Collaborative research center CRC 110

*"Symmetries and the emergence of structure in QCD"*

# Hi-Lites from the German side

## – Third funding period –

**Ulf-G. Meißner**

Deutsche Forschungsgemeinschaft DFG

国家自然科学基金委员会 National Natural Science Foundation of China

# Contents

# A.1: Analysis of rescattering effects in $3\pi$ final states

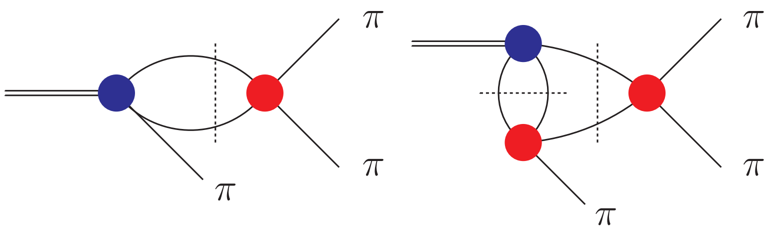
Stamen, Isken, Kubis, Mikhasenko, Niehus, Eur. Phys. J. C **83** (2023) 510

- nontrivial rescattering effects in $3\pi$ decays dominated by $\pi\rho$ :

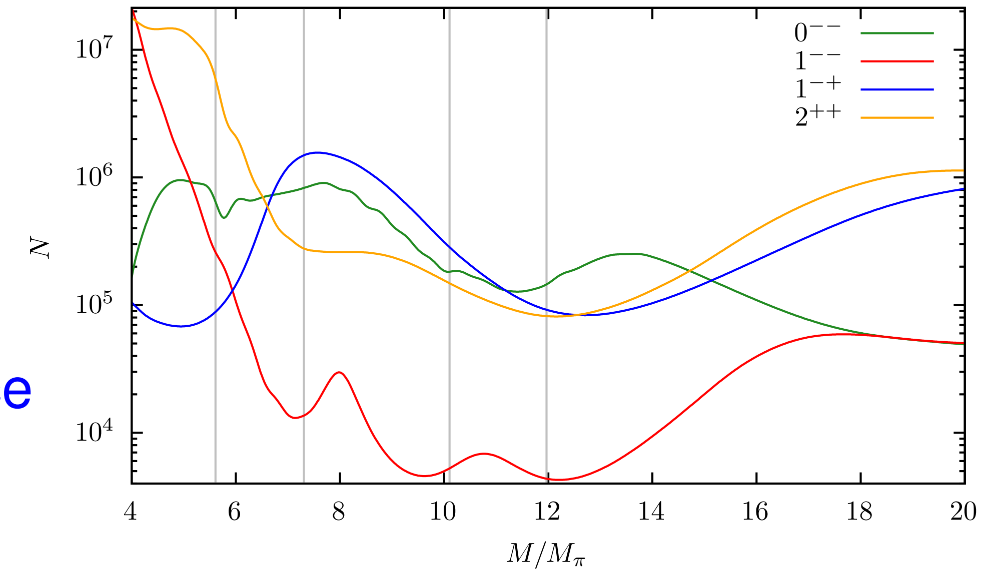
$$J^{PC} = \quad 0^{--}\ [\text{exotic}] \quad 1^{--}\ [\omega, \phi] \quad 1^{-+}\ [\pi_1] \quad 2^{++}\ [a_2]$$

$\longrightarrow$ $1^{-+}$ and $2^{++}$ relevant for COMPASS

- tool: Khuri–Treiman equations




- necess. events in Dalitz plot *N* to reject naïve isobar model ($\hat{=}$ undistorted $\rho$ lineshape) at $5\sigma$ significance?
  $\longrightarrow$ mass and $J^{PC}$ dependence



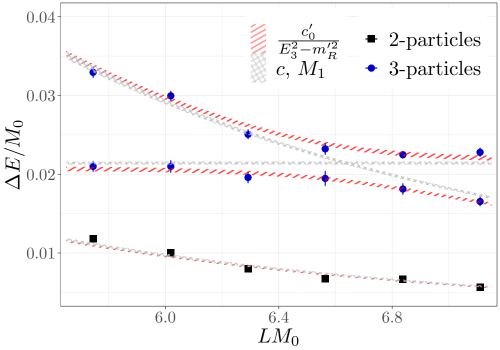

- related experimental analysis: in progress COMPASS

# Hi-Lite Project A.2: 3-Particle Resonance Avoided Level Crossing

- first observation of avoided level crossing in 3-particle resonance on the lattice
- model system: complex $\varphi^4$ theory

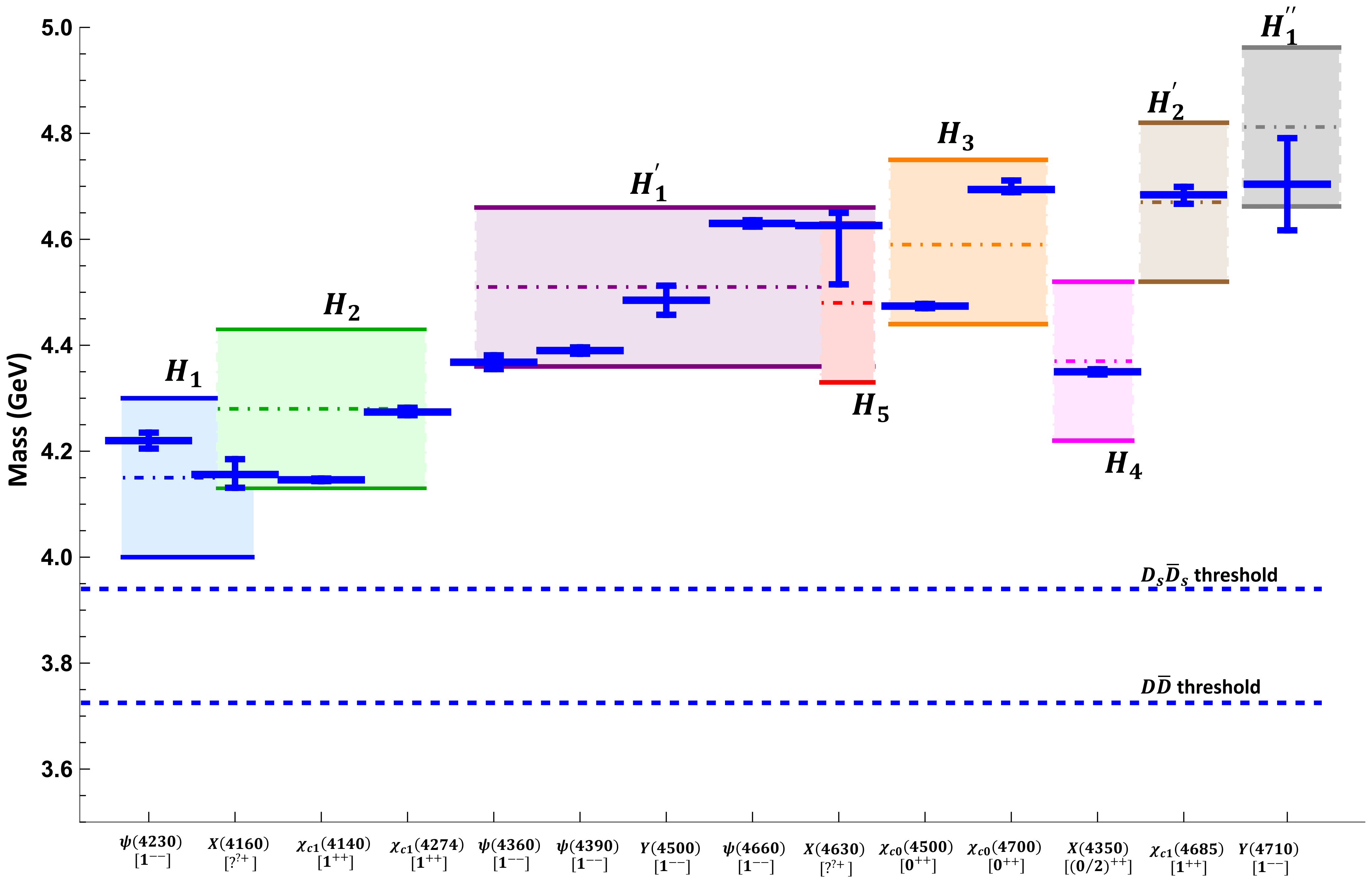
$$\mathcal{L} = \sum_{i=0,1} \left[ \frac{1}{2} \partial^\mu \varphi_i^\dagger \partial_\mu \varphi_i + \frac{1}{2} m_i^2 \varphi_i^\dagger \varphi_i + \lambda_i (\varphi_i^\dagger \varphi_i)^2 \right] + \frac{g}{2} \varphi_1^\dagger \varphi_0^3 + \text{h.c.}\,.$$

- comparison: resonance (red) versus no resonance (gray) scenario at $g = 8.87$
- excellent agreement between different finite volume formalism

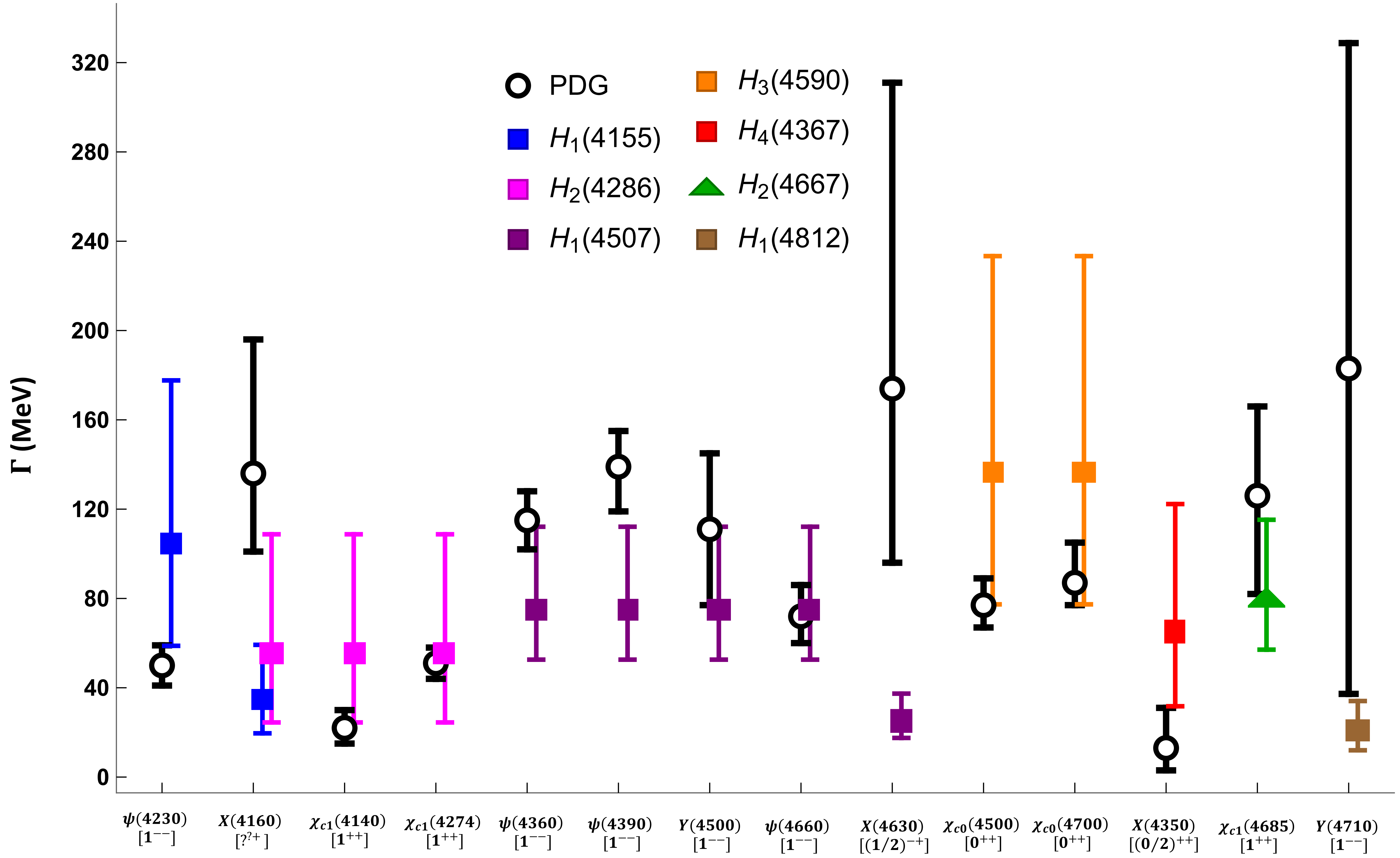



[M. Garofalo et al., JHEP 02 (2023) 252, arXiv:2211.05605]

# A3: BORN OPPENHEIMER EFT (BOEFT) CALCULATION of HYBRIDS DECAY




BOEFT prediction for hybrids multiplets (boxes) in comparison to neutral exotic charmonium states (crosses)




BOEFT predictions for the hybrids to quarkonium decays in comparison to the total decay widths of the neutral exotic charmonium states

Results are obtained also for bottomonia exotics

**This opens the way to a treatment of ALL XYZ exotics in the BOEFT framework: we are currently addressing Tetraquarks**

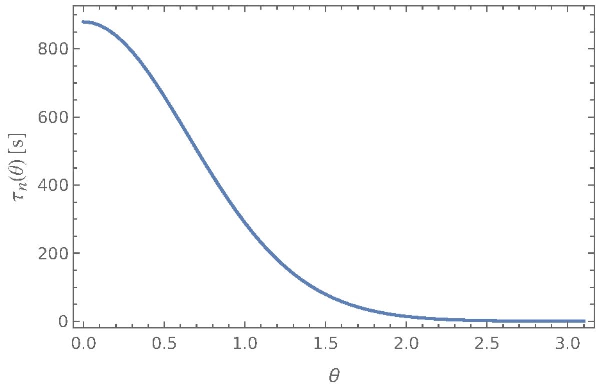
N. Brambilla, W.K. Lai, A. Mohapatra, A. Vairo *Phys.Rev.D* 107 (2023) 5, 054034

# A5: $\theta$-dependence of nuclei &Big Bang nucleosynthesis

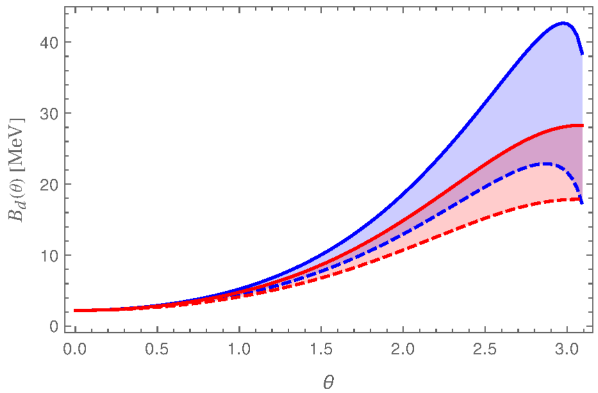
Lee, UGM, Olive, Shifman, Vonk, Phys. Rev. Res. **2** (2020) 033392

- Does BBN give bounds on the elusive $\theta$-parameter of QCD?
- Use chiral EFT and meson-exchange to $\theta$-dependent study nuclear properties

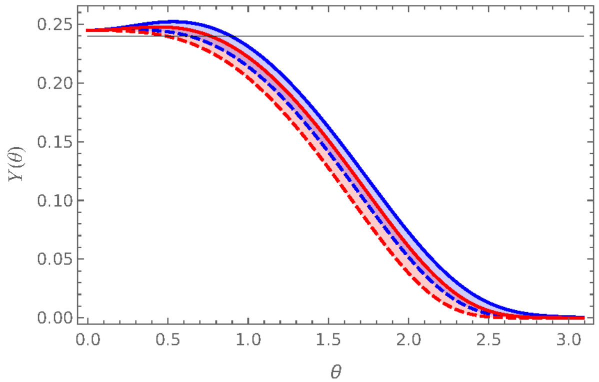
- neutron lifetime




- Deuteron BE




- $^4$He abundance



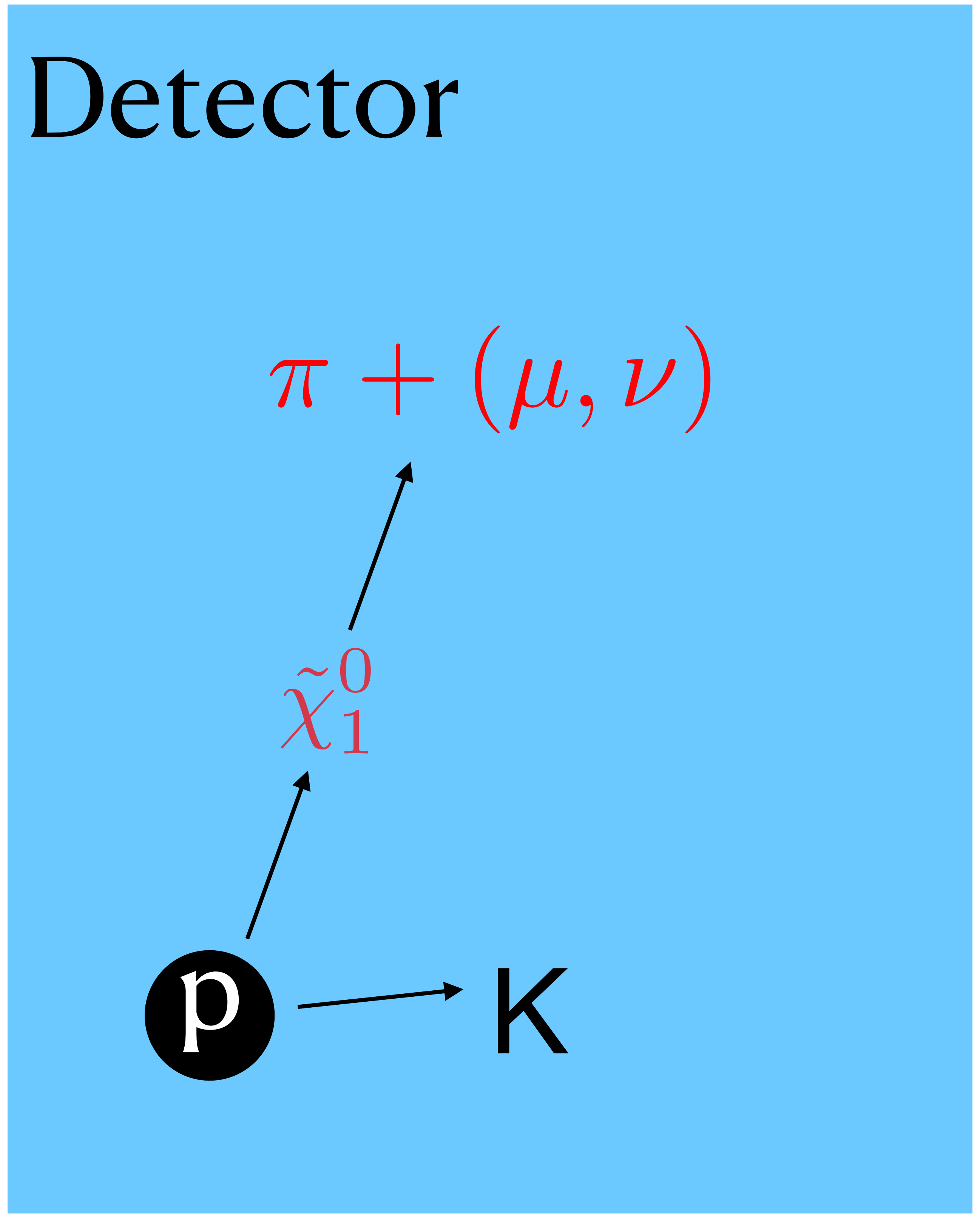

$\hookrightarrow$ di-proton and di-neutron get bound for $\theta = 0.7, 0.2$

$\hookrightarrow$ triple-$\alpha$ reaction affected, lack of $^{16}$O for $\theta \gtrsim 0.1$

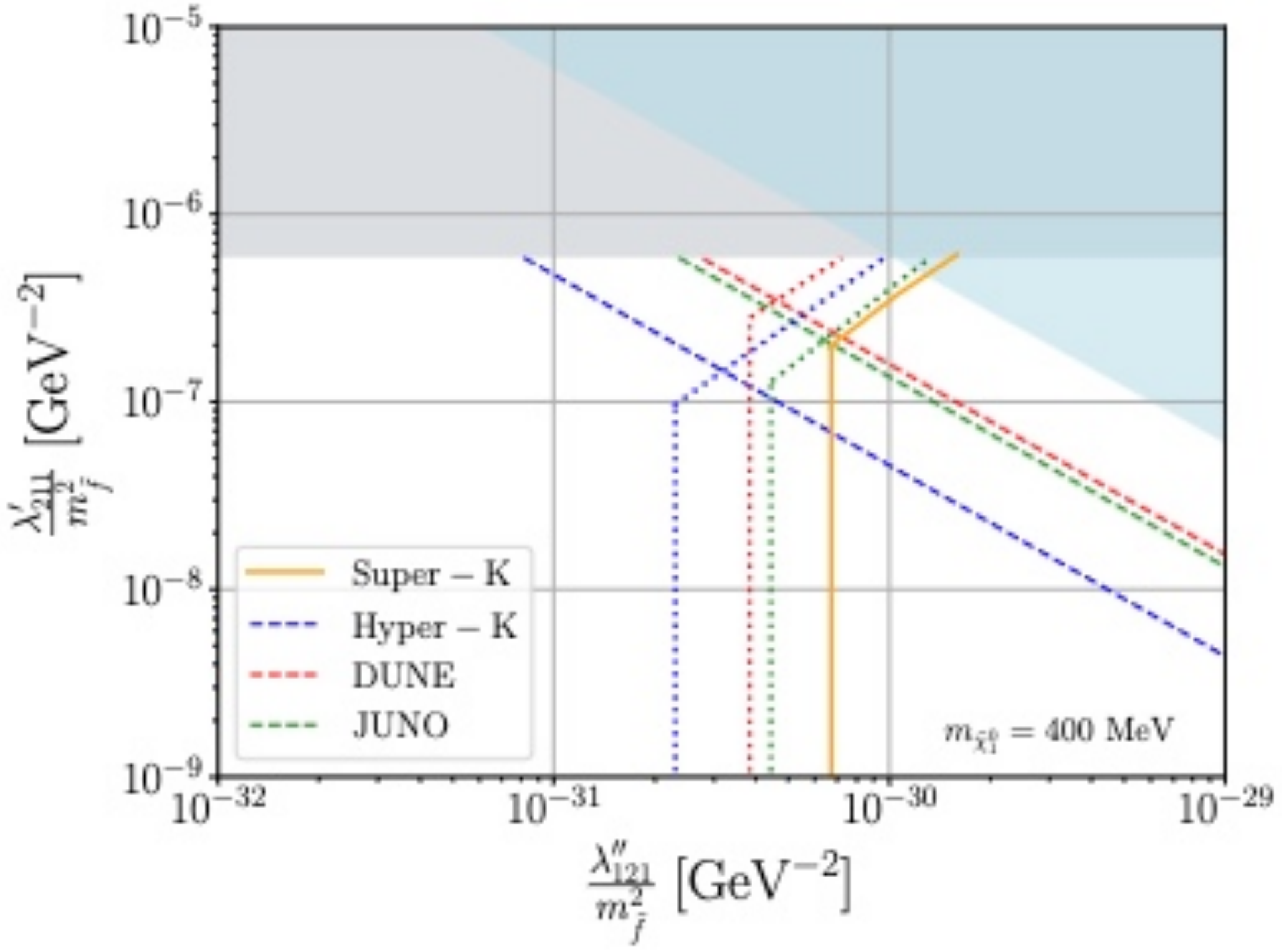
> Constraints on $\theta$, but no anthropics:
> Universe looks similar as long as $\theta \lesssim 0.1$

# Project A7: H. Dreiner & C.D. Lü

- Supersymmetric light long-lived neutralino: novel proton decay mode




- Proton decays to Kaon + light long-lived neutralino via UDD
- Neutralino flys and decays in detector via LQD
- Signature: Kaon + Neutralino decay




(to appear shortly)

- Light long-lived neutralinos at colliders:

(1) *Phys.Rev.D* 103 (2021) 7, 075013; (2) *JHEP* 03 (2021) 148; (3) *JHEP* 04 (2022) 057;

(4) SciPost Phys. 14 (2023) 134; (5) *JHEP* 02 (2023) 120; (6) e-Print: 2306.11803

# A.8 Charmless Exclusive B Decays — Highlights M. Beneke (TUM)

I. Factorization theorem for charmless and $B$ to charm hadronic two-body decays $B \to M_1 M_2(\gamma)$ including QED effects + analysis of branching fractions and CP asymmetry sum rules in $\pi K$ final states

[2008.10615 (charmless) and 2107.03819 (heavy-light + semi-leptonic)]

II. Definition, renormalization and evolution of light-cone distribution amplitudes in QCD+QED for light mesons ($\pi, \ldots$) and heavy mesons ($B$)

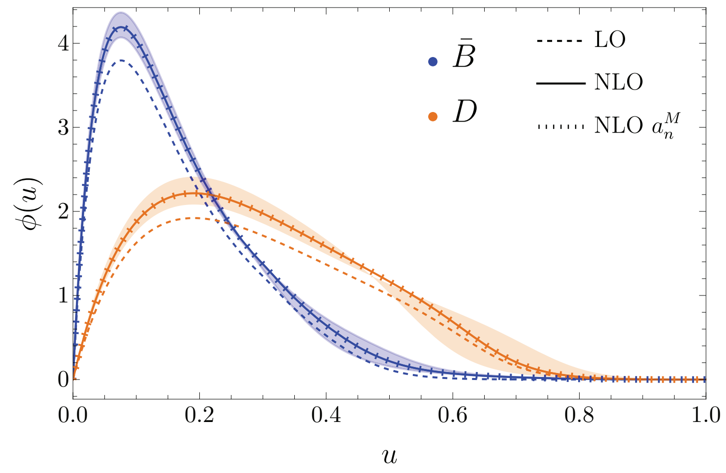
[2108.05589 (light mesons) + 2204.09091 (heavy mesons)]

$$\Gamma(u, v; \mu) = -\frac{\alpha_{\rm em} Q_M}{\pi}\, \delta(u-v) \left( Q_M \left( \ln \frac{\mu}{2E} + \frac{3}{4} \right) - Q_d \ln u + Q_u \ln \bar{u} \right) - \left( \frac{\alpha_s C_F}{\pi} + \frac{\alpha_{\rm em}}{\pi} Q_u Q_d \right) [\,\mathrm{ERBL}\,]_+$$

*(Evolution kernel)*

III. Mass-dependent LCDA of a heavy meson from the universal leading-twist HQET LCDA

[2305.06401]



# A9: EFT for Nuclear Electroweak Currents

- **N³LO EM current operator**: isoscalar part ✓ : isovector part *work in progress*

**Application:** $^4$He charge radius: effective field theory and experiment

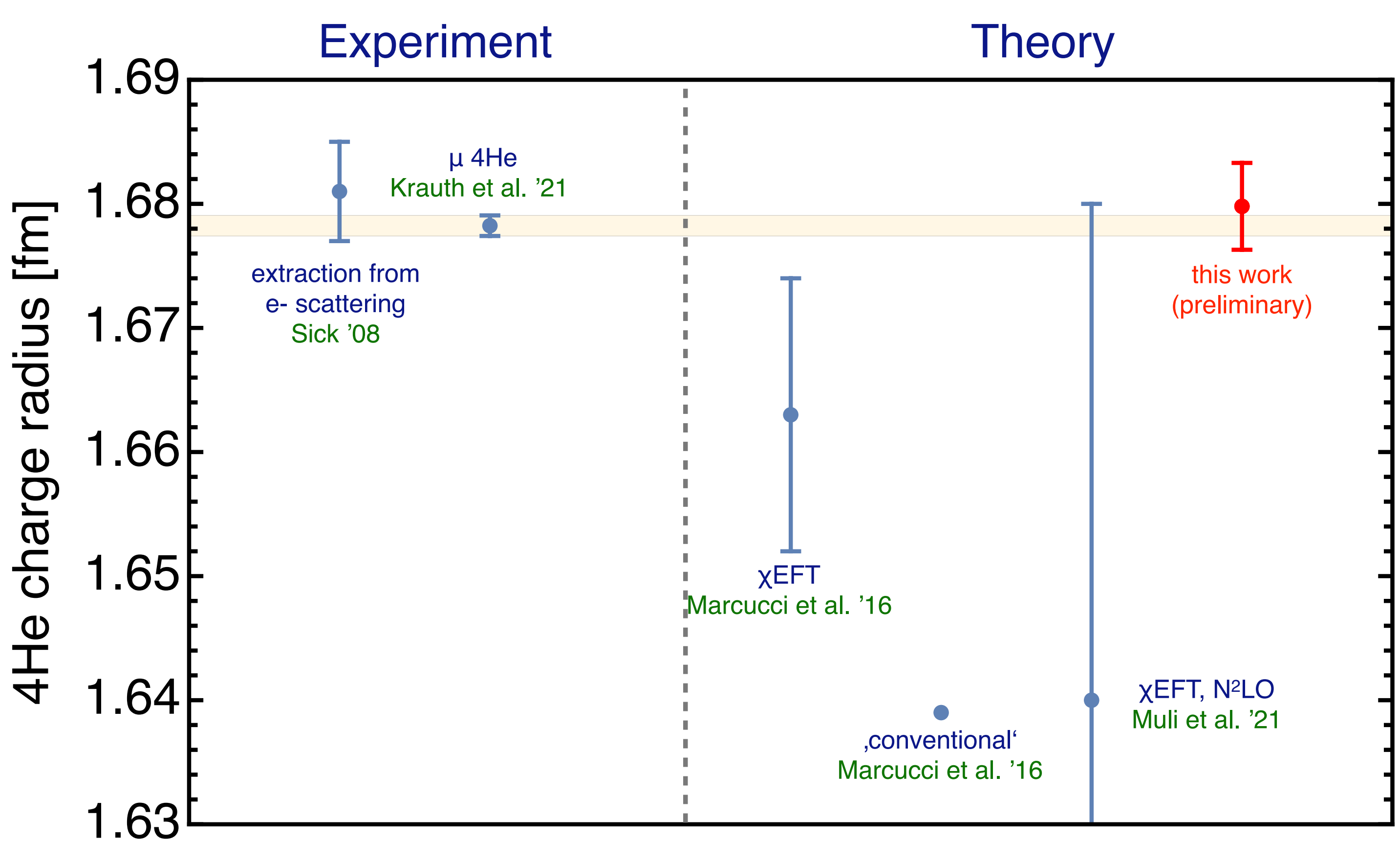
$$r_C(^4\text{He}) = r_{str}^2(^4\text{He}) + \left( r_p^2 + \frac{3}{4m_p^2} \right) + r_n^2$$

Our prediction for $^4$He **charge** radius

$$r_C(^4\text{He}) = (1.6798 \pm 0.0035)\, fm$$

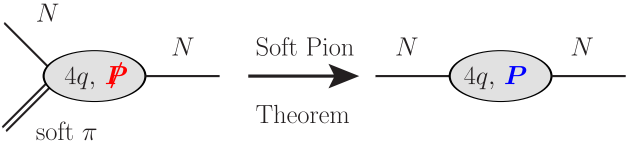
$$r_{str}(^4\text{He}) = 1.4784 \pm 0.0030_{\text{trunc}} \pm 0.0013_{\text{stat}} \pm 0.0007_{\text{num}}\ fm$$

Preliminary, using CODATA 2018 $r_p$ and own determination of $r_n$ PDG22




Our prediction for $^4$He charge radius is fully consistent with the muonic-atom spectroscopy

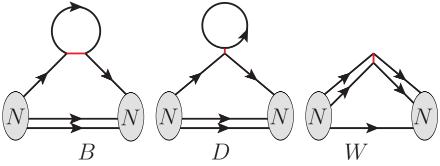
# A10: Parity-violating Pion-Nucleon coupling $h_\pi^1$ from Lattice QCD




$$\langle N\,\pi\,|\,\bar{q}\,\Gamma\boldsymbol{\gamma_5}\,q\,\bar{q}\,\Gamma\,q\,|\,N\rangle \qquad \langle N\,|\,\bar{q}\,\Gamma\,q\,\bar{q}\,\Gamma\,q\,|\,N\rangle$$

Exploratory Lattice QCD computation towards Parity-Violating $NN\pi$ coupling $h_\pi^1$

- first-time calculation of all diagrams, including quark-loops "*B*" and "*D*", from all light and strange flavored 4-quark operators




- bare coupling from connected "*W*" diagram at $M_\pi \approx 260\,\mathrm{MeV}$, lattice spacing $a \approx 0.9\,\mathrm{fm}$ and box size $L \approx 3\,\mathrm{fm}$

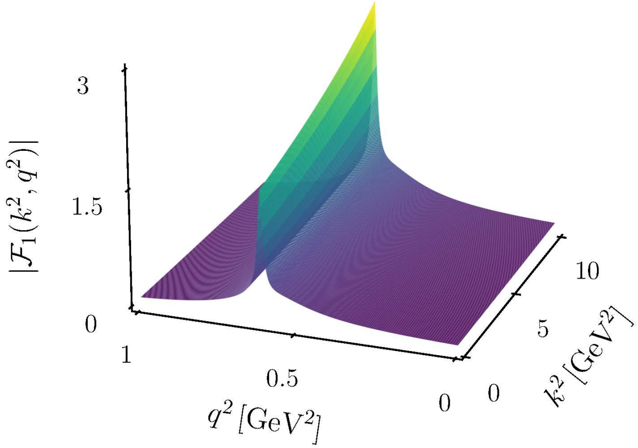
$$h_\pi^1\,(W,\,\mathrm{bare}) = 8.08\,(98)\cdot 10^{-7} \quad \mathrm{arXiv:2306.03211\ [hep-latt]}$$

# A.11: Dispersion relations for $B^- \to \ell^-\bar{\nu}_\ell \ell'\bar{\ell}'$

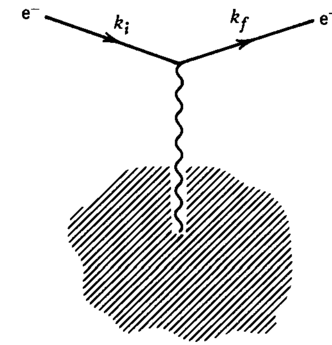
Kürten, Zanke, Kubis, van Dyk, Phys. Rev. D **107** (2023) 053006

- $B^- \to \ell^-\bar{\nu}_\ell\gamma$: access *B*-meson LCDA e.g. Beneke, Rohrwild 2011
- $B^- \to \ell^-\bar{\nu}_\ell \ell'\bar{\ell}'$: off-shell dependence of $B \to \gamma^*$ form factors LHCb
- goal: relate $B \to \gamma^*$ to $B \to \rho,\, \omega$ via dispersion relations
  $\longrightarrow$ need form factor basis free of kinematic singularities / zeros
  Bardeen, Tung 1968; Tarrach 1975
  $\longrightarrow$ BTT generalised from electromagnetic to weak form factors
- $z$-expansion of $B \to V$ form factors Bharucha, Straub, Zwicky 2016
- branching ratios, forward–backward asymmetry, form factors:

| Process | $\mathcal{B} \times 10^8$ | $A_{\text{FB}}$ |
|---|---|---|
| $B^- \to e^-\bar{\nu}_e\mu^-\mu^+$ | $3.19(43)_N(25)_{V_{ub}}$ | $-0.358(31)_N$ |
| $B^- \to \mu^-\bar{\nu}_\mu e^-e^+$ | $3.78(47)_N(30)_{V_{ub}}$ | $-0.398(38)_N$ |
| $B^- \to \tau^-\bar{\nu}_\tau e^-e^+$ | $2.75(27)_N(22)_{V_{ub}}$ | $-0.500(18)_N$ |
| $B^- \to \tau^-\bar{\nu}_\tau\mu^-\mu^+$ | $1.77(23)_N(14)_{V_{ub}}$ | $-0.458(15)_N$ |



# B1. New insights into the interpretation of hadronic form factors




$$\rho(r) = \int d^3q\, F(-\mathbf{q}^2)\, e^{-i\mathbf{q}\cdot\mathbf{r}}$$

⟵ The standard „Breit-frame“ density can ***not*** be interpreted as a charge density for light hadrons Burkardt, Miller, Jaffe, ….

⇒ no consistent definition of local spatial densities possible?

Define the charge density of a spin-0 system in terms of a generic wave packet state:

$$\rho_\phi(\mathbf{r}) \;=\; \langle \phi, \mathbf{0}\,|\,\hat\rho(\mathbf{r},0)\,|\,\phi, \mathbf{0}\rangle \;=\; \int \frac{d^3p\, d^3p'}{2(2\pi)^3\sqrt{EE'}}\, \phi^\star(\mathbf{p}')\, \underbrace{\langle p'\,|\,\hat\rho(\mathbf{r},0)\,|\,p\rangle}_{e^{-i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{r}}\,(E+E')\,F(q^2)}\, \phi(\mathbf{p})$$

For localized packets, $\rho_\phi(\mathbf{r})$ becomes independent of the wave packet state $\phi$:

$$\boxed{\rho(r) \;=\; \int \frac{d^3q}{(2\pi)^3}\, e^{-i\mathbf{q}\cdot\mathbf{r}} \int_{-1}^{+1} d\alpha\, \frac{1}{2}\, F\left[(\alpha^2-1)\,\mathbf{q}^2\right]}$$

⟵ valid in the frame with $\langle \mathbf{p}\rangle = 0$

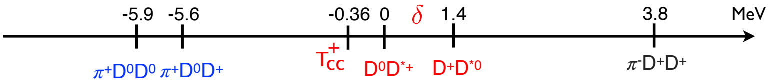
Epelbaum, Gegelia, Lange, Meißner, Polyakov, PRL129 (2022)

The new definition is valid for any particle’s mass, is consistent with special relativity and coincides with the known 2d-densities in the infinite-momentum frame.

Higher-spin systems and gravitational FFs: Panteleeva, Epelbaum, Gegelia, Meißner, PRD 106 (2022) 056019; e-Print: 2211.09596 (to appear in EPJC); e-Print: 2305.01491; Alharazin, Sun, Epelbaum, Gegelia, Meißner, JHEP 02 (2023) 163.

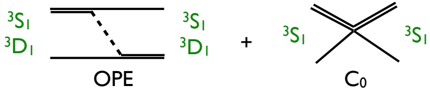
# B.3: $T_{cc}(3875)$

M. L. Du et al., PRD105(2022)014024; [arXiv:2303.09441 [hep-ph]], submitted to PRL




$\Longrightarrow$ Three-body dynamics and isospin violation must matter

We solve $T = V + VGT$ with $V_{LO} =$




@ LO: One free parameter (for each cut off) $\rightarrow$ Width fixed by mass

- Excellent description of the data
- Precision needs 3 body dynamics (problem: experimental resolution)
- $r = -2.4 \pm 0.9$ fm, but $r_0 = +1.4 \pm 0.9$ fm (corrected for isospin viol.)

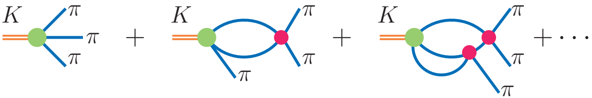
  $\Longrightarrow$ $T_{cc}^{+}$ qualifies as isoscalar $DD^*$ molecule
- OPE gives prominent left-hand cut $@M_\pi = 280$ MeV

  Effect should be visible in recent lattice data

# B4: Three-particle analog of the Lellouch-Lüscher formula

F. Müller and A. Rusetsky, JHEP 03 (2021) 152,
F. Müller, J.-Y. Pang, A. Rusetsky and J.-J. Wu, JHEP 02 (2023) 214.

- A three-particle analog of the Lüscher-Lellouch formula has beed derived, relating the finite- and infinite-volume three-particle decay matrix elements.




- The irregular volume-dependence in the matrix element is studied within the non-relativistic EFT. Short-distance effects are encoded in the effective couplings that feature only exponentially suppressed finite-volume corrections. The lattice calulations enable one to extract these couplings from the fit to the data.
- The framework can be formulated in a manifestly Lorentz-invariant form by choosing the quantization axis along the total four-momentum of the three-particle system: important for moving frames.

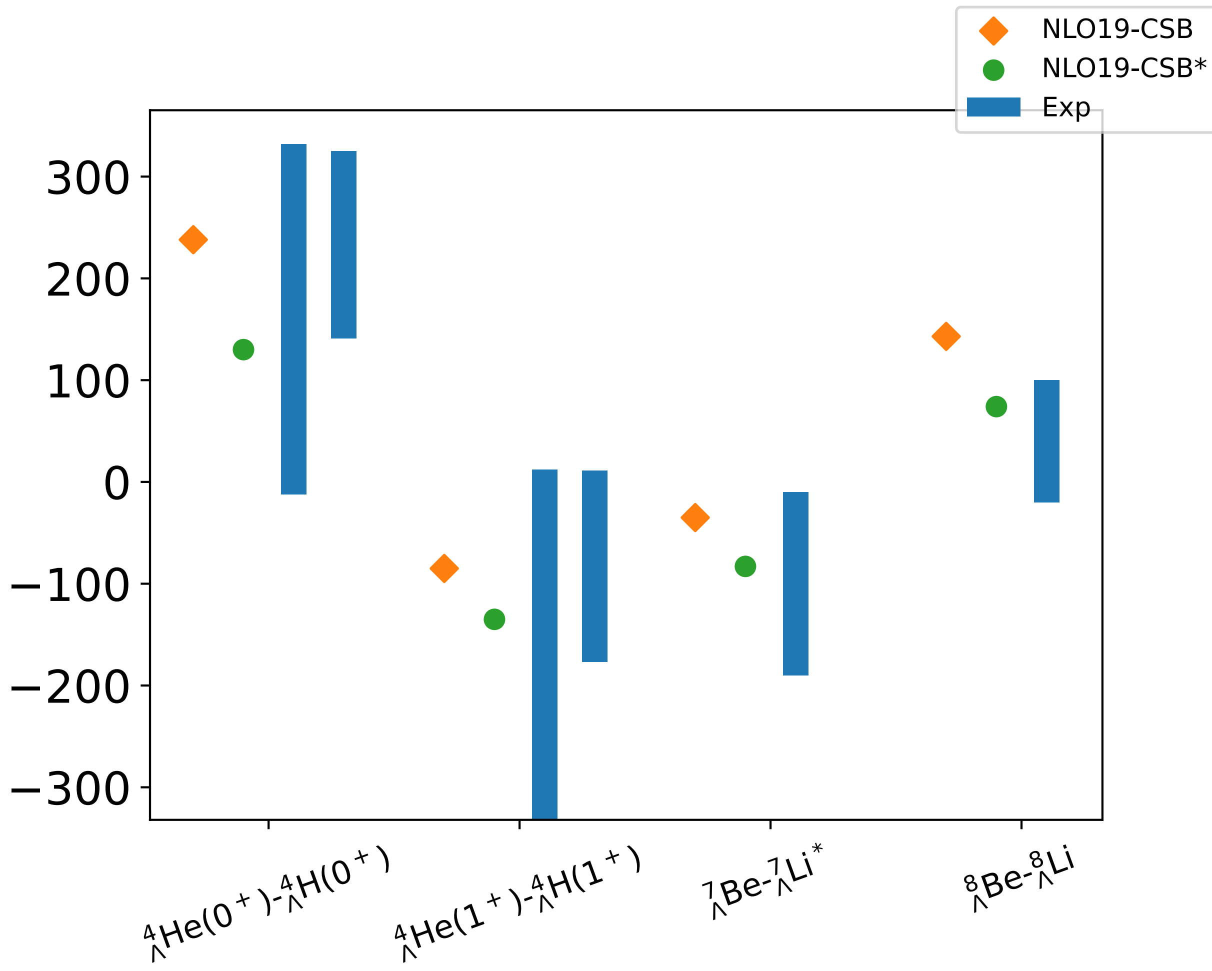
# B.6: Charge-Symmetry Breaking of A=7 and 8 hypernuclei

Large CSB contributions due to long-ranged pion exchange

- use ${}^4_\Lambda\mathrm{He} - {}^4_\Lambda\mathrm{H}$ to determine LECs
- first prediction of $\Lambda n$ scattering lengths    Haidenbauer et al., FBS62, 105 (2021)
- significant uncertainty in input data

Application to $A = 7$ and $8$

- benchmark confirms reliable predictions for
  SRG-evolved interactions
  up to 3-baryon level
- spin-dependence of CSB differs for $A = 7,8$
- comparison of two scenarios CSB/CSB*
- consistent description of $A = 4,7,8$
- hypernuclei provide constraints on $YN$




Hoai Le et al., PRC107, 024002 (2023)

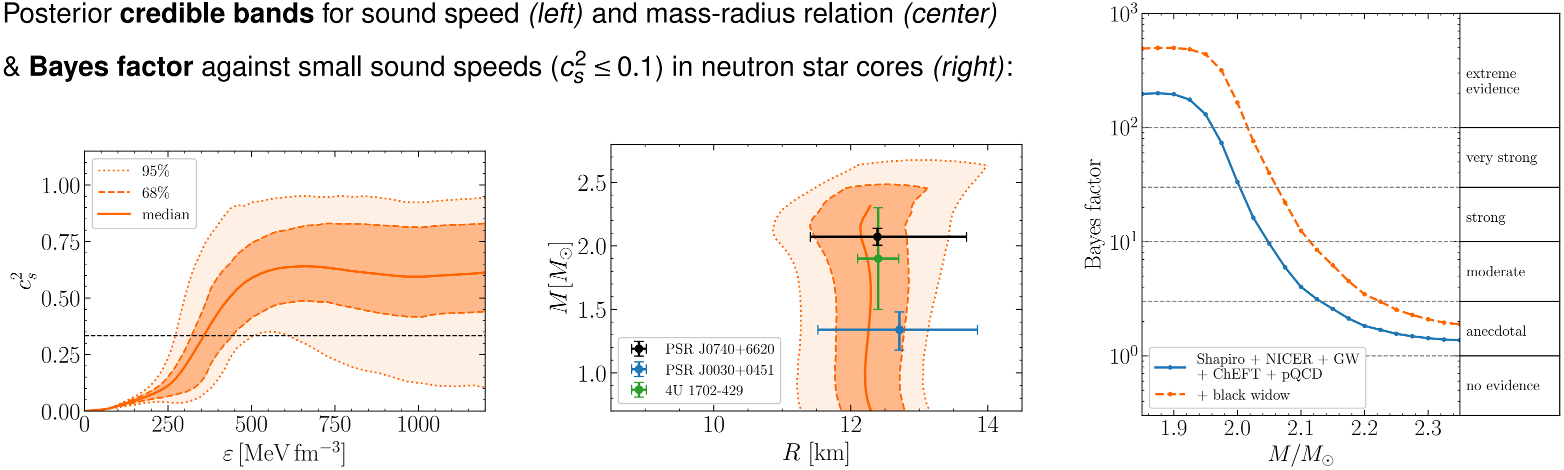
JÜLICH Forschungszentrum

# Evidence against a first-order phase transition in neutron star cores

CRC110, Project B7

Len Brandes, Wolfram Weise and Norbert Kaiser [arXiv:2306.06218]

- Bayesian inference of sound speed $c_s^2 = \partial P/\partial \varepsilon$ inside neutron stars based on available data: [Brandes, Weise and Kaiser, PRD 107 (2023)]
  - Shapiro time-delays
  - NICER X-ray measurements
  - Gravitational waves (GW) of binary neutron star mergers
  - ChEFT results at small densities
  - Perturbative QCD calculations at asymptotically high densities
  - New heavy-mass measurement ($M = 2.35 \pm 0.17\, M_\odot$) of black-widow PSR J0952-0607
- Posterior **credible bands** for sound speed *(left)* and mass-radius relation *(center)* & **Bayes factor** against small sound speeds ($c_s^2 \leq 0.1$) in neutron star cores *(right)*:

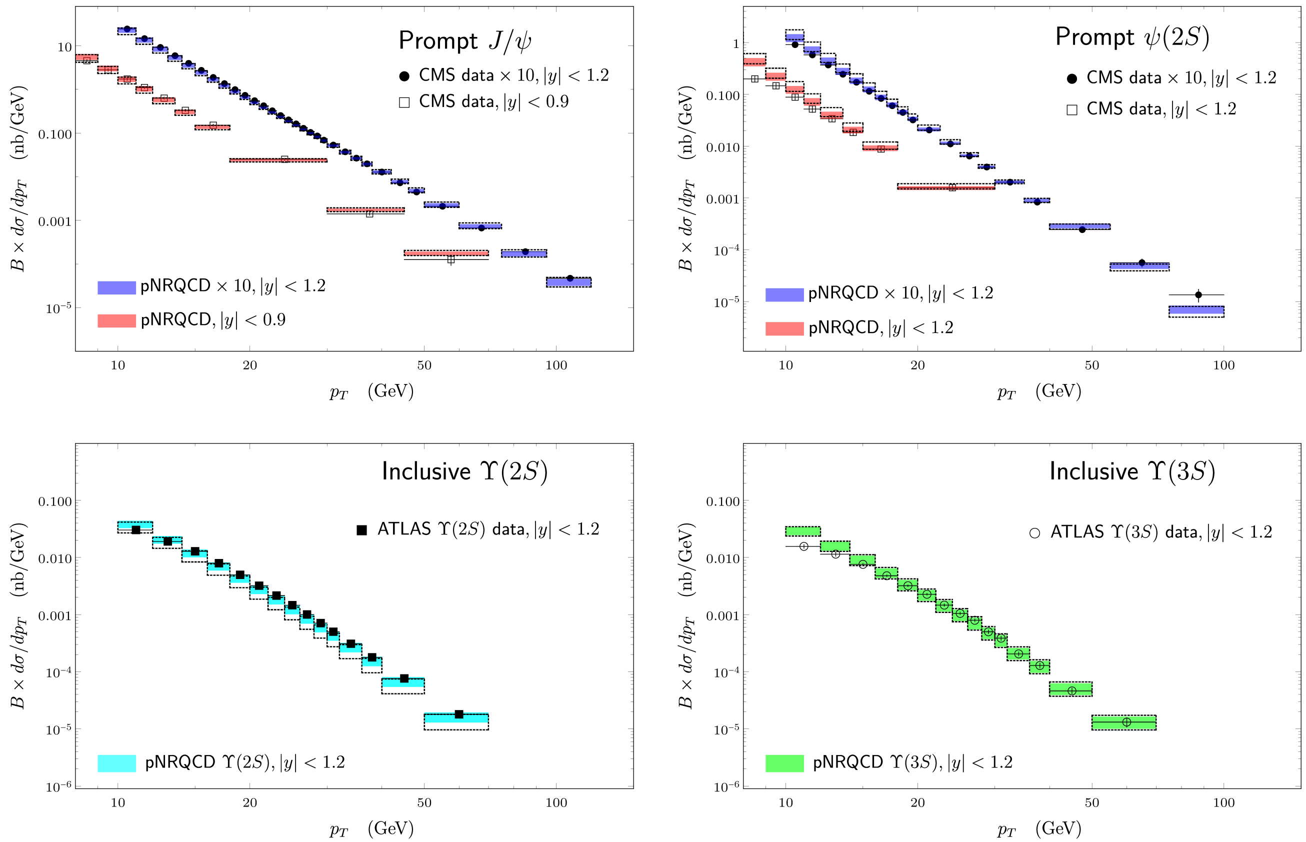



- With black-widow pulsar: strong evidence for $c_s^2 > 0.1$ in core of neutron stars with masses $M \leq 2.1\, M_\odot$

→ **First-order phase transition unlikely**

# B8: Quarkonium production cross sections @ LHC, $\sqrt{s} = 7$ TeV

Using pNRQCD factorization, the inclusive $J/\psi$, $\psi(2S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ production cross sections can be fitted with only 3 nonperturbative unknown instead of the 12 in NRQCD. The quality of the fit is very good. Also computed: photo-, EW ass. production, polarization.

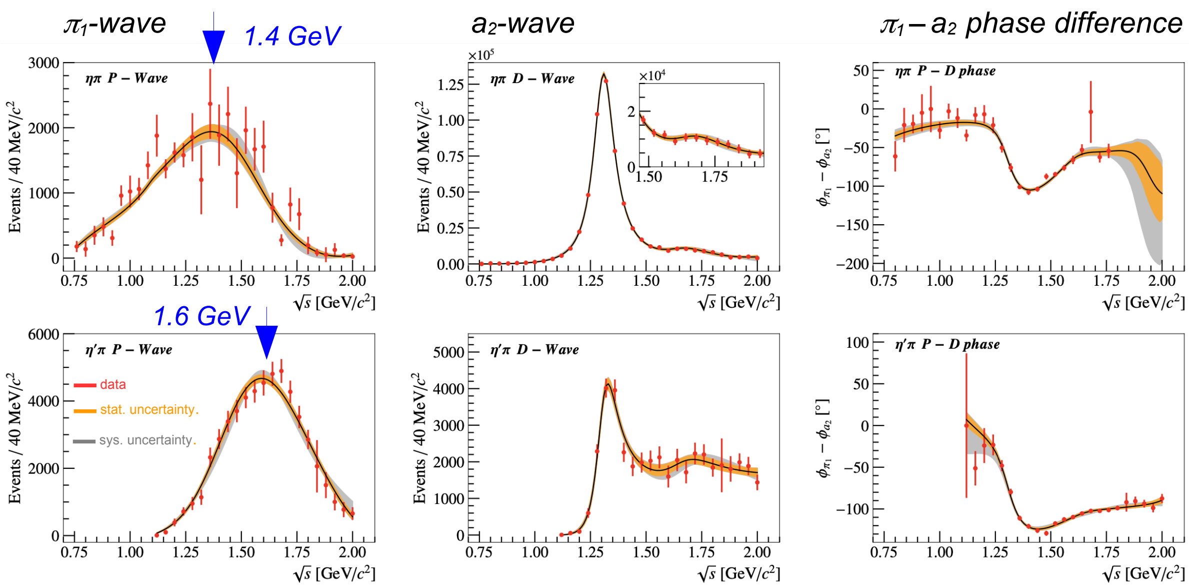



- Brambilla Chung Vairo Wang PRD 105 (2022) 11, JHEP 03 (2023) 242

# Investigation of the Lightest Hybrid Meson Candidate $\pi_1$

Kopf et al, Eur. Phys J. C(2021) 81, 1056

$\pi^- p \rightarrow \pi^- \eta^{(\prime)} p$ (COMPASS)




$\bar{p}p \rightarrow \pi^0 \pi^0 \eta$ (Crystal Barrel)

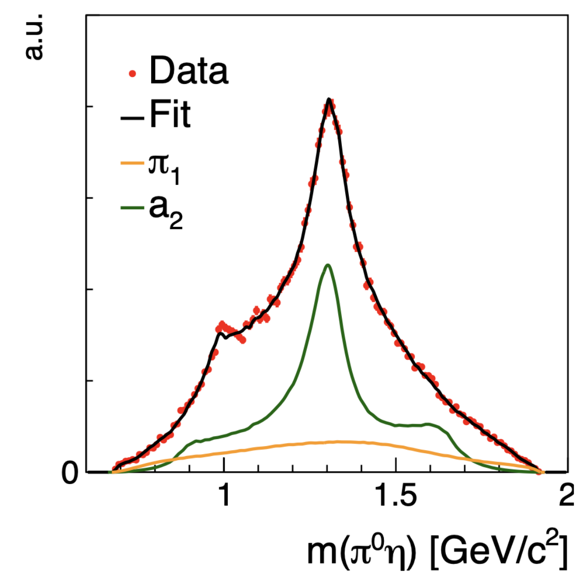



**Table 1** Obtained masses, total widths and ratios of partial widths for the pole of the spin-exotic $\pi_1$-wave and for the two poles in the $a_2$-wave, the $a_2(1320)$ and the $a_2(1700)$. The first uncertainty is the statistical and the second the systematic one

| Name | Pole mass (MeV/$c^2$) | Pole width (MeV) | $\Gamma_{\pi\eta'}/\Gamma_{\pi\eta}$ (%) | $\Gamma_{KK}/\Gamma_{\pi\eta}$ (%) |
|---|---|---|---|---|
| $a_2(1320)$ | $1318.7 \pm 1.9\,^{+1.3}_{-1.3}$ | $107.5 \pm 4.6\,^{+3.3}_{-1.8}$ | $4.6 \pm 1.5\,^{+7.0}_{-0.6}$ | $31 \pm 22\,^{+9}_{-11}$ |
| $a_2(1700)$ | $1686 \pm 22\,^{+19}_{-7}$ | $412 \pm 75\,^{+64}_{-57}$ | $3.5 \pm 4.4\,^{+6.9}_{-1.2}$ | $2.9 \pm 4.0\,^{+1.1}_{-1.2}$ |
| $\pi_1$ | $1623 \pm 47\,^{+24}_{-75}$ | $455 \pm 88\,^{+144}_{-175}$ | $554 \pm 110\,^{+180}_{-27}$ | – |

# Highlights B.11 “Coupled-channel dynamics”:

## PLs: D. Rönchen and B.-S. Zou

Extension of JüBo dynamical coupled-channel model to $K\Sigma$ photoproduction on the proton: EPJ A 58, 229 (2022)

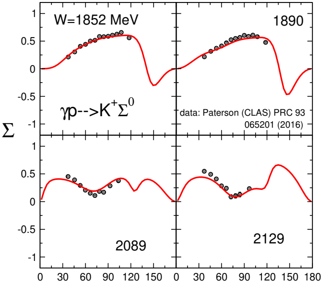
- Simultaneous analysis of $\pi N \to \pi N, \eta N, K\Lambda, K\Sigma$ and $\gamma p \to \pi N, \eta N, K\Lambda, K^+\Sigma^0$ & $K^0\Sigma^+$
- almost 72,000 data points in total, $W_{\text{max}} = 2.4$ GeV

Resonance analysis:

- all 4-star $N$ and $\Delta$ states up to $J = 9/2$ are seen + some states rated less than 4 stars (exception: $N(1895)1/2^-$)
- no additional $s$-channel diagrams had to be included, but indications for new dyn. gen. poles

$\Longrightarrow$ resonance parameters to be included in PDG averages

Selected fit results




Further highlights:

- Prediction of dynamically generated states in coupled $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$ system Zheng-Li Wang *et al.* EPJ C 82 (2022)
  Observation of several bound states, some close to LHCb pentaquarks
- Inclusion of the $\pi N \to \omega N$ channel in JüBo DCC model Yu-Fei Wang *et al.* PRD 106, 094031 (2022)
- In progress: JüBo DCC analysis of $\bar{K}N$ system (PhD S. Rawat): $S = -1$ hyperon resonance spectrum

# Computing transverse momentum dependent PDFs

$$f^{TMD}(x,b_\perp,\mu,\zeta) = H(\zeta_z,\mu)e^{-\ln\left(\frac{\zeta_z}{\zeta}\right)K(b_\perp,\mu)}S_r^{\frac{1}{2}}(b_\perp,\mu)f^{qTMD}(x,b_\perp,\mu,\zeta_z),$$

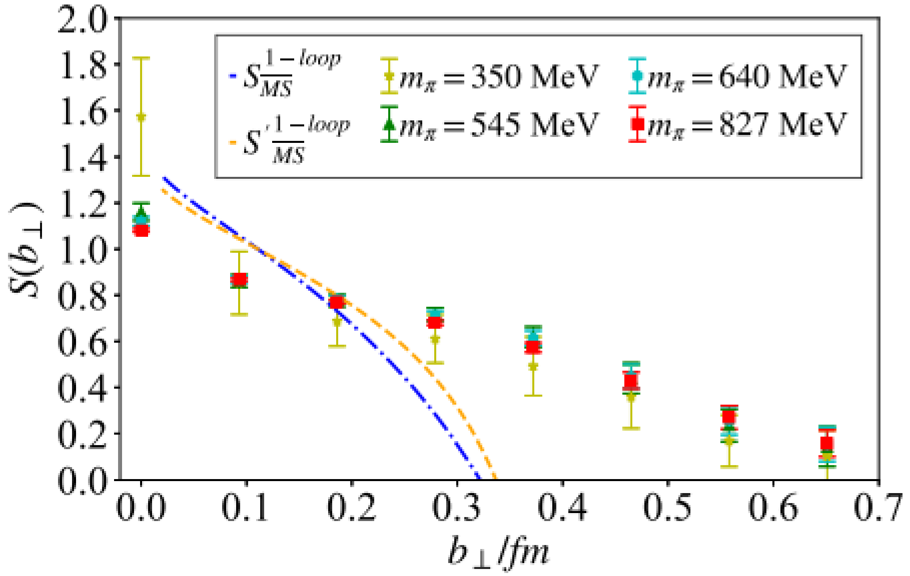
$\zeta$ : Collins-Soper scale

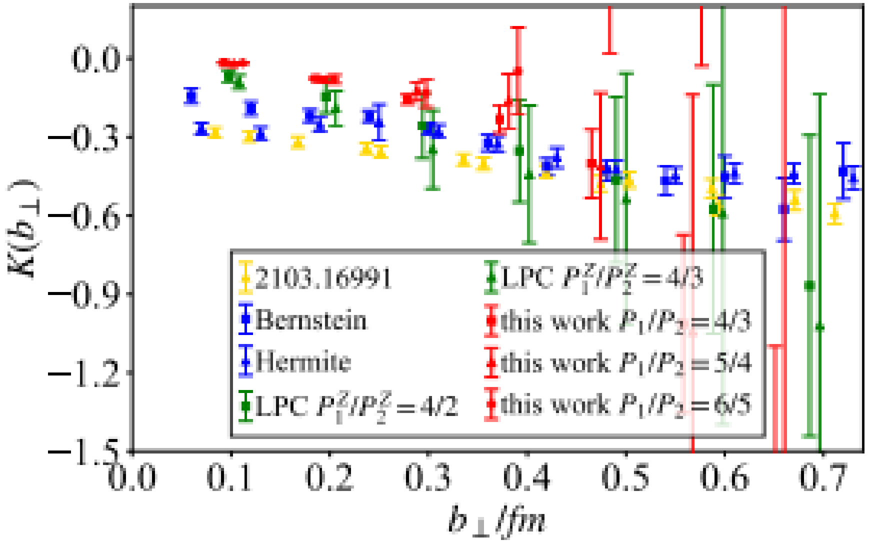
$K(b_\perp,\mu)$ : Collins-Soper kernel

Perturbative matching kernel

Computed in lattice QCD, with staple-shaped link

Reduced Soft function, computed in LQCD




PRL 128 (2022) 062002

Missing ingredient: the quasi-TMD PDF, $f^{qTMD}(x,b_\perp,\mu,\zeta_z)$

Its computation is underway, arXiv: 2305.11824