Connection between low- and high-energy measurements

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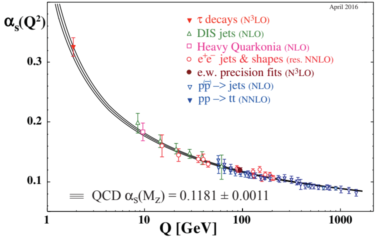
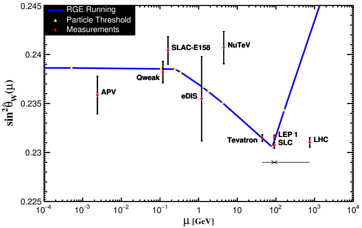
How to connect low-energy $\sim$ GeV with high-energy $\sim$ TeV?

Well-known answer: **Standard Model**

- All observables depend (at most) on the $\sim$ 20 SM parameters
- Fit parameters using observables especially sensitive to them (see Erler's talk)
- Make predictions for observables at any scale

The agreement is rather impressive

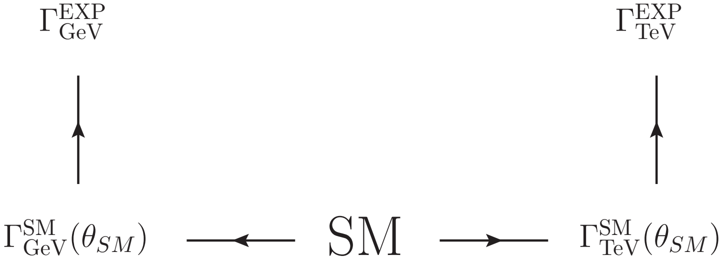


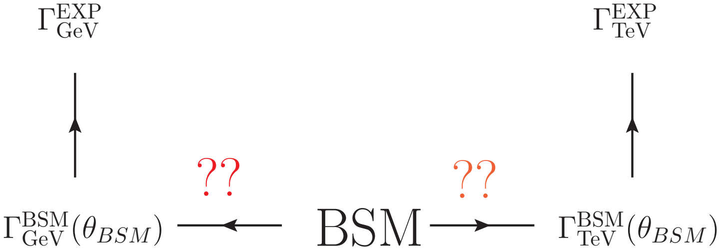


PDG plots

END OF TALK?

But SM may not be all we have up to the Planck scale





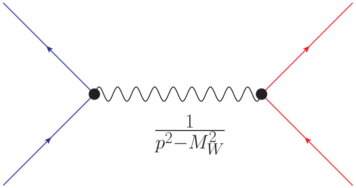
Try to extend the SM minimizing assumptions

Focus on interactions between lepton and light quark charged currents

- Dominant in many low-energy observables, leading to precise predictions
- Suppressed by $\sim E/v$ in the SM (they are weak interactions!)
- Natural connection to $pp \to$ leptons observables in LHC

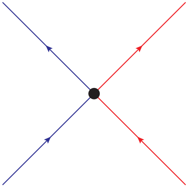
The low-energy Lagrangian

$$\mathcal{L}_{CC}^{SM} \sim W_\mu^\dagger \left(V_{NM}\, J_{NM}^{q\,\mu} + J_{NN}^{l\,\mu} \right) + h.c.$$



$$p^2 \ll M_W^2$$
$$\longrightarrow$$

$$\mathcal{L}_{CC}^{SM} \sim \frac{1}{M_W^2} V_{NM}^\dagger J_{NM}^{\dagger q\,\mu} J_{NN}^{l\,\mu} + h.c.$$



Assume now

- Absence of light nonstandard particles
- Lorentz, $U(1)_{em}$ and $SU(3)_c$ invariance
- SM interactions dominate

The low-energy Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\rm eff} &= \mathcal{L}_{\rm eff}(\epsilon_L^{Dl}, \epsilon_R^{Dl}, \epsilon_S^{Dl}, \epsilon_P^{Dl}, \epsilon_T^{Dl}) \\
&= -\frac{G_F V_{uD}}{\sqrt{2}} \Bigg[\left(1+\epsilon_L^{Dl}\right) \bar{l}\gamma_\mu (1-\gamma_5)\nu_l \cdot \bar{u}\gamma^\mu (1-\gamma_5) D \\
&\quad + \epsilon_R^{Dl}\ \bar{l}\gamma_\mu(1-\gamma_5)\nu_l\ \bar{u}\gamma^\mu(1+\gamma_5) D \\
&\quad + \bar{l}(1-\gamma_5)\nu_l \cdot \bar{u}\left[\epsilon_S^{Dl} - \epsilon_P^{Dl}\gamma_5\right] D \\
&\quad + \epsilon_T^{Dl}\, \bar{l}\sigma_{\mu\nu}(1-\gamma_5)\nu_l \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5) D \Bigg] + \text{h.c.}
\end{aligned}
$$

$$G_F\, \epsilon_i^{Dl} \sim \frac{1}{\Lambda_{NP}^2} \to \epsilon_i^{Dl} \sim \frac{v^2}{\Lambda^2}$$

Cirigliano '09, Bhattacharya '11

New physics parametrized in 5 ϵ_i^{Dl} couplings for every D (d or s) and l (e, μ, τ)

Low-energy sectors: β decays. The SM case

Start with the Lagrangian

$$\mathcal{L}_{\rm eff}^{SM} = -\frac{G_F V_{ud}}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + h.c.$$

Compute the nucleon matrix elements

$$\langle p(p_n)|\bar{u}\gamma_\mu d|n(p_p)\rangle \approx g_V(s)\bar{u}(p_p)\gamma_\mu u(p_n) \approx \bar{u}(p_p)\gamma_\mu u(p_n)$$

$$\langle p(p_n)|\bar{u}\gamma_\mu\gamma_5 d|n(p_p)\rangle \approx g_A(s)\,\bar{u}(p_p)\gamma_\mu\gamma_5 u(p_n) \approx g_A\,\bar{u}(p_p)\gamma_\mu\gamma_5 u(p_n)$$

Compute the decay rate (plus corrections) and compare to experiment

- $\tau_{n,\,th}^{1/2}(|V_{ud}|, g_A) \to |V_{ud}| = 0.9736(5)$
- $\mathcal{F}t_{th}(0^+ \to 0^+)(|V_{ud}|) \to |V_{ud}| = 0.97389(18)$ Czarnecki '19, Hardy '18

Low-energy sectors: β decays BSM

$\mathcal{L}_{\rm eff}(\epsilon_L^{de}, \epsilon_R^{de}, \epsilon_S^{de}, \epsilon_P^{de}, \epsilon_T^{de})$

$\Gamma = \{\gamma_\mu P_L, \gamma_\mu P_R, I, \gamma_5, \sigma_{\mu\nu}\}$

$\downarrow$ Nucleon matrix elements Weinberg '58, Bhattacharya '11

$\mathcal{L}_{\rm eff}^{LY}(C_j)$ Lee-Yang '56

- Now in terms of effective nucleon fields $(\bar{n}\,\Gamma\, p)$
- $C_j(\epsilon_i^{de}, g_i)$

$\downarrow d\Gamma \sim F(E_{e,\nu}, \vec{p}_{e,\nu}, \langle \vec{J} \rangle; g_i, \epsilon_i^{de}, \tilde{V}_{ud})$ Treiman '57, Bhattacharya '11

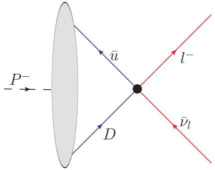
$$\begin{pmatrix} |\tilde{V}_{ud}| \\ \epsilon_R^{de} \\ \epsilon_S^{de} \\ \epsilon_T^{de} \end{pmatrix} = \begin{pmatrix} 0.97452(34)(19) & \\ 0.002(1)(21) & (90\%\ \text{CL}) \\ 0.0014(20)(3) & (90\%\ \text{CL}) \\ -0.0007(12)(1) & (90\%\ \text{CL}) \end{pmatrix}$$

Gonzalez-Alonso '18
...and improving fast!

Low-energy sectors: $P_{l2(\gamma)}$ decays in the SM

Same SM Lagrangian

$$\mathcal{L}_{\text{eff}}^{SM} = -\frac{G_F V_{uD}}{\sqrt{2}} \bar{l}\gamma_\mu(1-\gamma_5)\nu_l \cdot \bar{u}\gamma^\mu(1-\gamma_5)D + h.c.$$



$\downarrow$ Hadronic matrix elements $\langle 0|J_A^\mu|P(p)\rangle \sim ip_\mu f_P$

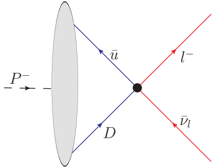
$$\Gamma_{P_{\ell 2(\gamma)}} = \frac{G_F^2 |\tilde{V}_{uD}^\ell|^2 f_{P^\pm}^2}{8\pi} m_{P^\pm} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{P^\pm}^2}\right)^2 \left(1 + \delta_{\text{em}}^{P\ell}\right)$$

$\delta_{\text{em}}^{P\ell}$ Radiative corrections $\longrightarrow$ Marciano '93 Cirigliano '07 Rosner '16

Both radiative and hadronic uncertainties reduced in K/π and μ/e ratios

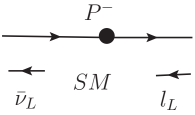
Low-energy sectors: $P_{l2(\gamma)}$ decays BSM

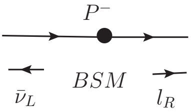
$$\mathcal{L}_{\rm eff}\left(\epsilon_L^{de}, \epsilon_R^{de}, \epsilon_S^{de}, \epsilon_P^{de}, \epsilon_T^{de}\right)$$



$\downarrow$ Hadronic matrix elements

$$\Gamma_{P_{\ell 2(\gamma)}} = \frac{G_F^2 |\tilde{V}_{uD}^{\ell}|^2 f_{P^\pm}^2}{8\pi} m_{P^\pm} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{P^\pm}^2}\right)^2 \left(1 + \delta_{\rm em}^{P\ell}\right) \left(1 + \Delta_{\ell 2}^P\right)$$





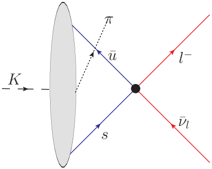
PCAC $P \sim q_\mu A^\mu/(m_u + m_d)$

ϵ_P^{Dl} contribution very enhanced!

Gonzalez-Alonso '16

Again uncertainties reduced in K/π and μ/e ratios

Low-energy sectors: $K_{l3(\gamma)}$ decays in the SM



Same SM Lagrangian

$$\mathcal{L}_{\rm eff}^{SM} = -\frac{G_F V_{uD}}{\sqrt{2}} \bar{l}\gamma_\mu(1-\gamma_5)\nu_l \cdot \bar{u}\gamma^\mu(1-\gamma_5)D + h.c.$$

Hadronic matrix elements

$$\langle \pi(p)|\bar{s}\gamma_\mu d|K(k)\rangle = A^\mu(k,p)\, f_+(q^2) + B^\mu(k,p)\, f_0(q^2)$$

- $f_+(q^2)/f_+(0)$. Parameters from the differential distribution
- Good theoretical knowledge of $\frac{f_0(q^2)}{f_+(0)}$

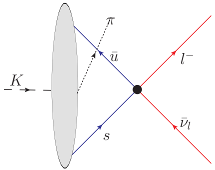
$$\downarrow$$

$$\Gamma(|V_{us}|f_+(0)) \to |V_{us}| = 0.2238 \pm 0.0007$$

Blucher '18

Low-energy sectors: $K_{l3(\gamma)}$ decays BSM

$$\mathcal{L}_{\text{eff}}(\epsilon_L^{de}, \epsilon_R^{de}, \epsilon_S^{de}, \epsilon_P^{de}, \epsilon_T^{de})$$



$$\downarrow$$

Hadronic matrix elements

$$\langle \pi(p)|\bar{s}\gamma_\mu u|K(k)\rangle = A^\mu(k,p)\, f_+(q^2) + B^\mu(k,p)\, f_0(q^2)$$
$$\langle \pi(p)|\bar{s}u|K(k)\rangle \sim A\, f_0(q^2)$$
$$\langle \pi(p)|\bar{s}\sigma_{\mu\nu}u|K(k)\rangle = A^{\mu\nu}(k,p)\, B_T(q^2)$$

$$\downarrow$$

ϵ_i^{sl} alters both the shape and the normalization!

Gonzalez-Alonso '16

Low-energy sectors: First two lepton families

Other observables giving information

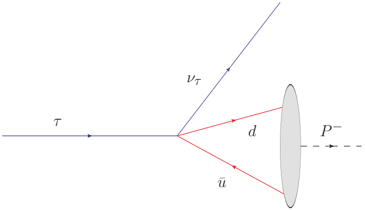
- **Hyperon β decays**. Similar formalism to nucleon β decay, but larger uncertainties ($SU(3)$ instead of $SU(2)$) Mateu '05, Chang '14
- **Pion β decays**. Similar formalism to $K_{l3(\gamma)}$. Good theoretical and experimental knowledge Pocanic '03
- $P_{l2\gamma}$. Strong bound on ϵ_T^{de} Bychkov '09

$$
\begin{pmatrix} \tilde{V}^e_{ud} \\ \Delta_{\mathrm{CKM}} \\ \Delta^s_L \\ \Delta^d_{LP} \\ \epsilon^{de}_P \\ \epsilon^{de}_R \\ \epsilon^{se}_P \\ \epsilon^{s\mu}_P \\ \epsilon^{s}_R \\ \epsilon^{s\mu}_S \\ \epsilon^{s\mu}_T \\ \epsilon^{de}_S \\ \epsilon^{de}_T \\ \epsilon^{se}_S \\ \epsilon^{se}_T \end{pmatrix} = \begin{pmatrix} 0.97451 \pm 0.00038 \\ -1.2 \pm 8.4 \\ 1.0 \pm 2.5 \\ 1.9 \pm 3.8 \\ 4.0 \pm 7.8 \\ -1.3 \pm 1.7 \\ -0.4 \pm 2.1 \\ -0.7 \pm 4.3 \\ 0.1 \pm 5.0 \\ -3.9 \pm 4.9 \\ 0.5 \pm 5.2 \\ 1.4 \pm 1.3 \\ 1.0 \pm 8.0 \\ -1.6 \pm 3.3 \\ 0.9 \pm 1.8 \end{pmatrix} \times 10^\wedge \begin{pmatrix} 0 \\ -4 \\ -3 \\ -2 \\ -6 \\ -2 \\ -5 \\ -3 \\ -2 \\ -4 \\ -3 \\ -3 \\ -4 \\ -3 \\ -2 \end{pmatrix}
$$

$$\epsilon \sim \frac{v^2}{\Lambda^2_{NP}}$$

Falkowski '17

Low energy sectors: $\tau \to P\nu_\tau$



Effective Lagrangian

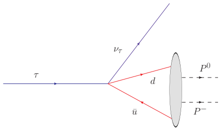
$$\mathcal{L}_{\text{eff}}(\epsilon_L^{D\tau}, \epsilon_R^{D\tau}, \epsilon_S^{D\tau}, \epsilon_P^{D\tau}, \epsilon_T^{D\tau})$$

$\downarrow$ Hadronic matrix elements $\langle 0|J_A^\mu|P(p)\rangle \sim ip_\mu f_P$

$$\Gamma(\tau \to P\nu_\tau) = \frac{m_\tau^3 f_P^2 G_F^2 |\tilde{V}_{uD}^e|^2}{16\pi}\left(1 - \frac{m_P^2}{m_\tau^2}\right)^2 (1 + \delta_{RC}^{(P)})\left(1 + \delta_{NP}^{(P)}\right)$$

Cirigliano '18

- Agreement at the $\sim 1\%$ level with SM
- Two bounds below 10^{-2} on $\epsilon_i^{D\tau}$



Effective Lagrangian

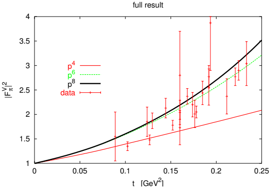
$$\mathcal{L}_{\text{eff}}^{SM} = -\frac{G_F V_{uD}}{\sqrt{2}} \bar{l}\gamma_\mu(1-\gamma_5)\nu_l \cdot \bar{u}\gamma^\mu(1-\gamma_5)D + h.c.$$

Hadronic matrix elements

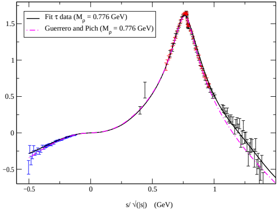
$$\langle P(p)P^-(k)|\bar{d}\gamma_\mu u|0\rangle = A^\mu(k,p)\, f_V(q^2) + B^\mu(k,p)\, f_S(q^2)$$

- In general limited theoretical knowledge on form factors
- Very rich phenomenology

Pich '13



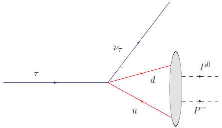
Bijnens '02



Guerrero '97

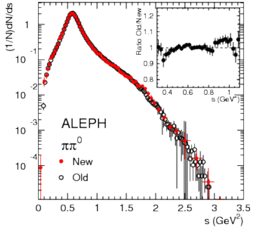
Effective Lagrangian

$$\mathcal{L}_{\rm eff}(\epsilon_L^{D\tau}, \epsilon_R^{D\tau}, \epsilon_S^{D\tau}, \epsilon_P^{D\tau}, \epsilon_T^{D\tau})$$



Hadronic matrix elements

$$\langle \pi(p)\pi^-(k)|\bar{d}\gamma_\mu u|0\rangle = A^\mu(k,p)\, f_V(q^2)$$
$$\langle \pi(p)\pi^-(k)|\bar{d}\sigma_{\mu\nu} u|0\rangle = A^{\mu\nu}(k,p) F_T(q^2)$$



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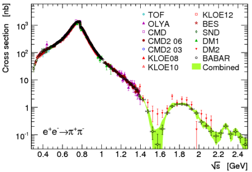


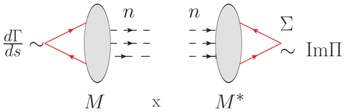
1801.06992

Form factor from electron-positron data → strong bound! Cirigliano '18

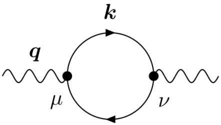
Low energy sectors: τ inclusive

Effective Lagrangian

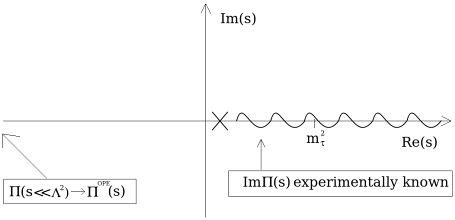
$$\mathcal{L}_{\rm eff}^{SM} = -\frac{G_F V_{uD}}{\sqrt{2}} \bar{l}\gamma_\mu (1-\gamma_5)\nu_l \cdot \bar{u}\gamma^\mu (1-\gamma_5) D + h.c.$$



e.g. De Rafael '97



$$\Pi_J^{\mu\nu}(q) \equiv i \int d^4x \, e^{iqx} \, \langle 0 | T[J^\mu(x) J^{\nu\dagger}(0)] | 0 \rangle$$



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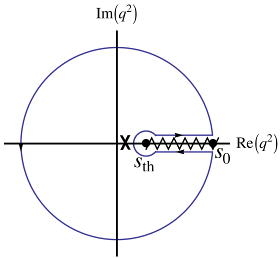
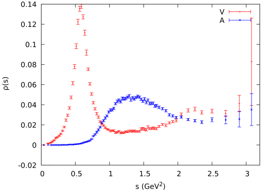
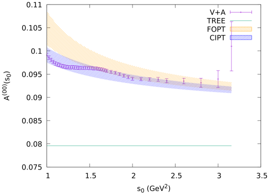


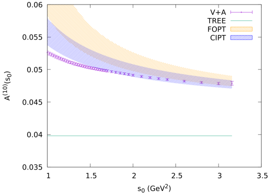
Braaten '92

Low energy sectors: τ inclusive phenomenology in the SM

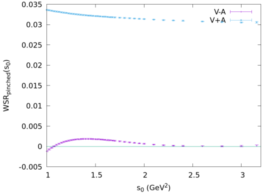
- **Non-strange V+A.** Perturbative QCD, $\alpha_s(m_\tau) = 0.328 \pm 0.014$ Pich '16

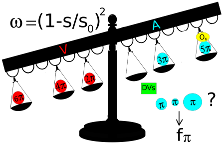


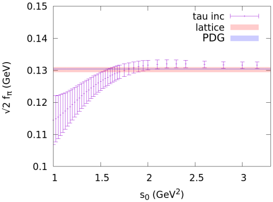




- **Non strange V-A**: very large cancellation!







- **Strange-Nonstrange comparison**$\rightarrow |V_{us}|$ Gamiz '13, RBC UKQCD '18

Low energy sectors: τ inclusive BSM

Relation between $\frac{d\Gamma}{ds}$ and $\mathrm{Im}\Pi$ modified by NP couplings

- **Non-strange V+A**. Take α_s from the lattice $\to$ make precise predictions for observables as a function of $\epsilon_i^{d\tau}$ and fit to data
- **Non strange V-A**. $V - A$ cancellation does not exist for BSM terms! Again, necessary inputs from the lattice.
- **Strange-Nonstrange comparison**. Poor experimental data beyond the ratio. Bound on strange couplings

$$\begin{pmatrix} \epsilon_L^{d\tau} - \epsilon_L^{de} + \epsilon_R^{d\tau} - \epsilon_R^{de} \\ \epsilon_R^{d\tau} \\ \epsilon_S^{d\tau} \\ \epsilon_P^{d\tau} \\ \epsilon_T^{d\tau} \end{pmatrix} = \begin{pmatrix} 1.0 \pm 1.5 \\ 0.2 \pm 1.6 \\ -0.6 \pm 1.5 \\ 0.6 \pm 1.4 \\ -0.06 \pm 0.75 \end{pmatrix} \times 10^{-2}$$

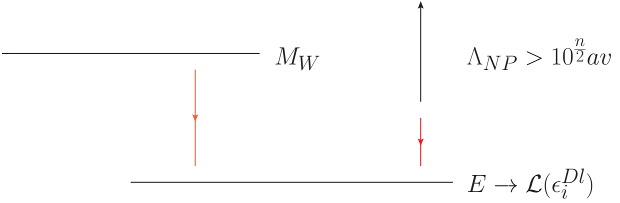
Cirigliano '18

Connecting bounds with other observables

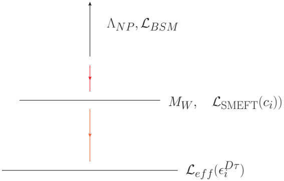
Effective Lagrangian

$$\mathcal{L}_{\text{eff}}(\epsilon_L^{D\tau}, \epsilon_R^{D\tau}, \epsilon_S^{D\tau}, \epsilon_P^{D\tau}, \epsilon_T^{D\tau})$$

$$|\epsilon_i^{Dl}| \sim a^2 \frac{v^2}{\Lambda_{NP}^2} < 10^{-n}$$



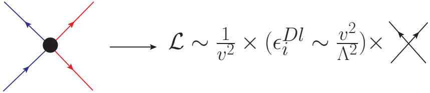
- If $E \sim M_W$ one cannot integrate it out
- Assume $\Lambda_{NP} > M_{W,Z,t}$
- SMEFT $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{D>4}$



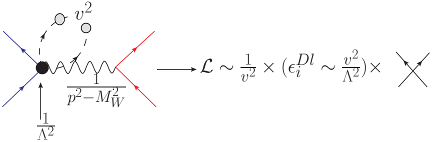
Connecting bounds with other observables

Tree-level matching. Two kind of contributions

$$\mathcal{Q}_{lq}^{(3)} = \bar{l}_p \gamma_\mu \tau^I l_r \, \bar{q}_s \gamma^\mu \tau^I q_t$$



$$\mathcal{Q}_{\varphi l}^{(3)} = \varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi \, \bar{l}_p \gamma^\mu l_r$$

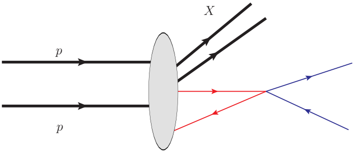


A consequence: $\epsilon_R^{de} = \epsilon_R^{d\mu} = \epsilon_R^{d\tau}$

Connection with other sectors

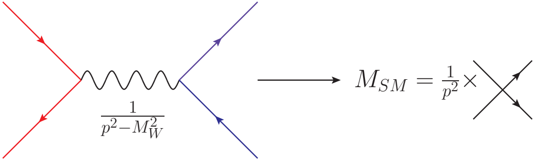
- Low-energy neutral current phenomenology Erler '18, Falkowski '17
- Z and W Pole observables Erler '18, Efrati '15

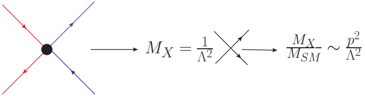
Connecting bounds with LHC measurements

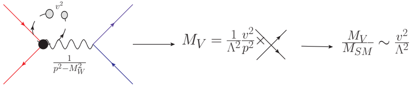


$$\Lambda_{NP} > E > M_W$$

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{D>4}$$



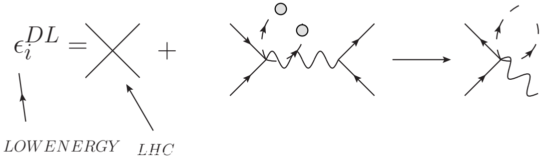


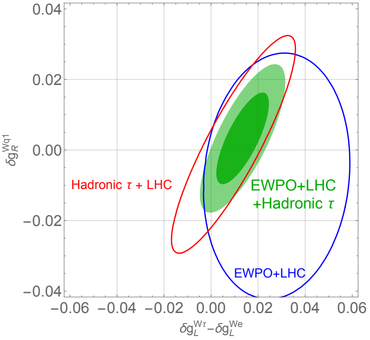


Connecting bounds with LHC measurements

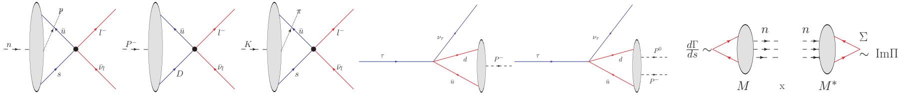
LHC observables ($pp \to l\nu_l$, $pp \to ll$) contain larger uncertainties than low energy precision observables

However relative contribution of contact terms is less suppressed in LHC wrt low-energy weak observables





Conclusions



Interactions between light quark and lepton charged currents lead to a very rich and precise low-energy phenomenology

Model-independent low-energy EFT Lagrangians with very few assumptions

Matching to SMEFT connects them to bounds in:

- Other Electroweak Precision Observables
- LHC measurements