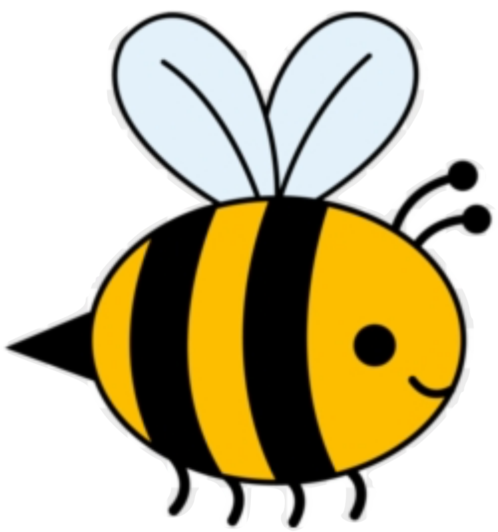
$B \to \pi \ell \nu$ using HISQ

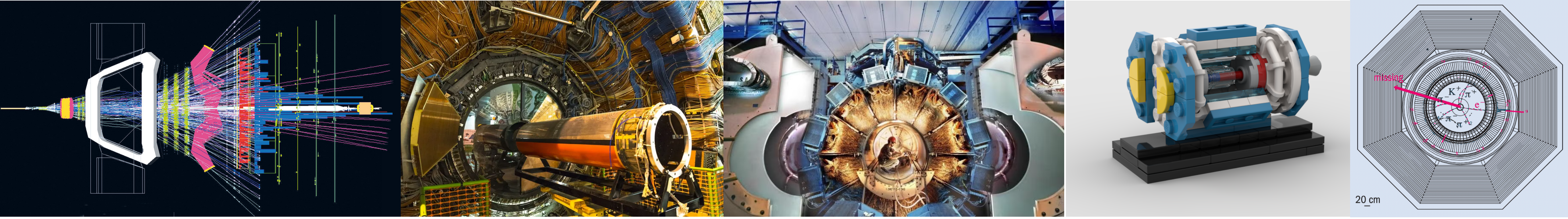


$\longrightarrow$

Lattice2026
July 27 - July 31

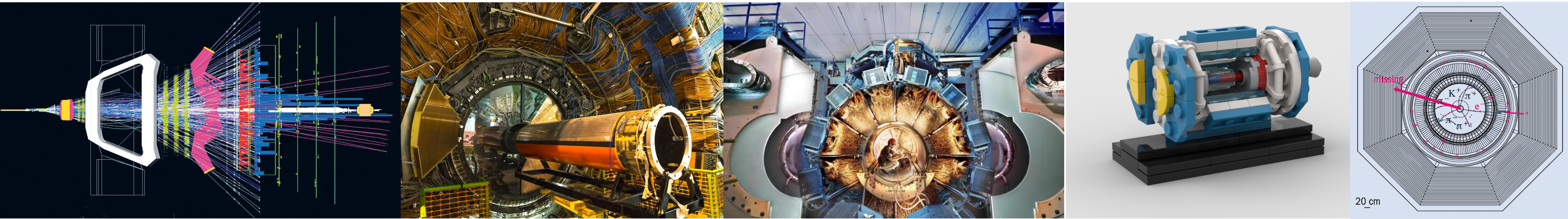
Nicholas Cassar

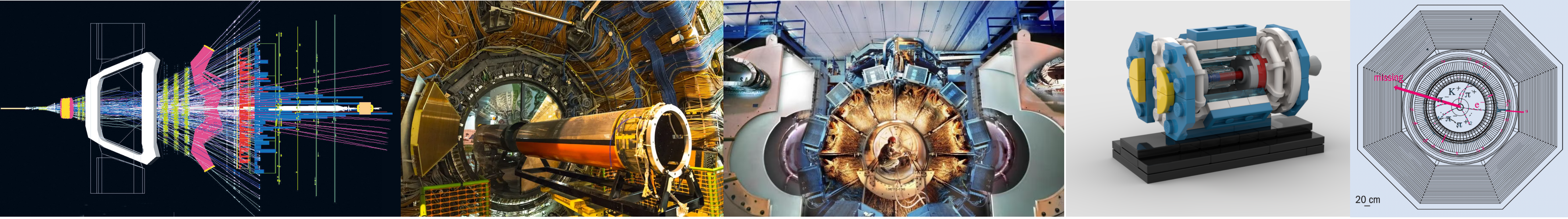
nick.cassar@colostate.edu



Special thanks to our collaborators:

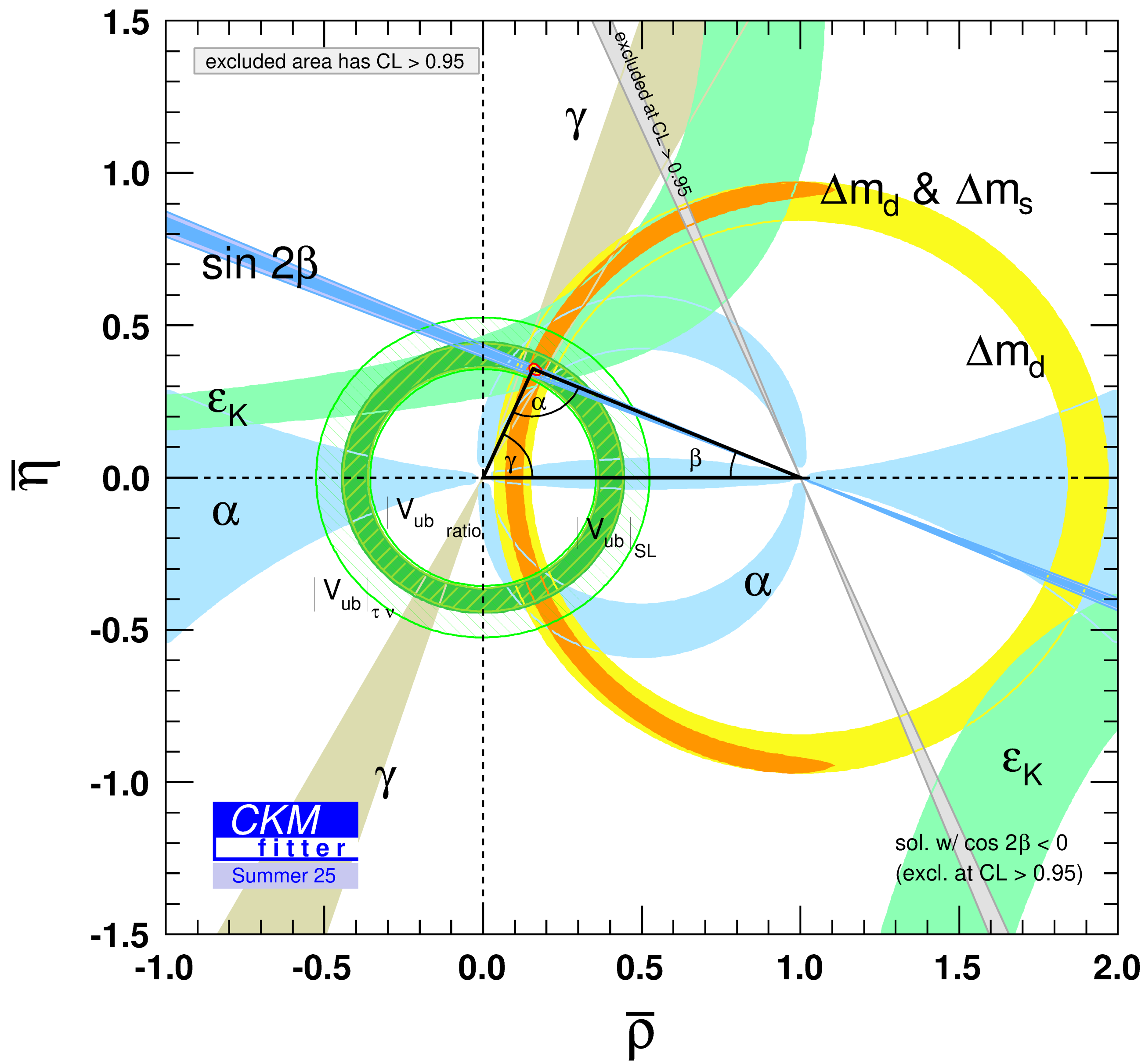
Nicholas Cassar, **Akhil Chauhan**, Carleton DeTar, Aida El-Khadra, Elvira Gámiz, Steven Gottlieb, William Jay, Andreas S. Kronfeld, Jack Laiho, Andrew Lytle, **Abishek Samlodia**, Alejandro Vaquero

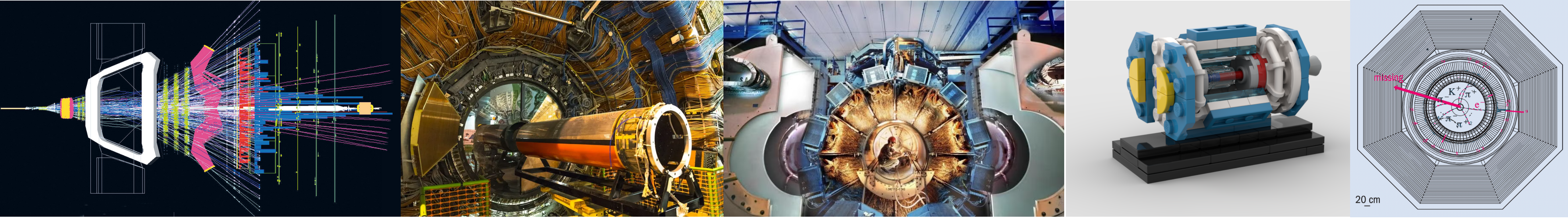




The Heavy Flavor Situation

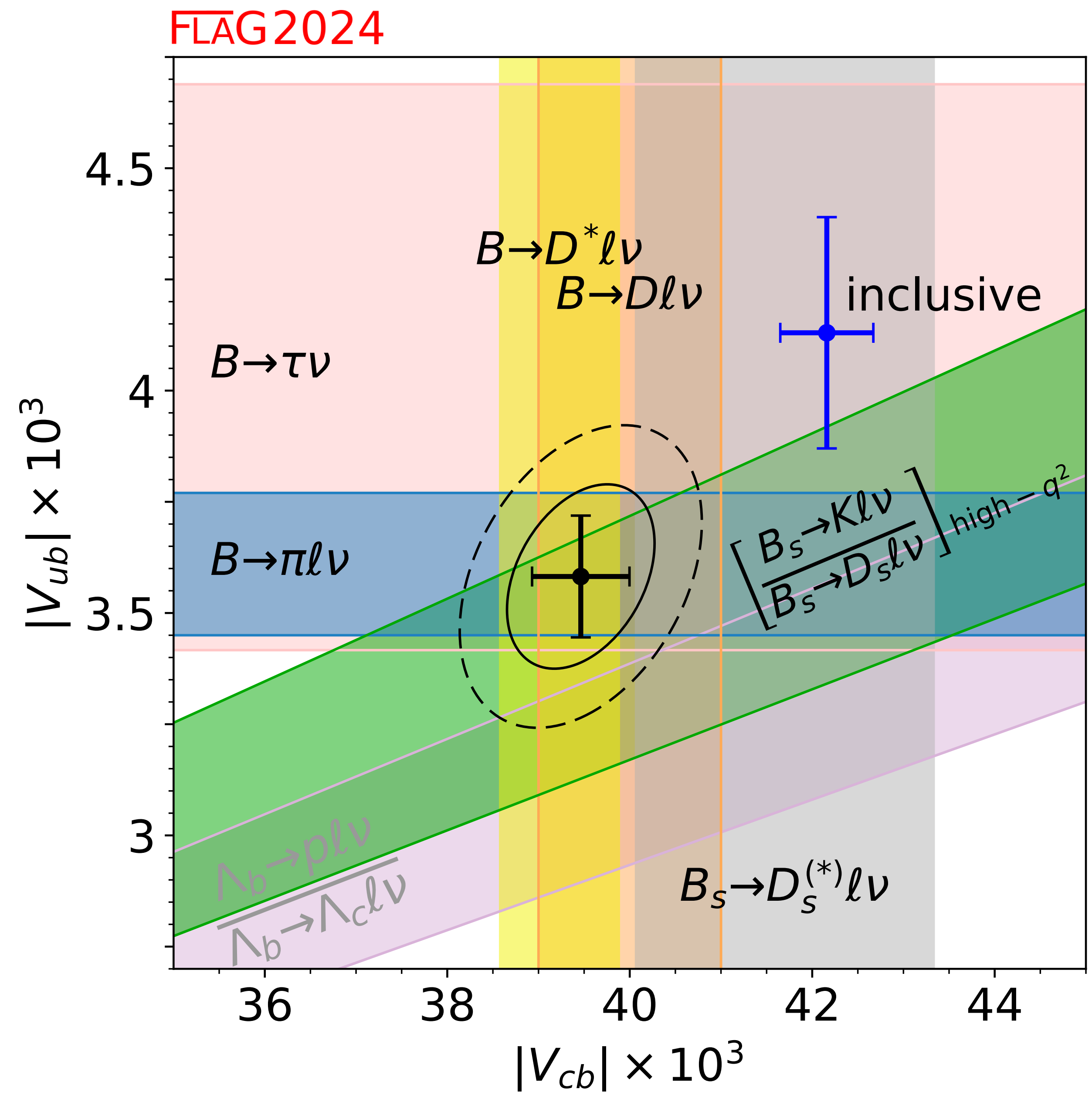
- $|V_{ub} / V_{cb}|$ determines vertex of unitarity triangle
- Unitarity is a prediction of the SM - violations could hint at new physics





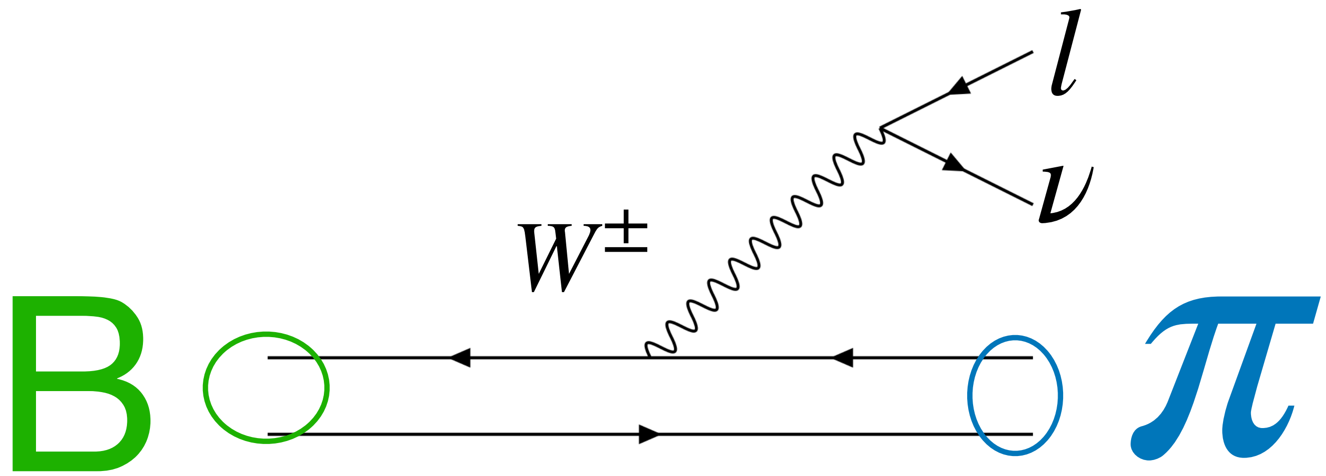
The Heavy Flavor Situation

- Inclusive/Exclusive Tension still around 2σ (for a few decades)
- Requires both theory input and experimental data… *Difficult!*



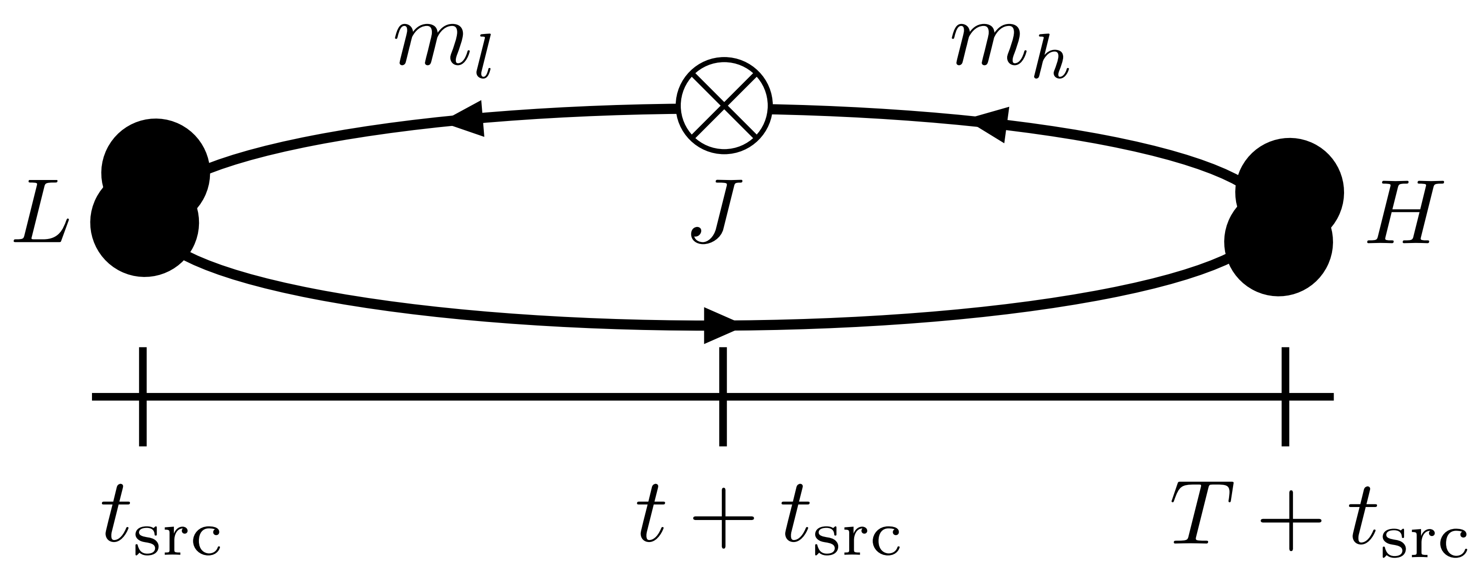
$B \to \pi l \nu$ Semileptonic Decay

- Exclusive decay



$$d\Gamma \propto |V_{ub}|^2 \text{ x (Kinematics) x (QCD)}$$

Weak Decay on the Lattice



$$C_{3pt}(t, T) = \langle\, \pi(t_{src}\,, \mathbf{p})\; J(t_{src} + t, -\,\mathbf{p})\; B(T + t_{src}\,, \mathbf{0})\,\rangle$$

Insert complete sets of states to extract matrix elements

$$|\,L\rangle\langle L\,| \qquad\qquad |\,H\rangle\langle H\,|$$

Form Factor Definitions

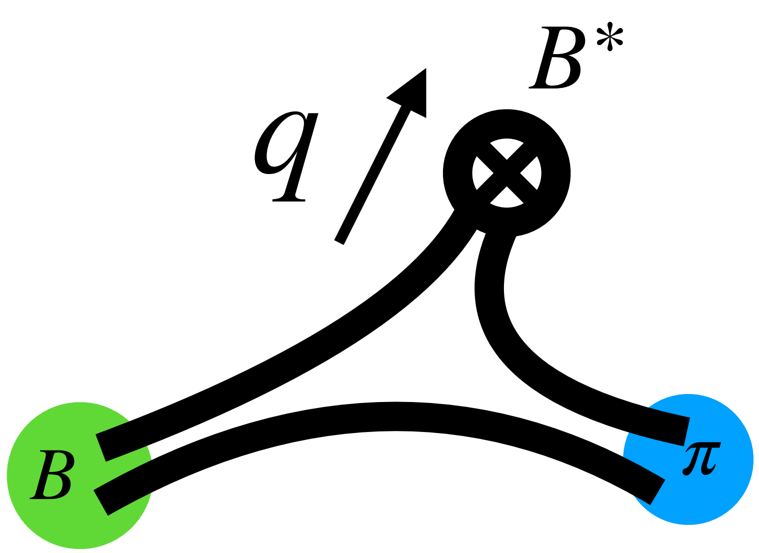
$$\langle \pi | V^\mu | B \rangle \propto \text{(kinematics) x } f_{||}(q^2) + \text{(kinematics) x } f_{\perp}(q^2)$$

$$f_{||}(q^2) \propto \langle L | V^0 | H \rangle$$

$$f_{\perp}(q^2) \propto \langle L | V^i | H \rangle$$

$$f_+(q^2) = \text{(kinematics) x } f_{\perp}(q^2) + \text{(kinematics) x } f_0(q^2)$$

$$f_0(q^2) \propto \langle L | S | H \rangle$$

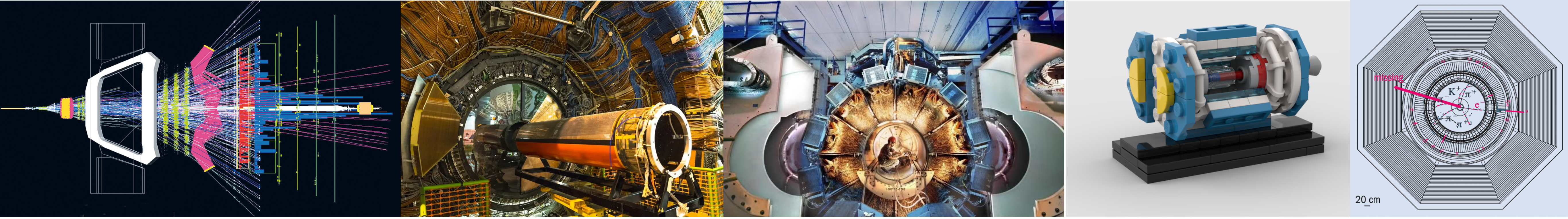


$$\propto \frac{1}{M_{B^*}^2 - q^2}$$

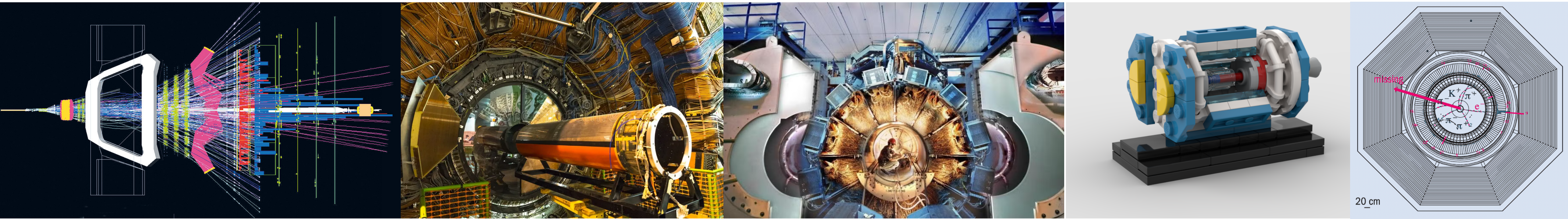
$B : J^P = 0^-$

$B^* : J^P = 1^-$

$? : J^P = 0^+$

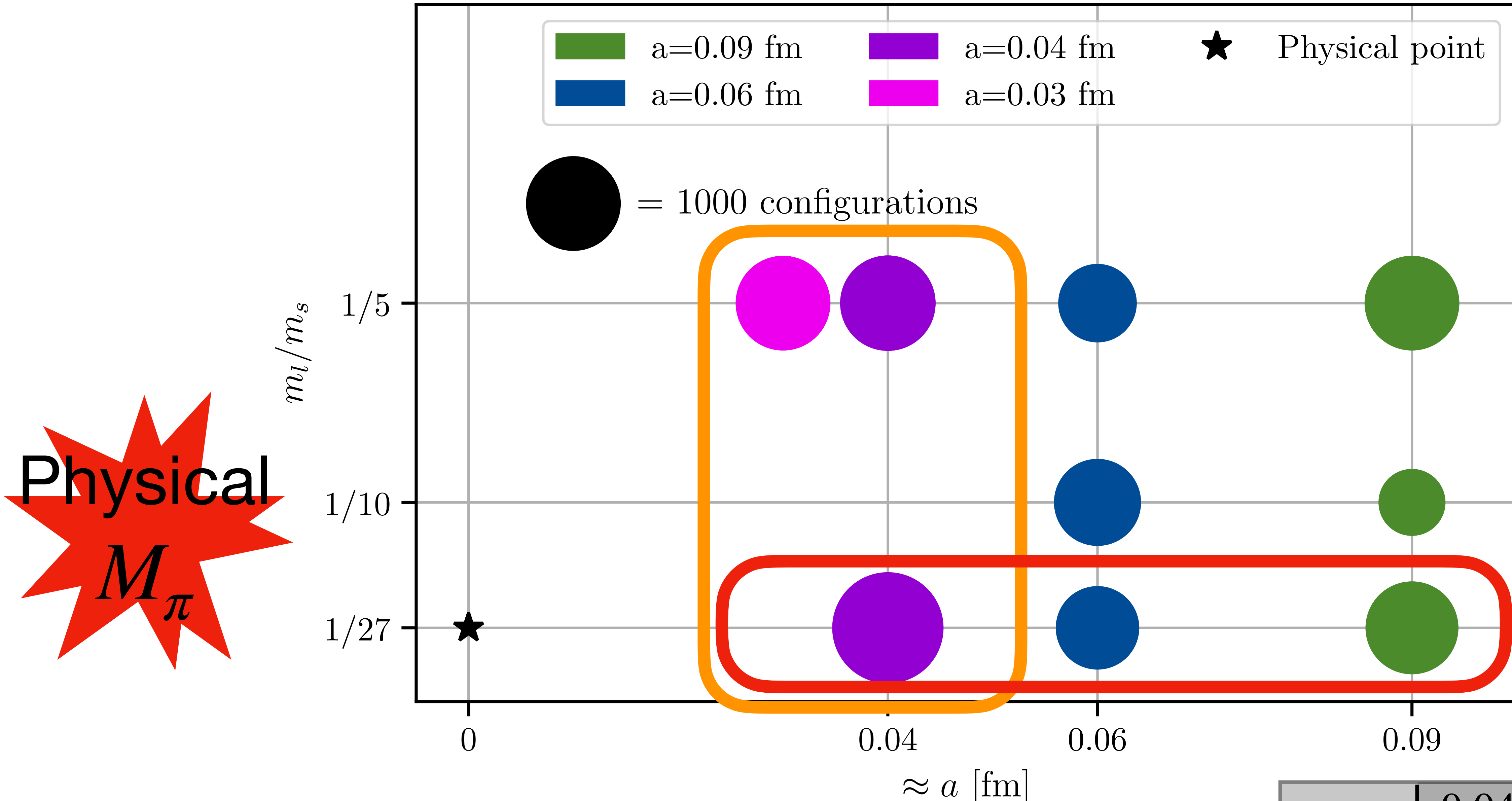


Fit Procedure



Gauge-Field Ensembles

$n_f = 2 + 1 + 1$ HISQ



Physical m_b below lattice cutoff →

	0.04fm	0.03fm
am_b	0.843	0.6084

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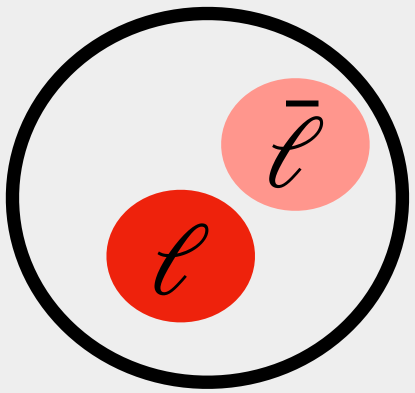
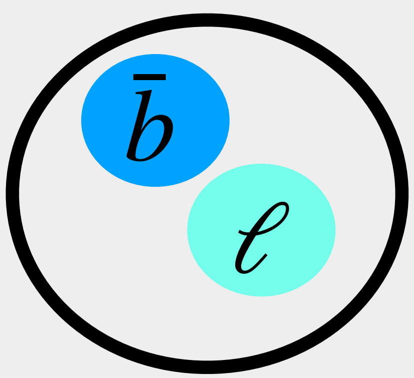
Meet the Players



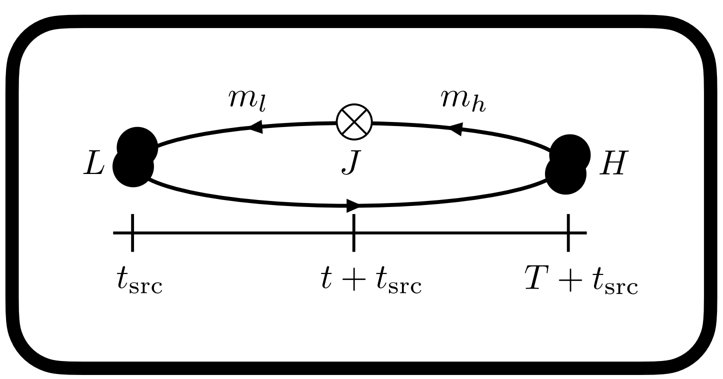
Pion 2pt function!

- computed at 8 momenta



B meson 2pt function!

- computed at rest
- heavy quark masses ranging from $\sim m_c$ up to and past m_b



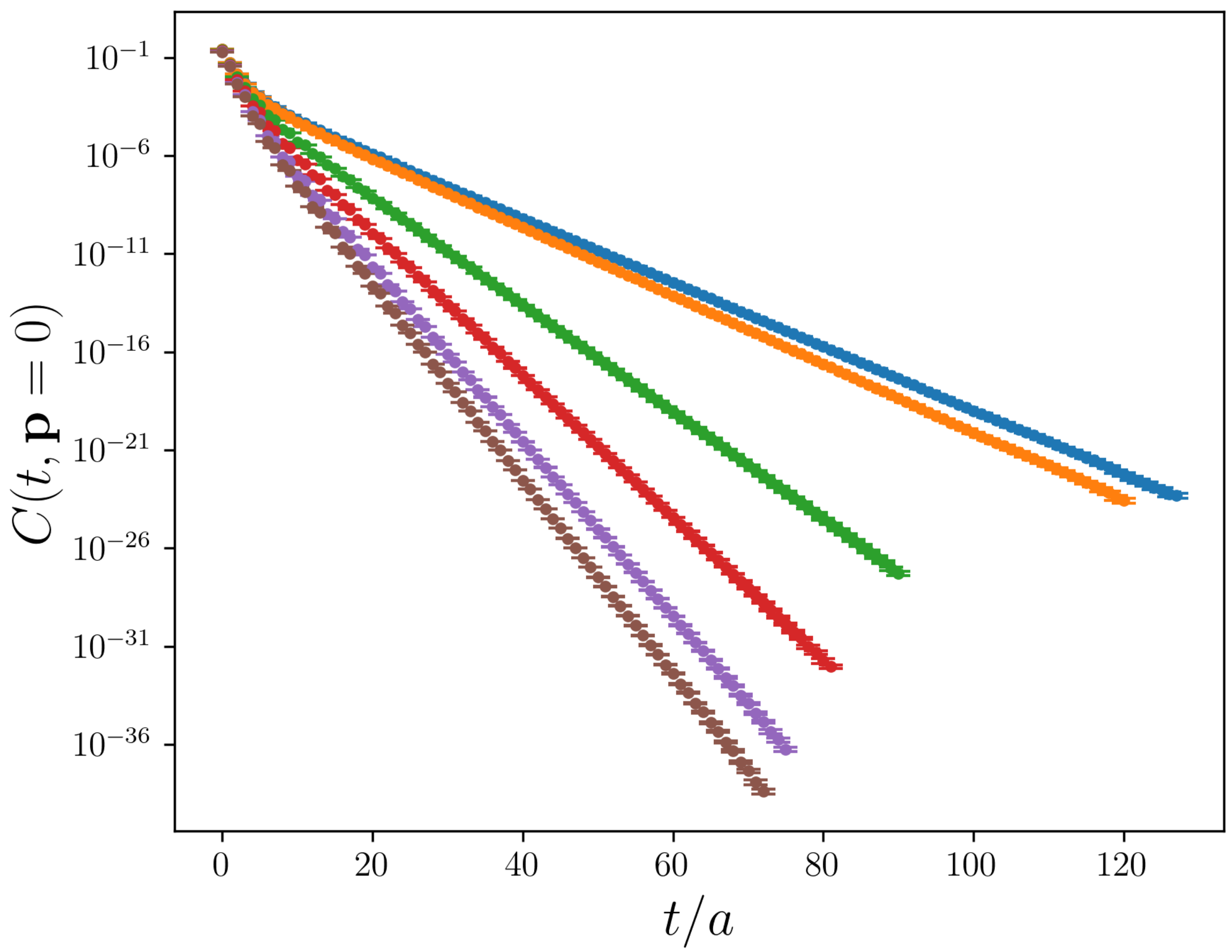
Heavy to Light 3pt function!

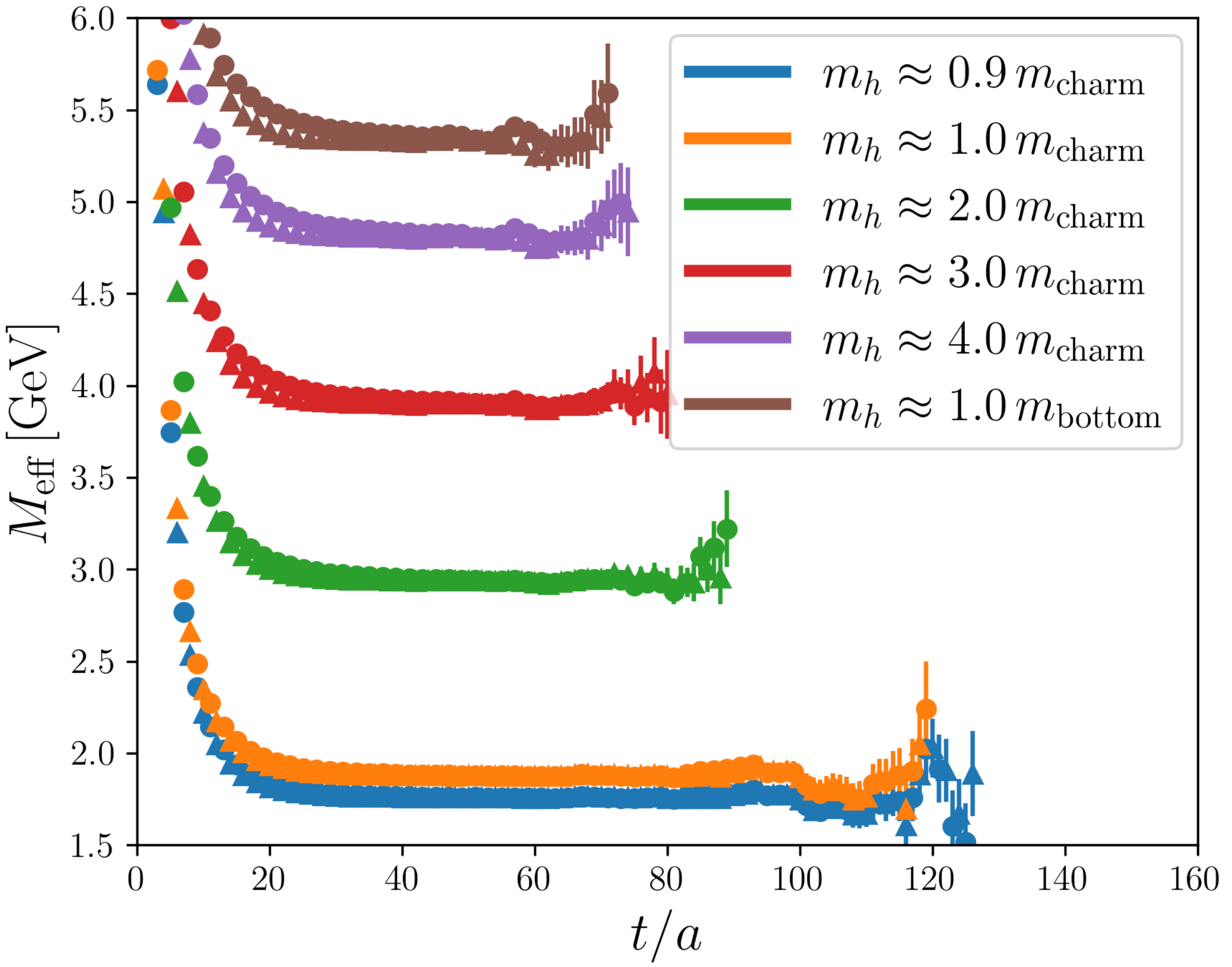
- 5 source-sink separations, up to ~3fm
- computed at 8 momenta, 5 heavy quark masses

Initial 2pt Fits

- We do Bayesian modeling to fit our correlator data to truncated spectral decompositions.
- Values for priors are based on the PDG, effective mass plateaus of the data, and naive multiparticle states
- We test for stability in the desired posteriors by choosing reasonable variations of t_{min}, as well as the number of states in the truncated spectral decomposition
- We also test for stability under inflation of prior widths, and shifting of the central values.

B-meson 2pt Functions

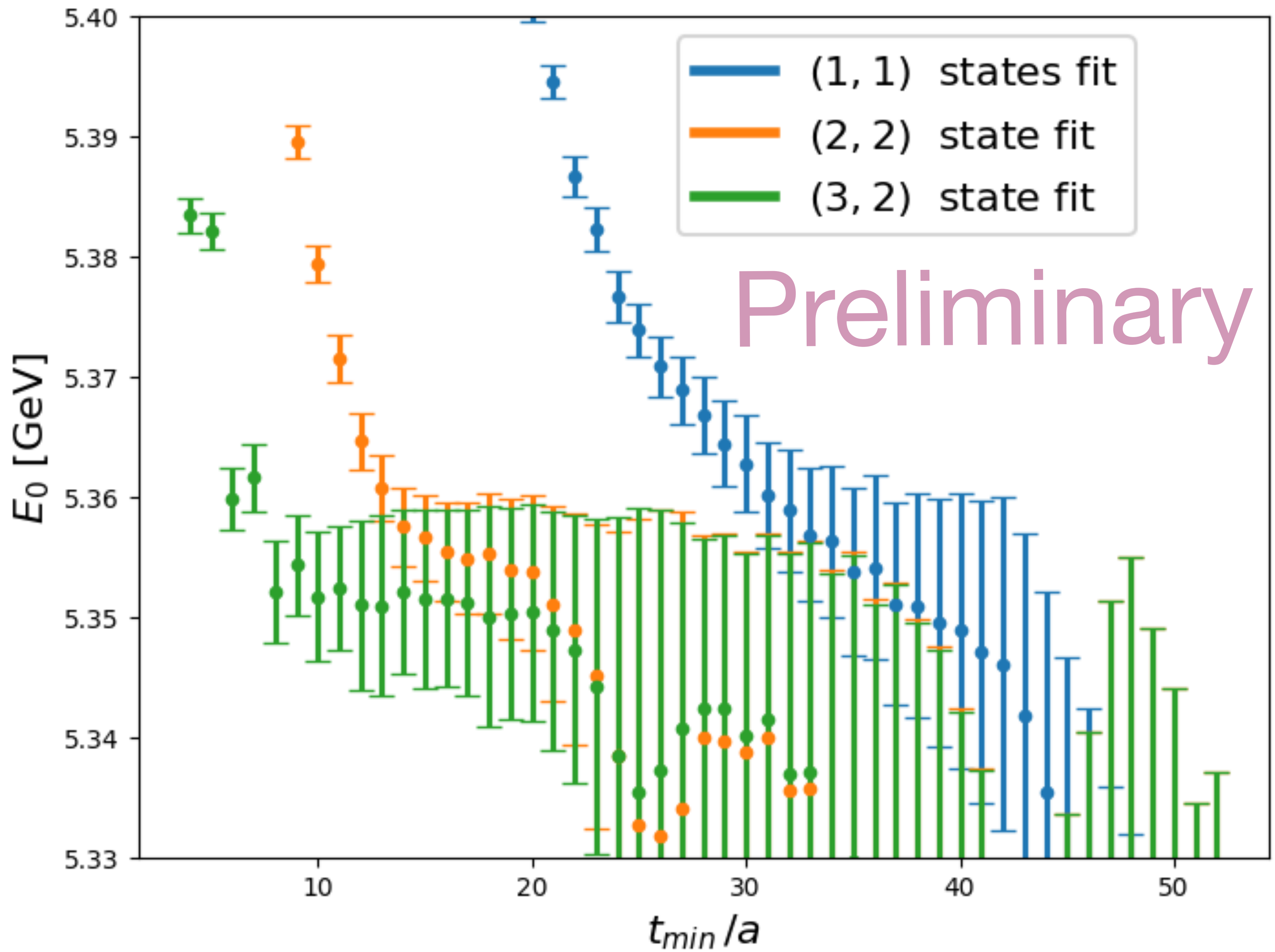




$a = 0.042\,\mathrm{fm}$

$M_\pi = 135\,\mathrm{MeV}$

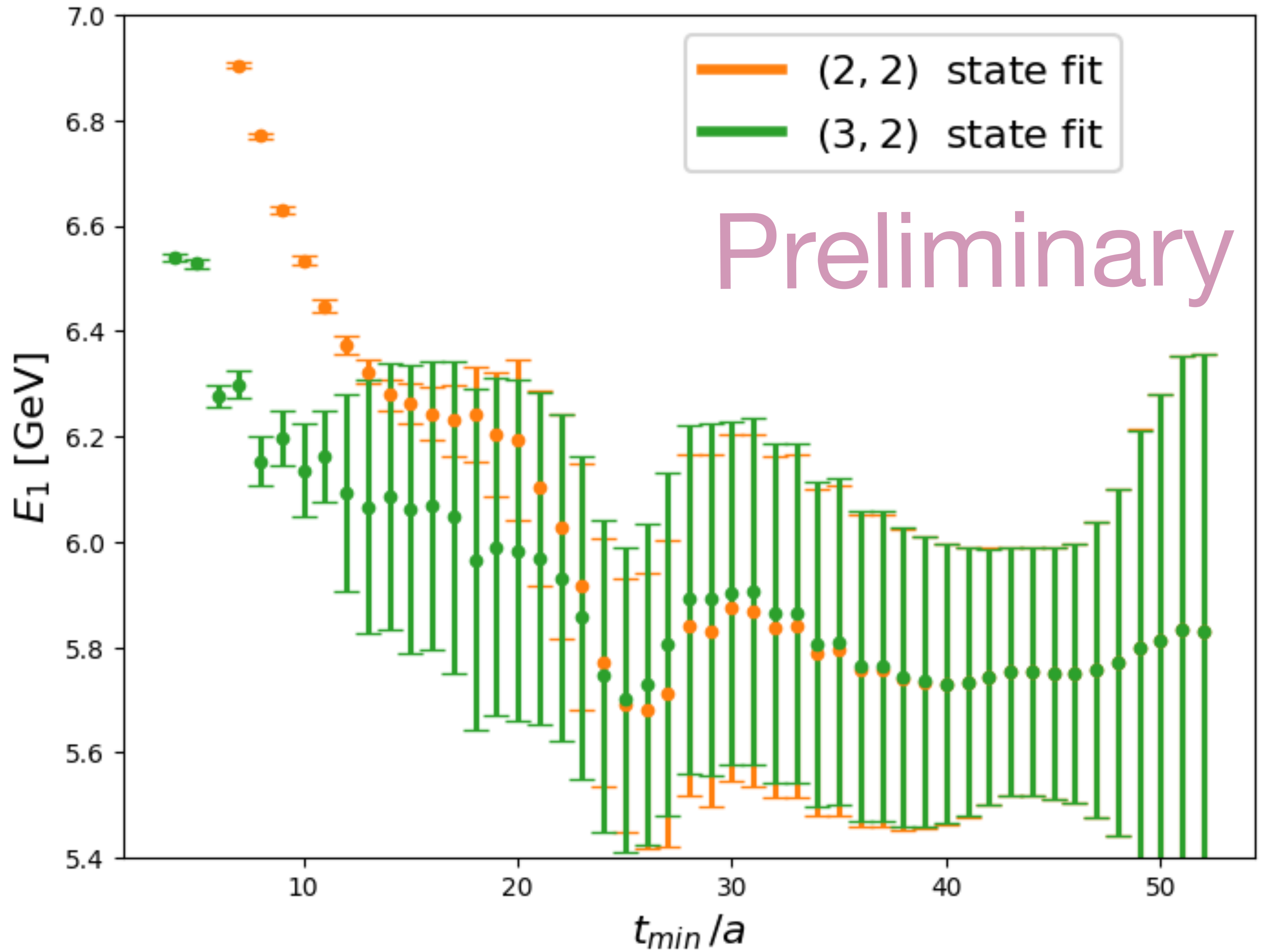
B-meson Ground State



a=0.042fm

$M_\pi = 135\,\mathrm{MeV}$

B-meson Excited State



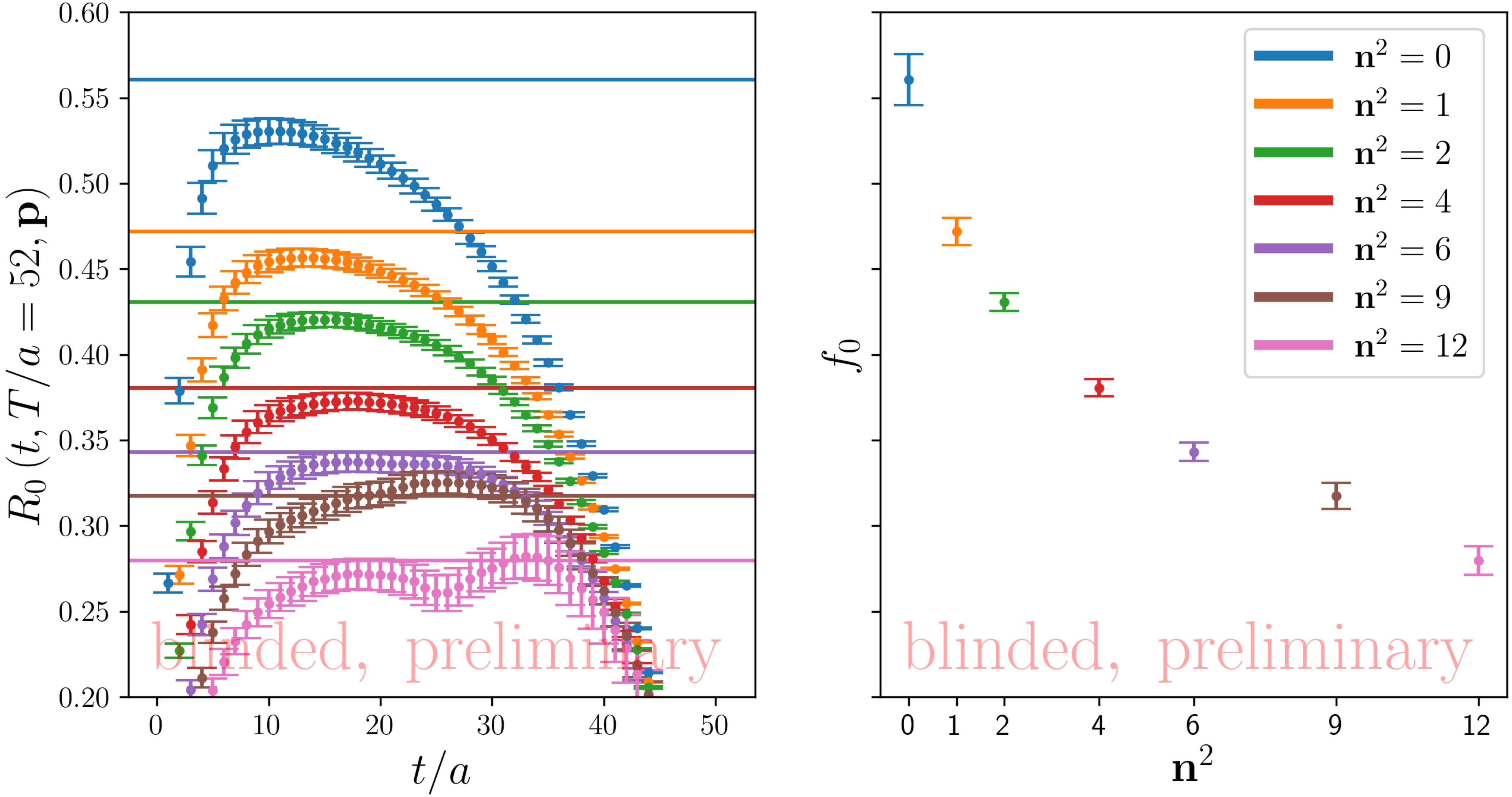
Joint 2pt + 3pt Fits

1. Do isolated 2pt fits
2. Assemble priors for joint fits
3. Simultaneously fit the pion 2pt function, B-meson 2pt function, and 3pt functions to truncated spec. decomp.
4. 2pt spectrum and 3pt spectrum enforced to be equivalent in joint fits
5. Extract matrix element for ground state

$$\left\{ \begin{array}{l} C_\pi(t, \mathbf{p}) \\ C_B(t, \mathbf{0}) \\ C_{3pt}(t, T_1, \mathbf{p}) \\ C_{3pt}(t, T_2, \mathbf{p}) \\ C_{3pt}(t, T_3, \mathbf{p}) \\ C_{3pt}(t, T_4, \mathbf{p}) \end{array} \right.$$

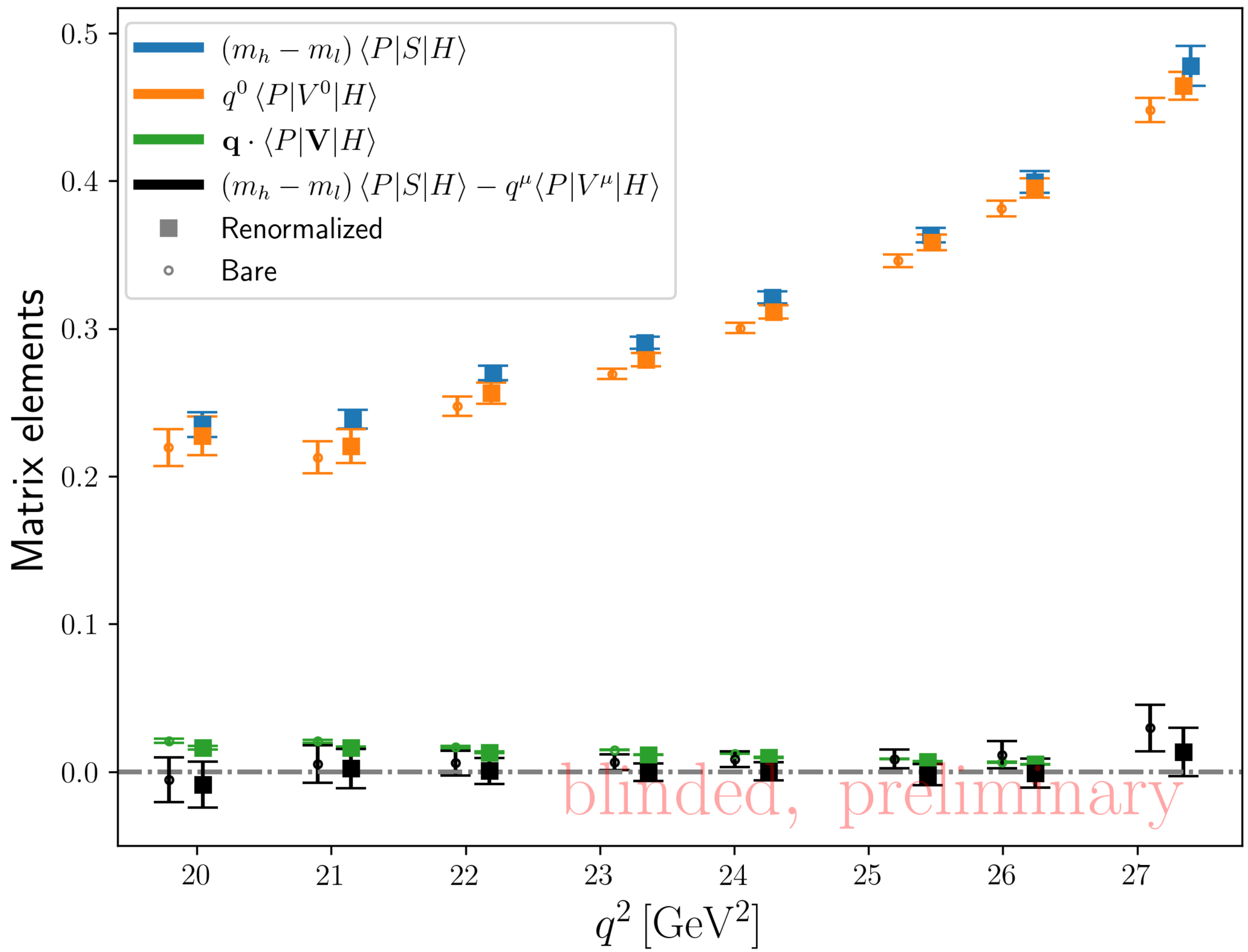
Extracting Matrix Elements

$$R_0(t, T, \mathbf{p}) \propto \frac{C^S_{H\to P}(t, T, \mathbf{p})}{\sqrt{C_P(t, \mathbf{p}) C_H(T-t)}}$$



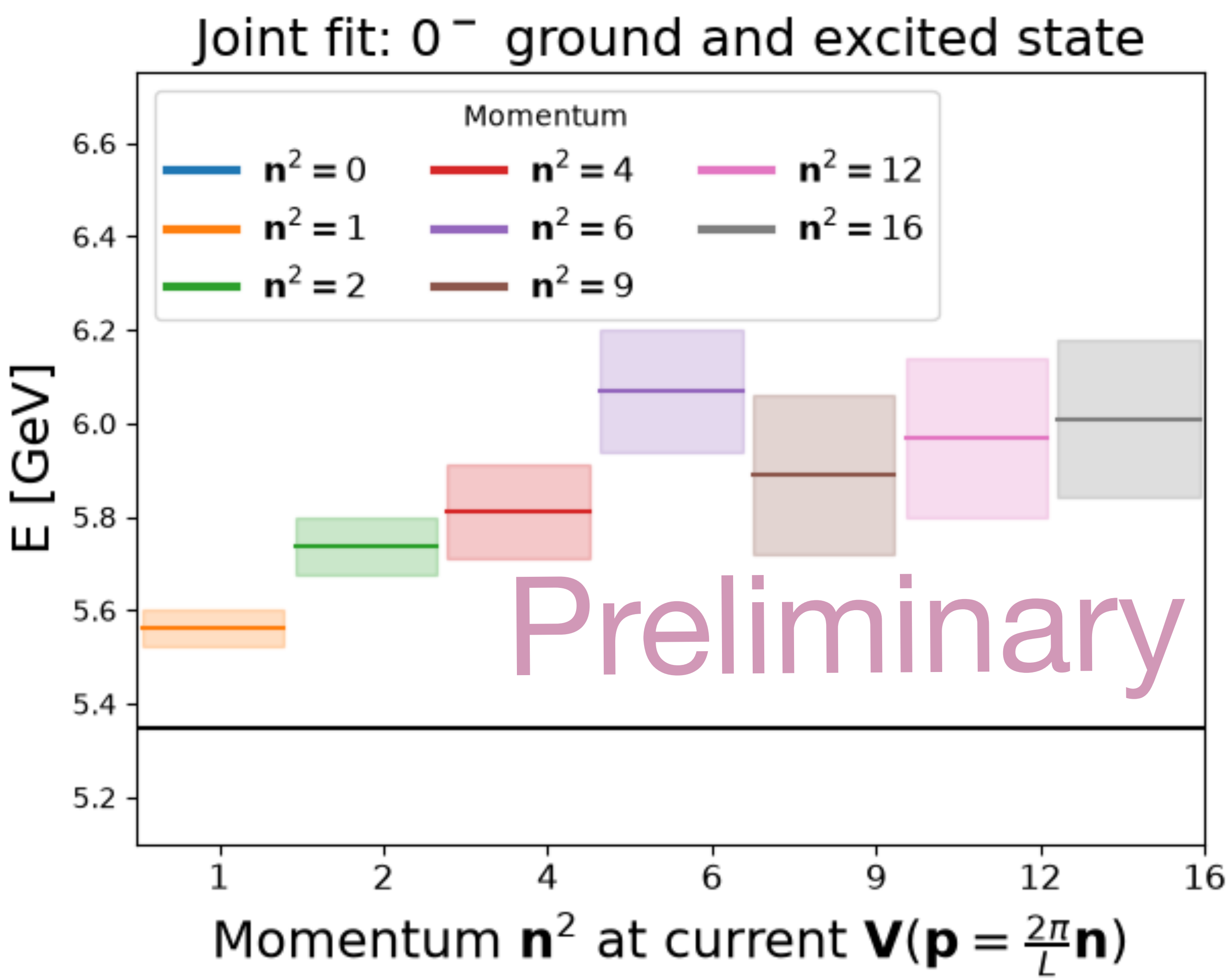
Partial Conservation of the Vector Current

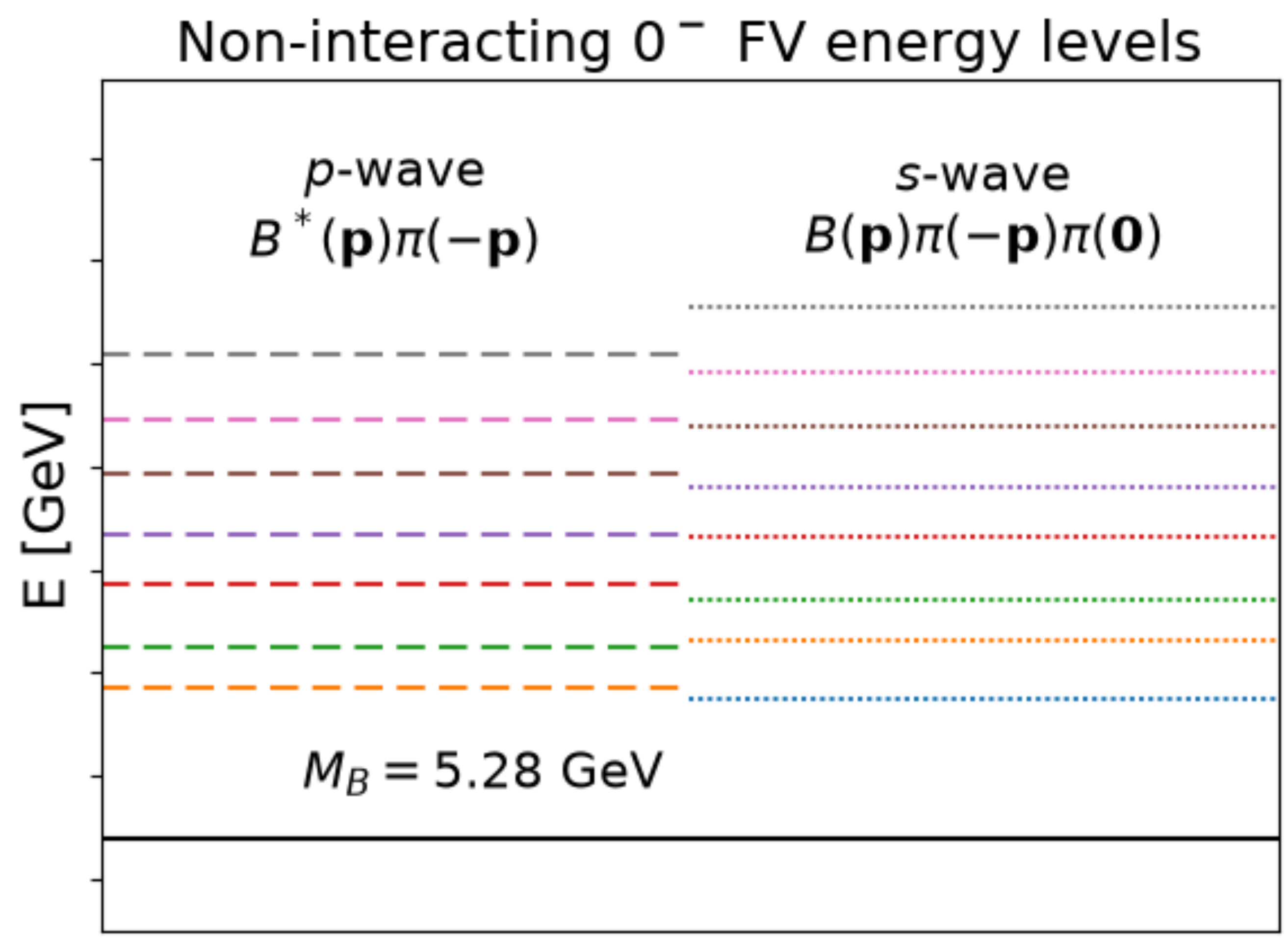
$$Z_{V^0}(M_H - E_P)\langle P\,|\,V^0\,|\,H\rangle + Z_{V^i}\,\mathbf{q}\cdot\langle P\,|\,\mathbf{V}\,|\,H\rangle = Z_M Z_S(m_h - m_x)\langle P\,|\,S\,|\,H\rangle$$

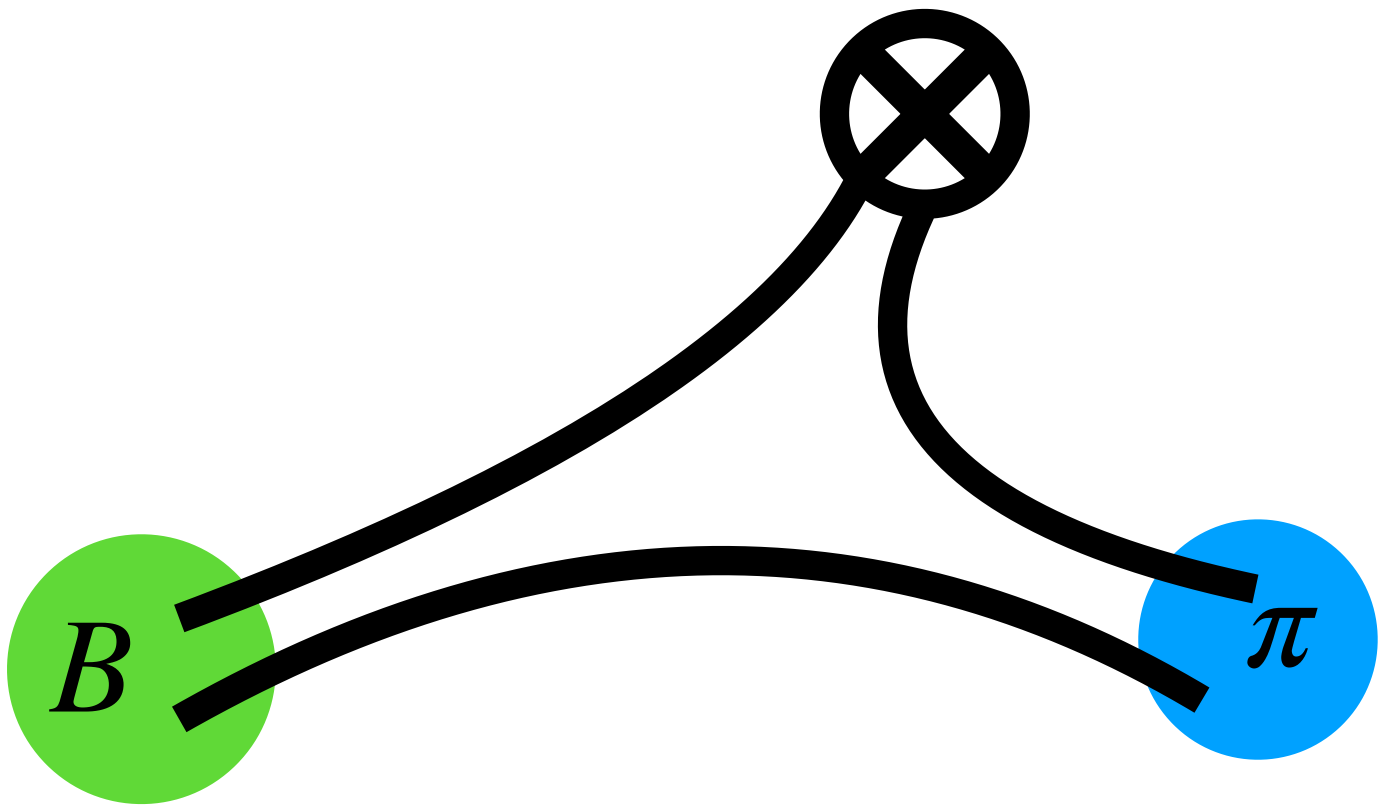


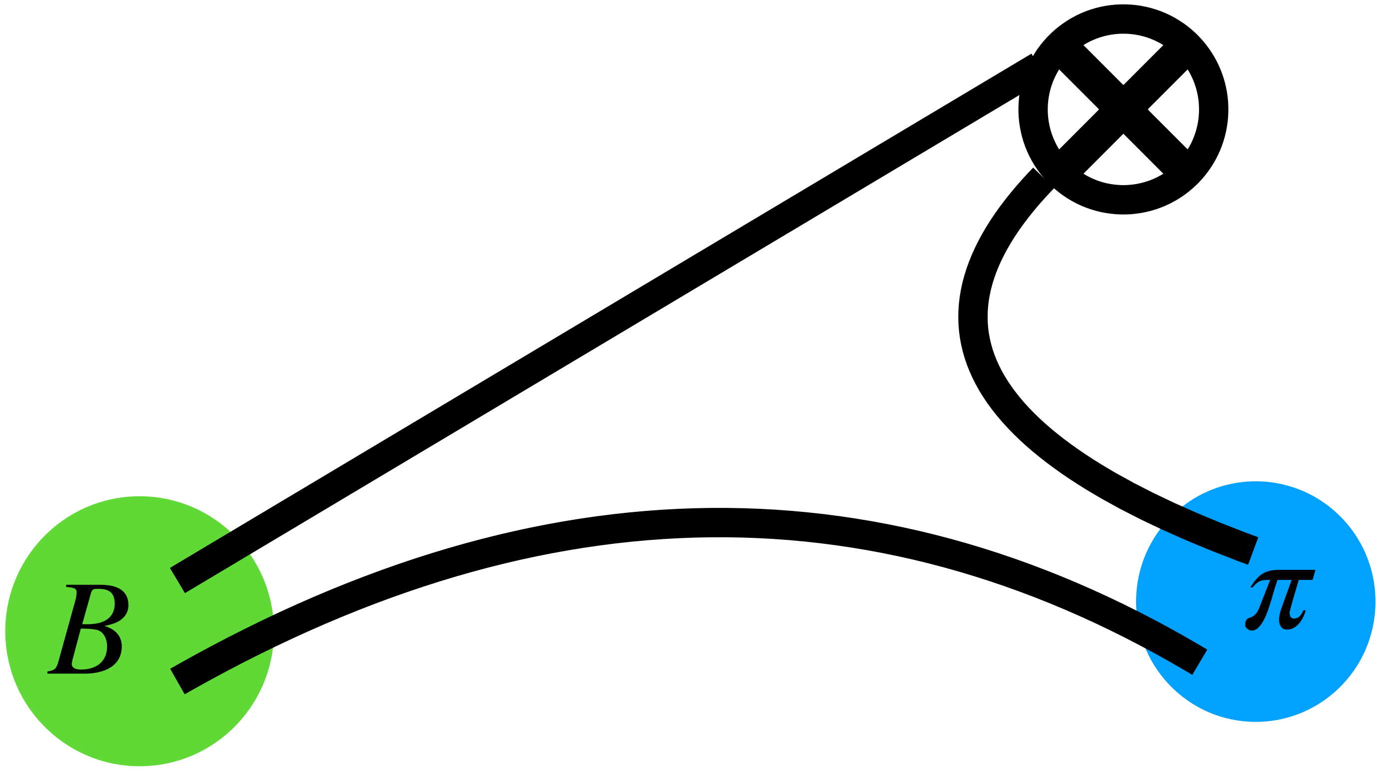
B-meson 0^- spectrum

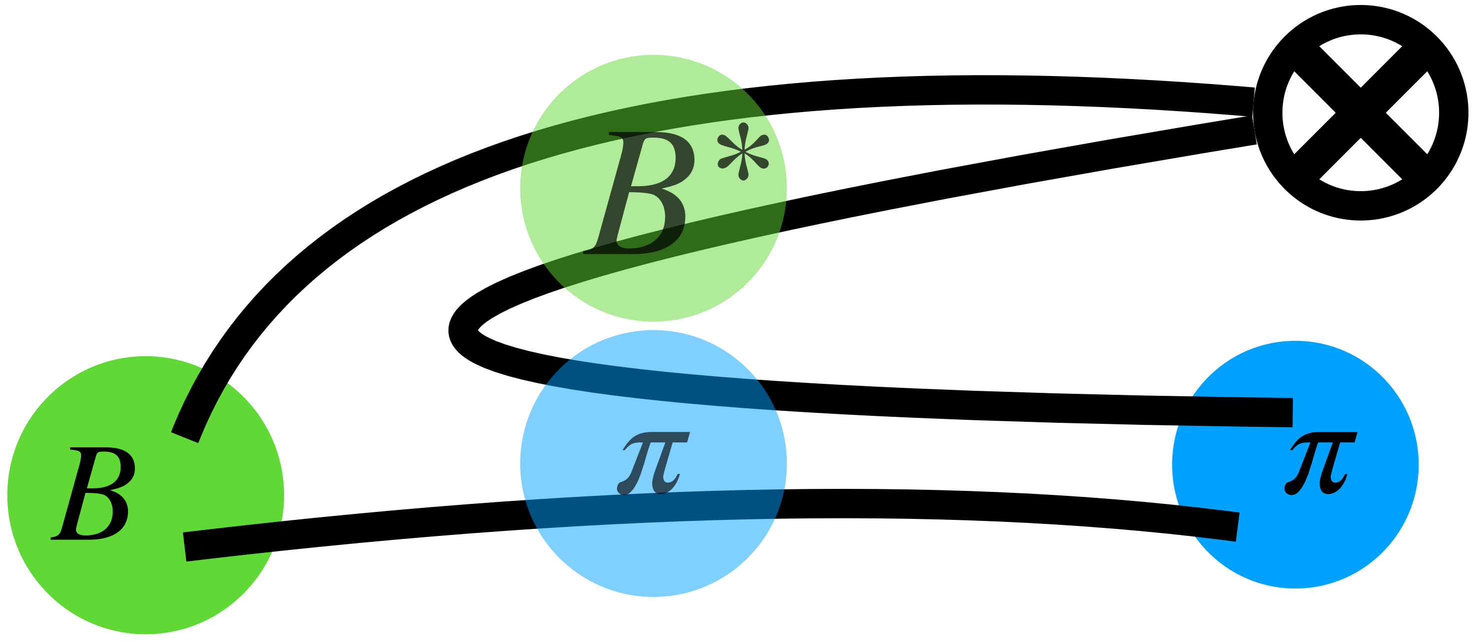
* Work in Progress





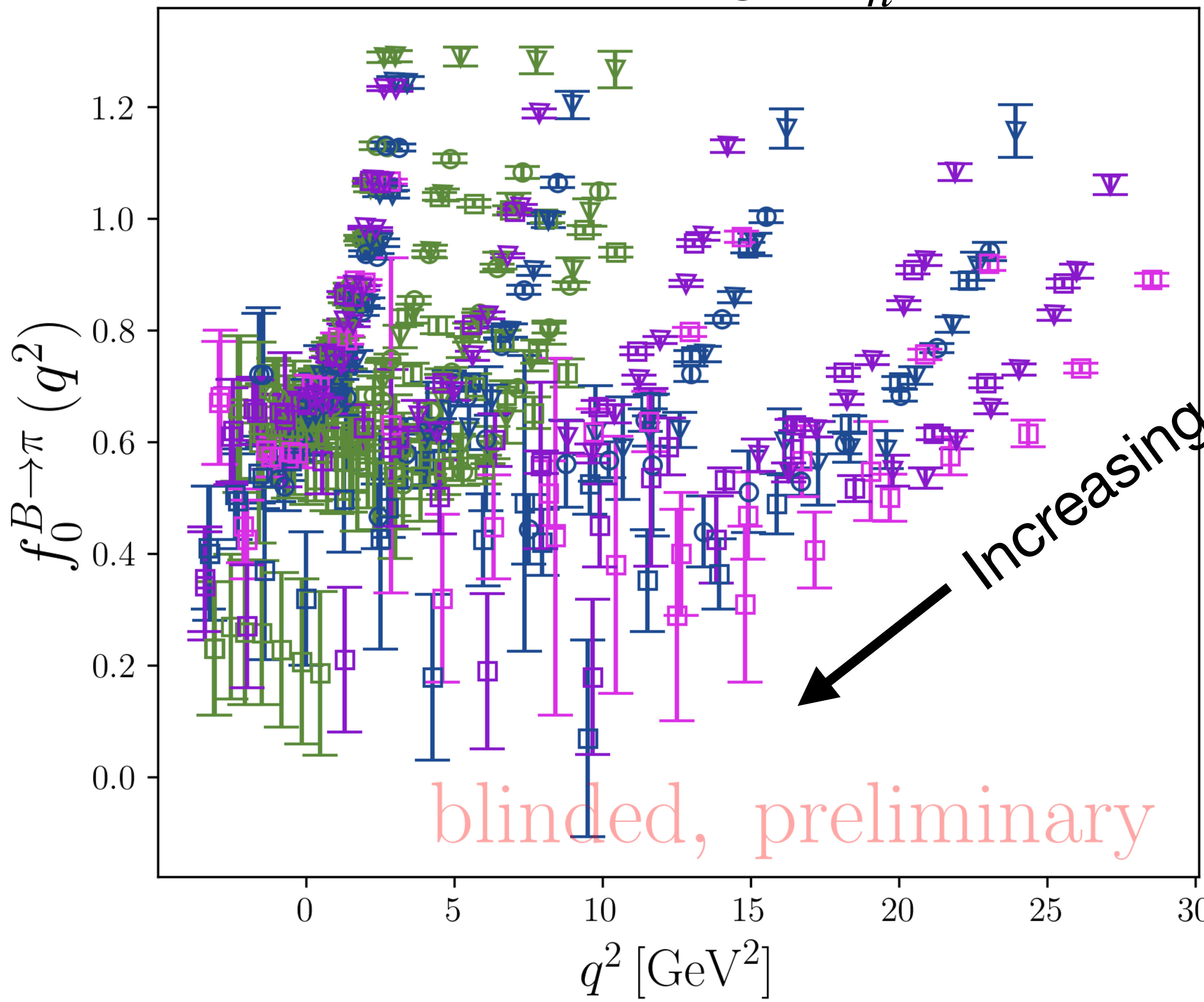

B
π


B
π

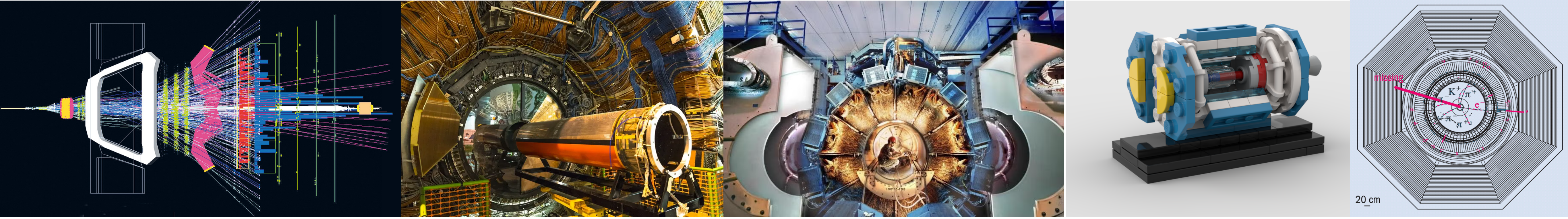

B^*
B
π
π

Form Factor Fits

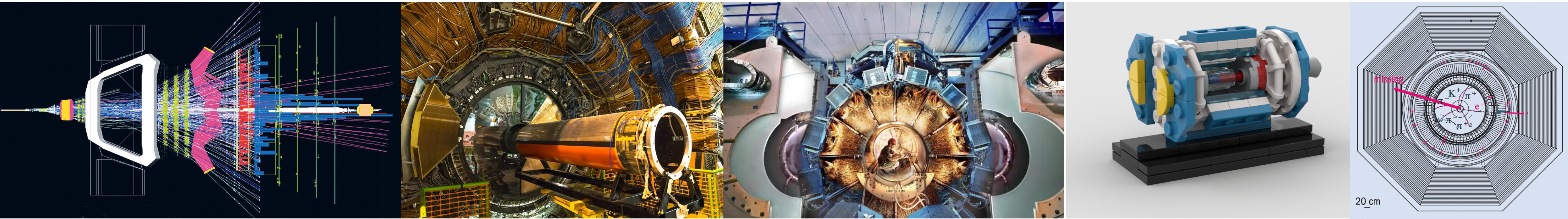
Increasing am_h



Increasing E_π



Journey to the Continuum



Continuum Fit Form

$$w_0^{d_P} f_P = \frac{c_0}{w_0 \left(E + \Delta_{xy,P}\right)} \text{ x } \left[1 + \delta \mathrm{f}_{\mathrm{logs}} + \text{ discretization} + \text{ mistunings}\right]$$

- Heavy Meson Rooted Staggered χPT

Continuum Fit Form

$$w_0^{d_P} f_P = \boxed{\frac{c_0}{w_0 \left(E + \Delta_{xy,P}\right)}} \text{ x } \left[1 + \delta \mathrm{f}_{\mathrm{logs}} + \text{ discretization} + \text{ mistunings}\right]$$

$$\boxed{\frac{1}{E + \Delta_{xy,P}}} = \frac{2M_{B_y}}{M_{B_x^*} - q^2} \quad \Rightarrow \quad \Delta_{xy,P} = \frac{M^2_{B_x^*(J^P)} - M_B^2 - M_\pi^2}{2M_B}$$

- The angular momentum that appears must match the current

$0^+ : B_0^* = ??$

$1^- : M_{B^*(PDG)} \approx 5325 \text{ [MeV]}$

Continuum Fit Form

$$w_0^{d_P} f_P = \frac{c_0}{w_0\,(E + \Delta_{xy,P})} \times \left[1 + \delta f_{\text{logs}} + \boxed{\text{discretization}} + \boxed{\text{mistunings}}\right]$$

Heavy Quark Discretization:

$$x_h^2 = \frac{2}{\pi}(am_h)^2$$

Can be suppressed by α_s, velocity, $\frac{\Lambda_{HQET}}{M_H}$, or combinations thereof

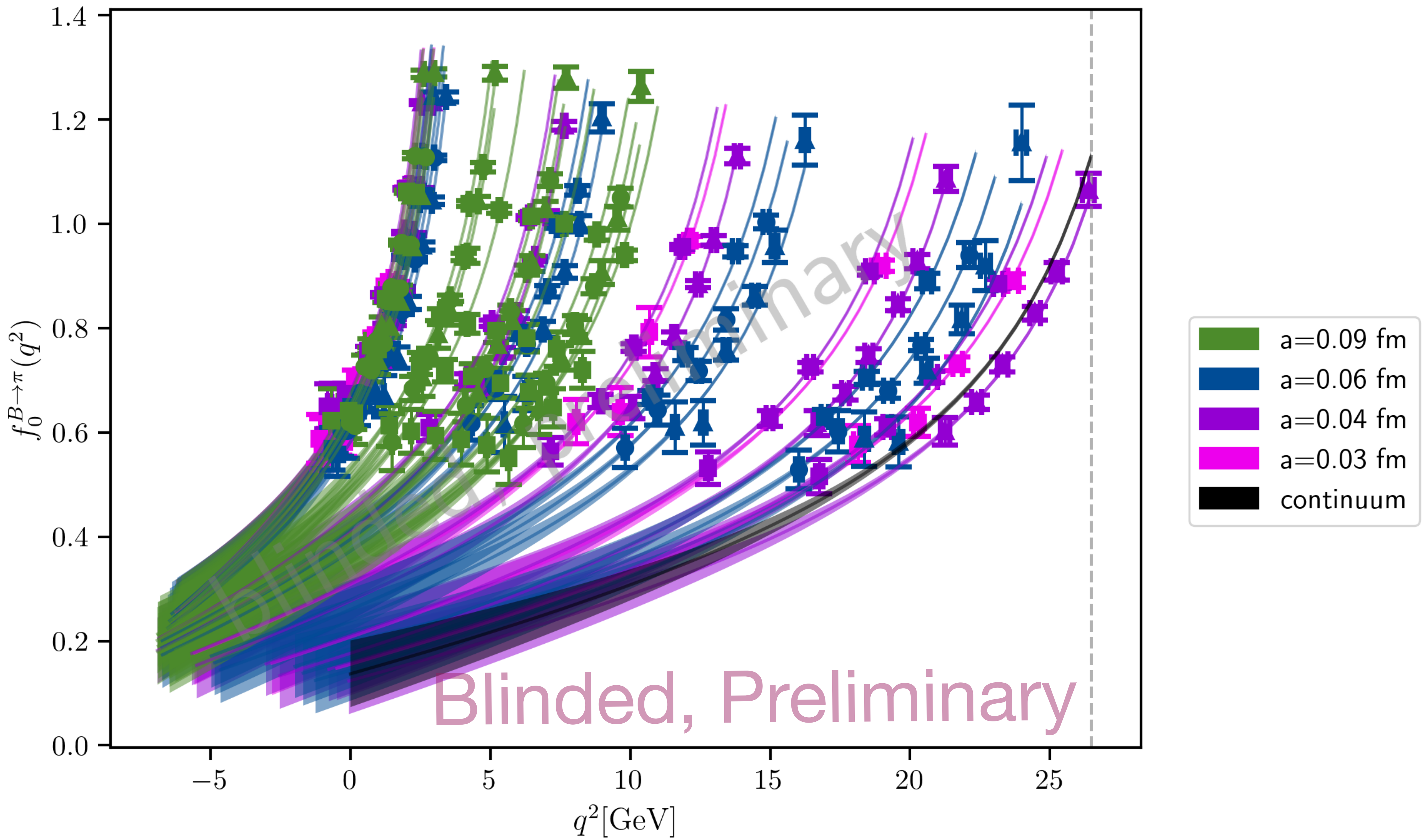
Heavy Quark Mistuning:

$$\chi_H = \frac{\Lambda_{HQET}}{M_H^{\text{sim}}} - \frac{\Lambda_{HQET}}{M_B^{\text{PDG}}}$$

Others:

$$\chi_l = \frac{(M_\pi^{sim})^2}{8\pi^2 f_\pi^2} \qquad \chi_E = \frac{\sqrt{2}E}{4\pi f_\pi} \qquad \chi_S = \frac{(M_K^{\text{sim}})^2 - (M_K^{\text{PDG}})^2}{8\pi^2 f_\pi^2}$$

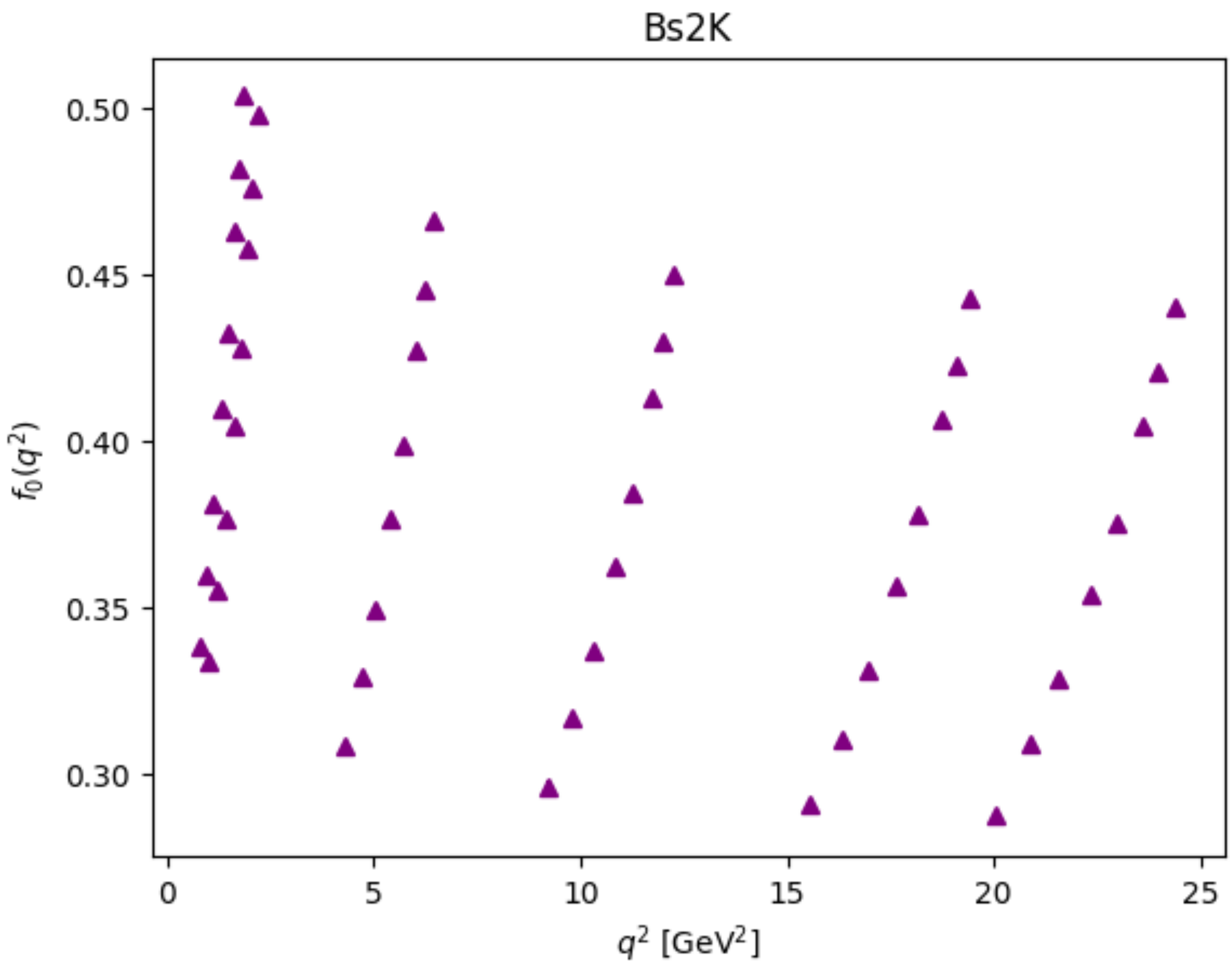
Chiral-Continuum Fit



Conclusions

- Simulations are now running with 4 flavors (2x light, strange, charm) HISQ with fine enough lattice spacings to reach the physical bottom quark mass
- We are currently working on taking the continuum limit
- Next steps will be combining our continuum form factors with experimental data to calculate $|V_{ub}|$
- Extract form factors for $B_S \to K\ell\nu$ and repeat

$B_S \to K$ Correlator Fits

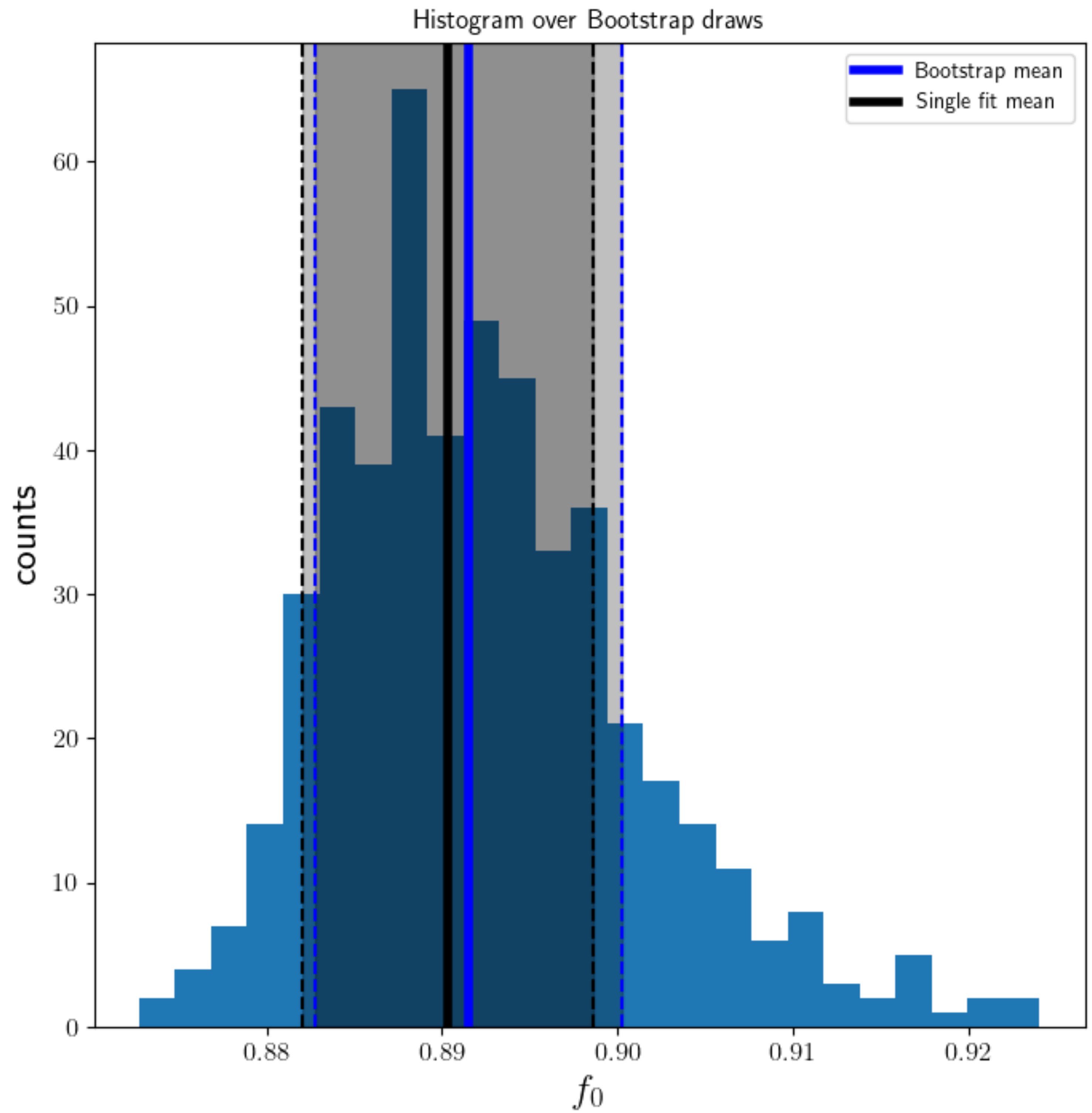


a=0.042fm

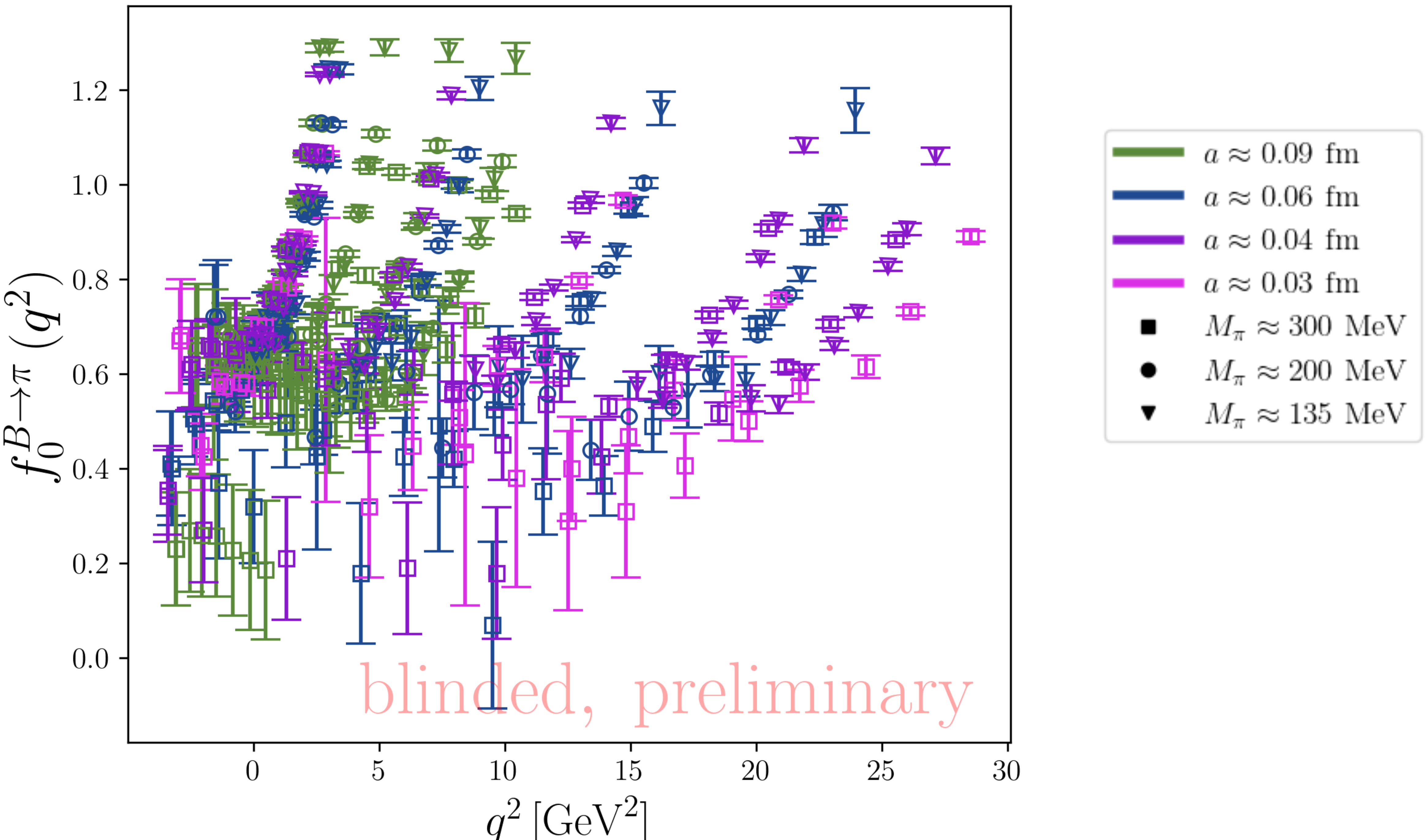
$M_\pi = 135\,\mathrm{MeV}$

Bootstraps

- Correlations are included in the error propagation via bootstrapping with 500 draws
- Single fit posteriors are seen to be statistically consistent with a similar size error bar
- $a = 0.042\,\mathrm{fm}$,
  $m_l = 0.2\,m_s$,
  $m_h = 1.0\,m_b$



All Form Factors: f_0



All Form Factors: f_+