Update on Semileptonic Decays via Lattice QCD

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for the Fermilab Lattice and MILC collaboration

2019 DPF Meeting, American Physical Society

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Outline:

1. Physics motivation
2. Lattice techniques
3. Preliminary results
4. Outlook

Thanks to my close collaborators

- Carleton DeTar
- Aida El-Khadra
- Elvira Gamiz
- Zech Gelzer
- Steve Gottlieb
- Andreas Kronfeld
- Jim Simone

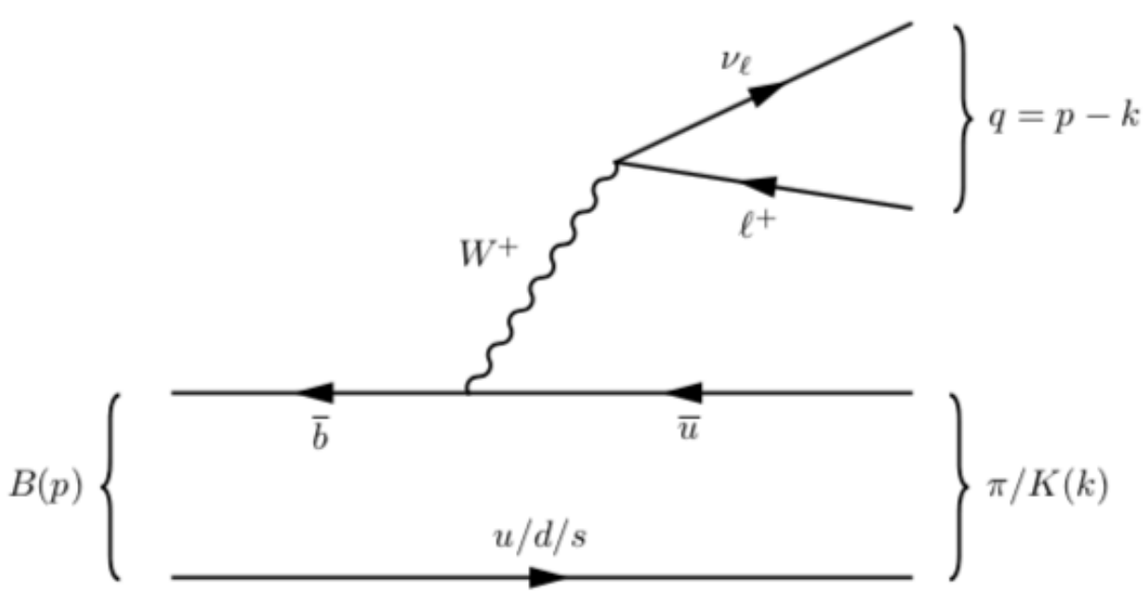
Note: Focus today on work by the Fermilab Lattice and MILC collaborations
See plenary talk by Andreas Kronfeld on Monday for more information
and an overview of what other groups are doing.

Physics overview

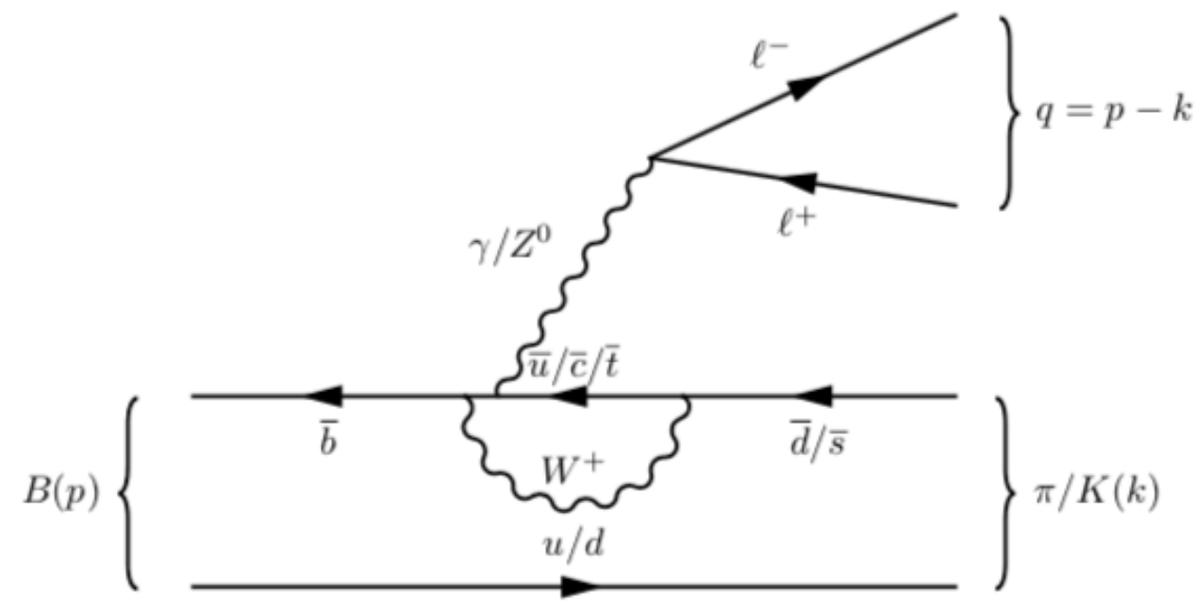
Flavor physics and lattice QCD

Two complementary goals

1. Determine CKM quark-mixing matrix elements
   - » Study tree-level decays dominated by Standard-Model processes



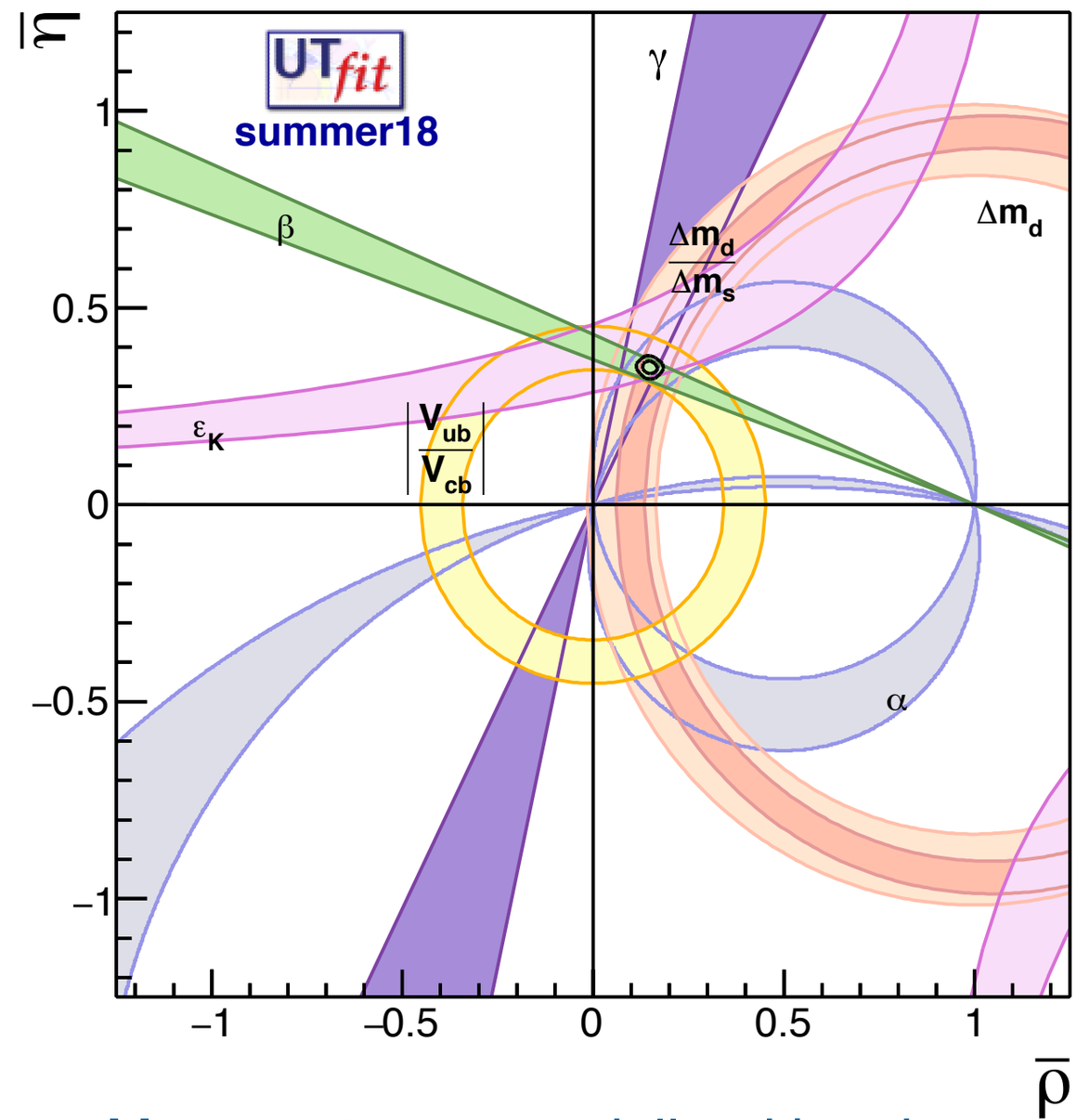
2. Constrain possible scenarios for physics beyond the Standard Model
   - » Study rare processes sensitive to contributions from new physics



Flavor physics and lattice QCD

CKM matrix elements

$\mathbf{V_{ud}}$	$\mathbf{V_{us}}$	$\mathbf{V_{ub}}$
$\pi \to \ell\nu$	$K \to \ell\nu$	$B \to \ell\nu$
	$K \to \pi\ell\nu$	$B \to \pi\ell\nu$
$\mathbf{V_{cd}}$	$\mathbf{V_{cs}}$	$\mathbf{V_{cb}}$
$D \to \ell\nu$	$D_s \to \ell\nu$	$B \to D\ell\nu$
$D \to \pi\ell\nu$	$D \to K\ell\nu$	$B \to D^*\ell\nu$
$\mathbf{V_{td}}$	$\mathbf{V_{ts}}$	$\mathbf{V_{tb}}$
$\langle B_d \vert \bar{B} \rangle$	$\langle B_s \vert \bar{B}_s \rangle$	
$B \to \pi\ell\ell$	$B \to K\ell\ell$	



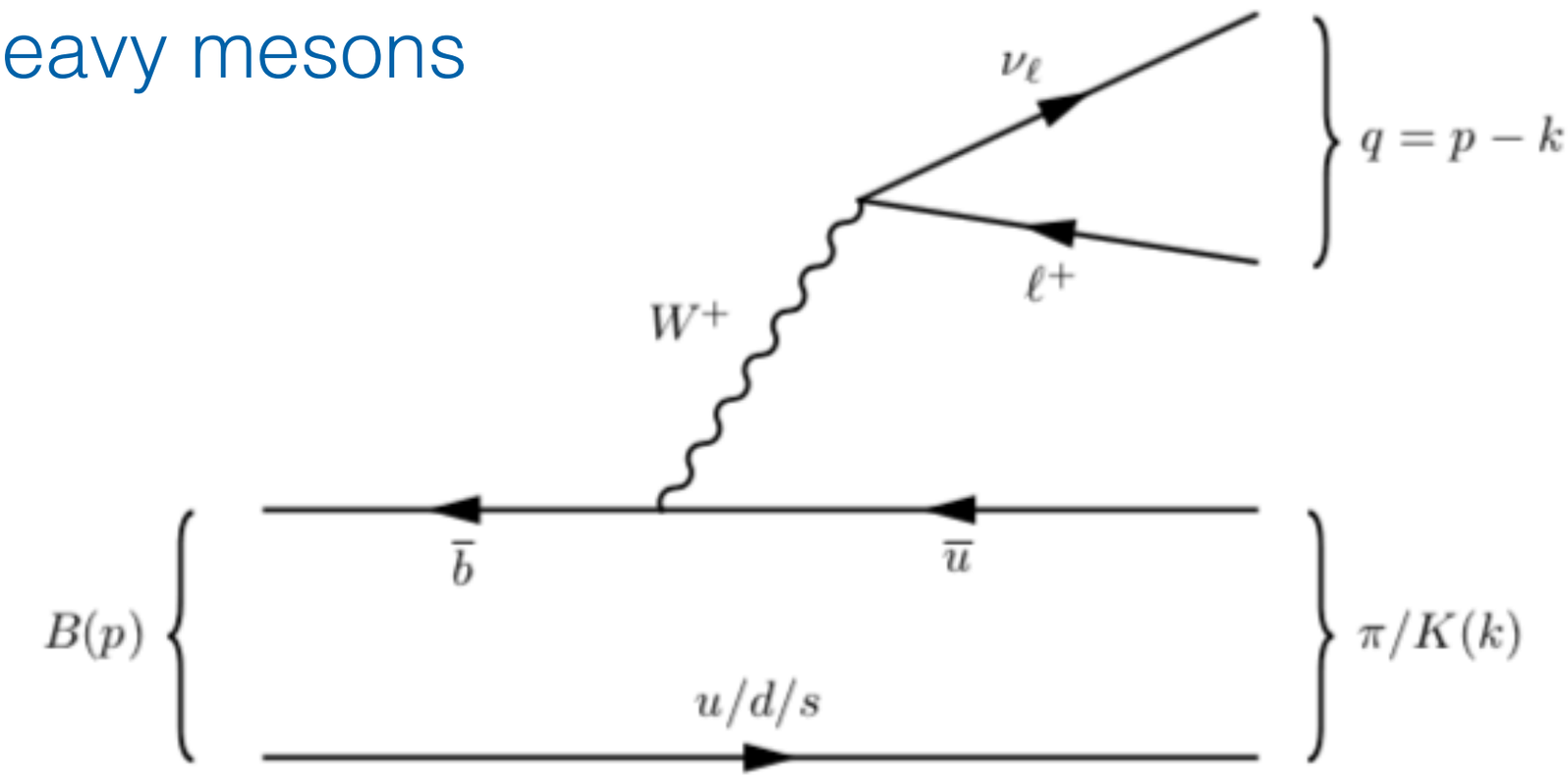
Columns orthogonal?

= today's main focus

More context, especially with pointers to the impressive experimental context in plenary talks from Monday morning

Flavor physics and the Standard Model

Tree-level decays of heavy mesons



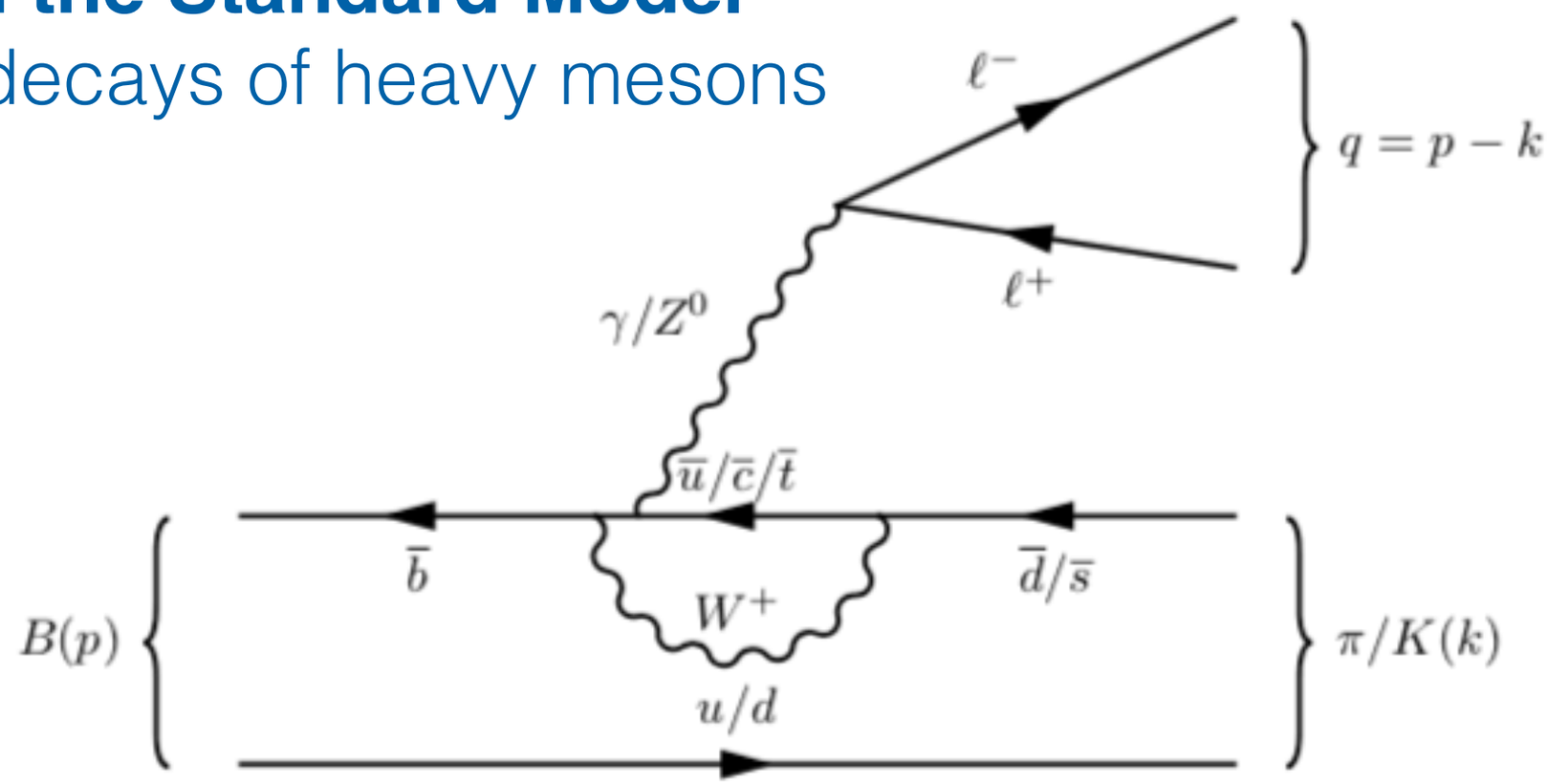
$$\frac{d\Gamma}{dq^2} = (\text{known factors}) \times |V_{\text{ub}}|^2 \times \begin{cases} |f_+(q^2)|^2 \\ |f_0(q^2)|^2 \end{cases}$$

Phase space, kinematics	CKM matrix element	Form factors/ QCD matrix elements

→ Form factors are necessary to extract CKM matrix elements

Flavor physics and the Standard Model

Rare loop-induced decays of heavy mesons



$$\frac{d\Gamma}{dq^2} = (\text{known factors}) \times |V_{\text{tb}} V_{\text{tf}}^*|^2 \times \begin{cases} |f_+(q^2)|^2 \\ |f_0(q^2)|^2 \\ |f_T(q^2)|^2 \end{cases}$$

Phase space, kinematics	CKM matrix element	Form factors/ QCD matrix elements

→ Form factors are necessary to extract CKM matrix elements

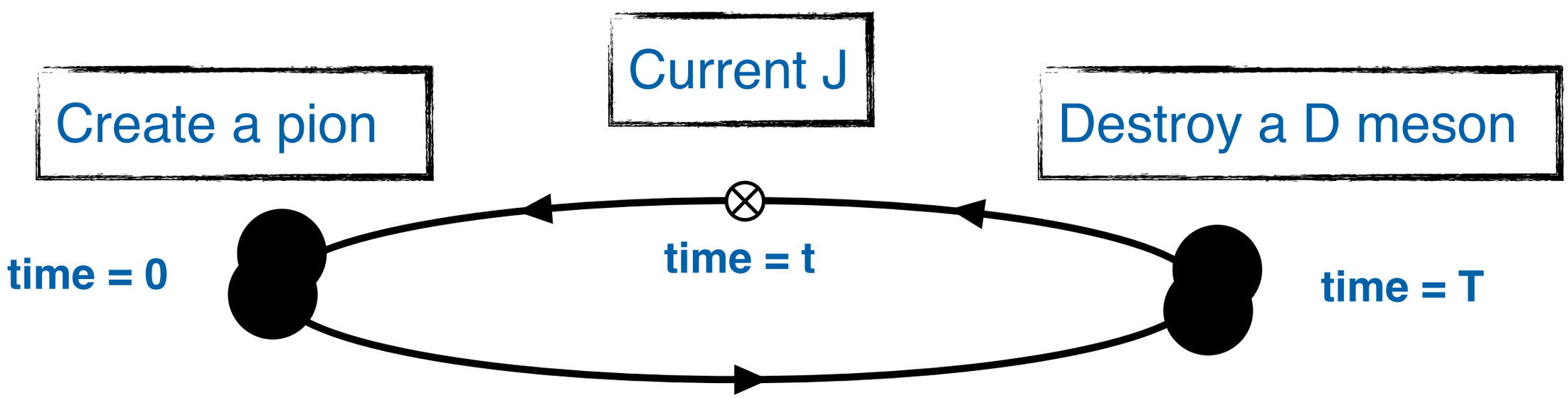
Lattice QCD

Computing form factors directly from QCD

Example: D to π

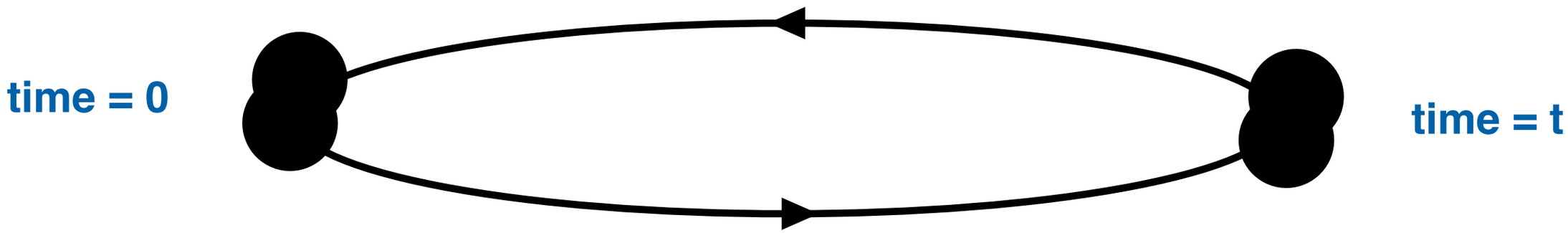
Slogan: $(\text{form factors}) \propto (\text{matrix elements})$

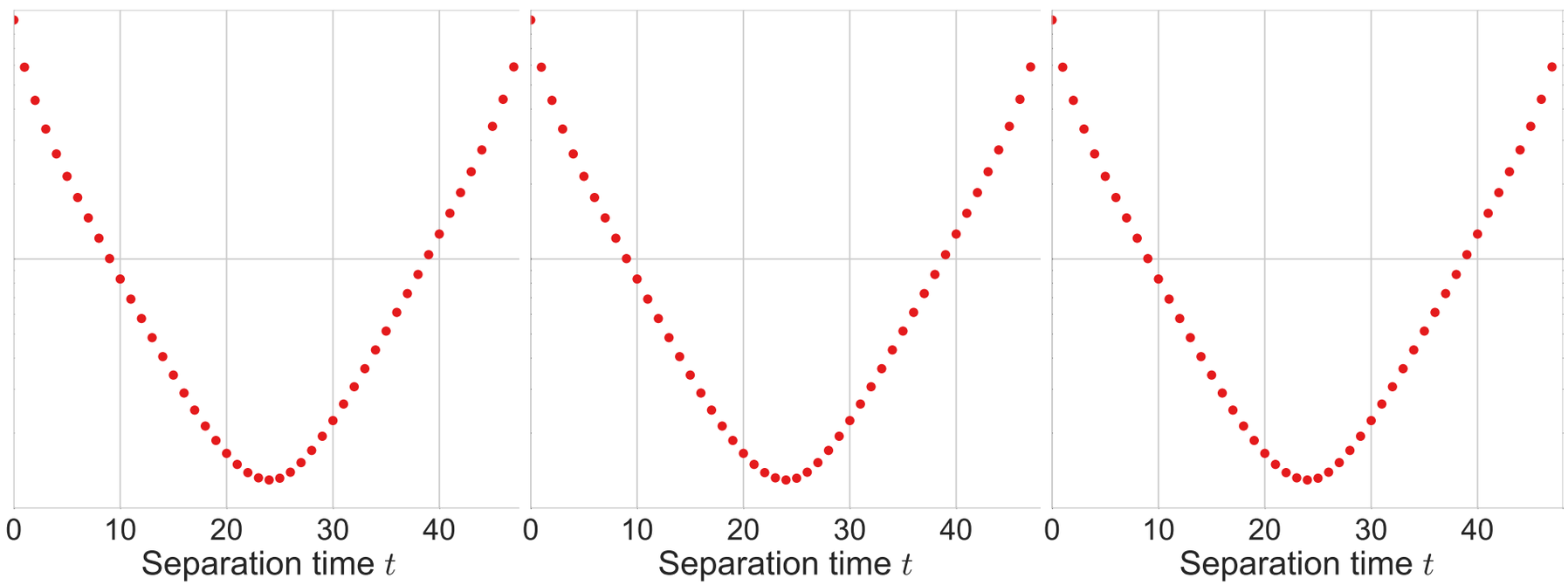
$$f_{\mathcal{J}} = \underbrace{(\text{known factors})}_{\text{Kinematics}} \times \underbrace{\langle D| \mathcal{J} |\pi\rangle}_{\text{Compute via three-point functions in lattice QCD}}$$



QCD on the lattice

Calculate the full non-perturbative path integral using Monte Carlo





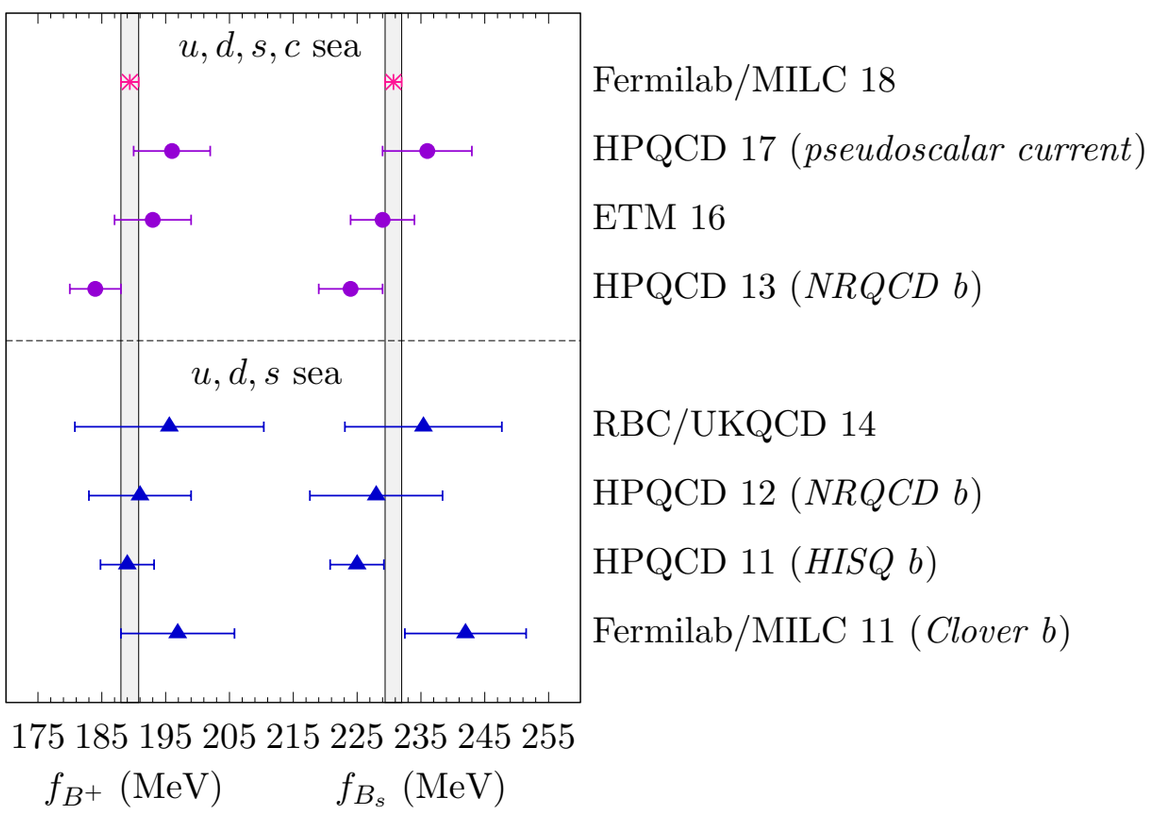
Extract energies and amplitudes (= matrix elements) from a fit

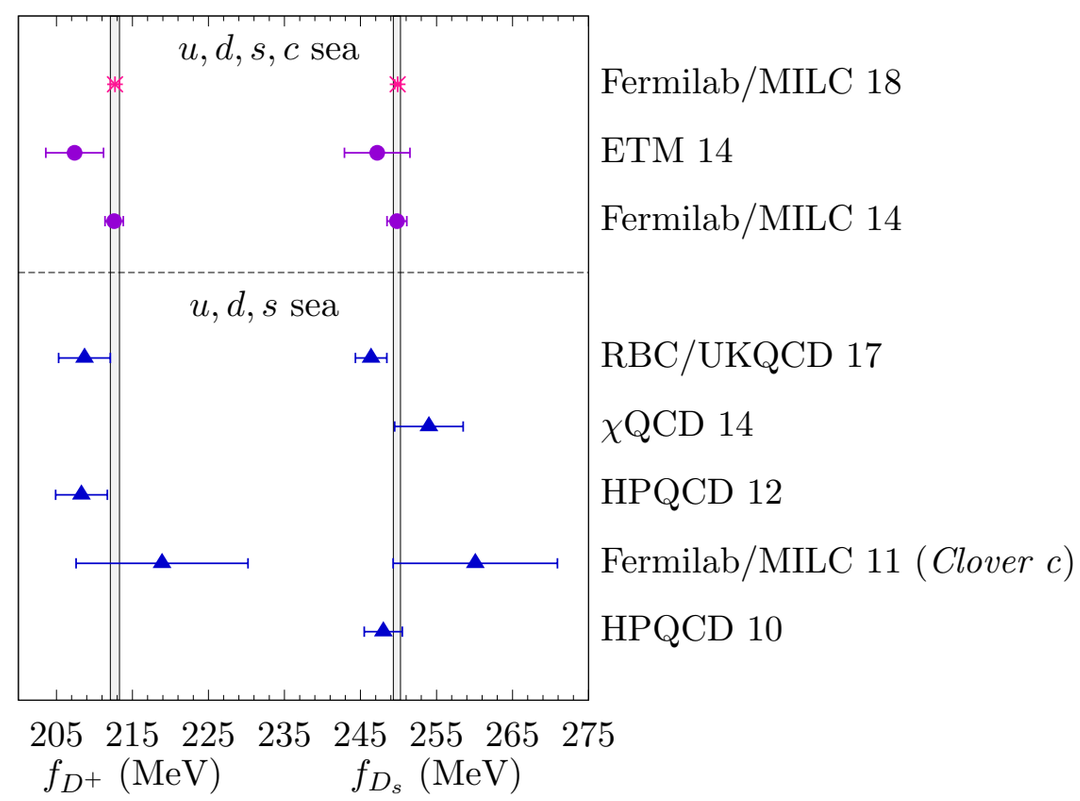
Some published results: Leptonic decay constants

MILC (2+1+1)-flavor HISQ ensembles

- *B- and D-meson leptonic decay constants from four-flavor lattice QCD* PRD 98, 074512 Fermilab Lattice and MILC Collaborations (1712.09262)
  - Most precise determination heavy decay constants f_B and f_D to date: < 1%
- The work described today uses the same gauge configurations, generated by the MILC collaboration

HISQ u/d/s/c and physical-mass b





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  - Most precise determination heavy decay constants f_B and f_D to date: < 1%
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Our goal is to build on this success and compute

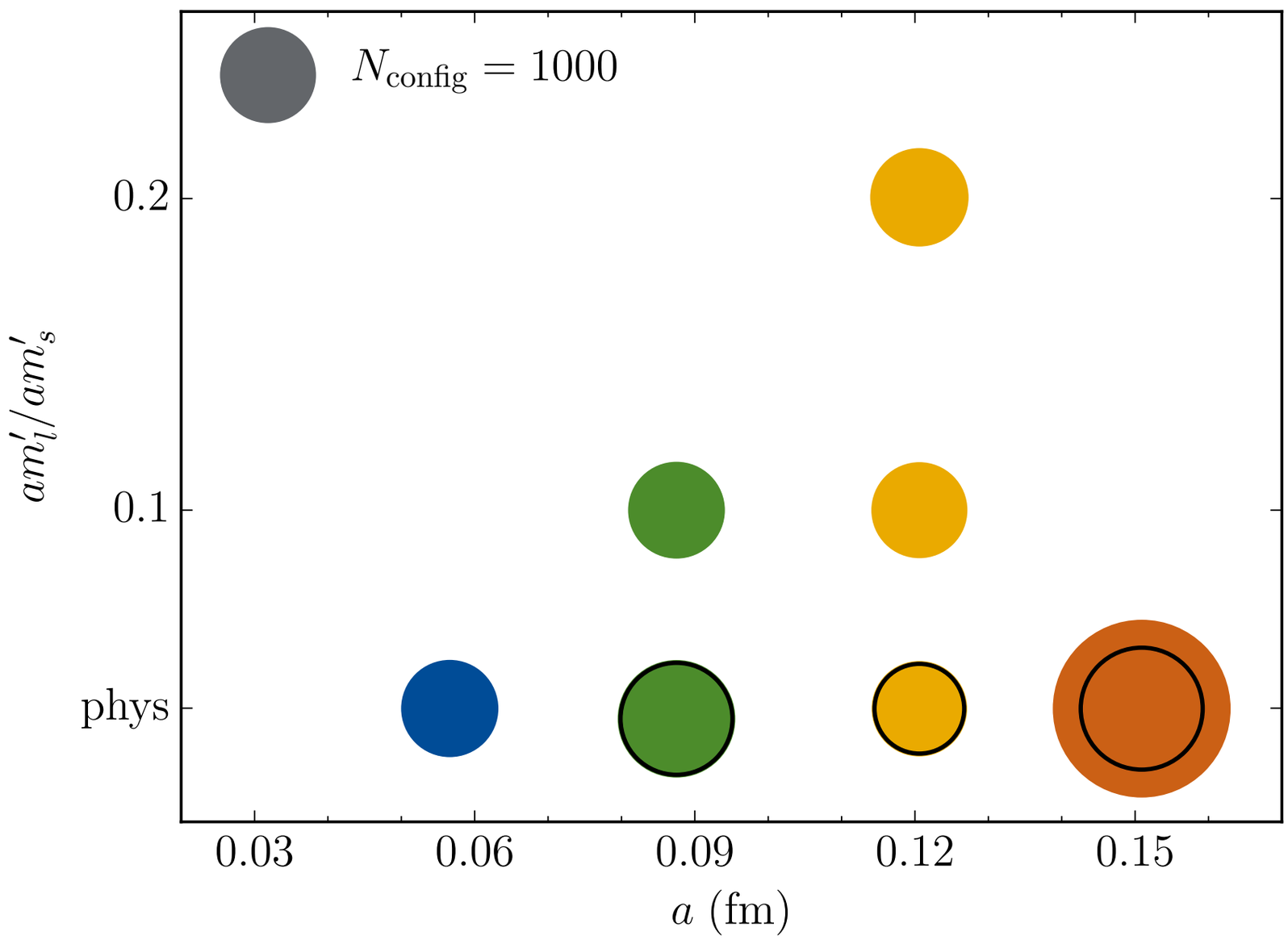
» Form factors for B-meson decays at the 1% level

» From factors for D-meson decays at less than 1% level

Preliminary Results

Overview of lattice ensembles

MILC (2+1+1)-flavor HISQ ensembles



Filled = "Fermilab" b quark

Open = HISQ "b" quark

Overview of lattice ensembles

MILC (2+1+1)-flavor HISQ ensembles

- Several different lattice spacings
- Several light quark masses, including the physical point

Filled = "Fermilab" b quark

- Nonrelativistic b quark, based on HQET
- Good statistics on many ensembles
- $B_S \to K$, $B \to K$
- Analysis led by Zech Gelzer

Open = HISQ b quark

- Fully relativistic b quark
- Improved lattice artifacts
- Advantageous renormalization properties
- Running is ongoing
- Analysis by WJ

Preliminary Results

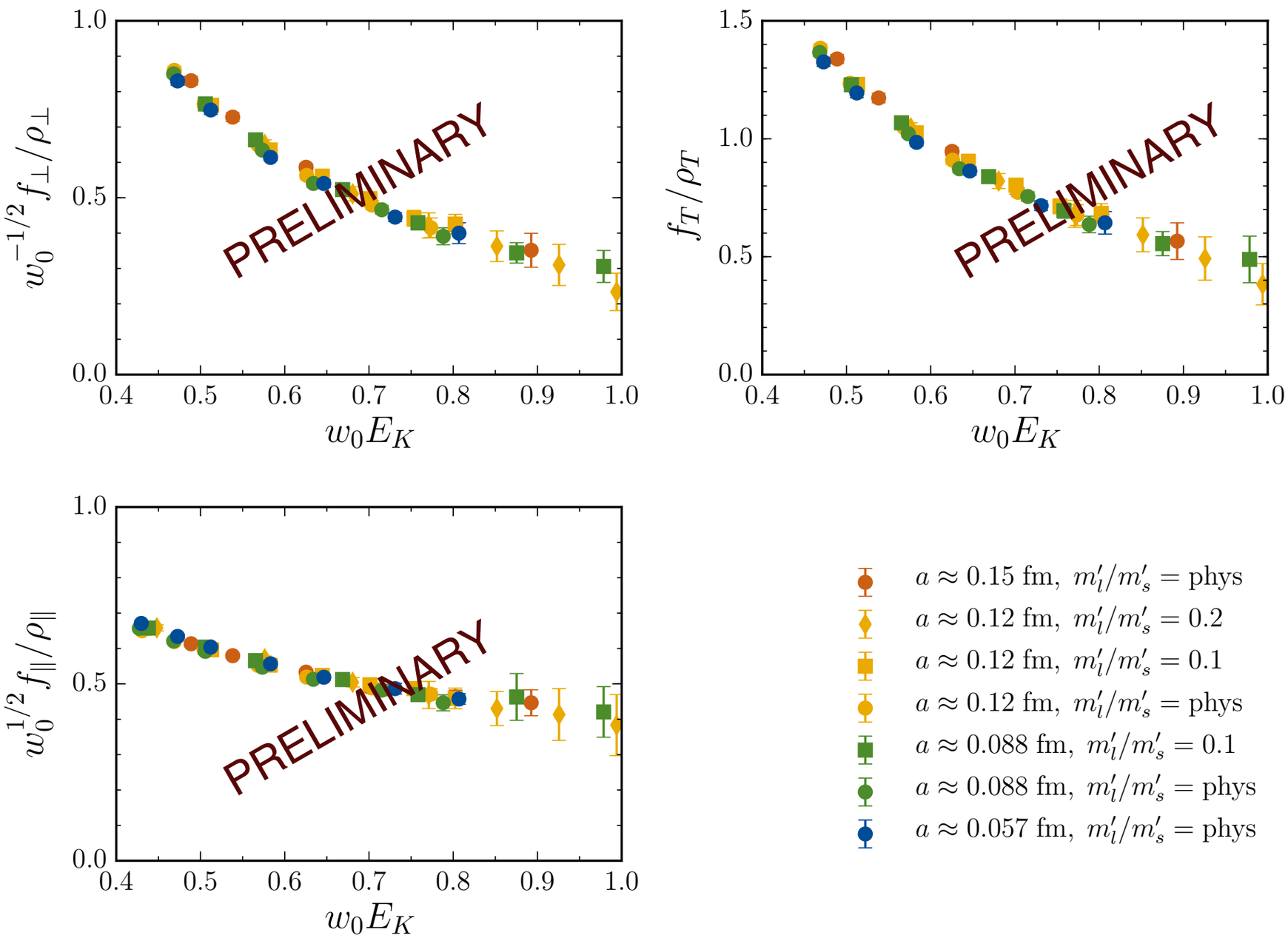
Fermilab b quark

Preliminary results

Credit: Zech Gelzer

$B_S \to K$

Valence: HISQ u/d/s + Fermilab b quark



$$f \propto \frac{1}{E_K + \text{shift}}$$

at leading-order in EFT description

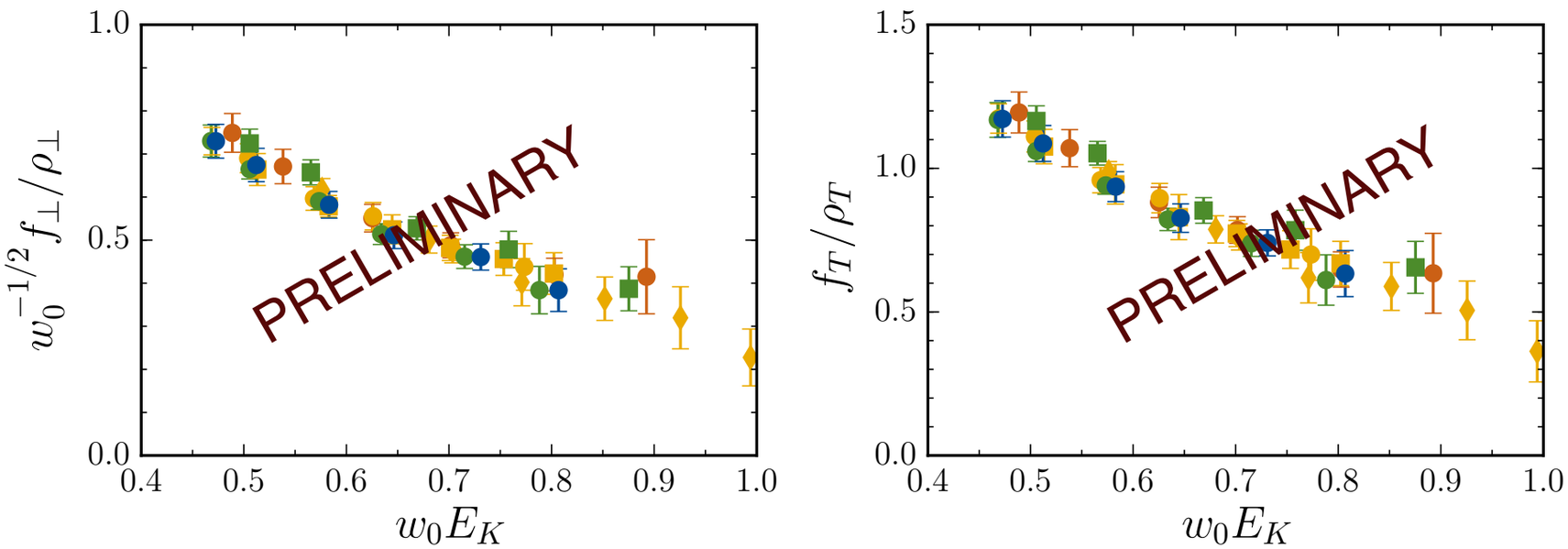
Fermilab

Preliminary results

Credit: Zech Gelzer

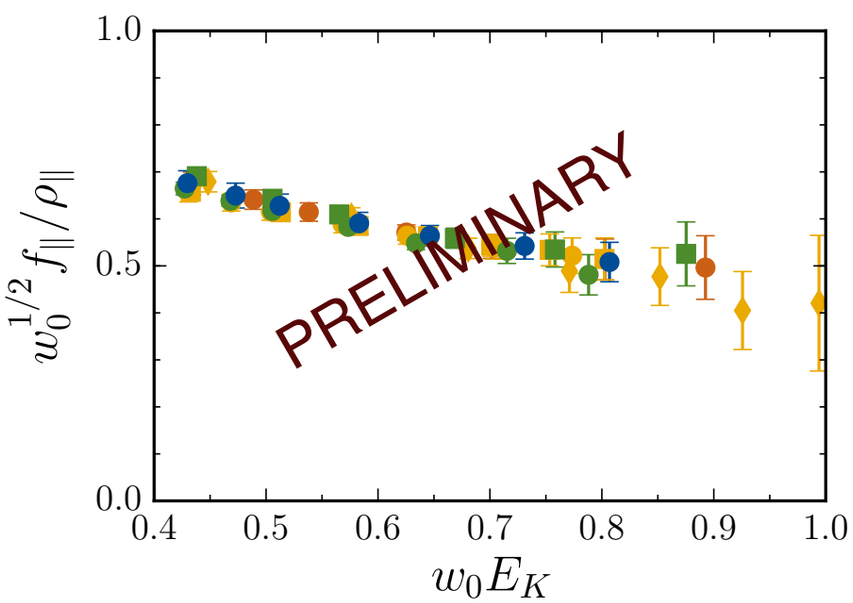
B → K

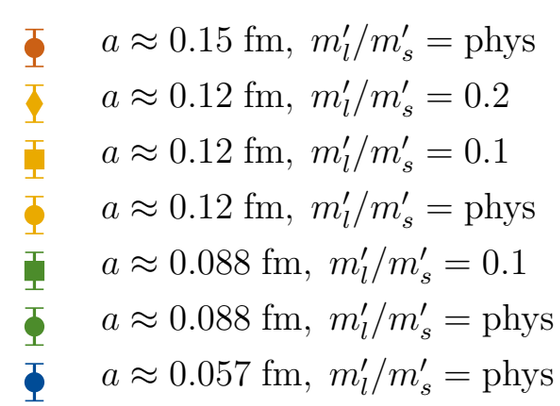
Valence: HISQ u/d + Fermilab b quark



$$f \propto \frac{1}{E_K + \text{shift}}$$

at leading-order in EFT description



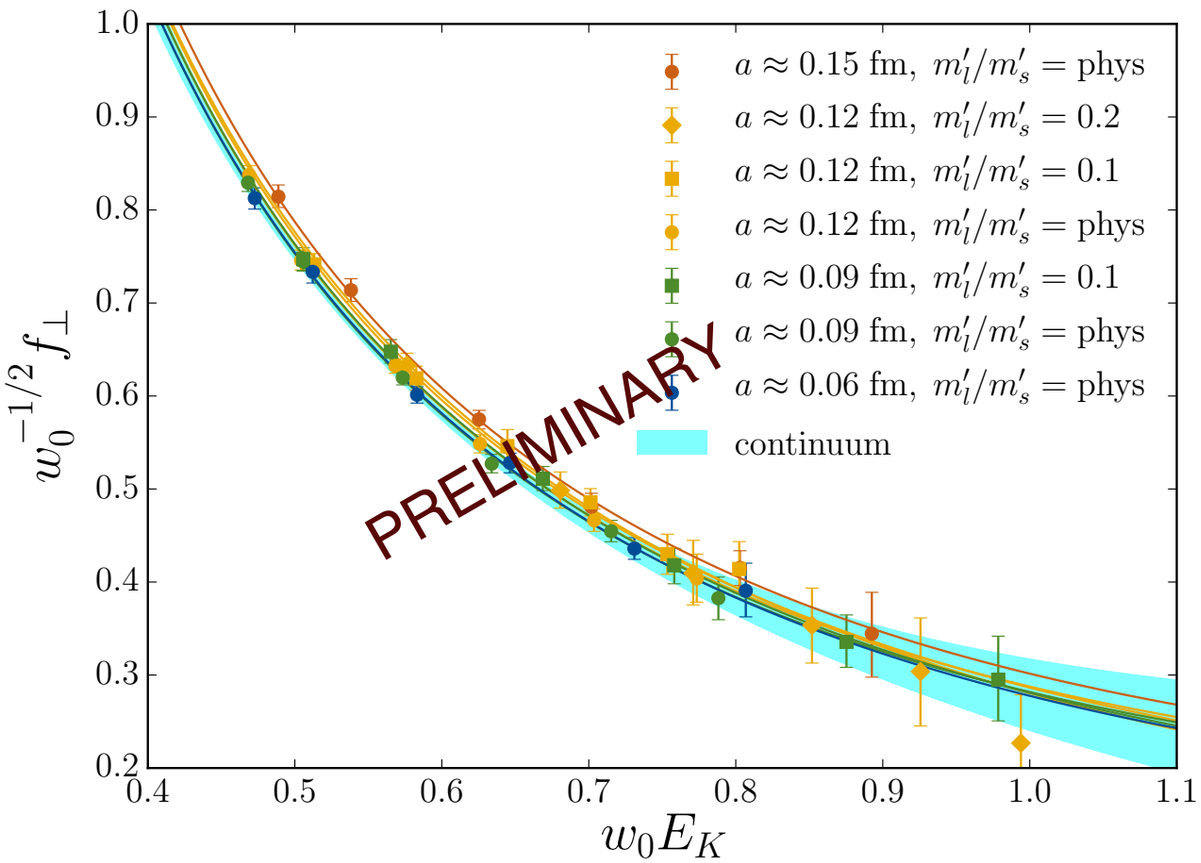


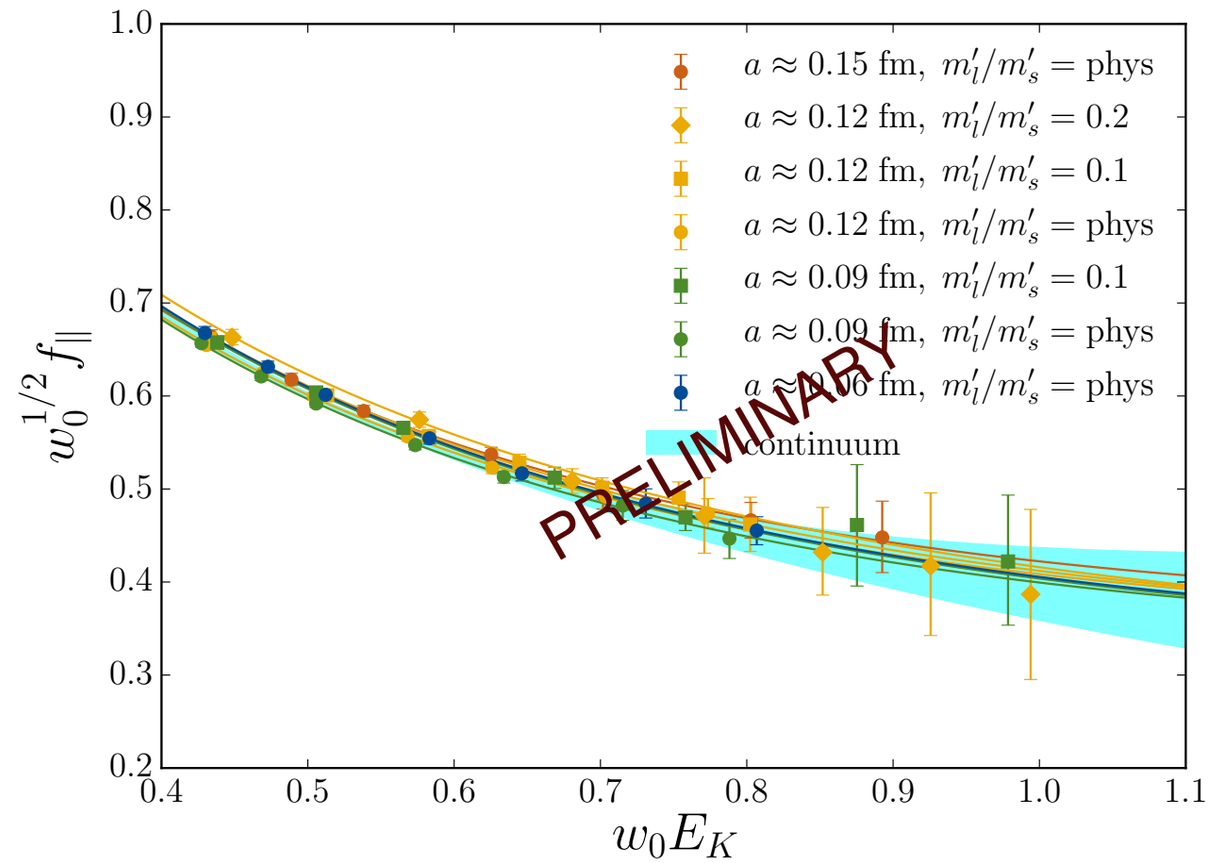
Preliminary results

Credit: Zech Gelzer

Continuum limit: $B_S \rightarrow K$

Valence: HISQ u/d/s + Fermilab b quark





- » Take the “chiral” and continuum limit using EFT
- » Extend results to full kinematic range using model-independent the “z-expansion”
- » Look for results this fall

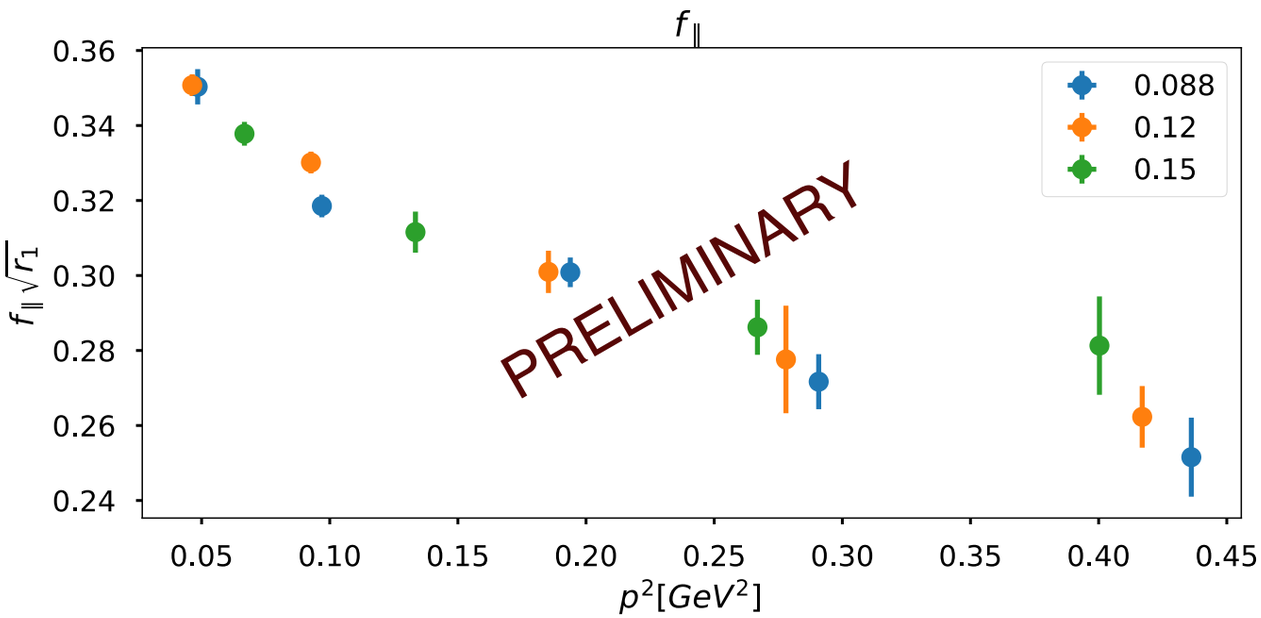
Preliminary Results

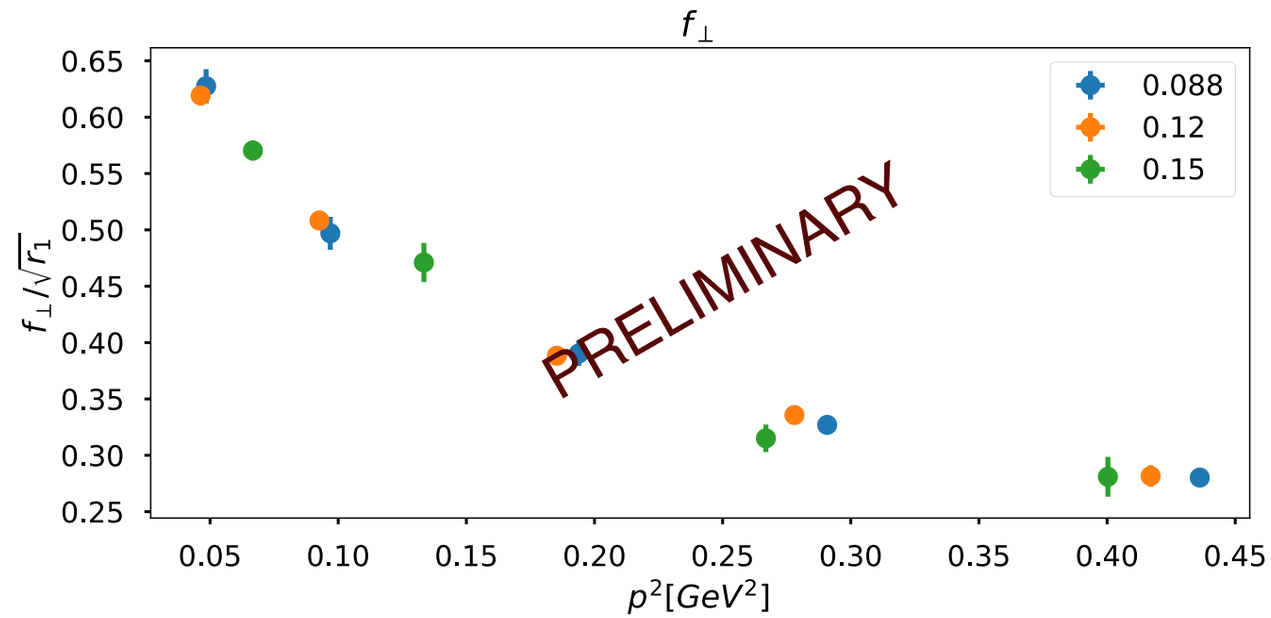
Heavy HISQ b

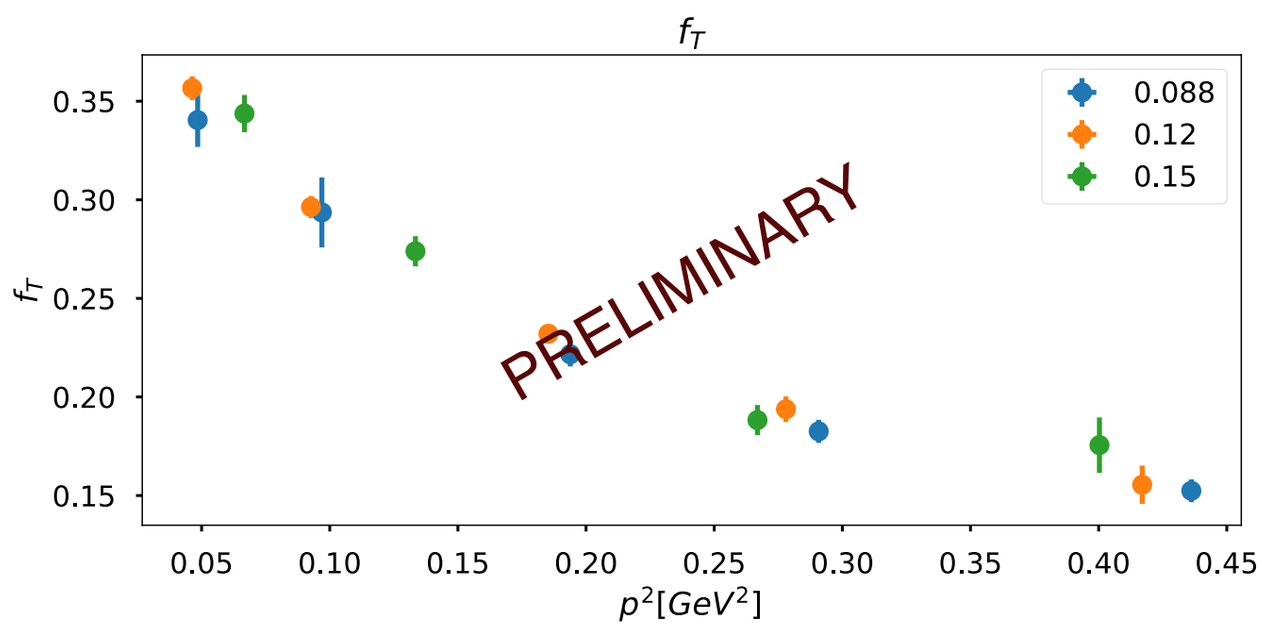
Preliminary results

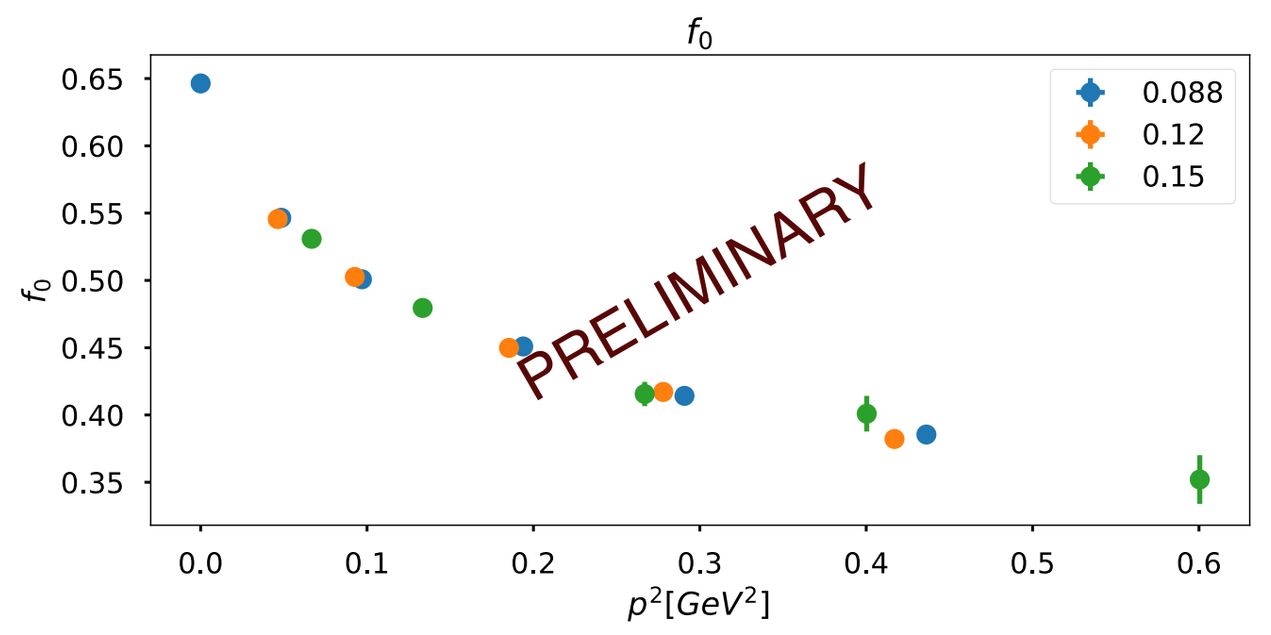
D → π: HISQ form factors, physical-mass ensembles

Valence: HISQ u/d/c + heavy HISQ "b"





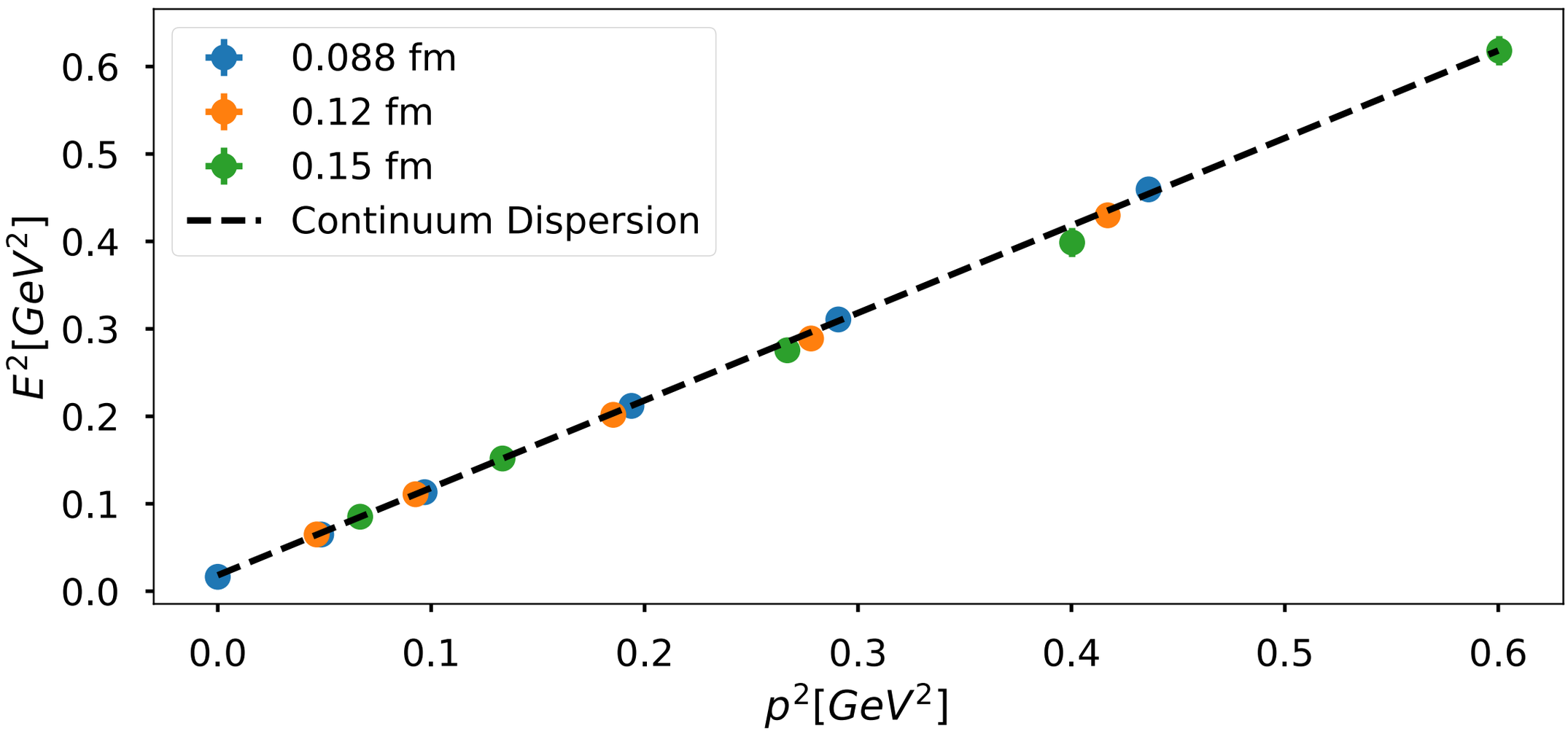




Preliminary results: Pion dispersion relation

Physical masses for light quarks

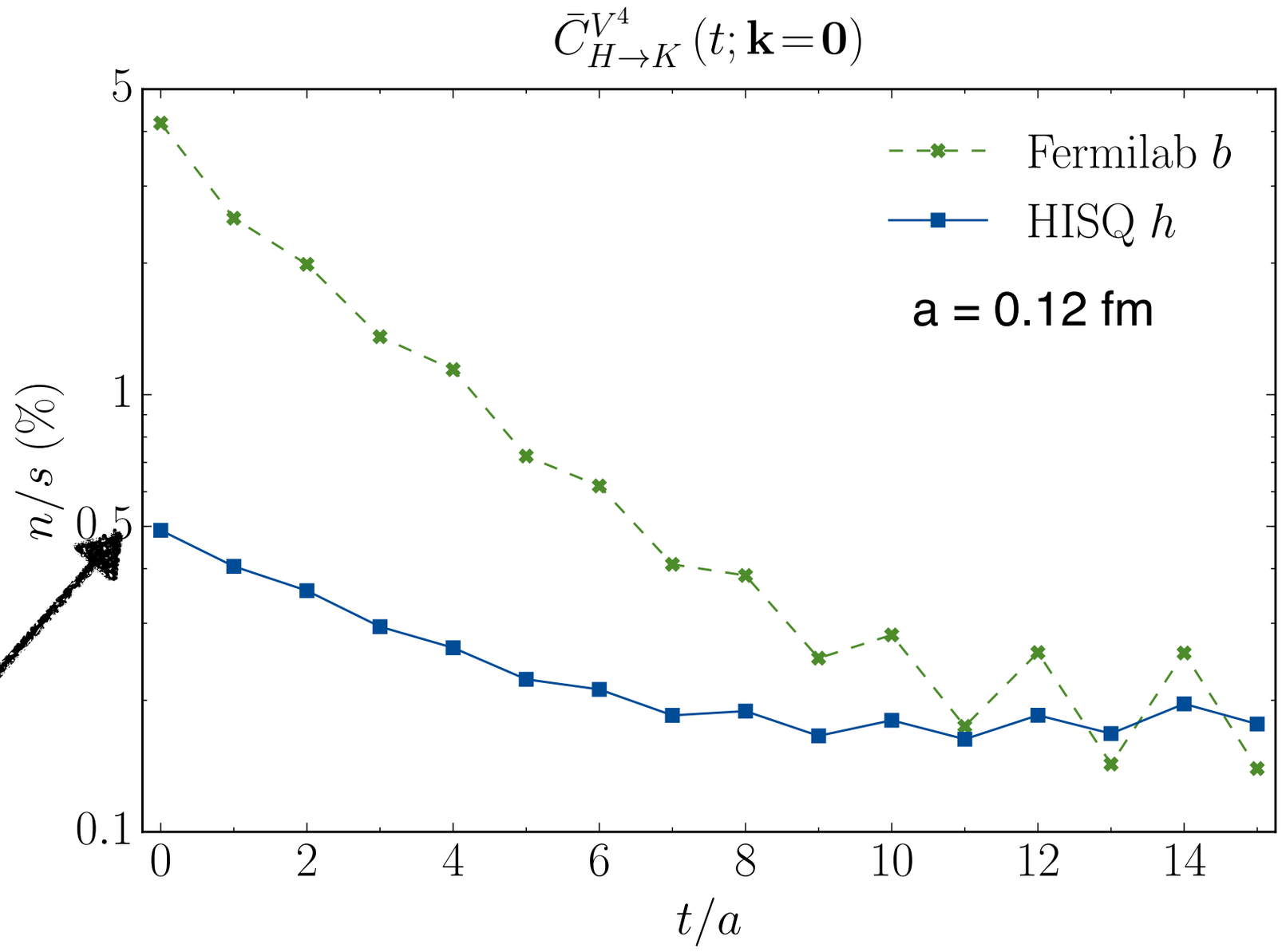
Three lattice spacings 0.088, 0.12, and 0.15 fm



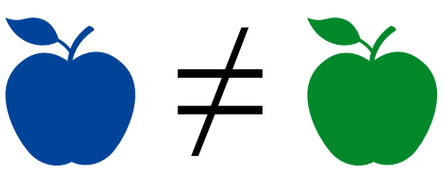
Preliminary results

Comparing heavy quarks

Noise / Signal (%) for three-point functions



HISQ correlators shows good statistical precision versus Fermilab b

Caveat: 

Fermilab b at physical m_b

Heavy HISQ h at 1.4 × m_c (more to follow at smaller a…)

Summary

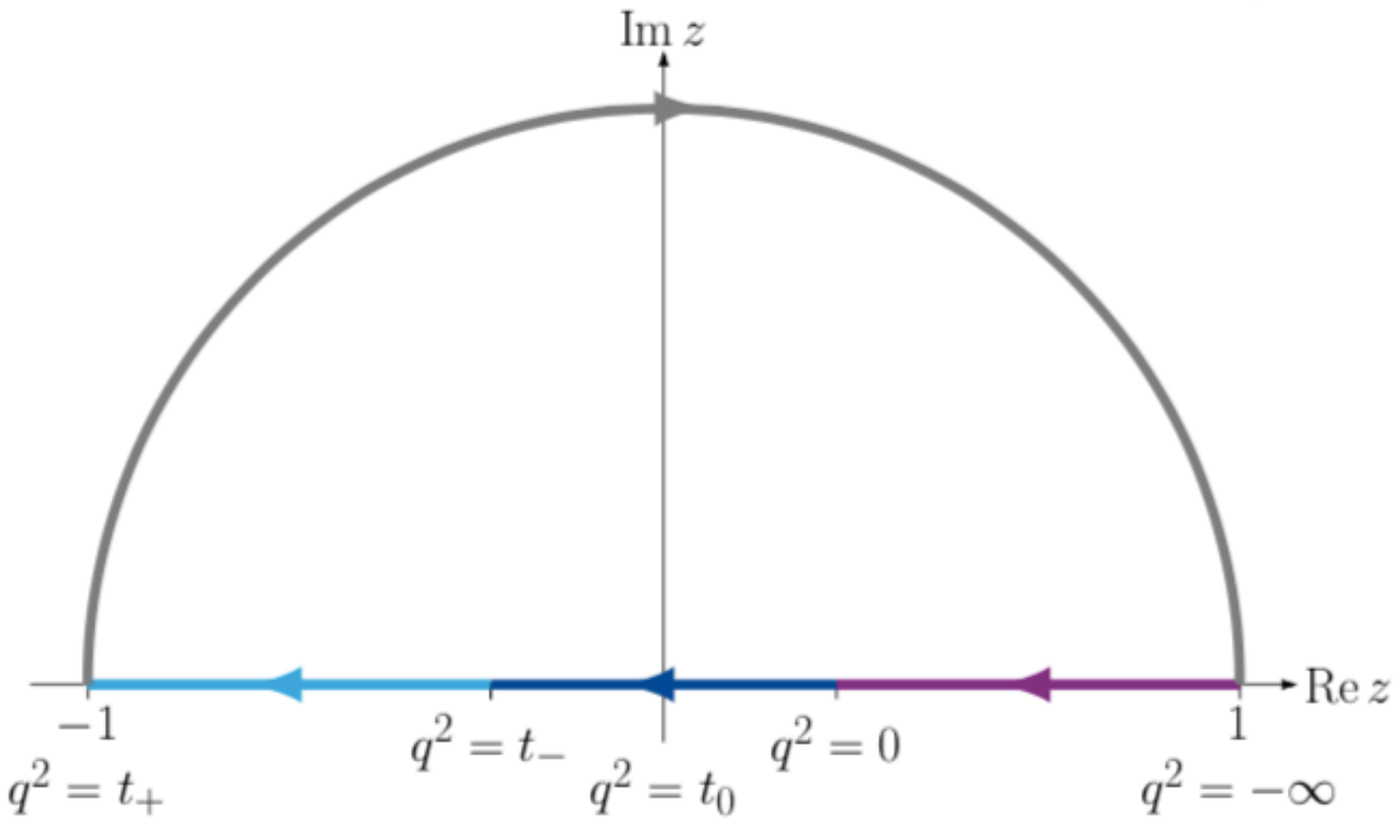
Summary and take-home points

- Overall goals:
  - Form factors for B-meson decays at the 1% level
  - Form factors for D-meson decays at less than 1% level
- What will make this possible?
  - Large statistics, large volumes, and small lattice artifacts with HISQ (2+1+1)-flavor ensembles generated by the MILC collaboration
  - Physical-mass light (u/d) quarks
  - Physical-mass b-quarks
- These ensembles have already yielded the most precise measurements of B- and D-meson decay constants
- Timeline for form factors?
  - Fall 2019: papers on arXiv using Fermilab b
  - Results for HISQ b to follow…
- Questions?

z expansion

Slide credit: Zech Gelzer

Conformal mapping $q^2 \mapsto |z| \leq 1$ exploits analytic structure in complex plane to extend chiral-continuum form factors to low q^2.



$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

where $t_\pm = (M_B \pm M_P)^2$

$\Downarrow$

$$f(q^2) = \frac{1}{1 - \frac{q^2}{M^2}} \sum_n a_n z^n(q^2)$$

- t_0^{opt} minimizes $|z|$ in physical region $\Rightarrow |z| \leq \{0.30, 0.15\}$ for $P = \{\pi, K\}$
- Smallness of $|z|$ controls truncation
- Unitarity guarantees convergence