ECT* Workshop on "Precise beta decay calculations for searches of new physics"
Trento, Apr 8-12 2019

BSM searches and beta decay

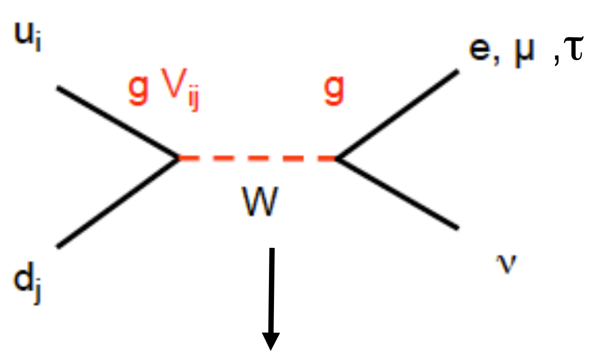
Vincenzo Cirigliano
Los Alamos National Laboratory

Outline

- New physics in beta decays: generalities and EFT framework
- Constraints on non-standard charged current interactions
  - global analysis of beta decays
  - collider input: LEP, LHC
  - comparison of sensitivities & complementarity
- Summary and outlook

Semileptonic processes: SM and beyond

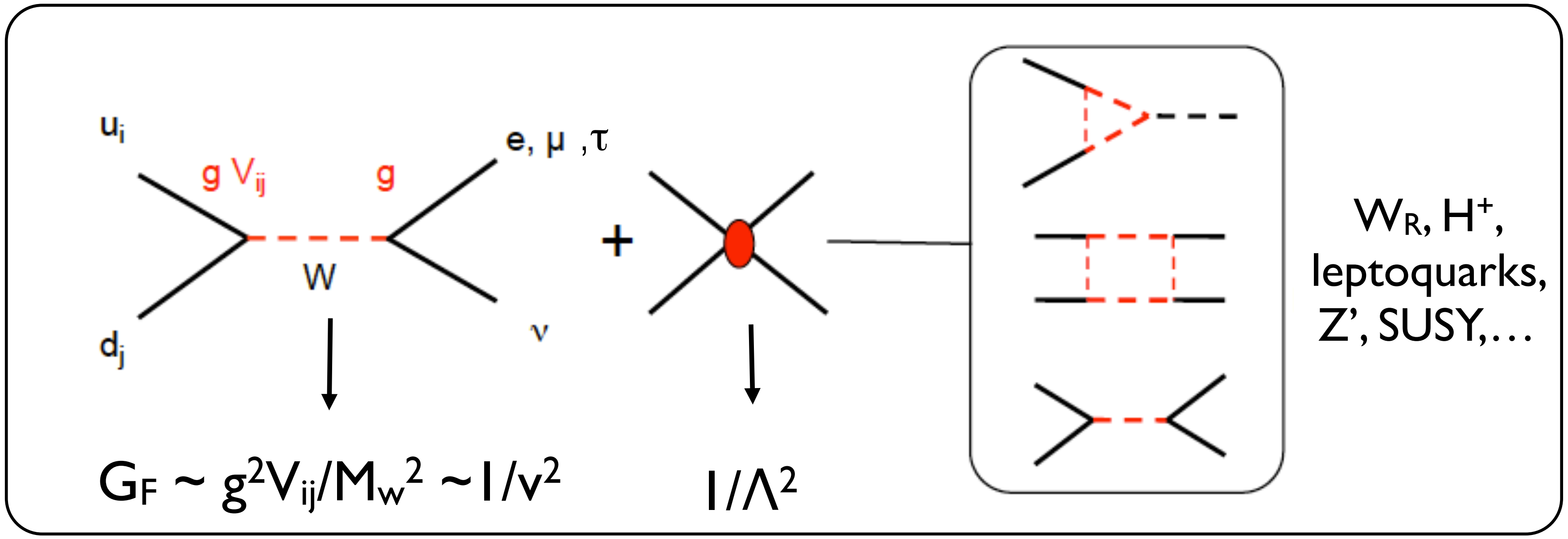
- In the SM, W exchange $\Rightarrow$ V-A currents, universality



$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

Semileptonic processes: SM and beyond

- In the SM, W exchange $\Rightarrow$ V-A currents, universality



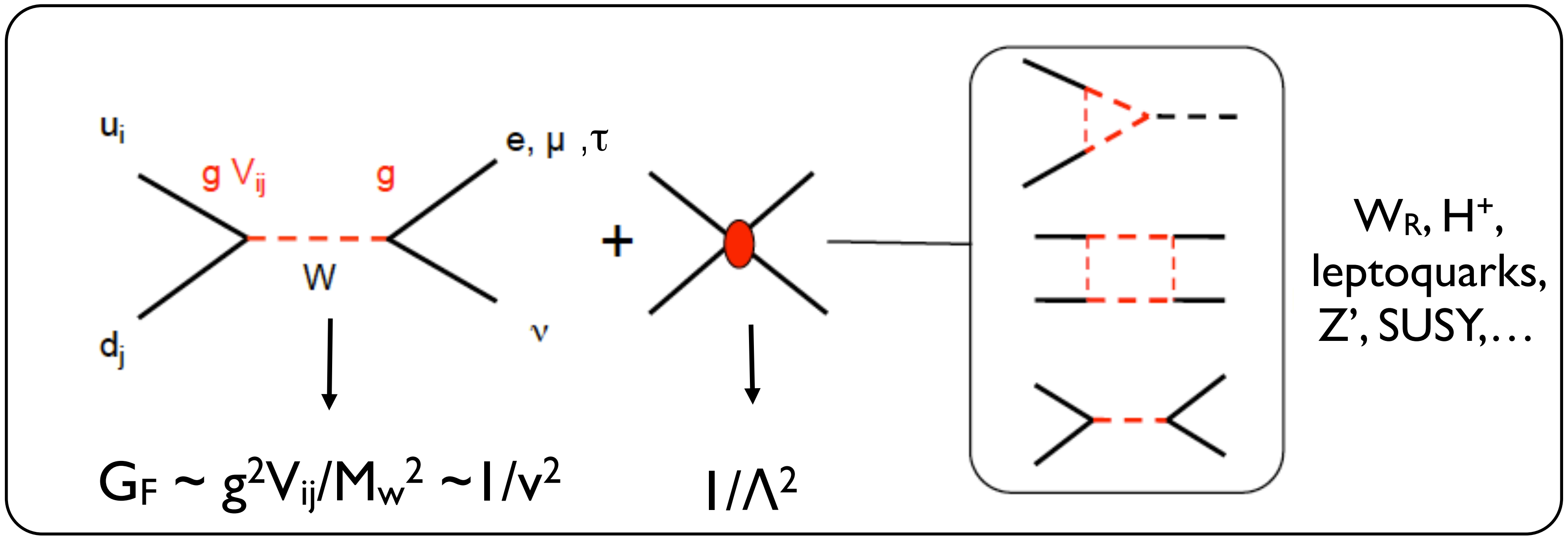
SUSY analyses:

Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035,
…
Kurylov & Ramsey-Musolf hep-ph/0109222.
…
Hagiwara et al1995
…
Barbieri et al 1985
…

- Broad sensitivity to BSM scenarios

Semileptonic processes: SM and beyond

- In the SM, W exchange $\Rightarrow$ V-A currents, universality



SUSY analyses:

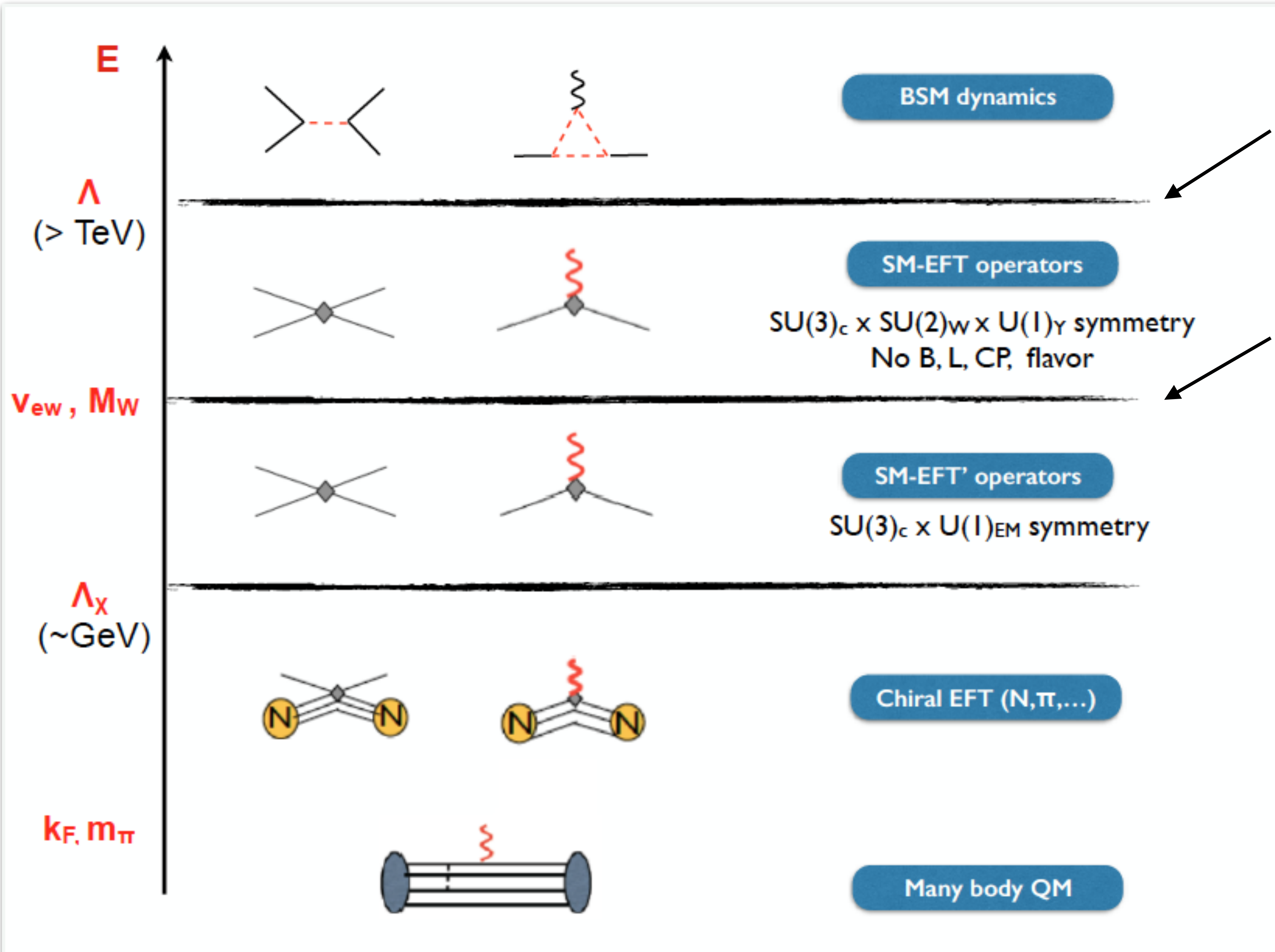
Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035,
…
Kurylov & Ramsey-Musolf hep-ph/0109222.
…
Hagiwara et al1995
…
Barbieri et al 1985
…

- Broad sensitivity to BSM scenarios

- Experimental and theoretical precision at <0.1% level $\Rightarrow$ probe effective scale Λ in the 5-10 TeV range

Connecting scales — EFT

To connect UV physics to neutron and nuclear beta decays, use EFT

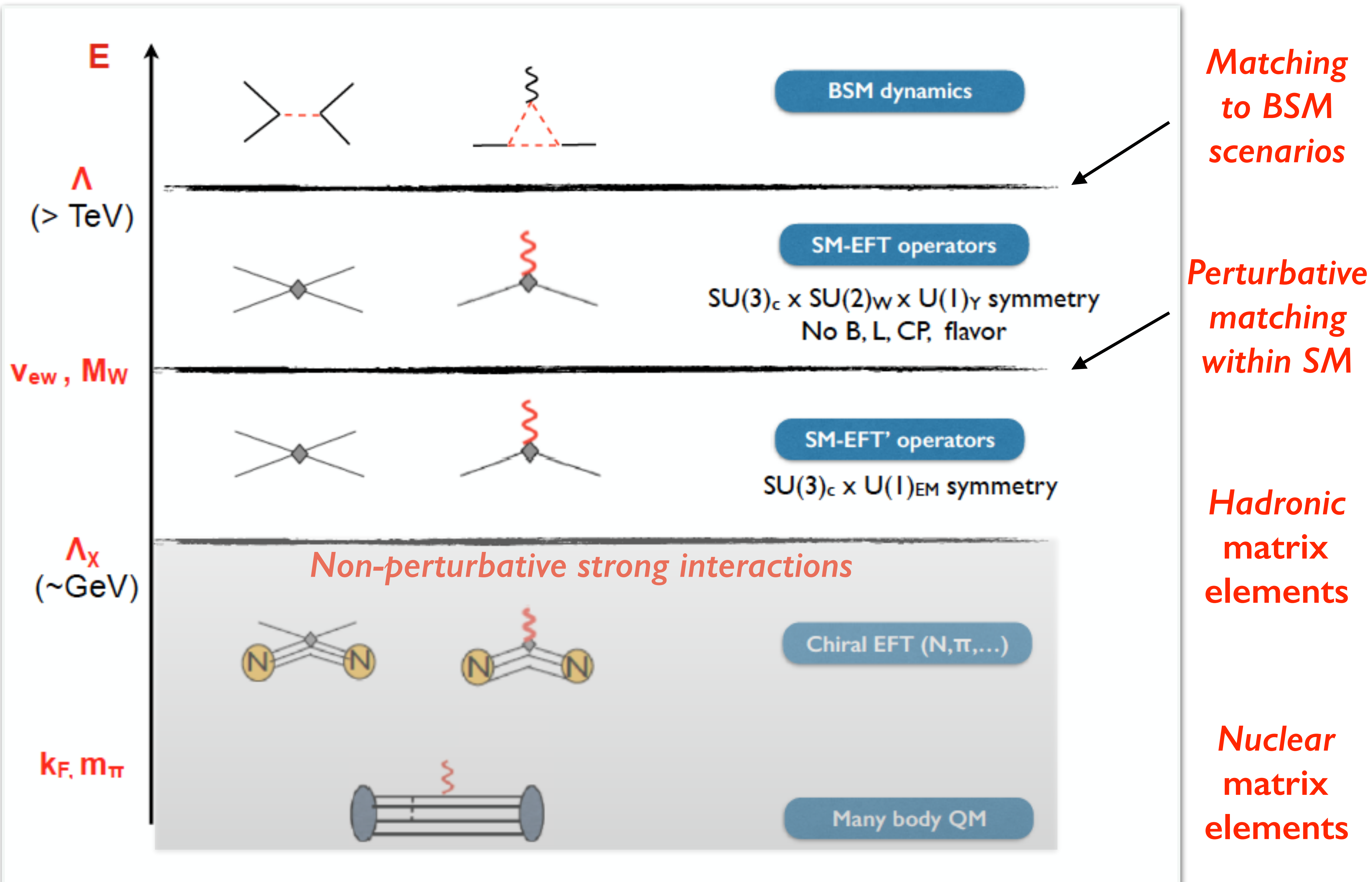


Matching to BSM scenarios

Perturbative matching within SM

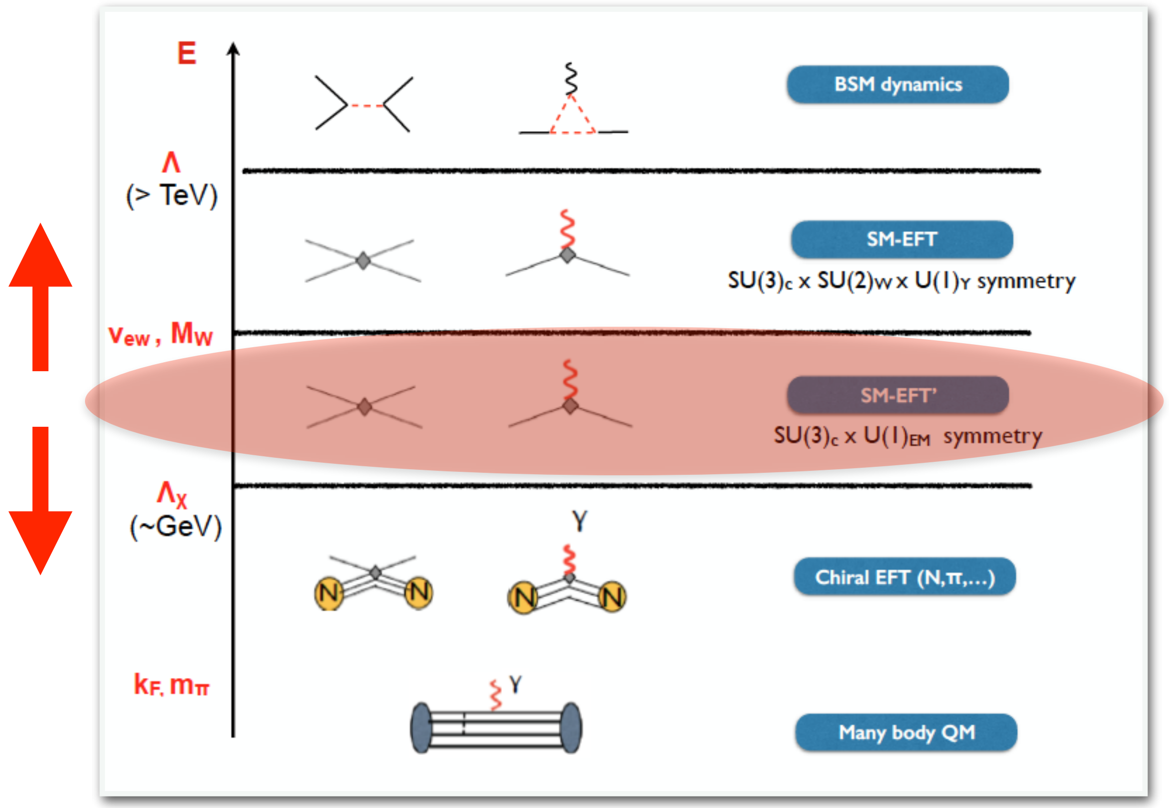
Connecting scales — EFT

To connect UV physics to neutron and nuclear beta decays, use EFT



Effective Lagrangian at E~GeV

- New physics effects are encoded in ten quark-level couplings



- Quark-level version of Lee-Yang effective Lagrangian, allows us to connect nuclear & high energy probes

Effective Lagrangian at E~GeV

VC, Gonzalez-Alonso, Jenkins 0908.1754 Bhattacharya et al., 1110.6448 VC, Graesser, Gonzalez-Alonso 1210.4553

- New physics effects are encoded in ten quark-level couplings

$$
\begin{aligned}
\mathcal{L}_{\rm CC} &= -\frac{G_F^{(\beta)}}{\sqrt{2}} V_{ud} \\
&\times \Big[\Big(1+\epsilon_L\Big) \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu(1-\gamma_5)d \\
&+ \epsilon_R \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu(1+\gamma_5)d \\
&+ \epsilon_S \; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}d \\
&- \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}\gamma_5 d \\
&+ \epsilon_T \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \; \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}
\end{aligned}
$$

$\epsilon_i \;, \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$

Can interfere with SM: linear sensitivity to ϵ_i

Effective Lagrangian at E~GeV

VC, Gonzalez-Alonso, Jenkins 0908.1754 Bhattacharya et al., 1110.6448 VC, Graesser, Gonzalez-Alonso 1210.4553

- New physics effects are encoded in ten quark-level couplings

$$
\begin{aligned}
\mathcal{L}_{\rm CC} \;=\; & -\frac{G_F^{(\beta)}}{\sqrt{2}} V_{ud} \\
\times & \Big[\Big(1+\epsilon_L\Big) \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ & \; \epsilon_R \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu(1+\gamma_5)d \\
+ & \; \epsilon_S \; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}d \\
- & \; \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}\gamma_5 d \\
+ & \; \epsilon_T \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \; \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}
\end{aligned}
$$

$\epsilon_i \; , \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$

Can interfere with SM: linear sensitivity to ε_i

$$+ \quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \xrightarrow{**!} (1+\gamma_5)\nu_\ell$$

Interference with SM suppressed by m_ν/E: quadratic sensitivity to $\tilde{\varepsilon}_i$

Effective Lagrangian at E~GeV

VC, Gonzalez-Alonso, Jenkins 0908.1754 Bhattacharya et al., 1110.6448 VC, Graesser, Gonzalez-Alonso 1210.4553

- Work to first order in rad. corr. and new physics

$$
\begin{aligned}
\mathcal{L}_{\rm CC} \; = \; & -\frac{G_F^{(\mu)}}{\sqrt{2}} V_{ud} \left(1+\delta_{\rm RC}\right) \left(1 - \frac{\delta G_F^{(\mu)}}{G_F^{(\mu)}}\right) \left(1 + \epsilon_L + \epsilon_R\right) \\
\times & \left[\bar{\ell}\gamma_\mu (1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu \left(1 - \left(1 - 2\,\epsilon_R\right)\gamma_5\right) d \right. \\
+ & \;\epsilon_S \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u} d \\
- & \;\epsilon_P \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}\gamma_5 d \\
+ & \;\epsilon_T \;\; \left. \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \; \bar{u}\sigma^{\mu\nu}(1-\gamma_5) d \right] + \text{h.c.}
\end{aligned}
$$

$G_F^{(\mu)}$

Fermi constant *extracted* fro muon lifetime, possibly "contaminated" by new physics

$\delta_{\rm RC}$

SM rad. corr.
⊃ "large log"
$(\alpha/\pi)\times \mathrm{Log}(M_Z/\mu)$

Marciano-Sirlin 1981
Sirlin 1982

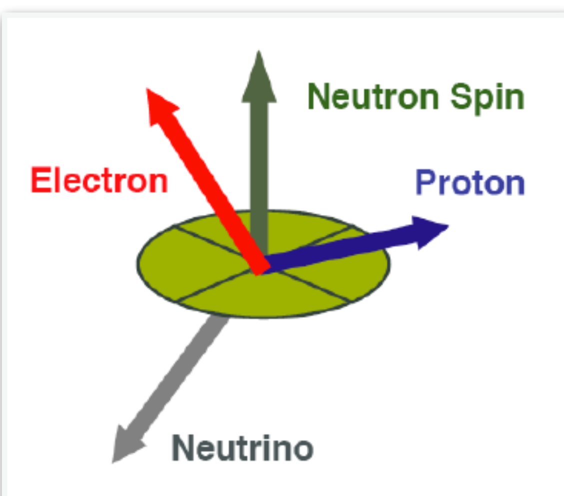
Note: besides the pre-factor, ϵ_R appears in nuclear decays in the combination $\bar{g}_A \equiv g_A \times (1 - 2\epsilon_R)$

How do we probe the ϵ_α? (1)

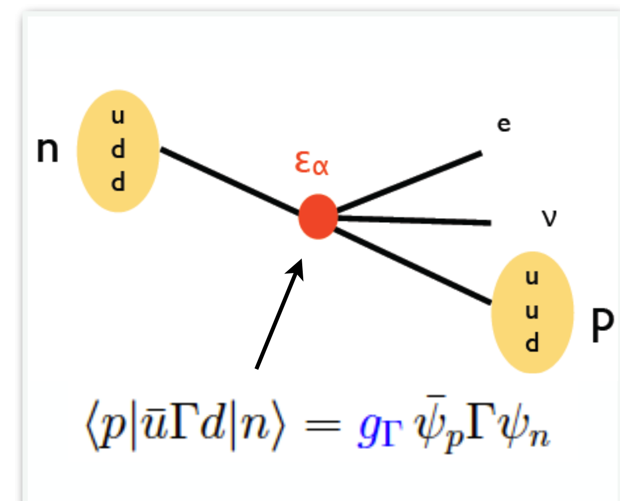
1. Differential decay distribution

$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

Lee-Yang, 1956 Jackson-Treiman-Wyld 1957



$a(g_A)$, $A(g_A)$, $B(g_A, g_\alpha\epsilon_\alpha)$, ...
isolated via suitable experimental asymmetries

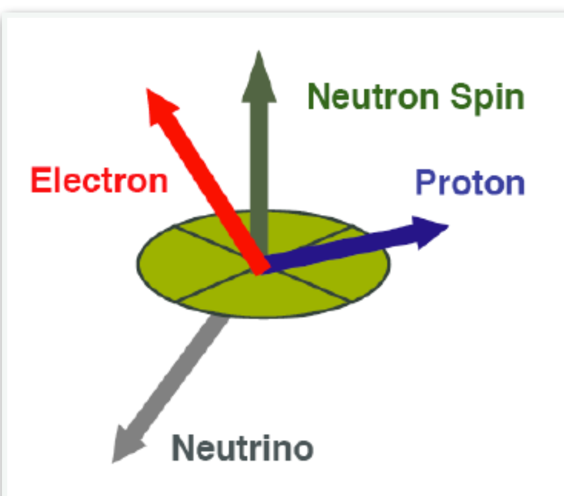


How do we probe the ε_α? (1)

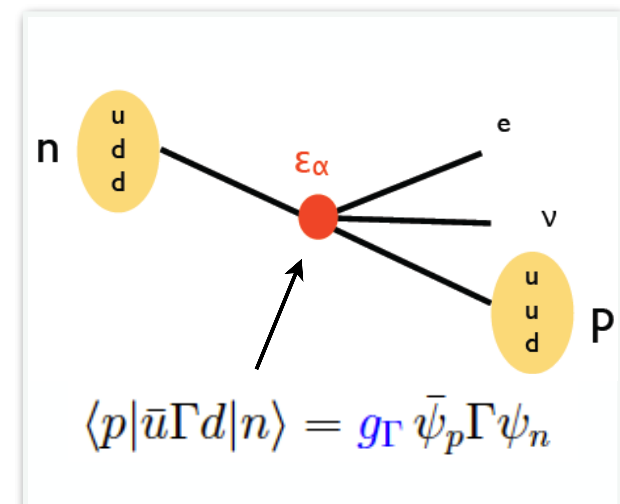
1. Differential decay distribution

$$d\Gamma \propto F(E_e) \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots \right] \right\}$$

Lee-Yang, 1956 Jackson-Treiman-Wyld 1957



$a(g_A)$, $A(g_A)$, $B(g_A, g_\alpha \varepsilon_\alpha)$, …
isolated via suitable experimental asymmetries



Theory input:

(1) Nucleon matrix elements ($g_{V,A,S,T}$ from lattice QCD), including $O(q/M_N)$

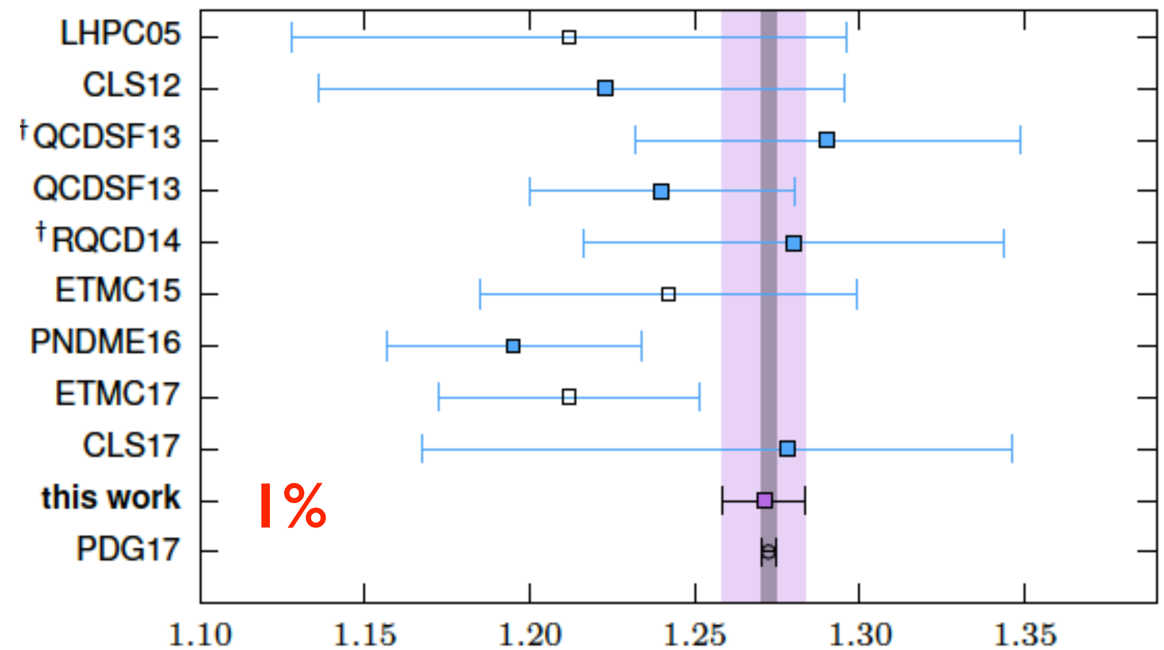
(2) Nuclear matrix elements (including recoil order terms $O(q/M_N)$)

(3) Radiative corrections

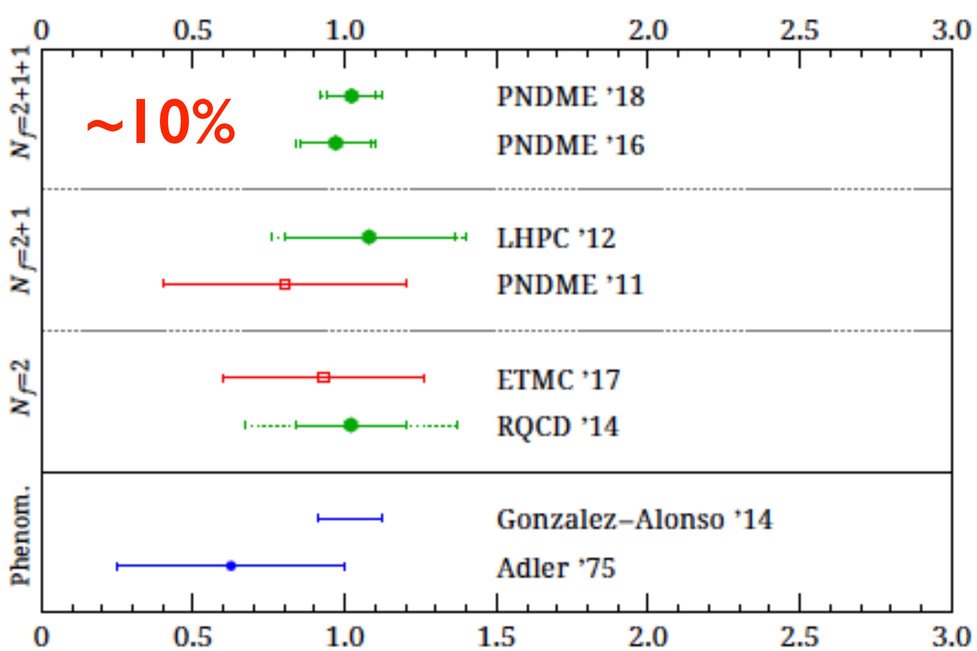
Nucleon charges from lattice QCD

With estimates of all systematic errors (m_q, a, V, excited states)

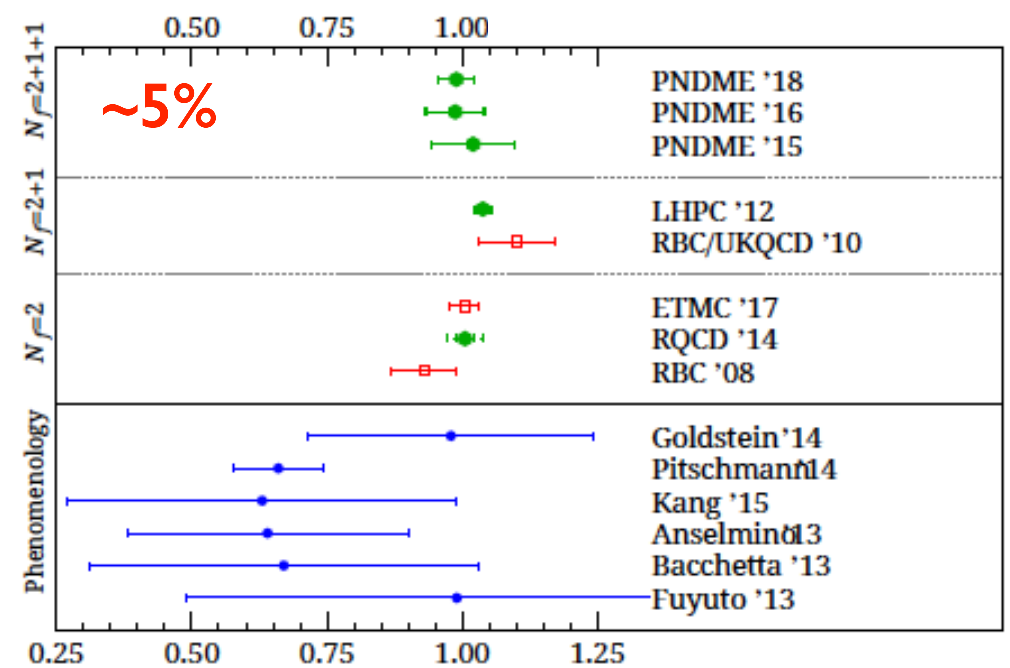
Chang et al. (CalLat) 1805.12030



g_S g_A g_T

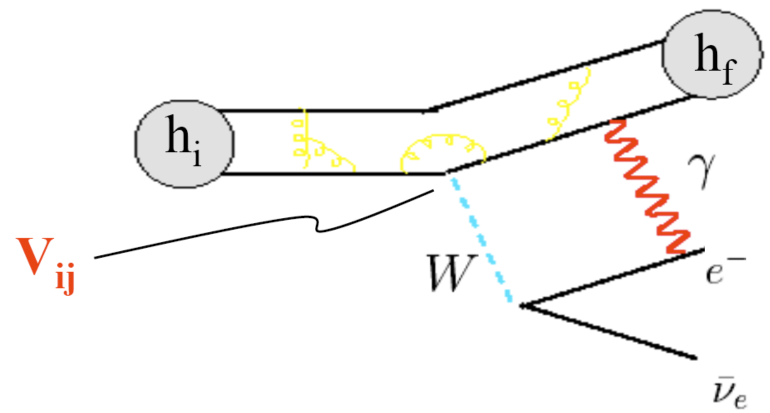


Bhattacharya et al. 1806.09006



How do we probe the ϵ_α? (2)

2. Total decay rates



$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

Channel-dependent effective CKM element

$$\bar{V}_{ud} = V_{ud}\left[1 + \epsilon_L + \epsilon_R + b(\epsilon_S, \epsilon_T)\,\widetilde{F}_{\rm kin}\right]$$

$$\boxed{|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)}$$

Global analysis: input

- Experimental precision between ~0.01% and few %

Ft (0+→0+) values

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

Correlation coefficients

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

Neutron data

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

* Average

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

Nuclei

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

Global analysis: results (1)

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

- Standard Model fit ($\lambda = g_A/g_V$)

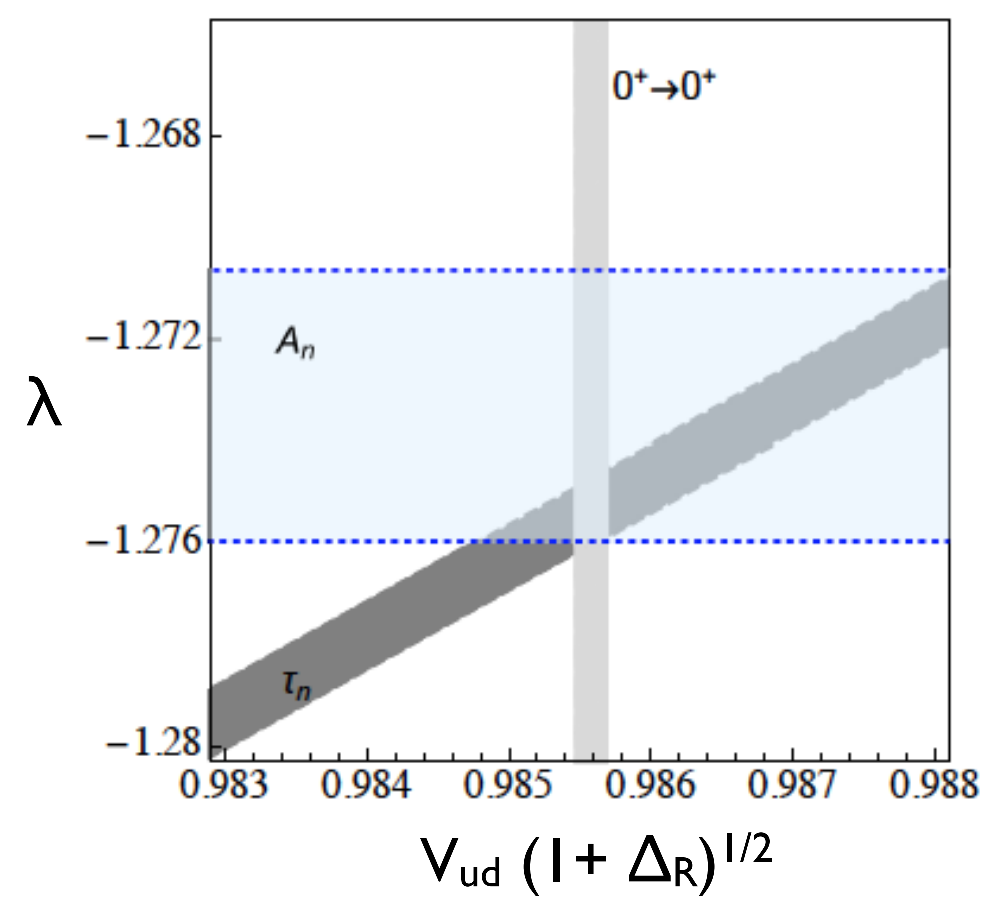
Radiative corrections (Δ_R)
[pre Seng et al. 1807.10197, …]

Experimental

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

$$
\begin{aligned}
\rho &= -0.13 \\
\chi^2_{\min}/\nu &= 0.57.
\end{aligned}
$$

- Fit driven by $\mathcal{F}t$'s ($0^+ \rightarrow 0^+$) and τ_n (not A_n)



Global analysis: results (1)

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

- Standard Model fit ($\lambda = g_A/g_V$)

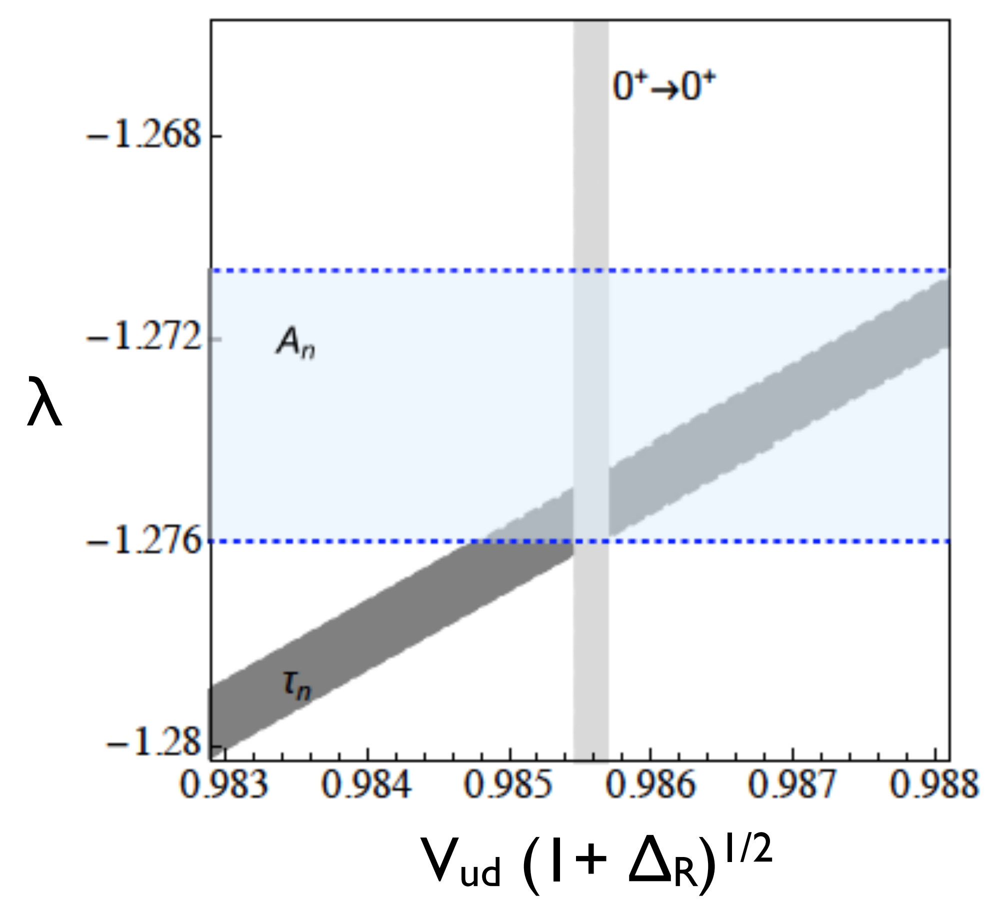
Experimental

New Radiative corrections (Δ_R)
[Seng et al. 1807.10197]

$$
\begin{aligned}
|V_{ud}| &= 0.97416(11)(12) = 0.97366(15) \\
\lambda &= 1.27510(66)
\end{aligned}
$$

$$
\begin{aligned}
\rho &= -0.13 \\
\chi^2_{\rm min}/\nu &= 0.57.
\end{aligned}
$$

- Fit driven by $\mathcal{F}t$'s ($0^+ \to 0^+$) and τ_n (not A_n)



Global analysis: results (2)

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

- Fit including BSM couplings (driven by $\mathcal{F}t$'s ($0^+ \rightarrow 0^+$), τ_n, and A_n)

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

1st error: experimental

2nd error: Δ_R, g_A, g_S, and g_T

$$\bar{g}_A = g_A\,(1-2\epsilon_R)$$

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

$\chi^2_{\rm min}/\nu = 0.46$.

~2 % → ~ 0.5% **

~0.2 %

~0.1 %

$$\rho = \begin{pmatrix} 1.00 & & & \\ 0.00 & 1.00 & & \\ 0.83 & 0.00 & 1.00 & \\ 0.28 & -0.04 & 0.31 & 1.00 \end{pmatrix}$$

** CalLat 1805.12030

CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

Extraction dominated by $0^+ \to 0^+$ nuclear transitions

Hardy-Towner 1411.5987
CKM 2016

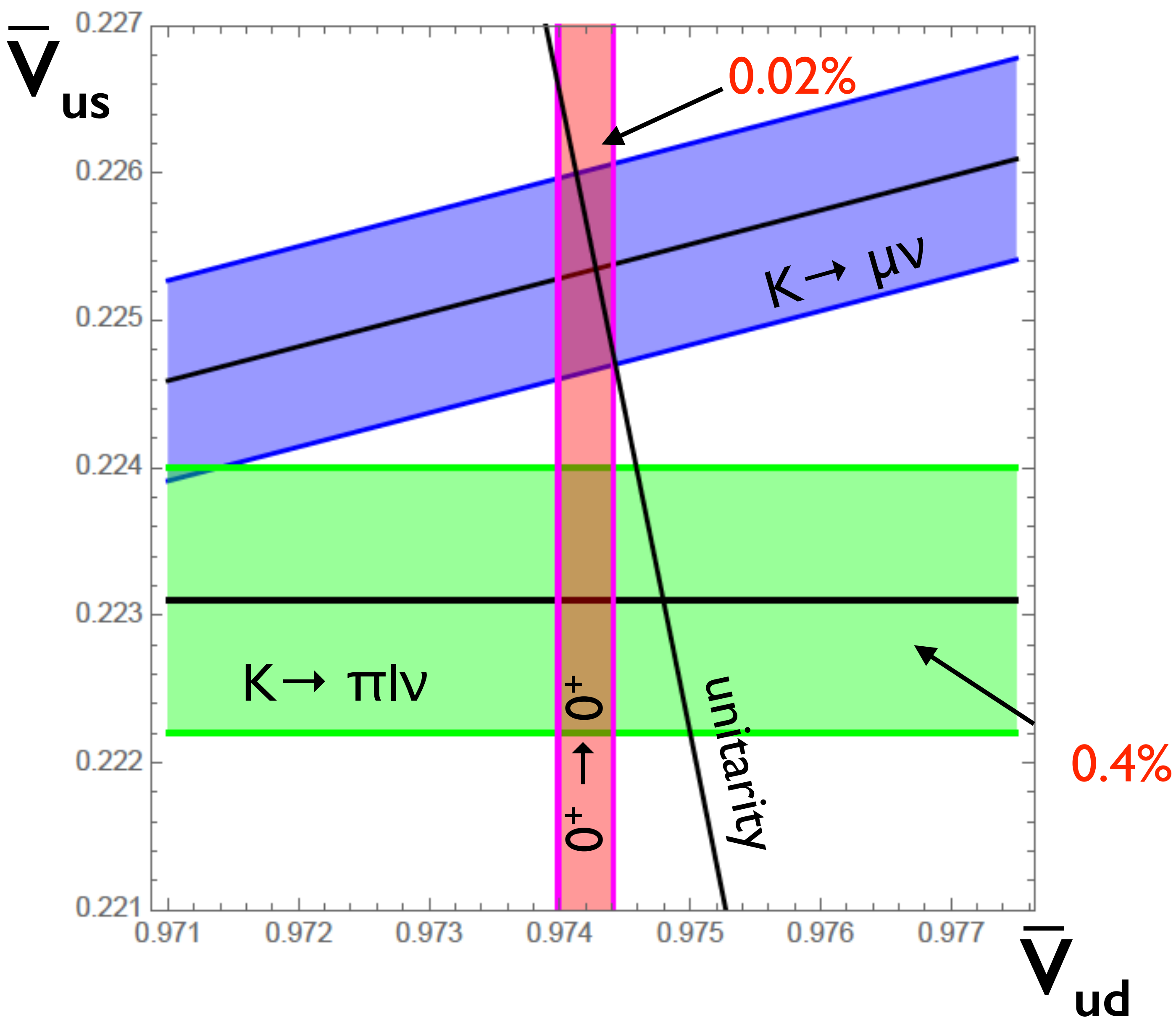
Extraction dominated by K decays:
$K \to \pi e \nu$ & $K \to \mu\nu$ vs $\pi \to \mu\nu$ (V_{us}/V_{ud})

FLAVIANET report 1005.2323 and refs therein

Lattice QCD input from FLAG 1607.00299 and refs therein
+ MILC 2018 1809.02827

CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\mathrm{CKM}}(\epsilon_i)$$



V_{us} from $K \to \mu\nu$

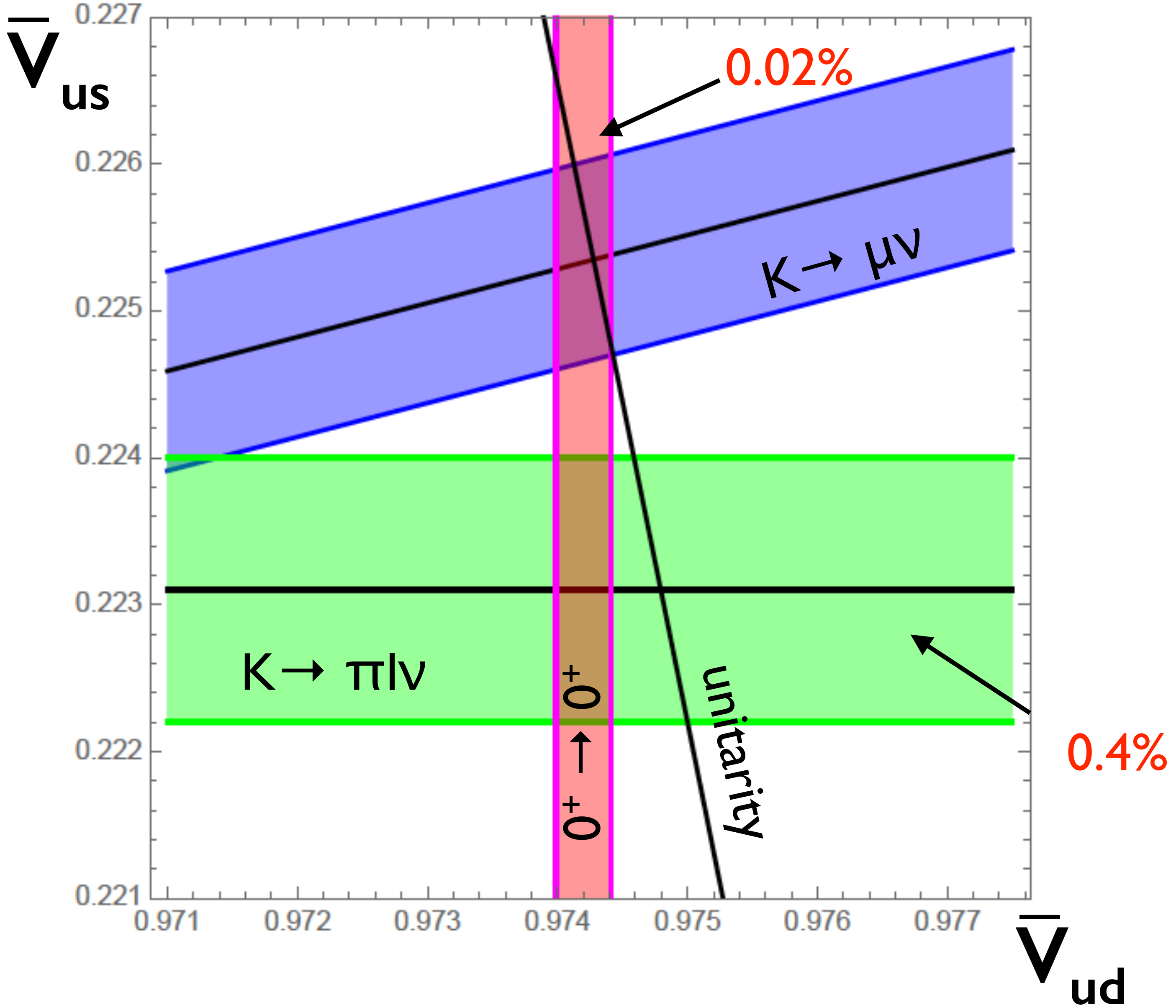
$\Delta_{\mathrm{CKM}} = -(4 \pm 5) * 10^{-4}$ ~ 1σ

$\Delta_{\mathrm{CKM}} = -(12 \pm 6) * 10^{-4}$ ~ 2σ

V_{us} from $K \to \pi l \nu$

CKM unitarity test

$$\boxed{|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)}$$



V_{us} from K→ μν

$\Delta_{\rm CKM}$ = - (4 ± 5) * 10^{-4} ~ 1σ

$\Delta_{\rm CKM}$ = - (12 ± 6) * 10^{-4} ~ 2σ

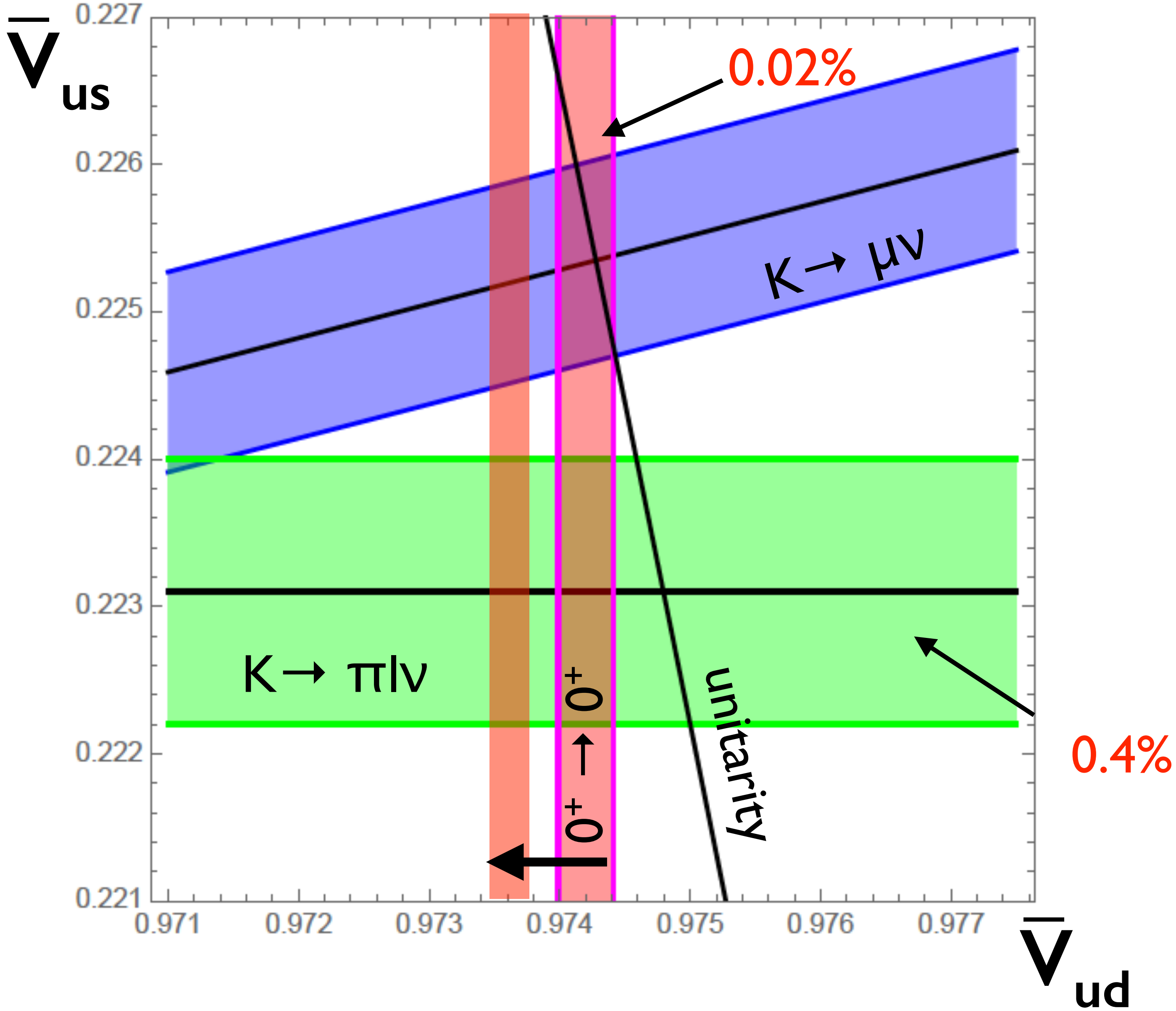
V_{us} from K→ πlν

Hint of something
[ε's ≠0] or SM theory input?

Worth a closer look:
at the level of the best LEP EW precision tests,
probing scale Λ~10 TeV

Cabibbo universality test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



V_{us} from K→ μν

$\Delta_{\rm CKM}$ = - (14 ± 4) ∗ 10^{-4} ~3.5σ

$\Delta_{\rm CKM}$ = - (22 ± 5) ∗ 10^{-4} ~4.5σ

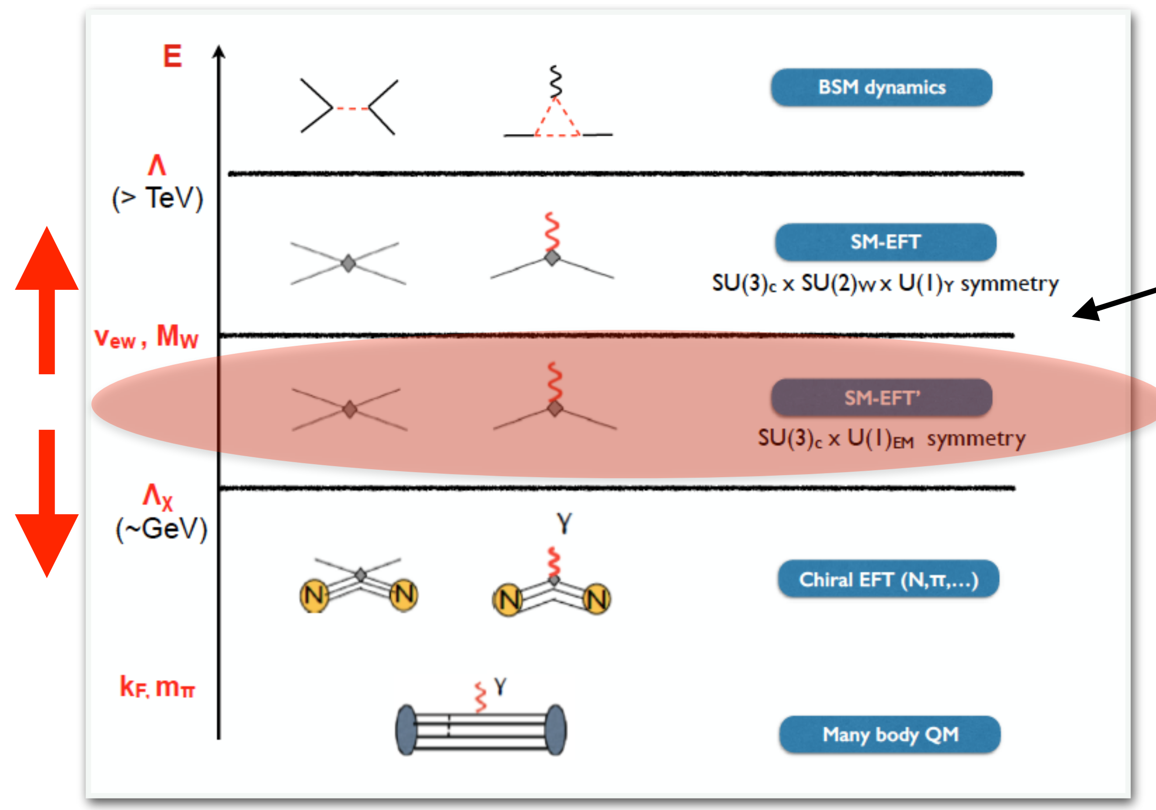
V_{us} from K→ πlν

With new radiative correction (Δ_R)

[Seng et al. 1807.10197]

Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α



At the weak scale
Match SM-EFT
and SM-EFT'

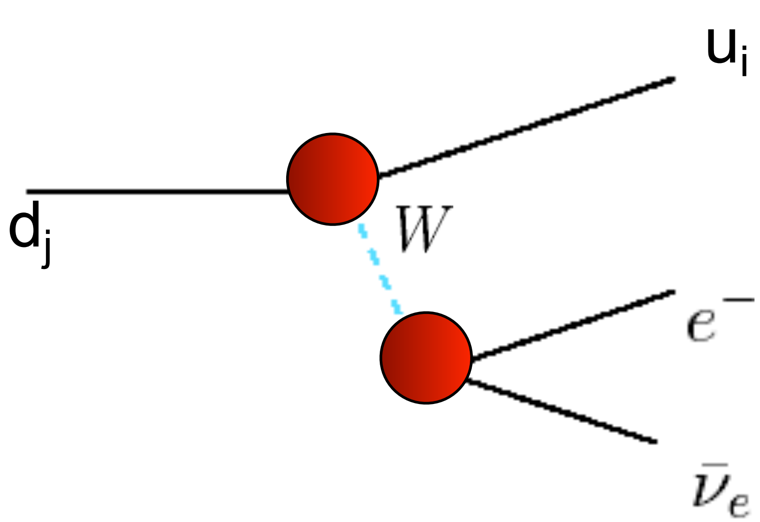
- Model-independent statements possible in <u>"heavy BSM" scenarios</u>:
M_{BSM} > TeV → new physics looks point-like at collider

VC, Gonzalez-Alonso, Jenkins 0908.1754

Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections

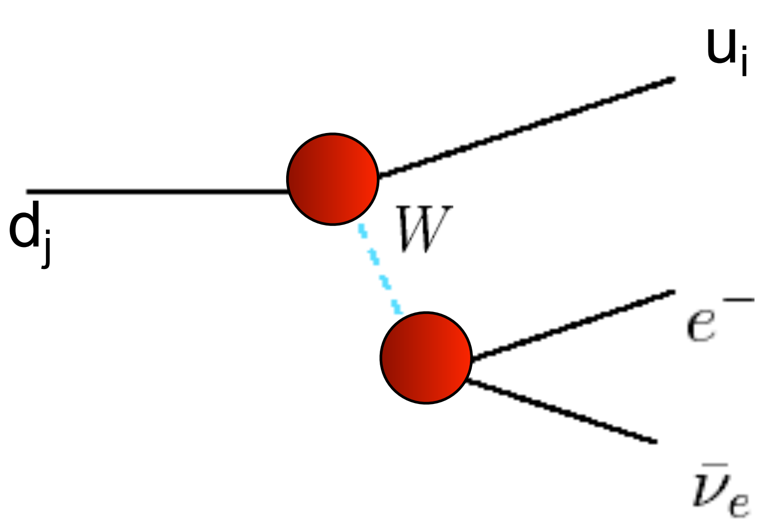


VC, Gonzalez-Alonso, Jenkins 0908.1754

Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

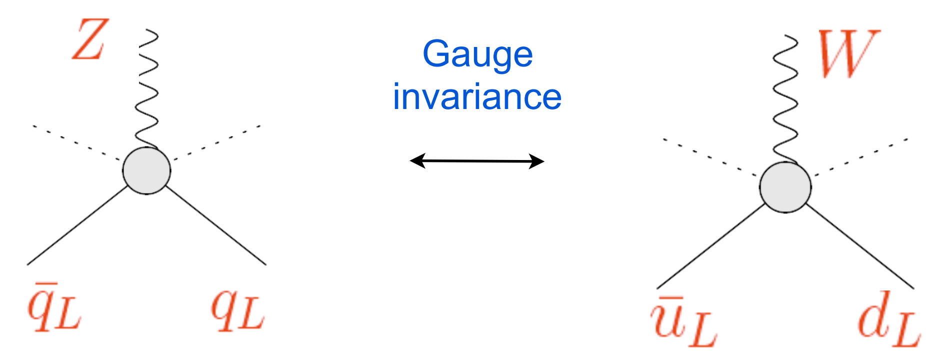
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



Building blocks

$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \qquad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \qquad \varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

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

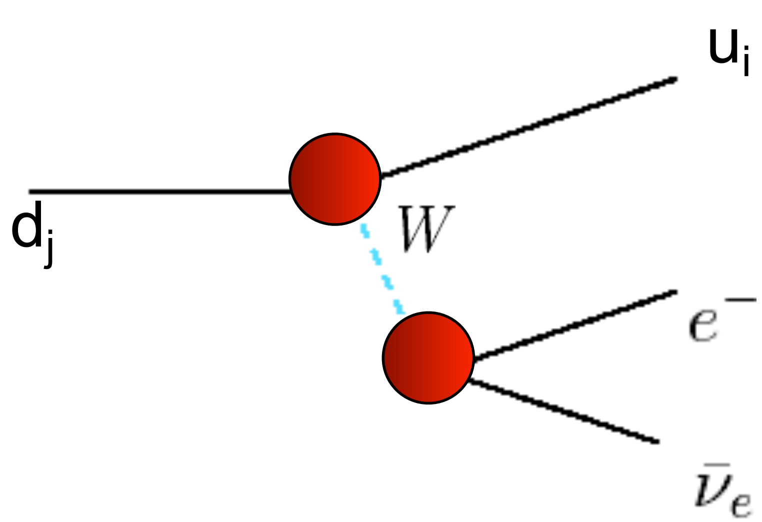


VC, Gonzalez-Alonso, Jenkins 0908.1754

Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

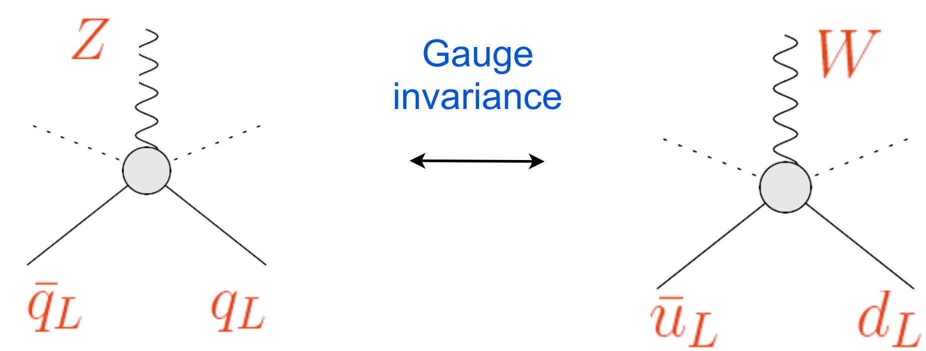
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



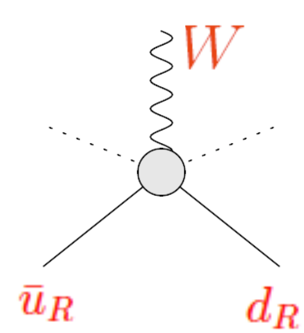
Building blocks

$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \qquad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \qquad \varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

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



$$O_{\varphi\varphi} = i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d)$$



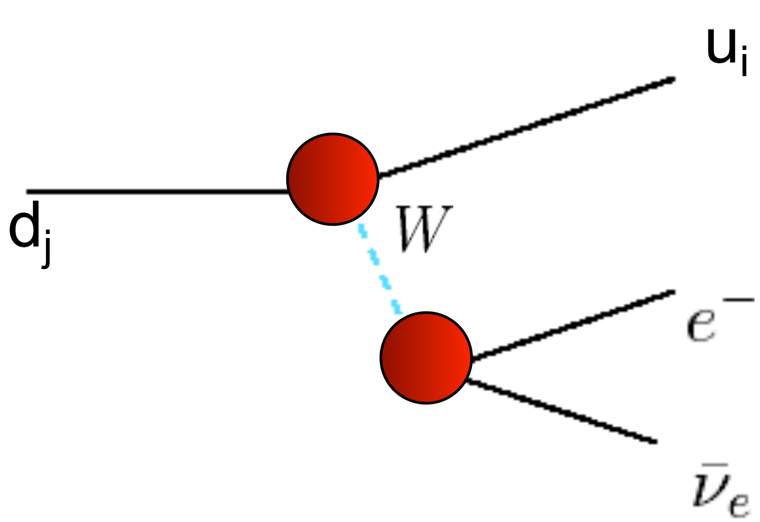
E.g. from W_L-W_R mixing in Left-Right symmetric models

VC, Gonzalez-Alonso, Jenkins 0908.1754

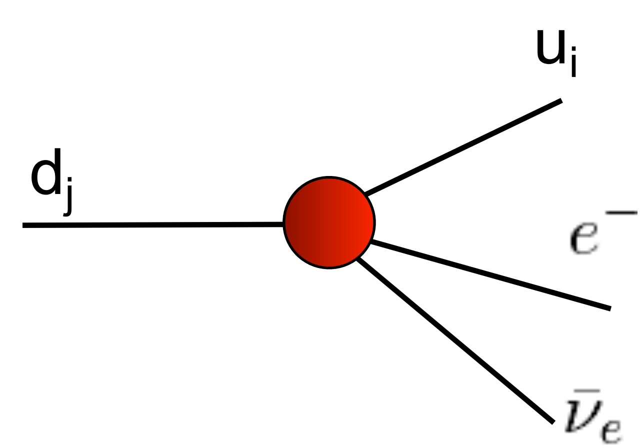
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



$\varepsilon_{S,P,T}$ and one contribution to ε_L arise from SU(2)xU(1) invariant 4-fermion operators



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

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

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

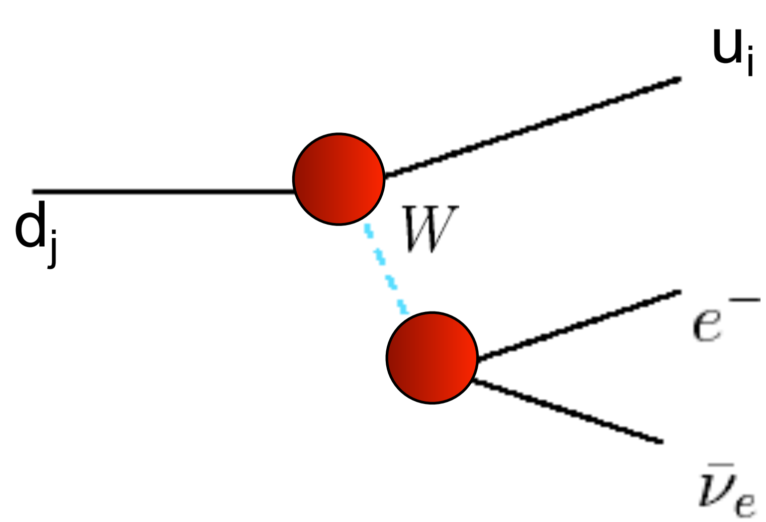
$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$

VC, Gonzalez-Alonso, Jenkins 0908.1754

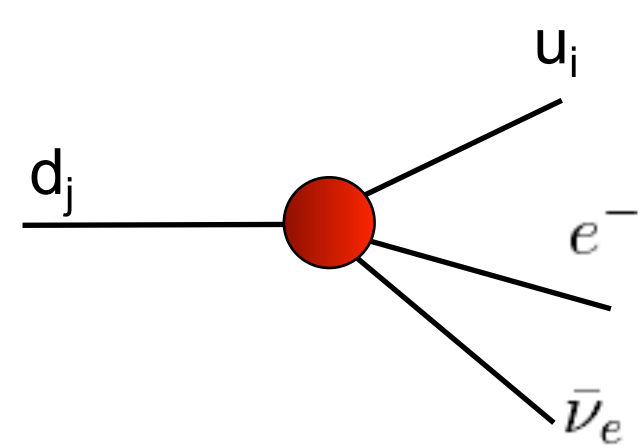
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



$\varepsilon_{S,P,T}$ and one contribution to ε_L arise from SU(2)xU(1) invariant 4-fermion operators

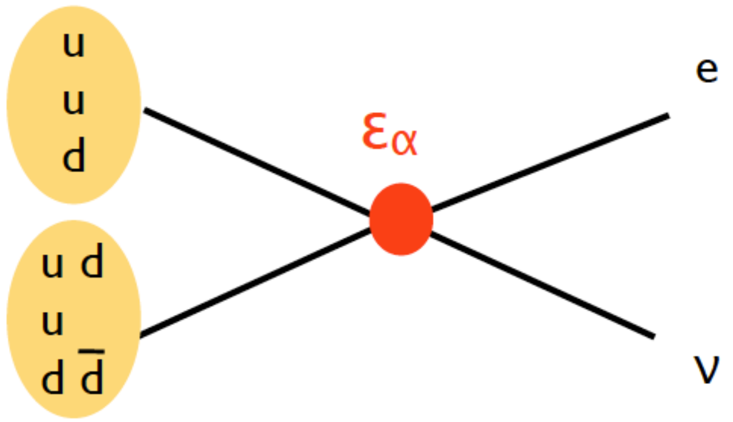


- LEP / SLC:
  - Strong constraints (<0.1%) on L-handed vertex corrections (Z-pole)
  - Weaker constraints on 4-fermion interactions (σ_{had})
- What about LHC?

LHC sensitivity: 4-fermions

Bhattacharya et al., 1110.6448, VC, Graesser, Gonzalez-Alonso 1210.4553

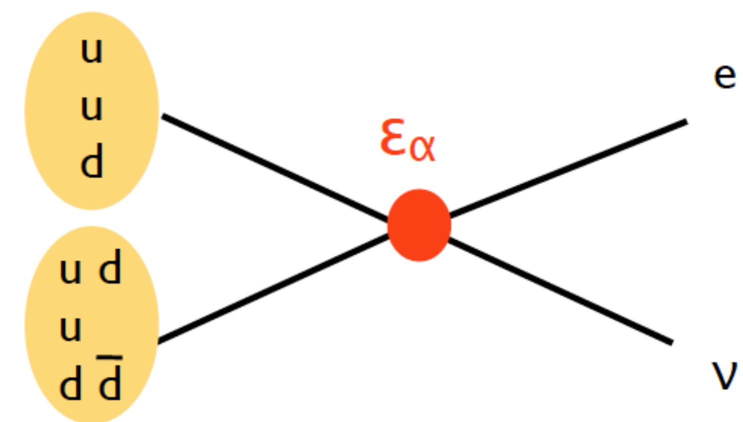
- The effective couplings ε_α contribute to the process $pp \rightarrow e\nu + X$



LHC sensitivity: 4-fermions

Bhattacharya et al., 1110.6448, VC, Graesser, Gonzalez-Alonso 1210.4553

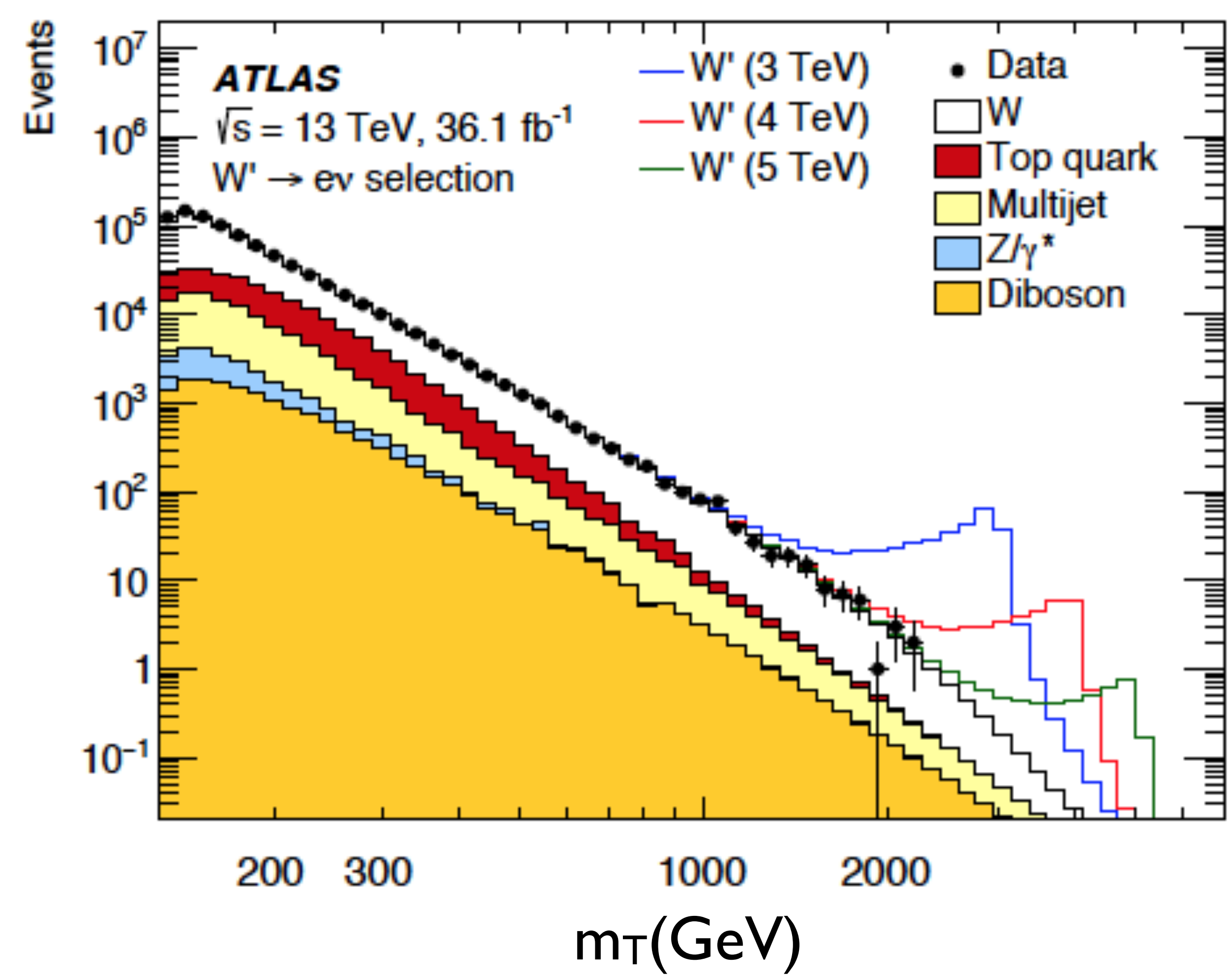
- The effective couplings ε_α contribute to the process $pp \to e\nu + X$



- No excess events in transverse mass distribution: bounds on ε_α

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

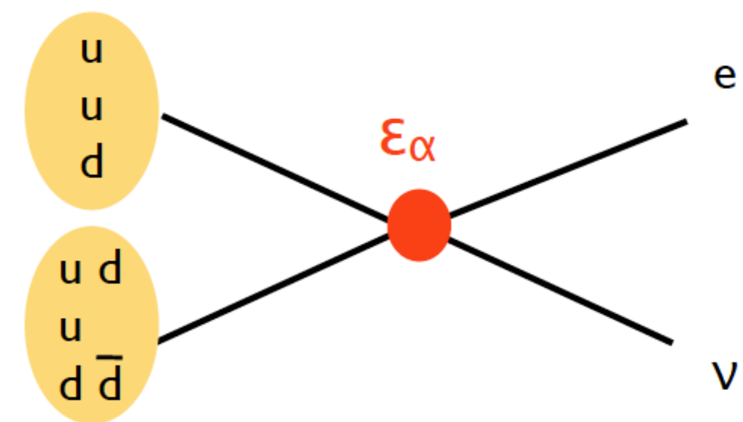
ATLAS: 1706.06786



LHC sensitivity: 4-fermions

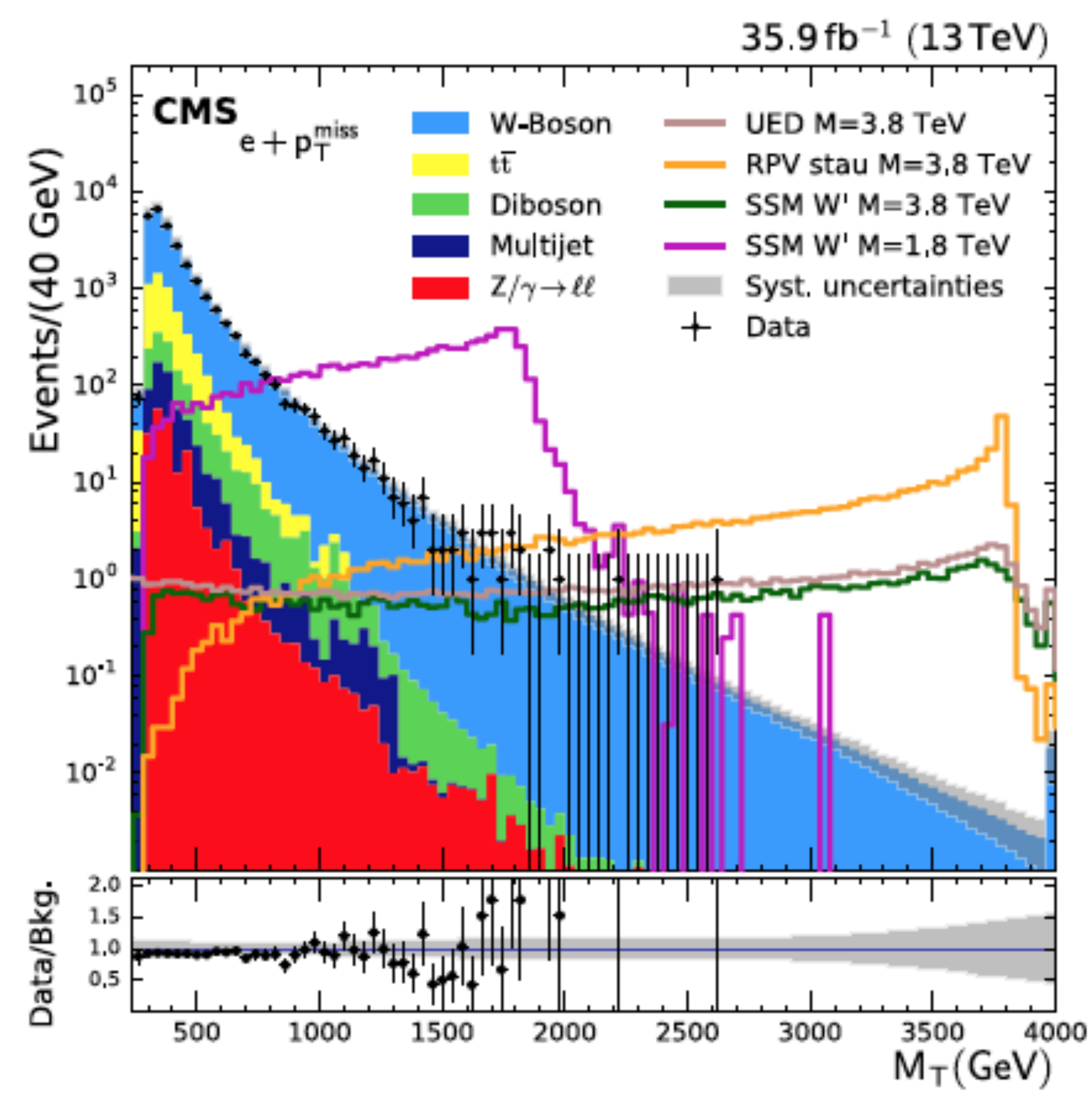
Bhattacharya et al., 1110.6448, VC, Graesser, Gonzalez-Alonso 1210.4553

- The effective couplings ε_α contribute to the process $pp \to e\nu + X$



- No excess events in transverse mass distribution: bounds on ε_α

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

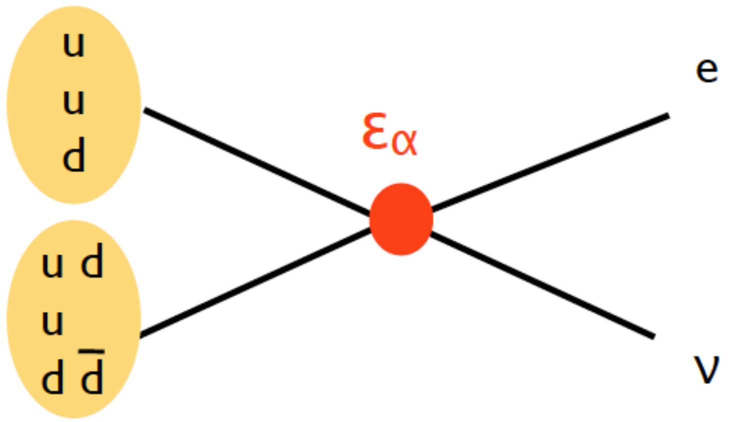


CMS: 1803.11133

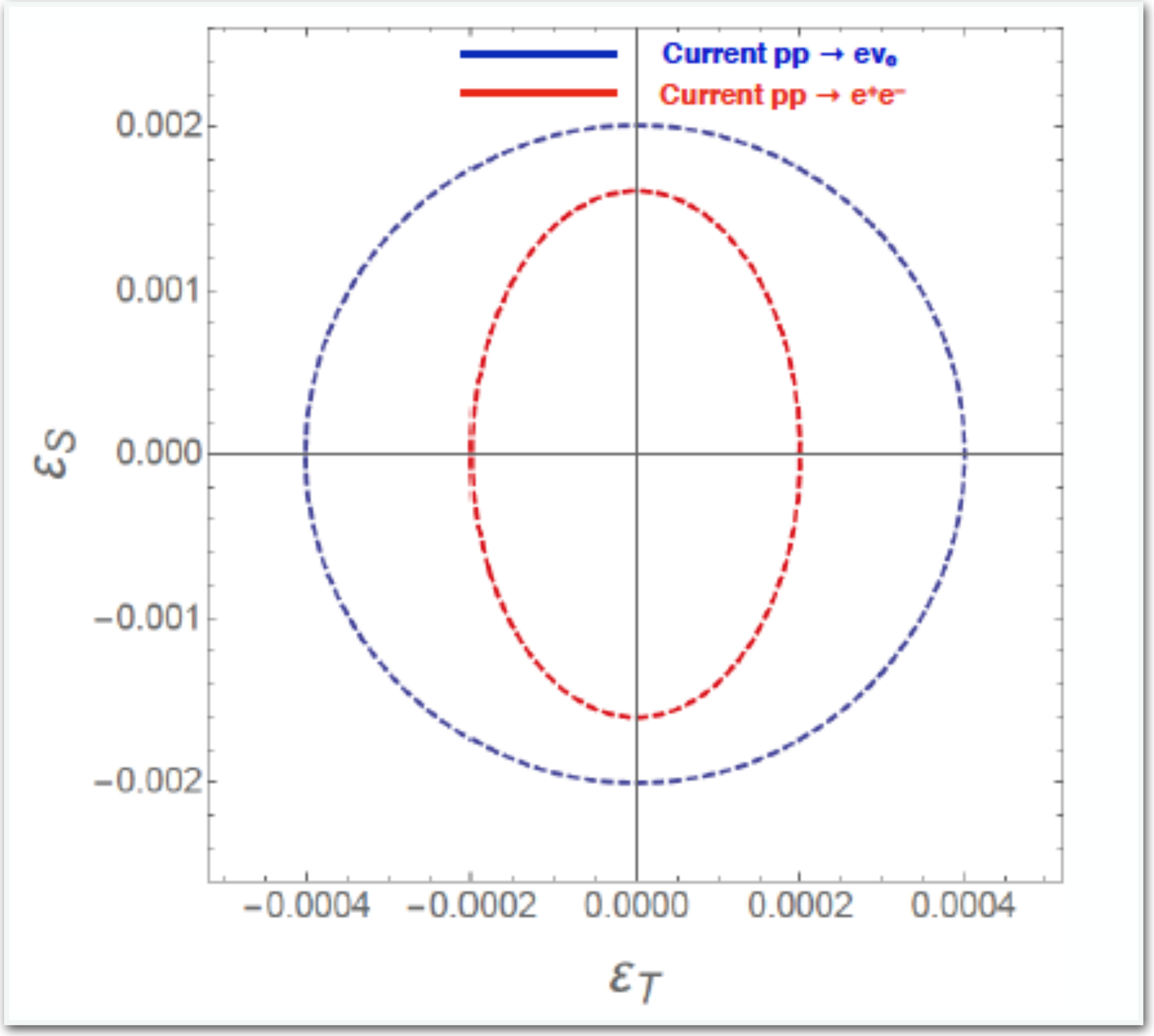
LHC sensitivity: 4-fermions

Bhattacharya et al., 1110.6448, VC, Graesser, Gonzalez-Alonso 1210.4553

- The effective couplings ε_α contribute to the process $pp \to e\nu + X$



- By SU(2) gauge invariance, ε_α contribute also to $pp \to e^+e^- + X$

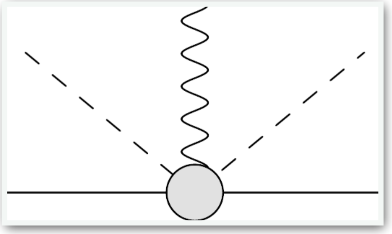


Gupta et al., 1006.09006

LHC sensitivity: vertex corrections

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

- Vertex corrections inducing $\varepsilon_{L,R}$ in the SM-EFT involve the Higgs field (due to SU(2) gauge invariance)



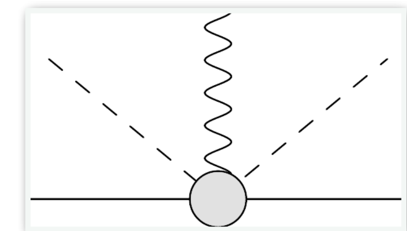
ε_L $\varphi^\dagger \tau^a D_\mu \varphi \;\; \bar{q}_L \tau^a \gamma^\mu q_L$

ε_R $\varphi^T \epsilon D_\mu \varphi \;\; \bar{u}_R \gamma^\mu d_R$

LHC sensitivity: vertex corrections

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

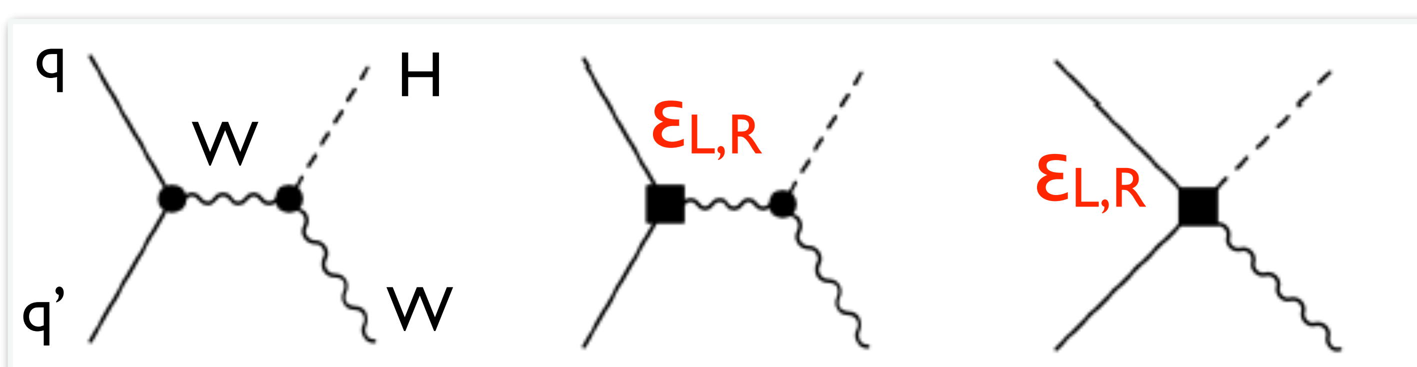
- Vertex corrections inducing $\varepsilon_{L,R}$ in the SM-EFT involve the Higgs field (due to SU(2) gauge invariance)



ε_L $\quad \varphi^\dagger \tau^a D_\mu \varphi \;\; \bar{q}_L \tau^a \gamma^\mu q_L$

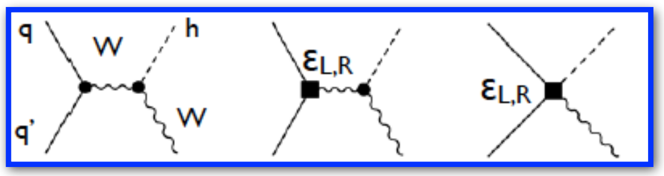
ε_R $\quad \varphi^T \epsilon D_\mu \varphi \;\; \bar{u}_R \gamma^\mu d_R$

- Can be probed at the LHC by associated Higgs + W production



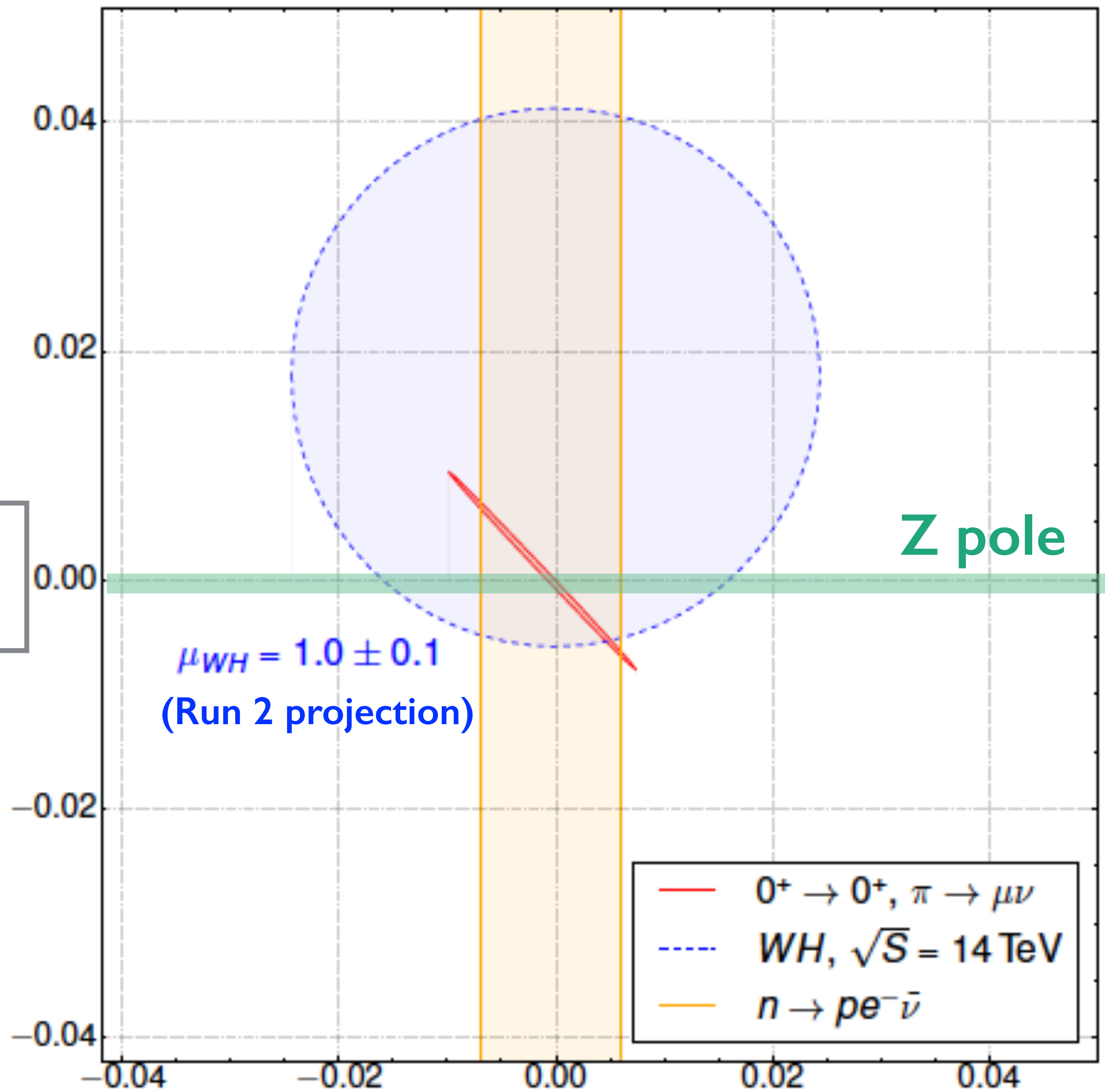
Example 1: ε_L and ε_R couplings

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751



Z-pole → $\varepsilon_L^{(\nu)}$
Falkowski et al
1706.03783

90%CL, assumes only two operators at high scale



ε_L

ε_R

Neutron decay:
$\lambda = g_A\,(1 - 2\,\varepsilon_R)$

Constraint on ε_R uses
g_A =1.271(13)
(CalLat 1805.12030)

$\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$

$\delta\Gamma_{(\pi\to\mu\nu)} \propto \varepsilon_L - \varepsilon_R$
[f_π from LQCD]

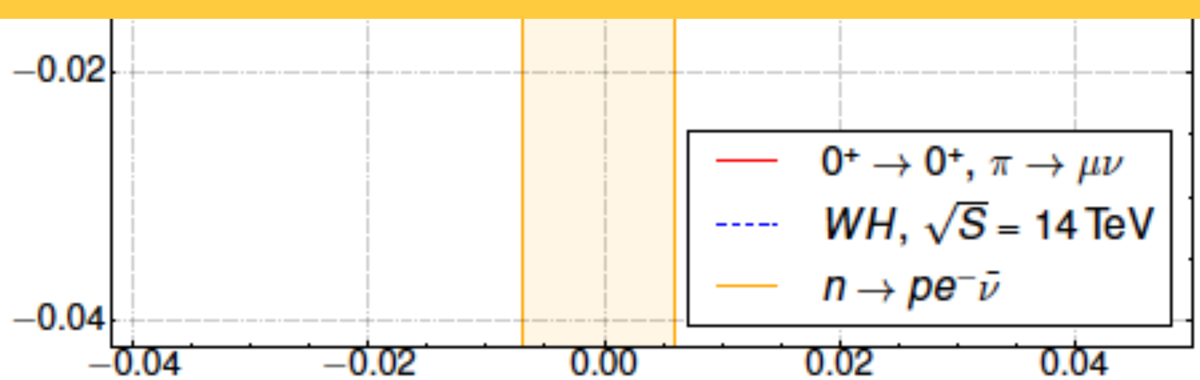
Example 1: ε_L and ε_R couplings

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

Several lessons:

- Beta decays can be quite competitive with collider
- Connection between CC and NC (gauge invariance!)
- Caveat: going beyond a 2-operator analysis relaxes some of these constraints (but not the one on ε_R from λ)
- All in all, beta decays provide *independent competitive constraints* in a global analysis

Z-pole → $\varepsilon_L^{(\nu)}$
Falkowski et al
1706.03783



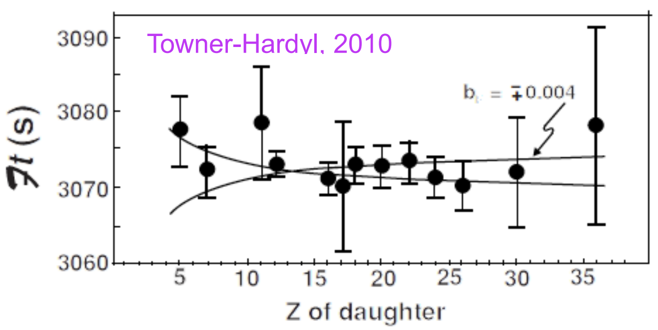
ε_R

$\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$

$\delta\Gamma_{(\pi \to \mu\nu)} \propto \varepsilon_L - \varepsilon_R$
[f_π from LQCD]

Example 2: ε_S and ε_T couplings

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



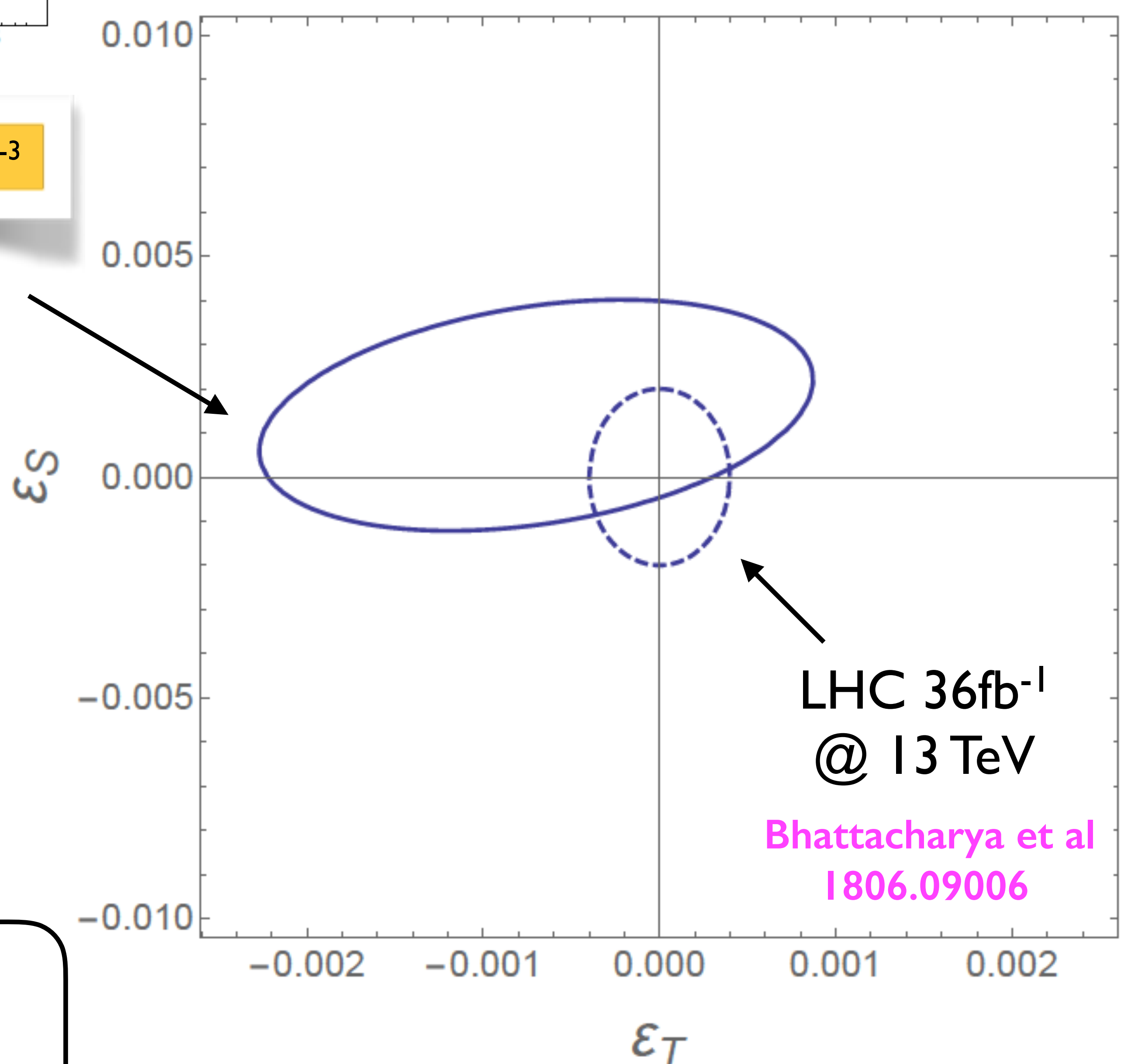
$-1.0\times10^{-3} < g_S\ \varepsilon_S < 3.2\times10^{-3}$

Current low-E data: dominated by $0^+ \to 0^+$, $\tau(n)$, $A(n)$

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

CURRENT

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



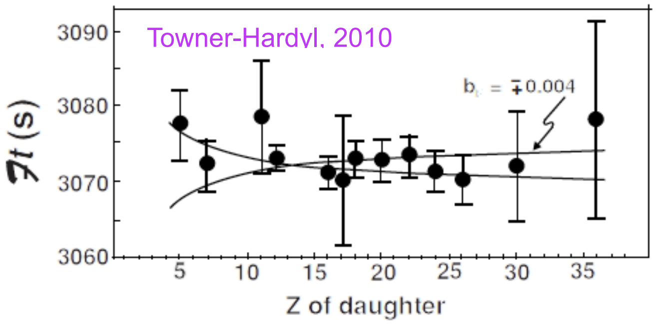
g_S =1.01(10)

g_T =0.99(4)

Bhattacharya et al (PNDME) 1806.09006

Example 2: ε_S and ε_T couplings

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



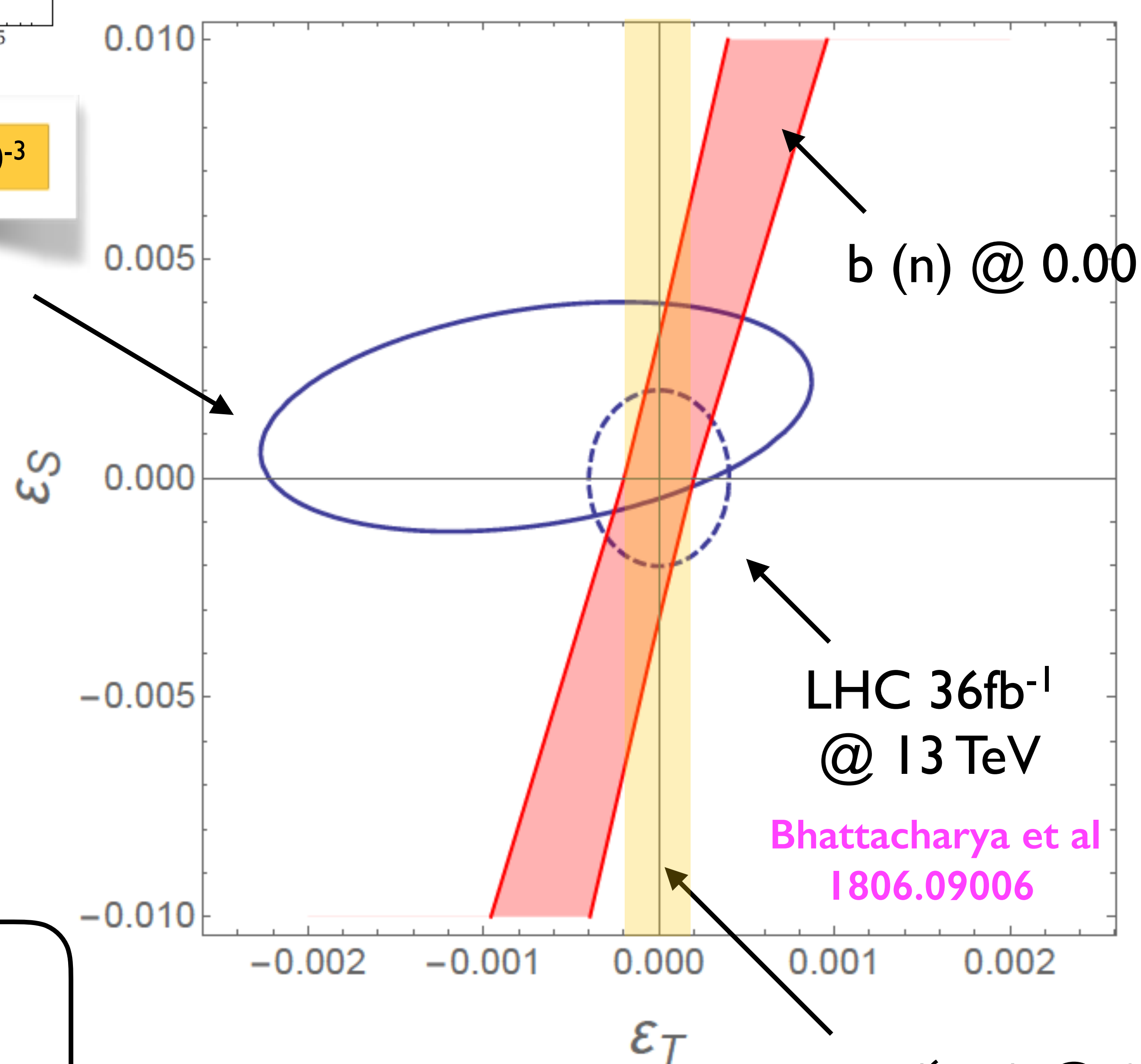
$-1.0\times10^{-3} < g_S\ \varepsilon_S < 3.2\times10^{-3}$

Current low-E data: dominated by $0^+ \to 0^+$, $\tau(n)$, $A(n)$

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

FUTURE

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



b (n) @ 0.001

LHC 36fb^{-1} @ 13 TeV

Bhattacharya et al 1806.09006

b (^{6}He) @ 0.001

LHC puts very strong constraints on 4-fermion interactions

Prospective beta decay measurements competitive, probing $\Lambda_{S,T} \sim$ 5-10 TeV

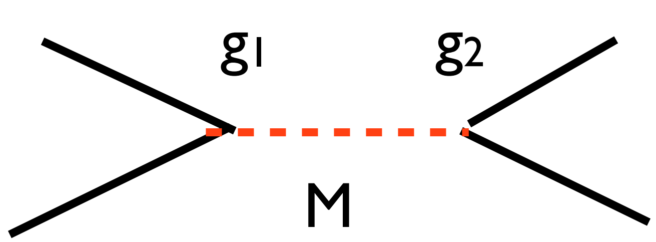
g_S =1.01(10)

g_T =0.99(4)

Bhattacharya et al (PNDME) 1806.09006

Reliability of EFT bounds @ LHC

- What if new interactions are not "contact" at LHC energy? How are the ε bounds affected?
- Explore classes of models generating $\varepsilon_{S,T}$ at tree-level. Low-energy vs LHC amplitude:



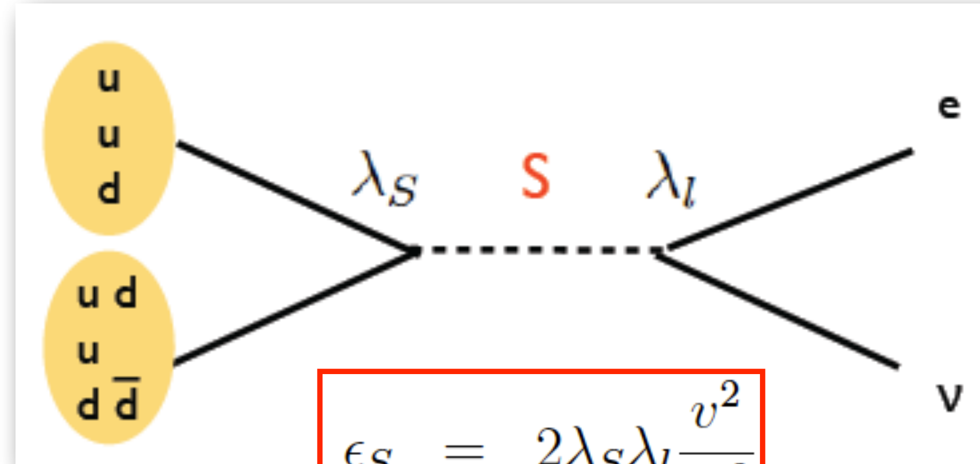
$$A_\beta \sim g_1 g_2/M^2 \equiv \varepsilon$$

$$A_{LHC} \sim \varepsilon\, F[\sqrt{s}/M, \sqrt{s}/\Gamma(\varepsilon)\,]$$

- Study dependence of the ε bounds on the mediator mass M

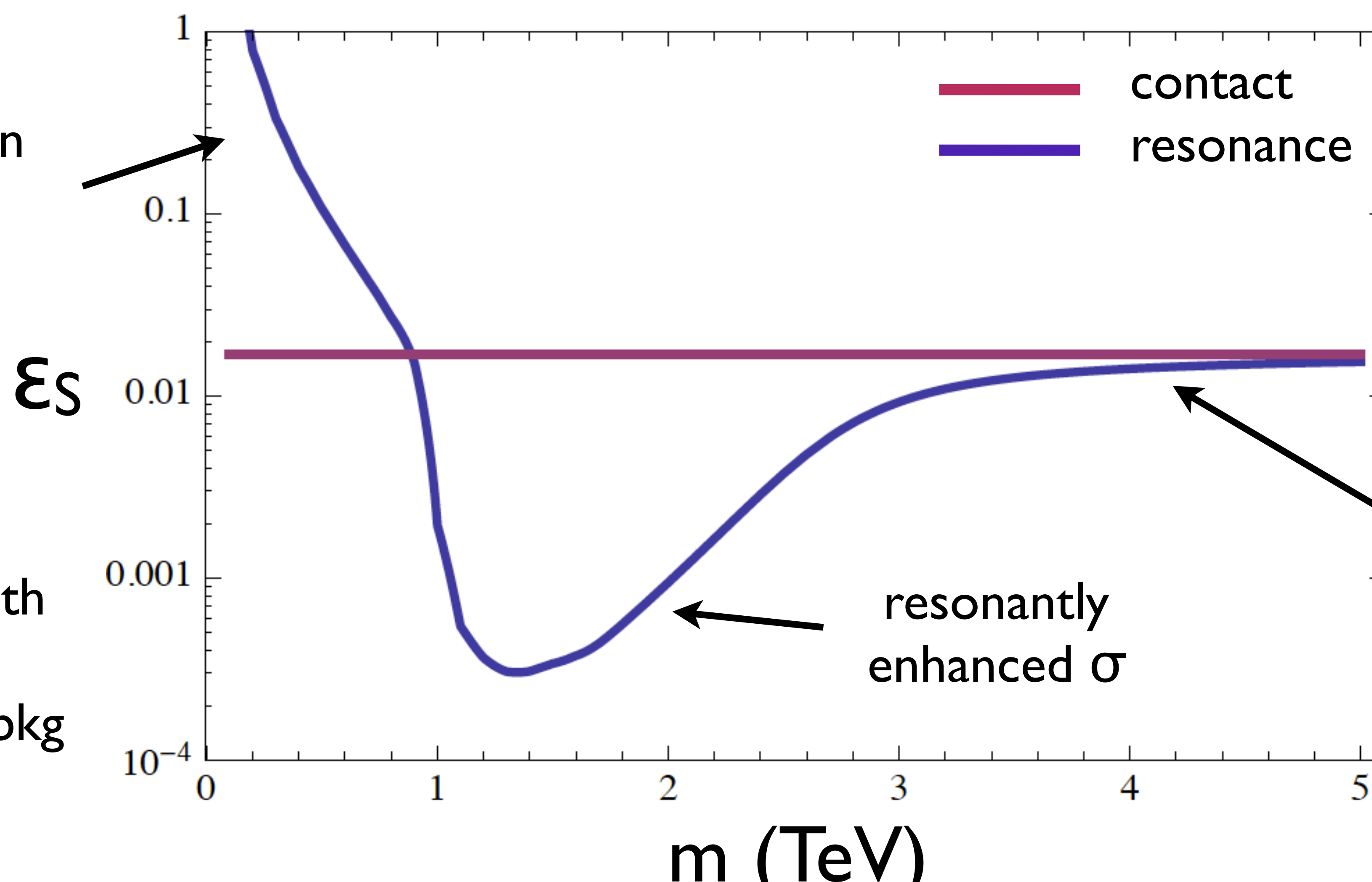
s-channel mediator

- Scalar resonance in s-channel
- Upper bound on ε_S based on $m_{T,cut}$ = 1 TeV



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

σ suppression due to $m < m_{T,cut}$



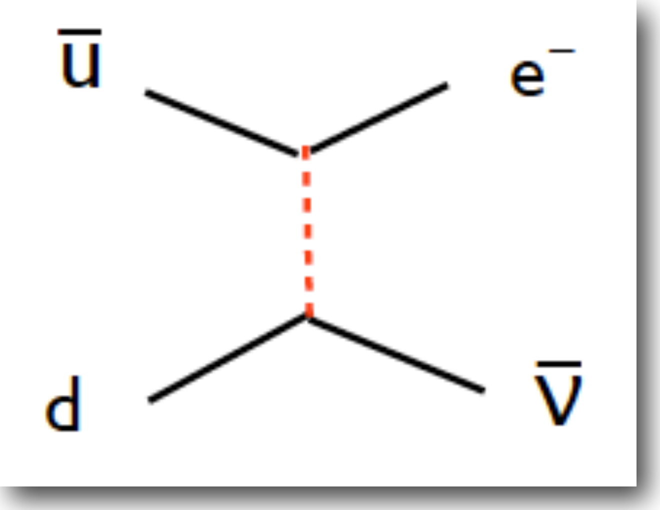
resonantly enhanced σ

decoupling regime

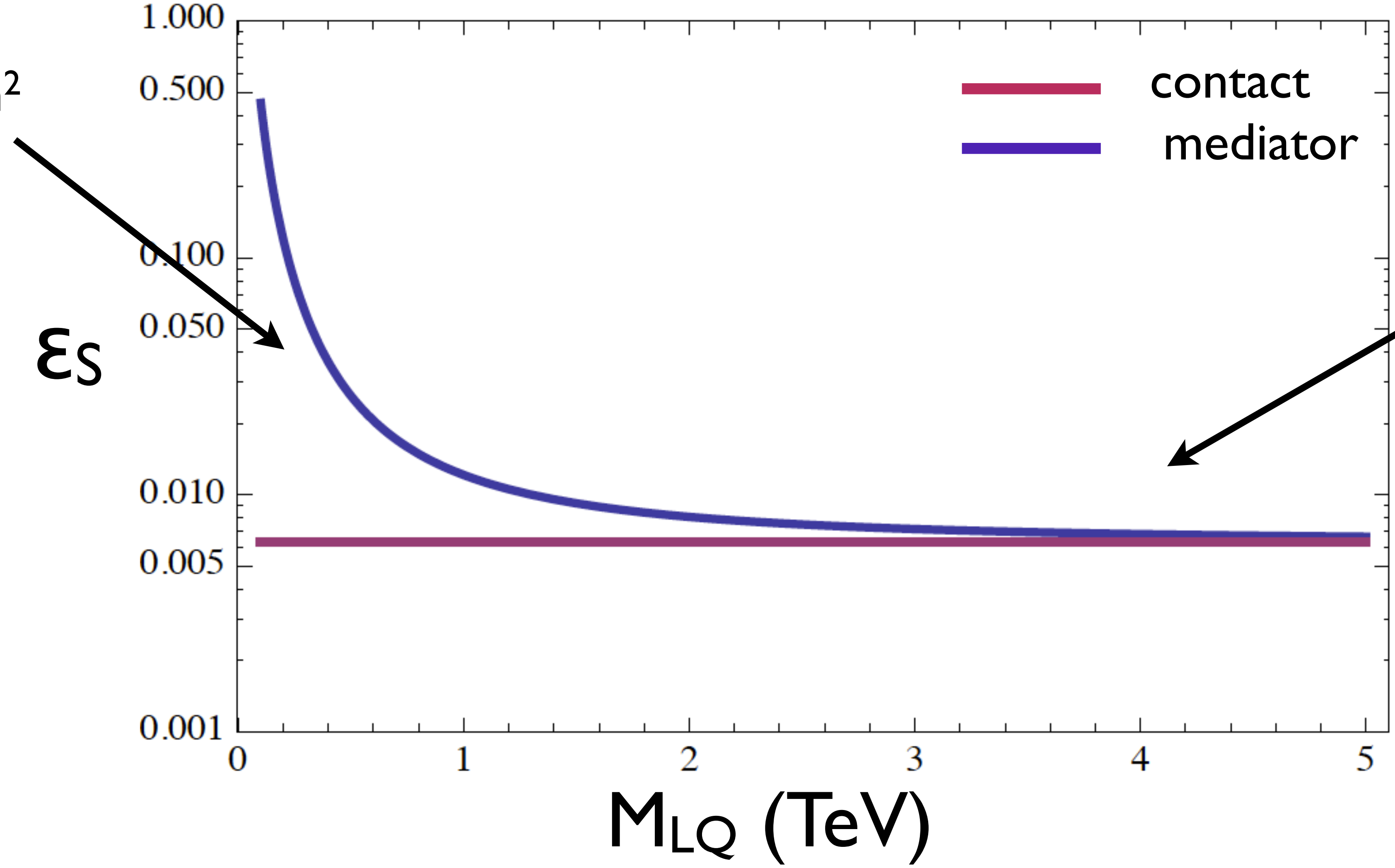
Improvable with lower $m_{T,cut}$
But larger SM bkg

t-channel mediator

- Scalar leptoquark S_0 $(3^*, 1, 1/3)$
- $\varepsilon_T = -1/4\ \varepsilon_S = -1/4\ \varepsilon_P$



σ suppression due to $1/(m^2 - t)$ vs $1/m^2$

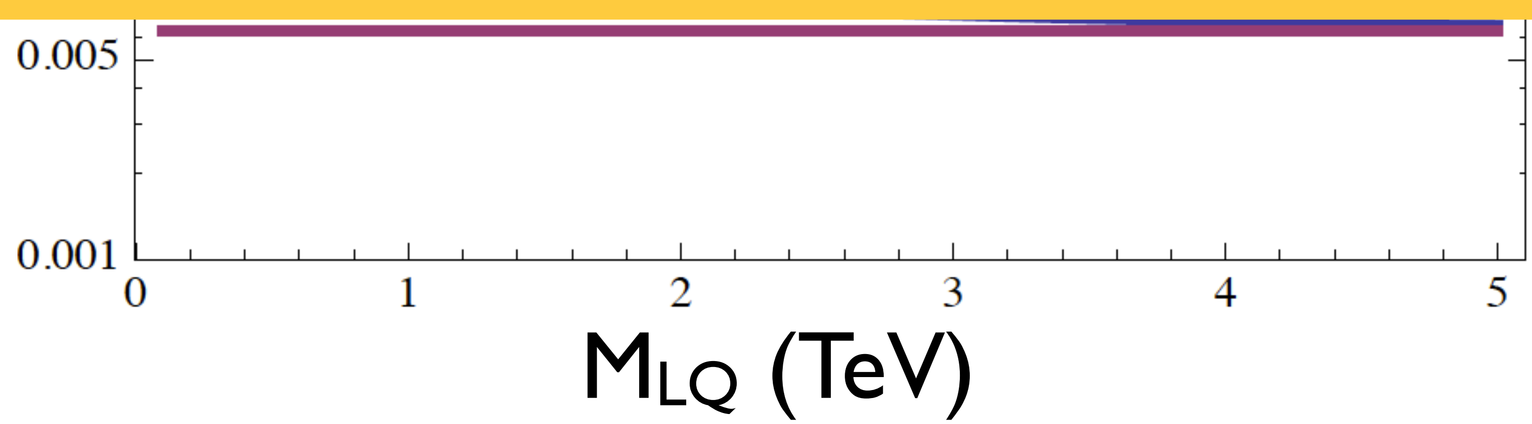


decoupling regime

t-channel mediator

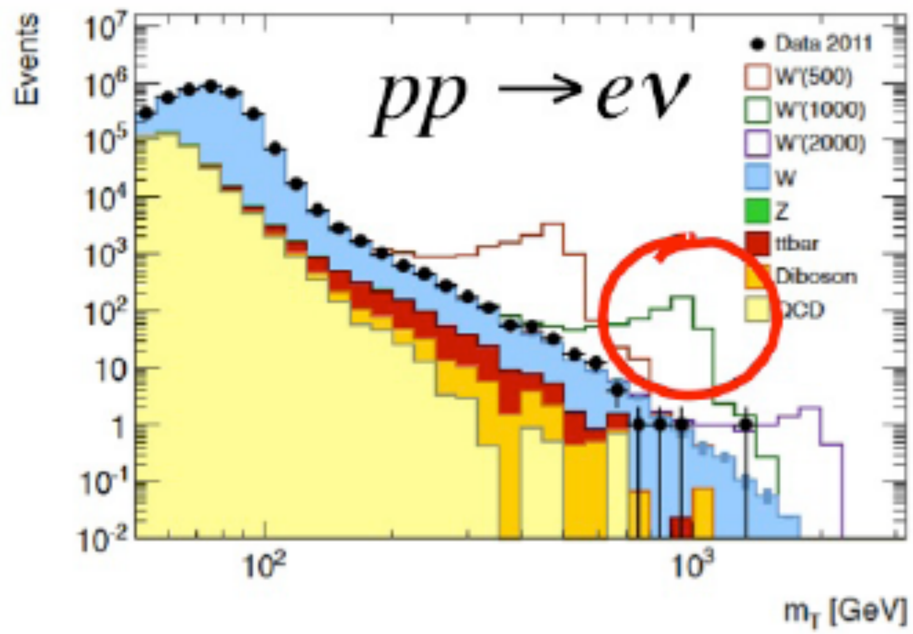
Messages

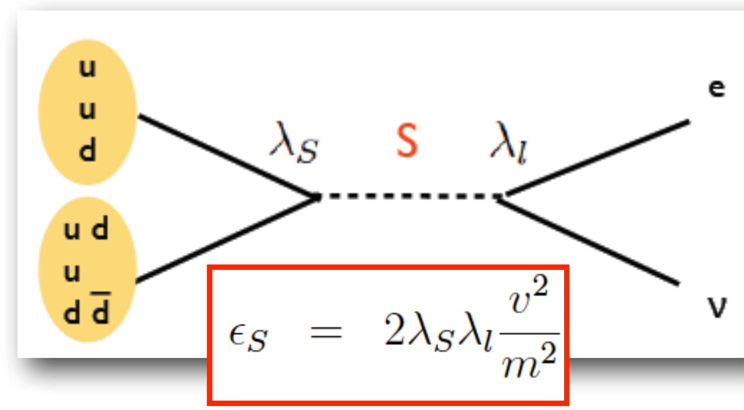
- For mediator mass >1TeV, LHC bounds on ε's based on contact interactions are "conservative": actual bound is stronger for s-channel resonance, comparable for t-channel
- For low mass mediators (m < 0.5 TeV), the LHC bounds on ε's quickly deteriorate: limits based on contact interactions are unreliable (and EFT practitioners would never dream to extrapolate the validity to such low masses!!)



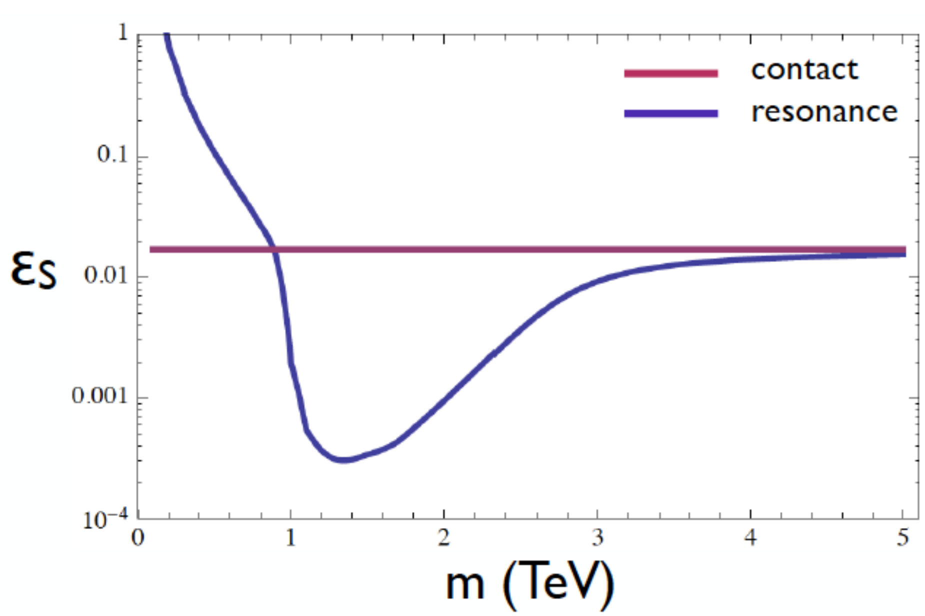
What if a bump is observed at LHC?

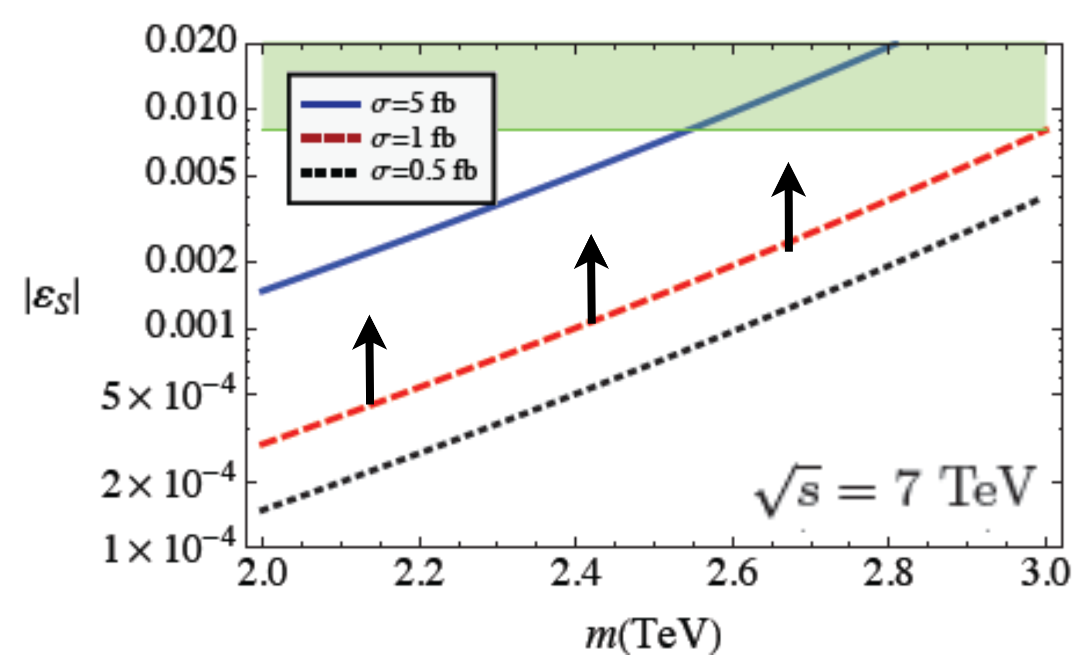
- If "bump" in m_T is due to a scalar resonance coupling to $e + \nu_e$





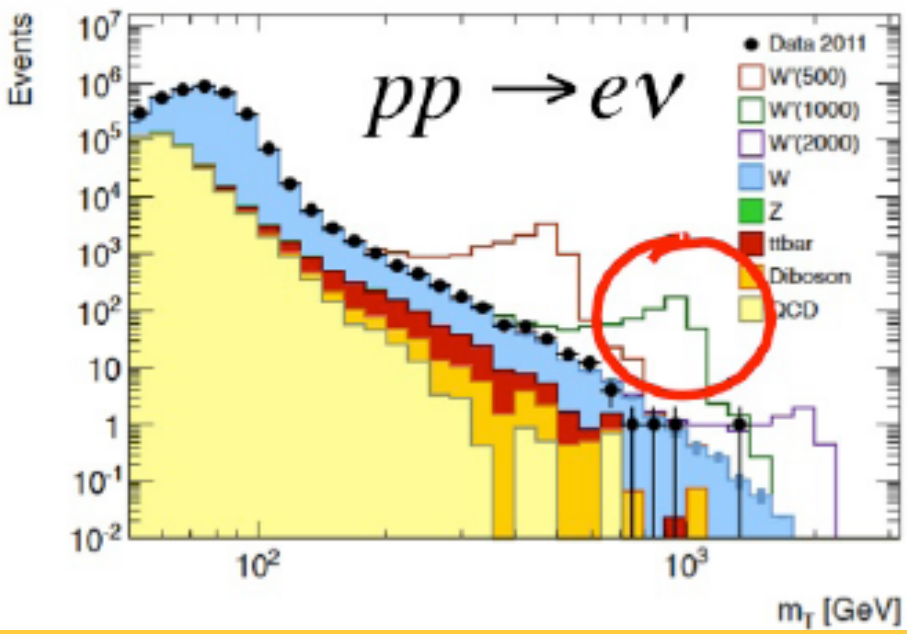
- ...then we a lower bound on ε_S: β-decays provide diagnosing power

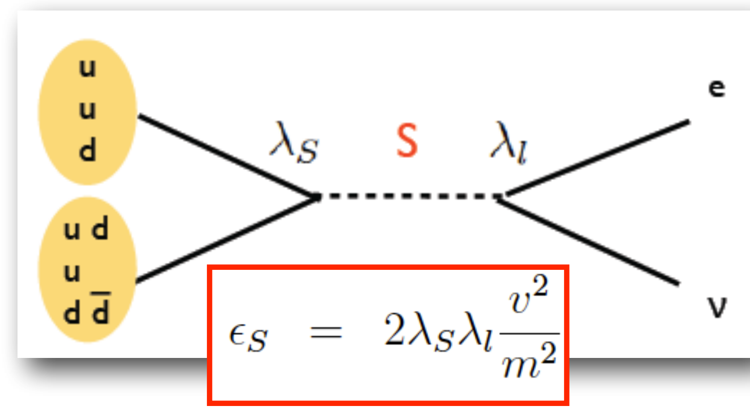




What if a bump is observed at LHC?

- If "bump" in m_T is due to a scalar resonance coupling to e + ν_e





Diagnosing power

- Spin of resonance
- Nature of "MET" (is it ν_e?)
- Additional scalars? (suppression of ε_S through interference)

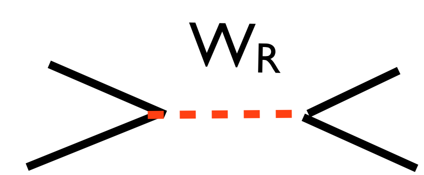
Beta decays in specific models

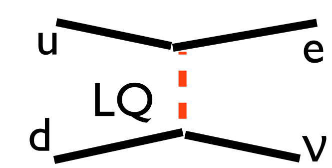
- Model → set overall size and pattern of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture: "DNA matrix"

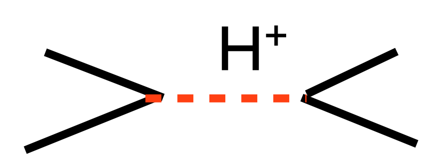
Can be made quantitative, including LHC constraints on each model

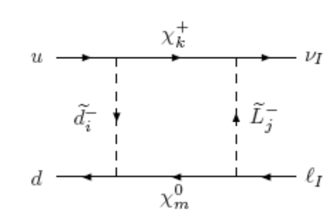
	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓

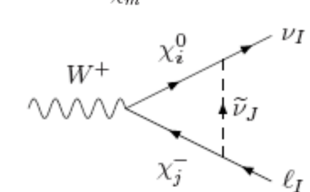
YOUR FAVORITE MODEL ... ...











Summary

- β decays with sufficient th. and expt. precision (< 0.1%) are a very competitive probe of new physics

- Discovery potential depends on the underlying model. However, EFT shows that a discovery window exists well into the LHC era
    - Beta decays play unique role in probing vertex corrections ε_L-ε_R (not enough precision at the LHC)
    - Beta decays can be competitive probes of scalar and tensor interactions if precision reaches < 0.1% (ε_S-ε_T plots)

- Beyond "race to discovery", interesting complementarity with LHC in diagnosing what one has discovered