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AGH UST, IFJ PAN, The M. Smoluchowski Scientific Consortium, Kraków
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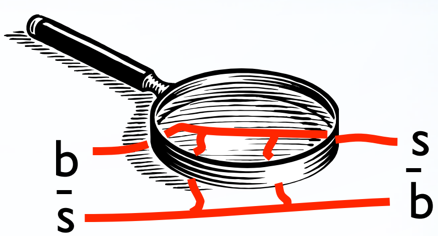
* Flavour and symmetries: experimental results.

Frederic Teubert

CERN, PH Department

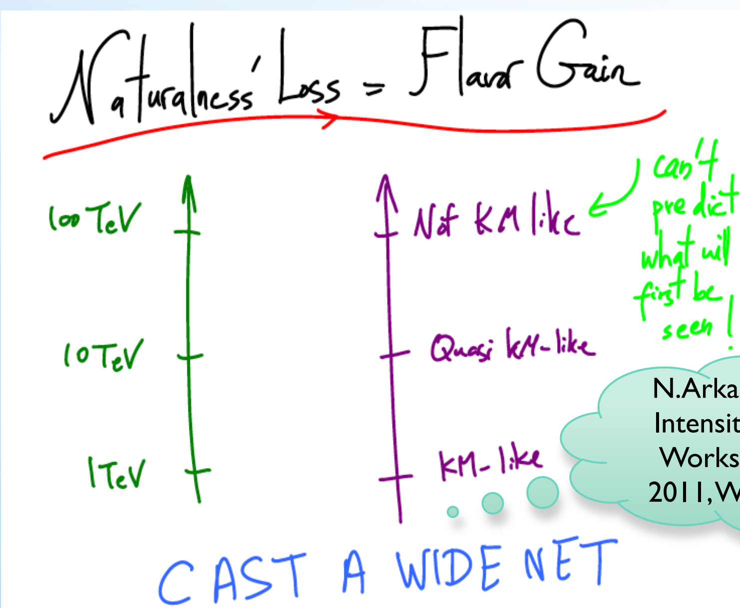


Status of Searches for NP

So far, no significant signs for NP from direct searches at LHC while a Higgs-like boson has been found with a mass of ~125 GeV/c^2.

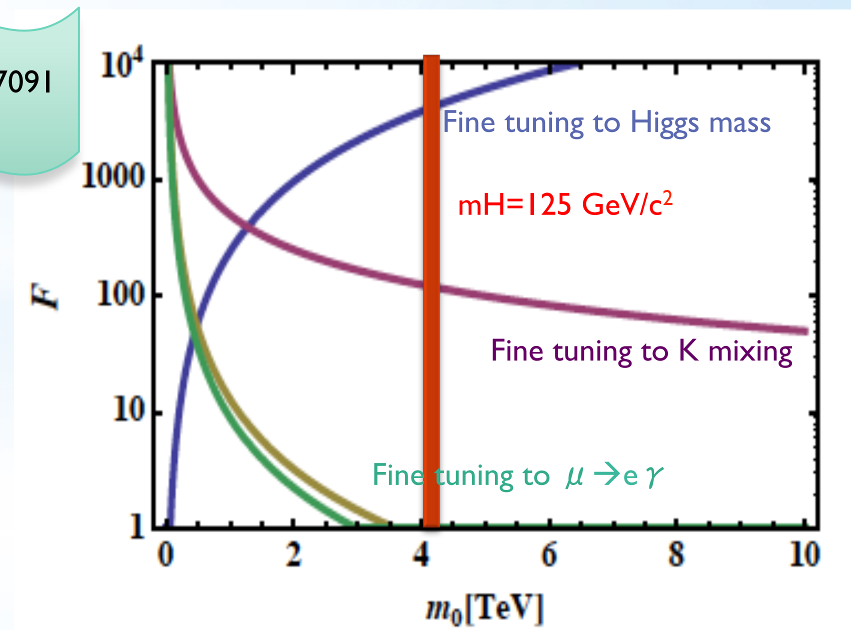
Before LHC, expectations were that *"naturally"* the masses of the new particles would have to be light in order to reduce the *"fine tuning"* of the EW energy scale. However, the absence of NP effects observed in flavour physics implies some level of *"fine tuning"* in the flavour sector → **NP FLAVOUR PROBLEM** → Minimal Flavour Violation (MFV).

As we push the energy scale of NP higher (within MSSM the measured value of the Higgs mass pushes the scale up), the NP FLAVOUR PROBLEM is reduced, hypothesis like MFV look less likely → **chances to see NP in flavour physics have, in fact, increased!**



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

arXiv:1205.7091



Indirect Searches for NP

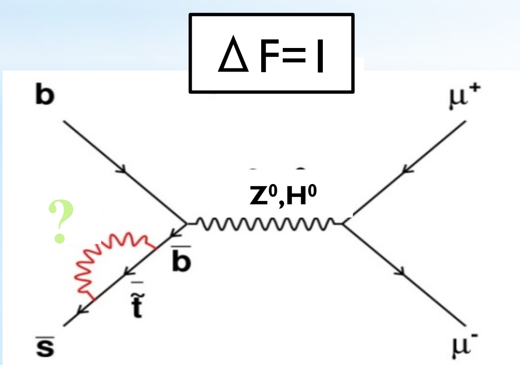
If the **energy** of the particle collisions is high enough, we can discover NP detecting the production of "real" new particles.

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

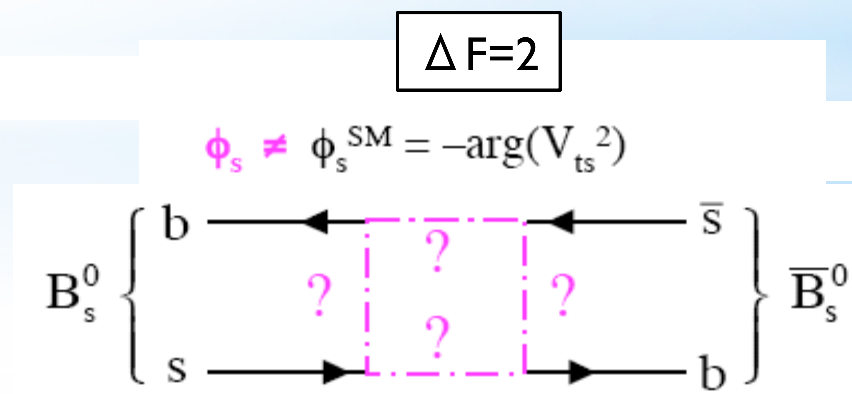
Contrary to what happens in "non-broken" gauge theories like QED or QCD, the effect of **heavy ($M>q^2$) new particles does not decouple** in weak and Yukawa interactions.

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.***



$B_s \rightarrow \mu^+\mu^-$ Higgs "Penguin"



B_s–$\bar{B}_s$ oscillations: "Box" diagram

FCNC in the SM

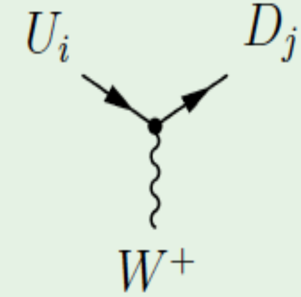
$U_i = \{u, c, t\}$:

$Q_U = +2/3$

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

$Q_D = -1/3$

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



$\sim$ Cabibbo-Kobayashi-Maskawa (CKM) matrix

In the SM quarks are allowed to change flavour as a consequence of the Yukawa mechanism which is parameterized in a complex CKM couplings matrix. Using Wolfenstein parameterization:

A=0.81±0.02
λ = 0.225±0.001

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

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

	b→s ($\lvert V_{tb}V_{ts}\rvert \alpha \lambda^2$)	b→d ($\lvert V_{tb}V_{td}\rvert \alpha \lambda^3$)	s→d ($\lvert V_{ts}V_{td}\rvert \alpha \lambda^5$)	c→u ($\lvert V_{cb}V_{ub}\rvert \alpha \lambda^5$)
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	**$A_{CP}(B_s \to \Phi\,\Phi)$**, $B \to X_s \gamma$	**$A_{CP}(B \to \Phi K)$**, $B \to X \gamma$	$K \to \pi^0 ll$, 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	**$B_s \to \mu\,\mu$**	**$B \to \mu\,\mu$**	$K \to \mu\,\mu$	**$D \to \mu\,\mu$**

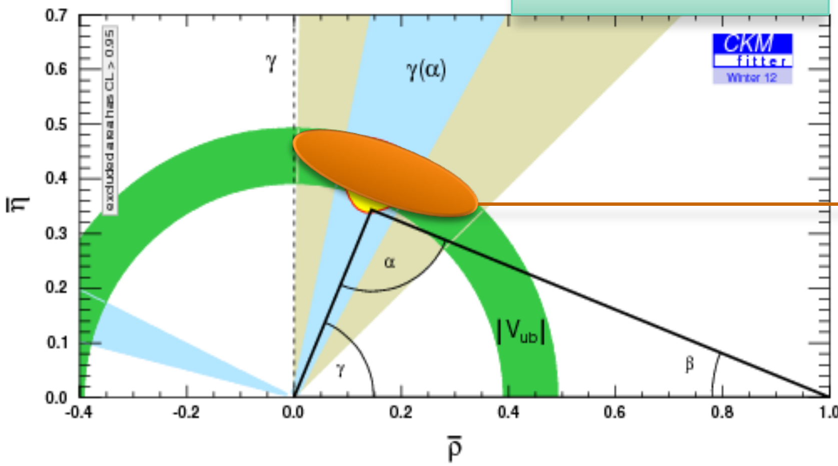
CP violation in the SM

Imposing unitarity to the CKM matrix results in six equations that can be seen as the sum of three complex numbers closing a triangle in the plane. Two of these triangles are relevant for the study of CP-violation in B-physics and define the angles:

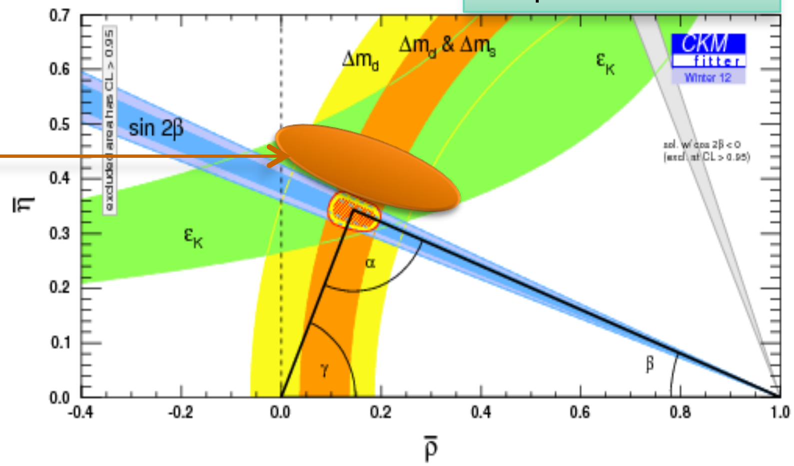
$$\alpha = \arg\left(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),\quad \beta = \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \text{ and } \gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \qquad \beta_s = \arg\left(\frac{-V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right)$$

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

Tree measurements



Loop measurements



Need to improve the precision of the measurements at tree level to (dis-)prove the existence on NP phases.

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 LHCb, I think the above mantra **is over simplistic and not true**.

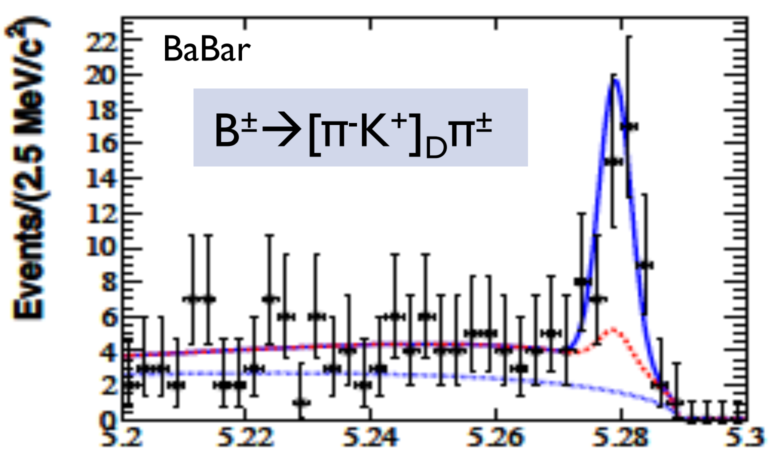
Lepton colliders have the advantage of a known CoM energy, and high luminosities (10^{34}-10^{36}) $cm^{-2}s$. However, at the Y(4S) only $_{B(d,u)}$ mesons are produced.

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

Rule of thumb:

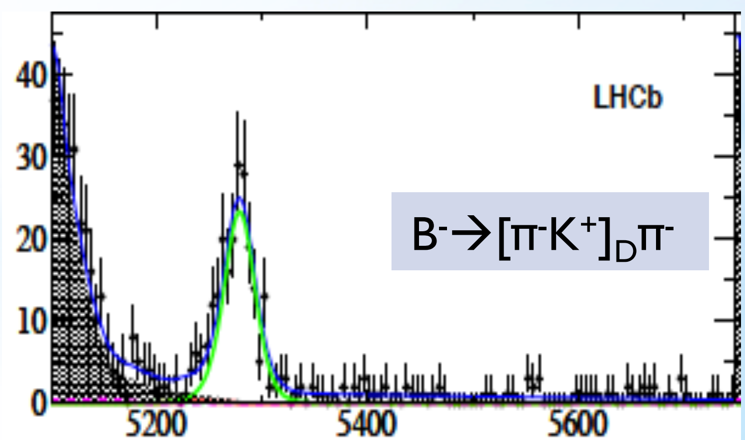
1/fb at 7TeV at LHCb is equivalent to (1-5)/ab at the B-factories before tagging.

arXiv:1006.4241



Energy-substituted mass (GeV/c^2)

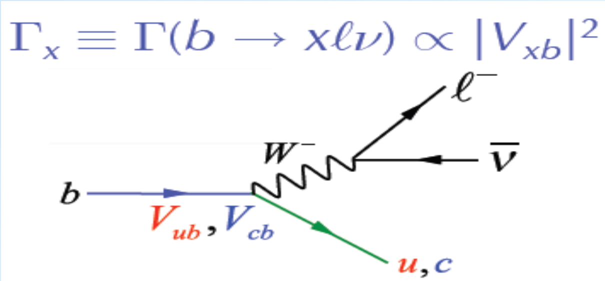
arXiv:1203.3662



Invariant mass (MeV/c^2)

Tree Level Measurements

b→u,c: Charged Currents (NP at tree level?)



Measured values of V_{ub} at B-factories using inclusive or exclusive methods show a discrepancy at the 2-3 σ level:

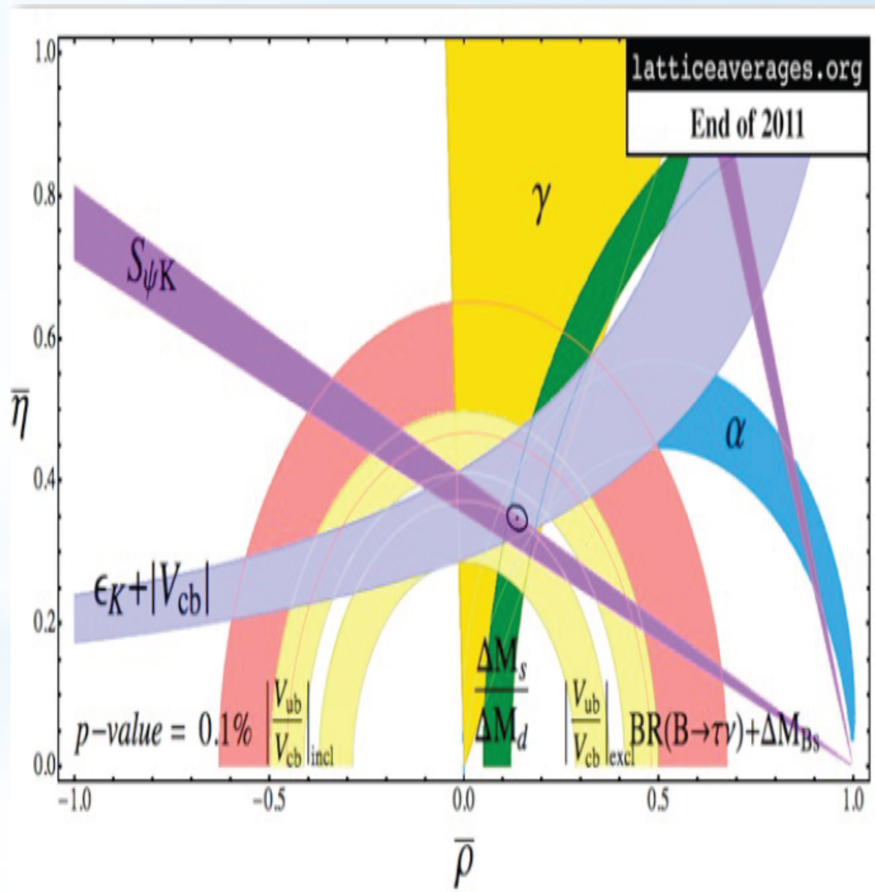
V_{ub}(incl.)~1.3V_{ub}(excl.).

Both methods suffer from **large theoretical and experimental uncertainties.** Next generation B-factories will produce hadronic tagged, high statistics, high purity samples. LHCb is expected to provide competitive results in exclusive modes.

Progress with lattice calculations but still a big challenge for theory!

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

Interestingly, there is also a hint from LEP:
W→ τ ν / W→l ν ~1.06±0.03



b→u,c: Charged Currents (NP at tree level?)

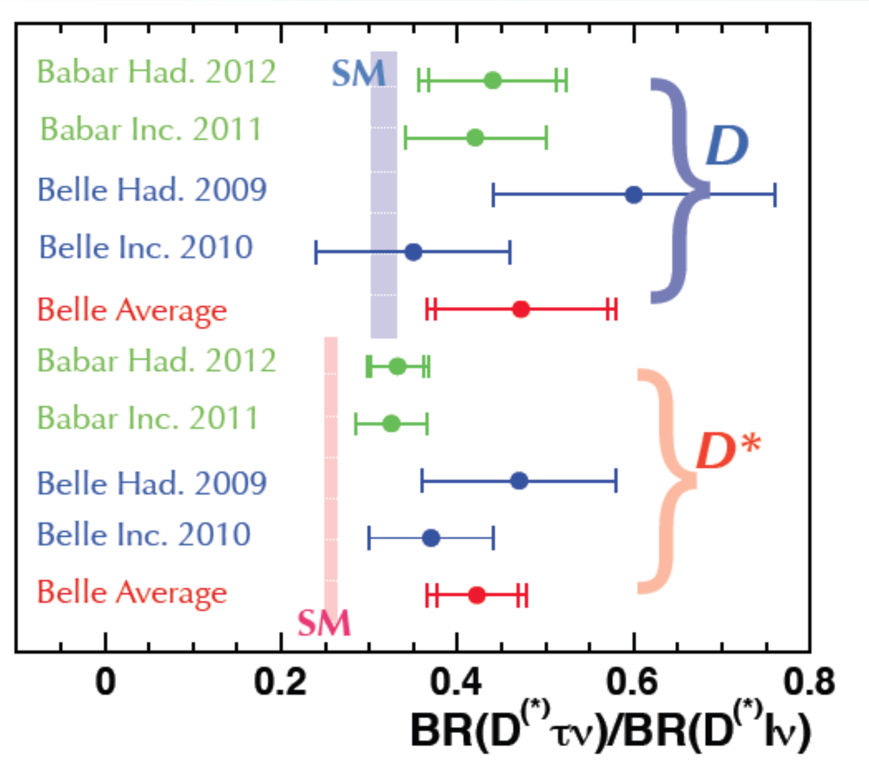
This summer **Belle** presented a more precise hadron tag analysis, in better agreement with the fitted CKM value:

BR(B→ $\tau\nu$))$_{exp}$= (1.14±0.23)x10^{-4} vs CKM fit:(0.83±0.09)x10^{-4}

BABAR also presented this summer a more precise measurement of BR(B→D(*) $\tau\nu$)/BR(B→D(*)l ν) which combi

are a bit more than **3 σ higher than SM**.

Not obvious NP explanation.



NA62 has measured (2011) the ratio

K→e ν /K→ $\mu\nu$ =2.487±0.013 in agreement with SM: 2.477±0.001

<u>Belle should be able to reduce the uncertainties on B→D(*) $\tau\nu$ soon at similar level than BABAR.</u>

V_{ub} phase: (SM value of $\rho\ \eta$)

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

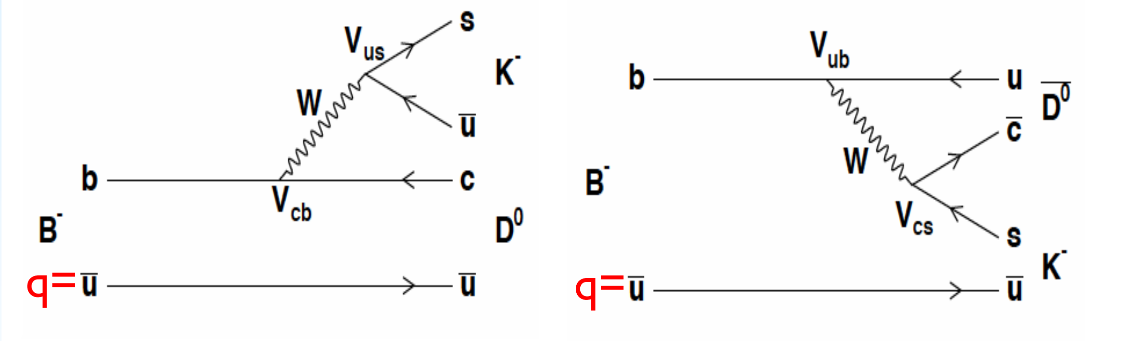
$B^{\pm}\to DX_s$ $X_s=\{K^{\pm}, K^{\pm}\pi\pi, K_s\pi\pi, K^{*\pm},\ldots\}$

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

$B\to DK^*$

q=s: Time dependent CP analysis.

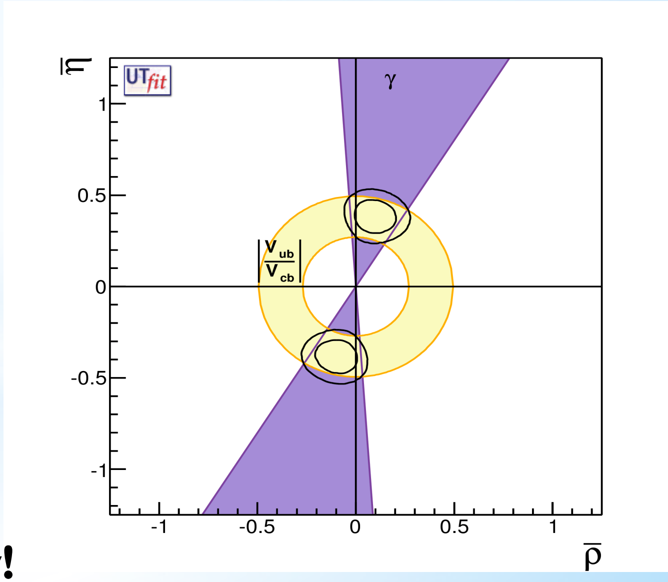
$B_s\to D_sK$



In the case q=u,c the experimental analysis is relatively simple, selecting and counting events to measure the ratios between B and anti-B decays. 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.**

The most precise determination of γ from B-factories is from the Dalitz analysis when $D\to K_s\pi\pi$.

$\gamma = 76 \pm 10°$



LHCb has already shown the largest signals and most precise measurements of the ratios between B and anti-B decays, and Dalitz analysis is on its way

→**expect competitive measurement already now!**

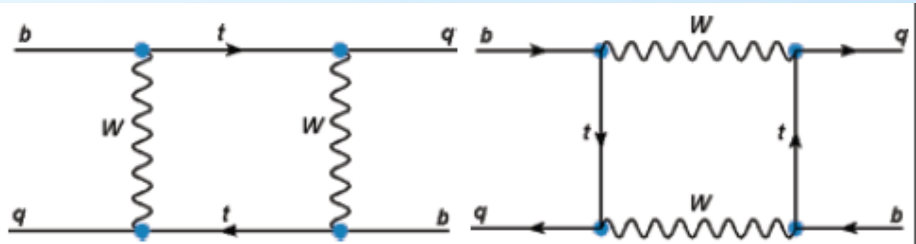
A precise determination of γ (O(1°)) is one of the highest priorities to be able to decide if there is new physics in ΔB=2 box diagrams!

$\Delta F=2$ Box Measurements

Δ F=2 box in b→q transitions

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

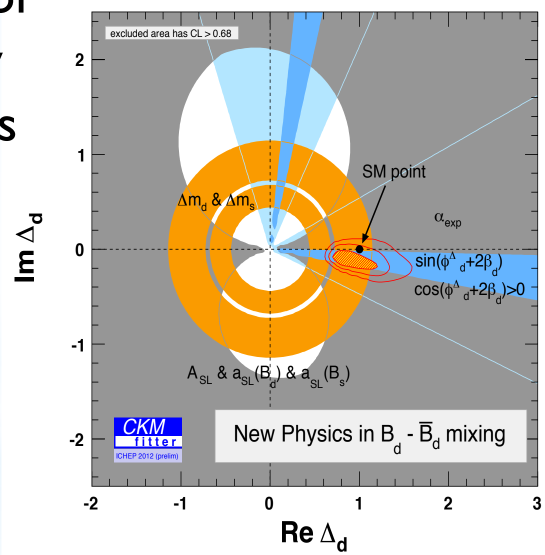
$$\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i\, \mathit{Im}(\Delta_q) = |\Delta_q| e^{i\phi^{\Delta}_q}$$

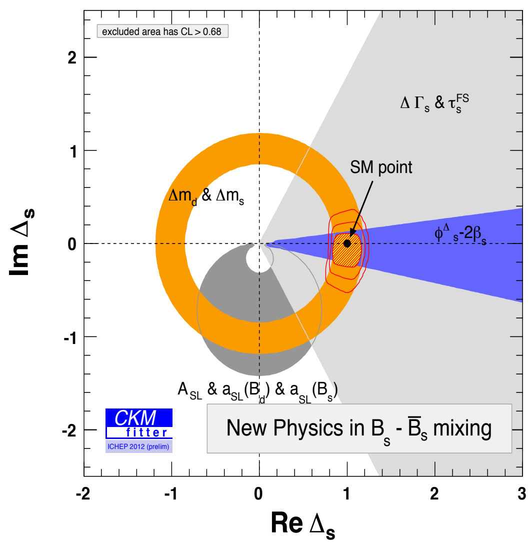


No significant evidence of NP in B_d or B_s mixing (B_d plot updated with new B→ τ ν results). B_s results much less sensitive to discrepancies in tree measurements.

New CP phases in dispersive contribution to box diagrams constrained to be <12% (<20%) for B_d(B_s).

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

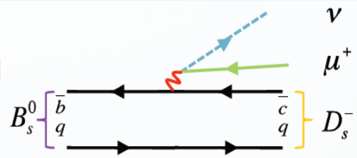




Need "percent" precision to disentangle new CP phases in B_d and B_s mixing

Δ F=2 box in b→q transitions

$B_q^0 \to D_q^- \mu^+ \nu_\mu$: Allowed



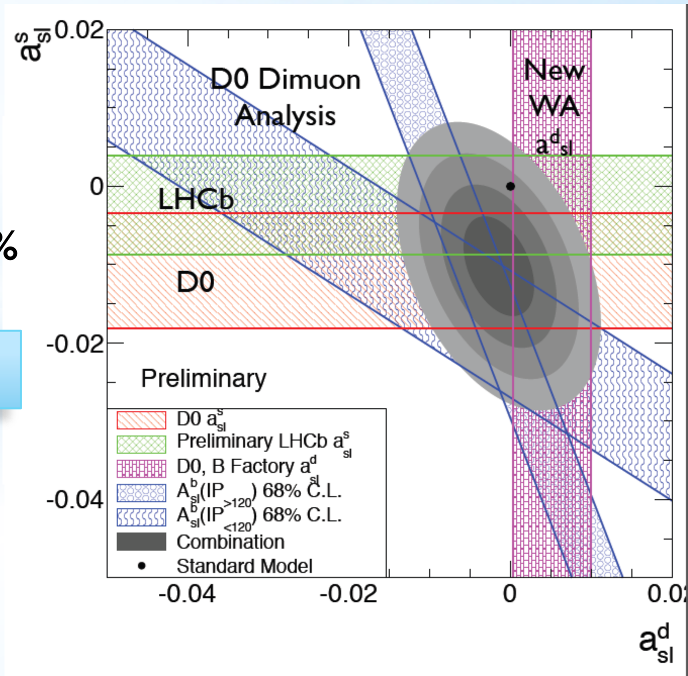
$\bar{B}_q^0 \to D_q^- \mu^+ \nu_\mu$: Not allowed directly

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

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

D0 measurement uses also the much larger sample of single muon decays (much reduced senstivity to a_{SL} but similar background than dimuon) to reduce drastically systematic uncertainties. The measurement is a linear combination of $a_{SL}(B_d)$ and $a_{SL}(B_s)$.

D0 Dimuon: $a_{SL}(B_d) = (-0.12 \pm 0.52)\%$, $a_{SL}(B_s) = (-1.81 \pm 1.06)\%$
D0 exclusive: $a_{SL}(B_d) = (0.93 \pm 0.47)\%$, $a_{SL}(B_s) = (-1.08 \pm 0.74)\%$
B-Factories average: $a_{SL}(B_d) = (-0.05 \pm 0.56)\%$
LHCb exclusive ($B_s \to D_s[\Phi\pi]\mu\nu X$): $\mathbf{a_{SL}(B_s) = (-0.24 \pm 0.63)\%}$

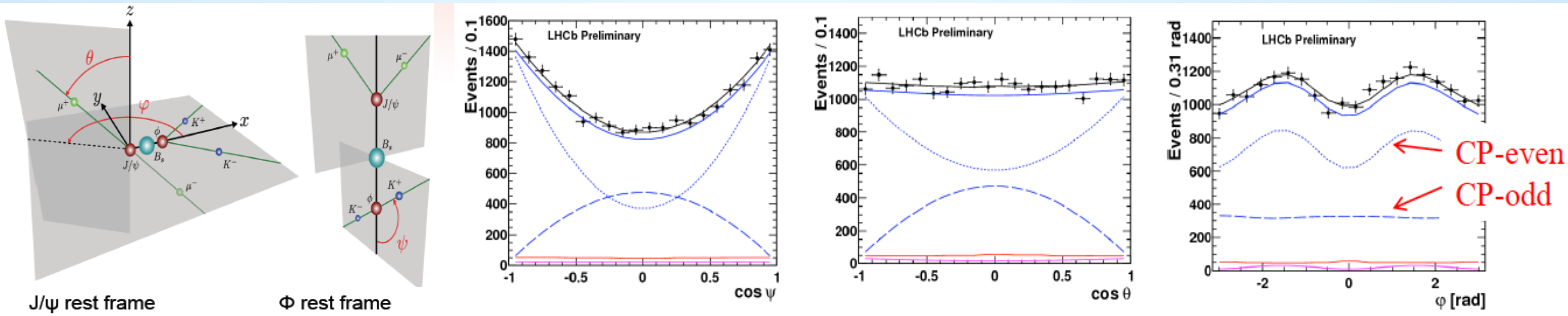


Combination: $a_{SL}(B_d) = (-0.15 \pm 0.29)\%$, $a_{SL}(B_s) = (-1.02 \pm 0.42)\%$

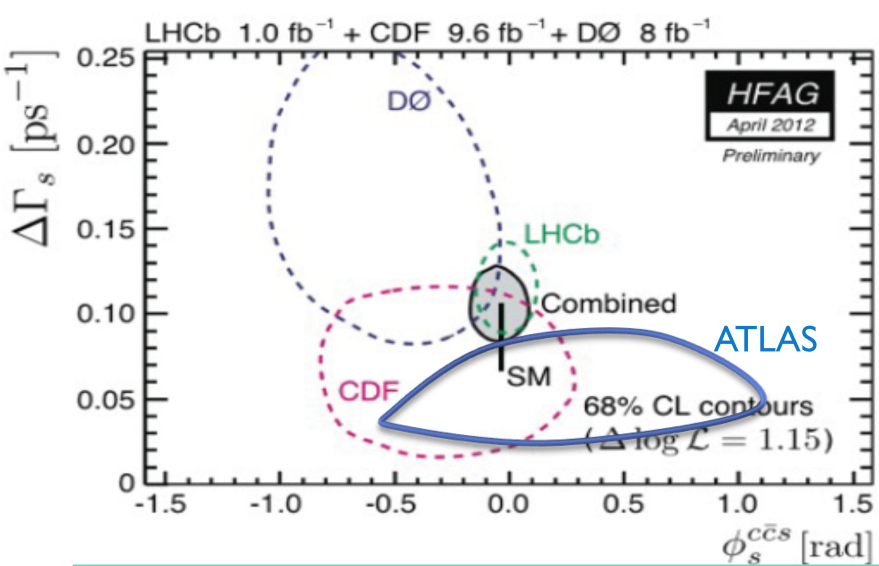
$a_{SL}(B_s)$ is 2.5 σ from SM. Need precision measurement (LHCb) to conclude on NP in a_{SL}.

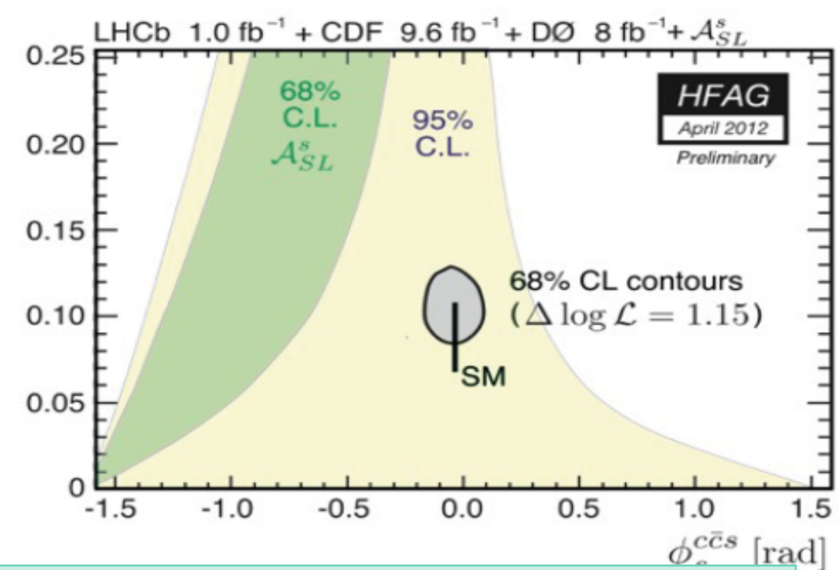
Δ F=2 box in b→s transitions

Large CP phases from NP contributing to the dispersive part (M_{12}) have already been excluded by the precise LHCb time-dependent angular analysis of the decay $B_s \to J/\Psi\,\Phi$.



Clear tension between $a_{SL}(B_s)$ and the indirect CP asymmetry measurements from LHCb.

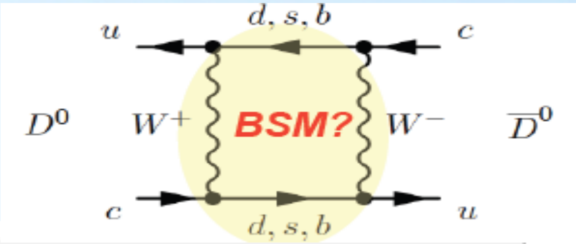




Looking now for NP effects of similar order than the SM CP phase in B_s.

Δ F=2 box in c→u transitions

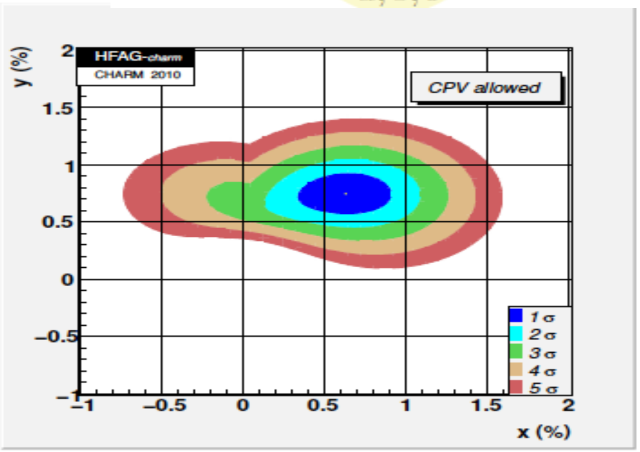
$$|D^0(t)\rangle = \left[|D^0\rangle cosh\left(\frac{ix+y}{2}t\right) + \frac{q}{p}|\bar{D}^0\rangle sinh\left(\frac{ix+y}{2}t\right)\right] \times e^{-\frac{1}{2}(1+\frac{im}{\Gamma})t}$$



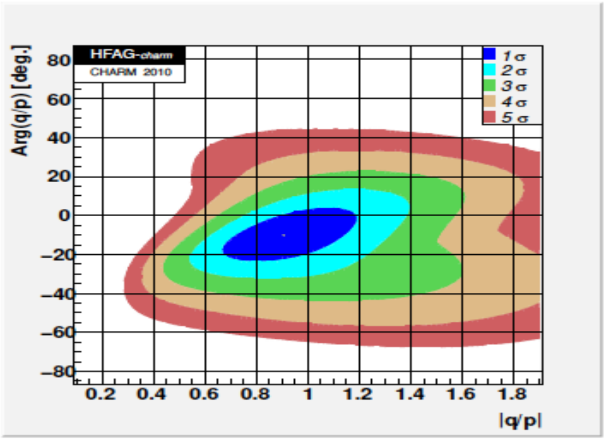
Charm mixing parameters dominated by (b&s)-quark box within SM, could be sensitive to "up" type of NP :

$$x=2(m_1-m_2)/(\Gamma_1+\Gamma_2)$$
$$y=(\Gamma_1-\Gamma_2)/(\Gamma_1+\Gamma_2)$$

Determined from several decays at B-factories. More than 10 σ evidence from the combination and compatible with SM expectations.



$$\begin{aligned} x &= (0.63 \pm 0.20)\% \\ y &= (0.80 \pm 0.13)\% \end{aligned}$$



$$\begin{aligned} |q/p| &= 0.91^{+0.18}_{-0.16} \\ \phi(^\circ) &= -10.0^{+9.4}_{-8.9} \end{aligned}$$

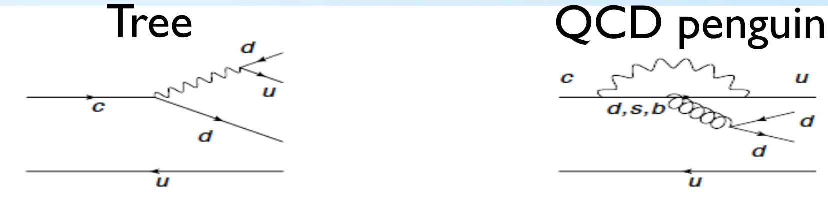
No CP violation ($q/p=1.\ \Phi=1$) is consistent with time dependent analysis at B-factories.

Next is to find clear evidence for indirect CP violation in charm mixing.

ΔF=1 QCD Penguins Measurements

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

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



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

But could we have large (unexpected) direct CP violation in Charm decays?
A priori, consensus was CP violation O(1%) would be "clear" sign for NP.

$D^{*\pm} \to D^0 \pi^\pm \to [h^+h^-] \pi^\pm$ charge of the pion determines the flavour of D^0.

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$ cancels detector and production asymmetries to first order.
The SM and most NP models predicts opposite sign for KK and ππ.

$\Delta A_{CP} = -0.82 \pm 0.24$ LHCb (PRL 108, 111602 (2012))
$\Delta A_{CP} = -0.62 \pm 0.23$ CDF (Preliminary CHARM 2012)
$\Delta A_{CP} = -0.87 \pm 0.41$ BELLE (Preliminary ICHEP 2012)

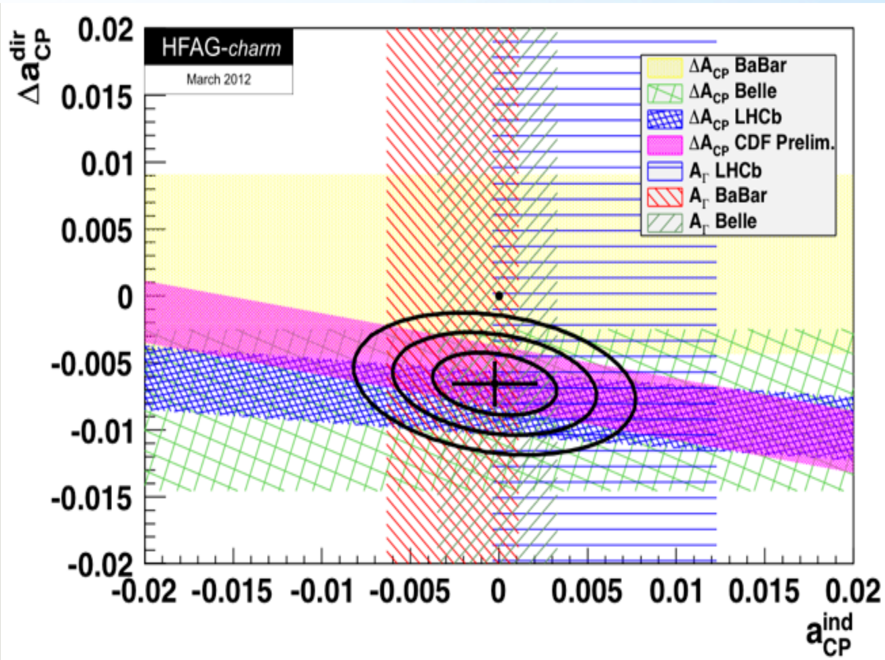
$$\Delta A_{CP} \approx \Delta a_{CP}^{dir} (1 + y_{CP} \overline{\langle t \rangle}/\tau) + a_{CP}^{ind} \Delta\langle t \rangle/\tau$$

Direct CPV evidence (>4σ)

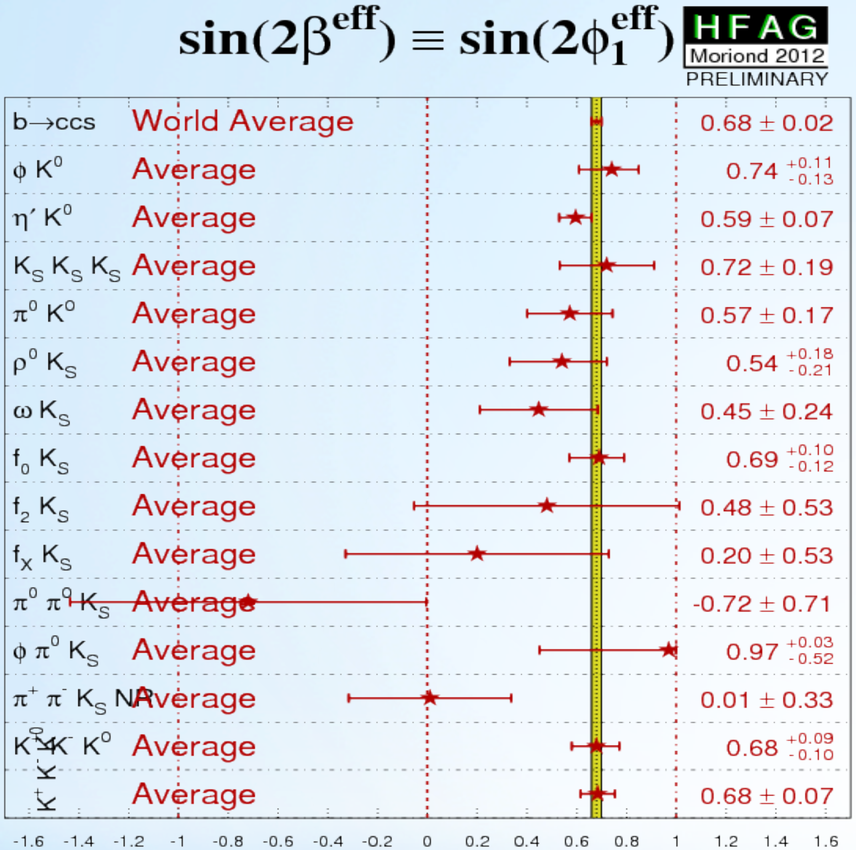
a_{CP}^{ind} =(-0.025±0.231)%

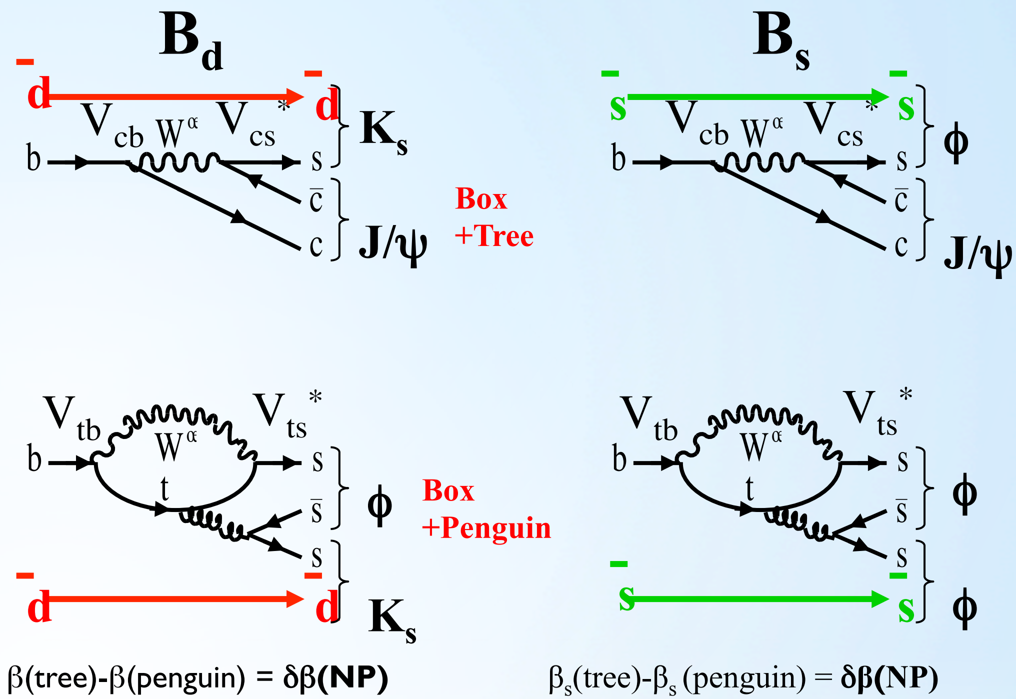
Δa_{CP}^{dir}=(-0.656±0.154)%

<u>Is it SM or not? More work for theorists and for experiments to find CPV in related channels!</u>



Δ F=1QCD penguins in b→q transitions





No significant discrepancy between b→ccs and s-penguin measurements. However, there may be a tendency and effects O(δβ~-10%) are not excluded.

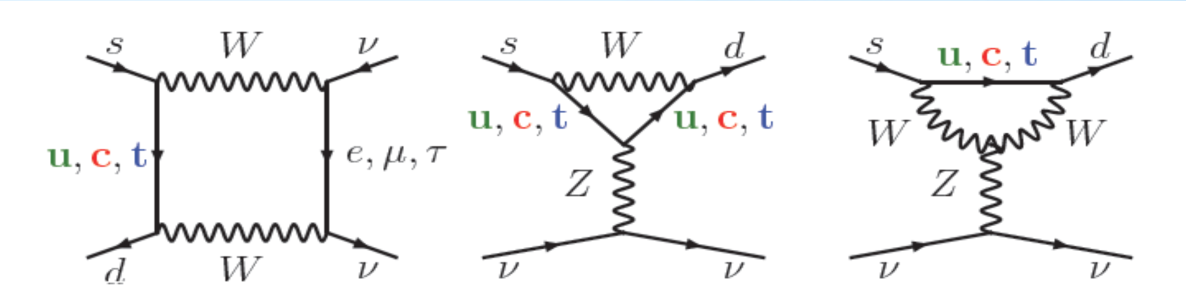
The effect of the same s-penguins can be measured precisely at LHCb both in the B_d and B_s system. Future super-B factories may improve further on B_d decays.

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

$\Delta F=1$ EW Penguins Measurements

Δ F=1 EW penguins in s→d transitions:Kaon decays

s→d ($|V_{ts}V_{td}| \alpha \lambda^5$)



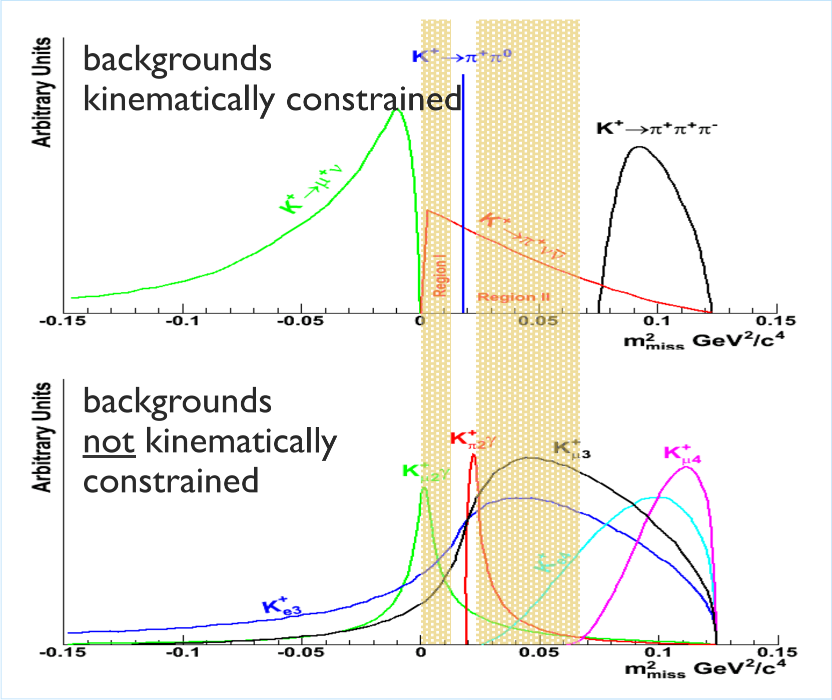
$K^+ \rightarrow \pi^+ \nu \nu$ and $K \rightarrow \pi^0 \nu \nu$ are certainly the "cleanest" Kaon decays (not long distance pollution affecting lepton modes, dominated by a single operator) and provide sensitivity to $|V_{td}|$.

$BR_{TH}(K^+ \rightarrow \pi^+ \nu \nu) = (7.8 \pm 0.8) \times 10^{-11}$ and **$BR_{TH}(K^0 \rightarrow \pi^0 \nu \nu) = (2.4 \pm 0.4) \times 10^{-11}$** both uncertainties are expected to be below 10% ultimately. The charged(neutral) mode is sensitive to CP-conserving(violating) NP.

BNL E787/E949 have observed 7 $K^+ \rightarrow \pi^+ \nu \nu$ candidates → **$BR = (17 \pm 11) \times 10^{-11}$**
KEK E391 has no $K^0 \rightarrow \pi^0 \nu \nu$ candidates → **$BR < 2.6 \times 10^{-8}$ @90% C.L.**

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

NA62 at CERN should start taking data when the SPS is available after the LS1 **(2014)**, using the technique of decay in flight expect to decrease the **experimental uncertainty to ~10% on BR($K^+ \to \pi^+ \nu \nu$).** After the LS2 **(2018)**, if a factor 10^8 π^0 rejection has been achieved, NA62 plans to attempt to measure the **neutral mode** (upgrades in the beam, target and detector would be needed). $K_L \to \pi^0 \pi^0$ is further suppressed by CP-conservation!



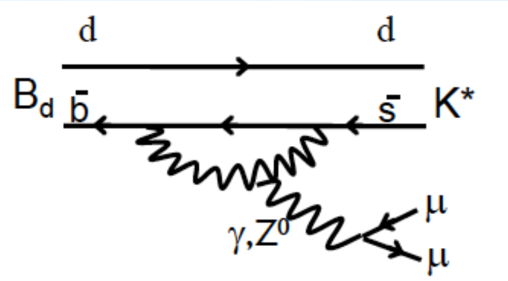
KOTO at J-PARC is expected to start data taking in **2014** and improve the limits on the neutral mode, eventually reaching the SM level. **KOTO-2** has the potential to even go further in precision.

In a somehow longer term **(2018) ORKA** (using stopped Kaons at Fermilab) may further improve the sensitivity in the charged mode **to 5%**. **Project-X** at Fermilab can improve on both modes in the future.

Expect significant improvements in both modes in the next 5 years

Δ F=1 EW penguins in b→s transitions: B→K* μ μ angular analysis

b→s ($|V_{tb}V_{ts}|$ α λ^2)

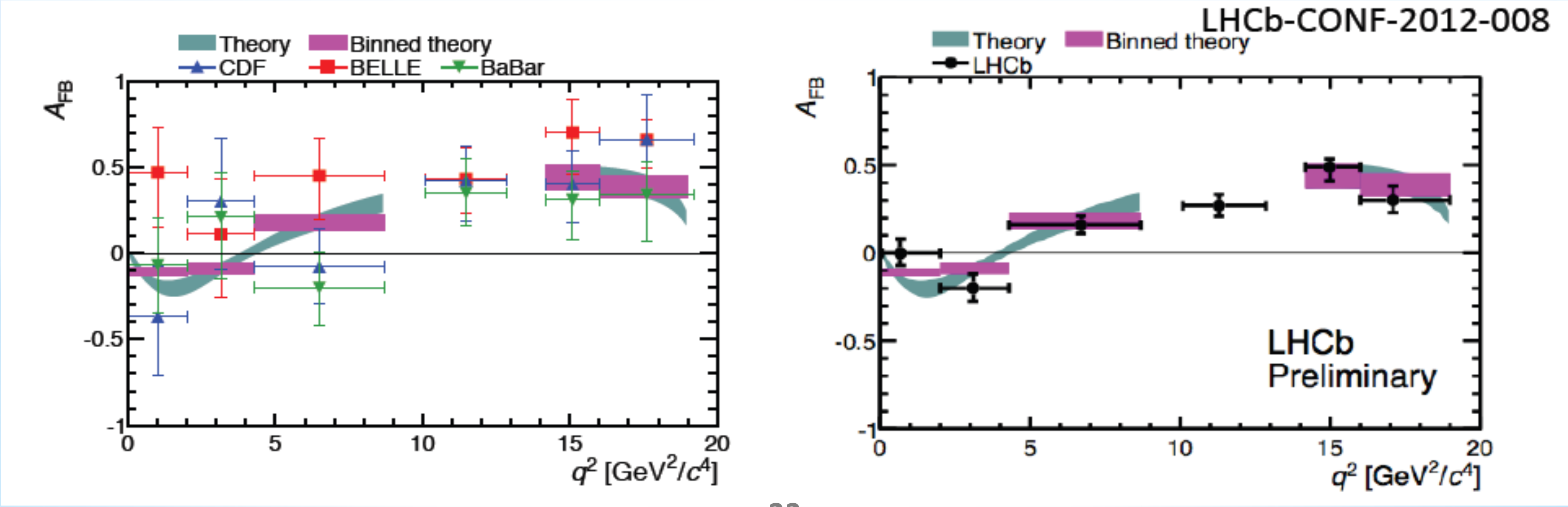


B→K* μ μ is the golden mode to test new vector(-axial) couplings in b→s transitions. K*→Kπ is self tagged, hence angular analysis ideal to test helicity structure.

Results from **B-factories and CDF** very much limited by the statistical uncertainty. **LHCb** already has in 2011 the largest sample (~900 candidates). A_{FB} vs q^2 found to be in good agreement with SM predictions, and allowed the first determination of the zero-crossing point:

$$q^2(A_{FB}=0)=4.9^{+1.1}_{-1.3}\ GeV^2/c^4$$

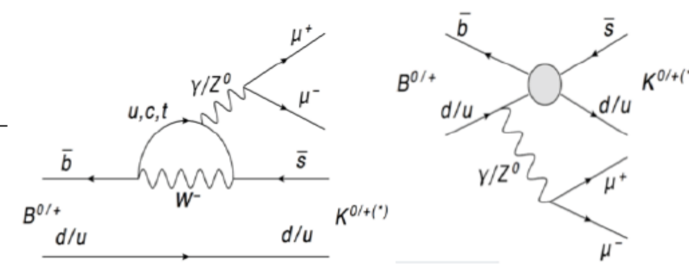
Many more theoretical clean observables are available with larger statistics.



Strong constraints in generic models of NP. Interest to improve the precision.

ΔF=1 EW penguins in b→s transitions: B→K(*) $\mu\,\mu$ Isospin analysis

# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb^{-1}	CDF 2011 6.8 fb^{-1}	LHCb 2011 1 fb^{-1}
$B^0 \to K^{*0}\ell\bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	164 ± 15	900 ± 34
$B^+ \to K^{*+}\ell\bar{\ell}$			20 ± 6	76 ± 16
$B^+ \to K^+\ell\bar{\ell}$	$153 \pm 41^\dagger$	$162 \pm 38^\dagger$	234 ± 19	1250 ± 42
$B^0 \to K^0_S\ell\bar{\ell}$			28 ± 9	60 ± 19

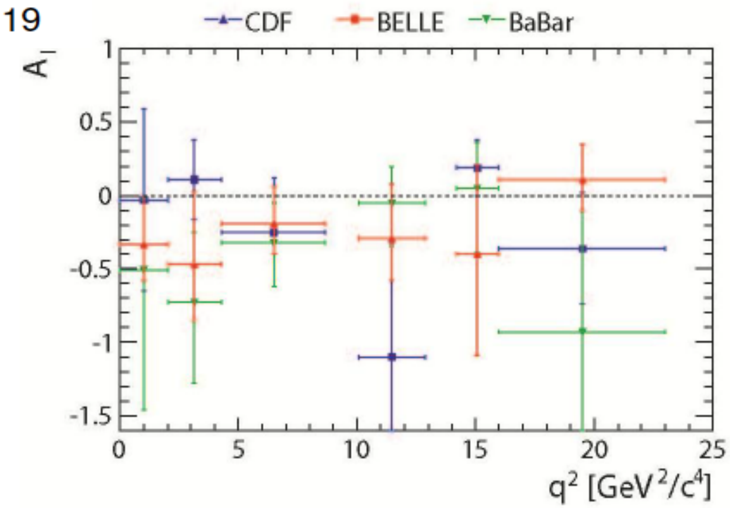


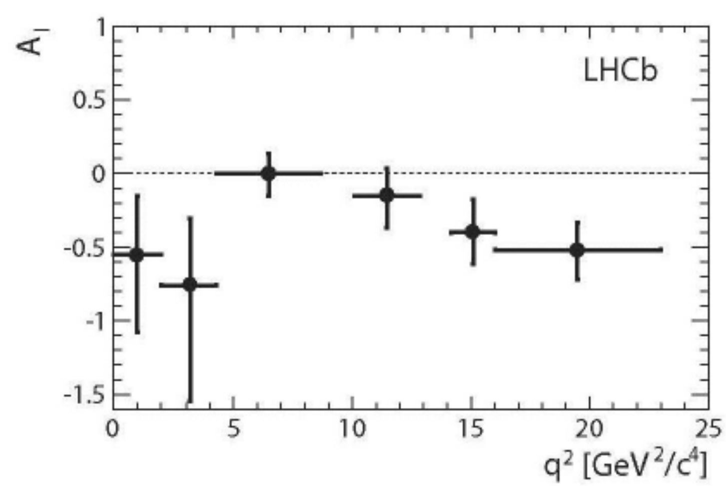
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

Within the SM the decays **B→K** $\mu\,\mu$ and **B⁺→K⁺** $\mu\,\mu$ are expected to have very similar BR, (O(%) differences at low q²).

While this is indeed what is observed for **B→K*** $\mu\,\mu$ and **B⁺→K*⁺** $\mu\,\mu$, **recent LHCb results** seem to confirm previous less precise measurements of the isospin asymmetry in B→K $\mu\,\mu$ decays to be significantly negative (>4 σ).

No clear interpretation so far.



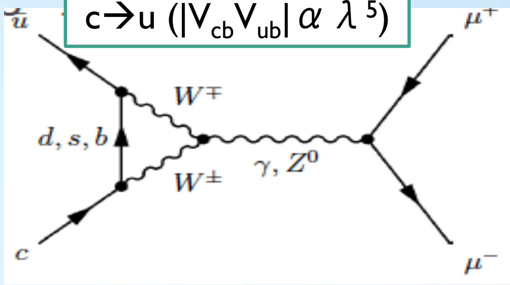


[arXiv:1205.3422]

$\Delta F=1$ Higgs Penguins Measurements

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

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



The pure leptonic decays of **D,K 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!**

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 6×10^{-11} from the existing limits on D→$\gamma\ \gamma$. **Charm decays complement K and B mesons decays.**

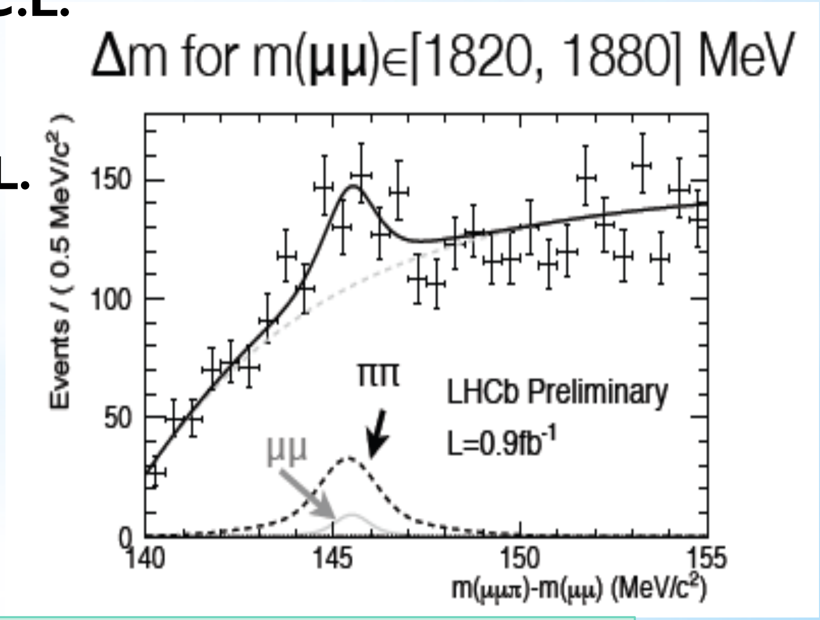
Experimental control of the peaking background is crucial (D→ππ). Best existing limit before this spring/summer was from **Belle, <1.4×10^{-7}@90%C.L.**

LHCb results this spring:

<$1.3(1.1)\times10^{-8}$@95(90)%C.L.

CMS results this summer: <5.4×10^{-7}@90%C.L.

And **BABAR** results this summer show a slight excess of candidates (8 observed, 3.9±0.6 bkg) which was interpreted as a **two-sided 90% C.L. limit, [0.6,8.1]$\times10^{-7}$, tension with LHCb results.**

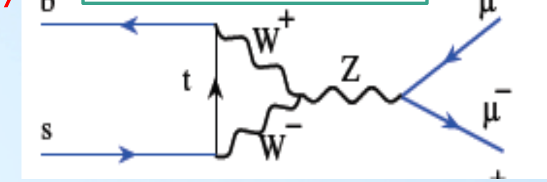


LHCb will study the theoretical clean region between 10^{-8} and 10^{-11}

$\Delta F=1$ Higgs penguins in $b\to d,s$ transitions: B decays

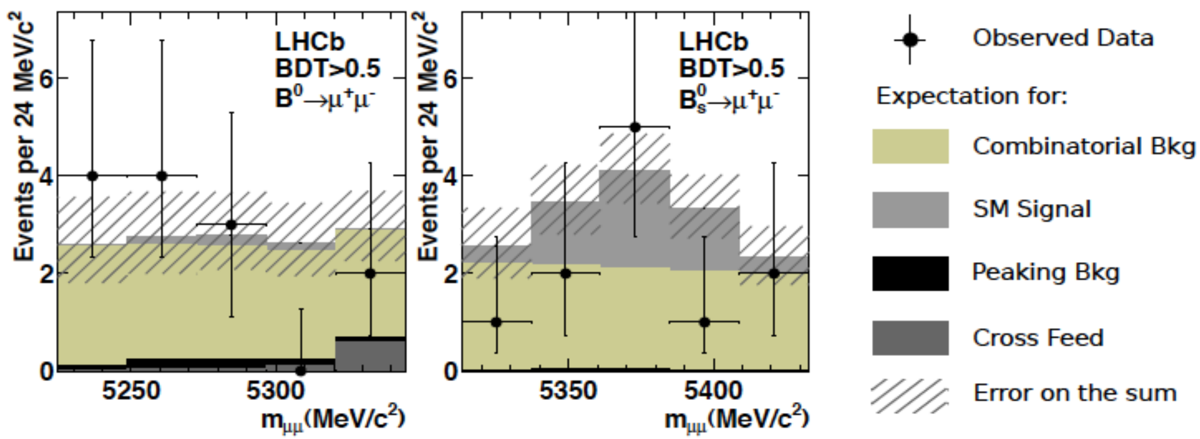
The pure leptonic decay of the B mesons is well predicted theoretically, and experimentally is exceptionally clean (in particular for B_s, peaking background is very small).

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



Within the SM, $BR_{SM}(B_s\to \mu\mu) = (3.2\pm0.3)\times10^{-9}$ (arXiv:1208.0934)

$BR_{SM}(B\to \mu\mu) = (1.0\pm0.1)\times10^{-10}$



Limits for B^0 at 95% C.L.

- CDF
  $BR(B^0\to\mu^+\mu^-) < 4.6\times10^{-9}$
- CMS
  $BR(B^0\to\mu^+\mu^-) < 1.8\times10^{-9}$
- LHCb
  $BR(B^0\to\mu^+\mu^-) < 1.0\times10^{-9}$

LHCb and CMS are the experiments **with highest sensitivity:** *1/fb(LHCb)~7/fb(CMS)* as in 2011 analysis.

Limits for B^0_s at 95% C.L.

- D0
  $BR(B^0_s\to\mu^+\mu^-) < 51\times10^{-9}$
- CDF
  $BR(B^0_s\to\mu^+\mu^-) < 31\times10^{-9}$
- ATLAS
  $BR(B^0_s\to\mu^+\mu^-) < 22\times10^{-9}$
- CMS
  $BR(B^0_s\to\mu^+\mu^-) < 7.7\times10^{-9}$
- LHCb
  $BR(B^0_s\to\mu^+\mu^-) < 4.5\times10^{-9}$

Preliminary upper limits (95% CL)

LHC combination: $BR(B_s\to \mu\mu) < 4.2\times10^{-9}$, $BR(B\to \mu\mu) < 8.1\times10^{-10}$

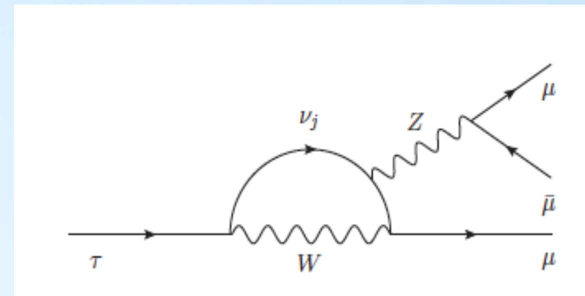
The probability that the observed number of B_s candidates is in agreement with **background only is 5%** (i.e. **~2σ evidence**)

Measurement of $BR(B_s\to \mu\mu)$ very soon. Next improve precision O(5%) and measure ratio $BR(B\to \mu\mu)/BR(B_s\to \mu\mu)$

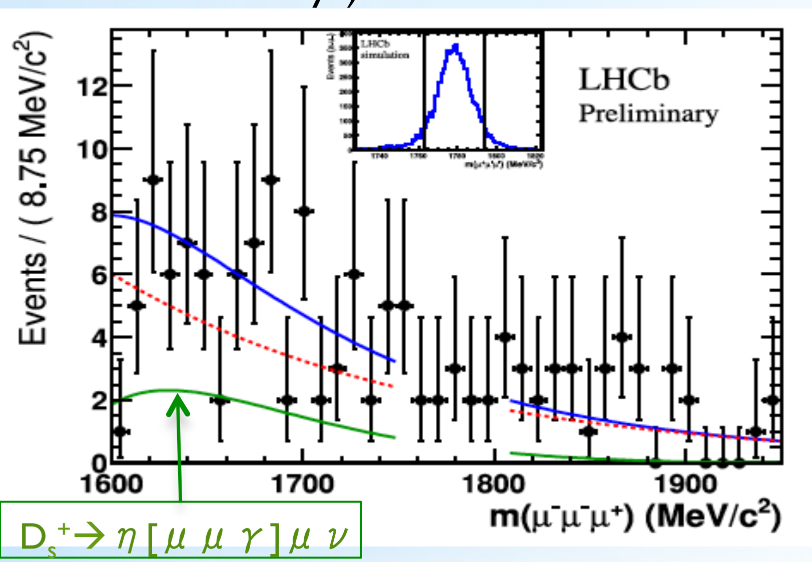
Charged Lepton Measurements

Tau Flavour Violation Decays: $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$

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).
The ratio between $\tau \to \mu\gamma$ and $\tau \to \mu\mu\mu$ is a very powerful test.



Taus are **copiously produced** both at flavour-factories and at LHC (mainly from charm decays).



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}
LHCb:	-	6.3×10^{-8}

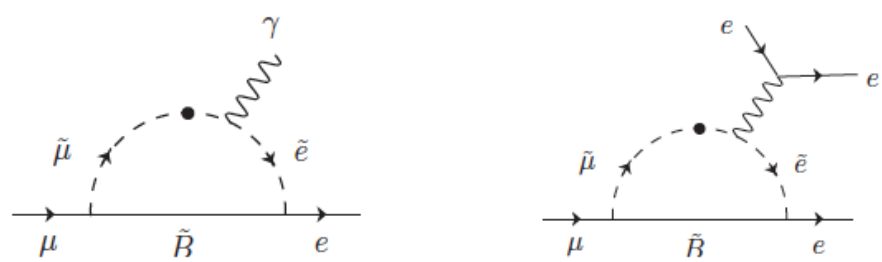
New preliminary result from LHCb with 1/fb at 7 TeV looks very promising. **More statistics and analysis improvements are already on hand.**

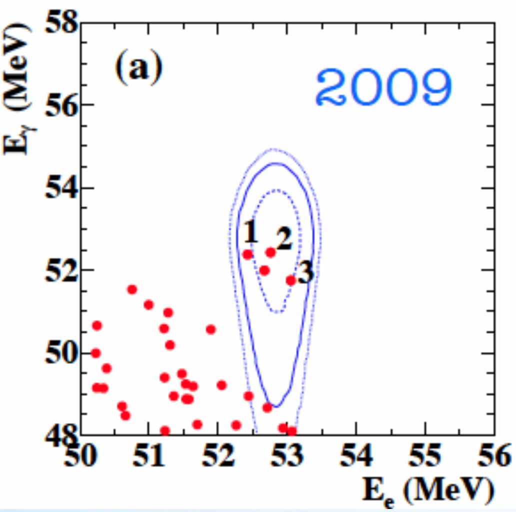
The **LHCb-upgrade** with 50/fb should reach **BR($\tau \to \mu\mu\mu$)<[0.1-8]x10^{-9}.**
A **super B-factory** with 50/ab should reach **BR($\tau \to \mu\mu\mu$)< [0.2-1]x10^{-9}** and **BR($\tau \to \mu\gamma$)<[2-3]x10^{-9}.**

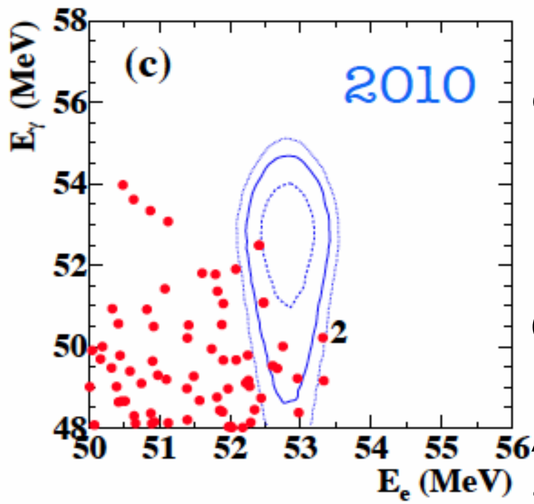
Very clear physics case to improve the sensitivity to tau flavour violating decays.
A factor 10-100 increase in sensitivity in the near future looks feasible!

Muon Flavour Violation Decays: $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$

CLFV do not have apparent mass scaling. Whether muon or taus are more important will depend on the nature of NP.







MEG recent results using 2010 data do not confirm 2009 slight excess of $\mu \to e\gamma$ candidates.

MEG(2010+11): BR($\mu \to e\gamma$)<2.4×10^{-12} @90%C.L.

Expected limit: 1.6×10^{-12}

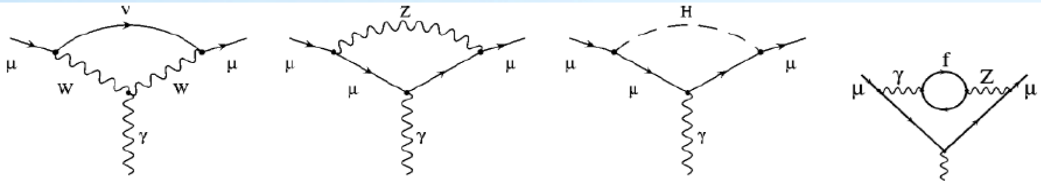
Analysis of 2011 data ongoing, expected sensitivity from **2011 data only ~1×10^{-12}.**

Interesting proposal in Europe (**μ3e at PSI)** to improve **$\mu \to eee$** by four orders of magnitude.

Very clear physics case to improve by several orders of magnitude the sensitivity to muon flavour violating decays.

Process	Current limit	Expected limit 5-10 years		Expected limit 10-20 years
$\mu^+ \to e^+\gamma$	2.4×10^{-12} PSI/MEG (2011)	1×10^{-13} PSI/MEG		1×10^{-14} PSI, Project X
$\mu^+ \to e^+e^-e^+$	1×10^{-12} PSI/SINDRUM-I (1988)	1×10^{-15} Osaka/MuSIC	1×10^{-16} PSI/μ3e	1×10^{-17} PSI, Project X
$\mu^-N \to e^-N$	7×10^{-13} PSI/SINDRUM-II (2006)	1×10^{-14} J-PARC/DeeMee	6×10^{-17} FNAL/Mu2e J-PARC/COMET	1×10^{-18} J-PARC, Project X

Muon magnetic and electric dipole moments



$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}, \qquad \vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s},$$

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = -\frac{Qe}{m}\left[a\vec{B} + \left(a - \left(\frac{m}{p}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right].$$

$$a_\mu(\text{Standard Model}) = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$

Eur. Phys. J. C71, 1515 (2011)

$a_\mu(\text{QED})$	=	116 584 718.09	$\pm\, 0.15(\alpha^5)$
$a_\mu(\text{HadVP; LO})$	=	6 923.	$\pm\, 42(\text{Exp})$
$a_\mu(\text{HadVP; HO})$	=	-97.9	$\pm\, 0.8(\text{Exp}) \pm 0.3(\text{Rad})$
$a_\mu(\text{Had; LBL})$	=	105.	$\pm\, 26$
$a_\mu(\text{Weak; 1 loop})$	=	194.8	
$a_\mu(\text{Weak; 2 loop})$	=	-40.7	$\pm\, 1(\text{Had}) \pm 2(\text{Higgs})$
⇒ $a_\mu(\text{SM})$	=	116 591 802.	$\pm\, 49 \times 10^{-11}$ (0.42 ppm)

E821 at Brookhaven stores muons at the "magic momentum" to cancel dependence with E, and using the decays **$\mu^\pm \to e^\pm \nu\,\nu$** reach an experimental precision of 0.54 ppm:

$\Delta a_\mu = (287\pm80)\times10^{-11}$ (3.6σ)

The observed discrepancy is large compared with weak contribution and uncertainty on hadronic terms.

E821 also provide the best limit on the muon dipole moment as a byproduct: **$|d_\mu| < 1.9\times10^{-19}$ e cm (@95% CL)**

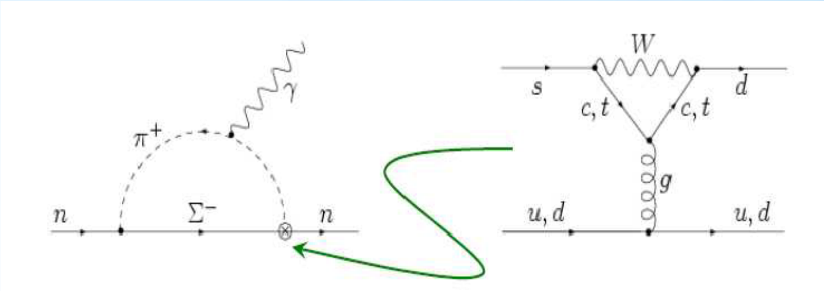
New proposal at Fermilab (P989) aims to reduce the uncertainty on a_μ down to 0.14 ppm by improving on **statistics (factor 4)** and **systematics (factor 3)**. They also expect to improve on d_μ down to ~10^{-21} e cm. An alternative approach to measure a_μ with comparable sensitivity is proposed at **J-PARC using muonium** (μ e) decays.

Precise measurements of a_μ and/or d_μ may very well be one of our best chances to see NP

Fundamental symmetries

Neutron electric dipole moment

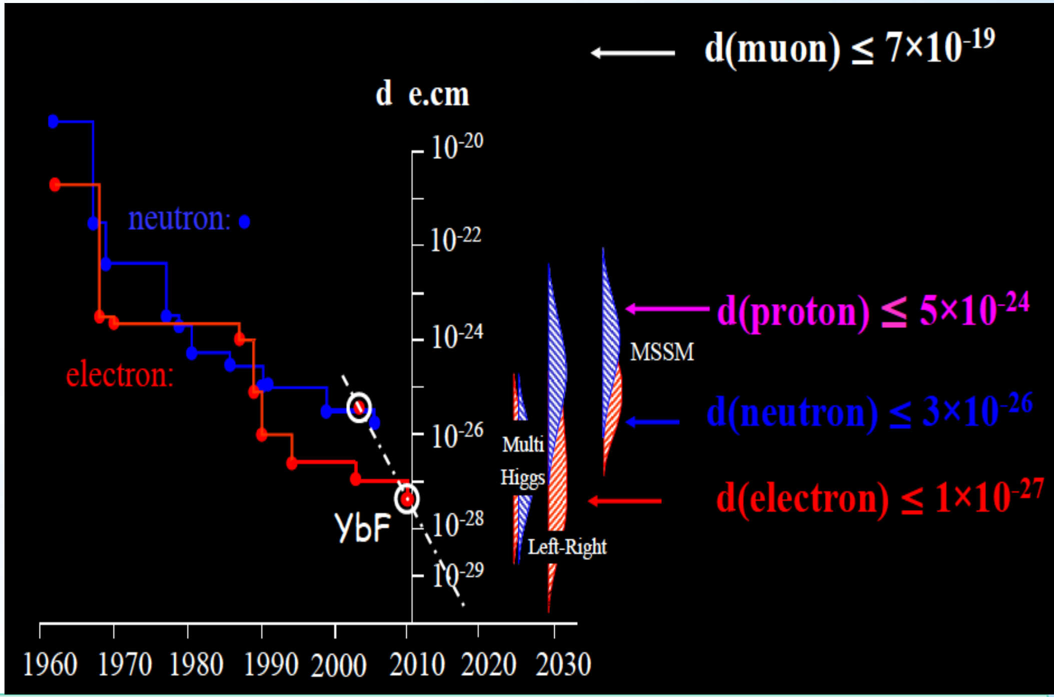
Why the SM does not include CP violation in the strong sector? One idea is the spontaneously broken **Peccei-Quinn** symmetry, but where's the axion?



Within the SM **d_n^{SM}~10^{-32} – 10^{-34} e cm.**
Present experimental status: **d_n<2.9×10^{-26} e cm @90%CL**. An observation of a non-zero **nEDM** in the foreseeable future will be a clear indication of NP (and **most probably CP violation in the strong interactions**)

Many proposal in the world to improve These limits, and in particular in Europe: **ILL,PNPI,PSI and FRM-2**. Essentially all projects aim at **10^{-28}** within the next decade. The nEDM experiment at PSI is already taking data.

There are also many proposal to improve precision on EDM in electrons, Nuclei, Atoms and Molecules.



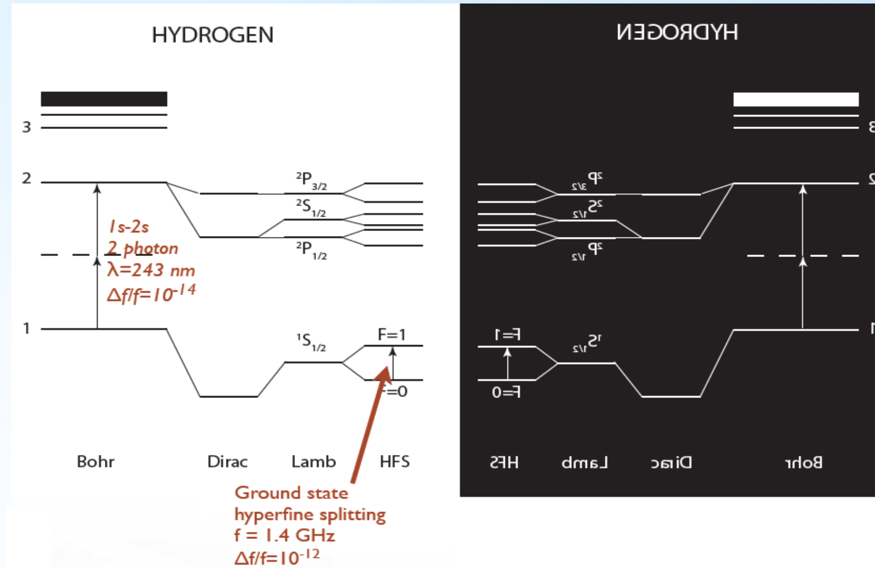
To find a non-zero nEDM in the foreseeable future will be a fantastic breakthrough

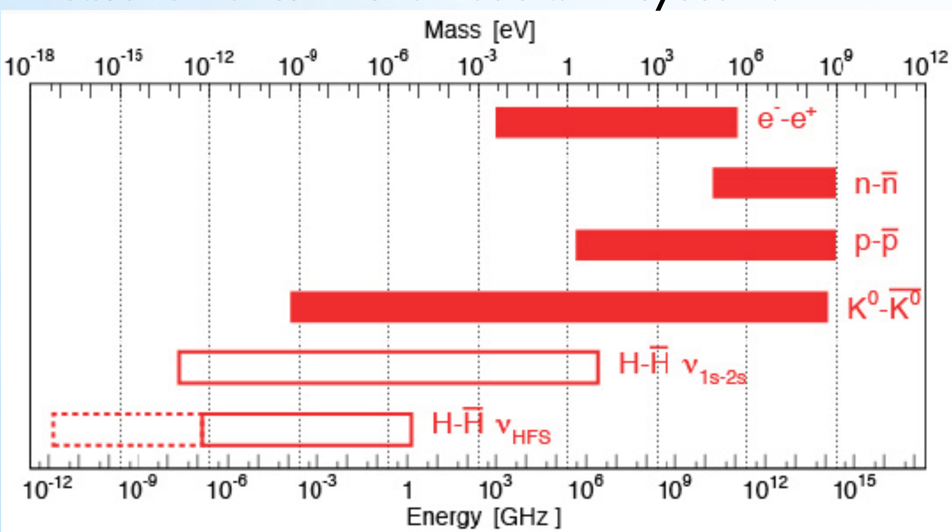
CPT symmetry: matter vs antimatter

What about if something **more fundamental is wrong** in our thinking: CPT violation?

The highest sensitivity (mass<10^{-9}) can only be achieved with antihydrogen. A precise measurement of the hyperfine structure of antihydrogen atoms will be a powerful test.

KLOE-2 will contribute with interferometry measurements in the neutral K system.





CERN AD is a unique facility:

2002 first formation of antihydrogen

2010 first trapping of antihydrogen.

First measurements by ALPHA as a proof of principle.

Further deceleration stage **(ELENA)** should increase **(x100)** the number of trapped antiprotons. Operational in 2017.

CPT violation could be the unexpected twist.

My Personal 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, most notably the observation of a large direct CP violation in charm decays, but in general the agreement with the SM is excellent → **large NP contributions ruled out in many cases.**

In my opinion, our best chances to find NP in flavour physics are:

- Precise determination of (ρ, η) with tree level processes.
- Precise determination of CP-violating in $\Delta B=2$ processes.
- Improved precision in rare penguins $\Delta F=1$ processes.
- LFV in muon and tau decays.
- EDM

My Personal Conclusions

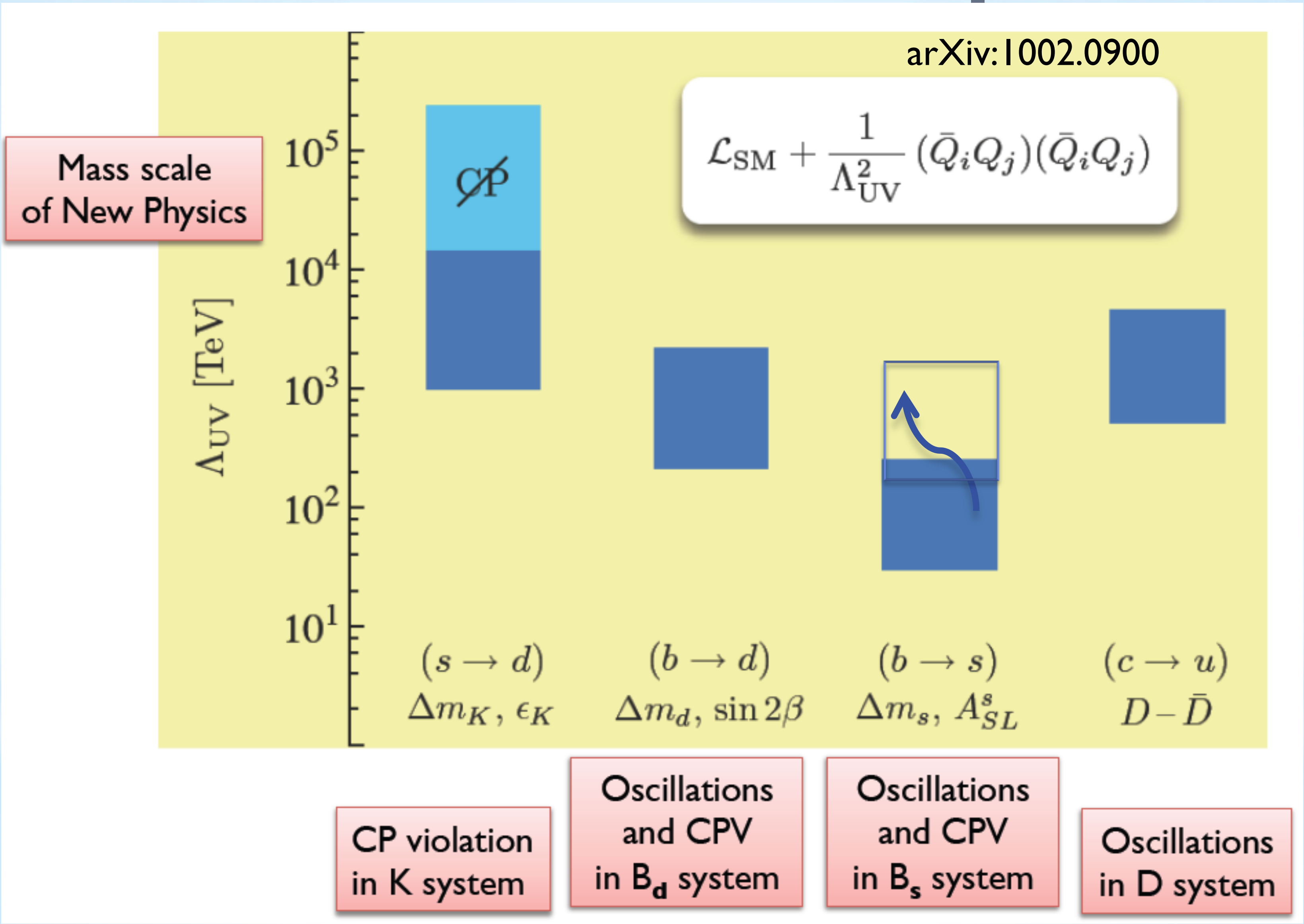
A large part of this program can be performed with upgrades of existing "large" experiments (S-LHCb, Belle-2) while new "smaller" experiments are being proposed for Kaons, LFV and EDM measurements.

There is a priory as many good reasons to find NP by measuring precisely the Higgs couplings as by precision measurements in the flavour sector!

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

Backup

Δ F=2 box implications

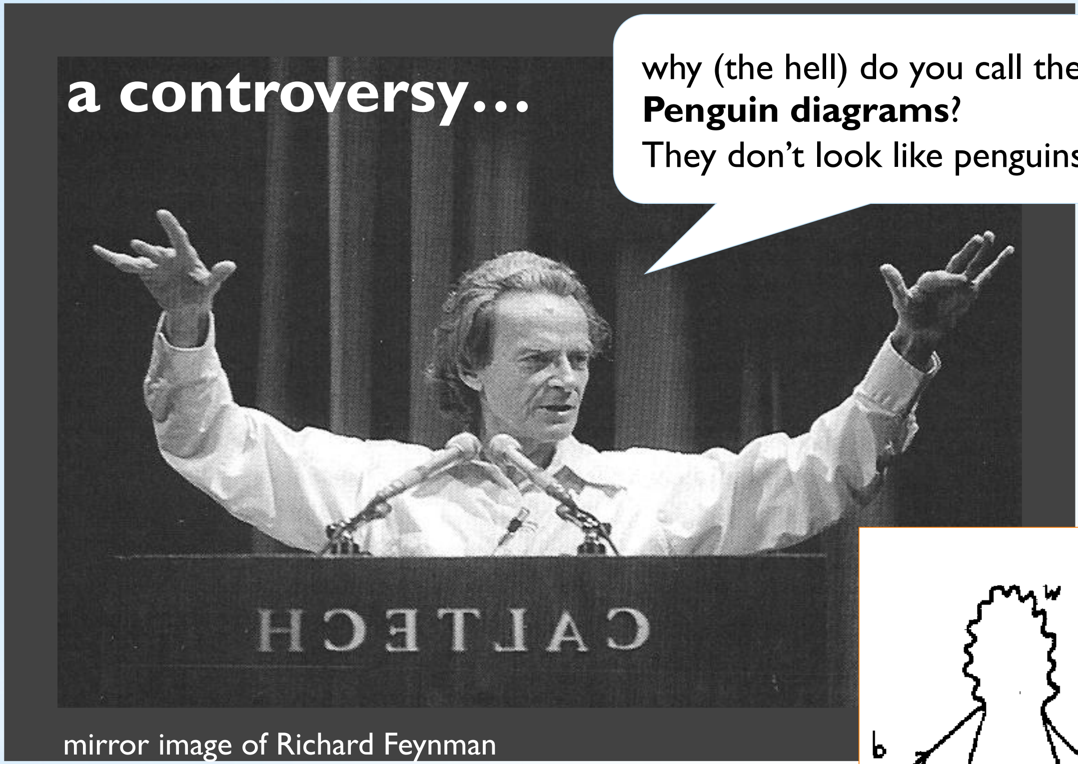


Summary of experimental results

Observable class of observables)	SM prediction	Ultimate th. error	Present result	Future (S)LHCb	Future SuperB	Future Other
$\|V_{us}\|$ $[K \to \pi\ell\nu]$	input	$0.1\%_{(Latt)}$	0.2252 ± 0.0009	-	-	
$\|V_{cb}\|$ $[\times 10^{-3}]$ $[B \to X_c\ell\nu]$	input	1%	40.9 ± 1.1	-	$1\%_{excl}$, $0.5\%_{incl}$	
$\|V_{ub}\|$ $[\times 10^{-3}][B \to \pi\ell\nu]$	input	$5\%_{(Latt)}$	4.15 ± 0.49	-	$3\%_{excl}$, $2\%_{incl}$	
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	-	
$A^d_{SL}[\times 10^{-3}]$	-0.5	0.1	-5.8 ± 3.4	0.2	4	
$A^s_{SL}[\times 10^{-3}]$	2.0×10^{-2}	$< 10^{-2}$	-2.4 ± 6.3	0.2	-	
$\mathcal{B}(B \to \tau\nu)[\times 10^{-4}]$	1	$5\%_{Latt}$	(1.14 ± 0.23)	-	4%	
$\mathcal{B}(B \to \mu\nu)[\times 10^{-7}]$	4	$5\%_{Latt}$	< 13	-	5%	
$\mathcal{B}(B \to D\tau\nu)[\times 10^{-2}]$	1.02 ± 0.17	$5\%_{Latt}$	1.02 ± 0.17	[under study]	2%	
$\mathcal{B}(B \to D^*\tau\nu)[\times 10^{-2}]$	1.76 ± 0.18	$5\%_{Latt}$	1.76 ± 0.17	[under study]	2%	
$\mathcal{B}(B_s \to \mu^+\mu^-)[\times 10^{-9}]$	3.5	$5\%_{Latt}$	< 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%	-	
$A^{(2)}_T(B \to K^*\mu^+\mu^-)$	$< 10^{-3}$			0.04	-	
$A_{CP}(B \to K^*\mu^+\mu^-)$	$< 10^{-3}$			0.5%	1%	
$B \to K\nu\bar{\nu}[\times 10^{-6}]$	4	$10\%_{Latt}$	< 16	-	0.7	
$\|q/p\|_{D-\mathrm{mixing}}$	1	$< 10^{-3}$	0.91 ± 0.17	$O(1\%)$	2.7%	
ϕ_D	$\lesssim 0.1\%$		$-$	$O(1^\circ)$	1.4°	
$a^{dir}_{CP}(\pi\pi)(\%)$	$\lesssim 0.3$		0.20 ± 0.22	0.015	[under study]	
$a^{dir}_{CP}(KK)(\%)$	$\lesssim 0.3$		-0.23 ± 0.17	0.010	[under study]	
$a^{dir}_{CP}(\pi\pi\gamma, KK\gamma)$	$\lesssim 0.3\%$			[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% CL)	1-80	2	
$\mathcal{B}(\mu \to e\gamma)[\times 10^{-12}]$	0		< 2.4(90% CL)			~ 0.1 MEG ~ 0.01 PSI-future ~ 0.01 Project X
$\mathcal{B}(\mu N \to eN)(Tl)$	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
$\mathcal{B}(K_L \to \pi^0 e^+e^-)_{SD}$	1.4×10^{-11}	30%	$< 28 \times 10^{-11}$			$\sim 10\%$ Project X

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 $\Upsilon(4S)$.

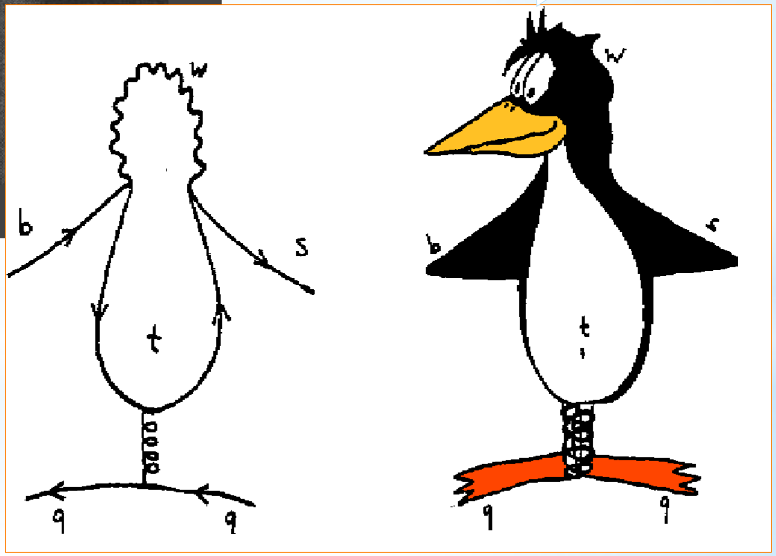
FCNC in the SM



mirror image of Richard Feynman

why (the hell) do you call these **Penguin diagrams**? They don't look like penguins!

I've never seen a **Feynman diagram** that looks like **you** ☺



Taken from A. Hoecker Summer Student lectures at CERN (2006)

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
$B_u \to D^0{}_{\text{CP}}\pi$	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