Standard Model (SM) or Standard Theory (ST)?

The many ways Beyond the SM (BSM)

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Torino, May 2, 2019

Some general introductory remarks

The potential of precision in the next decade, or so

More than one (motivated) scalar (if time permits)

The SM Lagrangian
(since 1973 in its full content)

$$\mathcal{L}_{\sim SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi}\, \not{D} \psi$$ (∿1975-2000)

$$+|D_\mu h|^2 - V(h)$$ (∿1990-2012-now)

$$+\psi_i \lambda_{ij} \psi_j h + h.c.$$ (∿2000- now)

In () the approximate dates of the experimental confirmation of the various lines (at different levels)

The synthetic nature of PP exhibited

The particles of the Standard Model (SM)

1973–2012

$J = 0$ $\quad h(2012)$

Quarks: $\frac{Q}{e} = 2/3$, $-1/3$ $\qquad$ Leptons: -1, 0 $\qquad$ "families" $i =$

$J = 1/2$ $\quad \Psi_i =$

$Q/e = 2/3$	$-1/3$	-1	0	$i =$
$u(1968)$	$d(1968)$	$e(1897)$	$\nu_e(1956)$	← 1
$c(1974)$	$s(1968)$	$\mu(1937)$	$\nu_\mu(1962)$	← 2
$t(1994)$ *	$b(1977)$	$\tau(1975)$	$\nu_\tau(2000)$ *	← 3

$H = (pe)$ $\qquad p = (uud)$ $\qquad n = (udd)$

$J = 1$			
$G^a_\mu(1978)$ *	$A_\mu(1905)$	$W_\mu(1984)$	$Z_\mu(1984)$

(* = without a Nobel)

All of Particle Physics in 1 page

1. Symmetry group $L \times \mathcal{G}$

L = Lorentz (space-time)

$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local)

2. Particle content (rep.s of $L \times \mathcal{G}$)

	h	Q	L	u	d	e
Lorentz	0	$1/2_L$	$1/2_L$	$1/2_R$	$1/2_R$	$1/2_R$
$SU(3)$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$
$SU(2)$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)$	$-1/2$	$1/6$	$-1/2$	$2/3$	$-1/3$	-1

3. All "operators" (products of $\Phi, \partial_\mu \Phi$) in $\mathcal{L}$ of dimension ≤ 4

$$\hbar = c = 1 \Rightarrow [A_\mu] = [\phi] = [\partial_\mu] = M, \quad [\Psi] = M^{3/2}, \quad [\mathcal{L}] = M^4$$

Problems of (questions for) the SM

0. Which rationale for matter quantum numbers?

$$|Q_n - Q_p - Q_e| < 10^{-21} e$$

1. Phenomena unaccounted for

neutrino masses
Dark matter
matter-antimatter asymmetry
inflation?

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$

Axions

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

neutrino masses
Are the protons forever?
What about individual L_i conservations?

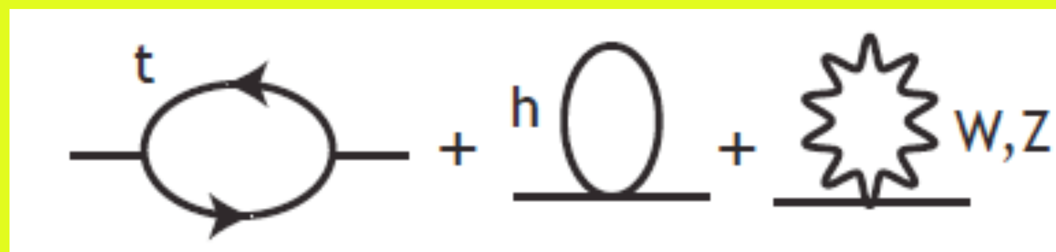
4. Lack of calculability (a euphemism)

$\Rightarrow$ the hierarchy problem
the flavour puzzle
$\Leftarrow$ none of the 15 masses predicted in the SM

The hierarchy problem, once again

Can we compute the Higgs mass/vev in terms of some fundamental dynamics?

NOT in the SM



$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_g'^2$$

The "standard" reaction

Introduce top "partners", J=0 or 1/2,

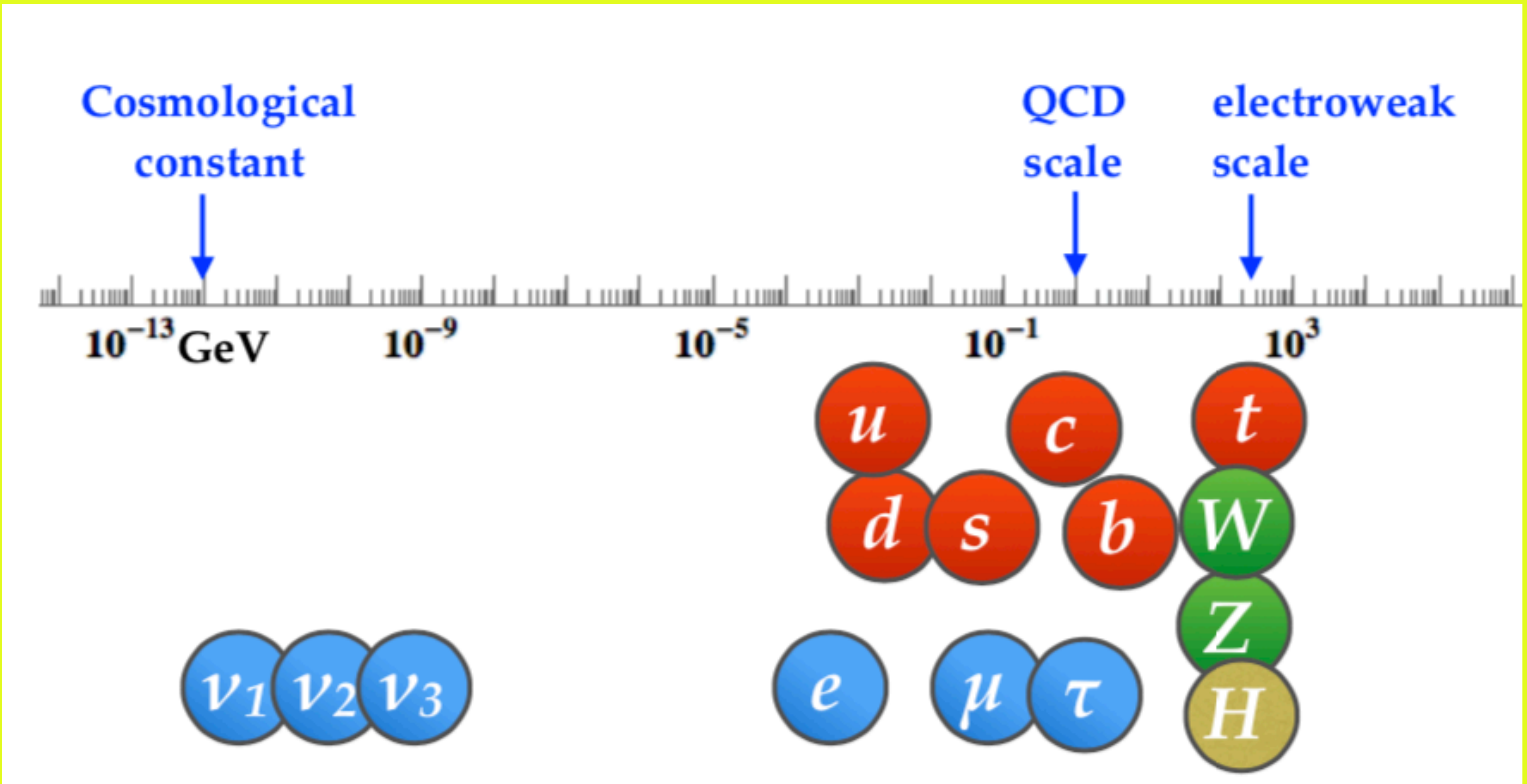
coloured or uncoloured, (see below)

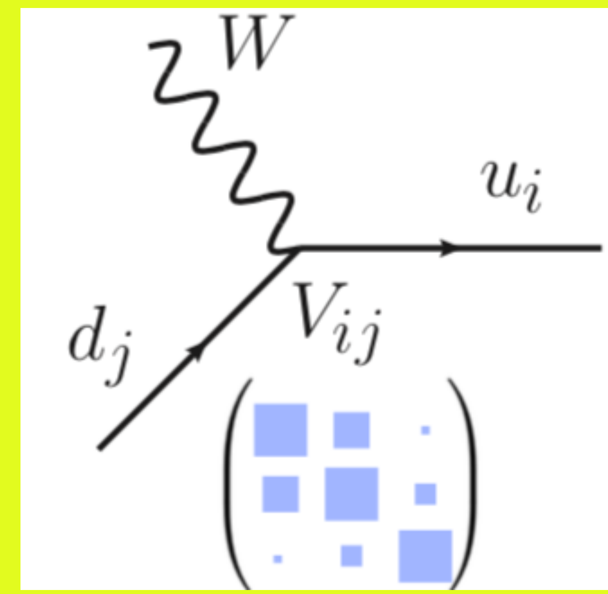
with a mass not far from a TeV,

capable to cutoff the Λ^2 divergence

No successful search, so far

None of these masses (17-2) or mixings



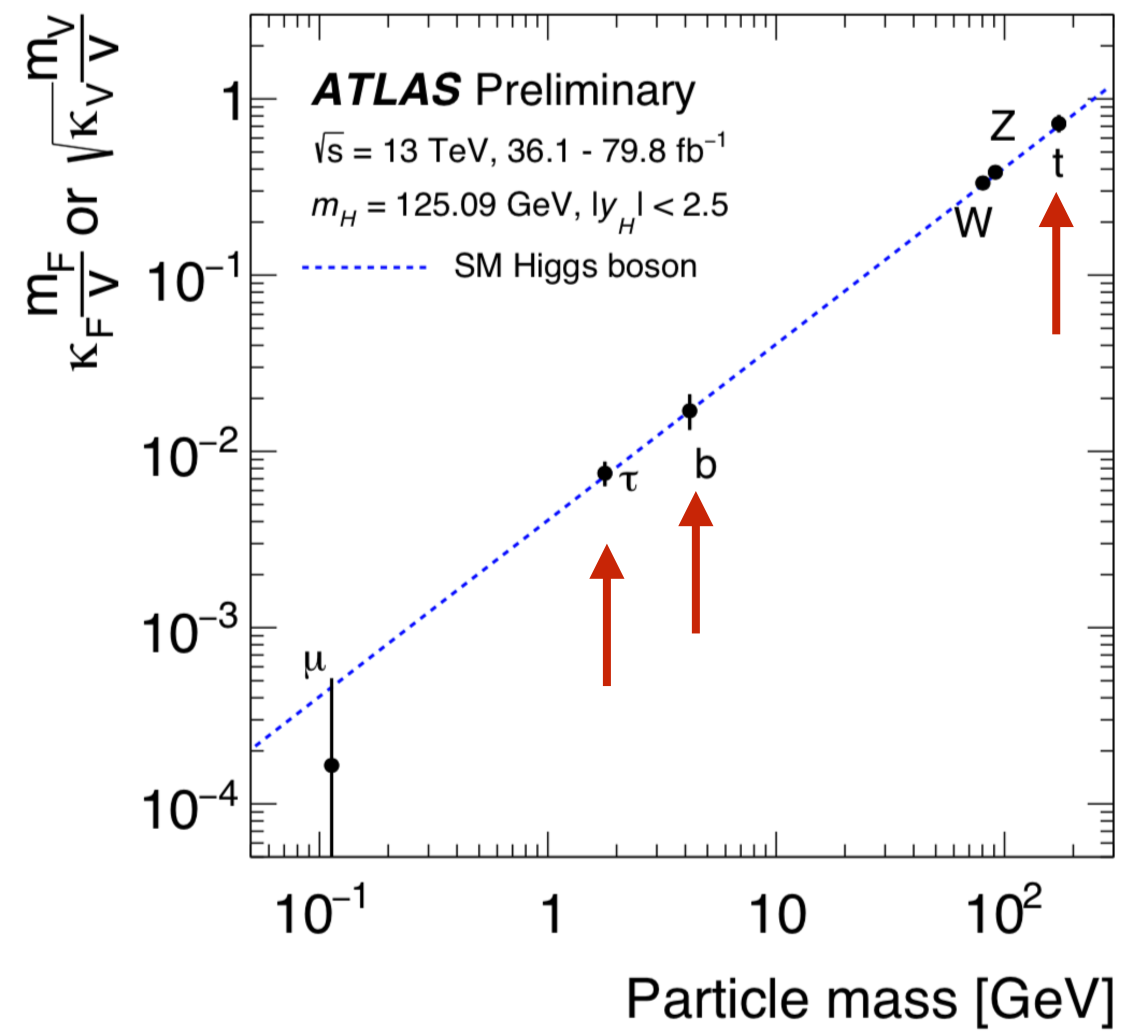


are predicted in the Standard Model

The flavour paradox $\lambda_{ij}\Psi_i\Psi_j$

The Yukawa couplings are progressively becoming a piece of physical reality

$$\mathcal{L}_Y = \lambda_i \bar{\Psi}_i \Psi_i h$$
$$\Rightarrow \lambda_i (v+H) \bar{\Psi}_i \Psi_i$$
$$\Rightarrow m_i = \lambda_i v$$



$$\left(\frac{\lambda_{e(\mu)}}{\lambda_\tau} < 0.2, \quad \frac{\lambda_{u(c)}}{\lambda_t} < 0.04, \quad \frac{\lambda_{d(s)}}{\lambda_b} < 0.7\right)$$

As opposed to the hard time in trying to explain the spectrum and the mixing of quarks and leptons

Not easy to improve without observing deviations from the SM

The many different directions in BSM

(for an audience of philosophers, sic)

1. Explore the space of theories

- Address a specific problem, theoretical or experimental

  E.g.: Supersymmetry, DM axions, Baryogenesis, ...

- Expand the set of consistent and potentially "true" theories

  E.g.: Supersymmetry, conformal field theory, string theory, ...

2. Explore the space of observables

- Test a "true" theory

  E.g.: Precision tests of the SM

- Extend the explorable territory

  E.g.: Where can one look for "DM"? Are there new light particles?

The emphasis on the specific direction is time dependent

To concentrate now on a single direction is dangerous

The potential of precision in the next decade

(mostly, but not only, at LHC)

- Higgs couplings

$$\mathcal{L} = -\lambda k_\lambda H^4 + g_f k_f H \bar{f} f + g_V k_V V_\mu H^+ \partial_\mu H$$

- ElectroWeak observables

Pole observables: $m_W, sin\theta^l_{eff}$

Drell-Yan $l^+ l^-, l\nu$ at high m_{ll}, m^T_{ll}

DiBoson production Wh, Zh, WZ, WW

- Flavour observables

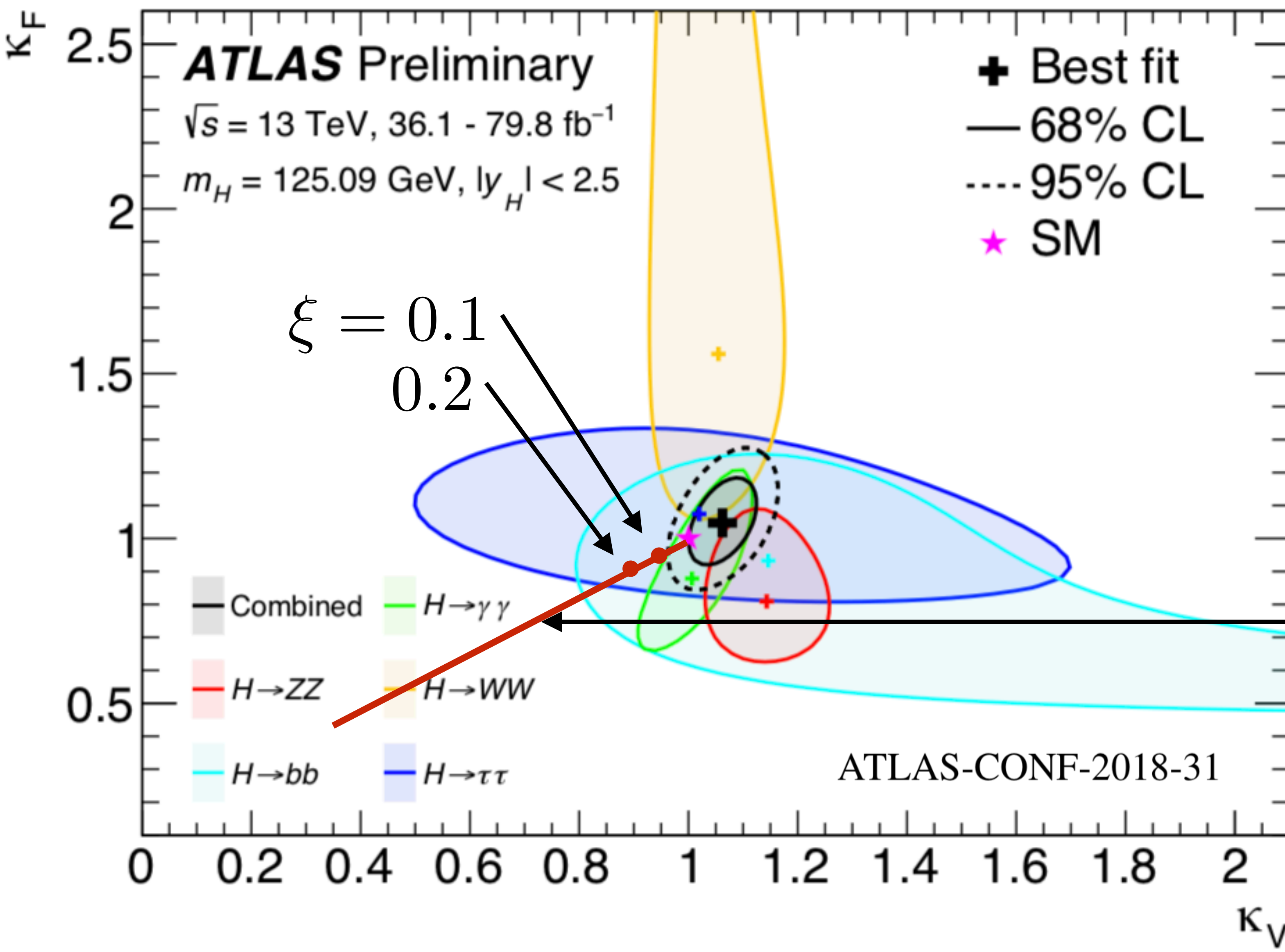
Testing the FCNC loops

Lepton Flavour Violation

The role of flavour in BSM

Higgs couplings

$$\mathcal{L} = g_f k_F H \bar{f} f + g_V k_V V_\mu H^+ \partial_\mu H$$



the scale f
of Higgs compositeness

$$\xi = \frac{v^2}{f^2} \qquad k_F = k_V = \sqrt{1-\xi}$$

Now $f \gtrsim 600 \div 800\ GeV$

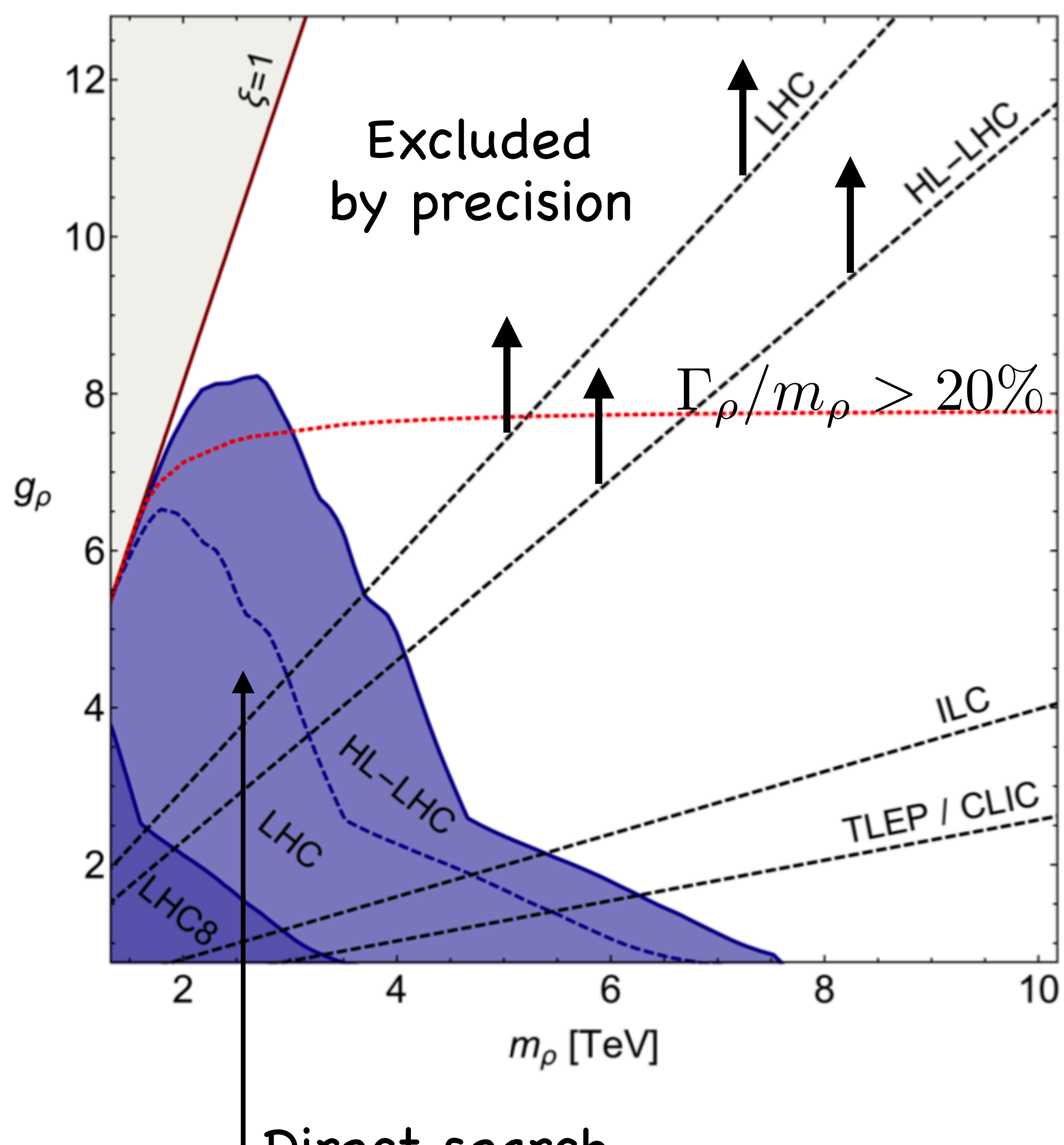
Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$

$$f \to 1 \div 1.5\ TeV$$

Direct versus indirect searches

Consider, e.g. $pp \to \rho \to WZ$ with $m_\rho = g_\rho f$ and $g_f = \dfrac{g^2}{g_\rho}$

$$\xi = \frac{v^2}{f^2} = g_\rho^2 \frac{v^2}{m_\rho^2}$$



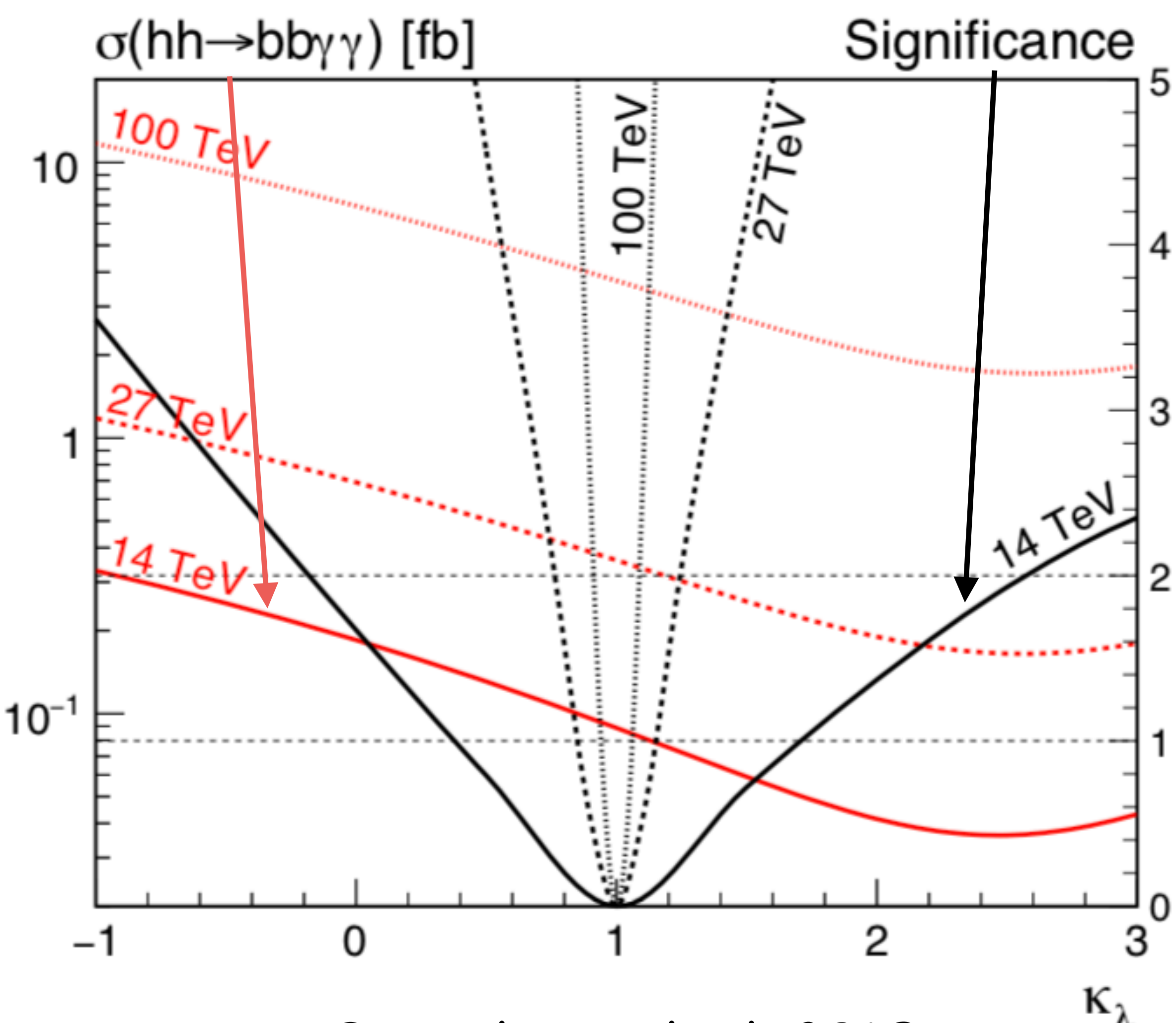
Collider	Energy	Luminosity	ξ $[1\sigma]$
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2×10^{-3}

Thamm, Torre, Wulzer 2015

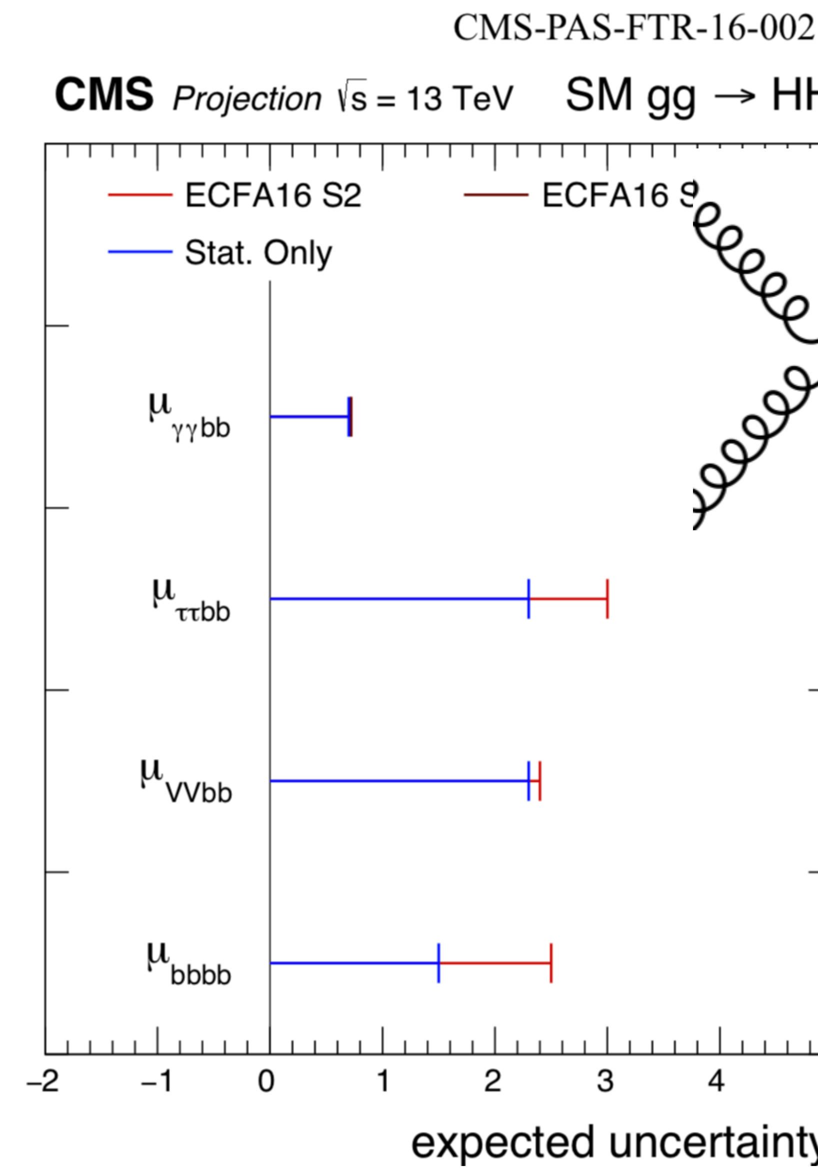
$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v} \boxed{k_\lambda} h^3 + \frac{m_h^2}{8v^2} h^4$$

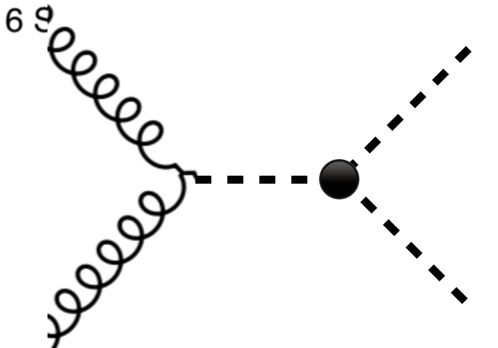
$k_\lambda = 1$ in the SM

Can one measure it directly?



Goncalves et al 2018



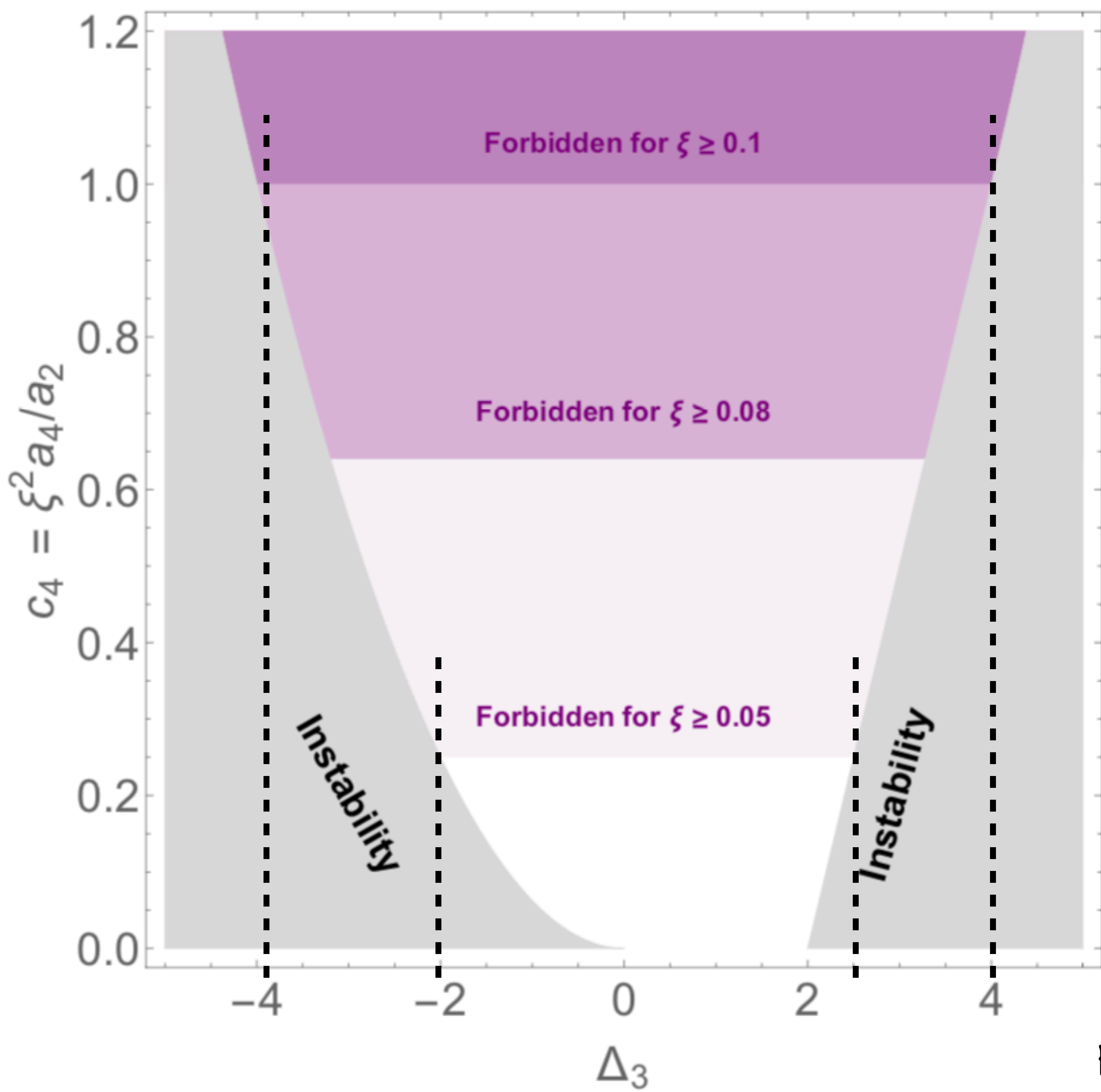


As difficult as important

significant deviations conceivable in BSM

Which deviations conceivable in BSM?

$$V(H) = \frac{m_*^2}{4g_*^2}\Sigma a_n\left(\frac{2H^2 - v^2}{f^2}\right)^n$$



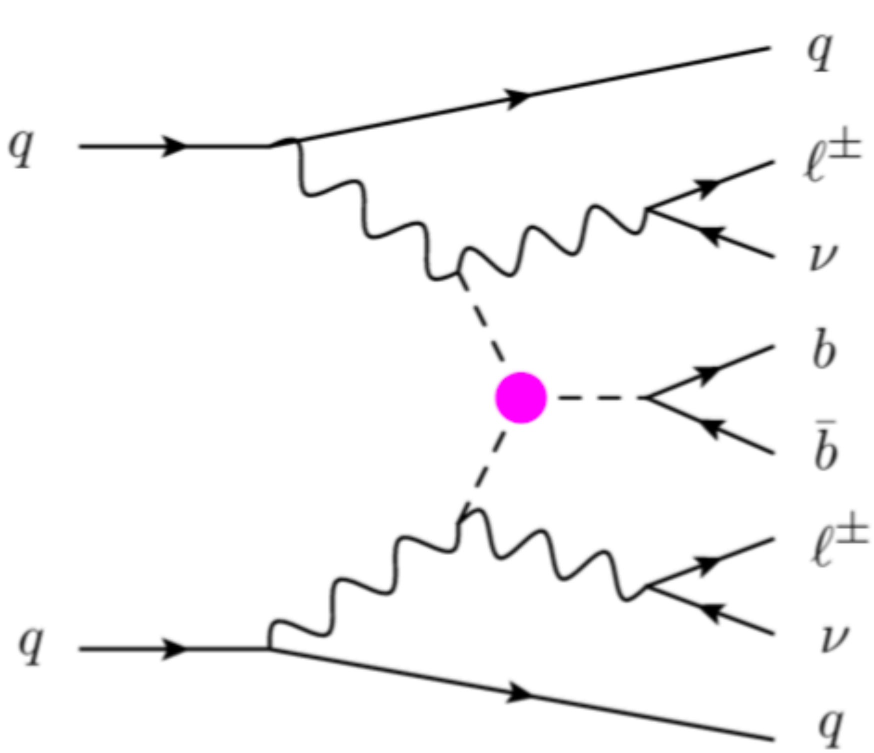
$$\Delta_3 \equiv k_\lambda - 1$$

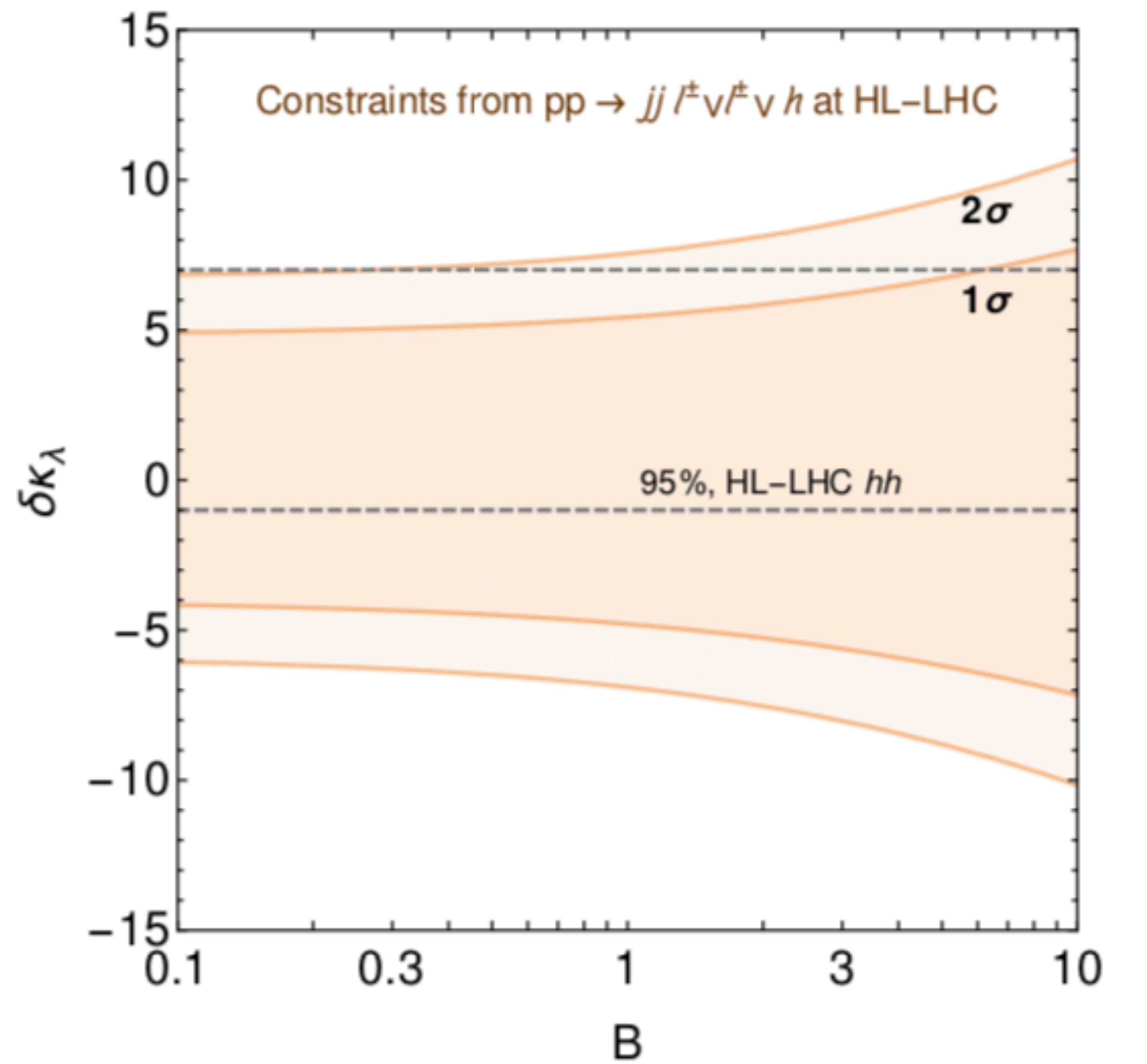
Falkowski, Rattazzi 2019

Taking advantage of the high energy growth

(in progress)

$$pp \to jjh + V_L V'_L$$





B= 1 (SM background)

Henning, Lombardo, Riembau, Riva 2018

The potential of precision in the next decade

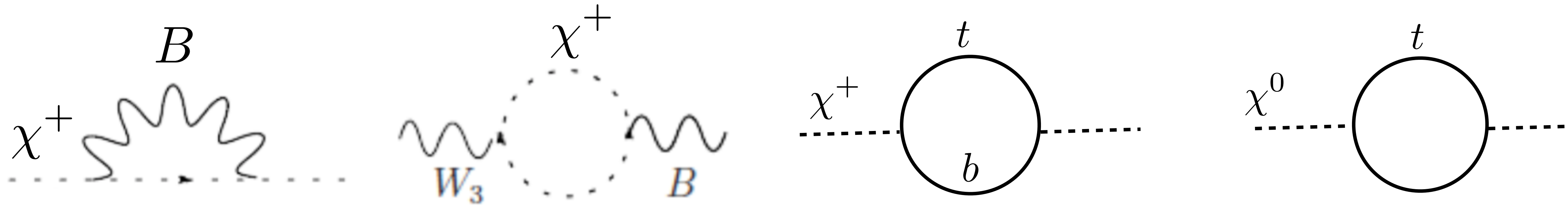
- ElectroWeak observables

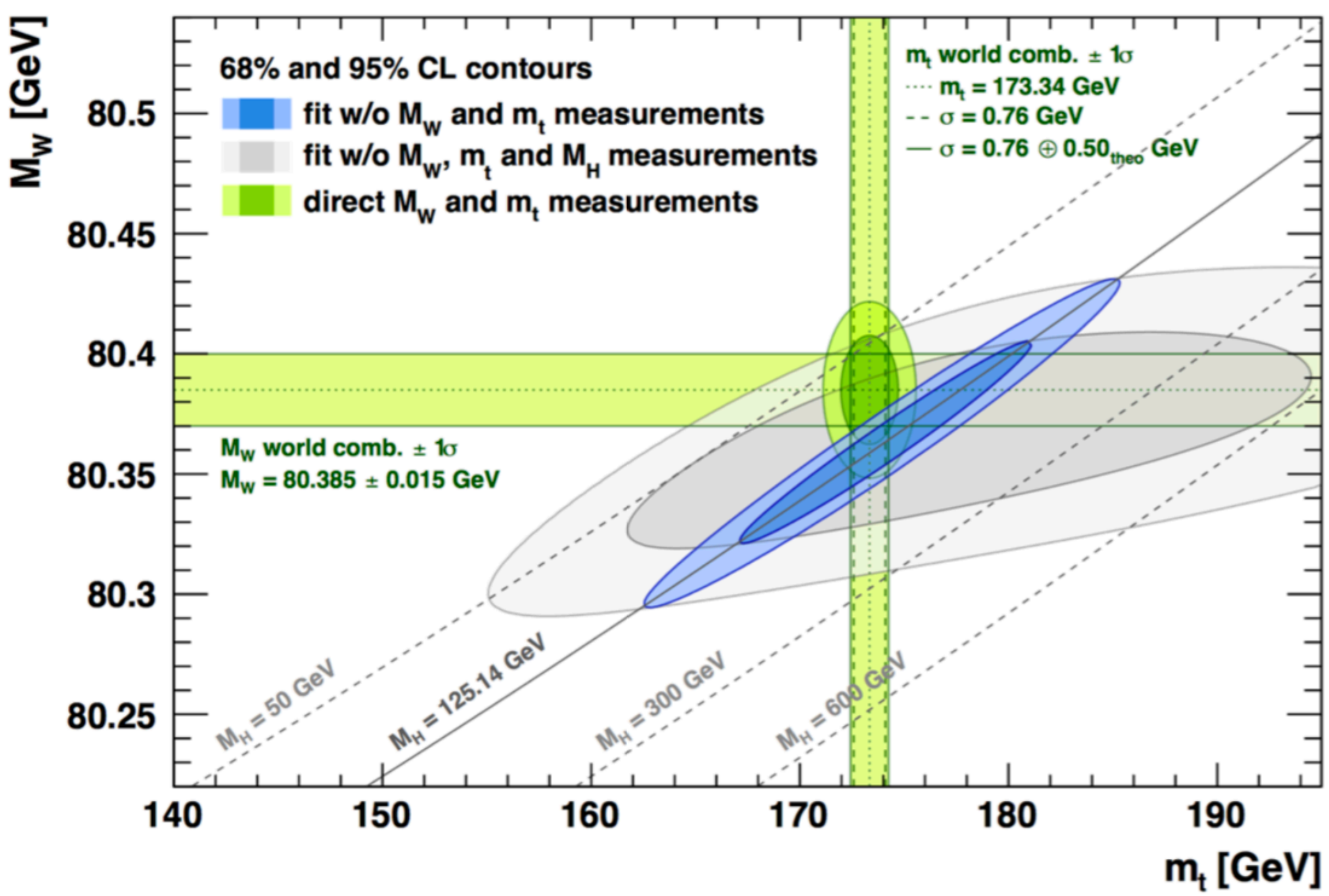
Pole observables: $m_W, sin\theta^l_{eff}$

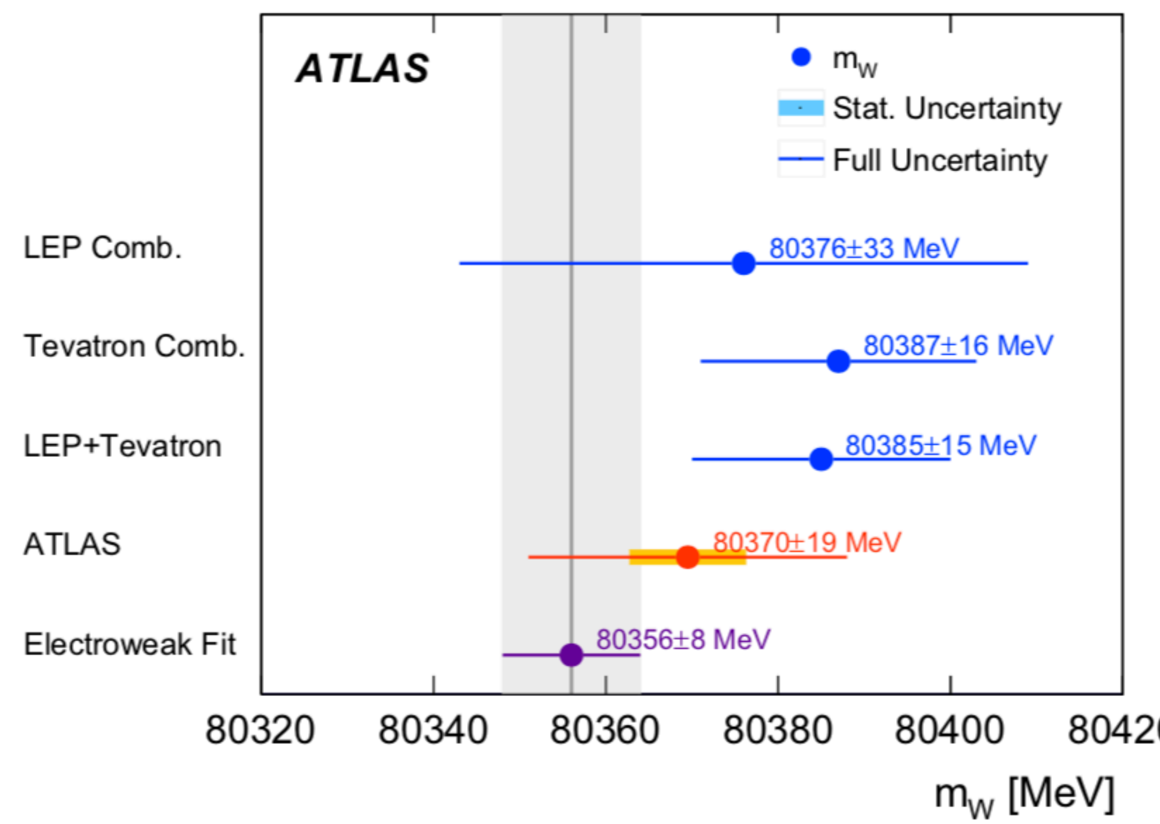
Drell-Yan $l^+l^-, l\nu$ at high m_{ll}, m^T_{ll}

DiBosons Wh, Zh, WZ, WW

Comparing direct measurements with virtual effects





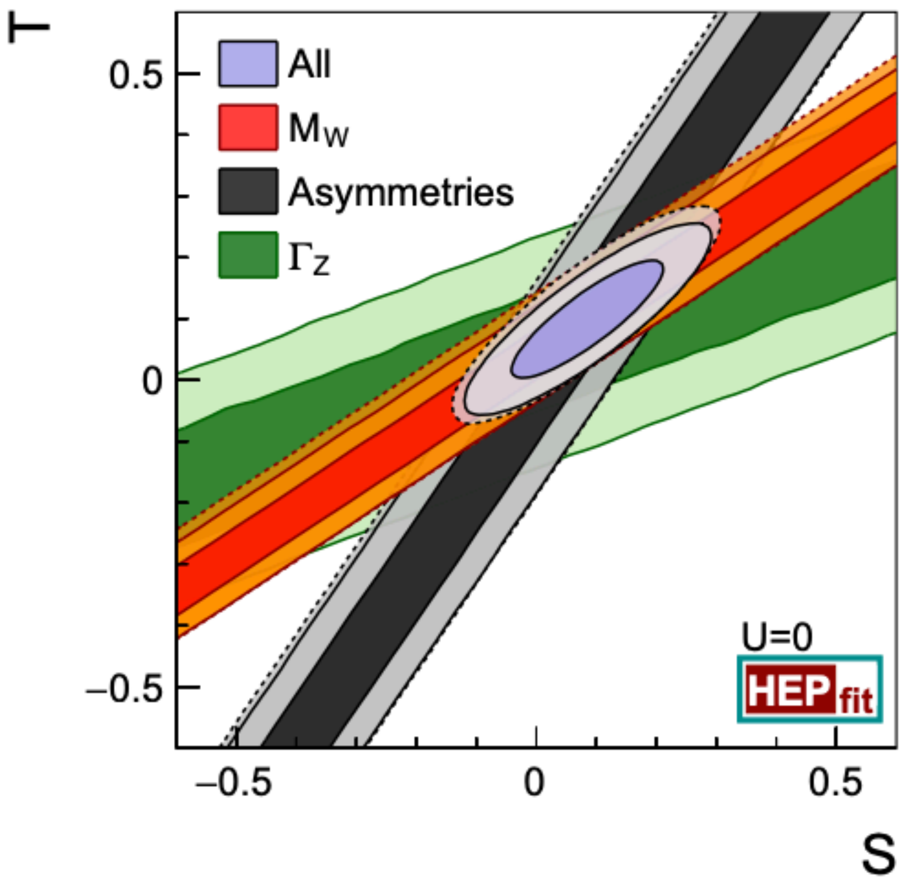


Blue = prediction of m_t, M_W by fitting "pole observables" in the SM, with crucial inclusion of loop effects

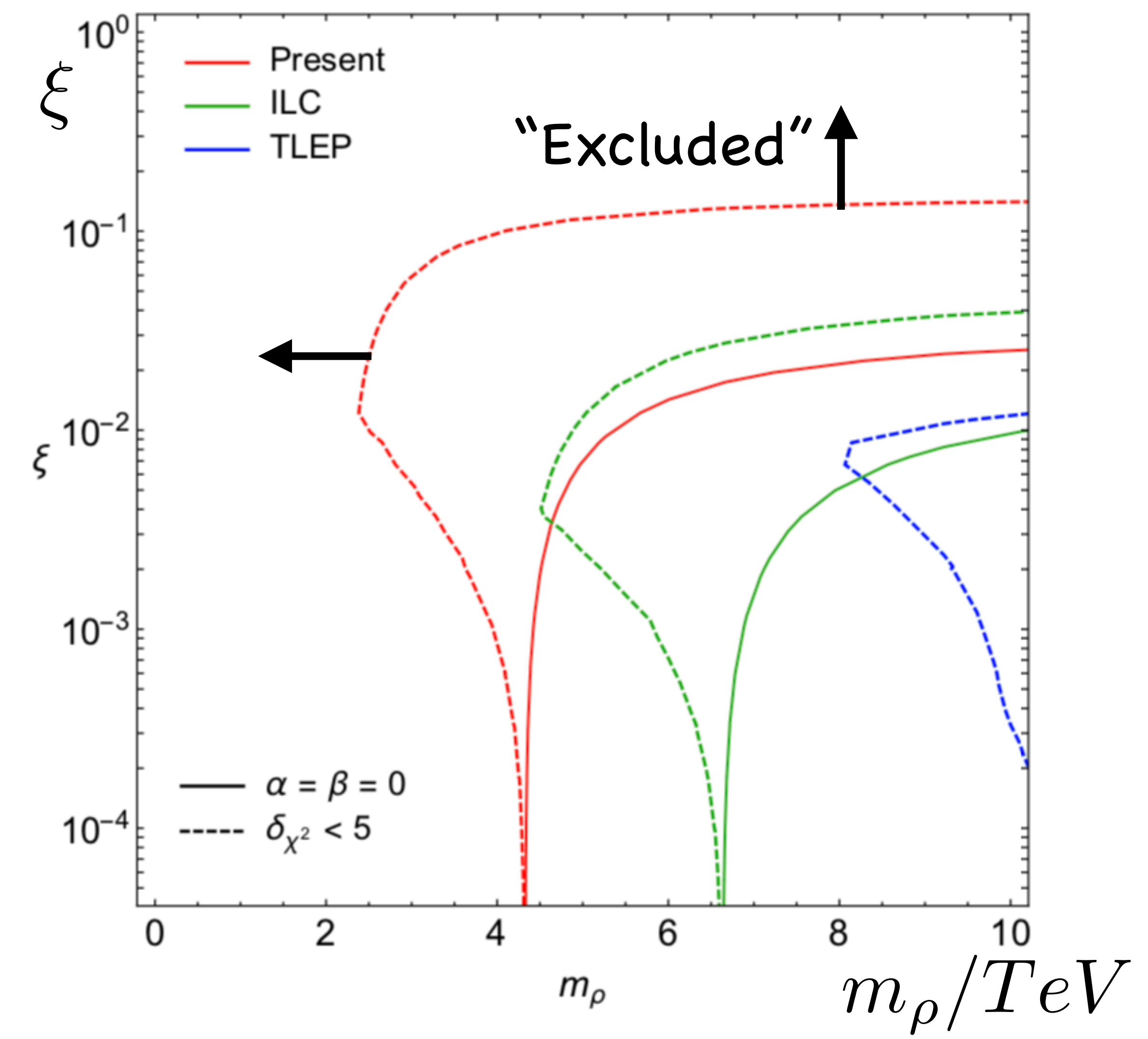
Green = direct measurements of m_t, M_W

Constraints from pole observables

Standard parameters: $\hat{S}, \hat{T}$ or ϵ_3, ϵ_1



Thamm, Torre, Wulzer 2015



In a composite Higgs picture:

$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi\log\left(\frac{\Lambda}{m_h}\right) + \frac{m_W^2}{m_\rho^2} + \alpha\frac{g^2}{16\pi^2}\xi\,,$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi\log\left(\frac{\Lambda}{m_h}\right) + \beta\frac{3y_t^2}{16\pi^2}\xi\,,$$

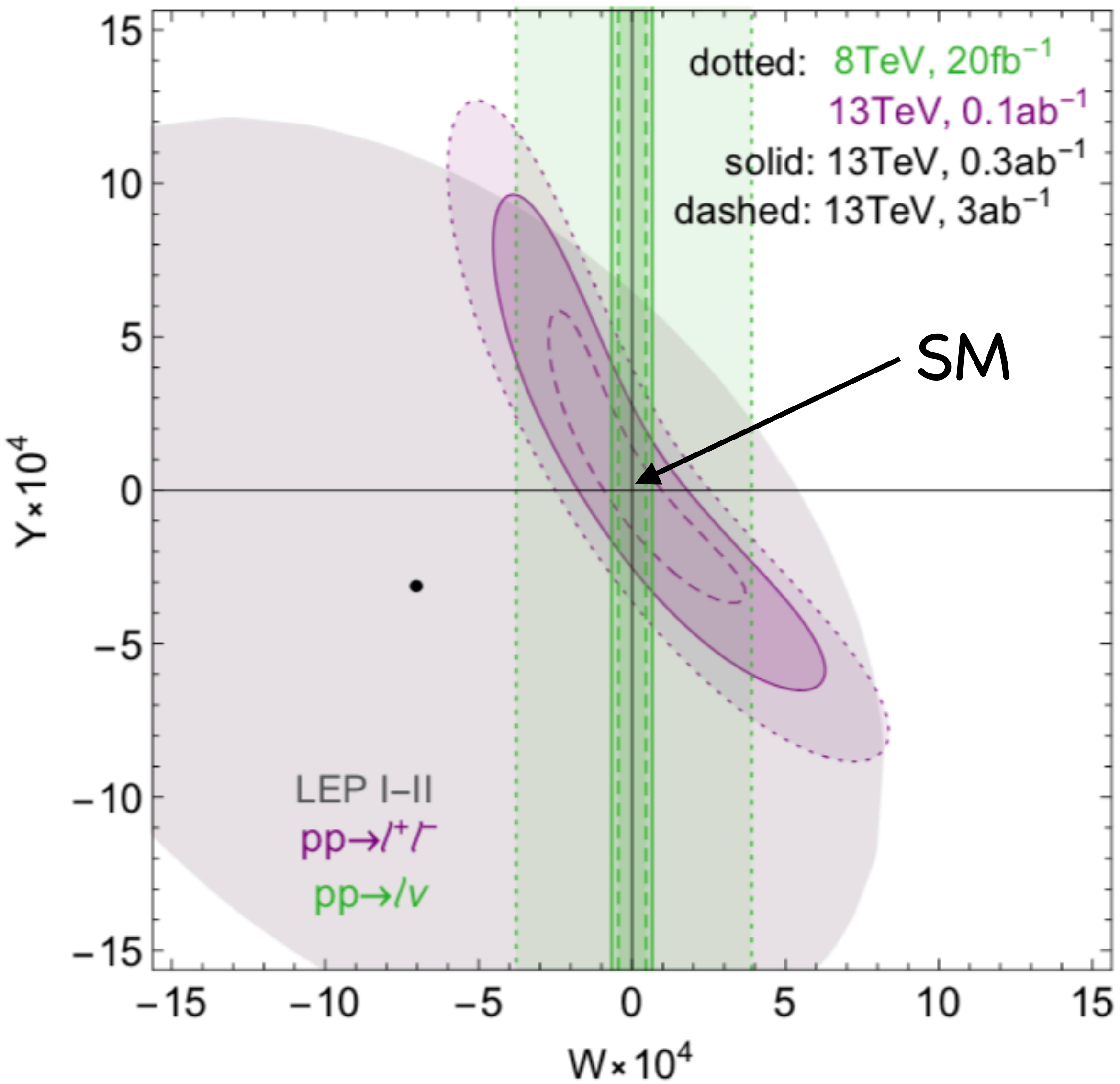
$k_V = \sqrt{1-\xi}$

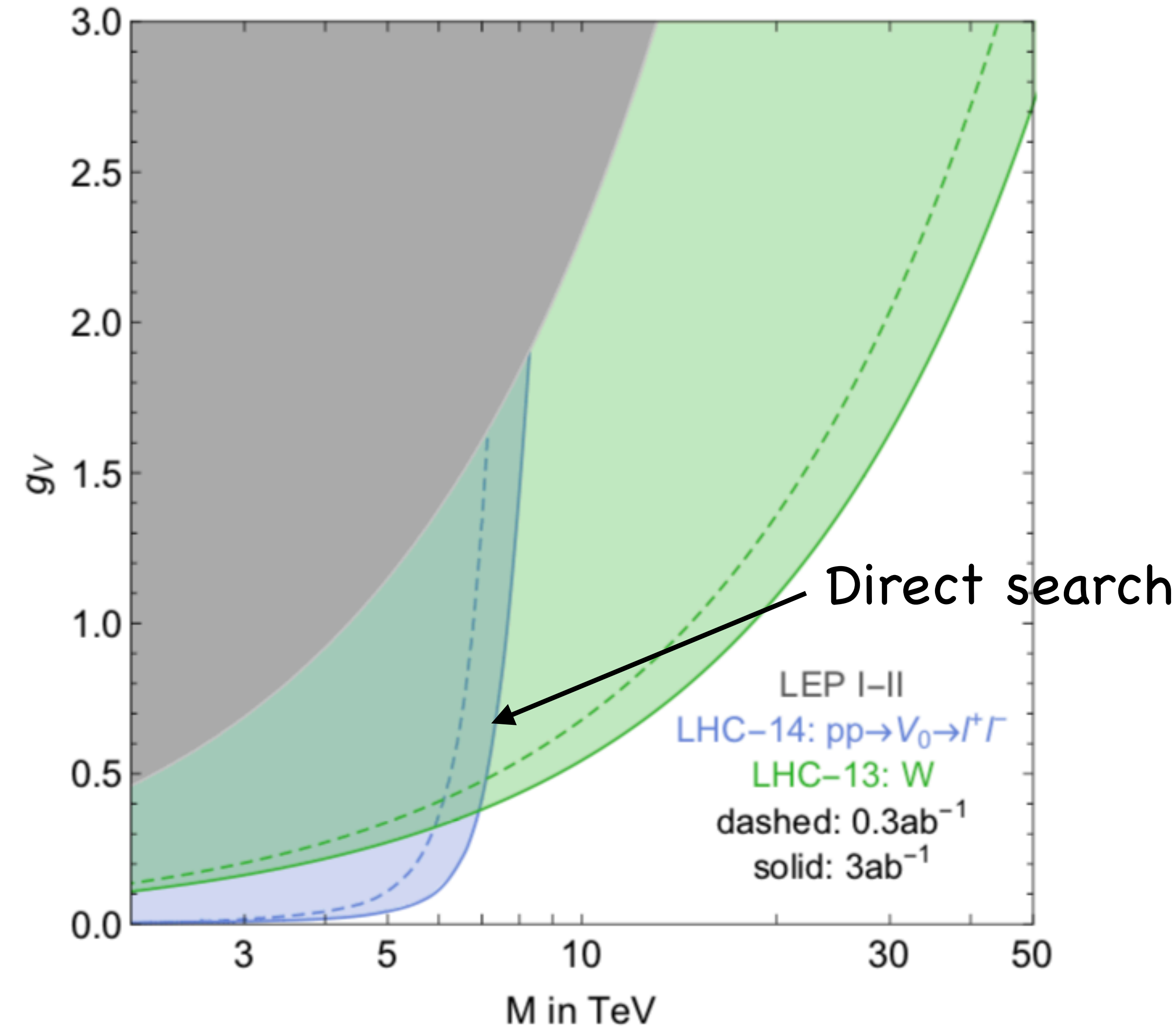
B, Bellazzini et al 2007

Nominally the limit on ξ, or on f better than from Higgs couplings, but the fudge factors α, β ...

$pp \to l^+ l^-, l\nu$ at high m_{ll}, m_{ll}^T

Farina et al 2016





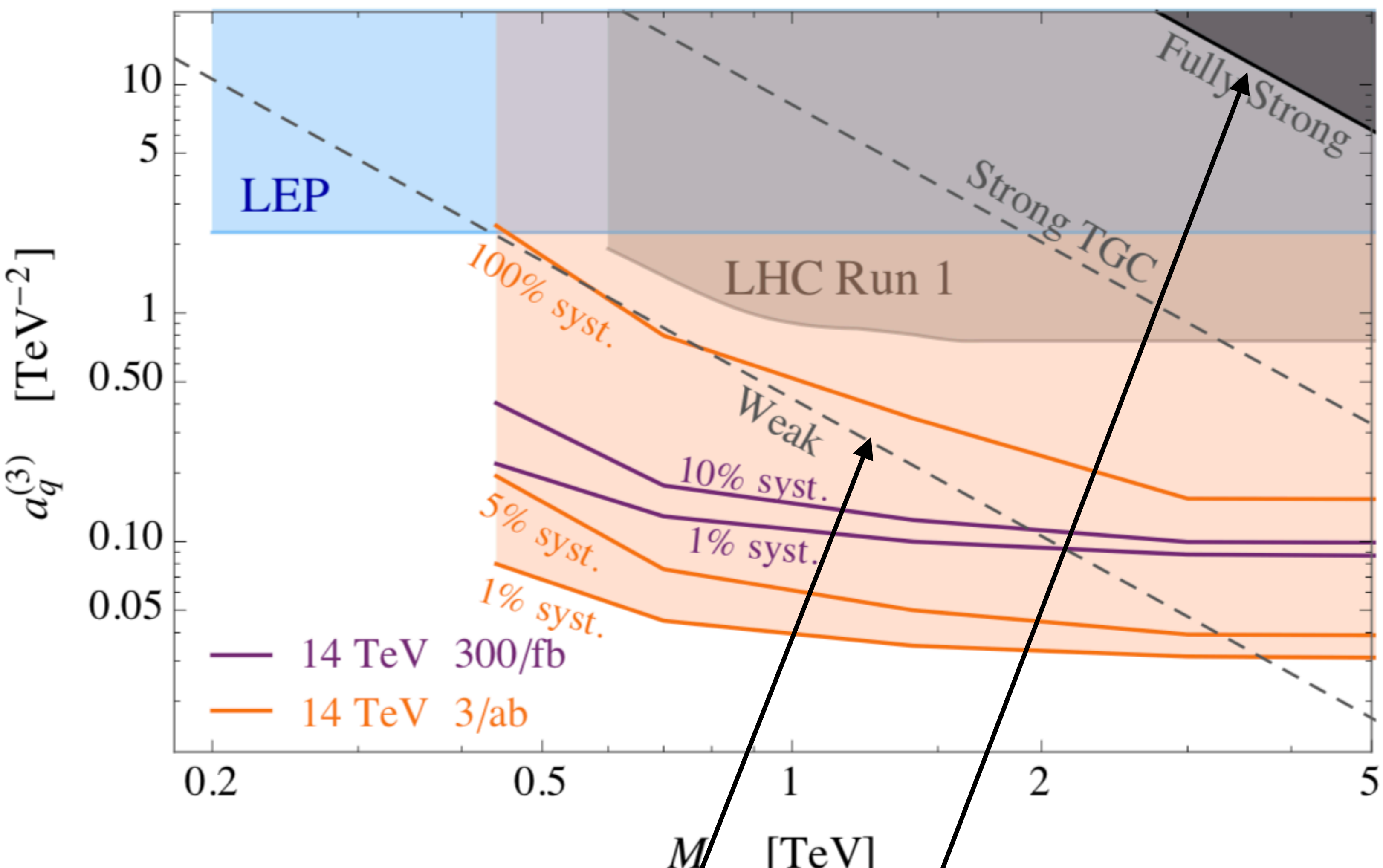
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$

$$\mathcal{L} = g_V V^a_\mu (f \tau^a \gamma_\mu f + i H^+ D_\mu H)$$

On some observables (W,Y) LEP beaten by LHC
(if suitable precision pursued)

DiBoson differential cross section with suitable angular analyses

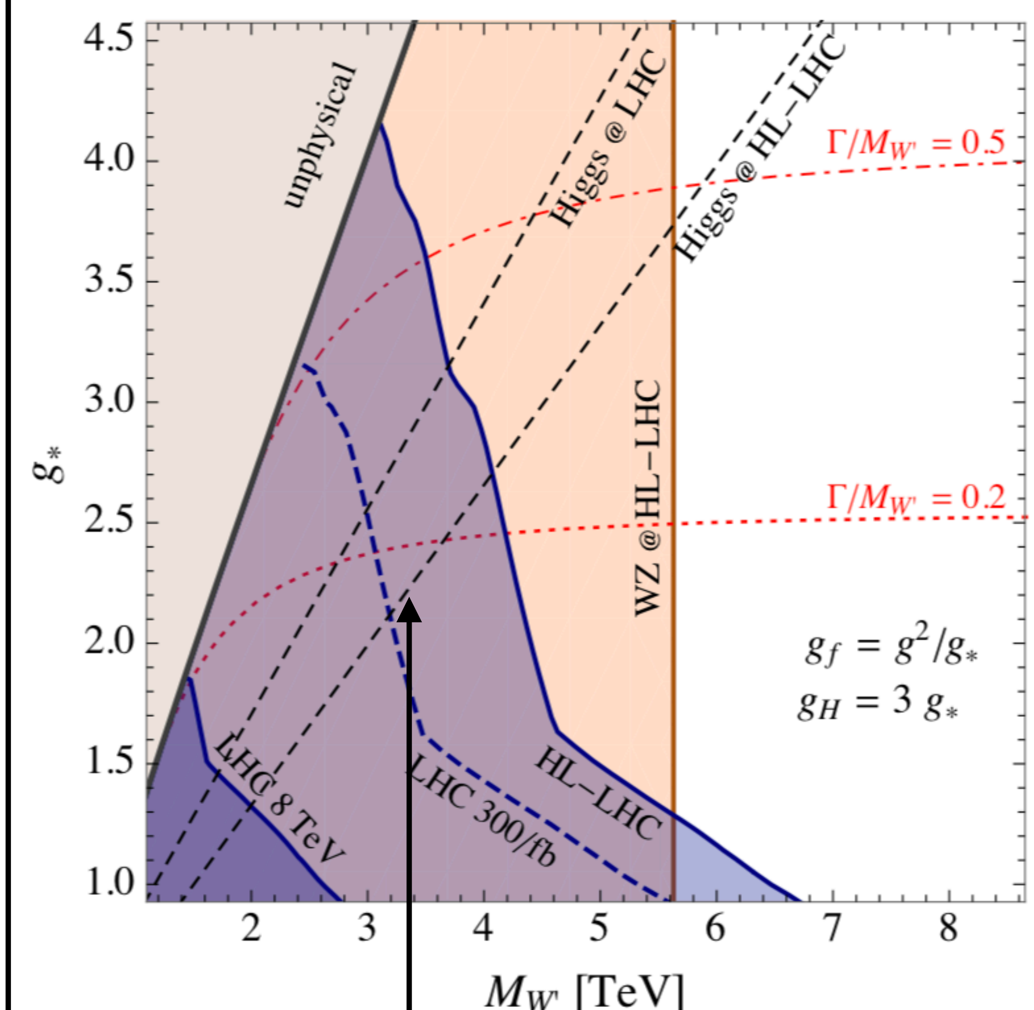
$$\delta A(\bar{q}q' \to WZ) \approx a_q^{(3)} E^2$$



$$a_q^{(3)} = \frac{g^2}{M^2} \div \frac{16\pi^2}{M^2}$$

(but not loop suppressed)

$$\mathcal{L} = V_\mu^a (g_f \bar{f} \tau^a \gamma_\mu f + g_H i H^+ D_\mu H)$$



Direct search

Franceschini et al 2018

The potential of precision in the next decade

- Flavour observables

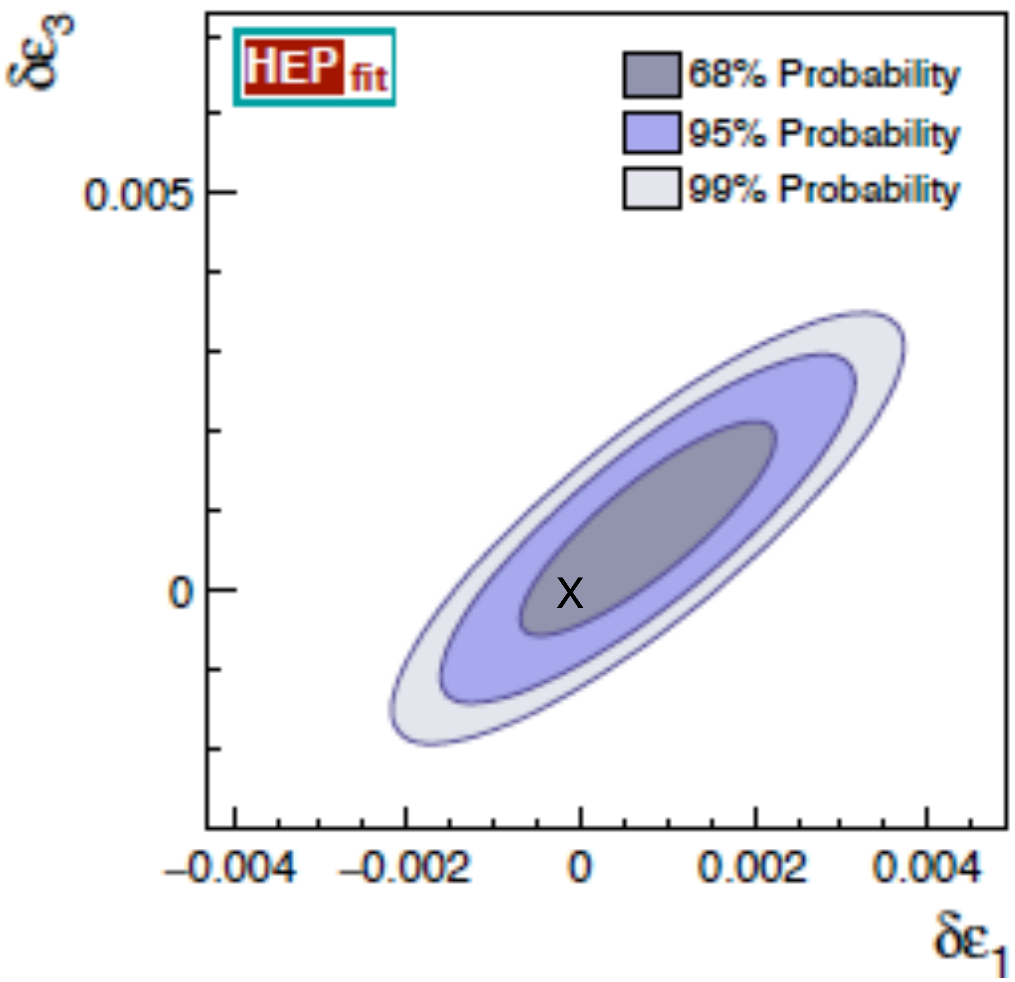
Testing the FCNC loops

Lepton Flavour Violation

The role of flavour in BSM

FCNC versus EWPT: a significant comparison

$\epsilon_1^{SM} = 5.21 \cdot 10^{-3}, \; \epsilon_3^{SM} = 5.28 \cdot 10^{-3}$

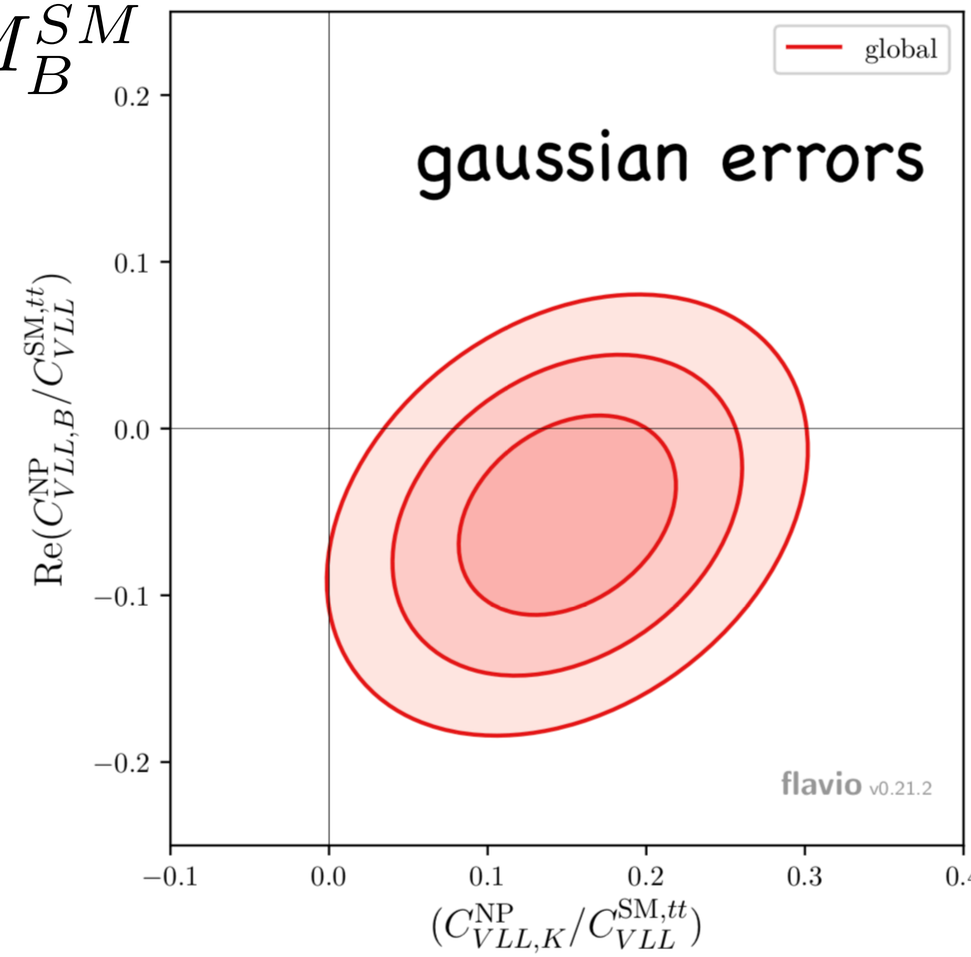


measures EW loops
at about 20% level

A future facility (FCCee, ...)
could go to 2% level

Straub 2016

$\dfrac{\Delta M_B}{\Delta M_B^{SM}}$

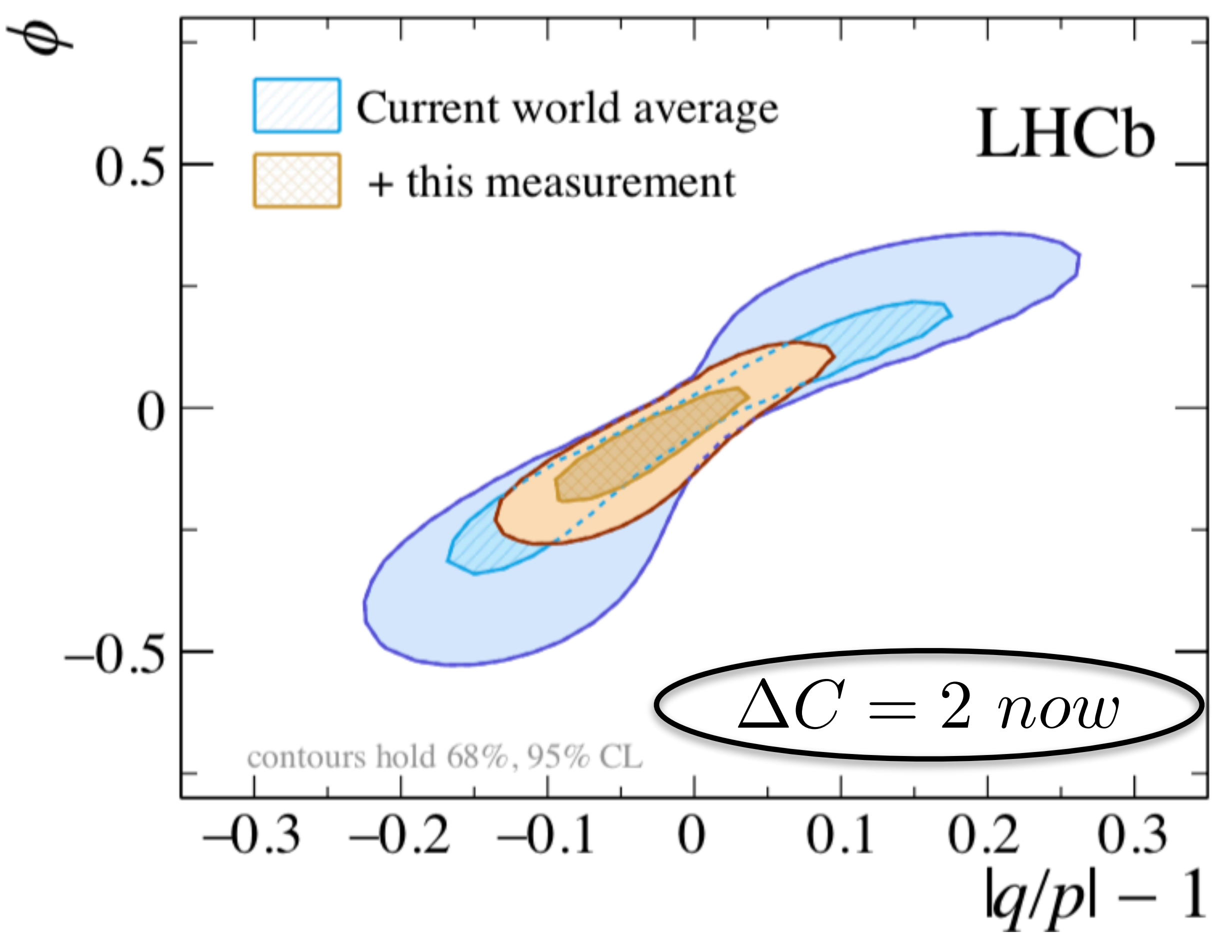


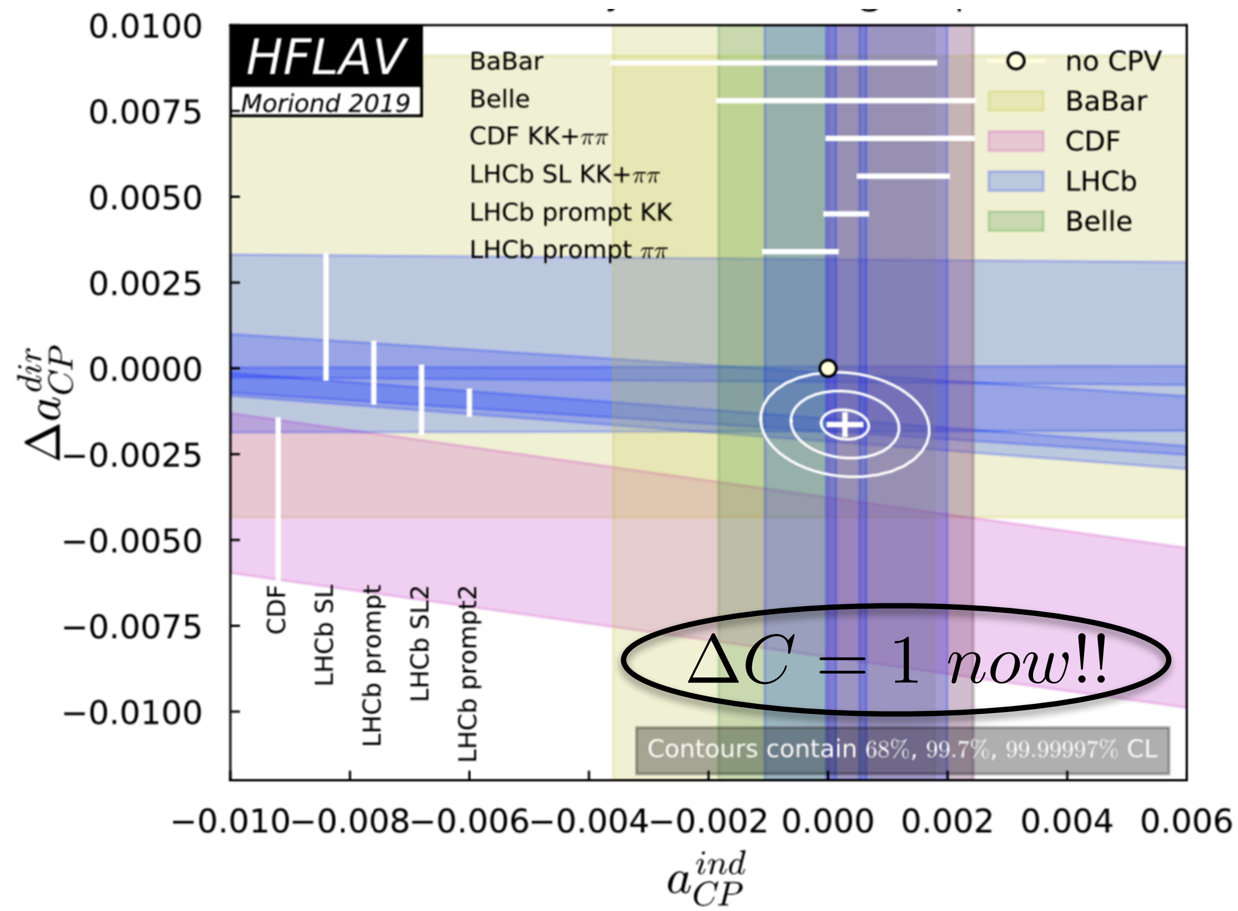
$\dfrac{\epsilon_K}{\epsilon_K^{SM}}$

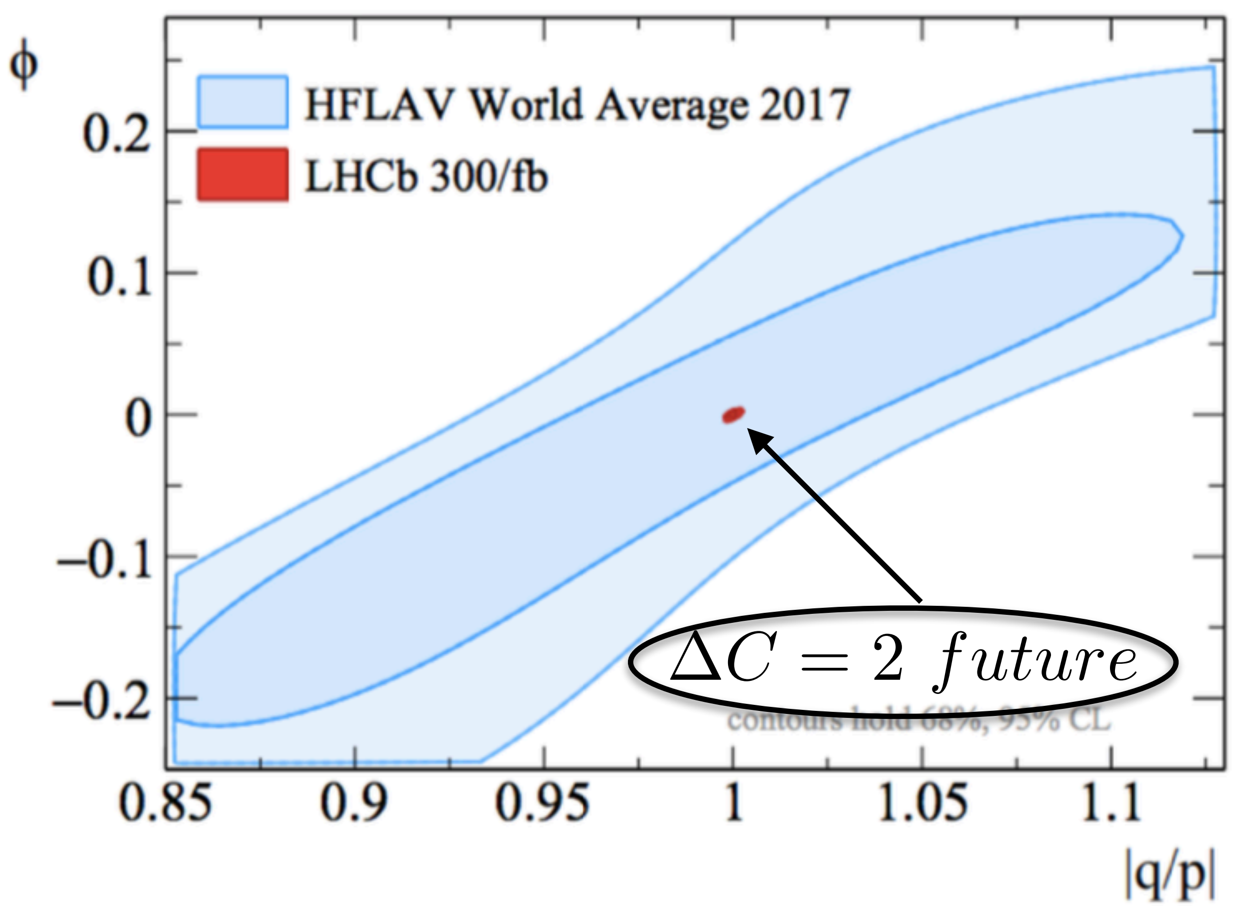
measures FCNC loops
at about 20% level

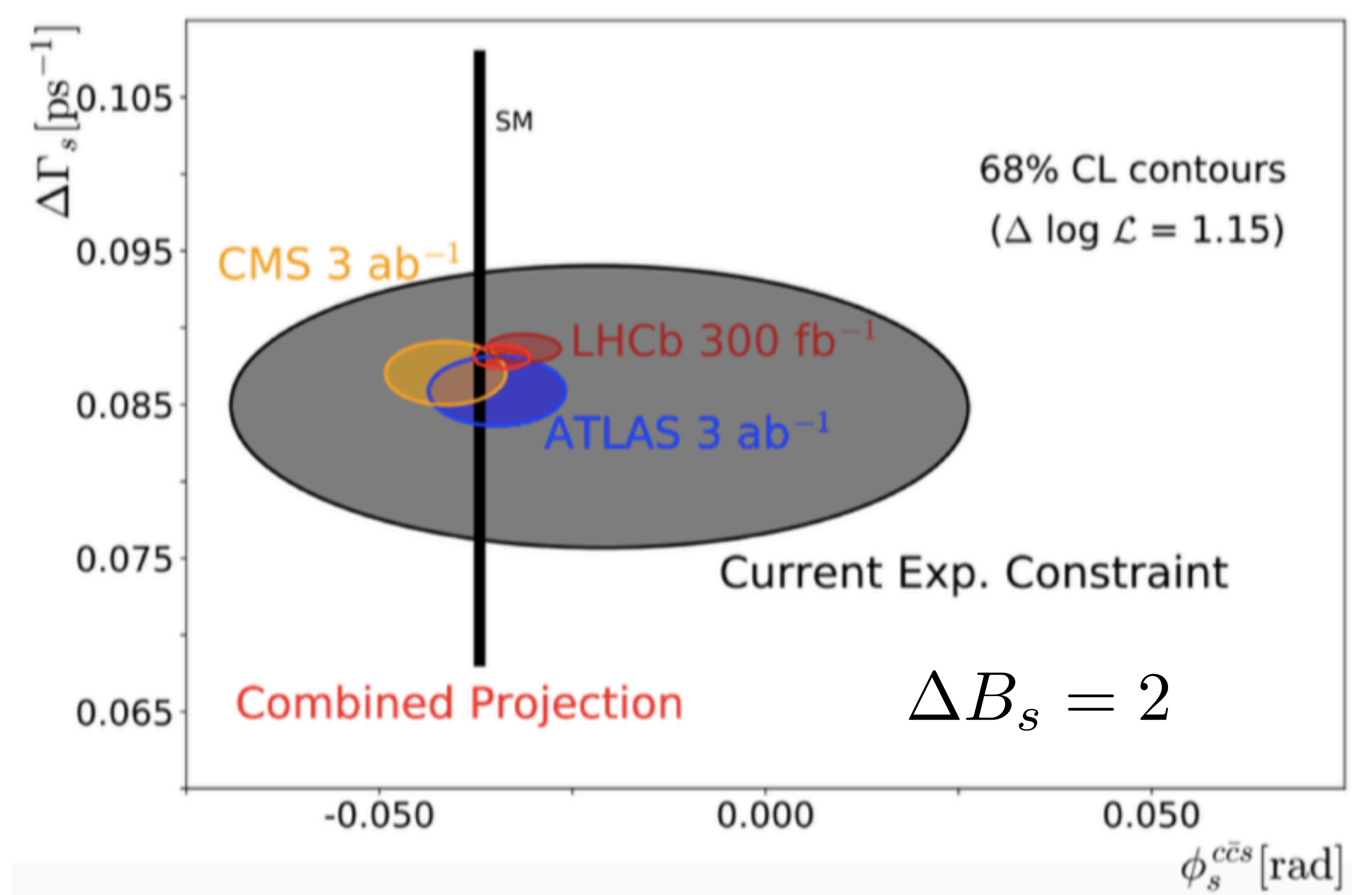
An "aggressive" flavour program
could go to 2% level

CPV now and in prospects





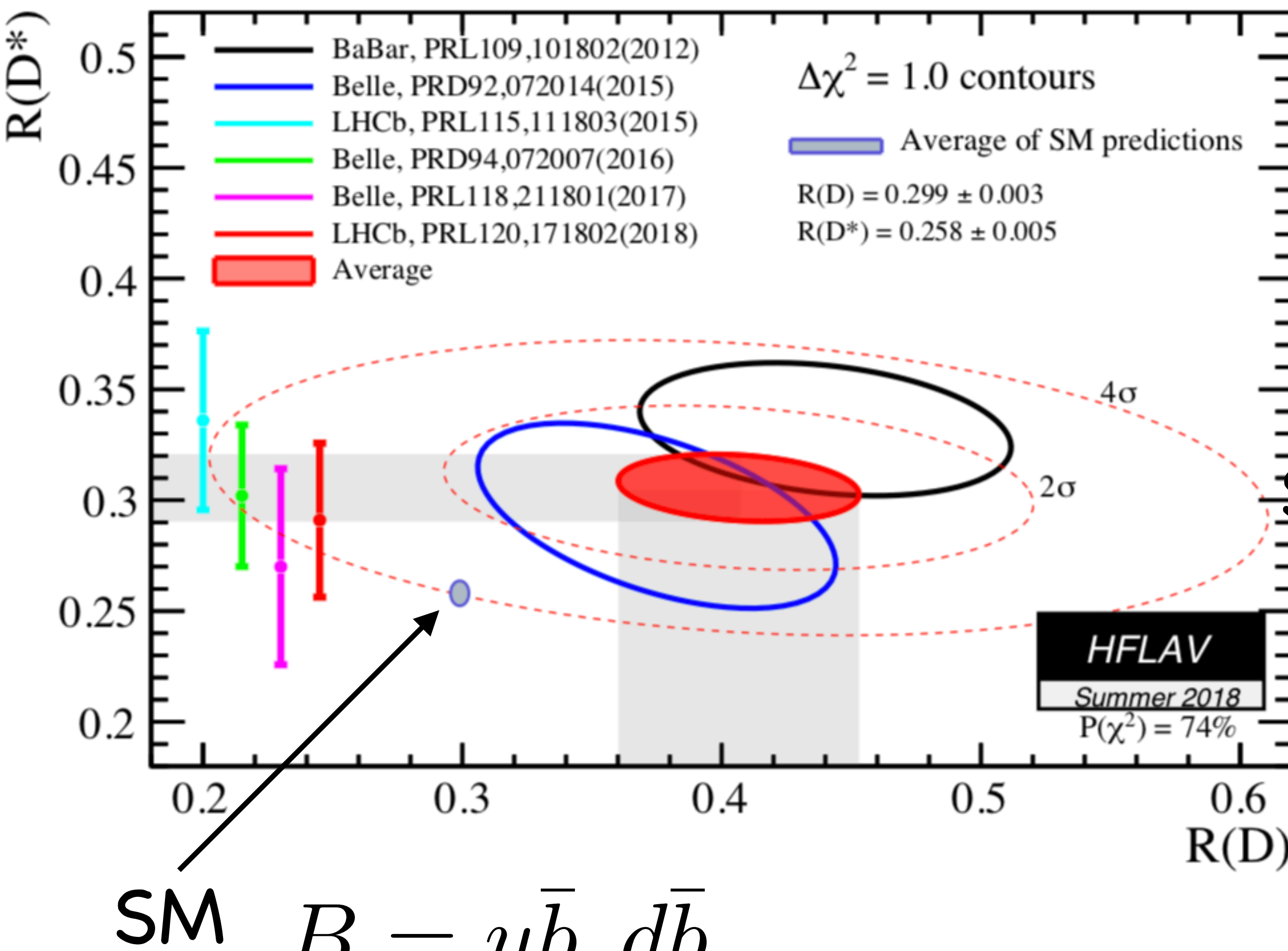


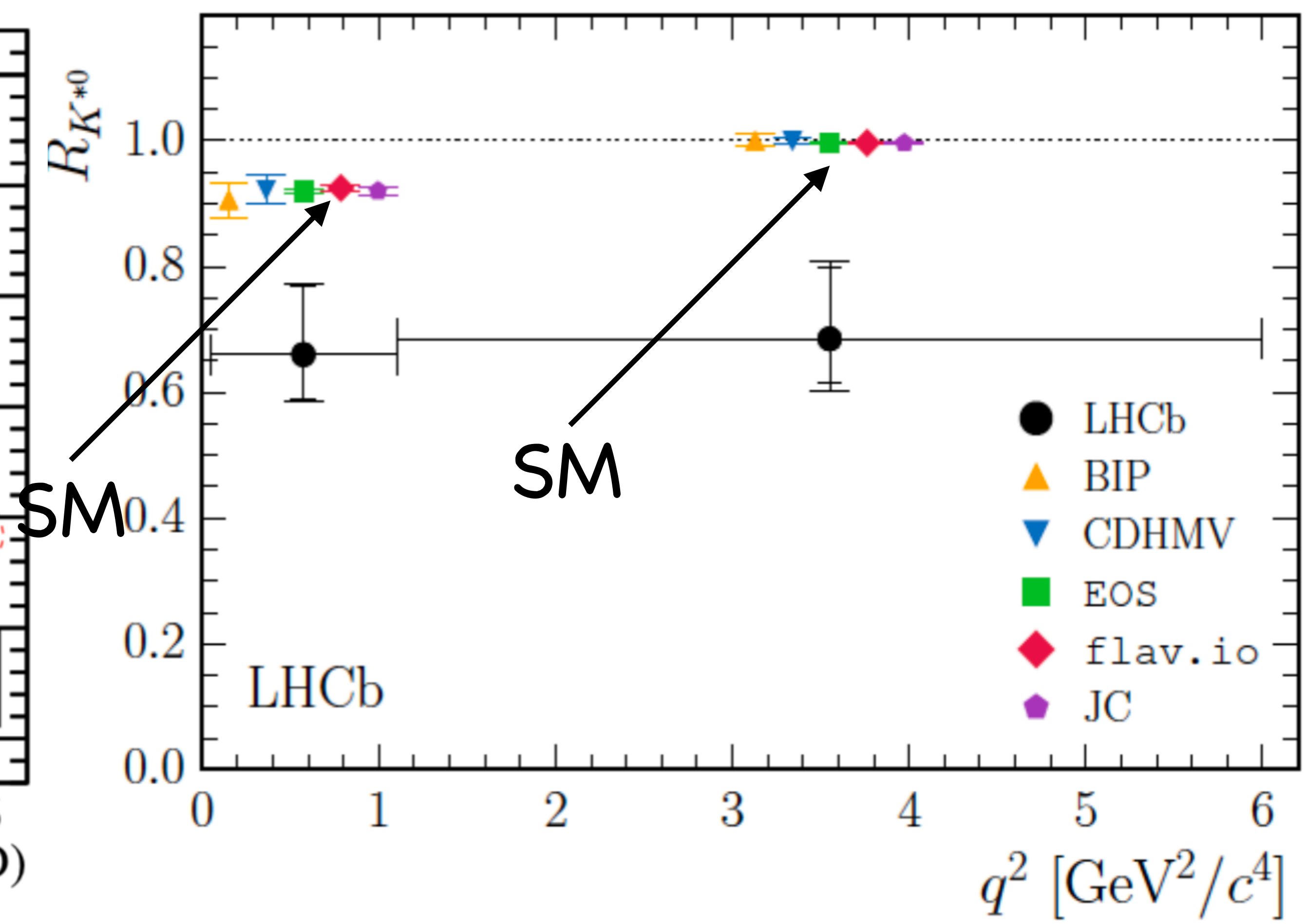


A violation of Lepton Flavour Universality?

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}l\nu, l = \mu, e)}$$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

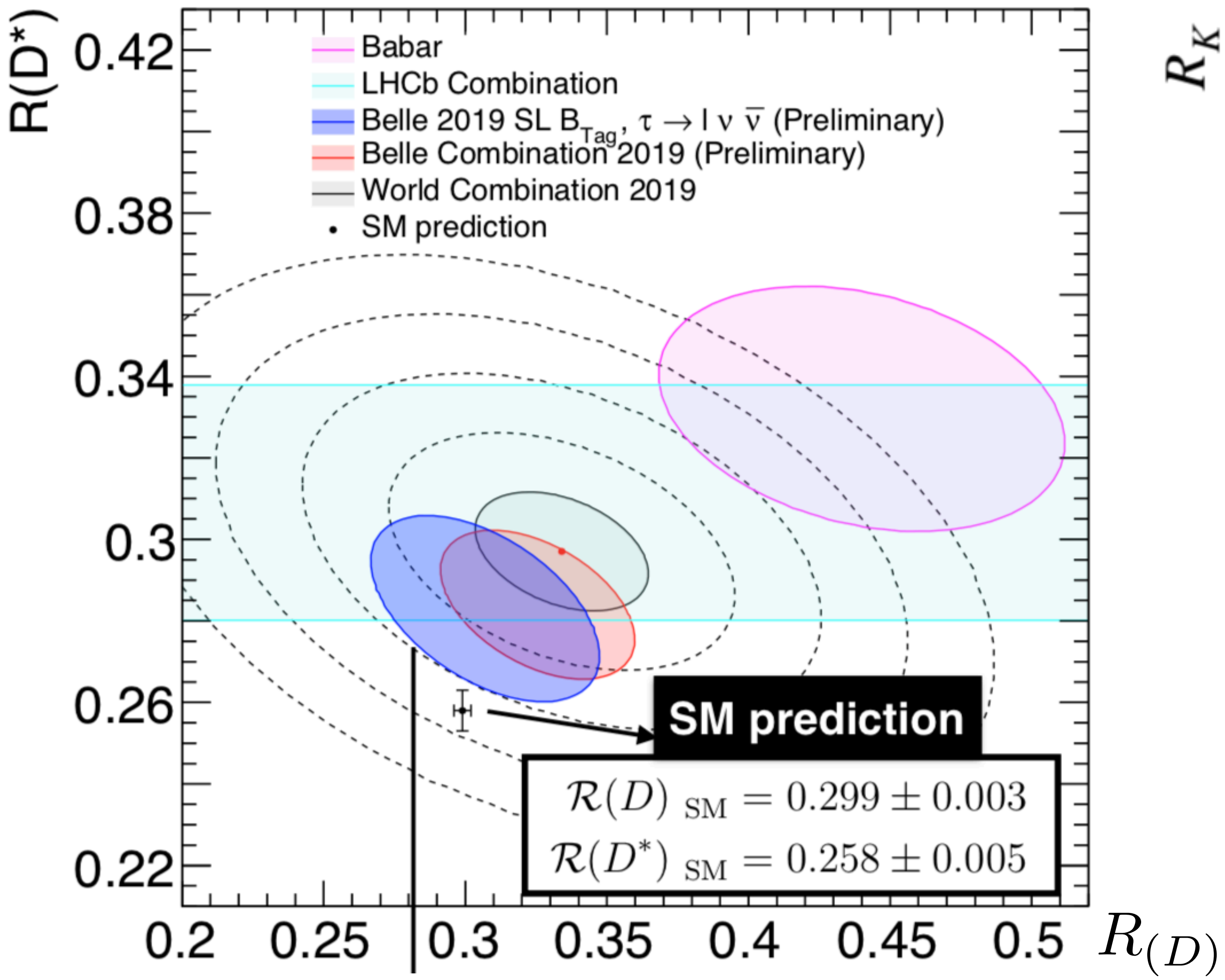


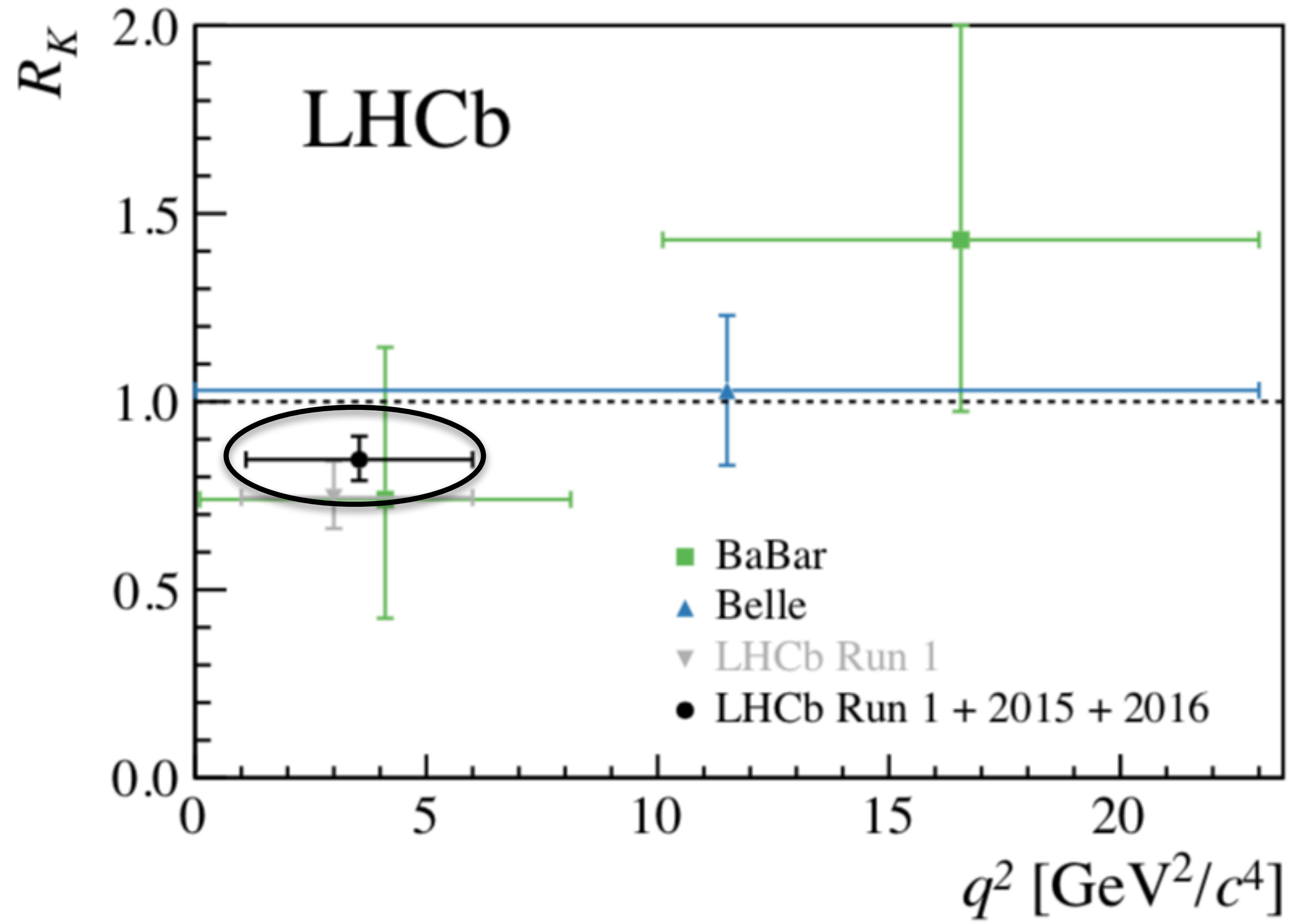


$$B = u\bar{b}, d\bar{b}$$
$$D = u\bar{c}, d\bar{c}$$
$$K = u\bar{s}, d\bar{s}$$

Much too early to say, but...

More data from a month ago





$$R_K = 0.846\ ^{+0.060}_{-0.054}\,(\text{stat.})\ ^{+0.016}_{-0.014}\,(\text{syst.})$$

Still in the limbo, but the future precision...

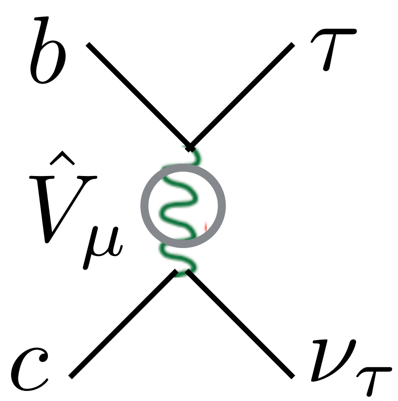
Observable	Current LHCb	LHCb 2025	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [4]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [5]	0.031	0.008
$b \to c\ell^-\bar{\nu}_l$ LUV studies			
$R(D^*)$	0.026 [15, 16]	0.0072	0.002
$R(J/\psi)$	0.24 [17]	0.071	0.02

My best prediction

with Robert Ziegler 2019

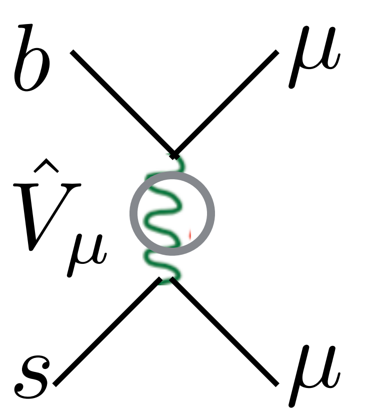
$$\Delta R_D \equiv \frac{R_{D^{(*)}}}{R_{D^{(*)}}^{SM}} - 1 \qquad \Delta C_9^{\mu} \approx -2\Delta R_K \approx -2\Delta R_{K^*}$$

From

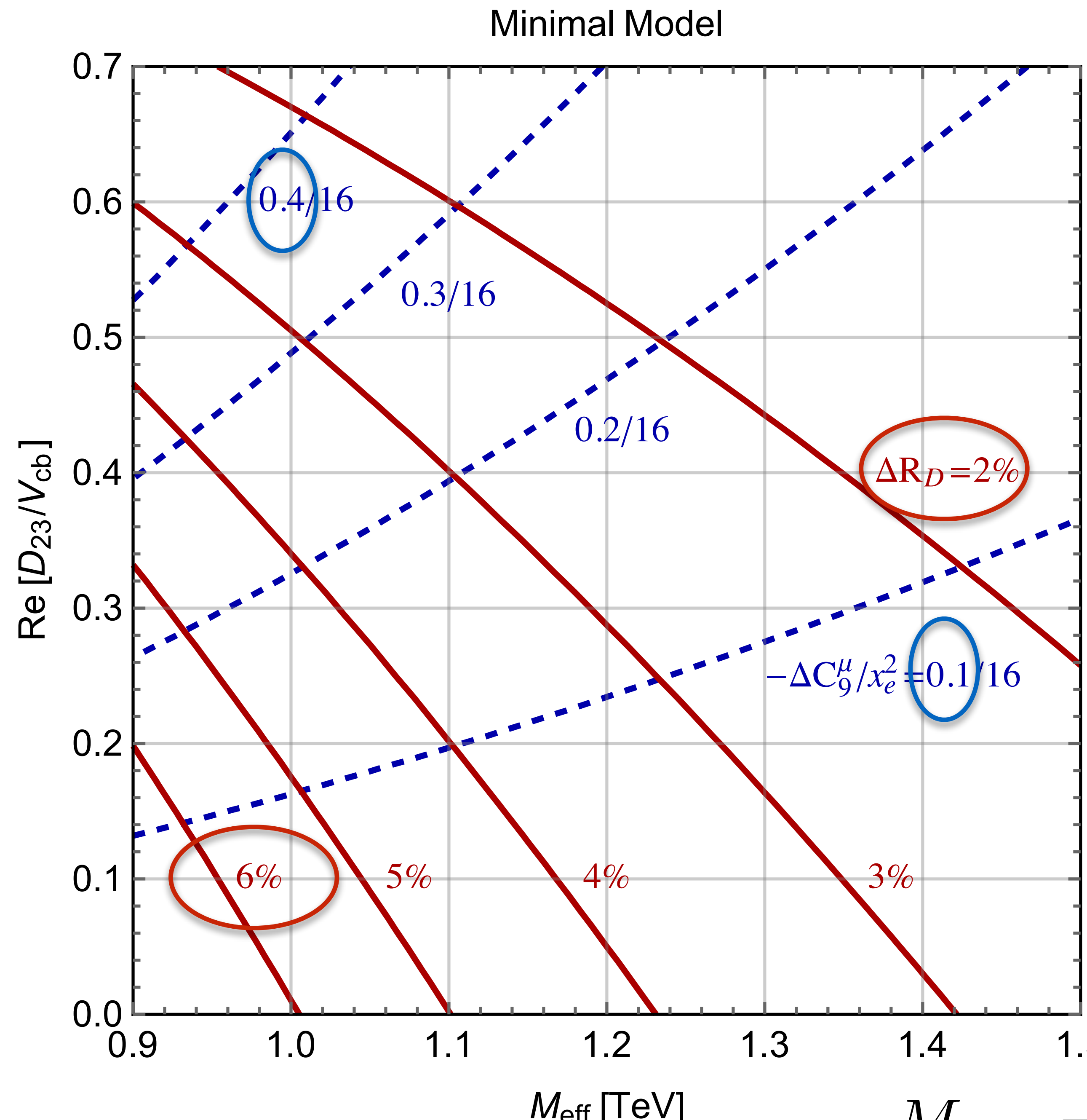


$b \to c\tau\nu$

and



$b \to s\mu\mu$

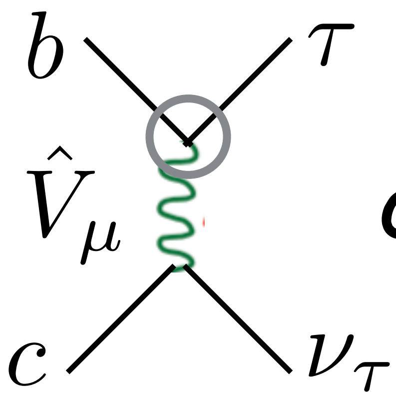


$$M_{eff} = \frac{M_V}{g_V}$$

Now $\quad \Delta R_D \approx 20\% \quad -\Delta C_9^{\mu} \approx 0.5$

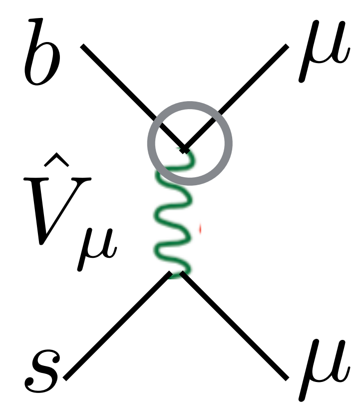
A perfect example of complementarity

If



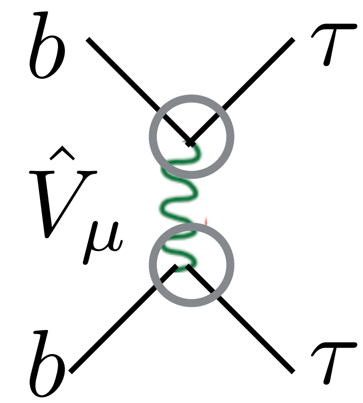
$b \to c\tau\nu$

and

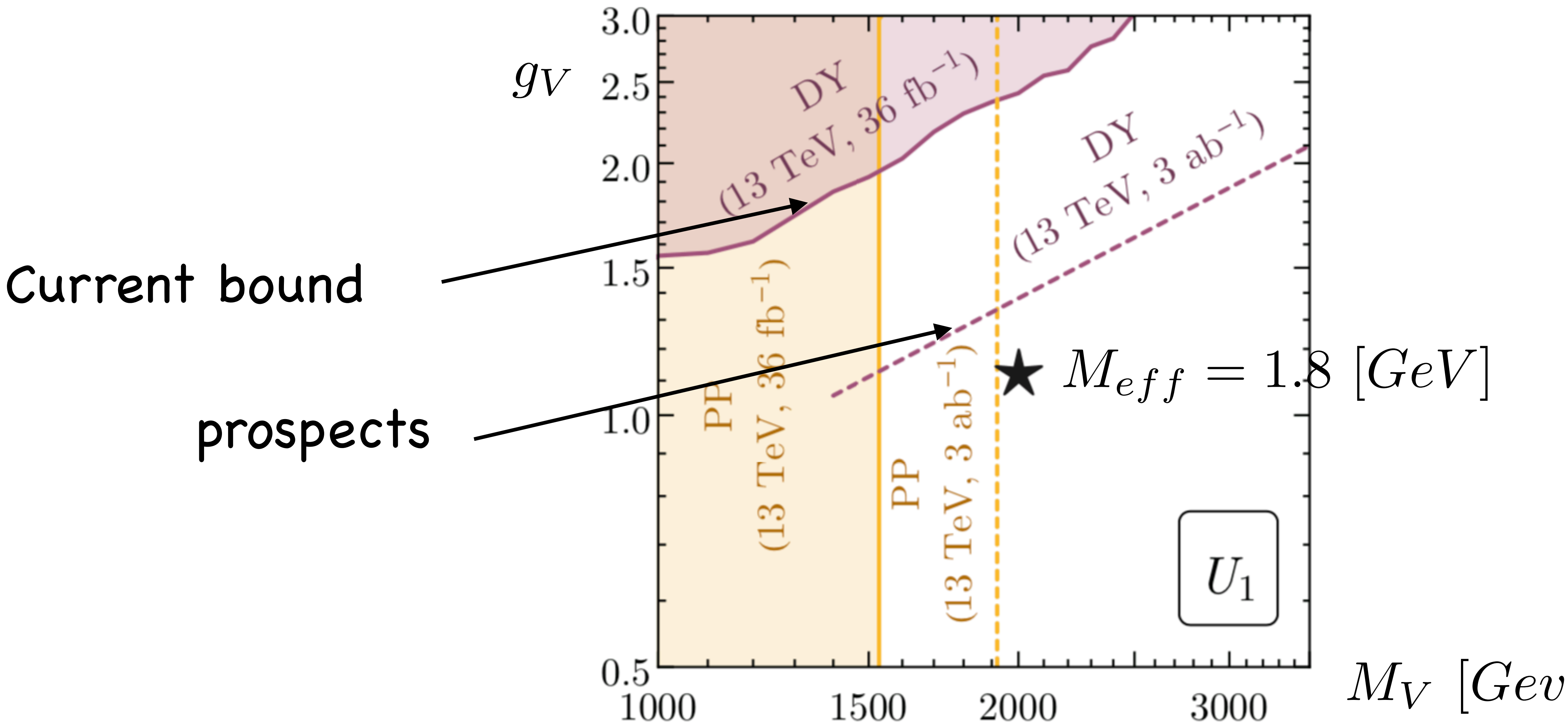


$b \to s\mu\mu$

then



$pp \to bb \to \tau\tau$



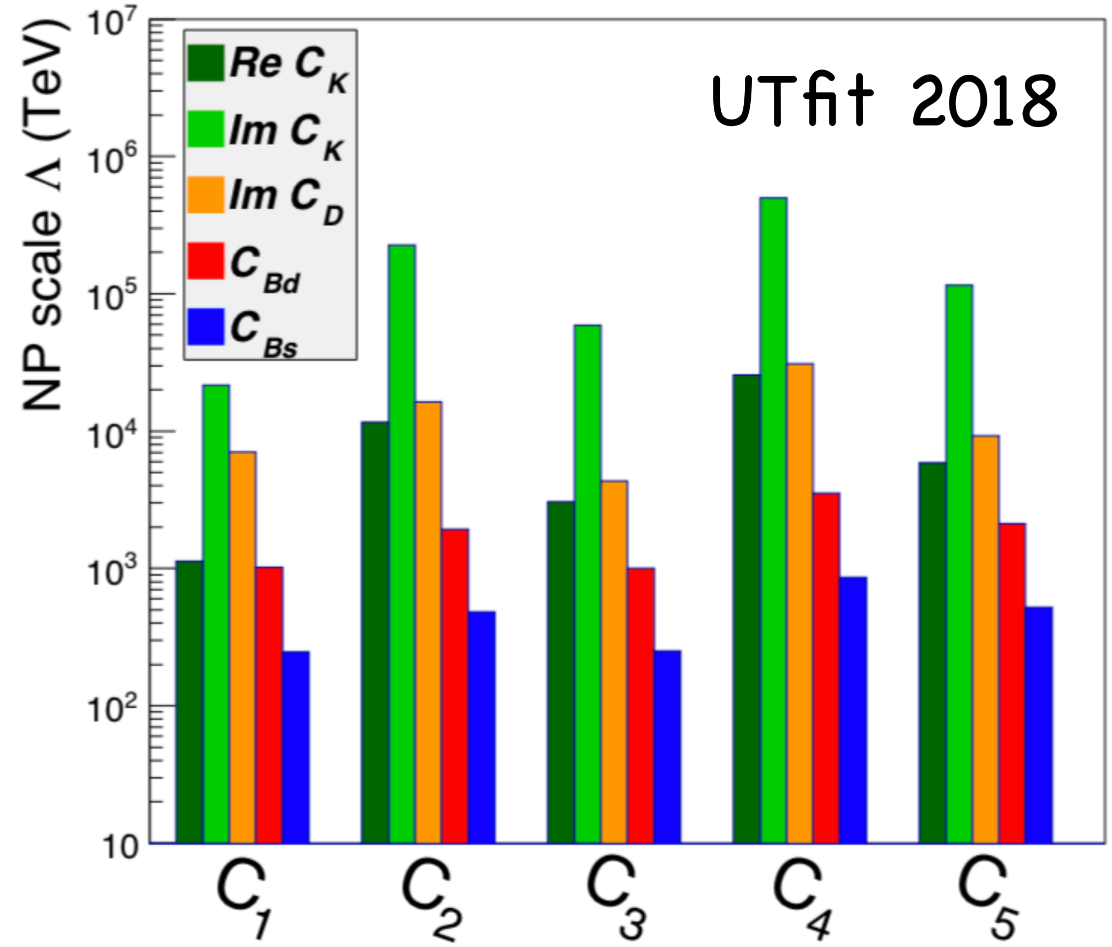
Schmaltz, Zhong 2018

Which attitude towards flavour in BSM?

1. Flavour physics confined to high energy
   (the prevailing lore)

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i^\alpha \frac{C_i^\alpha}{\Lambda_i^\alpha} (\bar{f} f \bar{f} f)_i^\alpha$$

i = 1,…,5 = different Lorentz structures



2. New physics at the TeV scale hidden by a suitable (approximate) flavour symmetry

If so, a special role played by the third generation, special because of its masses and (in the quarks) its small mixing with the first two generations $10^{-(2\div3)}$

An "Extreme Flavour" experiment?

Vagnoni – SNS, 7-10 Dec 2014

- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events and hadronic final states, but limited in luminosity, 50 fb^{-1} vs 3000 fb^{-1}
- Would an experiment capable of exploiting the full HL-LHC luminosity for flavour physics be conceivable?
  - Aiming at collecting O(100) times the LHCb upgrade luminosity → 10^{14} b and 10^{15} c hadrons in acceptance at $L=10^{35}$ $cm^{-2}s^{-1}$

Motivation: test CKM (FCNC loops) from ≃ 20% to ≲ 1%

More than one (motivated) scalar

(MSSM, NMSSM,etc)

- "Inert" doublet Dark Matter: H_1, H_2

$$H_2 : \qquad < H_2 >= 0, \quad H_2 \bar{f} f \text{ forbidden}$$

The lightest member of H_2, if neutral, is a DM candidate

- "Singlet-Catalysed" EW phase transition: H, S

$$\Delta V = \lambda_1 M (H^+ H) S + \lambda_2 (H^+ H) S^2$$

Can induce a first order phase transition, crucial to Baryogenesis

- "Twin" Higgs: H, H'

H' = doublet of a "twin" SU(2)

$$V(H, H') \to V(\mathcal{H}), \quad |\mathcal{H}|^2 = |H|^2 + |H'|^2$$

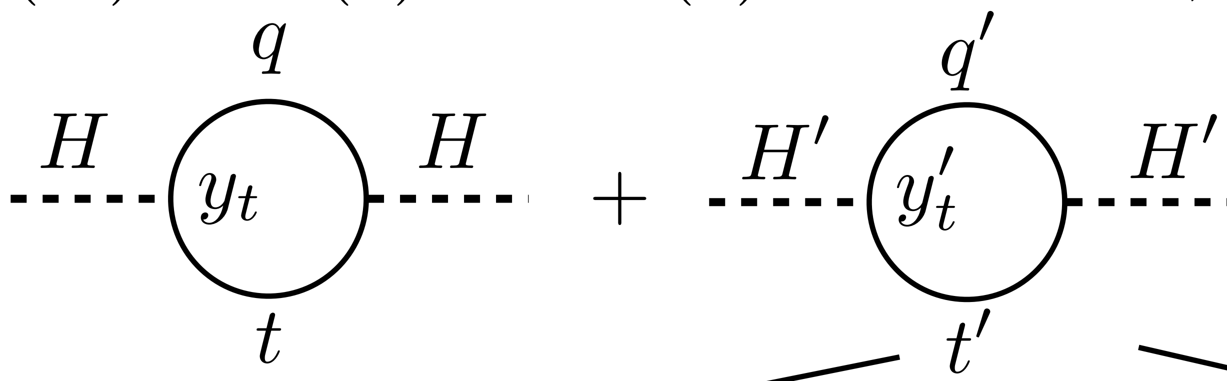
h is a pseudo-Goldstone

Twin Higgs: "Neutral" naturalness

Chacko, Goh, Harnik 2005
B, Hall, Gregoire 2005

$V(H,H') \to V(\mathcal{H}), \quad |\mathcal{H}|^2 = |H|^2 + |H'|^2$ is $SO(8)$-symmetric

$$V(\mathcal{H}) : SO(8) \to SO(7) \Rightarrow 7\ PGBs, \ SU(2)' \times U(1)' \to U(1)'_{em}$$



$$= \frac{3}{4\pi^2}(y_t^2 H^2 + y_t'^2 H'^2)\Lambda^2$$

"Fraternal Higgs"
(Neutral naturalness)
Replicate only $y_t H \bar{q} t$
(and rely on suitable initial conditions at the cutoff)

Craig, Katz, Strassler, Sundrum 2015

"Mirror World"
Replicate the full $\mathcal{L}_{321}$
$\mathcal{L}_{321} \leftrightarrow \mathcal{L}'_{321}$ by a Z_2-symmetry
$SO(4) \times SO(4) \to SO(8)$

Lee, Yang 1956
Koblarev, Okun, Pomeranchuk 1966

– "Twin" Higgs: H, H'

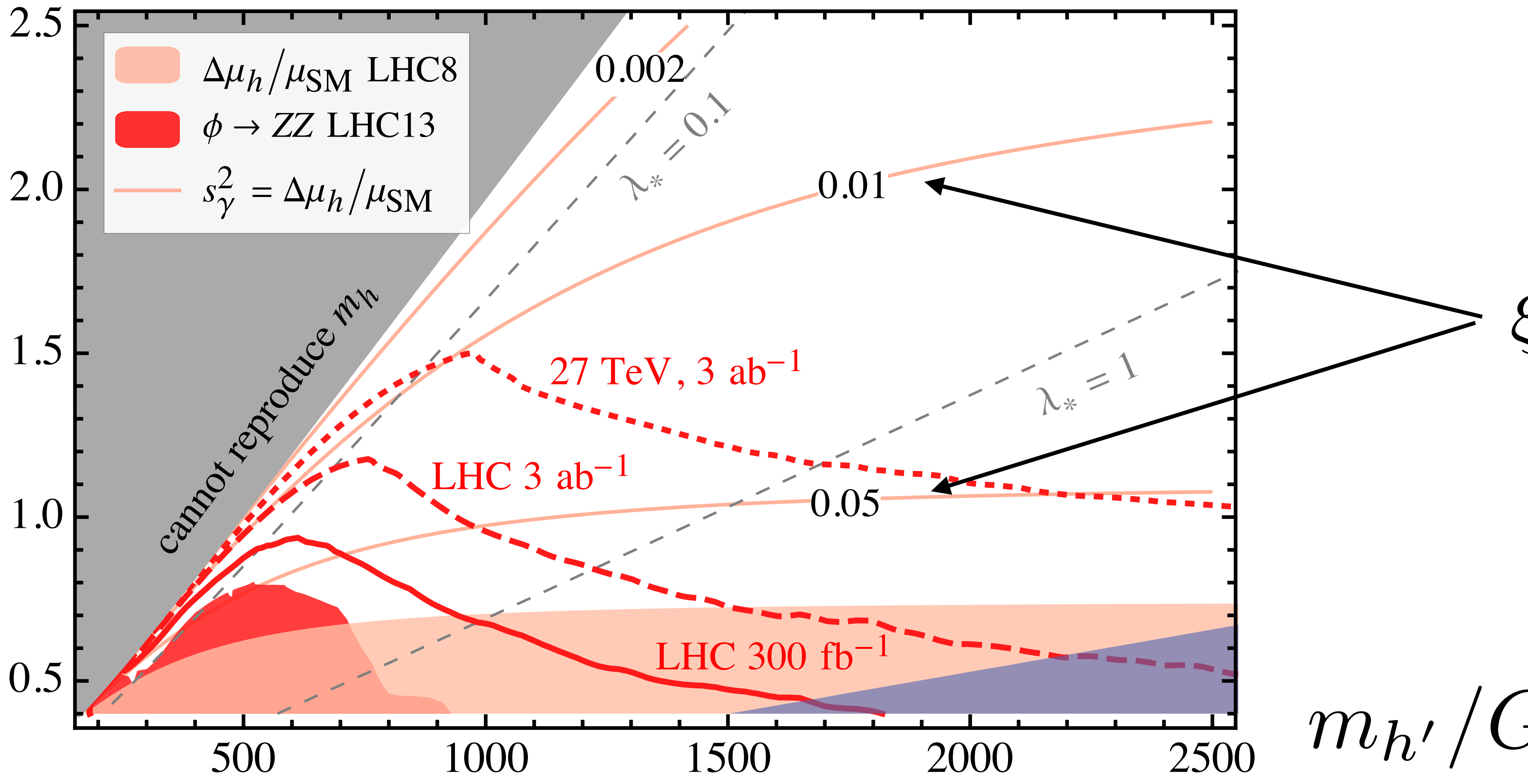
$$\sigma(pp \to h') \approx \xi \sigma(pp \to h_{SM}(m = m_{h'}))$$ via a top loop

Neglecting phase space $\quad \dfrac{\Gamma_L}{\Gamma_L + \Gamma_T} \to 1$

f	ZZ	WW	hh	$W'W'$	$Z'Z'$
$\Gamma(\tilde{h}' \to f)$	1	2	1	2	1

Buttazzo, Sala, Tesi 2018

f/TeV



$m_{h'}/GeV$

Summary

1. To turn the SM into a ST still premature

2. BSM more relevant then ever, though in more diversified directions than 10 years ago, rightly so

3. A significant discovery potential in precision at LHC

   - Higgs couplings
   - Extended EW precision tests
   - Flavour observables

   highly complementary between themselves and with direct searches

4. A pending question: why a single scalar?