Nuclear Science Computing Center at CCNU

Lattice QCD prediction of pion & kaon form factor at large momentum transfer Q^2

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Lattice 2023, Fermilab July 31 - August 4, 2023

Motivation

EPJA 48 (2012) 187 EPJA 52 (2016) 268 arXiv: 2102.09222

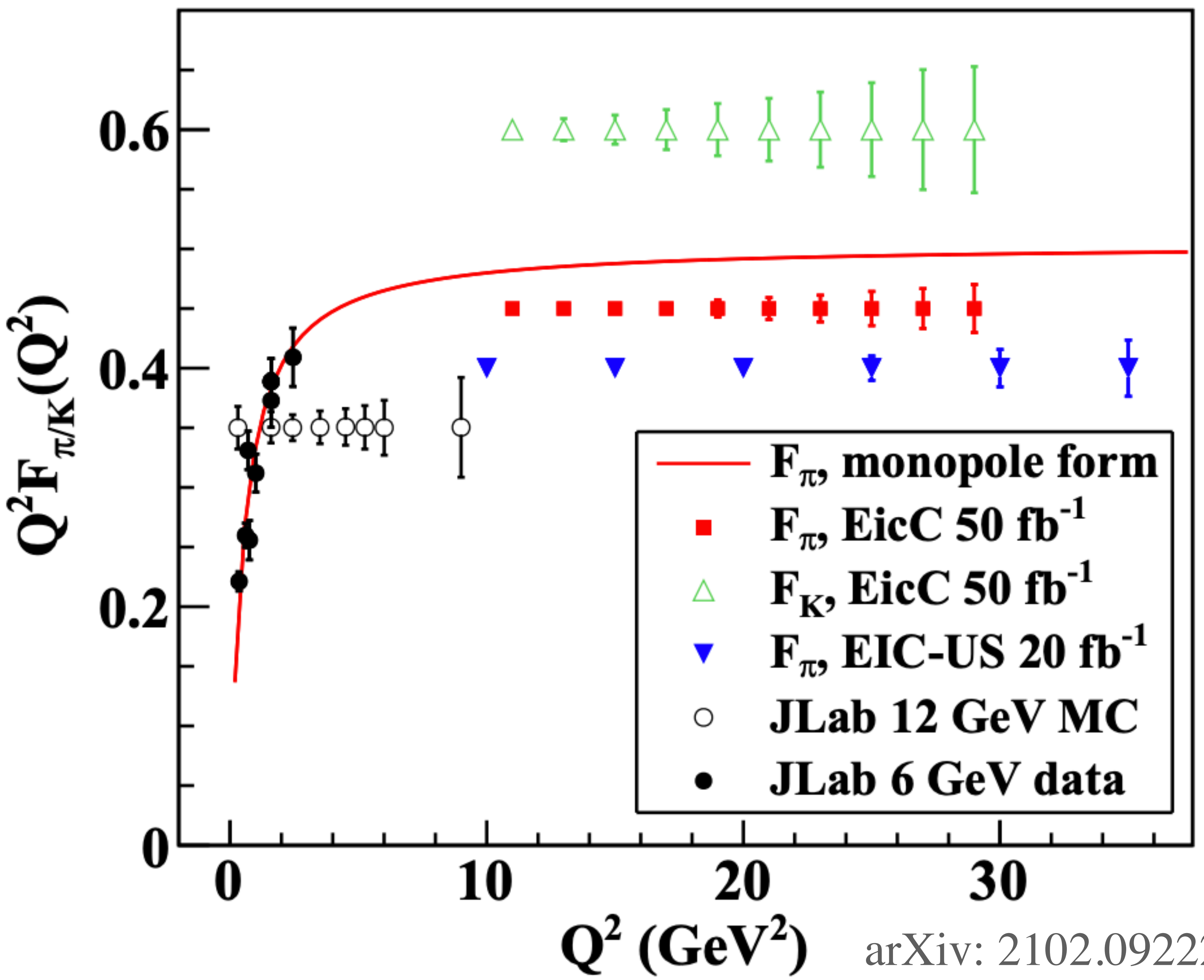
- Experiment: JLab, EIC, EicC …

Gao et al., PRD 96 (2017) 034024

- Effective theory: QCD sum rules, DSE …
- Lattice QCD

ETMC, PRD 105 (2022) 054502

  - State-of-the-art: $Q^2 \leq$ 2.5, 3 GeV^2
  - This work: Q^2 up to 10, 28 GeV^2



arXiv: 2102.09222

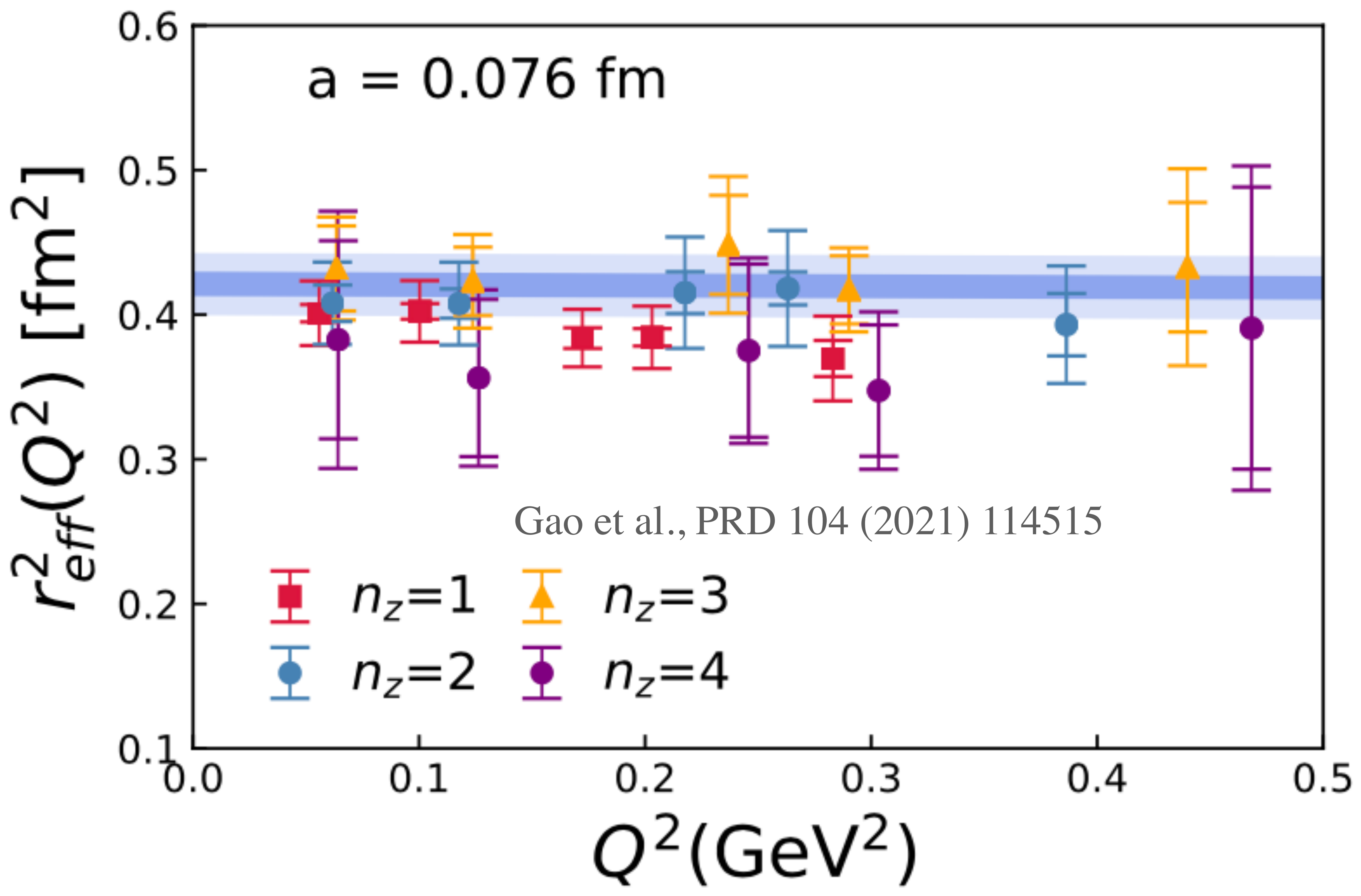
Small Q^2

Hadronic picture

Vector **M**eson **D**ominance

$$r^2_{\rm eff}(Q^2) = \frac{6[1/F_\pi(Q^2) - 1]}{Q^2}$$

$$\langle r^2_\pi \rangle = 0.42(2)\ \text{fm}^2, \langle r^2_\pi \rangle_{PDG} = 0.434(5)\ \text{fm}^2$$



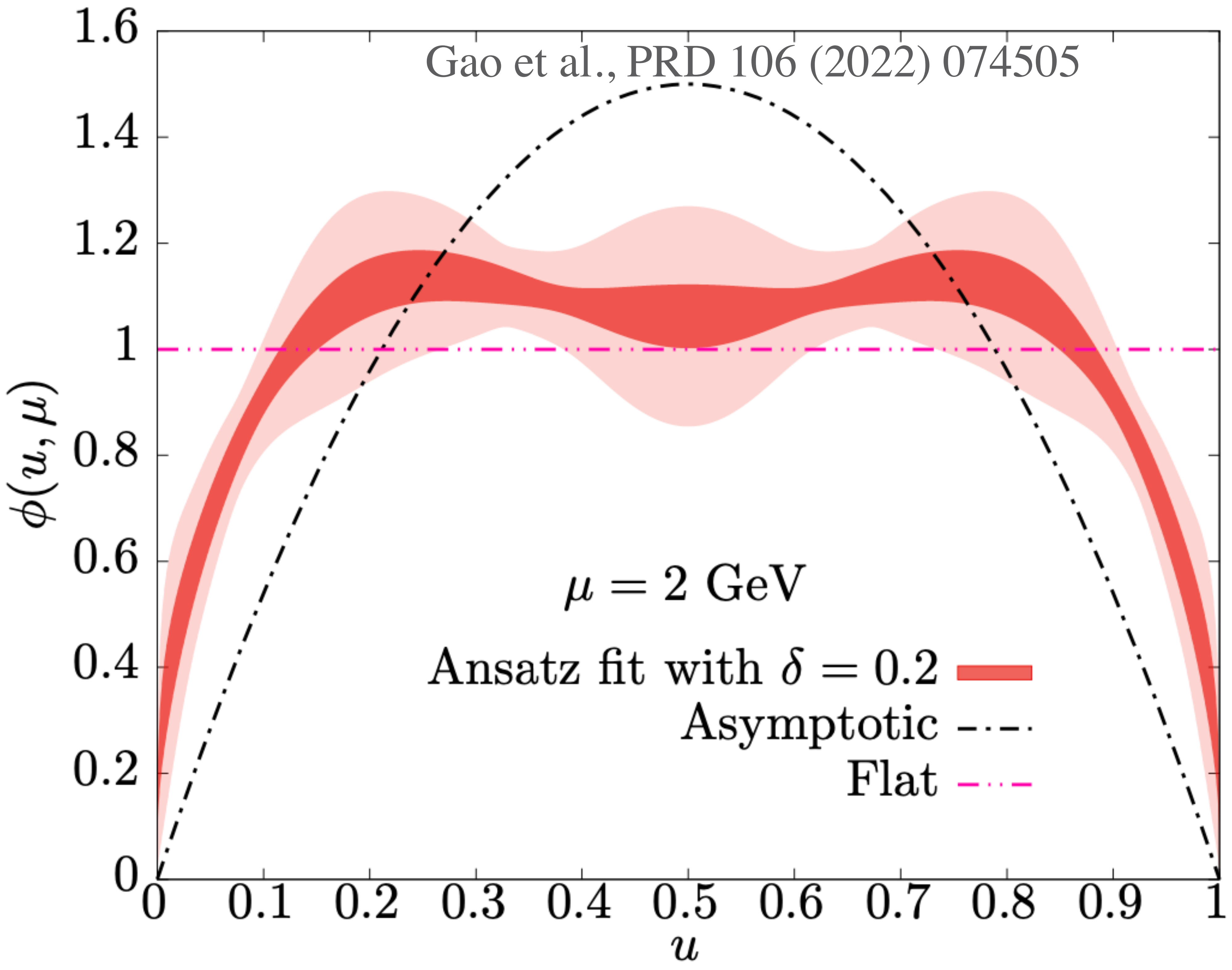
Large Q^2

Partonic picture

La**rge-M**omentum **E**ffective **T**heory

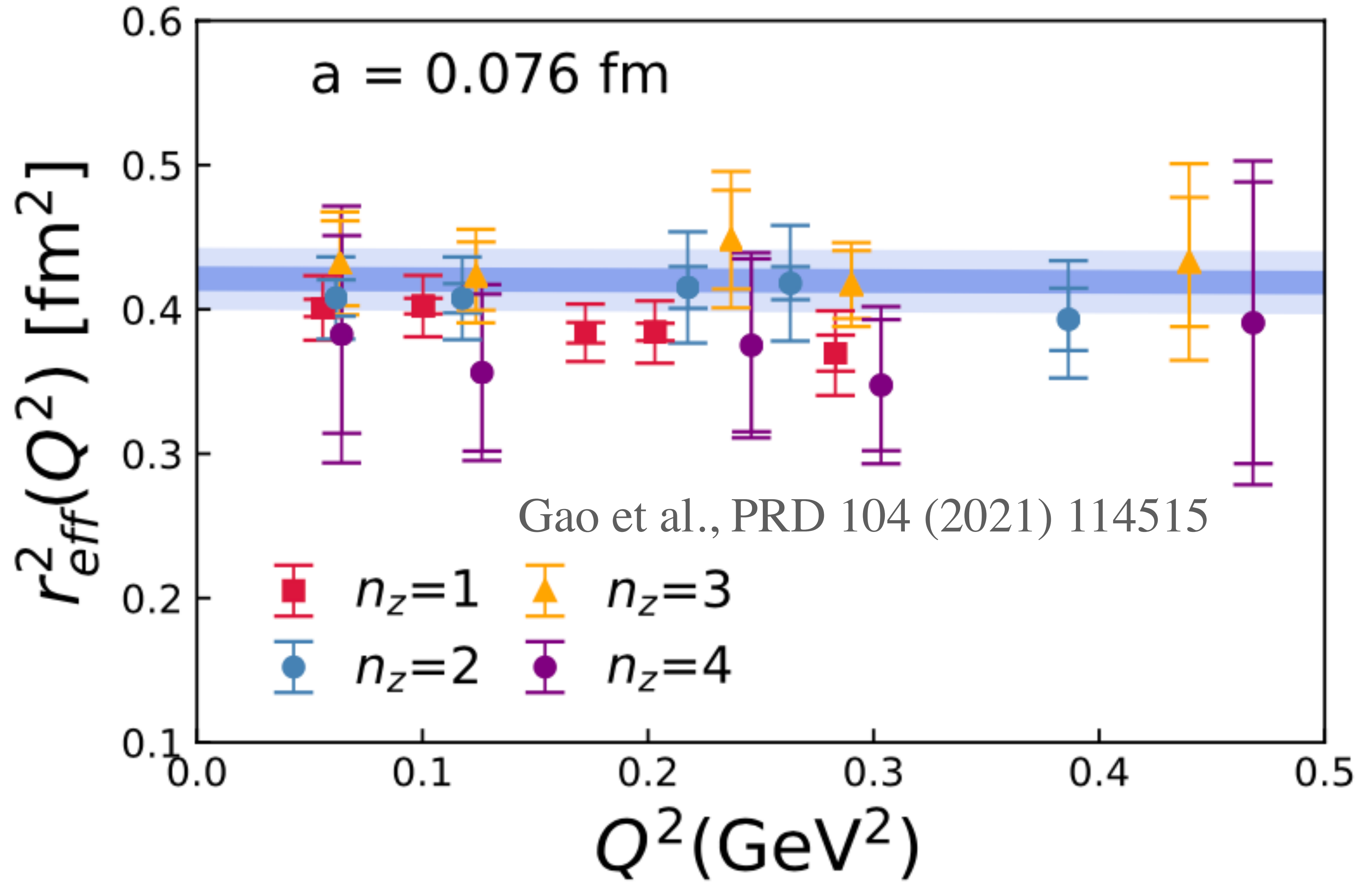
$$F(Q^2) = \int_0^1 \int_0^1 \mathrm{d}x\mathrm{d}y \phi^*(v, \mu_F^2) T_F(u, v, Q^2, \mu_R^2, \mu_F^2) \phi(u, \mu_F^2)$$

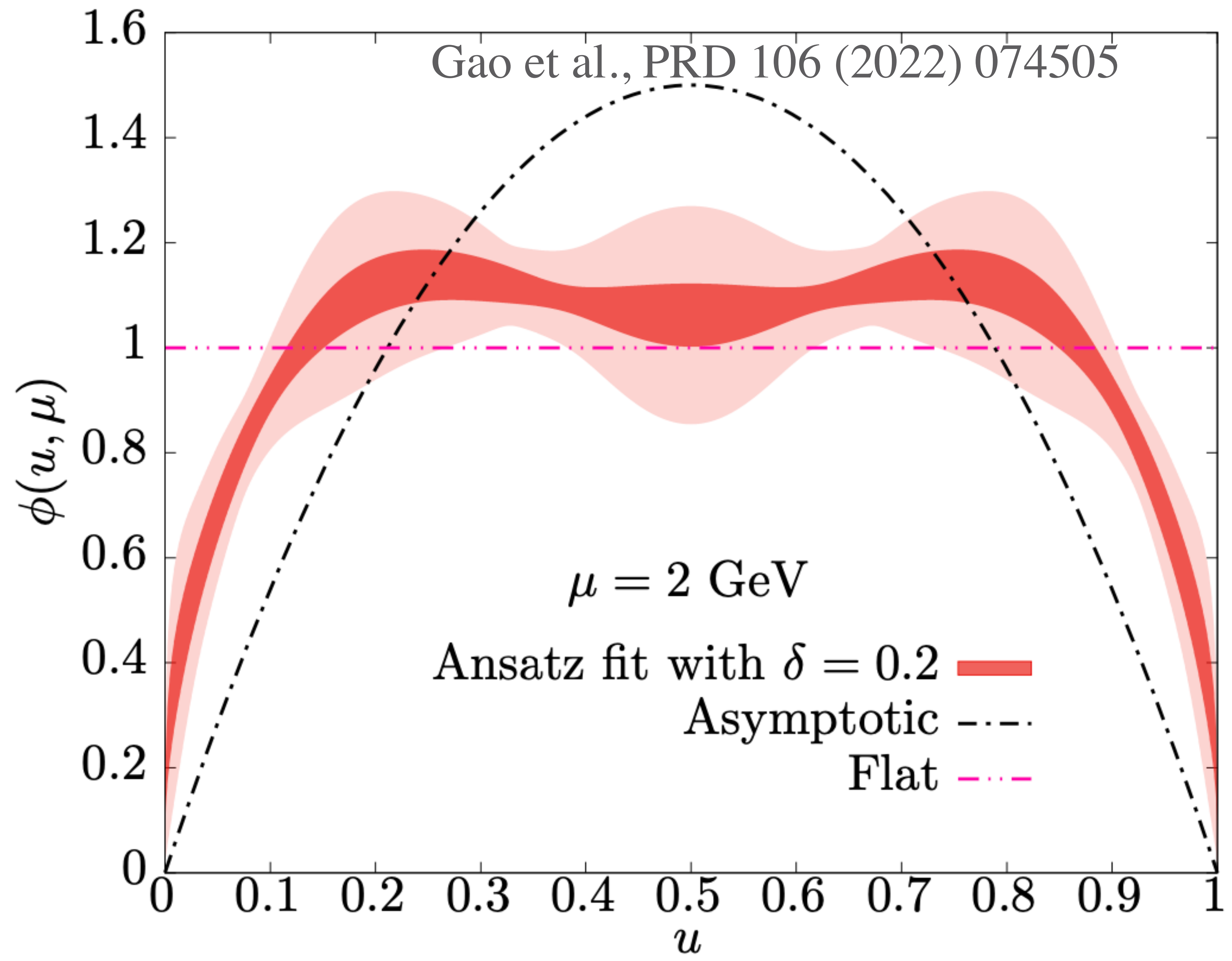
Hard-process kernel Distribution amplitude



Motivation

How about the intermediate range?





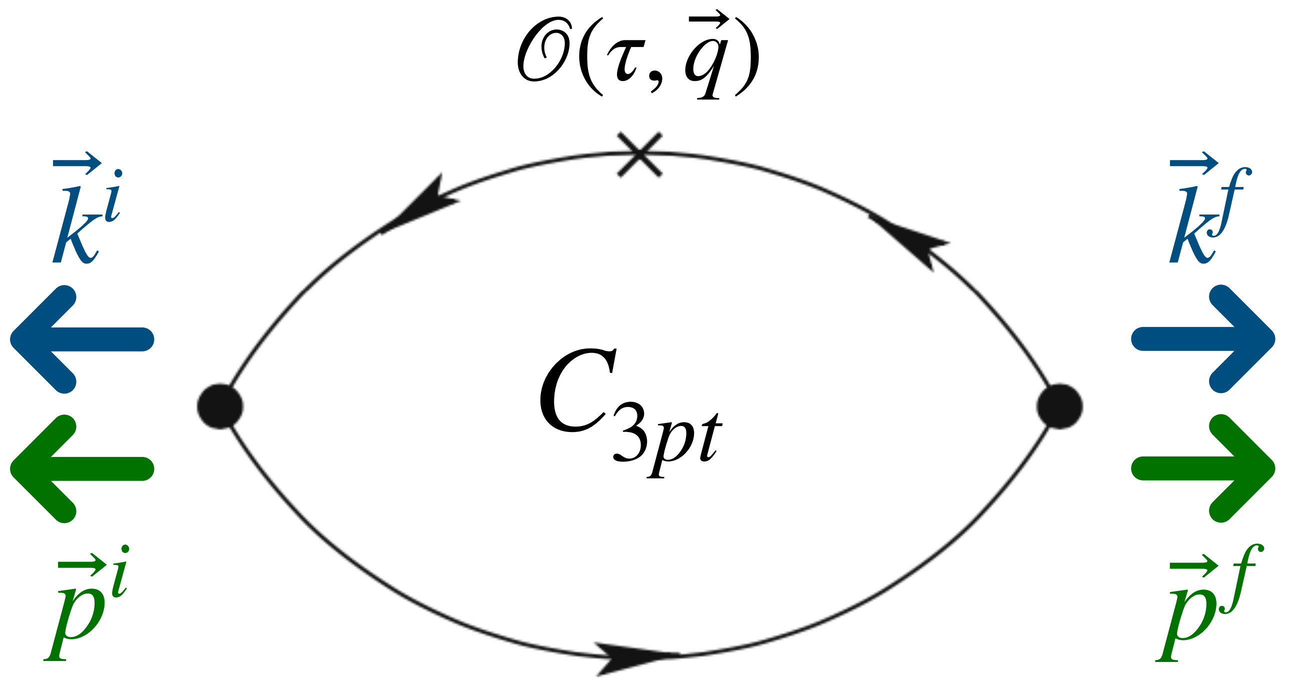
Lattice Setup

- $N_s^3 \times N_t = 64^3 \times 64$
- Pion / Kaon: $a = 0.076$ fm, $a = 0.04, 0.076$ fm
- HISQ action + Wilson-Clover action,

  ⇒ **at the physical point**
- Boost smearing back to back:

  quark boost momentum $\vec{k}$ & **quark momentum** $\vec{p}$

  ⇒ The largest Q^2 up to **10** (Pion) and **28 GeV^2** (Kaon)



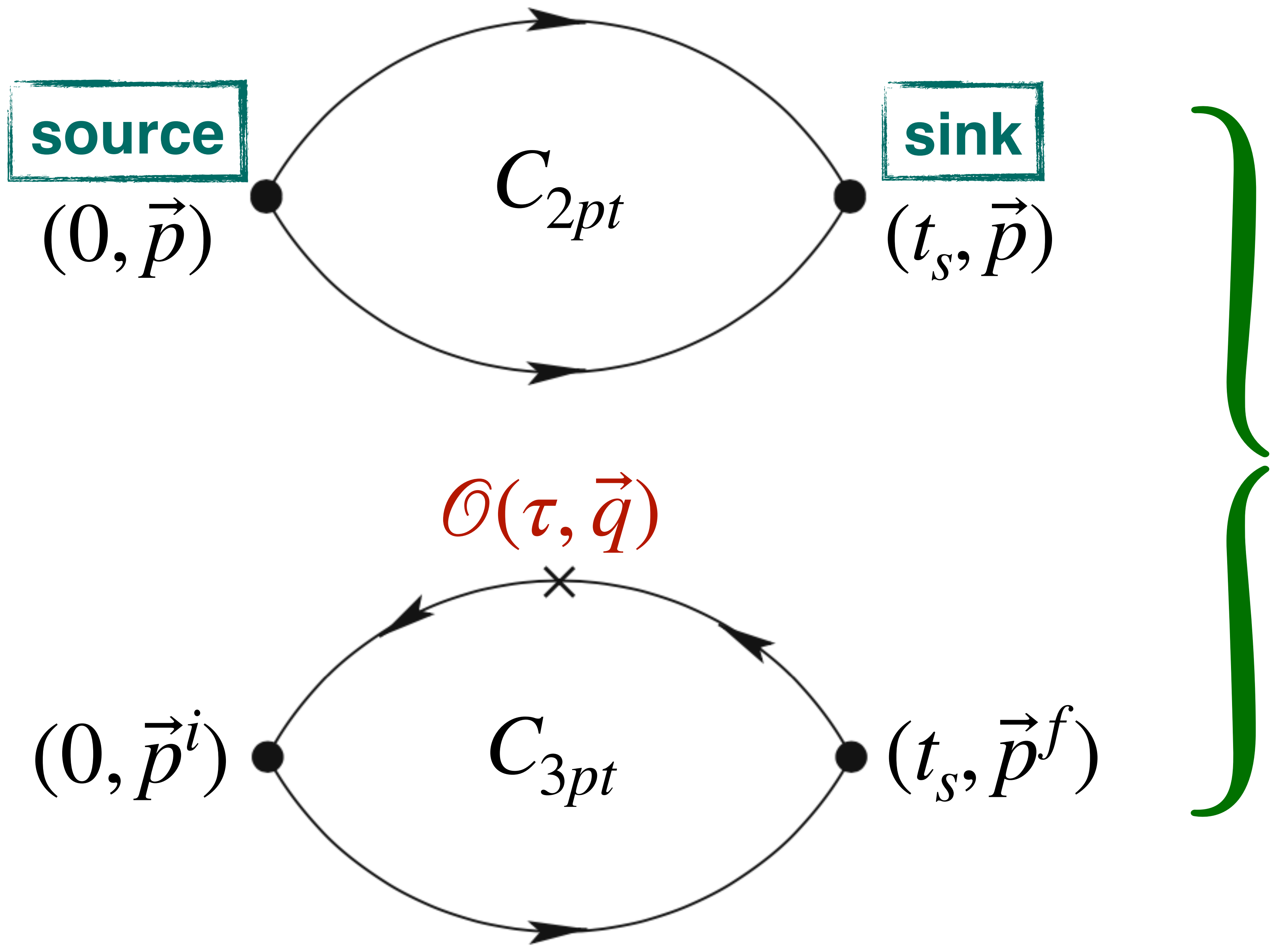
How to get form factor

$$C_{2pt}(t,\vec{p}) = \left\langle H(t_s,\vec{p})H^\dagger(0,\vec{p})\right\rangle$$

Insert $\mathcal{O}(\tau,\vec{q})$ ↓ $\vec{p}^f = \vec{p}^i + \vec{q}$

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

$\Gamma : \hat{1}, \gamma^\mu, \sigma^{\mu\nu}$



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

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

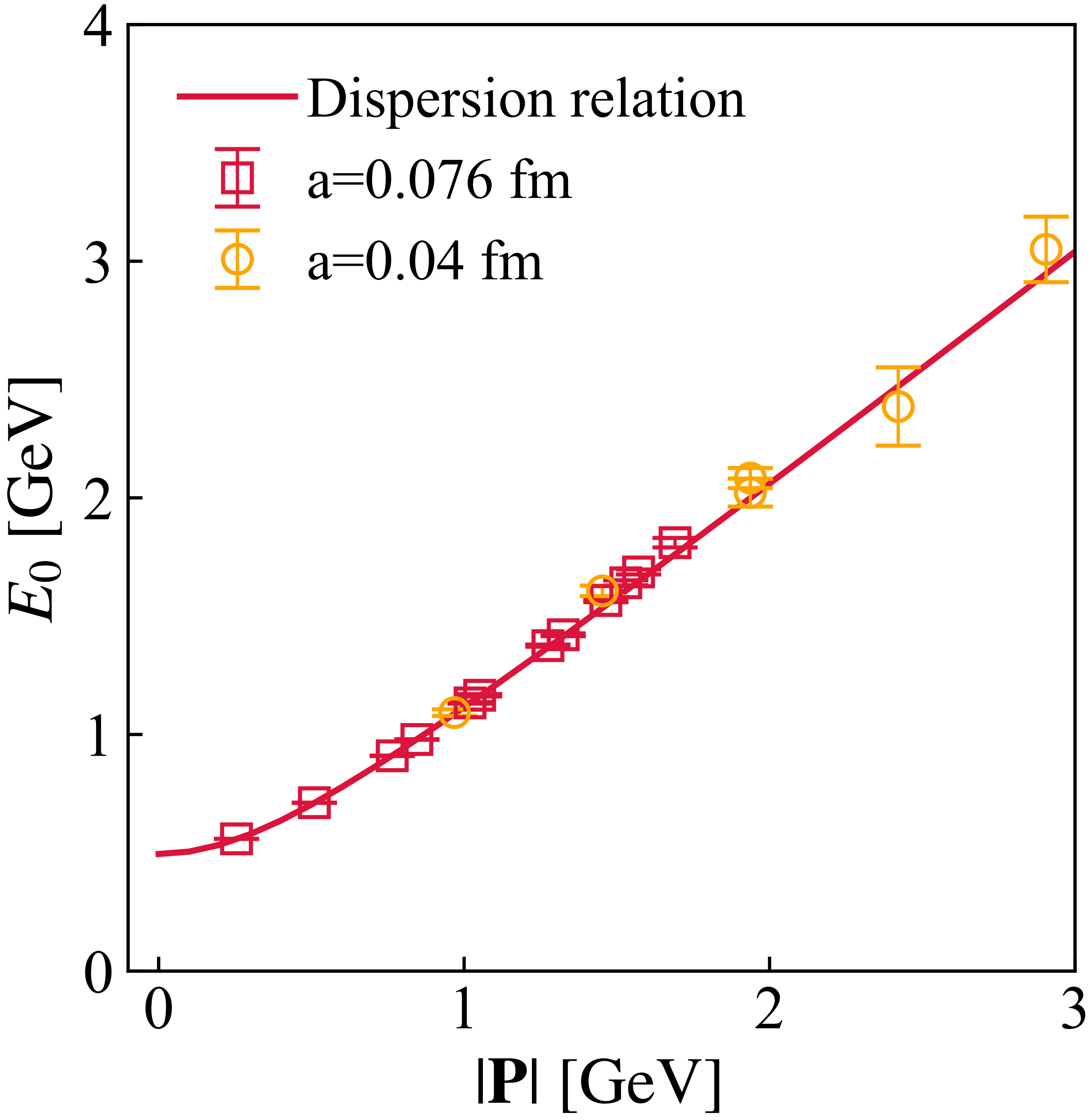
Renormalization →

$$F(Q^2) = F^B \times Z_V^{-1}$$

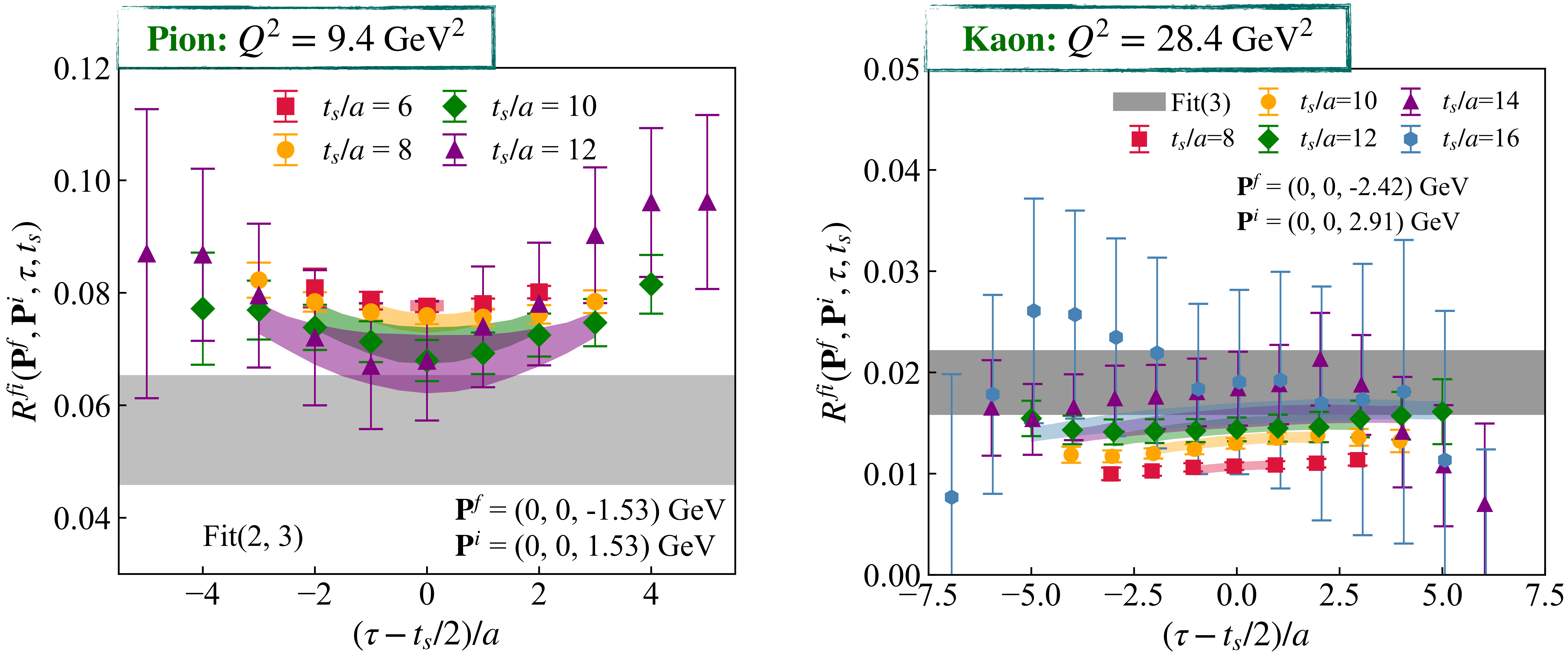
$$Q^2 = -q^2$$

Extract Energy and Amplitude

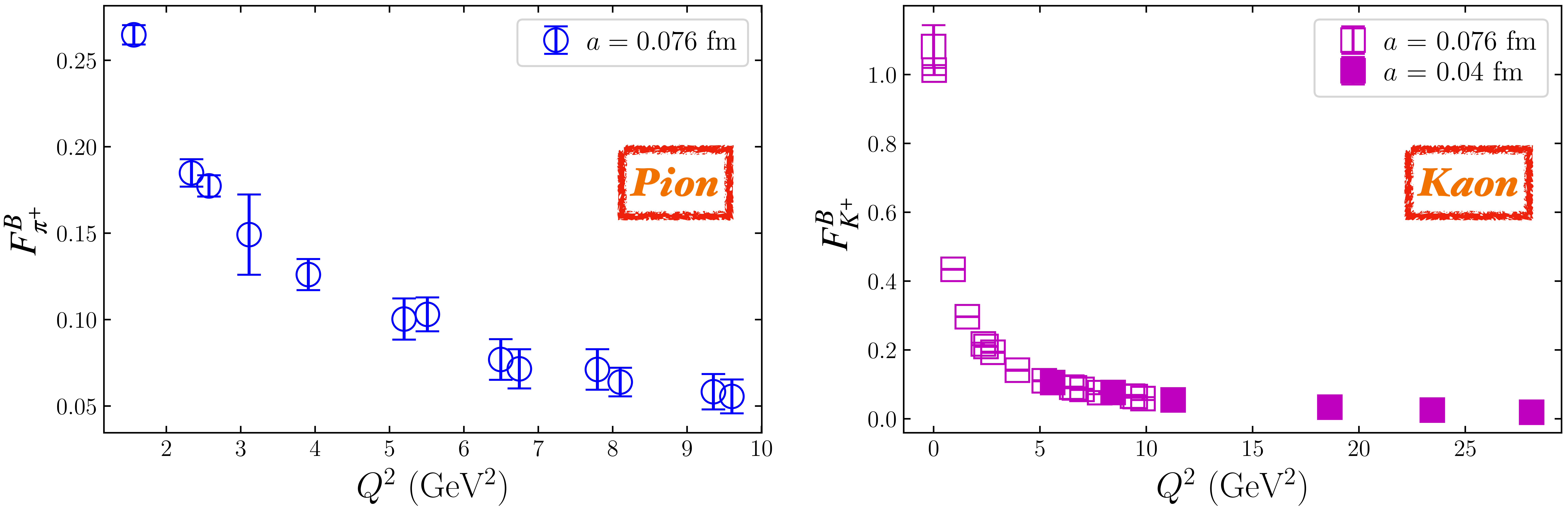
Take kaon data as an example



Extract Bare Form Factor



Renormalization

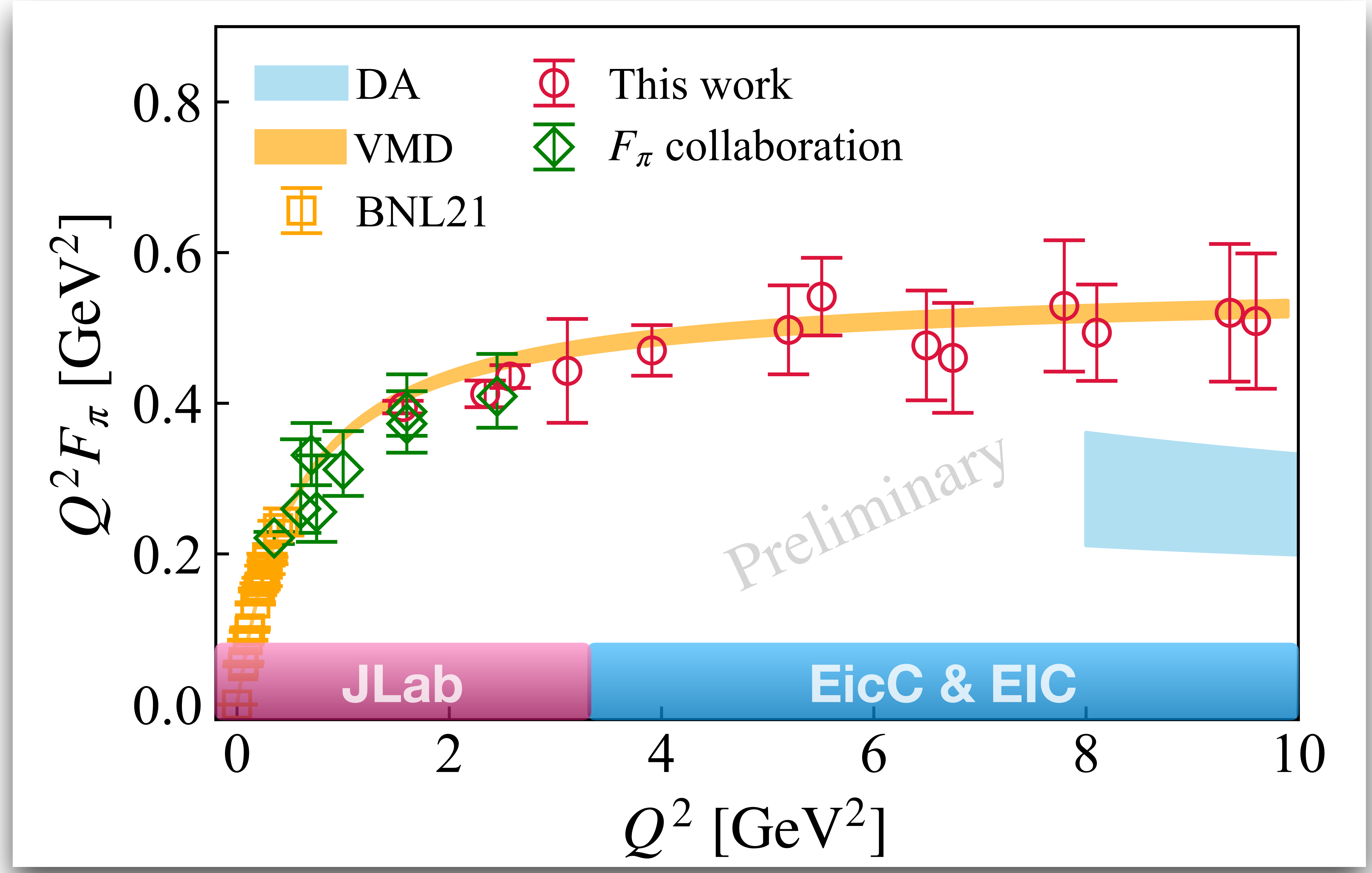


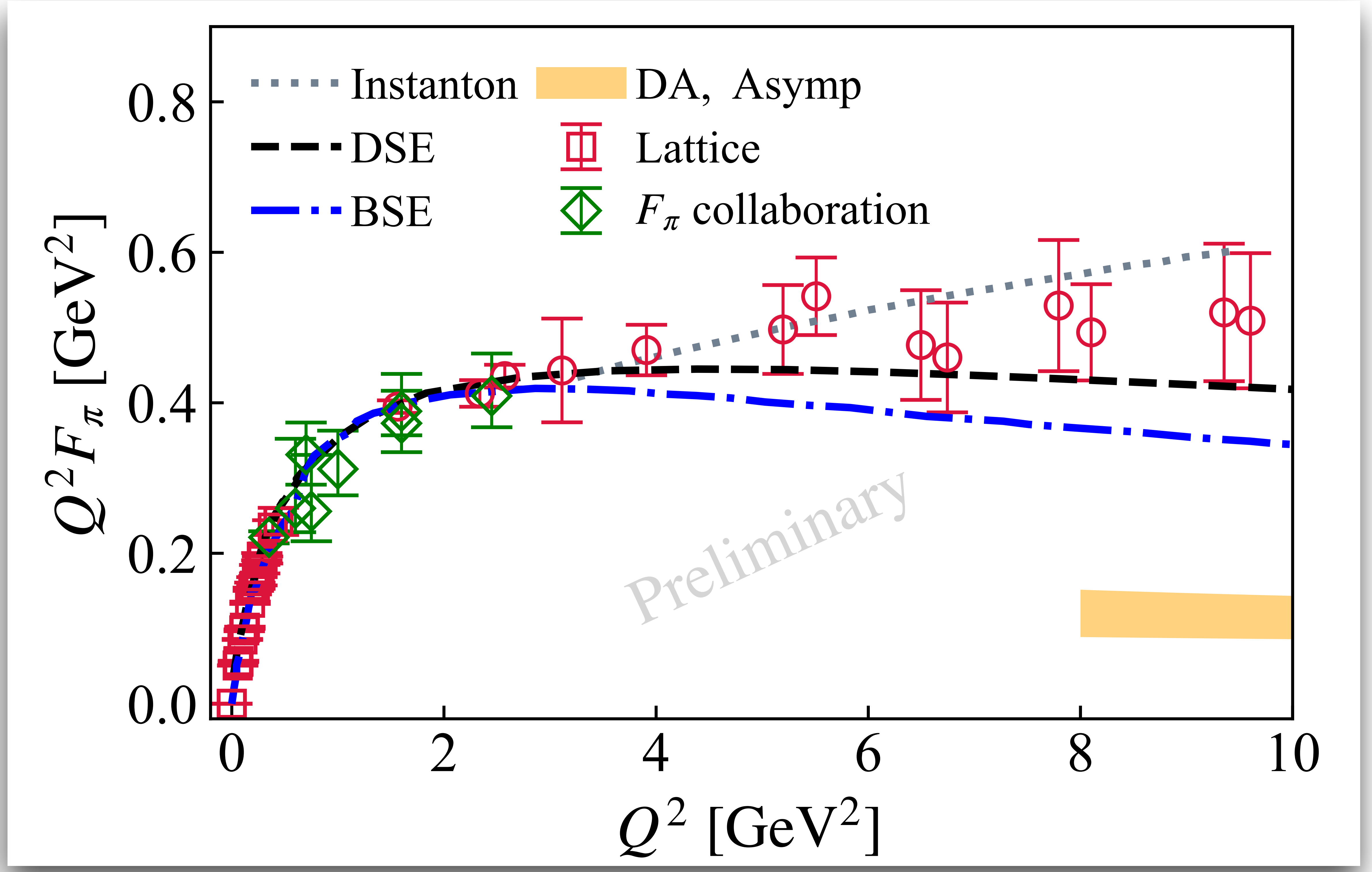
- Renormalization: $F = F^B \times Z_V^{-1}$

Gao et al., PRD 104 (2021) 114515

$Z_V = \left\langle 0; \vec{p} \,|\, \hat{\mathcal{O}} \,|\, \vec{p}; 0 \right\rangle = 1.048, 1.024$ for $a = 0.076, 0.04$ fm

Results of Pion

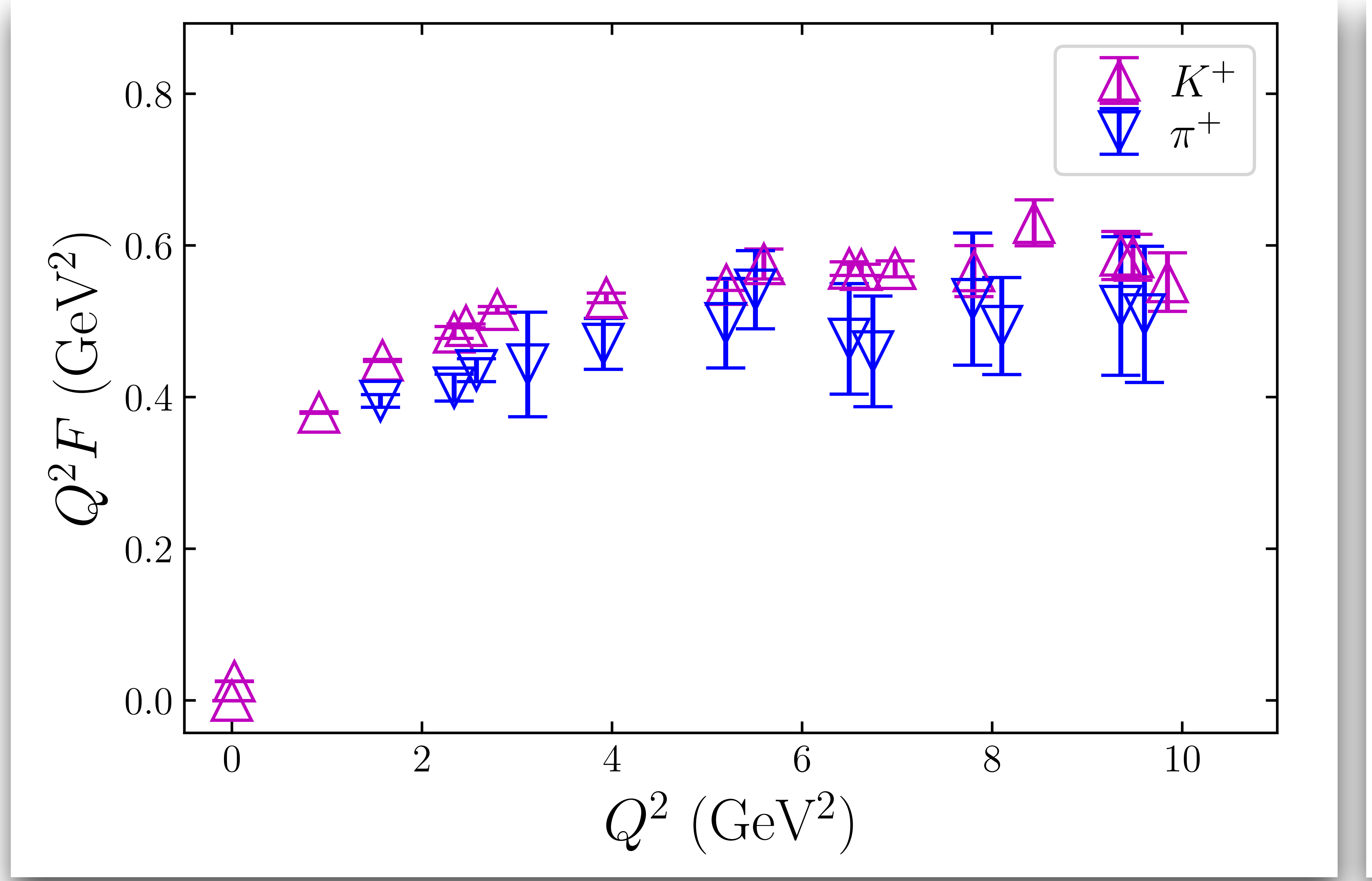


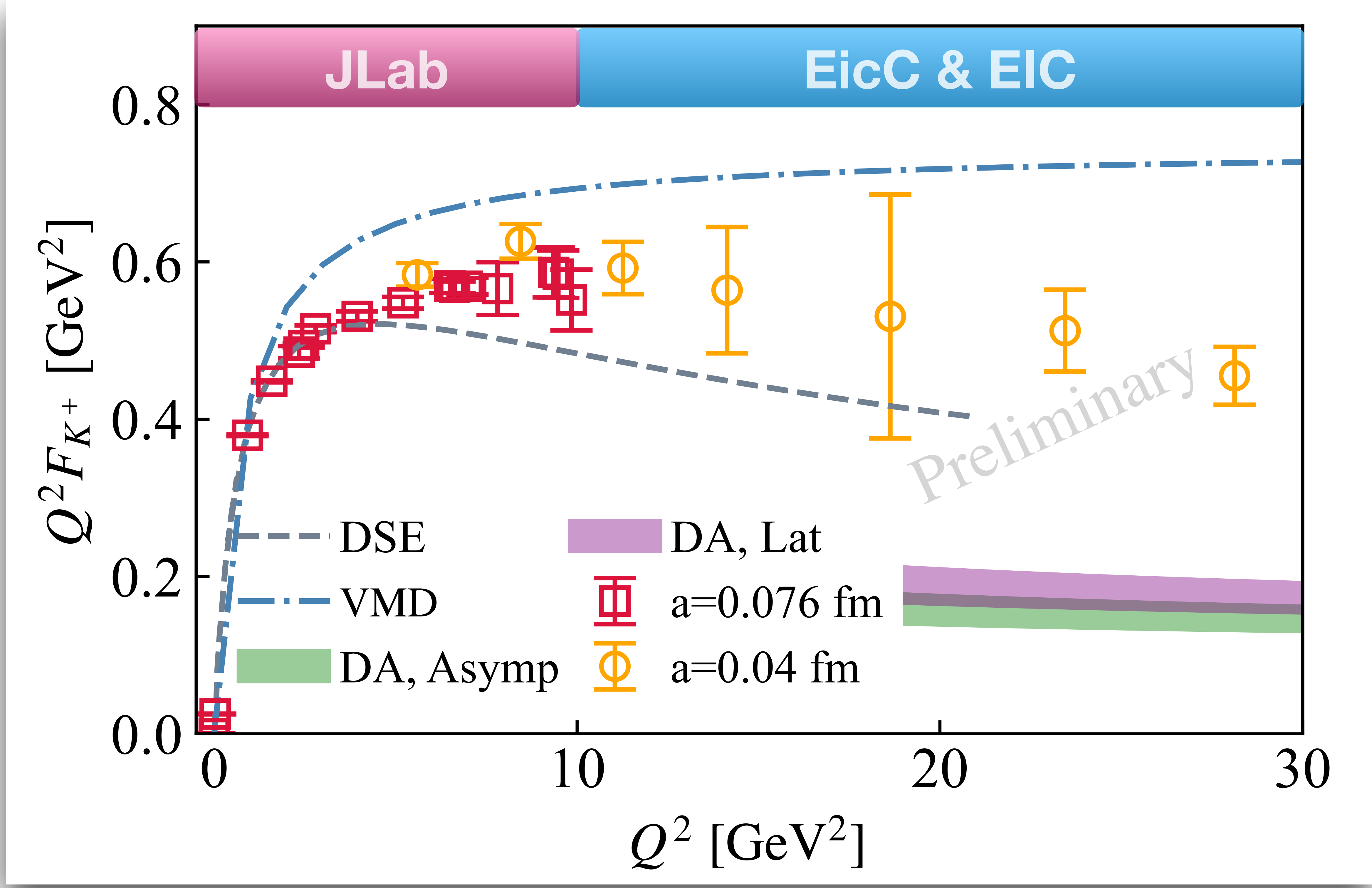


DA: Gao et al., arXiv:2206.04084
VMD: $Q^2/(1 + Q^2\langle r_\pi^2\rangle/6)$
BNL21: Gao et al., PRD 104 (2021) 114515
F^π collaboration: Huber et al., PRC 78 (2008) 045203

Instanton: Shuryak et al., PRD 103 (2021) 054028
DSE: Gao et al., PRD 96 (2017) 034024
BSE: Ydrefors et al., PLB 820 (2021) 136494
DA, Asymp: $\phi(x) = 6x(1-x)$

Results of Kaon





DSE: Gao et al., PRD 96 (2017) 034024
DA, Lat: Bali et al., JHEP 08 (2019) 065
VDM: $Q^2/(1+Q^2\langle r_K^2\rangle/6)$
DA, Asymp: $\phi(x) = 6x(1-x)$

Summary

- Pion and kaon electromagnetic form factor at the physical point.
- Up to 10 and 28 GeV^2 for pion and kaon.
- Up to $Q^2 \sim 10\,\mathrm{GeV}^2$, no significant flavor dependence

  Even up to $Q^2 \sim 30\,\mathrm{GeV}^2$, haven't reached the partonic picture

Thanks for your attention!