PRECISION MEASUREMENTS AS WINDOWS BEYOND THE STANDARD MODEL

STANDARD MODEL=

THE END OF A CERTAIN STORY…THE STORY HAS BEGAN

WITH THE DISCOVERY OF RADIOACTIVITY (1896)

AFTER 120 YEARS OF RESEARCH THIS CHAPTER IS NOW CLOSED

THE PROGRESS WAS DRIVEN BY VERY STRONG LINK BETWEEN EXPERIMENT AND THEORY, AND BETWEEN UNDERSTANDING ELECTROWEAK AND STRONG INTERACTIONS

THE CHAPTER HAS BEEN CLOSED BY THE DISCOVERY OF THE HIGGS PARTICLE.

This is a fundamental discovery for at least three reasons:

IT HAS CONFIRMED THE FUNDAMENTAL AND UNIVERSAL

ROLE OF SYMMETRIES AS THE BASIS FOR UNDERSTANDING

THE PHENOMENA AT THE QUANTUM LEVEL

EXPLAINS THE ORIGIN OF MASS

IT TURNS OUT, ONCE AGAIN, THAT WE CAN UNDERSTAND PHYSICAL PHENOMENA STEP BY STEP, THANKS TO MATHEMATICALLY CONSISTENT „COMPLETE" (BUT EFFECTIVE) THEORIES

AT THE SAME TIME, THE HIGGS PARTICLE – A BIG PUZZLE

IS THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE ?

YES!

RENORMALISABLE (HIGGS PARTICLE)

NO LANDAU POLE UP TO Mp

(ALMOST) STABLE VACUUM UP TO Mp

THOSE CONCLUSIONS STRONGLY DEPEND ON

$$m_t = 173GeV, \qquad m_h = 125GeV$$

THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE?

BUT….

ISNT IT JUST AN EFFECTIVE THEORY, AN APPROXIMATION TO A DEEPER ONE ?

(SIMILARLY AS QED, ALTHOUGH CONSITENT UP TO Mp, IS ONLY LOW ENERGY APPROXIMATION TO SM)

IN PARTICULAR, THE PUZZLING HIGGS PARTICLE!!

Higgs boson is the *only spin 0 particle* in the standard model

Looks very artificial: the only particle that is condensed in the universe but we still don't know the *dynamics* behind the Higgs condensate

(it decribes the Brout-Englert-Higgs mechanism but does not explain it dynamically)

Crucial for the SM & very special

SM CANNOT BE THE THEORY OF EVERYTHING

(PUZZLING HIGGS BOSON, NEUTRINO MASSES, DARK MATTER, MATTER-ANTIMATTER ASYMMETRY…)

BUT WHERE IS THE NEW SCALE?
CONTRARY TO THE PAST, WE ARE NOT DRIVEN BY EXP DATA NOR BY THEORETICAL CONSISTENCY

THE FERMI FOUR-FERMION THEORY FOR

THE NEUTRON $\beta-$ DECAY HAS

INTRODUCED A NEW MASS SCALE INTO

PARTICLE PHYSICS AND A GUARANTEE

OF NEW DISCOVERIES

$$\mathcal{L}_F \approx G_F \bar{\Psi}^p_L \gamma_\mu \Psi^n_L \bar{\Psi}^e_L \gamma^\mu \Psi^\nu_L$$

$$G_F \approx 1/10^5 GeV^2$$

BEFORE THE DISCOVERY OF THE HIGGS BOSON THERE WAS AGAIN
THE GUARANTEE THAT „SOMETHING" MUST HAPPEN TO UNITARIZE THE WW SCATTERING AMPLITUDE.

NOTHING SIMILAR NOW.....

BENEFITS AND DRAWBACKS OF RENORMALISABLE BUT EFFECTIVE THEORIES

WE CAN ORGANIZE PARTICLE PHYSICS ACCORDING TO THE HIERARCHICAL ENERGY SCALES THANKS TO THE APPELQUIST-CARAZZONE DECOUPLING THEOREM:

IF A RENORMALISABLE EFFECTIVE THEORY IS EMBEDDED INTO A LARGER THEORY WITH NEW PARTICLES OF MASS SCALE M, THE DEVIATIONS FROM THE PREDICTIONS OF THE EFFECTIVE THEORY FOR OBSERVABLES PROBED AT THE ENERGY E ARE SUPPRESSED BY POWERS OF

$$\frac{E^2}{M^2}$$

BLESSING:

ONE COULD CELEBRATE THE SUCCESS OF QED (E~1 GeV) WITHOUT UNDERSTANDING THE SM (E~100 GeV)

CURSE:

TO FIND LAWS OF PHYSICS BEYOND THE EFFECTIVE THEORY SUCCESSFUL AT E ONE NEEDS ENERGY OF ORDER OF THE NEW MASS SCALE M OR PRECISION OF ORDER E^2/M^2

THE POWER OF PRECISION MEASUREMENTS

Precision measurements of neutral current
(*i.e.* polarized *e+d*) predicted *mW*, *mZ*

UA1/UA2 discovered *W/Z* particles

LEP/SLC: precision measurements of *W* and *Z properties*
predicted *mt* and *mH*

Tevatron discovered top, LHC discovered
Higgs particle

Precision measurements of the lepton, top & Higgs sector

predict ???

HOT PRECISION CORNERS

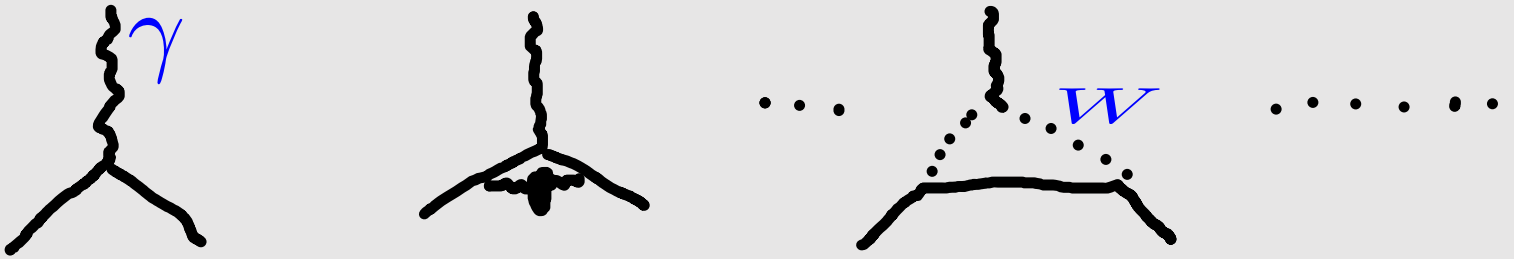
Muon g-2 (4 sigma deviation from the SM)

Electron EDM

Higgs decays

Flavour physics-rare decays (violation of lepton universality at 4 sigma level)

MUON MAGNETIC MOMENT



$$\frac{e}{2m}\mathbf{s}\times\mathbf{B}[2+\frac{\alpha}{\pi}+...+\mathcal{O}(\alpha\frac{m^2}{M_W^2})+BSM?]=\frac{e}{2m}\mathbf{s}\times\mathbf{B}\times g_\mu$$

$$a_\mu=\frac{g_\mu-2}{2} \qquad a_\mu^{W,Z,h}=152(4)\times10^{-11}$$

$$\Delta a_\mu=a_\mu^{exp}-a_\mu^{SM}=(251\pm59)\times10^{-11}$$

The deviation is of the same order of magnitude as the weak corrections.
New fermions and scalars (supersymmetry? new more exotic particles?)

PRECISION MEASUREMENTS IN THE HIGGS SECTOR

Properties of the Higgs boson- confirm the SM as the effective electroweak theory & at the same time this is a window to beyond the SM physics (once the precision of the measurements is increased).

EXTENDED HIGSS SECTOR IN MOST BSM THEORIES

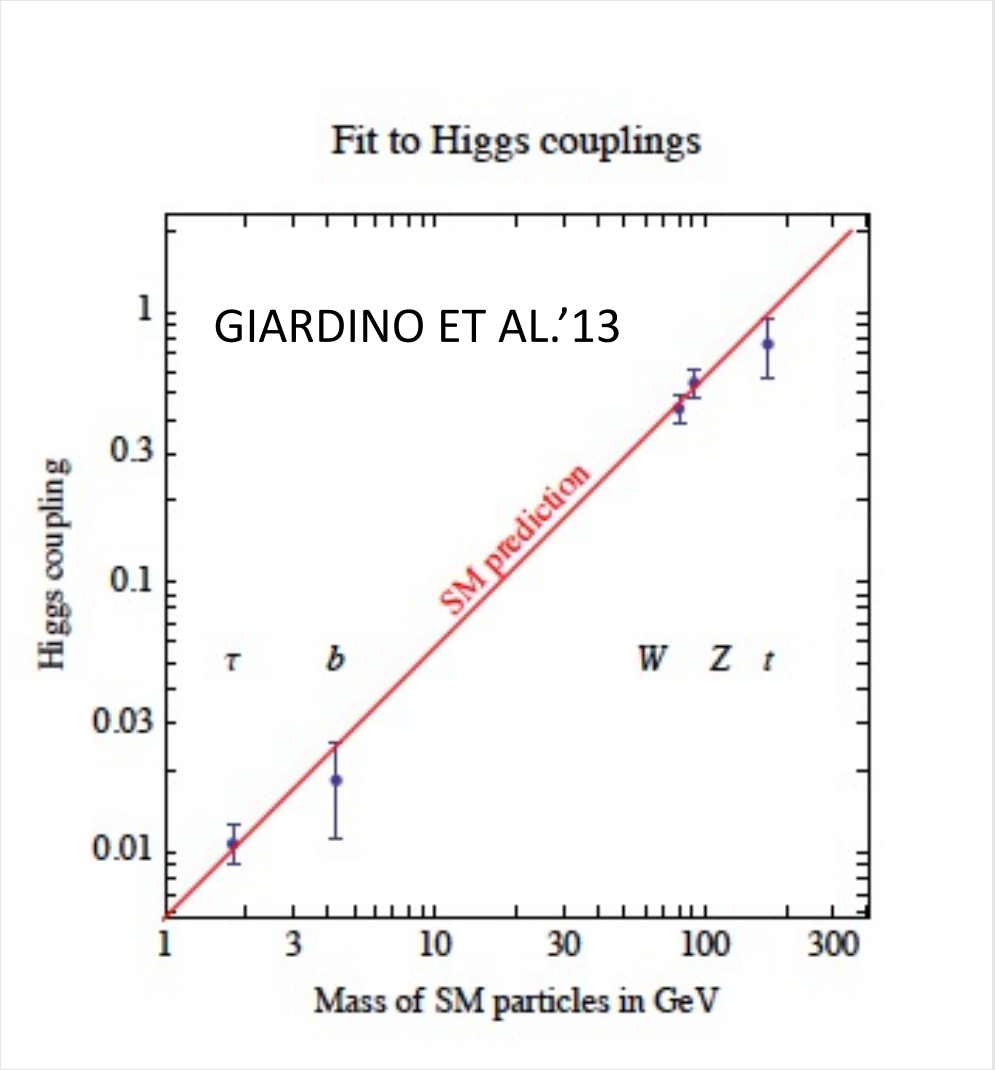
Supersymmetry : two or more elementary Higgs bosons ,
SUSY loops make *mh*2 negative and explain condensation

Composite Higgs boson: spins cancel among constituents (pNGBs),
condensate by a strong attractive force

Extra dimension: Higgs boson spinning in extra dimensions(gauge-Higgs unification)
KK particles

Hidden sector- Higgs portal

HIGGS COUPLINGS ARE WITHIN ~10-20% CONSISTENT WITH THE SM COUPLINGS $(g = \frac{m}{v})$



HIGGS COUPLINGS VERSUS NEW SCALES:

$M = 1TeV$ → O(1) % deviations from the SM couplings

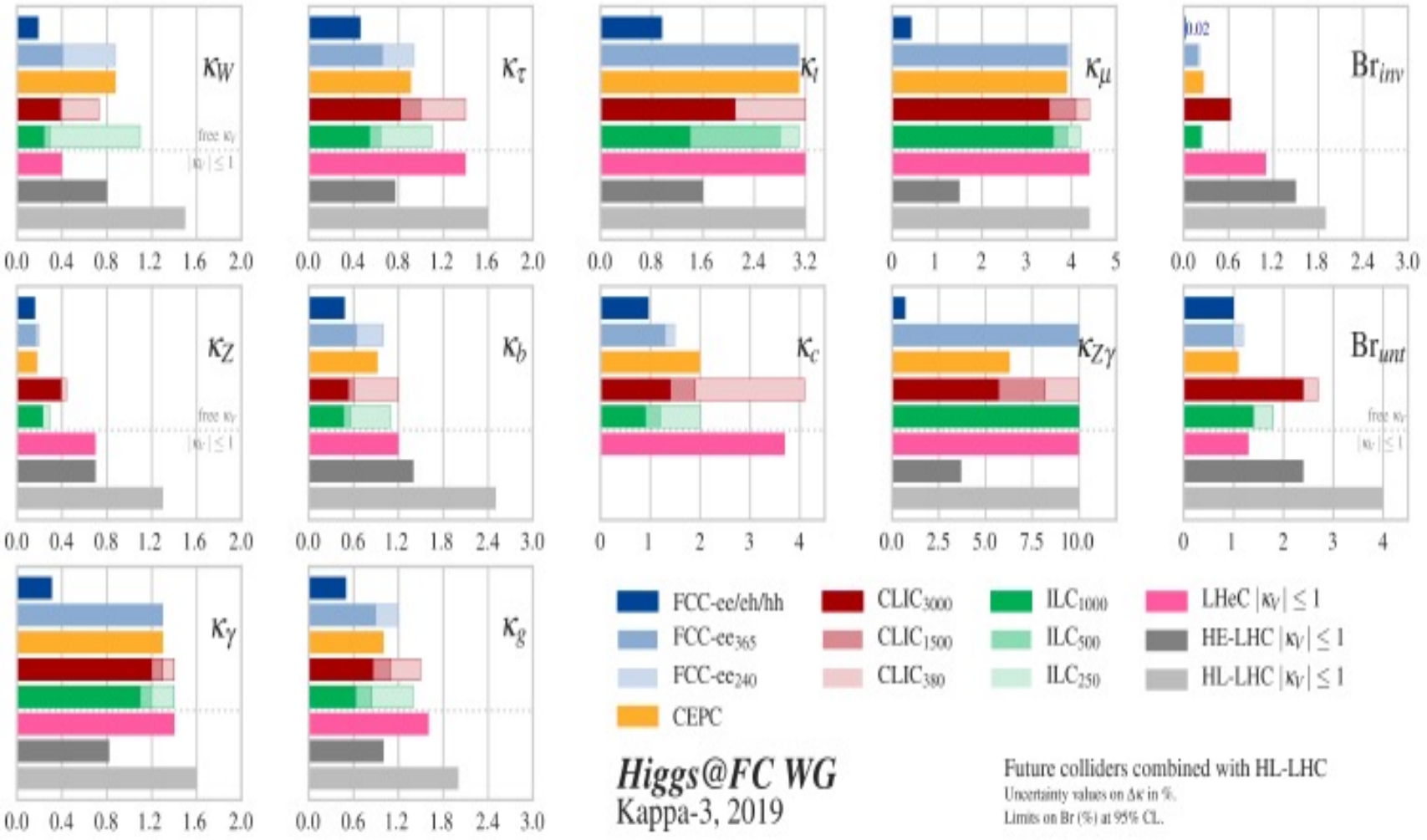
$$\kappa = \frac{g}{g_{SM}} \sim \mathcal{O}(m_H^2/M^2)$$

g -any higgs coupling

DEVIATIONS FROM THE SM IN THE COUPLINGS TO THE GAUGE BOSONS,
IN THE YUKAWA COUPLINGS (ALSO CP VIOLATION),
IN THE HIGGS SELF-COUPLINGS

INVISIBLE DECAYS TO BSM PARTICLES

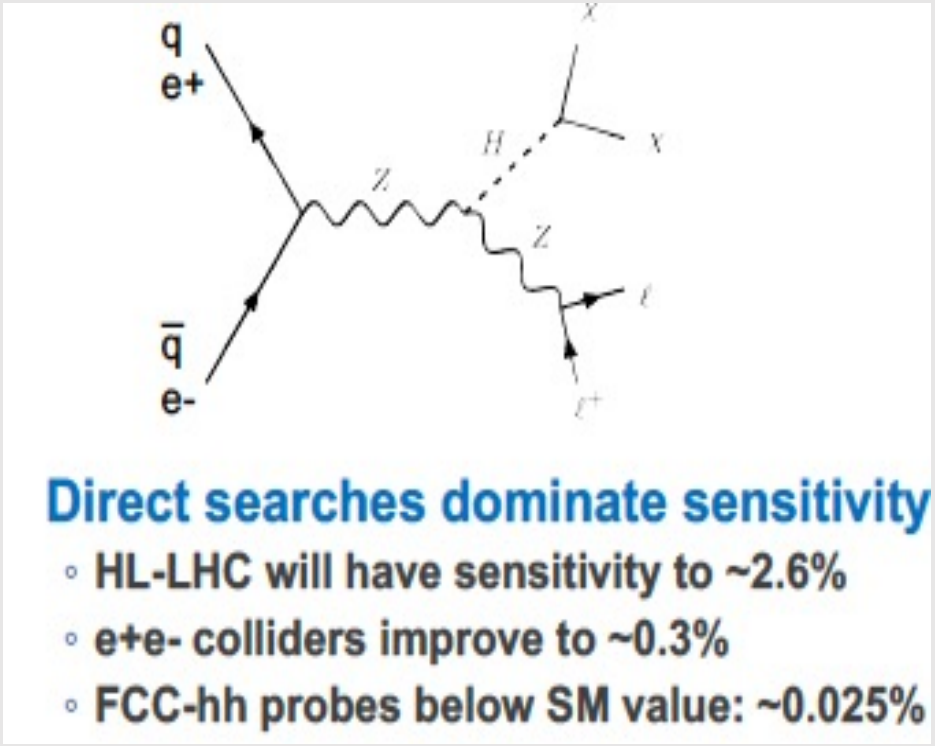
DM? ELECTROWEAK BARYOGENESIS? EXCITING LINK TO FLAVOUR PHYSICS


κ_W
κ_τ
κ_l
κ_μ
Br_{inv}
κ_Z
κ_b
κ_c
$\kappa_{Z\gamma}$
Br_{unt}
κ_γ
κ_g
free κ_V
$|\kappa_V| \leq 1$
FCC-ee/eh/hh
FCC-ee$_{365}$
FCC-ee$_{240}$
CEPC
CLIC$_{3000}$
CLIC$_{1500}$
CLIC$_{380}$
ILC$_{1000}$
ILC$_{500}$
ILC$_{250}$
LHeC $|\kappa_V| \leq 1$
HE-LHC $|\kappa_V| \leq 1$
HL-LHC $|\kappa_V| \leq 1$
Higgs@FC WG
Kappa-3, 2019
Future colliders combined with HL-LHC
Uncertainty values on $\Delta\kappa$ in %.
Limits on Br (%) at 95% CL.

INVISIBLE HIGGS DECAYS

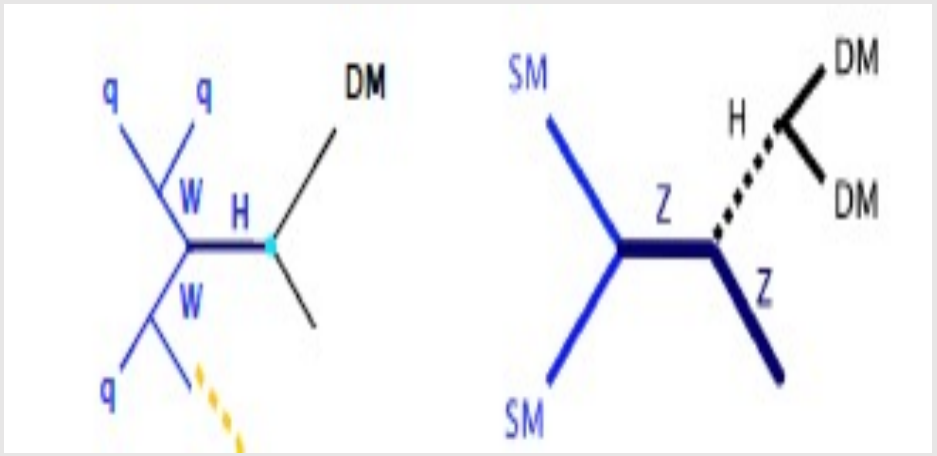
(TWIN HIGGS, HIDDEN SECTORS, DARK MATTER)

HIGGS PORTAL: $\lambda H^\dagger H S^2, \qquad \lambda H \bar{\psi} \psi$



Direct searches dominate sensitivity

- HL-LHC will have sensitivity to ~2.6%
- e+e- colliders improve to ~0.3%
- FCC-hh probes below SM value: ~0.025%



HIGGS PORTAL: $\lambda H^\dagger H S^2, \qquad \lambda H^\dagger H \bar{\psi}\psi$

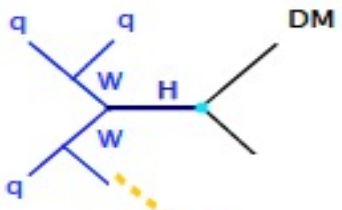
Higgs portal, plot for direct searches

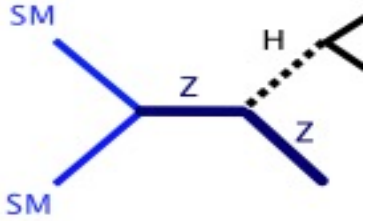
- Limits on BR can be translated to limits in the DM-nucleon plane

$$\sigma_{\chi N} = \Gamma_{\rm inv} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi \left(\frac{m_h}{m_\chi}\right), \qquad (15)$$

arXiv:1708.02245

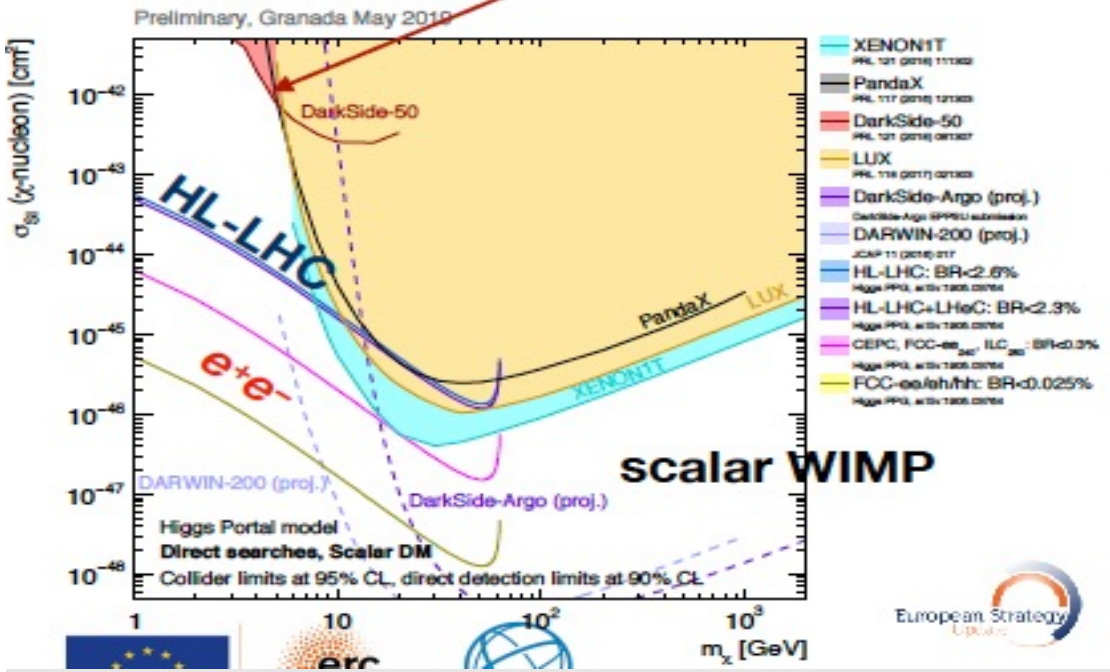
where $g_S(x) = 1$,
$g_f(x) = 2/(x^2-4)$, $\beta = \sqrt{1-4m_\chi^2/m_h^2}$, $v = 246\,\text{GeV}$

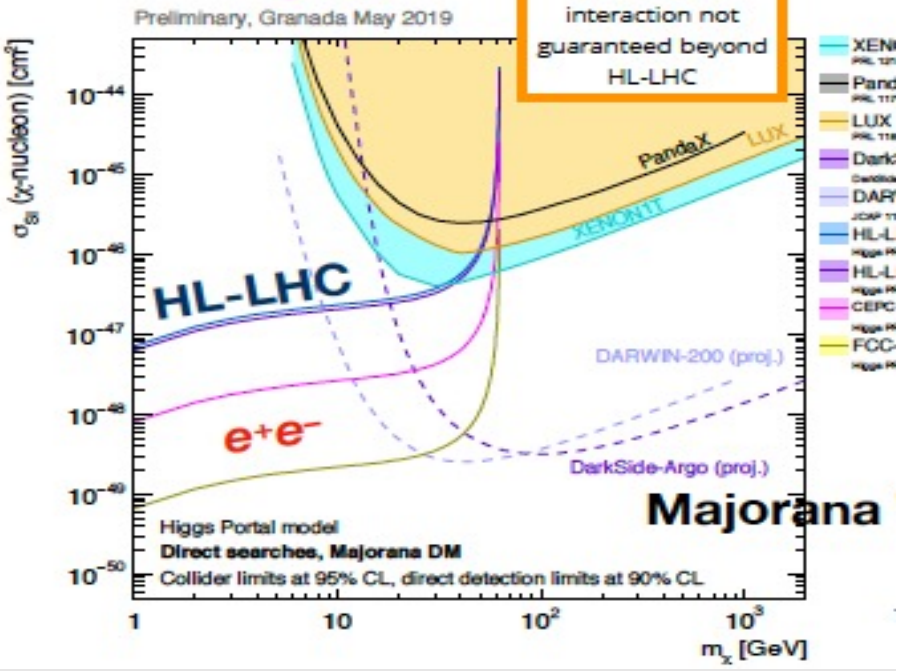




direct detection limits

Caveat: EFT validity in Higgs-DM interaction not guaranteed beyond HL-LHC





European Strategy Update

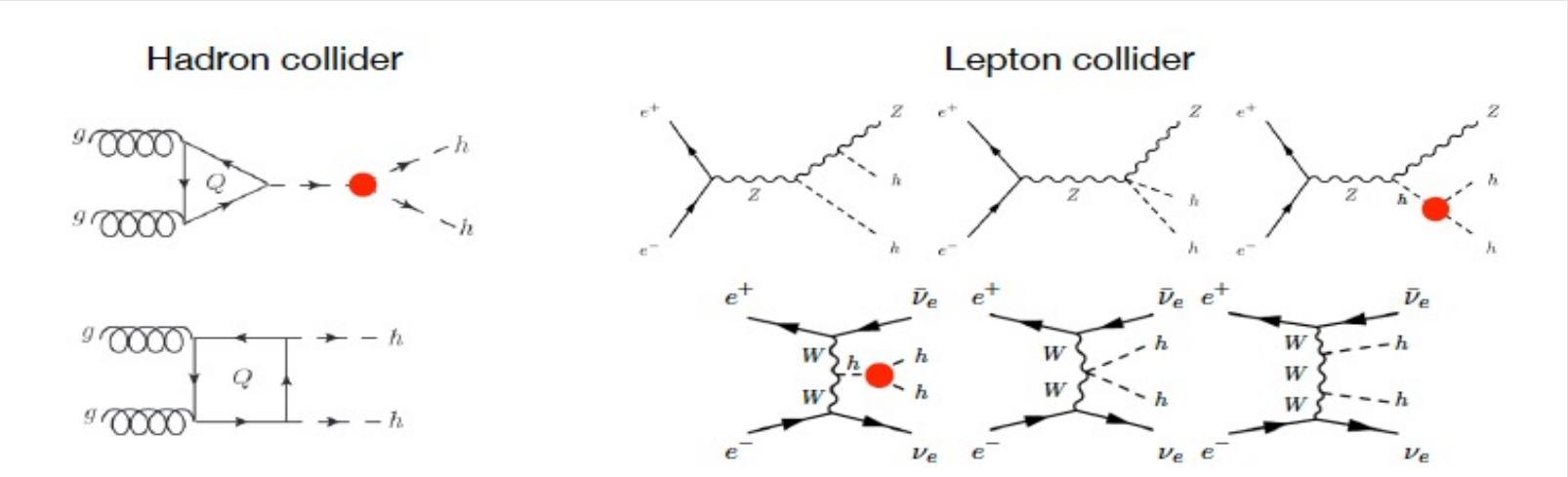
TRIPLE HIGGS COUPLING

RELEVANT FOR THE STRONG ENOUGH FOR BARYOGENESIS FIRST ORDER ELECTROWEAK PHASE TRANSITION AT HIGH TEMPERATURE

SM

$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4, \quad \text{with} \quad \lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \frac{m_H^2}{2v^2}.$$

LARGER VALUES NEEDED FOR EWPT



ELECTRON ELECTRIC DIPOLE MOMENT (EDM)

$$\mathscr{L}_{\rm EDM} = -d_e \frac{i}{2} \bar{e} \sigma^{\mu\nu} \gamma_5 e F_{\mu\nu} \qquad |d_e| < 1.1 \times 10^{-29}\ \text{e cm}$$

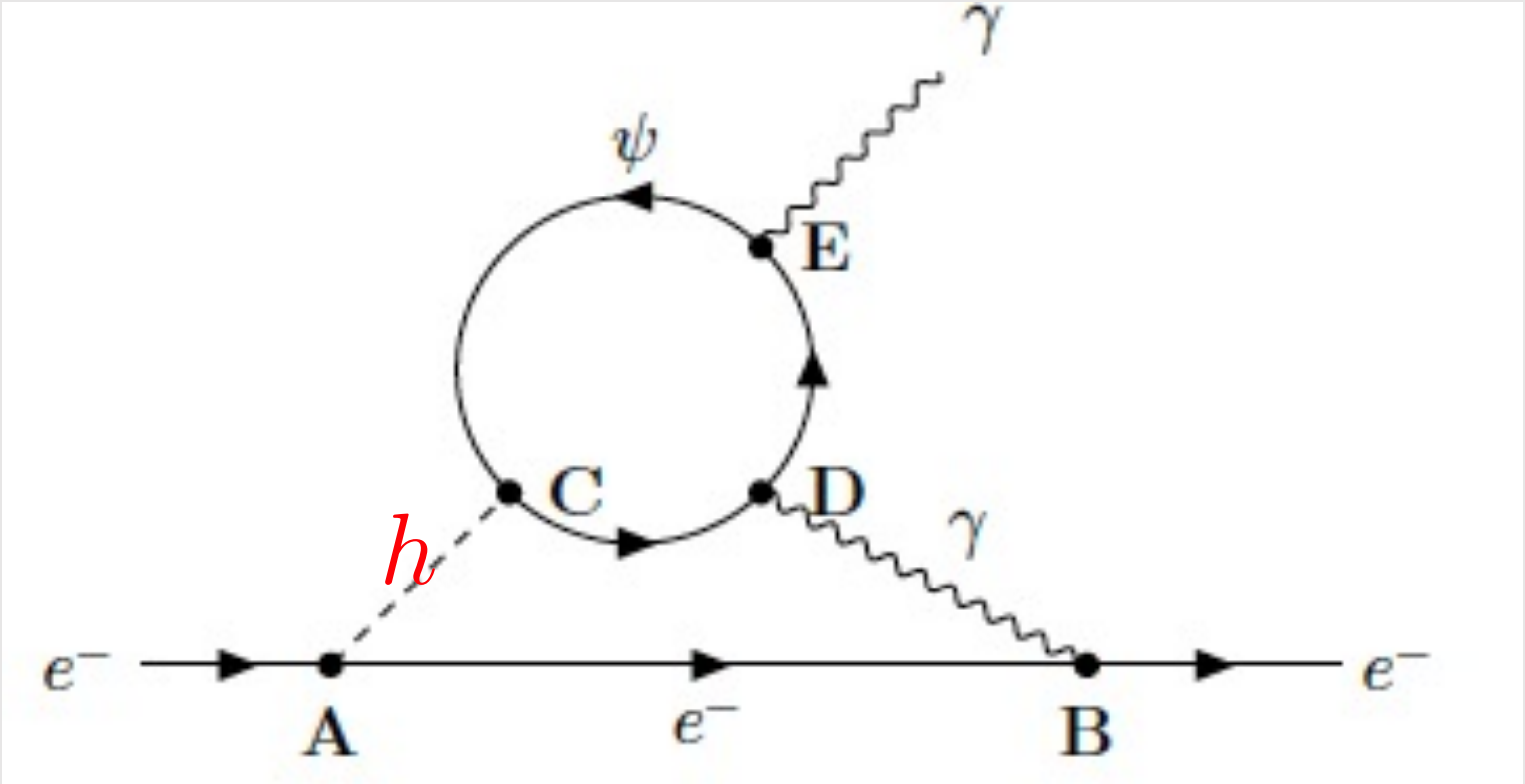
IT PUTS LIMITS ON THE IMAGINARY PARTS OF THE YUKAWA COUPLINGS

$$\mathscr{L}_{\rm eff} = -\frac{y_\psi}{\sqrt{2}} \left(\kappa_\psi \bar{\psi} \psi + i \tilde{\kappa}_\psi \bar{\psi} \gamma_5 \psi \right) h \,,$$

$\tilde{\kappa} = 0$ IN THE SM

$\tilde{\kappa} \neq 0$ NECESSARY FOR BARYOGENESIS AT THE ELECTROWEAK PHASE TRANSITION

EDM DEPENDS ON $\tilde{\kappa} \neq 0$ THROUGH THE SO-CALLED BARR-ZEE DIAGRAM



EFFECTIVE DESCRIPTION OF THE BSM CONTRIBUTION TO THE YUKAWA COUPLING

$$\mathscr{L} = -\overline{L'}HY'e'_R - \overline{L'}HC'e'_R\frac{H^\dagger H}{\Lambda^2} + \text{h.c.},$$

FLAVOR WINDOW TO PHYSICS BEYOND THE STANDARD MODEL

SM AND FLAVOR (= FERMION FAMILIES)

IN CERTAIN SENSE, FLAVOR IS A BEYOND THE SM CONCEPT!

3 FAMILIES OF QUARKS AND LEPTONS WITH IDENTICAL QUANTUM NUMBERS, AND IN CONSEQUENCE IDENTICAL GAUGE INTERACTIONS FOR LEPTONS

THE FAMILIES DIFFER ONLY BY THEIR INTERACTIONS WITH THE HIGGS FIELD, WHICH ARE NOT CONTROLLED BY ANY FLAVOUR SYMMETRY; FERMION MASSES AND MIXING ARE FREE PARAMETERS

FLAVOUR WINDOW IS VERY SPECIAL: TESTING UNIVERSALITY AND POSSIBLY HINTING TO FLAVOUR SYMMETRIES RATHER THAN TESTING THE DYNAMICS OF THE BROUT-ENGLERT-HIGGS MECHANISM

SM:
VERY IMPORTANT CONCLUSION FOR CHARGED LEPTONS (IN THE APPROXIMATION OF ZERO NEUTRINO MASSES):

LEPTON FLAVOUR CONSERVATION

$$\mu \rightarrow e\gamma$$ forbidden

UNIVERSALITY OF LEPTON GAUGE INTERACTIONS, BOTH IN CHARGED AND NEUTRAL CURRENTS

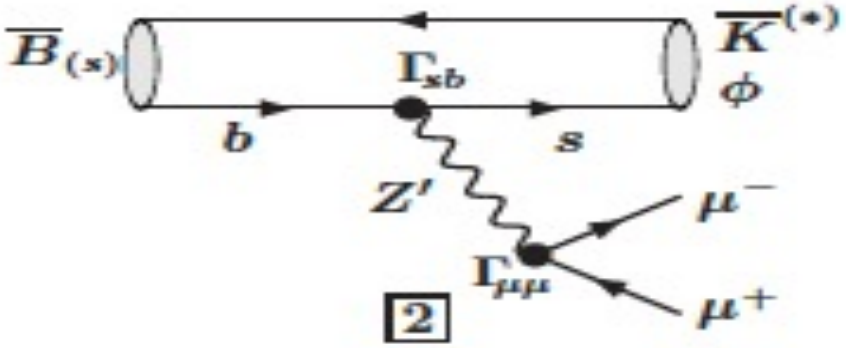
$$R_K = \frac{\mathrm{Br}[B \to K \mu^+ \mu^-]}{\mathrm{Br}[B \to K e^+ e^-]}$$

~ 4 sigma deviation from the SM prediction $(R_K = 1)$

AMONG SEVERAL POSSIBILITIES TO EXPLAIN IT, E.G. NEW U(1) GAUGE SYMMETRY

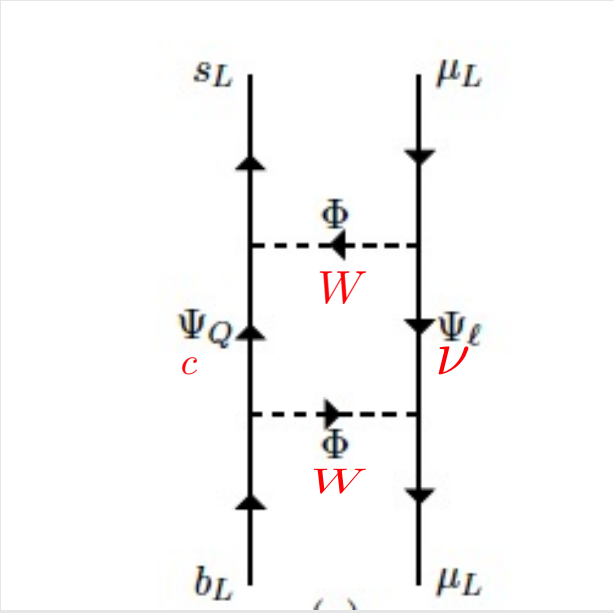
Z'

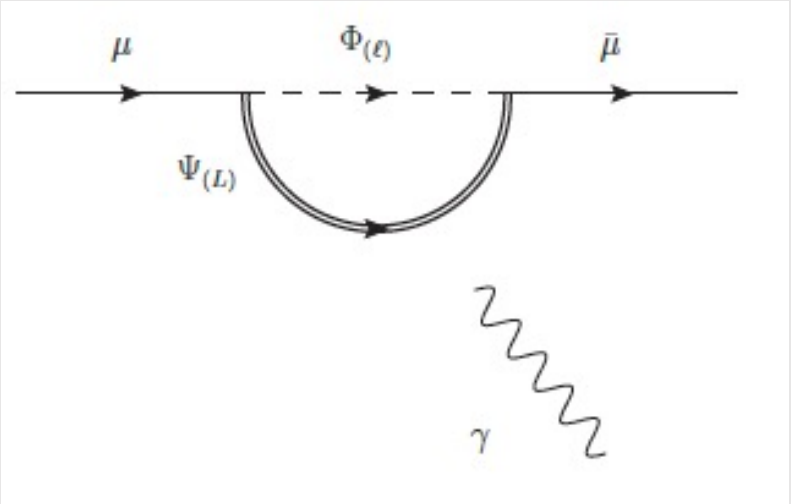
A GAUGE BOSON WITH FLAVOUR DEPENDENT COUPLINGS



ON THE THEORY SIDE, IT IS POSSIBLE TO EXPLAIN ALL THREE!

NEW LIGHT BSM PARTICLES PREDICTED BUT PRODUCTION CROSS SECTIONS TOO LOW FOR THE LHC





+DM

SUMMARY

PRECISION MEASUREMENTS HAVE PROOFED IN THE PAST TO BE A POWERFUL TOOL FOR INDIRECT DISCOVERIES IN THE SM

WILL THE HISTORY REPEAT ITSELF IN THE CASE OF BSM PHYSICS?

SEVERAL OBSERVABLES PARTICULARLY SENSITIVE TO NEW PHYSICS, SENSITIVE TO NON-STRONGLY INTERACTING NEW PARTICLES (WITH SMALL CROSS SECTIONS FOR DIRECT PRODUCTION): HIGGS SECTOR, LEPTON SECTOR

"PROMISING" DEVIATIONS FROM THE SM PREDICTIONS FOR g-2 AND IN LEPTON UNIVERSALITY TESTS IN B MESON DECAYS (R_K)

THE OBSERVED ANOMALIES CAN BE SIMULTANEOUSLY EXPLAINED THEORETICALLY (+ DM)

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NATIONAL SCIENCE CENTRE POLAND

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Understanding the Early Universe: interplay of theory and collider experiments

Joint research project between the University of Warsaw & University of Bergen

SM AS AN EFFECTIVE THEORY

L_{SM} + SU(2) x U(1) invariant higher dim operators

e.g. dim 6 four fermion operators contributing to

$M - \bar{M}$ mixing

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_{ijkl}}{\Lambda^2}(\bar{Q}_i Q_j \bar{Q}_k Q_l) + \dots .$$

$l_j \to l_i \gamma$ decays

$$\mathcal{L}_{eff} = \frac{C_{ij}}{\Lambda^2}(\bar{L}_j \sigma^{\mu\nu} E_i) H B^{\mu\nu}$$

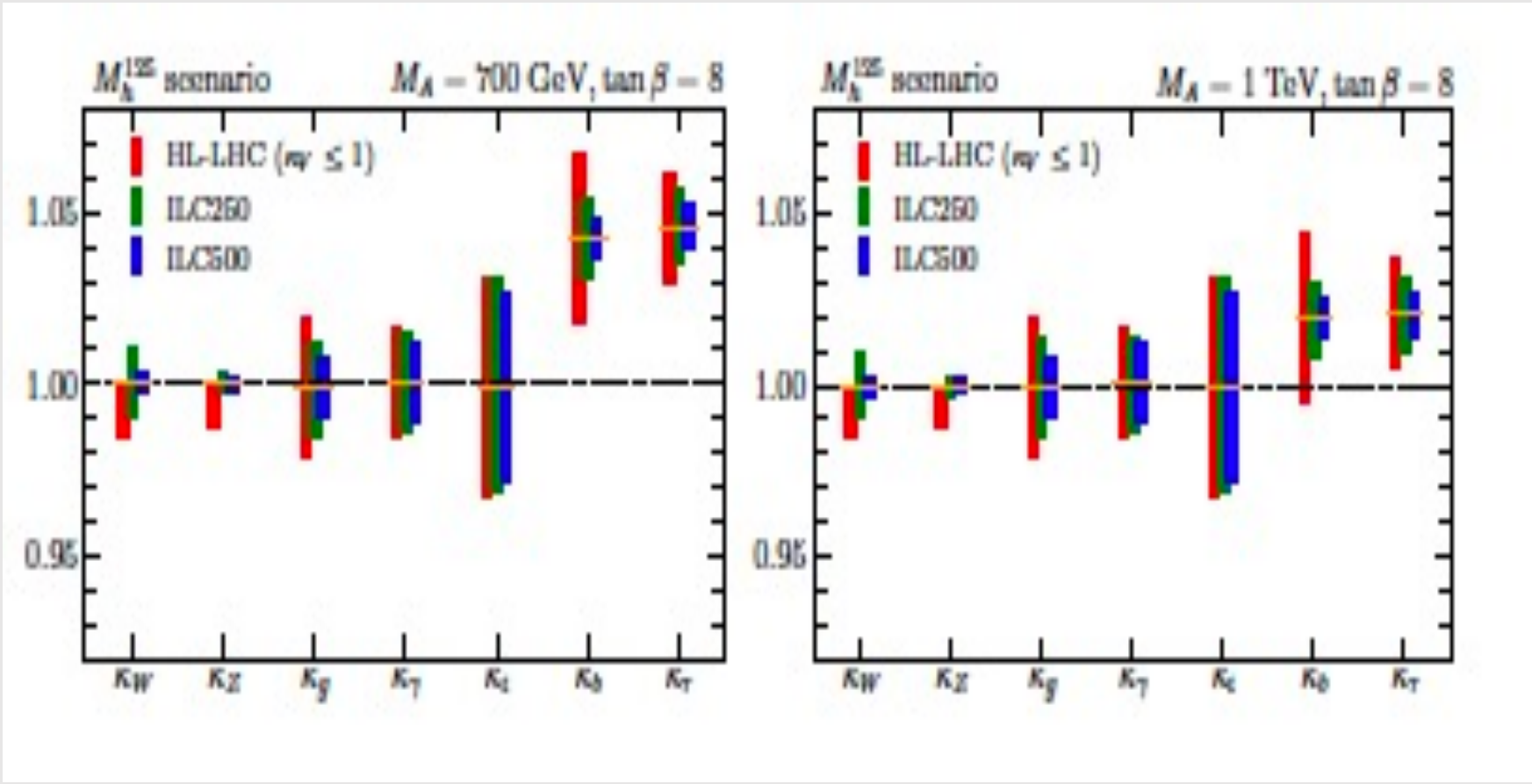
PRESENT BOUNDS ON THE WILSON COEFFICIENTS (EXP ERROR)

$K - \bar{K}$ **(0.1%)** $\Lambda > 10^5 \sqrt{C}\ TeV$

$B_d - \bar{B}_d$ **(1%)** $\Lambda > 10^2 \sqrt{C}\ TeV$

$B_s - \bar{B}_s$ **(10%)** $\Lambda > 10 \sqrt{C}\ TeV$

$BR(\mu \to e\gamma) < 10^{-13}$ $\Lambda > 10^4 \sqrt{C}\ TeV$


M_h^{125} scenario
$M_A = 700$ GeV, $\tan\beta = 8$
HL-LHC ($\kappa_V \leq 1$)
ILC250
ILC500
1.05
1.00
0.95
κ_W κ_Z κ_g κ_γ κ_t κ_b κ_τ
M_h^{125} scenario
$M_A = 1$ TeV, $\tan\beta = 8$
HL-LHC ($\kappa_V \leq 1$)
ILC250
ILC500
1.05
1.00
0.95
κ_W κ_Z κ_g κ_γ κ_t κ_b κ_τ