ACFI Workshop on "Beta decays as a probe of new physics"
Amherst, Nov 1-3 2018

BSM and beta decay

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Los Alamos
NATIONAL LABORATORY
EST. 1943

Outline

- New physics in beta decays: generalities and EFT framework

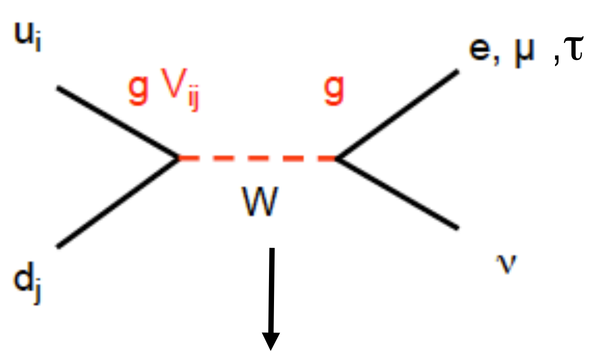
- Constraints on non-standard charged current interactions
  - global analysis of beta decays
  - collider input: LEP, LHC
  - comparison of sensitivities

- Summary and outlook

Special thanks to Martin Gonzalez-Alonso for sharing his slides from
the WE-Heraeus-Seminar on "Particle Physics with Cold and UltraCold Neutrons"
October 24-26, 2018, Bad Honnef

Semileptonic processes: SM and beyond

- In the SM, W exchange $\Rightarrow$ V-A currents, universality



$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

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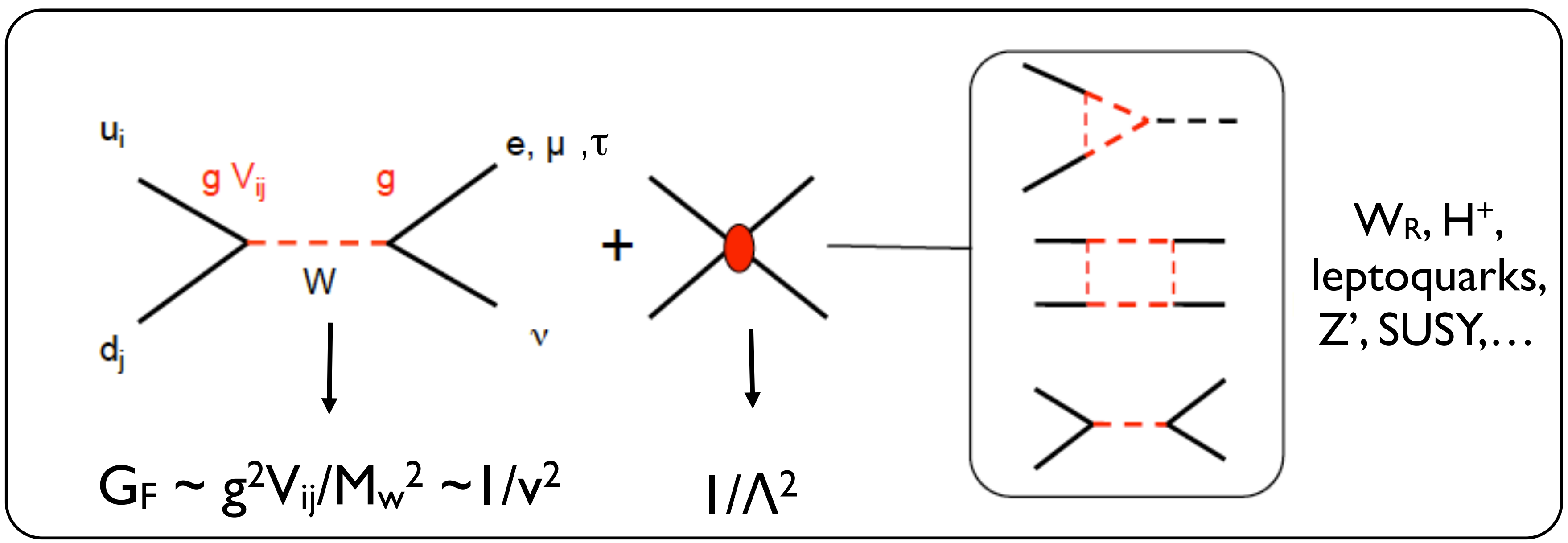


SUSY analyses:

Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035,

…

Kurylov & Ramsey-Musolf hep-ph/0109222.

…

Hagiwara et al1995

…

Barbieri et al 1985

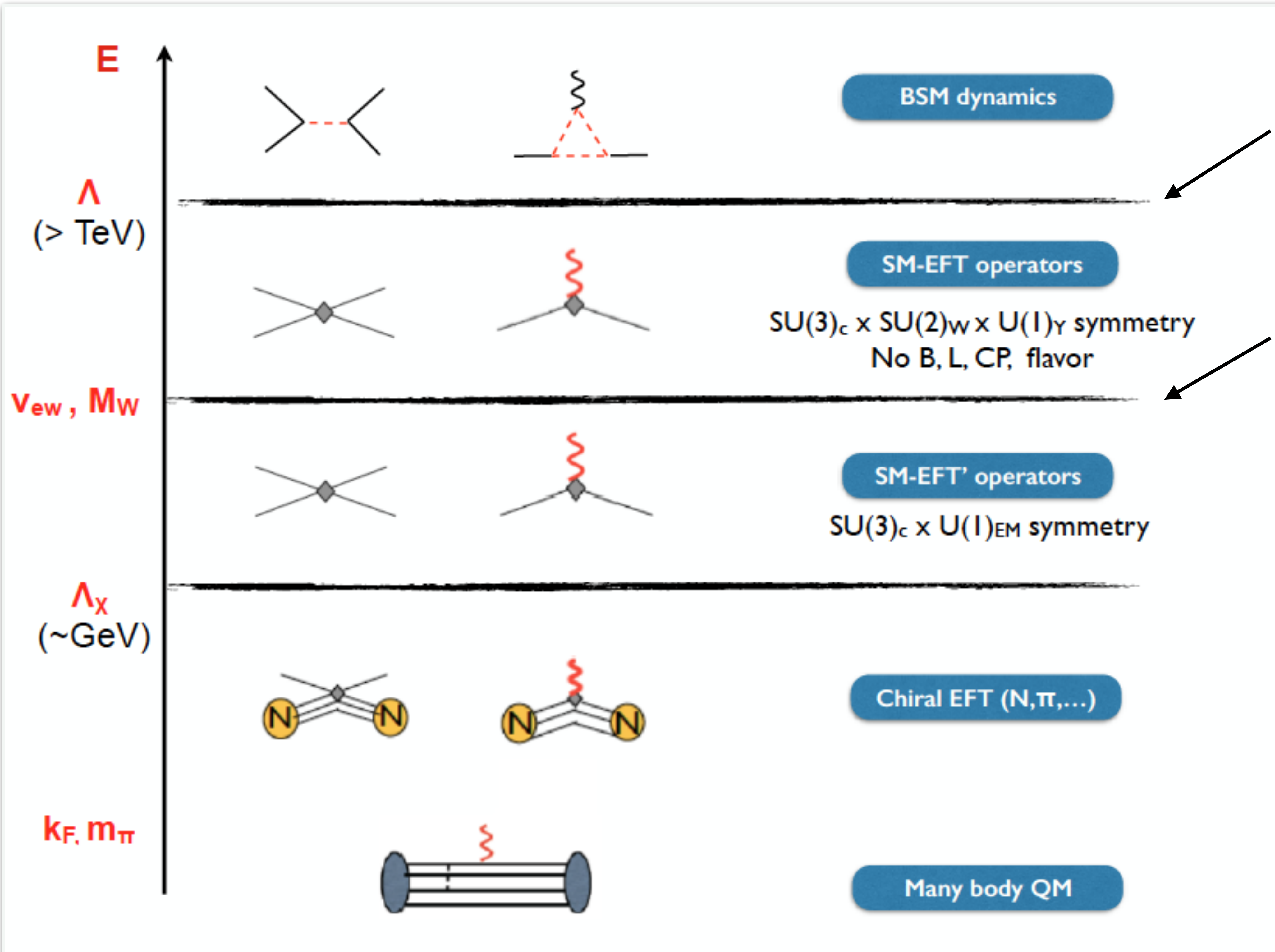
…

- Broad sensitivity to BSM scenarios

- Experimental and theoretical precision at or approaching 0.1% level
  Probe effective scale Λ in the 5-10 TeV range

Connecting scales — EFT

To connect UV physics to neutron and nuclear beta decays, use EFT



Matching to BSM scenarios

Perturbative matching within SM

Connecting scales — EFT

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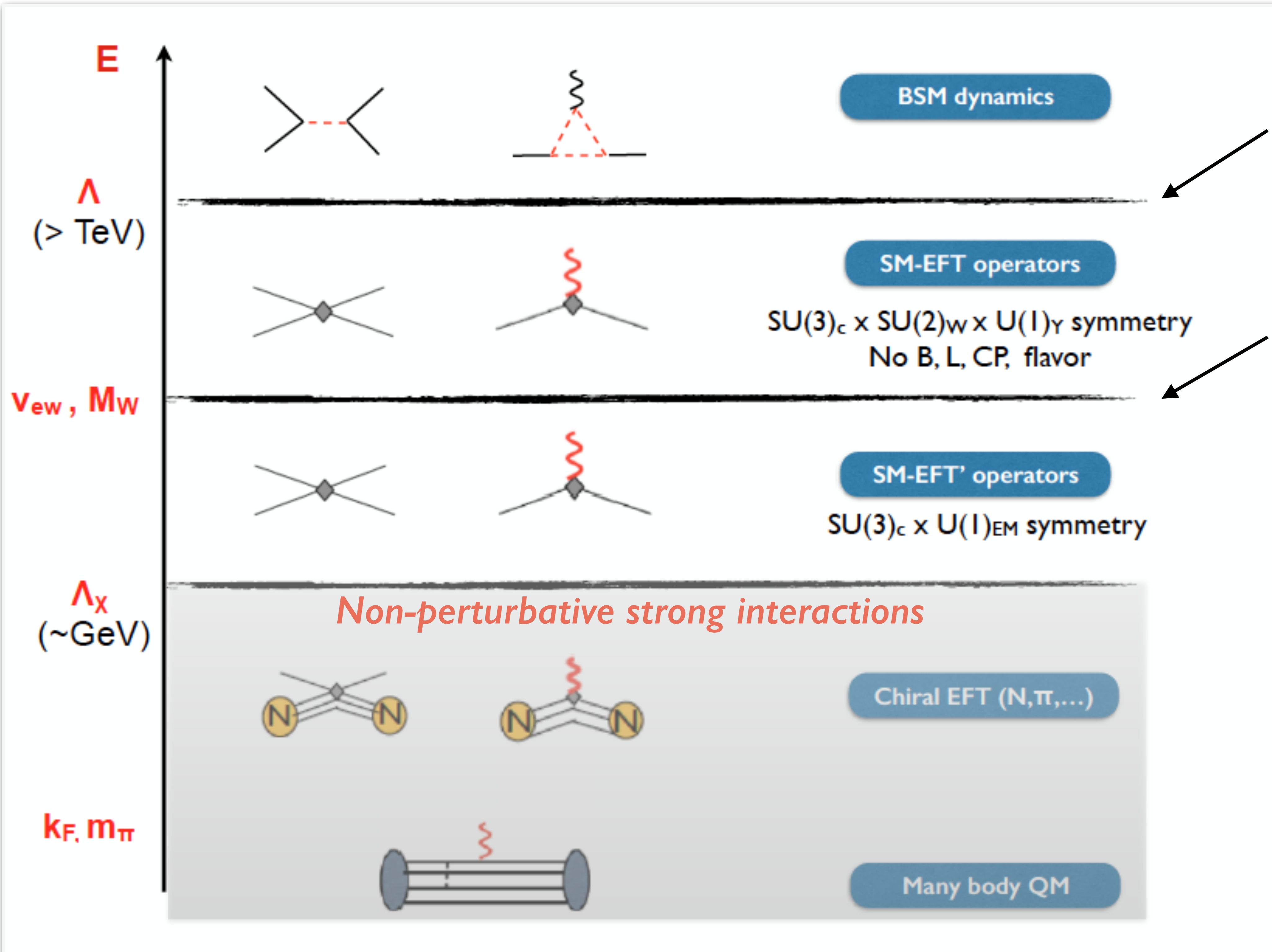


Matching to BSM scenarios

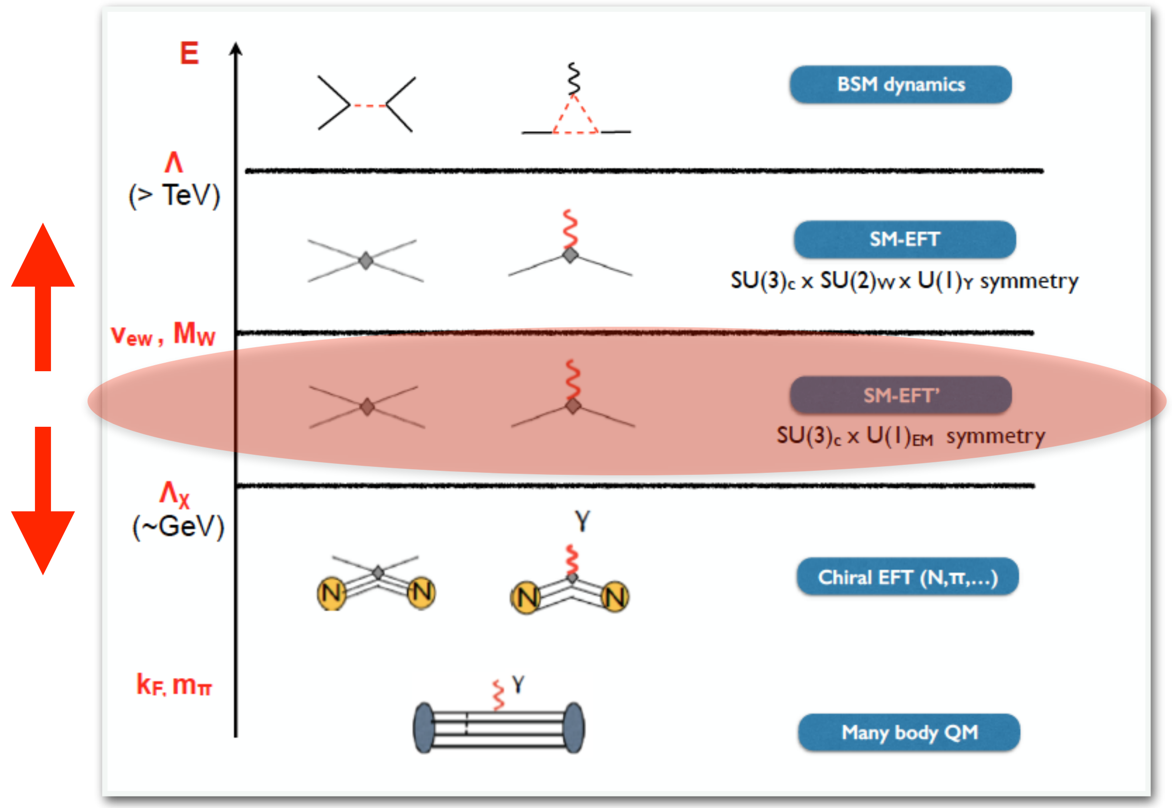
Perturbative matching within SM

Hadronic matrix elements

Nuclear matrix elements

Effective Lagrangian at E~GeV

- New physics effects are encoded in ten quark-level couplings



- Quark-level version of Lee-Yang effective Lagrangian, allows us to connect nuclear & high energy probes

Effective Lagrangian at E~GeV

Bhattacharya et al., 1110.6448 VC, Graesser, Gonzalez-Alonso 1210.4553

- New physics effects are encoded in ten quark-level couplings

$$
\begin{aligned}
\mathcal{L}_{\rm CC} \;=\; & -\frac{G_F^{(\beta)}}{\sqrt{2}} V_{ud} \\
\times\; & \Big[\Big(1+\epsilon_L\Big)\; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\; \bar{u}\gamma^\mu(1-\gamma_5)d \\
+\; & \epsilon_R\; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\; \bar{u}\gamma^\mu(1+\gamma_5)d \\
+\; & \epsilon_S\; \bar{\ell}(1-\gamma_5)\nu_\ell\; \bar{u}d \\
-\; & \epsilon_P\; \bar{\ell}(1-\gamma_5)\nu_\ell\; \bar{u}\gamma_5 d \\
+\; & \epsilon_T\; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\; \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}
\end{aligned}
$$

$\epsilon_i\;, \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$

Can interfere with SM: linear sensitivity to ε_i

Effective Lagrangian at E~GeV

Bhattacharya et al., 1110.6448   VC, Graesser, Gonzalez-Alonso 1210.4553

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+ & \;\epsilon_R \;\; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu(1+\gamma_5)d \\
+ & \;\epsilon_S \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}d \\
- & \;\epsilon_P \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}\gamma_5 d \\
+ & \;\epsilon_T \;\; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \; \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}
\end{aligned}
$$

$$\epsilon_i \;, \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$$

Can interfere with SM: linear sensitivity to ε_i

$$+ \quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

Interference with SM suppressed by m_ν/E: quadratic sensitivity to $\tilde{\varepsilon}_i$

Effective Lagrangian at E~GeV

Bhattacharya et al., 1110.6448 VC, Graesser, Gonzalez-Alonso 1210.4553

- Work to first order in rad. corr. and new physics

$$\begin{aligned}\mathcal{L}_{\rm CC} &= -\frac{G_F^{(\mu)}}{\sqrt{2}} V_{ud} \left(1+\delta_{\rm RC}\right)\left(1-\frac{\delta G_F^{(\mu)}}{G_F^{(\mu)}}\right)\left(1+\epsilon_L+\epsilon_R\right) \\ &\times \Big[\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \, \bar{u}\gamma^\mu\Big(1-\left(1-2\,\epsilon_R\right)\gamma_5\Big)d \\ &+ \epsilon_S \quad \bar{\ell}(1-\gamma_5)\nu_\ell \, \bar{u}d \\ &- \epsilon_P \quad \bar{\ell}(1-\gamma_5)\nu_\ell \, \bar{u}\gamma_5 d \\ &+ \epsilon_T \quad \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \, \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}\end{aligned}$$

$G_F^{(\mu)}$

Fermi constant *extracted* fro muon lifetime, possibly "contaminated" by new physics

$\delta_{\rm RC}$

SM rad. corr. $\supset$ "large log" $(\alpha/\pi)\times \mathrm{Log}(M_Z/\mu)$

Marciano-Sirlin 1981
Sirlin 1982

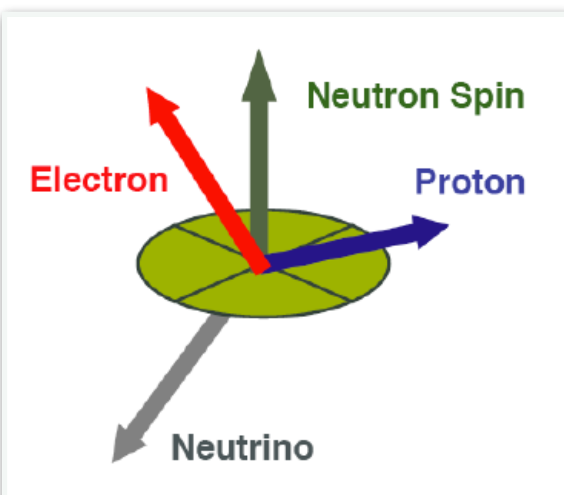
Note: besides the pre-factor, ϵ_R appears in nuclear decays in the combination $\bar{g}_A \equiv g_A \times (1-2\epsilon_R)$

How do we probe the ε_α? (I)

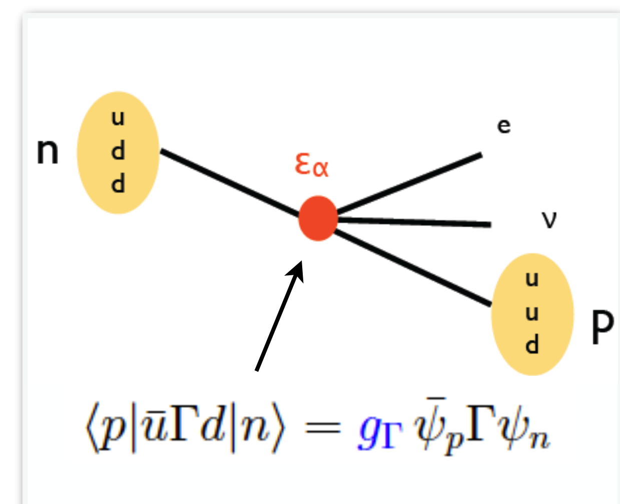
1. Differential decay distribution

$$d\Gamma \propto F(E_e)\left\{1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + \langle\vec{J}\rangle\cdot\left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

Lee-Yang, 1956 Jackson-Treiman-Wyld 1957



$a(g_A)$, $A(g_A)$, $B(g_A, g_\alpha\varepsilon_\alpha)$, …
isolated via suitable experimental asymmetries

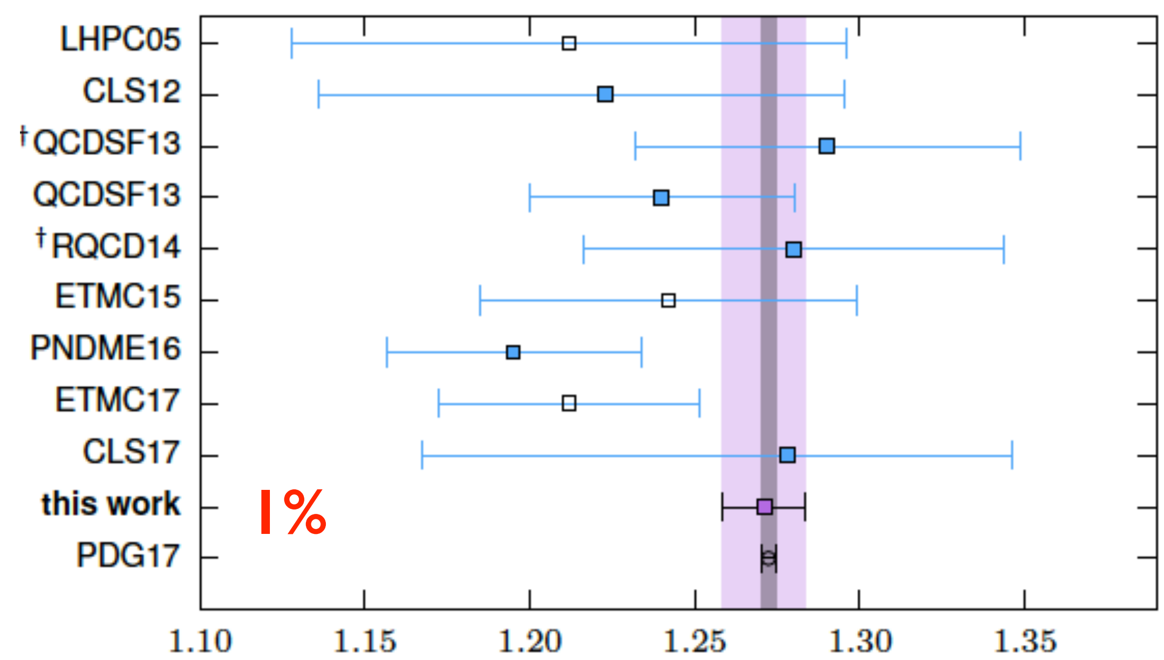


Theory input: $g_{V,A,S,T}$ (from lattice QCD) + rad. corr.

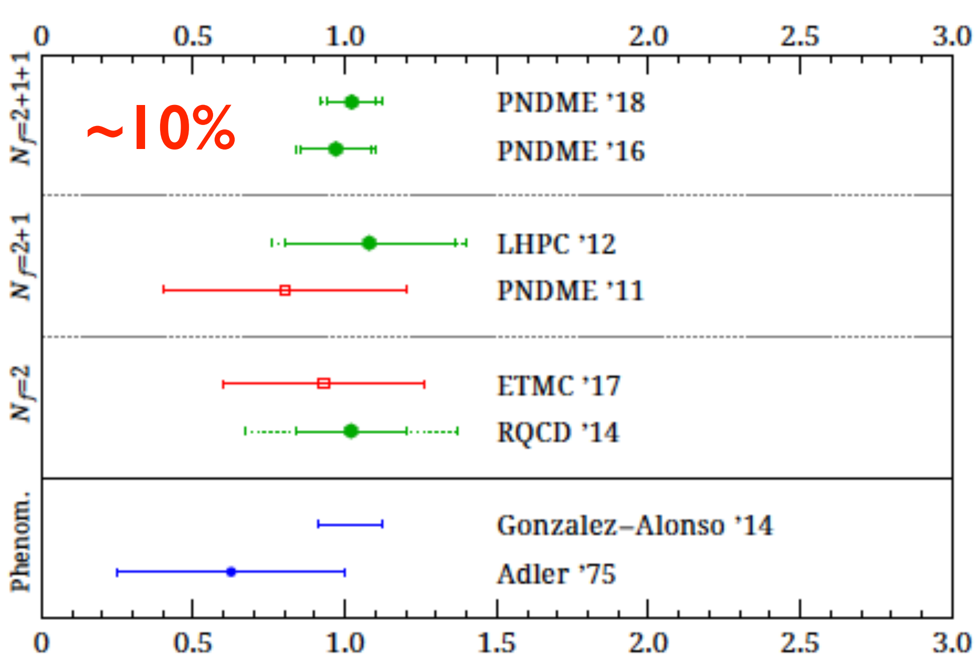
Nucleon charges from lattice QCD

With estimates of all systematic errors (m_q, a, V, excited states)

Chang et al. (CalLat) 1805.12030



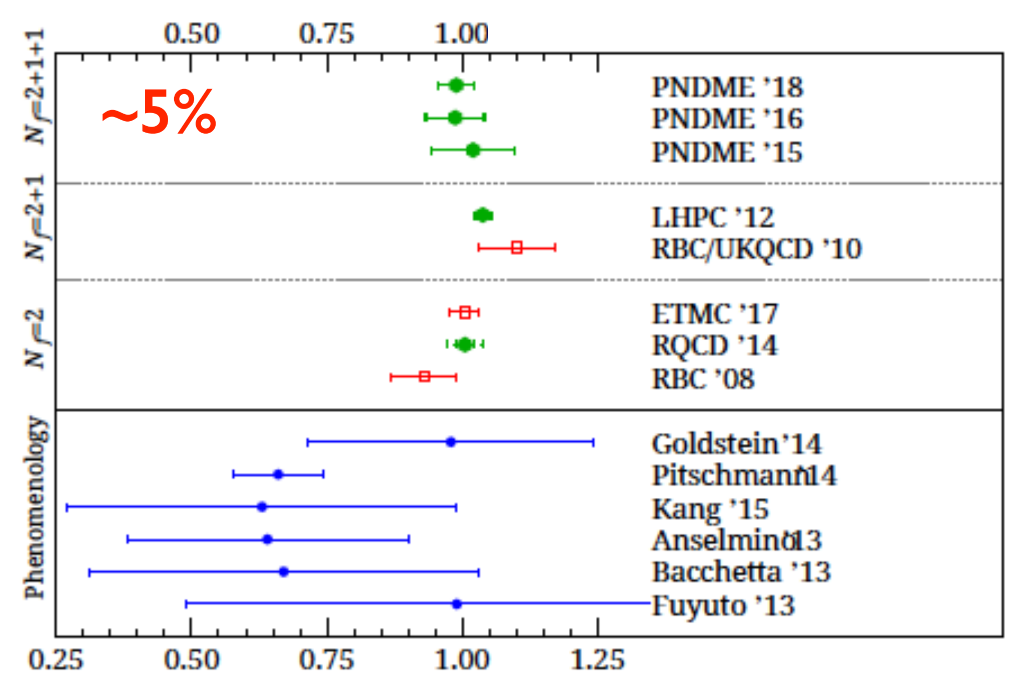
g_S



g_A

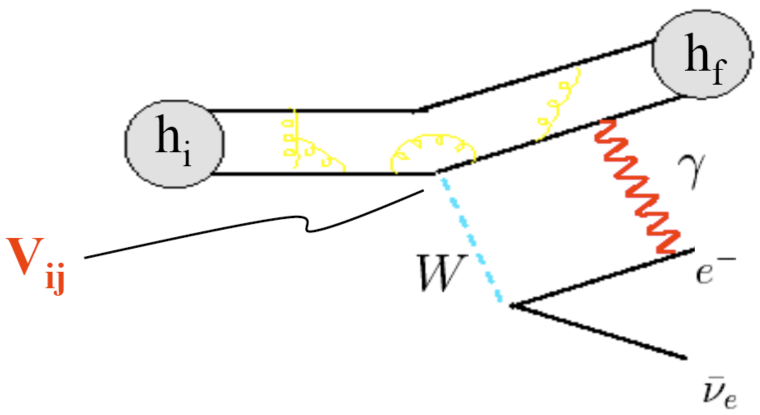
Bhattacharya et al. 1806.09006

g_T



How do we probe the ε_α? (2)

2. Total decay rates



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

How do we probe the ε_α? (2)

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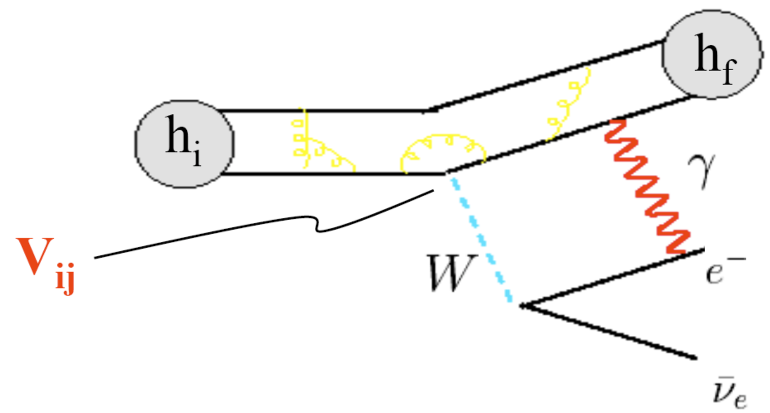


$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\text{had}}|^2 \times (1+\delta_{RC}) \times F_{\text{kin}}$$

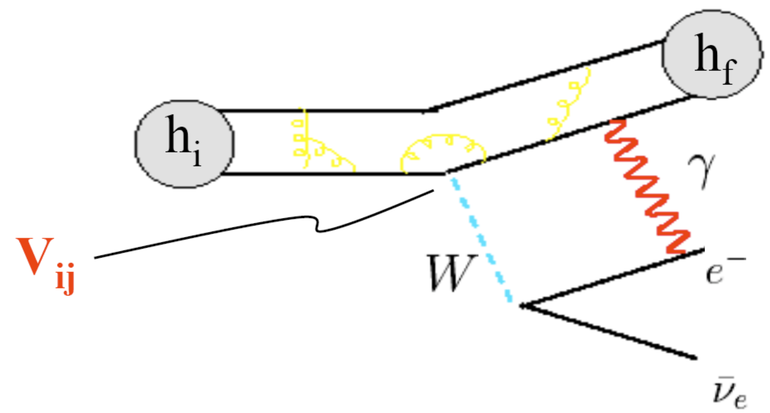
Lifetimes, BRs

Experimental input

Q-values → phase space

How do we probe the ε_α? (2)

2. Total decay rates



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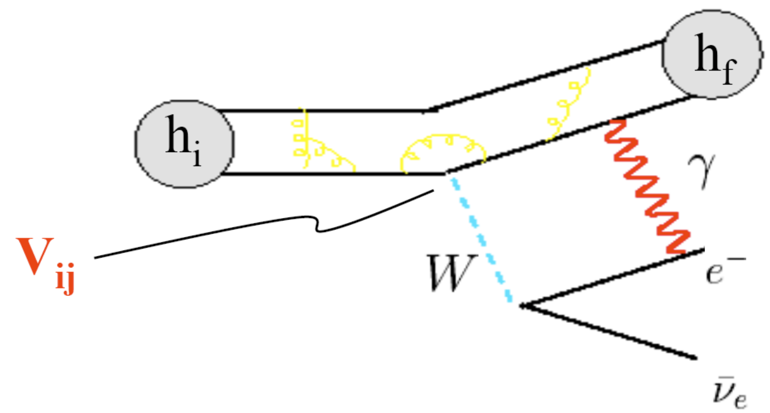
Theory input

Hadronic / nuclear
matrix elements
and radiative corrections

Lattice QCD, chiral EFT,
dispersion relations, …

How do we probe the ε_α? (2)

2. Total decay rates



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

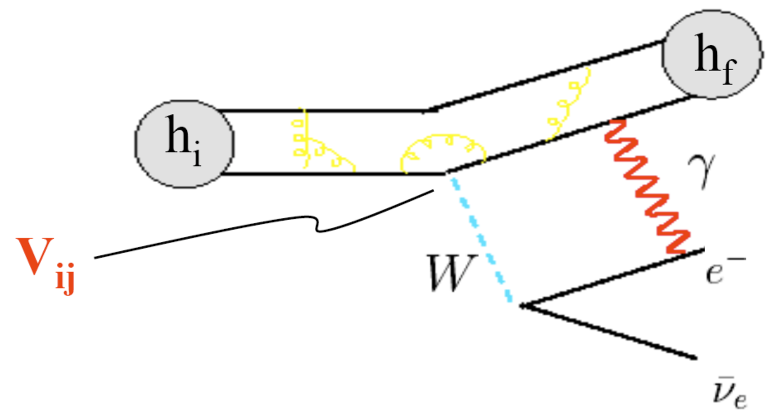
Channel-dependent effective CKM element

$$\bar{V}_{ud} = V_{ud}\left[1 + \epsilon_L + \epsilon_R + b(\epsilon_S, \epsilon_T)\, \widetilde{F}_{\rm kin}\right]$$

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

How do we probe the ε_α? (2)

2. Total decay rates



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For nuclei, rate traditionally written in terms of "corrected FT values"

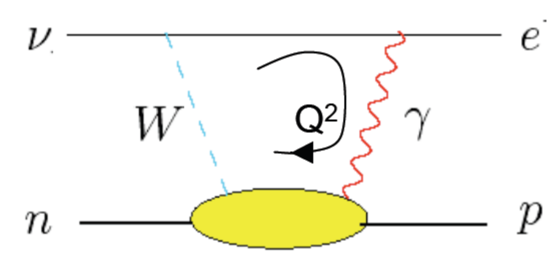
$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_F^2\, V_{ud}^2\, (1+\ \Delta_R^V)} \qquad K = \frac{2\pi^3 \log 2}{m_e^5}$$

Nucleus-dependent radiative & Isospin Breaking correction

"Inner" radiative correction

$\Delta_R{}^V$= (2.36 ± 0.04)%

[Marciano-Sirlin 2006]



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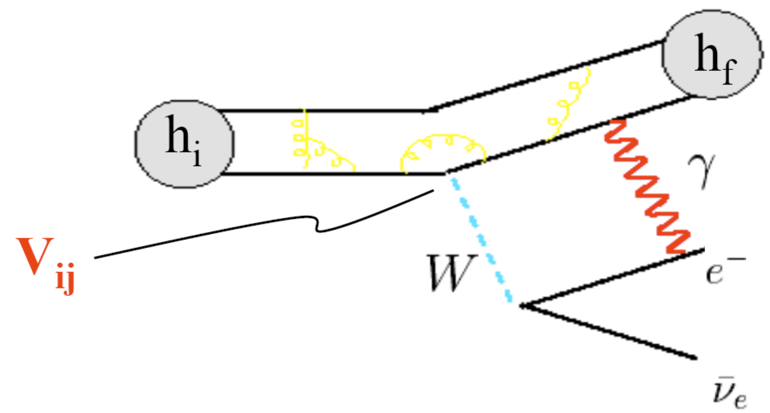

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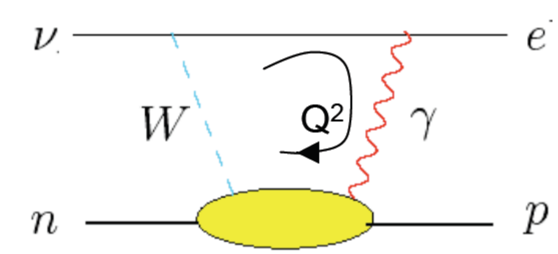
Nucleus-dependent radiative & Isospin Breaking correction

"Inner" radiative correction
$\Delta_R{}^V$= (2.467 ± 0.022)%
[Seng et al. 1807.10197]



Snapshot of the field

- Experimental precision between ~0.01% and few %

Ft (0+→0+) values

Parent	$\mathcal{F}t$ (s)
^{10}C	3078.0 ± 4.5
^{14}O	3071.4 ± 3.2
^{22}Mg	3077.9 ± 7.3
^{26m}Al	3072.9 ± 1.0
^{34}Cl	3070.7 ± 1.8
^{34}Ar	3065.6 ± 8.4
^{38m}K	3071.6 ± 2.0
^{38}Ca	3076.4 ± 7.2
^{42}Sc	3072.4 ± 2.3
^{46}V	3074.1 ± 2.0
^{50}Mn	3071.2 ± 2.1
^{54}Co	3069.8 ± 2.6
^{62}Ga	3071.5 ± 6.7
^{74}Rb	3076.0 ± 11.0

Correlation coefficients

Parent	Type	Parameter	Value
^{6}He	GT/β^-	a	$-0.3308(30)$[a)]
^{32}Ar	F/β^+	$\tilde{a}$	0.9989(65)
^{38m}K	F/β^+	$\tilde{a}$	0.9981(48)
^{60}Co	GT/β^-	$\tilde{A}$	$-1.014(20)$
^{67}Cu	GT/β^-	$\tilde{A}$	0.587(14)
^{114}In	GT/β^-	$\tilde{A}$	$-0.994(14)$
^{14}O/^{10}C	F-GT/β^+	P_F/P_{GT}	0.9996(37)
^{26}Al/^{30}P	F-GT/β^+	P_F/P_{GT}	1.0030 (40)
^{8}Li	GT/β^-	R	0.0009(22)

Neutron data

Parameter	Value	
τ_n (s)	879.75(76)	* (S = 1.9!!)
a_n	$-0.1034(37)$	*
$\tilde{a}_n$	$-0.1090(41)$	
$\tilde{A}_n$	$-0.11869(99)$	* (S = 2.6!!)
$\tilde{B}_n$	0.9805(30)	*
λ_{AB}	$-1.2686(47)$	
D_n	$-0.00012(20)$	*
R_n	0.004(13)	

* Average

$S = (\chi^2_{min}/dof)^{1/2}$

Nuclei

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732 & M. Gonzalez-Alonso slides

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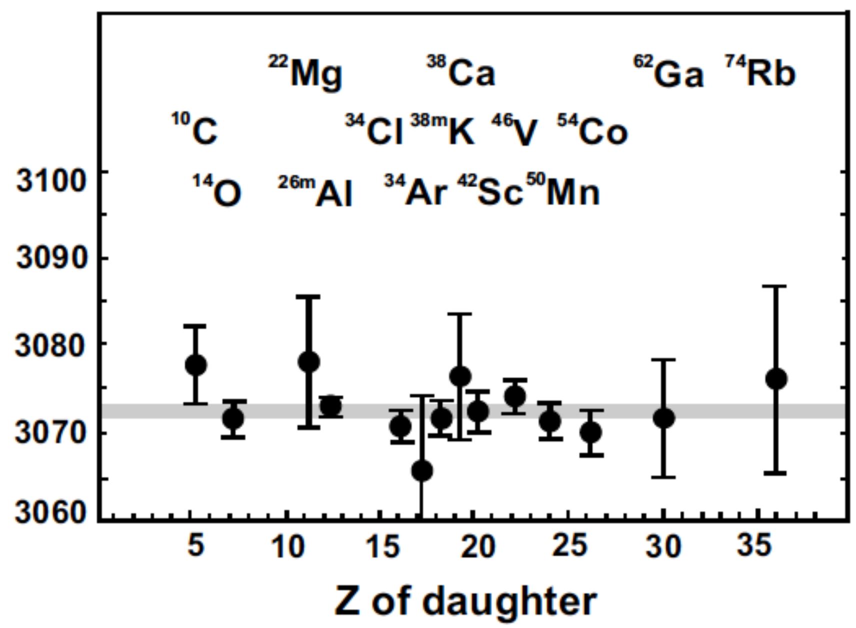
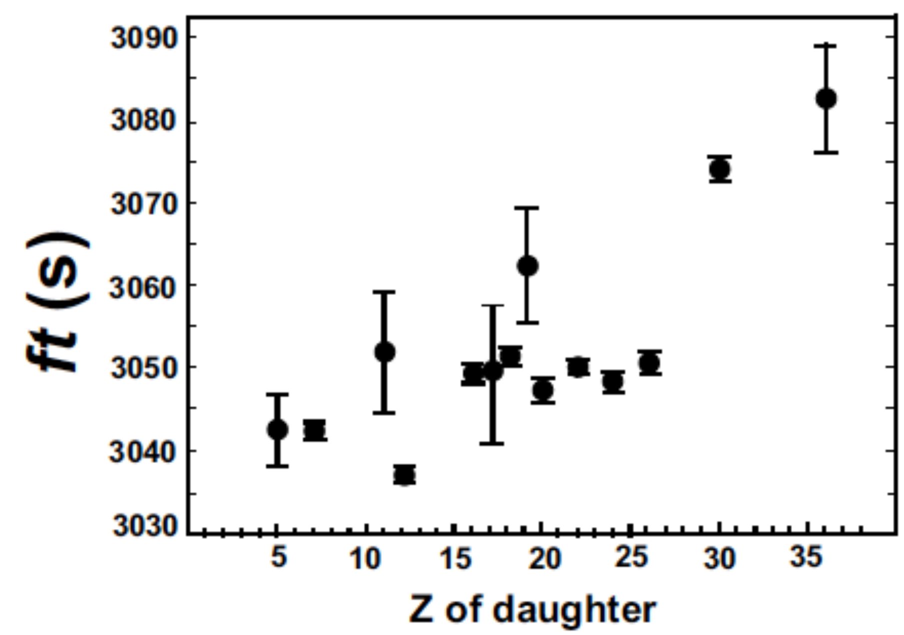
"Corrected" FT values



FT values before including nucleus-dependent radiative correction



Hardy-Towner 1411.5987

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732 & M. Gonzalez-Alonso slides

Snapshot of the field

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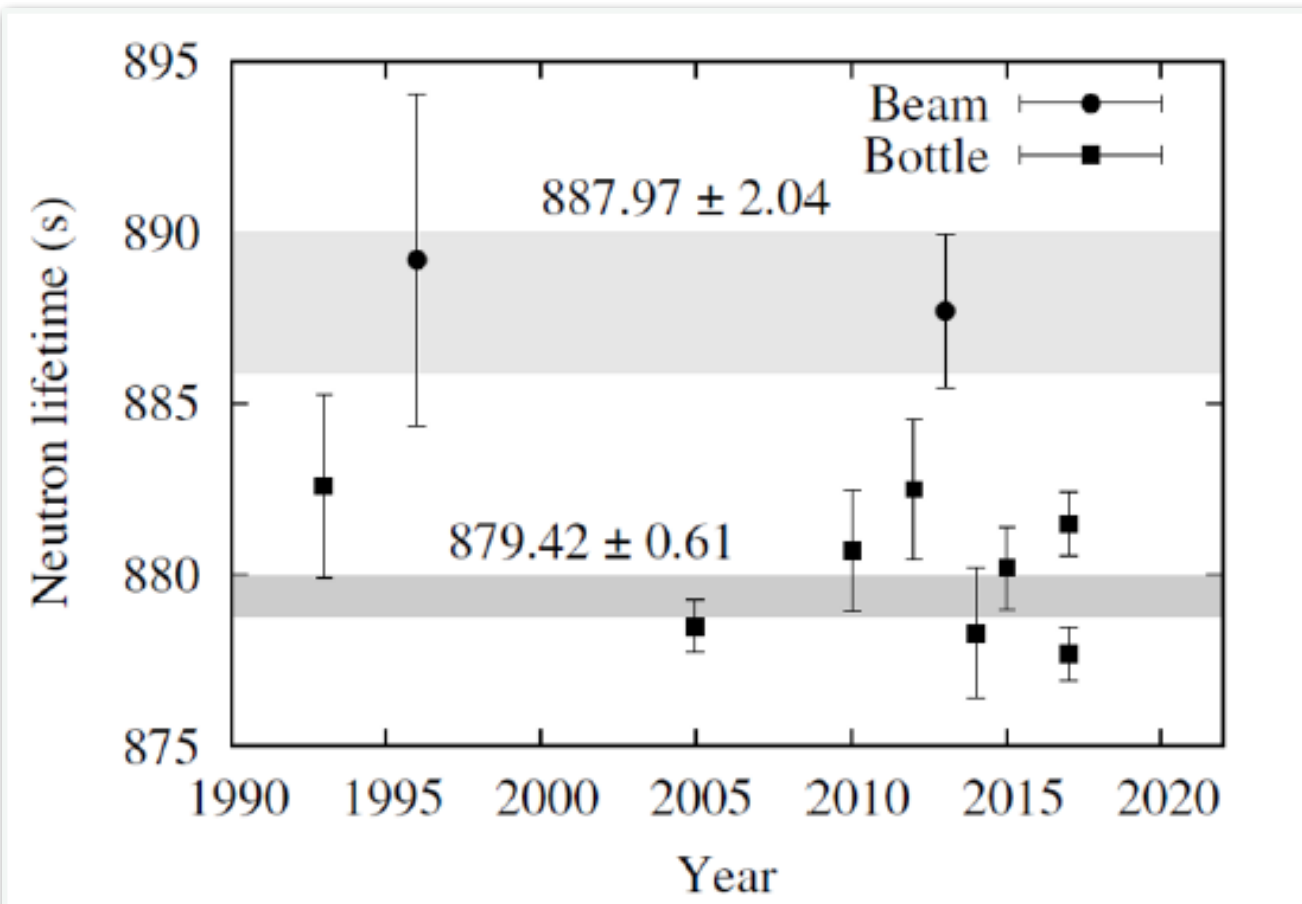

Neutron data

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* Average

$S = (\chi^2_{min}/dof)^{1/2}$

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732 & M. Gonzalez-Alonso slides

Results of global fit to low-E data

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

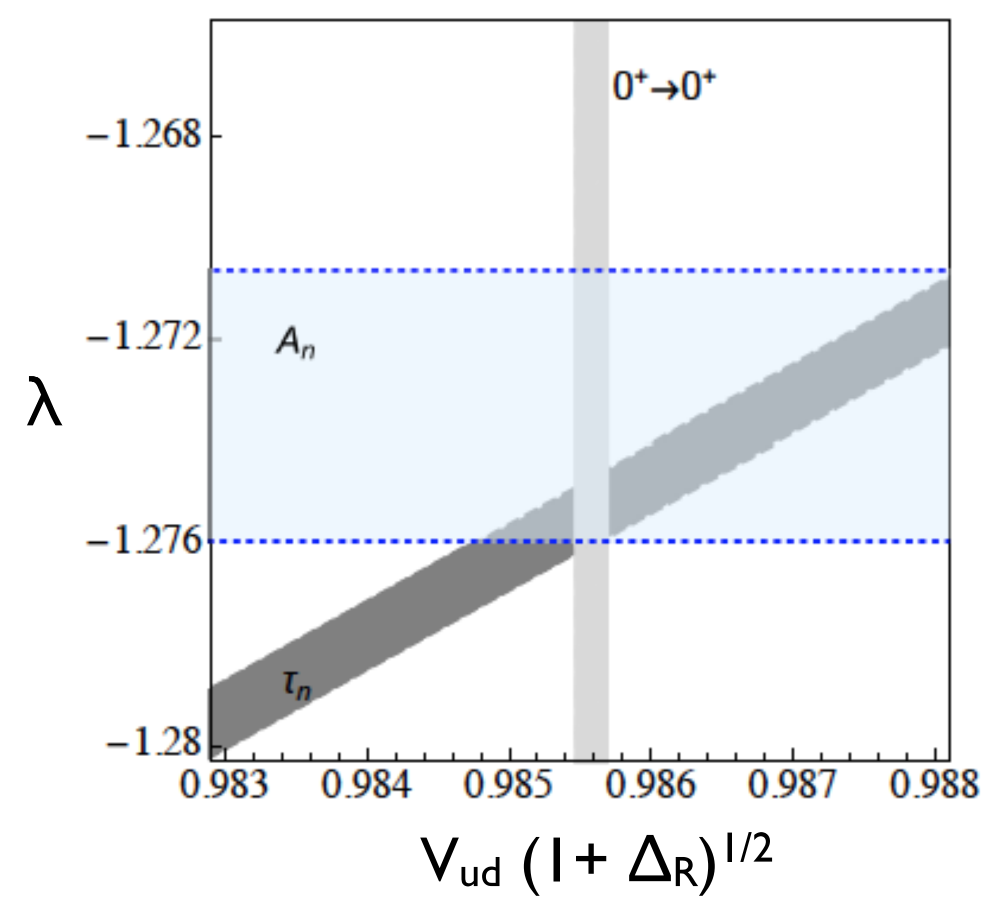
- Standard Model fit ($\lambda = g_A/g_V$)

Experimental Radiative corrections (Δ_R)

$$\begin{aligned} |V_{ud}| &= 0.97416(11)(19) = 0.97416(21) \\ \lambda &= 1.27510(66) \end{aligned}$$

$$\rho = -0.13$$
$$\chi^2_{\min}/\nu = 0.57.$$

- Fit driven by $\mathcal{F}t$'s ($0^+ \to 0^+$) and τ_n (not A_n)



Results of global fit to low-E data

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

- Standard Model fit ($\lambda = g_A/g_V$)

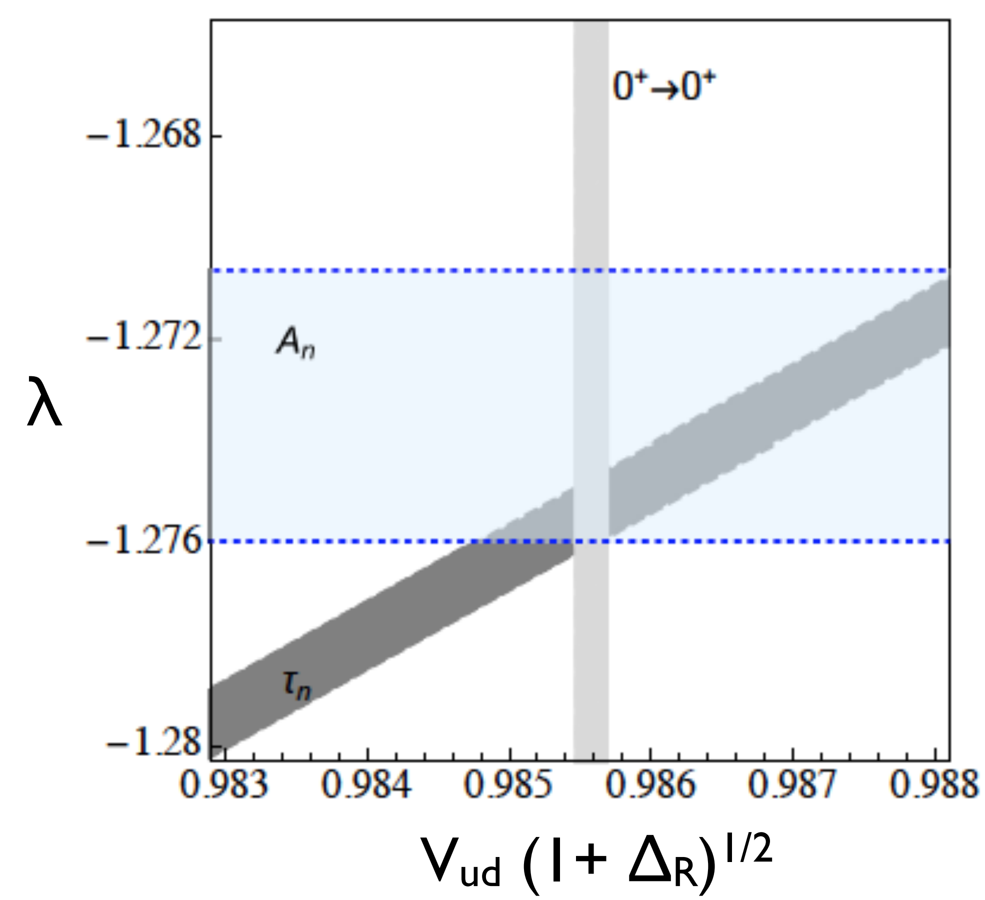
Experimental

New Radiative corrections (Δ_R)
[Seng et al. 1807.10197]

$$
\begin{aligned}
|V_{ud}| &= 0.97416(11)(12) = 0.97366(15) \\
\lambda &= 1.27510(66)
\end{aligned}
$$

$$\rho = -0.13$$
$$\chi^2_{\min}/\nu = 0.57.$$

- Fit driven by $\mathcal{F}t$'s ($0^+ \to 0^+$) and τ_n (not A_n)



Results of global fit to low-E data

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

- Fit including BSM couplings (driven by $\mathcal{F}t$'s ($0^+ \to 0^+$), τ_n, and A_n)

$$\tilde{V}_{ud} \equiv V_{ud}\,(1+\epsilon_L+\epsilon_R)\left(1-\frac{\delta G_F}{G_F}\right)$$

1st error: experimental

2nd error: Δ_R, g_A, g_S, and g_T

$$\bar{g}_A = g_A\,(1-2\epsilon_R)$$

~2 % → ~ 0.5% **

~0.2 %

~0.1 %

$$\begin{pmatrix} |\tilde{V}_{ud}| \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97452(34)(19) & \\ 0.002(1)(21) & (90\%\ \mathrm{CL}) \\ 0.0014(20)(3) & (90\%\ \mathrm{CL}) \\ -0.0007(12)(1) & (90\%\ \mathrm{CL}) \end{pmatrix}$$

$$\chi^2_{\min}/\nu = 0.46\,.$$

$$\rho = \begin{pmatrix} 1.00 & & & \\ 0.00 & 1.00 & & \\ 0.83 & 0.00 & 1.00 & \\ 0.28 & -0.04 & 0.31 & 1.00 \end{pmatrix}$$

** CalLat 1805.12030

Cabibbo universality test

$$\boxed{|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)}$$

Extraction dominated by $0^+ \to 0^+$ nuclear transitions

Hardy-Towner 1411.5987
CKM 2016

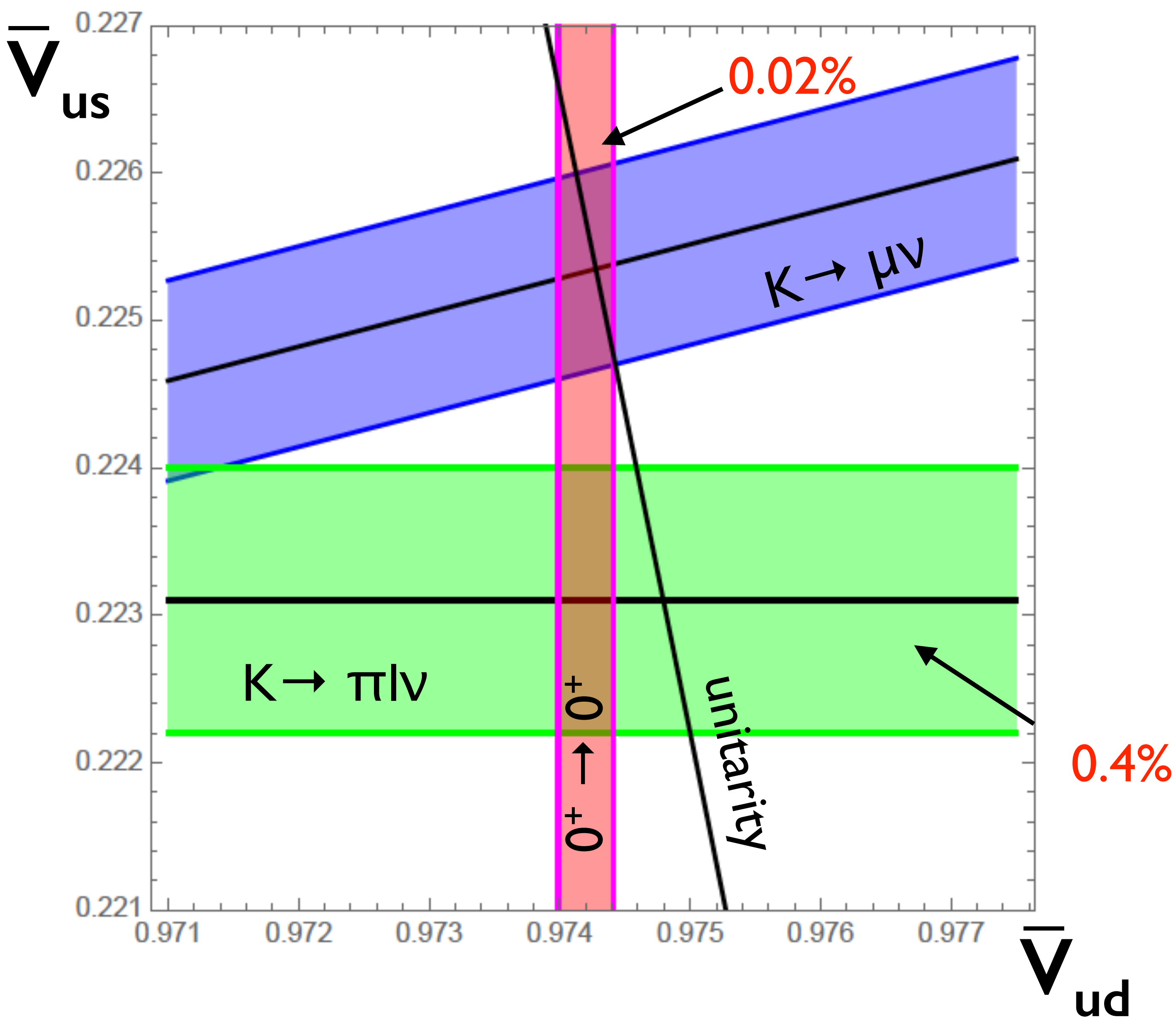
Extraction dominated by K decays:
$K \to \pi e \nu$ & $K \to \mu\nu$ vs $\pi \to \mu\nu$ (V_{us}/V_{ud})

FLAVIANET report 1005.2323 and refs therein

Lattice QCD input from FLAG 1607.00299 and refs therein
+ MILC 2018 1809.02827

Cabibbo universality test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



V_{us} from K→ μν

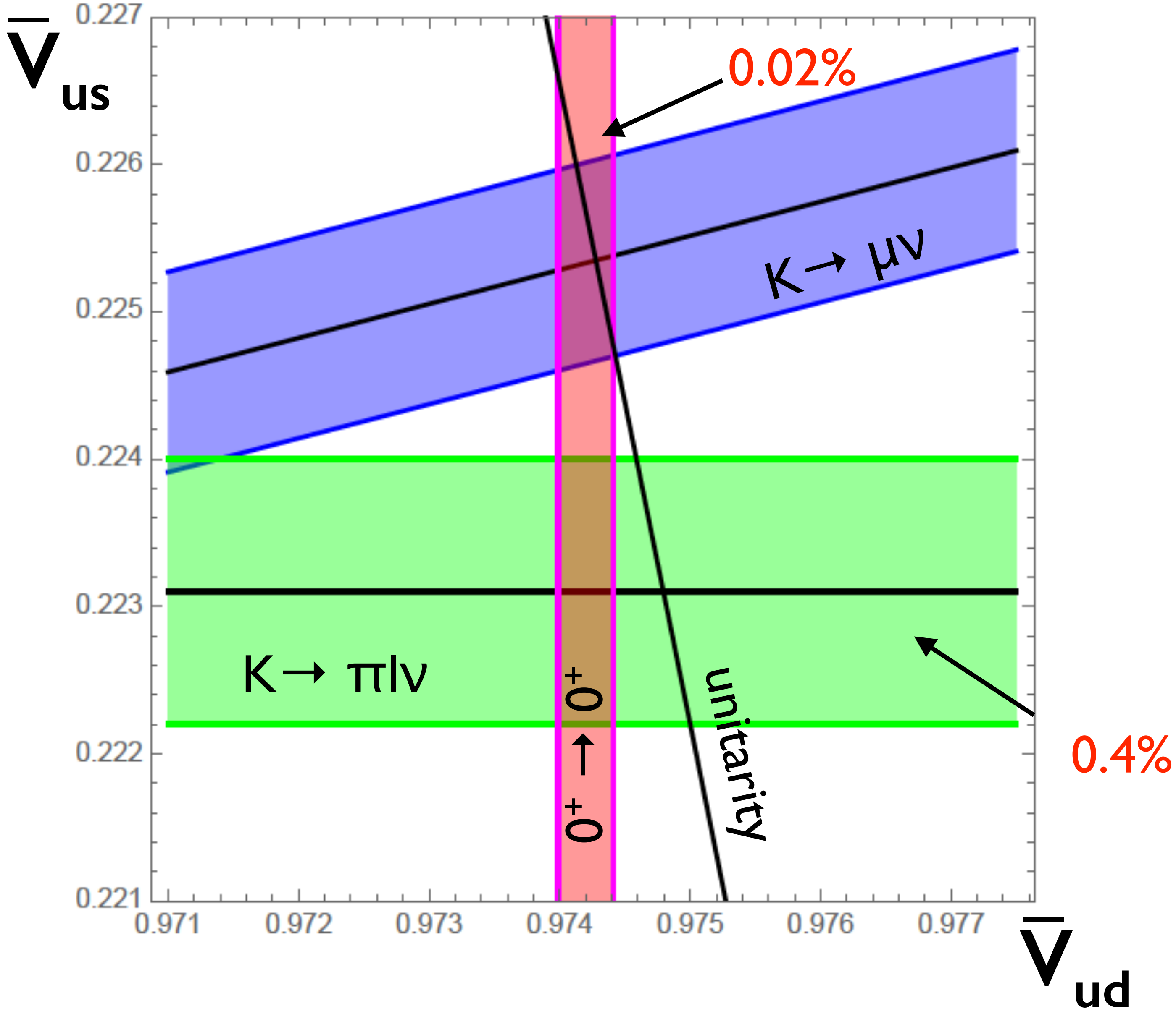
$\Delta_{\rm CKM}$ = - (4 ± 5) ∗ 10^{-4} ~ 1σ

$\Delta_{\rm CKM}$ = - (12 ± 6) ∗ 10^{-4} ~ 2σ

V_{us} from K→ πlν

Cabibbo universality test

$$\boxed{|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)}$$



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$\Delta_{\rm CKM}$ = - (12 ± 6) ∗ 10^{-4} ~ 2σ

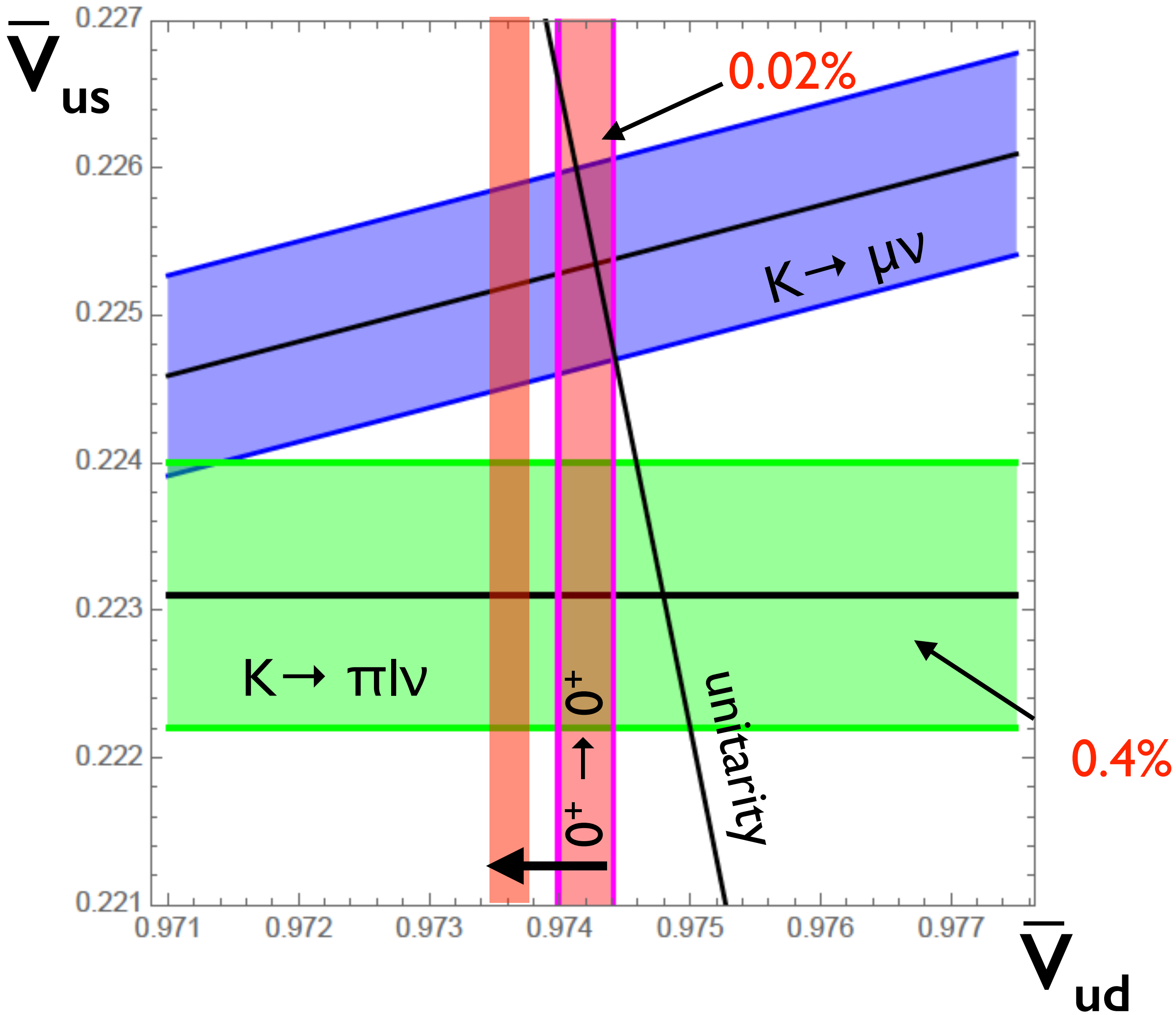
V_{us} from K→ πlν

Hint of something
[ε's ≠0] or SM theory input?

Worth a closer look:
at the level of the best LEP EW precision tests,
probing scale Λ~10 TeV

Cabibbo universality test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



V_{us} from K→ μν

$\Delta_{\rm CKM} = -(14 \pm 4) * 10^{-4}$ ~3.5σ

$\Delta_{\rm CKM} = -(22 \pm 5) * 10^{-4}$ ~4.5σ

V_{us} from K→ πlν

With new radiative corrections

[Seng et al. 1807.10197]

Impact of neutrons

- Independent extraction of V_{ud} @ 0.02% requires:

$\bar{g}_A = g_A \left(1 - 2\epsilon_R\right)$

$$\bar{V}_{ud} = \left[\frac{4908.6(1.9)\ s}{\tau_n\ \left(1 + 3\bar{g}_A^2\right)}\right]^{1/2}$$

Czarnecki, Marciano, Sirlin 1802.01804

$\delta\tau_n \sim 0.35$ s
$\delta\tau_n/\tau_n \sim 0.04$ %

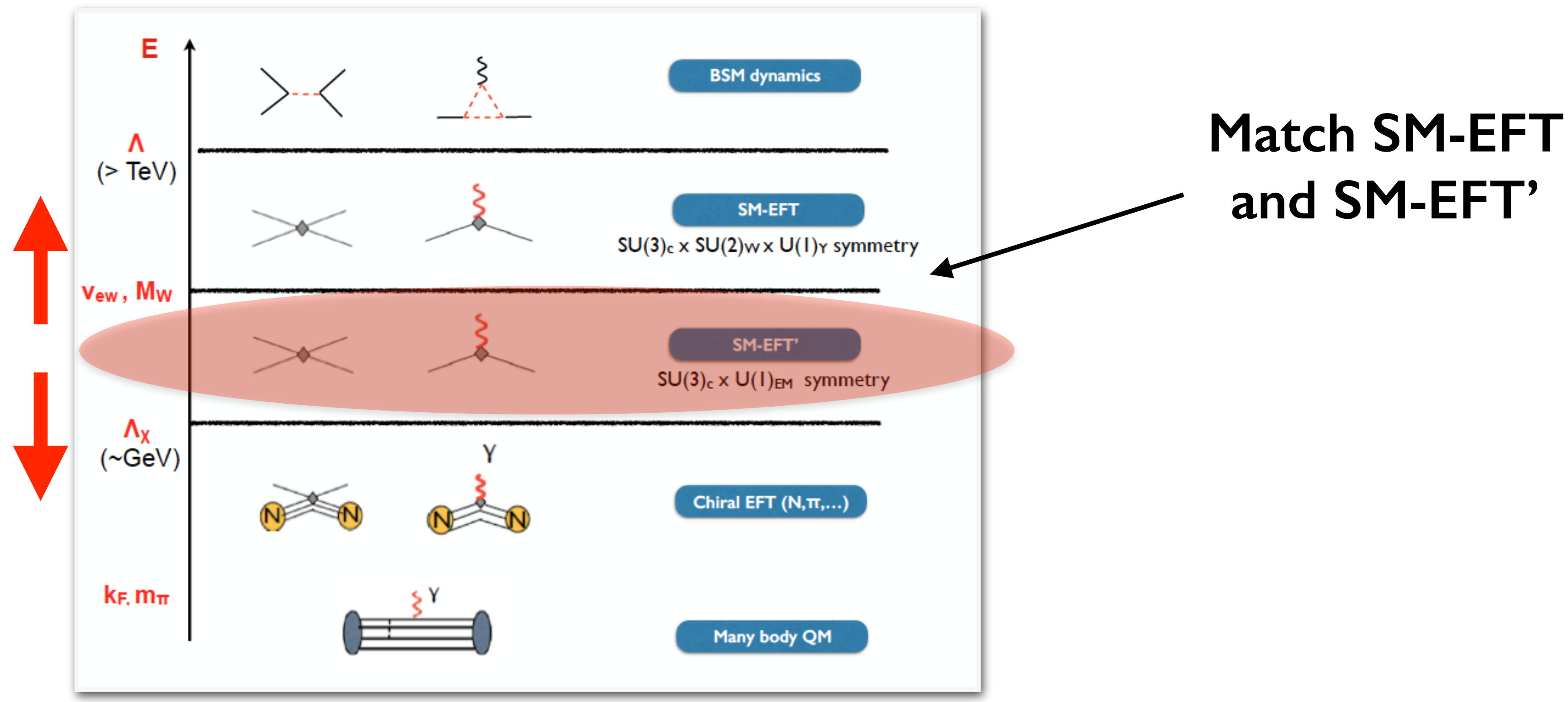
$\delta g_A/g_A \sim 0.15\% \rightarrow 0.03\%$
($\delta a/a$, $\delta A/A \sim 0.14\%$)

UCNτ @ LANL [$\tau_n \sim 877.7(7)(3)$s]
is almost there, will reach $\delta\tau_n \sim 0.2$ s
1707.01817

$\delta A/A < 0.2\%$ can be reached
by PERC, UCNA+
$\delta a/a \sim 0.1\%$ at Nab

Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α



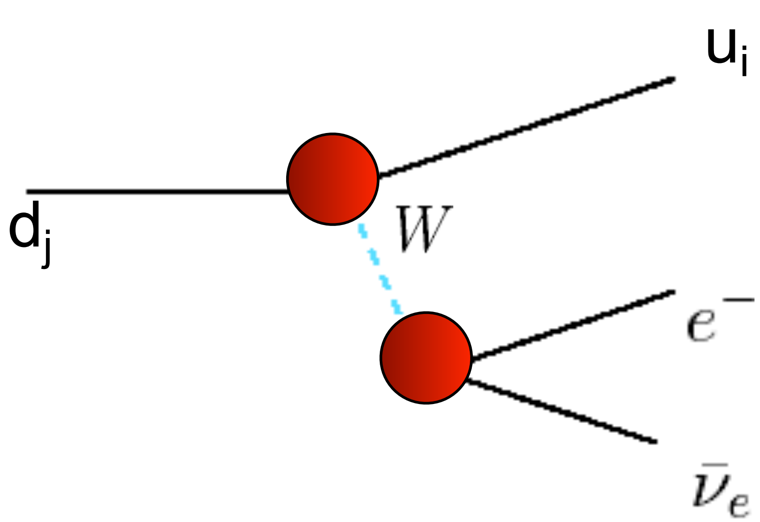
- Model-independent statements possible in <u>"heavy BSM" scenarios</u>: M_{BSM} > TeV → new physics looks point-like at collider

VC, Gonzalez-Alonso, Jenkins 0908.1754

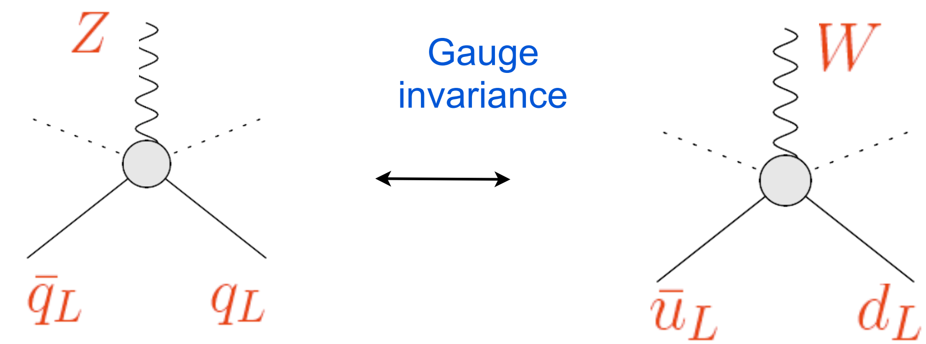
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

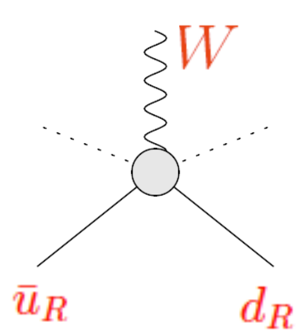
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\overline{q}\gamma_\mu \sigma^a q)$$



$$O_{\varphi\varphi} = i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d)$$



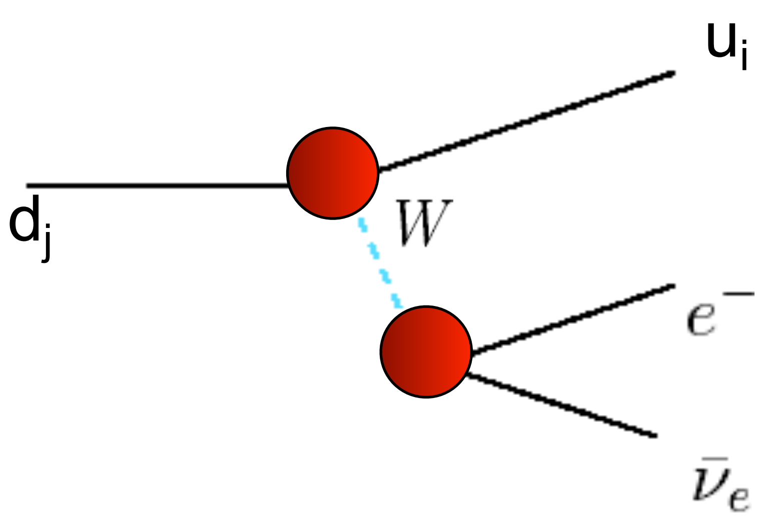
E.g. from W_L-W_R mixing in Left-Right symmetric models

VC, Gonzalez-Alonso, Jenkins 0908.1754

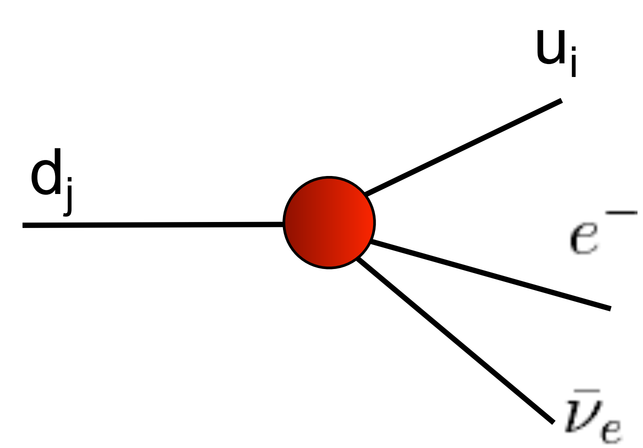
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



$\varepsilon_{S,P,T}$ and one contribution to ε_L arise from SU(2)xU(1) invariant 4-fermion operators



$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$

$$O_{qde} = (\bar{\ell}e)(\bar{d}q) + \text{h.c.}$$

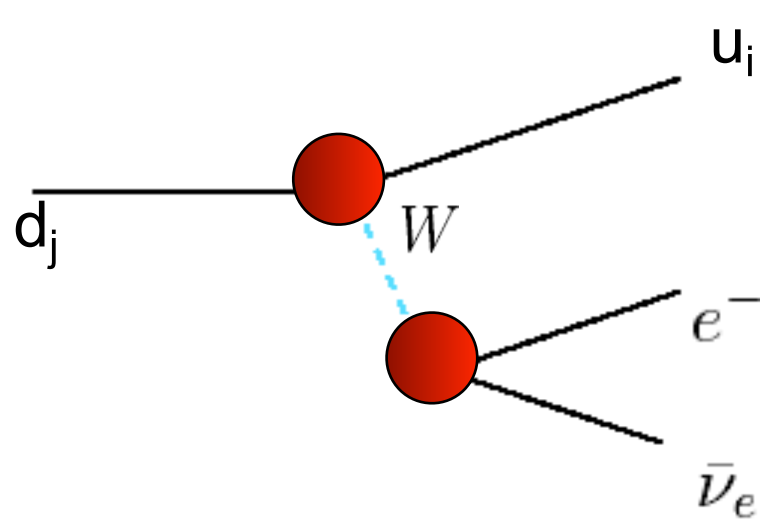
...

VC, Gonzalez-Alonso, Jenkins 0908.1754

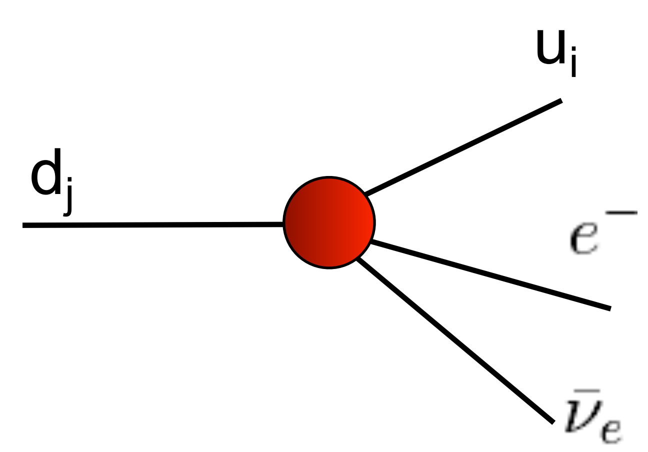
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



$\varepsilon_{S,P,T}$ and one contribution to ε_L arise from SU(2)xU(1) invariant 4-fermion operators

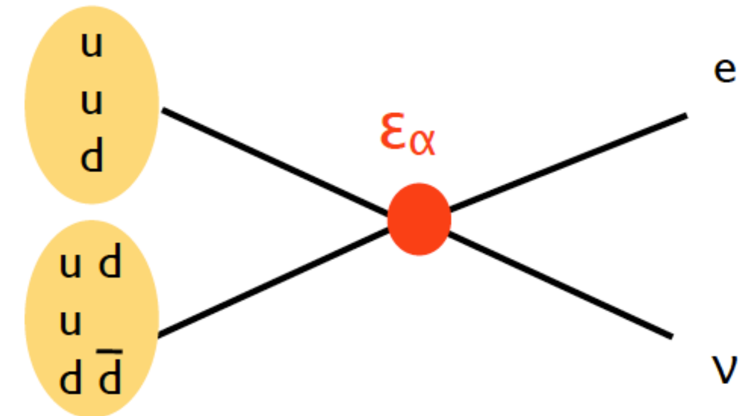


- LEP:
  - Strong constraints (<0.1%) on L-handed vertex corrections (Z-pole)
  - Weaker constraints on 4-fermion interactions (σ_{had})
- What about LHC?

LHC sensitivity: 4-fermions

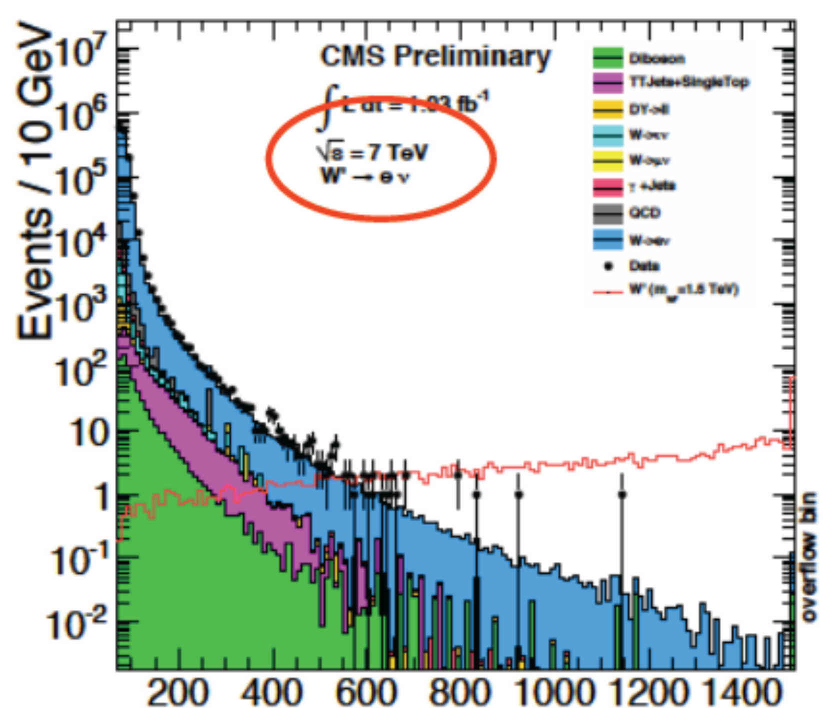
Bhattacharya et al., 1110.6448, VC, Graesser, Gonzalez-Alonso 1210.4553

- The effective couplings ε_α contribute to the process $pp \to e\nu + X$



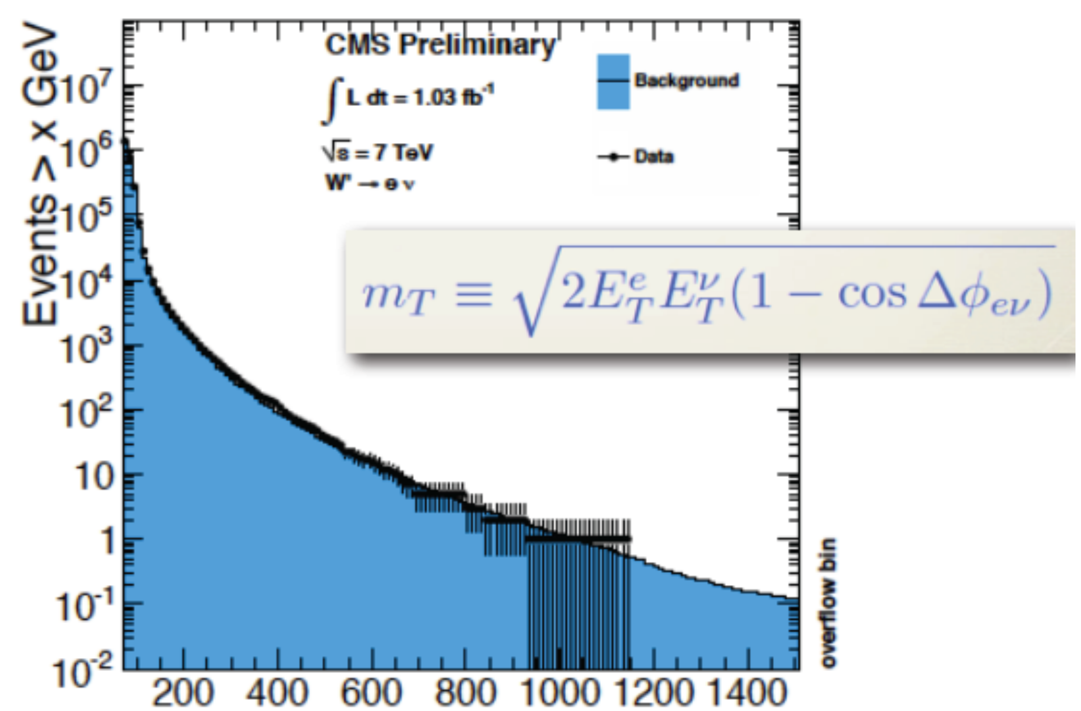
- No excess events in transverse mass distribution: bounds on ε_α

differential



m_T(GeV)

cumulative

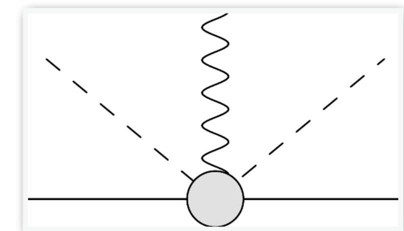


m_T(GeV)

LHC sensitivity: vertex corrections

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

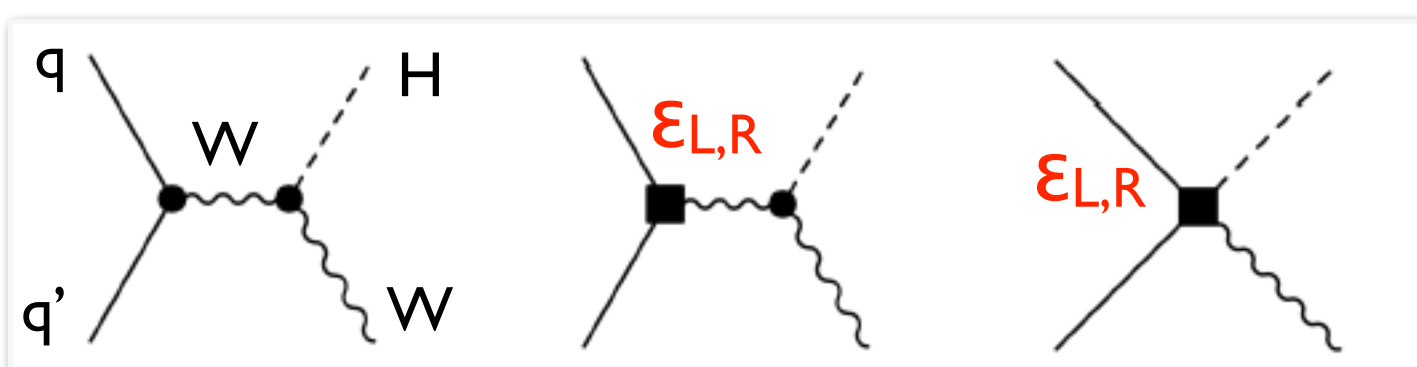
- Vertex corrections inducing $\varepsilon_{L,R}$ in the SM-EFT involve the Higgs field (due to SU(2) gauge invariance)



ε_L $\quad \varphi^\dagger \tau^a D_\mu \varphi \;\; \bar{q}_L \tau^a \gamma^\mu q_L$

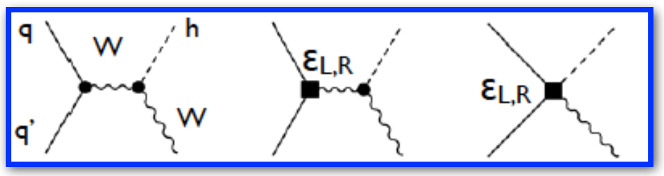
ε_R $\quad \varphi^T \epsilon D_\mu \varphi \;\; \bar{u}_R \gamma^\mu d_R$

- Can be probed at the LHC by associated Higgs + W production

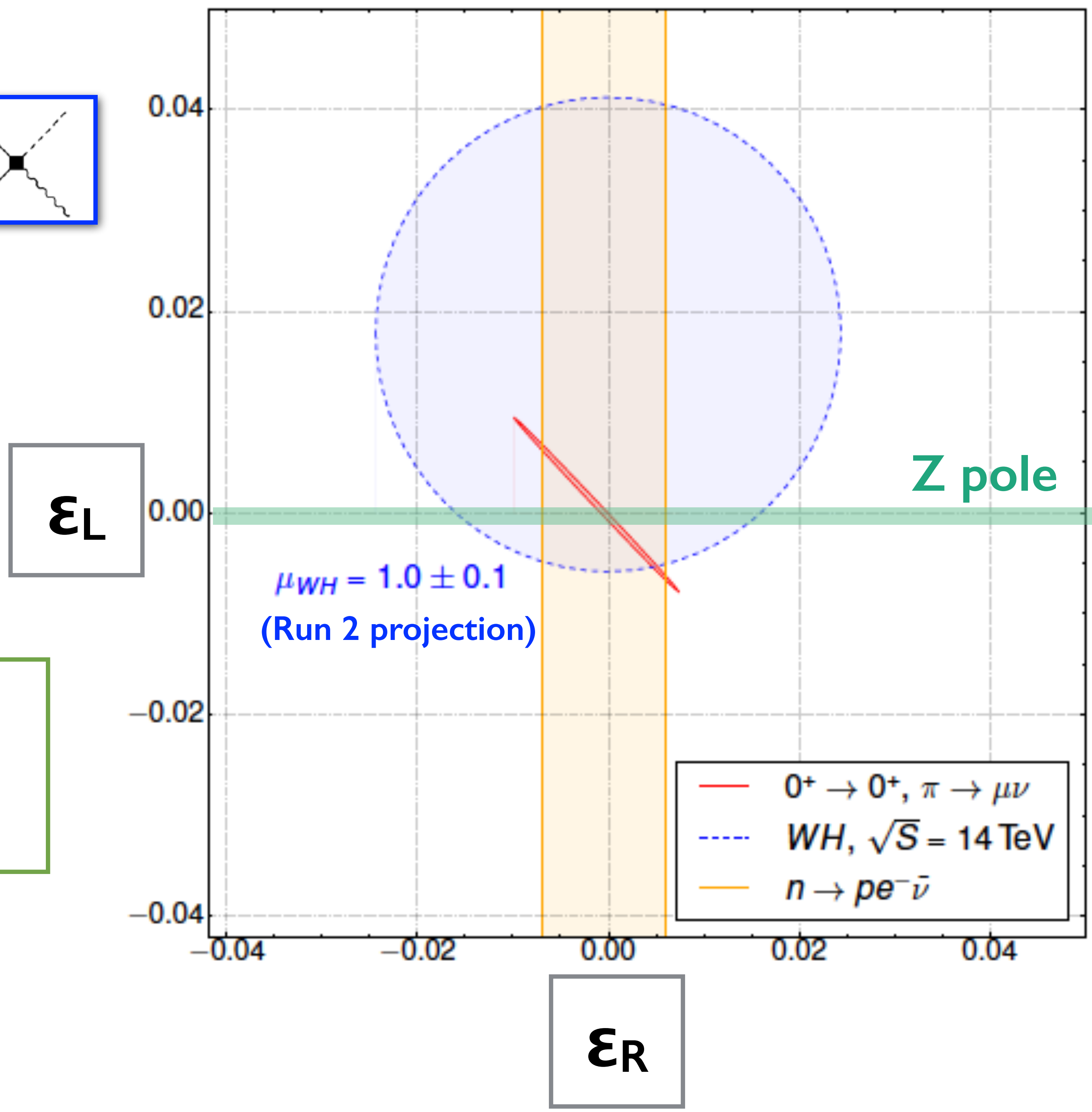


Example 1: ε_L and ε_R couplings

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751



90%CL, assumes only two operators at high scale



Z-pole → $\varepsilon_L^{(\nu)}$
Falkowski et al
1706.03783

Neutron decay:
$\lambda = g_A\,(1 - 2\,\varepsilon_R)$

Constraint on ε_R uses
$g_A = 1.271(13)$
(CalLat 1805.12030)

$\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$

$\delta\Gamma_{(\pi\to\mu\nu)} \propto \varepsilon_L - \varepsilon_R$
[f_π from LQCD]

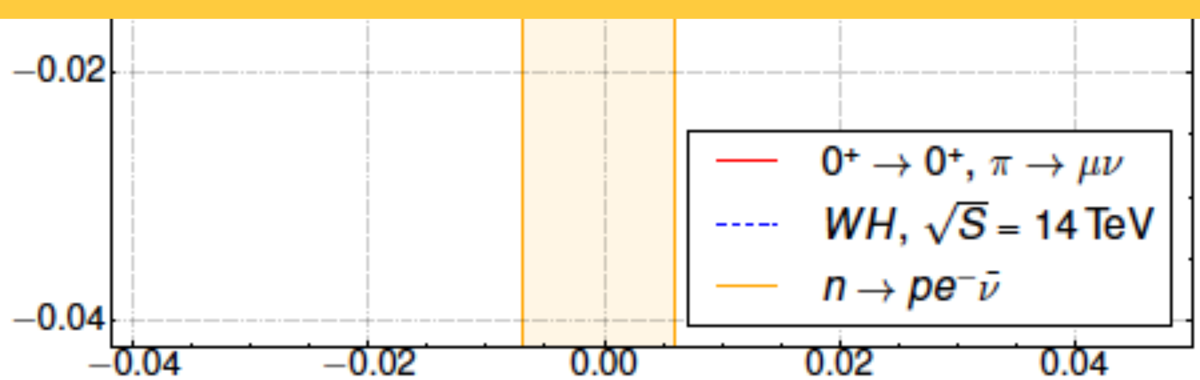
Example 1: ε_L and ε_R couplings

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

Several lessons:

- Beta decays can be quite competitive with collider
- Connection between CC and NC (gauge invariance!)
- Caveat: going beyond a 2-operator analysis relaxes some of these constraints (but not the one on ε_R from λ)
- All in all, beta decays provide *independent competitive constraints* in a global analysis

Z-pole → $\varepsilon_L^{(v)}$
Falkowski et al
1706.03783



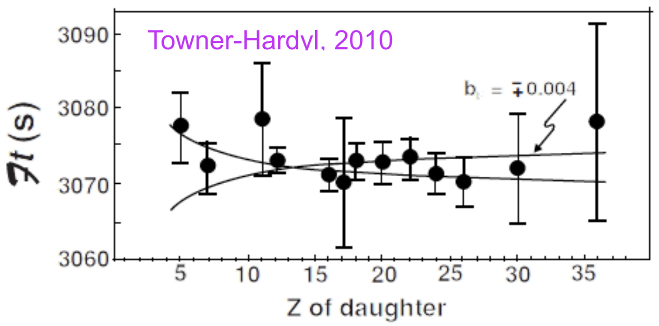
ε_R

$\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$

$\delta\Gamma_{(\pi\to\mu\nu)} \propto \varepsilon_L - \varepsilon_R$
[f_π from LQCD]

Example 2: ε_S and ε_T couplings

$0^+ \to 0^+$ (b_F)



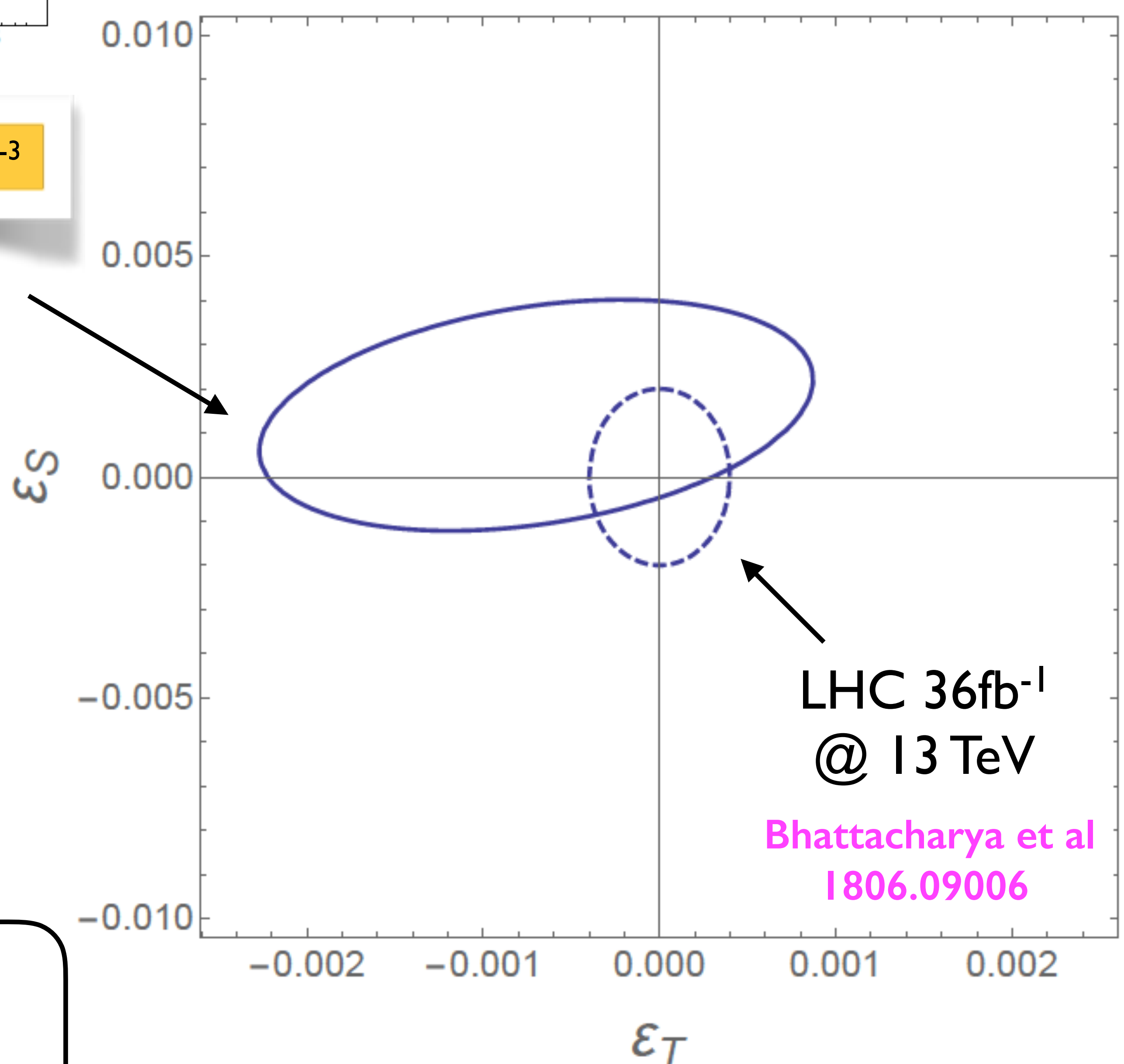
$-1.0\times10^{-3} < g_S\, \varepsilon_S < 3.2\times10^{-3}$

Current low-E data: dominated by $0^+\to 0^+$, $\tau(n)$, $A(n)$

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

CURRENT

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



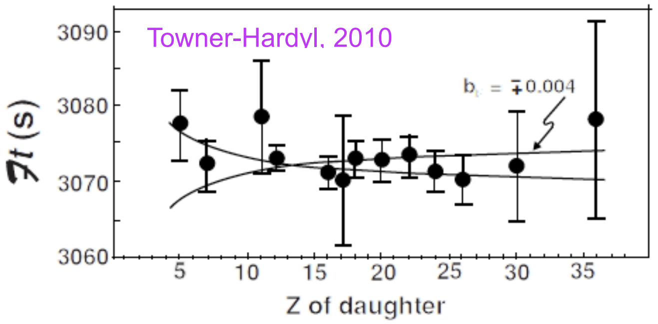
g_S =1.01(10)

g_T =0.99(4)

Bhattacharya et al (PNDME) 1806.09006

Example 2: ε_S and ε_T couplings

$0^+ \to 0^+$ (b_F)



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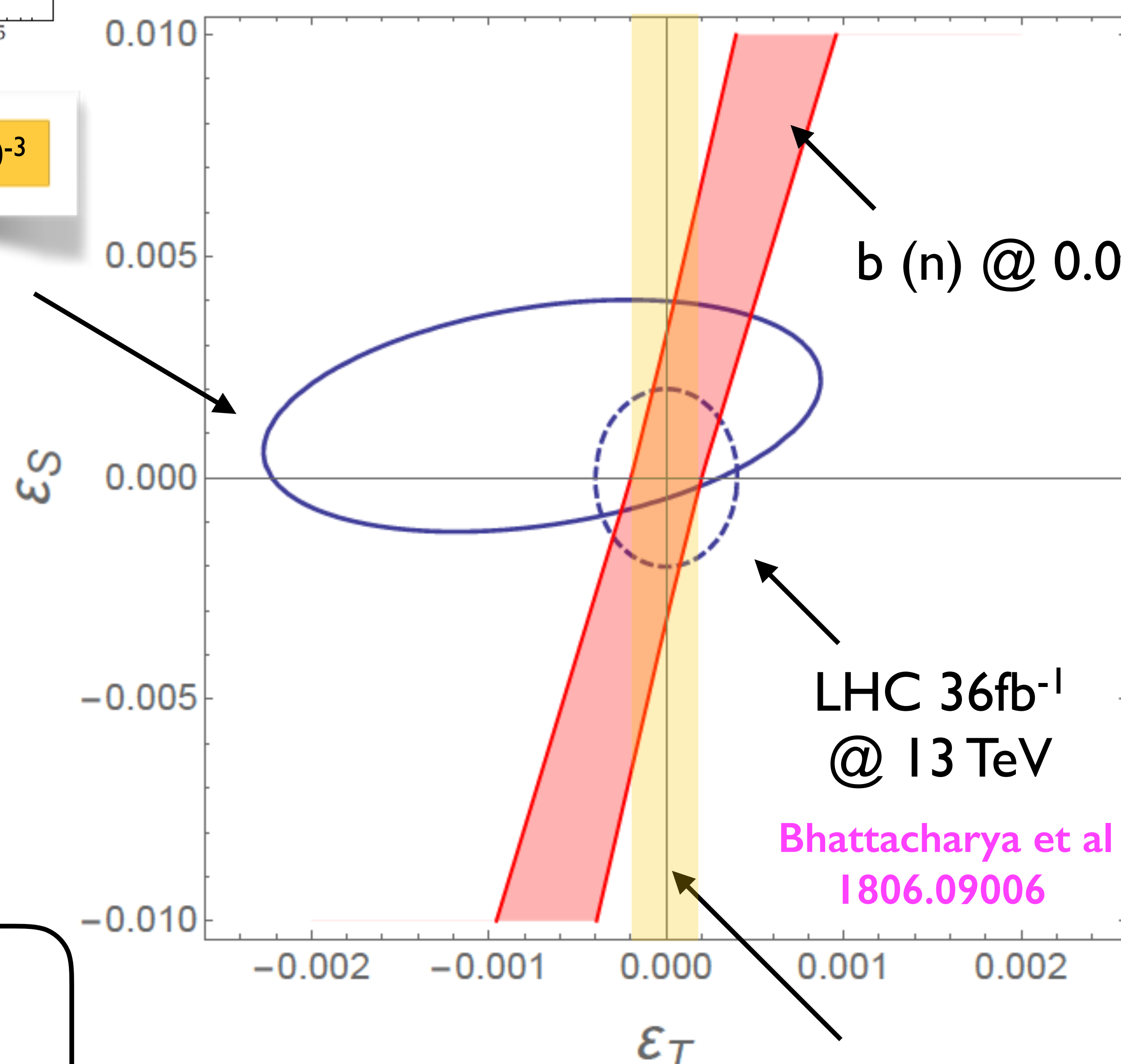
$g_S = 1.01(10)$

$g_T = 0.99(4)$

Bhattacharya et al (PNDME) 1806.09006

FUTURE

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



b (n) @ 0.001

LHC 36fb^{-1} @ 13 TeV

Bhattacharya et al 1806.09006

b (^{6}He) @ 0.001

LHC puts very strong constraints on 4-fermion interactions

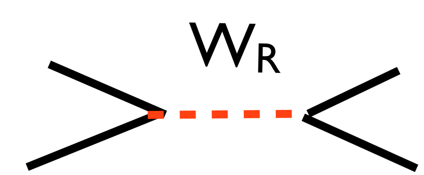
Prospective beta decay measurements competitive, probing $\Lambda_{S,T} \sim$ 5-10 TeV

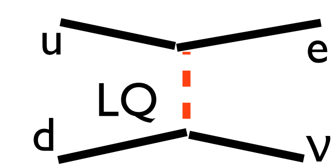
Beta decays in specific models

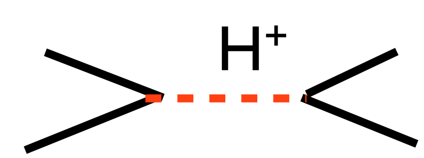
- Model → set overall size and pattern of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture: "DNA matrix"

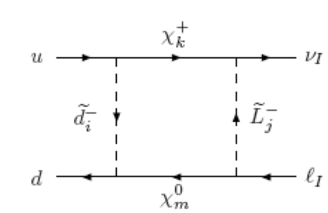
Can be made quantitative, including LHC constraints on each model

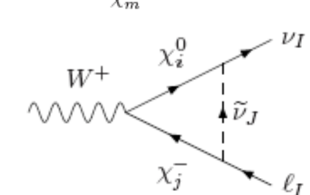
	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓
YOUR FAVORITE MODEL	…		…		









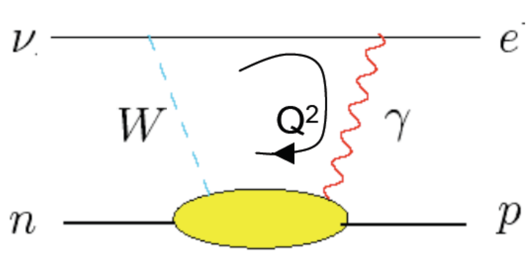


Summary

- β decays with sufficient th. and expt. precision ($< 0.1\%$) remain a very competitive probe of new physics
- Discovery potential depends on the underlying model. However, for heavy mediators, EFT shows that a discovery window exists well into the LHC era (simple examples: ε_L-ε_R and ε_S-ε_T plots)
- Beta decays play unique role in probing vertex corrections ε_L-ε_R (not enough precision at the LHC)
- Beta decays can be competitive probes of scalar and tensor interactions if precision reaches $< 0.1\%$

Outlook

- The next frontier in beta decays will likely include
  - Experiment:
    - $\delta\tau_n \sim 0.1$s
    - <0.1% precision in decay correlation coefficients
  - Theory:
    - g_A at sub-percent level from LQCD
    - Radiative corrections: improved data for dispersive method and lattice QCD analysis



Backup

Summary table

- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV (Λ_{SM} ≈ 0.2 TeV)

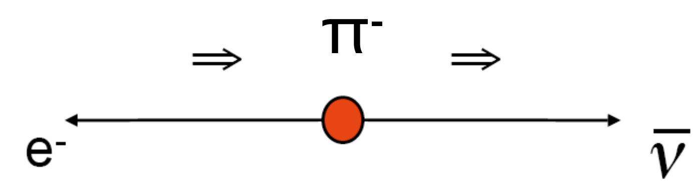
$$\tilde{Y}(E_e) = \frac{Y(E_e)}{1 + b m_e/E_e + \ldots}$$

Non-standard coupling	Observable	Current sensitivity	Prospective sensitivity
$\mathrm{Re}(\epsilon_L + \epsilon_R)$	Δ_{CKM}	$\sim 0.05\%$	$< 0.05\%$ *
$\mathrm{Im}(\epsilon_R)$	D_n	$\sim 0.05\%$	
$\epsilon_P, \quad \tilde{\epsilon}_P$	$R_\pi = \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)}$	$\sim 0.05\%$	
$\mathrm{Re}(\epsilon_S)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}]$	$\sim 0.5\%$	$< 0.3\%$
$\mathrm{Im}(\epsilon_S)$	R_n	$\sim 10\%$	
$\mathrm{Re}(\epsilon_T)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}], \quad \pi \to e\nu\gamma$	$\sim 0.1\%$	$< 0.03\%$
$\mathrm{Im}(\epsilon_T)$	$R_{^8Li}$	$\sim 0.2\%$	$\sim 0.05\%$
$\tilde{\epsilon}_{\alpha\neq P}$	a, b, B, A	$\sim 5 - 10\%$	

VC, S.Gardner, B.Holstein 1303.6953
Gonzalez-Alonso & Naviliat-Cuncic 1304.1759
Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

$R_\pi = \Gamma(\pi \to e\nu[\gamma])/\Gamma(\pi \to \mu\nu[\gamma])$

- Helicity suppressed in the SM (V-A)



- Predicted very precisely in the SM (0.01%): $R_\pi = 1.2352(1) \times 10^{-4}$

Marciano-Sirlin 93 VC-Rosell '07

- Experiment: $R_\pi = 1.2300(40) \times 10^{-4}$ will go down to 0.05% level

TRIUMF and PSI

- This ratio probes a whole set of ε_P couplings (ν flavor not observed)

$$\boxed{\mathcal{L}_{\rm eff} \supset \frac{G_F}{\sqrt{2}} V_{ud}\, \epsilon_P^{\alpha\beta}\, \bar{e}_\alpha (1-\gamma_5)\nu_\beta \cdot \bar{u}\gamma_5 d}$$

$\alpha = e, \mu$
$\beta = e, \mu, \tau$

- Neglecting non-enhanced ε_L-ε_R terms:

$$\boxed{\frac{R_\pi}{R_\pi^{SM}} = \frac{\left[\left(1-\frac{B_0}{m_e}\epsilon_P^{ee}\right)^2 + \left(\frac{B_0}{m_e}\epsilon_P^{e\mu}\right)^2 + \left(\frac{B_0}{m_e}\epsilon_P^{e\tau}\right)^2\right]}{\left[\left(1-\frac{B_0}{m_\mu}\epsilon_P^{\mu\mu}\right)^2 + \left(\frac{B_0}{m_\mu}\epsilon_P^{\mu e}\right)^2 + \left(\frac{B_0}{m_\mu}\epsilon_P^{\mu\tau}\right)^2\right]}}$$

$$B_0(\mu) \equiv \frac{M_\pi^2}{m_u(\mu)+m_d(\mu)}$$

$$B_0/m_e = 3.6 \times 10^3;$$

- No constraint if

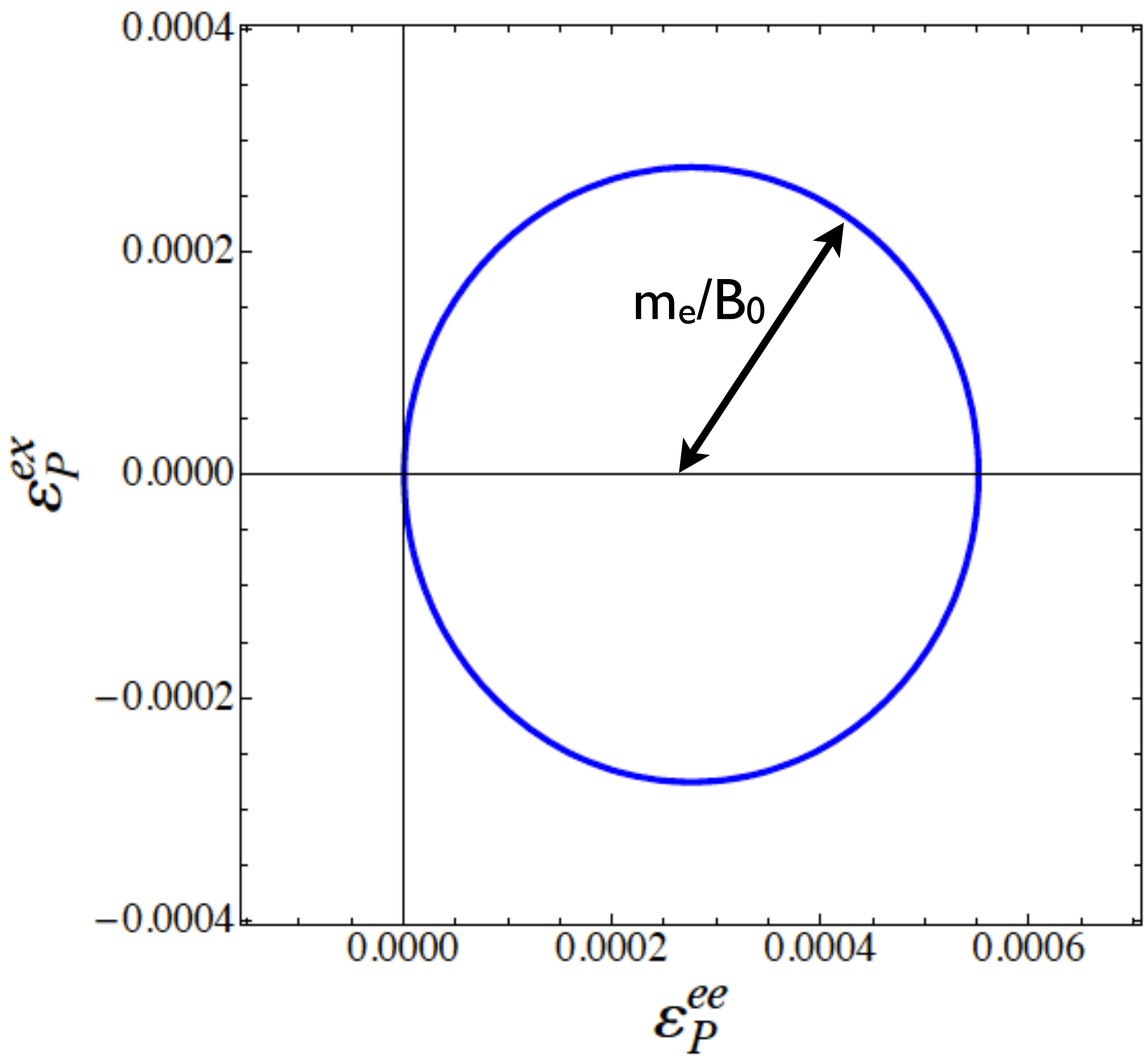
$$\epsilon_P^{e\alpha}/m_e = \epsilon_P^{\mu\alpha}/m_\mu;$$

- Assume all ε_P of similar size (neglect m_e/m_μ)

- Allowed region is an annulus of thickness 1.38×10^{-6}

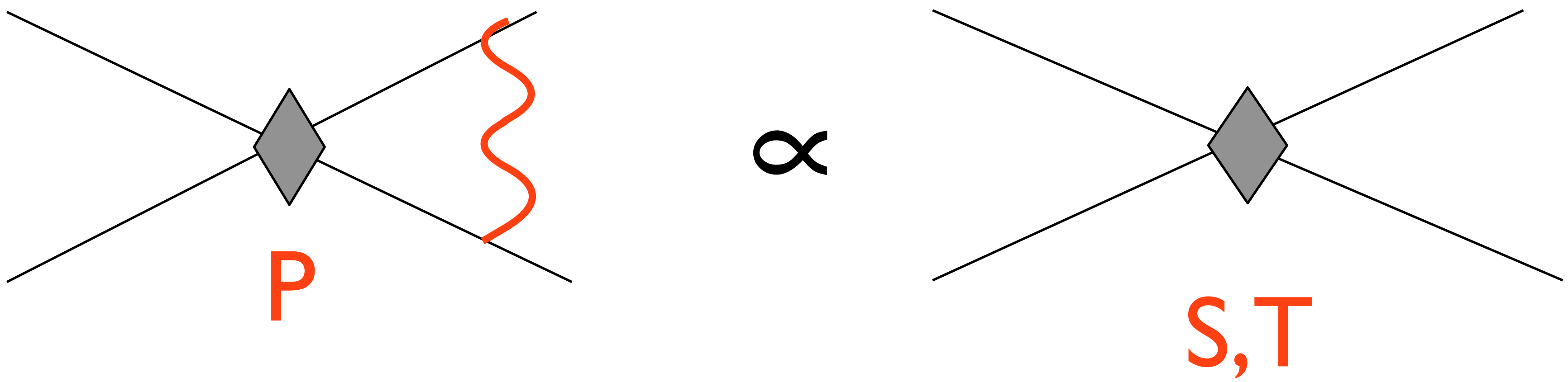
- Marginalize wrt ε_P^{ex}

$$\boxed{-1.4\times 10^{-7} < \epsilon_P^{ee} < 5.5\times 10^{-4};}$$



- Constraint on $\varepsilon_{S,T}$ via EW radiative corrections: P operator, generated at high scale Λ, induces S and T operators at low scale μ

Voloshin '92
Campbell-Maybury '05
Herczeg 95



$$\boxed{\frac{-1.4\times 10^{-7}}{\log(\Lambda/\mu)} < \gamma_{SP}\,\epsilon_S + \gamma_{TP}\,\epsilon_T < \frac{5.5\times 10^{-4}}{\log(\Lambda/\mu)}}$$

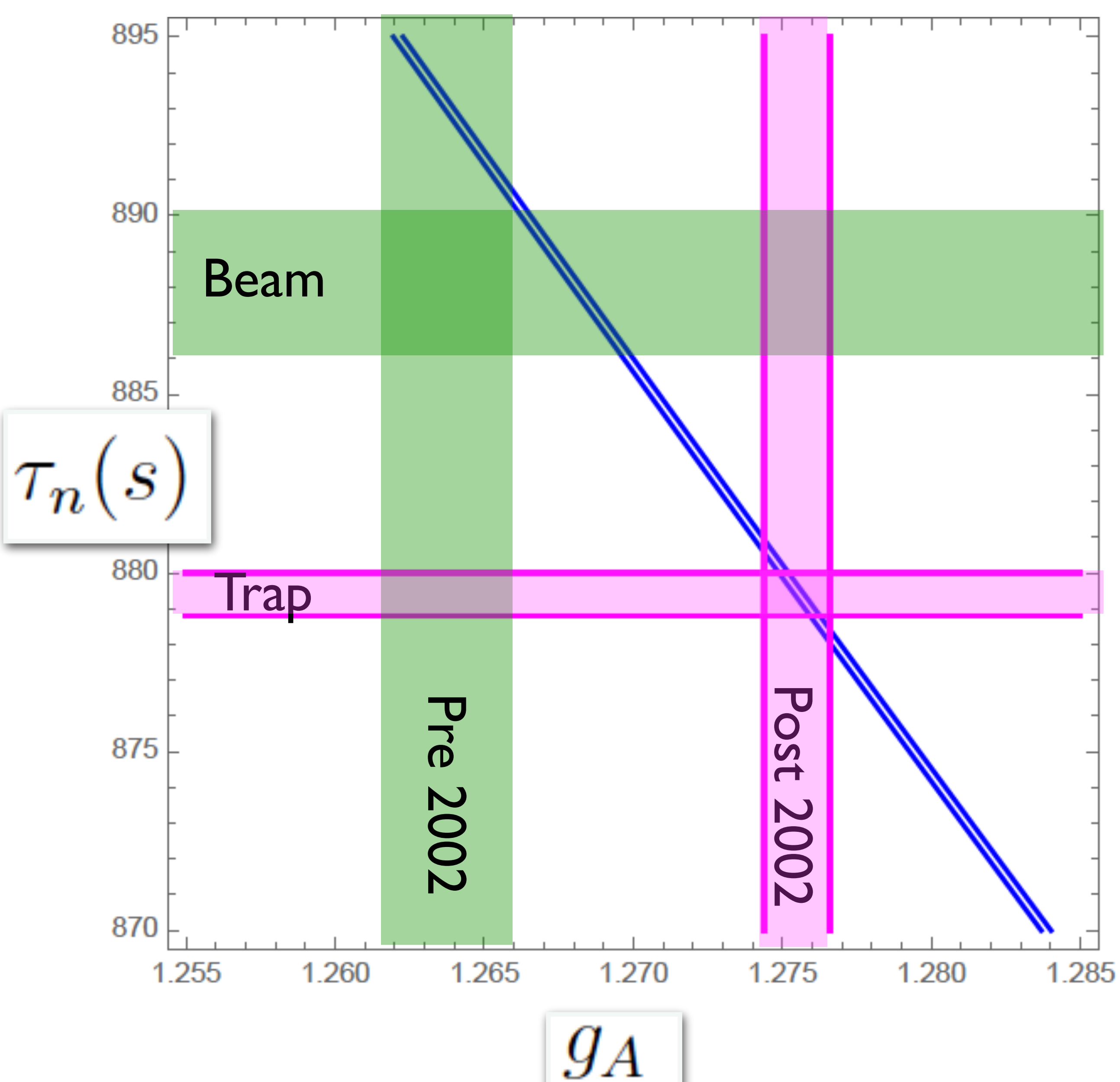
$$\gamma_{SP} = \frac{15}{72}\frac{\alpha_1}{\pi} \approx 6.7\times 10^{-4}$$
$$\gamma_{TP} = -\frac{9}{2}\frac{\alpha_2}{\pi} - \frac{15}{2}\frac{\alpha_1}{\pi} \approx -7.3\times 10^{-2}$$

- With $\log(\Lambda/\mu) \sim 10$, $|\varepsilon_S| < 8\times 10^{-2}$ and $|\varepsilon_T| < 10^{-3}$

Standard Model analysis

- ε_α=0 and take V_{ud} from $0^+ \rightarrow 0^+$: $\boxed{\tau_n(1+3g_A^2) = 5172.0(1.1)\mathrm{s}}$

Czarnecki, Marciano, Sirlin 1802.01804



- UCN lifetime and post-2002 g_A consistent with SM (blue line) ⇒
- "favored values" within the SM
- if confirmed, will put tightest constraints on BSM interactions

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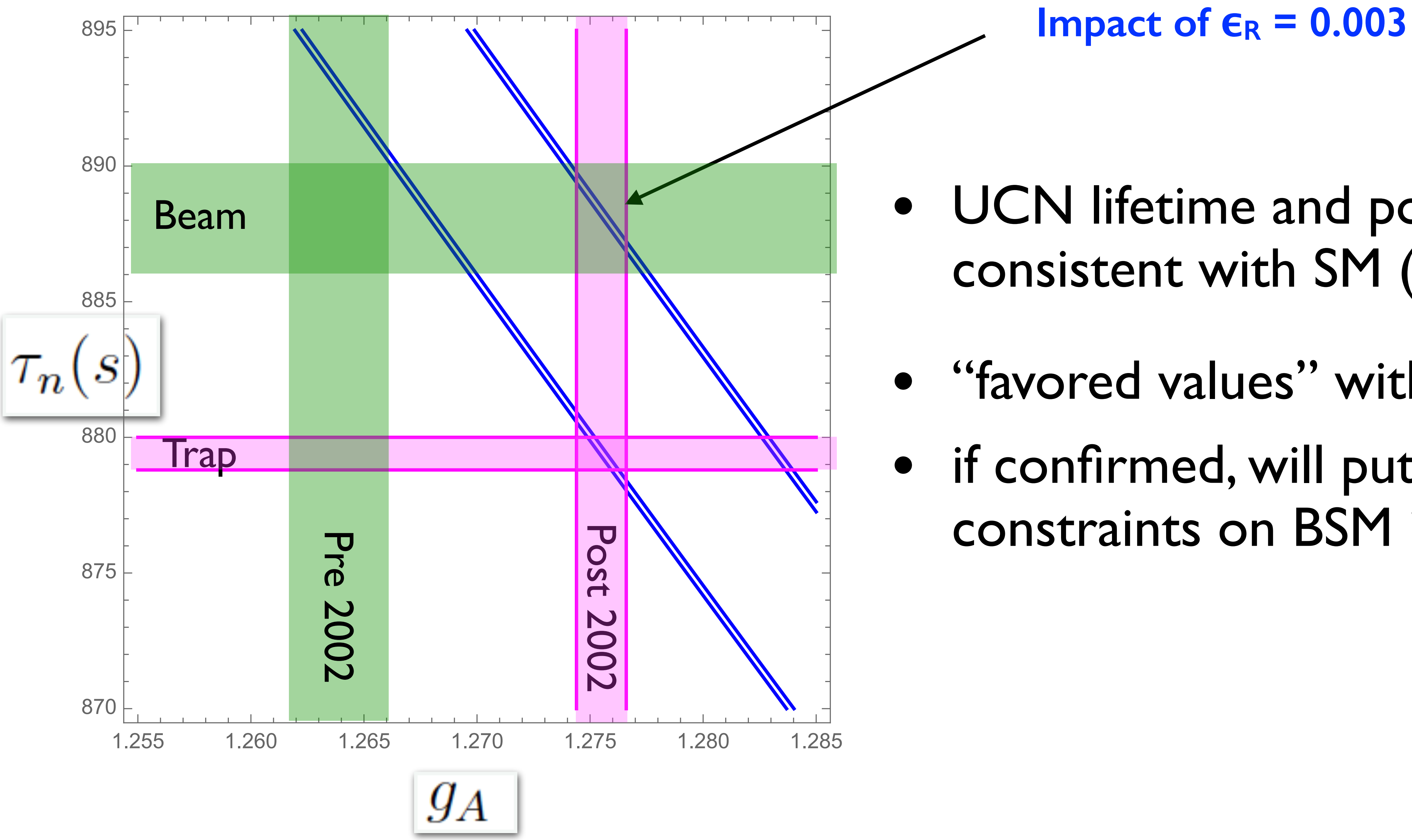

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- "favored values" within the SM
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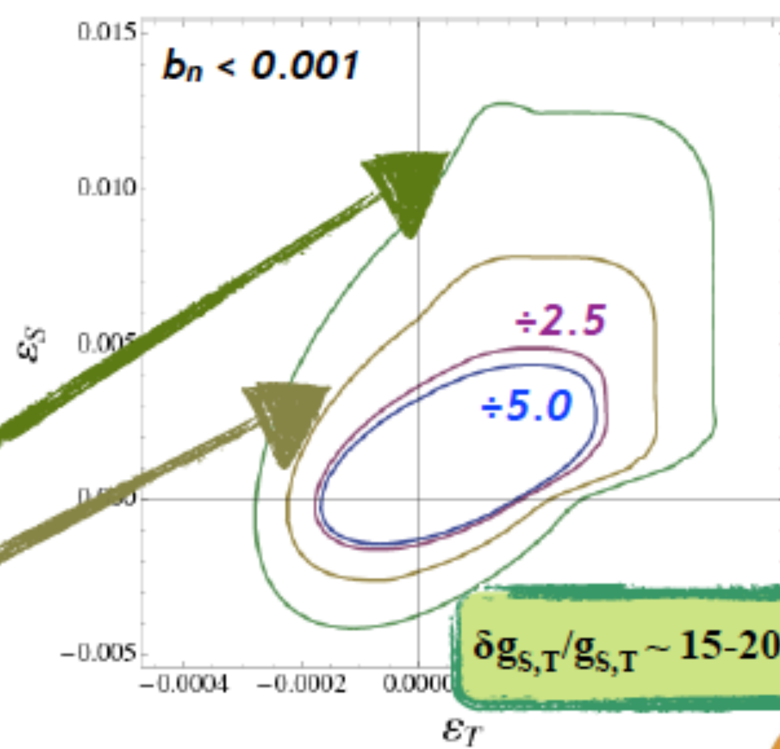
Status of scalar and tensor charges

From hadrons to quarks

$$C_V \sim g_V V_{ud}\,(1 + \mathrm{NP})\,(1 + \mathrm{RC})$$
$$C_A/C_V \sim -g_A/g_V\,(1 - \epsilon_R)$$
$$C_S \sim g_S \epsilon_S$$
$$C_T \sim g_T \epsilon_T$$

Scalar & tensor charges

	$\langle p\vert\bar{u}d\vert n\rangle$	$\langle p\vert\bar{u}\sigma_{\mu\nu}\gamma_5 d\vert n\rangle$
	g_S	g_T
Adler et al. '1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35)
LHPC 2012	1.08(32)	1.04(02)
RQCD 2014	1.02(35)	1.01(02)
PNDME 2013/15	0.72(32)	1.02(08)
ETMC 2015/17	0.93(33)	1.00(03)
CVC	1.02(11)	
PNDME 2016/18	1.02(10)	0.99(03)
JLQCD'18	0.88(11)	1.08(10)



$\delta g_{S,T}/g_{S,T} \sim$ 15-20%

$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u}\, g_V$$

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

g_S = 1.00(8) using (m_d - m_u) from 1802.04248 [FermiLab/MILC/TUMQCD]

Martin Gonzalez-Alonso

V_{ud} from $0^+ \to 0^+$ nuclear decays

- V_{ud} from $0^+ \to 0^+$ nuclear β decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\,(1+RC) \longrightarrow f\,t\,(1+RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

$$(1+RC) = (1-\delta_C)\,(1+\delta_R)\,(1+\Delta_C)$$

$$\langle f|\tau_+|i\rangle = \sqrt{2}\,(1-\delta_C/2)$$

Coulomb distortion
of wave-functions

$$\delta_C \sim 0.5\%$$

Towner-Hardy
Ormand-Brown

Ab initio methods?

Nucleus-dependent
rad. corr.
(Z, E^{max} ,nuclear structure)

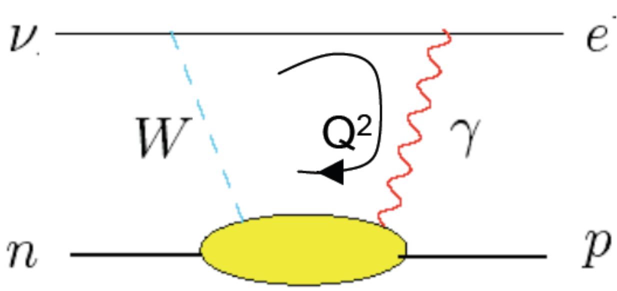
$$\delta_R \sim 1.5\%$$

Sirlin-Zucchini ‘86
Jaus-Rasche ‘87

Nucleus-independent
short distance rad. corr.

Δ_R =2.36(4)%

Marciano-Sirlin ‘06

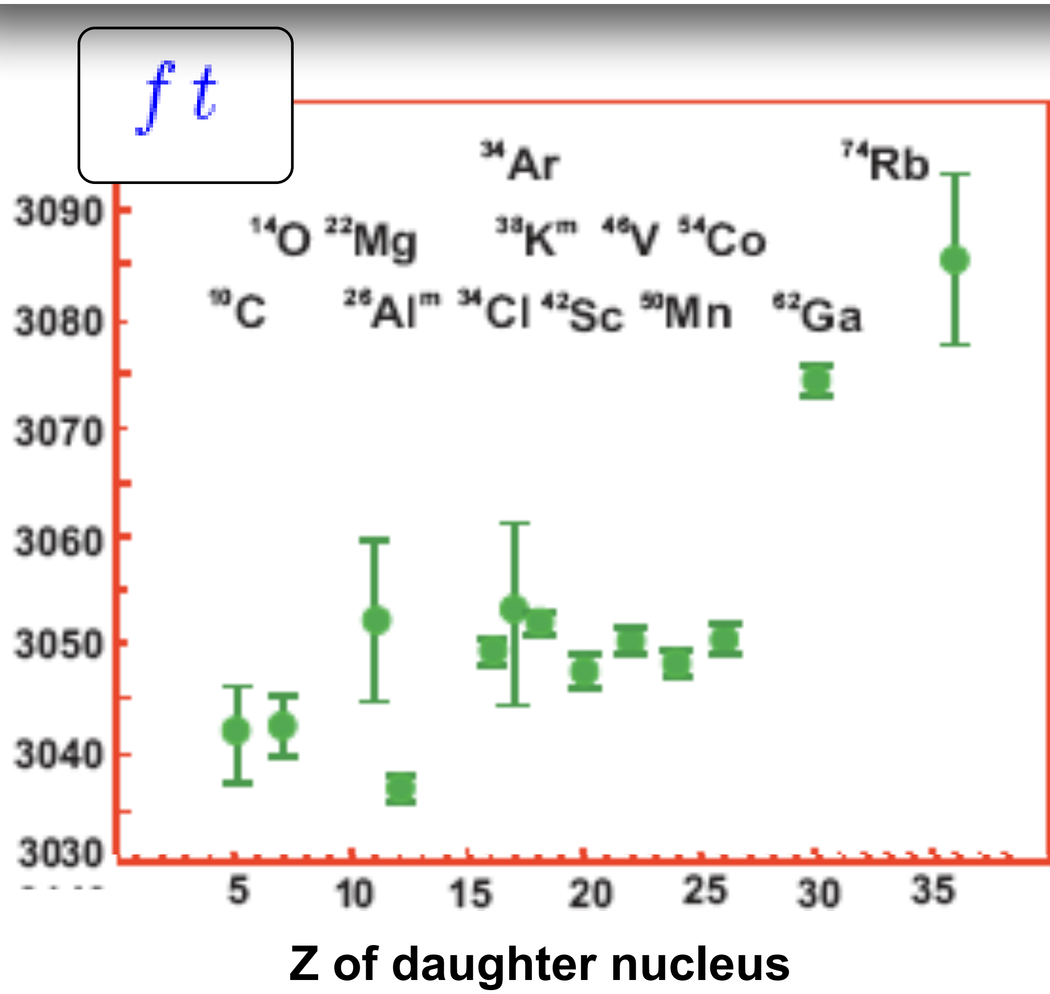


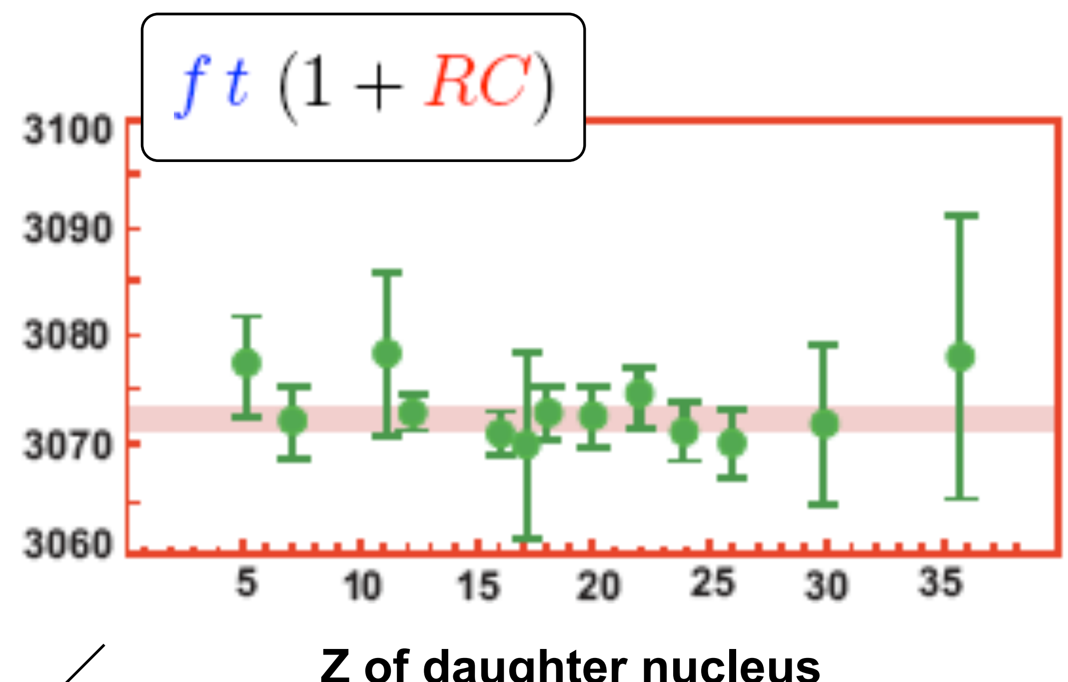
Further improvements with
dispersion relations, Lattice QCD?

V_{ud} from $0^+ \to 0^+$ nuclear decays

- V_{ud} from $0^+ \to 0^+$ nuclear β decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\,(1 + RC) \longrightarrow f\,t\,(1+RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$





V_{ud} = 0.97417 (21)

Hardy-Towner 1411.5987

V_{us} from K decays

$K \rightarrow \pi l \nu$

$$\langle \pi | V_\mu | K \rangle \propto f_+(0)(p_K + p_\pi)_\mu + \dots$$

$$V_\mu = \bar{s}\gamma_\mu u$$

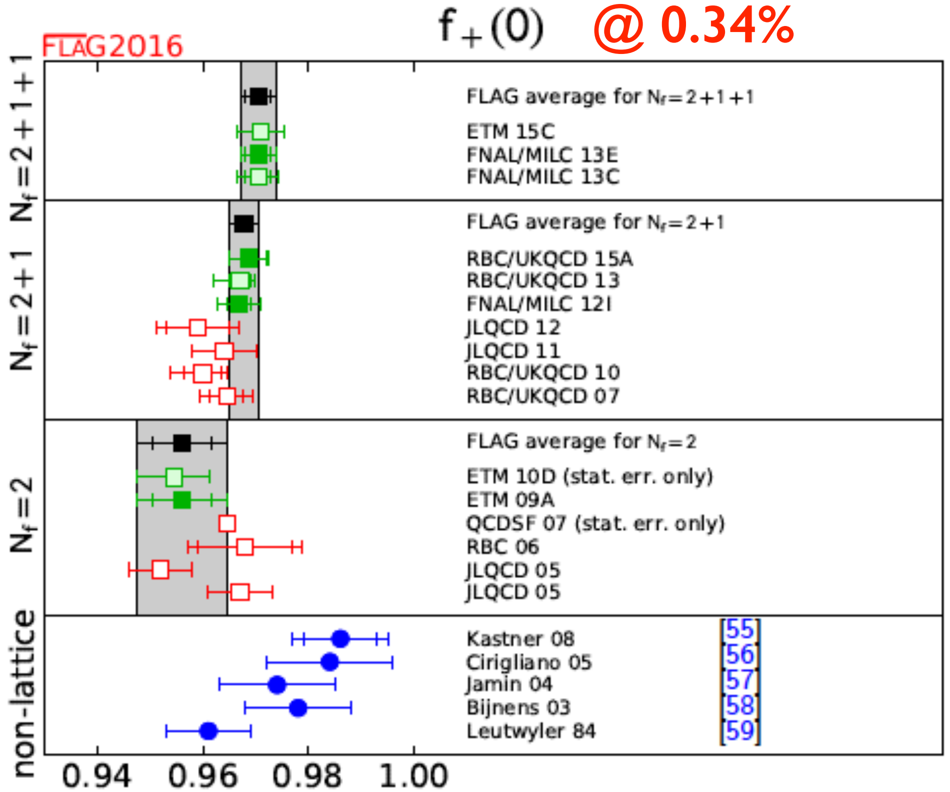
$K \rightarrow \mu\nu$ vs $\pi \rightarrow \mu\nu$

$$\langle 0 | A_\mu | K \rangle \propto F_K (p_K)_\mu$$

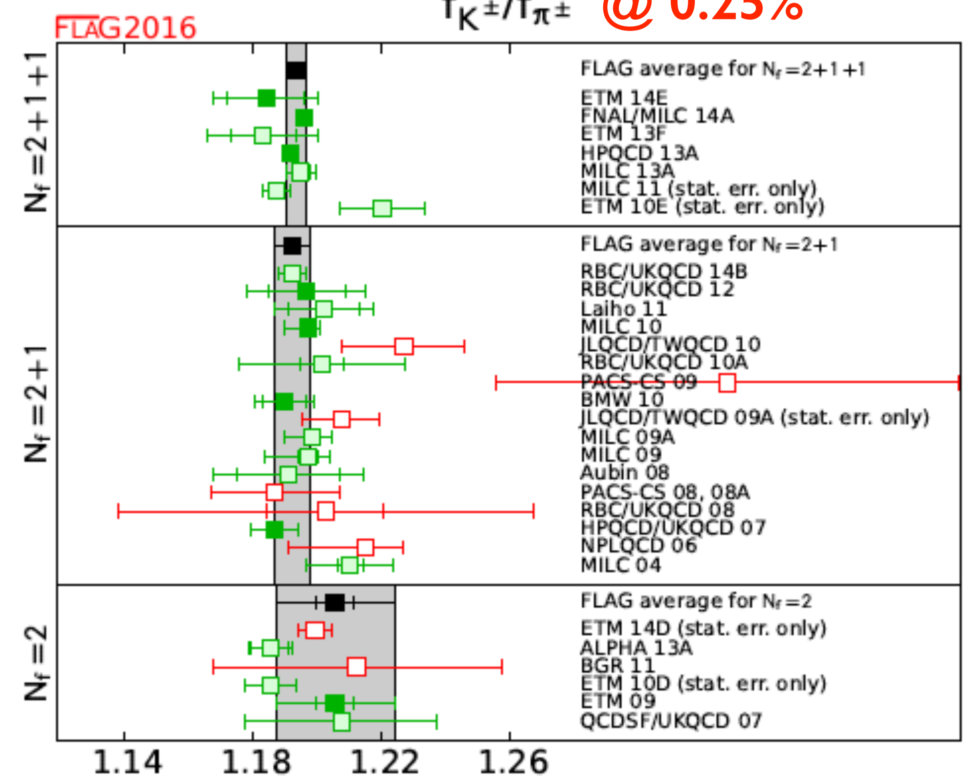
$$A_\mu = \bar{s}\gamma_\mu\gamma_5 u$$

- Lattice QCD calculations (summaries from FLAG 2016)

$f_+(0)$ @ 0.34%



$f_{K^\pm}/f_{\pi^\pm}$ @ 0.25%



V_{us} from K decays

$K \to \pi l \nu$

$$\langle \pi | V_\mu | K \rangle \propto f_+(0)(p_K + p_\pi)_\mu + \ldots$$
$$V_\mu = \bar{s}\gamma_\mu u$$

$K \to \mu\nu$ vs $\pi \to \mu\nu$

$$\langle 0 | A_\mu | K \rangle \propto F_K (p_K)_\mu$$
$$A_\mu = \bar{s}\gamma_\mu \gamma_5 u$$

- Lattice QCD calculations

$f_+^{K\to\pi}(0) = 0.959(5) \to 0.970(3)$
$V_{us} = 0.2254(13) \to 0.2231(9)$

$m_\pi \to m_\pi^{phys}$, $a \to 0$, dynamical charm

$F_K/F_\pi = 1.1960(25)$ [stable]
$V_{us} / V_{ud} = 0.2313(7)$

FLAG 2016 1607.00299 and refs therein

- Radiative corrections computed to $O(e^2p^2)$ in ChPT

VC, H. Neufeld 1107.6001
VC, M. Giannotti, H. Neufeld 0807.4507

- World data: FLAVIANET report 1005.2323 and refs therein