β decay as a probe of new physics

Confinement 2024

Cairns, Australia, August 19 - 24, 2024

André Walker-Loud

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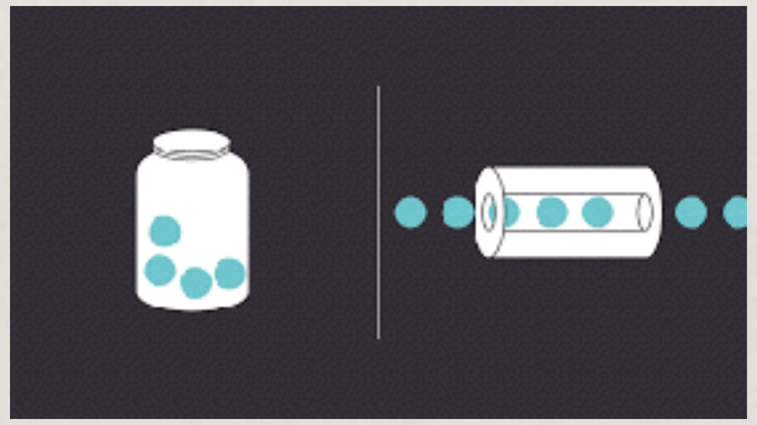
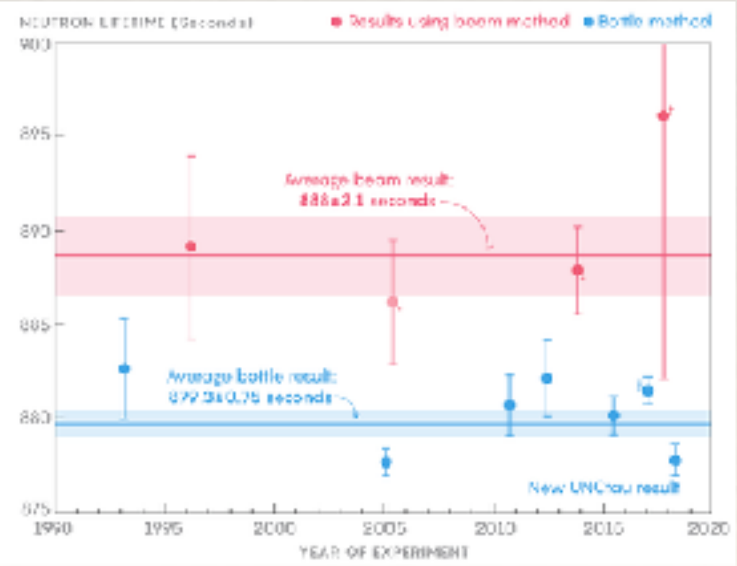
Searches for New Physics in Low Energy Nuclear Physics Environments

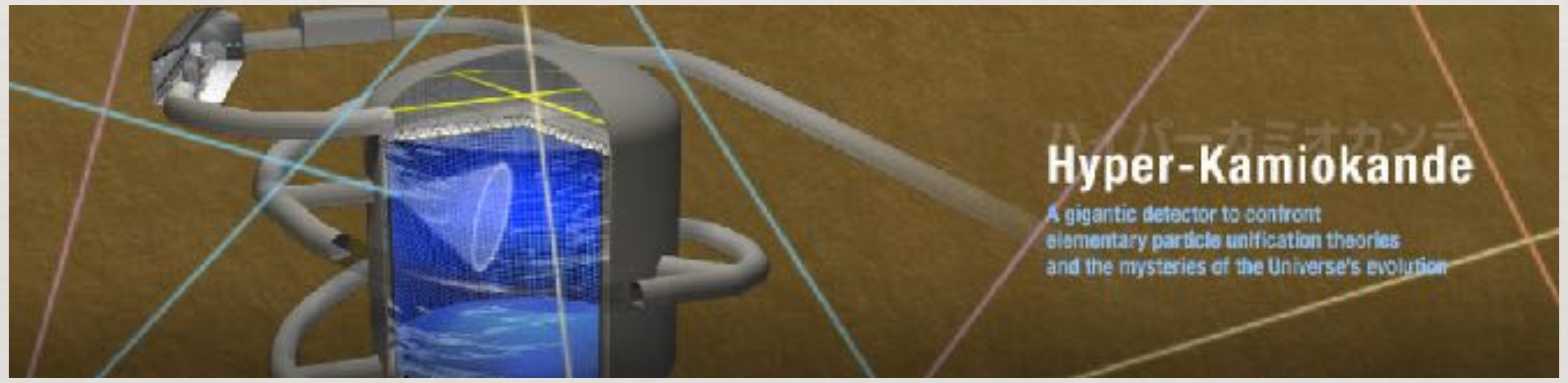
- Search for BSM (Beyond the Standard Model) physics in low-energy environments offers complimentary and competitive constraints to collider searches:

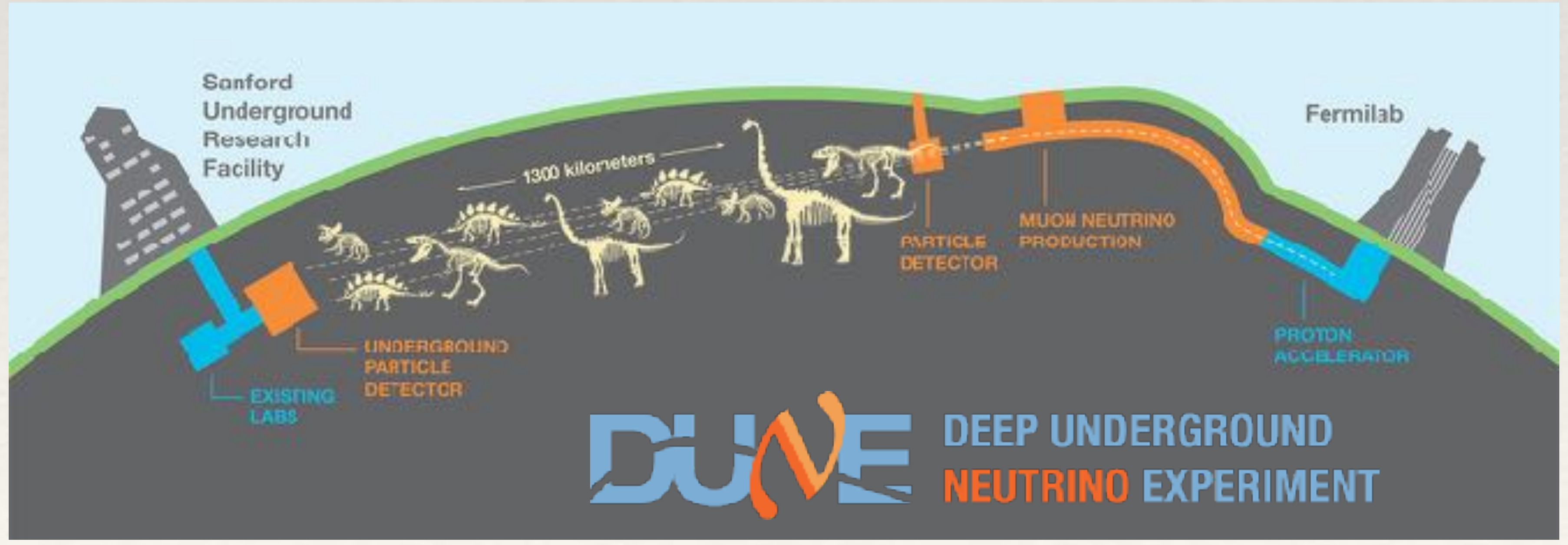
Precision comparison with experiment
- neutron, nuclear β-decay
- Kaon β-decay



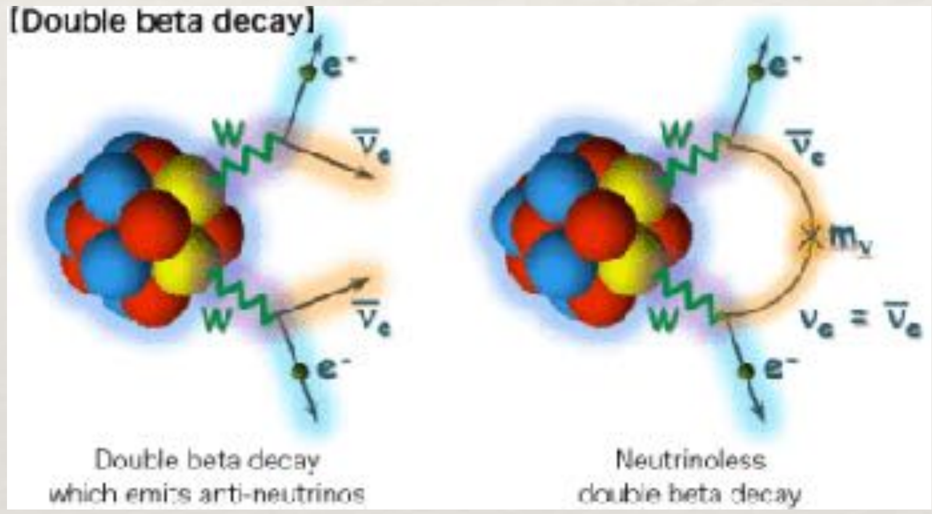


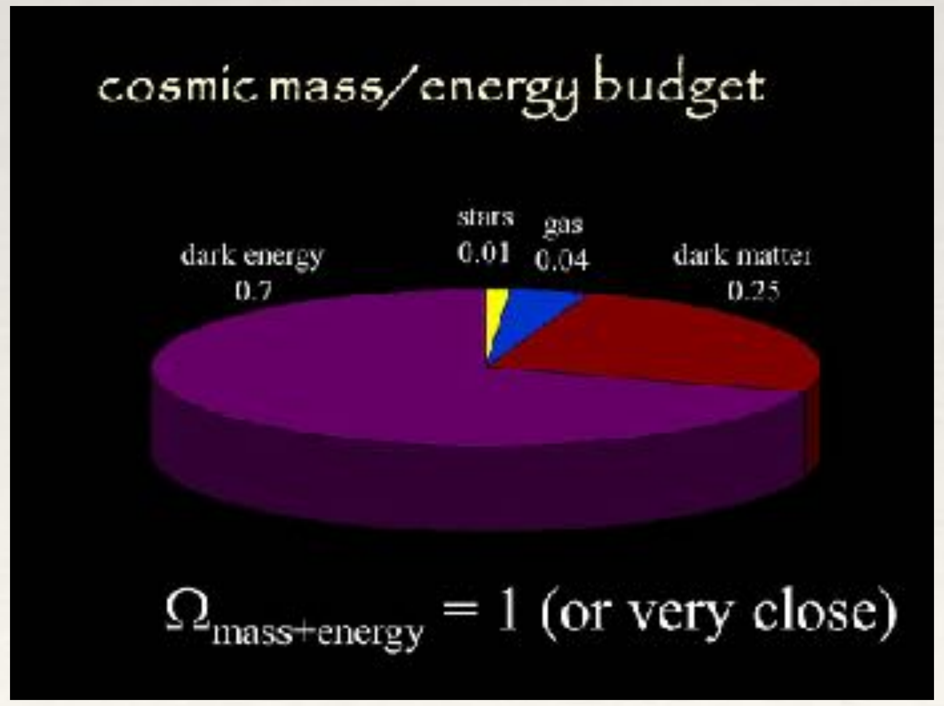
Nuclear Physics is the "background"
- long-baseline neutrino-nucleus scattering



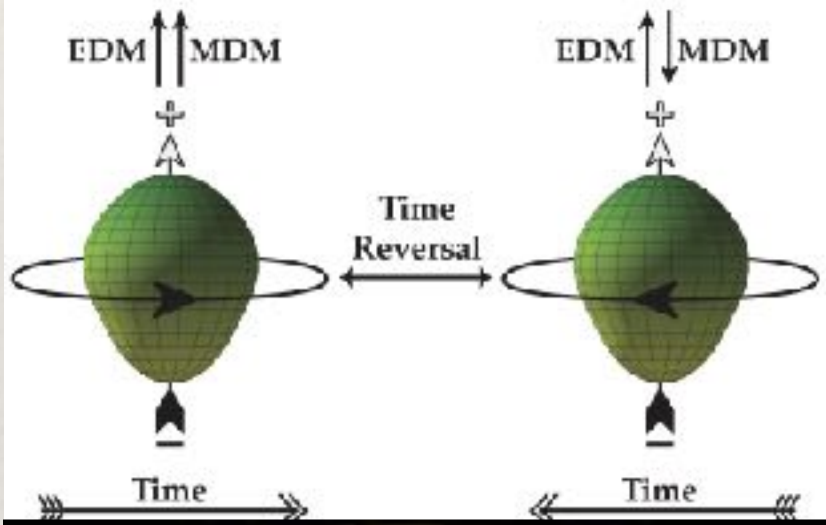


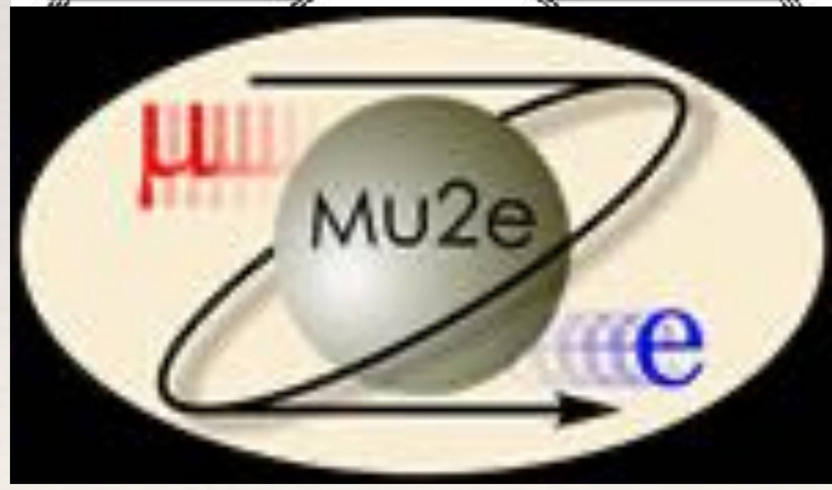
SM Forbidden
- $0\nu\beta\beta$
- Dark Matter





SM "absent"
- EDMs
- $\mu \to e$

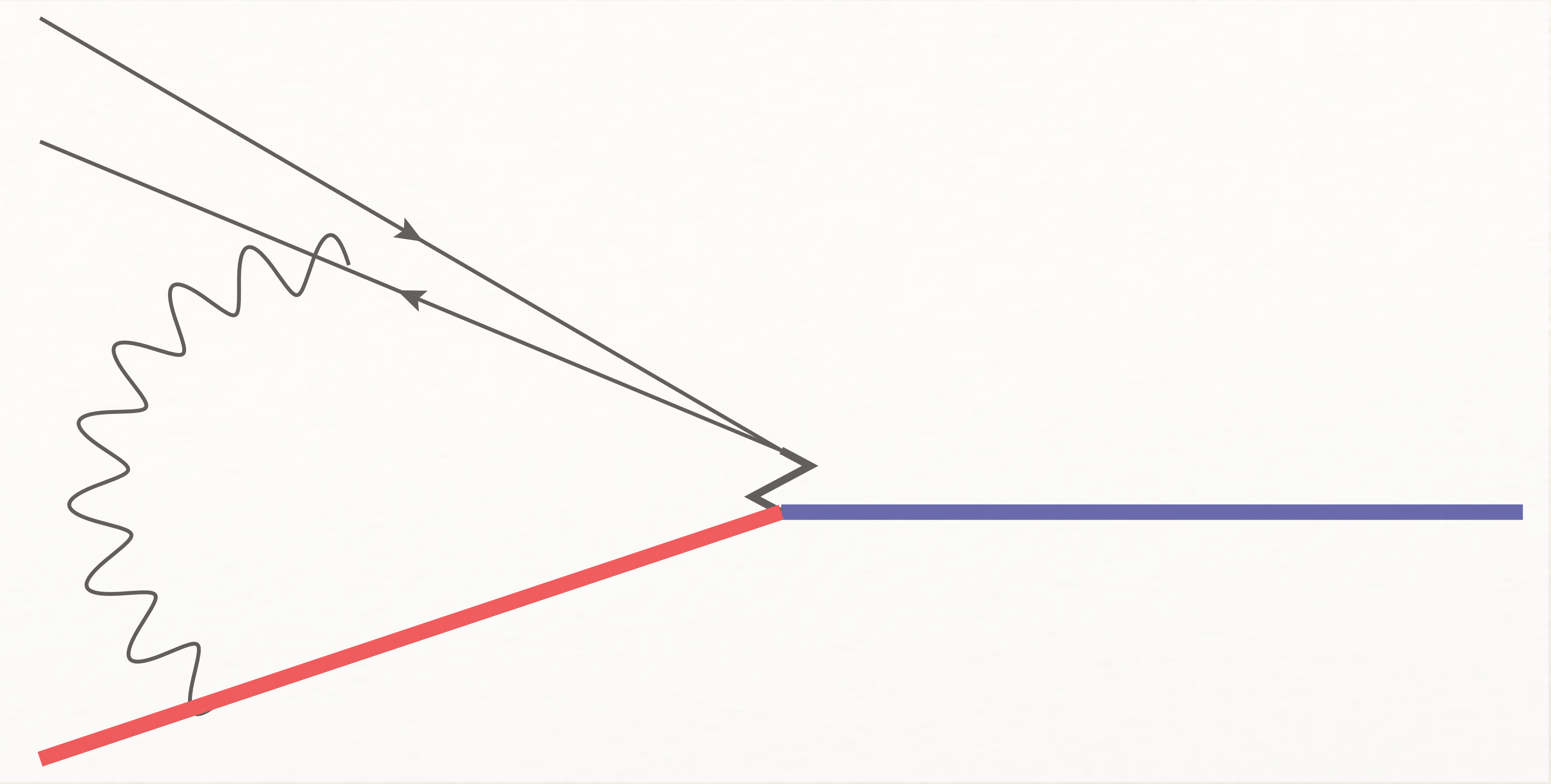




β-decay — precision tests of the Standard Model (SM)

- The generic β-decay rate is given by

$$\Gamma_k = \left(G_F^{(\mu)}\right)^2 \times |V_{ij}|^2 \times |M_{\text{had}}|^2 \times (1+\delta_{\text{RC}}) \times F_{\text{kin}}$$



Fermi's decay constant measured with μ-decay

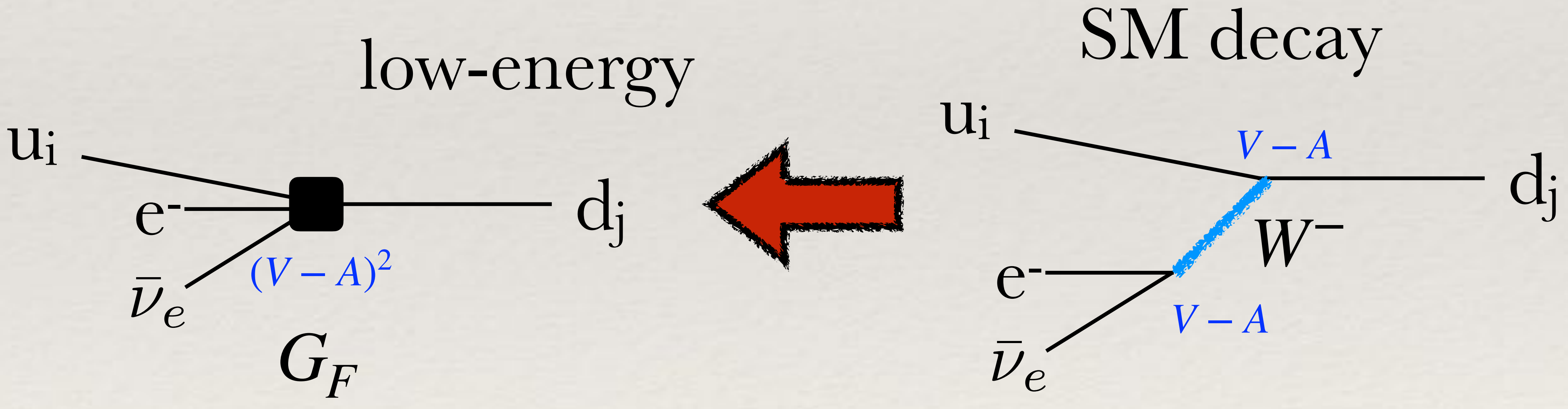
non-perturbative hadronic matrix elements

Quark mixing matrix elements
V_{CKM} = Cabibbo - Kobayashi - Maskawa matrix

radiative QED corrections

phase space kinematic factor

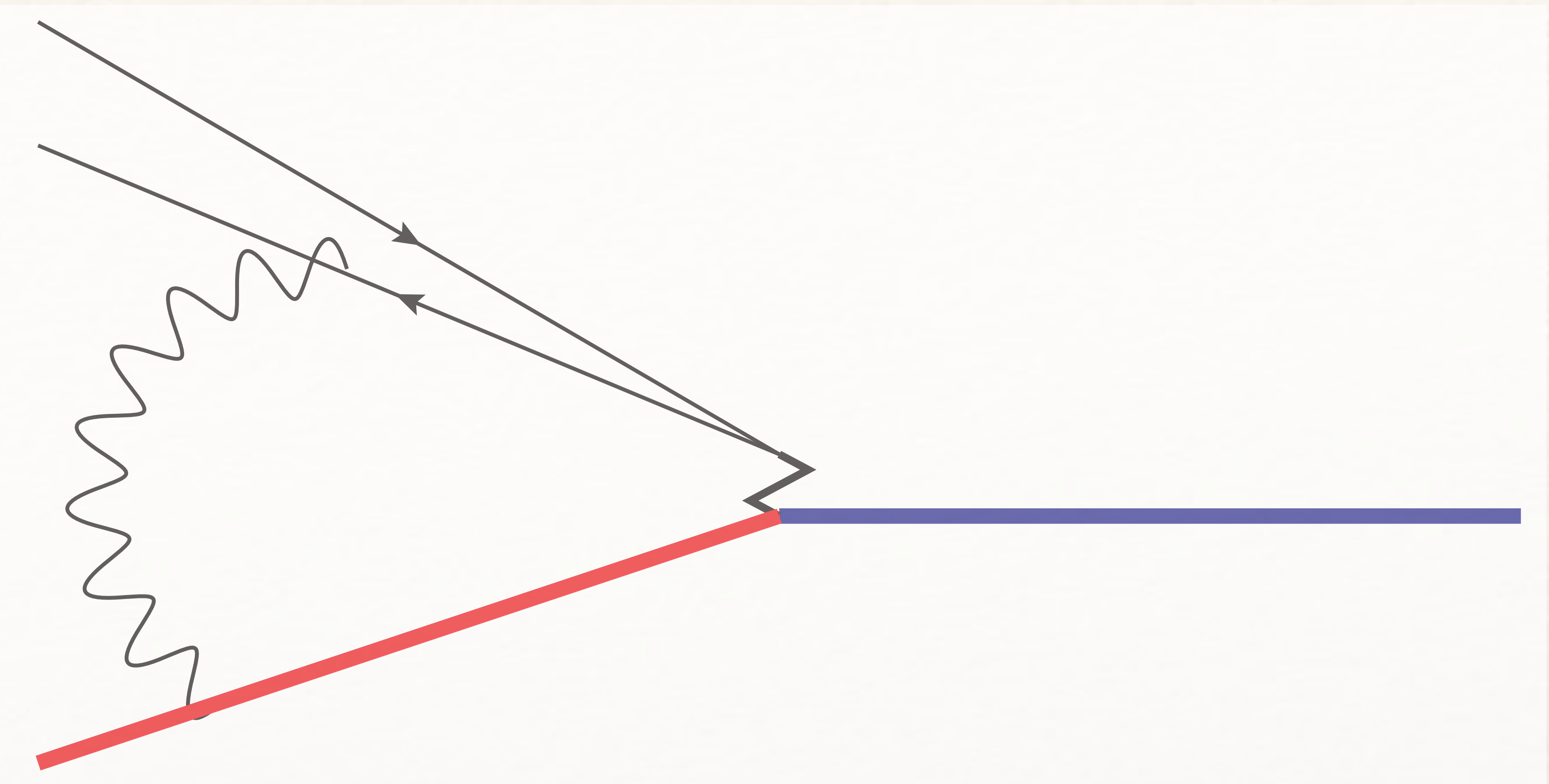
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{weak} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{QCD}$$



V_{CKM} is a unitary matrix — if SM only
no new physics: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Determining V_{ij} requires knowledge of $|M_{\text{had}}|$
⟶ we need LQCD (Lattice QCD)

β-decay — precision tests of the Standard Model (SM)



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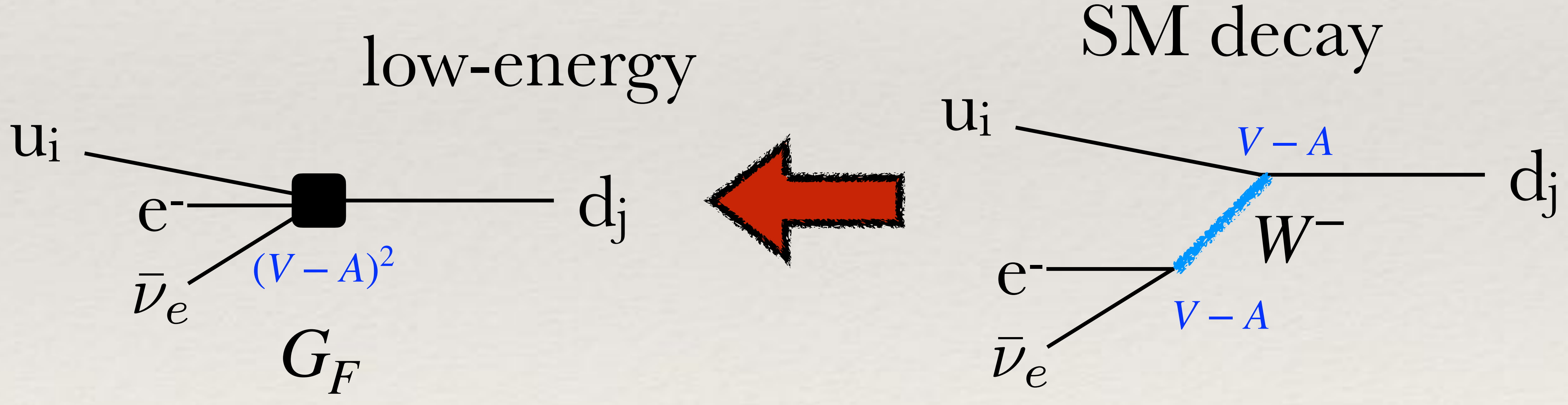
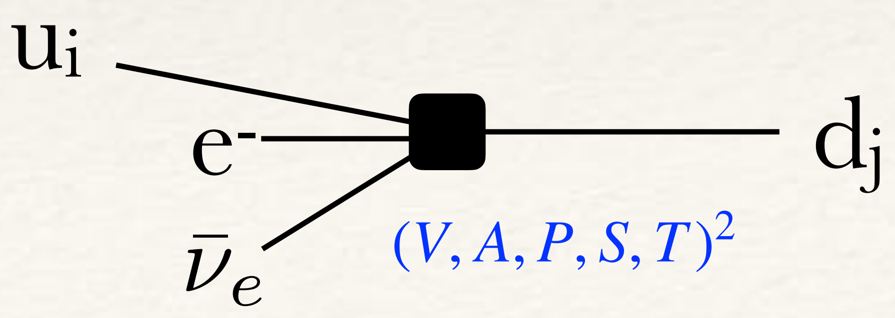
Determining V_{ij} requires knowledge of $|M_{\text{had}}|$

⟶ we need LQCD (Lattice QCD)



What would heavy BSM contribution look like?

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$



β-decay - determining V_{ij}

$$\Gamma_k = \left(G_F^{(\mu)}\right)^2 \times |V_{ij}|^2 \times |M_{had}|^2 \times (1+\delta_{RC}) \times F_{kin}$$

V_{ud}

$\pi^\pm \to \pi^0 e \bar{\nu}_e$

theoretically clean
experimentally noisy

nuclear $0^+ \to 0^+$

theoretically messy
experimentally clean

$n \to p e \bar{\nu}_e$

theoretically clean-ish
experimentally clean-ish

V_{us}

$K \to \pi \mu \bar{\nu}_\mu$

theoretically clean
experimentally clean

$$\left.\frac{q^\mu \langle \pi^-(p+q) | \bar{s}\gamma_\mu u | K^0(p)\rangle}{m_K^2 - m_\pi^2}\right|_{q^2\to 0} \to f_+(0)|V_{us}|$$

$\frac{V_{us}}{V_{ud}}$

$$\frac{K \to \mu \bar{\nu}_\mu}{\pi \to \mu \bar{\nu}_\mu}$$

$$\frac{\partial^\mu \langle 0 | \bar{s}\gamma_\mu\gamma_5 u | K^+\rangle}{\partial^\mu \langle 0 | \bar{d}\gamma_\mu\gamma_5 u | \pi^+\rangle} \to \frac{m_K^2\ F_K}{m_\pi^2\ F_\pi} \frac{|V_{us}|}{|V_{ud}|}$$

theoretically clean
experimentally clean

β-decay - determining V_{ij}

$$\Gamma_k = \left(G_F^{(\mu)}\right)^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{\rm RC}) \times F_{\rm kin}$$

V_{ud}

$\pi^\pm \to \pi^0 e \bar\nu_e$
theoretically clean
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nuclear $0^+ \to 0^+$
theoretically messy
experimentally clean

$n \to p e \bar\nu_e$
theoretically clean-ish
experimentally clean-ish

V_{us} $K \to \pi \mu \bar\nu_\mu$

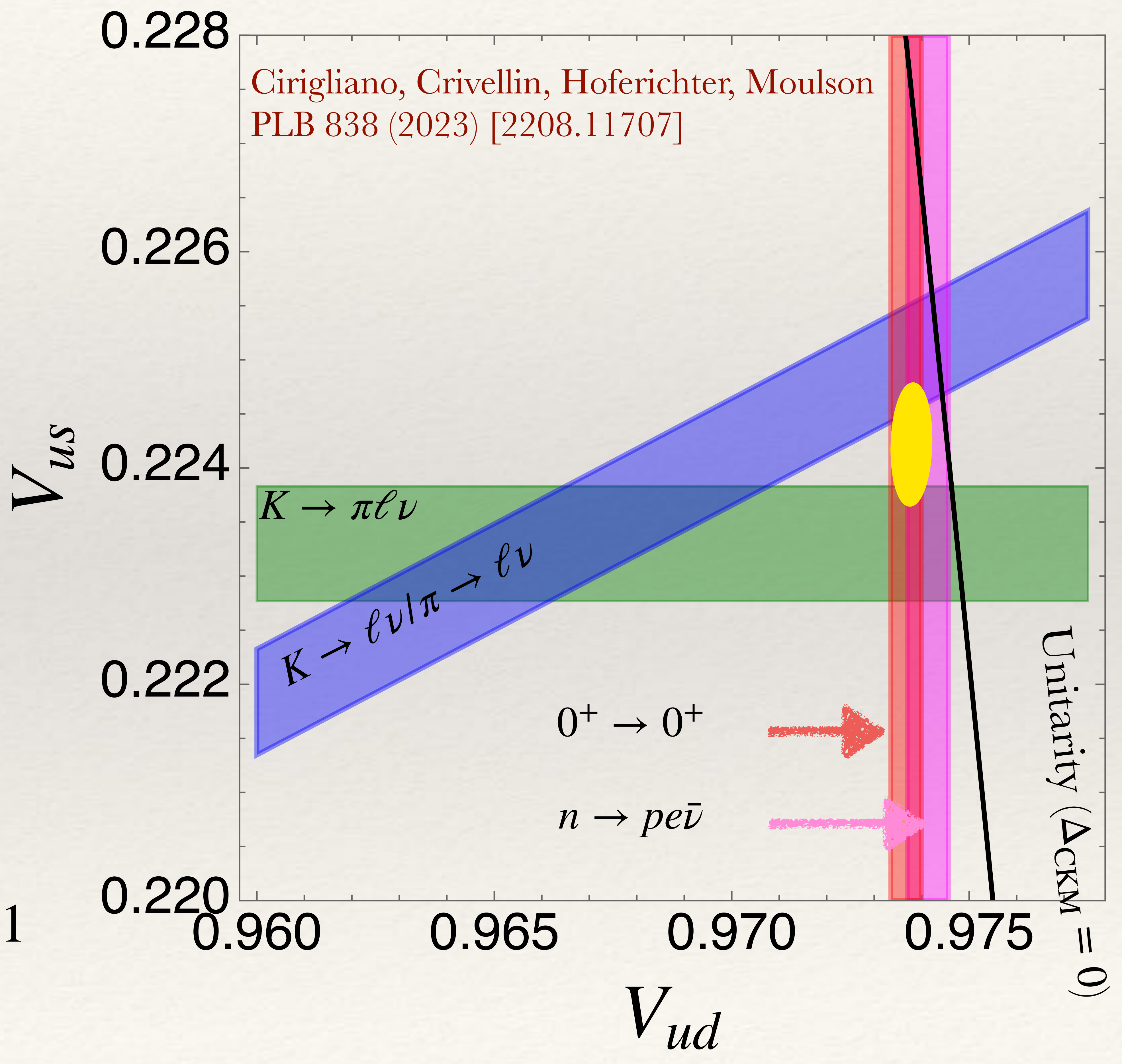
$$\left.\frac{q^\mu \langle \pi^-(p+q)|\bar s \gamma_\mu u|K^0(p)\rangle}{m_K^2 - m_\pi^2}\right|_{q^2\to 0} \to f_+(0)|V_{us}|$$

theoretically clean
experimentally clean

$\frac{V_{us}}{V_{ud}}$ $\frac{K \to \mu \bar\nu_\mu}{\pi \to \mu \bar\nu_\mu}$

$$\frac{\partial^\mu \langle 0|\bar s \gamma_\mu \gamma_5 u|K^+\rangle}{\partial^\mu \langle 0|\bar d \gamma_\mu \gamma_5 u|\pi^+\rangle} \to \frac{m_K^2\ F_K}{m_\pi^2\ F_\pi}\frac{|V_{us}|}{|V_{ud}|}$$

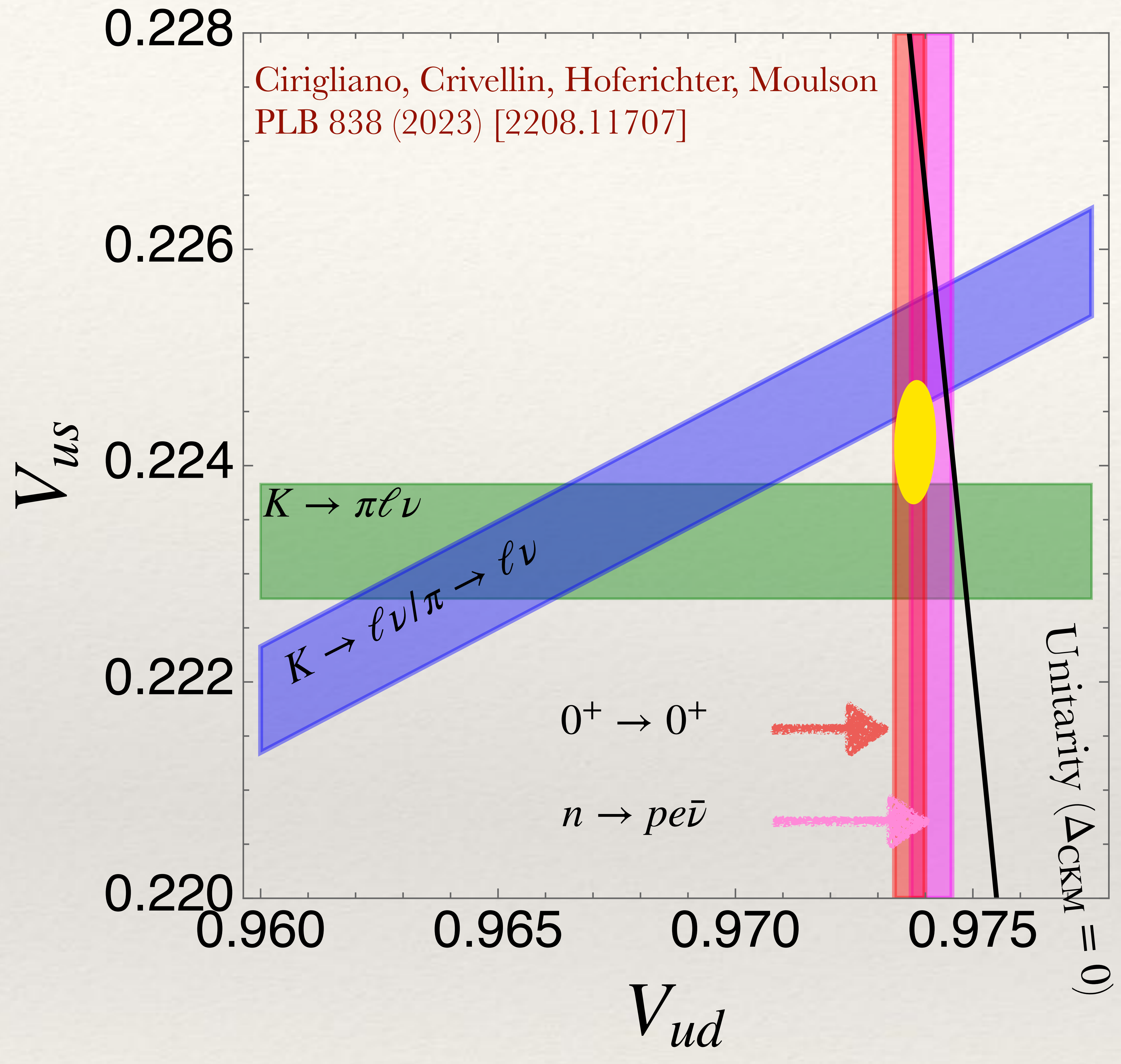
theoretically clean
experimentally clean



$$\Delta_{\rm CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.00176(56)$$

Cabibbo Angle Anomaly

β-decay - Tension in the first-row of CKM



$$\Delta_{\rm CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.00176(56)$$

Cabibbo Angle Anomaly

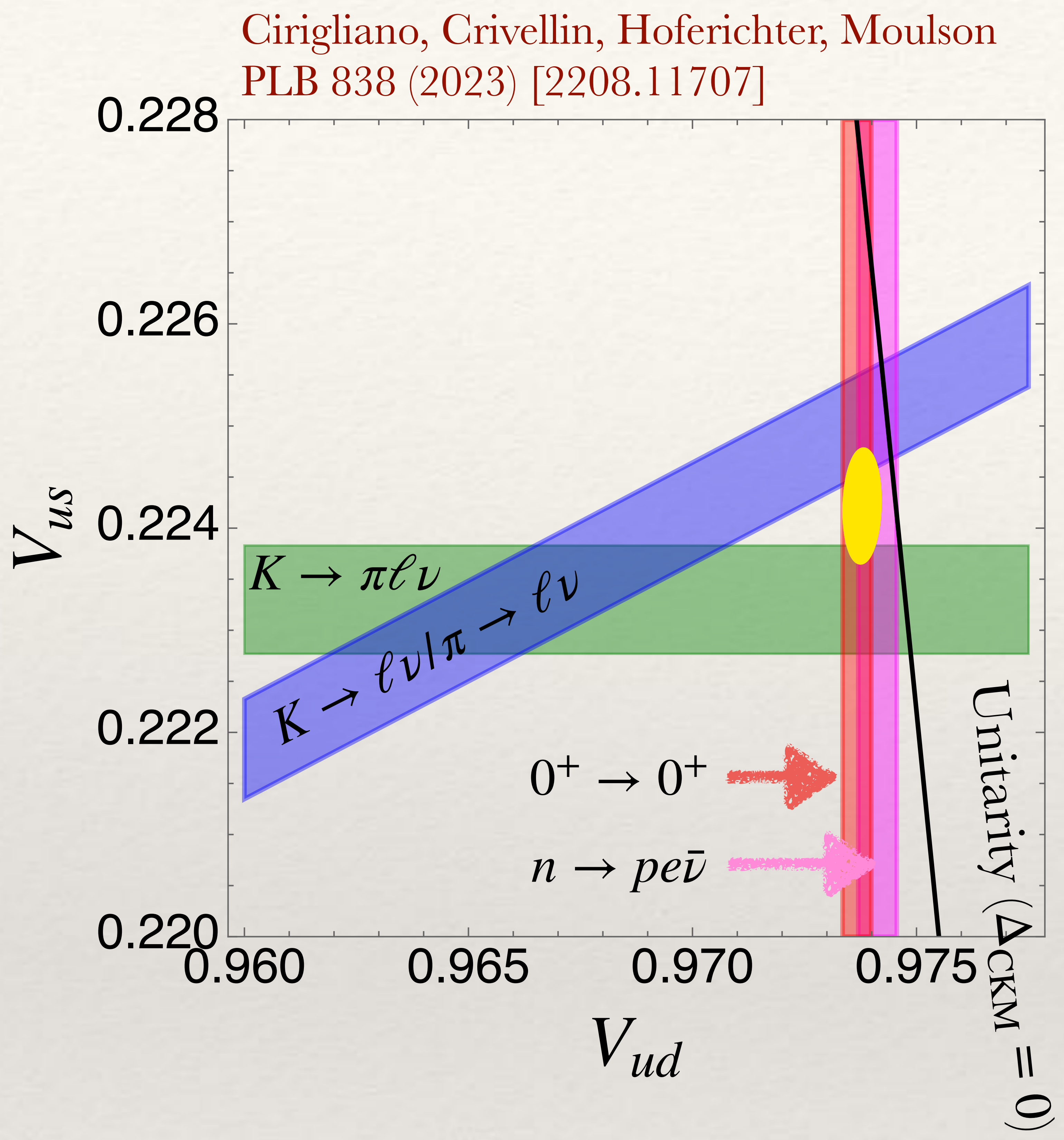
- Most significant tension with unitarity comes from Kaons
  $K \to \pi \ell \nu$ vs $K \to \ell \nu$ / $\pi \to \ell \nu$
  ($K_{\ell 3}$ vs $K_{\ell 2}/\pi_{\ell 2}$)

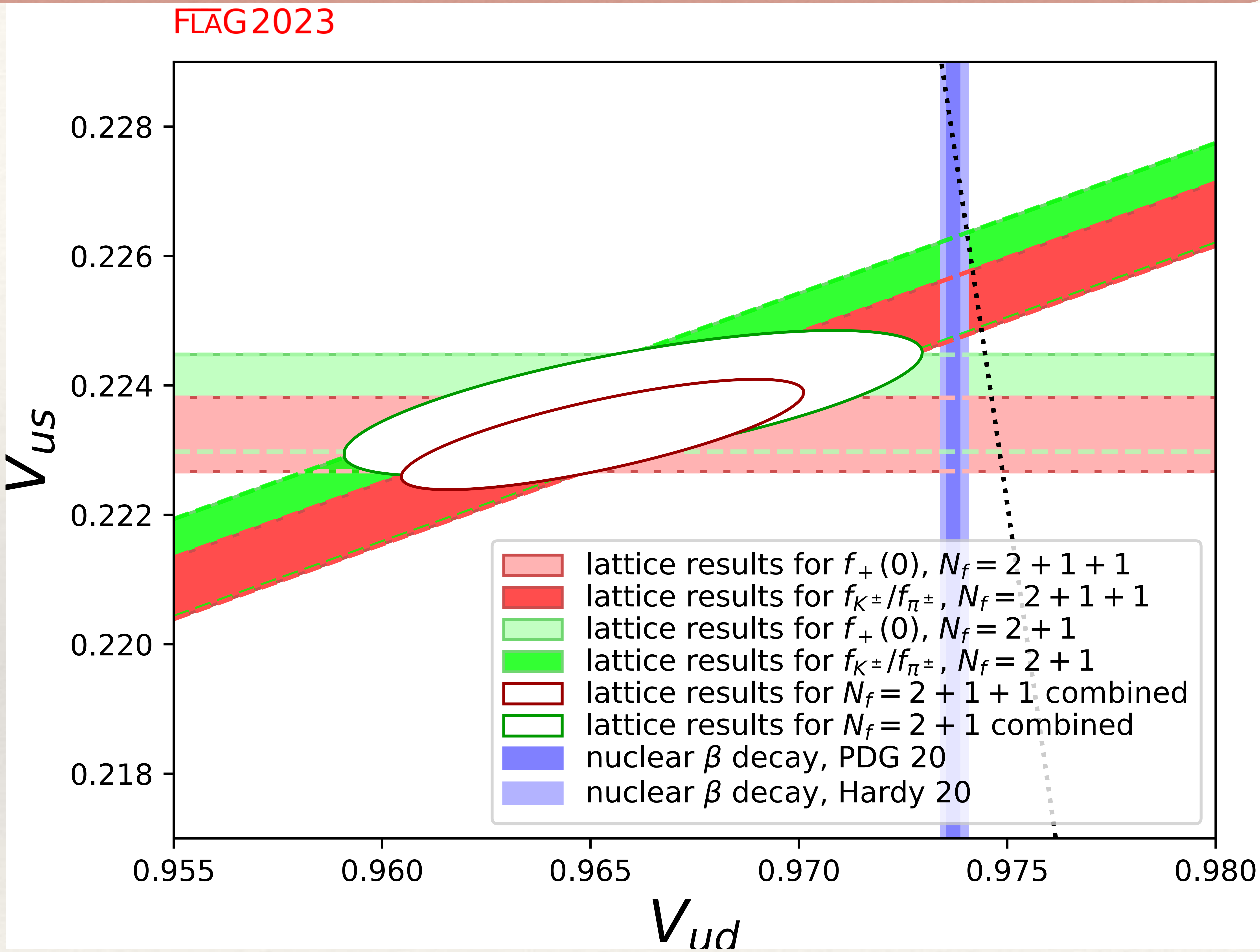
- Some determinations of these CKM elements

$$V_{ud}^{0^+\to 0^+} = 0.97367(11)_{\rm exp}(13)_{\Delta_V^R}(27)_{\rm NS}[32]_{\rm total}$$
$$V_{us}^{K_{\ell 3}} = 0.22330(35)_{\rm exp}(39)_{f_+}(8)_{\rm IB}[53]_{\rm total}$$

- At this level of precision, careful treatment of radiative QED corrections has become the frontier
  - Original Sirlin & Marciano et al approach (current algebra)
  - modern pheno and EFT treatments
  - lattice QCD + QED

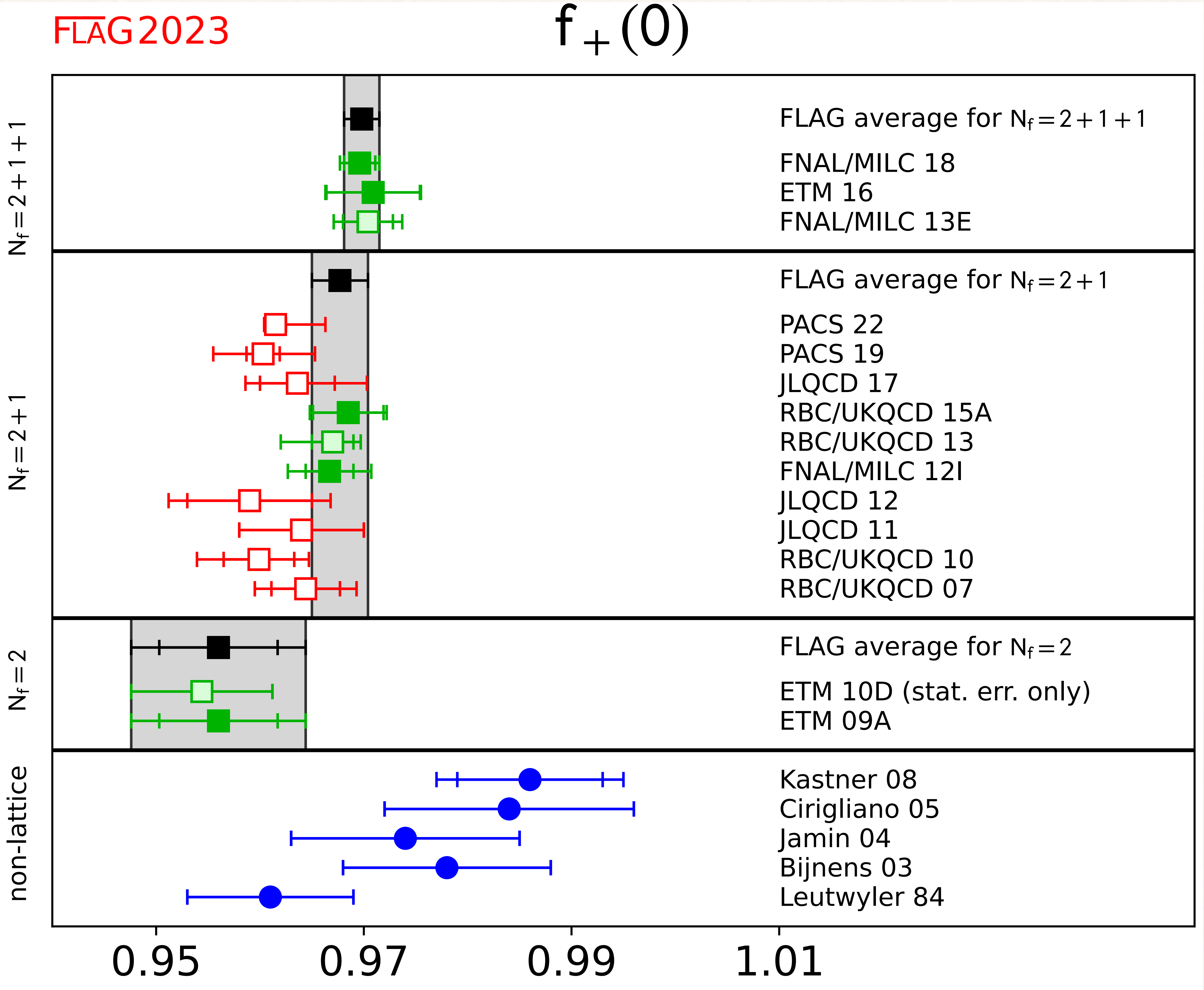
β-decay - Tension in the first-row of CKM

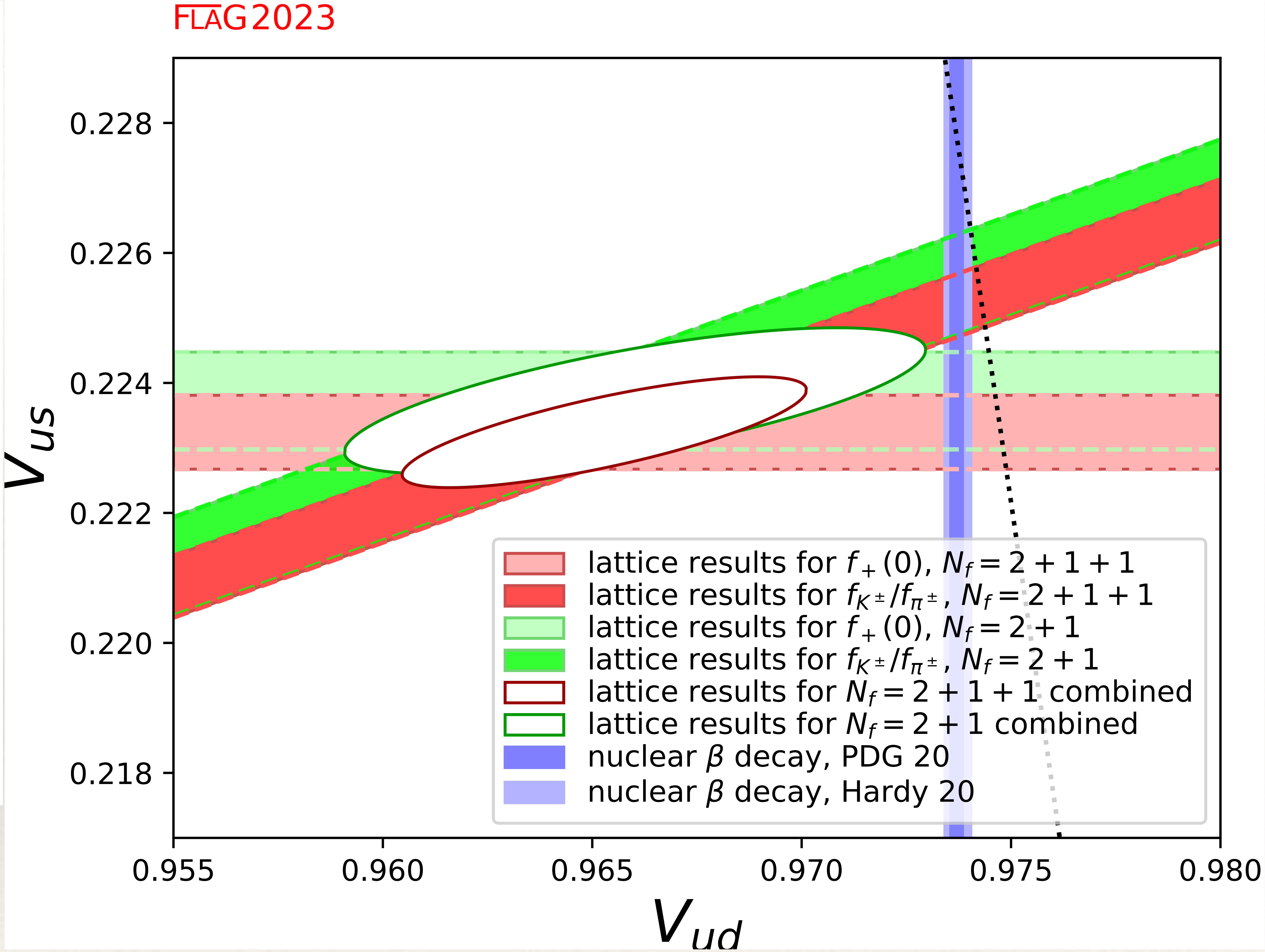




- 3σ tension is seen with $N_f = 2+1+1$
- less tension with $N_f = 2+1$

β-decay - Tension in the first-row of CKM

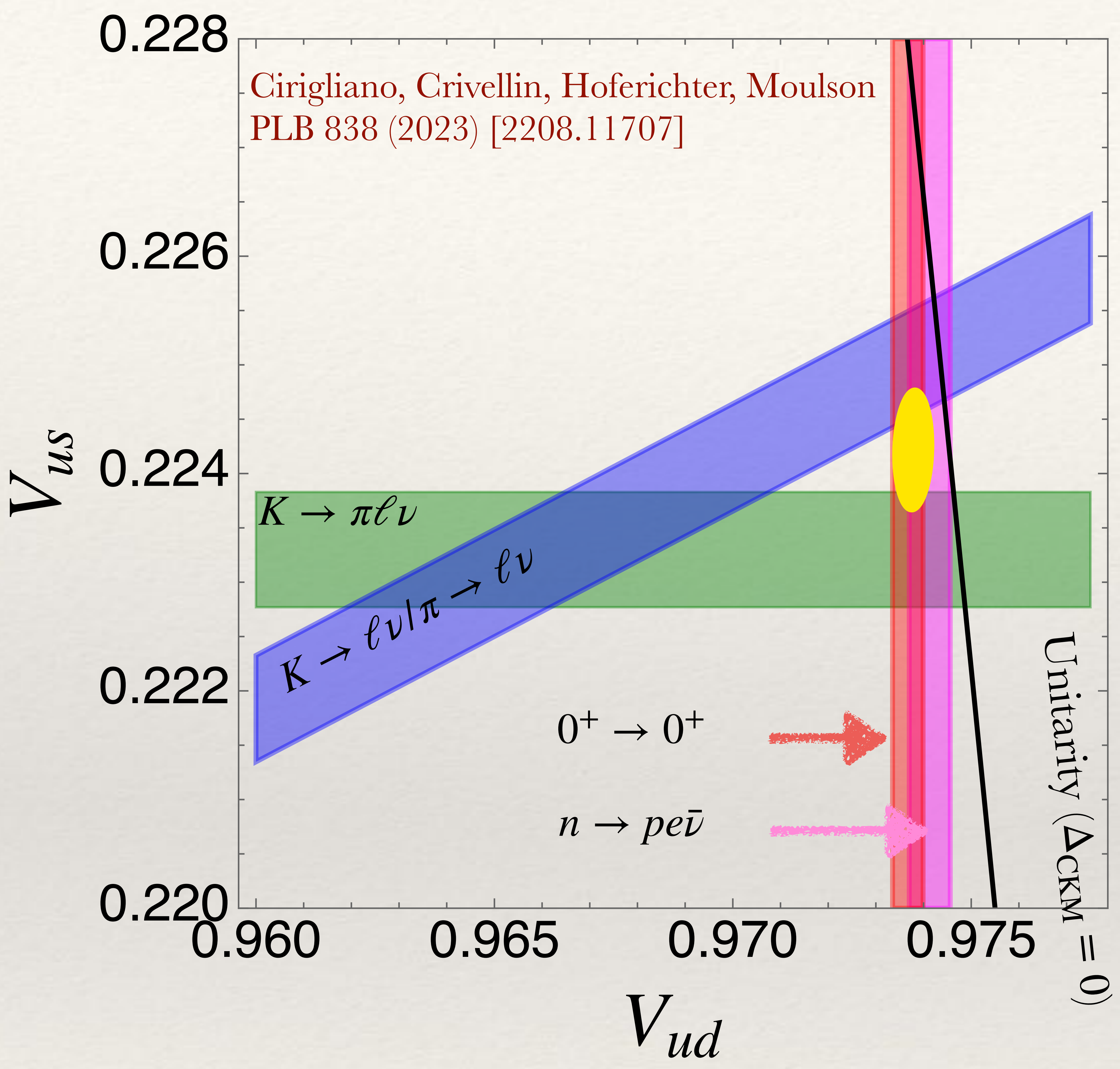




- Currently - $> 3\sigma$ tension is driven by a single $N_f = 2+1+1$ LQCD result for $f_+(0)$

- It is important for other LQCD results to be pushed to the same precision as FNAL/MILC
  PACS-CS is getting there with $N_f = 2+1$ [Lattice2023, 2311.16755] - we need more

β-decay - Prospects for improving experimental precision



- Current tension in global kaon fits: p-value < 1% [2208.11707]
  - $K_{\ell 2}$ measurement dominated by single experiment
  - $K_{\mu 3}/K_{\mu 2}$ measurement @ 0.2% will add clarity — NA62

Tomáš Husek
Mon. 16:40

- V_{ud} determination dominated by nuclear $0^+ \to 0^+$ decays
  - challenging to control nuclear structure corrections at 10^{-4} precision

    $V_{ud}^{0^+ \to 0^+} = 0.97367(11)_{\rm exp}(13)_{\Delta_V^R}(27)_{\rm NS}[32]_{\rm total}$

    $V_{ud}^{0^+ \to 0^+} = 0.97364(10)_{\rm exp}(12)_{g_V}(22)_{\mu}(12)_{\delta_C}(43)_{g_V^{NN}}(20)_{\delta_{\rm NS}^E}[56]_{\rm total}$ [2405.18464]

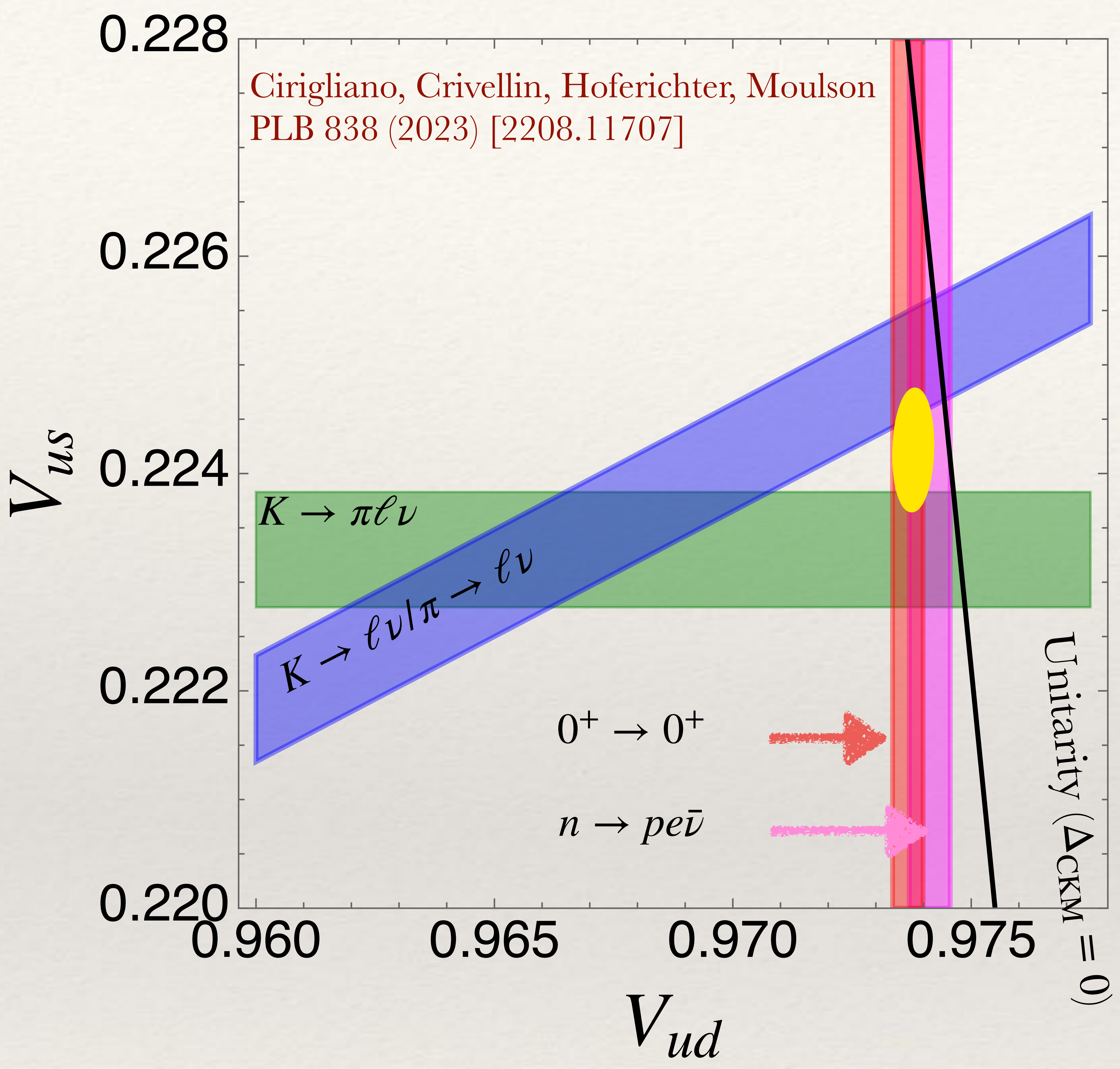
  - Take best τ_n and $\lambda = g_A/g_V$ measurement from $n \to p e \bar{\nu}$

    $V_{ud}^{n,{\rm PDG}} = 0.97441(3)_f(13)_{\Delta_V^R}(82)_{\lambda}(28)_{\tau_n}[88]_{\rm total}$

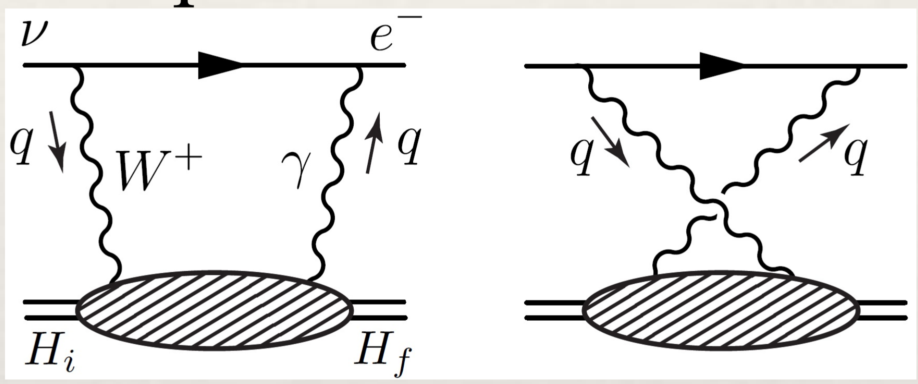
    $V_{ud}^{n,{\rm best}} = 0.97413(3)_f(13)_{\Delta_V^R}(35)_{\lambda}(20)_{\tau_n}[43]_{\rm total}$

  - Realistic nuclear structure corrections larger than typically quoted
  - Realistic to expect neutron decay measurements can match precision of nuclear decays
    - one more measurement of τ_n and λ that match best precision make neutron decay extraction competitive
  - PIONEER Experiment will measure $\pi \to e\bar{\nu}/\pi \to \mu\bar{\nu}$ and π_{e3} allowing for independent V_{ud} and V_{us}/V_{ud} determinations

β-decay - Prospects for improving theoretical precision



- SM predictions also need to be controlled at the O(0.2%) level
- Significant recent progress in understanding QED corrections beginning with
  - Built upon previous extensive work by Czarnecki, Marciano, Sirlin
  - Seng, Gorchtein, Patel, Ramsey-Musolf, PRL 121 (2018) [1807.10197]
  - Seng, Gorchtein, Ramsey-Mosolf, PRD 100 (2019) [1812.03352]
    - Dispersive methods used to provide more careful treatment of the $\Box_{\gamma W}$ arising in β-decay



- Inspired new LQCD calculations to determine non-perturbative contributions to $\Box_{\gamma W}$
  - Seng, Meissner PRL 122 (2019) [1903.07969]
  - Feng, Gorchtein, Jin, Ma, Seng PRL 124 (2020) [2003.09798]
  - …
  - Yoo, Bhattacharya, Gupta, Mondal, Yoon, PRD 108 (2023) [2305.03198]
  - Ma, Feng, Gorchtein, Jin, Liu, Seng, Wang, Zhang PRL 132 (2024) [2308.16755]
- Modern Effective Field Theory Treatments
  - Ando, Fearing Gudkov, Kubodera, Myhrer, Nakamura, Sato PLB 595 (2004) [nucl-th/0402100]
  - Cirigliano, deVries, Hayen, Mereghetti, Walker-Loud PRL 129 (2022) [2202.10439]
  - Cirigliano, Dekens, Mereghetti, Tomalak, PRD 108 (2023) [2306.03188]

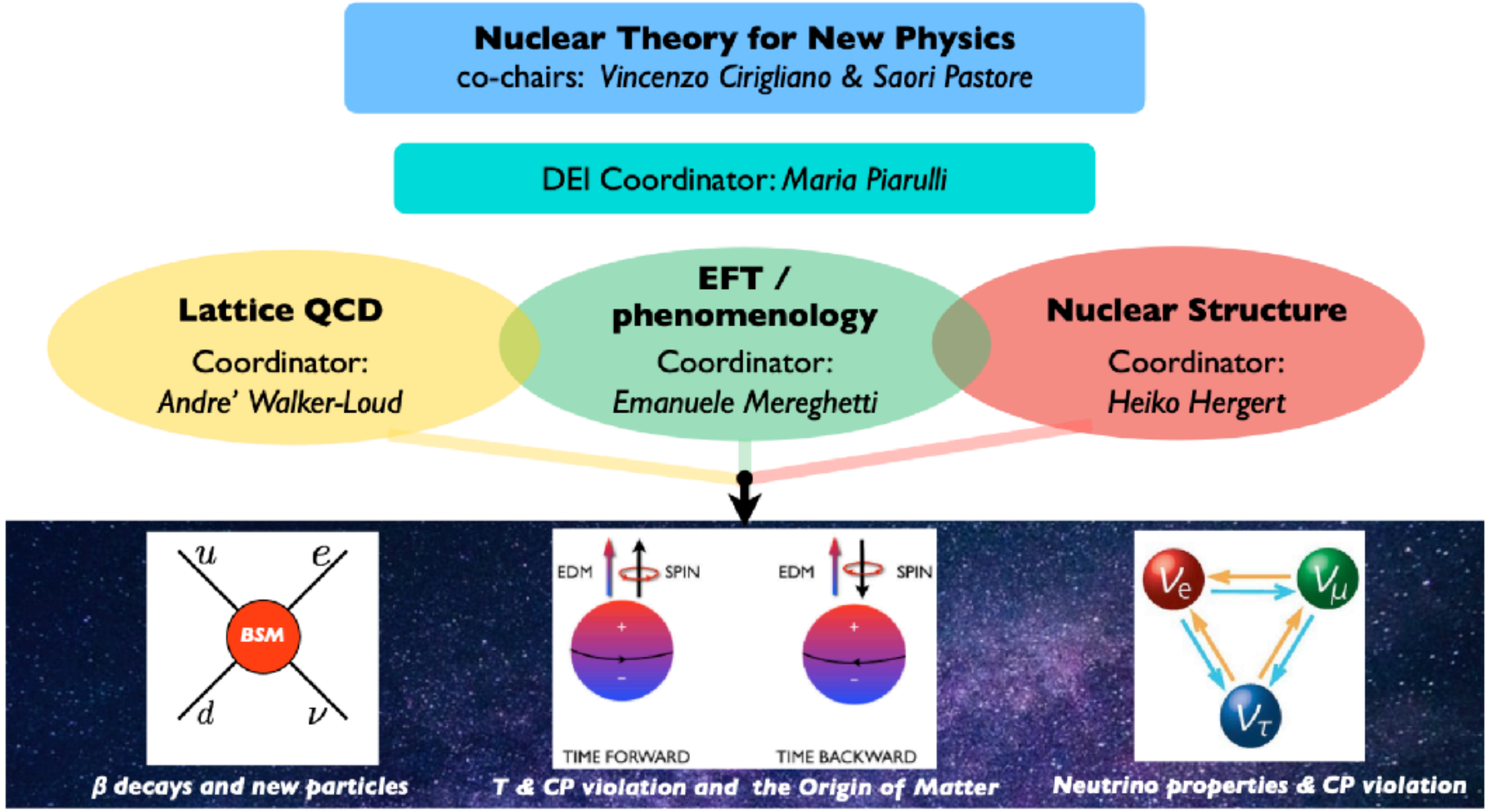
NTNP (Nuclear Theory for New Physics)

NTNP | Home | science | people | meetings | Code of Conduct

https://a51.lbl.gov/~ntnp/TC/

Nuclear Theory for New Physics

- About Us
- Commitment to Diversity
- Funding Acknowledgement

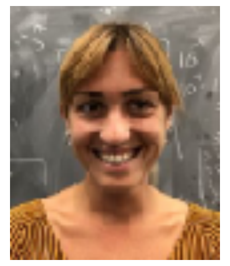


U.S. DEPARTMENT OF ENERGY | Office of Science

- We are a new DOE Topical Collaboration
- We are jointly funded by the Offices of Nuclear and High Energy Physics
- A main goals of our collaboration:
  - improve the theoretical understanding of
    - neutron β-decay
    - nuclear β-decay
- Expertise in
  - Phenomenology
  - Lattice QCD
  - Effective Field Theory
  - Many-body nuclear methods
- We are happy to collaborate with others
  - Get in touch!

NTNP

UW/INT
Vincenzo Cirigliano
Wouter Dekens
Chien-Yeah Seng
Ayala Glick-Magid
Maria Dawid

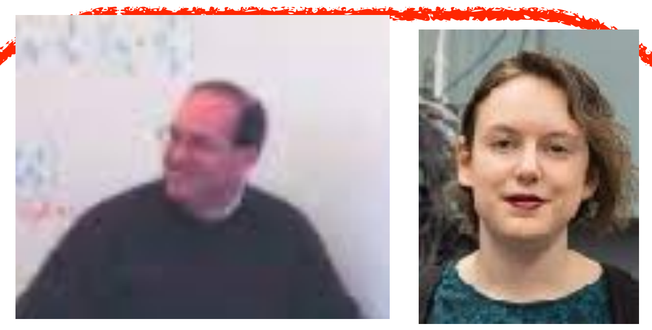


FNAL
Noemi Rocco

ANL
Alessandro Lovato
Anna McCoy
Robert Wiringa

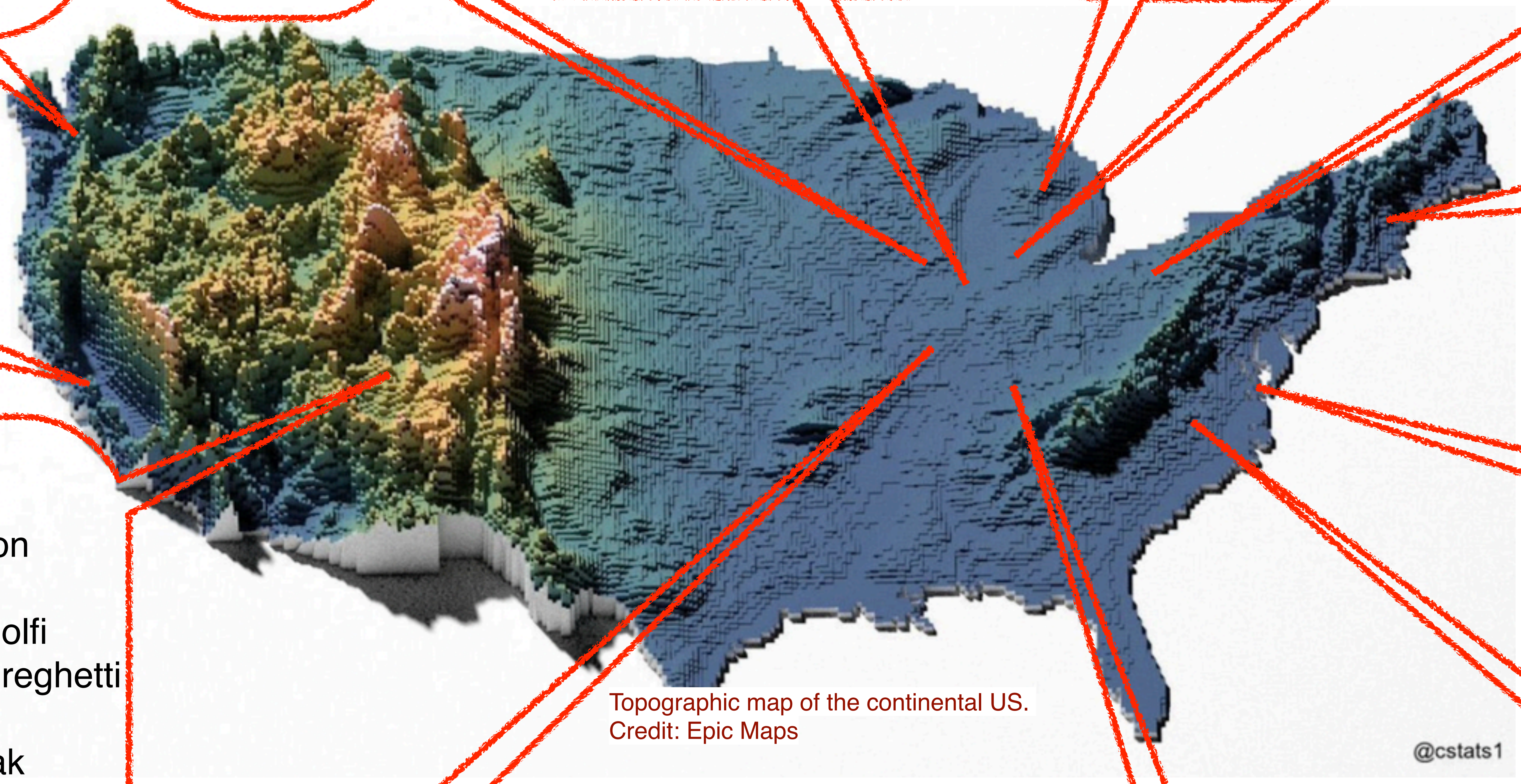
MSU (& FRIB)
Scott Bogner
Heiko Hergert

Notre Dame
Ragnar Stroberg



Carnegie Mellon University
Colin Morningstar
Sarah Skinner

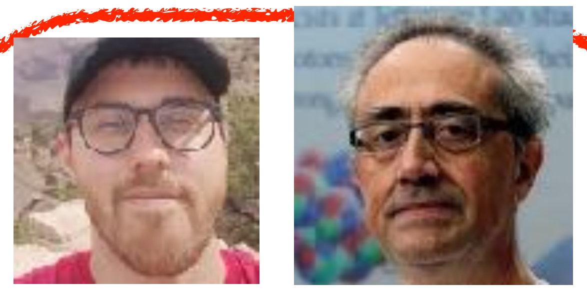
UC Berkeley/LBNL
Wick Haxton
André Walker-Loud
Andrea Shindler
Lukáš Gráf
Zack Hall



Topographic map of the continental US.
Credit: Epic Maps

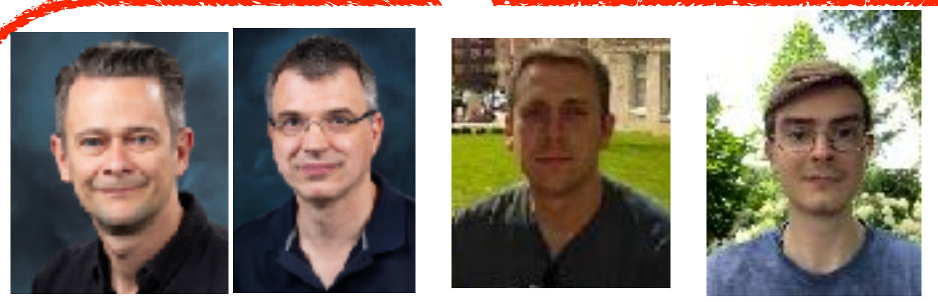
UMass Amherst
Michael Ramsey-Musolf
Leon Friedrich

LANL
Joseph Carlson
Kaori Fuyuto
Stefano Gandolfi
Emanuele Mereghetti
Ingo Tews
Sasha Tomalak
Jacky Kumar



ODU/JLab
Alex Gnech
Rocco Schiavilla

Wash. U. St Louis
Bhupal Dev
Saori Pastore
Maria Piarulli
Anna McCoy
Lorenzo Andreoli
Sam Novario
Jason Bub
Garrett King
Graham Chambers-Wall

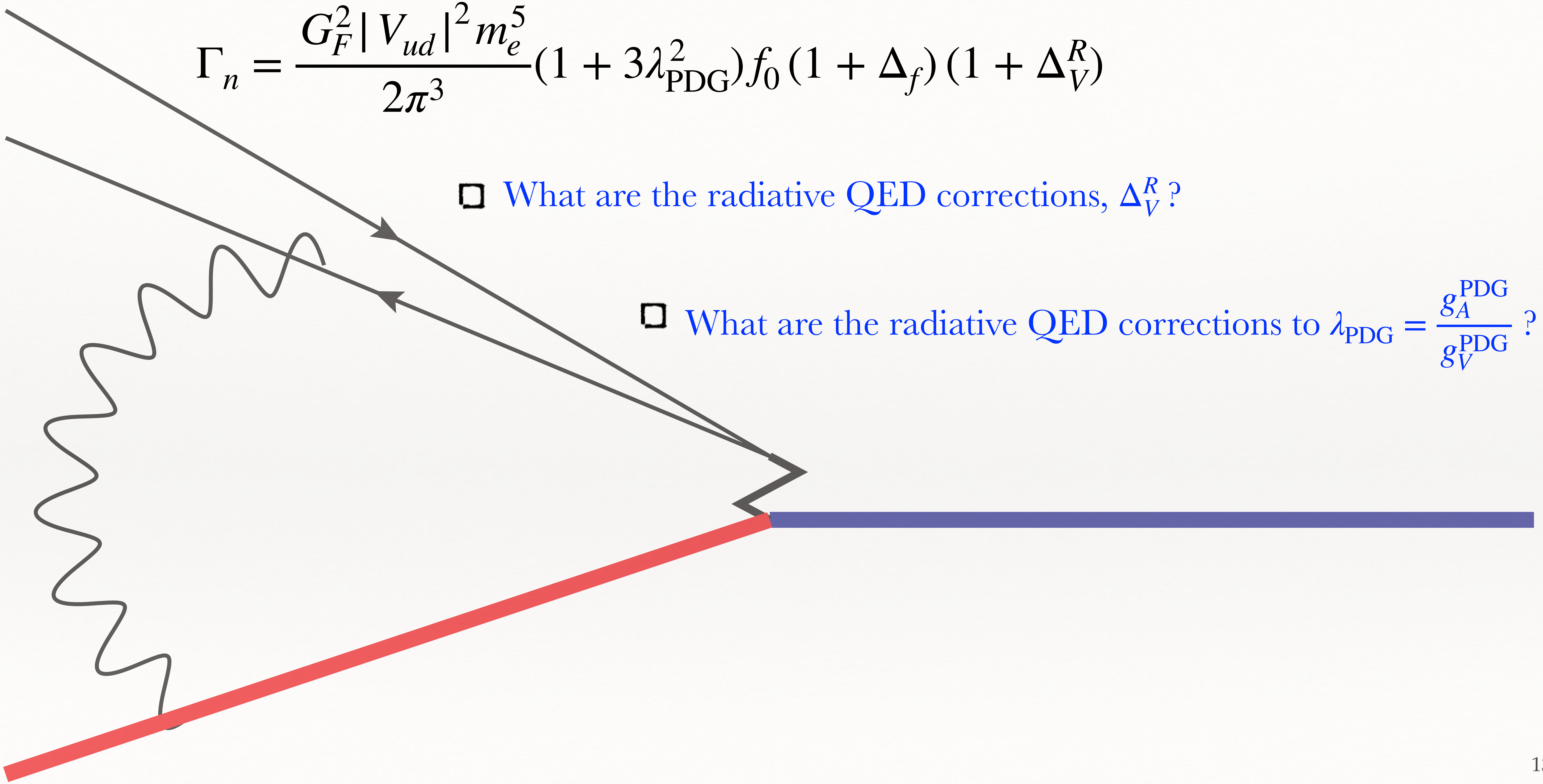


ORNL / University of Tennessee
Gaute Hagen
Thomas Papenbrock
Lucas Platter
Evan Combes

UNC Chapel Hill
Jon Engel
Amy Nicholson
Zack Hall
Joeseph Moscoso

β-decay - Two theoretical opportunities for $n \to pe\bar{\nu}$

$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3}(1 + 3\lambda_{\text{PDG}}^2) f_0 (1 + \Delta_f)(1 + \Delta_V^R)$$



- ❑ What are the radiative QED corrections, Δ_V^R ?
- ❑ What are the radiative QED corrections to $\lambda_{\text{PDG}} = \frac{g_A^{\text{PDG}}}{g_V^{\text{PDG}}}$?

β-decay - QED corrections, Δ_V^R

$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3}(1 + 3\lambda_{\rm PDG}^2) f_0 (1 + \Delta_f)(1+\Delta_V^R)$$

$$\Delta_V^R = \frac{\alpha}{2\pi}\left[3 \ln\frac{M_Z}{m_p} + \ln\frac{M_Z}{M_W} + \tilde{a}_g\right] + \delta_{\rm HO}^{\rm QED} + 2\,\Box_{\gamma W}^{VA}$$

$$\Box_{\gamma W}^{VA} = \frac{ie^2}{2M_N^2}\int \frac{d^4q}{(2\pi)^4}\frac{m_W^2}{m_W^2 - q^2}\frac{\epsilon^{\mu\nu\alpha\lambda} q_\alpha p_\lambda}{(q^2)^2} T_{\mu\nu}^{\gamma W}$$

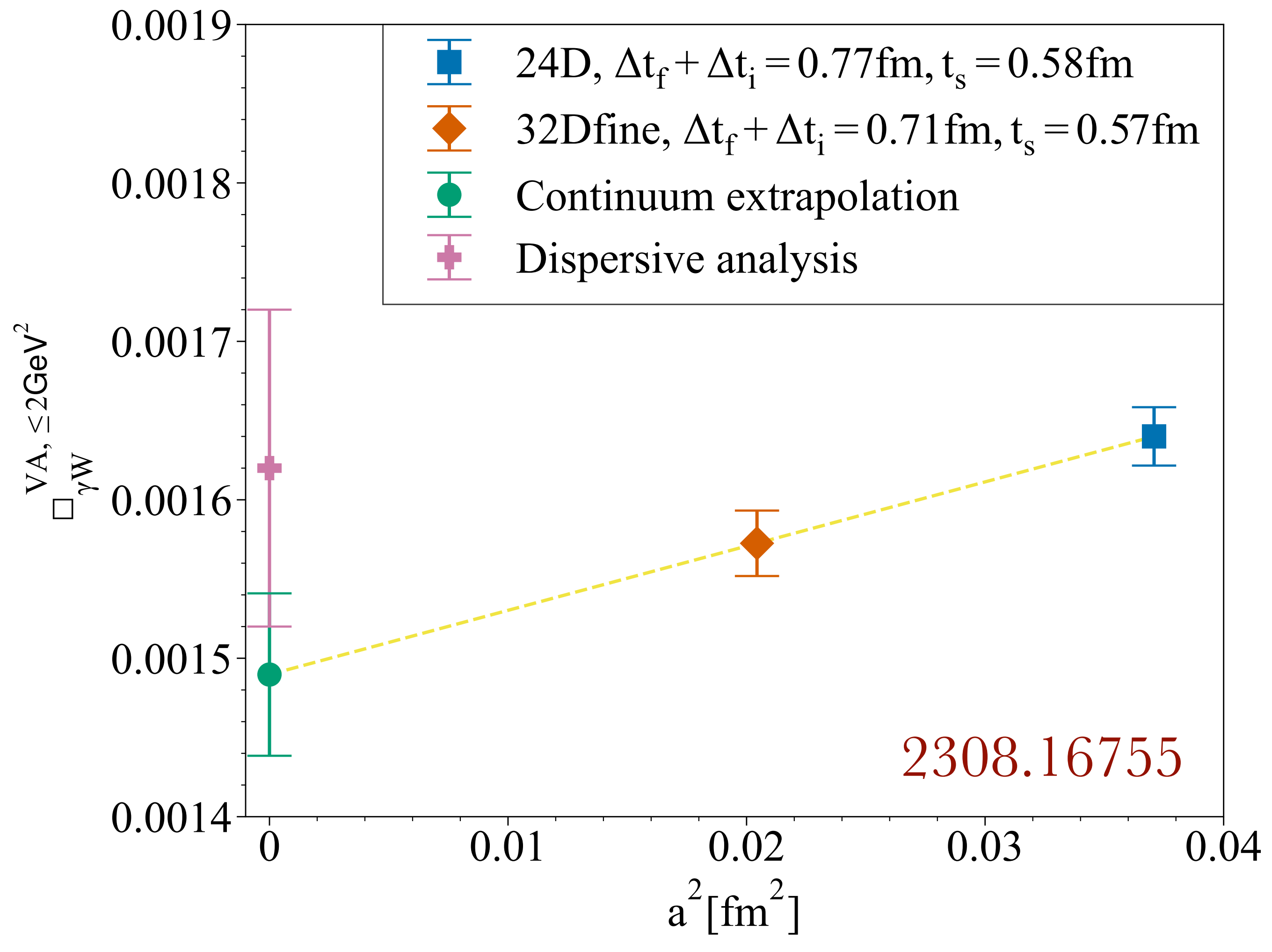
$$T_{\mu\nu}^{\gamma W} = \int d^4x e^{iq\cdot x}\langle p(p,S)\,|\,T\{J_\mu^{em}(x)J_\nu^W(0)\}\,|\,n(p,S)\rangle$$

- π Feng, Gorchtein, Jin, Ma, Seng PRL 124 (2020) [2003.09798]
- K Seng, Feng, Gorchhtein, Jin, Meissner JHEP 10 (2020) [2009.00459]
- K Ma, Feng, Gorchtein, Jin, Seng PRD 103 (2021) [2102.12048]
- π K Yoo, Bhattacharya, Gupta, Mondal, Yoon PRD 108 (2023) [2305.03198]
- n Ma, Feng, Gorchtein, Jin, Liu, Seng, Wang, Zhang PRL 132 (2024) [2308.16755]

- Challenging calculations — particularly for the neutron
  these are State-of-the-art LQCD results

  - requires an integral over two-current insertions between ground-state neutron and proton
  - many systematics need to be controlled
    - excited state contamination
    - separation between perturbative/non-perturbative Q^2 contributions
    - continuum limit
    - infinite volume limit
    - 2308.16755 was performed @ $m_\pi^{\rm phys}$!

Xu Feng
Mon. 17:00



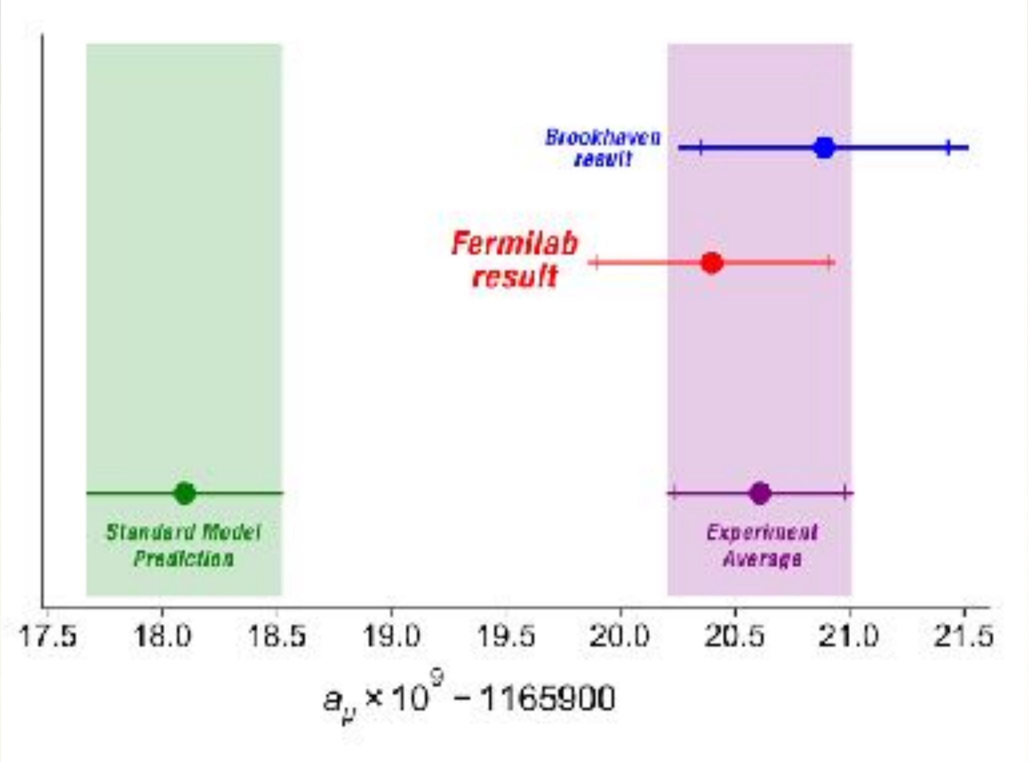
- I suspect the full systematic uncertainty is larger than currently quoted
  [don't let me take anything away from this very impressive work]

- It will be great to see more LQCD results to compare with

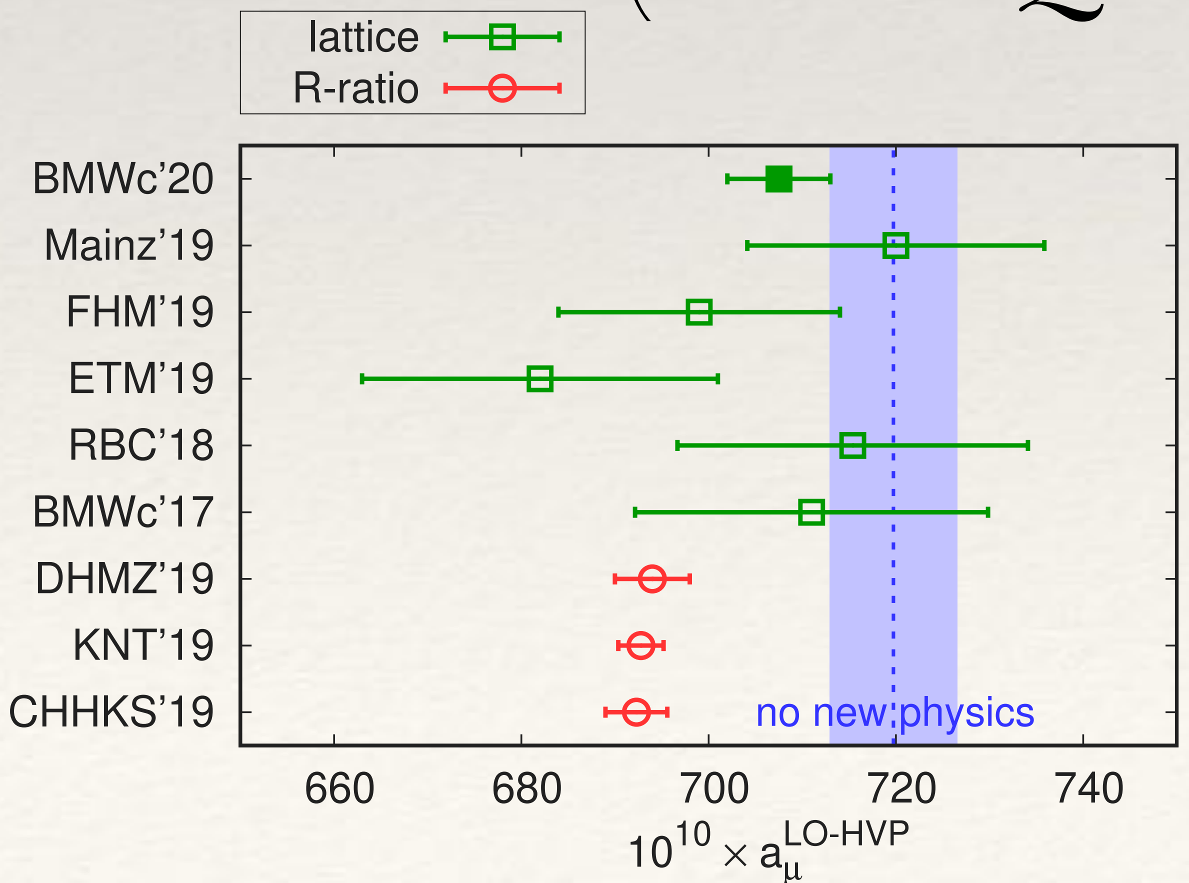
β-decay - QED corrections, Δ_V^R

$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3}(1 + 3\lambda_{\text{PDG}}^2) f_0 (1 + \Delta_f)(1 + \Delta_V^R)$$

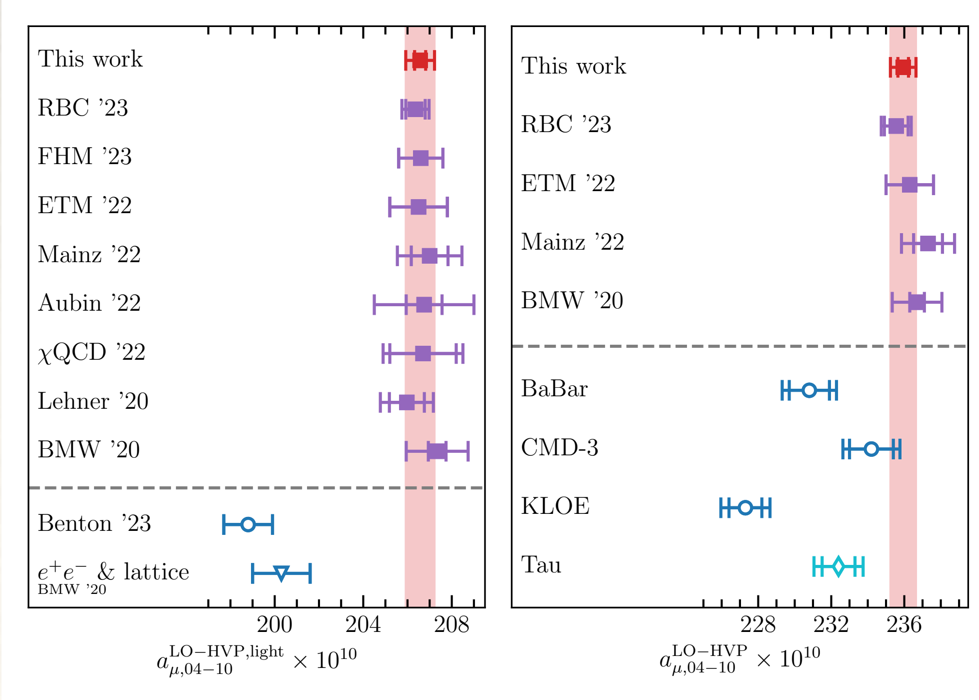
- It is worth considering a full LQCD+QED calculation of $n \to pe\bar{\nu}$
- This would be a challenging calculation
  — but possible on the time scale of new neutron τ_n and $\lambda = g_A/g_V$ measurements
- If first-row CKM approaches 5-sigma tension, we should have 2 or more methods
  - Look to muon $g-2$ as an example —
    - dispersion theory to determine hadronic vacuum polarization (HVP): $\approx 4\sigma$ tension
    - LQCD determination of HVP: $\approx 1\sigma$ tension (not a LQCD consensus yet, but moving this way)



precise LQCD 2020



LQCD consensus on pieces of calc 2024

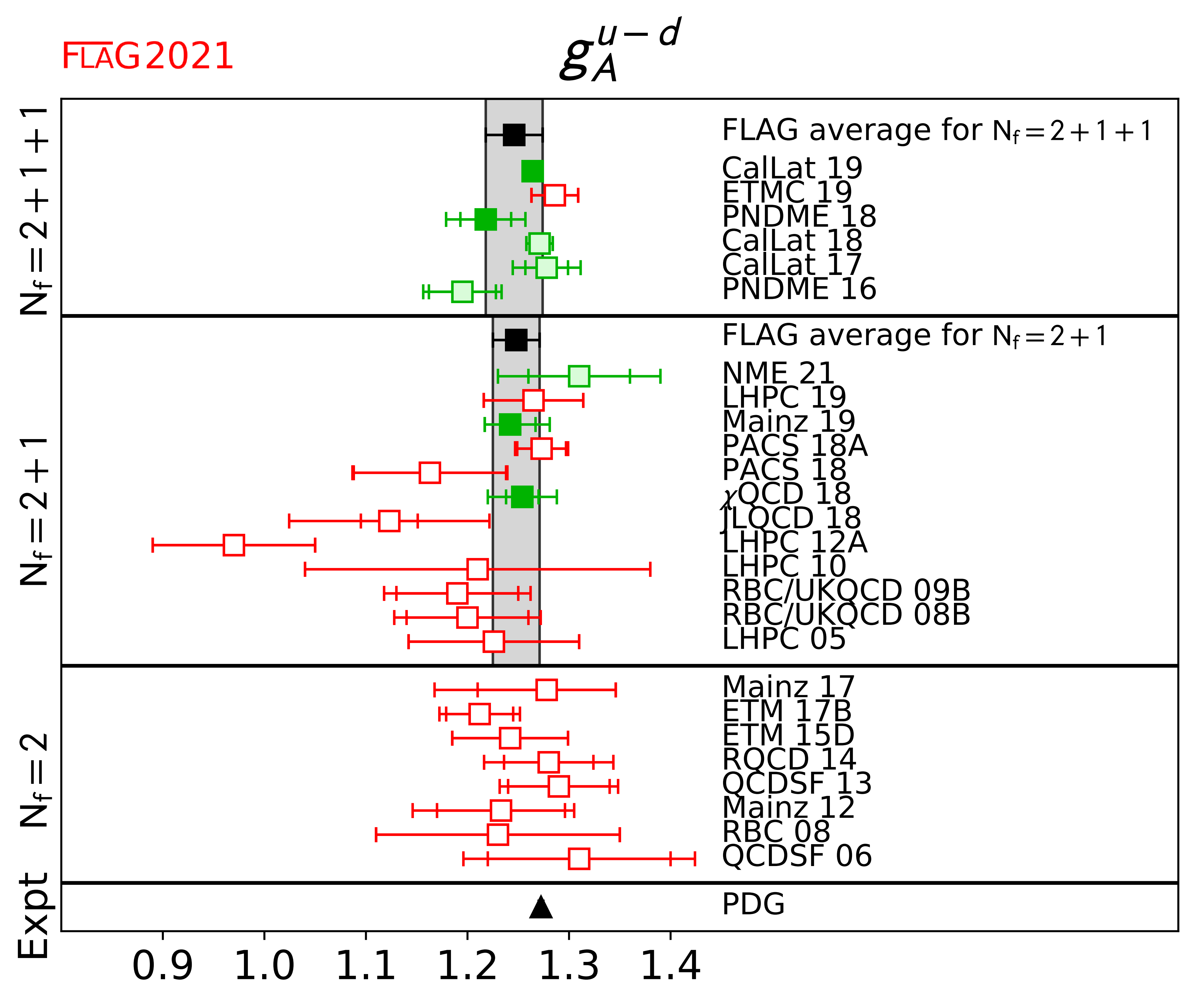


β-decay - QED corrections to $\lambda_{\rm PDG} = g_A^{\rm PDG}/g_V^{\rm PDG}$

$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3}(1+3\lambda_{\rm PDG}^2) f_0 (1+\Delta_f)(1+\Delta_V^R)$$

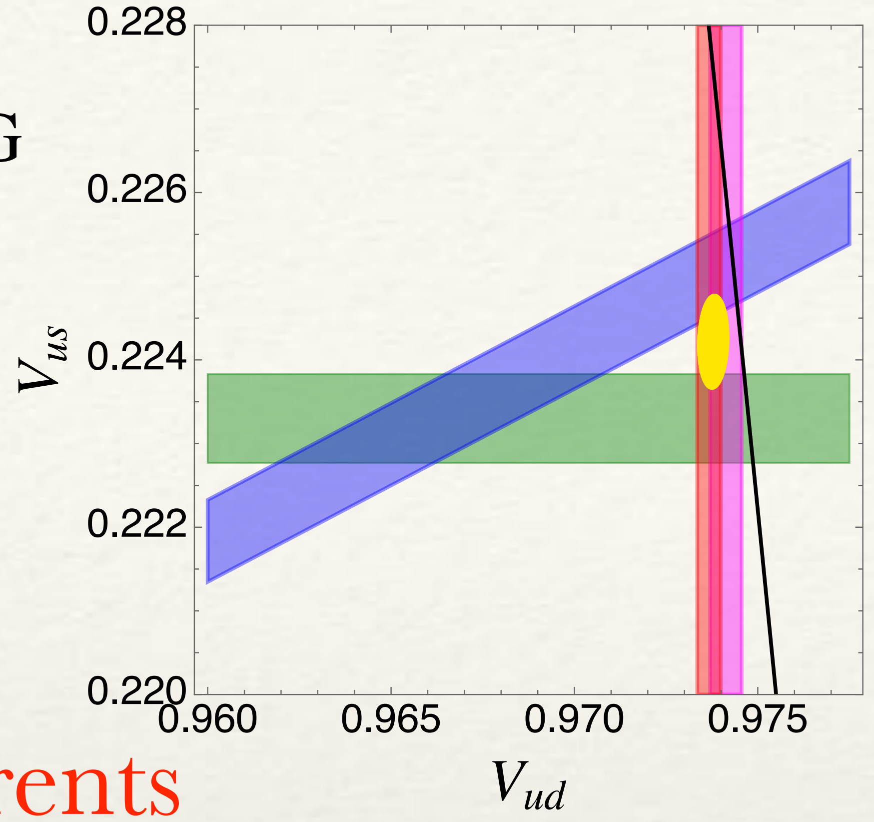
$$\lambda_{\rm PDG} \approx \lambda_{\rm "exp"} - \Delta_A^{R,Sirlin,analytic} = \lambda_{\rm QCD-iso} + \Delta_A^{R,other}$$

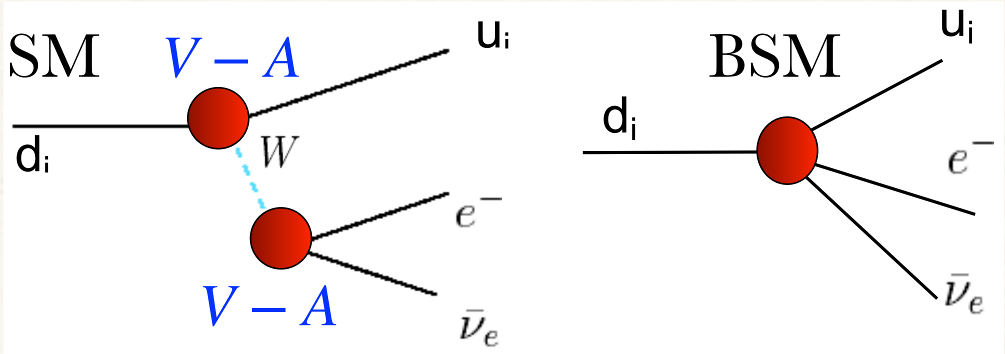
- $\lambda_{\rm PDG}$ is determined with *some* QED corrections subtracted
- Additional QED corrections to $g_A^{\rm PDG}$ ($\Delta_A^{R,other}$) do not impact V_{ud} extraction — the $(1+\Delta_A^R)$ cancels in Γ_n and $\lambda_{\rm PDG}$
- Comparing LQCD calculations of $g_A^{\rm QCD-iso}$ to $g_A^{\rm PDG}$ can constrain BSM right-handed currents
- Previously, we thought $\Delta_A^{R,other} \approx O(0.2\%)$
- Potentially significant low-energy nucleon structure corrections may spoil this comparison, $\Delta_A^{R,other} \simeq O(2\%)$
  Cirigliano, de Vries, Hayen, Mereghetti, Walker-Loud
  PRL 129 (2022) [2202.10439]



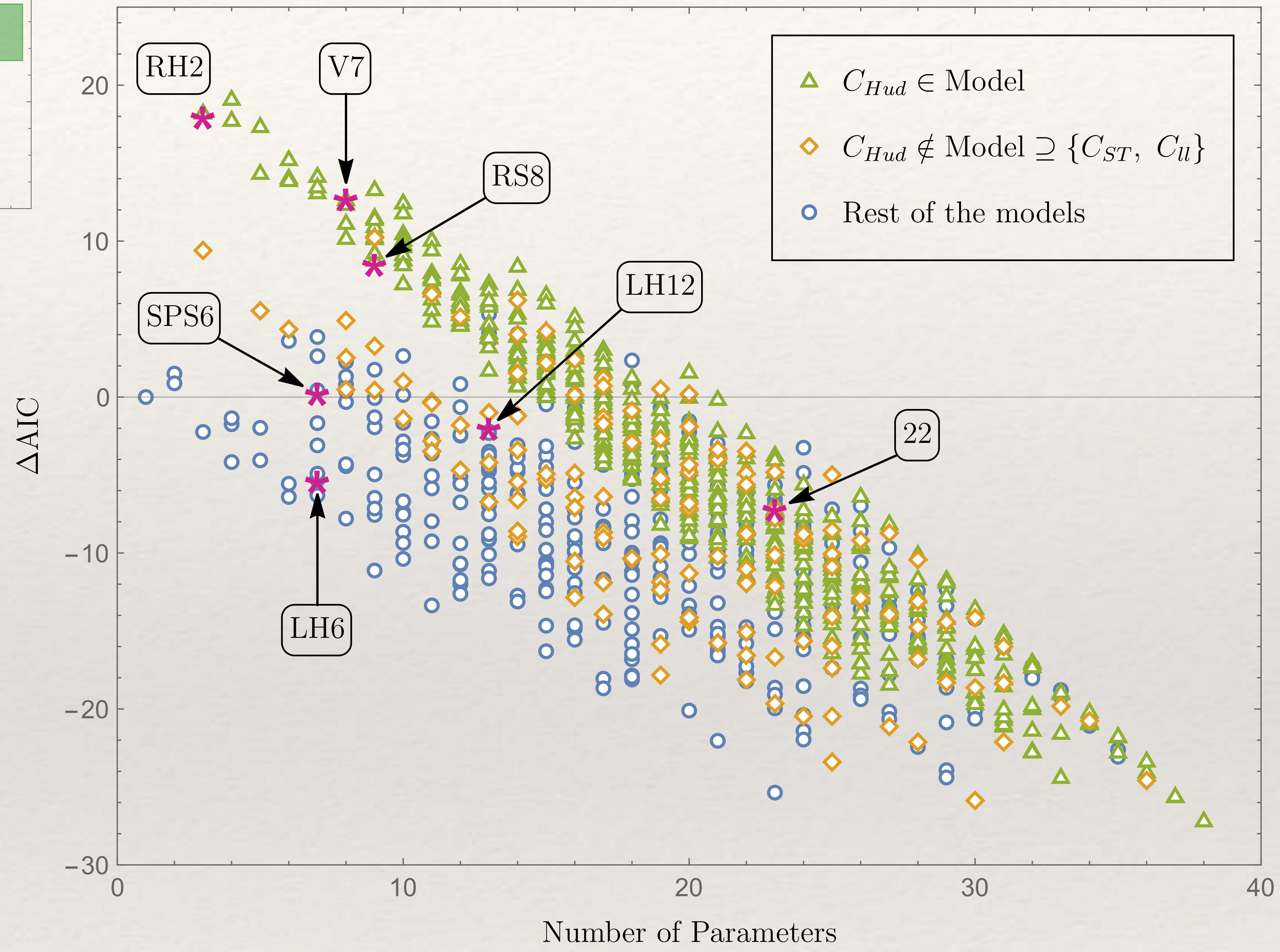
β-decay - QED corrections to $\lambda_{\text{PDG}} = g_A^{\text{PDG}}/g_V^{\text{PDG}}$

- While QED corrections to λ_{PDG} do not directly impact V_{ud}
- Global analysis of first-row CKM constraints including collider constraints, favors BSM Right-handed currents
  Cirigliano, Dekens, de Vries, Mereghetti, Tong, JHEP 03 (2024) [2311.00021]
  see also:
  Belfatto, Trifinopoulos, PRD 108 (2023) [2302.14097]





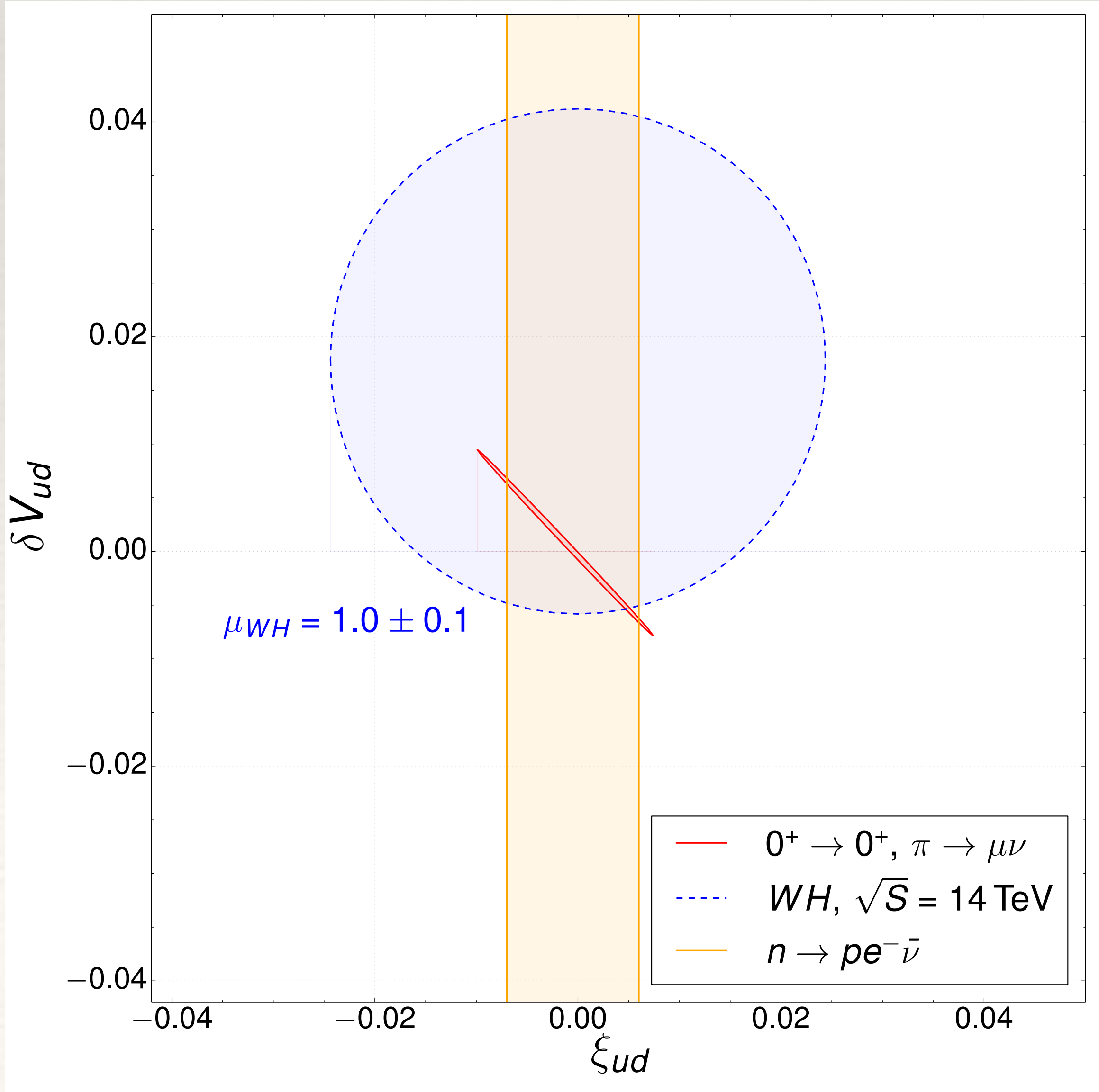
$(V-A)_L \times (V+A)_H$



More favored (by AIC)

Standard Model

Less favored (by AIC)



- If we can quantitatively understand QED corrections to λ_{PDG}
  Particularly in a correlated way with isospin symmetric LQCD results
- We can turn this into the most precise constraint on BSM Right-Handed currents

Pion-induced radiative corrections to neutron beta-decay

Cirigliano, de Vries, Hayen, Mereghetti & Walker-Loud, PRL 129 (2022) [2202.10439]

- Systematic, EFT treatment of neutron β-decay

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{(G_F V_{ud})^2}{(2\pi)^5}(1+3\lambda^2)w(E_e) \times \left[1 + \bar{a}(\lambda)\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \bar{A}(\lambda)\frac{\vec{\sigma}_n\cdot\vec{p}_e}{E_e} + \dots\right]$$

The parameters can be measured

If we want to connect them to Standard Model (SM) parameters
we need to start from a Lagrangian with parameters related to SM parameters

pion-less low-energy EFT

$$\lambda = \frac{g_A}{g_V}$$

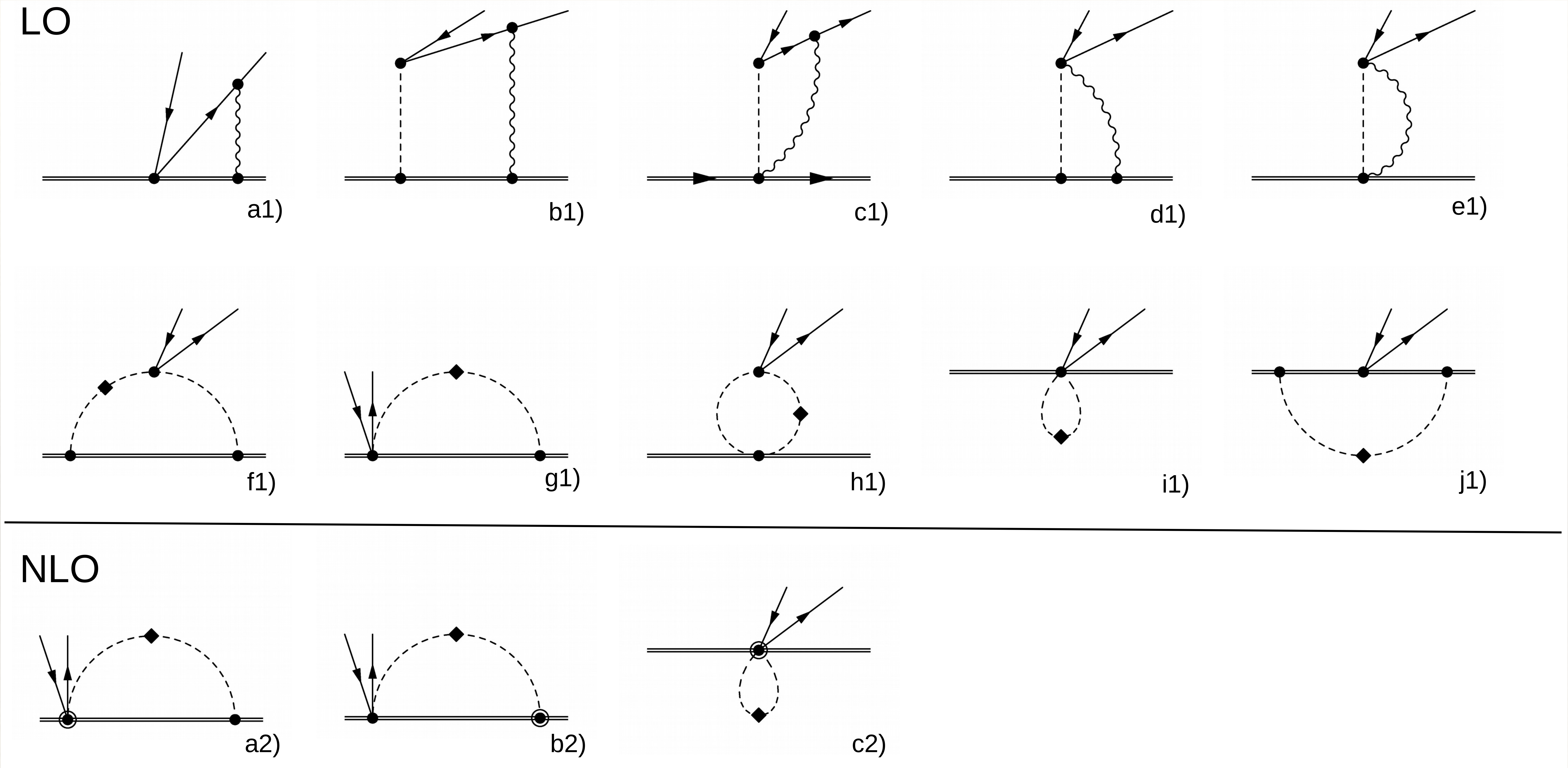
$$\begin{aligned}\mathcal{L}_{\not\pi} = -\sqrt{2}G_F V_{ud}\Big[\bar{e}\gamma_\mu P_L \nu_e \Big(\bar{N}\left(g_V v_\mu - 2g_A S_\mu\right)\tau^+ N \\ + \frac{i}{2m_N}\bar{N}(v^\mu v^\nu - g^{\mu\nu} - 2g_A v^\mu S^\nu)(\overleftarrow{\partial} - \overrightarrow{\partial})_\nu \tau^+ N\Big) \\ + \frac{ic_T m_e}{m_N}\bar{N}\left(S^\mu v^\nu - S^\nu v^\mu\right)\tau^+ N\ \left(\bar{e}\sigma_{\mu\nu}P_L\nu\right) \\ + \frac{i\mu_{\rm weak}}{m_N}\bar{N}[S^\mu, S^\nu]\tau^+ N\,\partial_\nu\left(\bar{e}\gamma_\mu P_L \nu\right)\Big] + \dots \qquad (2)\end{aligned}$$

Perform the calculation with SU(2) heavy-baryon χPT and match the results to this pion-less EFT whose parameters can be matched to experimentally measured quantities

Pion-induced radiative corrections to neutron beta-decay

Cirigliano, de Vries, Hayen, Mereghetti & Walker-Loud, PRL 129 (2022) [2202.10439]

- Sub-set of O(50) diagrams



Pion-induced radiative corrections to neutron beta-decay

Cirigliano, de Vries, Hayen, Mereghetti & Walker-Loud, PRL 129 (2022) [2202.10439]

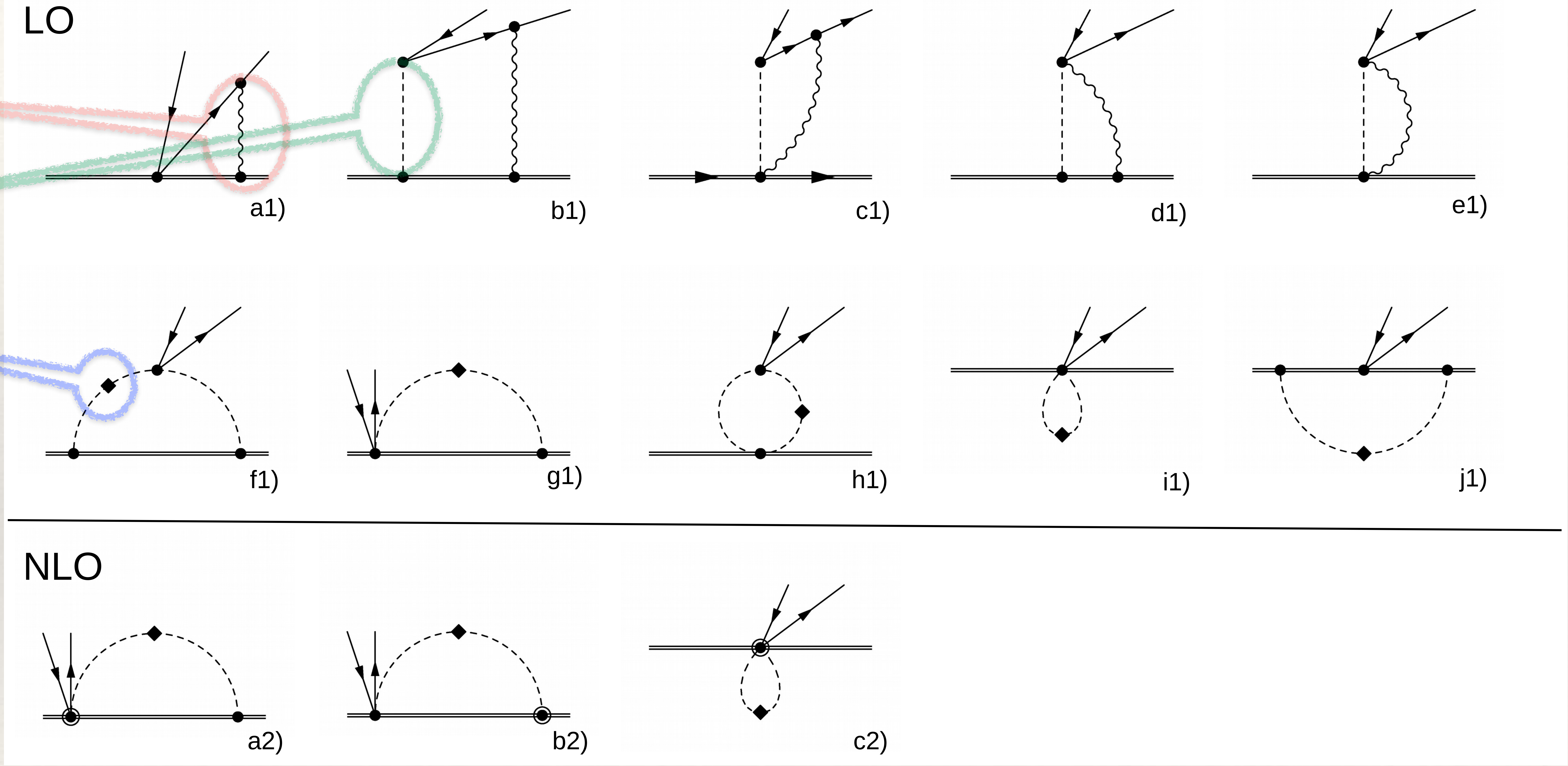
- Sub-set of O(50) diagrams

photons

pions

pion electromagnetic mass splitting

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = 2e^2 F_\pi^2 Z_\pi$$



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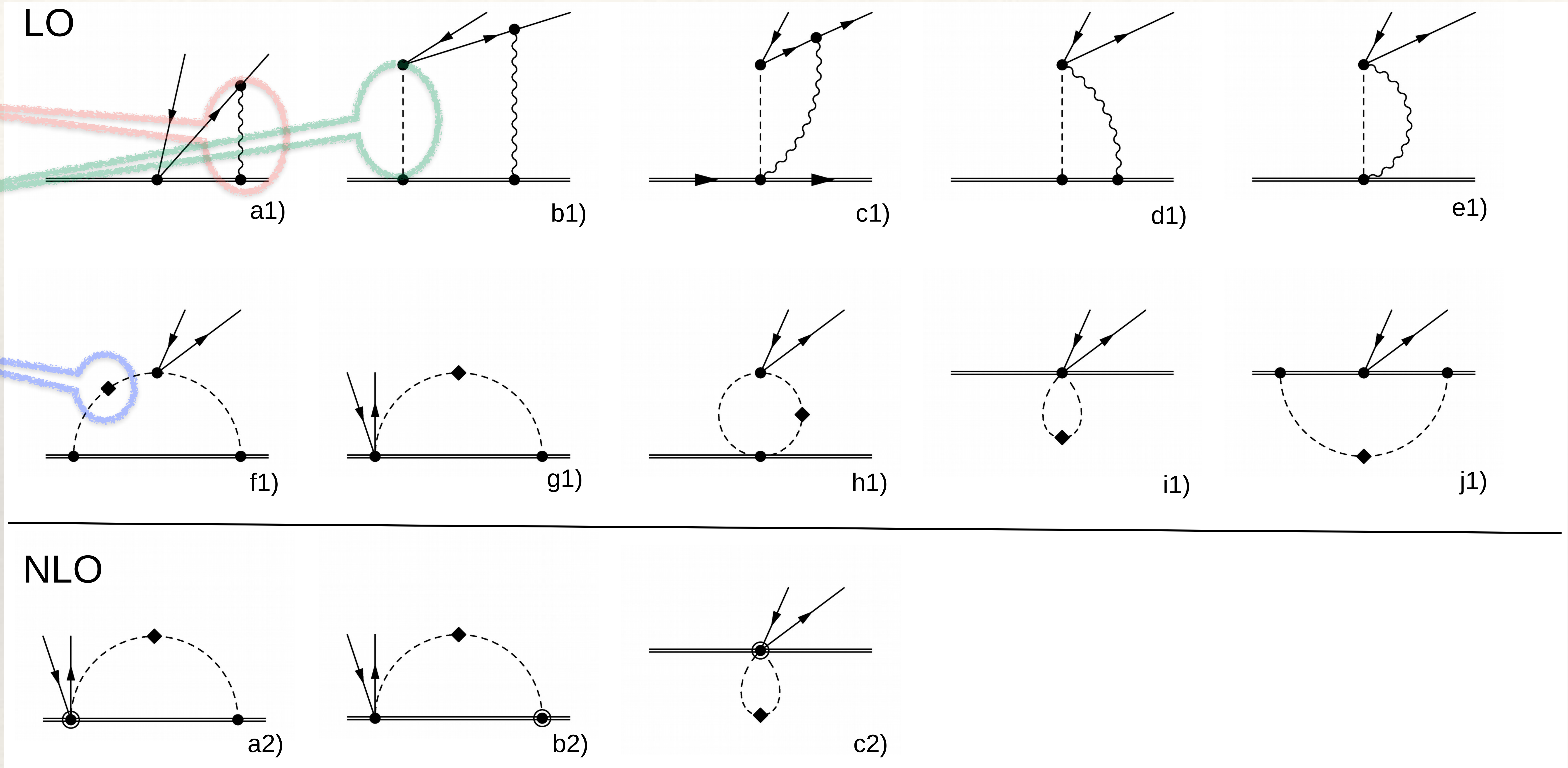

NOTE: at this order, we also include QED, m_d-m_u corrections to M_n-M_p

- iso-vector contributions to M_n-M_p vanish from symmetry constraints for τ^+ current
- iso-scalar contributions do not vanish - but the sum of all of them does vanish through NLO

Pion-induced radiative corrections to neutron beta-decay

Cirigliano, de Vries, Hayen, Mereghetti & Walker-Loud, PRL 129 (2022) [2202.10439]

- Matching $\lambda_{\rm PDG} = g_A^{\rm QCD}\left(1+\delta_{\rm RC}^{(\lambda)} - 2{\rm Re}(\epsilon_R)\right)$

$$\delta_{\rm RC}^{(\lambda)} = \frac{\alpha}{2\pi}\left(\Delta_{A,em}^{(0)} + \Delta_{A,em}^{(1)} - \Delta_{V,em}^{(0)}\right)$$

$$\Delta_{A,\rm em}^{(0)} = Z_\pi\left[\frac{1+3g_A^{(0)2}}{2}\left(\ln\frac{\mu^2}{m_\pi^2} - 1\right) - g_A^{(0)2}\right] + \hat{C}_A(\mu)$$

$$\Delta_{Z,\rm em}^{(0)} = \hat{C}_V(\mu)$$

$$\Delta_{A,\rm em}^{(1)} = Z_\pi 4\pi m_\pi\left[c_4 - c_3 + \frac{3}{8m_N} + \frac{9}{16m_N}g_A^{(0)2}\right]$$

$$g_{V/A} = g_{V/A}^{(0)}\left[1 + \sum_{n=2}^{\infty}\Delta_{V/A,\chi}^{(n)} + \frac{\alpha}{2\pi}\sum_{n=0}^{\infty}\Delta_{V/A,\rm em}^{(n)} + \left(\frac{m_u - m_d}{\Lambda_\chi}\right)^{n_{V/A}}\sum_{n=0}^{\infty}\Delta_{V/A,\delta m}^{(n)}\right]$$

$\Delta_{\chi,\rm em,\delta m} \sim O(\epsilon_\chi^n)$

$\epsilon_\chi = \dfrac{m_\pi}{4\pi F_\pi}$

CVC $n_V = 2$ $\quad n_A = 1$

explicit calculation:

$\Delta_{A,\delta m}^{(0),(1)} = 0$

$\Delta_{V,\delta m}^{(0)} = 0$

Low-Energy-Constants (LECs)

$\hat{C}_{A,V}(\mu)$ - completely unknown

$c_{3,4}$ are estimated from literature (large)

Using Naive Dimensional Analysis (NDA) to estimate $C_A(\mu)$ and $c_{3,4}$ from the literature

$\delta_{\rm RC}^{(\lambda)} \in \{1.4, 2.6\}\cdot 10^{-2}$ an order of magnitude larger than previous estimates

Pion-induced radiative corrections to neutron beta-decay

Cirigliano, de Vries, Hayen, Mereghetti & Walker-Loud, PRL 129 (2022) [2202.10439]

- Sub-set of O(50) diagrams

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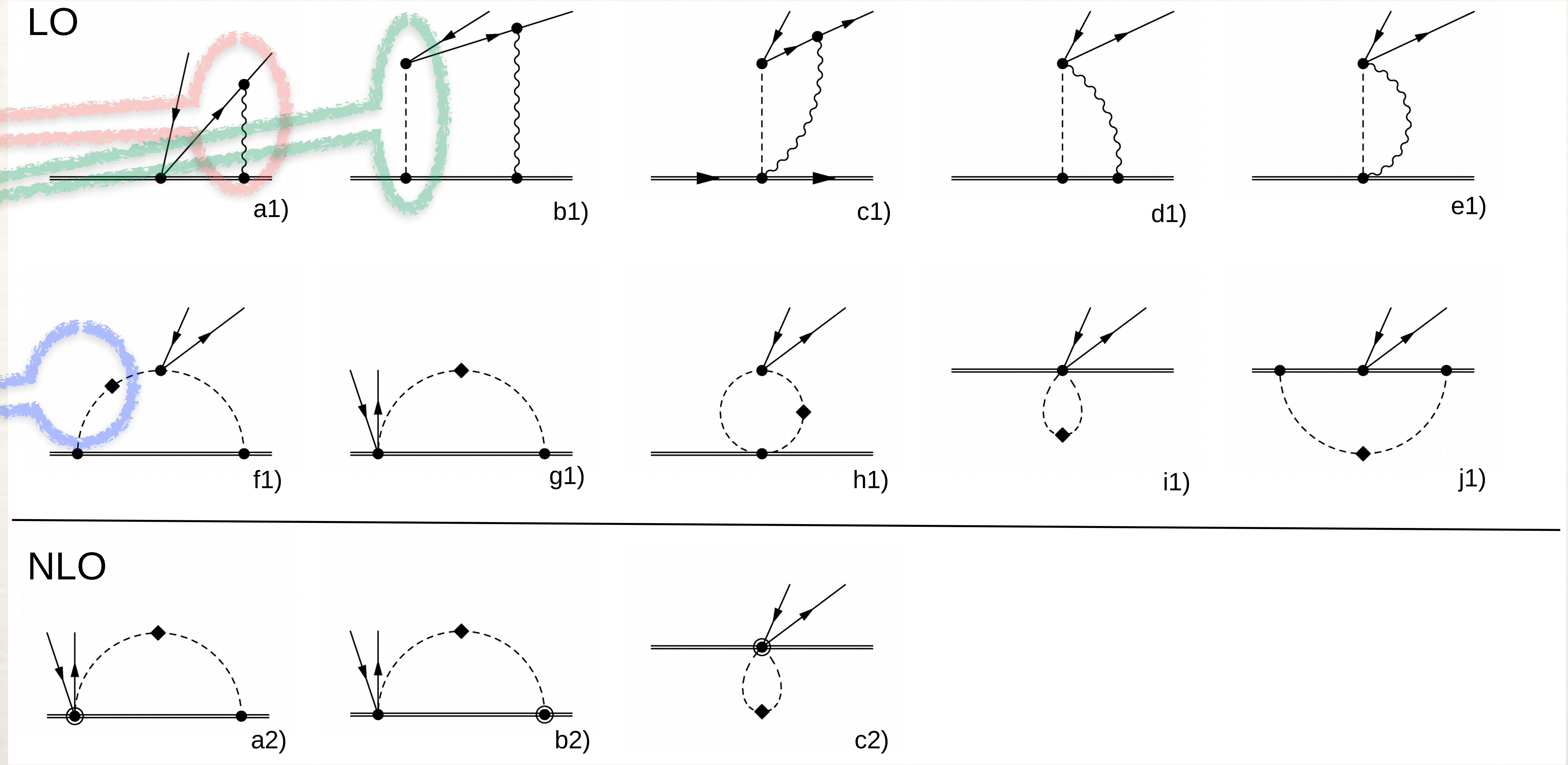
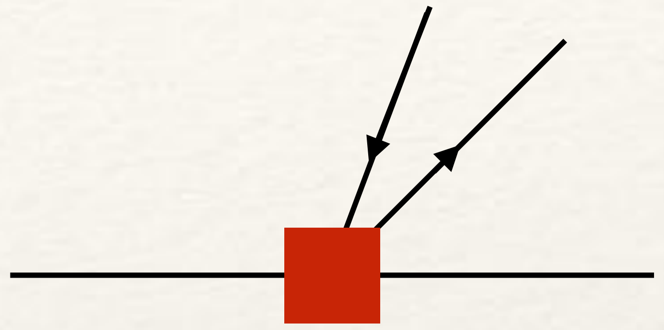


$+$ 

$\hat{C}_A(\mu)$

Low-Energy-Constants (LECs)

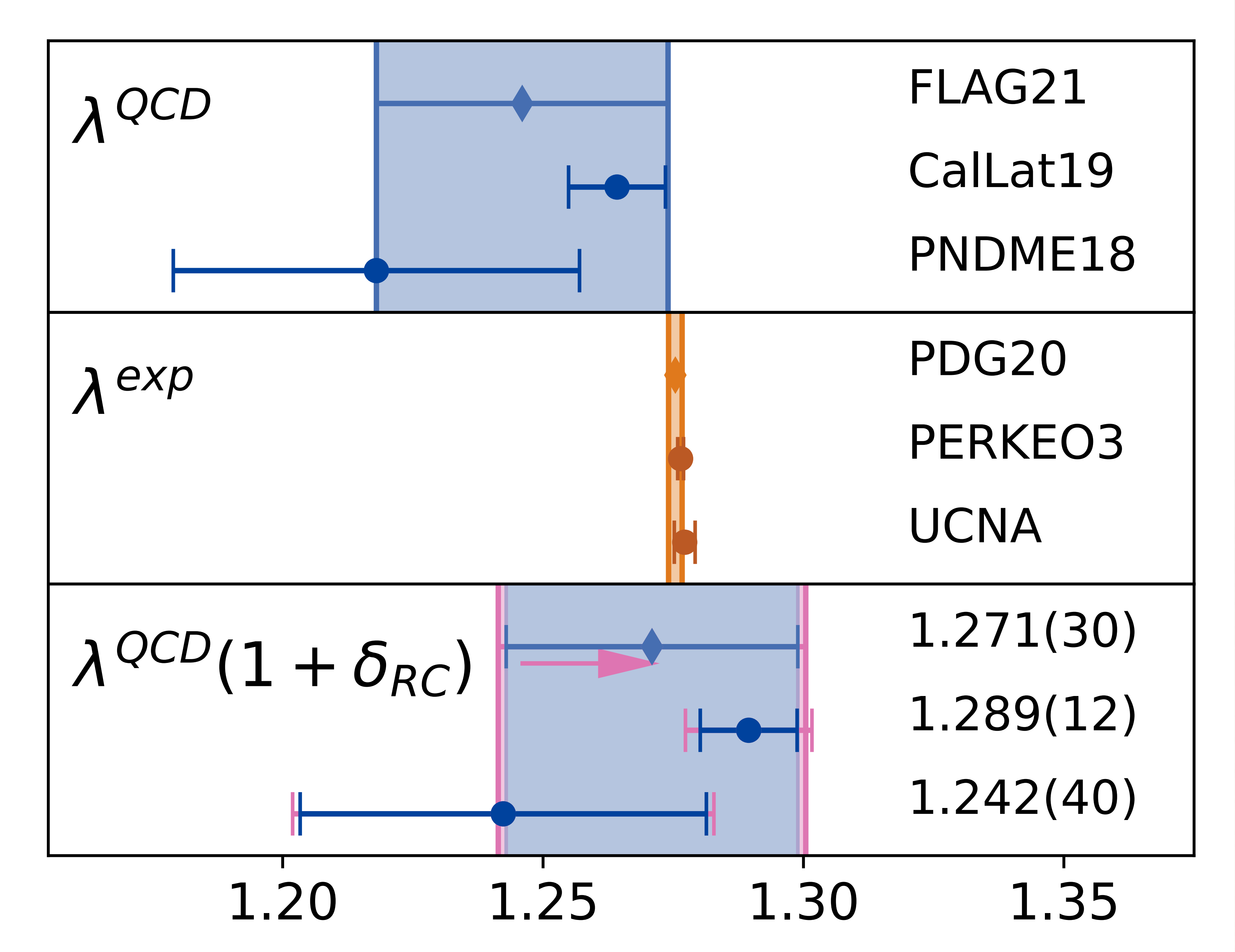
pion electromagnetic mass splitting

$$m^2_{\pi^\pm} - m^2_{\pi^0} = 2e^2 F_\pi^2 Z_\pi$$

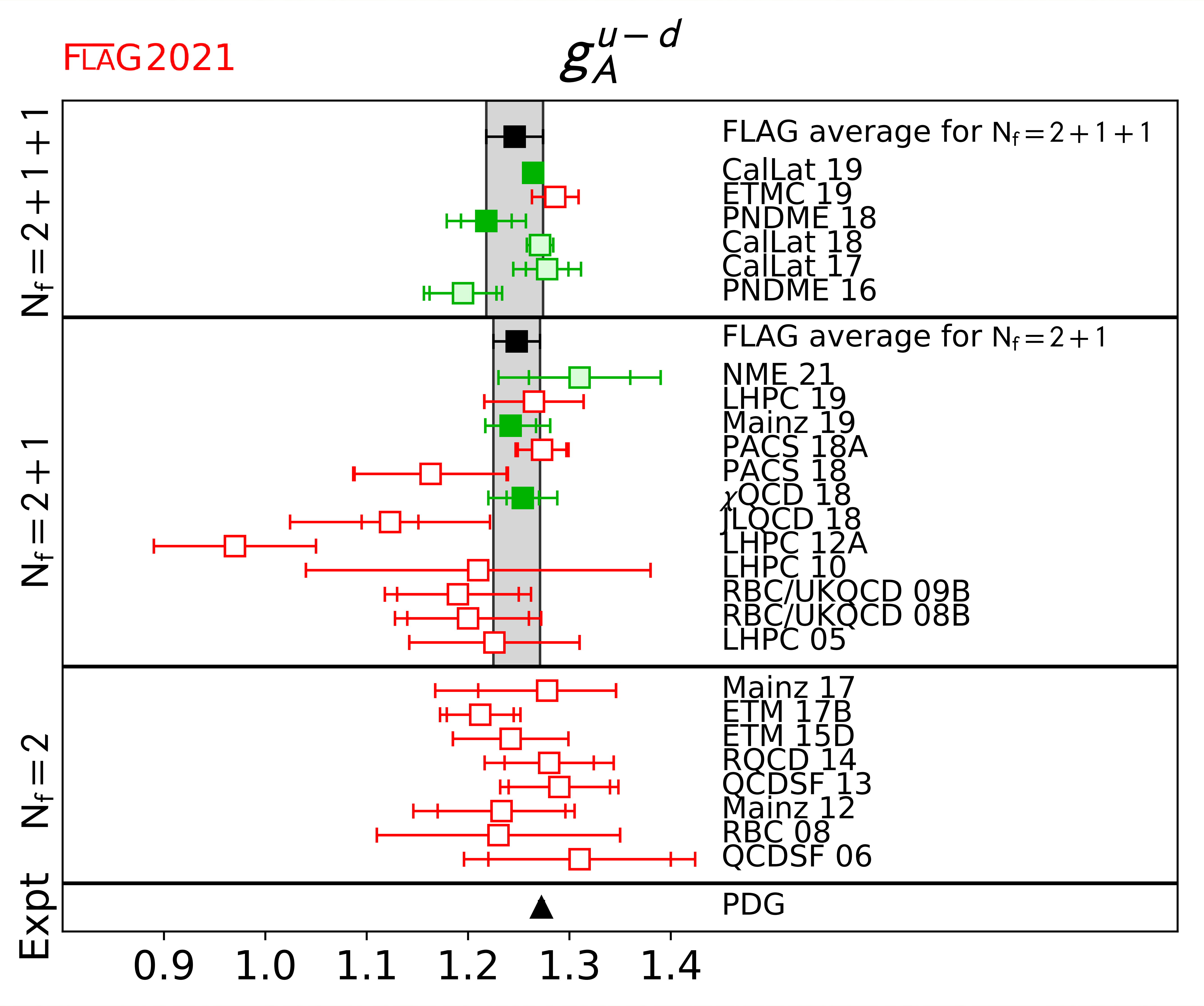
$$g_A^{\rm PDG} = g_A^{\rm QCD-iso} + \delta_{\rm RC}^{(\lambda)}(\alpha_{fs}, \hat{C}_A(\mu), \dots)$$

$$\delta_{\rm RC}^{(\lambda)} \in \{1.4,\ 2.6\} \cdot 10^{-2}$$

- seems to move g_A^{QCD} towards $g_A^{\rm exp}$
- need LQCD+QED calculation to determine $\delta_{\rm RC}^{(\lambda)}$
- requires careful understanding of
  - renormalization
  - QED gauge/scheme choice to handle IR/UV



Status of LQCD results for $g_A^{\text{QCD−isosymmetric}}$



- Many groups obtain values of g_A fully extrapolated to the physical point (green)
  - physical pion mass
  - continuum
  - infinite volume

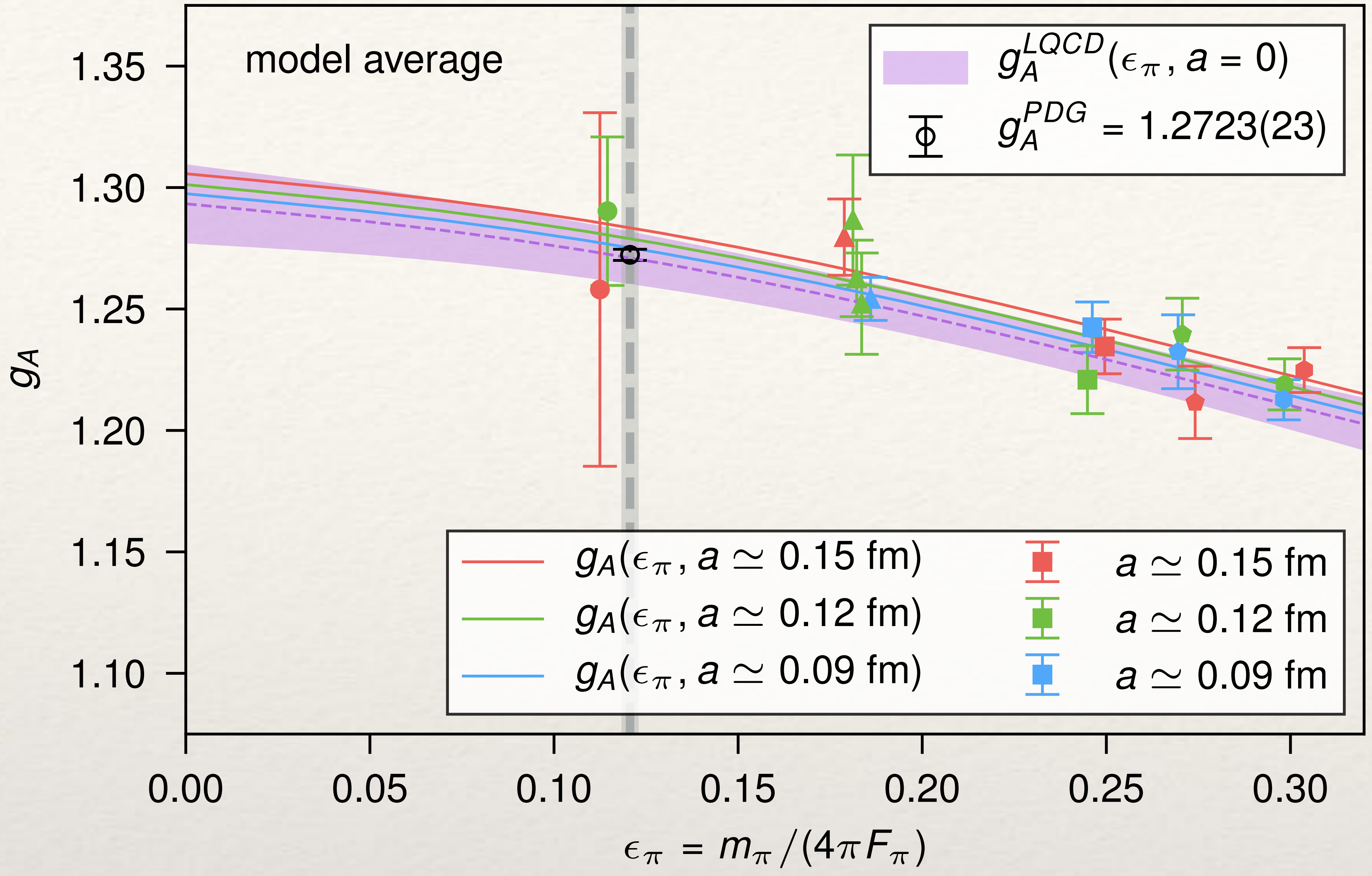
- CalLat results
  - CalLat 18: $g_A = 1.271(13)$ 1%
  - CalLat 19: $g_A = 1.2642(93)$ 0.74%
  - CalLat 24/25: ~0.5% ?

- Experiment:
  - $|g_A^{\text{PDG}}| = 1.27540(130)$
  - $|g_A^{\text{PERKEO−III}}| = 1.27641(046)$

- In order to take advantage of these precise results — we must determine QED corrections to g_A!

Nature 558 (2018) no. 7708, 91-94
Chang et al. [arXiv:1805.12130]

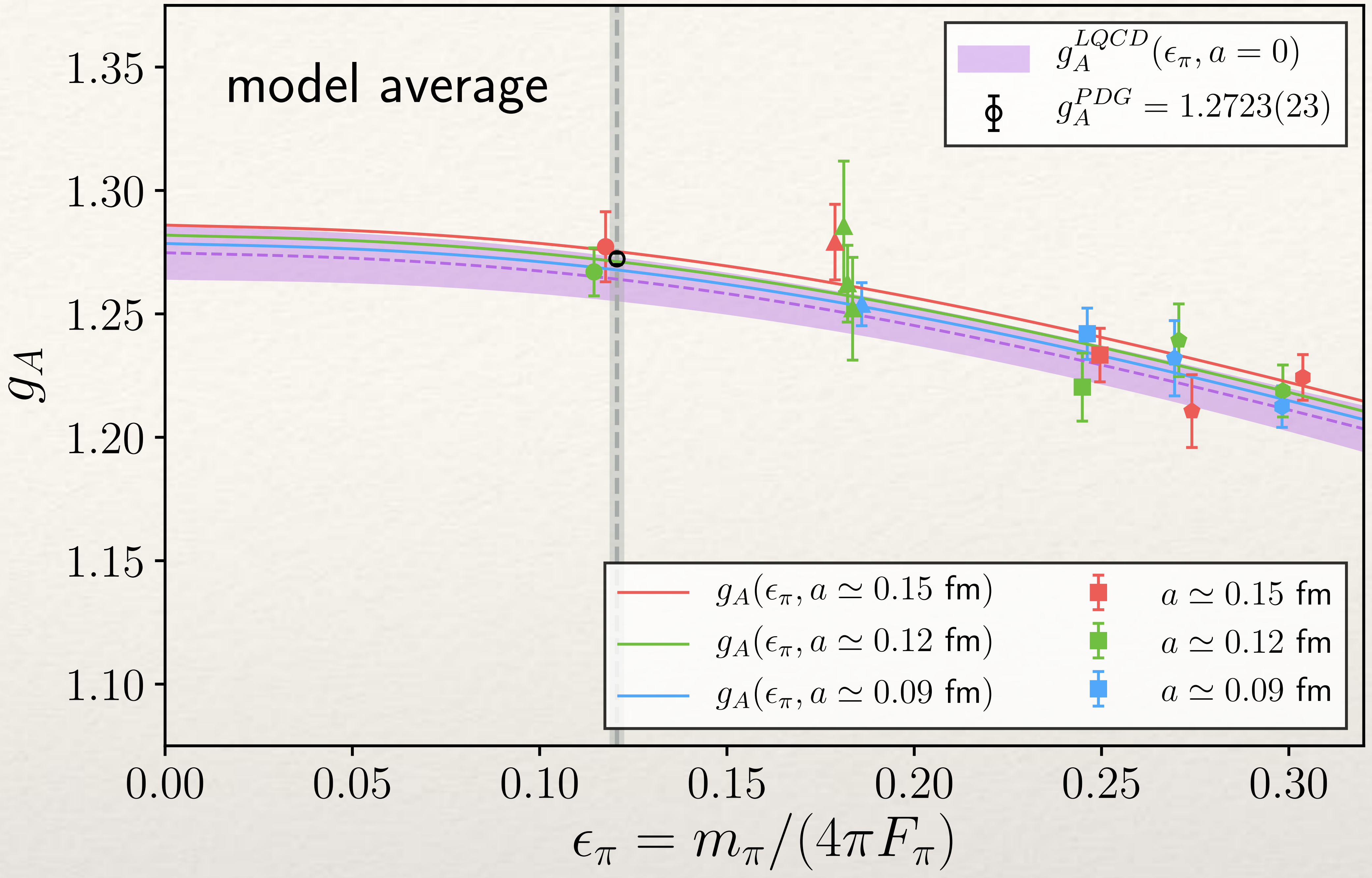
1 year on Titan (ORNL) + 2 years on GPU machines at LLNL



California Lattice Collaboration

Sierra Early Science

PRELIMINARY



- The a12m130 (48^3 x 64 x 20) with 3 sources cost as much as all other ensembles combined
  - 2.5 weekends on Sierra → 16 srcs
  - Now, 32 srcs (un-constrained, 3-state fit)
- We generated a new a15m135XL (48^3 x 64) ensemble (old a15m130 is 32^3 x 48)
  - $M\pi L = 4.93$ (old $M\pi L = 3.2$)
  - $L_5 = 24$, $N_{src} = 16$

$$g_A = 1.2711(125) \to 1.2641(93) \quad [0.74\%]$$

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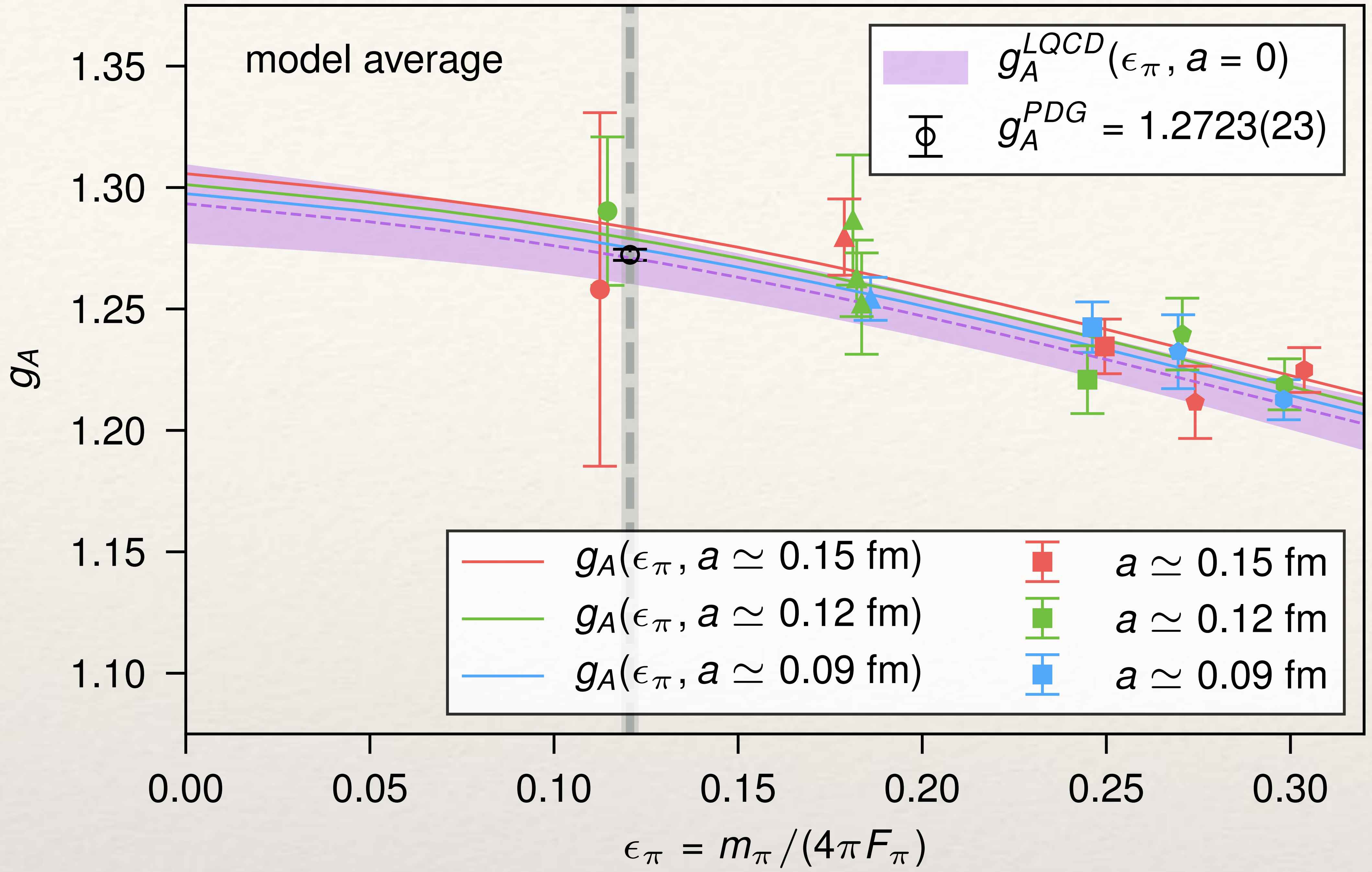

PRELIMINARY

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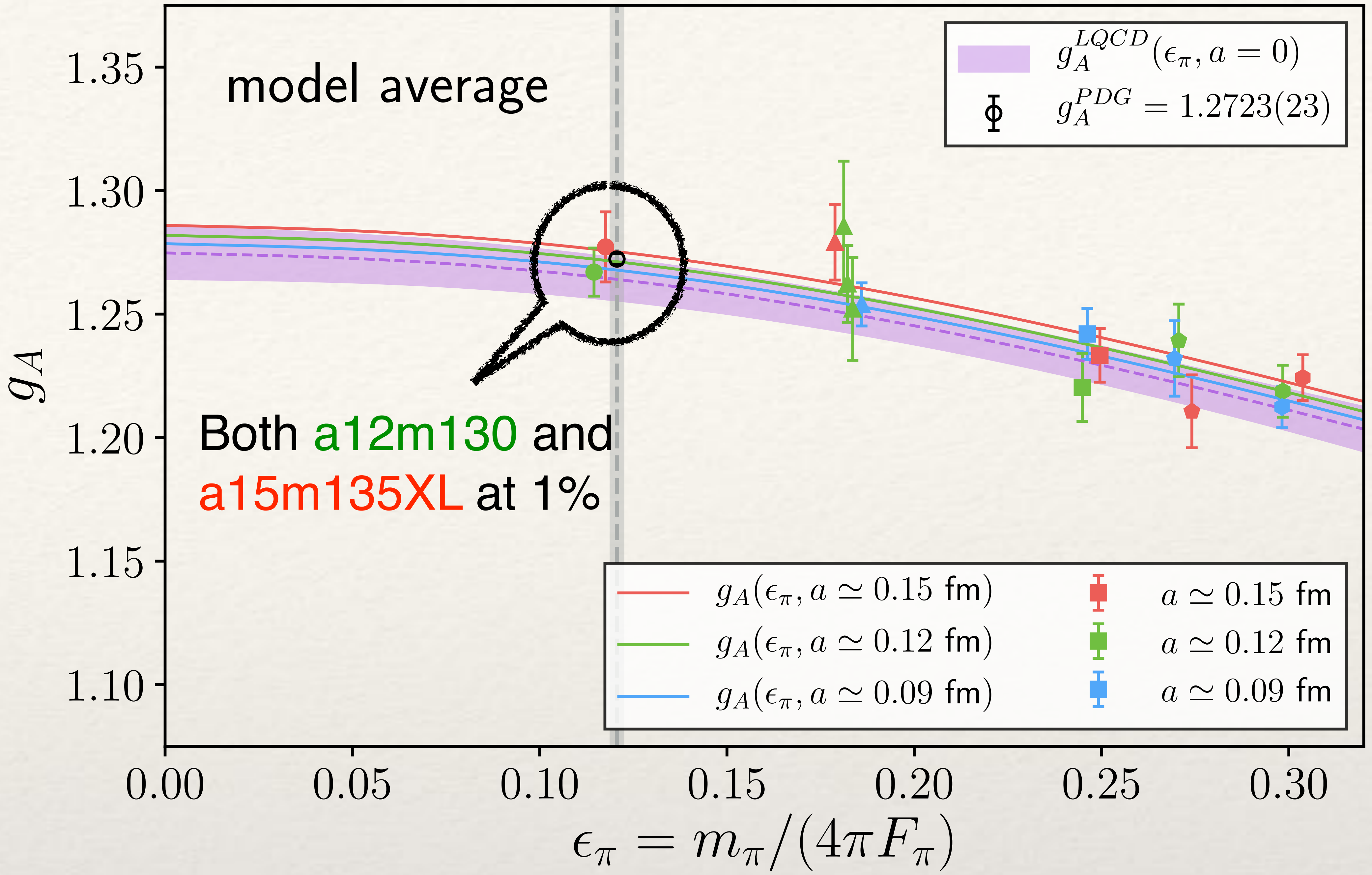

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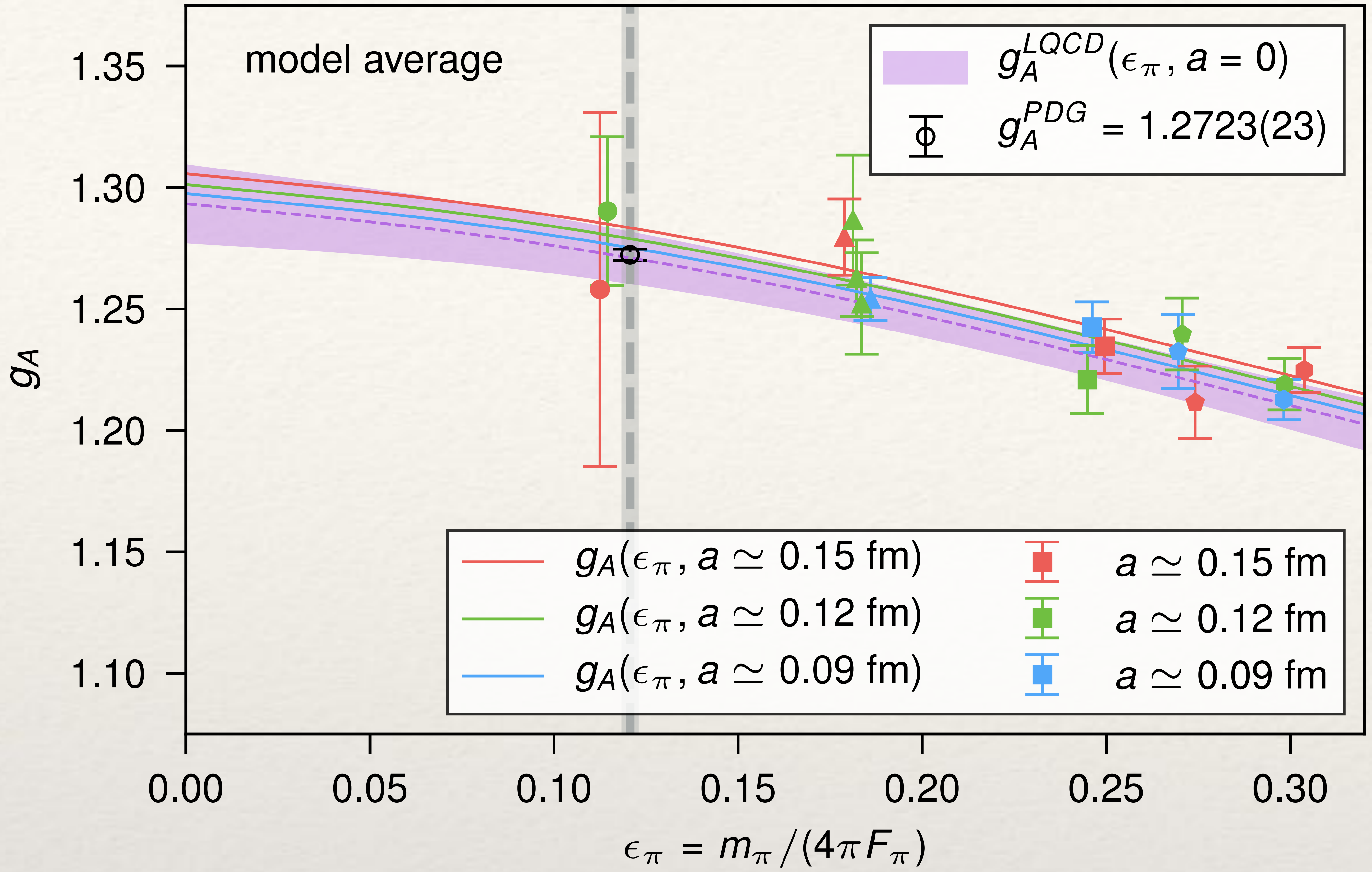

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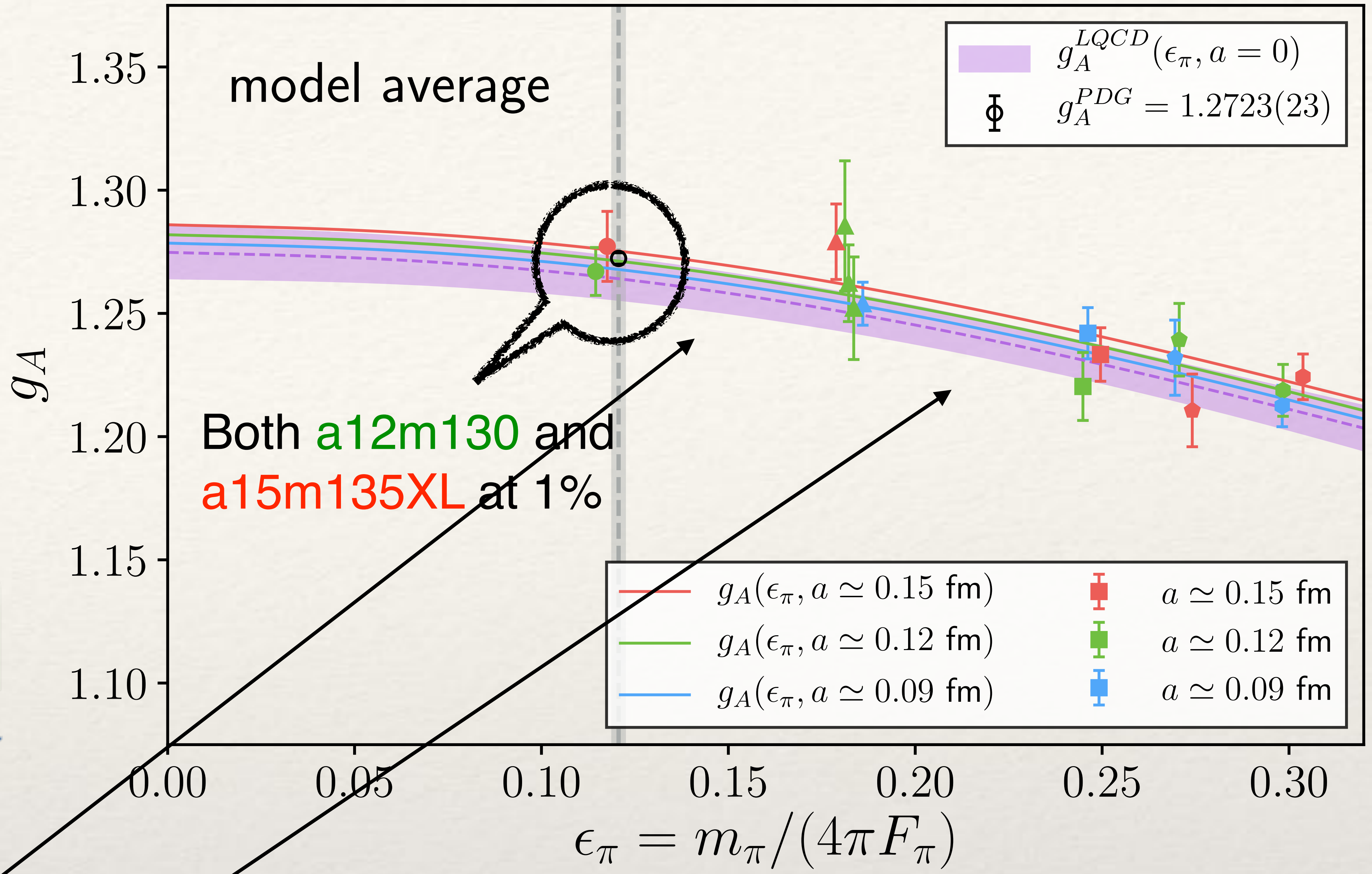

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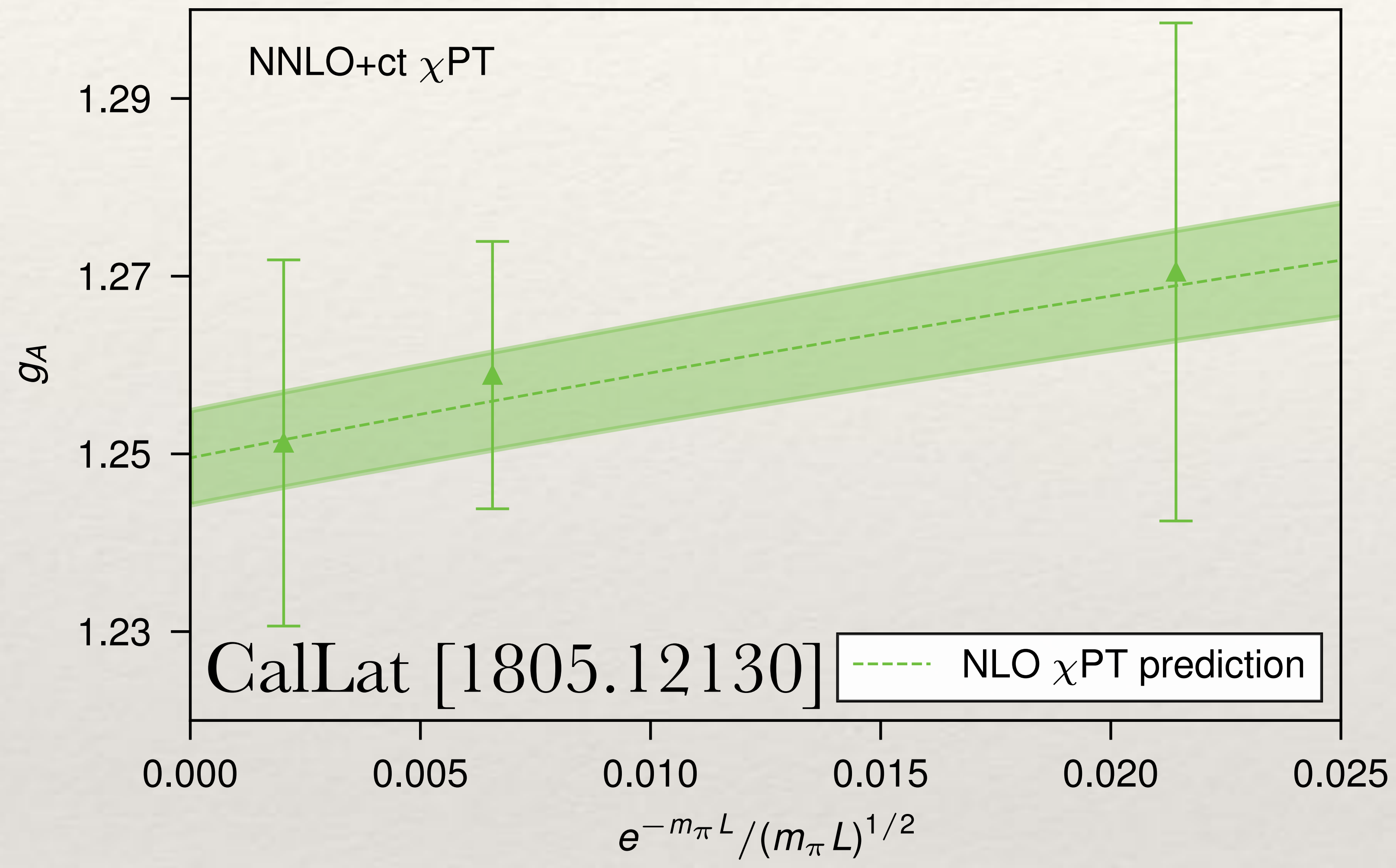
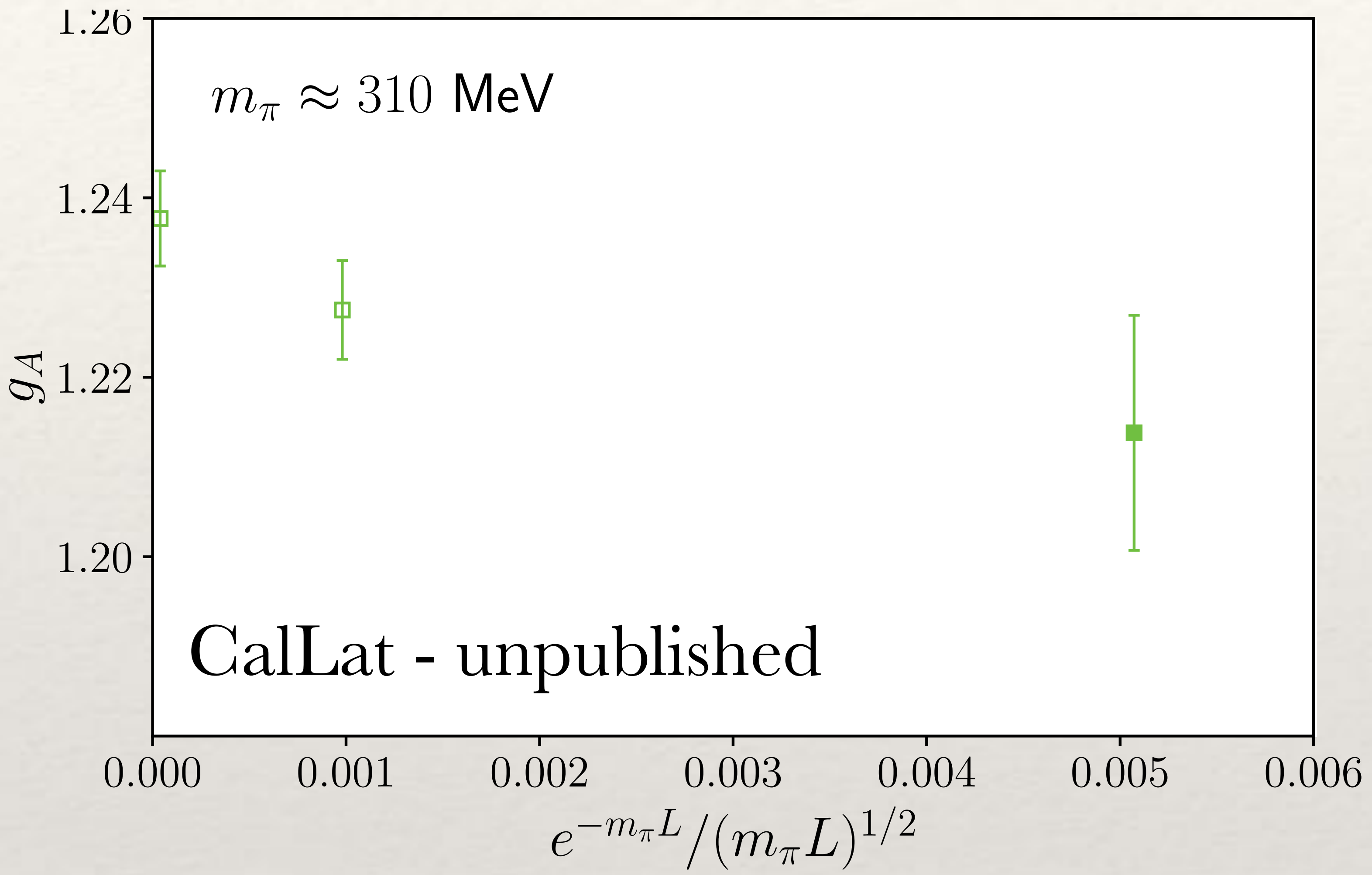
- We have 2 additional pion masses (180, 260) and a 4th finer lattice spacing, a≈0.06fm @ $M\pi \approx$ 220, 310 MeV
  - We anticipate improving g_A to ~0.5% — we need to address the radiative QED correction to make this useful

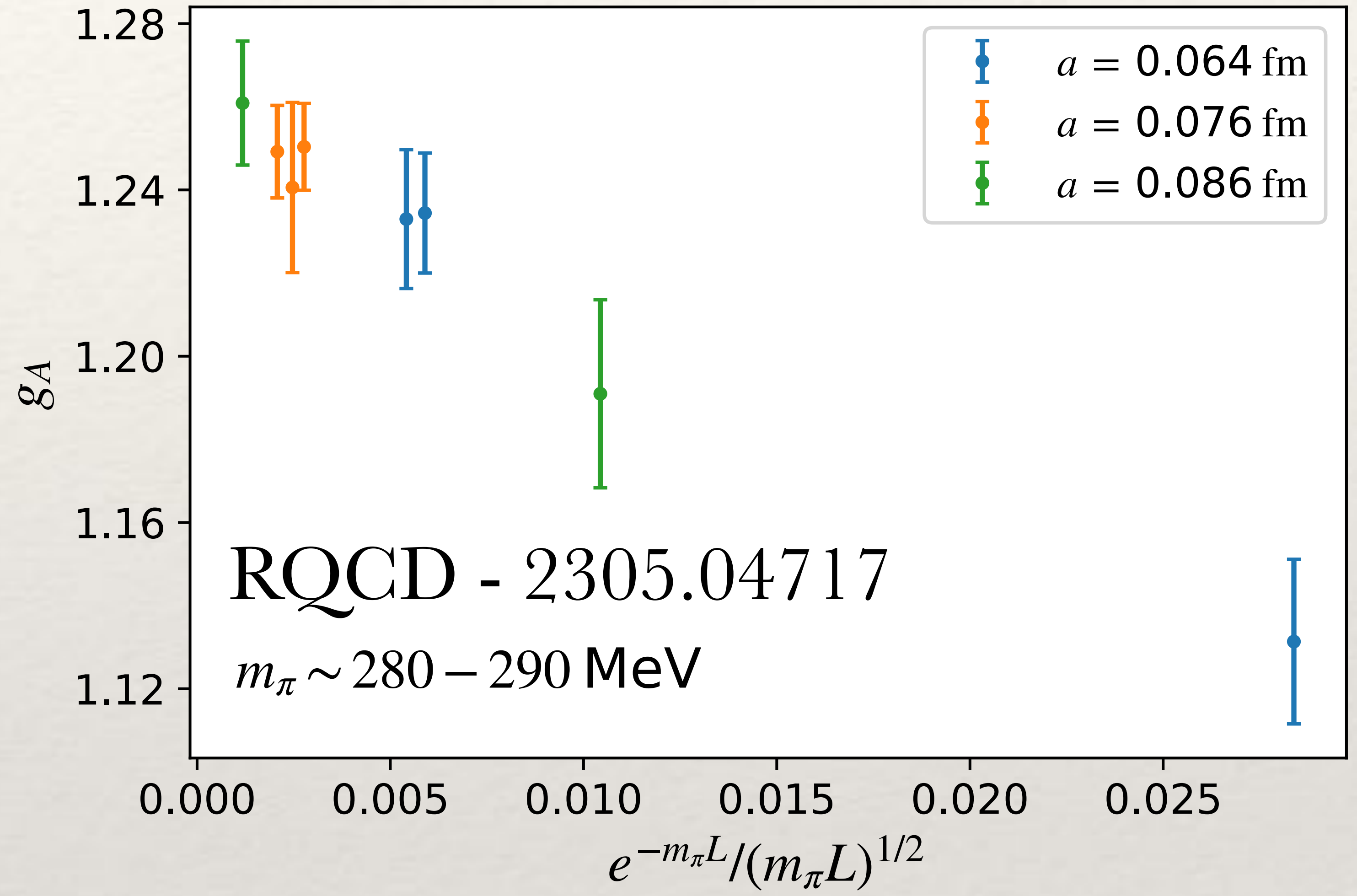
Sub-percent determination of $g_A^{\text{QCD}-\text{isosymmetric}}$

- At sub-percent precision — we have to worry about non-monotonic finite volume corrections to g_A

Z. Hall, D. Pefkou, A.S. Meyer, R. Briceño, M.A. Clark, M. Hoferichter, E. Mereghetti, H. Monge-Camacho, C. Morningstar, A. Nicholson, P. Vranas, A. Walker-Loud — *In preparation*

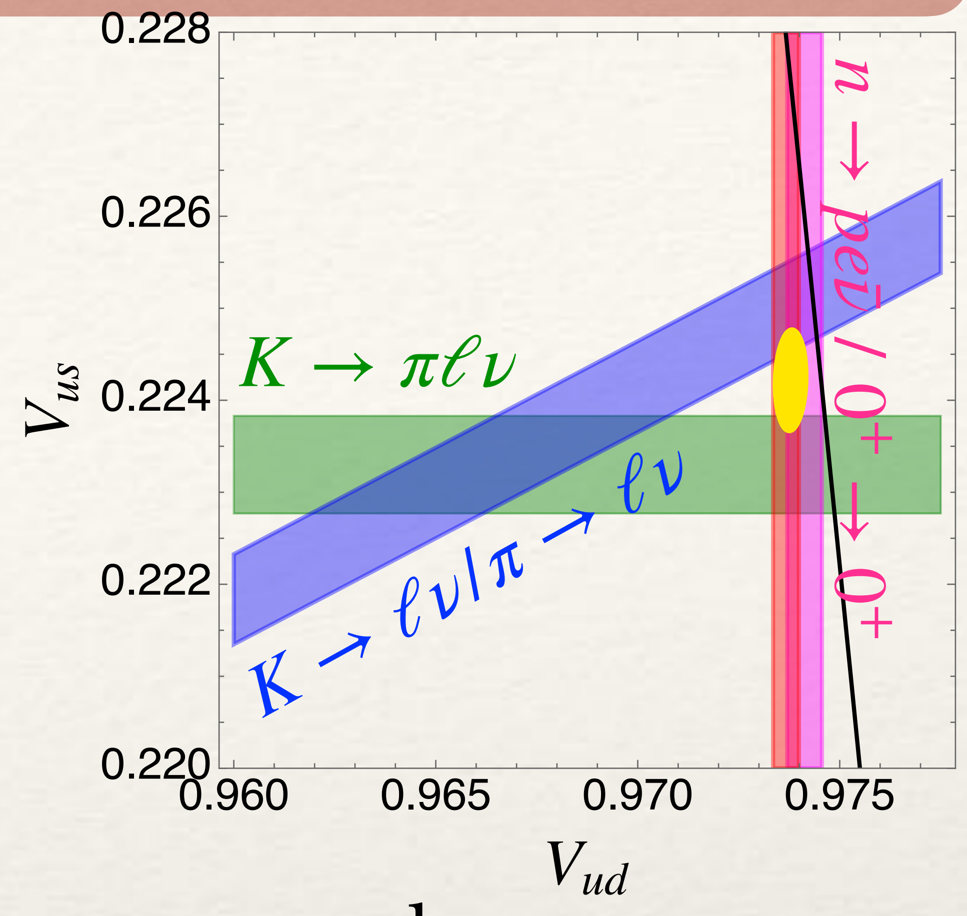






- Sign change versus m_π is expected from baryon χPT
- Current strategy of most groups: $g_A(L) = g_A + c_2 \frac{m_\pi^2}{(4\pi F_\pi)^2} \frac{e^{-m_\pi L}}{\sqrt{m_\pi L}}$ fit c_2 at heavy m_π, apply to all
- We need to add sub-leading FV corrections $+c_3 \frac{m_\pi^3}{(4\pi F_\pi)^3} \frac{e^{-m_\pi L}}{m_\pi L} + \cdots$
- and simultaneously understand discretization errors…

Summary & Outlook



- Interesting $\approx 3\sigma$ tension in the first row CKM unitarity

- Experimental prospects to
  - Improve the precision of $K_{\ell 2}$ (currently dominated by single experiment) and determine $K_{\mu 3}/K_{\mu 2}$ — NA62
  - Improve V_{us}/V_{ud} and determine V_{ud} from π^+ decays — PIONEER
  - Improve measurements of neutron lifetime and axial coupling to get competitive precision on V_{ud} as compared to superallowed nuclear decay

- In order to take advantage of the anticipated experimental precision — we need to provide SM theory prediction with O(0.2%) uncertainty
  - We need more LQCD calculations of $K_{\ell 3}$ — both pure QCD and QCD+QED

  - Requires understanding radiative QED corrections down to O(0.2%)
    - Exciting new LQCD determinations of electroweak $\square_{\gamma W}$ contribution to pion, kaon and now nucleon Agrees with previous (and recent) dispersive determinations

  - BSM Right-Handed currents provide more statistically favored solutions to CKM unitarity tension
    - LQCD calculations of g_A can be compared with $\lambda_{\mathrm{PDG}} = g_A^{\mathrm{PDG}}/g_V^{\mathrm{PDG}}$ to constrain right-handed currents
    - Unexpected O(2%) QED correction to g_A spoils this comparison
    - Need LQCD+QED calculation to determine it

Thank You