Application of GPU computation toward particle physics

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2013年度理研シンポジウム　理研RICC新搭載GPUと科学へのアプリケーション、6/27/2013

Overview

- Introduction
- Precision physics in the particle physics
  - Muon g-2
  - Nucleon EDM
  - Proton decay
- Application of GPU
  - Status of lattice QCD calculation
  - Perspectives
- Summary

Introduction:
Grand challenges

Can we understand the origin of nature ?

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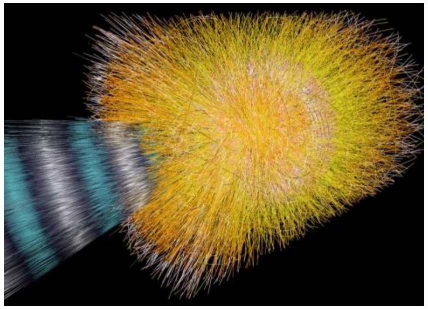
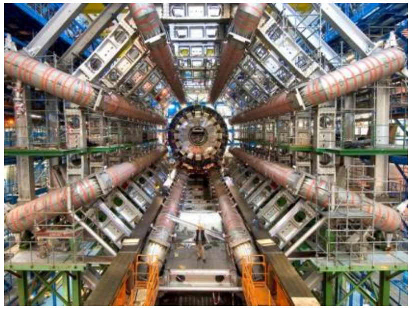
- Energy frontier

  High energy collider (LHC),

  Collision of proton-proton

  Analysis of $O(10^{10})$ events





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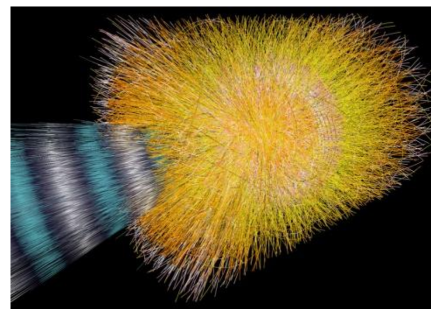
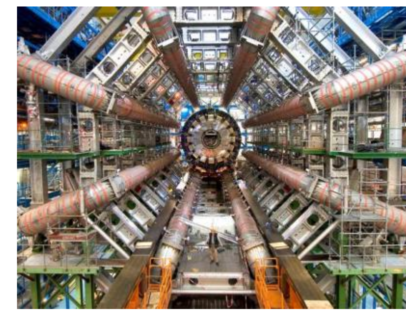




- Intensity frontier

  Sensitive detector (Kamioka, …),
  Detect a rare event
  in $O(10^{-10})$ probability

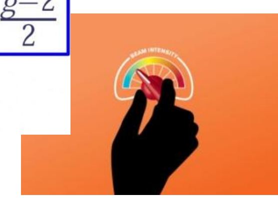
Putting it all together…

a_μ^{exp} = 116 592 089 (63) x 10^{-11}

a_μ^{thy} = 116 591 802 (49) x 10^{-11}

$a_\mu^{exp} - a_\mu^{thy}$ = 287 (80) x 10^{-11}

$$a_\mu = \frac{g-2}{2}$$



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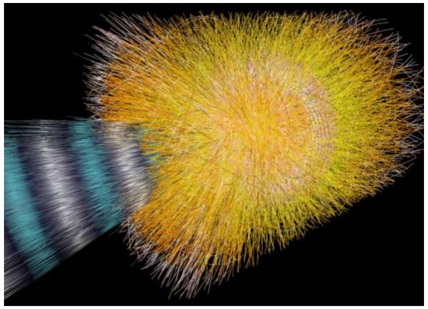

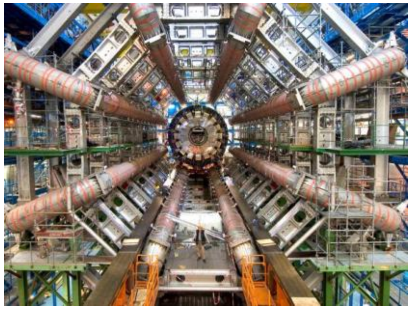

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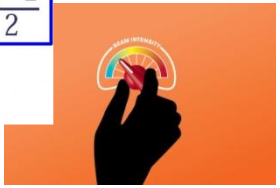
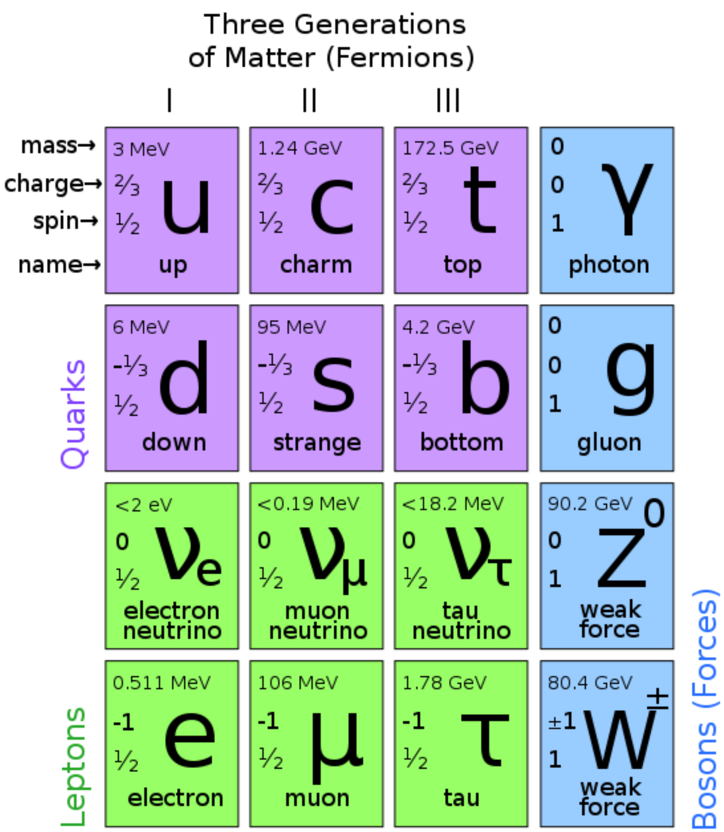


- Cosmic frontier
  Look up the sky carefully !

Introduction:

What has been interesting so far ?

- Making comprehensive list of fund. particles



- Established in the experiment
  - Quarks (3 generations)
    - u, d, s, c, b, t
  - Leptons (3 generations)
    - electron, muon, tau, and neutrino
  - Bosons
    - γ, g, Z, W (spin-1)
- Almost established in LHC
  - Higgs (spin-0) → discovery is very soon ?
- Not yet
  - Graviton (spin-2)

Theory:

Standard Model (QED, QCD, EW)

Introduction:
Quantum chromodynamics

- Treating *the fascinating problems* in hadron physics
  - How is the constitution of O(100) hadrons with 12 quarks ?
  - Why quarks (and gluon) are not directly visible ?
  - Why meson mass is so different (π ~135MeV, η' ~960MeV) ?
  - Why quark has fractional charge ?

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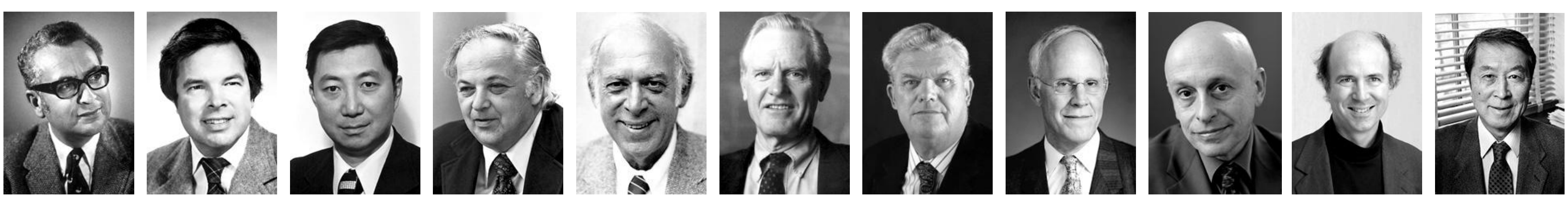
- QCD provides the *smart* solutions (asymptotic freedom, spontaneous sym. breaking, anomaly, …) using *very* simple formula

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

This is one of the most successful theory beyond perturbation !



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    - Why neutrino has mass ?
    - Why T(time-reversal)-violation in QCD and BSM is so small ?
    - Why proton does not decay ?
    - …

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  These problems have not been clear due to extremely tiny signal ($\langle O \rangle < 10^{-10}$, less than single precision)

$\Rightarrow$ need to the precision physics

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QCD (hadron) effect is important for these observables !

Some aspects from *effective models* but it has not been solid statement.
To know *hadron effect* exactly, we should deal with non-perturbative method.

Precision physics:

Muon g-2

- The extremely precise measurement

E821 Experiment (BNL): $a_\mu^{\mathrm{Exp}} = 116\,592\,089(54)(33) \times 10^{-11}$

$a_\mu^{SM} = 116\,591\,802(2)_{EW}\,(42)_{HLO}\,(26)_{HNLO} \times 10^{-11}$

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$a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = +287(63)_{\mathrm{Exp}}\,(49)_{\mathrm{SM}} \times 10^{-11}$ ~ 3.6 σ discrepancy !

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SUSY particle, dark photon, … ?

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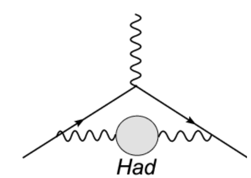
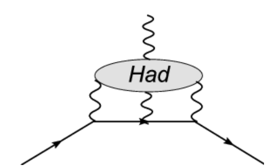
SUSY particle, dark photon, … ?

- Main uncertainties in the SM
  - Leading order of hadronic contribution (HVP);
    ~90% of error
  - Next-to-leading order of hadronic contribution (light-by-light);
    ~ *unknown*, may be large uncertainty





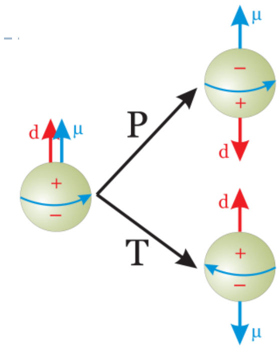
Need to precisely calculate HVP and LbyL, being independent from models.

Precision physics:

Nucleon EDM

- Sensitive to Parity, T-violation of fund. particle

  but this is almost zero; upper limit: $< 2.9 \times 10^{-26}$ e·cm



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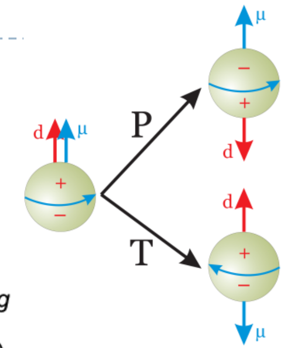

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  Very tiny, which is 3-loop : $d_N^{KM} \simeq 10^{-30}$ -- 10^{-32} e·cm

  Khriplovich and Zhitnitsky, PLB109, 490 (1982);
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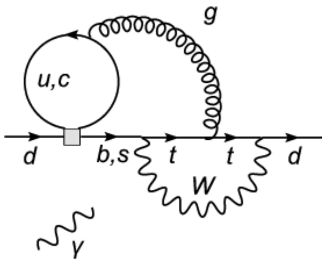

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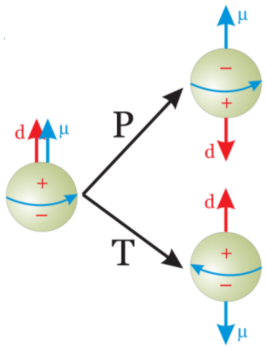

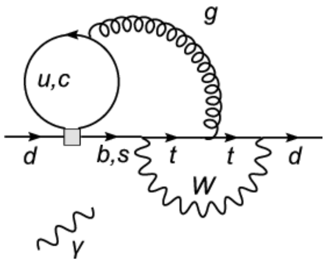

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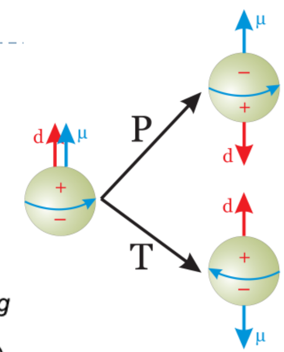

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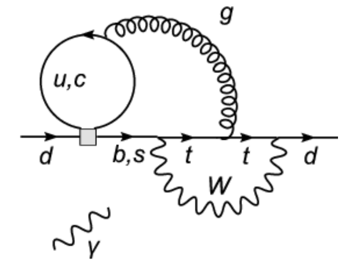

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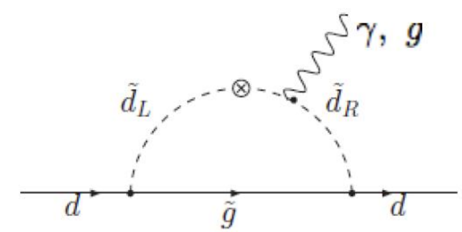
- Contribution from BSM: dim-5,6 operator

$$\mathcal{O}_{\rm qEDM} = d_q \bar{q}(\sigma \cdot F)\gamma_5 q, \quad \mathcal{O}_{\rm cEDM} = d_q^c \bar{q}(\sigma \cdot G)\gamma_5 q$$



$$\begin{aligned} d_N &= d_N^{\rm QCD}\bar{\theta} + d_N(d_q, d_q^c) + d_N(d^G) \\ &\sim 10^{-17}[{\rm e\cdot cm}]\bar{\theta} + (1.4\text{--}0.47)d_d - (0.12\text{--}0.35)d_u + O(10^{-2})d_q^c \\ &\sim O(10^{-25}\text{--}10^{-27})\,{\rm e\cdot cm} \end{aligned}$$

→ Close to the bound of experiment

Hisano, Shimizu (04), Ellis, Lee, Pilaftsis (08),
Hisano, Lee, Nagata, Shimizu (12)

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Proton decay

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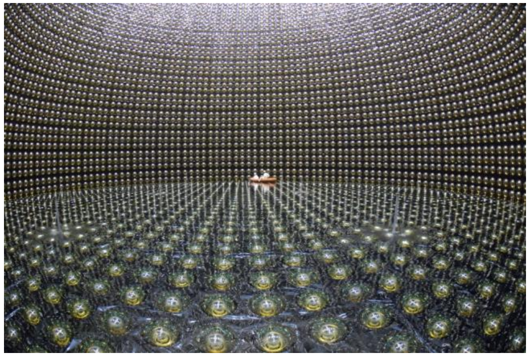
- Experiments
  - Super-Kamiokande leads to bound:

    $\tau(pe^+\pi^0) > 8.2 \times 10^{33}$ years

  Nishino et al. (Super-Kamiokande), PRD85, 112001(2012)

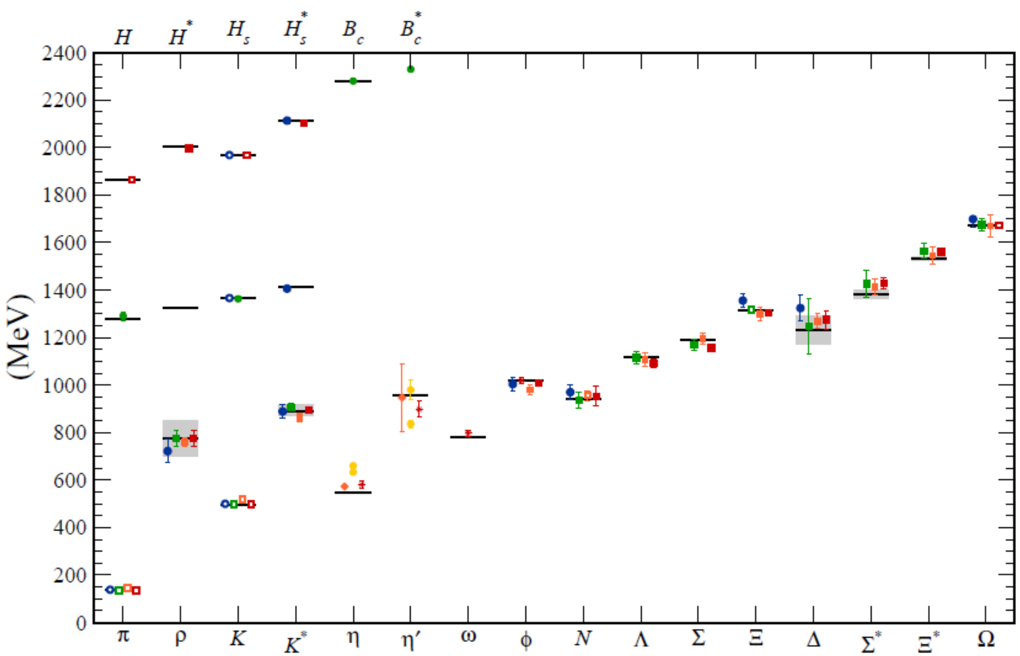
We should make sure whether GUTs are excluded or not ?



Precision physics:

Lattice QCD

- Appropriate tool to precisely investigate hadron effect
  - Enable us to evaluate hadron contribution in the particle physics.
  - Elegant methodology
    - Gauge symmetry and renormalizability
    - A few input parameters (cut-off scale, and quark mass)

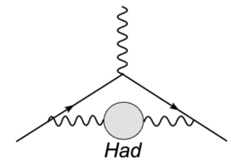


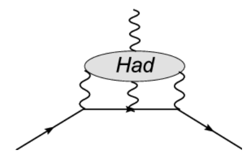
Lattice QCD provides almost consistent values of hadron spectroscopy, including heavy quarks, with experiment.

Kronfeld, 1209.3468

Application of GPU:
Status & Perspectives

- Lattice calculation in Nf = 2+1 DWFs
  - Muon g-2
    - Leading order hadron contribution:
      10% accuracy → a few % required
    - The next-to-leading order :
      unknown → around10% accuracy





  - Nucleon EDM
    - Recently we have 30 % precision (stat.) of nucleon EDM.
    - To establish it, we require less than 10 % total error.
  - Proton decay
    - Recent result shows that p→π channel has 30% total error.
    - It is possible to reduce the error to around a few %. Aoki, ES, Soni, 1304.7424

Note : these are estimate using AMA algorithm (× 5 faster).

Blum, Izubuchi, ES, 1208.4349

Application of GPU:

Error reduction techniques

Blum, Izubichi, ES, 1208.4349

- Covariant approximation averaging (CAA)
  - For original observables O, (unbiased) improved estimator

$$\mathcal{O}^{(\mathrm{imp})} = \mathcal{O}^{(\mathrm{rest})} + \frac{1}{N_G}\sum_{g\in G}\mathcal{O}^{(\mathrm{appx}),g}, \quad \mathcal{O}^{(\mathrm{rest})} = \mathcal{O} - \mathcal{O}^{(\mathrm{appx})}$$

which satisfies <O> = <O^{imp}> if approximation is covariant under lattice symmetry g, and error becomes $\mathrm{err}^{\mathrm{imp}} \simeq \mathrm{err}/\sqrt{N_G}$

  - All-mode averaging (AMA)

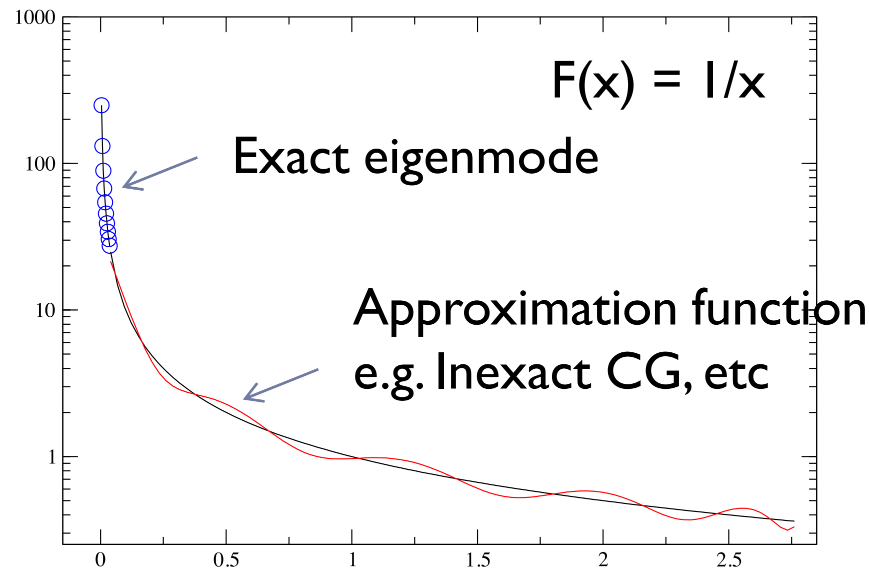
$$\mathcal{O}^{(\mathrm{appx})} = \mathcal{O}[S_l],$$

$$S_l = \sum_\lambda v_\lambda F(\lambda) v_\lambda^\dagger,$$

$$F(\lambda) = \begin{cases} \lambda^{-1}, & |\lambda| < \lambda_{\mathrm{cut}} \\ P_n(\lambda) \simeq \lambda^{-1} & |\lambda| > \lambda_{\mathrm{cut}} \end{cases}$$

accuracy control :

- low mode part : # of eig-mode
- mid-high mode : degree of poly.



Application of GPU:

GPU accelerator of lattice QCD

- GPU computation becomes the big stream in lattice QCD
  - Reasonable cost-performance and potential of improvement
  - Alternative resource to CPU cluster
  - Take advantage of fast implementation of CG inverter
  - Interesting applications *(for me)*
    - HMC applications

      There have been many trials using staggered fermion or Wilson fermion.
    - Fast implementation of Dirac inverter as preconditioner

      Mixed precision seems to be efficient. Mike's and Hyung-Jin's talk
    - Computation of eigenmode of Dirac matrix

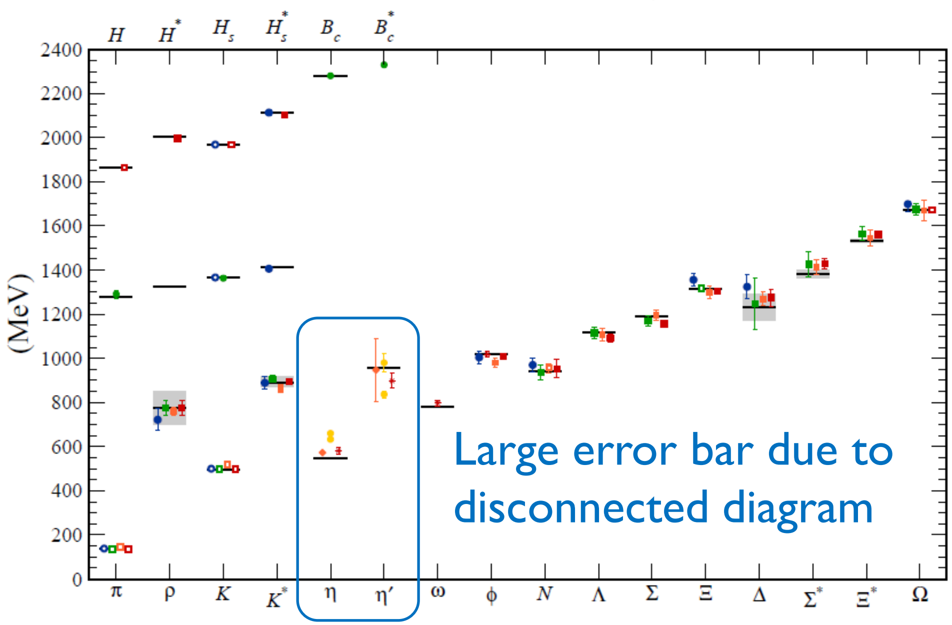
      Important, but huge memory size might be bottom neck.
    - Application to stochastic method

Application of GPU:
Example

- Disconnected diagram
  - *can of the worm*
  - Computation of trace of the matrix inverse using stochastic method:

$$\mathrm{Tr}\, D^{-1}(x,x) \simeq N^{-1}\sum_i \eta_i^\dagger(x) D^{-1}(x,y)\eta_i(y),\ \eta_i(x) = e^{i\xi_i(x)}$$

ξ_i : random number from $[0{:}2\pi)$



- This is based on approximation

$$\delta_{x,y} \simeq \sum_i \eta_i^\dagger(x)\eta_i(y)/N$$

- Additional CG iteration of noise number is needed ($\times$ O(100))
- Disconnected diagram has rich info. of isospin breaking etc.

Fast CG algorithm or preconditioning is very useful.

Application of GPU:

Study of lattice QCD with GPU

- There are several publications

Testing HMC with staggered fermion

• Egri, et al., "Lattice QCD as a video game", Comput.Phys.Commun.177,631(207).

• Bonati et al."QCD simulations with staggered fermion on GPUs", Comput.Phys.Commun.183,853 (2012).

Study of finite temperature

• Aoki et al.," The QCD transition temperature: results with physical masses in the continuum limit II", JHEP 0906 (2009) 088.

• Endrodi et al., "The QCD phase diagram at nonzero quark density", JHEP 1104 (2011) 001.

Algorithm with mixed precision

• Clark, et al.,"Solving Lattice QCD systems of equations using mixed precision solvers on GPUs", Comupt.Phys.Commun.181,1517(2010).

• Babich, et al.,"Scaling Lattice QCD beyond 100 GPUs", arXiv: 1109.2935

• Jang, et al. "Multi GPU Performance of Conjugate Gradient Solver with Staggered fermions in Mixed Precision", arXiv: 1111.0125

Application of GPU:

Request from precision physics

- Domain-Wall fermion (DWF) is important to control the systematic error of lattice artifacts.
- Now preparing the gauge configurations including physical quarks in 5 fm volume. RBC/UKQCD collaboration
- Target simulation size:
  - $48^3 \times 96 \times 16$ lattice in physical pion mass : $m_\pi = 135$ MeV
  - >200 eigenmodes of even-odd DWF kernel
  - Required performance:

    Memory ~ 4 TB, Flops > 40TFlops/job

    → excellent scalability is needed (as well as Blue Gene series …)

Summary

- Particle physics is being precision physics.
- Reliable calculation in the SM plays an essential role to proceed to BSM search.
- Lattice QCD is the most appropriate.
- To confirm the SM prediction for muon g-2, nucleon EDM and proton decay, GPU computation is helpful.
- We have to search the best way for the implementation:
  - Mixed precision ?
  - Hybrid with CPU ?
- Expect GPU has a lot of potential.

Thank you for your attention !