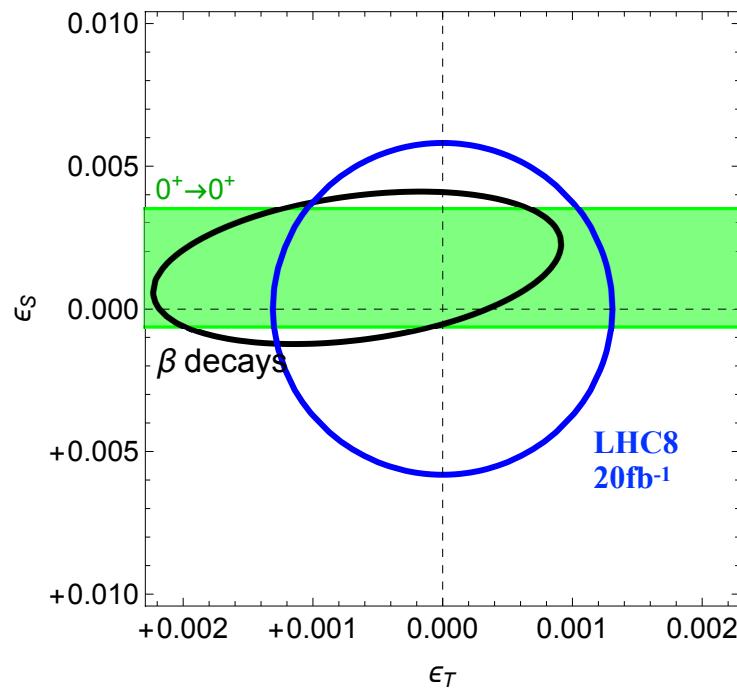


# Standard Model tests in nuclear $\beta$ decay

ISOLDE workshop & users meeting

CERN Dec 2018



Martín González-Alonso

CERN-TH



# The search for ‘New Physics’

## Standard Model

	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	
charge→	2/3	2/3	2/3	
spin→	1/2	1/2	1/2	
name→	u up	c charm	t top	
Quarks	d down	s strange	b bottom	g gluon
mass→	4.8 MeV	104 MeV	4.2 GeV	
charge→	-1/3	-1/3	-1/3	
spin→	1/2	1/2	1/2	
name→	d down	s strange	b bottom	g gluon
Leptons	v <sub>e</sub> electron neutrino	v <sub>μ</sub> muon neutrino	v <sub>τ</sub> tau neutrino	Z weak force
mass→	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
charge→	0	0	0	0
spin→	1/2	1/2	1/2	1
name→	v <sub>e</sub> electron neutrino	v <sub>μ</sub> muon neutrino	v <sub>τ</sub> tau neutrino	Z weak force
Bosons (Forces)	e electron	μ muon	τ tau	W weak force
mass→	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
charge→	-1	-1	-1	±1
spin→	1/2	1/2	1/2	1
name→	e electron	μ muon	τ tau	W weak force

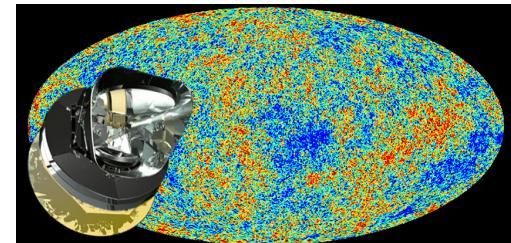
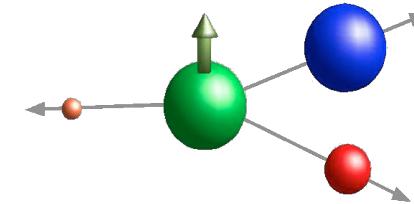
+Higgs!

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

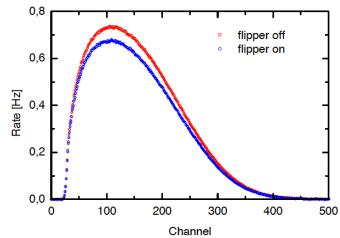
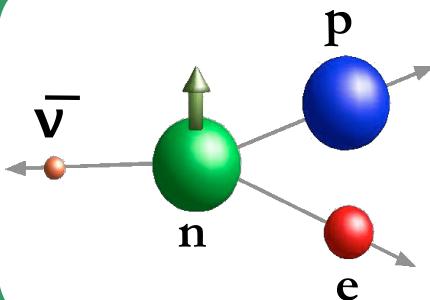
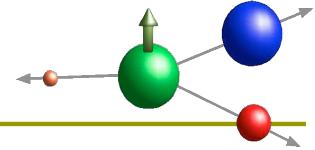


## New Physics experimental searches...

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



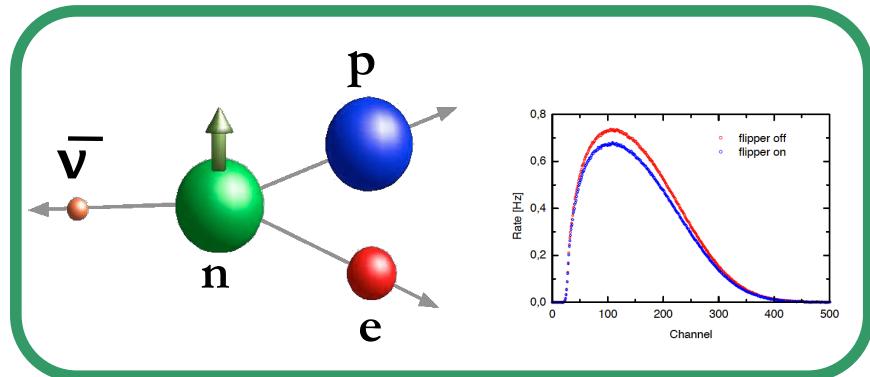
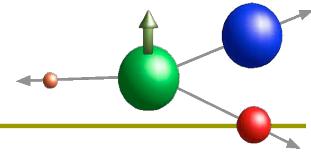
# New Physics searches with $\beta$ decays



Precise data  
+  
Precise SM predictions

[ $V_{ud} = 0.97416(21)!!!$ ]  
**[Hardy & Towner'15]**

# New Physics searches with $\beta$ decays



Precise data  
+  
Precise SM predictions

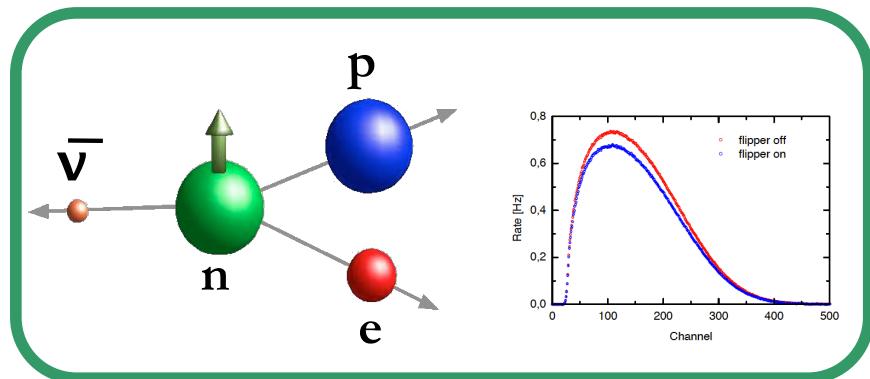
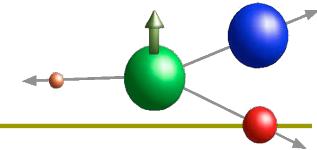
[ $V_{ud} = 0.97416(21)!!!$ ]  
[Hardy & Towner'15]

## 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!**



# New Physics searches with $\beta$ decays



Precise data  
+  
Precise SM predictions

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

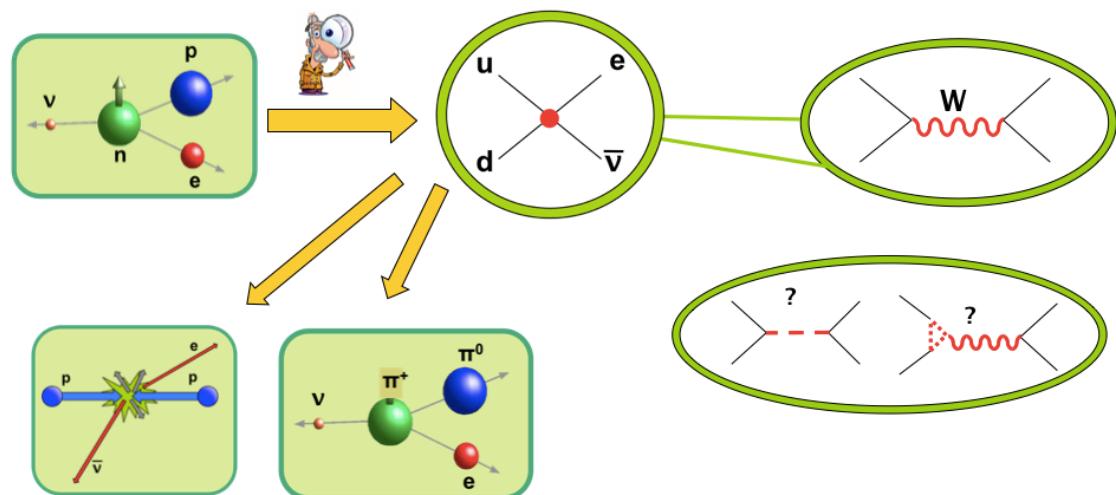
[Hardy & Towner'15]

## Implications for New Physics?

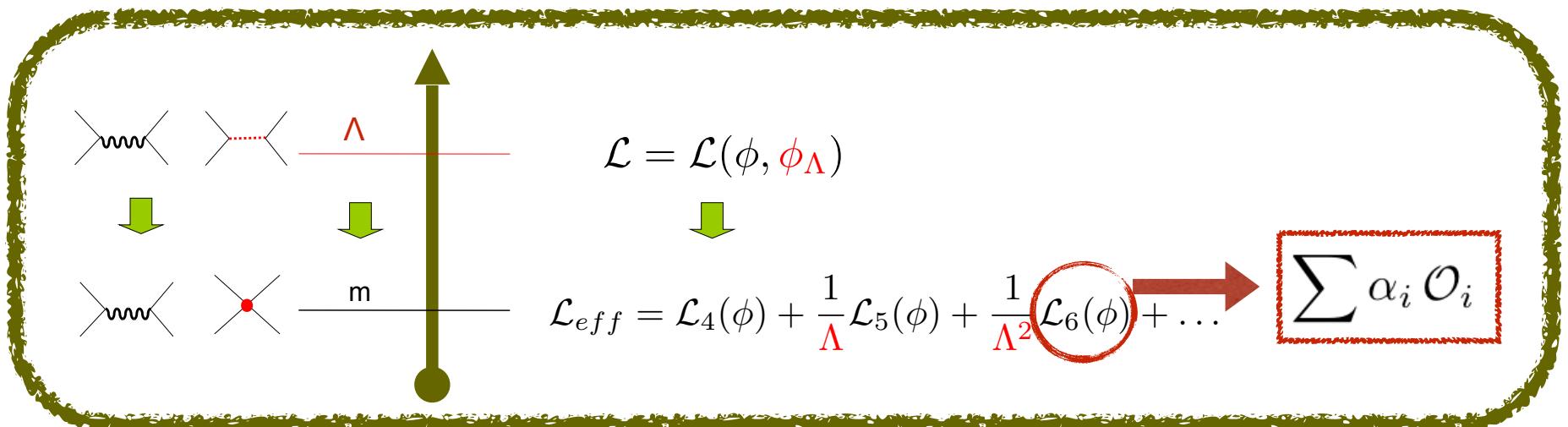
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- **Something more model-indep? EFTs!**

## Competitive probes?

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



# What's an EFT?



$\alpha_i$  : Wilson coefficients.

Effective Field Theory = Fields + Symmetries

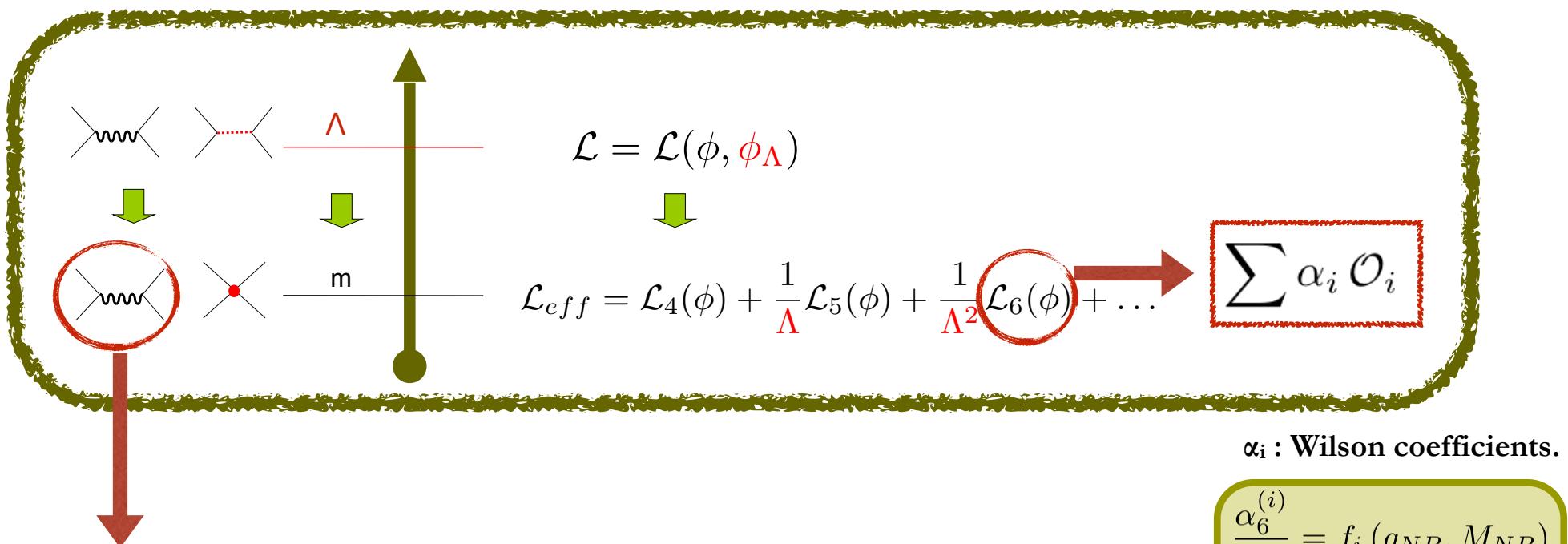
- nuclei, e, v
- hadrons, e, v
- q, u, d, l, e
- W, Z,  $\gamma$ , g
- ...

- Lorentz
- QED
- SU(2)  $\times$  U(1)
- Flavour sym?
- B, L;

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

Not assumption  
independent!

# What's an EFT?

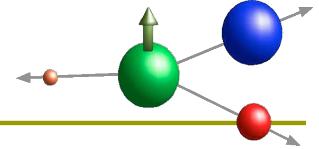


$$-\frac{4G_F}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\mu$$

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

## Wilson coefficient

# Comparing experiments



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

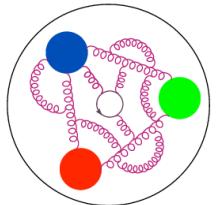
$$\begin{aligned}
 -\mathcal{L}_{n \rightarrow p e^- \bar{\nu}_e} = & \bar{p} n (C_S \bar{e} \nu_e - C'_S \bar{e} \gamma_5 \nu_e) \\
 & + \bar{p} \gamma^\mu n (C_V \bar{e} \gamma_\mu \nu_e - C'_V \bar{e} \gamma_\mu \gamma_5 \nu_e) \\
 & + \frac{1}{2} \bar{p} \sigma^{\mu\nu} n (C_T \bar{e} \sigma_{\mu\nu}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

[Lee & Yang'1956]

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

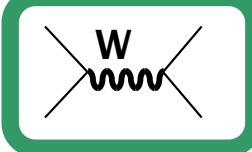
$$\mathcal{L}_{d \rightarrow u \ell^- \bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}} \left[ \bar{\ell}_L \gamma_\mu \nu \cdot \bar{u} \gamma^\mu d_L + \sum_{\rho\delta\Gamma} \epsilon_{\rho\delta}^\Gamma \bar{\ell}_\rho \Gamma \nu \cdot \bar{u} \Gamma d_\delta \right]$$

$$\mathbf{C_i} \sim \mathbf{FF} \times \boldsymbol{\varepsilon_i}$$



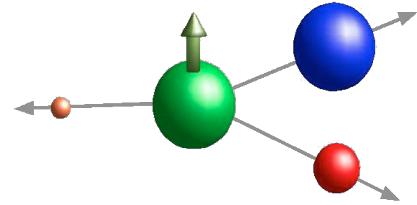
- How to compare with LHC experiments?
  - Effective Lagrangian at the **quark** level at the EW scale!

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



Hadrons:

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



# Hadronic EFT

---

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

# Hadronic EFT

---

SM terms

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

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*SM terms*

~~+ terms with RH neutrinos~~

*Linear approx:*

*SM + small + (small)<sup>2</sup>*

(Or simply no  $\nu_R$ :  $C_i = C'_i$ )

# Hadronic EFT

---

$$-\mathcal{L}_{n \rightarrow p e^- \bar{\nu}_e} = C_V \left( \bar{p} \gamma^\mu n + \frac{C_A}{C_V} \bar{p} \gamma^\mu \gamma_5 n \right) \times \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \\ + C_S \bar{p} n \times \bar{e} (1 - \gamma_5) \nu_e + \frac{1}{2} C_T \bar{p} \sigma^{\mu\nu} n \times \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_e$$

SM terms

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

~~+ terms with RH neutrinos~~

“since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted”

Linear approx:  
SM + small + (small)<sup>2</sup>

(Or simply no  $\nu_R$ :  $C_i = C'_i$ )

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

Real reason: the bounds on  $\epsilon_P$  from pion decays are much stronger!!!

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

# Hadronic EFT

[Lee & Yang'1956]

---

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

# Hadronic EFT

[Lee & Yang'1956]

$G_F V_{ud}$  (1 + NP)

[Lifetime shift]

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

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

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$g_A$  (1 + NP)

Only way out:  
lattice QCD!

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$g_A \text{ (1 + NP)}$

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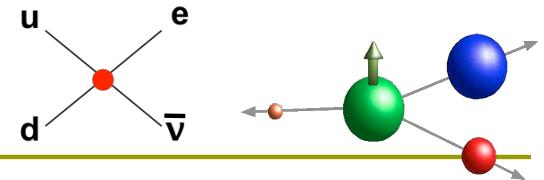
S and T affect the angular distributions and the spectrum!!

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

$$b_{(B)} = \# C_S + \# C_T \quad \text{Fierz term [1937]}$$

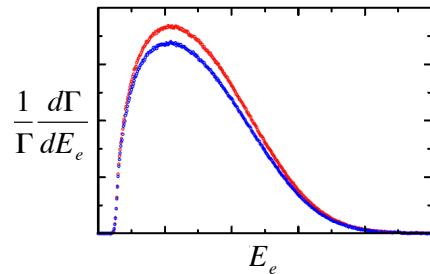
[+ CPV effects]

# Probing the Fierz term

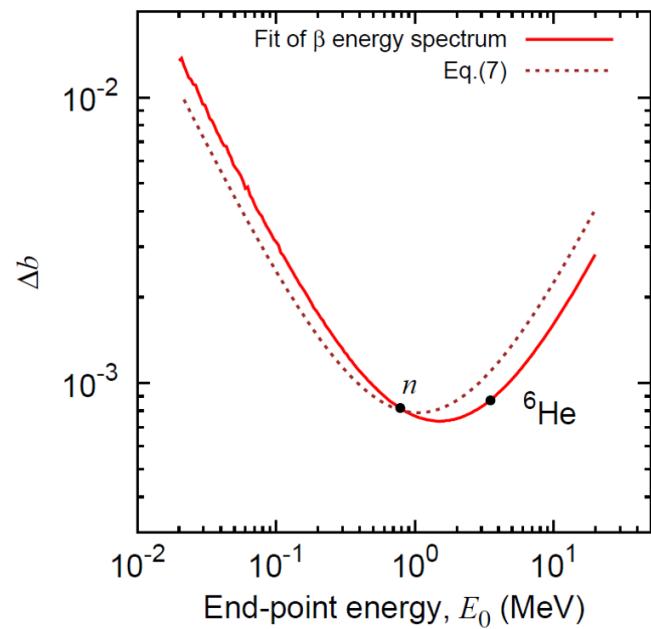


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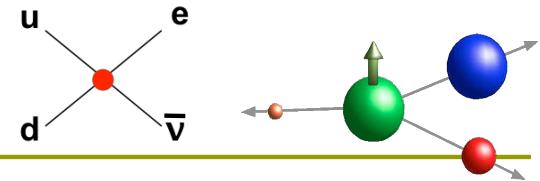
✓ Direct effect in the spectrum:



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

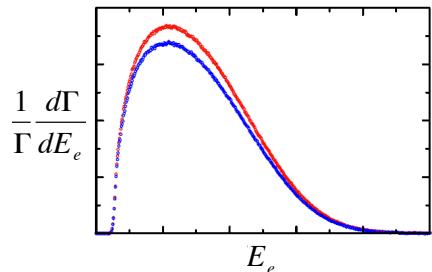


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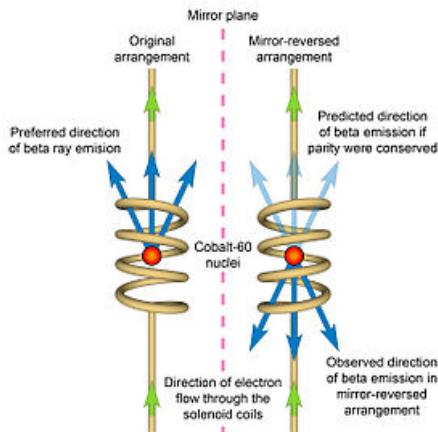


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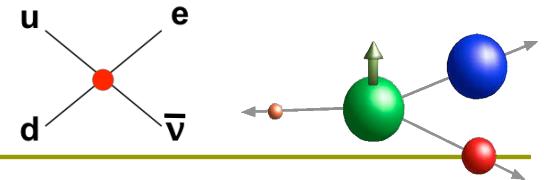
- ✓ Indirect effect in the asymmetries:

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

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

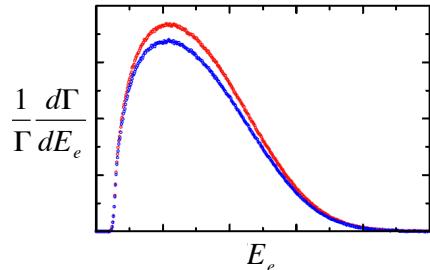


# Probing the Fierz term



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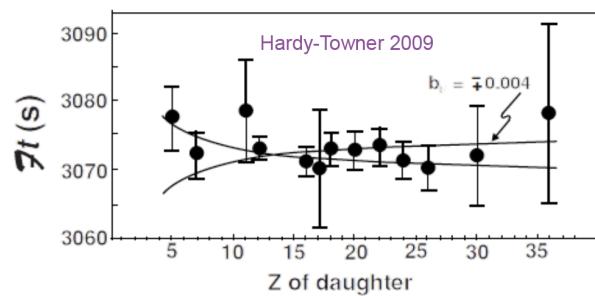
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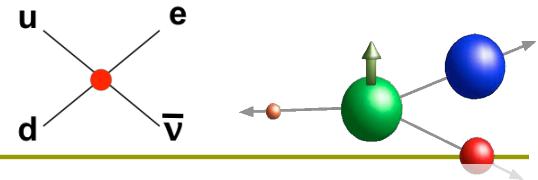
- ✓ Indirect effect in the Ft-values & neutron lifetime:



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

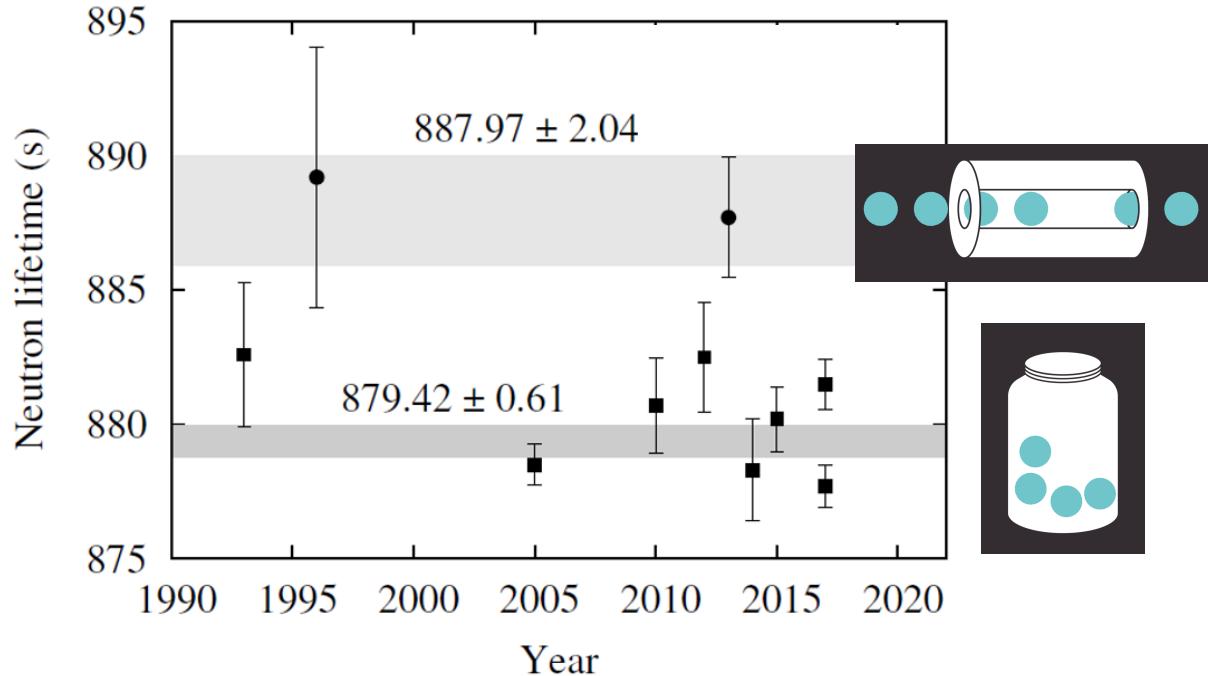


# Probing the Fierz term



Heavy NP cannot explain the beam vs. bottle tension

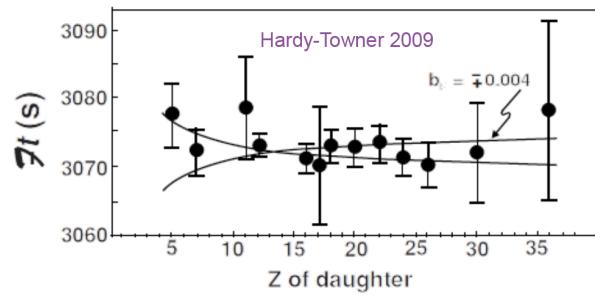
.... Light NP?  
[Fornal & Grinstein PRL (120 (2018))]



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

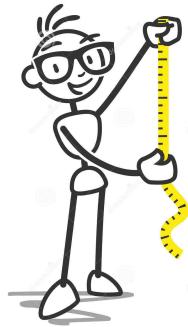


$$\delta\tau_n, \delta\mathcal{F}t \sim -b \left\langle \frac{m_e}{E_e} \right\rangle$$



# Current data (+ TH!!)

Precision:  
 $0(0.01 - 1)\% !!$



## Nuclei

$\mathcal{F}t (0^+ \rightarrow 0^+)$  values

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

Correlation coefficients

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

Neutron data

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

\* Average

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

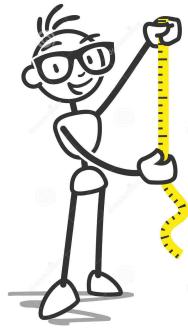
[Hardy-Towner'2015]

Exp Input:

BRs, half-lives, Q-values

# Current data (+ TH!!)

Precision:  
0(0.01 - 1)% !!



Nuclei

$\mathcal{F}t (0^+ \rightarrow 0^+)$  values

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

Correlation coefficients

Parent	Type	Parameter	Value
$^6\text{He}$	GT/ $\beta^-$	$a$	$-0.3308(30)^{\text{a)}$
$^{32}\text{Ar}$	F/ $\beta^+$	$\tilde{a}$	$0.9989(65)$
$^{38n}$	F/ $\beta^+$	$\tilde{a}$	$0.9981(48)$
$^{60}\text{Co}$	GT/ $\beta^-$	$\tilde{A}$	$-1.014(20)$
$^{67}\text{Cu}$	GT/ $\beta^-$	$\tilde{A}$	$0.587(14)$
$^{11}\text{B}$	GT/ $\beta^-$	$\tilde{A}$	$-0.994(14)$
$^{14}\text{O}/^{10}\text{C}$	F-GT/ $\beta^+$	$P_F/P_{GT}$	$0.9996(37)$
$^{26}\text{Al}/^{30}\text{P}$	F-GT/ $\beta^+$	$P_F/P_{GT}$	$1.0030(40)$
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\* Average

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

[Hardy-Towner'2015]

Exp Input:

BRs, half-lives, Q-values

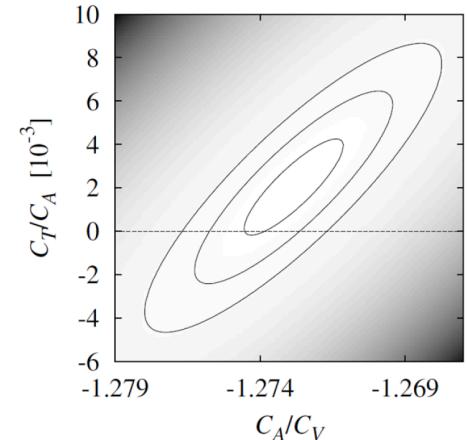
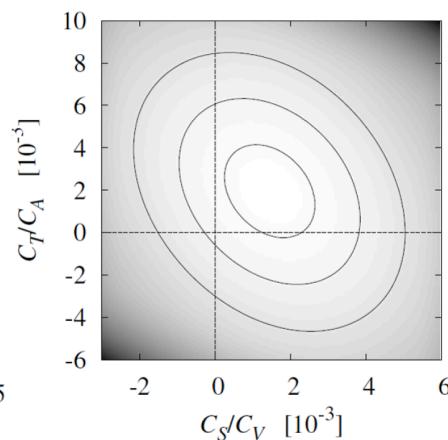
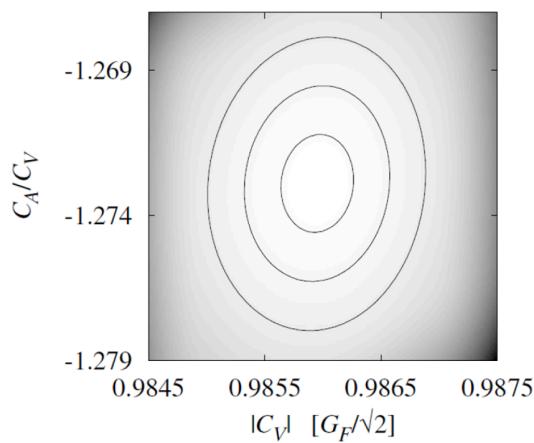
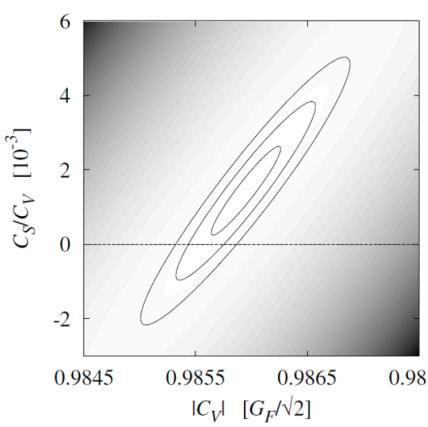


ISOLDE



# 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  
Fl's, Th, An!



# Current data → Results

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

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



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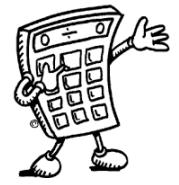
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WISARD ( $^{32}\text{Ar}$ ) aims at 0.1%!!



**ISOLDE**



# Current data → Results

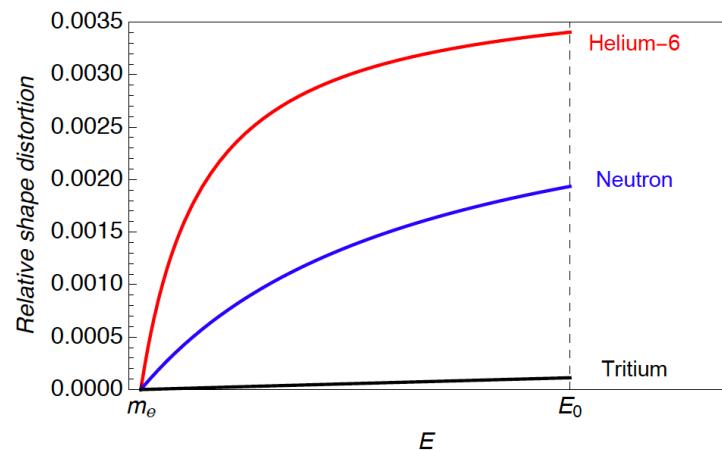
$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34) G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix} \quad \text{with} \quad \rho = \begin{pmatrix} 1.00 & & & \\ 0.08 & 1.00 & & \\ 0.94 & 0.08 & 1.00 & \\ -0.32 & 0.85 & -0.31 & 1.00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

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

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

WISArD ( $^{32}\text{Ar}$ ) aims at 0.1%!!

Ex. #2: Spectrum shape measurements



ISOLDE





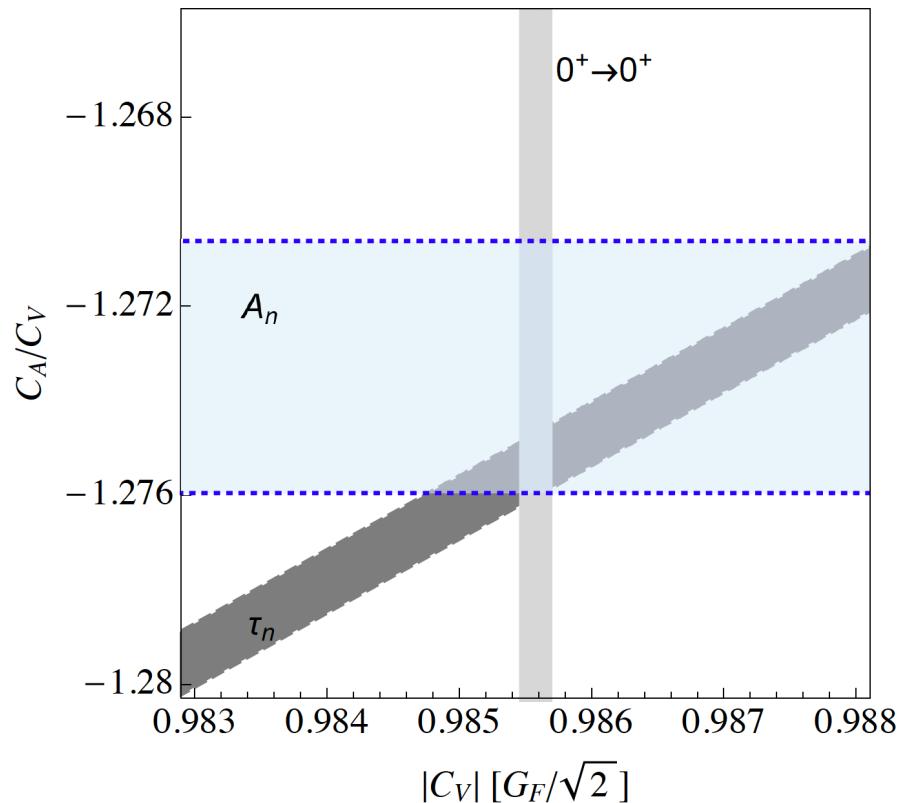
# Current data → Results

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

SM Limit



$$\boxed{|C_V| = 0.98559(11) G_F/\sqrt{2}} \\ C_A/C_V = -1.27510(66), \\ (\rho = 0.25)}$$





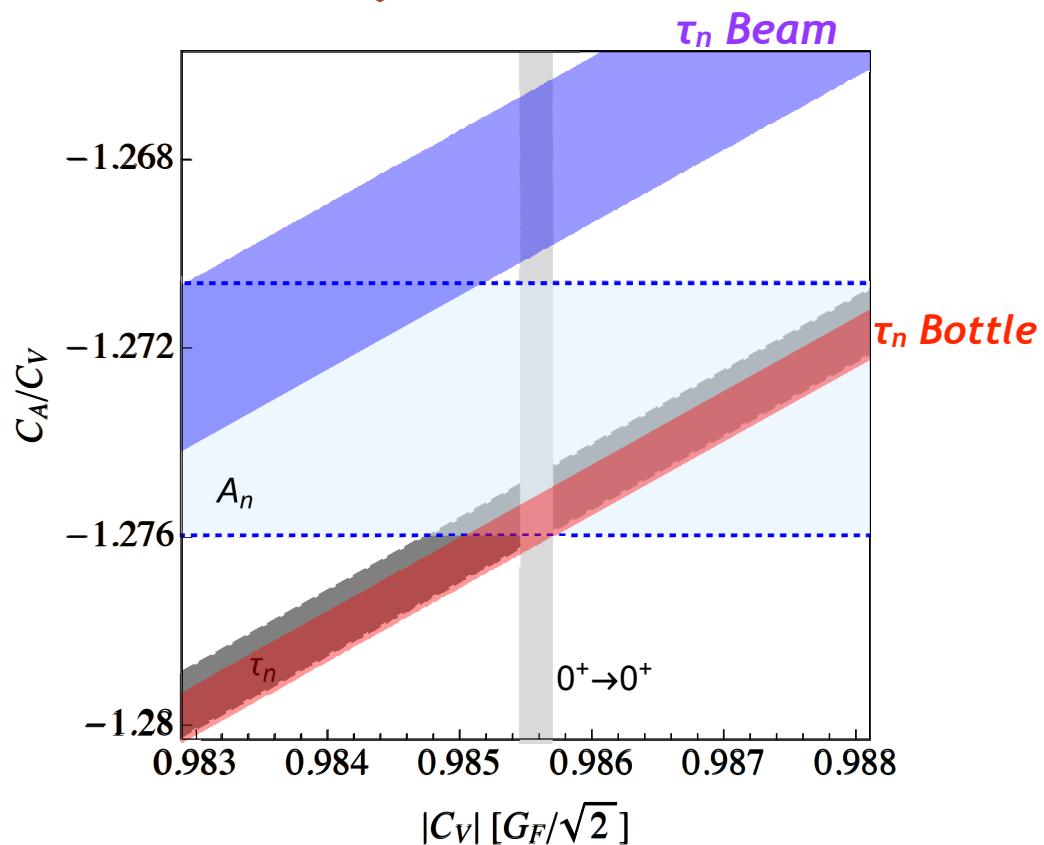
# Current data → Results

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

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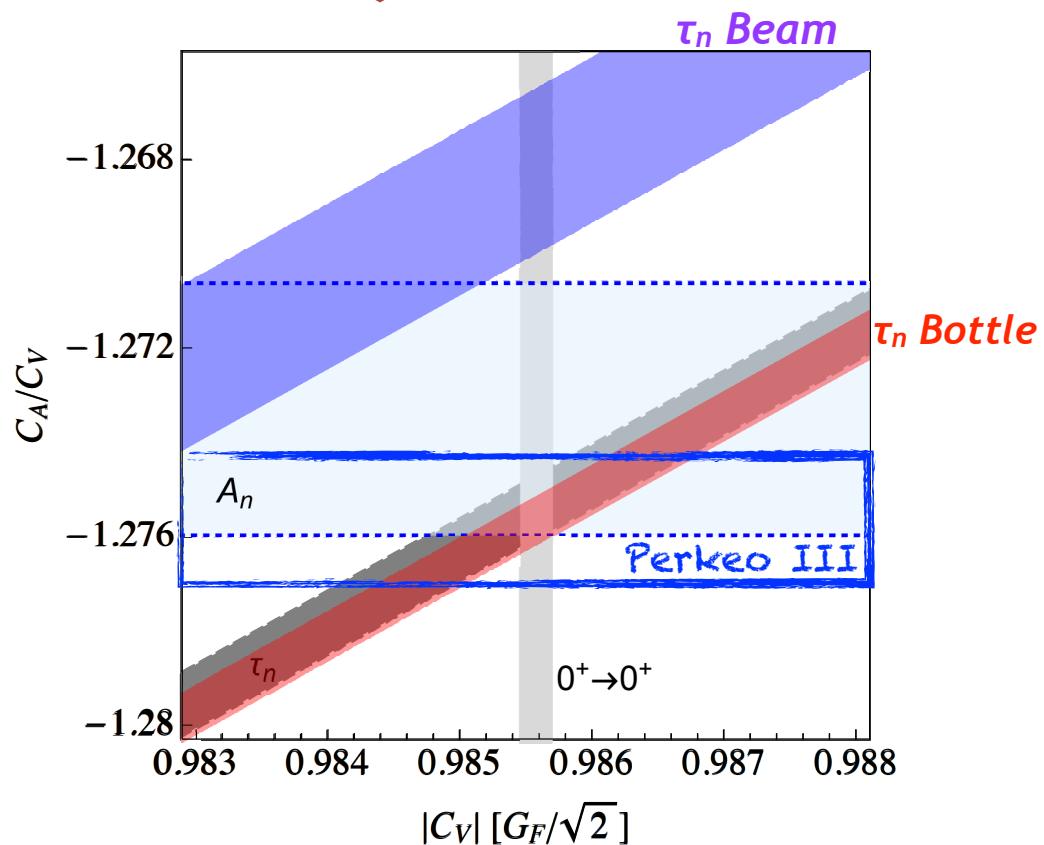
SM Limit



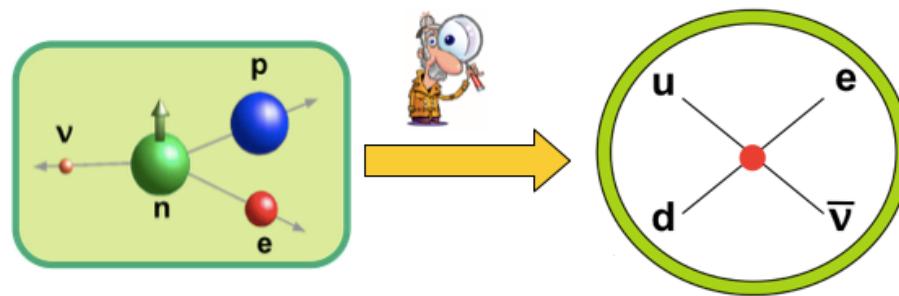
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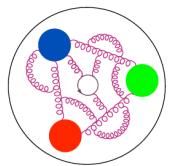
**NEW**

$A_n = -0.11983(21)$  [Perkeo III, 2.5x!]  
→ no dark channel



Quarks (low-E):  
 $d \rightarrow u e^- \bar{\nu}$

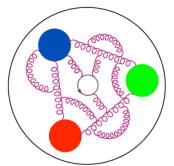




# From hadrons to quarks

$$\begin{aligned} C_V &\sim g_V G_F^\mu V_{ud} (1 + \text{NP}) (1 + \text{RC}) \\ C_A/C_V &\sim -g_A/g_V (1 - \epsilon_R) \\ C_S &\sim g_S \epsilon_S \\ C_T &\sim g_T \epsilon_T \end{aligned}$$

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



# From hadrons to quarks

 $\tilde{V}_{ud}$ 

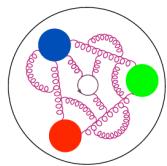
$$C_V \sim g_V G_F^\mu \boxed{V_{ud} (1 + \text{NP})} (1 + \text{RC})$$

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

$$C_S \sim g_S \epsilon_S$$

$$C_T \sim g_T \epsilon_T$$

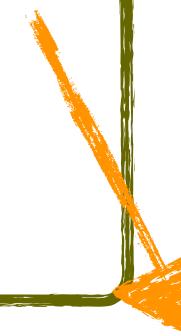
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# From hadrons to quarks

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 C_V &\sim g_V G_F^\mu \tilde{V}_{ud} (1 + \text{NP}) (1 + \text{RC}) \\
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 \end{aligned}$$

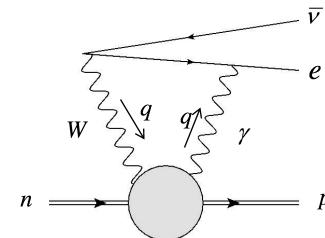
$\tilde{V}_{ud}$



Inner RC:

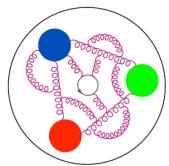
2.361(38)% [Marciano-Sirlin, PRL96 (2006)]

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



[ 2.4  $\sigma$  ]

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



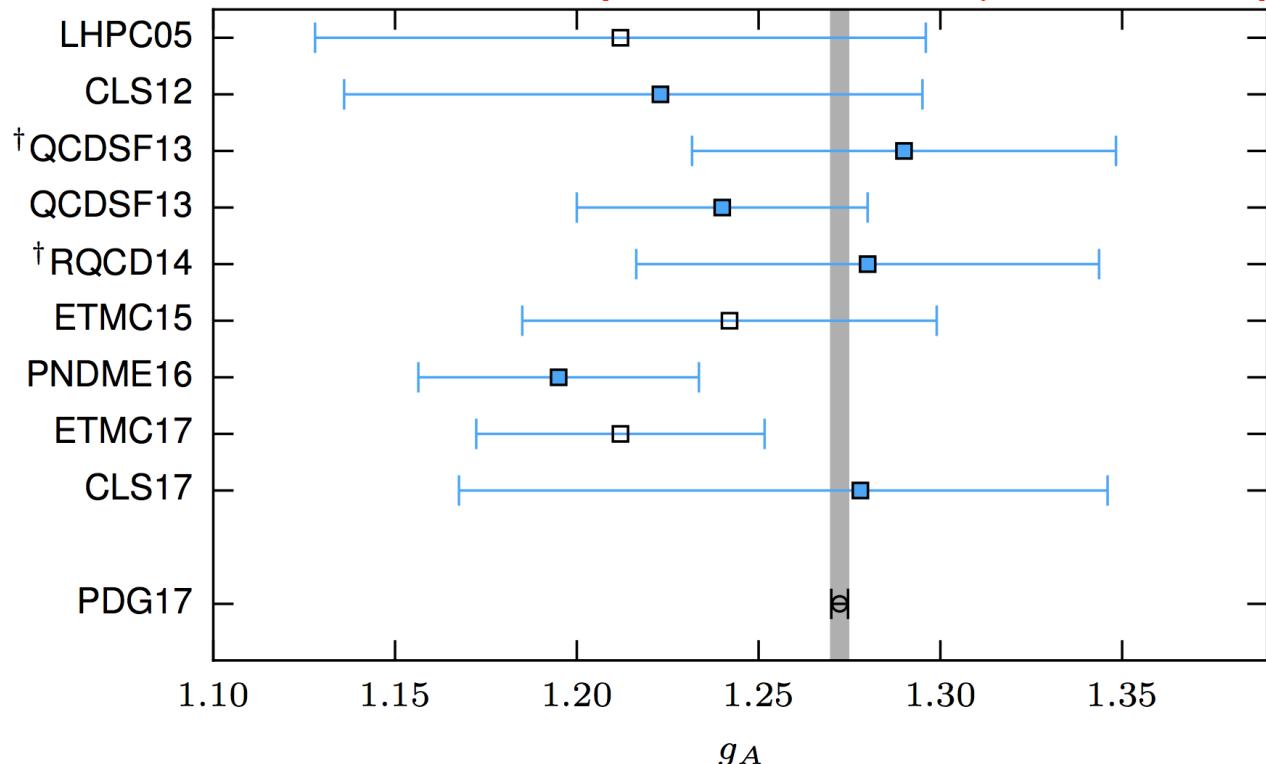
# From hadrons to quarks

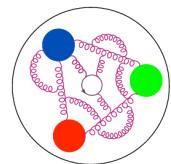
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Axial charge

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

[A. Nicholson's talk, CIPANP2018]





# From hadrons to quarks

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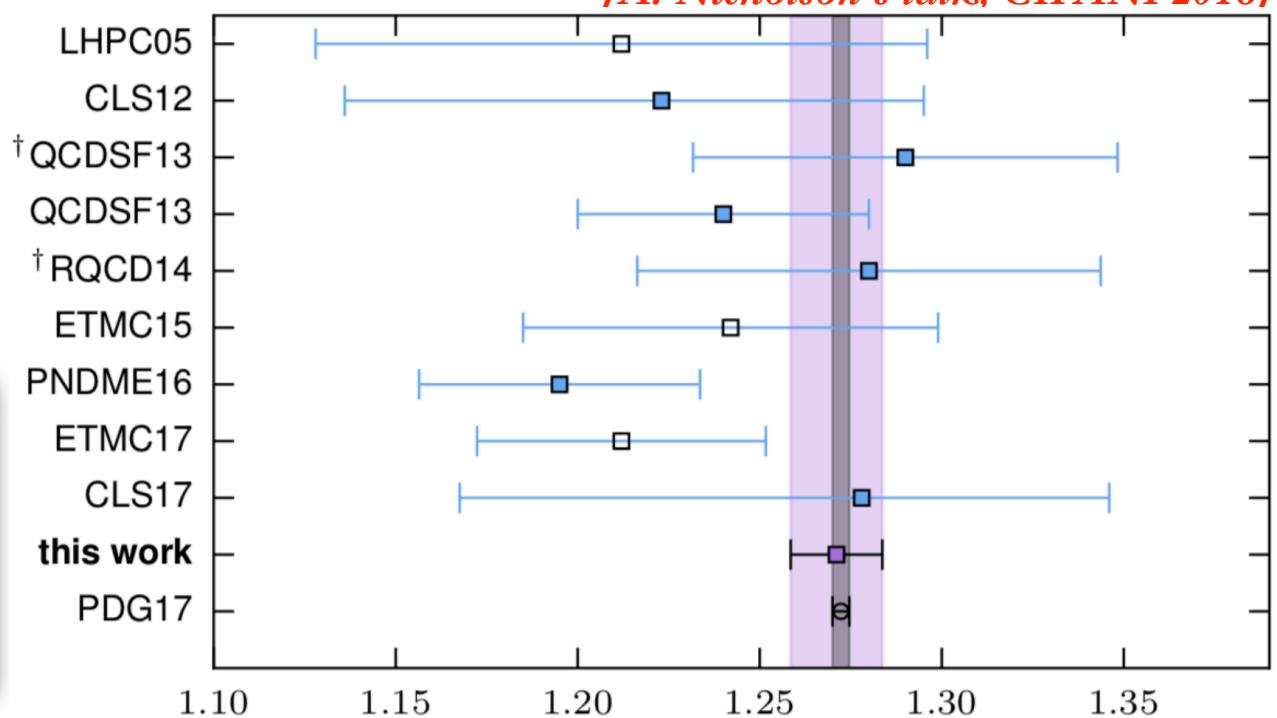
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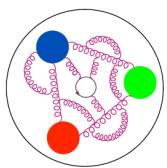


$$g_A^{\text{LQCD}} = 1.271 \pm 0.013$$

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



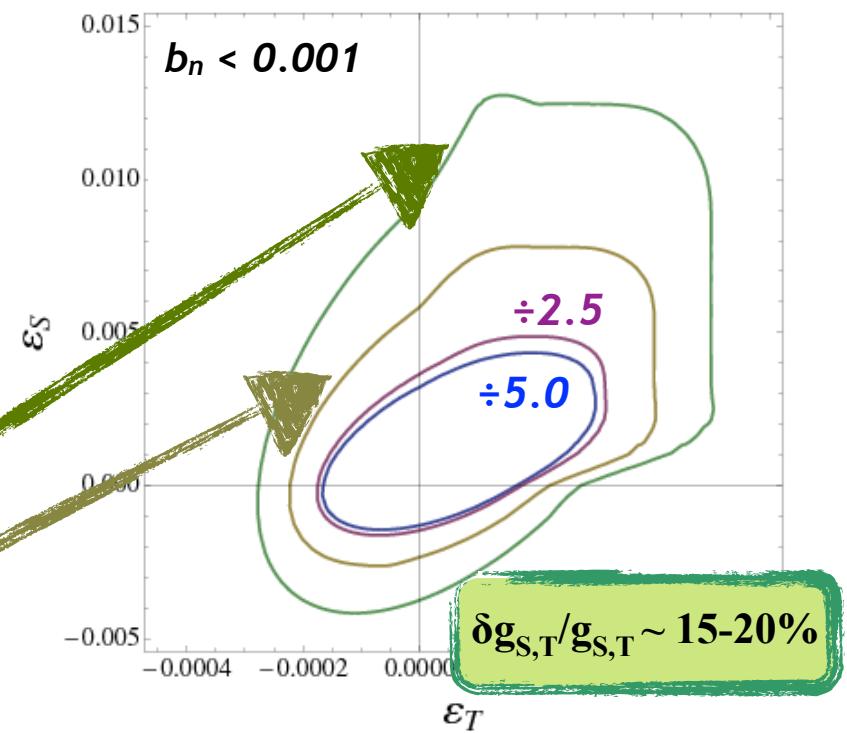


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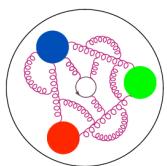
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*Scalar & tensor charges*

	$\langle p \bar{u}d n\rangle$	$\langle p \bar{u}\sigma_{\mu\nu}\gamma_5 d n\rangle$
	$g_S$	$g_T$
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)]



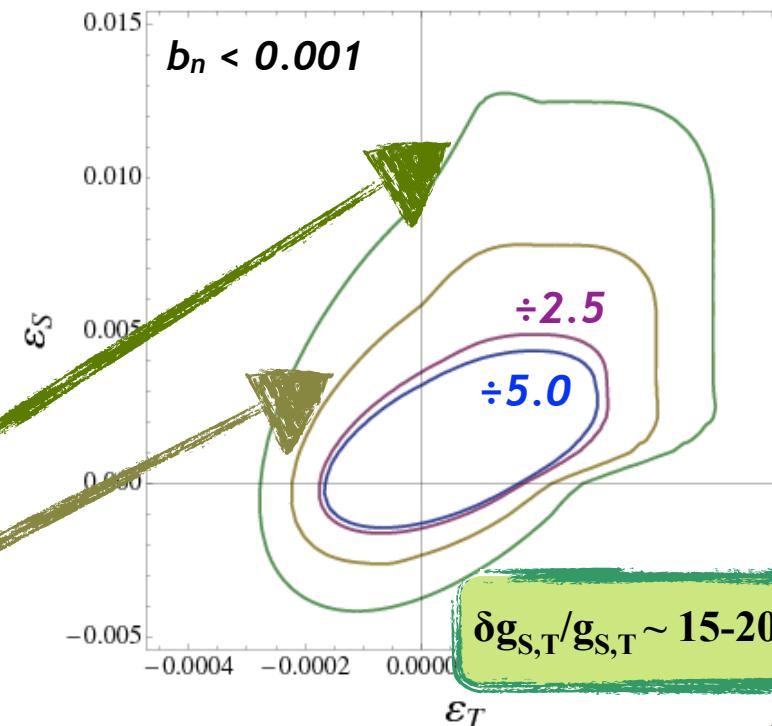
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*Scalar & tensor charges*

$$\langle p | \bar{u}d | n \rangle \quad \langle p | \bar{u} \sigma_{\mu\nu} \gamma_5 d | n \rangle$$

	$g_S$	$g_T$
Adler et al. '1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35)
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) <i>All syst!</i>
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)



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

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

[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**

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

# From hadrons to quarks

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## SM fit

$$\begin{aligned} |V_{ud}| &= 0.97416(11)(19)_{\text{RC}} = 0.97416(21) , \\ \lambda &= 1.27510(66) , \end{aligned} \quad (\rho = -0.13)$$

# From hadrons to quarks

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$$\begin{aligned} |V_{ud}| &= 0.97416(11)(19)_{\text{RC}} = 0.97416(21) , \\ \lambda &= 1.27510(66) , \end{aligned} \quad (\rho = -0.13)$$

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

[MGA & Martin Camalich, JHEP (2016)]

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

# From hadrons to quarks

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

## BSM fit

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

## SM fit

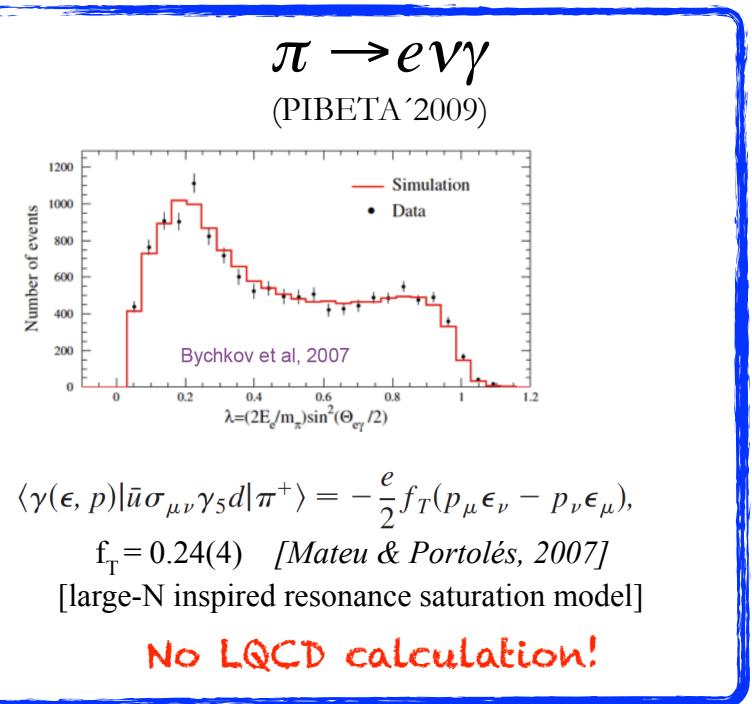
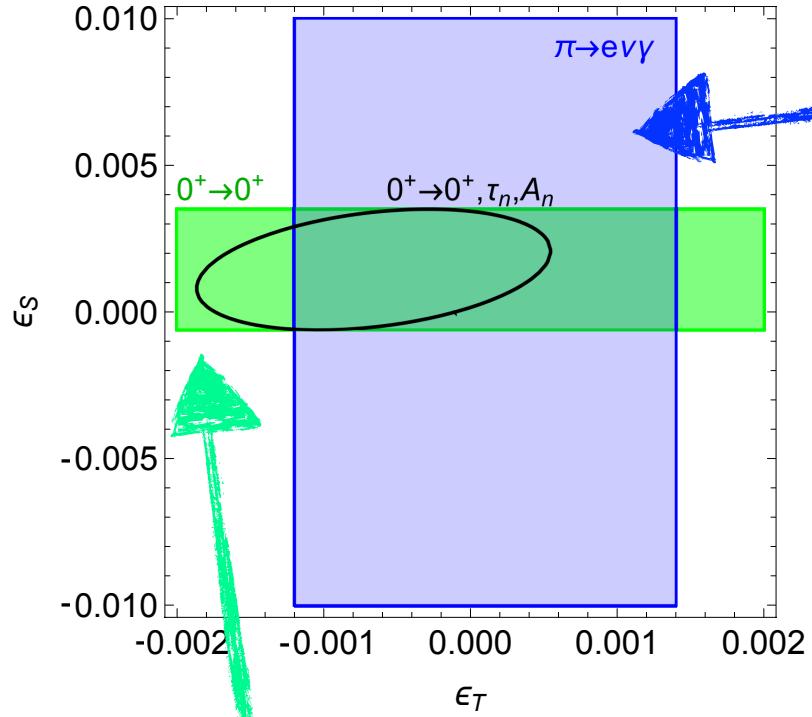
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$$\lambda = 1.27510(66) , \quad (\rho = -0.13)$$

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

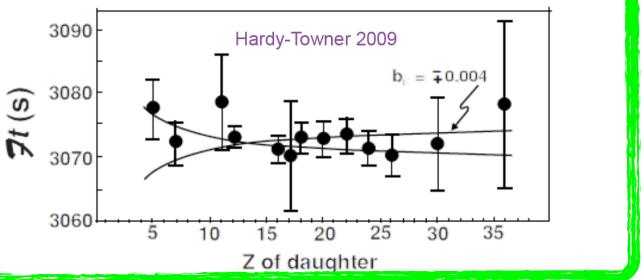
0.9983(4)  
with RC by Seng et al.'18



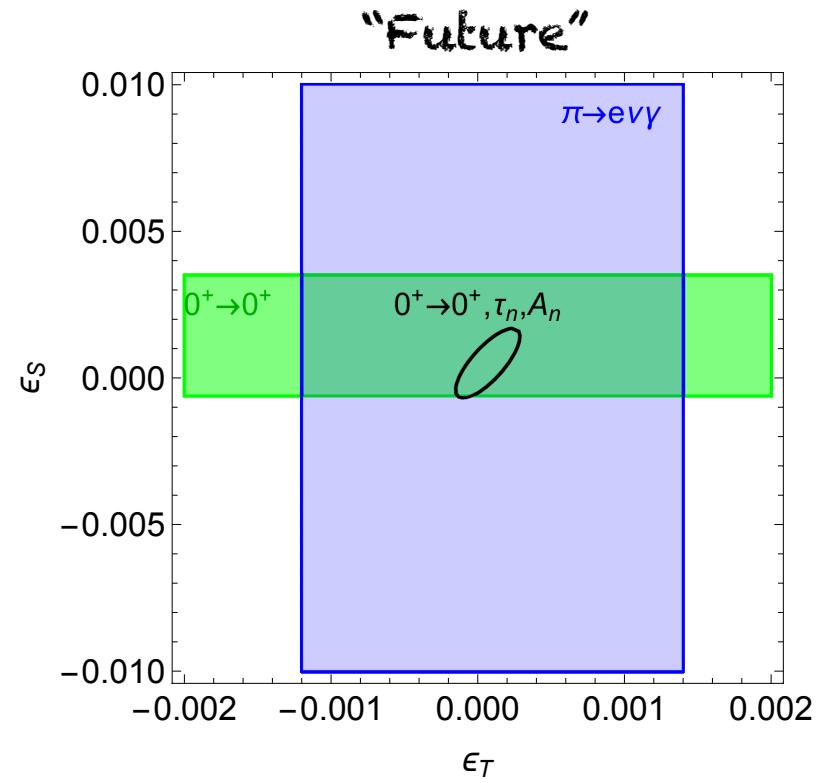
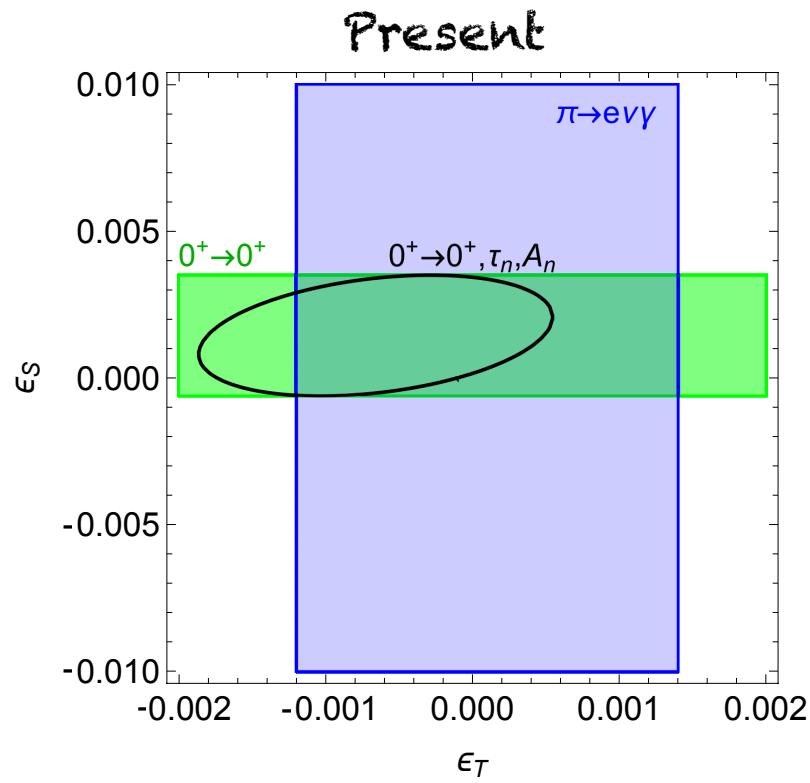
# From hadrons to quarks



Superallowed nuclear  $\beta$  decays



# From hadrons to quarks



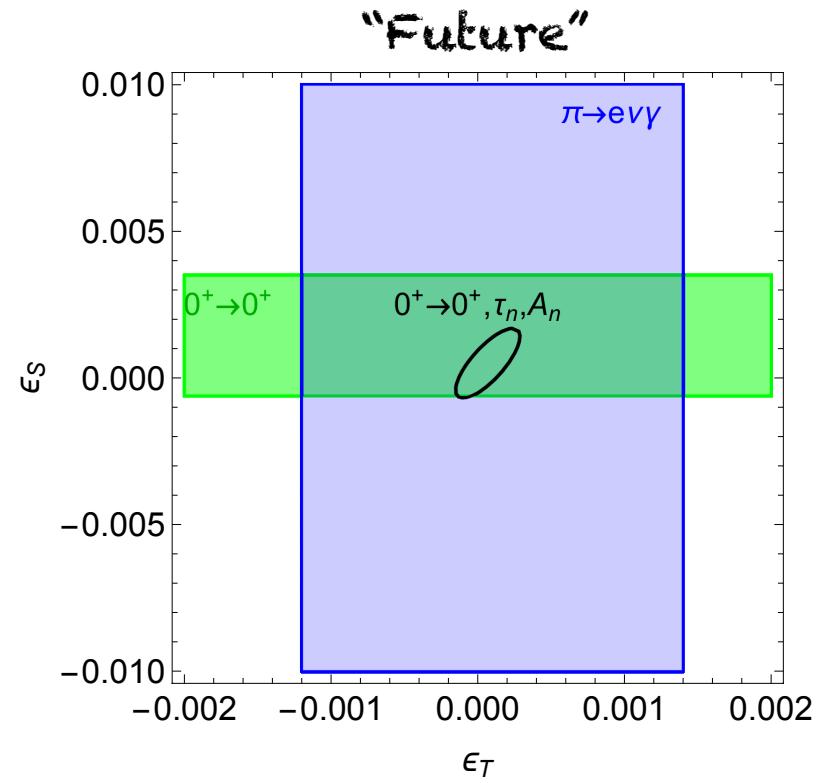
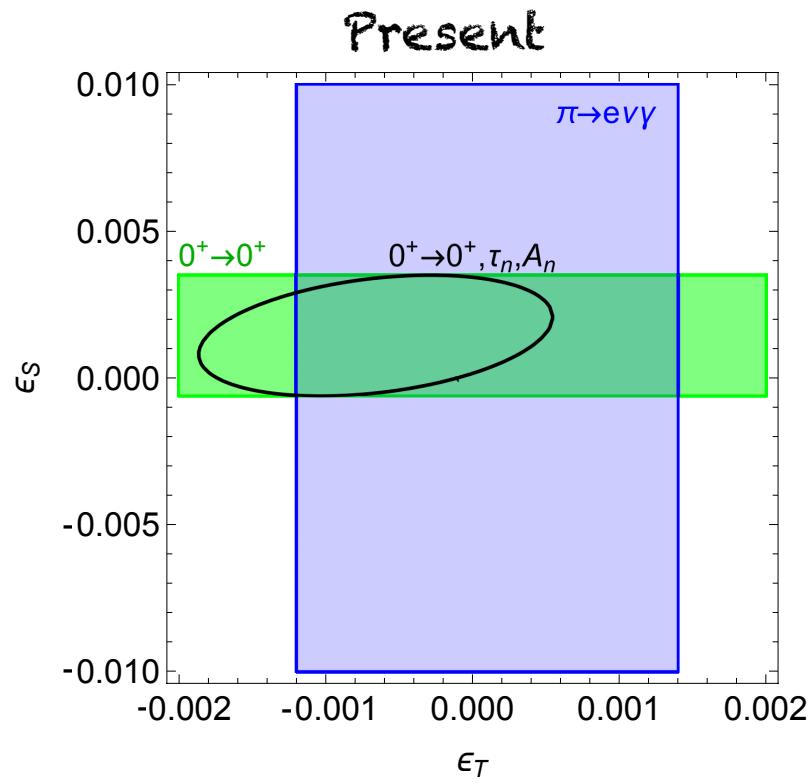
Benchmark numbers  
(from ongoing / planned experiments):

$$\delta\tau_n = 0.1 s$$

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

$$b_{GT} = 0.001$$

# From hadrons to quarks



WISArD ( $^{32}\text{Ar}$ )  
+ TRIUMF  
+ TA&M



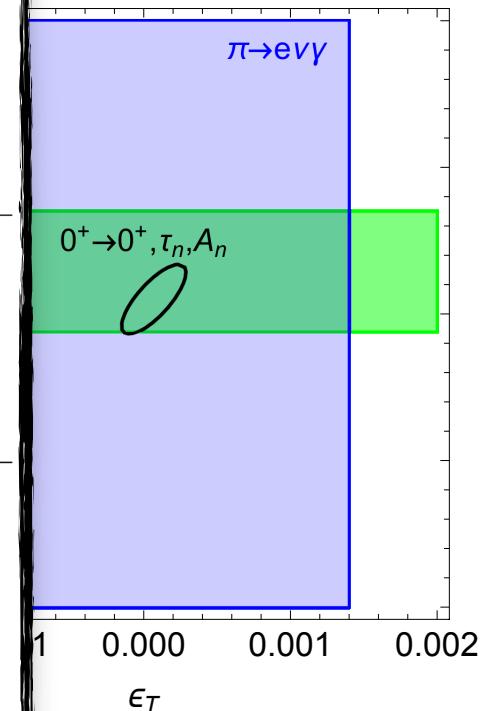
Benchmark numbers  
(from ongoing / planned experiments):

$\delta\tau_n = 0.1 \text{ s}$   
 $\tilde{A}_n, a_n, \tilde{a}_F, a_{GT} \text{ at } 0.1\%$   
 $b_{GT} = 0.001$

# From hadrons to quarks

Coefficient	Precision goal	Experiment (Laboratory)	Comments
$\tau_n$	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]	UCN $\tau$ (LANL) [188,189,223,224]	Ongoing
	0.5 s [225]	HOPE (ILL) [188,225,226]	Proof of principle Ref. [226]
$\beta$ -spectrum	0(0.01) [256]	Supercond. spectr. (Madison) [256]	Shape factor Eq. (51). Ongoing
	0(0.01) [253]	Si-det. spectr. (Saclay) [253,254]	Shape factor Eq. (51). Ongoing
	0.001	Calorimetry (NSCL) [115,260]	Analysis ongoing ( ${}^6\text{He}, {}^{20}\text{F}$ )
	0(0.001) [270]	miniBETA (Krakow–Leuven) [263–265,270]	Being commissioned
	0(0.001) [276]	UCNA-Nab-Leuven (LANL) [271,272,276]	Analysis ongoing ( ${}^{45}\text{Ca}$ )
	<0.05 [293,294]	UCNA (LANL) [390]	Ongoing with $A_n$ data
	0.03 [295]	PERKEO III (ILL) [295]	Possible with $A_n$ data
$b_n$	0.003 [289]	Nab (LANL) [188,289,357,358]	In preparation
	0.001 [291]	PERC (Munich) [291,292]	Planned
	0.1% [306]	TRINAT (TRIUMF) [306,310]	Planned ( ${}^{38}\text{K}$ )
	0.1% [343]	TAMUTRAP (TA&M) [343]	Superallowed $\beta p$ emitters
	0.1% [79]	WISARD (ISOLDE) [79,177]	In preparation ( ${}^{32}\text{Ar} \beta p$ decay)
	not stated	Ne-MOT (SARAF) [311,312]	In preparation ( ${}^{18}\text{Ne}, {}^{19}\text{Ne}, {}^{23}\text{Ne}$ )
	0(0.1)% [315]	${}^6\text{He}$ -MOT (Seattle) [313,315]	Ongoing ( ${}^6\text{He}$ )
$a$	not stated	EIBT (Weizmann Inst.) [316–318]	In preparation ( ${}^6\text{He}$ )
	0.5% [182]	LPCTrap (GANIL) [182,321,323,324]	Analysis ongoing ( ${}^6\text{He}, {}^{35}\text{Ar}$ )
	0.5% [273]	NSL-Trap (Notre Dame) [273,344,345]	Planned ( ${}^{11}\text{C}, {}^{13}\text{N}, {}^{15}\text{O}, {}^{17}\text{F}$ )
	1.0% [350]	$a$ CORN (NIST) [350,352–354]	Data taking ongoing
	1.0 – 1.5% [351]	$a$ SPECT (ILL) [228,229,351]	Analysis being finalized
	0.15% [188,358]	Nab (LANL) [188,289,357,358]	In preparation
	0.14% [391]	UCNA (LANL) [390]	Data taking planned
$\tilde{A}_n$	0.18% [295]	PERKEO III (ILL) [295]	Analysis ongoing
	0(0.1)% [78]	TRINAT (TRIUMF) [78]	Planned
$\tilde{B}_n$	0.01% [397]	UCNB (LANL) [397]	Planned
$\tilde{A}_n (a_n, \tilde{B}_n, \dots)$	0.05% [291]	PERC (Munich) [291,292]	In preparation
	<0(0.1)% [399]	BRAND (ILL/ESS) [399,400]	Proposed
$D$	$\mathcal{O}(10^{-4})$ [418]	MORA (GANIL/JYFL) [418]	In preparation ( ${}^{23}\text{Mg}$ )
$R$	$\mathcal{O}(10^{-3})$ [427]	MTV (TRIUMF) [427–429]	Data taking ongoing ( ${}^8\text{Li}$ )
$D, R$	$\mathcal{O}(0.1)\%$ [399]	BRAND (ILL) [399,400]	Proposal

"Future"

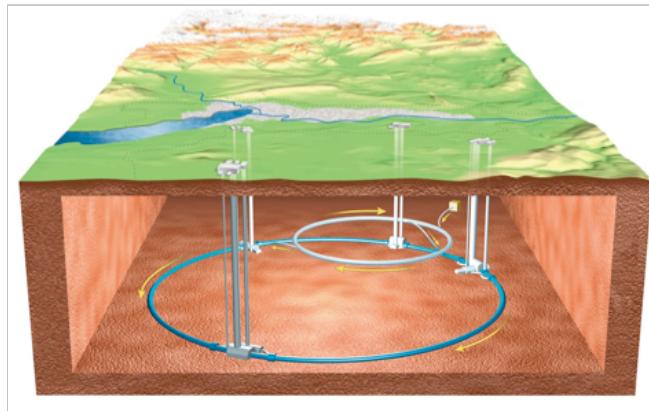


numbers  
/ planned experiments):

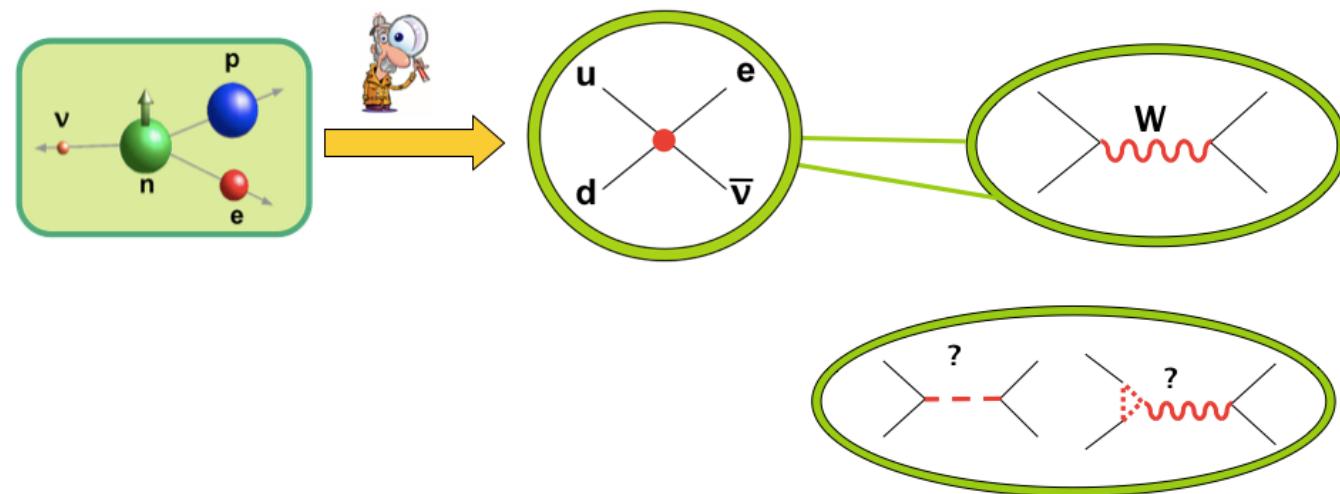
s

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

001

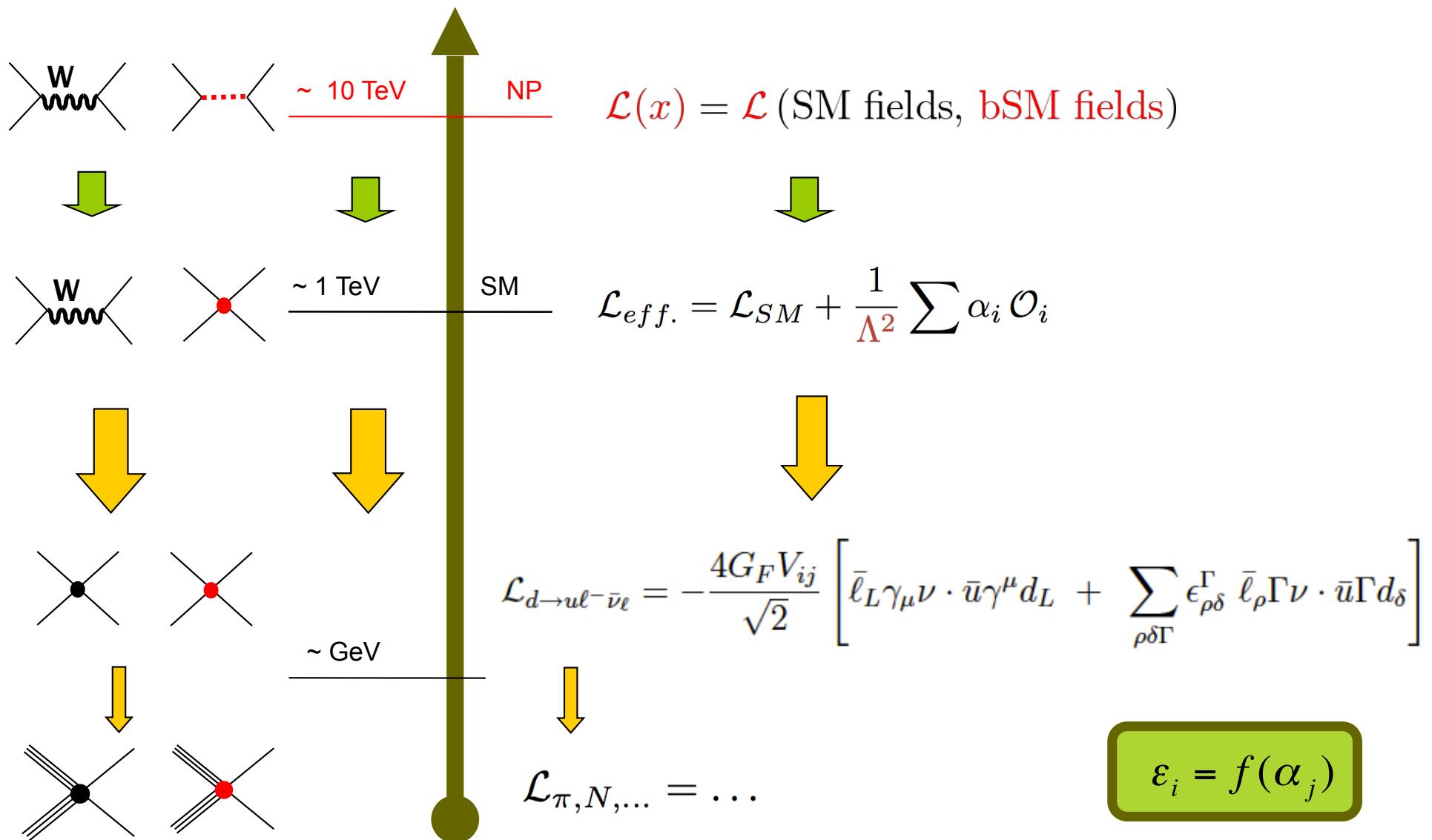


# Quarks, W, Z, ...



# Matching with high-E EFT

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



# Matching with high-E EFT

Low-E EFT

SMEFT

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

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

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

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

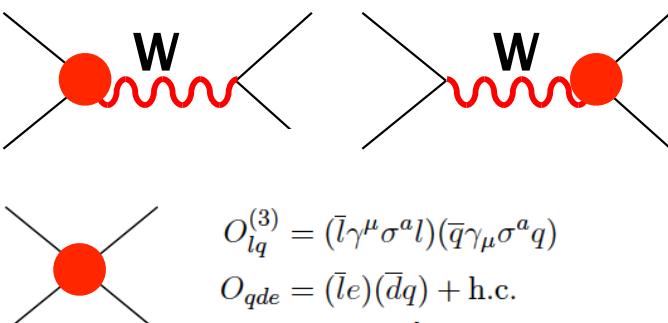
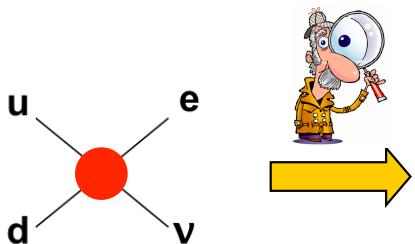
$$V_{1j} \cdot \epsilon_{s_L}^{j\ell} = - [\hat{\alpha}_{lq}]_{\ell\ell j 1}^*,$$

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

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

$$\hat{\alpha} = \alpha \frac{v^2}{\Lambda^2}$$

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



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

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

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

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

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

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

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

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

# Matching with high-E EFT

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

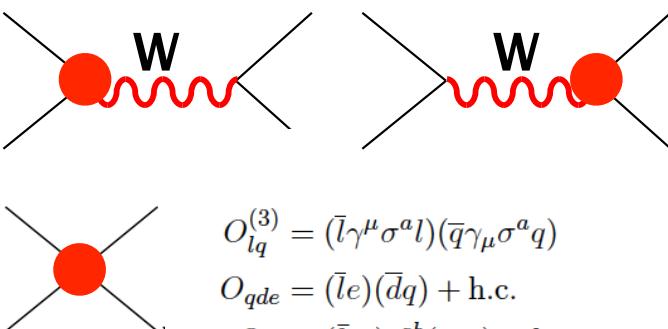
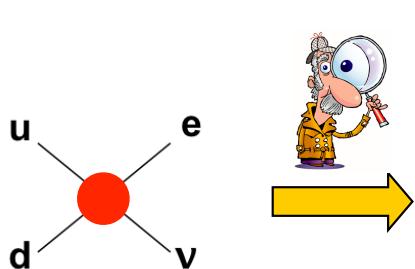
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$$\hat{\alpha} = \alpha \frac{v^2}{\Lambda^2}$$

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

Beta decays  
sensitive to a few  
EFT coefficients



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

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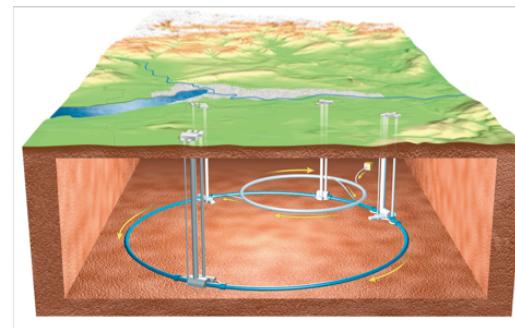
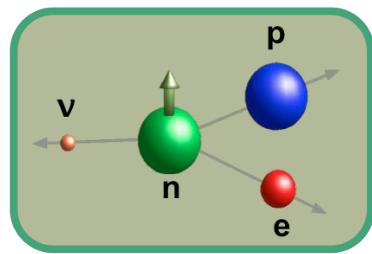
$$O_{lq}^{(3)} = (\bar{l} \gamma^\mu \sigma^a l)(\bar{q} \gamma_\mu \sigma^a q)$$

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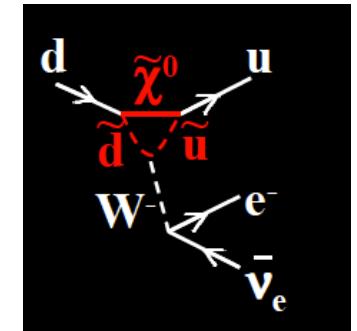
# V-A interactions: CKM unitarity test vs LEP



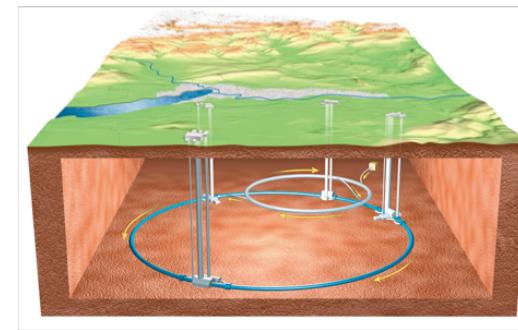
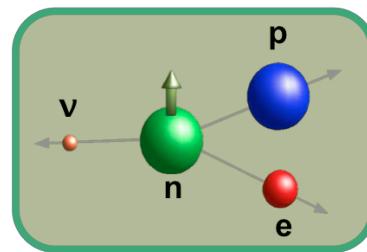
Many examples:

- 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),  
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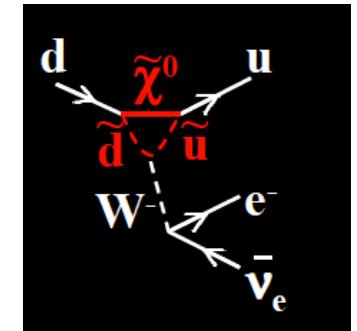
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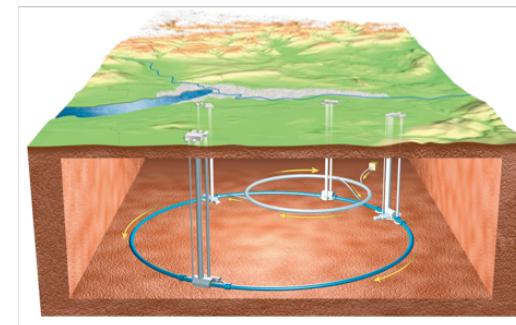
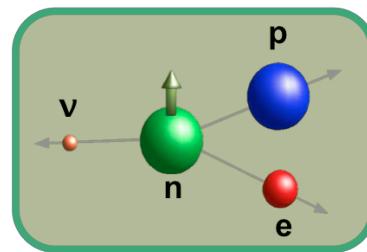
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## V-A interactions: CKM unitarity test vs LEP



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

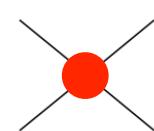
# CKM unitarity vs HEP

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

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

$\delta g_L^{Wq}$

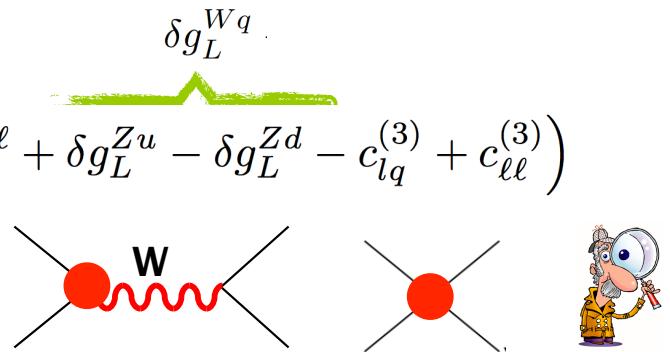




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[From Falkowski, MGA & Mimouni, 2017]

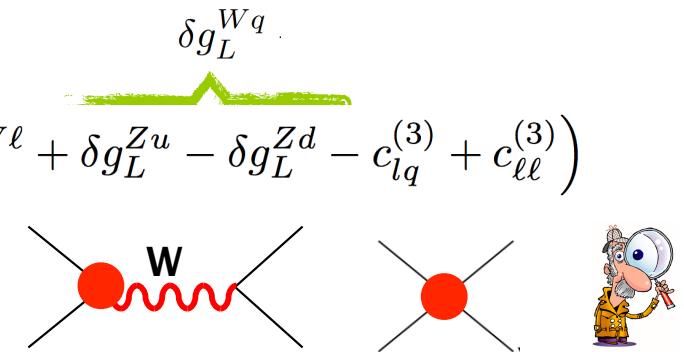
$$\begin{pmatrix} \delta g_L^{W\ell} \\ \delta g_L^{Zu} \\ \delta g_L^{Zd} \\ c_{\ell\ell}^{(3)} \\ c_{\ell q}^{(3)} \end{pmatrix} \times 10^3 = \begin{pmatrix} 0.15 \pm 0.18 \\ 0.48 \pm 0.45 \\ -0.05 \pm 0.27 \\ -0.40 \pm 0.37 \\ -1.11 \pm 0.89 \end{pmatrix}_{\text{LEP/EWPO}} \quad \text{vs.} \quad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



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[From Falkowski, MGA & Mimouni, 2017]

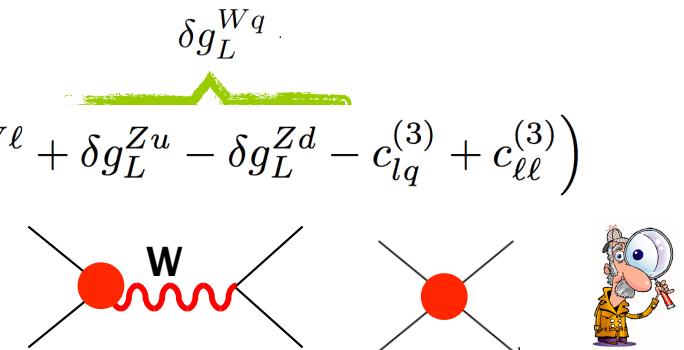
$$\begin{array}{c} \text{Feynman diagram with a red wavy line} \\ \left( \begin{array}{c} \delta g_L^{W\ell} \\ \delta g_L^{Zu} \\ \delta g_L^{Zd} \\ c_{\ell\ell}^{(3)} \\ c_{\ell q}^{(3)} \end{array} \right) \times 10^3 = \left( \begin{array}{c} 0.15 \pm 0.18 \\ 0.48 \pm 0.45 \\ -0.05 \pm 0.27 \\ -0.40 \pm 0.37 \\ -1.11 \pm 0.89 \end{array} \right) \text{LEP/EWPO} \end{array} \quad \text{vs.} \quad \left( \begin{array}{c} 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \end{array} \right)_{\Delta_{\text{CKM}}} \quad \text{LHC } (pp \rightarrow ev, ee) \text{ can't compete here}$$



# CKM unitarity vs HEP

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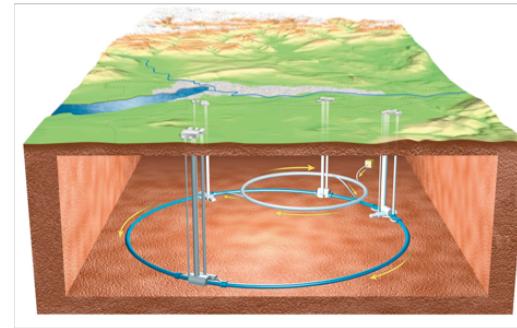
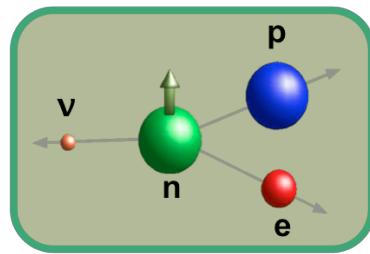
[From Falkowski, MGA & Mimouni, 2017]

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LHC reaching this level...



# Scalar & tensor interactions: $b_{\text{Fierz}}$ vs LHC

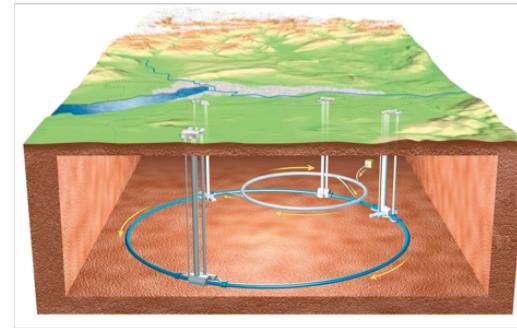
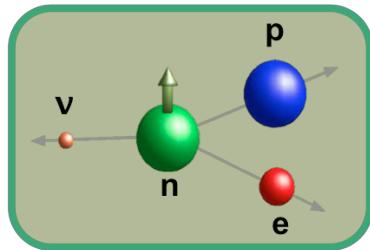


Models:

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

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

## Scalar & tensor interactions: $b_{\text{Fierz}}$ vs LHC



Models:

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

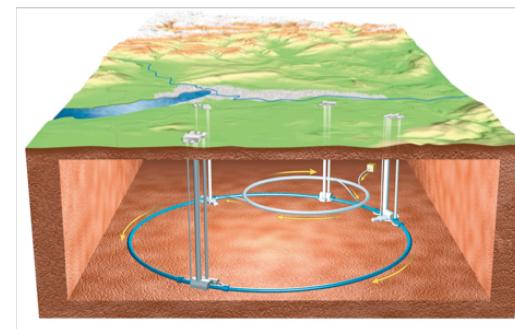
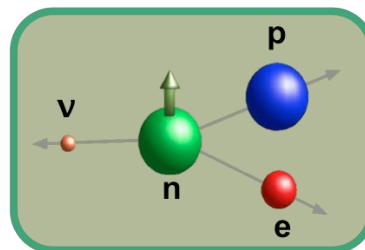
[Herczeg (2001), Profumo et al (2007),  
Yamanaka et al. (2010)]

But... Extremely hard to avoid  $\pi \rightarrow \ell\nu$

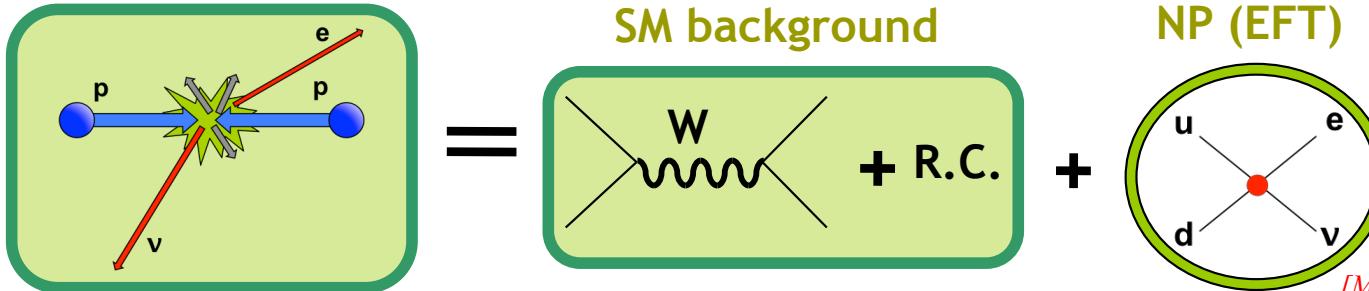
- Tree: chiral theories... ( $1 \pm \gamma_5$ )
- Loop: QED & EW mixing ( $S, T \rightarrow P$ )

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

## Scalar & tensor interactions: $b_{\text{Fierz}}$ vs LHC



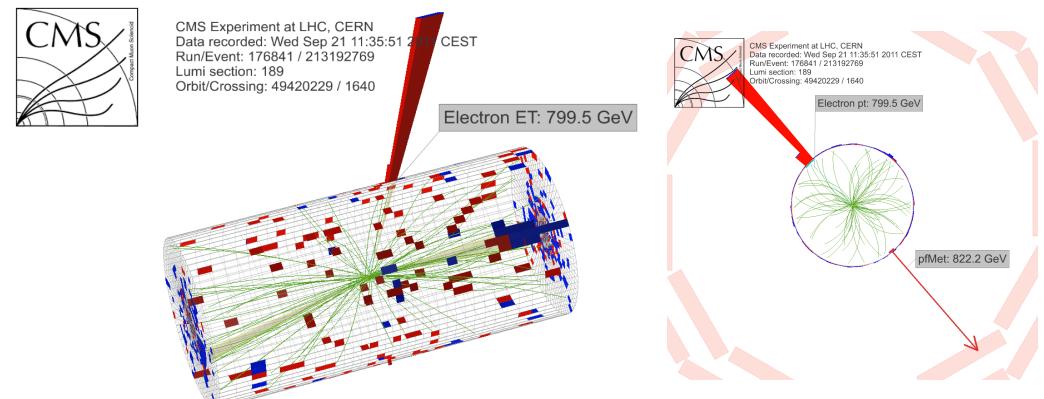
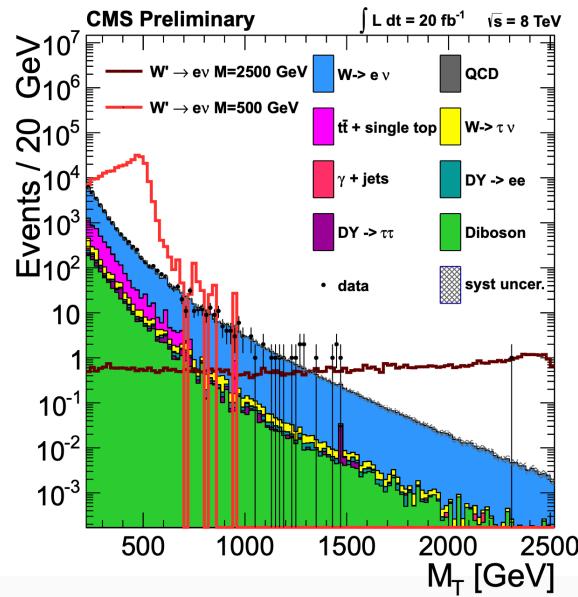
# LHC limits on $\varepsilon_{S,T}$



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

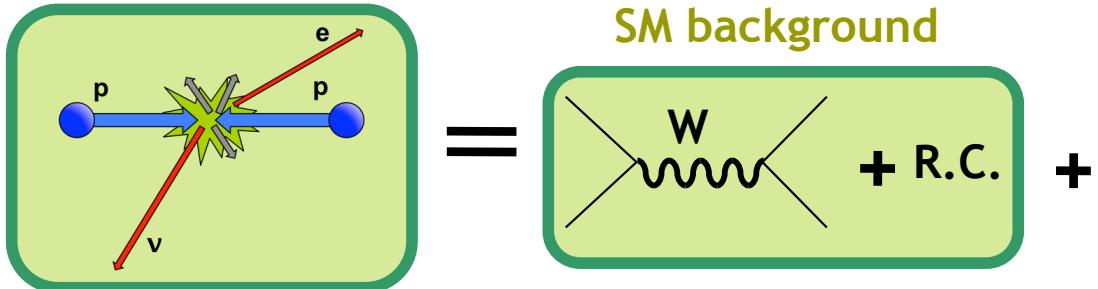
$$N_{pp \rightarrow evX} (m_T^2 > m_{T,cut}^2) = \varepsilon \times L \times \sigma_{pp \rightarrow evX} (m_T^2 > m_{T,cut}^2) = \varepsilon \times L \times (\sigma_W + \sigma_S \varepsilon_S^2 + \sigma_T \varepsilon_T^2)$$

(Interference w/ SM  $\sim m/E$ )



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

# LHC limits on $\epsilon_{S,T}$

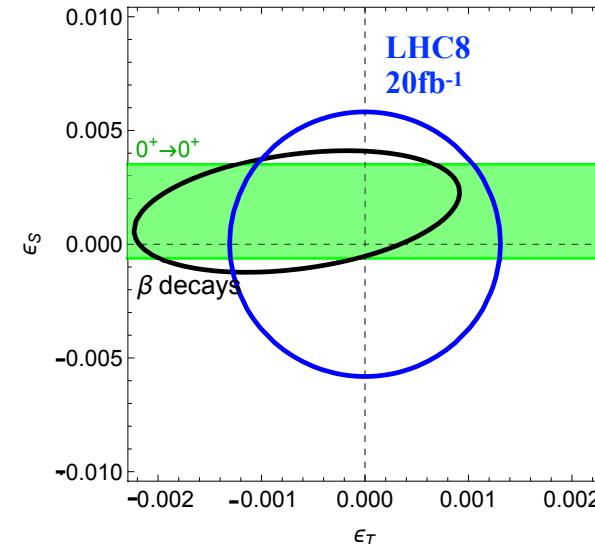
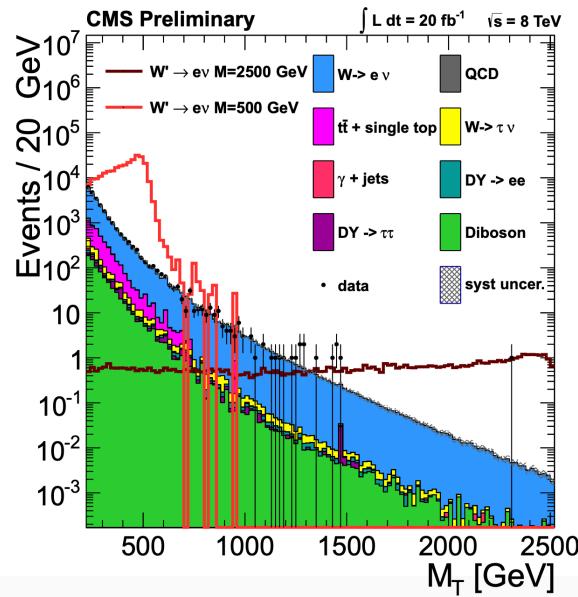


NP (EFT)

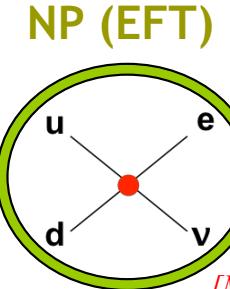
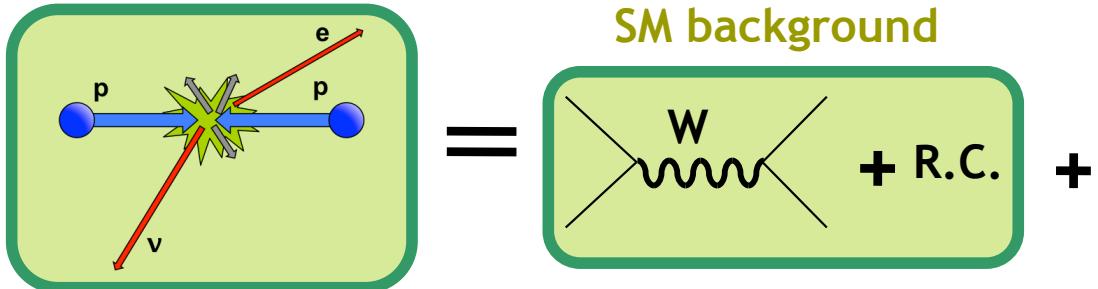
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(Interference w/ SM  $\sim m/E$ )



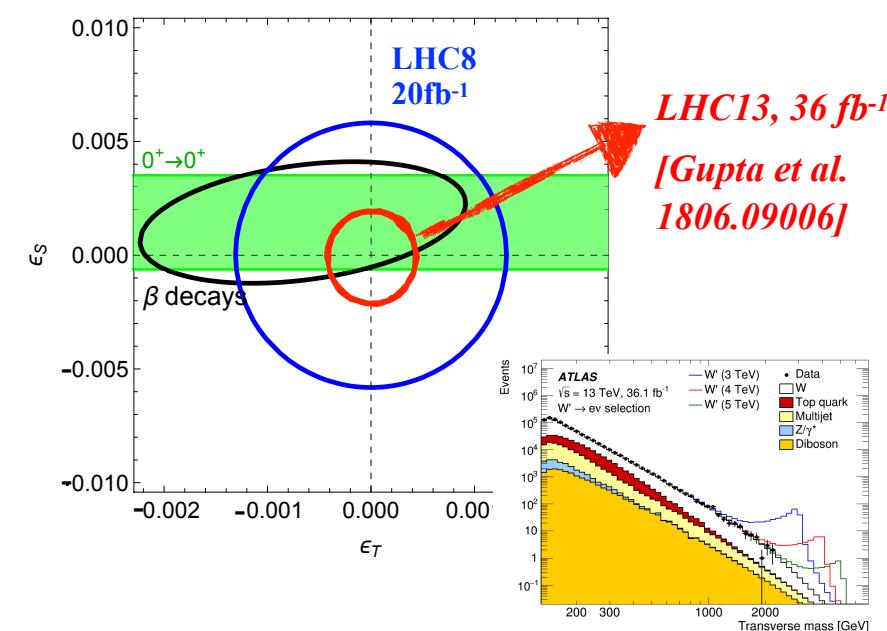
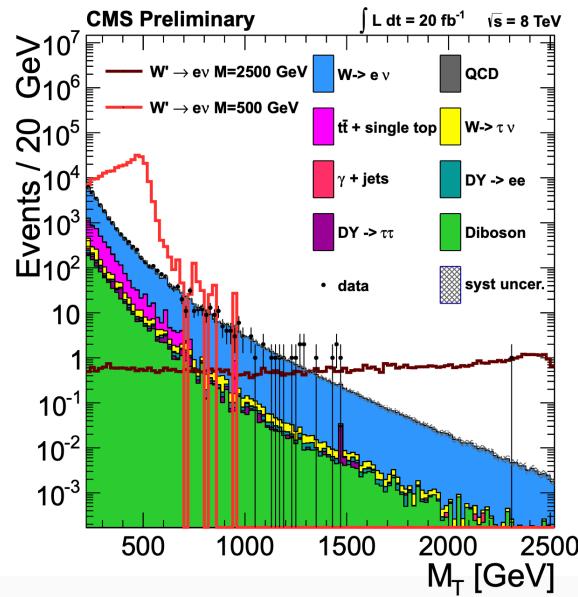
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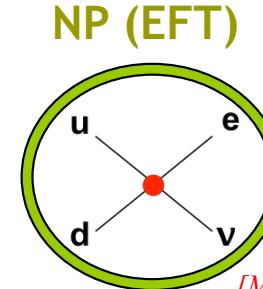
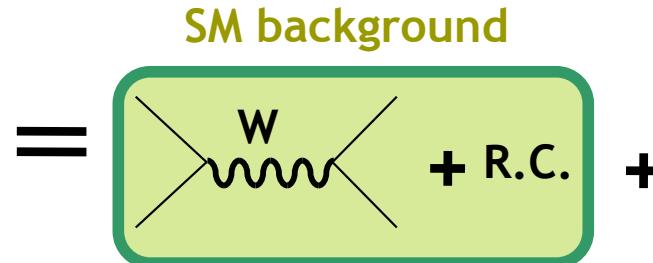
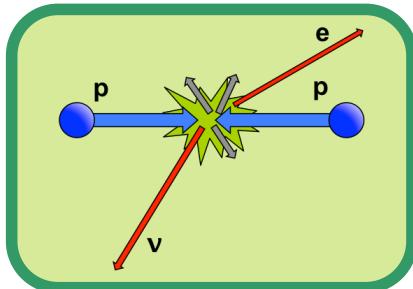
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(Interference w/ SM  $\sim m/E$ )



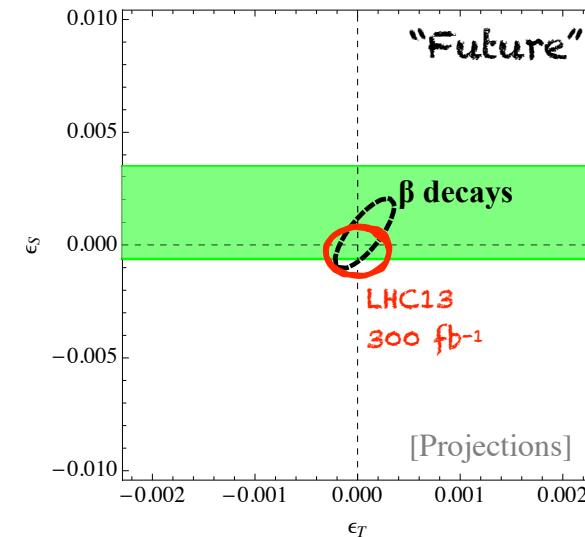
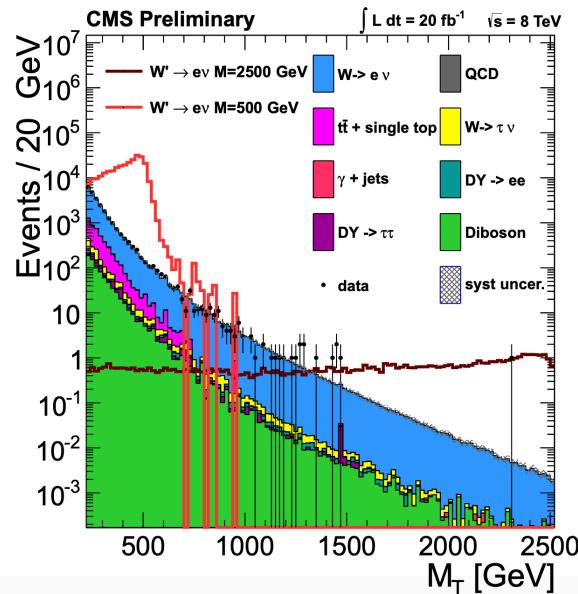
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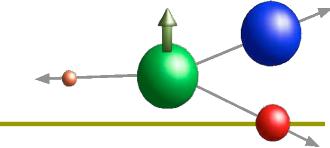
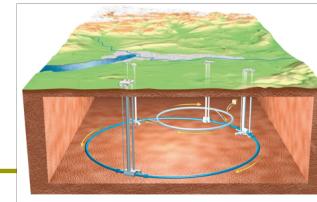
(Interference w/ SM  $\sim m/E$ )



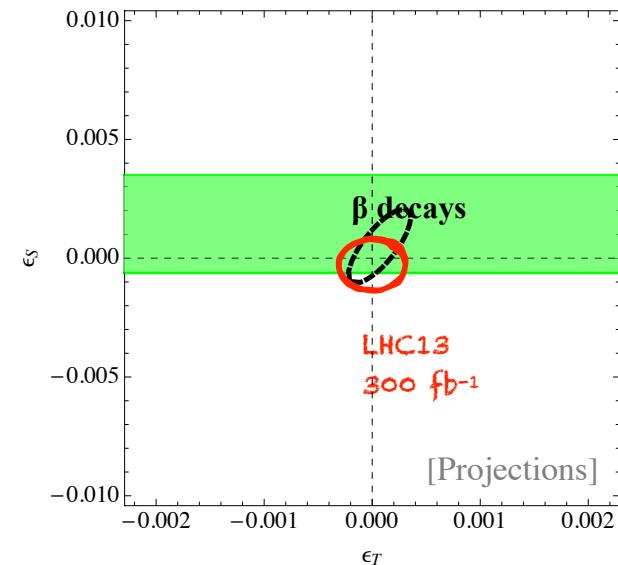
[MGA, O. Naviliat Cuncic, N. Severijns, 1803.08732;  
 Gupta et al. 1806.09006]

# Conclusions

- (Sub) permil-level precision in  $\beta$  decays
  - Great QCD progress
  - Experimental progress too (ISOLDE!)
  - Inner RC?
- General EFT analysis available
  - Comparison between  $\beta$ -decay observables;
  - Comparison with APV, LEP, LHC, ...
  - $\beta$  decays are competitive TeV probes;
- More weak interaction physics at ISOLDE:  
EDMs, atomic parity violation, ...



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

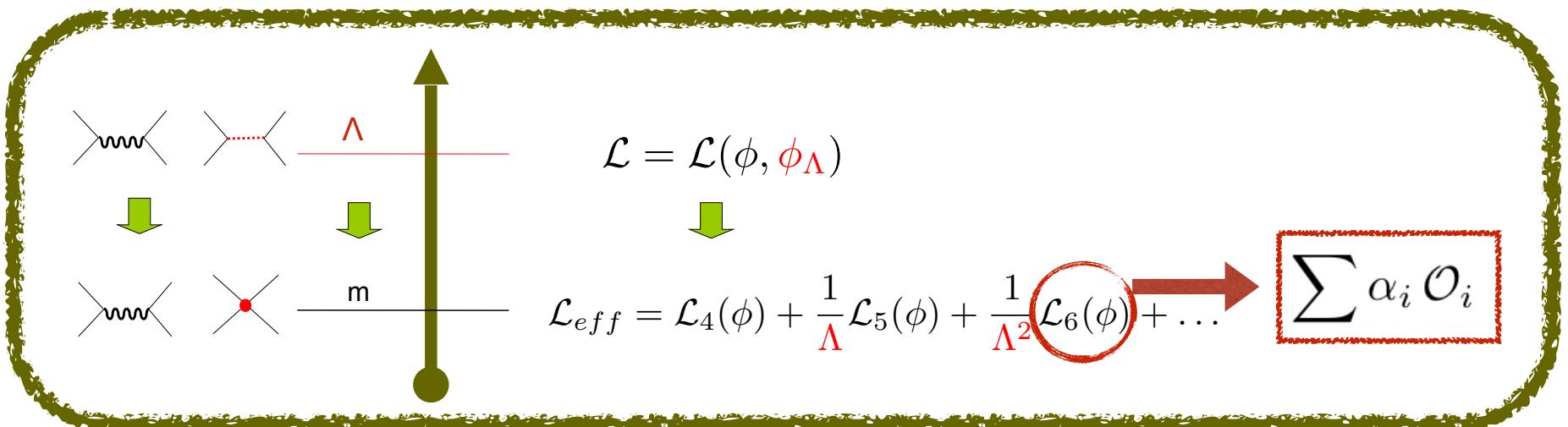


$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i(g_{NP}, M_{NP})$$

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# Backup slides

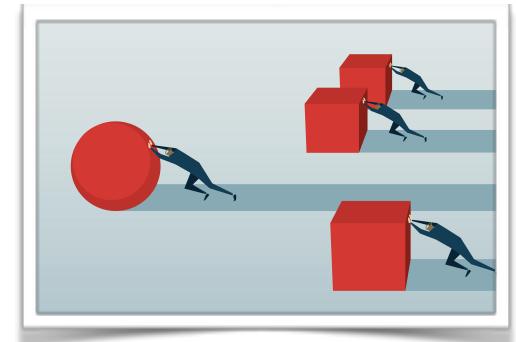
# What's an EFT?



$\alpha_i$  : Wilson coefficients.

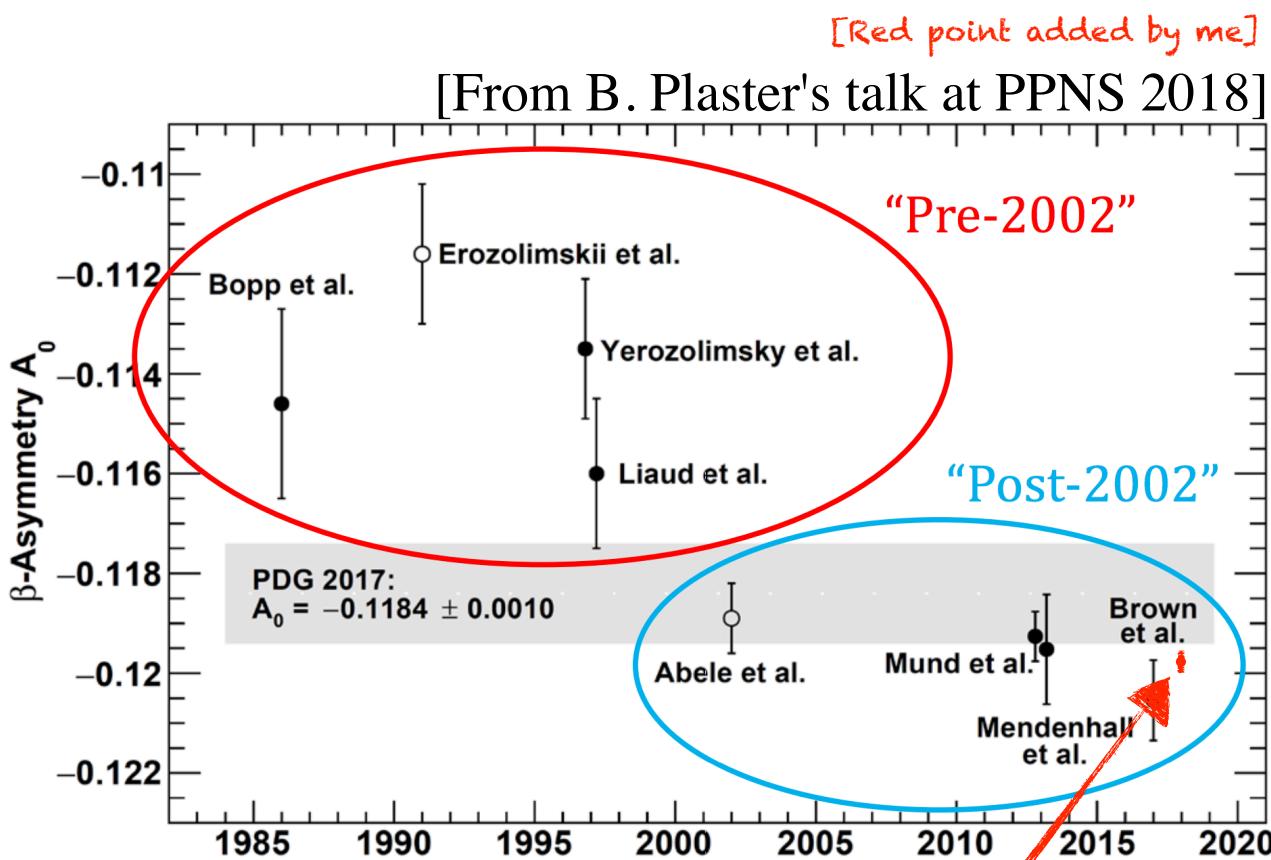
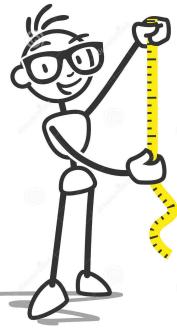
- Pros:
  - Comparison with other probes, under general assumptions;
  - Efficiency: the analysis is done once and for all!
  - Connection with HEP

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



# Current data (+ TH!!)

Precision:  
 $0(0.01 - 1)\%$  !!



**NEW**

PPNS 2018 (May'18):  
 $A_n = -0.11983(21)$   
 $\sigma_A = 1.2764(6) [0.04\%]$   
 Perkeo III (2.5x!)

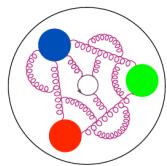
Neutron data

Parameter	Value
$\tau_n$ (s)	879.75(76) * ( $S = 1.9!!$ )
$a_n$	-0.1034(37) *
$\tilde{a}$	-0.1090(41)
$\tilde{A}_n$	-0.111869(99) * ( $S = 2.6!!$ )
$\tilde{B}_n$	0.9805(30) *
$\lambda_{AB}$	-1.2686(47)
$D_n$	-0.00012(20) *
$R_n$	0.004(13)

\* Average

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





# From hadrons to quarks

Likewise...

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

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

Implications? It almost compensates the bilinear suppression!

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

*“since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted”*

[Jackson, Treiman & Wyld, 1957]

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

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

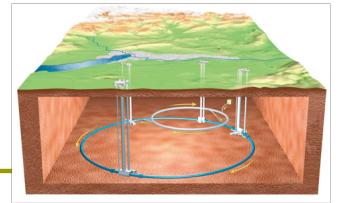
From current data:

$$\epsilon_P = -0.08(15) \text{ (90%CL)}$$

But... the bounds on  $\epsilon_P$  from pion decays are much stronger!!!

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

# If we see a bump...



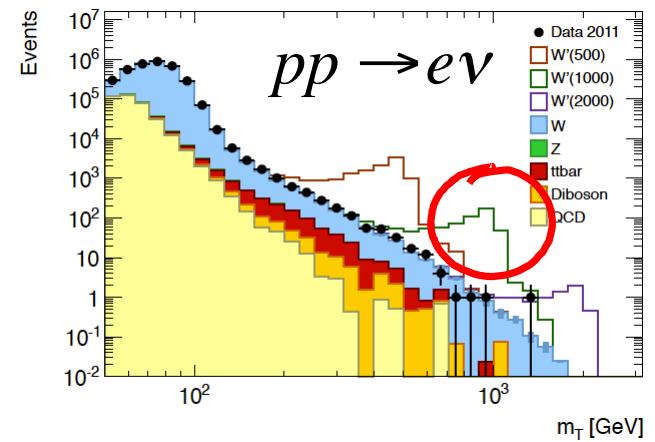
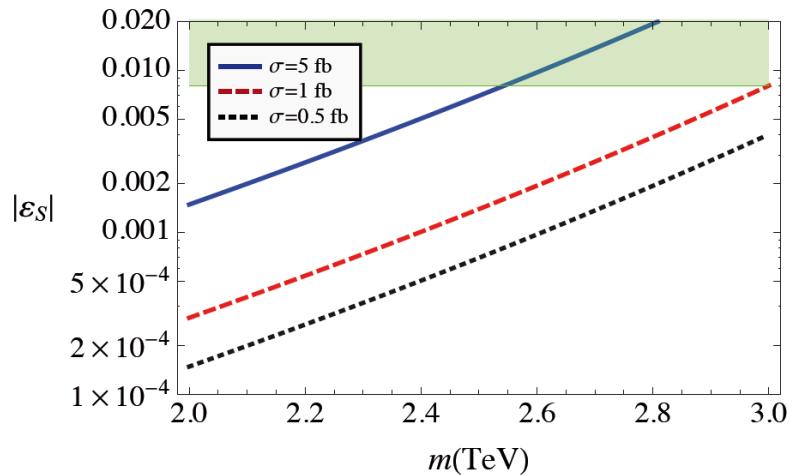
- EFT breaks down...

Toy model: scalar resonance:

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

- Then we have a lower-limit value for  $\varepsilon_S$ :

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



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

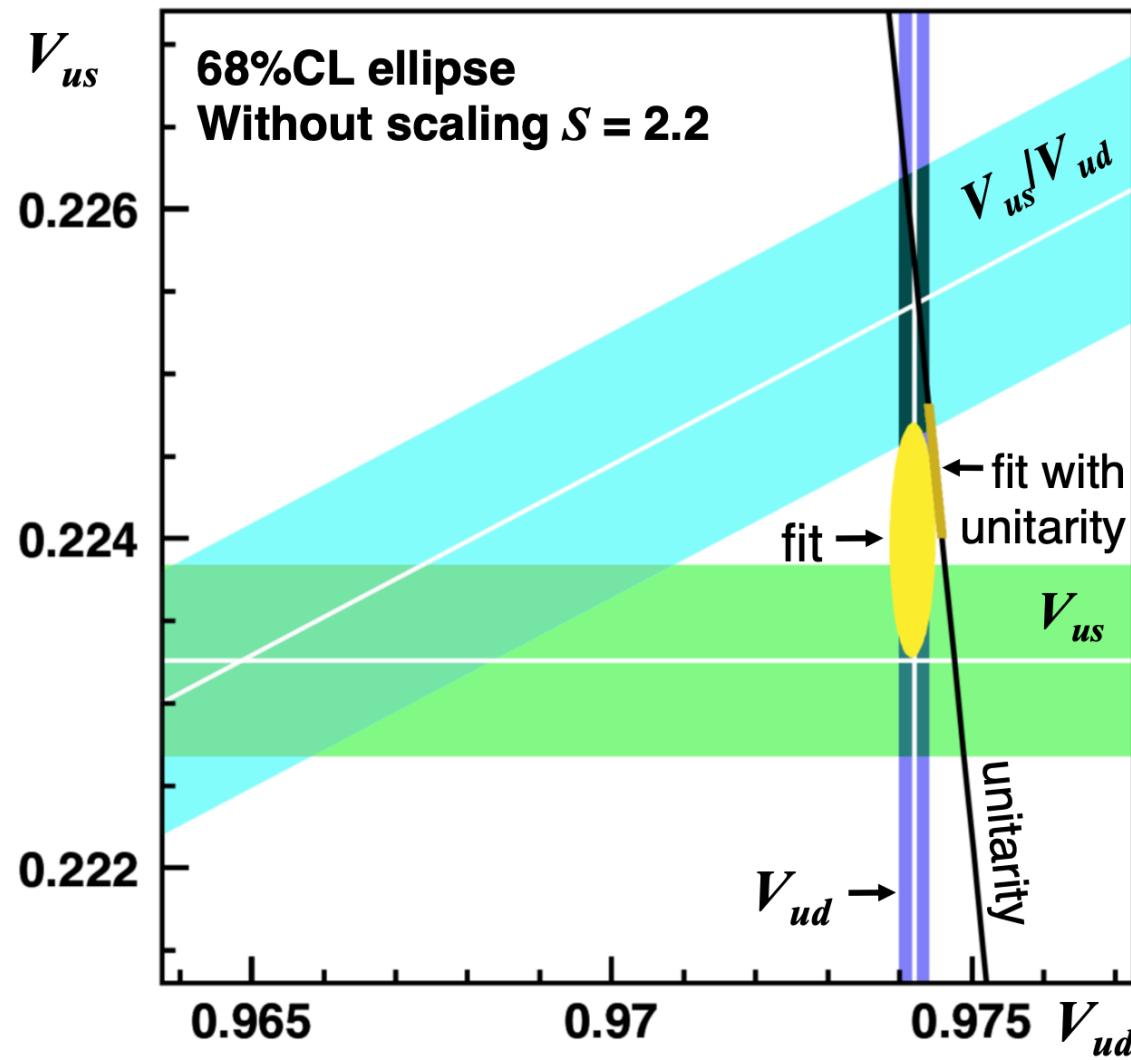
$$\tau = m^2/s$$

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

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

[T. Bhattacharya et al., 2012]

# CKM unitarity



Matthew Moulson & Emilie Passemar