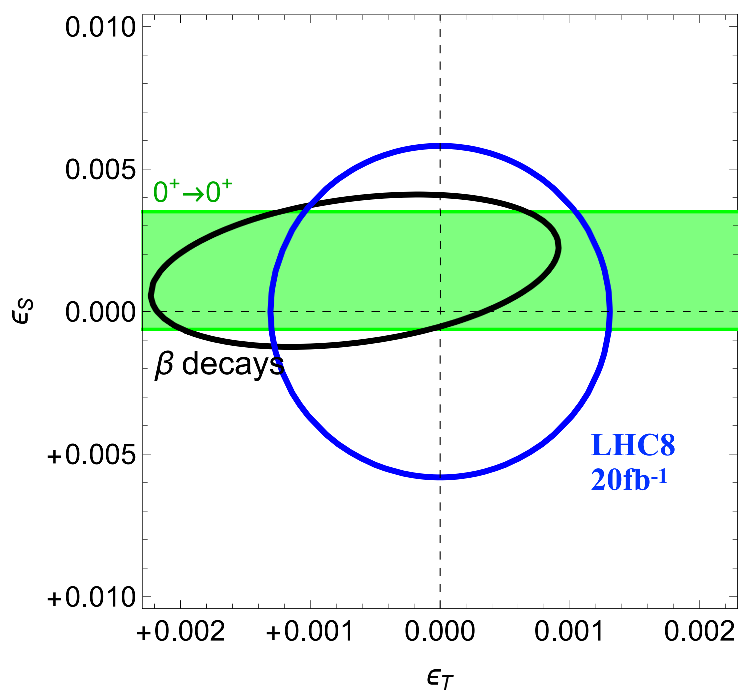
Standard Model tests
in neutron & nuclear β decay

CIPANP 2018 May 2018



Martín González-Alonso

CERN-TH

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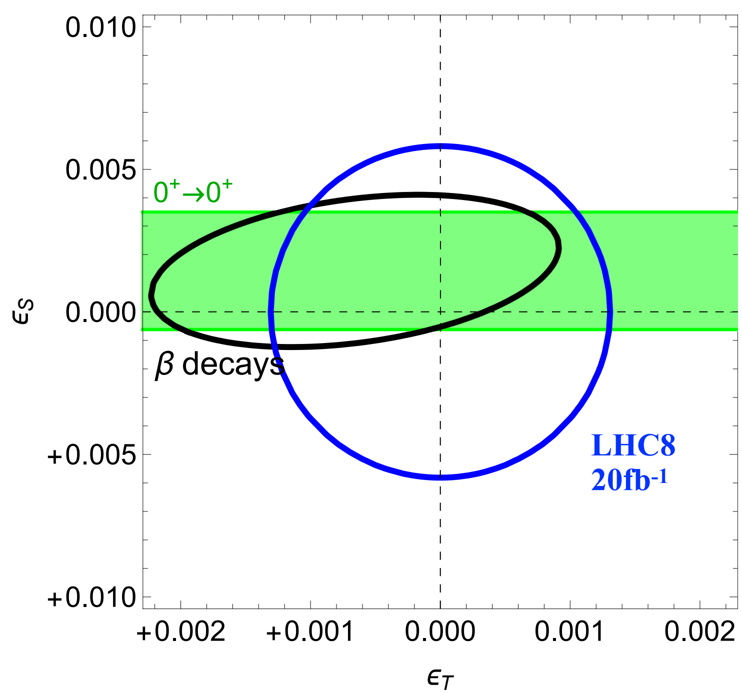


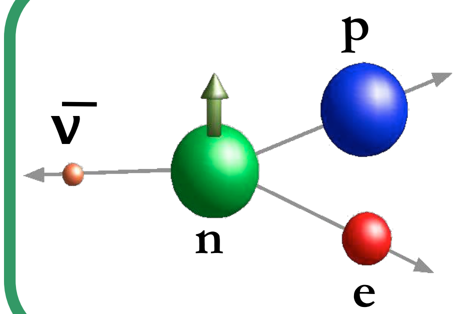
Martín González-Alonso

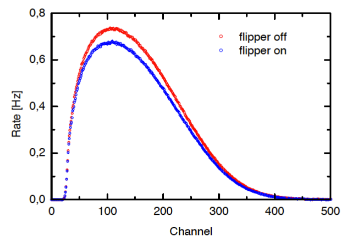
CERN-TH

Talk strongly influenced by my various collaborations with V. Cirigliano, A. Falkowski, M. Graesser, J. Martin Camalich, O. Naviliat Cuncic, N. Severijns, …

[Recent review: MGA, O. Naviliat Cuncic, N. Severijns, 1803.08732]

Motivation





Precise data

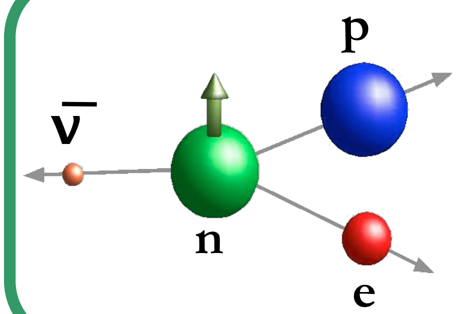
+

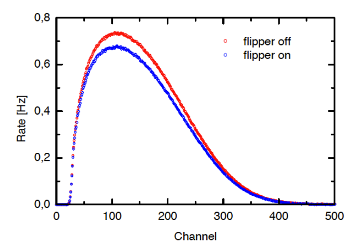
Precise SM predictions

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

[Hardy & Towner'15]

Motivation





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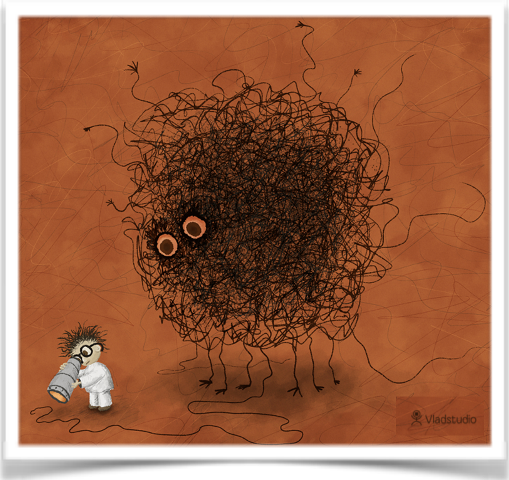
Precise SM predictions

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

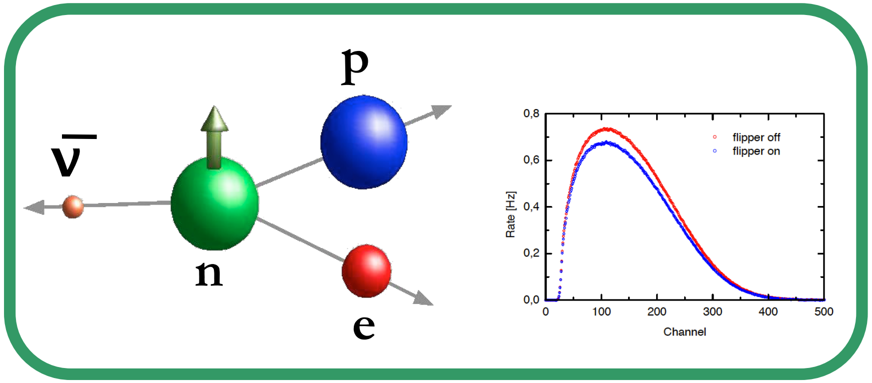
[Hardy & Towner'15]

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!**



Motivation



Precise data

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[Hardy & Towner'15]

Implications for New Physics?

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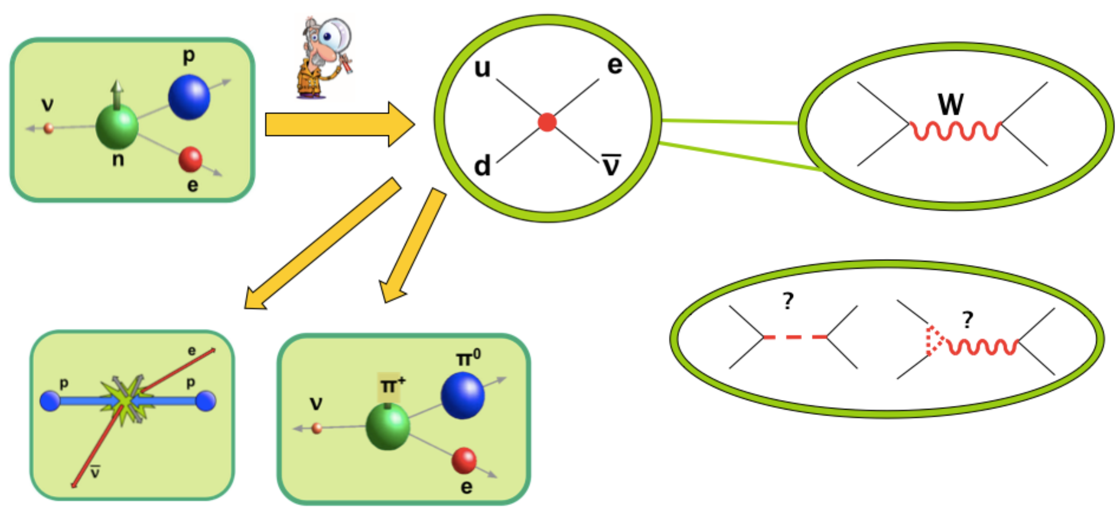
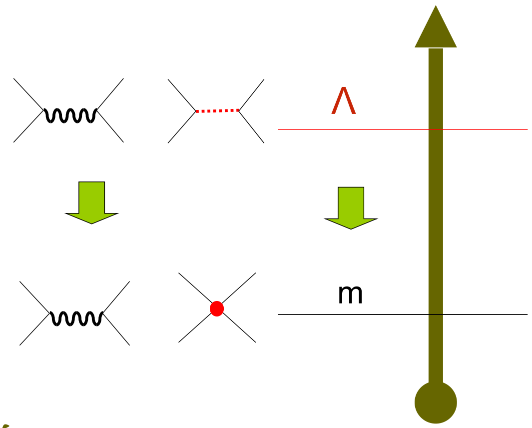
- **Something more model-indep? EFTs!**

Competitive probes?

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



What's an EFT?



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

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

α_i : Wilson coefficients.

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

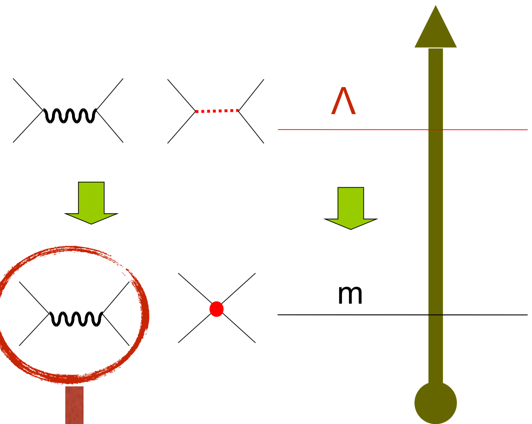
Effective Field Theory = Fields + Symmetries

Fields	Symmetries
- nuclei, e, ν	- Lorentz
- hadrons, e, ν	- QED
- q, u, d, l, e	- SU(2) x U(1)
- W, Z, γ, g	- Flavour sym?
- …	- B, L;

Not assumption independent!

E.g. BSM setups with light d.o.f.
require a separate study

What's an EFT?



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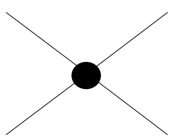
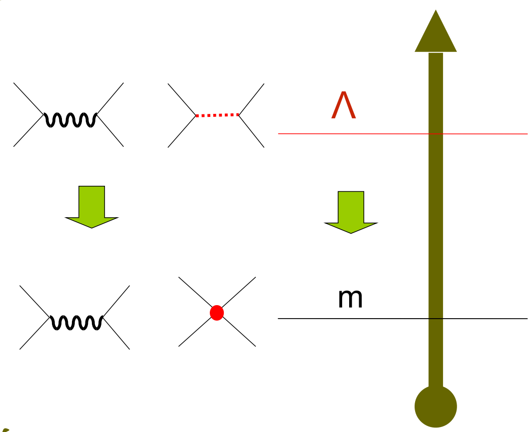


$$-\frac{4G_F}{\sqrt{2}}\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\mu$$

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

Wilson coefficient

What's an EFT?



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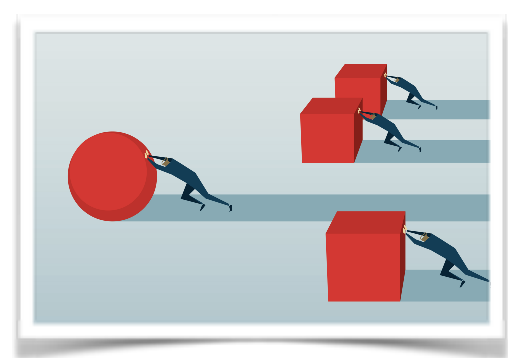
α_i : Wilson coefficients.

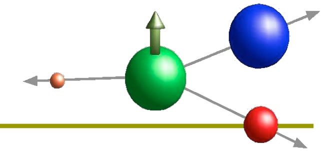
$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$$

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

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



Comparing experiments



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

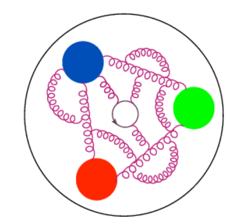
$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar\nu_e} = \; & \bar p\, n\; (C_S \bar e \nu_e - C_S' \bar e \gamma_5 \nu_e) \\
& + \bar p \gamma^\mu n\, (C_V \bar e \gamma_\mu \nu_e - C_V' \bar e \gamma_\mu \gamma_5 \nu_e) \\
& + \frac{1}{2} \bar p \sigma^{\mu\nu} n\, (C_T \bar e \sigma_{\mu\nu} \nu_e -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

[Lee & Yang'1956]

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

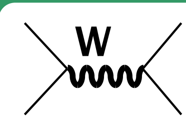
$$
\mathcal{L}_{d\to u\ell^-\bar\nu_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}} \left[\bar\ell_L \gamma_\mu \nu \cdot \bar u \gamma^\mu d_L \; + \; \sum_{\rho\delta\Gamma} \epsilon^\Gamma_{\rho\delta}\, \bar\ell_\rho \Gamma \nu \cdot \bar u \Gamma d_\delta \right]
$$

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



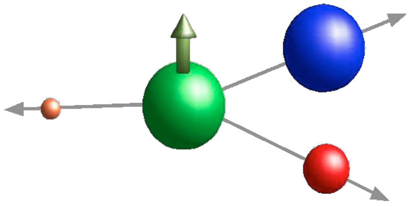
- How to compare with LHC experiments?
  - ➔ Effective Lagrangian at the **quark** level at the EW scale!

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



Hadrons:

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



Hadronic EFT

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

+ terms with RH neutrinos

Hadronic EFT

SM terms

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

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

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~~+ terms with RH neutrinos~~

Linear approx:
SM + small + (small)²

(Alternatively:
no RH neutrinos: $C_i = C_i'$)

Hadronic EFT

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

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

+ terms with RH neutrinos

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

(Alternatively:
no RH neutrinos: $C_i = C_i'$)

Hadronic EFT

$$
\begin{aligned}
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$$

Hadronic EFT

Vud (1 + NP)   [Lifetime shift]

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

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

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g_A (1 + NP)

Only way out: lattice QCD!

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

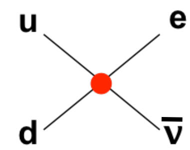
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

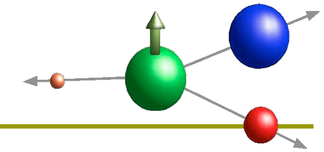
$$b_{(B)} = \#\, C_S + \#\, C_T$$

Fierz term!
[Fierz'1937]

[+ CPV effects]

Probing the Fierz term





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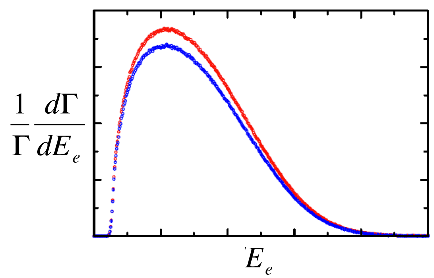
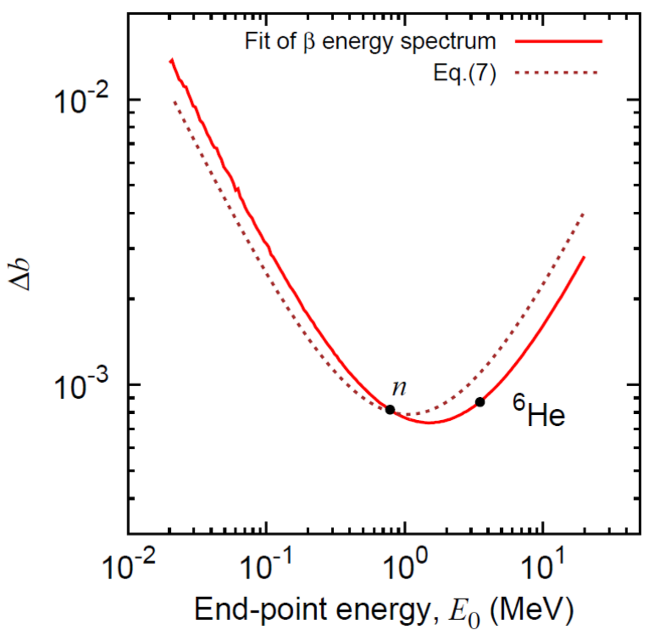
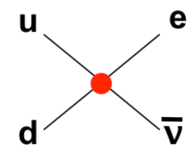
✓ Direct effect in the spectrum:

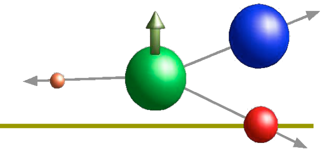


A large endpoint kills the effect…
but so does it a small one!
[MGA & Naviliat-Cuncic, PRC94 (2016)]



Probing the Fierz term





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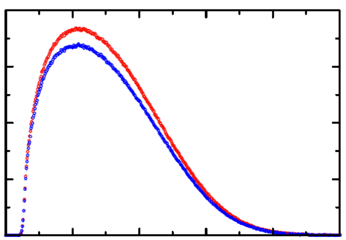
✓ Direct effect in the spectrum:

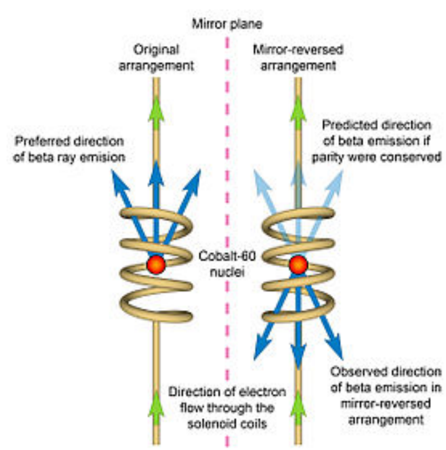


A large endpoint kills the effect… but so does it a small one!
[MGA & Naviliat-Cuncic, PRC94 (2016)]

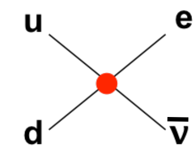
✓ Indirect effect in the asymmetries:

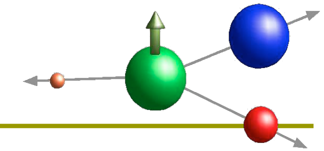
$$\tilde{X} = \frac{X}{1 + b\langle m/E_e\rangle}$$

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



Probing the Fierz term





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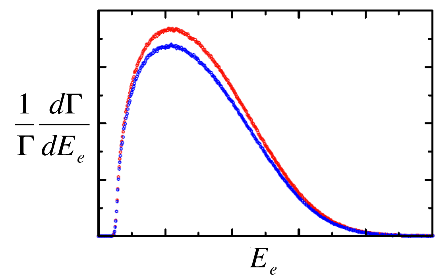
✓ Direct effect in the spectrum:



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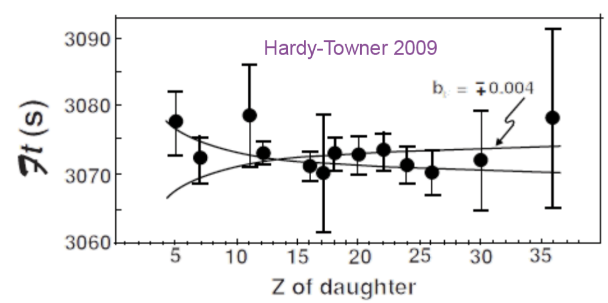
$$\tilde{X} = \frac{X}{1 + b\langle m/E_e\rangle}$$

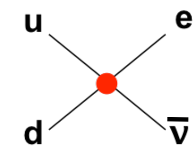
Not always valid! (proton spectrum)
[MGA & Naviliat-Cuncic, PRC94 (2016)]

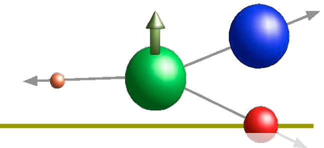
✓ Indirect effect in the Ft-values & neutron lifetime:

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



Probing the Fierz term





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

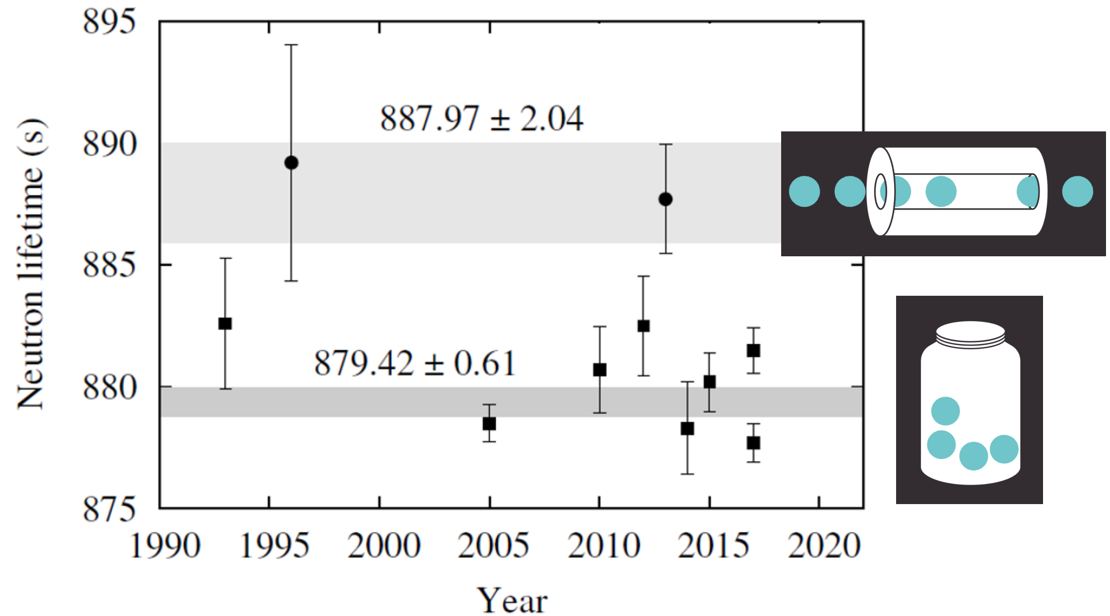
✓ Dir…

✓ Ind…

Heavy NP cannot explain the beam vs. bottle tension

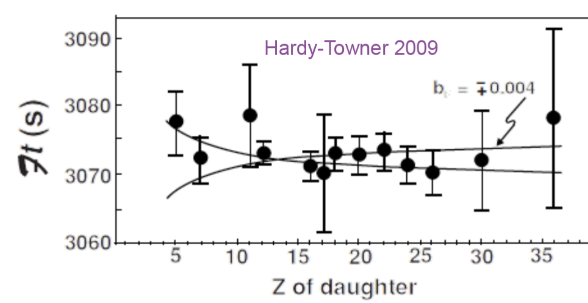
…. But light NP could do the job [Fornal & Grinstein PRL (120 (2018)]

[See talks by Fornal, Swank, Cornell, …]



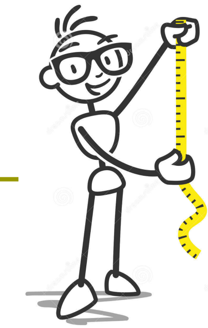
✓ Indirect effect in the Ft-values & neutron lifetime:

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



Current data (+ TH!!)

Precision:
O(0.01 – 1)% !!



Nuclei

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

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

[Hardy-Towner'2015]

[See talks by Hardy & Leach]

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)

[See talks by Callahan's, Wietfeldt, Dees & Melconian]

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)

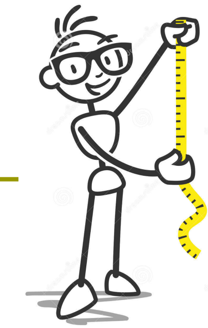
* Average

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

Many recent data:
τ_n (UCNτ'17, Gravitrap'17),
A_n (UCNA'18), a_n (aCORN'17), ...

Current data (+ TH!!)

Precision:
O(0.01 - 1)% !!



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Many recent data:
τ_n (UCNT'17, Gravitrap'17),
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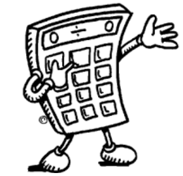
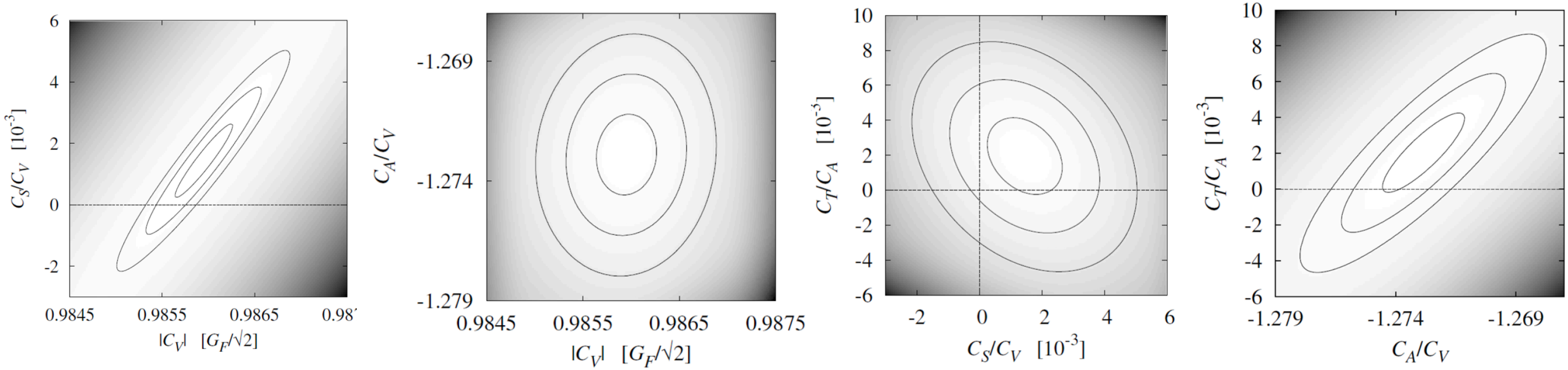
PPNS 2018 (Last week!):
$A_n = -0.11983(21)$
Perkeo III (2.5x!)



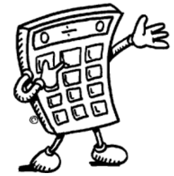
Current data → Results

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



Driven by Ft's, τ_n, A_n!

Current data → Results



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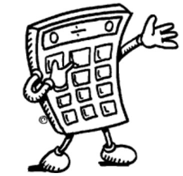
- One can trivially calculate the precision needed in any other observable to compete:

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

PS: the precision needed in a_n is much higher!

Current data → Results



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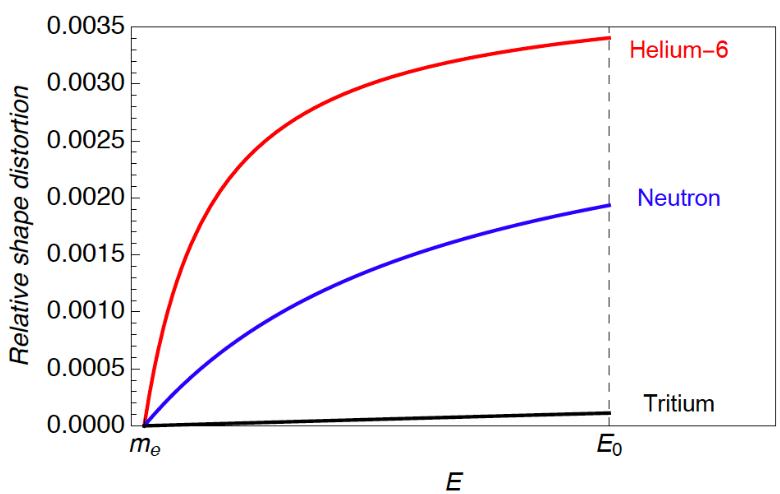
Ex. #2: Spectrum shape measurements



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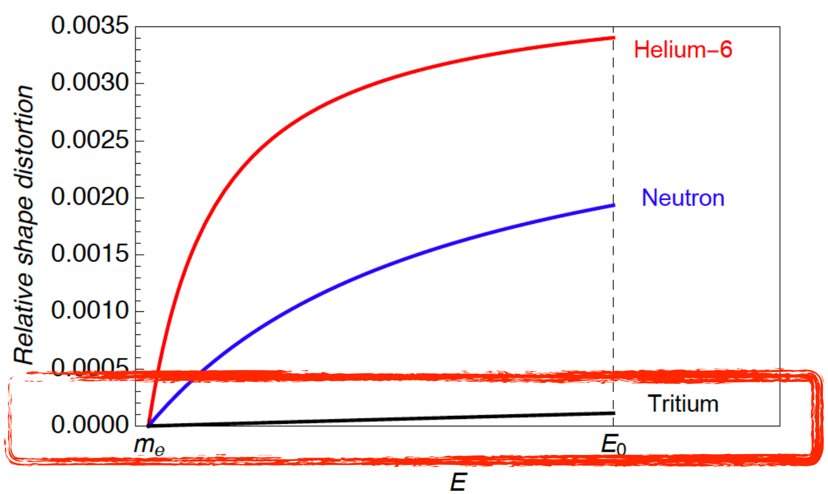
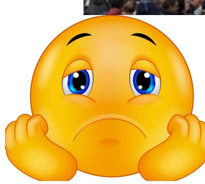
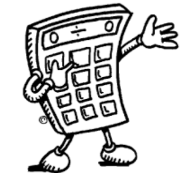


NP < SM TH errors



[Contrary to the claim in Ludl-Rodejohann, JHEP06(2016)040]

Current data → Results



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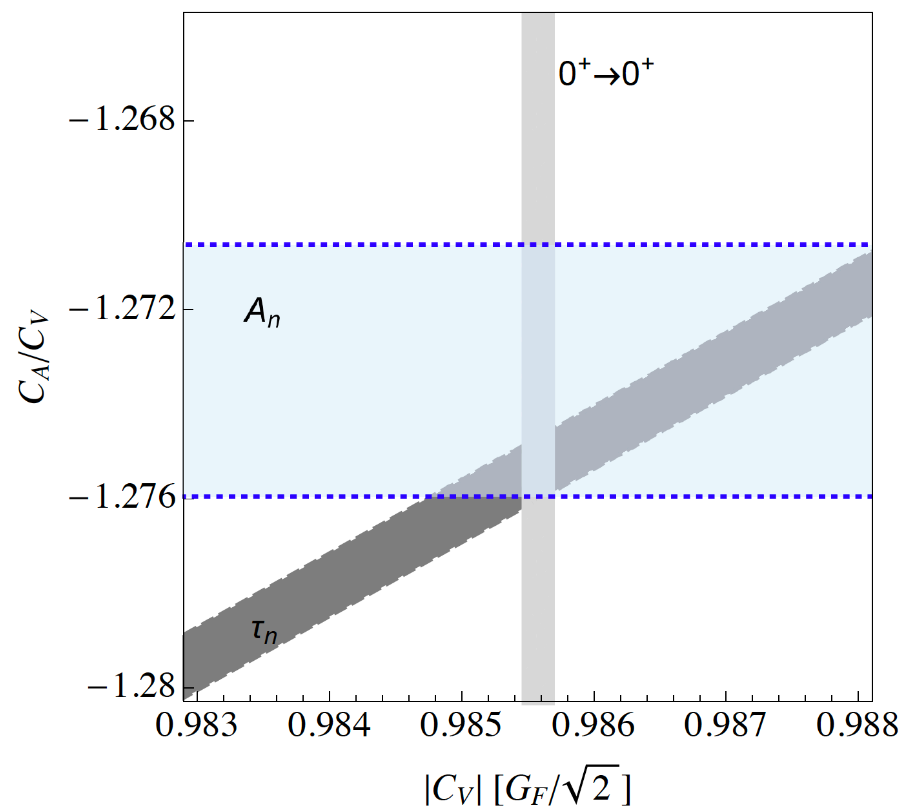
SM limit

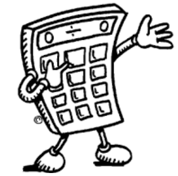
$$|C_V| = 0.98559(11)\, G_F/\sqrt{2}$$
$$C_A/C_V = -1.27510(66)\ ,$$

($\rho = 0.25$)

- Fit driven by Ft's & τ_n (not A_n!)
- Nice (& nontrivial) agreement;



Current data → Results



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$$

SM limit

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

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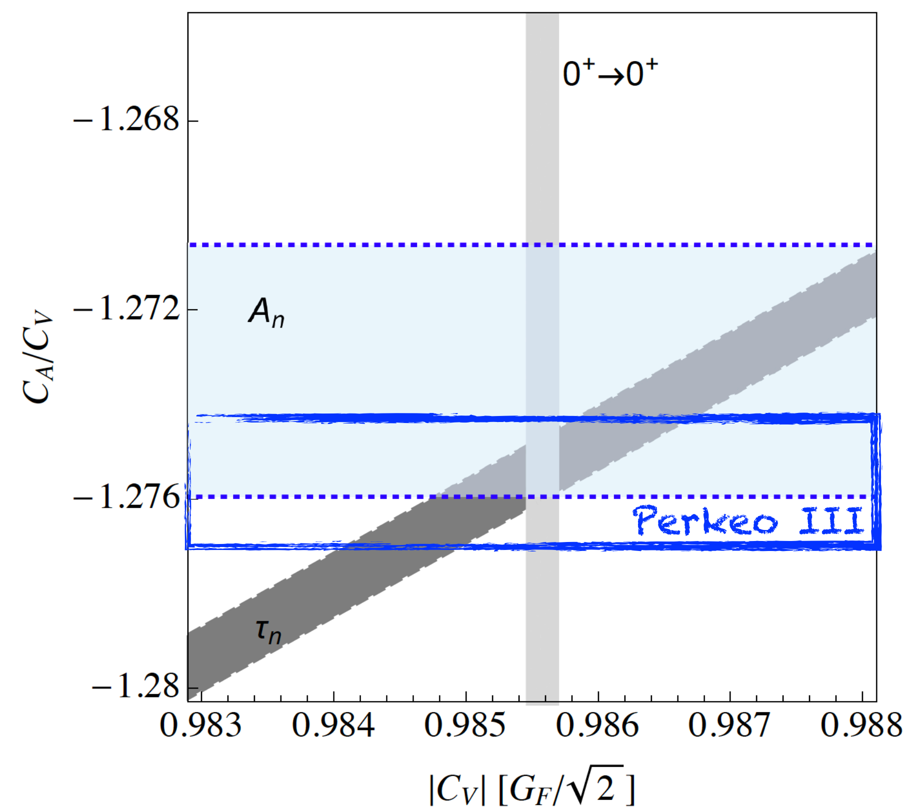
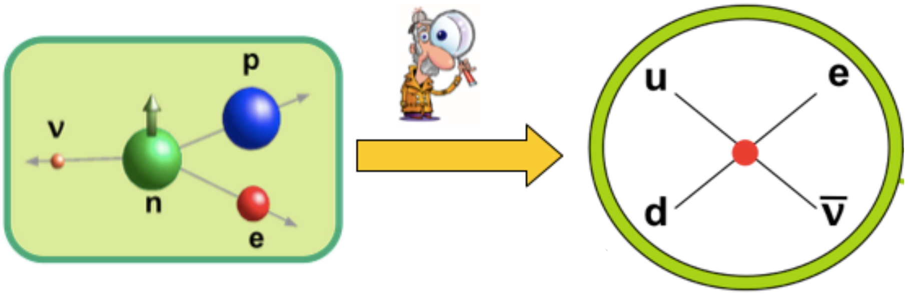


Quarks (low-E):

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



From hadrons to quarks

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

From hadrons to quarks

$\tilde{V}_{ud}$

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

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

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From hadrons to quarks

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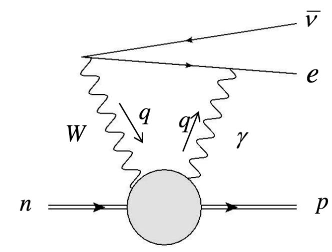
Inner RC: 2.361(38)%
[Marciano-Sirlin, PRL96 (2006)]



[Gorshteyn's talk]

From hadrons to quarks

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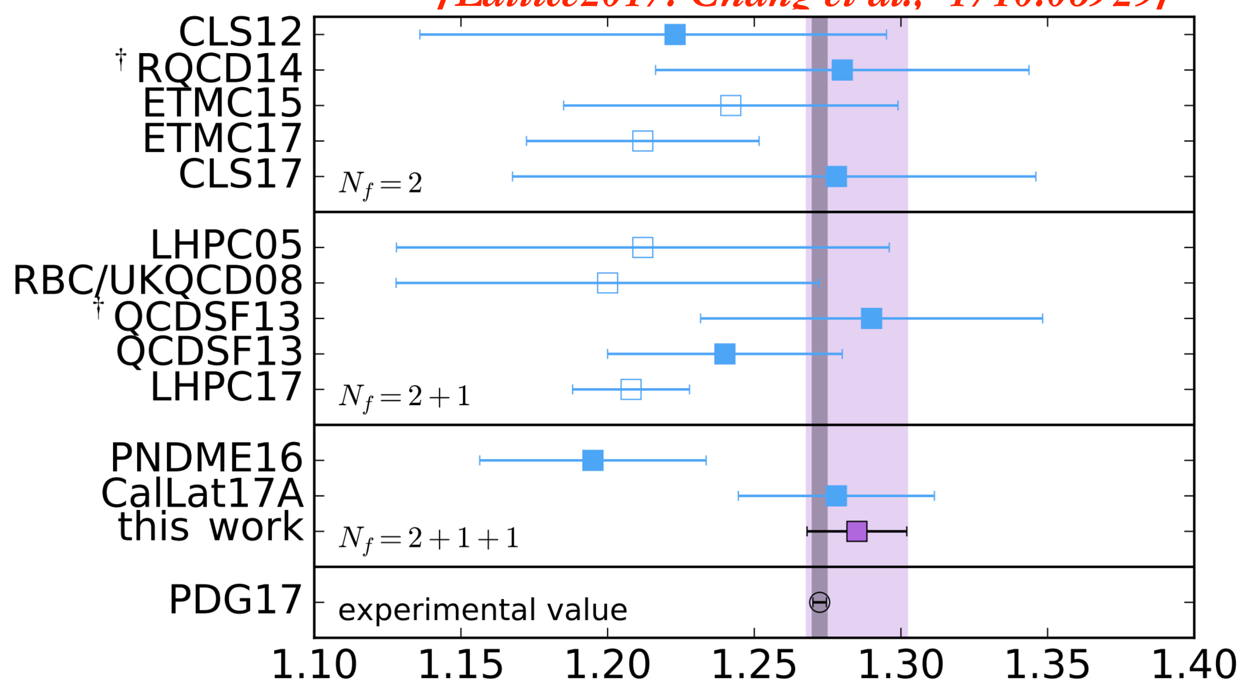
Axial charge

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

[Lattice2017: Chang et al., 1710.06523]



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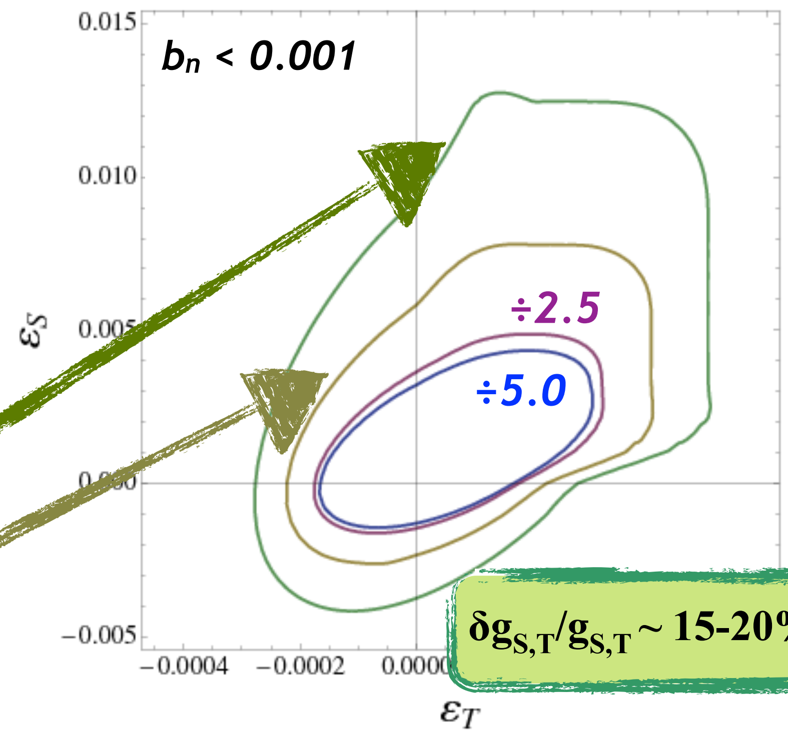
Scalar & tensor charges

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



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

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

From hadrons to quarks

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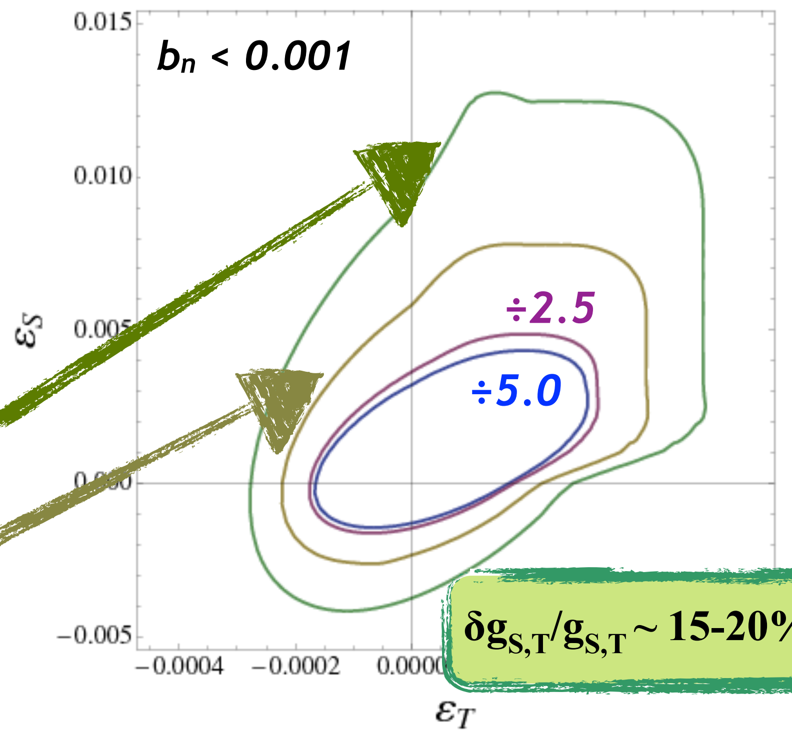
ETMC 2015	1.21(42)	1.03(06)

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



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

PS: Pheno dets. are also posible, but less precise

$$g_T = \int \left(h_1^u(x) - h_1^d(x)\right) dx$$

From hadrons to quarks

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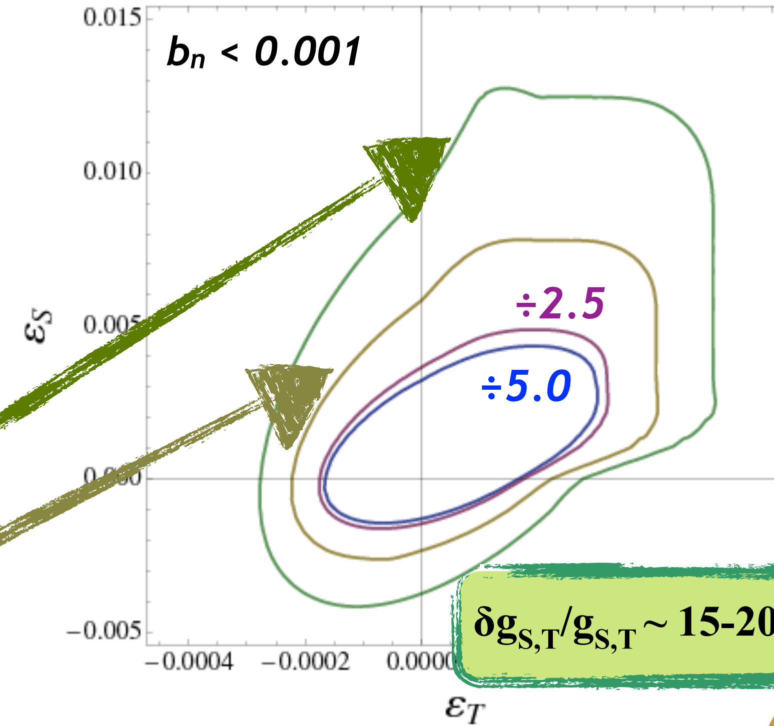


$\delta g_{S,T}/g_{S,T} \sim$ 15-20%

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

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

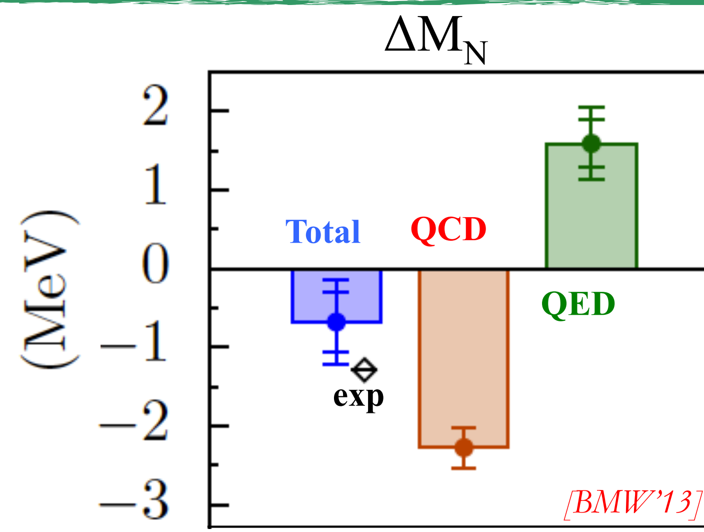
From hadrons to quarks

Well known, used in many other processes, e.g. EDMs or K→πeν…

[e.g. Anselm et al'1985,
Ellis et al'2008,
Engel et al'2013, …]

$$\left(M_n - M_p\right)_{exp} = 1.2933322(4)\ \text{MeV}$$

$$M_n - M_p = \left(M_n - M_p\right)_{QCD} + \left(M_n - M_p\right)_{QED}$$



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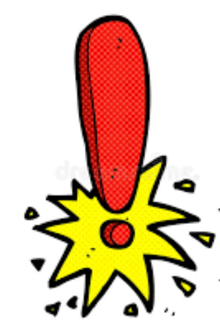
$\delta g_{S,T}/g_{S,T} \sim 15\text{-}20\%$ ✔



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[e.g. Anselm et al'1985, Ellis et al'2008, Engel et al'2013, …]

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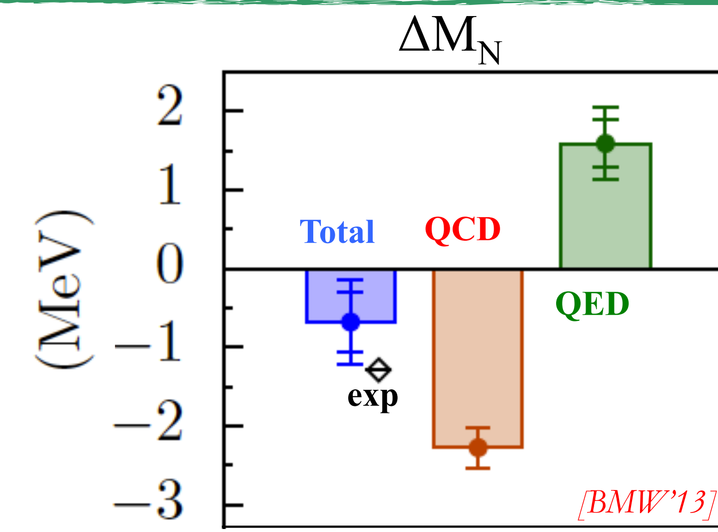

ΔM_QCD = 2.59(49) MeV

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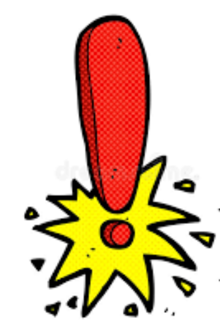
LHPC 2012	1.08(32)	1.04(02)
RQCD 2014	1.02(35)	1.01(02)
PNDME 2013/15	0.72(32)	1.02(08)
ETMC 2015	1.21(42)	1.03(06)
CVC	1.02(11)	
PNDME 2016	0.97(13)	0.99(06)
JLQCD'18	0.88(11)	1.08(10)

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

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



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]

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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)

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

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

From hadrons to quarks

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

BSM fit

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

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$$\Rightarrow \quad |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 = 0.9999(14) \xrightarrow{S,T=0} 0.9995(8)$$

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

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From hadrons to quarks

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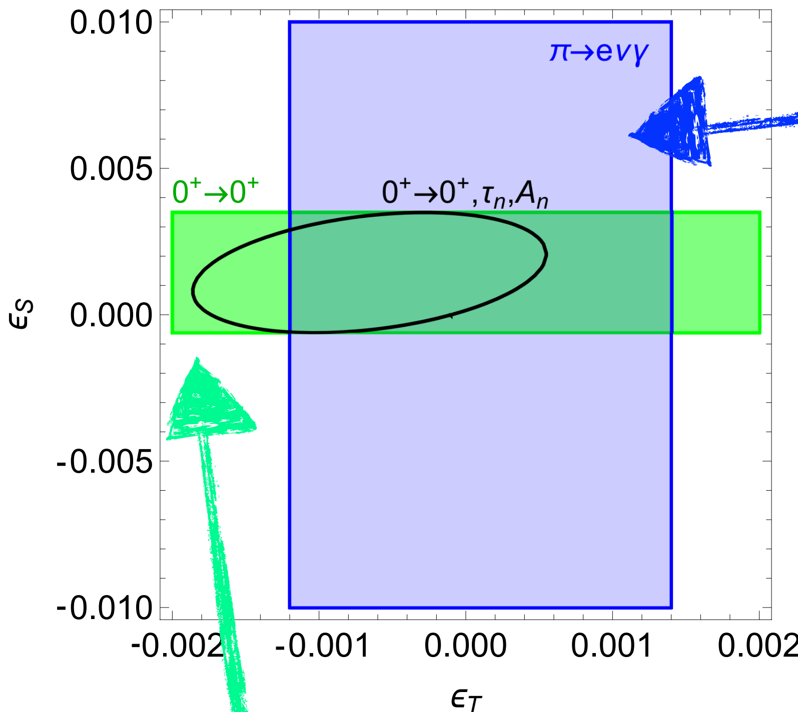
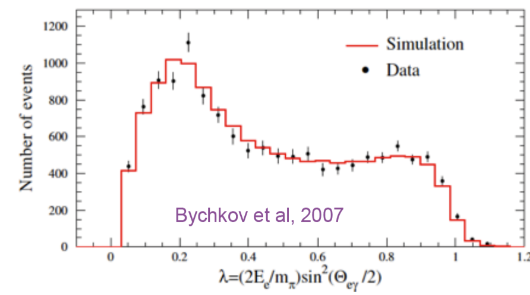
From hadrons to quarks



$\pi \to e\nu\gamma$

(PIBETA´2009)



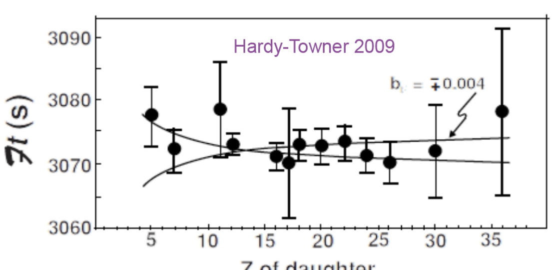
$$\langle \gamma(\epsilon, p)|\bar{u}\sigma_{\mu\nu}\gamma_5 d|\pi^+\rangle = -\frac{e}{2} f_T (p_\mu \epsilon_\nu - p_\nu \epsilon_\mu),$$

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

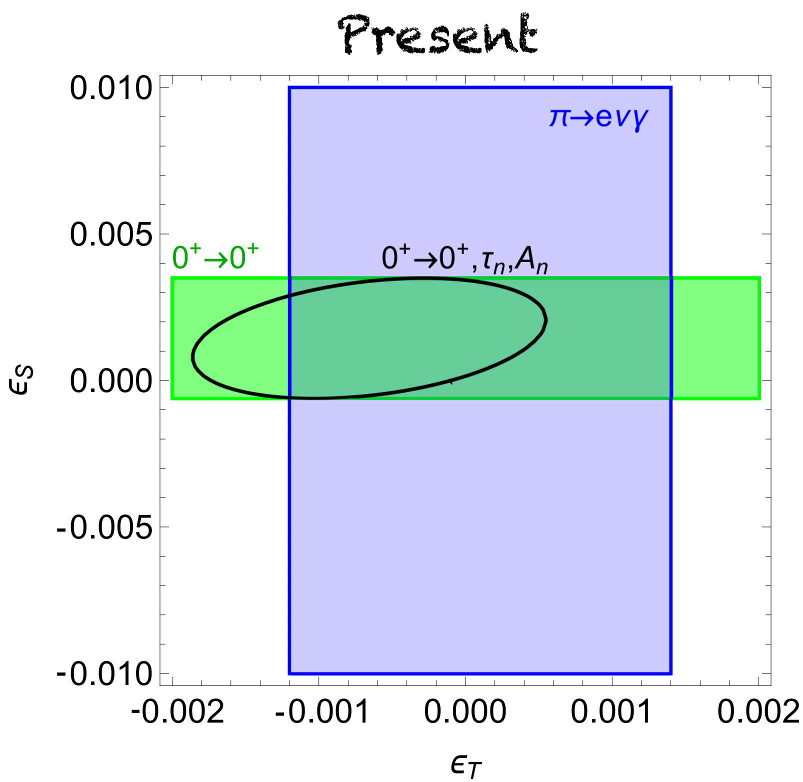
[large-N inspired resonance saturation model]

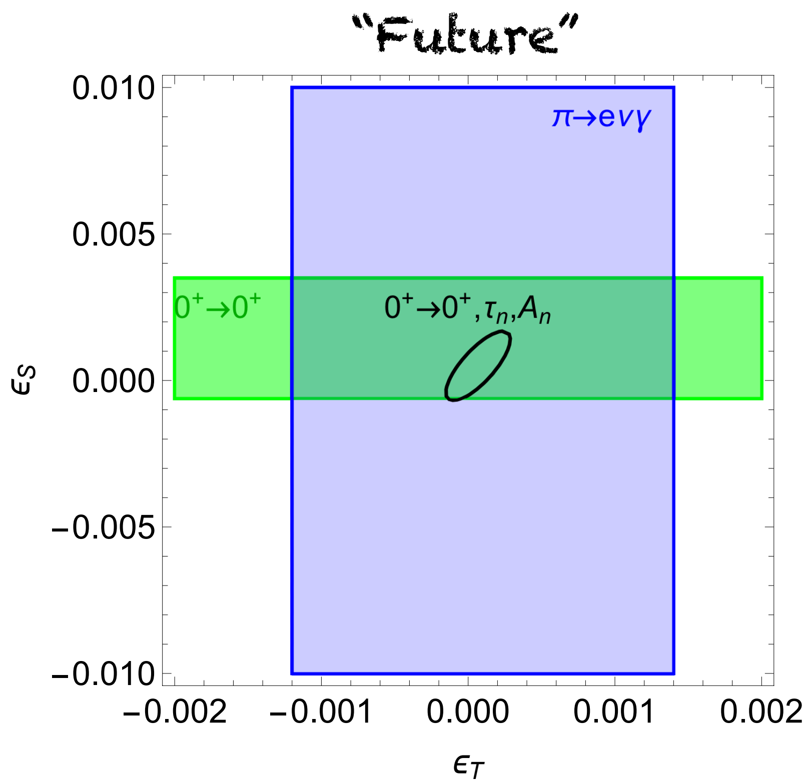
No LQCD calculation!

Superallowed nuclear β decays



From hadrons to quarks





Benchmark numbers (from ongoing / planned experiments):

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

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

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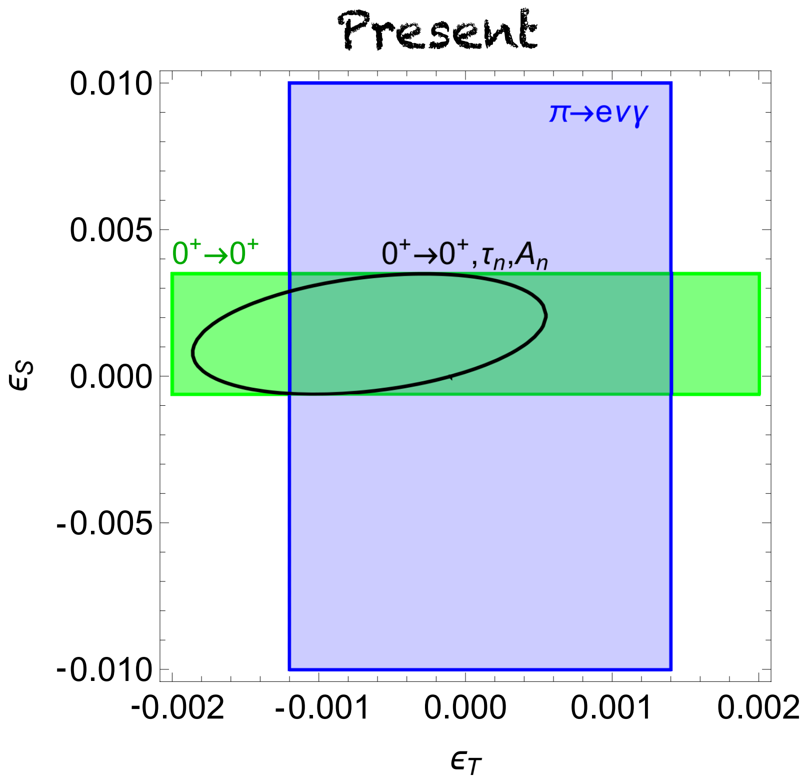
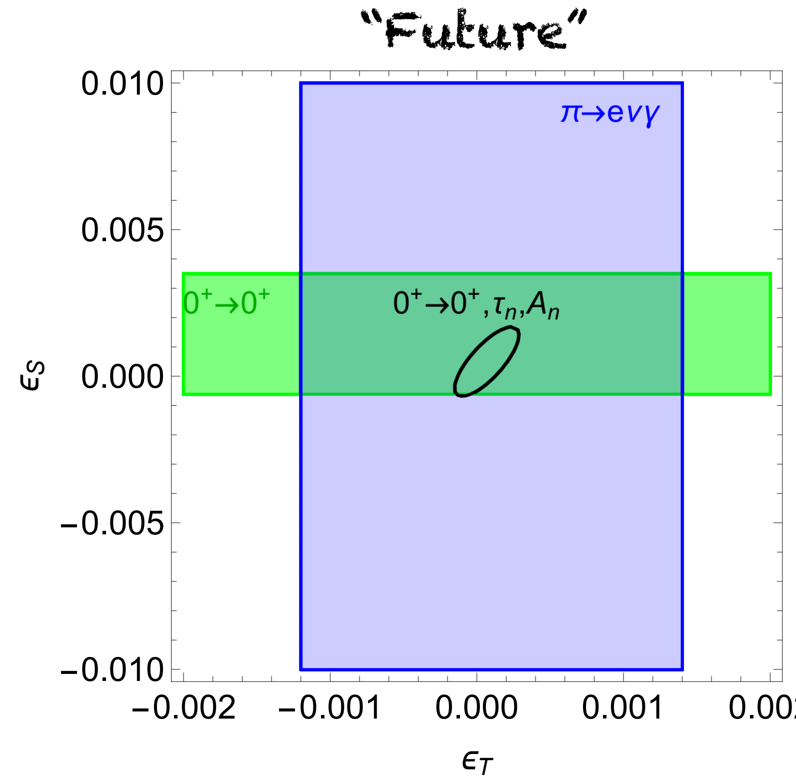
From hadrons to quarks





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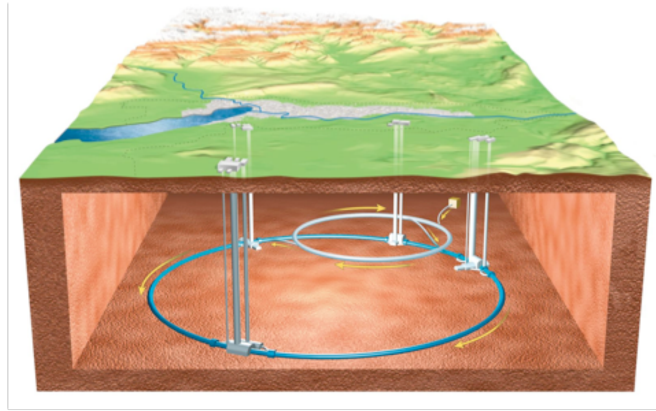
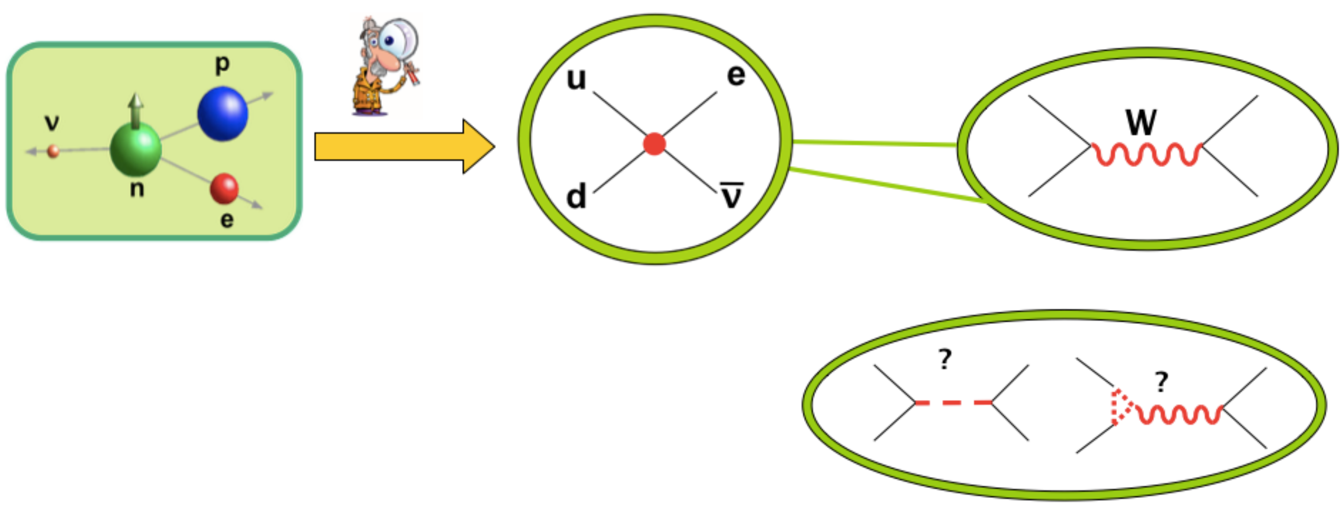
Pocanic's talk:
π→eνγ will also improve (PEN)... ~ x2?
"take it with a rock of salt"

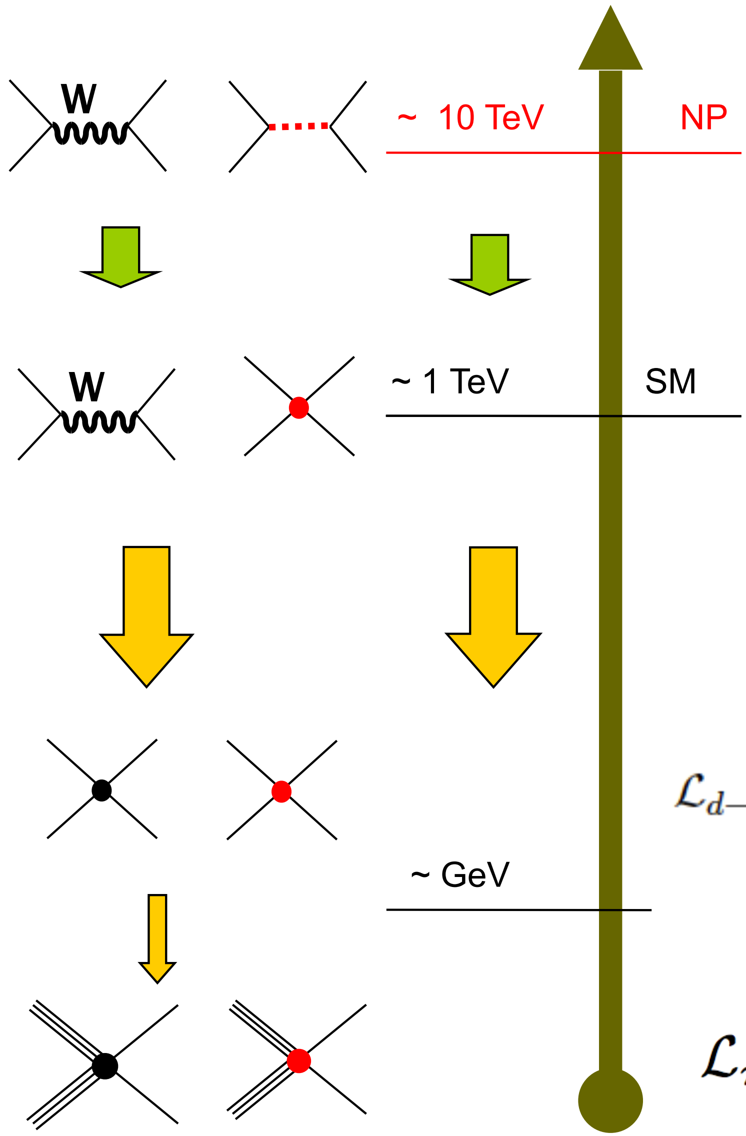


Quarks, W, Z, …



Matching with SMEFT

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



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

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

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

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

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

Matching with SMEFT

[Cirigliano, MGA, Jenkins'2010; MGA, Camalich, Mimouni'2017]

- Running + Matching with HEP Model/EFT:

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

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

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

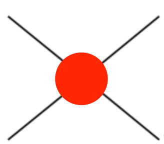
$$V_{1j}\cdot\epsilon^{j}_R = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

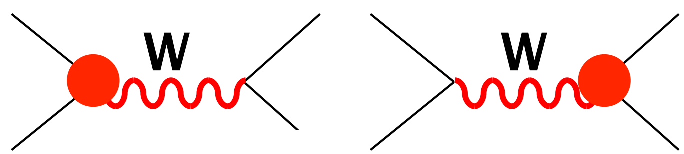
$$V_{1j}\cdot\epsilon^{j\ell}_{s_L} = -\,[\hat{\alpha}_{lq}]^*_{\ell\ell j1}\,,$$

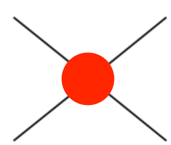
$$V_{1j}\cdot\epsilon^{j\ell}_{s_R} = -\,\left[V\hat{\alpha}^{\dagger}_{qde}\right]_{\ell\ell 1j},$$

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

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







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

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

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

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

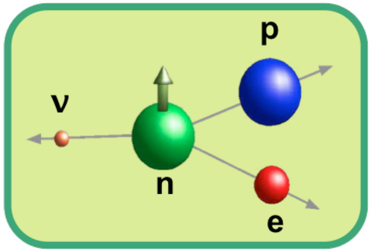
$$O^{(3)}_{lq} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$

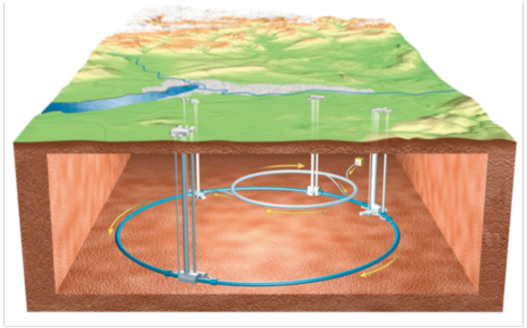
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$

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

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

V-A interactions:
CKM unitarity test vs LEP

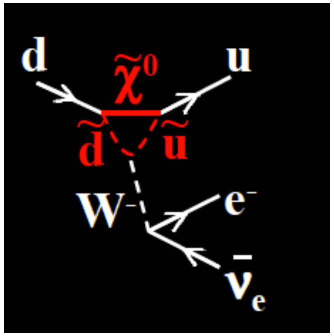




Many examples:

- Tree: W', RPV-MSSM, ...
- Loop: Z', RPC-MSSM, ...

[Barbieri et al. (1985), Marciano & Sirlin (1987), Hagiwara et al. (1995), Kurylov & Ramsey-Musolf (2002), Marciano (2007), Gauld et al. (2014), ...]



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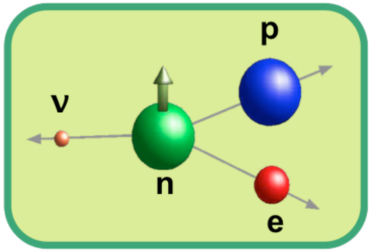

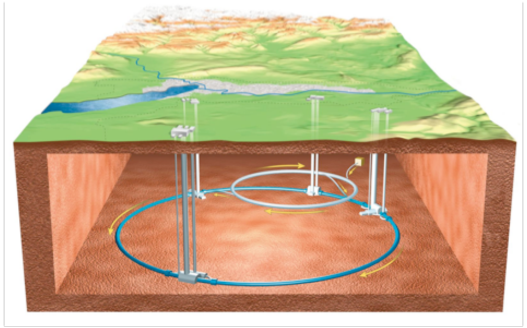

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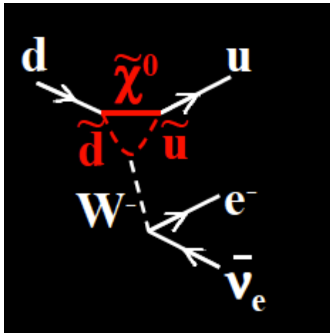

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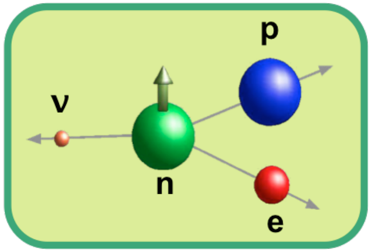
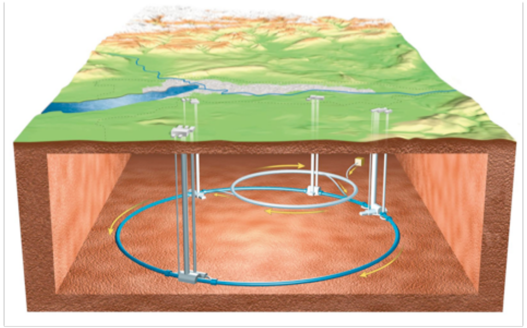




U(3)⁵ symmetry

$$\begin{pmatrix} l_e \\ l_\mu \\ l_\tau \end{pmatrix}, \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}, \begin{pmatrix} q_u \\ q_c \\ q_t \end{pmatrix}, \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

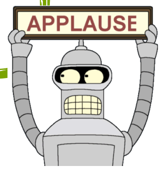
⇒ Only V-A interactions ⇒

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

CKM unitarity vs HEP

[Hardy & Towner'15,
Flavianet'16,
MGA & Martin Camalich'16,
MGA, Naviliat Cuncic, Severijns'18]

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



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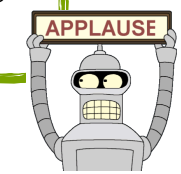

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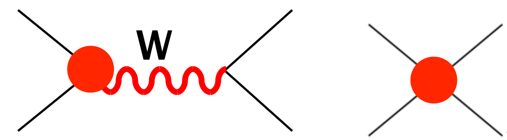

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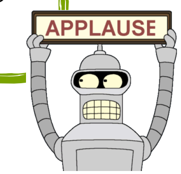

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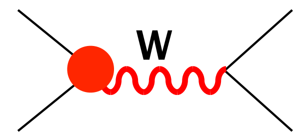

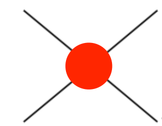

[From Falkowski, MGA & Mimouni, 2017]

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

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MGA, Naviliat Cuncic, Severijns'18]

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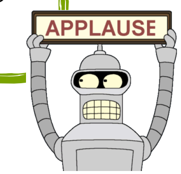
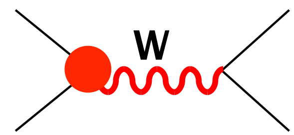
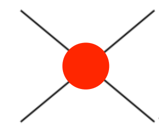
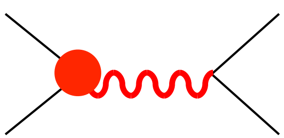


$$\rightarrow \Delta_{\rm CKM} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = 2\left(-\delta g_L^{W\ell} + \overbrace{\delta g_L^{Zu} - \delta g_L^{Zd}}^{\delta g_L^{Wq}} - c_{lq}^{(3)} + c_{\ell\ell}^{(3)}\right)$$





[From Falkowski, MGA & Mimouni, 2017]



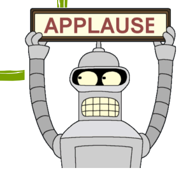
$$\begin{pmatrix} \delta g_L^{W\ell} \\ \delta g_L^{Zu} \\ \delta g_L^{Zd} \\ c_{\ell\ell}^{(3)} \\ c_{\ell q}^{(3)} \end{pmatrix} \times 10^3 = \begin{pmatrix} 0.15 \pm 0.18 \\ 0.48 \pm 0.45 \\ -0.05 \pm 0.27 \\ -0.40 \pm 0.37 \\ -1.11 \pm 0.89 \end{pmatrix}_{\rm LEP/EWPO} \quad \text{vs.} \quad \begin{pmatrix}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

LHC can't compete here

CKM unitarity vs HEP

*[Hardy & Towner'15,
Flavianet'16,
MGA & Martin Camalich'16,
MGA, Naviliat Cuncic, Severijns'18]*

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



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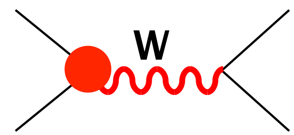

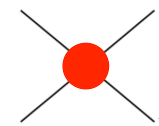

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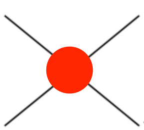
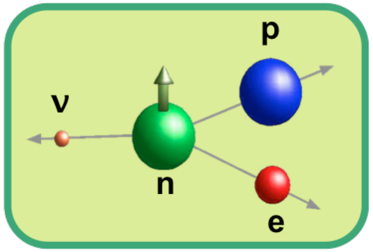


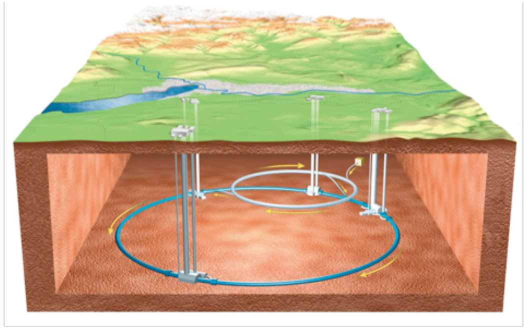
$$\begin{pmatrix} \delta g_L^{W\ell} \\ \delta g_L^{Zu} \\ \delta g_L^{Zd} \\ c_{\ell\ell}^{(3)} \\ c_{\ell q}^{(3)} \end{pmatrix} \times 10^3 = \begin{pmatrix} 0.15 \pm 0.18 \\ 0.48 \pm 0.45 \\ -0.05 \pm 0.27 \\ -0.40 \pm 0.37 \\ -1.11 \pm 0.89 \end{pmatrix}_{\rm LEP/EWPO} \quad \text{vs.} \quad \begin{pmatrix}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

pp → e⁺e⁻
LHC reaching this level…
HL-LHC x10

[Falkowski, MGA & Mimouni'17, Greljo & Marzocca'17]

Scalar & tensor interactions: b_{Fierz} vs LHC



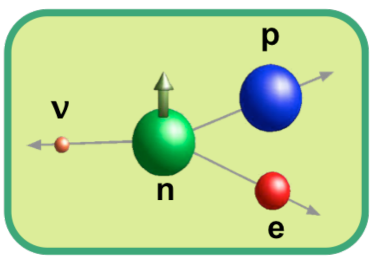


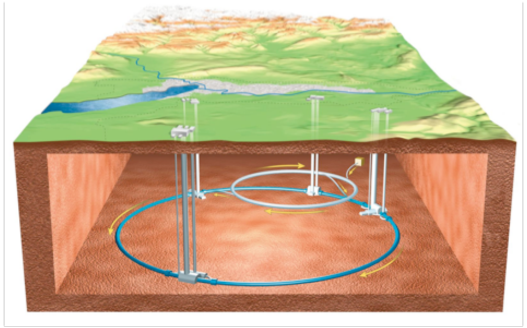
Very hard to avoid $\pi \to l\nu$

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

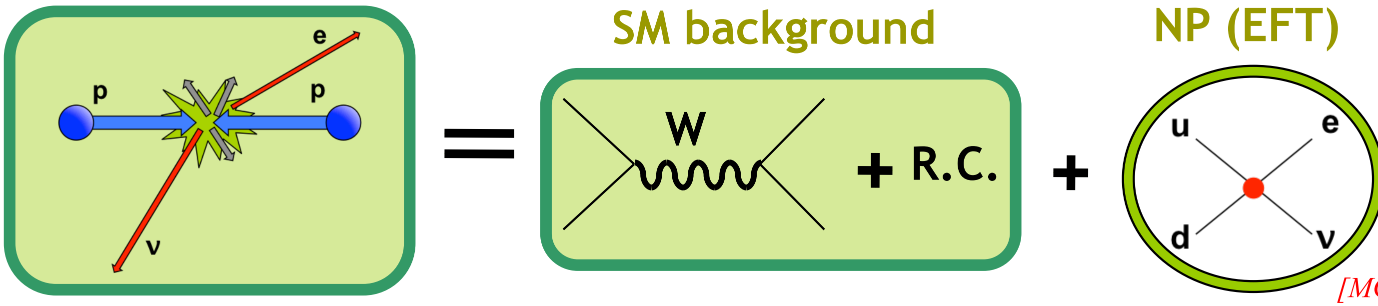
$$|\mathcal{A}(\pi \to \ell\nu)|^2 \quad \sim \quad m_\ell^2 \left(1 + \frac{M_{QCD}}{m_\ell} \epsilon_P\right)^2$$

Scalar & tensor interactions: b_{Fierz} vs LHC





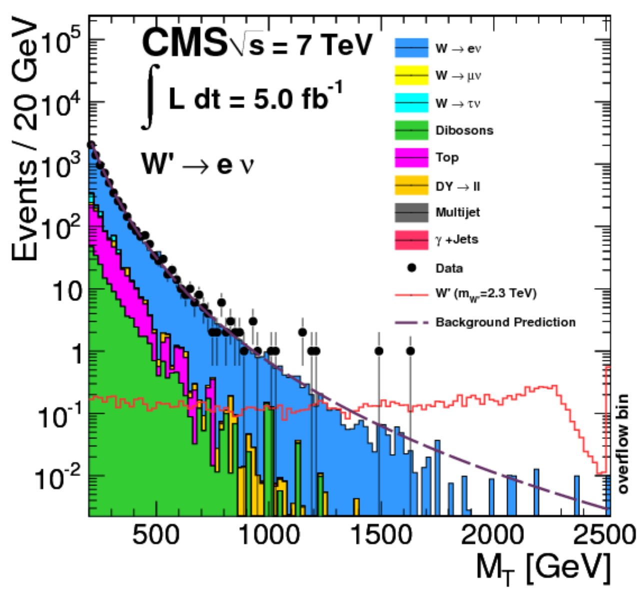
LHC limits on $\varepsilon_{S,T}$

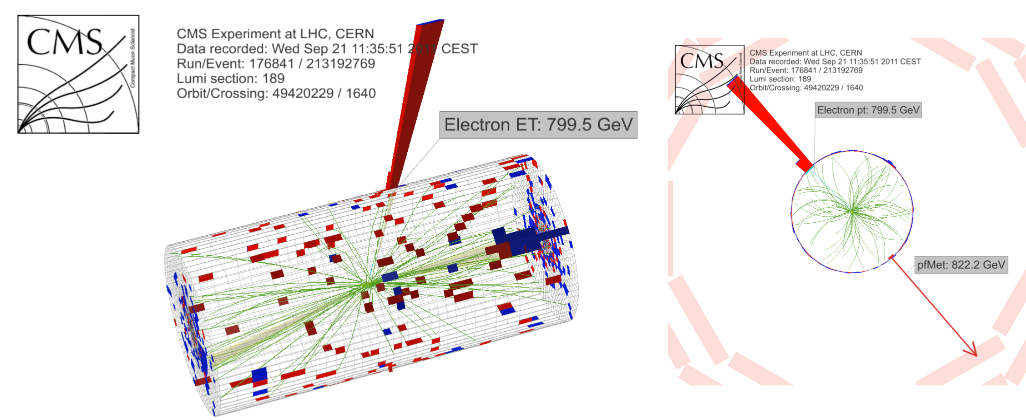


[MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)*]*
[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*
[Bhattacharya et al, PRD85 (2012)*]*

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

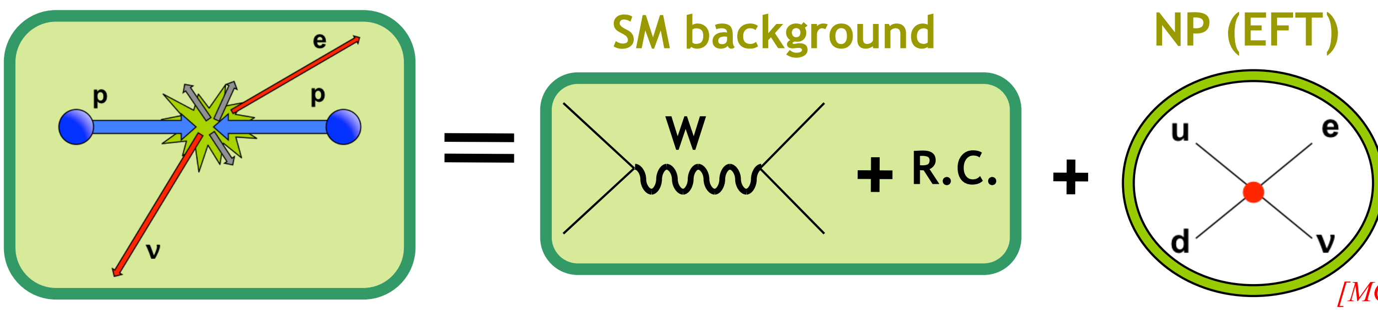
(Interference w/ SM ~ m/E)





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

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



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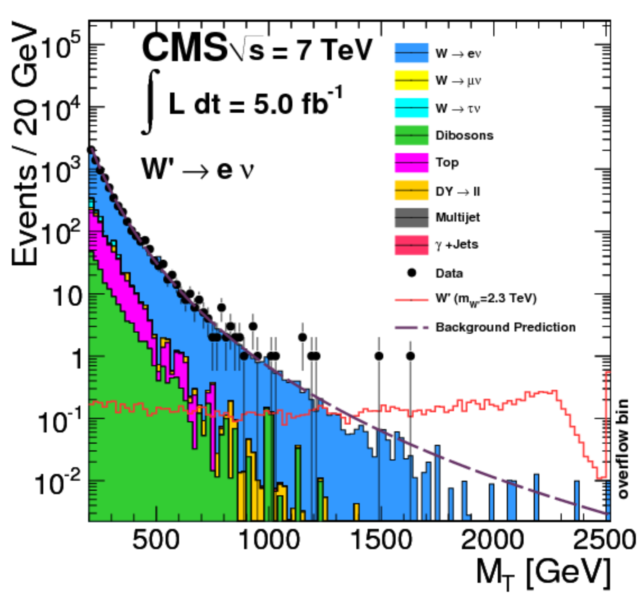
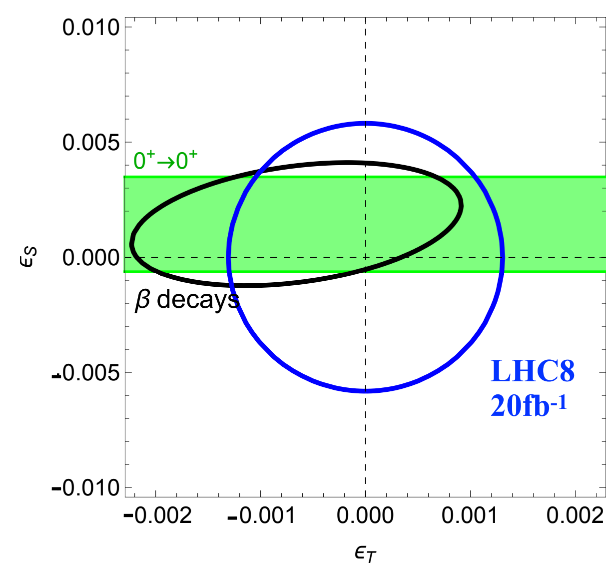
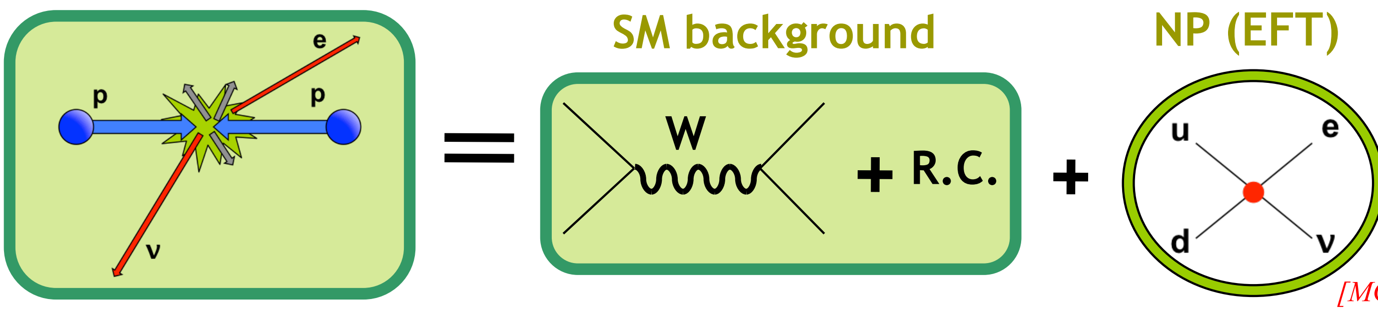




LHC limits on $\varepsilon_{S,T}$



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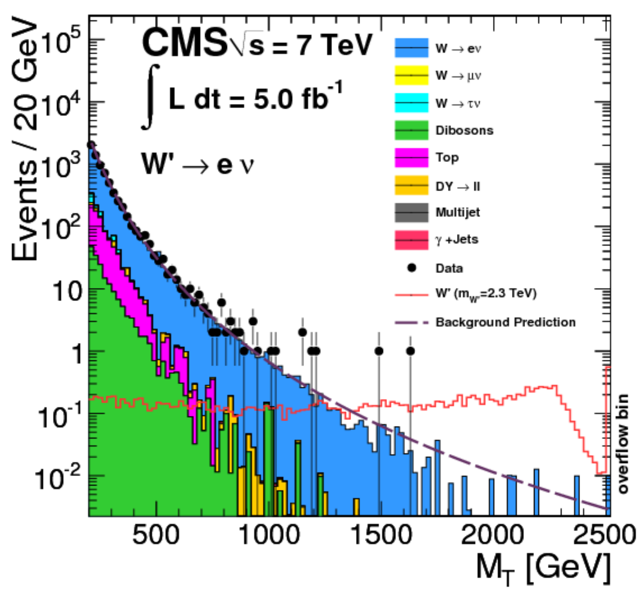
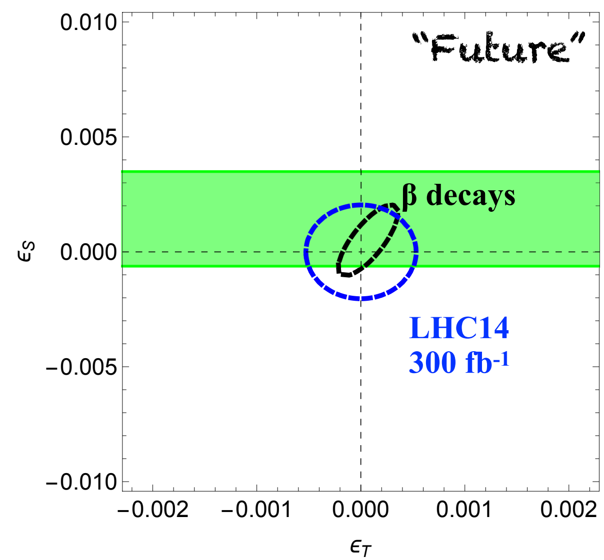
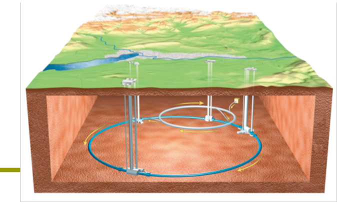


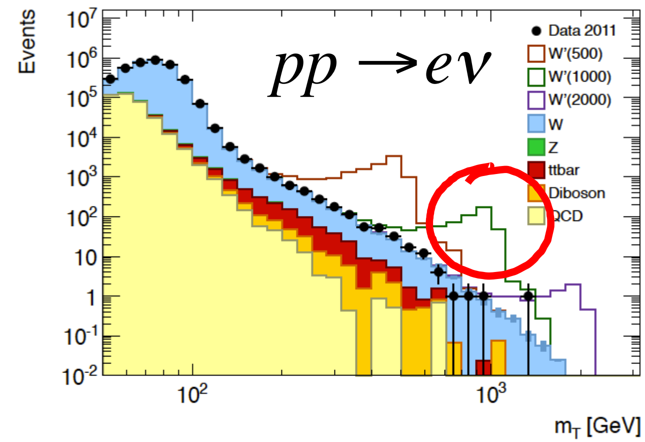


If we see a bump...



- EFT breaks down…
  Toy model: scalar resonance:

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



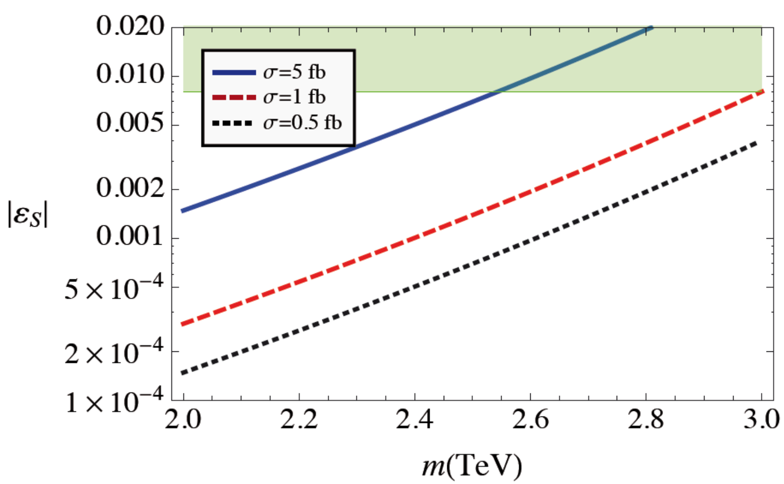
- Then we have a lower-limit value for ε_S:

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

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

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

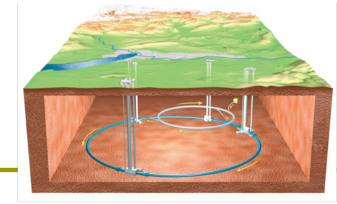
$$\epsilon_S = 2 \lambda_S \lambda_l \frac{v^2}{m^2}$$

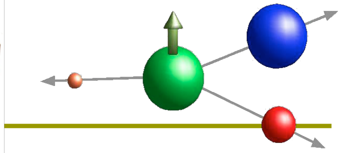


Nice interplay of two experiments separated for so many orders of magnitudes!!!!

[T. Battacharya et al., 2012]

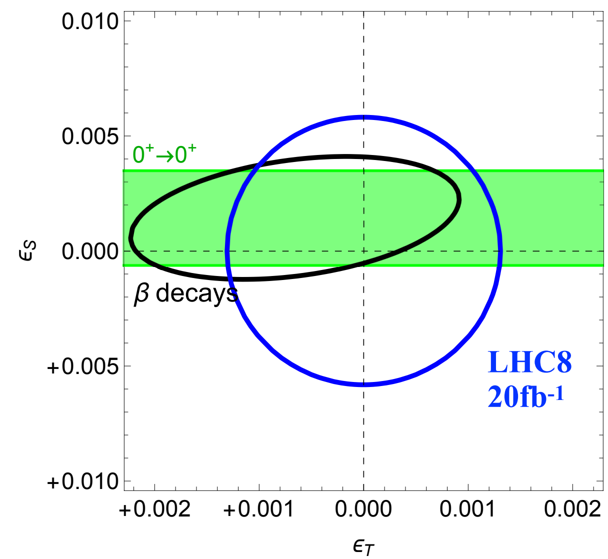
Conclusions





- (Sub) permil-level precision in β decays
  - Great QCD progress (charges);
  - Experimental progress too;
  - Inner RC? (Wγ box);
- General EFT analysis available
  → Comparison with APV, LEP, LHC, ...
  → β decays are competitive TeV probes;

$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u} = 1.02(11)$$

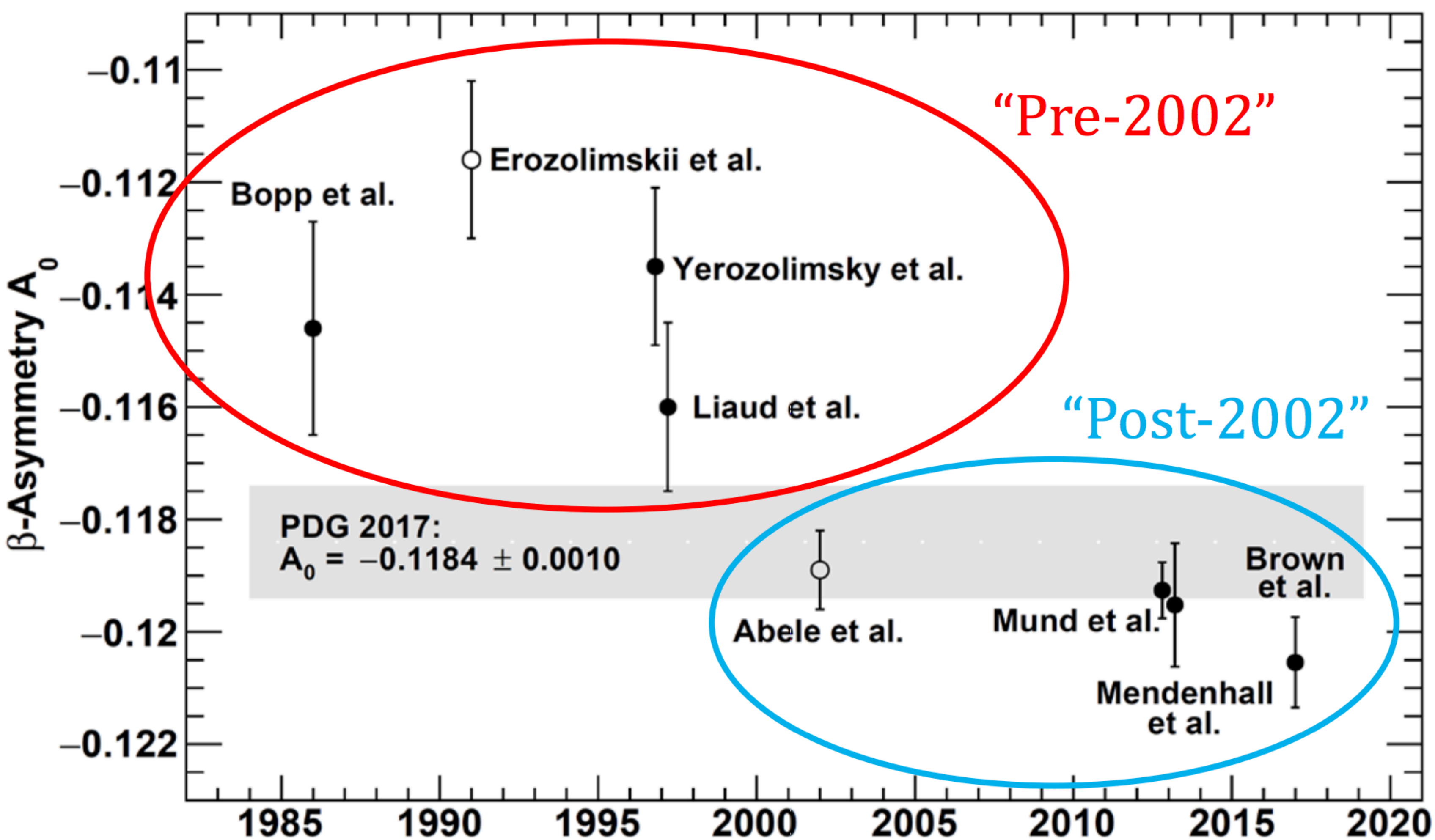


$$\begin{pmatrix} |C_V| \\ C_A/C_V \\ C_S/C_V \\ C_T/C_A \end{pmatrix} = \begin{pmatrix} 0.98595(34)\, G_F/\sqrt{2} \\ -1.2728(17) \\ 0.0014(12) \\ 0.0020(22) \end{pmatrix}$$

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

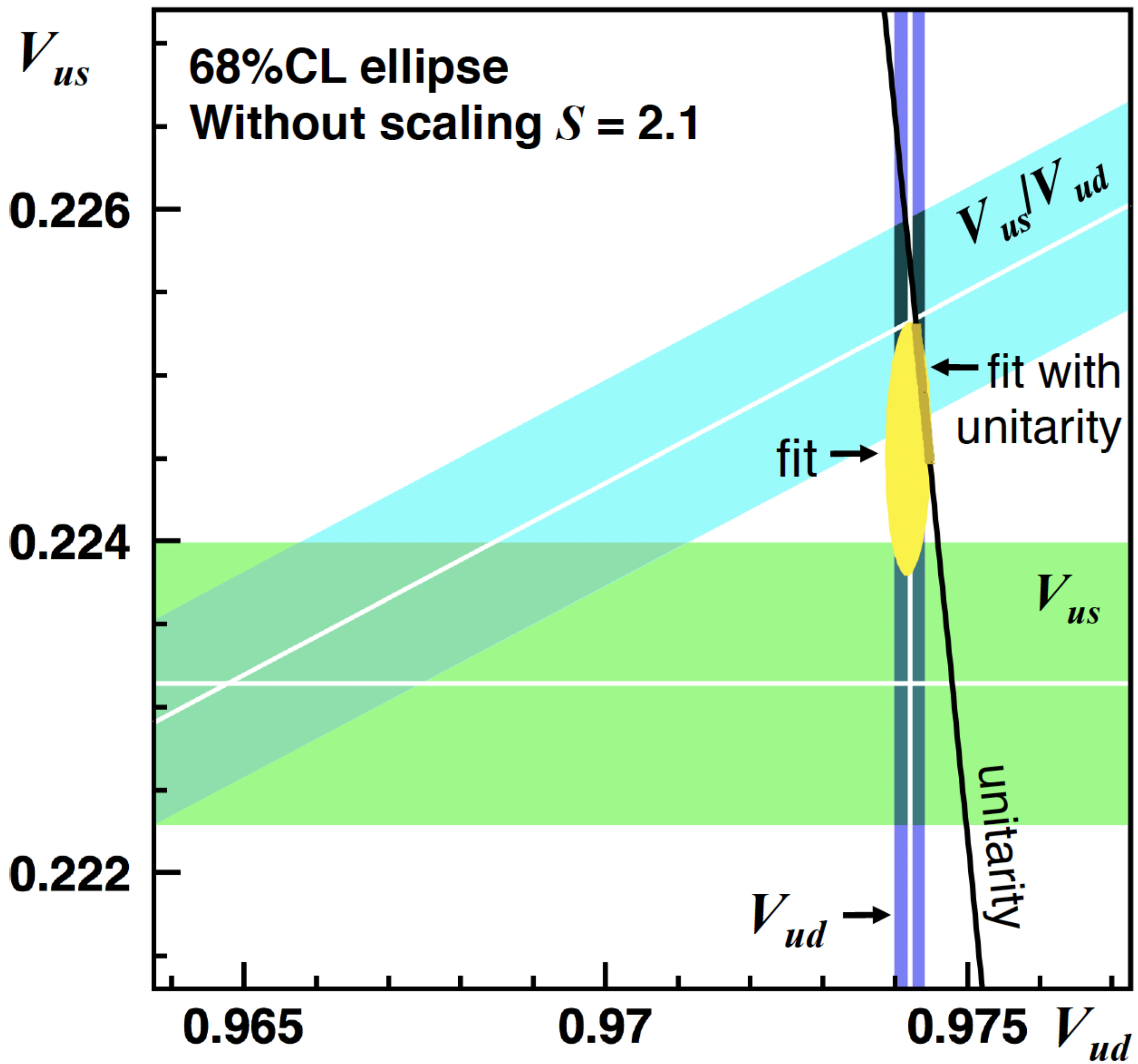
Backup slides

Beta asymmetry



[From B. Plaster's talk at PPNS 2018]

CKM unitarity



[Moulson'17, Nf=2+1+1]

g_S & the nucleon splitting

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

$$\partial_\mu (\bar{u}\gamma^\mu d) = -i(m_d - m_u)\bar{u}d$$

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

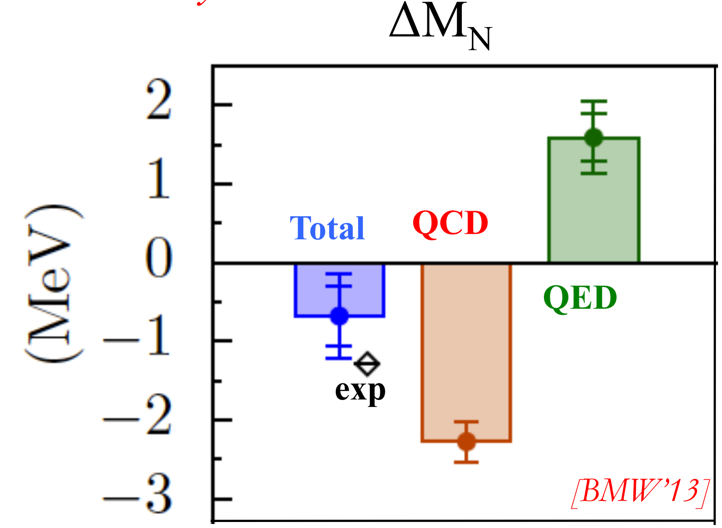
Isospin splitting in the nucleon

$$(M_n - M_p)_{exp} = 1.2933322(4)\ \text{MeV}$$

$$M_n - M_p = (M_n - M_p)_{QCD} + (M_n - M_p)_{QED}$$

It turns out lattice-QCD is being calculating this recently!!!!

Useful connection between two different Lattice efforts!



Well known, used in many other processes, e.g. EDMs or K→πeν…

$$f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$$

[e.g. Anselm et al'1985, Ellis et al'2008, Engel et al'2013, …]