From a first order transition in QCD with up, down and strange quarks to a dark QCD matter scenario

Matthias F.M. Lutz

GSI Helmholtzzentrum für Schwerionenforschung GmbH and TU Darmstadt

- ✔ **Chiral extrapolation for baryon masses and a first order transition**
- ✔ **A generalized Higgs potential for dark QCD matter**
- ✔ **Dark QCD matter in a Higgs bubble**
- ✔ **Summary and outlook**

arXiv:1801.06417, arXiv:1907.00714, arXiv:1907.00237

The chiral Lagrangian with baryon fields

$$\Phi = \sqrt{2}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\frac{2}{\sqrt{6}}\,\eta \end{pmatrix}$$

Goldstone boson octet $(J^P = 0^-)$

baryon octet $(J^P = \frac{1}{2}^+)$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\,\Lambda \end{pmatrix}$$

✔ Leading order terms

covariant derivative $\partial_\mu = \partial_\mu + \cdots$

$$\begin{aligned}
\mathcal{L} \;=\;& \mathrm{tr}\left\{\bar B (i\,\partial\cdot\gamma - M_{[8]})\,B\right\} + F\,\mathrm{tr}\left\{\bar B\,\gamma^\mu\gamma_5\,[i\,U_\mu, B]\right\} + D\,\mathrm{tr}\left\{\bar B\,\gamma^\mu\gamma_5\,\{i\,U_\mu,\, B\}\right\} \\
-\;& \mathrm{tr}\left\{\bar B_\mu\cdot\Big((i\,\partial\cdot\gamma - M_{[10]})\,g^{\mu\nu} - i\,(\gamma^\mu\partial^\nu + \gamma^\nu\partial^\mu) + \gamma^\mu(i\,\partial\cdot\gamma + M_{[10]})\gamma^\nu\Big)\,B_\nu\right\} \\
+\;& C\left(\mathrm{tr}\left\{(\bar B_\mu\cdot i\,U^\mu)\,B\right\} + \mathrm{h.c.}\right) + H\,\mathrm{tr}\left\{(\bar B^\mu\cdot\gamma_\nu\gamma_5\,B_\mu)\,i\,U^\nu\right\}
\end{aligned}$$

- $U_\mu = \frac{1}{2}\,u^\dagger\left(\partial_\mu\,e^{i\,\frac{\Phi}{f}}\right)u^\dagger - \frac{i}{2}\,u^\dagger\,(v_\mu + a_\mu)\,u + \frac{i}{2}\,u\,(v_\mu - a_\mu)\,u^\dagger$ with $u = e^{i\,\frac{\Phi}{2\,f}}$
- from $B \to B' + e + \bar\nu_e$: $F \simeq 0.45$ and $D \simeq 0.80$
- from large-N_c: $H = 9\,F - 3\,D$ and $C = 2\,D$

Chiral symmetry breaking terms

$$
\begin{aligned}
\mathcal{L}_\chi^{(2)} &= 2\, b_0 \,\mathrm{tr}\,\left(\bar{B}\, B\right) \mathrm{tr}\,(\chi_+) + 2\, b_D \,\mathrm{tr}\,\left(\bar{B}\,\{\chi_+,\, B\}\right) + 2\, b_F \,\mathrm{tr}\,\left(\bar{B}\,[\chi_+,\, B]\right) \\
&- 2\, d_0 \,\mathrm{tr}\,\left(\bar{B}_\mu \cdot B^\mu\right) \mathrm{tr}\,(\chi_+) - 2\, d_D \,\mathrm{tr}\,\left(\left(\bar{B}_\mu \cdot B^\mu\right) \chi_+\right)
\end{aligned}
$$

$$
\chi_+ = \chi_0 - \frac{1}{8\, f^2}\,\{\Phi, \{\Phi,\, \chi_0\}\} + \mathcal{O}\left(\Phi^4\right)
$$

quark mass matrix $\qquad \chi_0 \sim \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$

✔ Relevance of low-energy parameters

- quark-mass dependence of the baryon masses $\leftrightarrow$ lattice QCD
- meson-baryon scattering $\leftrightarrow$ resonances in QCD
- nucleon sigma terms, $\langle N|\bar{u}\, u|N\rangle$, $\langle N|\bar{d}\, d|N\rangle$ and $\langle N|\bar{s}\, s|N\rangle$ relevant in WIMP scenarios – ATLAS

see e.g. arXiv:1805.09795

Quark-mass dependence of the baryon masses

✔ A challenge

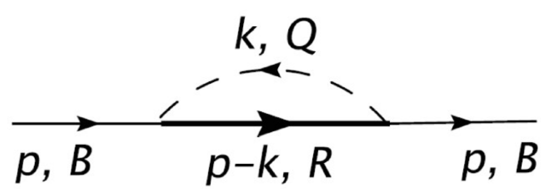
- 'poor' convergence in the heavy-baryon formulation of χPT

  e.g. $\quad M_\Xi = (1018 + 1311 - 1007)\,\mathrm{MeV} = 1322\,\mathrm{MeV}$

- conventional χPT inconsistent with three-flavor QCD lattice simulations

✔ One-loop depends sensitively on internal masses

$$\Sigma_B(p) = \sum_{Q\in[8]} \sum_{R\in[8],[10]}$$

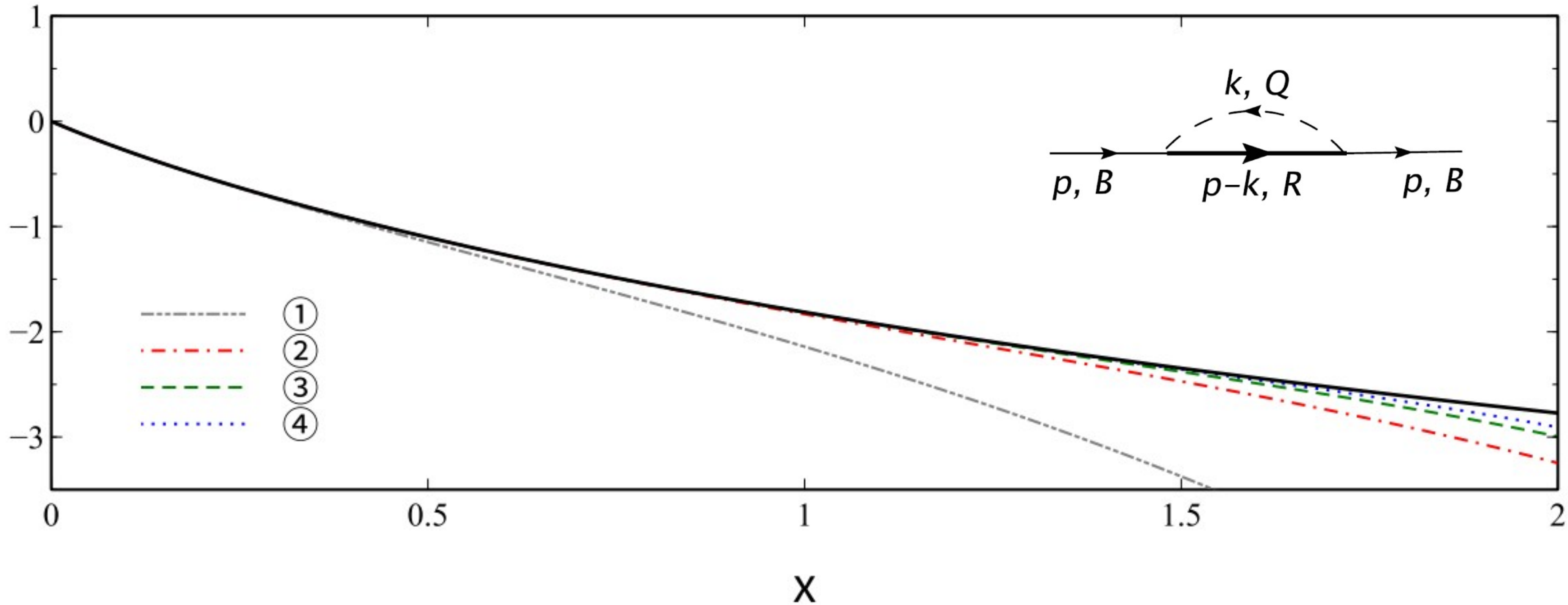


$$+\cdots$$

- chiral expansion in terms of physical meson and baryon masses
- reorganize conventional χPT keeping its model independence
- renormalization scale and reparametrization invariance

Phys.Rev. D51 (1995) 3697
Phys.Rev. D85 (2012) 034001
Phys.Rev. D86 (2012) 091502
Phys.Rev. D90 (2014) 054505

Chiral expansion of the scalar loop function $(4\pi)^2 \bar{I}_{QR}$



✔ **Convergence study for $M_R = M_B$ and $x = m_Q/M_R$**

- $(4\pi)^2 \, \bar{I}_{QR} = -\pi \sqrt{x^2} \, f_1(x^2) + x^2 \, f_2(x^2) - \frac{1}{2} \, x^2 \, f_3(x^2) \, \log x^2$
- the functions $f_n(x^2)$ are analytic in x^2 for $|x| < 2$

  $f_n(x^2) = 1 + \#x^2 + \#x^4 + \cdots$
- good convergence even for $m_K = M_N$ with $x \simeq 1$!

arXiv:1801.06417

Quark-mass dependence of the baryon masses

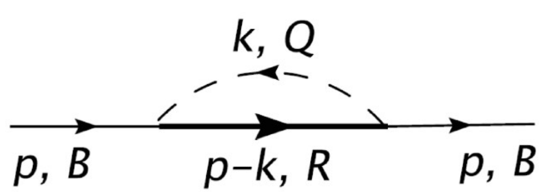
✔ Good convergence of reordered chiral expansion

- use physical meson and baryon masses
- the full one-loop contributions can be decomposed into chiral moments
- taking empirical masses the $\mathrm{N}^4\mathrm{LO}$ effects are less than 8 MeV

✔ Baryon masses determined by a non-linear system

$$M_B - \Sigma_B(M_B) = \begin{cases} M_{[8]} & \text{for} \quad B \in [8] \\ M_{[10]} & \text{for} \quad B \in [10] \end{cases}$$

$$\Sigma_B(p) = \sum_{Q \in [8]} \sum_{R \in [8],[10]}$$



$$+ \cdots$$

- numerical challenge

arXiv:1801.06417

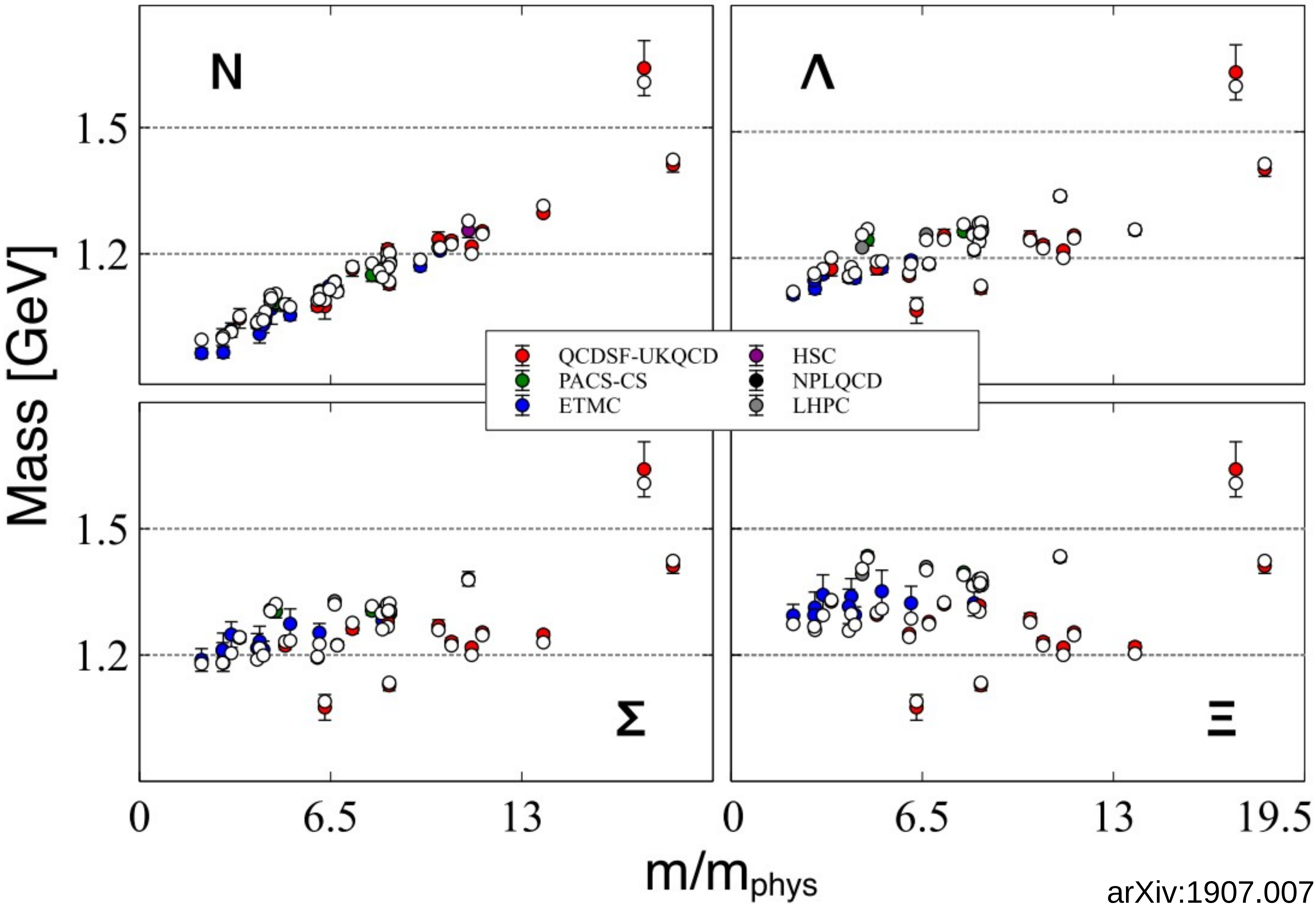
Low-energy parameters from lattice QCD simulations

✔ QCD Lattice simulations

- consider data from PACS-CS, HSC, LHPC, NPLQCD, QCDSF-UKQCD and ETMC
- finite volume effects are considered
- data are not always at physical strange-quark mass
- there are about 300 data points with $m_\pi, m_K < 600$ MeV
- physical baryon octet and decuplet masses are always reproduced $\to$ global lattice scale setting
- lattice spacing effects are ignored in this work
- assume an ad-hoc size for the systematic error of about 10 MeV
- achieve a data reproduction with $\chi^2/N \simeq 1$

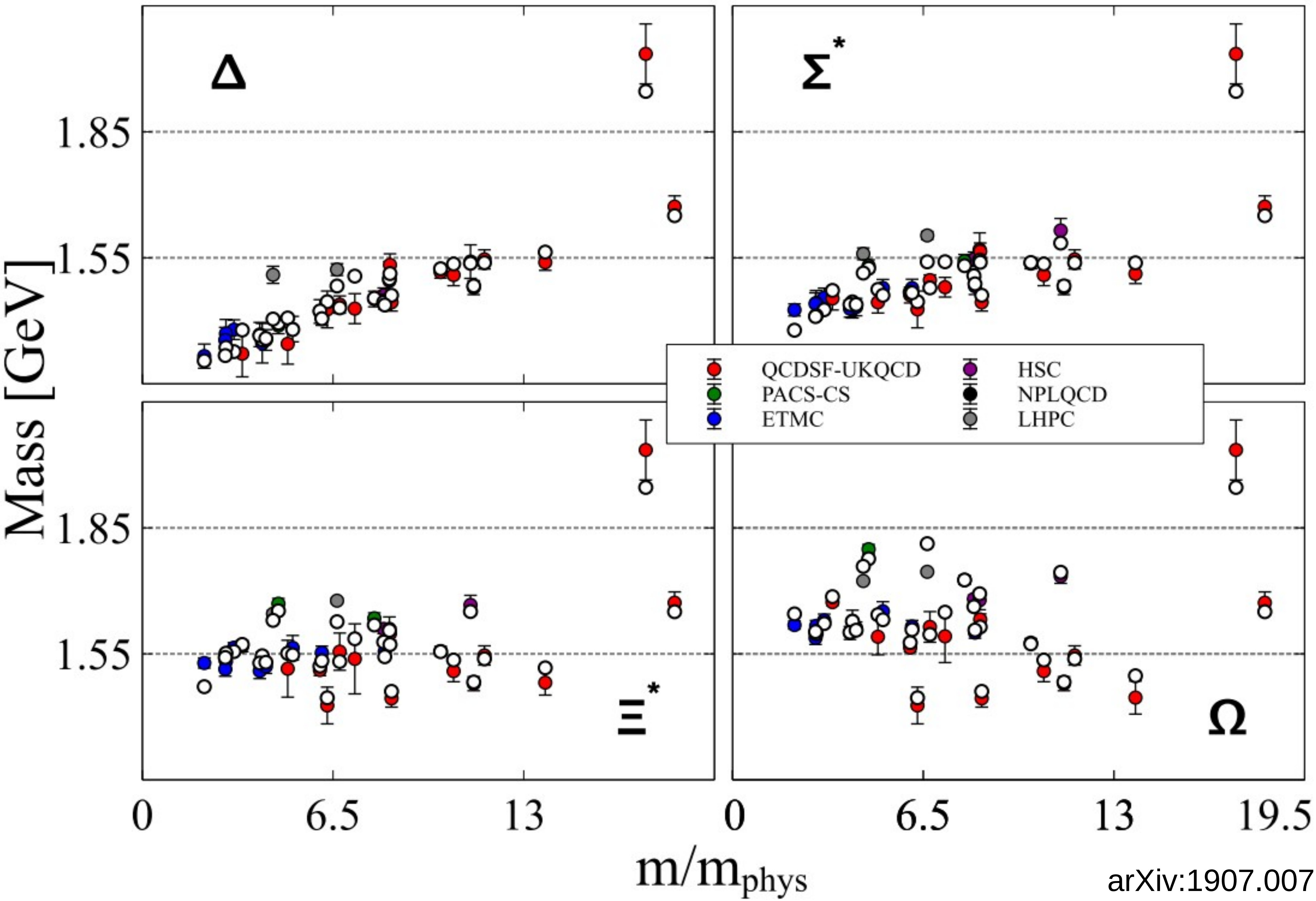
arXiv:1801.06417

Quark-mass dependence of the baryon octet masses



arXiv:1907.00714

Quark-mass dependence of the baryon decuplet masses



arXiv:1907.00714

Quark-mass dependence of the baryon masses

✔ Baryon masses as a function of $m_u = m_d = m$ shown

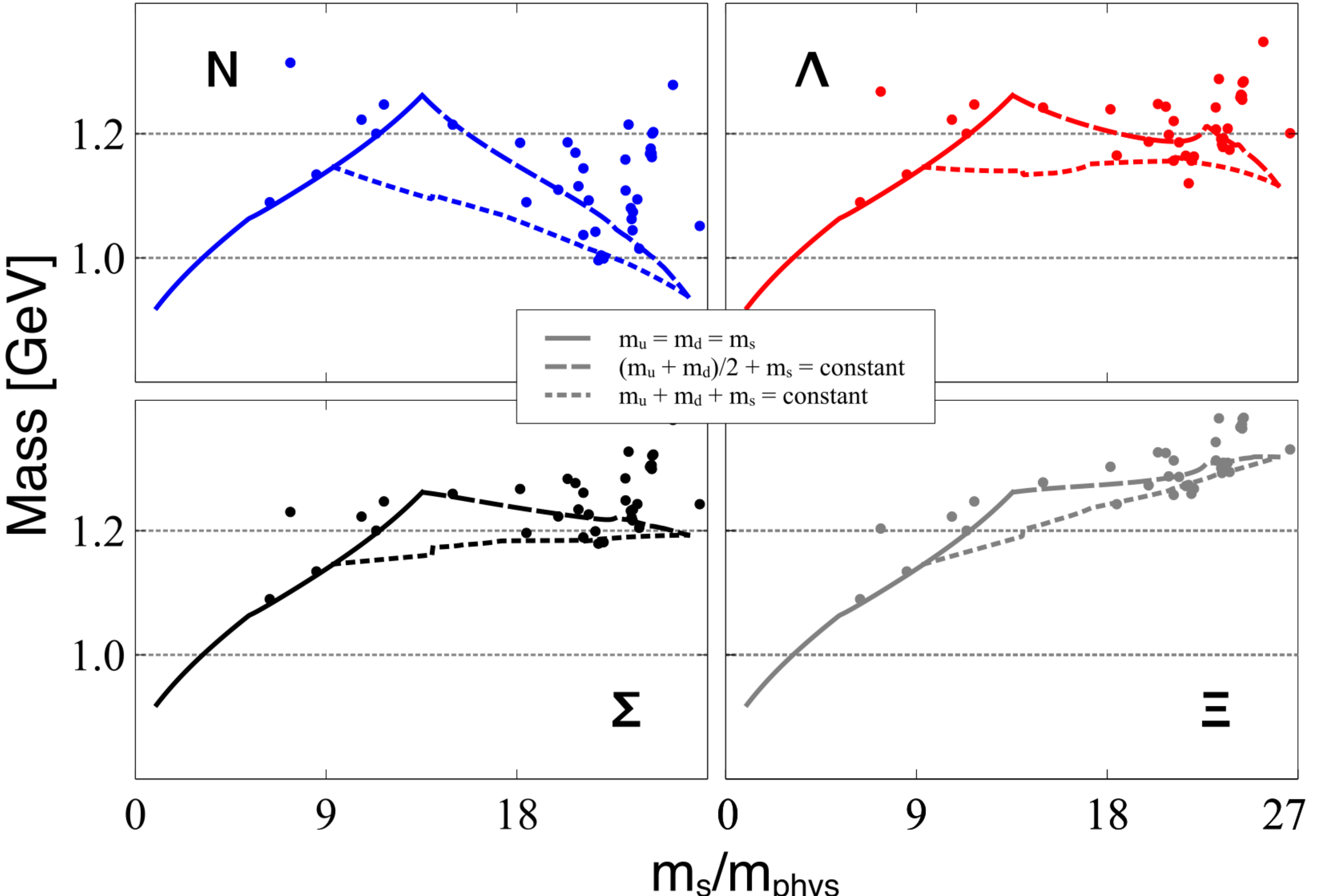
- unphysical strange quark mass as chosen by the lattice group

✔ Baryon masses on different m_s trajectories

- flavour symmetric case :: $m_u = m_d = m_s$
- fan plot :: $m_u + m_d + m_s$ fixed
- kaon mass :: at $(m_u + m_d)/2 + m_s \sim m_K^2$ fixed
- pion mass :: $m_u + m_d \sim m_\pi^2$ fixed

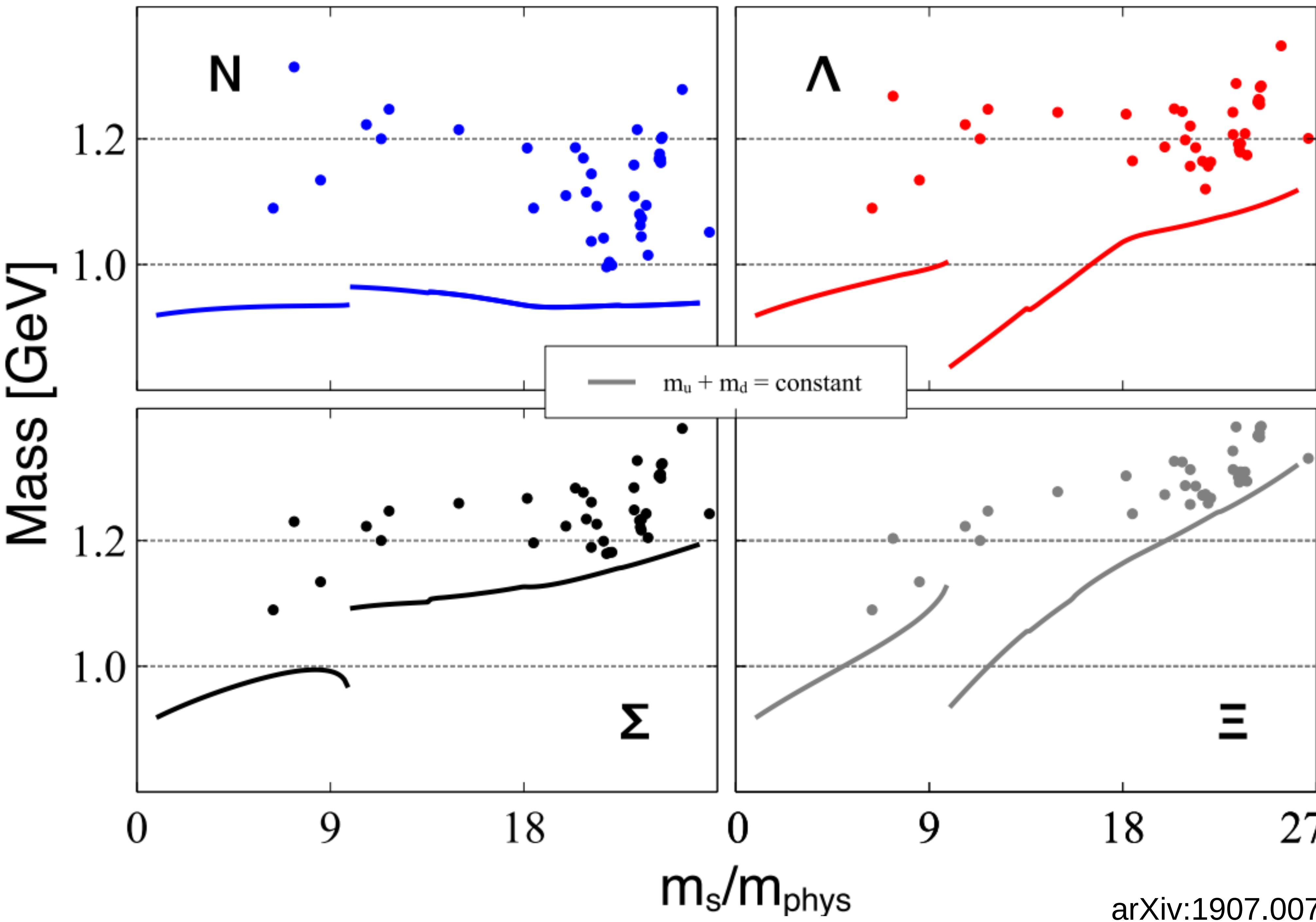
arXiv:1907.00714

Baryon masses on different m_s trajectories



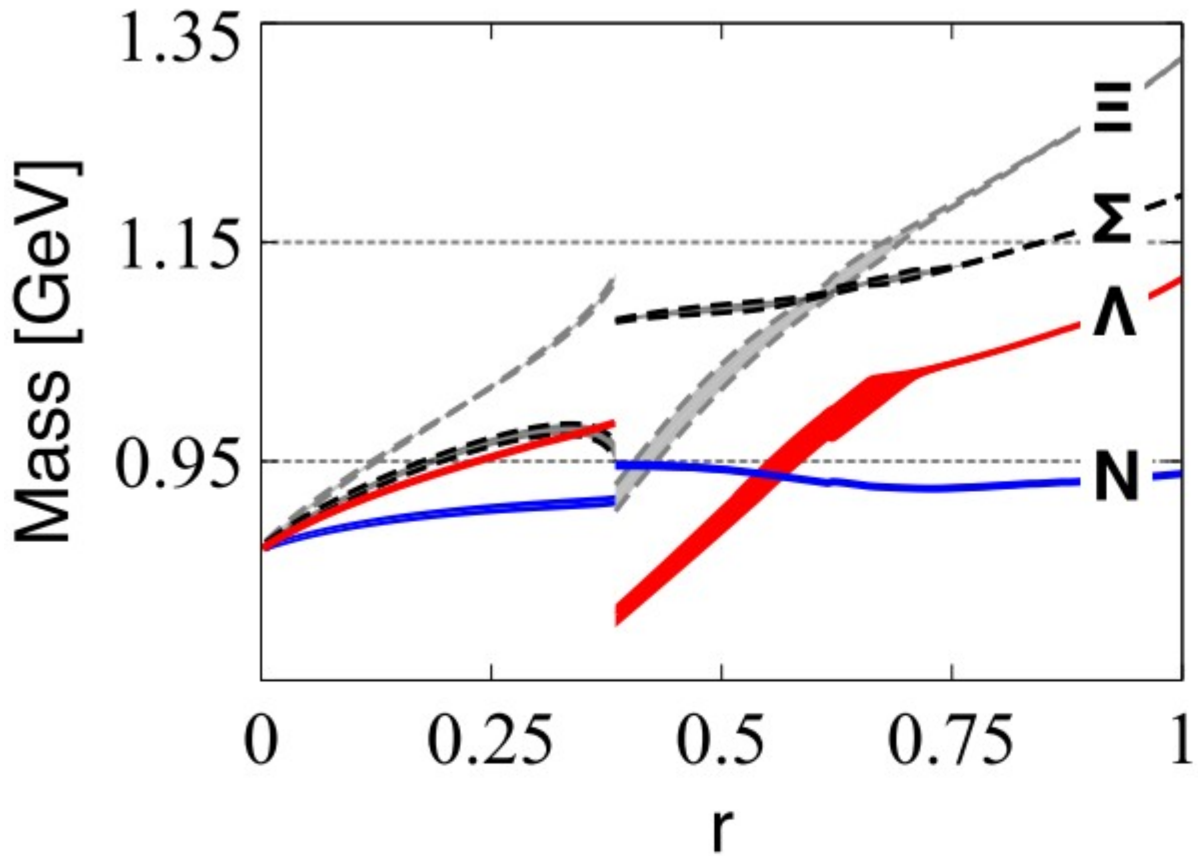
arXiv:1907.00714

1st order transition at physical $m_u = m_d$



arXiv:1907.00714

Baryon masses depend on the Higgs field

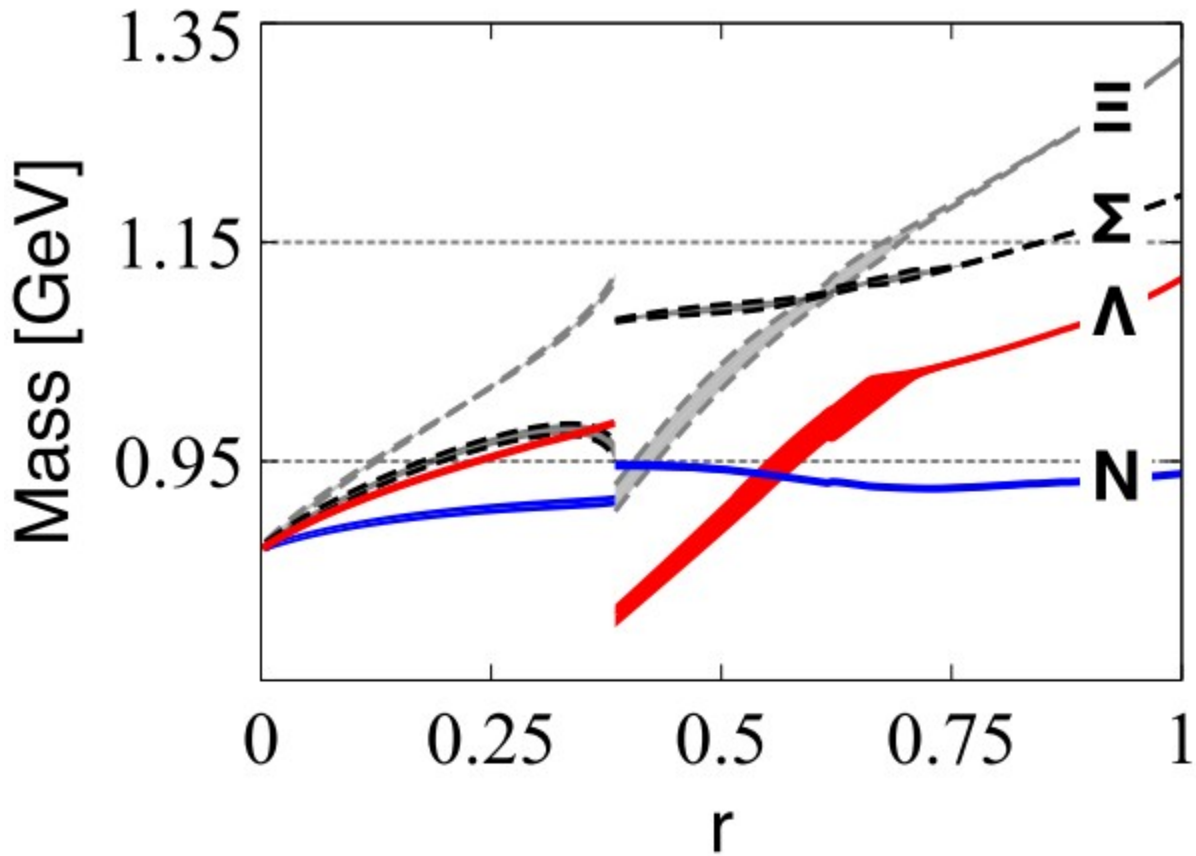


- quark masses in QCD are proportional to $v \sim r$

$$V(H) = \frac{M_h^2}{2\,v^2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \qquad \text{from Standard Model}$$

arXiv:1907.00237

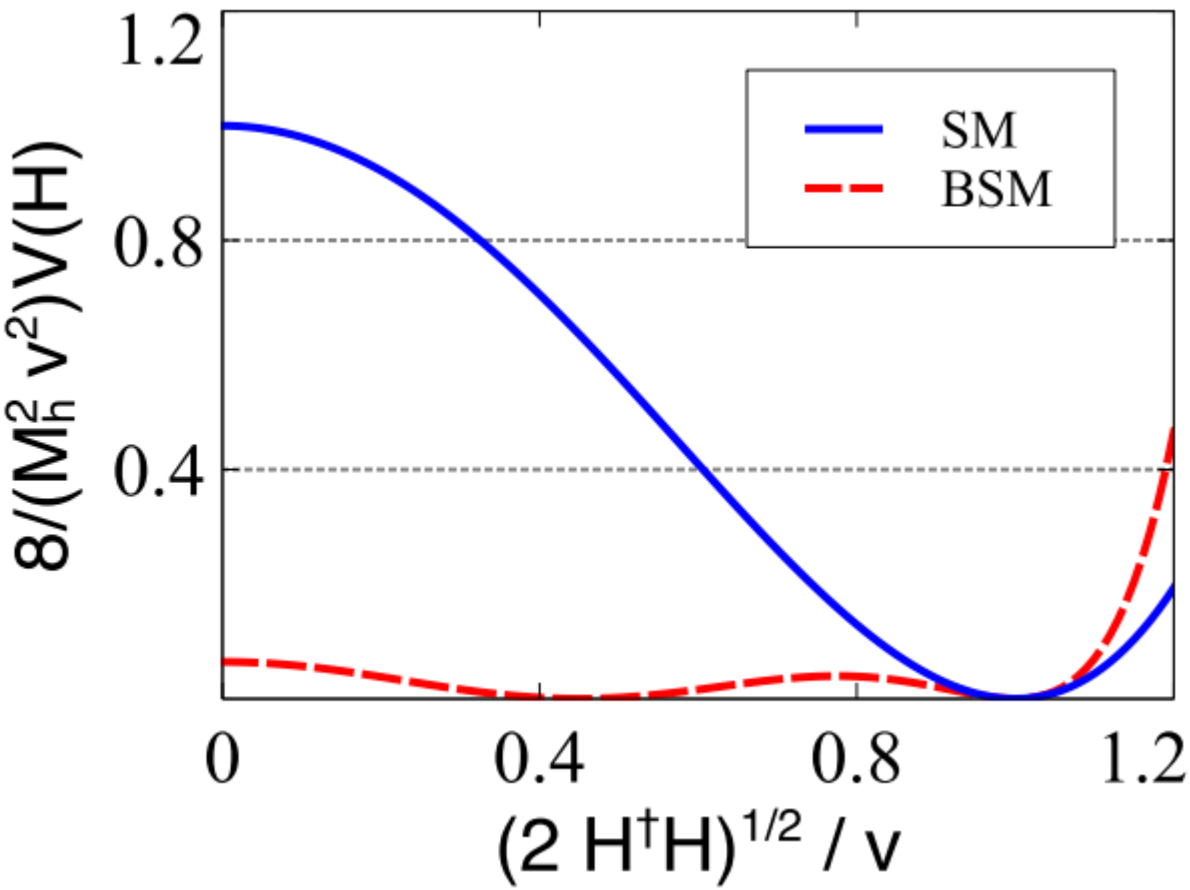
Baryon masses depend on the Higgs field



- is such a first order transition of physical relevance?
- lattice QCD simulations should see that transition
- in the standard model $r = 1$ :: physics beyond the SM?

arXiv:1907.00237

A generalization of the Higgs potential with two minima

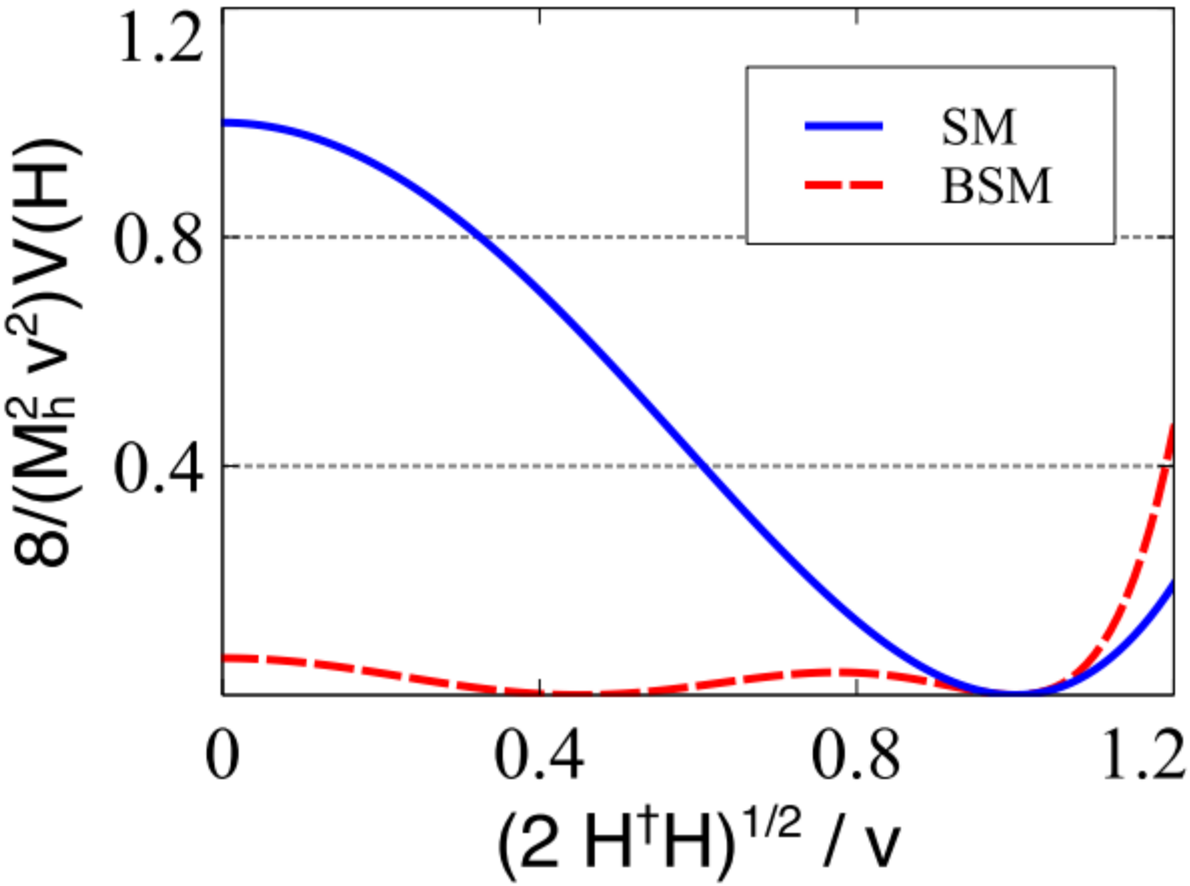


$$V_{\mathrm{BSM}}(H) = \frac{2\,M_h^2}{v^6\,(1-r^2)^2}\left(H^\dagger H - \frac{v^2}{2}\right)^2\left(H^\dagger H - \frac{v_a^2}{2}\right)^2,$$

and $\qquad r = v_a/v = m_s/m_s^{\mathrm{phys}}\,,$

arXiv:1907.00237

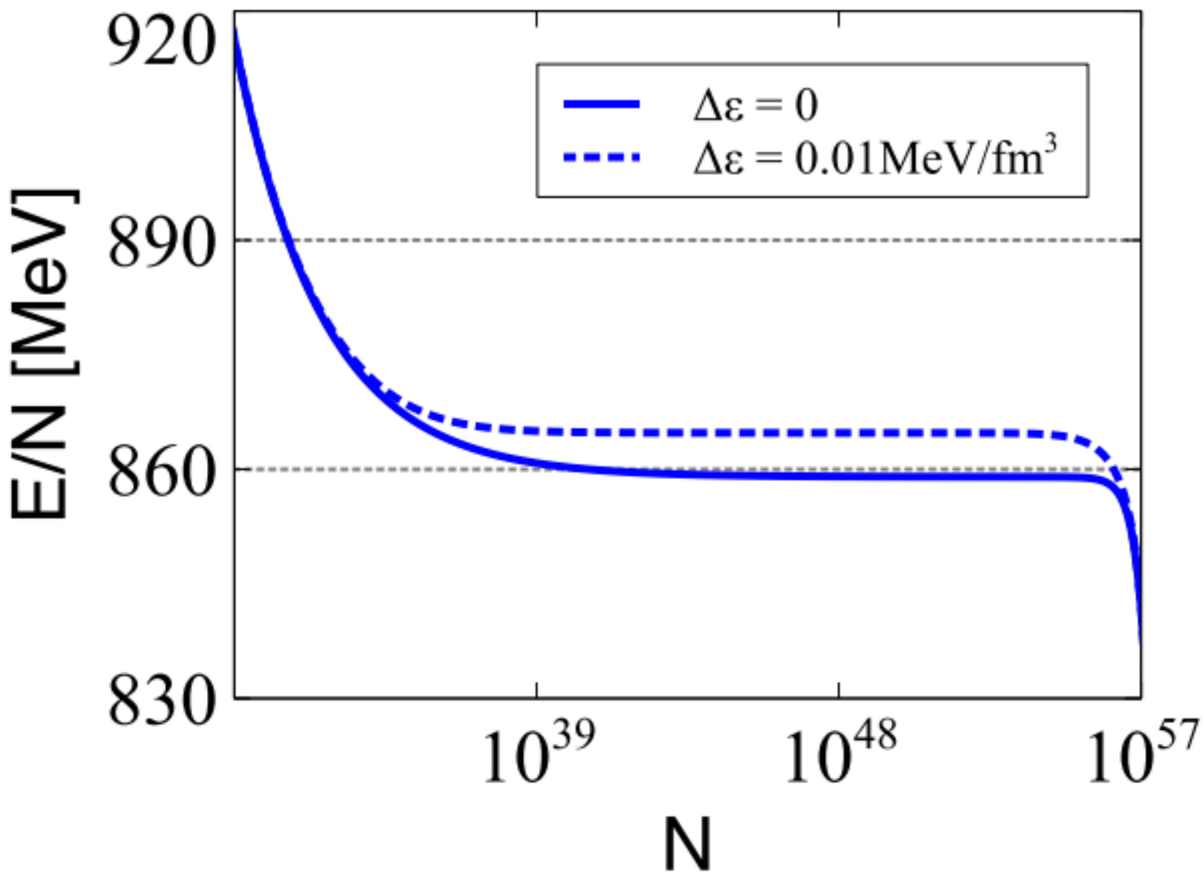
A generalization of the Higgs potential with two minima



- current data from CERN do not rule out such a potential
- 3-Higgs coupling $\kappa_\lambda \simeq 6$ versus $\kappa_\lambda = 1$ from SM
- 2-σ range $-5.0 < \kappa_\lambda < 12.1$ from ATLAS

arXiv:1907.00237

Dark QCD matter in a Higgs bubble

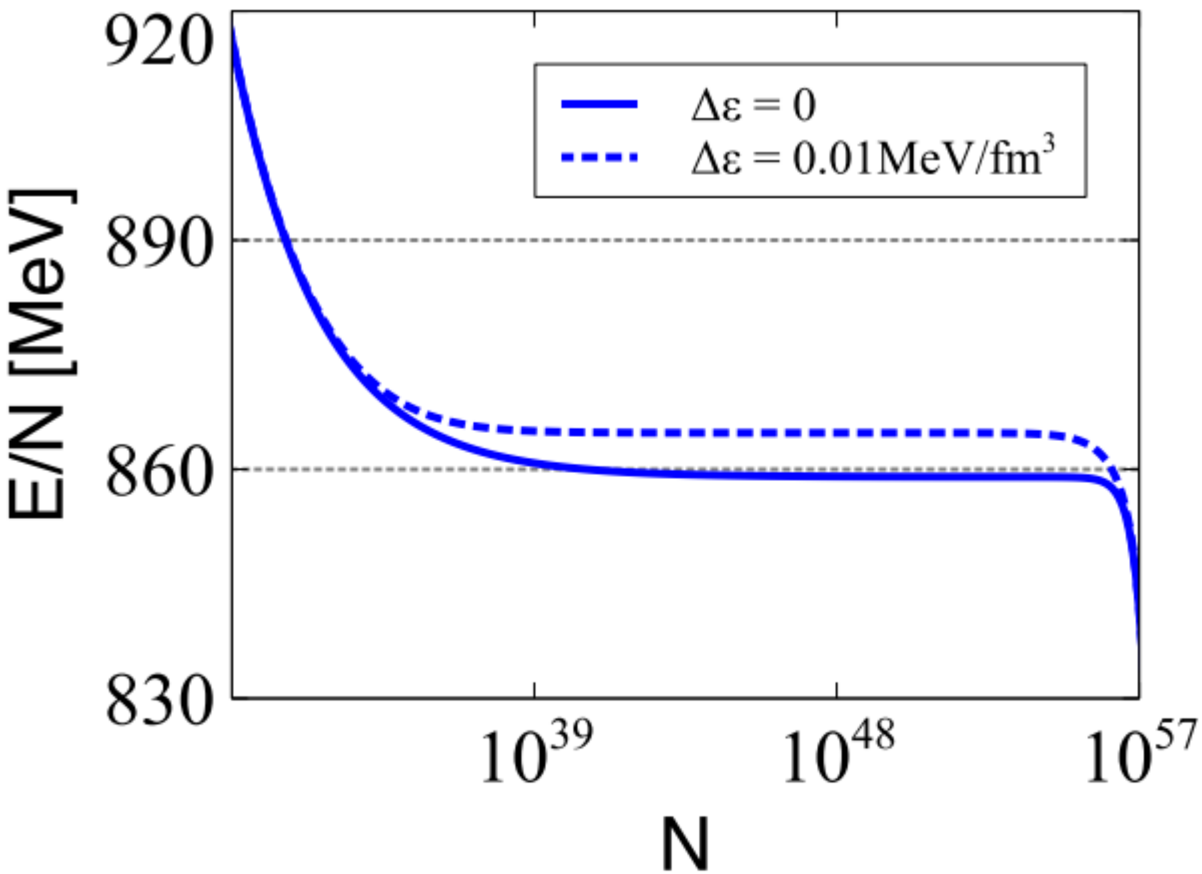


$$N_{\rm Sun} \simeq M_{\rm Sun}/M_N \simeq 1.2 \times 10^{57}$$

- consider Λ baryons with $M_\Lambda \simeq 860$ MeV in 'false' vacuum
- total energy per particle E/N smaller than M_N for large N
- dark matter in a Higgs bubble is stable

arXiv:1907.00237

Dark QCD matter in a Higgs bubble



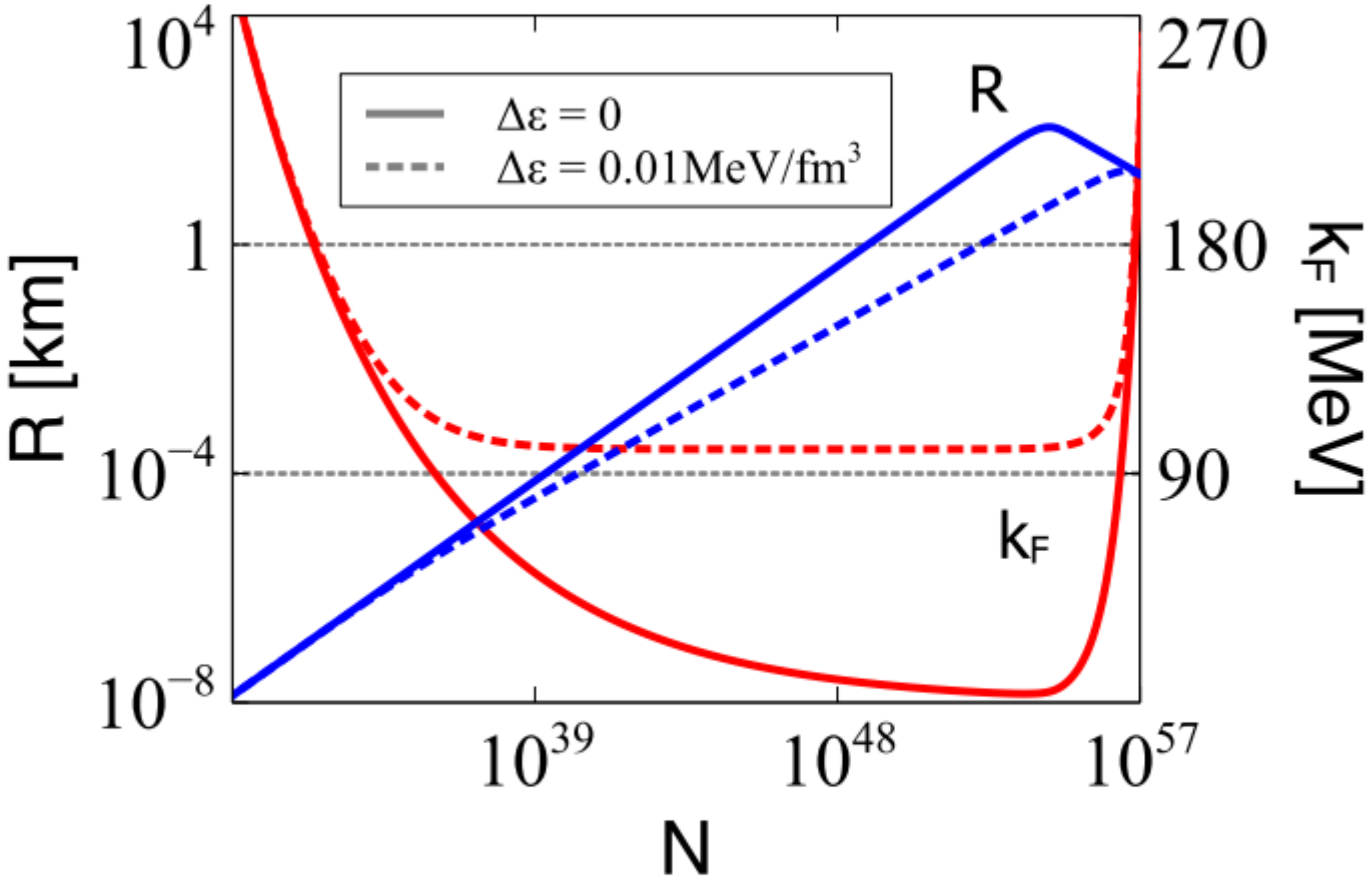
$$N_{\rm Sun} \simeq M_{\rm Sun}/M_N$$
$$\simeq 1.2 \times 10^{57}$$

$$N = \frac{4\,(R\,k_F)^3}{9\,\pi}$$

- volume effects: fermi gas + gravitation + $\Delta\epsilon$
- surface effects: value of Higgs field changes from v_a to v
- large amount of energy stored in Higgs shell

arXiv:1907.00237

Radius and density of the Higgs bubble



$$\rho = k_F^3/(3\,\pi^2)$$

$$N = \frac{4\,(R\,k_F)^3}{9\,\pi}$$

- predict maximum radius of Higgs bubble
- for $N > 10^{57}$ sensitive to EOS of Λ's in the bubble

arXiv:1907.00237

Summary & Outlook

✔ Chiral extrapolation of baryon octet and decuplet masses

- resumed χPT : use on-shell masses in the loops
  - solve system of coupled and non-linear equations
  - chiral expansion with up, down and strange quarks is well convergent
  - reproduce the QCD Lattice data set at $m_{\pi,K} < 600$ MeV
  - predict a large number of low-energy constants for the chiral Lagrangian of QCD
- predict first order transition for the baryon masses
  - the nature of the baryonic ground state in QCD depends on the quark masses
  - the nature of the baryonic ground state depends on the choice of Higgs field

✔ A dark matter scenario with Λ baryons in a Higgs bubble

- Generalize the Higgs potential to support two degenerate minima
  - large fraction of (dark) baryonic matter in Higgs bubbles (here $M_\Lambda < M_N$)
  - derive a maximum radius of such bubbles ($<$ 800 km)
- future request: derive equation of state of Λ baryons in the Higgs bubble ...
- possibility of strange dark matter objects with masses larger than neutron stars

thanks to collaborators: Yonggoo Heo and Xiao-Yu Guo