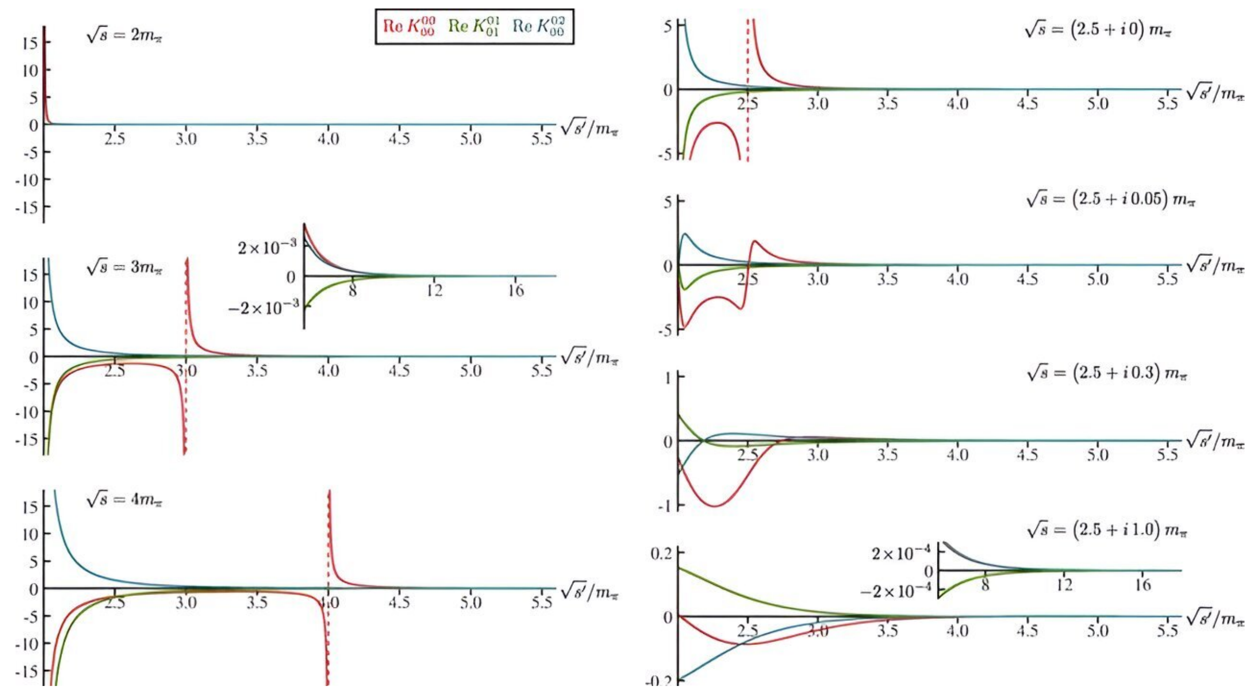
PHYS.ORG

Physicists pool skills to better describe the unstable sigma meson particle

July 16 2024



Real part of kernel functions contributing to dispersion of S0, Re $K_{0\ell'}^{0I'}$, plotted in units where 1 on the y-axis represents a value $4m_\pi^2$. Left column: functions evaluated on the real s′–axis for three values of s—inset indicates the behavior in the high-energy region. Right column: Kernel functions evaluated for complex values of s. Credit: *Physical Review D* (2024). DOI: 10.1103/PhysRevD.109.034513

While nuclear physicists know the strong interaction is what holds together the particles at the heart of matter, we still have a lot to learn about this fundamental force. Results published earlier this year in *Physical Review D* by three researchers in the Center for Theoretical and Computational Physics at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility bring us closer to understanding an important piece of the strong interaction puzzle.

This piece is known as the sigma meson. Like the more familiar protons and neutrons, the sigma is made of quarks. It's created when two other quark-based particles, called pions, collide. In this collision, the pions' quarks can briefly reconfigure themselves via the strong interaction to form the sigma meson.

The particle is unstable and is one of the shortest lived, decaying back into a pair of pions within an unfathomably teensy fraction of a second. This makes it difficult to study the sigma meson using the data from accelerator experiments, even though it is thought to play a significant role in many nuclear physics processes, including the interactions between protons and neutrons.

"The sigma is a long-standing weird guy," said author Jozef Dudek, a jointly appointed staff scientist at Jefferson Lab and associate physics professor at William & Mary. "We couldn't reliably determine its properties with simple traditional methods."

With a mass that is half that of the proton, the sigma meson is the lightest unstable particle involved with the strong force. Studying the strong interaction at the lightest scales will help physicists figure out how this force forms us and our world at heavier scales.

"This is important for basically understanding why we are here," said author Arkaitz Rodas Bilbao, a jointly appointed staff scientist at Jefferson Lab and assistant physics professor at Old Dominion

University. "How do the particles that we are made of stick together? Can we know all that is happening inside each of us to the most basic level?"

Supercomputing for sigma

Dudek, Rodas Bilbao, and Jefferson Lab Principal Staff Scientist Robert Edwards joined forces to lead work on learning more about the sigma meson. They felt their best chance at better describing it would come from a different tool: supercomputing.

"The idea is to rely on supercomputers to create virtual experiments," said Rodas Bilbao.

Supercomputers allow scientists to do complex calculations faster. Divvying up calculation steps among the thousands of computers that make up a supercomputer means many steps can be done at once, saving time. It would take a laptop hundreds to thousands of years to do the calculations for this project.

"If I want to be alive when the project finishes, it's better to use a supercomputer," Rodas Bilbao said.

Using supercomputers at Jefferson Lab and DOE's Oak Ridge National Laboratory, the team simulated the pion-pion reactions necessary to learn about the sigma meson. These calculations are based on quantum chromodynamics, or QCD, the theory that describes the strong interaction.

QCD cannot be solved algebraically, and when using supercomputers to overcome this, some basic principles have to be sacrificed. In this work, for the first time, the authors were able to reintroduce those principles in the form of mathematical constraints called "dispersion relations."

Collaborative calculations

This technical challenge required the expertise of Rodas Bilbao, who studied dispersion relations previously and worked on the project as a postdoctoral researcher at William & Mary.

The challenge also required the experience of Dudek and Edwards in QCD numerical calculations.

The three are members of the Hadron Spectrum Collaboration (HadSpec), a small but international group that originated at Jefferson Lab, and the Exotic Hadron (ExoHad) Topical Collaboration, a group that studies exotic particles. This work is a milestone of the ExoHad collaboration, and it exemplifies the type of relationships the group wants to form.

"It's this idea that you combine skill sets and work together to solve problems that neither one could solve on their own," said Dudek, who is co-principal investigator of ExoHad. "We also couldn't have done the calculations at all without the SciDAC side of things."

Edwards leads the DOE-sponsored software project "Fundamental Nuclear Physics at the Exascale and Beyond" under the Scientific Discovery through Advanced Computing (SciDAC) program.

"This effort allows us to try and develop tools that we need for advanced scientific computing or, in this case, high-performance computing. These tools that we've developed, software and algorithmic infrastructure, are now actually at the heart of our programs in science," Edwards said. "It has been through these kinds of computing resources that we can carry out the science, so it's been an integral part of our whole process."

The combination of techniques used in this work could be extended to study mysterious particles similar to sigma, such as the kappa. If a pion interacts with a kaon instead of another pion, it can form an intermediate particle known as a kappa, whose existence and properties are even more unclear than the sigma's.

This work also reveals a path forward for further study of the sigma, whose internal structure is still mysterious. Learning about the sigma's compositeness, however, will require even more complicated calculations.

"So, the first step, which is this one, has to be as sound and as accurate as possible," Rodas Bilbao said.

One limitation of these calculations is the fact that they give the quarks, and thus pions, more mass than these particles have in reality. This made the calculations more practical to carry out, but in future work these masses must inch closer to their true values.

"Eventually you have to put those parameters to the right value," Dudek said.

This is especially true because research from Jefferson Lab's Theory Center informs the lab's experimentalists, whom the theorists work closely with. In any experiment in which there are two pions, the effect of the sigma will be felt.

"Everything we do feeds into the experimental program," he said.

But this "first step" is a good start.

More information: Arkaitz Rodas et al, Determination of crossing-symmetric ππ scattering amplitudes and the quark mass evolution of the

σ constrained by lattice QCD, *Physical Review D* (2024). DOI: 10.1103/PhysRevD.109.034513

Provided by Thomas Jefferson National Accelerator Facility