Lattice QCD for Neutrino Physics:

Toward *Ab-initio* Calculations of the νN Interaction

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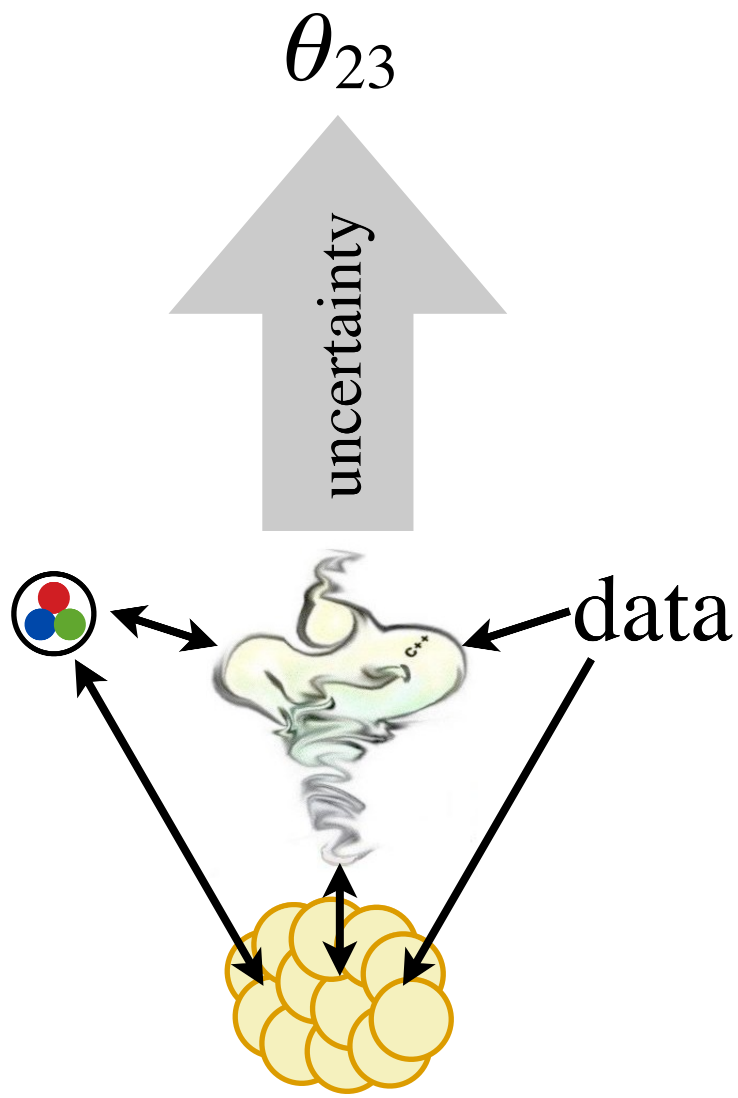
Neutrino Experiments

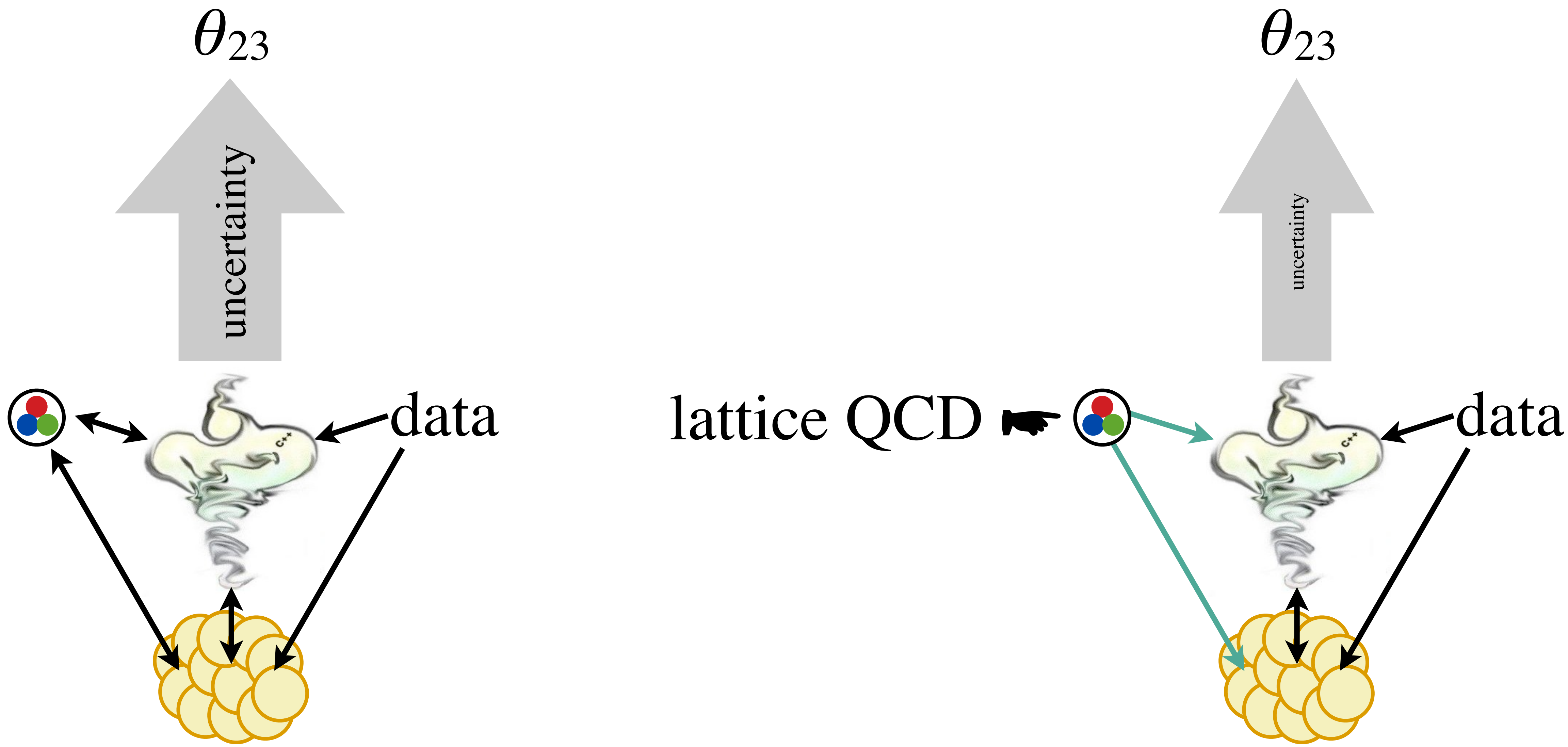
- Neutrino-nucleus scattering data are asked to determine:



  - fundamental physics (PMNS, NSI, ...);
  - hadronic physics, e.g., $F_A(q^2)$;
  - nuclear structure, nucleons in medium.
- Interfaced to event generator, *e.g.*, GENIE.
- Hard to disentangle uncertainties.
- Need to disrupt this vicious cycle!

Disruptive Technology

- The situation would change with *ab-initio* nucleon-level QCD information.



- Many lattice-QCD calculations: time to interface with neutrino physicists.

Axial-Vector Form Factor

- First key deliverable is the slope of the axial-vector form factor of the nucleon.

- Often fit to a dipole Ansatz:

$$F_A(q^2) \stackrel{?}{=} \frac{g_A}{(1 - q^2/M_A^2)^2} \qquad g_A \text{ from neutron } \beta \text{ decay}$$

  but data's precision has outgrown it—inconsistent M_A "measurements".

- Form factors have three distinct regions:
  - $q^2 > t_{\mathrm{cut}}$, where $l\nu$ (s-channel) scattering cuts and resonances appear;
  - $0 < q^2 < (M_n - M_p)^2$, for $n \to pl\nu$ semileptonic (aka β) decay;
  - $q^2 < 0$, the νN (t-channel) scattering of interest here.

} lattice QCD

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We plan to use lattice QCD to compute F_A and the model-independent z expansion to extend it.

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Definitions

$$\langle p(\boldsymbol{p})|\mathcal{V}_\mu^+|n(\boldsymbol{k})\rangle = \bar{u}_p(\boldsymbol{p})\left[\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N}F_2(q^2)\right]\tau^+ u_n(\boldsymbol{k})$$

$$\langle p(\boldsymbol{p})|\mathcal{A}_\mu^+|n(\boldsymbol{k})\rangle = \bar{u}_p(\boldsymbol{p})\left[\left(\gamma_\mu - \frac{2M_N q_\mu}{q^2}\right)\gamma^5 F_A(q^2) + \frac{2M_N q_\mu}{q^2}\gamma^5 F_P(q^2)\right]\tau^+ u_n(\boldsymbol{k})$$

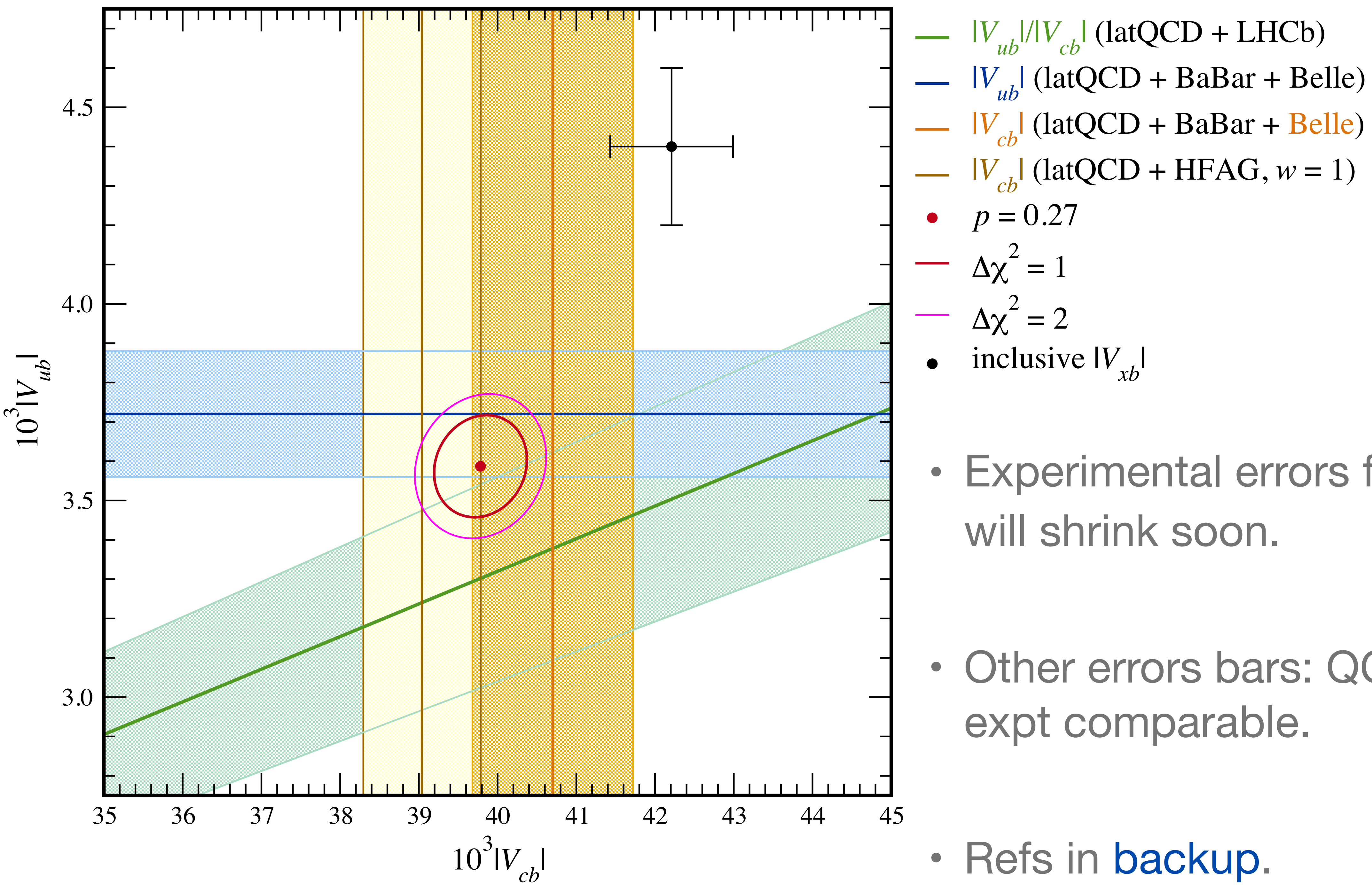
$$\langle \pi(\boldsymbol{p})|\mathcal{V}_\mu^+|B(\boldsymbol{k})\rangle = \left(k_\mu + p_\mu - \frac{M_B^2 - M_\pi^2}{q^2}q_\mu\right) f_+(q^2) + \frac{M_B^2 - M_\pi^2}{q^2}\, q_\mu f_0(q^2),$$

$$q = k - p$$

Semileptonic Decays in b Physics

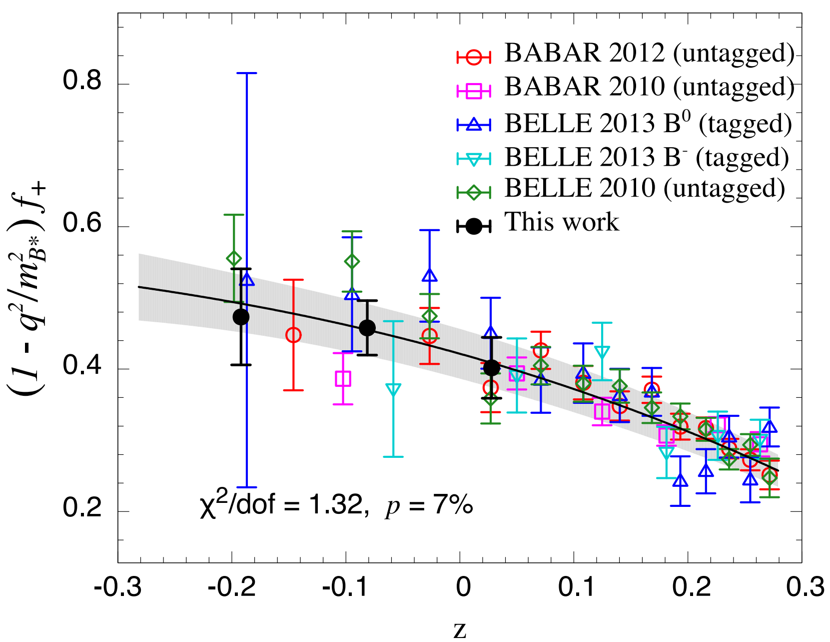
- A lot of activity in the past few months.
- $|V_{ub}|$ from $B \to \pi l \nu$, with z expansion to combine lattice QCD and experiment:
    - RBC/UKQCD [arXiv:1501.05373], Fermilab/MILC [arXiv:1503.07839].
- $|V_{cb}|$ from $B \to D l \nu$, over full kinematic range:
    - Fermilab/MILC [arXiv:1503.07237], HPQCD [arXiv:1505.03925].
- $|V_{ub}|/|V_{cb}|$ from $\Lambda_b \to p l \nu$ & $\Lambda_b \to \Lambda_c l \nu$, again with z over full kinematic range:
    - Detmold, Lehner, Meinel [arXiv:1503.01421] on RBC/UKQCD ensembles.

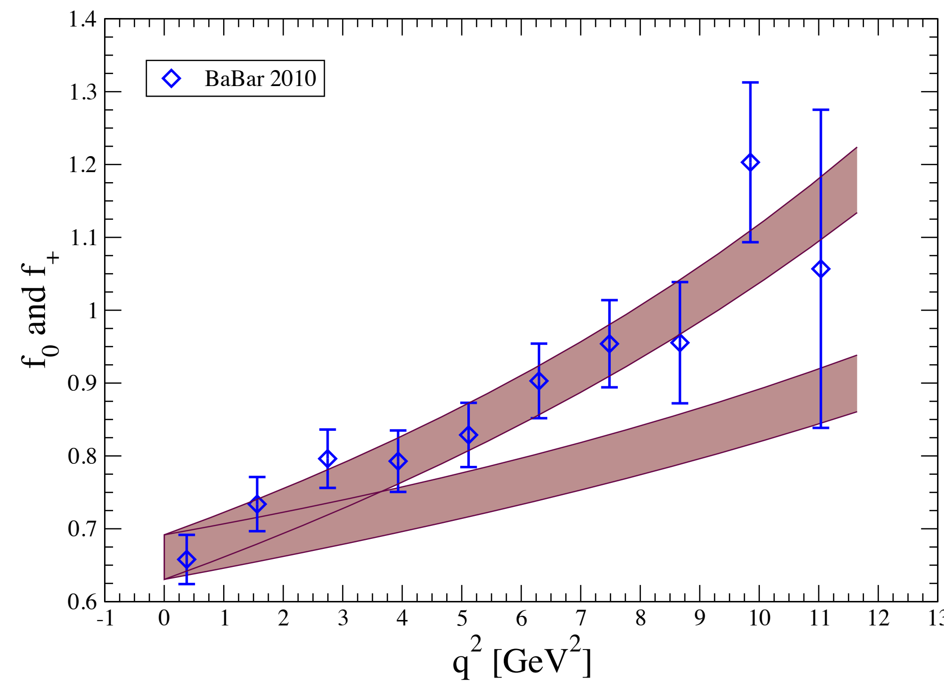
Synthesis of $|V_{ub}|$ & $|V_{cb}|$ Calculations

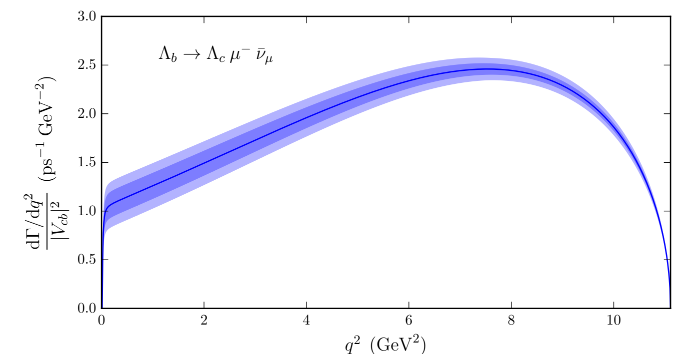


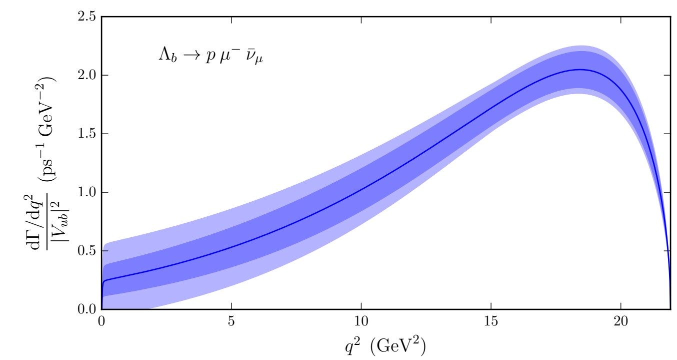
- Experimental errors for $B \to D$ will shrink soon.
- Other errors bars: QCD and expt comparable.
- Refs in backup.

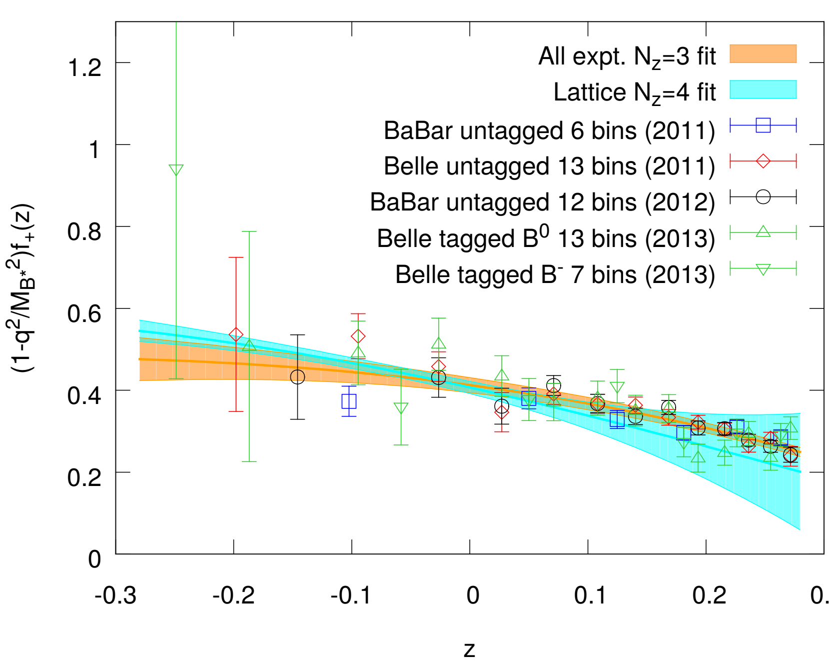
Combining Lattice QCD with Experiment

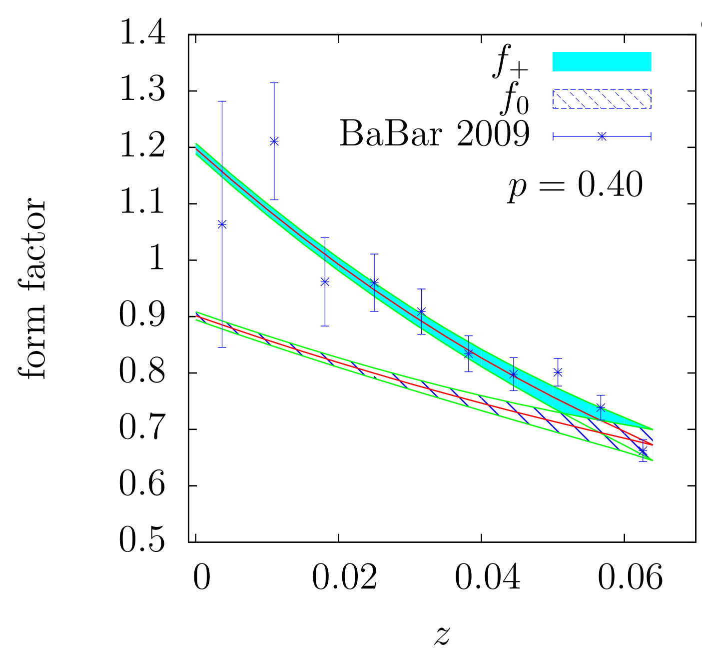


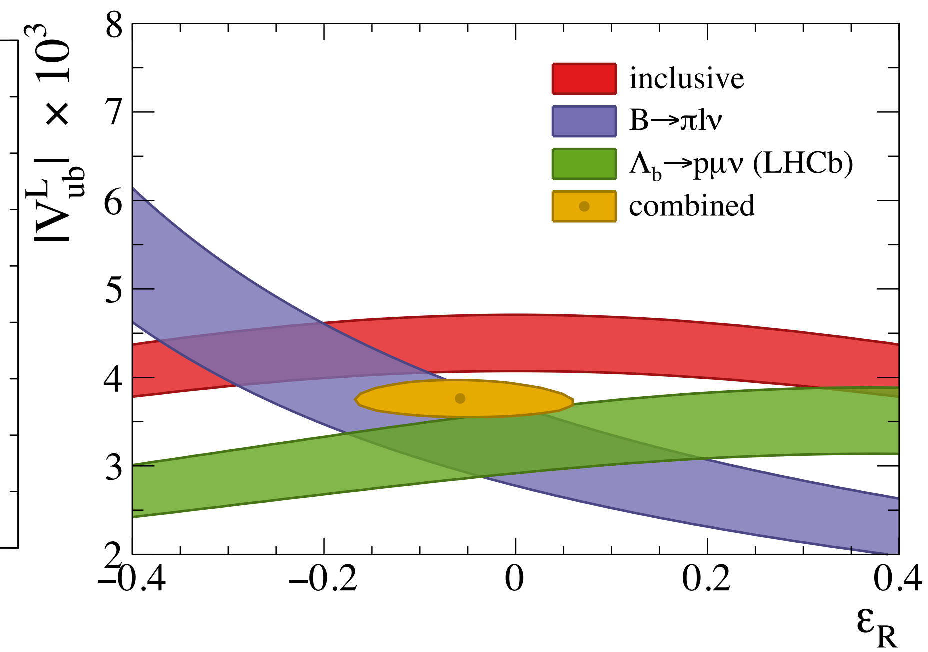












Lattice Status: Nucleons

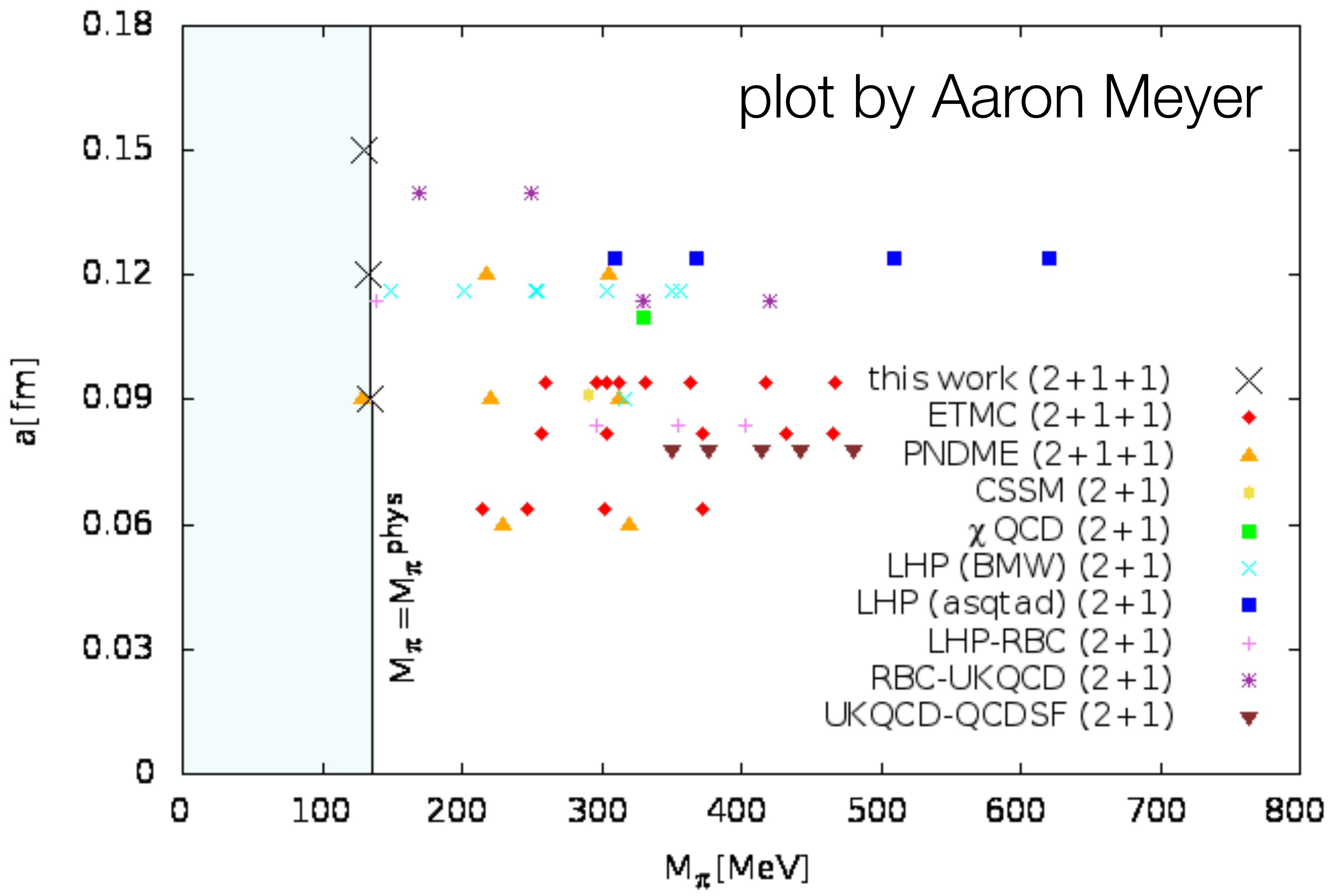
- Nucleons are technically more difficult—greater statistical noise:
  - compute correlation functions from functional integral—10^9 dimensions;
  - Monte Carlo with importance sampling;
  - masses & matrix elements, like $F_A(q^2)$, from fits to these MC data:

$$C_{ab}(t,\bar{t}) := \langle N_a(t) A(0) \bar{N}_b(\bar{t}) \rangle = \sum_{r,r'} \langle 0 | \hat{N}_a | N_r \rangle \langle N_r | \hat{A} | N_{r'} \rangle \langle N_{r'} | \hat{\bar{N}}_b | 0 \rangle e^{-M_r t - M_{r'} \bar{t}}$$

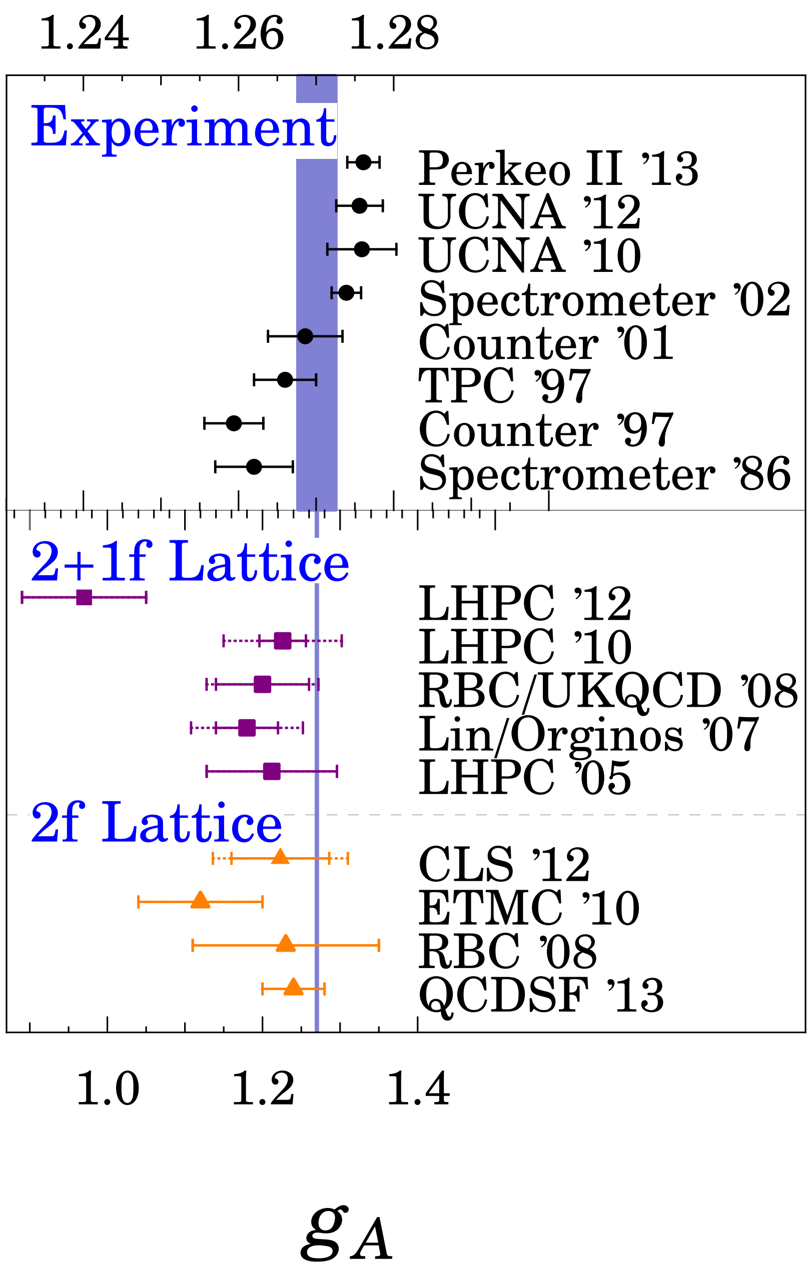
- Empirically (in lattice QCD), nucleon mx elements have more serious issues with excited states and with the chiral extrapolation $m_l^{\text{sim}} \to \frac{1}{2}(m_u + m_d)$.

Lattice Status: Axial Charge $g_A = F_A(0)$

- World-wide activity!

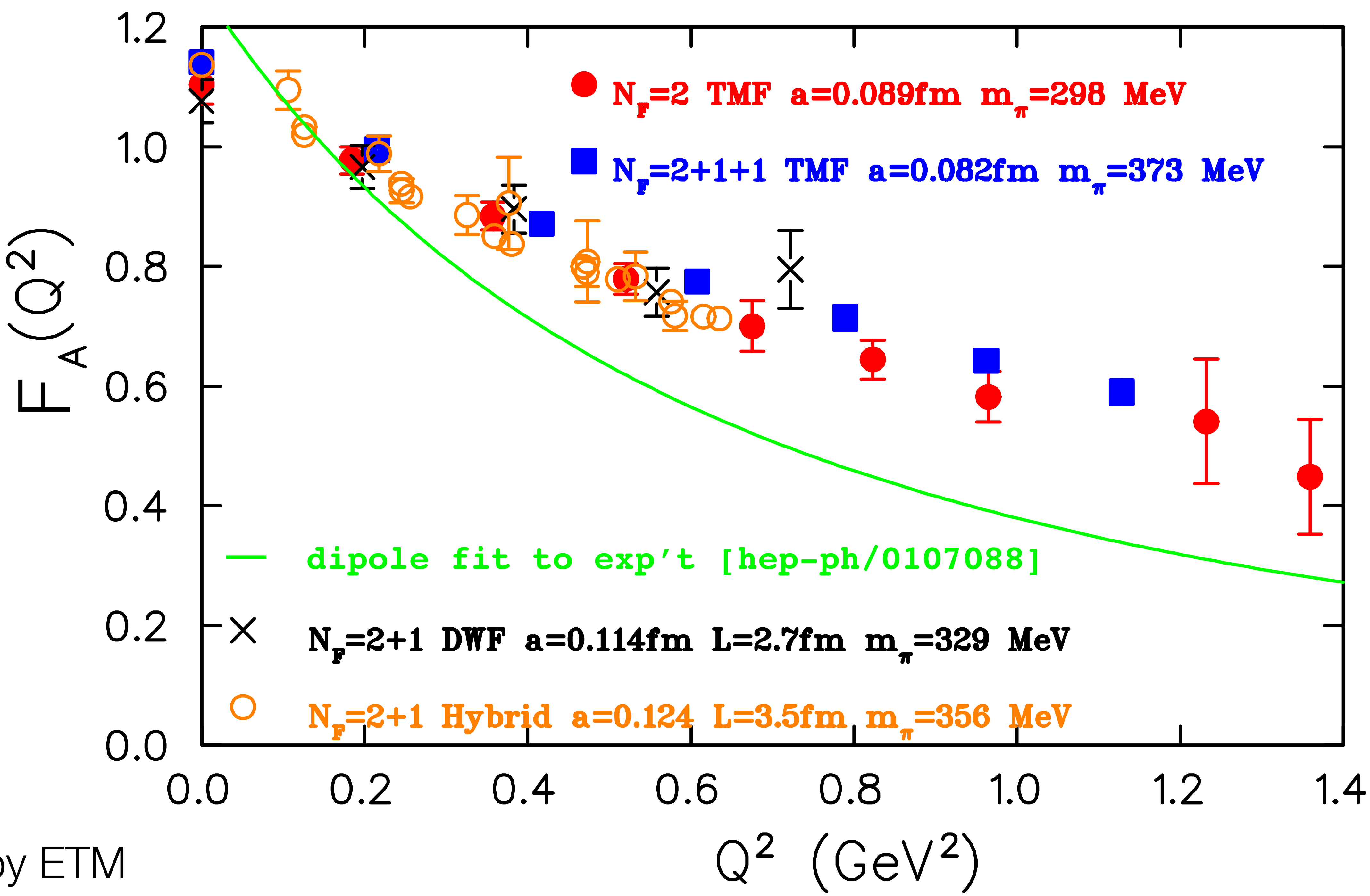


plot by PNDME



- On brink of utility to experiment/phenomenology.

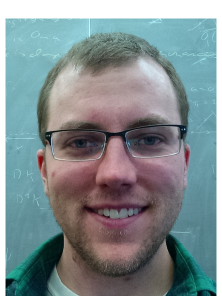
Lattice Status: Nucleon Form Factors

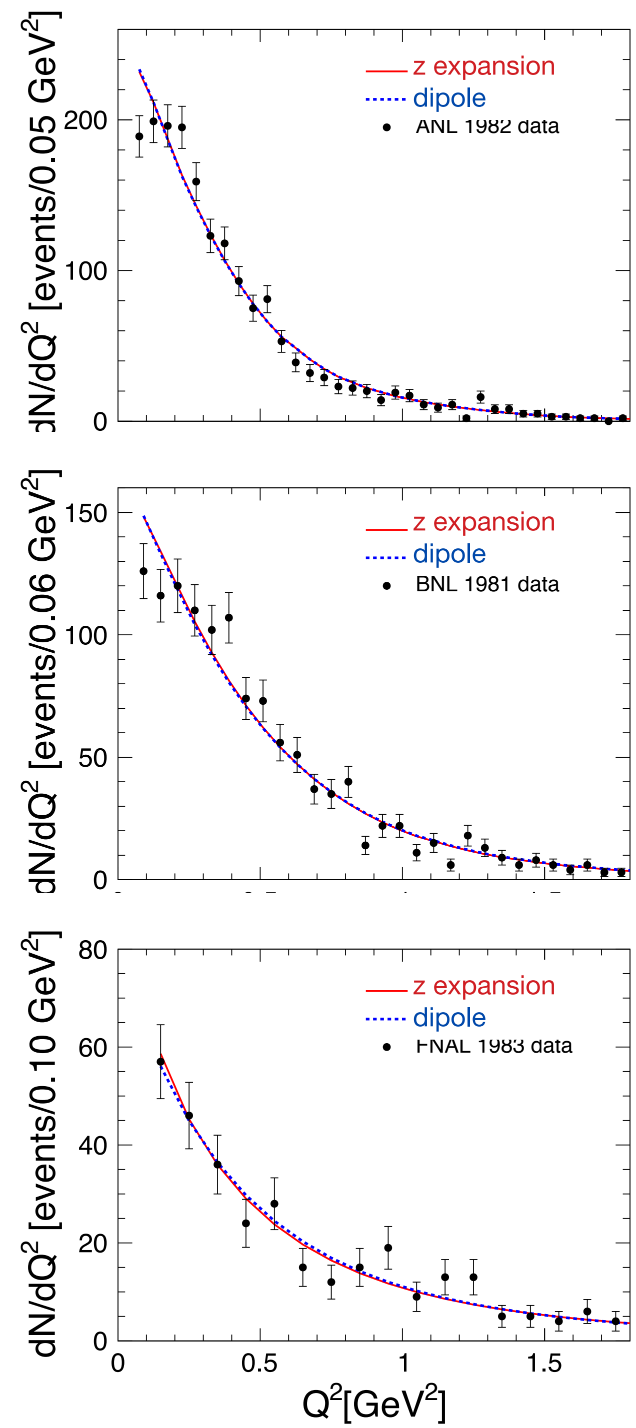


plot by ETM

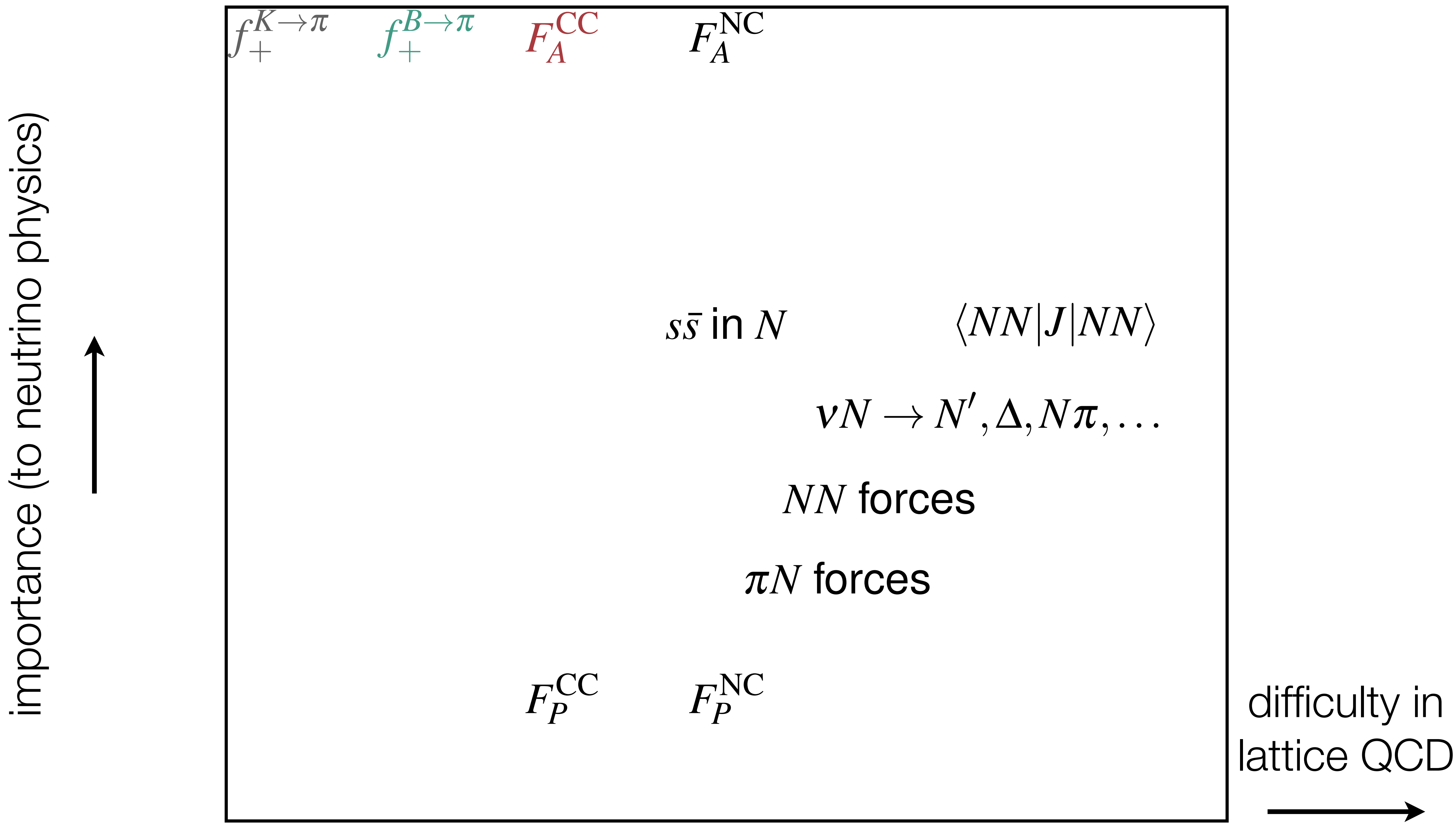
Combining Neutrino Experiment with z Expansion

- Meyer, Betancourt, Gran, and Hill have fit 1980s neutrino-deuteron scattering to the z expansion.





Further Calculations of Interest



Summary, Plans, and Outlook

- Replace Ansätze for nucleon-level physics with *ab-initio* QCD (*i.e.*, continuum limit of lattice QCD).
- Two community efforts needed:
  - nucleon lattice QCD has to match meson lattice QCD in thoroughness of error budgets: a lot of human effort to accompany computing;
  - neutrino event generators and nuclear models need hooks to input this information, as it becomes available.
- Then neutrino-nucleus scattering data can be used to reduce the nuclear effects to understandable uncertainties on fundamental measurements, while using the same data to understand the nucleus better.