

Interplay of (1st row) CKM-unitarity tests and collider searches

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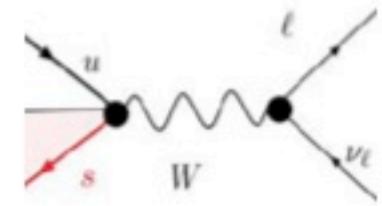
University of Wisconsin - Madison



Outline

- Introduction: Semileptonic decays of light quarks;
- Effective operators analysis to make contact with collider physics;
- Simple flavor structure: MFV
 - (1st row) CKM-unitarity test.
- General flavor structure:
 - Example: neutron beta decay;

Introduction



- Semileptonic decays of light quarks...
 - Theoretically errors below 1%;
 - A lot of precise experimental data;
- Usefulness:
 - In the SM... $G_F V_{ij}$ are extracted;

For example...

$$V_{ud} = 0.97425(22)$$

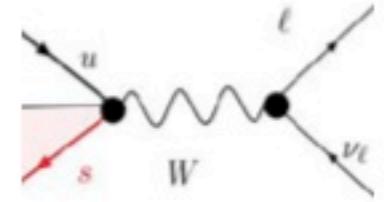
$$V_{us} = 0.2252(9)$$

$$V_{ub} \sim 10^{-3}$$

(Hardy & Towner, 2008)

(Antonelli et al., 2009)

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



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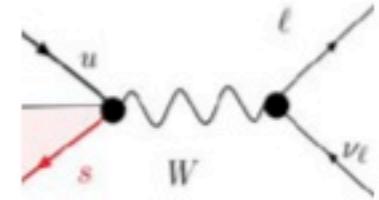
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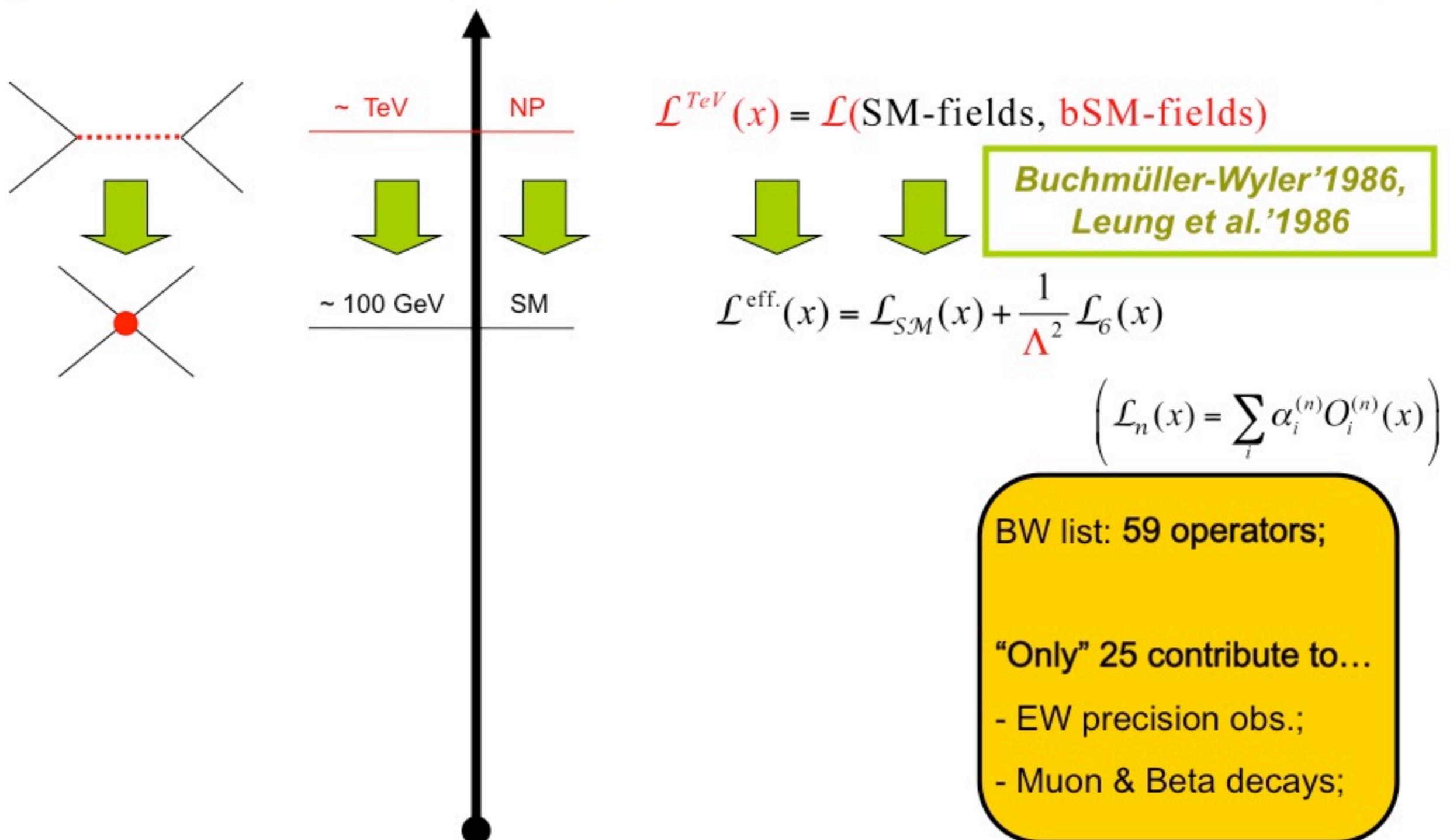
Introduction

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 - Theoretically errors below 1%;
 - A lot of precise experimental data;
- Usefulness:
 - In the SM... $G_F V_{ij}$ are extracted;
 - Beyond the SM... $|\epsilon| \ll 1$
- How can we compare with collider bounds?
 - Model-dep. / model-indep. analysis!

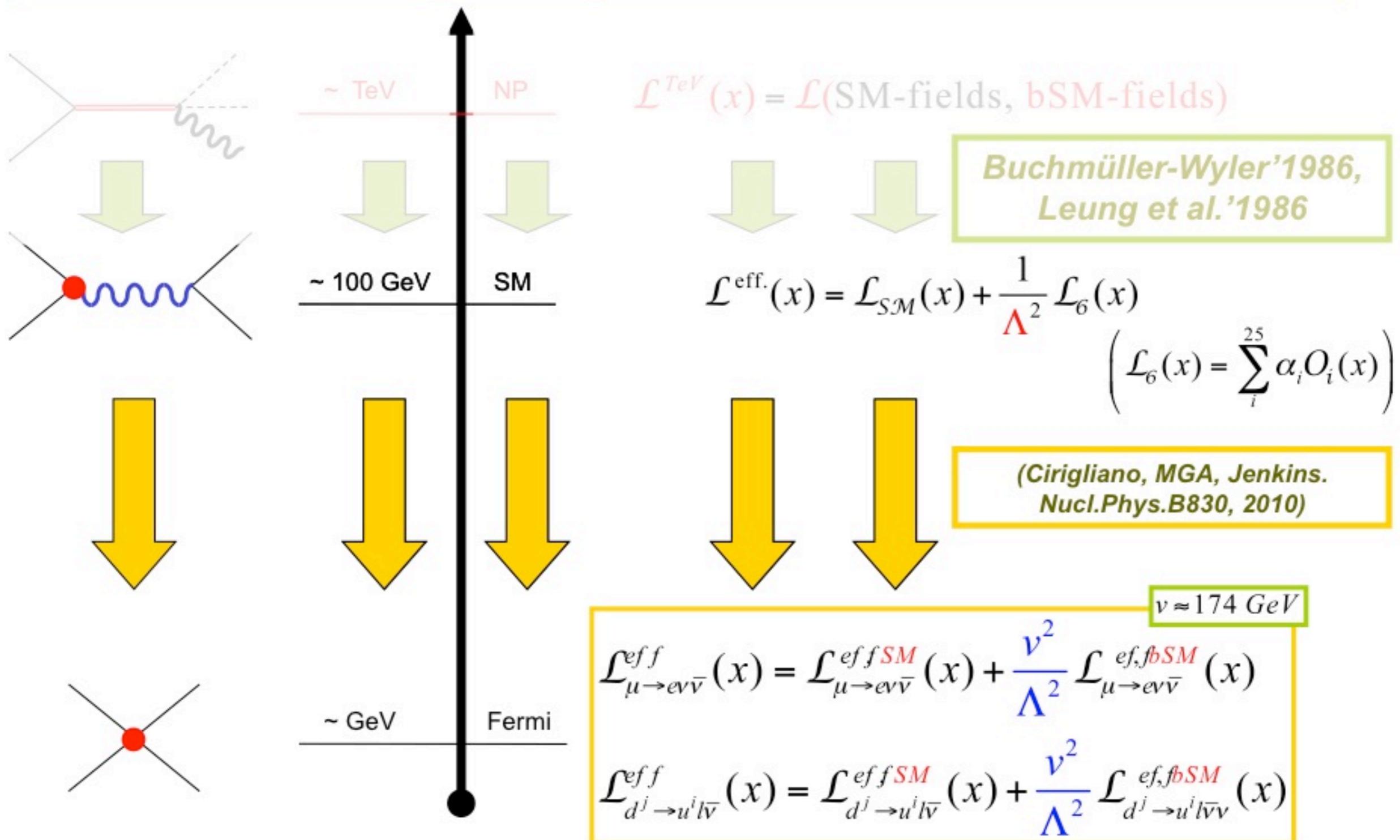
Can they be considered EW precision observables?

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

The eff. Lagrangian for E~100 GeV



The eff. Lagrangian for $E \sim 1 \text{ GeV}$



The eff. Lagrangian for E~1 GeV

- Muon decay:

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

$$\mathcal{L}_{\mu \rightarrow e \nu \bar{\nu}}^{eff}(x) = \frac{-g^2}{2m_W^2} \left[(1 + \tilde{v}_L) (\bar{e}_L \gamma_\mu \nu_{eL}) (\bar{\nu}_{\mu L} \gamma_\mu \mu_L) + \tilde{s}_L (\bar{e}_R \nu_{eL}) (\bar{\nu}_{\mu L} \mu_R) \right] + h.c..$$

where...

$$\tilde{v}_L = 2 [\hat{\alpha}_{\varphi l}^{(3)}]_{11+22^*} - [\hat{\alpha}_{ll}^{(1)}]_{1221} - 2[\hat{\alpha}_{ll}^{(3)}]_{1122-\frac{1}{2}(1221)}$$

$$\tilde{s}_R = +2[\hat{\alpha}_{le}]_{2112},$$

$$\left(\hat{\alpha}_X \equiv \alpha_X \frac{v^2}{\Lambda^2} \right)$$

(Cirigliano, MGA, Jenkins.
Nucl.Phys.B830, 2010)

The eff. Lagrangian for E~1 GeV

- Beta decay:

$$d^j \rightarrow u^i l \bar{\nu}_l$$

$$\mathcal{L}_{d^j \rightarrow u^i l \bar{\nu}_l}^{eff}(x) = \frac{-g^2}{2m_W^2} V_{ij} \left[\begin{array}{c} (\text{V-A}) \bullet (\text{V-A}) \\ (1 + \nu_L)(\bar{u}_L^i \gamma^\mu d_R^j)(\bar{l}_L \gamma_\mu \nu_{IL}) + \nu_R(\bar{u}_R^i \gamma^\mu d_R^j)(\bar{l}_L \gamma_\mu \nu_{IL}) \\ \\ (\text{S-P}) \bullet (\text{S+P}) \quad (\text{S+P}) \bullet (\text{S+P}) \\ + s_L(\bar{u}_R^i d_L^j)(\bar{l}_R \nu_{IL}) + s_R(\bar{u}_L^i d_R^j)(\bar{l}_R \nu_{IL}) \\ \\ (\text{T-T'}) \bullet (\text{T-T'}) \\ + t_L(\bar{u}_R^i \sigma^{\mu\nu} d_L^j)(\bar{l}_R \sigma_{\mu\nu} \nu_{IL}) \end{array} \right] + h.c.$$

where...

$$V_{ij} \cdot [v_L]_{\ell\ell ij} = 2 V_{ij} [\hat{\alpha}_{\varphi l}^{(3)}]_{\ell\ell} + 2 V_{im} [\hat{\alpha}_{\varphi q}^{(3)}]_{jm}^* - 2 V_{im} [\hat{\alpha}_{lq}^{(3)}]_{\ell\ell jm}$$

$$V_{ij} \cdot [v_R]_{\ell\ell ij} = -[\hat{\alpha}_{\varphi\varphi}]_{ij}$$

$$V_{ij} \cdot [s_L]_{\ell\ell ij} = -[\hat{\alpha}_{lq}]_{\ell\ell ji}^*$$

$$V_{ij} \cdot [s_R]_{\ell\ell ij} = -V_{im} [\hat{\alpha}_{qde}]_{\ell\ell jm}^*$$

$$V_{ij} \cdot [t_L]_{\ell\ell ij} = -[\hat{\alpha}_{lq}^t]_{\ell\ell ji}^*$$

(Cirigliano, MGA, Jenkins.
Nucl.Phys.B830, 2010)

NP flavor structure

$$i(\varphi^\dagger D^\mu \sigma^a \varphi) \begin{pmatrix} \bar{l}_e \\ \bar{l}_\mu \\ \bar{l}_\tau \end{pmatrix} \gamma_\mu \sigma^a \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} l_e & l_\mu & l_\tau \end{pmatrix}$$



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- Flavor blind...

(More precisely, $U(3)^5$ invariant)

$$\alpha_{ql}^{(3)} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} = \bar{\alpha}_{ql}^{(3)} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

\approx MFV...

$$\alpha_{ql}^{(3)} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} = \bar{\alpha}_{ql}^{(3)} \mathbf{I}_{3 \times 3} + \bar{\beta}_{ql}^{(3)} \Delta_{LL}^{(l)} + \dots$$

$$\begin{aligned} \Delta_{LL}^{(q)} &= V^\dagger \bar{\lambda}_u^2 V \\ \Delta_{LL}^{(\ell)} &= \frac{\Lambda_{LN}^2}{v^4} U \bar{m}_\nu^2 U^\dagger \end{aligned}$$

$$= \bar{\alpha}_{ql}^{(3)} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \bar{\beta}_{ql}^{(3)} 10^{-4} \begin{pmatrix} \sim 0.1 & \sim 0.1 & \sim 0.1 \\ \sim 0.1 & \sim 1 & \sim 1 \\ \sim 0.1 & \sim 1 & \sim 1 \end{pmatrix} + \dots$$

- More generic structure...

$$\alpha_{ql}^{(3)} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

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Flavor blind case:

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

$$\mathcal{L}_{\mu \rightarrow e \bar{\nu} \bar{\nu}}^{eff}(x) = \frac{-g^2}{2m_W^2} \left[(1 + \tilde{\nu}_L)(\bar{e}_L \gamma_\mu \nu_{eL})(\bar{\nu}_{\mu L} \gamma_\mu \mu_L) + \tilde{s}_L (\bar{e}_R \nu_{eL})(\bar{\nu}_{\mu L} \mu_R) \right] + h.c.$$

where... $\tilde{\nu}_L = 4\bar{\alpha}_{ql}^{(3)} - 2\bar{\alpha}_{ll}^{(3)}$

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where... $[\nu_L]_{llij} = 2\bar{\alpha}_{ql}^{(3)} + 2\bar{\alpha}_{qq}^{(3)} - 2\bar{\alpha}_{lq}^{(3)}$

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$$G_F^{pheno(\mu)} = G_F^{(0)} (1 + \tilde{v}_L)$$

$$d^j \rightarrow u^i l \bar{\nu}_l$$

$$(1 + v_L) (\bar{u}_L^i \gamma^\mu d_R^j) (\bar{l}_L \gamma_\mu \nu_{lL}) + \cancel{v_R} (\bar{u}_R^i \gamma^\mu d_R^j) (\bar{l}_L \gamma_\mu \nu_{lL})$$

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Flavor blind case:

- Thus, all the NP are:

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- Just shifts of G_F and V_{ij} !!! (no channel-dependence, no new FFs)
→ Only one place where we are sensitive to this...

$$\Delta_{CKM} \equiv |V_{ud}^{pheno}|^2 + |V_{us}^{pheno}|^2 + |V_{ub}^{pheno}|^2 - 1 \rightarrow \Delta_{CKM} = 4(-\bar{\alpha}_{ql}^{(3)} + \bar{\alpha}_{qq}^{(3)} - \bar{\alpha}_{lq}^{(3)} + \bar{\alpha}_{ll}^{(3)})$$

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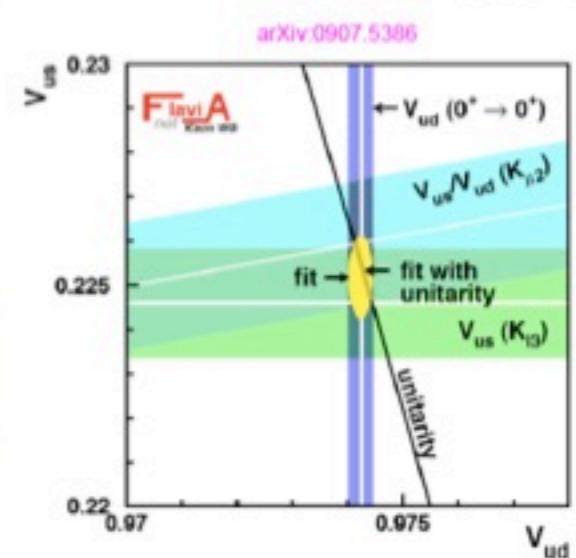
- How well known is Δ_{CKM} ?

$$V_{ud} = 0.97425(22)$$

$$V_{us} = 0.2252(9)$$

$$V_{ub} \sim 10^{-3}$$

$$\Delta_{CKM} = -(0.1 \pm 0.6) \cdot 10^{-3}$$



Δ_{CKM} vs. EWPT

$$\Lambda_{NP}^{eff} = \frac{\Lambda_{NP}}{\sqrt{\hat{\alpha}}} > 11 \text{ TeV} \text{ (90% CL)}$$

$$\Delta_{CKM} = 4 \left(-\hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)} - \hat{\alpha}_{lq}^{(3)} + \hat{\alpha}_{ll}^{(3)} \right) = -(1 \pm 6) \cdot 10^{-4}$$

$$O_{ll}^{(3)} = \frac{1}{2} (\bar{l} \gamma^\mu \sigma^a l) (\bar{l} \gamma_\mu \sigma^a l)$$

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

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

What did we know about them from EWPT?

Δ_{CKM} vs. EWPT

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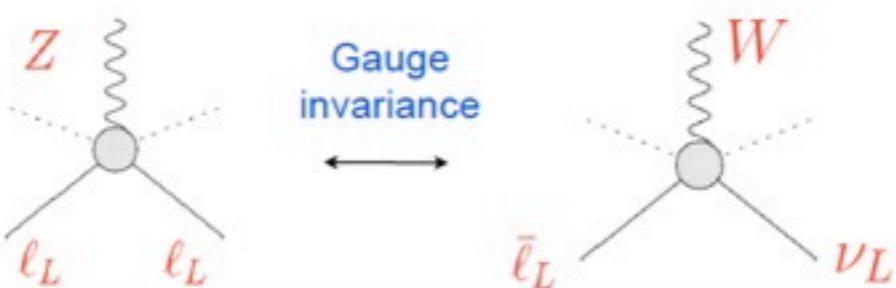
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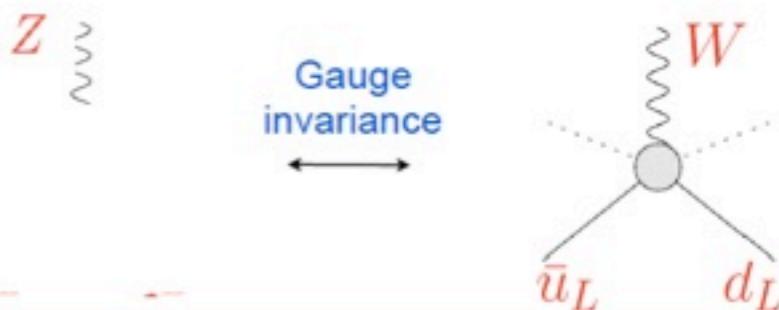


G_F-extraction
from mu-decay

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



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



Δ_{CKM} vs. EWPT

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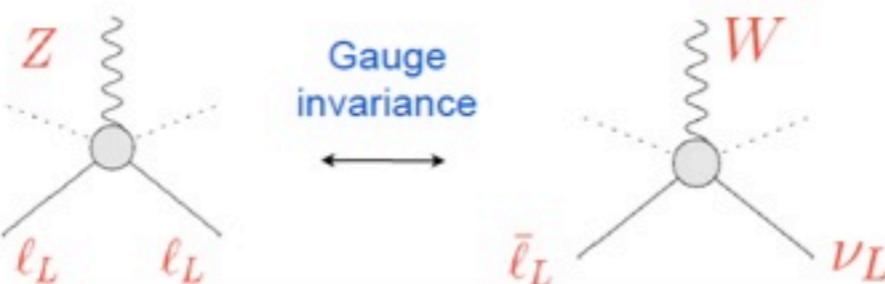
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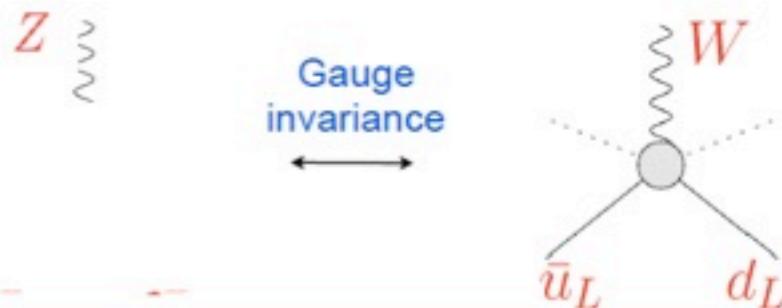
LEPII: $e^+ e^- \rightarrow q \bar{q}$

G_F-extraction
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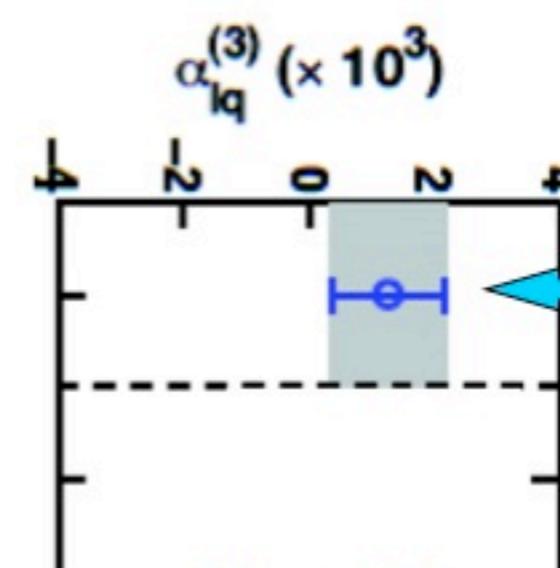
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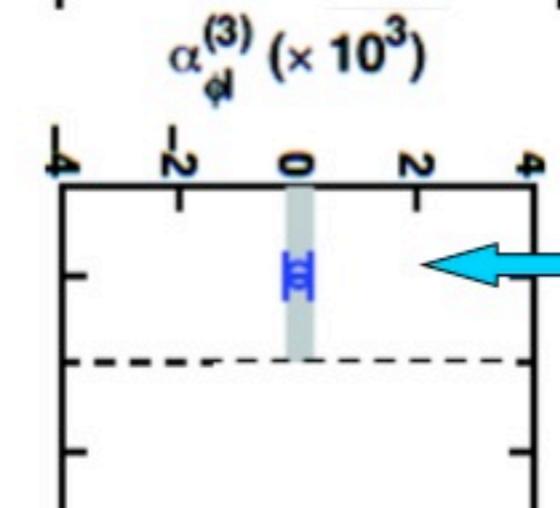
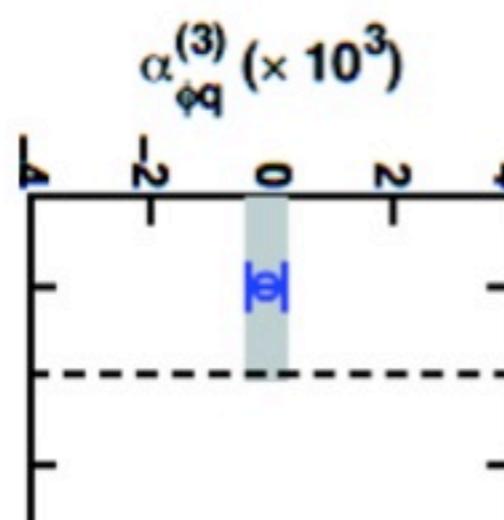
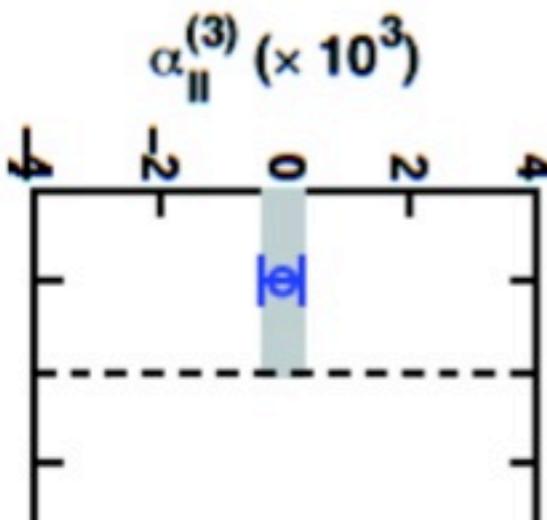
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What did we know about them from EWPT?



Han & Skiba,
PRD71, 2005.

EWPT



EWPT

Δ_{CKM} vs. EWPT

$$\Lambda_{NP}^{eff} = \frac{\Lambda_{NP}}{\sqrt{\hat{\alpha}}} > 11 \text{ TeV} \text{ (90% CL)}$$

$$\Delta_{CKM} = 4 \left(-\hat{\alpha}_{ql}^{(3)} + \hat{\alpha}_{qq}^{(3)} - \hat{\alpha}_{lq}^{(3)} + \hat{\alpha}_{ll}^{(3)} \right) = -(1 \pm 6) \cdot 10^{-4}$$

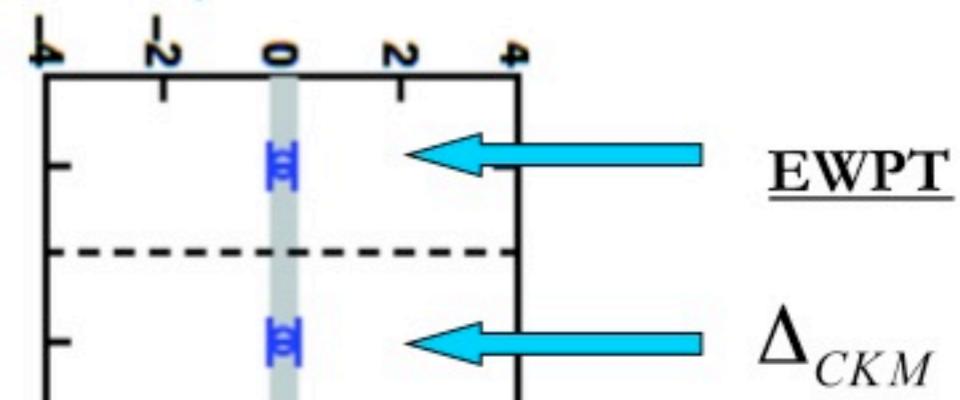
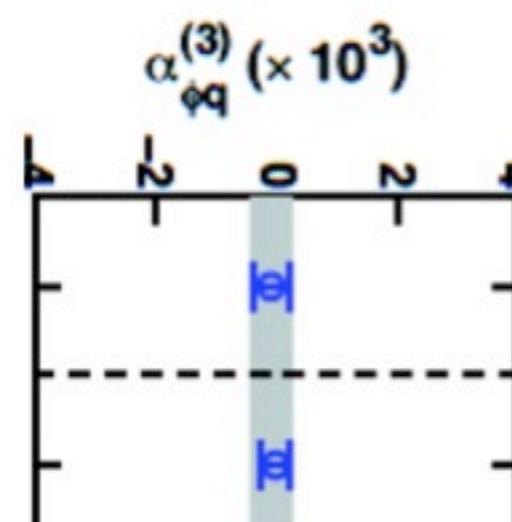
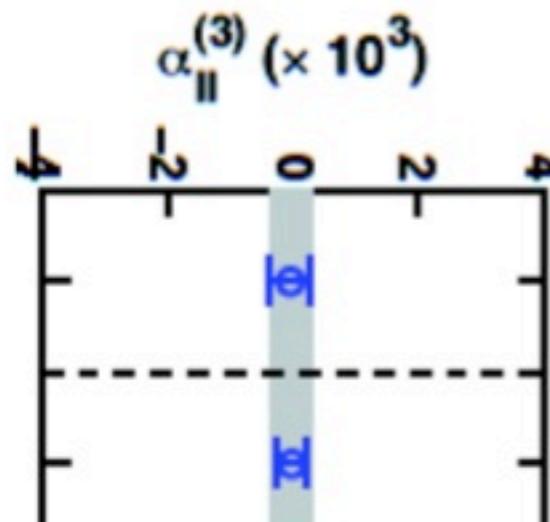
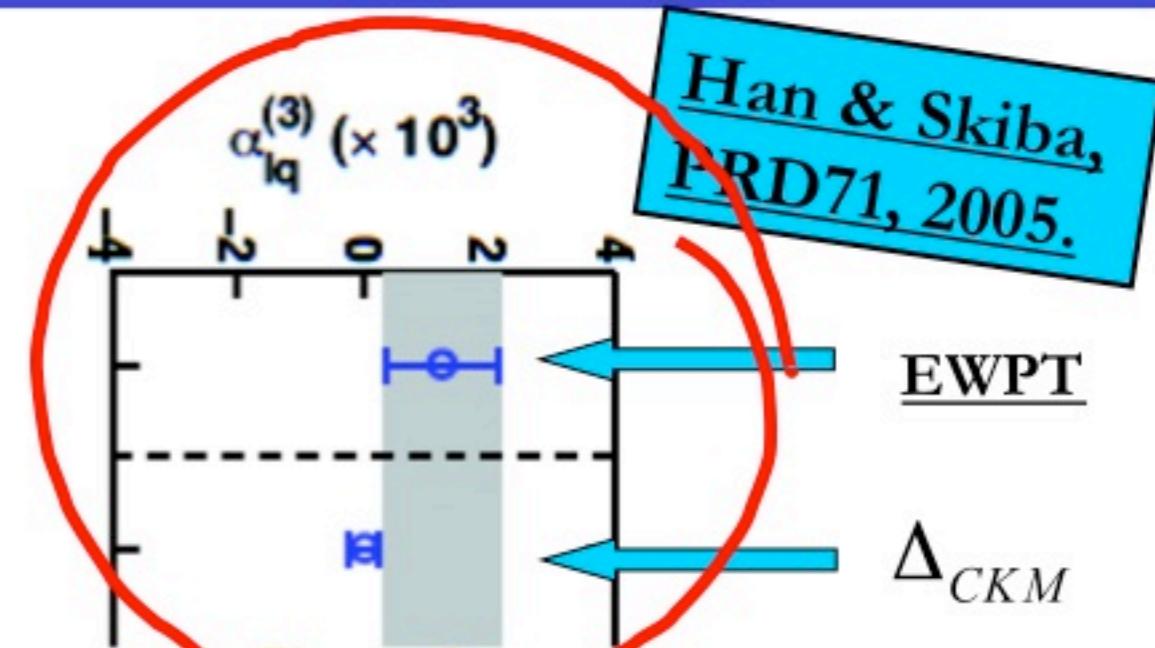
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$$O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi) (\bar{q} \gamma_\mu \sigma^a q) + \text{h.c.}$$

What did we know about them from EWPT?



General flavor structure

□ Beyond MFV...

$$\mathcal{L}_{d^j \rightarrow u^i l \bar{v}_l}^{eff}(x) = \frac{-g^2}{2m_W^2} V_{ij} \left[(1 + \textcolor{blue}{v}_L)(V - A)(V - A) + \textcolor{blue}{v}_R(V + A)(V - A) \right. \\ \left. + \textcolor{blue}{s}_L(S - P)(S + P) + \textcolor{blue}{s}_R(S + P)(S + P) + \textcolor{blue}{t}_L(T - T')(T - T') \right]$$

- New Lorentz structures → Very rich phenomenology...
 - V_{ij} are channel-dependent;
 - New hadronic form factors;
 - No Han-Skiba analysis for other EWPT
- Example: neutron beta decay.

Example: neutron beta decay

- After hadronization...

$$\lambda_X \equiv g_X/g_V$$

$$\tilde{\lambda}_A \equiv \lambda_A(1 - 2v_R)$$

$$\begin{aligned} \mathcal{L}_{n \rightarrow pe^-\bar{\nu}} = & \frac{-g^2}{4m_W^2} V_{ud} g_V \left(\underline{1 + [v_L + v_R]} \right) \left[\bar{\ell}_L \gamma_\mu \nu_{\ell L} \cdot \bar{p} \left(\gamma^\mu - \tilde{\lambda}_A \gamma^\mu \gamma_5 \right) n \right. \\ & \left. + \lambda_S \underline{[s_L + s_R]} \bar{\ell}_R \nu_{\ell L} \cdot \bar{p} n + 2\lambda_T \underline{[t_L]} \bar{\ell}_R \sigma_{\mu\nu} \nu_{\ell L} \bar{p}_R \sigma^{\mu\nu} n_L \right] \end{aligned}$$

- $[v_L + v_R] \rightarrow$ CKM-unitarity tests*
- $[s_L + s_R]$ and $[t_L] \rightarrow$ correlation coeff. (angular distribution), giving us access to three new effective operators of our list:

$$\begin{aligned} O_{lq}^t &= (\bar{l}_a \sigma^{\mu\nu} e) \epsilon^{ab} (\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.} \\ O_{qde} &= (\bar{\ell} e)(\bar{d} q) + \text{h.c.}, \\ O_{lq} &= (\bar{l}_a e) \epsilon^{ab} (\bar{q}_b u) + \text{h.c.} \end{aligned}$$

*The lattice value of g_A is not precise enough to give strong bounds on v_R .

Example: neutron beta decay

- After hadronization...

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- $[v_L + v_R] \rightarrow$ CKM-unitarity tests*
- $[s_L + s_R]$ and $[t_L] \rightarrow$ correlation coeff. (angular distribution), giving us access to three new effective operators of our list:

... only if know the new hadronic FFs!

*The lattice value of g_A is not precise enough to give strong bounds on v_R .

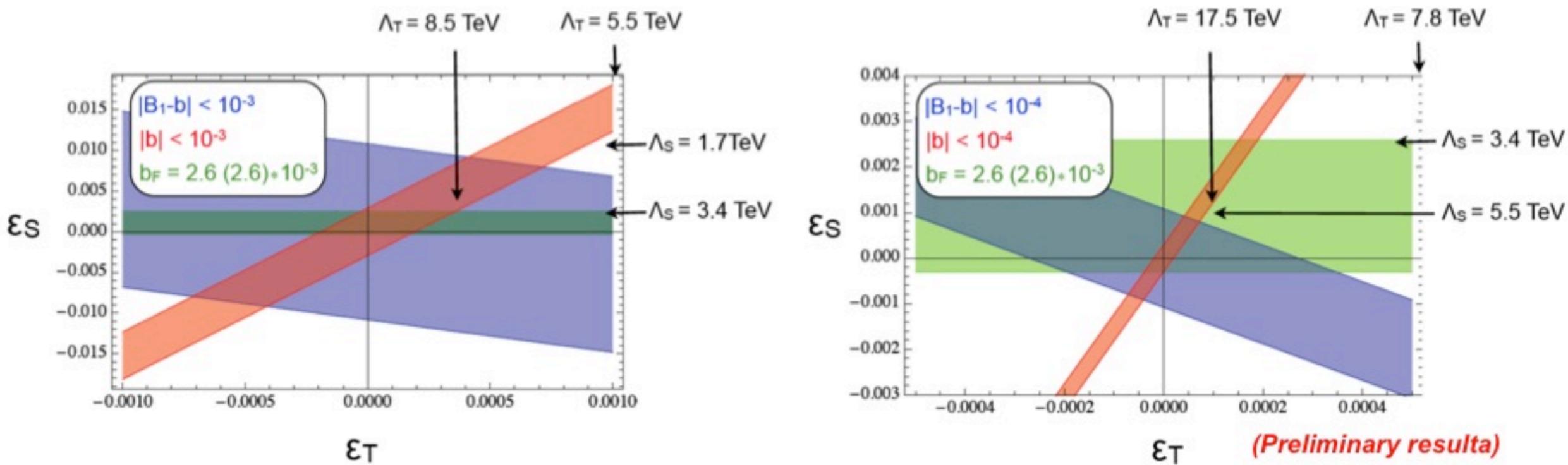
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Example: neutron beta decay

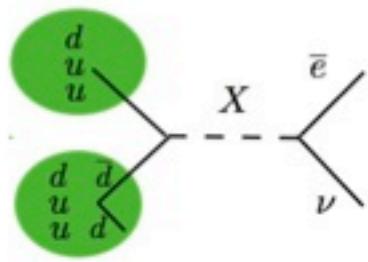
- Lattice determination of the scalar and tensor FFs;
- Precise experimental measurements of the b and b_ν parameters:
(1st direct experimental measurements expected soon!)

*(Ultra)cold neutrons...
 $E_n \sim 10^{-7} - 10^{-2}$ eV!!!*

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \sim 1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\mathbf{J}}{J} \cdot \left[A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} + b_\nu \frac{m_e \mathbf{p}_\nu}{E_e E_\nu} \right]$$

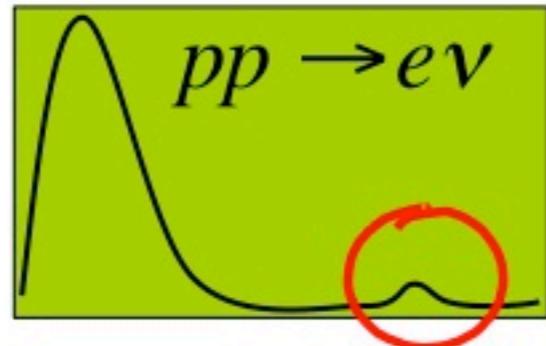


*(Work in progress, in collaboration with...
Bhattacharya, Cirigliano, Cohen, Filipuzzi, Grasser, Gupta, Lin)*



Example: neutron beta decay

- Interplay with colliders... just an example...
 - Let's assume we observe a resonance in the channel $pp \rightarrow e\nu$



$$\begin{aligned}\mathcal{L} &= g_L Q d^c S + g_R u^c Q S^* + g_l e^c L S \\ S &\sim (1, 2, -1/2)\end{aligned}$$

- Could it be a scalar resonance?
 - It could, but it'd imply a deviation in the neutron correlation coeff. wrt SM.
 - Conversely, the precise measurement of neutron correlation coefficient rules out part of the parameter space (M, σ) for a scalar resonance at the LHC.

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

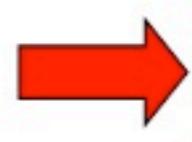
(Work in progress, in collaboration with...
 Bhattacharya, Cirigliano, Cohen, Filipuzzi, Grasser, Gupta, Lin)

Conclusions

- Semileptonic decays of light quarks are EWPO.
- We have studied them in a “model-independent” framework, identifying the 4(9) operators involved.

- Flavor blind NP:

$$\Delta_{CKM} = 4 \left(-\bar{\alpha}_{ql}^{(3)} + \bar{\alpha}_{qq}^{(3)} - \bar{\alpha}_{lq}^{(3)} + \bar{\alpha}_{ll}^{(3)} \right) = -(0.1 \pm 0.6) \cdot 10^{-3}$$

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

$\Lambda_i^{eff} > 11 \text{ TeV (90% CL)}$

- General flavor structure NP: Rich phenomenology.

- Example: neutron beta decay gives us access to scalar and tensor interactions (exp. 0.1% → >1 TeV)

$$\begin{aligned} O_{lq}^t &= (\bar{l}_a \sigma^{\mu\nu} e) \epsilon^{ab} (\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.} \\ O_{qde} &= (\bar{\ell} e)(\bar{d} q) + \text{h.c.}, \\ O_{lq} &= (\bar{l}_a e) \epsilon^{ab} (\bar{q}_b u) + \text{h.c.} \end{aligned}$$

Backup slides

The eff. Lagrangian for E~100 GeV

Vectors and Scalars:

$$O_{WB} = (\varphi^\dagger \sigma^a \varphi) W_{\mu\nu}^a B^{\mu\nu} \quad O_\varphi^{(3)} = |\varphi^\dagger D_\mu \varphi|^2 \quad O_W = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\lambda} W_\lambda^{c\mu}$$

4-Fermion operators:

$$O_{ll}^{(1)} = \frac{1}{2}(\bar{l}\gamma^\mu l)(\bar{l}\gamma_\mu l), \quad O_{ll}^{(3)} = \frac{1}{2}(\bar{l}\gamma^\mu \sigma^a l)(\bar{l}\gamma_\mu \sigma^a l)$$

$$O_{lq}^{(1)} = (\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q), \quad O_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$

$$O_{le} = (\bar{l}\gamma^\mu l)(\bar{e}\gamma_\mu e), \quad O_{qe} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e),$$

$$O_{lu} = (\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u), \quad O_{ld} = (\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d),$$

$$O_{ee} = \frac{1}{2}(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e), \quad O_{eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u), \quad O_{qe} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e), \quad O_{qd} = (\bar{q}\gamma^\mu q)(\bar{d}\gamma_\mu d), \quad O_{qe} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e), \quad O_{qd} = (\bar{q}\gamma^\mu q)(\bar{d}\gamma_\mu d), \quad O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}, \quad O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$

2-Fermions + V + S:

$$O_{\varphi l}^{(1)} = i(\varphi^\dagger D^\mu \varphi)(\bar{l}\gamma_\mu l) + \text{h.c.}, \quad O_{\varphi l}^{(3)} = i(h^\dagger D^\mu \sigma^a \varphi)(\bar{l}\gamma_\mu \sigma^a l) + \text{h.c.},$$

$$O_{\varphi q}^{(1)} = i(\varphi^\dagger D^\mu \varphi)(\bar{q}\gamma_\mu q) + \text{h.c.}, \quad O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q) + \text{h.c.},$$

$$O_{\varphi u} = i(\varphi^\dagger D^\mu \varphi)(\bar{u}\gamma_\mu u) + \text{h.c.}, \quad O_{\varphi d} = i(\varphi^\dagger D^\mu \varphi)(\bar{d}\gamma_\mu d) + \text{h.c.}$$

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

21 $U(3)^5$ inv. operators

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

4 non- $U(3)^5$ inv. ops

The eff. Lagrangian for E~100 GeV

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21 $U(3)^5$ inv. operators

$\begin{pmatrix} l_e \\ l_\mu \\ l_\tau \end{pmatrix}$	$\begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$	$\begin{pmatrix} q_u \\ q_c \\ q_t \end{pmatrix}$	$\begin{pmatrix} u \\ c \\ t \end{pmatrix}$	$\begin{pmatrix} d \\ s \\ b \end{pmatrix}$
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$$O_{\varphi u} = i(\varphi^\dagger D^\mu \varphi)(\bar{u}\gamma_\mu u) + \text{h.c.}, \quad O_{\varphi d} = i(\varphi^\dagger D^\mu \varphi)(\bar{d}\gamma_\mu d) + \text{h.c.}$$

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

4 non- $U(3)^5$ inv. ops

Δ_{CKM} vs. EW precision measurements



Han & Skiba (2005)

- ❖ U(3)⁵ limit;
- ❖ 237 measurements;
- ❖ 21 parameters (α 's);

Classification	Standard Notation	Measurement
Atomic parity violation (Q_W)	$Q_W(\text{Cs})$ $Q_W(\text{Tl})$	Weak charge in Cs Weak charge in Tl
DIS	g_L^2, g_R^2 R^ν κ $g_V^{\nu e}, g_A^{\nu e}$	ν_μ -nucleon scattering from NuTeV ν_μ -nucleon scattering from CDHS and CHARM ν_μ -nucleon scattering from CCFR ν -e scattering from CHARM II
Zline (lepton and light quark)	Γ_Z σ_0 $R_f^0(f = e, \mu, \tau)$ $A_{FB}^{0,f}(f = e, \mu, \tau)$	Total Z width e^+e^- hadronic cross section at Z pole Ratios of lepton decay rates Forward-backward lepton asymmetries
pol	$A_f(f = e, \mu, \tau)$	Polarized lepton asymmetries
bc (heavy quark)	$R_f^0(f = b, c)$ $A_{FB}^{0,f}(f = b, c)$ $A_f(f = b, c)$	Ratios of hadronic decay rates Forward-backward hadronic asymmetries Polarized hadronic asymmetries
LEPII Fermion production	$\sigma_f(f = q, \mu, \tau)$ $A_{FB}^f(f = \mu, \tau)$	Total cross sections for $e^+e^- \rightarrow f\bar{f}$ Forward-backward asymmetries for $e^+e^- \rightarrow f\bar{f}$
eOPAL	$d\sigma_e/d\cos\theta$	Differential cross section for $e^+e^- \rightarrow e^+e^-$
WL3	$d\sigma_W/d\cos\theta$	Differential cross section for $e^+e^- \rightarrow W^+W^-$
MW	M_W	W mass
Q_{FB}	$\sin^2\theta_{eff}^{lept}$	Hadronic charge asymmetry

Δ_{CKM} vs. EW precision measurements

Han & Skiba (2005)

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- ❖ 237 measurements;
- ❖ 21 parameters (α 's);

Classification	Standard Notation	Measurement
Atomic parity	$Q_W(Cs)$	Weak charge in Cs
	$\chi^2(\hat{\alpha}_k) = \sum_{i,j} \left(X_{\text{th}}^i(\hat{\alpha}_k) - X_{\text{exp}}^i \right) \left(\sigma^2 \right)^{-1}_{ij} \left(X_{\text{th}}^j(\hat{\alpha}_k) - X_{\text{exp}}^j \right)$	
Zline (lepton and heavy quark)	$g_V^{\nu e}, g_A^{\nu e}$ Γ_Z σ_0	
		This leaves ample room for a sizeable violation of CKM-unitarity hadronic cross section at Z pole
	$A_{FB}^{0,f}(f = b, c)$	$\Delta_{\text{CKM}}^{\text{HEP-fit}} = 4 \left(-\bar{\alpha}_{ql}^{(3)} + \bar{\alpha}_{qq}^{(3)} - \bar{\alpha}_{lq}^{(3)} + \bar{\alpha}_{ll}^{(3)} \right) = -(4.7 \pm 2.9) \cdot 10^{-3}$
		$\Delta_{\text{CKM}}^{\text{exp.}} = -(0.1 \pm 0.6) \cdot 10^{-3}$ ← 5 times more precise!
		Forward-backward hadronic asymmetries

Then, let's do it in the other way around!

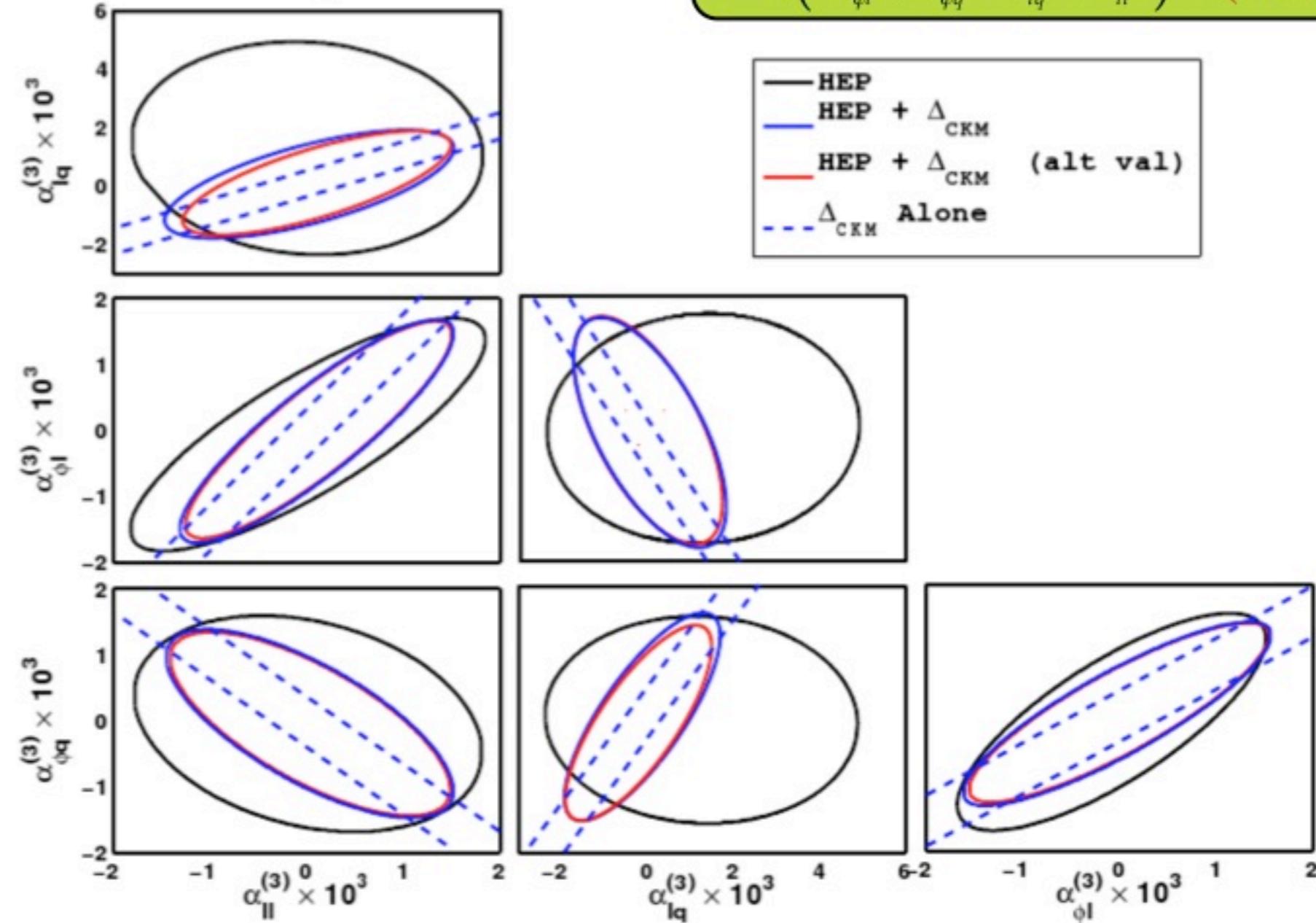
Adding Δ_{CKM} to the fit will improve the NP bounds.

Global analysis → Weaker bounds on NP (cancellations);

Single-operator analysis → Stronger bounds and correlations;

Δ_{CKM} vs. EW precision measurements

□ Global analysis

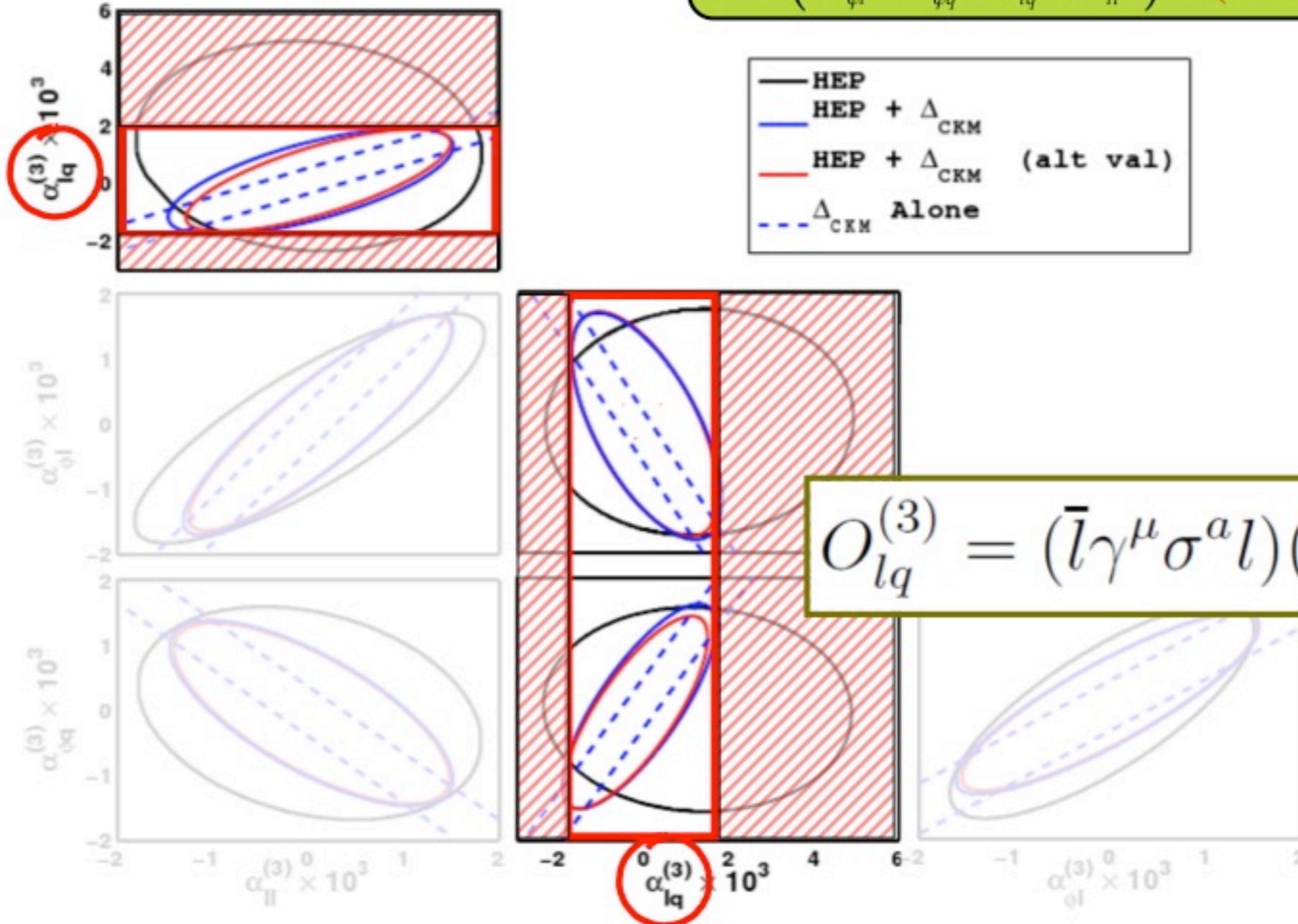


$$4(-\bar{\alpha}_{ql}^{(3)} + \bar{\alpha}_{qq}^{(3)} - \bar{\alpha}_{lq}^{(3)} + \bar{\alpha}_{ll}^{(3)}) = -(0.1 \pm 0.6) \cdot 10^{-3}$$

$$4(-\bar{\alpha}_{ql}^{(3)} + \bar{\alpha}_{qq}^{(3)} - \bar{\alpha}_{lq}^{(3)} + \bar{\alpha}_{ll}^{(3)}) = -(2.5 \pm 0.6) \cdot 10^{-3}$$

Δ_{CKM} vs. EW precision measurements

□ Global analysis



Δ_{CKM} vs. EW precision measurements

- Single operator analysis:

$$\pm 4\alpha_X = -(0.1 \pm 0.6) \cdot 10^{-3}$$

$$\Lambda > 11 \text{ TeV} \text{ (90% CL)}$$

