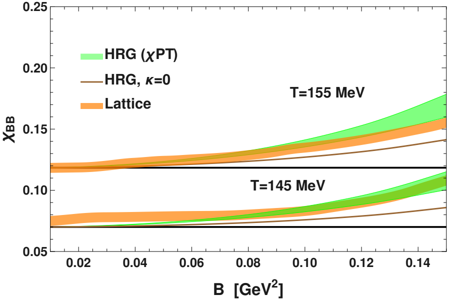

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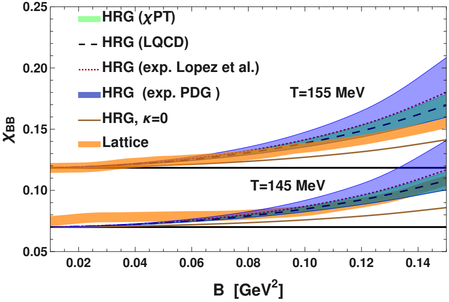
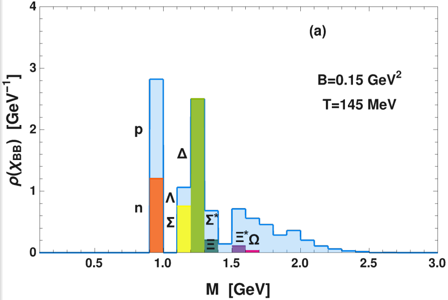
- Error bands $\longrightarrow$ uncertainty in the estimate/measurement of $\mu_{\Delta^{++}}$



Anatomy of χ_{BB}

- $\rho(\chi_{BB}) \rightarrow$ relative contributions of baryon states



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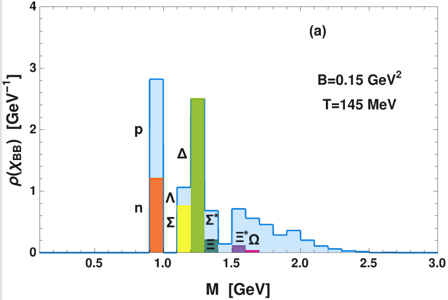

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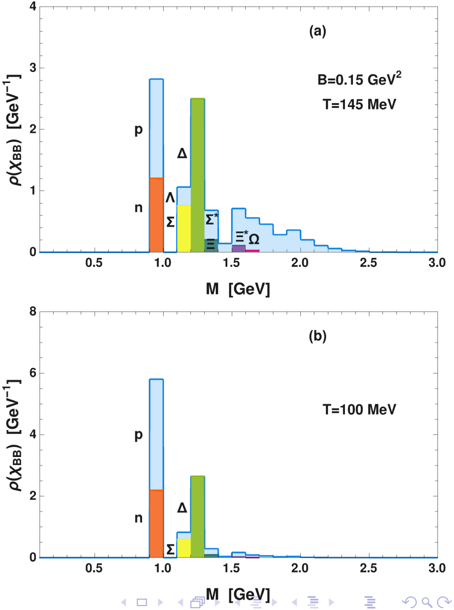
- T decreases $\rightarrow$ higher mass states are thermally suppressed, nucleons largely dominate. At $T = 100$ MeV, $(p \approx n)(60\%) + \Delta(25\%) = 85\%$



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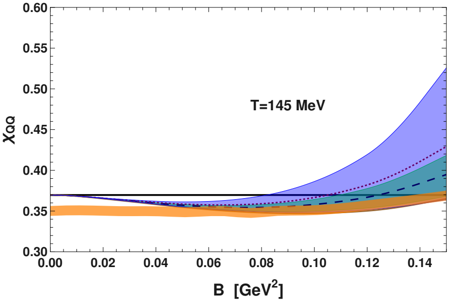

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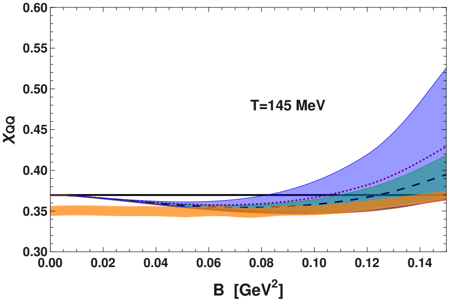

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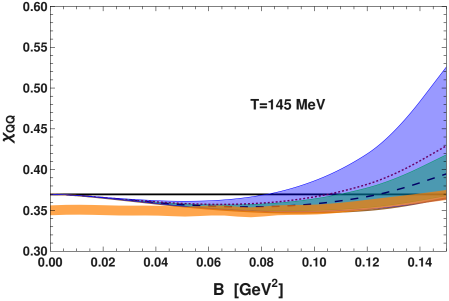

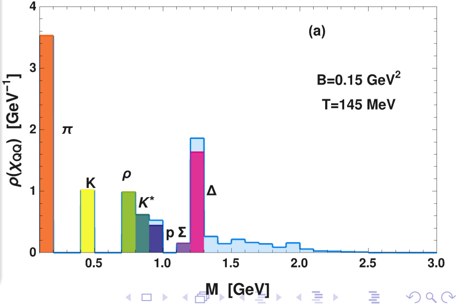

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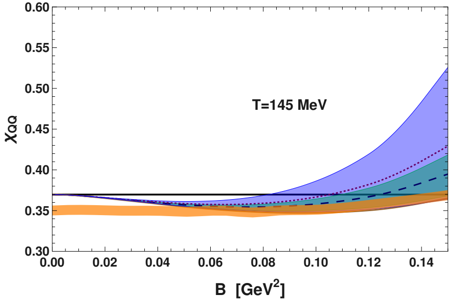

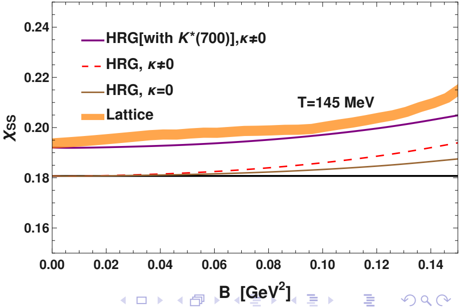

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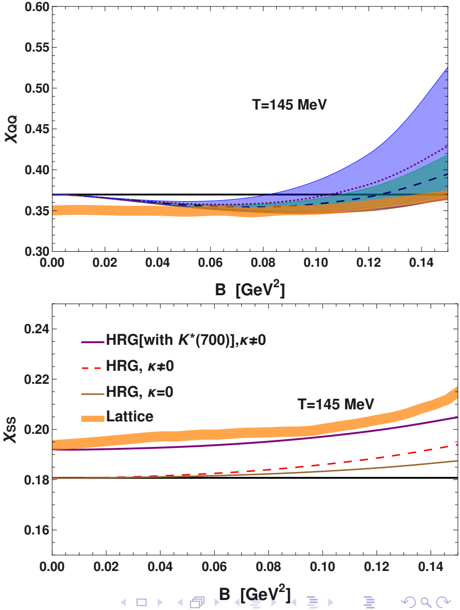
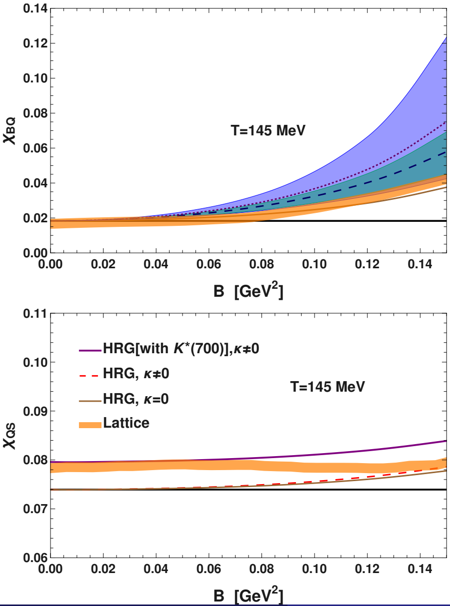
- **Standard list of hadrons do not reproduce the lattice data for χ_{SS} (even at $\mathcal{B} = 0$).$\longrightarrow$ inclusion of $\kappa(K^*(700))$ state makes up the gap and align with the data.**



Results: non-diagonal susceptibilities (χ_{BQ}, χ_{BS} and χ_{QS})



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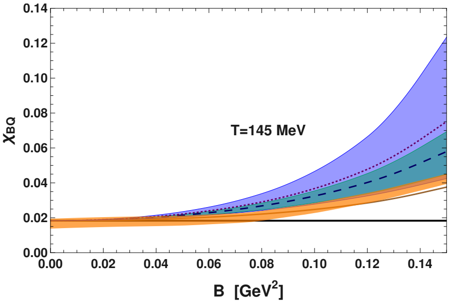

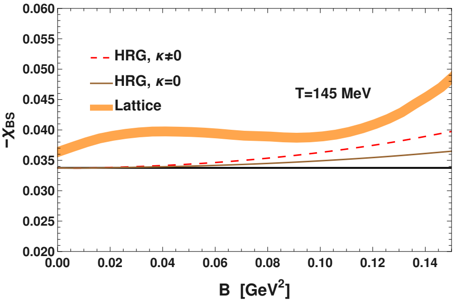

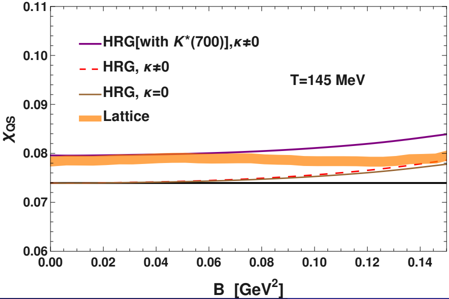

- χ_{BQ} : **not affected by κ of neutral baryons.**
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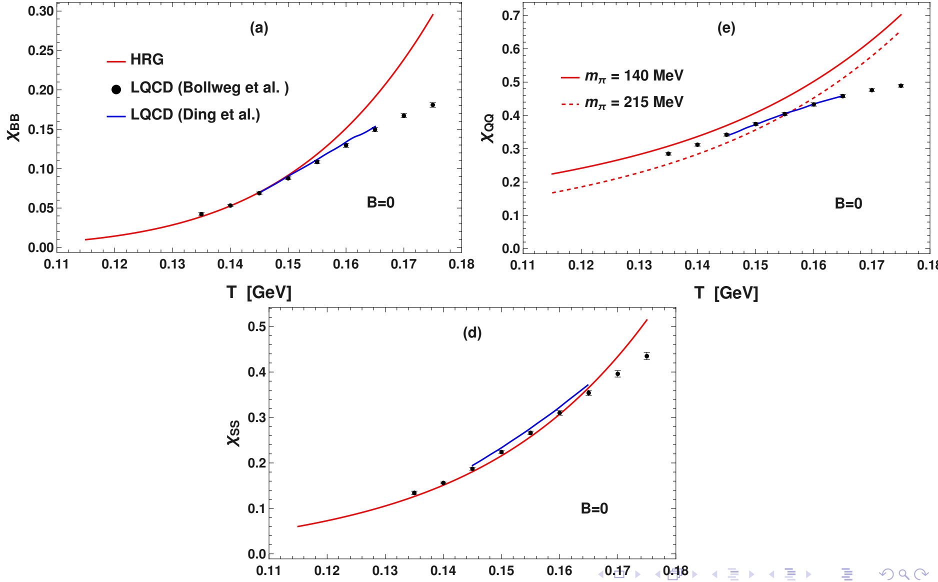
- A second $\kappa : K^*(700)$ state is necessary to describe strange susceptibilities.
- **HRG works in magnetic field !**

Thank you !

Backup

Susceptibility at $\mathcal{B}$=0



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