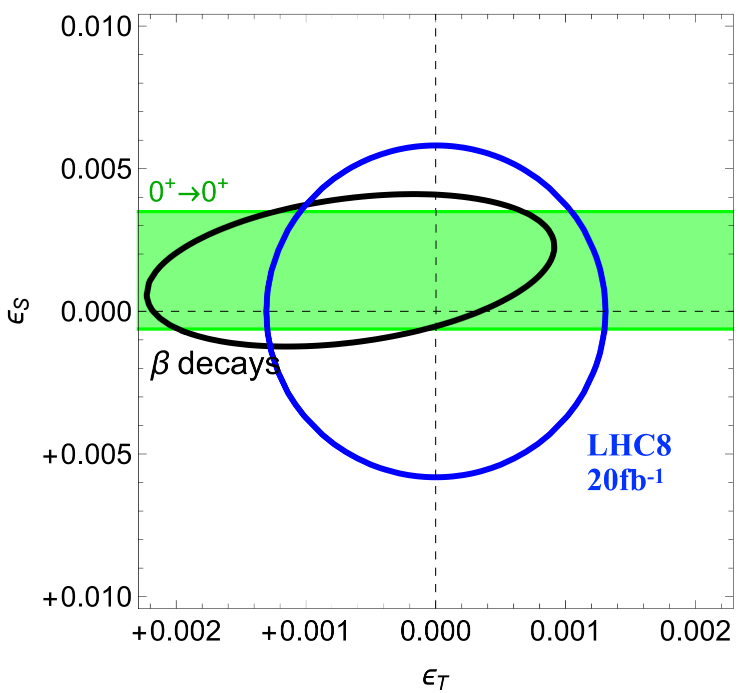
NP effects in neutron β decay: a theory view

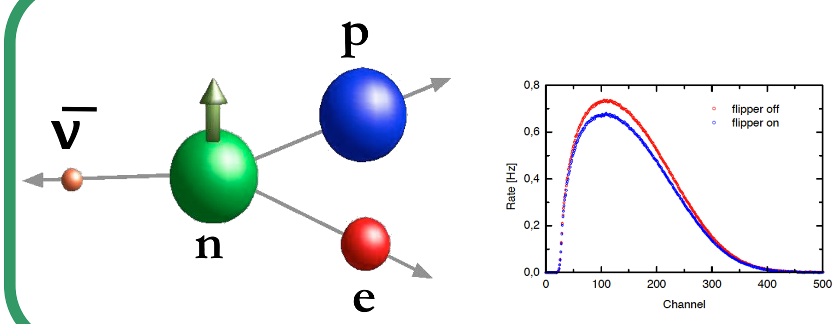
Nordita workshop - ESS | Stockholm Dec 2018



Martín González-Alonso
CERN-TH

[Recent review: MGA, O. Naviliat Cuncic, N. Severijns, Prog. Part. Nucl. Phys. 104 (2019) 165-223*]*

New Physics searches with β decays



Precise data

+

Precise SM predictions

[V_{ud} = 0.97416(21)!!!]

[Hardy & Towner'15]

Implications for New Physics? Competitive probes?

- **Specific model;** *Beg et al. (1977), Barbieri et al. (1985), Marciano & Sirlin (1987), Hagiwara et al. (1995), Kurylov & Ramsey-Musolf (2002), Marciano (2007), Bauman et al. (2012), …*
- **Something more model-indep? Effective Field Theory approach!**

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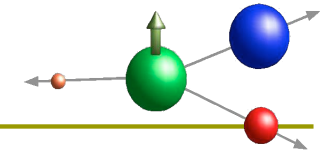

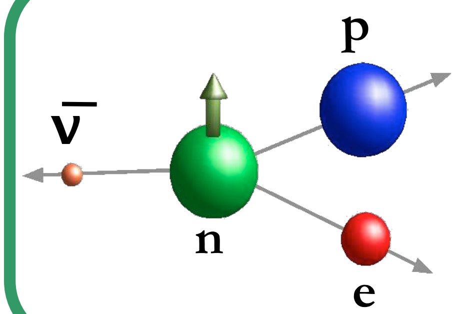

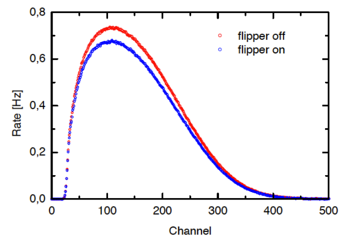

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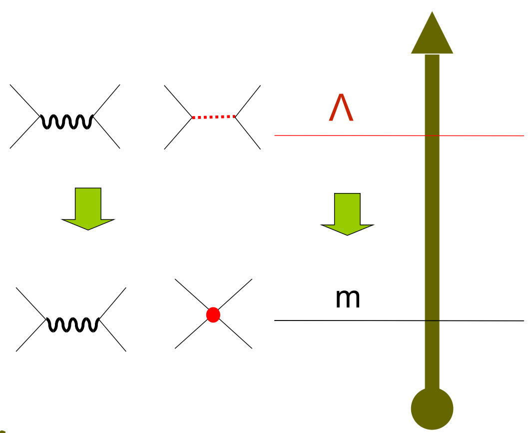
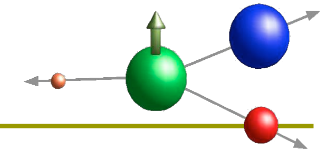


$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

$$\mathcal{L}_{eff} = \mathcal{L}_4(\phi) + \frac{1}{\Lambda}\mathcal{L}_5(\phi) + \frac{1}{\Lambda^2}\mathcal{L}_6(\phi) + \ldots \rightarrow \sum \alpha_i \mathcal{O}_i$$

Comparing experiments



- How to compare different nuclear beta decays?
  - ➔ Effective Lagrangian at the **hadron** level!

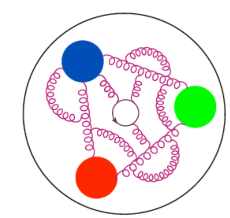
$$\begin{aligned}-\mathcal{L}_{n\to pe^-\bar\nu_e} \;=\;& \bar p\, n\;(C_S\bar e\nu_e - C_S'\bar e\gamma_5\nu_e)\\ &+\bar p\gamma^\mu n\,(C_V\bar e\gamma_\mu\nu_e - C_V'\bar e\gamma_\mu\gamma_5\nu_e)\\ &+\frac{1}{2}\bar p\sigma^{\mu\nu}n\,(C_T\bar e\sigma_{\mu\nu}\nu_e - C_T'\bar e\sigma_{\mu\nu}\gamma_5\nu_e)\\ &-\bar p\gamma^\mu\gamma_5 n\,(C_A\bar e\gamma_\mu\gamma_5\nu_e - C_A'\bar e\gamma_\mu\nu_e)\\ &+\bar p\gamma_5 n\;(C_P\bar e\gamma_5\nu_e - C_P'\bar e\nu_e) + \text{h.c.}\end{aligned}$$

[Lee & Yang'1956]

- How to compare with e.g. pion decays?
  - ➔ Effective Lagrangian at the **quark** level!

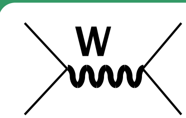
$$\mathcal{L}_{d\to u\ell^-\bar\nu_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar\ell_L\gamma_\mu\nu\cdot\bar u\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^\Gamma_{\rho\delta}\,\bar\ell_\rho\Gamma\nu\cdot\bar u\Gamma d_\delta\right]$$

$C_i \sim$ FF x ε_i



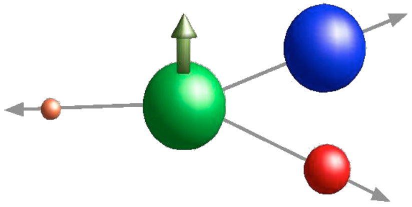
- How to compare with LHC experiments?
  - ➔ Effective Lagrangian at the **quark** level at the EW scale!

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\,\mathcal{O}_i$$



Hadrons:

$$n \longrightarrow p\, e^{-}\, \bar{\nu}$$



Hadronic EFT

$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar\nu_e} \quad = \quad & C_V\,\left(\bar p\gamma^\mu n \;+\; \frac{C_A}{C_V}\,\bar p\gamma^\mu\gamma_5 n\right)\;\times\;\bar e\gamma_\mu\,(1-\gamma_5)\,\nu_e \\
& + C_S\,\bar p\,n\;\times\;\bar e\,(1-\gamma_5)\,\nu_e \;+\; \frac{1}{2}\,C_T\,\bar p\sigma^{\mu\nu}n\;\times\;\bar e\sigma_{\mu\nu}\,(1-\gamma_5)\,\nu_e \\
& - C_P\,\bar p\gamma_5 n\;\times\;\bar e\,(1-\gamma_5)\,\nu_e + \text{h.c.}
\end{aligned}
$$

+ terms with RH neutrinos

Hadronic EFT

SM terms

$$-\mathcal{L}_{n\to pe^-\bar{\nu}_e} = C_V\left(\bar{p}\gamma^\mu n + \frac{C_A}{C_V}\,\bar{p}\gamma^\mu\gamma_5 n\right) \times \bar{e}\gamma_\mu(1-\gamma_5)\,\nu_e$$

$$+ C_S\,\bar{p}\,n \times \bar{e}\,(1-\gamma_5)\,\nu_e + \frac{1}{2}\,C_T\,\bar{p}\sigma^{\mu\nu}n \times \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\,\nu_e$$

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Linear approx:
SM + small + (small)^2

(Or simply no ν_R: $C_i = C_i'$)

Hadronic EFT

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~~$- C_P\,\bar p\gamma_5 n \times \bar e(1-\gamma_5)\nu_e + \text{h.c.}$~~

~~+ terms with RH neutrinos~~

"since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted"

Wrong reason... $C_P = 348(11)\,\epsilon_P$

[MGA & Camalich, PRL 112 (2014)]

Linear approx:
SM + small + (small)²

(Or simply no ν_R: $C_i = C_i'$)

Real reason: the bounds on ϵ_P from pion decays are much stronger!!!

$$|\mathcal{A}(\pi\to\ell\nu)|^2 \sim m_\ell^2\left(1+\frac{M_{QCD}}{m_\ell}\epsilon_P\right)^2$$

Hadronic EFT

[Lee & Yang'1956]

SM + NP

$$-\mathcal{L}_{n\to pe^-\bar{\nu}_e} = C_V\left(\bar{p}\gamma^\mu n + \frac{C_A}{C_V}\bar{p}\gamma^\mu\gamma_5 n\right) \times \bar{e}\gamma_\mu\,(1-\gamma_5)\,\nu_e$$

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S and T affect the angular distributions and the spectrum!!

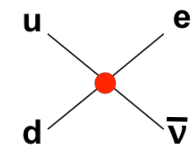
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

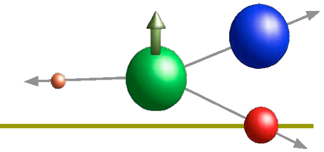
$$b_{(B)} = \#\, C_S + \#\, C_T$$

Fierz term [1937]

[+ CPV effects]

Probing the Fierz term





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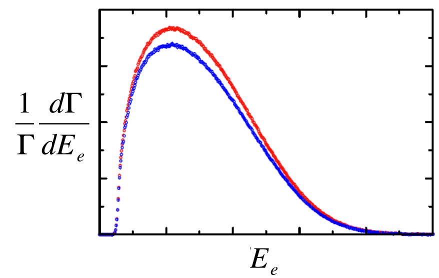
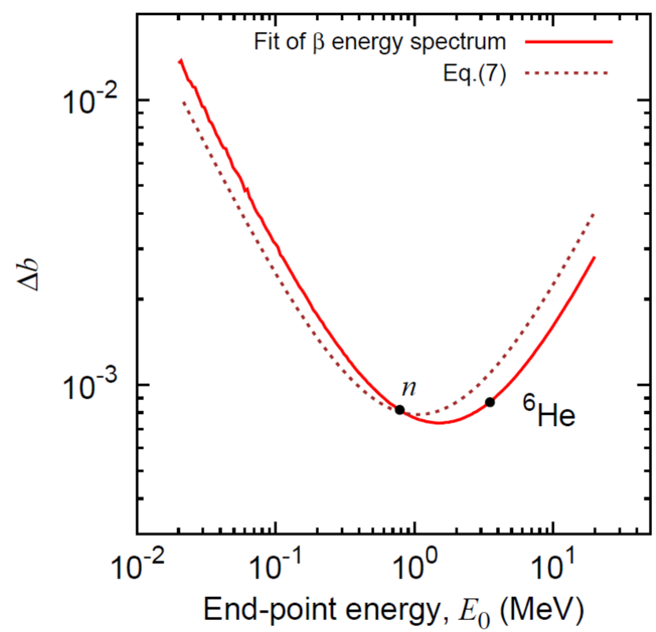
✓ Direct effect in the spectrum:



Optimal endpoint: 1-4 MeV

[MGA & Naviliat-Cuncic, PRC94 (2016)]



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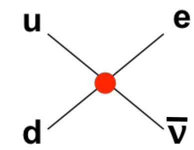

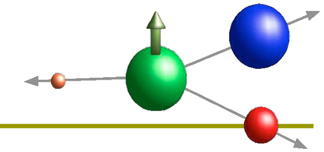

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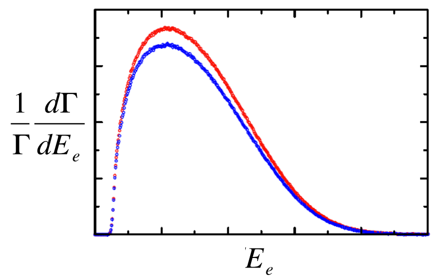

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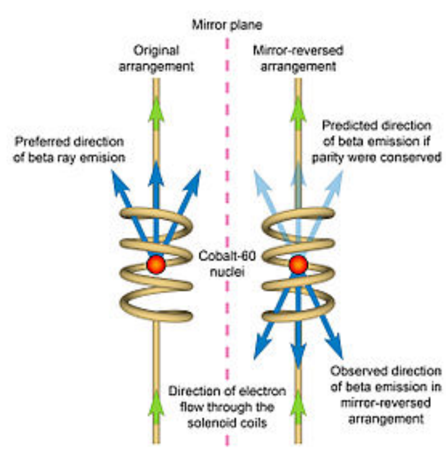
✓ Indirect effect in the asymmetries:

$$\tilde{X} = \frac{X}{1 + b\langle m/E_e\rangle}$$

PS: Not always valid!
(proton spectrum)

[MGA & Naviliat-Cuncic, PRC94 (2016)]



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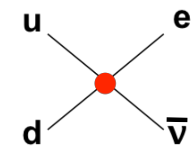

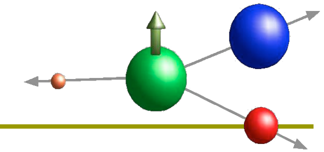

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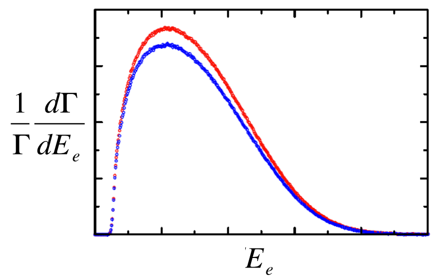

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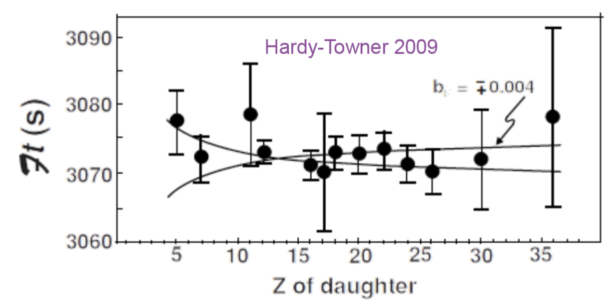
✓ Indirect effect in the Ft-values & neutron lifetime:

$$\delta\tau_n, \delta\mathcal{F}t \;\sim\; -b\,\langle\frac{m_e}{E_e}\rangle$$



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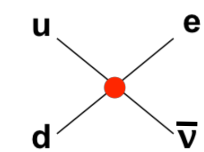
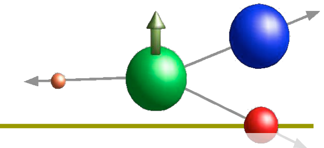
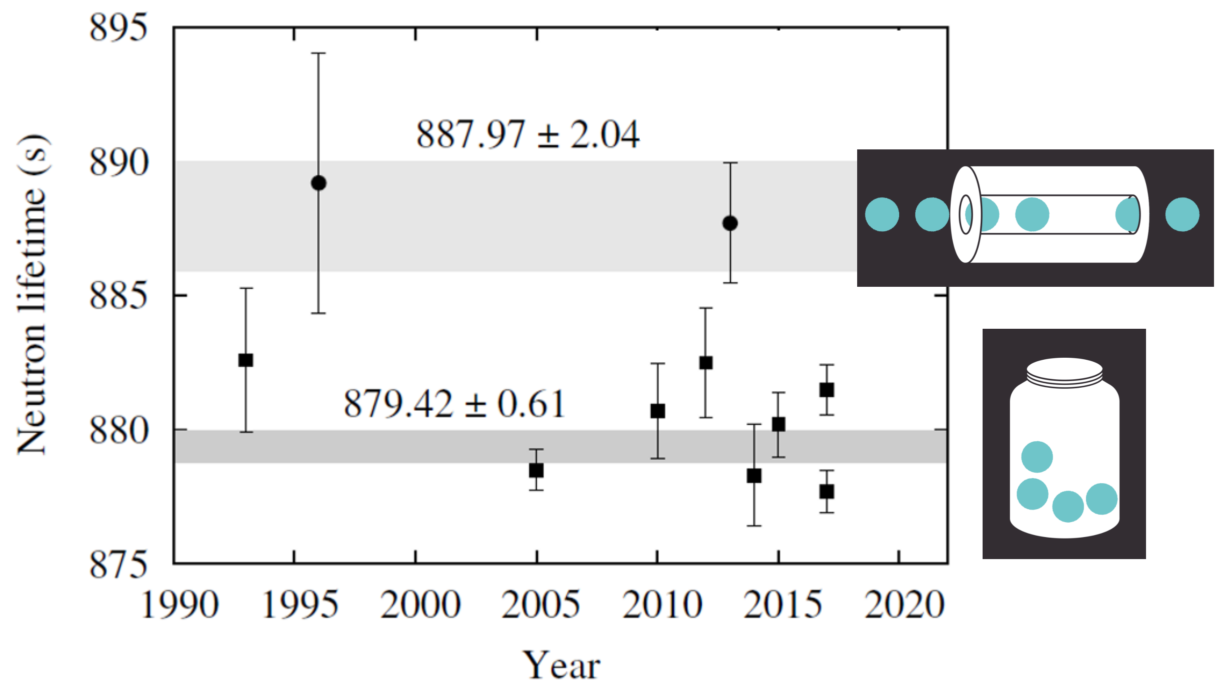




Heavy NP cannot explain the beam vs. bottle tension

.... Light NP?

[Fornal & Grinstein PRL (120 (2018)]



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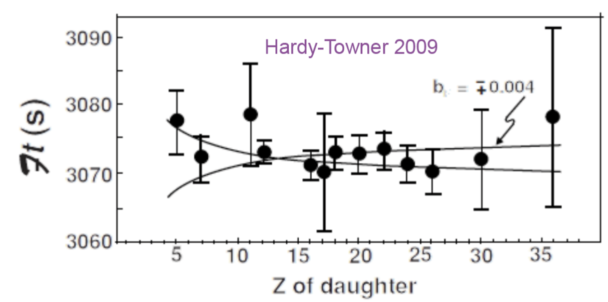
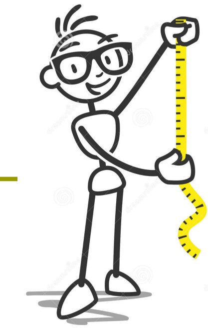


Current data (+ TH!!)

Precision:
O(0.01 - 1)% !!



Nuclei

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

[Hardy-Towner'2015]

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

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

Exp Input: BRs, half-lives, Q-values

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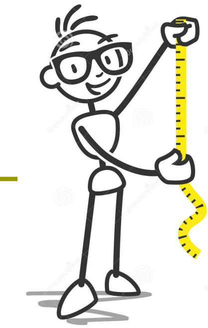

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NEW

Nuclear structure-dep. corrections???
[Seng, Gorshteyn, & Ramsey-Musolf, 1812.03352]
[Gorshteyn, 1812.04229]

Current data (+ TH!!)

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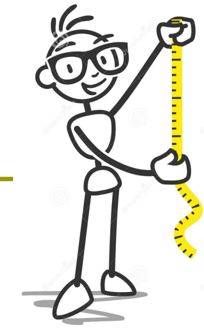

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Parent	$\mathcal{F}t$ (s)
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^{14}O	3071.4 ± 3.2
^{22}Mg	3077.9 ± 7.3
^{26m}Al	3072.9 ± 1.0
^{34}Cl	3070.7 ± 1.8
^{34}Ar	3065.6 ± 8.4
^{38m}K	3071.6 ± 2.0
^{38}Ca	3076.4 ± 7.2
^{42}Sc	3072.4 ± 2.3
^{46}V	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

[Hardy-Towner'2015]

Exp Input: BRs, half-lives, Q-values
Th: QED + Isospin symmetry breaking corrections

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

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

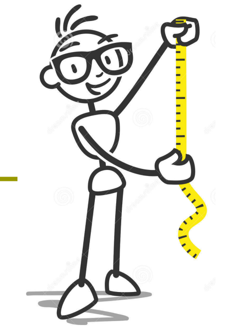
RC to correlations in neutron decay known today with enough precision for ESS measurements?

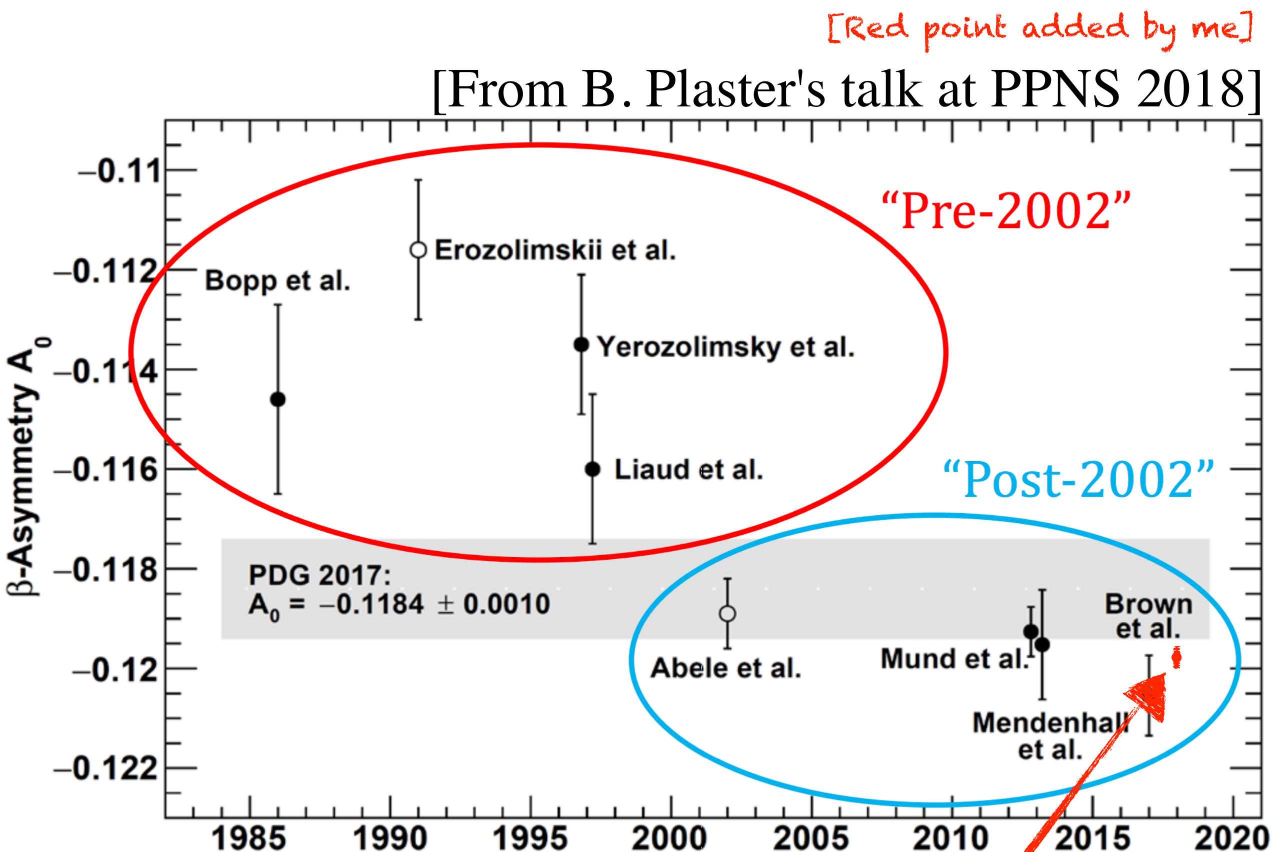
NEW

Nuclear structure-dep. corrections???
[Seng, Gorshteyn, & Ramsey-Musolf, 1812.03352]
[Gorshteyn, 1812.04229]

Current data (+ TH!!)

Precision:
O(0.01 – 1)% !!





Neutron data

Parameter	Value	
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a_n	−0.1034(37)	*
$\tilde{a}$	−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

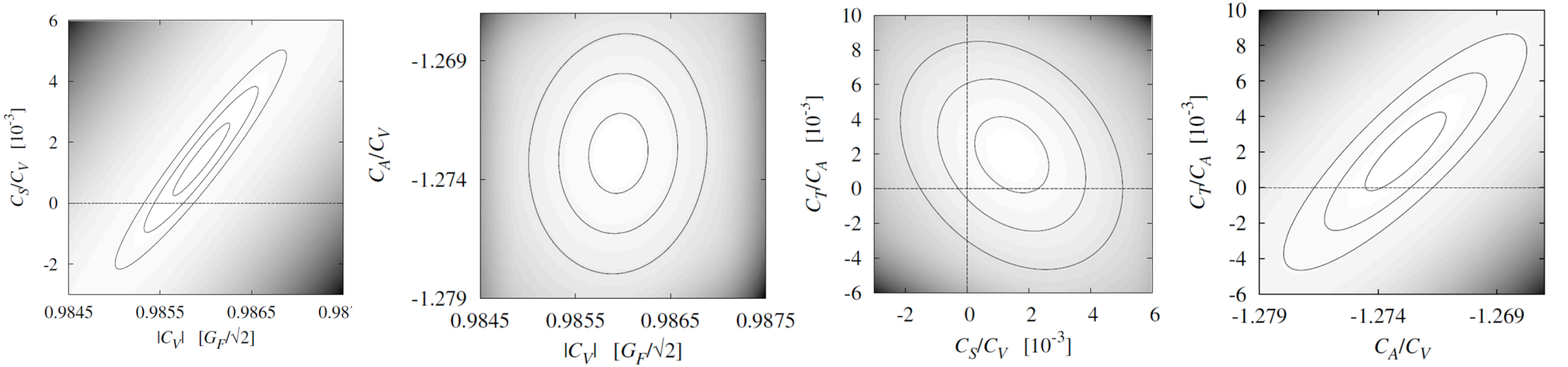
$S = (\chi^2_{min}/dof)^{1/2}$

NEW

A_n = −0.11985(21)
g_A = 1.27641(56) [0.04%!]
Perkeo III (2.5x!)

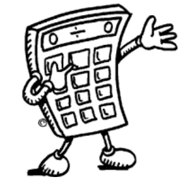
Current data → Results

$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.08 & 1.00 & & \\ 0.94 & 0.08 & 1.00 & \\ -0.32 & 0.85 & -0.31 & 1.00 \end{pmatrix}$$



Driven by Ft's, τ_n, A_n!

Current data → Results



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- One can trivially calculate the precision needed in any other observable to compete:

Ex. #1 $\quad \tilde{a}_n = f(C_i) \quad \rightarrow \quad \delta\tilde{a}_n = 0.6\%$

Current data → Results

$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.08 & 1.00 & & \\ 0.94 & 0.08 & 1.00 & \\ -0.32 & 0.85 & -0.31 & 1.00 \end{pmatrix}$$

- One can trivially calculate the precision needed in any other observable to compete:

Ex. #1 $\tilde{a}_n = f(C_i) \quad \rightarrow \quad \delta\tilde{a}_n = 0.6\%$

Coefficient	Absolute uncertainty	Relative uncertainty	SM value
b_n	3.2×10^{-3}		0
a_n	4.7×10^{-4}	4.4×10^{-3}	−0.10648(19)
$\tilde{a}_n$	6.4×10^{-4}	6.1×10^{-3}	−0.10648(19)
A_n	5.9×10^{-4}	5.0×10^{-3}	−0.11935(24)
$\tilde{A}_n$	7.8×10^{-4}	6.5×10^{-3}	−0.11935(24)
$\tilde{B}_n$	1.2×10^{-4}	1.2×10^{-4}	0.98713(5)
b_F	2.3×10^{-3}		0
b_{GT}	3.9×10^{-3}		0
a_F	6.4×10^{-6}	6.4×10^{-6}	1
$\tilde{a}_F$	4.7×10^{-4}	4.7×10^{-4}	1
a_{GT}	4.0×10^{-6}	1.2×10^{-5}	−1/3
$\tilde{a}_{GT}$	3.7×10^{-4}	1.1×10^{-3}	−1/3

Current data → Results

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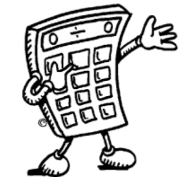
b_F	2.3×10^{-3}		0
b_{GT}	3.9×10^{-3}		0
a_F	6.4×10^{-6}	6.4×10^{-6}	1
$\tilde{a}_F$	4.7×10^{-4}	4.7×10^{-4}	1
a_{GT}	4.0×10^{-6}	1.2×10^{-5}	−1/3
$\tilde{a}_{GT}$	3.7×10^{-4}	1.1×10^{-3}	−1/3

Perkeo-III: ~0.2%
→ x2 improvement
on A & T !

Current data → Results

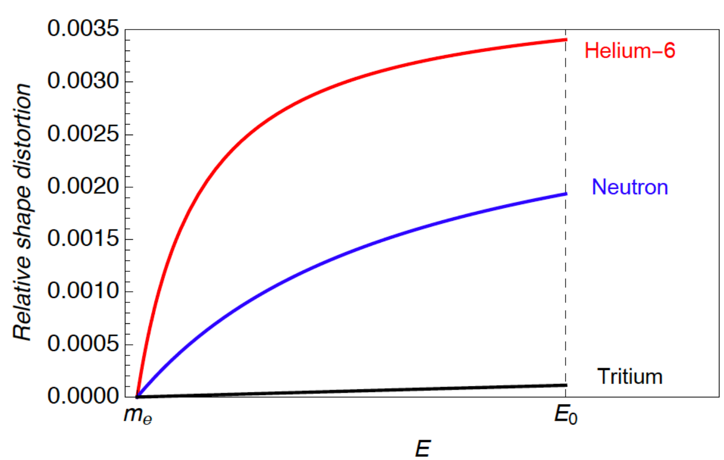


$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.08 & 1.00 & & \\ 0.94 & 0.08 & 1.00 & \\ -0.32 & 0.85 & -0.31 & 1.00 \end{pmatrix}$$

- One can trivially calculate the precision needed in any other observable to compete:

Ex. #1 $\tilde{a}_n = f(C_i) \quad \rightarrow \quad \delta\tilde{a}_n = 0.6\%$

Ex. #2: Spectrum shape measurements



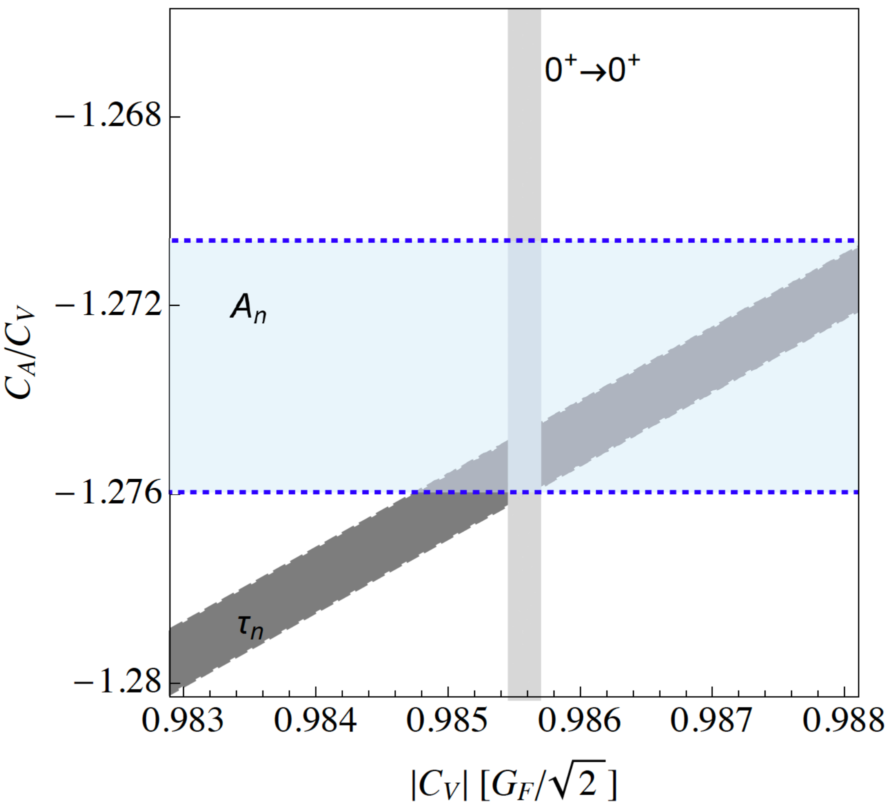
Current data → Results

$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.08 & 1.00 & & \\ 0.94 & 0.08 & 1.00 & \\ -0.32 & 0.85 & -0.31 & 1.00 \end{pmatrix}$$

SM Limit

$$|C_V| = 0.98559(11)\, G_F/\sqrt{2}$$
$$C_A/C_V = -1.27510(66) \,,$$

(ρ = 0.25)



Current data → Results

$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.08 & 1.00 & & \\ 0.94 & 0.08 & 1.00 & \\ -0.32 & 0.85 & -0.31 & 1.00 \end{pmatrix}$$

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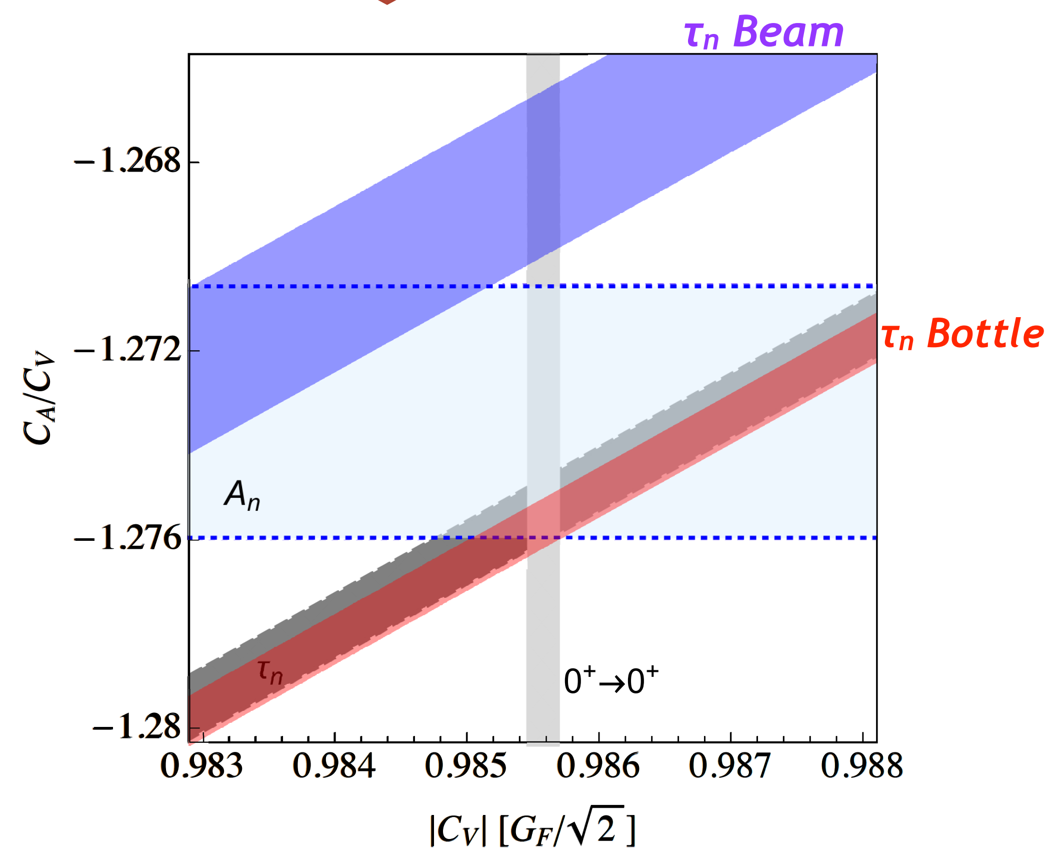

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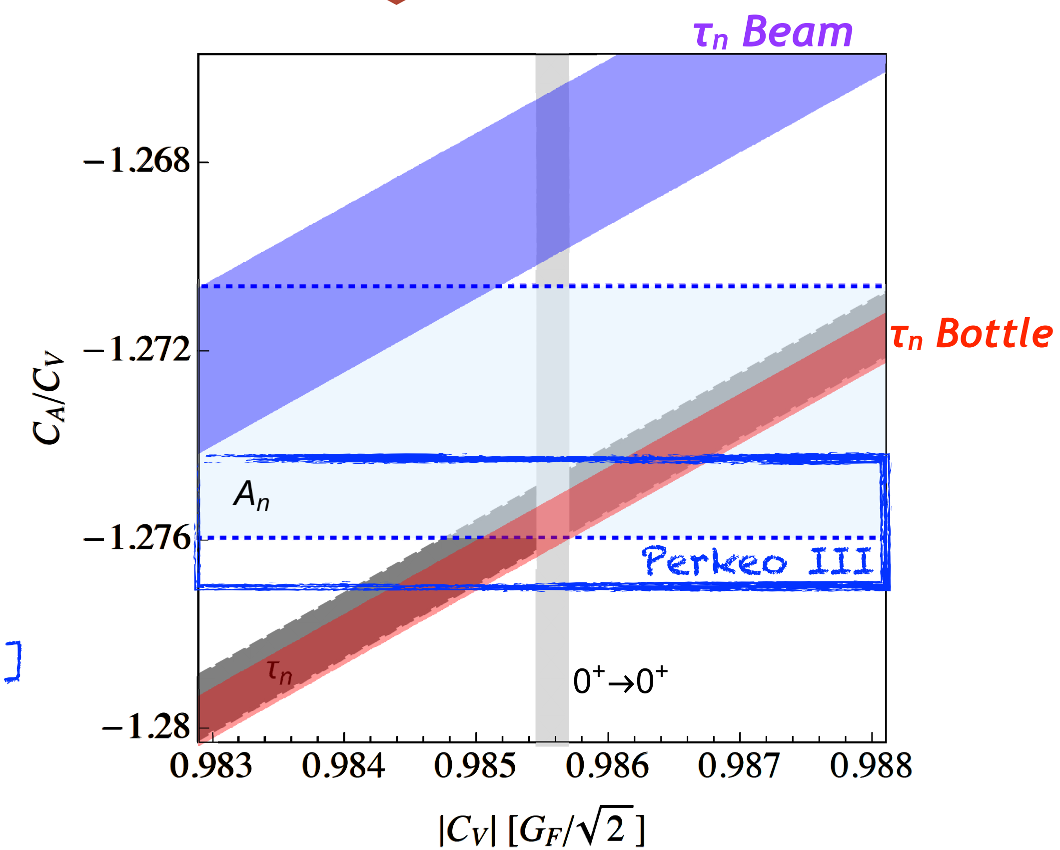
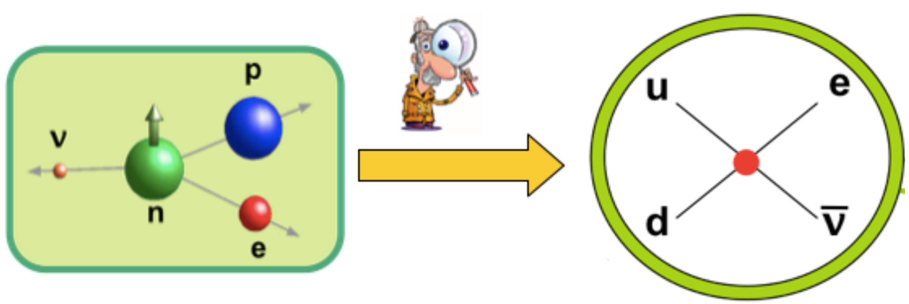


NEW

A_n = −0.11985(21) [Perkeo III, 2.5x!]
→ no dark channel
[Dubbers et al, 1812.00626]

Quarks (low-E):

$$d \to u\ e^- \ \bar{\nu}$$



From hadrons to quarks

$$C_V \sim g_V \, G_F^\mu \, V_{ud} \, (1 + \text{NP}) \, (1 + \text{RC})$$

$$C_A/C_V \sim -\, g_A/g_V \, (1 - 2\, \epsilon_R)$$

$$C_S \sim g_S \, \epsilon_S$$

$$C_T \sim g_T \, \epsilon_T$$

[Lifetime shift]

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

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

From hadrons to quarks

$\tilde{V}_{ud}$

$$C_V \sim g_V\, G_F^\mu\, V_{ud}\,(1+\mathrm{NP})\,(1+\mathrm{RC})$$

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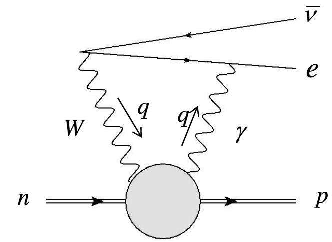
$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$

Inner RC:

2.361(38)% [Marciano-Sirlin, PRL96 (2006)]

2.467(22)% [Seng et al., 1807.10197]

NEW



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From hadrons to quarks

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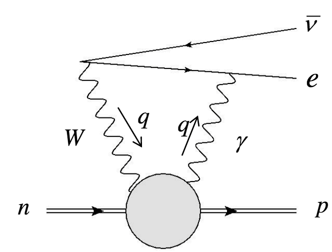
NEW



Can the lattice say anything about it in the near future?

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

From hadrons to quarks

$$C_V \sim g_V\, G_F^{\mu}\, V_{ud}\, (1 + \mathrm{NP})\, (1 + \mathrm{RC})$$

$$C_A/C_V \sim -g_A/g_V\, (1 - 2\,\epsilon_R)$$

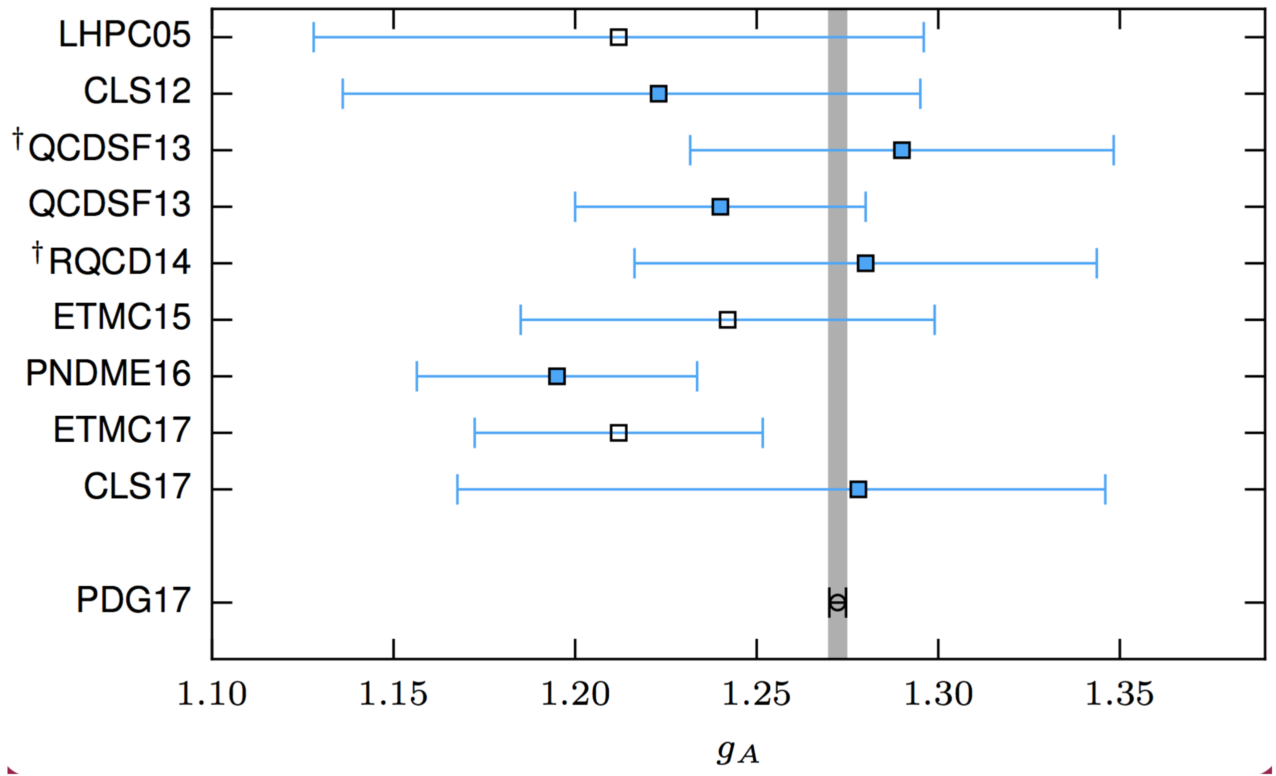
$$C_S \sim g_S\, \epsilon_S$$

$$C_T \sim g_T\, \epsilon_T$$

Axial charge

$$g_A \to \langle p | \bar{u} \gamma_\mu \gamma_5 d | n \rangle$$

[A. Nicholson's talk, CIPANP2018]



From hadrons to quarks

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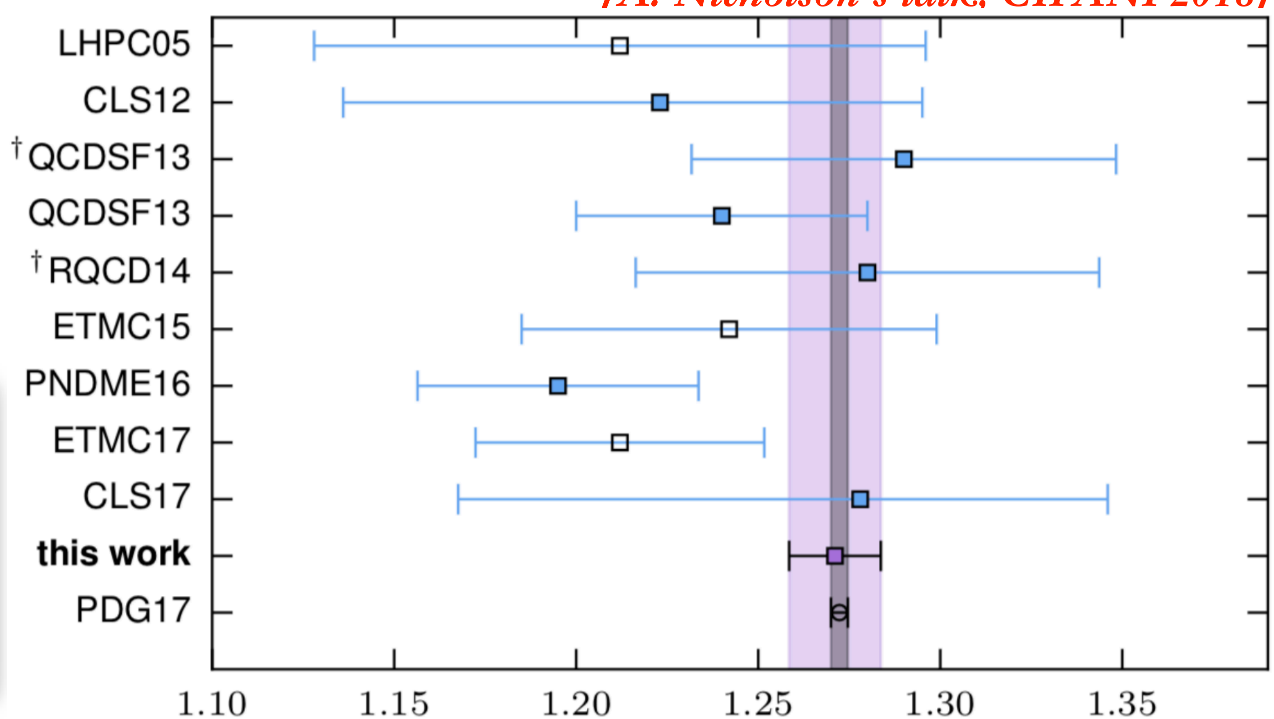

g_A^{LQCD} = 1.271 ± 0.013

Nature, May 30, 2018

C.C. Chang, A.N., E. Rinaldi, E. Berkowitz, N. Garron, D. Brantley, H. Monge-Camacho, C. Monahan, C. Bouchard, M.A. Clark, B. Joo, T. Kurth, K. Orginos, P. Vranas, A. Walker-Loud

From hadrons to quarks

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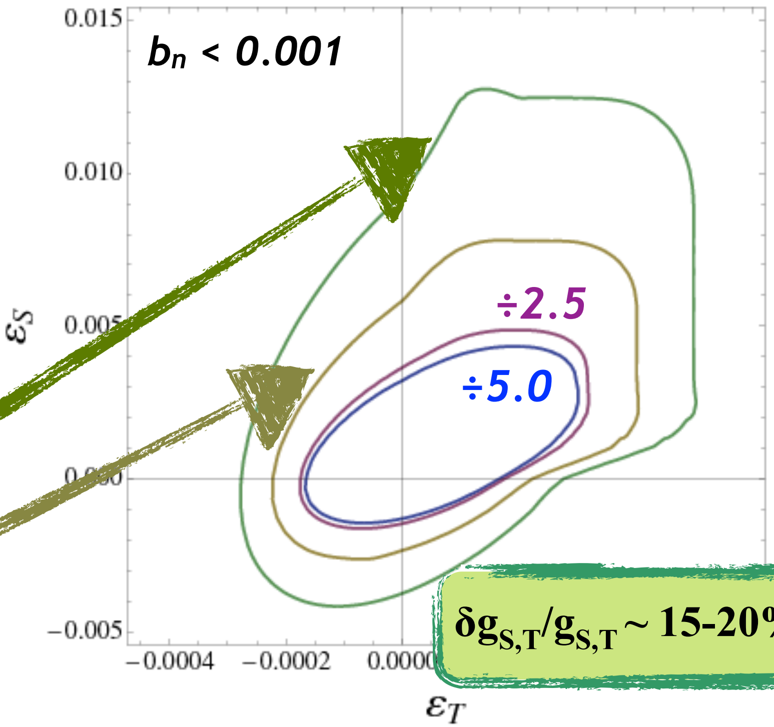
$$C_A/C_V \sim -\,g_A/g_V\,(1-2\,\epsilon_R)$$

$$C_S \sim g_S\,\epsilon_S$$

$$C_T \sim g_T\,\epsilon_T$$

Scalar & tensor charges

	g_S $\langle p\vert\bar{u}d\vert n\rangle$	g_T $\langle p\vert\bar{u}\sigma_{\mu\nu}\gamma_5 d\vert n\rangle$
Adler et al.'1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35) *[average]*



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

[Bhattacharya, Cirigliano, Cohen, Filipuzzi, MGA, Graesser, Gupta, Lin, PRD85 (2012)]

From hadrons to quarks

$$C_V \sim g_V\, G_F^{\mu}\, V_{ud}\, (1+\text{NP})\,(1+\text{RC})$$
$$C_A/C_V \sim -\,g_A/g_V\,(1-2\,\epsilon_R)$$
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Scalar & tensor charges

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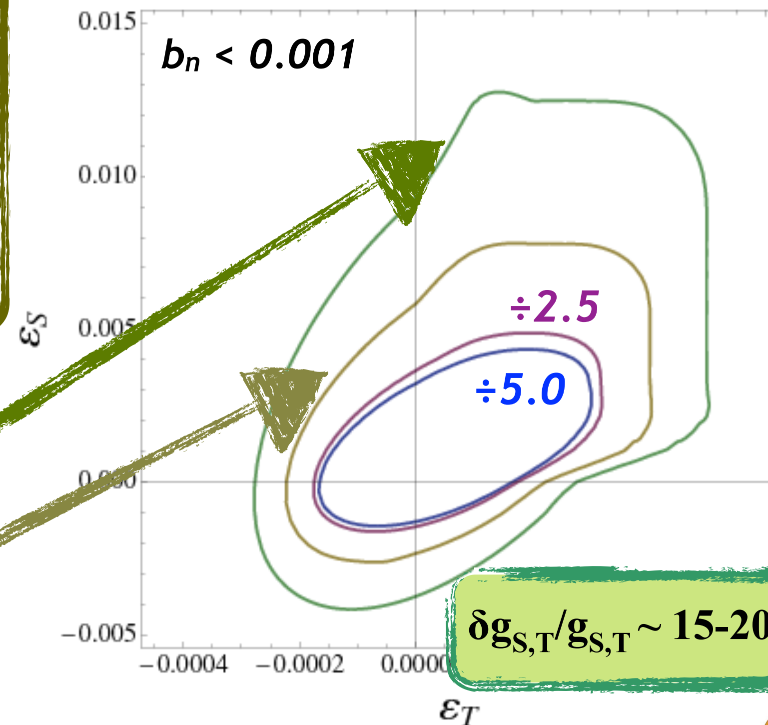
Adler et al. '1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35)
LHPC 2012	1.08(32)	1.04(02)
RQCD 2014	1.02(35)	1.01(02)
PNDME 2013/15	0.72(32)	1.02(08)
ETMC 2015/17	0.93(33)	1.00(03)
CVC	1.02(11)	-
PNDME 2016/18	1.02(10)	0.99(03)
JLQCD'18	0.88(11)	1.08(10)

All syst!

[Bhattacharya et al., Phys. Rev. Lett. 115 (2015)]



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

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

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

g_S = 1.00(8)

using (m_d -m_u) from 1802.04248

From hadrons to quarks

Using these RC + charges, the C_i bounds translate into...

BSM fit

$$\begin{pmatrix} |\tilde{V}_{ud}| \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97452(34)(19) & \\ 0.002(1)(21)_{g_A} & (90\%\ \mathrm{CL}) \\ 0.0014(20)(3)_{g_S} & (90\%\ \mathrm{CL}) \\ -0.0007(12)(1)_{g_T} & (90\%\ \mathrm{CL}) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.00 & 1.00 & & \\ 0.83 & 0.00 & 1.00 & \\ 0.28 & -0.04 & 0.31 & 1.00 \end{pmatrix}$$

From hadrons to quarks

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SM fit

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

(ρ = - 0.13)

[MGA & Martin Camalich, JHEP (2016)]

+ Updates: f_K/f_π , $f_+(0)$ at 0.2% ! [FermiLab/MILC'17,'18]

From hadrons to quarks

Using these RC + charges, the C_i bounds translate into...

BSM fit

$$\begin{pmatrix} |\tilde{V}_{ud}| \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97452(34)(19) & \\ 0.002(1)(21)_{g_A} & (90\%\ \mathrm{CL}) \\ 0.0014(20)(3)_{g_S} & (90\%\ \mathrm{CL}) \\ -0.0007(12)(1)_{g_T} & (90\%\ \mathrm{CL}) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.00 & 1.00 & & \\ 0.83 & 0.00 & 1.00 & \\ 0.28 & -0.04 & 0.31 & 1.00 \end{pmatrix}$$

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

(ρ = - 0.13)

CKM unitarity? $V_{us} = 0.22441(39)$* → $|\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 = 0.9993(5)$

[MGA & Martin Camalich, JHEP (2016)]
+ Updates: f_K/f_π , $f_+(0)$ at 0.2% ! [FermiLab/MILC'17,'18]

From hadrons to quarks

Using these RC + charges, the C_i bounds translate into...

BSM fit

$$\begin{pmatrix} |\tilde{V}_{ud}| \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97452(34)(19) & \\ 0.002(1)(21)_{g_A} & (90\%\ \mathrm{CL}) \\ 0.0014(20)(3)_{g_S} & (90\%\ \mathrm{CL}) \\ -0.0007(12)(1)_{g_T} & (90\%\ \mathrm{CL}) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.00 & 1.00 & & \\ 0.83 & 0.00 & 1.00 & \\ 0.28 & -0.04 & 0.31 & 1.00 \end{pmatrix}$$

SM fit

$$|V_{ud}| = 0.97416(11)(19)_{RC} = 0.97416(21)\ ,$$
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(ρ = - 0.13)

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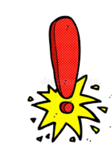
RC by Seng et al., 1807.10197 → 0.9983(4)



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RC by Seng et al., 1807.10197 → 0.9983(4)

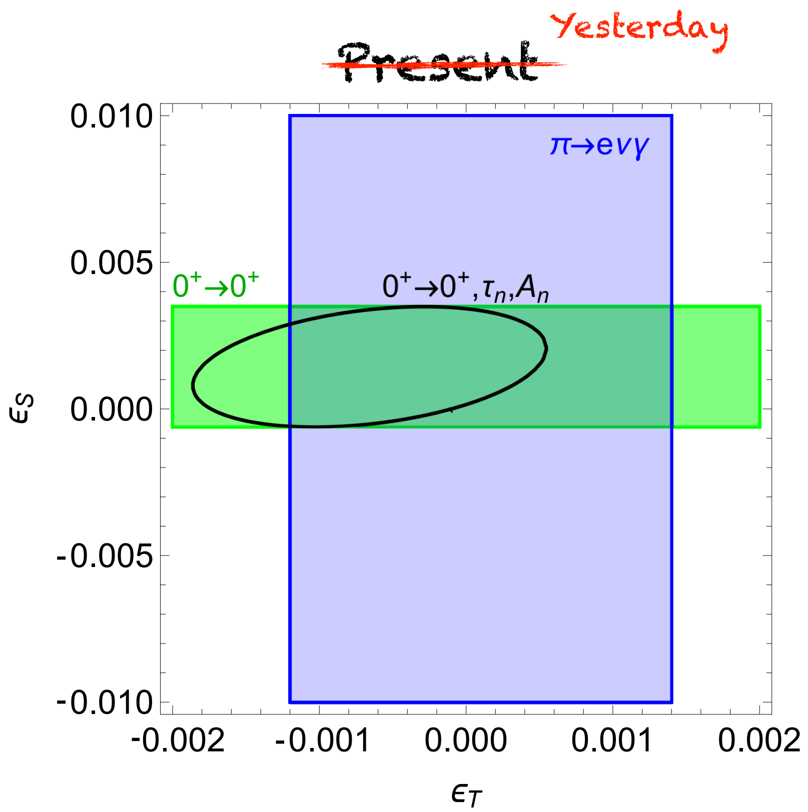
Seng et al., 1812.03352 → 0.9988(4)

Gorshteyn, 1812.04229 → 0.9984(6)

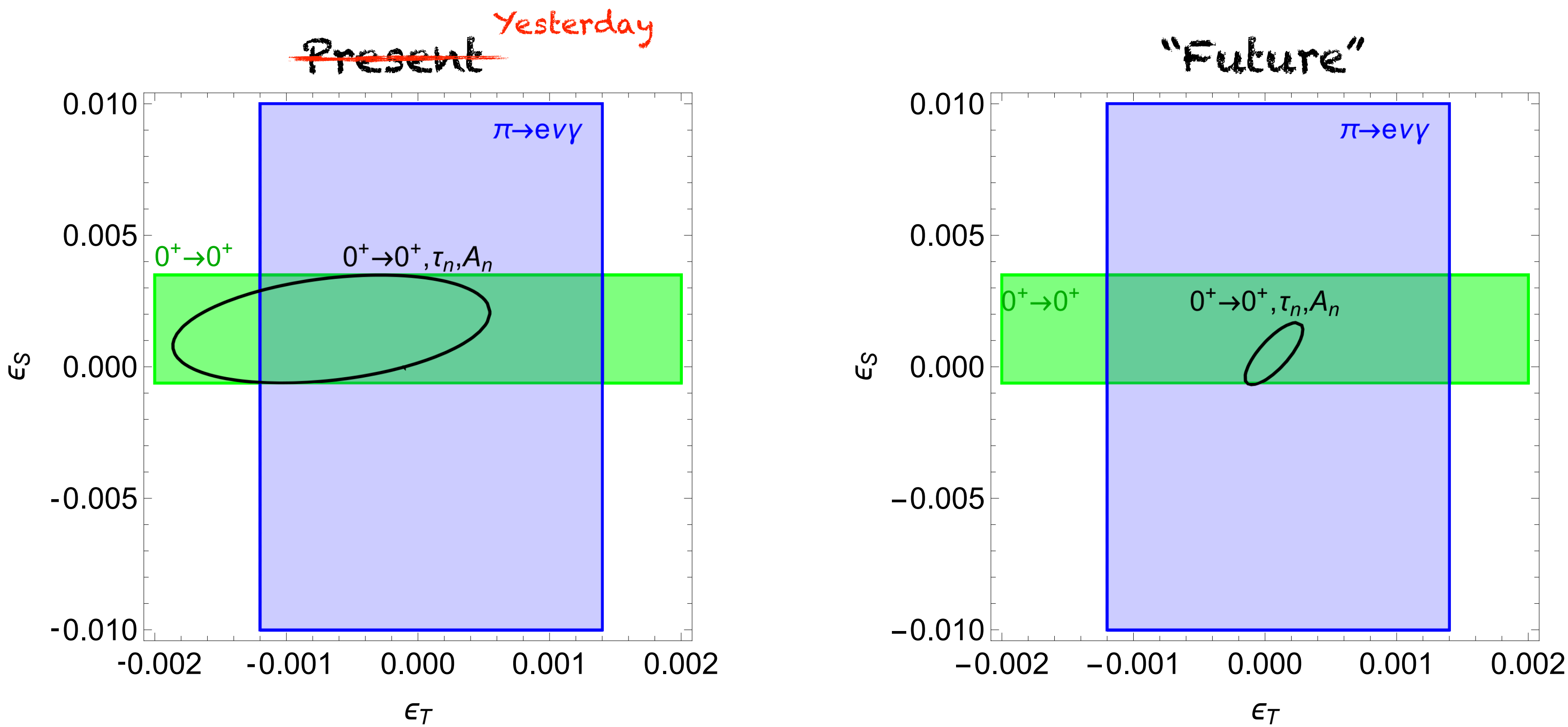
[MGA & Martin Camalich, JHEP (2016)]

+ Updates: f_K/f_π , $f_+(0)$ at 0.2% ! [FermiLab/MILC'17,'18]

From hadrons to quarks



From hadrons to quarks



Benchmark numbers
(from ongoing / planned experiments):

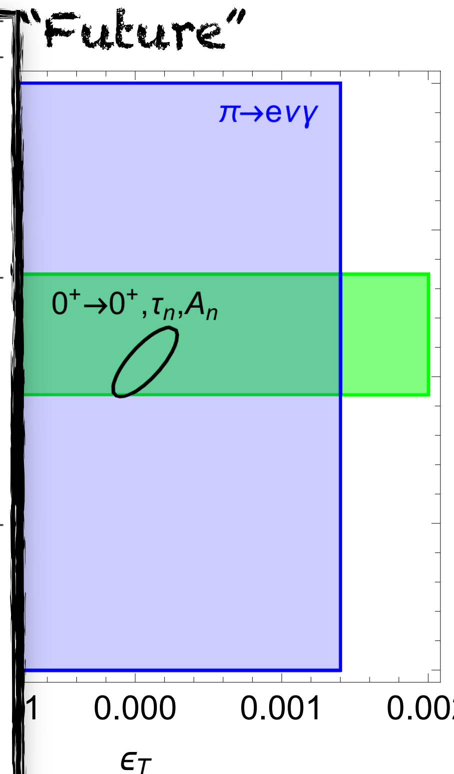
$$\delta\tau_n = 0.1\, s$$

$$\tilde{A}_n,\ a_n,\ \tilde{a}_F,\ a_{GT} \quad \text{at } 0.1\%$$

$$b_{GT} = 0.001$$

From hadrons to quarks

Coefficient	Precision goal	Experiment (Laboratory)	Comments
τ_n	1.0 s; 0.1 s [210]	BL2, BL3 (NIST) [210]	In preparation; two phases
	1.0 s; 0.3 s [214]	LiNA (J-PARC) [211,214]	In preparation; two phases
	0.2 s [215]	Gravitrap (ILL) [203,215]	Apparatus being upgraded
	0.3 s [201]	Ezhov (ILL) [201]	Under construction
	0.1 s [222]	PENeLOPE (Munich) [222]	Being developed
	$\lesssim$0.1 s [223]	UCNτ (LANL) [188,189,223,224]	Ongoing
	0.5 s [225]	HOPE (ILL) [188,225,226]	Proof of principle Ref. [226]
	1.0 s; 0.2 s [188]	τSPECT (Mainz) [188,227]	Taking data; two phases
β-spectrum	$\mathcal{O}(0.01)$ [256]	Supercond. spectr. (Madison) [256]	Shape factor Eq. (51). Ongoing
β-spectrum	$\mathcal{O}(0.01)$ [253]	Si-det. spectr. (Saclay) [253,254]	Shape factor Eq. (51). Ongoing
b_{GT}	0.001	Calorimetry (NSCL) [115,260]	Analysis ongoing (^{6}He,^{20}F)
	$\mathcal{O}(0.001)$ [270]	miniBETA (Krakow–Leuven) [263–265,270]	Being commissioned
	$\mathcal{O}(0.001)$ [276]	UCNA-Nab-Leuven (LANL) [271,272,276]	Analysis ongoing (^{45}Ca)
b_n	<0.05 [293,294]	UCNA (LANL) [390]	Ongoing with A_n data
	0.03 [295]	PERKEO III (ILL) [295]	Possible with A_n data
	0.003 [289]	Nab (LANL) [188,289,357,358]	In preparation
	0.001 [291]	PERC (Munich) [291,292]	Planned
a_F	0.1% [306]	TRINAT (TRIUMF) [306,310]	Planned (^{38}K)
	0.1% [343]	TAMUTRAP (TA&M) [343]	Superallowed β p emitters
	0.1% [79]	WISArD (ISOLDE) [79,177]	In preparation (^{32}Ar β p decay)
a	not stated	Ne-MOT (SARAF) [311,312]	In preparation (^{18}Ne,^{19}Ne,^{23}Ne)
a_{GT}	$\mathcal{O}(0.1)$% [315]	^{6}He-MOT (Seattle) [313,315]	Ongoing (^{6}He)
	not stated	EIBT (Weizmann Inst.) [316–318]	In preparation (^{6}He)
	0.5% [182]	LPCTrap (GANIL) [182,321,323,324]	Analysis ongoing (^{6}He,^{35}Ar)
a_{mirror}	0.5% [273]	NSL-Trap (Notre Dame) [273,344,345]	Planned (^{11}C,^{13}N,^{15}O,^{17}F)
$\tilde{a}_n$	1.0% [350]	aCORN (NIST) [350,352–354]	Data taking ongoing
a_n	1.0 – 1.5% [351]	aSPECT (ILL) [228,229,351]	Analysis being finalized
	0.15% [188,358]	Nab (LANL) [188,289,357,358]	In preparation
$\tilde{A}_n$	0.14% [391]	UCNA (LANL) [390]	Data taking planned
	0.18% [295]	PERKEO III (ILL) [295]	Analysis ongoing
$\tilde{A}_{mirror}$	$\mathcal{O}(0.1)$% [78]	TRINAT (TRIUMF) [78]	Planned
$\tilde{B}_n$	0.01% [397]	UCNB (LANL) [397]	Planned
$\tilde{A}_n$ (a_n, $\tilde{B}_n$, ...)	0.05% [291]	PERC (Munich) [291,292]	In preparation
$\tilde{A}_n$ (a_n, $\tilde{B}_n$, ...)	<$\mathcal{O}(0.1)$% [399]	BRAND (ILL/ESS) [399,400]	Proposed
D	$\mathcal{O}(10^{-4})$ [418]	MORA (GANIL/JYFL) [418]	In preparation (^{23}Mg)
R	$\mathcal{O}(10^{-3})$ [427]	MTV (TRIUMF) [427–429]	Data taking ongoing (^{8}Li)
D, R	$\mathcal{O}(0.1)$% [399]	BRAND (ILL) [399,400]	Proposal



mbers

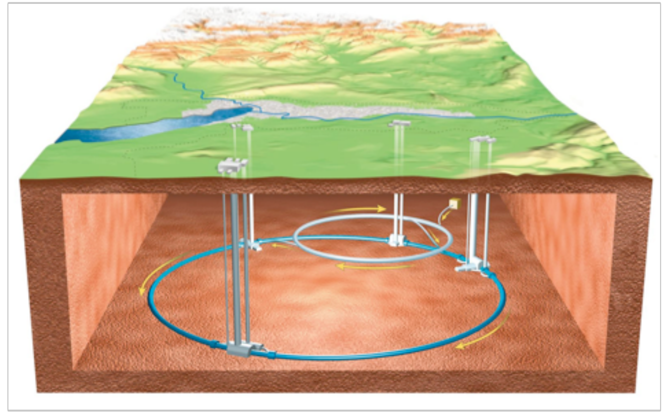
/ planned experiments):

s

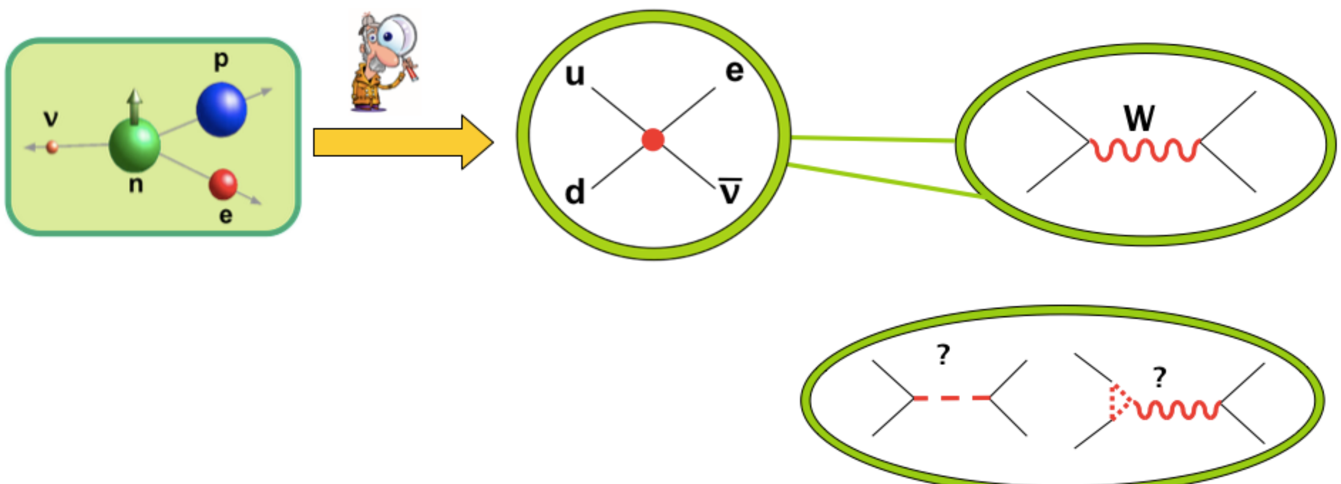
$\tilde{a}_F$, a_{GT} at 0.1%

001

[MGA, O. Naviliat Cuncic, N. Severijns,
Prog. Part. Nucl. Phys. 104 (2019) 165-223]

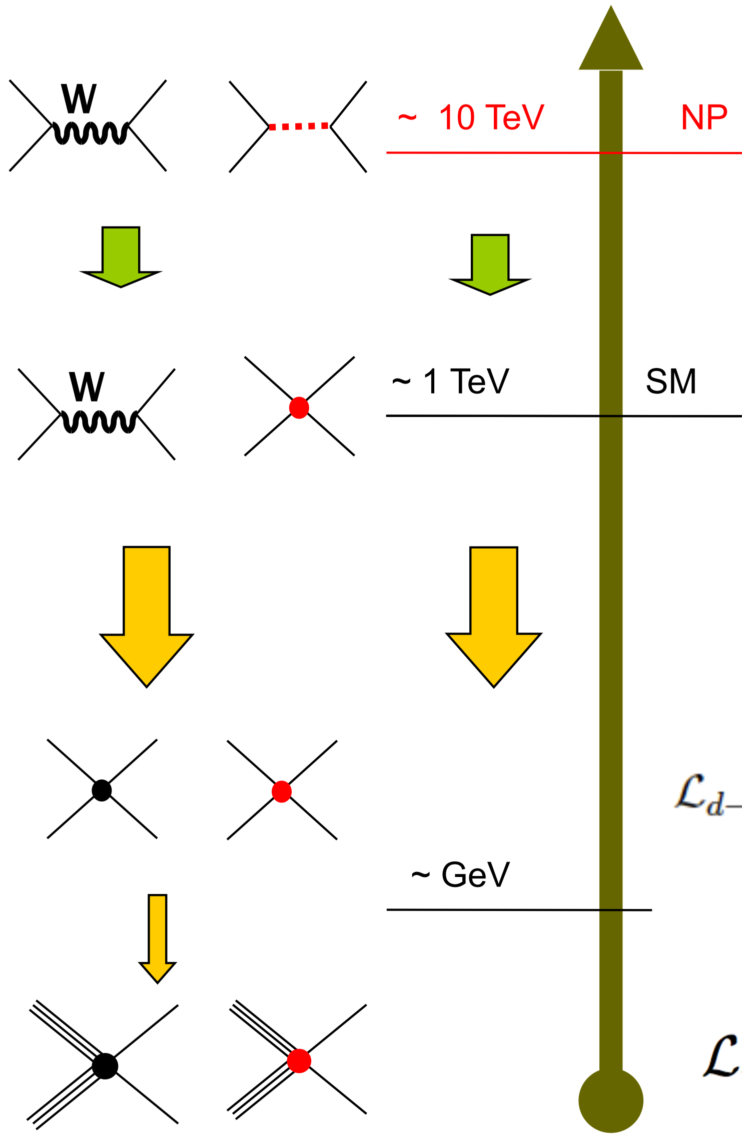


Quarks, W, Z, …



Matching with high-E EFT

$$\frac{d\vec{\epsilon}(\mu)}{d\log\mu} = \left(\frac{\alpha(\mu)}{2\pi}\gamma_{\rm ew} + \frac{\alpha_s(\mu)}{2\pi}\gamma_s\right)\vec{\epsilon}(\mu),$$



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\,\mathcal{O}_i$$

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \; + \; \sum_{\rho\delta\Gamma}\epsilon^\Gamma_{\rho\delta}\;\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

$$\varepsilon_i = f(\alpha_j)$$

Matching with high-E EFT

Low-E EFT → ϵ_i ; SMEFT → α_j

$$\left[\epsilon_i = f(\alpha_j)\right]_{\mu=M_Z}$$

[Cirigliano, MGA, Jenkins'2010; Cirigliano, MGA, Graesser'2012]

$$\frac{\delta G_F}{G_F} = 2\,[\hat{\alpha}^{(3)}_{\varphi l}]_{11+22} - [\hat{\alpha}^{(1)}_{ll}]_{1221} - 2[\hat{\alpha}^{(3)}_{ll}]_{1122-\frac{1}{2}(1221)}\,,$$

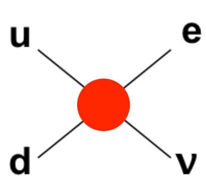
$$V_{1j}\cdot\epsilon^{j\ell}_L = 2\,V_{1j}\left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\,\left[V\hat{\alpha}^{(3)}_{\varphi q}\right]_{1j} - 2\,\left[V\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell 1j}\,,$$

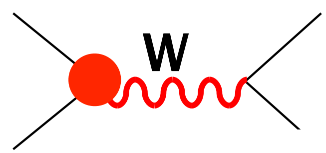
$$V_{1j}\cdot\epsilon^{j}_R = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

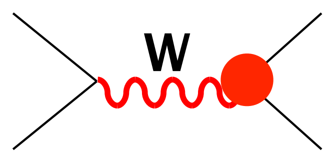
$$V_{1j}\cdot\epsilon^{j\ell}_{s_L} = -\,[\hat{\alpha}_{lq}]^*_{\ell\ell j1}\,,$$

$$V_{1j}\cdot\epsilon^{j\ell}_{s_R} = -\,\left[V\hat{\alpha}^{\dagger}_{qde}\right]_{\ell\ell 1j}\,,$$

$$V_{1j}\cdot\epsilon^{j\ell}_T = -\,[\hat{\alpha}^t_{lq}]^*_{\ell\ell j1}\,, \qquad \hat{\alpha} = \alpha\frac{v^2}{\Lambda^2}$$





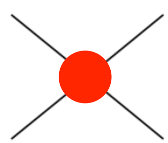


$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$

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

$$O^{(3)}_{\varphi l} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{l}\gamma_\mu\sigma^a l) + \text{h.c.}$$

$$O'_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{\nu}\gamma^\mu e) + \text{h.c.}$$



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

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

$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$

$$O^t_{lq} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}$$

Matching with high-E EFT

Low-E EFT → ϵ_i; SMEFT → α_j

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$$V_{1j}\cdot\epsilon_R^{j} = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

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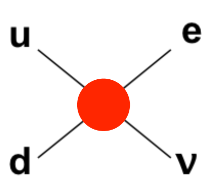
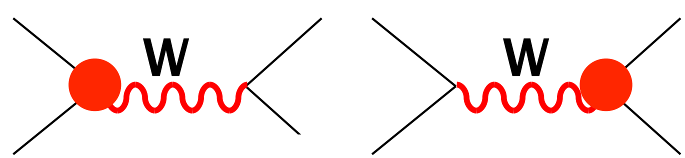
$$V_{1j}\cdot\epsilon_{s_R}^{j\ell} = -\,\left[V\hat{\alpha}^{\dagger}_{qde}\right]_{\ell\ell 1j}\,,$$

$$V_{1j}\cdot\epsilon_T^{j\ell} = -\,[\hat{\alpha}^t_{lq}]^*_{\ell\ell j1}\,,\qquad \hat{\alpha} = \alpha\,\frac{v^2}{\Lambda^2}$$

Beta decays sensitive to a few EFT coefficients





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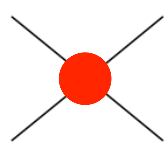

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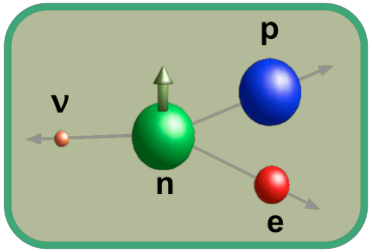
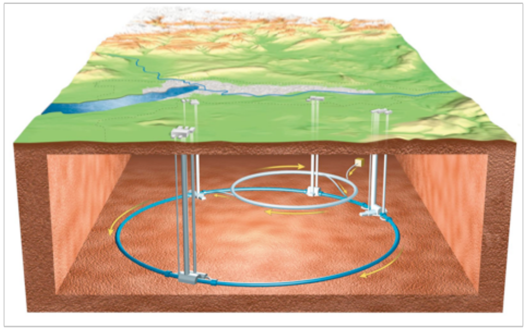
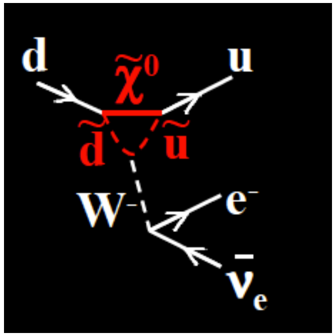
V-A interactions:
CKM unitarity test vs LEP





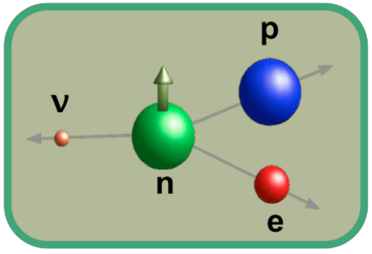
Many examples:

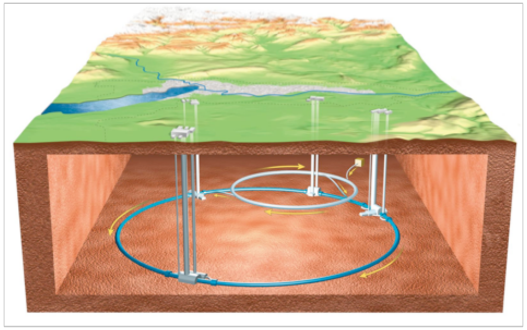
- Tree: W', RPV-MSSM, ...
- Loop: Z', RPC-MSSM, ...
- $U(3)^5$ inv. SMEFT



[Barbieri et al. (1985), Marciano & Sirlin (1987), Barger et al. (1989), Hagiwara et al. (1995), Cirigliano et al (2009), Gauld et al. (2014), …]

V-A interactions: CKM unitarity test vs LEP





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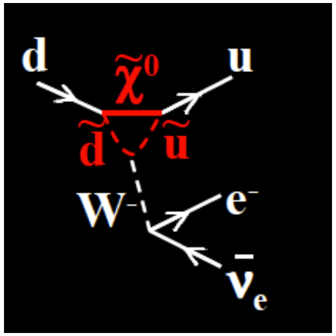
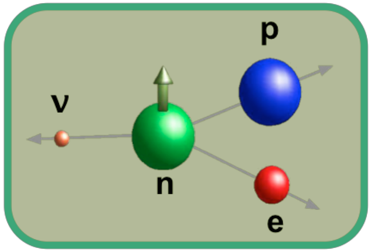
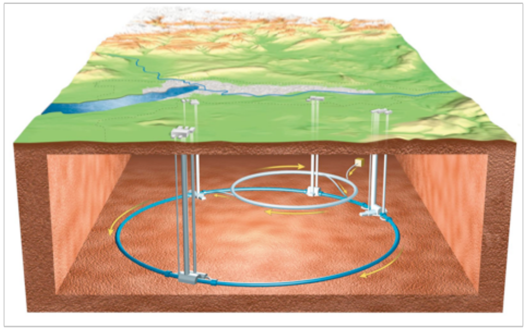


V-A interactions: CKM unitarity test vs LEP



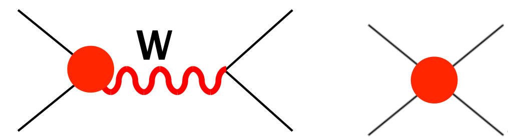


$$\tilde{V}_{ud} = V_{ud}\,(1 + \text{NP}) \quad \rightarrow \quad |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 \neq 1$$

CKM unitarity vs HEP

$$\begin{pmatrix} \tilde{V}_{ud} \\ \tilde{V}_{us} \end{pmatrix} = \begin{pmatrix} 0.97416(21) \\ 0.22484(64) \end{pmatrix} \Rightarrow \Delta_{\mathrm{CKM}} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = -(4.6 \pm 5.2) \times 10^{-4}$$

$$\Rightarrow \Delta_{\mathrm{CKM}} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = 2\left(-\delta g_L^{W\ell} + \overbrace{\delta g_L^{Zu} - \delta g_L^{Zd}}^{\delta g_L^{Wq}} - c_{lq}^{(3)} + c_{\ell\ell}^{(3)}\right)$$



CKM unitarity vs HEP

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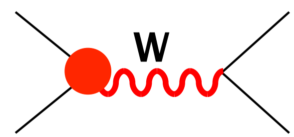
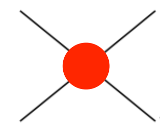
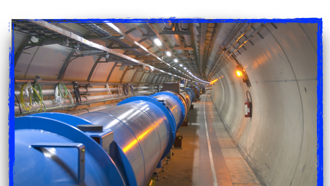




[From Falkowski, MGA & Mimouni, 2017]

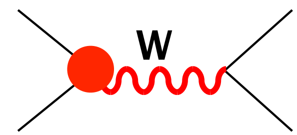
$$\begin{pmatrix} \delta g_L^{W\ell} \\ \delta g_L^{Zu} \\ \delta g_L^{Zd} \\ c_{\ell\ell}^{(3)} \\ c_{\ell q}^{(3)} \end{pmatrix} \times 10^3 = \begin{pmatrix} 0.15 \pm 0.18 \\ 0.48 \pm 0.45 \\ -0.05 \pm 0.27 \\ -0.40 \pm 0.37 \\ -1.11 \pm 0.89 \end{pmatrix}_{\rm LEP/EWPO} \quad \text{vs.} \quad \begin{pmatrix} 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \end{pmatrix}_{\Delta_{CKM}}$$

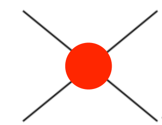


CKM unitarity vs HEP

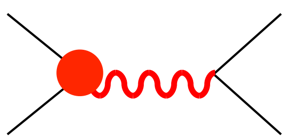
$$\begin{pmatrix} \tilde{V}_{ud} \\ \tilde{V}_{us} \end{pmatrix} = \begin{pmatrix} 0.97416(21) \\ 0.22484(64) \end{pmatrix} \;\rightarrow\; \Delta_{\rm CKM} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = -(4.6 \pm 5.2) \times 10^{-4}$$

$$\rightarrow\; \Delta_{\rm CKM} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = 2\left(-\delta g_L^{W\ell} + \underbrace{\delta g_L^{Zu} - \delta g_L^{Zd}}_{\delta g_L^{Wq}} - c_{lq}^{(3)} + c_{\ell\ell}^{(3)}\right)$$



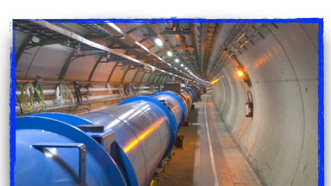


[From Falkowski, MGA & Mimouni, 2017]



$$\begin{pmatrix} \delta g_L^{W\ell} \\ \delta g_L^{Zu} \\ \delta g_L^{Zd} \\ c_{\ell\ell}^{(3)} \\ c_{\ell q}^{(3)} \end{pmatrix} \times 10^3 = \begin{pmatrix} 0.15 \pm 0.18 \\ 0.48 \pm 0.45 \\ -0.05 \pm 0.27 \\ -0.40 \pm 0.37 \\ -1.11 \pm 0.89 \end{pmatrix}_{\rm LEP/EWPO} \quad \text{vs.} \quad \begin{pmatrix} 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \end{pmatrix}_{\Delta_{CKM}}$$

LHC (pp→eν, ee) can't compete here



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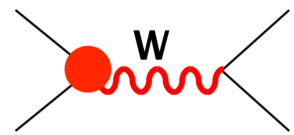

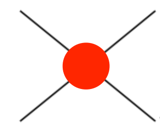

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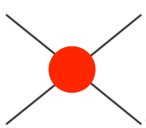

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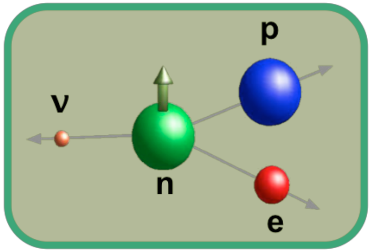
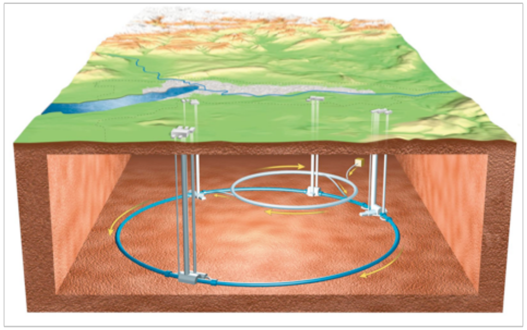
LHC reaching this level…

Scalar & tensor interactions: b_{Fierz} vs LHC





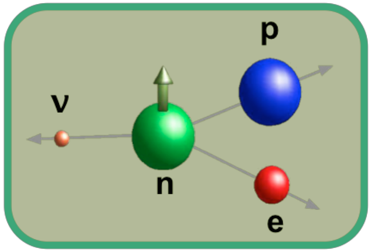
Models:

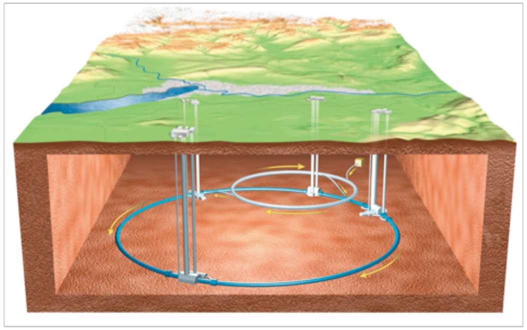
- Tree: RPV-MSSM;

- Loop: RPC-MSSM;

[Herczeg (2001), Profumo et al (2007), Yamanaka et al. (2010)]

Scalar & tensor interactions: b_{Fierz} vs LHC





Models:

- Tree: RPV-MSSM;
- Loop: RPC-MSSM;

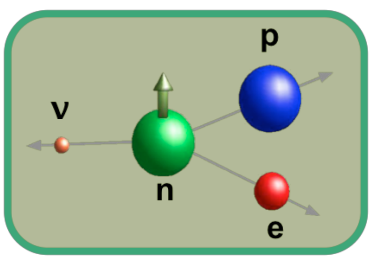
[Herczeg (2001), Profumo et al (2007), Yamanaka et al. (2010)]

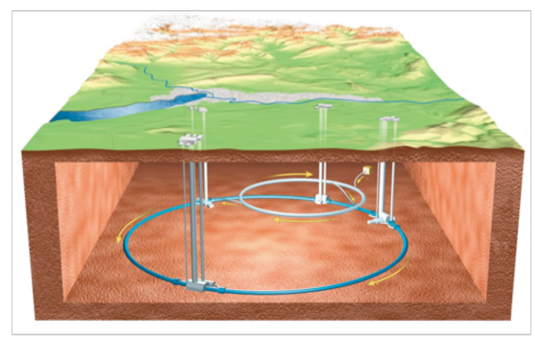
But... Extremely hard to avoid $\pi \to l\nu$

- Tree: chiral theories... $(1 \pm \gamma_5)$
- Loop: QED & EW mixing $(S,T \to P)$

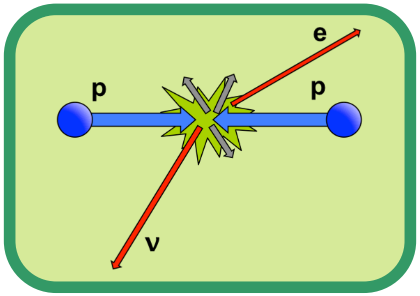
$$|\mathcal{A}(\pi \to \ell\nu)|^2 \sim m_\ell^2 \left(1 + \frac{M_{QCD}}{m_\ell}\epsilon_P\right)^2$$

Scalar & tensor interactions: b_{Fierz} vs LHC



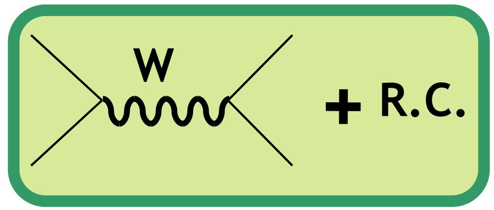


LHC limits on $\varepsilon_{S,T}$



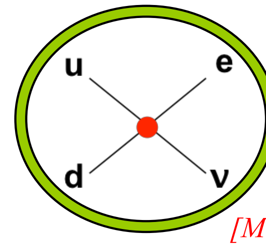
=

SM background



+

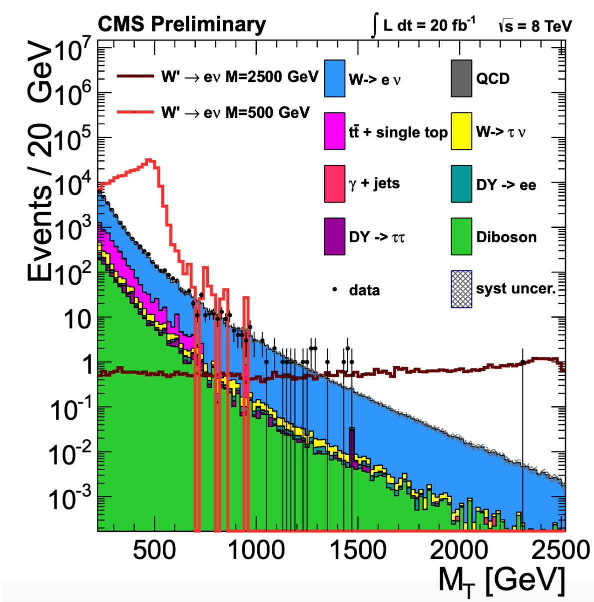
NP (EFT)

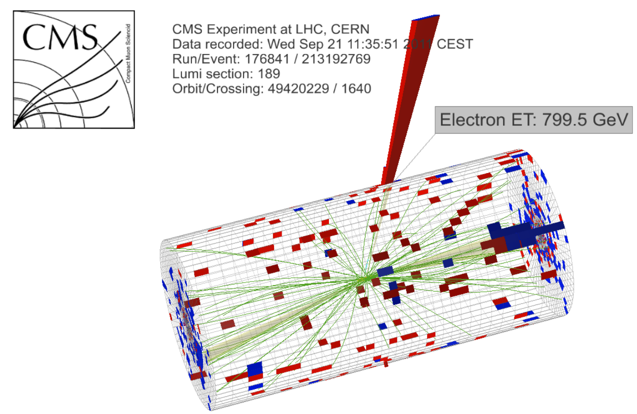


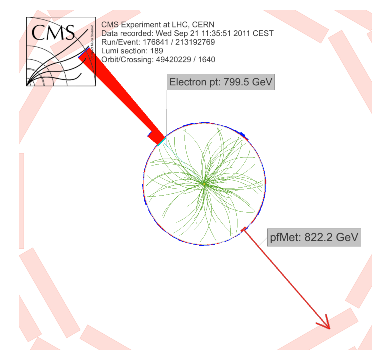
[MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)*]*
[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*
[Bhattacharya et al, PRD85 (2012)*]*

$$N_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \sigma_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \left(\sigma_W + \sigma_S\,\varepsilon_S^2 + \sigma_T\,\varepsilon_T^2\right)$$

(Interference w/ SM ~ m/E)

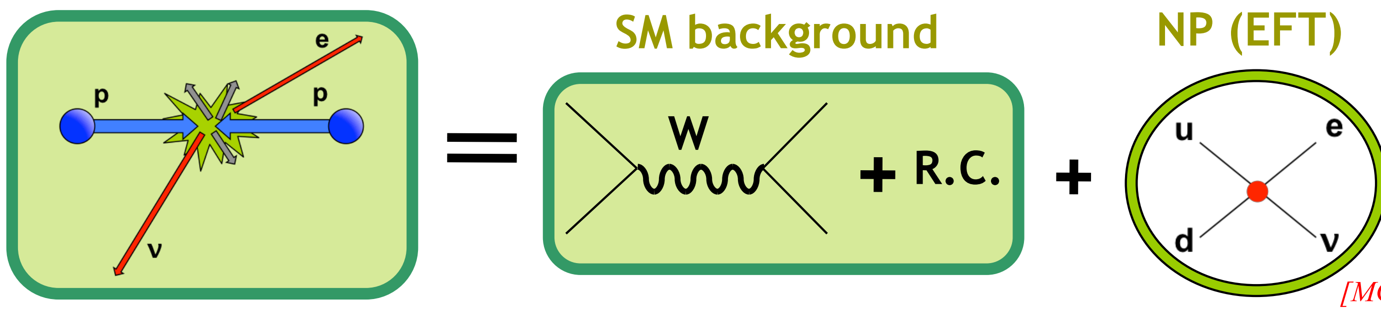






$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1-\cos\Delta\phi_{e\nu})}$$

LHC limits on $\varepsilon_{S,T}$



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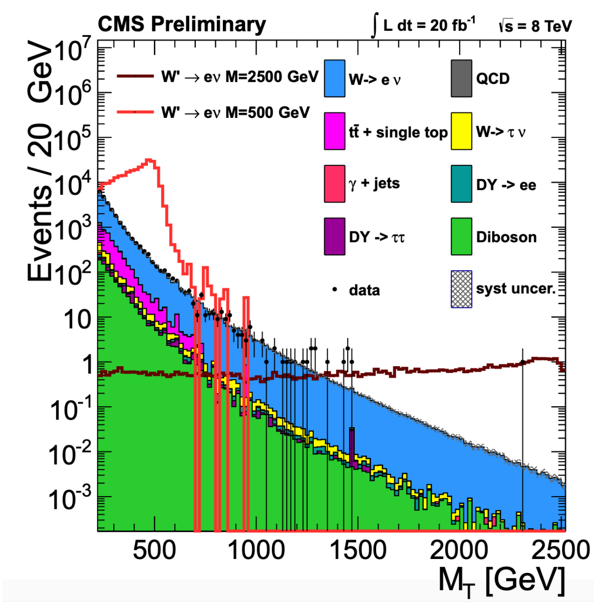

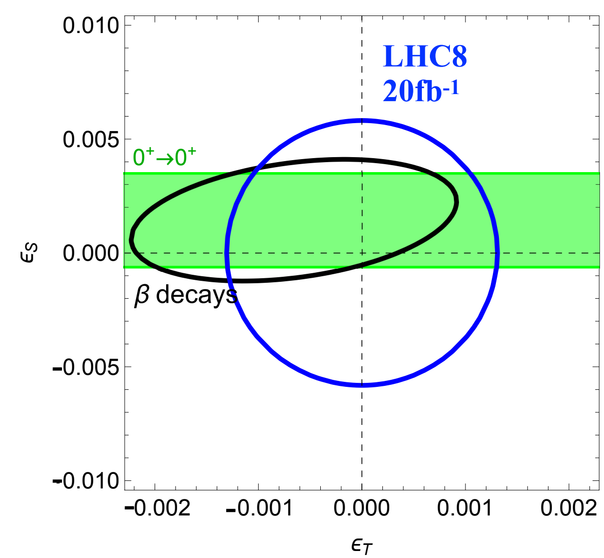

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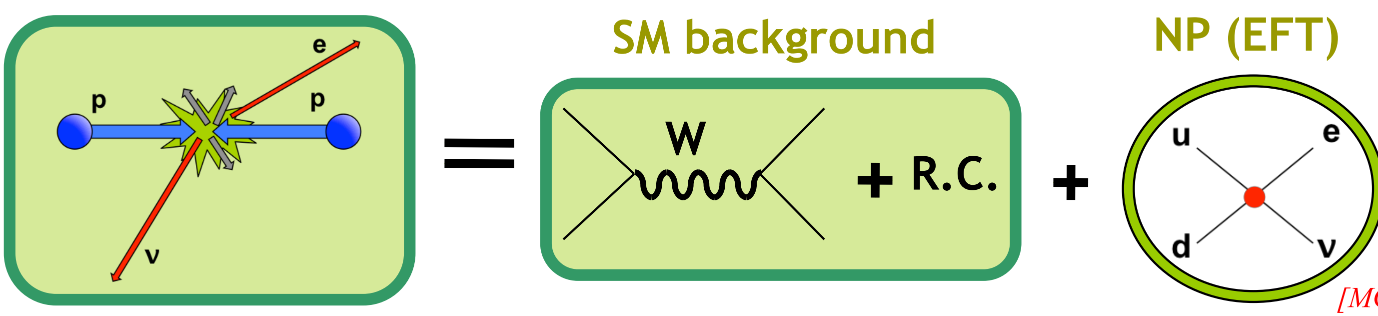

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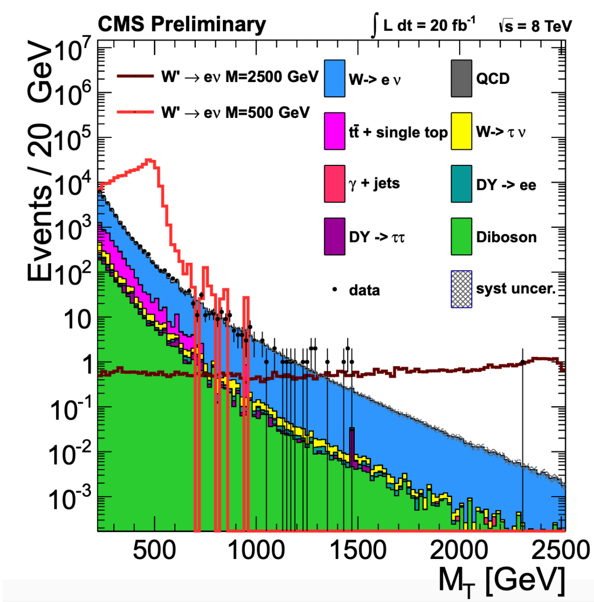

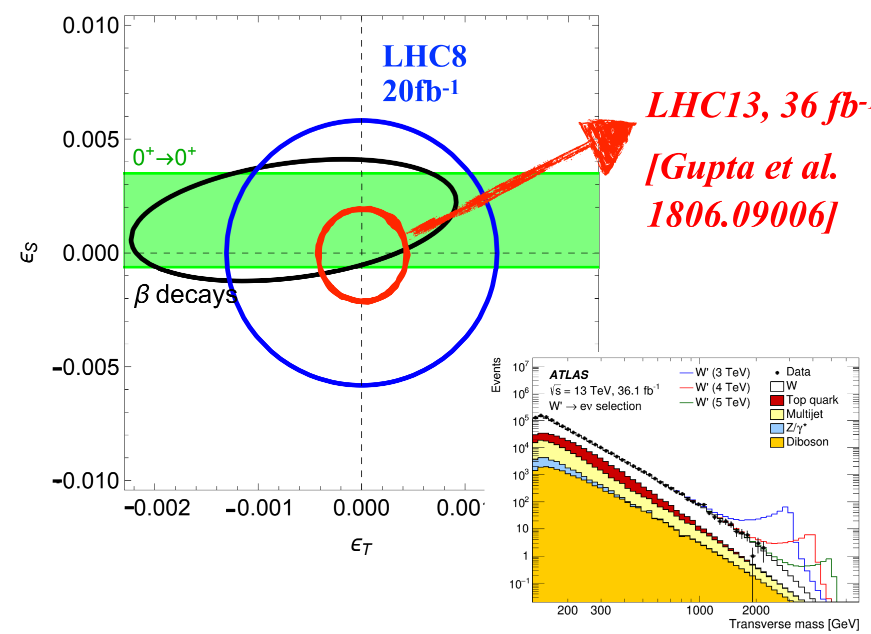

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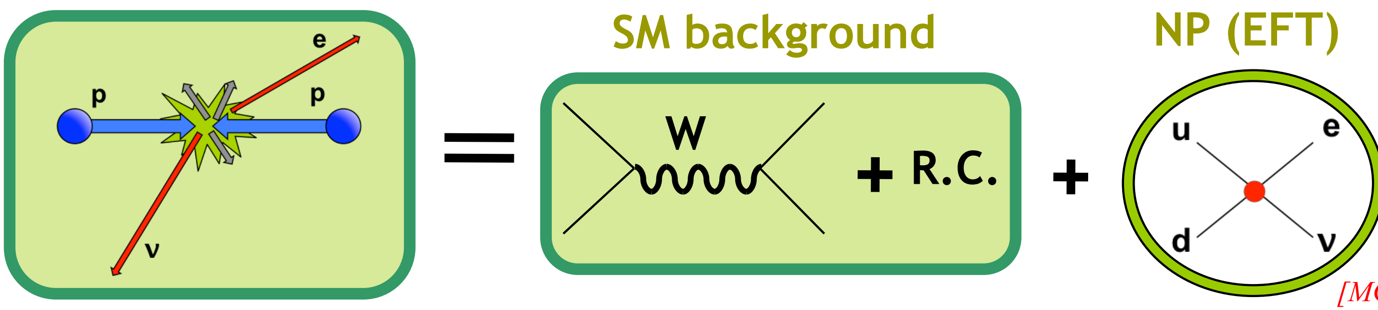

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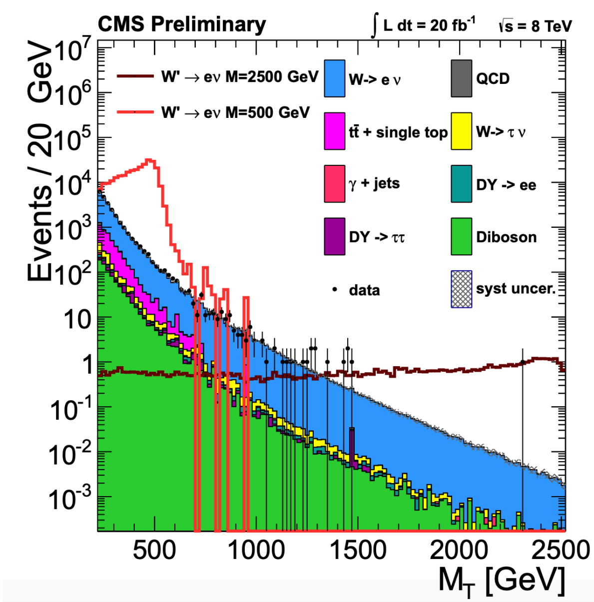
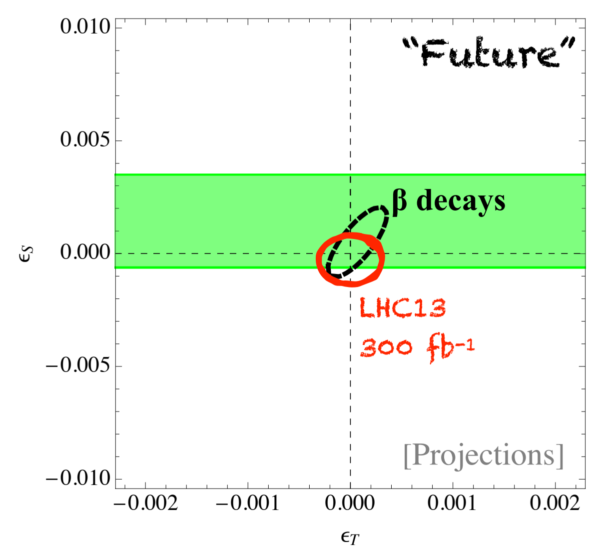
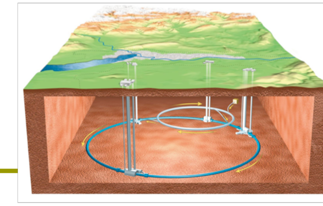
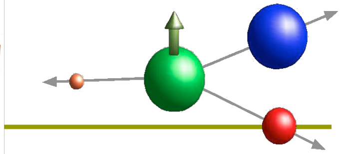




[MGA, O. Naviliat Cuncic, N. Severijns, 1803.08732;
Gupta et al. 1806.09006]

Conclusions

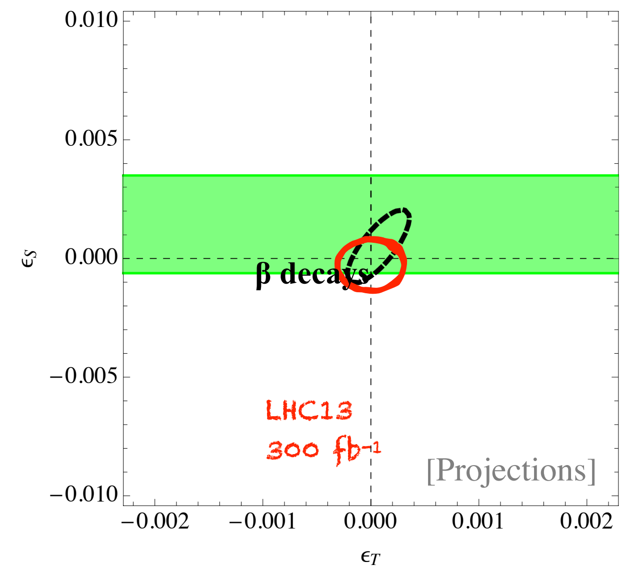




- (Sub) permil-level precision in β decays

$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix}$$

- A lot of progress!
  (4 papers cited in this talk appeared in the last 10 days)
  - QCD (charges)
  - Experiment
  - Inner RC?? Nuclear corr??



- General EFT analysis available
  → Comparison between β-decay observables;
  → Comparison with APV, LEP, LHC, …
  → β decays are competitive TeV probes;
  → ESS role can be clearly established

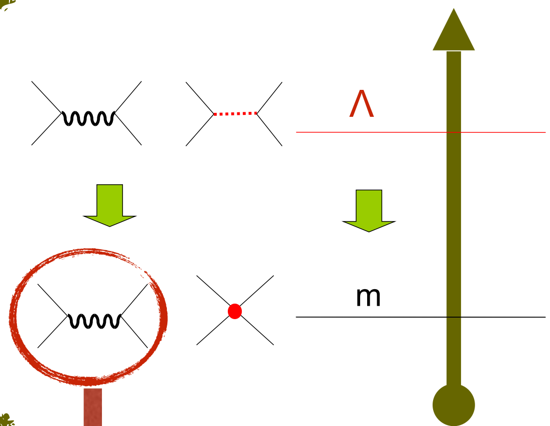
$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$$

Backup slides

What's an EFT?

Not assumption independent!

EFT = Fields + Symmetries

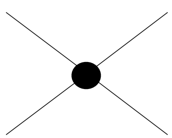


$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

$$\mathcal{L}_{eff} = \mathcal{L}_4(\phi) + \frac{1}{\Lambda}\mathcal{L}_5(\phi) + \frac{1}{\Lambda^2}\mathcal{L}_6(\phi) + \dots \rightarrow \sum \alpha_i \mathcal{O}_i$$

α_i : Wilson coefficients.

$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$$



$$-\frac{4G_F}{\sqrt{2}}\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\mu$$

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient

Data → **(Correlated) bounds on the EFT Wilson Coefficients** → **Matching with a specific NP model**

From hadrons to quarks

Likewise...

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

$$\partial_\mu \left(\bar{u}\gamma^\mu\gamma_5 d\right) = i(m_d + m_u)\bar{u}\gamma_5 d \quad \Rightarrow \quad g_P = \frac{M_n + M_p}{m_d + m_u} g_A = 348(11)$$

Implications? It almost compensates the bilinear suppression!

$$\langle p(p_p)|\bar{u}\gamma_5 d|n(p_n)\rangle = g_P(q^2)\bar{u}_p(p_p)\gamma_5 u_n(p_n) \quad \sim q/M \sim 10^{-3}$$

"since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted"

[Jackson, Treiman & Wyld, 1957]

The same β decay experiments that set bounds on S & T, are also sensitive to P!

$$\langle b\frac{m}{E}\rangle \approx 0.23\epsilon_S - 3.45\epsilon_T - 0.03\epsilon_P$$

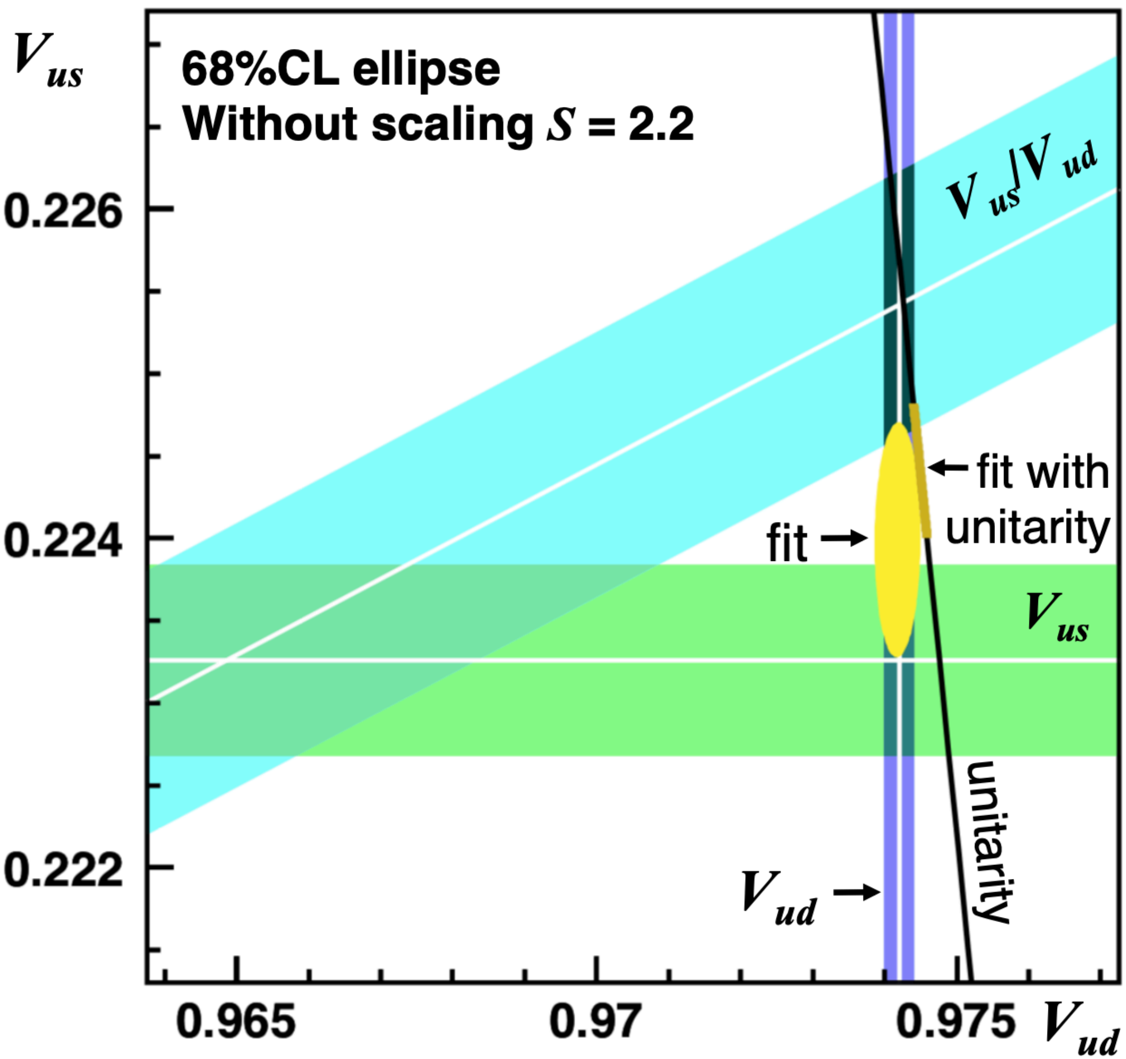
From current data:

ε_P = - 0.08(15) (90%CL)

But... the bounds on ε_P from pion decays are much stronger!!!

$$|\mathcal{A}(\pi \to \ell\nu)|^2 \sim m_\ell^2 \left(1 + \frac{M_{QCD}}{m_\ell}\epsilon_P\right)^2$$

CKM unitarity



Matthew Moulson & Emilie Passemar