Effective Field Theory analysis at high energy

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IFAE / DESY

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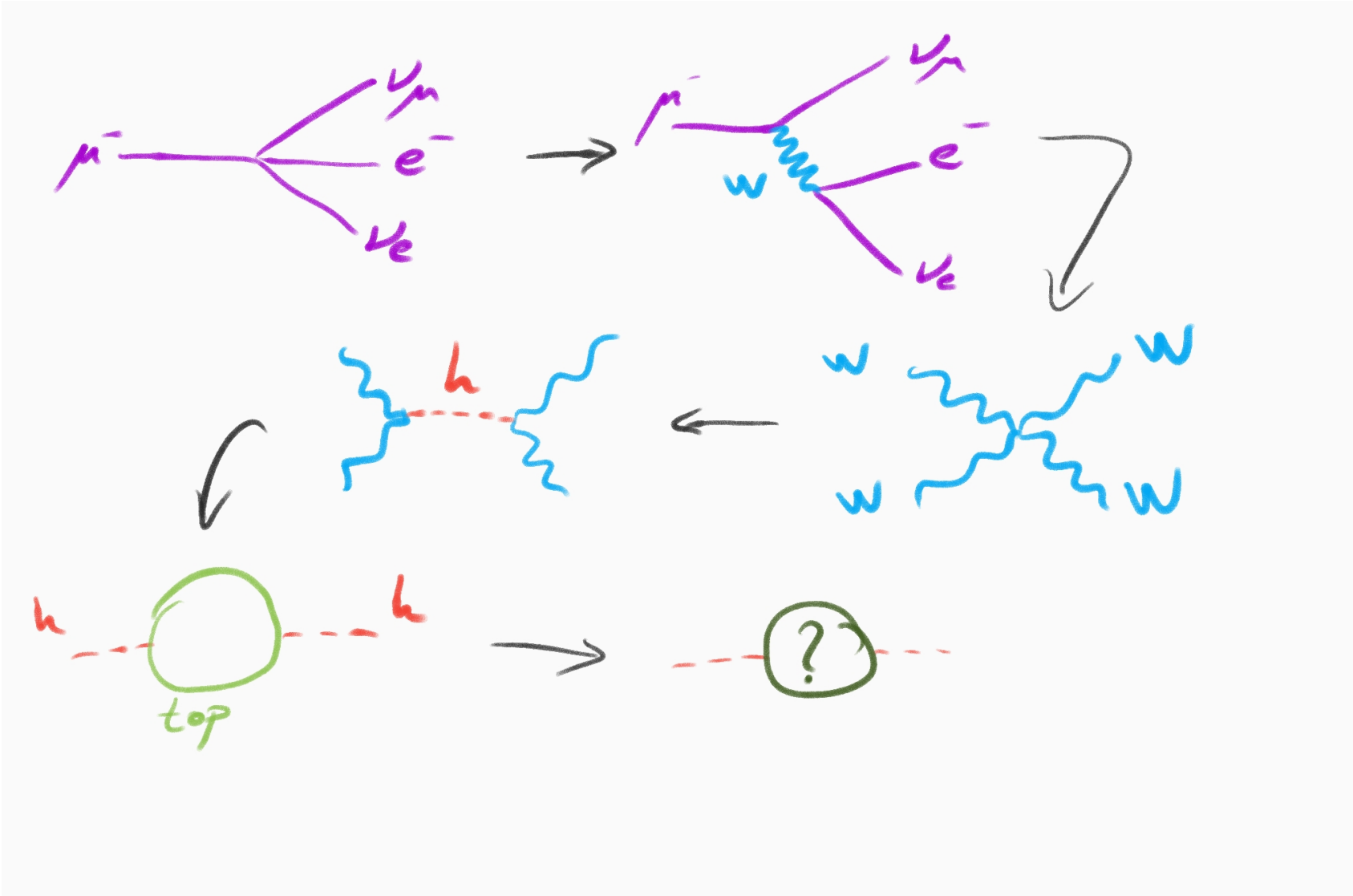
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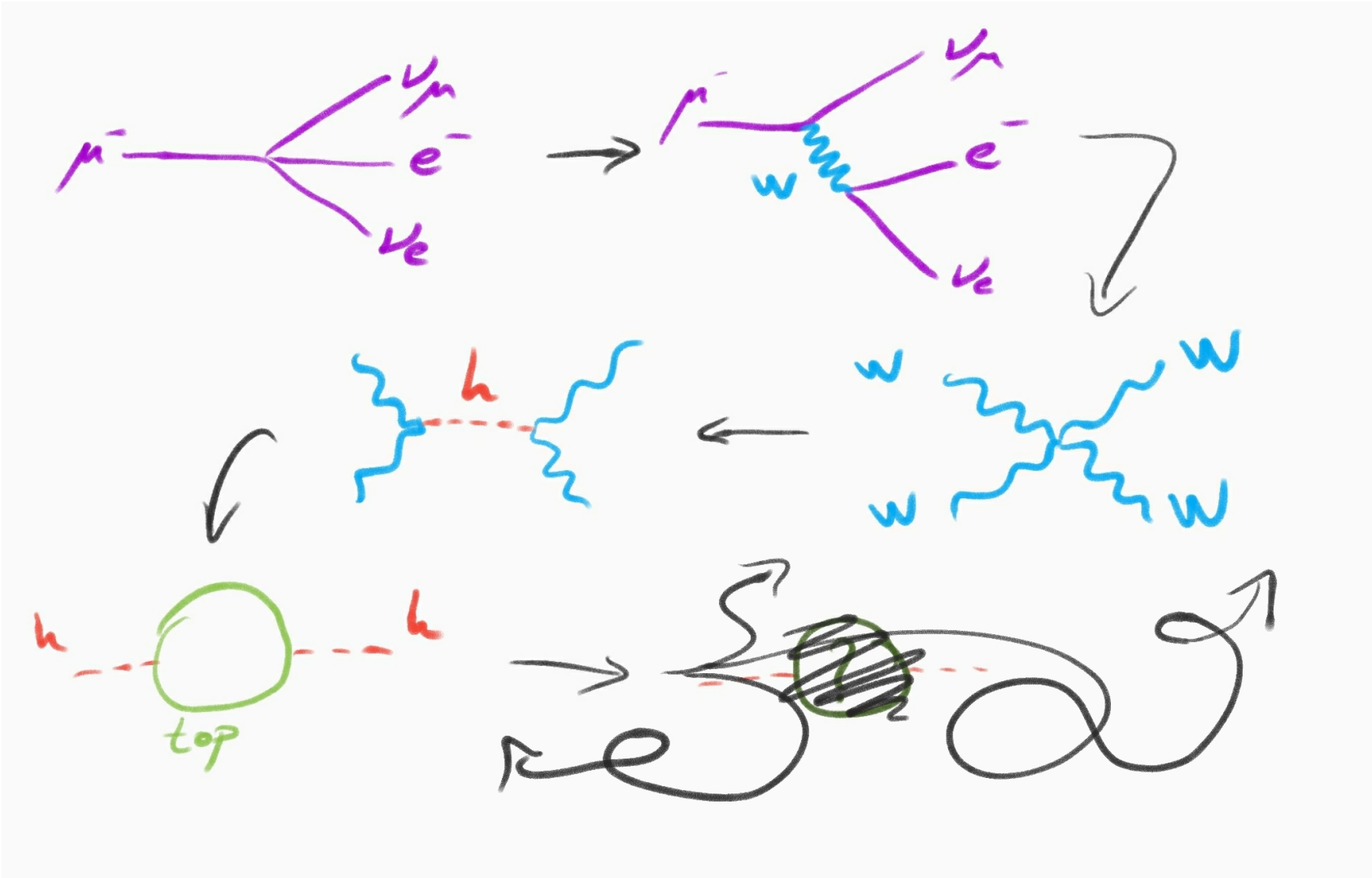
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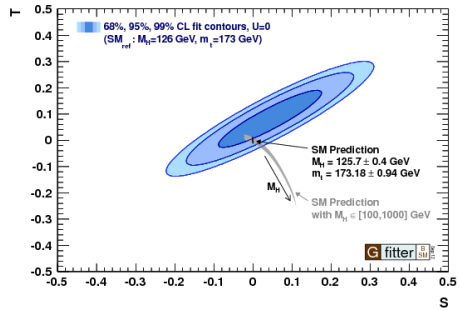
Where to go? No guaranteed path.
A mandatory program to pursue is to **stress-test the SM**.



Very useful program at LEP, told us that the mass and interaction eigenstates of the EW bosons are aligned to a high degree.

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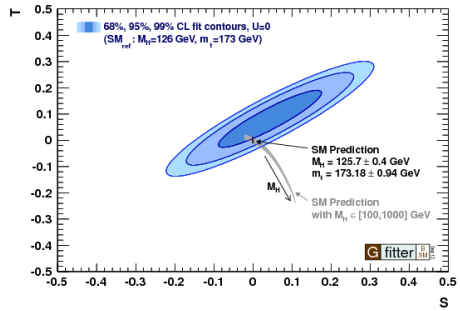

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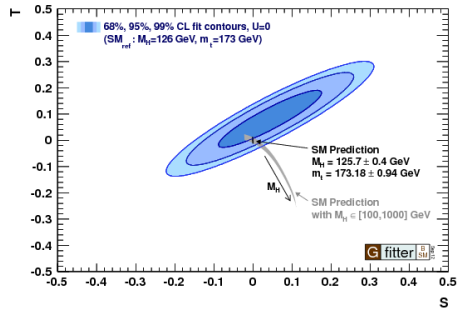

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However, *"Energy helps accuracy"*

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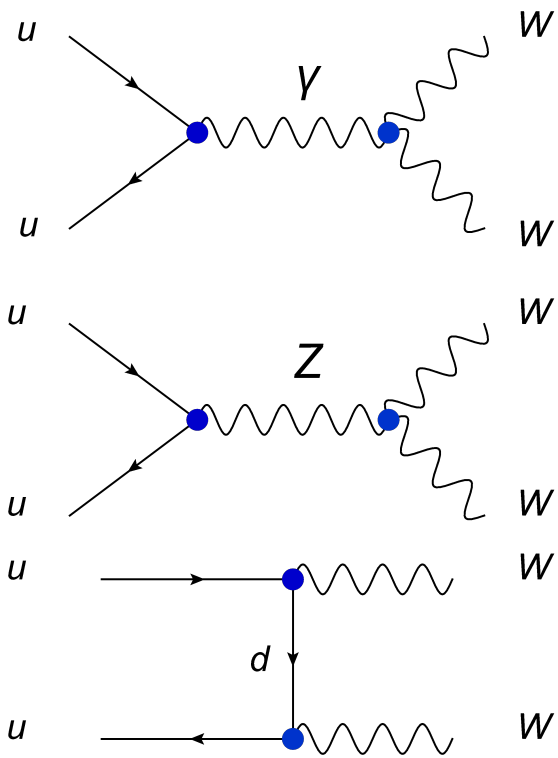
High energy enhancement: a proof of concept



$$\mathcal{M}_\gamma = -i\frac{e^2 \sin\theta}{2m_W^2}\, s\, Q_f$$

$$\mathcal{M}_Z = -i\frac{e^2 \sin\theta}{2m_W^2}\,\frac{s}{s_W^2}\,(T_f^3 - s_W^2 Q_f)$$

$$\mathcal{M}_t = +i\frac{e^2 \sin\theta}{2m_W^2}\,\frac{s}{2s_W^2}$$

Sum does not grow with energy, as expected.
However, it is obvious that a generic deviation from the SM relation will be amplified at large energies.

-If a deformation gets enhanced at high energy

$$\sigma \sim \sigma_{SM} \left(1 + c\, E^2/\Lambda^2 \right)$$

0.1% precision at E ∼100GeV $\leftrightarrow$ 10% precision at E ∼1TeV

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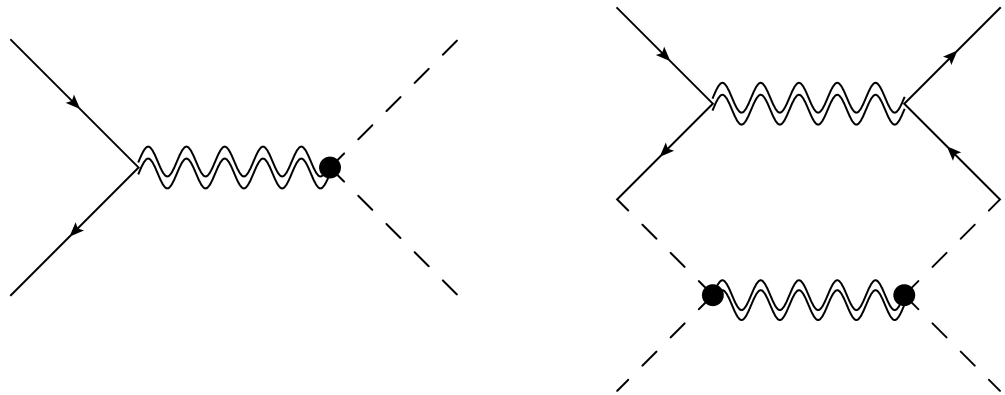
∼1% precision at E ∼30TeV $\leftrightarrow$ $10^{-5} - 10^{-6}$ precision at E ∼100GeV.

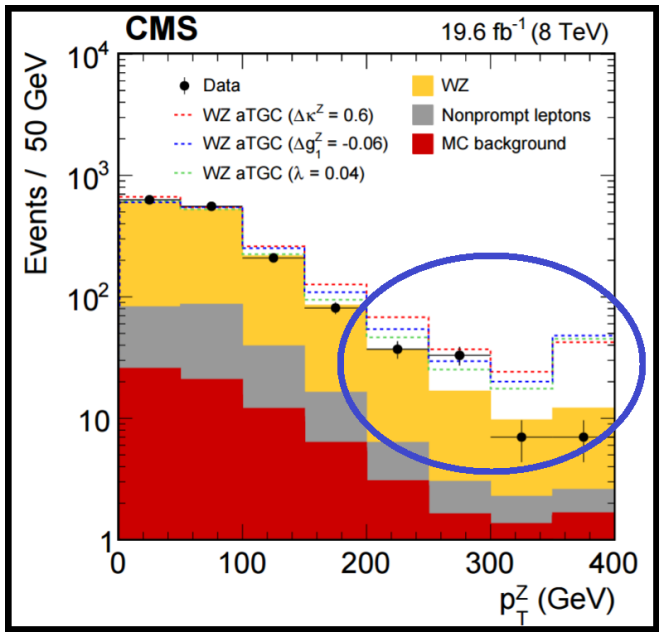
A 30TeV lepton collider will allow to test the SM to extreme levels.

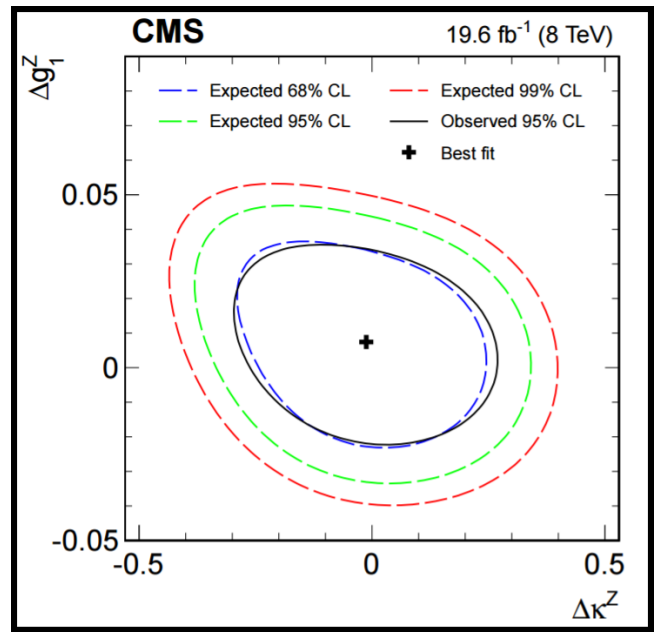
The SM is unique at $d = 4$, so deformations away from the SM cannot be arbitrary, they are organized in dimension six operators, which encode the low energy remnants of higher energy physics.



$$\mathcal{L} = \frac{c_{Hf}}{\Lambda^2}(\bar{f}\gamma_\mu f)(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{c_{4f}}{\Lambda^2}(\bar{f}\gamma_\mu f)(\bar{f}\gamma_\mu f) + \frac{c_H}{\Lambda^2}(H^\dagger D_\mu H)(H^\dagger D_\mu H)$$
$$+ \frac{1}{\Lambda^4}\mathcal{O}^{(8)} + \frac{1}{\Lambda^6}\mathcal{O}^{(10)} + \dots$$

LHC diboson analyses



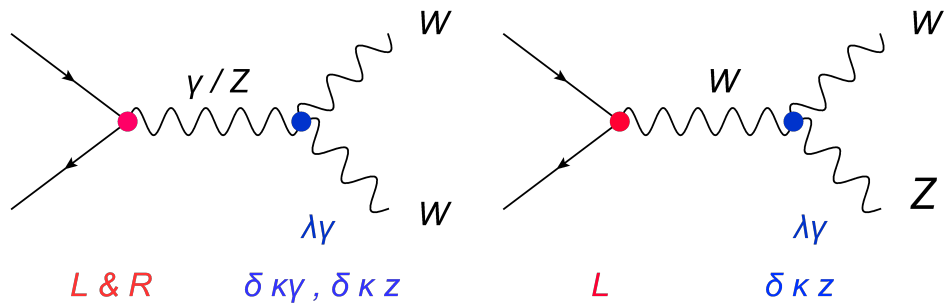


$$\text{LEP2} \quad : \quad \delta g_1^z = 0.051 \pm 0.031, \quad \delta\kappa_\gamma = -0.067 \pm 0.061, \quad \lambda_\gamma = -0.067 \pm 0.036$$

$$\text{LHC} \quad : \quad \delta g_1^z = 0.010 \pm 0.008, \quad \delta\kappa_\gamma = 0.017 \pm 0.028, \quad \lambda_\gamma = 0.0029 \pm 0.0057$$

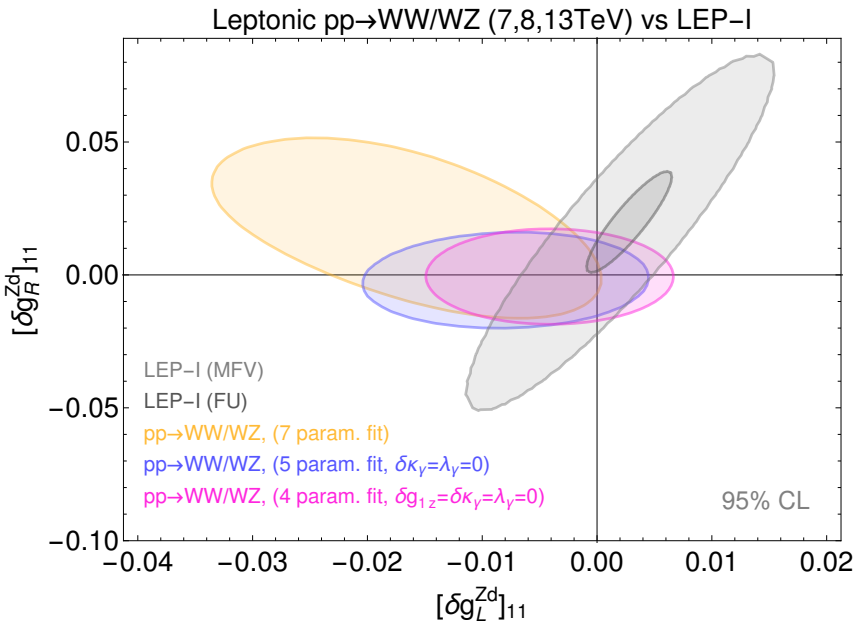
LHC already surpasses LEP in setting contraints to anomalous couplings among electroweak gauge bosons.

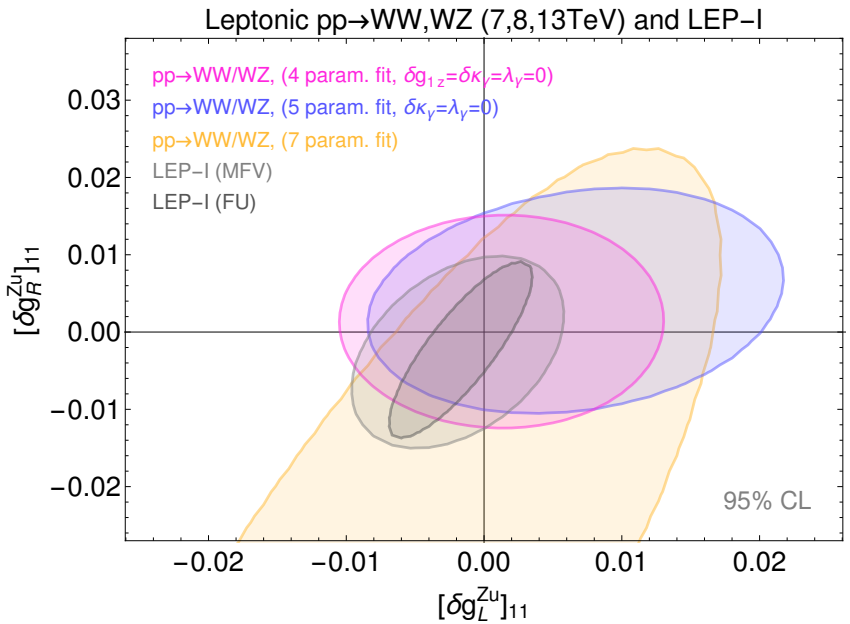
Light quark - electroweak anomalous couplings



$$
\begin{aligned}
\mathcal{L}_{V\bar{q}q} &= \sqrt{g^2+g'^2}\,Z_\mu \left[\sum_{f\in u,d} \bar{f}_L \gamma_\mu \left(T_f^3 - s_\theta^2 Q_f + \delta g_L^{Zf} \right) f_L \right. \\
&+ \left. \sum_{f\in u,d} \bar{f}_R \gamma_\mu \left(-s_\theta^2 Q_f + \delta g_R^{Zf} \right) f_R \right] \\
&+ \frac{g}{\sqrt{2}} \left(W_\mu^+ \bar{u}_L \gamma_\mu \left(I_3 + \delta g_L^{Wq} \right) d_L + \text{h.c.} \right) .
\end{aligned}
$$

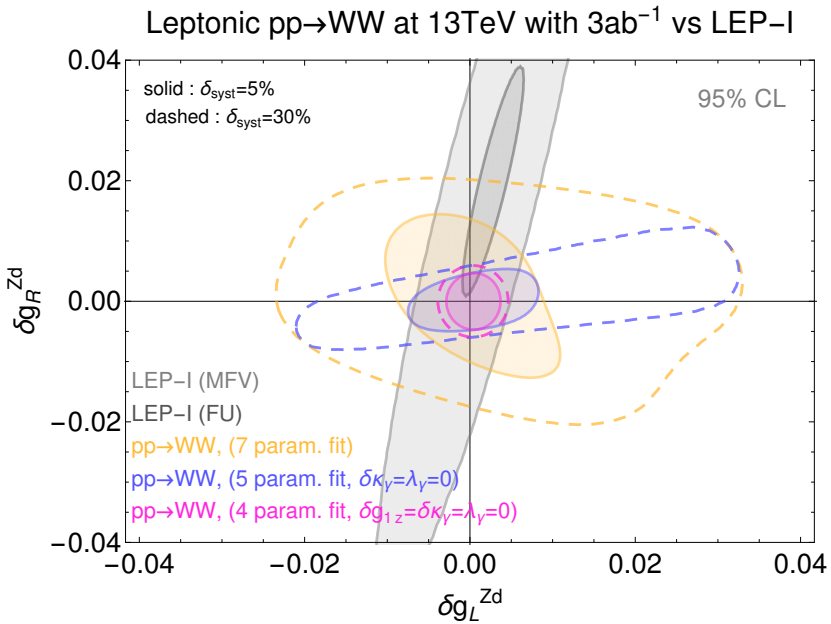
Light quark - electroweak anomalous couplings

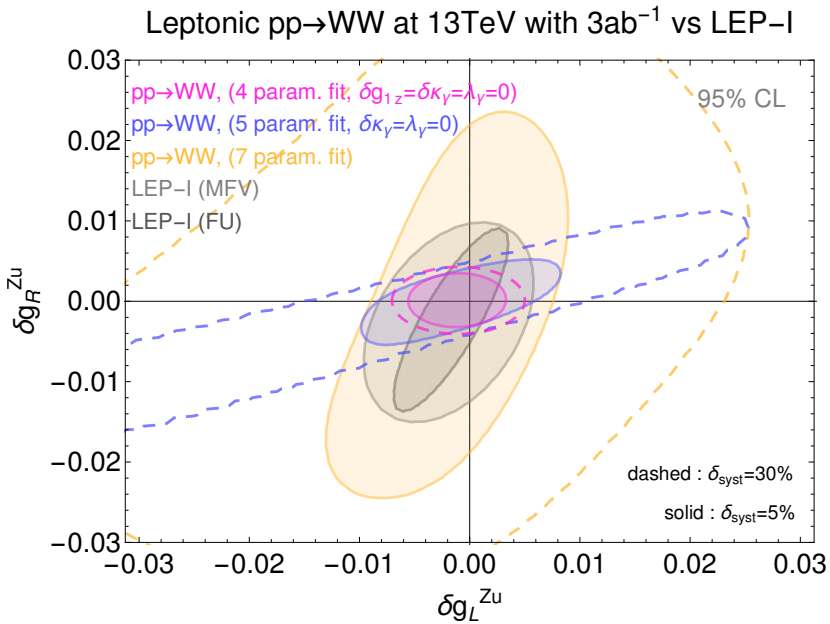




And already offers a better probe of some anomalous couplings among light quarks and electroweak gauge bosons.

Light quark - electroweak anomalous couplings





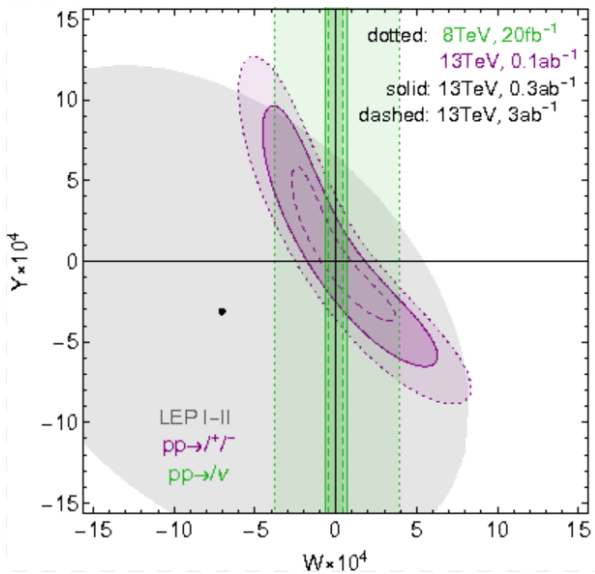
Single channel for diboson at HL-LHC will push LEP constraints for MFV and FU schemes.

Oblique parameters

The two point function $\Pi_{ij}(p)$ of $V_i = (W^1, W^2, W^3, B)$ gets corrections from S, T, W, Y

$$\delta\Pi_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & T & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \left(\frac{p}{m_W}\right)^0 + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S \\ 0 & 0 & S & 0 \end{pmatrix} \left(\frac{p}{m_W}\right)^2 + \begin{pmatrix} W & 0 & 0 & 0 \\ 0 & W & 0 & 0 \\ 0 & 0 & W & 0 \\ 0 & 0 & 0 & Y \end{pmatrix} \left(\frac{p}{m_W}\right)^4$$

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{q^2} - \frac{t_W^2 W + Y}{m_Z^2} & \frac{t_W(Y+T)c_W^2 + s_W^2 W - S}{(c^W - s^2)(q^2 - m_Z^2)} + \frac{t_W(Y-W)}{m_Z^2} \\ \star & \frac{1 + T - W - t_W^2 Y}{q^2 - m_Z^2} - \frac{t_W^2 Y + Z}{m_Z^2} \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix}$$



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Oblique parameters

S and T do not deform Drell-Yan in a way that increases at high energy, but they deform the production of (the longitudinal polarizations of) diboson,

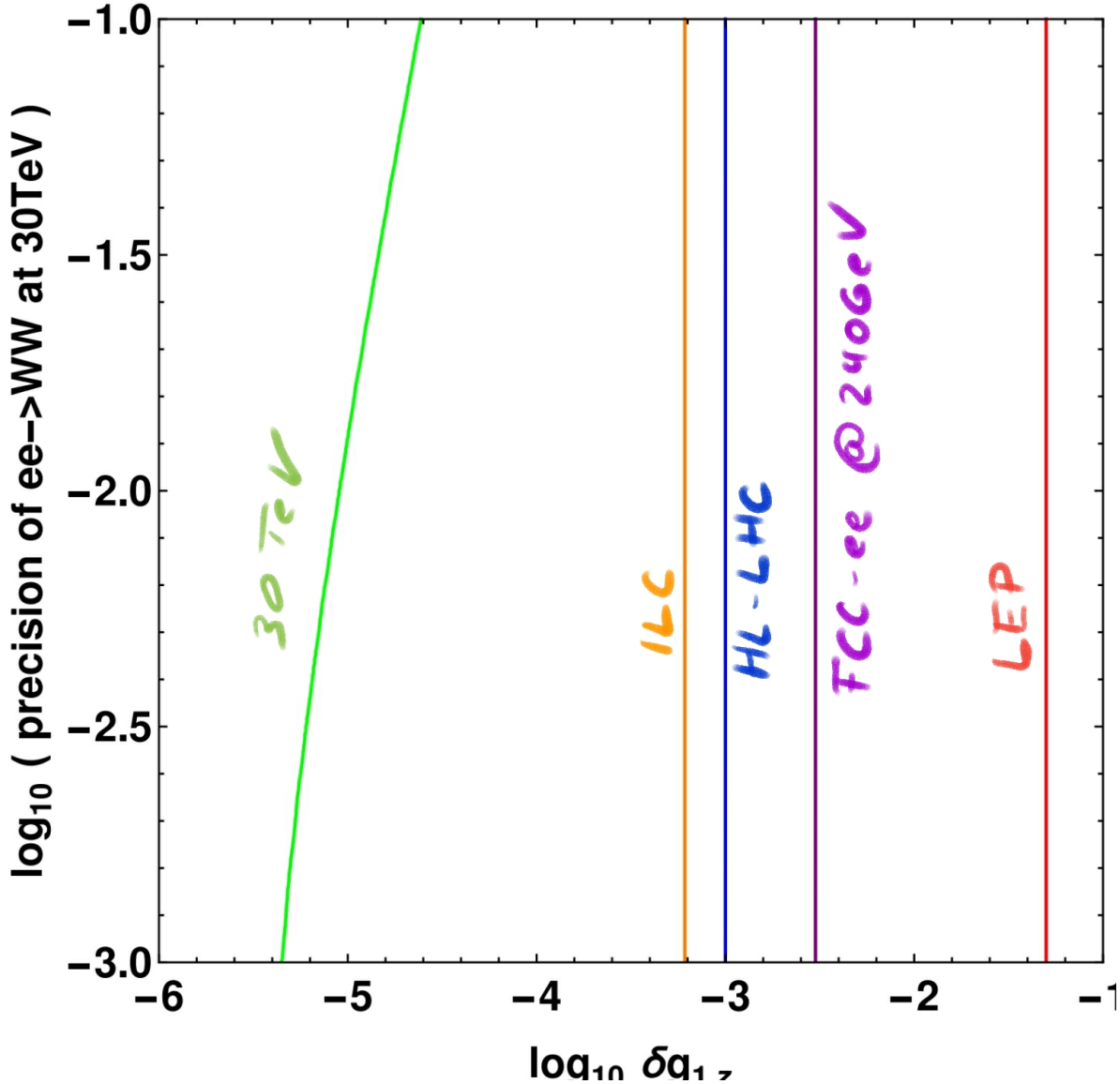
$$\mathcal{M}(LL;00) = i\frac{s}{m_W^2}\frac{e^2\,\sin\theta}{2s_W^2}\left[(2T_f^3)\,\delta g_L^{Wq} - \delta g_L^{Zq} - \delta g_{1z}(T_f^3 - s_W^2 Q_f) + \delta\kappa_\gamma t_W^2(T_f^3 - Q_f)\right] + \cdots$$

$$\mathcal{M}(RR;00) = i\frac{s}{m_W^2}\frac{e^2\,\sin\theta}{2s_W^2}\left[\delta g_R^{Zq} - \delta g_{1z} Q_f s_W^2 + \delta\kappa_\gamma Q_f s_W^2\right] + \cdots$$

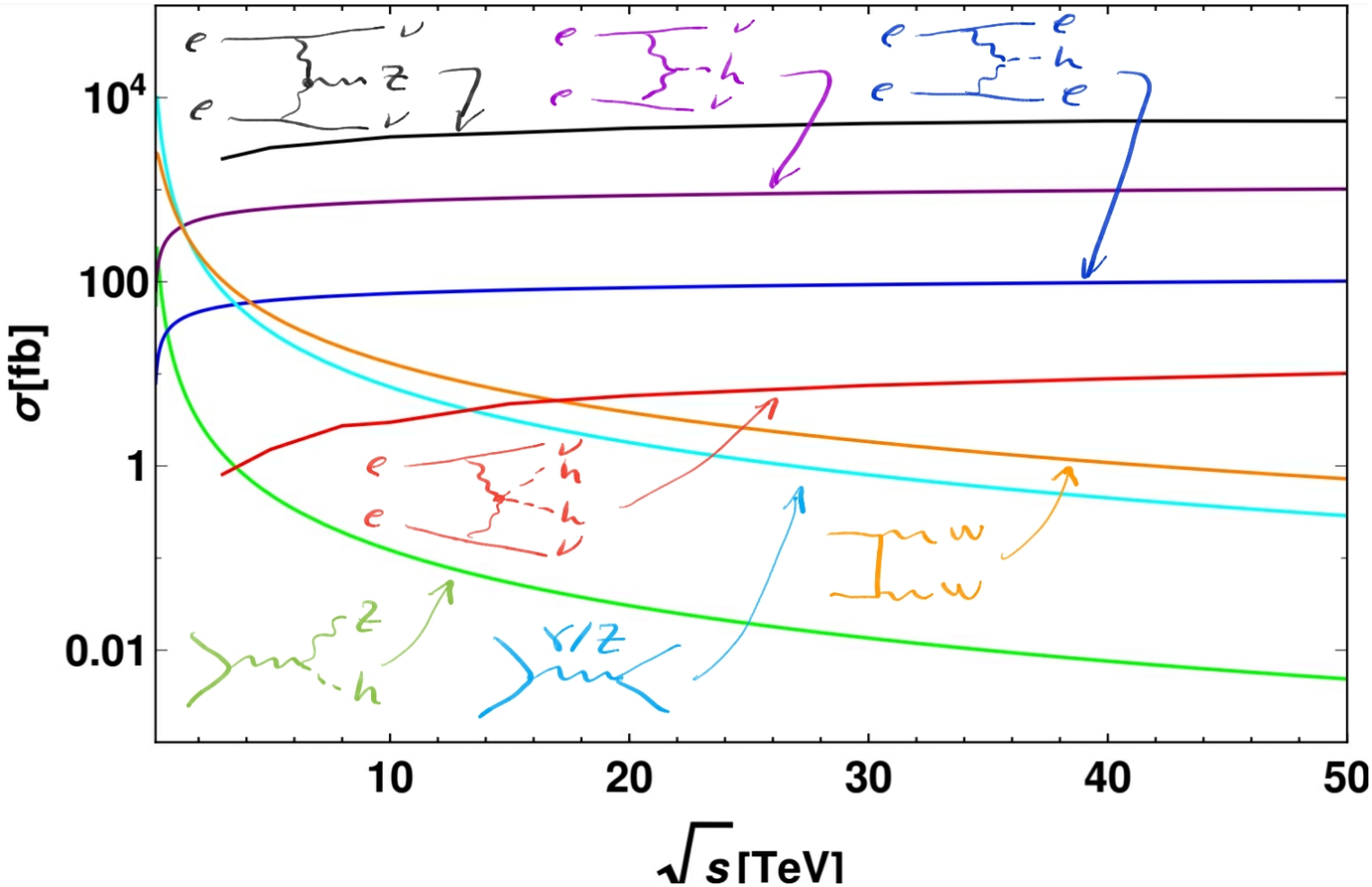
$$\delta g_{L,R}^{Zf} = \frac{1}{2}T_f^3\left(-W - Yt_W^2 + T\right) + \frac{1}{2}Q_f\frac{s_W^2}{c_{2W}}\left(W + Y(2 - t_W^2) + T - 2S\right),$$

$$\delta g_{1z} = \frac{1}{2c_{2W}}\left(T + W + Yt_W^2 - (S - S^T) - (S + S^T)t_W^2\right),$$

Back of the envelope estimate at 30TeV



Hierarchy of cross sections at high energy



Conclusions

- Deformations of the SM enhance some processes at high energy

- 30-ish TeV lepton collider will be able to test the SM not only at high energy, but also to high accuracy.

- Hierarchy of cross sections is peculiar, not clear what would be the important channels to look at.

Thank you