MITP, May 1 2018

Non-standard charged-current interactions

(from beta decays to the LHC)

Vincenzo Cirigliano
Los Alamos National Laboratory

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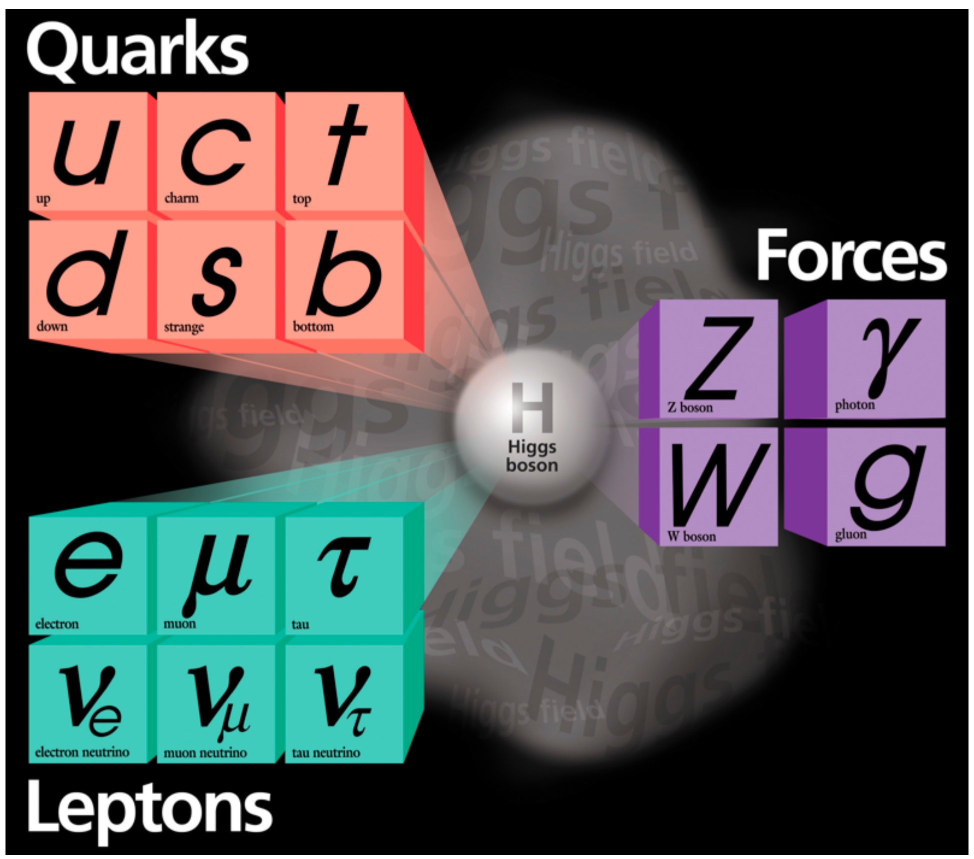
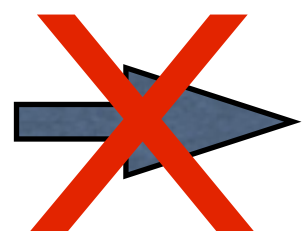
NATIONAL LABORATORY
EST. 1943

New physics: why?

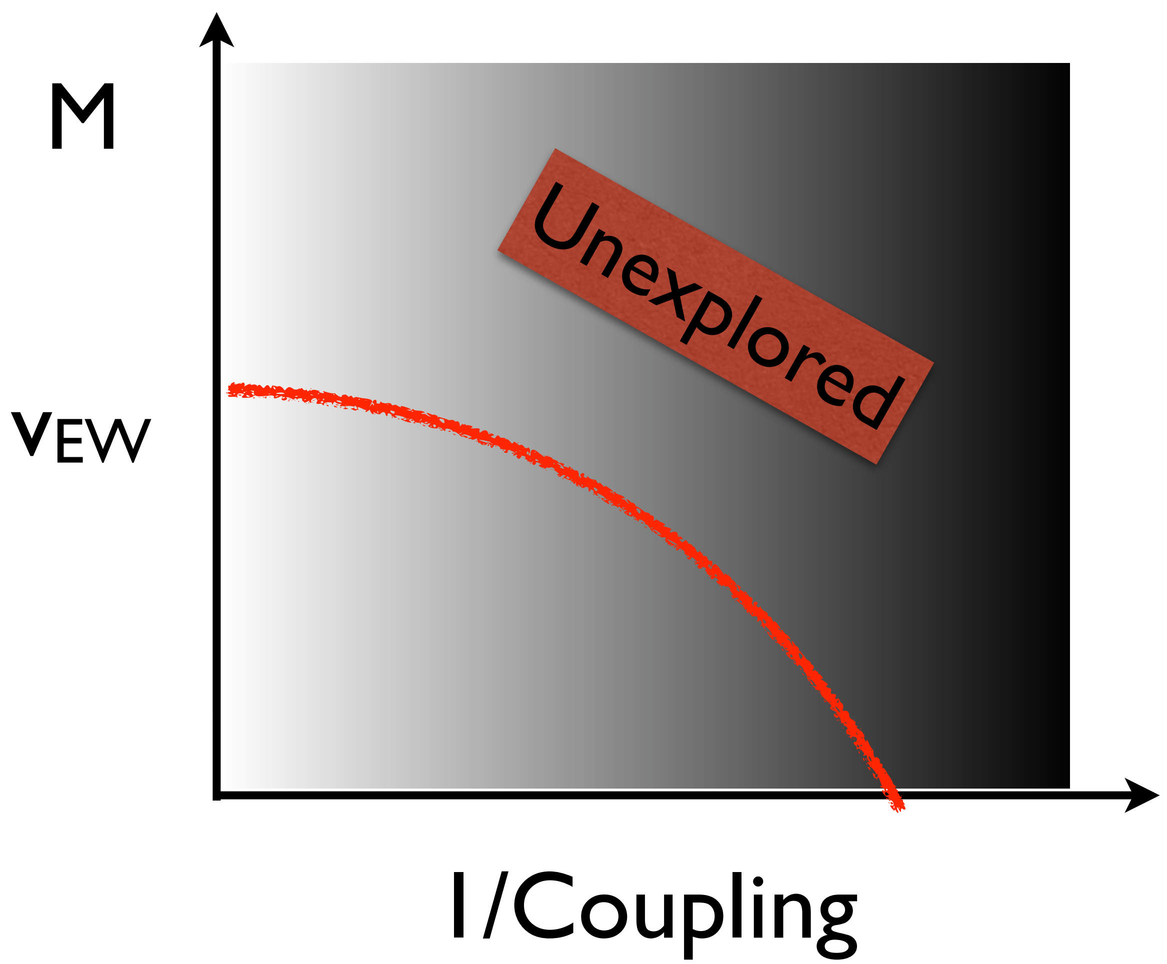
- The SM is remarkably successful, but it's probably not the whole story





New physics: where?

- New degrees of freedom: Heavy? Light & weakly coupled?
- Two complementary laboratory paths to probe $\mathcal{L}_{BSM}$: energy and intensity / precision frontiers



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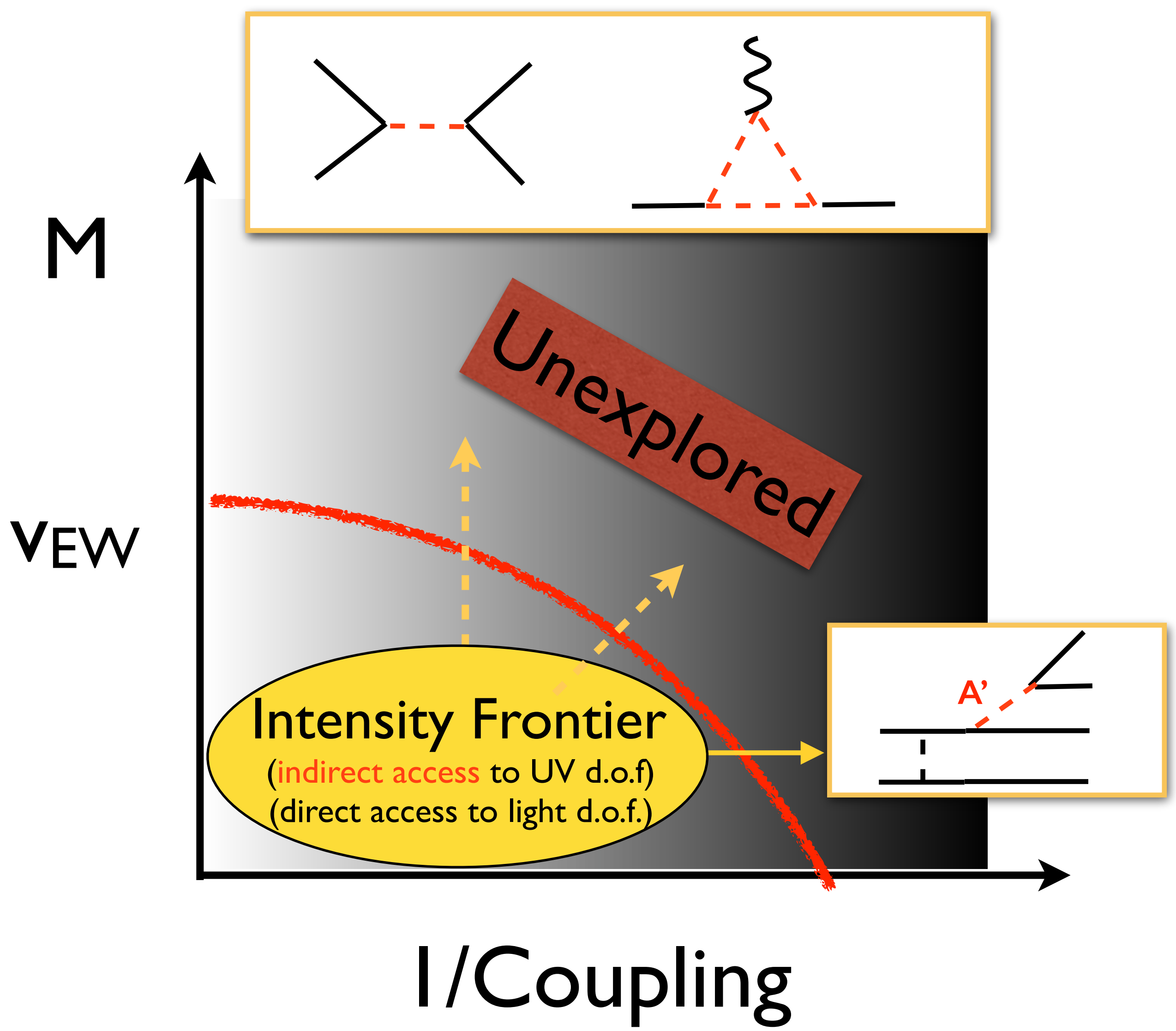

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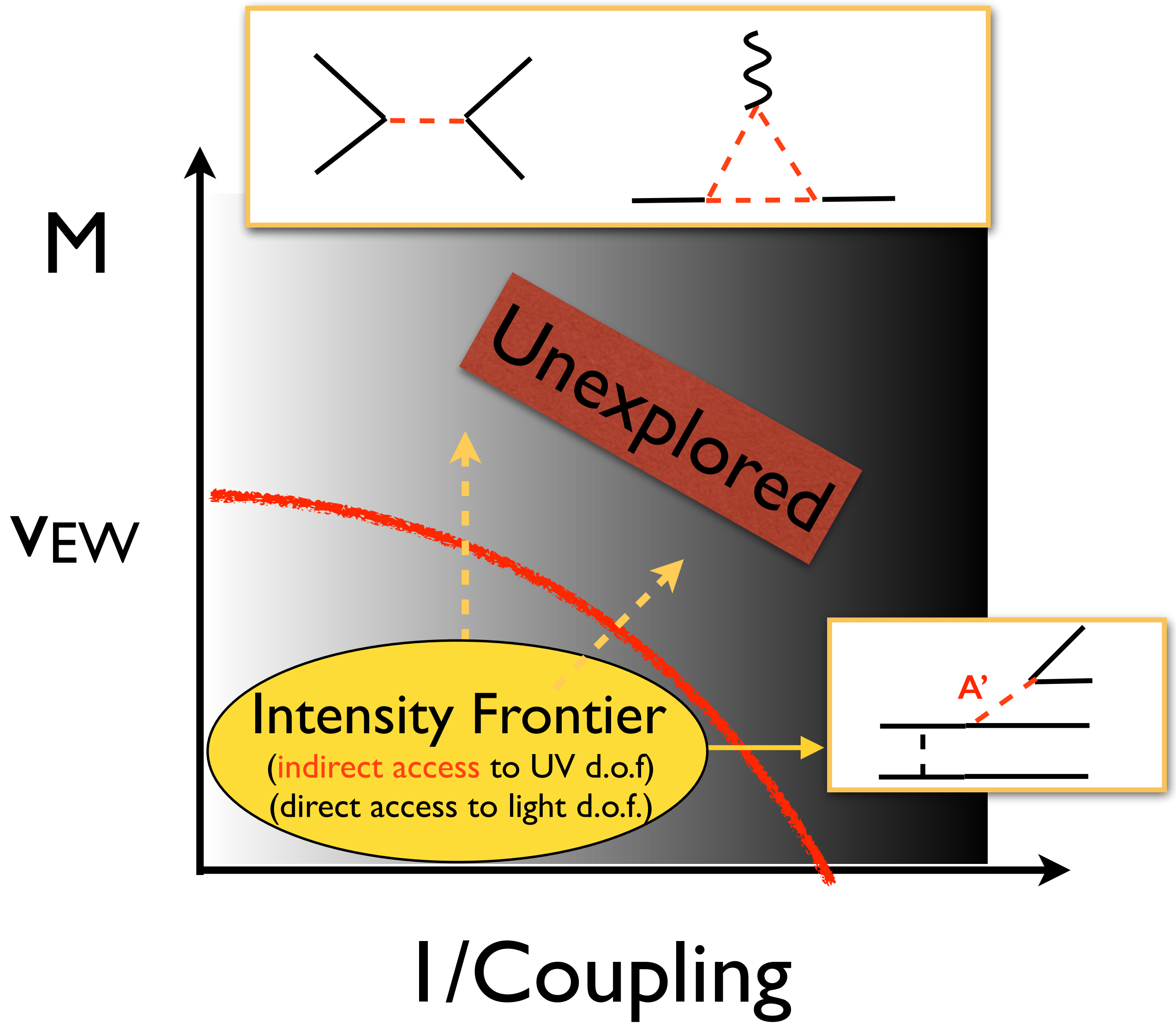


In this talk assume new physics at $M > v_{EW}$

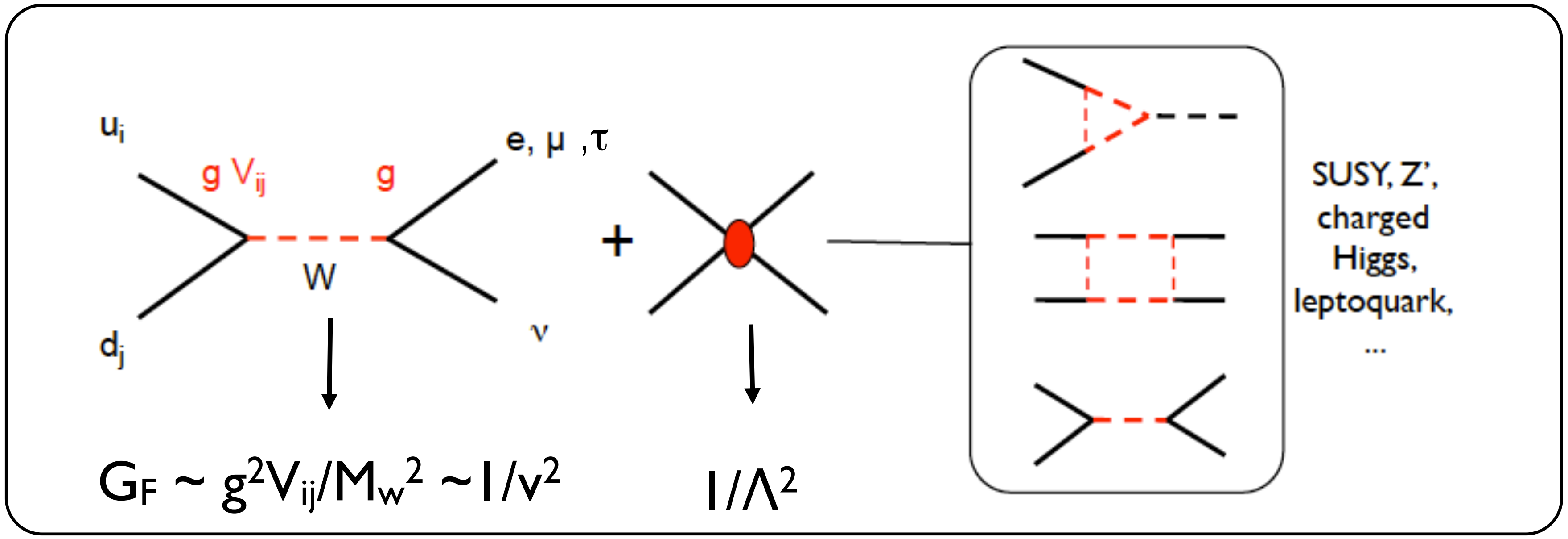
Outline

- Charged current interactions in the "Standard Model EFT"
- Probing first-generation quarks and lepton couplings:
    - precision beta decay measurements $\rightarrow$ LHC
- Probing tau lepton couplings to light quarks
    - Inclusive and exclusive tau decays $\rightarrow$ LHC
- Conclusion

Charged currents and new physics

CC processes in the SM and beyond

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



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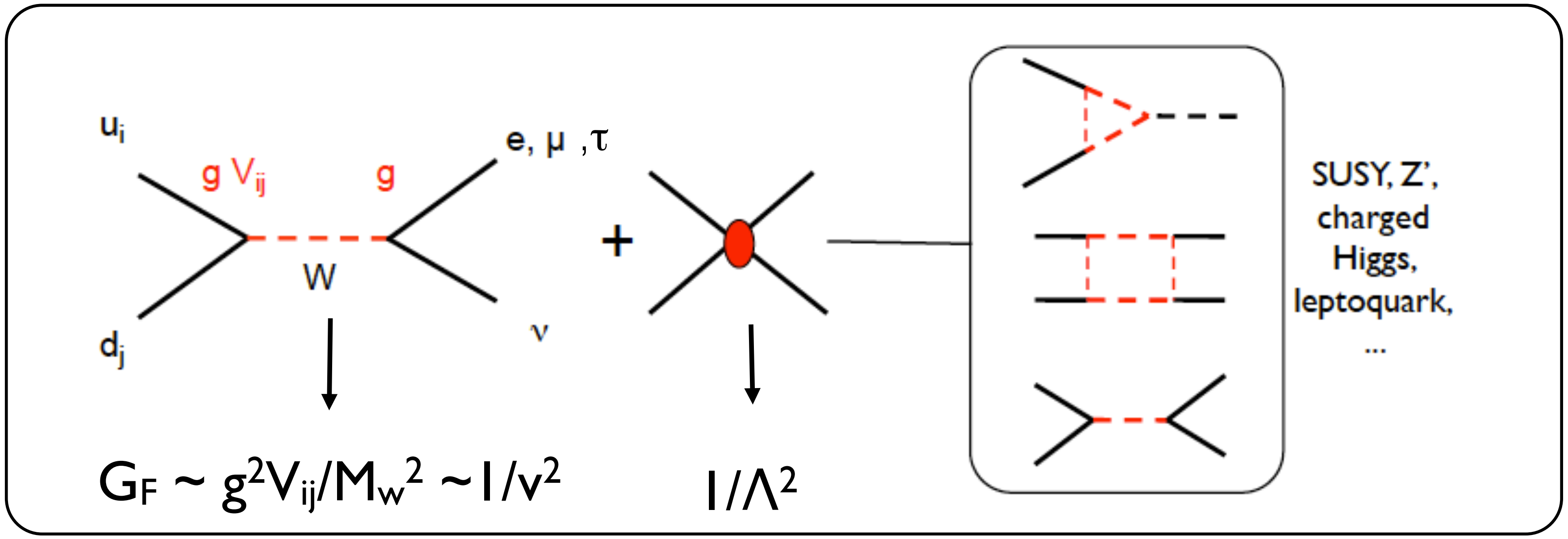


SUSY analyses:

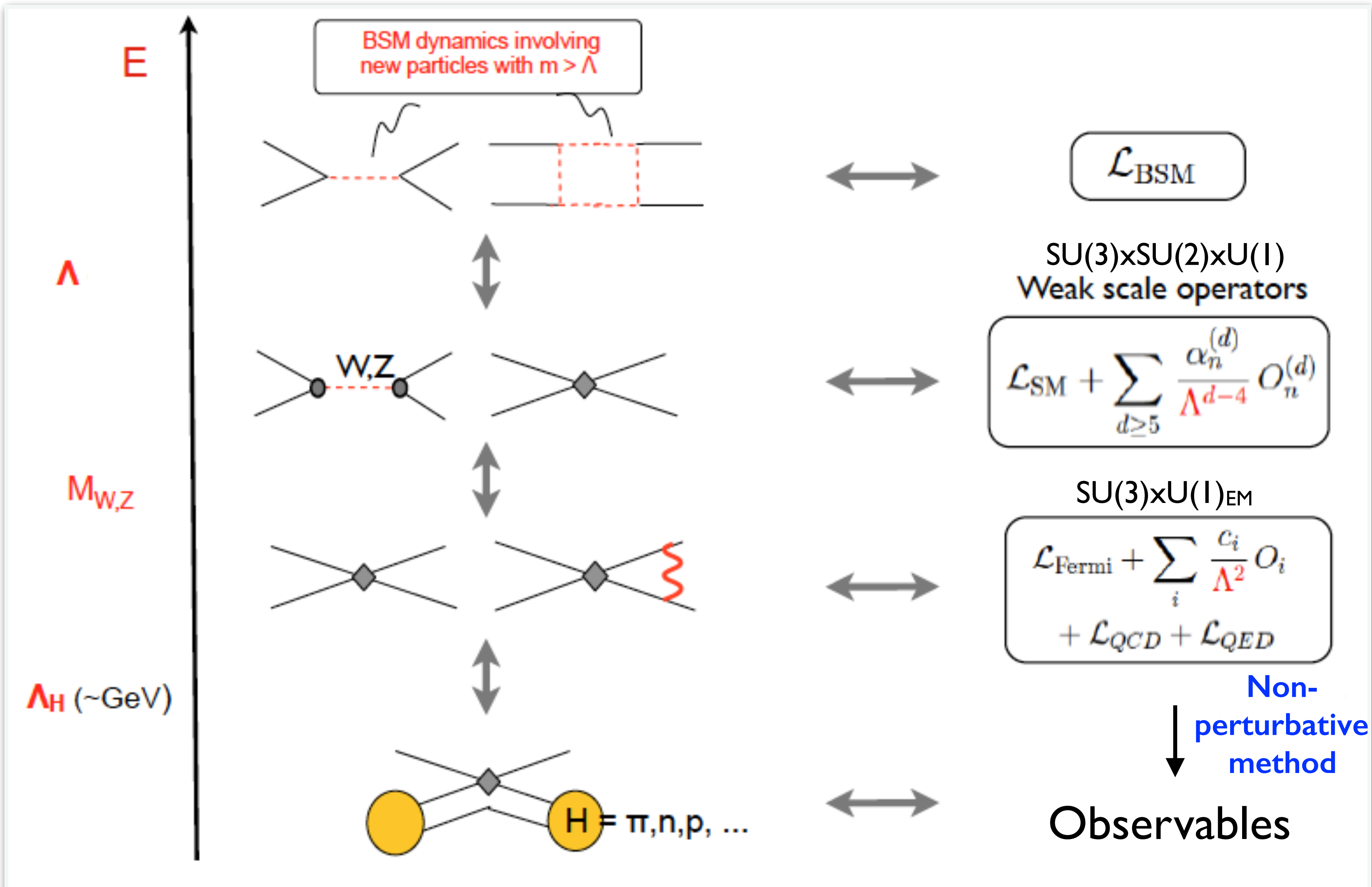
Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035,
...
Hagiwara et al1995
...
Barbieri et al 1985
...

- Sensitivity to broad variety of BSM scenarios

- Experimental and theoretical precision at or approaching 0.1% level
  Probe effective scale Λ in the 5-10 TeV range

EFT framework: connecting scales

- To interpret (positive or null) searches in terms of new physics at $\Lambda > v_{ew}$ need several steps



"SM EFT"

Chiral EFT, Lattice QCD, dispersion relations, …

EFT framework: connecting scales

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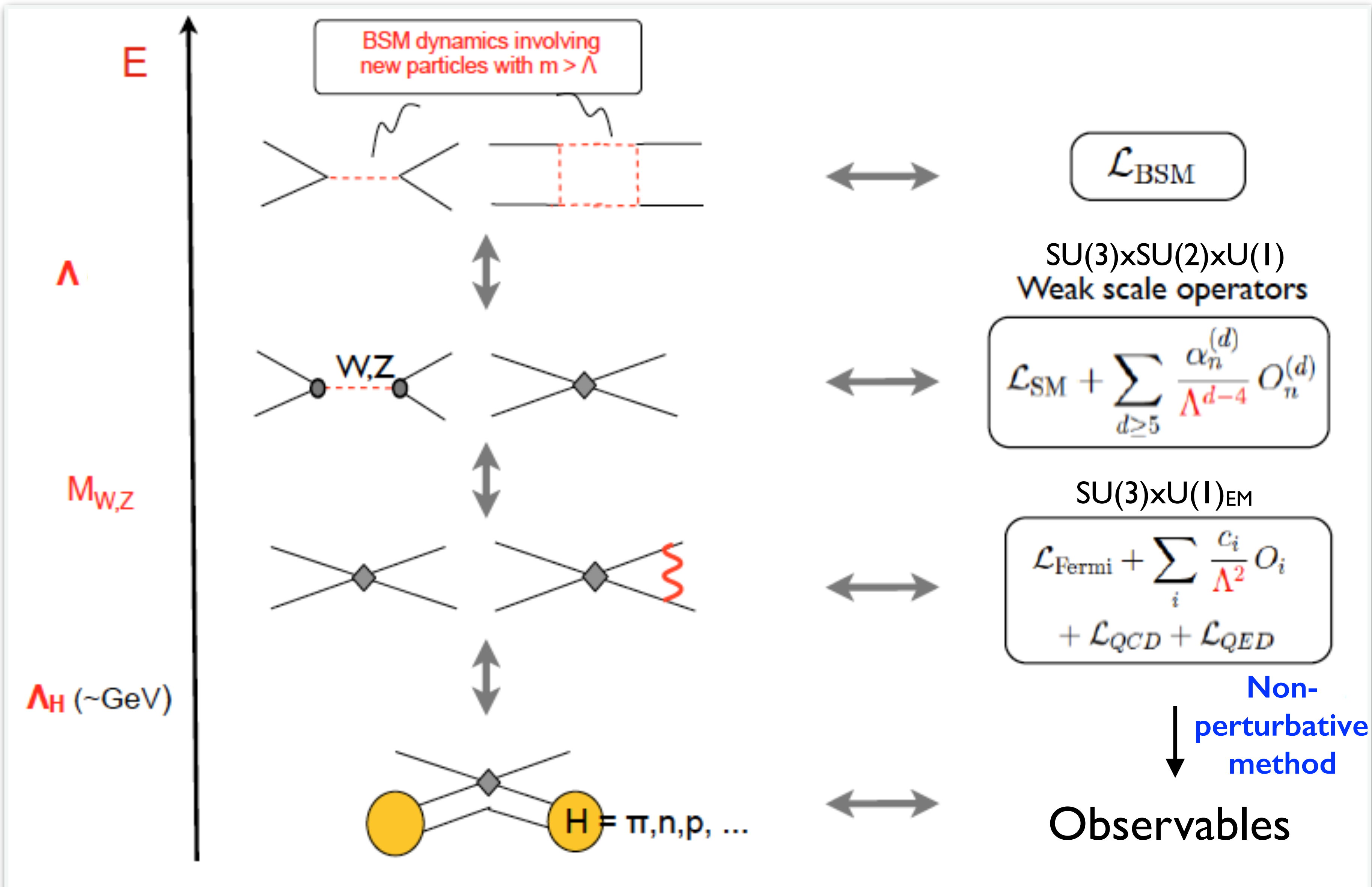


LHC phenomenology

"SM EFT"

Chiral EFT, Lattice QCD, dispersion relations, …

- If Λ > few TeV, can use EW-scale L_{eff} for LHC: connection of low-E and collider phenomenology

Effective Lagrangian at E~GeV

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

$$
\begin{aligned}
\mathcal{L}_{\rm CC} = & -\frac{G_F^{(0)} V_{u_i d_j}}{\sqrt{2}} \\
& \times \Big[(1 + \delta_{RC} + \epsilon_L) \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma^\mu(1-\gamma_5)d_j \\
& + \epsilon_R \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma^\mu(1+\gamma_5)d_j \\
& + \epsilon_S \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i d_j \\
& - \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma_5 d_j \\
& + \epsilon_T \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\sigma^{\mu\nu}(1-\gamma_5)d_j \Big] + \text{h.c.}
\end{aligned}
$$

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

← Linear sensitivity to ϵ_i (interference with SM)

Effective Lagrangian at E~GeV

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

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{u_i d_j}}{\sqrt{2}}$$
$$\times \Big[(1 + \delta_{RC} + \epsilon_L) \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma^\mu(1-\gamma_5)d_j$$
$$+ \; \epsilon_R \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma^\mu(1+\gamma_5)d_j$$
$$+ \; \epsilon_S \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i d_j$$
$$- \; \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma_5 d_j$$
$$+ \; \epsilon_T \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\sigma^{\mu\nu}(1-\gamma_5)d_j \Big] + \text{h.c.}$$

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

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

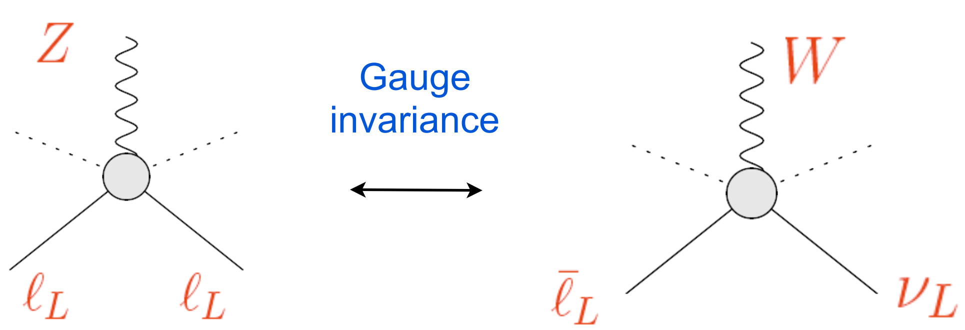
Linear sensitivity to ϵ_i (interference with SM)

Quadratic sensitivity to $\tilde{\epsilon}_i$ (interference suppressed by m_ν/E)

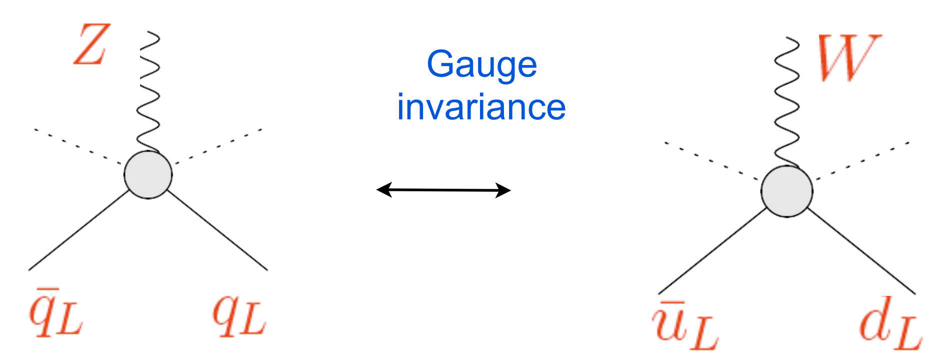
Relation to weak-scale operators

- ε_L : vertex corrections and 4-fermion contacts

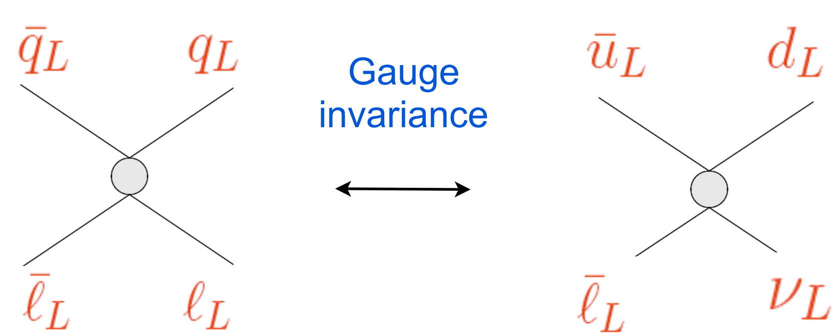
$$O_{\varphi l}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi))(\bar{l}\gamma_\mu \sigma^a l)$$



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



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



$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

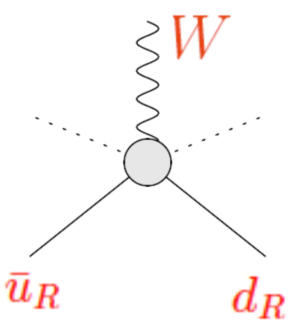
$$q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$$

$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

Relation to weak-scale operators

- ε_R ⇔ weak-scale R-handed quark coupling

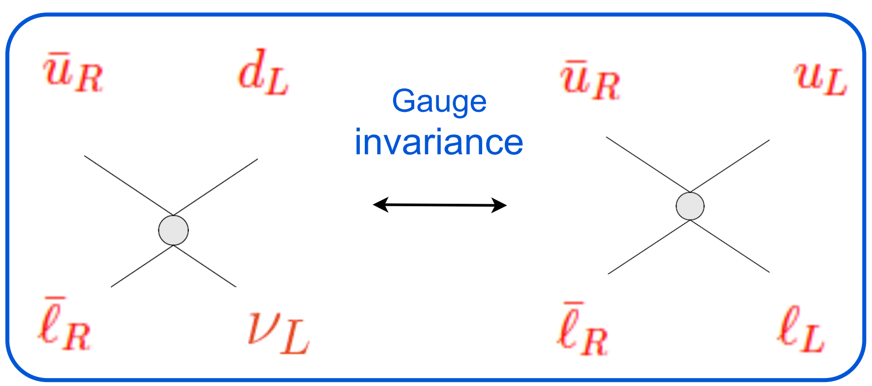
$$O_{\varphi\varphi} = i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d)$$



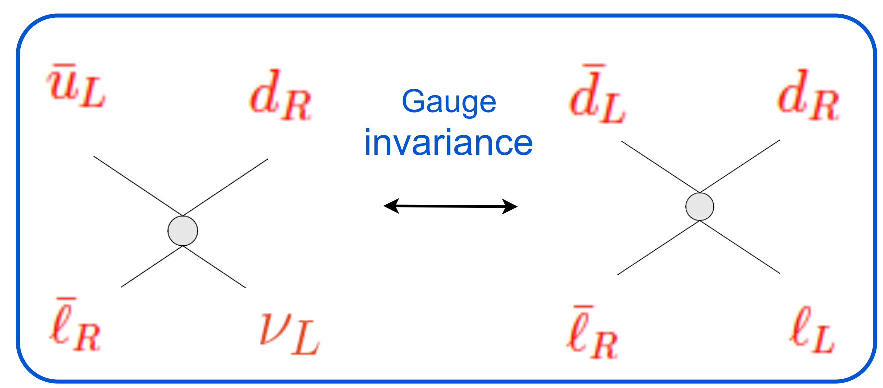
- $\varepsilon_{S,P}$ ⇔ 2 independent scalar structures

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

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



$\varepsilon_S+\varepsilon_P$



$\varepsilon_S-\varepsilon_P$

- ε_T ⇔ weak-scale tensor structure

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

How to probe the ε_α

- $(\varepsilon_\alpha)^{de}$
  - Beta decays: half-lives (weak universality), correlations
  - LHC ($pp \to e\nu + X$, $pp \to e\bar{e} + X$), if $\Lambda >$ few TeV

RECENT REVIEW: Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

- $(\varepsilon_\alpha)^{d\tau}$
  - Hadronic tau decays (exclusive and inclusive)
  - LHC ($pp \to \tau\nu + X$, $pp \to \tau\bar{\tau} + X$), if $\Lambda >$ few TeV

First generation couplings:

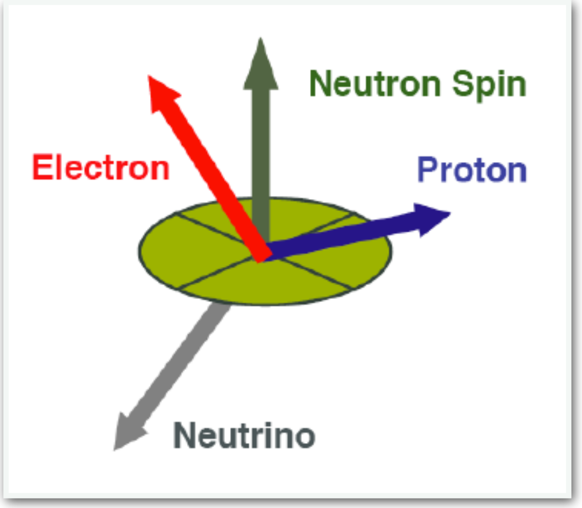
$(\varepsilon_\alpha)^{de}$

Beta decay sensitivity to the ε_α

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



$a(g_A, g_\alpha \varepsilon_\alpha)$, $A(g_A, g_\alpha \varepsilon_\alpha)$, $B(g_A, g_\alpha \varepsilon_\alpha)$,

...

isolated via suitable experimental asymmetries

Beta decay sensitivity to the ϵ_α

1. Differential decay distribution

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

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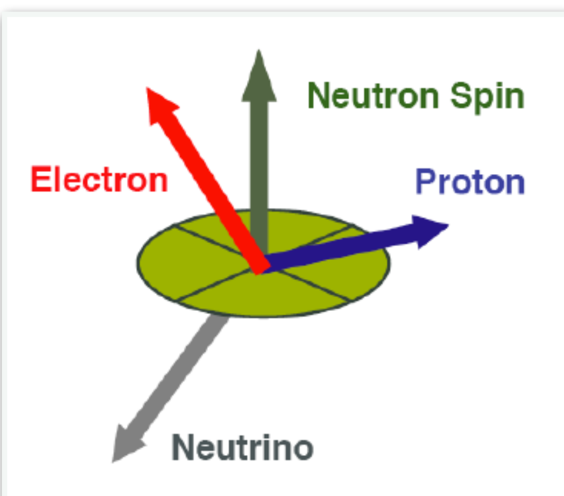

$a(g_A, g_\alpha \epsilon_\alpha)$, $A(g_A, g_\alpha \epsilon_\alpha)$, $B(g_A, g_\alpha \epsilon_\alpha)$, ...

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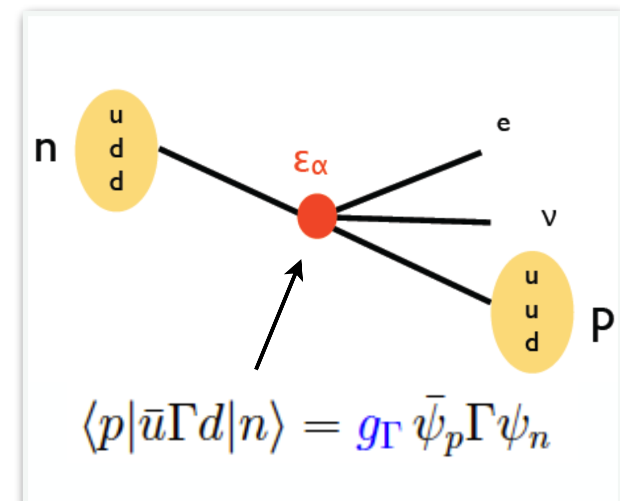
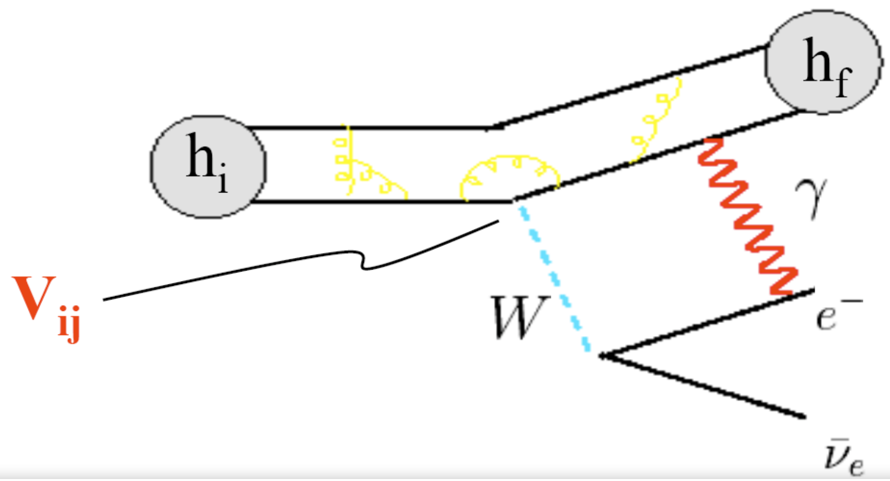


Theory input: $g_{V,A,S,T}$ (great progress in lattice QCD) + rad. corr.

LANL results: Bhattacharya, et al 1606.07049

Beta decay sensitivity to the ε_α

2. Decay rate



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

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

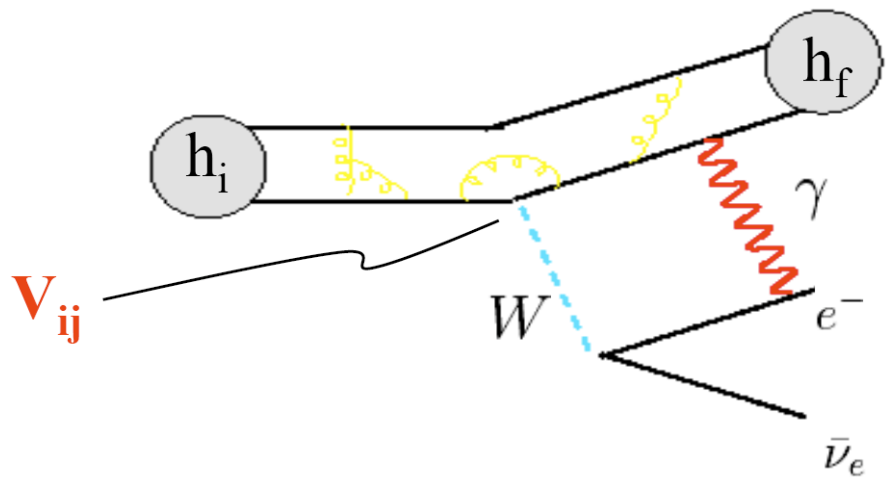
Channel-dependent effective CKM element**

Hadronic / nuclear matrix elements (ε_α) and radiative corrections

LQCD, χPT, dispersion relations, …

Beta decay sensitivity to the ε_α

2. Decay rate



Neutron case:

$$|\bar{V}_{ud}|^2 \, \tau_n \, (1 + 3\bar{g}_A^2) = 4908.6(1.9) \, s$$

Czarnecki, Marciano, Sirlin 1802.01804

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

Channel-dependent effective CKM element**

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

Axial charge contaminated by R-handed coupling

Snapshot of the field

- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV ($\Lambda_{SM} \approx 0.2$ TeV)

$$\tilde{Y}(E_e) = \frac{Y(E_e)}{1 + b\, m_e/E_e + \ldots}$$

Non-standard coupling	Observable	Current sensitivity	Prospective sensitivity
$\mathrm{Re}(\epsilon_L + \epsilon_R)$	Δ_{CKM}	$\sim 0.05\%$	$< 0.05\%$ *
$\mathrm{Im}(\epsilon_R)$	D_n	$\sim 0.05\%$	
$\epsilon_P, \quad \tilde{\epsilon}_P$	$R_\pi = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)}$	$\sim 0.05\%$	
$\mathrm{Re}(\epsilon_S)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}]$	$\sim 0.5\%$	$< 0.3\%$
$\mathrm{Im}(\epsilon_S)$	R_n	$\sim 10\%$	
$\mathrm{Re}(\epsilon_T)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}], \quad \pi \to e\nu\gamma$	$\sim 0.1\%$	$< 0.03\%$
$\mathrm{Im}(\epsilon_T)$	$R_{^8Li}$	$\sim 0.2\%$	$\sim 0.05\%$
$\tilde{\epsilon}_{\alpha \neq P}$	a, b, B, A	$\sim 5 - 10\%$	

VC, S.Gardner, B.Holstein 1303.6953
Gonzalez-Alonso & Naviliat-Cuncic 1304.1759
Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

Snapshot of the field

- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV ($\Lambda_{SM} \approx$ 0.2 TeV)
- Probes that depend on the ε's *linearly*

$$\tilde{Y}(E_e) = \frac{Y(E_e)}{1 + b\, m_e/E_e + \dots}$$

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CKM unitarity test

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

Currently, extraction dominated by $0^+ \to 0^+$ nuclear transitions

Hardy-Towner 1411.5987

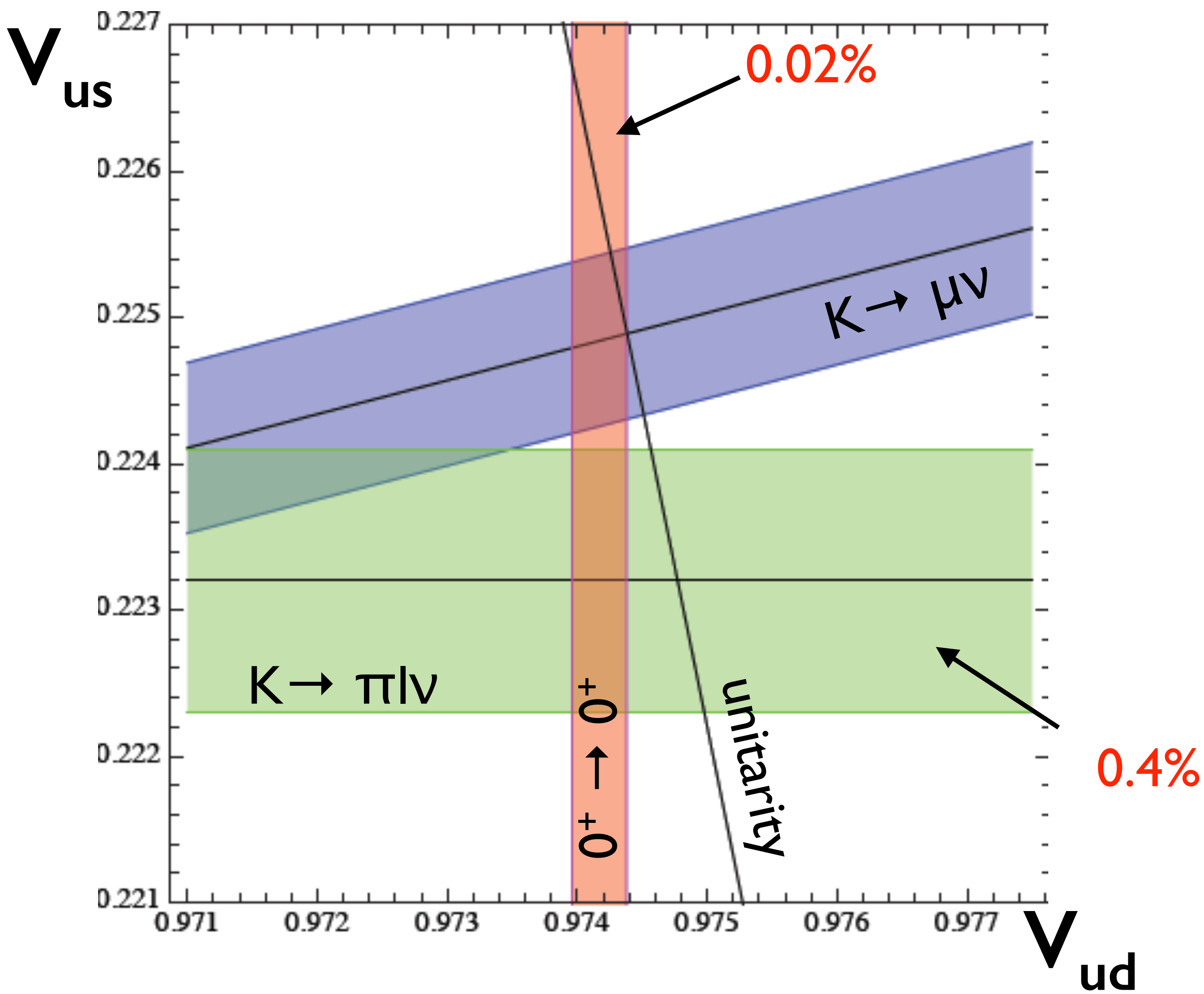
Extraction dominated by Kaon decays

FLAVIANET report 1005.2323 and refs therein

Lattice QCD input from FLAG 1607.00299 and refs therein

CKM unitarity test

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



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

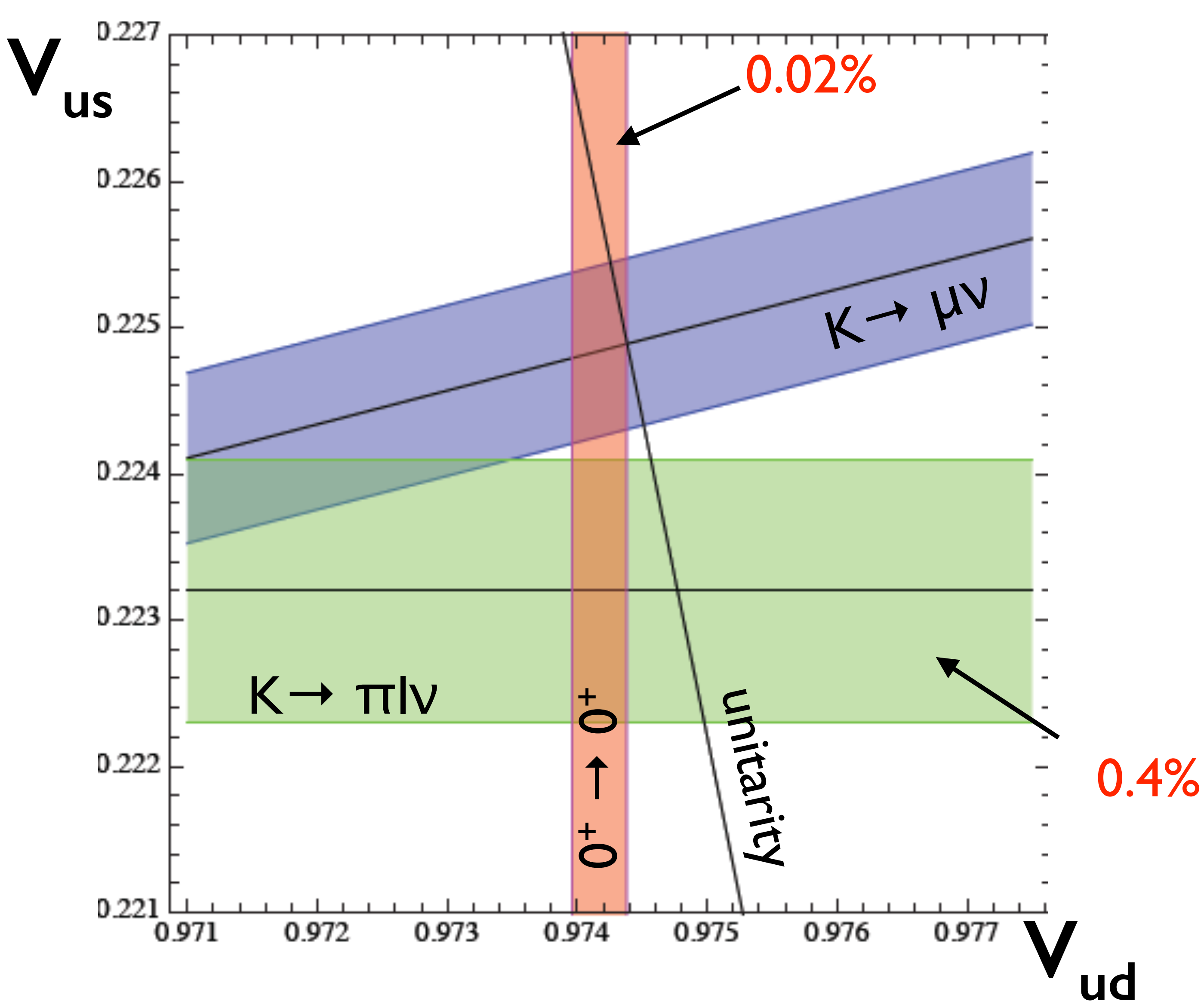
$\Delta_{CKM} = -(4 \pm 5) * 10^{-4}$ ~ 1σ

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

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

CKM unitarity 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

Δ_{CKM} = - (4 ± 5) ∗ 10^{-4} ~ 1σ

Δ_{CKM} = - (12 ± 6) ∗ 10^{-4} ~ 2σ

V_{us} from K→ πlν

Hint of something?

[$\varepsilon_{R,P}^{(s)}$, $\varepsilon_L + \varepsilon_R$, SM th input]

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

Impact of neutrons

- Independent extraction of V_{ud} @ 0.02% requires:

$$\bar{V}_{ud} = \left[\frac{4908.6(1.9)\ s}{\tau_n\ (1+3\bar{g}_A^2)}\right]^{1/2}$$

Marciano, Sirlin 2006

$\delta\tau_n \sim 0.35$ s

$\delta\tau_n/\tau_n \sim 0.04$ %

$\delta g_A/g_A \sim 0.15\% \rightarrow 0.03\%$

($\delta a/a$, $\delta A/A \sim 0.14\%$)

UCNτ @ LANL [$\tau_n \sim 877.7(7)(3)$s]
is almost there, will reach $\delta\tau_n \sim 0.2$ s
1707.01817

$\delta A/A < 0.2\%$ can be reached
by PERC, UCNA+

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$\delta\tau_n/\tau_n$ ~ 0.04 %

$\delta g_A/g_A$ ~0.15% → 0.03%
($\delta a/a$, $\delta A/A$ ~ 0.14%)

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1707.01817

$\delta A/A$ < 0.2% can be reached
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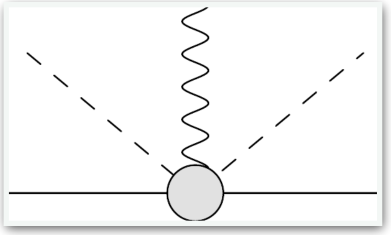
- V_{ud} (n) and V_{ud} ($0^+ \to 0^+$) sensitive to different new physics: not a duplicate measurement (similar to Kl2 vs Kl3 in V_{us})

$$\frac{\bar{V}_{ud}|_n}{\bar{V}_{ud}|_{0^+}} = 1 + c_S\,\epsilon_S + c_T\,\epsilon_T$$

c_S, c_T ~O(1)

Probing $\varepsilon_{L,R}$ couplings

- *Assume* $\varepsilon_{L,R}$ are induced by gauge vertex corrections at high scale (SM-EFT)



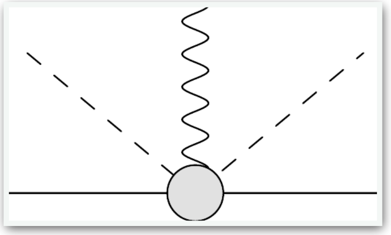
$$\varphi^\dagger \tau^a D_\mu \varphi \;\; \bar{q}_L \tau^a \gamma^\mu q_L$$

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

Probing $\varepsilon_{L,R}$ couplings

- *Assume* $\varepsilon_{L,R}$ are induced by gauge vertex corrections at high scale (SM-EFT)

- Low energy probes:
    - $\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$
    - $\delta\Gamma_{(\pi\to\mu\nu)} \propto \varepsilon_L - \varepsilon_R$ [f_π from LQCD]
    - Neutron decay correlations (A, a, B) → $\lambda = g_A\,(1 - 2\,\varepsilon_R)$
    - QWeak, Z-pole → ε_L



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

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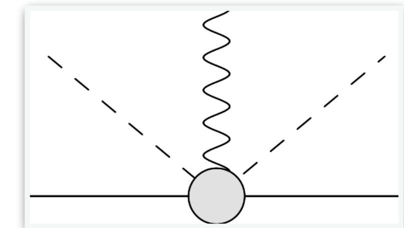

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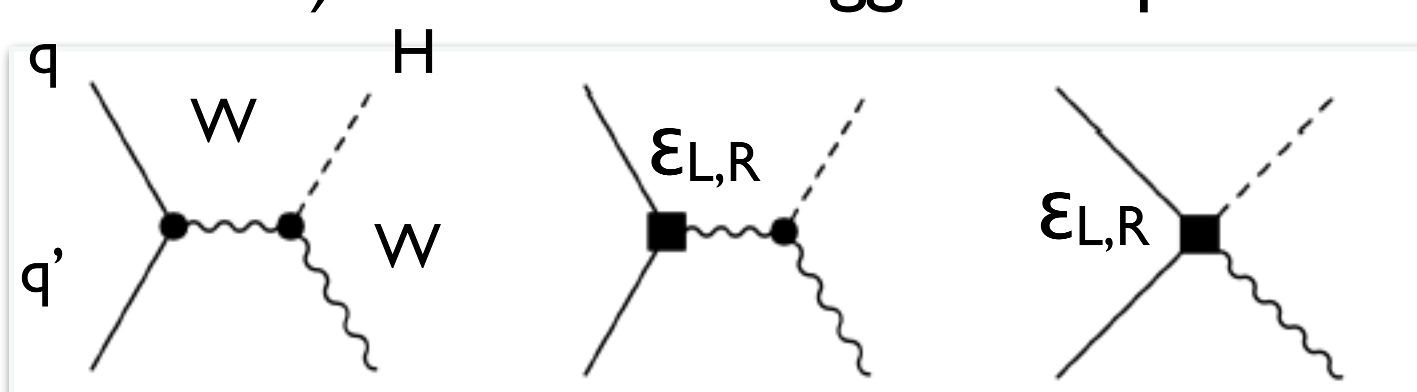
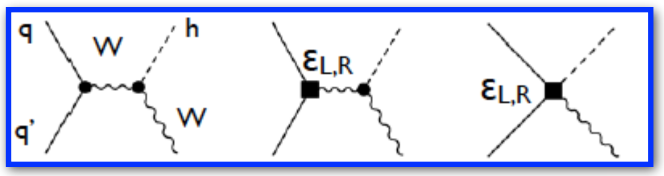
- LHC (if Λ > few TeV): associated Higgs + W production

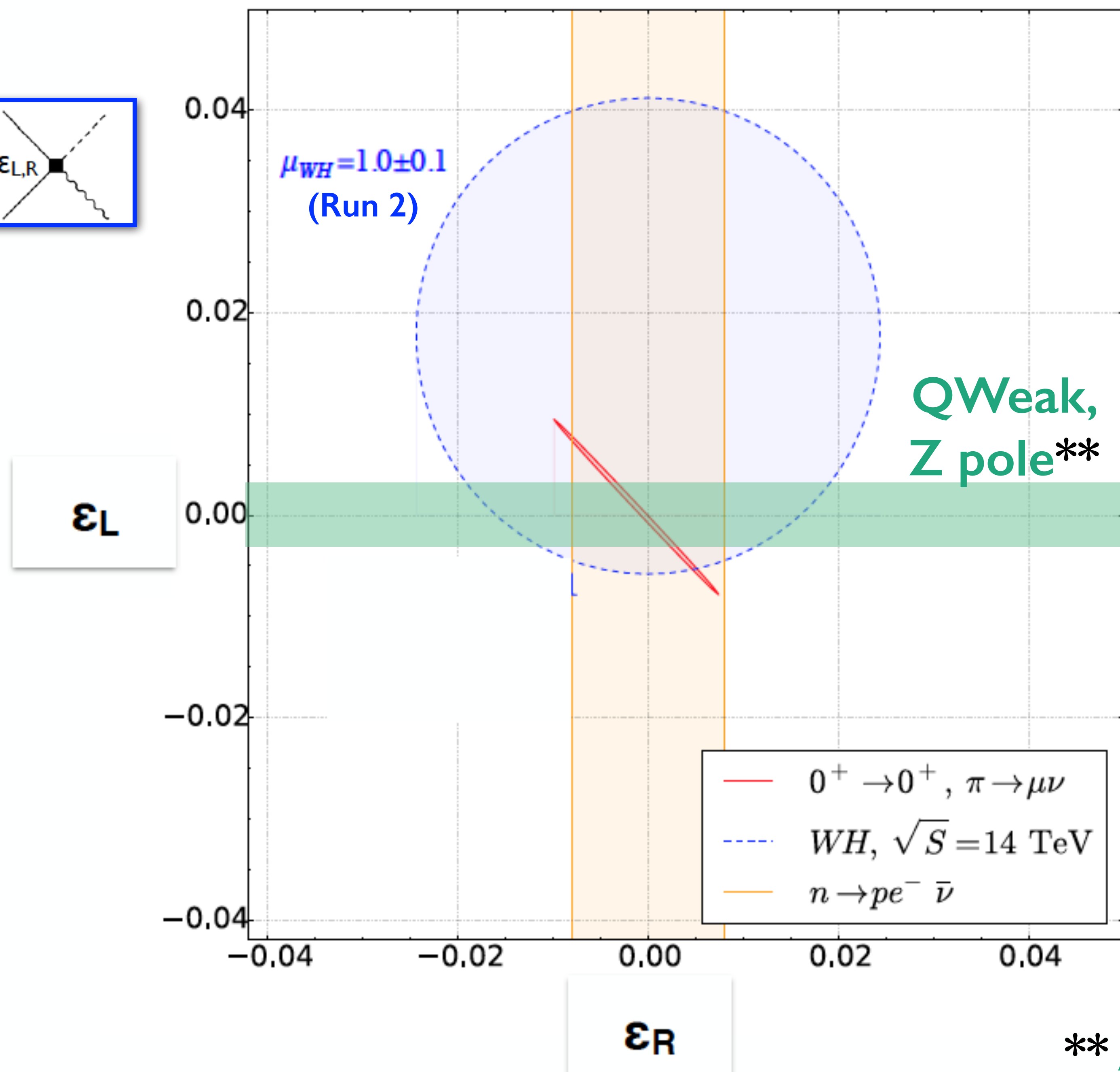


Probing $\varepsilon_{L,R}$ couplings

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

Updated plot courtesy of E. Mereghetti





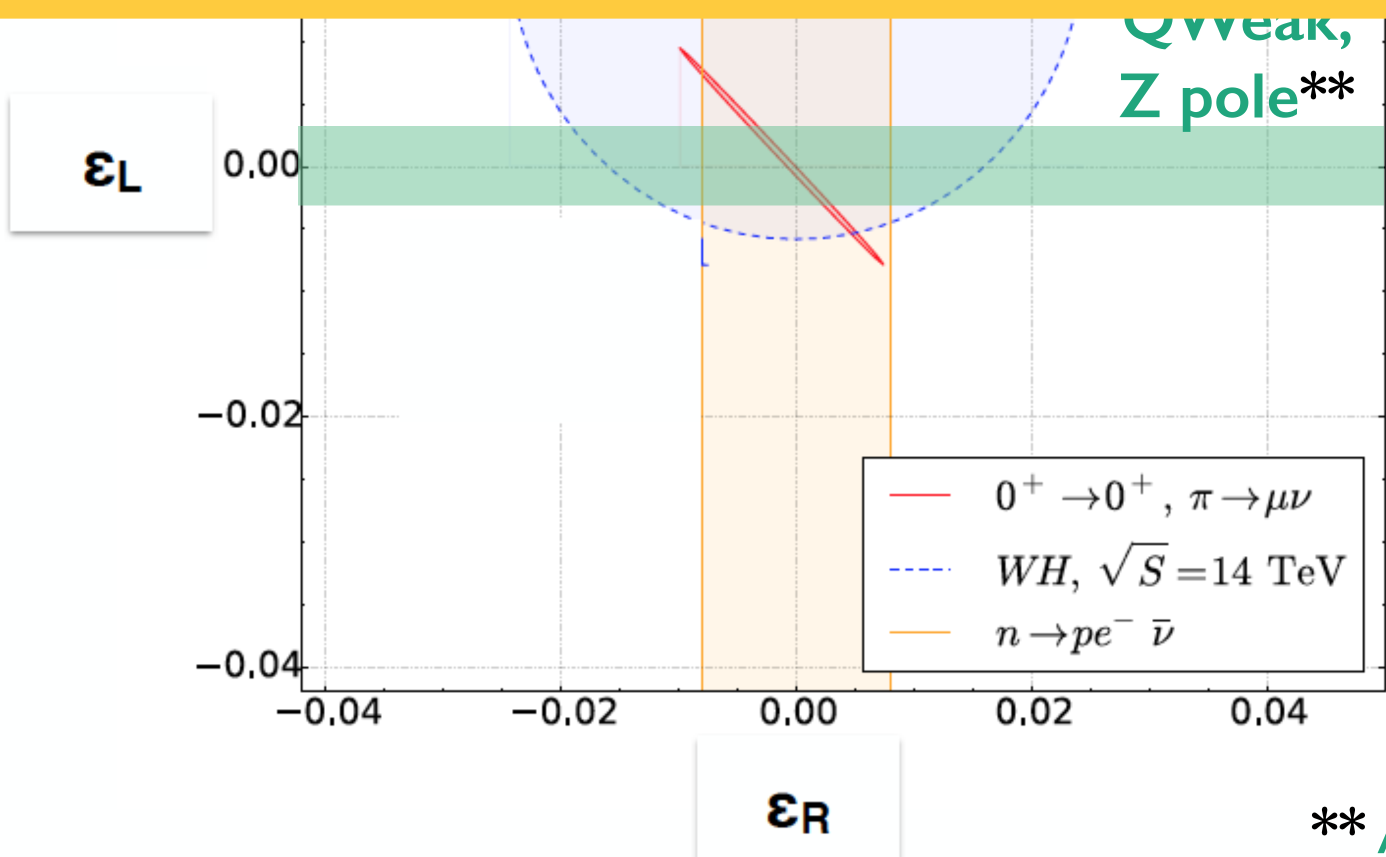
- Δ_{CKM} provides strongest constraint, followed by QWeak
- Neutron decay + LQCD: approaching competitive sensitivity to ε_R

Constraint on ε_R uses g_A =1.285(17) (CalLat 1710.06523)

** Adam Falkowski, private communication, PRELIMINARY

Probing $\varepsilon_{L,R}$ couplings

- Several lessons:
  - Low-energy can be quite competitive with collider bounds
  - Connection between CC and NC (gauge invariance!)
  - Caveat: additional BSM operators can relax these constraints. Combination of low- and high-energy constraints helps reducing "flat directions"



LQCD: approaching competitive sensitivity to ε_R

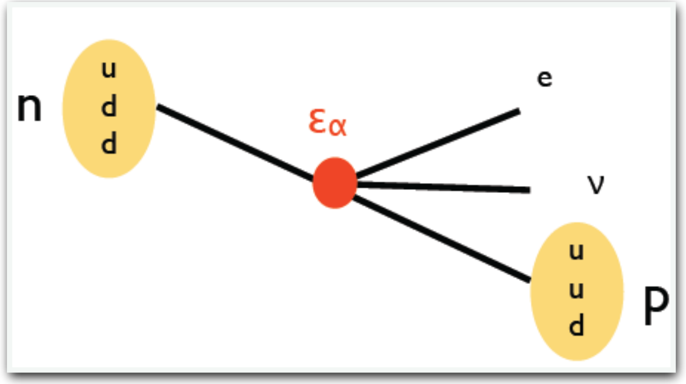
Constraint on ε_R uses g_A =1.285(17) (CalLat 1710.06523)

** Adam Falkowski, private communication, PRELIMINARY

Probing $\varepsilon_{S,T}$ couplings

- π, neutron & nuclear decays:
  - Current: $b(0^+ \to 0^+)$ [ε_S]; $\pi \to e \nu \gamma$ [ε_T]
  - Future: b_n, B_n [$\varepsilon_{S,T}$] @ 10^{-3}; b_{GT} [ε_T](^{6}He, ...) @10^{-3}

$n \to p\, e\, \nu$



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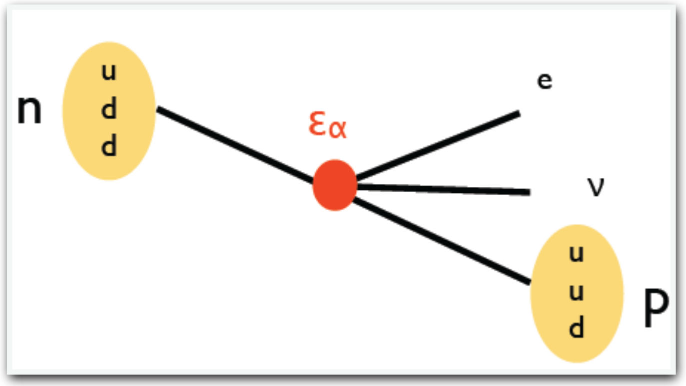
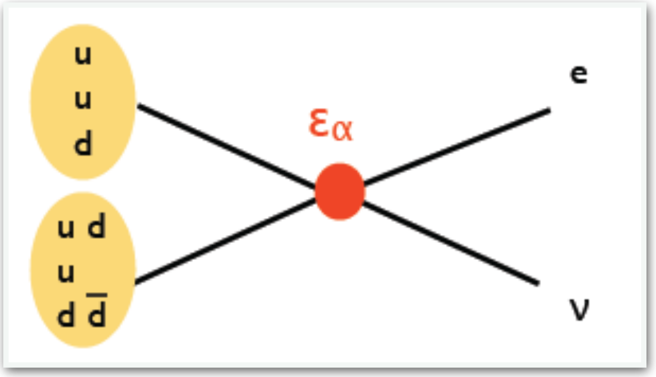
- Collider: for heavy new mediators probe *same* $\varepsilon_{S,T}$

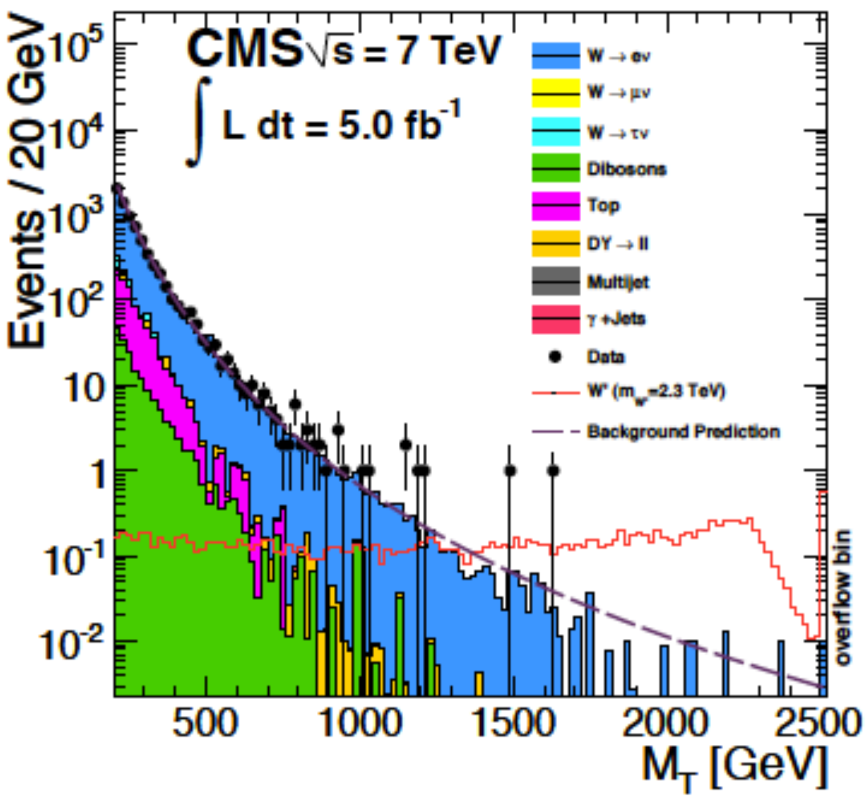
$n \to p\, e\, \nu$



$pp \to e\,\nu + X$



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



$$n_{obs}(m_T > m_{T,cut}) = \varepsilon_{eff} \times L \times (\sigma_W + \sigma_S \times |\varepsilon_S|^2 + \sigma_T \times |\varepsilon_T|^2)$$

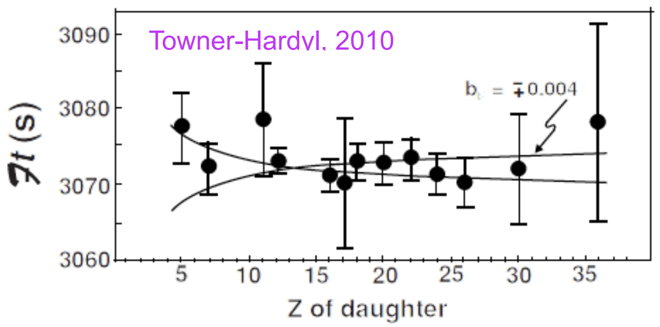
T. Bhattacharya et al, 1110.6448

VC, Gonzalez-Alonso, Graesser, 1210.4553

...

Probing $\varepsilon_{S,T}$ couplings

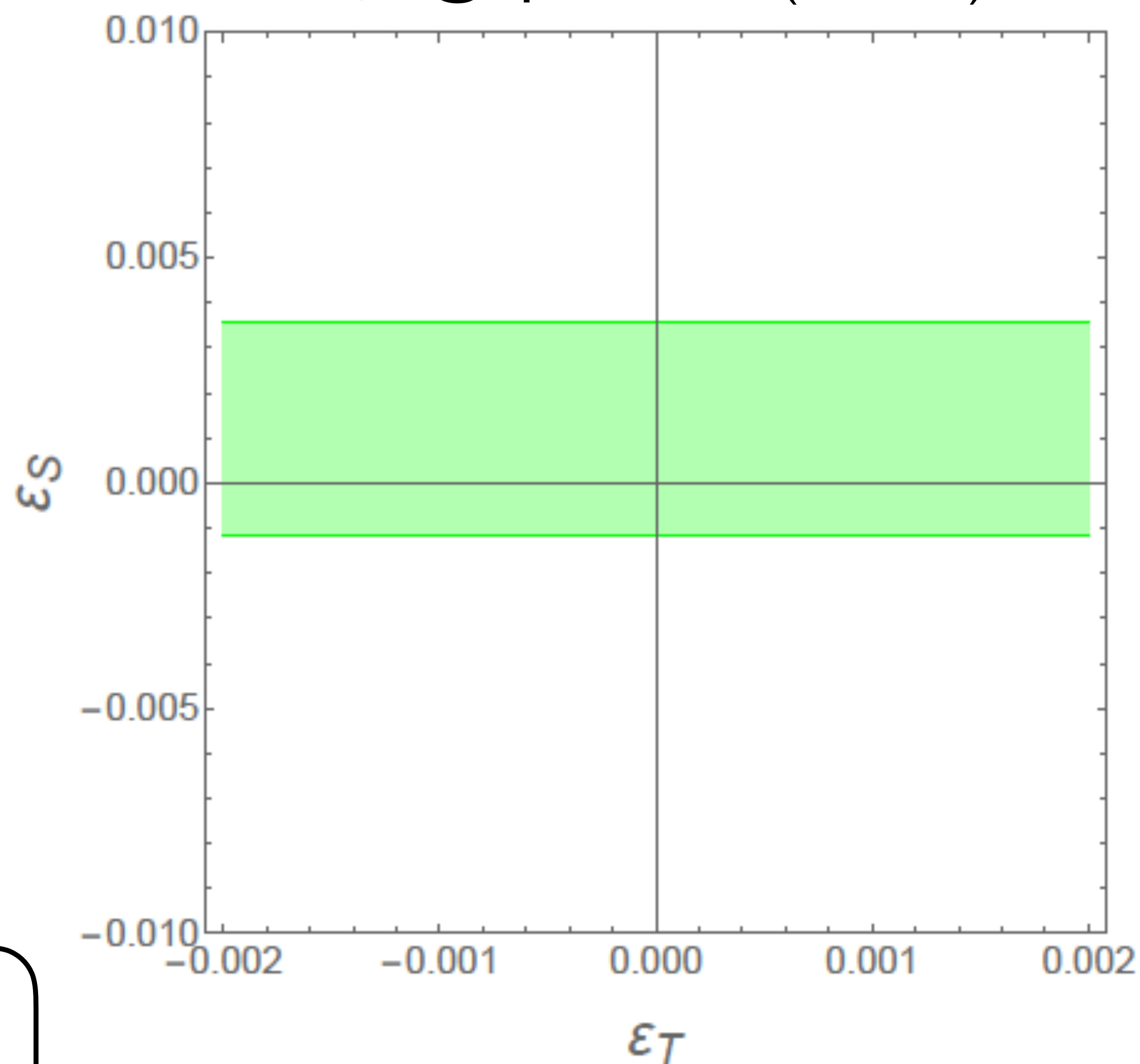
$0^+ \rightarrow 0^+$ (b_F)



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

CURRENT

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



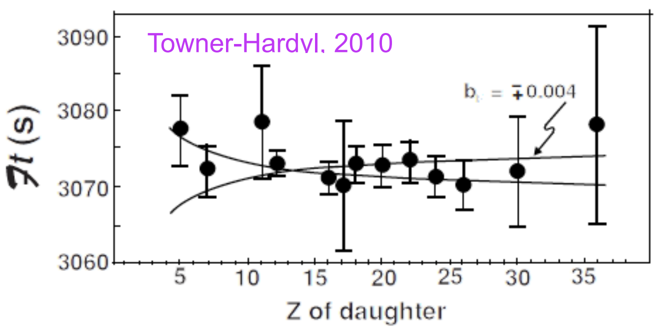
g_S =1.01(10)

g_T =0.99(4)

Bhattacharya et al (PNDME) 2018, to appear

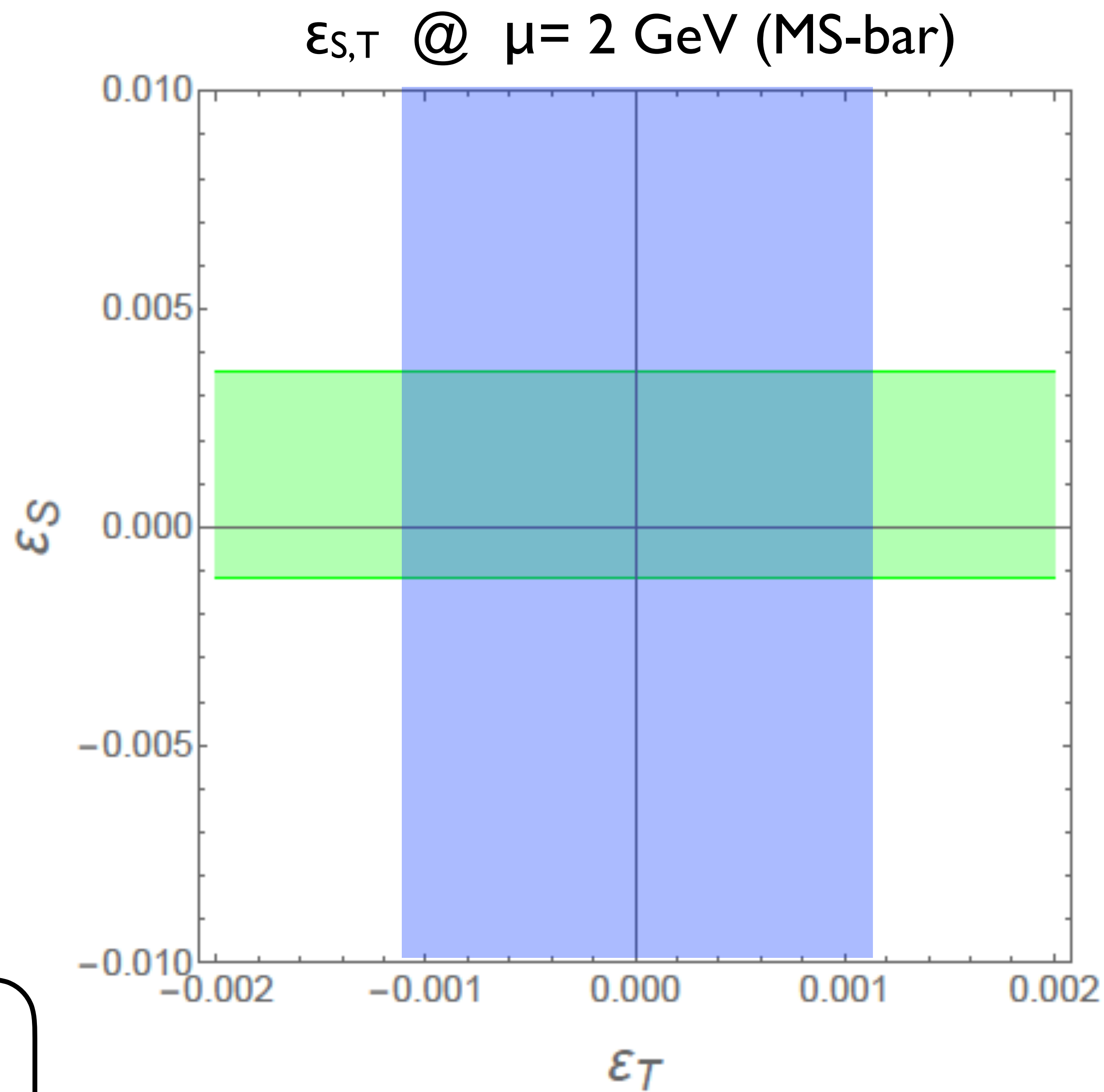
Probing $\varepsilon_{S,T}$ couplings

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

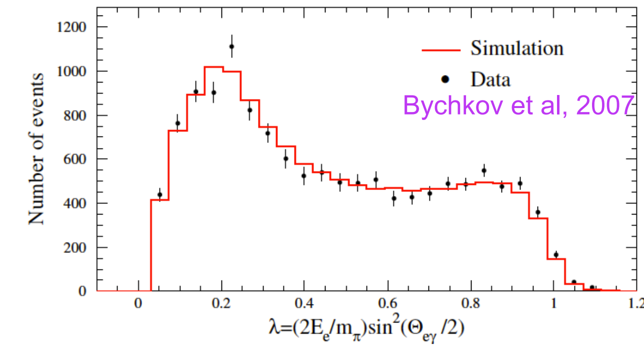


$-1.0\times10^{-3} < g_S\ \varepsilon_S < 3.2\times10^{-3}$

CURRENT



$\pi \rightarrow e\,\nu\,\gamma$



$-2.0\times10^{-4} < f_T\ \varepsilon_T < 2.6\times10^{-4}$

f_T = 0.24(4)

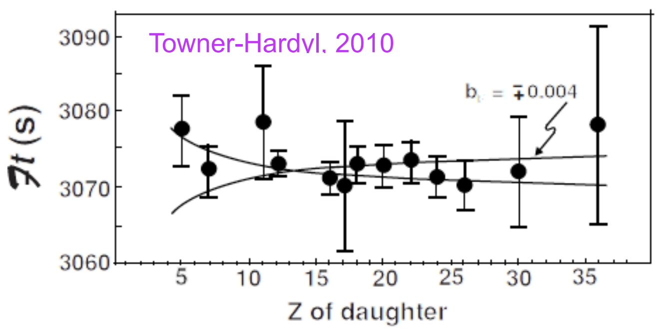
g_S = 1.01(10)

g_T = 0.99(4)

Bhattacharya et al (PNDME) 2018, to appear

Probing $\varepsilon_{S,T}$ couplings

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



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CURRENT

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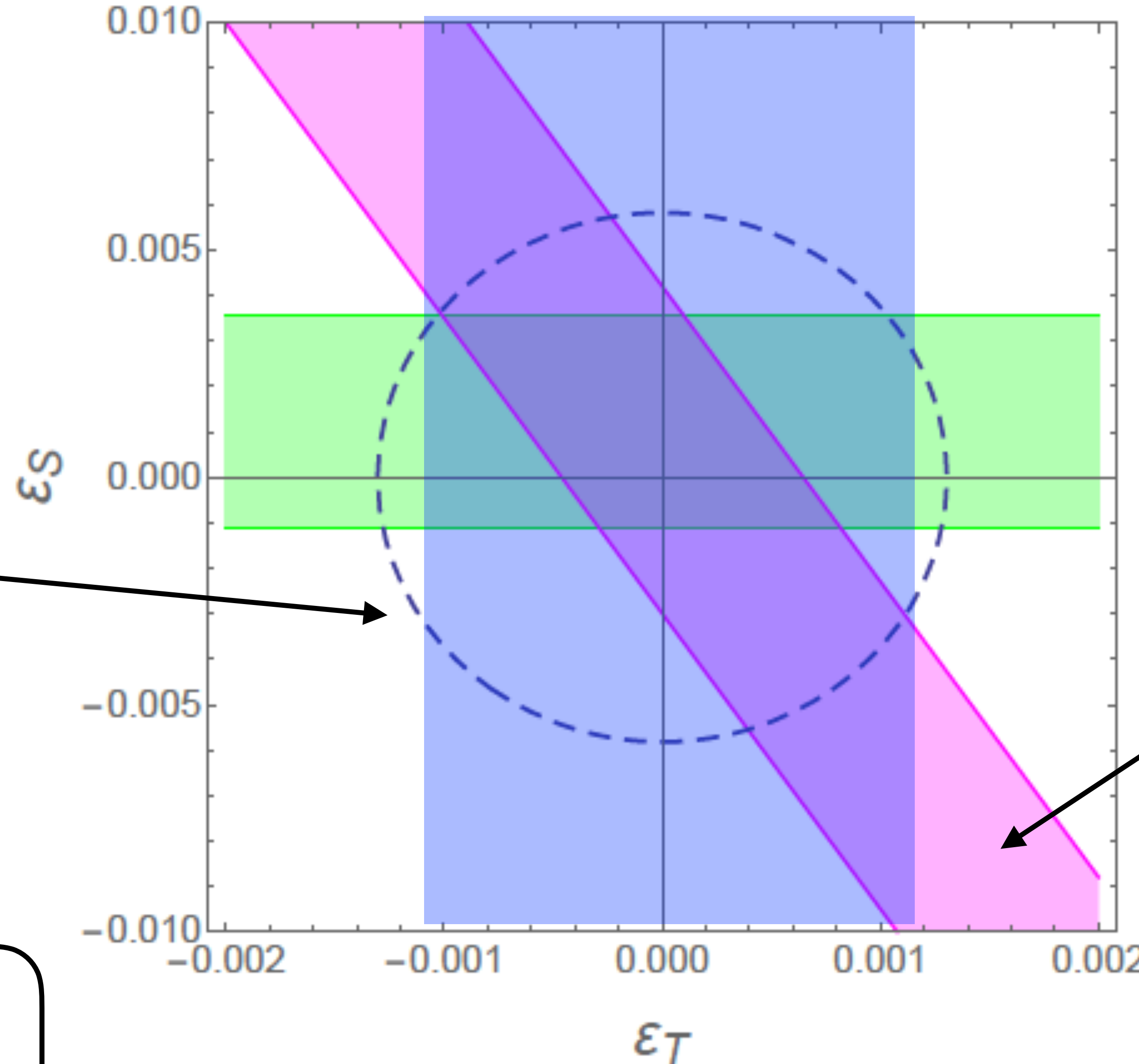
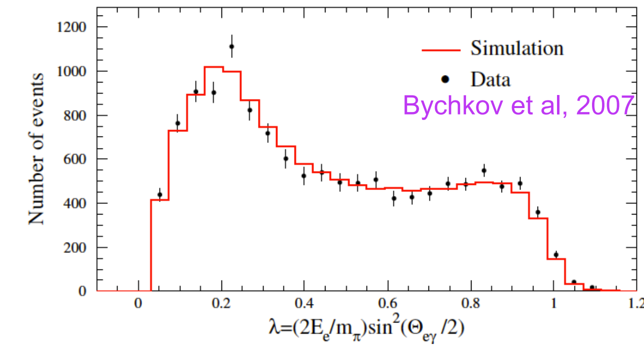


$\pi \rightarrow e\, \nu\, \gamma$



$-2.0\times10^{-4} < f_T\, \varepsilon_T < 2.6\times10^{-4}$

f_T = 0.24(4)

LHC 20 fb^{-1}
@ 8 TeV

Gonzalez-Alonso 2013
Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

$V_{ud}(0^+)/V_{ud}(n)$
$\delta\tau_n$= 0.8 s

Pattie-Hickerson-Young 1309.2499

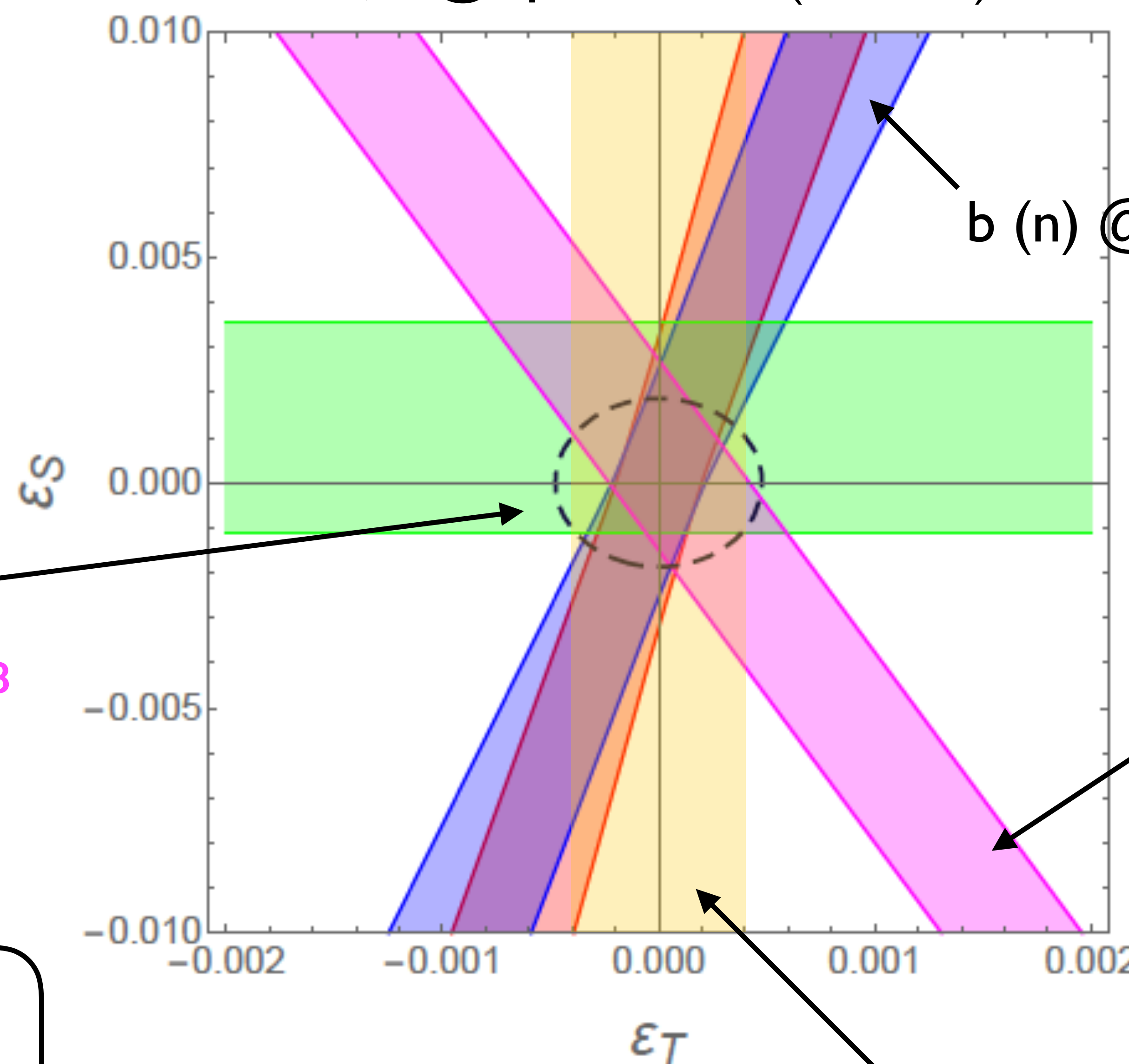
g_S =1.01(10)
g_T =0.99(4)

Bhattacharya et al (PNDME) 2018, to appear

Probing $\varepsilon_{S,T}$ couplings

FUTURE

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



b (n) @ 0.001

Prospective beta decay measurements competitive with LHC ~5 years from now, probing mass scales $\Lambda_{S,T}$ ~ 5-10 TeV

LHC 300 fb^{-1} @ 14 TeV

Bhattacharya et al 1110.6448

Alioli-Dekens-Girard-Mereghett- 1804.07407

V_{ud} $(0^+)/V_{ud}(n)$:

$\delta A/A$ ~ 0.1%

$\delta\tau_n$= 0.3 s

Pattie-Hickerson-Young 1309.2499

g_S =1.01(10)

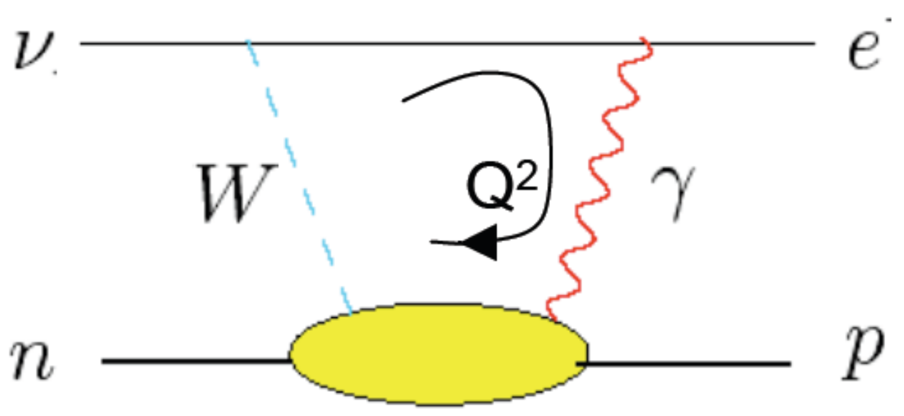
g_T =0.99(4)

Bhattacharya et al (PNDME) 2018, to appear

b (^{6}He) @ 0.001

Looking ahead

- The next frontier in beta decays will likely include:
  - $\delta\tau_n \sim 0.1$s (UCNτ2, …)
  - <0.1% precision in neutron and nuclear correlation coefficients (PERC,…)
  - Improved calculations of radiative corrections**: dispersive methods and lattice QCD (first results for meson decays)



** This is currently the dominant contribution to V_{ud} error from $0^+ \to 0^+$: $\Delta_R = (2.38 \pm 0.4)\%$ [Marciano-Sirlin 2005]

τ couplings to light quarks: $(\varepsilon_\alpha)^{d\tau}$

Based on ongoing work with Adam Falkowski, Martin Gonzalez-Alonso, Antonio Rodriguez-Sanchez

Special thanks to Antonio Rodriguez-Sanchez for input on the slides

PRELIMINARY RESULTS

τ couplings to light quarks: $(\epsilon_\alpha)^{d\tau}$

Based on ongoing work with Adam Falkowski, Martin Gonzalez-Alonso, Antonio Rodriguez-Sanchez

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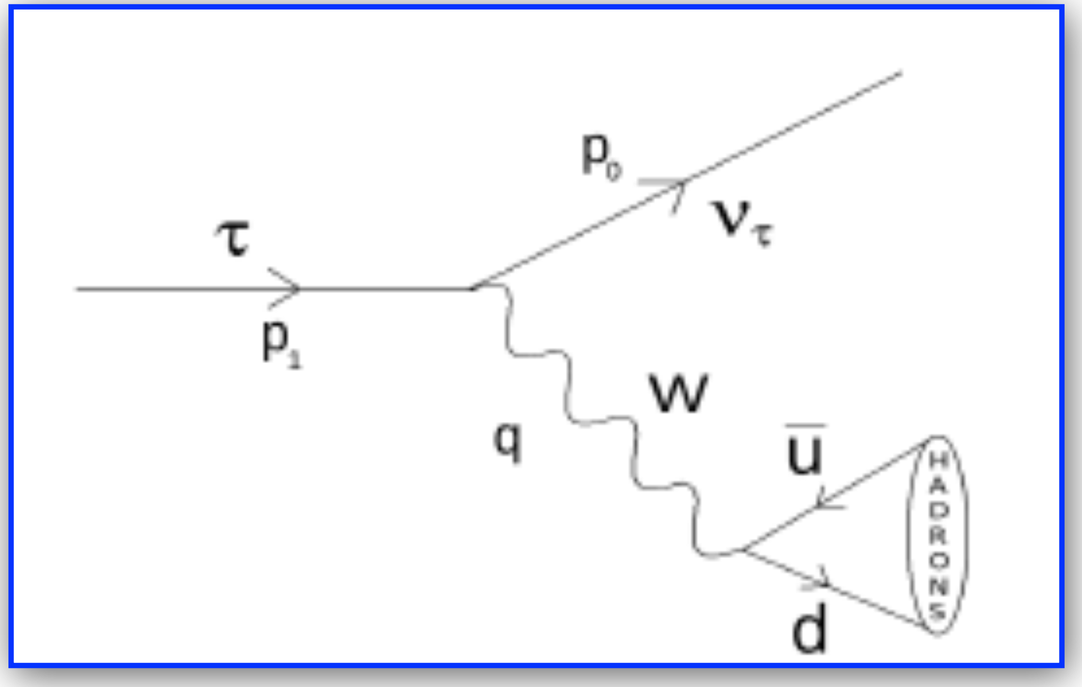
Hadronic tau decays



$$\frac{d\Gamma_{BSM}(s) - d\Gamma_{SM}(s)}{d\Gamma_{SM}} = \sum a_i(s)\epsilon_i^{d\tau}$$

- Experimental precision at sub-% level
- Theory:
  - Exclusive decays: requires decay constants, form-factors
  - Inclusive: requires spectral functions. Use "quark-hadron duality"

Exclusive processes (1)

- One-meson decay: $\tau \to \pi \nu_\tau$

$$\Gamma(\tau^- \to \pi^- \nu_\tau) = \frac{m_\tau^2 f_\pi^2 G_F^{(e)2} |V_{ud}^{(e)}|^2}{16\pi} (1 + \delta_{RC}^\pi)(1 + 2(\epsilon_L^{d\tau} - \epsilon_L^{de} - \epsilon_R^{d\tau} - \epsilon_R^{de} - \frac{B_0}{m_\tau}\epsilon_P^{d\tau}))$$

f_π : FLAG 2017 (and refs therein)
δ_{RC} : Deker-Finkemeier 1994 and VC-Rosell 2007

$$\epsilon_L^{d\tau} - \epsilon_L^{de} - \epsilon_R^{d\tau} - \epsilon_R^{de} - \frac{B_0}{m_\tau}\epsilon_P^{d\tau} = -(1.5 \pm 6.7) \cdot 10^{-3}$$

Error dominated by f_π (2x exp. and 5x rad. corr)

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Error dominated by f_π (2x exp. and 5x rad. corr)

- Two-meson decay: $\tau \to \eta\pi\nu_\tau$ suppressed in the SM

$$a_s(s) = \mathcal{O}(\frac{m_\tau}{m_u - m_d}) \to \epsilon_s \approx -(2 \pm 7) \cdot 10^{-3}$$

Graces et al 1708.07802

Exclusive processes (2)

- Two-meson decay: $\tau \rightarrow \pi\pi\nu_\tau$

$$\frac{d\Gamma_{exp}(s)}{ds} = \frac{d\Gamma_{SM}(s)}{ds}\left[1 + 2(\epsilon_L^{d\tau} + \epsilon_R^{d\tau} - \epsilon_L^{de} - \epsilon_R^{de}) + a_T(s)\epsilon_T\right]$$

Known at (sub)% level

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Tensor FF: use resonance saturation (shape) + LQCD (normalization)

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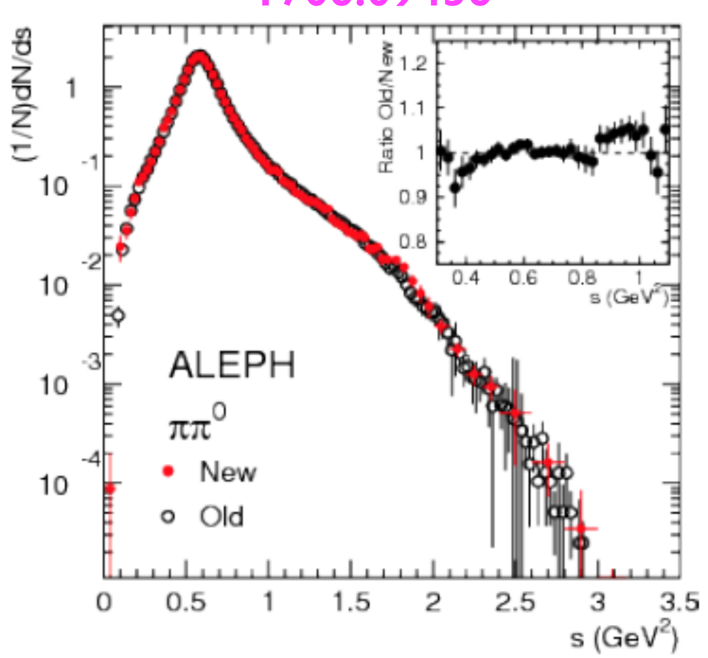
Known at (sub)% level

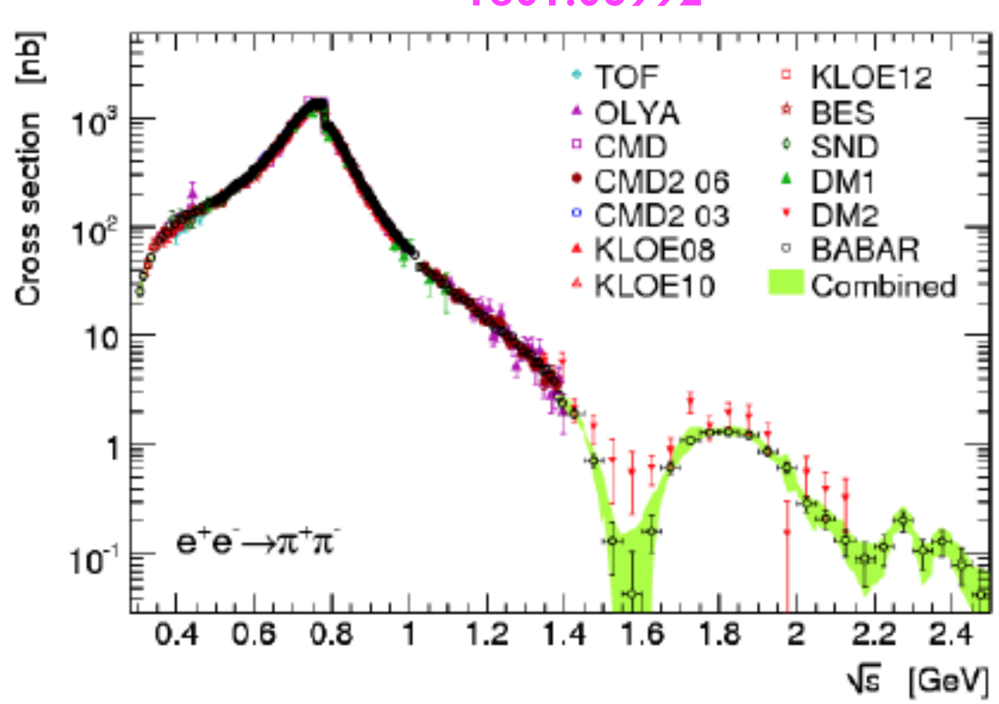
Requires $F_V^\tau(s)$. Use $F_V^{e^+e^-}(s) = F_V^\tau(s) \times (1 + \delta_{IB})$

$e^+e^- \to \pi^+\pi^-$ insensitive to new physics (s/Λ^2 effect)

1706.09436



1801.06992



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$e^+e^- \to \pi^+\pi^-$ insensitive to new physics (s/Λ^2 effect)

- Use integral constraint: $\pi\pi$ contribution to the HVP for $(g\text{-}2)_\mu$

Davier et al 1312.1501, 1706.09436

$$\frac{a_\mu^\tau - a_\mu^{ee}}{2\, a_\mu^{ee}} = \epsilon_L^{d\tau} - \epsilon_L^{de} + \epsilon_R^{d\tau} - \epsilon_R^{de} + 0.64\, \epsilon_T^{d\tau} = 0.0089(44)$$

Inclusive processes: generalities

- Total widths into "V" and "A" final states related to spectral functions

$$d\Gamma_V(s) = f_{VV}(s)(1 + 2\epsilon^{\tau}_{L+R} - 2\epsilon^{e}_{L+R})\,\mathrm{Im}\,\Pi_{VV}(s) + \epsilon_T f_{VT}(s)\frac{\mathrm{Im}\,\Pi_{VT}(s)}{m_\tau}$$

$$d\Gamma_A(s) = f_{AA}(s)(1 + 2\epsilon^{\tau}_{L-R} - 2\epsilon^{e}_{L+R})\,\mathrm{Im}\,\Pi_{AA}(s)$$

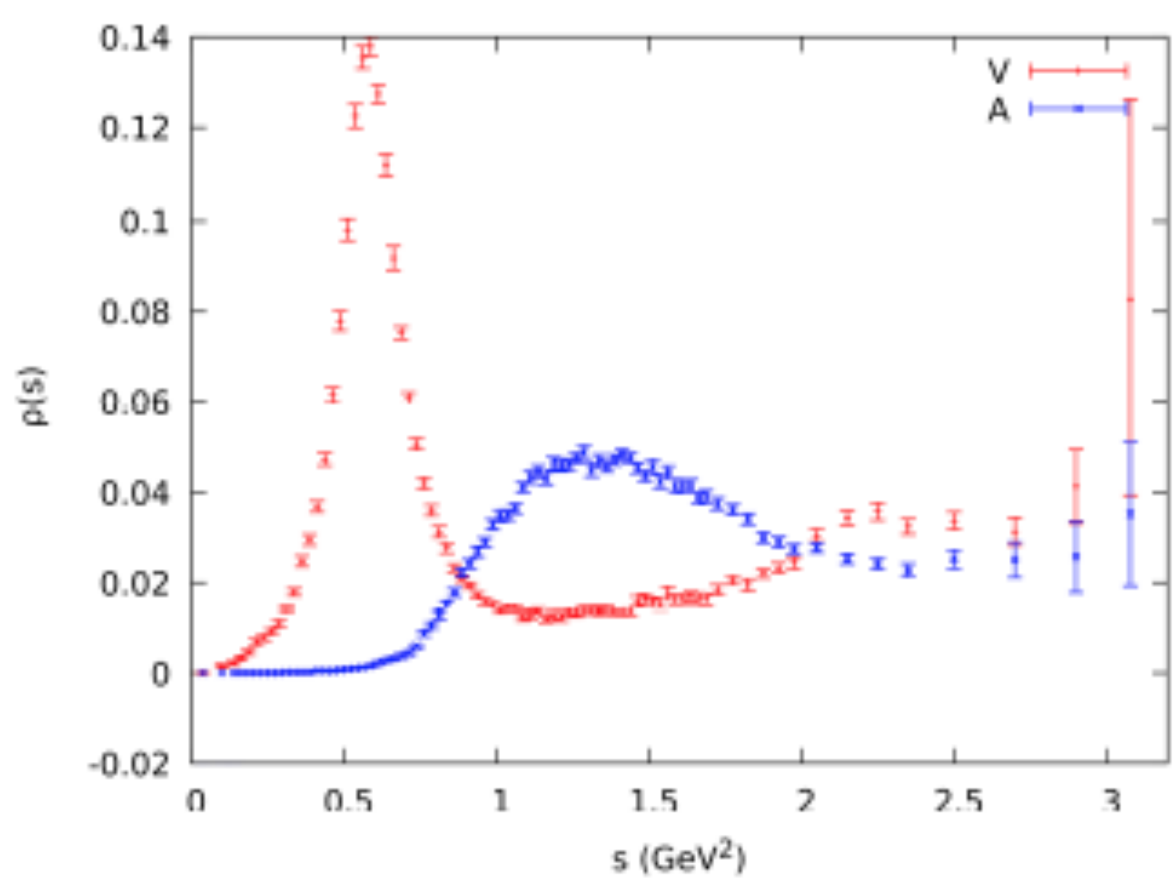
$s > 4m_\pi^2$

$$\Pi_{ij}(q) \sim \int dq\, e^{iqx} \langle 0|\, T(J_i(x)J_j(0))\,|0\rangle$$

$$\mathrm{Im}\,\Pi_{ij}(s) \equiv \pi\rho_{ij}(s)$$

Spectral functions

ALEPH



Inclusive processes: generalities

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$$d\Gamma_V(s) = f_{VV}(s)(1 + 2\epsilon^T_{L+R} - 2\epsilon^e_{L+R})\,\mathrm{Im}\,\Pi_{VV}(s) + \epsilon_T f_{VT}(s)\frac{\mathrm{Im}\,\Pi_{VT}(s)}{m_\tau}$$

$$d\Gamma_A(s) = f_{AA}(s)(1 + 2\epsilon^T_{L-R} - 2\epsilon^e_{L+R})\,\mathrm{Im}\,\Pi_{AA}(s)$$

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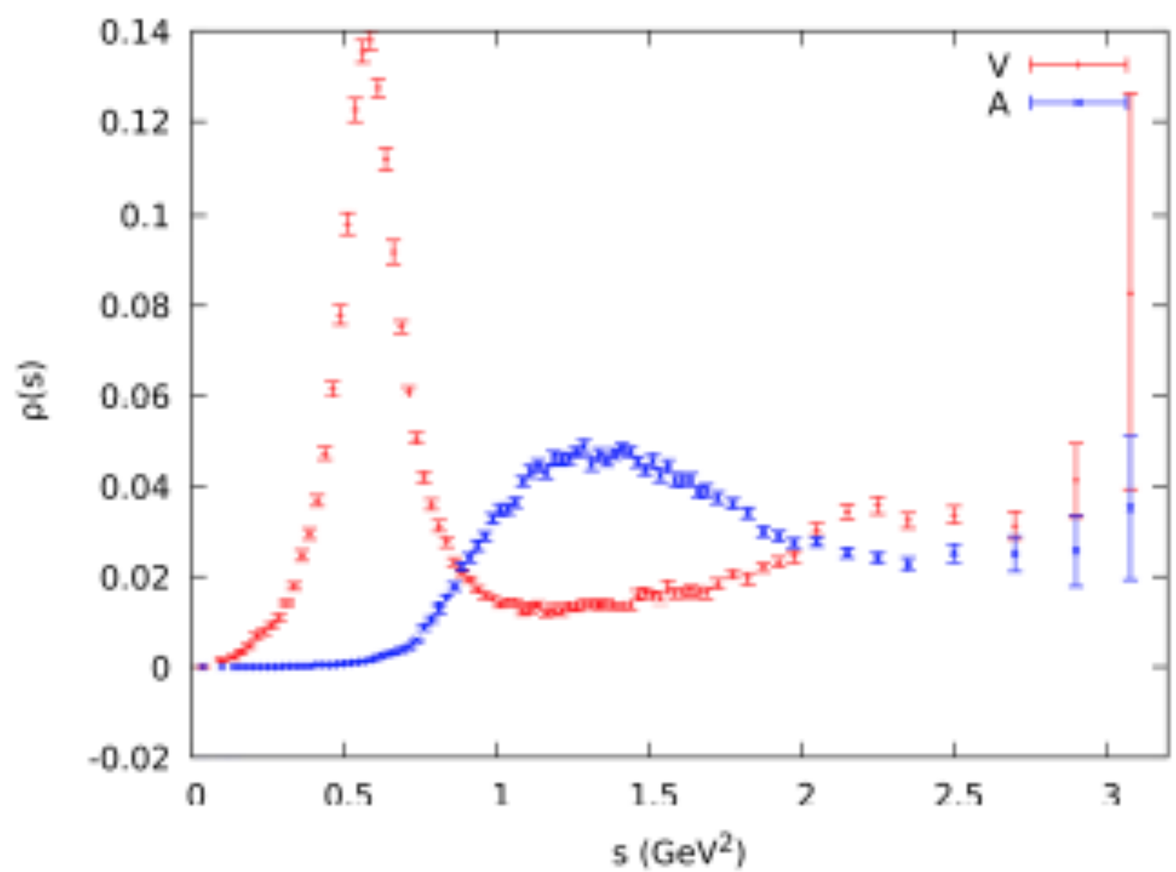
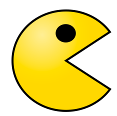
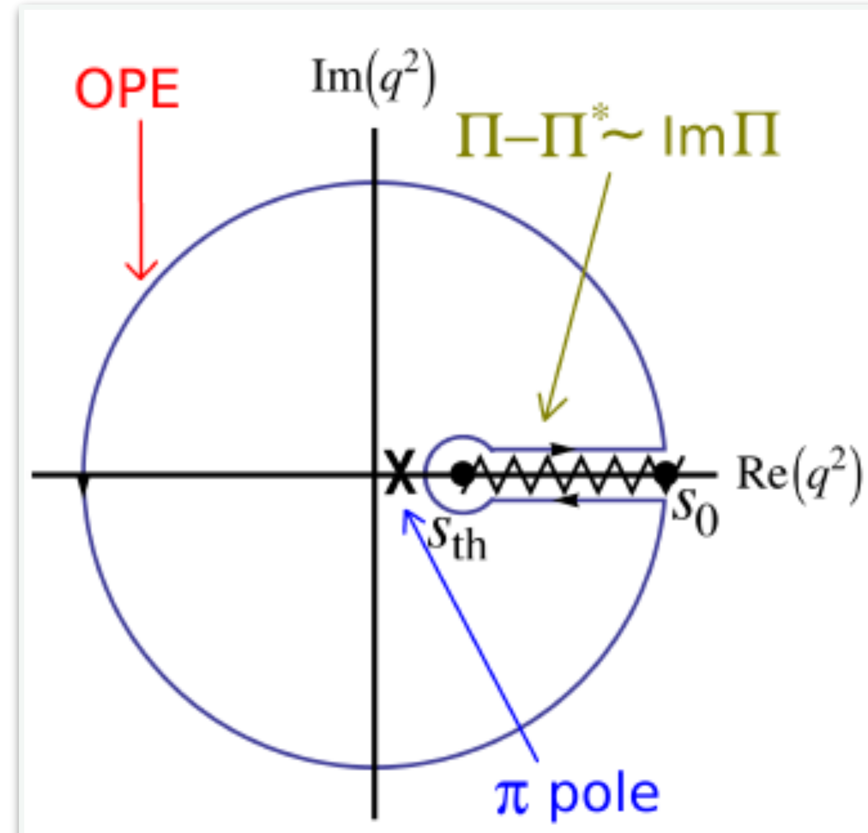
ALEPH



Inclusive processes: method

$$\Pi^{\mathrm{OPE}}(Q^2=-q^2)=\sum_i c_i(\mu,Q^2)\frac{\mathcal{O}_{i,D}(\mu)}{Q^D}$$

- Use Cauchy's theorem for $\omega(s)\Pi(s)$ on the pac-man contour 
- $\Pi(s) \rightarrow \Pi_{\mathrm{OPE}}(s)$ on the circle
- Method used to successfully extract SM parameters (α_s, m_s, chiral LECs). Here put constraints on new physics



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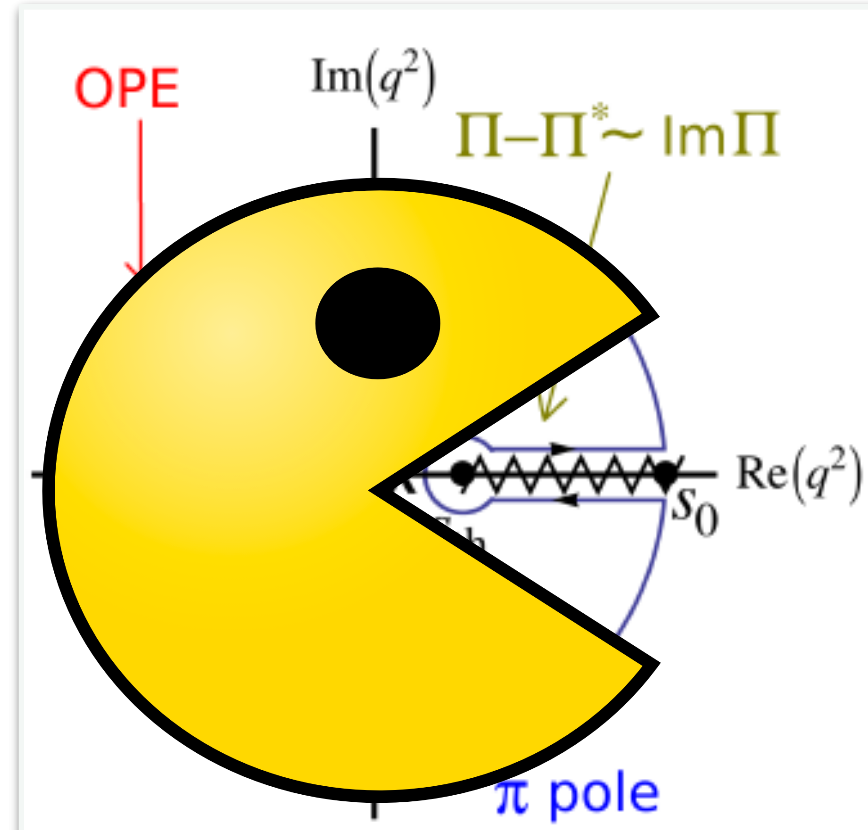


$$\underbrace{\int_{s_{th}}^{s_0}\frac{ds}{s_0}\omega(s)\,\mathrm{Im}\,\Pi^{(1+0)}_{V\pm A}}_{\text{Experiment-BSM}(\epsilon)\,=\,\text{QCD}} \pm 2\pi\frac{f_\pi^2}{s_0}\omega(m_\pi^2)=\frac{i}{2}\oint_{|s|=s_0}\frac{ds}{s_0}\omega(s)\Pi^{(1+0),\,OPE}_{V\pm A}+\delta^{(\omega)}_{DV,\,V\pm A}(s_0)$$

Duality Violation: $\Pi \neq \Pi_{OPE}$

Inclusive processes: results

- Four weakly correlated constraints
- V+A: ω(s)=1, $\omega(s)=\omega_{kin,\tau}(s)$

$$\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} - 0.89\epsilon^{d\tau}_{R} + 0.73\epsilon^{d\tau}_{T} = (8.5 \pm 8.5)\cdot 10^{-3}$$

$$0.72(\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R}) - 0.56\epsilon^{d\tau}_{R} + \epsilon^{d\tau}_{T} = (3.2 \pm 11.8)\cdot 10^{-3}$$

OPE side dominated by perturbative term. Use α_s from lattice QCD

- V-A: $\omega(s)=1-s/s_0$, $\omega(s)= (1-s/s_0)^2$ [to reduce duality violations].

$$0.15(\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R}) + 0.46\epsilon^{d\tau}_{R} + \epsilon^{d\tau}_{T} = (0.8 \pm 7.6)\cdot 10^{-3}$$

$$0.15(\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R}) + 0.29\epsilon^{d\tau}_{R} + \epsilon^{d\tau}_{T} = (0.8 \pm 1.5)\cdot 10^{-3}$$

OPE side has no perturbative term. Condensates from NDA and kaon physics + chiral symmetry

Constraints from τ decays: summary

$$\begin{pmatrix} \epsilon_L^{d\tau} - \epsilon_L^{de} + \epsilon_R^{d\tau} - \epsilon_R^{de} \\ \epsilon_R^{d\tau} \\ \epsilon_S^{d\tau} \\ \epsilon_P^{d\tau} \\ \epsilon_T^{d\tau} \end{pmatrix} = \begin{pmatrix} 9.6 \pm 6.1 \\ 1.3 \pm 9.0 \\ -2.0 \pm 7.0 \\ -6.1 \pm 11.5 \\ -1.1 \pm 3.8 \end{pmatrix} \times 10^{-3}$$

Connection to “SM-EFT”

$$\epsilon_L^{d\tau} - \epsilon_L^{de} = \underbrace{\delta g_L^{W\tau} - \delta g_L^{We}}_{\text{Independently constrained by EWPO}} - [c_{\ell q}^{(3)}]_{\tau\tau 11} + \underbrace{[c_{\ell q}^{(3)}]_{ee11}}_{\text{Independently constrained by EWPO}}$$

$$\epsilon_R^{d\tau} = \epsilon_R^{de} = \underbrace{\delta g_R^{Wq_1}}_{\text{Independently constrained by EWPO}}$$

EWPO = A. Falkowski et al, 1706.03783

$$\epsilon_{S,P}^{d\tau} = -\frac{1}{2}[c_{lequ} \pm c_{ledq}]^*_{\tau\tau 11}$$

$$\epsilon_T^{d\tau} = -\frac{1}{2}[c_{lequ}^{(3)}]^*_{\tau\tau 11}$$

Connection to "SM-EFT"

$$\epsilon_L^{d\tau} - \epsilon_L^{de} = \underbrace{\delta g_L^{W\tau} - \delta g_L^{We}}_{\text{Independently constrained by EWPO}} - [c_{\ell q}^{(3)}]_{\tau\tau 11} + \underbrace{[c_{\ell q}^{(3)}]_{ee11}}_{\text{Independently constrained by EWPO}}$$

$$\epsilon_R^{d\tau} = \epsilon_R^{de} = \underbrace{\delta g_R^{Wq_1}}_{\text{Independently constrained by EWPO}}$$

EWPO = A. Falkowski et al, 1706.03783

$$\epsilon_{S,P}^{d\tau} = -\frac{1}{2}[c_{lequ} \pm c_{ledq}]^*_{\tau\tau 11}$$

$$\epsilon_T^{d\tau} = -\frac{1}{2}[c_{lequ}^{(3)}]^*_{\tau\tau 11}$$

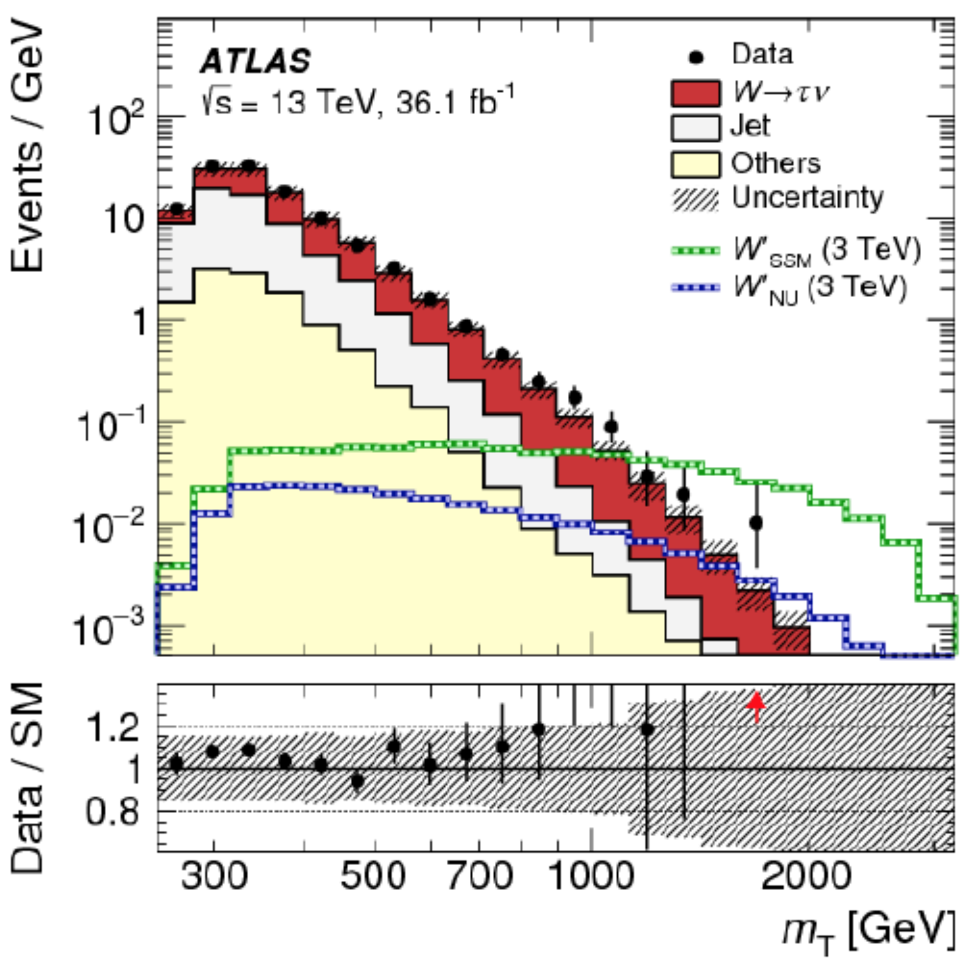
New low-energy constraints on SM-EFT couplings:

$$[c_{lq}^{(3)}, c_{lequ}, c_{ledq}, c_{lequ}^{(3)}]_{\tau\tau 11} = (1.0 \pm 2.9, 0.66 \pm 0.71, -0.43 \pm 0.66, -0.02 \pm 0.82) \times 10^{-2}$$

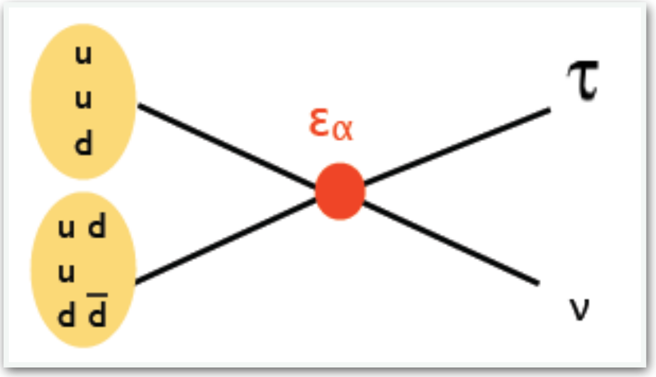
Constraints from the LHC

- Similar to electron case:

1801.06992



pp → τν + X



Coefficient	ATLAS $\tau\nu$	Hadronic τ decays
$[c_{\ell q}^{(3)}]_{\tau\tau 11}$	$[0.0, 1.1]$	$[-12.8, 0.0]$
$[c_{\ell equ}]_{\tau\tau 11}$	$[-4.6, 4.6]$	$[-3.9, 8.6]$
$[c_{\ell edq}]_{\tau\tau 11}$	$[-4.6, 4.6]$	$[-7.7, 4.8]$
$[c_{\ell equ}^{(3)}]_{\tau\tau 11}$	$[-2.7, 2.7]$	$[-8.8, 1.8]$

95% CL intervals (in 10^{-3} units) for the Wilson coefficients at $\mu = 1$ TeV

Impact on gauge vertex corrections

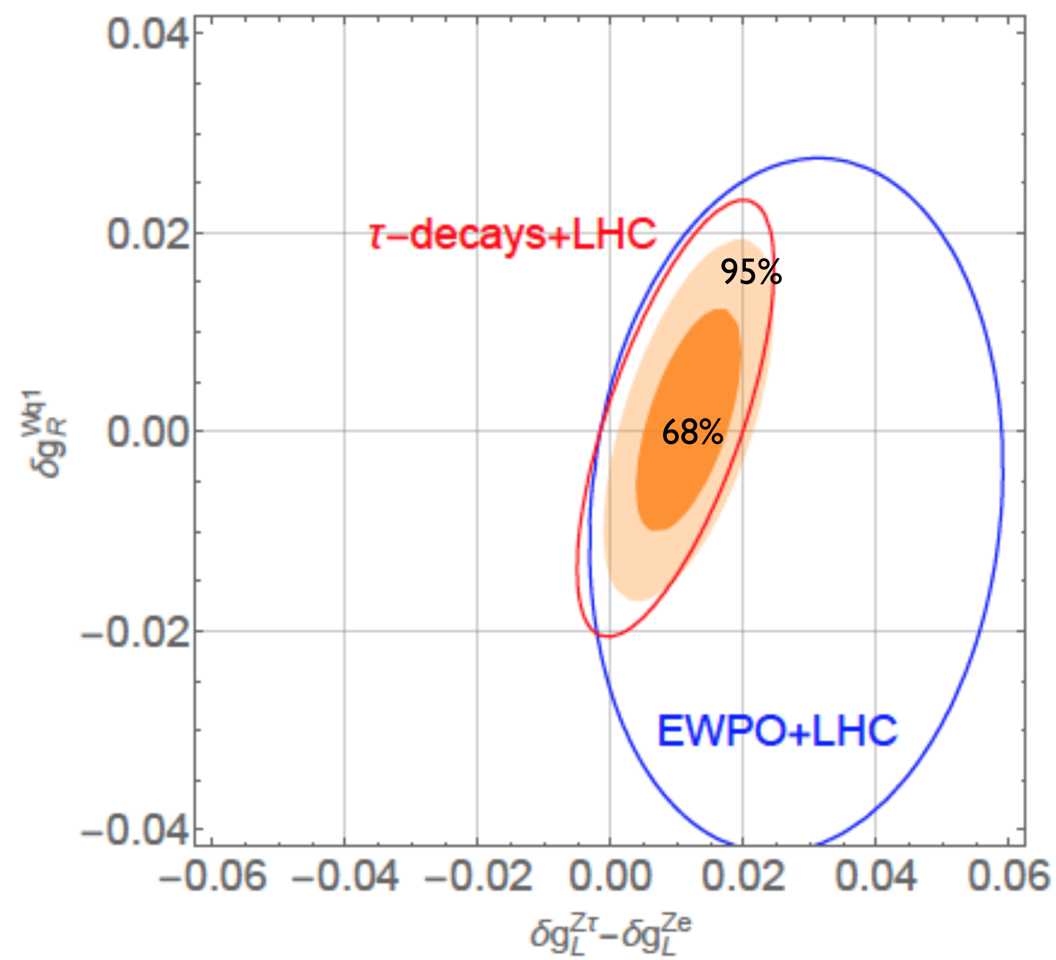
- LHC input constrains 4-fermion "L" couplings at 10^{-3} level

$$\epsilon_L^{d\tau} - \epsilon_L^{de} = \delta g_L^{W\tau} - \delta g_L^{We} - \underbrace{[c_{\ell q}^{(3)}]_{\tau\tau 11} + [c_{\ell q}^{(3)}]_{ee11}}_{\text{constrained by LHC at 0.1\% level}}$$

$$\epsilon_R^{d\tau} = \epsilon_R^{de} = \delta g_R^{Wq_1}$$

Our analysis + Greljo-Marzocca 1704.09015

- Hadronic tau decays become a new %-level probe of lepton flavor universality of vertex corrections



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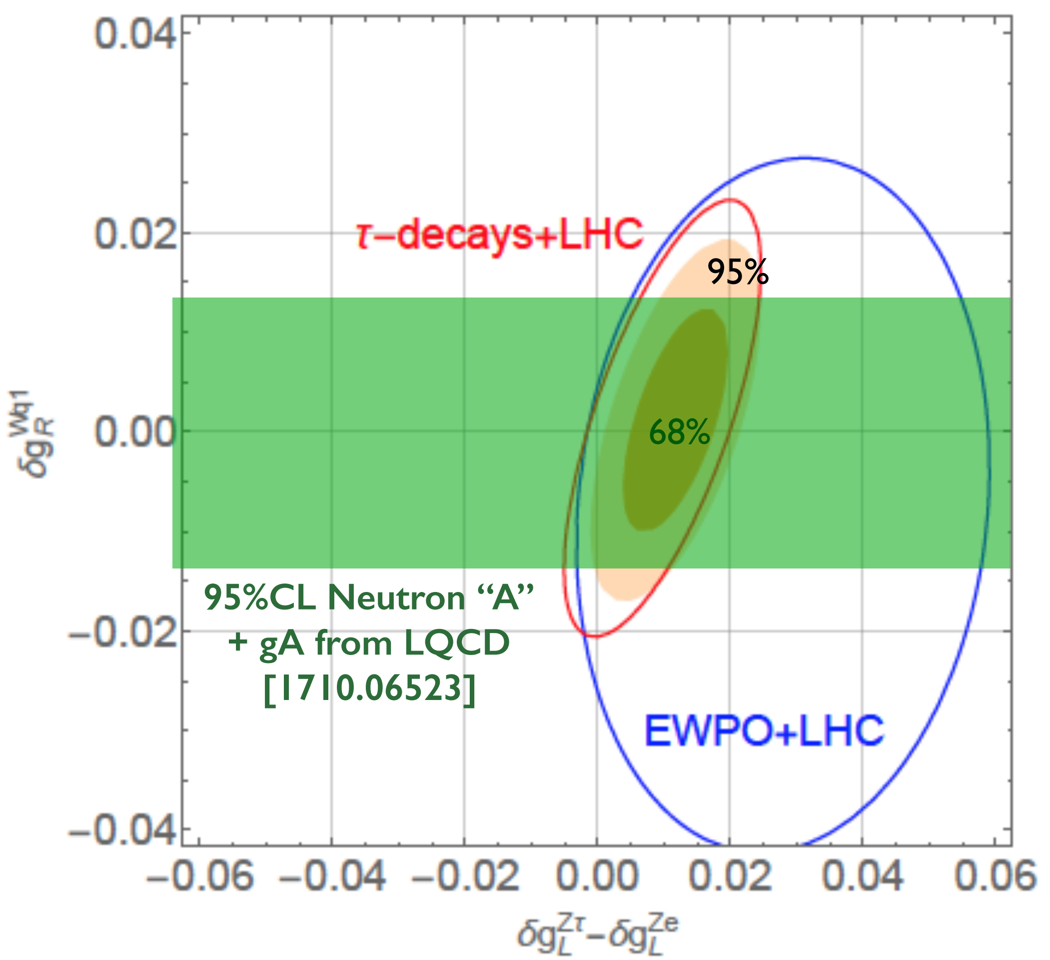

Summary

- CC transitions with sufficient th. and expt. precision (β decays at < 0.1%, τ decays at <1%) provide "broad band" probe of new physics

- Discovery potential depends on the underlying model. However, for heavy mediators, EFT shows that a discovery window exists well into the LHC era (simple examples: ε_L-ε_R and ε_S-ε_T plots)

- In general, combination of low- and high-E measurements can
  - provide stronger constraints on certain couplings
  - break coupling degeneracies
  - reduce "flat directions" in space of effective couplings

- Example of global analysis in next talk