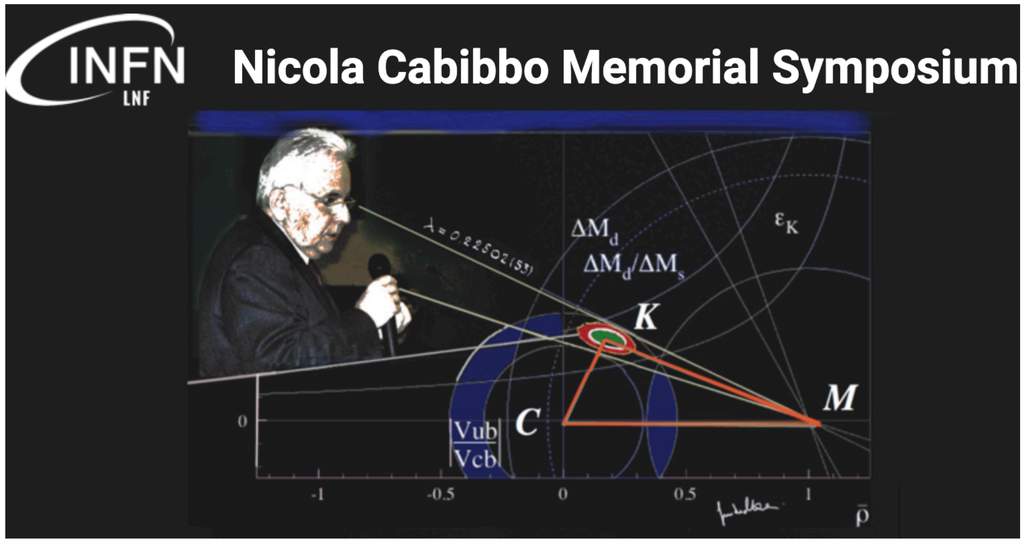
Modello Standard o Teoria Standard?

(Standard Model o Beyond the Standard Model?)

Ricordando Nicola Cabibbo



Riccardo Barbieri

15 Dicembre, 2020

1. **Muon Number Nonconserving Processes in Gauge Theories of Weak Interactions**
Guido Altarelli (Ecole Normale Superieure), L. Baulieu (Ecole Normale Superieure), N. Cabibbo (Rome U.), L. Maiani (Rome U.), R. Petronzio (Rome U.) (Mar 1, 1977)

2. **Bounds on the Fermions and Higgs Boson Masses in Grand Unified Theories**
N. Cabibbo (Rome U. and INFN, Rome), L. Maiani (CERN), G. Parisi (Frascati), R. Petronzio (CERN) (Jun 1, 1979)

3. **Massive Photinos: Unstable and Interesting** #
N. Cabibbo (Rome U. and INFN, Rome), G.R. Farrar (Rutgers U., Piscataway and INFN, Rome), L. Maiani (Rome U. and INFN, Rome) (Jul 1, 1981)

4. **MASSIVE STATES FROM MASSLESS MULTIPLETS OF THE N EXTENDED SUPERSYMMETRY**
Guido Altarelli (Rome U.), N. Cabibbo (Rome U.), L. Maiani (Rome U.) (Jan 1, 1982)

5. **AN ALTERNATIVE TO PERTURBATIVE GRAND UNIFICATION: HOW ASYMPTOTICALLY NONFREE THEORIES CAN SUCCESSFULLY PREDICT LOW-ENERGY GAUGE COUPLINGS**
N. Cabibbo (Rome U. and INFN, Rome), G.R. Farrar (Rutgers U., Piscataway) (Jan 1, 1982)

6. **Supersymmetric Decay Modes of the W and Single Electron Production in $p\bar{p}$ Collisions**
Riccardo Barbieri (Pisa U. and INFN, Pisa), N. Cabibbo (Rome U. and INFN, Rome), L. Maiani (Rome U. and INFN, Rome), S. Petrarca (Rome U. and INFN, Rome) (May 1, 1983)

7. **Signature for Scalar Electrons From Z Production in $p\bar{p}$ Collisions** #
N. Cabibbo (Rome U., Tor Vergata), L. Maiani (Rome U. and INFN, Rome), S. Petrarca (Rome U. and INFN, Rome) (Jun 1, 1983)

8. **Anomalous Z Decays: Excited Leptons?**
N. Cabibbo (Rome U. and INFN, Rome), L. Maiani (Rome U. and INFN, Rome), Y. Srivastava (Frascati) (Nov 1, 1983)

2.

(5.)

Bounds on the Fermions and Higgs Boson Masses in Grand Unified Theories

N. Cabibbo (Rome U. and INFN, Rome), L. Maiani (CERN), G. Parisi (Frascati), R. Petronzio (CERN) (Jun 1, 1979)

- For a sufficiently large number of families $N \approx 8$
  all gauge interactions may become simultaneously strong at $\Lambda \approx M_{Pl}$

Parisi 1975

Maiani, Parisi, Petronzio 1977

(5. Unification in IR-free Susy theories and 5 generations)

- The asymptotic divergence of Yukawa and quartic Higgs couplings, for $N = 3$
  binds the top and the Higgs mass, depending on Λ

EPS Conference, Madrid 1989

Λ	10^4	10^7	10^{10}	10^{15}
m_H	610	360	300	260
m_t	460	290	260	230

$/GeV$

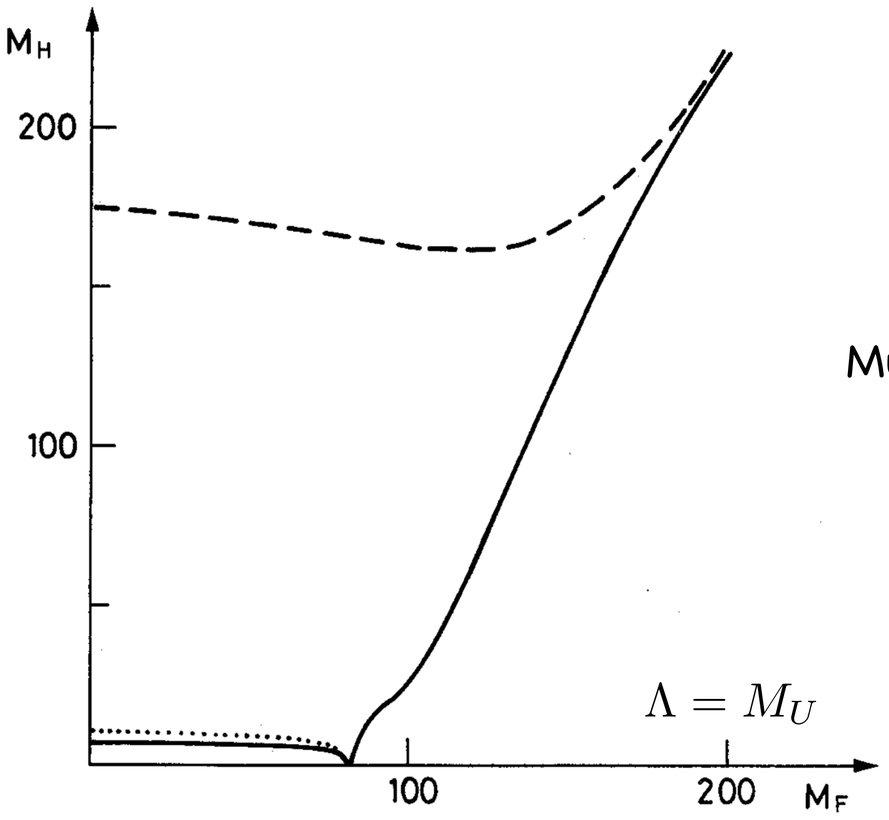
Veltman bound (1977) from $\delta\rho$: $m_{top} \lesssim 450\ GeV$

Only after the first Z-mass measurement 1989 $40\ GeV < m_t < 210\ GeV\ (90\%C.L.)$

Bounds on the Fermions and Higgs Boson Masses in Grand Unified Theories

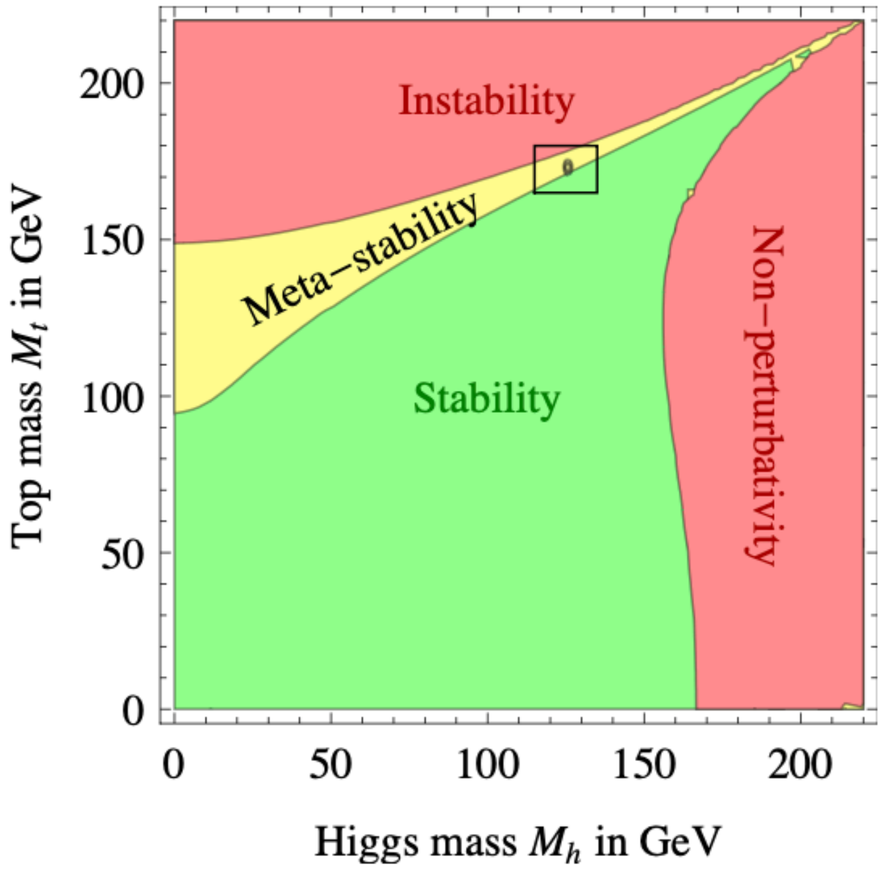
N. Cabibbo (Rome U. and INFN, Rome), L. Maiani (CERN), G. Parisi (Frascati), R. Petronzio (CERN) (Jun 1, 1979)

- One of the first integrations of RGEs in the SM for α_i, y_t, λ



$\Longrightarrow$

Mutatis mutandis



Cabibbo, Maiani, Parisi, Petronzio 1979

Degrassi et al 2013

3.

Massive Photinos: Unstable and Interesting #

N. Cabibbo (Rome U. and INFN, Rome), G.R. Farrar (Rutgers U., Piscataway and INFN, Rome), L. Maiani (Rome U. and INFN, Rome) (Jul 1, 1981)

$$\lambda_\gamma \to \lambda_g + \gamma$$

$$\tau_{\tilde{\gamma}} = 8\pi d^2/(m_{\tilde{\gamma}})^5$$

$$\tau_{\tilde{\gamma}} = 1.65 \times 10^{30} [d/(100\ \mathrm{GeV})^2]^2 (1\ \mathrm{eV}/m_{\tilde{\gamma}})^5$$

Now $$\tau \approx 10^{-4} sec \left(\frac{d}{10\ TeV}\right)^2 \left(\frac{500\ GeV}{m_\chi}\right)^5$$

LHC/FCC: $pp \to \chi\chi\gamma$

6.

(7. 8.)

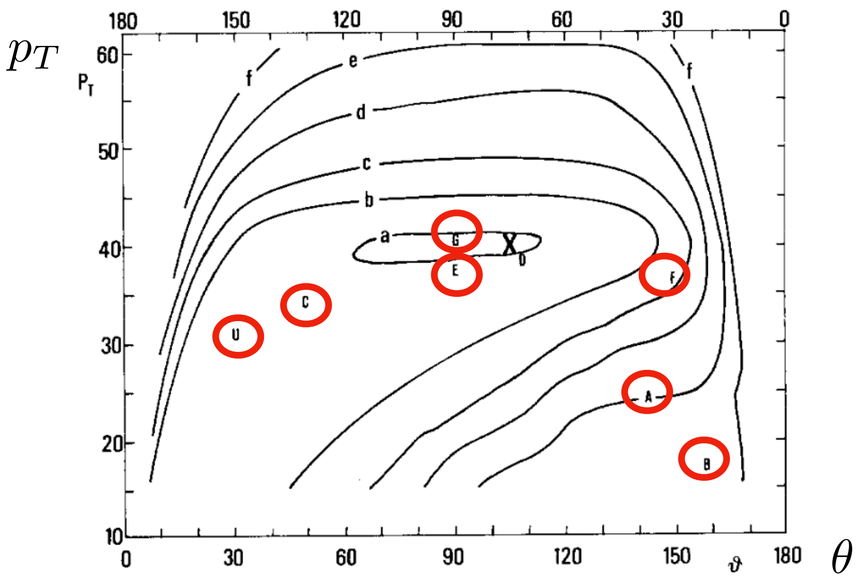
Supersymmetric Decay Modes of the W and Single Electron Production in $p\bar{p}$ Collisions

Riccardo Barbieri (Pisa U. and INFN, Pisa), N. Cabibbo (Rome U. and INFN, Rome), L. Maiani (Rome U. and INFN, Rome), S. Petrarca (Rome U. and INFN, Rome) (May 1, 1983)

UA1, UA2, Feb 1983 $p + \bar{p} \to e$ + missing energy + hadrons

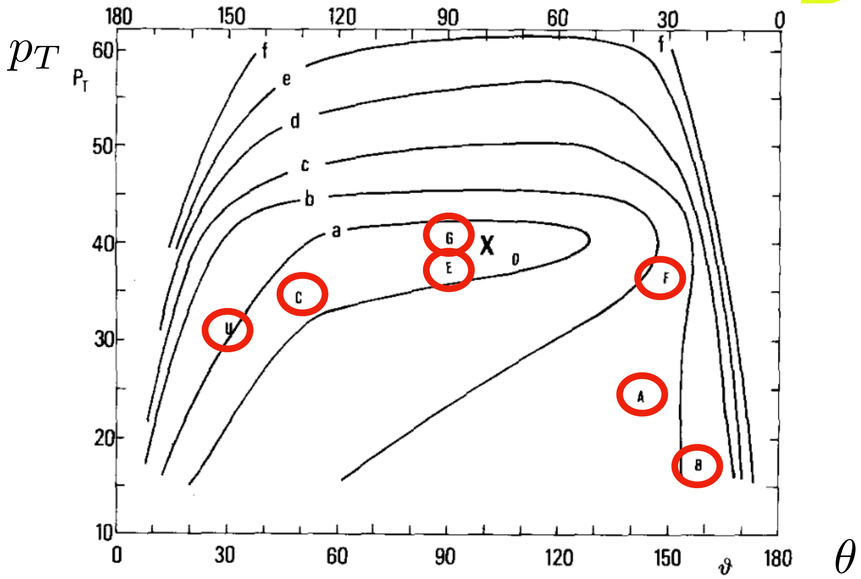
$W \to e\nu$

$d\sigma/dp_T d\theta \propto (1-\cos\theta)^2$



$W \to \tilde{e}\tilde{\nu} \to e + missing\ neutrals$

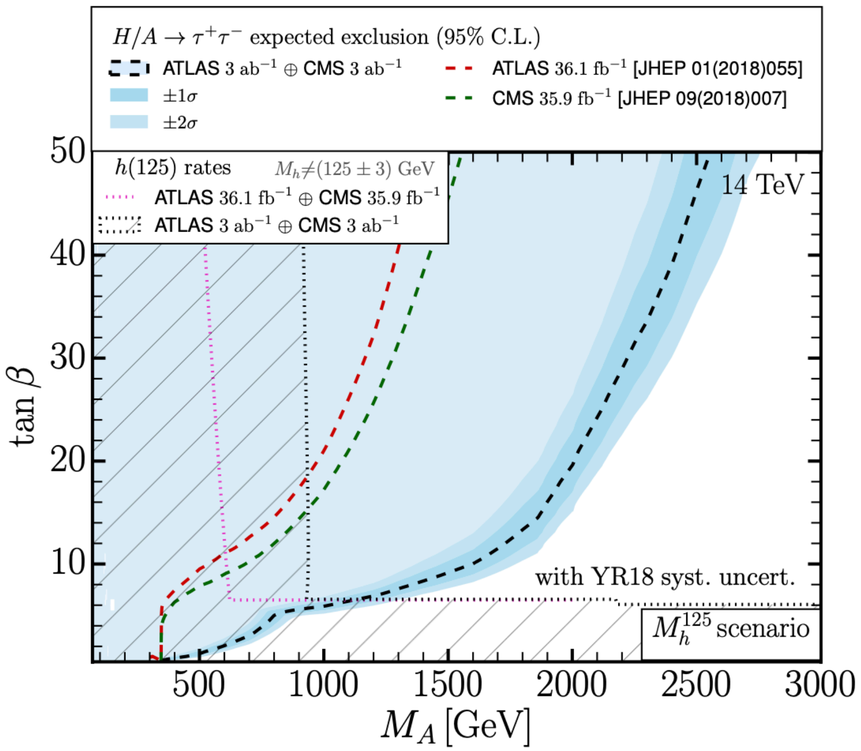
$d\sigma/dp_T d\theta \propto sin^2\theta$

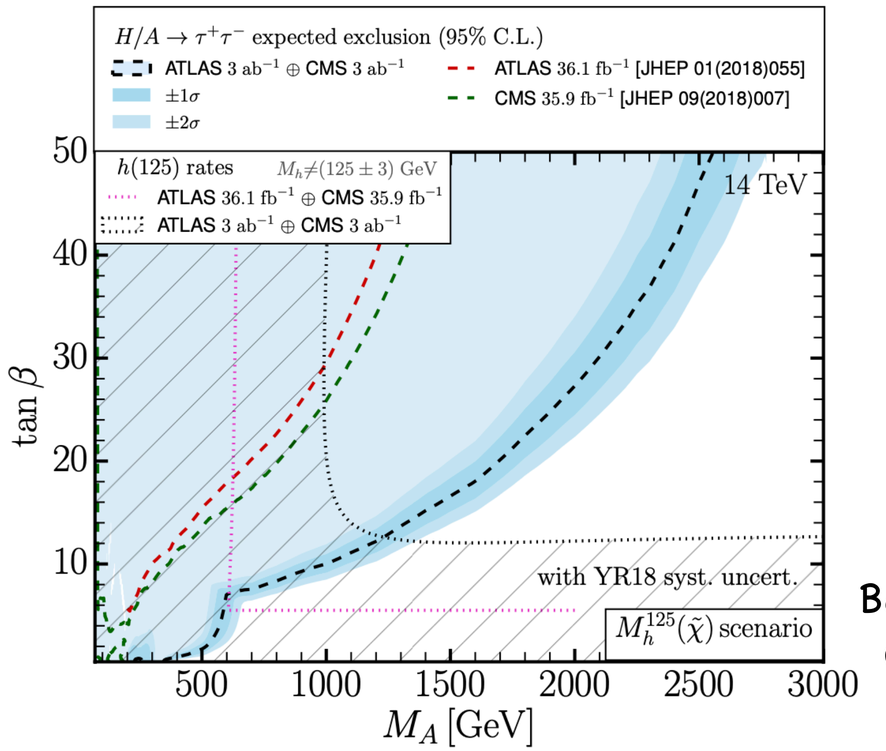


2 years later, about 150 events with a perfect distribution $(1-\cos\theta)^2$

Since 5/8 of Nicola works on BSM are in supersymmetry:

Prospects for H/A searches in a simplified SSM at HL-LHC





Bagnaschi et al 2019
Cepeda et al 2019

Left: heavy superpartners

Right: lighter charginos/neutralinos

The direct search for supersymmetry is among the important motivations for the next HE accelerator

Remembering Nicola Cabibbo, the father of flavour in the SM

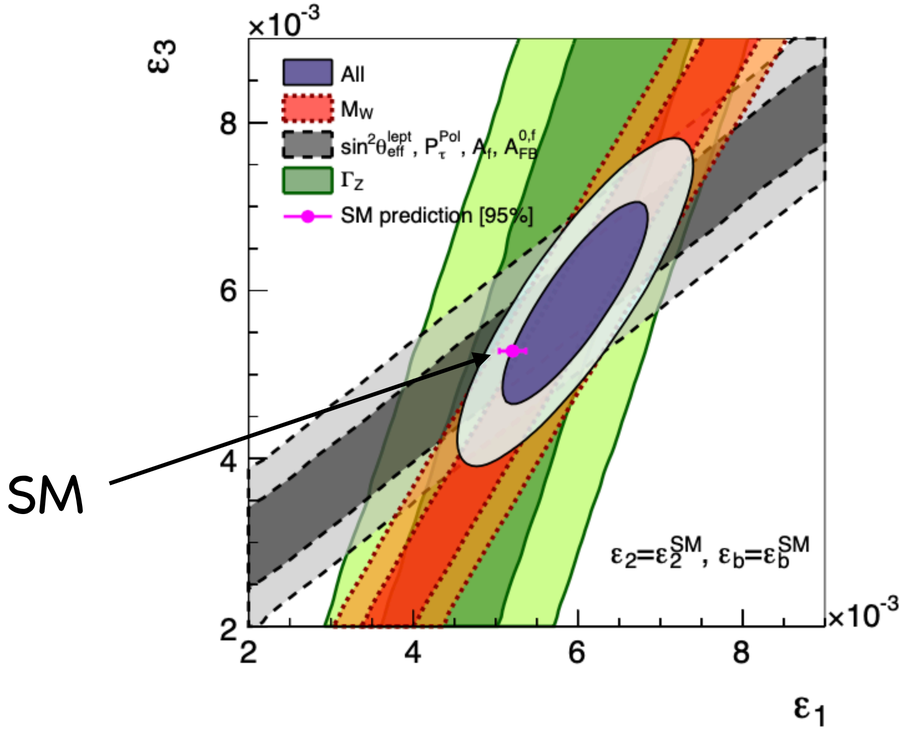
(No work in BSM after 1983)

1984 → APE

2005 → NA48

EWPT versus FCNC: a significant comparison

De Blas et al, 2019

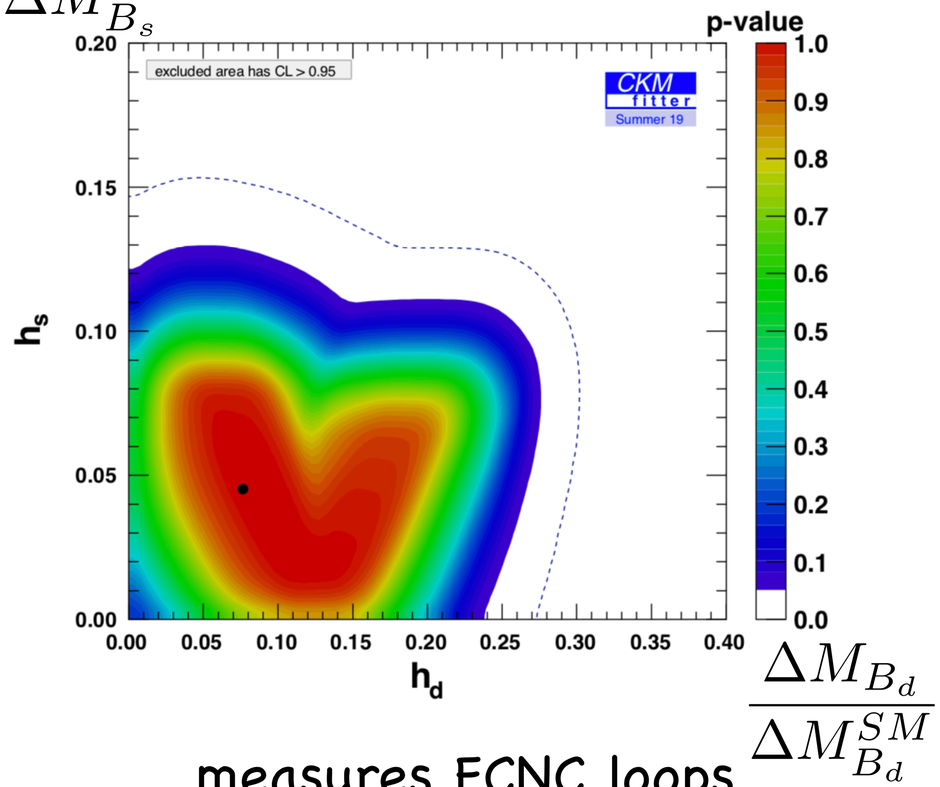


measures EW loops
at about 20% level

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

$$\frac{\Delta M_{B_s}}{\Delta M_{B_s}^{SM}}$$

Charles et al, 2020

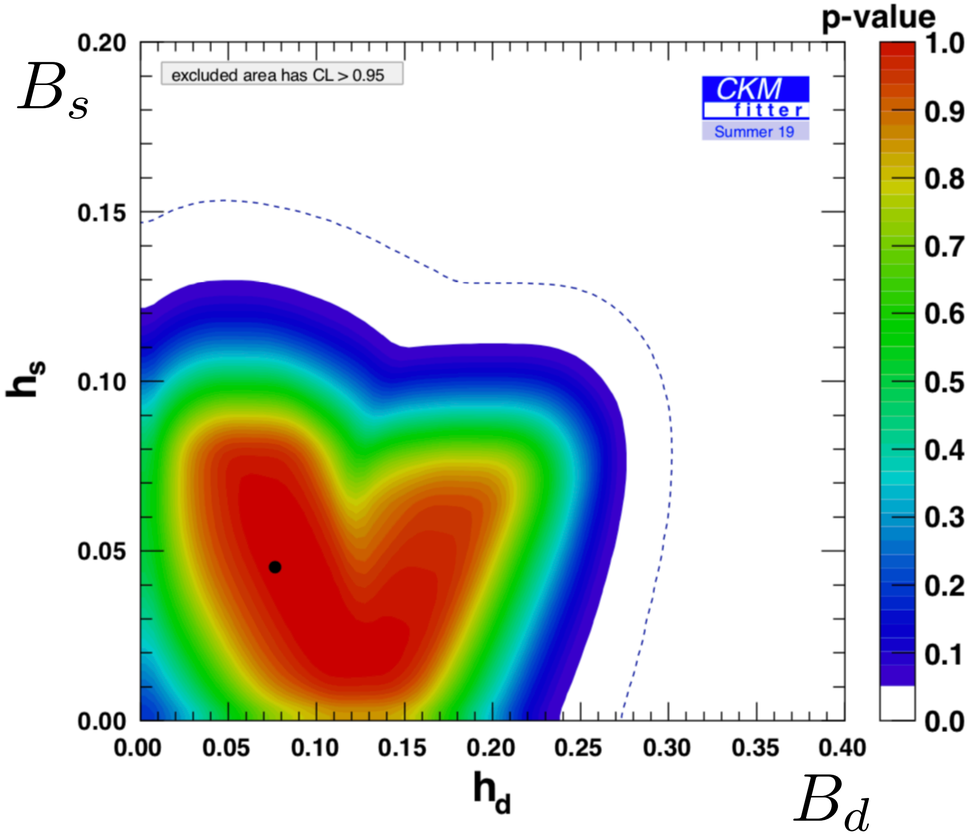


$$\frac{\Delta M_{B_d}}{\Delta M_{B_d}^{SM}}$$

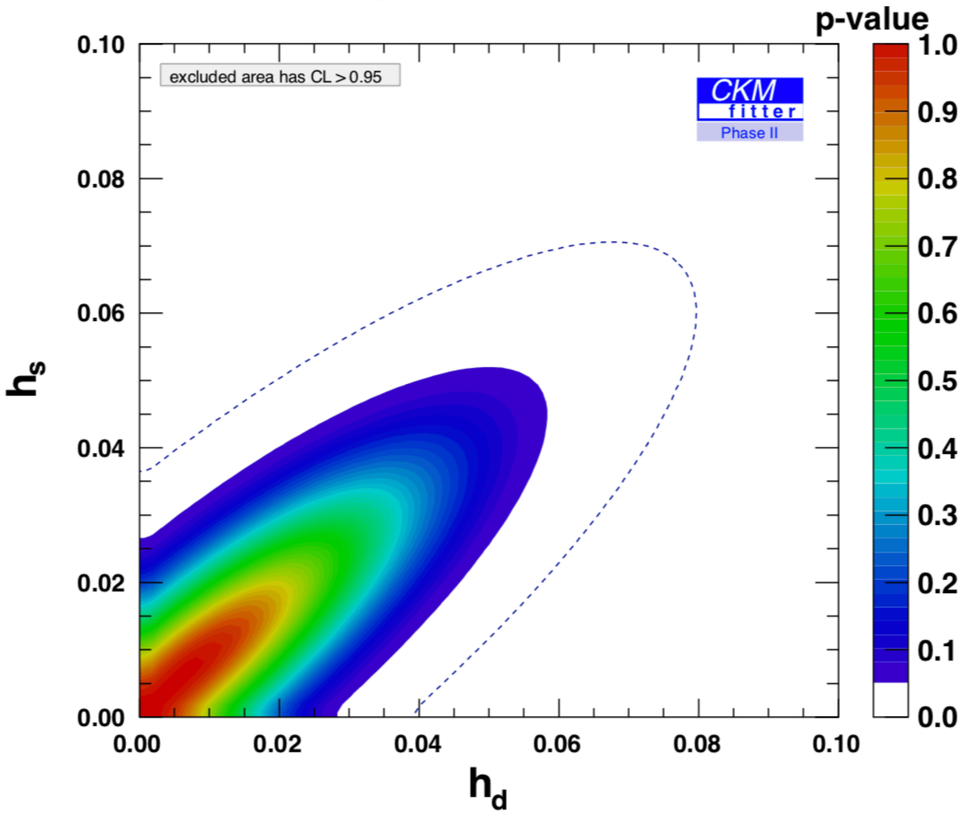
measures FCNC loops
at about 20% level

An "aggressive" flavour program
could go to 2-4% level

current



"phase II"



Phase II: LHCb 300/fb, Belle II 250/ab

$$M_{12} = (M_{12})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

Charles et al, 2020

Current constraints from selected EFT operators

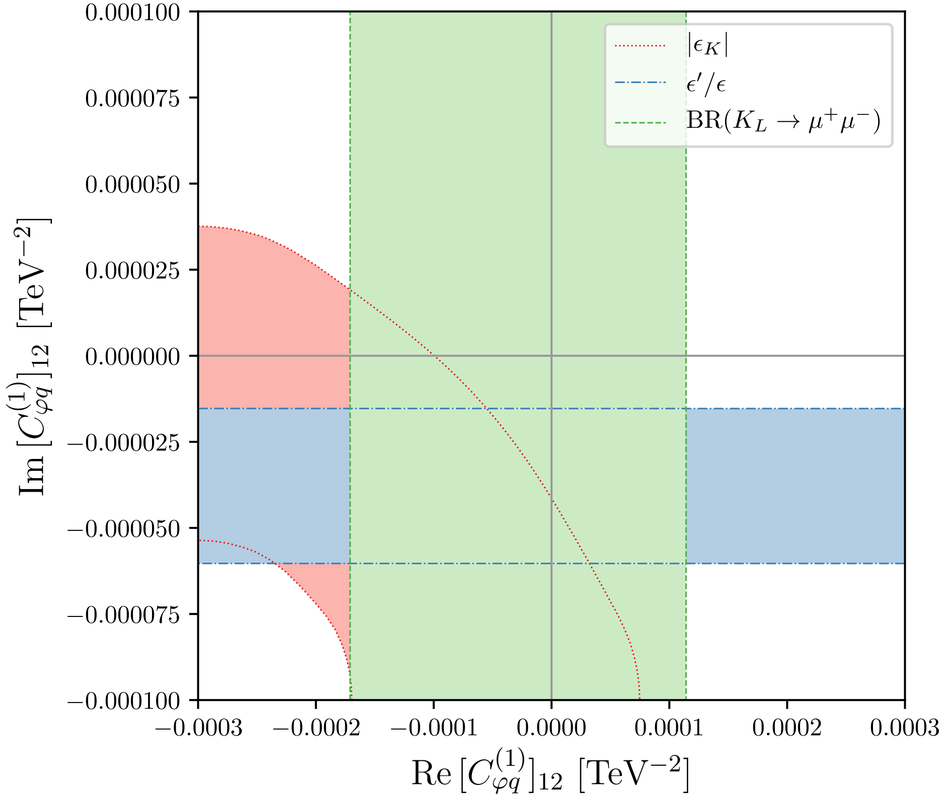
(in view of the following)

$Observable$	$Operator$	$\Lambda/TeV(pres)$
ϵ_K $(*)$	$\mathcal{Q}_1^{sd} = (\bar{s}_L\gamma_\mu d_L)^2$	$2 \cdot 10^4$
ΔM_{B_d}	$\mathcal{Q}_1^{bd} = (\bar{b}_L\gamma_\mu d_L)^2$	10^3
ΔM_{B_s}	$\mathcal{Q}_1^{bs} = (\bar{b}_L\gamma_\mu s_L)^2$	$2 \cdot 10^2$
$\Delta M_D, p/q$ $(*)$	$\mathcal{Q}_1^{cu} = (\bar{c}_L\gamma_\mu u_L)^2$	10^4
$b \to s\ \bar{l}l$	$(\bar{s}_L\gamma_\mu b_L)H^+ i\mathcal{D}_\mu H$	22
$s \to d\ \bar{l}l(\bar{q}q)$	$(\bar{d}_L\gamma_\mu s_L)H^+ i\mathcal{D}_\mu H$	130
$neutronEDM$ $(*)$	$m_t(\bar{t}_L\sigma_{\mu\nu}T^a t_R)g_S G_a^{\mu\nu}$	5.5
$electronEDM$ $(*)$	$\approx (g^2/16\pi^2)m_e(\bar{e}_L\sigma_{\mu\nu}e_R)eF^{\mu\nu}$	≈ 50

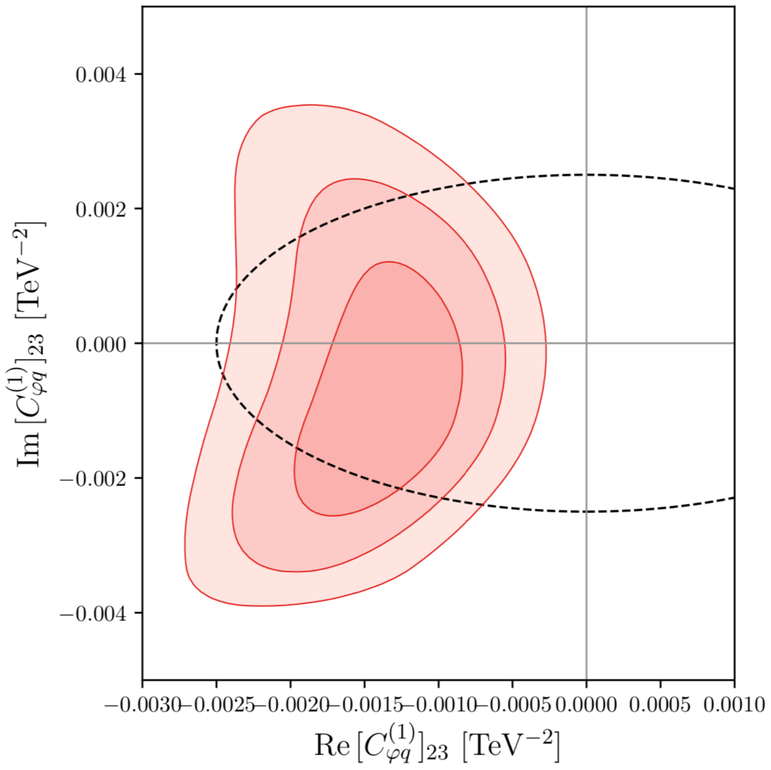
(*) = assuming maximal phases

Without proper suppression,
exclude even a weakly coupled NP at the MultiTeV

$$(\bar{d}_L \gamma_\mu s_L) H^+ i\mathcal{D}_\mu H$$



$$(\bar{s}_L \gamma_\mu b_L) H^+ i\mathcal{D}_\mu H$$



Straub, 2018

If $K^+ \to \pi^+ \nu\nu$ at 10%, crucial

mainly

$B_s \to \mu^+\mu^-$ $B \to K^* \mu^+\mu^-$

Letter of intent to measure the rare decay K+ ---> pi+ nu anti-nu at the CERN SPS

D. Munday (Cambridge U.), N. Cabibbo (CERN), A. Ceccucci (CERN), V. Falaleev (CERN), F. Formenti (CERN) et al.

(Oct, 2004)

Possible reactions

1. Assume NP WITHOUT any flavour violation

WHY, given that flavour IS violated in the SM?

In any case, watch $pp \to jj$ from 4q op.s $\Lambda \gtrsim 10\ TeV$

2. "Strong" MFV

$$U(3)_q \times U(3)_u \times U(3)_d$$ minimally broken by

$$Y_u = (3, \bar{3}, 1) \quad Y_d = (3, 1, \bar{3})$$

AD HOC: $Y_u^{33} = y_t$ is not a small breaking parameter

Flavour symmetric interactions still need to be blocked

3. "Weak" MFV

$$U(2)_q \times U(2)_u \times U(2)_d$$ minimally broken by

$$\Delta_u = (2, \bar{2}, 1) \quad \Delta_d = (2, 1, \bar{2}) \quad V = (2, 1, 1)$$

Explains qualitatively the pattern of masses and mixings in terms of $\Delta_u,\ \Delta_d,\ V \lesssim 4 \cdot 10^{-2}$

Main constraints from weak MFV $(U(2)^3)$

(Similar, with some specific correlations in strong MFV $(U(3)^3)$)

$Observable$	$Operator$	$U(2)(pres)$	$U(2)(fut)$
ϵ_K	$\mathcal{Q}_1^{sd} = (\bar{s}_L \gamma_\mu d_L)^2$	7	13
ΔM_{B_d}	$\mathcal{Q}_1^{bd} = (\bar{b}_L \gamma_\mu d_L)^2$	8	18
ΔM_{B_s}	$\mathcal{Q}_1^{bs} = (\bar{b}_L \gamma_\mu s_L)^2$	9	20
$\Delta M_D, p/q$	$\mathcal{Q}_1^{cu} = (\bar{c}_L \gamma_\mu u_L)^2$	1.5	5
$b \to s\ \bar{l}l$	$(\bar{s}_L \gamma_\mu b_L) H^+ i\mathcal{D}_\mu H$	4.5	12
$s \to d\ \bar{l}l(\bar{q}q)$	$(\bar{d}_L \gamma_\mu s_L) H^+ i\mathcal{D}_\mu H$	1.7	5
$neutronEDM\ (*)$	$m_t(\bar{t}_L \sigma_{\mu\nu} T^a t_R) g_S G_a^{\mu\nu}$	5.5	16
$electronEDM\ (*)$	$\approx (g^2/16\pi^2) m_e (\bar{e}_L \sigma_{\mu\nu} e_R) e F^{\mu\nu}$	≈ 50	?

(*) = assuming maximal phases

Λ/TeV

An estimate

Competitive with direct searches in strongly coupled theories

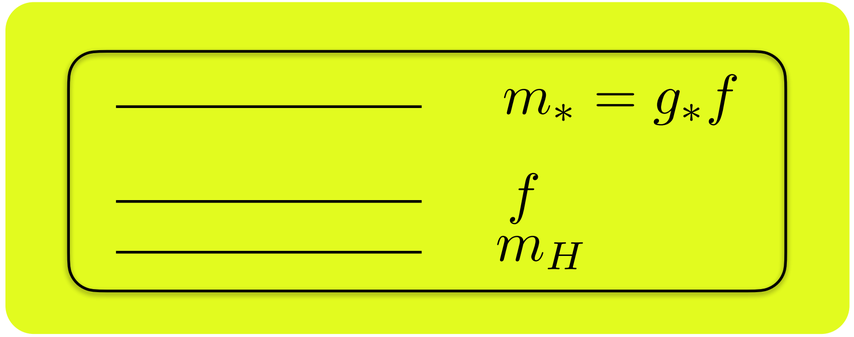
Flavour in composite Higgs

What is the radius of Higgs compositeness, if any? $l_H = 1/m_*$

H = pNGB

f = scale of symmetry breaking

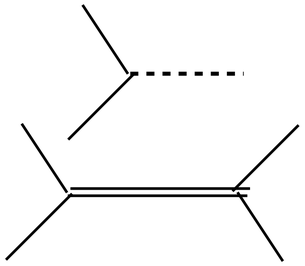
m_* = scale of Higgs compositeness



$+ \; q_i, l_i, V^a_\mu$

1. The top

$\mathcal{O}_H : \quad < 0|\mathcal{O}_H|H > \neq 0$



$$\mathcal{L}_Y^{top}(m^*) = g^* x_L x_R \bar{q}_{L3} H t_R, \qquad x_{L,R} \leq 1 \qquad y_t = g^* x_L x_R$$

$$\mathcal{L}^{4top} = \frac{y_t^2}{m_*^2}[x_t^2(\bar{q}_{L3}\gamma_\mu q_{L3})^2 + (\bar{q}_{L3}t_R)(\bar{t}_R q_{L3}) + \frac{1}{x_t^2}(\bar{t}_R\gamma_\mu t_R)^2] \qquad \frac{y_t}{g^*} < x_t = \frac{x_L}{x_R} < \frac{g^*}{y_t}$$

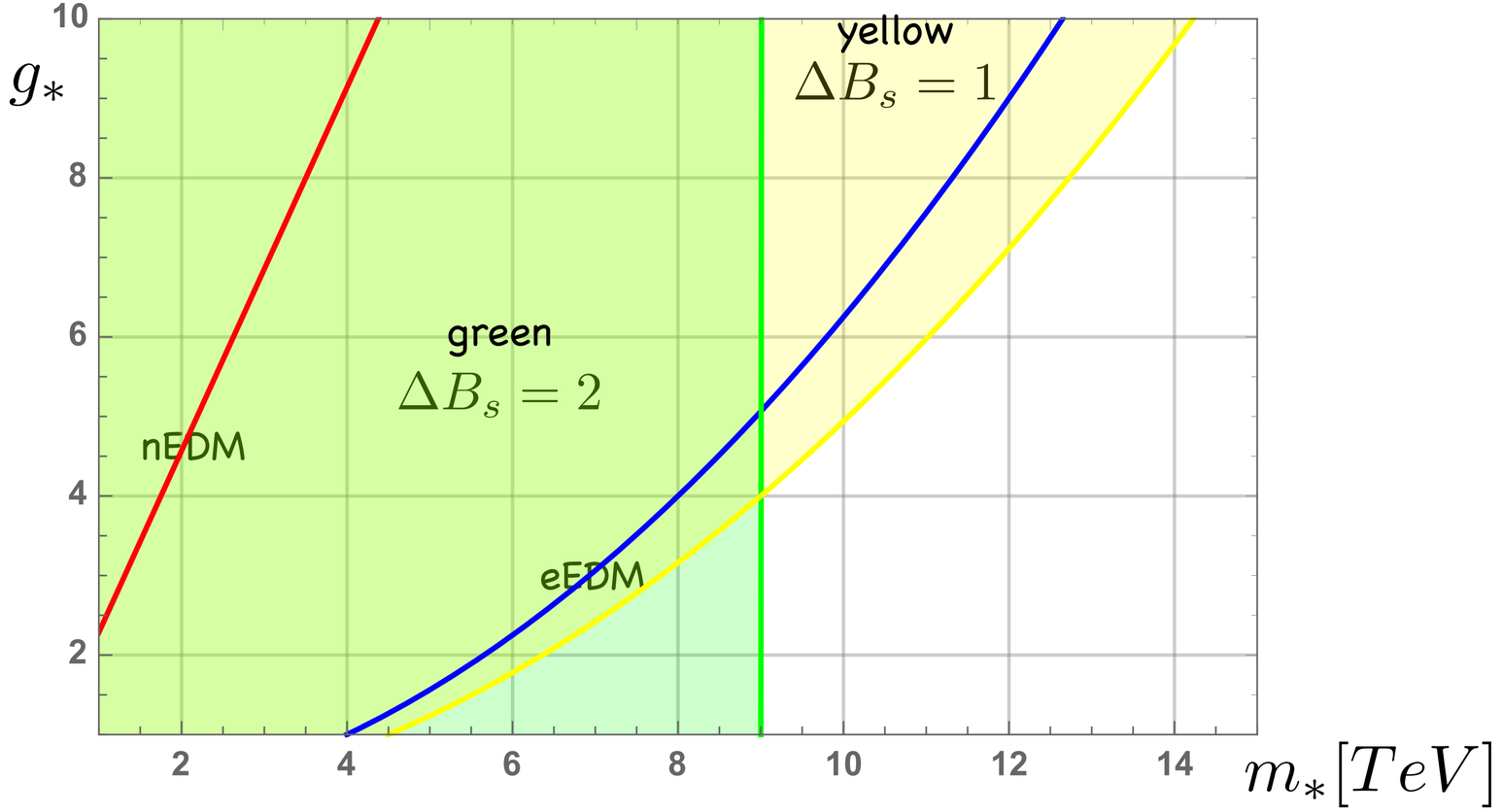
2. The other fermions

$$\mathcal{L}_Y^{top} \to \mathcal{L}_Y^{full}; \qquad \mathcal{L}^{4top} \to \mathcal{L}^{full}_{(d>4)}$$

Use weak/strong MFV as minimal choice to "align" $\mathcal{L}_Y^{full}$ and $\mathcal{L}^{full}_{(d>4)}$

Current (main) flavour bounds with weak MFV

Exclusion plot $x_t = 1$

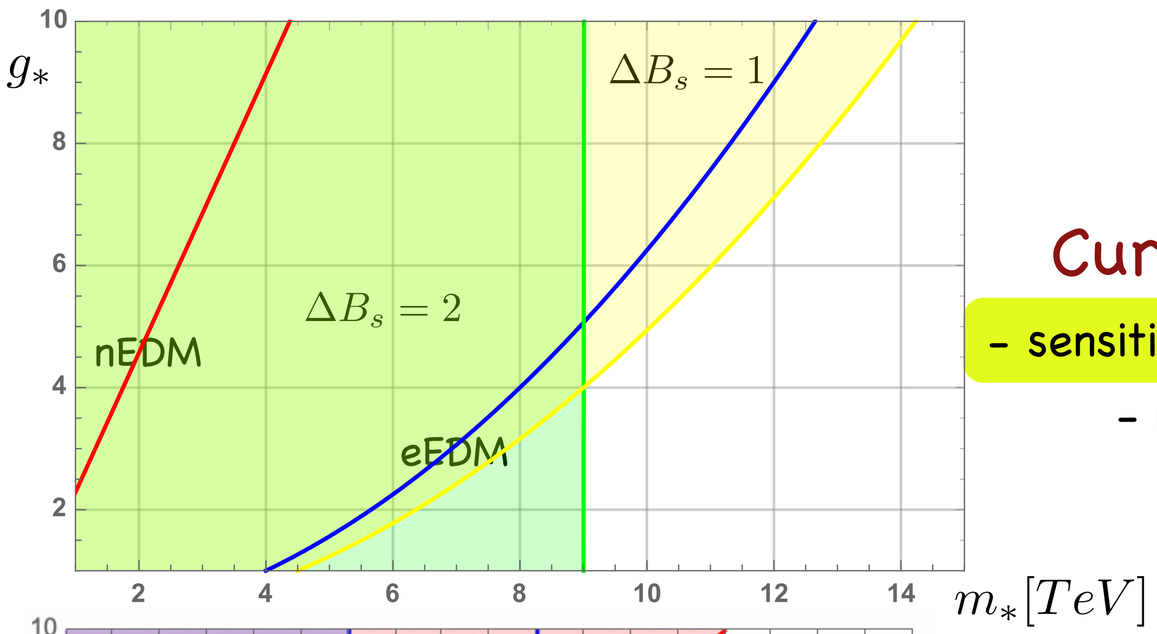


$\sqrt{\mathcal{O}(1)}$ -factors possible in either direction

- maximal phases assumed for the EDMs

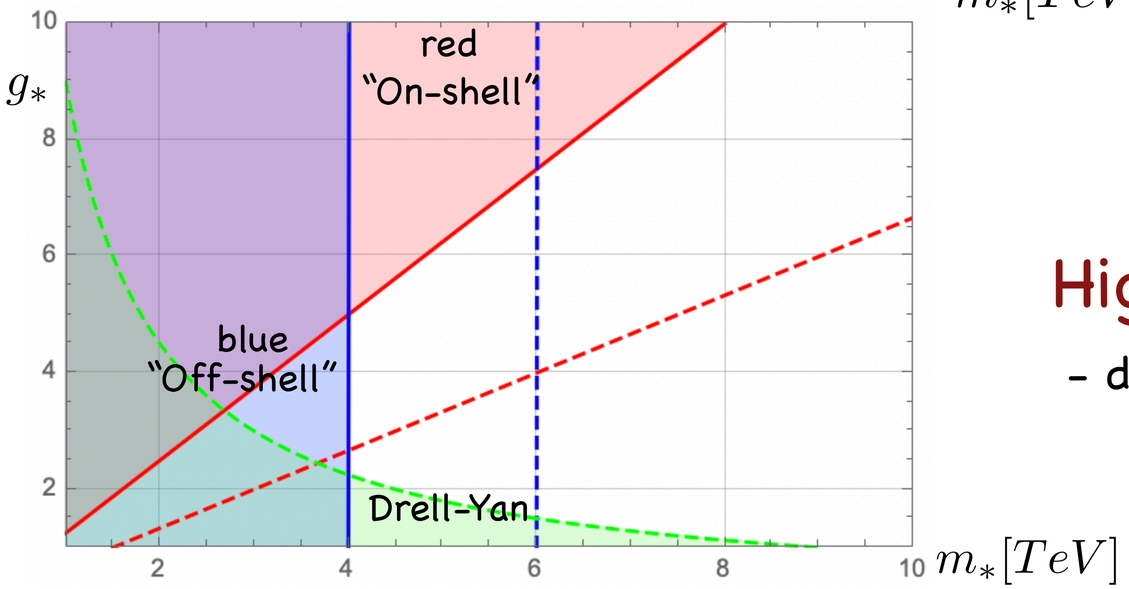
- sensitivity on $\Delta B_s = 1, 2$ improvable by a factor of 2

Exclusion plots compared



Current flavour with weak MFV

- sensitivity on $\Delta B_s = 1, 2$ improvable by a factor of 2
- maximal phases assumed for the EDMs



Higgs couplings, EWPT summary

- dotted lines = foreseen sensitivity at HL-LHC

$\sqrt{\mathcal{O}(1)}$-factors possible in either direction

Remembering Nicola Cabibbo, the father of flavour in the SM

1. To turn the SM into a ST still premature,
   in spite of its empirical success
   (in my view mostly because of its unpredicted 17-2=15 masses)
   The strongest motivation for the next HE collider

2. Precision in flavour offers an "indirect" discovery
   potential for NP at MultiTeV, if any, before
   the next HE collider

3. The scale of Higgs compositeness explorable
   beyond the reach of direct searches at LHC
   with a key "unavoidable" role of flavour

Back up

Precision in composite Higgs

What is the radius of Higgs compositeness, if any? $l_H = 1/m_*$

$m_* = g_* f$

f

m_H

H = pNGB

f = scale of symmetry breaking

m_* = scale of Higgs compositeness

- Higgs couplings $c_\phi \sim g_*^2/m_*^2$

- flavour-less ElectroWeak observables

Pole observables: $m_W, sin\theta^l_{eff}$ $c_W \sim 1/m_*^2$

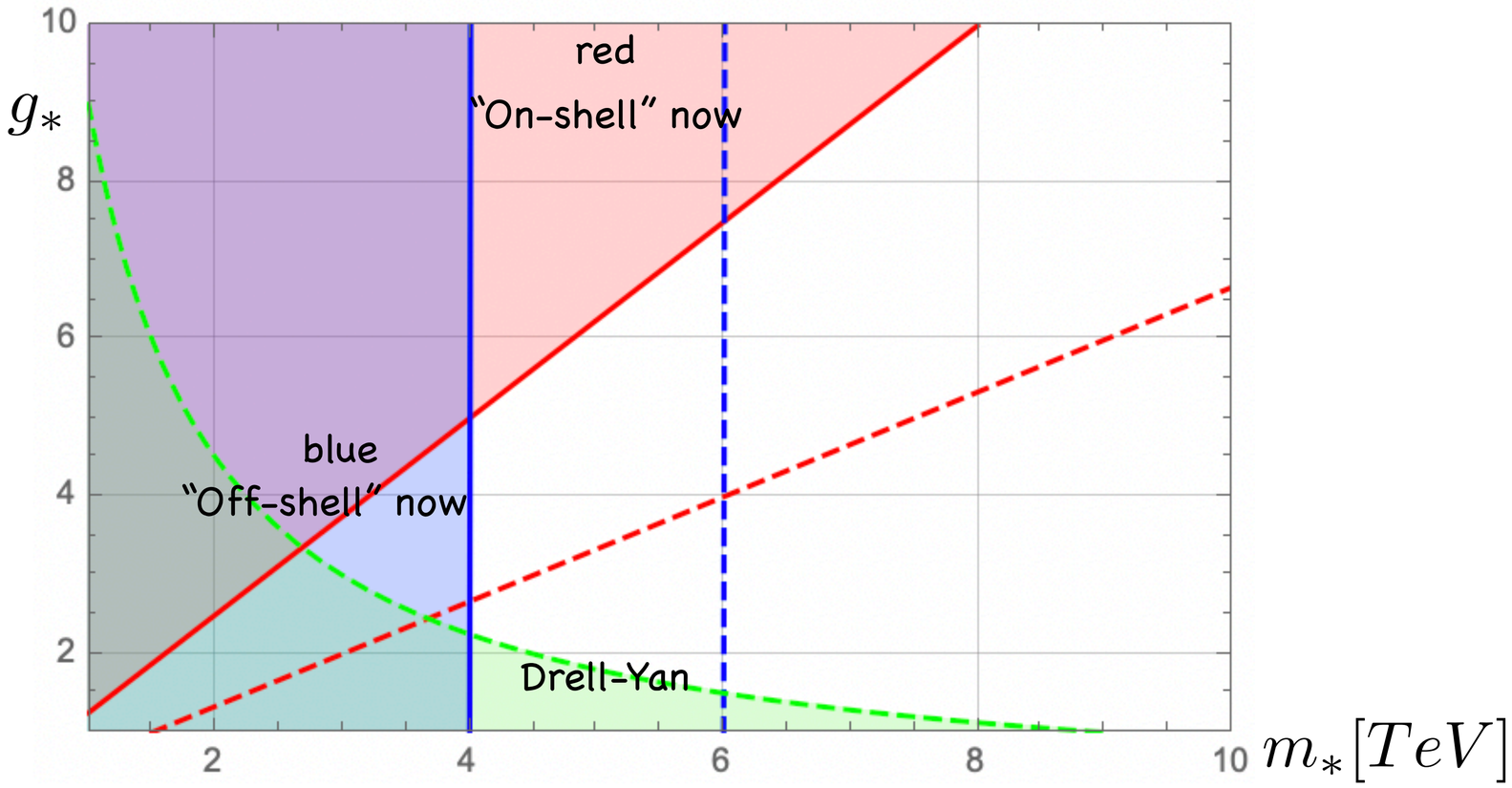
DiBoson production: Wh, Zh, WZ, WW $c_W \sim 1/m_*^2$

Drell-Yan $l^+l^-, l\nu$ at high m_{ll}, m_{ll}^T $c_{2W} \sim 1/g_*^2 m_*^2$

- flavour observables $g_*^2/m_*^2, g_*/m_*^2, 1/m_*^2$

Higgs couplings, EWPT summary

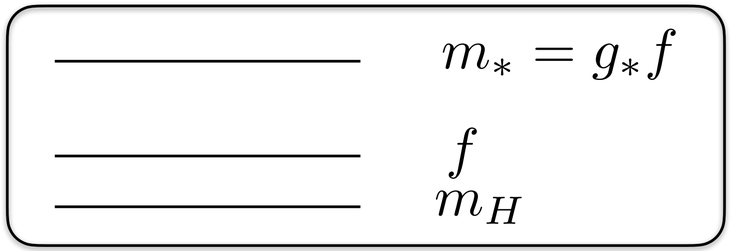
Exclusion plot



$\sqrt{\mathcal{O}(1)}$ -factors possible in either direction

- dotted lines = foreseen sensitivity at HL-LHC

Flavour in composite Higgs



H = pNGB

m_* = scale of Higgs compositeness

- standard fermions f_i^a elementary, but connected in some (unspecified) way to a composite operator $\mathcal{O}_H$: $< 0|\mathcal{O}_H|H > \neq 0$

- below a scale Λ_F , $t_{L,R}$ enter $\mathcal{L}_Y$ multiplied by dimensionless $\lambda_{L,R}$

- from NDA: $([\mathcal{O}_H] \equiv d_H \geq 2)$

$$\mathcal{L}^{top} = \frac{\Lambda_F^4}{g_{\Lambda_F}^2}[\mathcal{L}^0(\frac{\lambda_L^t q_{L3}}{\Lambda_F^{3/2}}, \frac{\lambda_R^t t_R}{\Lambda_F^{3/2}}, \frac{D_\mu}{\Lambda_F}, \frac{\mathcal{O}_H}{\Lambda_F^{d_H}}) + \frac{g_{\Lambda_F}^2}{16\pi^2}\mathcal{L}^1 + \ldots]$$

$$\Rightarrow \quad \mathcal{L}_Y^{top}(\Lambda_F) = \frac{x_L x_R}{\Lambda_F^{d_H-1}}\bar{q}_{L3}\mathcal{O}_H t_R, \qquad x_{L,R} = \frac{\lambda_{L,R}^t}{g_{\Lambda_F}}$$

or, after $\mathcal{O}_H \to g_* m_*^{d_H-1} H$, $\quad y_t = g_* x_L x_R (\frac{m_*}{\Lambda_F})^{d_H-1}$

Flavour observables in composite Higgs

How m_* scales with g_* in a meaningful composite Higgs picture

$Observable$	$Operator$	$U(2)(pres)$	$U(2)(fut)$	m_*/Λ
ϵ_K	$\mathcal{Q}_1^{sd} = (\bar{s}_L\gamma_\mu d_L)^2$	7	13	x_t
ΔM_{B_d}	$\mathcal{Q}_1^{bd} = (\bar{b}_L\gamma_\mu d_L)^2$	8	18	x_t
ΔM_{B_s}	$\mathcal{Q}_1^{bs} = (\bar{b}_L\gamma_\mu s_L)^2$	9	20	x_t
$\Delta M_D, p/q$	$\mathcal{Q}_1^{cu} = (\bar{c}_L\gamma_\mu u_L)^2$	1.5	5	x_t
$b \to s\ \bar{l}l$	$(\bar{s}_L\gamma_\mu b_L)H^+ i\mathcal{D}_\mu H$	4.5	12	$\sqrt{g^* x_t}$
$s \to d\ \bar{l}l(\bar{q}q)$	$(\bar{d}_L\gamma_\mu s_L)H^+ i\mathcal{D}_\mu H$	1.7	5	$\sqrt{g^* x_t}$
$neutronEDM\ (*)$	$m_t(\bar{t}_L\sigma_{\mu\nu}T^a t_R)g_S G_a^{\mu\nu}$	5.5	16	$g^*/4\pi$
$electronEDM\ (*)$	$\approx (g^2/16\pi^2)m_e(\bar{e}_L\sigma_{\mu\nu}e_R)eF^{\mu\nu}$	≈ 50	?	$\sqrt{g^* x_t}/(4\pi)$

(*) = assuming maximal phases

Λ/TeV as above

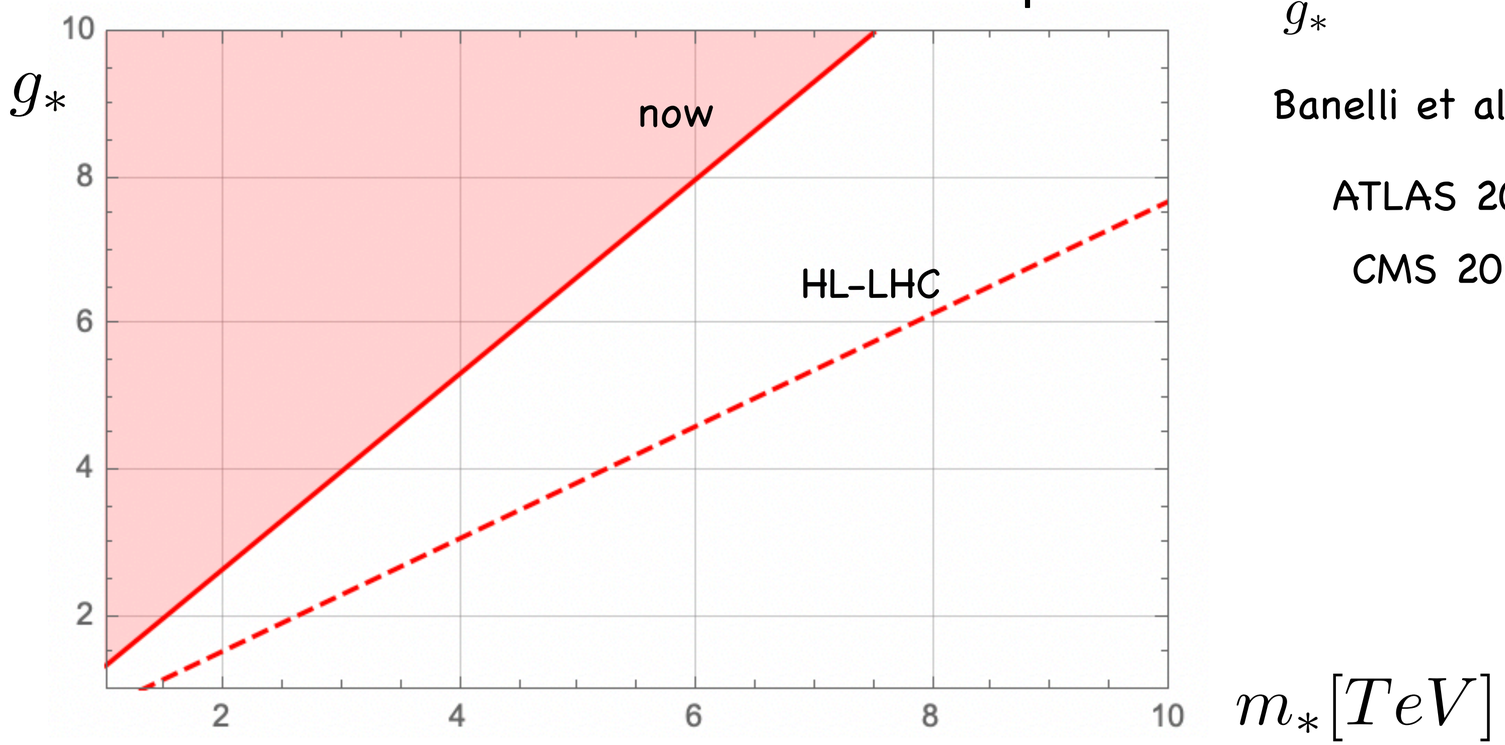
$$\frac{y_t}{g_*} < x_t < \frac{g_*}{y_t}$$

Four tops $pp \to t\bar{t}t\bar{t}$ in weak MFV

$$\mathcal{L}^{4top} = \frac{y_t^2}{m_*^2}[x_t^2(\bar{q}_{L3}\gamma_\mu q_{L3})^2 + (\bar{q}_{L3}t_R)(\bar{t}_R q_{L3}) + \frac{1}{x_t^2}(\bar{t}_R\gamma_\mu t_R)^2]$$

$$\frac{y_t}{g_*} < x_t = \frac{x_L}{x_R} < \frac{g_*}{y_t}$$

Exclusion plot $x_t = \frac{y_t}{g_*}$ or $x_t = \frac{g_*}{y_t}$



Banelli et al 2020

ATLAS 2019

CMS 2019

(With some excesses in multilepton + jets in current data)

Comparable, but conceptually very different from Higgs, EWPT "on-shell"

Mass-angle relations in $U(2) \equiv SU(2)_f \times U(1)_f$

B, Dvali, Hall 1995

1. Under U(2): $Q_{1,2} \equiv Q; \quad u_{1,2} \equiv u; \quad d_{1,2} \equiv d \quad = \quad \mathbf{2}_1$

$Q_3; \quad u_3; \quad d_3 \quad = \quad \mathbf{1}_0$

2. U(2) broken by $$U(2) \xrightarrow{\Sigma^a = \bar{\mathbf{2}}_{-1}} U(1)_f \xrightarrow{\eta^{[ab]} = \mathbf{1}_{-2}} 0$$

$$\mathcal{L}_Y = [\lambda_{33} Q_3 u_3 + \lambda_{23}(Q\Sigma)u_3 + \lambda_{32} Q_3(\Sigma u) + \lambda_{22}(Q\Sigma)(\Sigma u) + \lambda_{12}(Q\eta u)]H$$

(in full generality) $< \Sigma >= \begin{pmatrix} 0 \\ \epsilon \end{pmatrix} \qquad < \eta >= \epsilon' \epsilon^{ab}$

$$\Rightarrow \quad Y^{U,D} = \begin{pmatrix} 0 & \lambda_{12}\epsilon' & 0 \\ -\lambda_{12}\epsilon' & \lambda_{22}\epsilon^2 & \lambda_{23}\epsilon \\ 0 & \lambda_{32}\epsilon & \lambda_{33} \end{pmatrix}$$

(with different λ's for Y^U and Y^D)

Still pending question: Why $Y^U \neq Y^D \quad (m_t >> m_b)$?

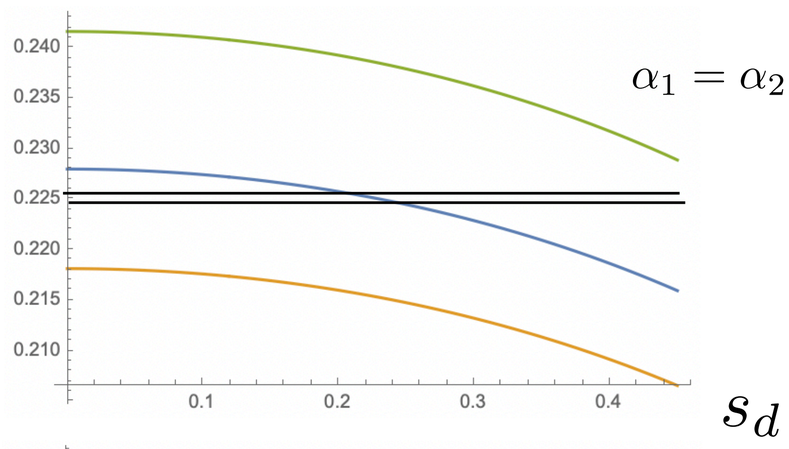
Mass-angle relations as functions of $sin\theta_d$

$$\frac{Y_{23}^D}{Y_{33}^D} \equiv \tan\theta_d$$

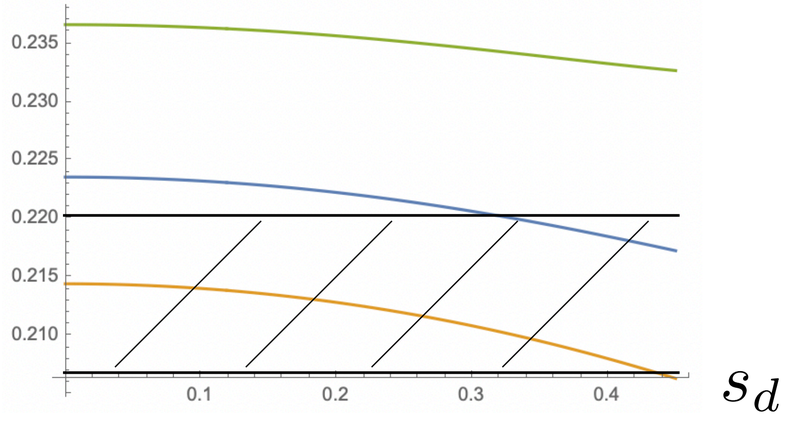
Roberts et al 2001

$$V_{us} = \left| \sqrt{\frac{m_d}{m_s}}\sqrt{c_d} - e^{i\alpha_1}\sqrt{\frac{m_u}{m_c}} \right|$$

$$\alpha_1 = \alpha_2 = \pi/2$$



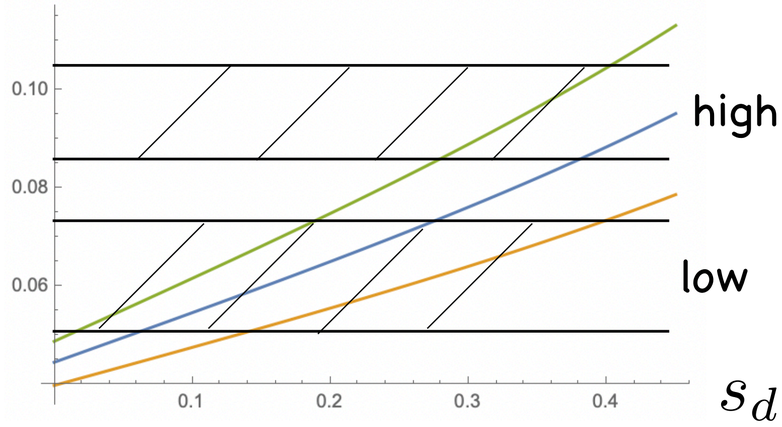
$$\left| \frac{V_{td}}{V_{cb}} \right| = \left| \sqrt{\frac{m_d}{m_s}}\sqrt{c_d} - e^{i\alpha_2} R \right|$$



$$\left| \frac{V_{ub}}{V_{cb}} \right| = \left| \sqrt{\frac{m_u}{m_c}} - e^{-i(\alpha_1+\alpha_2)} R \right|$$

$$R = \frac{s_d}{\sqrt{c_d}}\sqrt{\frac{m_d}{m_s}}\frac{m_s}{m_b|V_{cb}|}$$

$$c_d = \cos\theta_d, \;\; s_d = \sin\theta_d$$

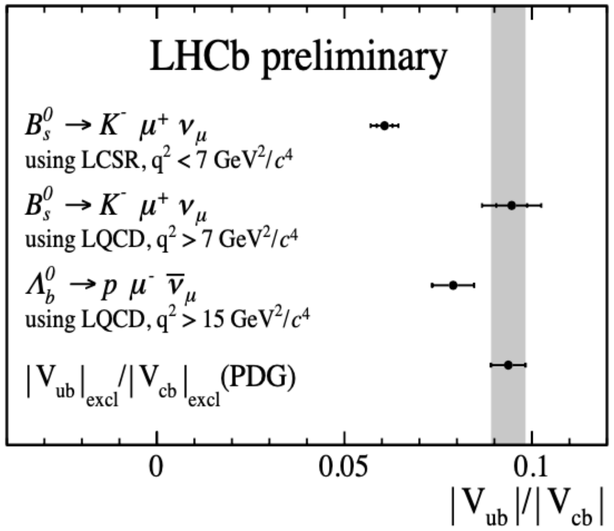


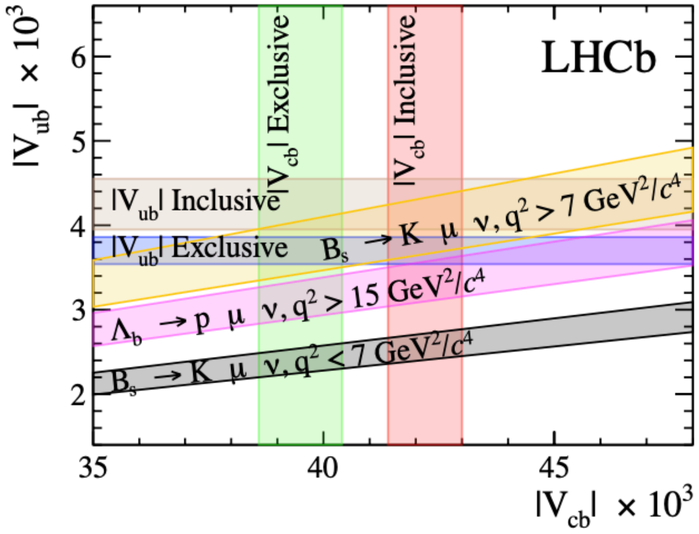
LHCb 2020

Results: $|V_{\rm ub}|/|V_{\rm cb}|$

$$|V_{\rm ub}|/|V_{\rm cb}|({\rm low}) = 0.0607 \pm 0.0015({\rm stat}) \pm 0.0013({\rm syst}) \pm 0.0008({\rm D_s}) \pm 0.0030(FF)$$

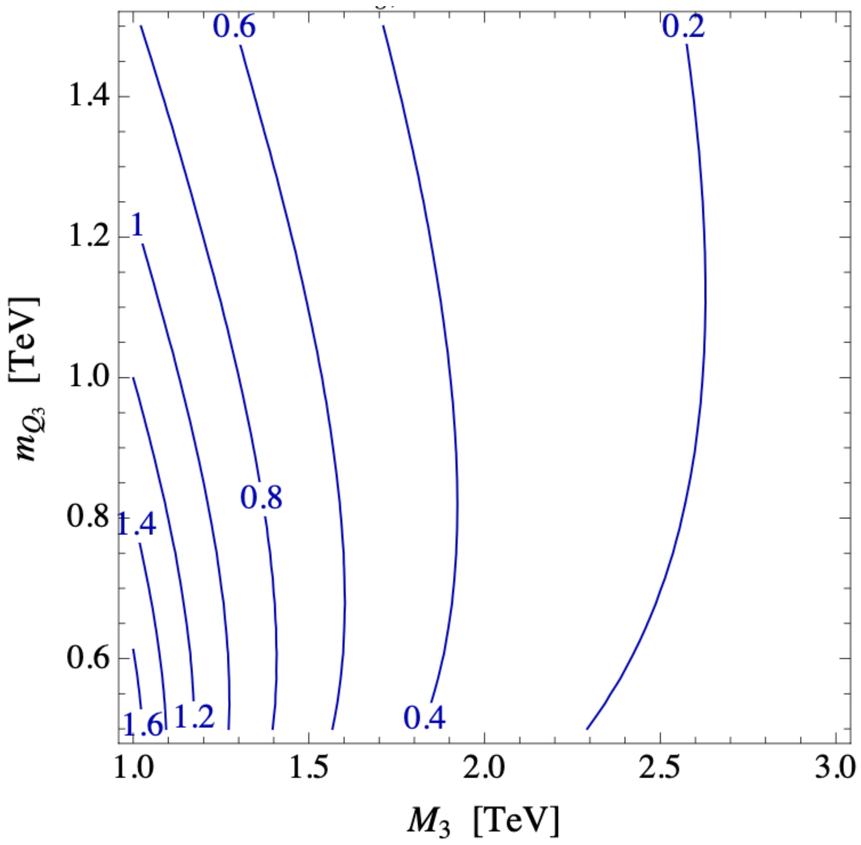
$$|V_{\rm ub}|/|V_{\rm cb}|({\rm high}) = 0.0946 \pm 0.0030({\rm stat})^{+0.0024}_{-0.0025}({\rm syst}) \pm 0.0013({\rm D_s}) \pm 0.0068(FF)$$





$$R \approx \frac{\Delta\epsilon_K^{susy}}{\epsilon_K^{SM}}$$ from LR gluino-sbottom box diagram

at $sin\theta_d \approx V_{cb}$ and maximal phase



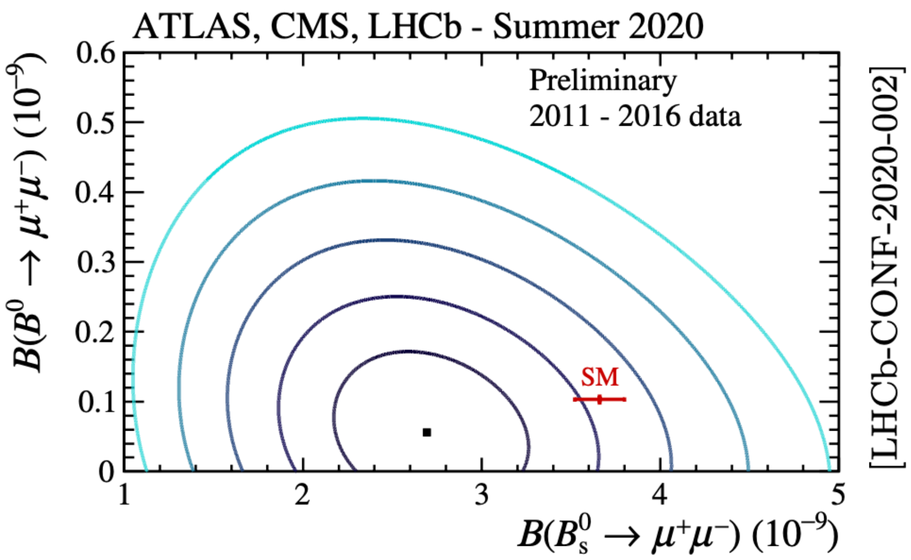
Now $R \lesssim 0.2$

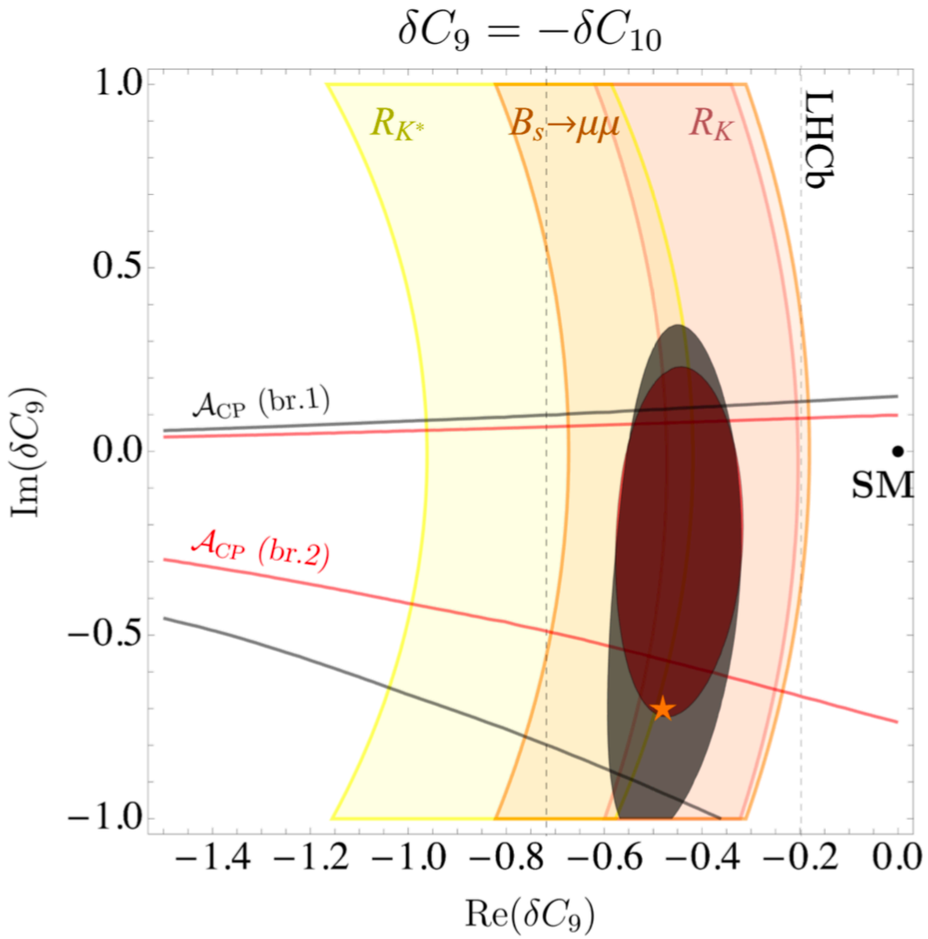
R scales as $(\frac{s_d}{V_{cb}}\frac{1}{M})^2$

$$M \approx M_3 \approx m_{\tilde{b}_L} \approx m_{\tilde{b}_R}$$

R dominates over other flavour observables due to LR enhancement

News on B-decay anomalies





$$\mathcal{A}_{CP}^{K^{(*)}} = \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) - \mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) + \mathcal{B}(B \to K^{(*)}\mu\mu)}$$

Becirevic et al, 2020

Still in the limbo, but

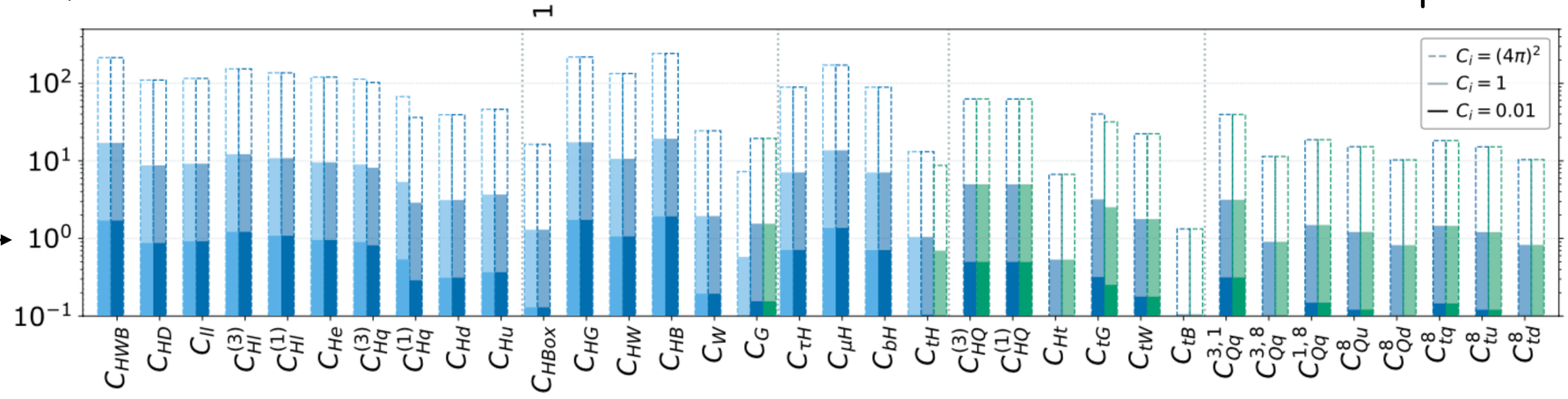
Observable	Current LHCb	LHCb 2025	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [4]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [5]	0.031	0.008
$b \to c\ell^-\bar{\nu}_l$ LUV studies			
$R(D^*)$	0.026 [15, 16]	0.0072	0.002
$R(J/\psi)$	0.24 [17]	0.071	0.02

the expected future precision will settle the issue

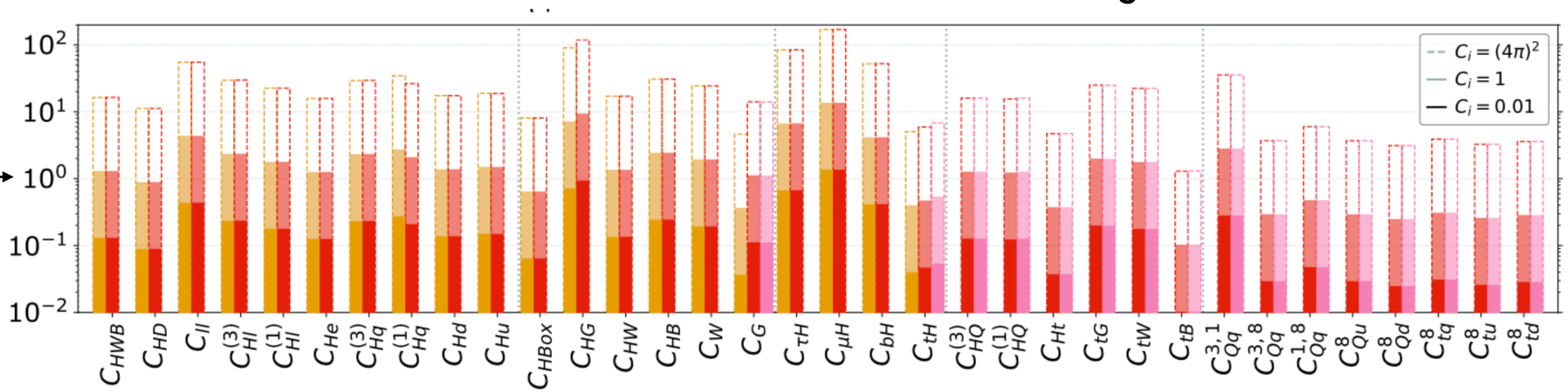
If they are roses...

Λ/TeV

Individual operators



Marginalised over the others



No flavour violation

Ellis et al, 2020