Lattice QCD: Past, present, & future

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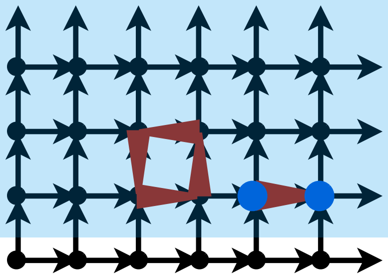
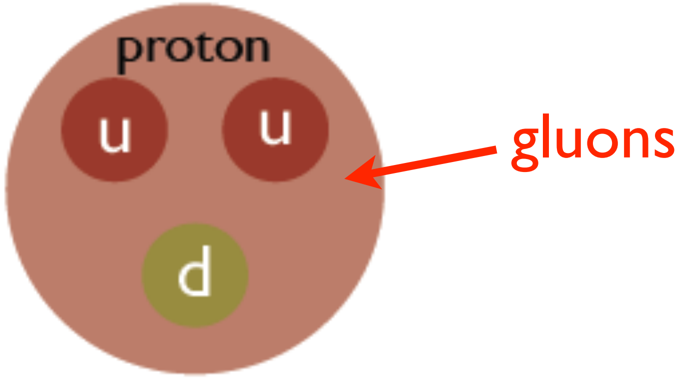
University of Washington

Workshop on Lattice QCD, SNU, 5/23/25



Overview

- Quantum ChromoDynamics is a peculiar theory
  - Quarks are absolutely confined
  - Quark properties are obscured



- QCD is a "background" in search for new physics
  - Must understand "old physics" of the standard model (SM) to find "new physics"
- QCD is strongly coupled, non-perturbative
- Lattice QCD allows us to make precise predictions for a range of properties of QCD
  - Recent extensions of LQCD methods greatly expand range of predictions

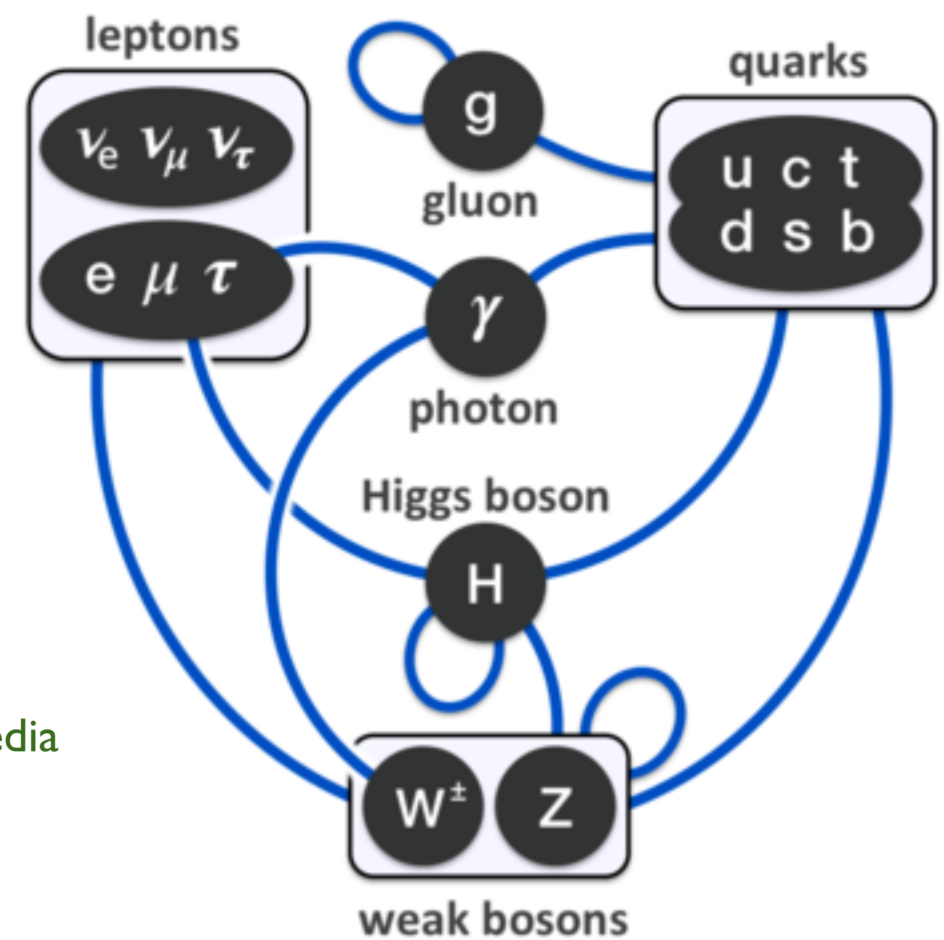
Workshop overview

- This talk: "Lattice QCD: Past, present, & future"
  - Introduction & overview
- Prof. Aida El-Khadra: "Finding Beauty: The role of lattice QCD in precision physics"
  - Applications of lattice QCD (LQCD) to charm and b physics
- Prof. Maarten Golterman: "Frontiers of Lattice Gauge Theory: muon g-2 and lattice chiral gauge theories"

Outline of this talk

- Standard model & searching for physics beyond
- QCD & Lattice QCD
- High precision LQCD
- Constraining the Standard Model with LQCD
- Extending the LQCD frontier
- Summary

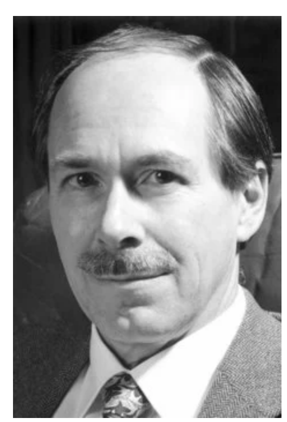
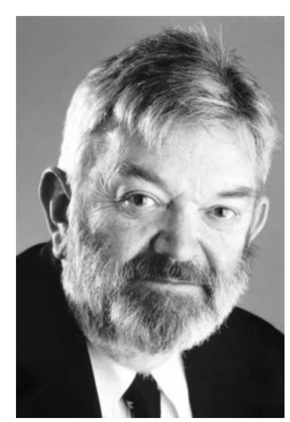
Standard Model (SM)



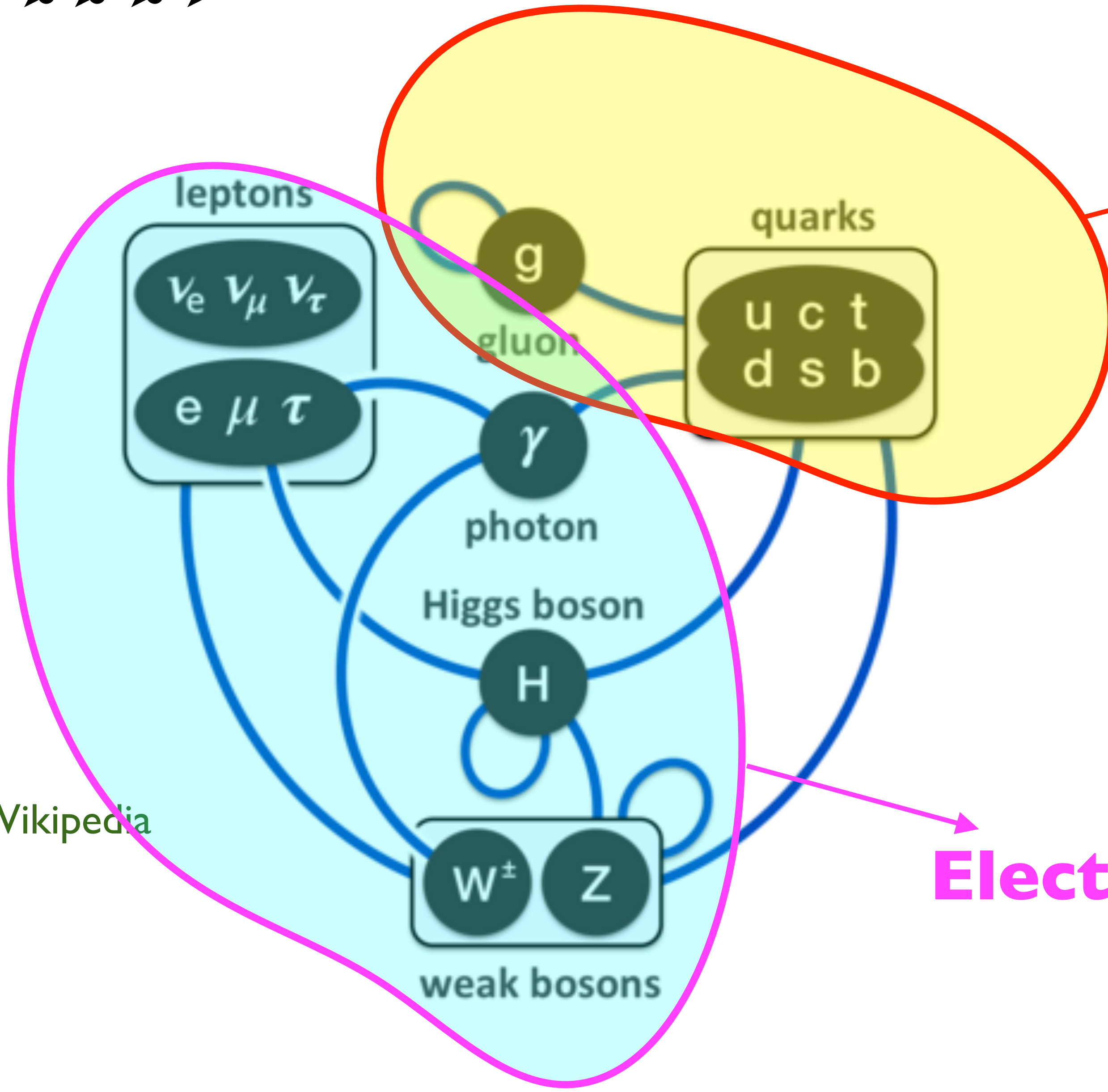
Wikipedia

nobelprize.org



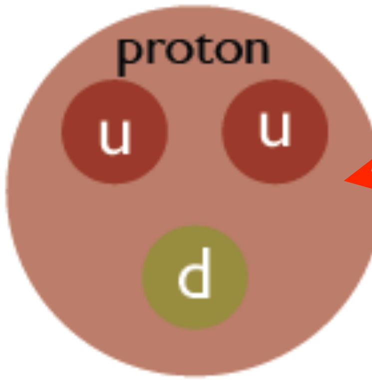




Standard Model (SM)



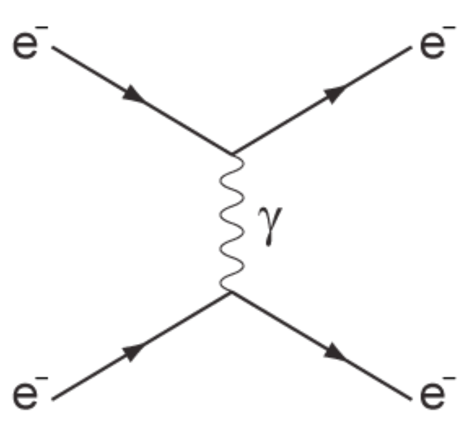
Wikipedia

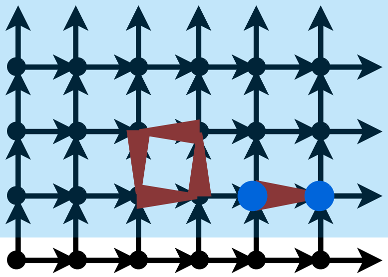
QCD is non-perturbative



gluons &
sea quarks:
"brown muck"

Electroweak sector is perturbative





SM is extremely successful

- EM sector tested to extraordinary precision

$$\frac{4\pi}{e^2} = \frac{1}{\alpha} = 137.035999166(15)$$

Electron g-2 [Fan et al, PRL, 2022]

$$\frac{4\pi}{e^2} = \frac{1}{\alpha} = 137.035999206(11)$$

Rubidium recoil + Rydberg
[Morel et al, Nature, 2020]

- Weak sector tested to few parts in 1000

This is possible because couplings are weak enough to use perturbation theory

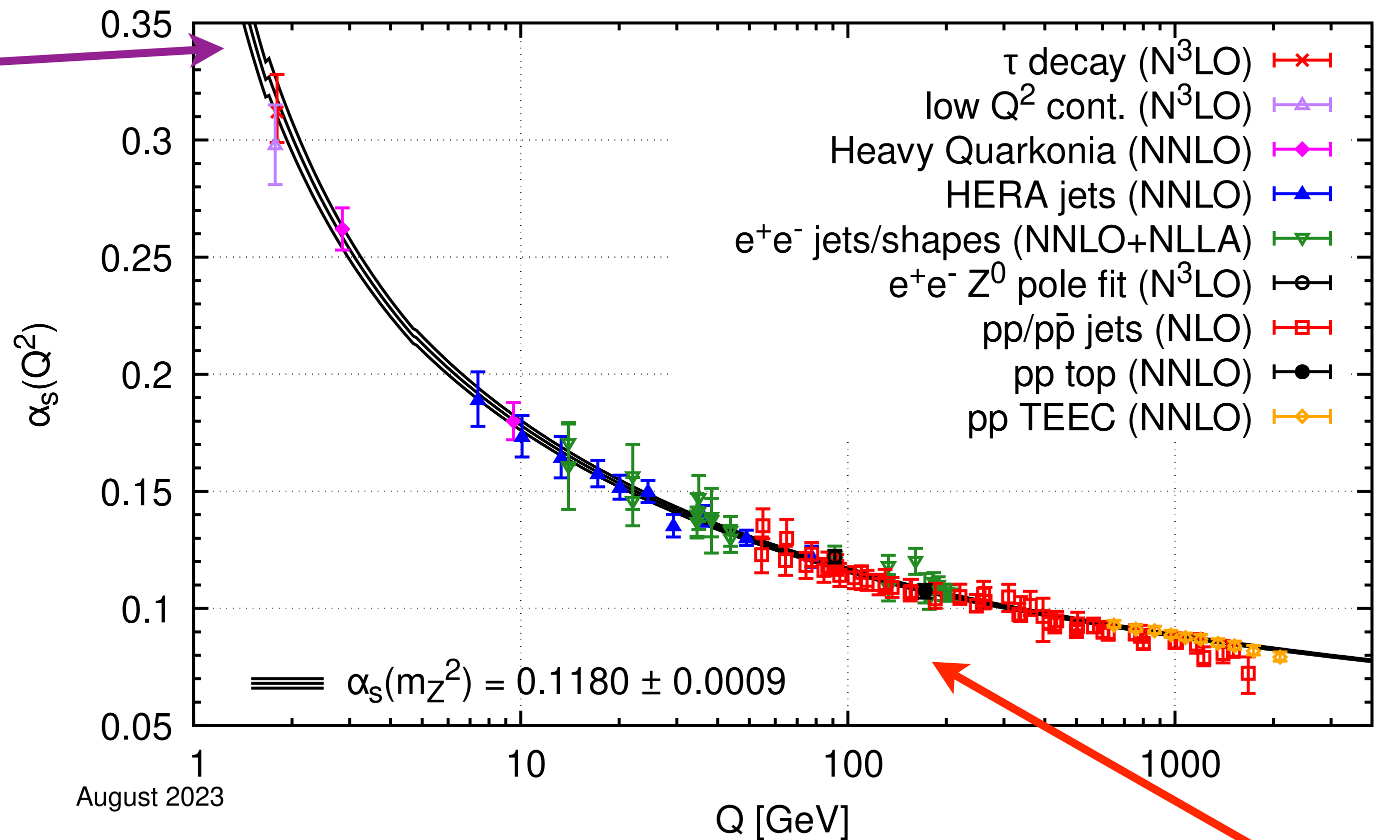
$$g_e - 2 = \frac{\alpha}{\pi} + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + C_5\left(\frac{\alpha}{\pi}\right)^5 + \ldots$$

QCD is more challenging

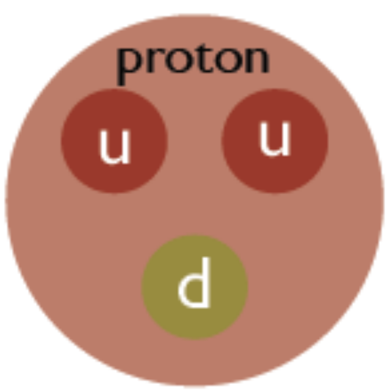
PDG, 2023

Need non-perturbative method here

$$\frac{g^2}{4\pi} =$$



1fm=10^{-15}m



a=0.2 fm

a=0.002 fm

Asymptotic freedom: can use perturbation theory at high energies

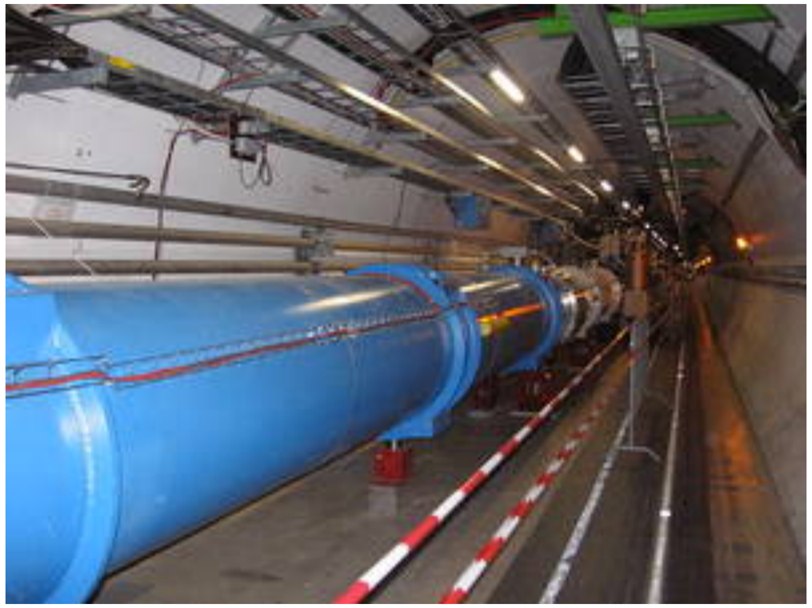
Shortcomings of the SM

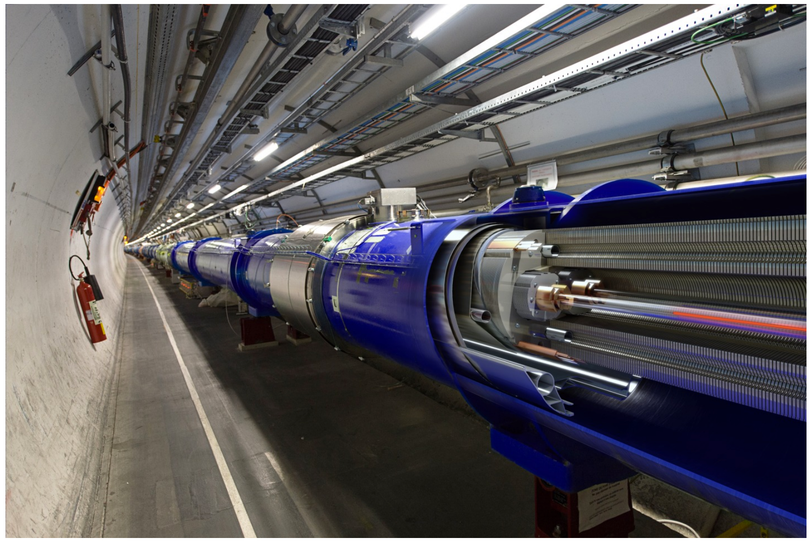
NASA

- No dark matter or dark energy
- Predicts insufficient baryogenesis
- Why 3 generations? Why the observed pattern of quark & lepton masses and weak couplings?
- Weak scale relative to Planck scale
- …

Searching for new physics

- At the highest energies—LHC

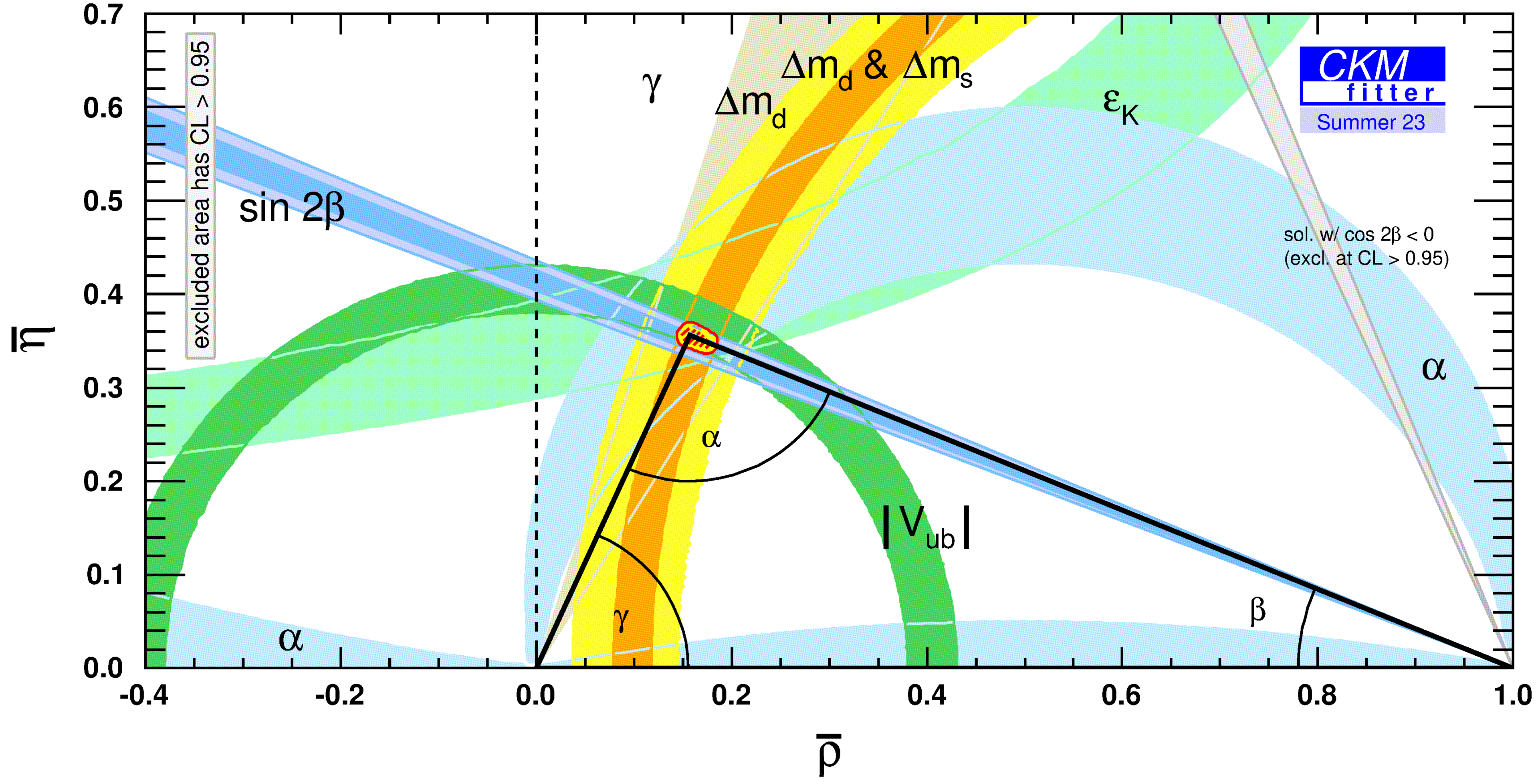




coffeeshopphysics.com

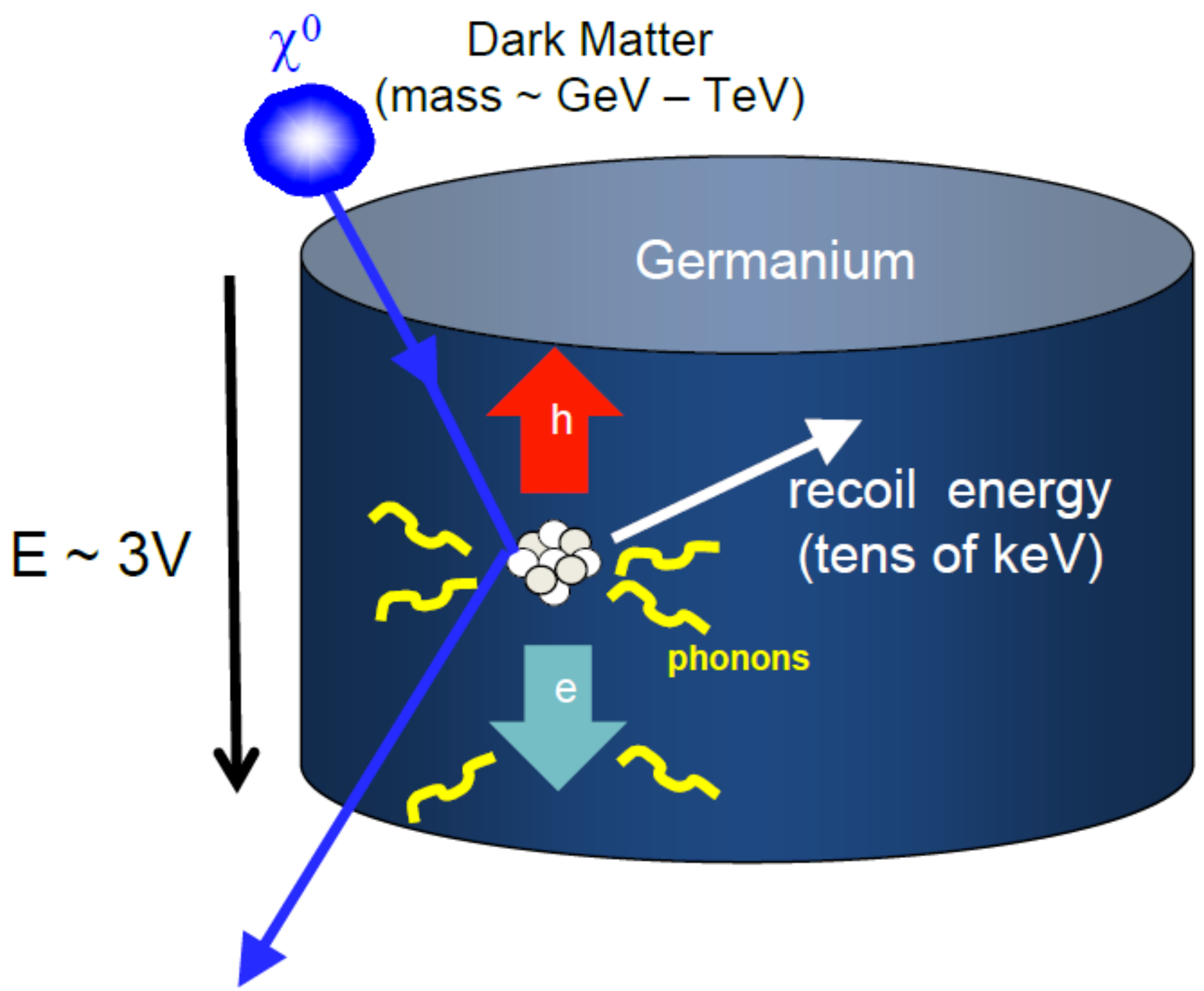
Searching for new physics

- In rare decays or precision measurements
  - Do all CP-violating processes and other precision results in K and B decays agree with the SM?



Searching for new physics

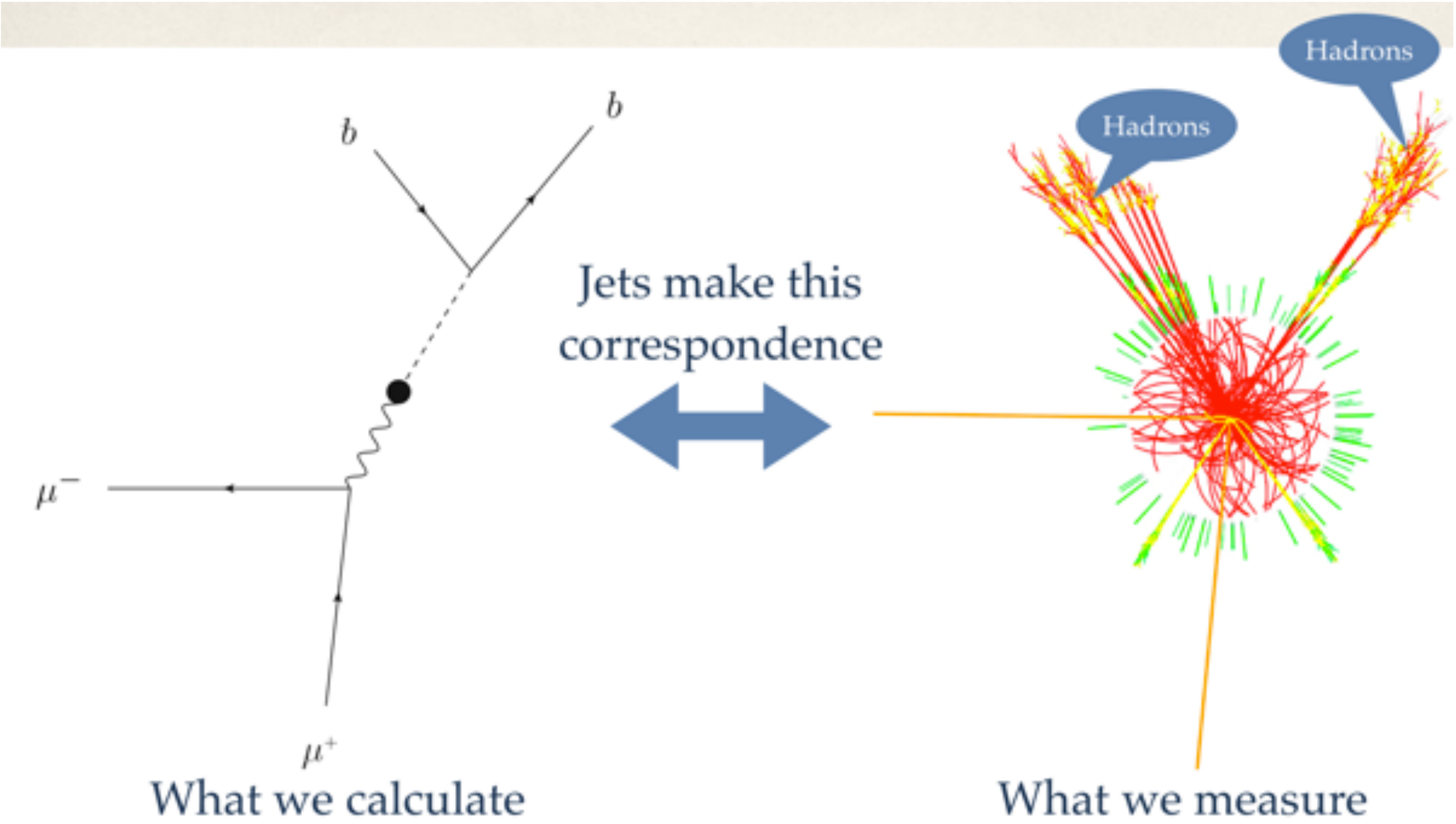
- Dark matter and axion searches



CDMS—graphic from SLAC

QCD as a background

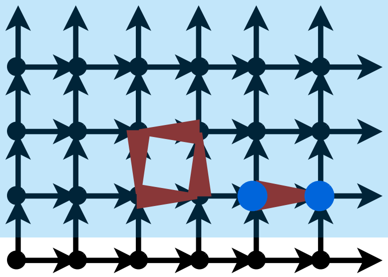
- Quarks become jets at the LHC

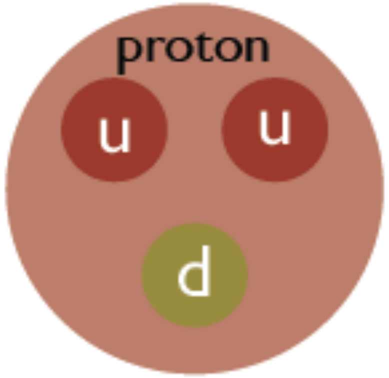


Disentangling requires perturbative QCD and modeling of non-perturbative confinement physics

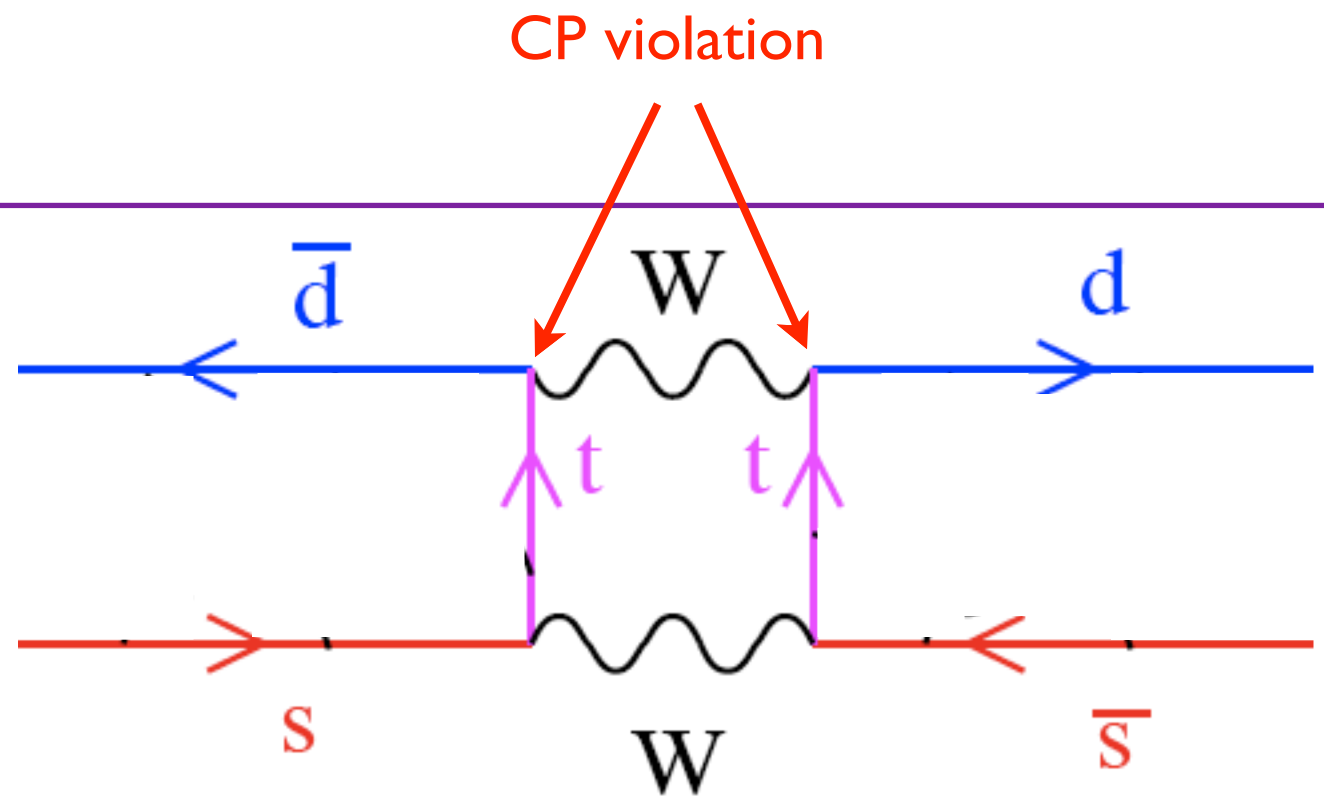
quantumdiaries.org

QCD as a background

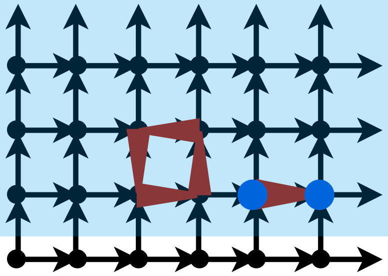




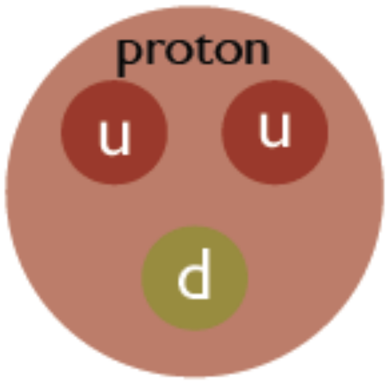
- "Brown muck" distorts hadronic decays
- E.g. CP-violation in kaon-antikaon mixing



Quark level process that one might hope to calculate in perturbation theory
is really a hadronic process that involves non-perturbative QCD



QCD as a background



- "Brown muck" distorts hadronic decays
- Distortions can be huge, e.g. ΔI=½ rule

$$\frac{\Gamma(K_S^0 \to \pi\pi)}{\Gamma(K^+ \to \pi\pi)} \approx 330$$

Same underlying quark weak decay: $s \longrightarrow \bar{u}ud$

- Must be able to calculate these "distortions" to interpret many rare decay experiments

Outline

- Standard model & searching for physics beyond
- QCD & Lattice QCD
- High precision lattice QCD
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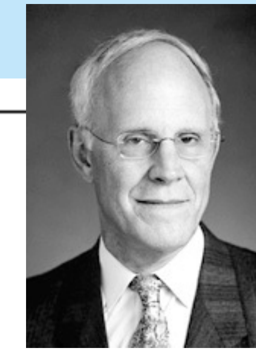
What is QCD?



$$\mathcal{L}_{QCD} = \bar{q}_{a,i}\left[\left(i\gamma^\mu\partial_\mu - m_i\right)\delta_{ab}\delta_{ij}\right]q_{b,j} - g\, G^a_\mu\, \bar{q}_{i,b}\gamma^\mu T^a_{bc}\, q_{i,c} - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

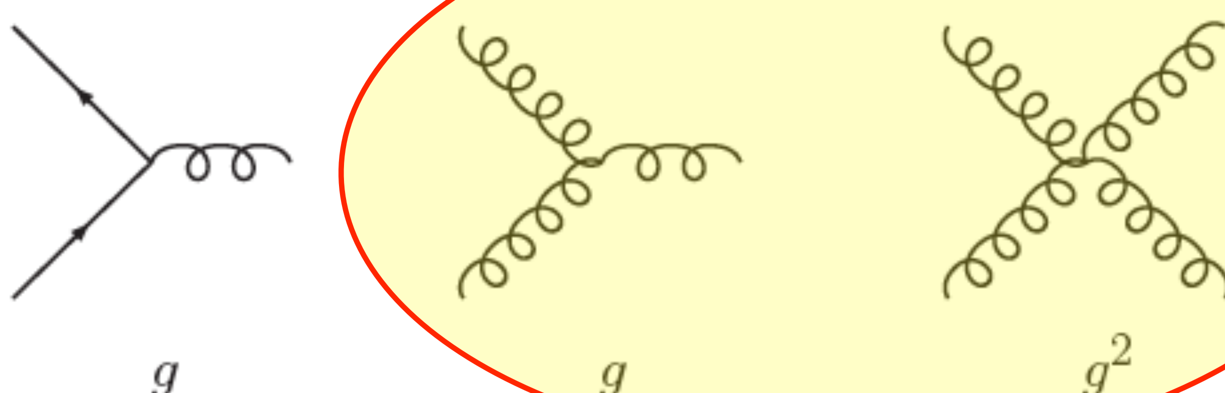
$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g\; f^{abc}G^b_\mu G^c_\nu$$

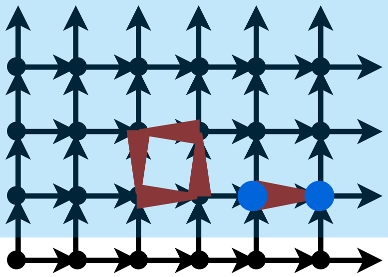
$q_{a,i} =$ quark, 3 colors "a" and 6 flavors "i"

$G^a_\mu =$ gluon, 8 colors "a"

$g =$ QCD coupling

These make QCD challenging!

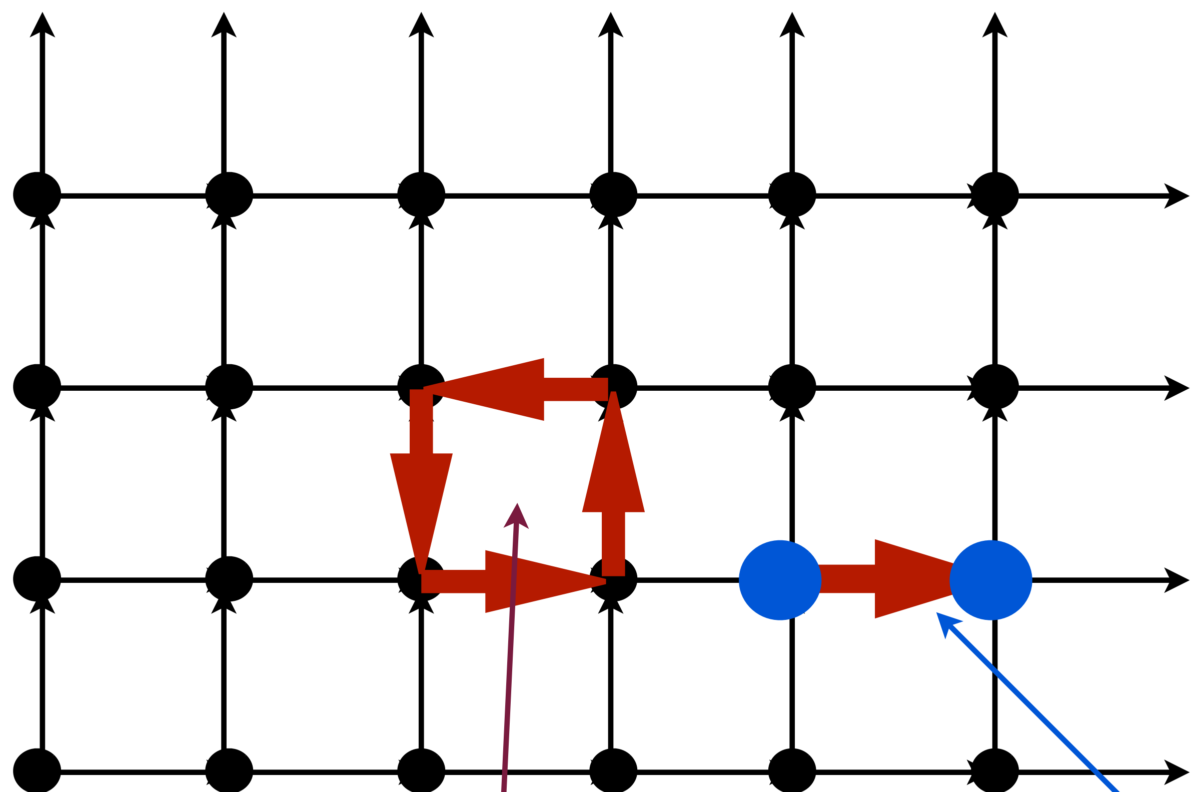




Lattice QCD

Ken Wilson, 1974

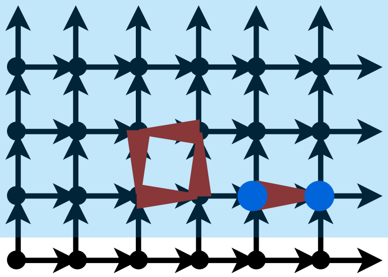
Space
3-dim



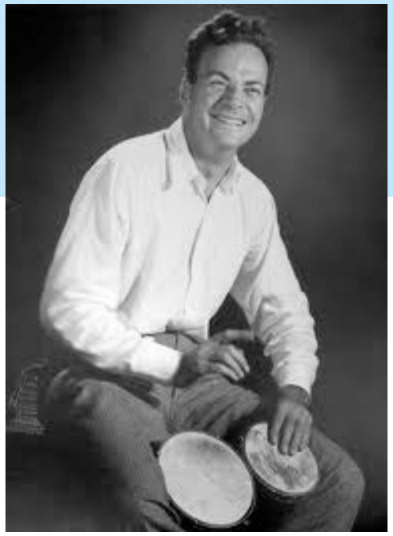
Euclidean
time

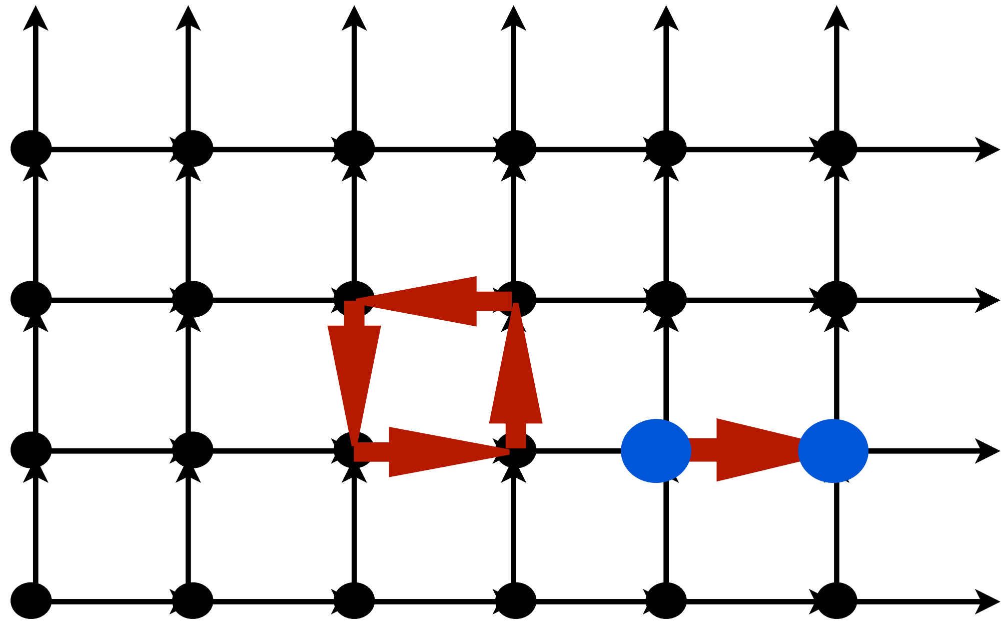
$$S_E^{\mathrm{latt}} = -\sum_{\Box} \frac{6}{g^2} \,\mathrm{Re}\,\mathrm{tr}_N(U_{\Box,\mu\nu}) - \sum_q \bar{q}(D_\mu^{\mathrm{lat}}\gamma_\mu + a m_q)q$$

Wilson gauge action   Lattice fermion action



Lattice QCD

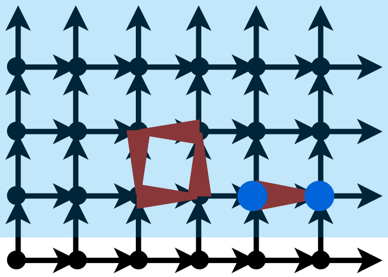




Use Feynman path integral definition of QM

$$Z_E = \int \prod dU\, d\bar{q}\, dq\, e^{-S_E^{\text{lat}}}$$

- Non-perturbative regularization of QFT
- Provides rigorous definition of QCD
  - Take a→0 by sending g(a)→0
- Amenable to numerical simulation using Monte Carlo methods



Simulating fermions is hard

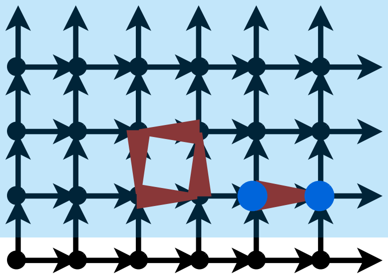
$$Z_{\mathrm{QCD}} = \int \prod dU\, d\bar{q}\, dq\, e^{-S_E^{\mathrm{lat}}}$$

$$= \int dU\, e^{-S_{\mathrm{glue}}^{\mathrm{lat}}} \prod_q \det\left(D_\mu^{\mathrm{lat}} \gamma_\mu + m\right)$$

gluon loops

fermion loops

- Fermion determinant leads to non-local effective gauge action
- Orders of magnitude more difficult to simulate than the “pure gluon” theory



Timeline

- 1974, invention of lattice QCD (K.Wilson)
- 1980, simulations of pure gluon theory demon[illegible]ate confinement (M. Creutz)
- 1980's: "quenched era" (no quar[illegible]
- 1987, Hybrid Mon[illegible]
- 199[illegible] [illegible]rk loops)
- [illegible] (Kaplan)
- [illegible]p fermions (Neuberger)
- 2000's: fully unquenched era (light quark loops)
- 2009-10: simulations with physical up, down and strange quark masses
- 2010's: inclusion of electromagnetism, isospin breaking
- 2020's: many extensions: inclusive processes, multi particle scattering

CPU speedup, theoretical & algorithmic advances have allowed lattice QCD to become a precision tool

Cray 1, 1MFlop/s

Cray 2, 1GFlop/s

1TFlop/s

Blue gene P, 1PFlop/s

Blue gene Q, 10 PFlop/s

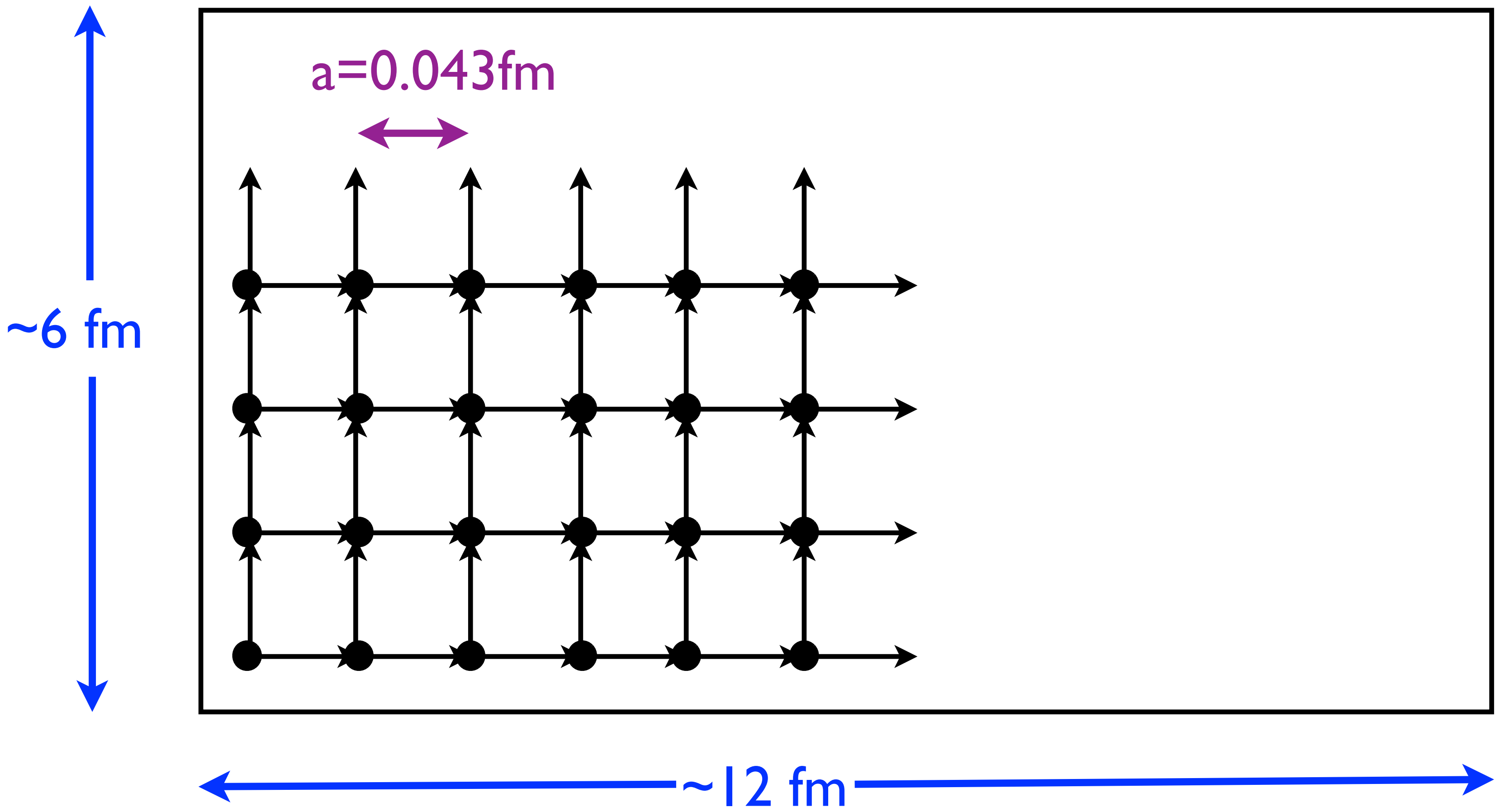
Summit, 100 PFlop/s

El Capitan, > 1 ExaFlop/s

State of the art

144x144x144x288 lattice [MILC collaboration]

Highly Improved Staggered (HISQ) fermions
Physical quark masses (in isospin limit: $m_u = m_d$)

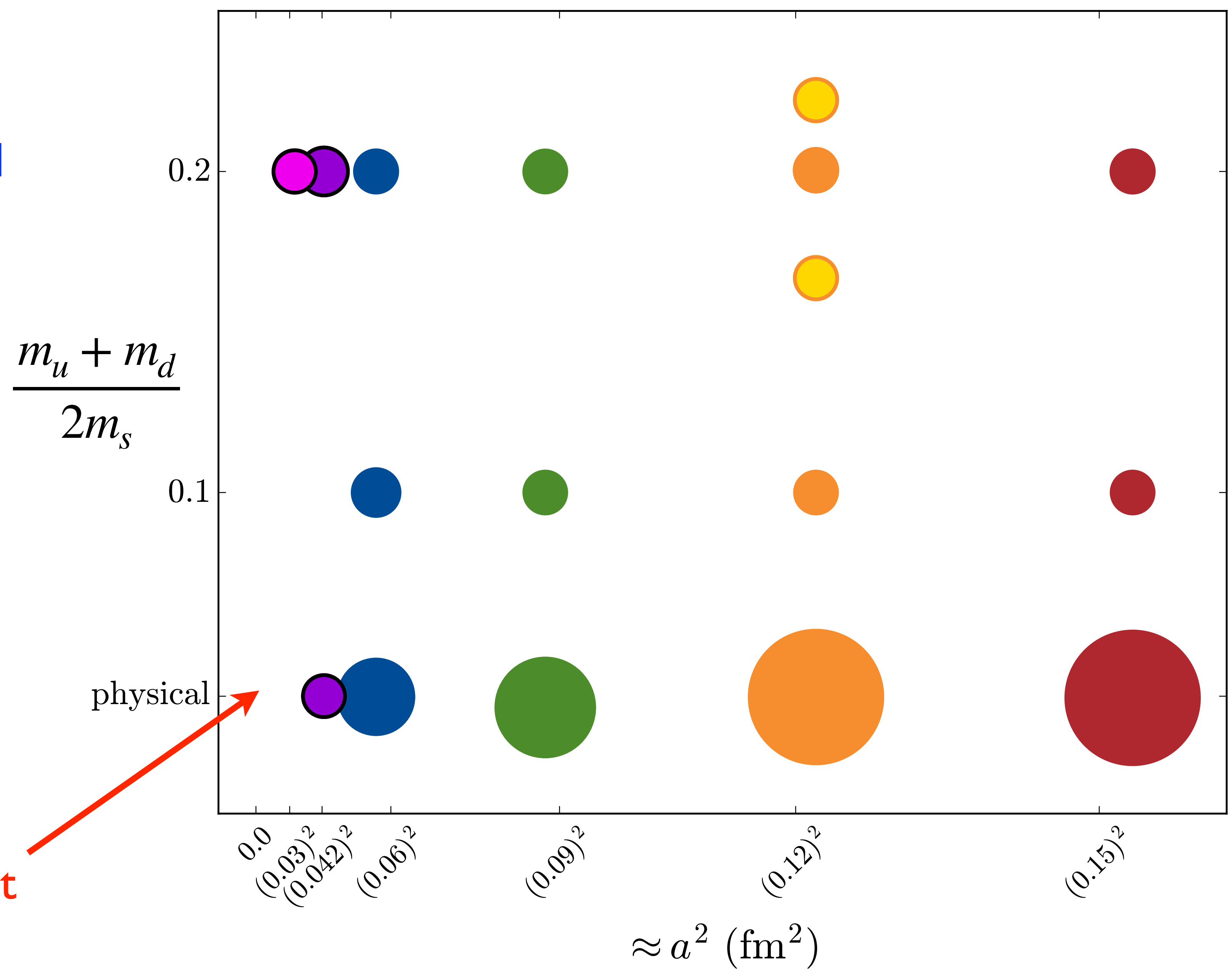


Need to invert matrices of size $\sim (3 \times 10^9) \times (3 \times 10^9)$

State of the art

Extrapolating to the physical point

Decreasing u,d quark masses



physical point

continuum limit

S. Gottlieb,
talk at NERSC@50, 2025

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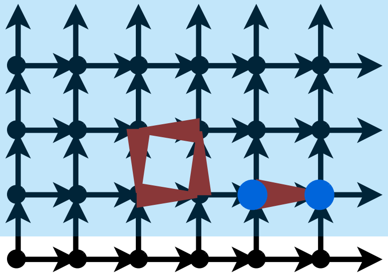
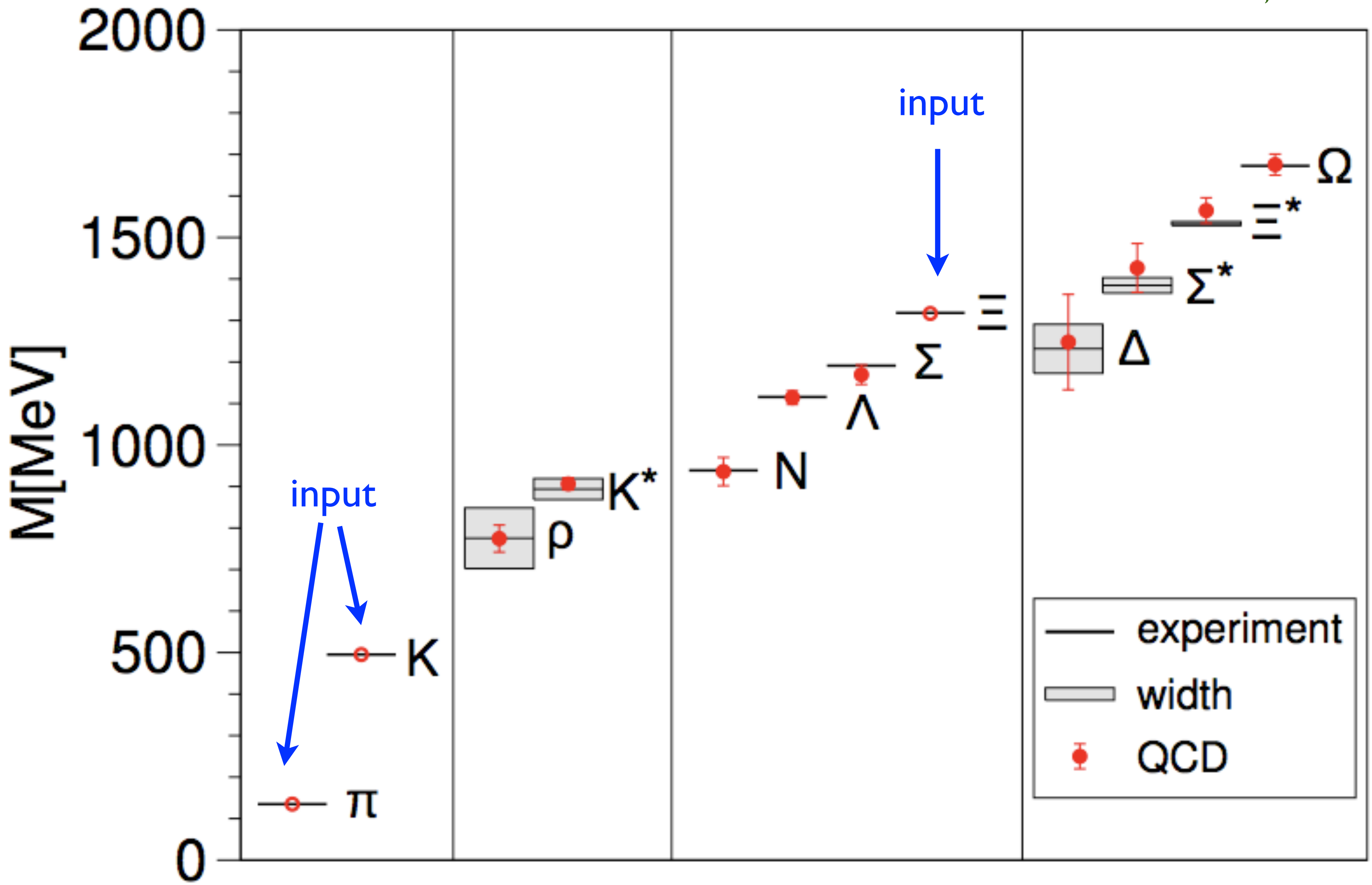


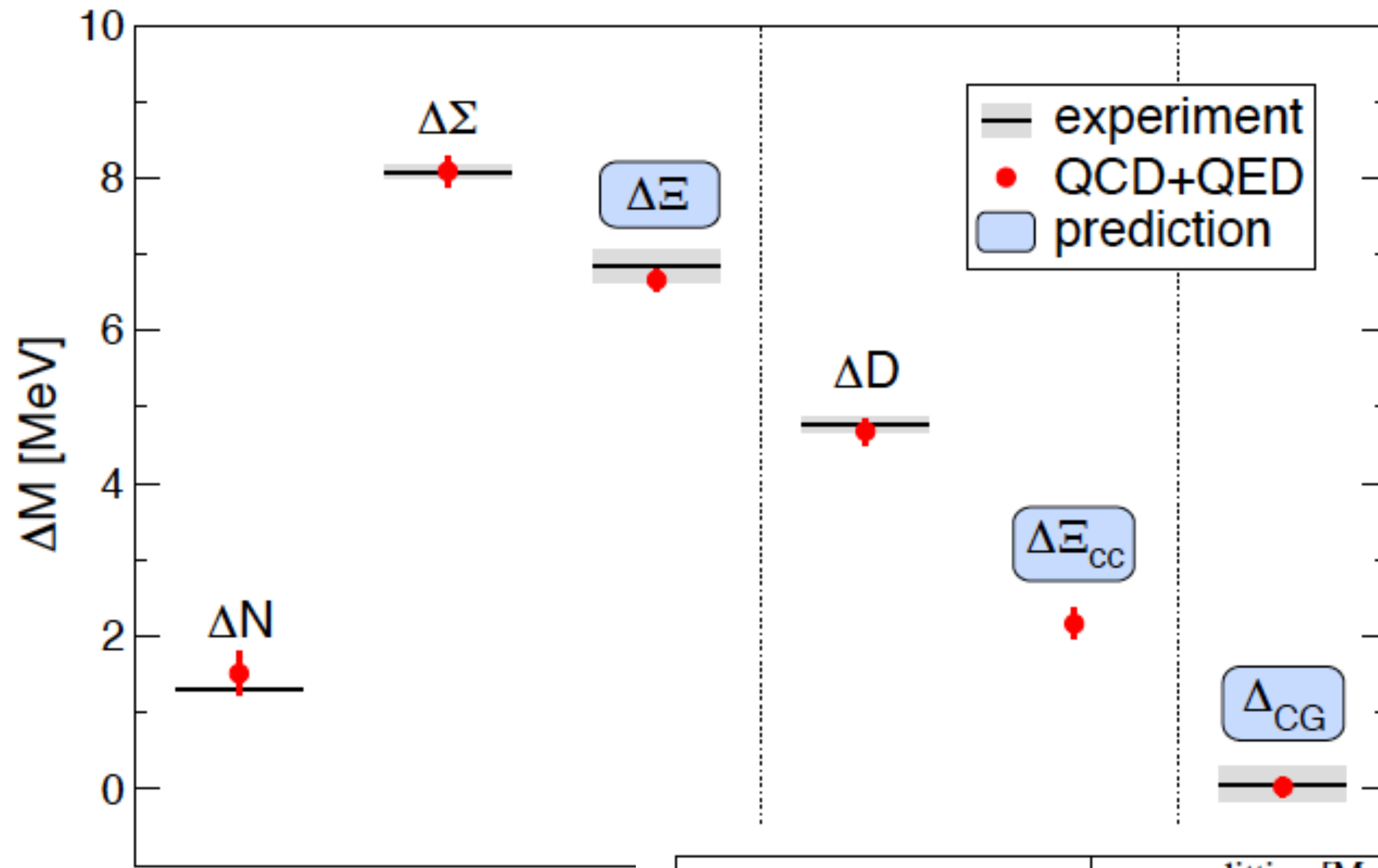
Postdiction: spectrum

BMW Collaboration, 2008



Few percent accuracy, and complete consistency

Isospin splittings



BMW Collaboration
2014

u, d, s & c in loops

$m_u \neq m_d$

QED included

quark masses & scale determined using $\pi^+, K^+, K^0, D^0, \Omega$

	mass splitting [MeV]	QCD [MeV]	QED [MeV]
$\Delta N = n - p$	1.51(16)(23)	2.52(17)(24)	-1.00(07)(14)
$\Delta\Sigma = \Sigma^- - \Sigma^+$	8.09(16)(11)	8.09(16)(11)	0
$\Delta\Xi = \Xi^- - \Xi^0$	6.66(11)(09)	5.53(17)(17)	1.14(16)(09)
$\Delta D = D^\pm - D^0$	4.68(10)(13)	2.54(08)(10)	2.14(11)(07)
$\Delta\Xi_{cc} = \Xi_{cc}^{++} - \Xi_{cc}^{+}$	2.16(11)(17)	-2.53(11)(06)	4.69(10)(17)
$\Delta_{CG} = \Delta N - \Delta\Sigma + \Delta\Xi$	0.00(11)(06)	-0.00(13)(05)	0.00(06)(02)

Errors ~ 0.2 MeV !

arXiv:2411.04268v2 [hep-lat] 17 Jan 2025

FLAG Review 2024 (6th edition)

Flavour Lattice Averaging Group (FLAG)

Y. Aoki[1], T. Blum[2,3], S. Collins[4], L. Del Debbio[5], M. Della Morte[6], P. Dimopoulos[7,8], X. Feng[9,10,11,12], M. Golterman[13], Steven Gottlieb[14], R. Gupta[15], G. Herdoiza[16], P. Hernandez[17], A. Jüttner[18,19,20], T. Kaneko[21,22], E. Lunghi[14], S. Meinel[23], C. Monahan[24,25], A. Nicholson[26], T. Onogi[27], P. Petreczky[28], A. Portelli[1,5,20], A. Ramos[17], S. R. Sharpe[29], J. N. Simone[30], S. Sint[31], R. Sommer[32,33], N. Tantalo[34], R. Van de Water[30], A. Vaquero[35,36], U. Wenger[37], and H. Wittig[38,39]

- Reviews every ~3 years: "vetted" averages of 72 LQCD results with full error budgets
- "PDG (Particle Data Group) or HFLAV (Heavy Flavor Working Group) for Lattice QCD"

FLAG6: QCD parameters

- **Strong coupling constant**

$$\alpha^{(5)}_{\overline{\mathrm{MS}}}(M_Z) = 0.1183(7) \qquad \text{[0.6\% error]}$$

Compare to

$$\alpha_s(m_Z^2) = 0.1175 \pm 0.0010 \qquad \text{(PDG 2023 without lattice)}$$

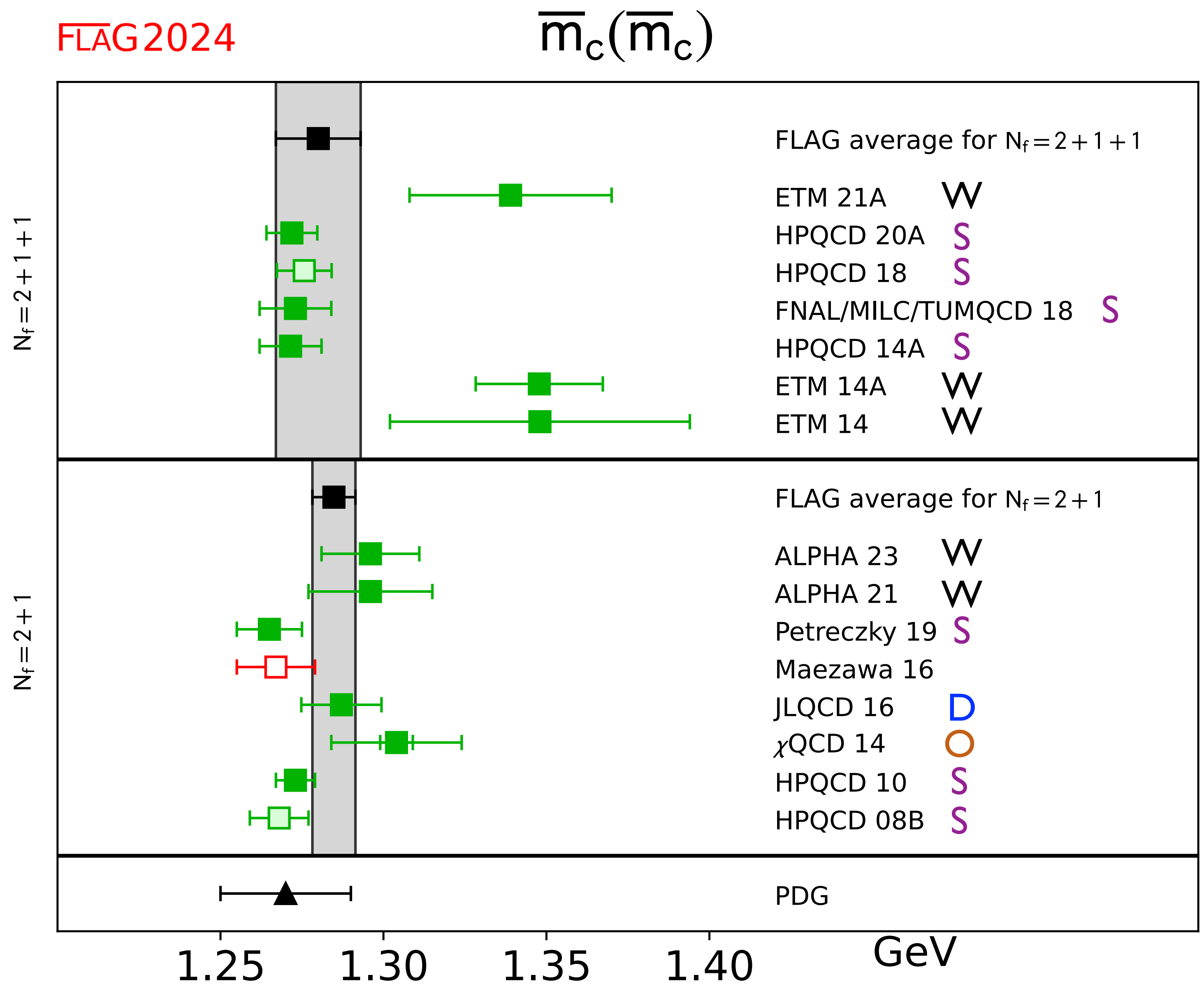
- **Quark masses**

$$m_u[4\%],\ m_d[2\%],\ m_s[1\%],\ m_c[1\%],\ m_b[0.3\%]$$

$$\frac{m_u + m_d}{m_s}[0.3\%],\ \ \frac{m_s}{m_c}[0.3\%]$$

Example: charm quark mass

$$\overline{m}_c(\overline{m}_c) = 1.278(6)\,\mathrm{GeV}\ [N_f = 2+1]$$



W=Wilson fermions

S=staggered fermions

D=domain-wall fermions

O=overlap fermions

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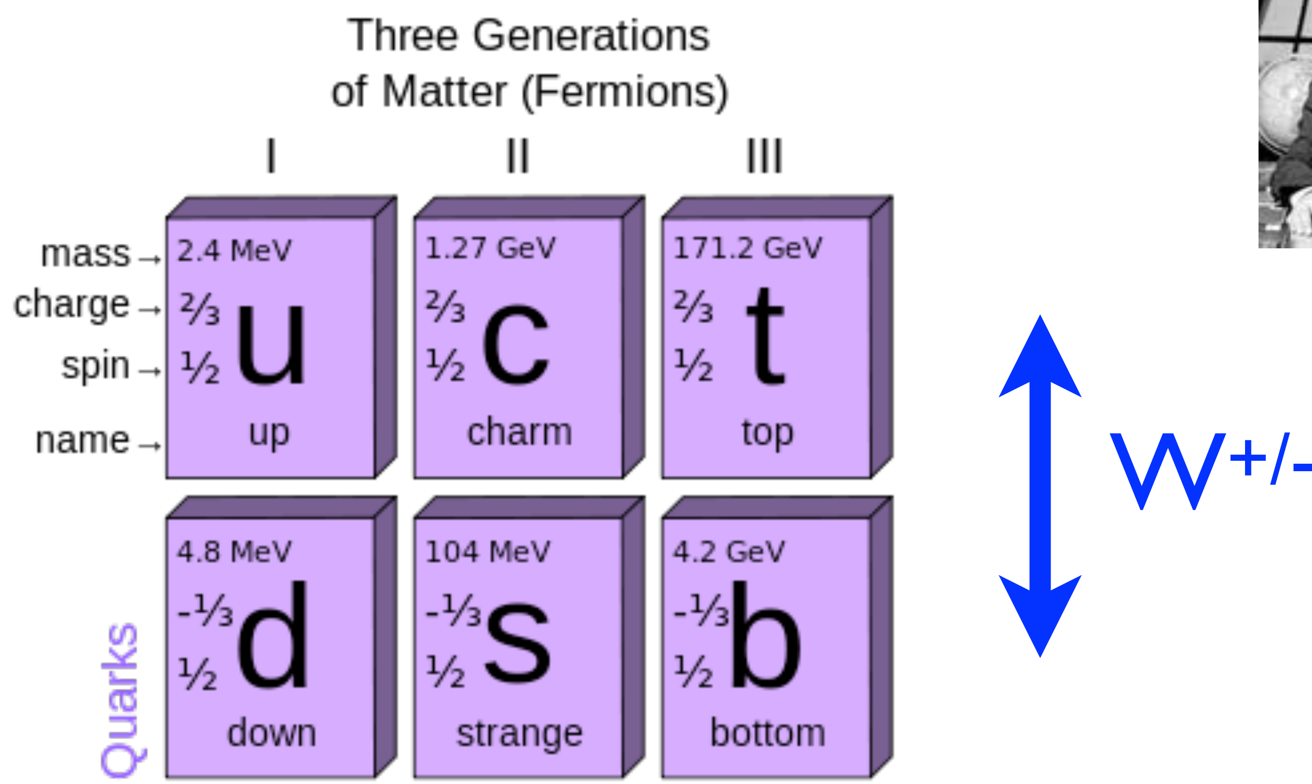
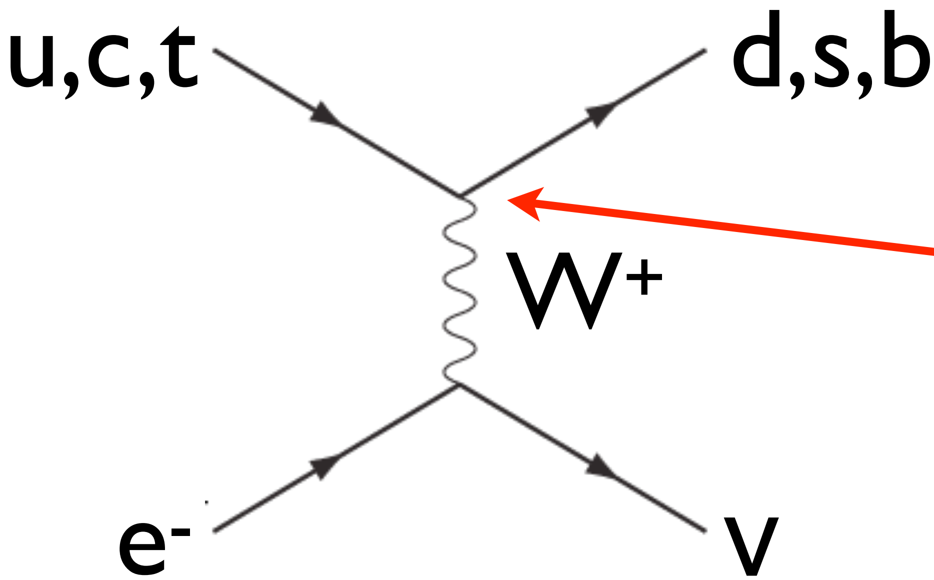
CKM matrix & CP violation





$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Fundamental parameters of the SM

CKM matrix & CP violation

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}.$$

Unitary matrix

CP violation!

- Each element can be measured in several ways
- Consistency of SM requires all measurements to agree, and that V_{CKM} be unitary
- The CP violating parameter η must explain observed CP violation in Kaon and B meson (and D) systems
- New physics would shows up as inconsistencies

Need for non-perturbative QCD

$$\left(\begin{array}{c:c:c}
\mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\
\pi \to \ell\nu & K \to \ell\nu & B \to \pi\ell\nu \\
 & K \to \pi\ell\nu & \\
\hdashline
\mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\
D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu \\
D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\
\hdashline
\mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\
B_d \leftrightarrow \overline{B}_d & B_s \leftrightarrow \overline{B}_s & \\
K_0 \leftrightarrow \overline{K}_0 & K_0 \leftrightarrow \overline{K}_0 &
\end{array}\right)$$

$$\text{Experiment} = \text{known factors} \times V_{CKM} \times \text{Hadronic matrix element}$$

Perturbative SM

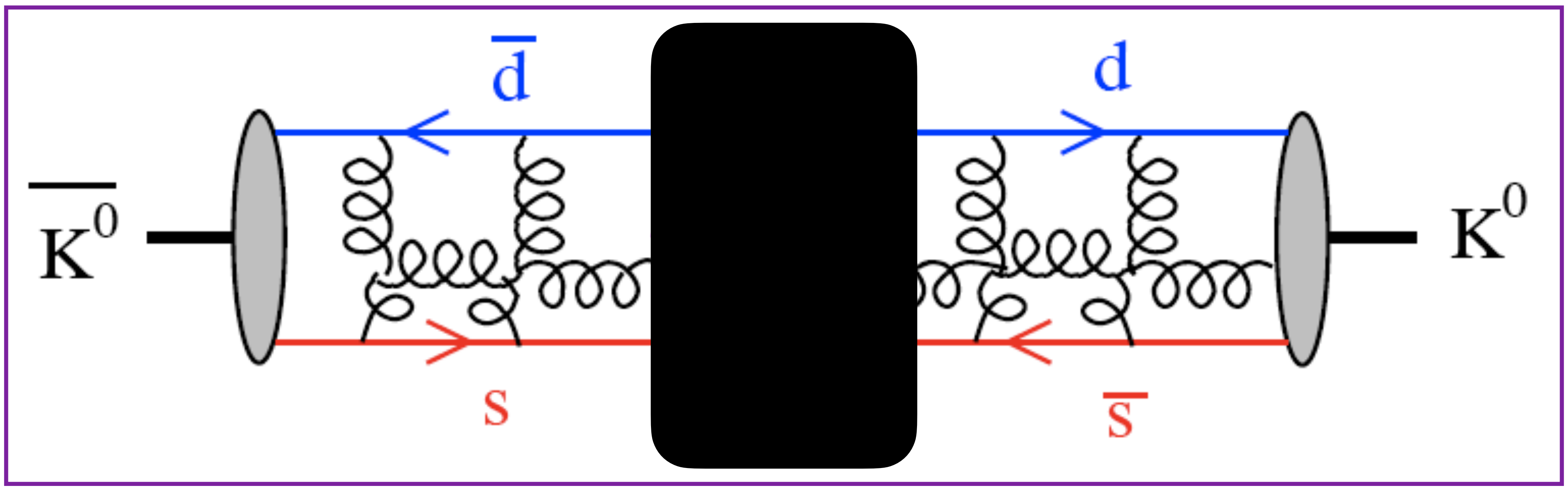
Lattice QCD

Measure

to determine this

Example of hadronic matrix

- $\hat{B}_K$: CP-violation in kaon-antikaon mixing



Integrate out W (and Z) and t (and c) to obtain local operator

$$\hat{B}_K \sim \frac{\langle \bar{K}_0 \,|\, [\bar{s}\gamma_\mu(1-\gamma_5)d][\bar{s}\gamma^\mu(1-\gamma_5)d] \,|\, K_0 \rangle}{\frac{8}{3} f_k^2 m_K^2}$$

FLAG6: matrix elements

- Decay constants, e.g. $\langle \pi^+ | \bar{u}\gamma^\mu\gamma_5 d | 0 \rangle \propto p_\pi^\mu f_\pi$

  $f_\pi[0.6\%]$, $f_K[0.2\%]$, $f_D[0.3\%]$, $f_{D_s}[0.2\%]$, $f_B[0.7\%]$ $f_{B_s}[0.5\%]$

- B-parameters, e.g. $\langle \bar{K}_0 | [\bar{s}\gamma_{\mu,L} d][\bar{s}\gamma_L^\mu d] | K_0 \rangle \sim B_K$

  $B_K[1\%]$, $B_B[5\%]$, $B_{B_s}[5\%]$, $B_{\rm BSM}[\lesssim 3\%]$

- Form factors, e.g. $\langle K^-(p) | \bar{s}\gamma^\mu u | \pi^+(k) \rangle$

  $f_+^{K\to\pi}(0)[0.2\%]$, $f_+^{D\to\pi}(0)[1\%]$, $f_+^{D\to K}(0)[0.3\%]$

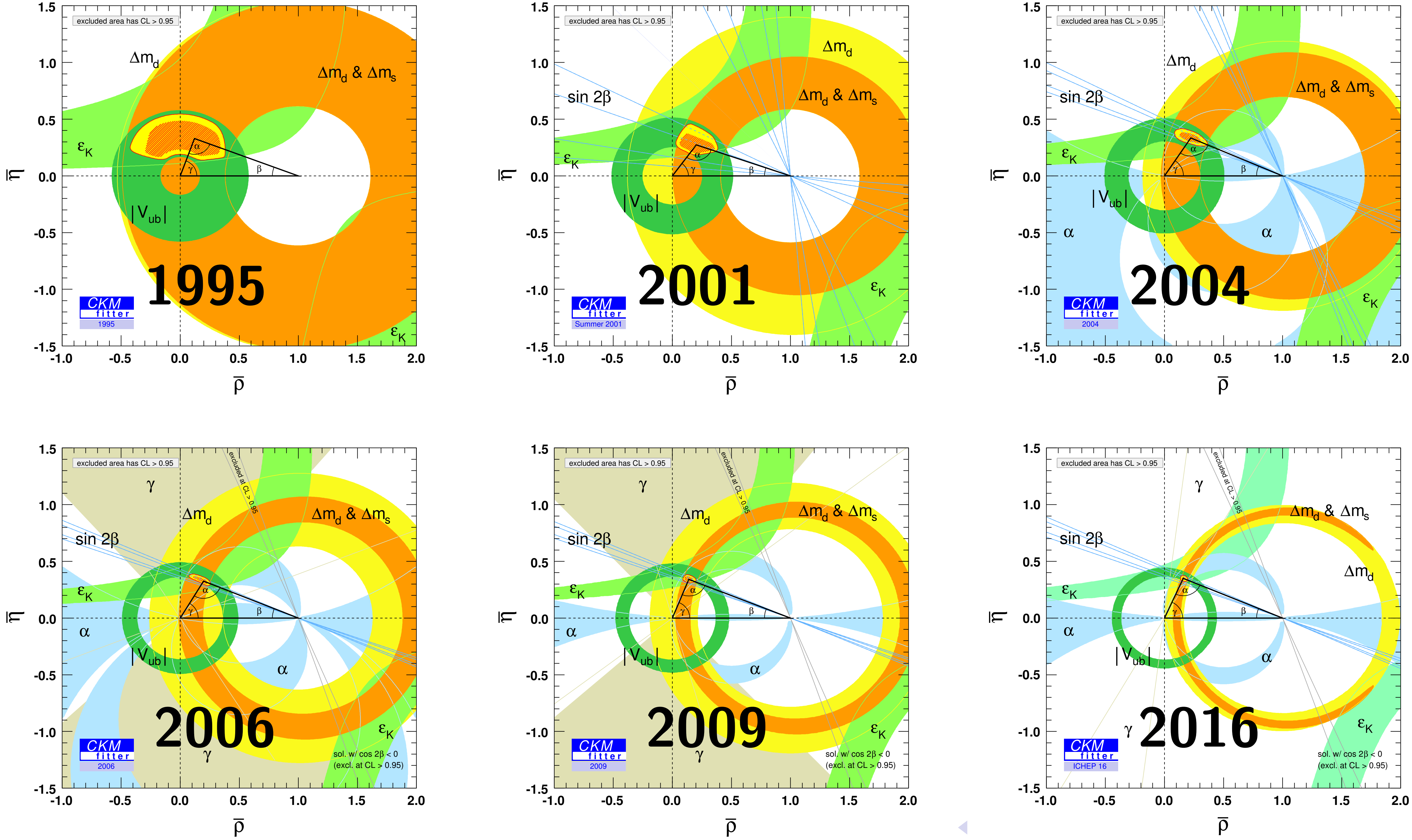
  $B \to \pi\ell\nu$, $B_s \to K\ell\nu$, $B \to D\ell\nu$, $B \to D^*\ell\nu$, $B \to D_s\ell\nu$, $B \to K\ell^+\ell^-$, …

Aida will discuss some of these

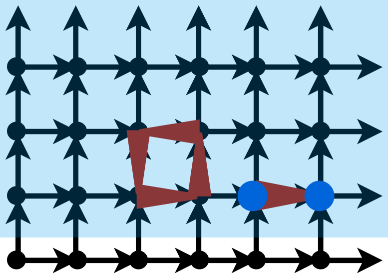
- Nucleon matrix elements, e.g. $\langle N | \bar{s}s | N \rangle \propto \sigma_s$

  $g_A^{u-d}[1\%]$, $\sigma_{\pi N}[5\%]$, $\sigma_s[15\%]$, $\langle x \rangle_{u-d}$ $[10\%]$, …

History of steady progress

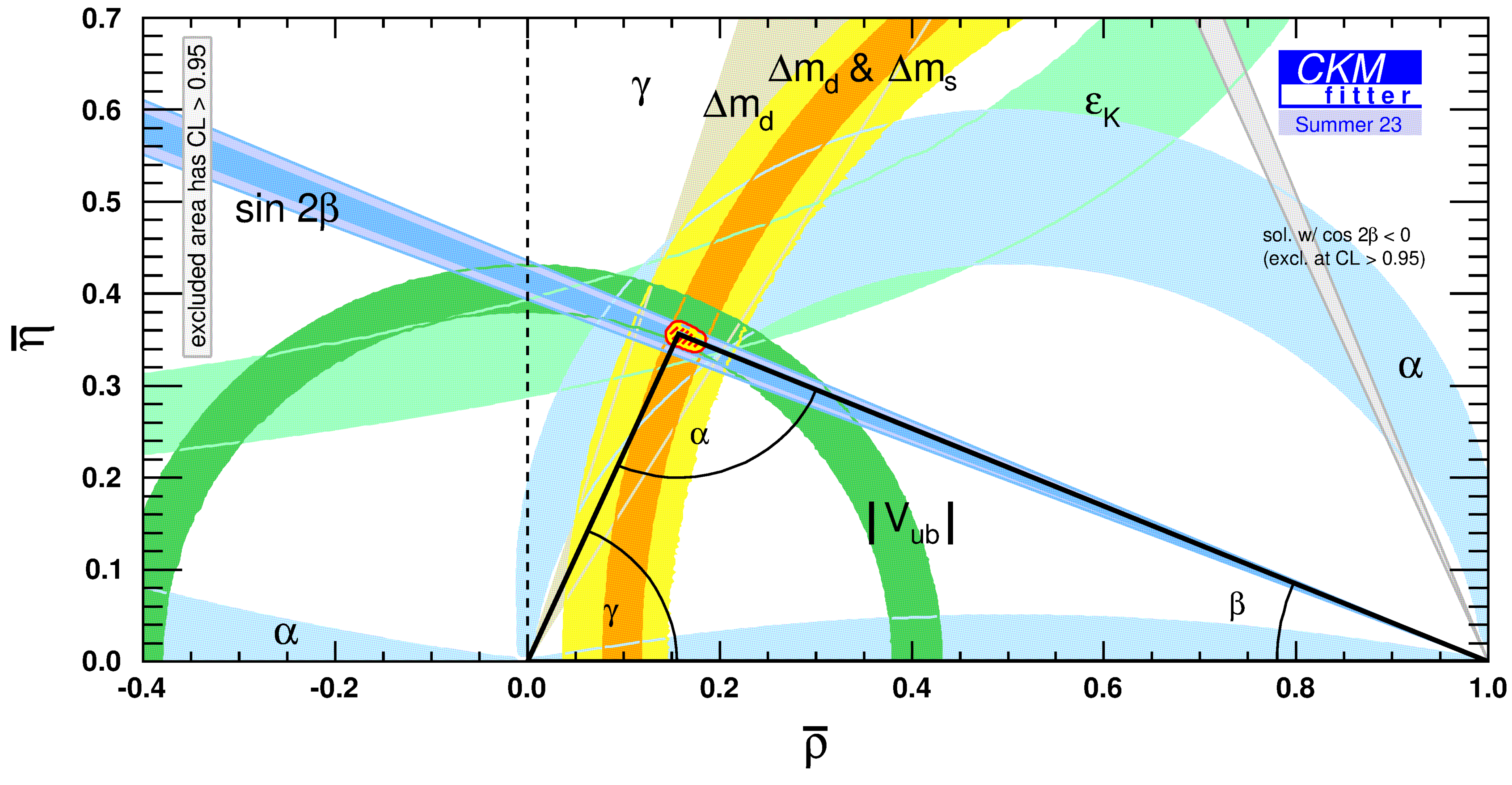


CKMfitter (ckmfitter.in2p3.fr): talk by Luiz Silva, 9/2018



...but overall consistency

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



…though this is controversial

2025 update on ε_K in the Standard Model with lattice QCD inputs

Seungyeob Jwa,[1] Jeehun Kim,[1] Sunghee Kim,[1] Sunkyu Lee,[2] Weonjong Lee,[1,*] and Sungwoo Park[3]
(SWME Collaboration)

arXiv:2503.00351v3 [hep-lat] 13 Mar 2025

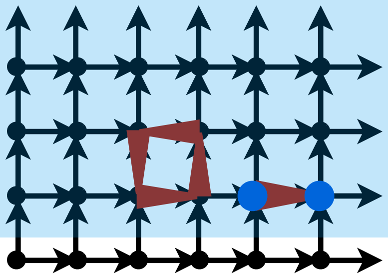
TABLE XXIV. Results for $\Delta\varepsilon_K$. They are obtained using the RBC-UKQCD estimate for ξ_{LD}, the indirect method for ξ_0, the traditional method for η_i of $c-t$ unitarity, the FLAG results for $\hat{B}_K$, the AOF results for the Wolfenstein parameters, and so on.

Input from HQET

Input from LQCD

year	Inclusive $\lvert V_{cb}\rvert$	Exclusive $\lvert V_{cb}\rvert$
2015	0.33σ	3.4σ
2018	1.1σ	4.2σ
2024	1.4σ	5.1σ

- There are several other $\sim 3\sigma$ tensions between theory & experiment in flavor physics

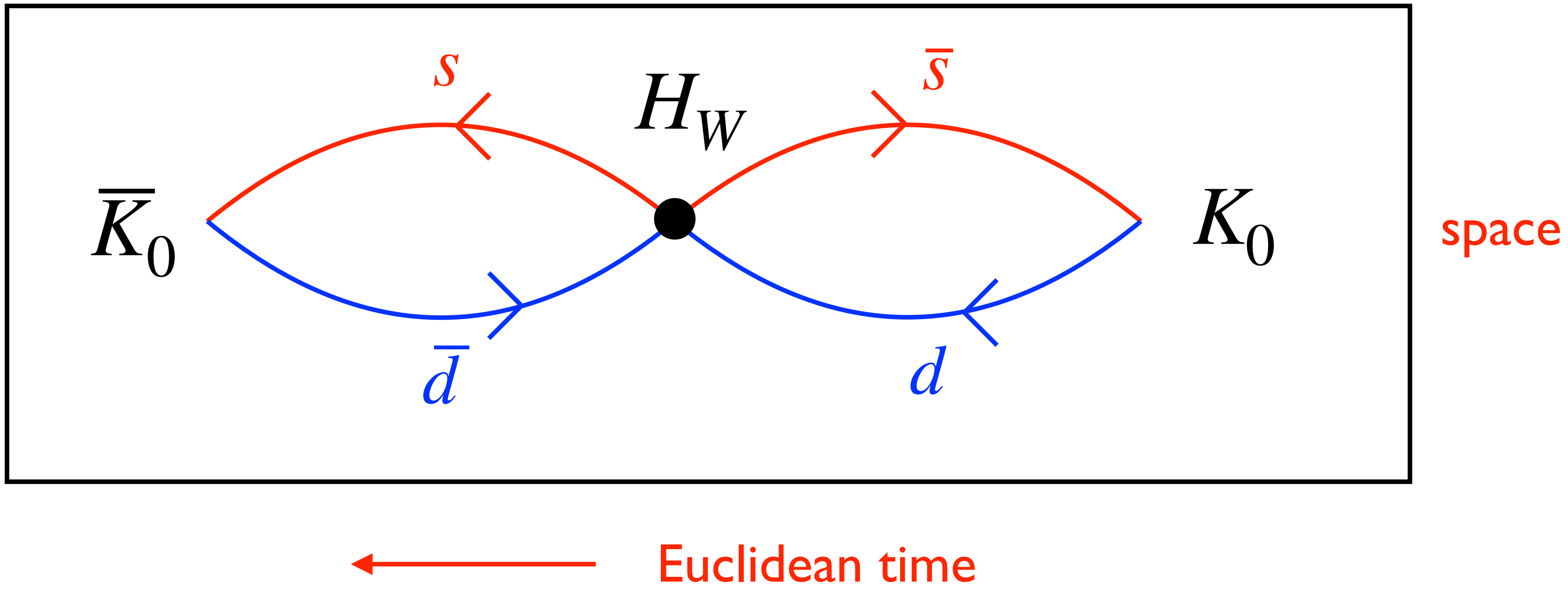


Outline

- Standard model & searching for physics beyond
- QCD & Lattice QCD
- High precision lattice QCD
- Constraining the Standard Model with LQCD
- **Extending the LQCD frontier**
- Summary

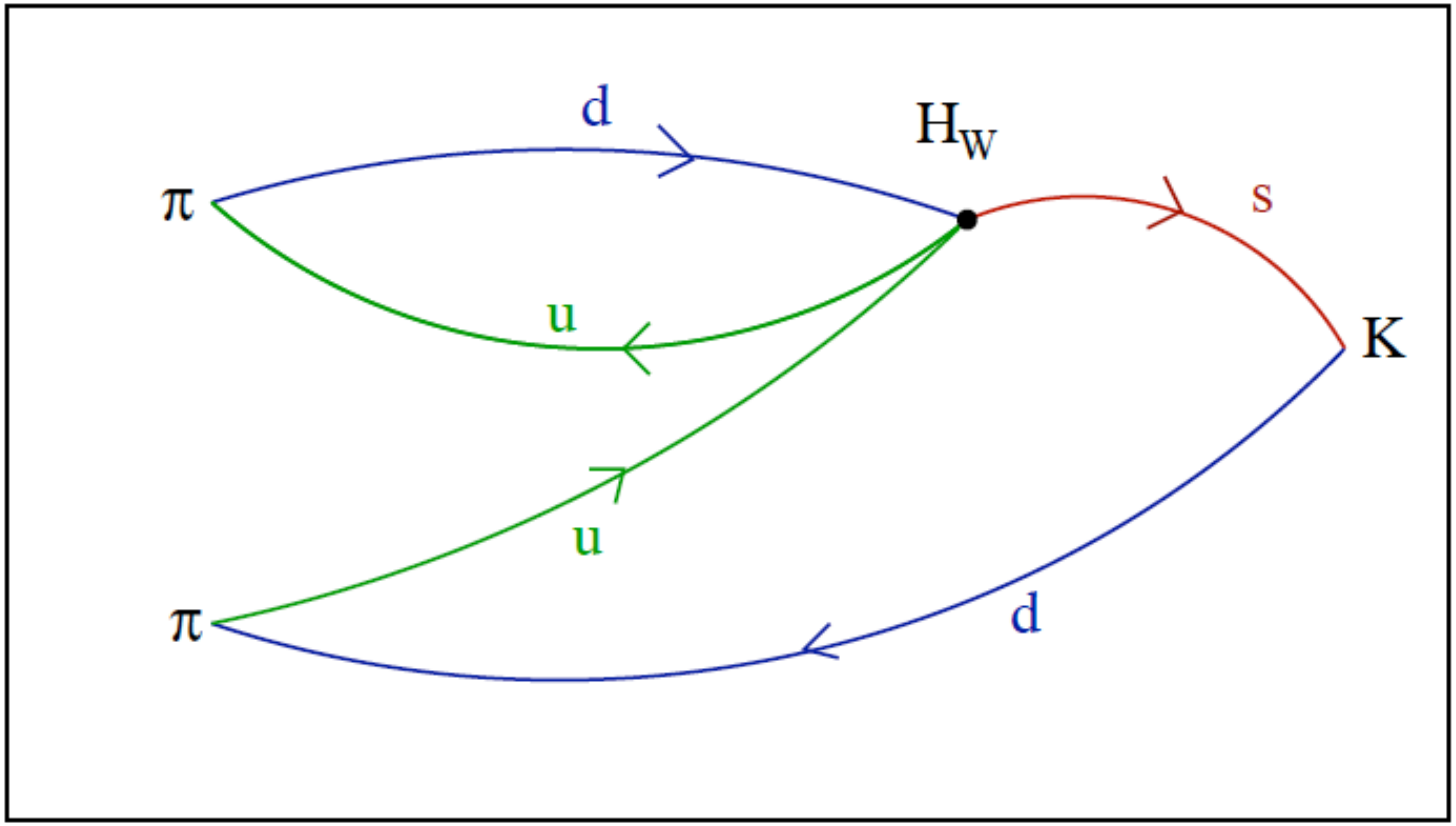
Present frontier

- Present "FLAG ready" LQCD calculations almost all involve <u>single hadrons</u>, e.g. B_K



Present frontiers

- Processes involving 2+ hadrons are more challenging
  - Major progress on $\mathscr{A}(K \to \pi\pi)$: now "FLAG-ready" with ~10% errors [RBC-UKQCD collaboration]



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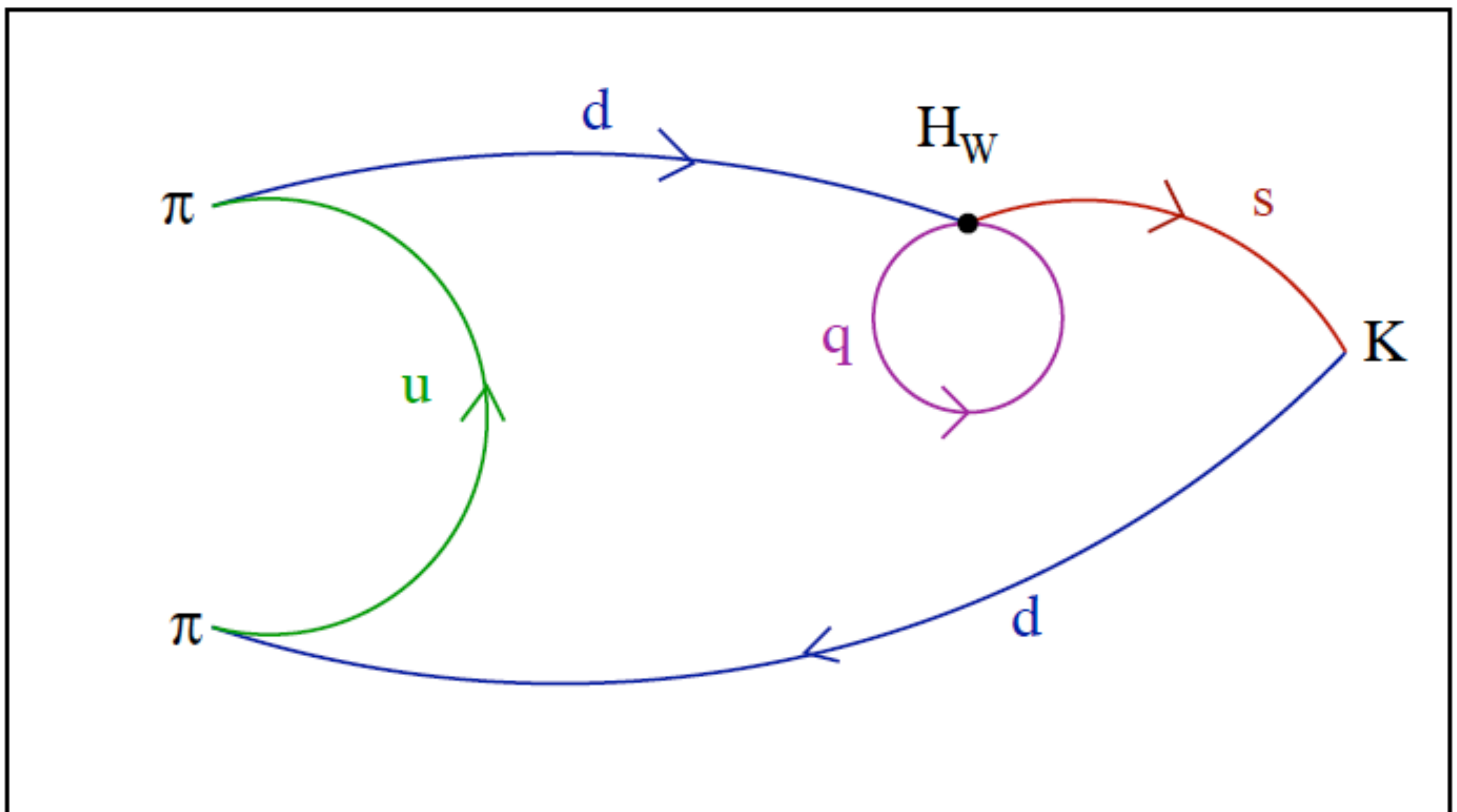

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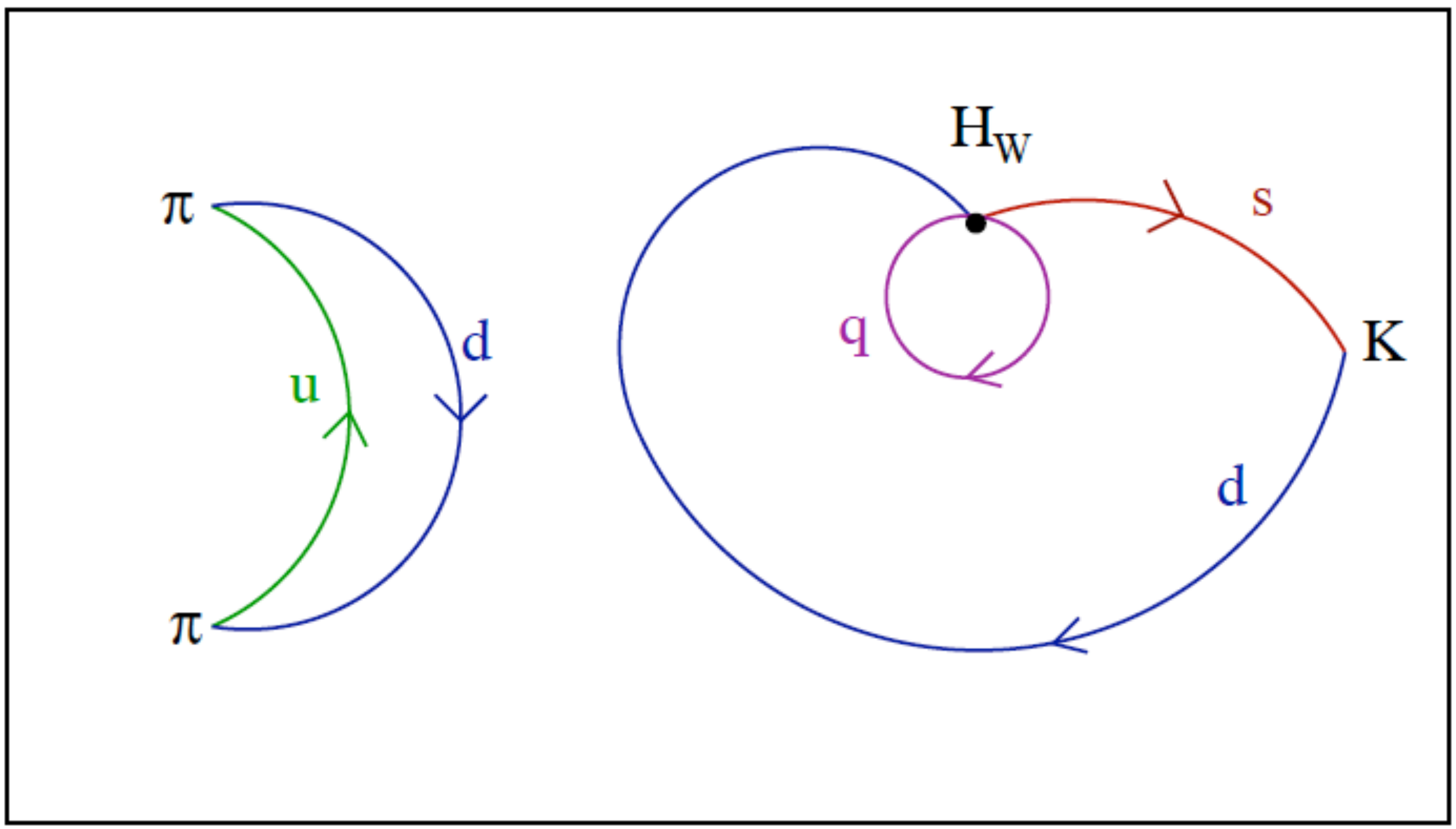


Present frontiers

- Processes involving 2+ hadrons are more challenging

  - Major progress on $\mathscr{A}(K \to \pi\pi)$: now “FLAG-ready” with ~10% errors [RBC-UKQCD collaboration]

  - Quantitative understanding of $\Delta I = 1/2$ rule

$$\frac{\Gamma(K_S^0 \to \pi\pi)}{\Gamma(K^+ \to \pi\pi)} \approx 330$$

  - Quantitative prediction of CP-violating parameter ε'

    - LQCD matrix elements + other inputs predict [UTfit, 2212.03894]

$$\varepsilon'/\varepsilon = 15.2(4.7) \cdot 10^{-4}$$

    - Agreement with experiment [$\varepsilon'/\varepsilon = 16.6(3.3) \cdot 10^{-4}$] constrains theories of new physics

Many other frontiers

Maarten & Aida will discuss

- Testing the Standard Model
  - Isospin breaking & EM, $(g-2)_\mu$, inclusive decay rates, Δm_K, $D-\overline{D}$ mixing, CP-violation in $D \to \pi\pi, K\overline{K}, \ldots$
- Understanding the strong interactions
  - Nucleon axial form factors, structure fcns, GPDs, TMDs, finite density, NN and NNN interactions, multiparticle scattering and exotic hadrons, …

I will discuss

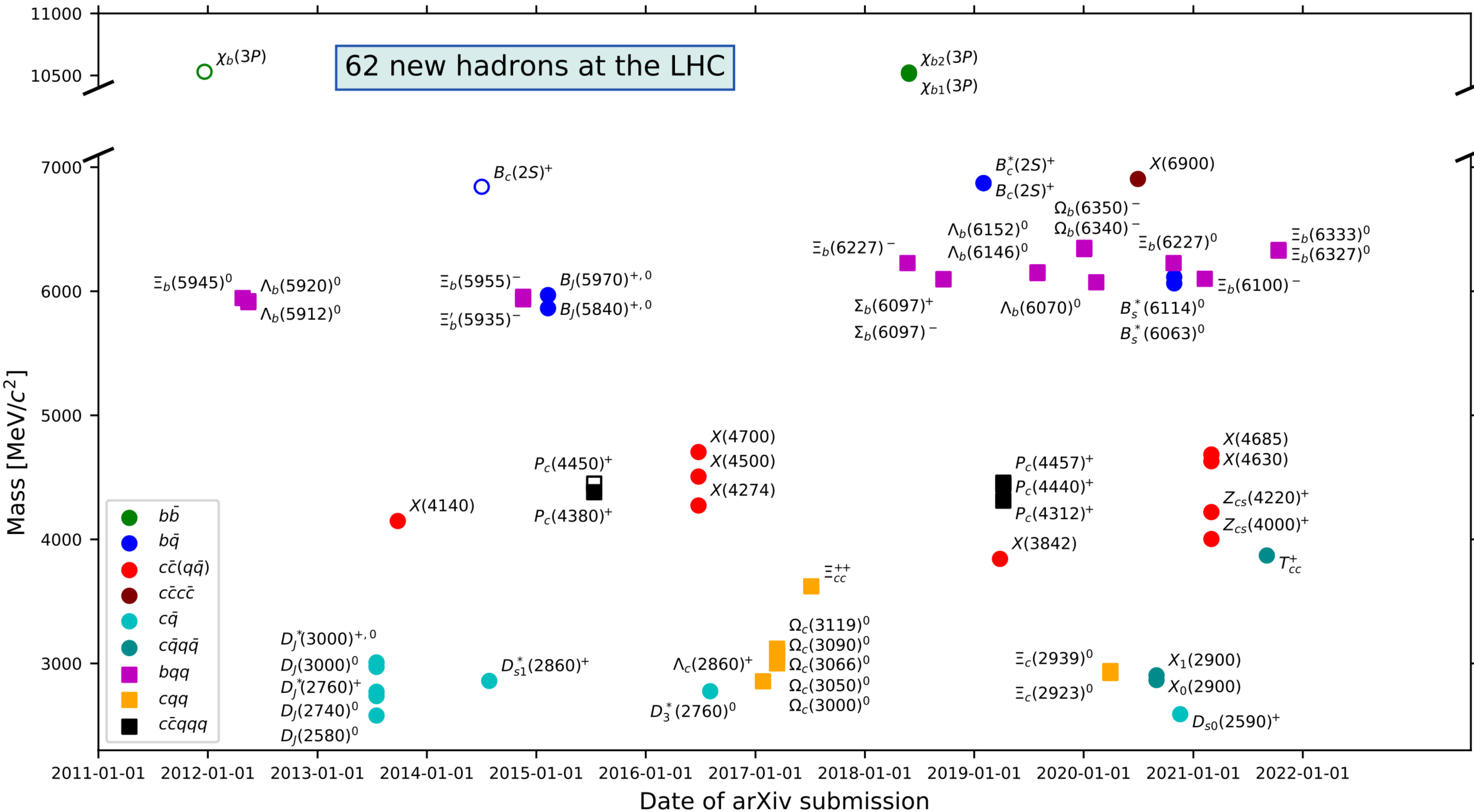
- Beyond LQCD
  - Formulating chiral gauge theories, nearly-conformal theories with more flavors, symmetric mass generation, …

Maarten will discuss

Why multiparticle amplitudes?

- Calculate properties of strong interaction resonances
  - E.g. exotics such as $T_{cc}(3875)^+ \to DD^* \to DD\pi$

Cornucopia of resonances



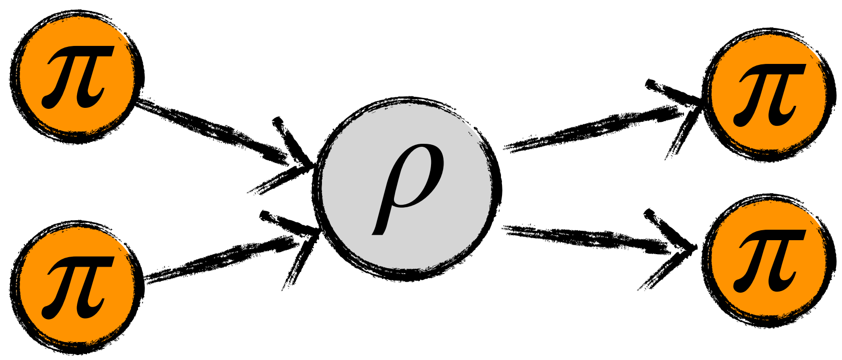
[I. Danilkin, talk at INT workshop, March 23]

+ data from Babar, Belle, COMPASS, …

Why multiparticle amplitudes?

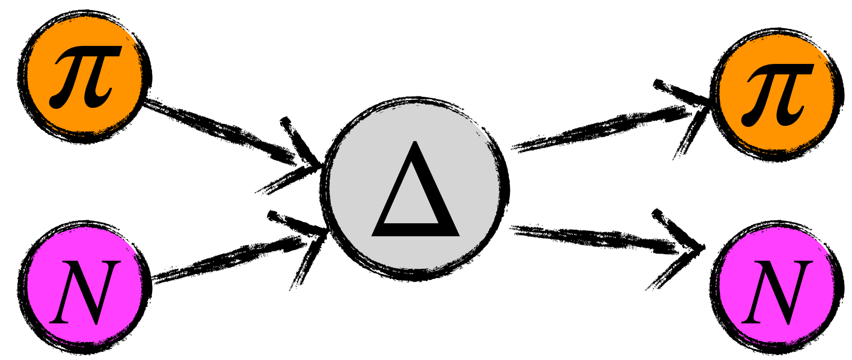
- Calculate properties of strong interaction resonances
  - E.g. exotics such as $T_{cc}(3875)^+ \to DD^* \to DD\pi$
- Determine three particle "forces" for $3n,\ 3\pi,\ 3K, \ldots$
  - Needed for neutron star EoS, properties of large nuclei, …
- Calculate multiparticle weak decay amplitudes
  - $K \to 3\pi$ (method known), & $D \to \pi^+\pi^-,\ K^+K^-$ (open question)

Present status



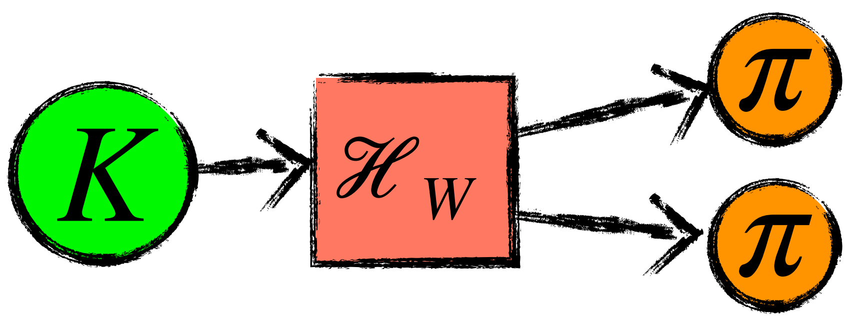
Physical quark masses

E.g.: Wang, Leinweber, Liu, Liu, Sun, Thomas, Wu, Xing, Yu, 2502.03700



$M_\pi = 200$ MeV

Bulava, Hanlon, Hörz, Morningstar, Nicholson, Romero-López, Skinner, Varnas, Walker-Loud, 2208.03867

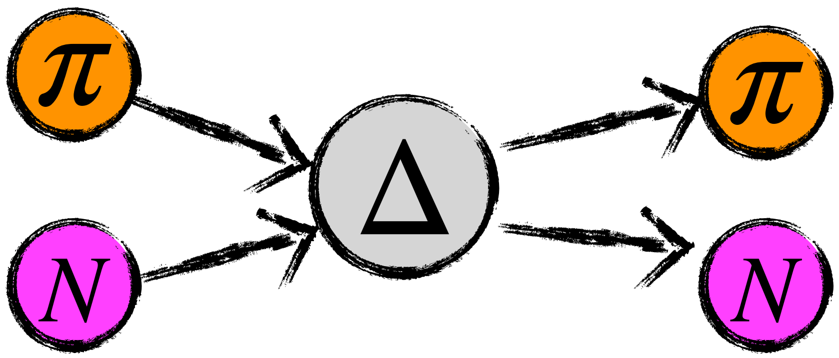


“FLAG-ready”, i.e. fully controlled

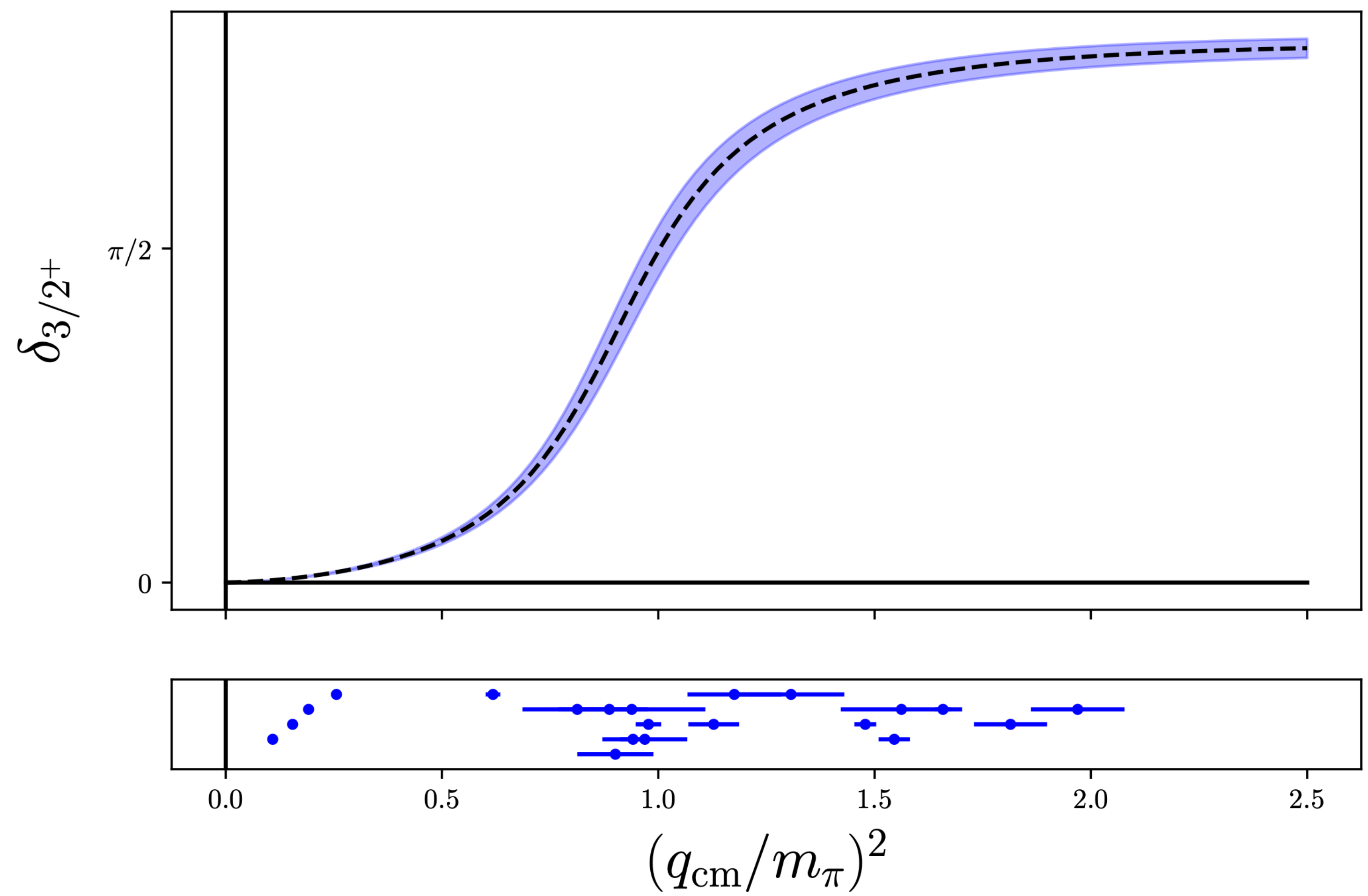
Abbott et al. [RBC-UKQCD collaboration], 2004.09440

Δ resonance

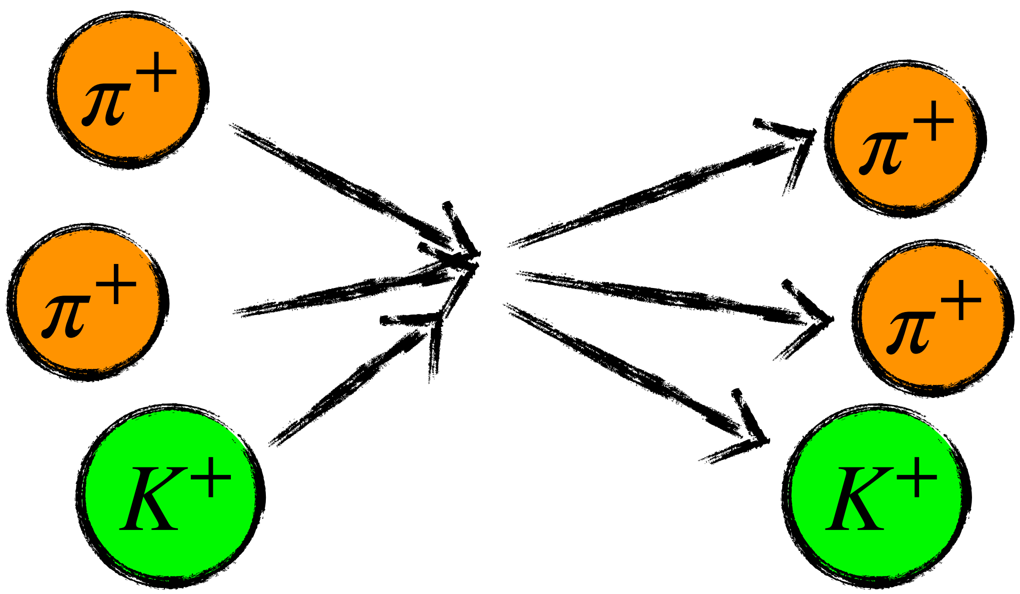
Bulava, Hanlon, Hörz, Morningstar, Nicholson, Romero-López, Skinner, Varnas, Walker-Loud, 2208.03867



$M_\pi \approx 200$ MeV
$M_N \approx 950$ MeV
$a = 0.063$ fm
$L^3 \times T = 64^3 \times 128$
Clover fermions (CLS)

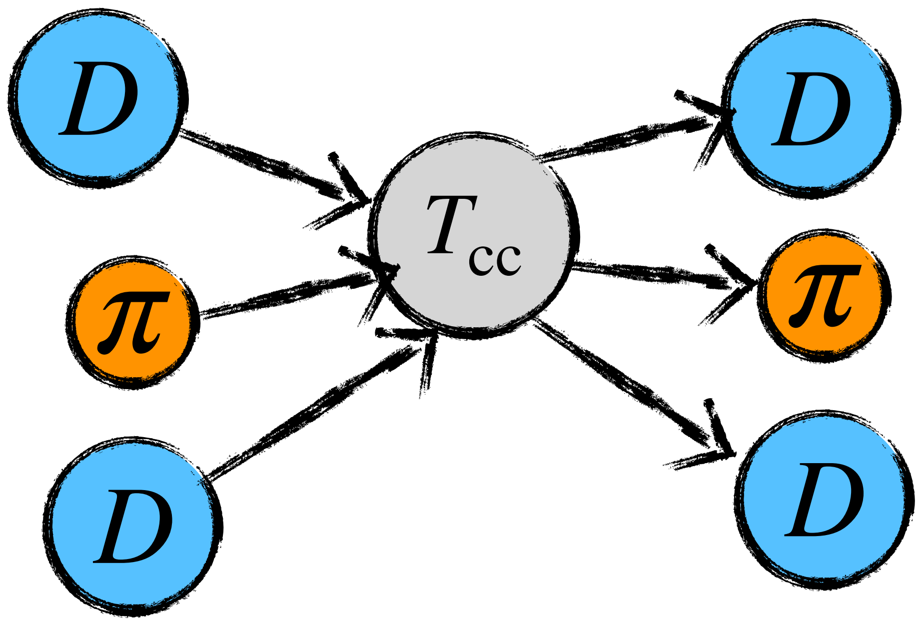


Present frontier



Physical quark masses

Dawid, Draper, Hanlon, Hörz, Morningstar, Romero-López, SRS, Skinner, 2502.14348 & 2502.17976

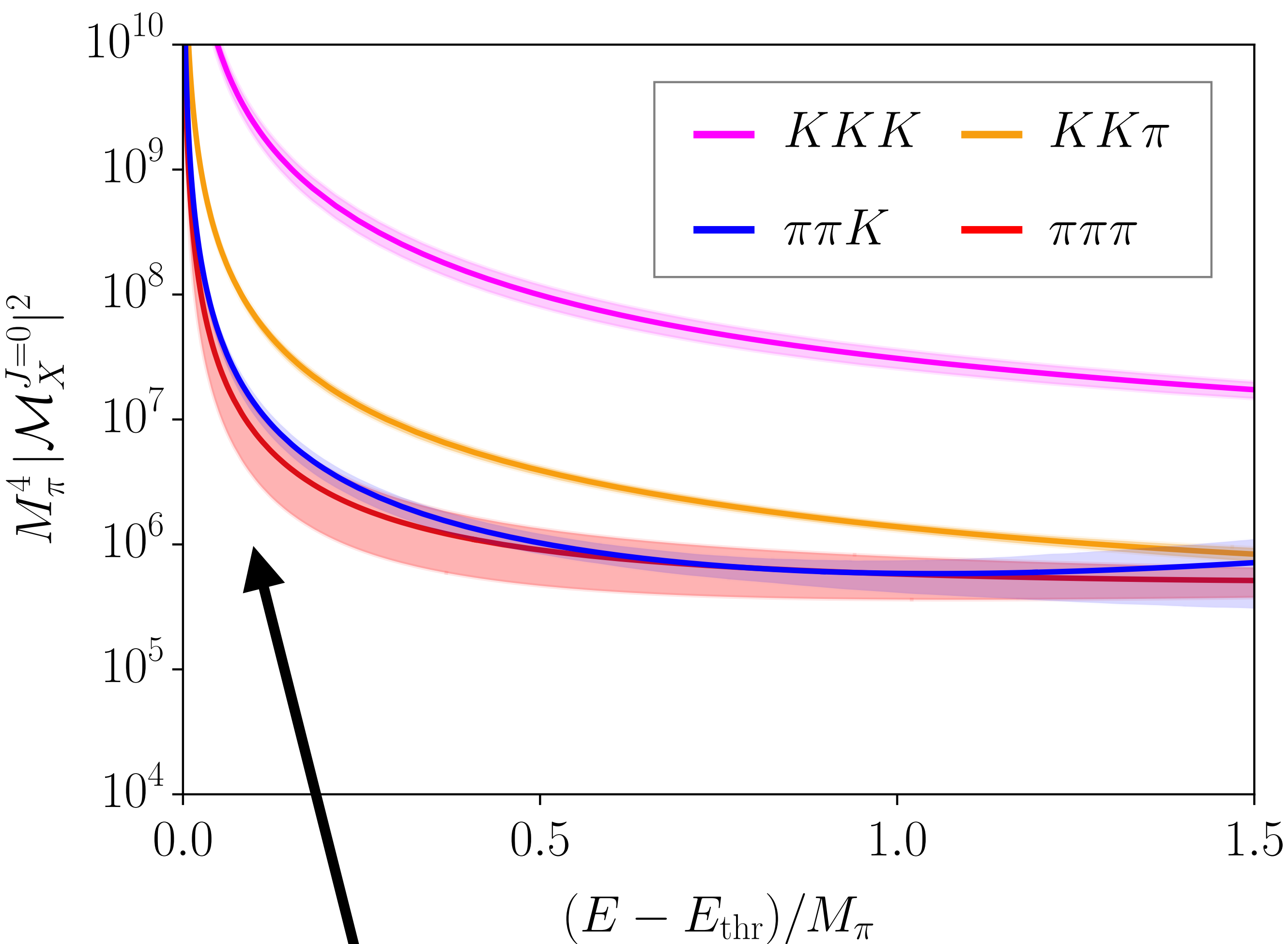


$M_\pi = 200$ MeV

Padmanath, Prelovsek, 2202.10110
…
Dawid, Romero-López, SRS, 2409.17059

3-meson amplitudes

$M_\pi^4|\text{Amplitude}|^2 \quad (J^P = 0^-)$

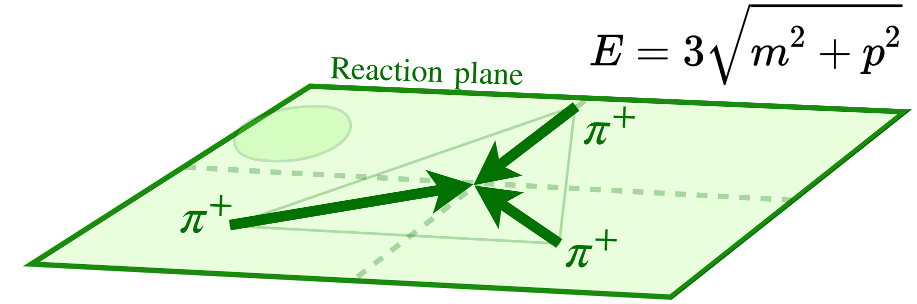


$m_\pi = 130\,\text{MeV},\ m_K = 500\,\text{MeV}$

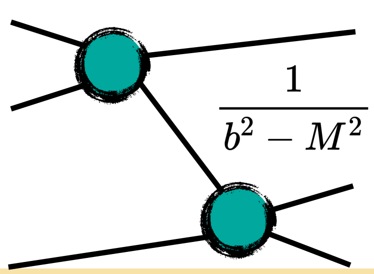
Lattice spacing $a = 0.063\,\text{fm}$

Lattice size $96^3 \times 192$

Equilateral kinematic configuration

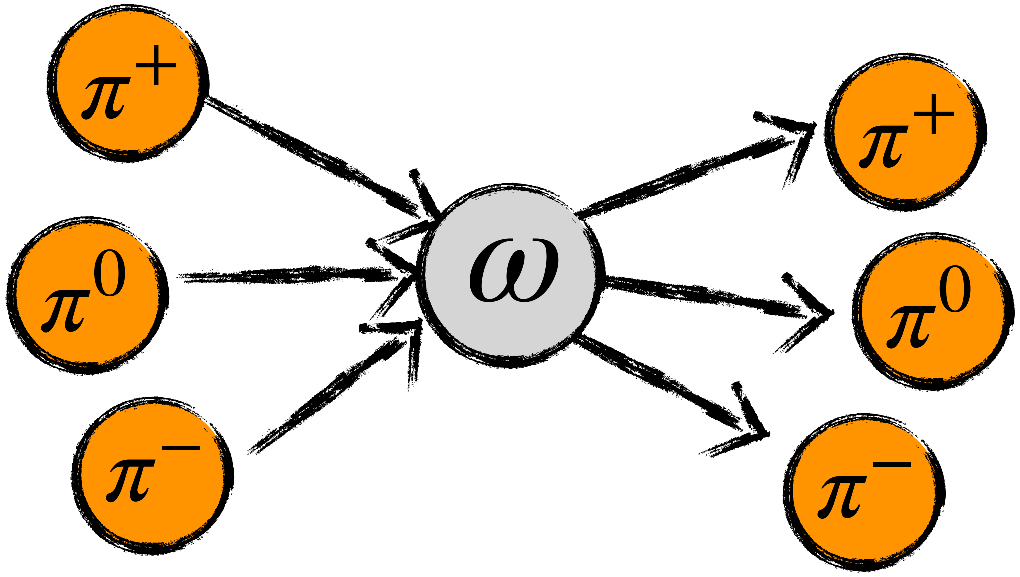


Divergent at threshold

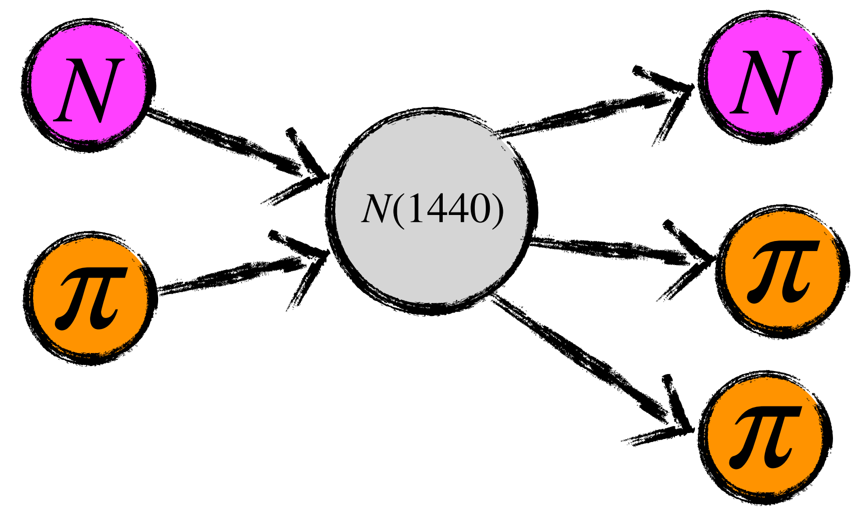


Dawid, Draper, Hanlon, Hörz, Morningstar, Romero-López, SRS, & Skinner, 2502.14348 & 2502.17976

Near future

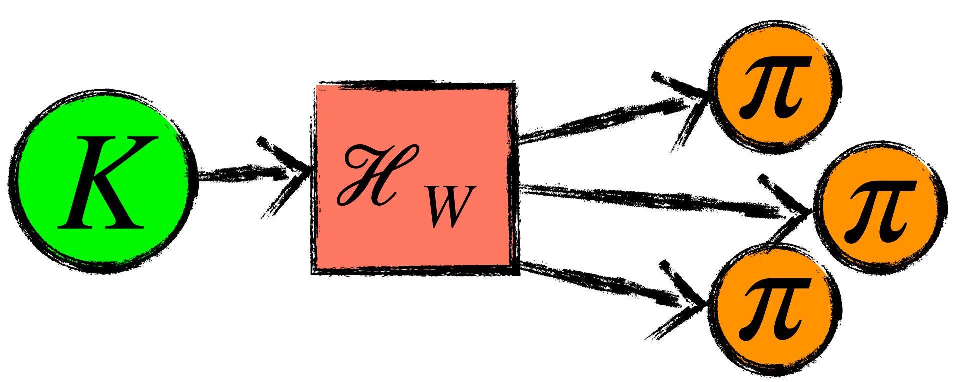


Formalism: Hansen, Romero-López, SRS, 2003.10974
First LQCD results and alternative formalism:
Yan, Mai, Garofalo, Meißner, Liu, Liu, Urbach, 2407.16659

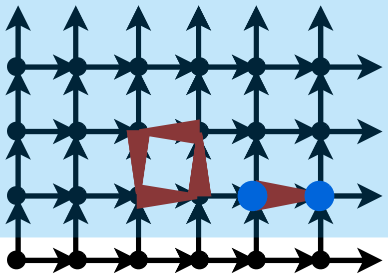


Roper resonance

Formalism: Briceño, Dawid, Hansen, Jackura, Romero-López, Smith, SRS, in prep.



Formalism: Hansen, Romero-López, SRS, 2101.10246



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Summary

- Lattice QCD provides precise results for a large number of quantities, with complete error budgets
    - It plays a crucial role in the interpretation of an increasing number of experiments looking for new physics at the "intensity frontier"

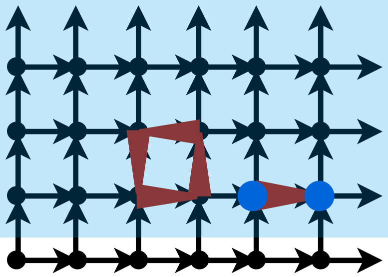
Connection to experiments

- FNAL & JPARC $(g-2)_\mu$—HVP & LBL
- LHCb & BELLE II—Exclusive & inclusive matrix elements
- Neutrino experiments (DUNE, …)—axial form factors
- Rare kaon decay experiments (JPARC, CERN)—matrix elements
- Dark Matter searches (SCDMS,…)—scalar form factors,…
- Heavy Ion colliders (Alice@LHC, BNL)—phase diagram, …
- Higgs factory—precise quark masses, α_s
- …

Summary

- Lattice QCD provides precise results for a large number of quantities, with complete error budgets
  - It plays a crucial role in the interpretation of an increasing number of experim… looking for new physics at th… r"
- Many ne… …ment that will significan… …quantities that can be reliably calculated over the next 5-10 years
  - If quantum computers fulfill their promise, many further extensions will be possible, e.g. to real-time quantities

The future of LQCD is very bright!



Thank you!
Questions?