Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

EFT bounds from VV production

at hadron colliders

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3rd FCC Physics and Experiments Workshop
CERN, 15-01-2020

based on an ongoing project with De Curtis, Delgado, Panico, Redi
with material from Panico's slides

Precision at Hadron Colliders

Can we perform "**precision measurements**" at the **hadron colliders**?

- ☑ Obvious answer:
  yes, for previously untested observables

for example:

- ✱ Higgs couplings at the LHC (can reach a precision better than 10%)
- ✱ Higgs trilinear coupling at the FCC (can reach ~5% precision)

- ☑ Are there other precision observables that we can access at the hadron colliders?
- ☑ Can we take advantage of the high energy to improve EW precision measurements?

Energy and accuracy

If new physics is heavy, low-energy effects are well described in the EFT framework:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

with the leading corrections arising from the dimension-6 operators

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with the leading corrections arising from the dimension-6 operators

* the deviations from the SM predictions typically grow with the energy

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

* hadronic machines can match lepton collider accuracies by exploiting the high energy reach

e.g. LEP vs LHC

$$0.1\ \%\ \ \text{at}\ \ 100\ \text{GeV} \longrightarrow 10\ \%\ \ \text{at}\ \ 1\ \text{TeV}$$

A comment on the EFT validity

Corrections can not be arbitrarily large

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

Restrictions:

* consistency condition: $E \lesssim \Lambda$
* typically (for weakly coupled models) $\# < 1$ $\longrightarrow$ $\frac{\delta A}{A_{SM}} \lesssim 1$

* leading effects are linear in BSM from the interference with the SM

* a reliable bound can be extracted only if the accuracy is better than the SM (*need for clean channels with low systematic and statistical uncertainties*)

* the cut-off restricts the analysis only to acceptable kinematic regions

Channels for EW precision tests

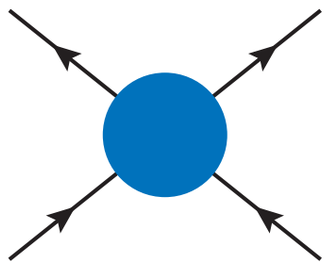
* large cross sections (*low statistical uncertainties*)

* small background and good theoretical control (*low systematic uncertainties*)

* good sensitivity to new physics effects (*corrections growing with energy*)

$2 \to 2$ scattering processes are the natural candidates

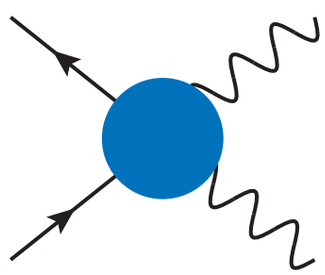
Classes of $2 \to 2$ channels



* large cross sections
* background is ok
* large NP effects

[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 2017]

[Alioli, Farina, Pappadopulo, Ruderman, 2017]



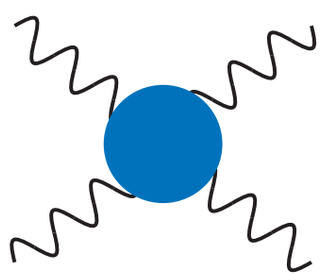
* cross section is ok
  (*pay BRs*)
* background is ok
  (*especially in leptonic channels*)

[Franceschini, Panico, Pomarol, Riva, Wulzer, 2018]

[Panico, Riva, Wulzer, 2018]

[Banerjee, Englert, Gupta, Spannowsky, 2018]

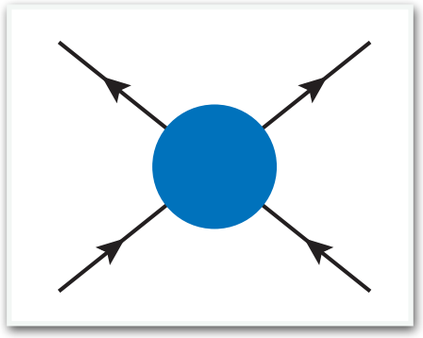
[Azatov, Barducci, Venturini, 2019]



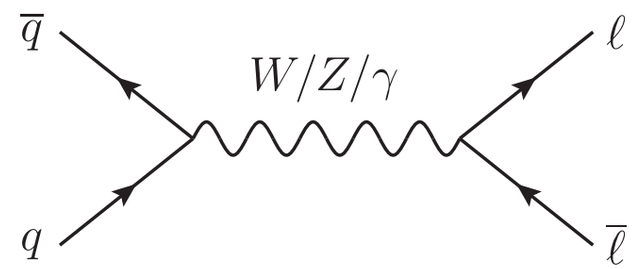
* cross sections are small
* channels are dirtier

[.....]

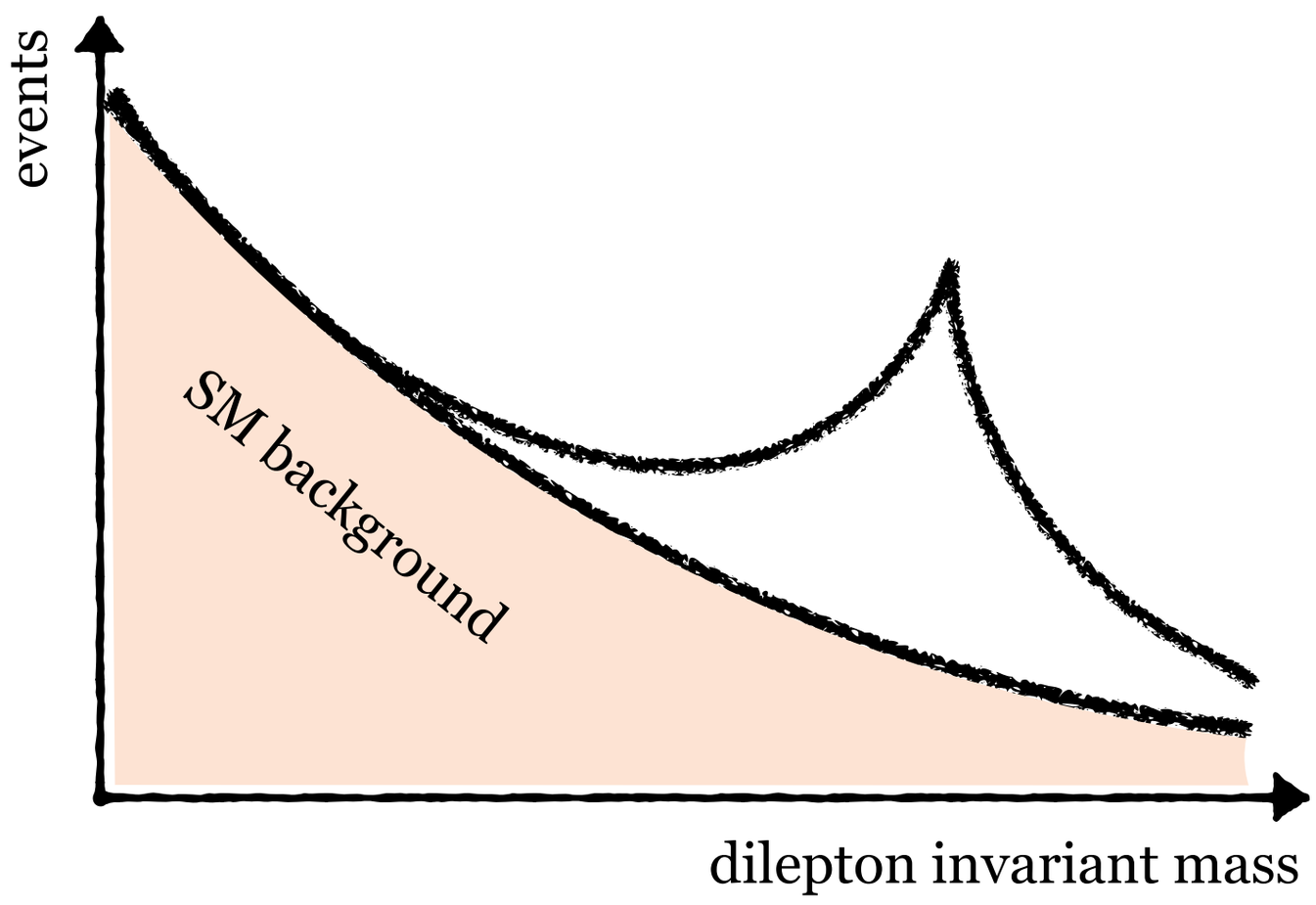
Drell-Yan



Drell-Yan production (neutral or charged)

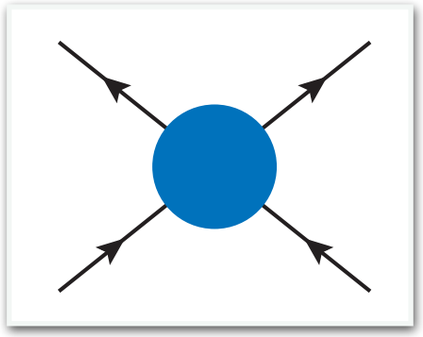


* Large cross section and interference at leading order with the SM

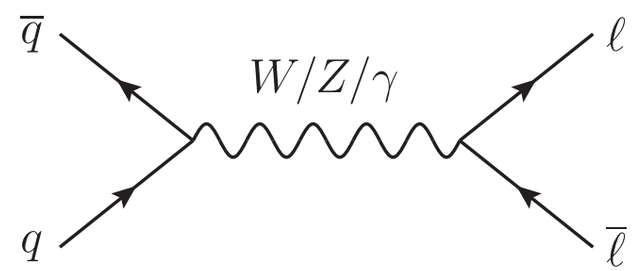


direct searches for new resonances

Drell-Yan



Drell-Yan production (neutral or charged)



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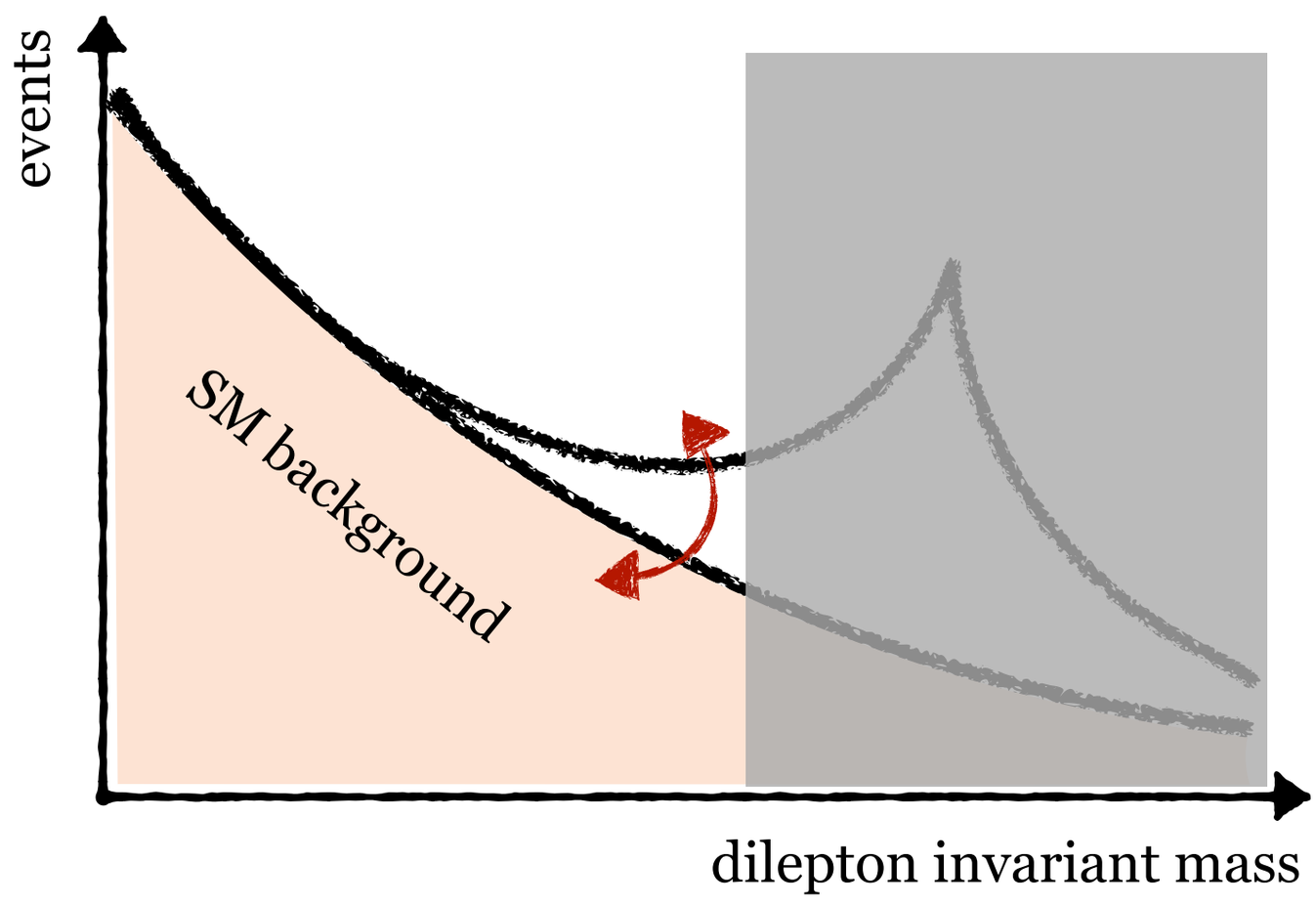
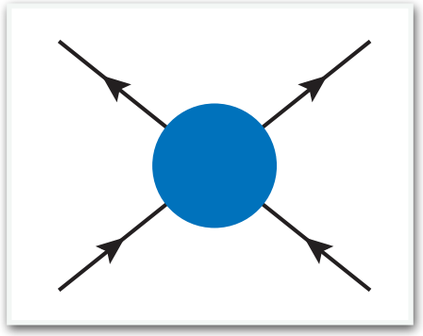


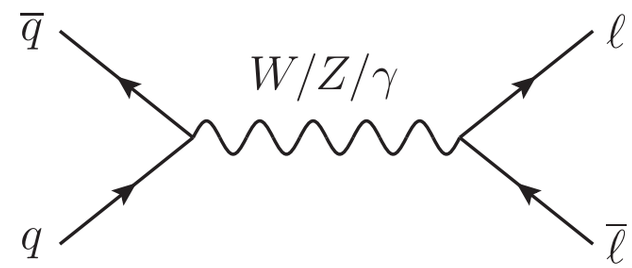
NP is too heavy:

indirect searches for deformations from the SM

Drell-Yan



Drell-Yan production (neutral or charged)



* Large cross section and interference at leading order with the SM

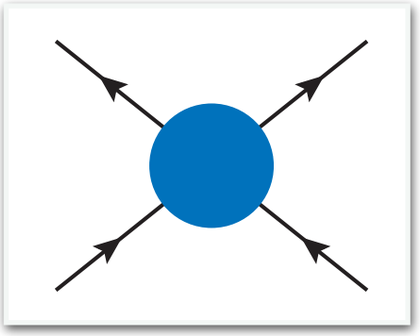
* NP effects can be parameterised by oblique parameters

$$\frac{gg'\hat{S}}{16m_{\rm W}^2}(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu} \qquad -\frac{g^2\hat{T}}{2m_{\rm W}^2}|H^\dagger D_\mu H|^2$$

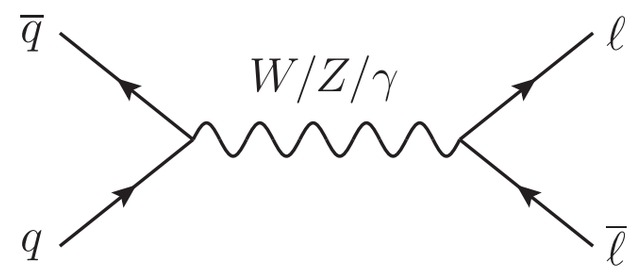
$$-\frac{W}{4m_{\rm W}^2}(D_\rho W^a_{\mu\nu})^2 \qquad -\frac{Y}{4m_{\rm W}^2}(\partial_\rho B_{\mu\nu})^2$$

* Bounds from LEP are at ~ 0.1% level

Drell-Yan



Drell-Yan production (neutral or charged)



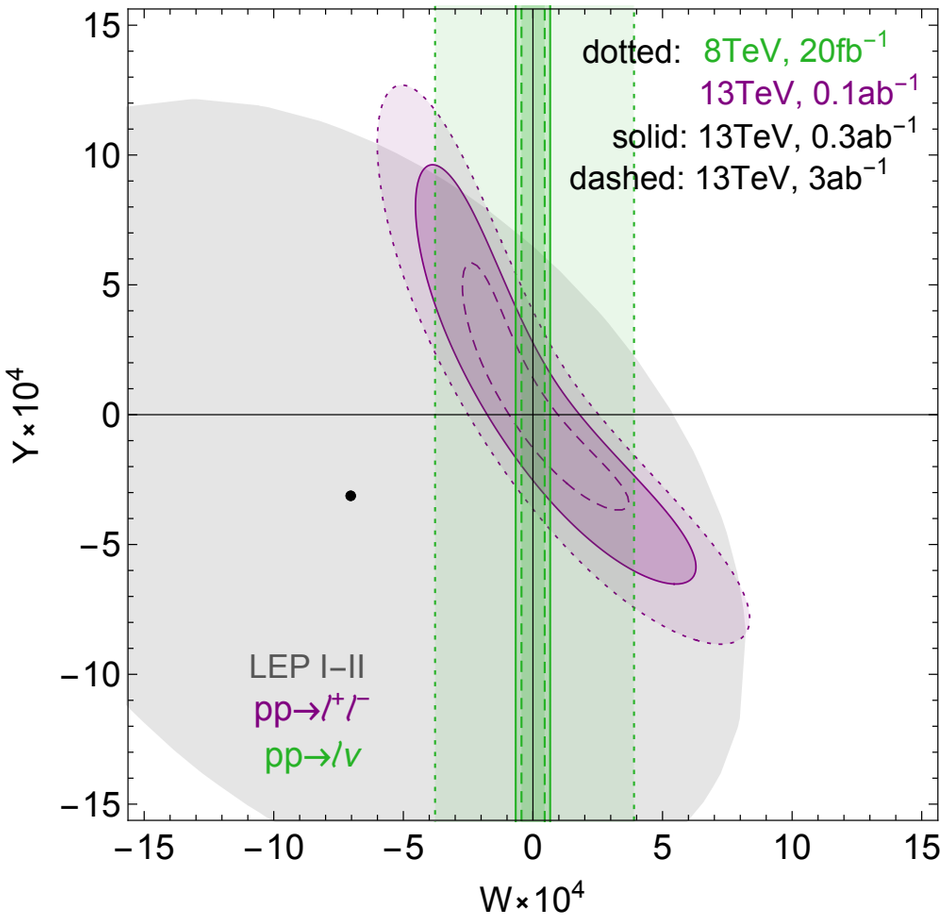
$$P_{\mathrm{N}} = \begin{bmatrix} \frac{1}{q^2} - \frac{t_{\mathrm{W}}^2 W + Y}{m_{\mathrm{Z}}^2} & \frac{t_{\mathrm{W}}((Y+\hat{T})c_{\mathrm{W}}^2 + s_{\mathrm{W}}^2 W - \hat{S})}{(c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2)(q^2 - m_{\mathrm{Z}}^2)} + \frac{t_{\mathrm{W}}(Y-W)}{m_{\mathrm{Z}}^2} \\ \star & \frac{1+\hat{T}-W-t_{\mathrm{W}}^2 Y}{q^2 - m_{\mathrm{Z}}^2} - \frac{t_{\mathrm{W}}^2 Y + W}{m_{\mathrm{Z}}^2} \end{bmatrix}$$

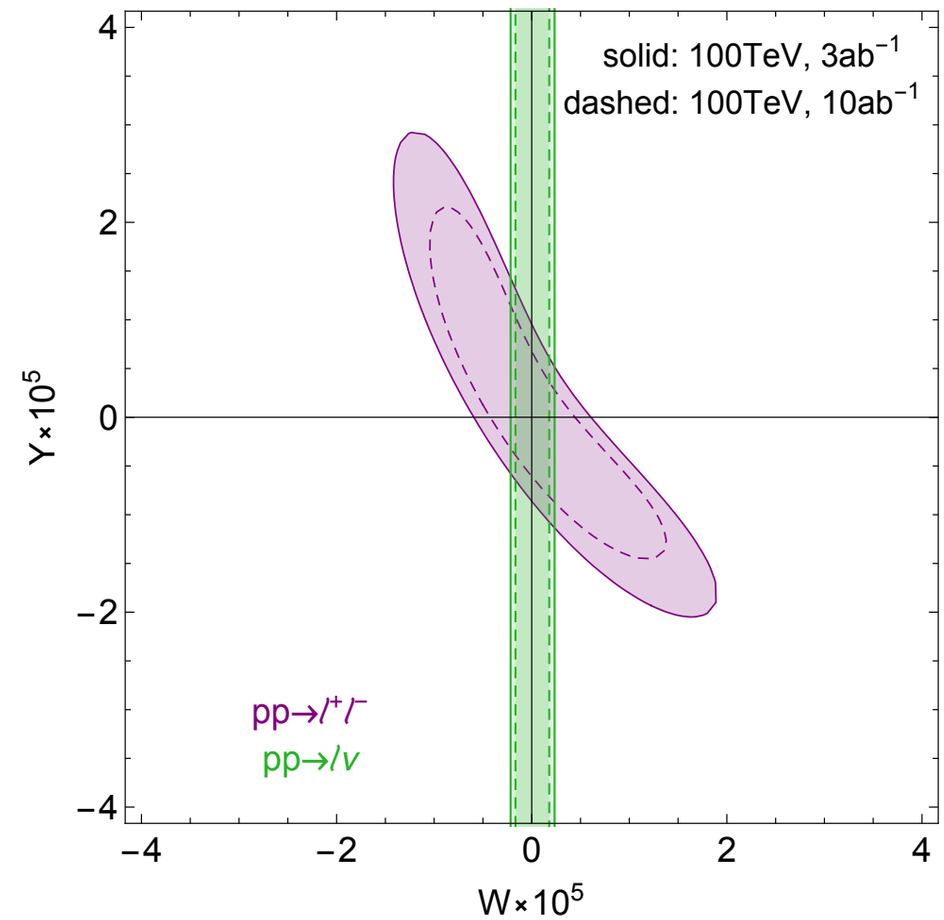
$$P_{\mathrm{C}} = \frac{1+((\hat{T}-W-t_{\mathrm{W}}^2 Y) - 2t_{\mathrm{W}}^2(\hat{S}-W-Y))/(1-t_{\mathrm{W}}^2)}{q^2 - m_{\mathrm{W}}^2} - \frac{W}{m_{\mathrm{W}}^2}$$

* $\hat{S}$ and $\hat{T}$ only affect the total cross section through a modification of the residue of the poles in the propagators (*not competitive with LEP*)

* W and Y introduce constant terms and thus induce an enhancement at high energy

Drell-Yan





[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 2017]

* 13 TeV measurements much better than LEP

* FCC-hh more than one order of magnitude better than HL-LHC

		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	CEPC	ILC 500 GeV
luminosity		$2 \times 10^7\ Z$	19.7 fb^{-1}	20.3 fb^{-1}	0.3 ab^{-1}	3 ab^{-1}	10 ab^{-1}	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3 ab^{-1}
NC	$W \times 10^4$	$[-19, 3]$	$[-3, 15]$	$[-5, 22]$	± 1.5	± 0.8	± 0.04	± 4.2	± 1.2	± 3.6	± 0.3
	$Y \times 10^4$	$[-17, 4]$	$[-4, 24]$	$[-7, 41]$	± 2.3	± 1.2	± 0.06	± 1.8	± 1.5	± 3.1	± 0.2
CC	$W \times 10^4$	–	± 3.9		± 0.7	± 0.45	± 0.02	–	–	–	–

VV production

We are interested in processes that fulfil two conditions:

* BSM effects growing with E^2 at leading order (in d=6 EFT)

* SM amplitudes constant and sizeable at high E

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

opposite chirality $q, \bar{q}$ initial states are suppressed by Yukawa couplings in the SM

$V_L V_L$ and $V_L h$ are the only processes that display quadratic energy growth at the interference level

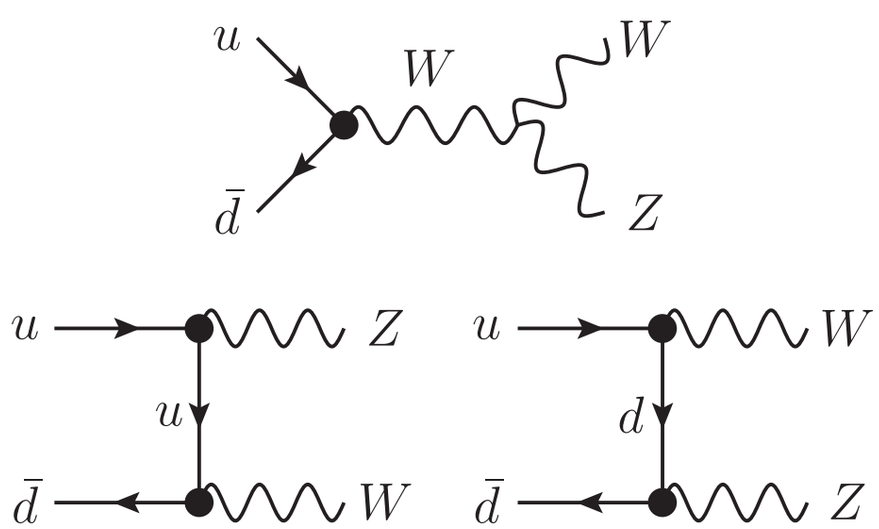
Growing with the energy

All d =6 operators induce an energy growth but not in all channels

Example: the *WZ* channel

the triplet operator

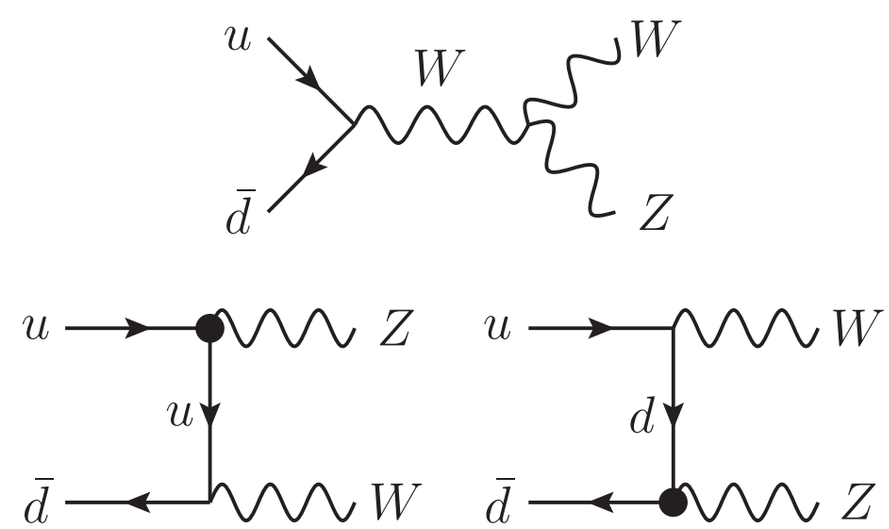
$$\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$



* corrections to *W* and *Z* vertices
* growth with E^2

the singlet operator

$$\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$$



* corrections to *Z* vertices
* no growth

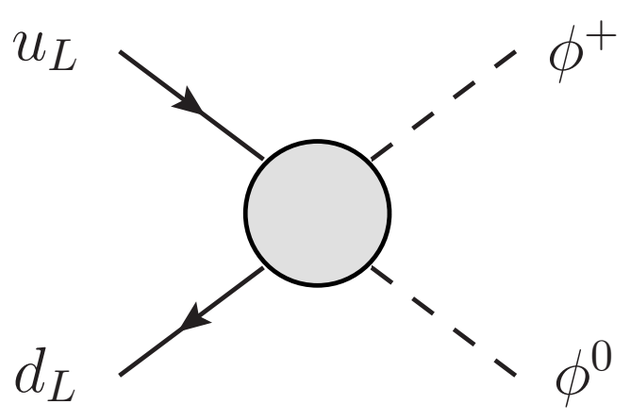
Growing with the energy

very easy to understand by exploiting the equivalence theorem

$W^\pm, Z \quad \rightarrow \quad \phi^\pm, \phi^0$ at high energy

the triplet operator

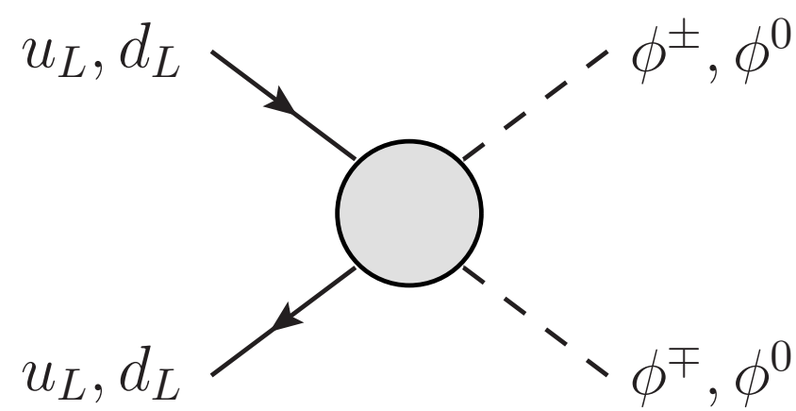
$$\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$



contributes to $W_L Z_L$

the singlet operator

$$\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$$



does not contribute to $W_L Z_L$
(but to $W_L W_L$ and $Z_L h$)

probing di-boson at high-energy is a way to test the Higgs dynamics

The relevant operators

the relevant BSM effects (d=6 EFT) can be parameterised by:

$$\delta A(q'_\pm \bar{q}_\mp \to \Phi\Phi') = \frac{1}{4} A^{\Phi\Phi'}_{q'_\pm \bar{q}_\mp} E^2 \sin\theta^*$$

the coefficients $A^{\Phi\Phi'}_{q'_\pm \bar{q}_\mp}$ are subject to constrains:

- flavour universality in the light quark generations
- the coefficients can be taken real
- SM symmetry is restored in the high-energy limit

only 4 high-energy primaries

$$WZ, Wh: \quad a_q^{(3)}$$
$$WW, Zh: \quad a_q^{(3)}, a_q^{(1)}, a_u, a_d$$

Amplitude	High-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f

[Franceschini, Panico, Pomarol, Riva, Wulzer, 2018]

The relevant operators

the fact that only 4 HEP parameters produce the sizeable effects is non-trivial since a generic d=6 EFT contributes to $V_L V_L$ with 6 anomalous couplings

$$\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} &= \delta g^Z_{uL}\left[Z^\mu \bar{u}_L\gamma_\mu u_L + \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.}) + \cdots\right] + \delta g^Z_{uR}\left[Z^\mu \bar{u}_R\gamma_\mu u_R + \cdots\right] \\
&+ \delta g^Z_{dL}\left[Z^\mu \bar{d}_L\gamma_\mu d_L - \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.}) + \cdots\right] + \delta g^Z_{dR}\left[Z^\mu \bar{d}_R\gamma_\mu d_R + \cdots\right] \\
&+ igc_{\theta_W}\delta g^Z_1\left[(Z^\mu(W^{+\nu}W^-_{\mu\nu} - \text{h.c.}) + Z^{\mu\nu}W^+_\mu W^-_\nu + \cdots\right] \\
&+ ie\,\delta\kappa_\gamma\left[(A_{\mu\nu} - t_{\theta_W}Z_{\mu\nu})W^{+\mu}W^{-\nu} + \cdots\right],
\end{aligned}$$

[Gupta, Pomarol, Riva, 2015]

the 4 high-energy primaries can be easily related to explicit operator basis

for instance, there is a 1-1 correspondence with operators in the Warsaw basis

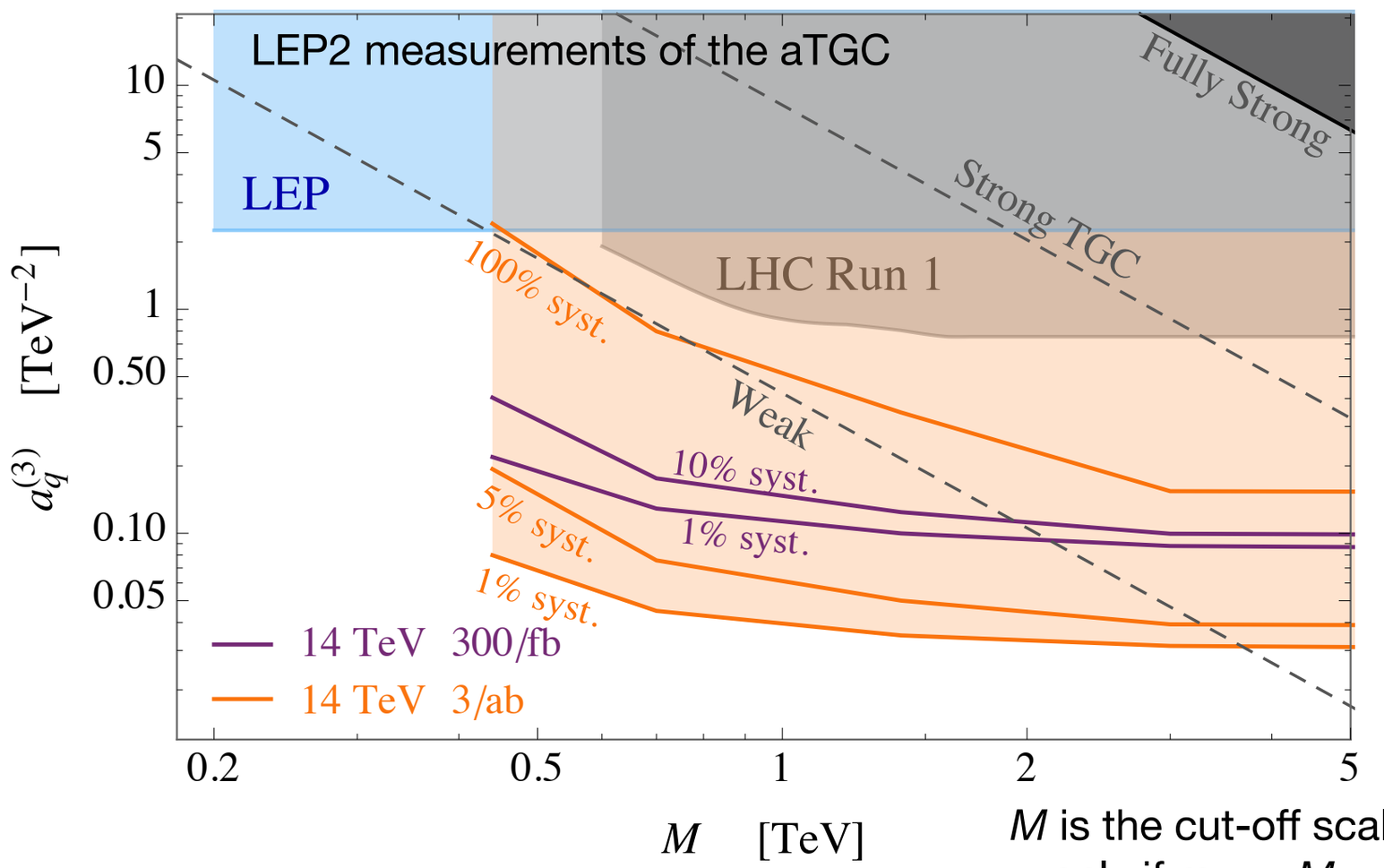
$$\mathcal{O}^3_L = (\bar{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H) \qquad \mathcal{O}^u_R = (\bar{u}_R\gamma^\mu u_R)(iH^\dagger\overleftrightarrow{D}_\mu H)$$

$$\mathcal{O}_L = (\bar{q}_L\gamma^\mu q_L)(iH^\dagger\overleftrightarrow{D}_\mu H) \qquad \mathcal{O}^d_R = (\bar{d}_R\gamma^\mu d_R)(iH^\dagger\overleftrightarrow{D}_\mu H)$$

$$a_u = 4\frac{c^u_R}{M^2}\,,\quad a_d = 4\frac{c^d_R}{M^2}\,,\quad a^{(1)}_q = 4\frac{c^{(1)}_L}{M^2}\,,\quad a^{(3)}_q = 4\frac{c^{(3)}_L}{M^2}$$

Reach at the LHC from *WZ*

Estimate of the bounds on $a_q^{(3)}$ from *WZ* (fully leptonic)



M is the cut-off scale, events are included only if $m_{WZ} < M$, where EFT is testable

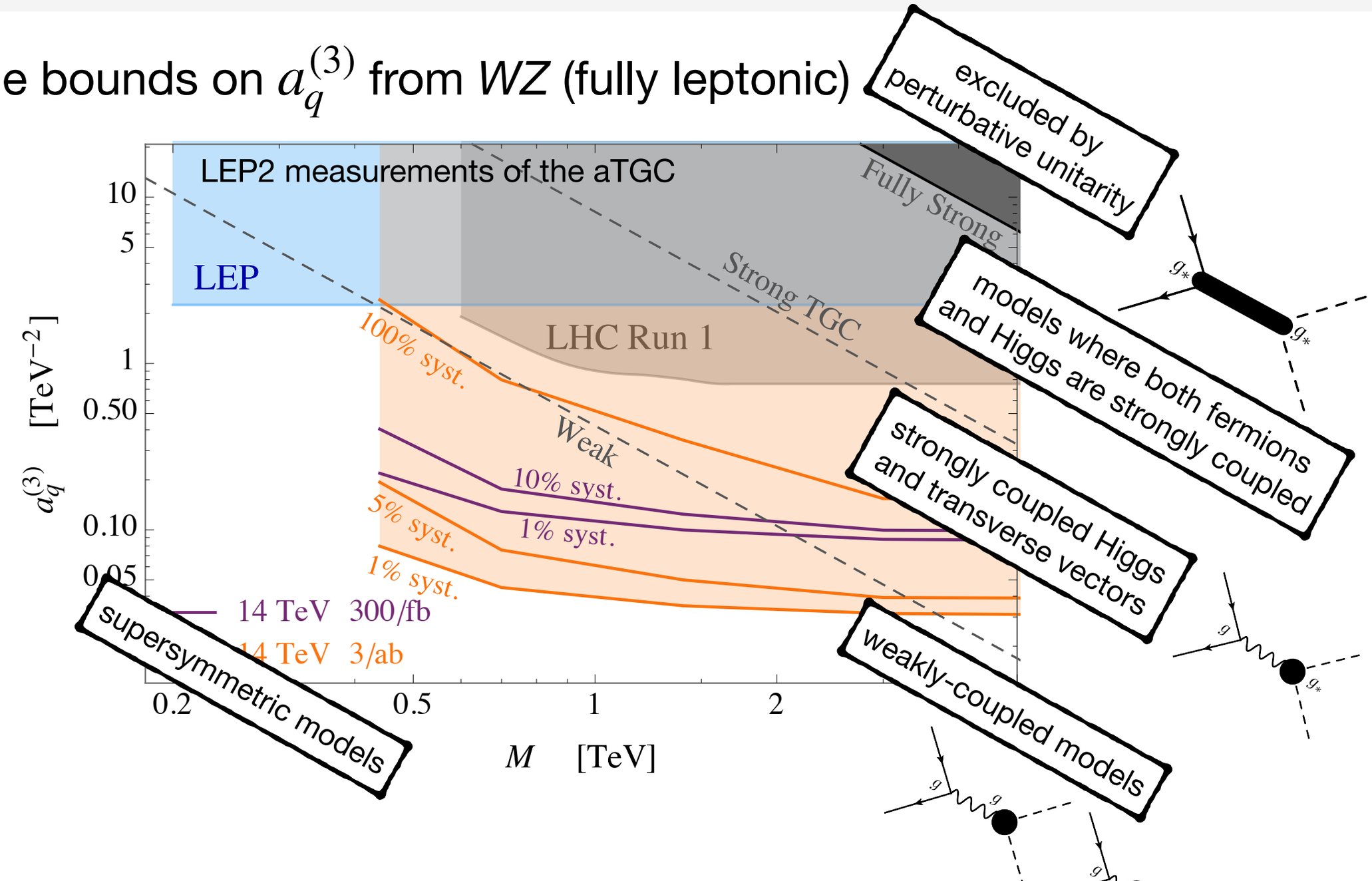
[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 2017]

$$a \sim \frac{g_{BSM}^2}{M^2} \quad \rightarrow \quad \frac{A_{BSM}}{A_{SM}} \sim \left(\frac{g_{BSM}}{g}\right)^2 \left(\frac{E}{M}\right)^2$$

the departure from the SM can be larger than one even for $E \ll M$

Reach at the LHC from *WZ*

Estimate of the bounds on $a_q^{(3)}$ from *WZ* (fully leptonic)

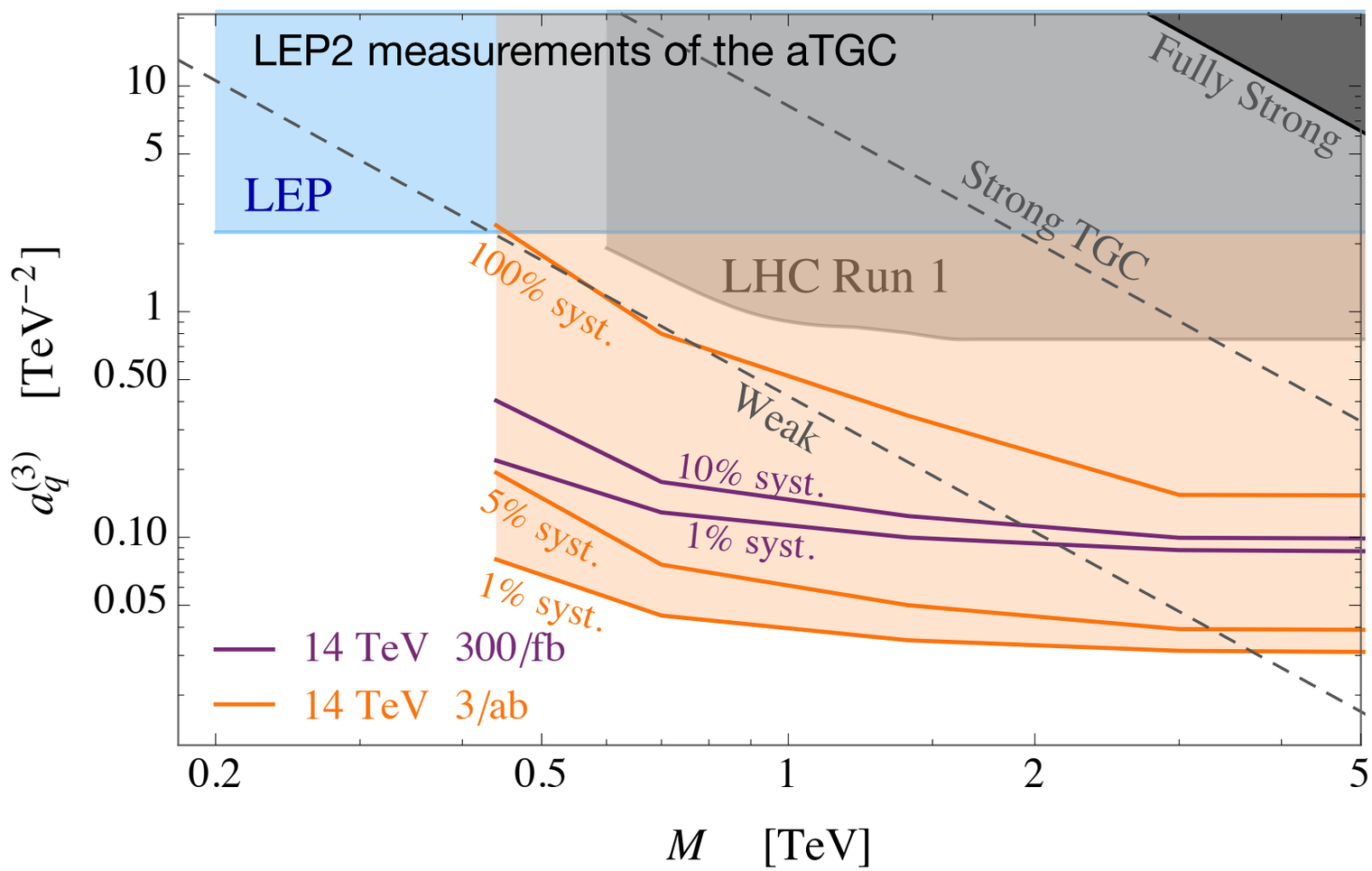


$$a \sim \frac{g_{BSM}^2}{M^2} \quad \rightarrow \quad \frac{A_{BSM}}{A_{SM}} \sim \left(\frac{g_{BSM}}{g}\right)^2 \left(\frac{E}{M}\right)^2$$

the departure from the SM [illegible] larger than one even for $E \ll M$

Reach at the LHC from *WZ*

Estimate of the bounds on $a_q^{(3)}$ from *WZ* (fully leptonic)

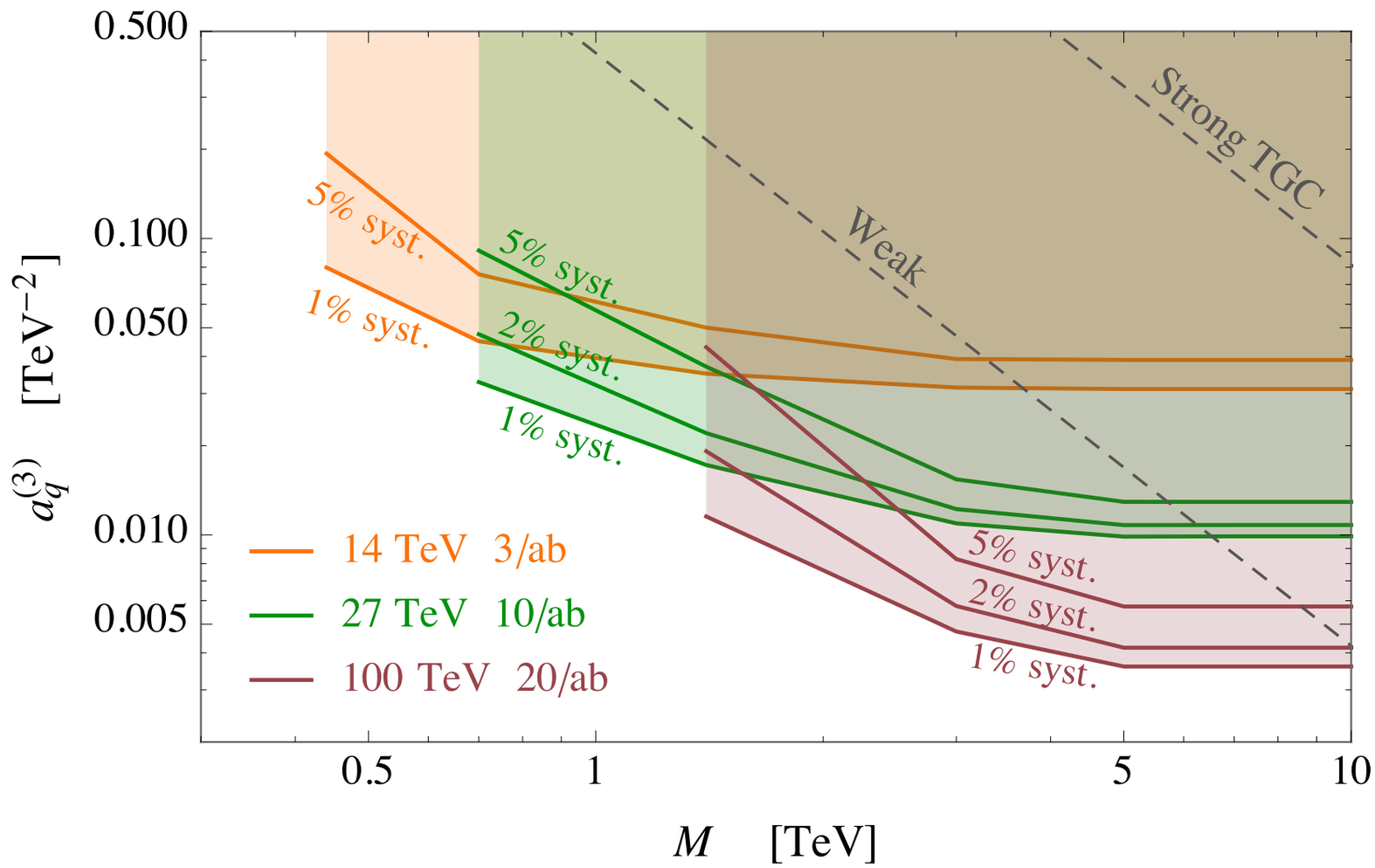


[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 2017]

* big improvement with respect to LEP and LHC run1
* systematics play an important role in the precision reach
* wide range of weakly-coupled BSM is covered (but accuracy is important!)

Reach at future colliders from *WZ*

Estimate of the bounds on $a_q^{(3)}$ from *WZ* (fully leptonic)



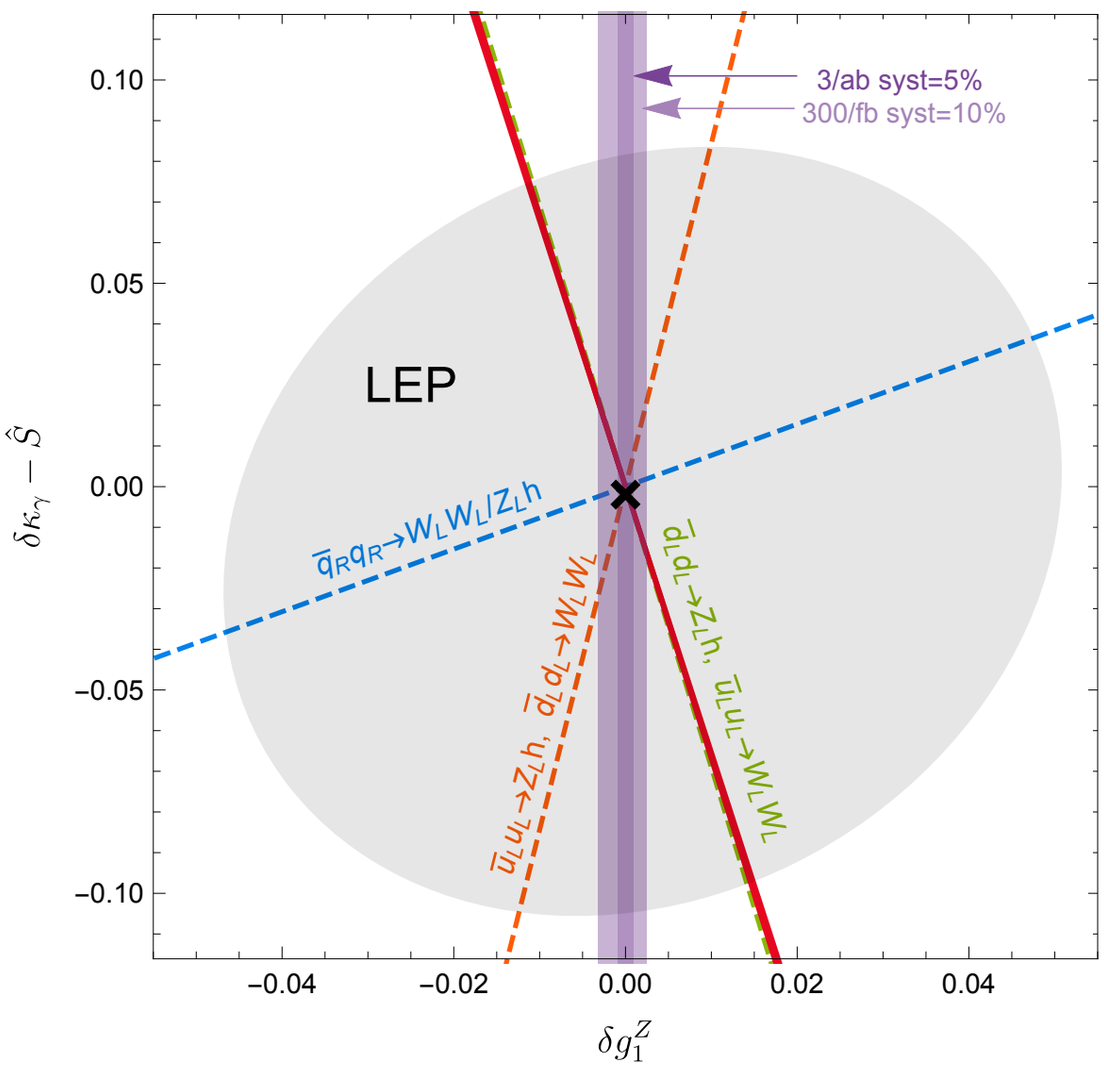
[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 2017]

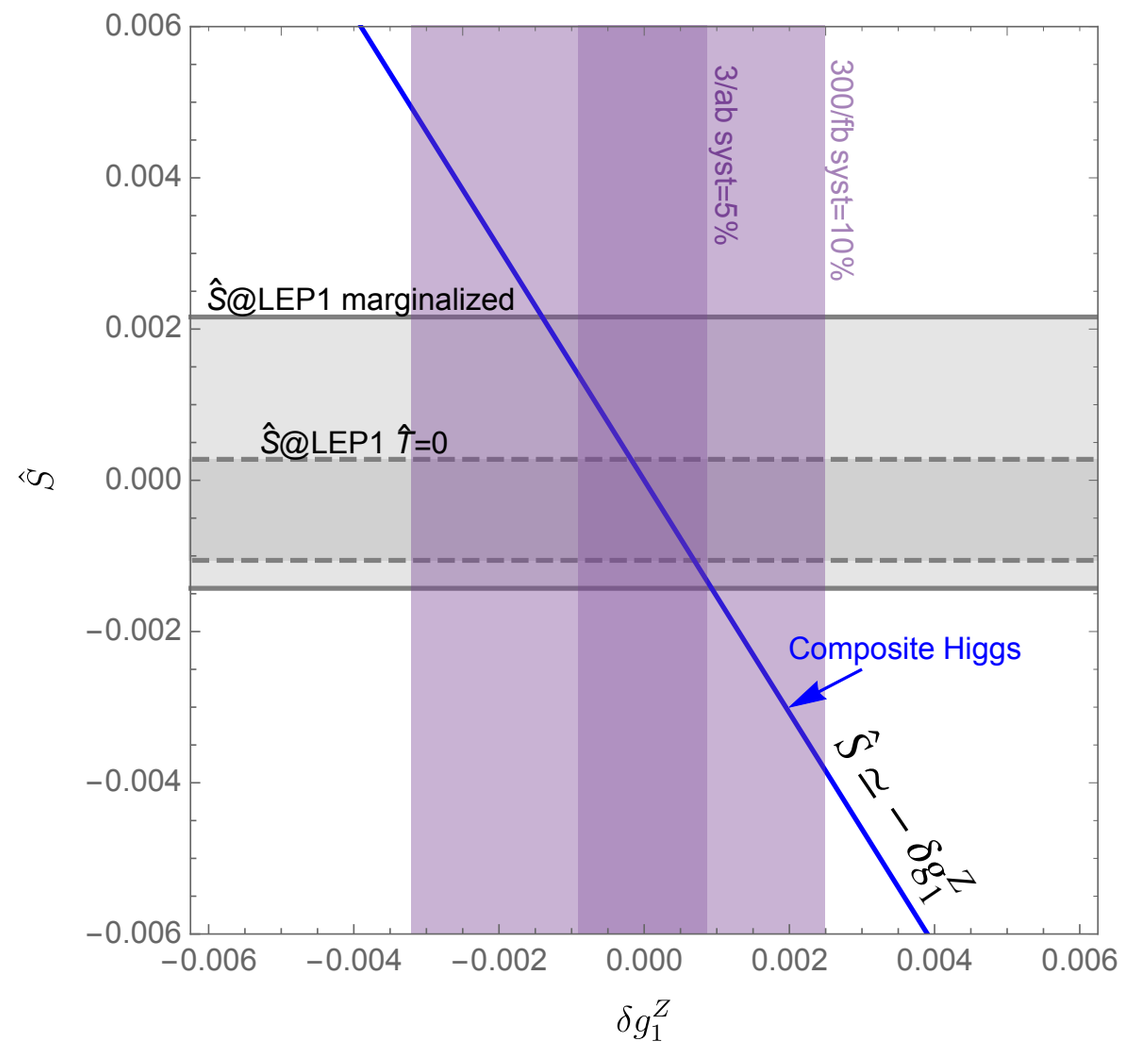
* reach at the FCC-hh is more than one order of magnitude better than HL-LHC

Bounds on universal theories

Comparison of LHC bounds with LEP ones on universal theories

$$a_q^{(3)} = -\frac{g^2}{m_W^2} c_{\theta_w}^2 \, \delta g_1^Z \qquad a_q^{(1)} = \frac{g'^2}{3m_W^2}\left(\hat{S} - \delta\kappa_\gamma + c_{\theta_w}^2 \, \delta g_1^Z\right) \qquad W, Y \ll 0$$



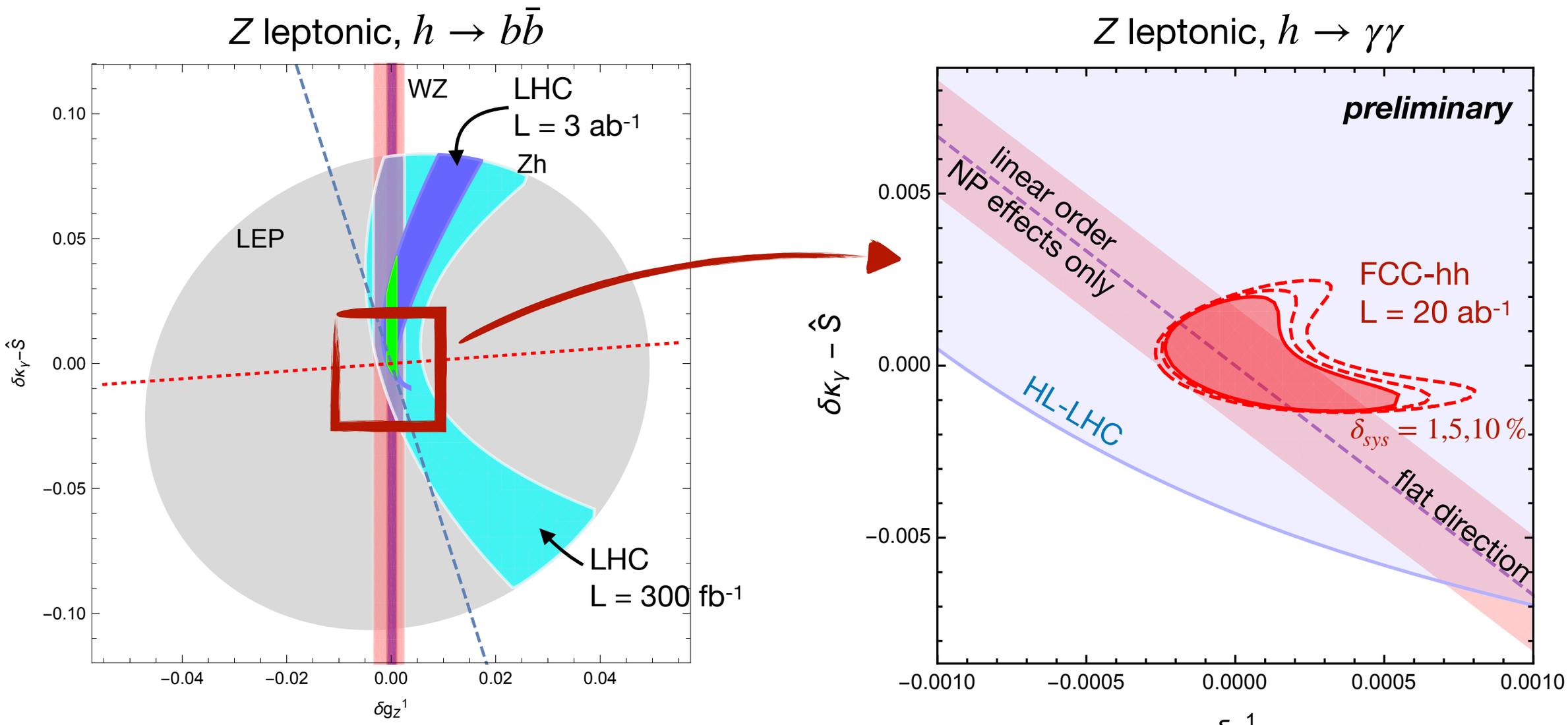


[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 2017]

* big improvement on δg_1^Z with respect to LEP
* hadron colliders are probing an independent direction

Reach at future colliders from *Zh*

Estimate of the bounds from $pp \to Zh$ on universal theories:



[Banerjee, Englert, Gupta, Spannowsky, 2018]

* reach at the FCC-hh is more than one order of magnitude better than HL-LHC (*the analysis is still very preliminary!*)

Conclusions

- ☑ **Hadron colliders** can be used to perform **EW precision tests** exploiting:

  energy growth of new-physics effects and **accurate measurements**

- ☑ Challenges:
  - accessing the **high-energy** tails (*need for good statistics*)
  - **accuracy** (*need for low systematics, eg. in leptonic final states*)

- ☑ Hadron colliders can be competitive or even better than lepton ones
  - di-lepton DY production
  - di-boson production

- ☑ FCC-hh can improve of (*more than*) one order of magnitude on HL-LHC

- ☑ Outlook:
  - study of other channels/signatures
  - exploit full kinematic distributions