Nuclear Science Computing Center at CCNU

Lattice QCD prediction of kaon form factor at large Q^2 up to 10 GeV^2

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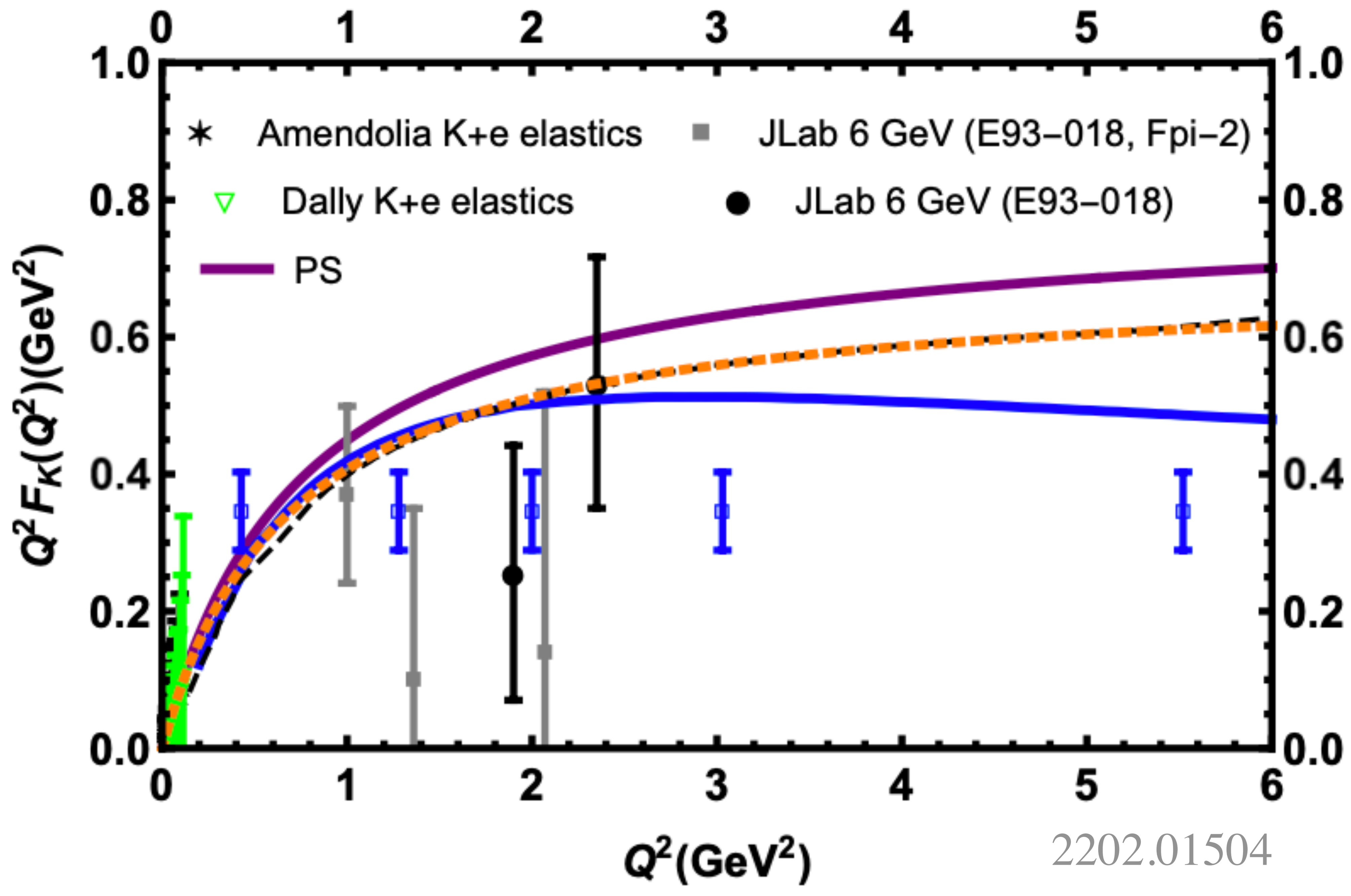
Motivation

☞ Form factor: the Fourier transform of electromagnetic current distribution in space

- The hadron structure
- The interplay between the emergent hadron mass (EHM) & the Higgs-mass mechanism
- FF + PDF -> GPD, three-dimensional image of the hadron
- Nucleon & Pion & **Kaon**



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☞ Kaon:

- Experiment: JLab, EIC, EicC … 2102.11788, 2102.09222
- Effective theories: QCD sum rules, DSE … 1703.04875
- **Lattice QCD: from first principle**
  - ❍ **State-of-the-art: $Q^2 \leq$ 3 GeV^2** 2111.08135
  - ❍ **This work: Q^2 up to 10 GeV^2**

Lattice setup:

- Lattice size: $N_s^3 \times N_t = 64^3 \times 64$, lattice spacing: $a = 0.076$ fm
- Sea quark: Highly Improved Staggered Quark (HISQ) action

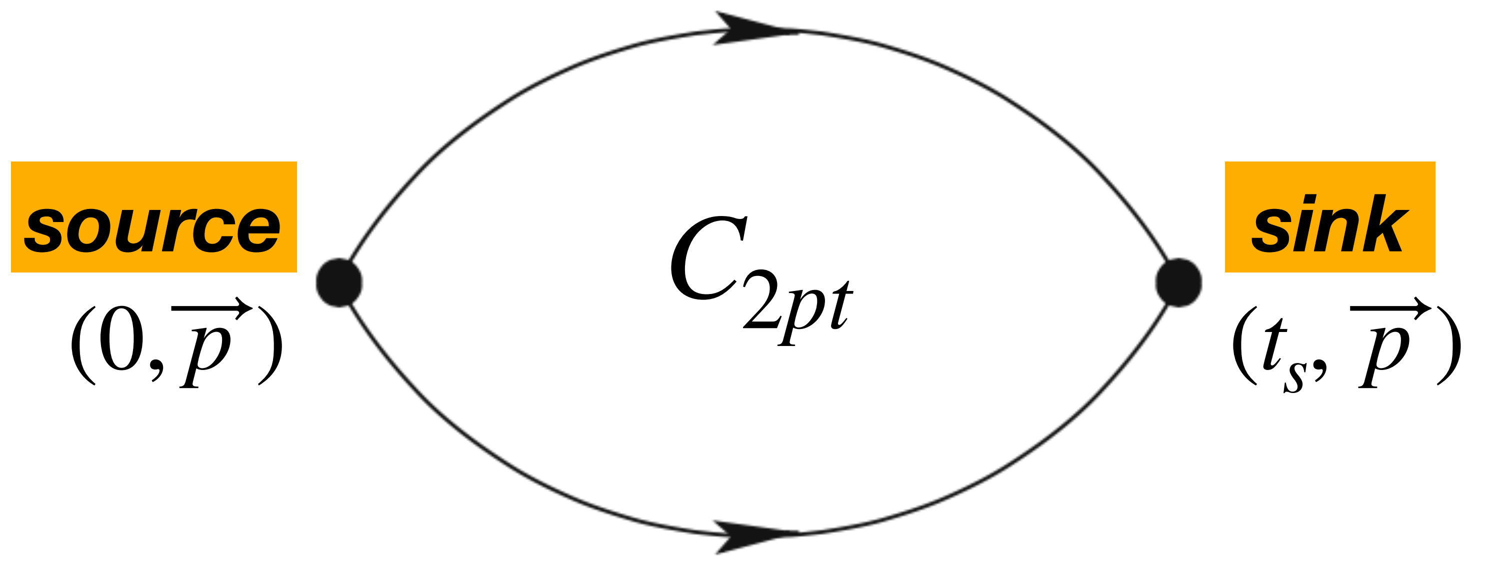
  Valence quark: Wilson-Clover action

  ⇒ $m_{\pi^+} = 140$ MeV, $m_{K^+} = 497$ MeV **at the physical point**
- Use boost smearing at source & sink time position to enhance the signal

  ⇒ The wide range of Q^2 is **1~10 GeV^2**

Compute form factor on the Lattice

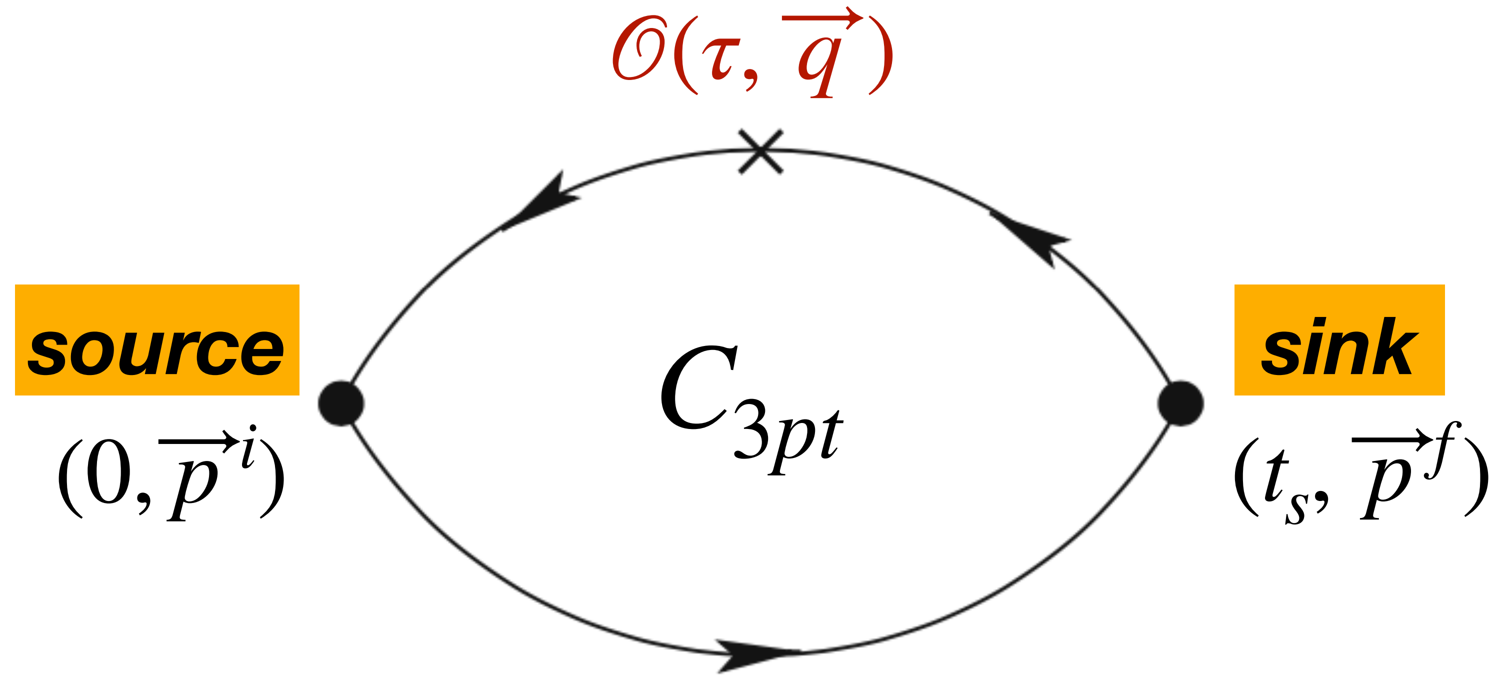
Construct a hadron state: $C_{2pt}(t, \vec{p}) = \langle H(t_s, \vec{p}) H^\dagger(0, \vec{p}) \rangle$



Insert an electromagnetic current $\mathcal{O}(\tau, \vec{q})$ to probe the hadron

$\vec{p}^f = \vec{p}^i + \vec{q}$

$C_{3pt}(\tau, t_s; \vec{p}^i, \vec{p}^f) = \langle H(t_s, \vec{p}^f) \hat{\mathcal{O}}_{\gamma^\mu}(\tau, \vec{q}) H^\dagger(0, \vec{p}^i) \rangle$



Extract the bare form factor:

$F^B = \langle E_0, \vec{p}^f | \hat{\mathcal{O}}_{\gamma^\mu}(\tau, \vec{q}) | E_0, \vec{p}^i \rangle$

from ~ C_{3pt} / C_{2pt}

Renormalization

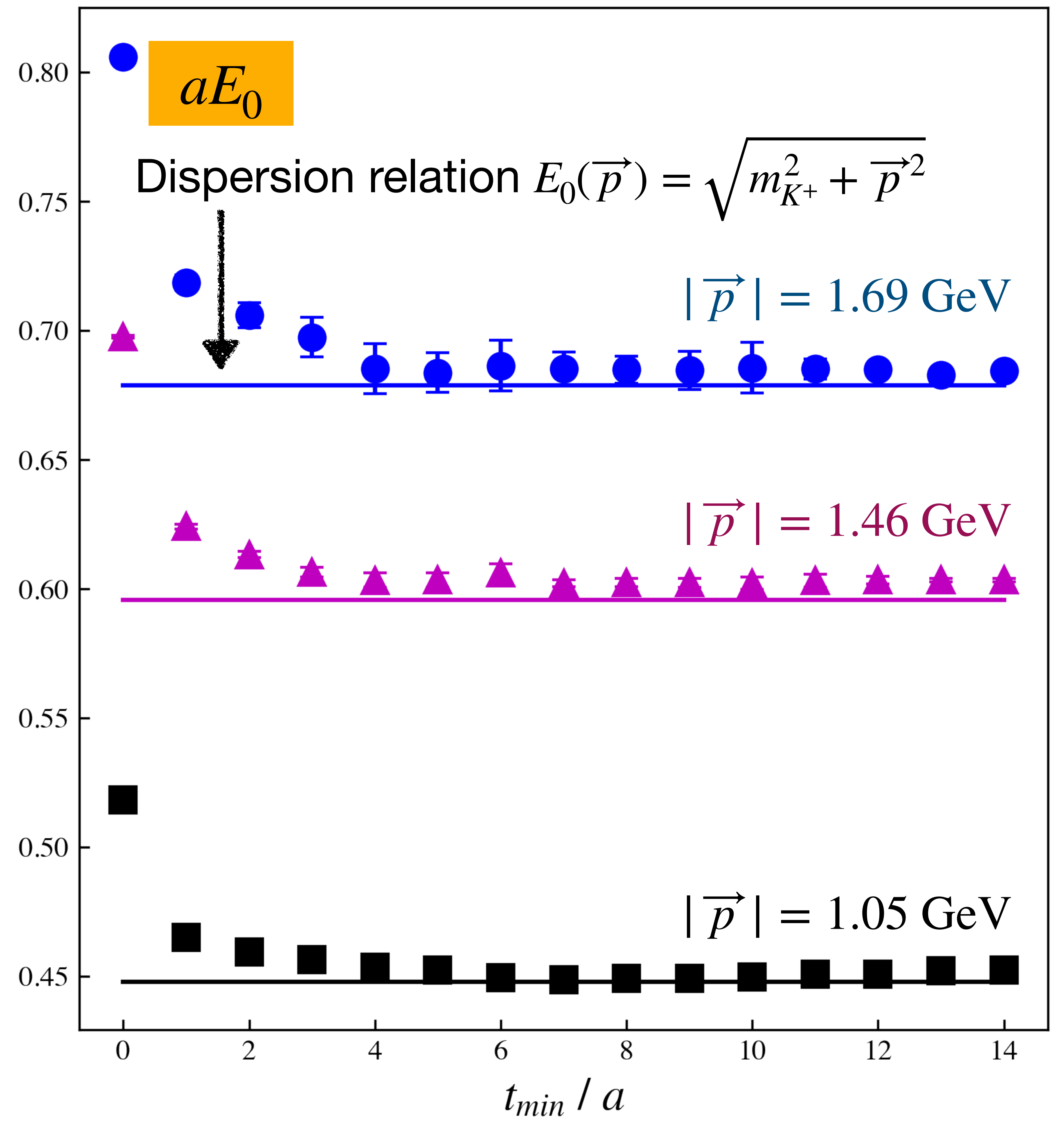
Form factor: $F(Q^2) = F^B \times Z_V$

with $Q^2 = -q^2$

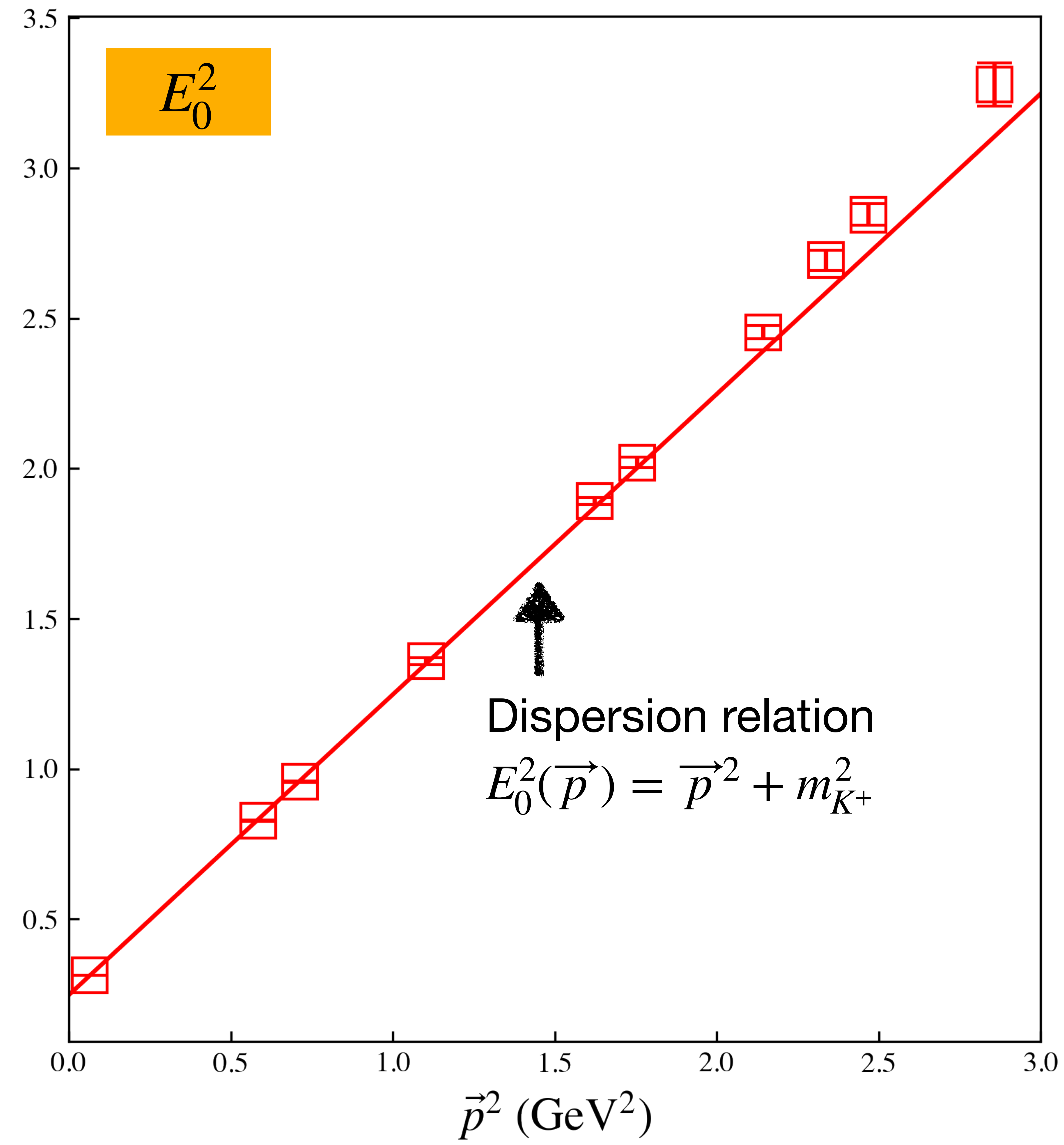
1. Construct the hadron state C_{2pt}

$$C_{2pt}(t_s) = \sum_{k=0}^{N_{state}-1} A_k \left[e^{-E_k t_s} + e^{-E_k(aN_t - t_s)}\right]$$

Fit with $N_{state} = 2$ → $E_0, E_1;\ A_0, A_1$



Fit with different range of $t_s/a \in [t_{min}/a, N_t/2]$



All results of E_0

2. Extract the bare form factor

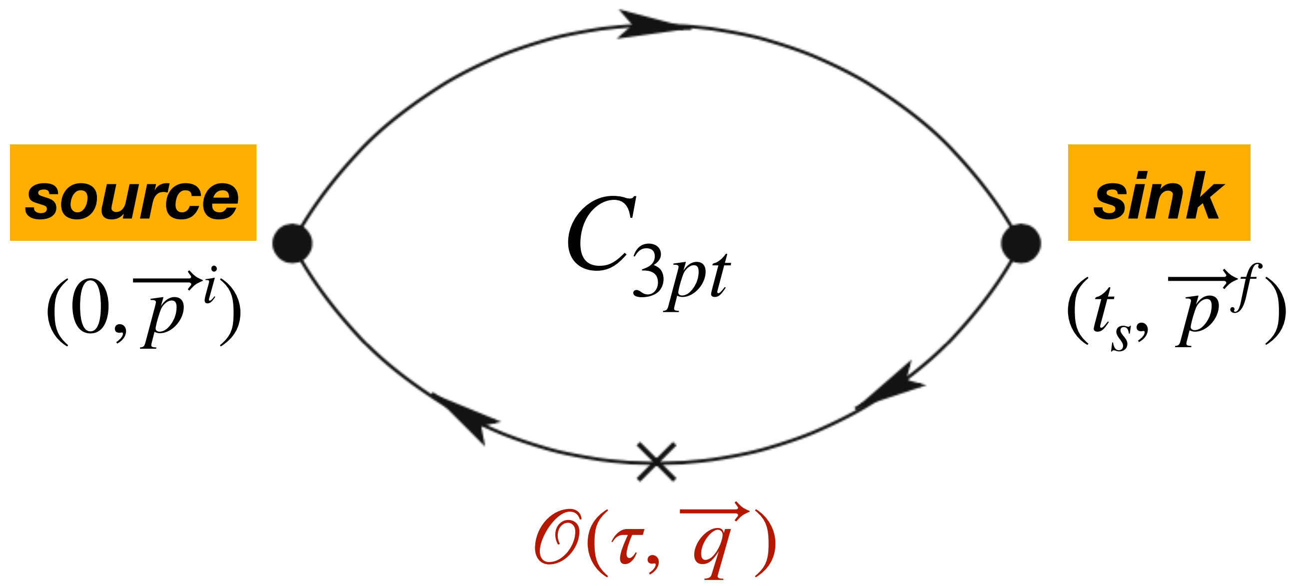
$$C_{3pt}(\vec{p}^f, t_s; \vec{q}, \tau; \vec{p}^i, 0) = \sum_{n,k=0}^{N_{state}-1} \left\langle \Omega \left| H(\vec{p}^f) \right| n \right\rangle \left\langle k \left| H^\dagger(\vec{p}^i) \right| \Omega \right\rangle e^{-(E_k^{\vec{p}^i} - E_n^{\vec{p}^f})\tau} e^{-E_n^{\vec{p}^f} t_s} \times \left\langle n \left| \hat{\mathcal{O}}_\Gamma(\tau) \right| k \right\rangle$$

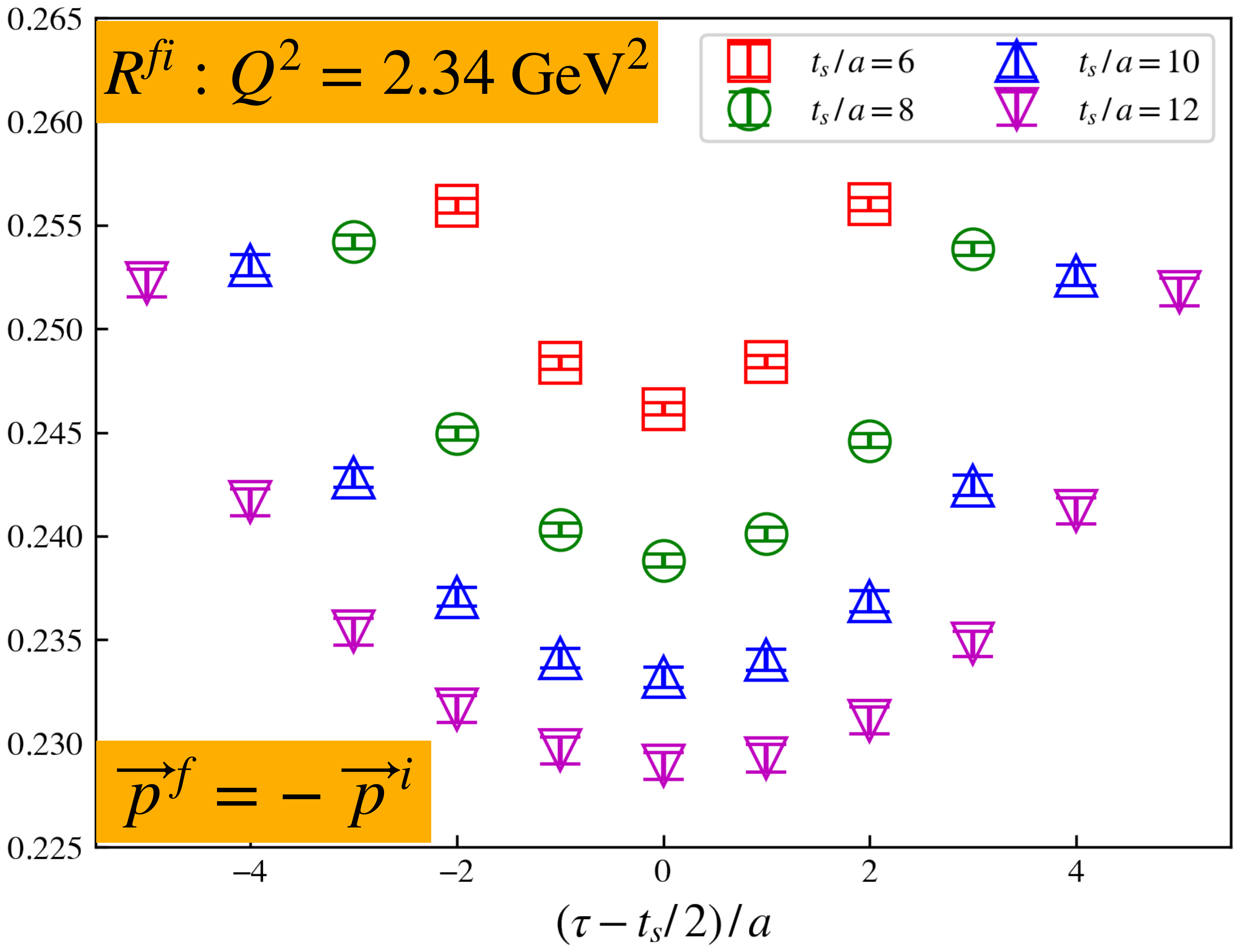
Can be suppressed by C_{2pt}

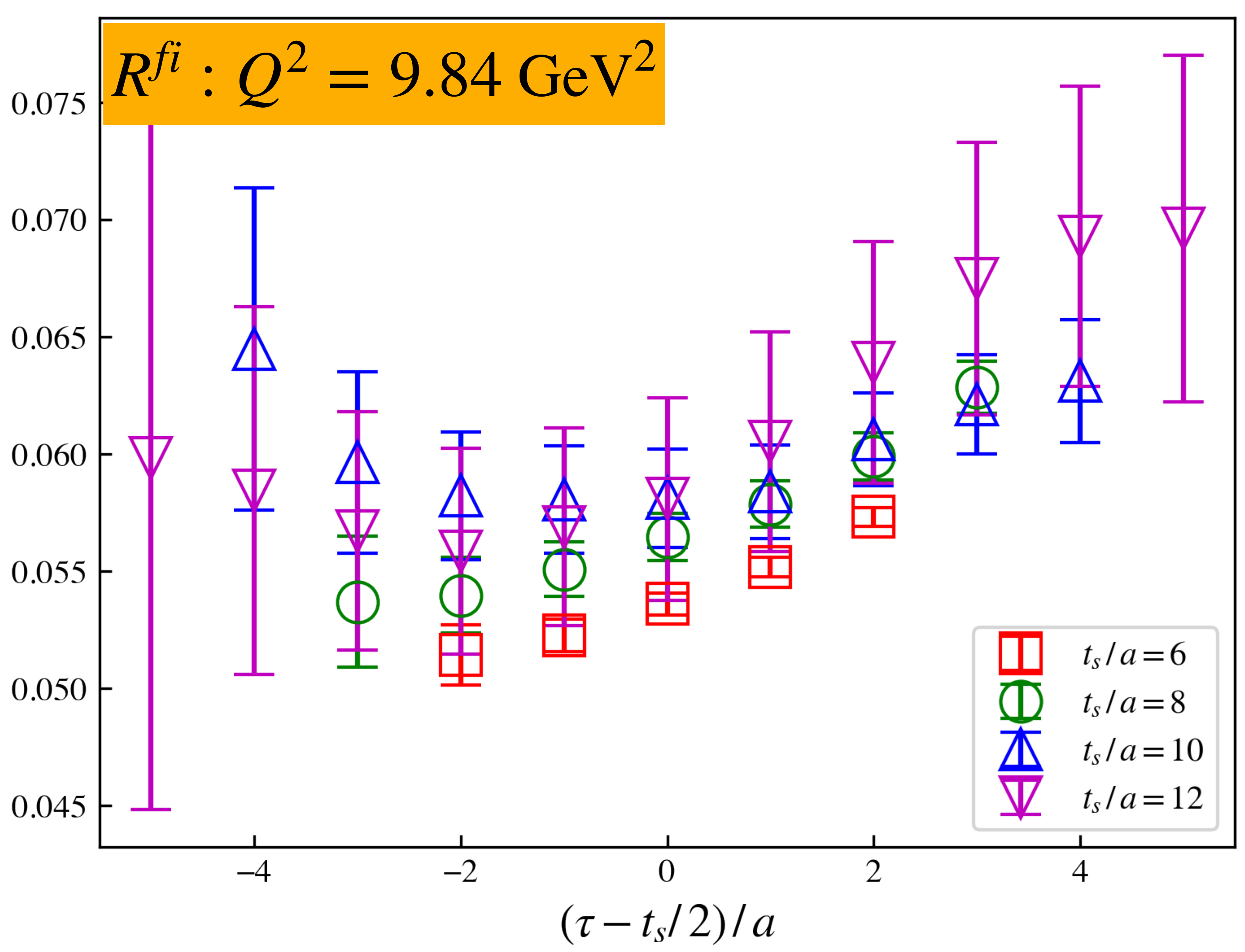
$n = k = 0$ → F^B

- Take a special case $\vec{p}^f = -\vec{p}^i$ as an example 2102.06047

$$R^{fi}(\vec{p}^f, t_s; \vec{q}, \tau; \vec{p}^i, 0) \equiv \frac{C_{3pt}(\tau, t_s; \vec{p}^i, \vec{p}^f)}{C_{2pt}(t_s, \vec{p}^f)}, \quad F^B = \lim_{\tau, (t_s-\tau), t_s \to \infty} R^{fi}$$





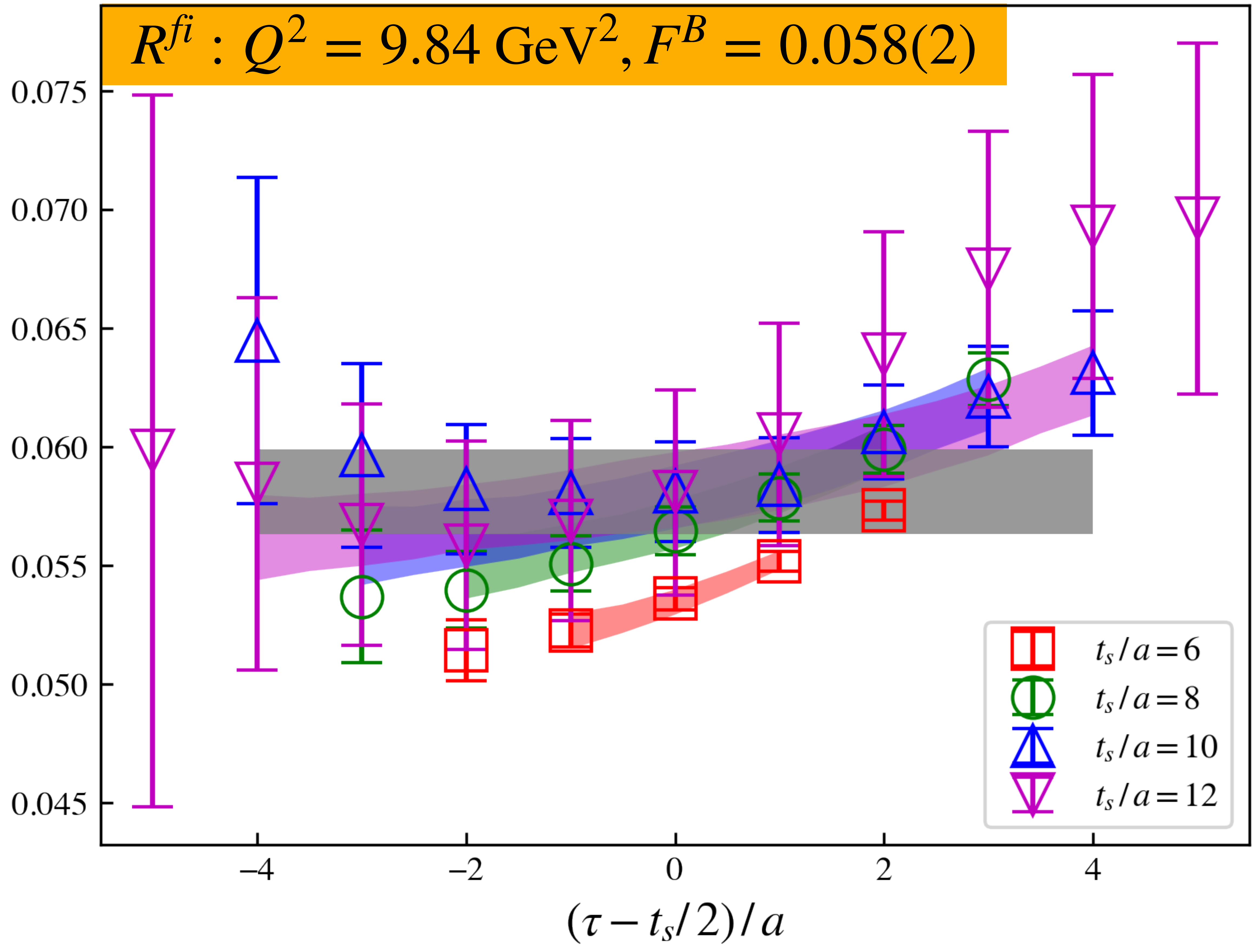


2. Extract the bare form factor

$$N_{state} = 2:\ R^{fi}(\tau, t_s) = \left(\mathcal{O}_{00} + \frac{A_1}{A_0}\mathcal{O}_{11} e^{-t_s \Delta E} + \sqrt{\frac{A_1}{A_0}}\mathcal{O}_{01} e^{-\tau \Delta E} + \sqrt{\frac{A_1}{A_0}}\mathcal{O}_{10} e^{-(t_s-\tau)\Delta E} \right) \Big/ \left(1 + \frac{A_1}{A_0} e^{-t_s \Delta E} \right),\ \Delta E = E_1 - E_0$$

$\mathcal{O}_{00}$: F^B

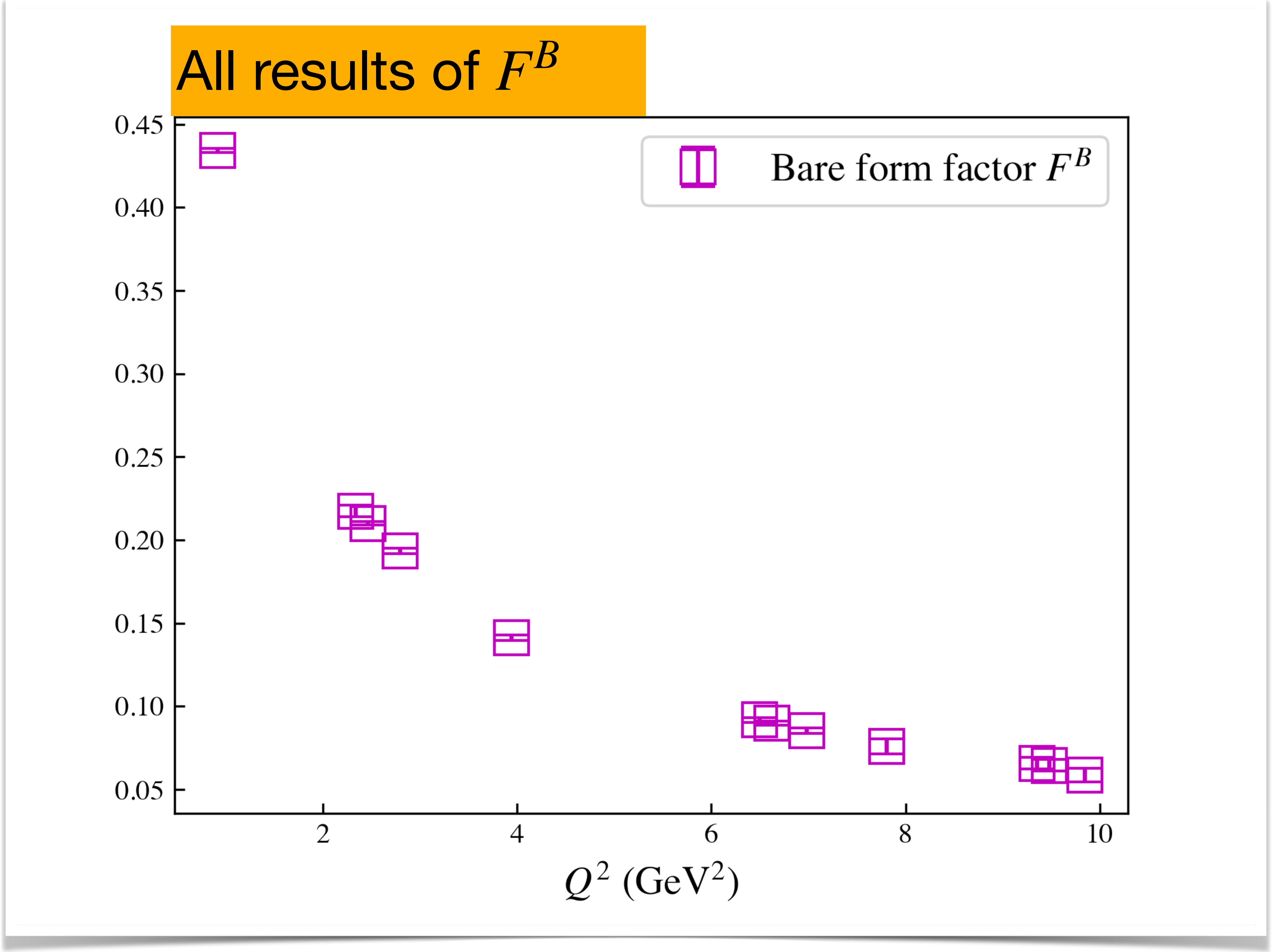
- Use the values of energy E_n and amplitude A_n extracted from C_{2pt}
- Perform a 4-parameter fit to the ratio R^{fi} to extract F^B



Extrapolation -> Grey band

$$F^B = \lim_{\tau,\ (t_s-\tau),\ t_s \to \infty} R^{fi}$$

3. Renormalization



- F^B decreases as Q^2 increases

- Renormalization:

$$F = F^B \times Z_V$$

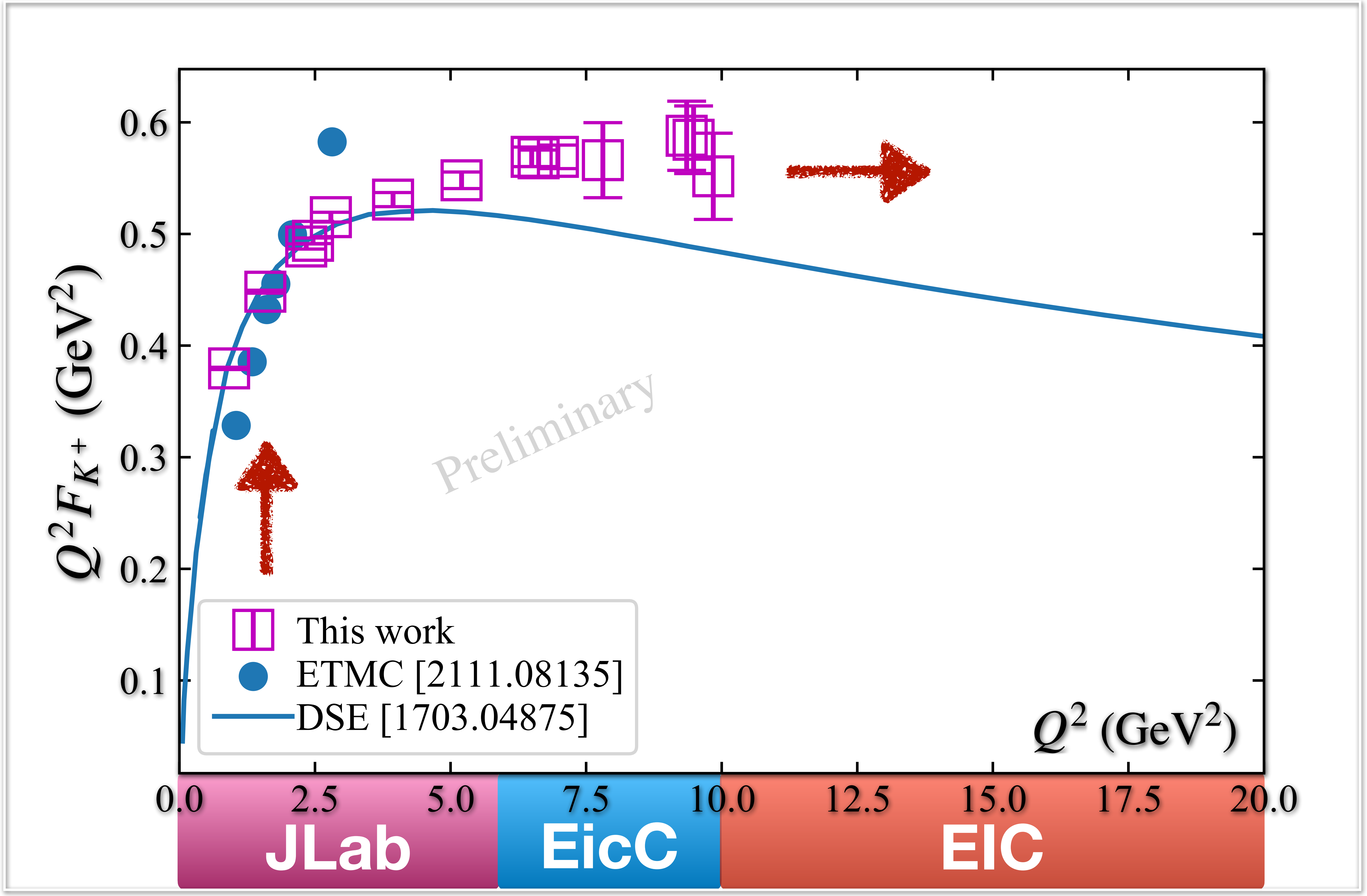
$$Z_V^{-1} = \left\langle E_0, 0 \,|\, \hat{\mathcal{O}} \,|\, E_0, 0 \right\rangle = 1.048$$

extracted in our previous work of pion

2102.06047

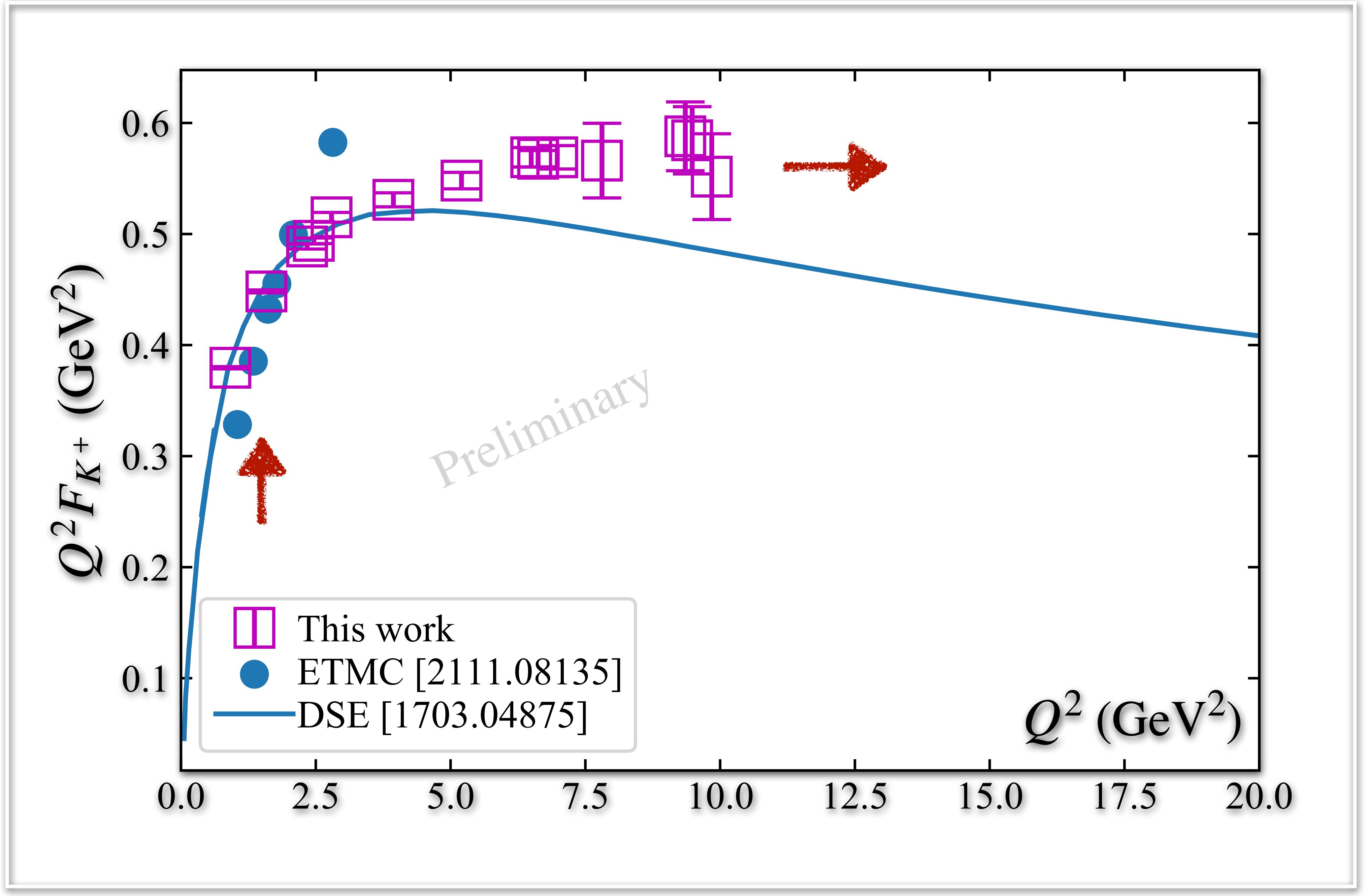
Results

Our results are the first Lattice QCD prediction of the kaon form factor at $Q^2 \geq 3$ GeV^2



Summary & Outlook

- We study the K^+ electromagnetic form factor at the physical point from the first principle Lattice QCD
- We use different boost smearing at the source & sink time position to achieve good signals with large Q^2 up to 10 GeV^2
- Our results of the $Q^2F_{K^+}$ form factor increase at lower Q^2 and then become flat at higher Q^2



➢ Systematic errors: Discretization effects, …

➢ The u & $\bar{s}$ quark contributions to the form factor

Thanks