



XXIV Workshop on Weak Interactions and Neutrinos

WIN 2013

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XXIV Workshop on Weak Interactions and Neutrinos - WIN'13

* Indirect Searches for NP in Flavour Physics.

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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. D 11 (1975) 2856) makes sure that the contributions of **heavy ($M \gg q^2$) 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 are **suppressed** by the size of the **isospin breaking** value Δm^2 . **Larger effects** of NP expected in **(t,b)/ τ** -physics.

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 $\sim 126 \text{ GeV}/c^2$.

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 \rightarrow **NP FLAVOUR PROBLEM**

“Non-natural” solution:

\rightarrow 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 \rightarrow **chances to see NP in flavour physics have, in fact, increased** when Naturalness (in the SM Scalar sector) seems to be less plausible!

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

Naturalness' Loss = Flavour Gain

100 TeV
10 TeV
1 TeV

Not KM-like
Quasi KM-like
KM-like

can't predict what will first be seen!

CAST A WIDE NET

FCNC in the SM

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

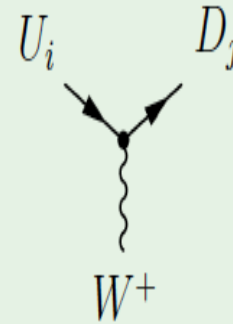
$$Q_U = +2/3$$

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

$$Q_D = -1/3$$

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

~ Cabibbo-Kobayashi-Maskawa (CKM) matrix



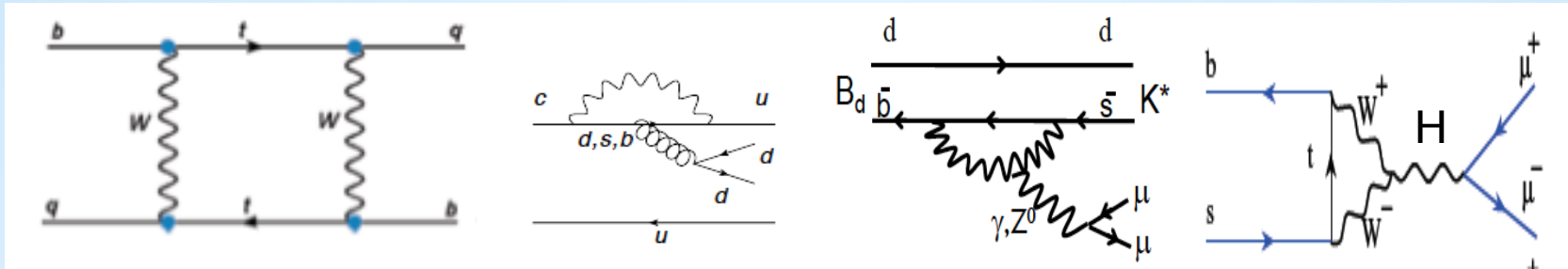
In the SM quarks are allowed to **change flavour** as a consequence of the **Yukawa mechanism** which is parameterized in a complex CKM couplings matrix.

Using Wolfenstein parameterization:

$$\begin{aligned} A &= 0.80 \pm 0.02 \\ \lambda &= 0.225 \pm 0.001 \end{aligned}$$

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

Loops zoology



$\Delta F=2$ box

QCD Penguin

EW Penguin

Higgs Penguin

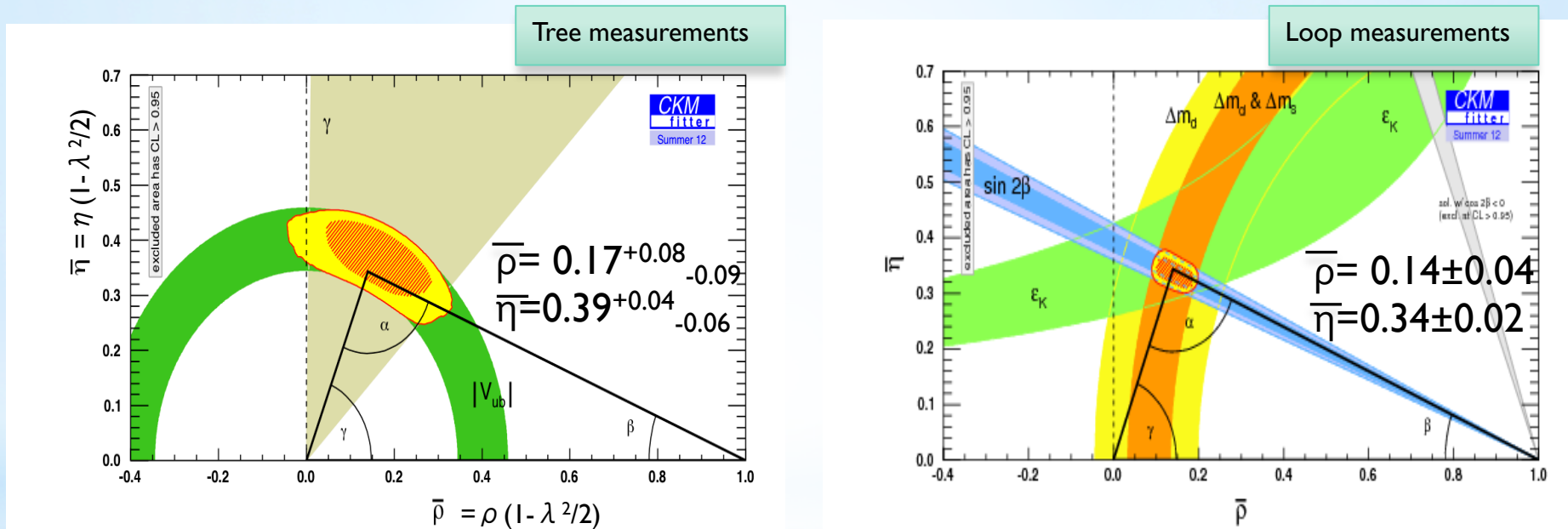
Map of Flavour transitions and type of loop processes: \rightarrow **Map of this talk!**

	$b \rightarrow s$ ($ \mathbf{V}_{tb}\mathbf{V}_{ts} \propto \lambda^2$)	$b \rightarrow d$ ($ \mathbf{V}_{tb}\mathbf{V}_{td} \propto \lambda^3$)	$s \rightarrow d$ ($ \mathbf{V}_{ts}\mathbf{V}_{td} \propto \lambda^5$)	$c \rightarrow u$ ($ \mathbf{V}_{cb}\mathbf{V}_{ub} \propto \lambda^5$)
$\Delta F=2$ box	$\Delta M_{B_s}, A_{CP}(B_s \rightarrow J/\Psi \Phi)$	$\Delta M_B, A_{CP}(B \rightarrow J/\Psi K)$	$\Delta M_K, \epsilon_K$	$x, y, q/p, \Phi$
QCD Penguin	$A_{CP}(B \rightarrow hhh), B \rightarrow X_s \gamma$	$A_{CP}(B \rightarrow hhh), B \rightarrow X \gamma$	$K \rightarrow \pi^0 \Pi, \epsilon'/\epsilon$	$\Delta a_{CP}(D \rightarrow hh)$
EW Penguin	$B \rightarrow K^{(*)} \Pi, B \rightarrow X_s \gamma$	$B \rightarrow \pi \Pi, B \rightarrow X \gamma$	$K \rightarrow \pi^0 \Pi, K^\pm \rightarrow \pi^\pm \nu \nu$	$D \rightarrow X_u \Pi$
Higgs Penguin	$B_s \rightarrow \mu \mu$	$B \rightarrow \mu \mu$	$K \rightarrow \mu \mu$	$D \rightarrow \mu \mu$

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, \dots) with the ones from **loop diagrams** $(\Delta M_d \& \Delta M_s, \beta, \varepsilon_K, \dots)$.



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.**

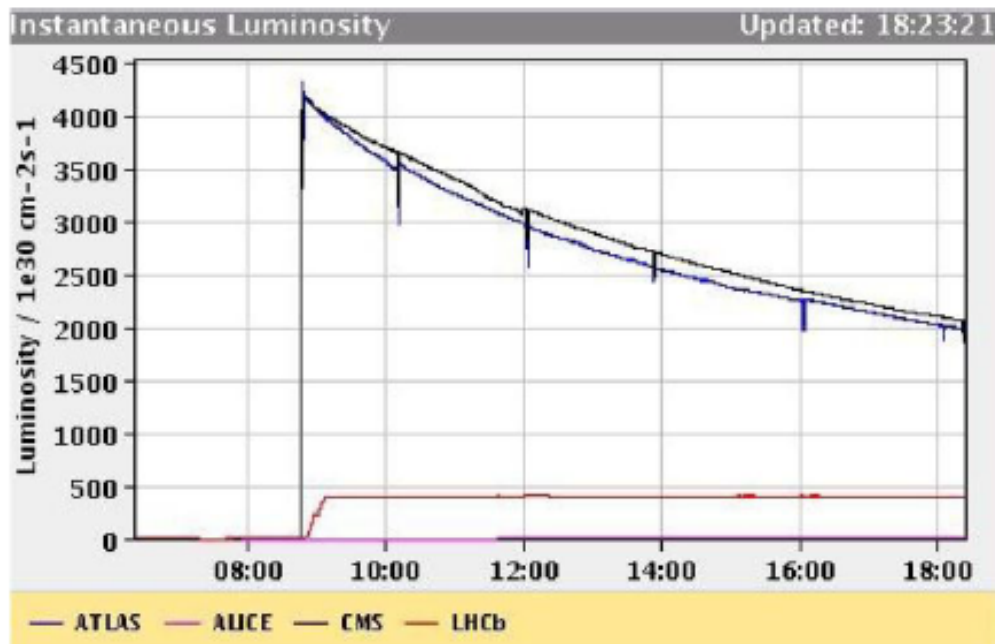


Experimental Facilities

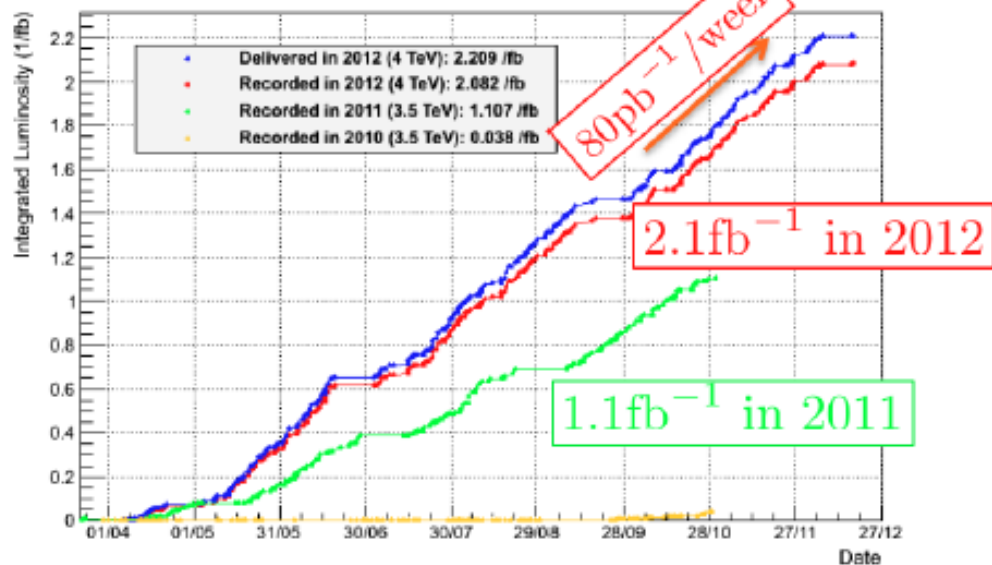
LHC is working like a dream!

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 $4 \times 10^{33}/\text{cm}^2/\text{sec}$ at 8 TeV, for a total of 23/fb to ATLAS&CMS (6/fb in 2011 at 7 TeV).



LHCb Integrated Luminosity pp collisions 2010-2012



LHCb took data at a constant luminosity $0.4 \times 10^{33}/\text{cm}^2/\text{sec}$ 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: 3×10^{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** \rightarrow extra dilution factor in the tagging of neutral mesons.

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

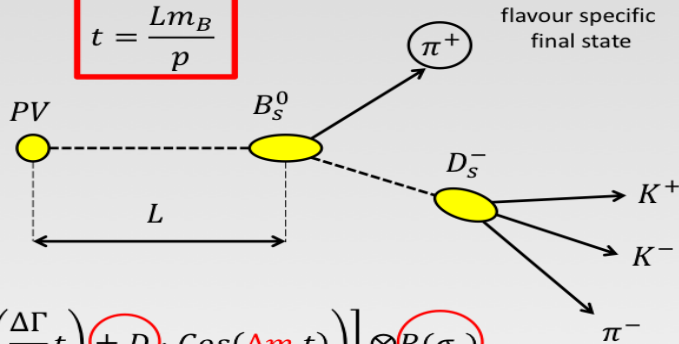
Rule of thumb:

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!

Need decay time dependent analysis

$$t = \frac{Lm_B}{p}$$



Decay time PDF:

$$PDF \propto \left[e^{-\Gamma t} \cdot \left(\text{Cosh}\left(\frac{\Delta\Gamma}{2}t\right) \pm D \cdot \text{Cos}(\Delta m t) \right) \right] \otimes R(\sigma_t)$$

Production flavour from tagging algorithms
 $D = (1 - 2\omega_{mistag})$

Need excellent decay time resolution



Hadron trigger $\sim 34k$ candidates/fb

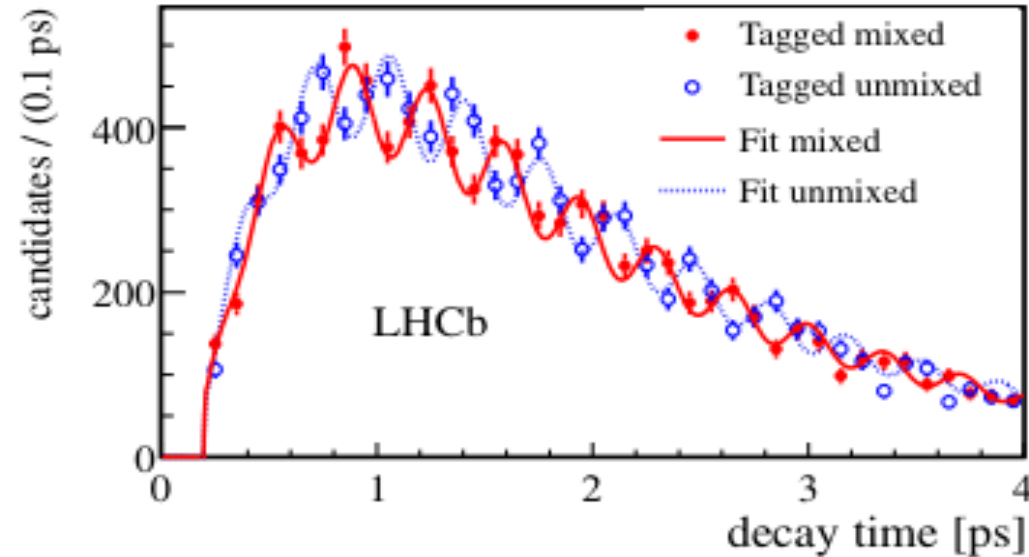
Proper time resolution ~ 44 fs
 (to be compared with $2\pi^{-1} \Delta m_s^{-1} \sim 350$ fs)

Effective tagging $\sim 3.5\%$

New J. Phys. (2013) 053021

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

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



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

(Parenthesis)Advantages/Disadvantages of Existing Facilities

Common “past” knowledge:

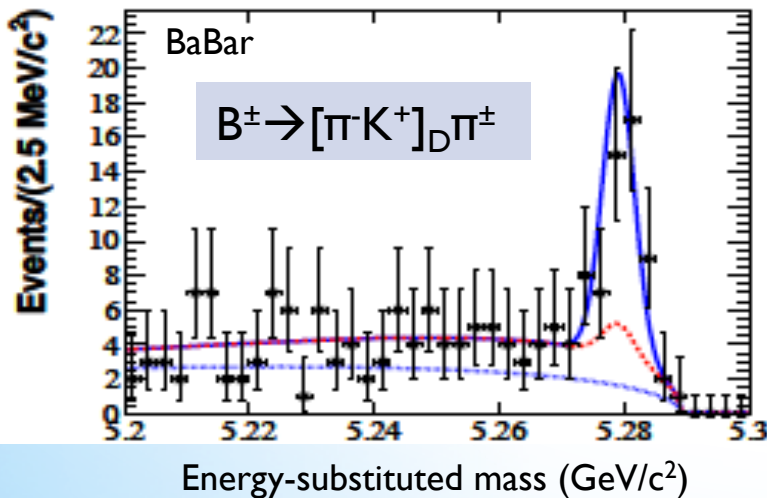
lepton colliders → **precision measurements** vs **hadron colliders** → **discovery machines**

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.**

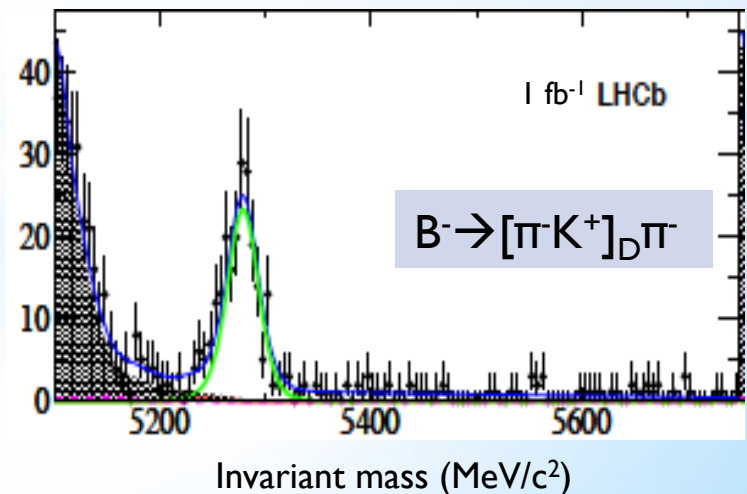
Lepton colliders have the advantage of a **known CoM energy**, **better selection efficiencies** and **high peak luminosities** (10^{34} - 10^{36}) cm^{-2}s . However, at the $\Upsilon(4S)$ only $B_{(d,u)}$ mesons are produced.

Hadron colliders have a **very large cross-section** ($\sigma_{bb}(\text{LHC7}) \sim 3 \times 10^5 \sigma_{bb}(\Upsilon(4S))$), very **performing detectors** and trigger system. Effective tagging efficiency is typically $\times 10$ better at lepton colliders.

arXiv:1006.4241



arXiv:1203.3662





**Tree Level
Measurements:
 $\arg(\mathbf{V}_{ub})$**

V_{ub} phase: Experimental Strategies

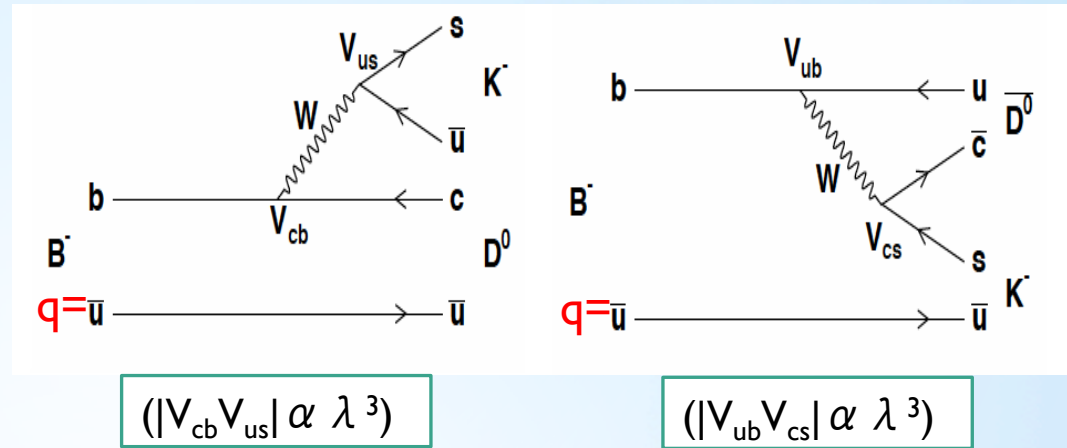
$q=u$: with D and anti-D in same final state

$$B^\pm \rightarrow D X_s \quad X_s = \{K^\pm, K^\pm \pi \pi, K^{*\pm}, \dots\}$$

$q=s$: Time dependent CP analysis.

Interference between B_s mixing and decay.

$$B_s \rightarrow D_s^\pm K^\mp$$



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

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

favoured mode

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

ADS mode

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

$$\Gamma(B^\pm \rightarrow [K\pi]_D K^\pm)$$

favoured mode

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

average of KK and $\pi\pi$ modes

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

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

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

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

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

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

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

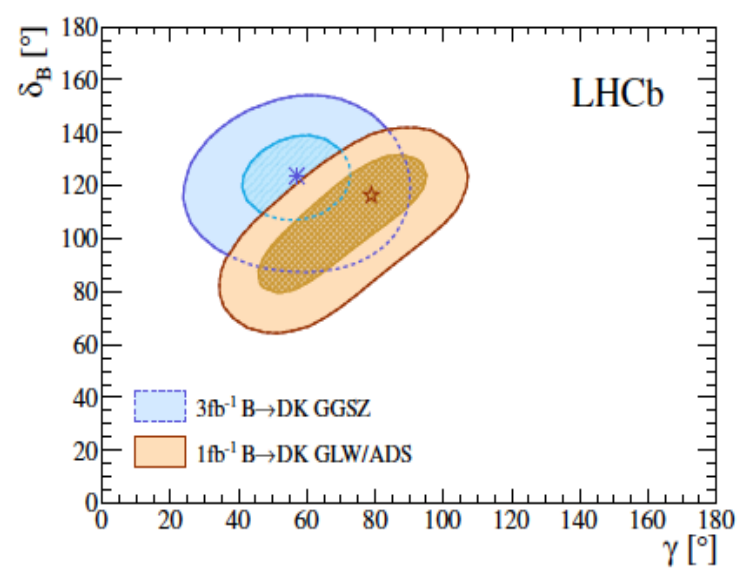
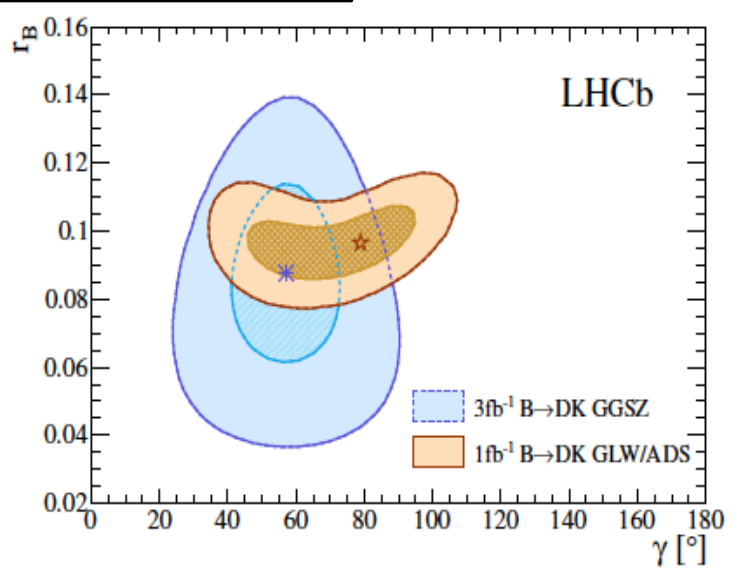
Same argument works for $D\pi$ final states, but r_B (hence interference) is ~ 10 smaller.

A variation of the above methods, is when $D \rightarrow K_s h^+ h^-$ (Giri, Grossman, Soffer and Zupan, PRD68, 054018 (2003)).

A Dalitz analysis of the three-body decays allows for an increase in sensitivity.

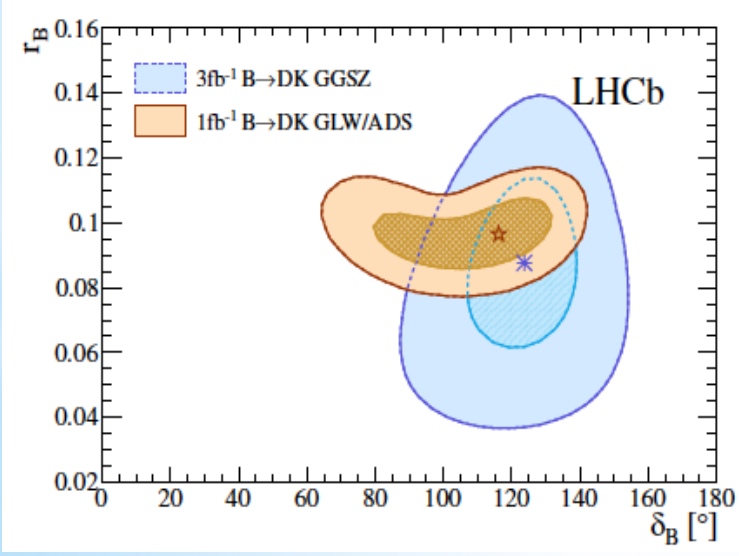
V_{ub} phase: LHCb combination

LHCb-CONF-2013-006



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

See S. Ricciardi talk for details



LHCb preliminary ($B \rightarrow DK$):

$$\gamma = 67 \pm 12^\circ \quad (r_B(DK) = 0.092 \pm 0.008)$$

Excellent internal compatibility of GGSZ and GLW/ADS.

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



$\Delta F=2$ Box Measurements

$\Delta F=2$ box in $b \rightarrow d$ transitions: CP asymmetries in $B_s \rightarrow J/\psi K_s$

CKMFITTER (BABAR+Belle)
combination: $\beta = 21.38^{+0.79}_{-0.77}^\circ$

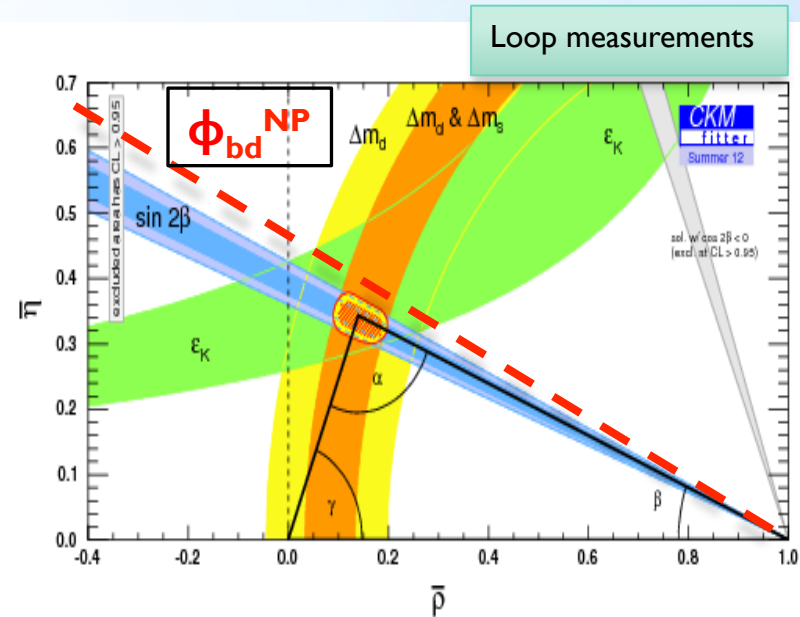
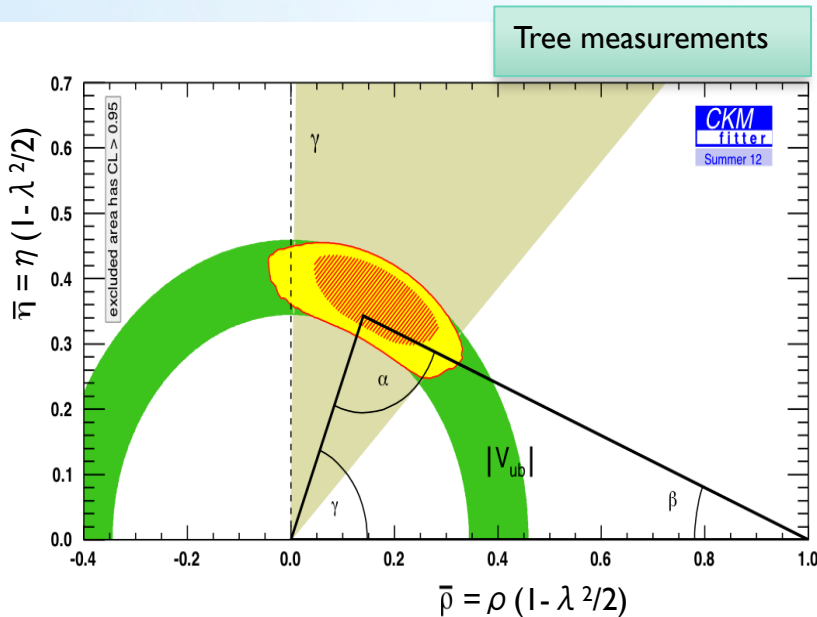
PLB 721 (2013) 24

LHCb (1/fb): $\beta = 23.4^{+3.6}_{-3.2}^\circ$

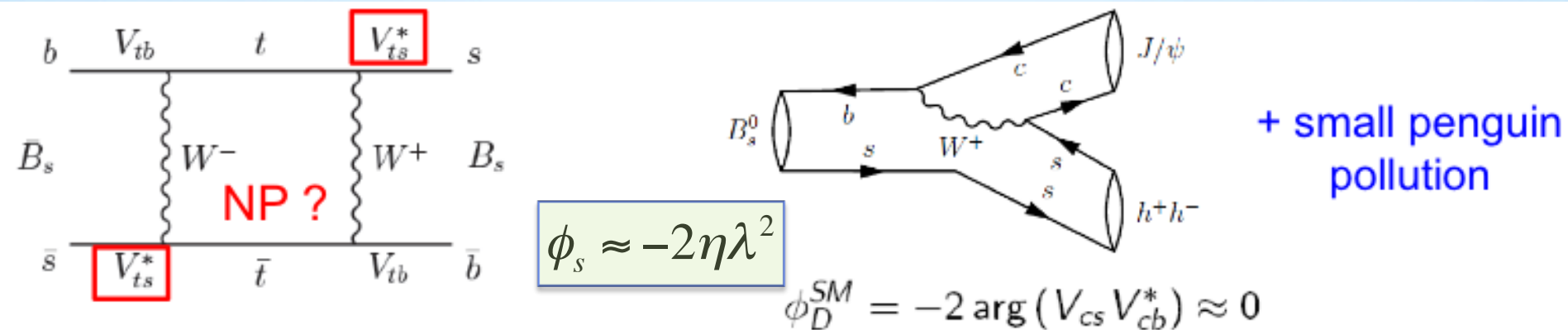
$$\tan \beta \approx \frac{\eta}{1-\rho} \left(1 - \frac{\lambda^2}{2}\right)$$

To be compared with the indirect determination using “tree level measurements”: $\beta = 24.9+0.8-1.9^\circ$

If we assume the SM, B-factories have measured the **phase of V_{td}** better than **4%** from $b \rightarrow d$ 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 $(\beta + \phi_{bd}^{NP})$** . ϕ_{bd}^{NP} can be as large as **$O(5^\circ)$** and still be consistent!

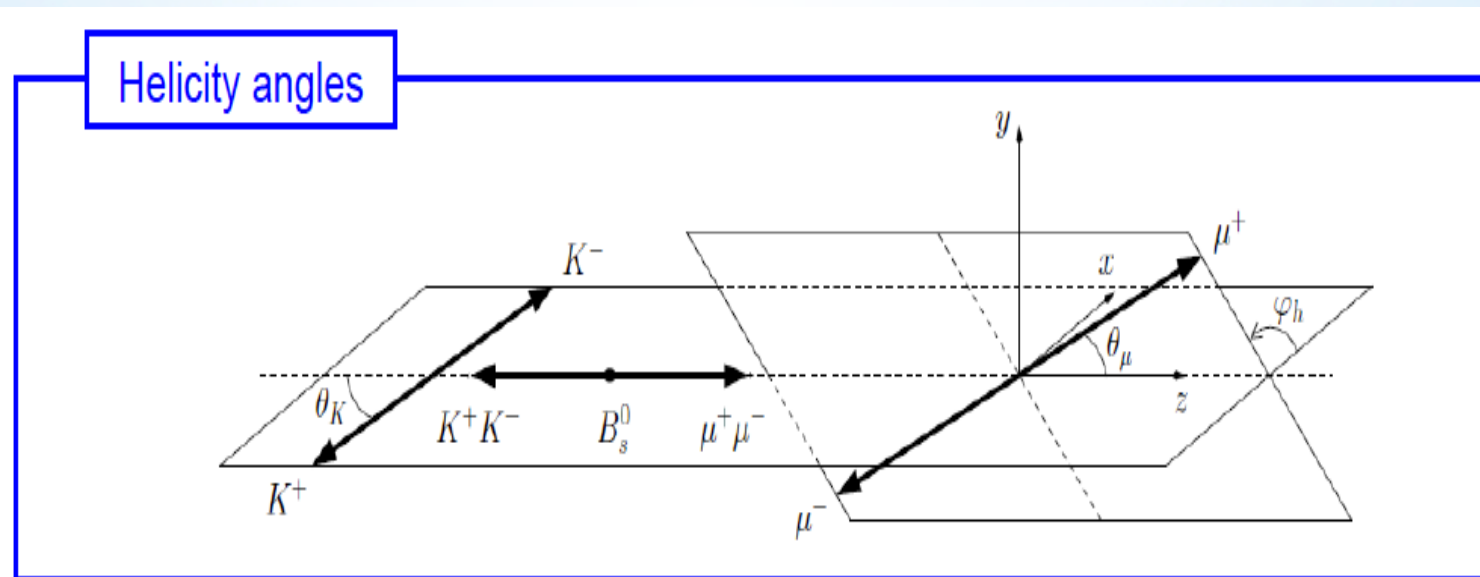


$\Delta F=2$ box in $b \rightarrow s$ transitions: CP asymmetries in $B_s \rightarrow J/\psi \Phi$



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

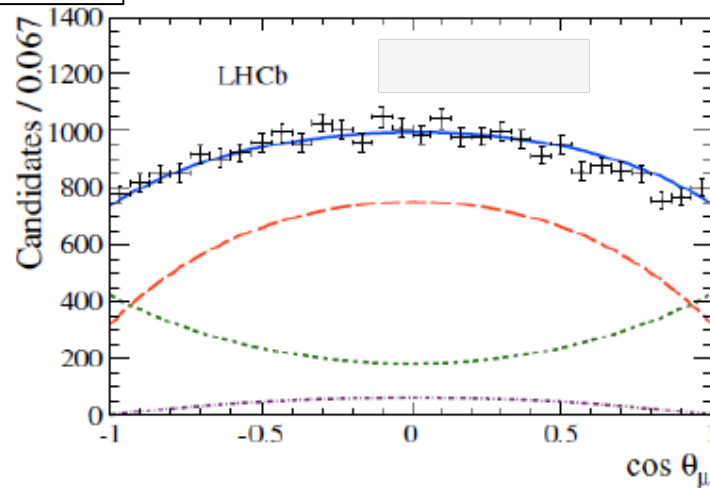
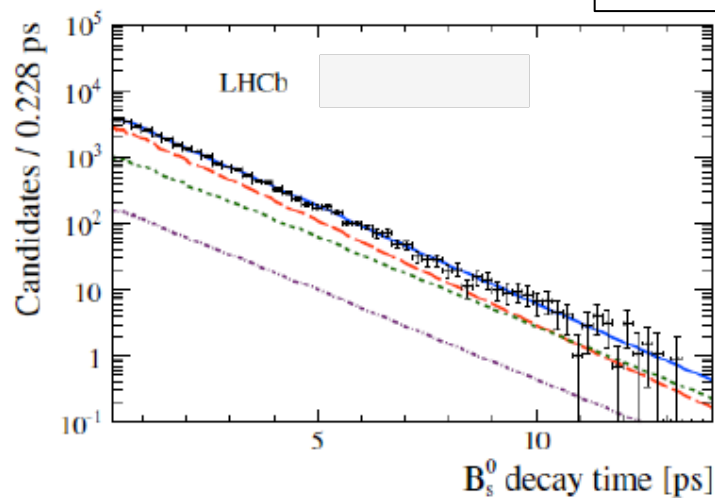
Angular analysis is needed in $B_s \rightarrow J/\psi \Phi$ decays, to disentangle statistically the CP-even and CP-odd components. Use the **helicity frame** to define the angles: $\theta_K, \theta_\mu, \phi_h$.



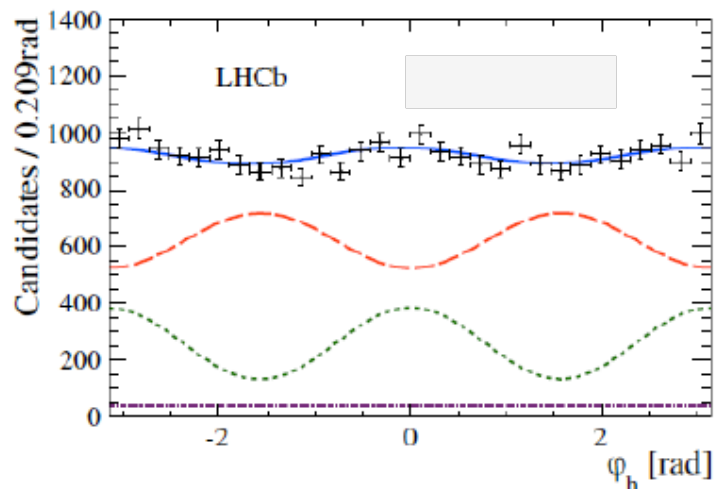
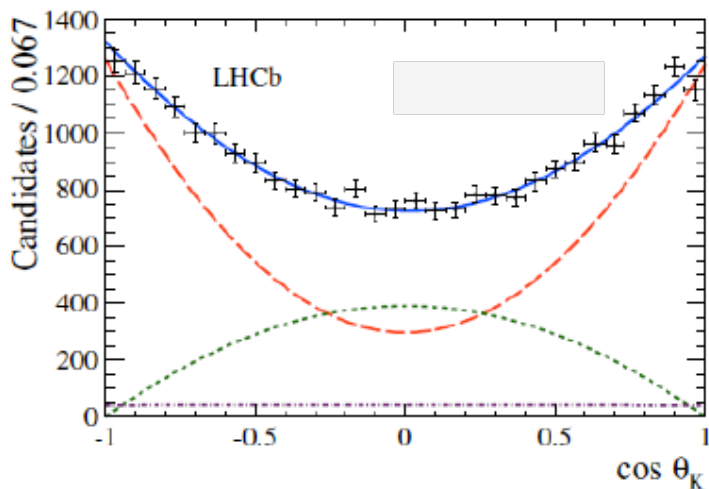
$\Delta F=2$ box in $b \rightarrow s$ transitions

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

PRD 87 (2013) 112010



--- CP-even --- CP-odd -.-.- S-wave

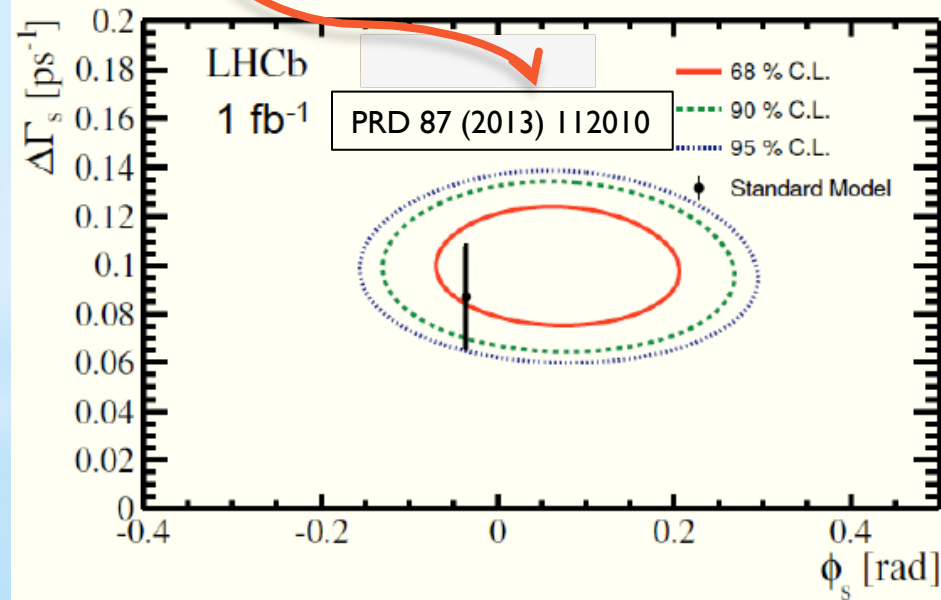


$\Delta F=2$ box in $b \rightarrow s$ transitions

The result of the LHCb **angular analysis of $B_s \rightarrow J/\psi \Phi$** decays with $1/\text{fb}$ (27.6k candidates) gives:

$$\begin{aligned}\phi_s &= 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ rad,} \\ \Gamma_s &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst)} \text{ ps}^{-1} \\ |\lambda| &= 0.94 \pm 0.03 \pm 0.02 \text{ (compatible w/ no CPV in decay)}\end{aligned}$$

See F. Dordei talk for more details.

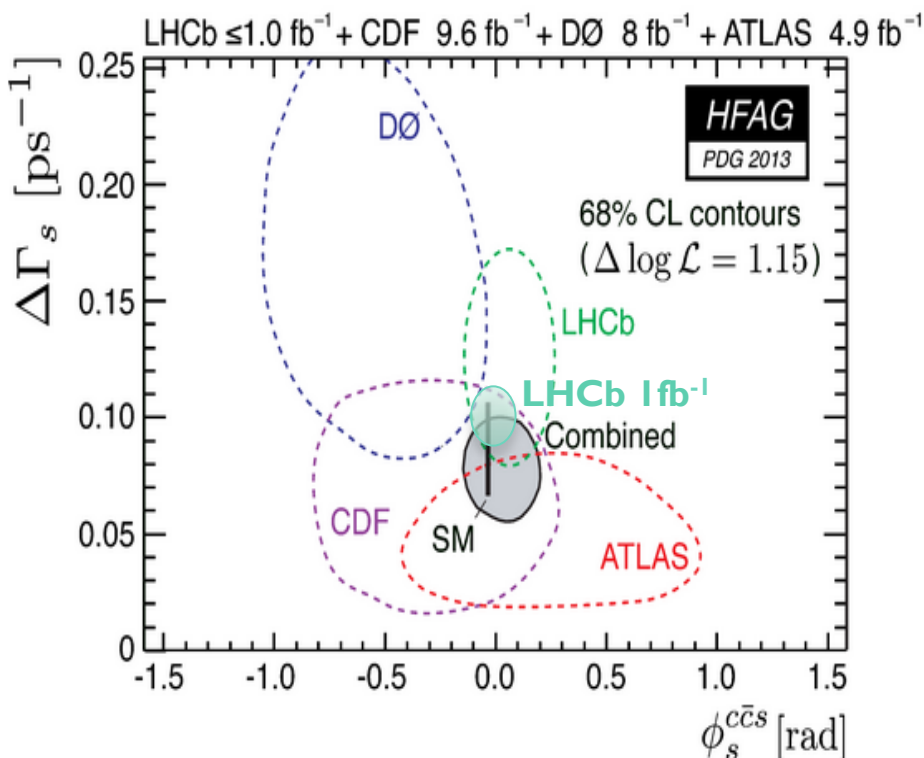


Moreover, the decays $B_s \rightarrow J/\psi \pi\pi$ (PLB 713 (2012) 378) are in a **pure CP-odd** state and don't require angular analysis. A **simultaneous fit** to both decays gives:

$$\begin{aligned}\phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ rad} \\ \Gamma_s &= 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst)} \text{ ps}^{-1}\end{aligned}$$

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

The **LHCb measurement**: $\Phi_s = 0.6 \pm 4.0^\circ$ can be compared with the indirect determination using “**tree measurements**”, $\Phi_s = -2.3^{+0.1}_{-0.3}^\circ$. 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 experiments have started contributing. **ATLAS tagged** analysis with 5/fb (22.6k candidates) and ($\epsilon \mathbf{D}^2 = (1.45 \pm 0.05)\%$) of $\mathbf{B}_s \rightarrow \mathbf{J}/\Psi \Phi$ decays gives:

ATLAS-CONF-2013-039

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

$$\Delta \Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.009 \text{ (syst.) ps}^{-1}$$

$$\Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1}$$

which corresponds to $\Phi_s = 7 \pm 16^\circ$.

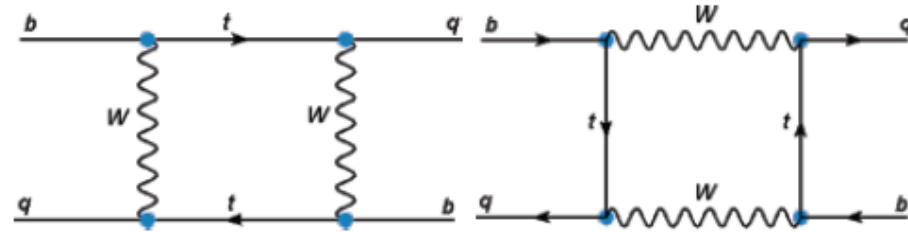
CMS has also perform an **untagged analysis** with 5/fb (14.5k candidates) to measure: CMS-PAS-BPH-11-006

$$\Delta \Gamma_s = 0.048 \pm 0.024 \text{ (stat)} \pm 0.003 \text{ (syst) ps}^{-1}$$

$\Delta F=2$ box in $b \rightarrow q$ transitions

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

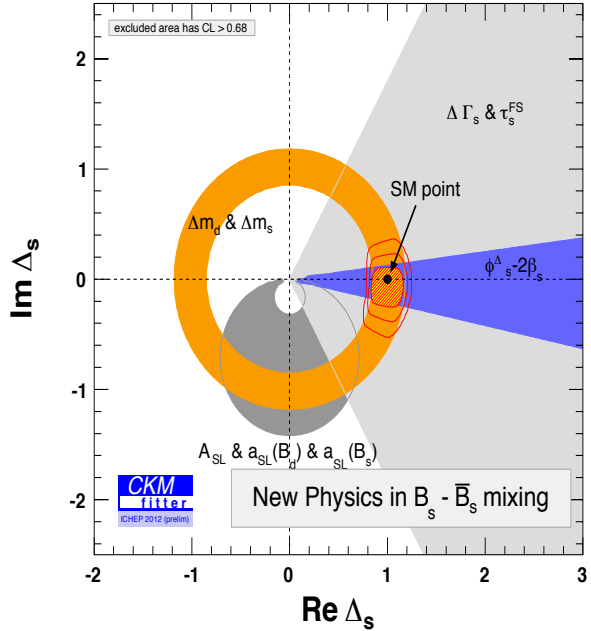
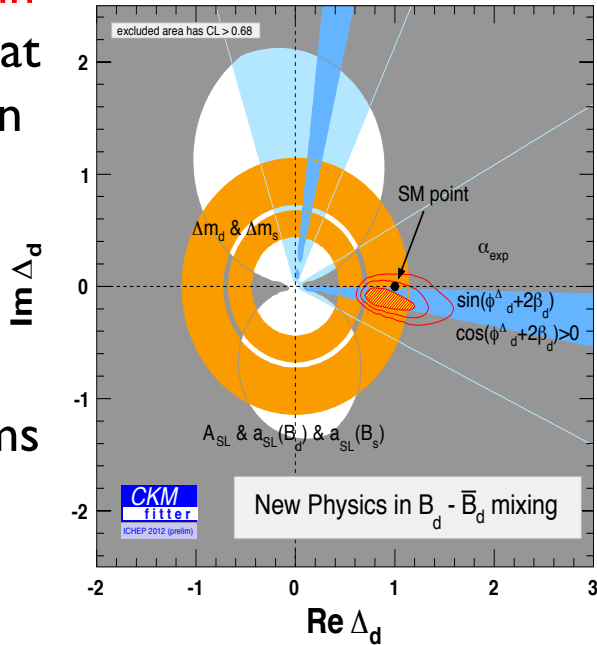
$$\Delta_q^{NP} = \text{Re}(\Delta_q) + i \text{Im}(\Delta_q) = |\Delta_q| e^{i\phi^{\Delta_q}}$$



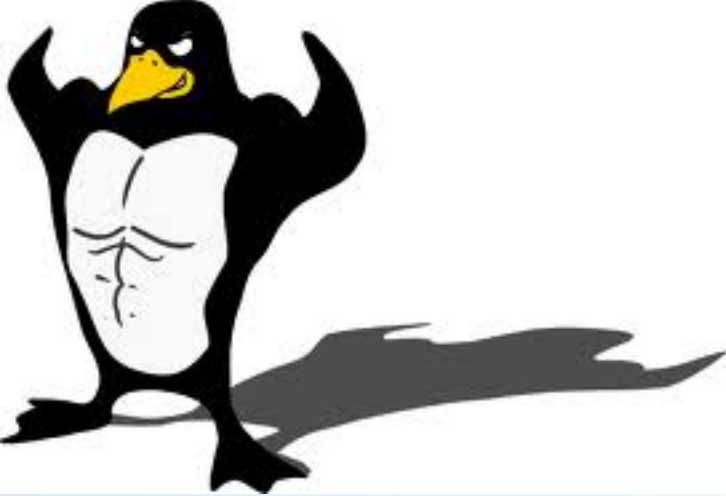
See D. Derkach talk for the UTfit point of view.

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 $B_d(B_s)$.



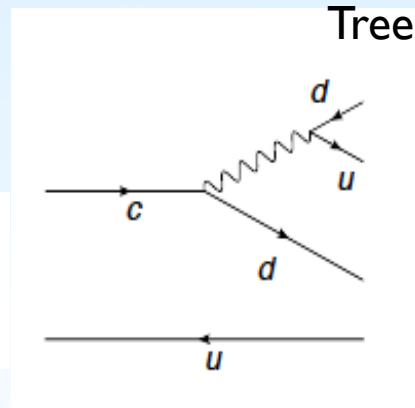
Need to increase precision to disentangle NP phases of few percent in B_d and B_s mixing



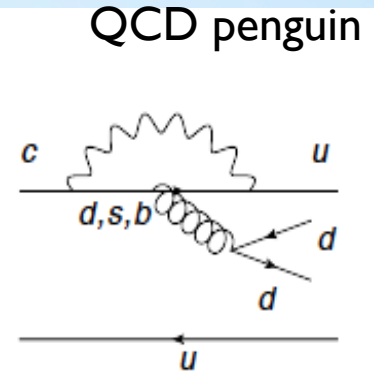
**$\Delta F=1$ QCD
(Strong)
Penguins**

$\Delta F=1$ in $c \rightarrow u$ QCD penguins: “Direct” CP violation in Charm decays

$$A_{CP}(D^0 \rightarrow h^+h^-) = \frac{\Gamma(D^0 \rightarrow h^+h^-) - \Gamma(\bar{D}^0 \rightarrow h^+h^-)}{\Gamma(D^0 \rightarrow h^+h^-) + \Gamma(\bar{D}^0 \rightarrow h^+h^-)}$$



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



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

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 $\Delta A_{CP} \sim 4 \text{ Penguin/Tree} \sim 0.04\%$.

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

$$\Delta A_{CP} = (-0.82 \pm 0.24)\% \text{ LHCb (0.6/fb)} \quad (\text{PRL 108, 111602 (2012)})$$

confirmed later by:

$$\Delta A_{CP} = (-0.62 \pm 0.23)\% \text{ CDF} \quad (\text{PRL 109, 111801 (2012)})$$

$$\Delta A_{CP} = (-0.87 \pm 0.41)\% \text{ BELLE (Preliminary ICHEP 2012)}$$

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

See M. Smith
talk for details

$$\Delta A_{CP} = (-0.34 \pm 0.18)\% \text{ LHCb (1/fb)} \quad (\text{LHCb-CONF-2013-003})$$

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:

$$\Delta A_{CP} = (0.49 \pm 0.33)\% \text{ LHCb (semil, 1/fb)} \quad (\text{PLB 723, (2013) 33})$$

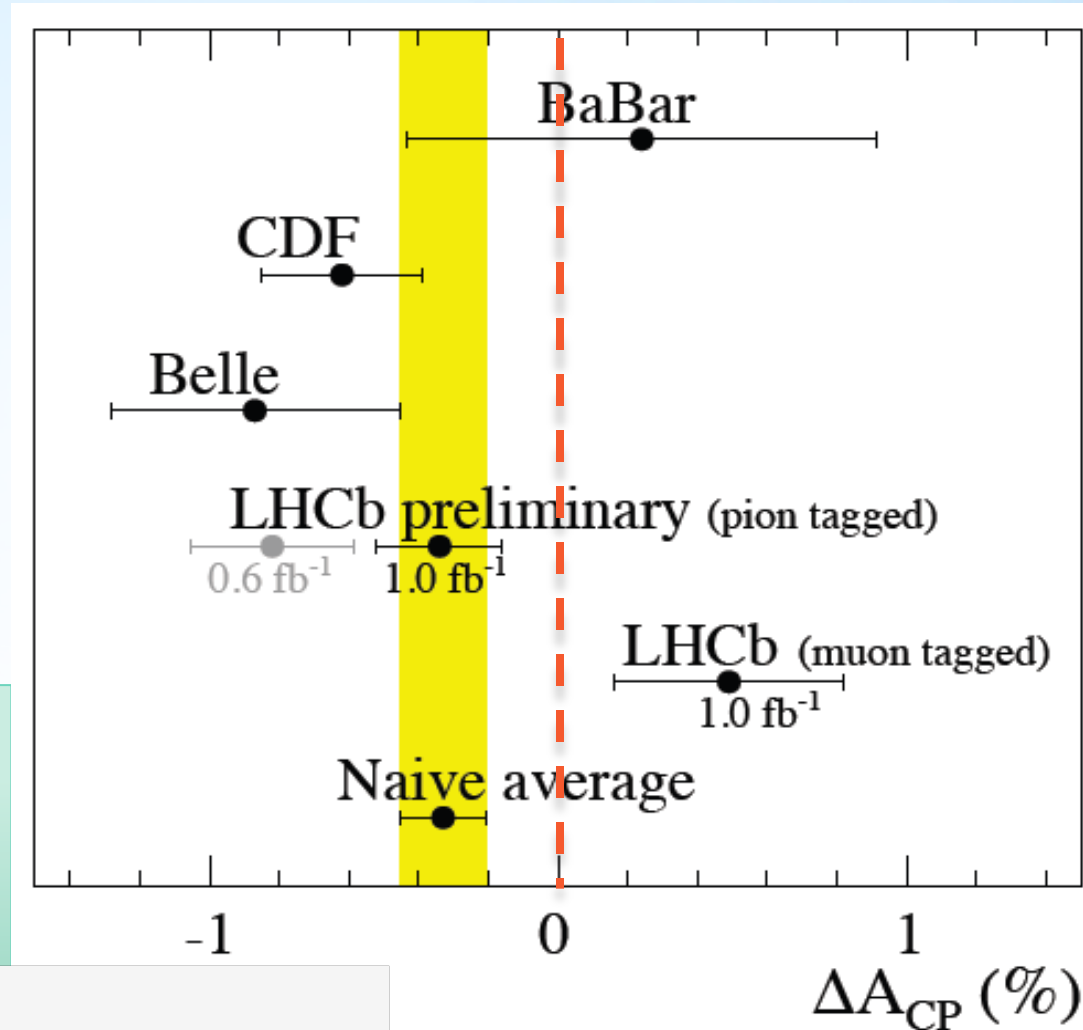
Naïve average

$\Delta A_{CP} = (-0.35 \pm 0.12)\%$

p-value average = 2.4%
(or equivalent to 2.3σ)

p-value (no CP-violation) = 0.15%
(or equivalent to 3.2σ)

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**.



$\Delta F = I \cdot EW$
Penguins

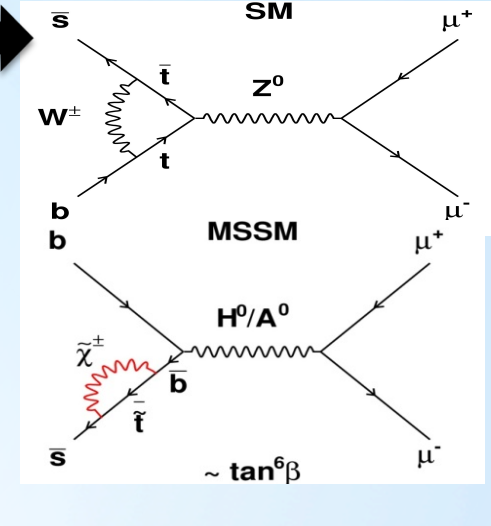
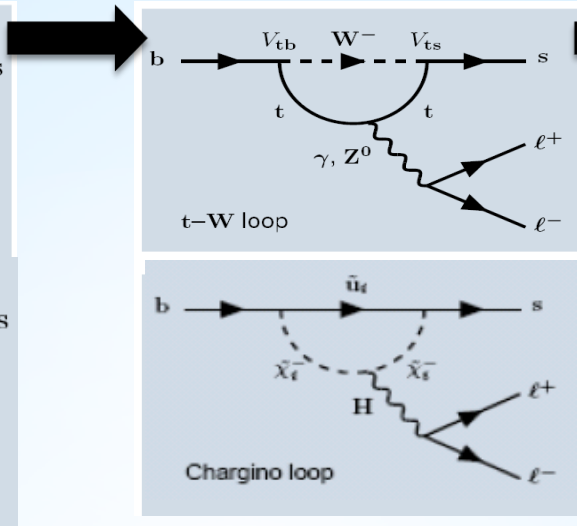
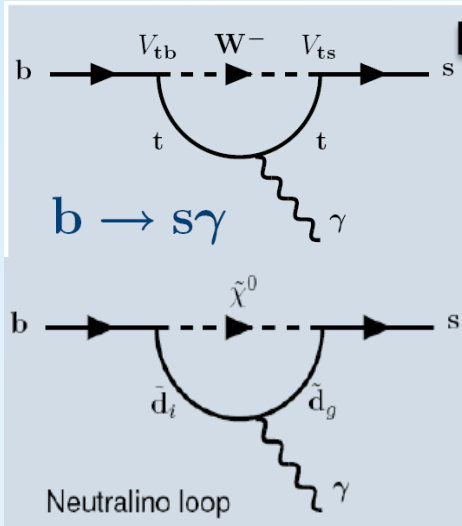
Three impersonations of the EW penguin

SM

MSSM

α_{QED} suppression

helicity suppression



Relevant Operators

$BR(\text{SM})$

$BR \text{ exp}$

$B_s \rightarrow \phi \gamma$

$$\mathcal{O}_{\gamma\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

$B^0 \rightarrow K^* \mu^+ \mu^-$

$$\mathcal{O}_{\gamma\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

$$\mathcal{O}_{9\ell(10\ell)} \sim \bar{s}_L \gamma_\mu b_L \ell^\mu (\gamma_5) \ell$$

$B_s \rightarrow \mu^+ \mu^-$

$$\mathcal{O}_{S(P)} \sim \bar{s}_L b_R \bar{\ell} (\gamma_5) \ell$$

Large theory uncertainties
 $\mathcal{O}(20\%)$

$(3.5 \pm 0.4) \cdot 10^{-5}$
LHCb: arXiv:1209.0313

$(1.16 \pm 0.19) \cdot 10^{-6}$
LHCb: arXiv:1205.3422

$(3.6 \pm 0.5) \cdot 10^{-9}$
helicity suppressed

$(3.2^{+1.5}_{-1.2}) \cdot 10^{-9}$
LHCb: arXiv:1205.3422

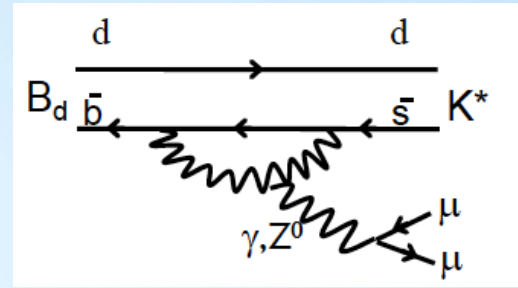
γ polarization

angular distributions

BR

$\Delta F=1EW$ penguins in $b \rightarrow s$ transitions: $B \rightarrow K^* \mu \mu$ angular analysis

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

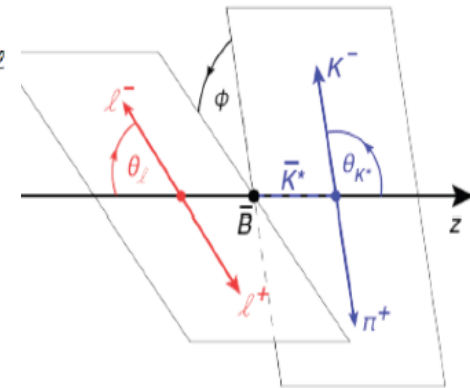


$B \rightarrow K^* \mu \mu$ is the **golden mode** to test **new vector(-axial) couplings** in $b \rightarrow s$ transitions.

$K^* \rightarrow K \pi$ 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.

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



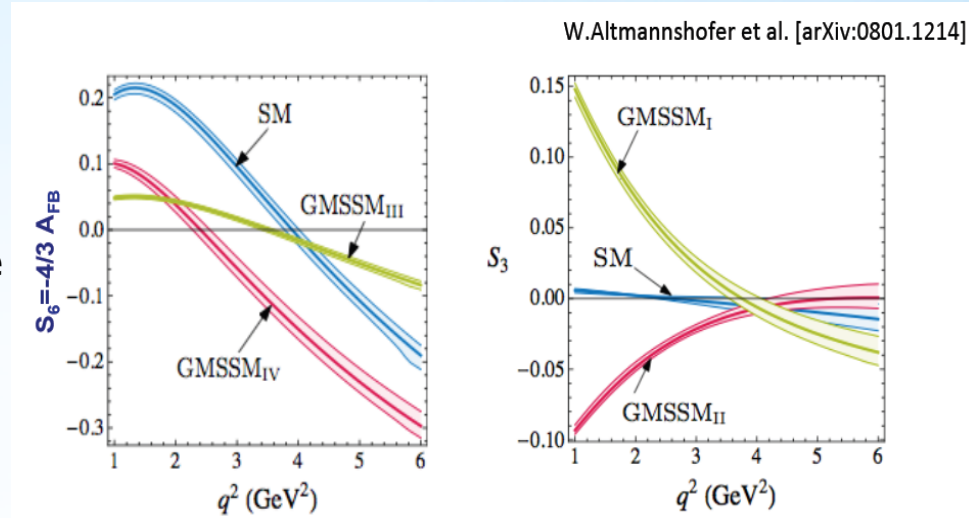
Results from **B-factories** and **CDF** very much **limited by the statistical** uncertainty. **LHCb** already has with 1/fb the **largest sample** (0.9k candidates).

$\Delta F=1EW$ penguins in $b \rightarrow s$ transitions: $B \rightarrow K^* \mu \mu$ angular analysis

Hadronic uncertainties under reasonable control for:

- F_L : Fraction of K^* longitudinal polarization.
- $S_6 = -4/3 A_{FB}$: Forward-Backward asymmetry of the lepton.
- $S_3 \propto A_T^2 (1 - F_L)$: 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:

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

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

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

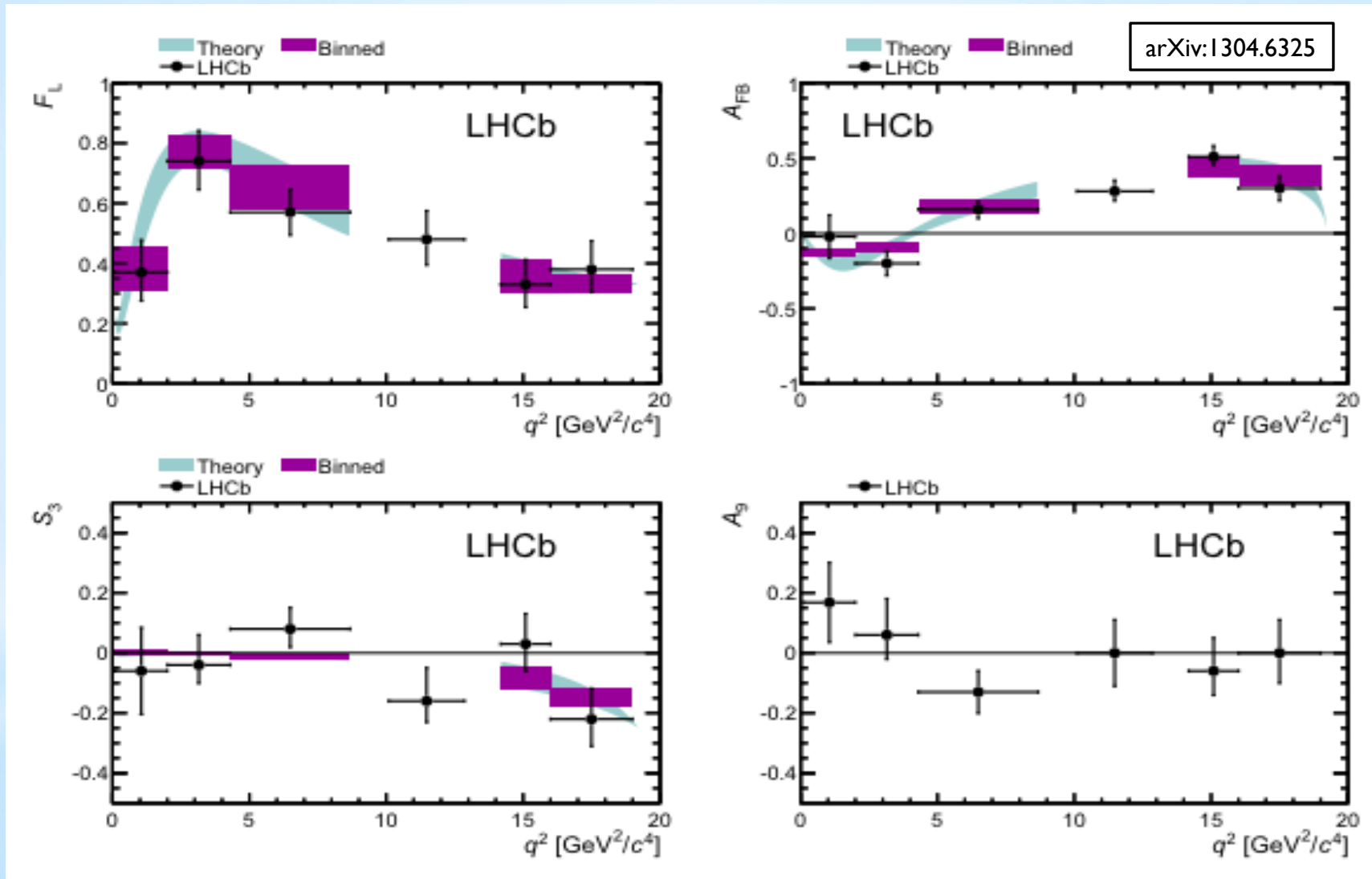
$$P_5' = \frac{S_5}{\sqrt{(1 - F_L)F_L}}$$

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

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

$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{d \cos \theta_\ell d \cos \theta_K d\phi} = \frac{9}{32\pi} \left[\frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ - F_L \cos^2 \theta_K \cos 2\theta_\ell + \frac{1}{2} (1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + \\ \sqrt{F_L(1 - F_L)} P_4' \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \sqrt{F_L(1 - F_L)} P_5' \sin 2\theta_K \sin \theta_\ell \cos \phi + \\ (1 - F_L) A_T^{Re} \sin^2 \theta_K \cos \theta_\ell + \sqrt{F_L(1 - F_L)} P_6' \sin 2\theta_K \sin \theta_\ell \sin \phi + \\ \left. \sqrt{F_L(1 - F_L)} P_8' \sin 2\theta_K \sin 2\theta_\ell \sin \phi + (S/A)_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

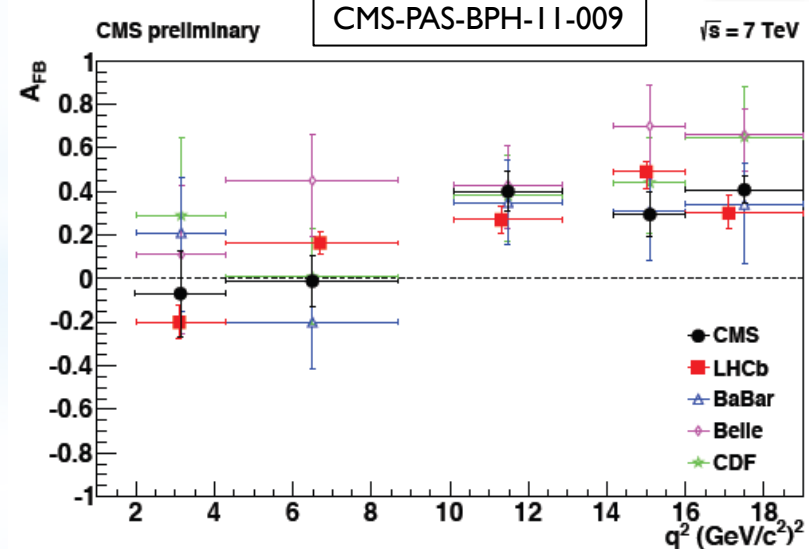
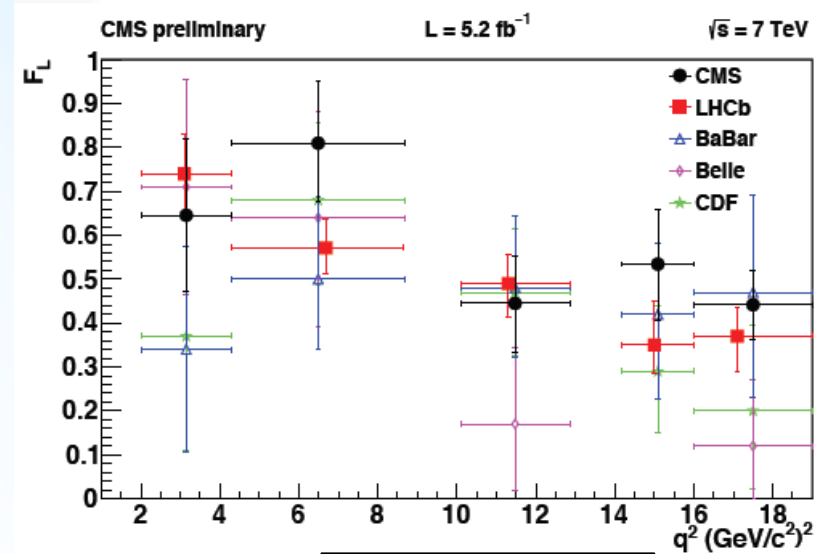
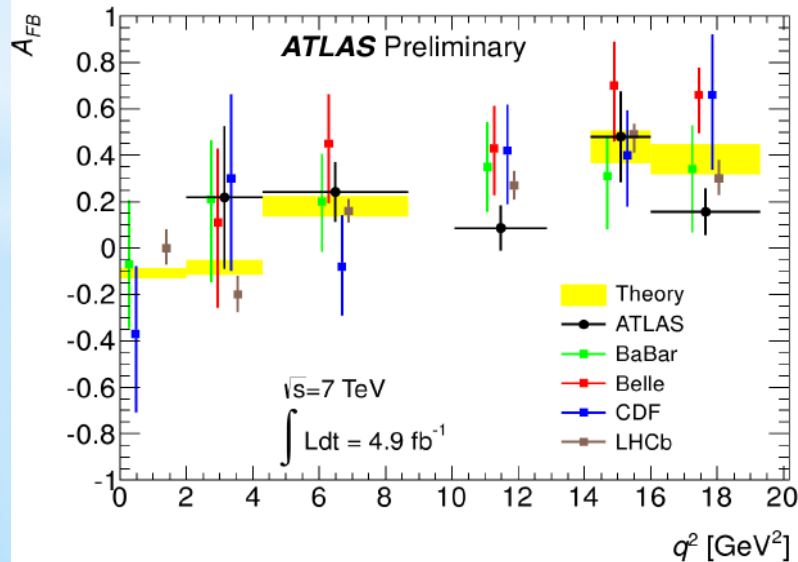
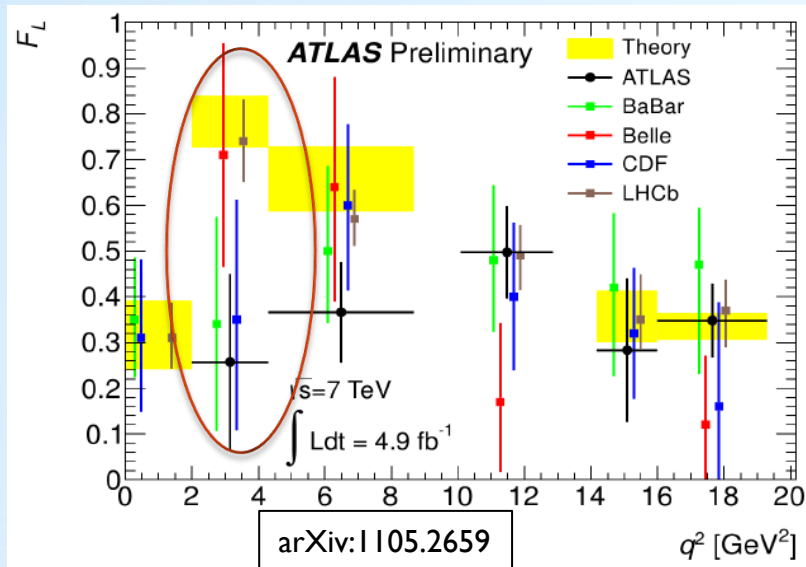
Folding technique ($\Phi \rightarrow \Phi + \pi$) for $\Phi < 0$, reduces the number of parameters to fit: F_L, S_3, S_6 and S_9 .



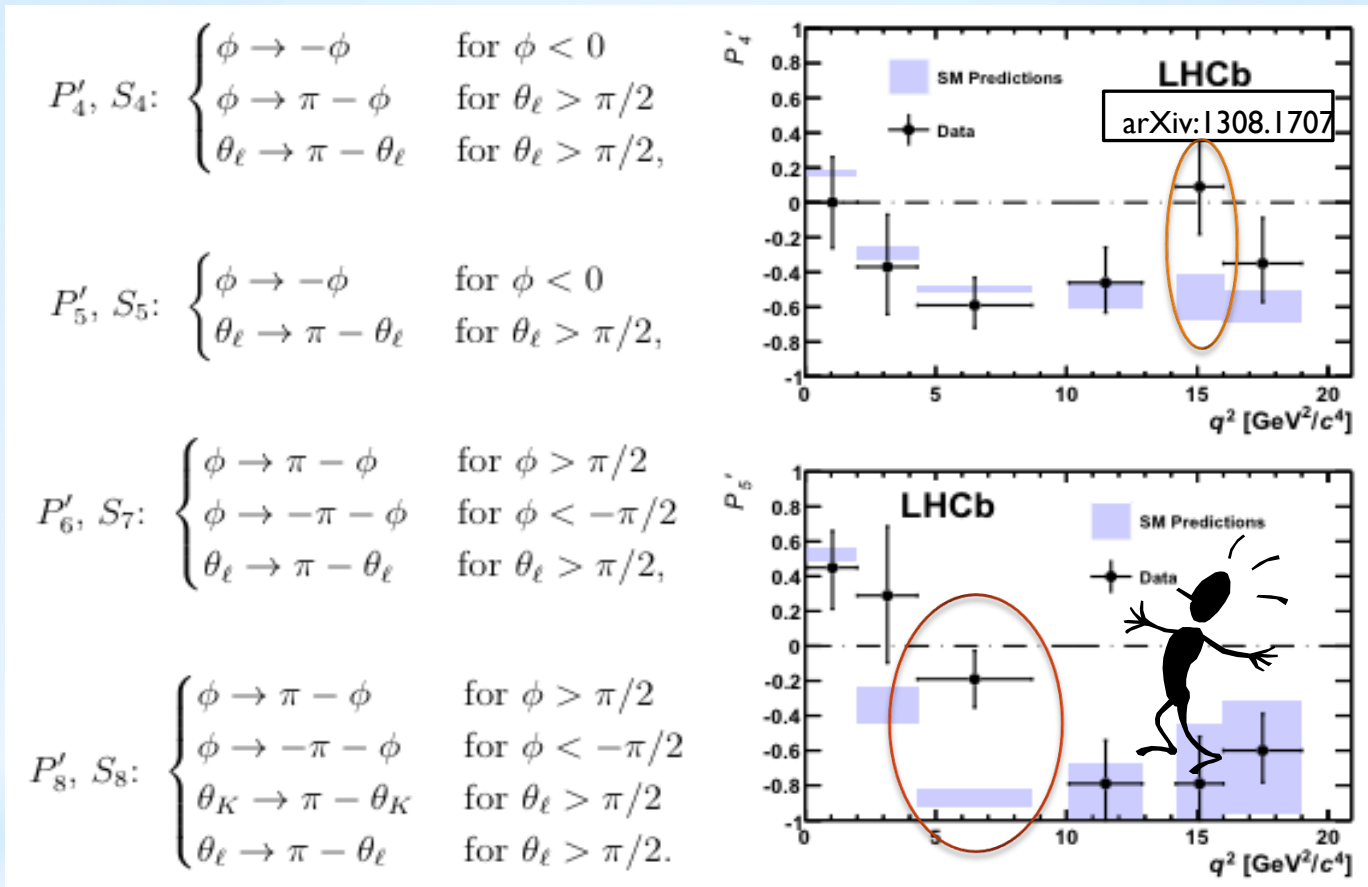
Within uncertainties observables are consistent with the SM.

ATLAS, CMS $B \rightarrow K^* \mu \mu$ angular analysis

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



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



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.

See J. Hernando talk for more details.

$\Delta F=1EW$ penguins in $b \rightarrow s$ transitions: Implications

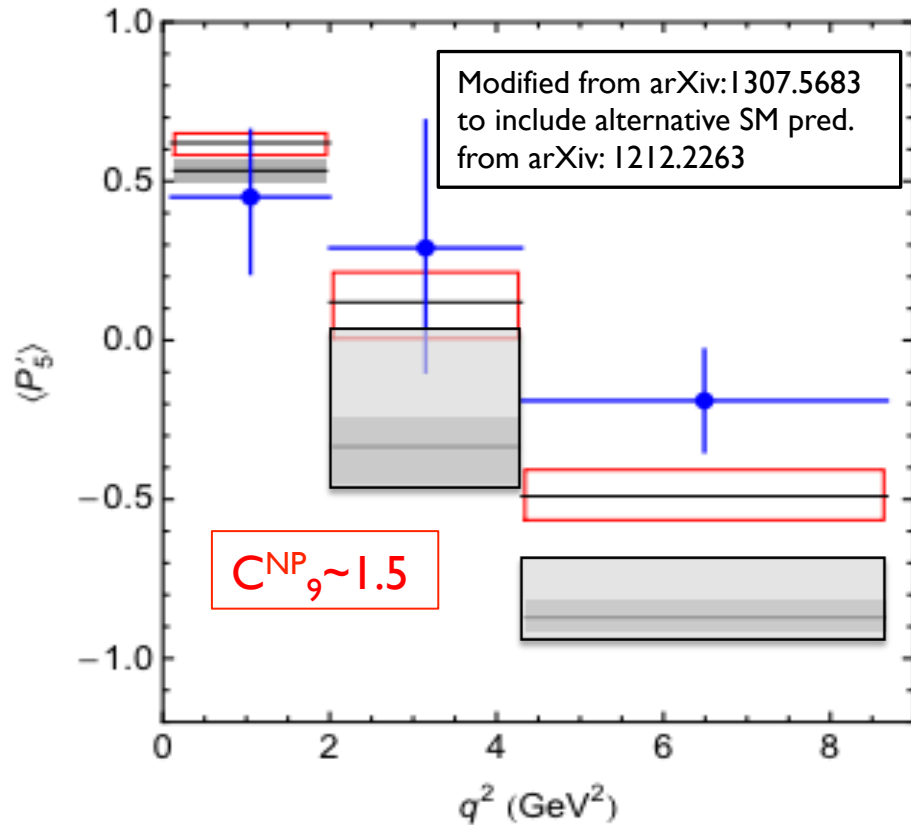
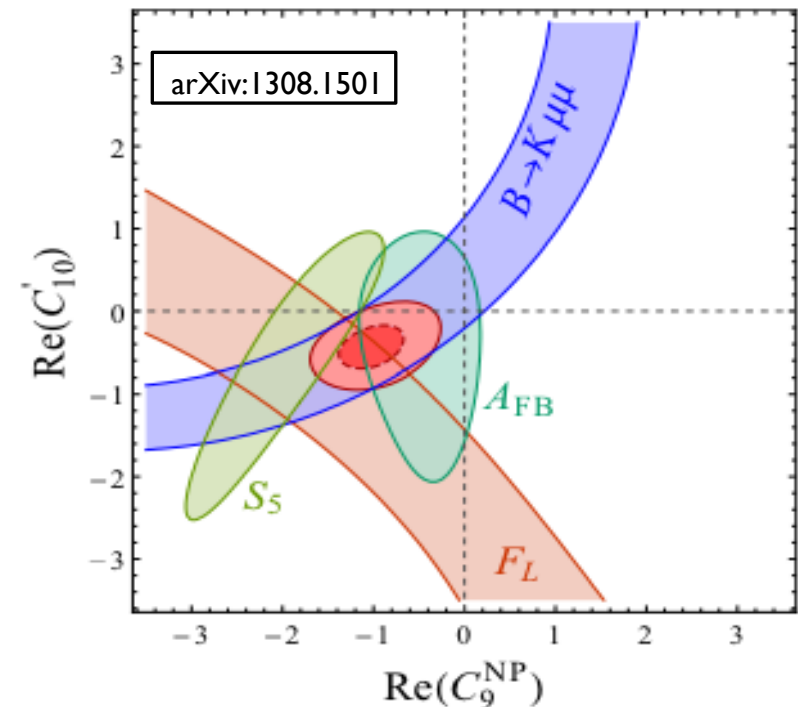


FIG. 4: Improvement in the q^2 -dependence of P'_5 in the illustrative case $C_9^{\text{NP}} - C_{9'}^{\text{NP}} = -1.5$ (and NP contributions to the other Wilson coefficients set to zero).

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.



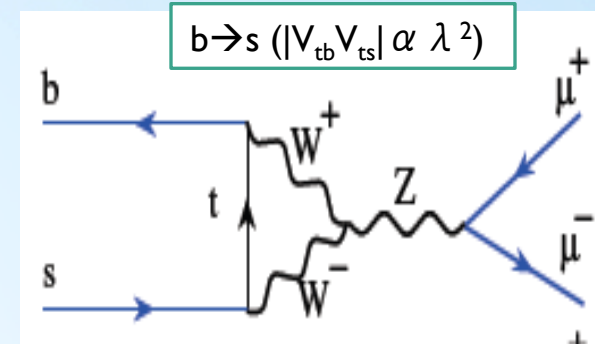
$$\begin{aligned}
 O_7 &= \frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu}, & O_8 &= \frac{g m_b}{e^2} (\bar{s} \sigma_{\mu\nu} T^a P_R b) G^{\mu\nu a}, \\
 O_9 &= (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell), & O_{10} &= (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \gamma_5 \ell),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



**$\Delta F=1$ Higgs
Penguins**

$\Delta F=1$ Higgs penguins in $b \rightarrow d, s$ 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 \rightarrow **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.

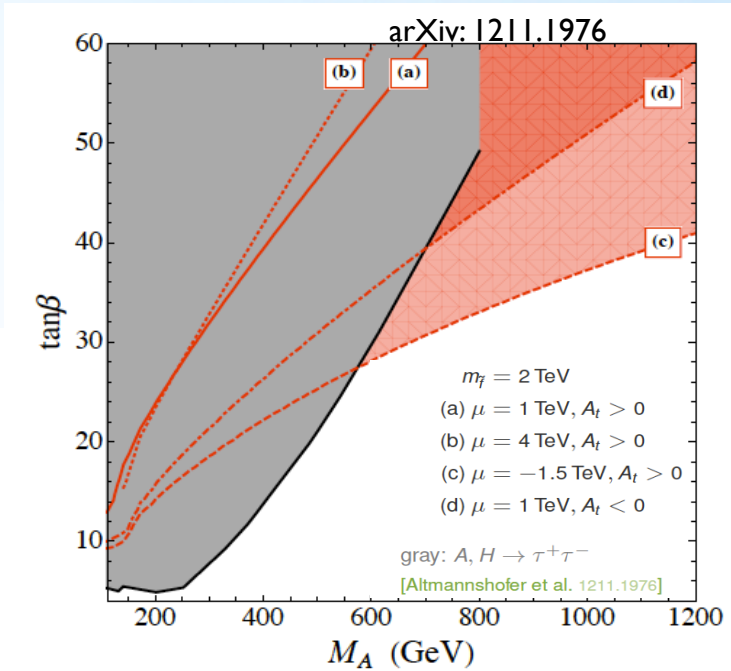
$$BR_{SM}(B_s \rightarrow \mu \mu) \langle t \rangle = (3.56 \pm 0.29) \times 10^{-9}$$

$$BR_{SM}(B \rightarrow \mu \mu) \langle t \rangle = (1.07 \pm 0.10) \times 10^{-10}$$

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

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

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 $\tan^6 \beta / M_A^4$

$\Delta F=1$ Higgs penguins in $b \rightarrow d, s$ 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 $\sim 0.26 B_s \rightarrow \mu \mu$ 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/c²

Therefore, for equal analyses strategies:

$\sim 1/\text{fb}$ at LHCb is equivalent to $\sim 10/\text{fb}$ at CMS, $\sim 20/\text{fb}$ at ATLAS/CDF.

Δ F=I Higgs penguins in b→d,s transitions: ATLAS/CDF/D0 Results

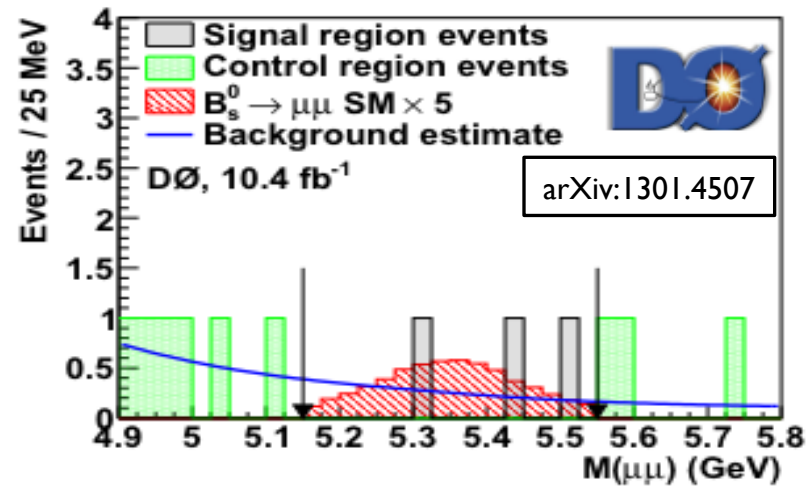
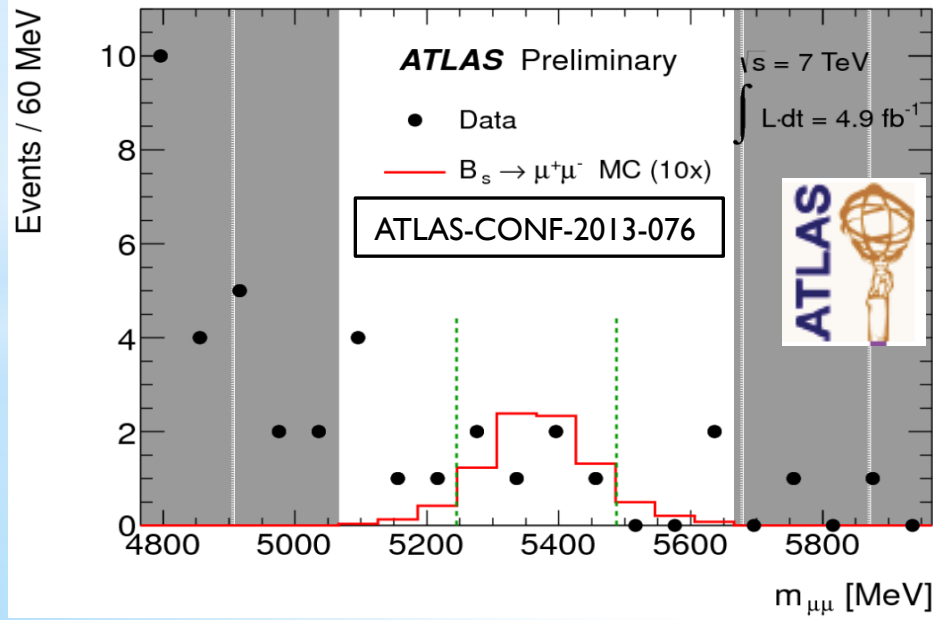
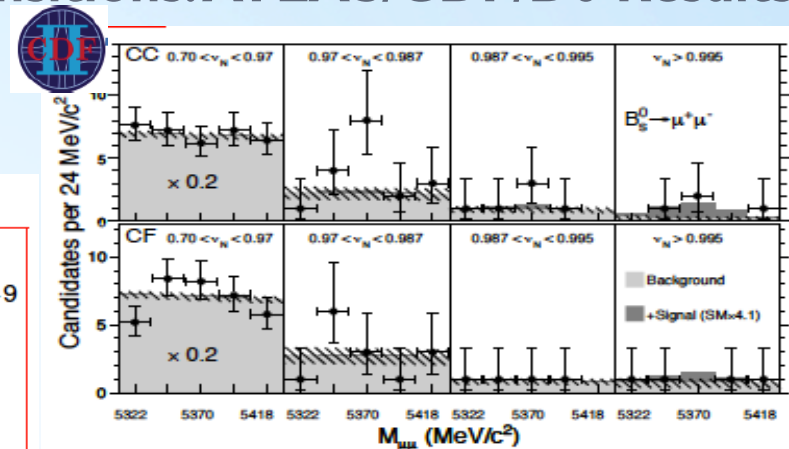
CDF analysis strategy very similar than LHCb. **Small excess** observed over the **background-only hypothesis** in the B_s mass window (**p-value = 0.9%**). **CDF: 10 fb⁻¹** [PRD 87, 072003 (2013)]

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

D0: 10.4 fb⁻¹ [arXiv:1301.4507]

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

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



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%**).

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

$\Delta F=1$ Higgs penguins in $b \rightarrow d, s$ transitions: CMS/LHCb Results

CMS (25 fb⁻¹) and **LHCb** (3 fb⁻¹) have sensitivity to $BR(B_s \rightarrow \mu^+ \mu^-) = 3 \times 10^{-9}$, with **4.8 σ (CMS)** and **5.0 σ (LHCb) expected** excess w.r.t. background-only hypothesis in the B_s mass window.

Observed:

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

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



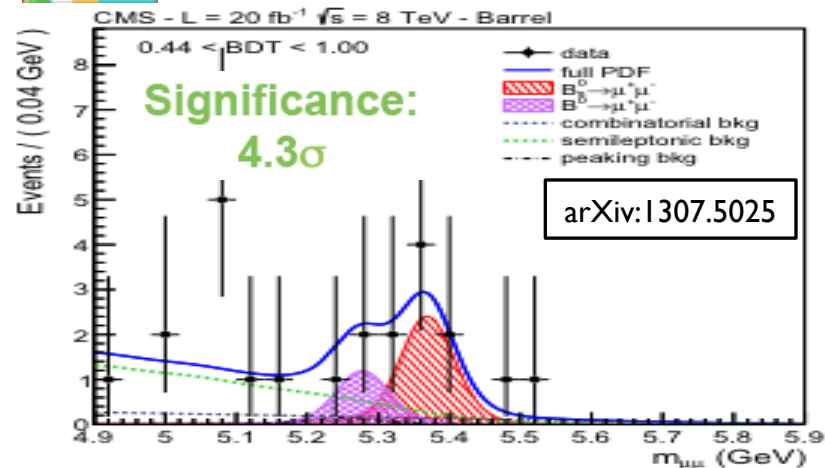
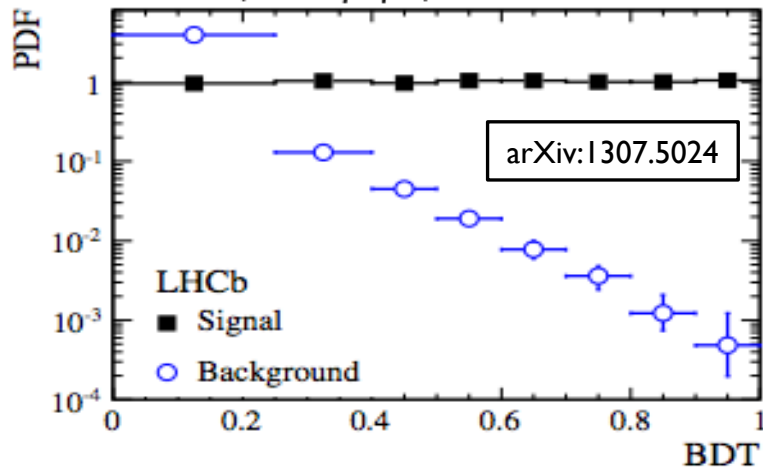
$$BR(B^0 \rightarrow \mu^+ \mu^-) = (3.7_{-2.1}^{+2.4}) \times 10^{-9}$$

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

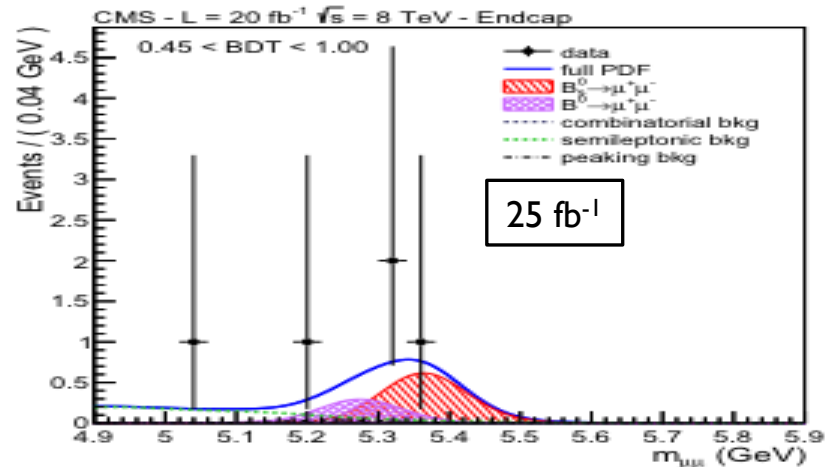
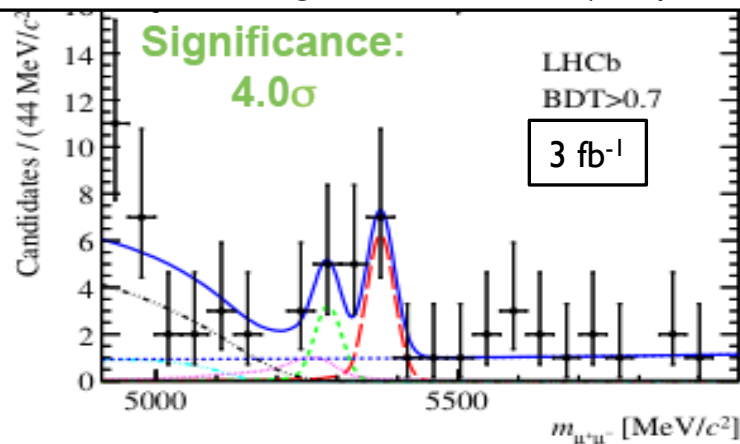


$$BR(B^0 \rightarrow \mu^+ \mu^-) = (3.5_{-1.8}^{+2.1}) \times 10^{-9}$$

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



PDF calibrated using control channels (indep. of MC)



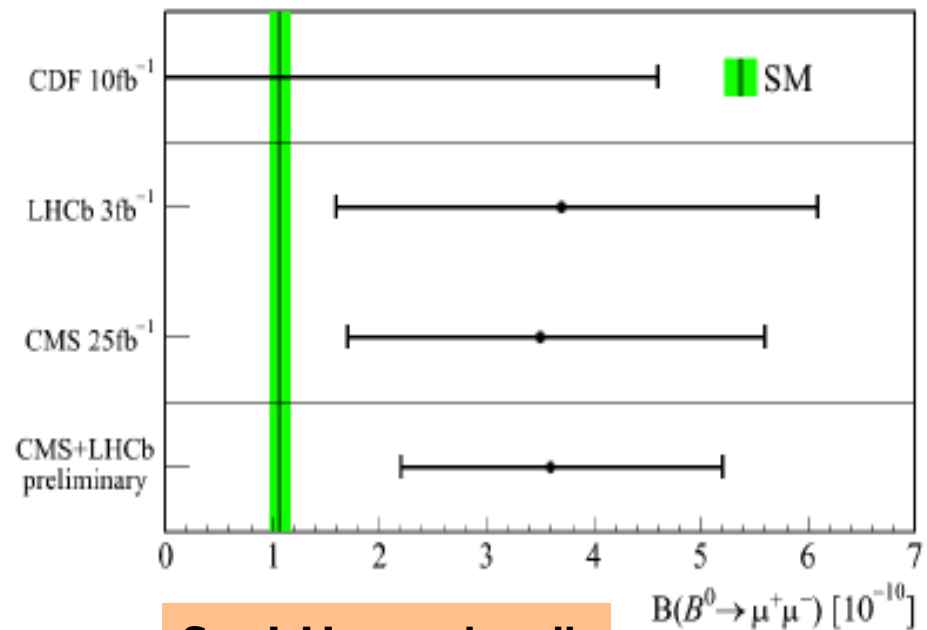
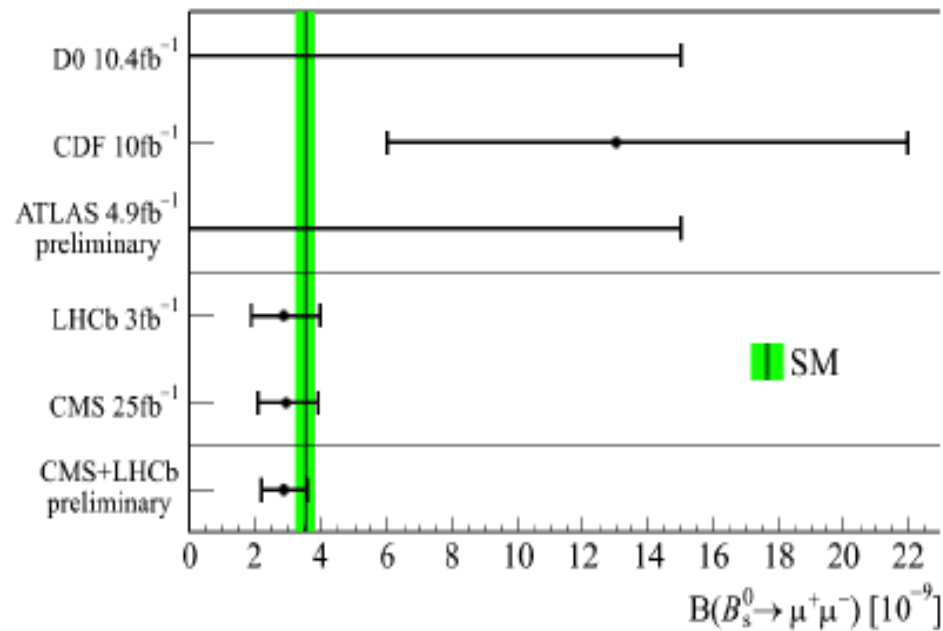
$\Delta F=1$ Higgs penguins in $b \rightarrow d, s$ transitions: Results

Observation:

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



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



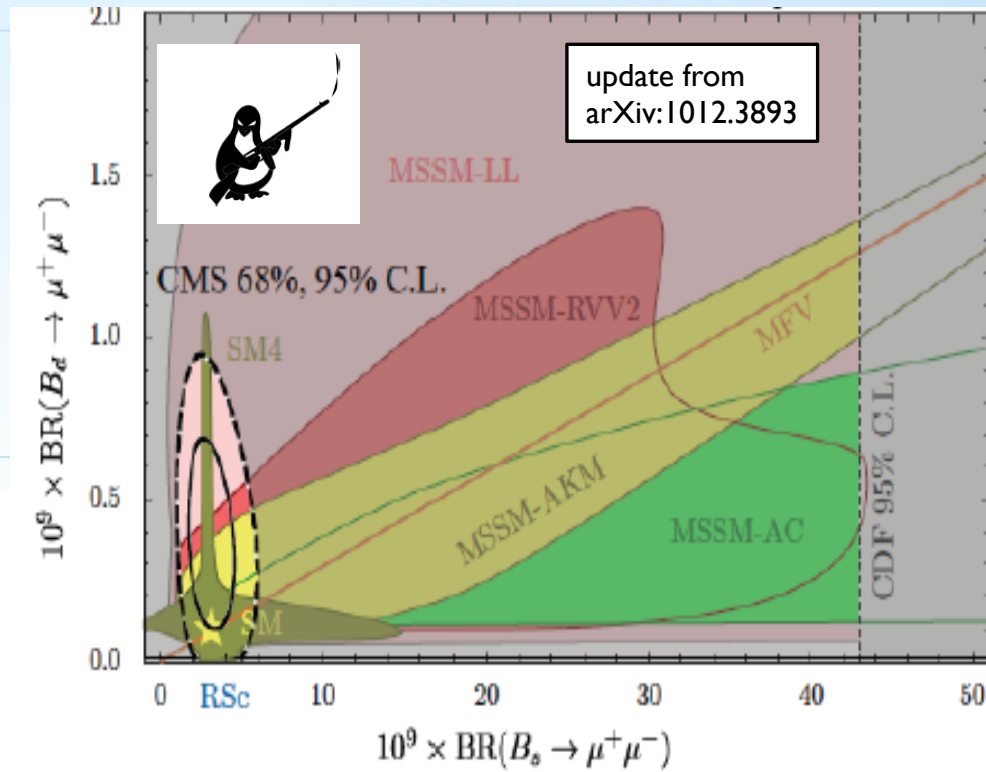
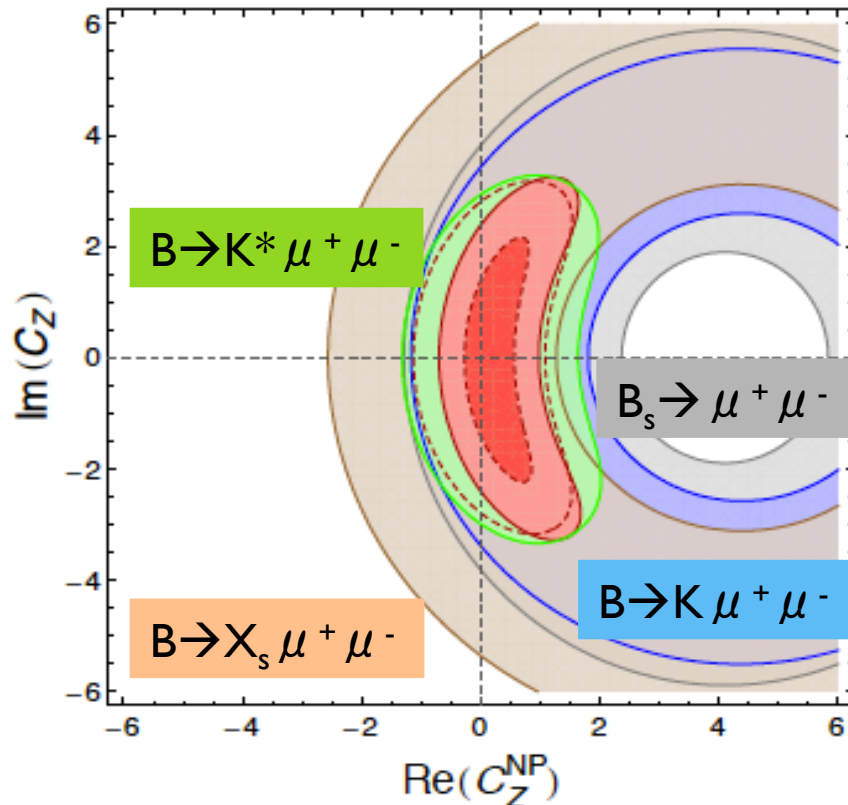
See J. Hernando talk for more details.

$\Delta F=1$ Higgs penguins in $b \rightarrow s, d$ transitions: Implications

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

In particular, **large $\tan \beta$** with **light pseudo-scalar Higgs** in CMSSM is strongly **disfavored**.

arXiv:1206.0273



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

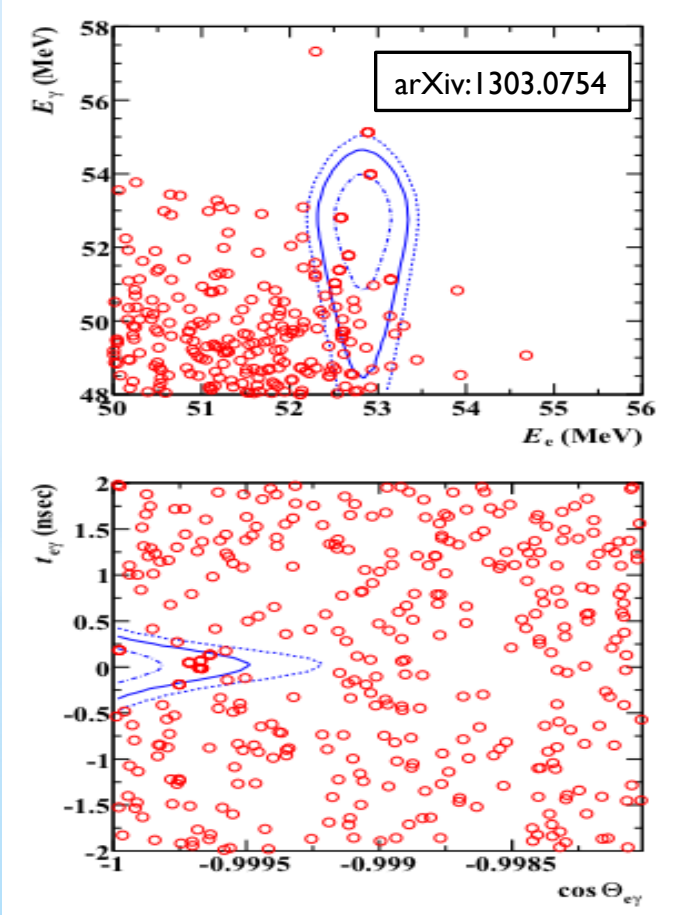


Charged Lepton Flavour Violation

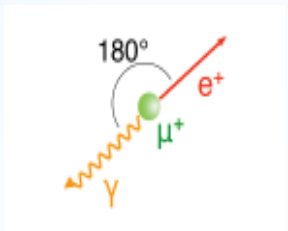
CLFV: Muon Decays

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.**



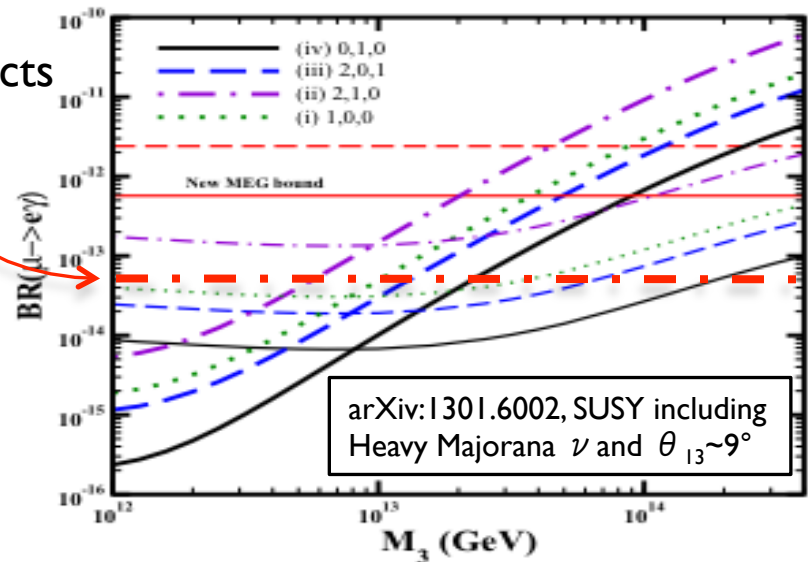
The **MEG collaboration** at PSI using **stopped muons** have achieved an amazing sensitivity to $\mu \rightarrow e \gamma$.



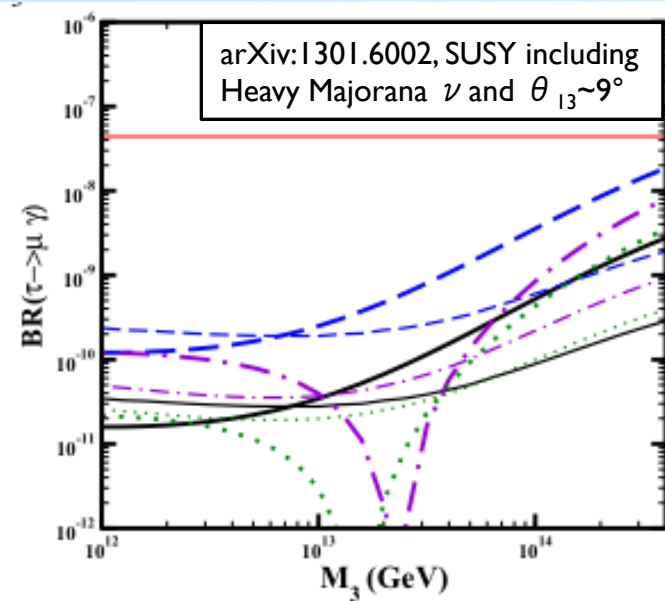
	Best fit	Upper limit (90% C.L.)	Sensitivity
2009-2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	5.7×10^{-13}	7.7×10^{-13}

MEG upgrade expects to reach 5×10^{-14} .

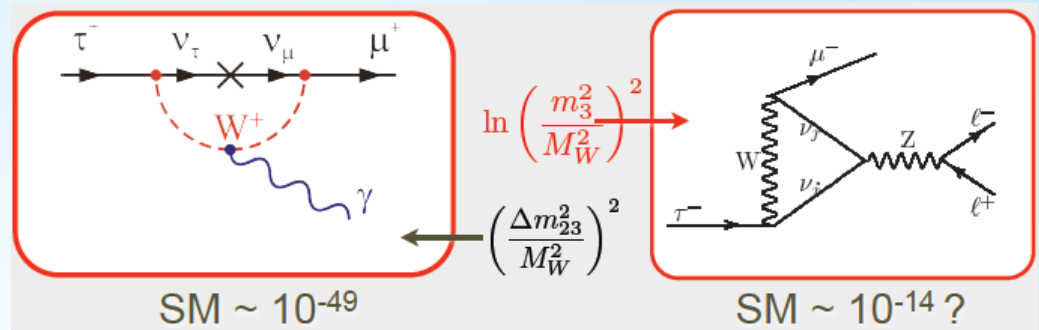
See **S. Dussoni** talk for more details.



CLFV: Tau Decays



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



The ratio between $\tau \rightarrow \mu \gamma$ and $\tau \rightarrow \mu \mu \mu$ is a very powerful test of NP models. The decay in 3μ 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 $3 \times 10^7 \mu^+/\text{sec}$ have been achieved at PSI, the B-factories have produced the best limits on CLFV tau decays with production rates of $\sim 2 \times 10^9 \tau/\text{ab}^{-1}$ or $\sim 10^2 \tau/\text{sec}$.

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

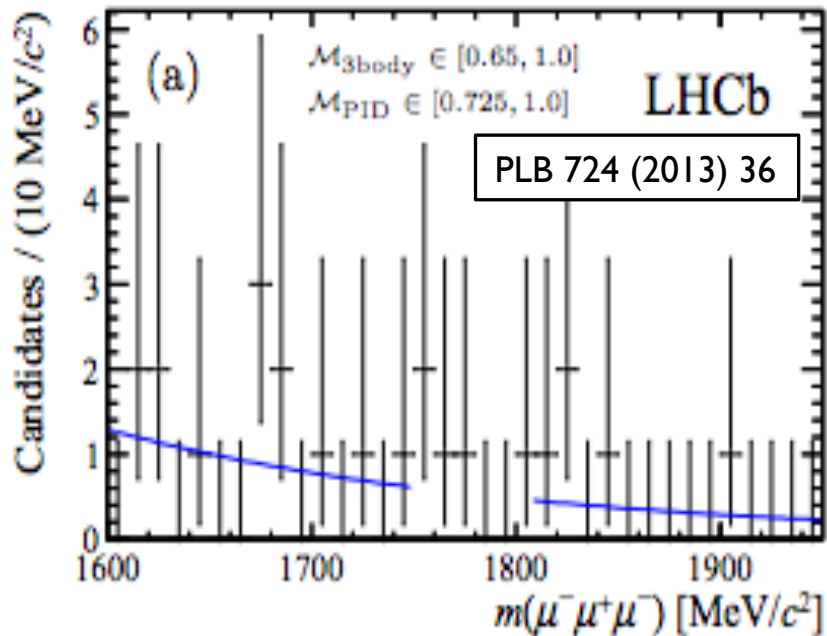
Best limits at 90% C.L., so far, from **B-factories**:

	$\text{BR}(\tau \rightarrow \mu \gamma)$	$\text{BR}(\tau \rightarrow \mu \mu \mu)$	
BELLE:	4.5×10^{-8}	2.1×10^{-8}	arXiv:1001.3221, arXiv:1002.4550
BABAR:	4.4×10^{-8}	3.3×10^{-8}	

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

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

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



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

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

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

BELLE sensitivity x4 better with $\sim 0.8 \text{ ab}^{-1}$.

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

See O.Vives
talk for more
on the future.

A green scroll graphic with a white border and rounded corners. The scroll is partially unrolled at the top and bottom. The word "Conclusions" is written in a bold, black, sans-serif font in the center of the scroll.

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**, as by precision measurements in the **flavour and neutrino sectors!**

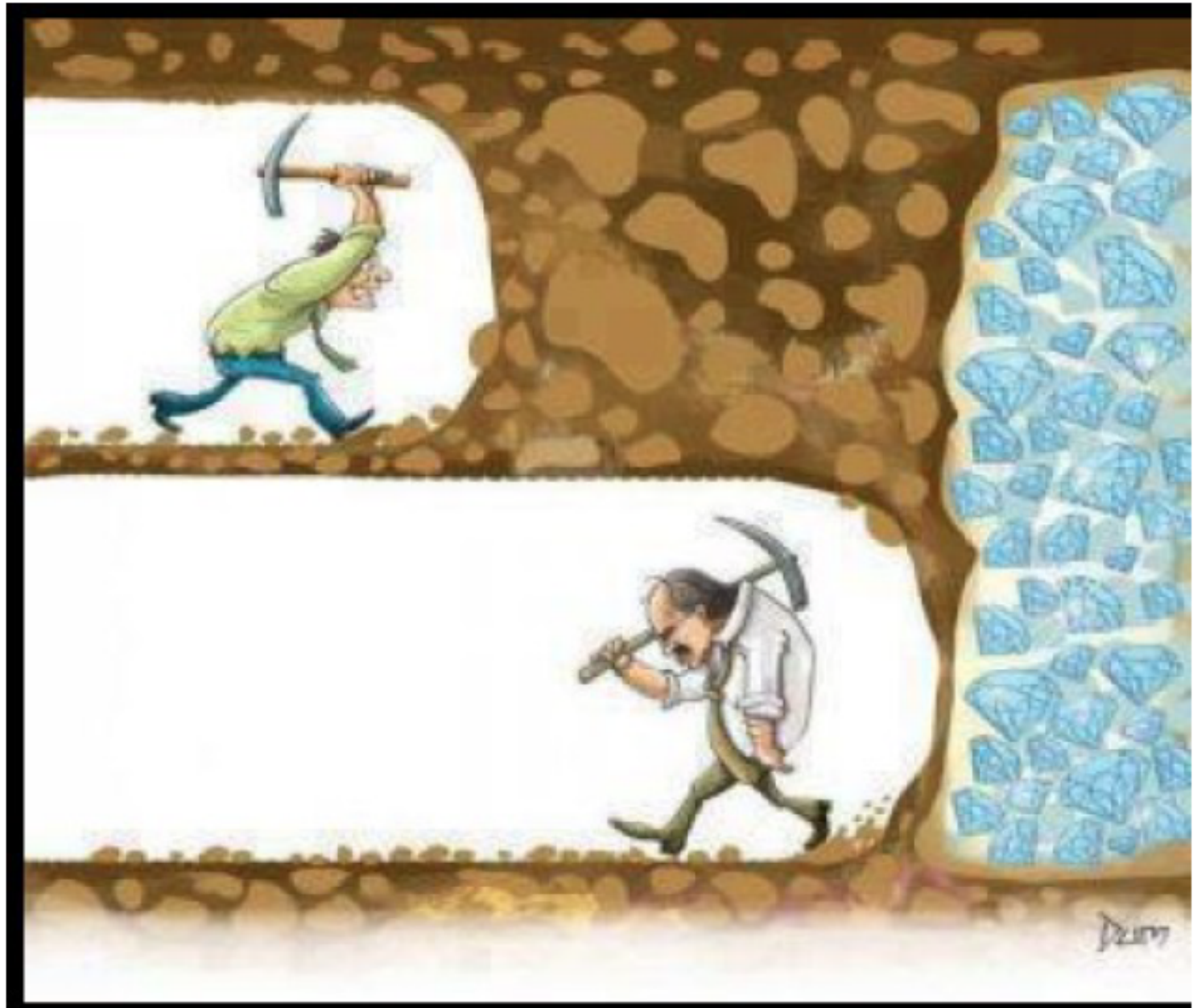
The search has just started at LHCb with $(1+2)/fb$ at LHC(7+8)TeV.

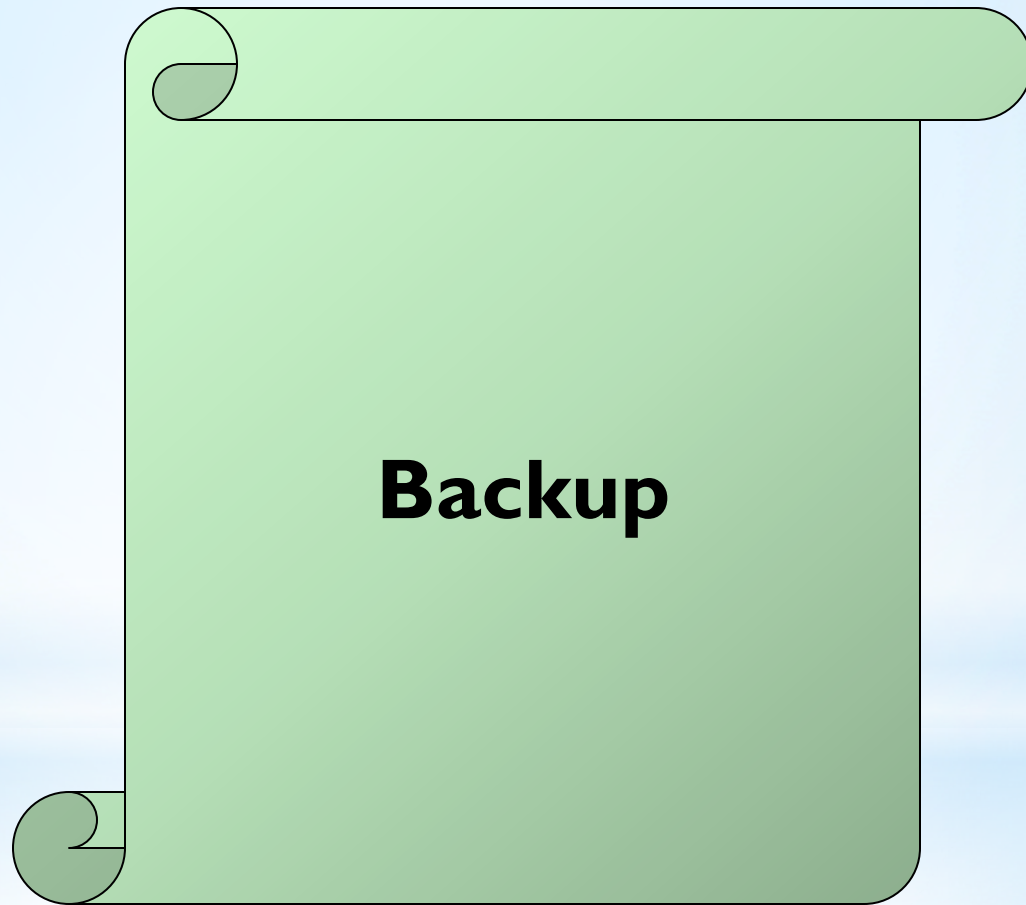
LHCb upgrade plans to collect $\sim 50/fb$ with a factor ~ 2 increase in **bb and cc cross-section**. **ATLAS/CMS** plan to collect $\sim 300/fb$ and **Belle-II** plans to collect $\sim 50/ab$ before HL-LHC.

See **G. Branco**
perspectives talk

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

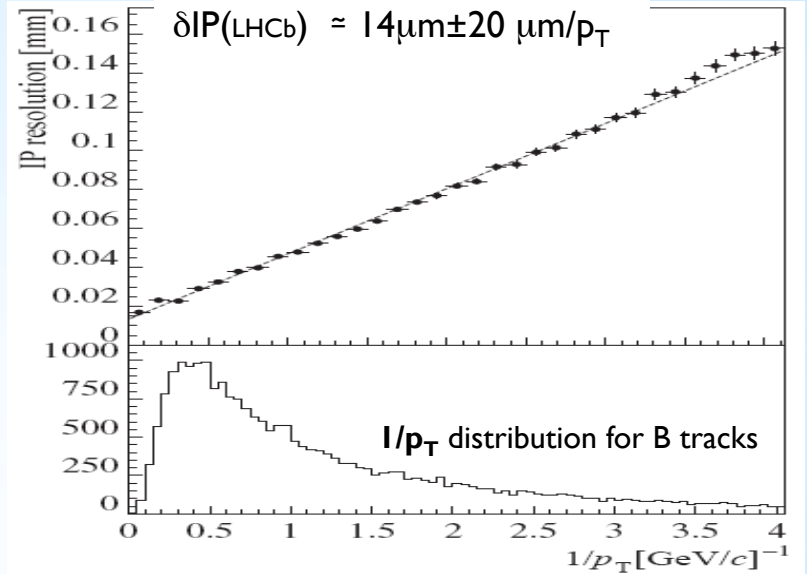
Don't give up yet!





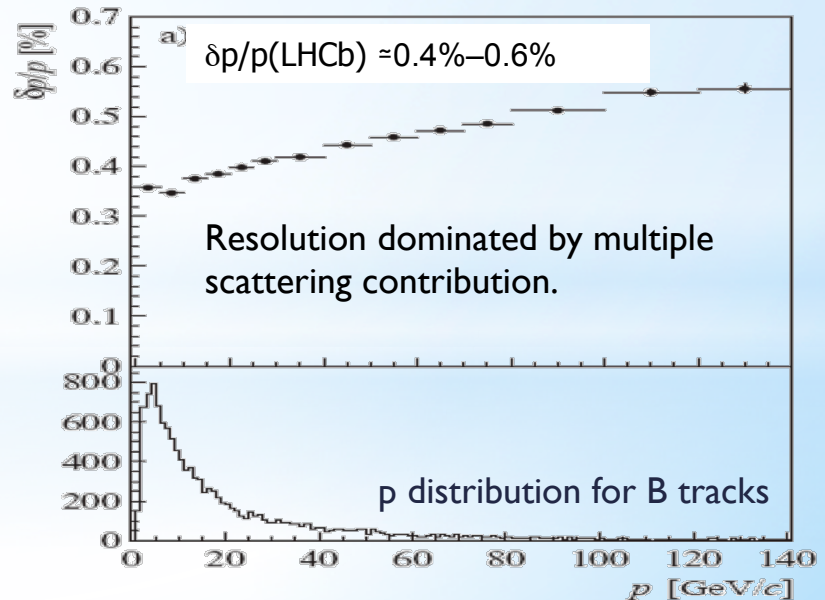
Tracking performance: Momentum and impact parameter resolution

	ATLAS Si Pixel	CMS Si Pixel	LHCb Si VELO
N channels	80 M	66 M	170 k
Size	50x400 μm (pixel)	100x150 μm (pixel)	40 μm (strip)
Distance to beam	8.8 cm	4.4 cm	0.8 cm

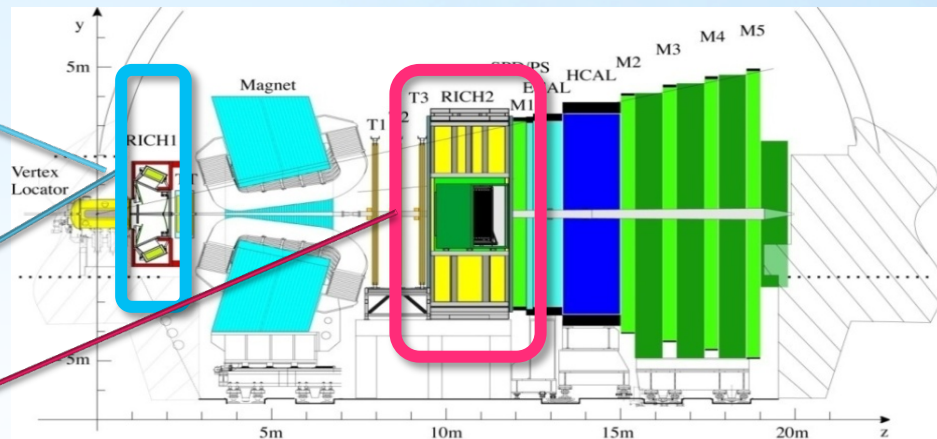
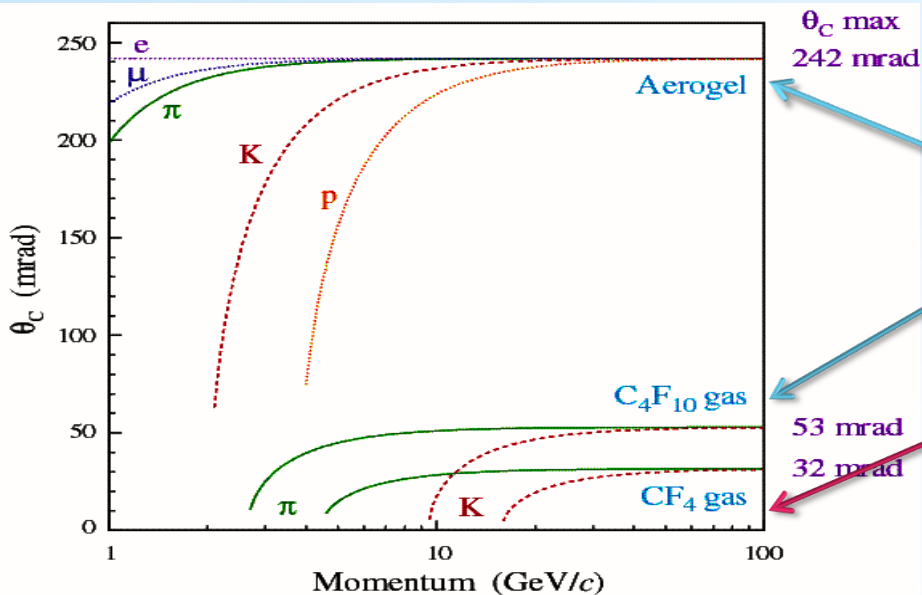


Integral Bdl: CMS/LHCb ~ 4 Tm, ATLAS ~2.5 Tm

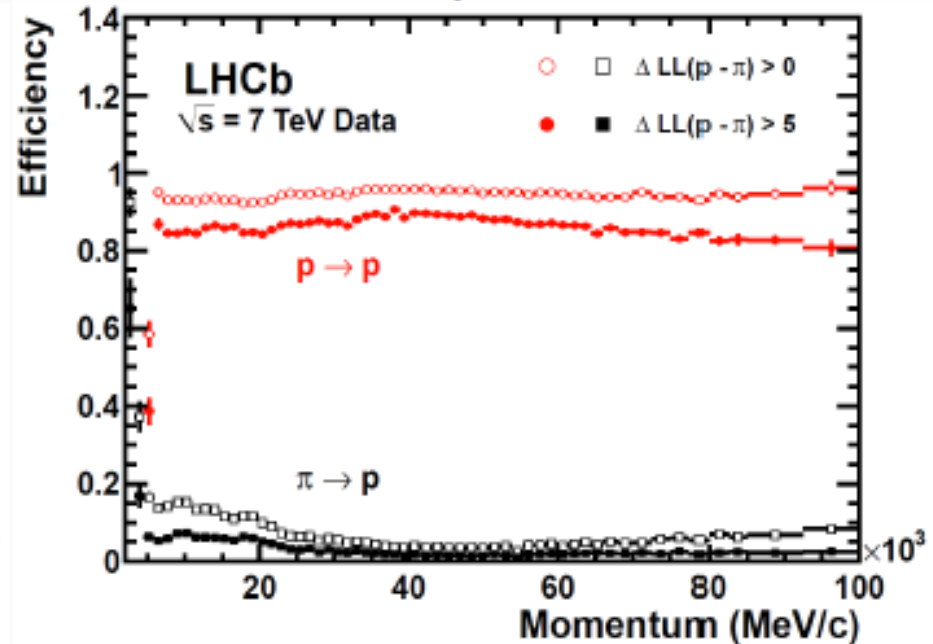
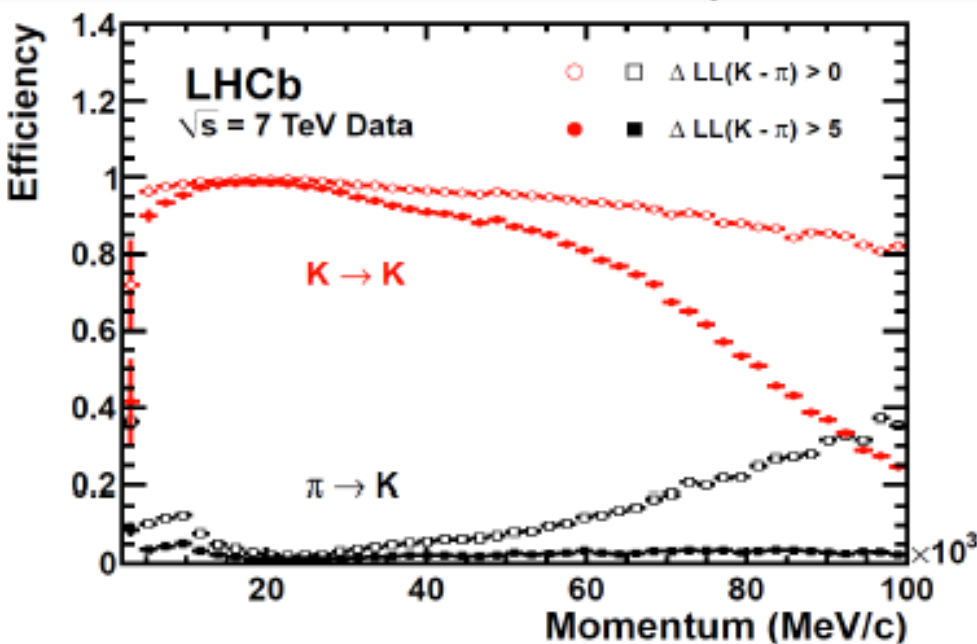
	ATLAS	CMS	CDF	LHCb
Decay time resolution (B_s)	~100 fs	~70 fs	87 fs	45 fs
Invariant Mass resolution (2-body)	80 MeV/c ²	45 MeV/c ²	25 MeV/c ²	22 MeV/c²



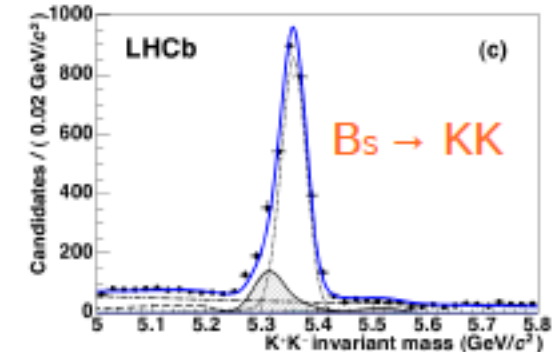
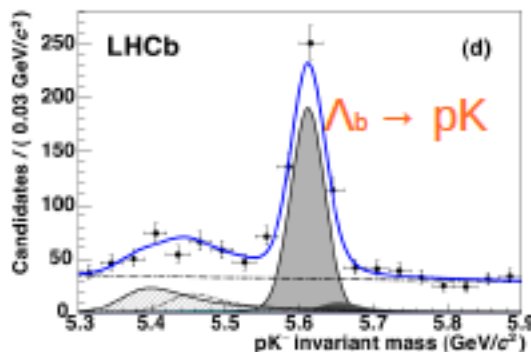
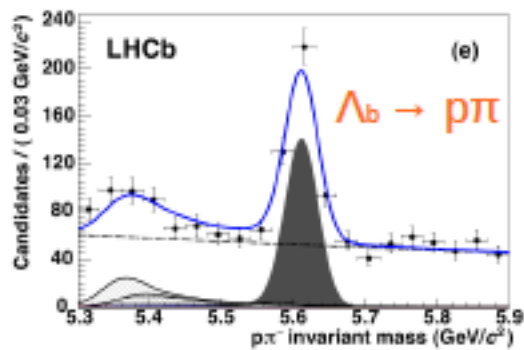
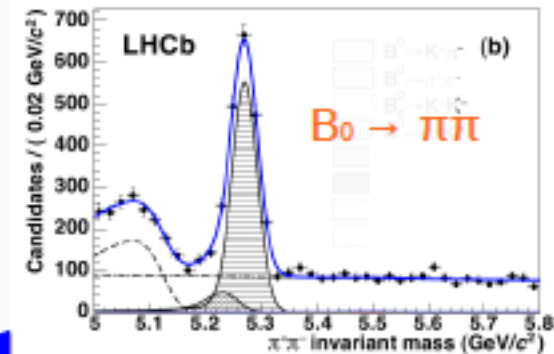
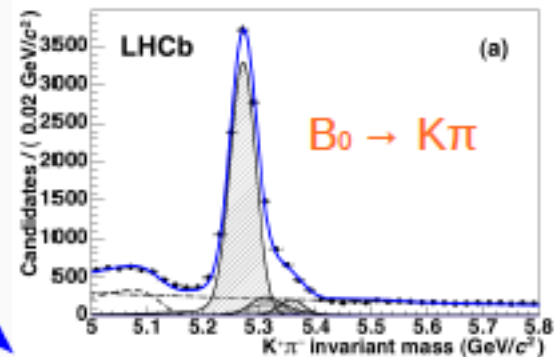
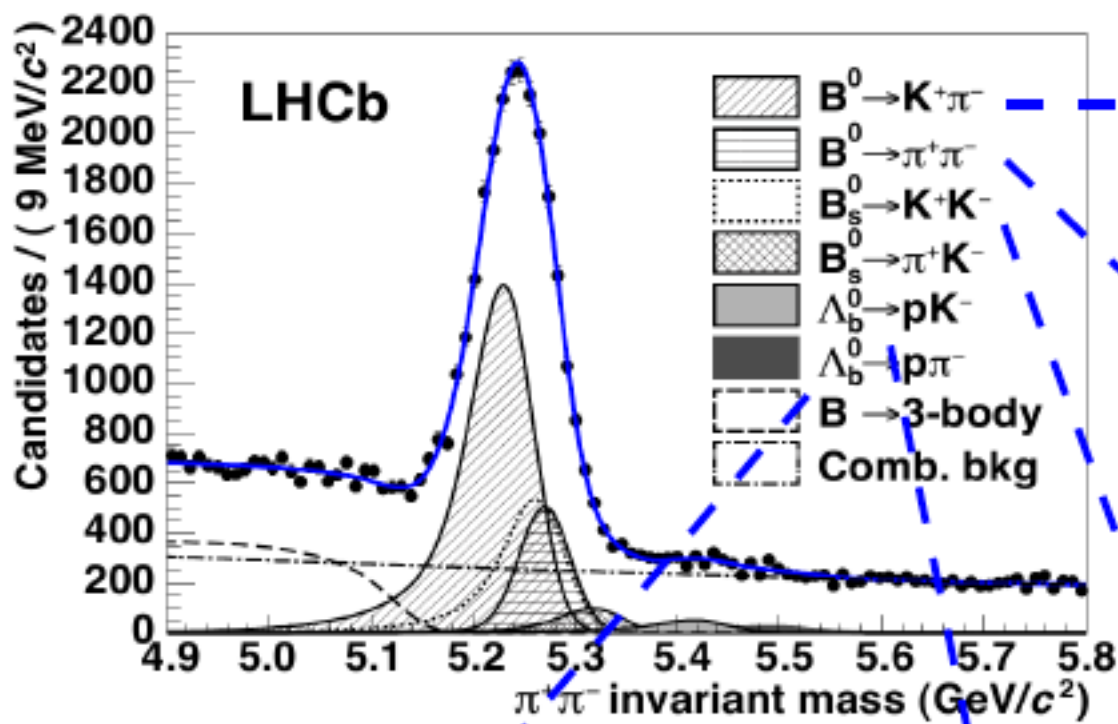
LHCb Particle Identification



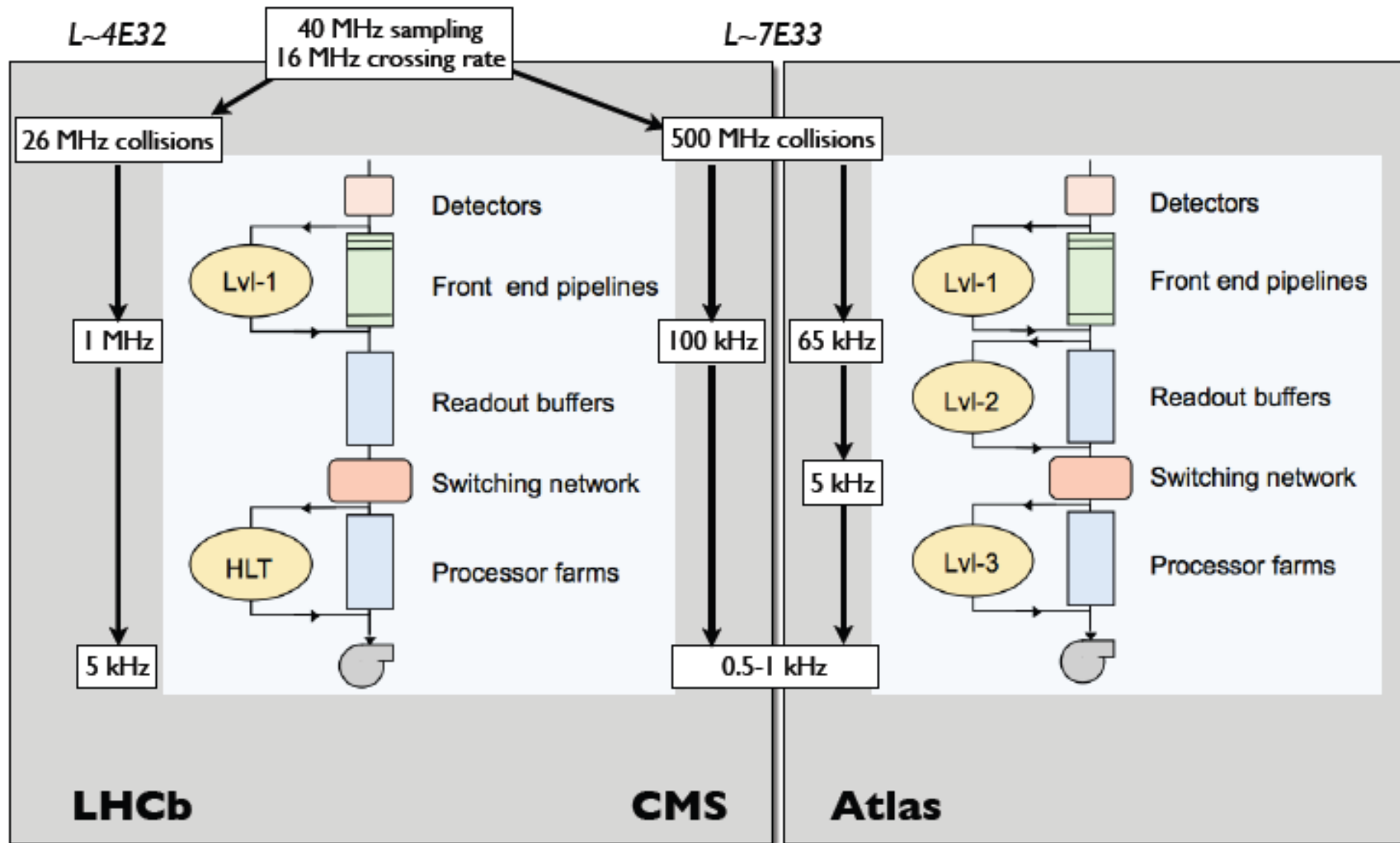
Efficiencies computed from data: pure samples of kinematically selected $K_s \rightarrow \pi^+\pi^-$, $\Lambda^0 \rightarrow p\pi^-$, $D^0 \rightarrow K^+\pi^-$



LHCb Particle Identification



Trigger systems at LHC



LHCb Trigger System

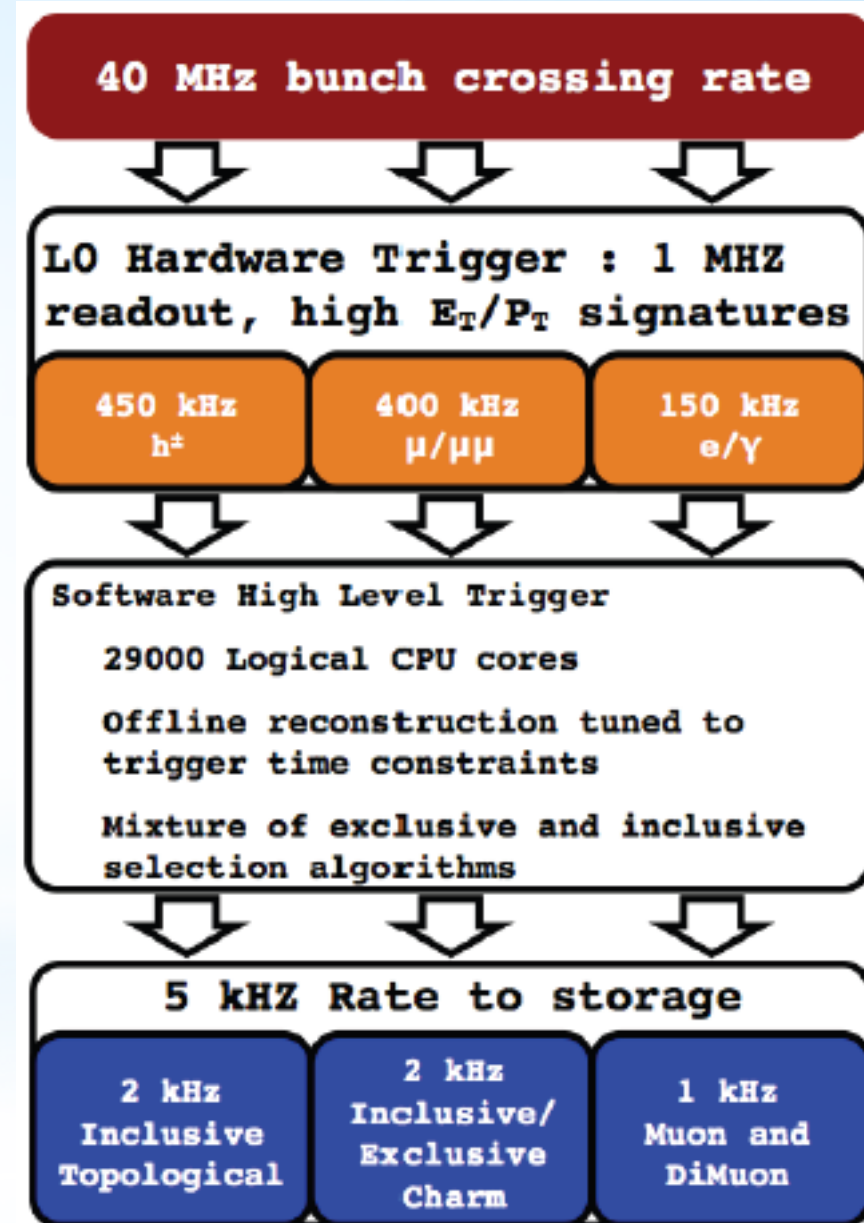
LHCb trigger output rate completely saturated by **bb/cc** events. However, only interested in relatively rare events ($BR < 10^{-3}$) \rightarrow the **LHCb trigger is what is called b-tagging** at ATLAS/CMS!

For **bb** an **inclusive approach** just works fine, but need **exclusive selections for cc**.

One synchronous **hardware** level, DAQ rate limited to **1 MHz**.

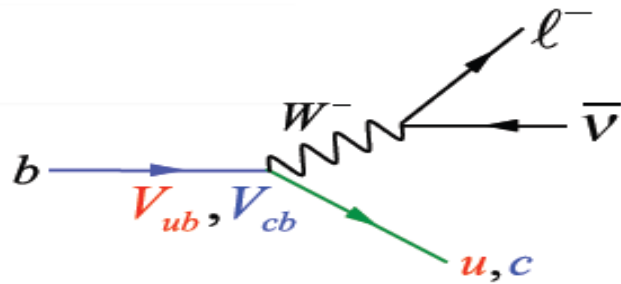
Computing farm with **software HLT**.

- First rate reduction based on track reconstruction (**~ 80 kHz**).
- Final inclusive/exclusive algorithms reconstruct B/D candidates (**~ 5 kHz**).



$b \rightarrow u, c$: Charged Currents (NP at tree level?)

$$\Gamma_x \equiv \Gamma(b \rightarrow xlv) \propto |V_{xb}|^2$$

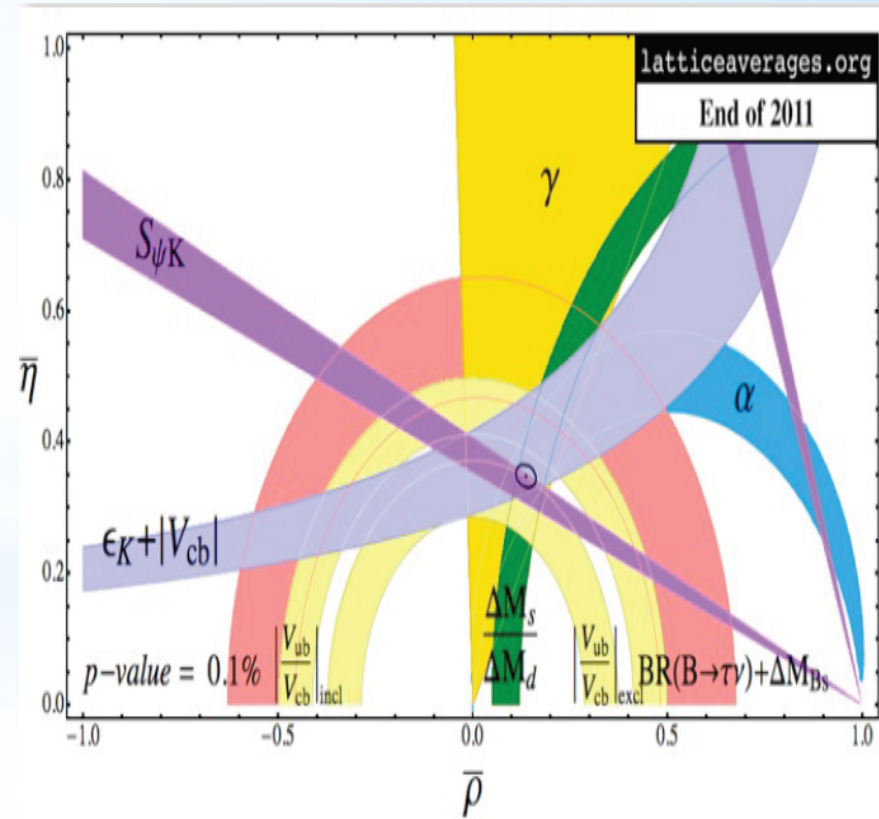


Measured values of V_{ub} at B-factories using **inclusive or exclusive** methods show a discrepancy at the 2-3 σ level:

$$V_{ub}(\text{incl.}) \sim 1.3 V_{ub}(\text{excl.}).$$

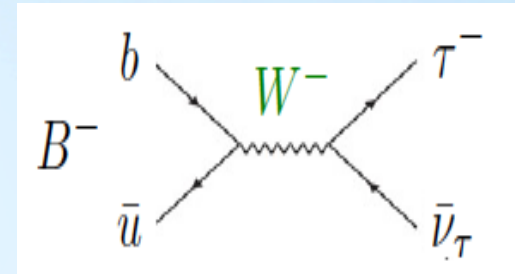
Both methods suffer from **large theoretical and experimental uncertainties**. Next generation B-factories will produce hadronic tagged, high statistics, high purity samples. LHCb is expected to provide competitive results in exclusive modes.

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

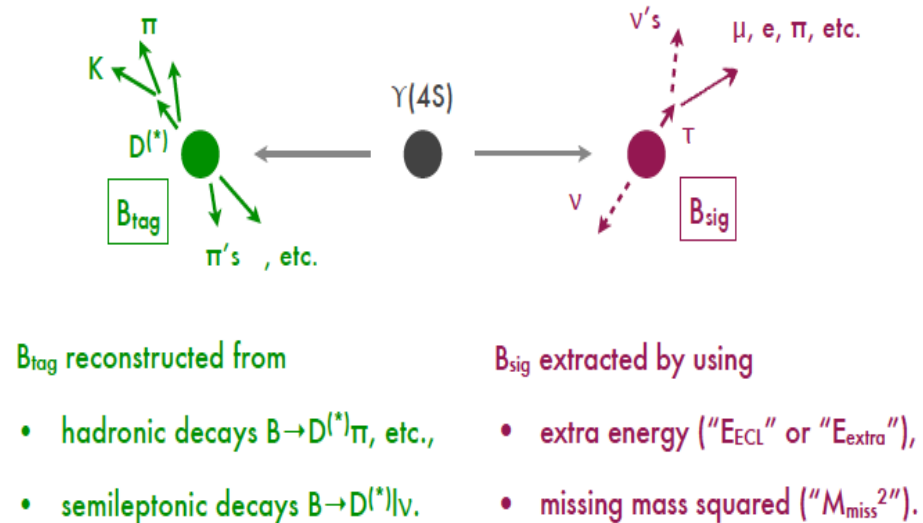
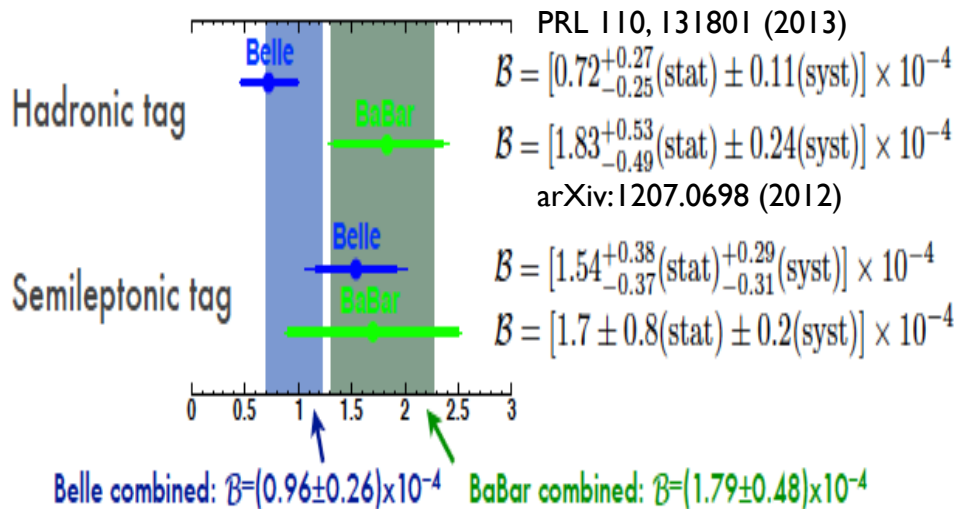


$b \rightarrow u$: Charged Currents (NP at tree level?)

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



On the other hand, we knew from LEP: $W \rightarrow \tau \nu / W \rightarrow l \nu \sim 1.06 \pm 0.03$

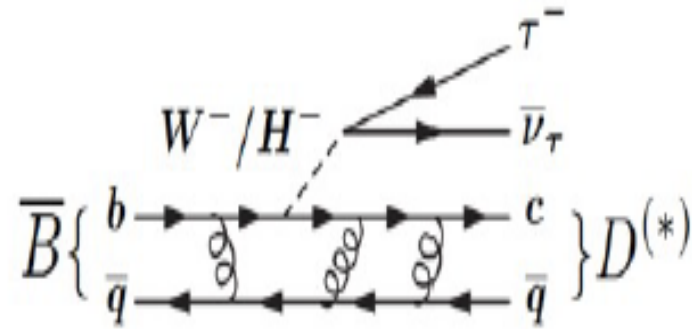


Summer 2012 **Belle** presented a more precise hadron tag analysis, in better agreement with the fitted CKM value:

World average $\text{BR}(B \rightarrow \tau \nu)_{\text{exp}} = (1.15 \pm 0.23) \times 10^{-4}$ vs **CKM fit:** $(0.83 \pm 0.09) \times 10^{-4}$

$b \rightarrow c$: Charged Currents (NP at tree level?)

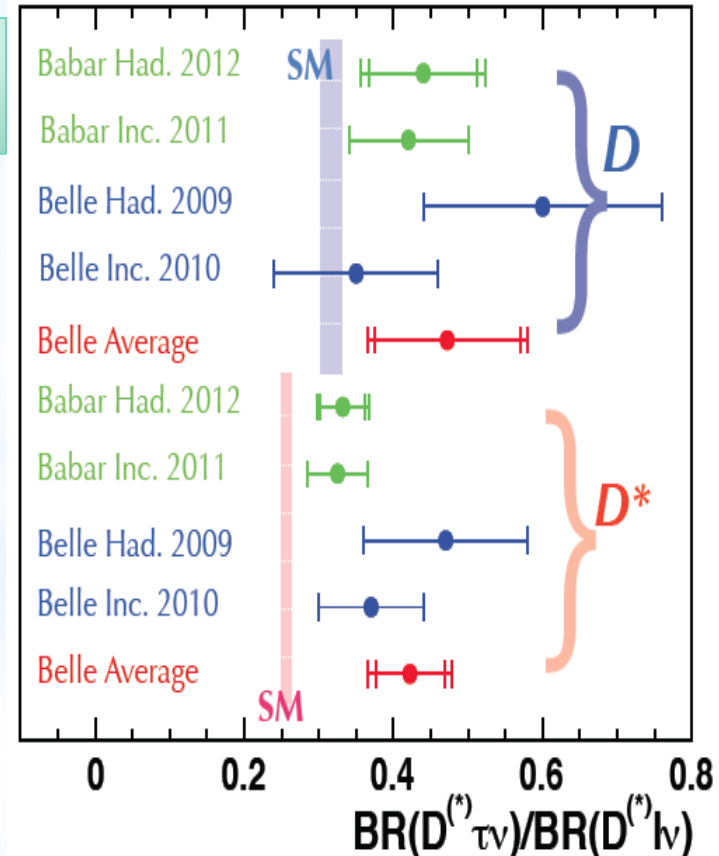
BABAR also presented by Summer 2012 a more precise measurement of $BR(B \rightarrow D^{(*)} \tau \nu) / BR(B \rightarrow D^{(*)} l \nu)$. Ratio cancels V_{cb} and QCD uncertainties. Combined D and D* BABAR results are **3.4σ higher than SM**



Belle should be able to reduce the uncertainties on $B \rightarrow D^{(*)} \tau \nu$ soon at similar level than BABAR.

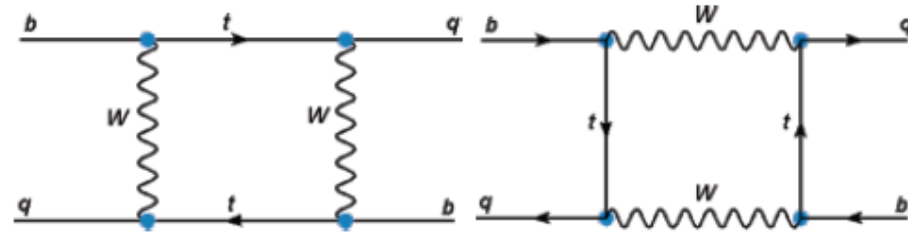
Not obvious NP explanation.

2HDM need to be stretched to be able to explain the measured ratio at BABAR, and in any case would be in tension with the latest measurements of $BR(B \rightarrow \tau \nu)$.

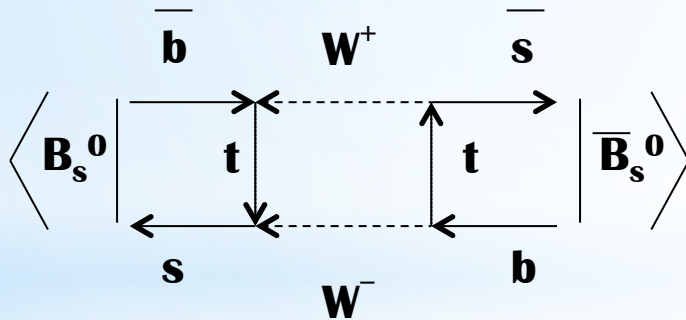


$\Delta F=2$ box transitions theory

$$i \frac{d}{dt} \begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \begin{pmatrix} \text{dispersive} \\ \hat{M}^q - \frac{i}{2} \hat{\Gamma}^q \end{pmatrix} \begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$



In principle one expects **NP to affect the dispersive part**, i.e. new heavy particles ($M > q^2$) contributing virtually to the box diagram. The **absorptive part** is dominated by the production of **real light particles** ($M < q^2$).



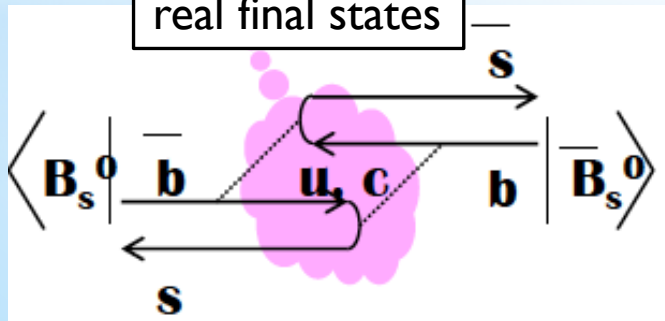
Dispersive part: M_{12}

$$\Delta m_s = 2 |M_{12}| \propto B_s f_s^2 |V_{ts}|^2 |V_{tb}|^2$$

$$\arg M_{12} = \arg (V_{ts}^* V_{tb})^2 + \pi = \varphi_s + \pi$$

Absorptive part: Γ_{12}

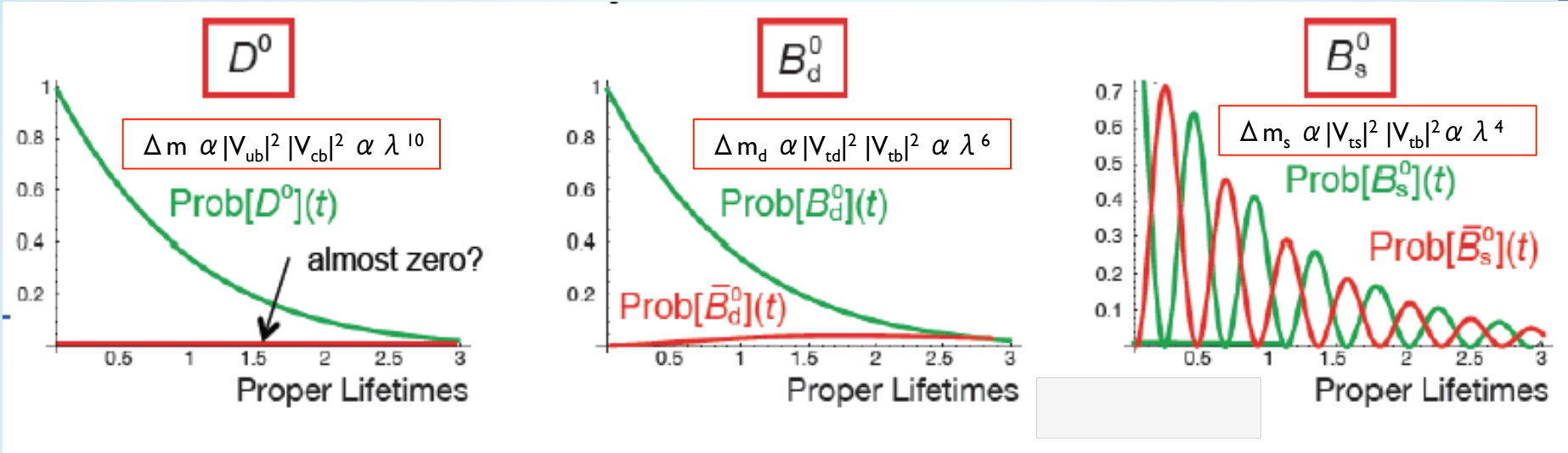
$$\Delta \Gamma = 2 |\Gamma_{12}| \quad \frac{\Delta \Gamma}{\Delta m} = \frac{3\pi m_b^2}{2m_W^2 S(x_t)} \approx 5 \times 10^{-3}$$



$$\Delta \Gamma_d \propto 0.004 \times \Gamma_d$$

$$\Delta \Gamma_s \propto 0.1 \times \Gamma_s$$

$\Delta F=2$ box transitions theory



The **oscillation frequency** is given by $\Delta M_q \sim 2|M^q_{12}|$.

The **width difference** by $\Delta \Gamma_q \sim 2|\Gamma^q_{12}|\cos(\varphi_q)$ with $\varphi_q = \arg(-M^q_{12}/\Gamma^q_{12})$.

Expect **very small CP violation in the oscillation**, or equivalently very small values for flavour-specific CP asymmetries:

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

Best chance to see SM-level CP asymmetries in the **interference between mixing and decay**.

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

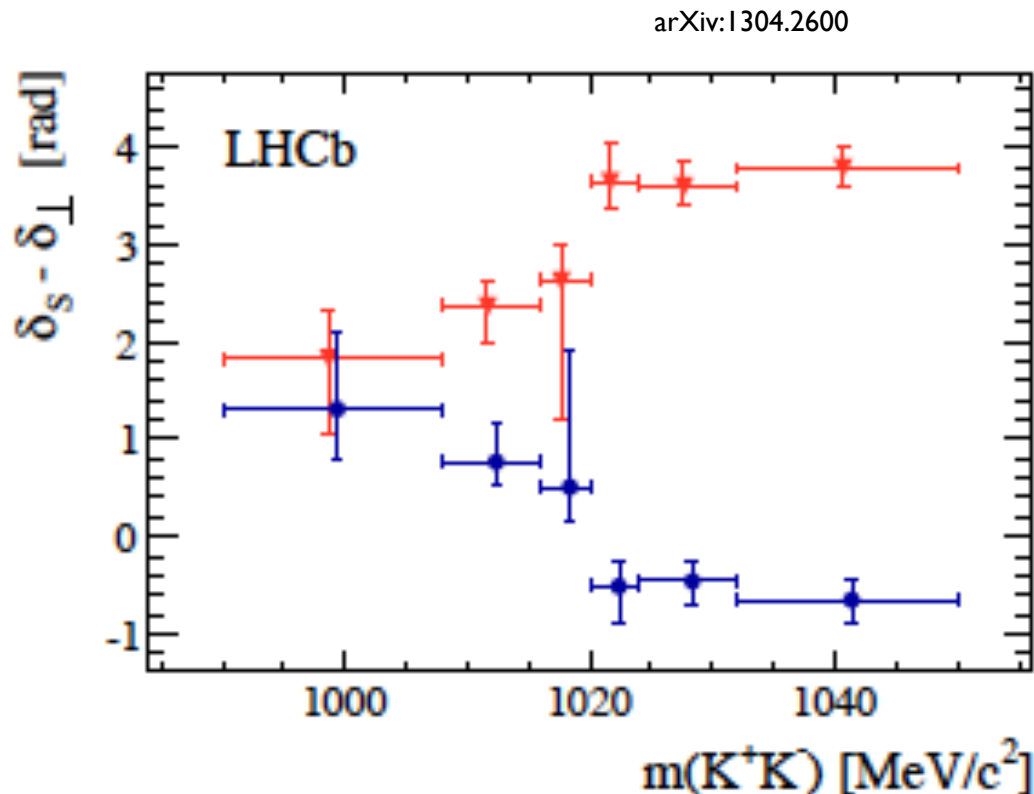
However, there is a two fold ambiguity in the differential decay rates:

$$(\phi_s, \Delta\Gamma_s, \delta_0, \delta_{\parallel}, \delta_{\perp}, \delta_S) \mapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_{\parallel}, \pi - \delta_{\perp}, -\delta_S)$$

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:

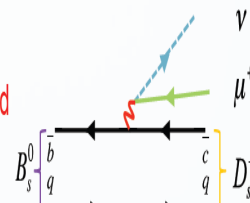
$$\Delta\Gamma_s > 0$$



$\Delta F=2$ box in $b \rightarrow q$ transitions (D0 flavour specific asymmetries)

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

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



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

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

$a_{fs}^q = |\Gamma_{12}^q / M_{12}^q| \sin(\varphi_q)$

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: $\mathbf{A}_{SL}^b = (-0.787 \pm 0.172(\text{stat}) \pm 0.093(\text{syst}))\%$ (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**:

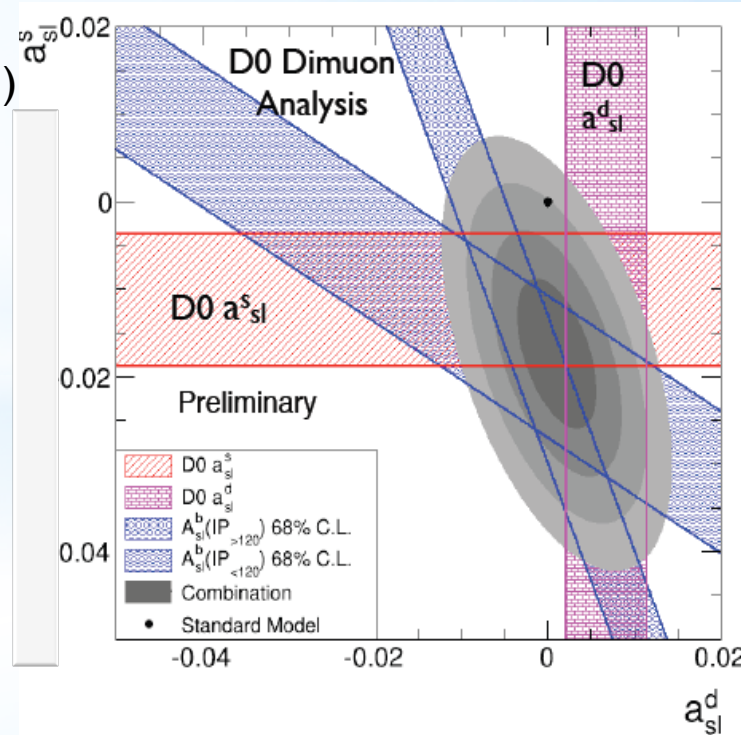
$a_{SL}(B_d) = (-0.12 \pm 0.52)\%$, $a_{SL}(B_s) = (-1.81 \pm 1.06)\%$

Moreover, D0 has also measured:

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

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

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



$\Delta F=2$ box in $b \rightarrow q$ transitions (LHCb flavour specific asymmetries)

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

LHCb ($B_s \rightarrow D_s [\Phi \pi] \mu \nu X$): arXiv:1308.1048
 $a_{SL}(B_s) = (-0.06 \pm 0.50(\text{stat}) \pm 0.36(\text{syst}))\%$

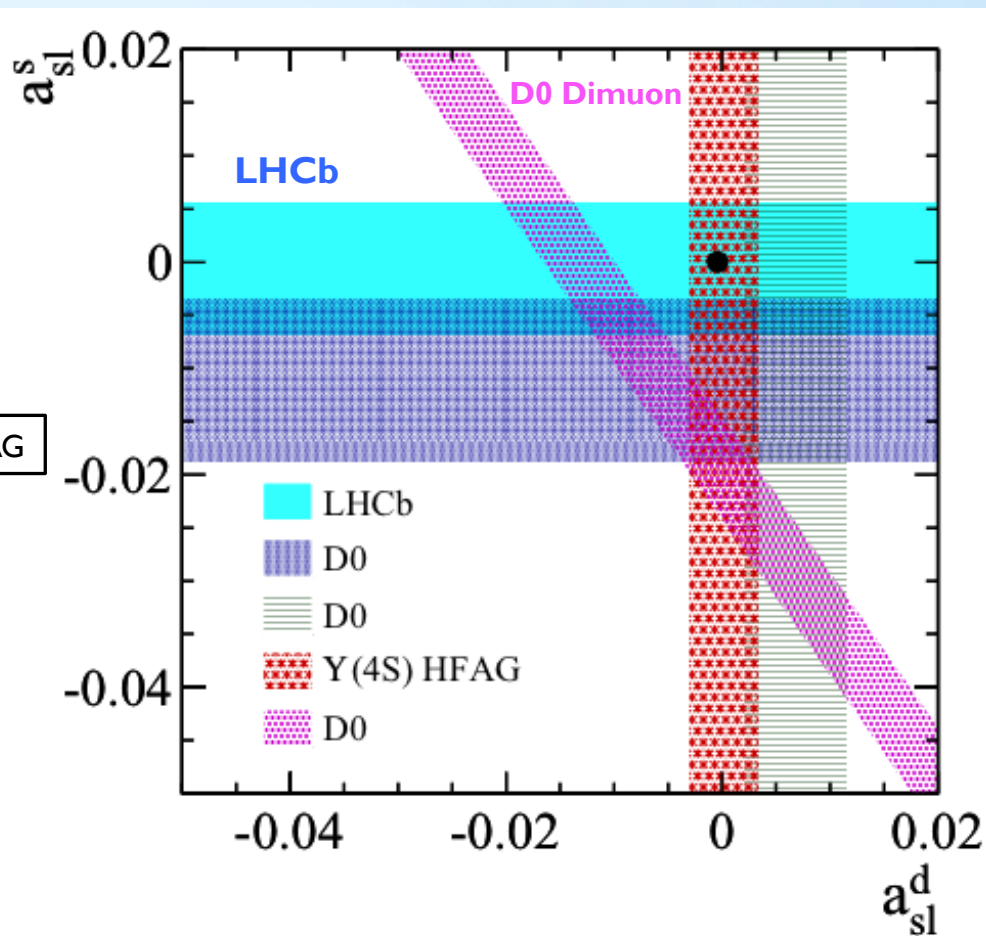
Also taking into account the measurement at the B-factories of $a_{SL}(B_d) = (0.02 \pm 0.31)\%$ HFAG

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.



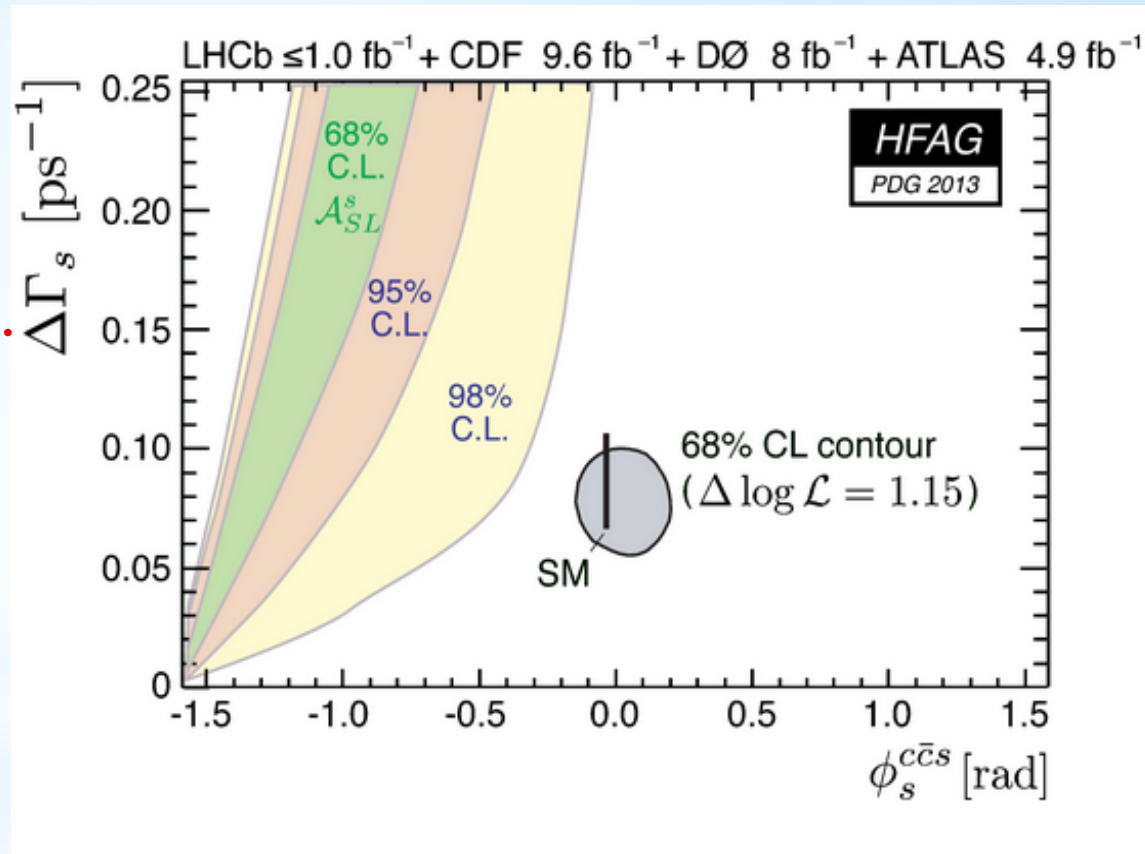
LHCb needs to add more channels and more data and a precise measurement of $A_{SL}(B_d)$ to be able to conclude. However there is already a **clear tension between D0 $a_{SL}(B_s)$ and the measurements of $(\Delta \Gamma_s, \Phi_s)$**

$\Delta F=2$ box in $b \rightarrow q$ transitions: (NP in absorptive part)

LHCb needs to add more channels and more data and a precise measurement of $A_{SL}(B_d)$ to be able to conclude.

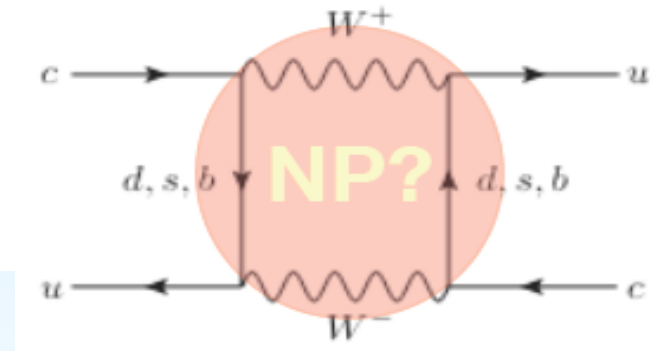
However there is already a clear tension between D0 $a_{SL}(B_s)$ and the measurements of $(\Delta \Gamma_s, \Phi_s)$.

Getting more difficult to get a coherent picture.



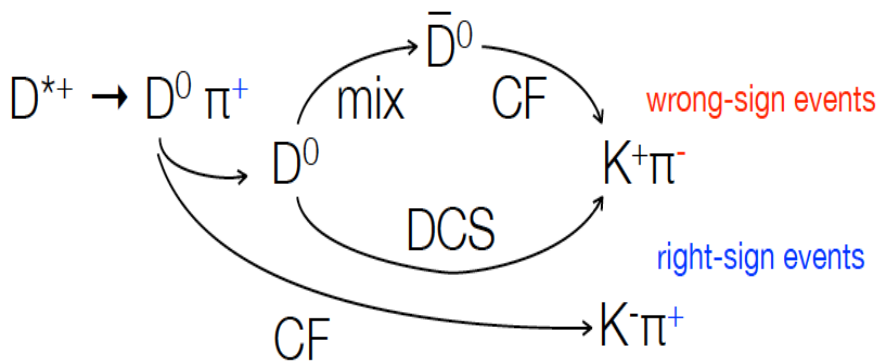
$\Delta F=2$ box in $c \rightarrow u$ transitions: NP in charm mixing?

$$x = \frac{\Delta M}{\Gamma} = \frac{M_H - M_L}{(\Gamma_H + \Gamma_L)/2}, \quad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{(\Gamma_H + \Gamma_L)}$$



In Charm mixing absorptive part dominant, therefore large theoretical uncertainties in the SM prediction. Charm mixing has been confirmed combining BaBar, Belle and CDF.

However, **no observation** ($>5\sigma$) by a **single experiment until 2013!**



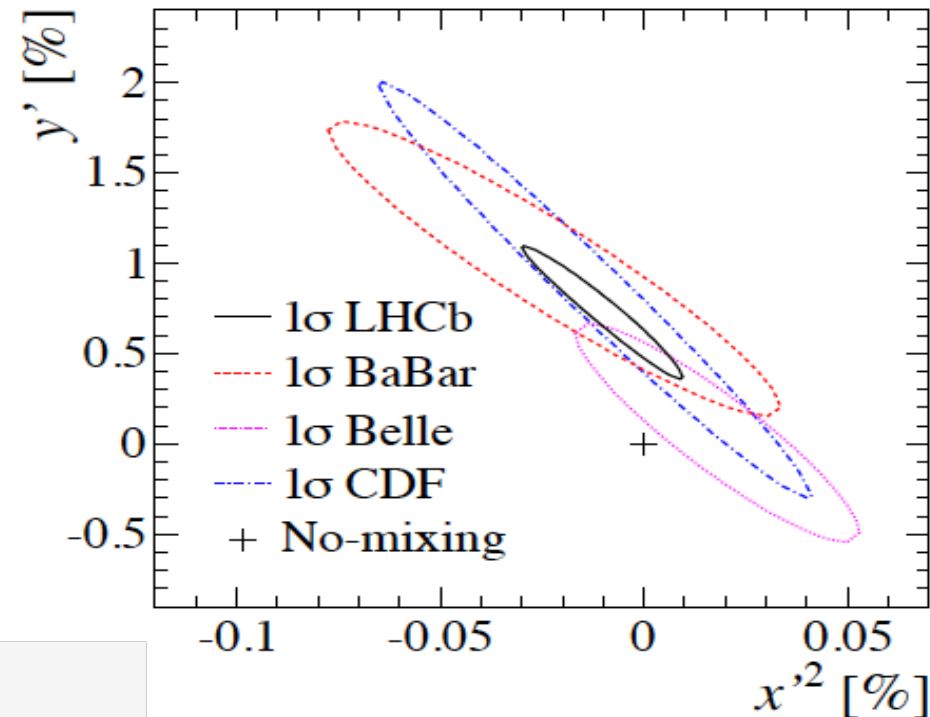
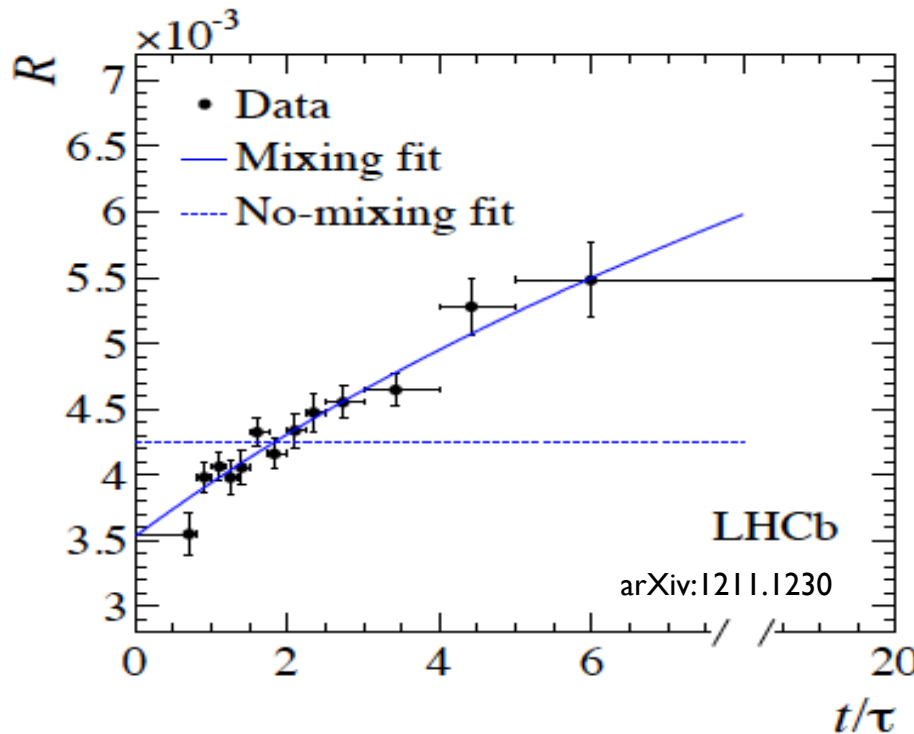
Assuming $|x|, |y| \ll 1$ and no CPV:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t^2$$

$$x' = x \cos \delta + y \sin \delta \quad y' = y \cos \delta - x \sin \delta$$

$\Delta F=2$ box in $c \rightarrow u$ transitions: NP in charm mixing?

LHCb strategy similar than CDF: use ratio of **WS to RS events** as a function of t in $D^* \rightarrow D\pi$ events. Charge of **soft pion tags** the D^0 flavour.

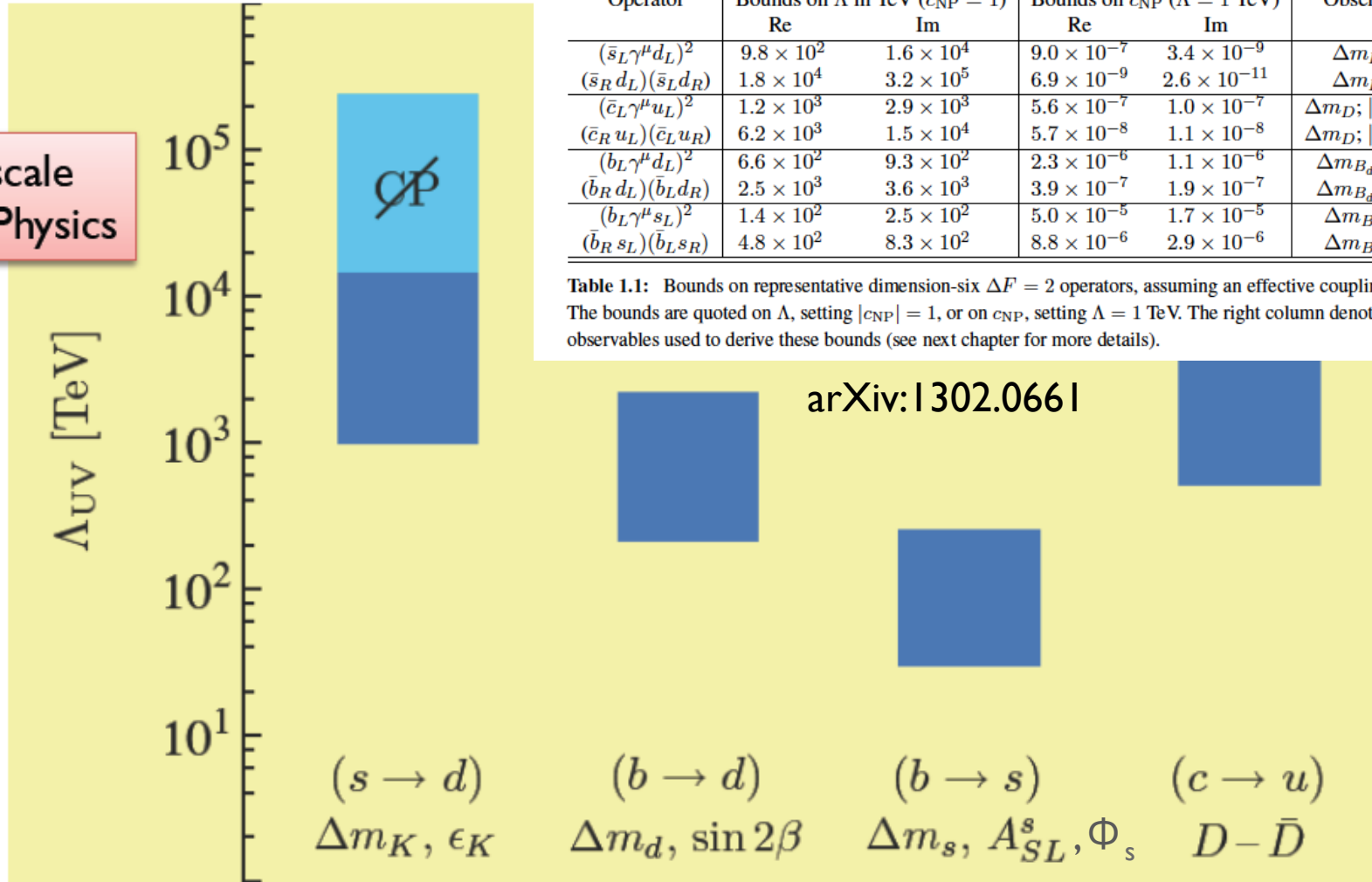


No mixing hypothesis excluded at 9.1σ by LHCb.

Recent CDF update (at Beauty, April 2013) using same experimental strategy, excludes no-mixing hypothesis at 6.1σ

$\Delta F=2$ box implications

Mass scale of New Physics



CP violation in K system

Oscillations and CPV in B_d system

Oscillations and CPV in B_s system

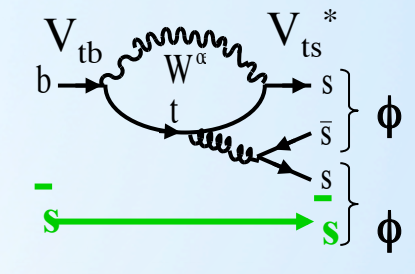
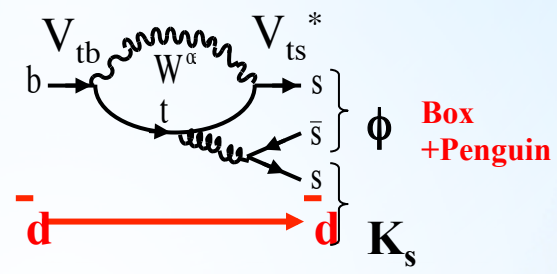
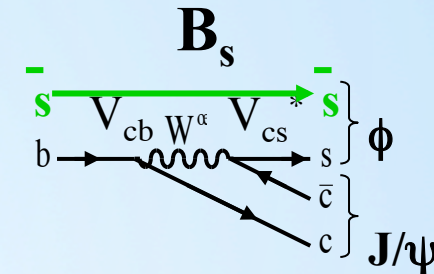
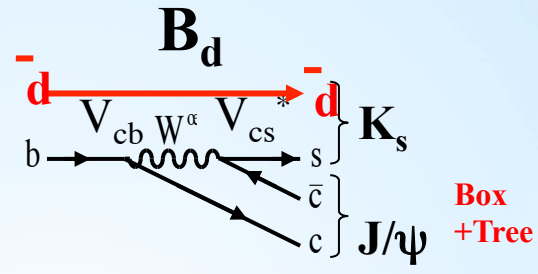
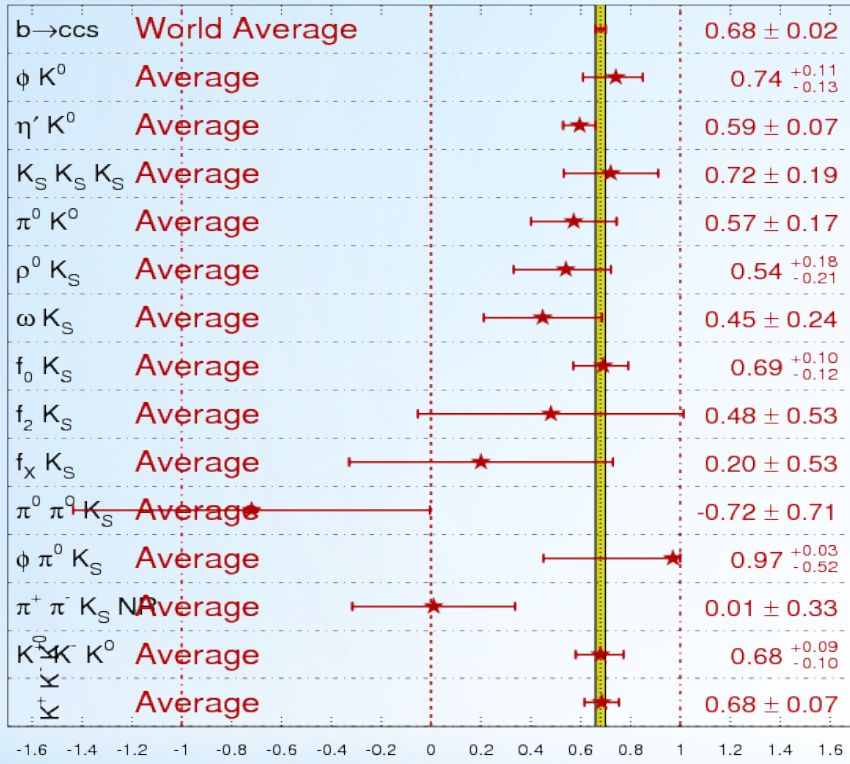
Oscillations in D system

Operator	Bounds on Λ in TeV ($c_{NP} = 1$)		Bounds on c_{NP} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D; q/p , \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D; q/p , \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s}; S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s}; S_{\psi\phi}$

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

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

$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$ **HFAG**
Moriond 2012
PRELIMINARY



$\beta(\text{tree}) - \beta(\text{penguin}) = \delta\beta(\text{NP})$

$\beta_s(\text{tree}) - \beta_s(\text{penguin}) = \delta\beta(\text{NP})$

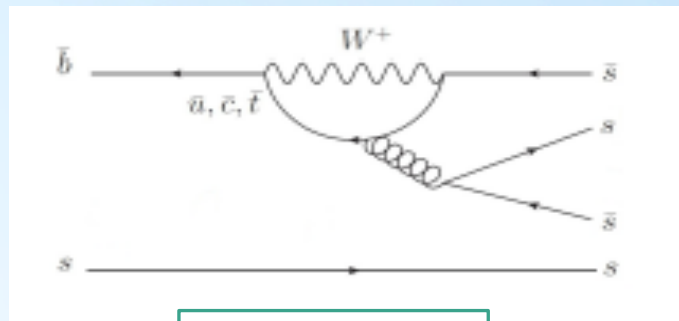
No significant discrepancy between $b \rightarrow ccs$ and s -penguin measurements. However, there may be a tendency and effects $O(\delta\beta \sim 4^\circ)$ are not excluded.

The effect of the 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

$\Delta F=1$ box in $b \rightarrow s$ QCD penguin: $B_s \rightarrow \Phi \Phi$

The phase in the $b \rightarrow s$ box diagram is constrained to be small (within $\pm 4.0^\circ$ from direct or $\pm 0.9^\circ$ indirect measurements).



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

Angular analysis is needed in $B_s \rightarrow \Phi \Phi$ decays, to disentangle statistically the CP-even and CP-odd components.

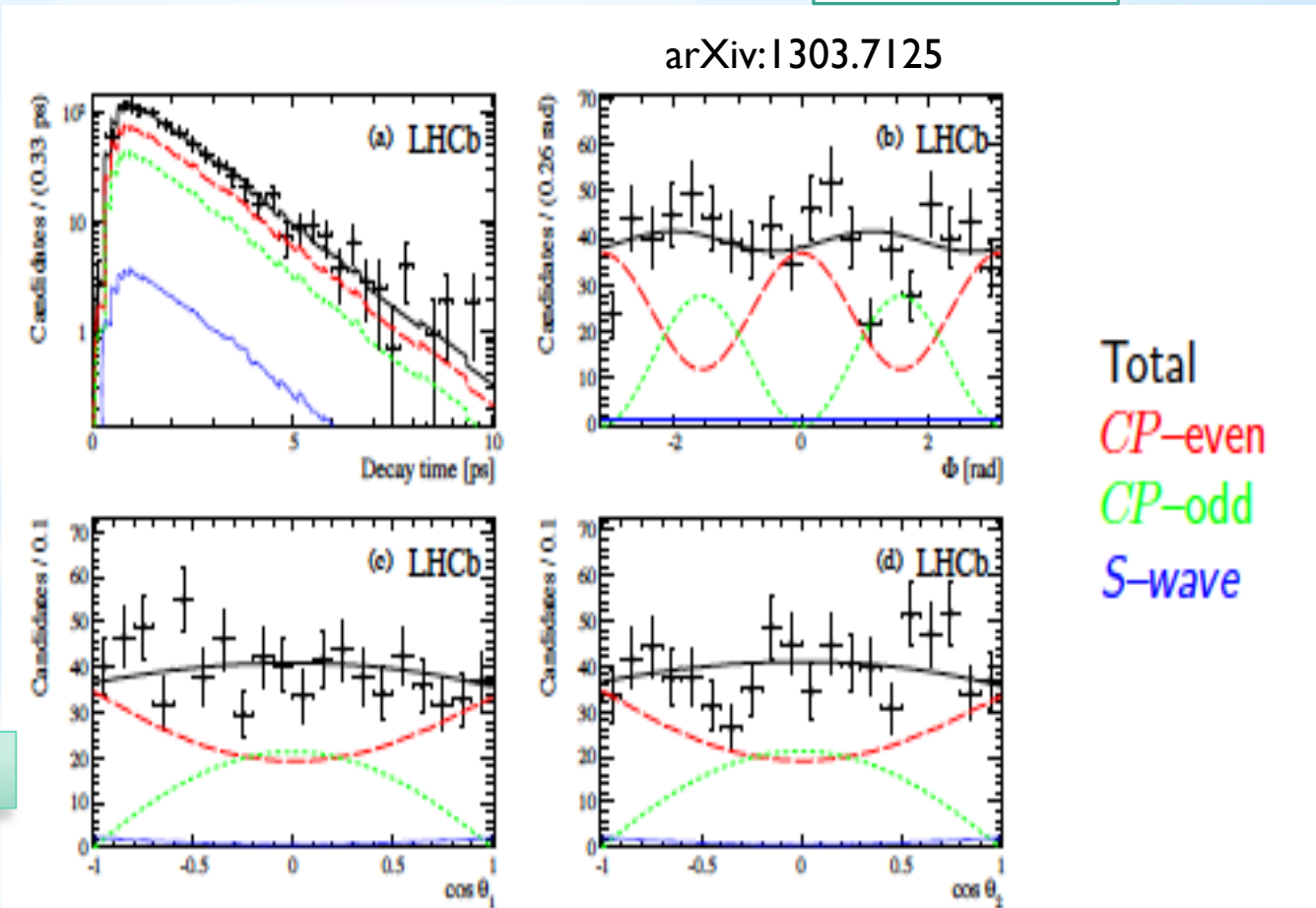
$$\varepsilon D^2 = (3.29 \pm 0.48)\%$$

The analysis with 1/fb (0.8k candidates) results in a non-parabolic likelihood profile:

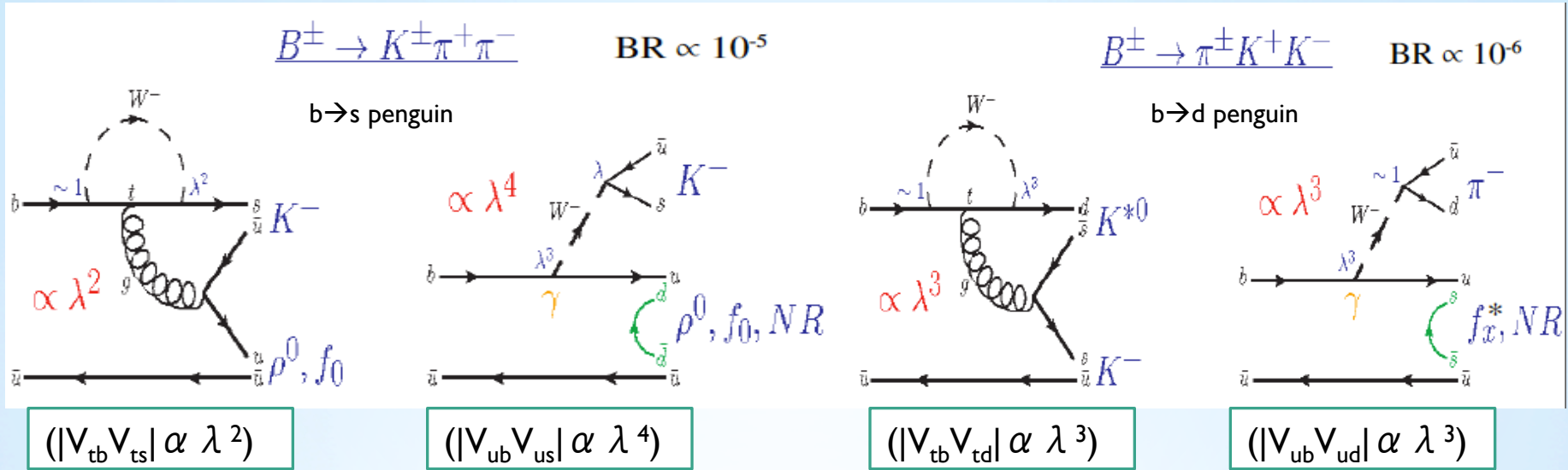
$$\Phi_s \text{ is within } [-136, -53]^\circ \text{ at 68\% CL}$$

With a p-value of 16% for the SM hypothesis.

Still a long path to walk



$\Delta F=1$ b \rightarrow s, d QCD penguins: Direct CP violation in $B \rightarrow 3h$



In principle, **3-body charmless B** decays is also a way to access γ , through the interference between tree and penguin decays \rightarrow **not a tree level measurement.**

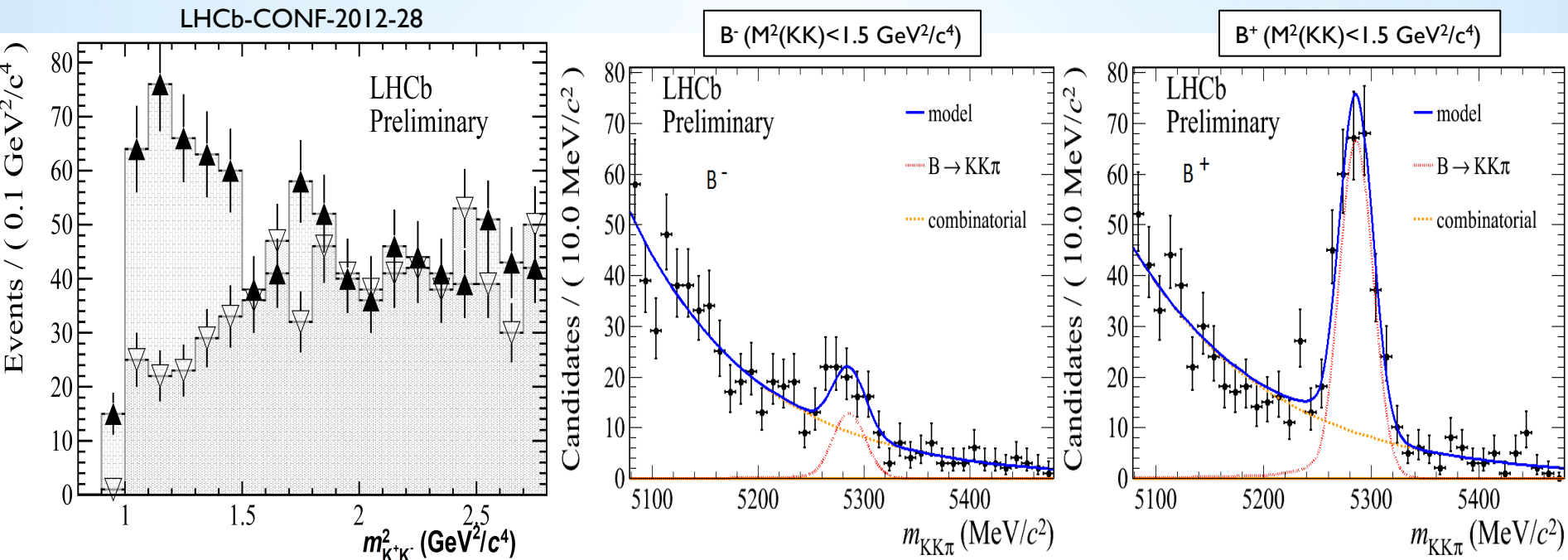
LHCb has **preliminary** measurements of **large integrated** along Dalitz plot **CP asymmetries:**

b \rightarrow s QCD penguin (LHCb-CONF-2012-18)
 $A_{CP}(B^\pm \rightarrow K^\pm \pi \pi) = 0.034 \pm 0.009 \pm 0.008$
 $A_{CP}(B^\pm \rightarrow K^\pm K K) = -0.046 \pm 0.009 \pm 0.009$

b \rightarrow d QCD penguin (LHCb-CONF-2012-28)
 $A_{CP}(B^\pm \rightarrow \pi^\pm K K) = -0.153 \pm 0.046 \pm 0.020$
 $A_{CP}(B^\pm \rightarrow \pi^\pm \pi \pi) = 0.120 \pm 0.020 \pm 0.020$

$\Delta F=1$ $b \rightarrow s, d$ QCD penguins: Direct CP violation in $B \rightarrow 3h$

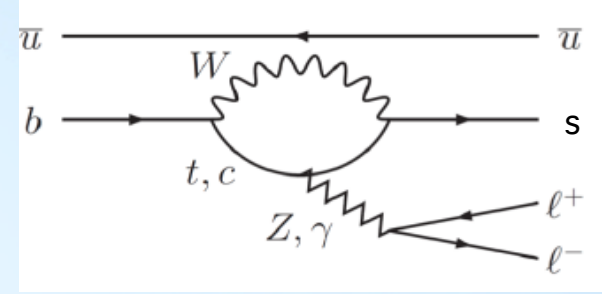
Interestingly, the larger CP violation effects **appear in special kinematic regions** not dominated by narrow resonances. For example, for the decay $B^\pm \rightarrow \pi^\pm KK$ a large excess of B^+ over B^- decays is observed for $M^2(KK) < 1.5 \text{ GeV}^2/c^4$, as previously indicated by BABAR.



Some kind of hadron dynamics is working to generate such large A_{CP} .

$\Delta F=1$ EW penguins in $b \rightarrow s$ transitions: $B^\pm \rightarrow K^\pm \mu \mu$

The decay $B^\pm \rightarrow K^\pm \mu \mu$ is complementary to $B \rightarrow K^* \mu \mu$, as the spin of K^\pm implies much larger **sensitivity to new scalar and tensor contributions**.



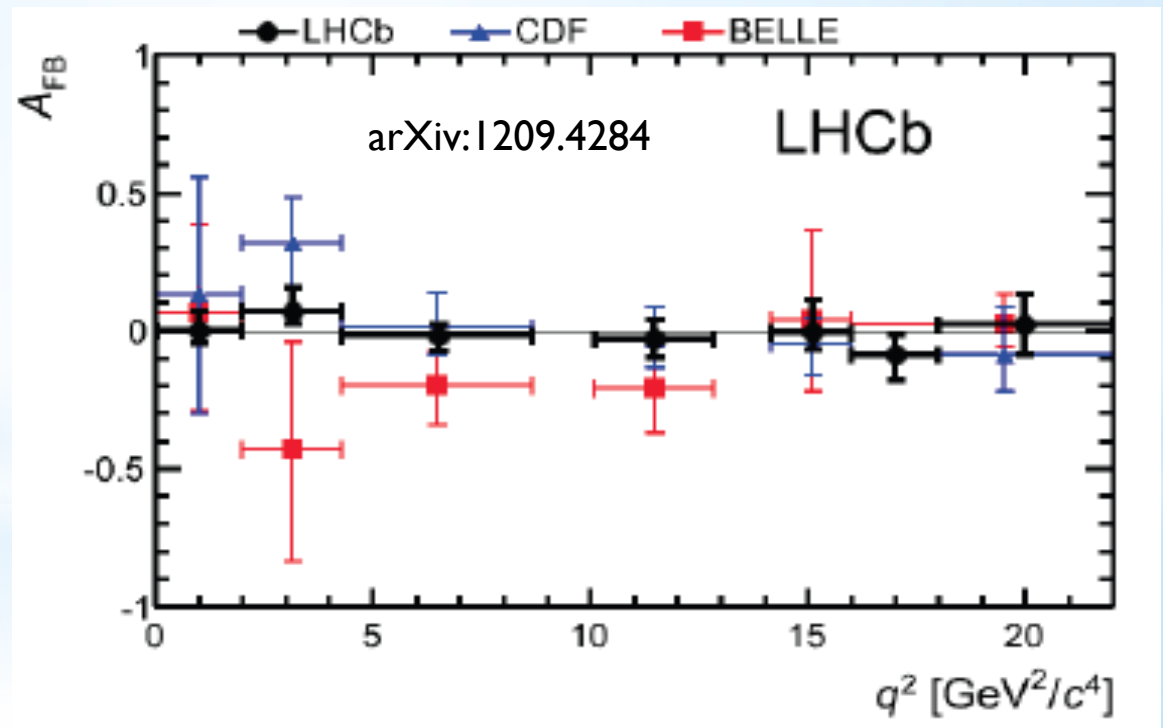
$$b \rightarrow s (|V_{tb} V_{ts}| \alpha \lambda^2)$$

Angular analysis only depends on one angle, and A_{FB} is **expected to be very close to zero** in the SM.

LHCb measurement:

$$BR(B^\pm \rightarrow K^\pm \mu \mu) = (4.36 \pm 0.15 \pm 0.18) \times 10^{-7}$$

compared with previous W.A. $(4.8 \pm 0.4) \times 10^{-7}$



$\Delta F=1$ EW penguins in $b \rightarrow d$ transitions: $B^\pm \rightarrow \pi^\pm \mu \mu$

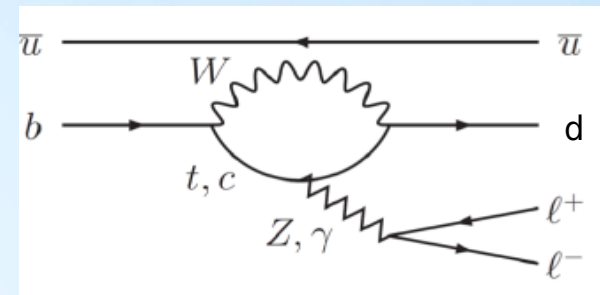
The decay $B^\pm \rightarrow \pi^\pm \mu \mu$ is suppressed by $|V_{td}|/|V_{ts}|$.

LHCb has a first observation (5.2σ) of this decay with 1/fb data.

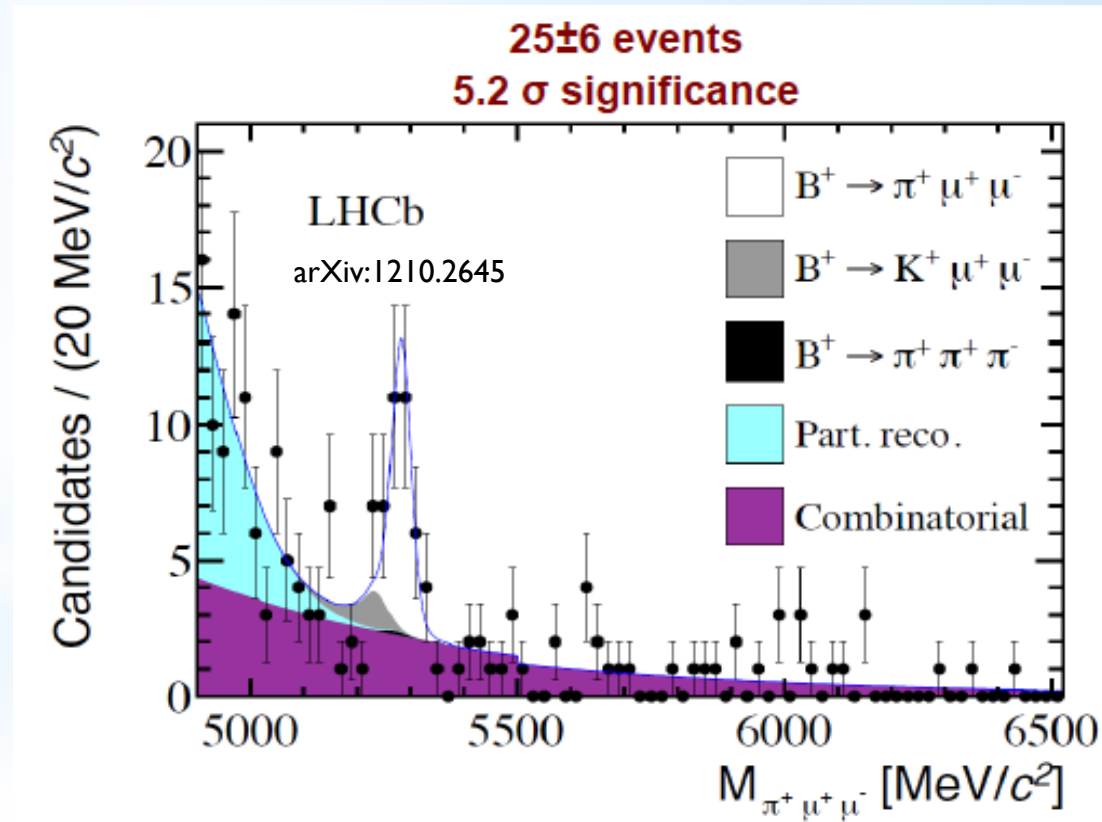
$$\text{BR}(B^\pm \rightarrow \pi^\pm \mu \mu) = (2.3 \pm 0.6 \pm 0.2) \times 10^{-8}$$

in agreement with SM expectations.

The rarest B decay ever observed, as we wait for $B_s \rightarrow \mu \mu$ to reach 5σ .

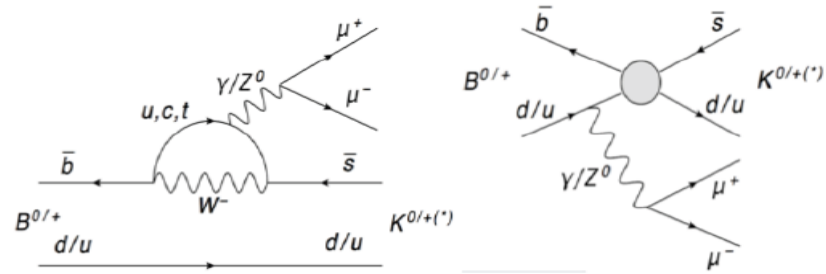


$$b \rightarrow d \quad (|V_{tb} V_{td}| \propto \lambda^3)$$



$\Delta F=1EW$ penguins in $b \rightarrow s$ transitions: $B \rightarrow K^{(*)} \mu \mu$ Isospin analysis

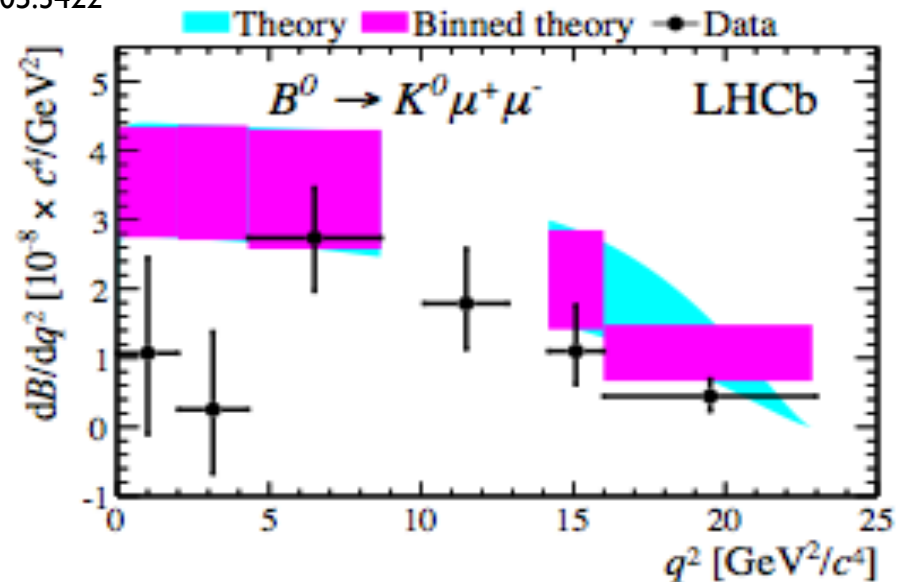
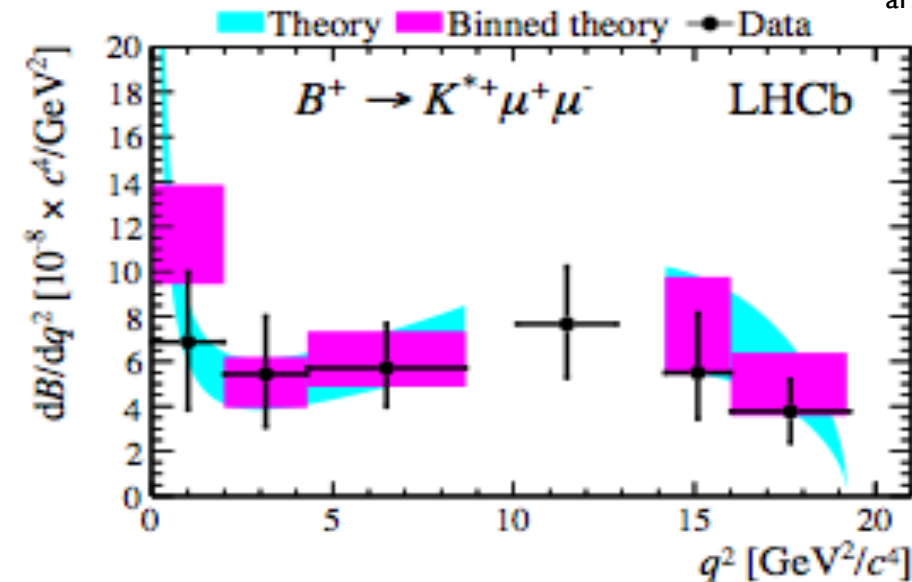
# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb $^{-1}$	CDF 2011 6.8 fb $^{-1}$	LHCb 2011 1 fb $^{-1}$
$B^0 \rightarrow K^{*0} \ell \bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	164 ± 15	900 ± 34
$B^+ \rightarrow K^{*+} \ell \bar{\ell}$			20 ± 6	76 ± 16
$B^+ \rightarrow K^+ \ell \bar{\ell}$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



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

Within the SM the decays $B \rightarrow K^{(*)} \mu \mu$ and $B^+ \rightarrow K^{(*)+} \mu \mu$ are expected to have very similar BR, (O(%) differences at low q^2) $\rightarrow A_I(B \rightarrow K^* \gamma) = 0.07 \pm 0.03$.

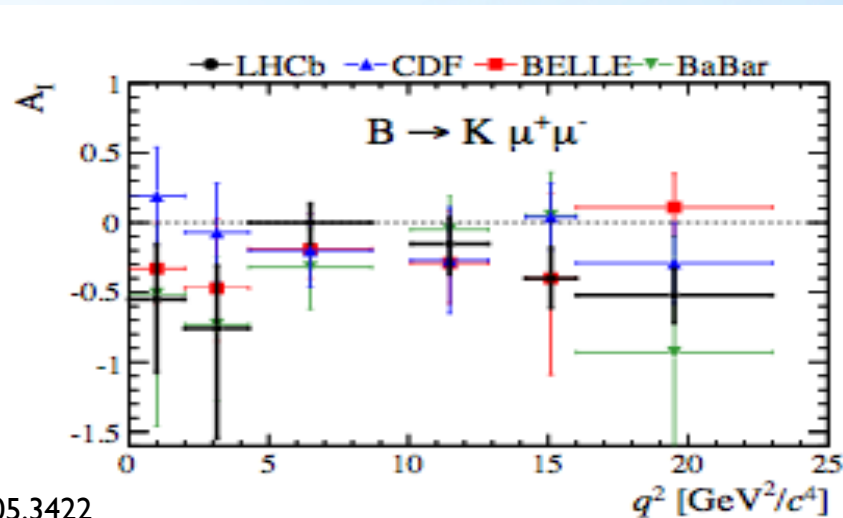
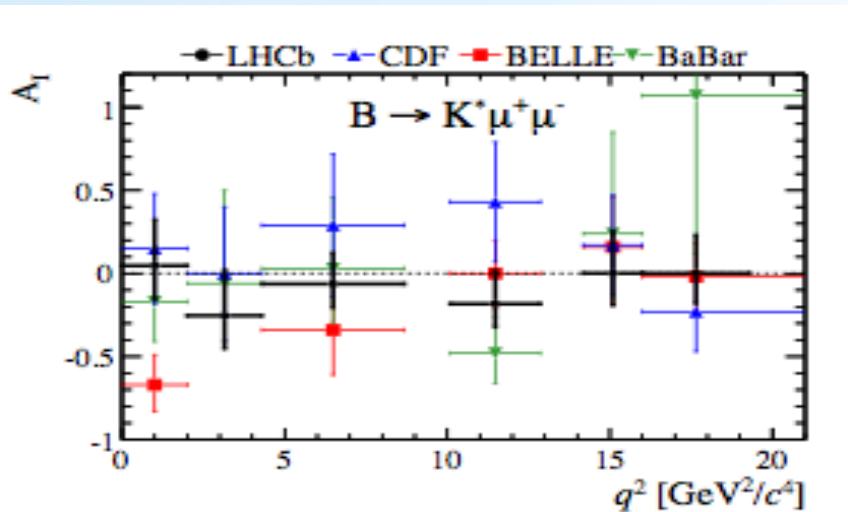
arXiv:1205.3422



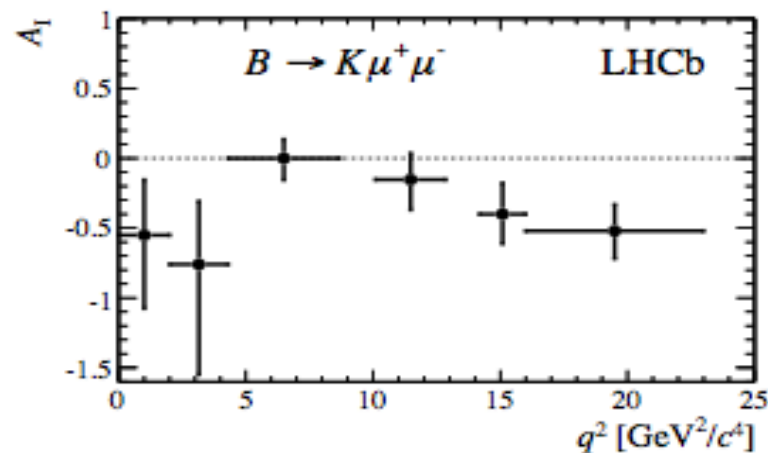
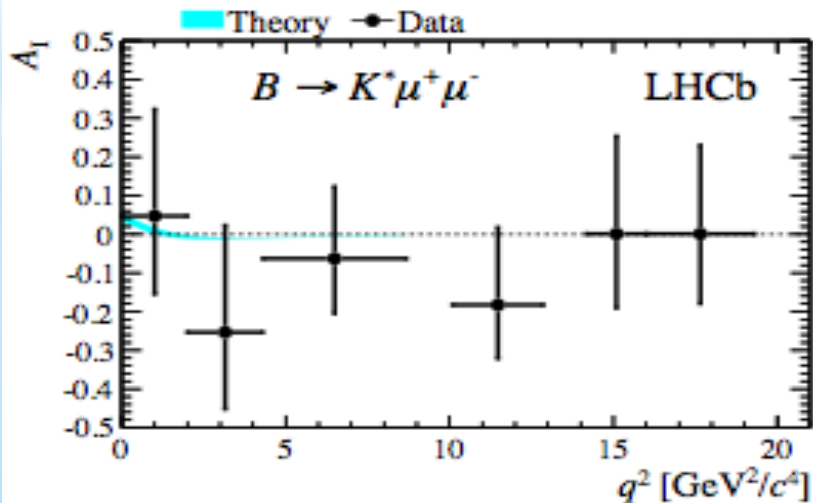
$\Delta F=1EW$ penguins in $b \rightarrow s$ transitions: $B \rightarrow K(*) \mu \mu$ Isospin analysis

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

No physics model can explain this results... **looking forward to the analysis of 3/fb at LHCb.**



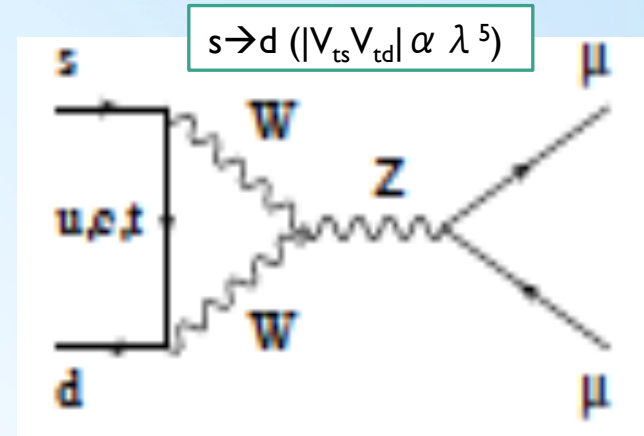
arXiv:1205.3422



$\Delta F=1$ Higgs penguins in $s \rightarrow d$ 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 \rightarrow **Higgs penguins!**



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

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

$$BR(K_s \rightarrow \mu \mu) < 3.2 \times 10^{-7} \text{ (PLB44 (1973))}$$

$$BR(K_s \rightarrow ee) < 9 \times 10^{-9} \text{ (KLOE, PLB672 (2009))}$$

In particular a measurement of $BR(K_s \rightarrow \mu \mu)$ 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 $K^+ \rightarrow \pi^+ \nu \nu$** .

$\Delta F=1$ Higgs penguins in $s \rightarrow d$ transitions: Kaon decays

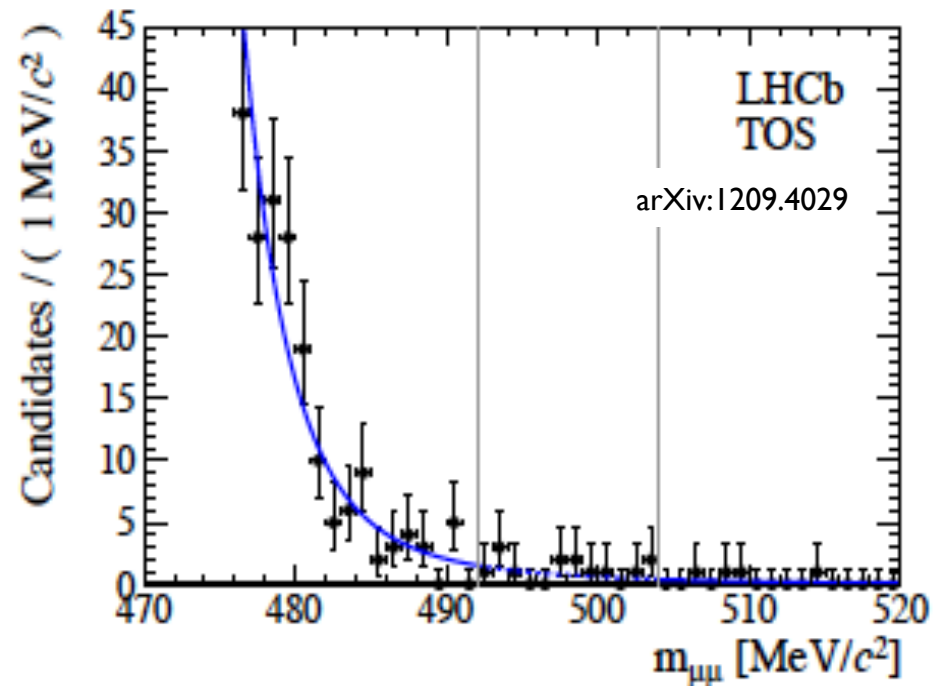
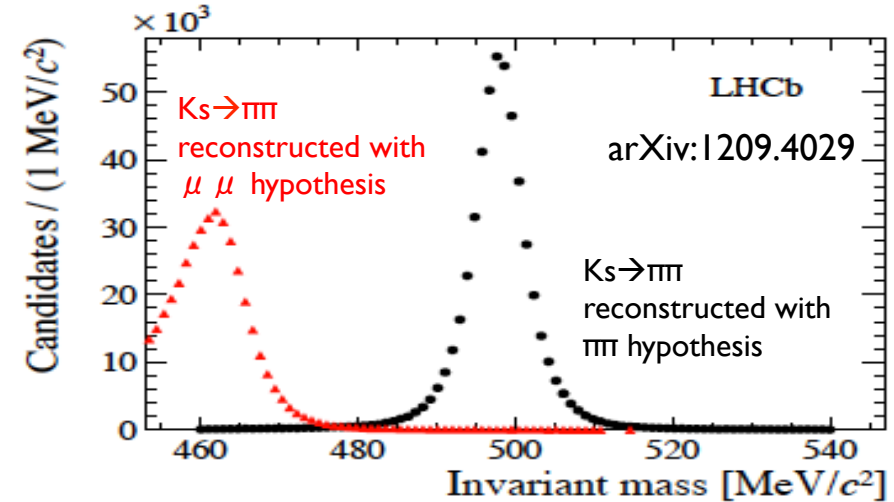
LHC produces 10^{13} K_s /fb in the LHCb acceptance. **Trigger was not optimized** for this search in 2011 (it is for the 2012 data taking period).

Excellent LHCb **invariant mass resolution** critical to reduce peaking bkg.

Mass distribution compatible with bkg hypothesis:

$BR(K_s \rightarrow \mu \mu) < 11(9) \times 10^{-9}$ at 95(90)% C.L.
x30 improvement!

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

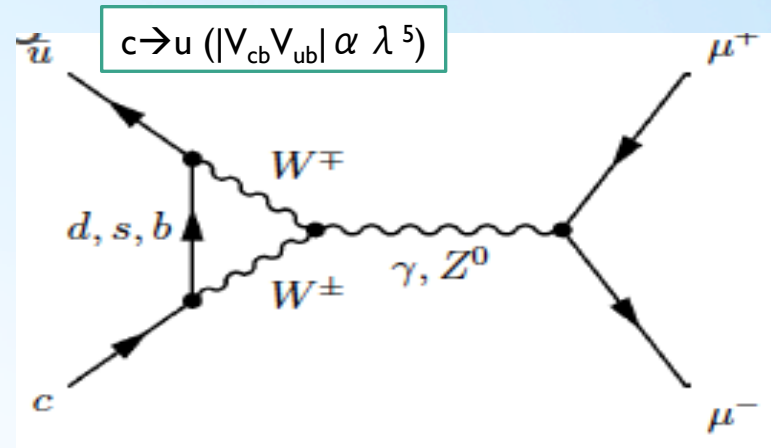


$\Delta F=1$ Higgs penguins in $c \rightarrow u$ transitions: Charm decays

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 $D \rightarrow \mu \mu$ 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 $D \rightarrow \gamma \gamma$** :



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

BABAR result $BR(D \rightarrow \gamma \gamma) < 2.2 \times 10^{-6}$ @90% C.L.)

Phys. Rev. D85 (2012) 091107

Charm decays complement K and B mesons decays.

$\Delta F=1$ Higgs penguins in $c \rightarrow u$ transitions: Charm decays

Experimental control of the **peaking background is crucial ($D \rightarrow \pi\pi$)**.

Best existing limit before spring 2012 was from **Belle**, $<1.4 \times 10^{-7}$ @90% C.L.

LHCb-PAPER-2013-013

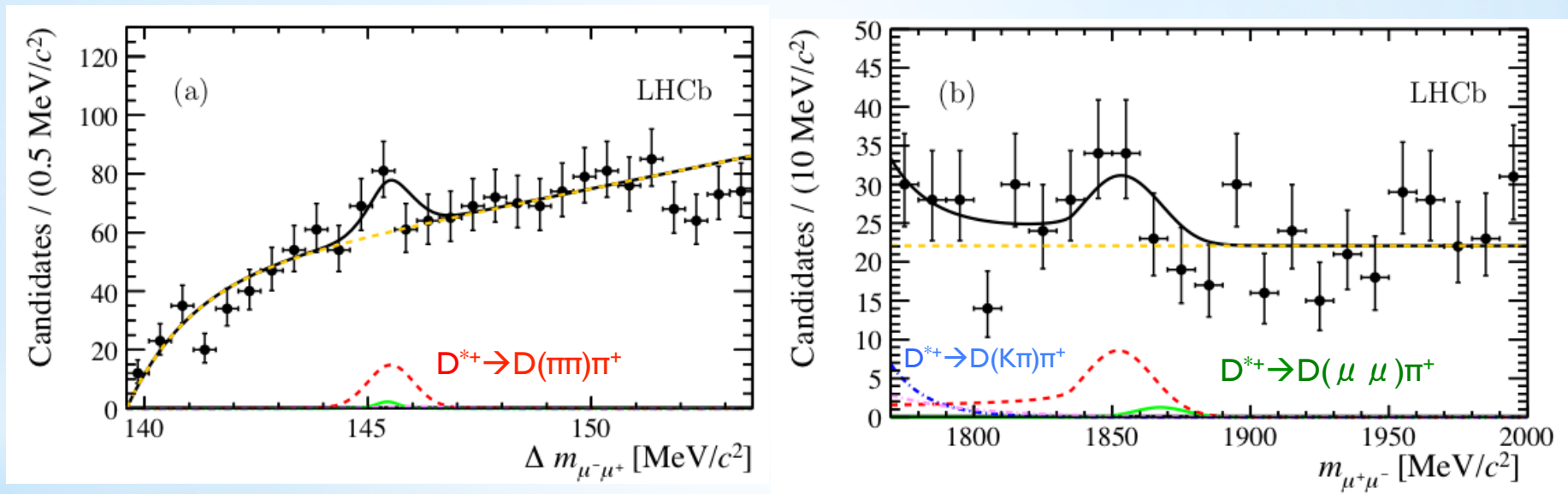
LHCb results using 0.9/fb of $D^* \rightarrow D\pi$:

$<7.6 \times 10^{-9}$ @95% C.L. (factor ~ 20 improvement)

CMS results with 0.09/fb:

CMS-PAS-BPH-11-017

$<5.4 \times 10^{-7}$ @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**, $[6,8] \times 10^{-8}$, in tension with **LHCb results**.



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

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

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 50ab^{-1} at the $\Upsilon(4S)$.

Yields at LHCb and B-factories

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