Fundamental interaction studies with nuclear β decay

21st Colloque GANIL | **Strasbourg, Sept 2019**

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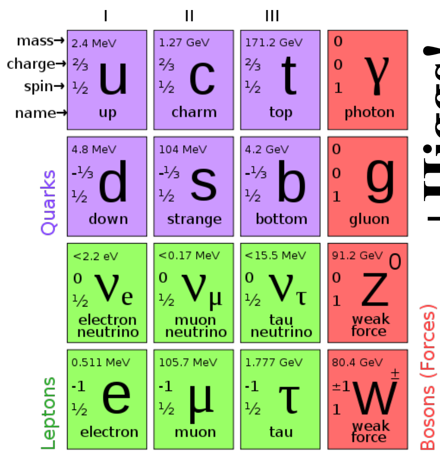
EXCELENCIA SEVERO OCHOA

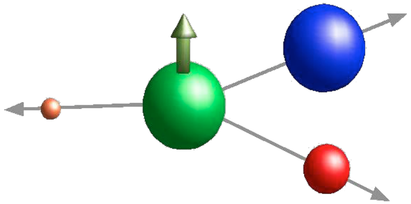
The search for 'New Physics'

Standard Model



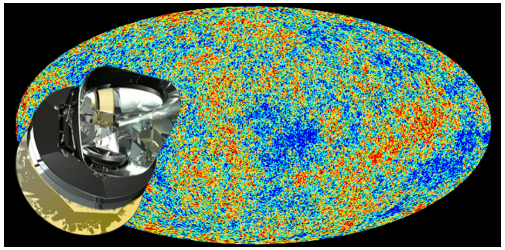
+Higgs!

NEW PHYSICS : a new theory that completes the SM and solves (at least some of) the current puzzles.

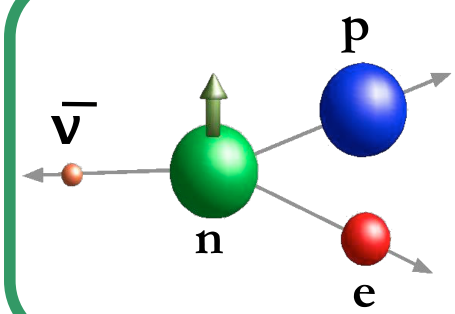


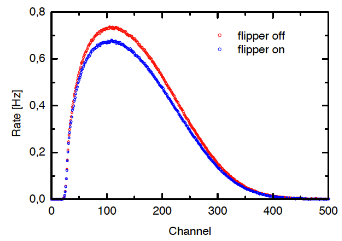
New Physics experimental searches...

- **Energy frontier ➔ LHC, ...**
- **Intensity frontier ➔ Nuclear physics, muon, ...**
- **Cosmic frontier ➔ Planck, ...**



New Physics searches with β decays





Precise data

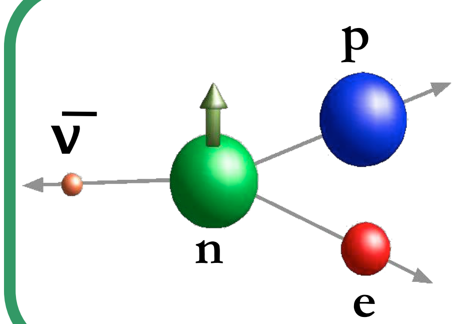
+

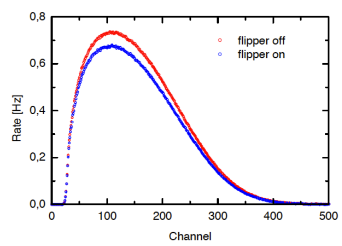
Precise SM predictions

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

[Hardy & Towner'15]

New Physics searches with β decays





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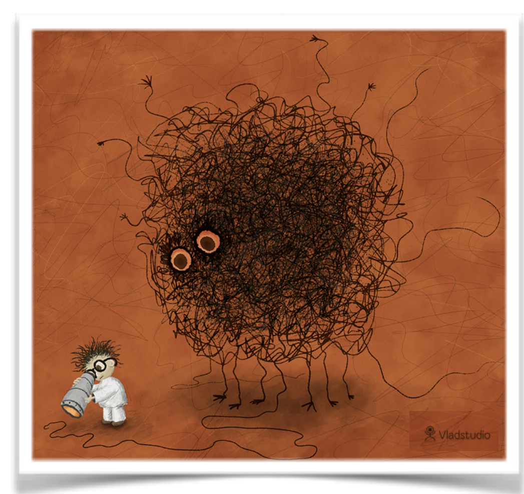
Implications for New Physics?

- **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? EFTs!**



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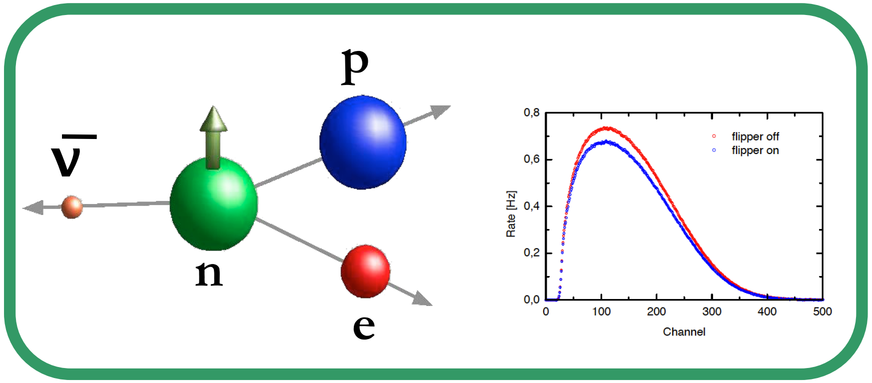

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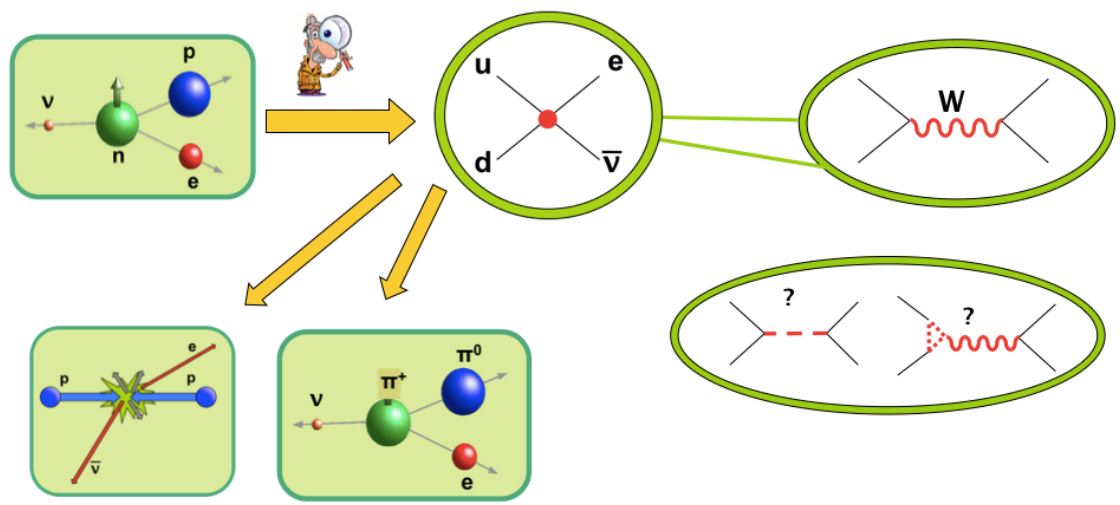
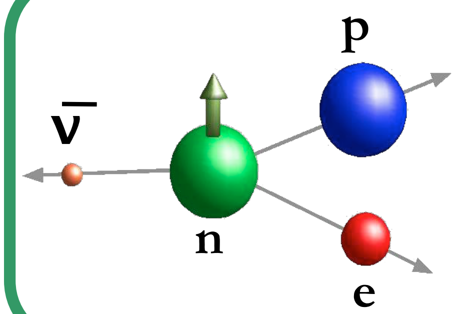
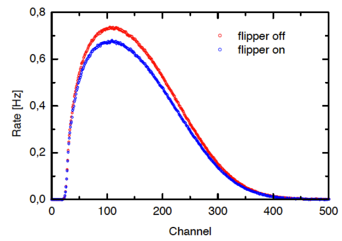
Competitive probes?

- **Other low-E searches**
- **High-E (LHC!!)**



New Physics searches with β decays





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Competitive probes?

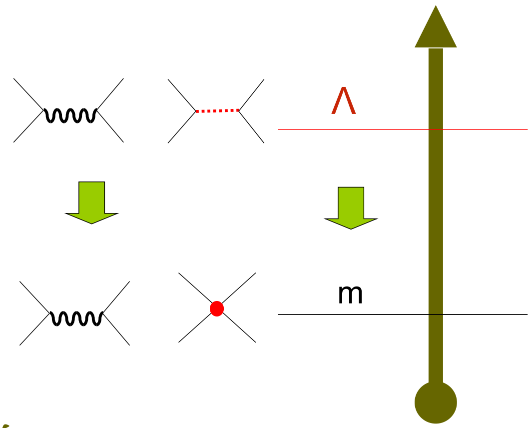
- **Other low-E searches**
- **High-E (LHC!!)**

Very active field!

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

… outdated a few months afterwards!

What's an EFT?



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

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

α_i : **Wilson coefficients.**

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

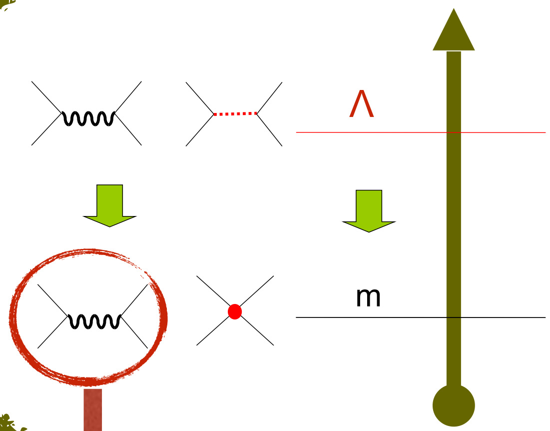
Effective Field Theory = Fields + Symmetries

Fields:
- nuclei, e, ν
- hadrons, e, ν
- q, u, d, l, e
- W, Z, γ, g
- …

Symmetries:
- Lorentz
- QED
- SU(2) x U(1)
- Flavour sym?
- B, L;

Not assumption independent!

What's an EFT?



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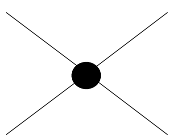
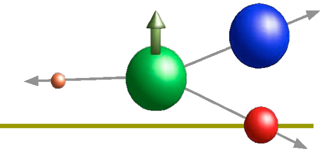


$$-\frac{4G_F}{\sqrt{2}}\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\mu$$

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

Wilson coefficient

Comparing experiments



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

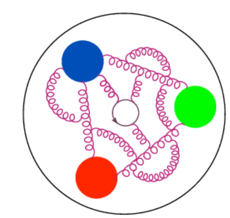
$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar{\nu}_e} = \; & \bar{p}\, n \; (C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5\nu_e) \\
& + \bar{p}\gamma^\mu n \,(C_V \bar{e}\gamma_\mu\nu_e - C'_V \bar{e}\gamma_\mu\gamma_5\nu_e) \\
& + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \,(C_T \bar{e}\sigma_{\mu\nu}\nu_e - C'_T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

[Lee & Yang'1956]

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

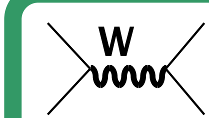
$$
\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu \cdot \bar{u}\gamma^\mu d_L \; + \; \sum_{\rho\delta\Gamma} \epsilon^\Gamma_{\rho\delta}\, \bar{\ell}_\rho\Gamma\nu \cdot \bar{u}\Gamma d_\delta\right]
$$

$$C_i \sim FF \times \varepsilon_i$$



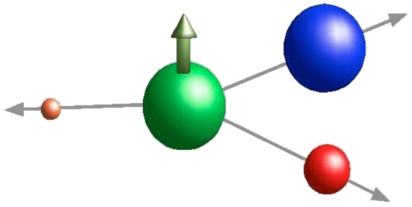
- How to compare with LHC experiments?
  - ➔ Effective Lagrangian at the **quark** level at the EW scale!

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



Hadrons:

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



Hadronic EFT

[Lee & Yang'1956]

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

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

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

+ terms with RH neutrinos

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Linear approx:
SM + small + (small)²

(Or simply no ν_R: $C_i = C_i'$)

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~~+ terms with RH neutrinos~~

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

Linear approx:
SM + small + (small)²

(Or simply no ν_R: $C_i = C_i'$)

Wrong reason... $C_P = 348(11)\,\epsilon_P$
[MGA & Camalich, PRL 112 (2014)]

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

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

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$G_F V_{ud}$ (1 + NP)   [Lifetime shift]

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

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g_A (1 + NP)

Only way out: lattice QCD!

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

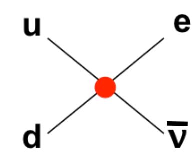
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E) \left\{ 1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J} \right\}$$

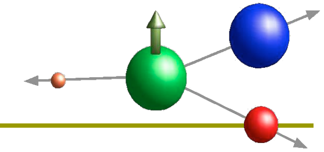
$$b_{(B)} = \#\, C_S + \#\, C_T$$

Fierz term [1937]

[+ CPV effects]

Probing the Fierz term





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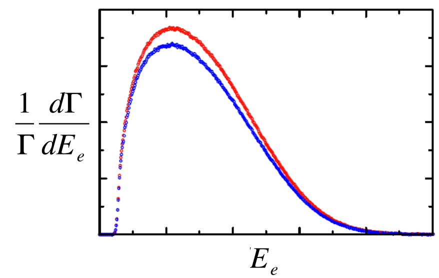
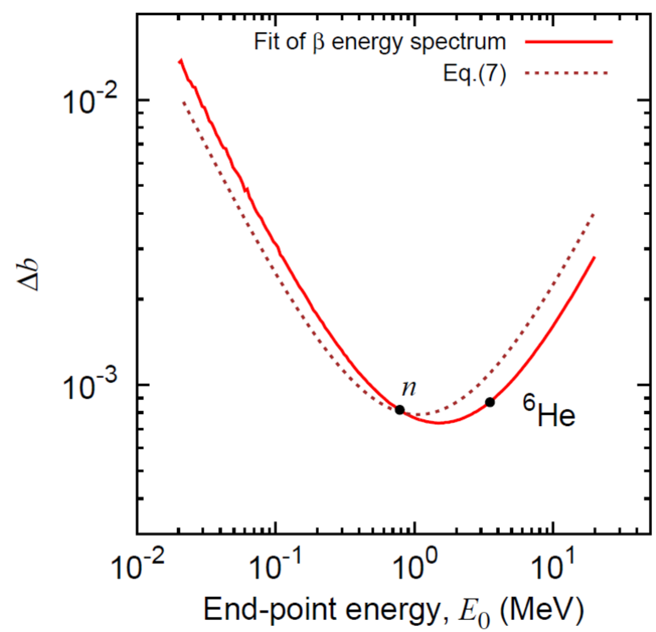
✓ Direct effect in the spectrum:

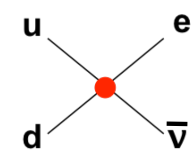


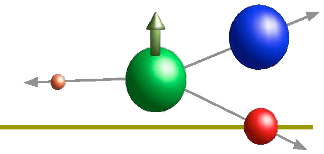
Optimal endpoint: 1-4 MeV

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



Probing the Fierz term





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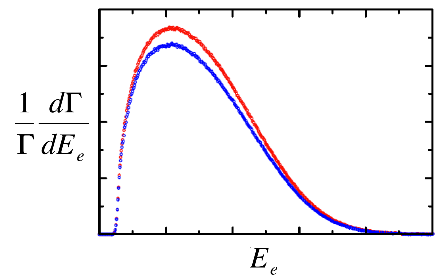
✓ Direct effect in the spectrum:



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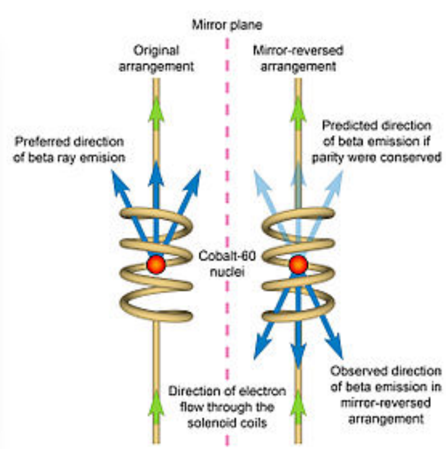
[MGA & Naviliat-Cuncic, PRC94 (2016)]

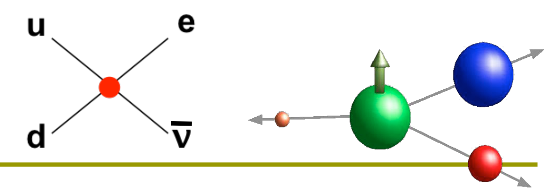
✓ Indirect effect in the asymmetries:

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

PS: Not always valid!
(proton spectrum)
[MGA & Naviliat-Cuncic, PRC94 (2016)]



Probing the Fierz term



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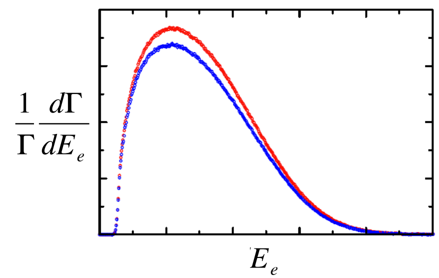

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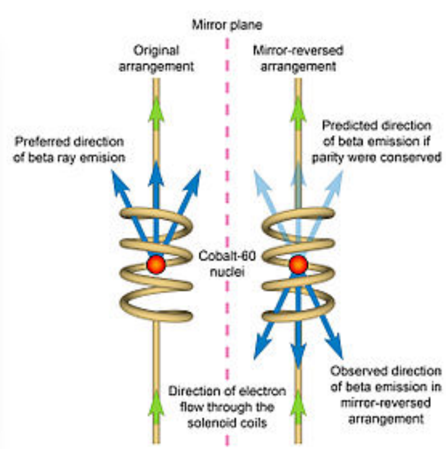
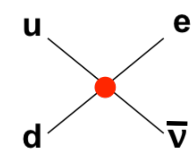
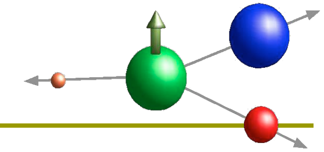


Talks by X. Flechard & R. Combe on Thursday about these measurements in GANIL & ISOLDE

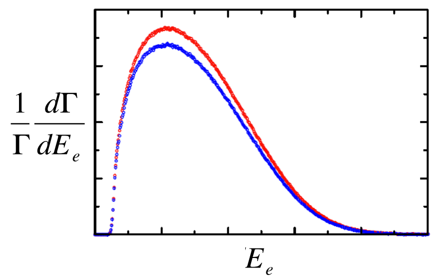
Probing the Fierz term





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

✓ Direct effect in the spectrum:



Optimal endpoint: 1-4 MeV
[MGA & Naviliat-Cuncic, PRC94 (2016)]

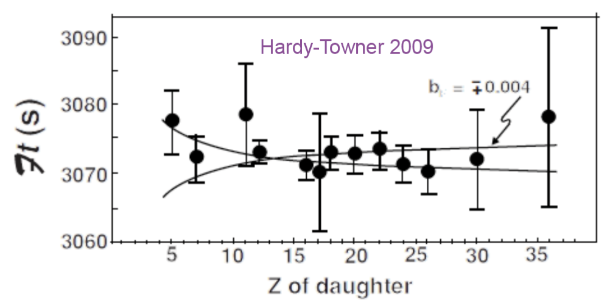
✓ Indirect effect in the asymmetries:

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

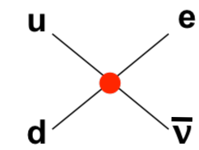
PS: Not always valid!
(proton spectrum)
[MGA & Naviliat-Cuncic, PRC94 (2016)]

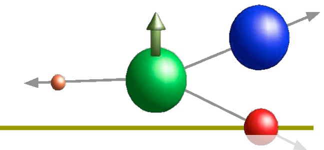
✓ Indirect effect in the Ft-values & neutron lifetime:

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



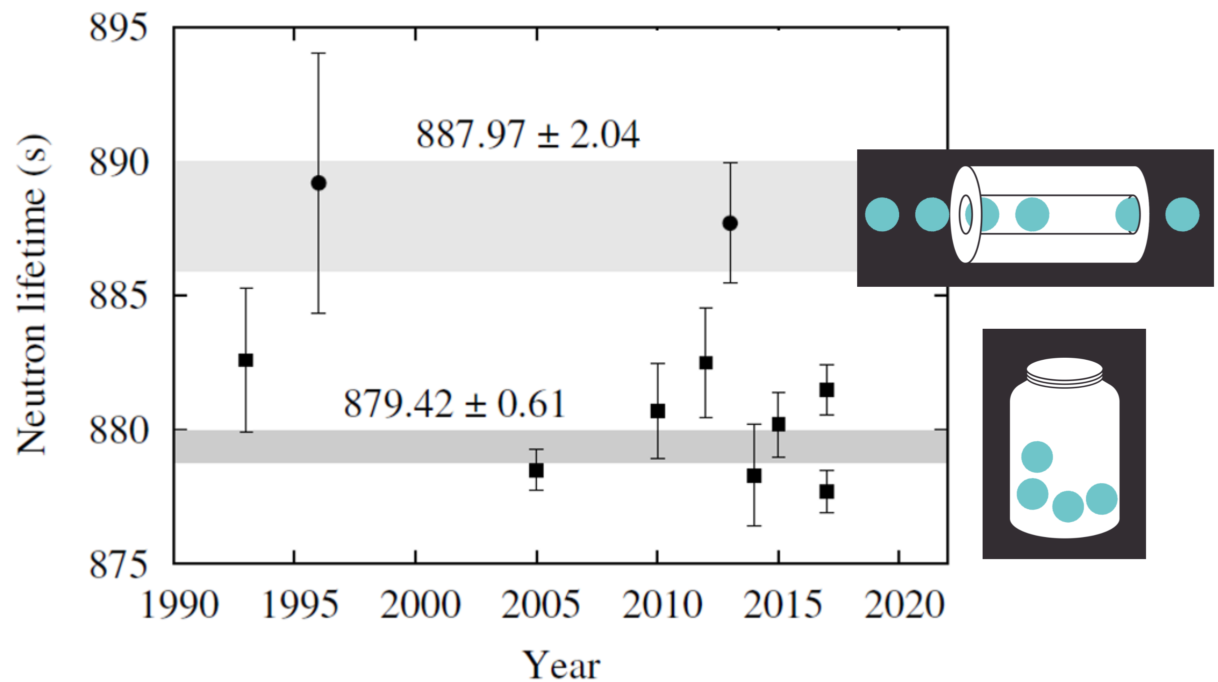
Probing the Fierz term





Heavy NP cannot explain the beam vs. bottle tension

.... Light NP?
[Fornal & Grinstein PRL (120 (2018)]



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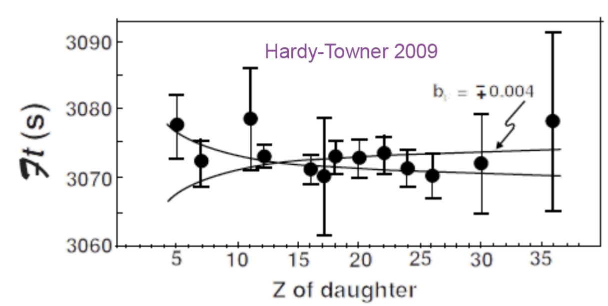
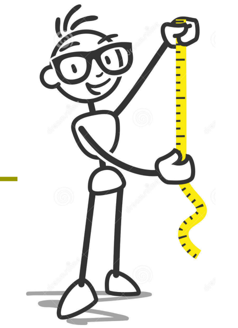


Current data

Precision:
O(0.01 – 1)% !!



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

Nuclei

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

[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

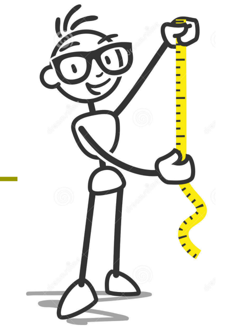
Parameter	Value
τ_n (s)	879.75(76) * (S = 1.9!!)
a_n	$-0.1034(37)$ *
$\tilde{a}_n$	$-0.1090(41)$
$\tilde{A}_n$	$-0.11869(99)$ * (S = 2.6!!)
$\tilde{B}_n$	0.9805(30) *
λ_{AB}	$-1.2686(47)$
D_n	$-0.00012(20)$ *
R_n	0.004(13)

* Average

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

Current data (+ TH!!)

Precision:
O(0.01 – 1)% !!



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

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Th: QED + Isospin symmetry breaking corrections

$$\mathcal{F}t_i \equiv ft_i\,(1+\delta_R')\,(1+\delta_{NS}-\delta_C)$$

Current data (+ TH!!)

Precision:
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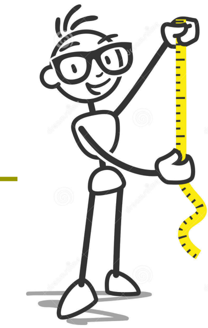

[MGA, O. Naviliat Cuncic, N. Severijns, Prog. Part. Nucl. Phys. 104 (2019) 165-223]

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R_n	0.004(13)

* Average

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

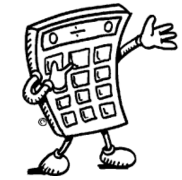
NEW Including Perkeo-III, PRL122 (2019):
$A_n = -0.11958(18)$ [S=1] → 5x!

NEW Including aSPECT (1908.04785):
$a_n = -0.10426(82)$ → 6x!

Th: QED + Isospin symmetry breaking corrections

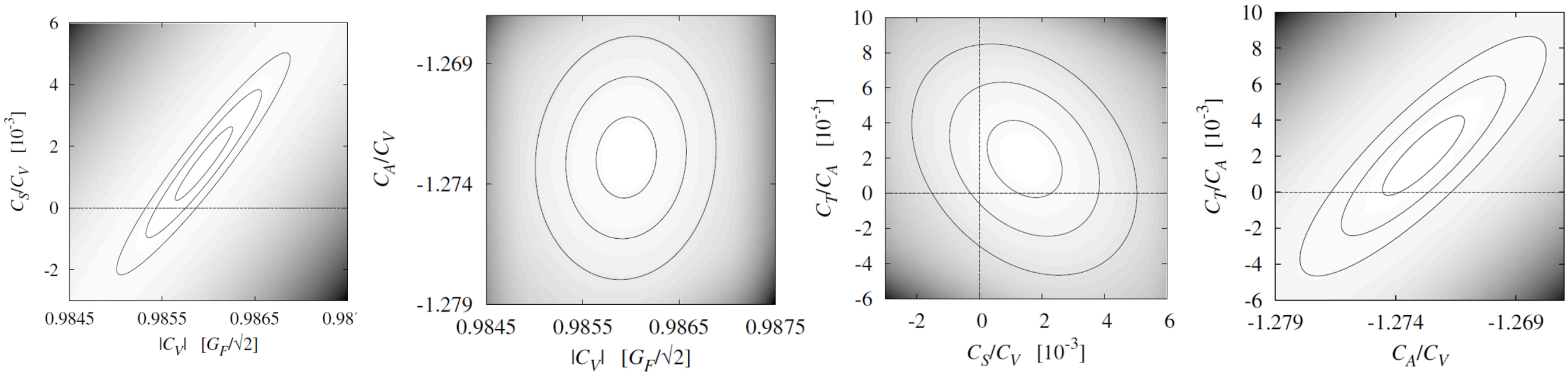
$$\mathcal{F}t_i \equiv ft_i\,(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

NEW Nuclear structure-dep. corrections ?
[Seng, Gorchtein, & Ramsey-Musolf, PRD100 (2019)]
[Gorchtein, PRL123 (2019)]



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, τn, An!

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

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

Example: $b_{GT} = f(C_i) \quad \rightarrow \quad \delta b_{GT} = 0.004$

Reachable! (NSCL, UW-Seattle?, GANIL?)!

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

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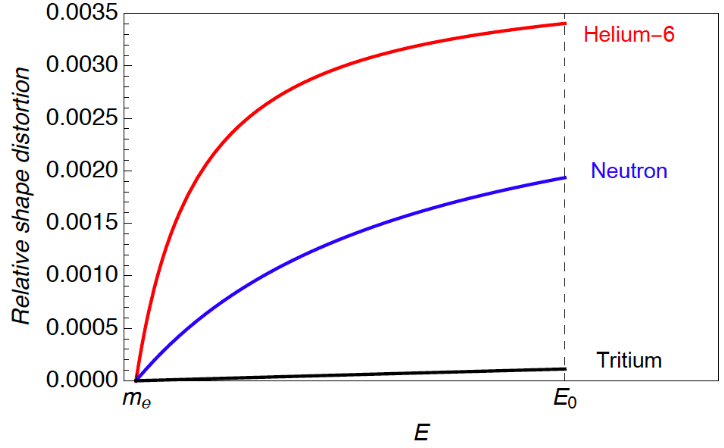
Spectrum shape measurements



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

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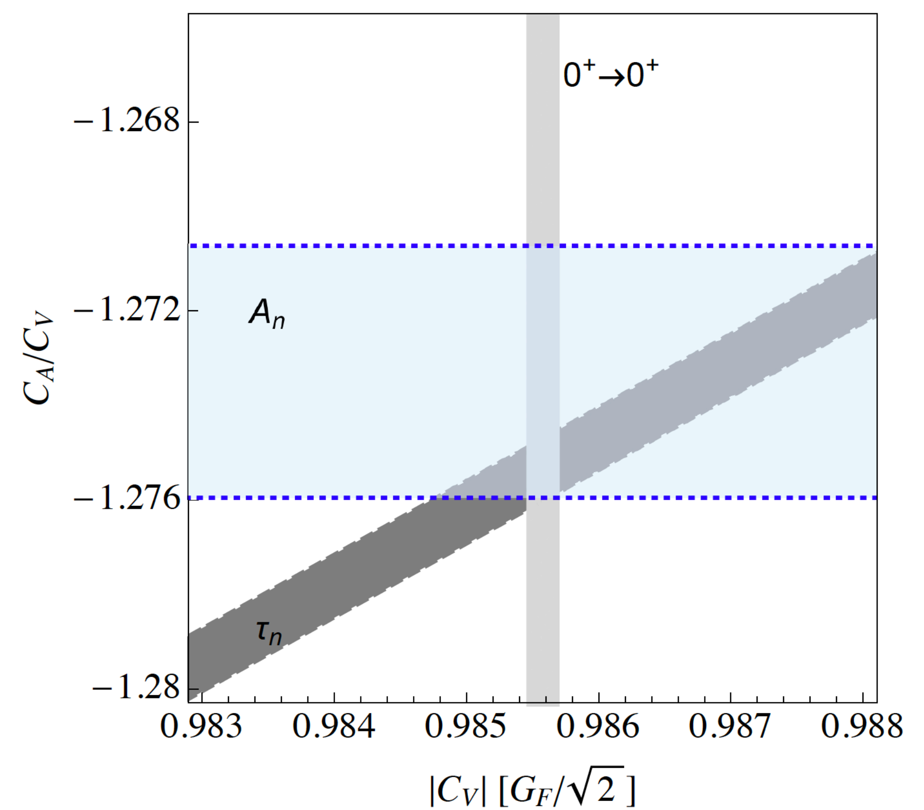
SM Limit

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

(ρ = 0.25)



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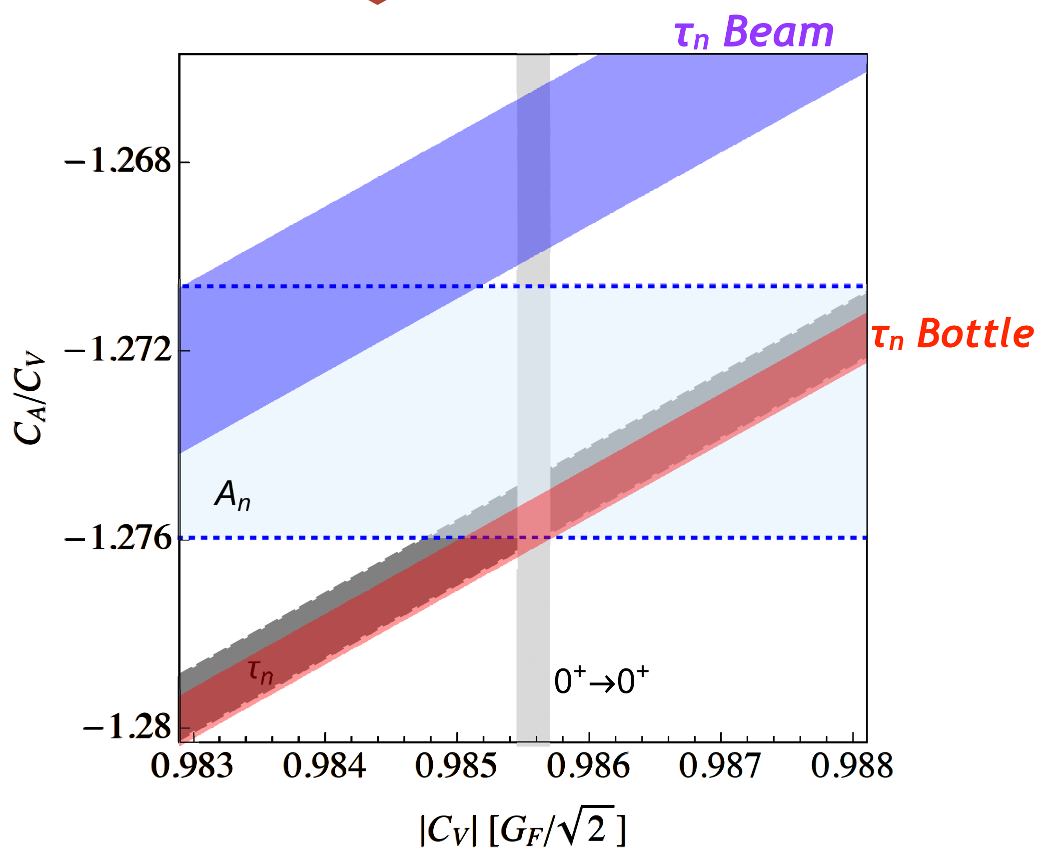

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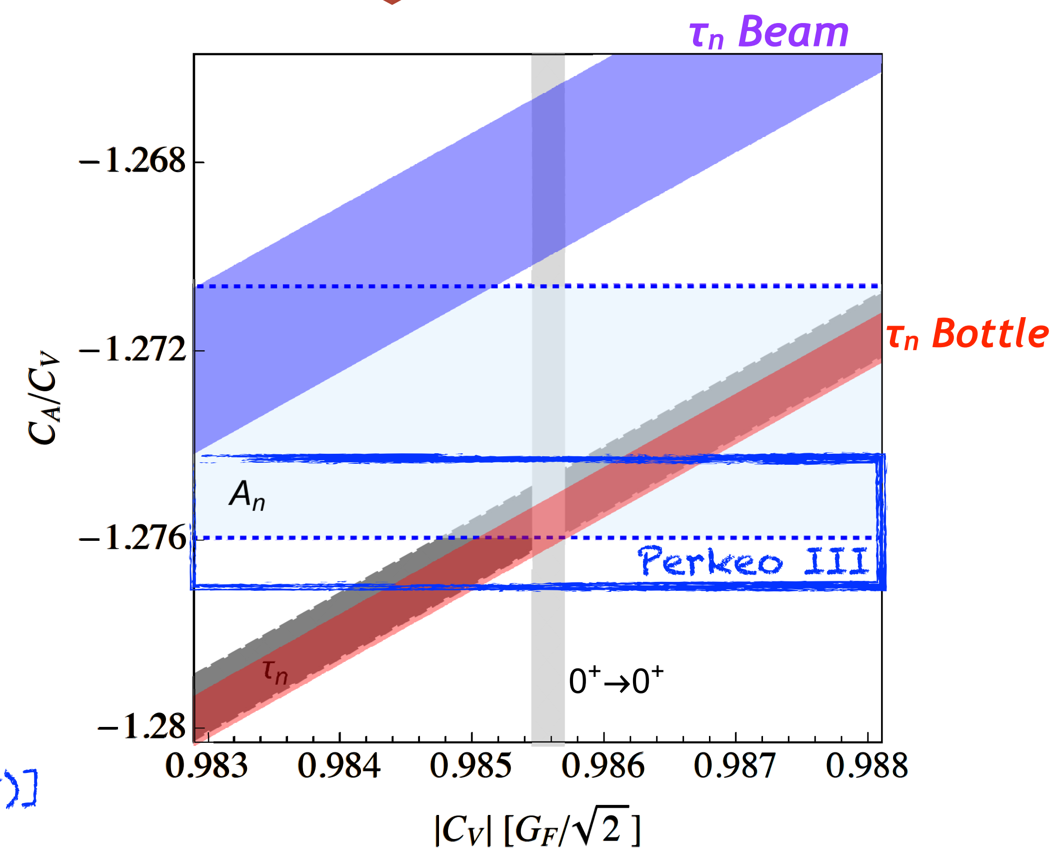


NEW

A_n = −0.11983(21) [Perkeo III, 2.5x!]
→ no dark channel
[Dubbers et al, PLB791 (2019);
Czarnecki-Marciano-Sirlin, PRL120 (2018)]

Interlude I: mirror beta decays?

- β transitions between isobaric analog states in T = 1/2 isospin doublets;
  → $|M_F|^2 = 1$ and nonzero F/GT mixing ratio (neutron!).

- Many per-mil level determinations of the Ft values! (Exp + Th)
  [Severijns et al, PRC78 (2008); Hayen & Severijns, 1906.09870; etc.]

- But mixing ratios are unknown
  → another observable (asymmetries!) needed;

${}^{A}_{J}$Decay	$\mathcal{F}t$ [sec]	asymmetry
${}^{19}_{1/2}$Ne → F	1721.44(92) [10]	$A_{\beta,0}$=-0.0391(14)
${}^{21}_{3/2}$Na → Ne	4071(4) [11]	$\tilde{a}_{\beta\nu}$=0.5502(60)
${}^{35}_{3/2}$Ar → Cl	5688.6(7.2)	$\tilde{A}_{\beta}$=0.430(22)
${}^{37}_{3/2}$K → Ar	4605.4(8.2) [12]	$\tilde{A}_{\beta}$=-0.5707(19) [13]

NOTE: LPCTrap analysis ongoing for Ne-19 & Ar-35

- SM analysis: [Naviliat-Cuncic & Severijns, PRL102 (2009)]
  V_{ud} can be extracted with 0.1% precision!
  Although (*currently!*) not competitive, it's a nontrivial crosscheck;

- What about BSM? [Falkowski, MGA & Naviliat-Cuncic, work in progress]
  - In the absence of RH neutrinos, the situation is much like in the SM;
  - Once RH neutrinos are introduced that's not the case.

Interlude II: CP violation?

- If the EFT coefficients are complex, CP-violating effects appear;
- CP violation of "standard" origin is way too small in β decays;
- Beta decay data (D & R correlations) →

$$\mathrm{Im}(C_A/C_V) = -0.00034(59)\,,$$
$$\mathrm{Im}(C_S/C_V) = -0.007(30)\,,$$
$$\mathrm{Im}(C_T/C_A) = 0.0004(33)\,,$$

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

- Improvements also expected:

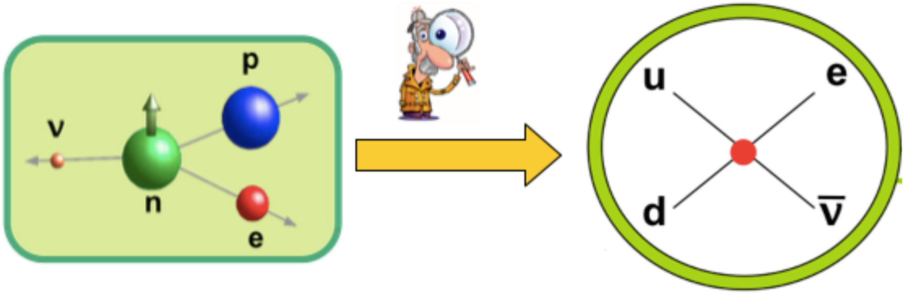
Coefficient	Precision goal	Experiment (Laboratory)	Comments
D	$\mathcal{O}(10^{-4})$ [418]	MORA (GANIL/JYFL) [418]	In preparation (^{23}Mg)
R	$\mathcal{O}(10^{-3})$ [427]	MTV (TRIUMF) [427–429]	Data taking ongoing (^{8}Li)
D, R	$\mathcal{O}(0.1)$% [399]	BRAND (ILL) [399,400]	Proposal

ANR funded!

[E. Liénard's talk, Thu 11:10]

Quarks (low-E):

$$d \rightarrow u\, e^- \bar{\nu}$$



From hadrons to quarks

[Lifetime shift]

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

$$C_V \sim g_V\, G_F^\mu\, V_{ud}\,(1 + \mathrm{NP})\,(1 + \mathrm{RC})$$
$$C_A/C_V \sim -\,g_A/g_V\,(1 - 2\,\epsilon_R)$$
$$C_S \sim g_S\,\epsilon_S$$
$$C_T \sim g_T\,\epsilon_T$$

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

From hadrons to quarks

$\tilde{V}_{ud}$

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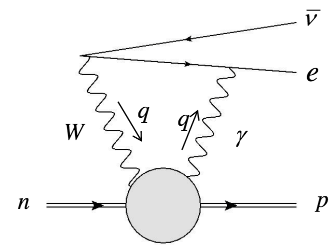
Inner RC:

2.361(38)% [Marciano-Sirlin, PRL96 (2006)]
2.467(22)% [Seng et al., PRL121 (2018)]
2.426(32)% [Czarnecki et al., 1907.06737]



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From hadrons to quarks

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

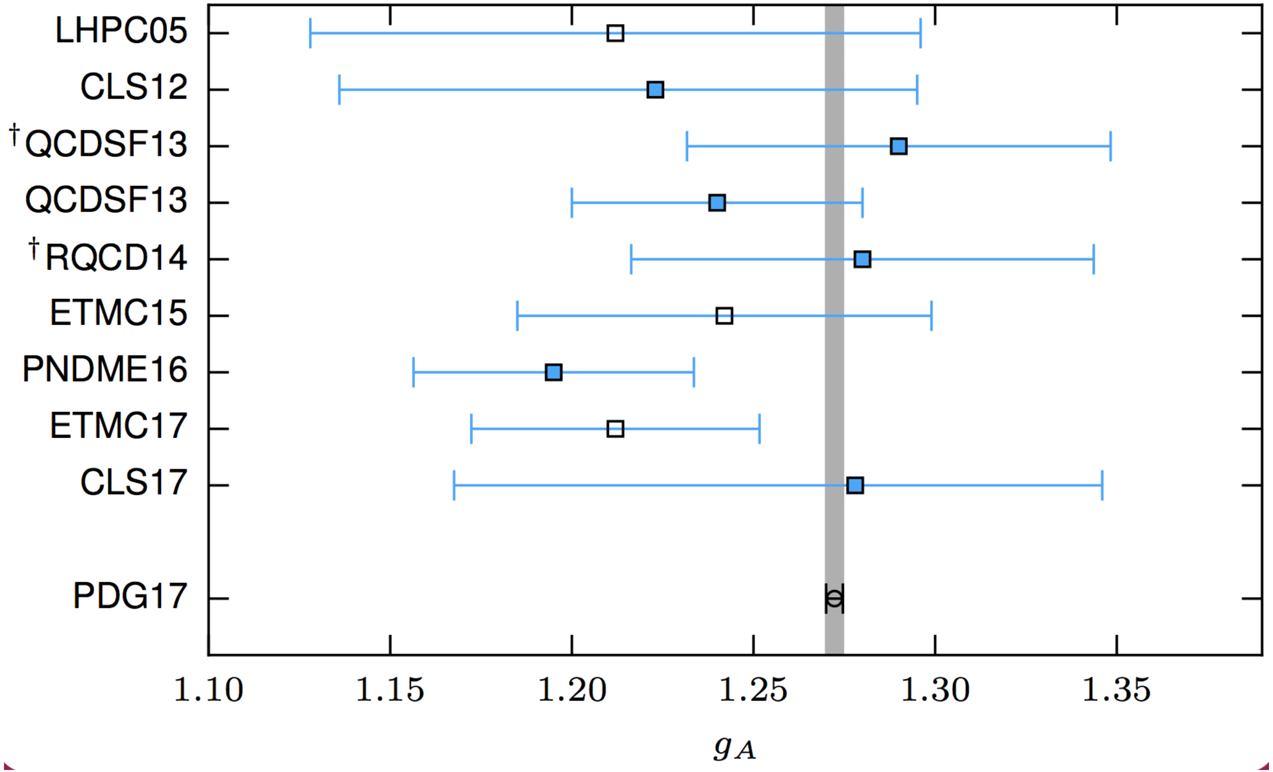
$$C_S \sim g_S\, \epsilon_S$$

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

Axial charge

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

[A. Nicholson's talk, CIPANP2018]



From hadrons to quarks

$$
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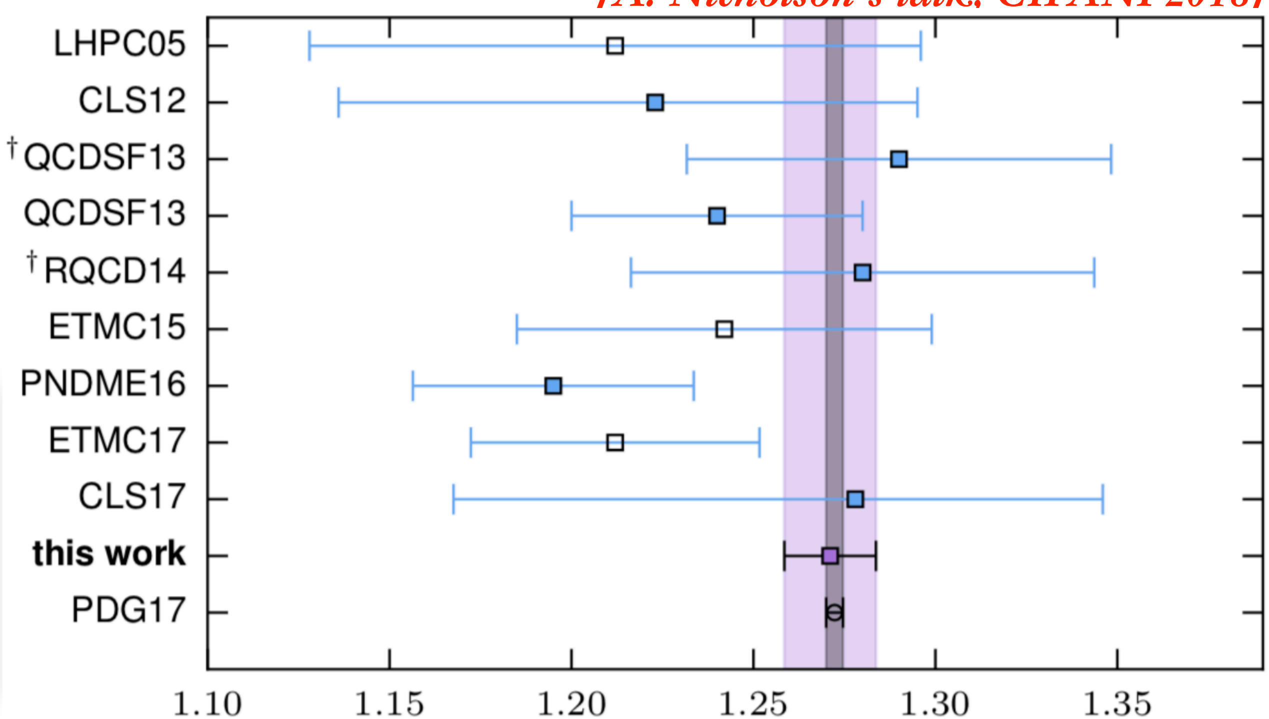
C_S &\sim g_S\, \epsilon_S \\
C_T &\sim g_T\, \epsilon_T
\end{aligned}
$$

Axial charge

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

[A. Nicholson's talk, CIPANP2018]



!!

$g_A^{LQCD} = 1.271 \pm 0.013$

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

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

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

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

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

Axial charge

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BUT...

- PNDME'18: g_A = 1.218(39)
  "We argue that our error estimate is more realistic"

- FLAG average: g_A = 1.251(33)

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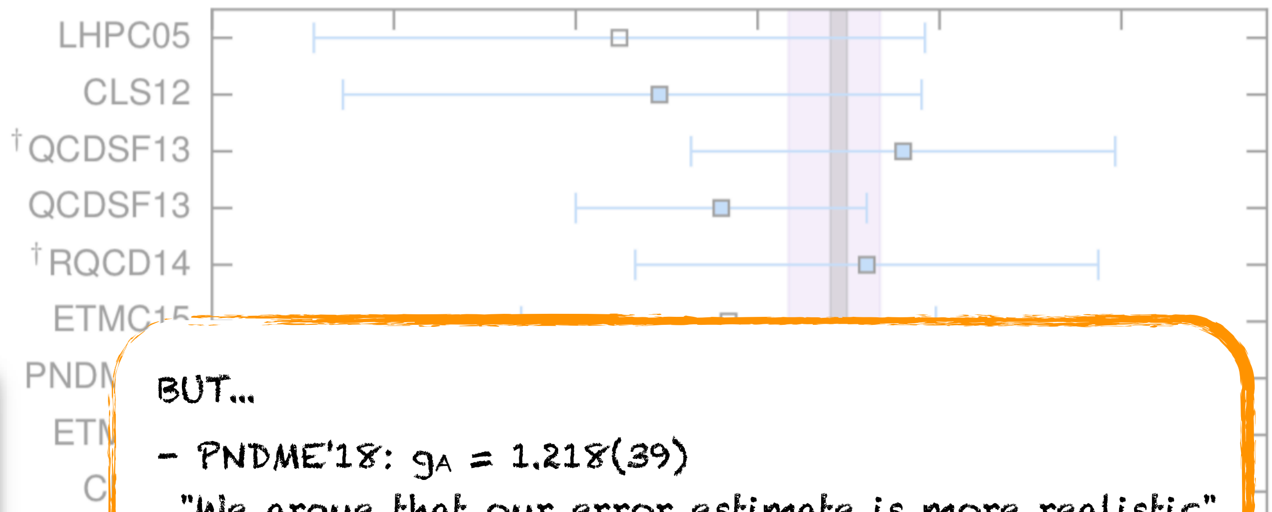

!!

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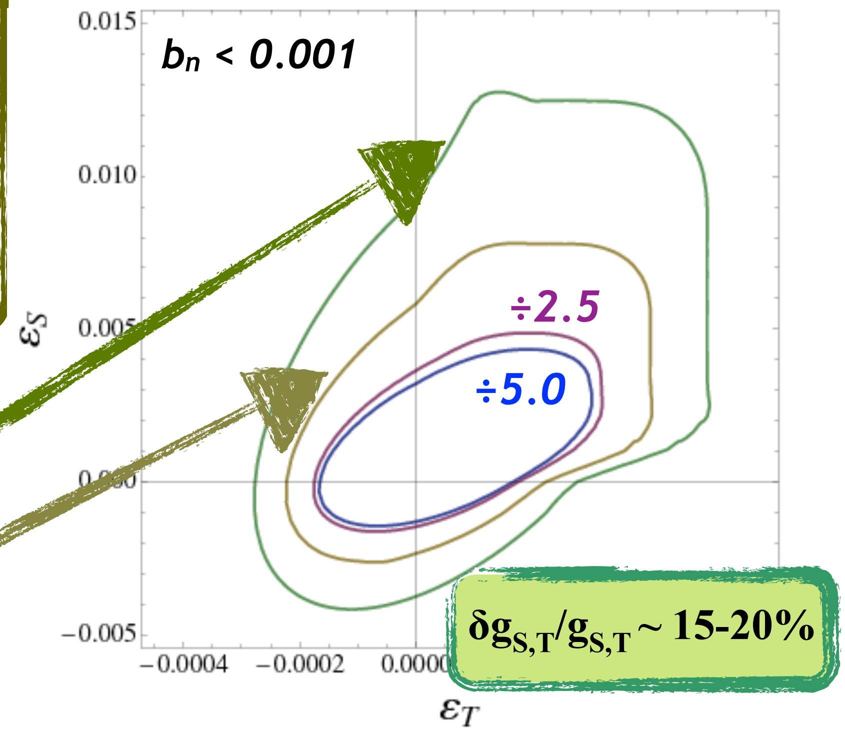
Scalar & tensor charges

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



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

From hadrons to quarks

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$$C_A/C_V \sim -g_A/g_V\,(1-2\,\epsilon_R)$$
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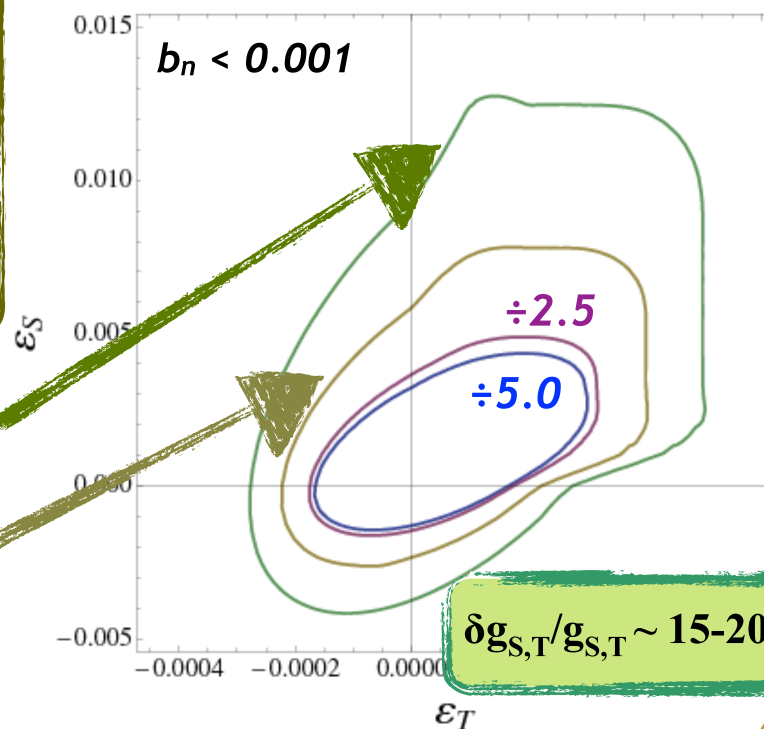
Adler et al. '1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35)
LHPC 2012	1.08(32)	1.04(02)
RQCD 2014	1.02(35)	1.01(02)
PNDME 2013/15	0.72(32)	1.02(08)
ETMC 2015/17	0.93(33)	1.00(03)
CVC	1.02(11)	-
PNDME 2016/18	1.02(10)	0.99(03)
JLQCD'18	0.88(11)	1.08(10)
…	…	…

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

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

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

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

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SM fit

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

$$\lambda = 1.27510(66)\ ,$$

(ρ = - 0.13)

From hadrons to quarks

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

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

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SM fit

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

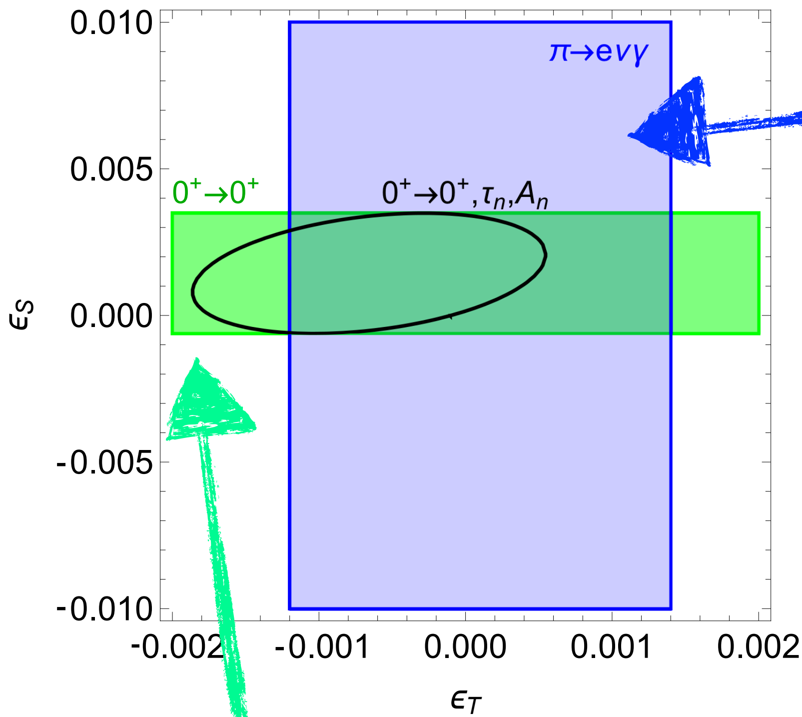
(ρ = - 0.13)

→

0.97370(14) Seng et al. PRL121 (2018)
0.97389(22) Seng et al. PRD100 (2019)
0.97365(28) Gorchtein, PRL123 (2019)
0.97389(18) Czarnecki et al. 1907.06737

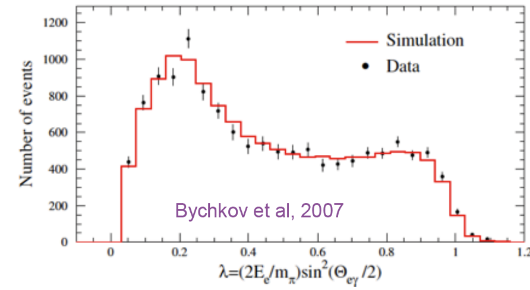
From hadrons to quarks

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



$\pi \to e\nu\gamma$

(PIBETA´2009)



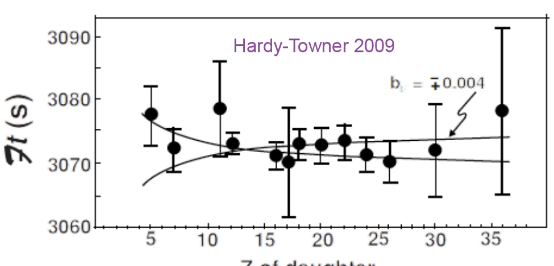
$$\langle \gamma(\epsilon, p)|\bar{u}\sigma_{\mu\nu}\gamma_5 d|\pi^+\rangle = -\frac{e}{2} f_T (p_\mu \epsilon_\nu - p_\nu \epsilon_\mu),$$

$f_T = 0.24(4)$ *[Mateu & Portolés, 2007]*

[large-N inspired resonance saturation model]

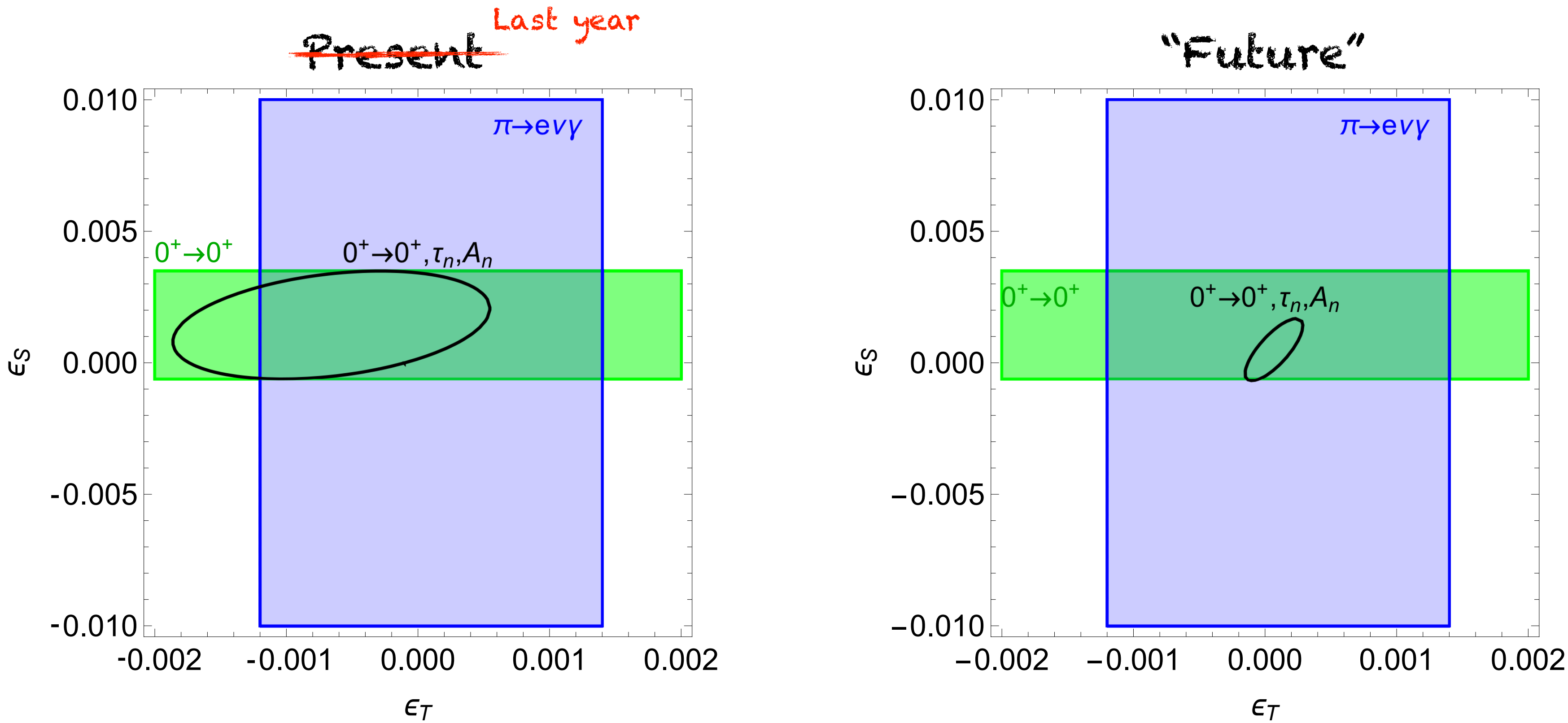
No LQCD calculation!

Superallowed nuclear β decays



From hadrons to quarks

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



Benchmark numbers
(from ongoing / planned experiments):

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

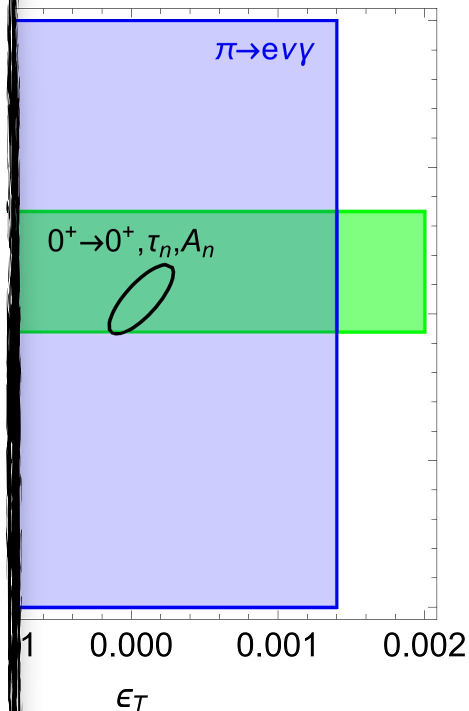
$$\tilde{A}_n,\ a_n,\ \tilde{a}_F,\ a_{GT}\ \text{ at } 0.1\%$$

$$b_{GT} = 0.001$$

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 $\beta\,p$ emitters
	0.1% [79]	WISArD (ISOLDE) [79,177]	In preparation (^{32}Ar $\beta\,p$ 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

"Future"



mbers

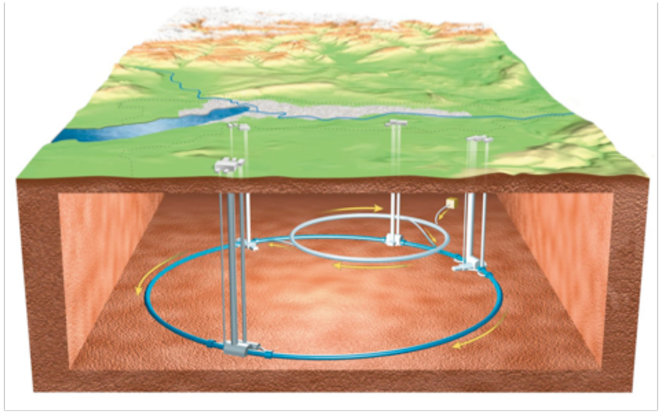
/ planned experiments):

s

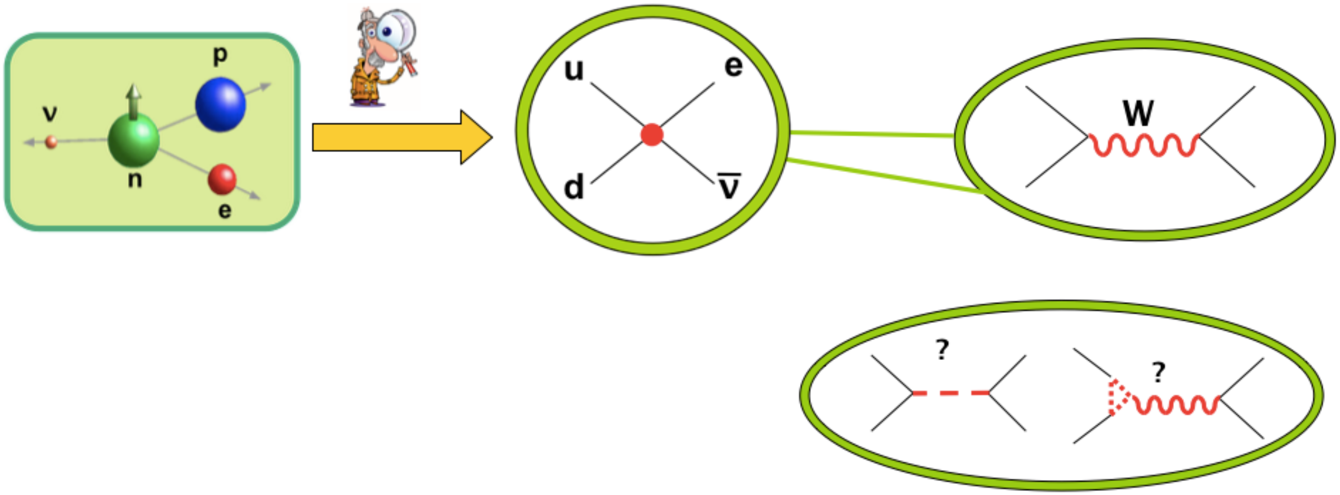
$\tilde{a}_F$, a_{GT} at 0.1%

001

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

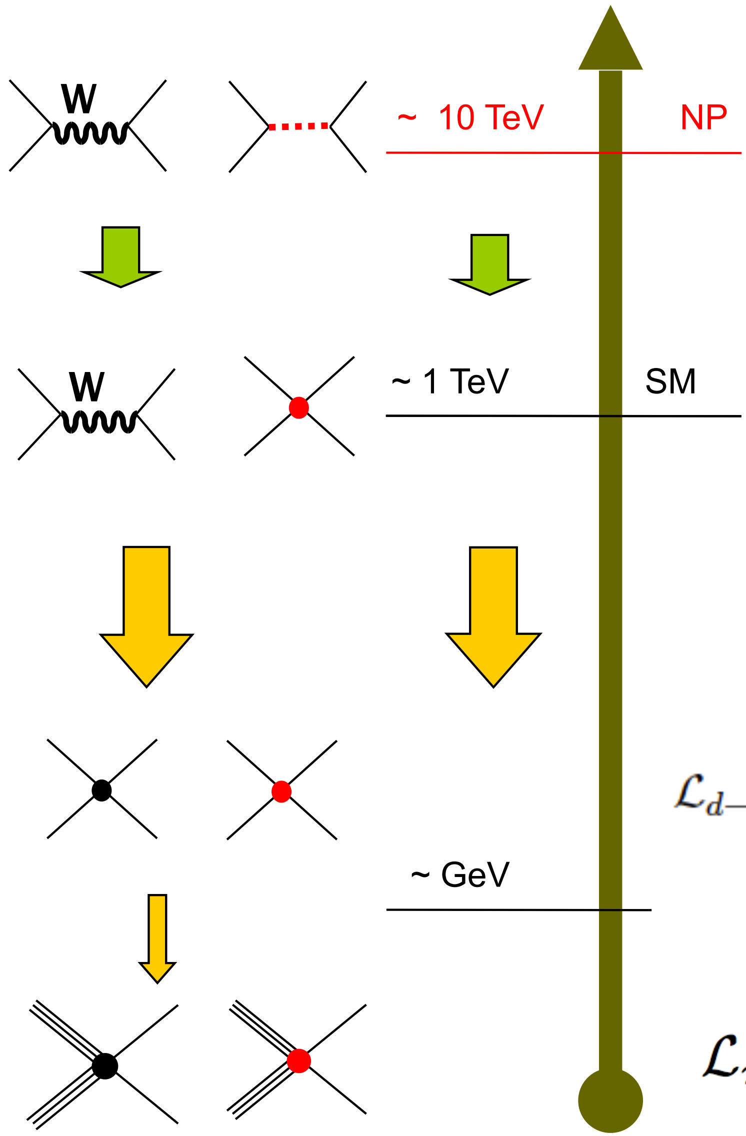


Quarks, W, Z, …



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]

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

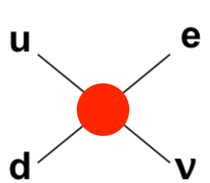
$$V_{1j}\cdot\epsilon^{j\ell}_L = 2\,V_{1j}\left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\,\left[V\hat{\alpha}^{(3)}_{\varphi q}\right]_{1j} - 2\,\left[V\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell 1j}\,,$$

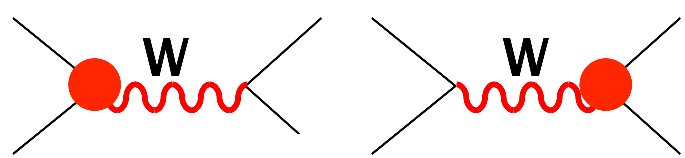
$$V_{1j}\cdot\epsilon^{j}_R = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

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

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

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



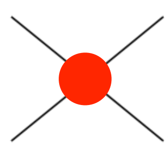


$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$

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

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

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



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

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

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

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

Matching with high-E EFT

Low-E EFT → ϵ_i, *SMEFT* → α_j

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

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

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

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

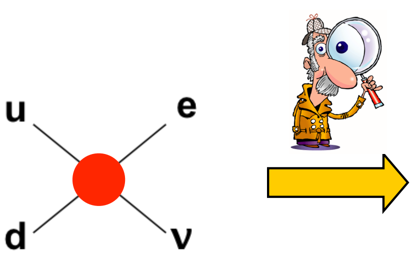
$$V_{1j}\cdot\epsilon_R^{j} = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

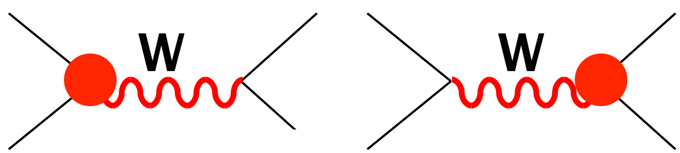
$$V_{1j}\cdot\epsilon_{s_L}^{j\ell} = -\,[\hat{\alpha}_{lq}]^*_{\ell\ell j1}\,,$$

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

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

Beta decays sensitive to a few EFT coefficients



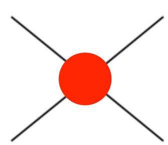


$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$

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

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

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



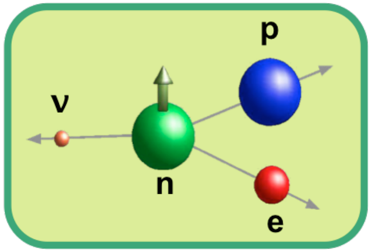
$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$

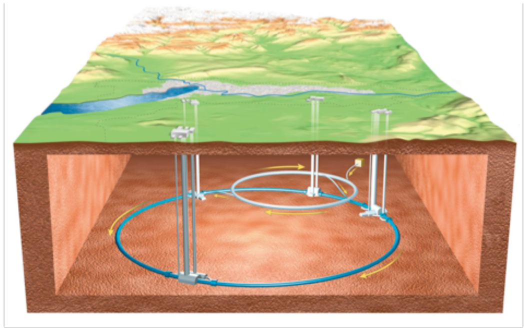
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$

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

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

Scalar & tensor interactions: b_{Fierz} vs LHC





Models:

- Tree: RPV-MSSM;

- Loop: RPC-MSSM;

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

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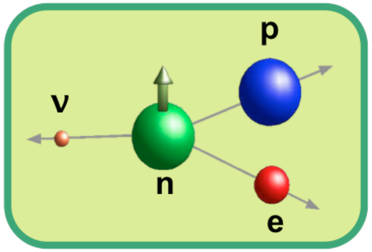

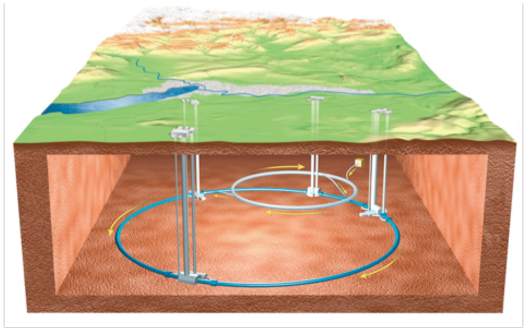

Models:

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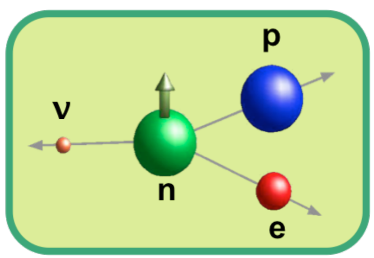
[Herczeg (2001), Profumo et al (2007), Yamanaka et al. (2010)]

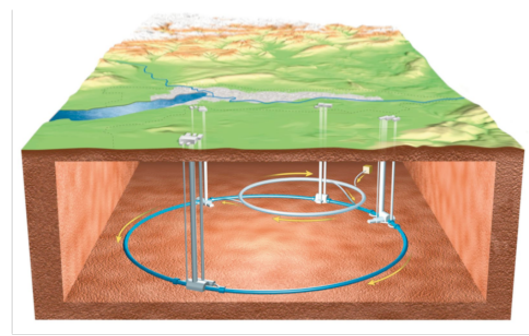
But... Extremely hard to avoid $\pi \to l\nu$

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

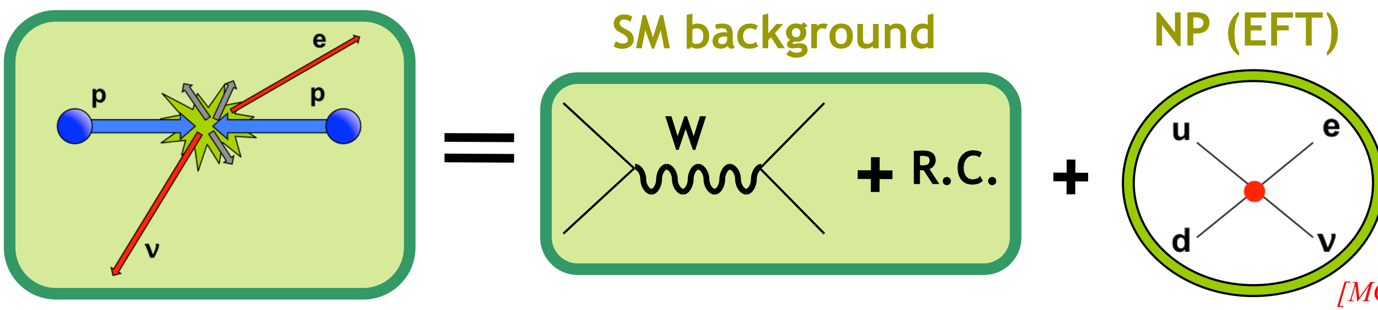
$$|\mathcal{A}(\pi \to \ell\nu)|^2 \sim m_\ell^2 \left(1 + \frac{M_{QCD}}{m_\ell}\epsilon_P\right)^2$$

Scalar & tensor interactions: b_{Fierz} vs LHC





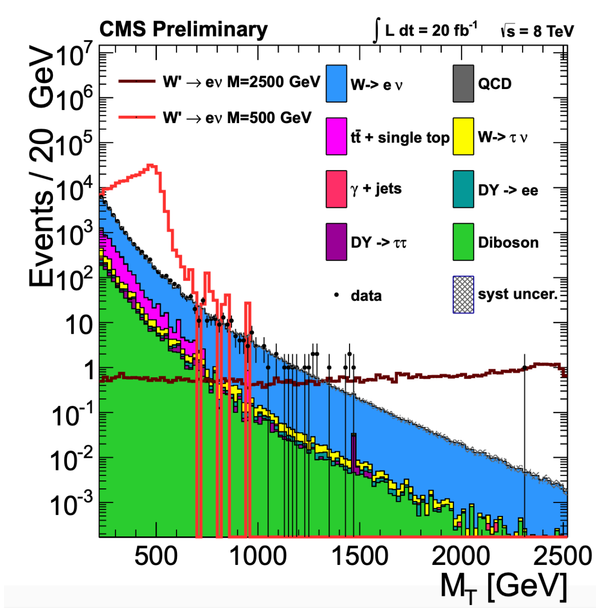
LHC limits on $\varepsilon_{S,T}$

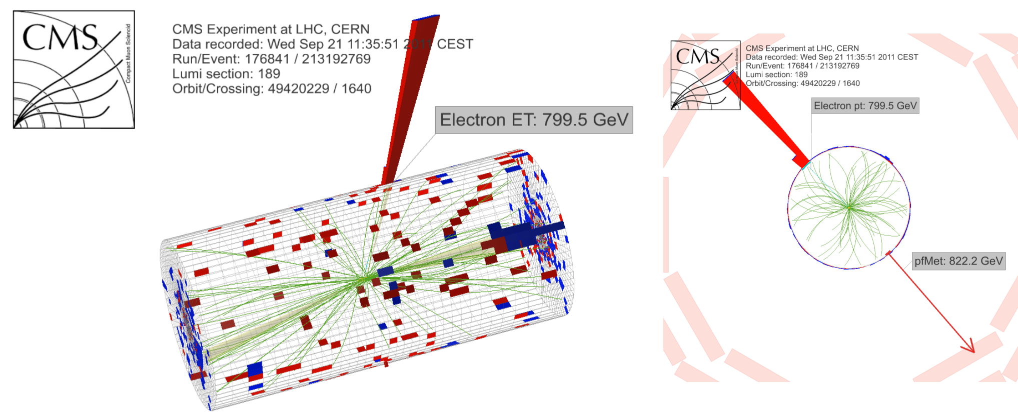


[MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)*]*
[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*
[Bhattacharya et al, PRD85 (2012)*]*

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

(Interference w/ SM ~ m/E)





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

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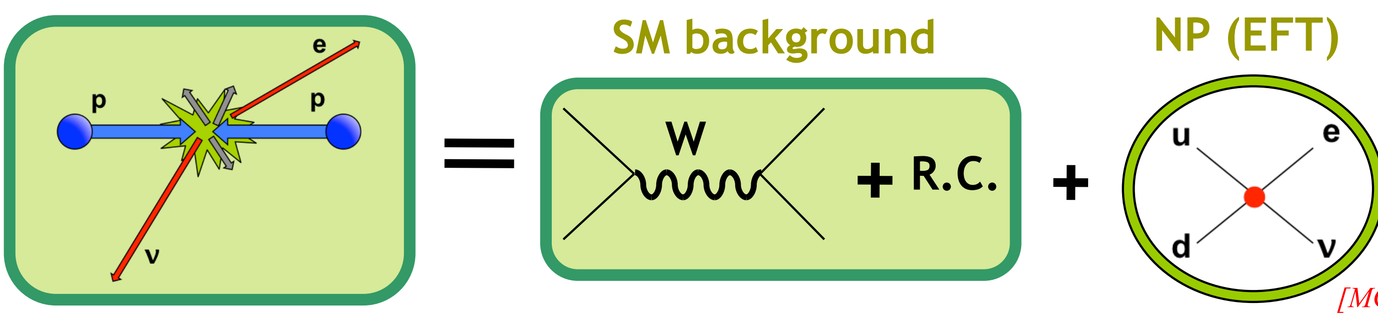

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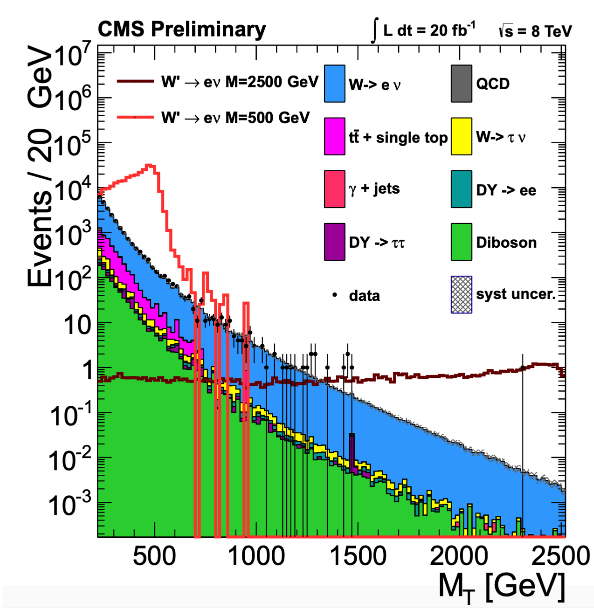

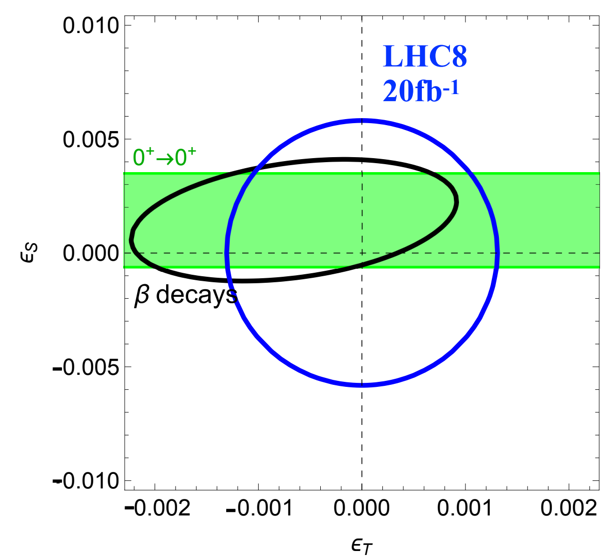

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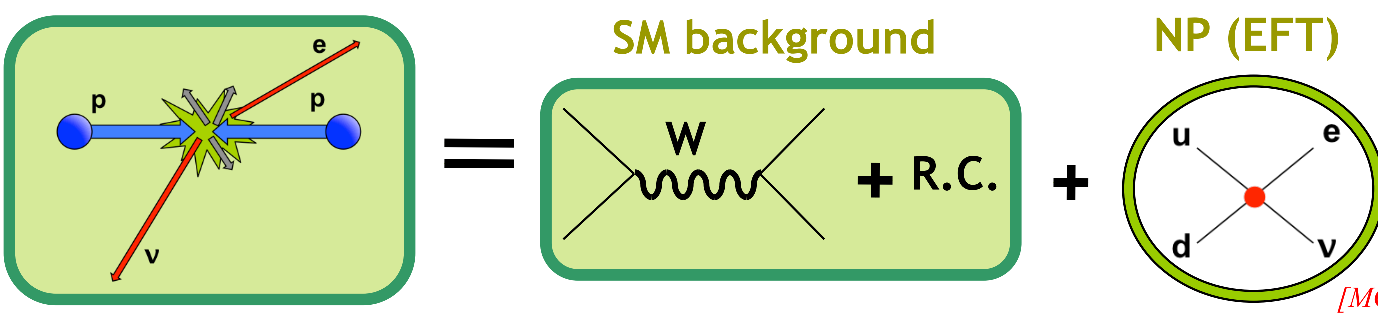

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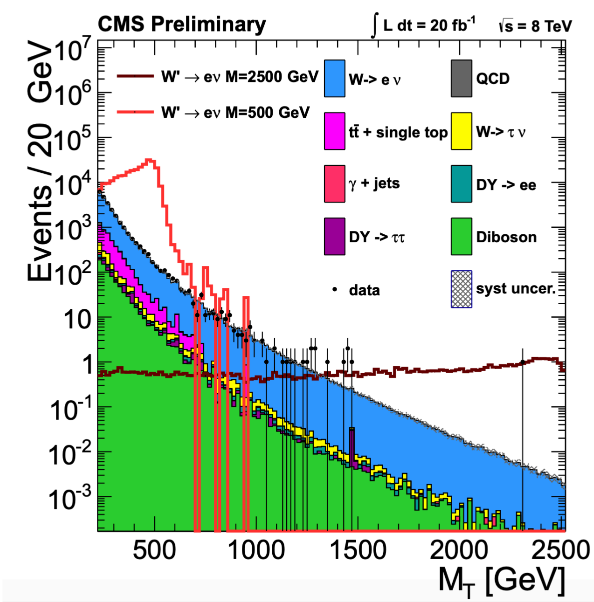

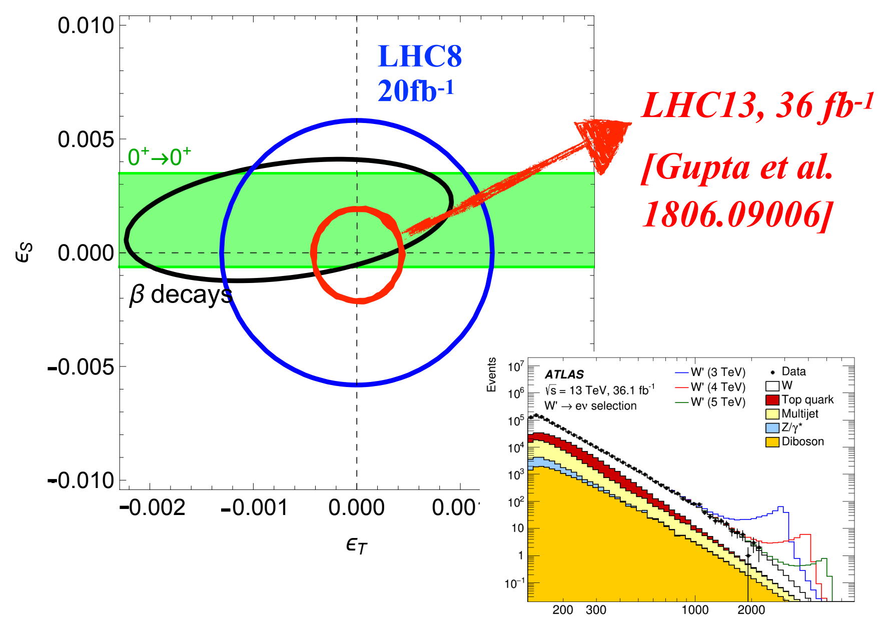

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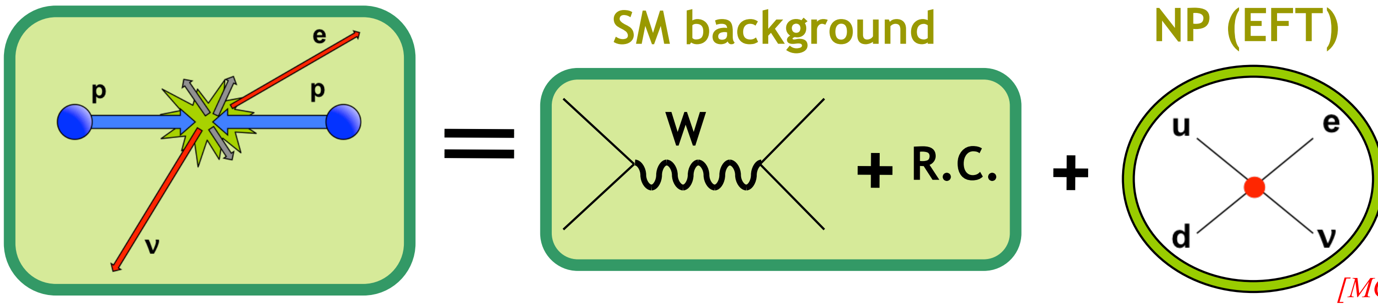

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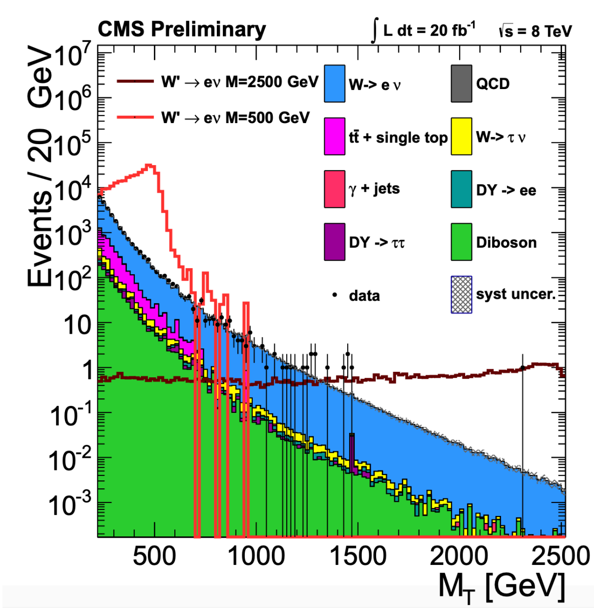
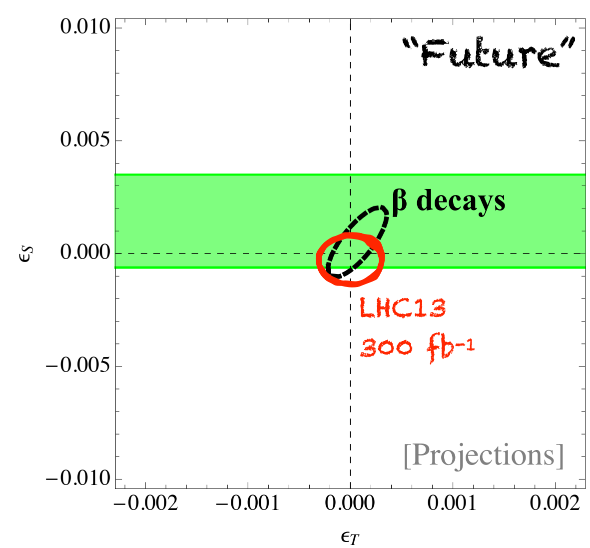
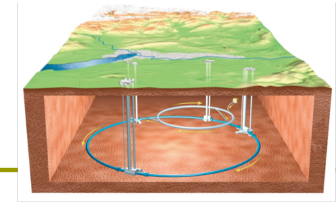
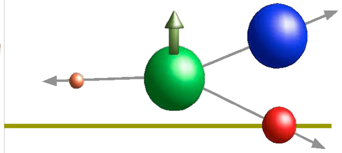




[MGA, O. Naviliat Cuncic, N. Severijns, 1803.08732; Gupta et al. 1806.09006]

Conclusions





- (Sub) permil-level precision in β decays
  - Great QCD progress
  - Experimental progress too
  - Rad. Corrections?

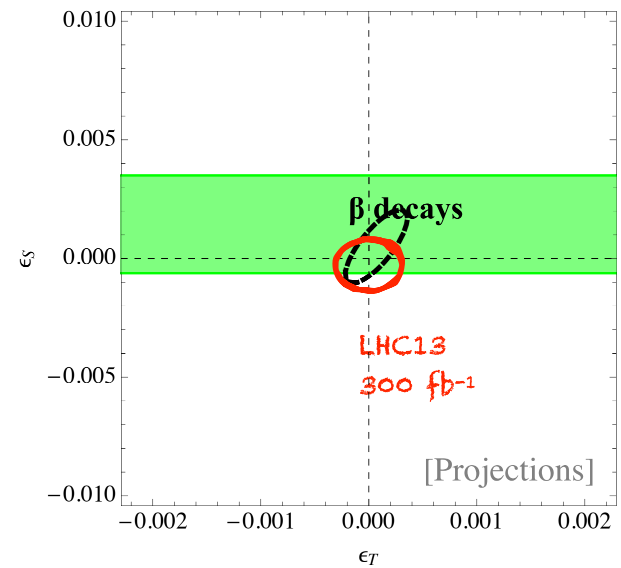
$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix}$$

- General EFT analysis available

  → Comparison between β-decay observables;

  → Comparison with APV, LEP, LHC, …

  → β decays are competitive TeV probes;



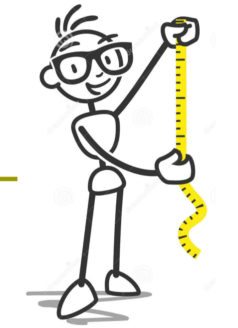
- More (Exp + Th) results expected in the near future

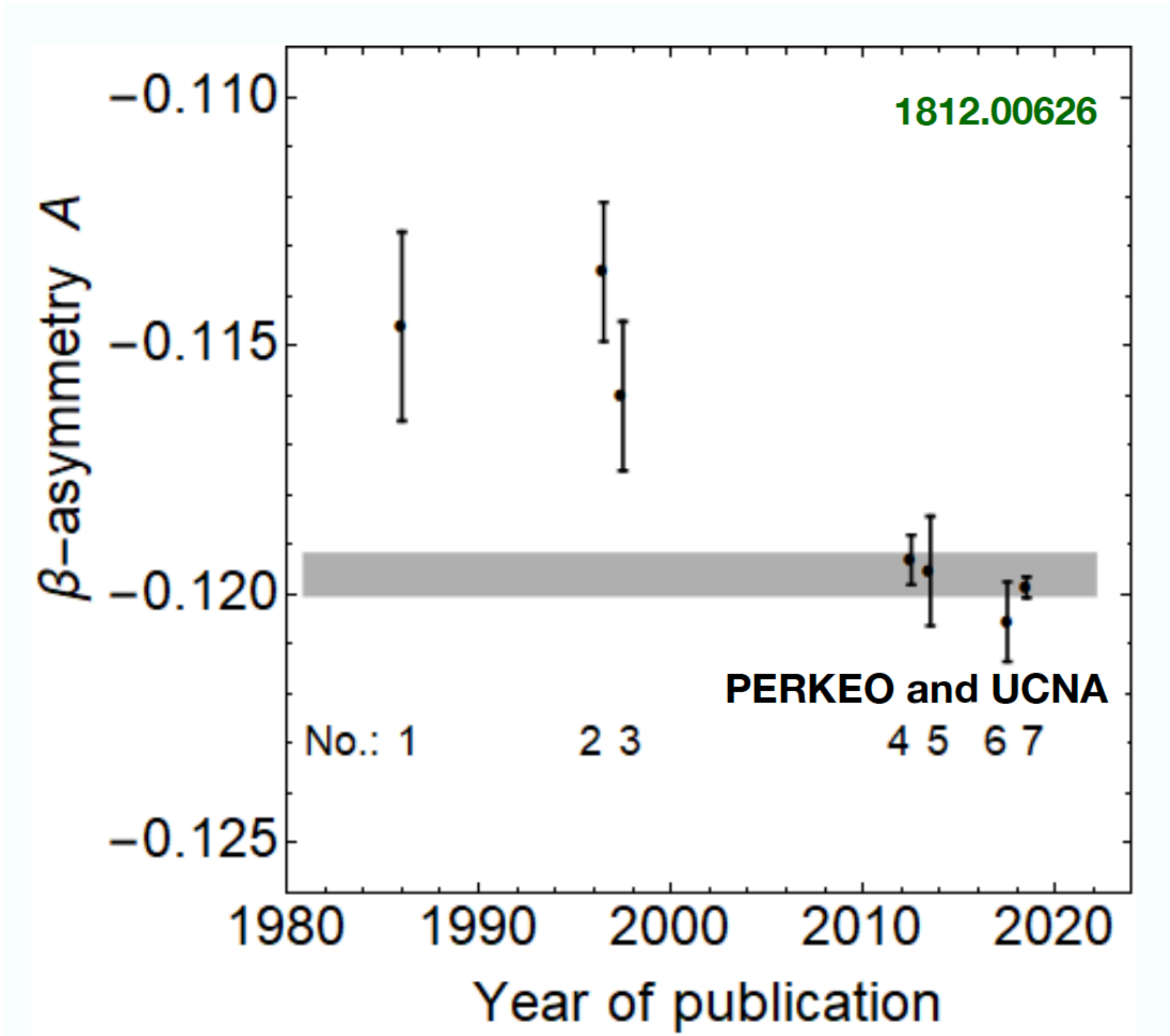
$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$$

Backup slides

Neutron beta asymmetry

Precision:
O(0.01 - 1)% !!





From hadrons to quarks

Likewise...

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

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

Implications? It almost compensates the bilinear suppression!

$$\langle p(p_p)|\bar{u}\gamma_5 d|n(p_n)\rangle = g_P(q^2)\bar{u}_p(p_p)\gamma_5 u_n(p_n)$$

$\sim q/M \sim 10^{-3}$

"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!

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

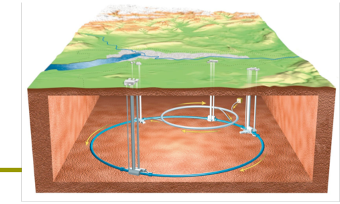
From current data:

ϵ_P = - 0.08(15) (90%CL)

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

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

If we see a bump…

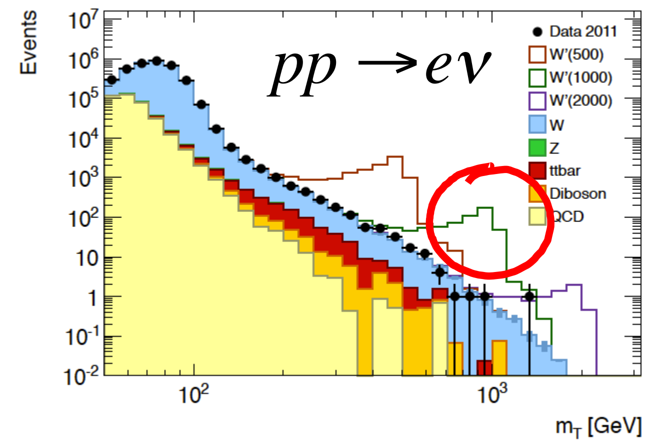


- EFT breaks down…
  Toy model: scalar resonance:

$$\mathcal{L} \;=\; \lambda_S V_{ud}\phi^+\overline{u}d + \lambda_l \phi^- \overline{e} P_L \nu_e$$

- Then we have a lower-limit value for ε_S:

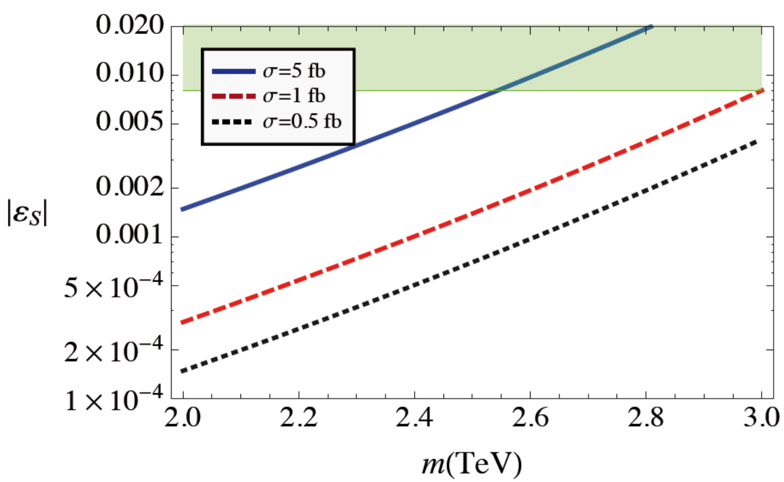
$$\sigma \cdot \mathrm{BR} \;\leq\; \frac{|V_{ud}|}{12v^2}\frac{\pi}{\sqrt{2N_c}}|\epsilon_S|\tau L(\tau)$$



$$L(\tau) = \int_\tau^1 dx\, f_q(x) f'_q(\tau/x)/x$$

$$\tau = m^2/s$$

$$\epsilon_S \;=\; 2\lambda_S\lambda_l \frac{v^2}{m^2}$$



Nice interplay of two experiments separated for so many orders of magnitudes!!!!

[T. Battacharya et al., 2012]