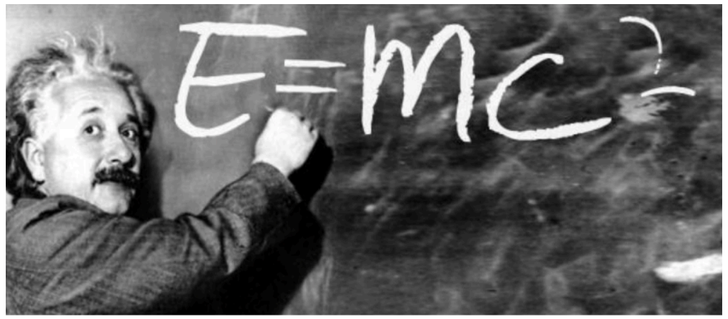
物理科学学院 青年教师线上论坛

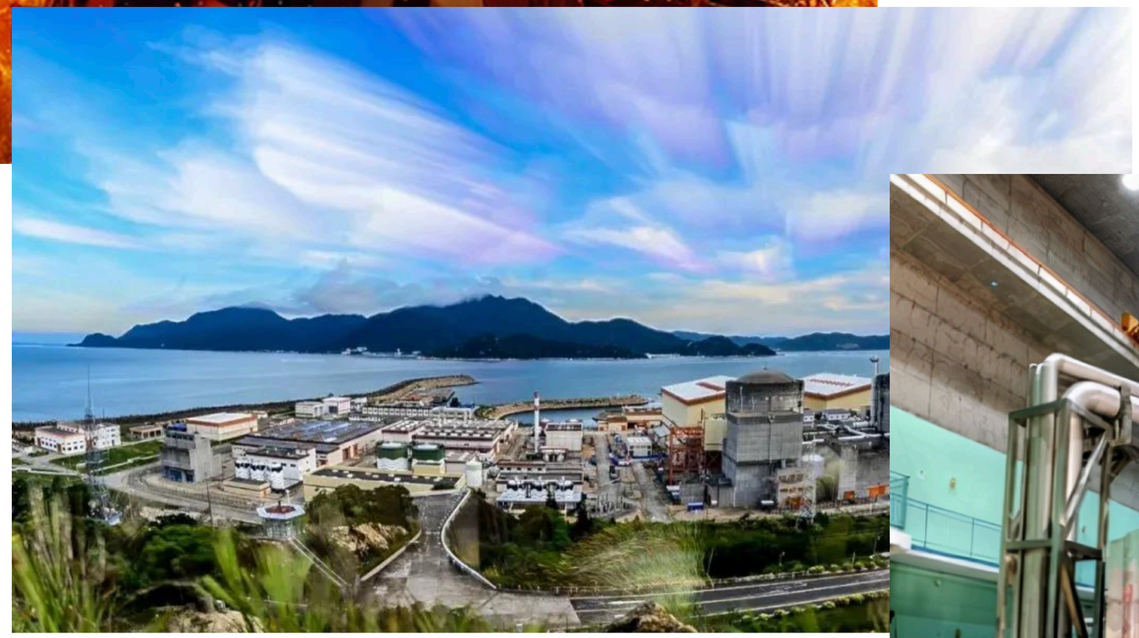
核能从哪里来：
质量的强相互作用起源

杨一玻

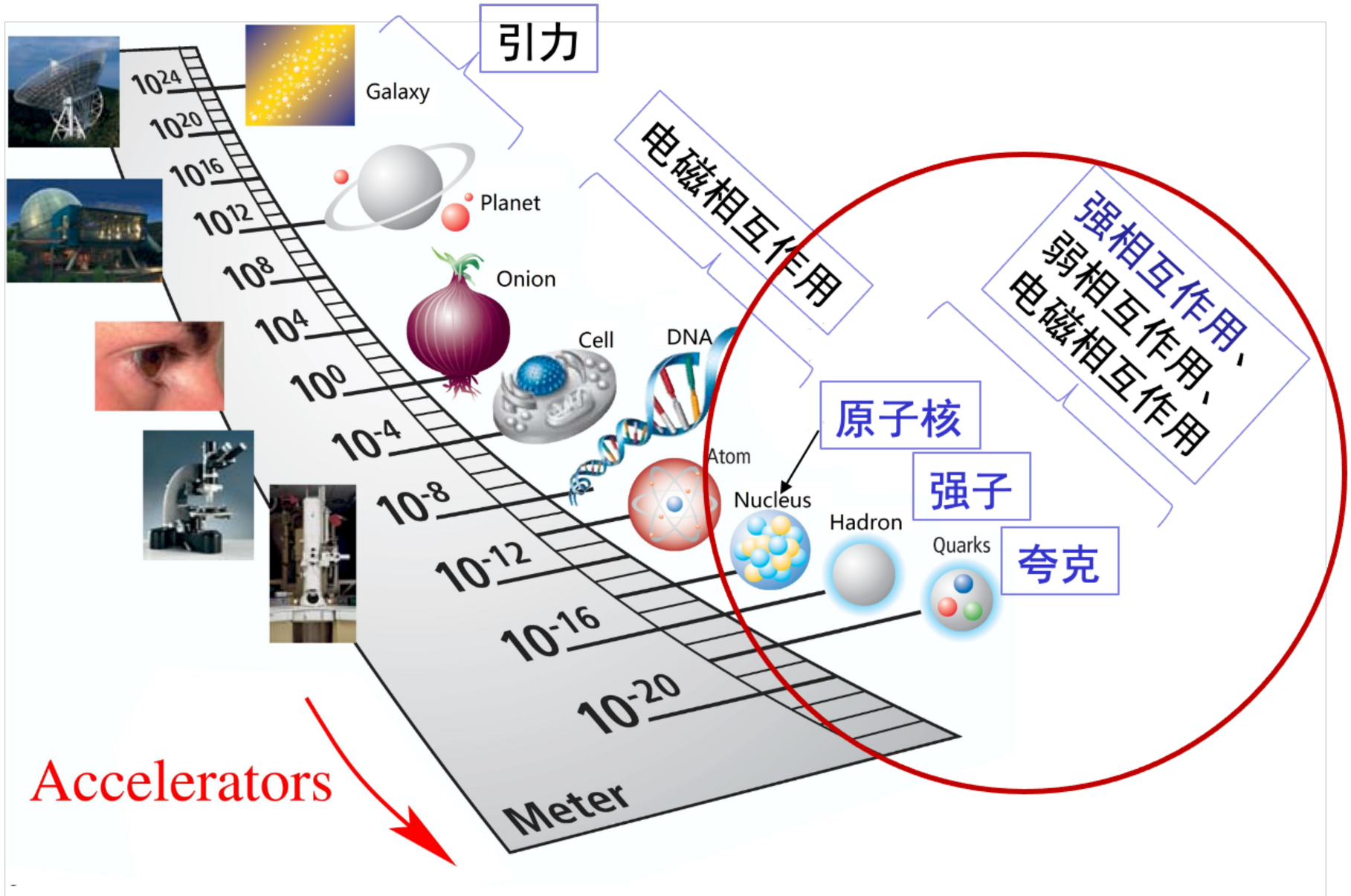
2024年11月24日

从原子弹到能源圣杯

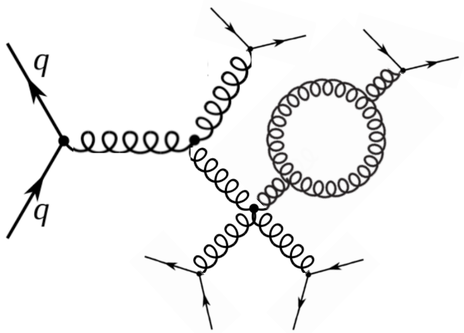




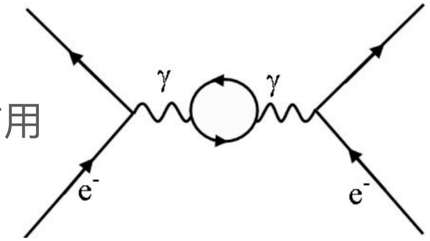
研究对象



强相互作用

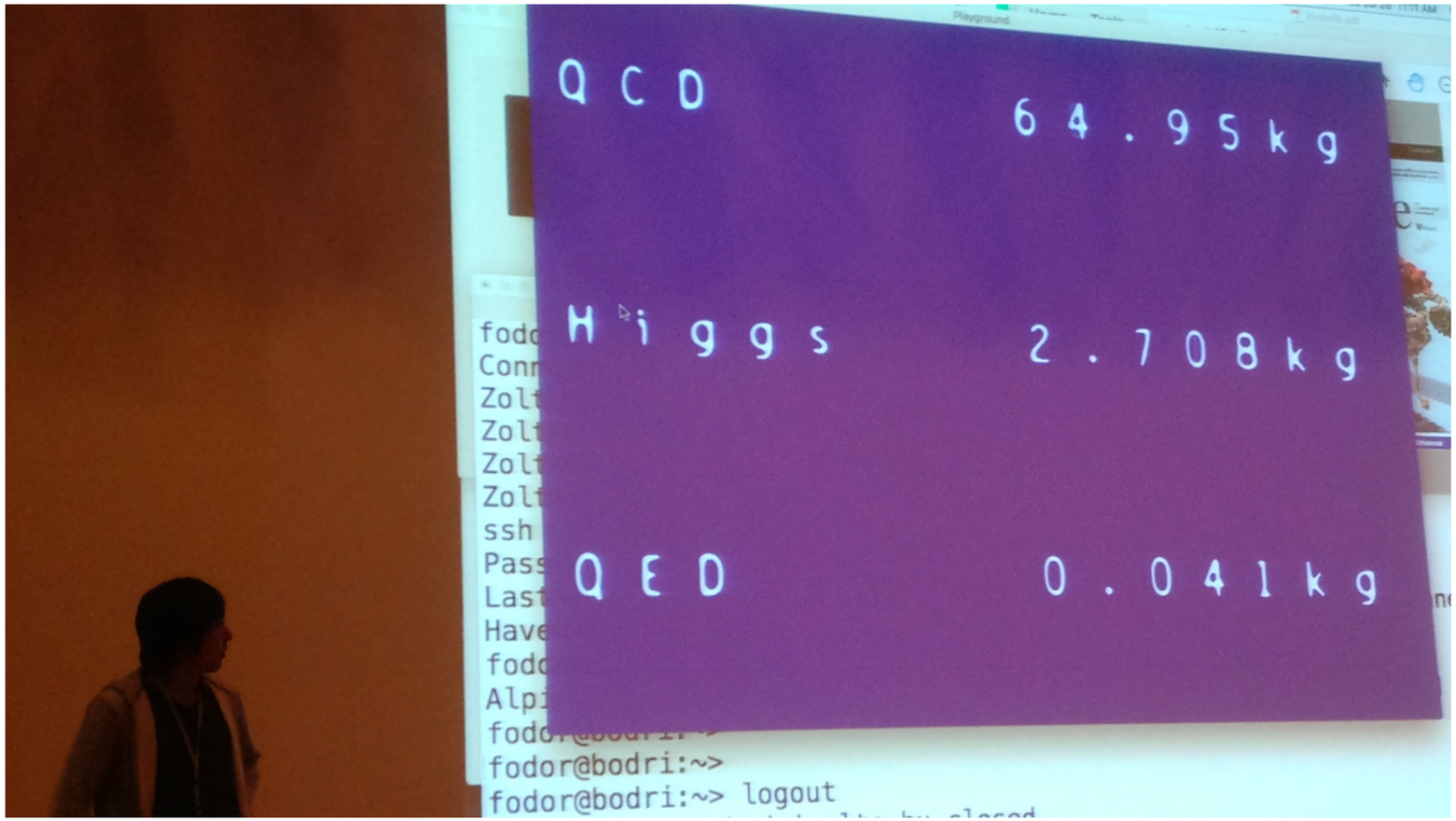


电磁相互作用



研究对象

强相互作用物质



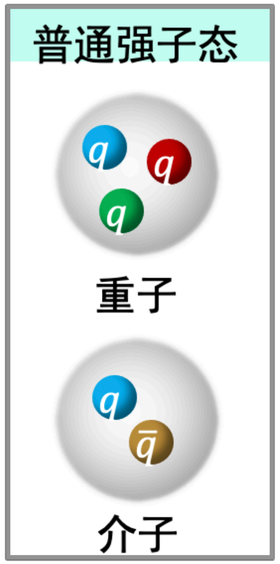
- 色禁闭：低能强相互作用的研究即是对强子结构、强子相互作用以及核结构的研究；
- 世界性难题: 色禁闭的本质是什么?

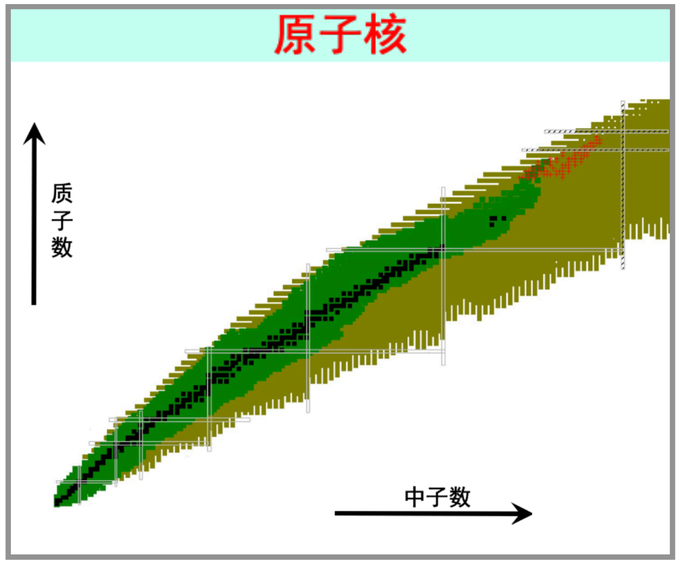
- 强相互作用核心问题：夸克和胶子如何组成强子？组成什么样的强子？

- 难以处理的非微扰问题
  - ➢格点 QCD：第一性原理数值计算
  - ➢有效场论、唯象模型

研究对象

强相互作用物质



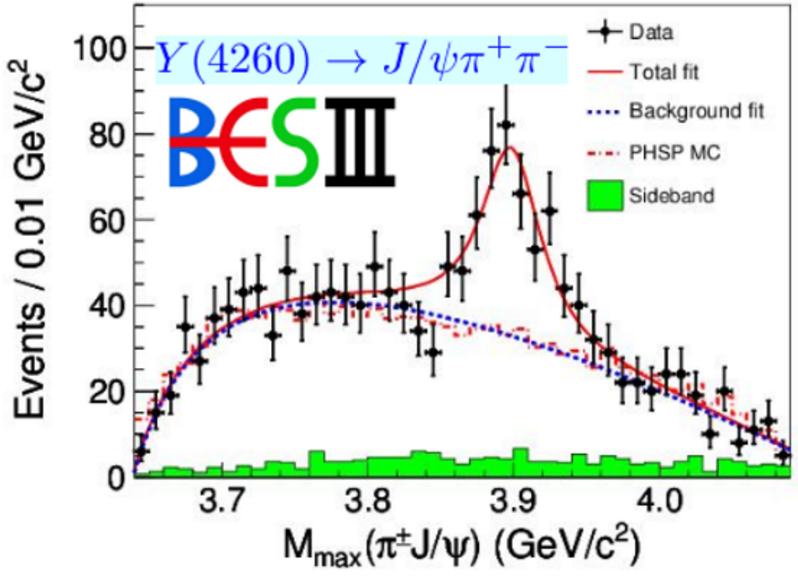


- 强相互作用物质的研究对象主要分为三类：
  - 普通强子态：质量、自旋和内部结构，以及在极端条件下如何退禁闭；
  - 奇特强子态：如何分类，是否都可以用多个普通强子组成的分子态解释？
  - 原子核：电荷极限、弱束缚极限、奇异数极限、高速转动极限、密度极限……

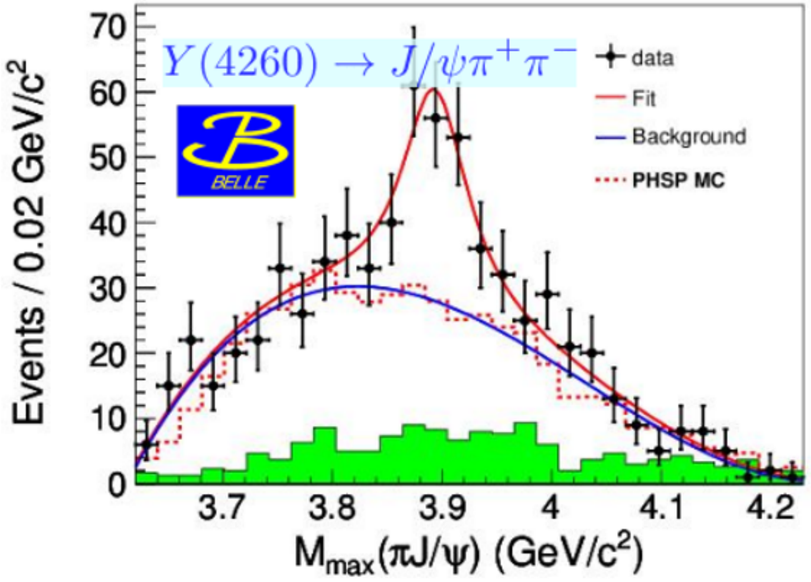
上一代	BABAR, BELLE, CLEO-c, CDF, D0
运行中	BESIII, Belle II, LHCb, CMS, ATLAS EXPERIMENT
建设中	BEPCII-U, panda, EIC
讨论中	STCF, CEPC,

强相互作用

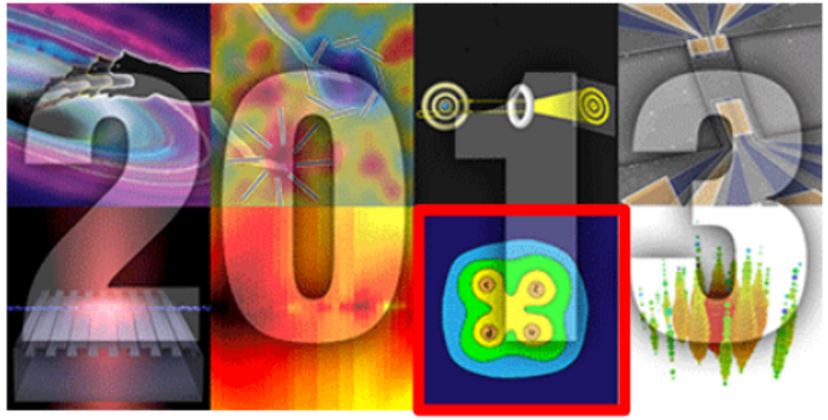
APS 2013年度亮点：四夸克态

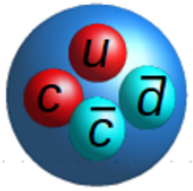


BESIII, PRL110(2013)252001



Belle, PRL110(2013)252002





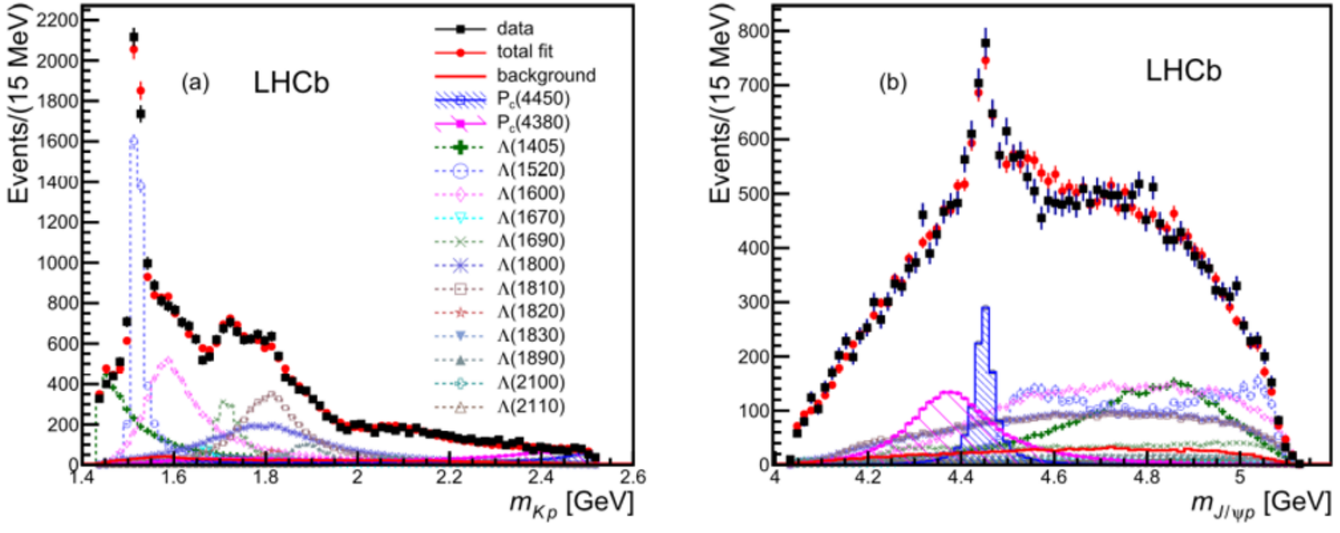
强相互作用

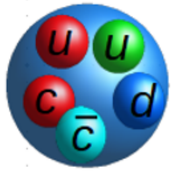
APS 2015年度亮点：五夸克态

PRL115(2015)072001 [arXiv:1507.03414]

appeared on arXiv on 14.07.2015, and accepted by PRL on 24.07.2015!

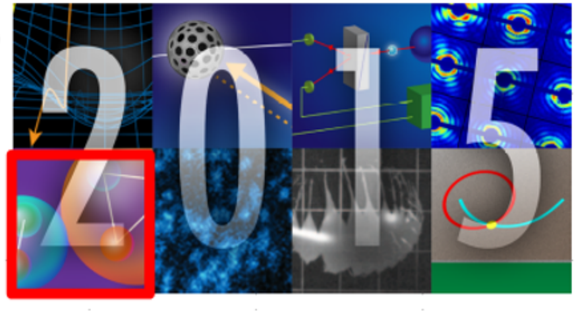
$\Lambda_b \to K\, p\, J/\psi$





$M_1 = (4380 \pm 8 \pm 29)$ MeV, $\Gamma_1 = (205 \pm 18 \pm 86)$ MeV,

$M_2 = (4449.8 \pm 1.7 \pm 2.5)$ MeV, $\Gamma_2 = (39 \pm 5 \pm 19)$ MeV.



The first prediction on hidden-charm pentaquarks:

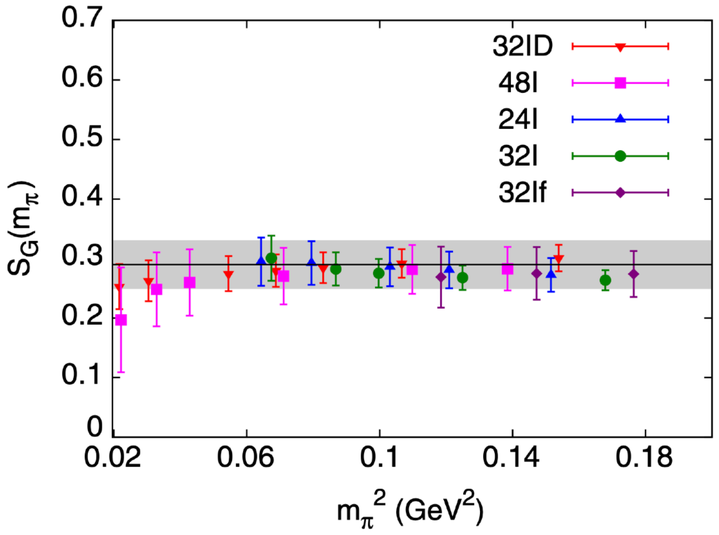
PRL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

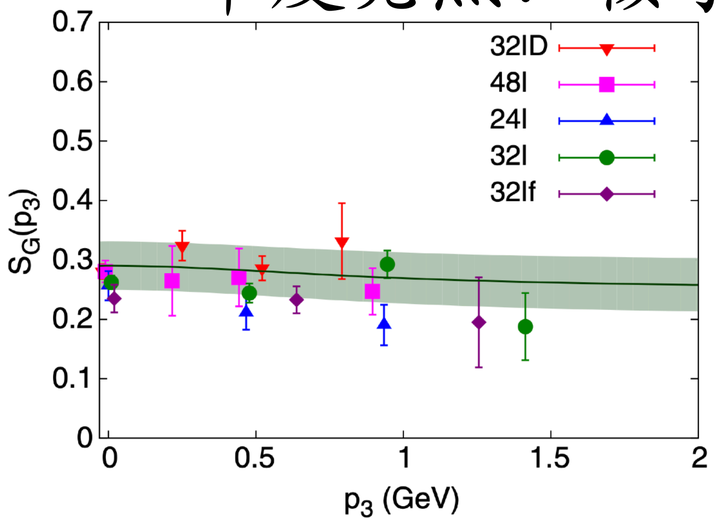
Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

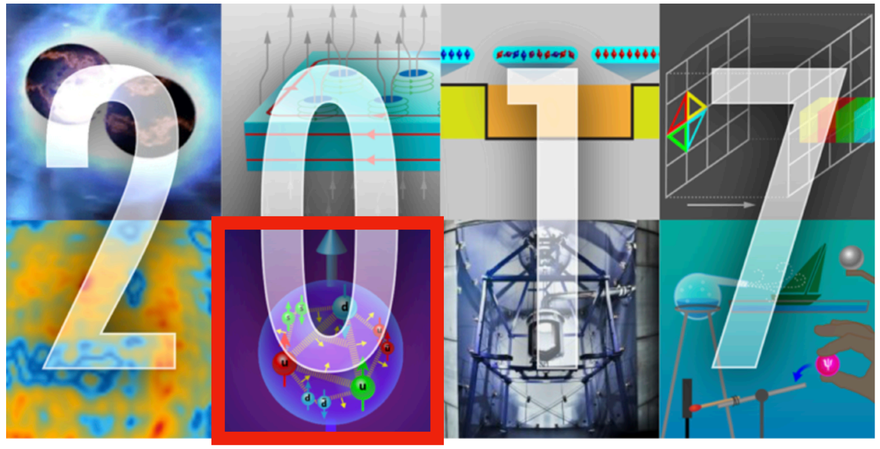
Jia-Jun Wu,[1,2] R. Molina,[2,3] E. Oset,[2,3] and B. S. Zou[1,3]

强相互作用

APS 2017年度亮点：核子自旋







□质子自旋

➢夸克模型：自旋来自于夸克

➢夸克极化分布函数的唯象分析： Δu~0.8，Δd~-0.4，Δs~-0.1，Δg~0.4;

➢格点QCD：精确计算夸克自旋贡献，预言胶子自旋贡献约占 50%。

Selected for a Viewpoint in *Physics*

PRL **118,** 102001 (2017) PHYSICAL REVIEW LETTERS week ending 10 MARCH 2017

Glue Spin and Helicity in the Proton from Lattice QCD

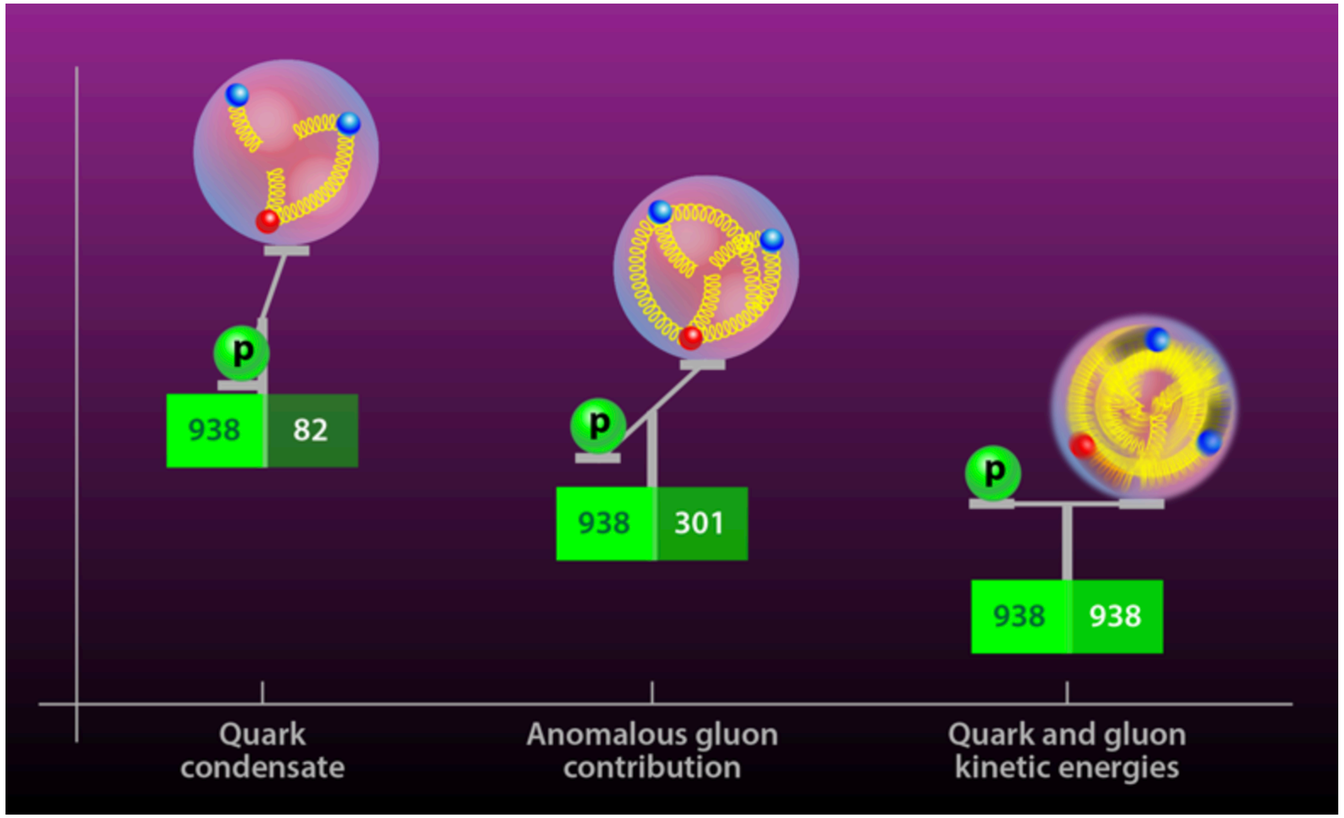
Yi-Bo Yang,[1] Raza Sabbir Sufian,[1] Andrei Alexandru,[2] Terrence Draper,[1] Michael J. Glatzmaier,[1] Keh-Fei Liu,[1] and Yong Zhao[3,4]

(χQCD Collaboration)

格点QCD

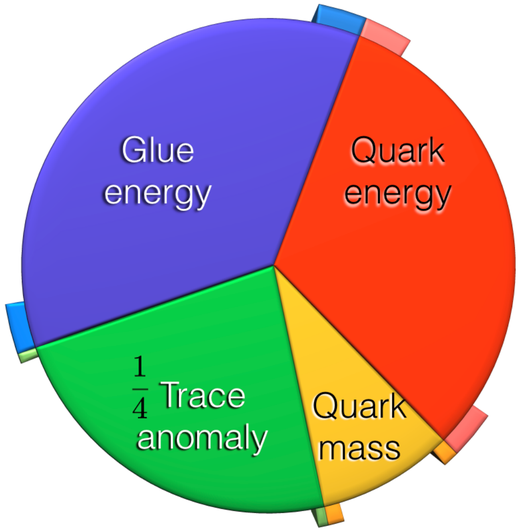
核子（质子与中子）的大部分质量来自于胶子的量子反常和夸克胶子的运动：

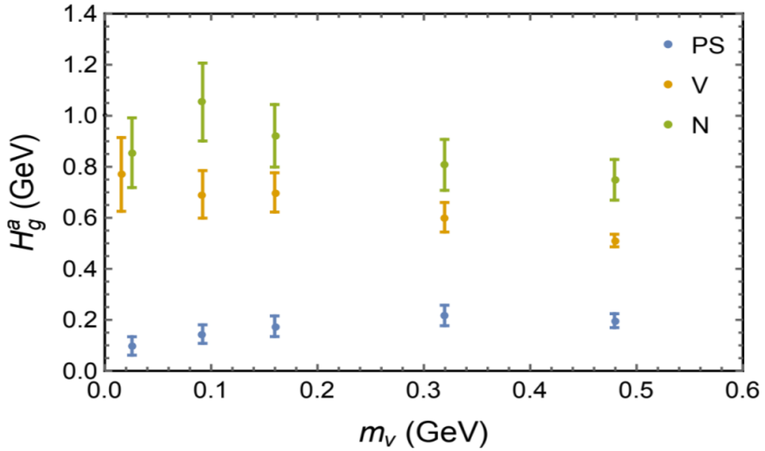
- ➢核子质量的分布和电荷分布有多大的差别，为什么?
- ➢如果夸克没有质量，核子还有多少质量?
- ➢核子的质量是否在特殊条件下能够转换为能量?



YBY, J. Liang, et. al., χQCD, PRL121(2018)212001, **ViewPoint and Editor's suggestion**

质子的质量之谜





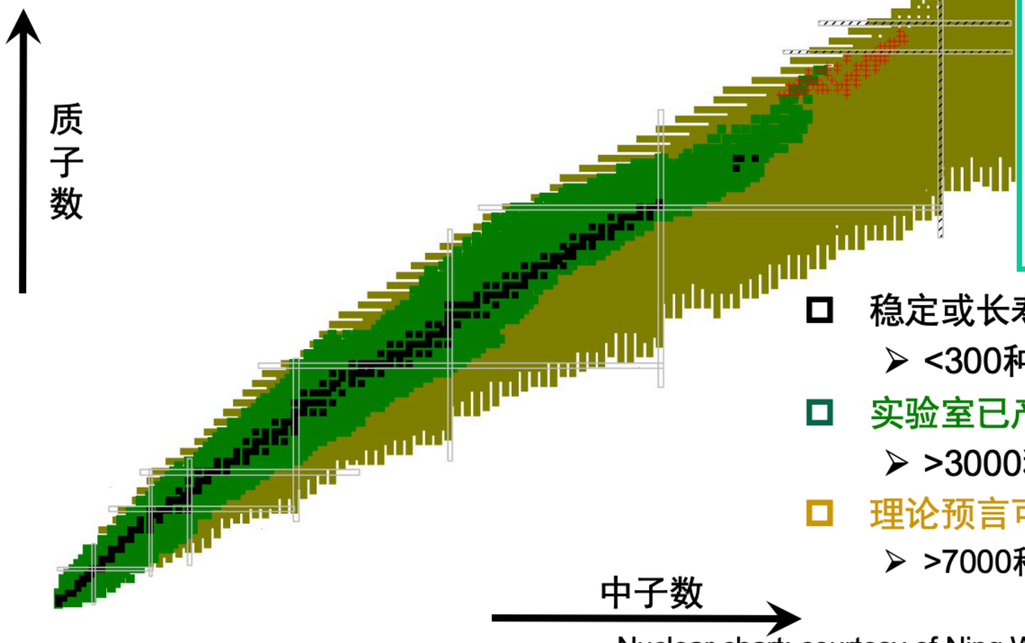
F. He, P. Sun, **YBY**, χQCD, Phys.Rev.D 104(2021)074507

核物理

从核子到原子核

核素图

核物理研究版图



大科学实验装置

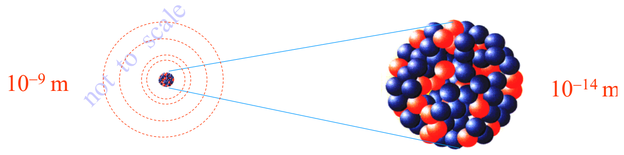
- ✓ RIBF（日本）
- ✓ SPIRAL（法国）
- ✓ FAIR（德国）
- ✓ FRIB（美国）
- ✓ HIRFL（中国）
- ✓ ……

正在建造：

- ✓ FAIR（德国）
- ✓ SPIRAL2（法国）
- ✓ RAON（韩国）
- ✓ HIAF（中国）
- ✓ ……

- 稳定或长寿命的核素
  - <300种，分布在 β 稳定线上
- 实验室已产生的不稳定核素
  - >3000种，逐渐远离 β 稳定线
- 理论预言可能存在的核素
  - >7000种，远离 β 稳定线直至滴线

Nuclear chart: courtesy of Ning Wang (王宁)

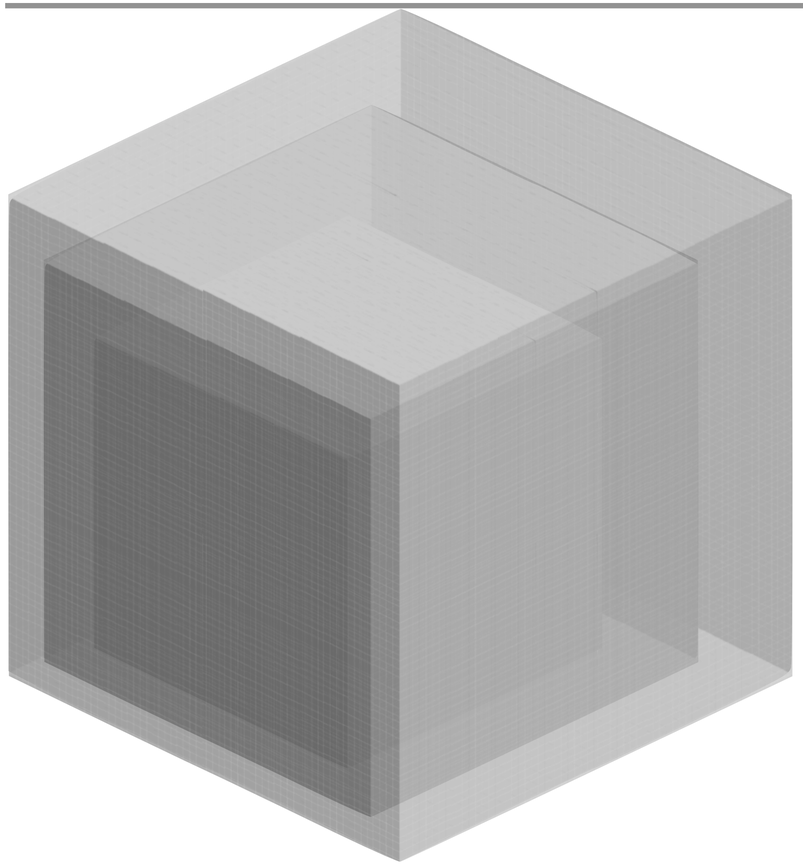


原子核由一定数目的质子和中子组成，

- 理论上能够通过格点量子色动力学计算；
- 实践上有效场论在同等计算开销下有更强的预言能力；
- 强子分子态研究的原型和最终目标。

格点QCD

理论框架



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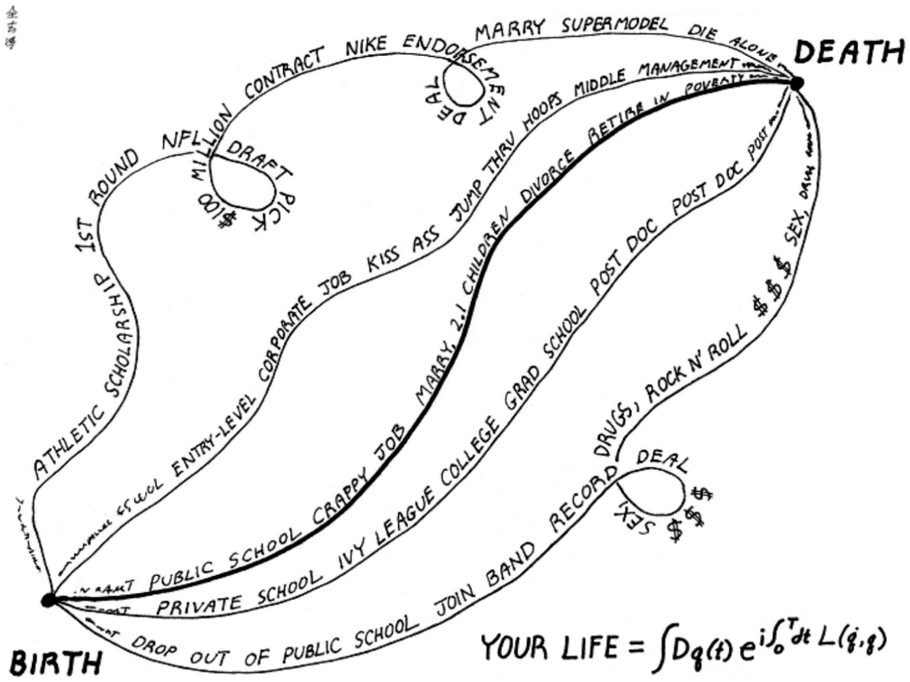
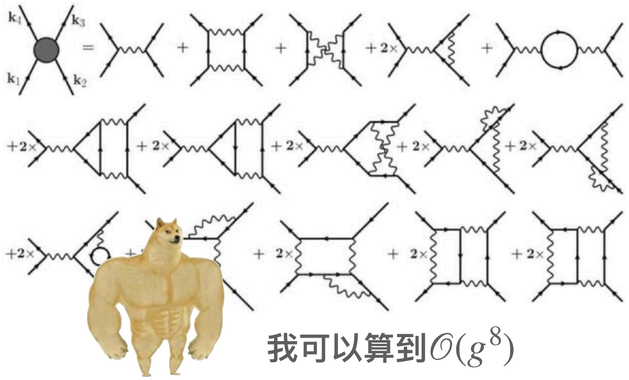




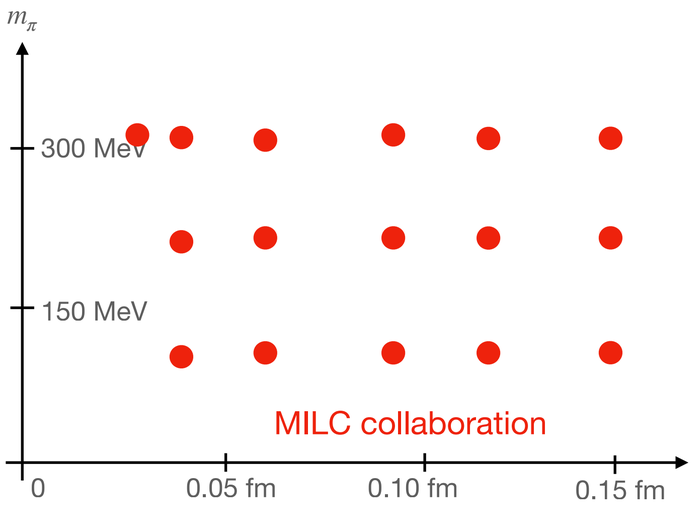
四维时空离散化 + 路径积分 = 格点量子场论

- 理论上可以得到超越微扰展开的精确结果；
- 实践上存在有限采样数的统计误差，同时计算开销随精度提高快速增长；
- 基于物理直觉的算法改进必不可少！

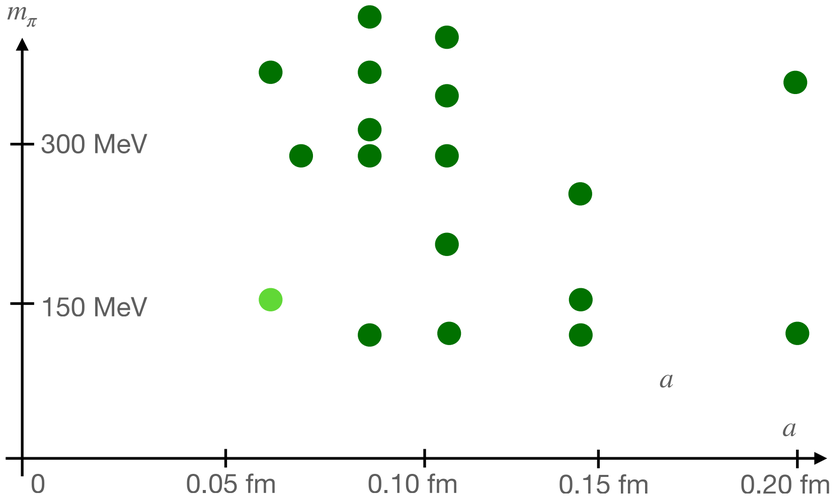
格点QCD

世界范围内的“大模型”

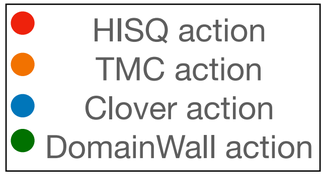
- 必须覆盖多种格距以得到可靠的连续极限；
- 应当包含多种夸克质量和体积以覆盖完整参数空间。

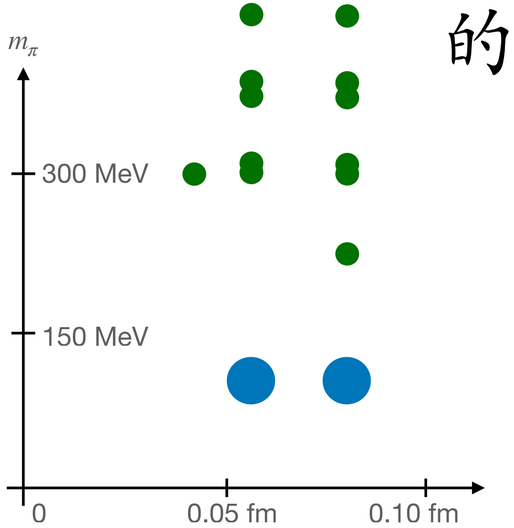


MILC collaboration



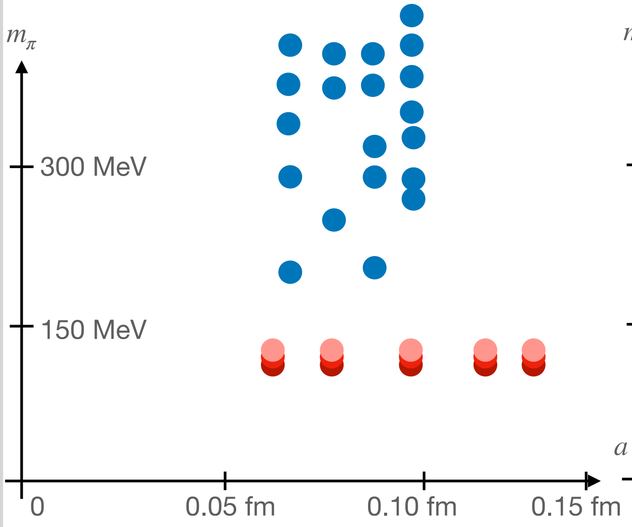
RBC/UKQCD collaboration



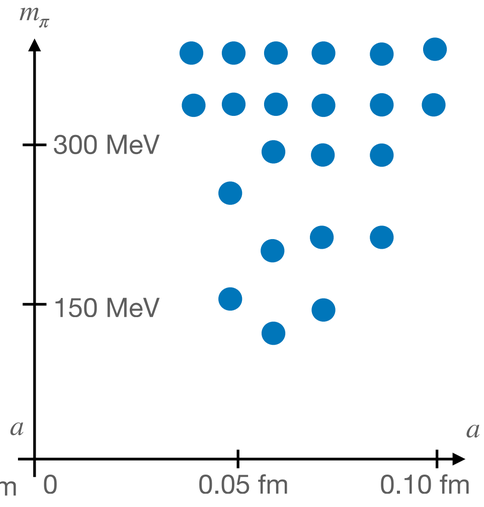


JLQCD collaboration

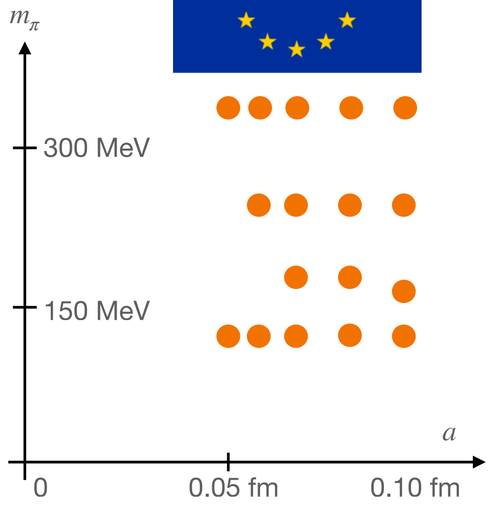
PACS collaboration



BMW collaboration



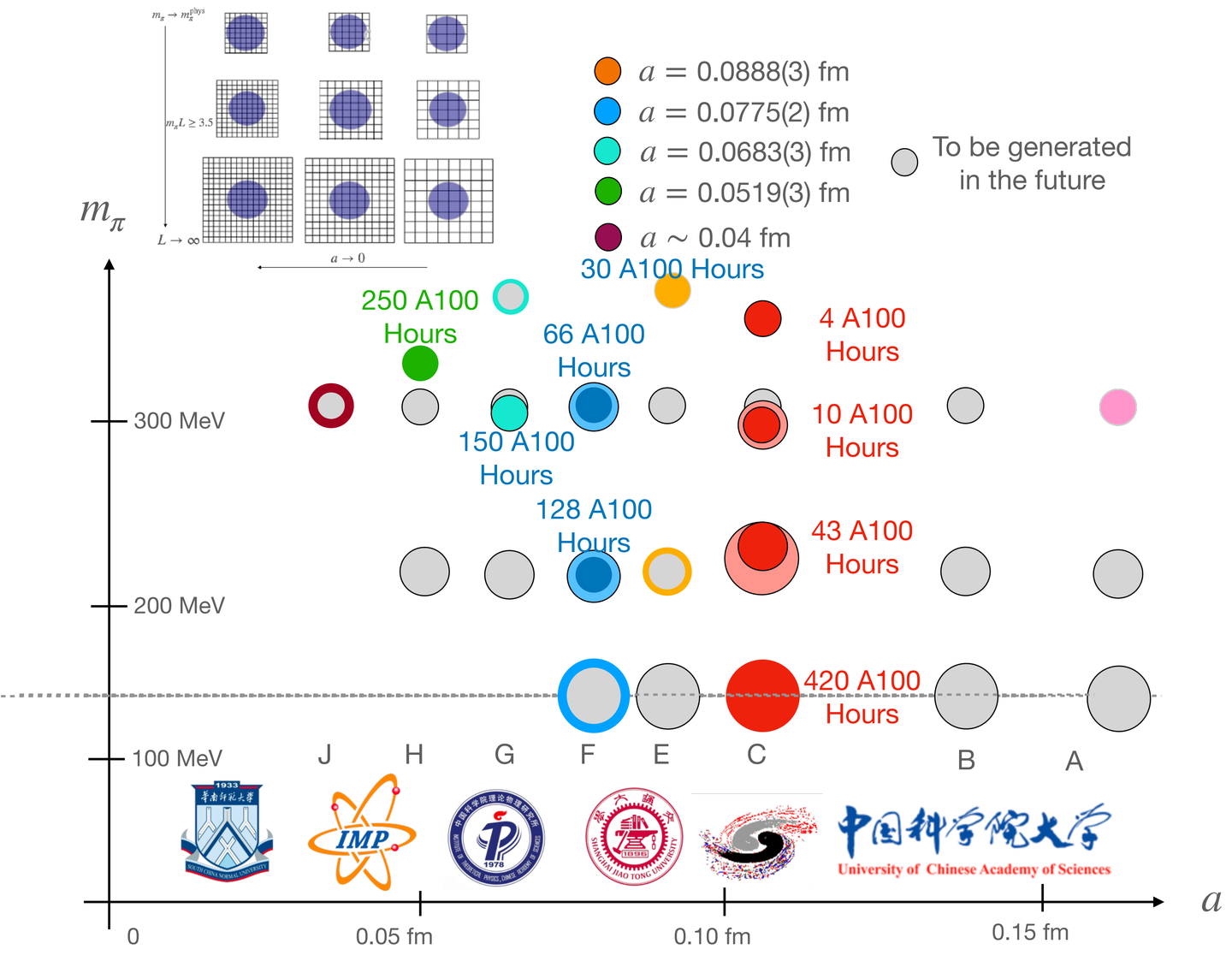
CLS collaboration



ETM collaboration

格点QCD

自主的“大模型”



经过多年来数千万GPU小时的计算，已经产生了能够精确计算强相互作用的路径积分样本集合：

➢覆盖强耦合常数、夸克质量、时空体积的完整参数空间；
➢能够可靠地外推到连续极限、无穷大体积极限；
➢具备了产生更高精度样本集合，近一步揭示强相互作用本质的能力。

基于该“大模型”发表的论文：

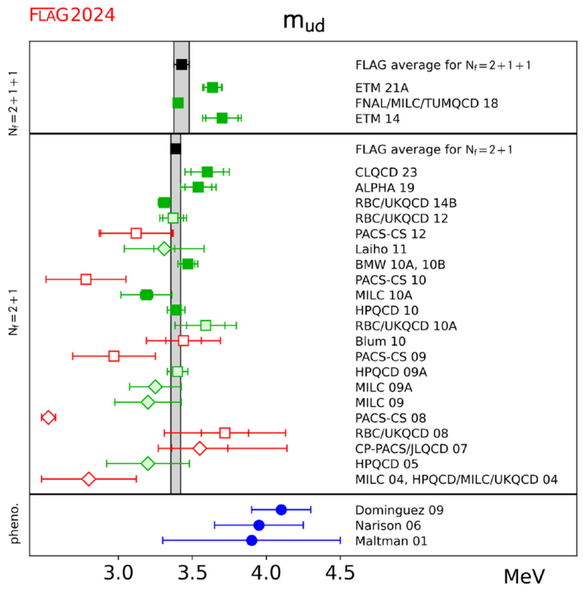
- H.B. Yan et.al. PRL accepted (**2024**)
- Y. Meng et.al. PRD 110(**2024**)074510
- Z.C. Hu et.al. PRD 109(**2024**)054507
- Y. Meng et.al. PRD 109(**2024**)074511
- H. Liu et.al. SCPMA 67(**2024**)1, 211011
- H. Liu et.al. PRD 109(**2024**)036037

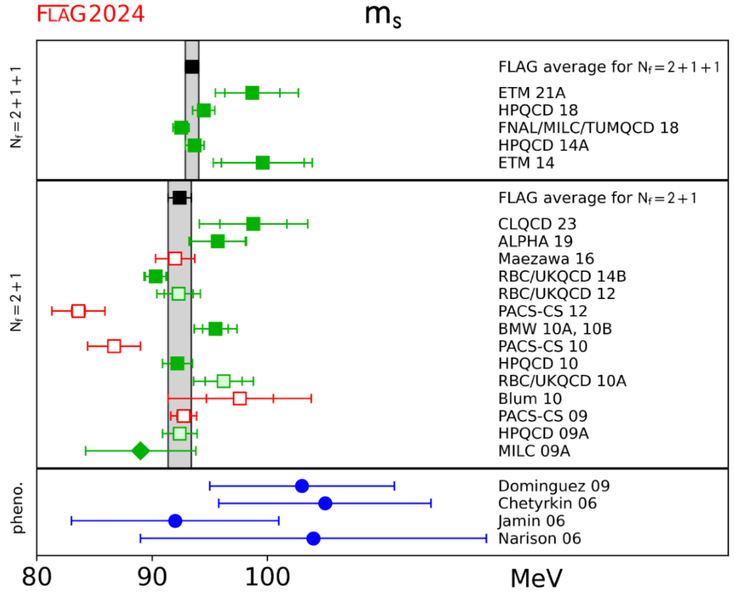
- H. Liu et.al. PLB 841(2023)137941
- D.J. Zhao et.al. PRD 107(2023)L091501

- Q.A. Zhang et.al. CPC 46 (**2022**)

格点QCD

基于自主“大模型”的夸克质量





Y. Aoki et al. *FLAG Review 2024* 2411.04268

Collaboration	Ref.	publication status	chiral extrapolation	continuum extrapolation	finite volume	renormalization	running	m_{ud}	m_s
CLQCD 23	[10]	A	★	★	★	★	e	3.60(11)(15)	98.8(2.9)(4.7)
ALPHA 19	[11]	A	○	★	★	★	e	3.54(12)(9)	95.7(2.5)(2.4)
Maezawa 16	[12]	A	■	★	★	★	d	–	92.0(1.7)
RBC/UKQCD 14B$^{\ominus}$	[13]	A	★	★	★	★	d	3.31(4)(4)	90.3(0.9)(1.0)
RBC/UKQCD 12$^{\ominus}$	[9]	A	★	○	★	★	d	3.37(9)(7)(1)(2)	92.3(1.9)(0.9)(0.4)(0.8)
PACS-CS 12*	[14]	A	★	■	■	★	b	3.12(24)(8)	83.60(0.58)(2.23)
Laiho 11	[15]	C	○	★	★	○	–	3.31(7)(20)(17)	94.2(1.4)(3.2)(4.7)
BMW 10A, 10B^{+}	[16, 17]	A	★	★	★	★	c	3.469(47)(48)	95.5(1.1)(1.5)
PACS-CS 10	[18]	A	★	■	■	★	b	2.78(27)	86.7(2.3)
MILC 10A	[19]	C	○	★	★	○	–	3.19(4)(5)(16)	–
HPQCD 10**	[20]	A	○	★	★	–	–	3.39(6)	92.2(1.3)
RBC/UKQCD 10A	[21]	A	○	○	★	★	a	3.59(13)(14)(8)	96.2(1.6)(0.2)(2.1)
Blum 10†	[22]	A	○	■	○	★	–	3.44(12)(22)	97.6(2.9)(5.5)
PACS-CS 09	[23]	A	★	■	■	★	b	2.97(28)(3)	92.75(58)(95)
HPQCD 09A$^{\oplus}$	[24]	A	○	★	★	–	–	3.40(7)	92.4(1.5)
MILC 09A	[25]	C	○	★	★	○	–	3.25 (1)(7)(16)(0)	89.0(0.2)(1.6)(4.5)(0.1)
MILC 09	[26]	A	○	★	★	○	–	3.2(0)(1)(2)(0)	88(0)(3)(4)(0)
PACS-CS 08	[27]	A	★	■	■	■	–	2.527(47)	72.72(78)
RBC/UKQCD 08	[28]	A	○	■	★	★	–	3.72(16)(33)(18)	107.3(4.4)(9.7)(4.9)
CP-PACS/ JLQCD 07	[29]	A	■	★	★	■	–	$3.55(19)(^{+56}_{-20})$	$90.1(4.3)(^{+16.7}_{-4.3})$
HPQCD 05	[30]	A	○	○	○	○	–	$3.2(0)(2)(2)(0)^{\ddagger}$	$87(0)(4)(4)(0)^{\ddagger}$
MILC 04, HPQCD/ MILC/UKQCD 04	[31, 32]	A	○	○	○	■	–	2.8(0)(1)(3)(0)	76(0)(3)(7)(0)

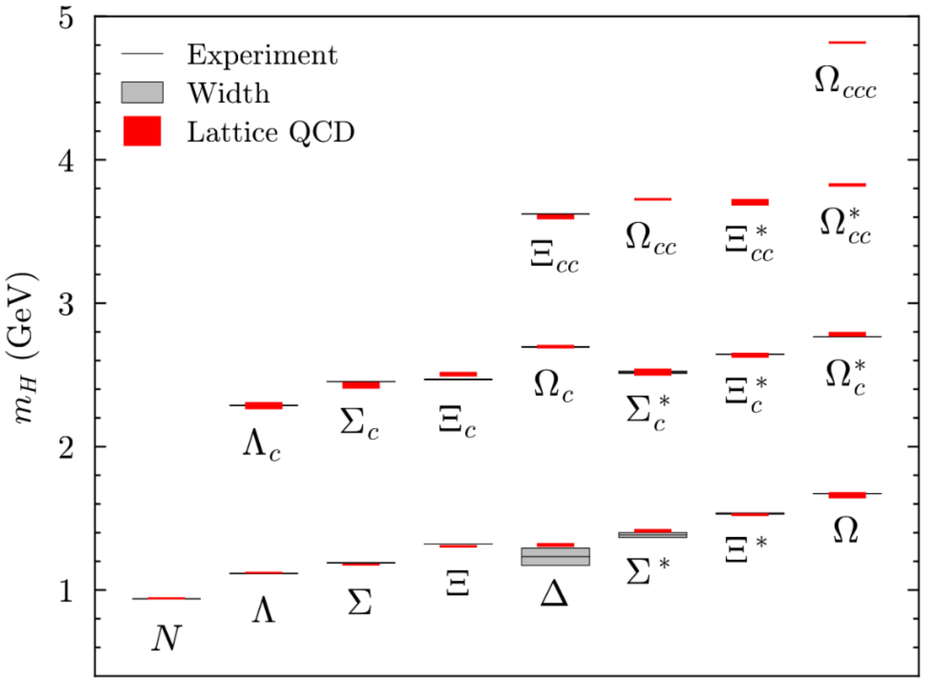
Flavor lattice average group, 2411.04268

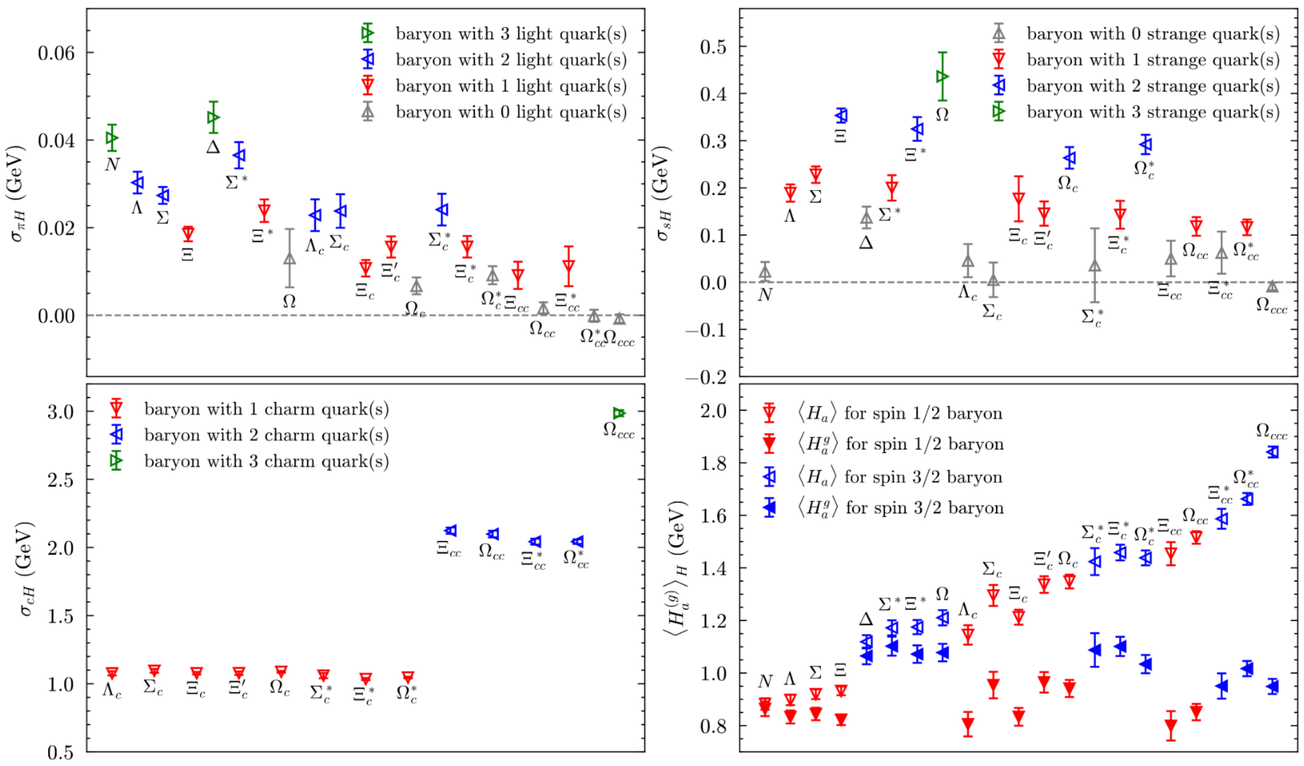
- ➢基于夸克质量依赖最强的π和K介子标定夸克质量，国内首个基于自主“大模型”进入格点世界平均值的结果；
- ➢在轻夸克质量外推、连续极限、无限大体积极限和非微扰重整化上均达到国际先进水平；
- ➢进而能够对强相互作用的各种性质给出误差可控的精确预言。

Z.-H. Hu, B.-L. Hu, J.-H. Wang, et. al., CLQCD, PRD109(2024) 054507

格点QCD

基于自主“大模型”的重子质量起源



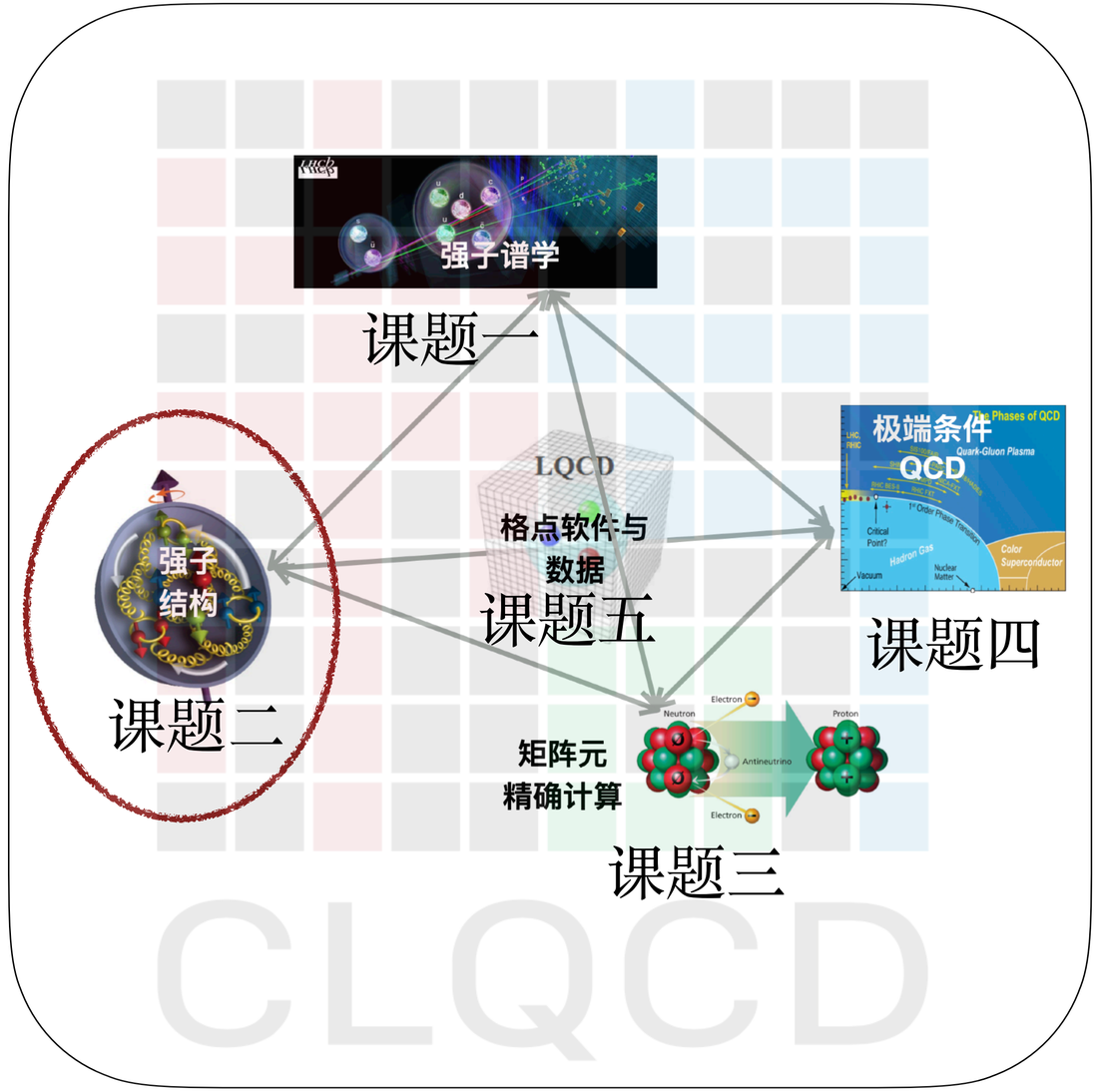


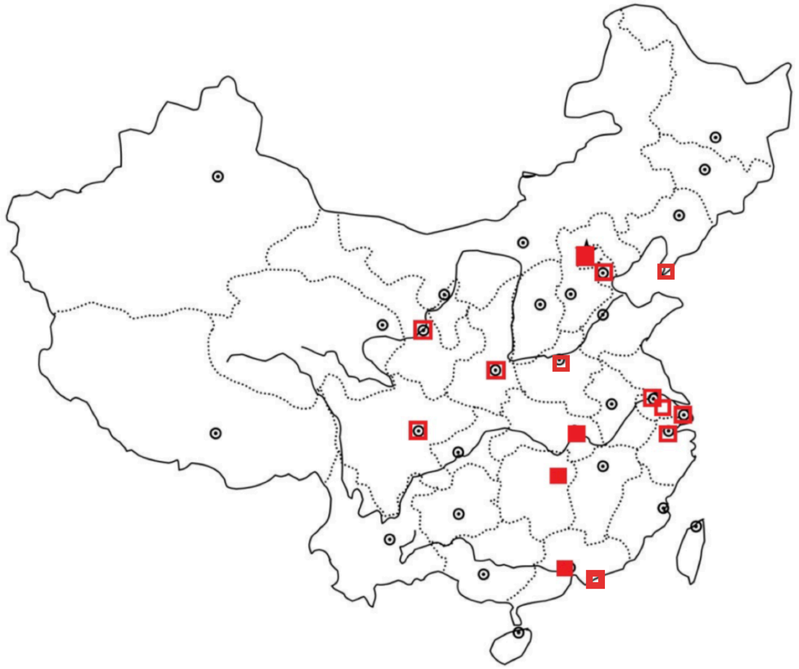
B.-L. Hu, et. al., CLQCD, in preparation

- 以夸克质量和强相互作用耦合强度为输入，可以以1%或者更高精度预言基态重子质量；
- 强相互作用能将上/下、奇异、粲夸克对重子质量的贡献放大约5、2、1.3倍；
- 强相互作用中“无质量”的胶子对所有重子的质量均有约1GeV的贡献。

国家自然科学基金委重大项目

“基于国产超算的格点量子色动力学关键科学问题研究”





课题一：强子谱学	近物所
课题二：强子结构	理论所
课题三：矩阵元精确计算	北京大学
课题四：极端条件QCD	华中师大
课题五：格点软件与数据	高能所

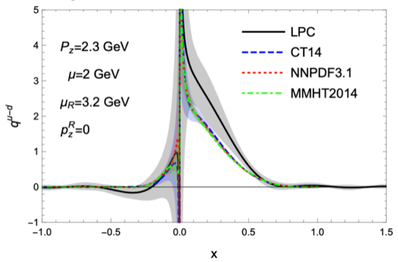
- 依托五个课题支持全国格点QCD研究；
- 课题二“强子结构及其重整化的格点量子色动力学研究”在完成研究目标的同时，也为重大项目各课题提供计算方案与技术支持。

格点QCD

➢来自十余个研究机构的数十人组成的中国格点合作组强子结构部门；
➢2019年成立以来发表/接收文章11篇，举办数值格点场论培训班6届。

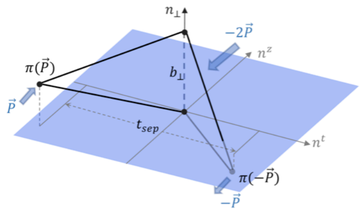
Lattice Parton合作组

Unpolarized nucleon PDF



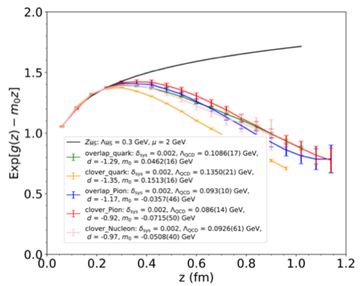
Y. Liu, et.al., LPC, PRD101(2020)034020

2020 TMD Soft function



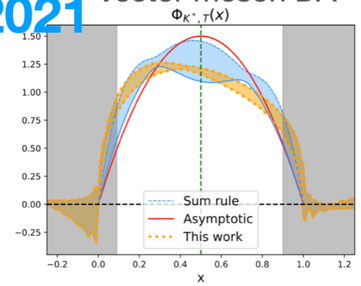
Q.-A. Zhang. et.al., LPC, PRL125(2020)192001

Self renormalization



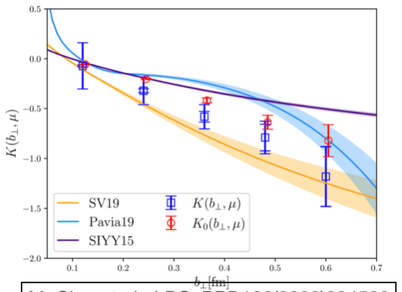
Y.-K. Huo. et.al., LPC, NPB969(2021)115443

2021 Vector meson DA



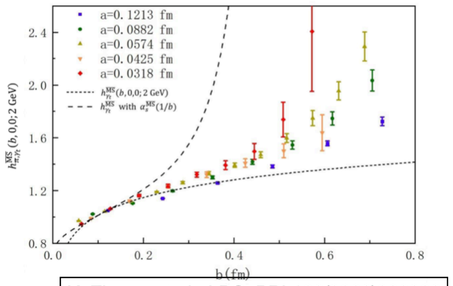
J. Hua. et.al., LPC, PRL127(2021)062002

CS-Kernel with 1-loop matching



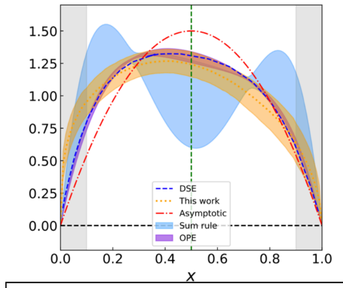
M. Chu. et.al., LPC, PRD106(2022)034509

Renormalization of quasi-TMD



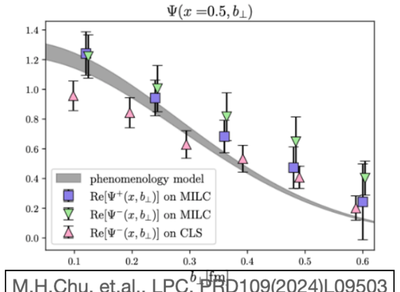
K. Zhang. et.al., LPC, PRL129(2022)082002

2022 Kaon DA



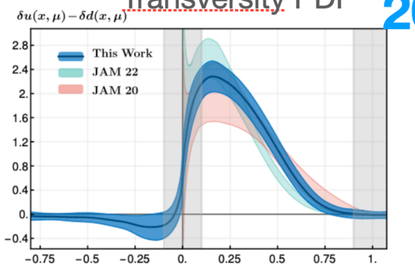
J. Hua, et.al., LPC, PRL129(2022)132001

TMD WF **2024**



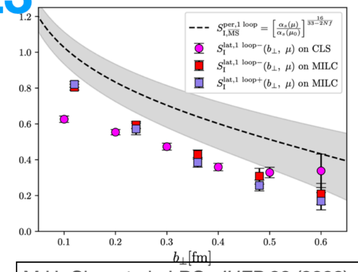
M.H.Chu. et.al., LPC, PRD109(2024)L09503

Transversity PDF **2023**



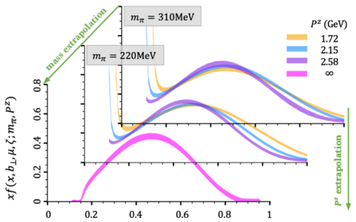
F. Yao. et.al., LPC, PRL131(2023)261901

CS-kernel



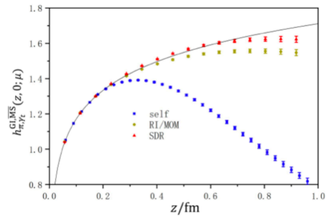
M.H. Chu. et.al., LPC, *JHEP* 08 (2023) 172

TMD PDF



J.S. He. et.al., LPC, PRD109(2024)114513

General renormalization



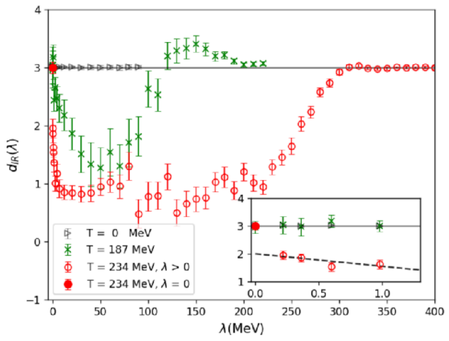
K. Zhang. et.al., LPC, PRD110(2024)074505

- **Permanent members:**
  - Xiangdong Ji (U. Maryland)
  - Jun Hua (SCNU)
  - Peng Sun (IMP/CAS)
  - Andreas Schaefer (U. Reg.)
  - Wei Wang (SJTU)
  - Xiao-Nu Xiong (CSU)
  - **Yi-Bo Yang (ITP/CAS, spokesperson)**
  - Jian-hui Zhang (CUHK-Shenzhen)
  - Qi-An Zhang (BHU)
- **PI members:**
  - Long-Cheng Gui (HNNU)
  - Jian liang (SCNU)
  - Liuming Liu (IMP/CAS)
  - Han Liu (SNU)

格点QCD

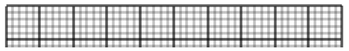
自主“大模型”的路线图

$D = 4,\ N_c = 3,\ T \to \infty$

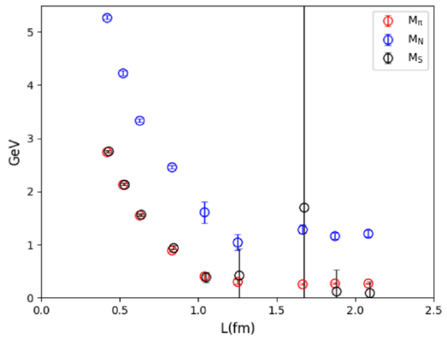


$T = 234$ MeV, $1/T \sim 0.84$ fm

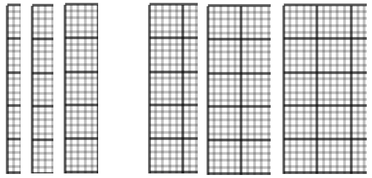
$T = 187$ MeV, $1/T \sim 1.05$ fm



$D = 4,\ N_c = 3,\ L \to 0$



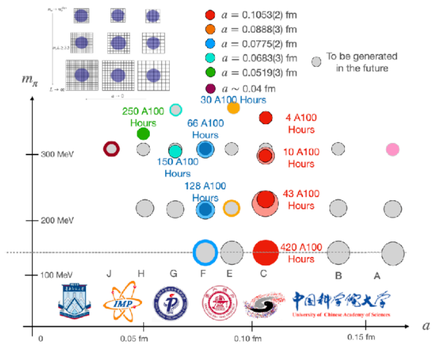
$L > 1$ fm



$L \leq 1$ fm

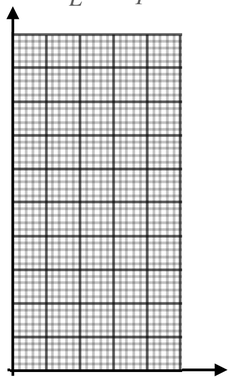
$D = 4,\ N_c = 3,\ L \to \infty, T \to 0$

$a \to 0,\ m_{l,s,c,b} \to m_{l,s,c,b}^{\text{phys}}$



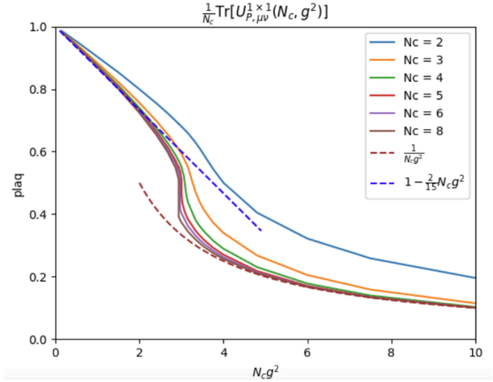
$n_T = \dfrac{1}{Ta}$

$n_L^3 \times n_T$



$n_L = L/a$

$D = 4,\ N_c = 3,4,5,6,8...,\ N_f = 0$



$D = 4,\ N_c = 3,4,5,6,8...,\ N_f = 2,2+1...$

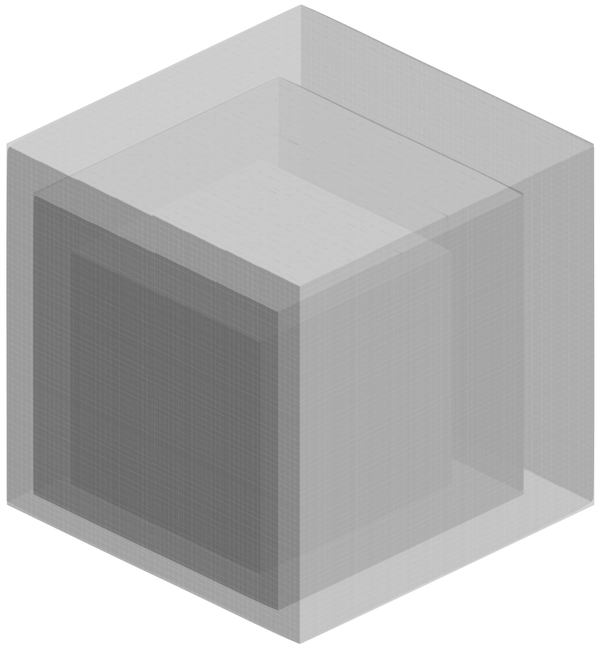
$D = 2,3,\ N_c = 3,4,5,6,8...,$

$D = 4,\ N_c = 3,\ L \to \infty, T \to 0,\ m_\pi L \ll 1$

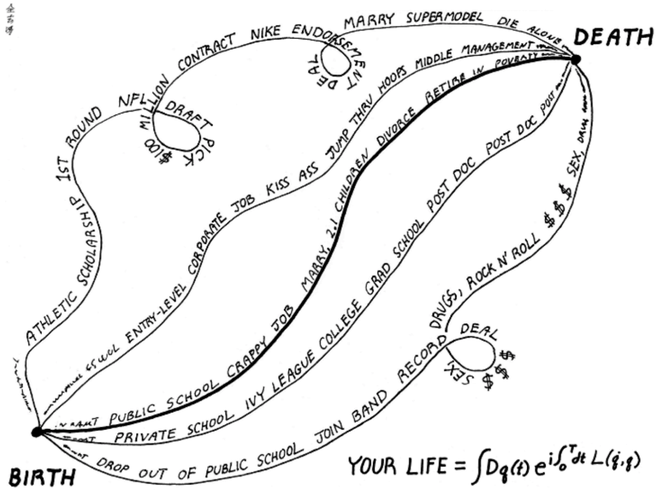
In progress

格点QCD

小结

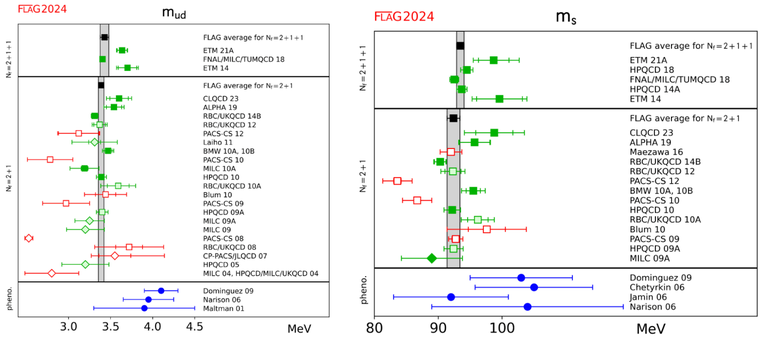


+

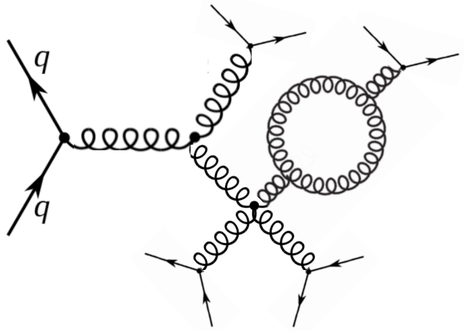


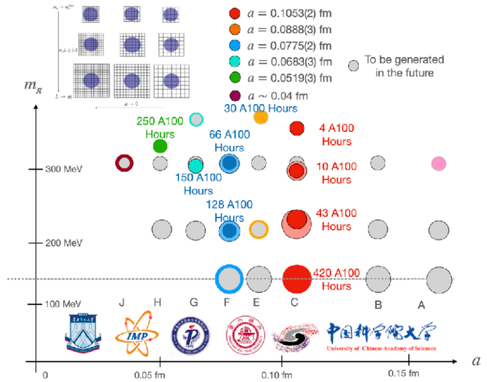
四维时空离散化 + 路径积分 = 格点量子场论

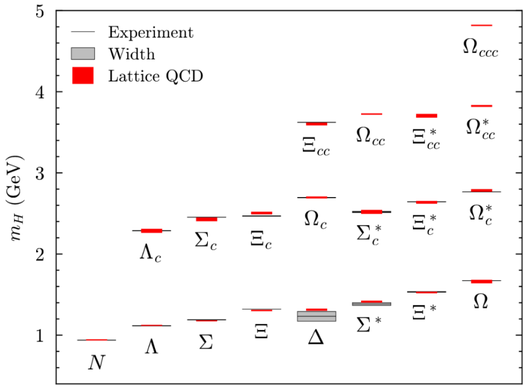
格点量子场论 + 超级计算机 = 强相互作用“大模型”



强相互作用







强相互作用“大模型” + 高精度标准模型参数标定
= 质量的强相互作用起源的精确预言