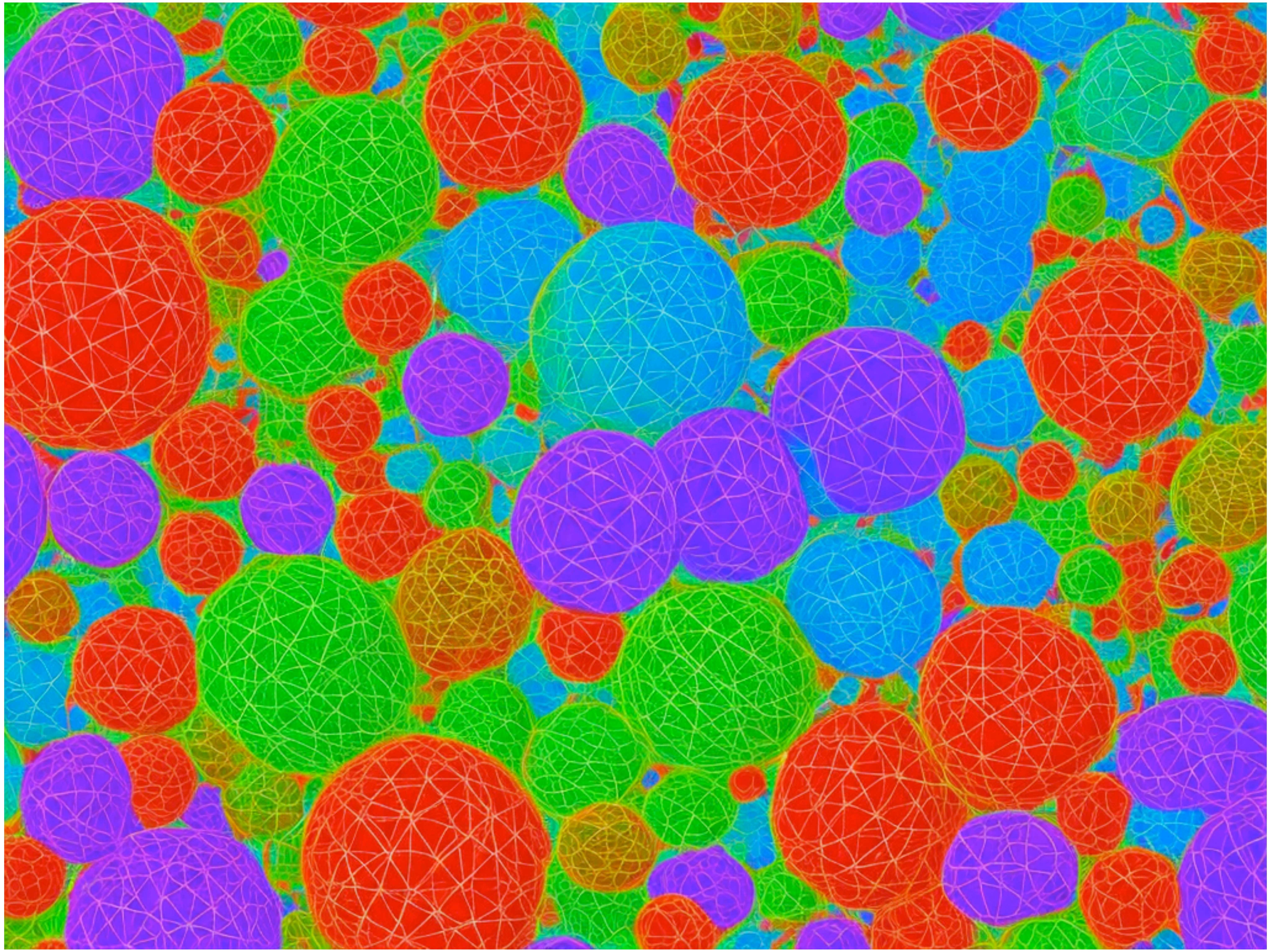
(image courtesy of Stable Diffusion)

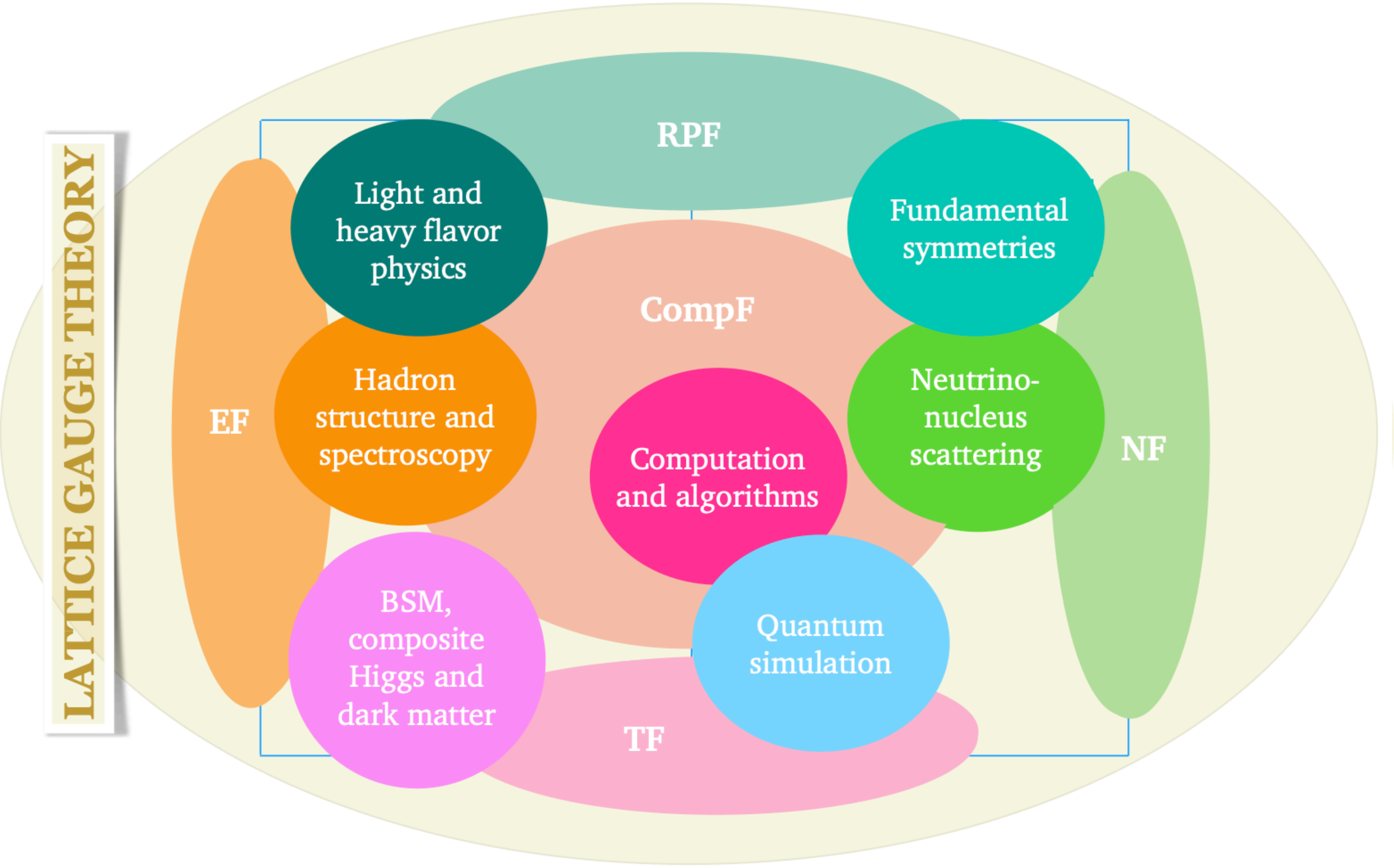


Lattice field theory and high-energy physics

Ethan T. Neil (Colorado)
P5 Town Hall - SLAC
May 4, 2023

Overview

- **Lattice field theory** is a non-perturbative and computational approach to particle theory calculations. Numerical, precise, systematically improvable! It provides:
  - Predictions for present and future experiments where QCD is involved;
  - Exploration of strongly-coupled quantum field theory more broadly. (QCD is the only example we have so far in the lab!)
- **Deep connections** across theoretical particle physics, and with many experimental efforts at hadron colliders, rare/precision searches, neutrino experiments, and more!



(from Z. Davoudi/Snowmass Report on Lattice Field Theory, arXiv:2209.10758)

What are some things lattice QFT can calculate?

- Leptonic decay constants, e.g. f_D, f_B (CKM, NP)
- Semi-leptonic form factors, e.g. D->Klν (CKM, NP)
- Hadronic contributions to muon (g-2)
- Other SM parameters: quark masses, α_s (Higgs physics)

- Nucleon EDMs and B/L violating processes
- Various nuclear form factors/charges (νN, dark matter)
- Parton distribution functions (νN, LHC)
- Multi-nucleon systematic effects

- Theoretical frameworks: large-Nc expansion, holography, …
- BSM models: composite Higgs, composite dark matter, …
- Emergent symmetries and phases: conformal symmetry, symmetric mass generation, …

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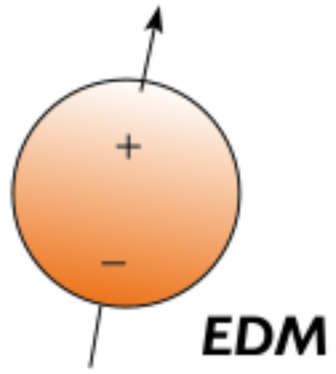

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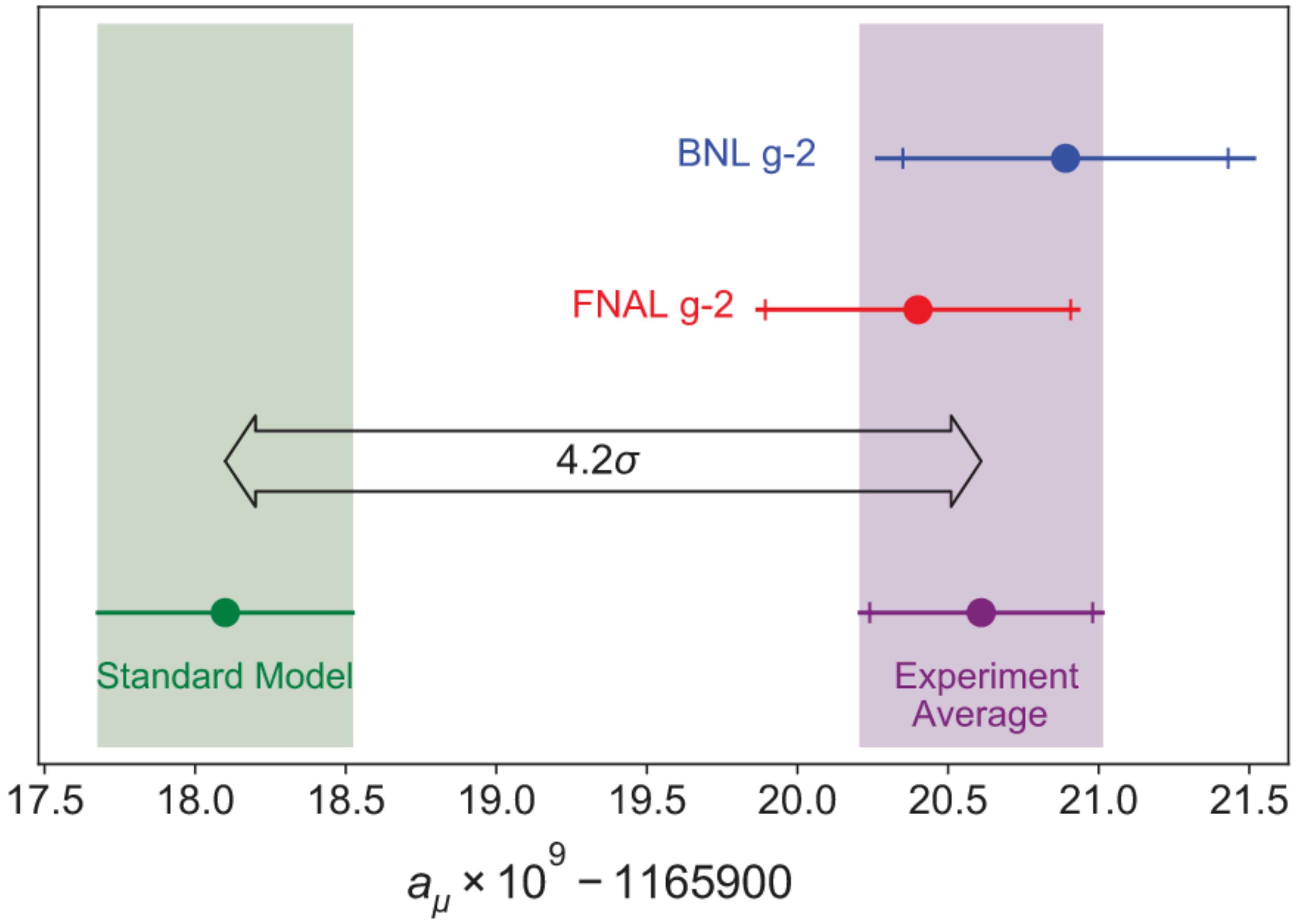
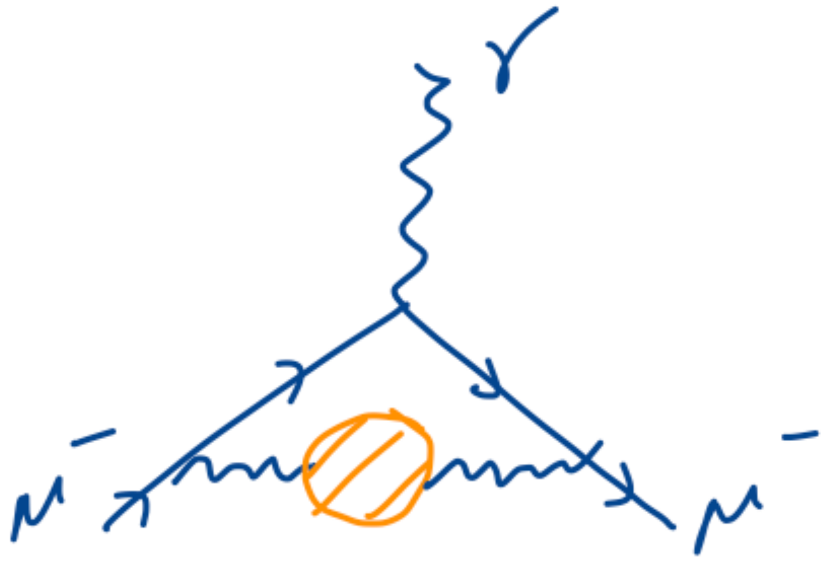
(see talk by A. El-Khadra, Fermilab/Argonne P5 Town Hall)

Highlight: muon (g-2)

(plot from Muon (g-2) Experiment)



- Comparison between theory and experiment with precision ~**100 ppb**; one of the most precise tests in all of science, maybe new physics!
- To clarify, must reduce Standard Model uncertainty from QCD corrections: HVP (bottom left), HLbL (top right)



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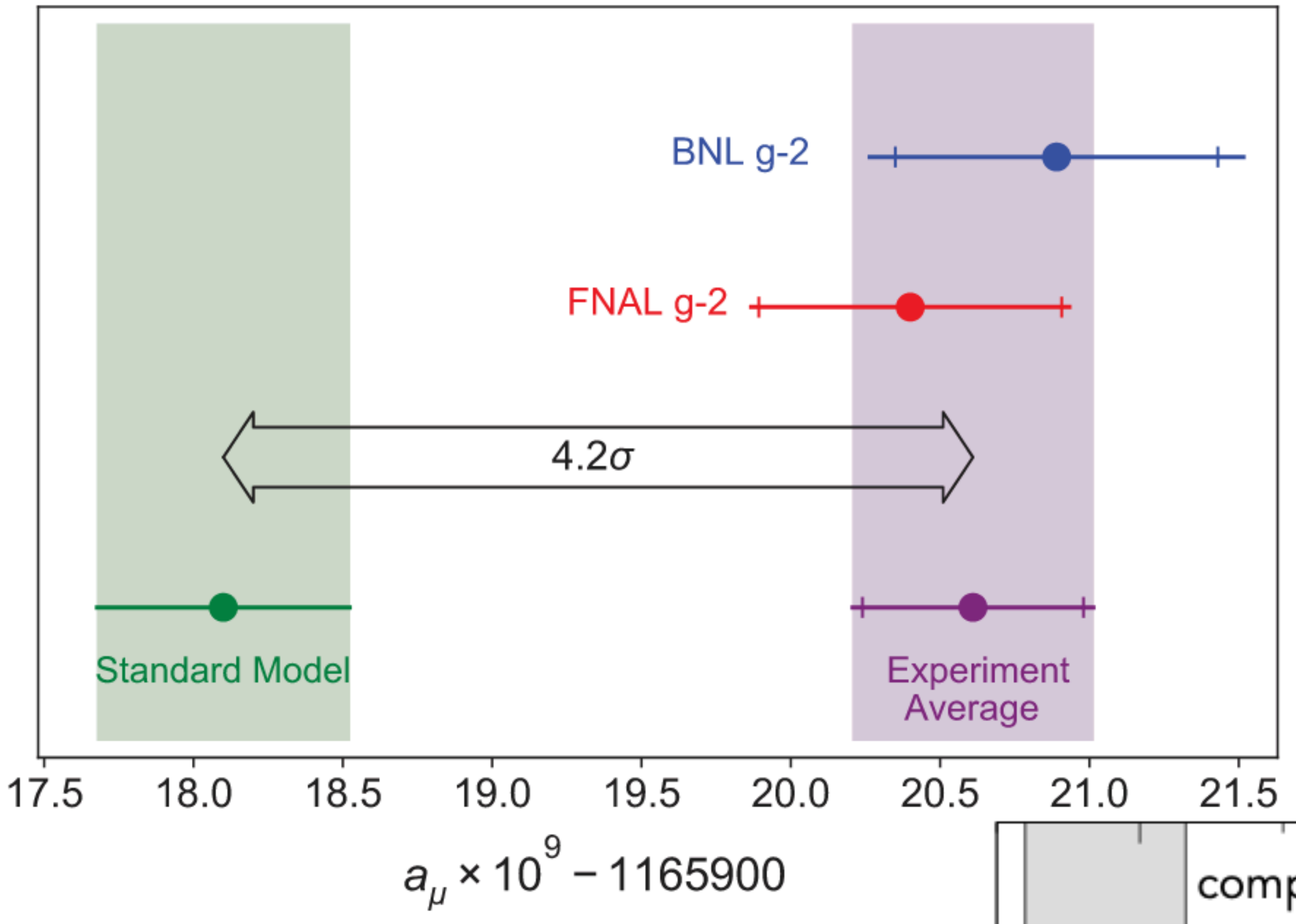

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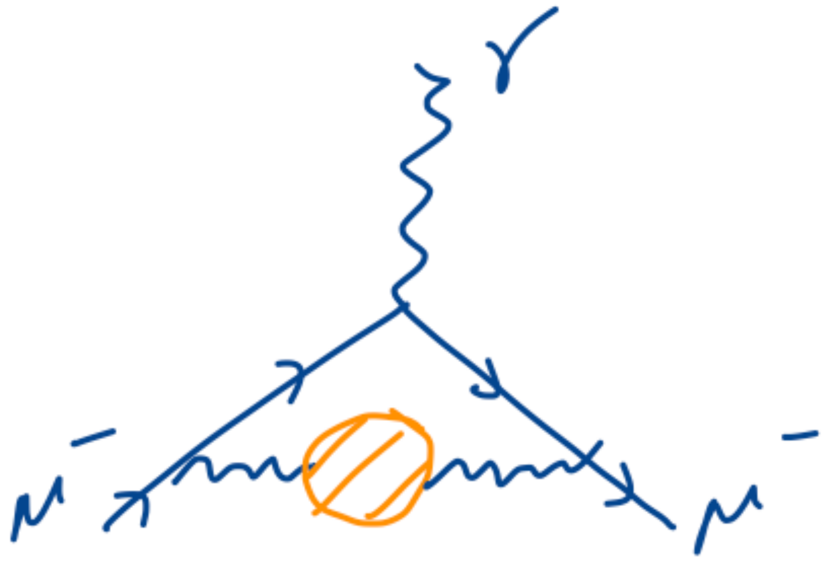

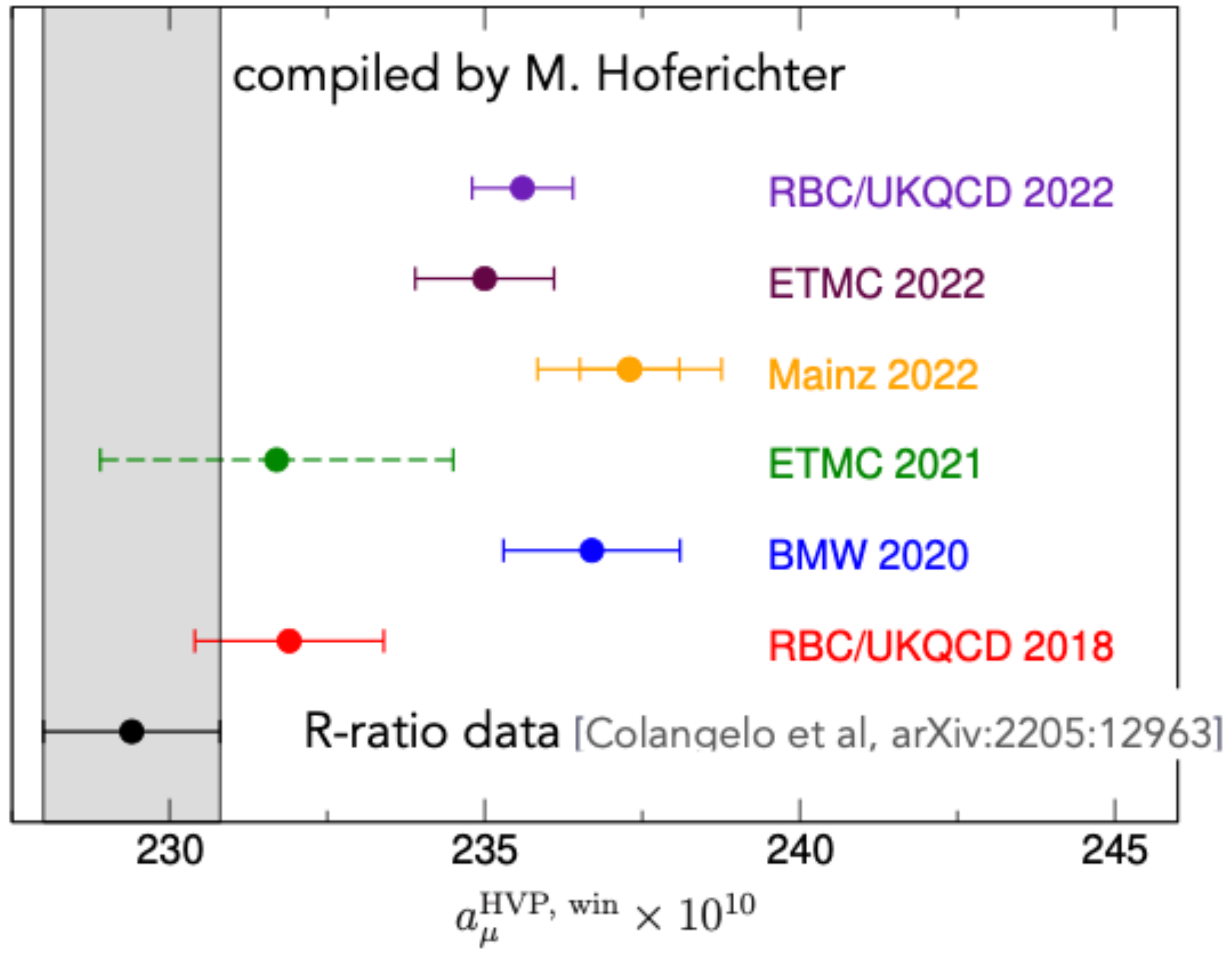

- *Left*: growing tension between lattice QCD and data-driven HVP in intermediate-energy "window". Further lattice study may help to clarify experimental picture.

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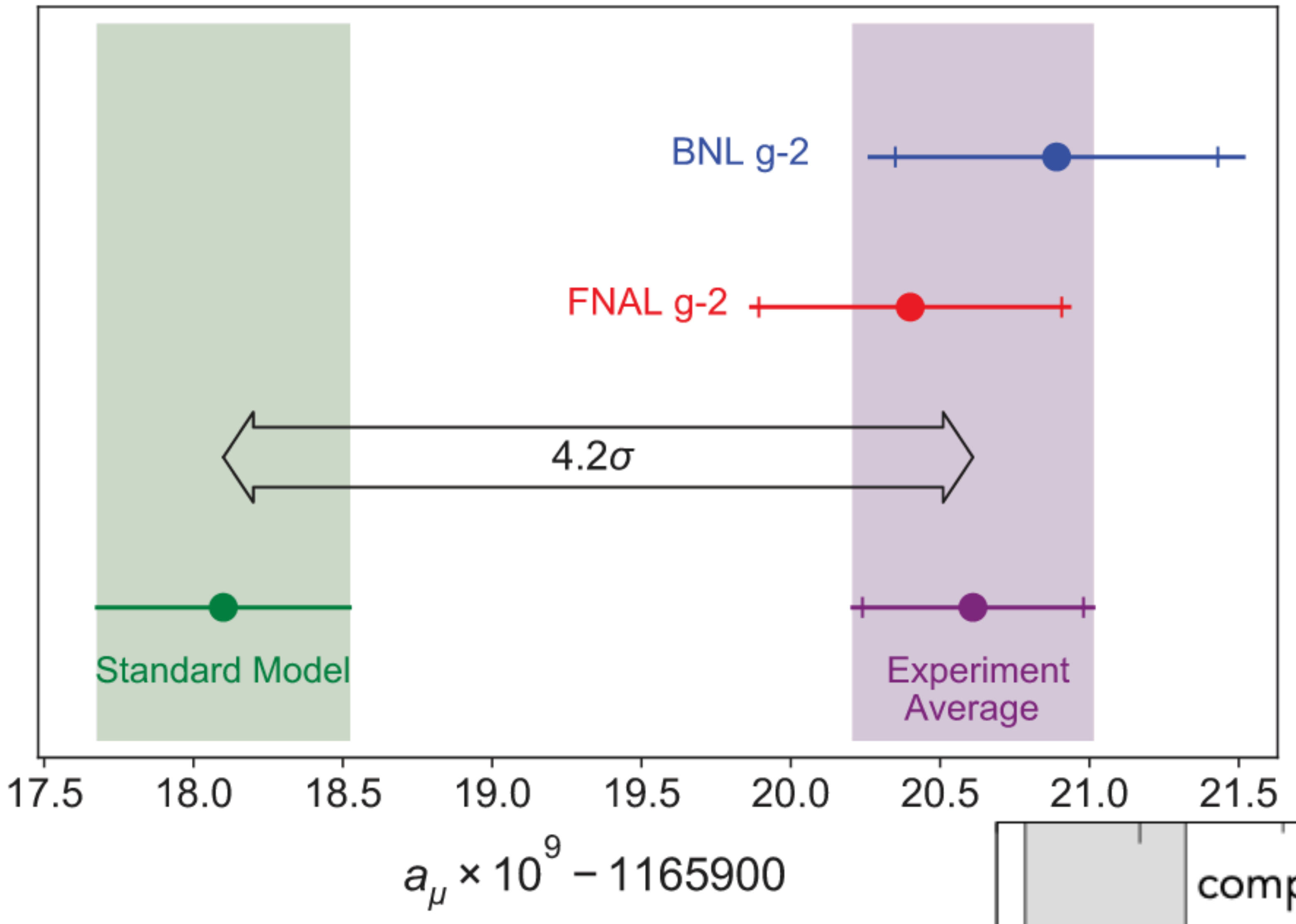

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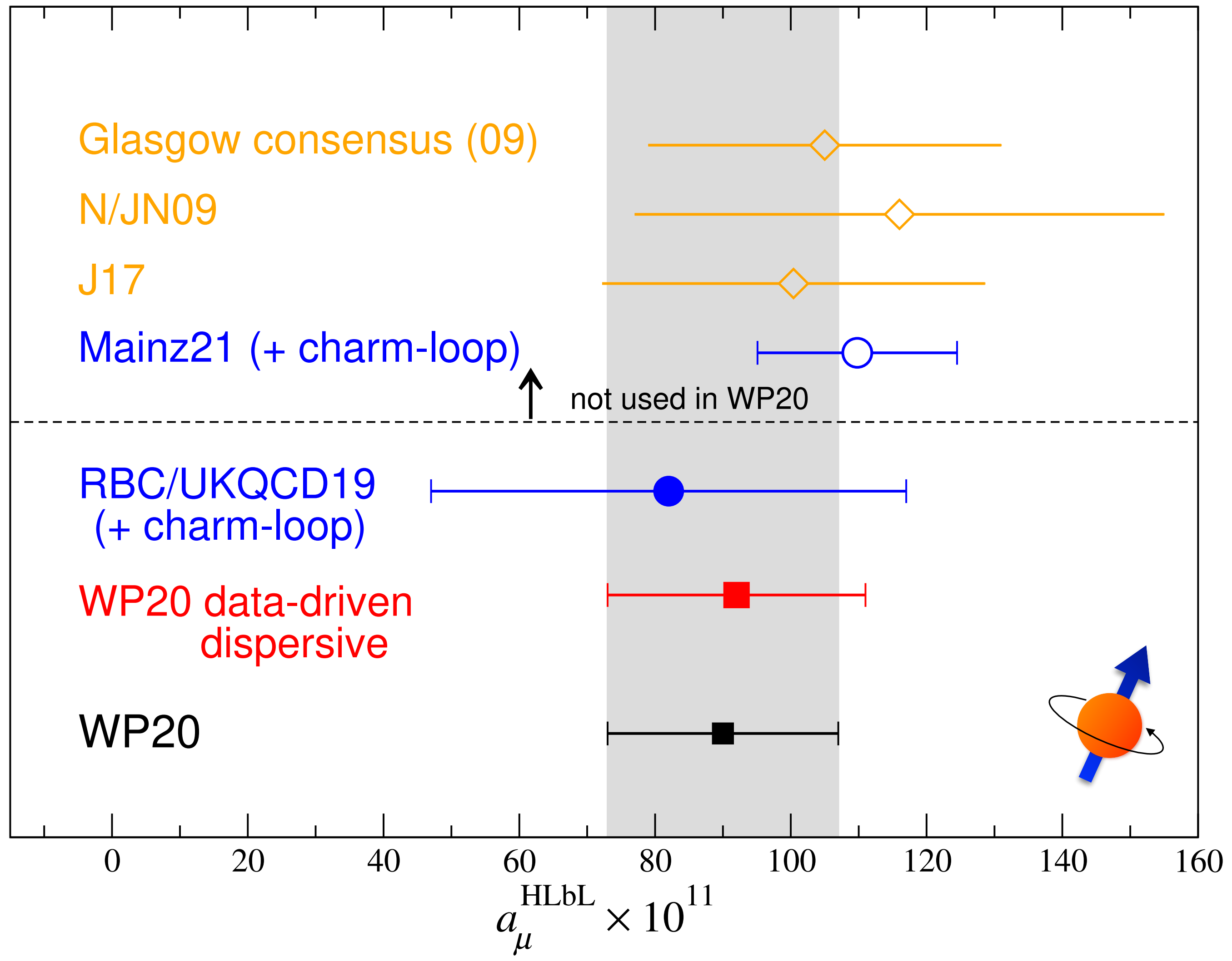
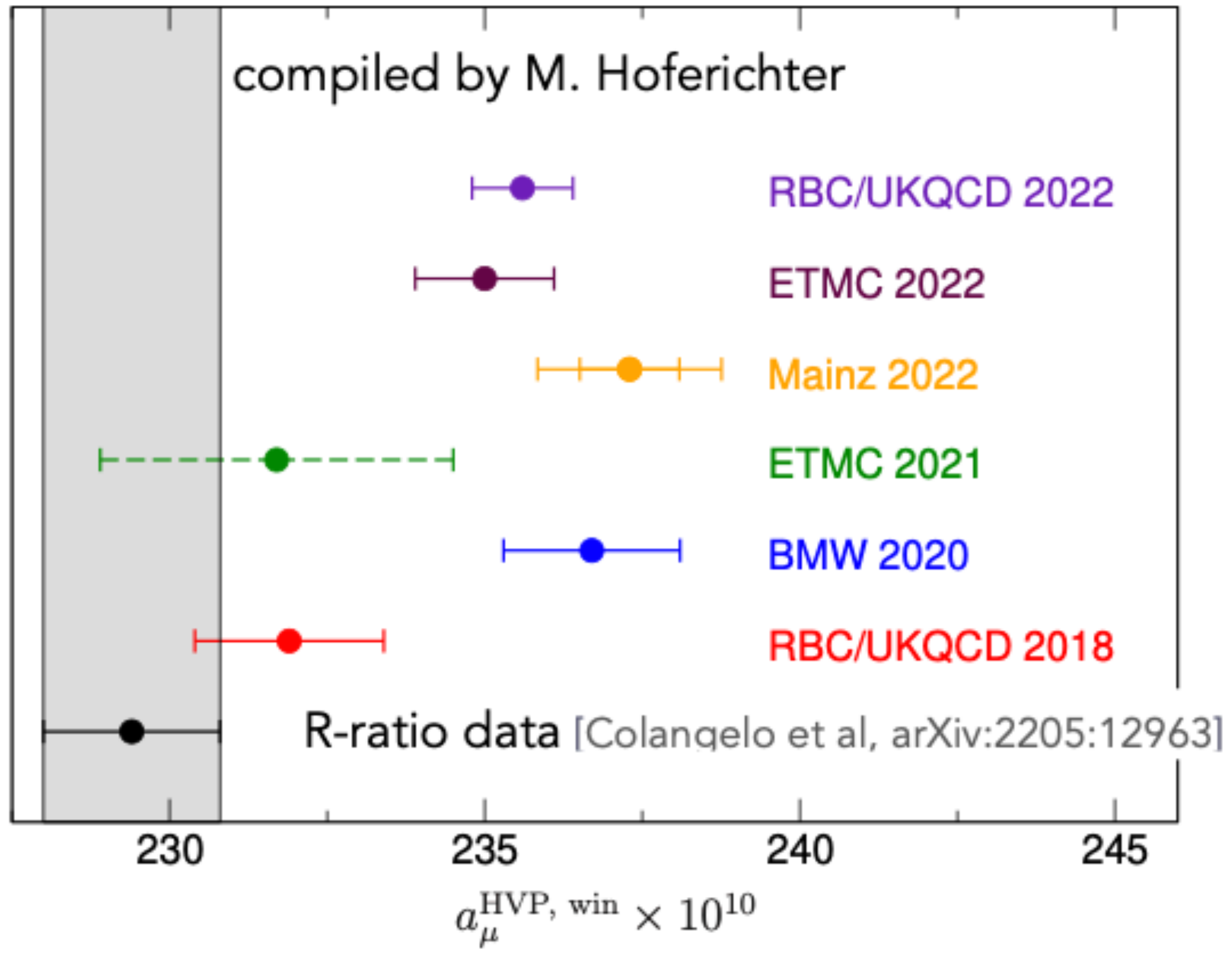
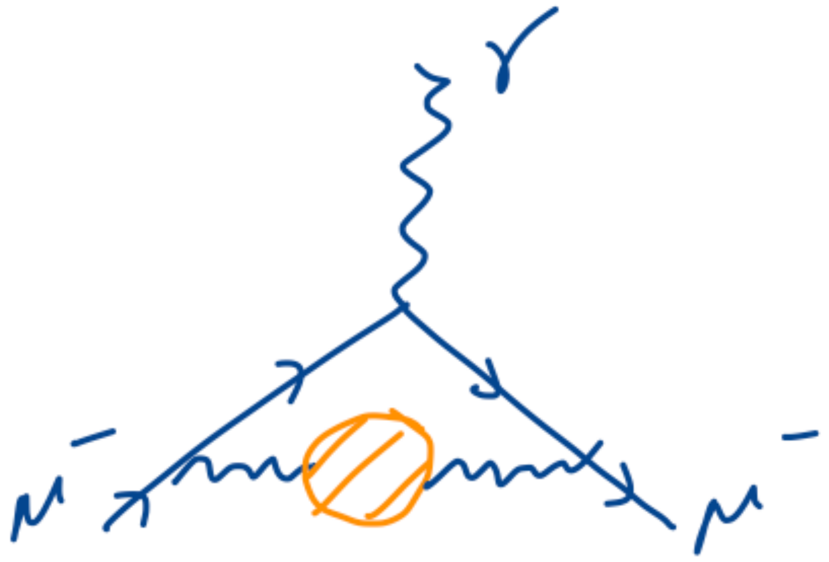
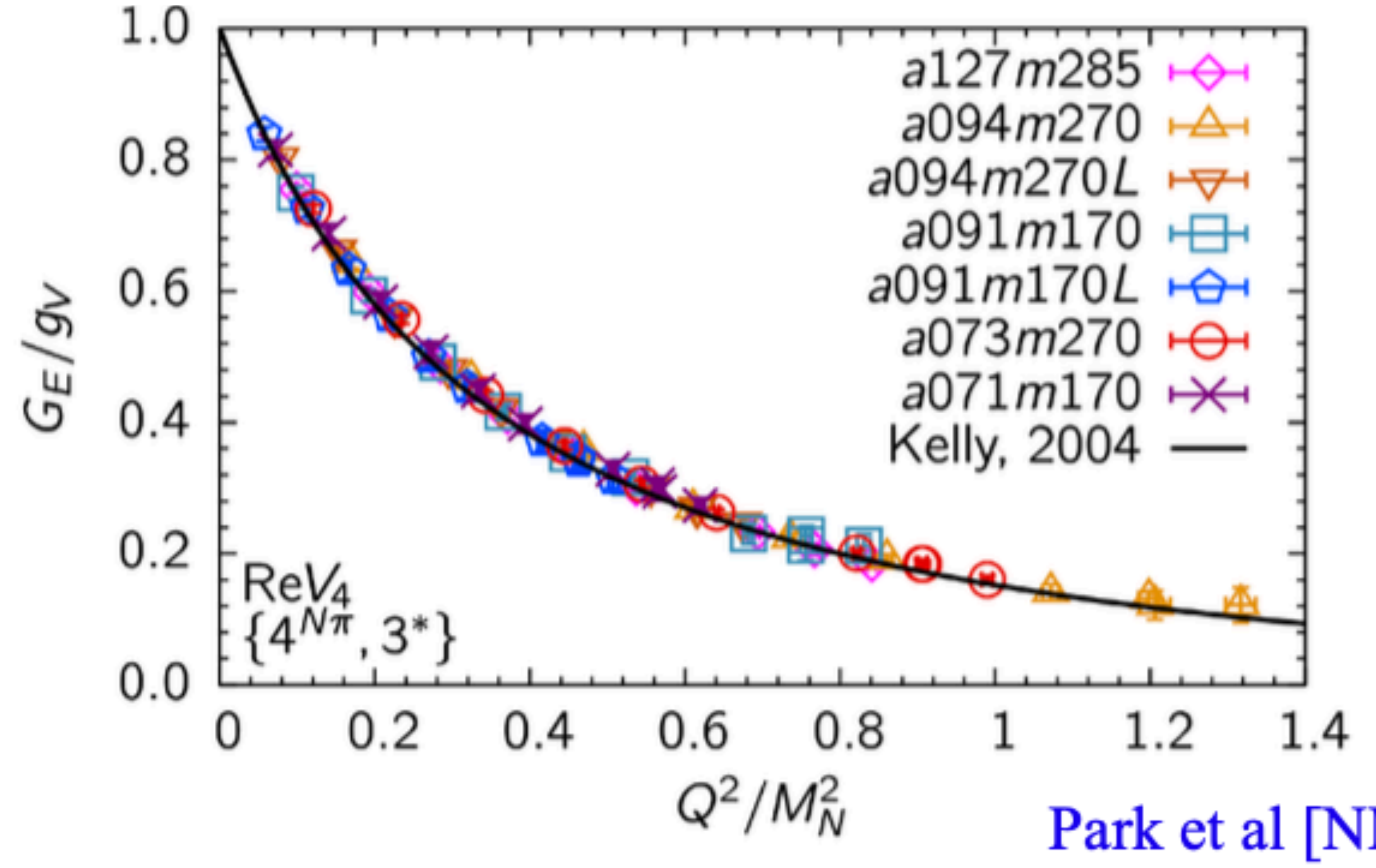


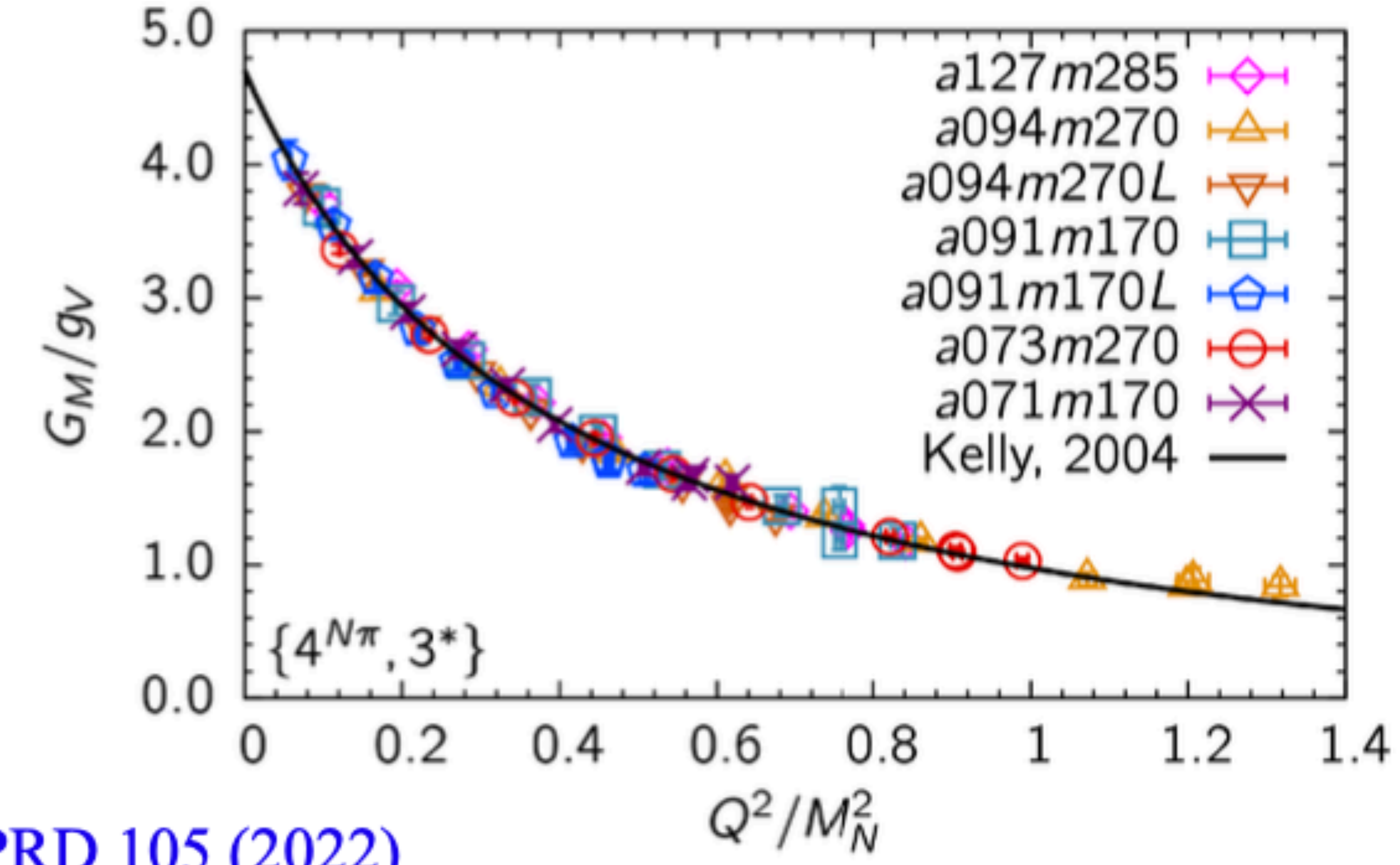


- *Left*: growing tension between lattice QCD and data-driven HVP in intermediate-energy "window". Further lattice study may help to clarify experimental picture.
- *Above*: lattice light-by-light already commensurate precision with other analytic/dispersive estimates. Important confirmation!

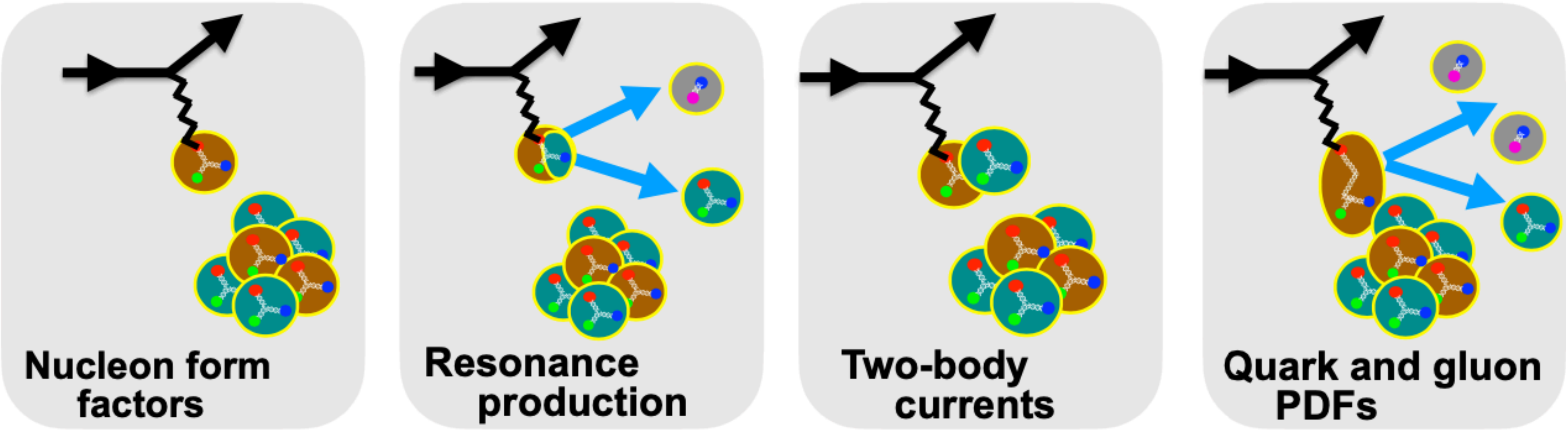


Highlights: form factors





Park et al [NME], PRD 105 (2022)

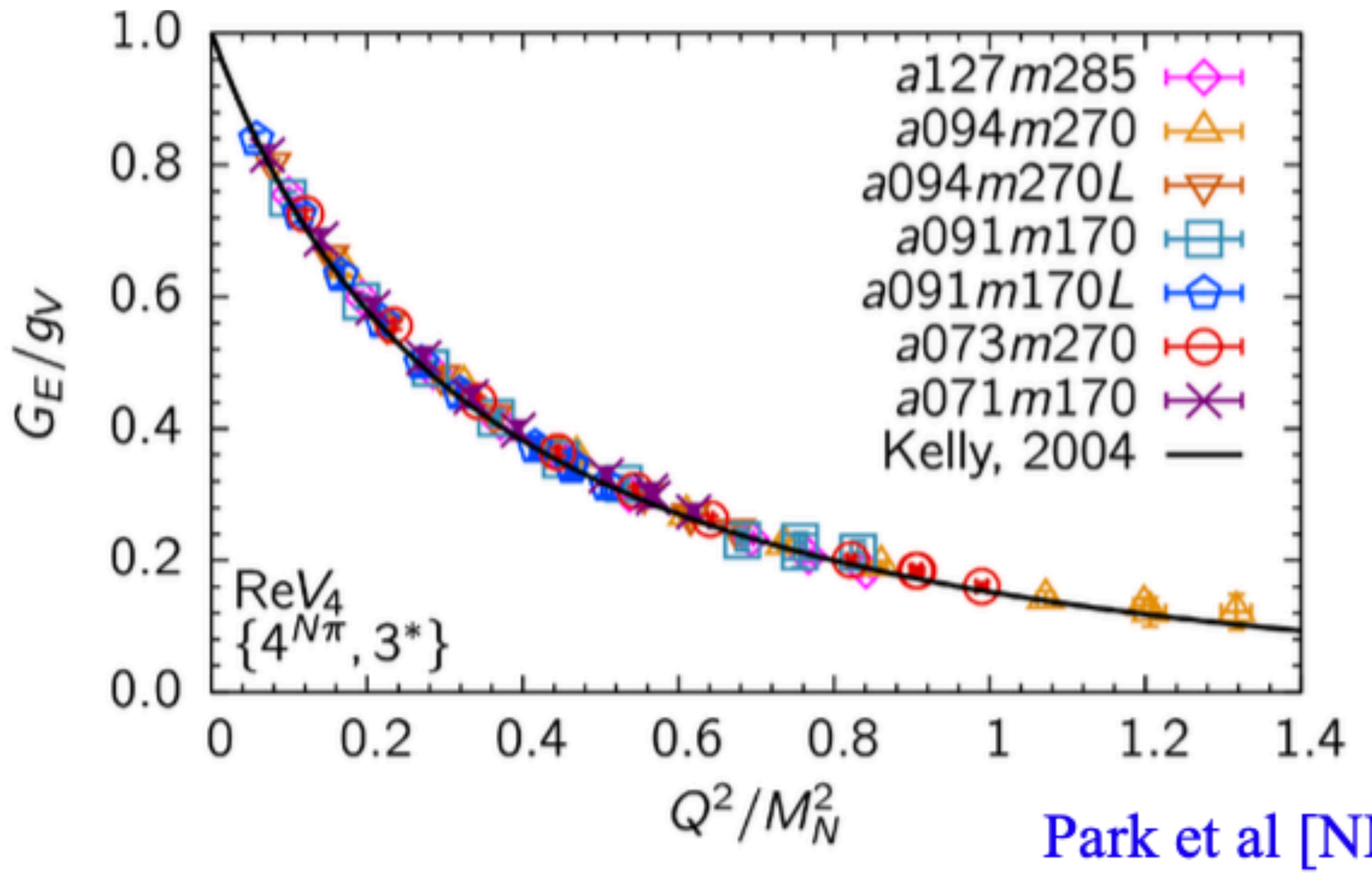


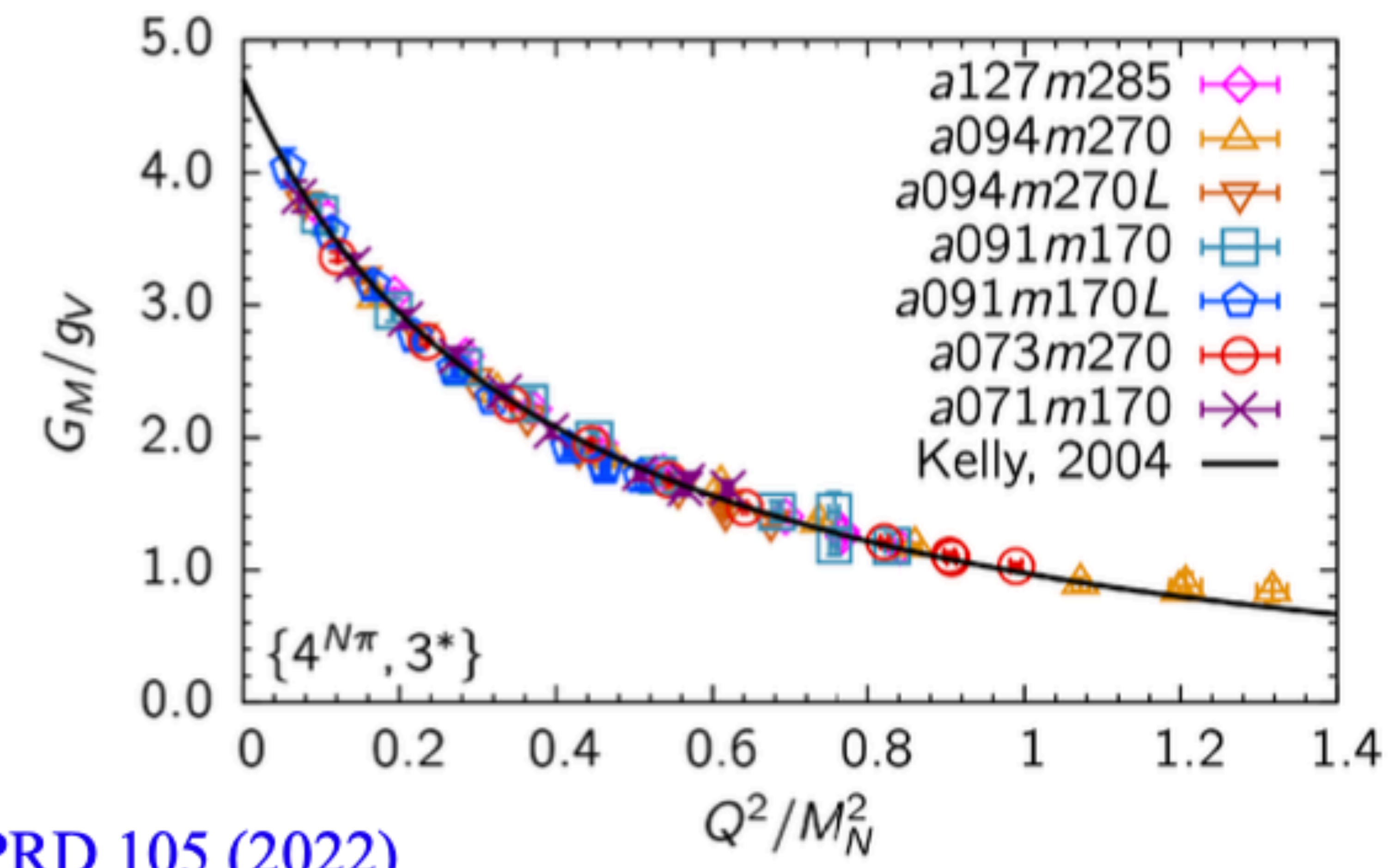
- *Left:* Neutrino-nucleon interactions have inputs from many processes at many scales. Lattice can contribute to understanding of all processes; single-nucleon form factors are most straightforward

Highlights: form factors

(LQCD result: S. Meinel **2016**, 1611.09696)

(Data: BES-III experiment, **2022**, 2207.14149)





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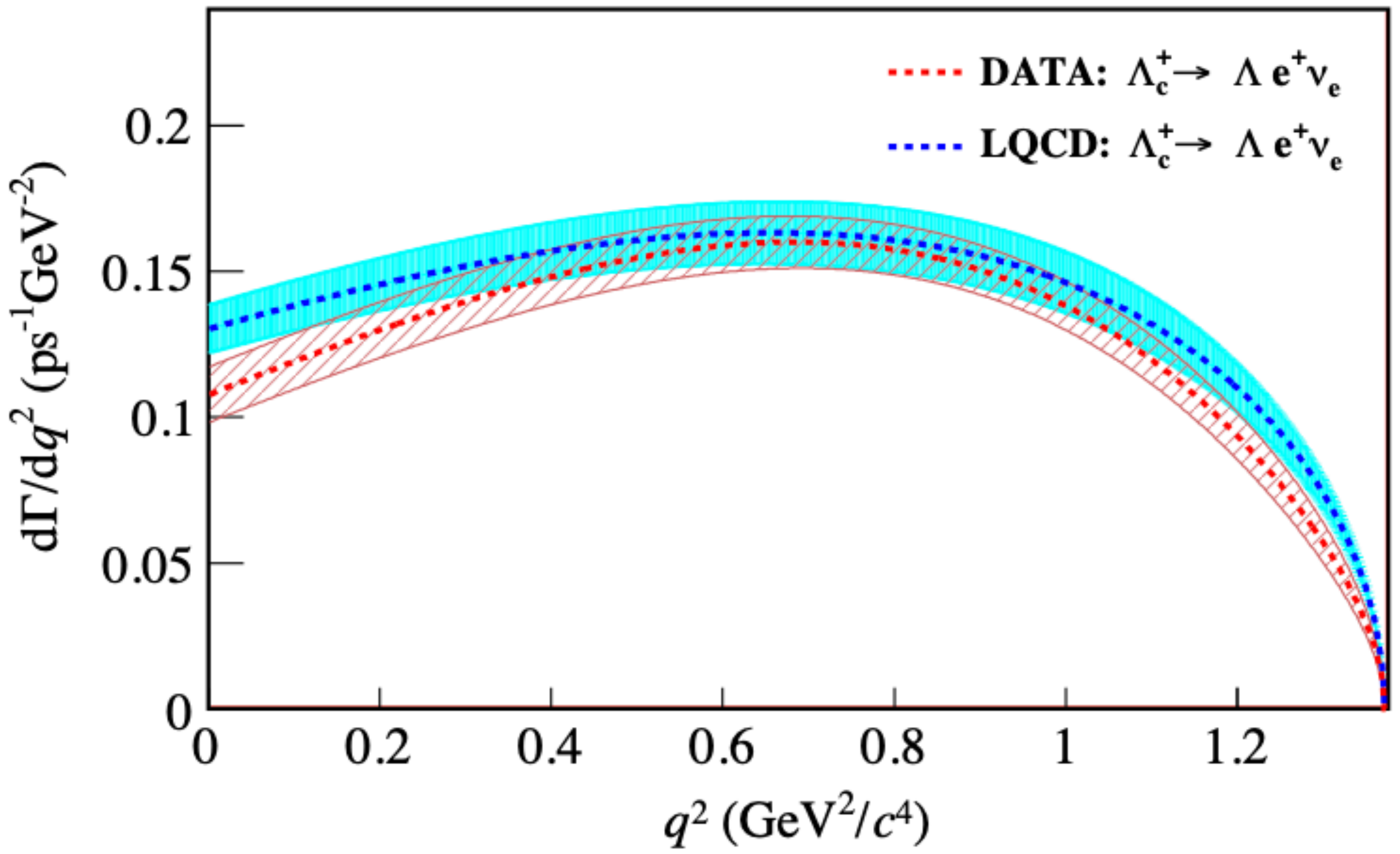

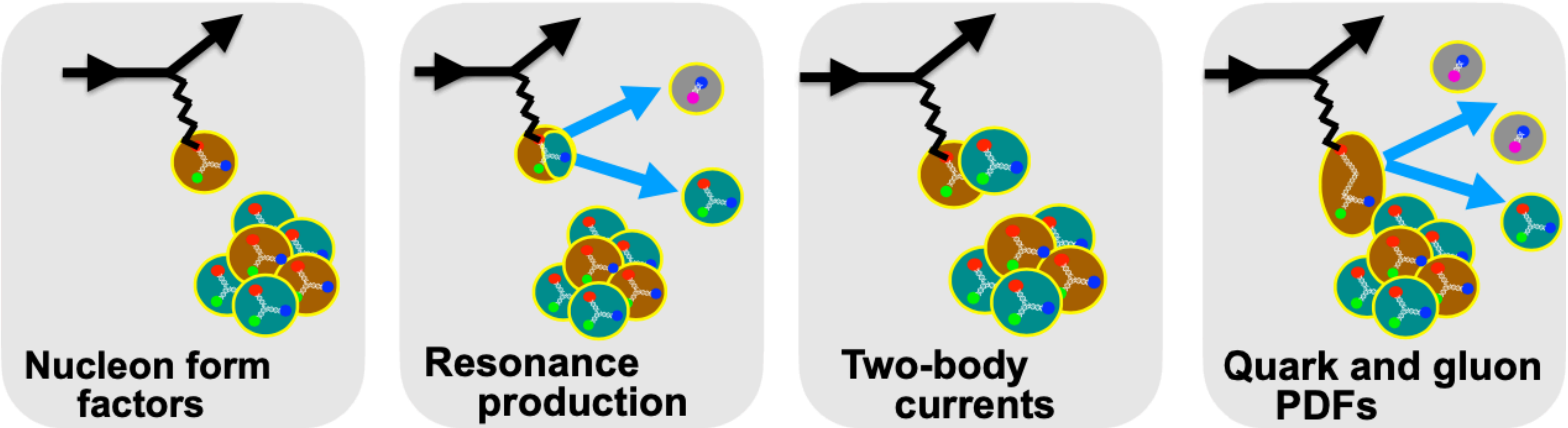

- *Left:* Neutrino-nucleon interactions have inputs from many processes at many scales. Lattice can contribute to understanding of all processes; single-nucleon form factors are most straightforward
- *Top:* Lambda baryon decay, form factor was predicted on lattice first (2016) and verified by experiment in 2022. Lattice result enables extraction of $|V_{cs}|$ from expt!

Highlights: beyond the Standard Model

- Lattice provides a way to learn about strongly-coupled QFTs more broadly - a “**numerical laboratory**”.

- Can be “top-down”, studying a particular new-physics theory (e.g. composite dark matter); or “bottom-up” studying classes of theories (e.g. large-Nc expansion, holography); or, just **pure exploration**!

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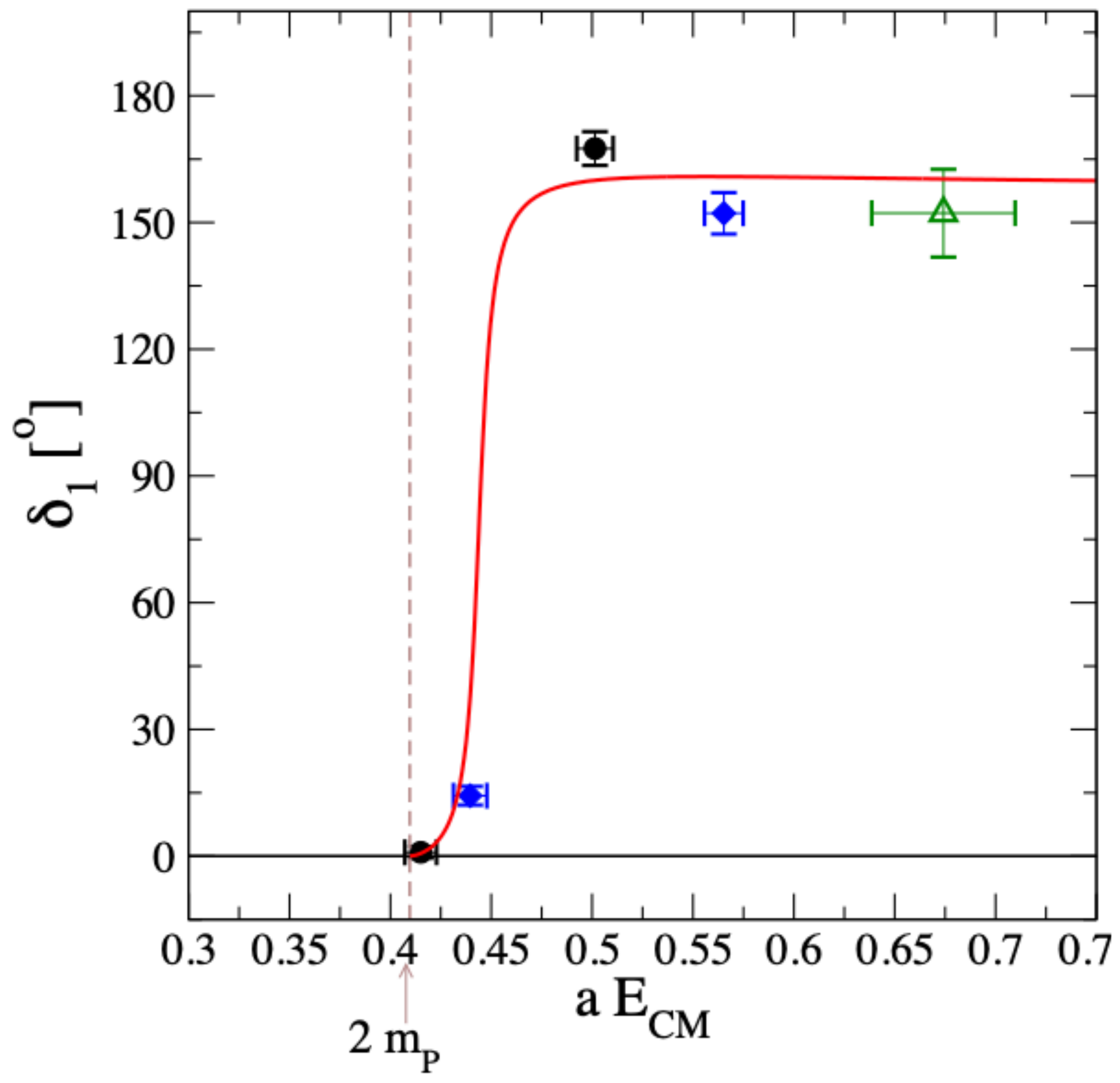
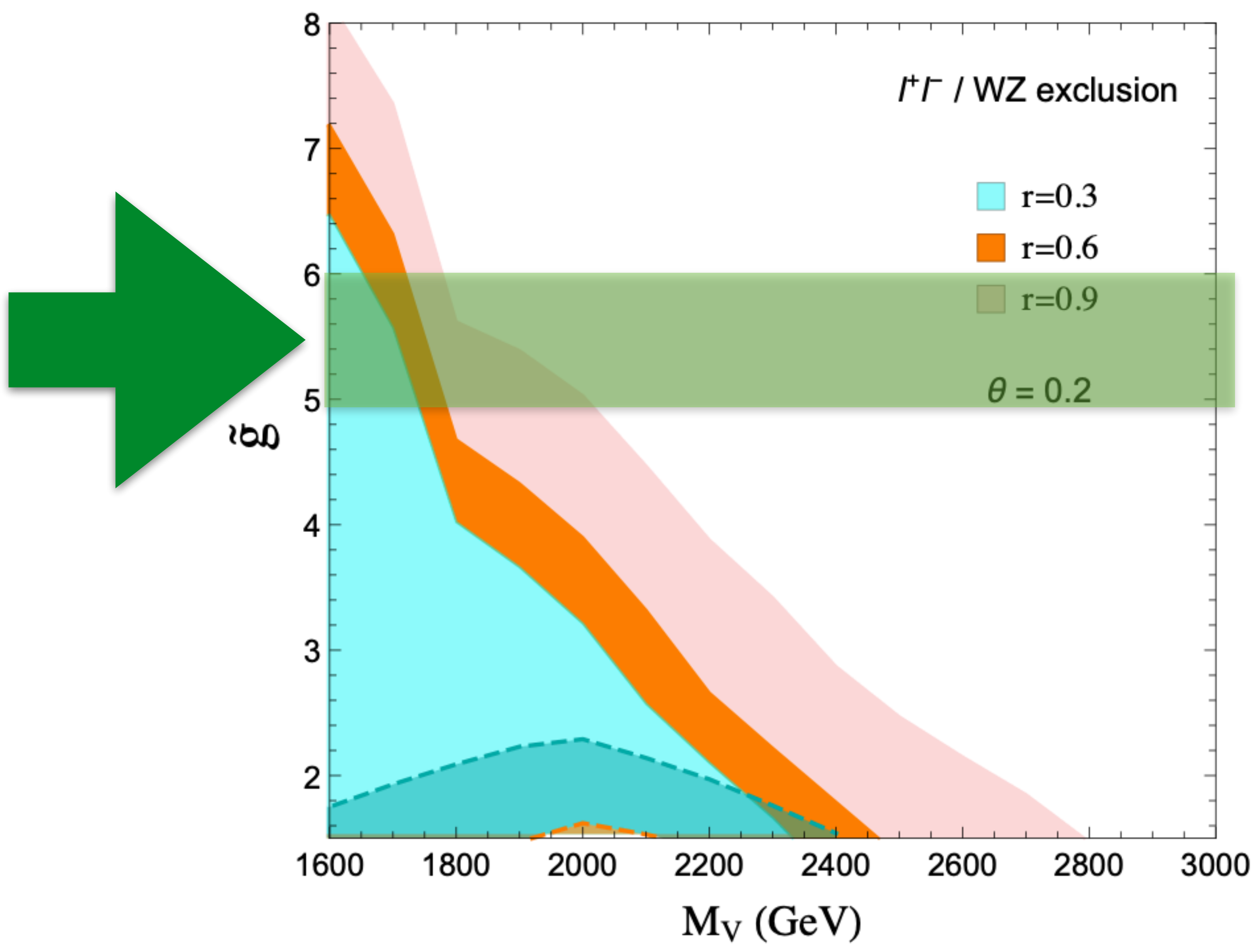


(Drach et al, arXiv:2012.09761)



(Franzosi et al, arXiv:1605.01363)

- *Left:* SU(2), Nf=2 "minimal composite Higgs". Lattice calculation of ρ-π-π resonance coupling (left) **constrains ATLAS bounds** from LHC (WZ search) in mass/coupling space.

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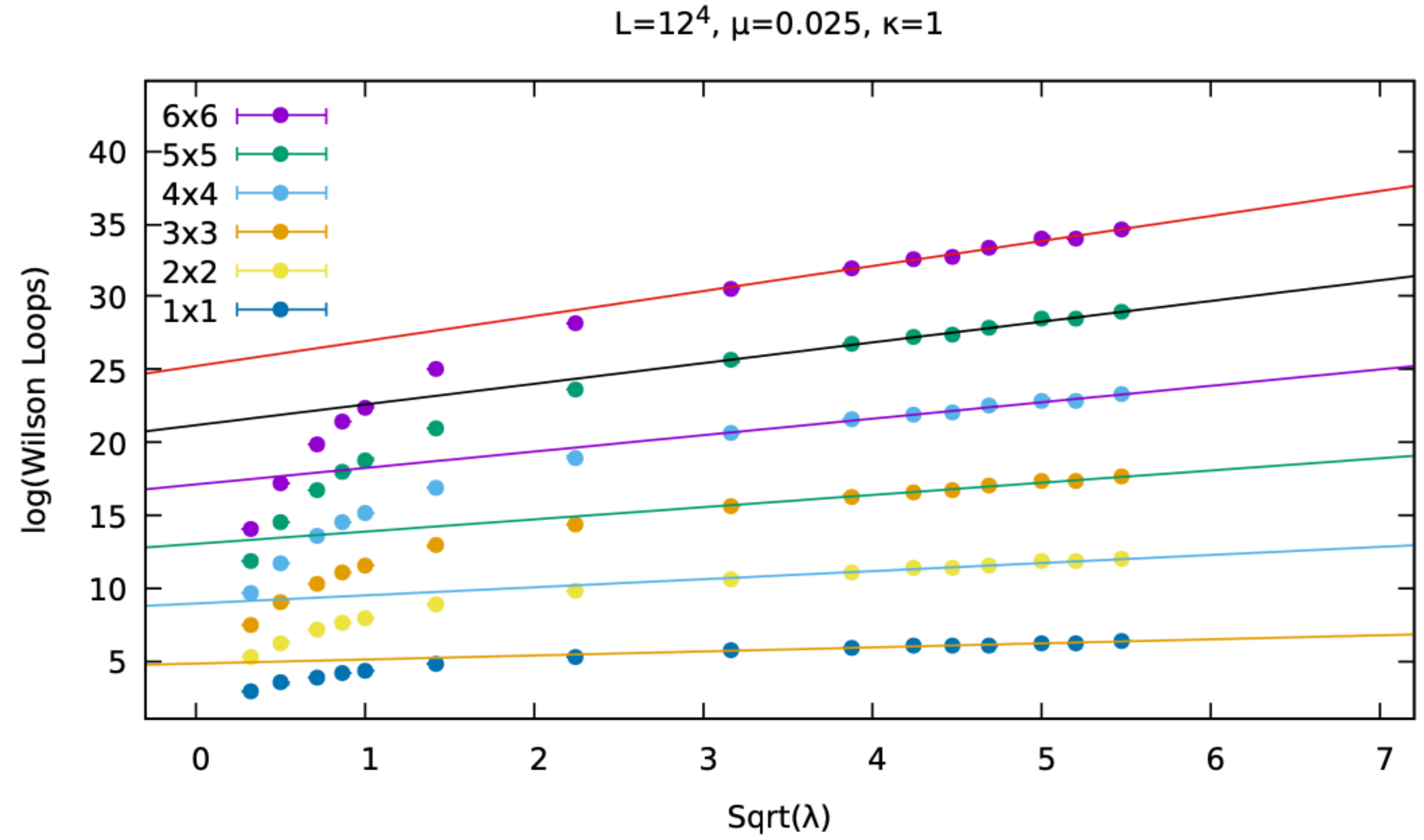
(Snowmass WP on lattice SUSY, Catterall and Giedt, arXiv:2202.08154)



- *Above:* scaling of Wilson loops vs. 't Hooft coupling λ, from lattice; lines show **holography-predicted**, *non-perturbative* scaling behavior.
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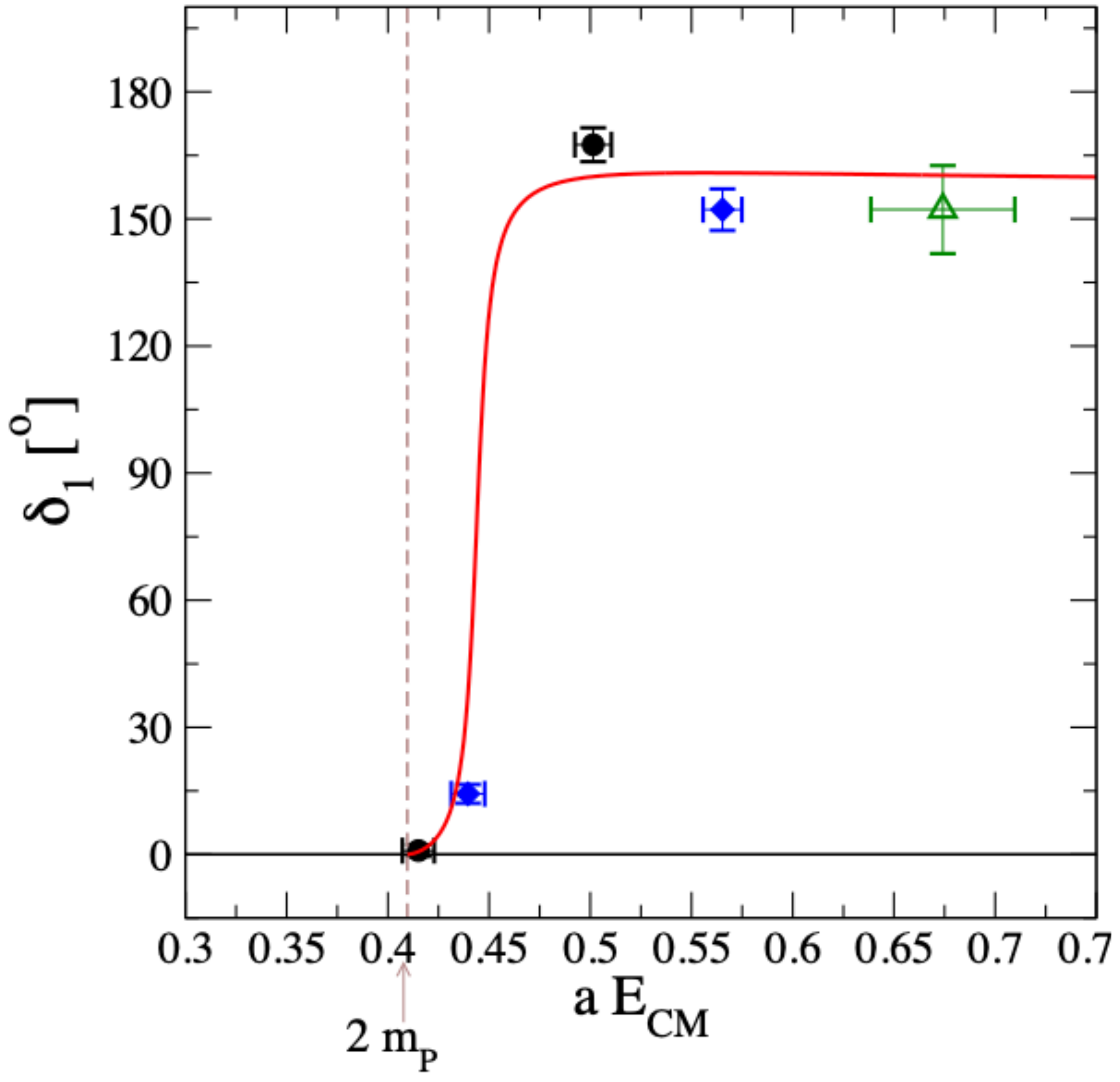

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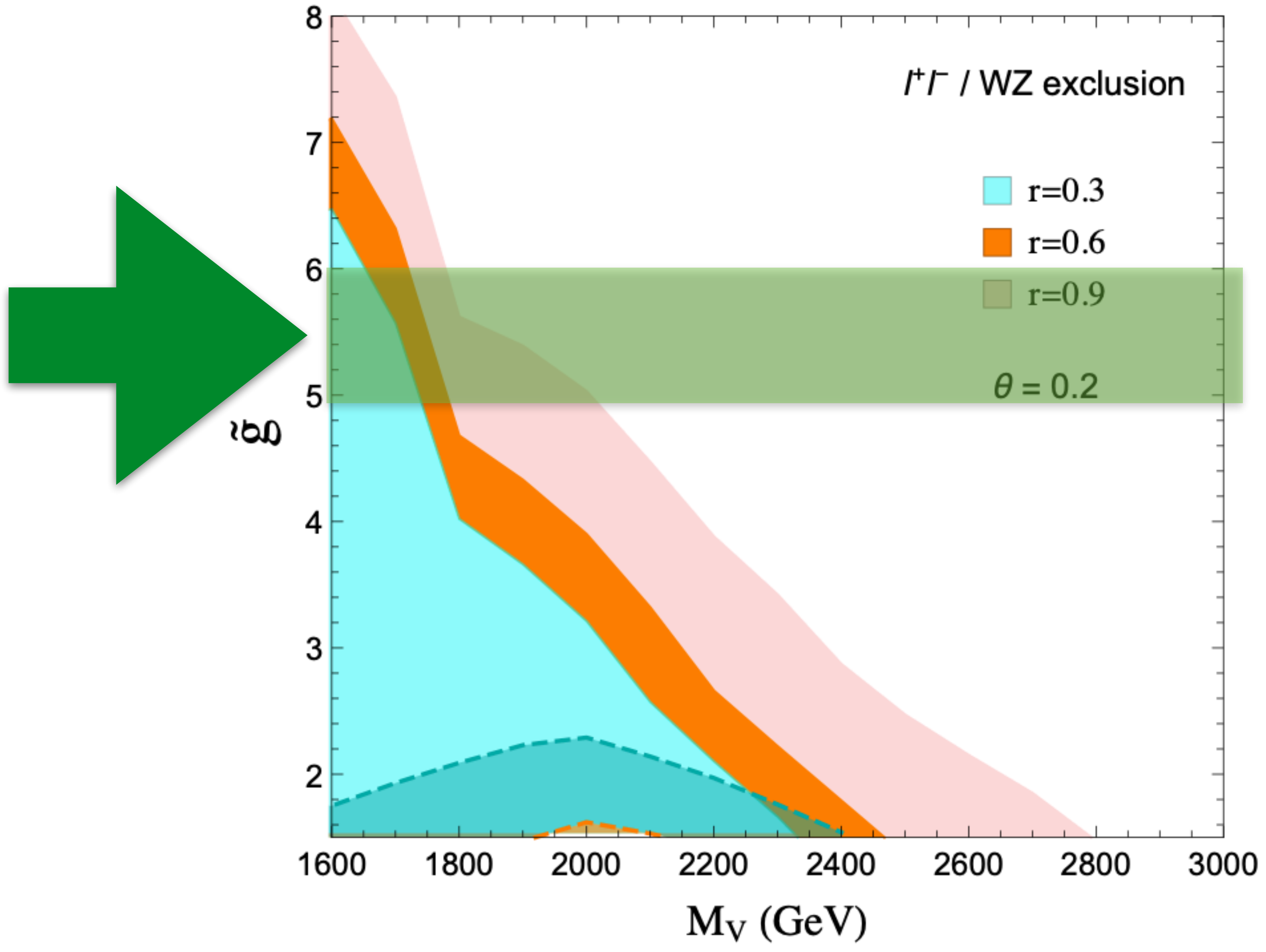

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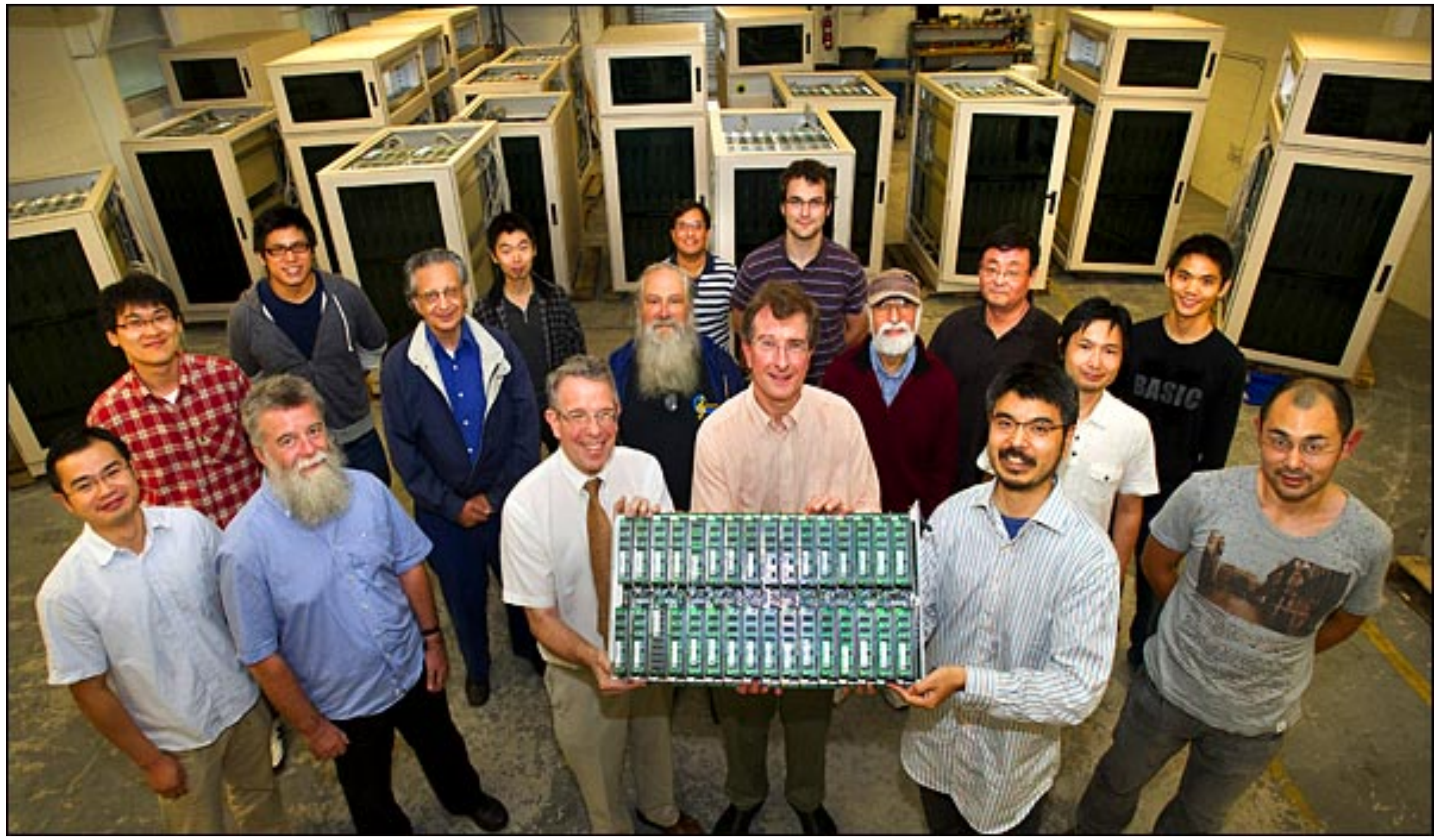
Resource needs for lattice theory

- As with theory overall, the greatest resource needed is **people** - a healthy career pipeline from grad students to senior researchers.
- In addition, the health of lattice field theory relies on **computing** at all scales - from small clusters to leadership-class supercomputers.
- *Synergistic relationship* between lattice field theory and high-performance computing; lattice theorists drive developments, growing resources enable new calculations. (e.g. MILC LQCD code is used for benchmarking; involvement in Exascale Computing Project.)

(Lattice researchers and the retired QCDOC, BNL news, 10/31/11)



Resource needs for computational HEP

- This talk is from a lattice theorist's perspective, but a similar picture of resource needs applies **broadly to computational theory in HEP** (including conformal bootstrap, event generators, broader ML/AI applications, and more!)

(from "The Present and Future of QCD", NSAC Long Range Plan Whitepaper, arXiv:2303.02579)

Recommendation 4: Computing *(Yes: 302; No: 20; No Answer: 20)*

High-performance and high-throughput computing are essential to advance nuclear physics at the experimental and theory frontiers. Increased investments in computational nuclear physics will facilitate discoveries and capitalize on previous investments.

basic theory/R&D →

- We recommend increased investments for software and algorithm development, including in AI/ML, by strengthening and expanding programs and partnerships, such as the DOE SciDAC and NSF CSSI and AI institutes.
- We recommend increased support for dedicated high-performance and high-throughput mid-scale computational hardware and high-capacity data systems, as well as expanding access to leadership computing facilities.
- Advanced computing is an interdisciplinary field. We recommend establishing programs to support the development and retention of a diverse multi-disciplinary workforce in high-performance computing and AI/ML.

← computing at all scales

workforce development ↗

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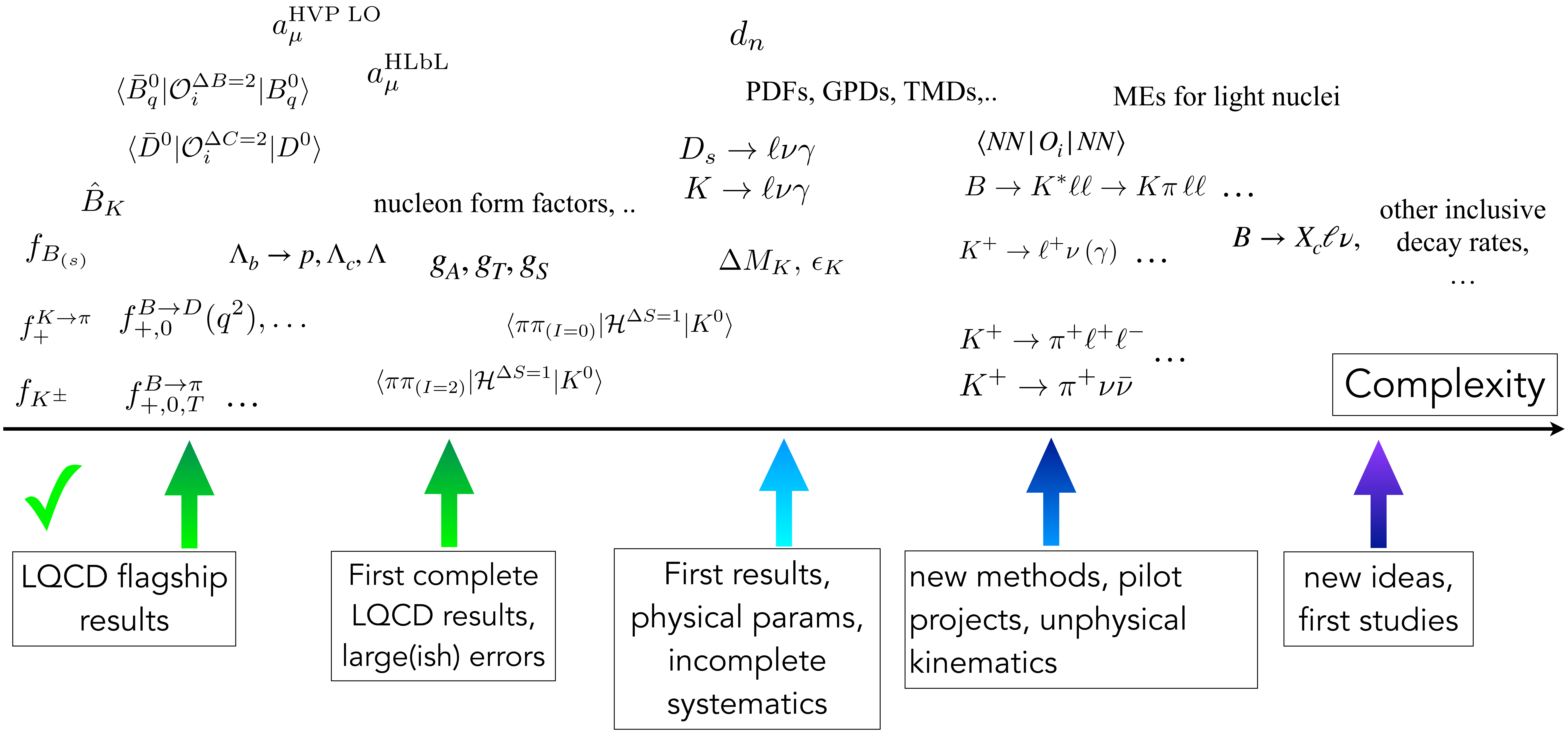
(plot courtesy of A. El-Khadra, Fermilab/Argonne P5 Town Hall)



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$a_\mu^{\text{HVP LO}}$ d_n

$\langle \bar{B}_q^0 | \mathcal{O}_i^{\Delta B=2} | B_q^0 \rangle$ a_μ^{HLbL} PDFs, GPDs, TMDs,.. MEs for light nuclei

$\langle \bar{D}^0 | \mathcal{O}_i^{\Delta C=2} | D^0 \rangle$ $D_s \to \ell\nu\gamma$ $\langle NN | O_i | NN \rangle$

$\hat{B}_K$ nucleon form factors, .. $K \to \ell\nu\gamma$ $B \to K^*\ell\ell \to K\pi\,\ell\ell\ \ldots$

$f_{B_{(s)}}$ $\Lambda_b \to p, \Lambda_c, \Lambda$ g_A, g_T, g_S $\Delta M_K,\ \epsilon_K$ $K^+ \to \ell^+\nu\,(\gamma)\ \ldots$ $B \to X_c\ell\nu,$ other inclusive decay rates, …

$f_+^{K\to\pi}$ $f_{+,0}^{B\to D}(q^2), \ldots$ $\langle \pi\pi_{(I=0)} | \mathcal{H}^{\Delta S=1} | K^0 \rangle$ $K^+ \to \pi^+\ell^+\ell^-$ …

$f_{K^\pm}$ $f_{+,0,T}^{B\to\pi}\ \ldots$ $\langle \pi\pi_{(I=2)} | \mathcal{H}^{\Delta S=1} | K^0 \rangle$ $K^+ \to \pi^+\nu\bar{\nu}$

Complexity

Computing resources (and time, R&D - human resources!)

(plot courtesy of A. El-Khadra, Fermilab/Argonne P5 Town Hall)

$a_\mu^{\text{HVP LO}}$ ← d_n $a_\mu^{\text{HVP LO}}$ (2013-2017) ← $a_\mu^{\text{HVP LO}}$ (2003)

Lattice Calculation of the Lowest-Order Hadronic Contribution to the Muon Anomalous Magnetic Moment

T. Blum

Phys. Rev. Lett. **91**, 052001 – Published 30 July 2003

a_μ^{HLbL}

$\langle \bar{B}_q^0 | \mathcal{O}_i^{\Delta B=2} | B_q^0 \rangle$

$\langle \bar{D}^0 | \mathcal{O}_i^{\Delta C=2} | D^0 \rangle$

$\hat{B}_K$

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$\Lambda_b \to p, \Lambda_c, \Lambda$

$f_+^{K\to\pi}$ $f_{+,0}^{B\to D}(q^2), \ldots$

$f_{K^\pm}$ $f_{+,0,T}^{B\to\pi}$ $\ldots$

nucleon form factors, ..

g_A, g_T, g_S

$\langle \pi\pi_{(I=0)} | \mathcal{H}^{\Delta S=1} | K^0 \rangle$

$\langle \pi\pi_{(I=2)} | \mathcal{H}^{\Delta S=1} | K^0 \rangle$

PDFs, GPDs, T

$D_s \to \ell\nu\gamma$

$K \to \ell\nu\gamma$

$\Delta M_K, \epsilon_K$

$B \to K^*\ell\ell \to K\pi\ell\ell$ $\ldots$

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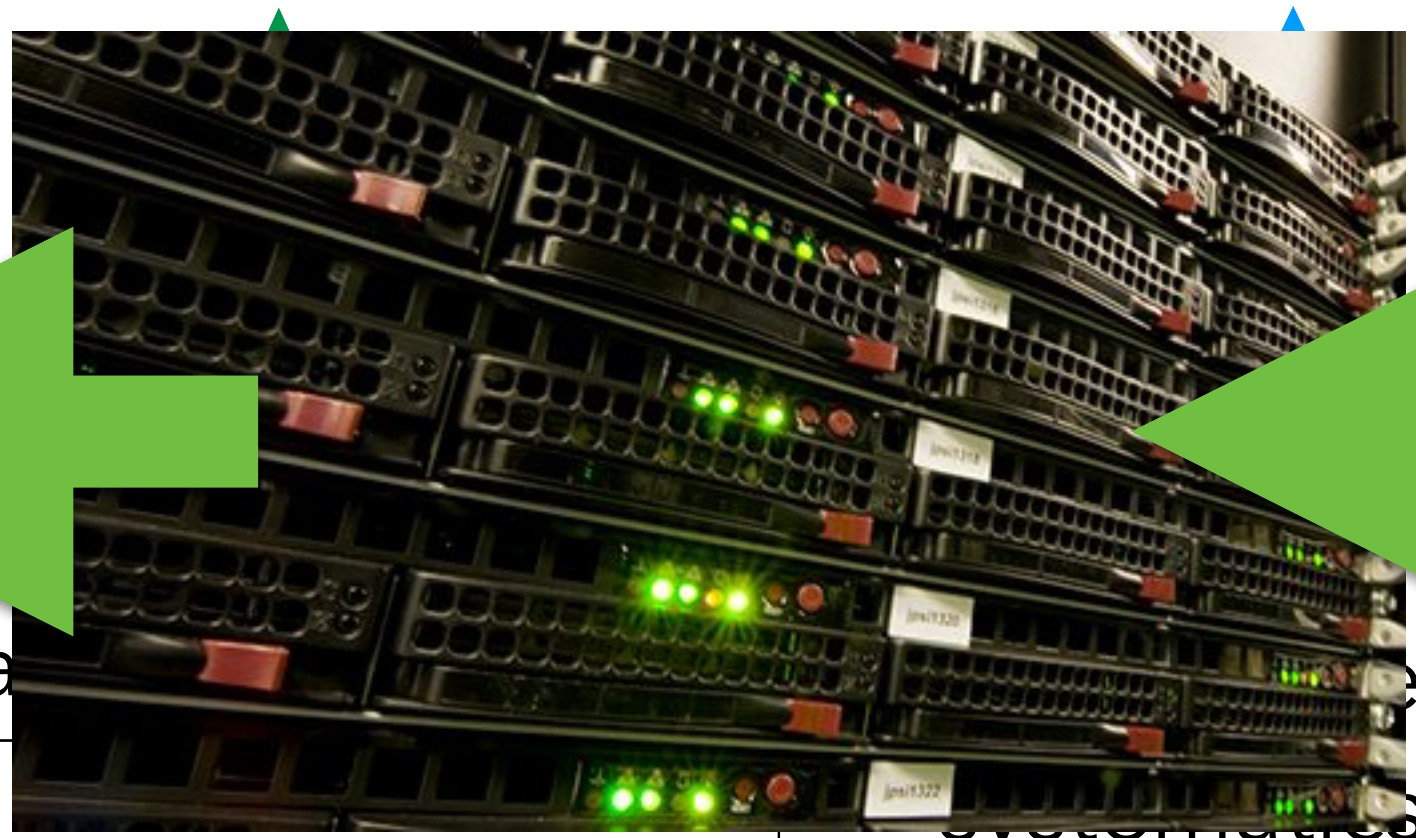

Computing resources (and time, R&D - human resources!)

Future of computing: AI/ML, QIS

(see next talk by C. Bauer) (images from P. Shanahan, BNL/P5 Town Hall)

- AI/ML and quantum computing* both represent opportunities for new ways to perform lattice calculations that are otherwise infeasible. Interdisciplinary growth of lattice methods; connections to HEP, other parts of physics, computer science, and industry.

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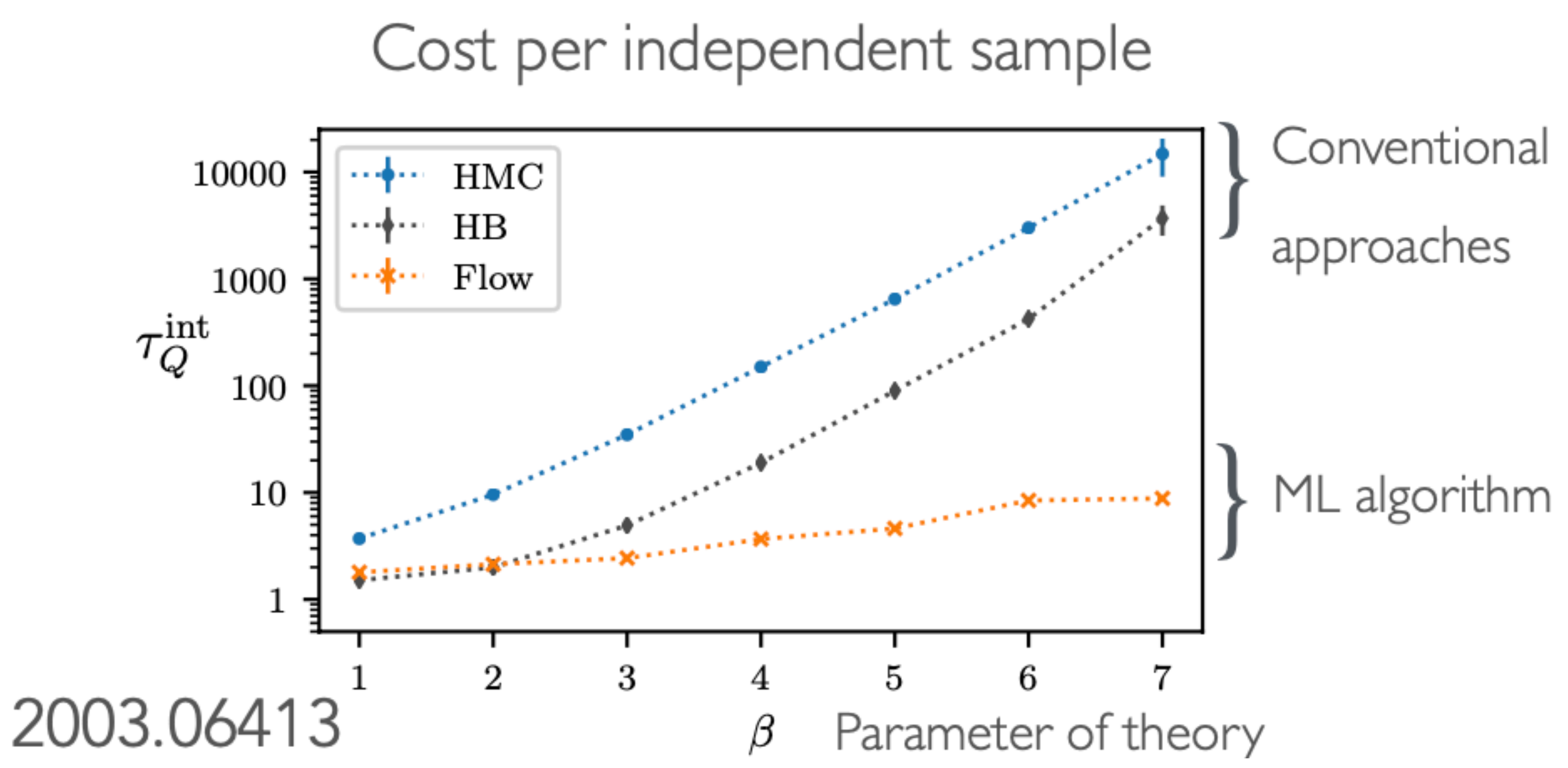
- AI work on lattice QFT has resulted in advances like **symmetry-equivariant ML sampling**, which can feed back into broader applications (e.g. Hamiltonian MC, developed for lattice QCD)



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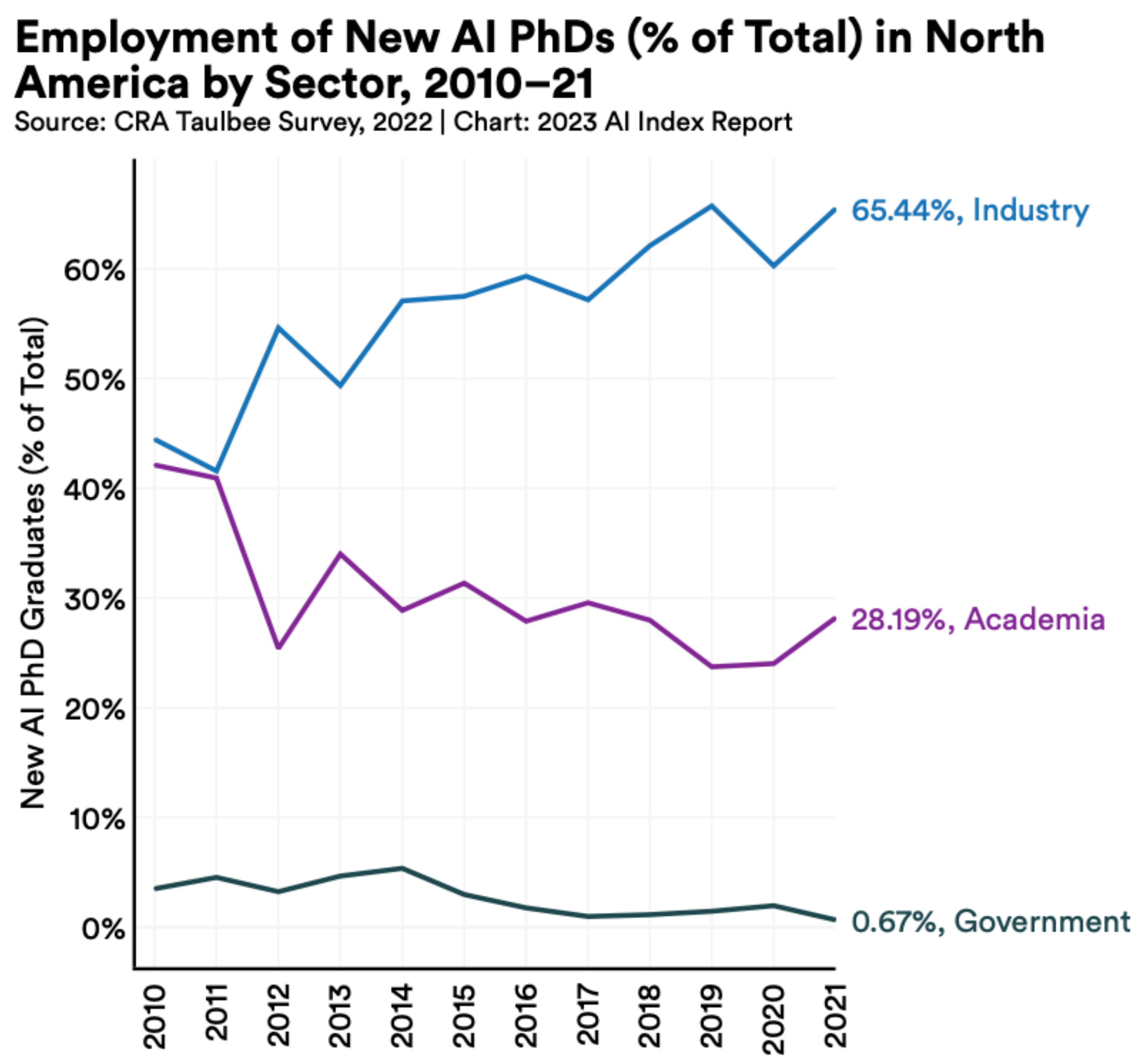
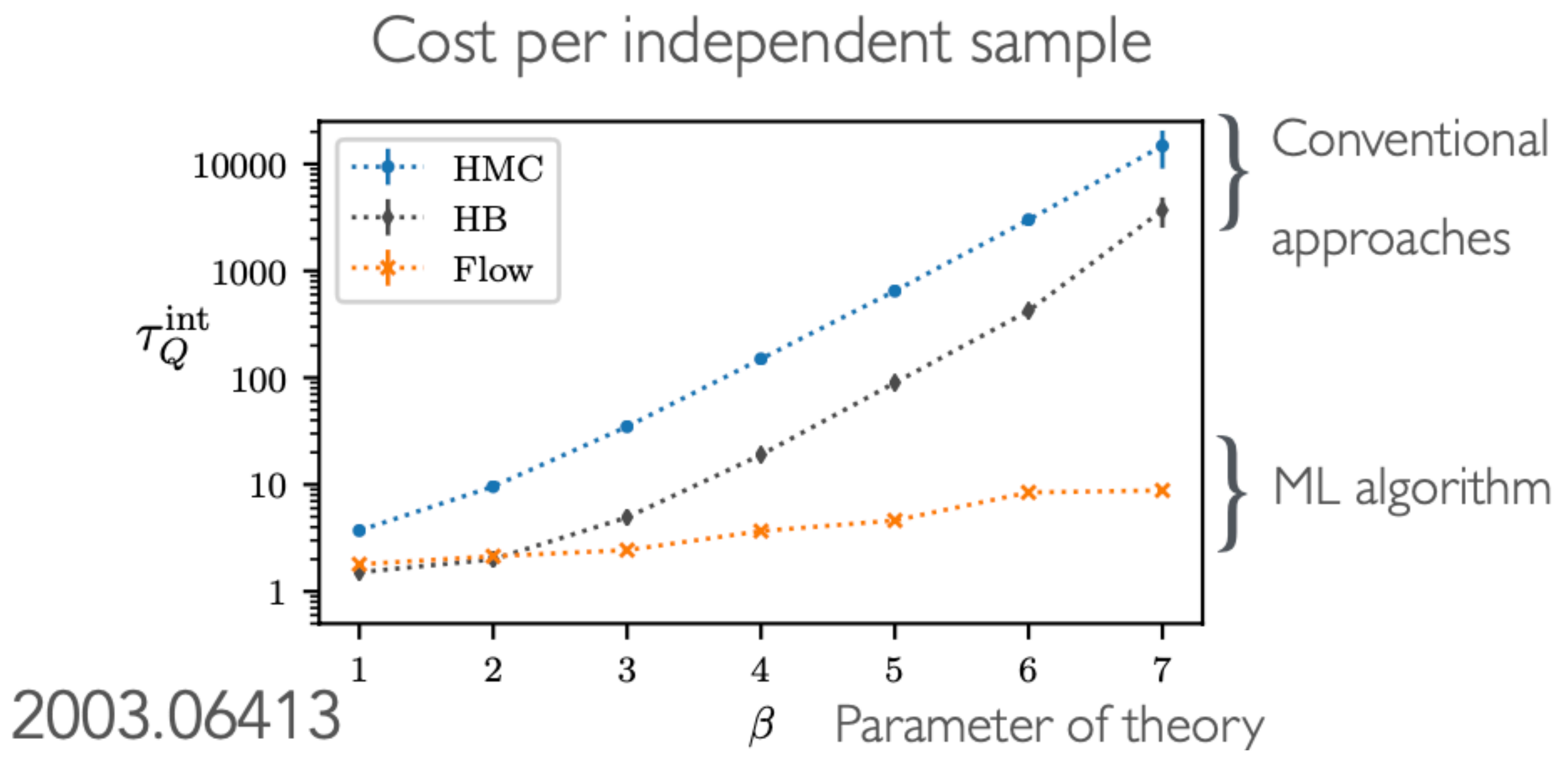
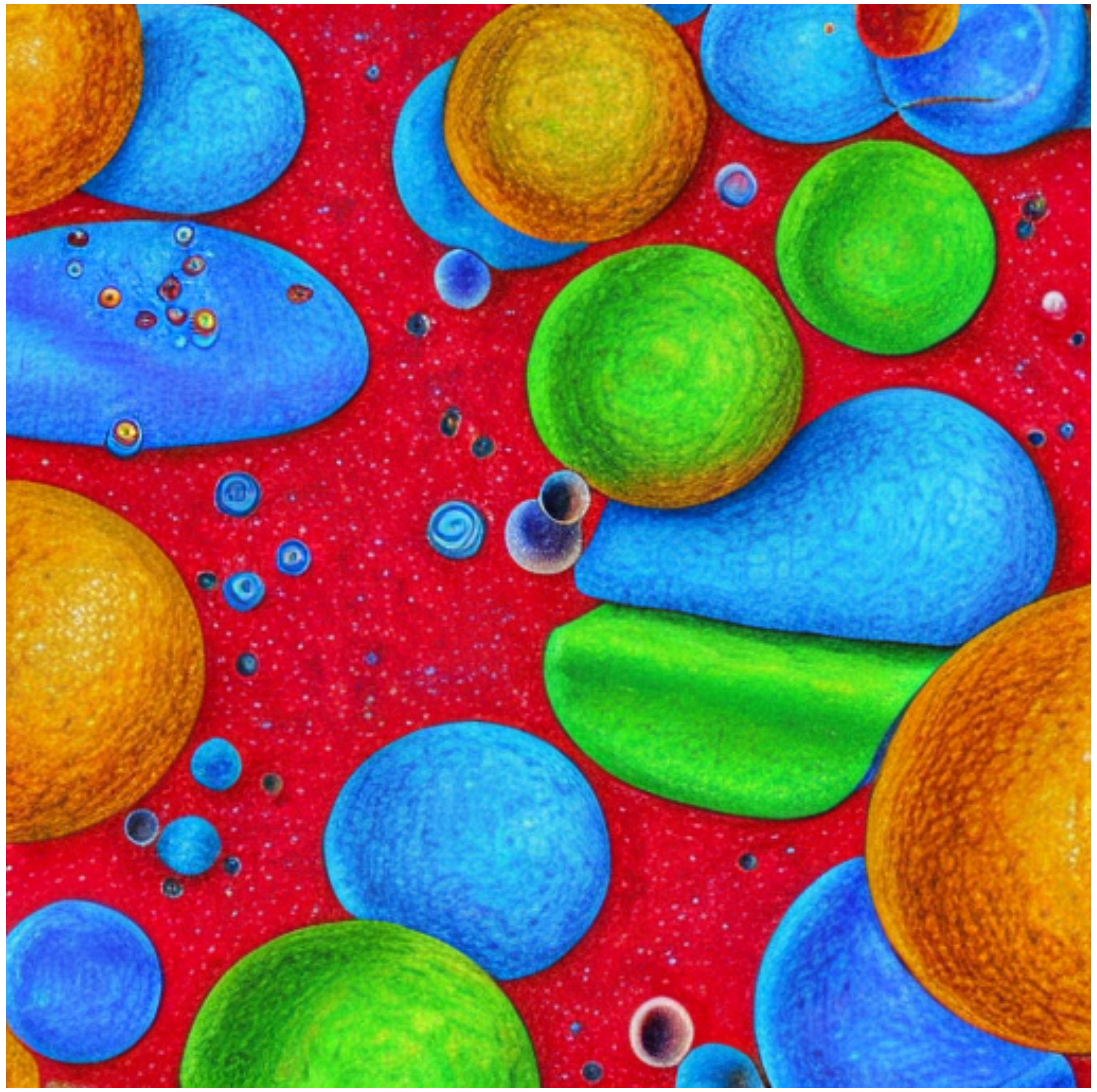




- Advances in industry are great and can feed back into HEP, but "off the shelf" commercial software is not enough - solving HEP problems requires **domain knowledge** (e.g. symmetries)

- Unique resource requirements compared to other lattice calculations; challenge to keep junior researchers in the field, pull of industry is strong!

Conclusion



(image courtesy of Stable Diffusion)

- Lattice field theory is deeply connected to many parts of theory and experiment, providing **precise and improvable inputs** wherever QCD is involved and a “**numerical laboratory**” to gain qualitative insights about other new physics.

- Lattice field theory has **strong interdisciplinary links** with computer science, enabling physics and driving software/hardware development, continuing with cutting-edge methods like AI and quantum computing.

- **Continued support of computing resources** is important for HEP computational theory (but, historically sufficient for LFT).

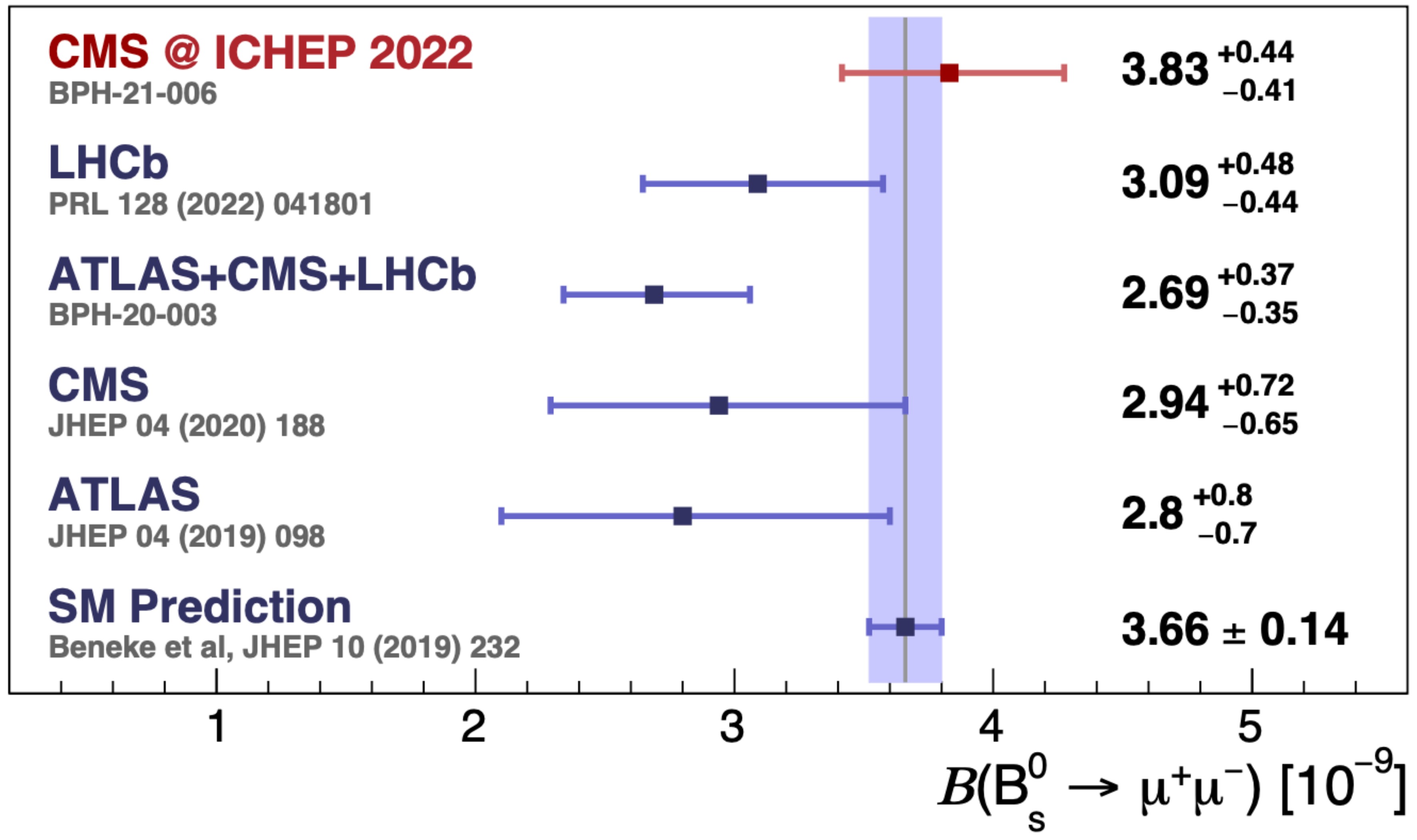
- A strong **workforce pipeline** for junior researchers to thrive at universities and labs and become mentors/leaders is crucial! This likely includes* maintaining staff positions for software experts, and joint positions with labs.

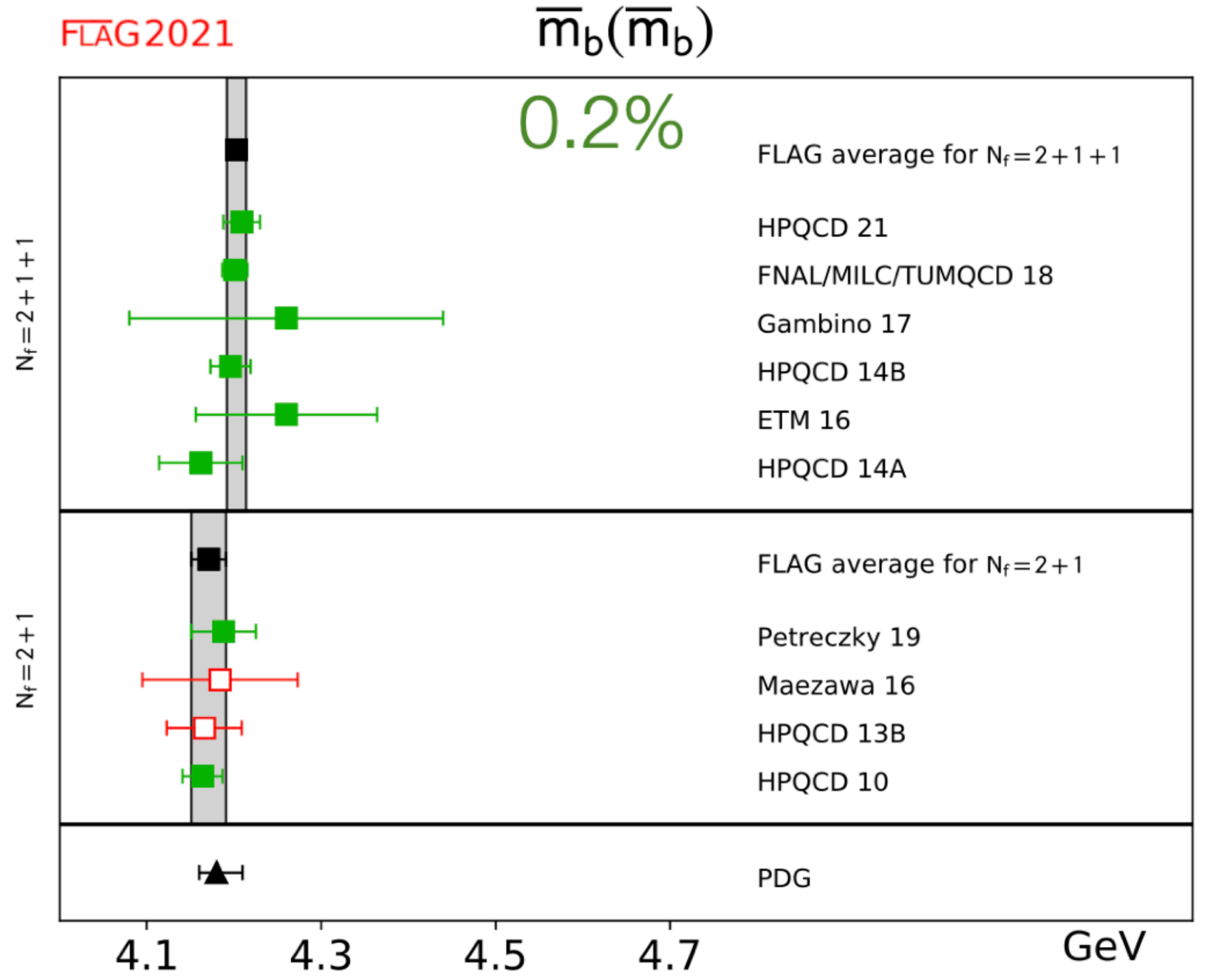
(Snowmass WP “Lattice QCD and the Computational Frontier”, P. Boyle et al, arXiv:2204.00039)

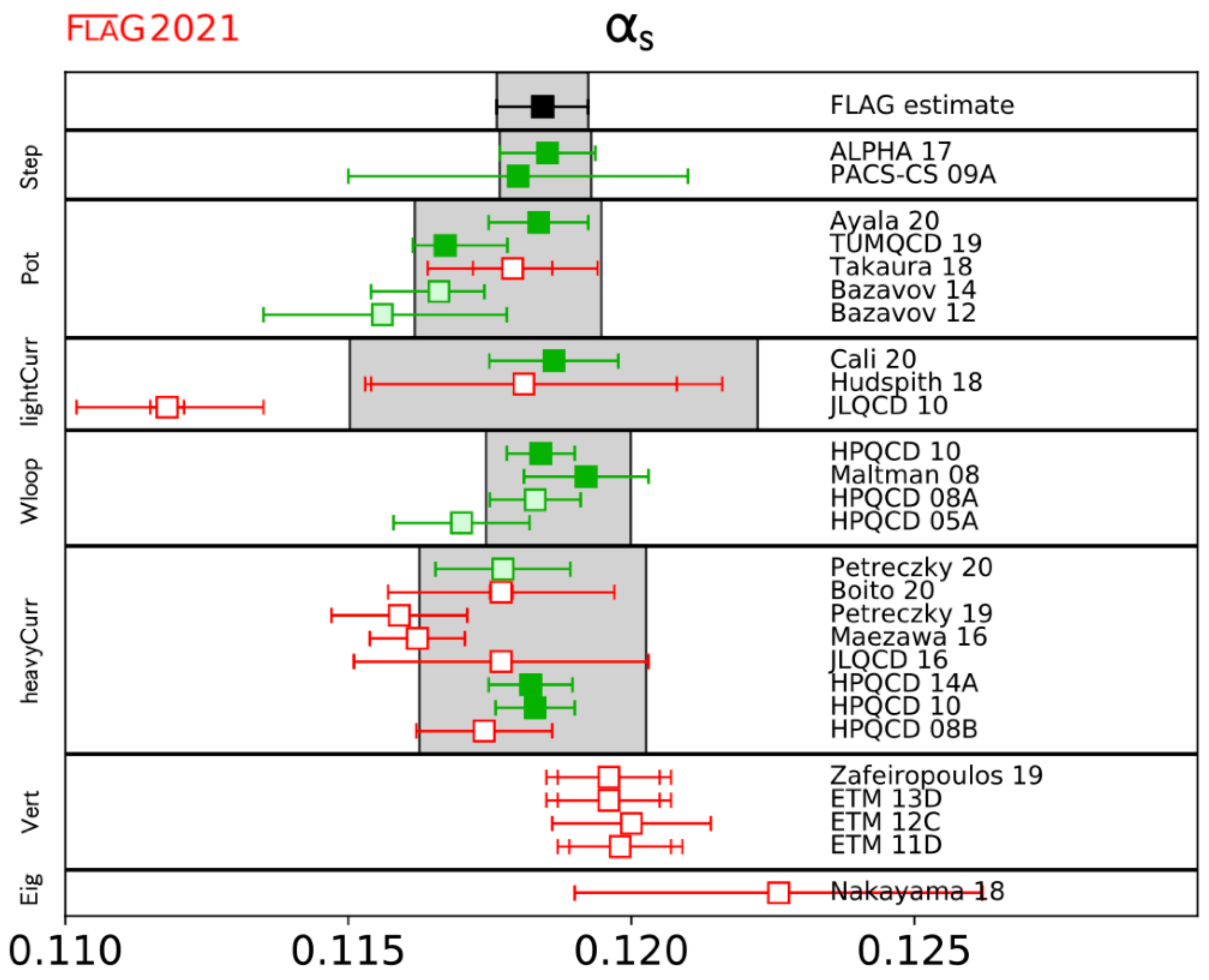
Backup

Highlights: flavor physics

(from talk by A. Kronfeld, Snowmass Summer Meeting '22)







- *Top*: lattice calculation of decay constants f_B, f_{B_s} are essential for prediction of $B_s \to \mu\mu$ rate (sensitive to BSM), and $B \to \tau\nu$ (determination of $|V_{ub}|$.)

- *Right*: heavy quark masses m_b, m_c and strong coupling determined at high precision from lattice. The former are already more than sufficient for prediction at future Higgs factories!

HEP-inspired AI/ML can have broad impact

Long history of HEP driving innovation leading to interdisciplinary advances!

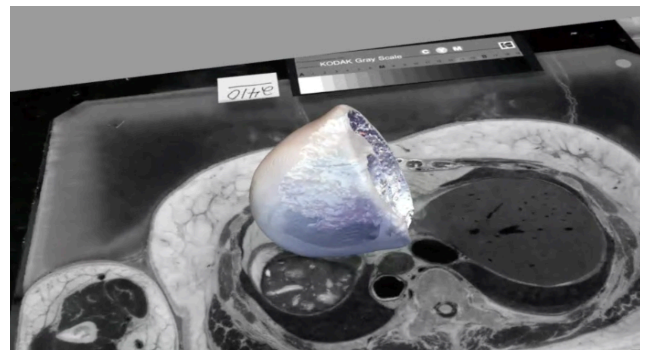
Theory case study: **Lattice QCD**

Numerical first-principles approach to non-perturbative QCD calculations

- Hamiltonian/Hybrid Monte Carlo (1980s)
- QCDOC ➡ Blue Gene supercomputers (2000s)
- Symmetry-equivariant ML sampling (2020s)

Same potential for technology transfer of future HEP-driven advancements in AI/ML!

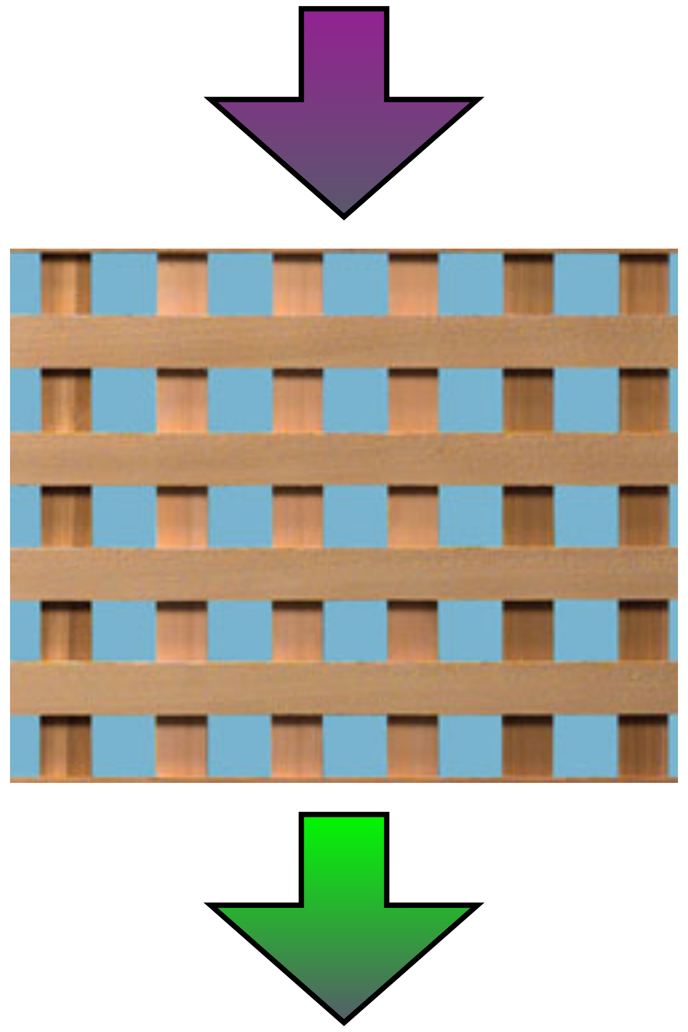
- Universities/lab/industry (IBM) collaboration developed **massively parallel** architecture "QCD on a chip (QCDOC)" with **small footprint and power efficiency** that revolutionised HPC
- Pre-cursor of successful Blue Gene/L
- Enabled breakthrough applications in diverse areas e.g., tissue-level cardiac models



[IBM Cardioid Cardiac Modeling Project]

What is lattice field theory?

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}U \mathcal{D}\bar{\psi} \mathcal{D}\psi \ \mathcal{O}(U, \bar{\psi}, \psi) \exp\left(-S[U, \bar{\psi}, \psi]\right)$$



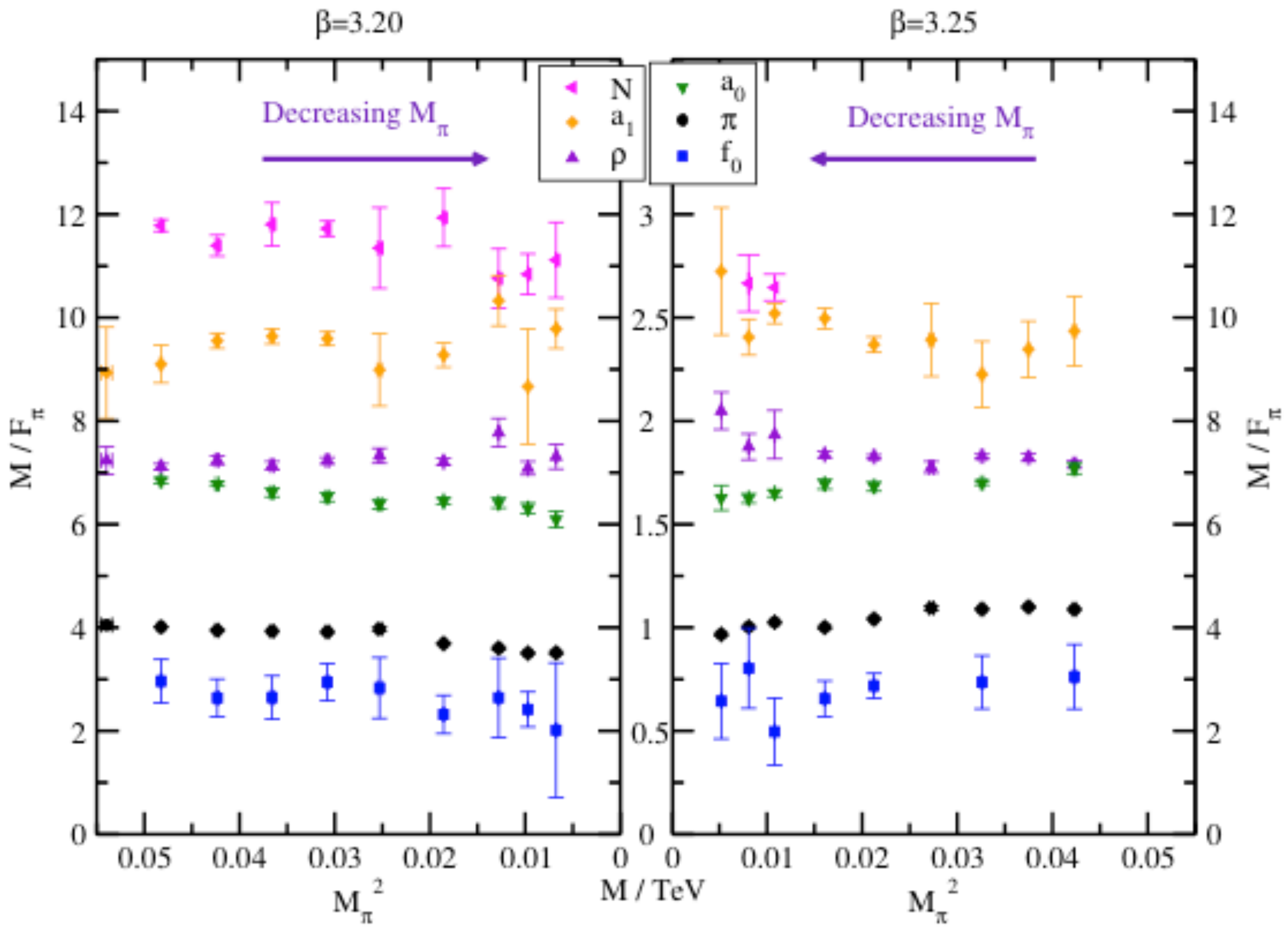
$$\langle \mathcal{O} \rangle = \frac{1}{N} \sum_{U \in \mathcal{U}} \langle \mathcal{O} \rangle_U$$

- Discretize spacetime to make the path integral finite dimensional

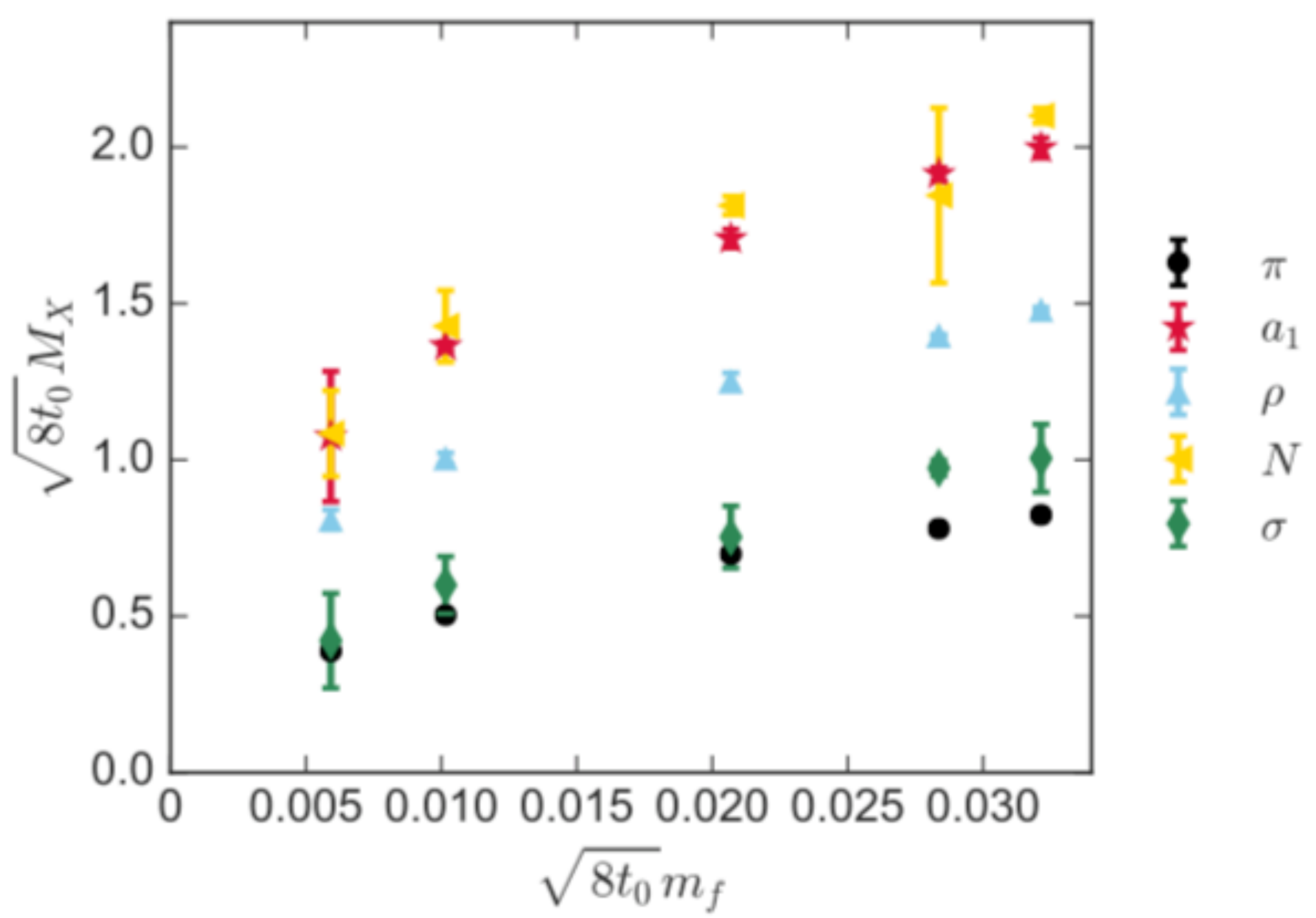
- Monte Carlo evaluation of the integral on high-performance computers (*importance sampling* weighted by exp(-S))

- Obtain weighted gauge ensemble. Can measure many observables with one ensemble!

Fodor, Holland, Kuti, Wong (**LatHC collab**), arXiv:1901.06324)



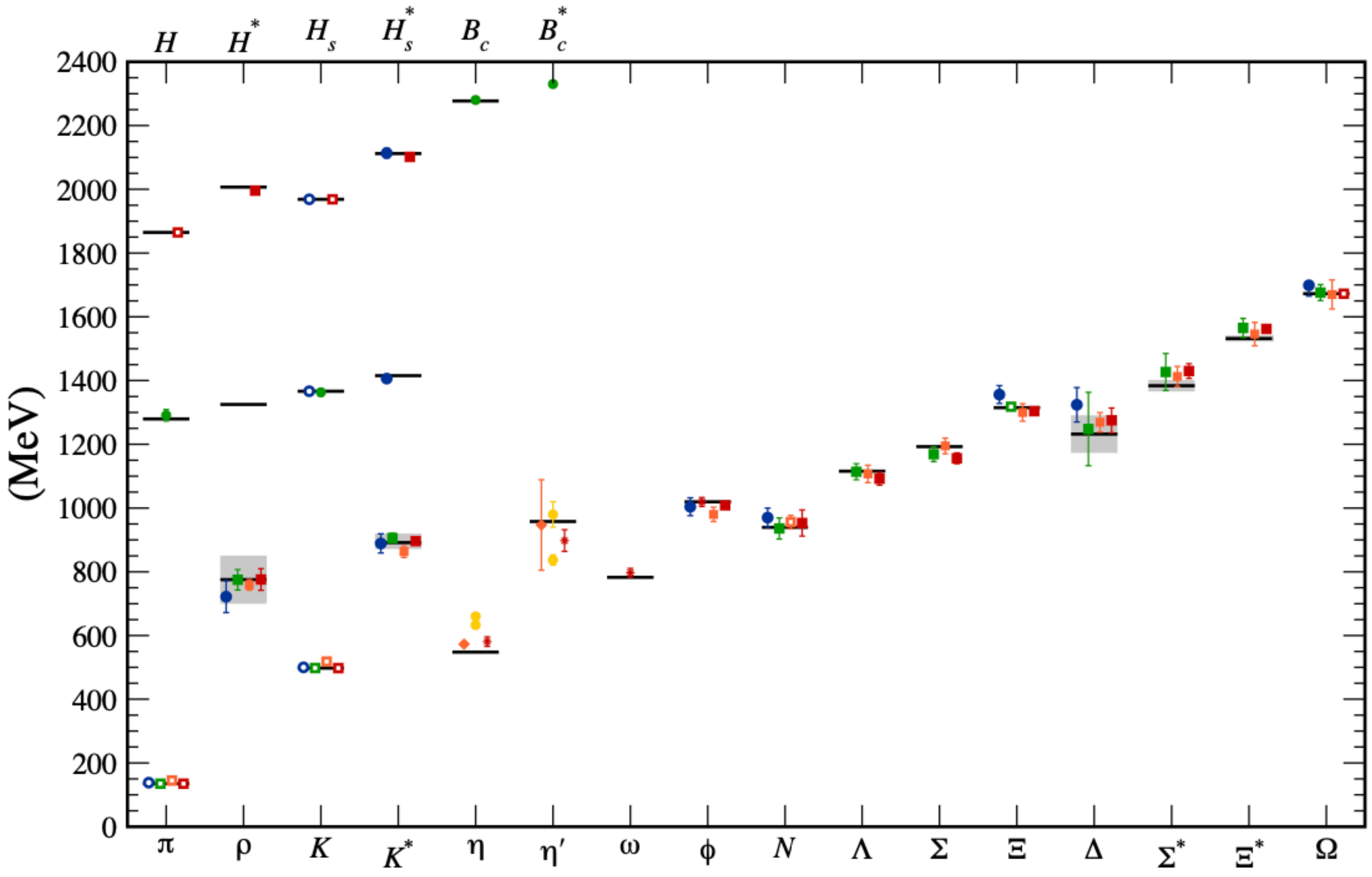
T. Appelquist et al (**LSD collab**), arXiv:1807.08411



- Emergence of light 0++ state near conformal transition - “pseudo-dilaton” - in multiple theories. Above: SU(3) Nf=2 sextet (left), SU(3) Nf=8 fundamental (right). Dynamical surprise (although speculation in literature earlier) - first indications from lattice!

- Model-building work is ongoing to understand the effective theory of pions + light scalar (“dilaton EFT”). Some work on pheno-viable composite Higgs models based on such theories, e.g. arXiv:2205.03320.

(from A. Kronfeld, *Ann.Rev.Nucl.Part.Sci. 62* (2012), arXiv:1203.1204)

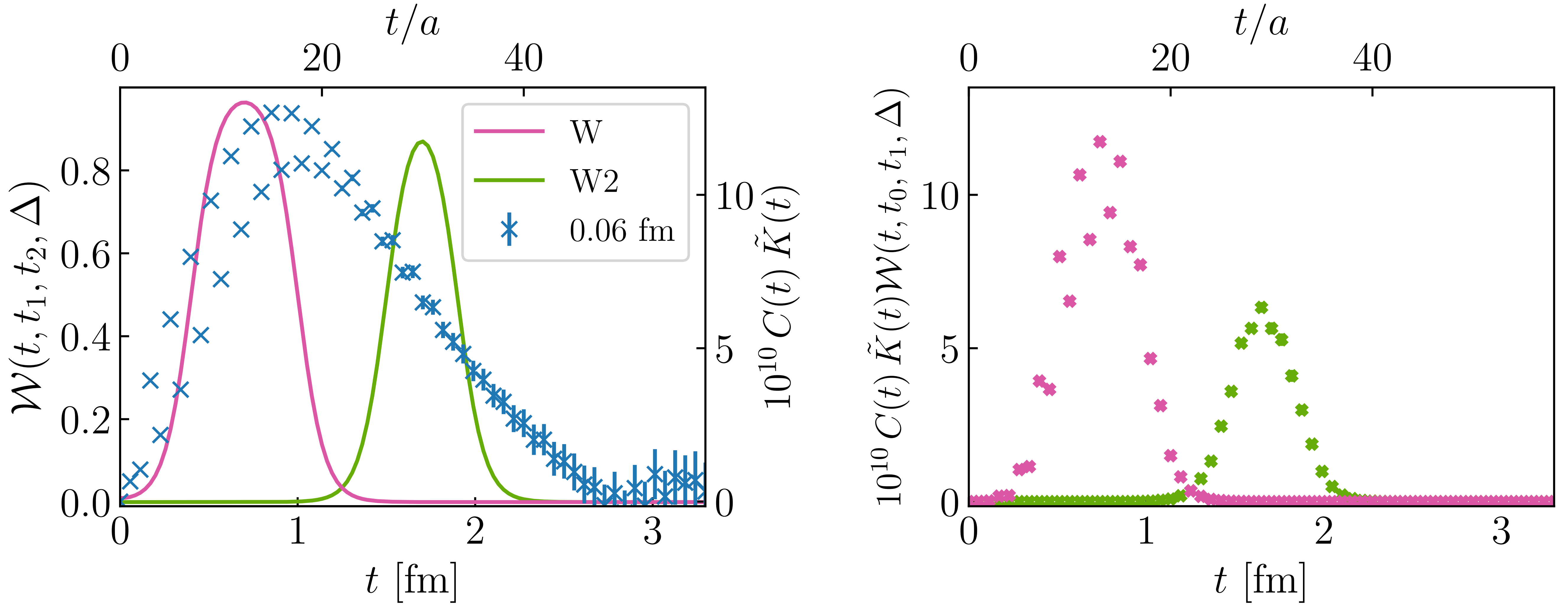


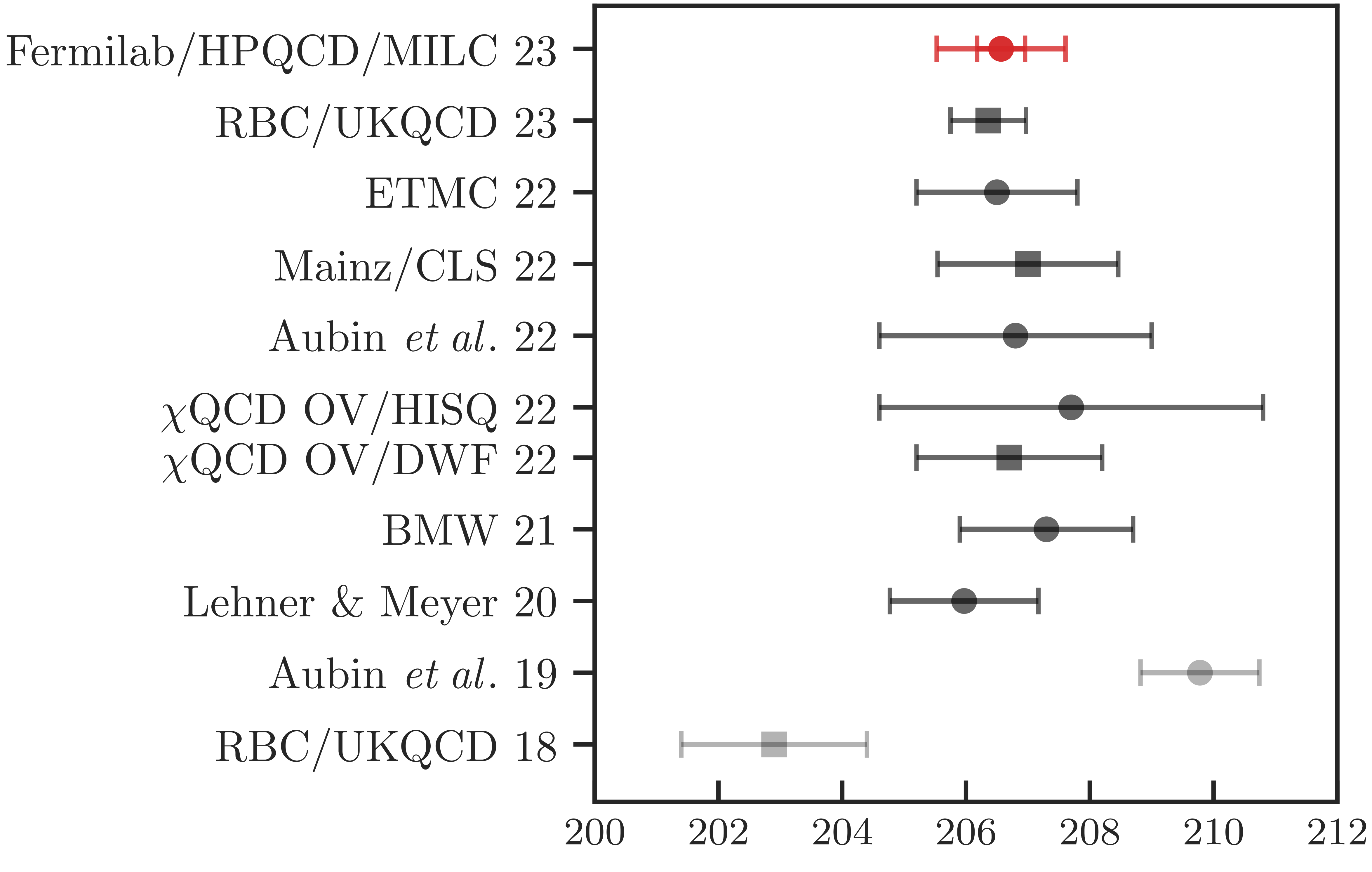
- Modern lattice QCD is well-tested and reliable, for a wide variety of *ab initio* predictions - like the hadron spectrum above!

(Fermilab/HPQCD/MILC collaborations, arXiv:2301.08274)

- Recent focus on lattice calculations for (g-2) HVP has been the “intermediate window” W - includes only medium-distance (moderate-energy from [0.8,] GeV) contributions to HVP

- (Also excludes some QED, quark mass effects)





- The window is a good cross-check for a variety of systematic effects, while being precise to calculate on lattice.

- Many lattice groups have now produced new results and overall agreement is excellent

- Tension with experimental value inferred for window, as noted in main slides; further study is needed to understand

Approaches to lattice BSM*

- 1) "**Top-down BSM**": pick a specific strongly-coupled model, put it on the lattice, calculate things of pheno relevance.

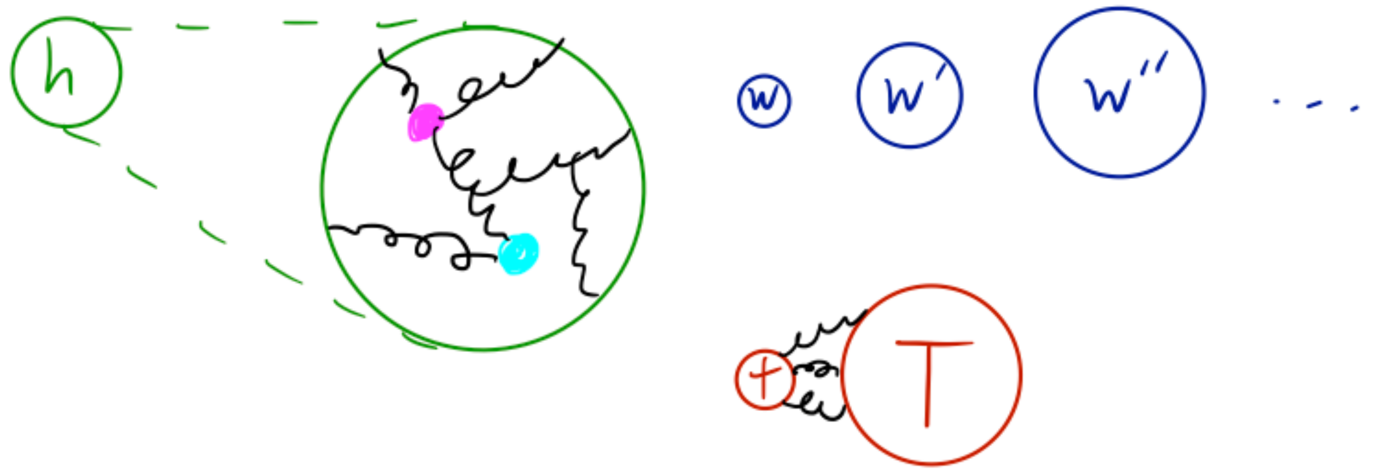
- 2) "**Bottom-up BSM**": choose a class of theories with common properties or shared description: large-Nc expansion, near-conformal (dilaton EFT), etc. Try to study the broad

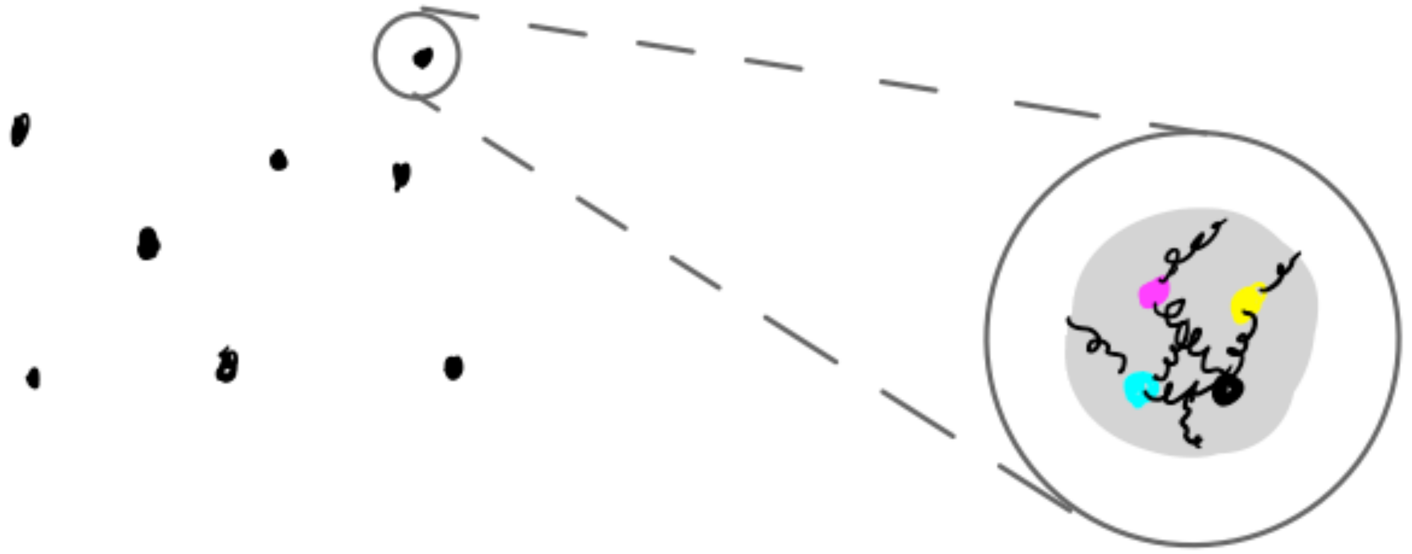
- 3) "**Pure exploration**": studies of non-perturbative phenomena, strongly-coupled QFT purely for theory interest, with no immediate pheno connection.

*not a unique way to organize; many lattice calculations have motivation/application in more than one area. Never a "waste" even if we rule out a specific theory…

1) (Example) top-down models

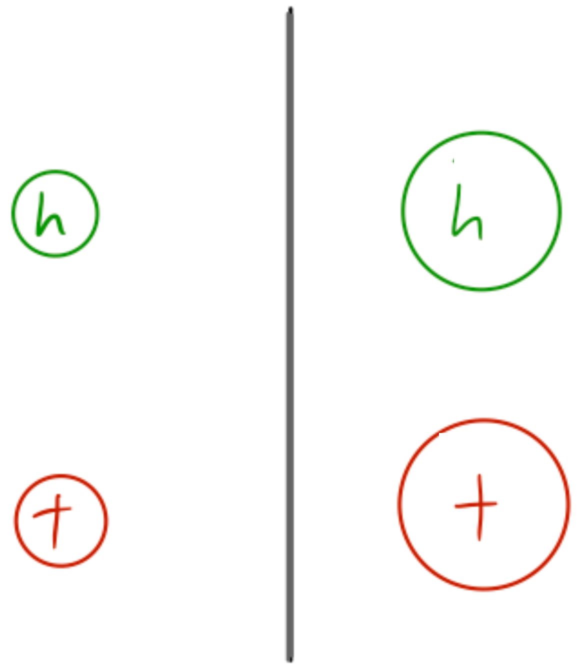
Composite Higgs: new strongly-coupled sector at the electroweak scale; Higgs is a composite bound state. (W/Z, top often have some composite part too.)





Composite dark matter: dark "hidden sector" which is strongly coupled. Rich spectrum of possible DM candidates: dark baryons, dark mesons (e.g. SIMPs), dark glueballs…

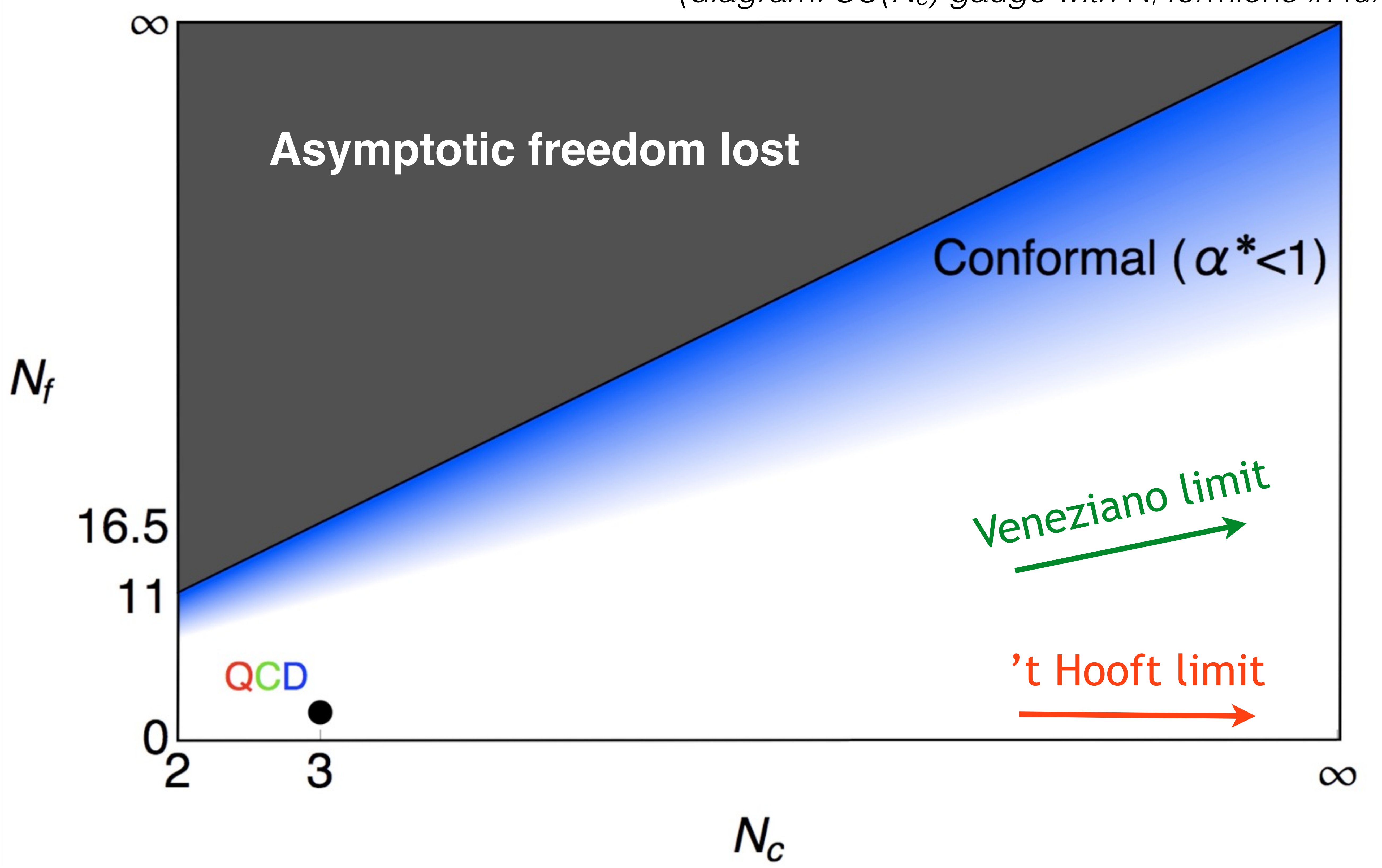
Neutral naturalness: mirror copy of SM components in hidden sector. Rich structure for e.g. dark matter. Lattice SU(3) results (particularly w/ heavy quarks) can be relevant.



Snowmass WP: Batell, Low, EN, Verhaaren, arXiv:2203.05531

2) Understanding the larger space

(diagram: SU(N_c) gauge with N_f fermions in fundamental irrep)



Large-N limit(s) provide analytic structure for predictions; lattice can **test** these analytic expansion and **compute** numerical values for expansion coefficients.

Conformal phase transition cuts across the parameter space; low-energy theory near the edge (**dilaton EFT**) can be tested and probed by lattice.

What about effective theories?

- We can take a more bottom-up approach and say: just identify the right effective field theory (EFT) for collider physics, dark matter detection, etc.

- Nothing wrong with this approach, but using *only* the EFT has limited predictive power: need to fix many (infinite!) low-energy constants from experiment.

- Plus, EFT comes with an energy cutoff: fine for working in the low-energy limit at the threshold of discovery, but many details of the full theory are out of reach.

- **EFT + lattice** allows analytic calculation but many LECs are determined from a handful of underlying UV parameters - best of both worlds!