Probing the Higgs mechanism with Flavour Physics: status and perspectives.

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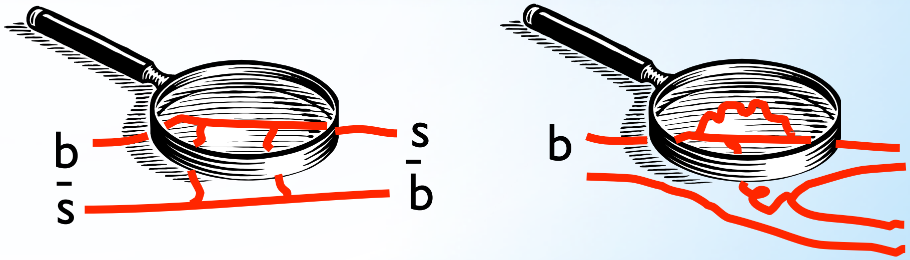


Indirect Searches for NP

If the **energy** of the particle collisions is high enough, we can discover NP detecting the production of "real" new particles.

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.

Indirect Searches for NP

Therefore, **NP** contributions in loops are **suppressed by** the size of the **isospin breaking** value $\Delta \mathbf{m}^2$. Larger effects of NP expected in (t,b)/ τ .

Moreover, through the study of **the interference of different quantum paths** one can access not only to the magnitude of the couplings of NP, 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?).

Therefore, 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.*

Status of Searches for NP

So far, no significant signs for NP from direct searches at the LHC while a (the SM?) Scalar Boson has been found with a mass of ~126 GeV/c^2.

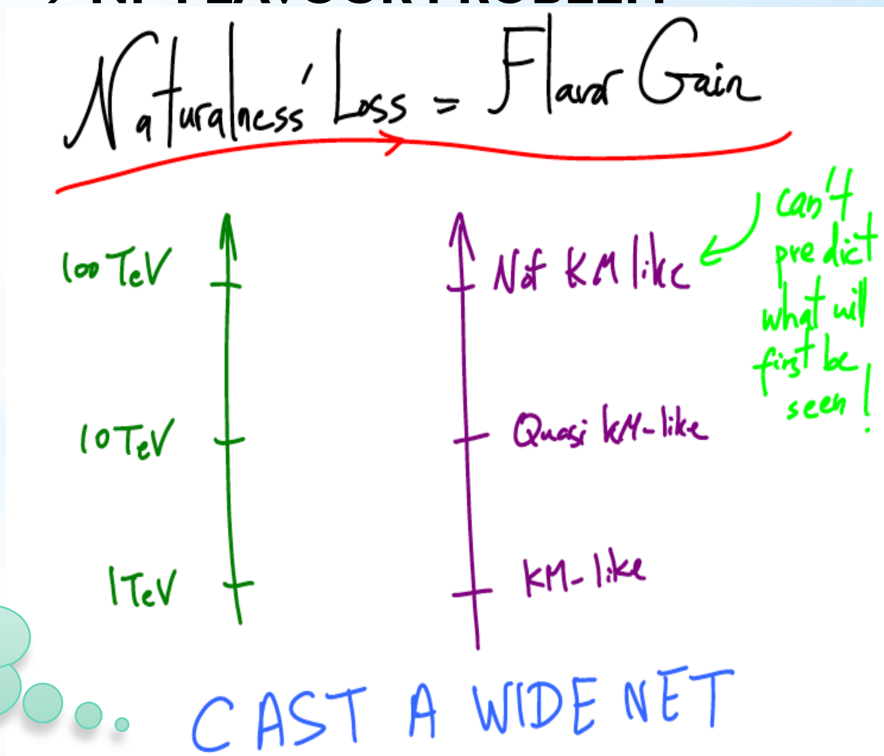
Before LHC, expectations were that *"naturally"* the masses of the new particles would have to be light in order to reduce the *"fine tuning"* of the EW energy scale. Theory departments were (are?) full of advocates of supersymmetric particles appearing at the TeV energy scale.

However, the absence of NP effects observed in flavour physics, even before LHC, implies some level of *"fine tuning"* in the flavour sector → **NP FLAVOUR PROBLEM**

"Non-natural" solution:
→ Minimal Flavour Violation (MFV).

As we push the energy scale of NP higher, the NP FLAVOUR PROBLEM is reduced, hypothesis like MFV look less likely → **chances to see NP in flavour physics have, in fact, increased** when Naturalness (in the SM Scalar sector) seems to be less plausible!

N.Arkani-Hamed, Intensity Frontier Workshop (Nov 2011, Washington)



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 Yukawa couplings and 4 CKM parameters. In practice, is convenient to move the CKM matrix from the Yukawa sector to the weak current sector:

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

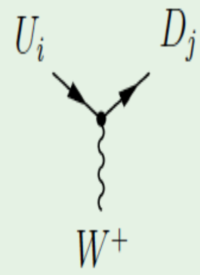
$Q_U = +2/3$

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

$Q_D = -1/3$

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

~ Cabibbo-Kobayashi-Maskawa (CKM) matrix

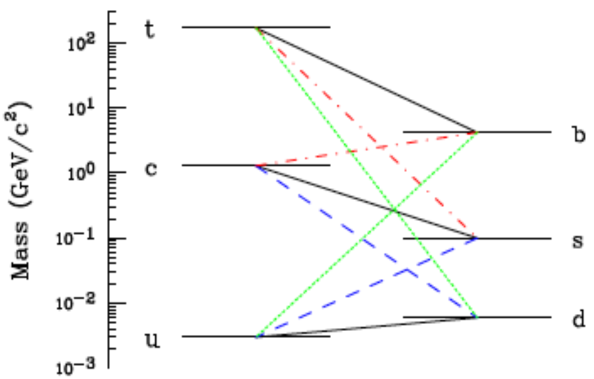


In the SM quarks are allowed to change flavour as a consequence of the Yukawa mechanism.

Using Wolfenstein parameterization (A, λ, ρ, η):

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

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

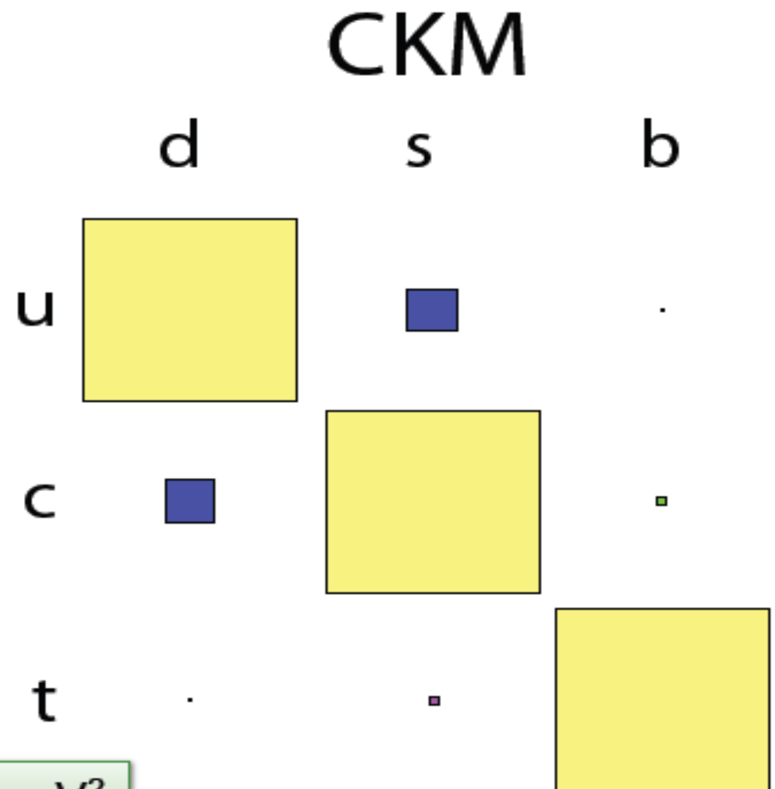


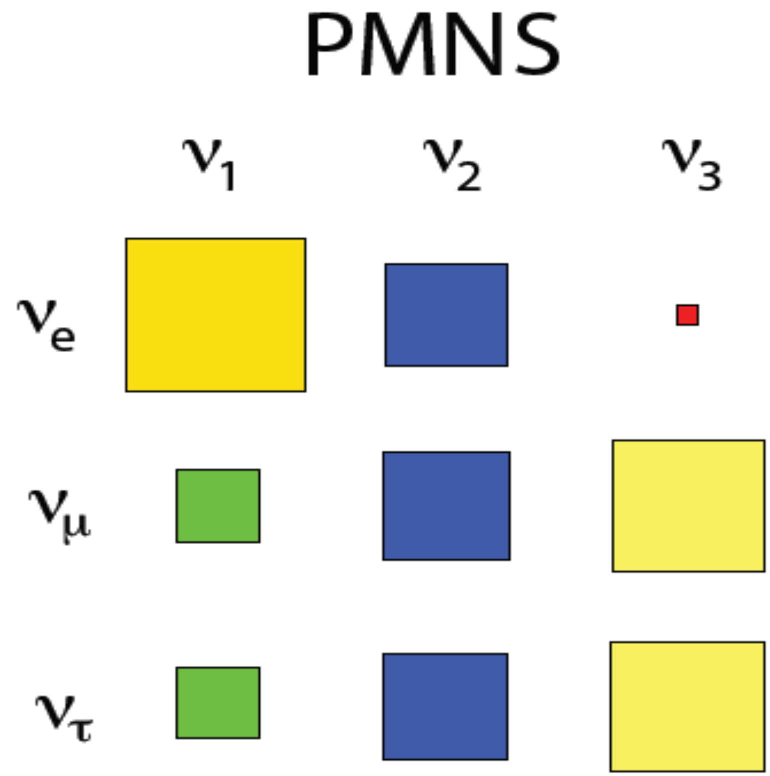
Flavour Structure is not simple.

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

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

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





Area ~V^2

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

Flavour Beyond the SM

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

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

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

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**. But then, at some energy scale, this symmetry breaks → expect **again large FCNC**, if the SUSY scale is not far away.

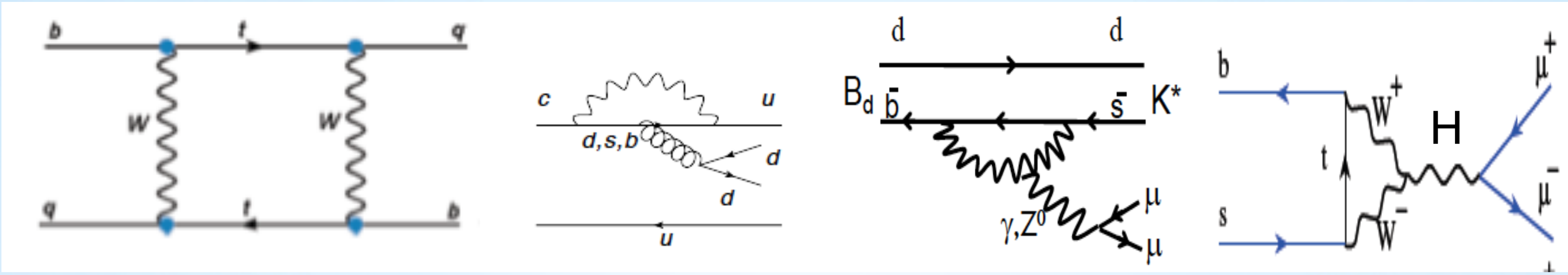
Minimal Flavour Violation: at tree level the quarks and squarks are diagonalized by the same matrices → **no FCNC at tree level**, like in the SM.

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

Two indirect paths to study Higgs BSM:

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

Loops zoology



ΔF=2 box QCD Penguin EW Penguin Higgs Penguin

*Map of Flavour transitions and type of loop processes: → **Map of this talk!***

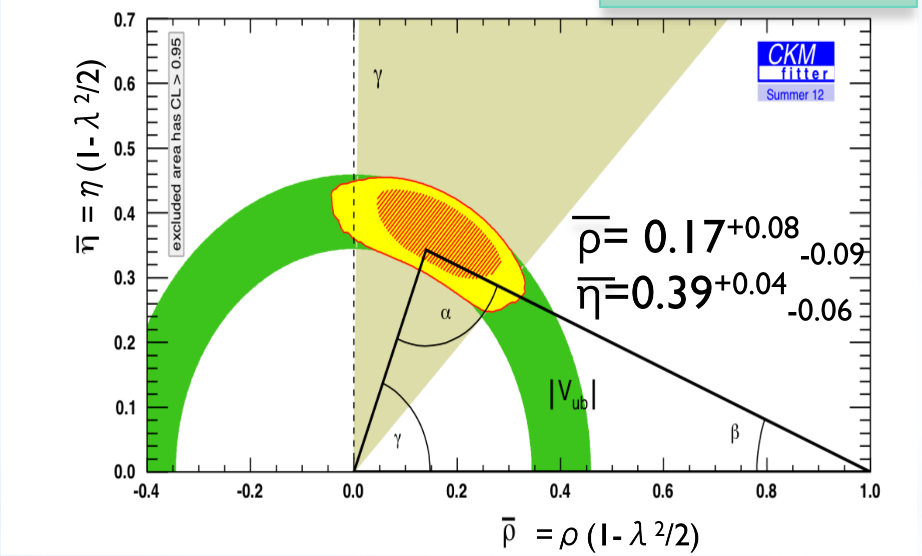
	b→s ($\|V_{tb}V_{ts}\| \alpha\ \lambda^2$)	b→d ($\|V_{tb}V_{td}\| \alpha\ \lambda^3$)	s→d ($\|V_{ts}V_{td}\| \alpha\ \lambda^5$)	c→u ($\|V_{cb}V_{ub}\| \alpha\ \lambda^5$)
ΔF=2 box	ΔM_{Bs}, $A_{CP}(B_s \to J/\Psi\ \Phi)$	ΔM_B, $A_{CP}(B \to J/\Psi K)$	ΔM_K, ε_K	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s \gamma$	$A_{CP}(B \to hhh)$, $B \to X \gamma$	$K \to \pi^0 ll$, 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

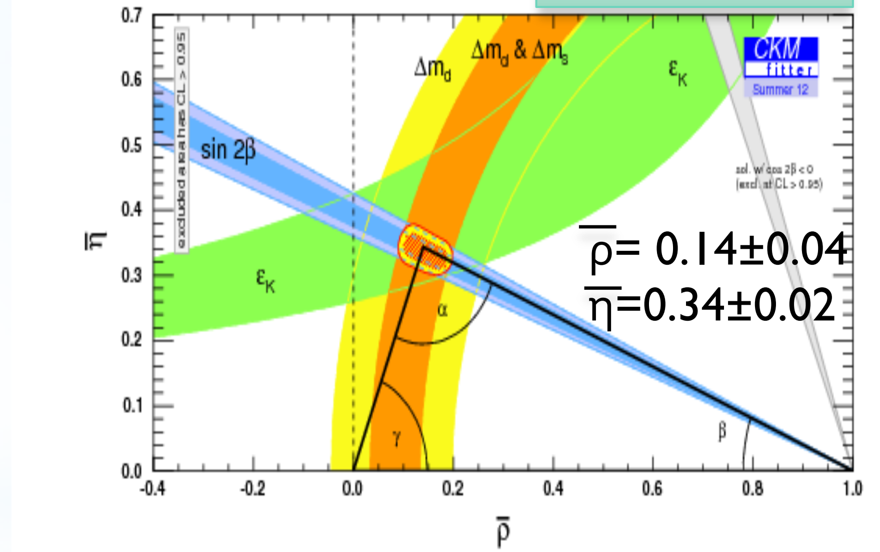
(A, λ, ρ, η) are not predicted by the SM. They need to be measured!

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.

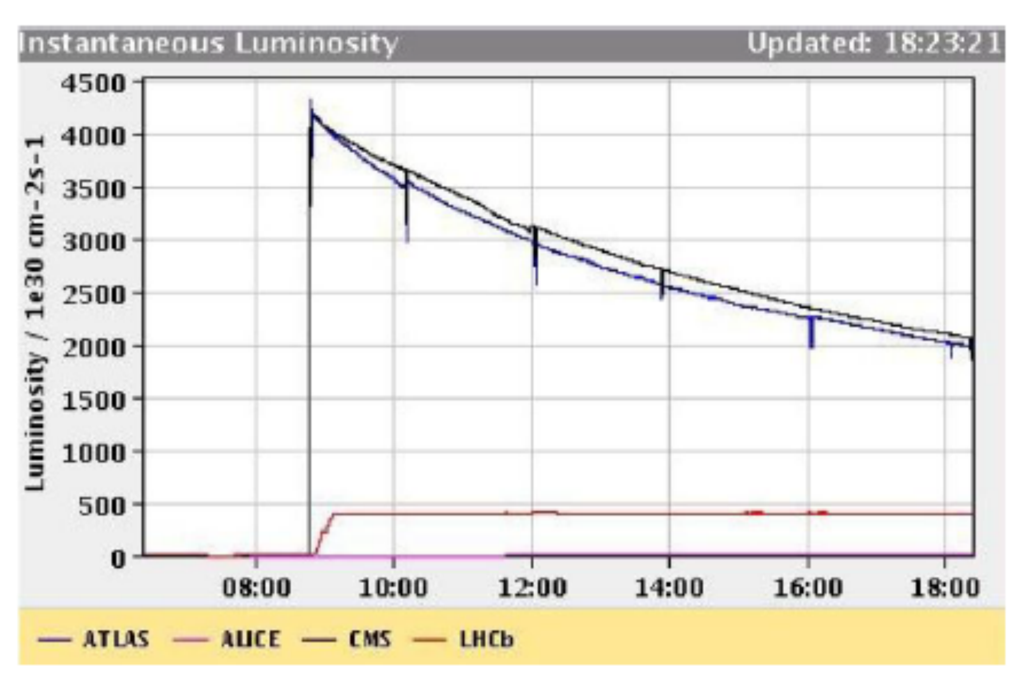
Need to improve the precision of the measurements at tree level to (dis-)prove the existence of NP contributions in loops.

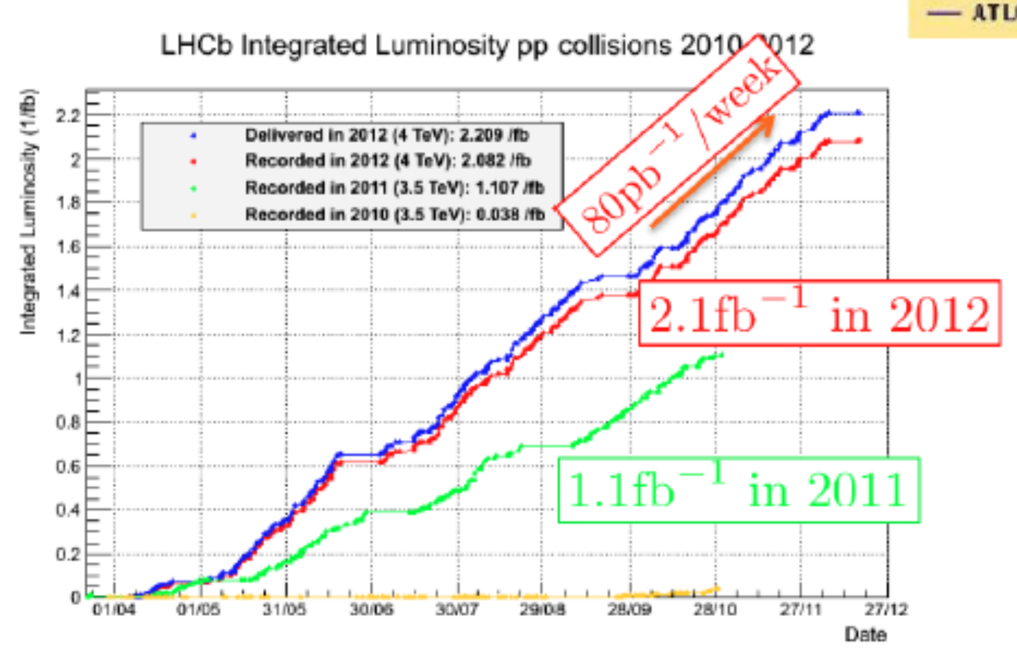
Experimental Facilities

LHC is working like a dream!

Since the first proton-proton collisions at the LHC at 7 TeV in Spring 2010, the progress has been fantastic!

In 2012 LHC delivered routinely peak luminosities of $4 \times 10^{33}/cm^2/sec$ at 8 TeV, for a total of 23/fb to **ATLAS&CMS** (6/fb in 2011 at 7 TeV).





LHCb took data at a constant luminosity $0.4 \times 10^{33}/cm^2/sec$ thanks to luminosity leveling, for a total of 2.2/fb at 8 TeV delivered (1.2/fb in 2011 at 7 TeV).

LHCb average number of visible pp collisions per bunch crossing ~2, while for ATLAS/CMS is ~20.

LHC is working like a dream!

The bb x-section was measured by LHCb at 7/8 TeV to be: $3x10^{11}$ fb (PLB 694 (2010) 209 and JHEP 06 (2013) 064). The cc x-section ~20 times higher! (Nuclear Physics B 871 (2013) 1)

About 40% of the b-quarks produced at the LHC fragments into $B^{\pm}$ and another 40% into B^0, while 10% fragments into B_s and 10% into baryons.

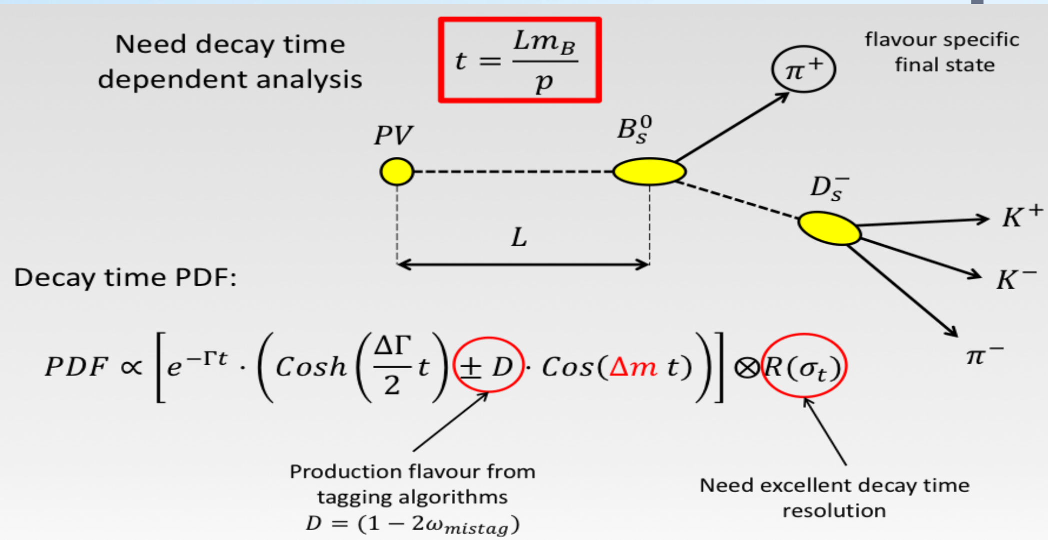
However at the LHC, the two b-quarks are produced incoherently → extra dilution factor in the tagging of neutral mesons.

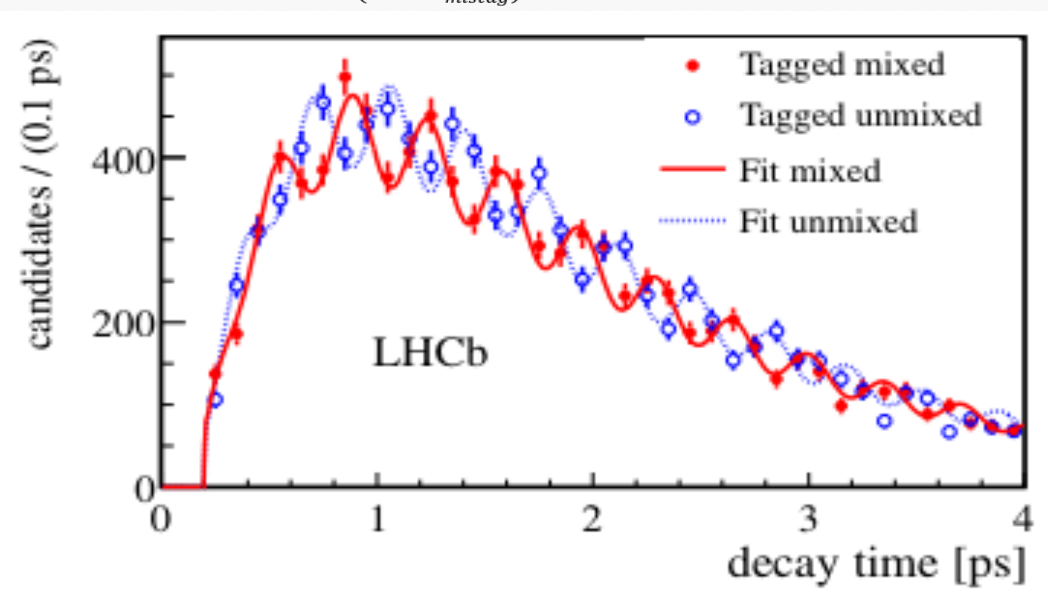
The LHCb detector acceptance ranges between ~10% for $B_s \to \mu^+ \mu^-$ decays to, for instance, ~5% for $B_s \to J/\Psi[\mu^+ \mu^-]\Phi[K^+K^-]$.

Rule of thumb:

1/fb at 7TeV at LHCb is equivalent to (1k-5k)/fb at the e^+e^- B-factories before tagging for $B^0/B^{\pm}$ decays into charged particles.

…and the LHCb performance is up to it!





$B_s \rightarrow D_s^- [K^-K^+\pi^-]\pi^+$

Hadron trigger **~34k candidates/fb**

Proper time resolution **~ 44 fs**
(to be compared with $2\pi^{-1}\Delta m_s^{-1}$~350 fs)

Effective tagging **~3.5%**

New J. Phys. (2013) 053021

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ ps^{-1}$

c.f. CDF with proper time resol. ~87 fs
$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$.

Precision measurements at hadron colliders are not any more a dream!

(Parenthesis)Advantages/Disadvantages of Existing Facilities

Common "past" knowledge:

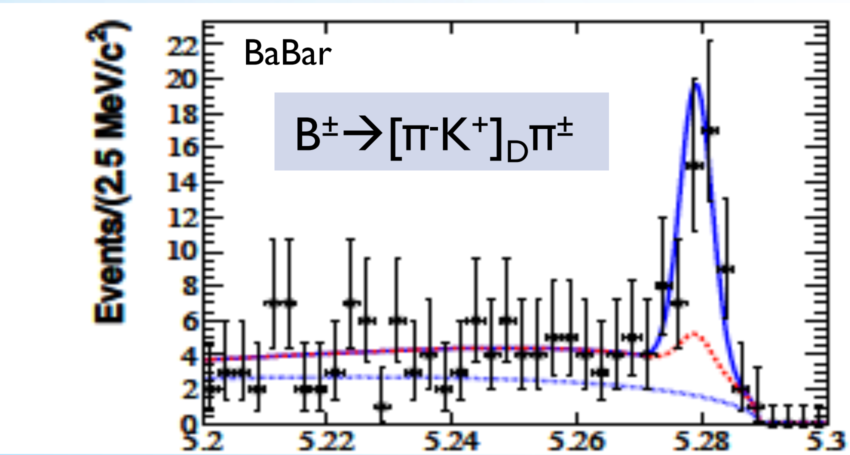
lepton colliders → precision measurements vs **hadron colliders** → discovery machines

After the achievements at the Tevatron in precision EW measurements (W mass) and B-physics results (Δm_s) and in particular the astonishing initial performance of the LHC detectors (LHCb in particular), I think the above mantra **is over simplistic and not true**.

Lepton colliders have the advantage of a known CoM energy, better selection efficiencies and high peak luminosities (10^{34}-10^{36}) $cm^{-2}s$. However, at the Y(4S) only $_{B(d,u)}$ mesons are produced.

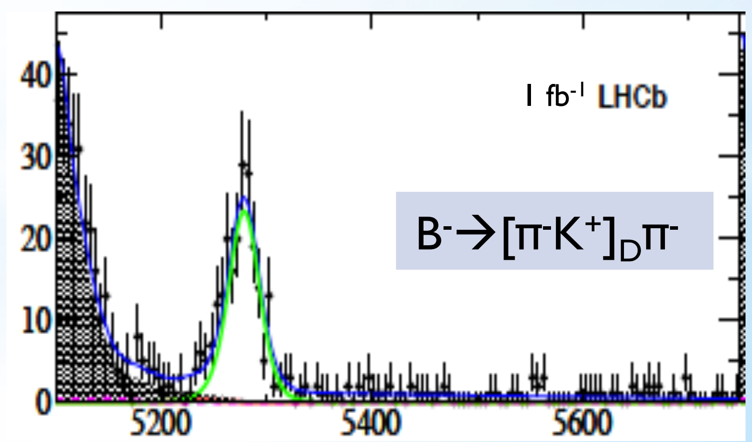
Hadron colliders have a very large cross-section (σ_{bb}(LHC7)~3×10^5 σ_{bb}(Y(4S))), very performing detectors and trigger system. Effective tagging efficiency is typically x10 better at lepton colliders.

arXiv:1006.4241



Energy-substituted mass (GeV/c^2)

arXiv:1203.3662

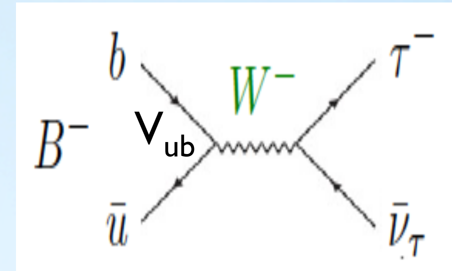


Invariant mass (MeV/c^2)

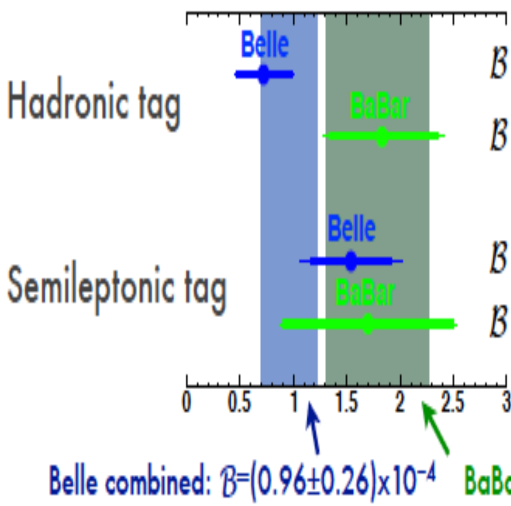
Tree Level Measurements: arg(V_{ub})

b→u: Charged Higgs at tree level?

For some time the measured BR($B\to\tau\nu$) has been about **a factor two higher than the CKM fitted** value (3σ), in better agreement with the **inclusive V_{ub}** result (about 30% higher than exclusive). Measurement very challenging at hadron colliders.



On the other hand, we knew from LEP: $W\to\tau\nu / W\to l\nu \sim 1.06\pm0.03$



PRL 110, 131801 (2013)

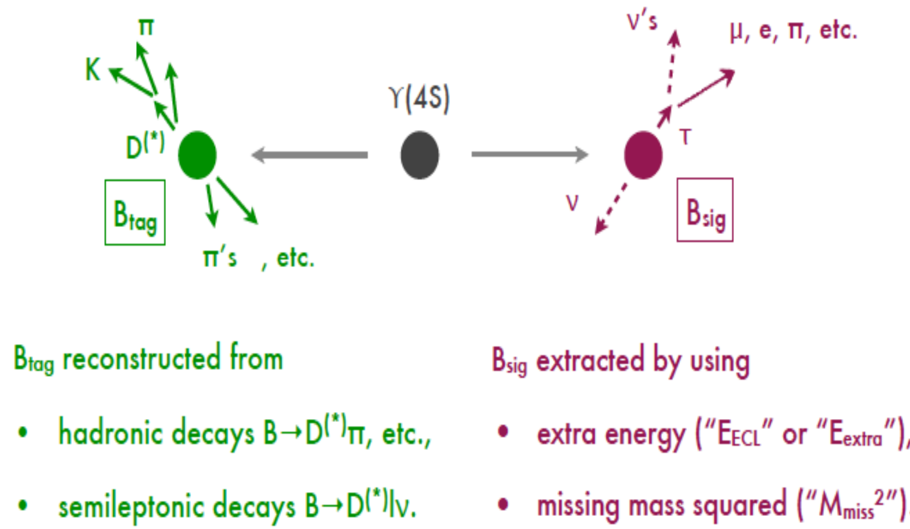
$\mathcal{B} = [0.72^{+0.27}_{-0.25}(\mathrm{stat}) \pm 0.11(\mathrm{syst})] \times 10^{-4}$

$\mathcal{B} = [1.83^{+0.53}_{-0.49}(\mathrm{stat}) \pm 0.24(\mathrm{syst})] \times 10^{-4}$

arXiv:1207.0698 (2012)

$\mathcal{B} = [1.54^{+0.38}_{-0.37}(\mathrm{stat})^{+0.29}_{-0.31}(\mathrm{syst})] \times 10^{-4}$

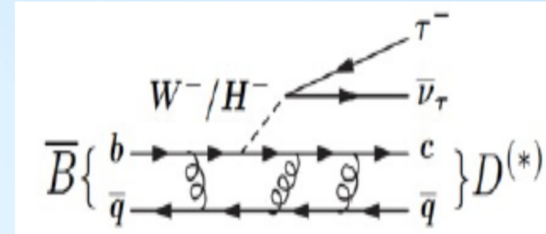
$\mathcal{B} = [1.7 \pm 0.8(\mathrm{stat}) \pm 0.2(\mathrm{syst})] \times 10^{-4}$



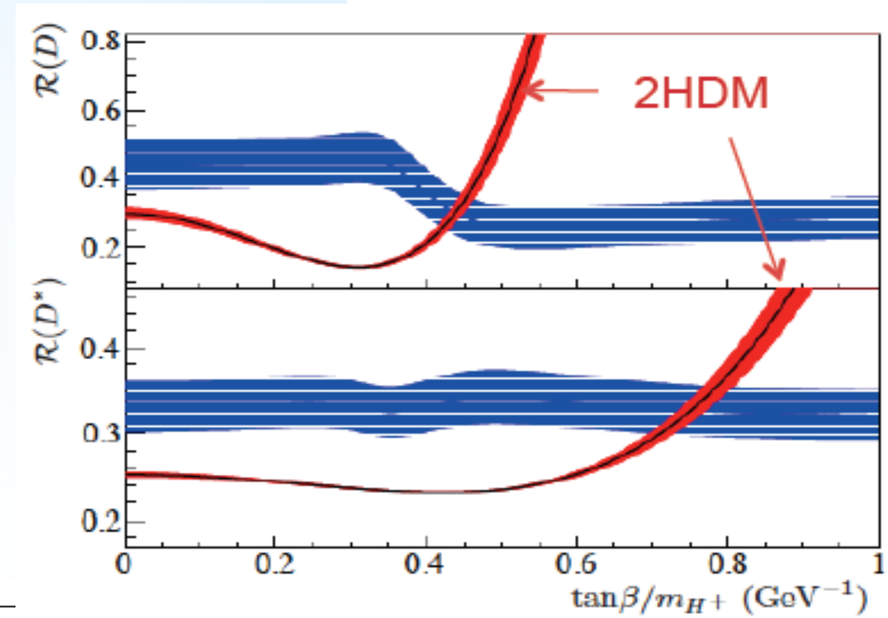
Summer 2012 **Belle** presented a more precise hadron tag analysis, in better agreement with the fitted CKM value:

World average **BR($B\to\tau\nu$)$_{exp}$= (1.15 ± 0.23)x10^{-4}** **vs** **CKM fit:(0.83 ± 0.09)x10^{-4}**

b→c: Charged Higgs at tree level?



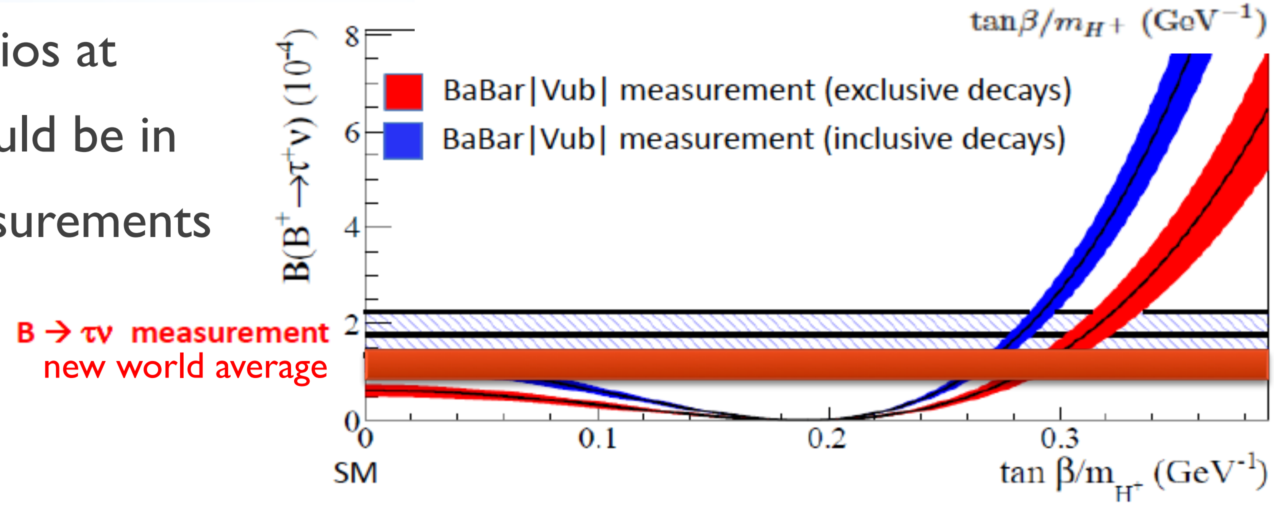
BABAR also presented by Summer 2012 a more precise measurement of BR(B→D(*) τ ν)/BR(B→D(*)l ν). Ratio cancels V_{cb} and QCD uncertainties. Combined D and D* BABAR results are **3.4 σ higher than SM**



Belle should be able to reduce the uncertainties on B→D(*) τ ν at similar level than BABAR.

Not obvious NP explanation.

2HDM does not seem to be able to explain the measured ratios at BABAR, and in any case would be in tension with the latest measurements of BR(B→ τ ν).



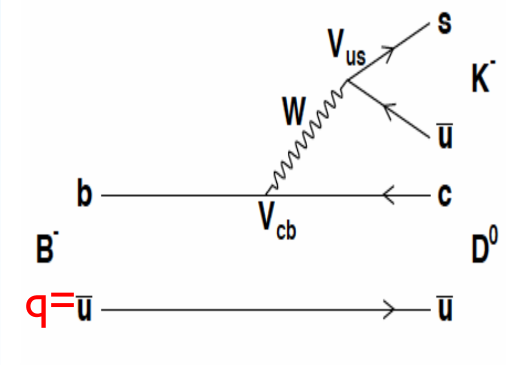
V_{ub} phase: Experimental Strategies

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

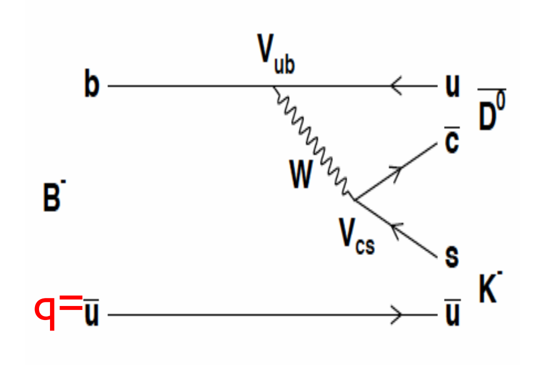
$B^{\pm} \rightarrow DX_s$ $X_s=\{K^{\pm}, K^{\pm}\pi\pi, K^{*\pm},\ldots\}$

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: $B^{\pm}$ Decays

CP modes

average of *KK* and *ππ modes*

$$\frac{\langle \Gamma(B^{\pm}\to[\pi\pi]_D K^{\pm}), \Gamma(B^{\pm}\to[KK]_D K^{\pm}) \rangle}{\Gamma(B^{\pm}\to[K\pi]_D K^{\pm})}$$

favoured mode

$$\frac{\Gamma(B^-\to D_{CP}K^-) - \Gamma(B^+\to D_{CP}K^+)}{\Gamma(B^-\to D_{CP}K^-) + \Gamma(B^+\to D_{CP}K^+)}$$

$$R_{CP+} = 1 + {r_B}^2 + 2r_B \cos\delta_B \cos\gamma$$

$$A_{CP+} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + {r_B}^2 + 2r_B \cos\delta_B \cos\gamma}$$

ADS mode

$$\frac{\Gamma(B^{\pm}\to[\pi K]_D K^{\pm})}{\Gamma(B^{\pm}\to[K\pi]_D K^{\pm})}$$

favoured mode

$$\frac{\Gamma(B^-\to D_{ADS}K^-) - \Gamma(B^+\to D_{ADS}K^+)}{\Gamma(B^-\to D_{ADS}K^-) + \Gamma(B^+\to D_{ADS}K^+)}$$

$$R^{ADS} = \frac{{r_B}^2 + {r_D}^2 + 2r_B r_D \cos(\delta_B+\delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2r_B r_D \cos(\delta_B-\delta_D)\cos\gamma}$$

$$A^{ADS} = \frac{2r_B r_D \sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2 + {r_D}^2 + 2r_B r_D \cos(\delta_B+\delta_D)\cos\gamma}$$

$B^{\pm}\to D[KK,\pi\pi]K^{\pm}$ with D decays in CP modes *(Gronau, London, Wyler) PLB 253 (1991) 483 and PLB265 (1991) 172.*

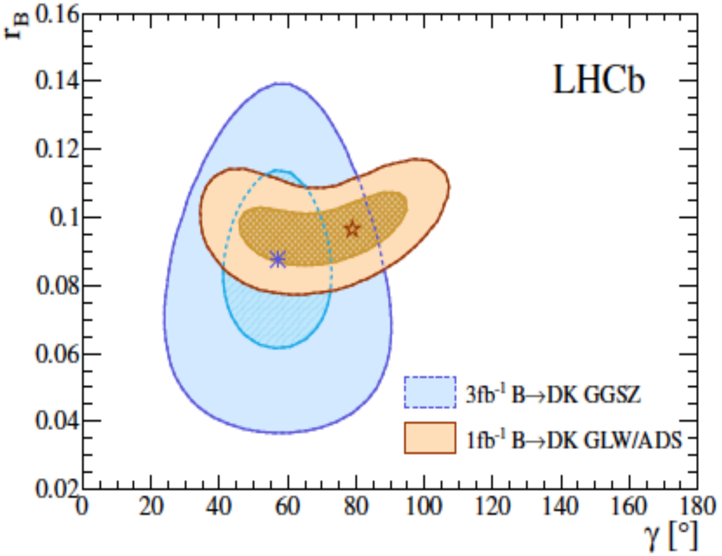
$B^{\pm}\to D[K\pi]K^{\pm}$ *(Atwood, Dunietz, Soni) PRL 78 (1997) 3257..*

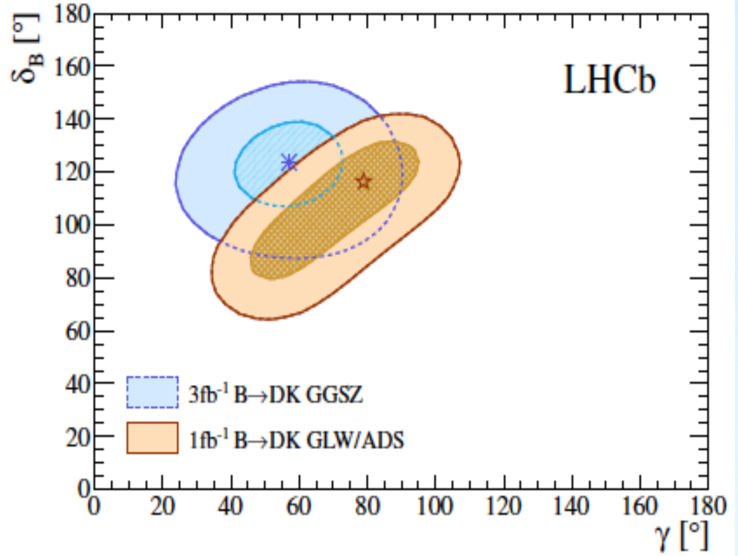
Same argument works for $D\pi$ final states, but r_B (hence interference) is ~10 smaller.

A variation of the above methods, is when $D\to K_s h^+h^-$, *(Giri, Grossman, Soffer and Zupan,* PRD68, 054018 (2003)) .
A Dalitz analysis of the three-body decays allows for an increase in sensitivity.

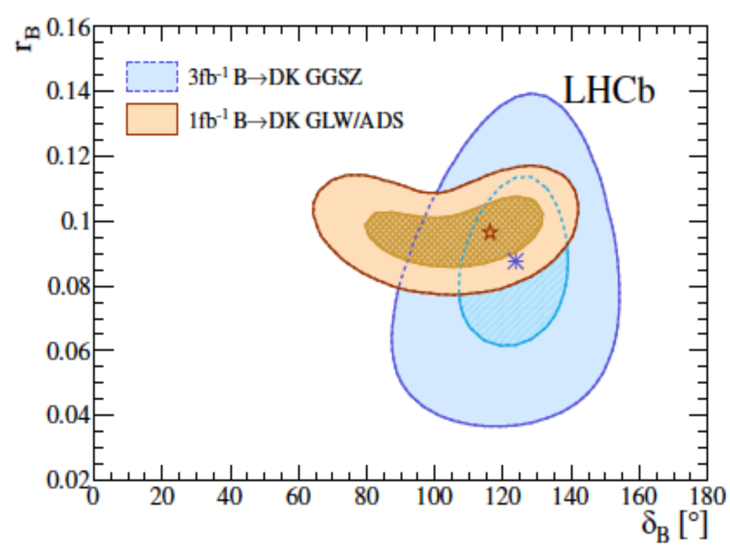
LHCb-CONF-2013-006

V_{ub} phase: LHCb combination





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



LHCb preliminary (B→DK):

γ = 67±12° (r_B(DK)=0.092±0.008)

Excellent internal compatibility of GGSZ and GLW/ADS.

LHCb (γ = 67±12°) and B-factories (γ = 66±12°) tree level measurements are in **good agreement** with the indirect determination from loop measurements ($\gamma = 66.6^{+6.4}_{-6.3}$°).

ΔF=2 Box Measurements

Δ F=2 box in b→d transitions: CP asymmetries in $B_s \to J/\Psi K_s$

CKMFITTER (BABAR+Belle) combination: β = **21.38 $^{+0.79}_{-0.77}$°**

PLB 721 (2013) 24

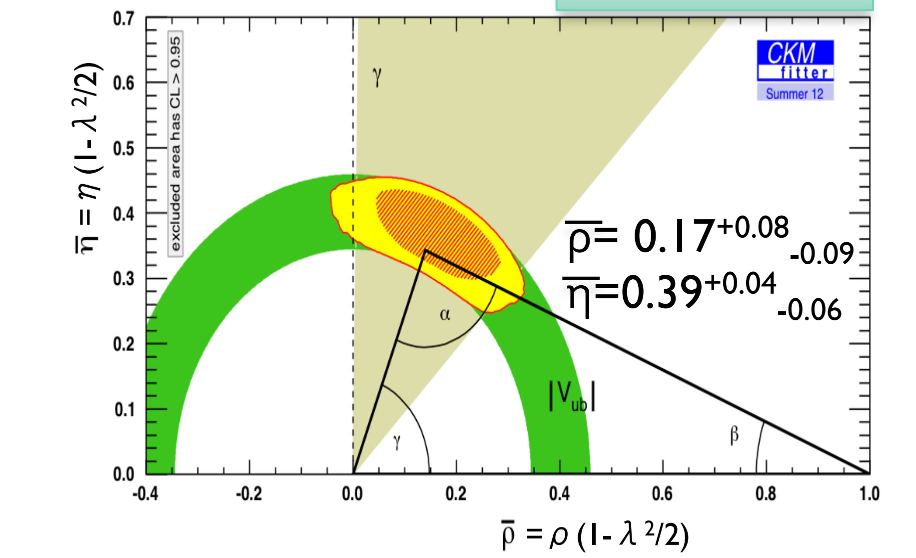
LHCb (1/fb): β = **23.4 $^{+3.6}_{-3.2}$°**

$$\tan\beta \approx \frac{\eta}{1-\rho}\left(1-\frac{\lambda^2}{2}\right)$$

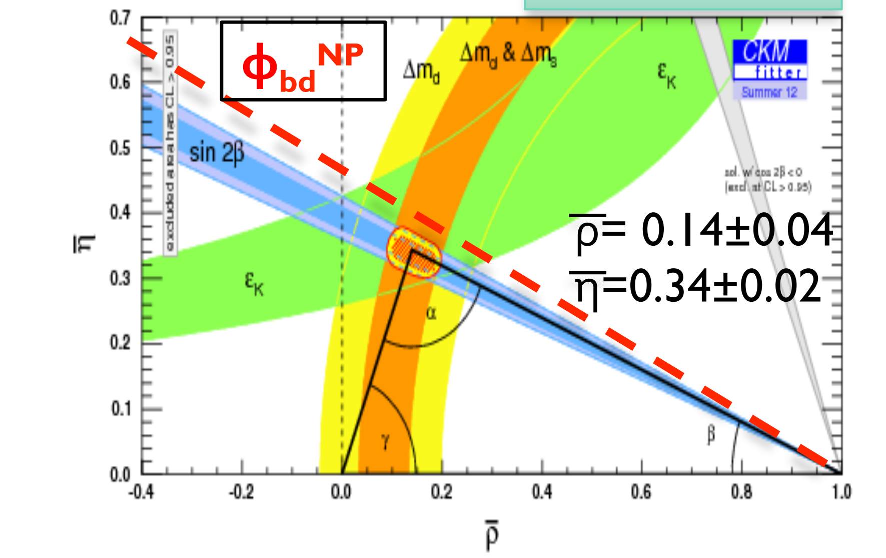
To be compared with the indirect determination using "tree level measurements": β = **24.9+0.8-1.9°**

If we assume the SM, B-factories have measured the phase of V_{td} better than 4% from b→d transitions in box diagrams. However, NP must be contributing at some level! Therefore, the precise measurement of β is in fact, a precise measurement of (β + ϕ_{bd}^{NP}). ϕ_{bd}^{NP} can be as large as O(5°) and still be consistent!

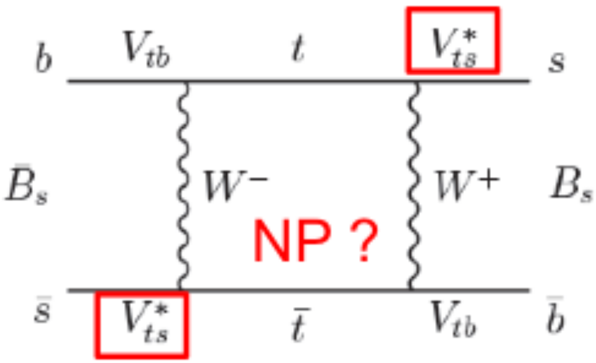
Tree measurements



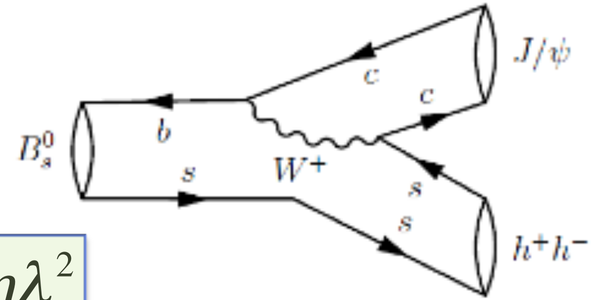
Loop measurements



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



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

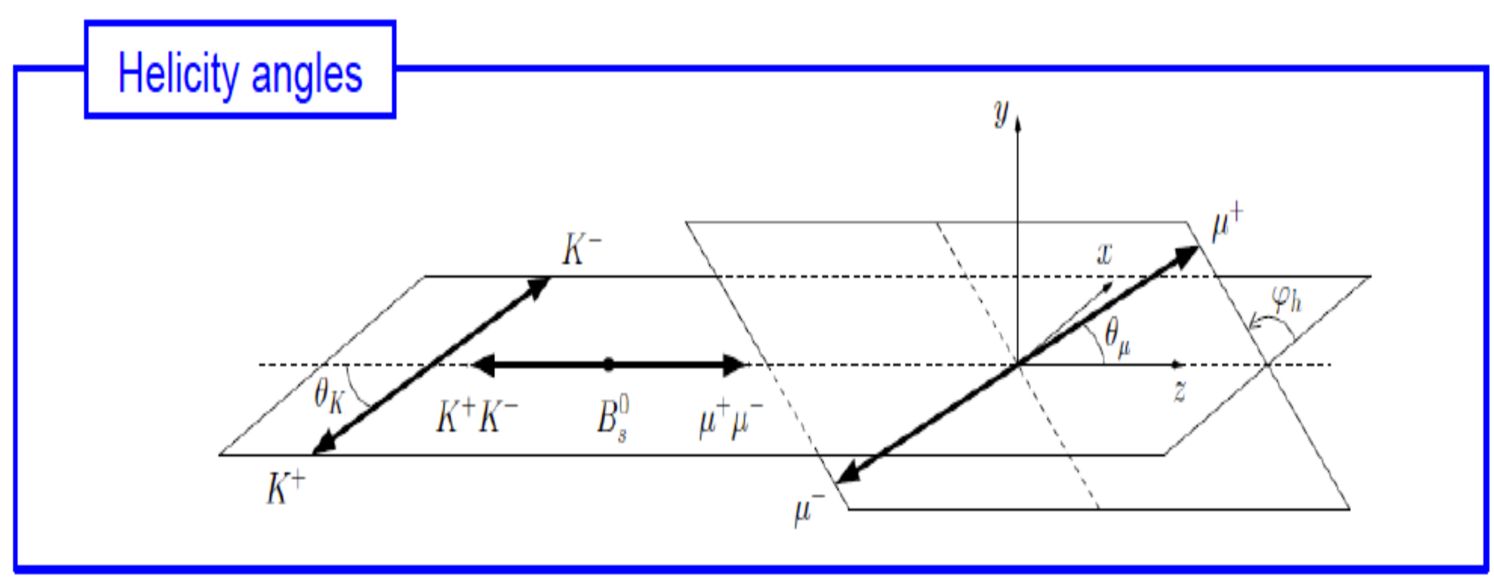


+ small penguin pollution

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

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

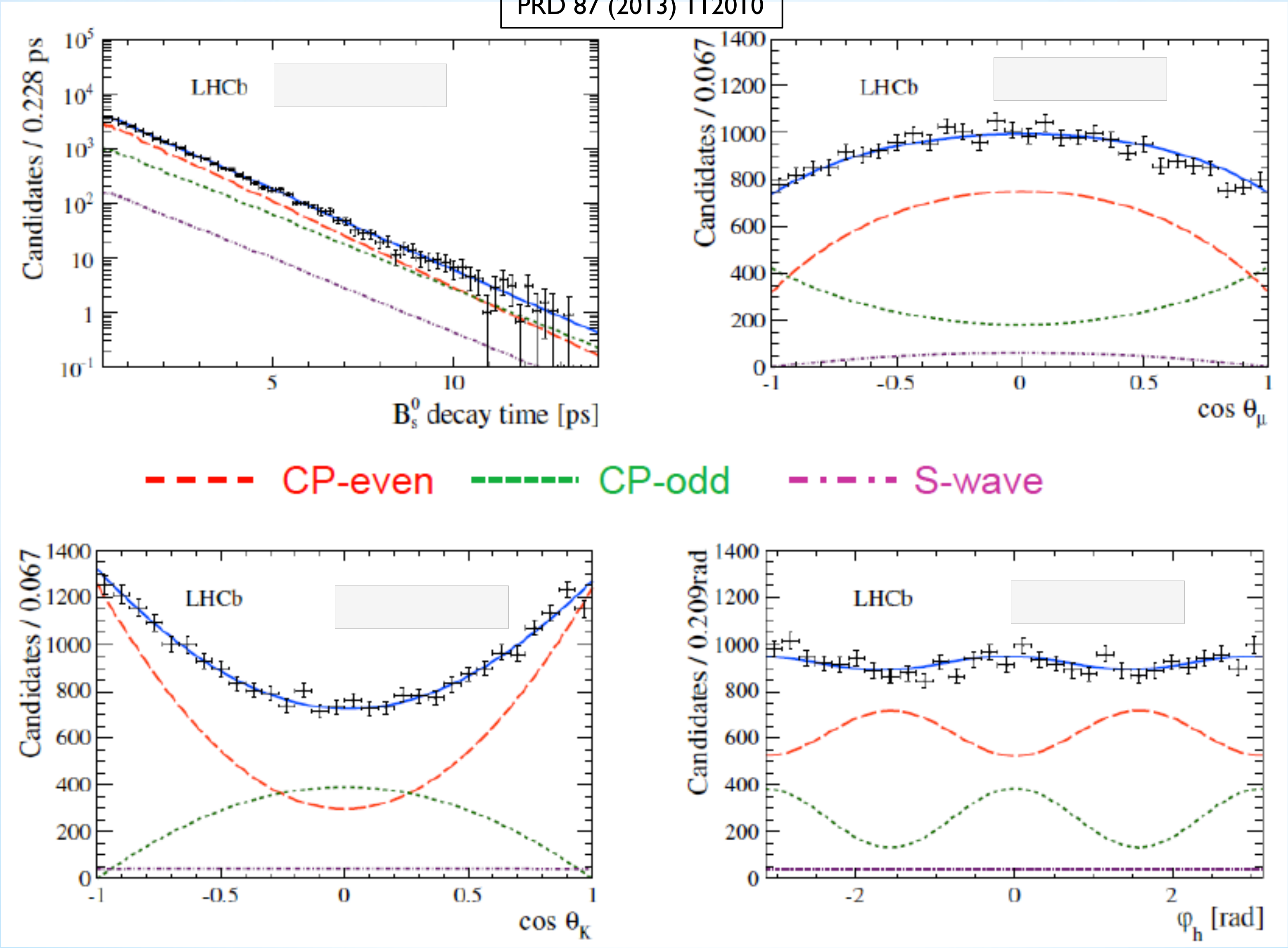
Angular analysis is needed in **B_s→J/Ψ Φ** decays, to disentangle statistically the CP-even and CP-odd components. Use the helicity frame to define the angles: θ_K, θ_μ, ϕ_h.



Δ F=2 box in b→s transitions

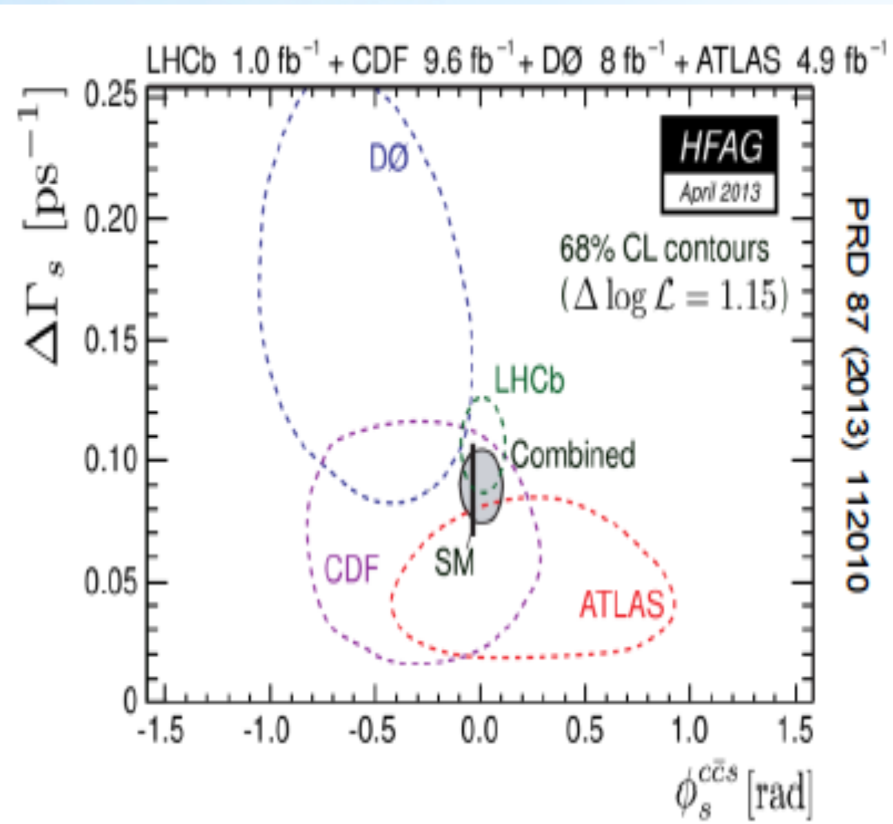
LHCb flavour tagging improved with the inclusion now of Kaon Same Side Tag: ε **D² = (3.13 ± 0.23)%**

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 1/fb (27.6k candidates, PRD 87 (2013) 112010) combined with the results using $B_s \to J/\Psi\, \pi\pi$ decays (PLB 713 (2012) 378) gives: $\Phi_s = 0.01 \pm 0.07\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad}$, i.e., $\Phi_s = 0.6 \pm 4.0°$



This result can be compared with the indirect determination using "tree measurements", $\mathbf{\Phi_s = -2.3^{+0.1}_{-0.3}}$**°**.

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

Meanwhile, other LHC experiments have started contributing. ATLAS tagged analysis with 5/fb (22.6k candidates) and **(** $\boldsymbol{\varepsilon D^2 = (1.45 \pm 0.05)\%}$ **)** of $B_s \to J/\Psi\, \Phi$ decays gives:

ATLAS-CONF-2013-039

$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$

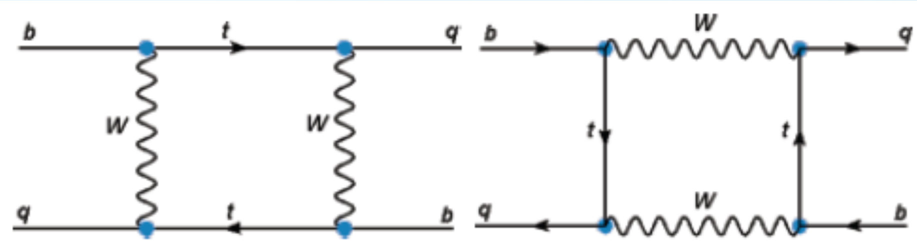
which corresponds to $\mathbf{\Phi_s = 7 \pm 16°}$ **.**

So far there is no evidence for NP contributions neither on b→d nor on b→s box diagrams.

Δ F=2 box in b→q transitions

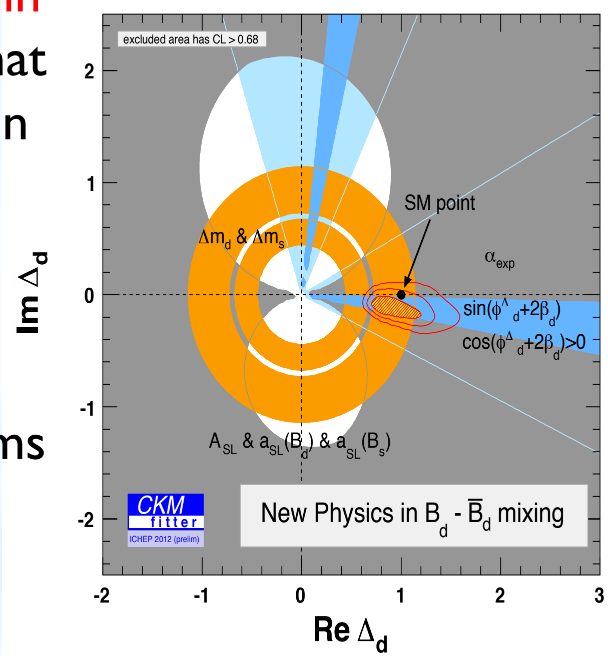
$$\left\langle B_q^0 \right| M_{12}^{SM+NP} \left| \overline{B}_q^0 \right\rangle \equiv \Delta_q^{NP} . \left\langle B_q^0 \right| M_{12}^{SM} \left| \overline{B}_q^0 \right\rangle$$

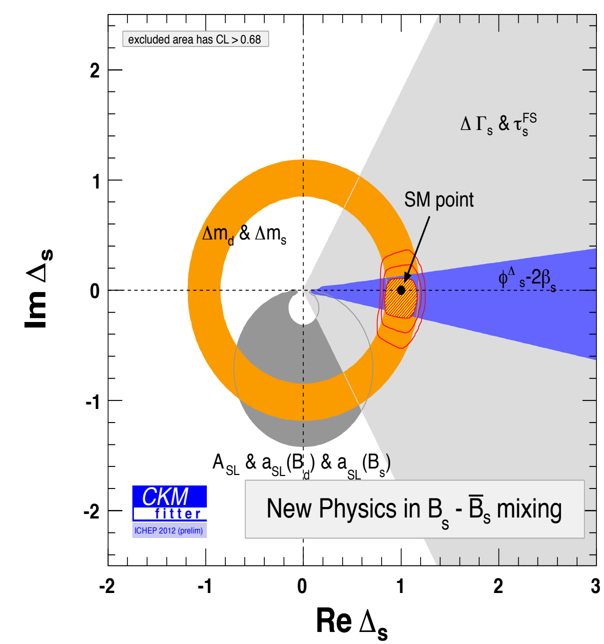
$$\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i\ \mathrm{Im}(\Delta_q) = |\Delta_q| e^{i\phi_q^\Delta}$$



No significant evidence of NP in B_d or B_s mixing . Remember that what is named SM prediction in these plots, is in fact the determination from other measurements (tree level).

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



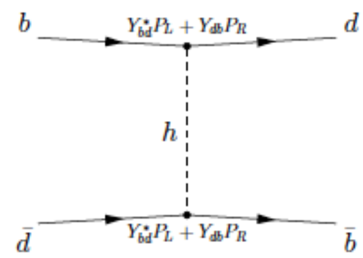


<u>Need to increase precision to disentangle NP phases of few percent in B_d and B_s mixing</u>

Δ F=2 box: Yukawa couplings constraints

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

Meson Mixing

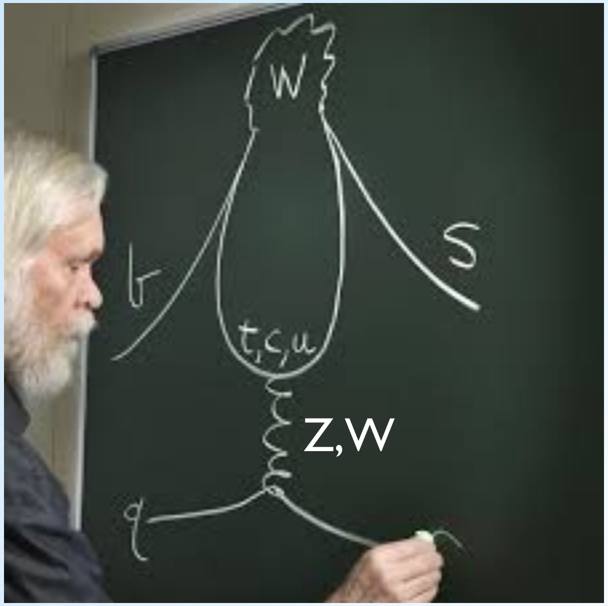


* Meson mixing's powerful:

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^0_d 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^0_s 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]	$\mathrm{Re}(Y^2_{ds})$, $\mathrm{Re}(Y^2_{sd})$	$[-5.9 \ldots 5.6] \times 10^{-10}$	
	$\mathrm{Im}(Y^2_{ds})$, $\mathrm{Im}(Y^2_{sd})$	$[-2.9 \ldots 1.6] \times 10^{-12}$	8×10^{-9}
	$\mathrm{Re}(Y^*_{ds} Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$	
	$\mathrm{Im}(Y^*_{ds} Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$	

Upper values expected for "natural" models

"Natural" models are constrained!



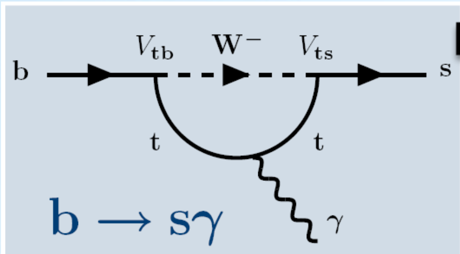
ΔF=1 EW Penguins

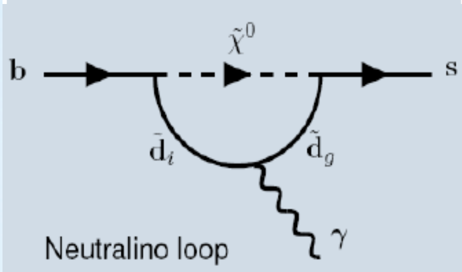
Three impersonations of the EW penguin

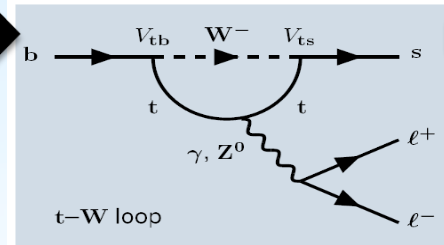
α_{QED} suppression → helicity suppression

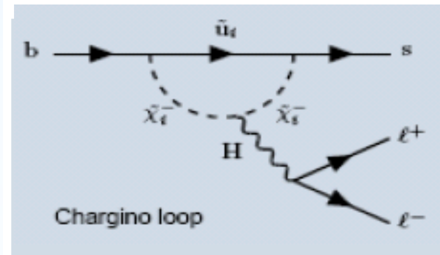
SM

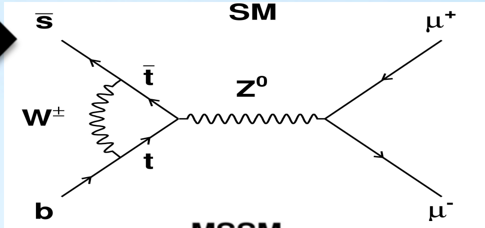
MSSM

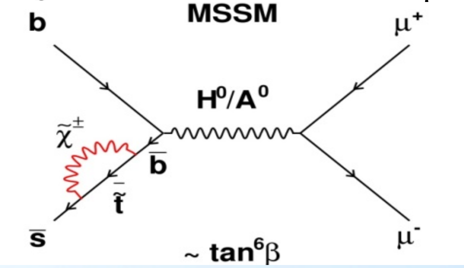








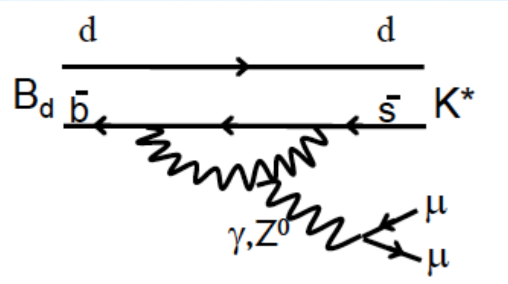




	Relevant Operators	*BR*(SM)	*BR* exp	
$B_s \to \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	Large theory uncertainties O(20%)	$(3.5\pm0.4)\cdot10^{-5}$ LHCb: arXiv:1209.0313	γ polarization
$B^0 \to K^* \mu^+\mu^-$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu (\gamma_5) \ell$		$(1.16\pm0.19)\cdot10^{-6}$ 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 EW penguins in b→s transitions: B→K*$\mu\mu$ angular analysis

b→s ($|V_{tb}V_{ts}| \alpha \lambda^2$)

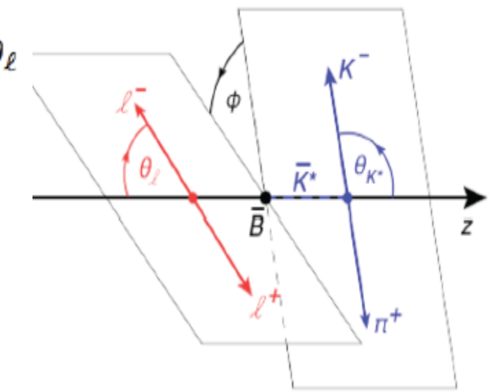


B→K*$\mu\mu$ is the golden mode to test new vector(-axial) couplings in b→s transitions.

K*→Kπ is self tagged, hence angular analysis ideal to test helicity structure.

Sensitivity to O_7, O_9 and O_{10} and their primed counterparts. This analysis is bound to be **one of the stronger constraints** in models for NP with future statistics.

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

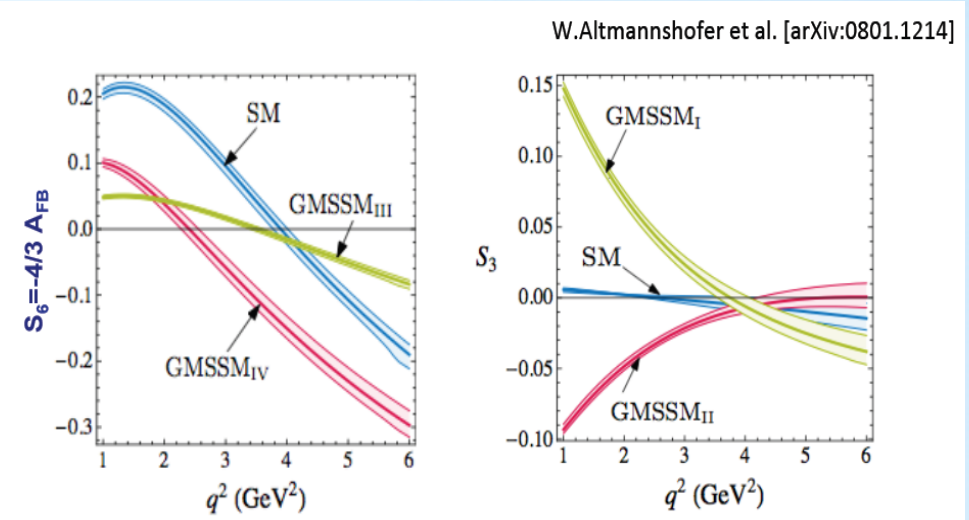


Results from **B-factories and CDF** very much limited by the statistical uncertainty. **LHCb** already has with 1/fb the largest sample (0.9k candidates).

Hadronic uncertainties under reasonable control for:

- **F_L:** Fraction of K* longitudinal polarization.
- **$S_6=-4/3A_{FB}$**: Forward-Backward asymmetry of the lepton.
- **S_3 α $A^2_T(1-F_L)$**: Asymmetry in K* transverse polarization.

A_{FB} zero crossing point particularly well predicted within the SM.



Moreover, the dependence with form factors can be further reduced with a redefinition of observables:

$$A_T^{(2)} = \frac{2S_3}{(1-F_L)}$$

$$A_T^{Re} = \frac{S_6}{(1-F_L)}$$

$$P_4' = \frac{S_4}{\sqrt{(1-F_L)F_L}}$$

$$P_5' = \frac{S_5}{\sqrt{(1-F_L)F_L}}$$

$$P_6' = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$

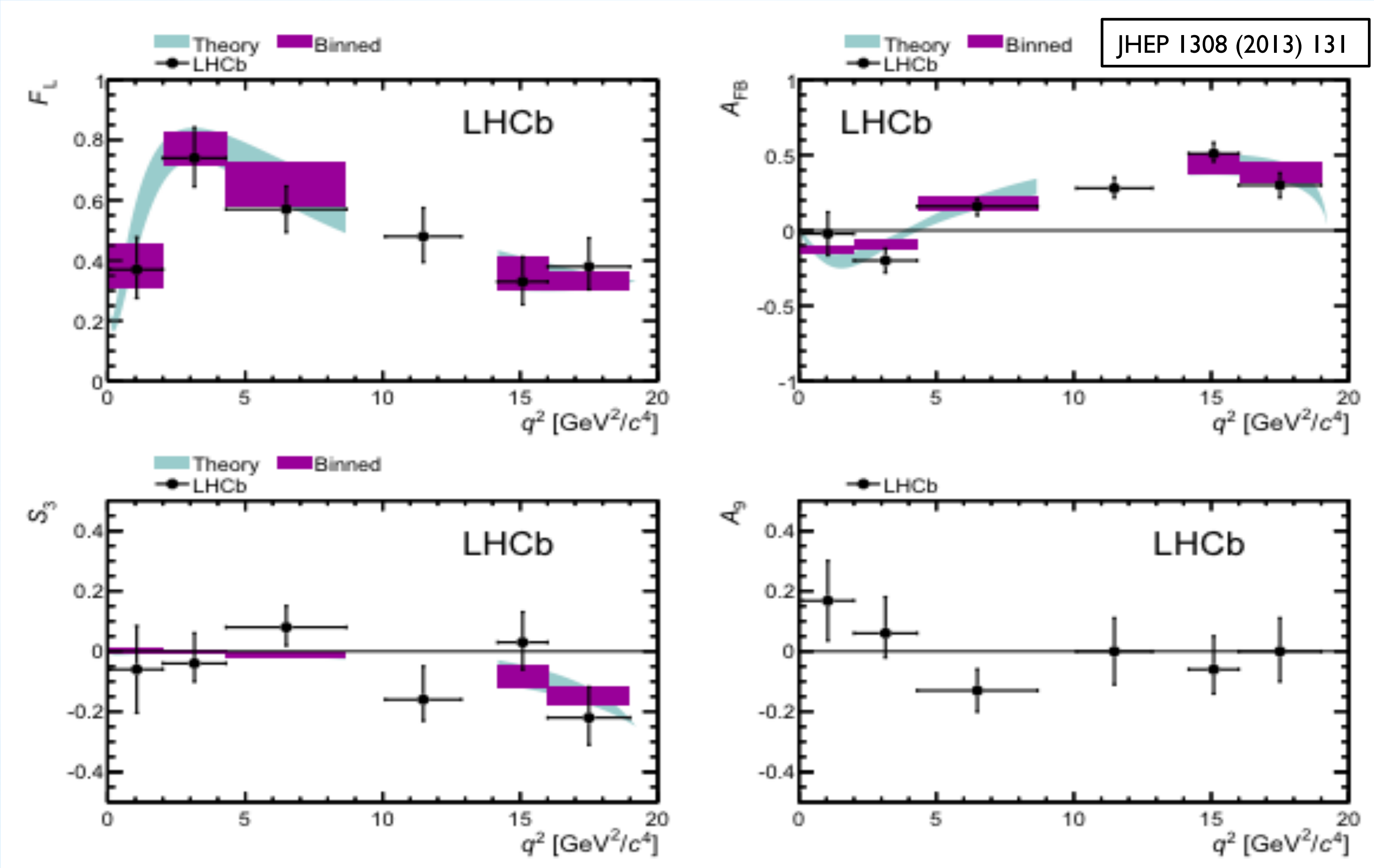
$$P_8' = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

B→K* μ μ Angular Analysis Results

Folding technique (Φ→Φ+π) for Φ<0, reduces the number of parameters to fit: F_L, S_3,S_6 and S_9.

JHEP 1308 (2013) 131

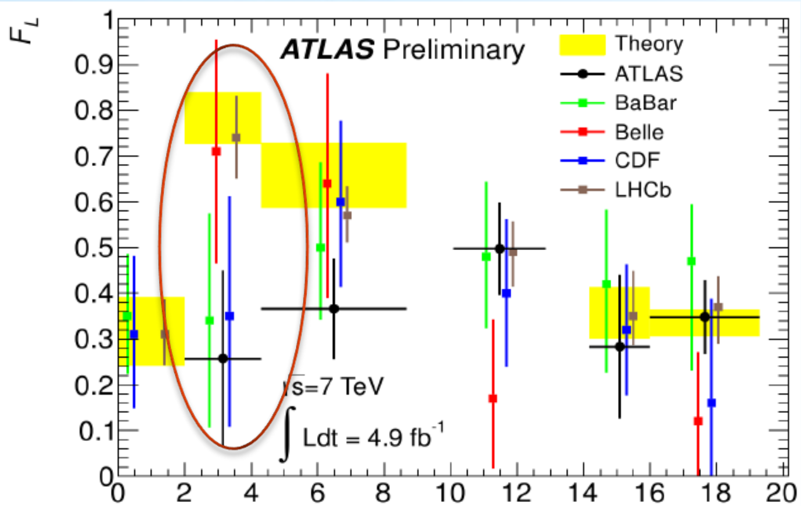


Within uncertainties observables are consistent with the SM.

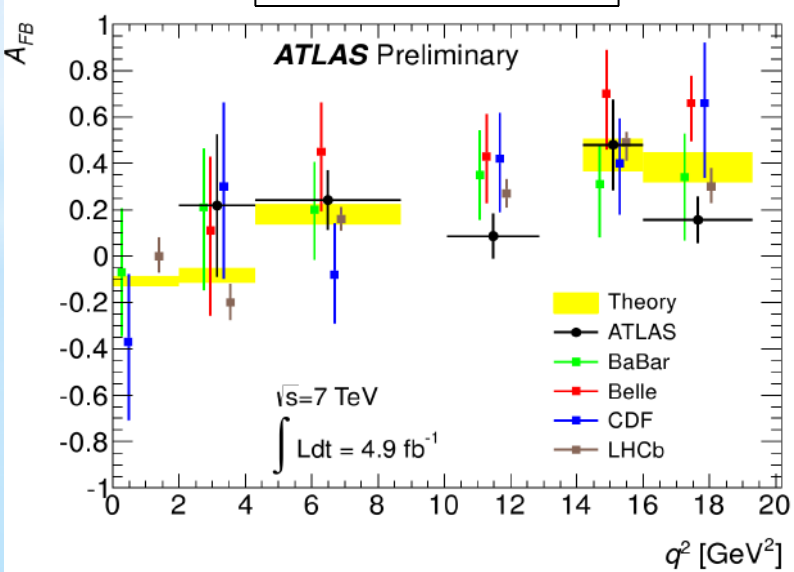
$q^2(A_{FB}=0)=4.9\pm0.9$ GeV^2/c^4

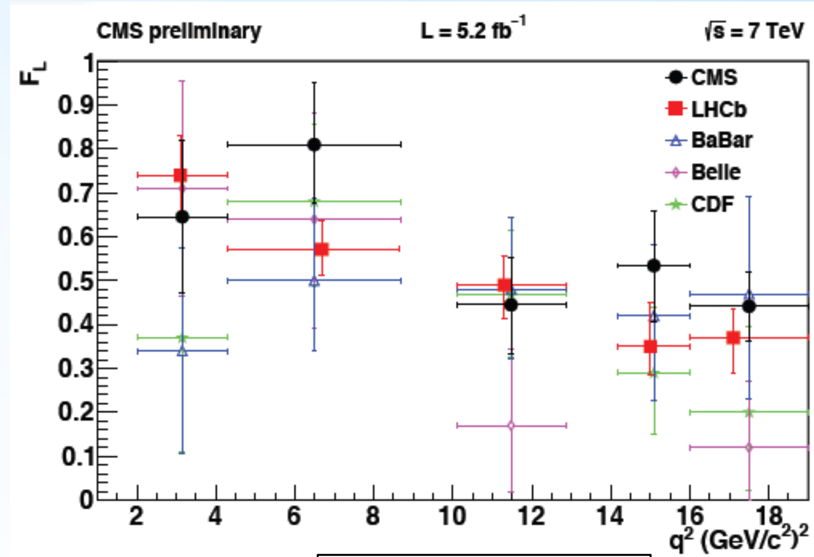
ATLAS, CMS B→K* μ μ angular analysis

And fortunately also ATLAS and CMS with ~0.4k candidates in 5/fb start to contribute to this analysis. They are particularly competitive at large q^2.

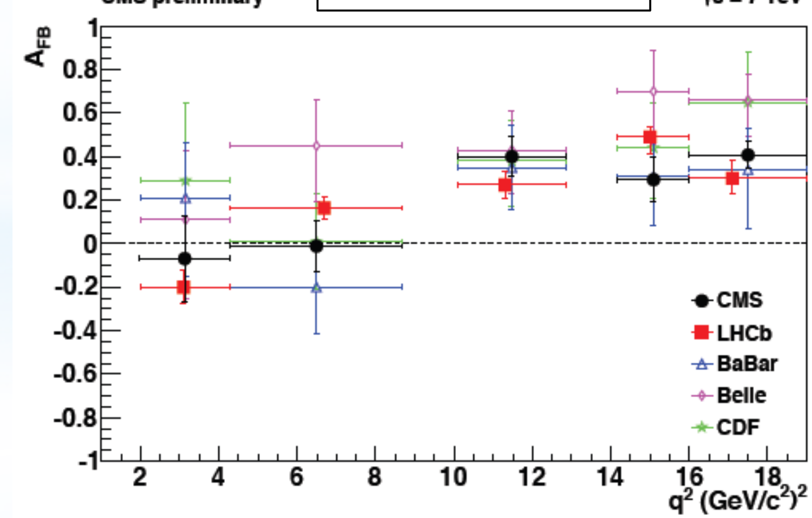


ATLAS-CONF-2013-038





CMS-PAS-BPH-11-009



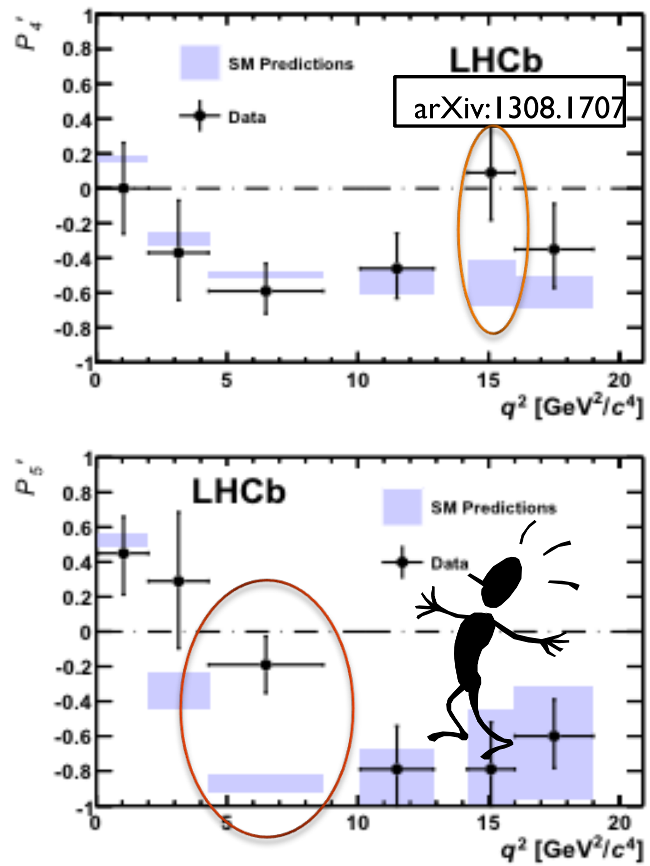
Other folding techniques, can give access to the rest of observables.

$$P'_4,\ S_4:\ \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_5,\ S_5:\ \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_6,\ S_7:\ \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_8,\ S_8:\ \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \to \pi - \theta_K & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases}$$



Most of measurements in good agreement with SM predictions. Only a hint of disagreement in P'_5 at low q^2. With more luminosity a full angular analysis (no folding) will allow to exploit the full statistical power of the data.

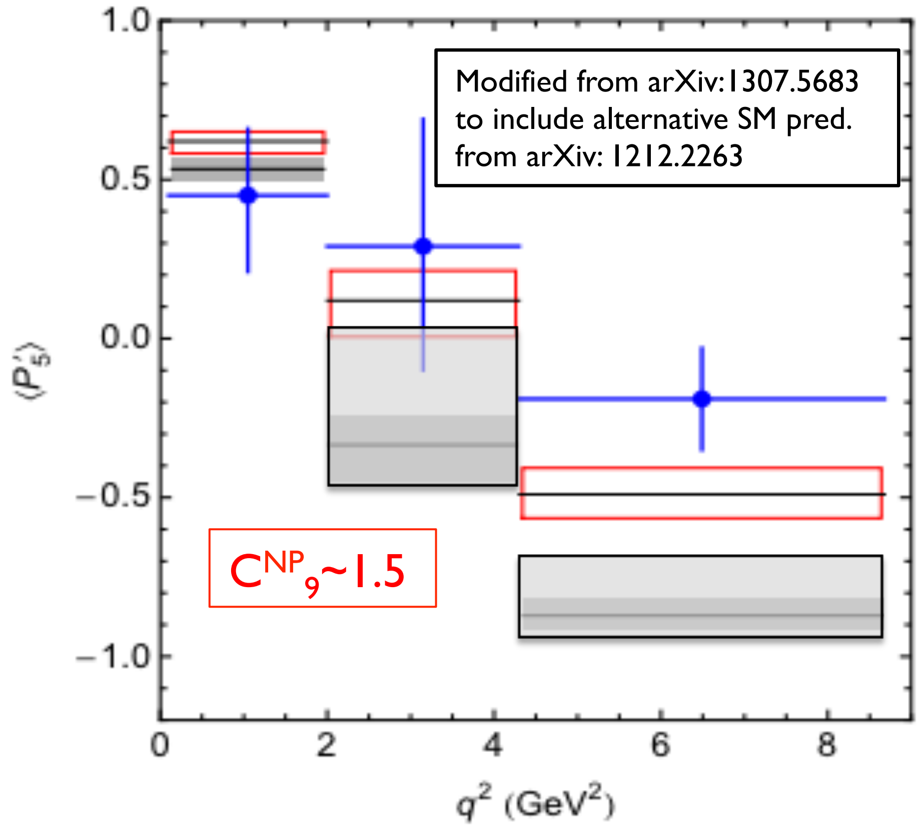


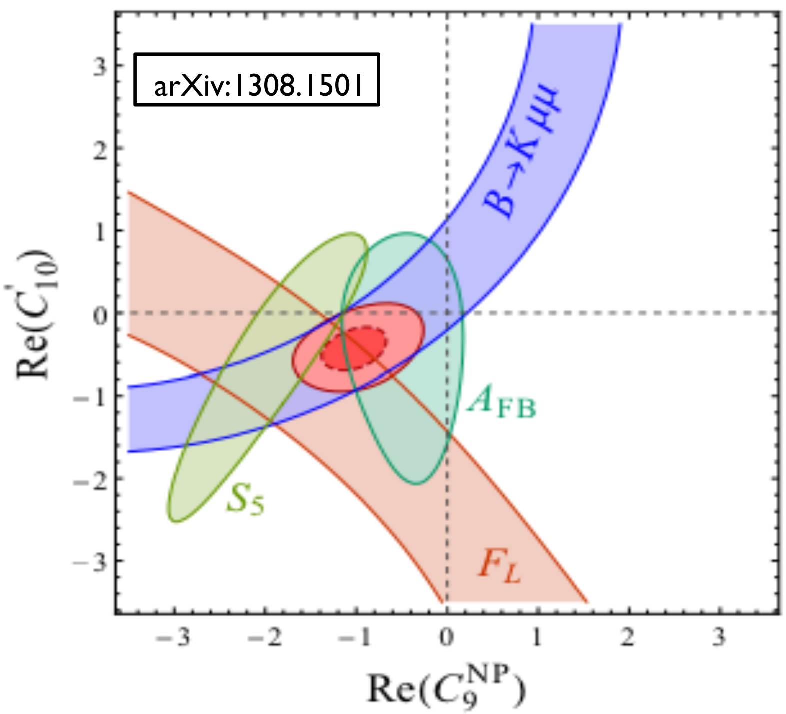
FIG. 4: Improvement in the q^2-dependence of P_5' in the illustrative case $C_9^{NP} = C_{9'}^{NP} = -1.5$ (and NP contributions to the other Wilson coefficients set to zero).

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\, a},$$
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell),$$
$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell), \qquad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell),$$

SM predictions for P'_5 differ significantly between different authors.

Nevertheless, NP contributing to C_9 could provide a better fit to the data, and still be compatible with other measurements.

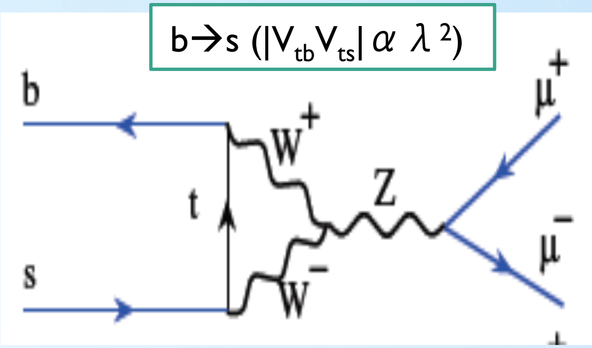
The increase in sensitivity of the analysis with 3/fb could already be tale-telling.



$\Delta F=1$ Higgs Penguins

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,

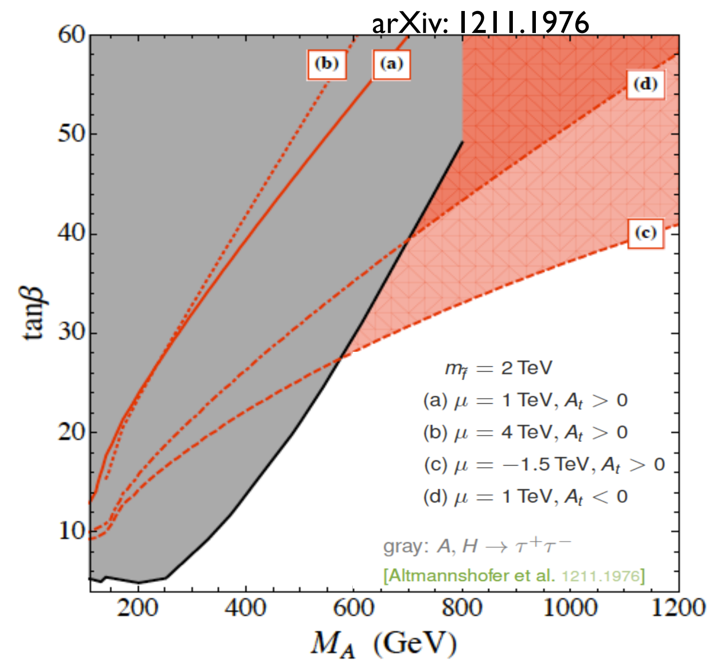
arXiv:1208.0934
arXiv:1303.3820
PRL 109, 041801 (2012)
with input from HFAG.

$BR_{SM}(B_s \to \mu\mu)$ <t> = $(3.56 \pm 0.29)\times 10^{-9}$

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

$$BR(B_q \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3\sin^4\theta_W}|V_{tb}^* V_{tq}|^2\,\tau_{Bq} M_{Bq}^3 f_{Bq}^2 \sqrt{1-\frac{4m_\mu^2}{M_{Bq}^2}}\times$$
$$\times\left\{M_{Bq}^2\left(1-\frac{4m_\mu^2}{M_{Bq}^2}\right)\left(\frac{C_S-\cancel{\mu_q}C_S'}{1+\cancel{\mu_q}}\right)^2+\left[M_{Bq}\left(\frac{C_P-\cancel{\mu_q}C_P'}{1+\cancel{\mu_q}}\right)+\frac{2m_\mu}{M_{Bq}}\left(C_A-C_A'\right)\right]^2\right\}$$

with $\mu_q = m_q/m_b \ll 1$ and $m_\mu/m_B \ll 1$. 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 $\tan^6\beta / M_A^4$

Δ F=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:

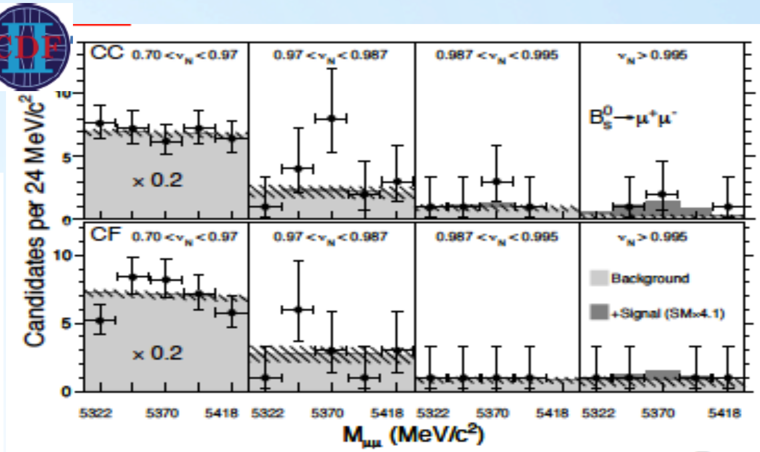
~1/fb at LHCb is equivalent to ~10/fb at CMS, ~20/fb at ATLAS/CDF.

$\Delta F=1$ Higgs penguins in $b \to d,s$ transitions: ATLAS/CDF/D0 Results

CDF analysis strategy very similar than LHCb. Small excess observed over the background-only hypothesis in the B_s mass window (p-value = 0.9%).

CDF: 10 fb^{-1} [PRD 87, 072003 (2013)]

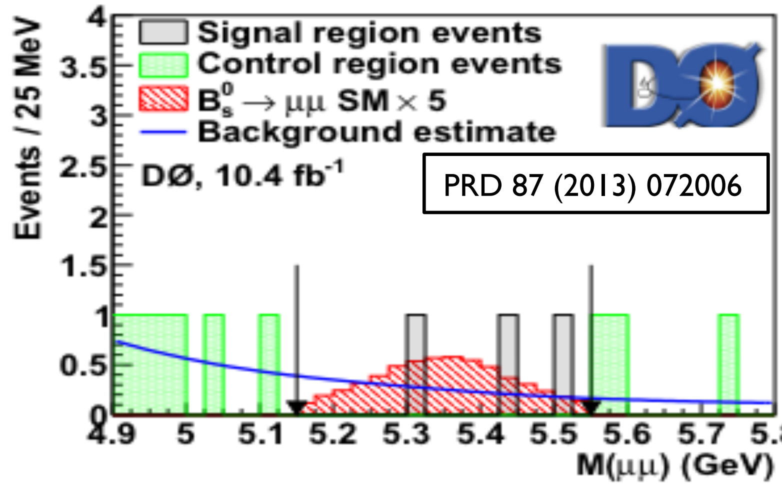
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \in [0.8, 34] \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.6 \cdot 10^{-9}$$
@ 95 % C.L.

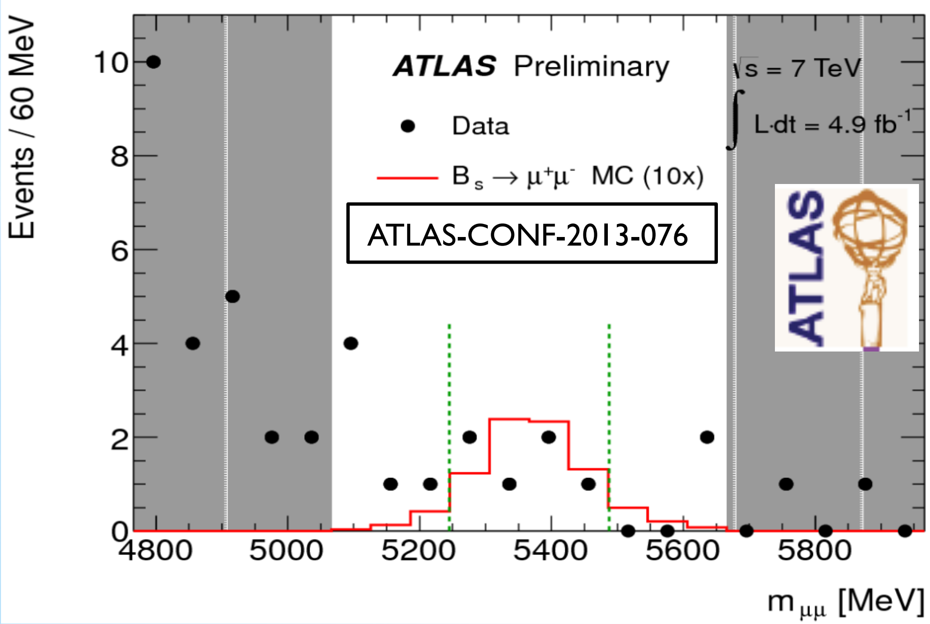


D0 however sees no excess (p-value = 77%).

D0: 10.4 fb^{-1} PRD 87 (2013) 072006

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 15 \cdot 10^{-9} \text{ @ } 95\ \%\ \text{C.L.}$$





ATLAS (like D0) cannot distinguish B_s from B_d and does not observe any excess w.r.t. background-only hypothesis (p-value = 58%).

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 15 \cdot 10^{-9} \text{ @ } 95\ \%\ \text{C.L.}$$

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

CMS (25 fb^{-1}) and **LHCb** (3 fb^{-1}) have sensitivity to BR($B_s \rightarrow \mu^+\mu^-$) =3x10^{-9}, with 4.8$\sigma$ (CMS) and 5.0σ (LHCb) expected excess w.r.t. background-only hypothesis in the B_s mass window.

Observed:

$$\boxed{BR(B_s \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}}$$

$$\boxed{BR(B_s \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}}$$

LHCb

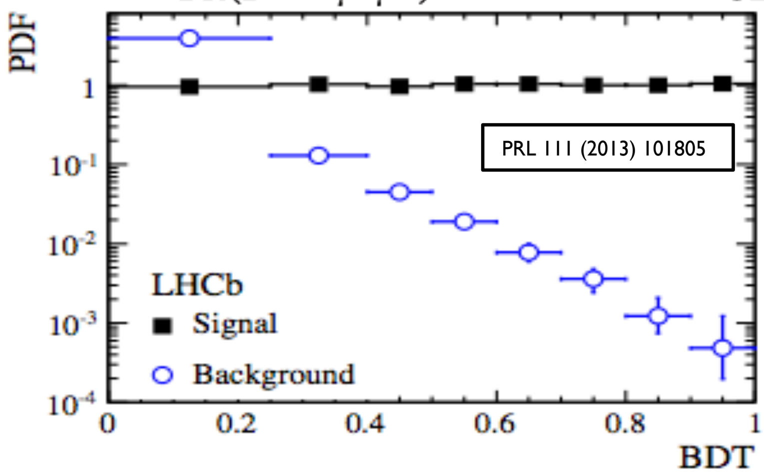
$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-9}$$

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

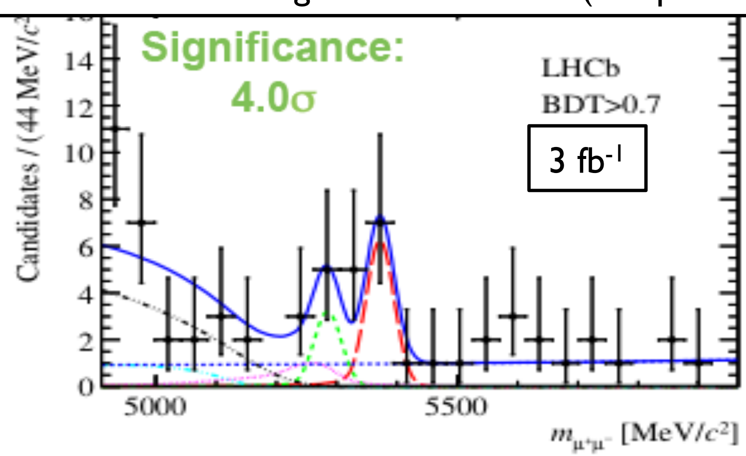
CMS

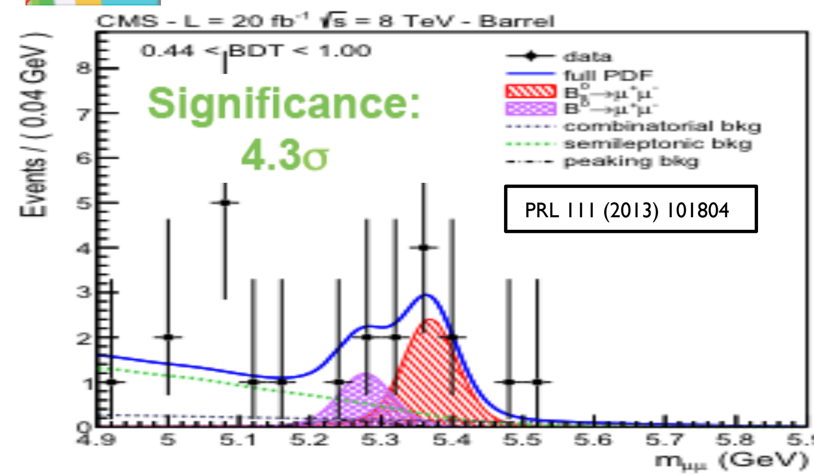
$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-9}$$

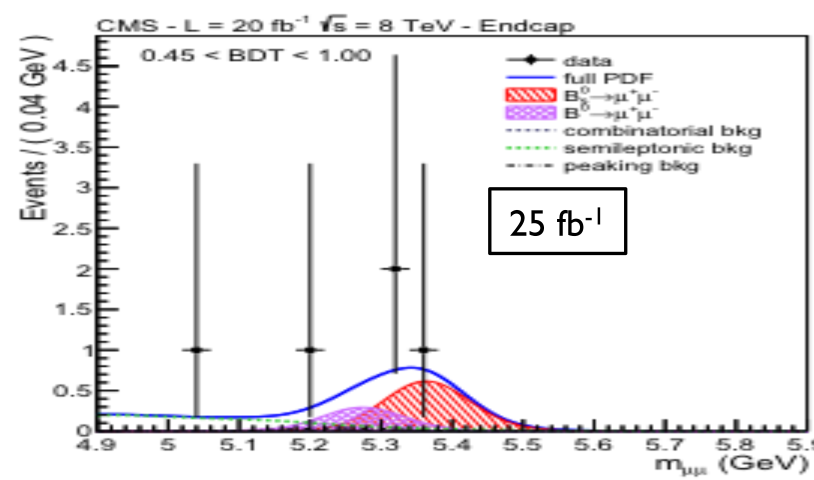
$$BR(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9} \ @95\%CL$$



PDF calibrated using control channels (indep. of MC)





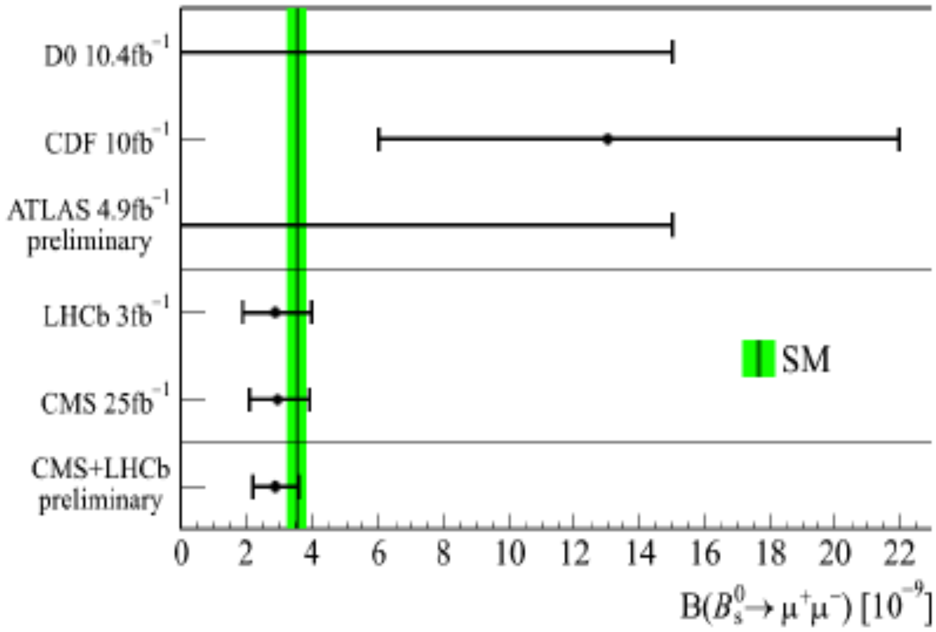


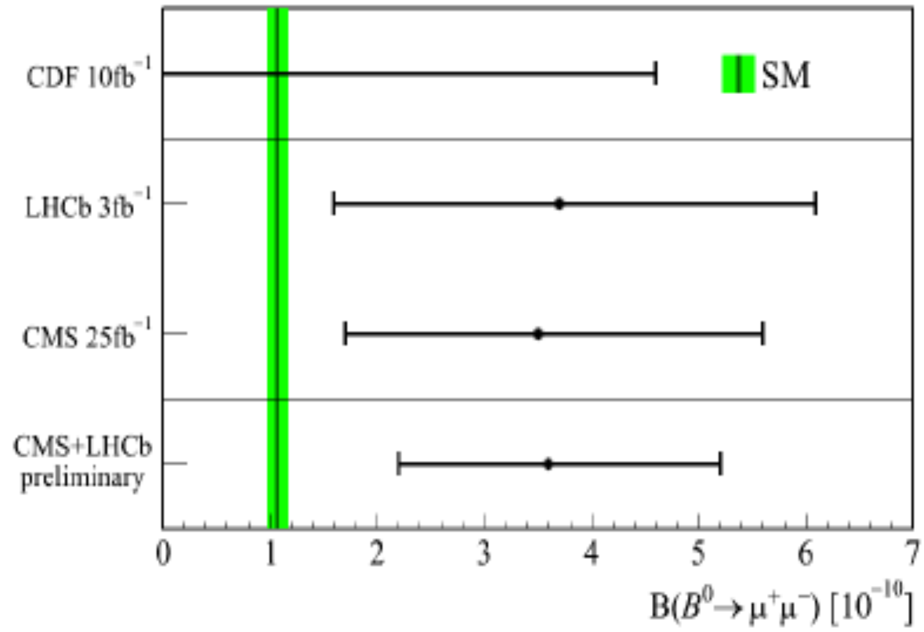
Δ F=1 Higgs penguins in b→d,s transitions: Results

Observation:

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

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

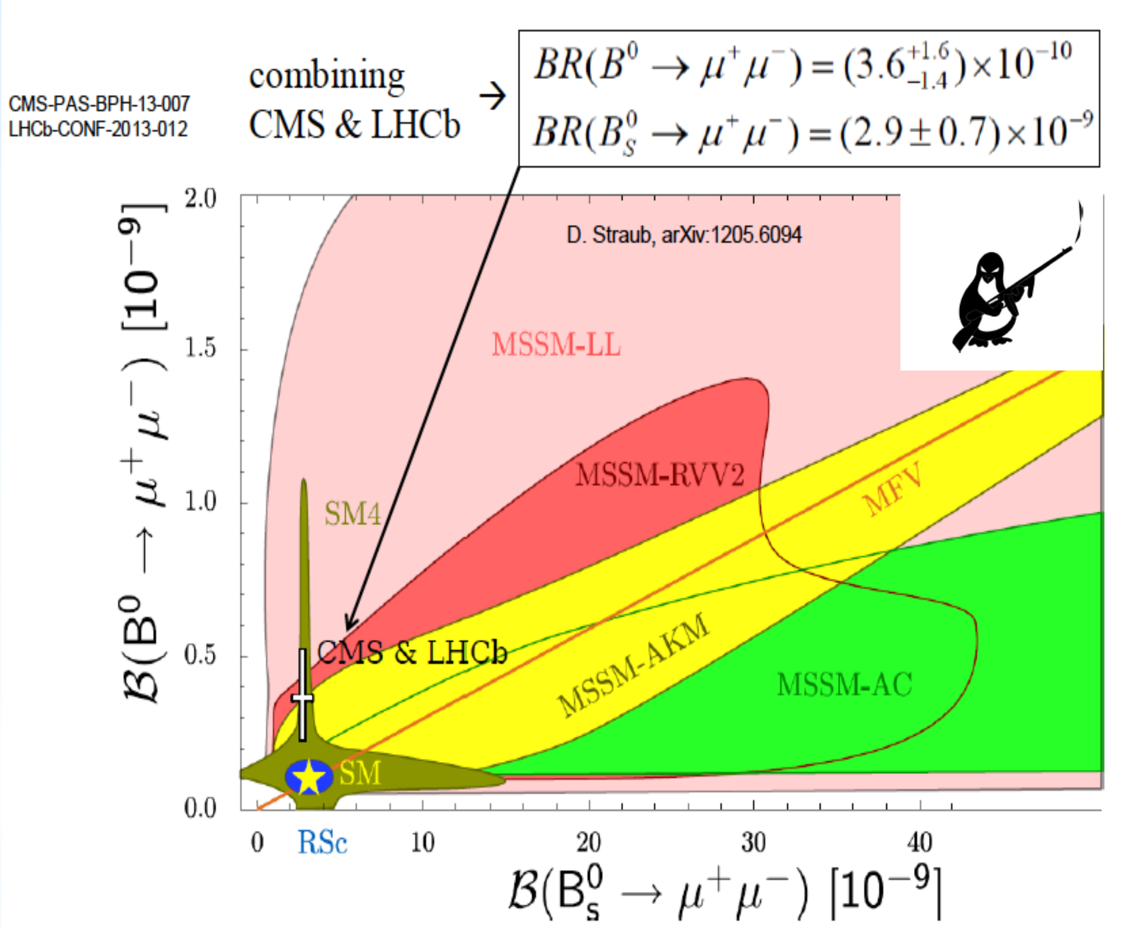


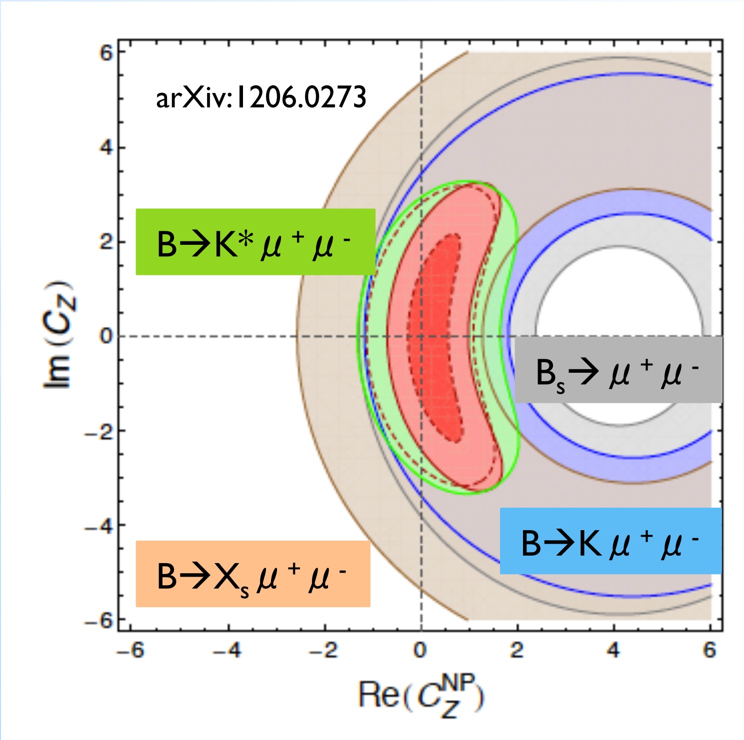


Δ F=1 Higgs penguins in b→s,d transitions: Implications

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.





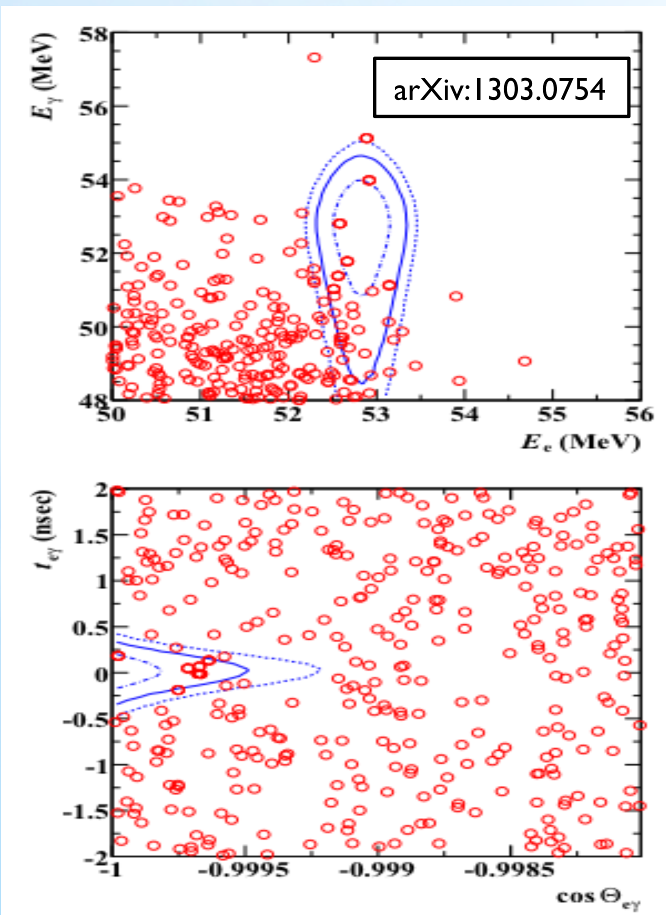
The precision achieved now is such that $B_{(s)} \to \mu^+\mu^-$ sensitivity to (Z, γ) penguin starts to compete with the golden mode $B \to K^*\mu^+\mu^-$.

Charged Lepton Flavour Violation

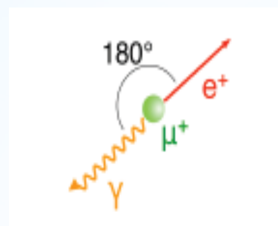
CLFV: Muon Decays

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, Dirac vs Majorana). Hence, CLFV is very relevant for "Flavour" and "Neutrino" physics!

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.**

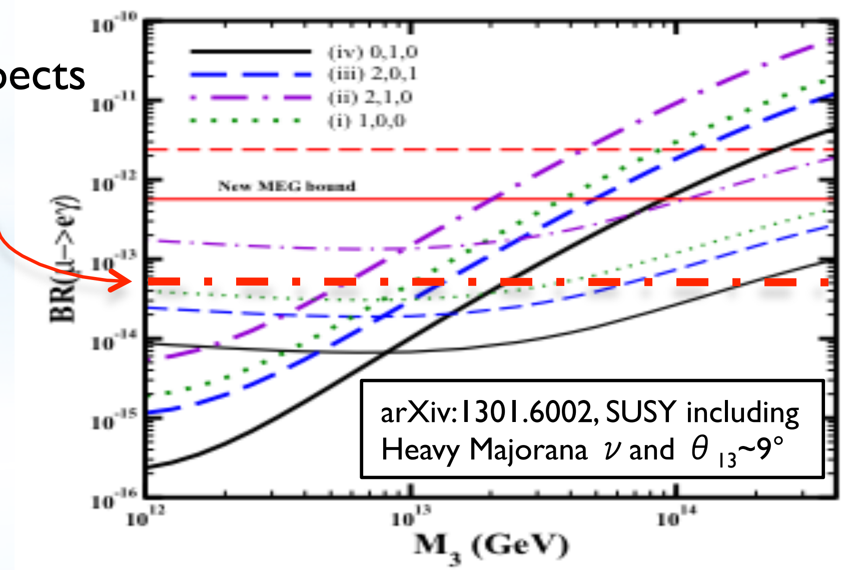


The **MEG collaboration** at PSI using stopped muons have achieved an amazing sensitivity to $\mu \to e\gamma$.

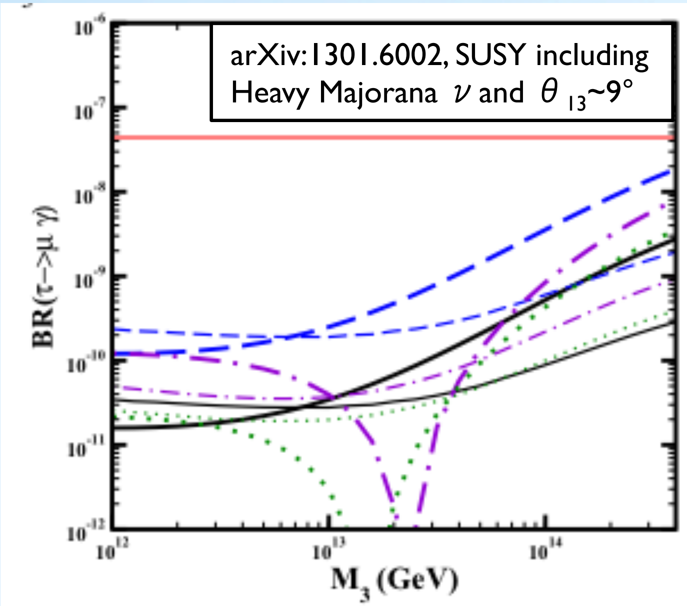


	Best fit	Upper limit (90% C.L.)	Sensitivity
2009-2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	$\boxed{5.7\times10^{-13}}$	7.7×10^{-13}

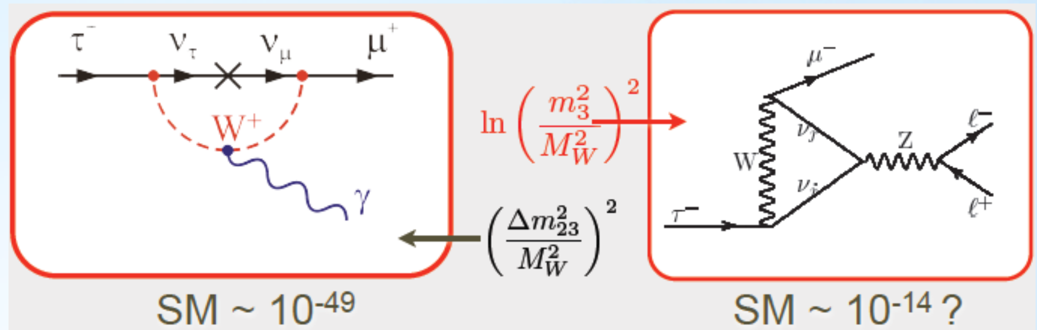
MEG upgrade expects to reach $5\text{x}10^{-14}$.



CLFV: Tau Decays



Tau Decays are less suppressed in the SM with Dirac massive ν.



The ratio between $\tau \to \mu\ \gamma$ and $\tau \to \mu\ \mu\ \mu$ is a very powerful test of NP models. The decay in 3 μ is interesting in models with no dipole dominance (e.g. scalar currents). Typically SUSY predictions in the range [10^{-11}-10^{-9}].

Taus are harder to produce. While rates of **3×10^7 μ^+/sec** have been achieved at PSI, the B-factories have produced the best limits on CLFV tau decays with production rates of ~2×10^9 τ /ab^{-1} or **~10^2 τ /sec**.

However, **at the LHC taus are copiously produced** (mainly from charm decays, $D_s \to \tau\ \nu$). At 7 TeV pp collisions, ~8×10^{10} τ /fb^{-1} are produced or **~10^5 τ /sec**. At 14 TeV pp collisions expect to double the rate (higher xsection) and double again (luminosity)!.

Best limits at 90% C.L. , so far, from B-factories:

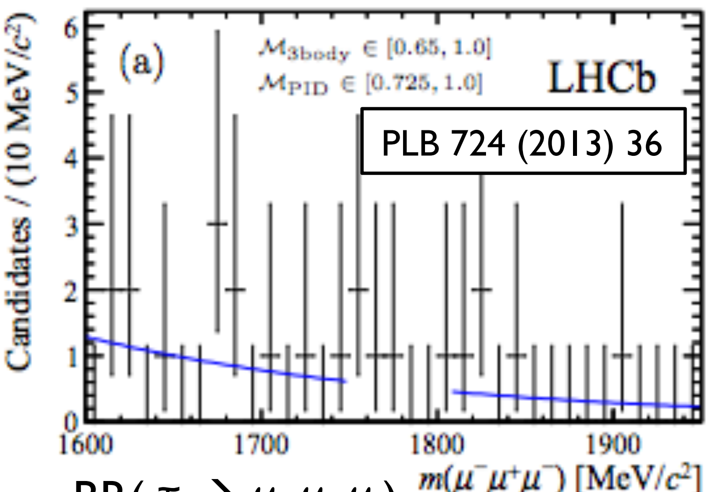
	BR($\tau \to \mu\ \gamma$)	BR($\tau \to \mu\ \mu\ \mu$)
BELLE:	4.5×10^{-8}	2.1×10^{-8}
BABAR:	4.4×10^{-8}	3.3×10^{-8}

arXiv:1001.3221,
arXiv:1002.4550

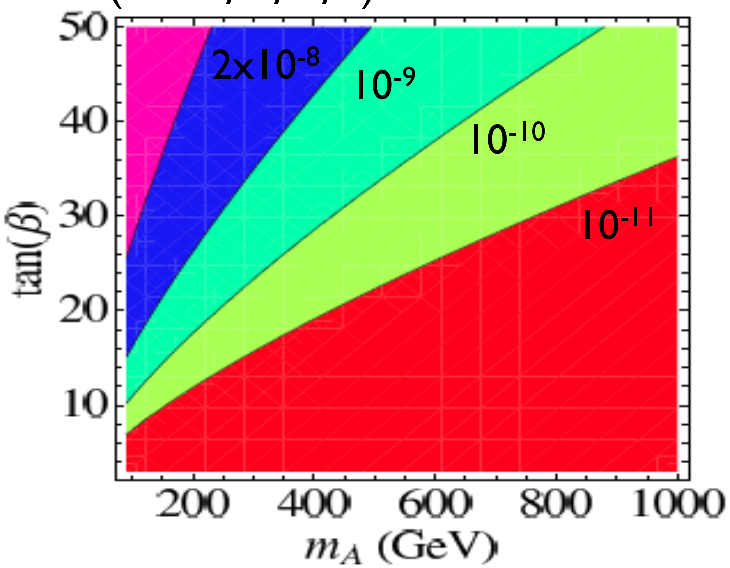
Is it possible to exploit this large sample of taus at the LHC?

Tau Flavour Violation Decays at LHCb: $\tau \to \mu\ \mu\ \mu$

LHCb has performed for the first time at hadron colliders a search for $\tau \to \mu\ \mu\ \mu$ in 1/fb at √s=7 TeV. The number of candidates is normalized to the number of $D_s \to \phi[\mu\ \mu]\pi$, the measured bb and cc cross-section at LHCb, and the fractions of B→ τ and D→ τ from LEP/B-factories.



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



Search in bins of invariant mass, PID and topological discriminant. Distribution compatible with background hypothesis.

Main background in the sensitive bins ($D_s^+ \to \eta[\mu\ \mu\ \gamma]\mu\ \nu$). LHCb results:

BR($\tau \to \mu\ \mu\ \mu$)<9.8(8.0)x10^{-8} at 95(90)% CL.

BELLE sensitivity x4 better with ~0.8 ab^{-1}.

Again, expect large LFV effects at large tan β

The **LHCb-upgrade** with 50 fb^{-1} at √s~14 TeV and **BELLE-II** with 50 ab^{-1} should reach **BR($\tau \to \mu\ \mu\ \mu$)<[10^{-10}-10^{-9}] at 90% CL.**

Into the Future…

Observable (class of observables)	SM prediction	Ultimate th. error	Present result	Future (S)LHCb	Future SuperB	Future Other
$\lvert V_{us}\rvert$ $[K \to \pi\ell\nu]$	input	$0.1\%_{(\rm Latt)}$	0.2252 ± 0.0009	-	-	
$\lvert V_{cb}\rvert$ $[\times 10^{-3}]$ $[B \to X_c\ell\nu]$	input	1%	40.9 ± 1.1	-	$1\%_{\rm excl}$, $0.5\%_{\rm incl}$	
$\lvert V_{ub}\rvert$ $[\times 10^{-3}]$ $[B \to \pi\ell\nu]$	input	$5\%_{(\rm Latt)}$	4.15 ± 0.49	-	$3\%_{\rm excl}$, $2\%_{\rm incl}$	
γ $[B \to DK]$	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	0.9°	1.5°	
$S_{B_d\to\psi K}$	2β	$\lesssim 0.01$	0.671 ± 0.023	0.0035	0.0025	
$S_{B_s\to\psi\phi,\psi f_0(980)}$	$2\beta_s$	$\lesssim 0.01$	-0.002 ± 0.087	0.008	-	
$S_{[B_s\to\phi\phi]}$	$2\beta_s^{eff}$	$\lesssim 0.05$	-	0.03	-	
$S_{[B_s\to K^{*0}\bar{K}^{*0}]}$	$2\beta_s^{eff}$	$\lesssim 0.05$	-	0.02	-	
$S_{[B_d\to\phi K^0]}$	$2\beta^{eff}$	$\lesssim 0.05$	-	0.03	0.02	
$S_{[B_d\to K^0_S\pi^0\gamma]}$	0	$\lesssim 0.05$	-0.15 ± 0.20	-	0.02	
$S_{[B_s\to\phi\gamma]}$	0	$\lesssim 0.05$	-	0.02	-	
$A^d_{\rm SL}[\times 10^{-3}]$	-0.5	0.1	-5.8 ± 3.4	0.2	4	
$A^s_{\rm SL}[\times 10^{-3}]$	2.0×10^{-2}	$< 10^{-2}$	-2.4 ± 6.3	0.2	-	
$\mathcal{B}(B \to \tau\nu)[\times 10^{-4}]$	1	$5\%_{\rm Latt}$	(1.14 ± 0.23)	-	4%	
$\mathcal{B}(B \to \mu\nu)[\times 10^{-7}]$	4	$5\%_{\rm Latt}$	< 13	-	5%	
$\mathcal{B}(B \to D\tau\nu)[\times 10^{-2}]$	1.02 ± 0.17	$5\%_{\rm Latt}$	1.02 ± 0.17	[under study]	2%	
$\mathcal{B}(B \to D^*\tau\nu)[\times 10^{-2}]$	1.76 ± 0.18	$5\%_{\rm Latt}$	1.76 ± 0.17	[under study]	2%	
$\mathcal{B}(B_s \to \mu^+\mu^-)[\times 10^{-9}]$	3.5	$5\%_{\rm Latt}$	< 4.2	0.15	-	
$R(B_{s,d} \to \mu^+\mu^-)$	0.29	$\sim 5\%$	-	$\sim 35\%$	-	
$q_0(A^{FB}_{B\to K^*\mu^+\mu^-})[\mathrm{GeV}^2]$	4.26 ± 0.34			2%	-	
$A_T^{(2)}(B \to K^*\mu^+\mu^-)$	$< 10^{-3}$			0.04	-	
$A_{\rm CP}(B \to K^*\mu^+\mu^-)$	$< 10^{-3}$			0.5%	1%	
$B \to K\nu\bar{\nu}[\times 10^{-6}]$	4	$10\%_{\rm Latt}$	< 16	-	0.7	
$\lvert q/p\rvert_{D-\rm mixing}$	1	$< 10^{-3}$	0.91 ± 0.17	$O(1\%)$	2.7%	
ϕ_D	$\lesssim 0.1\%$		$-$	$O(1^\circ)$	1.4°	
$a^{\rm dir}_{\rm CP}(\pi\pi)(\%)$	$\lesssim 0.3$		0.20 ± 0.22	0.015	[under study]	
$a^{\rm dir}_{\rm CP}(KK)(\%)$	$\lesssim 0.3$		-0.23 ± 0.17	0.010	[under study]	
$a^{\rm dir}_{\rm CP}(\pi\pi\gamma, KK\gamma)$	$\lesssim 0.3\%$			[under study]	[under study]	
$\mathcal{B}(\tau \to \mu\gamma)[\times 10^{-9}]$	0		< 44	-	2.4	
$\mathcal{B}(\tau \to 3\mu)[\times 10^{-10}]$	0		$< 210(90\%\ \mathrm{CL})$	1-80	2	
$\mathcal{B}(\mu \to e\gamma)[\times 10^{-12}]$	0		$< 2.4(90\%\ \mathrm{CL})$			~ 0.1 MEG; ~ 0.01 PSI-future; ~ 0.01 Project X
$\mathcal{B}(\mu N \to eN)(Ti)$	0		$< 4.3 \times 10^{-12}$			10^{-18} PRISM
$\mathcal{B}(\mu N \to eN)(Al)$	0		-			10^{-16} COMET, Mu2e
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})[\times 10^{-11}]$	8.5	8%	$17.3^{+11.5}_{-10.5}$			$\sim 10\%$ NA62; $\sim 5\%$ ORKA; $\sim 2\%$ Project X
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})[\times 10^{-11}]$	2.4	10%	< 2600			$\sim 100\%$ KOTO; $\sim 5\%$ Project X
$\mathcal{B}(K_L \to \pi^0e^+e^-)_{SD}$	1.4×10^{-11}	30%	28×10^{-11}			$\sim 10\%$ Project X

Isidori, Martinez-Santos (Open Symposium ESPG)

Table 5: Status and future prospects of selected $B_{s,d}$, D, K, and LFV observables. The SuperB column refers to a generic super B factory, collecting $50\mathrm{ab}^{-1}$ at the $\Upsilon(4S)$.

Conclusions

Conclusions

Interest in precision flavour measurements is stronger than ever. In some sense it would have been very "unnatural" to find NP at LHC7 from direct searches with the SM CKM structure.

There are few interesting anomalies, but in general the agreement with the SM is excellent → **large NP contributions, O(SM), ruled out in many cases.**

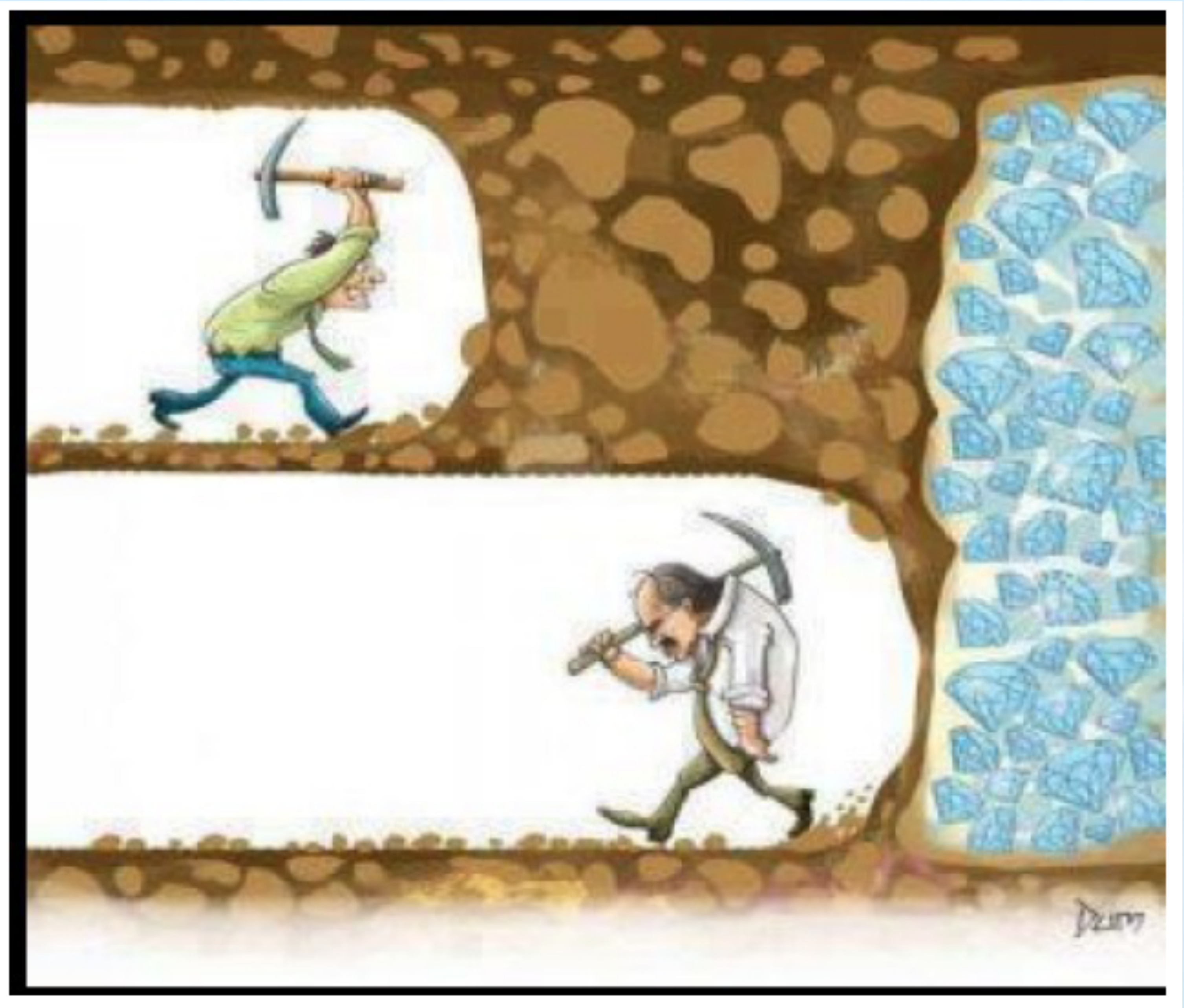
There is a priory as many good reasons to find NP by measuring precisely the couplings of the new scalar boson, as by precision measurements in the flavour and neutrino sectors!

The search has just started at LHCb with (1+2)/fb at LHC(7+8)TeV.

LHCb upgrade plans to collect ~50/fb with a factor ~2 increase in bb and cc cross-section. **ATLAS/CMS** plan to collect ~300/fb and **Belle-II** plans to collect ~50/ab before HL-LHC era.

<u>We don't know yet what is the scale of NP→ cast a wide net!</u>

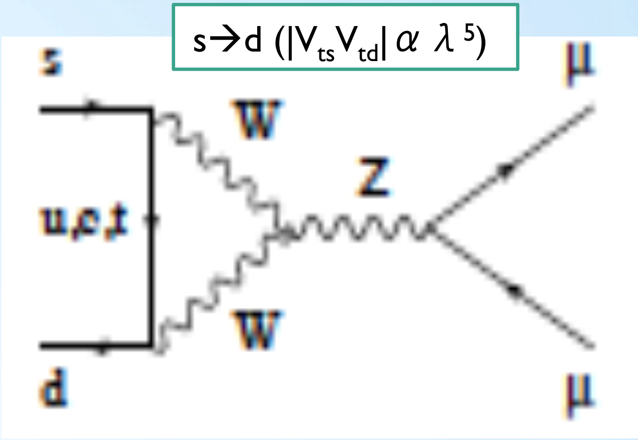
Don’t give up yet!



Backup

ΔF=1 Higgs penguins in s→d transitions: Kaon 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!**

BR($K_L \to \mu\mu$)=(6.84±0.11)x10^{-9} (BNL E871, PRL84 (2000)) measured to be in agreement with SM, but completely dominated by absorptive (long distance) contributions. In the case of $K_s \to \mu\mu$ the absorptive part is calculated to be 5x10^{-12} as it is proportional to Im($V_{td}V_{ts}$). NP enhancement up to 10^{-11} is possible.

The best existing limits on $K_s \to ll$ at 90% C.L. are:

BR($K_s \to \mu\mu$)<3.2x10^{-7} (PLB44 (1973))
BR($K_s \to ee$) <9x10^{-9} (KLOE, PLB672 (2009))

In particular a measurement of BR($K_s \to \mu\mu$) of O(10^{-10}-10^{-11}) would be a clear indication of NP in the dispersive part, and would increase the interest of a precise measurement of $K^+ \to \pi^+ \nu\nu$.

ΔF=1 Higgs penguins in s→d transitions: Kaon decays

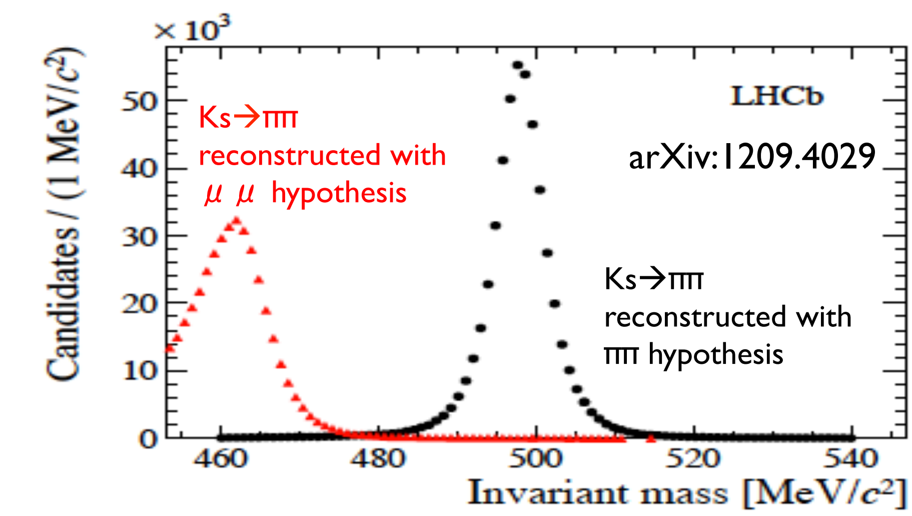
LHC produces 10^{13} K_s/fb in the LHCb acceptance. Trigger was not optimized for this search in 2011 (it is for the 2012 data taking period).

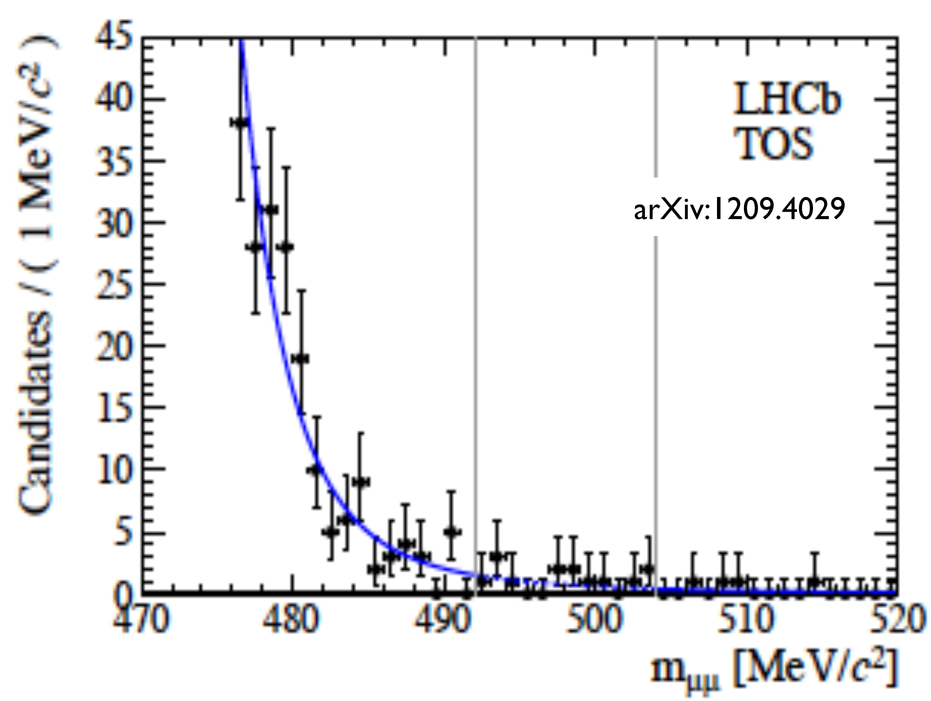
Excellent LHCb invariant mass resolution critical to reduce peaking bkg.

Mass distribution compatible with bkg hypothesis:

BR($K_s \to \mu\mu$)<11(9)x10^{-9} at 95(90)% C.L.
x30 improvement!

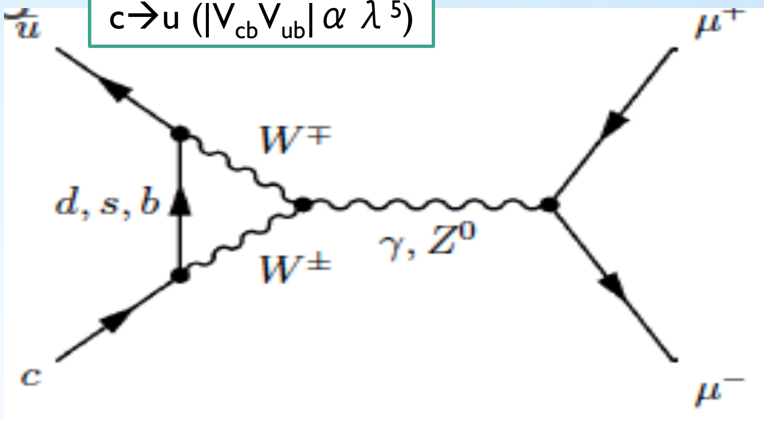
Excellent prospects to reach the interesting region ~10^{-11} with the LHCb upgrade.





ΔF=1 Higgs penguins in c→u transitions: Charm decays

c→u ($|V_{cb}V_{ub}| \alpha\ \lambda^5$)



Charm decays are complementary to B and K decays, because in the loops the relevant quarks are down-type rather than up-type.

Short distance contribution to **D→$\mu\ \mu$** decays is **O(10^{-18})** within the SM.

Long distance contributions could be indeed much larger, but they are limited to be **below 6x10^{-11}** from the existing **limits on D→$\gamma\ \gamma$**:

$$\mathcal{BR}^{(\gamma\gamma)}(D^0 \to \mu^+\mu^-) \simeq 2.7 \times 10^{-5} \mathcal{BR}(D^0 \to \gamma\gamma)$$ Phys.Rev. D66 (2002) 014009

BABAR result BR(D→$\gamma\ \gamma$<2.2x10^{-6} @90% C.L.) Phys. Rev. D85 (2012) 091107

Charm decays complement K and B mesons decays.

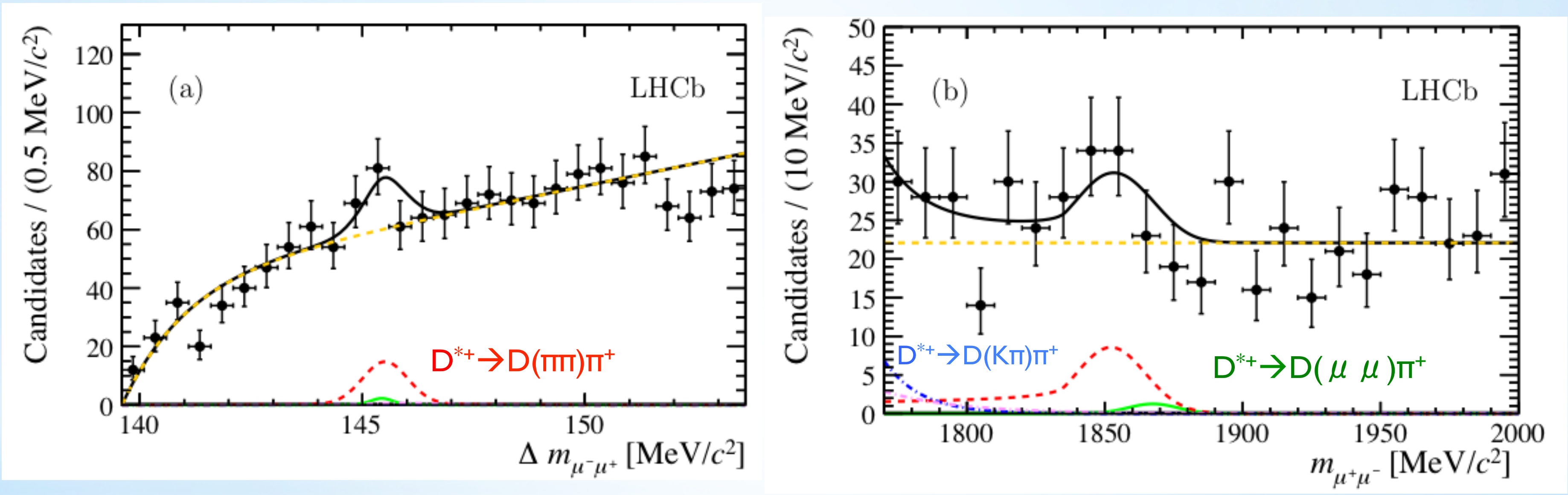
ΔF=1 Higgs penguins in c→u transitions: Charm decays

Experimental control of the peaking background is crucial (D→ππ).
Best existing limit before spring 2012 was from **Belle, <1.4x10^{-7}@90%C.L.**

LHCb-PAPER-2013-013

LHCb results using 0.9/fb of D*→Dπ: **<7.6x10^{-9}@95%C.L.** *(factor ~20 improvement)*

CMS results with 0.09/fb: CMS-PAS-BPH-11-017 <5.4x10^{-7}@90%C.L.



BABAR, arXiv:1206.5419 ,update for summer 2012 show a slight excess of candidates (8 observed, 3.9±0.6 bkg) which was interpreted as a **two-sided 90% C.L. limit, [6,81]x10^{-8}, in tension with LHCb results.**

LHCb will study the theoretical clean region between 8x10^{-9} and 10^{-11}

Δ F=2 box in b→s transitions

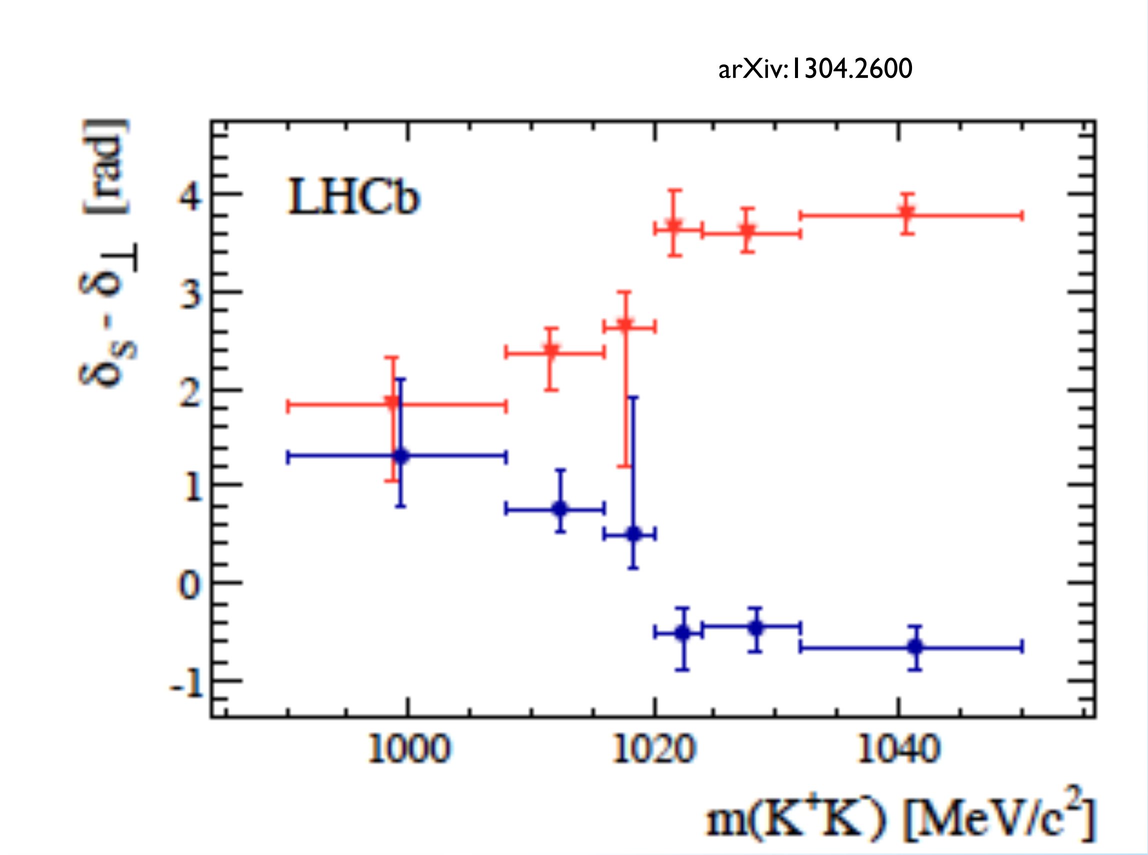
However, there is a two fold ambiguity in the differential decay rates:

$$(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_S) \longmapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_S)$$

This ambiguity is resolved by LHCb using the dependence of the phase difference between P-wave and S-wave.

The physical solution is found to be the blue points (the other solution, red points, is not compatible), therefore:

$\boxed{\Delta\Gamma_s>0}$

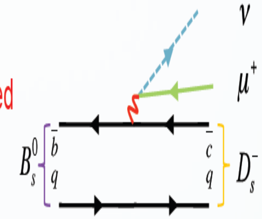


ΔF=2 box in b→q transitions (D0 flavour specific asymmetries)

Could it be that we have large NP effects in the absorptive part?

$a^q_{fs}=|\Gamma^q_{12}/M^q_{12}|\sin(\varphi_q)$

$B^0_q \to D^-_q \mu^+ \nu_\mu$: Allowed



$\bar{B}^0_q \to D^-_q \mu^+ \nu_\mu$: Not allowed directly

$$a^q_{SL} = \frac{\Gamma(\bar{B}(t)\to f) - \Gamma(B(t)\to \bar{f})}{\Gamma(\bar{B}(t)\to f) + \Gamma(B(t)\to \bar{f})} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

D0 inclusive measurement of the dimuon asymmetry is interpreted as a linear combination of $a_{SL}(B_d)$ and $a_{SL}(B_s)$ which depends on the fraction of B_d and B_s in the data sample. **No production asymmetry** at pp colliders. **Detector asymmetry** controlled by switching magnet polarity.

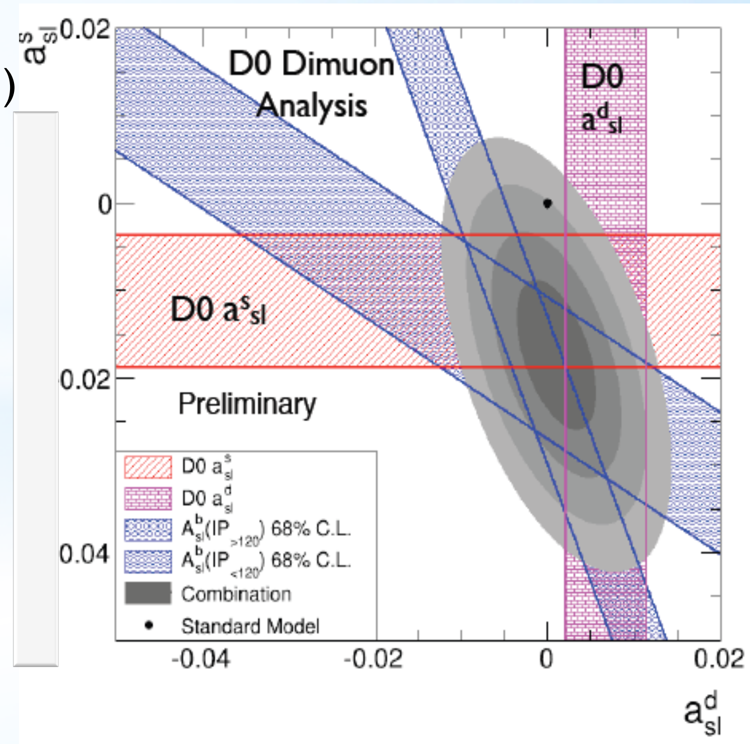
D0 Dimuon: $\mathbf{A^b_{SL} = (-0.787 \pm 0.172(stat) \pm 0.093(syst))\%}$ (3.9σ)

PRD 84 (2011) 052007

Systematic uncertainty drastically reduced by assuming the bkg from the single-muon asymmetry.

and splitting the data sample in **low(high) IP**:

$\mathbf{a_{SL}(B_d) = (-0.12 \pm 0.52)\%}$, $\mathbf{a_{SL}(B_s) = (-1.81 \pm 1.06)\%}$



Moreover, D0 has also measured:

PRD 86 (2012) 072009,
PRL 110 (2013) 011801

Using $B_d \to \mu^+ D^{(*)-}$: $\mathbf{a_{SL}(B_d) = (0.68 \pm 0.45(stat) \pm 0.14(syst))\%}$

Using $B_s \to \mu^+ D_s^-$: $\mathbf{a_{SL}(B_s) = (-1.12 \pm 0.74(stat) \pm 0.17(syst))\%}$

Δ F=2 box in b→q transitions (LHCb flavour specific asymmetries)

LHCb cannot really follow the same inclusive approach due to the relatively large production asymmetry (for B_s roughly ~1%).

LHCb ($B_s \to D_s[\Phi\pi]\mu\nu X$): arXiv:1308.1048

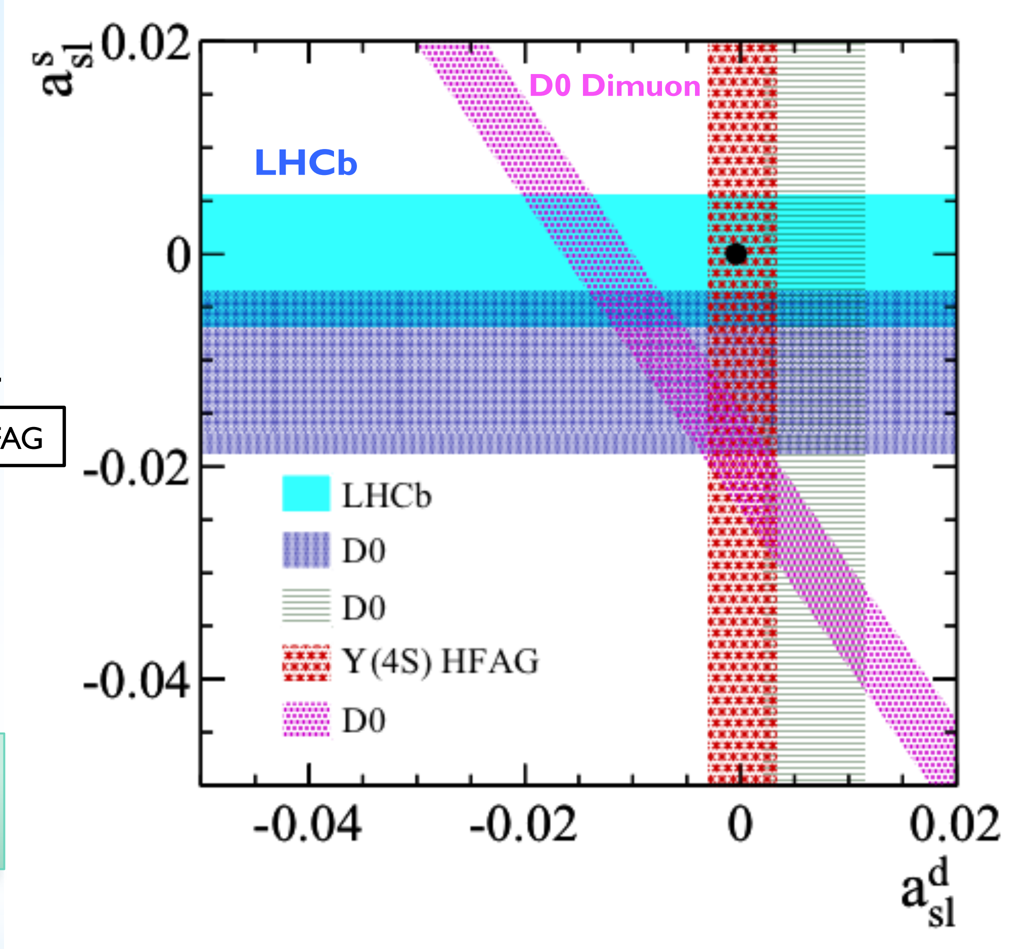
$$a_{SL}(B_s) = (-0.06 \pm 0.50(stat) \pm 0.36(syst))\%$$

Also taking into account the measurement at the B-factories of $a_{SL}(B_d) = (0.02 \pm 0.31)\%$ HFAG

World naïve average:

$$a_{SL}(B_d) = (0.13 \pm 0.21)\% \ ,$$
$$a_{SL}(B_s) = (-0.71 \pm 0.44)\%$$

The world averaged values are in reasonable agreement with the SM.



LHCb needs to add more channels and more data and a precise measurement of $A_{SL}(B_d)$ to be able to conclude. However there is already a clear tension between D0 $a_{SL}(B_s)$ and the measurements of ($\Delta\Gamma_s, \Phi_s$.)

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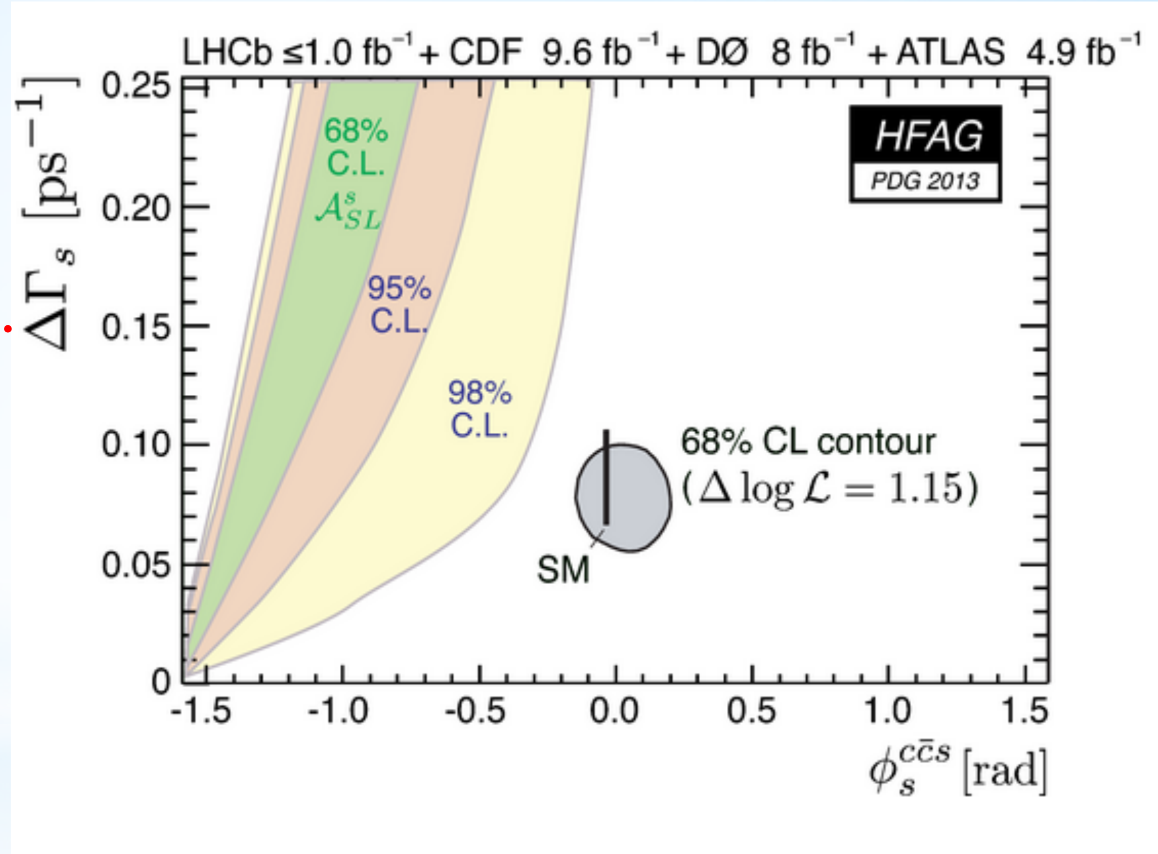
However there is already a clear tension between D0 $a_{SL}(B_s)$ and the measurements of $(\Delta\Gamma_s, \Phi_s)$.

Getting more difficult to get a coherent picture.



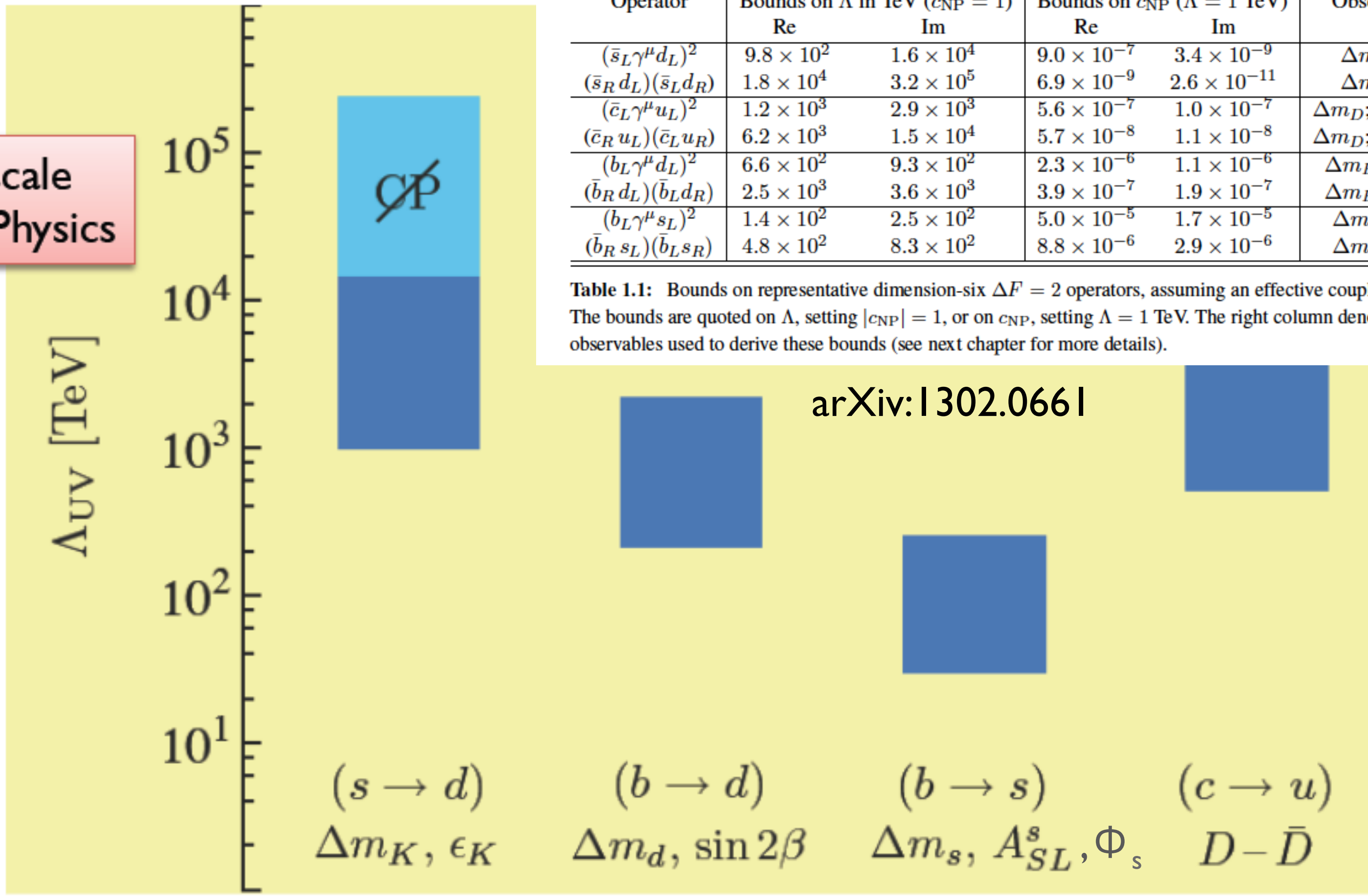
Δ F=2 box implications

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar s_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar s_R d_L)(\bar s_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar c_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar c_R u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_R d_L)(\bar b_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar b_R s_L)(\bar b_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Table 1.1: Bounds on representative dimension-six $\Delta F = 2$ operators, assuming an effective coupling $c_{\rm NP}/\Lambda^2$. The bounds are quoted on Λ, setting $|c_{\rm NP}| = 1$, or on $c_{\rm NP}$, setting $\Lambda = 1$ TeV. The right column denotes the main observables used to derive these bounds (see next chapter for more details).

arXiv:1302.0661

Mass scale of New Physics

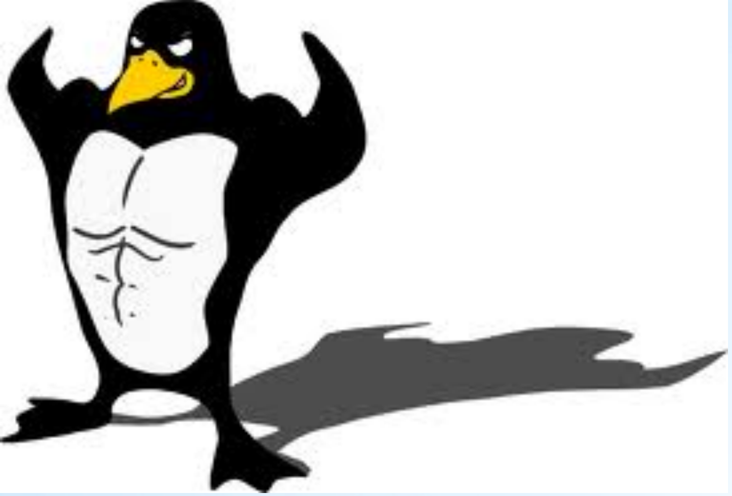


CP violation in K system

Oscillations and CPV in B_d system

Oscillations and CPV in B_s system

Oscillations in D system



$\Delta F=1$ QCD (Strong) Penguins

$\Delta F=1$ in $c \to u$ QCD penguins: "Direct" CP violation in Charm decays

$$A_{CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}.$$

($|V_{cd}V_{ud}| \alpha\ \lambda$)

($|V_{cb}V_{ub}| \alpha\ \lambda^5$)

No evidence yet of CP violation in the interference between mixing and decay in the Charm system. Could we have large (unexpected) "direct" CP violation in Charm (penguin) decays?

A priori, consensus was CP violation O(1%) would be "clear" sign for NP.

Within the SM, use of U-spin and QCD factorization leads to ΔA_{CP}~4 Penguin/Tree ~0.04%.

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$ cancels detector and production asymmetries to first order. The SM and most NP models predicts opposite sign for KK and ππ, hence no sensitivity lost by taking the subtraction.

$D^{*\pm} \rightarrow D^0\,[h^+h^-]\,\pi^\pm$ charge of the pion determines the flavour of D^0. Most of the systematics cancel in the subtraction, and are controlled by swapping the LHCb magnetic field.

There is no problem to enhance ΔA_{CP} in NP models, the question is really if subleading SM contributions are well under control. For instance, the U-spin approximation is challenged by the measurement $B(D\rightarrow\pi\pi) \sim 2.8\, B(D\rightarrow KK)$.

LHCb first evidence for direct CP violation in charm decays with 0.6/fb:

ΔA_{CP}=(-0.82±0.24)% LHCb (0.6/fb) (PRL 108, 111602 (2012))

confirmed later by:
ΔA_{CP}=(-0.62±0.23)% CDF (PRL 109, 111801 (2012))
ΔA_{CP}=(-0.87±0.41)% BELLE (Preliminary ICHEP 2012)

However, a more precise LHCb update with 1/fb does not confirm the previous tendency:

ΔA_{CP}=(-0.34±0.18)% LHCb (1/fb) (LHCb-CONF-2013-003)

Moreover, an independent analysis using $B^{\pm} \rightarrow D^0 [h^+h^-] \mu^{\pm} \nu X$, where the charge of the muon determines the flavour of D^0, does not confirm either the initial hints:

ΔA_{CP}=(0.49±0.33)% LHCb (semil, 1/fb) (PLB 723, (2013) 33)

ΔF=1 in c→u QCD penguins: "Direct" CP violation in Charm decays

Naïve average

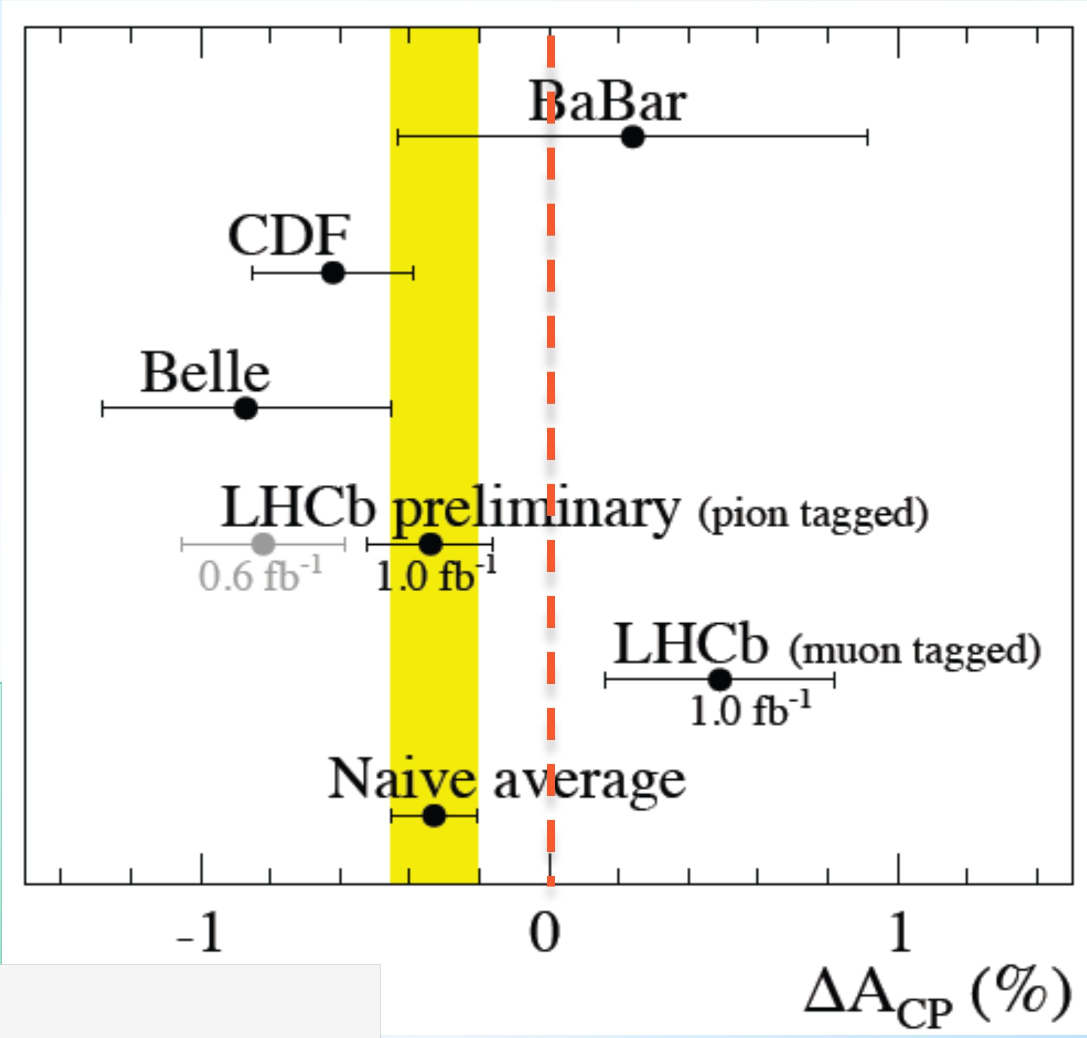
ΔA_{CP} **= (-0.35 ± 0.12)%**

p-value average = 2.4%

(or equivalent to 2.3 σ)

p-value (no CP-violation) = 0.15%

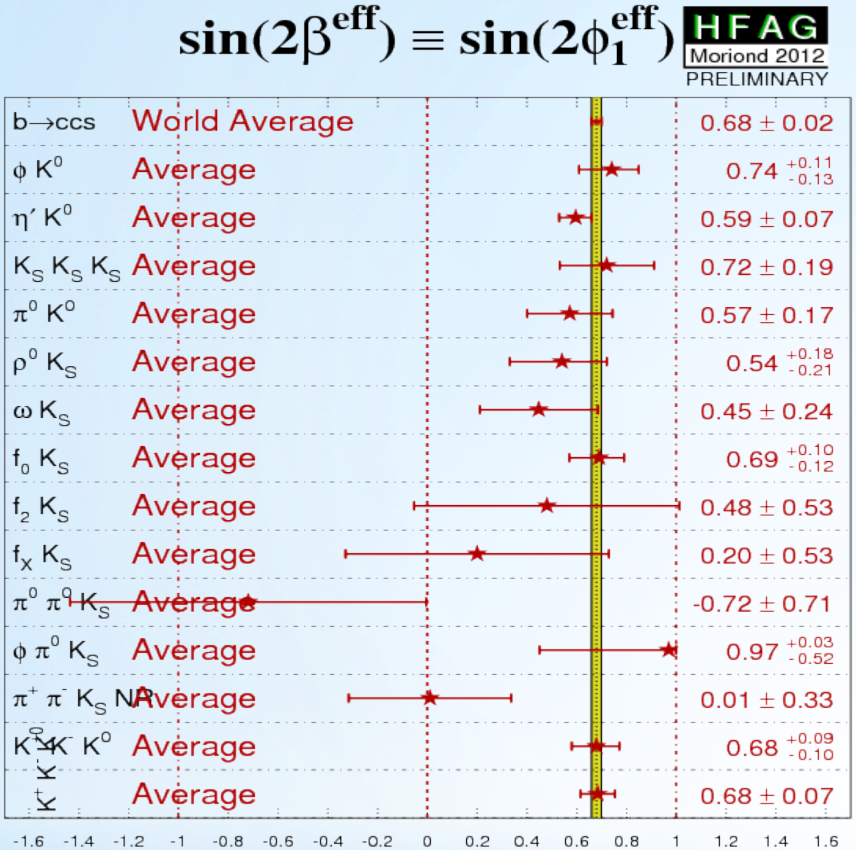
(or equivalent to 3.2 σ)

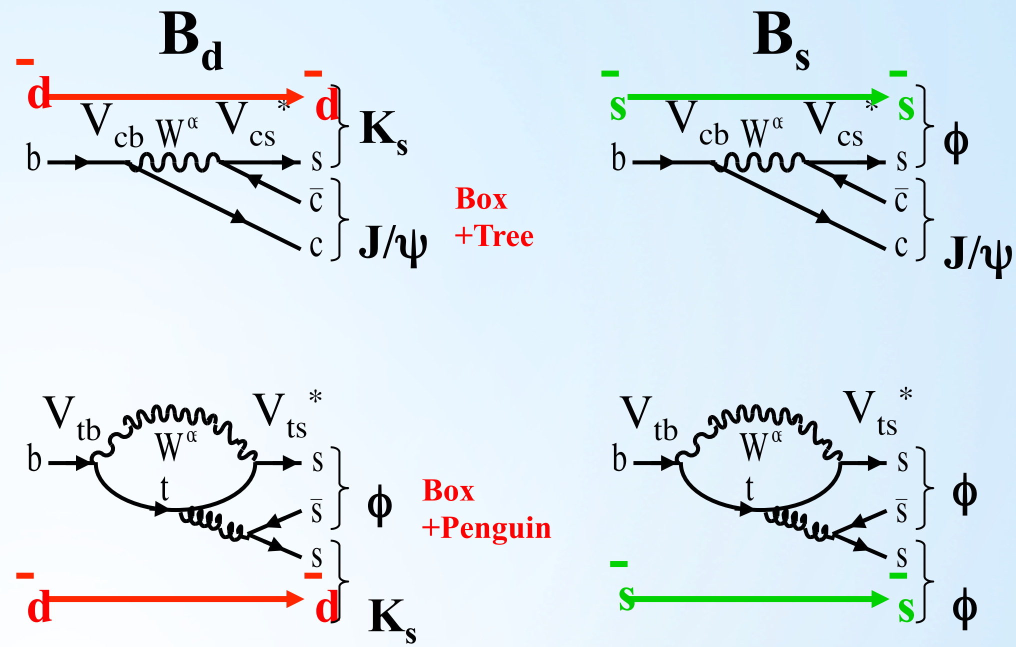


LHCb results dominated by statistics. Situation should become more clear with the analysis of the available 3/fb.

But it is clear that we are moving towards smaller effects, hence difficult to differentiate NP from SM.

$\Delta F=1\ b\rightarrow s$ QCD penguins





β(tree)-β(penguin) = $\delta\beta$(NP)

β_s(tree)-β_s (penguin) = $\delta\beta$(NP)

No significant discrepancy between b→ccs and s-penguin measurements. However, there may be a tendency and effects O($\delta\beta$~4°) are not excluded.

The effect of the same s-penguins can be measured at LHCb both in the B_d and B_s system.

Belle-II may improve further on B_d decays.

An O(few degrees) measurement can reveal NP effects in s-penguins

Yields at LHCb and B-factories

Decay	LHCb		Belle		Ratio
$B_u \to J/\psi K$	10049	34 pb^{-1}	41315	711 fb^{-1}	5.1
$B_u \to D^0{}_{\mathrm{CP}}\pi$	1270	34 pb^{-1}	2163	250 fb^{-1}	4.3
$B_d \to K\pi$	838	35 pb^{-1}	4000	480 fb^{-1}	2.9
$B_u \to K\ell\ell$	35	35 pb^{-1}	161	605 fb^{-1}	2.6
$B_d \to K^*\ell\ell$	144	165 pb^{-1}	230	605 fb^{-1}	2.3
$B_d \to J/\psi K_S^0$	1100	33 pb^{-1}	12681	711 fb^{-1}	1.9
$B_d \to K^*\gamma$	485	88 pb^{-1}	450	78 fb^{-1}	1.0
$B_s \to J/\psi\phi$	1414	95 pb^{-1}	45	24 fb^{-1}	7.9
$B_s \to J/\psi f_0$	111	33 pb^{-1}	63	121 fb^{-1}	6.5
$B_s \to \phi\gamma$	60	88 pb^{-1}	18	24 fb^{-1}	0.9
$D^+ \to \phi\pi$	90k	35 pb^{-1}	237k	955 fb^{-1}	10