Lattice QCD Approach to Radiative Leptonic Decays

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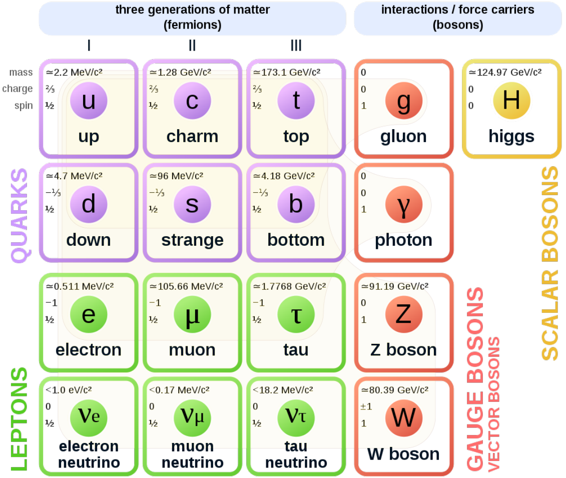
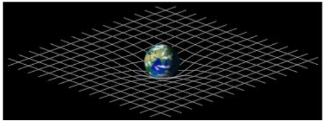
Standard Model of Elementary Particles

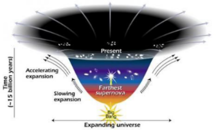


Unsolved problems in particle physics

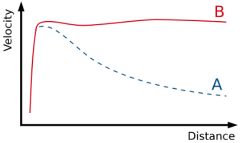
Quantum Gravity?



Dark Energy



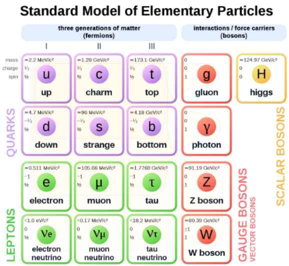
Dark Matter



Matter anti-matter asymmetry

Indirect detection methods

Calculate Decay Rate Using Standard Model



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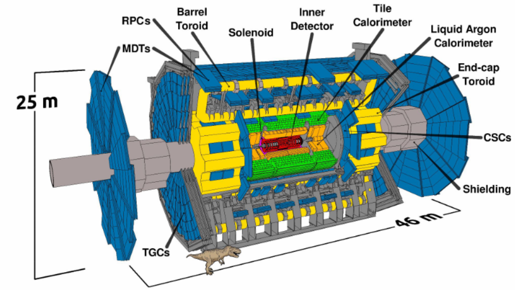
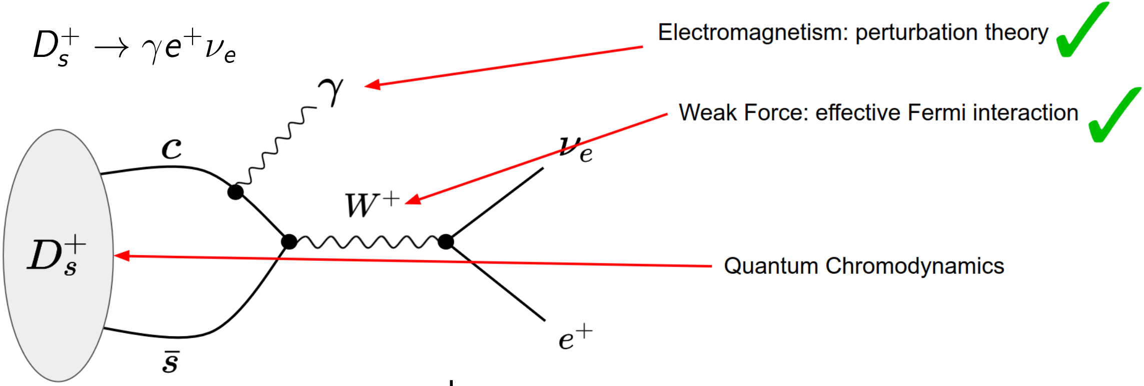
Measure Decay Rate experimentally



Radiative leptonic decays

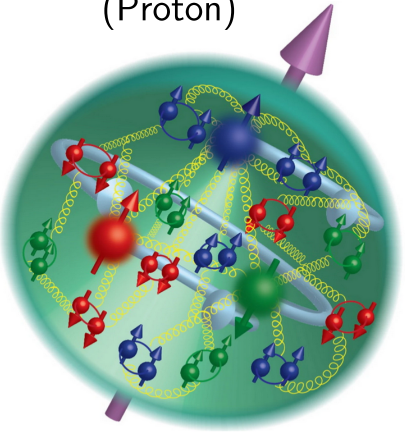
$D_s^+ \to \gamma e^+ \nu_e$



$$\frac{d\Gamma}{dE_\gamma} = \overbrace{\alpha_{\text{em}} \frac{G_F^2 |V_{cs}|^2}{6\pi^2} m_{D_s} E_\gamma^3 \left(1 - \frac{2E_\gamma}{m_{D_s}}\right)}^{\text{known}} \overbrace{\left(|F_V|^2 + F_{A,SD}|^2\right)}^{\text{QCD}}$$

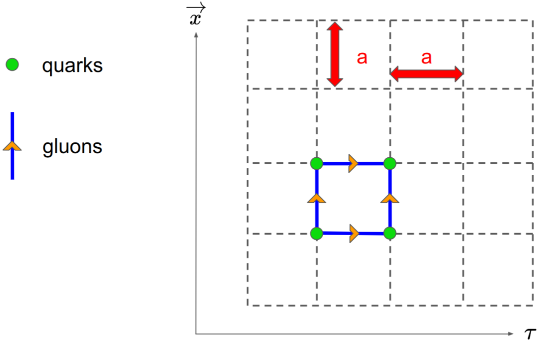
How to calculate the QCD piece?

- Stength of QCD is larger at smaller energy scales
- Inside the D_s^+ meson, quarks and gluons at low energy scales
- Perturbation theory not practical, expansion parameter is not small
- Need a non-perturbative method



Intro to lattice QCD

Goal: Numerically solve the QCD path integral



- Discretize space and time on a finite lattice
- Perform integral over quarks analytically
- Perform Wick rotation to imaginary time
  $\rightarrow$ replace $t = -i\tau$ with $\tau \in \mathbb{R}$

Intro to lattice QCD

Re-writing the path integral (schematically):

$$\langle \text{Object to calculate} \rangle = \langle f(M^{-1}[U]) \rangle = \frac{\int \mathcal{D}[U]\, \rho[U]\, f(M^{-1}[U])}{\int \mathcal{D}[U]\, \rho[U]}$$

- Probability density $\sim \rho[U] = \det(M[U]) e^{-S_G^E[U]}$
- Solve the integral over gluon fields U using Monte Carlo methods
- Calculate propagators $M^{-1}[U]$, plug into $f(M^{-1}[U])$

What is the typical size of matrix M?

$$\underbrace{32^3}_{\text{sites in x,y,z directions}} \times \underbrace{64}_{\text{sites in } \tau \text{ direction}} \times \underbrace{3}_{\text{quark colors}} \times \underbrace{4}_{\text{Dirac fermion indices}} \approx 25 \times 10^6 \text{rows/columns}$$

High performance computing centers utilized

Stampede2 Supercomputer

University of Texas

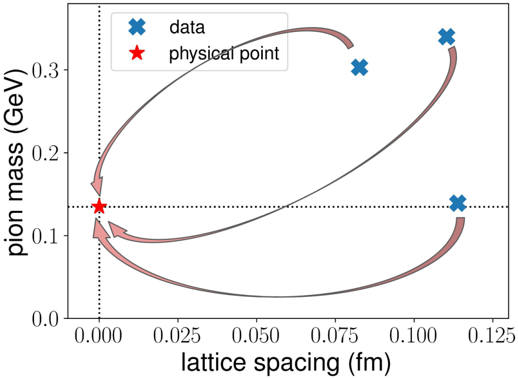
Supermuc-NG

Leibniz Supercomputing Centre, Germany

Lattice parameters

Outline of the calculation:

1. Perform calculation on multiple lattices
   - Different lattice spacing a
   - Different pion mass m_π (quark masses)
2. Extrapolate to physical result
   - lattice spacing $a \to 0$
   - pion mass $m_\pi \to m_{\pi,\text{physical}}$



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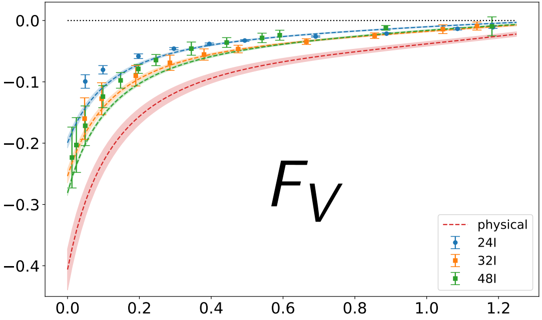
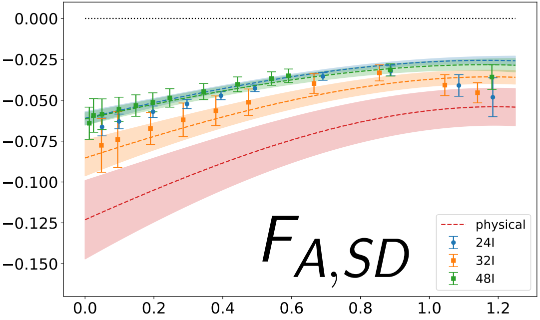
For showing plots that might still contain systematic errors

SOME MATERIAL MAY BE INAPPROPRIATE FOR CHILDREN UNDER 13

Lattice QCD results for F_V and $F_{A,SD}$





$x_\gamma = 2E_\gamma / m_{D_s}$ $\qquad$ $x_\gamma = 2E_\gamma / m_{D_s}$

Physical values: $0 < x_\gamma \leq 1$

Branching fraction prediction (preliminary)

- Branching fraction is fraction of D_s^+ events that decay into a particular final state

$$\mathcal{B}(D_s^+ \to \gamma e^+ \nu_e) = \text{Fraction of } D_s^+ \text{ that decay into } \gamma e^+ \nu_e$$

$$\text{Our prediction: } \mathcal{B}(D_s^+ \to \gamma e^+ \nu_e) = 2.8(4) \times 10^{-6}$$

$$\text{Experimental upper bound: } \mathcal{B}(D_s^+ \to \gamma e^+ \nu_e) < 1.3 \times 10^{-4}$$

- Upcoming experiments can improve the upper bound and possibly quote results

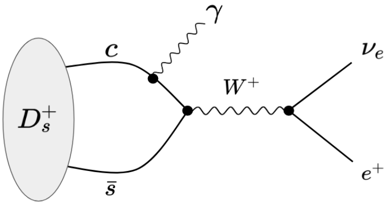
Quick digression: practicums

- Two practicums at Lawrence Berkeley National Lab
- Working on methods for quantum computer simulations of high energy physics
- The CSGF has changed the trajectory of my career in a hugely positive way

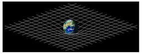
Thank you to everyone at the CSGF and Krell who has helped me along the way :)

Summary

- Standard model is incomplete
- Generally, calculations of bound states of quarks, i.e. protons, D_s meson, often require non-perturbative lattice QCD
- Radiative leptonic decays are an interesting process, and we are calculating the decay rate



Quantum Gravity?



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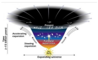

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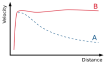

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