Indirect probes of the Higgs mechanism (mainly from Flavour Physics).

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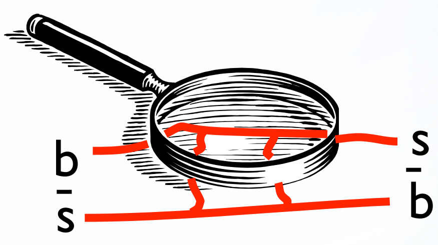
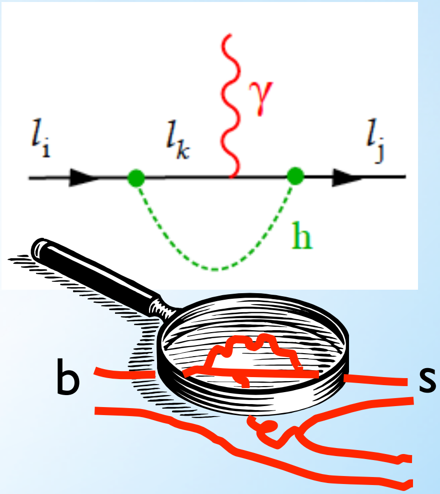




Loops approach

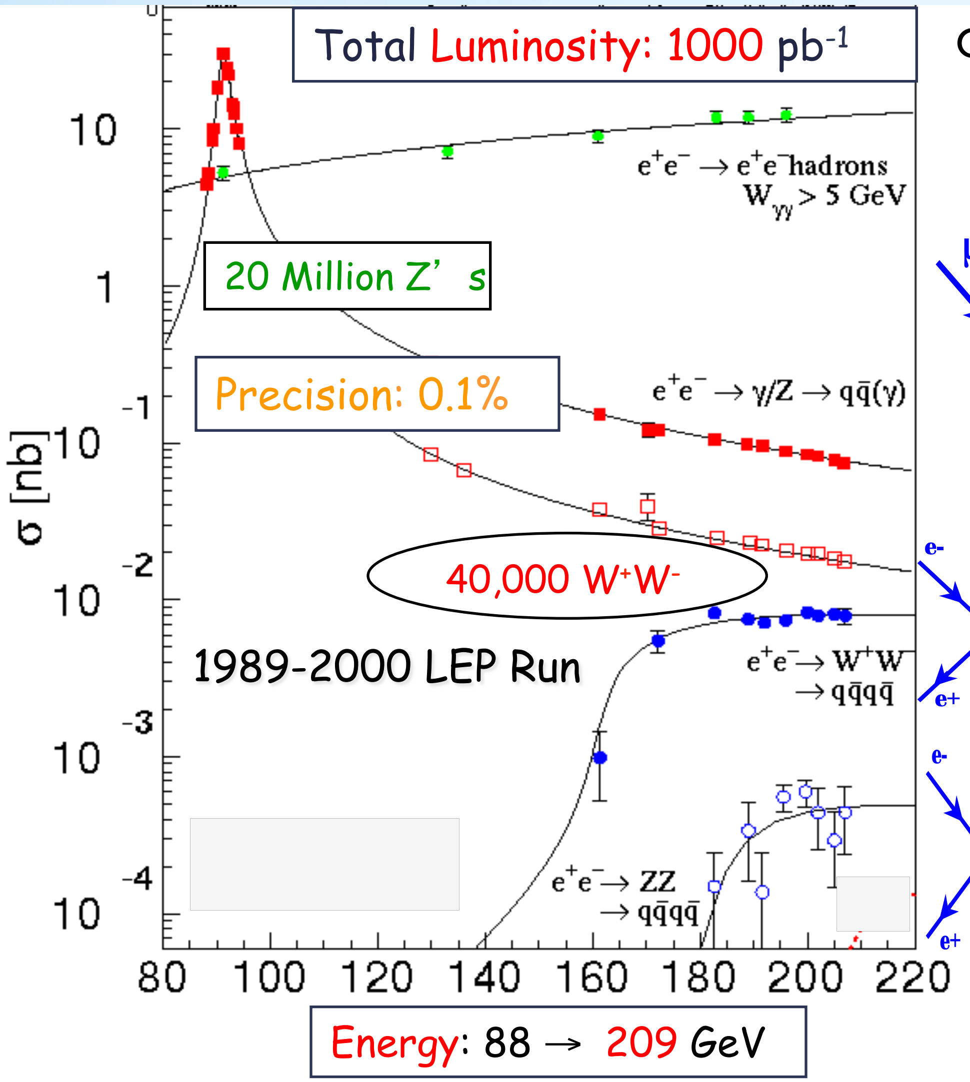
If the **precision** of the measurements is high enough, we can discover NP due to the effect of "virtual" new particles in loops.

But not all loops are equal… In **"non-broken" gauge theories** like QED or QCD the "decoupling theorem" (Phys. Rev. D11 (1975) 2856) makes sure that the contributions of **heavy ($M>q^2$) new particles are not relevant**. For instance, you don't need to know about the top quark or the Higgs mass to compute the value of $\alpha(M_Z^2)$.

However, in broken gauge theories, like the weak and yukawa interactions, radiative corrections are usually proportional to Δm^2.

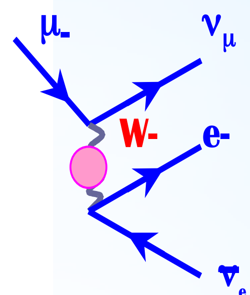
In general, larger effects of NP expected in loops involving 3rd family in the SM.

Loops approach at the Z.



Quantum loop generate corrections in three sectors:

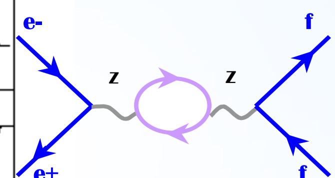
Let's define → $\sin^2\theta_W \equiv 1 - m^2_W/m^2_Z$



$$m_W^2 \sin^2(\theta_W) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

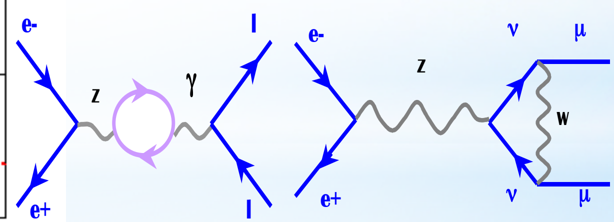
$\Delta r \approx \Delta\alpha + \Delta r_W (m_{Top}, m_{Higgs})$

$\approx 0.06 - 0.014$



$$Zff\,(axial) = I_3\sqrt{\rho} \equiv I_3\sqrt{\frac{\rho_0}{1-\Delta\rho}}$$

$\Delta\rho \approx \Delta\rho\,(m_{Top}, m_{Higgs}) \approx 0.005$



$\sin^2\theta_{eff}$

$$Zff\,(vector) = I_3\sqrt{\rho}(1 - 4|Q|\kappa\sin^2\theta_w)$$

$\kappa \approx 1 + \Delta\kappa_{QED} + \Delta\kappa_w\,(m_{Top}, m_{Higgs})$

$\approx 1 + 0.038 + 0.002$

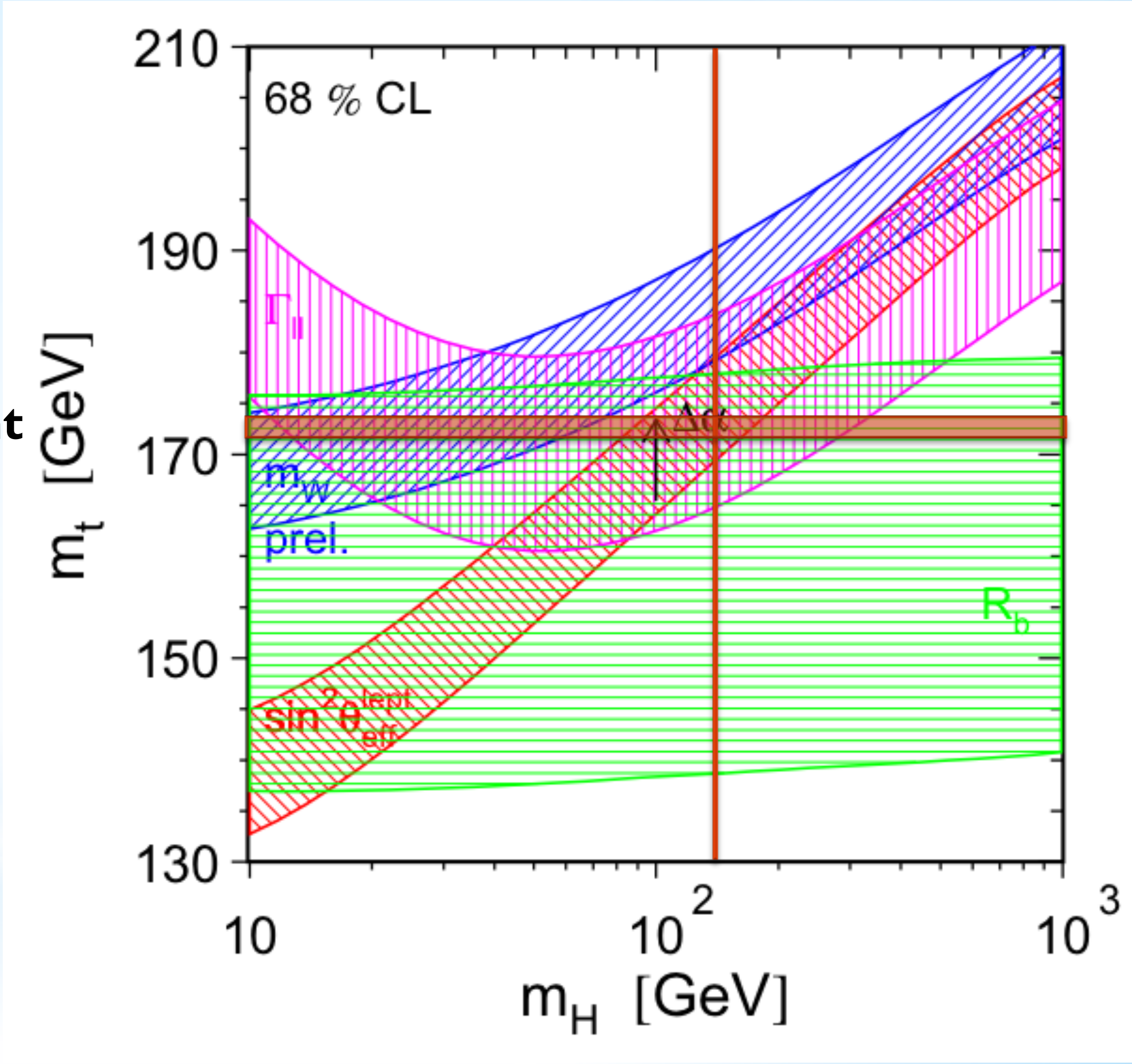
Loops approach at the Z.

Indirect determination of the top quark and Higgs mass obtained from precision measurements at the Z, are in good agreement with recent direct determinations.

SM has pass a very stringent test as a renormalizable QFT!

Moreover, the precision achieved put **strong constraints on Higgs gauge couplings**.

However, the Higgs mechanism is more than a scalar boson (~125 GeV) that gives masses to the weak bosons.



Flavour in the SM: Yukawa Mechanism in the quark sector.

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i\phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}_L^i\phi E_R^j + \text{h.c.}$$

$$\lambda_d = \text{diag}(y_d, y_s, y_b)\ , \quad \lambda_u = \text{diag}(y_u, y_c, y_t)\ , \qquad y_q = \frac{m_q}{v}\ .$$

$$Y_d = \lambda_d\ , \qquad Y_u = V^\dagger \lambda_u\ ,$$

The quark flavour structure within the SM is described by 6 couplings and 4 CKM parameters. In practice, is convenient to move the CKM matrix from the Yukawa sector to the weak current sector:

$U_i = \{u, c, t\}$:

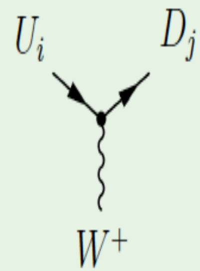
$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

$$\mathcal{L}_{CC} = \frac{g_2}{\sqrt{2}}(\bar{u}, \bar{c}, \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_\mu^+$$

~ Cabibbo-Kobayashi-Maskawa (CKM) matrix



In the SM quarks are allowed to change flavour as a consequence of the Higgs mechanism to generate quark masses. Using Wolfenstein parameterization (A, λ, ρ, η):

$A = 0.80 \pm 0.02$
$\lambda = 0.225 \pm 0.001$

CKM

$$V = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+A\lambda^4/2(1-2(\rho+i\eta)) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^5)$$

Flavour in the SM: Yukawa Mechanism in the lepton sector.

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i\phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}_L^i\phi E_R^j + {\rm h.c.}$$

In the SM the lepton Yukawa matrices can be diagonalized independently due to the global G_l symmetry of the Lagrangian, and therefore there are not FCNC.

$$\mathcal{G}_\ell = SU(3)_{L_L} \otimes SU(3)_{E_R}$$

However, the discovery that ν oscillate (and ν are massive) implies that Lepton Flavour is not conserved. The level of Charged Lepton Flavour Violation depends on the mechanism to generate neutrino masses (for instance, **Seesaw mechanism**).

PMNS

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$\theta_{12}[^\circ] = 33.36^{+0.81}_{-0.78}$$
$$\theta_{23}[^\circ] = 40.0^{+2.1}_{-1.5} \text{ or } 50.4^{+1.3}_{-1.3}$$
$$\theta_{13}[^\circ] = 8.66^{+0.44}_{-0.46}$$
$$\delta_{\rm CP}[^\circ] = 300^{+66}_{-138}$$

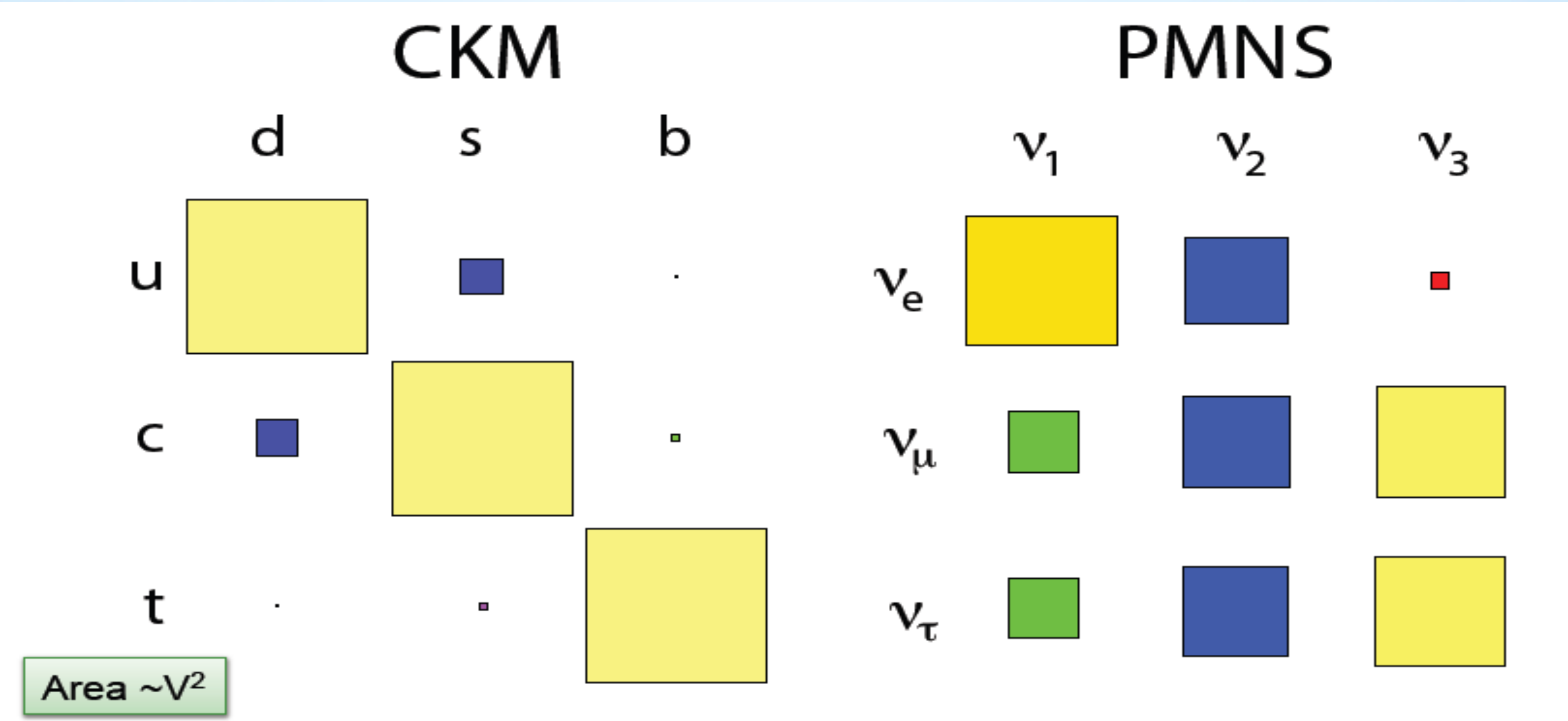
In general, while quark flavour changing Yukawa couplings to the Higgs are strongly suppressed by $\Delta f=2$ indirect measurements, processes like $H\to\tau\mu$ or $H\to\tau e$ are only loosely bounded (O(10%)).

Flavour Structure is not simple.

$V_{us} \sim \sqrt{(m_d / m_s)}$

$V_{cb} \sim (m_s / m_b)$

Can the "seesaw" mechanism explain the different structure between quarks and leptons?



Why these values? Are the two related? Are they related to masses?

Flavour Beyond the SM

Consider a two Higgs doublet model with different vacuum expected values, $\mathbf{v_1}$ and $\mathbf{v_2}$.

$$\overline{d}_{R,i}(\hat{h}^{ij}_{d,1}\,\phi_1 + \hat{h}^{ij}_{d,2}\,\phi_2)\,d_{L,j}$$

$$\hat{m}^{ij}_{d} = \hat{h}^{ij}_{d,1}\mathrm{v}_1 + \hat{h}^{ij}_{d,2}\mathrm{v}_2$$

In general, the diagonalization of the mass matrix will not give diagonal Yukawa couplings → **large FCNC**.

Ok, let's assume that each Higgs doublet couples only to one type of quarks, i.e. something like **SUSY** (or 2HDM type-II). But then, at some energy scale, this symmetry breaks → expect **again large FCNC**, if the SUSY scale is not far away.

Minimal Flavour Violation: at tree level the quarks and squarks are diagonalized by the same matrices → **no FCNC at tree level**, like in the SM.

At loop level, however, expect both Higgs doublets to couple to up and down sectors → expect **large FCNC at large tan** β .

At least two indirect paths to study Higgs BSM:

1. **Precise measurements of the Higgs boson properties.**
2. **Precise measurements of FCNC.**

Indirect Searches and CP violation

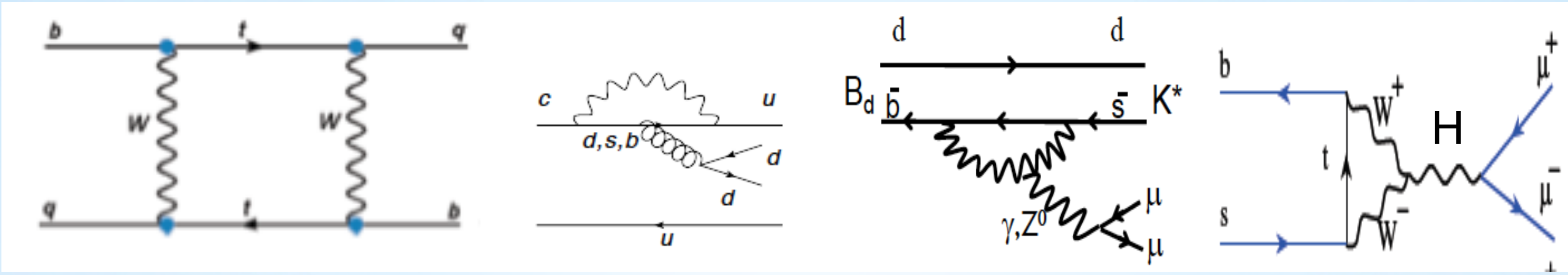
Moreover, through the study of **the interference of different quantum paths** one can access not only to the magnitude of the couplings, but also to their phase (for instance, by measuring CP asymmetries).

Within the SM, **only weak interactions through the Yukawa mechanism** can produce a non-zero CP asymmetry. It is indeed a big mystery why there is no CP violation observed in strong interactions (axions?).

Precision measurements of FCNC can reveal NP that may be **well above the TeV scale**, or can provide key information on the **couplings and phases** of these new particles if they are visible at the TeV scale.

Direct and indirect searches *are both needed and equally important, complementing each other.*

Quarks loops zoology



ΔF=2 box   QCD Penguin   EW Penguin   Higgs Penguin

Map of Flavour transitions and type of loop processes:

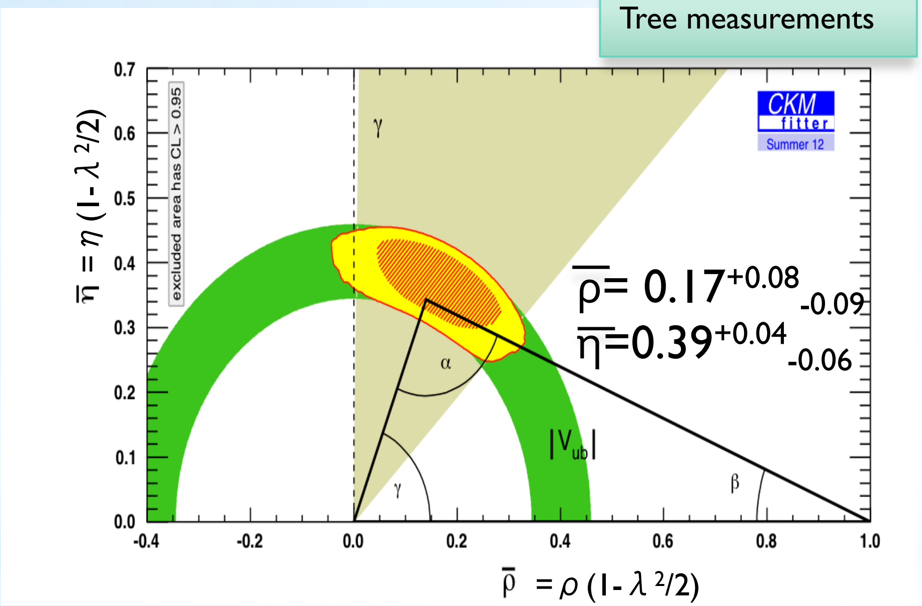
	b→s ($\lvert V_{tb}V_{ts}\rvert \propto \lambda^2$)	**b→d ($\lvert V_{tb}V_{td}\rvert \propto \lambda^3$)**	**s→d ($\lvert V_{ts}V_{td}\rvert \propto \lambda^5$)**	**c→u ($\lvert V_{cb}V_{ub}\rvert \propto \lambda^5$)**
ΔF=2 box	ΔM_{Bs}, $A_{CP}(B_s \to J/\psi\,\Phi)$	ΔM_B, $A_{CP}(B \to J/\psi K)$	ΔM_K, ε_K	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s\gamma$	$A_{CP}(B \to hhh)$, $B \to X\gamma$	$K \to \pi^0 ll$, ε'/ε	$\Delta a_{CP}(D \to hh)$
EW Penguin	$B \to K^{(*)}ll$, $B \to X_s\gamma$	$B \to \pi ll$, $B \to X\gamma$	$K \to \pi^0 ll$, $K^\pm \to \pi^\pm \nu\nu$	$D \to X_u ll$
Higgs Penguin	$B_s \to \mu\mu$	$B \to \mu\mu$	$K \to \mu\mu$	$D \to \mu\mu$

Tree vs loop measurements

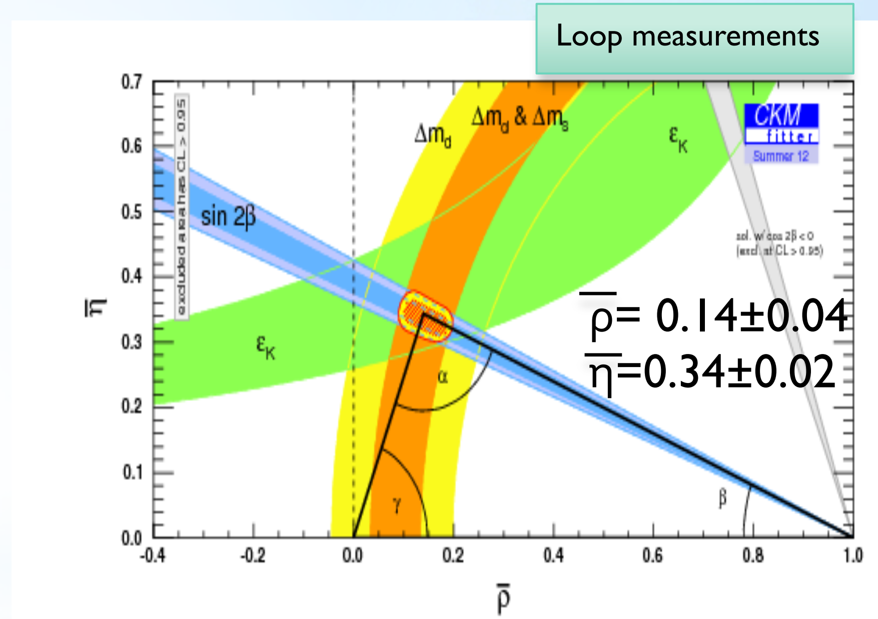
(A, λ , ρ , η) are not predicted by the SM. They need to be measured!

If we assume NP enters only (mainly) at loop level, it is interesting to compare the determination of the parameters (ρ , η) from processes dominated by tree diagrams **(V_{ub} , γ ,…)** with the ones from loop diagrams **(ΔM_d&ΔM_s, β , ε_K , …)**.

Tree measurements



Loop measurements



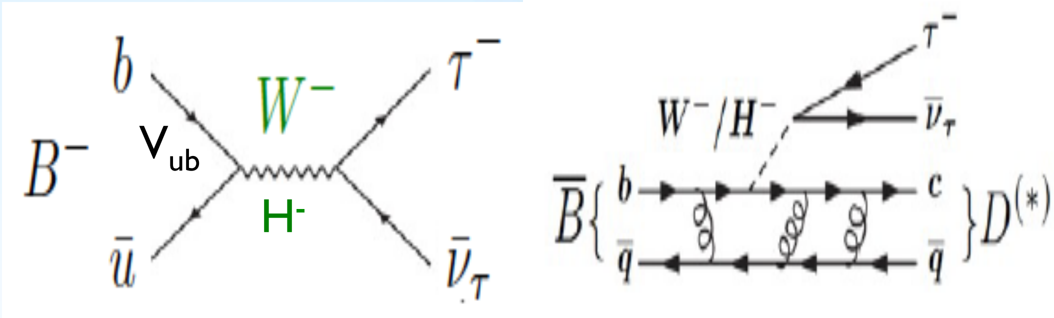
Courtesy S. Descotes-Genon on behalf of CKMfitter coll.

Need to improve the precision of the measurements at tree level to (dis-)prove the existence of NP contributions in loops.

Tree Level Measurements

b→u,c: Charged Higgs at tree level?

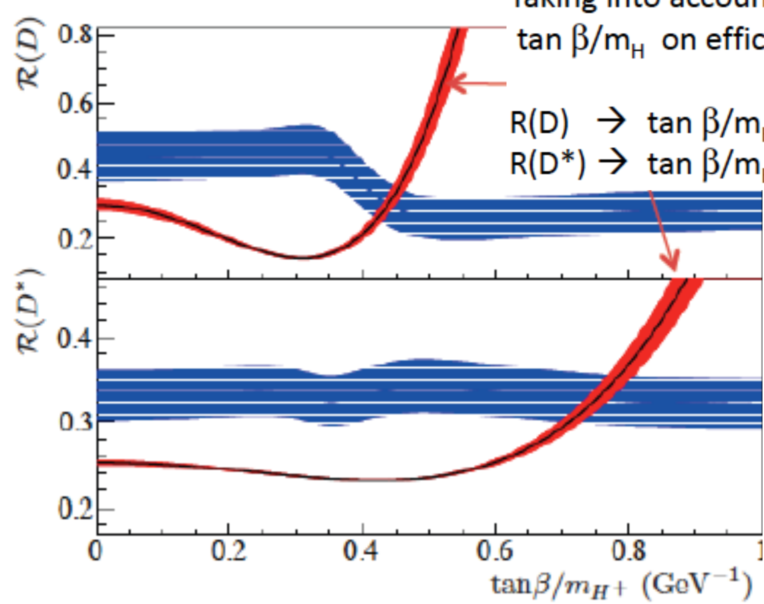
For some time the measured BR(B→ τ ν) has been about **a factor two higher than the CKM fitted** value (3 σ), in better agreement with the **inclusive V_{ub}** result (~30% higher than exclusive).



PRL 110, 131801 (2013)

Recently **Belle** published a more precise hadron tag analysis, in better agreement with the fitted CKM value: **World average BR(B→ τ ν))$_{exp}$= (1.15±0.23)x10^{-4} vs CKM fit:(0.83±0.09)x10^{-4}**

BABAR has also a more precise measurement of BR(B→D(*) τ ν)/BR(B→D(*)l ν). Ratio cancels V_{cb} and QCD uncertainties. Combined D and D* BABAR results are **3.4 σ higher than SM**



Taking into account the effect of tan β/m_H on efficiency

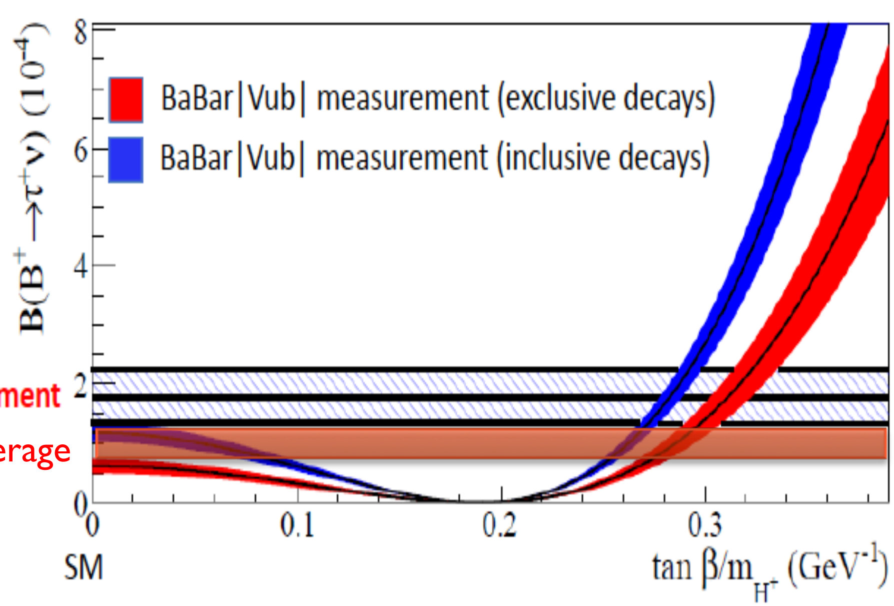
R(D) → tan β/m_H = 0.44 ± 0.02

R(D*) → tan β/m_H = 0.75 ± 0.04

2HDM

B → τν measurement

new world average



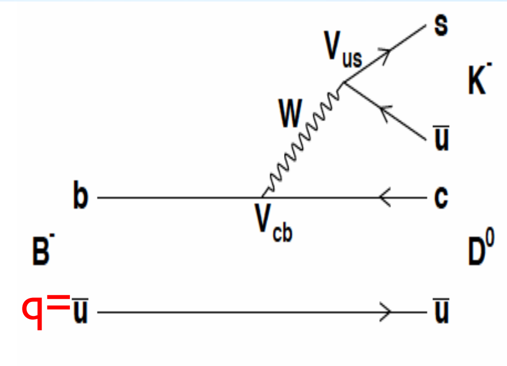
V_{ub} phase: Experimental Strategies

q=u: with D and anti-D in same final state

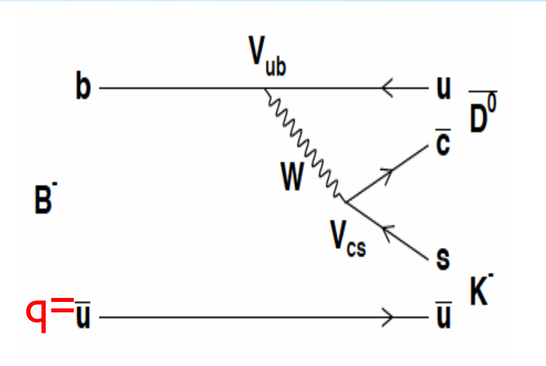
$B^{\pm} \rightarrow DX_s$ X_s={$K^{\pm}$, $K^{\pm}\pi\pi$, $K^{*\pm}$,…}

q=s: Time dependent CP analysis.
Inteference between B_s mixing and decay.

$B_s \rightarrow D^{\pm}_s K^{\mp}$



($|V_{cb}V_{us}| \alpha\ \lambda^3$)



($|V_{ub}V_{cs}| \alpha\ \lambda^3$)

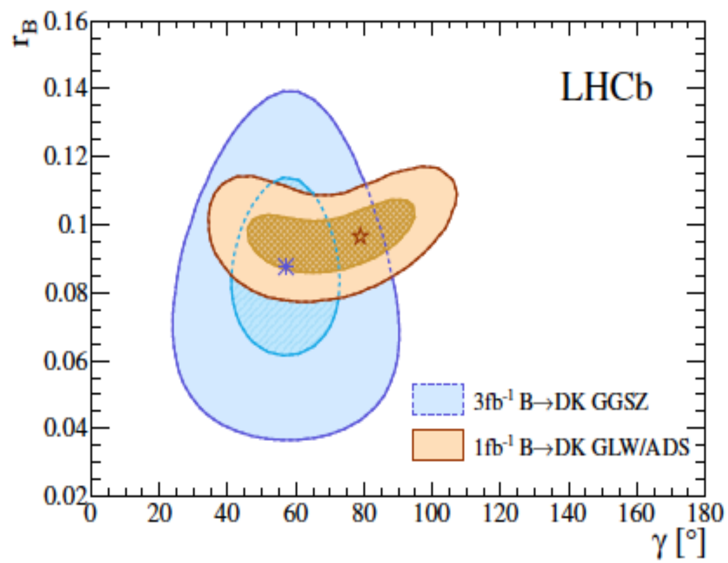
In the case q=u the experimental analysis is relatively simple, selecting and counting events to measure the ratios between B and anti-B decays. NP contributions to D mixing are assumed to be negligible or taken from other measurements.

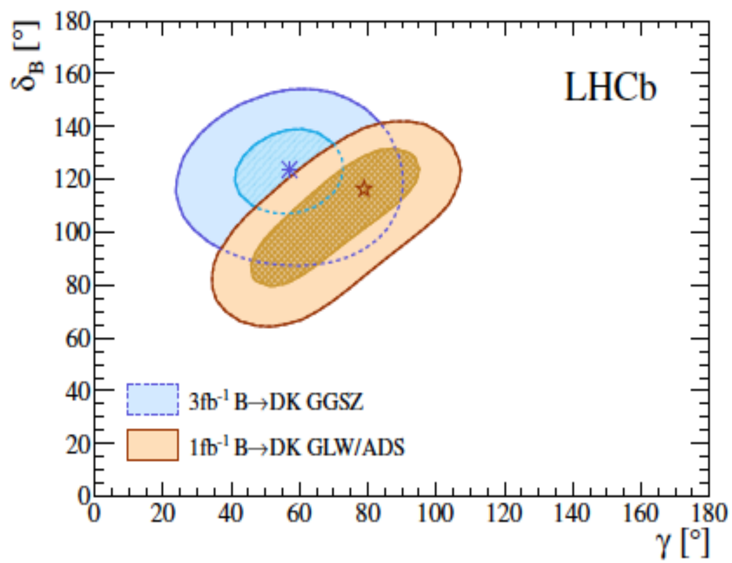
However the extraction of γ requires the knowledge of the ratio of amplitudes ($r_{B(D)}$) and the difference between the strong and weak phase in B and D decays ($\delta_{B(D)}$)
→charm factories input (CLEO/BESIII).

In the case q=s, a time dependent CP analysis is needed to exploit the interference between B_s mixing and decay. NP contributions to the mixing needs to be taken from other measurements ($B_s \rightarrow J/\Psi\phi$).

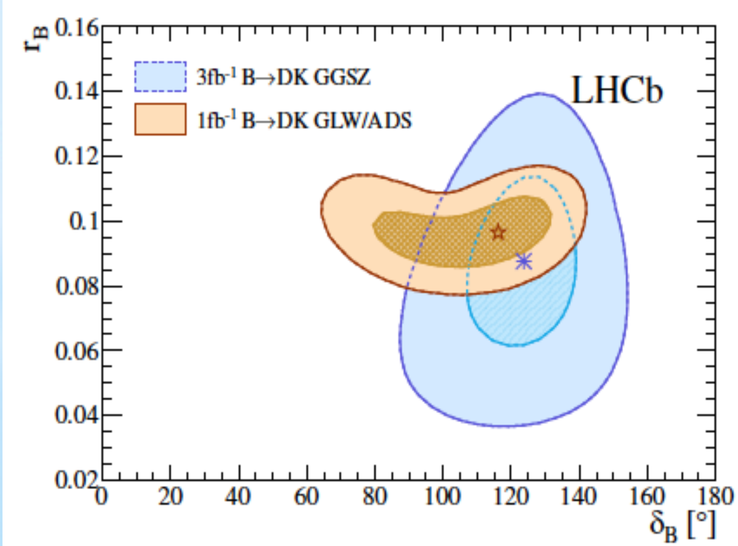
V_{ub} phase: LHCb combination

LHCb-CONF-2013-006





$$\tan\gamma \approx \frac{\eta}{\rho}$$



LHCb preliminary (B→DK):

γ = 67±12° (r_B(DK)=0.092±0.008)

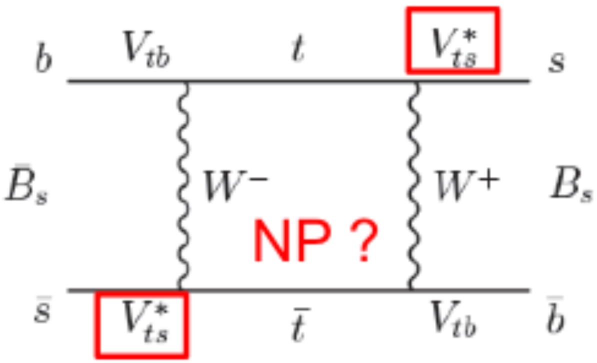
Excellent internal compatibility of GGSZ and GLW/ADS.
Expect **±6°** when all RUN-I data is analyzed.

LHCb and B-factories tree level measurements are in **good agreement and similar precision**, and agree with the indirect determination from loop measurements:

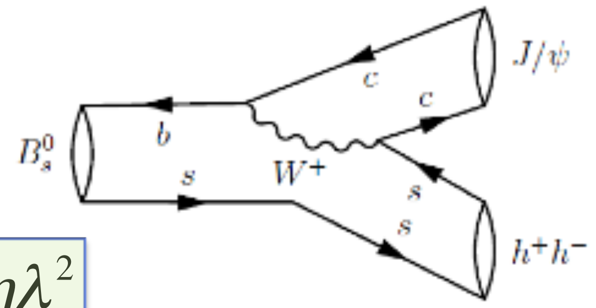
γ (tree)= $70.0^{+7.7}_{-9.9}$° vs γ (loop)= $66.5^{+1.3}_{-2.5}$°

ΔF=2 Box Measurements

Δ F=2 box in b→s transitions: CP asymmetries in B_s→J/Ψ Φ



$\phi_s \approx -2\eta\lambda^2$

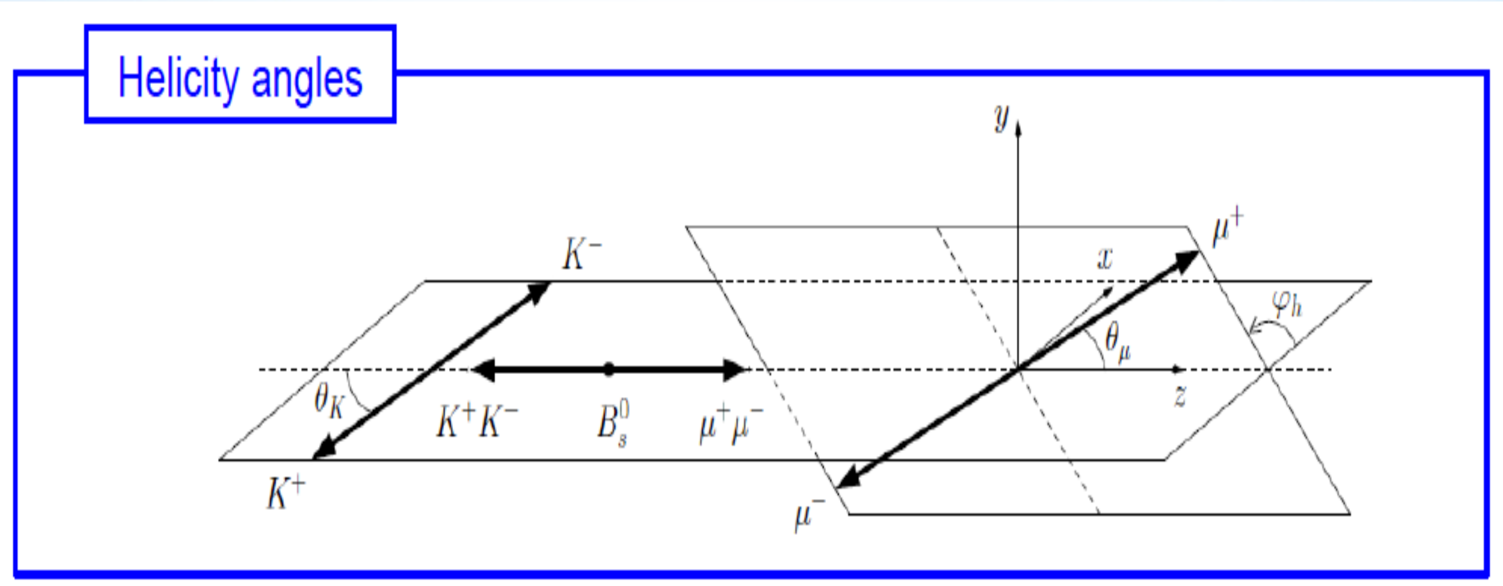


+ small penguin pollution

$$\phi_D^{SM} = -2\arg\left(V_{cs}V_{cb}^*\right) \approx 0$$

Sensitivity to the phase in the box diagram, through the interference between mixing and decay.

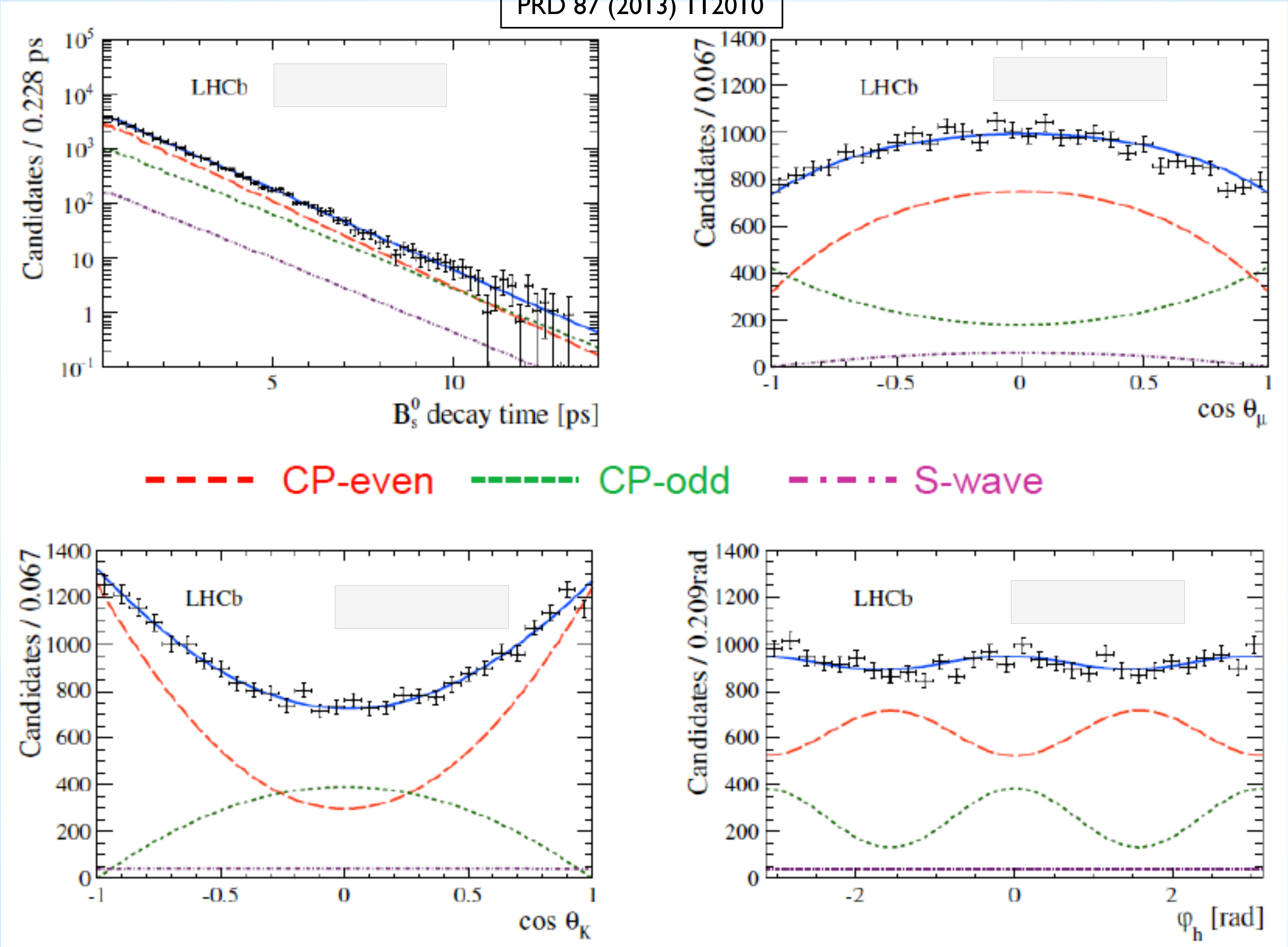
Angular analysis is needed in **B_s→J/Ψ Φ** decays, to disentangle statistically the CP-even and CP-odd components. Use the helicity frame to define the angles: $\theta_K, \theta_\mu, \phi_h$.



$\Delta F=2$ box in $b \to s$ transitions

LHCb flavour tagging improved with the inclusion of Kaon Same Side Tag: **$\varepsilon D^2 = (3.13 \pm 0.23)\%$**

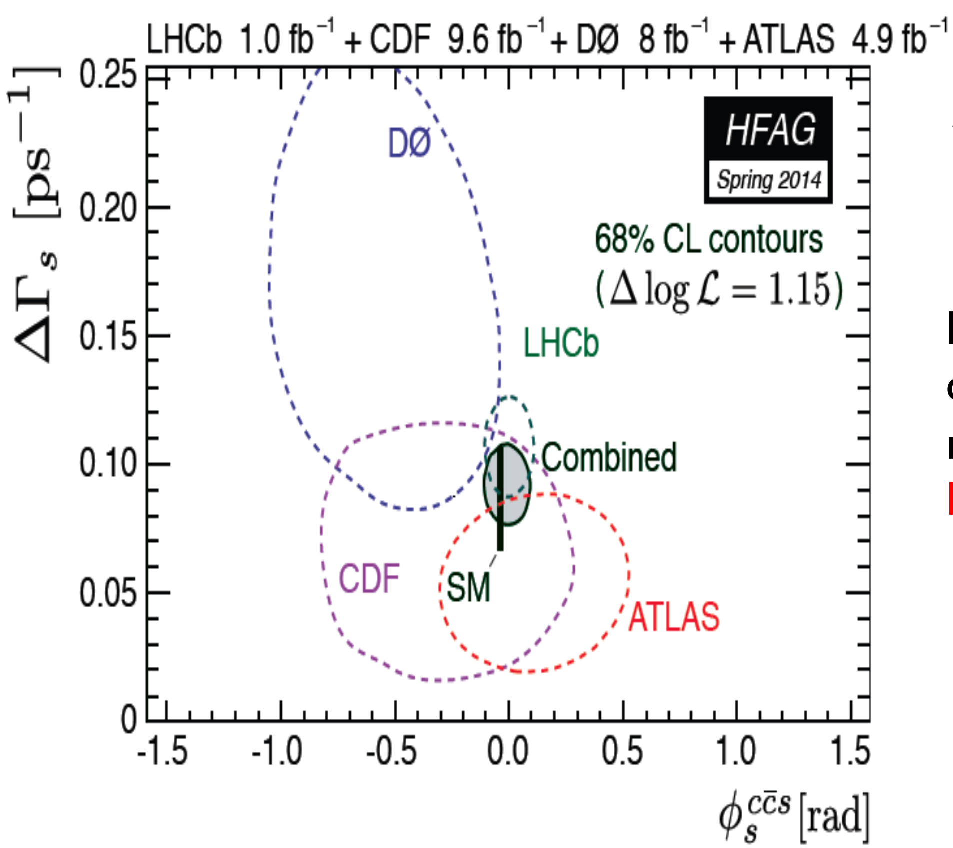
PRD 87 (2013) 112010



Δ F=2 box in b→s transitions

The result of the LHCb angular analysis of $B_s \to J/\Psi\,\Phi$ decays with $1fb^{-1}$ *(PRD 87 (2013) 112010)* combined with the new results using $3fb^{-1}$ $B_s \to J/\Psi\,\pi\pi$ decays (arXiv:1405.4140) gives:

Φ_s(LHCb) = 0.070 ±0.054(stat)±0.009(syst)



This result can be compared with the indirect determination: **Φ_s = -0.036±0.002.**

Although, there has been **impressive progress** since the initial measurements at CDF/D0, the uncertainty needs to be further reduced.

Meanwhile, other LHC experiments have started contributing. ATLAS tagged analysis with 5/fb and recently CMS tagged analysis with $20fb^{-1}$ of $B_s \to J/\Psi\,\Phi$ decays gives:

CMS-PAS-BPH-13-012

Φ_s(CMS) = -0.03 ±0.11(stat)±0.03(syst)

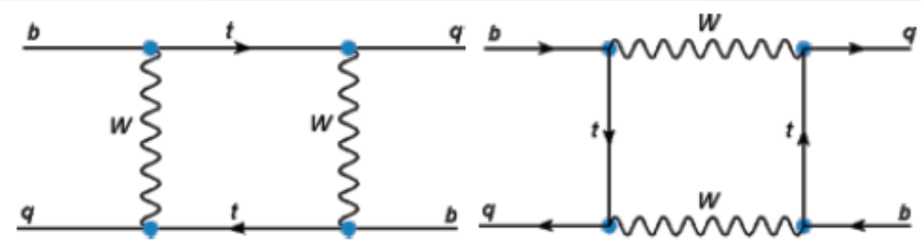
arXiv:1407.1796

Φ_s(ATLAS) = 0.12 ±0.25(stat)±0.05(syst)

Δ F=2 box in b→q transitions

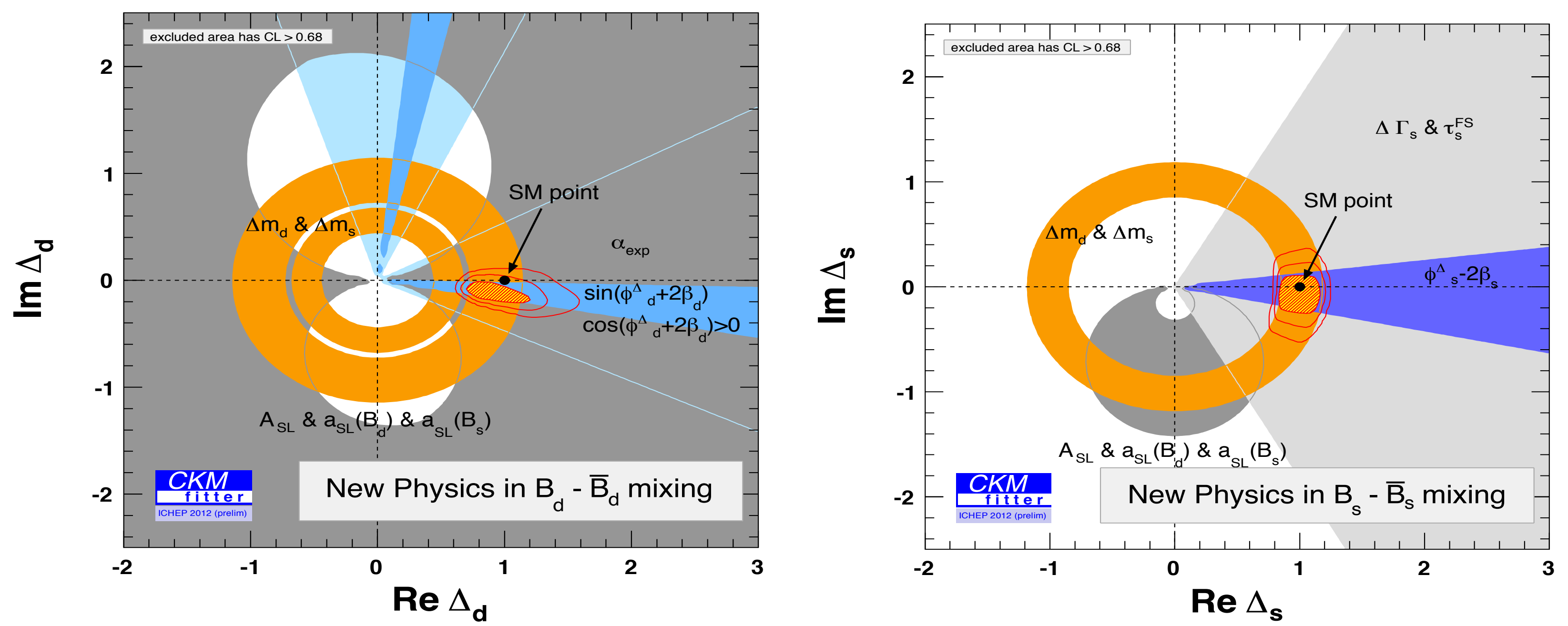
$$\left\langle B_q^0 \middle| M_{12}^{SM+NP} \middle| \overline{B}_q^0 \right\rangle \equiv \Delta_q^{NP} . \left\langle B_q^0 \middle| M_{12}^{SM} \middle| \overline{B}_q^0 \right\rangle$$

$$\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i\, \mathrm{Im}(\Delta_q) = |\Delta_q| e^{i\phi^{\Delta}_q}$$



No significant evidence of NP in B_d or B_s mixing .

New CP phases in box diagrams constrained @95%CL to be <12% (<20%) for $B_d(B_s)$.

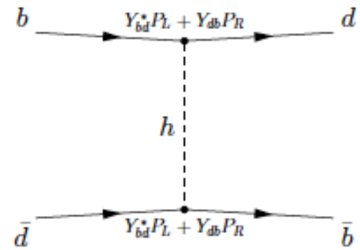


<u>Need to increase precision to disentangle NP phases of few percent in B_d and B_s mixing</u>

Δ F=2 box: Yukawa couplings constraints

Roni Harnik at
LHCb-TH workshop
(14-16) October 2013

Meson Mixing

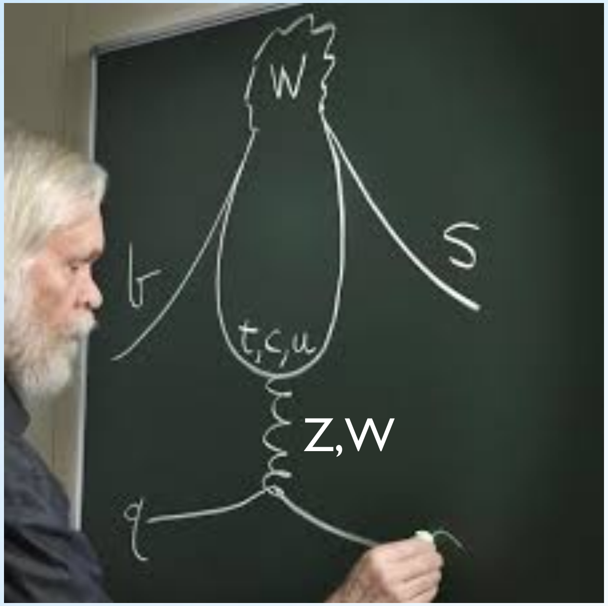


* Meson mixing's powerful:

Technique	Coupling	Constraint	$m_i m_j/v^2$
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$	5×10^{-8}
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$	
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$	3×10^{-7}
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$	
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$	7×10^{-6}
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$	
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$	8×10^{-9}
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$	
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$	
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$	

Upper values expected for "natural" models

"Natural" models are constrained!

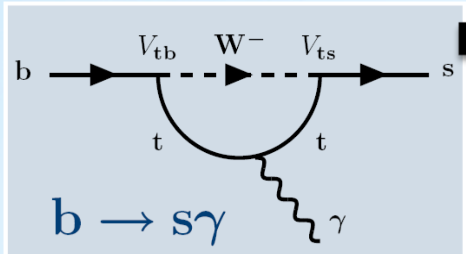


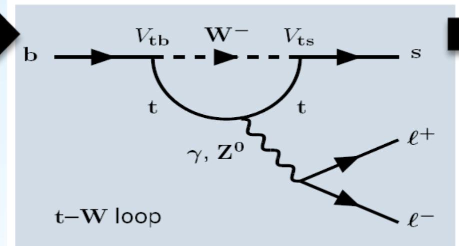
ΔF=1 EW Penguins

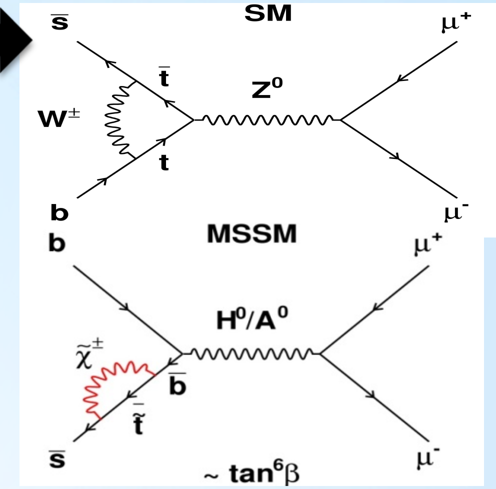
Three impersonations of the EW penguin

α_{QED} suppression → helicity suppression

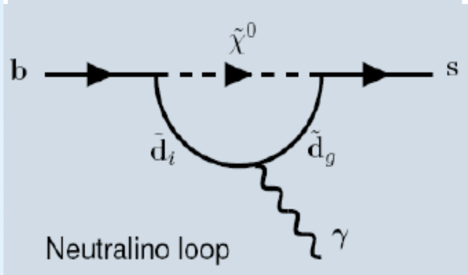
SM

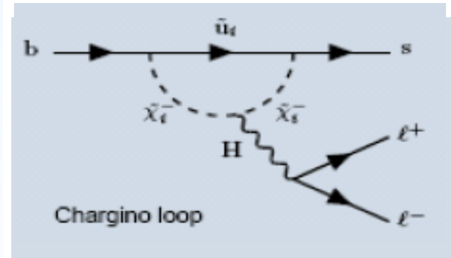






MSSM

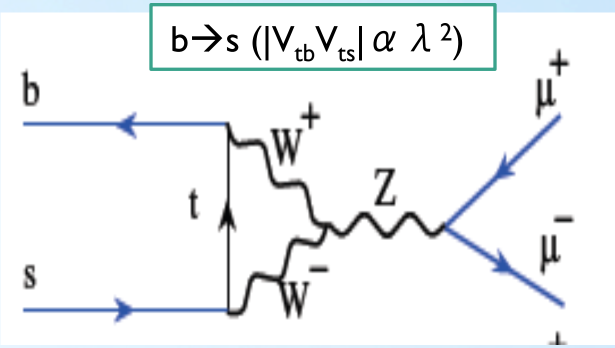




	Relevant Operators	*BR*(SM)	*BR* exp	
$B_s \to \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	Large theory uncertainties O(20%)	$(3.5\pm0.4)\cdot10^{-5}$ LHCb: arXiv:1209.0313	γ polarization
$B^0 \to K^* \mu^+\mu^-$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu (\gamma_5) \ell$		$(1.16\pm0.19)\cdot10^{-6}$ LHCb: arXiv:1205.3422	angular distributions
$B_s \to \mu^+\mu^-$	$\mathcal{O}_{S(P)} \sim \bar{s}_L b_R \bar{\ell} (\gamma_5) \ell$	$(3.6\pm0.5)\cdot10^{-9}$ helicity suppressed	$(3.2^{+1.5}_{-1.2})\cdot10^{-9}$ LHCb: arXiv:1205.3422	BR

ΔF=1 Higgs penguins in b→d,s transitions: B decays

The pure leptonic decays of **K,D and B** mesons are a particular interesting case of EW penguin. The **helicity suppression** of the vector(-axial) terms, makes these decays particularly sensitive to new (pseudo-)scalar interactions →**Higgs penguins!**



These decays are well predicted theoretically, and experimentally are exceptionally clean. Within the SM,

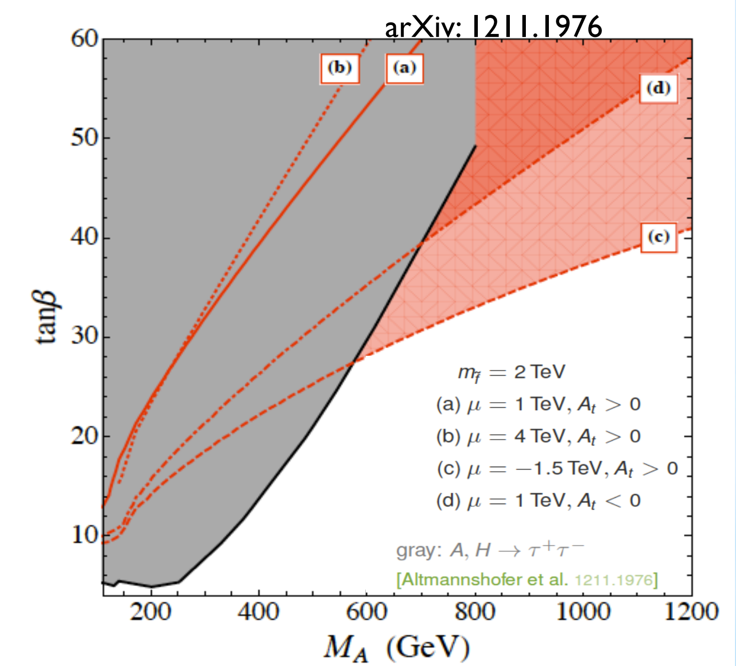
arXiv:1208.0934
arXiv:1303.3820
PRL 109, 041801 (2012)
with input from HFAG.

$BR_{SM}(B_s \to \mu\mu)$ <t> = (3.56±0.29)x10^{-9}

$BR_{SM}(B \to \mu\mu)$ <t> = (1.07±0.10)x10^{-10}

$$BR(B_q \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3 \sin^4\theta_W} |V_{tb}^* V_{tq}|^2 \tau_{Bq} M_{Bq}^3 f_{Bq}^2 \sqrt{1-\frac{4m_\mu^2}{M_{Bq}^2}} \times$$

$$\times \left\{ M_{Bq}^2 \left(1-\frac{4m_\mu^2}{M_{Bq}^2}\right)\left(\frac{C_S-\mu_q C_S'}{1+\mu_q}\right)^2 + \left[M_{Bq}\left(\frac{C_P-\mu_q C_P'}{1+\mu_q}\right) + \frac{2m_\mu}{M_{Bq}}(C_A - C_A')\right]^2 \right\}$$



with $\mu_q = m_q/m_b$ << 1 and m_μ/m_B << 1. Hence if $C_{S,P}$ are of the same order of magnitude than C_A they dominate by far.

Superb test for new (pseudo-)scalar contributions. Within the MSSM this BR is proportional to $\tan^6\beta / M_A^4$

ΔF=1 Higgs penguins in b→d,s transitions: B decays

Main difficulty of the analysis is large ratio B/S.

Assuming the SM BR then after the trigger and selection, CDF expects ~0.26 $B_s \to \mu\ \mu$ signal events/fb, ATLAS ~0.4, CMS ~0.8 while LHCb ~12 (6 with BDT>0.5).

The background is estimated from the mass sidebands. **LHCb** is also using the signal pdf shape from control channels, rather than just a counting experiment. All experiments normalize to a known B decay.

In the B_s mass window the background is completely dominated by combinations of real muons

(main handle is the invariant mass resolution: *a factor two better invariant mass resolution is equivalent to a factor two increase in luminosity*).

	ATLAS	CMS	CDF	LHCb
Decay time resolution (B_s)	~100 fs	~70 fs	87 fs	**45 fs**
Invariant Mass resolution (2-body)	80 MeV/c^2	45 MeV/c^2	25 MeV/c^2	**22 MeV/c^2**

Therefore, for equal analyses strategies:

~1/fb at LHCb is equivalent to ~10/fb at CMS, ~20/fb at ATLAS/CDF.

ΔF=1 Higgs penguins in b→d,s transitions: CMS/LHCb

CMS (25 fb^{-1}) and **LHCb** (3 fb^{-1}) have sensitivity to the SM BR($B_s \to \mu^+\mu^-$), with **4.8σ (CMS)** and **5.0σ (LHCb)** expected excess w.r.t. background-only hypothesis in the B_s mass window.

Observed: $BR(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$ (LHCb) $BR(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ (CMS)

LHCb:

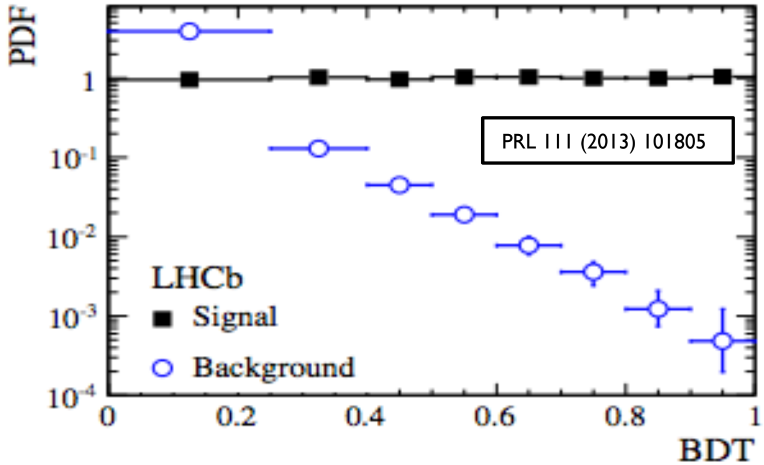
$BR(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-9}$

$BR(B^0 \to \mu^+\mu^-) < 0.7 \times 10^{-9}$ @95%CL

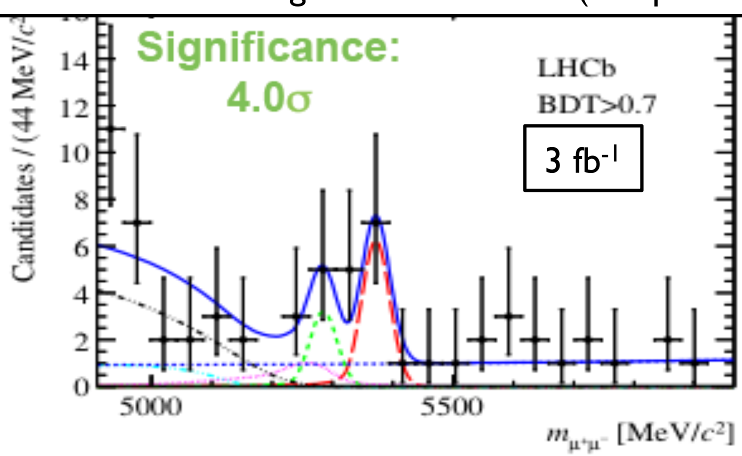
CMS:

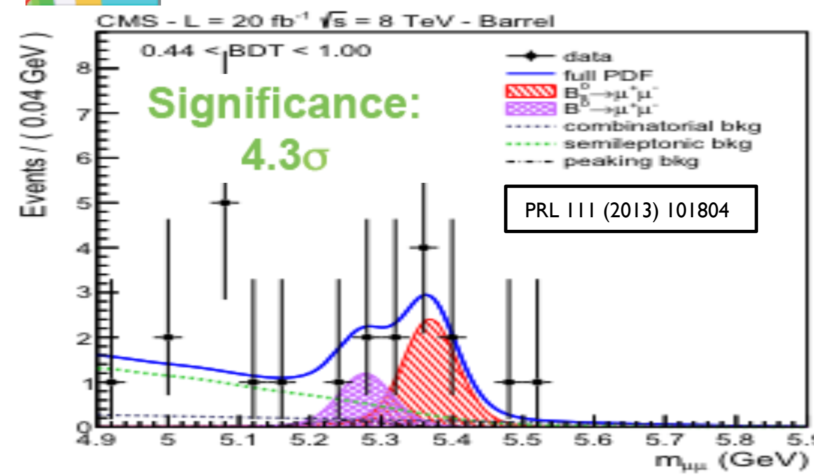
$BR(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-9}$

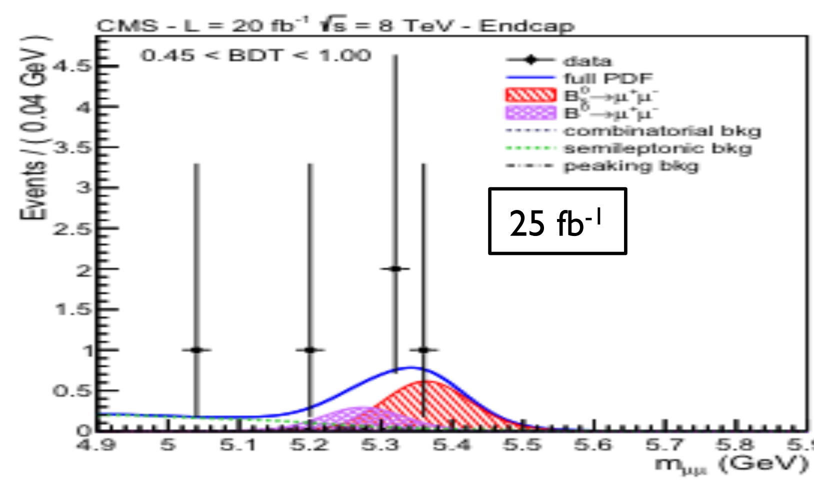
$BR(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ @95%CL



PDF calibrated using control channels (indep. of MC)





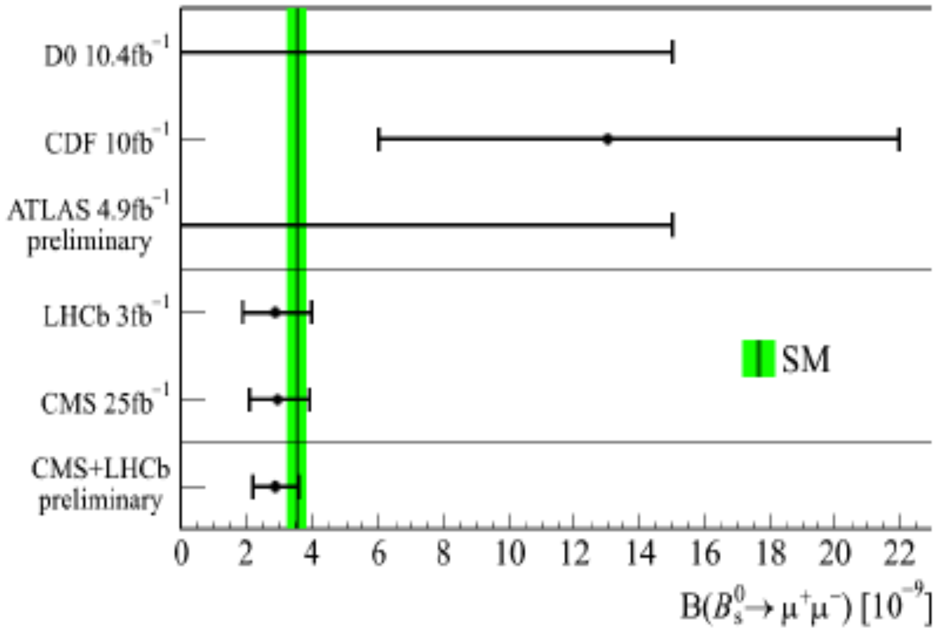


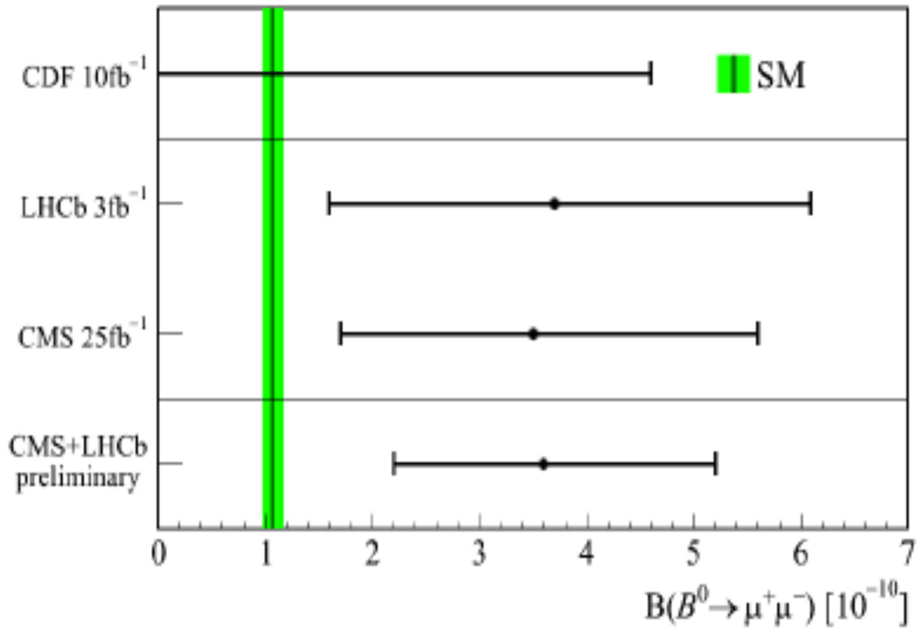
ΔF=1 Higgs penguins in b→d,s transitions:CMS/LHCb combination

Observation:

$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

$$\mathrm{BR}(B^0 \to \mu^+\mu^-) = 3.6^{+1.6}_{-1.4} \times 10^{-10}$$





Latest results on $B_{(s)} \to \mu^+\mu^-$ strongly constraint the parameter space for many NP models, complementing direct searches from ATLAS/CMS.

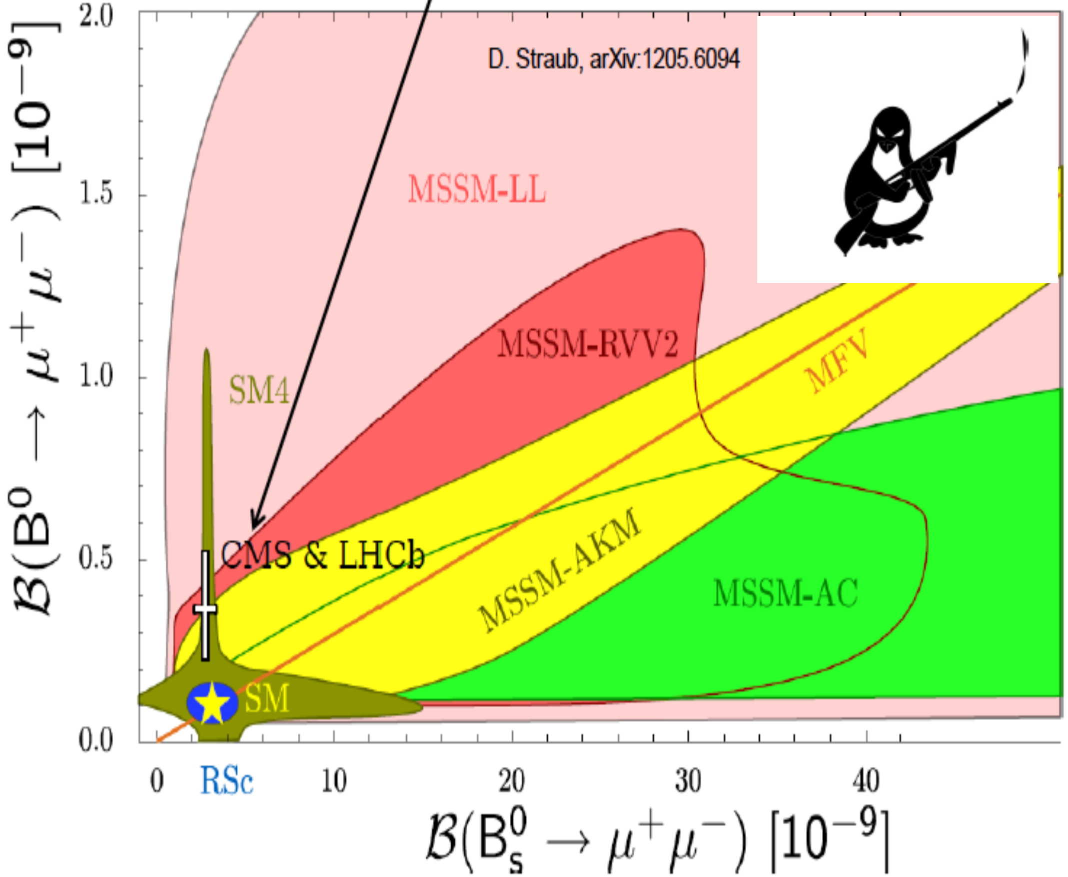
In particular, large tan β with light pseudo-scalar Higgs in CMSSM is strongly disfavored.

The precision achieved now is such that $B_{(s)} \to \mu^+\mu^-$ sensitivity to (Z, γ) penguin cannot longer be considered sub-leading.

CMS-PAS-BPH-13-007
LHCb-CONF-2013-012

combining CMS & LHCb →

$$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$
$$BR(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

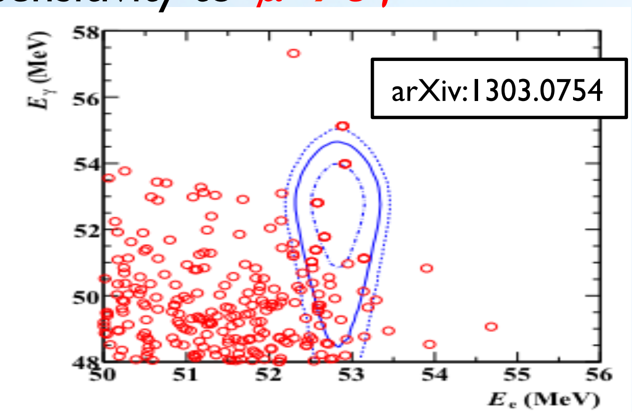


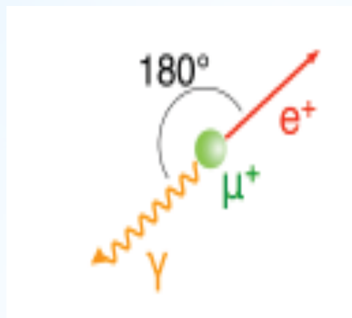
Charged Lepton Flavour Violation

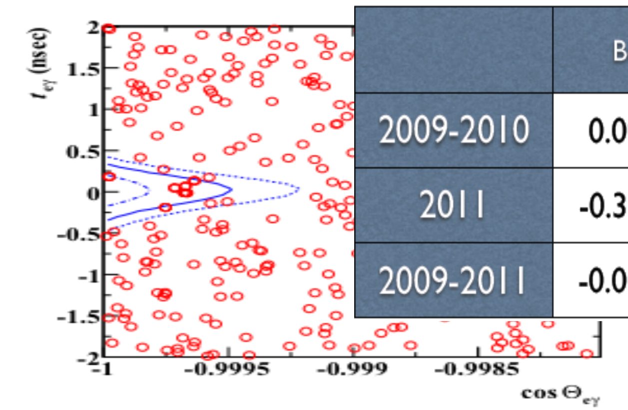
CLFV: Muon Decays

The discovery of neutrino oscillations implies CLFV at some level. Many extensions of the SM to explain neutrino masses, introduce large CLFV effects (depends on the nature of neutrinos). There is one more very important advantage w.r.t. the quark sector: **the reach for NP energy scale is not so much affected by QCD uncertainties in the SM predictions.**

The **MEG collaboration** at PSI using 3.6×10^{14} stopped muons have achieved an amazing sensitivity to $\mu \to e \gamma$



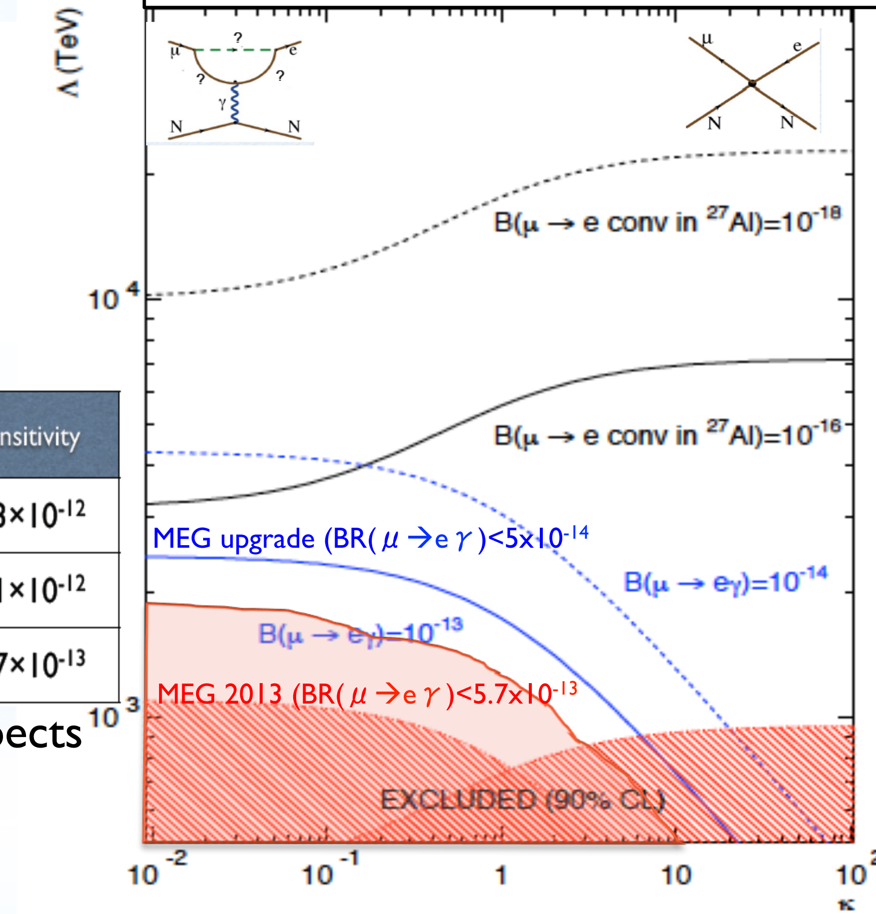




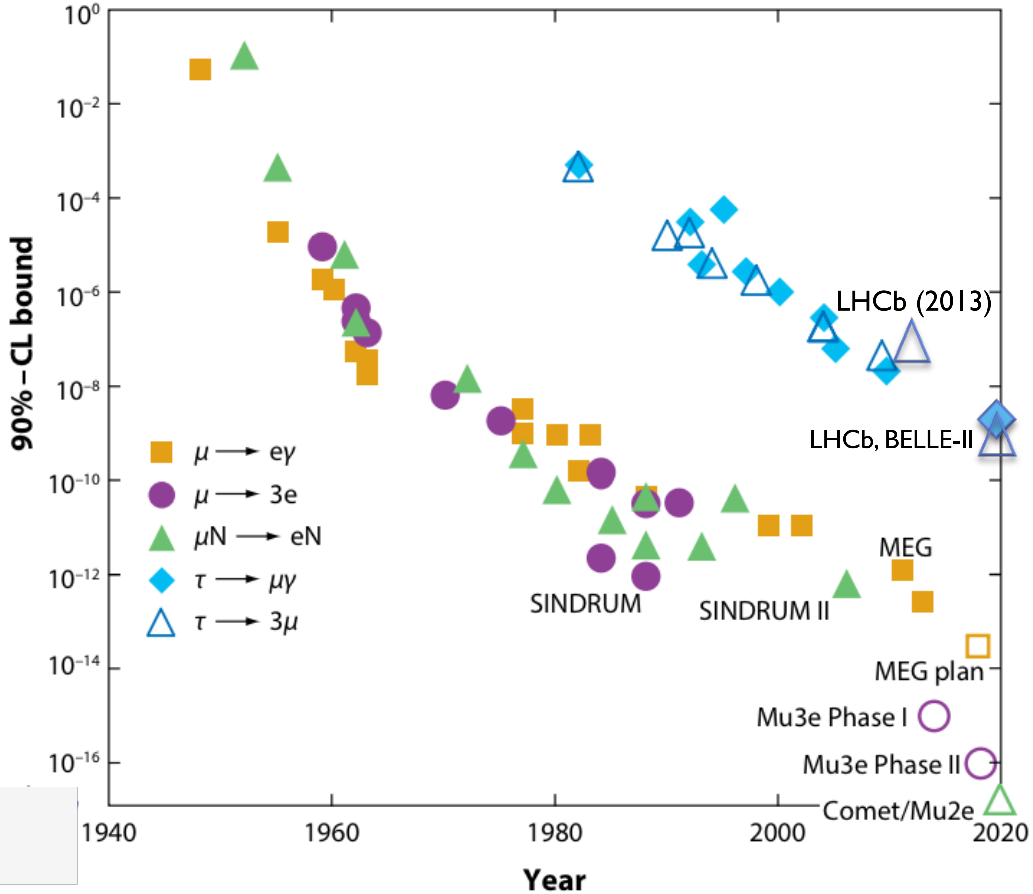
	Best fit	Upper limit (90% C.L.)	Sensitivity
2009-2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	5.7×10^{-13}	7.7×10^{-13}

MEG upgrade expects to reach $\mathbf{5\times10^{-14}}$

Modified from A.Gouvea and P.Vogel, arXiv:1303.4097



CLFV: Tau Decays



In principle τ are more sensitive per event than μ since mass typically decreases GIM suppression, (>500).

However, production rates at e^+e^- B-factories are much lower.

With ~1.4×10^9 τ events the best limits at 90% C.L. are:

arXiv:1001.3221, arXiv:1002.4550

	BR($\tau \rightarrow \mu\gamma$)	BR($\tau \rightarrow \mu\mu\mu$)
BELLE:	4.5×10^{-8}	2.1×10^{-8}
BABAR:	4.4×10^{-8}	3.3×10^{-8}

However, **at the LHC τ are copiously produced** (mainly from charm decays, $D_s \rightarrow \tau\nu$). At 7 TeV pp collisions, ~8×10^{10} τ/fb^{-1} are produced (~5×10^{14} at HL-LHC!). Recently, **LHCb** has reached similar sensitivities for BR($\tau \rightarrow \mu\mu\mu$) than B-factories using 1fb^{-1},

LHCb: BR($\tau \rightarrow \mu\mu\mu$)<9.8(8.0)x$10^{-8}$ at 95(90)% CL.

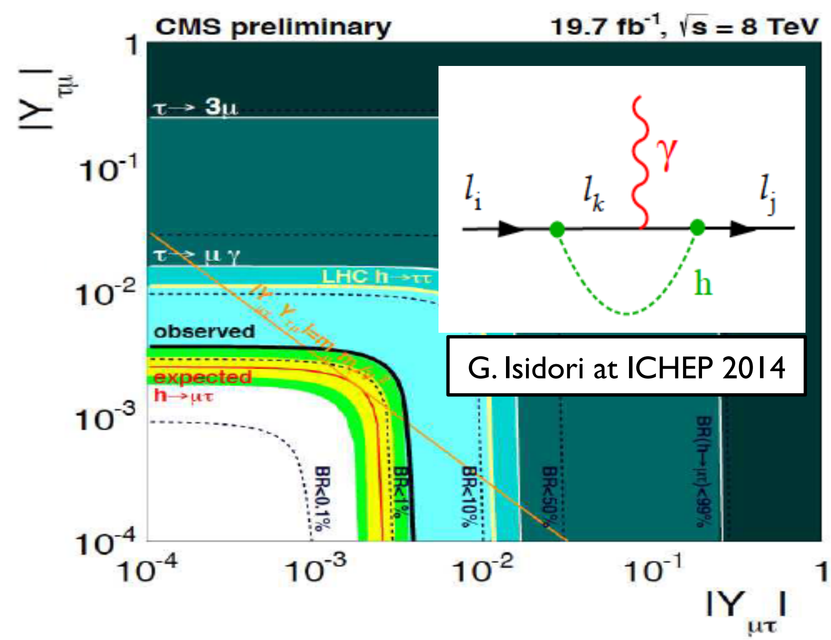
PLB 724 (2013) 36

Large bkg component in the most sensitive region is ($D_s^+ \rightarrow \eta[\mu\mu\gamma]\mu\nu$).

Higgs Flavour Violation Decays and CLFV

In a completely generic approach, CMS new results:

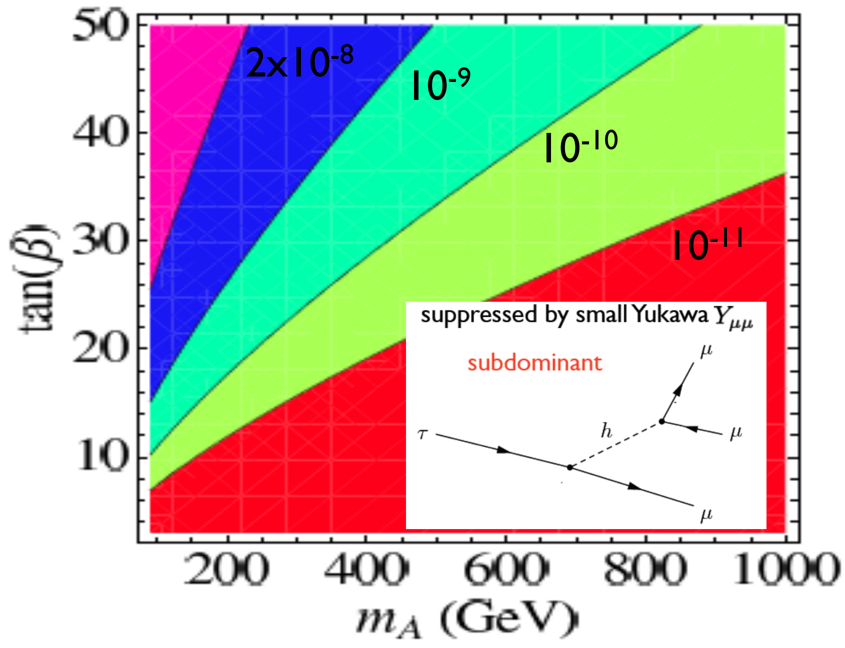
$$Br(H \to \mu\tau) < 1.57\% \quad (95\%\,CL)$$ *(CMS-PAS-HIG-14-005)*

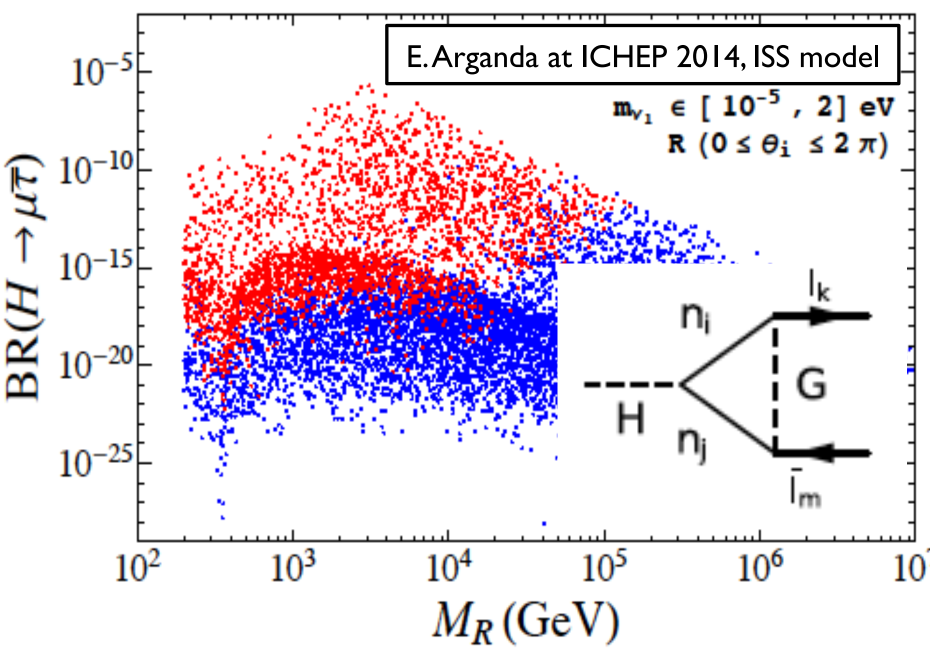


However, once a specific model to generate neutrino masses is defined (f.i. ISS), large effects in CLFV do not imply large effects in HFVD.

Interplay between low energy precision measurements and precise measurements of Higgs properties.

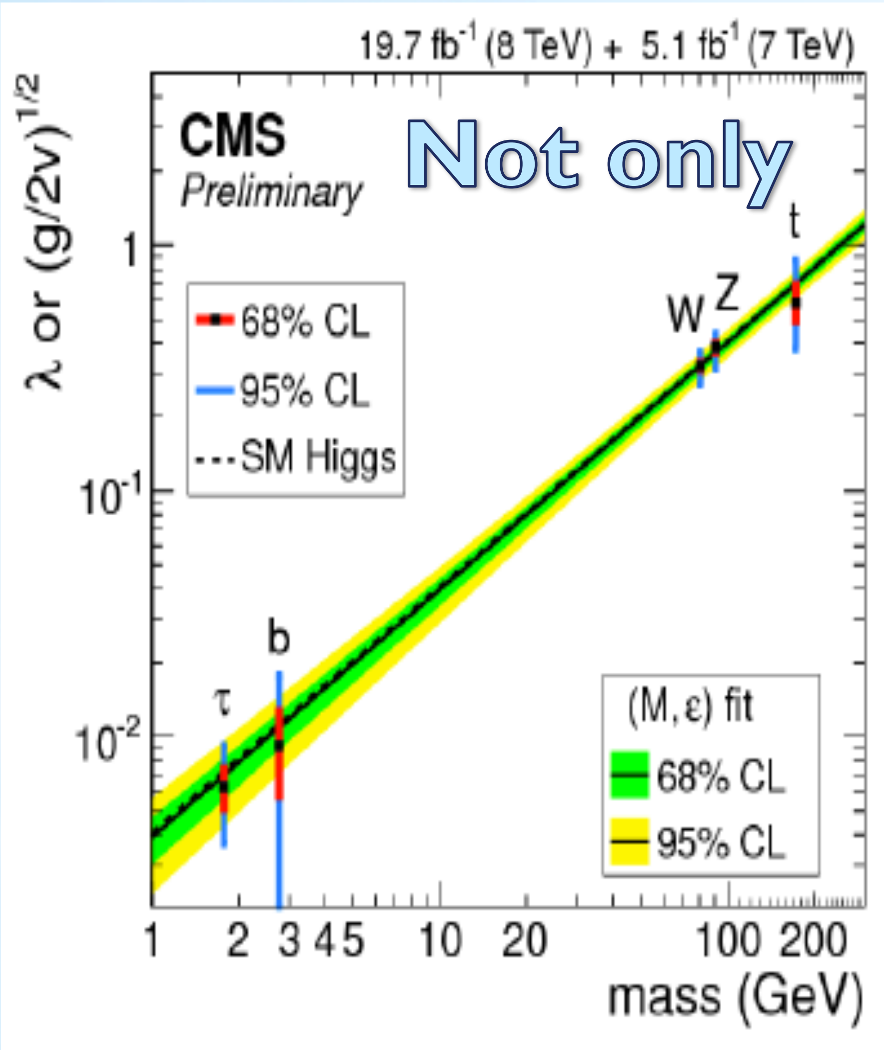
BR($\tau \to \mu\ \mu\ \mu$)





Conclusions

Take home messages.



No evidence of NP in Z observables → Strong constraints on the gauge Higgs sector.

No evidence of NP in quarks FCNC → Strong constraints on non-diagonal elements of the Higgs Yukawa couplings.

Strong constraints from μ LFV decays, however plenty of room in non-diagonal elements of the Higgs Yukawa couplings involving τ leptons.

Very special and clean decays like $B_s \to \mu^+ \mu^-$ in agreement with the SM → not much room for non SM-Higgs contributions with low M_A and large tan β.

Interplay between low energy precision measurements and precise measurements of Higgs properties, as strong as ever!

Don't give up yet!