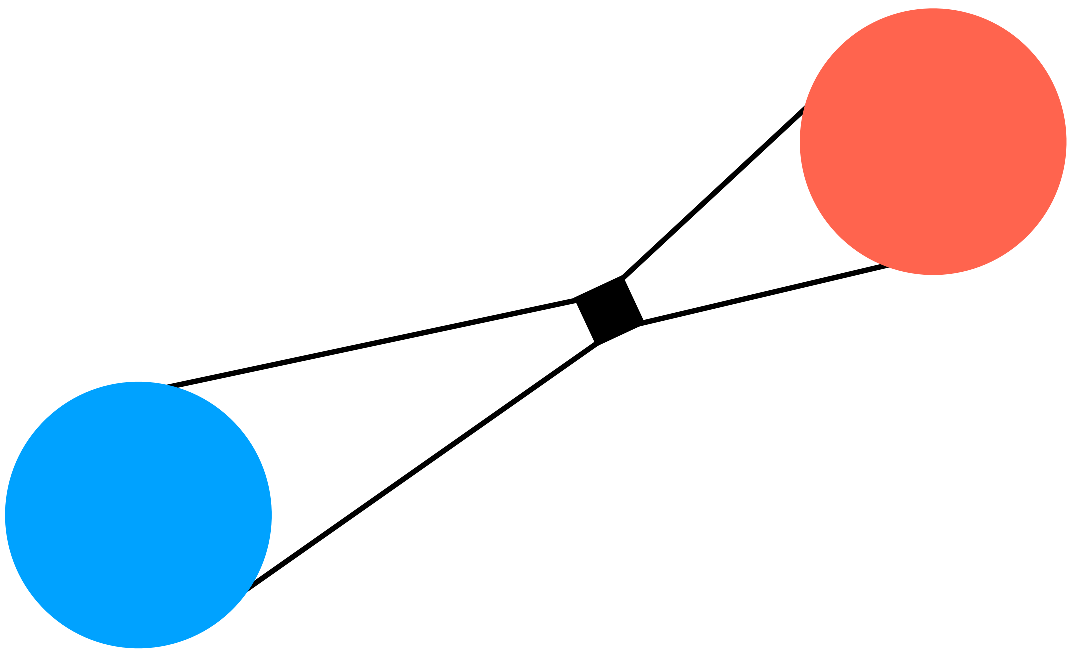
Short-distance hadronic contributions to *D*-meson mixing from Lattice QCD



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Lawrence Berkeley National Laboratory

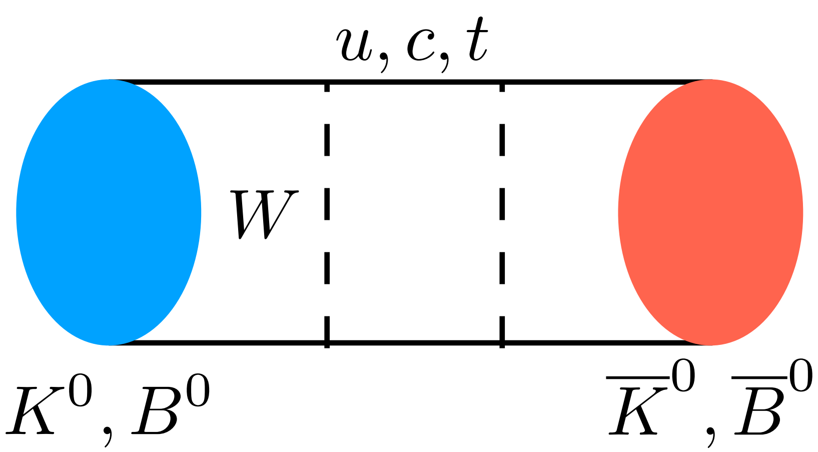
on behalf of the Fermilab/MILC collaborations

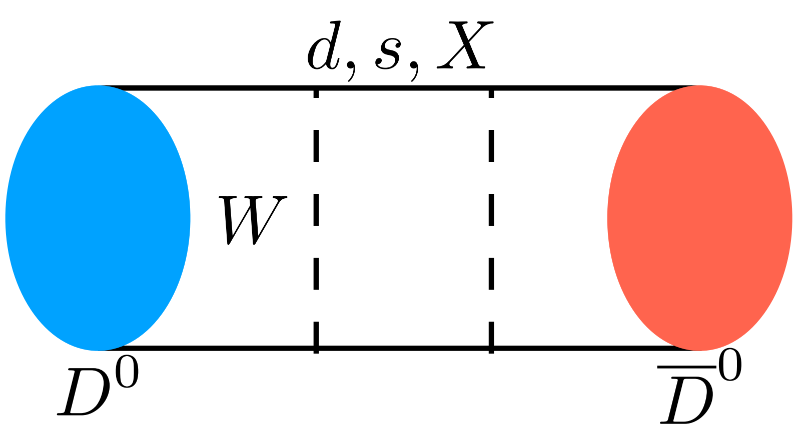
CHARM 2018, BINP Novosibirsk

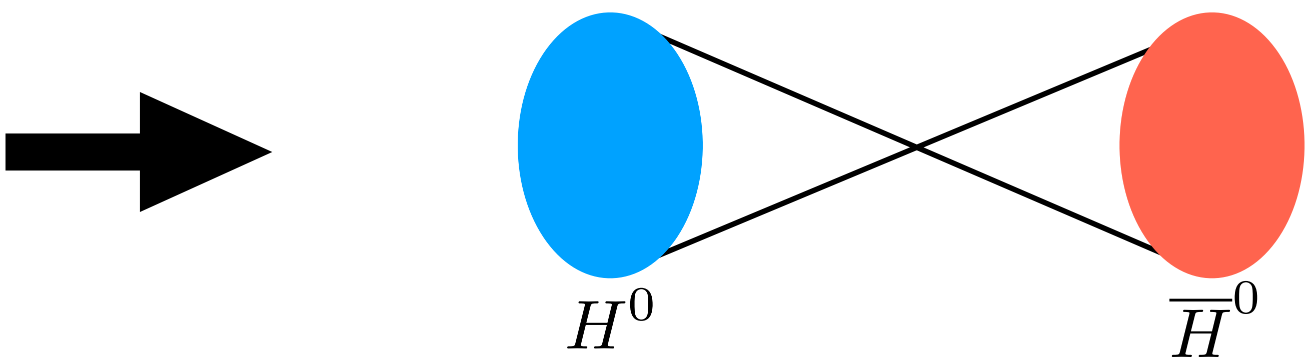
Probing new physics with mixing

Neutral meson mixing is tree-level suppressed in the Standard Model

Sensitive to Beyond Standard Model heavy degrees of freedom







Mixing through up-type quarks

Kaon mixing successfully predicted charm-quark mass

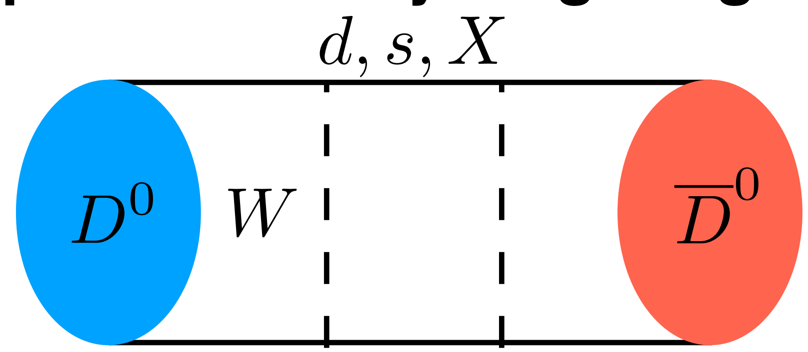
B-meson mixing inferred top-quark mass

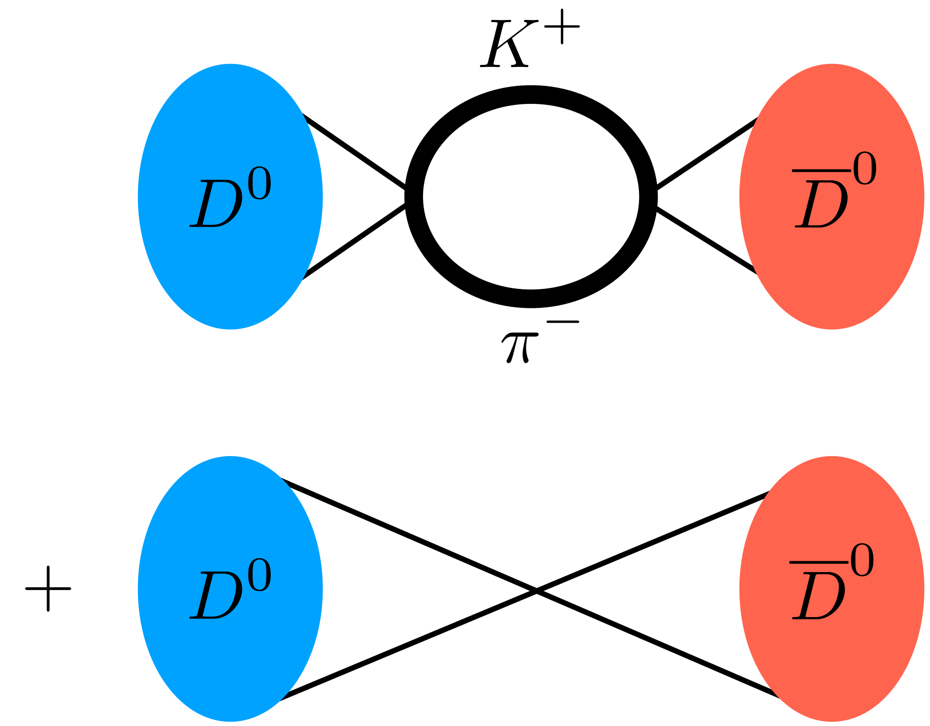
and through down-type quarks

D-meson mixing as window to new physics?

D-meson mixing constraints on NP

Standard Model D-meson mixing is predominantly long-ranged





Unfortunately a large number of multi-particle intermediate states makes long-distance hard.

Fortunately New Physics is only short-distance.

Lorentz invariant 4-quark operators

Same operators as *K* and *B*-meson mixing, and $\pi^+ \to \pi^-$ transition that enters short-range 0vbb [1805.02634].

$$\mathcal{O}_1 = (\bar{c}\gamma_\mu L u)[\bar{c}\gamma_\mu L u]$$
$$\mathcal{O}_2 = (\bar{c} L u)[\bar{c} L u]$$
$$\mathcal{O}_3 = (\bar{c} L u][\bar{c} L u)$$
$$\mathcal{O}_4 = (\bar{c} L u)[\bar{c} R u]$$
$$\mathcal{O}_5 = (\bar{c} L u][\bar{c} R u)$$

New Physics bound

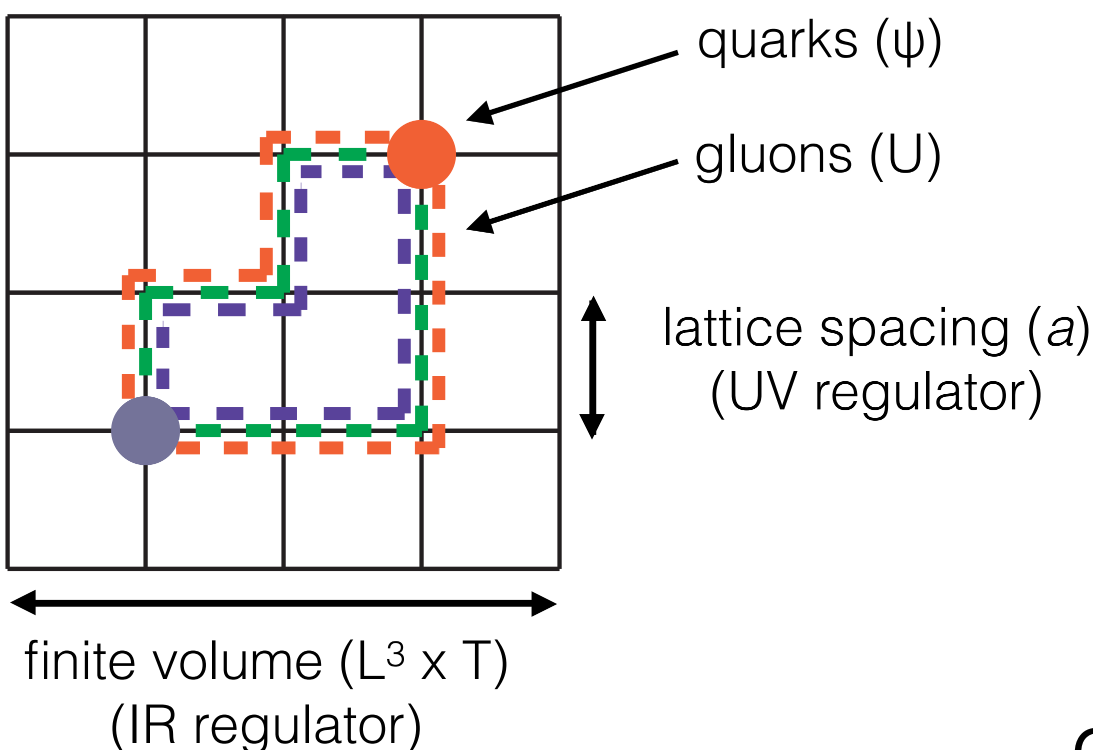
The intersection of theory and experiment provides bound of New Physics

$$x_{12}^{\mathrm{NP}} = \frac{1}{M_D \Gamma_D} \sum_i C_i^{\mathrm{NP}}(\mu) \langle \mathcal{O}_i \rangle (\mu)$$

experiment　　perturb. NP　　LQCD

Introduction to Lattice QCD

Lattice QCD is QCD with non-perturbative (lattice) regularization
Allows for first-principles approach to calculating hadronic observables



Evaluate Feynman path integral on the lattice
Wick rotate so domain of integration is finite

$$\langle \mathcal{A} \rangle = \frac{1}{\mathcal{Z}} \int [d\psi][d\bar{\psi}][dU] \mathcal{A} e^{-S[\bar{\psi},\psi,U]}$$
$$= \frac{1}{\mathcal{Z}} \int [dU] \det\left(\not{D} + m\right) e^{-S[U]} \mathcal{A}$$

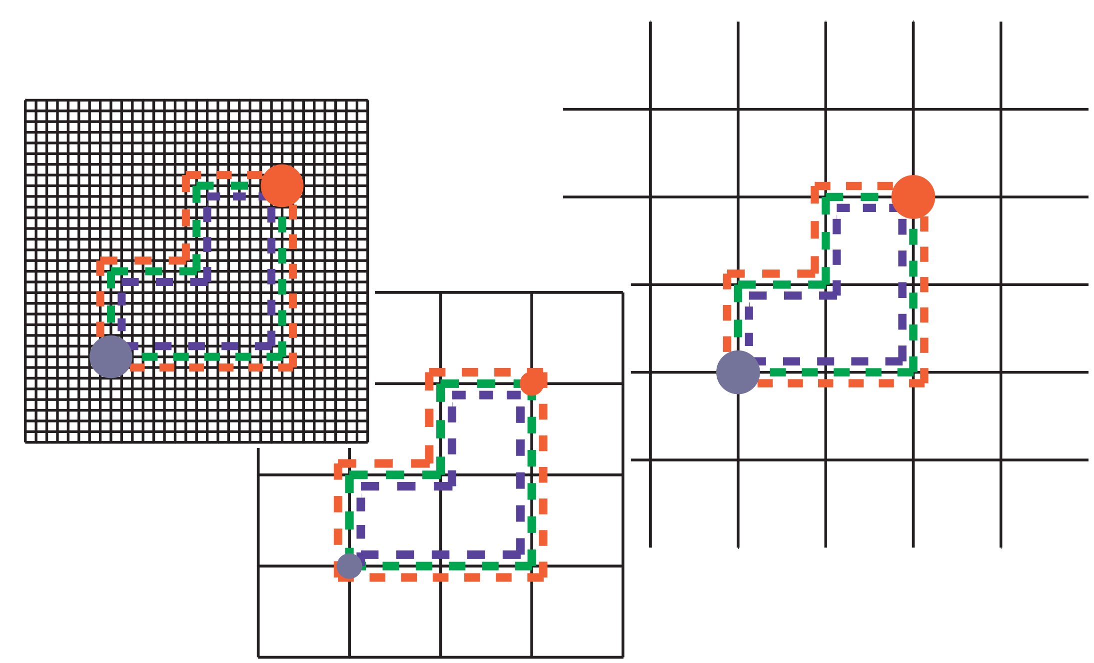
Importance sample gauge field ~ $e^{-S[U] - \ln\det \not{D}}$

Observables from simple average $\langle \mathcal{A} \rangle \approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{A}[U_i]$

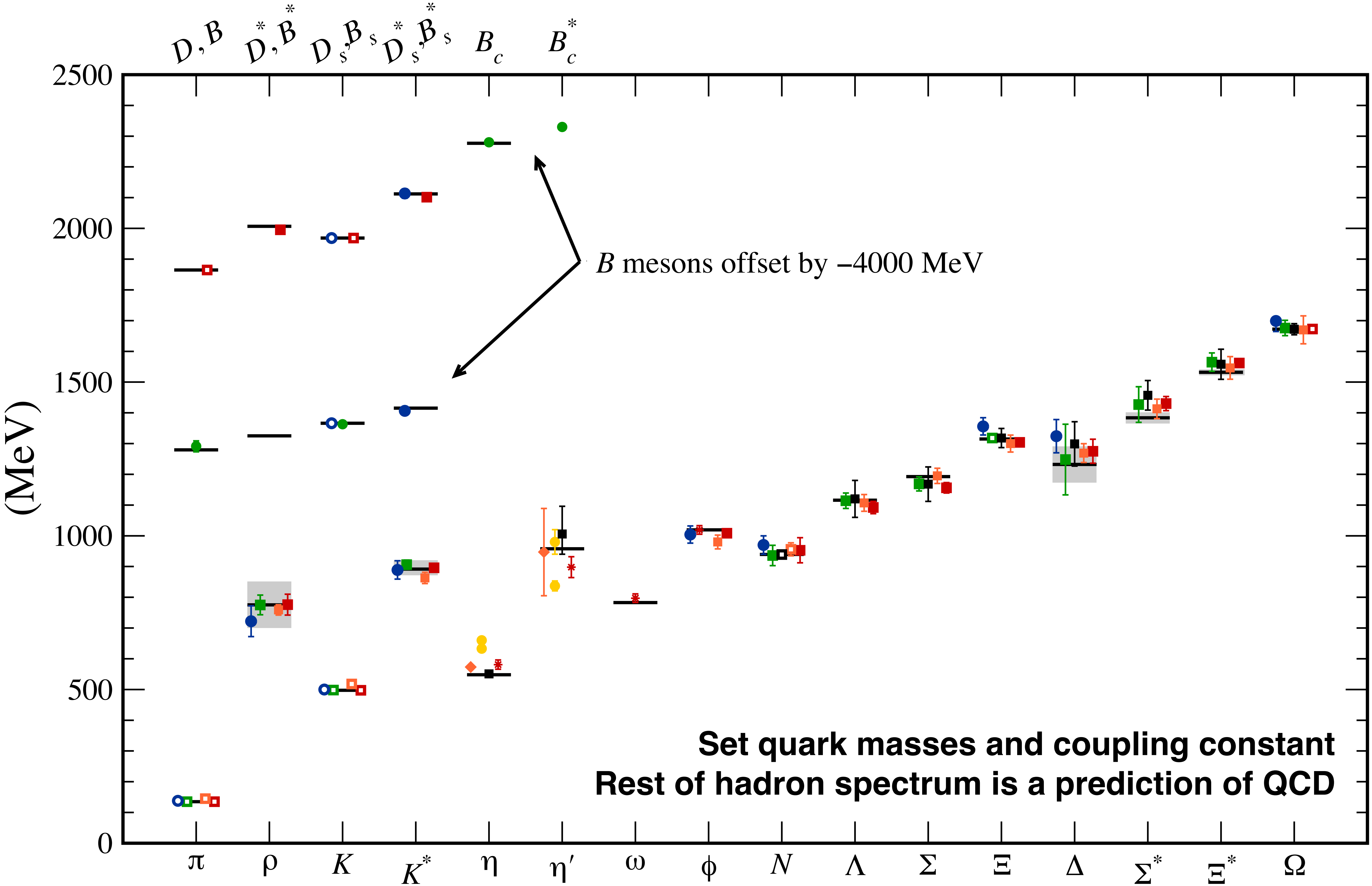
Major lattice uncertainties and related issues

- continuum limit $t_{\mathrm{comp.}} \propto 1/a^6$
- infinite volume $t_{\mathrm{comp.}} \propto V^{5/4}$
- light pion mass

exponentially bad
- condition number
- signal-to-noise



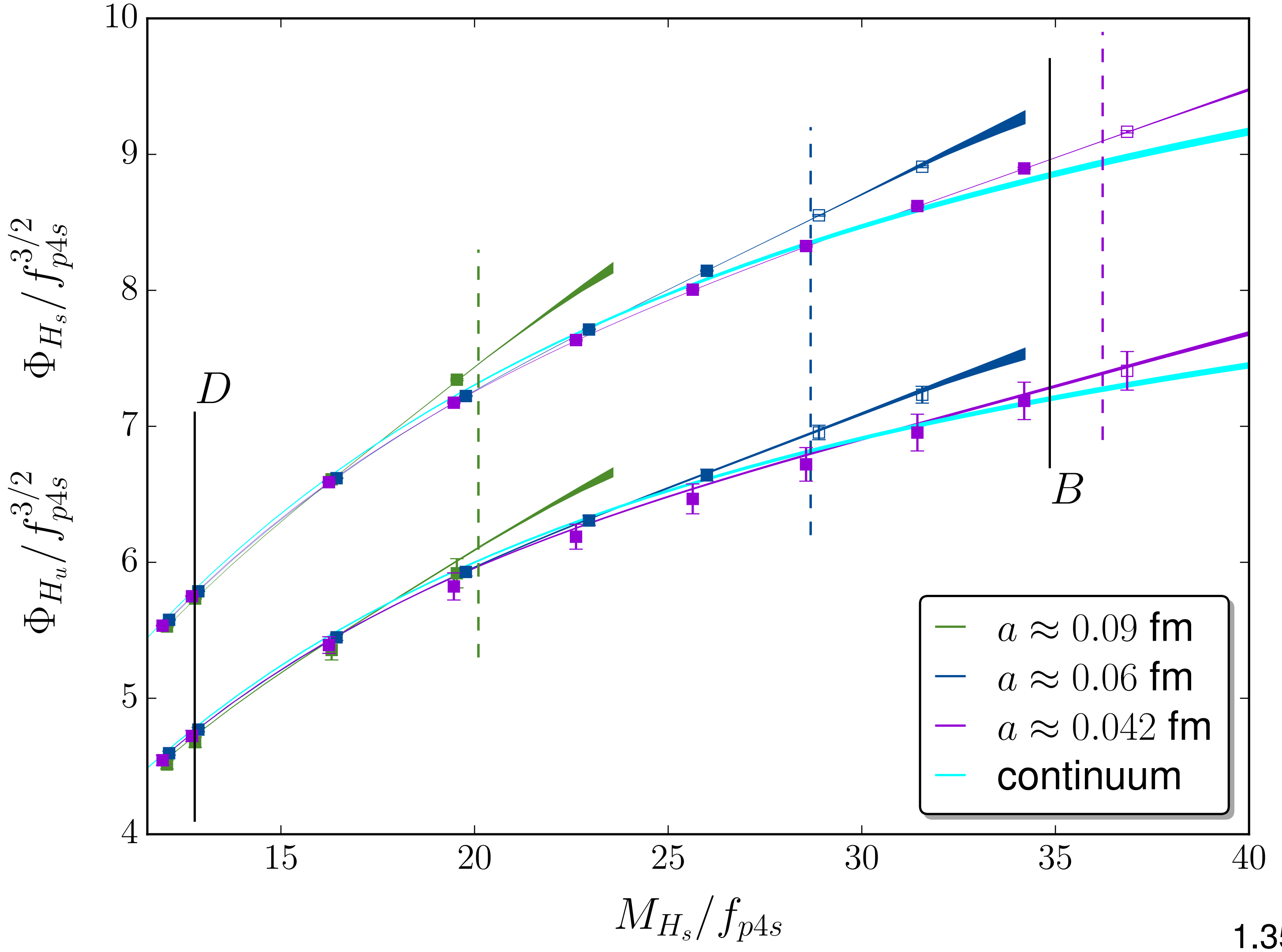
Hadron spectroscopy on the Lattice



Set quark masses and coupling constant
Rest of hadron spectrum is a prediction of QCD

updated of plot in [hep-lat/1203.1204]

Precision structure calculations



Sub-percent precision for heavy-light meson structure calculations

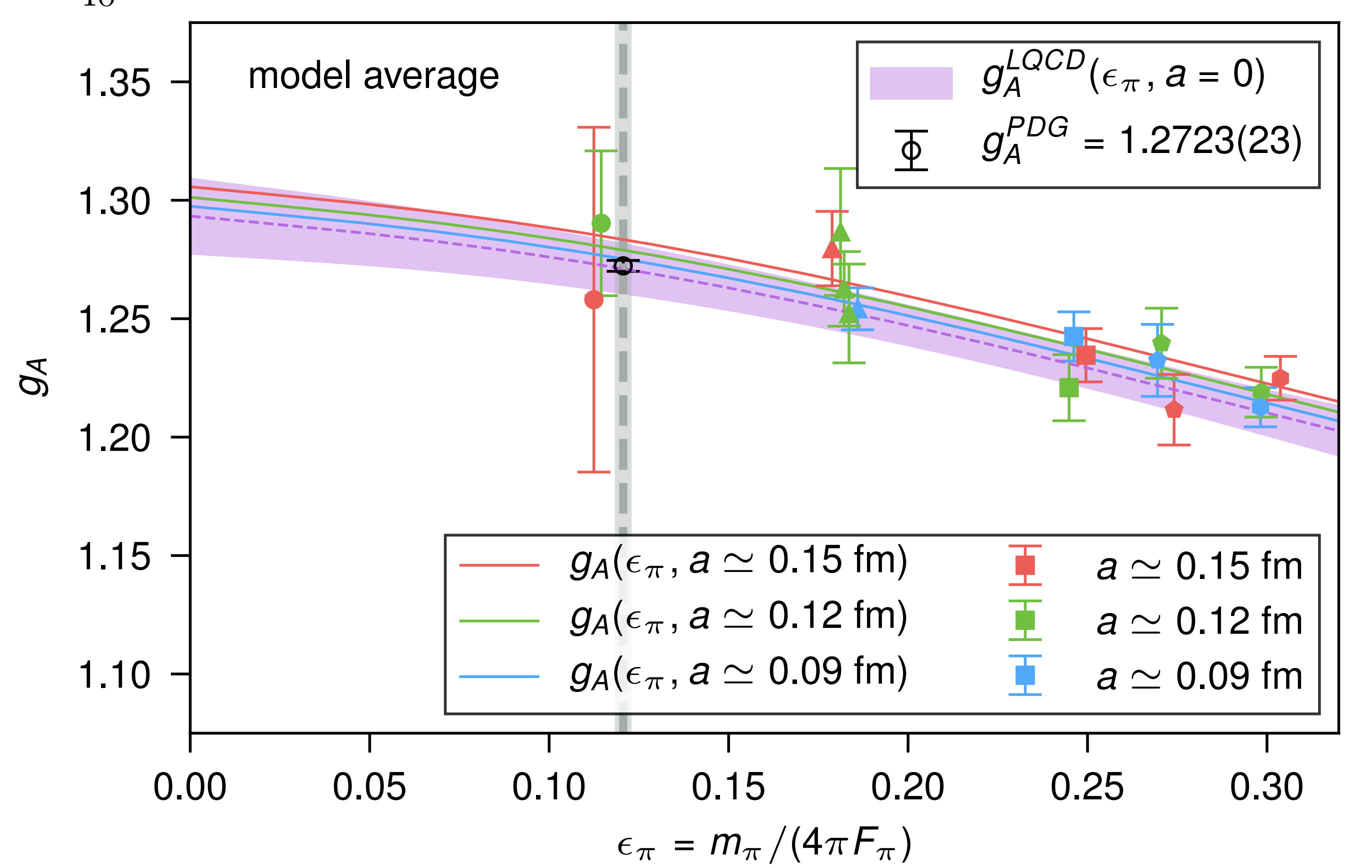
Example here is the *D*, *Ds*, *B*, and *Bs* decay constants from the Fermilab/MILC collaboration.

[1712.09262]

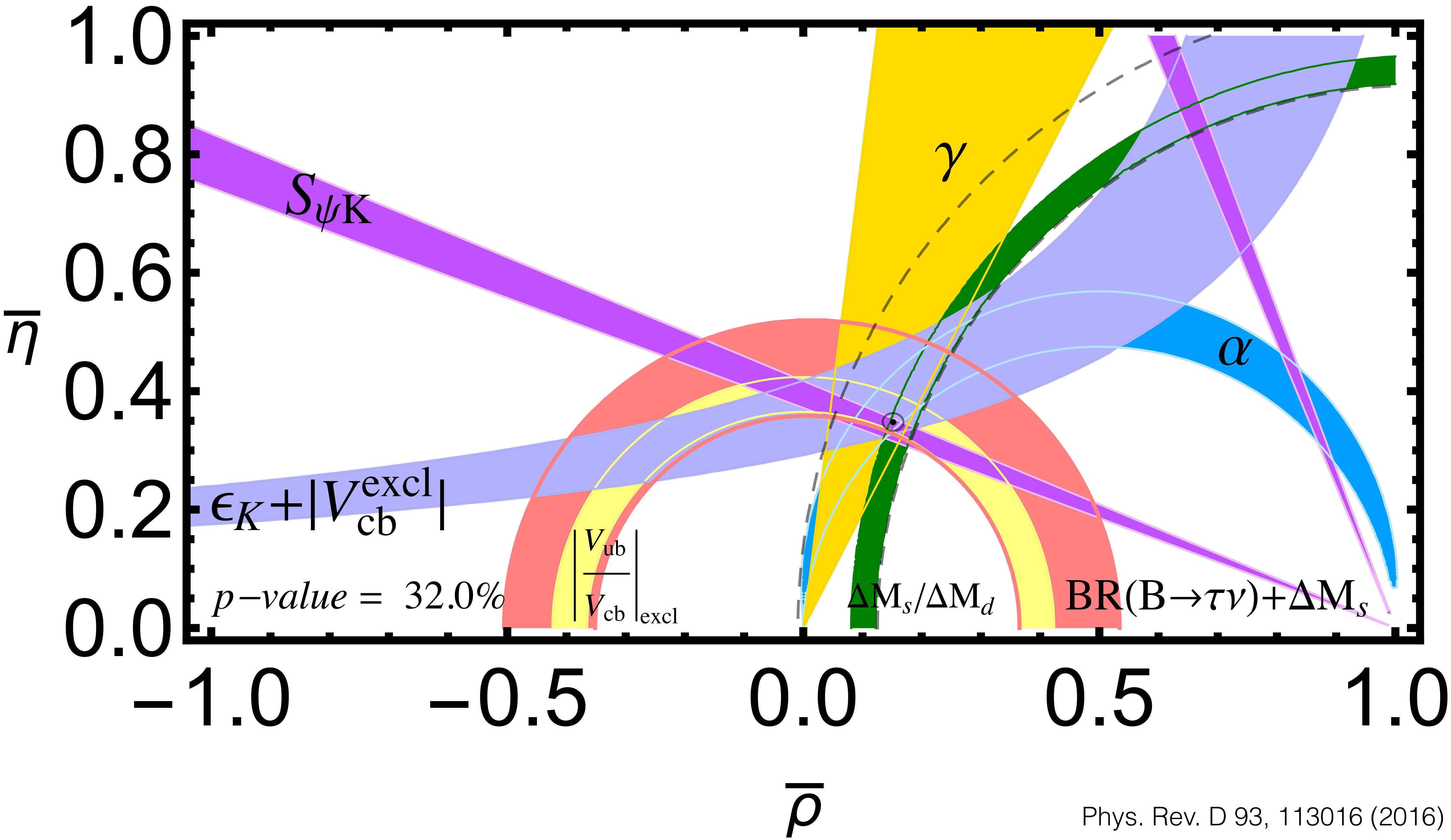
Lattice QCD is increasingly effective at precision calculations of more diverse observables.

Example here is the weak axial coupling of the nucleon determined to 1% precision.

Tentative publication date
May 30 2018 6pm London time



CKM triangle parameterization



Phys. Rev. D 93, 113016 (2016)

Precise *B*-meson mixing bag parameters

SU(3) breaking ratio at ~1.5% precision updating bound of CKM unitarity.

The FNAL/MILC result for *B*-meson mixing is the companion project to *D*-mixing of this talk.

Outline

Lattice corrlation functions

Renormalization and matching

The physical point extrapolation

Uncertainty budget

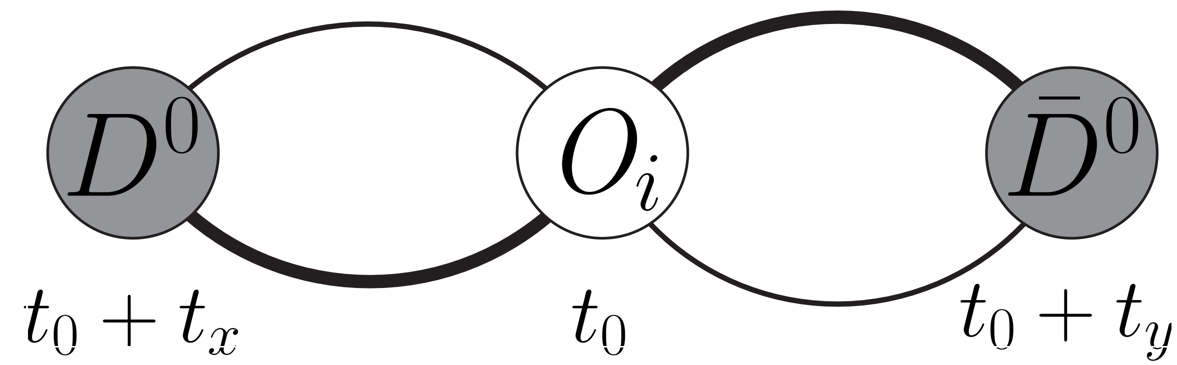
Implications of New Physics

Fermilab

Calculating observables on the lattice

Lattice correlation functions

Extracting the *D*-meson spectrum



$$D^\dagger(\mathbf{x}, t) \sim \bar{u}(\mathbf{x}, t)\gamma_5 c(\mathbf{x}, t)$$

$$O_i(\mathbf{0}, t_0) \sim \bar{c}(\mathbf{0}, t_0)\Gamma u(\mathbf{0}, t_0)\bar{c}(\mathbf{0}, t_0)\Gamma' u(\mathbf{0}, t_0)$$

$$C(t - t_0) = \sum_{\mathbf{x}} \langle D(\mathbf{x}, t) D^\dagger(\mathbf{0}, t_0)\rangle$$

and the matrix elements

$$C_{O_i}(t_x, t_y) = \sum_{\mathbf{x},\mathbf{y}} \langle D^\dagger(\mathbf{y}, t_0 + t_y)\, O(\mathbf{0}, t_0) D^\dagger(\mathbf{x}, t_0 + t_x)\rangle$$

Spectral decomposition

to extract the *D*-meson spectrum

$$C(t) \sim \sum_n |Z_n|^2 e^{-E_n t}$$

and the matrix elements

$$C_{O_i}(t_x, t_y) \sim \sum_{m,n} Z_n \mathcal{Z}^{O_i}_{nm} Z^\dagger_m e^{-E_n|t_x|} e^{-E_m t_y}$$

- Set $t_0 = 0$ without loss of generality
- The equations are (approximately) correct up to various lattice artifacts

Bayesian inference

Bayes Theorem

$$P(A|\text{data}) \propto P(\text{data}|A)P(A)$$

Likelihood and prior are Gaussian as a result of the *central limit theorem*

path integral average

$$P(A|\text{data}) \propto e^{-\chi^2_{\text{data}}} e^{-\chi^2_{\text{prior}}}$$

where

$$\chi^2 = \left(\frac{C^{\text{fit}} - C^{\text{data}}}{\sigma_{\text{data}}}\right)^2 + \left(\frac{A_i - \bar{A}_i}{\sigma_{A_i}}\right)^2$$

Fit strategy

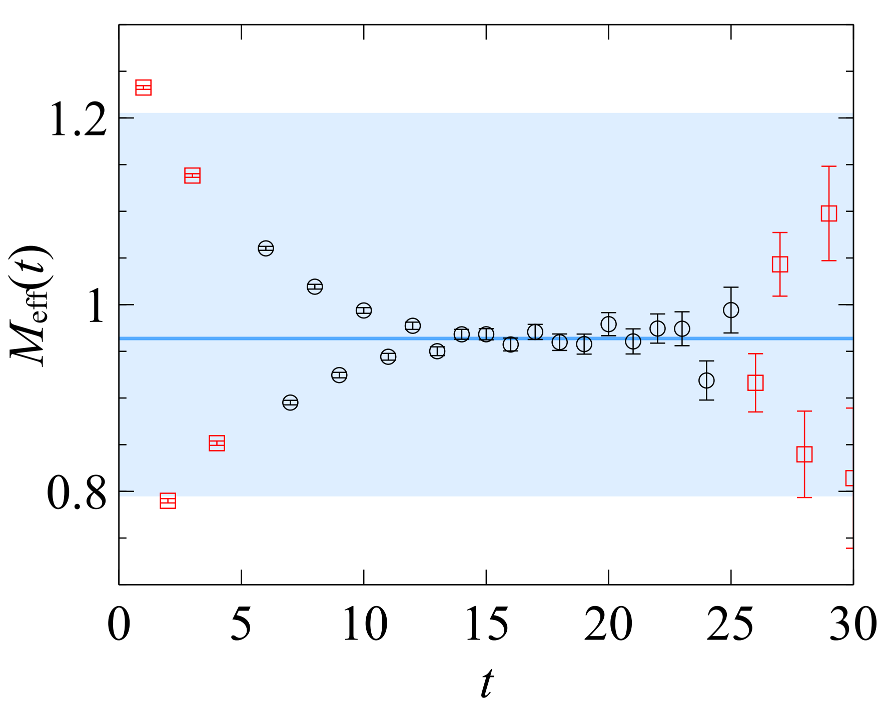
- Constrained curve fitting
- Simultaneously fit to 2 and 3pt correlator
- Loss function includes correlations

Gaussian distribution allows shortcuts

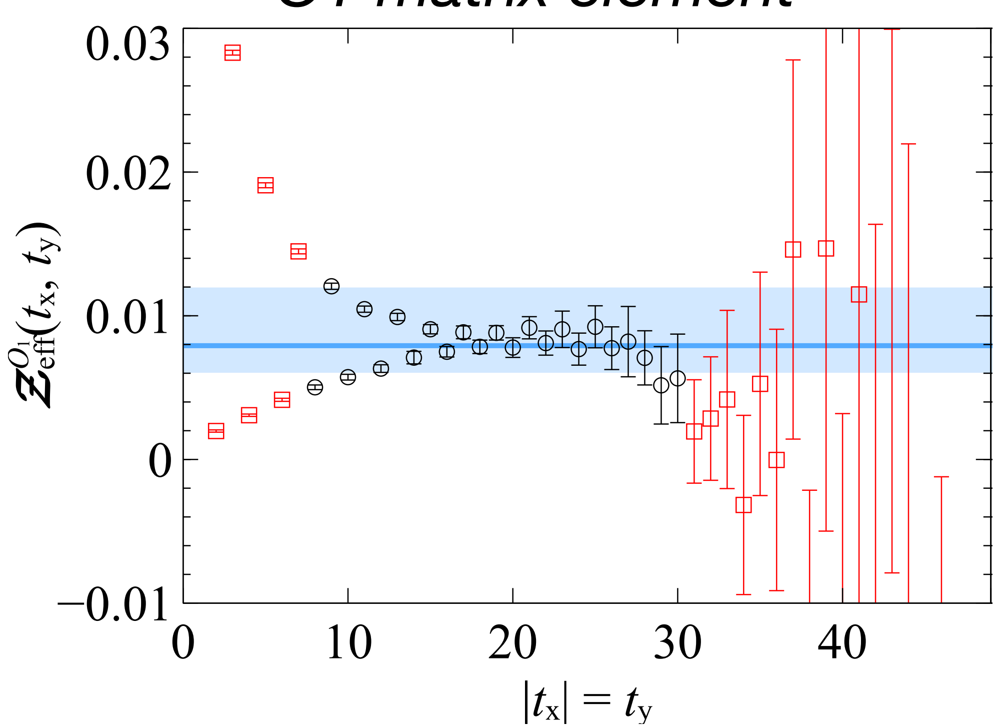
Perform maximum likelihood regression.
Bootstrap to obtain posterior distribution.
Circumvents MC'ing Bayes Theorem.

Examples

D-meson mass



O1 matrix element



Fit over **black** data pts.

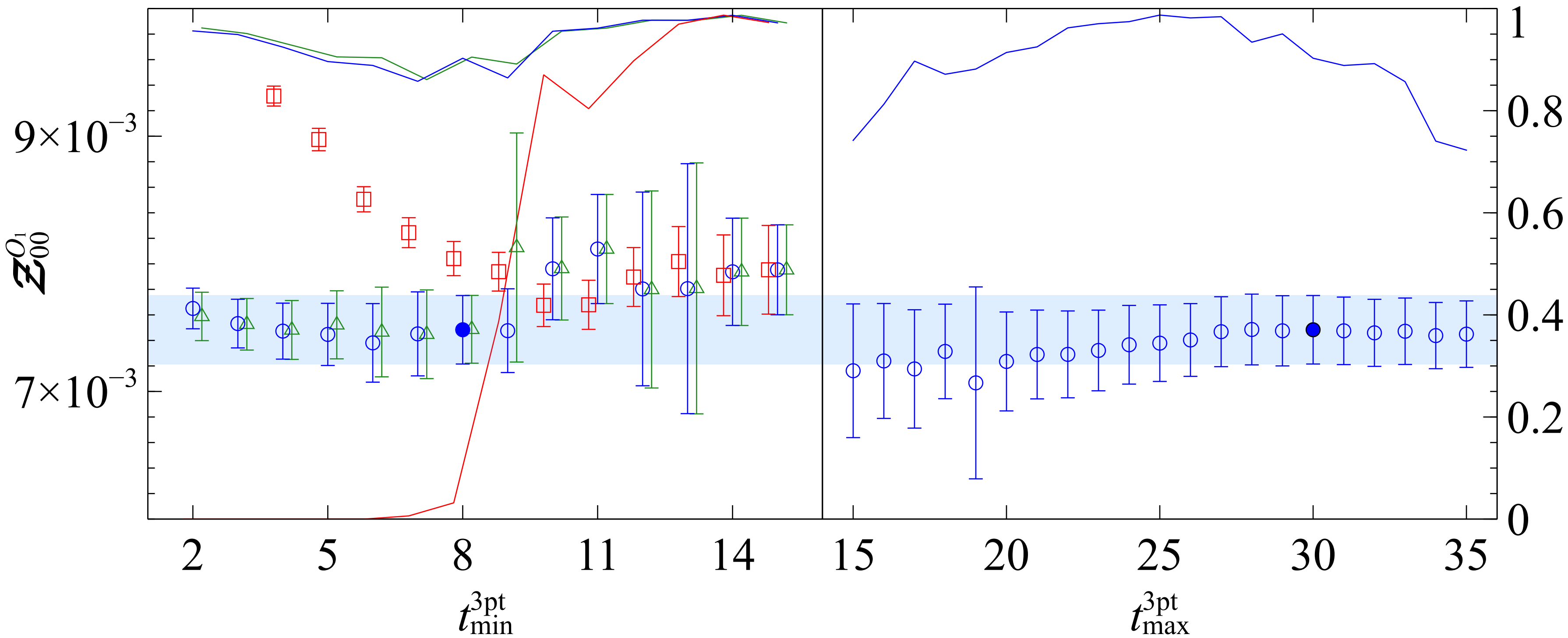
Ground state prior width in blue.

Ground state posterior in dark blue.

Ground state priors are unconstraining.

Sensitivity analysis

t_{min} and t_{max} stability plots



matrix element study

1 state fit

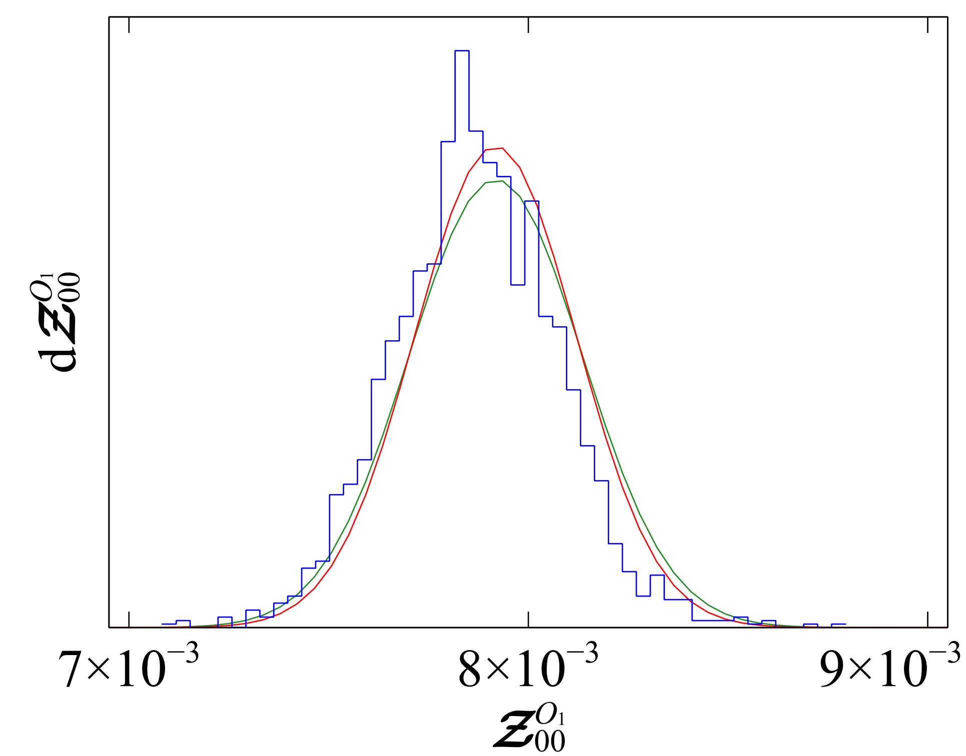
2 state fit

3 state fit

final fit t_{min}=8 t_{max}=30

lines and right axis shows (almost) the *p*-value

Bootstrap distribution



bootstrap

jackknife

naive error propagation

Imaginary time correlators decay exponentially.

$$C(t) \sim \sum_n |Z_n|^2 e^{-E_n t}$$

Excited-state contamination is exp. worse at short time.
Varying t_{min} studies excited-state systematic effects.

Large degrees-of-freedom with finite statistics lends to numerical instability.
Varying t_{max} studies statistical effects.

Bootstrap is Gaussian distributed.

Renormalization and heavy-quark mass correction

Renormalization

Discretizing QCD on the lattice non-perturbatively regulates the theory.
Renormalization sets different lattice spacings to the same scale.
Perform *mostly non-perturbative renormalization* (vertex renormalization is still perturbative).

$$Z_{ij} = Z_{V_{cc}^4} Z_{V_{ll}^4} \rho_{ij}$$

Renormalization coefficients with ρ to one-loop.

$$\rho_{ij} = \delta_{ij} + \sum_{l=1} \alpha_s^l \rho_{ij}^{[l]}(a\mu)$$

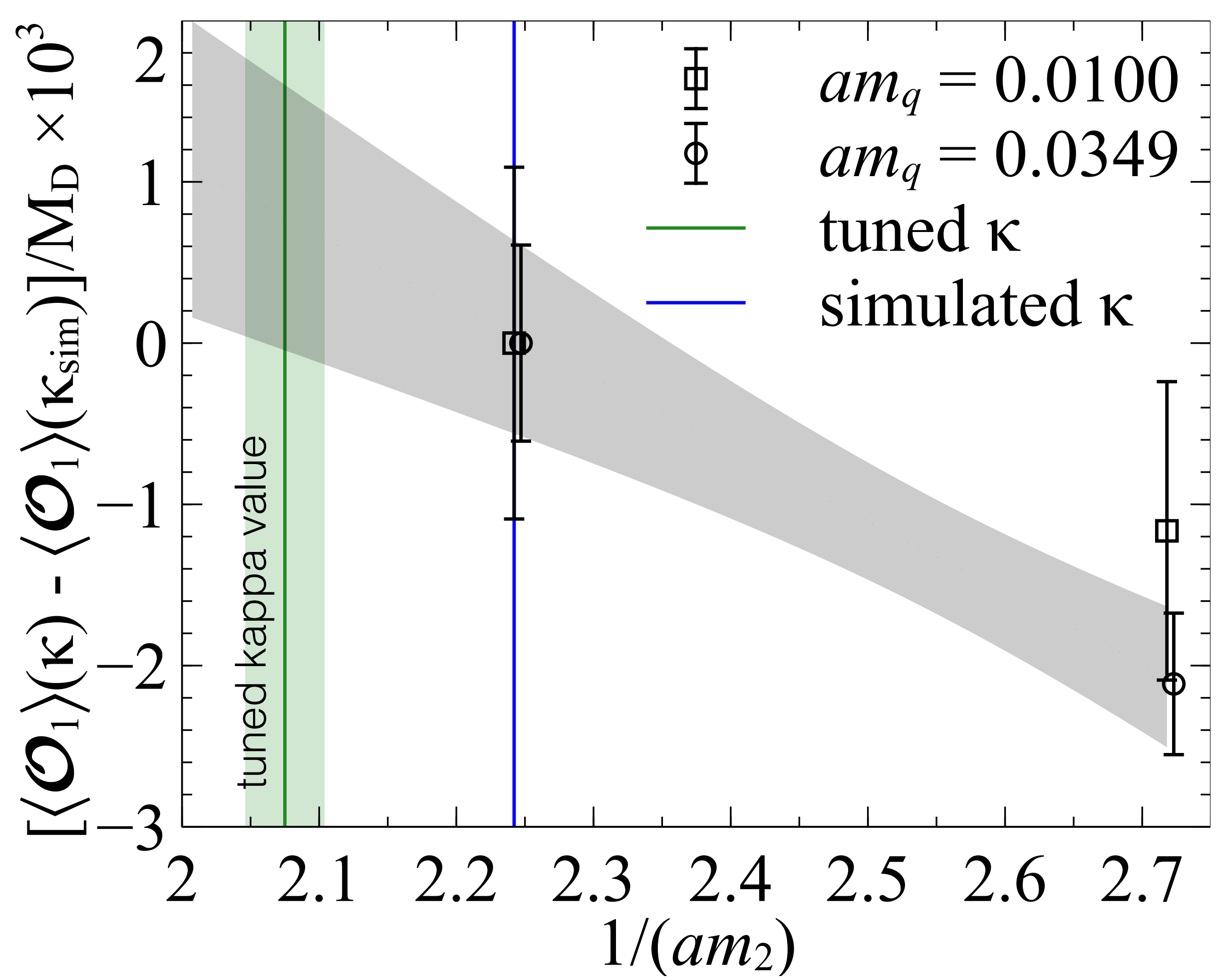
Determined for both BBGLN and BMU evanescent operators.

Heavy-quark mass correction

The input quark mass is a free parameter of QCD.

Slight mis-tunings are corrected by varying the input quark mass, and then extrapolating to the physical D_s mass.

Physical charm quark mass
Input charm quark mass
Extra charm quark mass for extrapolation
Linear extrapolation to physical mass



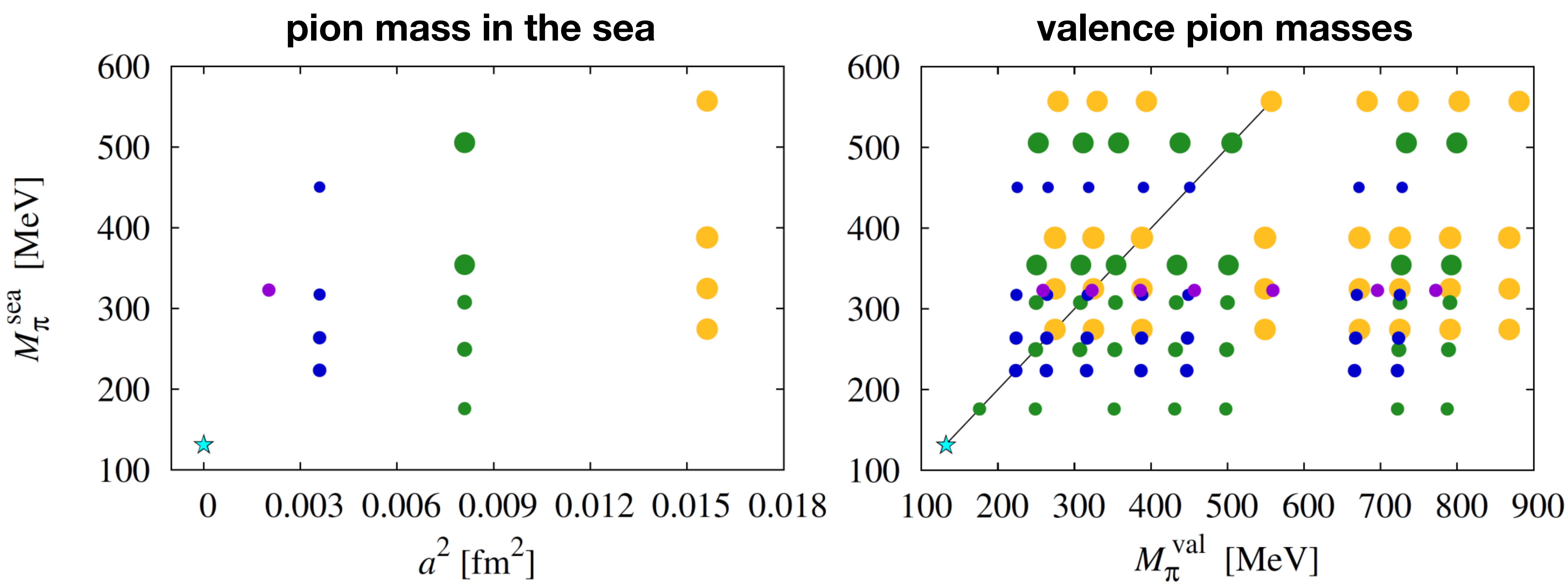
Asqtad gauge configurations and partial quenching

Lattice action details

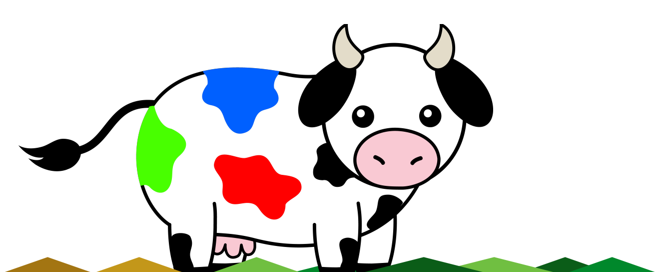
Light quark action
Asqtad staggered action
Error starting at $\mathrm{O}(\alpha_s a^2, a^4)$

Gluon action
Lüscher-Weisz action
Error starting at $\mathrm{O}(\alpha_s^2 a^2, a^4)$

Heavy-quark action
Fermilab clover action
Error starting at $\mathrm{O}(\alpha_s a, a^2)$



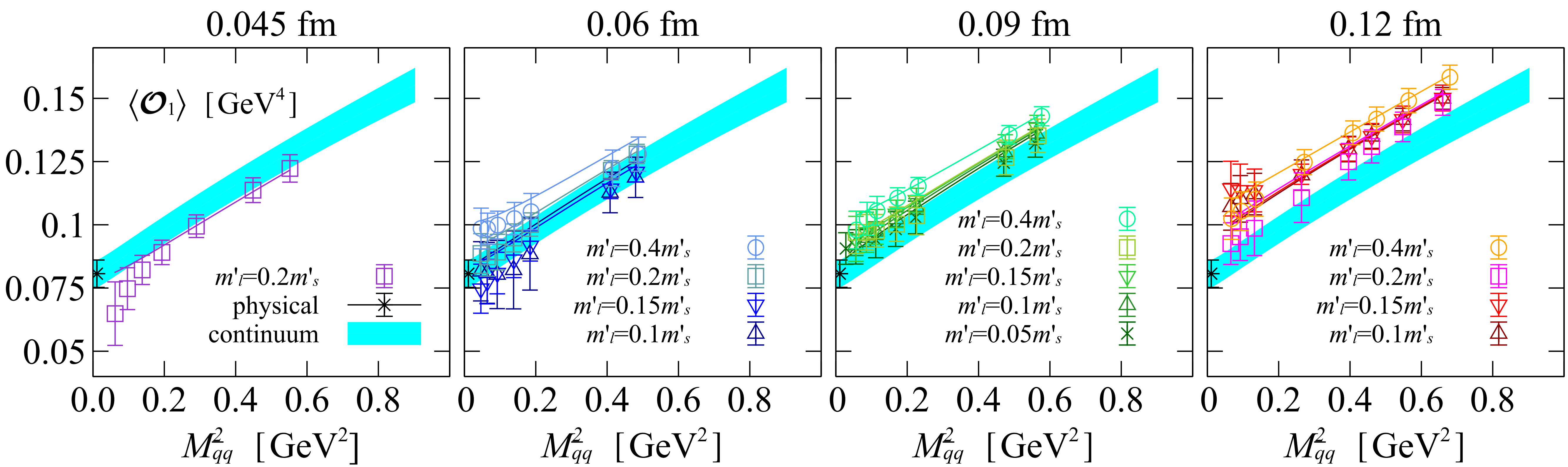
Multiple lattice spacing controls continuum extrapolation.
Large number of pion masses control pion mass extrapolation.
Physical values indicated by cyan star.



unofficial MILC cow
MILC = MIMD Lattice Computation
(the acronym has an acronym in the acronym)

Extrapolation to the physical point

Example chiral-continuum extrapolation for the Standard Model V-A operator



Cyan band is continuum QCD

Physical point given by black asterisk.

Extrapolation performed simultaneously for the five 4-quark operators (four not shown).

χ^2/d.o.f. = 122.5 / 510

SU(3) partially-quenched heavy meson rooted staggered chiral perturbation theory

$$F_i = F_i^{\text{logs.}} + F_i^{\text{analytic}} + F_i^{\text{HQdisc.}} + F_i^{\kappa} + F_i^{\text{renorm}}$$

Includes:

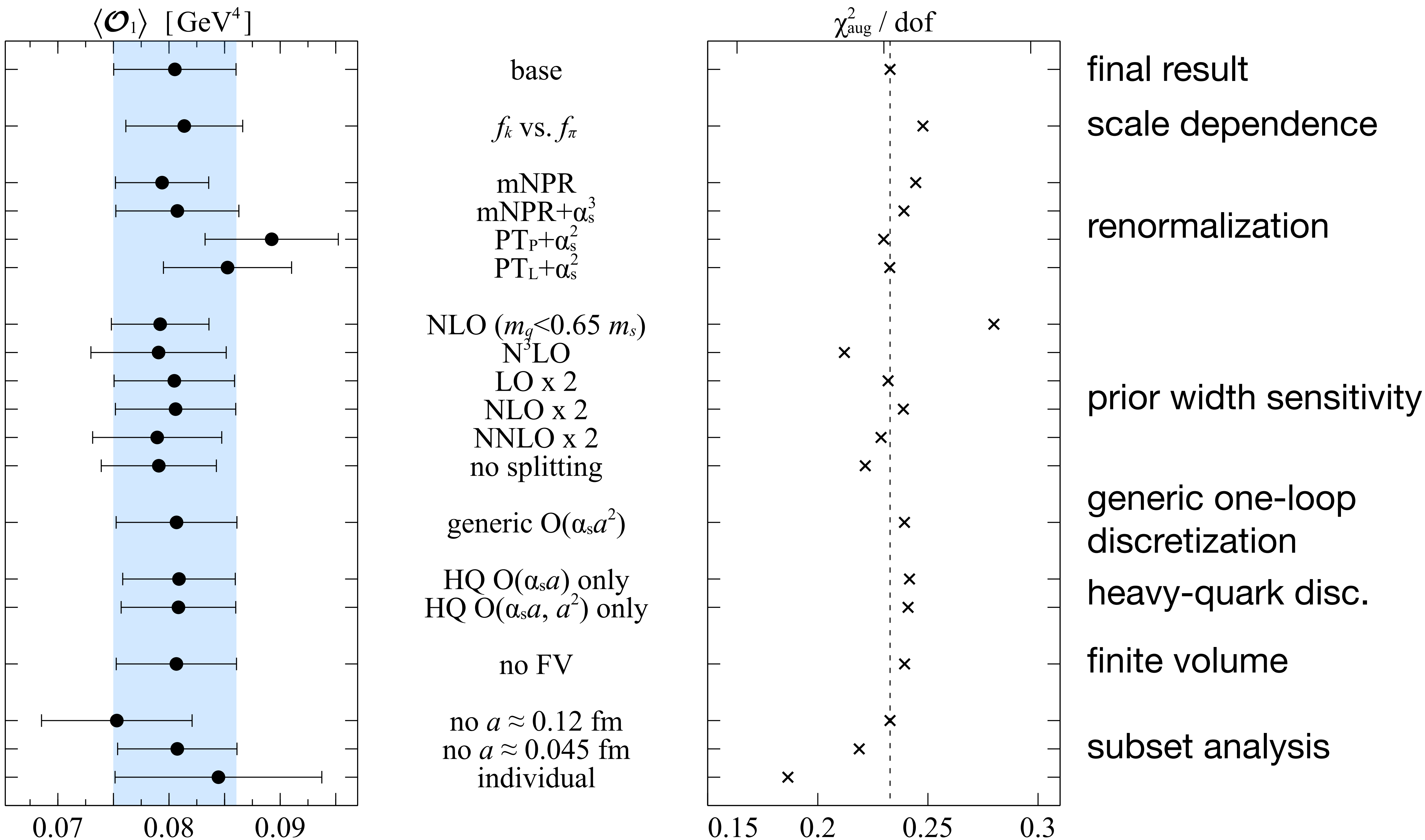
Staggered chiral logs + pion and lattice spacing polynomial expansion.

Beyond tree-level heavy-quark discretization estimates.

Correction to heavy-quark mass tuning.

Beyond one-loop renormalization estimates.

Sensitivity analysis



Final result is insensitive to sensible changes made to the extrapolation.

Result and uncertainty analysis

Error budget

	stat.	inputs	κ tuning	matching	chiral	LQ disc	HQ disc	r_1/a	fit total
$\langle \mathcal{O}_1 \rangle$	3.5	0.6	1.5	3.8	1.3	0.6	3.1	0.4	6.4
$\langle \mathcal{O}_2 \rangle$	1.8	0.5	0.4	2.2	0.8	0.4	2.4	0.5	4.0
$\langle \mathcal{O}_3 \rangle$	3.1	0.3	0.6	3.8	1.3	0.5	3.6	0.4	6.3
$\langle \mathcal{O}_4 \rangle$	2.2	0.6	0.5	2.0	0.9	0.3	2.6	0.5	4.2
$\langle \mathcal{O}_5 \rangle$	3.0	0.7	0.5	4.1	1.5	0.5	3.5	0.3	6.5

Total error budget

	Fit total	r_1	FV	EM	Total	Charm sea
$\langle \mathcal{O}_1 \rangle$	6.4	2.1	0.1	0.2	6.8	2.0
$\langle \mathcal{O}_2 \rangle$	4.0	2.1	0.3	0.2	4.5	2.0
$\langle \mathcal{O}_3 \rangle$	6.3	2.1	0.3	0.2	6.6	2.0
$\langle \mathcal{O}_4 \rangle$	4.2	2.1	0.2	0.2	4.7	2.0
$\langle \mathcal{O}_5 \rangle$	6.5	2.1	0.2	0.2	6.8	2.0

FV is uncertainty to IV extrapolation (estimated from NLO FV vs no FV fit)
EM from one-loop EM α_{QED}/π
Isospin comes in as $(m_d - m_u)^2$. χPT is symmetric under $m_d \leftrightarrow m_u$
Quenching charm sea quark comes in at $\alpha_s(\Lambda_{QCD}/2m_c)^2 \sim 2\%$

Result

	$\langle \mathcal{O}_1 \rangle$	$\langle \mathcal{O}_2 \rangle$	$\langle \mathcal{O}_3 \rangle$	$\langle \mathcal{O}_4 \rangle$	$\langle \mathcal{O}_5 \rangle$
BBGLN	0.0805(55)(16)	-0.1561(70)(31)	0.0464(31)(9)	0.2747(129)(55)	0.1035(71)(21)
BMU	0.0806(54)(16)	-0.1442(66)(29)	0.0452(30)(9)	0.2745(129)(55)	0.1035(71)(21)

ETMC has 2 and 2+1+1 flavor results. [Nf = 2: Phys. Rev. D 90, 014502, Nf = 2+1+1: Phys. Rev. D 92, 034516]

Implications for New Physics

Simple example where NP goes through O_5

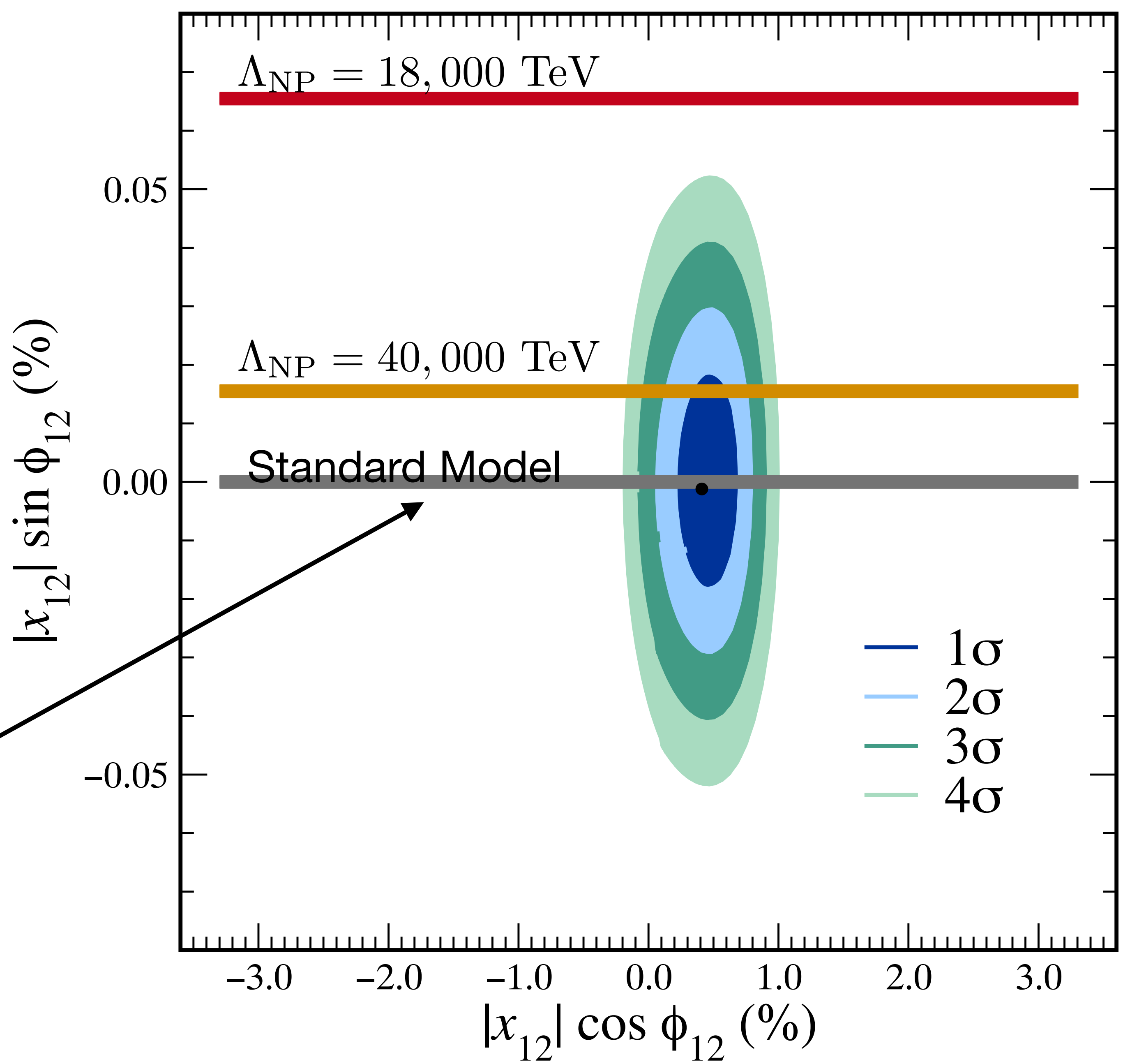
$$x_{12}^{\rm NP} = \frac{1}{M_D \Gamma_D} \sum_i C_i^{\rm NP}(\mu) \langle \mathcal{O}_i \rangle (\mu)$$

Assume sizable CP-violation

$$C_i^{\rm NP}(\Lambda_{\rm NP}) = \frac{{\rm Im} F_i L_i}{\Lambda_{i,{\rm NP}}^2} \qquad {\rm s.t.}\ F_i = L_i = 1$$

Length of grey band is the theory uncertainty from Standard Model long-distance.

Much more work needs to be done to understand resonant states.



CP-violating process pushes prediction along the y-axis

***D*-mixing can constrain BSM models with sizable CP-violation.**

CP-conserving process pushes prediction along the x-axis

Flavor-violating Higgs model

[JHEP 1303 (2013) 026]

Exclusion bands on the magnitude of Yukawa couplings

$$\mathcal{H}^{\rm NP}_{\Delta C=2} = C_2^{uc}(m_h)\mathcal{O}_2 + \tilde{C}_2^{uc}(m_h)\tilde{O}_2 + C_4^{uc}(m_h)\mathcal{O}_4$$

The Wilson coefficients are

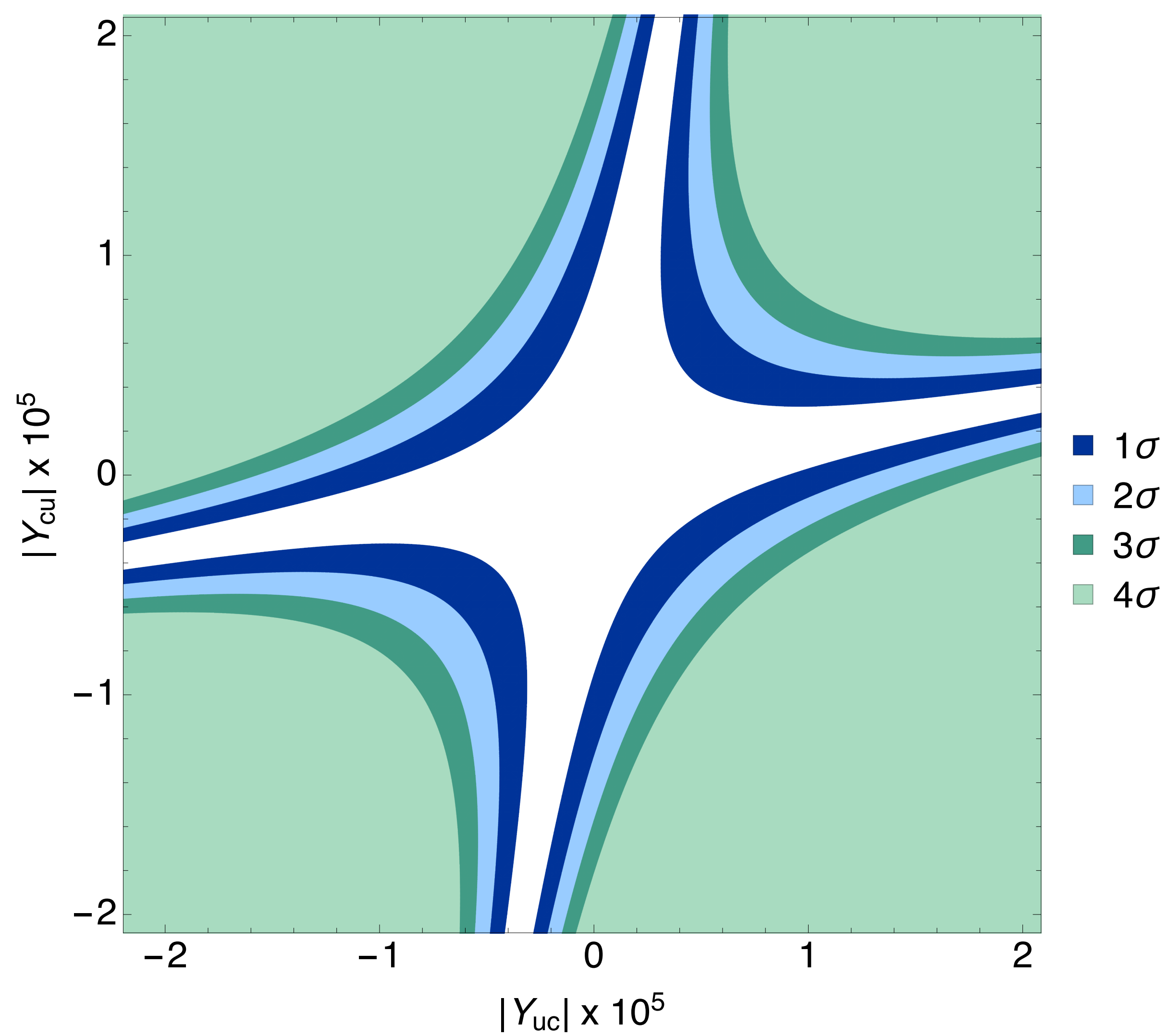
$$C_2^{uc}(m_h) = -\frac{Y_{uc}^{*2}}{2m_h^2}$$

$$\tilde{C}_2^{uc}(m_h) = -\frac{Y_{cu}^{2}}{2m_h^2}$$

$$C_4^{uc}(m_h) = -\frac{Y_{cu}Y_{uc}^{*}}{m_h^2}$$

where $Y_{uc} = |Y_{uc}|e^{i\phi_{uc}}$

marginalize over the phase to obtain exclusion contours in the Y_{cu}-Y_{uc} plane



Summary and outlook

We calculate short-distance matrix elements for D-meson mixing.

They offer useful constrains on BSM models, especially ones with sizable CP violation.

SM long-distance is still a very important piece that is missing, but very hard to calculate.

There is a lot of progress being made on multi-hadron systems for both theory and applications.

Collaborators

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