Properties of strongly interacting matter from Lattice QCD calculations

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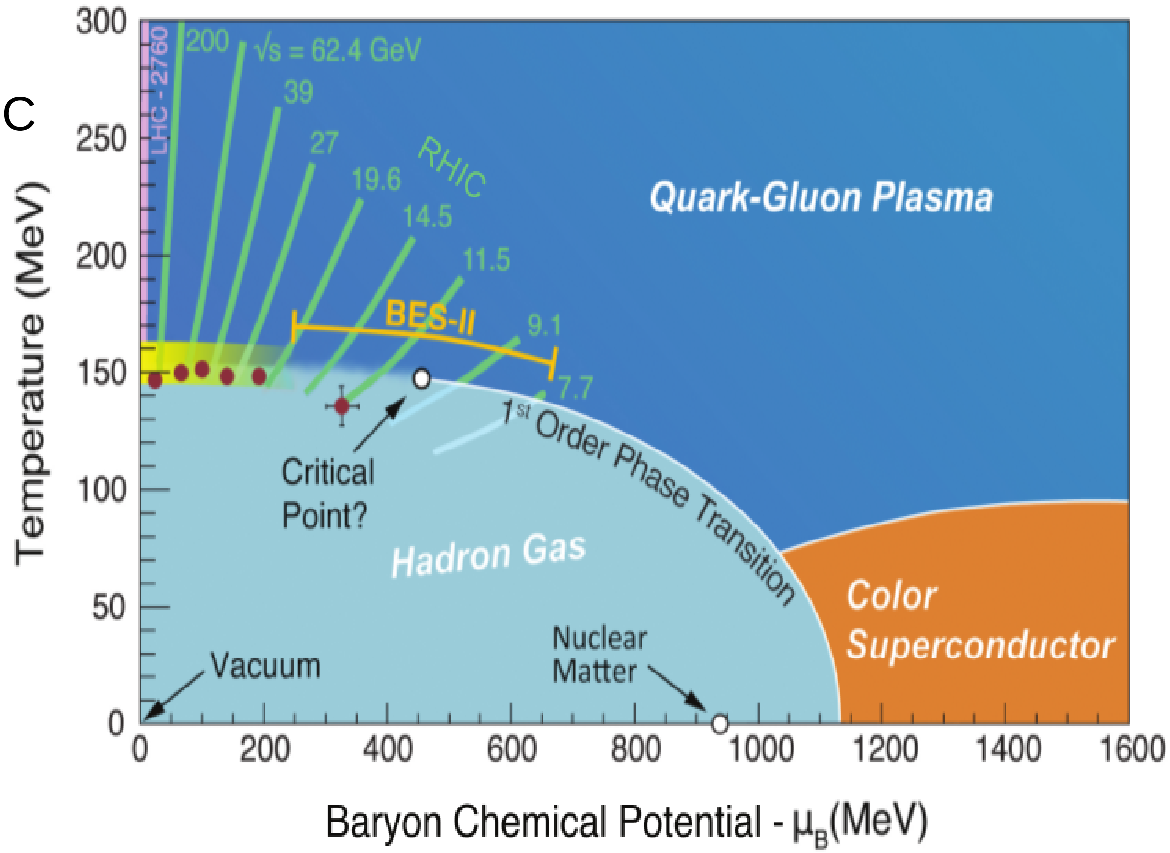
- current understanding of the QCD phase diagram based on lattice QCD calculations
- the search for a critical point
- heavy quarks at high temperature
- current and future challenges
- from petascale to exascale to zettascale calculations

CRC–TR 211 Strong-interaction matter under extreme conditions

Towards an understanding of the phase diagram of strongly interacting matter

- SPS
- Run 1&2 at LHC
- RHIC (beam energy scan)



– exploring the transition from hadrons to quarks& gluons
deconfinement, **chiral symmetry restoration**, **axial anomaly**

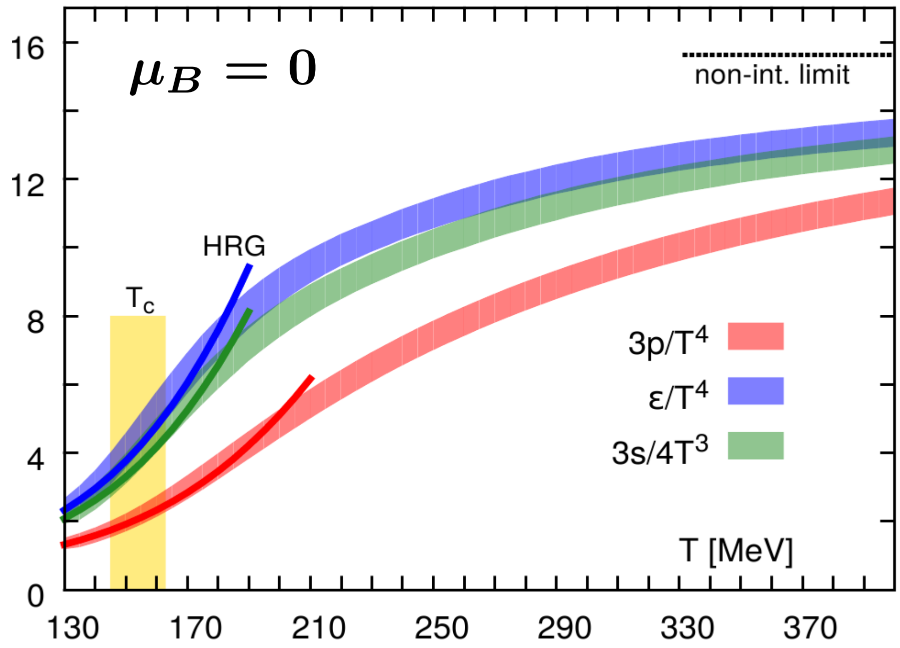
– search for the existence of the chiral critical point (RHIC)

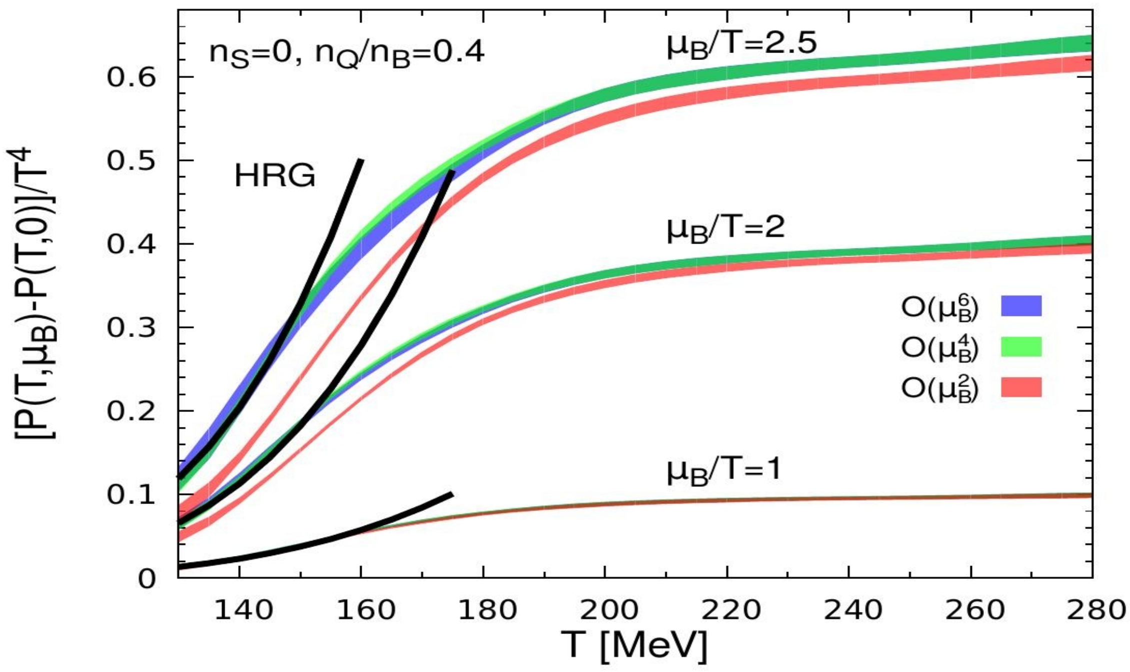
– establish the imprint of the chiral PHASE transition of QCD on properties of QCD matter with its physical quark mass spectrum (LHC)

Equation of state of (2+1)-flavor QCD: $\mu_B/T > 0$

$$\frac{\Delta(T,\mu_B)}{T^4} = \frac{P(T,\mu_B) - P(T,0)}{T^4} = \frac{\chi_2^B}{2}\left(\frac{\mu_B}{T}\right)^2 + \frac{\chi_4^B}{24}\left(\frac{\mu_B}{T}\right)^4 + \frac{\chi_6^B}{720}\left(\frac{\mu_B}{T}\right)^6 + \dots$$

(10-30)% contribution to total pressure at $\mu_B/T = 2$



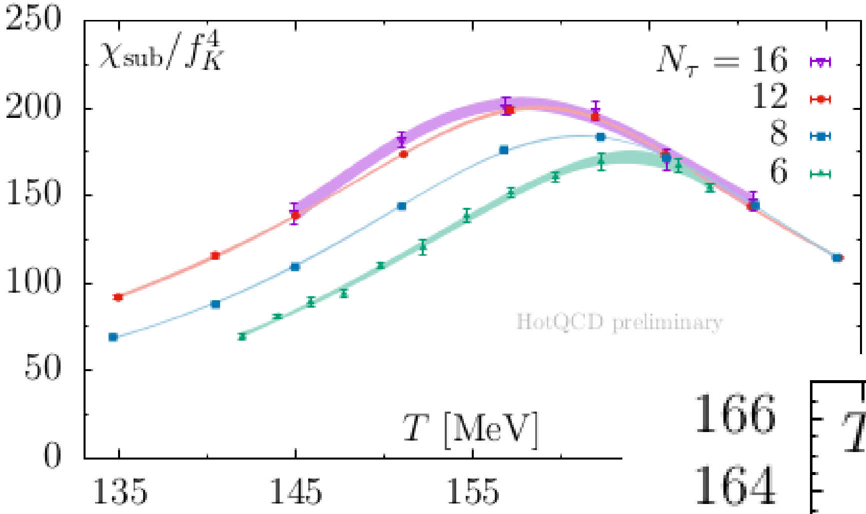


HISQ: Bielefeld-BNL-CCNU, arXiv:1701.04325

stout: Wuppertal-Budapest, arXiv:1607.02493

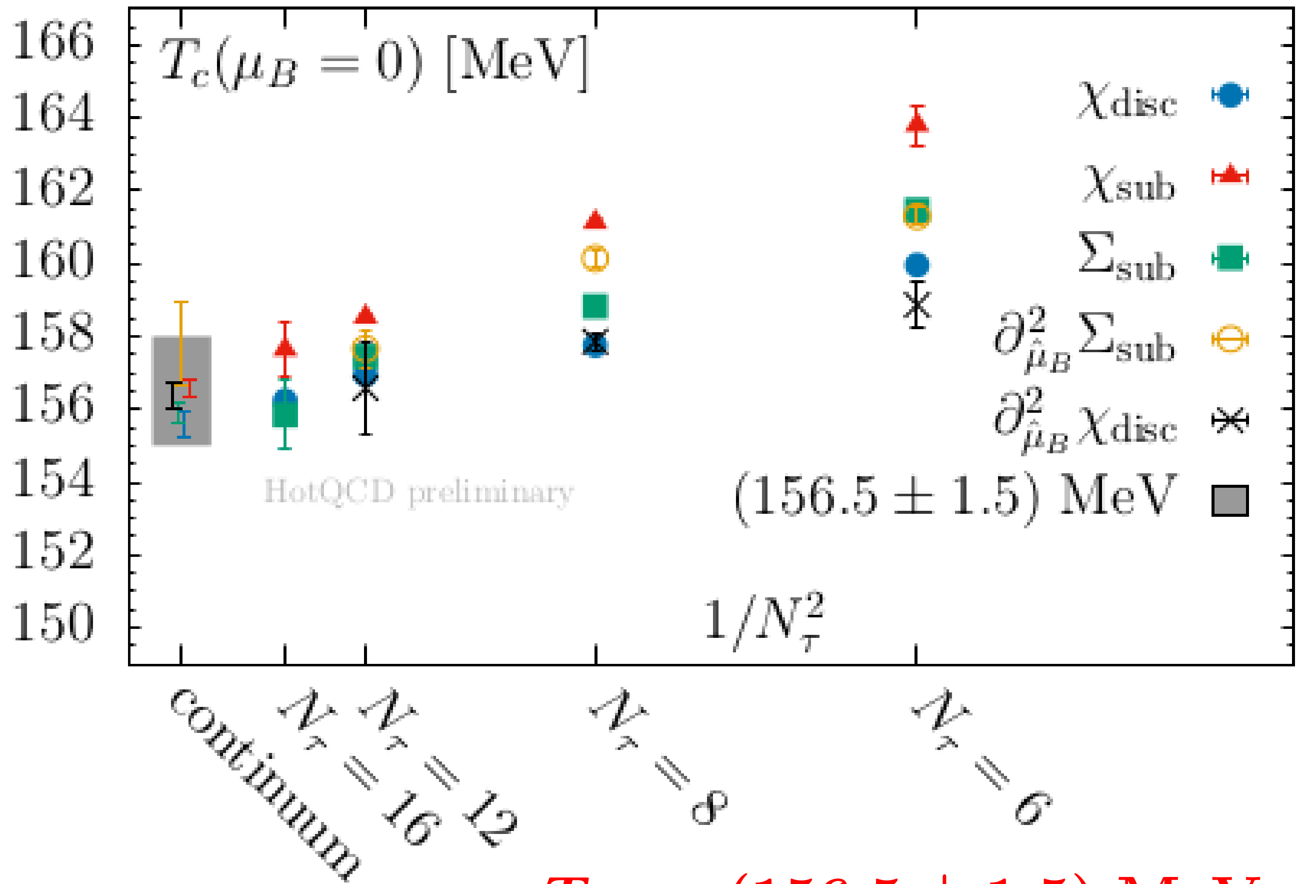
The EoS is well controlled for $\mu_B/T \leq 2$
or equivalently $\sqrt{s_{NN}} \geq 12$ GeV

A new determination of the chiral crossover temperature



P. Steinbrecher (hotQCD), arXiv;1807.05607

$$\frac{\chi_{sub}}{f_K^4} \sim \left. \frac{\partial^2 \ln Z}{\partial m_q^2} \right|_{\mu_B=0}$$



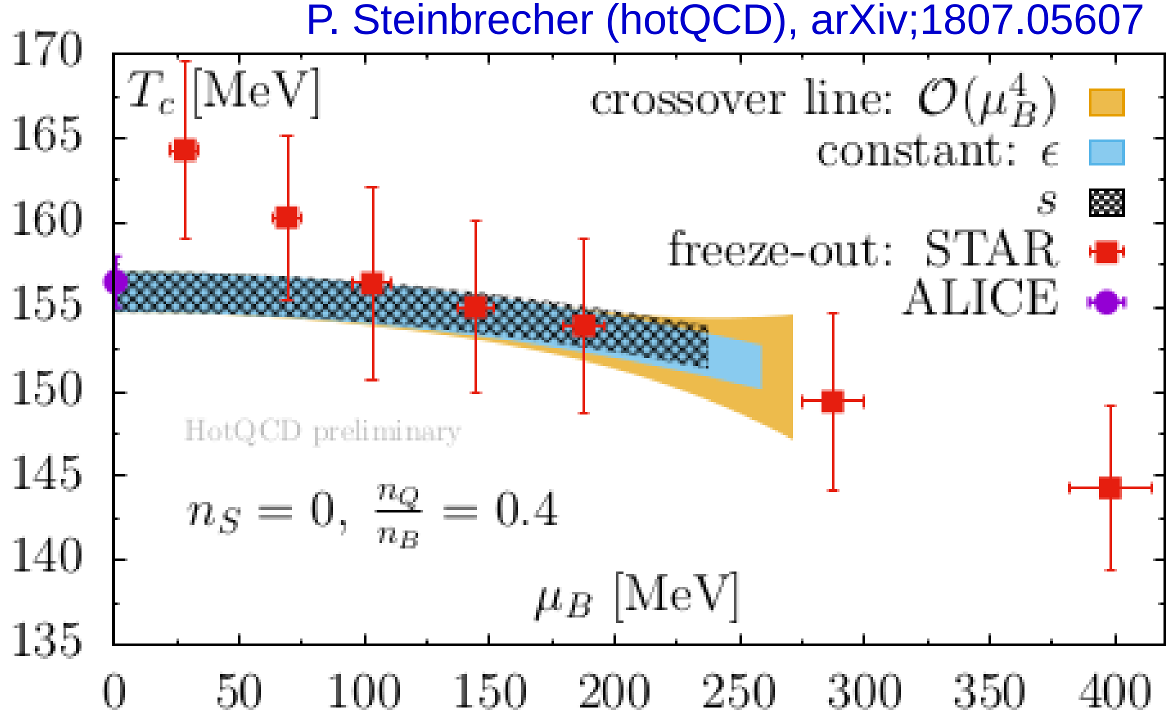
– (2+1)-flavor QCD
– physical quark masses
– continuum extrapolation

$$T_{pc} = (156.5 \pm 1.5)\ \mathrm{MeV}$$

The crossover line at non-zero baryon chemical potential

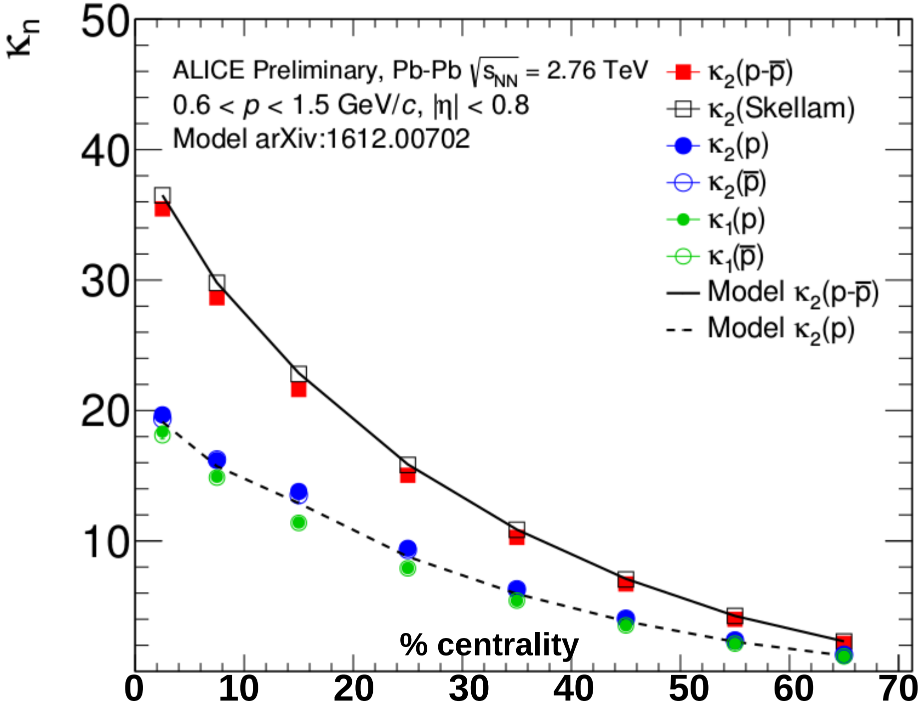
STAR, arXiv:1701.07065
ALICE, arXiv:1408.6403

P. Steinbrecher (hotQCD), arXiv;1807.05607



Taylor-expansion of physical observables, e.g. the chiral susceptibility:

$$\frac{\chi_{sub}}{f_K^4} = \sum_n \frac{c_n^\chi}{n!} \left(\frac{\mu_B}{T}\right)^n \quad \text{up to } \mathcal{O}(\mu_B^6)$$



Net proton number fluctuations at LHC:

probing the chiral phase transition

$$\kappa_1(X) = \langle X \rangle$$

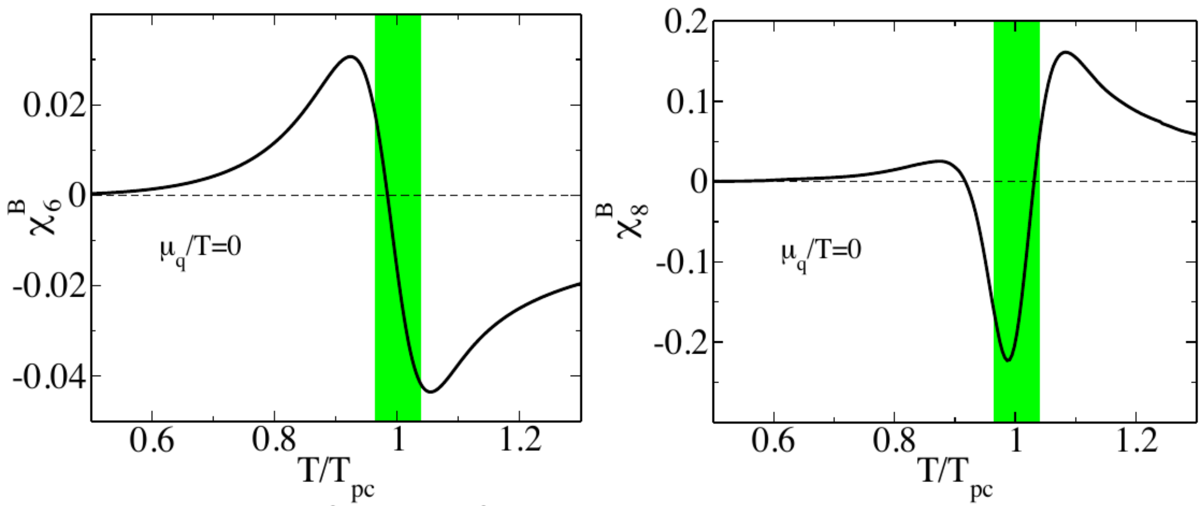
$$\kappa_2(X) = \langle (X - \langle X \rangle^2 \rangle$$

$$.....\kappa_4(X), \kappa_6(X)...$$

A. Rustamov (ALICE Collaboration),
Nucl. Phys. A967 (2017) 453, arXiv:1704.05329

What is next ? → Higher moments → Higher stat. + Good PID

Friman, B., Karsch, F., Redlich, K. et al. Eur. Phys. J. C (2011) 71: 1694



6th and 8th order cumulants of the net baryon number fluctuations at $\mu_q/T = 0$

RUN1: 2nd order (~13M events)

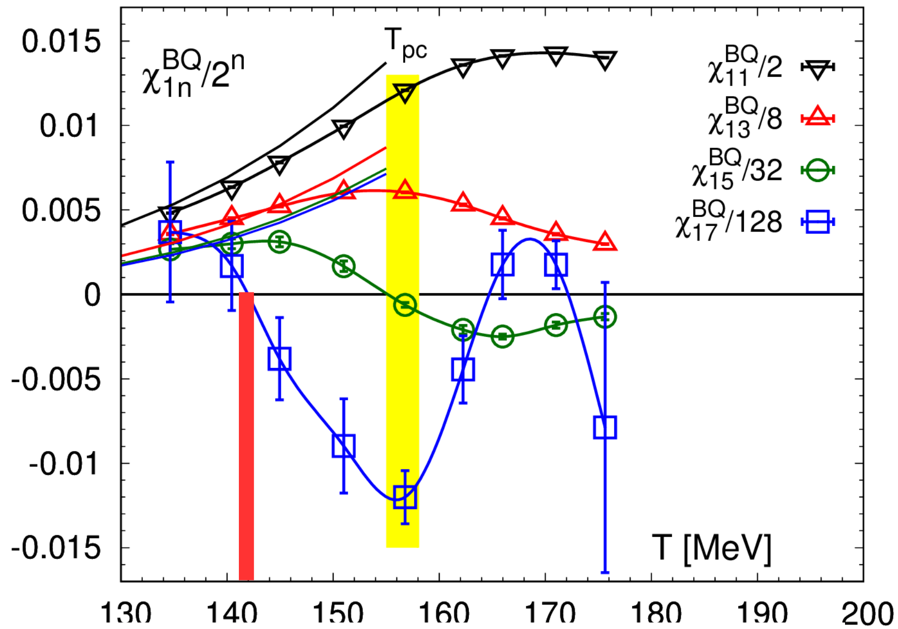
RUN2: 4th order (~150M events)

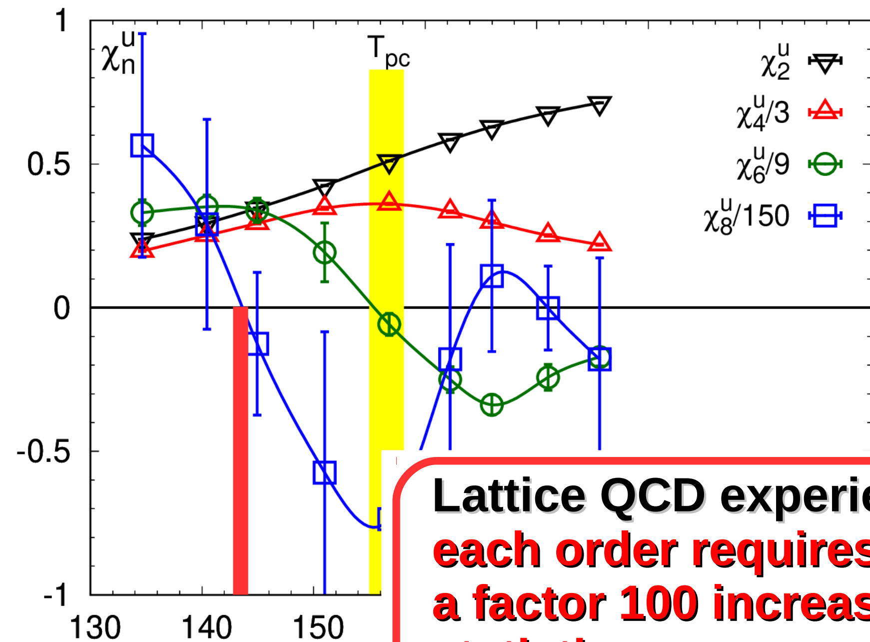
RUN3: ? ⇒ **FCC**

Lattice QCD experience:
each order requires about a factor 100 increase in statistics

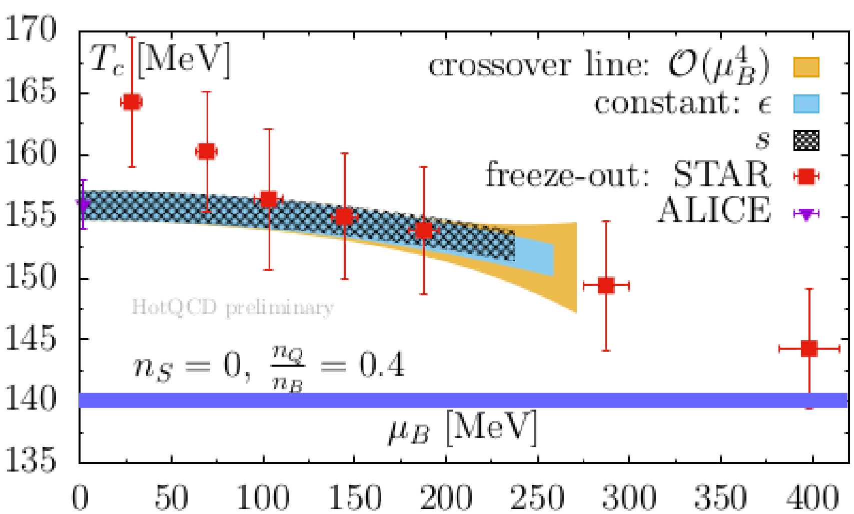
Critical behavior and higher order cumulants

$$\chi_{1n}^{BQ} = \left. \frac{\partial^{n+1} P/T^4}{\partial \hat{\mu}_B \partial \hat{\mu}_Q^n} \right|_{\mu_{B,Q,S}=0} \qquad \chi_n^u = \left. \frac{\partial^n P/T^4}{\partial \hat{\mu}_u^n} \right|_{\mu_{u,d,s}=0}$$





Lattice QCD experience:
each order requires about a factor 100 increase in statistics



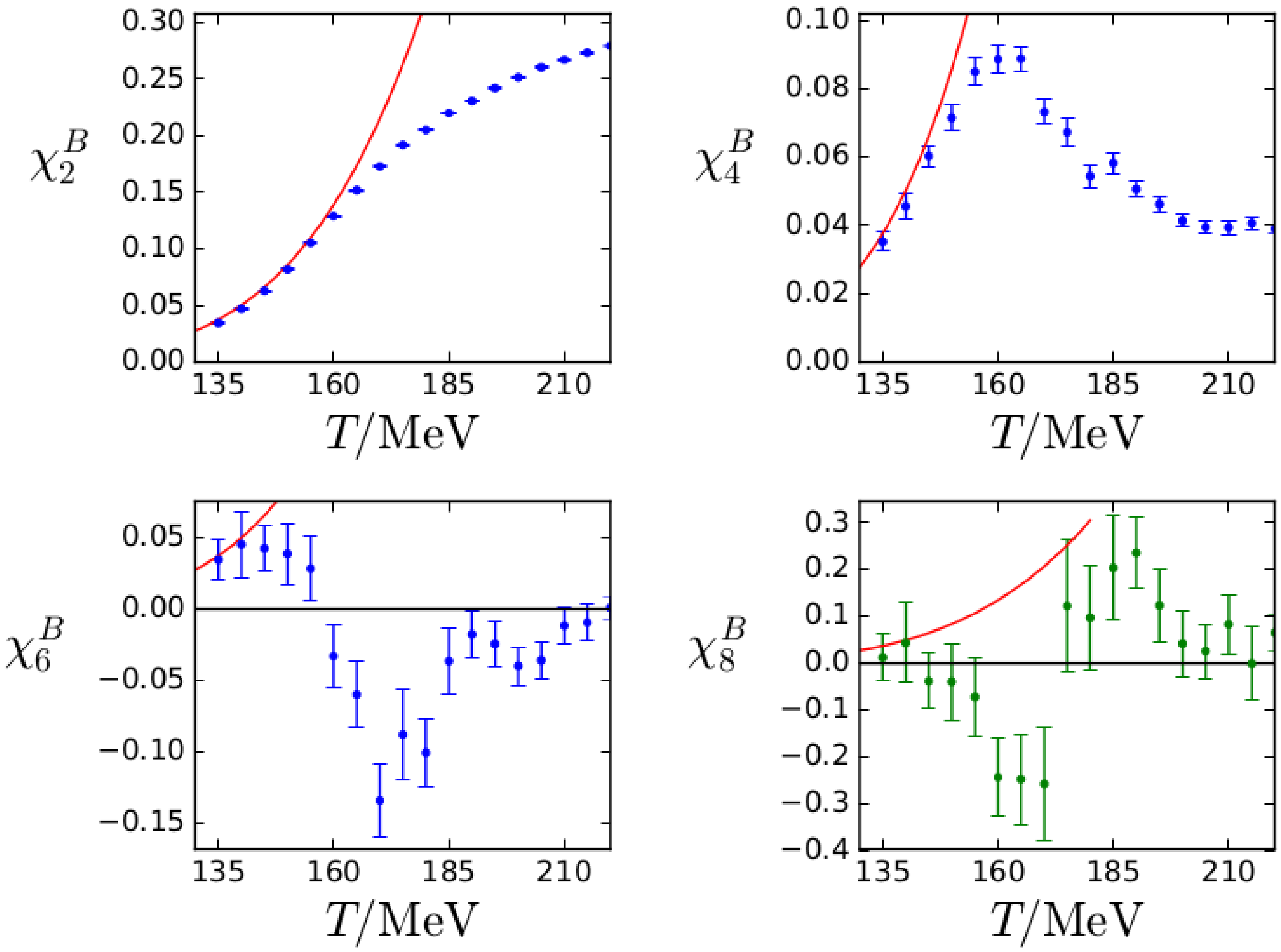
many 8th order cumulants turn negative for

$$T^- \gtrsim (140 - 145)\ \mathrm{MeV}$$

⇨ plausible scenario:

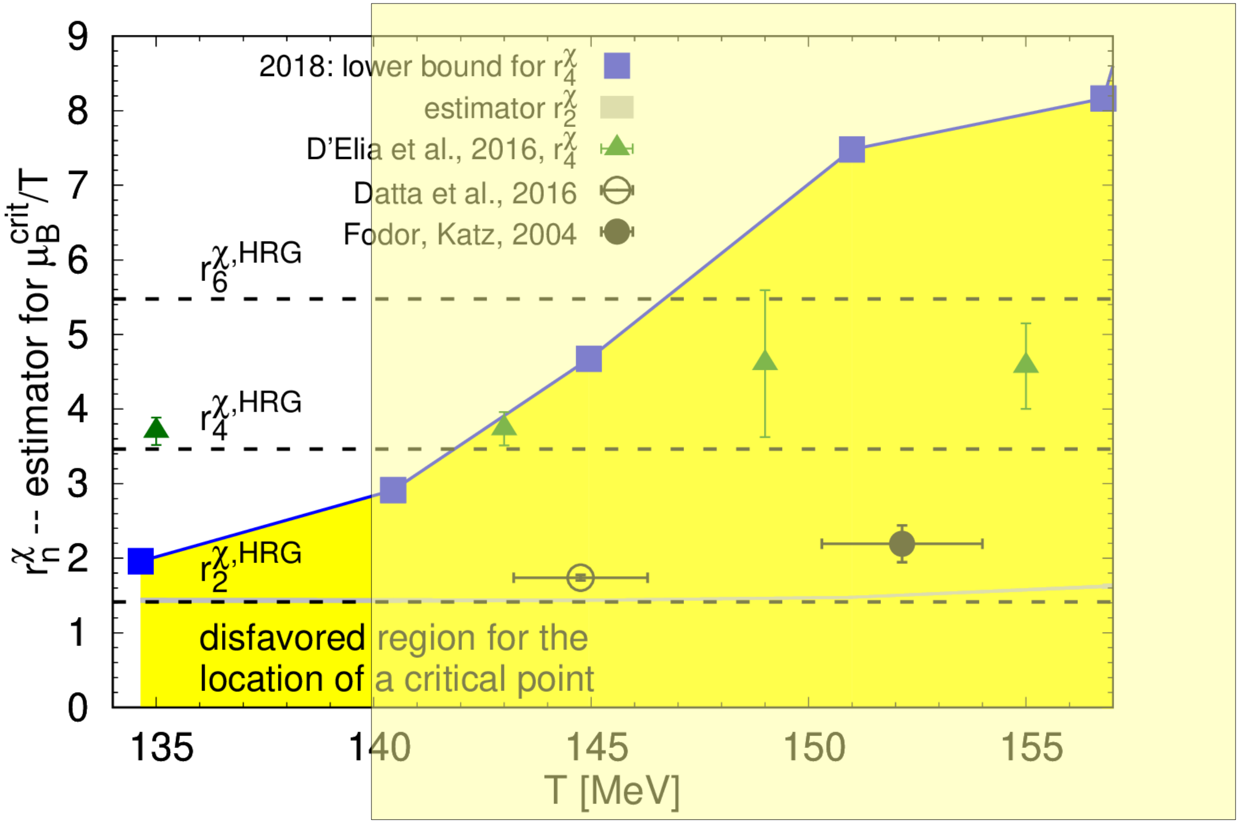
$$T_{cp} < 140\mathrm{MeV}\ ,\ \mu_B^{cp} > 400\mathrm{MeV}$$

Critical behavior and higher order cumulants



S. Borsanyi et al, arXiv:1805.04445

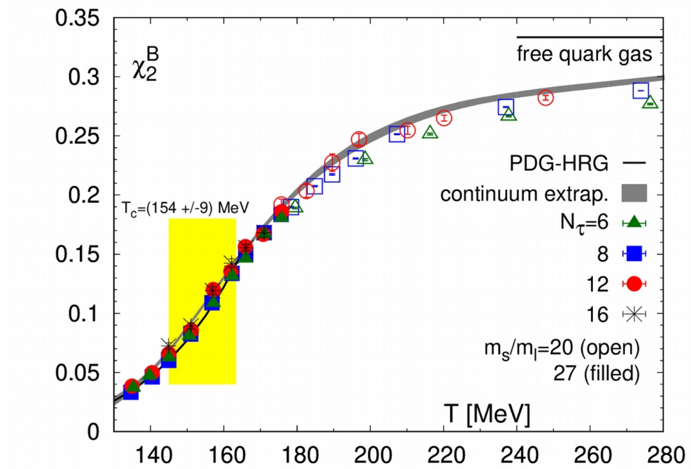
The radius of convergence of Taylor expansions constraints on the location of a possible critical point



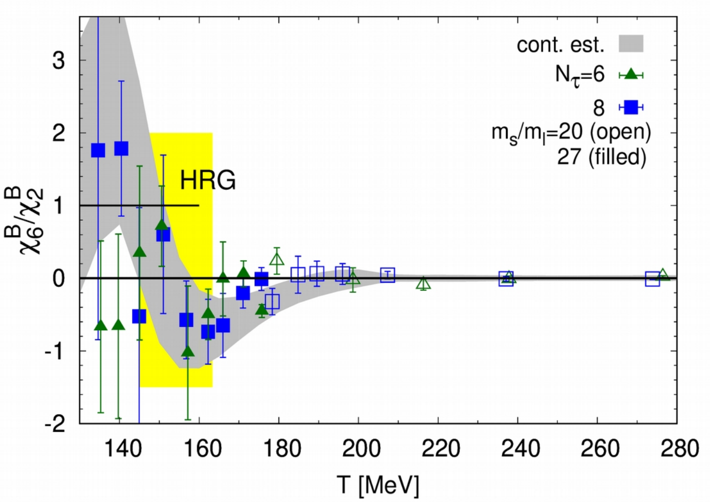
disfavored as expansion coefficients are no longer strictly positive

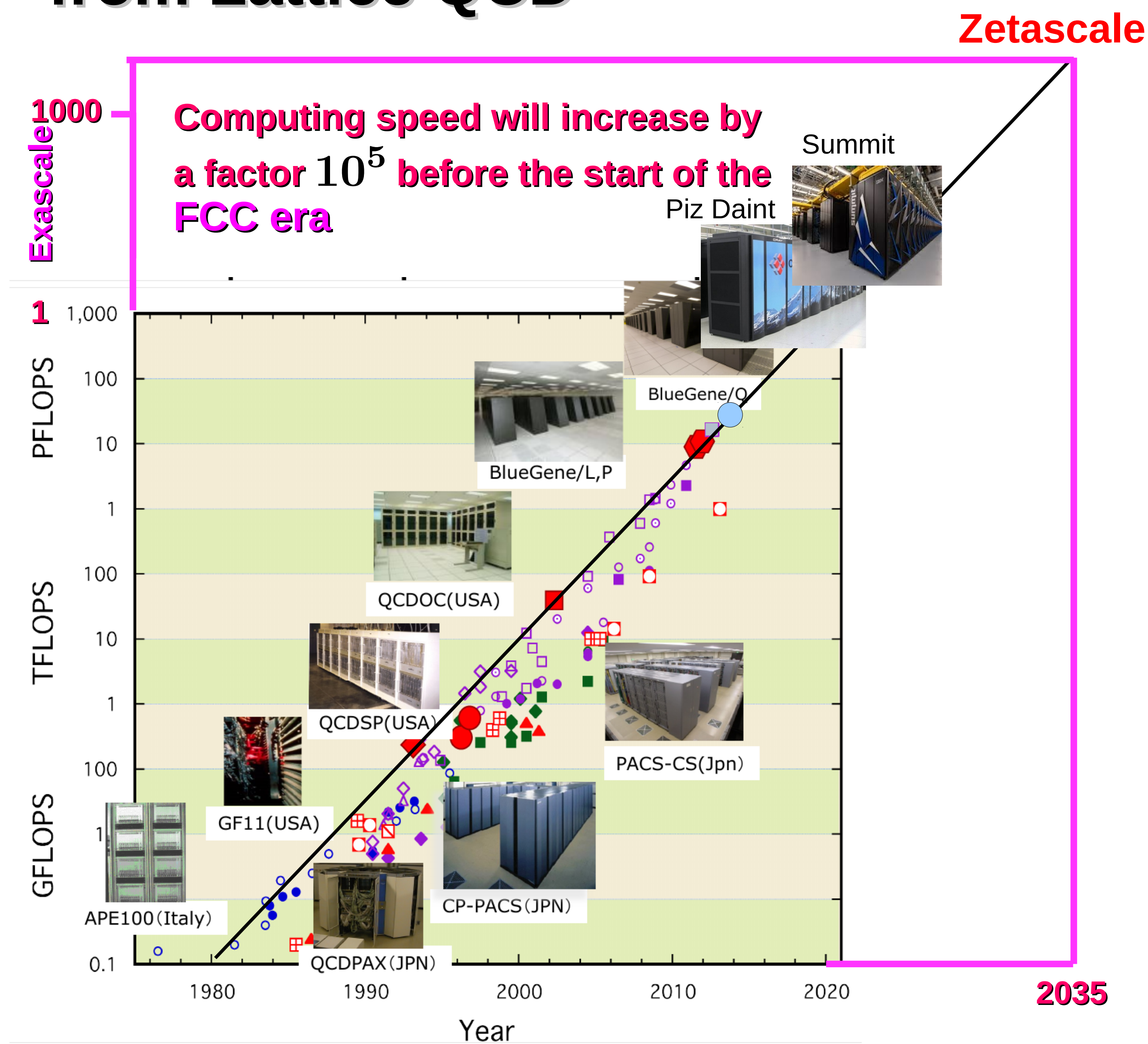
update of:
A. Bazavov et al. (hotQCD), arXiv:1701.04325

Cumulants of net-baryon number fluctuations from Lattice QCD



up to 10th order of net baryon-number cumulants will be known soon;
next step about 5 years





based on: A. Ukawa, HPC summer school, 2013

Transport and bound state properties from thermal hadron correlation functions

$$G(\tau,\vec{p},T) = \int_0^\infty \frac{d\omega}{2\pi} \rho(\omega,\vec{p},T) K(\tau,\omega,T)$$

$$K(\tau,\omega,T) = \frac{\cosh\left(\omega(\tau - \frac{1}{2T})\right)}{\sinh\left(\frac{\omega}{2T}\right)}$$

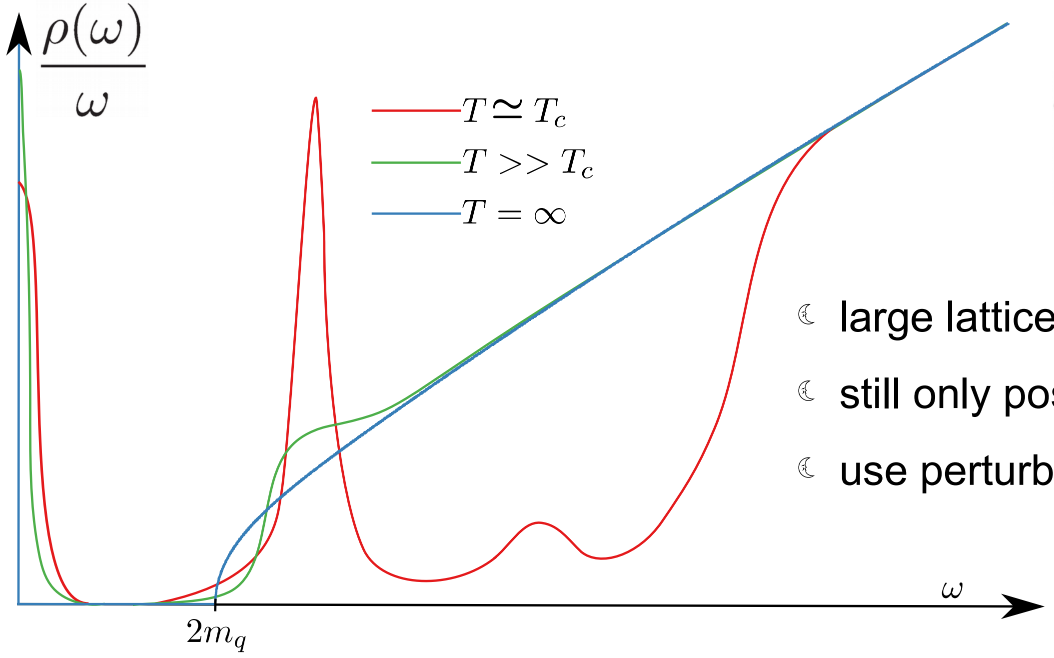
Different contributions and scales enter

in the spectral function

- **continuum at large frequencies**
- **possible bound states at intermediate frequencies**
- **transport contributions at small frequencies**
- **in addition cut-off effects on the lattice**

notoriously difficult to extract from correlation functions

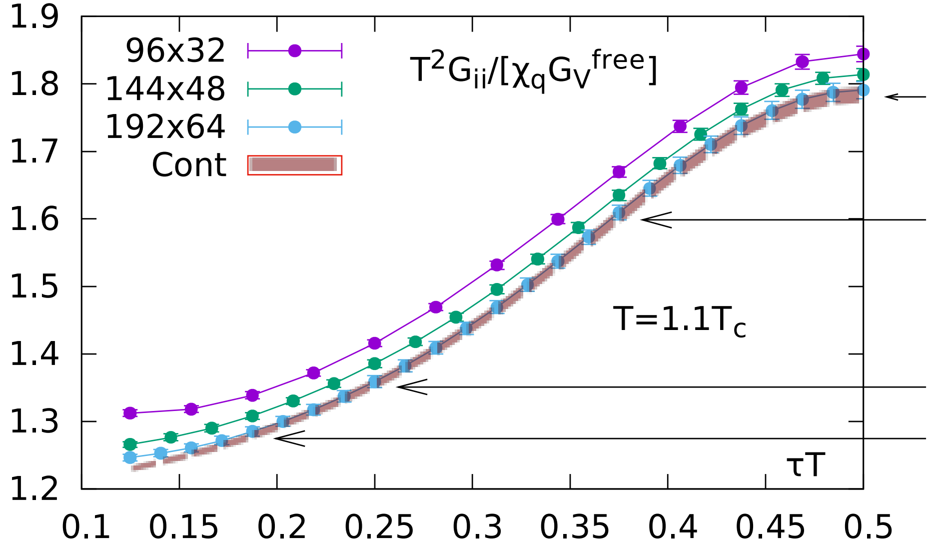
Spectral functions in the QGP

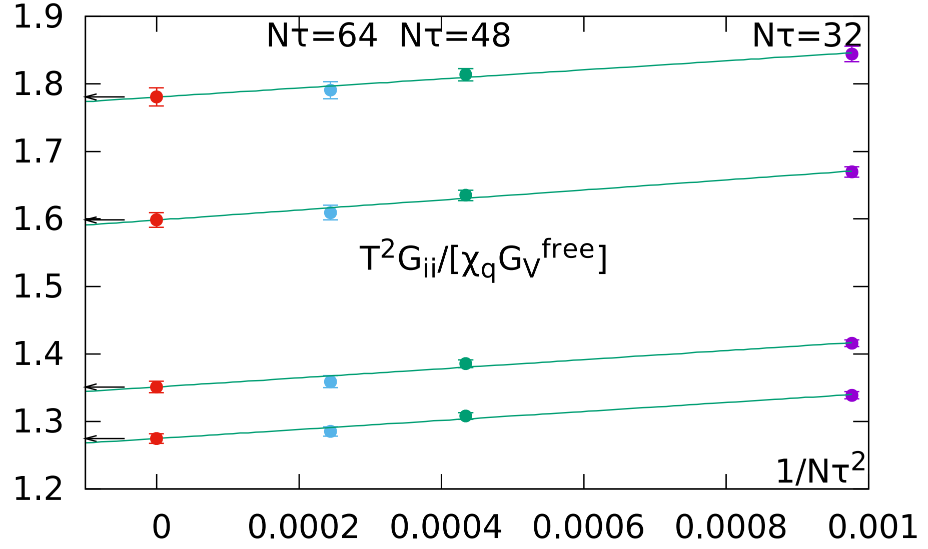


$$G_{\mu\nu}(\tau,\vec{x}) = \langle J_\mu(\tau,\vec{x}) J_\nu^\dagger(0,\vec{0})\rangle$$
$$J_\mu(\tau,\vec{x}) = 2\kappa Z_V \bar{\psi}(\tau,\vec{x})\Gamma_\mu \psi(\tau,\vec{x})$$

- large lattices and continuum extrapolation needed
- still only possible in the quenched approximation
- use perturbation theory to constrain the UV behavior

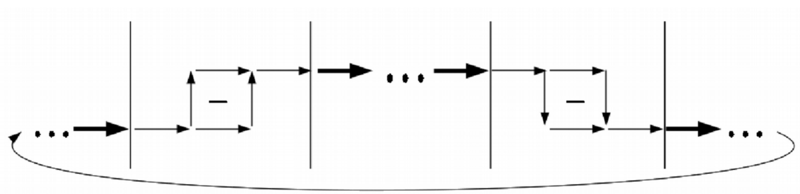
Transport and bound state properties from thermal hadron correlation functions





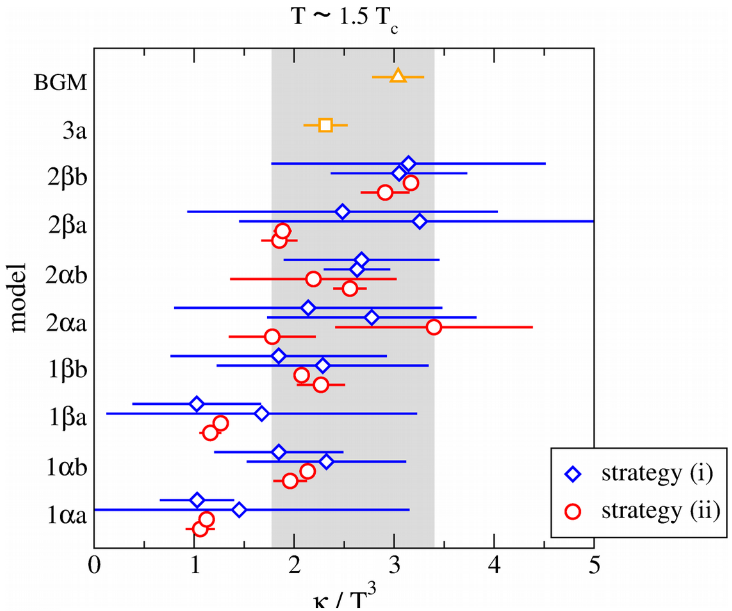
- state of the art lattice calculations with continuum extrapolated correlation functions are done in quenched QCD (no dynamical quarks)
- electrical conductivity: $$\frac{\sigma_{el}}{C_{em}T} = \frac{1}{6}\lim_{\omega\to 0}\frac{\rho_{ii}(\omega,\vec{p}=0,T)}{\omega T}$$
- heavy quark diffusion: $$\frac{\kappa}{T^3} \equiv \frac{1}{2TD} = \lim_{\omega\to 0}\frac{2T\rho_E(\omega,T)}{\omega}$$

$$G_E(\tau) \equiv -\frac{1}{3}\sum_{i=1}^{3}\frac{\left\langle \mathrm{Re\,Tr}\left[U(\tfrac{1}{T};\tau)\,g\,E_i(\tau,\mathbf{0})\,U(\tau;0)\,g\,E_i(0,\mathbf{0})\right]\right\rangle}{\left\langle \mathrm{Re\,Tr}[U(\tfrac{1}{T};0)]\right\rangle}$$



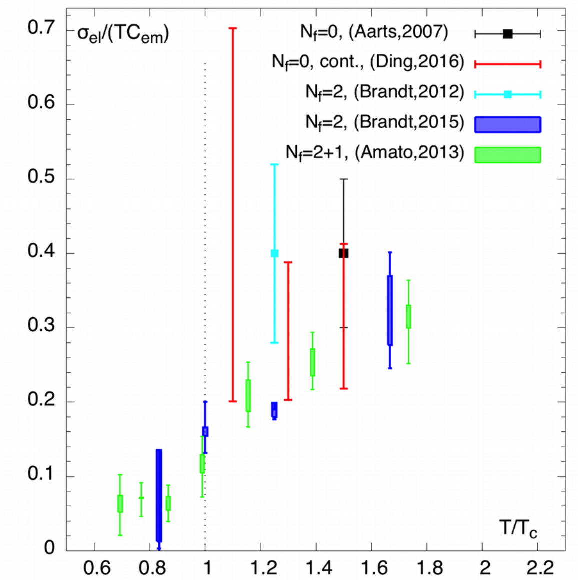
J.Casalderrey-Solana, D.Teaney, PRD74(2006) 085012
S.Caron-Huot,M.Laine,G.D. Moore,JHEP04(2009) 053

heavy quark diffusion



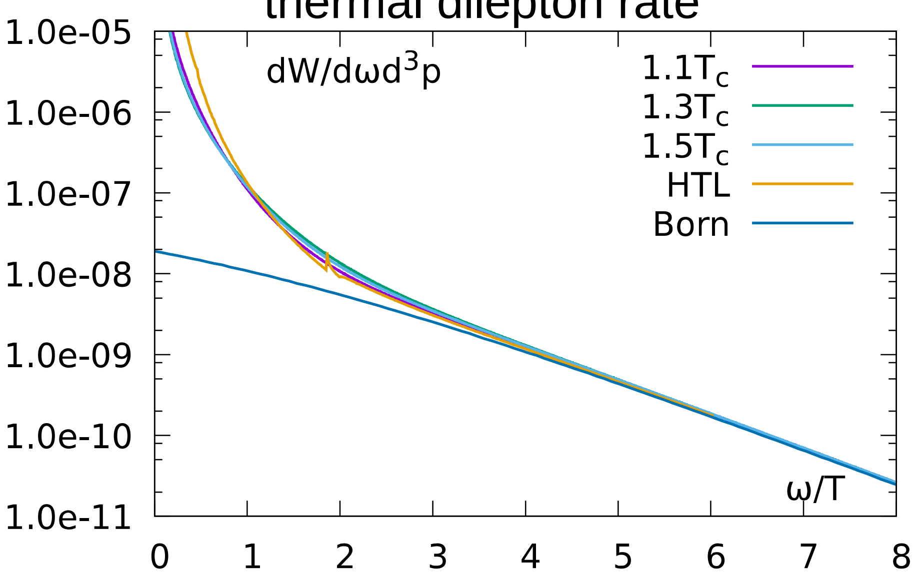
A.Francis et al., PRD92(2015)116003

electrical conductivity



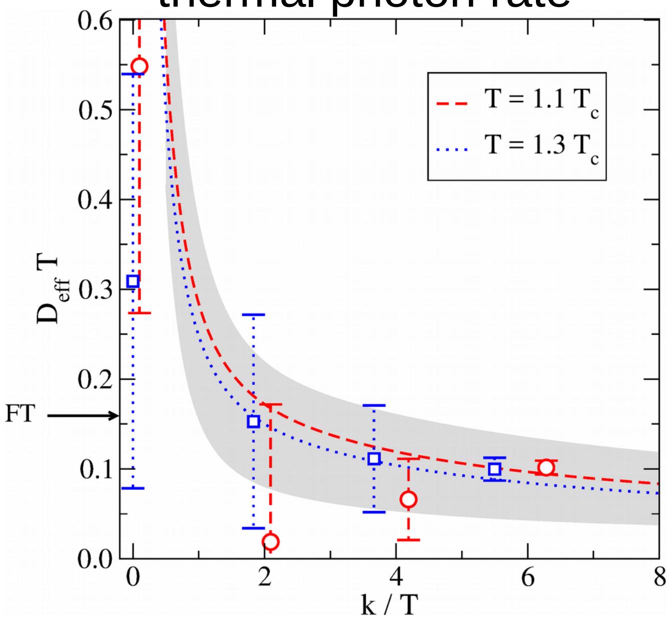
B.B. Brandt et al., PRD93 (2016) 054510

thermal dilepton rate



H-T.Ding et al., PRD94(2016)034504

thermal photon rate



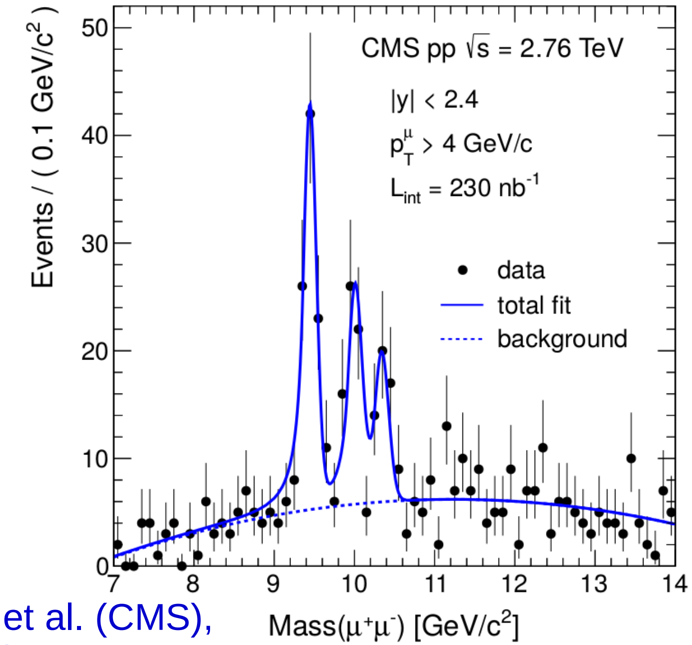
J.Ghiglieri et al., PRD94(2016)016005

Thermal bottomonium melting

bottomonium melting

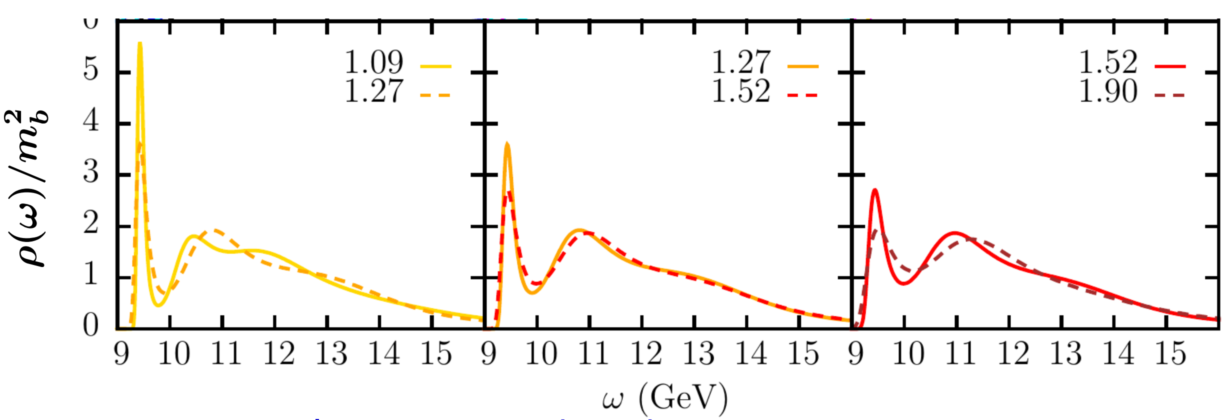
states	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$
$T_{\rm melt}^{\Gamma=E_{\rm bind}}/T_C$	$2.66^{+0.49}_{-0.14}$	$1.25^{+0.17}_{-0.05}$	$1.01^{+0.03}_{-0.03}$	< 0.95

Y. Burnier, O. Kaczmarek, A. Rothkopf, JHEP 1512 (2015) 101

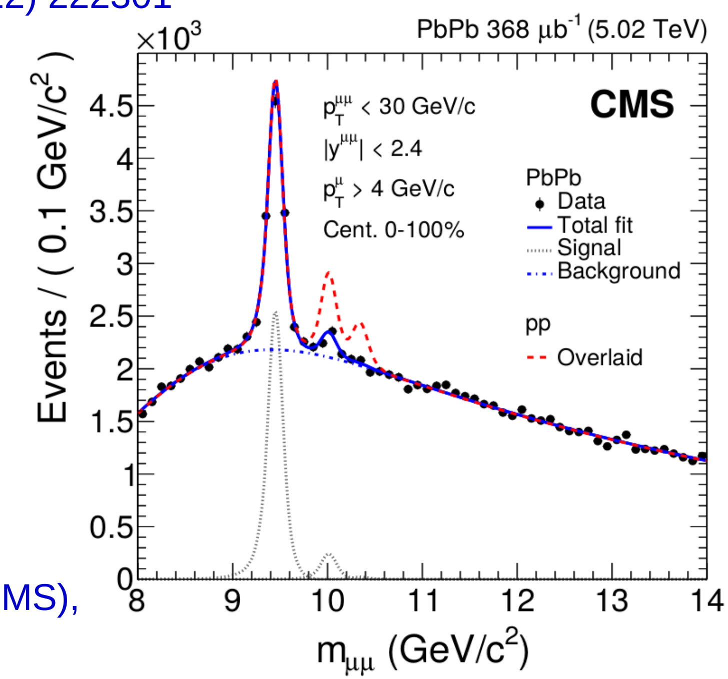


S. Chatrchyan et al. (CMS), PRL 109 (2012) 222301

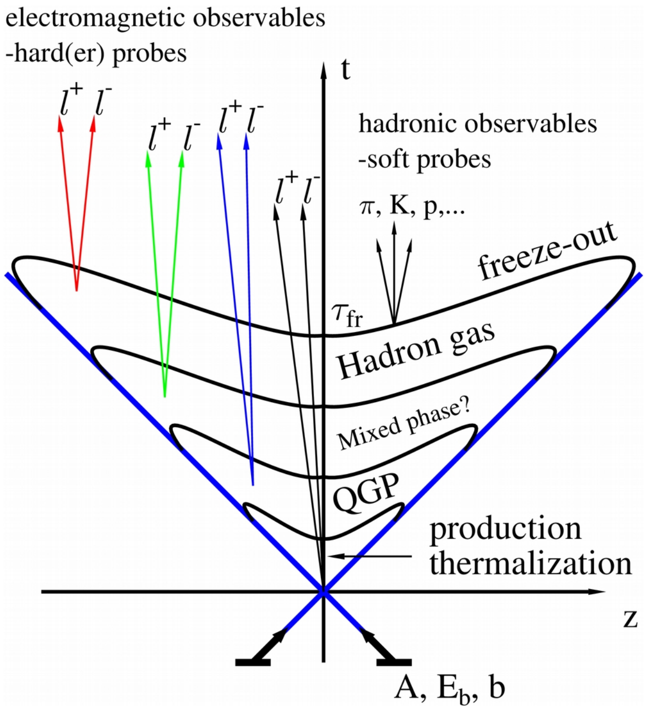
Lattice QCD spectral functions



G. Aarts et al., JHEP 1407 (2014) 097

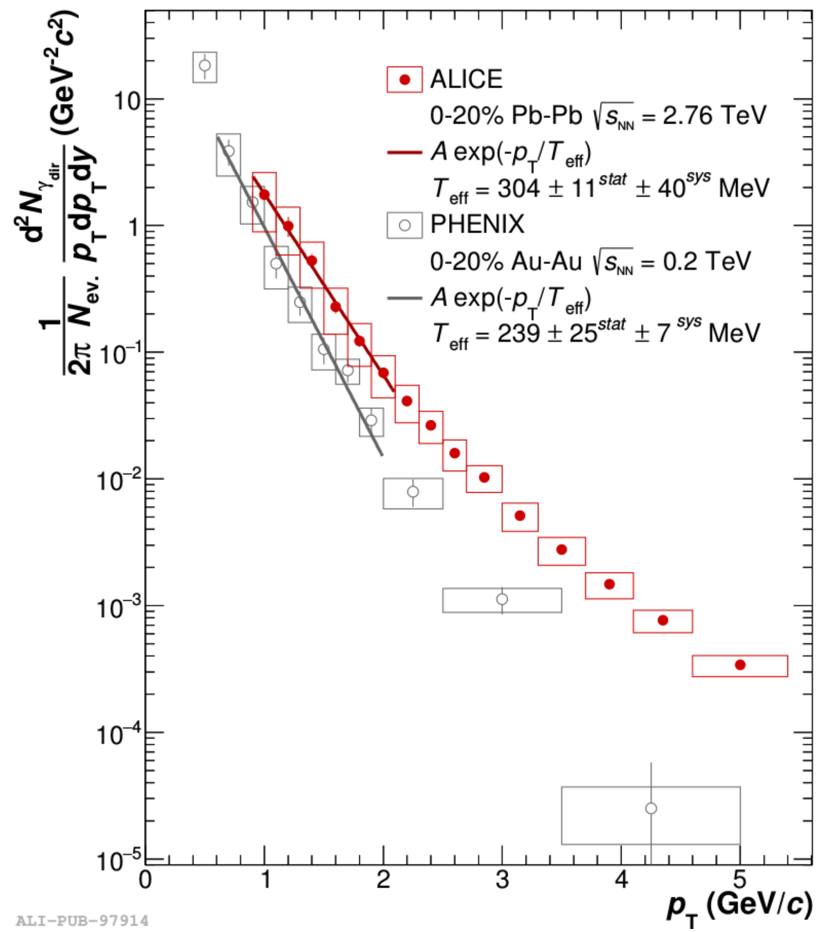


A.M. Sirunyan et al. (CMS), arXiv:1706.05984



FCC: high temperatures even after quarkonium formation time scale

direct photon yield at LHC and RHIC



quarkonium formation time: $\tau_{q\bar{q}} \simeq 0.5$ fm

temperature at $\tau_{q\bar{q}}$

collider	$T(\tau_{q\bar{q}})$ [MeV]	T/T_c
RHIC	230 - 280	1.5 - 1.8
LHC	300 - 360	1.9 - 2.3
FCC	370 - 450	2.4 - 2.9

$$T_{LHC} = (304 \pm 11^{stat} \pm 40^{sys})\text{MeV}$$

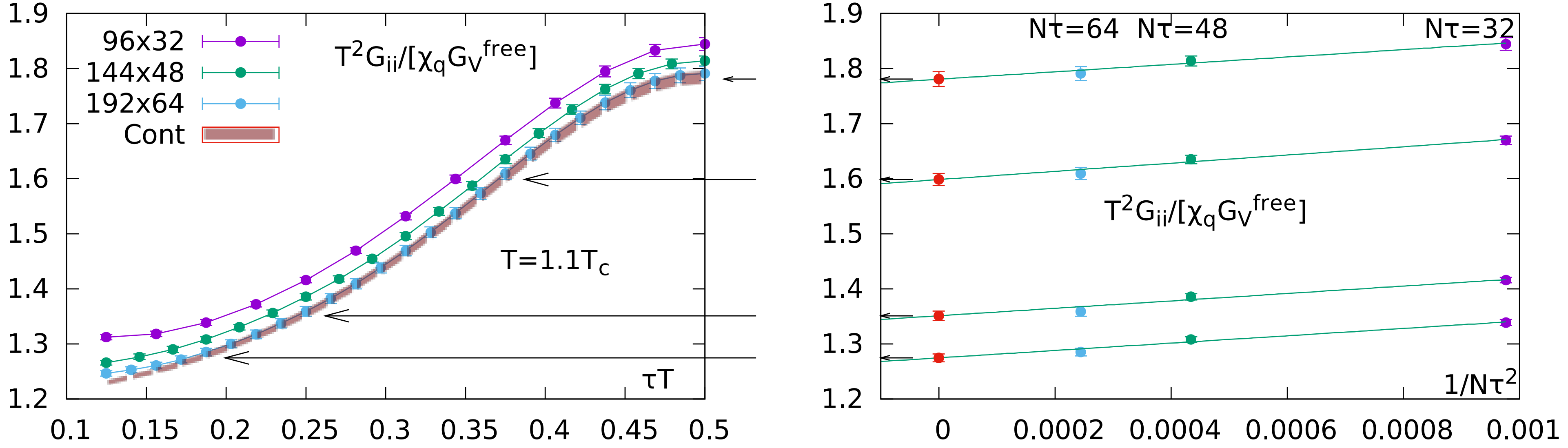
$$T_{RHIC} = (239 \pm 25^{stat} \pm 7^{sys})\text{MeV}$$

$Y(1s)$ will melt at the FCC

J/ψ does melt at RHIC&LHC

J. Adam, Phys. Lett. B754 (2016) 235
arXiv:1509.07324

Transport and bound state properties from thermal hadron correlation functions



– state of the art lattice calculations with continuum extrapolated correlation functions are done in quenched QCD (no dynamical quarks)

– quenched QCD, state-of-the-art lattices: $\mathbf{192^3 \times 64}$

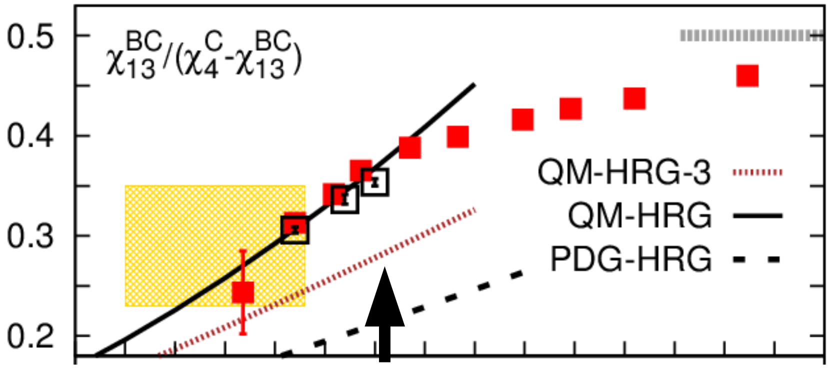
– QCD with physical light quarks, state-of-the-art lattices: $\mathbf{64^3 \times 16}$

about a factor 100 in compute performance is needed in order to do todays quenched studies in QCD with physical quark masses

$\mathcal{O}(5)$ **years**

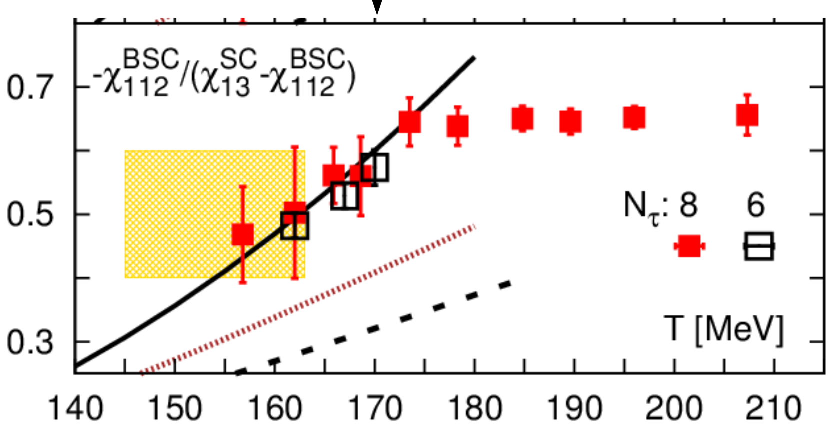
Evidence for many charmed baryons in QCD thermodynamics

close to Tc charmed baryon fluctuations are about 50% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG); missing states of QCD



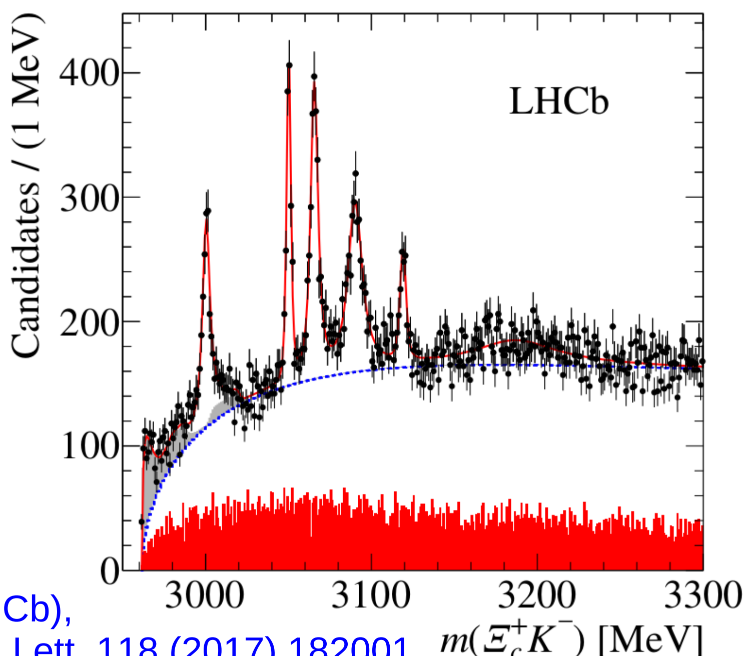
all charmed baryons/mesons

strange charmed baryons/mesons



A. Bazavov et al., Phys.Lett. B737 (2014) 210

observation of
5 new charmed baryons
by LHCb
arXiv:1703.04639



R. Aaij (LHCb),
Phys. Rev. Lett. 118 (2017) 182001

Conclusions

– lattice QCD have provided important input to the interpretation and modeling of heavy ion collisions (EoS, Tc, transport and diffusion constants)

– some of them are still lattice results and still need to be promoted to become QCD results: calculations with physical quark masses, continuum extrapolated

– the steady improvement of compute resources as well as new, more sophisticated simulation software guarantees steady improvements