Standard Model or Standard Theory?

The many ways Beyond the SM

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CMS School, Pisa, January 2019

Some general introductory remarks

The potential of precision at LHC

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

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

Problems of (questions for) the SM

0. Which rationale for matter quantum numbers?

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

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
Gravity

Are the protons forever?

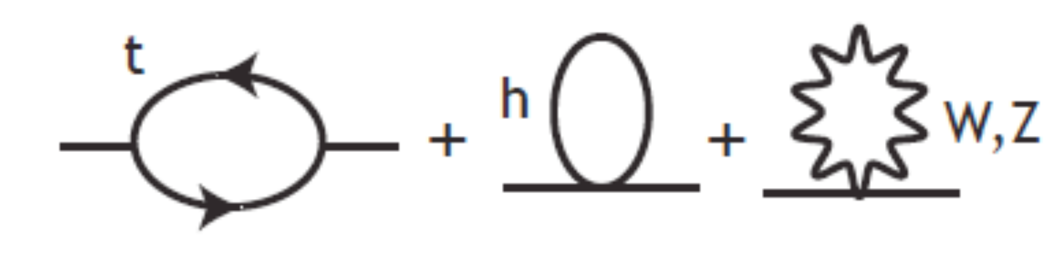
4. Lack of calculability (a euphemism)

⇒ the hierarchy problem
the flavour puzzle
⇐ 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



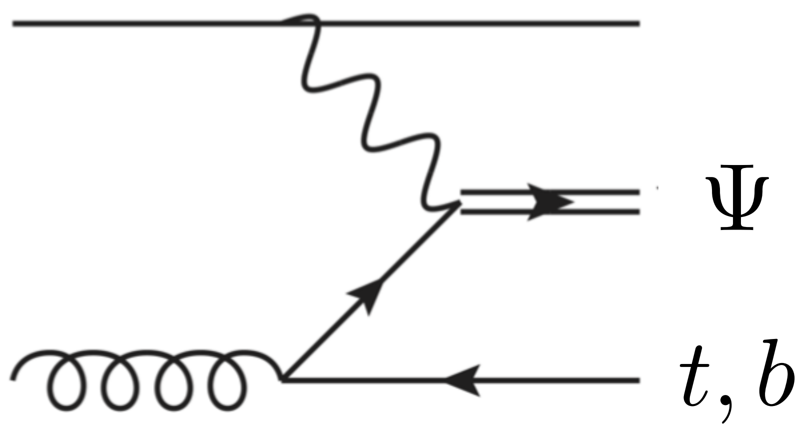
$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_g'^2$$

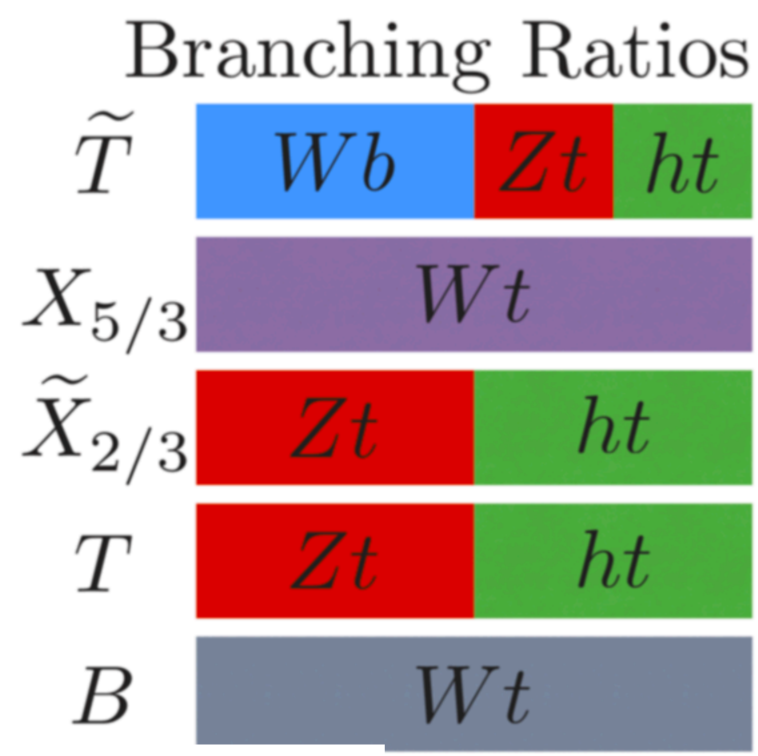
The standard reaction

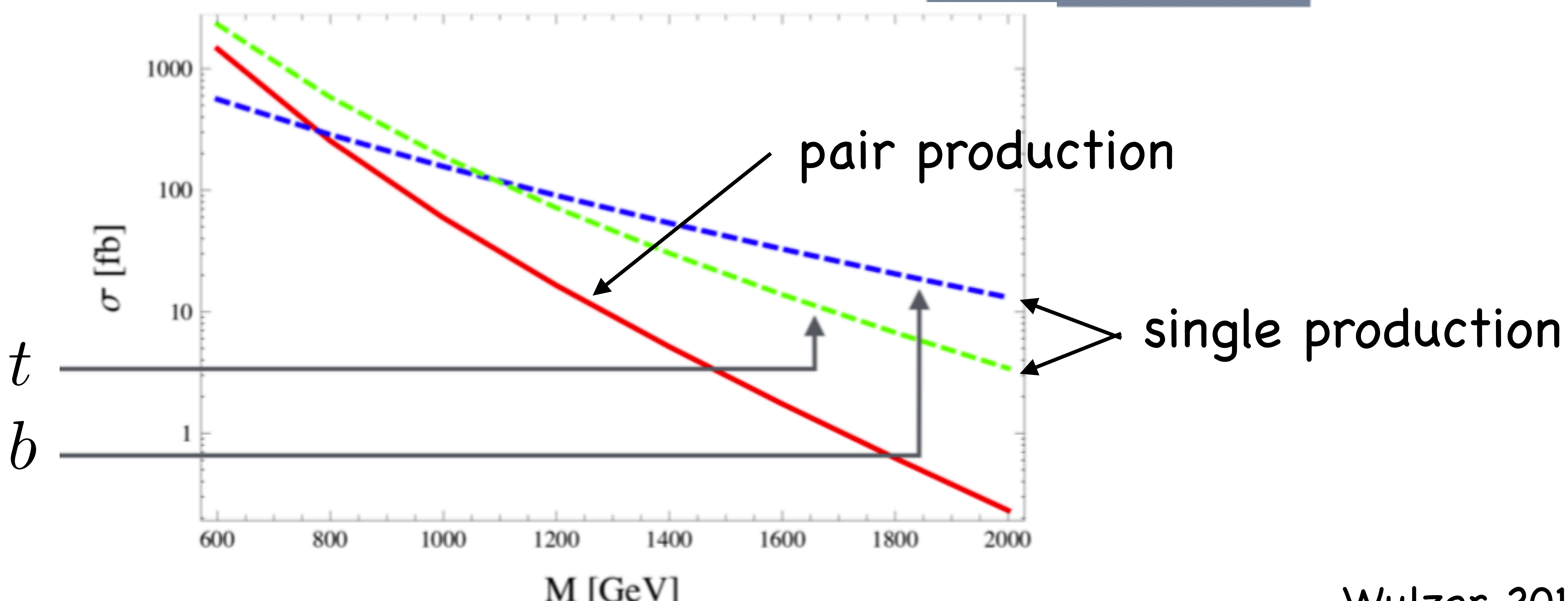
Look for top "partners", J=0 or 1/2,
coloured or uncoloured,
with a mass not far from a TeV,
capable to cutoff the Λ^2 divergence

Single production deserves attention

(although NOT generically present)

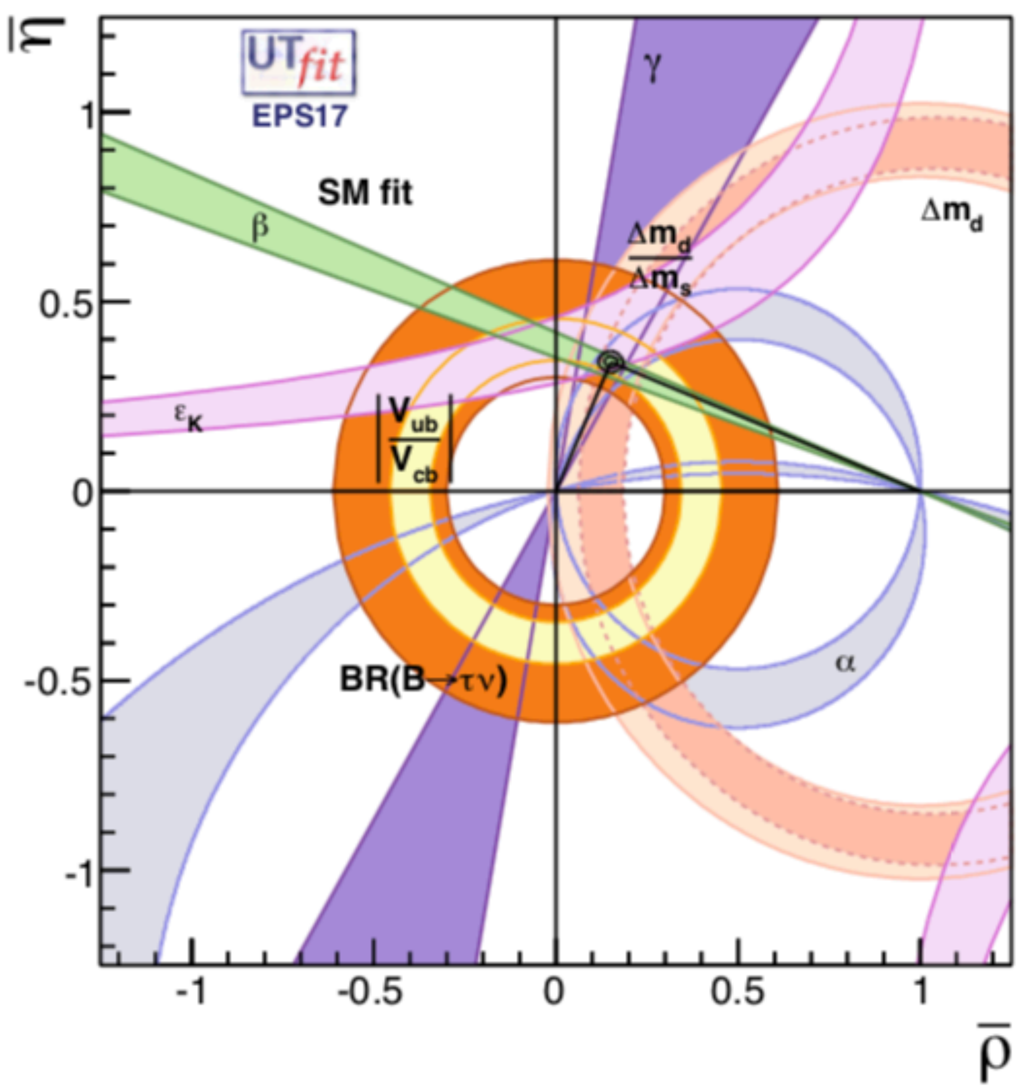


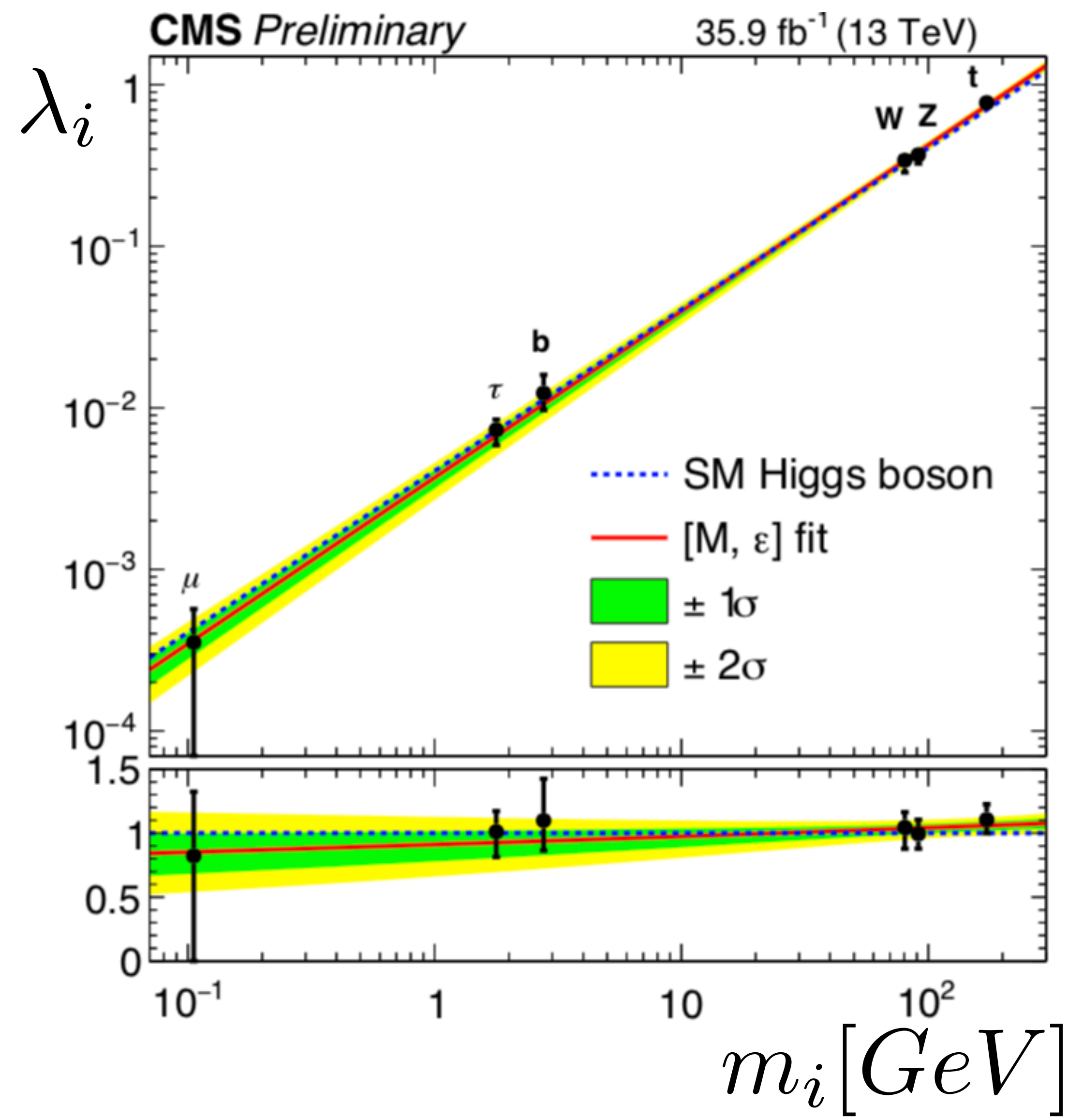




Wulzer 2018

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





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

(See below)

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 very dangerous

The potential of precision 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}

DiBosons Wh, Zh, WZ, WW

- Flavour observables

Testing the FCNC loops

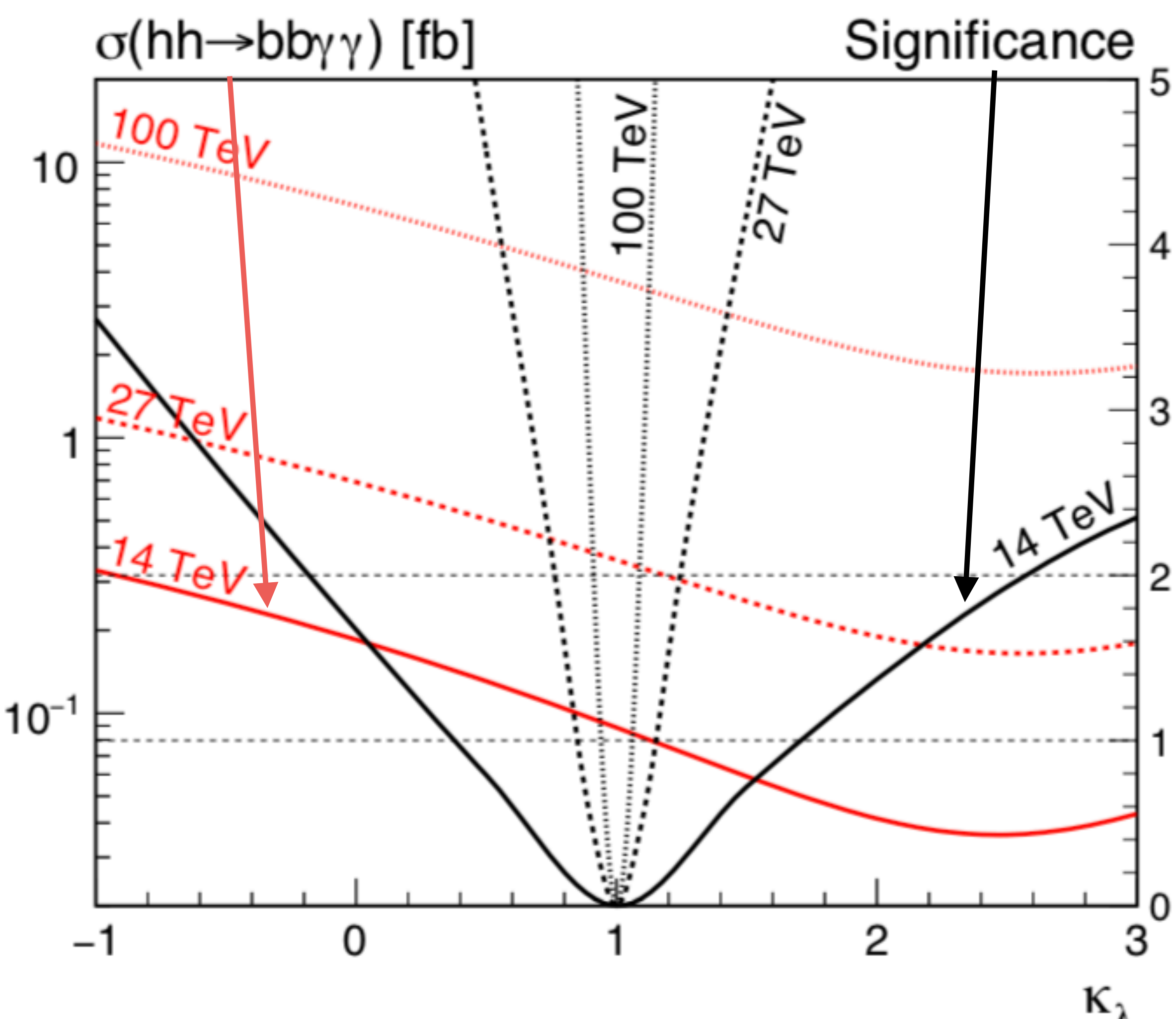
Lepton Flavour Violation

The role of flavour in BSM

$$V = \mu^2 H^2 + \lambda H^4$$

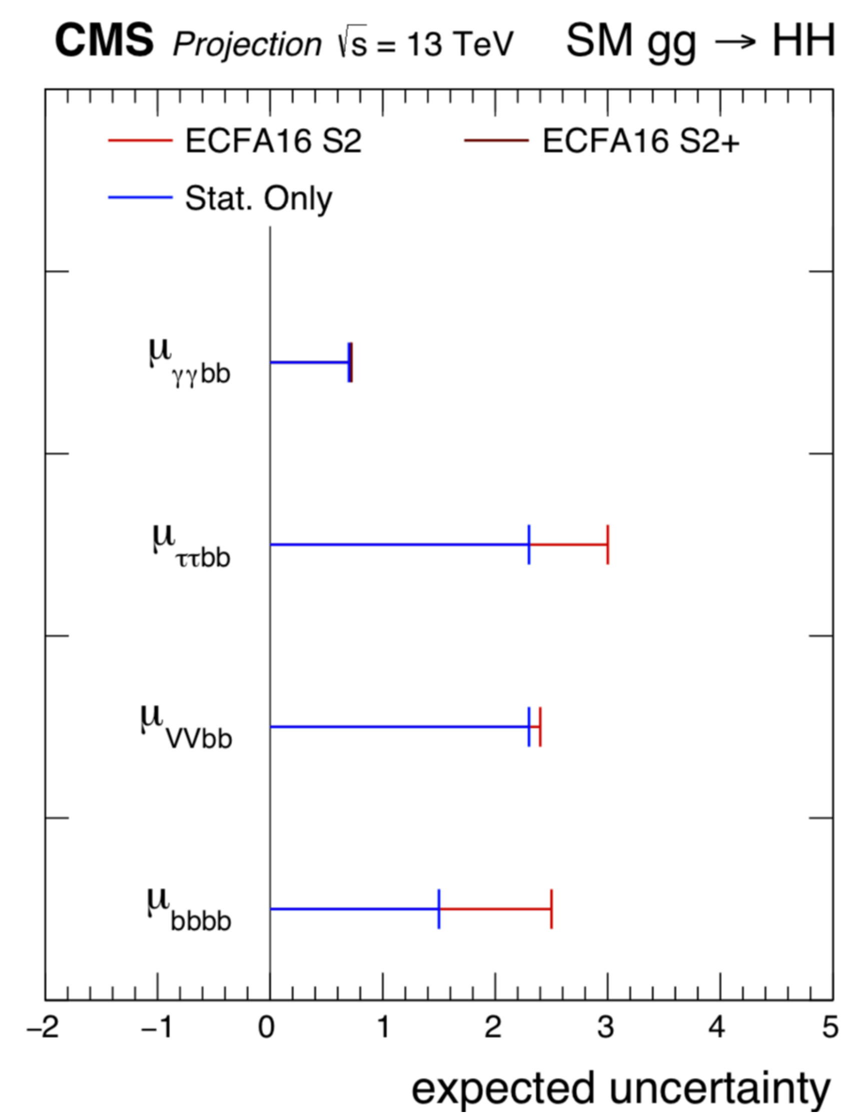
$$\lambda = \frac{G_\mu}{\sqrt{2}} m_h^2 \text{ + rad. corr.} = 0.12$$

Can one measure it directly?



Goncalves et al 2018

CMS-PAS-FTR-16-002

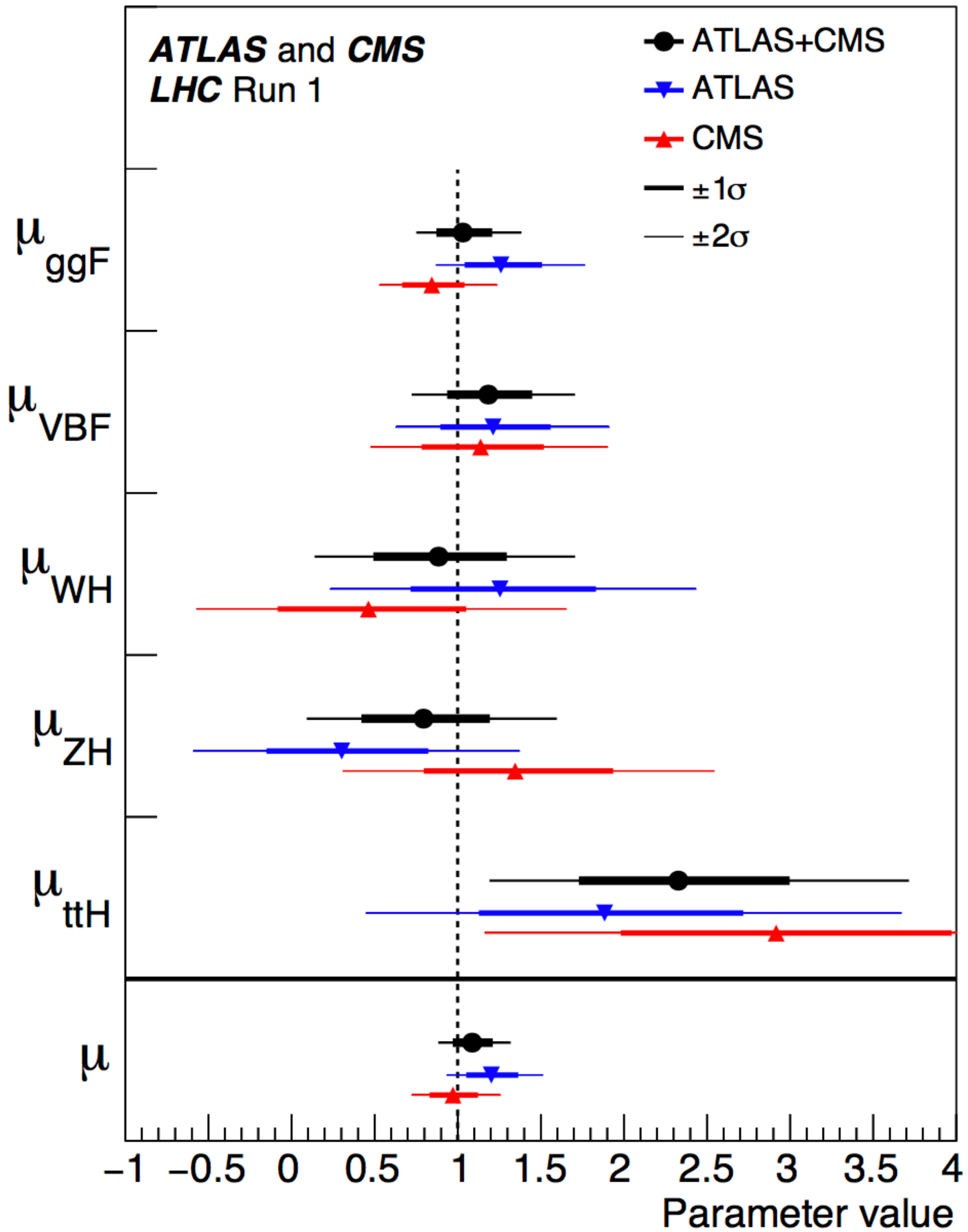


As difficult as important

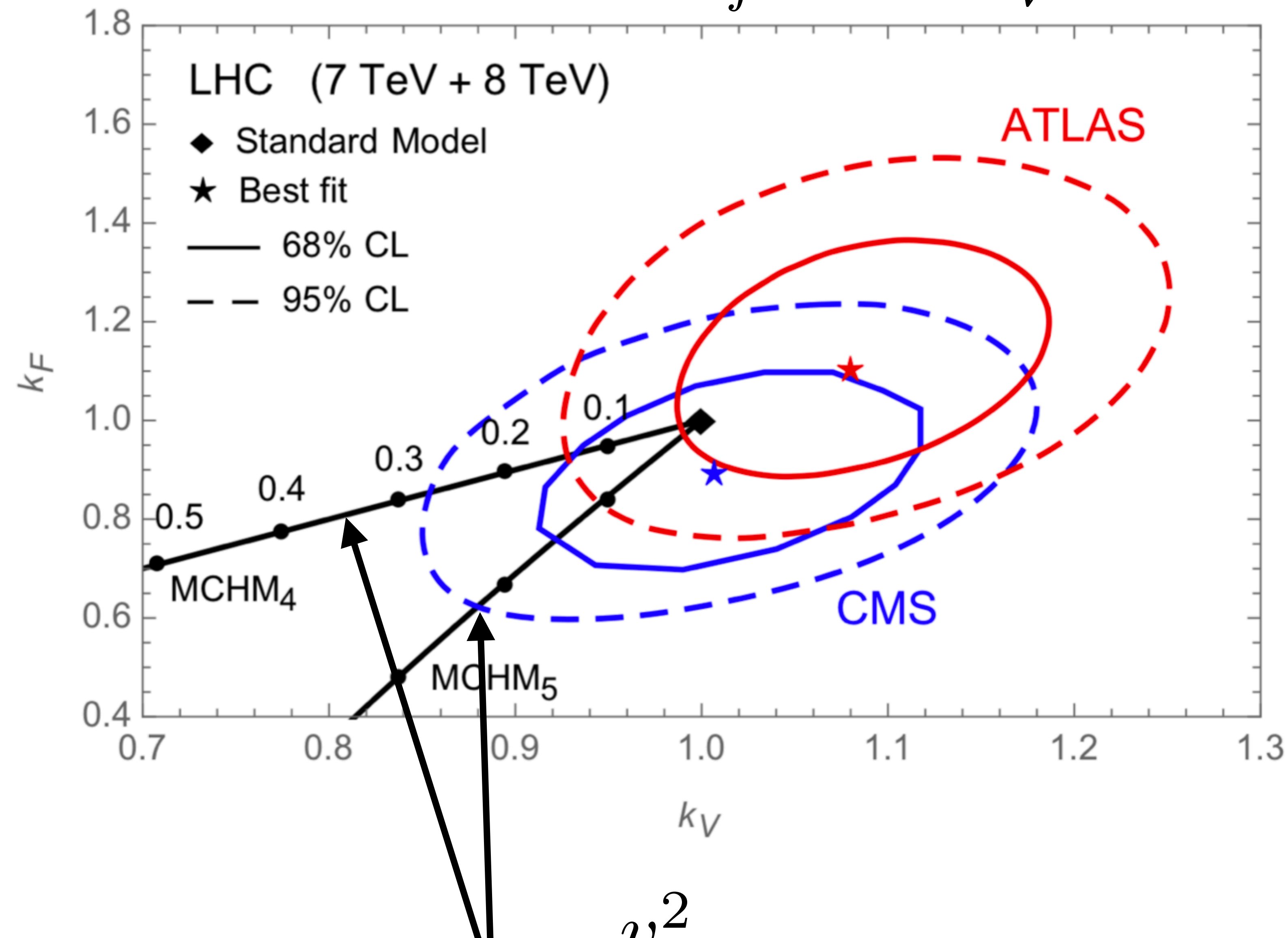
large deviations concevable in BSM

Higgs couplings

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



Universal k_f and k_V



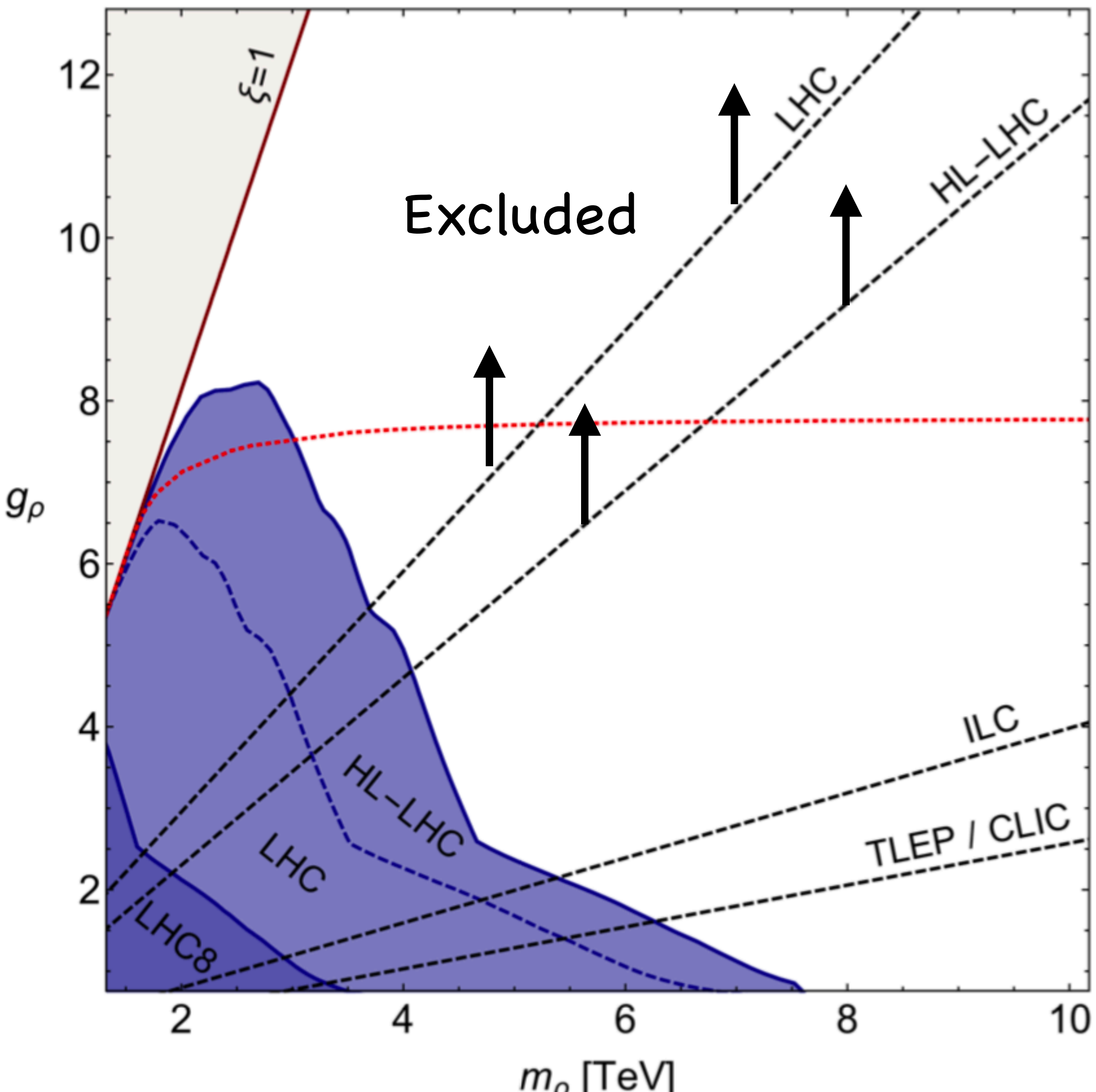
the scale f of Higgs compositeness $\xi = \frac{v^2}{f^2}$ $\quad k_V = \sqrt{1-\xi}$

Now $f \gtrsim 600\ GeV$ only!

Direct versus indirect searches

$$pp \to \rho \to WZ$$

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



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

$$g_f = \frac{g^2}{g_\rho}$$

Thamm, Torre, Wulzer 2015

The potential of precision 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

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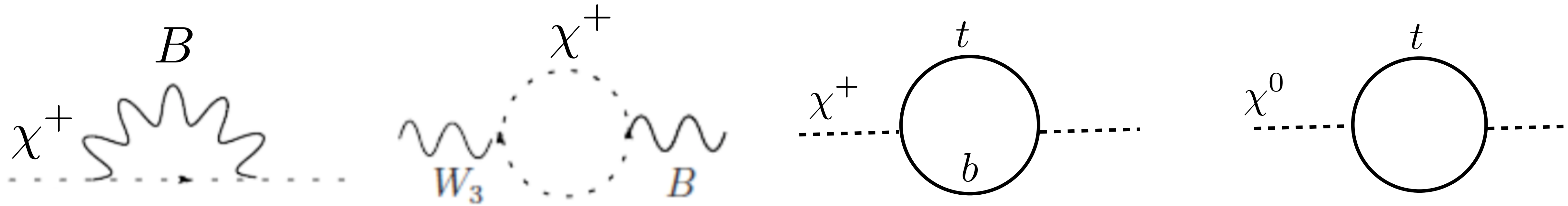
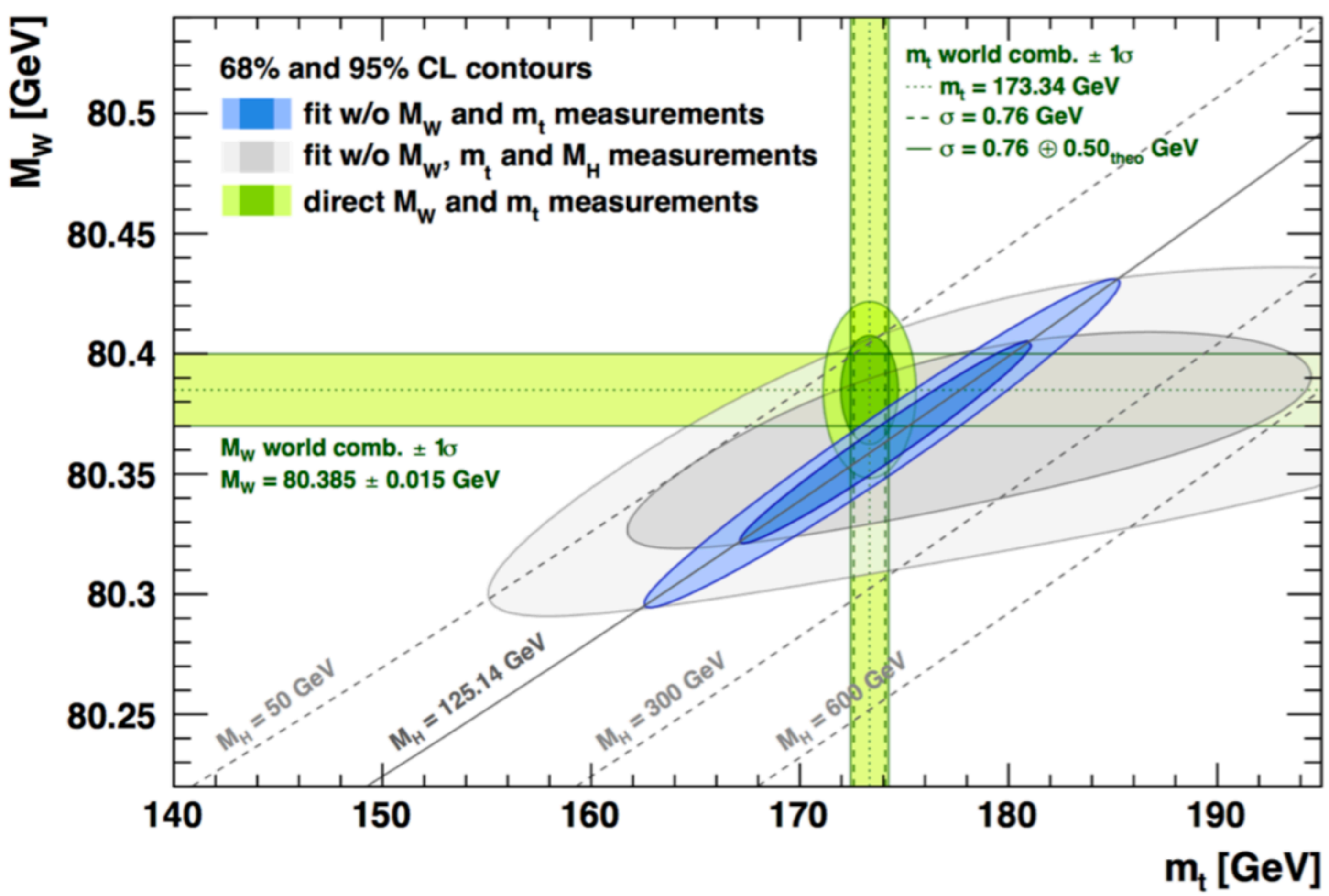
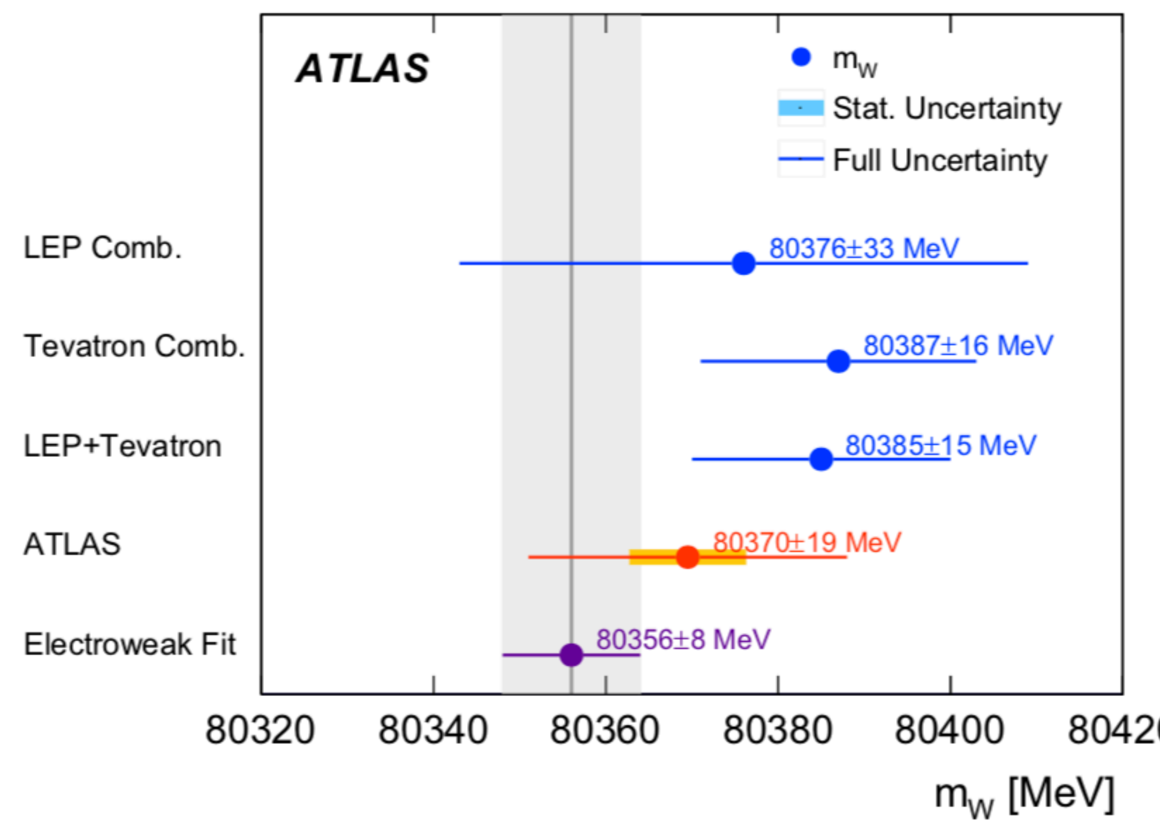
Comparing direct measurements with virtual effects





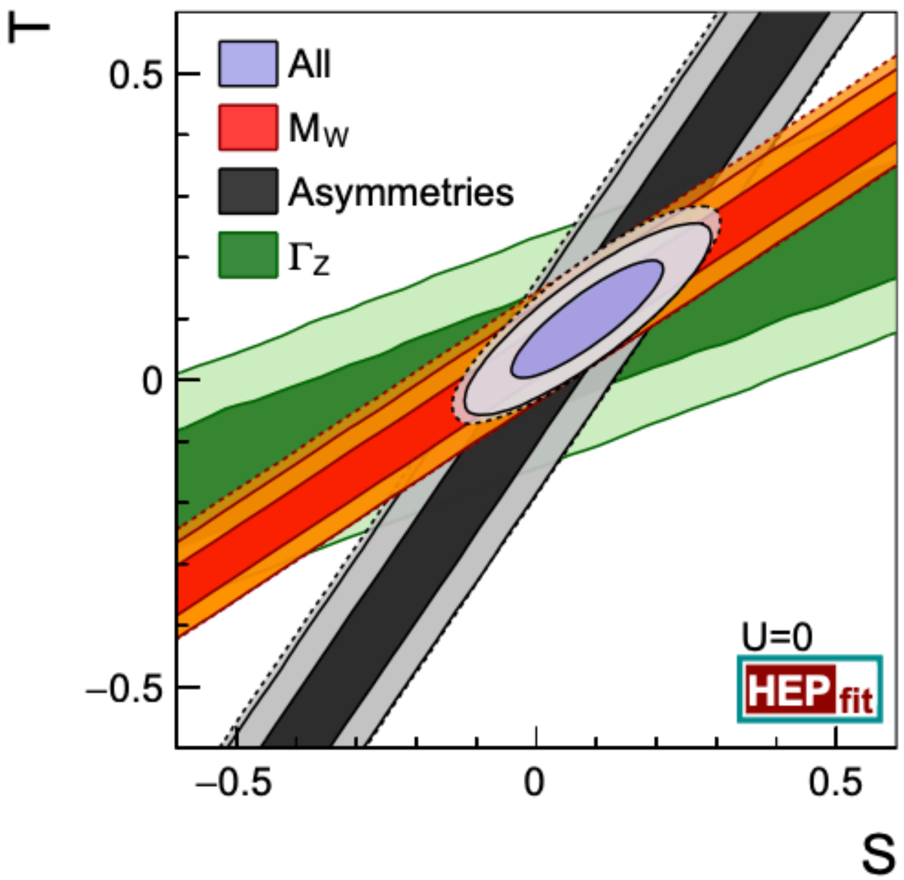


Blue = prediction of m_t, M_W by fitting "pole observables" in the SM, with crucial inclusion of loop effects

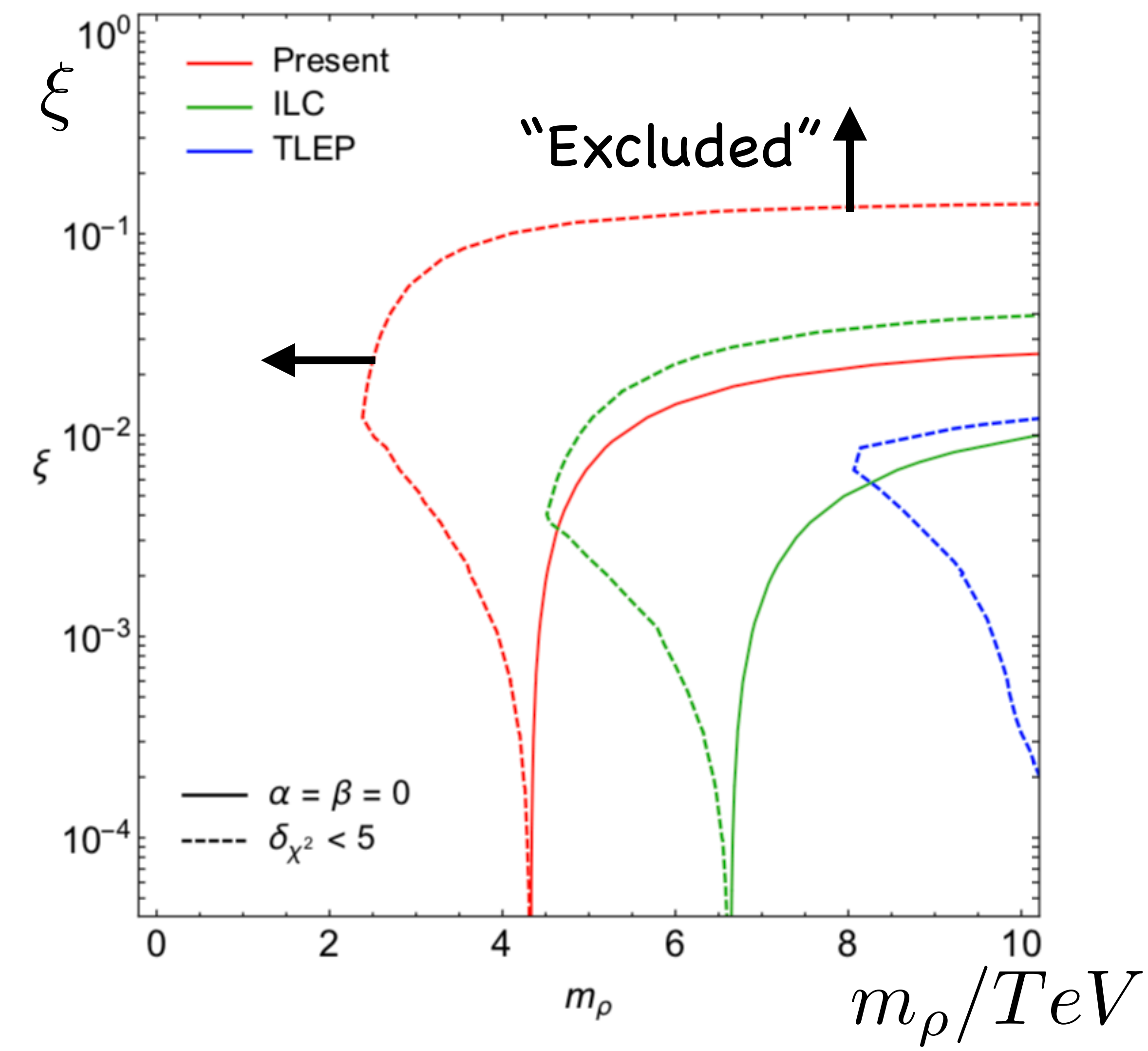
Green = direct measurements of m_t, M_W

Constraints from pole observables

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



Thamm, Torre, Wulzer 2015



In a composite Higgs picture:

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

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

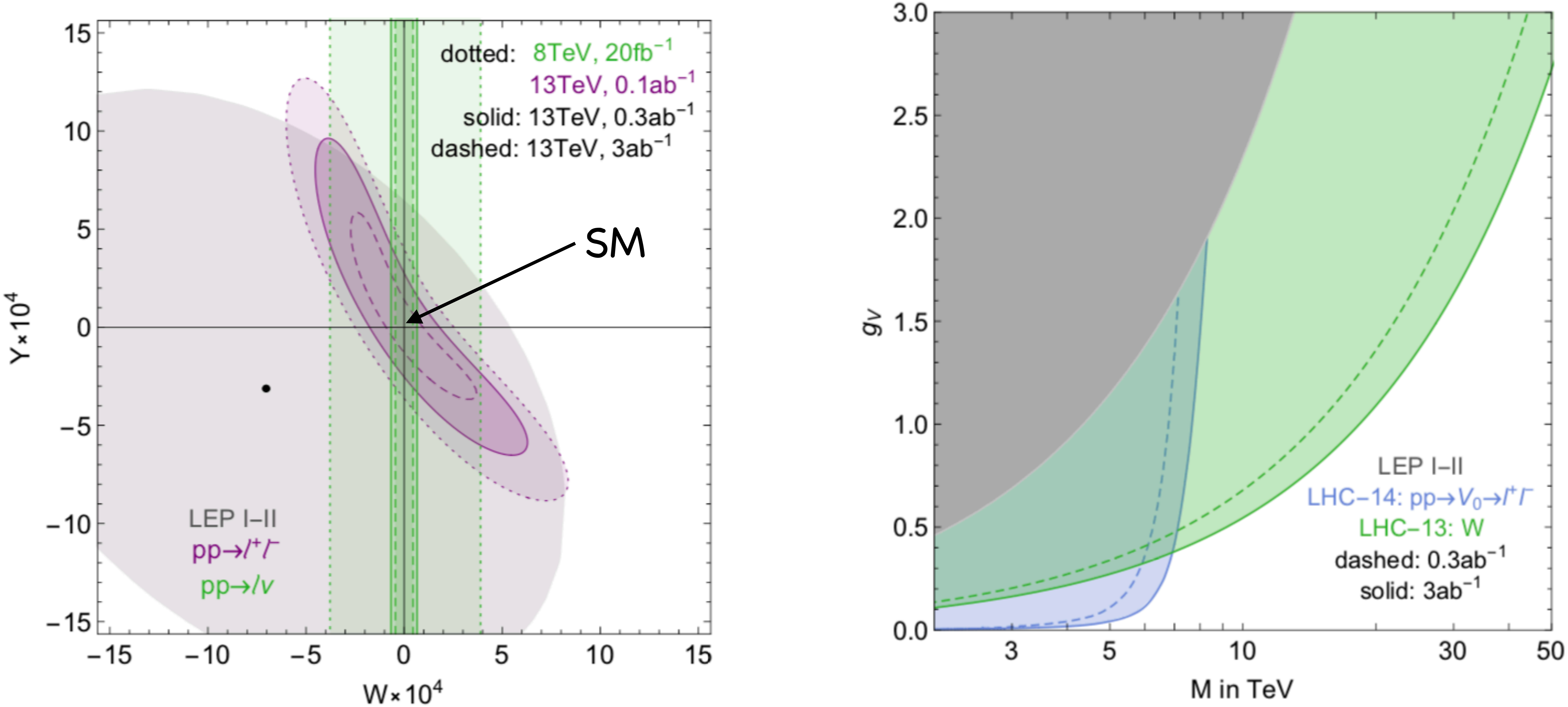
$k_V = \sqrt{1-\xi}$

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

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

$$pp \to l^+l^-, l\nu$$

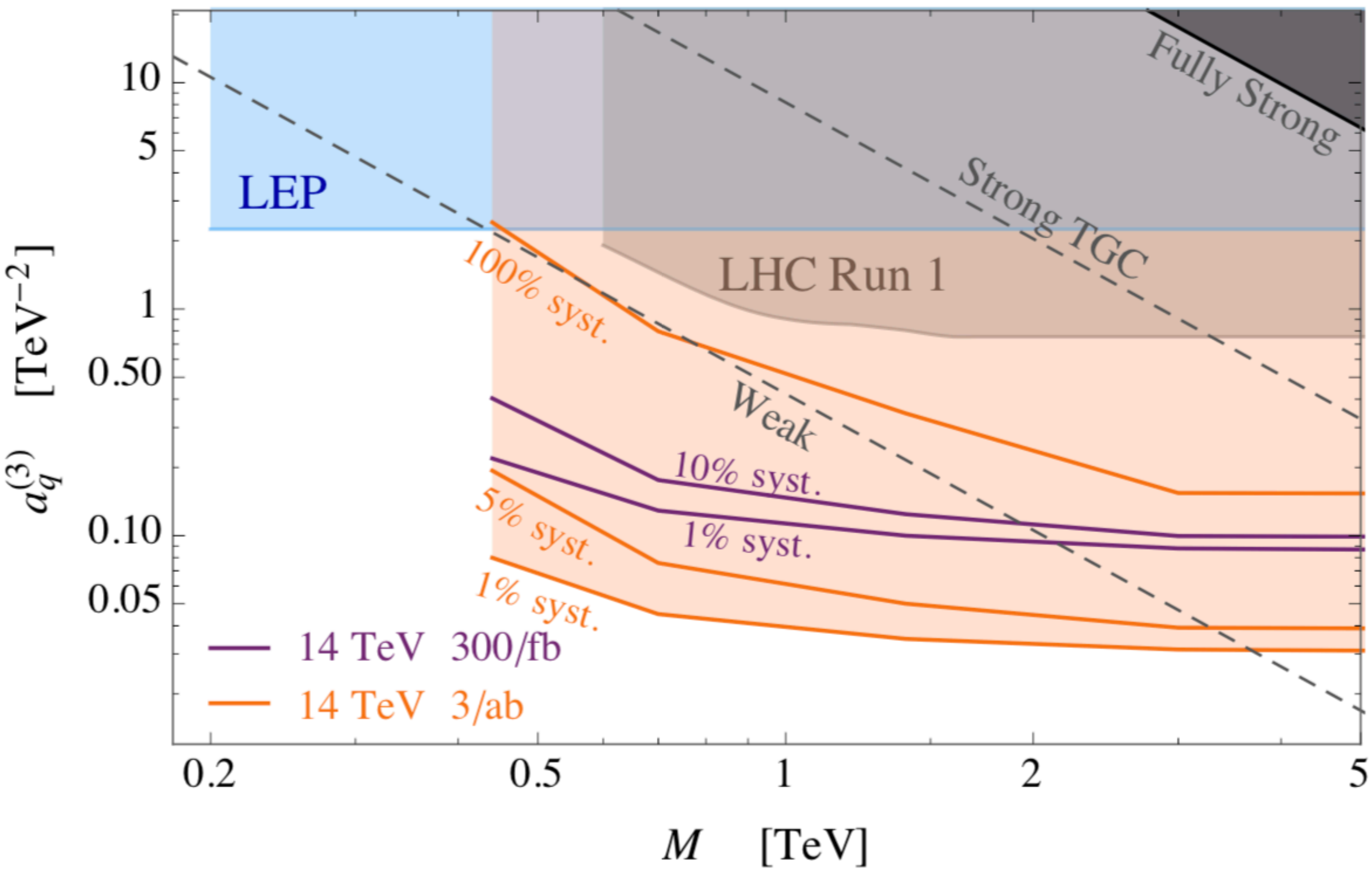
Farina et al 2016

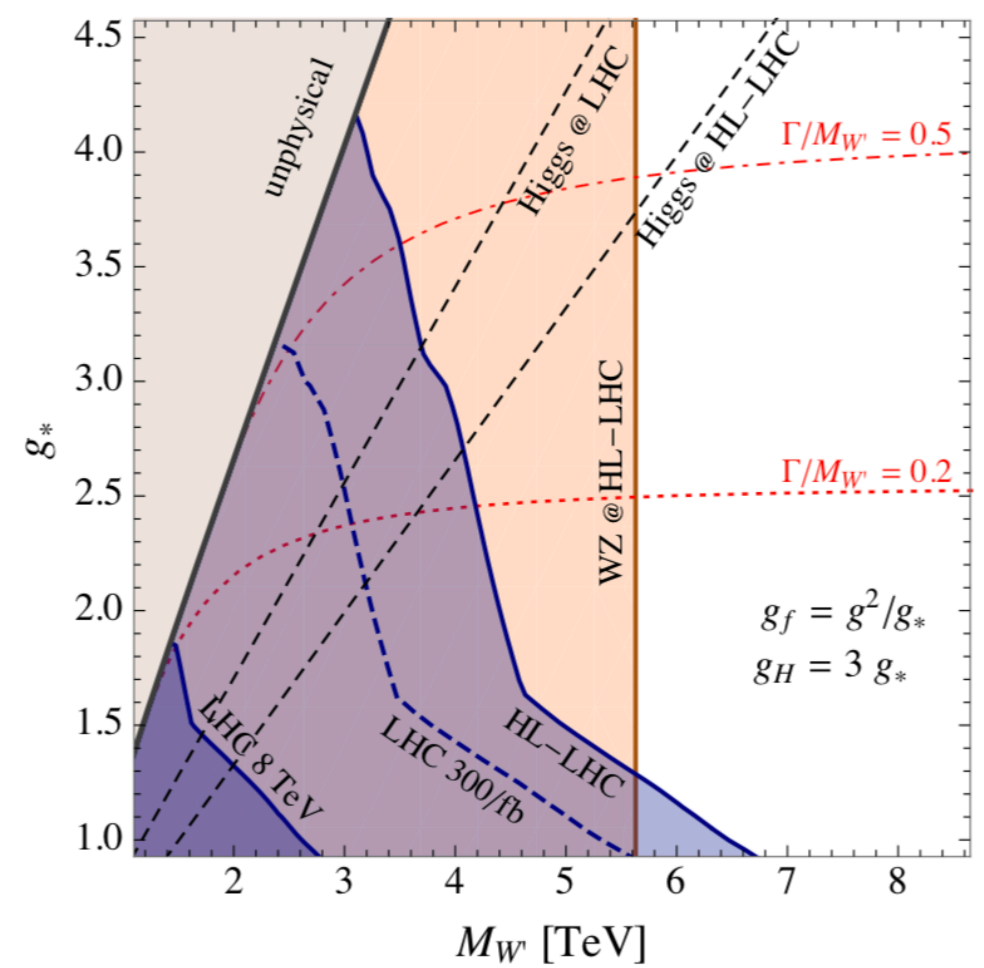


$$\mathcal{L} = g_V V_\mu^a (f \tau^a \gamma_\mu f + i H^+ D_\mu H)$$

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

DiBoson differential cross section with suitable angular analyses





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

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

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

Franceschini et al 2018

The potential of precision at LHC

- Higgs couplings

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

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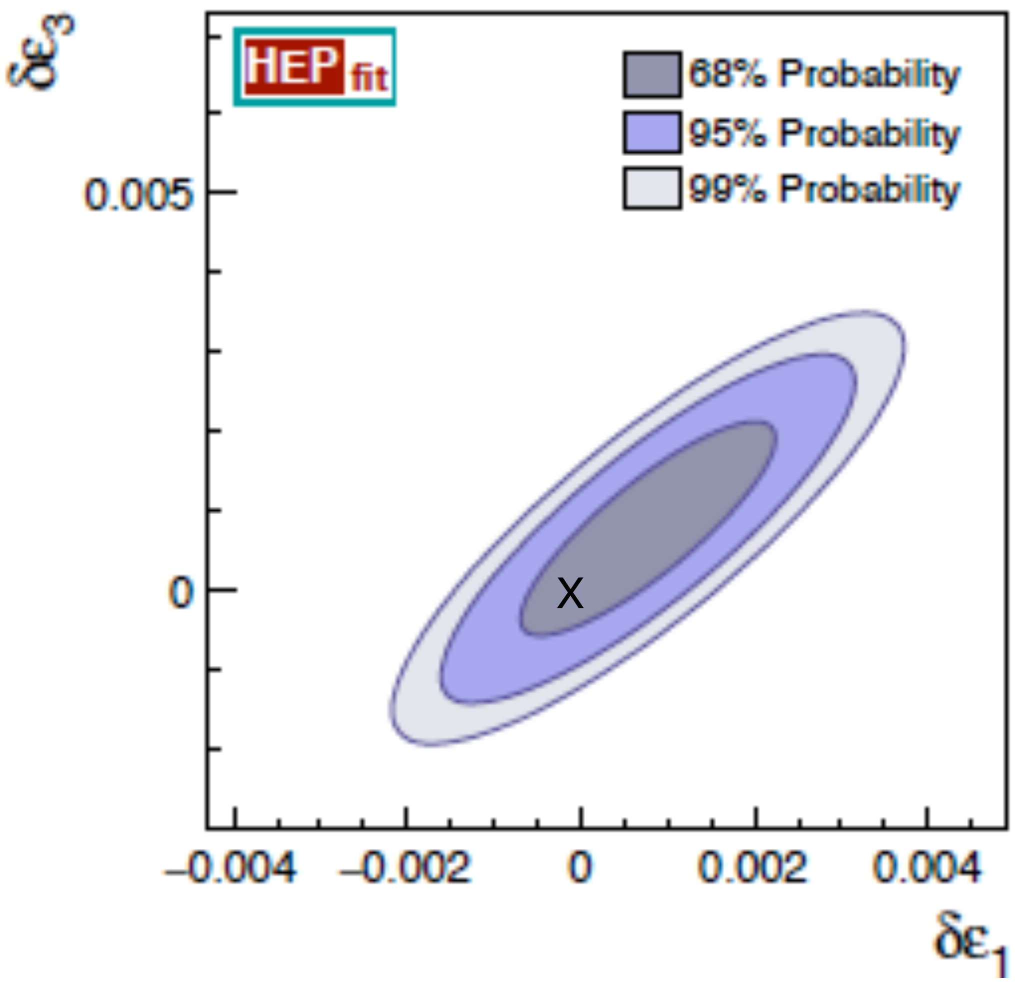
FCNC versus EWPT: a significant comparison

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

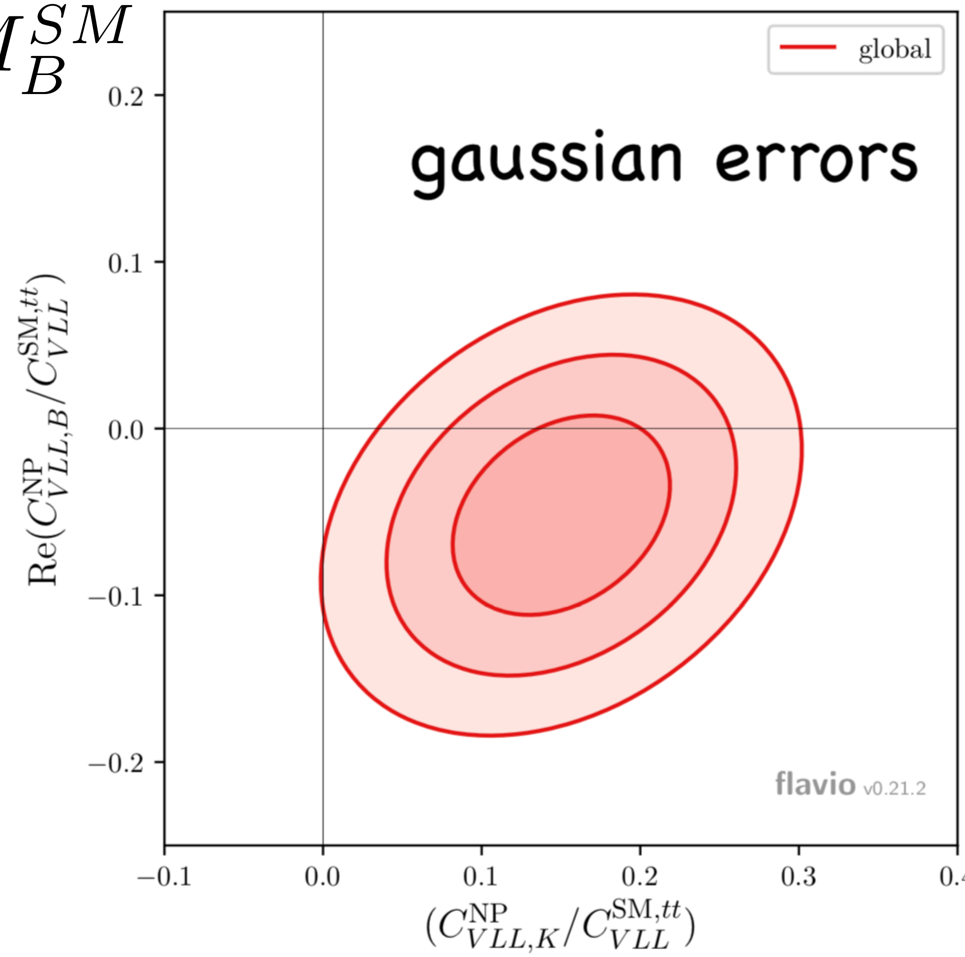


measures EW loops
at about 20% level

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

Straub 2016

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



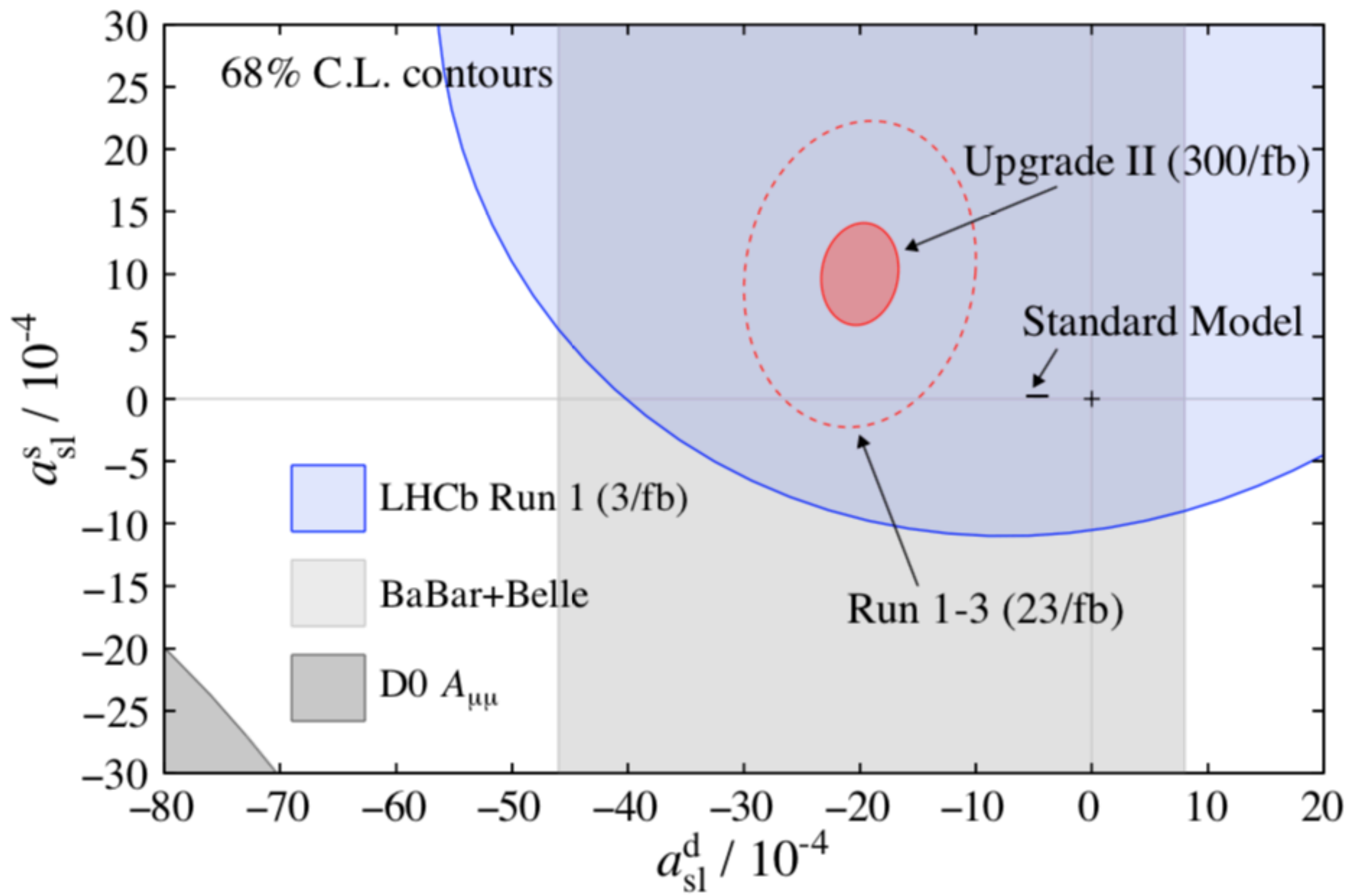
$\frac{\epsilon_K}{\epsilon_K^{SM}}$

measures FCNC loops
at about 20% level

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

Several totally clean observables

$$a_{\rm sl}^q = \frac{\Gamma(\overline{B}_q^0 \to f) - \Gamma(B_q^0 \to \bar{f})}{\Gamma(\overline{B}_q^0 \to f) + \Gamma(B_q^0 \to \bar{f})} \approx \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_{12}^q$$

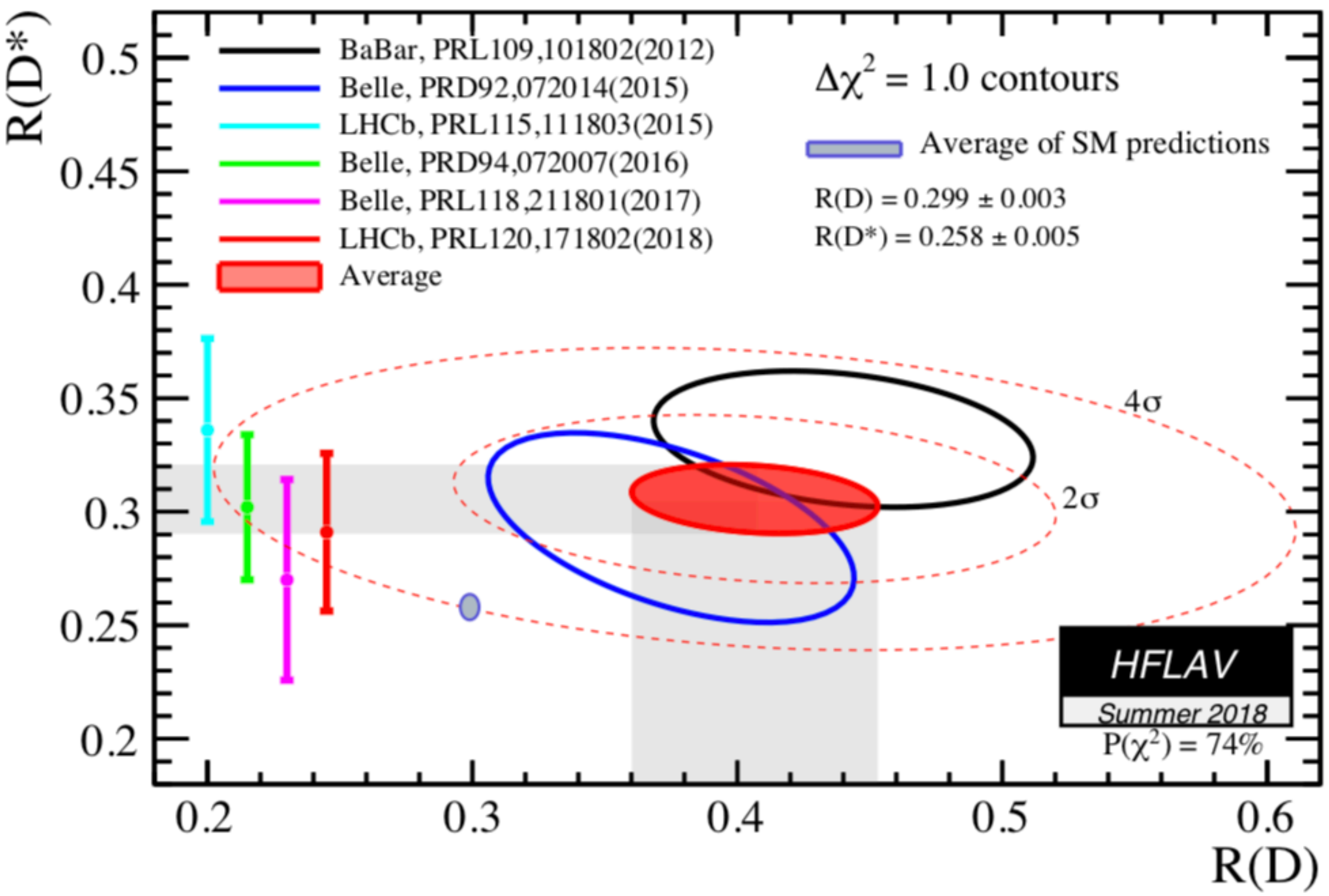


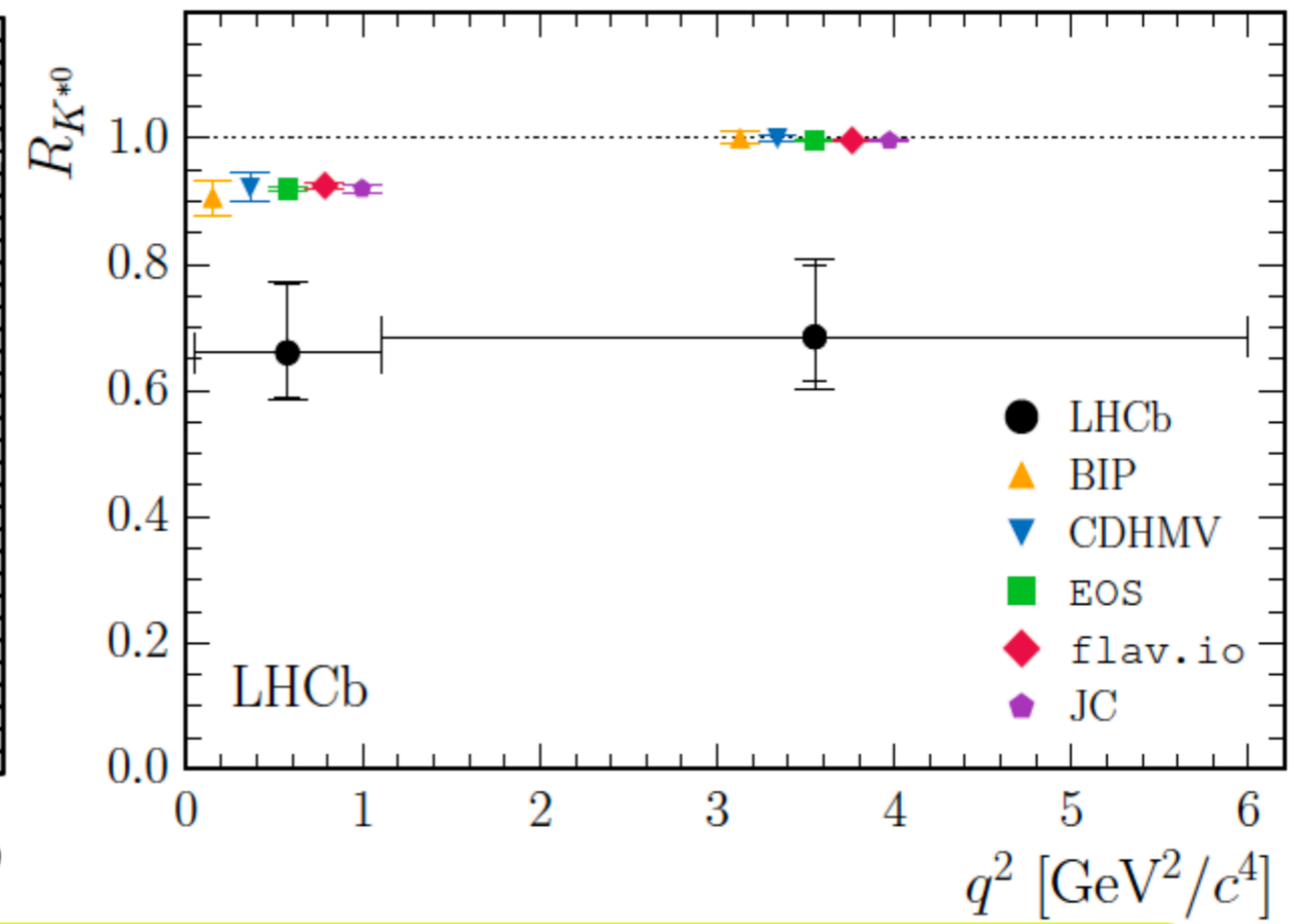
and many others controllable by multiple channel measurements (especially in the charm case)

Lepton Flavour Violation

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

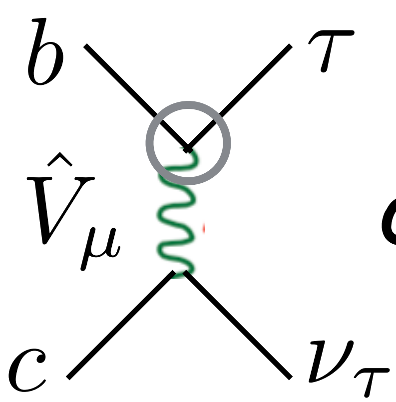
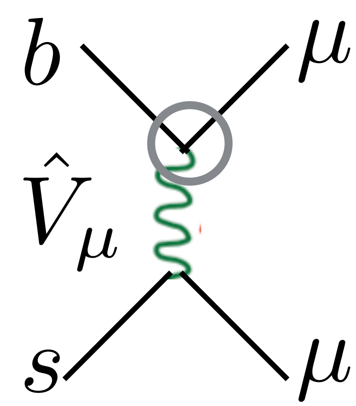
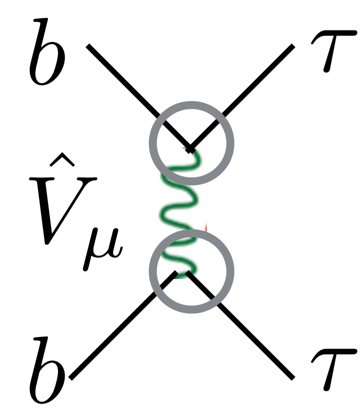
$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$





Observable	Current LHCb	LHCb 2025	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [4]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	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

A perfect example of complementarity

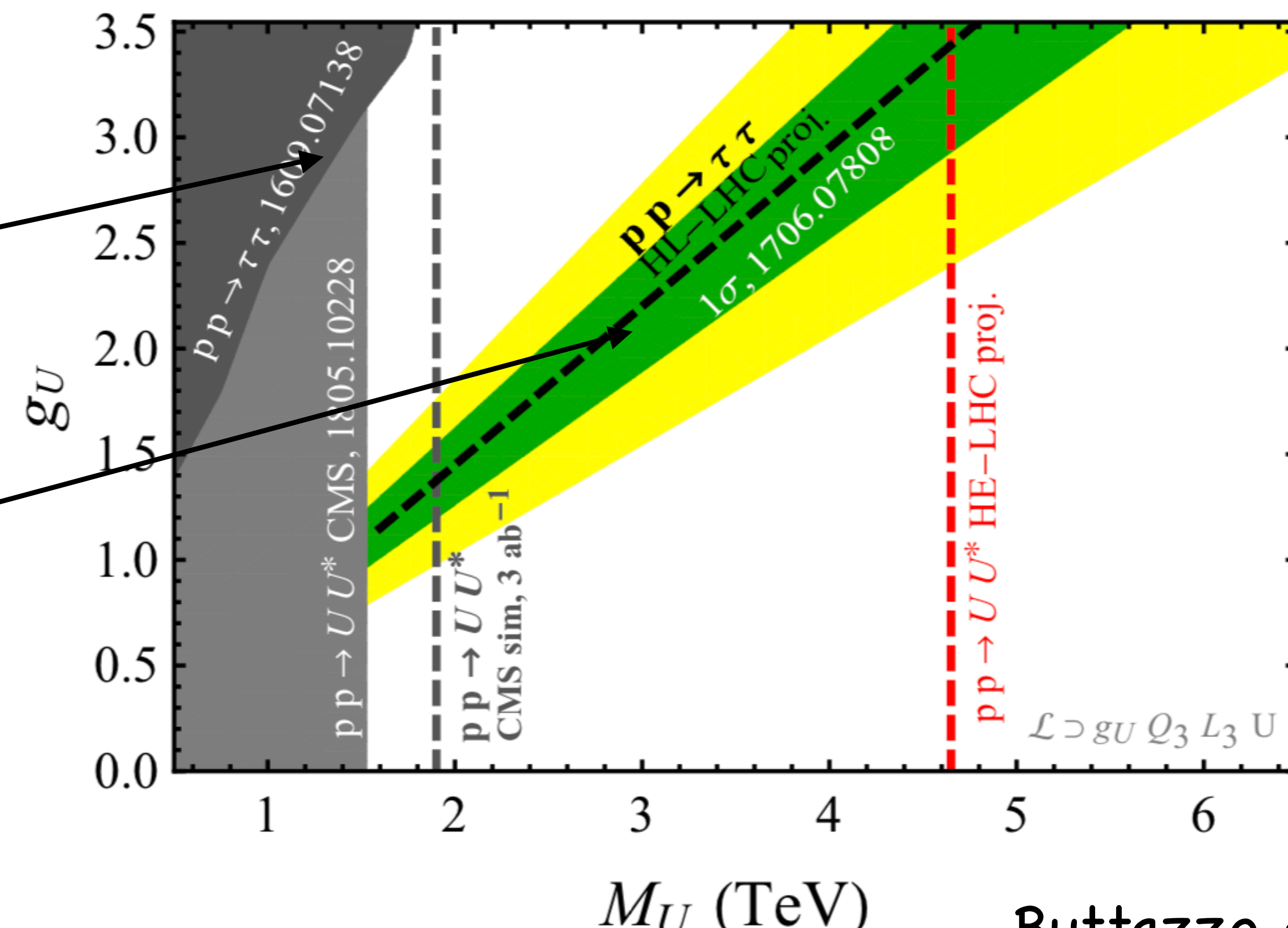
If  and  then 

$b \to c\tau\nu$ $\quad$ $b \to s\mu\mu$ $\quad$ $pp \to bb \to \tau\tau$

The only unknown is

$$\frac{g_V^{c\nu}}{g_V^{b\tau}} \approx V_{cb}$$

$$\frac{g_V^{c\nu}}{g_V^{b\tau}} \approx 5V_{cb}$$



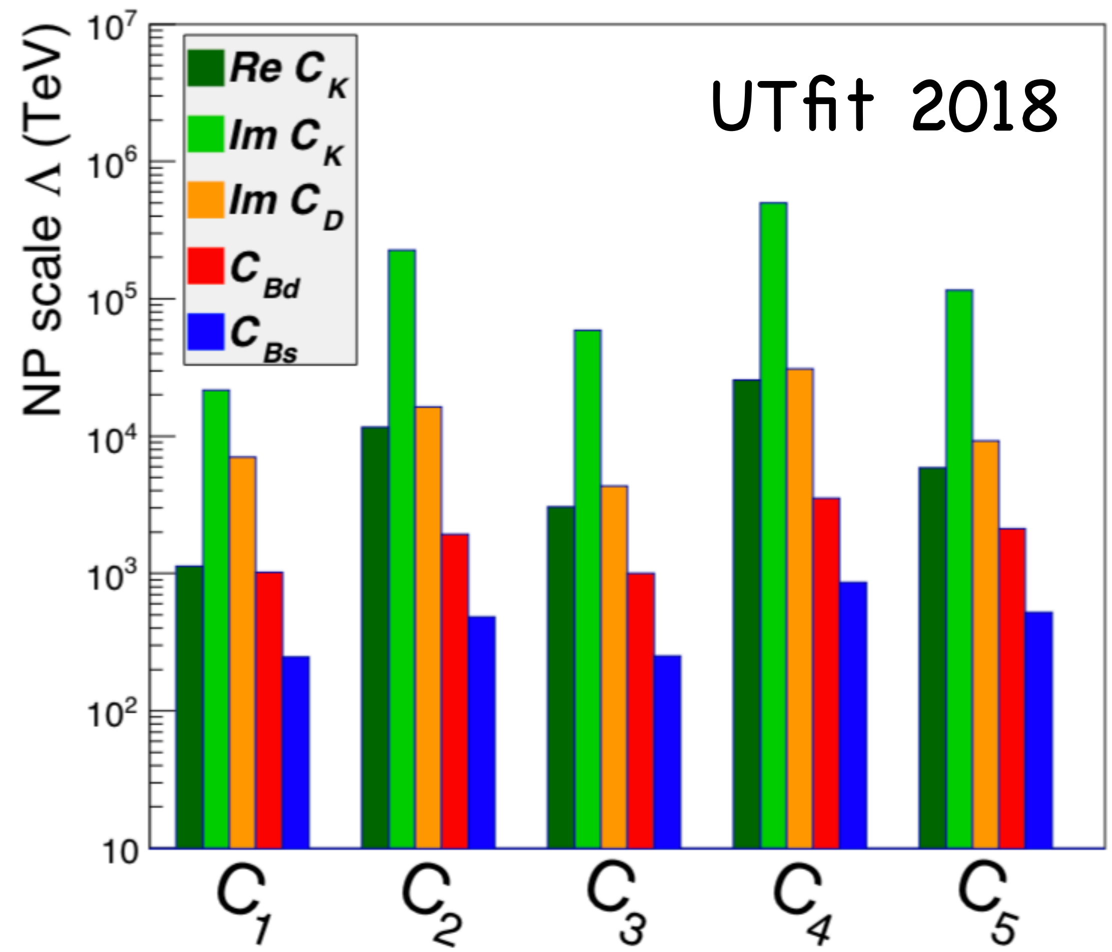
Buttazzo et al 2016

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 $10^{-(2 \div 3)}$

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

$H_2 : \qquad < H_2 >= 0, \quad H_2 \bar{f} f$ 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 indice a first order phase transition, crucial to Baryogenesis

- "Twin" Higgs: H, H'

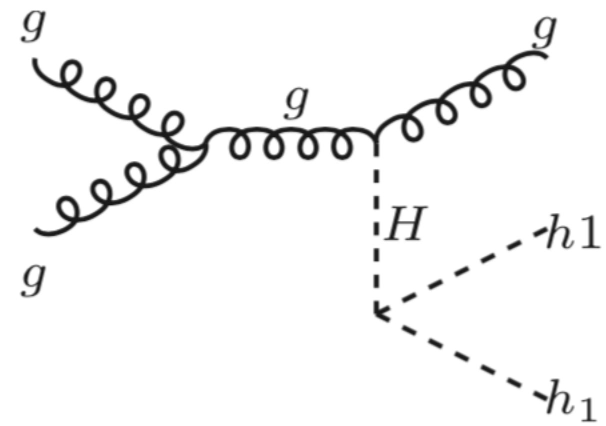
H' = doublet of a "twin" SU(2)

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

h is a pseudo-Goldstone

- “Inert” doublet Dark Matter: H_1, H_2

h_1 = Dark Matter



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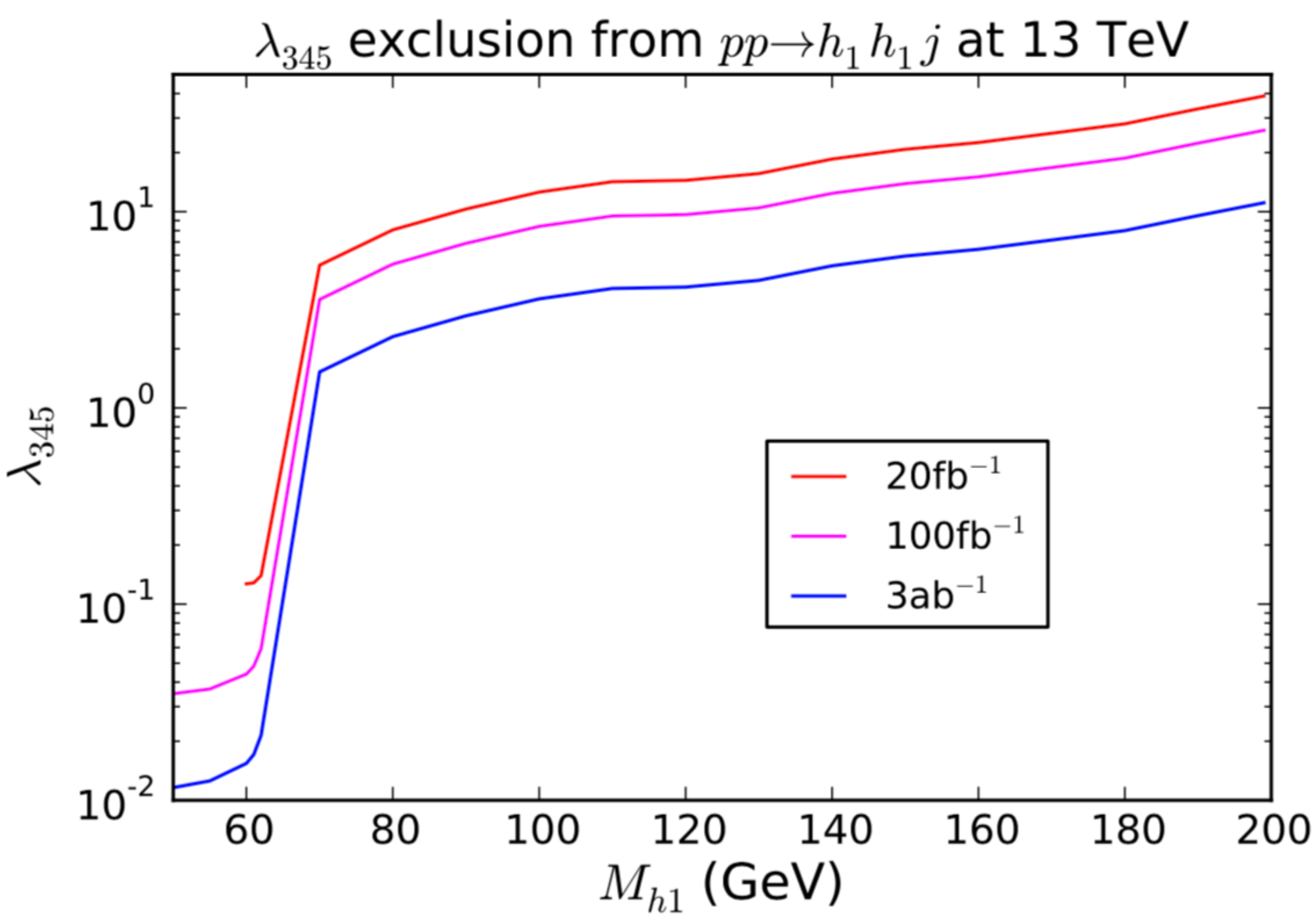
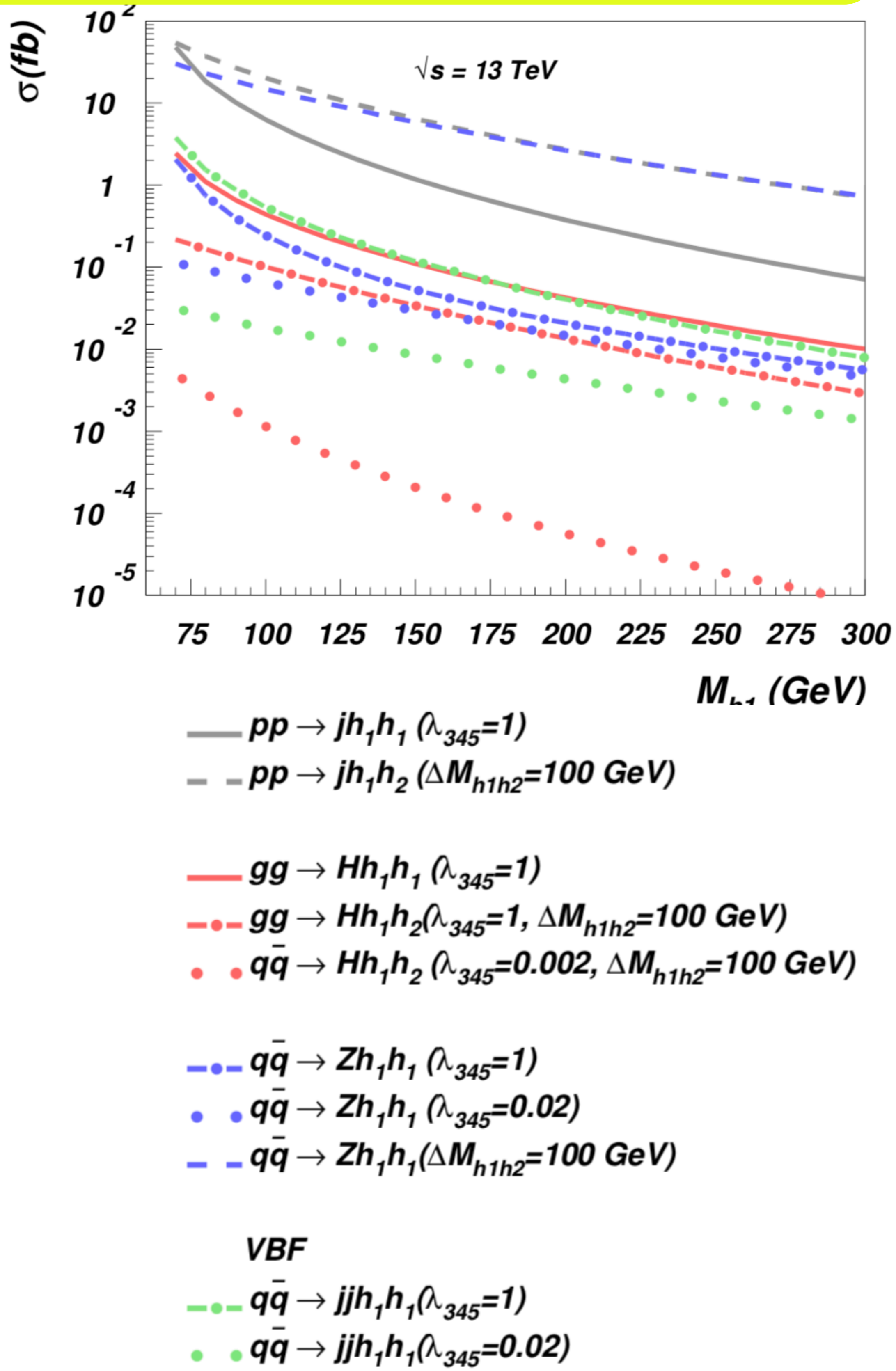


Cacciapaglia et al 2016



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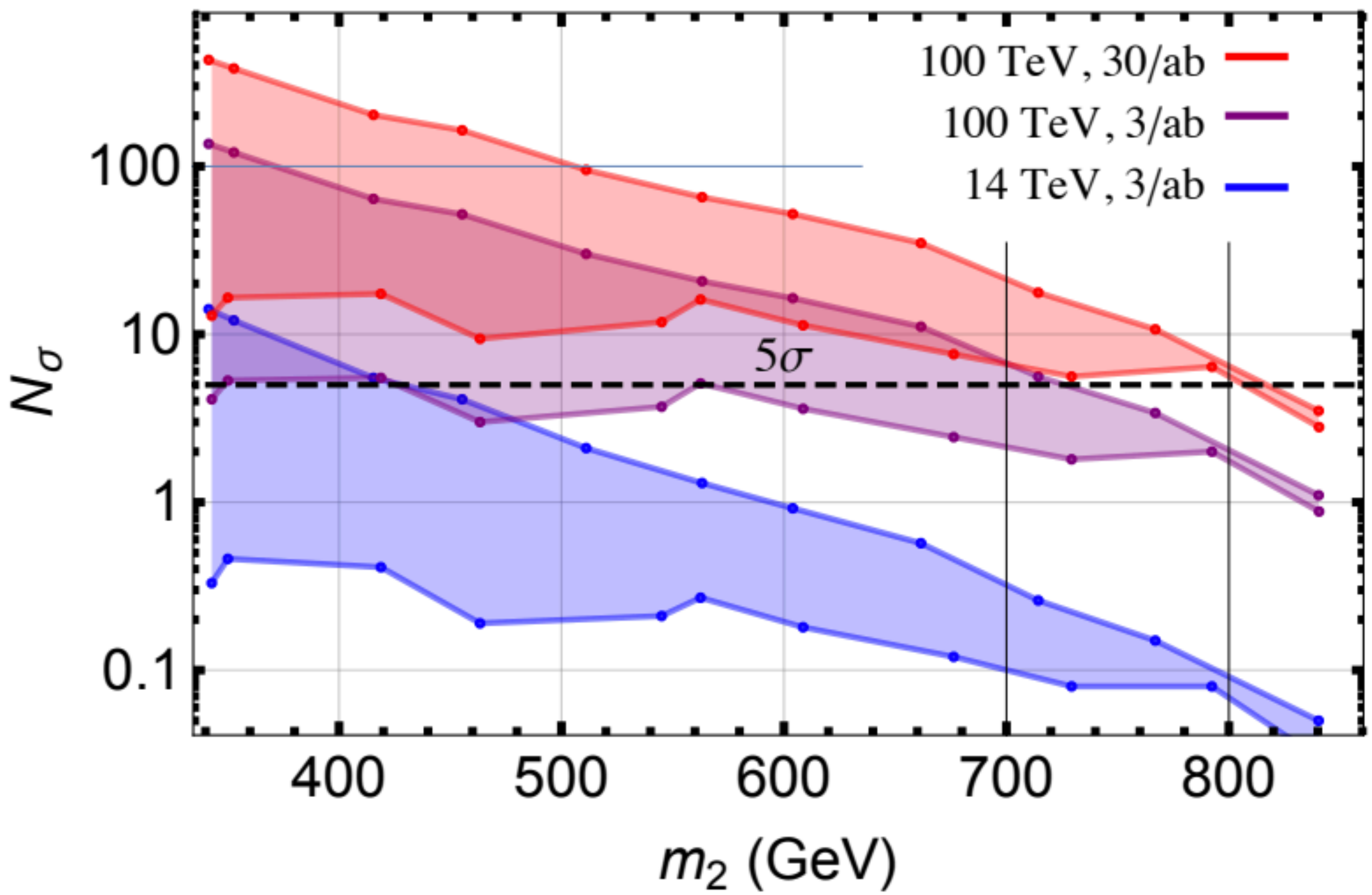


$$pp \to h_2 \to h_1 h_1 \to b\bar{b}\gamma\gamma, \tau\bar{\tau}\tau\bar{\tau}$$

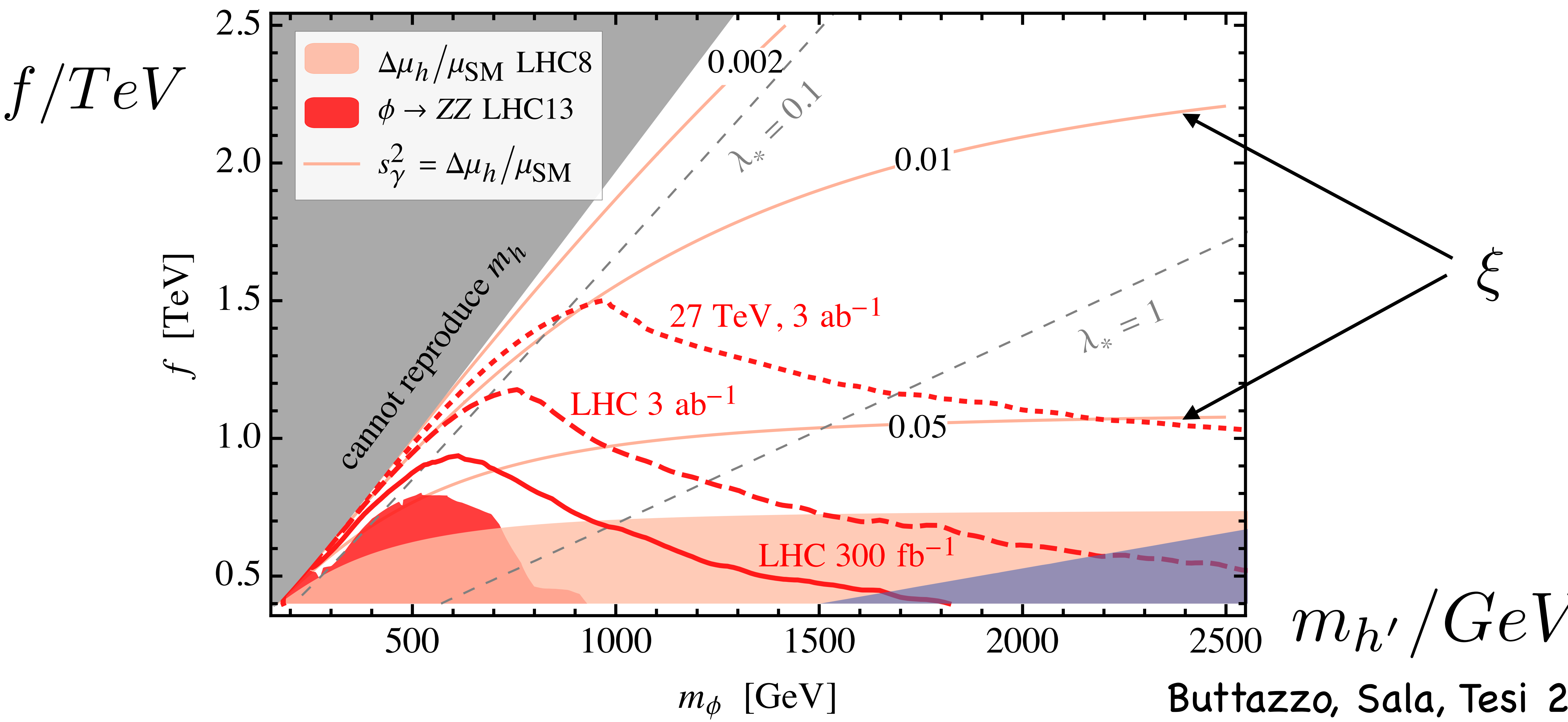
Kotwal et al 2016

– "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 $$\frac{\Gamma_L}{\Gamma_L + \Gamma_T} \to 1$$

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



Buttazzo, Sala, Tesi 2018

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?

Backup on B-anomalies

general caveats

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

Difficult and/or statistically limited experiments

Lepton Flavour Violation never seen before
in charged leptons $BR(K_L \to \mu e) < 4.7 \cdot 10^{-12}$

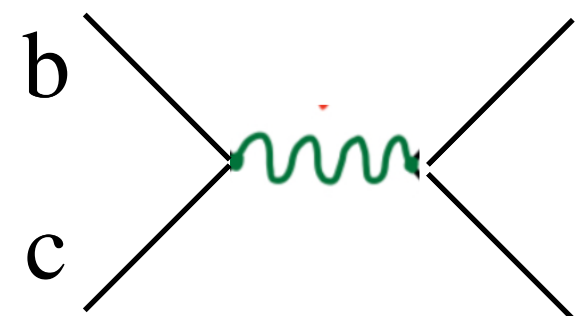
No "mediator" seen in LHC searches

In case one wants to see them correlated:
$b \to c\, l\nu$ tree level, $b \to s\, ll$ loop level

The need of a “mediator”

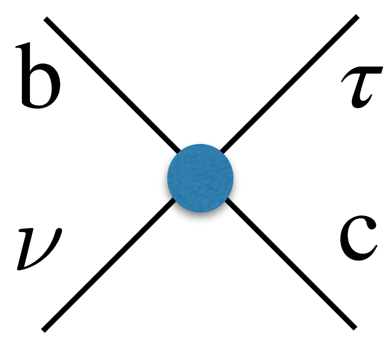
$$\frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}} = 1.237 \pm 0.053$$ is a deviation from the SM at about 20% level in $b \to c\tau\nu$

Need to interfere with



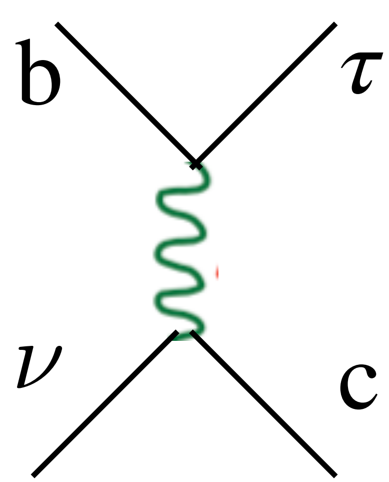
$$= \frac{g^2 V_{cb}}{m_W^2}$$

From



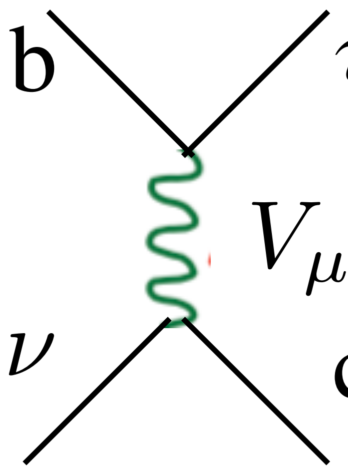
need $\Lambda \approx 500\ GeV \left(\frac{\mathcal{V}_{cb}\mathcal{V}_{\tau\nu}}{V_{cb}}\right)^{1/2}$

From



need $\frac{g}{m} \approx \frac{2}{TeV}\left(\frac{V_{cb}}{\mathcal{V}_{cb}\mathcal{V}_{\tau\nu}}\right)^{1/2}$

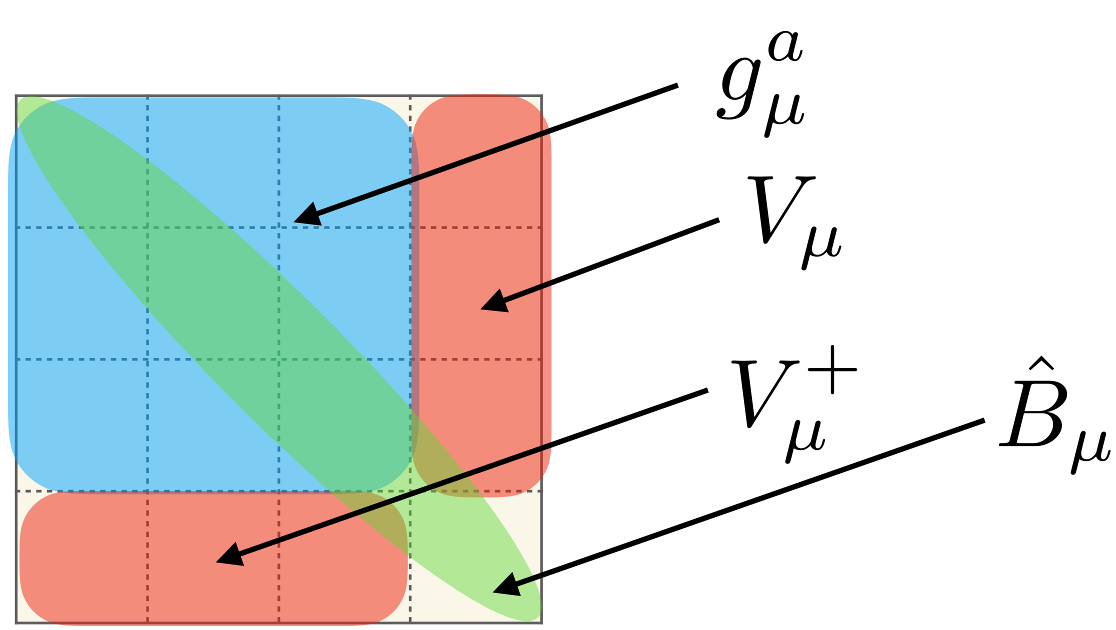
Can one make sense of a vector leptoquark?



$$V_\mu = (3,1)_{2/3}$$

$$V_\mu^a(\bar{q}_L^a \gamma_\mu l_L) = V_\mu^a(\bar{u}_L^a \gamma_\mu \nu_L + \bar{d}_L^a \gamma_\mu e_L)$$

Pati-Salam SU(4): L as a fourth colour

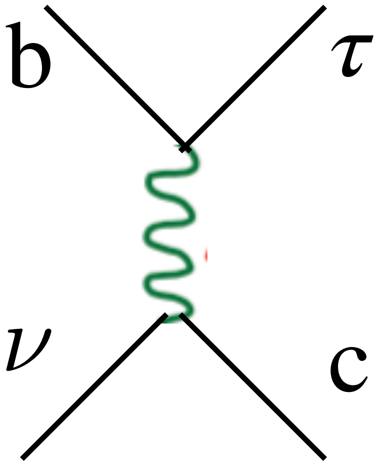


B, Isidori, Pattori, Senia 2015

B, Murphy, Senia 2016

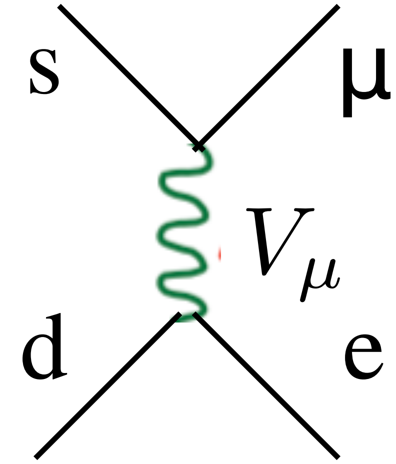
B, Tesi 2017

Back to $K_L \to \mu e$



$$V_\mu^a(\bar{q}_L^a \gamma_\mu l_L) = V_\mu^a(\bar{u}_L^a \gamma_\mu \nu_L + \bar{d}_L^a \gamma_\mu e_L)$$

➡



$$BR(K_L \to \mu e) < 4.7 \cdot 10^{-12}$$

(s^a, μ) and (d^a, e) cannot live in the same SU(4) quartet

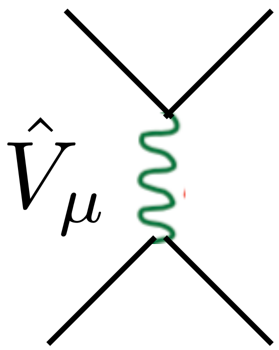
Way out:

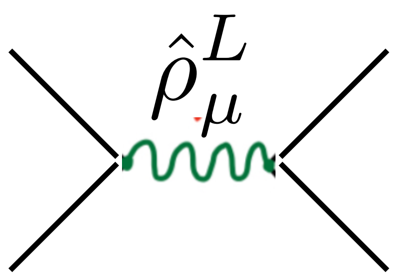
Consider heavy $(Q^a, L)_{Dirac}$ with $V_\mu^a(\bar{Q}_L^a \gamma_\mu L_L)$
and mix them appropriately with standard q_L, l_L

(not trivial if SU(4) is a standard gauge group)

Observed anomalies

$b \to c l \nu$

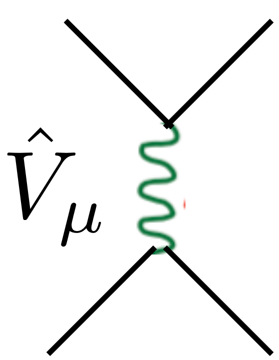




$$\frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}} = 1.237 \pm 0.053$$

$$\left(\frac{\hat{g}_G^2}{m_G^2} + \frac{\hat{g}_\rho^2}{m_\rho^2}\right) s_{l3}^2 s_{q3}^2 \approx 5/TeV^2$$

$b \to s \mu\mu$



$$\frac{R_{K^{(*)}}}{R^{SM}_{K^{(*)}}} = 0.70 \pm 0.10$$

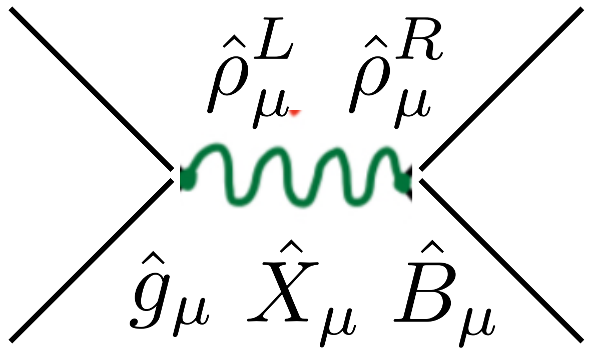
$$\frac{s_{q2} s_{l2}}{s_{q3} s_{l3}} \frac{E_{\mu 3}}{V_{ts}} \sim 5 \cdot 10^{-3}$$

Low energy observables

$$\frac{s_{q2}s_{l2}}{s_{q3}s_{l3}}\frac{E_{\mu 3}}{V_{ts}} \sim 5\cdot 10^{-3}$$

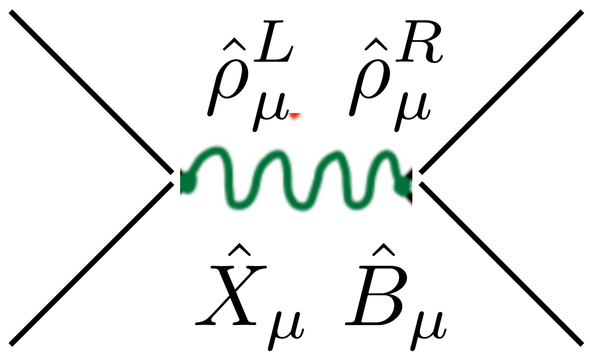
- $b \to c(u)\, l\nu$: $BR(B\to D^*\tau\nu)/BR_{SM} = BR(B\to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c\tau\nu)/BR_{SM}$
$= BR(B \to \pi\,\tau\nu)/BR_{SM} = BR(\Lambda_b \to p\,\tau\nu)/BR_{SM} = BR(B_u \to \tau\nu)/BR_{SM}$

$\Delta C = 2$



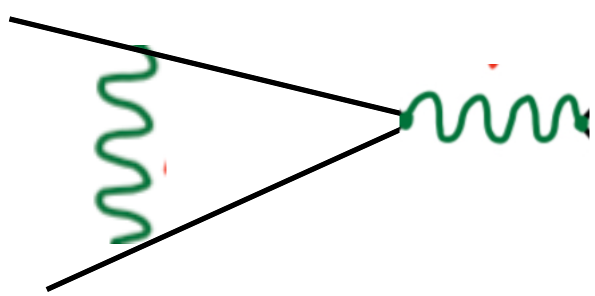
$$\frac{s_{q2}^2}{s_{q3}s_{l3}} \lesssim 10^{-3}$$

$\tau \to 3\mu$



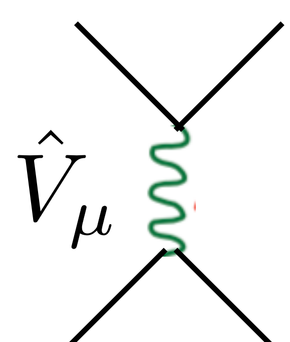
$$E_{\mu 3}\left(\frac{s_{l2}^2}{s_{l3}^2} + |E_{\mu 3}|^2\right) \lesssim 3\cdot 10^{-3}$$

$\tau \to \mu\gamma$



$$\left(A_G + \left(\frac{s_{l3}}{s_{q3}}\right)^2 A_\rho\right)E_{\mu 3} \lesssim 0.1$$

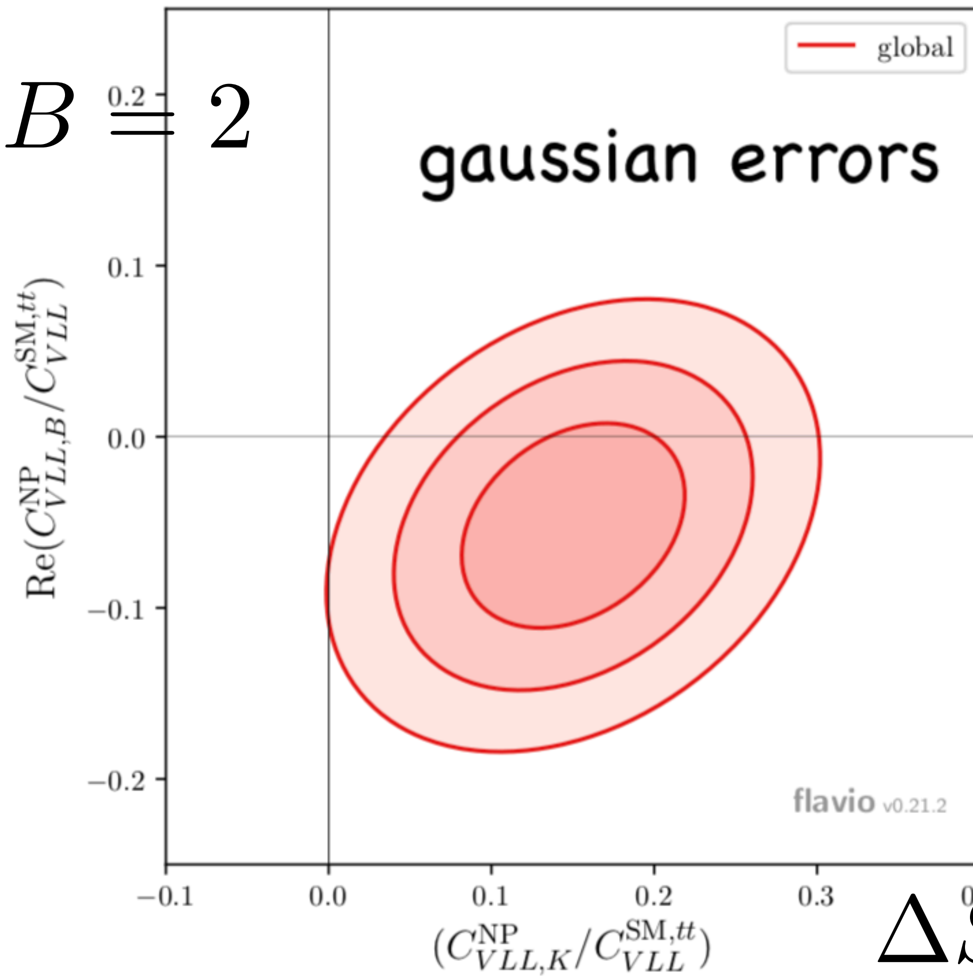
$B^+ \to K^+\mu^+\tau^-$



$$\frac{s_{q2}s_{l2}}{s_{q3}s_{l3}} \lesssim 10^{-2}$$

$\Delta B = 2$

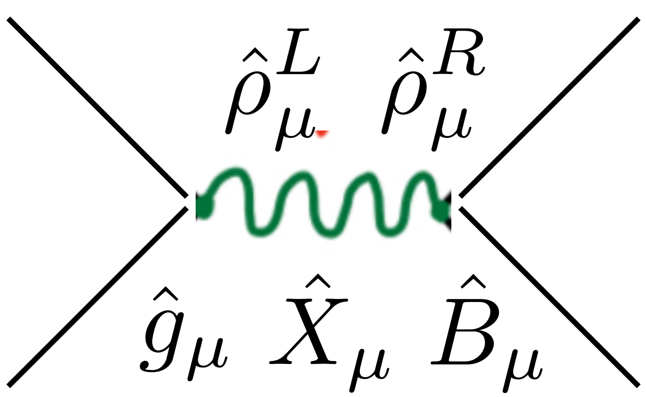
$\Delta B = 2$



Current status

Straub 2017

$\Delta S = 2$



$$\frac{s_{q3}}{s_{l3}} D_{s3} \lesssim 2 \cdot 10^{-3}$$

(against $V_{ts} \approx U_{t2} + D_{s3} = 4 \cdot 10^{-2}$)

Direct searches of the heavy vectors

Leptoquarks $\hat{V}_\mu$ pair produced: $gg \to \hat{V}_\mu^+ \hat{V}_\mu^-$

$\hat{V}_\mu \to t\nu, b\tau$

$\hat{V}_\mu$ exchanged in the t-channel: $b\bar{b} \to \tau\bar{\tau}$

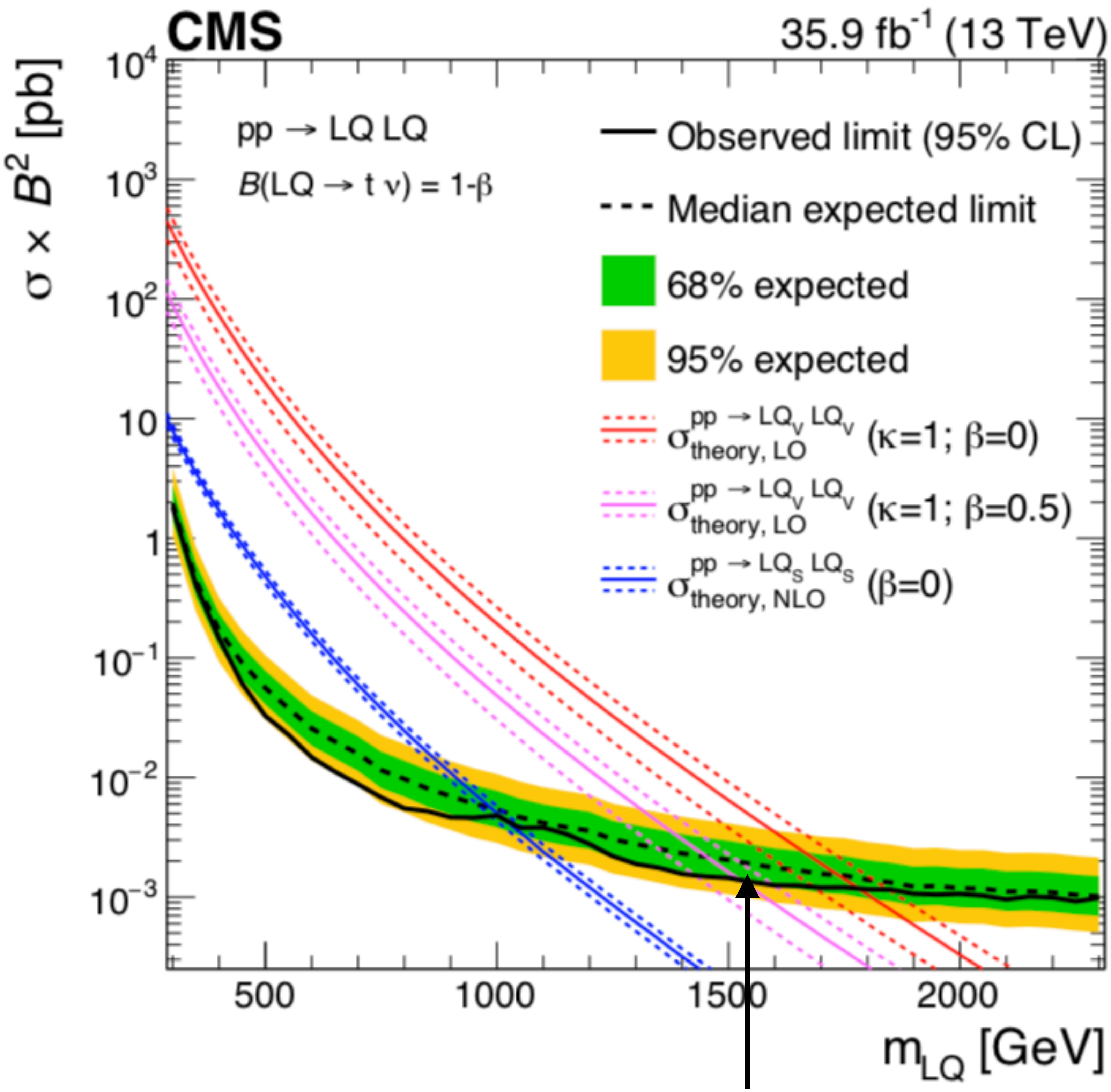
Single $\hat{V}_\mu$ production $gb \to \hat{V}_\mu \tau$

All other vectors but $\hat{\rho}_\mu^{R\pm}$: $\hat{G}_\mu^\alpha, \hat{B}_\mu, \hat{\rho}_\mu^{La}, \hat{\rho}_\mu^{R3}, \hat{X}_\mu$
couple to the light fermions by $F - f$ mixing (mostly f_3)
and, flavour universally, by vector mixing

$$\hat{G}_\mu^a = \frac{g_G \mathcal{G}_\mu^a - g_3 G_\mu^a}{\sqrt{g_G^2 + g_3^2}} \quad \Rightarrow \quad \frac{\Gamma_{\hat{G}\to t\bar{t}}}{m_G} \approx \frac{\Gamma_{\hat{G}\to b\bar{b}}}{m_G} \approx \frac{\hat{g}_G^2 s_{q3}^4}{48\pi}$$

$$\frac{\Gamma_{\hat{G}\to u\bar{u}}}{m_G} \approx \frac{\Gamma_{\hat{G}\to d\bar{d}}}{m_G} \approx \frac{g_3^4}{24\pi g_G^2}$$

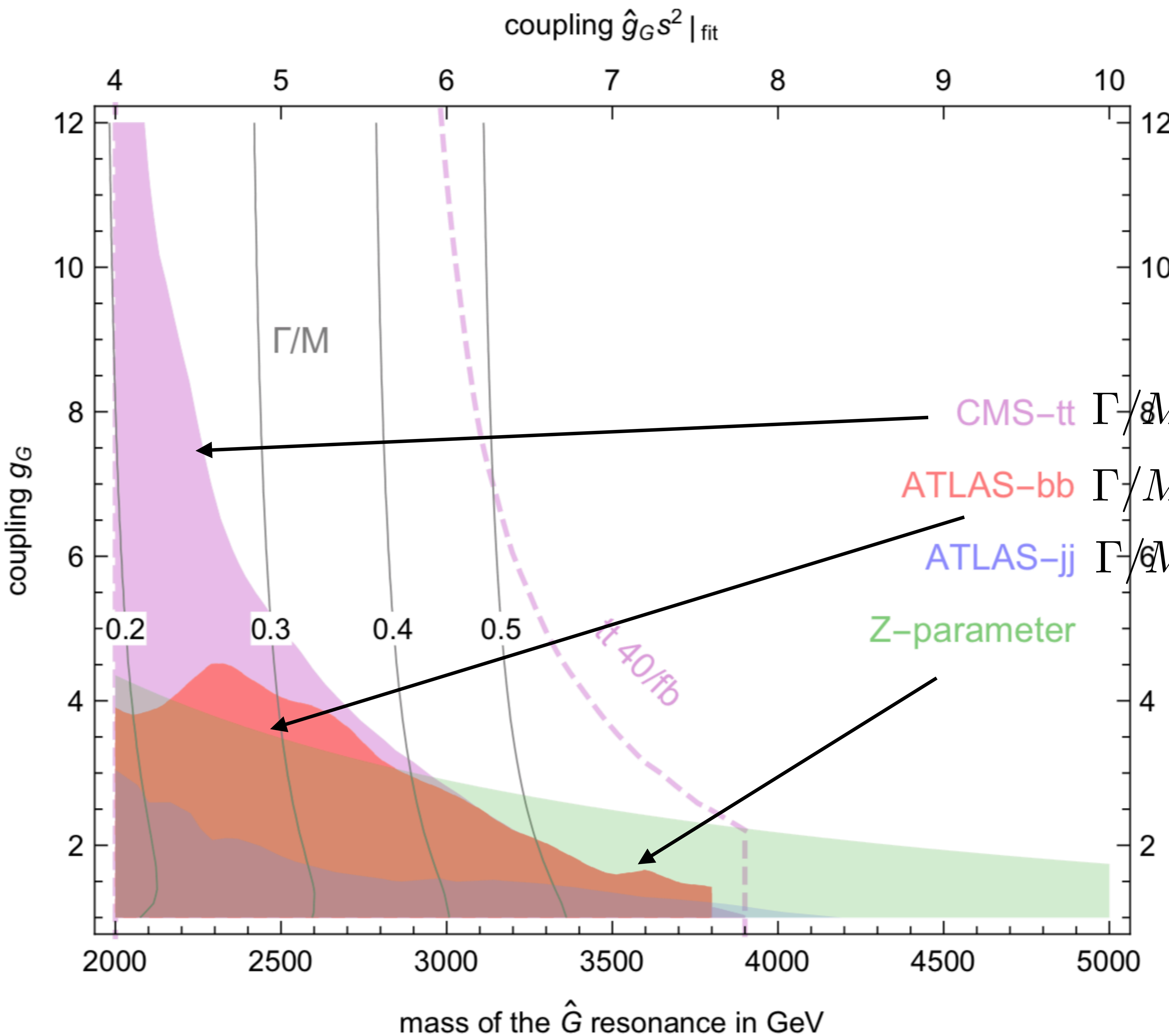
$$gg \to \hat{V}_\mu^+ \hat{V}_\mu^- \to (t\bar{\nu}_\tau)(\bar{t}\nu_\tau)$$



$$m_{\hat{V}} > 1.5\ TeV$$

$$u\bar{u}, d\bar{d}, b\bar{b} \to \hat{G} \to t\bar{t}, b\bar{b}, jj$$

$$\hat{g}_G s_{q3} s_{l3} = 2\frac{m_G}{TeV}$$



$\Gamma/M < 30\%$

$\Gamma/M < 15\%$

$\Gamma/M < 15\%$

$$m_{\hat{G}} > 2 \div 2.5\ TeV$$