Hadron Physics from the Lattice

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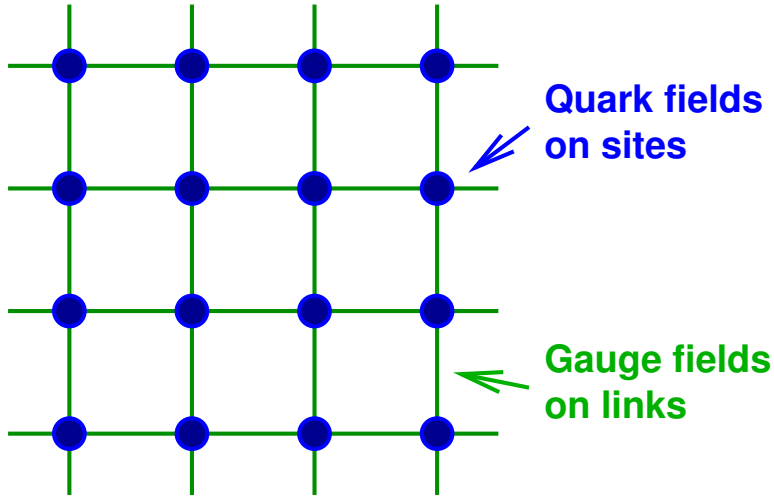
QCD on a lattice

- **Discretise Euclidean space-time on a 4d-lattice.**
- **Matter fields on sites, gauge fields on links.**



- **Provides a non-perturbative regulator of the QCD path integral.**
- **Enables importance-sampling Monte Carlo calculations.**

$$C(t_1 - t_0) = \langle 0|\phi(t_1)\phi^\dagger(t_0)|0\rangle = \sum_k \left|\langle 0|\phi|k\rangle\right|^2 e^{-E_k(t_1-t_0)}$$

QCD on a lattice

$$\int \mathcal{D}\bar{\psi}\mathcal{D}\psi \;\; \psi_a \bar{\psi}_b \, e^{-\bar{\psi} M \psi} = [M^{-1}]_{ab} \det M$$

- **Represent quarks in path-integral as Grassmann-valued fields.**
- **More numerically challenging to handle, both in importance sampling step and measurement of quark propagation.**
- **Advances in numerical methods and computer power mean we are now in the era of physically realistic calculations.**

Connections

- **Lattice practitioners typically work with experts in or have expertise in ...**

Hadron experiment	Phenomenology and EFT	High-Performance Computing	Data analysis and statistics

- **Significant expertise across Europe.**
- **Can we build stronger connections?**

Physics projects

Structure and precision physics:

- **Parameters:** α_s, m_u, m_d, ...
- **Decay constants:** f_B, f_{D_s}
- **Nucleons:** g_A, $\sigma_{\pi N}$, **pdfs,**
- **Matrix elements for CKM,** $g-2$

Beyond the standard model:

- **Composite Higgs models**
- **Supersymmetry**
- **g-2 and precision tests**
- **Dark matter searches**

Finite temperature and density:

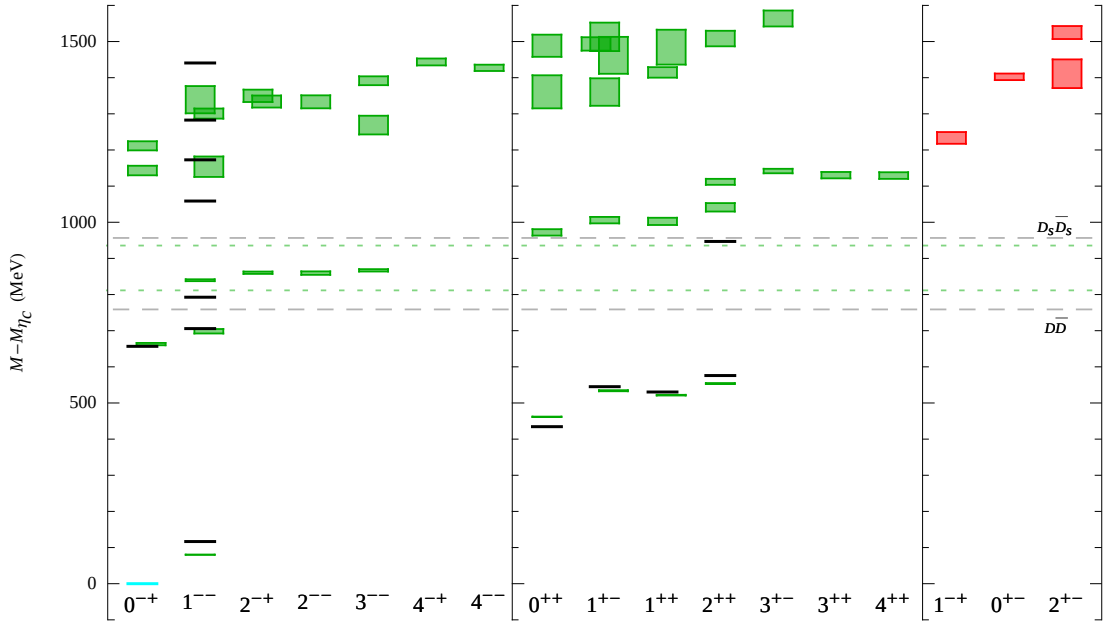
- **QCD phase diagram**
- **Transport properties**
- **Hadrons in hot, dense matter**

Spectroscopy:

- **Scattering and resonances**
- **Exotic hadrons, XYZs**
- **Internal excitations**

Spectroscopy

- Until few years ago, spectroscopy meant energies of “stable” hadrons.
- Excited states via variational methods.

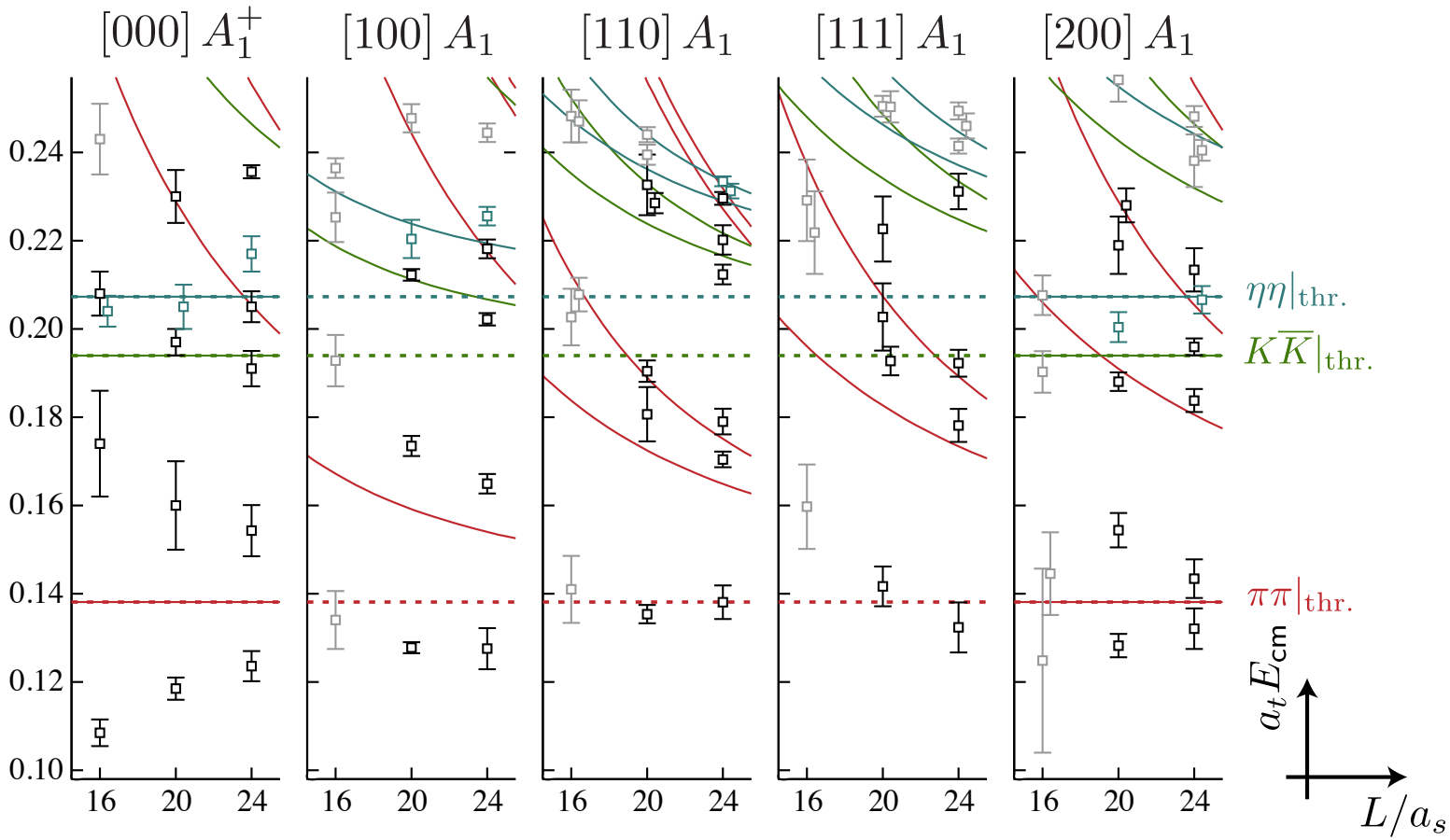


- Now - hadron elastic scattering including coupled-channel and resonances.
- Developments in numerical methods and use of Lüscher formalism for elastic scattering.
- Extend these ideas to matrix elements, three-body, ...

Lüscher formalism

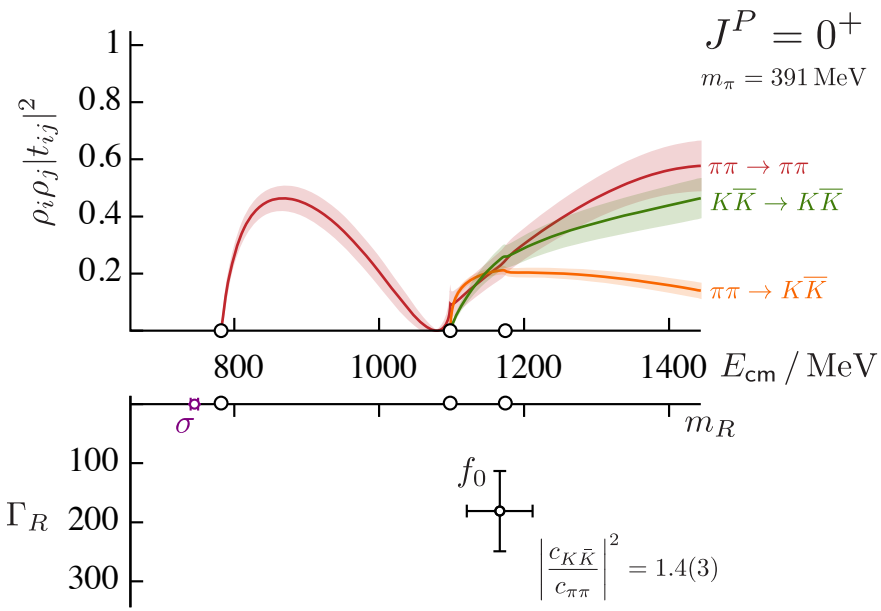
Recent review: Briceno, Dudek, Young (Rev.Mod.Phys 90 (2018) no.2, 025001)

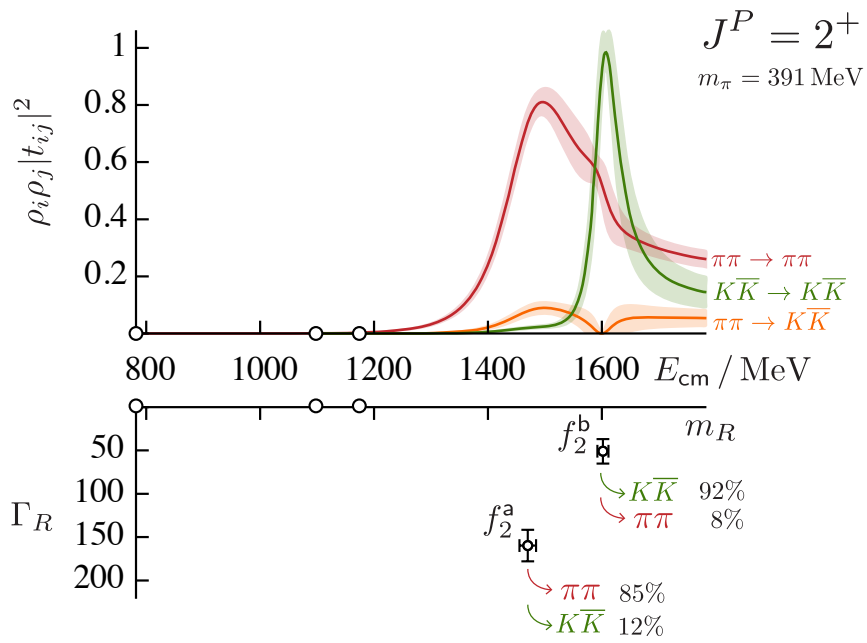
- **Lattice (Monte Carlo) calculations in Euclidean metric**
- **Lüscher: relate elastic scattering to the energy spectrum of field theory in a finite volume**



Coupled-channel $\pi\pi$, $K\bar{K}$

Taken from Briceno et. al. Phys.Rev.Lett 118 (2017) no 2, 022002





- **Scattering amplitudes including coupled $\pi\pi$ and $K\bar{K}$**
- $m_\pi = 391$ **MeV (so σ stable)**
- **Extended to matrix elements, three-body formalisms ...**

Future prospects

- Near future? European lattice groups working on
  - Precision tests of the standard model
  - Strong interactions in other gauge theories (BSM)
  - Hot, dense QCD
  - Deeper understanding of the internal structure of hadrons
- Better connections to experiments?
- Where next?
  - Machine learning?
  - quantum computing?