High Performance Computing and Lattice QCD

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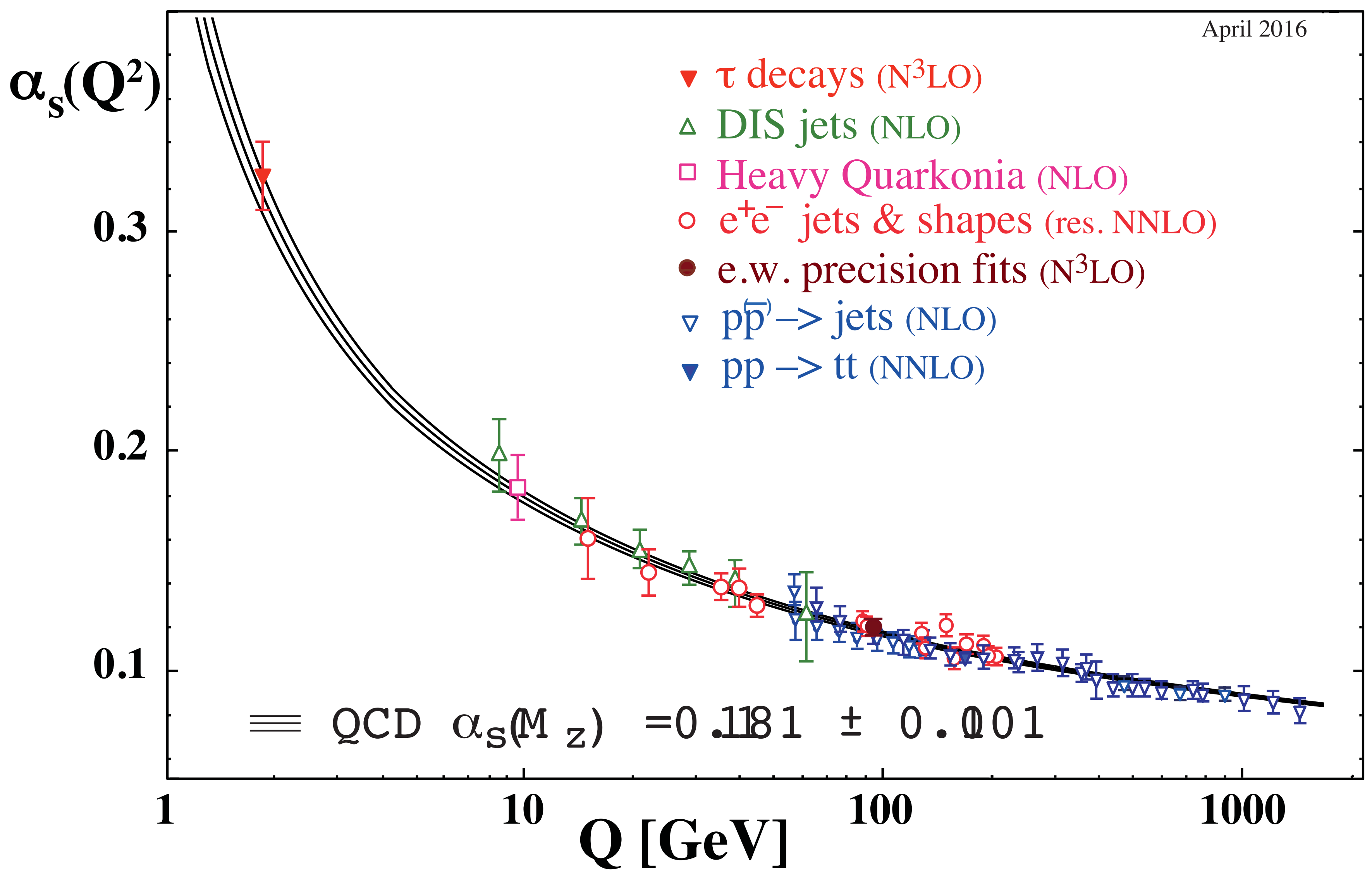
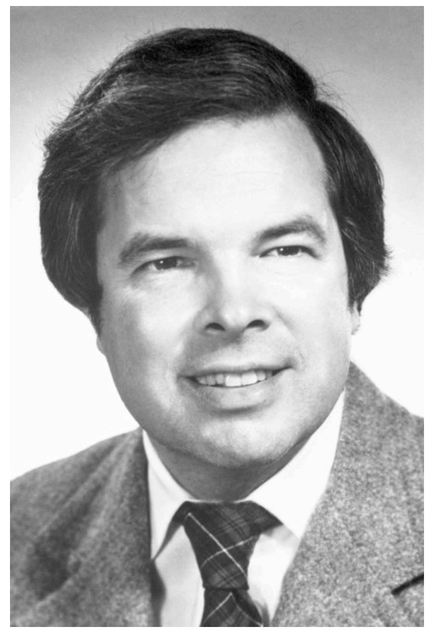
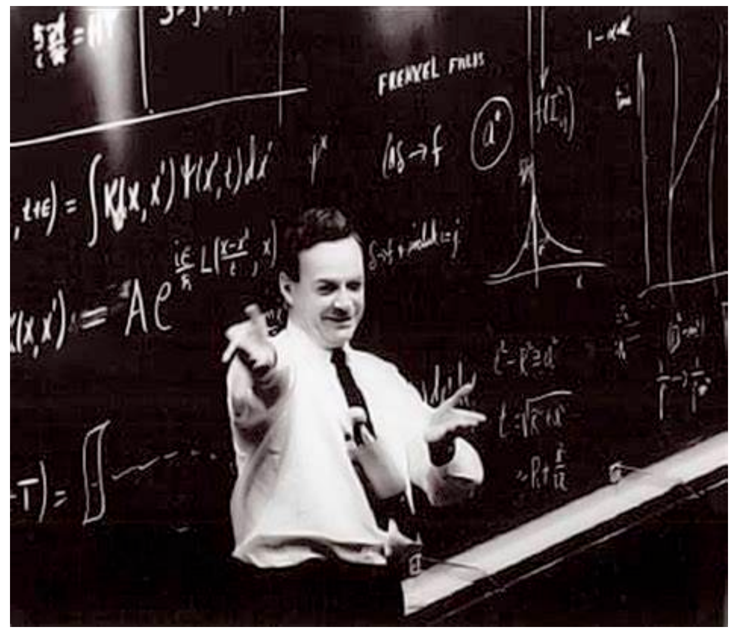
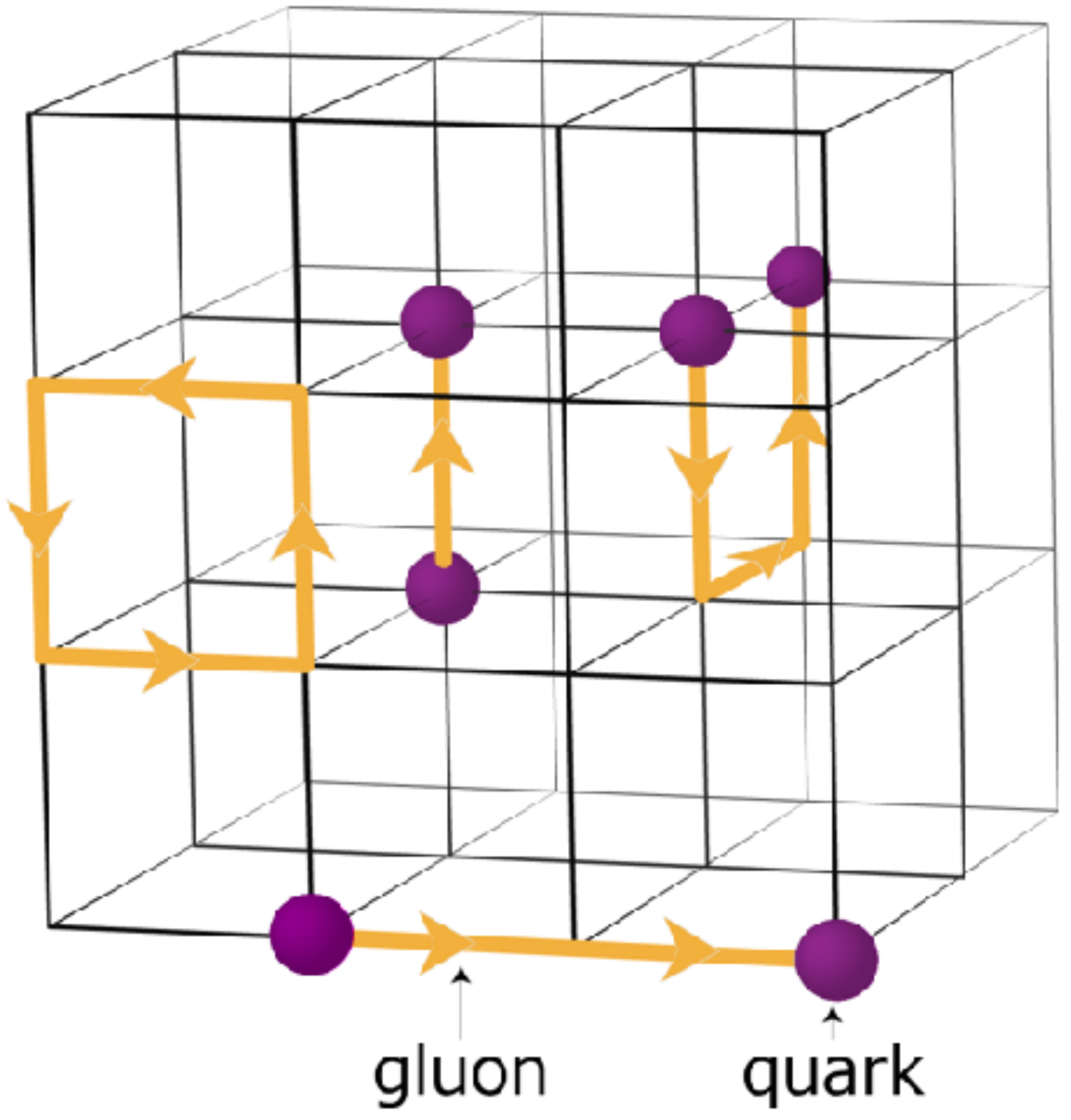
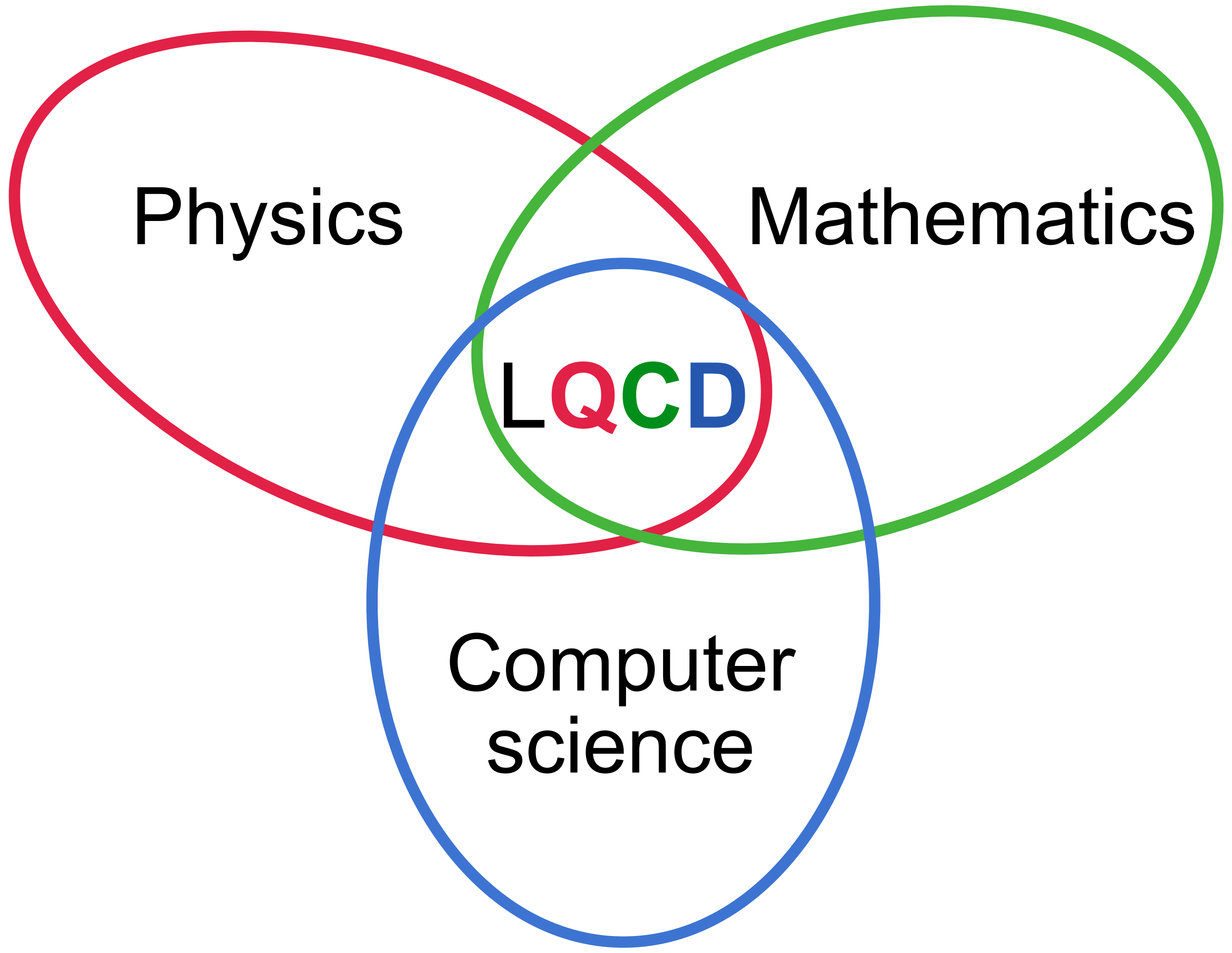
Introduction to LQCD







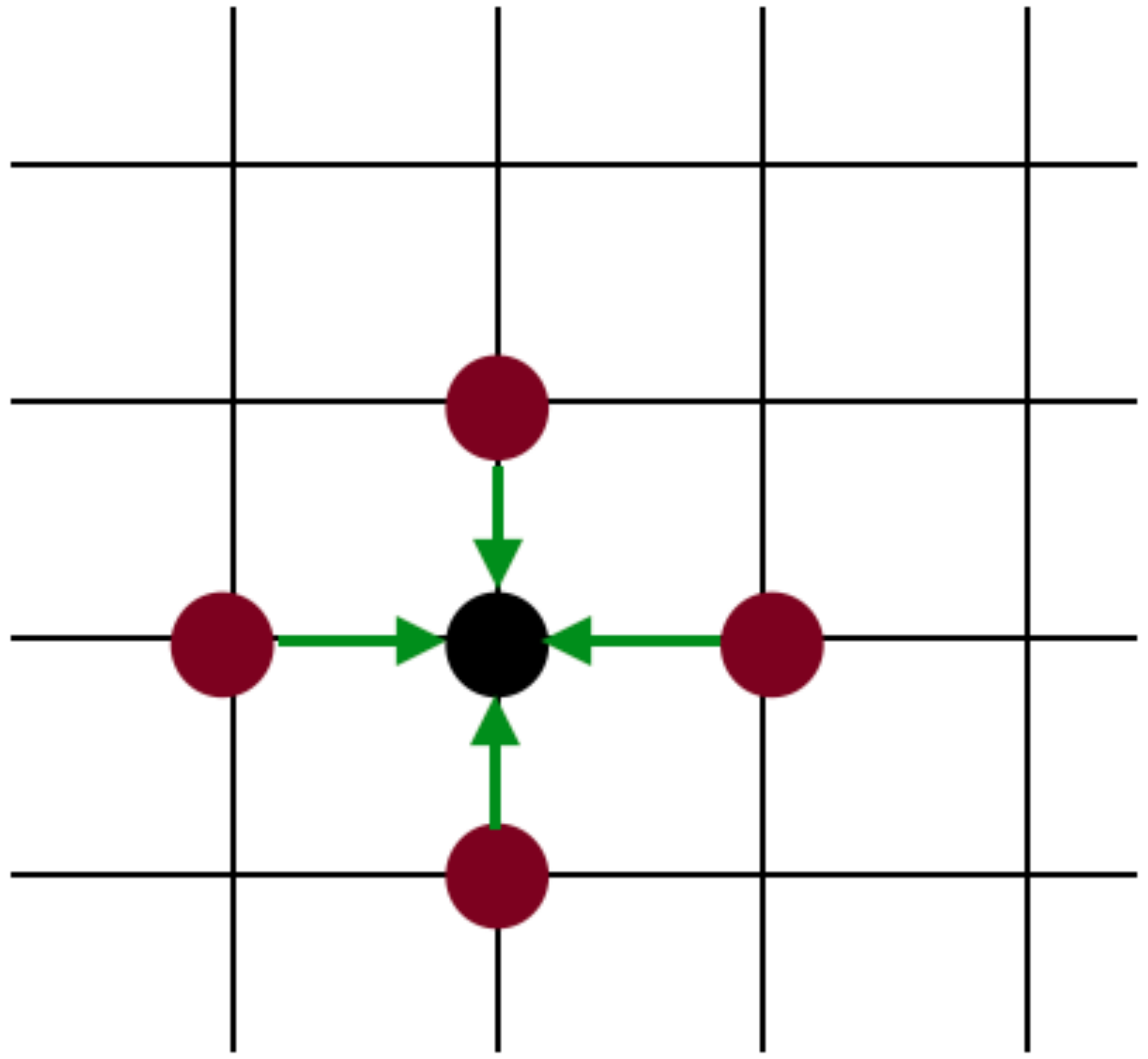




- Lattice QCD (LQCD) : QCD on a spacetime lattice
- Calculate QCD path integral with Monte Carlo method

Computational Perspectives of LQCD

- Dirac equation on the lattice is to solve the large sparse linear system $Mx = b$
- $M = m + 4 - \frac{1}{2}D$, D is the Dslash operation
- $$D_{x,y} = \sum_{\mu=1}^{4} U_\mu(x)(1-\gamma_\mu)\delta_{x+\hat{\mu},y} + U_\mu(x-\hat{\mu})^\dagger(1+\gamma_\mu)\delta_{x-\hat{\mu},y}$$
- 4 dimensional 8(9) point stencil operator
- Nearest neighbor communication, very suitable for parallel computing
- LQCD is expensive
  - $N_f = 2+1,\ 64^3 \times 128,\ m_\pi \approx 170\ MeV,\ \beta = 6.3$
  - 512 V100 GPUs
  - 700 GPU*Hour per gauge configuration
  - $O(1M)$ GPU*Hour for $O(1000)$ gauge configuration
  - $O(10-100)$ GB per quark propagator

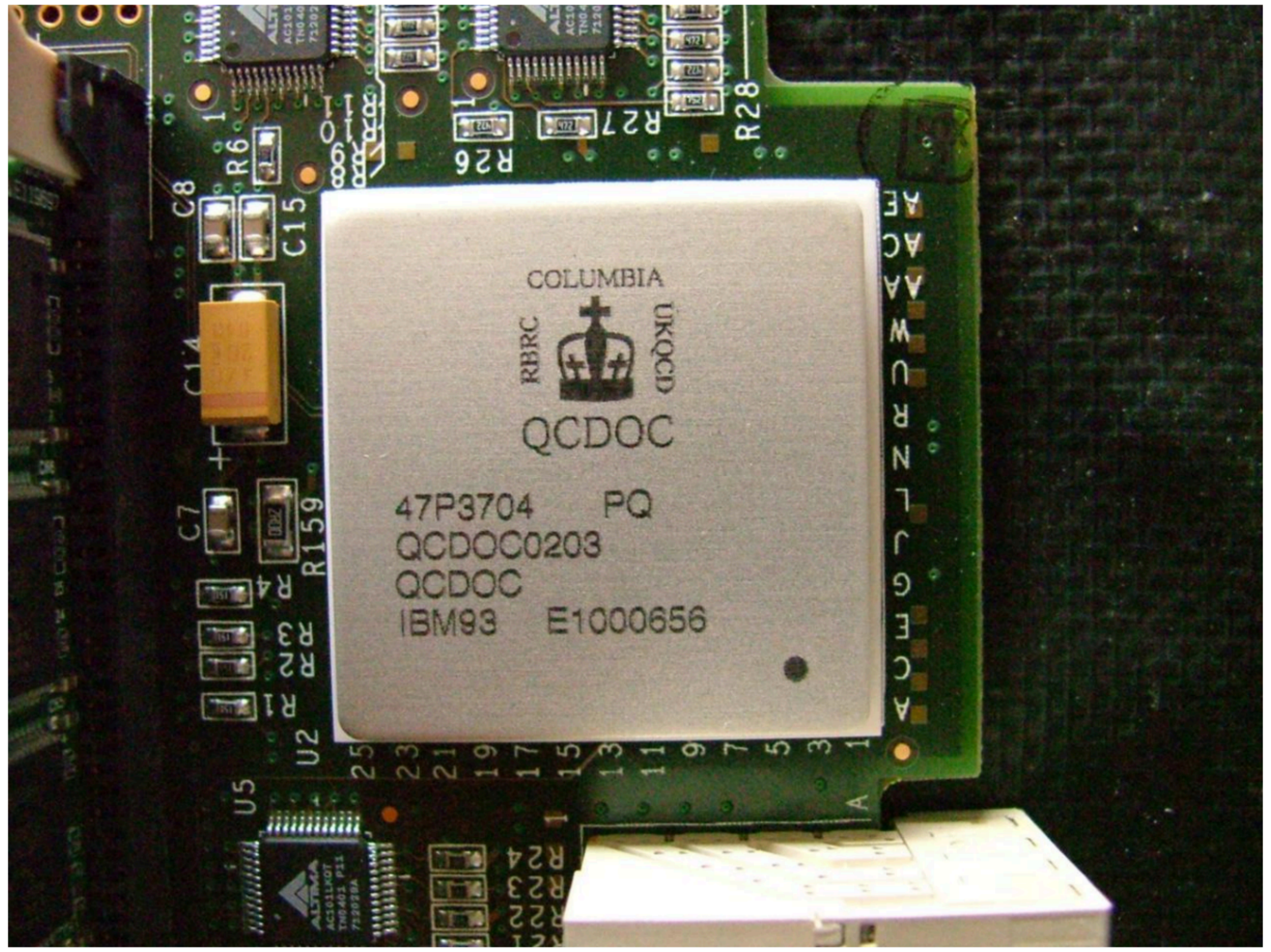


Computational Perspectives of LQCD

LQCD with HPC

- Decades ago - customized processors
- QCDOC (QCD On a Chip)

QCDOC Asic, 1 Gflop/s



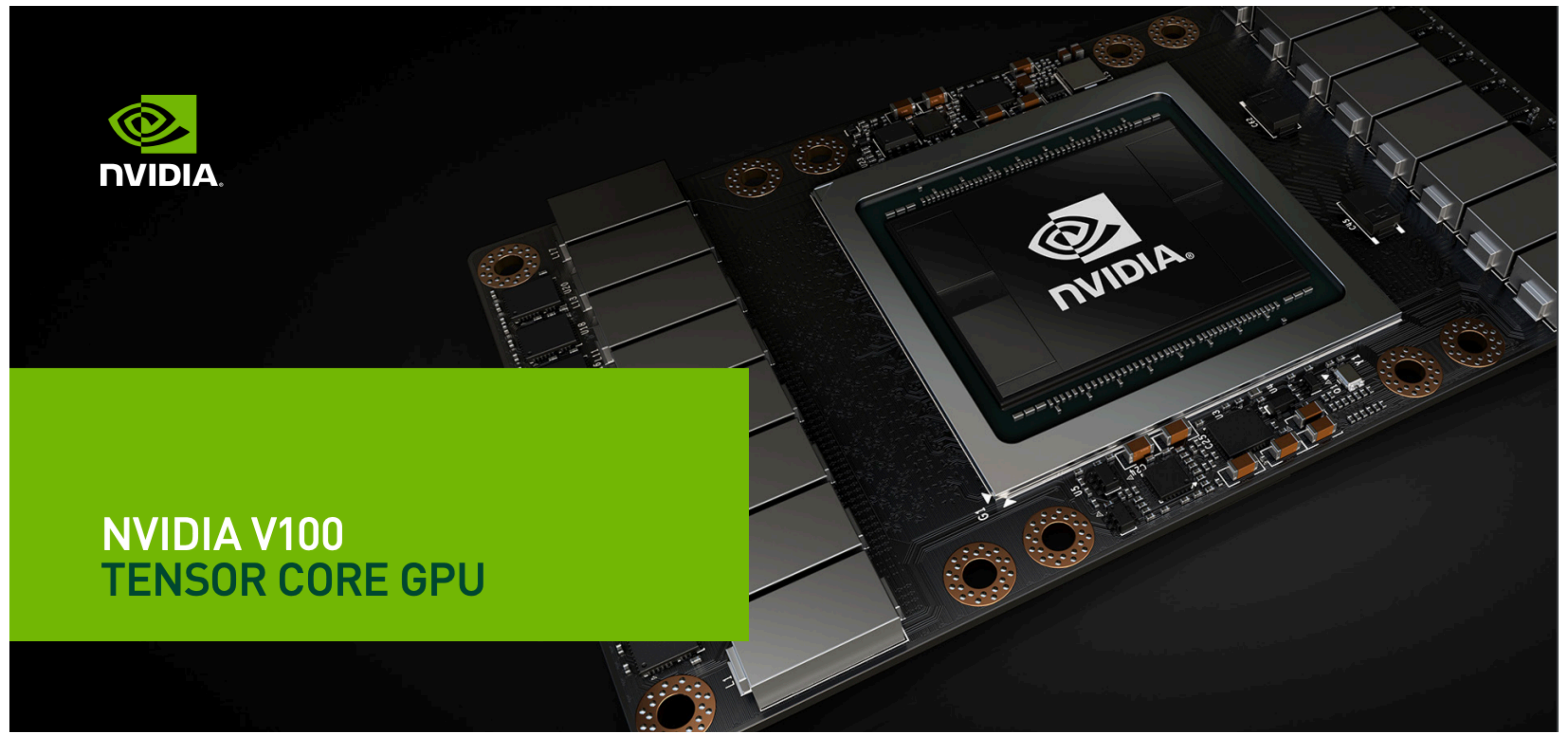
- Nowadays - supercomputers / clusters
- TOP 500

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	**Frontier** - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE DOE/SC/Oak Ridge National Laboratory United States	8,730,112	1,102.00	1,685.65	21,100
2	**Supercomputer Fugaku** - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,630,848	442.01	537.21	29,899
3	**LUMI** - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE EuroHPC/CSC Finland	1,110,144	151.90	214.35	2,942
4	**Summit** - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148.60	200.79	10,096
5	**Sierra** - IBM Power System AC922, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94.64	125.71	7,438

- LQCD awarded 1995,1998,2006 Goldon Bell Prize and 2018 finalist

Computational Perspectives of LQCD

Computing resources of IHEP LQCD group (after 2018)



Nvidia V100 GPU cards: 280 = 200 (Beijing) + 80 (Dongguan)

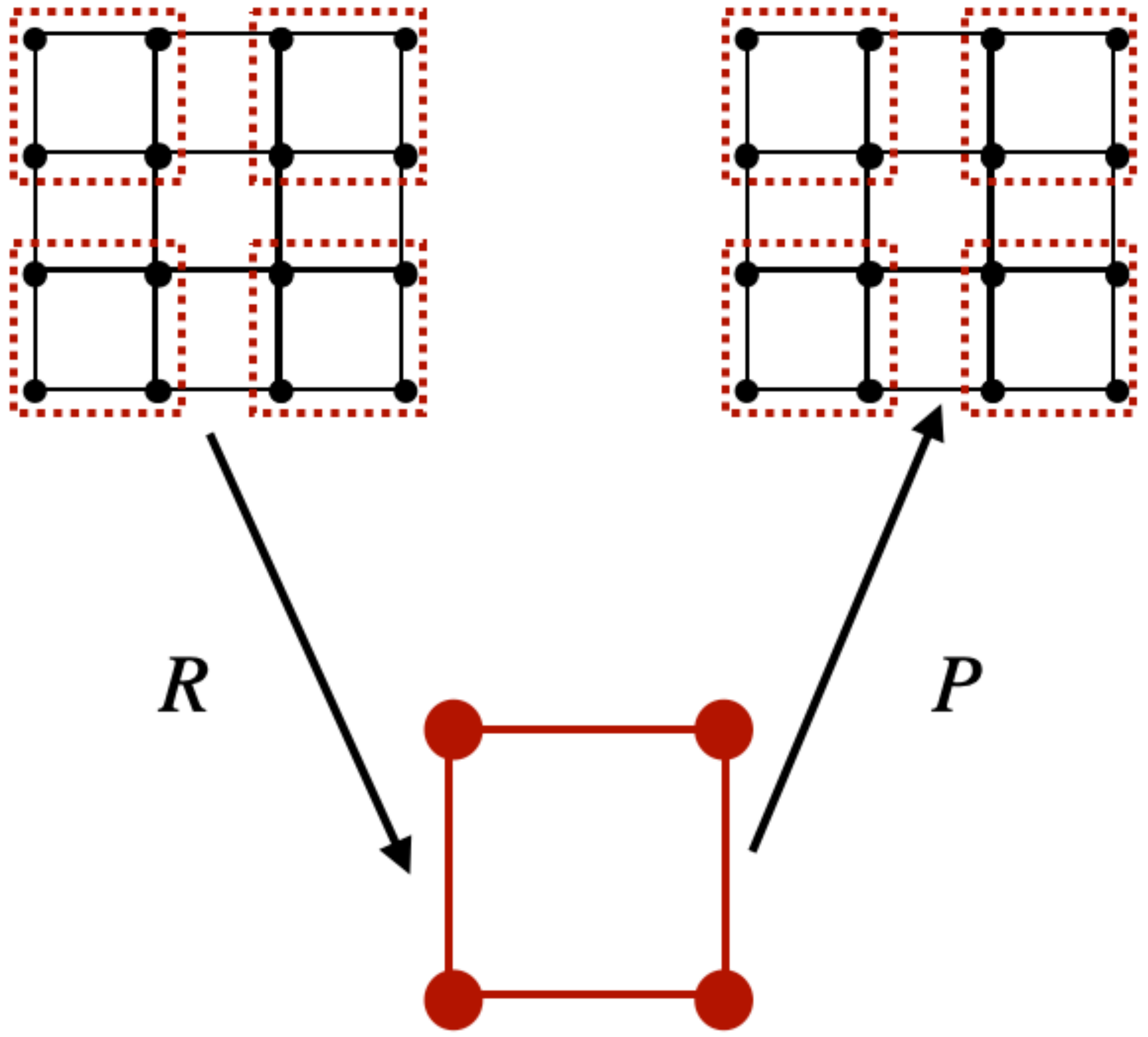
x86 CPU: ~ 12000 cores

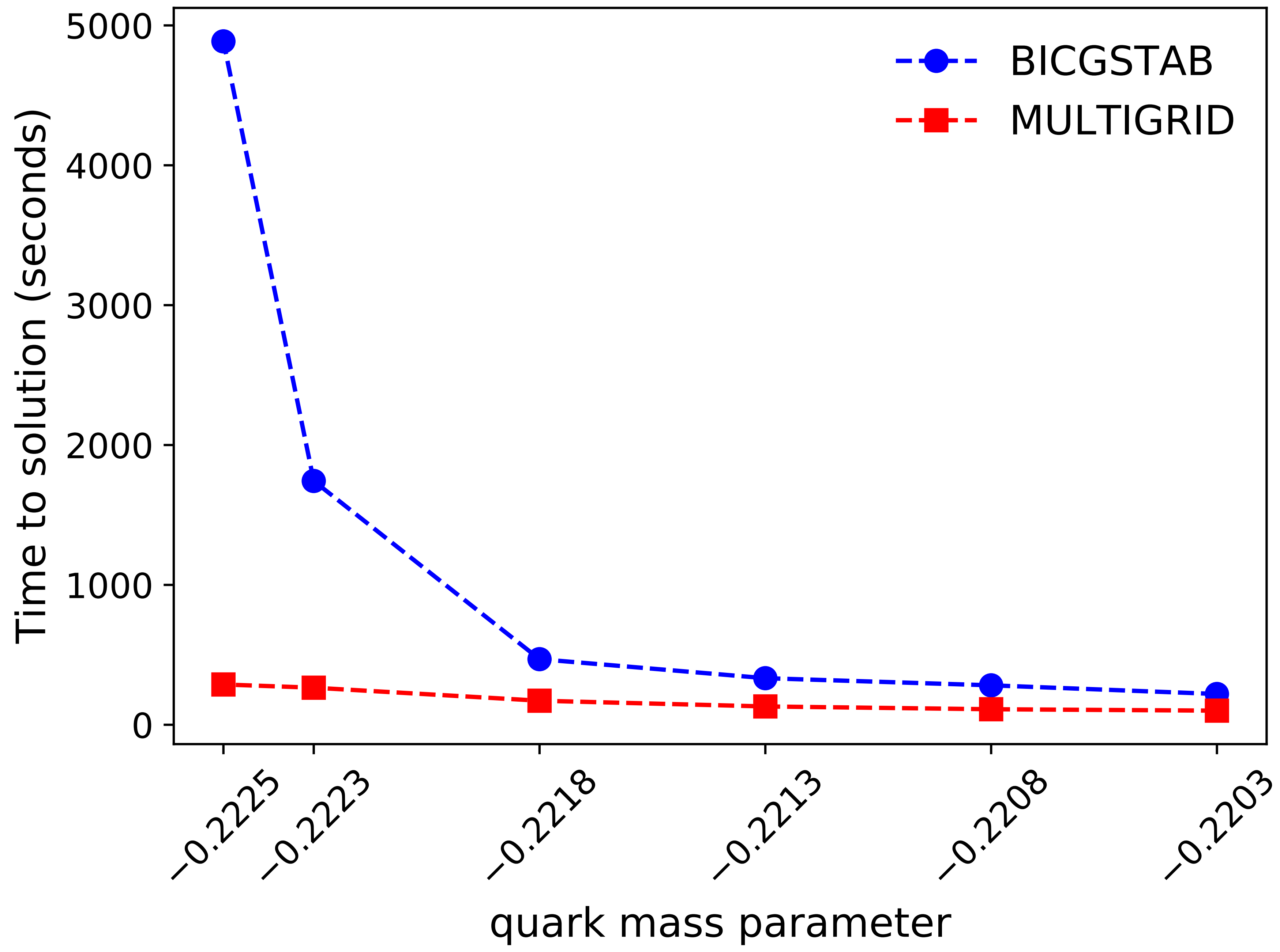
ARM CPU: ~ 10000 cores

Computational Perspectives of LQCD

Multigrid algorithm for LQCD

- Need to large amount of sparse linear system $Mx = b$
- Traditional Krylov Subspace method suffers critical slowing down problem
- Explore the multigrid algorithm



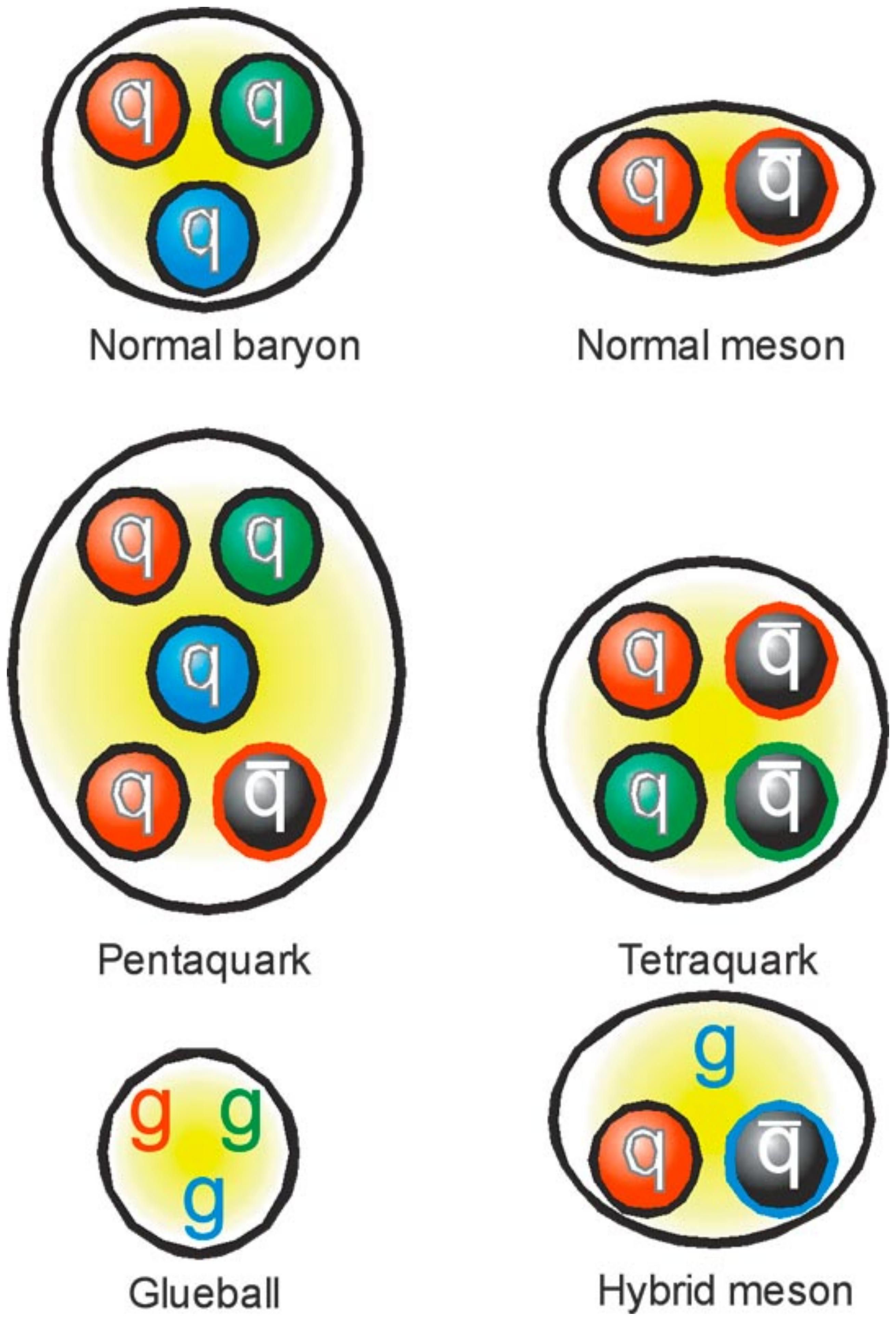


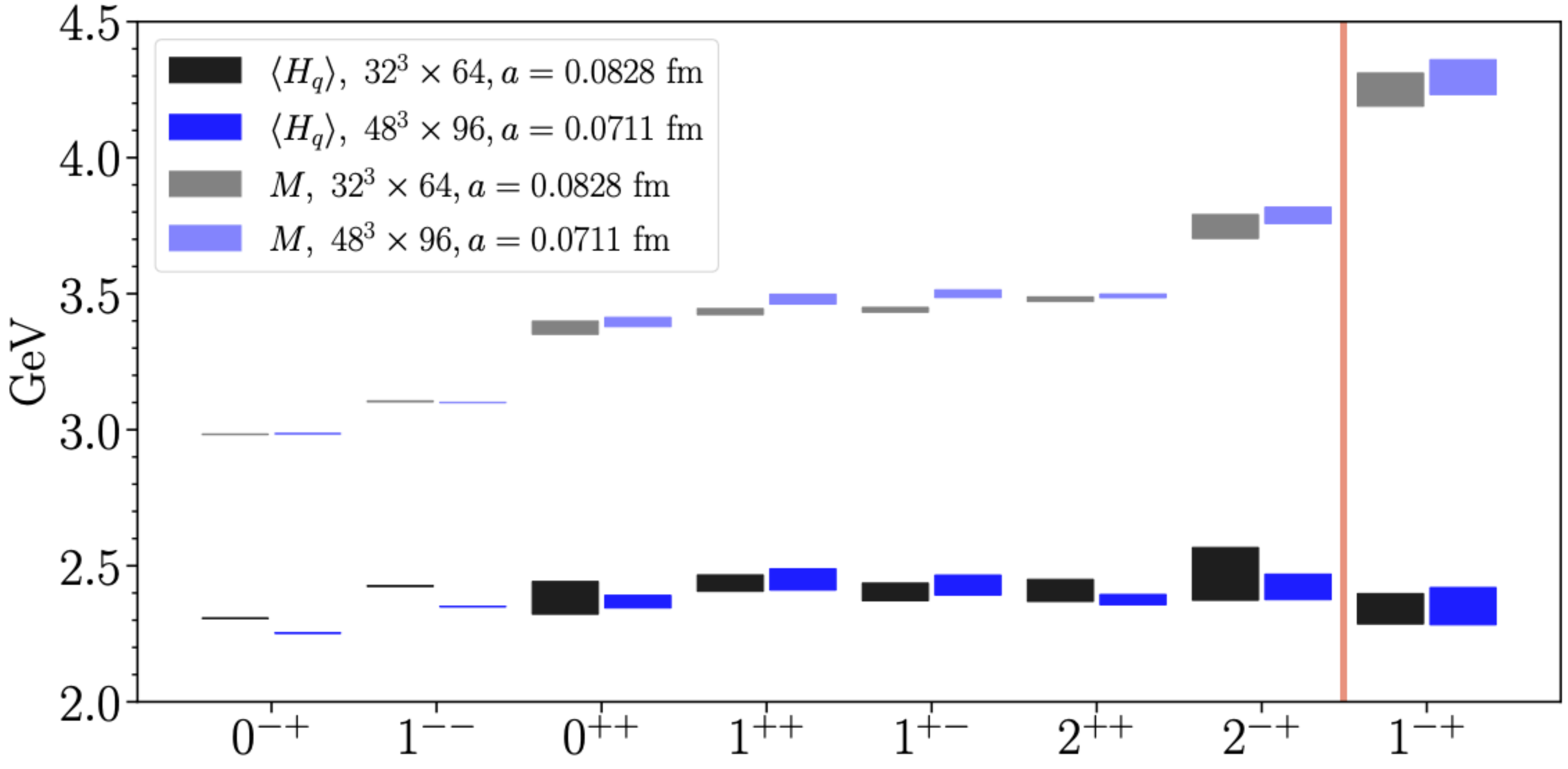
- Supported by China Postdoctoral Science Foundation

Charmonium related LQCD studies

Gluons in charmoniumlike states [**W.Sun**, Y.Chen, P.Sun, Y.B.Yang, *Phys.Rev.D* 103 (2021) 9, 094503]

- Mass decomposition of $1S, 1P, 2^{-+}, 1^{-+}$ charmoniumlike states





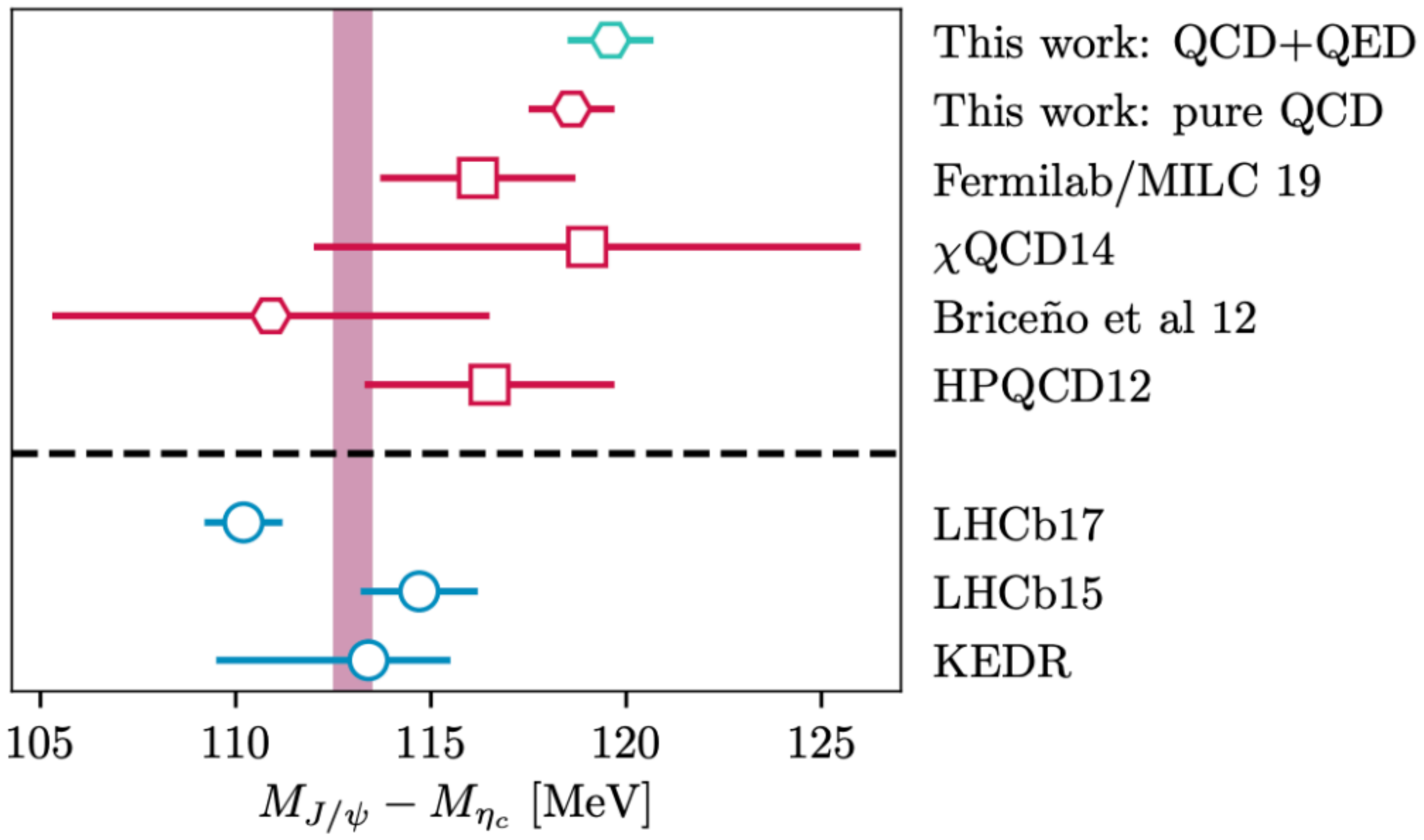
Charmonium related LQCD studies

The glueball content of η_c

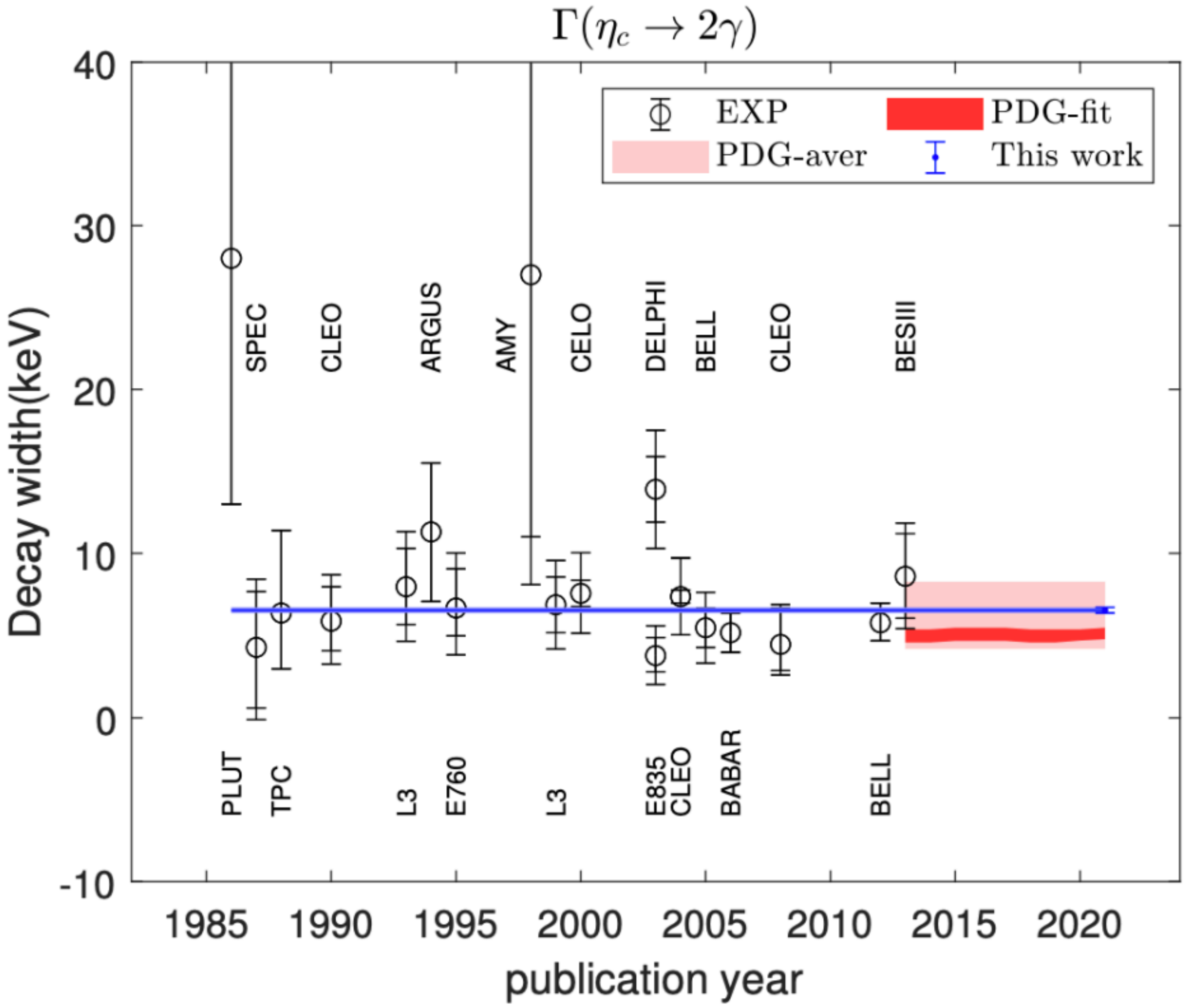
$\eta_c(1S)$ $I^G(J^{PC}) = 0^+(0^{-+})$

Large decay width compared to other charmonium

$\eta_c(1S)$ MASS	2983.9 ± 0.4 MeV (S = 1.2)
$\eta_c(1S)$ WIDTH	32.0 ± 0.7 MeV



D. Hatton et.al, Phys. Rev. D 102, 054511 (2020)



Y. Meng et.al, arXiv:2109.09381

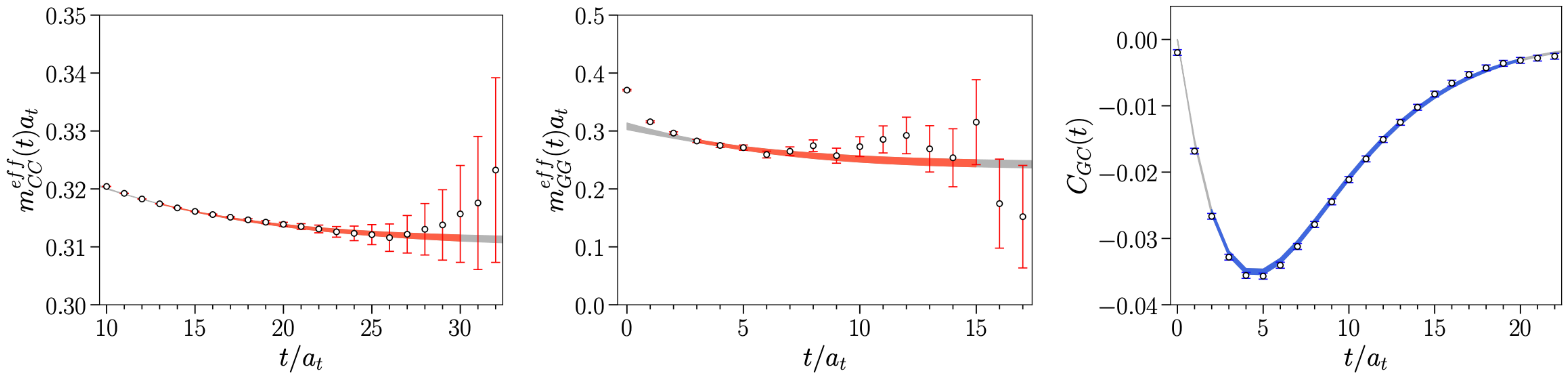
Charmonium hyperfine splitting: 120 MeV (lattice) vs. 113 MeV (exp.)

3.6 σ discrepancy of $\Gamma(\eta_c \to 2\gamma)$ between exp. and lattice

Charmonium related LQCD studies

The glueball content of η_c

[R.Zhang, **W.Sun**, Y.Chen et al., *Phys.Lett.B* 827 (2022) 136960]



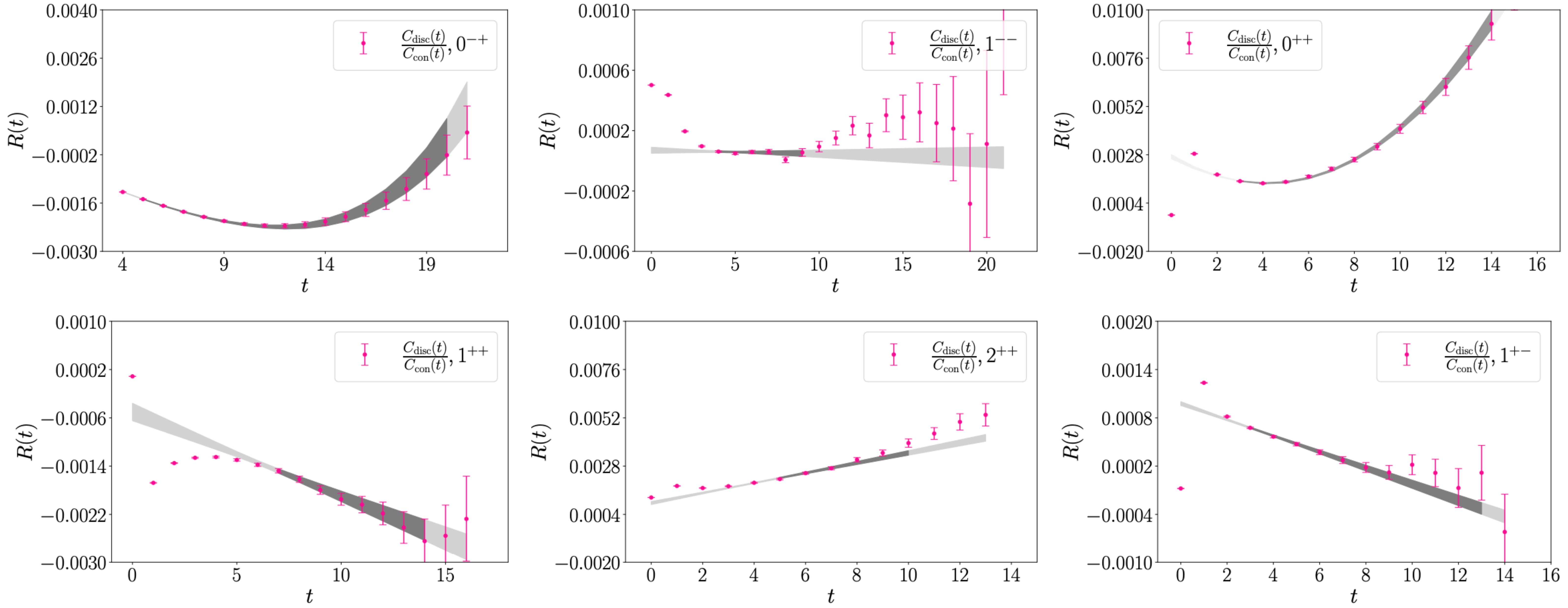
Ensemble	$L^3 \times T$	β	a_s(fm)	ξ	$N_{\rm cfg}$	$m_{J/\psi}$(MeV)
I	$16^3 \times 128$	2.8	0.1026	5	~ 7000	2743
II	$16^3 \times 128$	2.8	0.1026	5	~ 6000	3068

- mixing angle $\theta = 4.3(3)^\circ$, mixing energy $x = 49(6)$ MeV
- raise the decay width of $c\bar{c}$ by approximately 7 MeV
- shift the mass of pseudoscalar $c\bar{c}$ state upward by approximately 3.9(9) MeV

Charmonium related LQCD studies

Annihilation diagram contribution to charmonium masses

[R.Zhang, **W.Sun**, F.Chen et al., *Chin.Phys.C* 46 (2022) 043102]



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- No effect for J/ψ, increase η_c by 3-4 MeV
- Increase χ_{c1}, h_c by ~ 1 Mev
- Decrease χ_{c2} by ~ 3 MeV

Summary

- Progress of LQCD is strongly related to the development of HPC system
- LQCD is one of the most computing resource demanding research area in high energy physics
- LQCD is also an important application of high performance supercomputers and clusters
- We show some recent results related to charmoniumlike states from IHEP LQCD group