Ferrara International School Niccolò Cabeo 2013

Physics beyond the standard model:
the precision frontier

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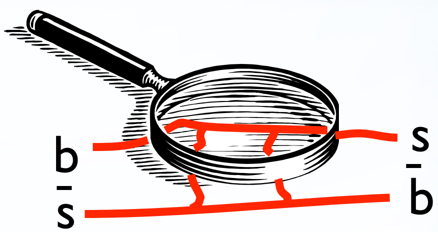
IUSS, Via Scienze 41b, 44100 Ferrara (Italy)

* Indirect Searches for NP in Flavour Physics.

Frederic Teubert

CERN, PH Department



Indirect Searches for NP

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

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

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

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

Indirect Searches for NP

Therefore, **NP** contributions are **suppressed by** the size of the **isospin breaking** value Δm^2. Best chances to find NP in (t,b)/ τ -physics, or with higher experimental precision in (c,s)/ μ -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).

When does one have CP violation? $\Gamma(a \to b + c) \neq \Gamma(\overline{a} \to \overline{b + c})$

The CP asymmetry will be non-zero when $\Gamma(a \to b + c) = |A_1|^2 + |A_2|^2 + 2\Re(A_1 A_2^*)$

$$\Re(A_1 A_2^*) \neq \Re(\overline{A_1}\,\overline{A_2^*}) \qquad \Gamma(\overline{a} \to \overline{b + c}) = |\overline{A_1}|^2 + |\overline{A_2}|^2 + 2\Re(\overline{A_1}\,\overline{A_2^*})$$

if the module of $A_{1,2}$ is invariant (as in the case of the SM). Therefore**, 2 phases are needed** one that changes with CP (weak phase) and another that is invariant (strong phase).

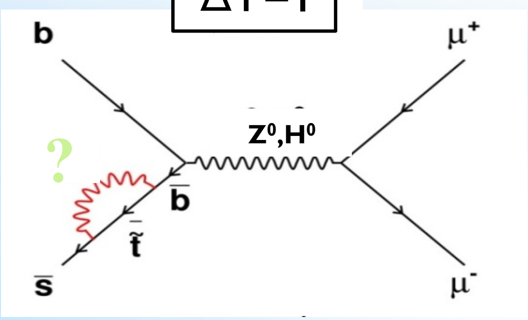
Indirect Searches for NP

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.*

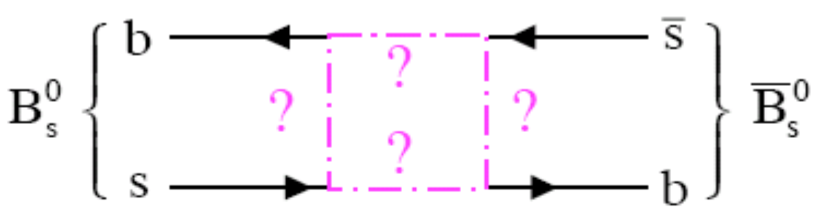
Δ F=1



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

Δ F=2

$\phi_s \neq \phi_s^{SM} = -\arg(V_{ts}^2)$



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

Status of Searches for NP

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

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

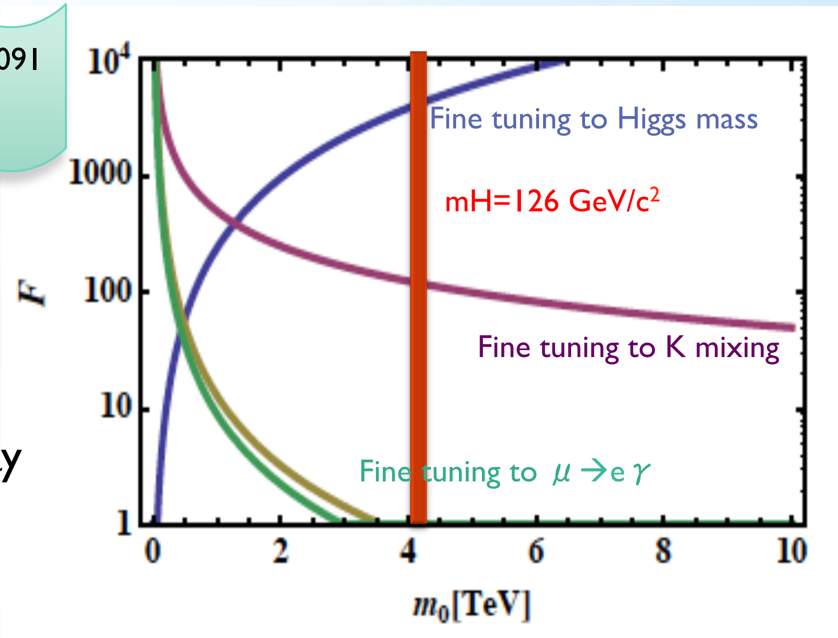
However, the absence of NP effects observed in flavour physics implies some level of *"fine tuning"* in the flavour sector. Why, if there is NP at the TeV energy scale, it does not show up in precision flavour measurements?

→ **NP FLAVOUR PROBLEM**

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

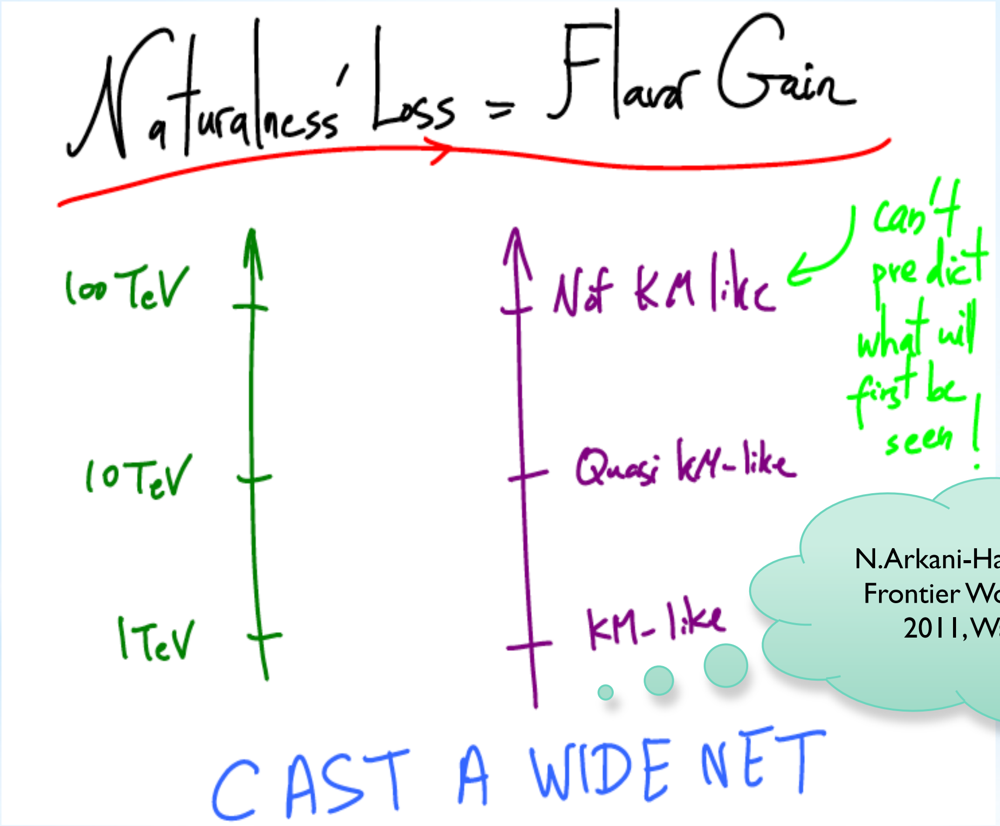
In models like CMSSM the situation now requires some level of fine-tuning in the Higgs sector, but may relax the requirements on the flavour sector!

arXiv:1205.7091
CMSSM



Status of Searches for NP

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

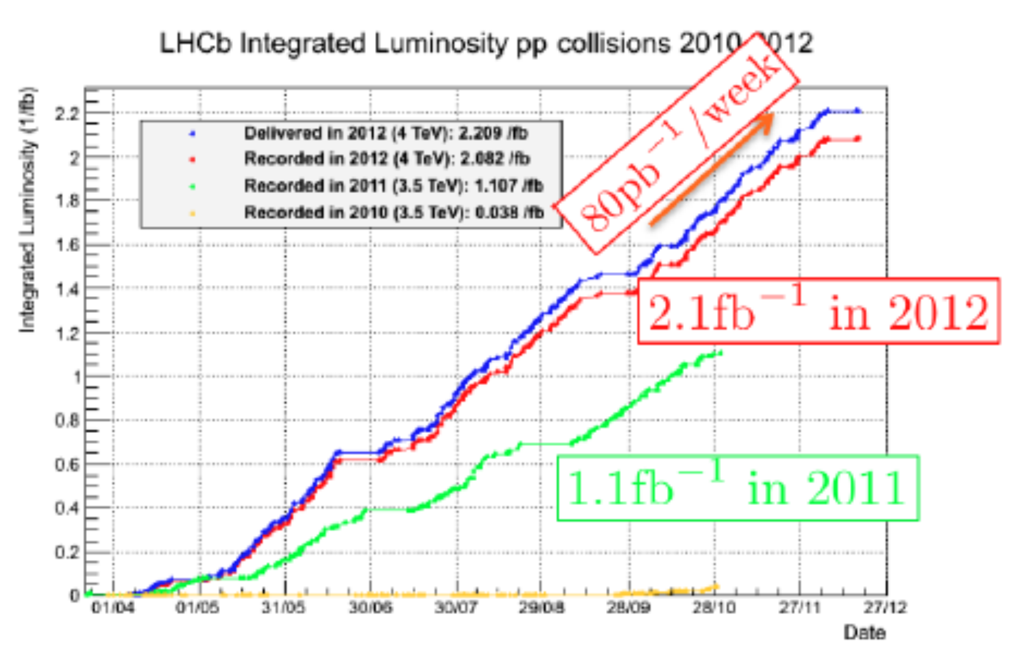


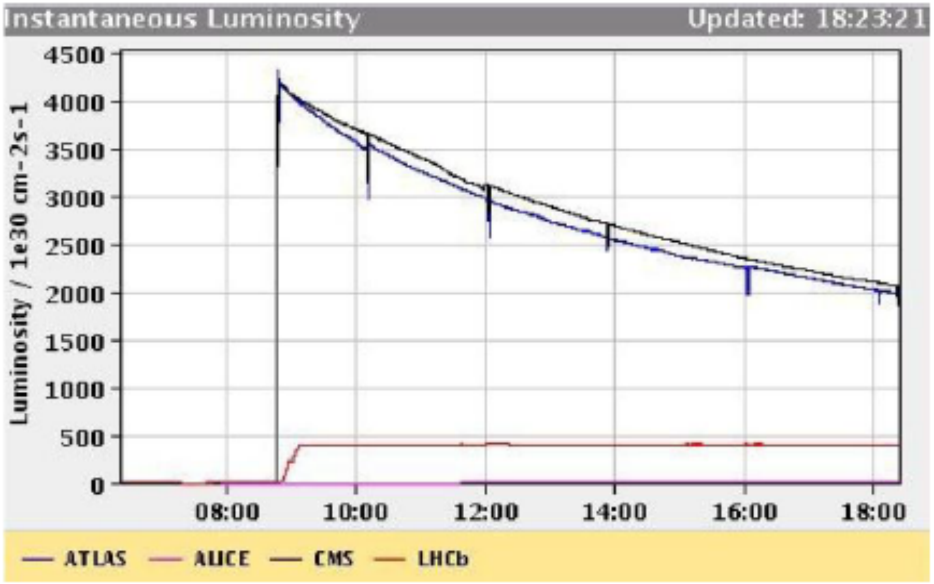
N.Arkani-Hamed, Intensity Frontier Workshop (Nov 2011, Washington)

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 $4\times10^{33}/cm^2/sec$ at 8 TeV, for a total of 23/fb to **ATLAS&CMS** (6/fb in 2011 at 7 TeV).





LHCb took data at a constant luminosity $0.4\times10^{33}/cm^2/sec$ thanks to luminosity leveling, for a total of 2.2/fb at 8 TeV delivered (1.2/fb in 2011 at 7 TeV).

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

LHC is working like a dream!

The bb x-section was measured by LHCb at 7 and 8 TeV to be: $(284\pm53)\times10^9$ fb (PLB 694, 209) and $(298\pm36)\times10^9$ fb (arXiv:1304.6977). The cc x-section ~20 times higher! (arXiv:1302.2864)

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

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

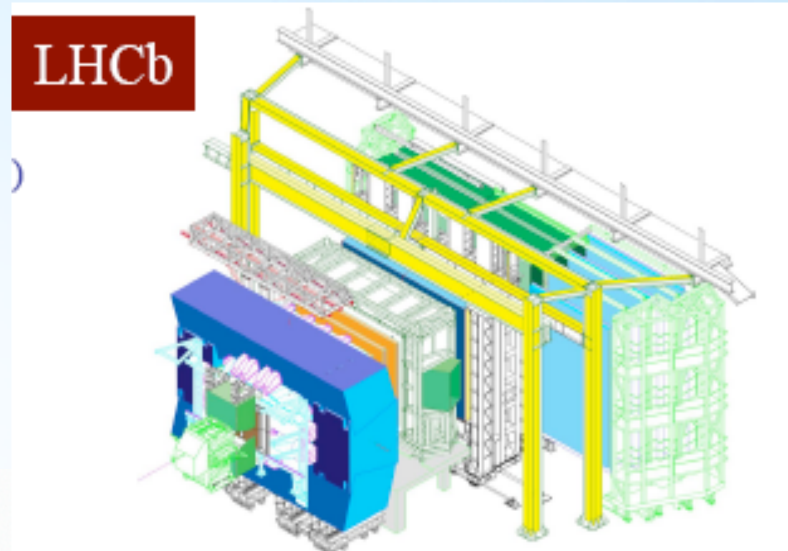
The LHCb detector acceptance ranges between ~10% for $B_s \to \mu^+\mu^-$ decays to, for instance, ~5% for $B_s \to J/\Psi[\mu^+\mu^-]\Phi[K^+K^-]$.

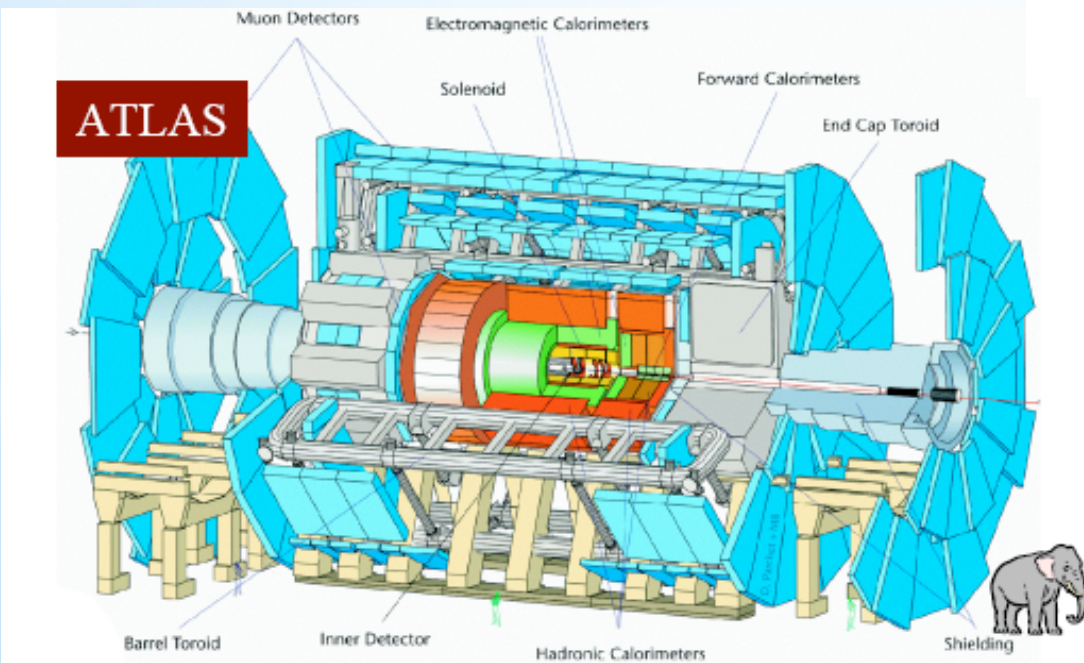
Rule of thumb:

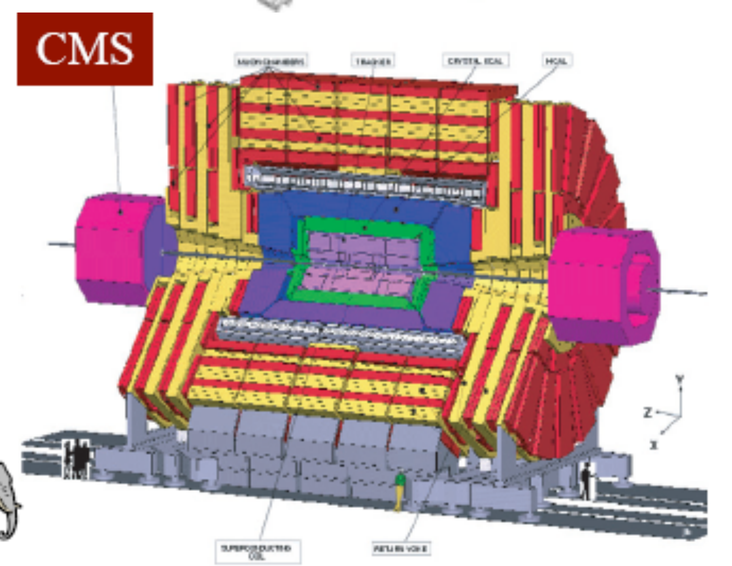
1/fb at 7TeV at LHCb is equivalent to (1k-5k)/fb at the e^+e^- B-factories before tagging for $B^0/B^{\pm}$ decays into charged particles.

LHC detectors with flavour physics capabilities

- **ATLAS/CMS**
  - General purpose experiments optimized for high Pt Physics at 10^{34} cm^{-2} s^{-1}
- **LHCb**
  - Dedicated (b,c)-Physics experiment



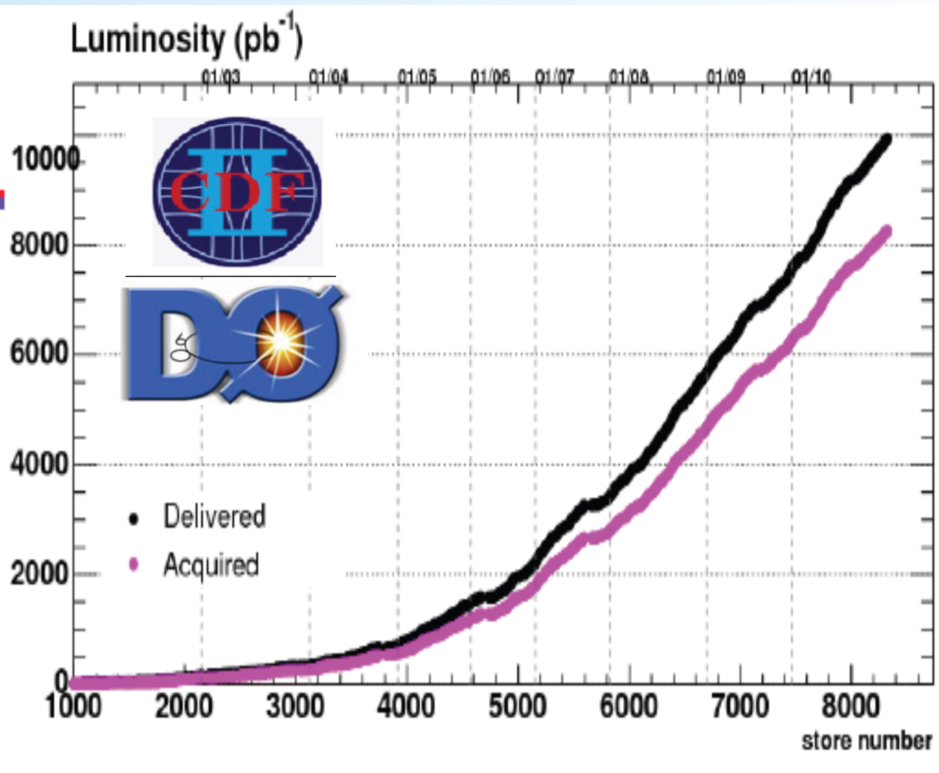


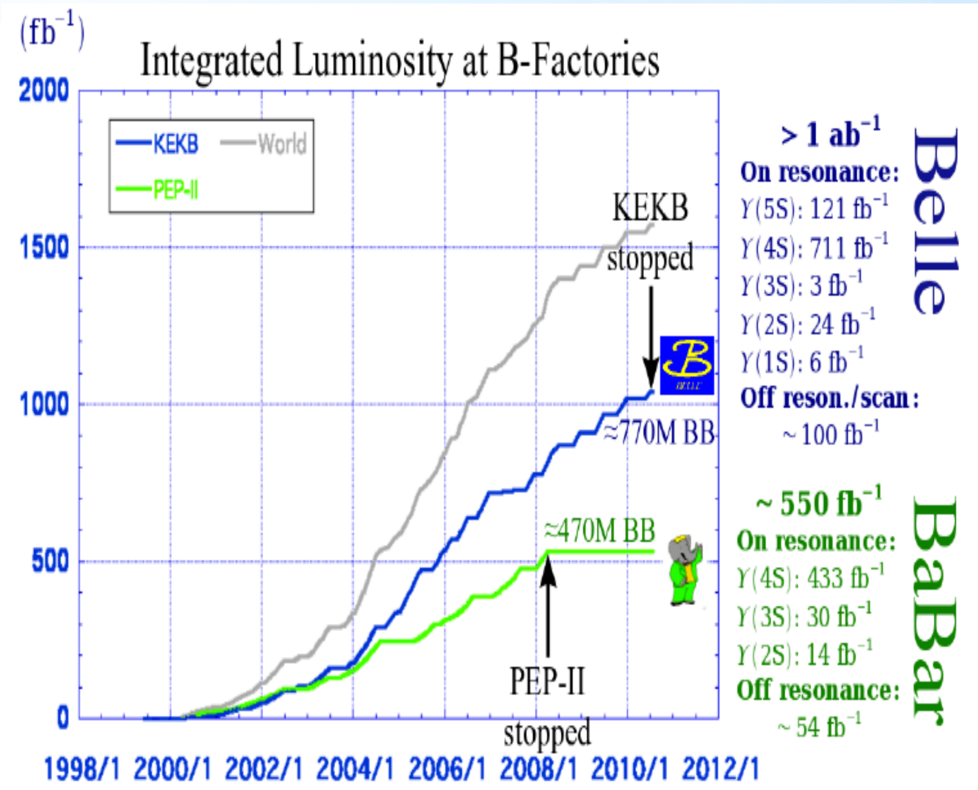


Standing on the shoulders of giants

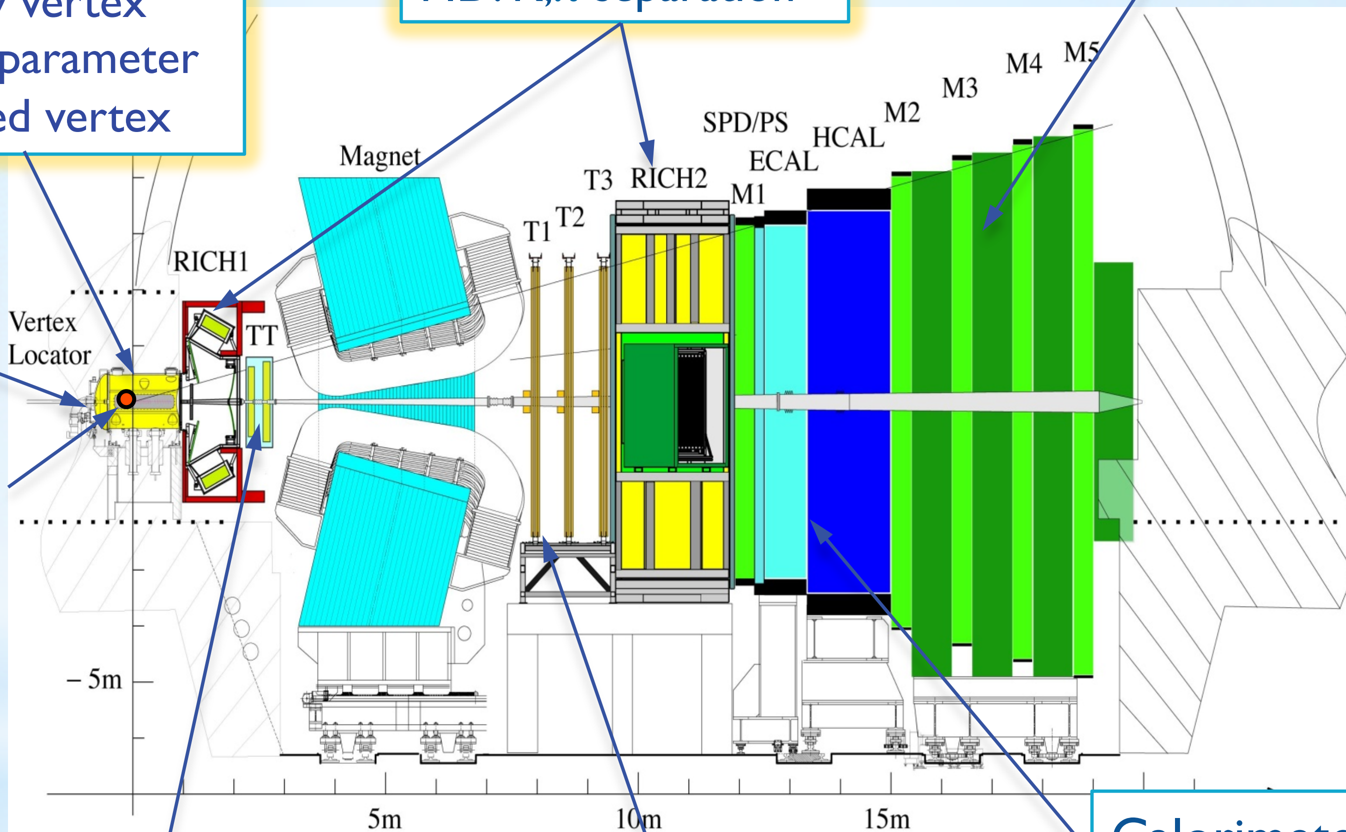
But the path the LHC experiments have just started to walk, has been paved by the amazing performance and results from the predecessors.

CDF pioneering work with the vertex trigger in a hadron collider deserves special mention (my personal bias).





LHCb detector



VELO:
primary vertex
impact parameter
displaced vertex

RICHES:
PID: K,π separation

Muon System

PileUp
System

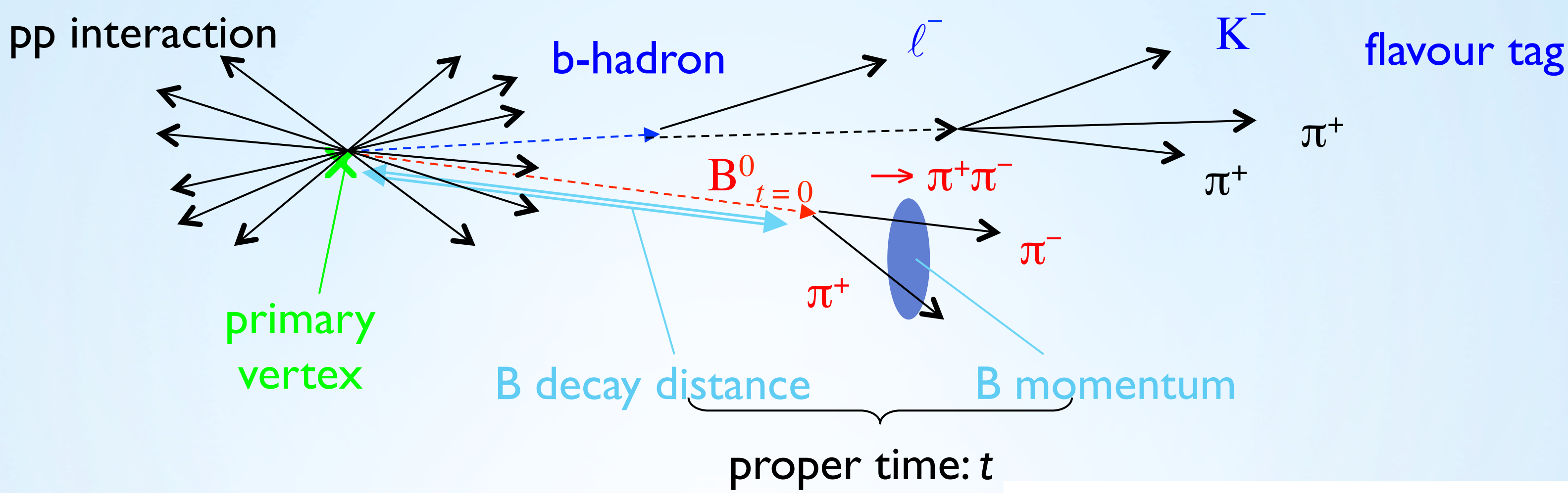
Interaction region

Trigger Tracker: p for trigger and K_s reco

Tracking Stations:
p of charged particles

Calorimeters:
PID: e,γ, π^0

Detector requirements

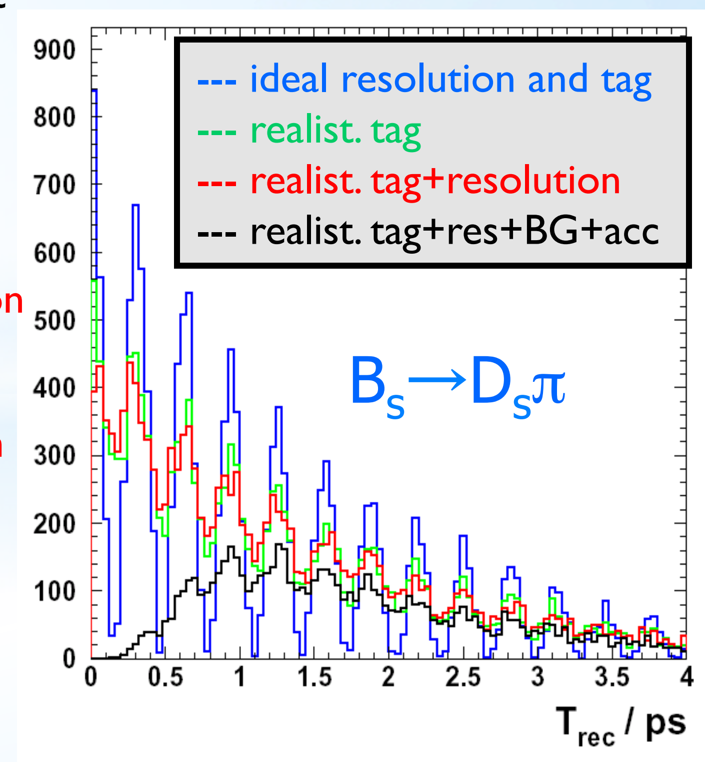


CP violating oscillation amplitudes are damped by

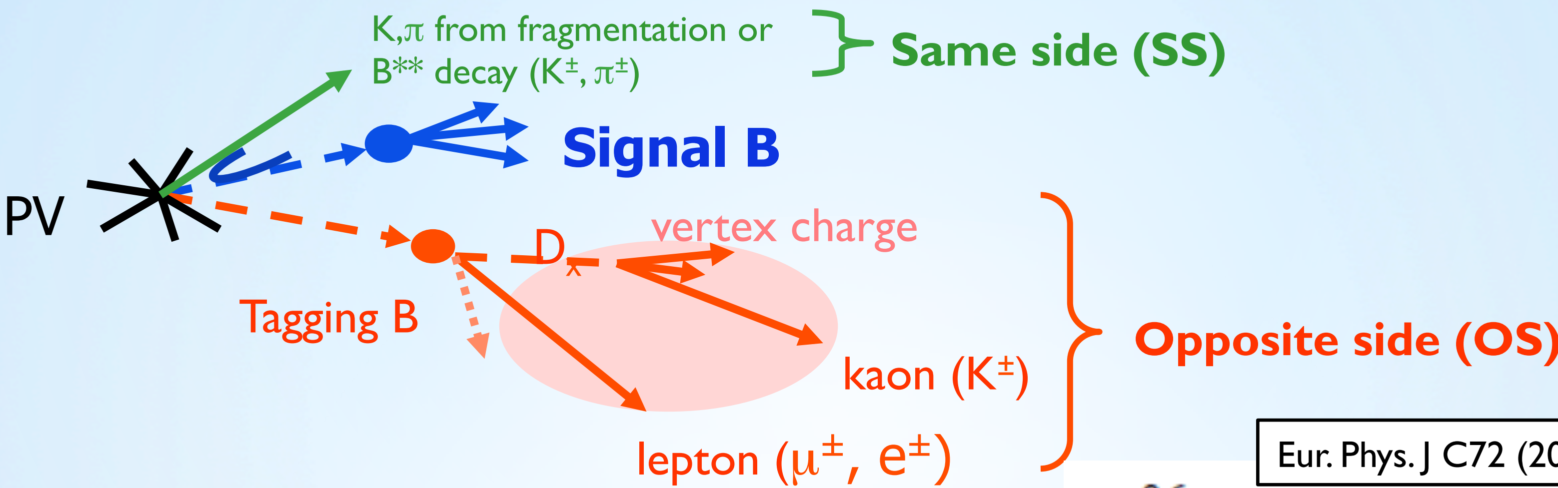
proper time resolution → good decay vertex resolution

wrong flavour tag → good momentum resolution

background → good particle identification



Flavour Tagging



Flavour tagging algorithms are not perfect!

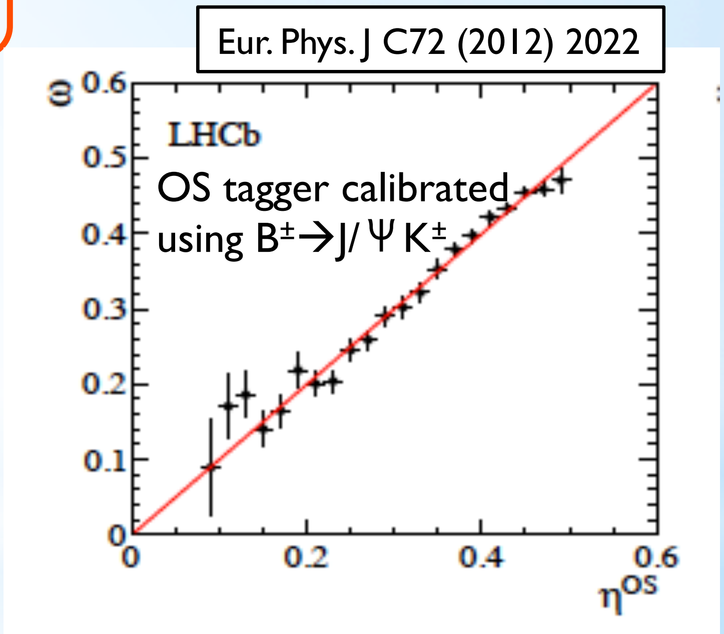
Backgrounds in tagger selections

The *tagging B* can oscillate incoherently (unlike in B-factories):

40% $B^{\pm}$, 10% baryons : no oscillation ☺

40% B_d: $\Delta m_d \sim \Gamma_d \Rightarrow$ oscillated 17.5% ☺

10% B_s: $\Delta m_s >> \Gamma_s \Rightarrow$ oscillated 50% ☹



Characterization of tagging algorithms:

ε^{tag}: fraction of events with a tag

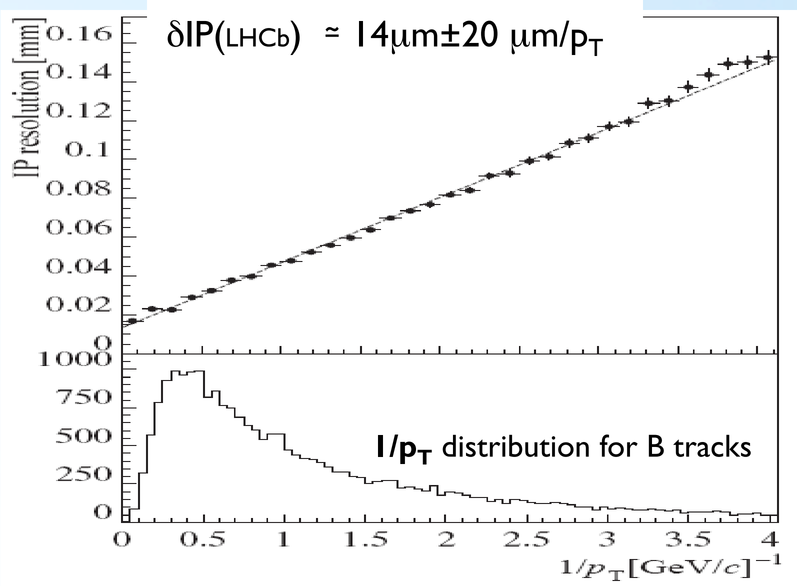
$\omega \equiv N^W/(N^W+N^R)$: wrong tag fraction

$\varepsilon^{eff} \equiv \varepsilon^{tag}(1-2\omega)^2$: effective tagging efficiency

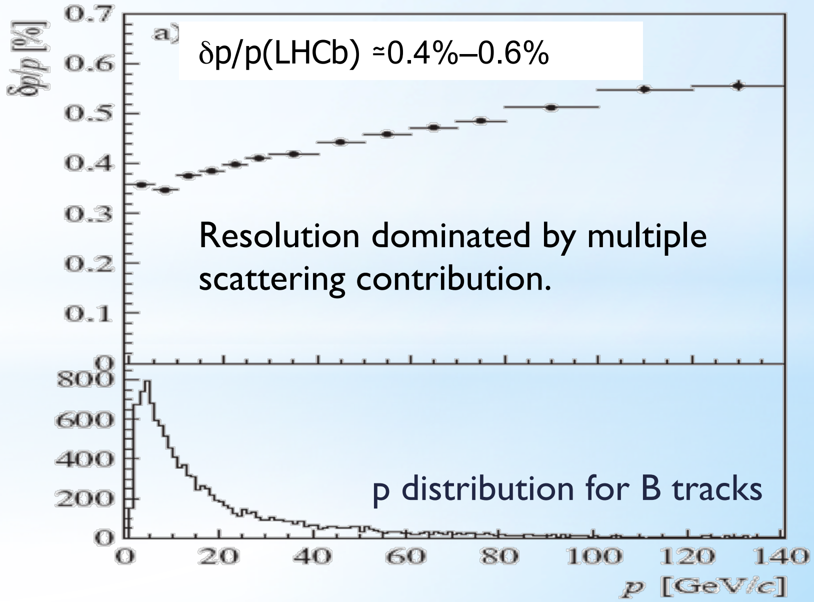
CDF/LHCb ε_{eff} ~4% for B_s
BABAR/BELLE ε_{eff} ~30% for B_d

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

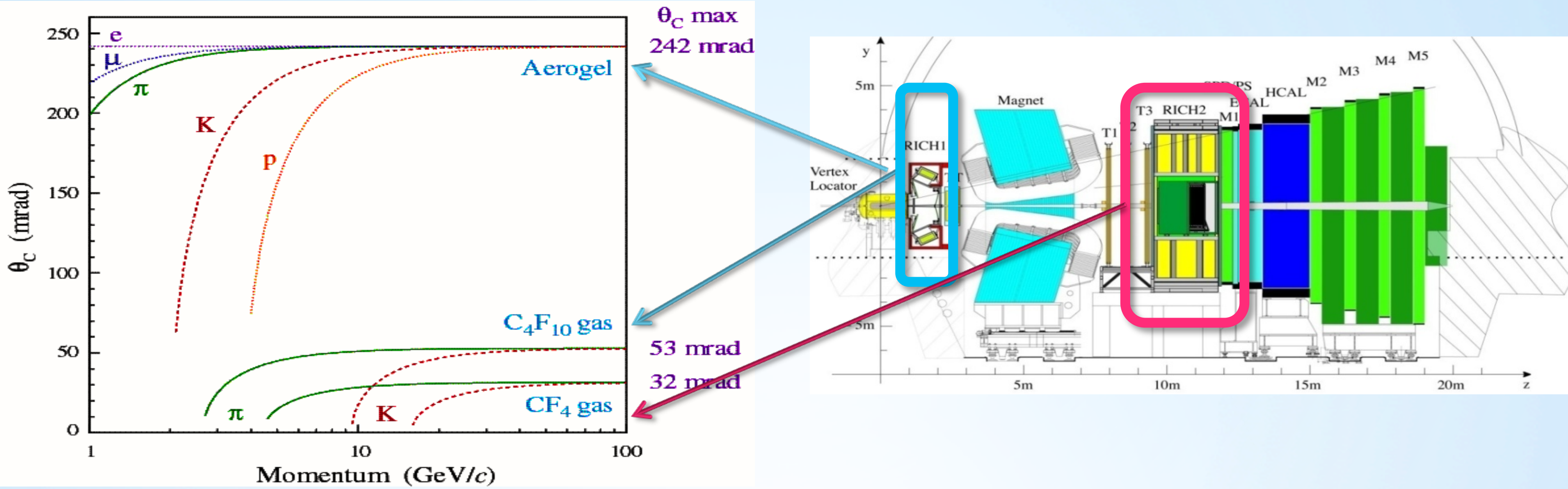


Integral Bdl: CMS/LHCb ~ 4 Tm, ATLAS ~2.5 Tm

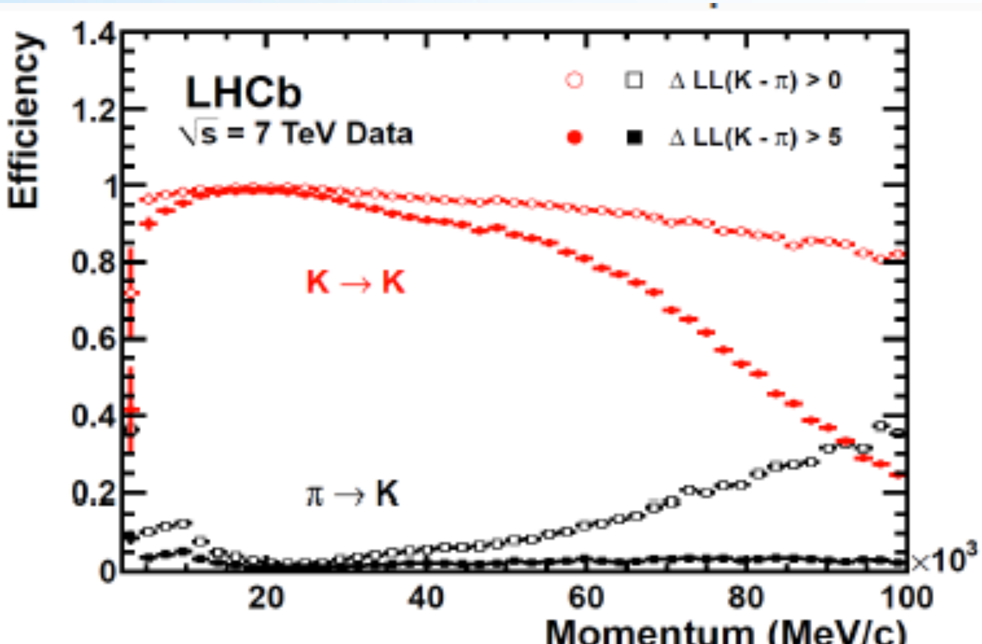


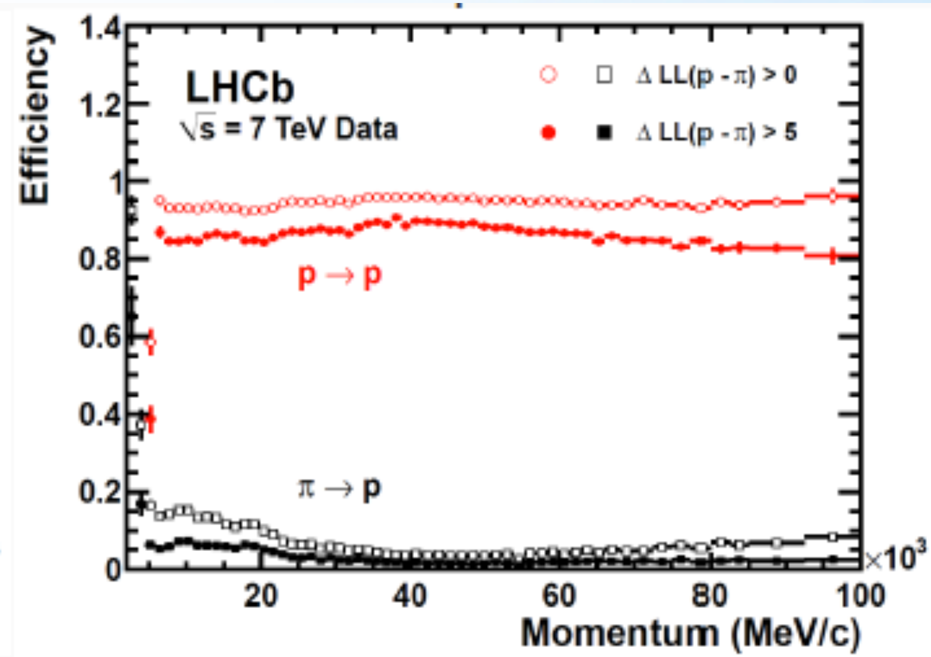
	ATLAS	CMS	CDF	LHCb
Decay time resolution (B_s)	~100 fs	~70 fs	87 fs	**45 fs**
Invariant Mass resolution (2-body)	80 MeV/c^2	45 MeV/c^2	25 MeV/c^2	**22 MeV/c^2**

LHCb Particle Identification

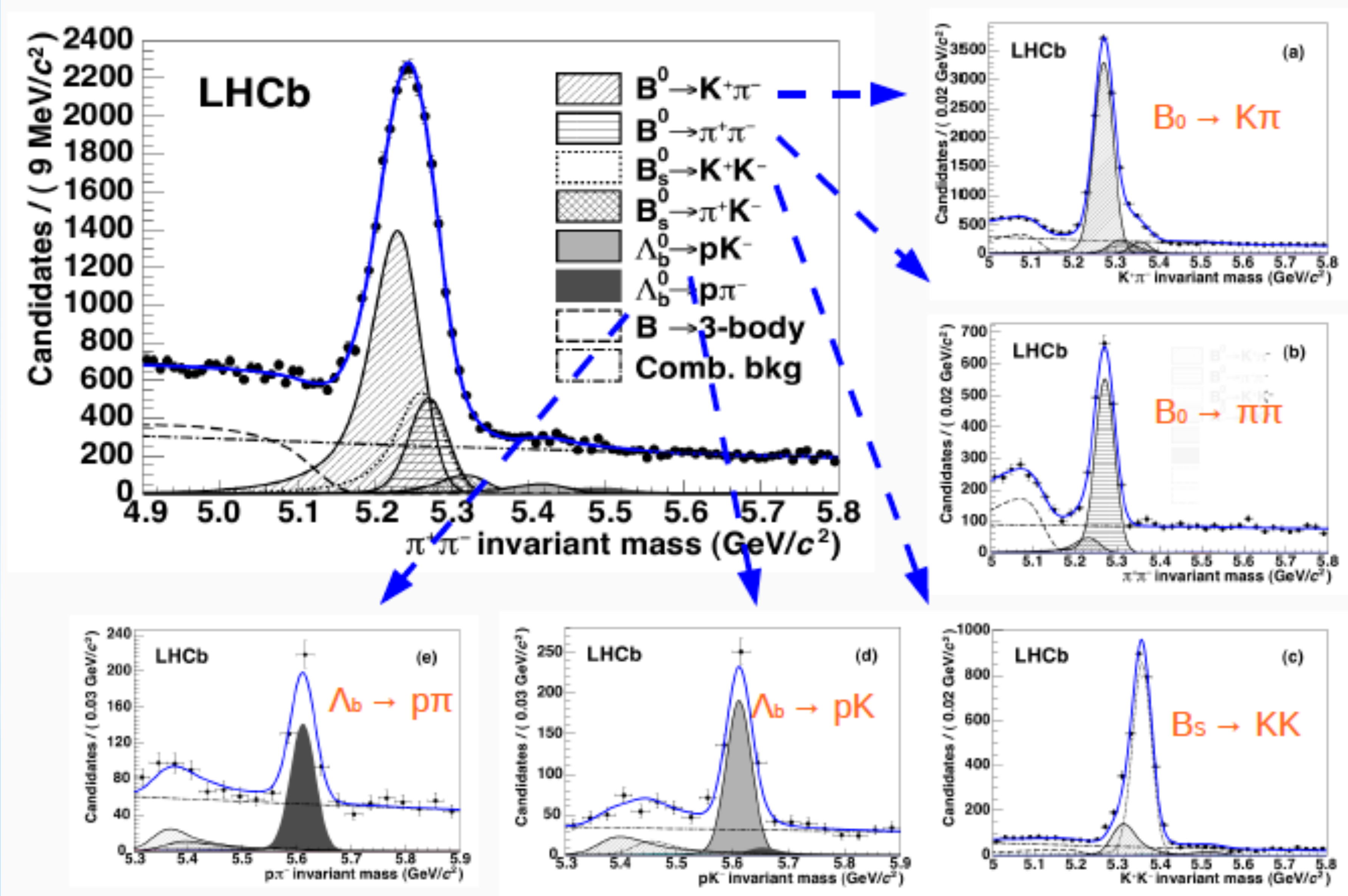


Efficiencies computed from data: pure samples of kinematically selected $K_s \rightarrow \pi^+\pi^-$, $\Lambda^0 \rightarrow p\pi^-$, $D^0 \rightarrow K^+\pi^-$



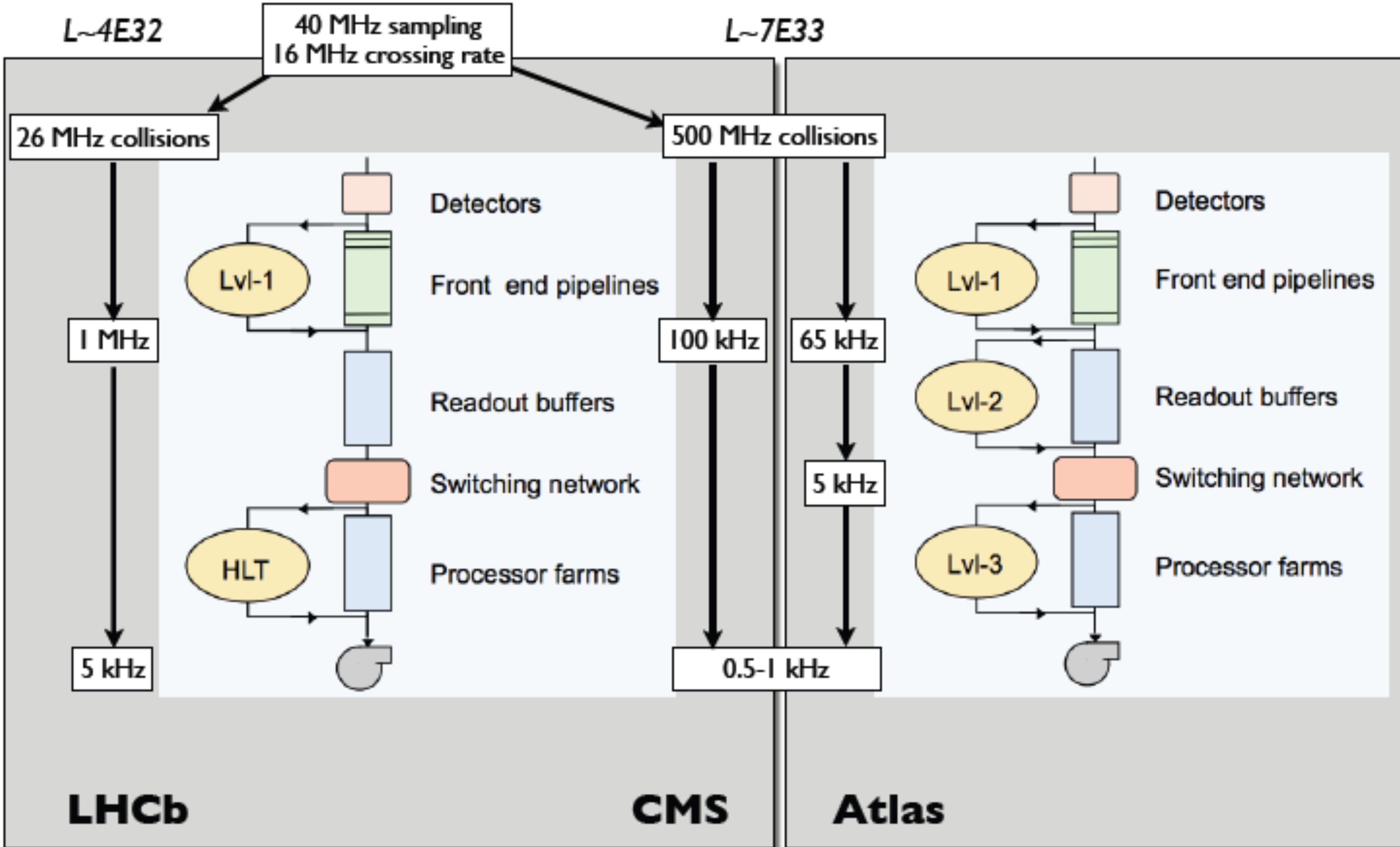


LHCb Particle Identification



JHEP10 (2012) 037

Trigger systems at LHC



LHCb Trigger System

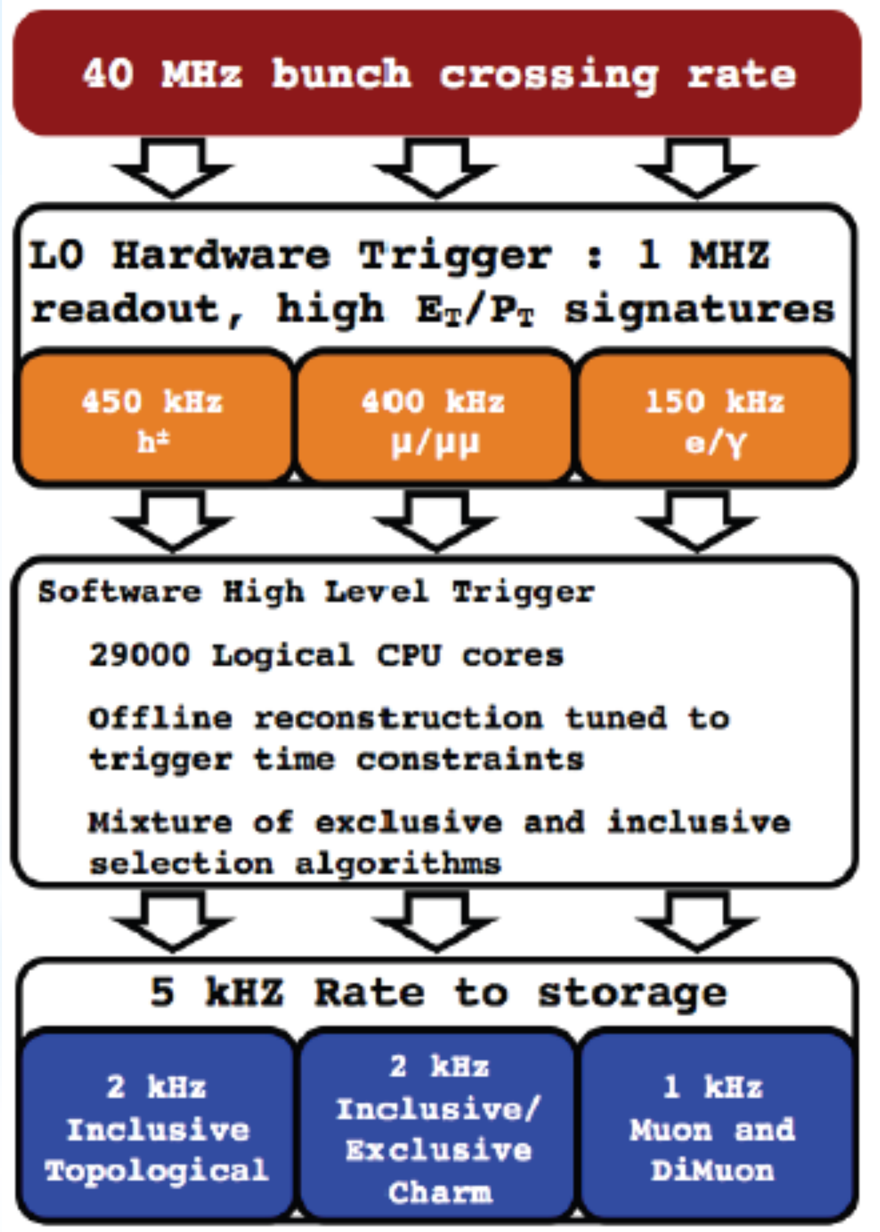
LHCb trigger output rate completely saturated by bb/cc events. However, only interested in relatively rare events (BR<10^{-3}) → the **LHCb trigger is what is called b-tagging** at ATLAS/CMS!

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

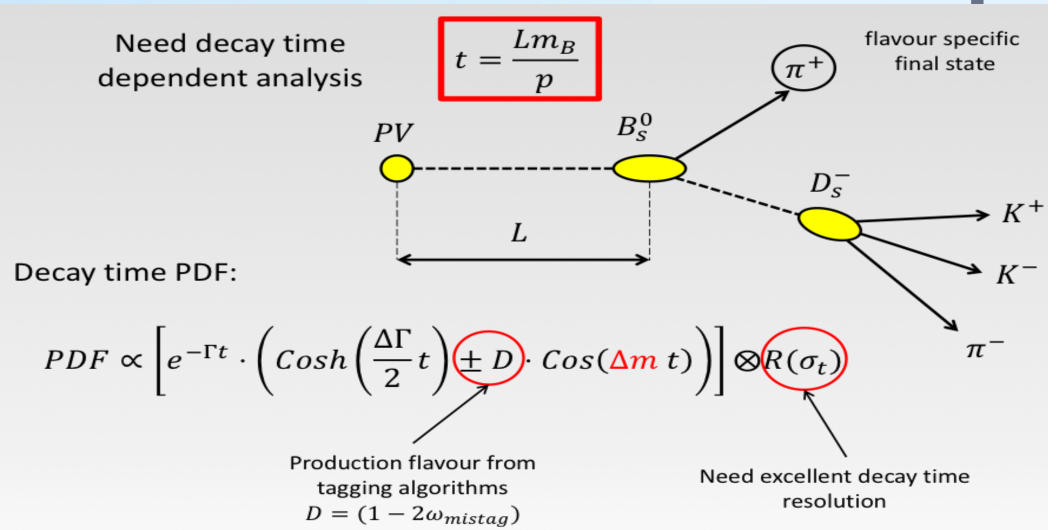
One synchronous **hardware** level, DAQ rate limited to **1 MHz.**

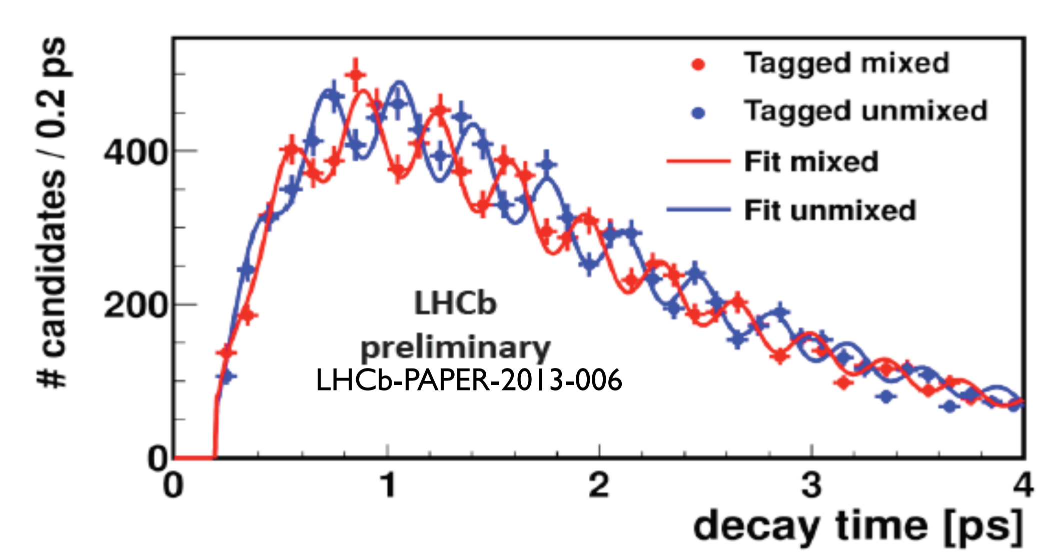
Computing farm with **software HLT.**

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



…and the LHCb performance is up to it!





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

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

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

Effective tagging **~3.5%**

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

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

<u>Precision measurements at hadron colliders are not any more a dream!</u>

LHCb popularity increasing: 893 members from 63 institutes in 17 countries!

(Parenthesis)Advantages/Disadvantages of Existing Facilities

Common "past" knowledge:

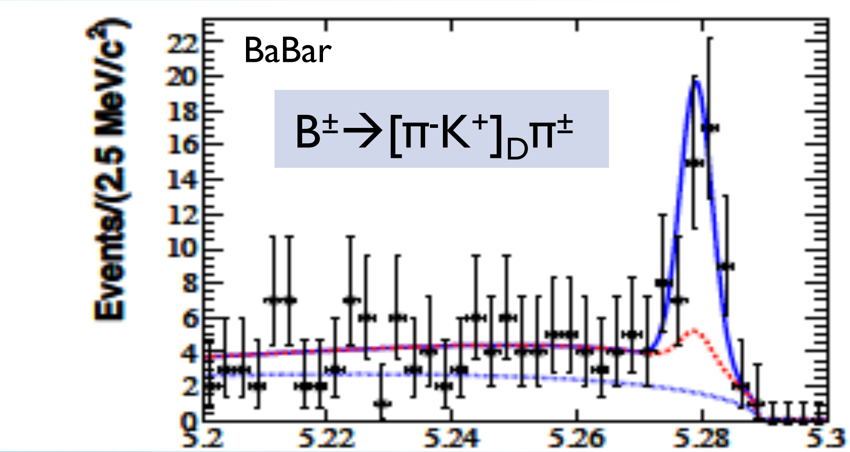
lepton colliders → precision measurements vs **hadron colliders** → discovery machines

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 LHCb, 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 luminosities (10^{34}-10^{36}) $cm^{-2}s$. However, at the Υ(4S) only $_{B(d,u)}$ mesons are produced.

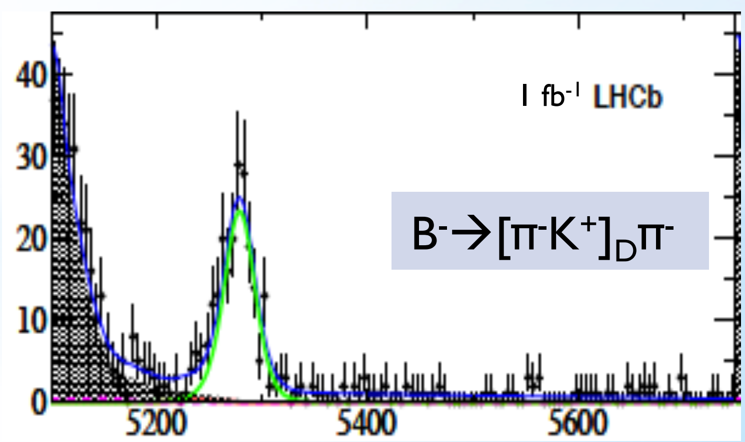
Hadron colliders have a very large cross-section (σ_{bb}(LHC7)~$3 \times 10^5 \sigma_{bb}(\Upsilon(4S))$), very performing detectors and trigger system. Effective tagging efficiency is typically x10 better at lepton colliders.

arXiv:1006.4241



Energy-substituted mass (GeV/c²)

arXiv:1203.3662



Invariant mass (MeV/c²)

FCNC in the SM

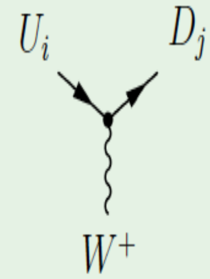
$U_i = \{u, c, t\}$:

$Q_U = +2/3$

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

$Q_D = -1/3$

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



$\sim$ 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:

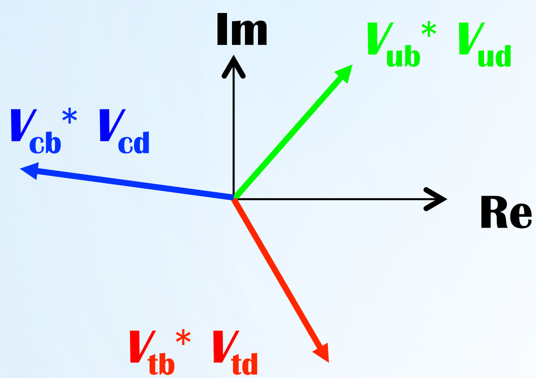
A=0.80±0.02
λ = 0.225±0.001

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

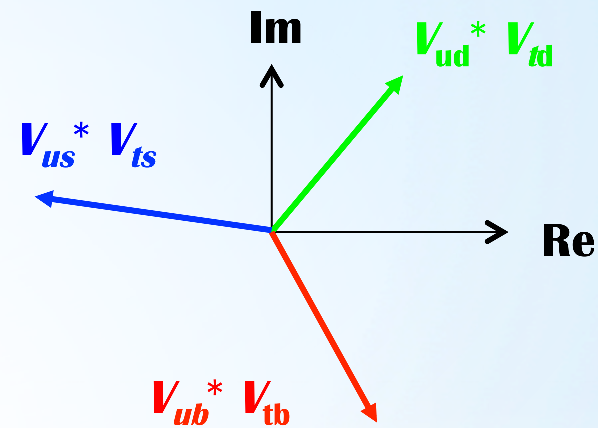
FCNC in the SM

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 complex plane. Two of these triangles are relevant for the study of CP-violation in B-physics and define the angles:

1) $V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0$



2) $V_{ud}^{*}V_{td} + V_{us}^{*}V_{ts} + V_{ub}^{*}V_{tb} = 0$



$$\alpha = \arg\left(\frac{-V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right),\quad \beta = \arg\left(\frac{-V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right)\quad \text{and}\quad \gamma = \arg\left(\frac{-V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)\quad \Phi_s/2 = \arg\left(\frac{-V_{cb}V_{cs}^{*}}{V_{tb}V_{ts}^{*}}\right)$$

$\arg V_{td} \approx -\beta$

$\arg V_{ub} \approx -\gamma$

$\arg V_{ts} \approx -\varphi_s/2$

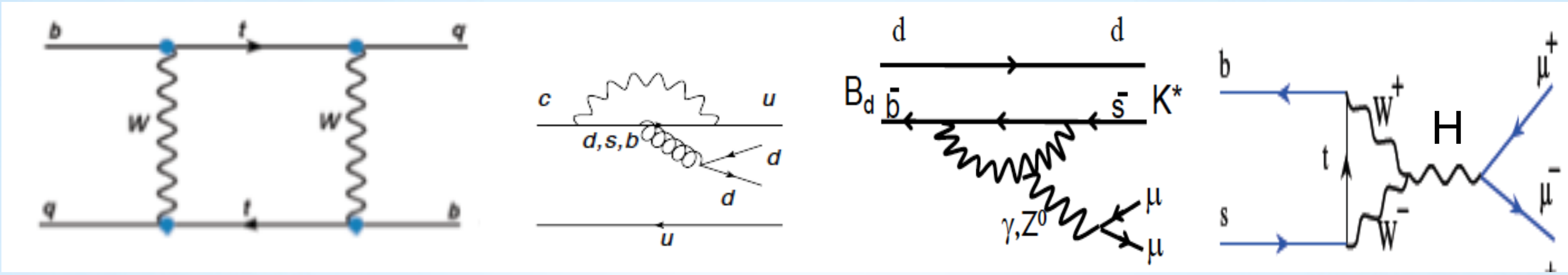
$\eta = 0.34 \pm 0.02$
$\rho = 0.14 \pm 0.03$

$$\tan\beta \approx \frac{\eta}{1-\rho}\left(1-\frac{\lambda^2}{2}\right) \approx \tan(23.6°)$$

$$\tan\gamma \approx \frac{\eta}{\rho} \approx \tan(66°)$$

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

FCNC in the SM



Δ F=2 box | QCD Penguin | EW Penguin | Higgs Penguin

*Map of Flavour transitions and type of loop processes: → **Map of these lectures!***

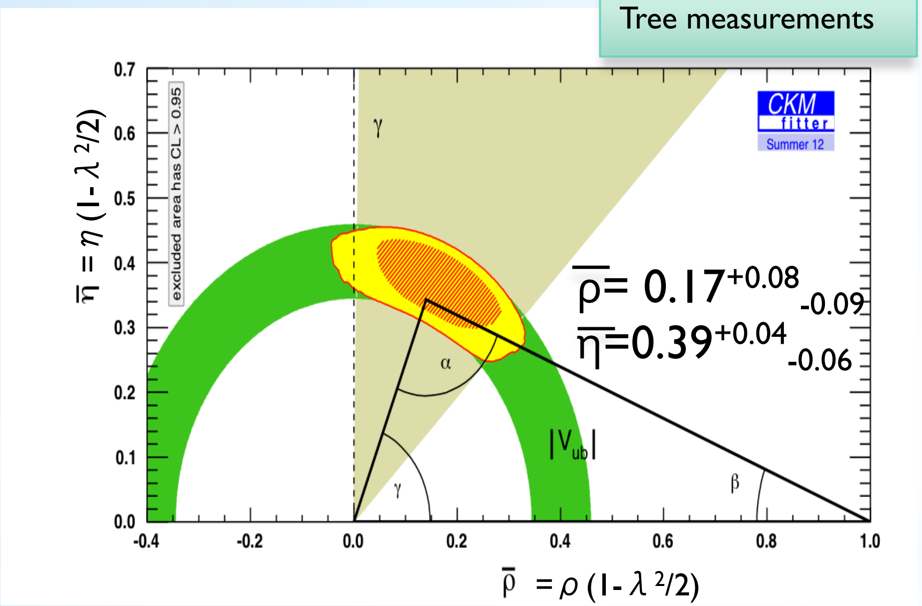
	b→s ($\|V_{tb}V_{ts}\| \alpha \lambda^2$)	b→d ($\|V_{tb}V_{td}\| \alpha \lambda^3$)	s→d ($\|V_{ts}V_{td}\| \alpha \lambda^5$)	c→u ($\|V_{cb}V_{ub}\| \alpha \lambda^5$)
Δ F=2 box	ΔM_{Bs}, $A_{CP}(B_s \to J/\Psi\, \Phi)$	ΔM_B, $A_{CP}(B \to J/\Psi\, K)$	ΔM_K, ε_K	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$,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

Tree vs loop measurements

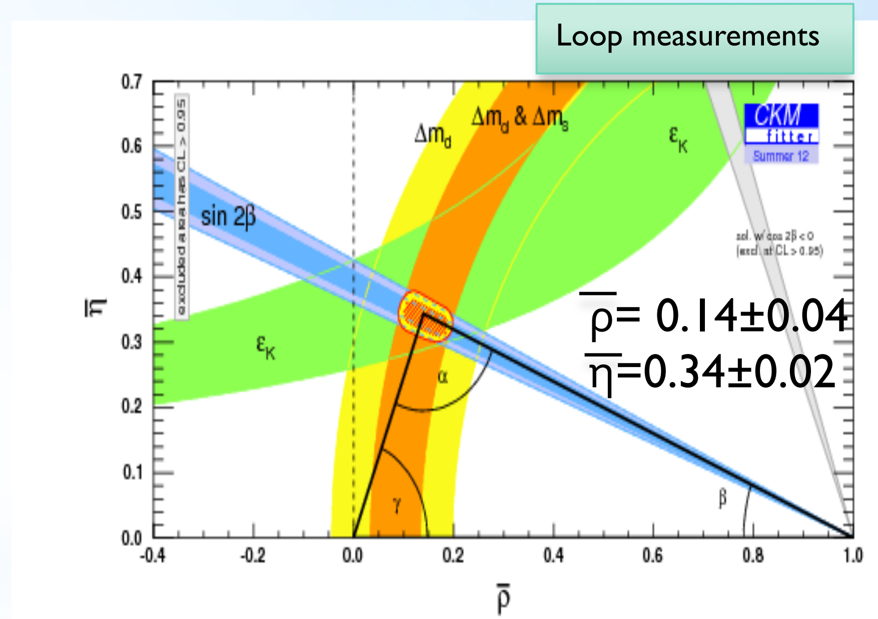
$(\mathbf{A}, \lambda, \rho, \eta)$ are not predicted by the SM. They need to be measured!

If we assume NP enters only at loop level, it is interesting to compare the determination of the parameters (ρ, η) from processes dominated by tree diagrams $(\mathbf{V_{ub}}, \gamma, \ldots)$ with the ones from loop diagrams $(\Delta \mathbf{M_d} \& \Delta \mathbf{M_s}, \beta, \varepsilon_K, \ldots)$.

Tree measurements



Loop measurements

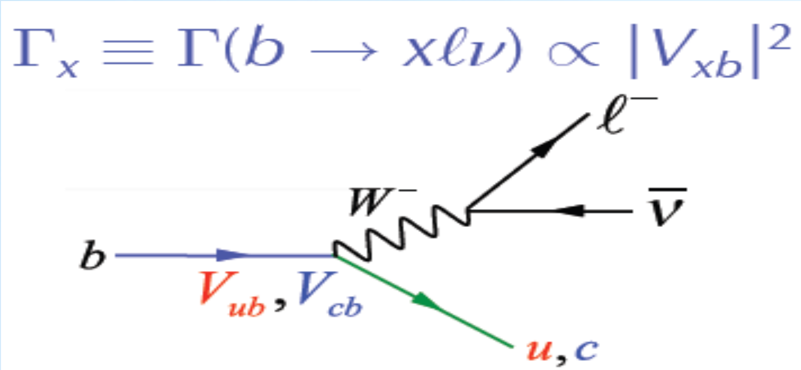


Courtesy S. Descotes-Genon on behalf of CKMfitter coll.

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

Tree Level Measurements: V_{ub},V_{cb},arg(V_{ub})

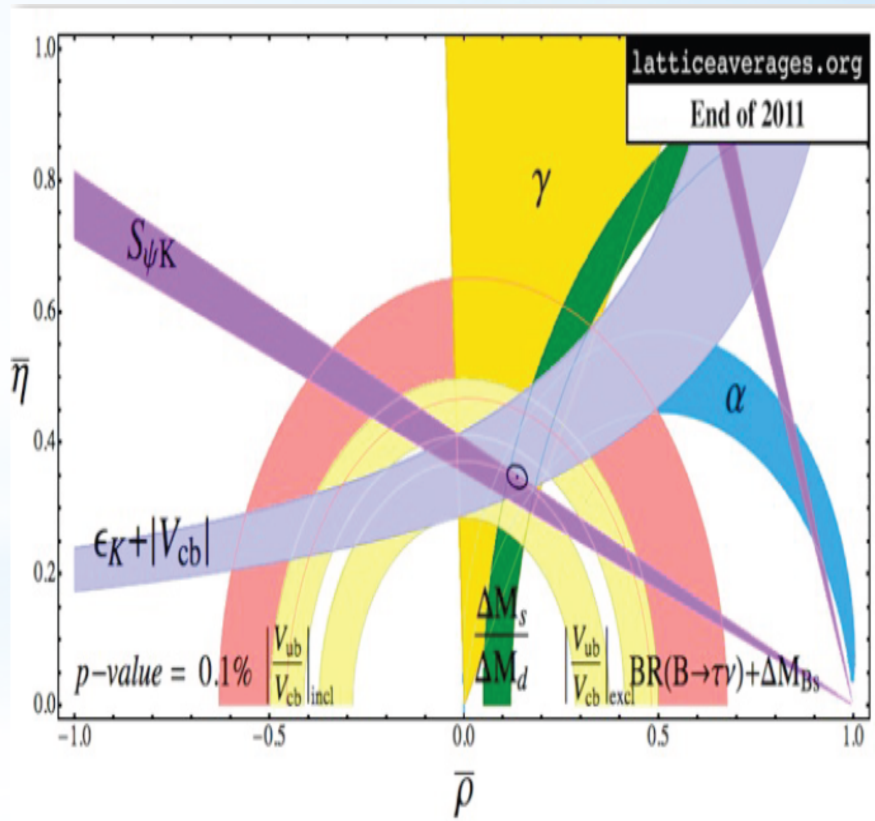
b→u,c: Charged Currents (NP at tree level?)



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.).

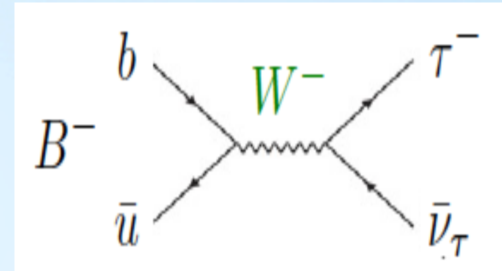
Both methods suffer from **large theoretical and experimental uncertainties.** Next generation B-factories will produce hadronic tagged, high statistics, high purity samples. LHCb is expected to provide competitive results in exclusive modes.



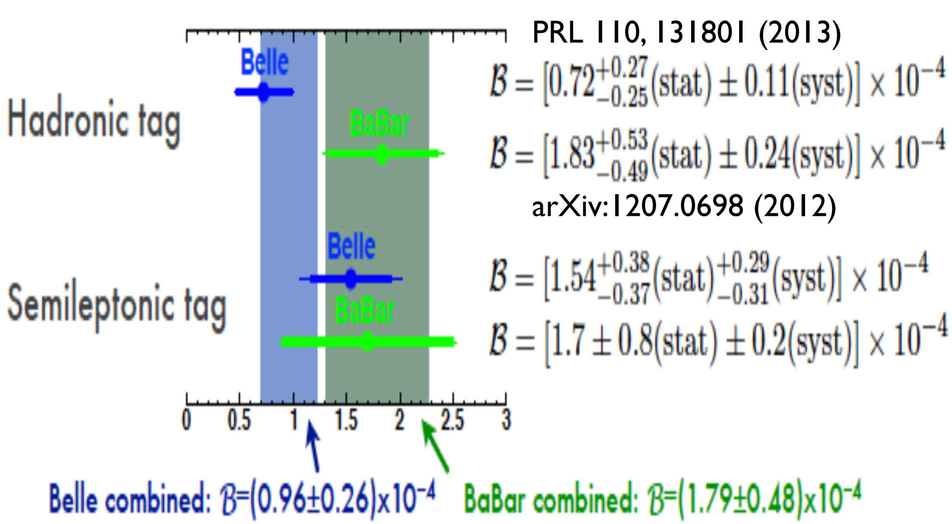
<u>**Progress with lattice calculations but still a big challenge for theory!**</u>

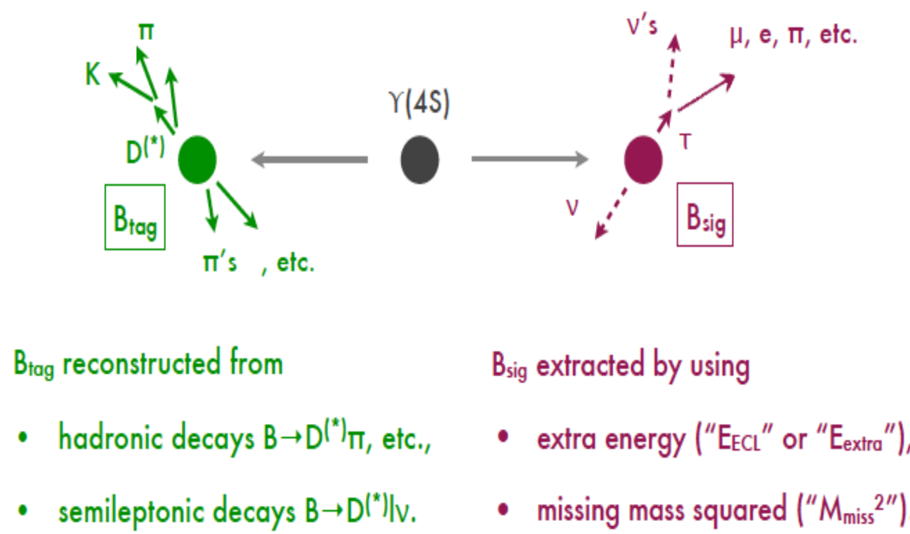
b→u: Charged Currents (NP at tree level?)

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



On the other hand, we knew from LEP: W→ $\tau\ \nu$ / W→l ν ~1.06±0.03



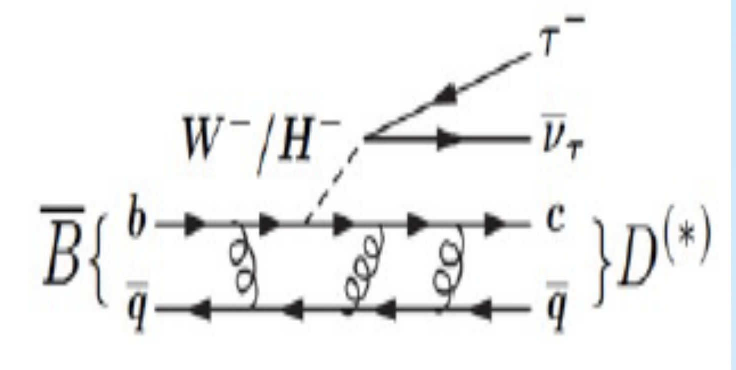


Last summer (2012) **Belle** presented a more precise hadron tag analysis, in better agreement with the fitted CKM value:

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

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

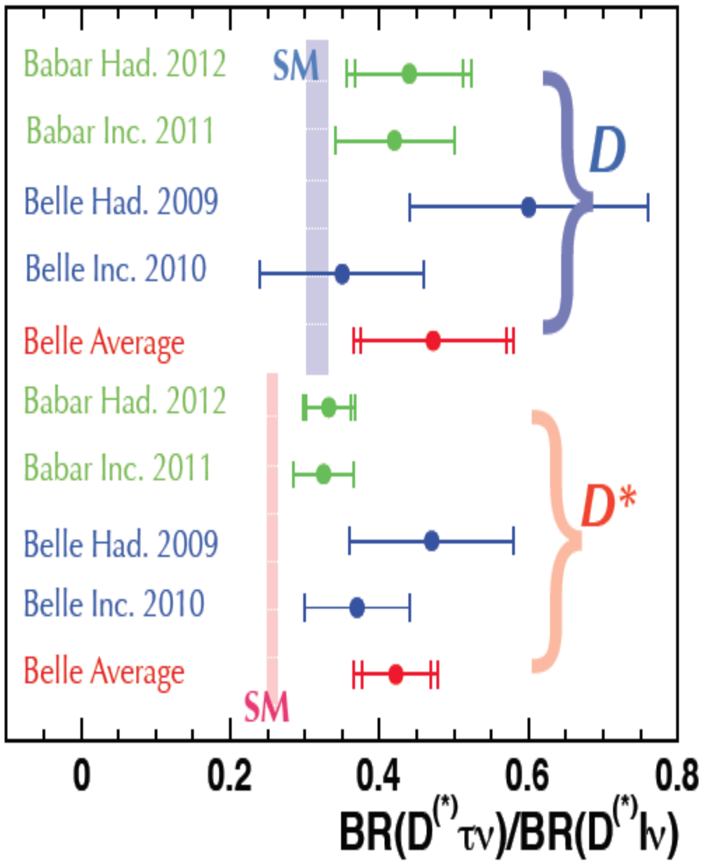
BABAR also presented last summer (2012) a more precise measurement of BR(B→D(*) $\tau\ \nu$)/BR(B→D(*)l ν). Ratio cancels V_{cb} and QCD uncertainties. Combined D and D* BABAR results are **3.4 σ higher than SM**



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

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→ $\tau\ \nu$).



V_{ub}, V_{cb} Personal Recap.

No convincing discrepancy to suggest NP at tree level in the measurements of the magnitudes of V_{ub}, V_{cb}.

However, the internal discrepancies between V_{ub} inclusive and exclusive measurements, makes more **difficult the comparison with loop** measurements.

This is certainly one of the **most interesting improvements** that could come from the **upgrade of Belle: Belle-II.** In addition to improved measurements in tau channels.

In parallel, new experimental studies of systematic uncertainties is probably worth the effort.

V_{ub} phase: (SM value of ρ , η)

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

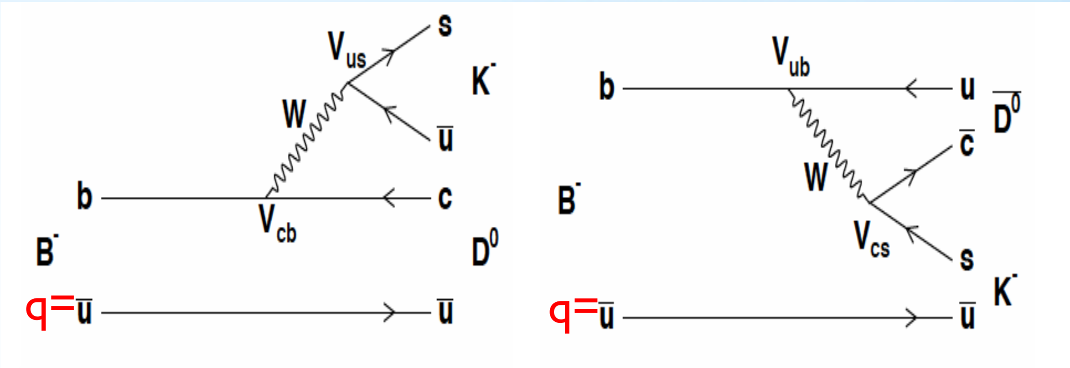
$B^{\pm} \rightarrow DX_s$ X_s={$K^{\pm}$, $K^{\pm}\pi\pi$, $K^{*\pm}$,…}

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

$B \rightarrow DK^*$

q=s: Time dependent CP analysis.

$B_s \rightarrow D_sK$



($|V_{cb}V_{us}|$ α λ^3)

($|V_{ub}V_{cs}|$ α λ^3)

In the case q=u,d 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 (CLEO/BESIII).

In the case q=s, a time dependent CP analysis is needed.

V_{ub} phase: (SM value of ρ , η)

$B^- \to DK^-$ $\quad D \to K^+K^-, \pi^+\pi^-$

favoured $\oplus$ suppressed $\otimes$ *CP* eigenstates

"*CP*" or "GLW" modes

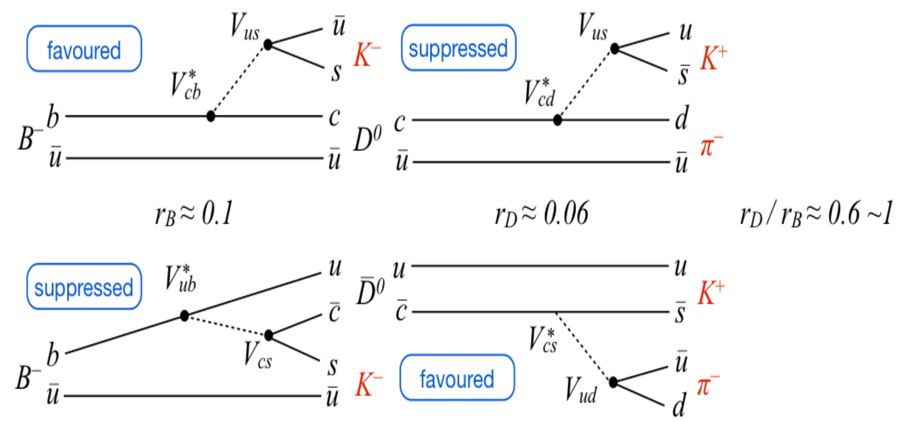
M. Gronau and D. London, *How to determine all the angles of the unitarity triangle from $B_d^0 \to DK_S^0$ and $B_s^0 \to D\phi$*, Phys. Lett. **B253** (1991) 483; M. Gronau and D. Wyler, *On determining a weak phase from CP asymmetries in charged B decays*, Phys. Lett. **B265** (1991)

$B^- \to DK^-$ $\quad D \to \pi^- K^+$

favoured $\oplus$ suppressed $\otimes$ suppressed $\oplus$ favoured

"ADS" mode

D. Atwood, I. Dunietz, and A. Soni, *Enhanced CP violation with $B \to KD^0(\bar{D}^0)$ modes and extraction of the CKM angle γ*, Phys.Rev.Lett. **78** (1997) 3257, arXiv:hep-ph/9612433;



CP modes

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

favoured mode

average of *KK* and *ππ modes*

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

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

ADS mode

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

favoured mode

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

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

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

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

V_{ub} phase: (SM value of ρ , η)

In fact, the most precise determination of γ from B-factories is from the Dalitz analysis (**GGSZ**) of the decays $B^{\pm}\rightarrow D(K_s\pi\pi)\, K^{\pm}$. But notice the higher value of r_B.

Combining with the decays $B\rightarrow D_{CP}X_s$ (**GLW)** and the decays $B\rightarrow D(K^+\pi^-(\pi^0))X_s$ (**ADS**):

Results shown at CKM2012

BABAR: $\gamma = 69\ ^{+17}_{-16}\ ^\circ$ ($r_B(DK)=0.092\pm0.013$)

Belle : $\gamma = 68\ ^{+15}_{-14}\ ^\circ$ ($r_B(DK)=0.112\pm0.015$)

CKMFITTER (BABAR+Belle) combination: $\gamma = 66 \pm 12^\circ$
to be compared with $\gamma = 67.7^{+4.1}_{-4.3}\ ^\circ$ from loops measurements.

Example from Belle:

for B→DK:

$r_B = 0.168^{+0.063}_{-0.064}$

$r_B = 0.108^{+0.045}_{-0.023}$

$r_B = 0.104^{+0.020}_{-0.021}$

$\mathbf{r_B = 0.112^{+0.014}_{-0.015}}$

GGSZ

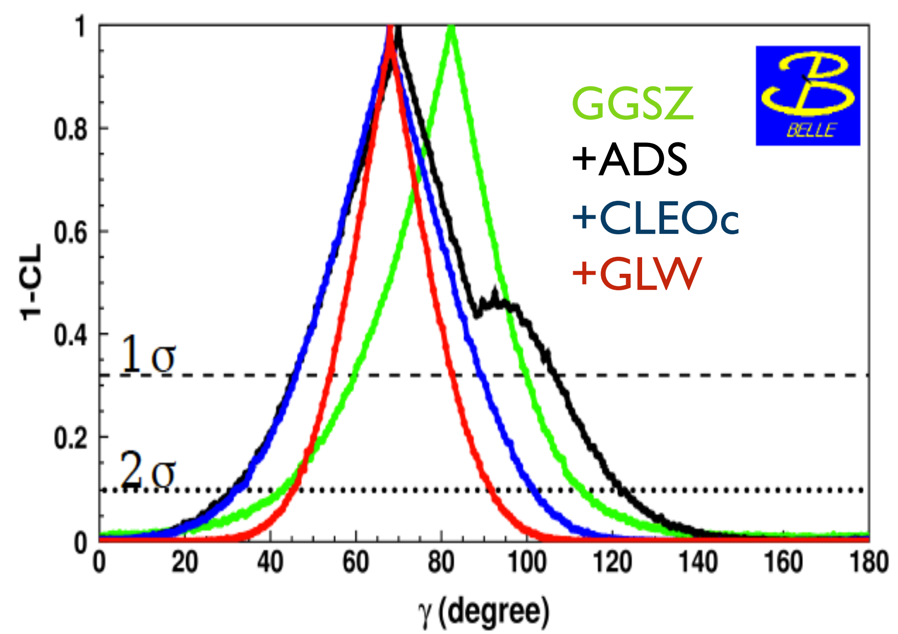
$\gamma = [82\ ^{+18}_{-23}]^\circ$

GGSZ+ADS

$\gamma = [70\ ^{+37}_{-24}]^\circ$

GGSZ+ADS+δ_D

$\gamma = [68 \pm 22]^\circ$



LHCb measurements using $B^{\pm}\to D[hh]h^{\pm}$ (*GLW*) and $B^{\pm}\to D[K\pi]h^{\pm}$ (*ADS*)

Exploit interference of D0/D0-bar decaying in the same final state, both CP eigenstate (GLW) and $D\to K\pi$ (ADS). Only 1/fb data analyzed so far.

Clear asymmetry observed in $B\to DK$ while only a small effect in $B\to D\pi$.

$R_{CP}(D[hh]) = 1.007 \pm 0.040$
$R^{ADS}(D[K\pi]) = 0.0152 \pm 0.0020$

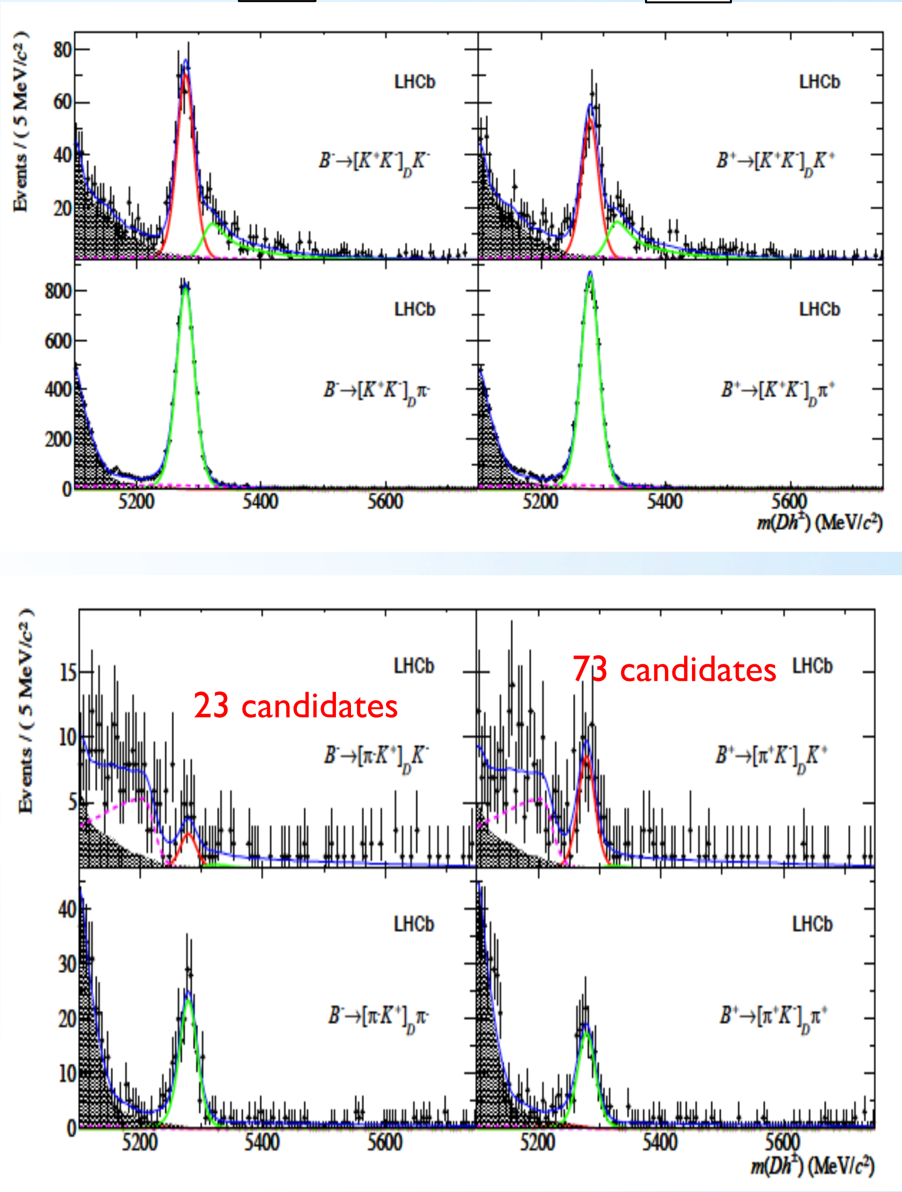
$A_{CP}(D[hh]) = 0.145 \pm 0.034$
$A^{ADS}(D[K\pi]) = -0.52 \pm 0.15$

Uncertainties in asymmetries reduced by a factor ~2 w.r.t. previous measurements at B-factories!

B-

PLB 712 (2012) 203

B+



LHCb measurements using $B^{\pm} \to D[K_s hh]K^{\pm}$ (*GGSZ*)

The difference between the strong phase of D0 and anti-D0 varies over the Dalitz bin. Rather than using a model, take bin by bin the measured values at CLEO → clean definition of systematic.

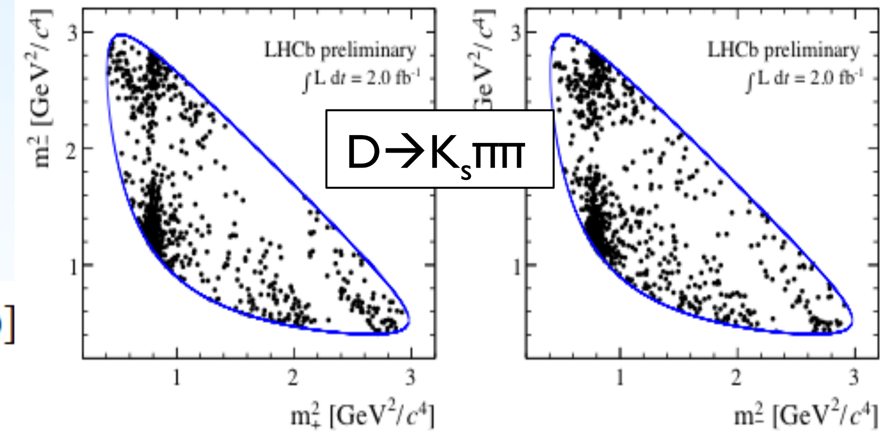
In each bin count the number of candidates:

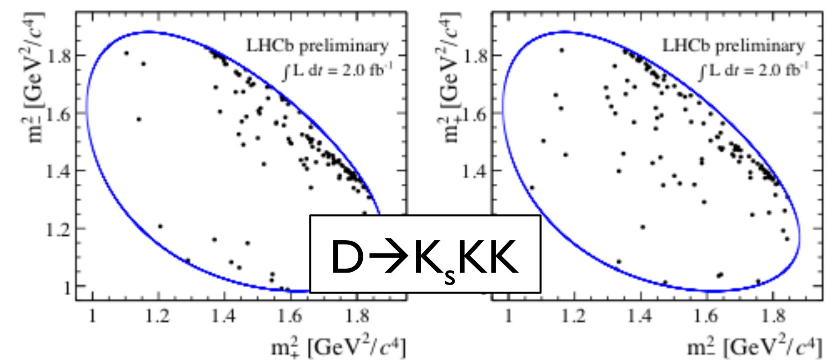
$$N^{+}_{+i} = n_{B^+}[K_{-i} + (x_+^2 + y_+^2)K_{+i} + 2\sqrt{K_{+i}K_{-i}}(x_+ c_{+i} - y_+ s_{+i})]$$

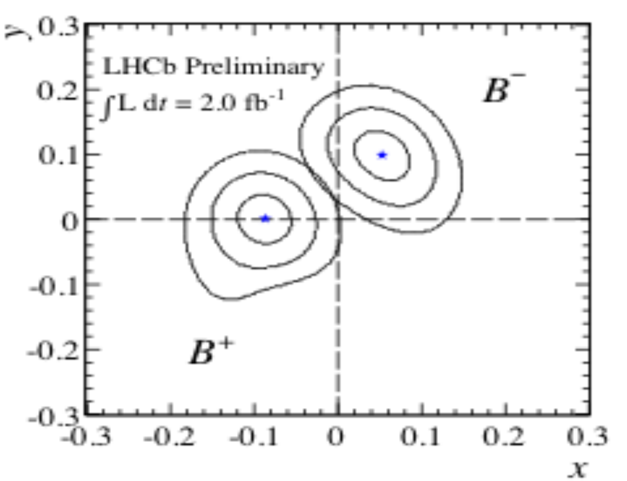
$$x_{\pm} = r_B \cos(\delta_B \pm \gamma), y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

where for each bin (i), K_i is the flavour tagged yield, c_i and s_i are CLEO inputs. Essentially a counting experiment in each bin of the Dalitz plot

B^- LHCb-CONF-2013-004 B^+





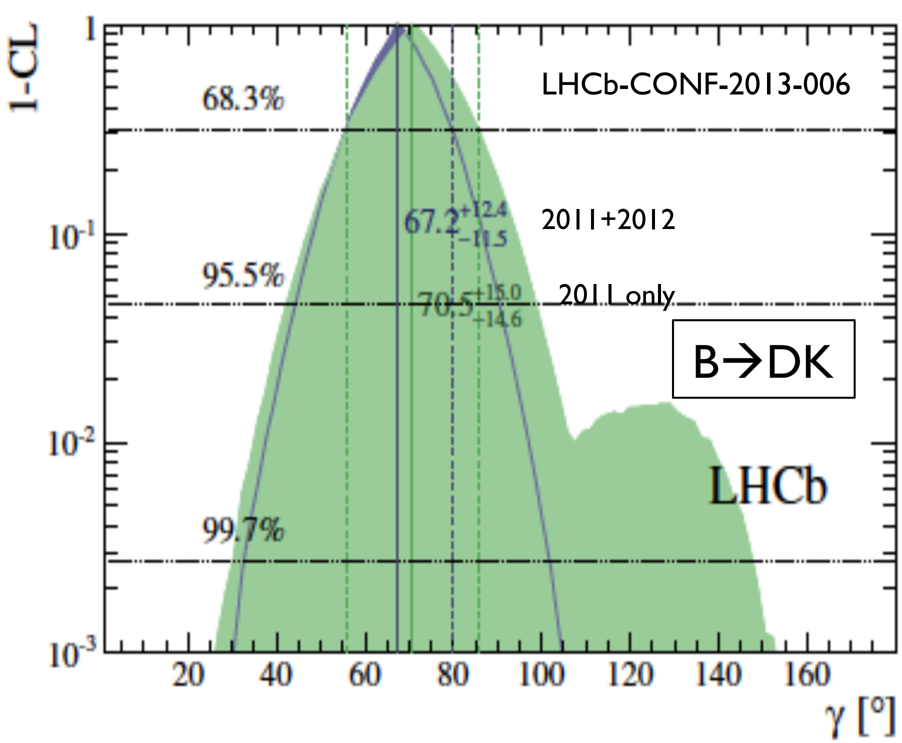


Combining 2/fb (2012) with 1/fb (2011) data the precision with only this decay mode is similar than the B-factories.

LHCb (GGSZ) : γ = 57±16° **(r_B=0.088±0.024)**

V_{ub} phase:LHCb combination

$B^\pm \to Dh^\pm$	CP-violating weak phase $\Gamma(B^- \to D^0K^-)/\Gamma(B^- \to D^0\pi^-)$	γ R_{cab}
$B^\pm \to D\pi^\pm$ $B^\pm \to DK^\pm$	$A(B^- \to \overline{D^0}\pi^-)/A(B^- \to D^0\pi^-) = r_B^\pi e^{i(\delta_B^\pi - \gamma)}$ $A(B^- \to \overline{D^0}K^-)/A(B^- \to D^0K^-) = r_B e^{i(\delta_B - \gamma)}$	r_B^π, δ_B^π r_B, δ_B
$D \to K^\pm\pi^\mp$	$A(D^0 \to \pi^-K^+)/A(D^0 \to K^-\pi^+) = r_{K\pi}e^{-i\delta_{K\pi}}$	$r_{K\pi}, -\delta_{K\pi}$
$D \to K^\pm\pi^\mp\pi^+\pi^-$	amplitude ratio and effective strong phase diff. coherence factor	$r_{K3\pi}, -\delta_{K3\pi}$ $\kappa_{K3\pi}$
direct CP asymmetries	in $D \to K^+K^-$ in $D \to \pi^+\pi^-$	$A_{CP}^{D\to KK}$ $A_{CP}^{D\to\pi\pi}$
Other D system parameters	D mixing Cabibbo-favoured rates	x_D, y_D $\Gamma(D \to K\pi)$ $\Gamma(D \to K\pi\pi\pi)$



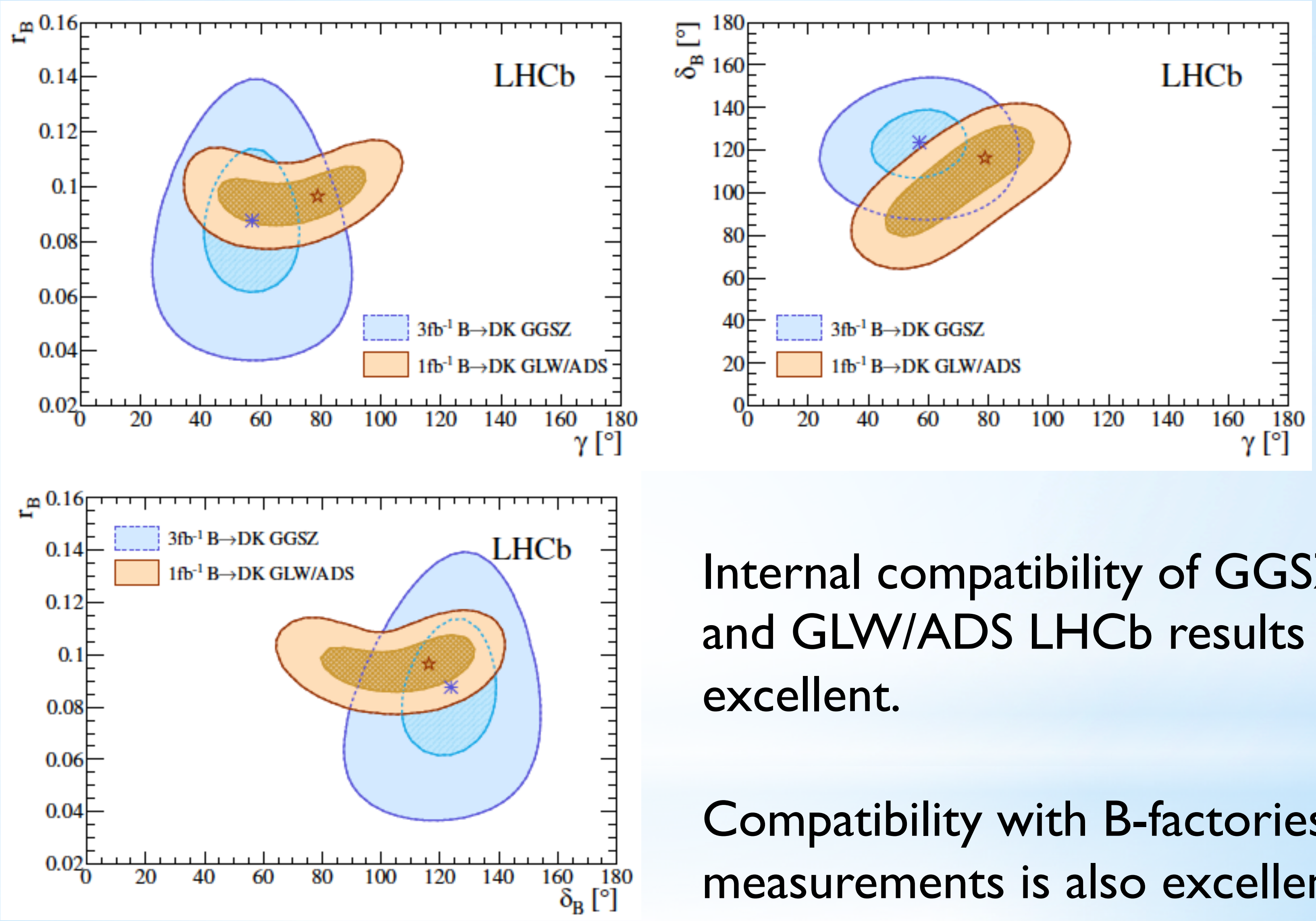
Available analysis combined to extract value of γ. However notice the large number of parameters in the fit!

Second solution appears when including B→Dπ, which is within one sigma of the B→DK.

LHCb preliminary (B→DK):

γ **= 67±12°** **(r_B(DK)=0.092±0.008)**

V_{ub} phase:LHCb combination



Internal compatibility of GGSZ and GLW/ADS LHCb results is excellent.

Compatibility with B-factories measurements is also excellent.

V_{ub} phase measurements: Recap.

LHCb ($\gamma = 67\pm12°$) and B-factories ($\gamma = 66\pm12°$) tree level measurements are in **good agreement** with the indirect determination from loop measurements ($\gamma = 66.6^{+6.4}_{-6.3}$ °).

However, at the current level of precision we cannot exclude NP phases contributing to the b→d box diagram at the O(10)% level.

The main progress should come from an **improved precision of the measurements at tree level.**

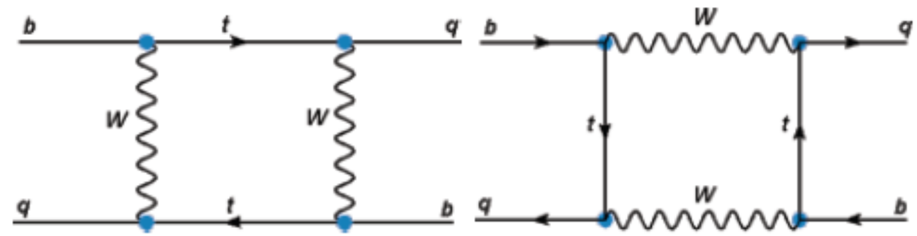
LHCb should reach **a few degrees precision** in few years from now and therefore have similar sensitivity from tree and loop measurements.

$\Delta F=2$ Box Measurements

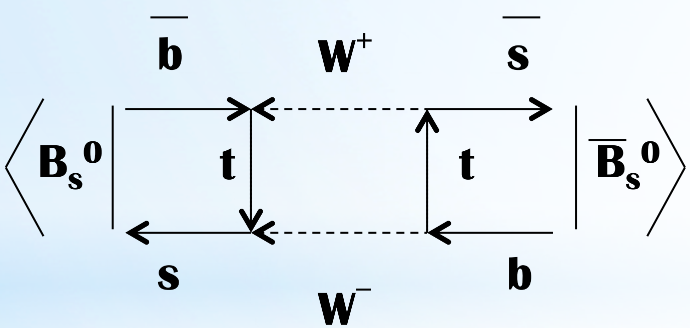
Δ F=2 box transitions theory

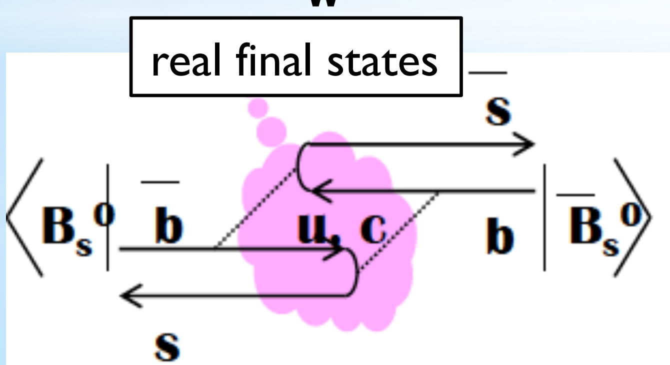
dispersive   absorptive

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



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}

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

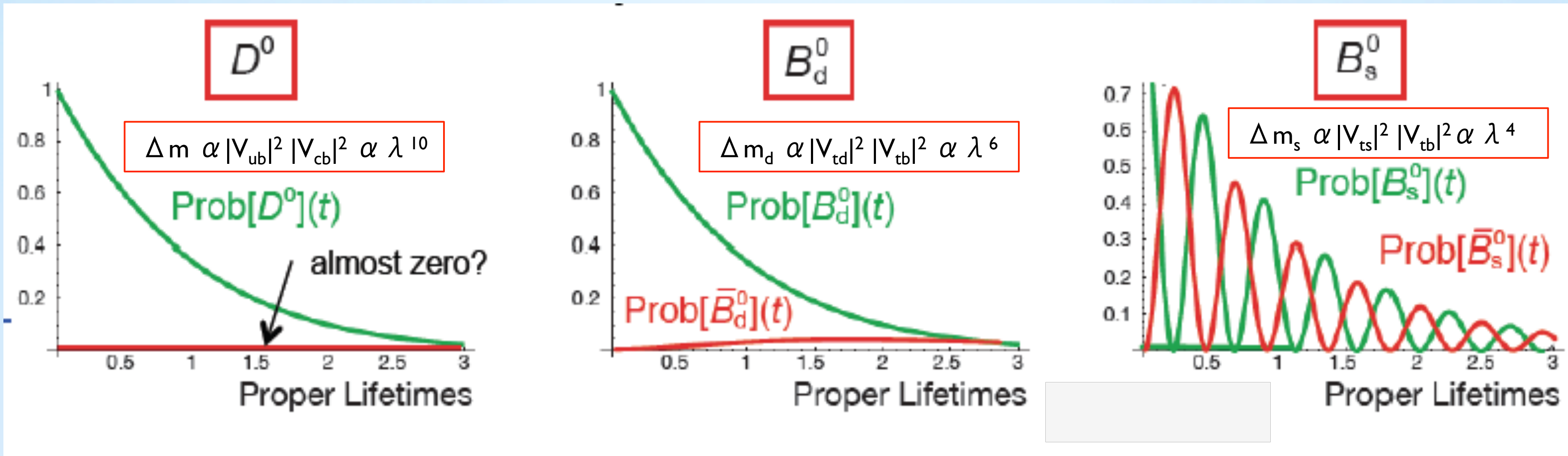
$$\arg M_{12} = \arg (V_{ts}^* V_{tb})^2 + \pi = \varphi_s + \pi$$

Absorptive part: Γ_{12}

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

$\Delta\Gamma_d \propto 0.004\times\Gamma_d$
$\Delta\Gamma_s \propto 0.1\times\Gamma_s$

Δ 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:

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

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

How do we measure these phases?

B^0 system

$$\begin{tikzcd} \bar{B}^0 \arrow[r] \arrow[ddr, "M_{12} \propto e^{2i\beta}"'] & \bar{B}^0 \arrow[dr] & \\ & & J/\psi\, K_S \\ & B^0 \arrow[ur] & \end{tikzcd}$$

$b \to \bar{c}+cs$: $V_{cb} V_{cs}^* \propto e^{i\,0}$

$\bar{b} \to \bar{c}+cs$: $V_{cb}^* V_{cs} \propto e^{i\,0}$

$A_{CP}(t) \propto \sin 2\beta \times \sin \Delta mt$

$$\begin{tikzcd} \bar{B}^0 \arrow[r] \arrow[ddr, "M_{12} \propto e^{2i\beta}"'] & \bar{B}^0 \arrow[dr] & \\ & & D^{(*)+}\, \pi^- \\ & B^0 \arrow[ur] & \end{tikzcd}$$

$r_B \approx \frac{A\lambda^2}{A\lambda^4 \sqrt{\rho^2+\eta^2}}$

$b \to \bar{c}+ud$: $V_{cb} V_{cd}^* \propto e^{i\,0}$

$\bar{b} \to \bar{u}+cd$: $V_{ub}^* V_{cd} \propto e^{i\gamma}$

$A_{CP}(t) \propto \sin(2\beta+\gamma) \times \sin \Delta mt$

B_s system

$$\begin{tikzcd} \bar{B}_s^0 \arrow[r] \arrow[ddr, "M_{12} \propto e^{i\varphi_s}"'] & \bar{B}_s^0 \arrow[dr] & \\ & & J/\psi\, \phi(\eta) \\ & B_s^0 \arrow[ur] & \end{tikzcd}$$

$b \to \bar{c}+cs$: $V_{cb} V_{cs}^* \propto e^{i\,0}$

$\bar{b} \to \bar{c}+cs$: $V_{cb}^* V_{cs} \propto e^{i\,0}$

$A_{CP}(t) \propto \sin \varphi_s \times \sin \Delta mt$

$$\begin{tikzcd} \bar{B}_s^0 \arrow[r] \arrow[ddr, "M_{12} \propto e^{i\varphi_s}"'] & \bar{B}_s^0 \arrow[dr] & \\ & & D_s^+\, K^- \\ & B_s^0 \arrow[ur] & \end{tikzcd}$$

$r_B \approx \frac{A\lambda^3}{A\lambda^3 \sqrt{\rho^2+\eta^2}}$

$b \to \bar{c}+us$: $V_{cb} V_{us}^* \propto e^{i\,0}$

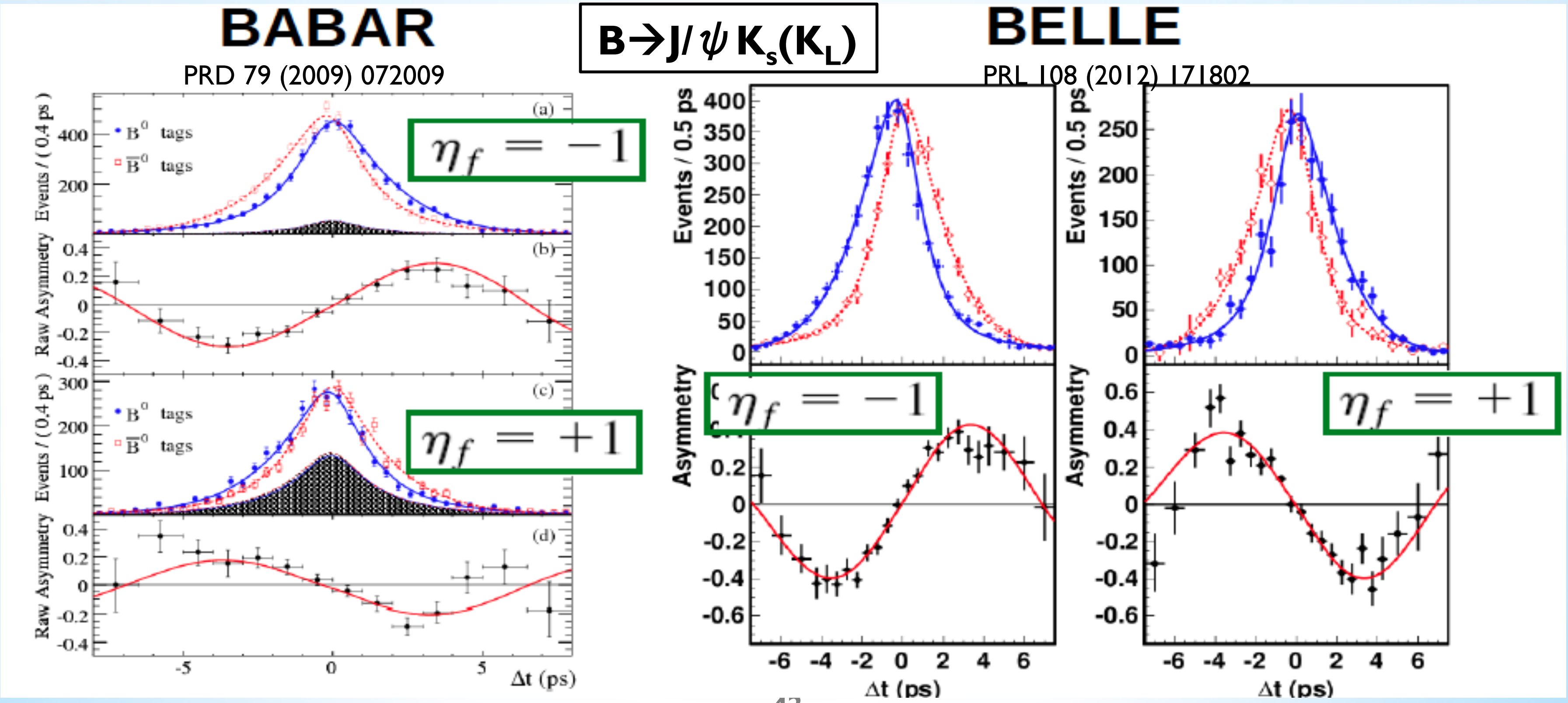
$\bar{b} \to \bar{u}+cs$: $V_{ub}^* V_{cs} \propto e^{i\gamma}$

$A_{CP}(t) \propto \sin(\varphi_s+\gamma) \times \sin \Delta mt$

Δ F=2 box in b→d transitions

Large phases from NP contributing to the dispersive part (M^q_{12}) should contribute to the measurements of the time dependent CP asymmetry in $B \to J/\psi K_s$ and/or $B_s \to J/\Psi\, \Phi$.

The CP asymmetry as a function of the lifetime distribution of tagged events shows an oscillation pattern. The frequency of these oscillations determine M_{12} while the amplitude is proportional to $\arg(M_{12})$.



Δ F=2 box in b→d transitions

CKMFITTER (BABAR+Belle) combination:

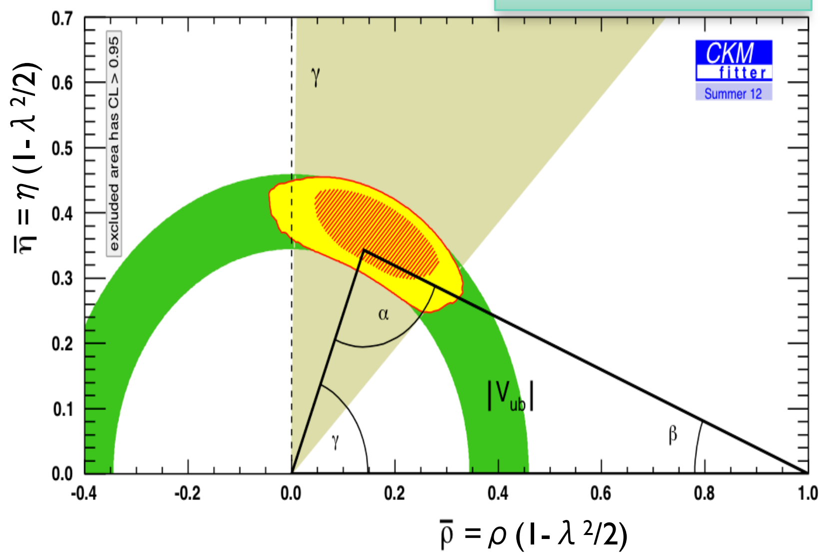
$\beta = 21.38^{+0.79}_{-0.77}$ °

Which can be compared with the indirect determination using "tree measurements": β = 24.9+0.8-1.9°

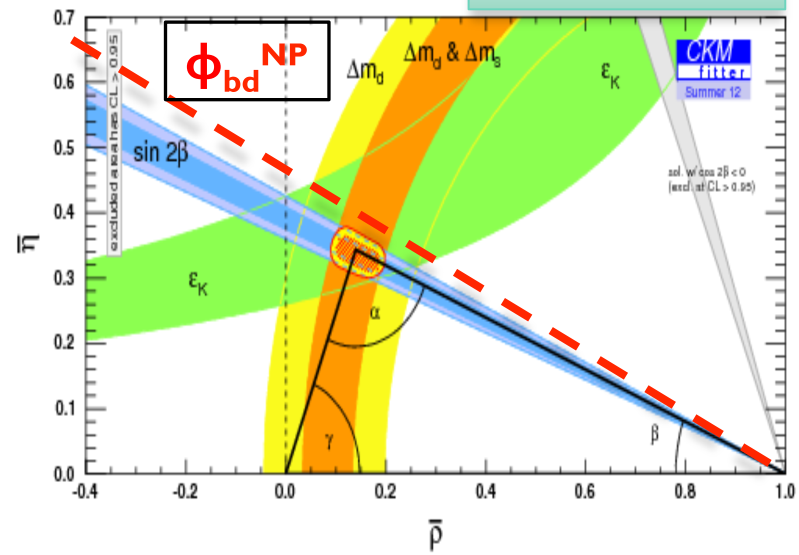
If we assume the SM, then we have measured the phase of V_{td} better than 4% from b→d transitions in box diagrams.

However, NP must be contributing to some level! Therefore, the precise measurement of β is in fact, a precise measurement of ($\beta + \phi_{bd}^{NP}$).

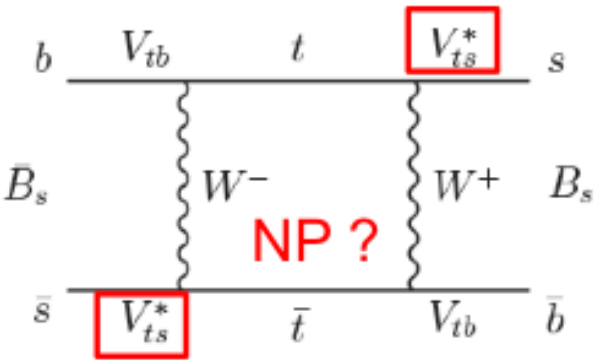
Tree measurements



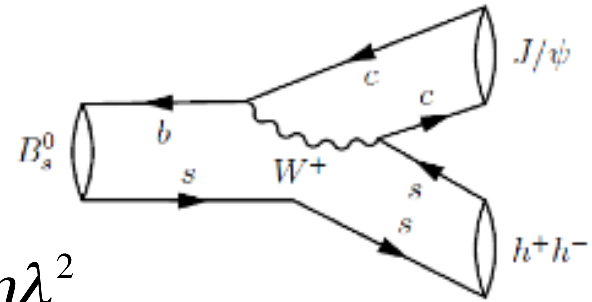
Loop measurements



Δ F=2 box in b→s transitions



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

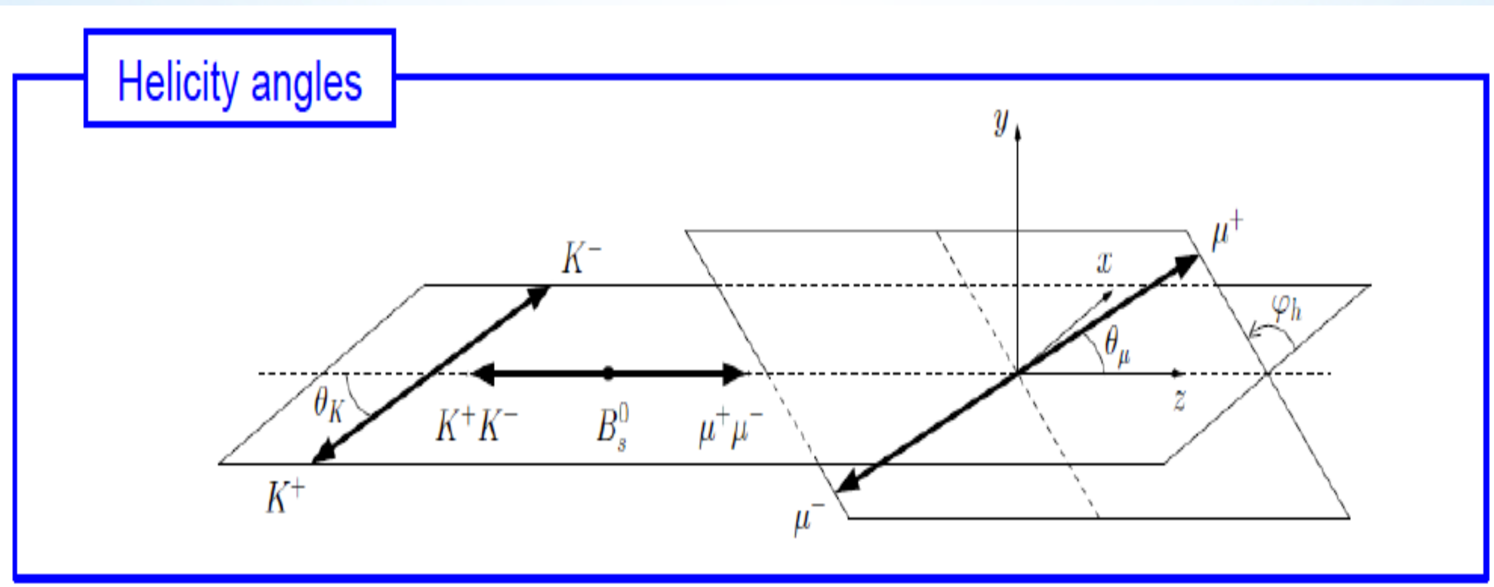


+ small penguin pollution

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

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

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

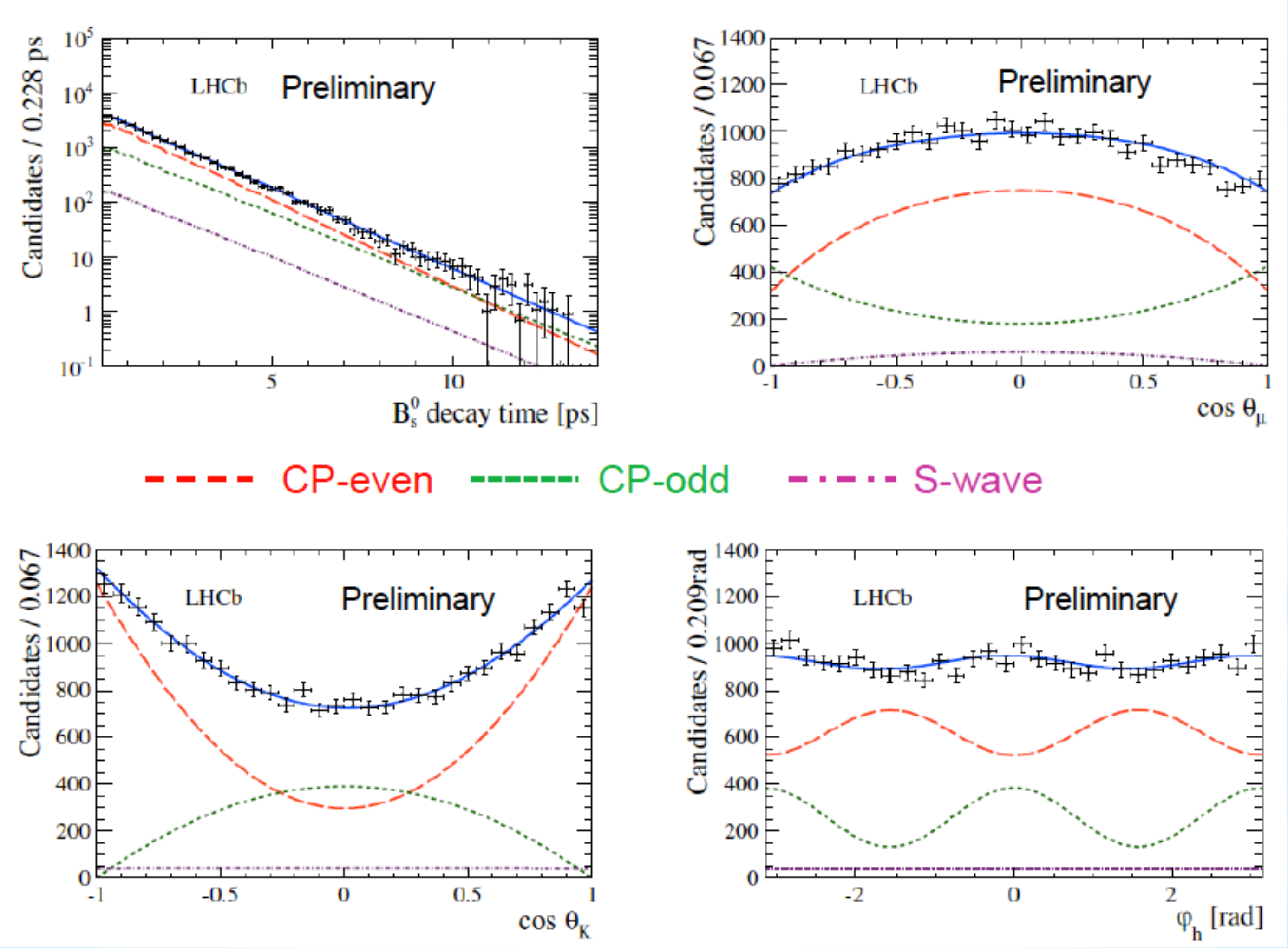


ΔF=2 box in b→s transitions

LHCb flavour tagging improved with the inclusion now of Kaon Same Side Tag:

LHCB-PAPER-2013-002

$\varepsilon D^2 = (3.13 \pm 0.23)\%$

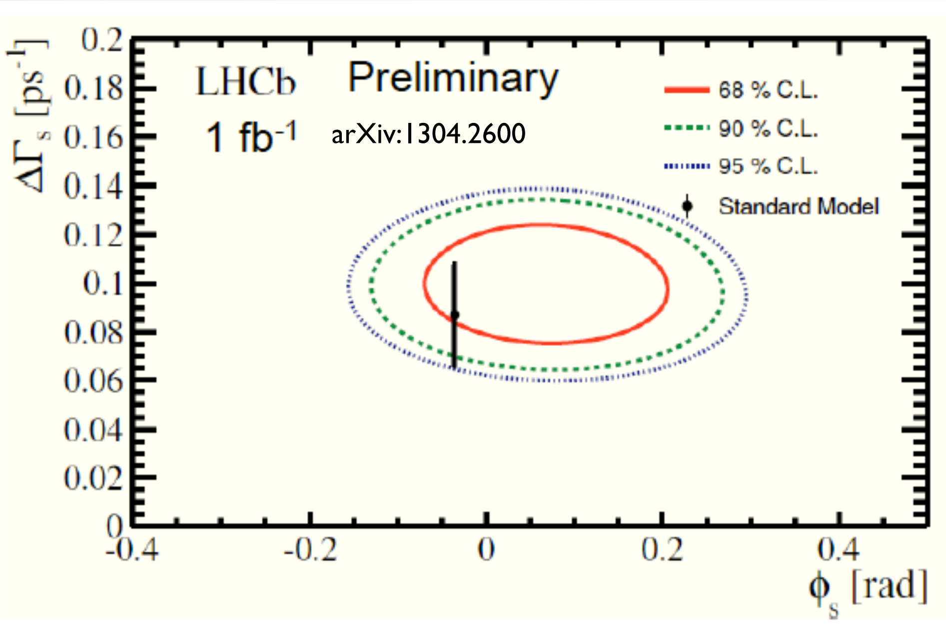


Δ F=2 box in b→s transitions

The result of the LHCb angular analysis of $B_s \to J/\Psi\,\Phi$ decays with 1/fb (27.6k candidates) gives:

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

Preliminary



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

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

Δ F=2 box in b→s transitions

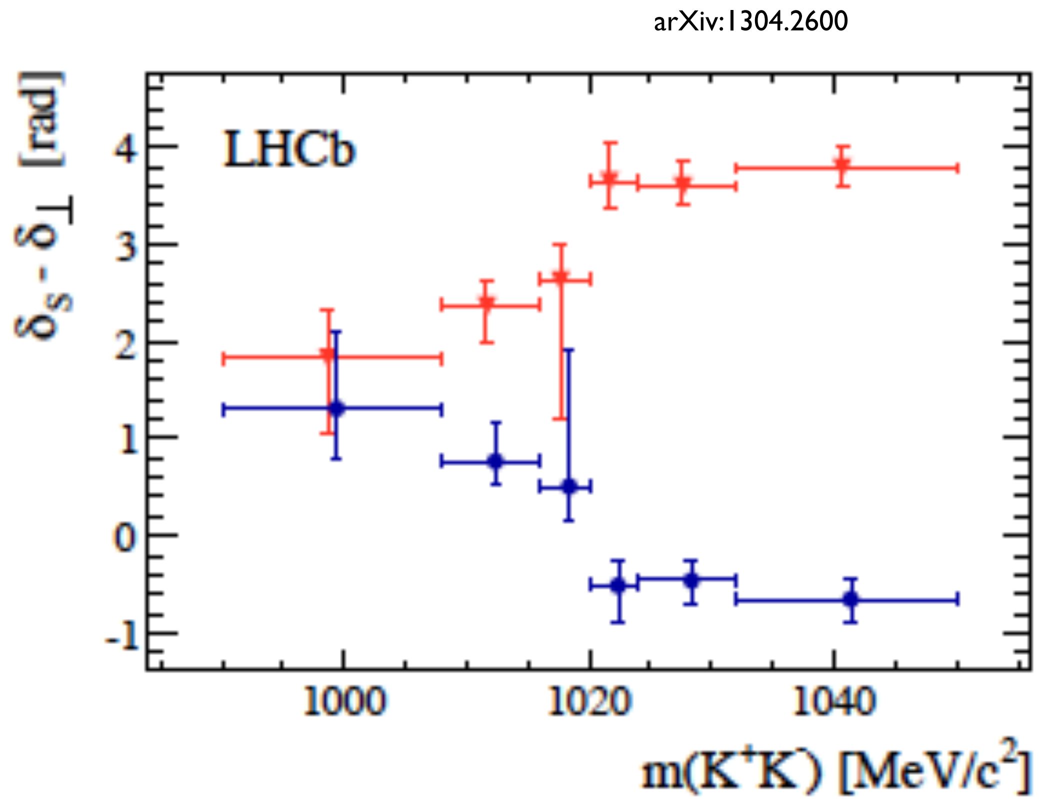
However, there is a two fold ambiguity in the differential decay rates:

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

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

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

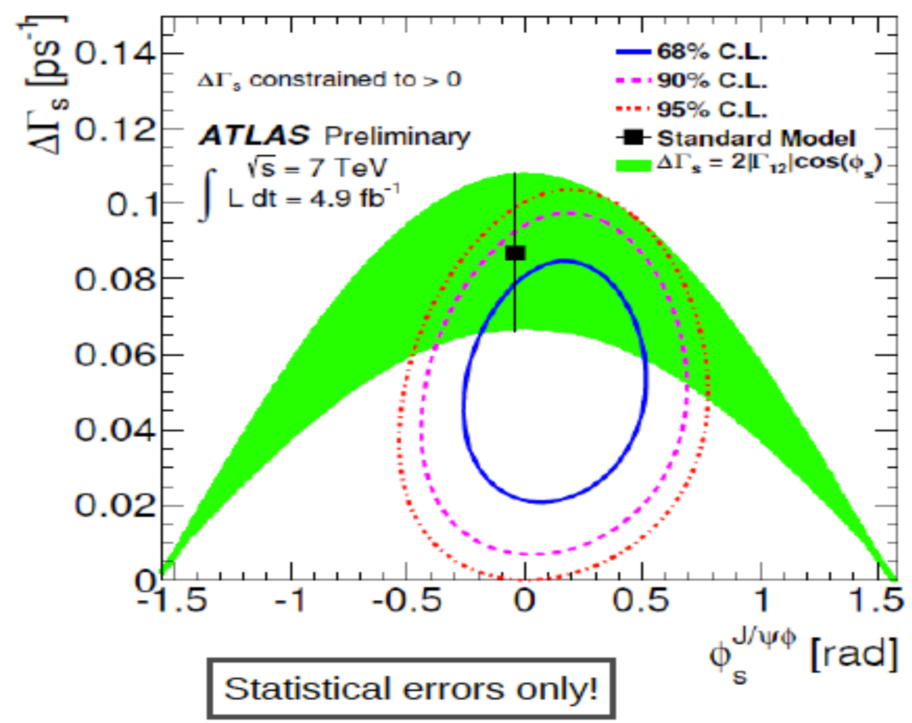
$\boxed{\Delta\Gamma_s > 0}$



Δ F=2 box in b→s transitions

The LHCb measurement: $\boxed{\Phi_s = 0.6 \pm 4.0°}$ can be compared with the indirect determination using "tree measurements", Φ_s **= -2.3** $^{+0.1}_{-0.3}$**°** or from other "loop measurements", Φ_s **= -2.1 ± 0.1°** . Although, there has been **impressive progress** since the initial measurements at CDF/D0, the uncertainty needs to be further reduced for a meaningful comparison.

ATLAS-CONF-2013-039



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

$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$

which corresponds to Φ_s **= 7 ± 16°** .

CMS has also perform an untagged analysis with 5/fb (14.5k candidates) to measure:

CMS-PAS-BPH-11-006

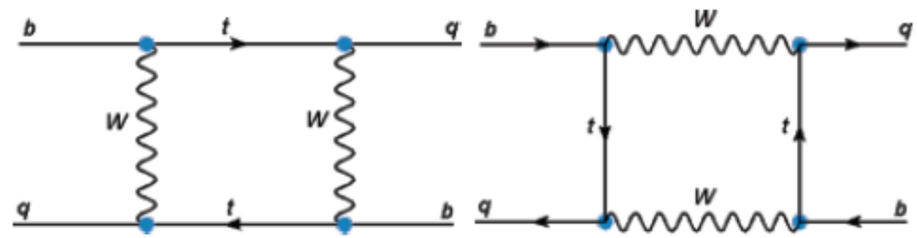
$\Delta\Gamma_s$ **= 0.048 ± 0.024 (stat) ± 0.003 (syst) ps^{-1}**

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

ΔF=2 box in b→q transitions: NP in dispersive part

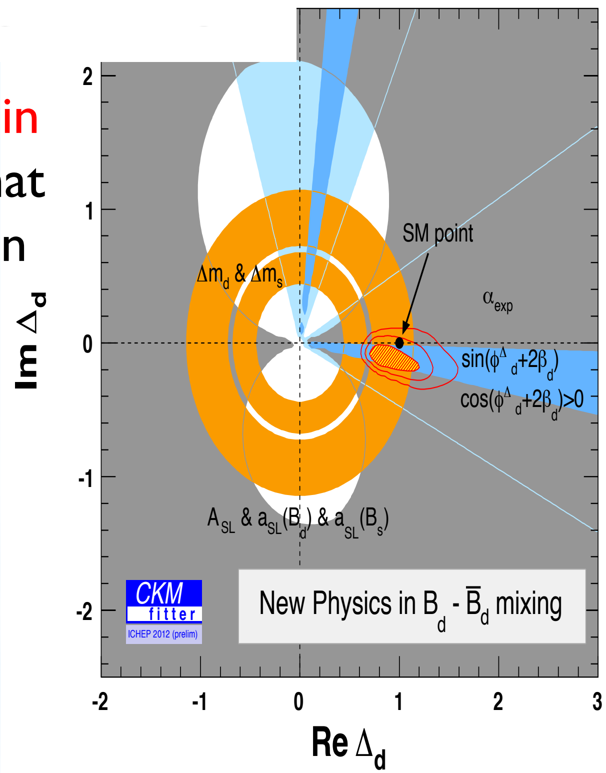
$$\left\langle B_q^0 \middle| M_{12}^{SM+NP} \middle| \overline{B}_q^0 \right\rangle \equiv \Delta_q^{NP} \cdot \left\langle B_q^0 \middle| M_{12}^{SM} \middle| \overline{B}_q^0 \right\rangle$$

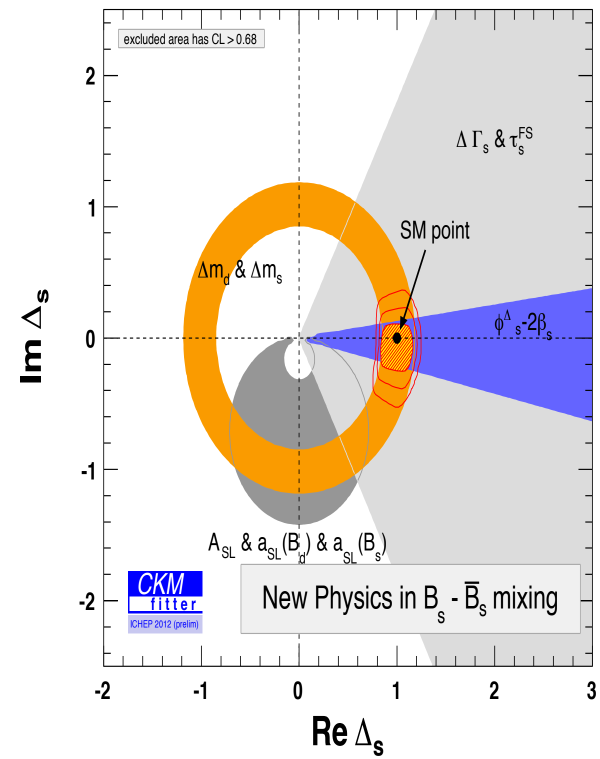
$$\Delta_q^{NP} = \mathrm{Re}(\Delta_q) + i\ \mathrm{Im}(\Delta_q) = |\Delta_q| e^{i\phi^{\Delta}_q}$$



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

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





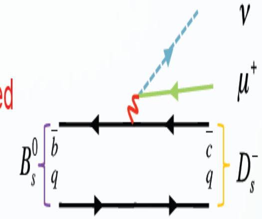
Need to increase precision to disentangle NP phases of few percent in B_d and B_s mixing

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

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

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

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



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

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

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

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

arXiv:1106.6308

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

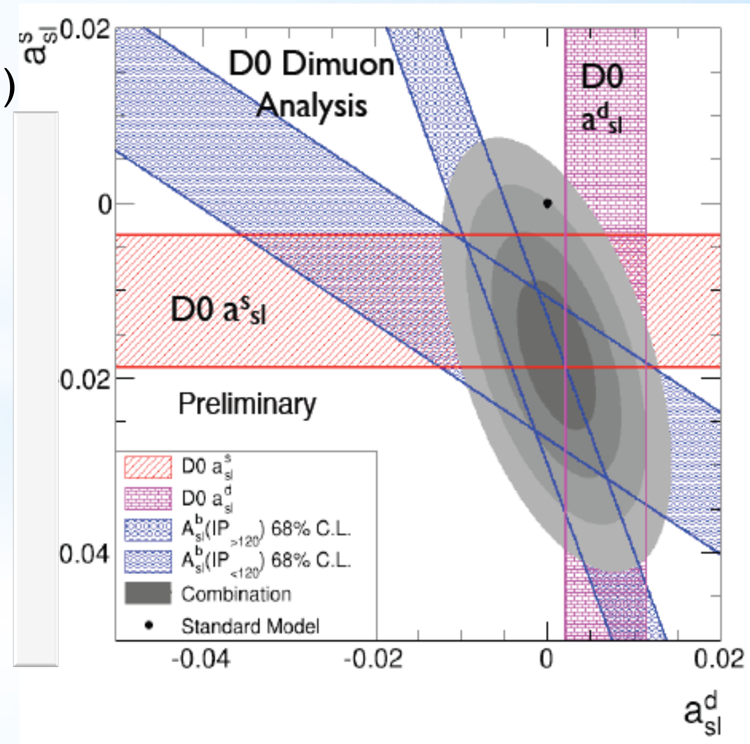
and splitting the data sample in **low(high) IP**:

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

Moreover, D0 has also measured:

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

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



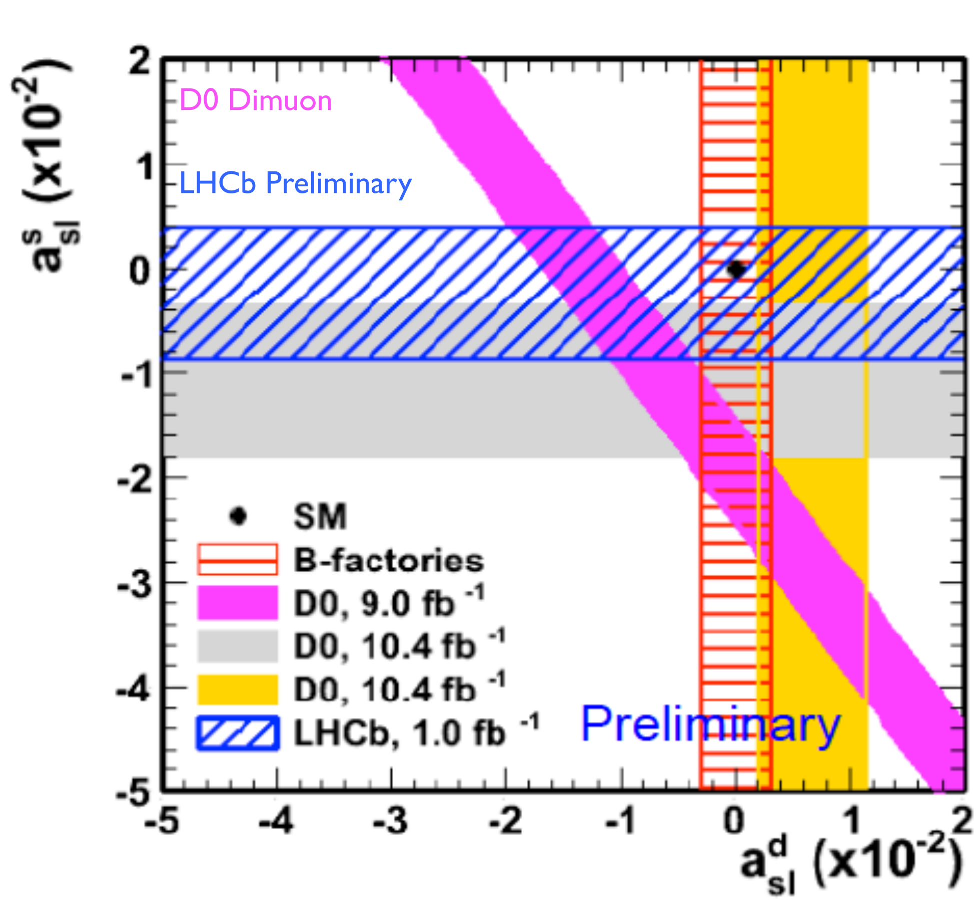
ΔF=2 box in b→q transitions (LHCb flavour specific asymmetries)

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

LHCb-2012-022

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

$a_{SL}(B_s)$ = (-0.24±0.54(stat) ±0.33(syst))%



Also taking into account the measurement at the B-factories of **$a_{SL}(B_d)$ = (-0.38±0.36)%**

$a_{SL}(B_d)$ = (-0.07±0.25)% ,
$a_{SL}(B_s)$ = (-1.07±0.41)%

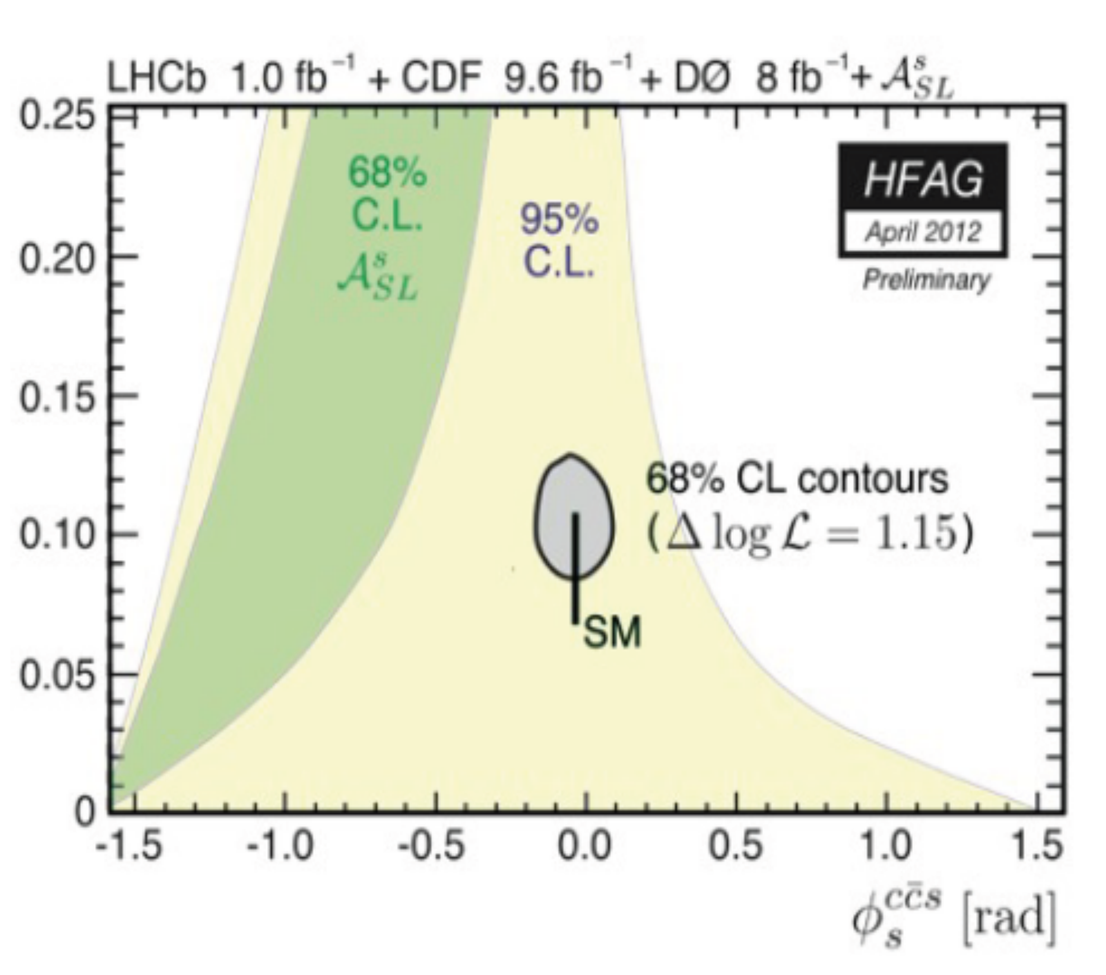
The world averaged value of $a_{SL}(B_s)$ is ~2.5 σ from SM.

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 ($\Delta\Gamma_s$, Φ_s.)

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

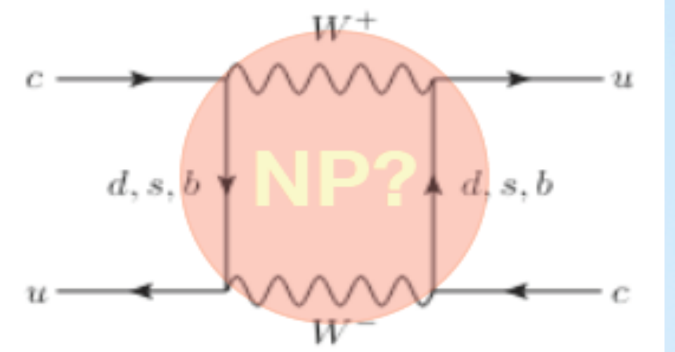
However there is already a clear tension between D0 $a_{SL}(B_s)$ and the measurements of $(\Delta\Gamma_s, \Phi_s)$.

Getting more difficult to get a coherent picture.



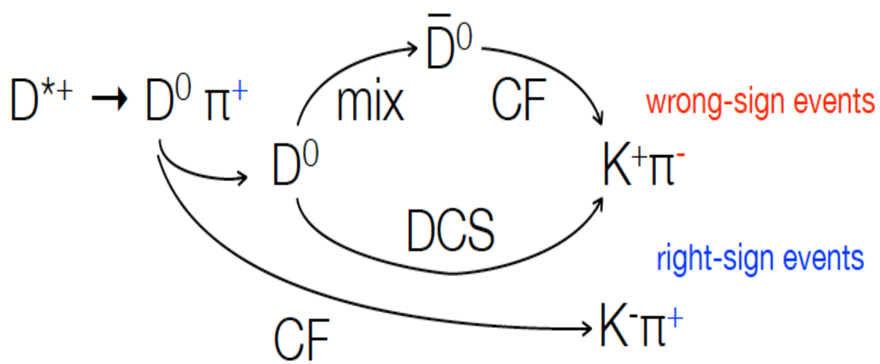
Δ F=2 box in c→u transitions: NP in charm mixing?

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



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 σ) by a single experiment until 2013!



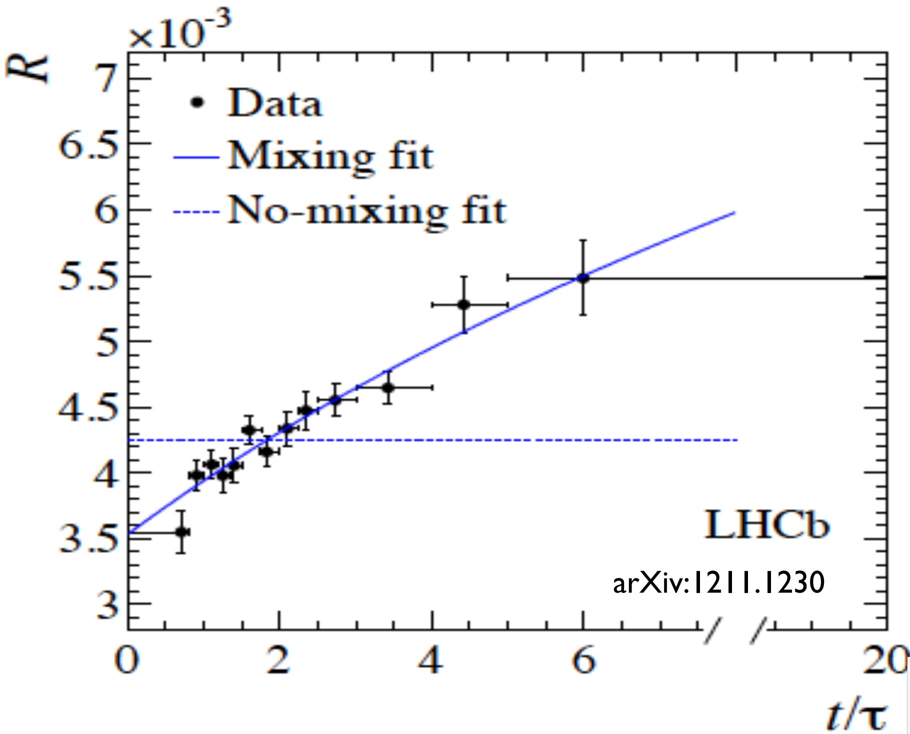
Assuming |x|,|y|<<1 and no CPV:

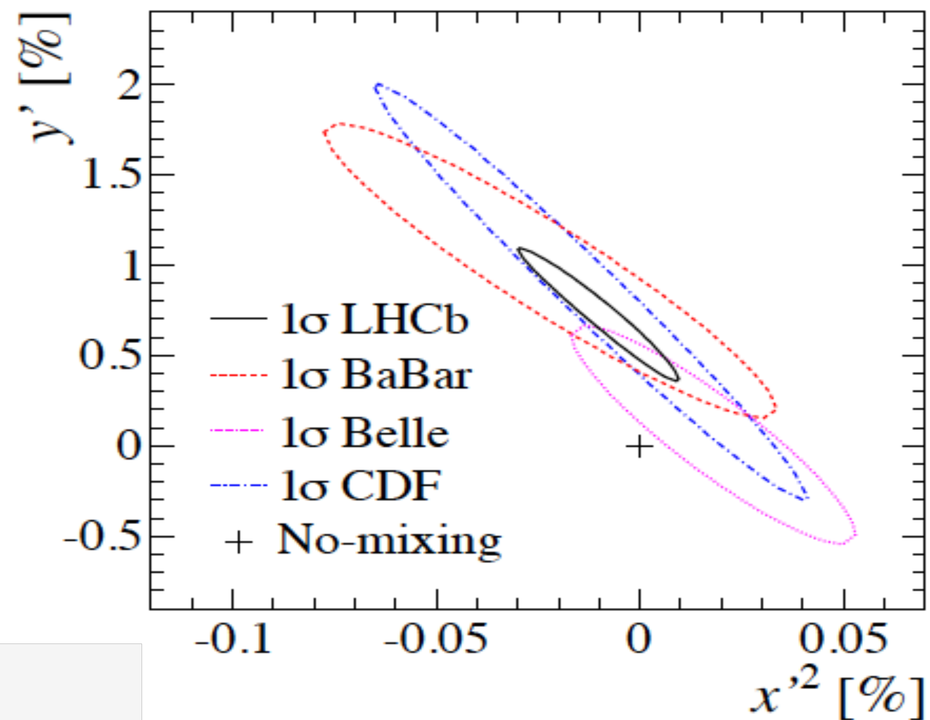
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2$$

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

$\Delta F=2$ box in c→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*→Dπ events. Charge of soft pion tags the D^0 flavour.





No mixing hypothesis excluded at 9.1 σ by LHCb.

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

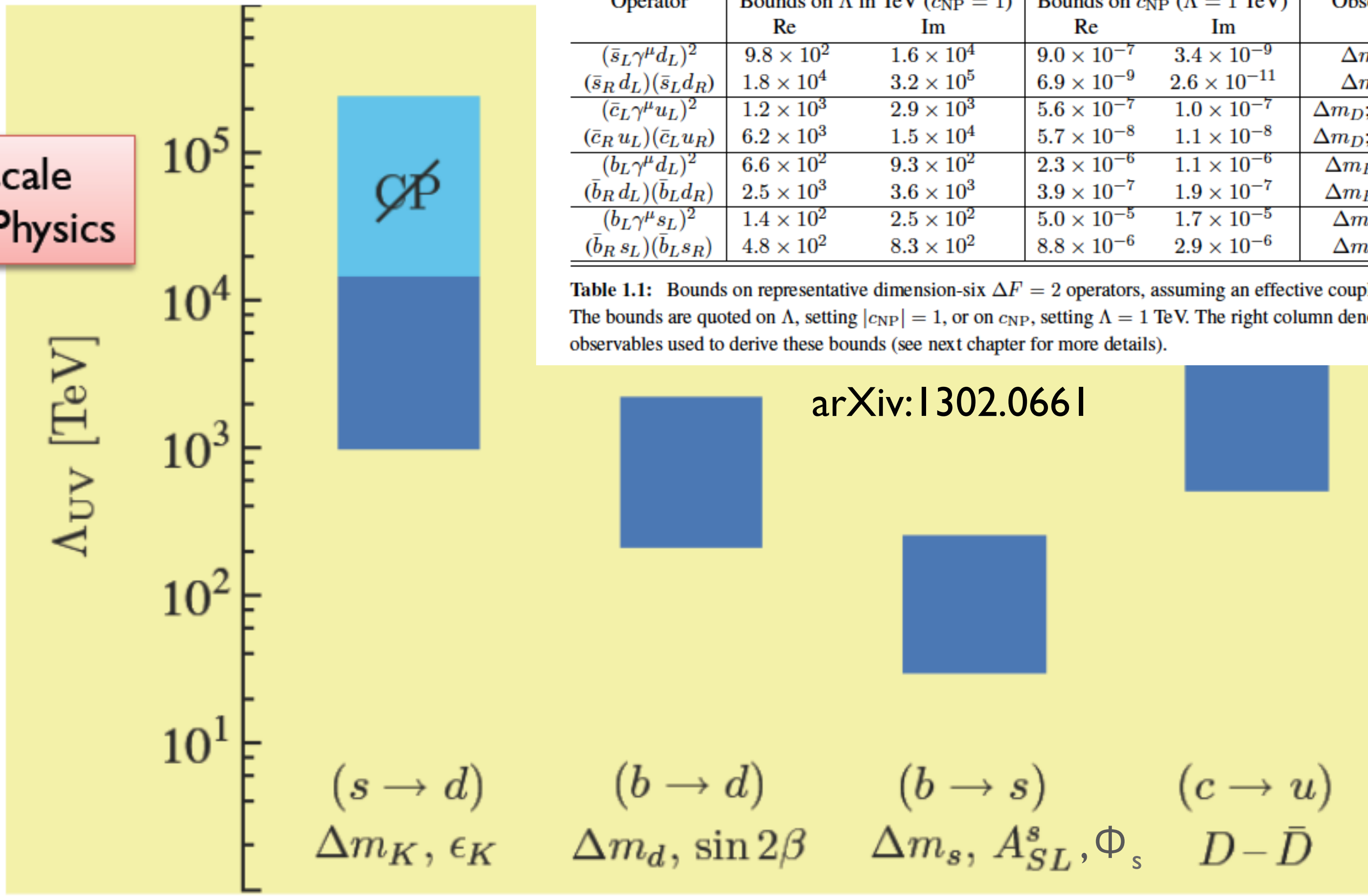
Δ F=2 box implications

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

Table 1.1: Bounds on representative dimension-six $\Delta F = 2$ operators, assuming an effective coupling c_{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).

arXiv:1302.0661

Mass scale of New Physics

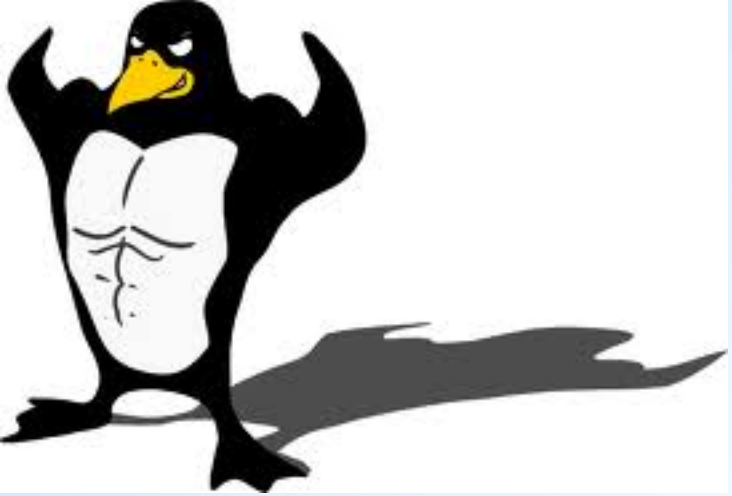


CP violation in K system

Oscillations and CPV in B_d system

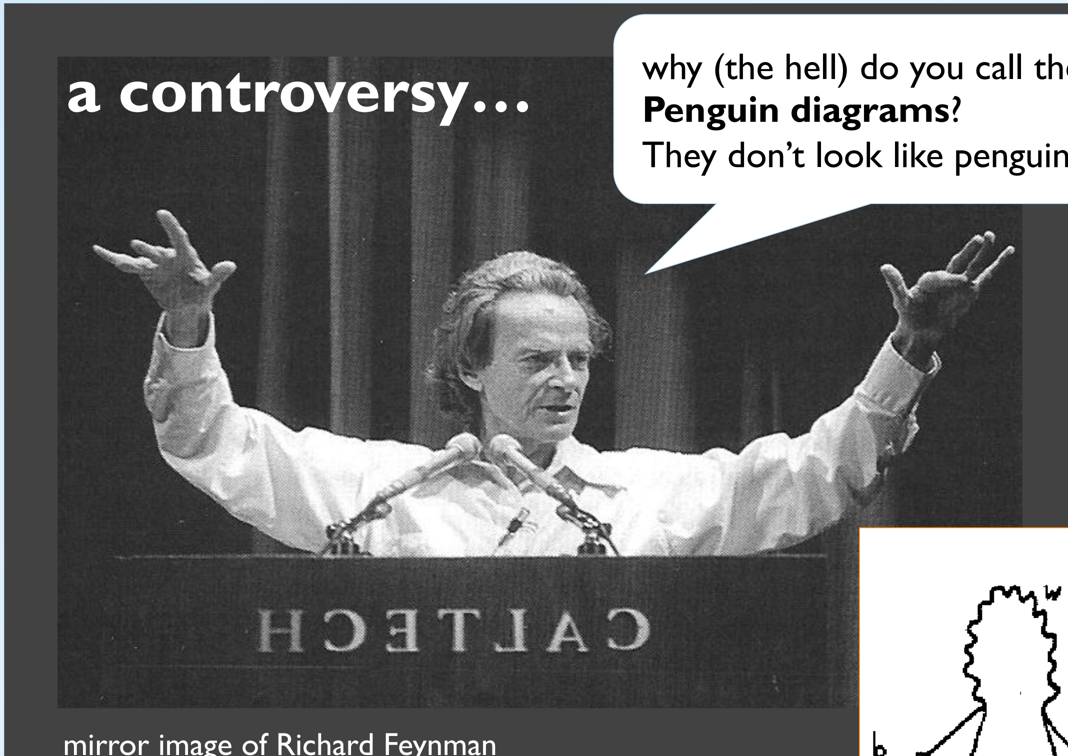
Oscillations and CPV in B_s system

Oscillations in D system



$\Delta F=1$ QCD Penguins

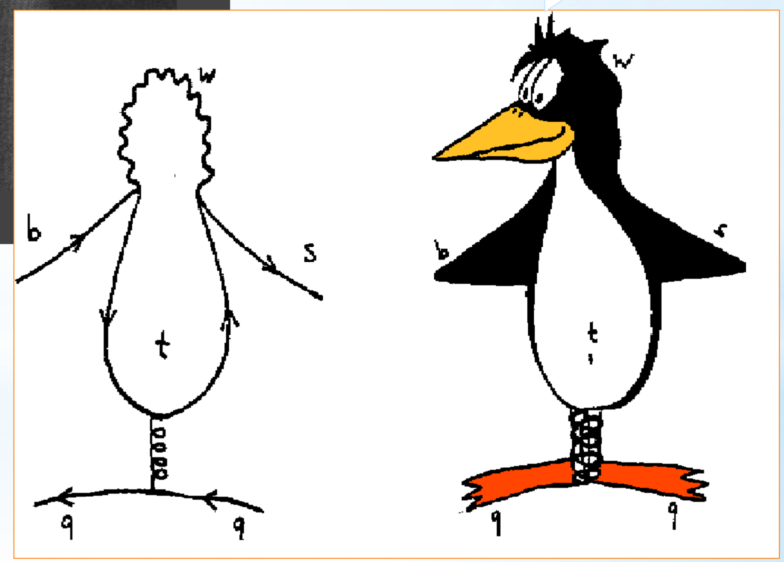
Why Penguins?



mirror image of Richard Feynman

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

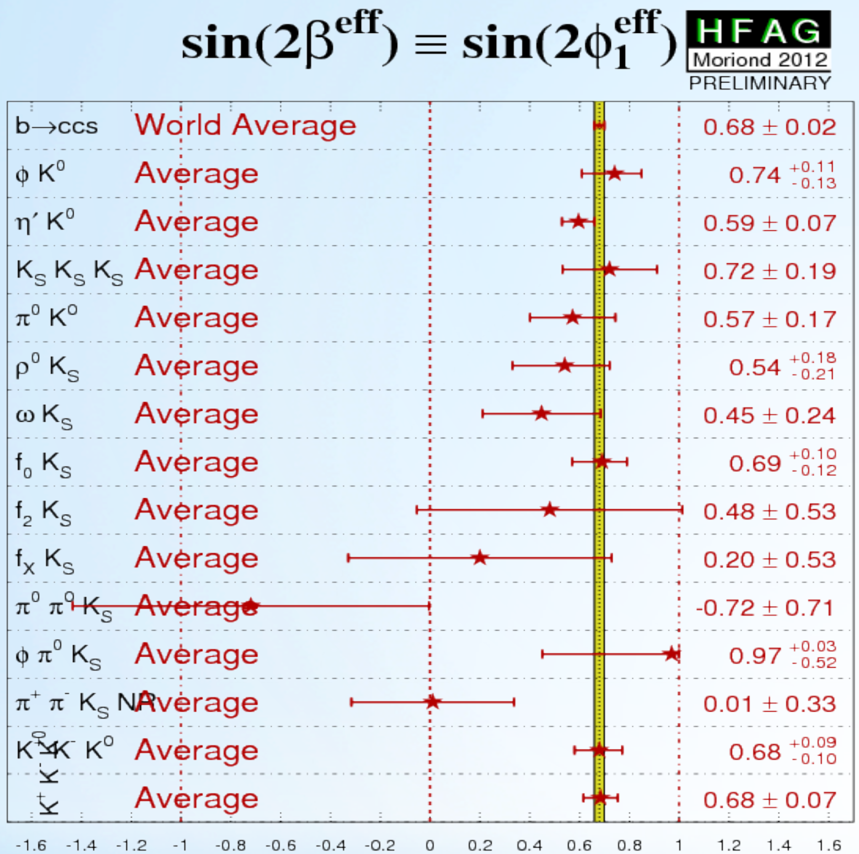
I've never seen a
Feynman diagram
that looks like **you** ☺

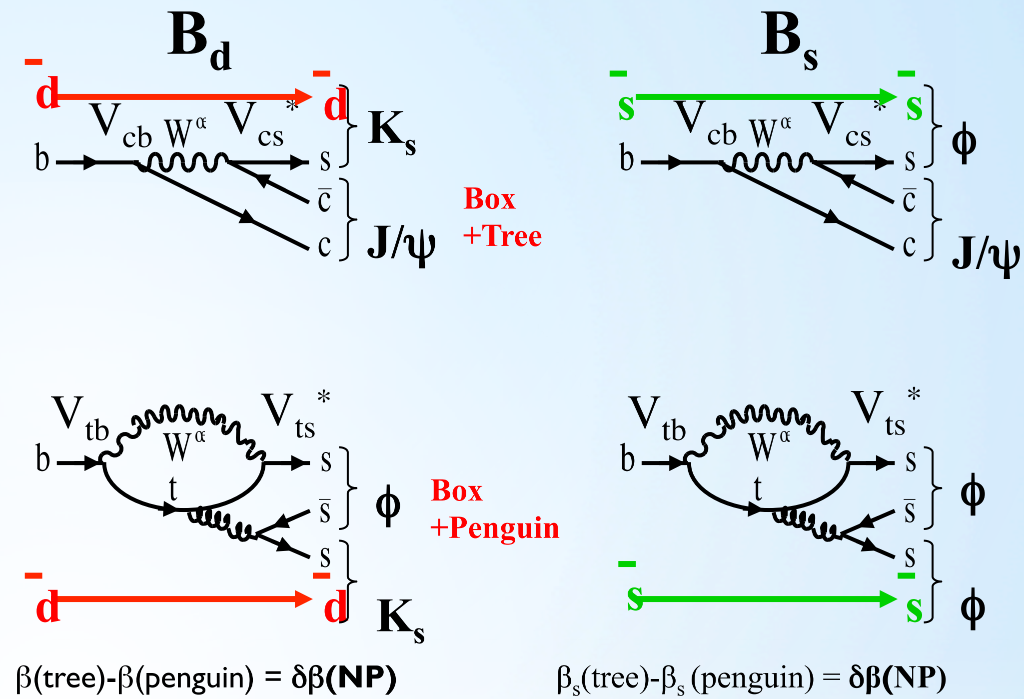


Taken from A. Hoecker Summer Student lectures at CERN (2006)

For the wikipedia version of the history, see:
http://en.wikipedia.org/wiki/Penguin_diagram

Δ F=1 b→s QCD penguins





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

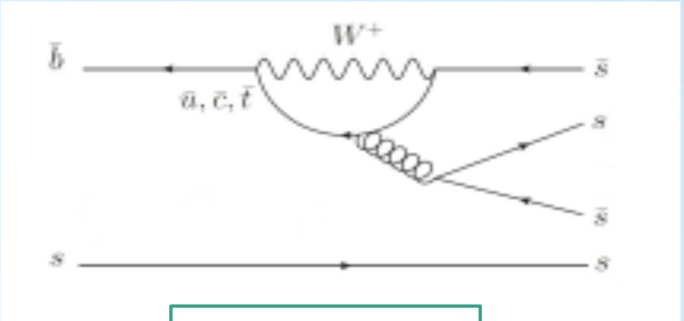
The effect of the same s-penguins can be measured at LHCb both in the B_d and B_s system.

Belle-II may improve further on B_d decays.

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

Δ F=1 box in b→s QCD penguin: $B_s \to \Phi\,\Phi$

The phase in the b→s box diagram is constrained to be small (within± 4.0° from direct or ± 0.9° indirect measurements).



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

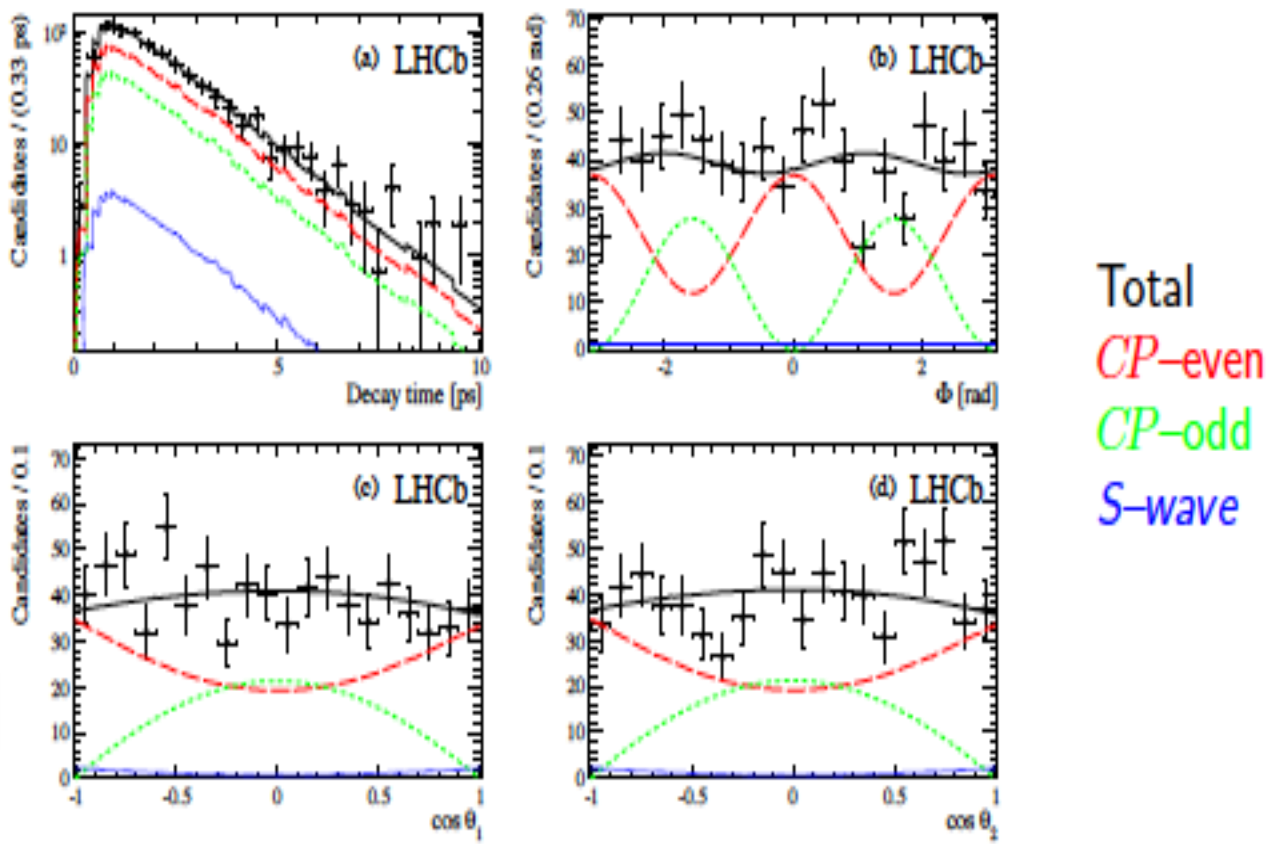
Angular analysis is needed in $B_s \to \Phi\,\Phi$ decays, to disentangle statistically the CP-even and CP-odd components.

εD^2 = (3.29 ± 0.48)%

arXiv:1303.7125

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

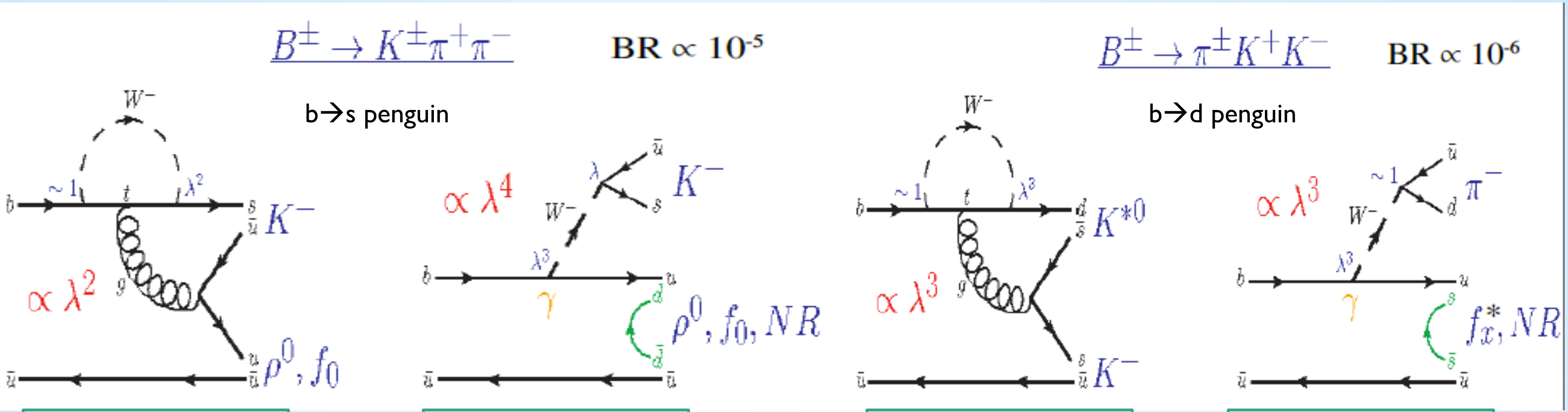
Φ_s is within [-136,-53)° at 68% CL



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

Still a long path to walk

ΔF=1 b→s,d QCD penguins: Direct CP violation in B→3h



($|V_{tb}V_{ts}| \alpha\ \lambda^2$) ($|V_{ub}V_{us}| \alpha\ \lambda^4$) ($|V_{tb}V_{td}| \alpha\ \lambda^3$) ($|V_{ub}V_{ud}| \alpha\ \lambda^3$)

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

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

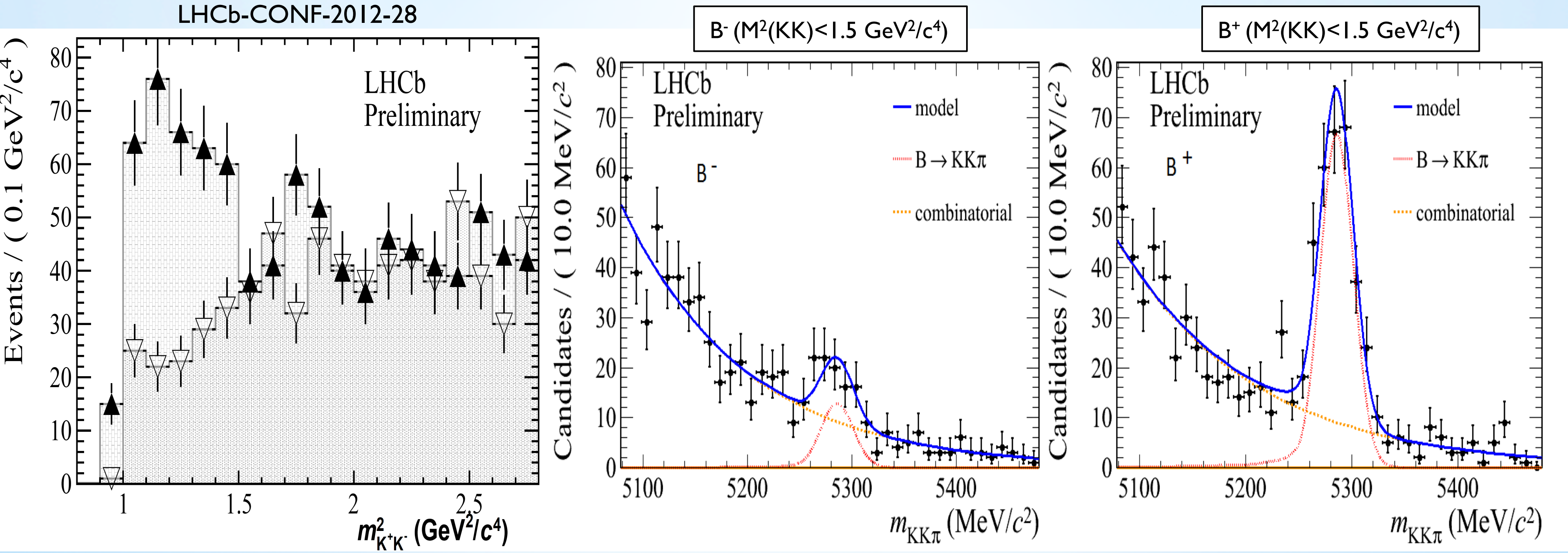
b→s QCD penguin (LHCb-CONF-2012-18)
$A_{CP}(B^\pm \to K^\pm\pi\pi)$=0.034±0.009±0.008
$A_{CP}(B^\pm \to K^\pm KK)$=-0.046±0.009±0.009

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

ΔF=1b→s,d QCD penguins: Direct CP violation in B→3h

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

LHCb-CONF-2012-28

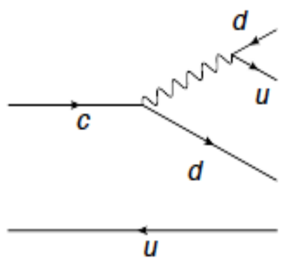


Some kind of hadron dynamics is working to generate such large A_{CP}.

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

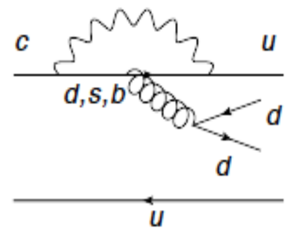
$$A_{CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)},$$

Tree



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

QCD penguin



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

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

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

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

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

There is no problem to enhance this 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→ππ)~2.8 B(D→KK).

$D^{*\pm} \to D^0\ [h^+h^-]\ \pi^\pm$ 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.

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

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

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

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

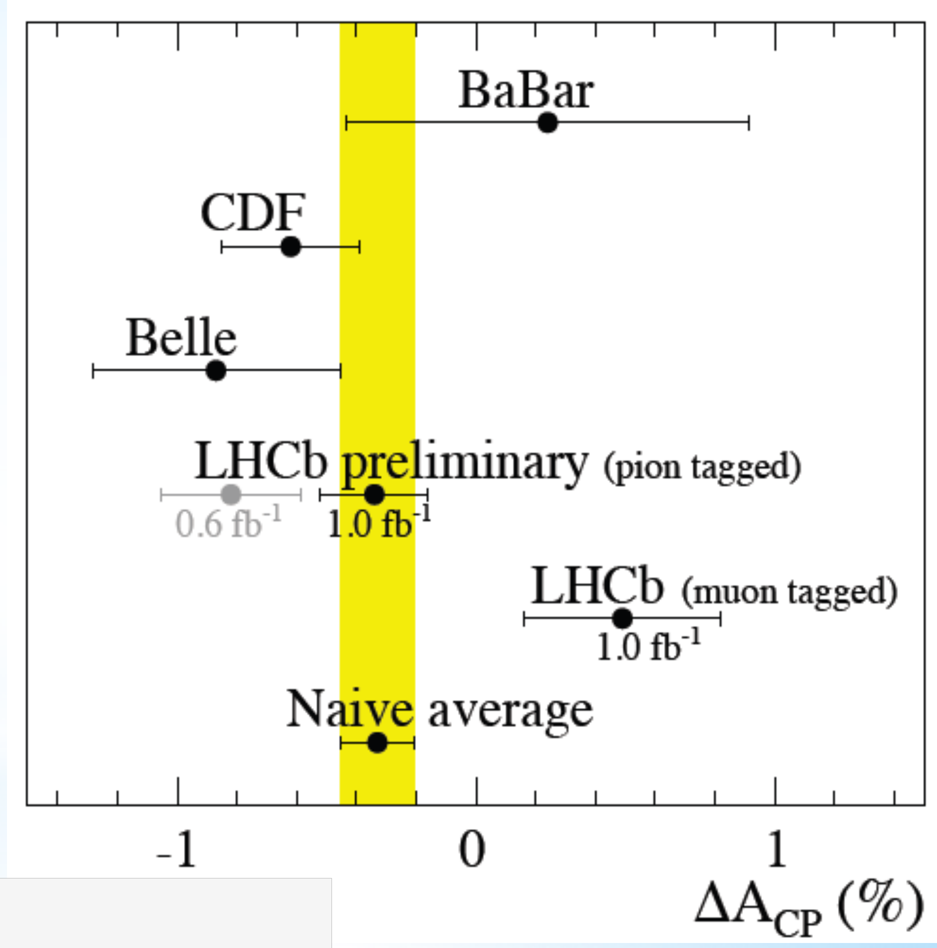
ΔA_{CP}=(-0.34±0.18)% LHCb (1/fb) (LHCb-CONF-2013-003)

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

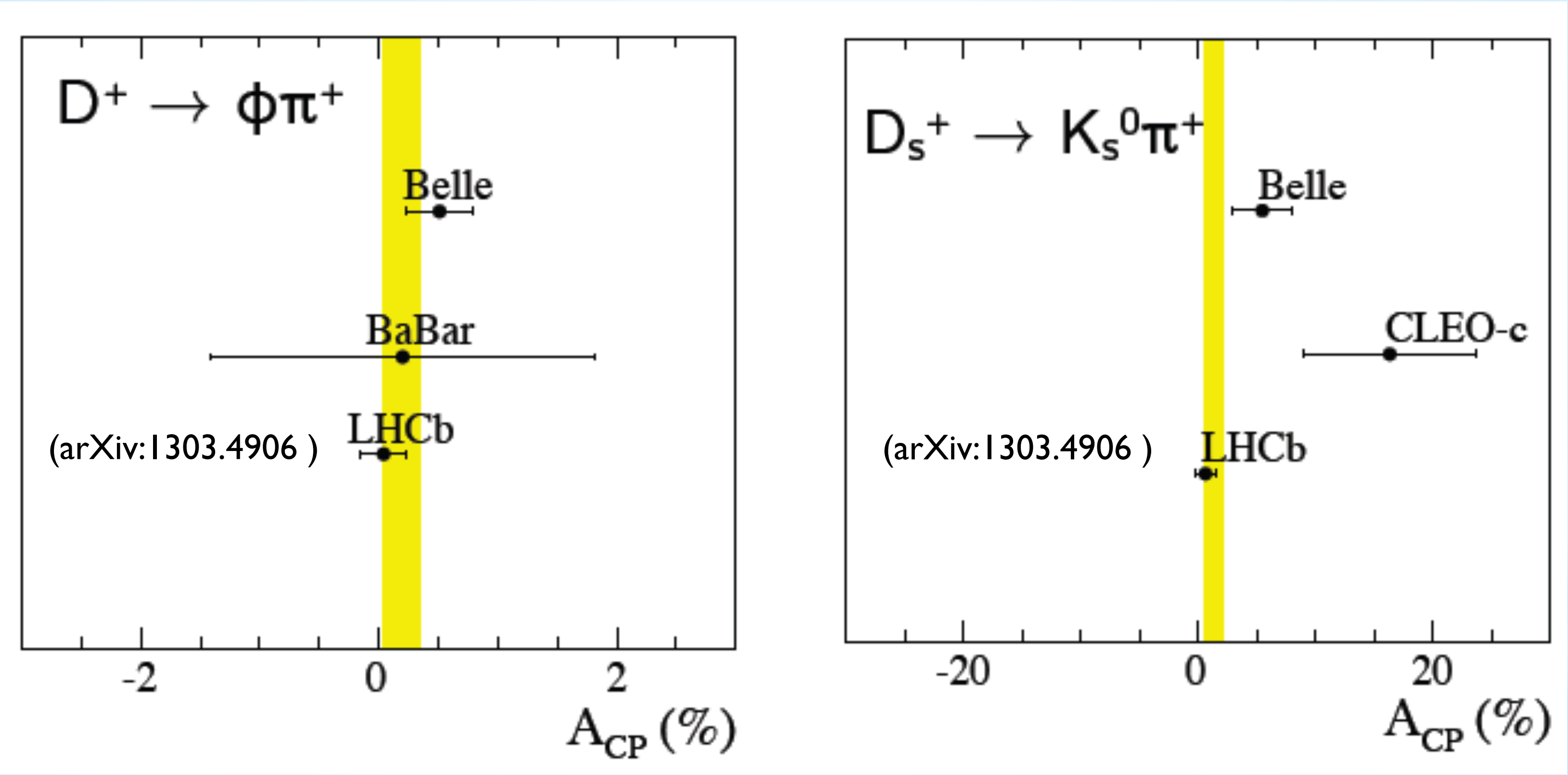
ΔA_{CP}=(0.49±0.33)% LHCb (semil, 1/fb)
(arXiv:1303.2614)

Naïve average
ΔA_{CP}= (-0.33 ± 0.12)%
p-value average=3.7% (2.1 σ)

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



Moreover, LHCb has also searched for direct CP violation in other charm decays, $\mathbf{D^+ \rightarrow \Phi\pi^+}$ and $\mathbf{D_s^+ \rightarrow K_s\pi^+}$. The Cabbibo favoured modes are used to subtract production and detection asymmetries.



No evidence for CP violation in D^+ decays at the 0.2% level.

$\Delta F=1$ QCD penguins: Personal Recap.

Many interesting measurements involving QCD penguins… but can we ever be sure what we see is not our limitations to do SM calculations?

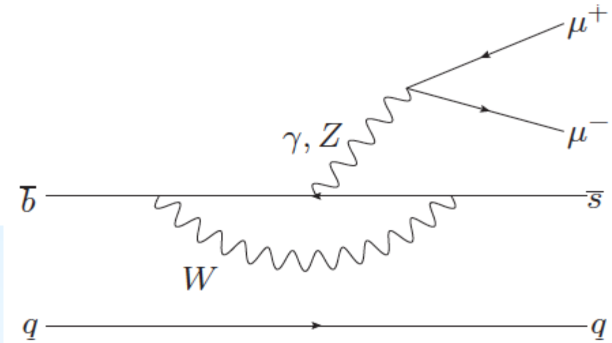
On the other hand, by cleverly combining different measurements we may be able to understand better hadronic physics.

But for now… let's move towards my favorite penguins.

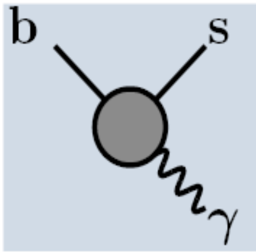
ΔF=1 EW Penguins

Δ F=1 EW penguins in b→s transitions: Theoretical framework

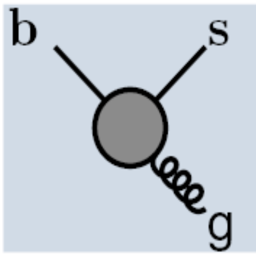
$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + {\rm h.c.}$$



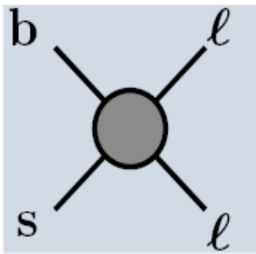
$\mathcal{O}_{7\gamma}$



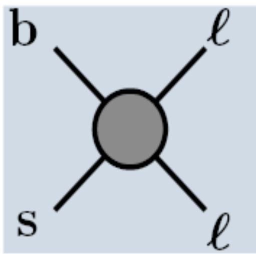
$\mathcal{O}_{8g}$



$\mathcal{O}_{9\ell,10\ell}$



$\mathcal{O}_{S,P}$



Describe b→s transitions by an effective Hamiltonian.

Long distance effects absorbed in the definition of the operators O_i, while the interesting short distance can be computed perturbatively in the Wilson coefficients C_i.

$$O_7 = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2} (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a},$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

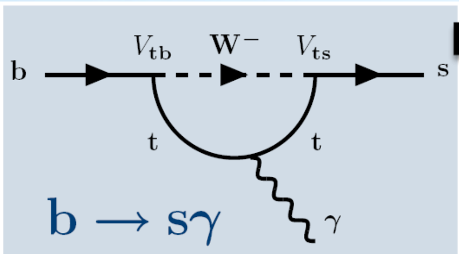
$$O_S = m_b (\bar{s} P_R b)(\bar{\ell}\ell)\,, \qquad O_P = m_b (\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)\,,$$

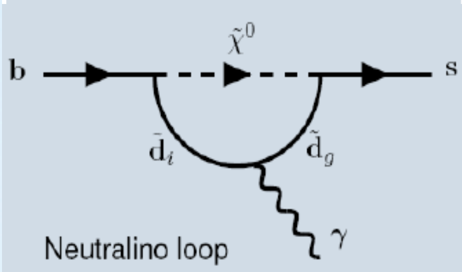
Three impersonations of the EW penguin

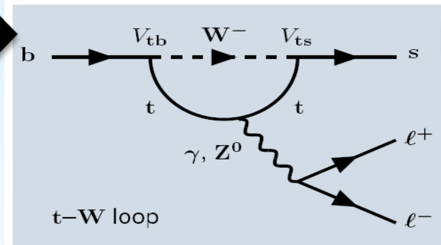
α_{QED} suppression → helicity suppression

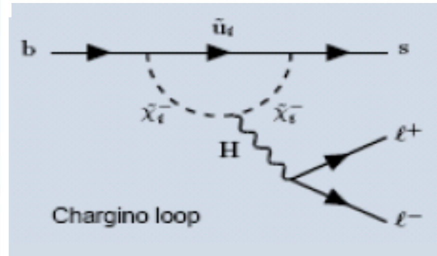
SM

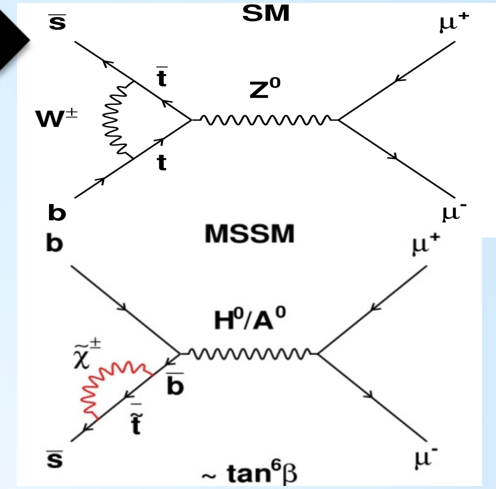
MSSM





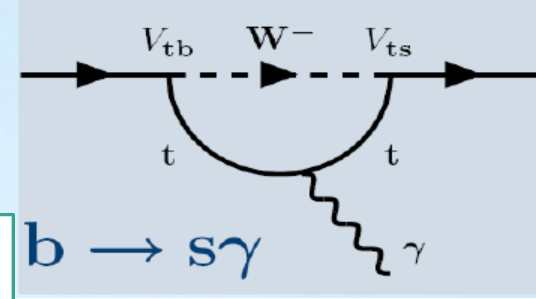






	Relevant Operators	*BR*(SM)	*BR* exp	
$B_s \rightarrow \phi\gamma$	$\mathcal{O}_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	Large theory uncertainties O(20%)	$(3.5\pm0.4)\cdot10^{-5}$ LHCb: arXiv:1209.0313	γ polarization
$B^0 \rightarrow K^*\mu^+\mu^-$	$\mathcal{O}_{7\gamma} \sim m_b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

Radiative Decays



The inclusive process has been measured at the B-factories/CLEO/LEP very precisely,

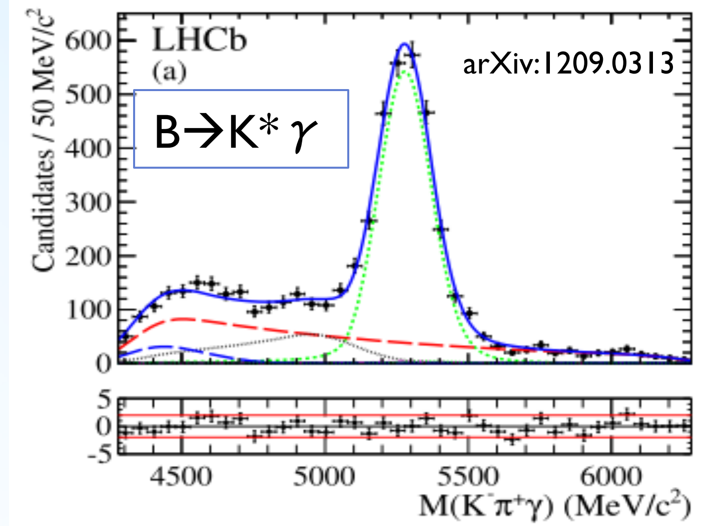
$b \to s$ ($|V_{tb}V_{ts}|$ α λ^2)

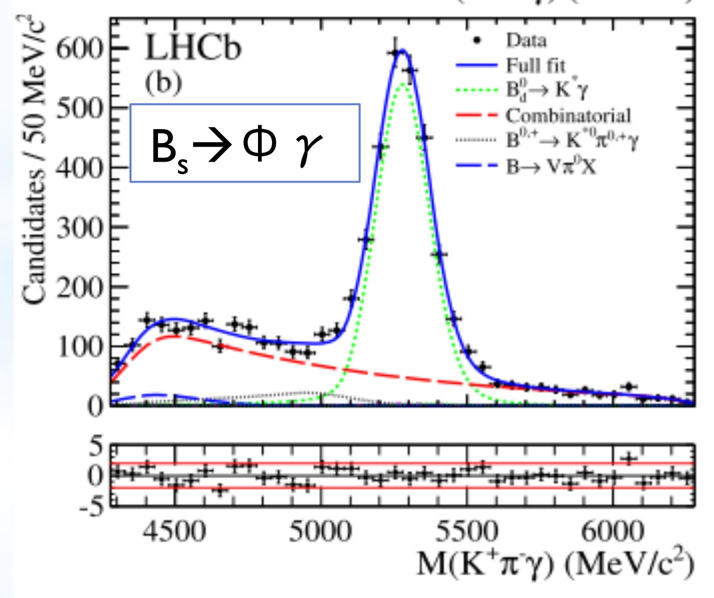
BR($b \to s\gamma$) = (3.55±0.26)x10^{-4}
in agreement with the SM prediction (3.15±0.23)x10^{-4}

Known as one of the strongest constraint in MSSM, together with the Higgs mass measurement, only O(%) of the a-priory phase space left! Sensitive to O_7.

Inclusive measurements difficult at hadron colliders. However, exclusive radiative decays are copiously measured **at LHCb**, with 1/fb (**5.3k $B \to K^*\gamma$, 0.7k $B_s \to \Phi\gamma$** candidates), measures:

BR($B \to K^*\gamma$)/BR($B_s \to \Phi\gamma$)=1.23±0.06(stat)±0.12(syst)

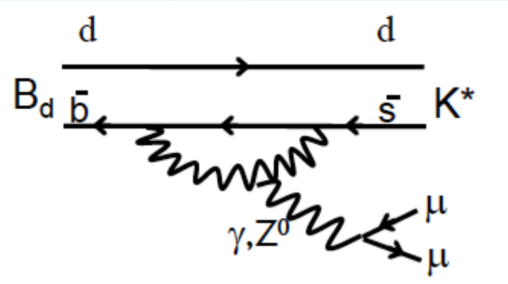




and using the world average for BR($B \to K^*\gamma$) gives:

BR($B_s \to \Phi\gamma$)= (3.5 ± 0.4)•10^{-5}

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



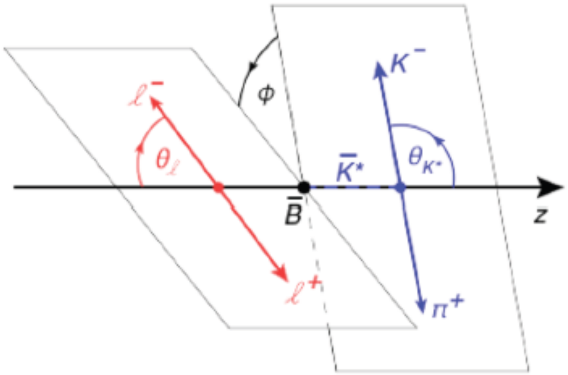
B→K* μ μ is the golden mode to test new vector(-axial) couplings in b→s transitions.

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

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.

Folding technique ($\Phi \to \Phi+\pi$) for $\Phi<0$, reduces the number of parameters to fit:

$$\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} \propto F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\phi + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\phi$$



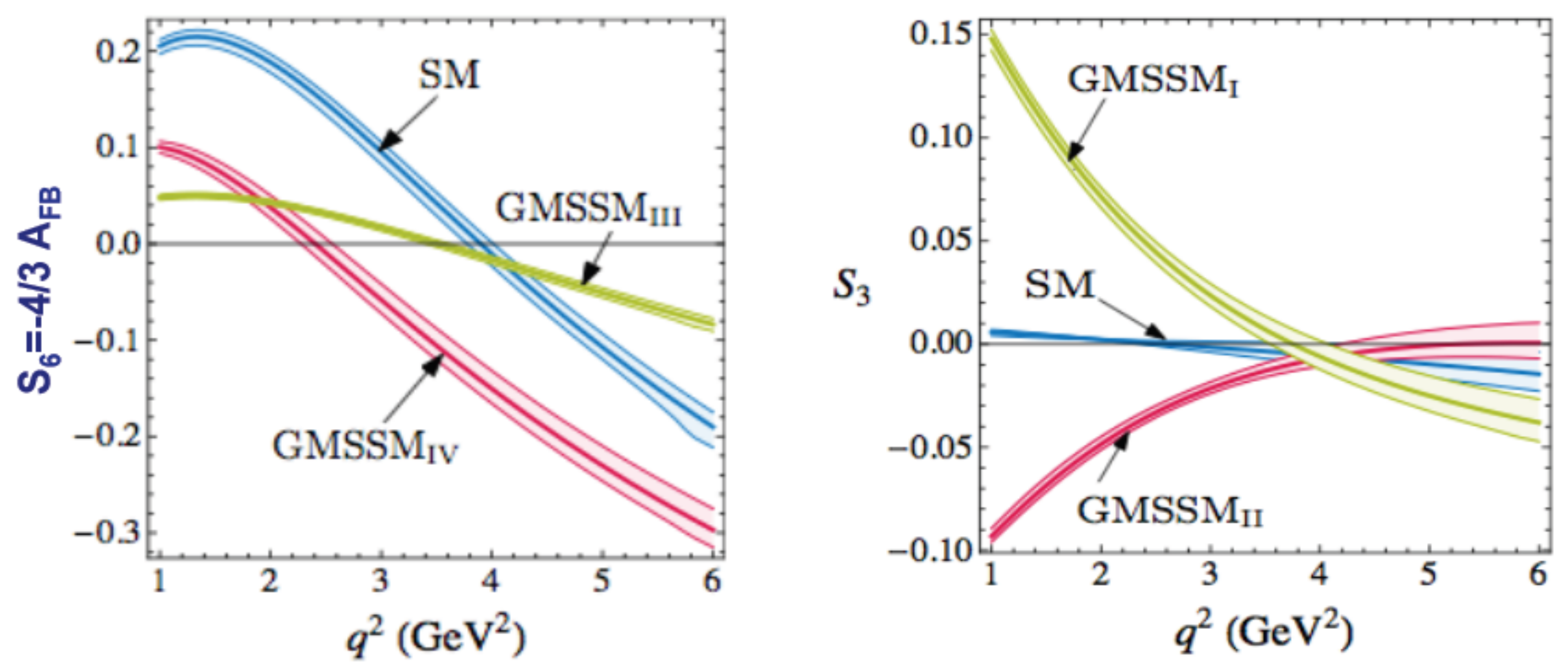
Results from **B-factories and CDF** very much limited by the statistical uncertainty. **LHCb** already has with 1/fb the largest sample (0.9k candidates).

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

Hadronic uncertainties under control for:

- **F_L:** Fraction of K* longitudinal polarization.
- **A_{FB}**: Forward-Backward asymmetry of the lepton.
- **S_3** α $A^2_T(1-F_L)$: Asymmetry in K* transverse polarization.
- **A_{IM}**, T-odd CP asymmetry.

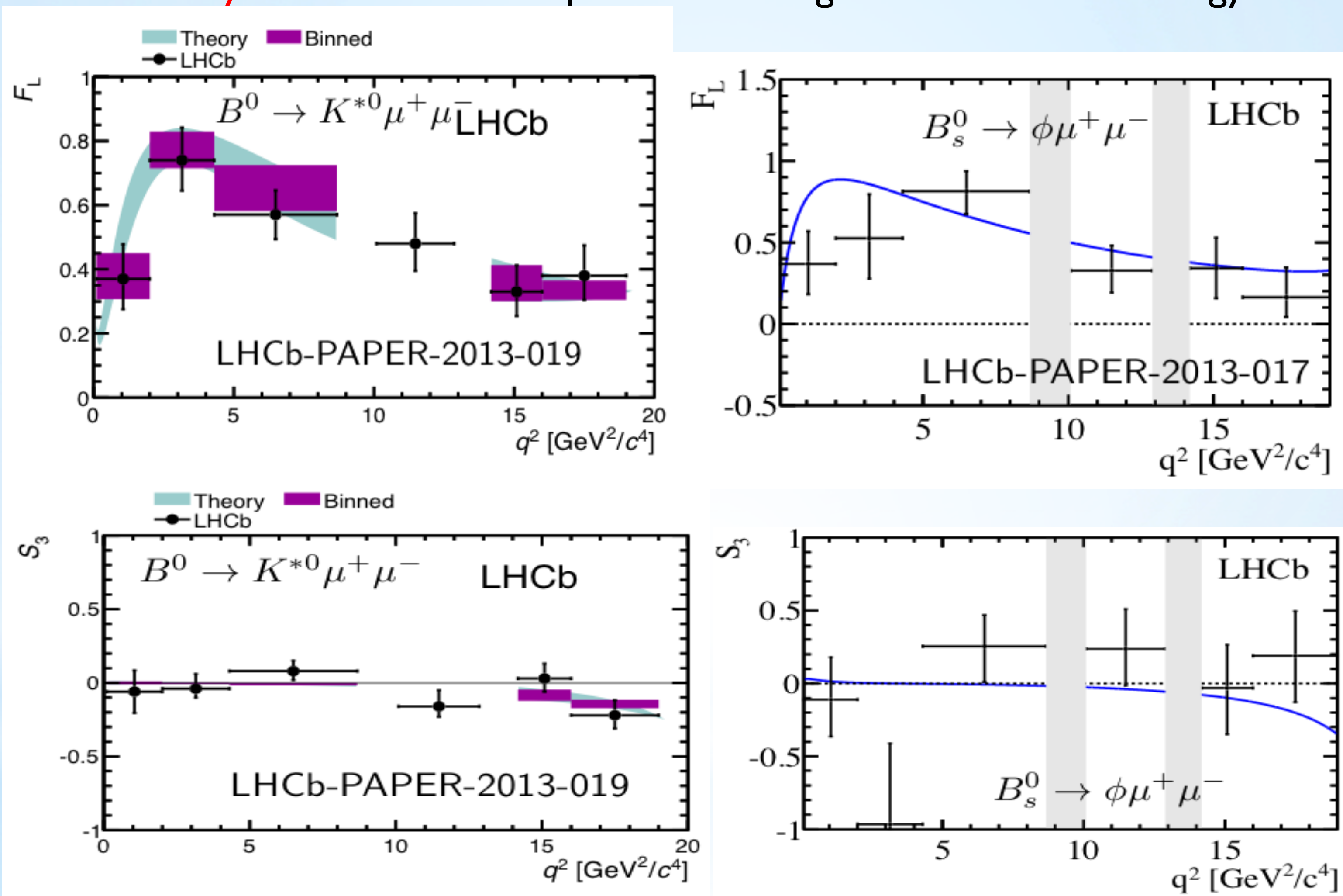
W.Altmannshofer et al. [arXiv:0801.1214]



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

$B \rightarrow K^* \mu\mu$ ($B_s \rightarrow \Phi \mu\mu$) angular analysis

LHCb measures also ~0.17k $B_s \rightarrow \Phi \mu\mu$ candidates with 1/fb. This decay is not self tagging, hence no sensitivity to AFB without explicit flavour tag. Otherwise the strategy is very similar.

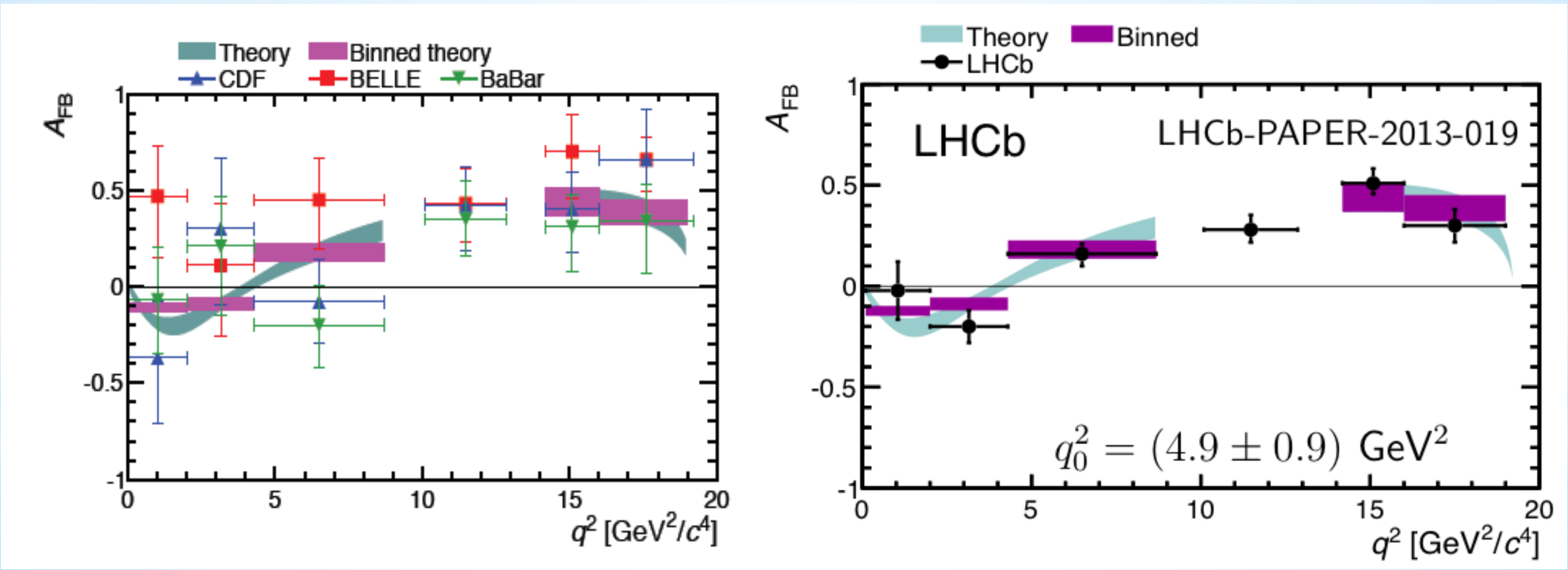


Within uncertainties F_L and S_3 are consistent with the SM and between B_d and B_s.

A_{FB} vs q^2 found to be in good agreement with SM predictions. LHCb precision allows for the first determination of the zero-crossing point:

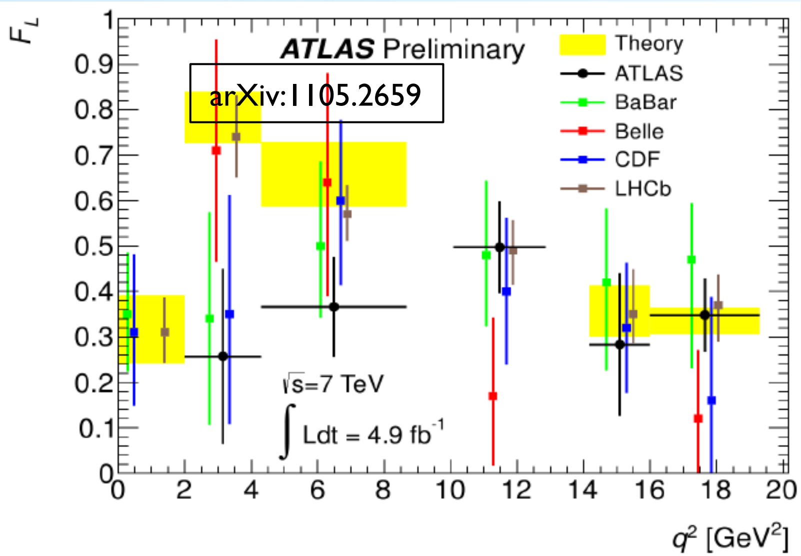
LHCb Preliminary: $\boxed{q^2(A_{FB}=0)=4.9\pm0.9\ \mathrm{GeV}^2/c^4}$

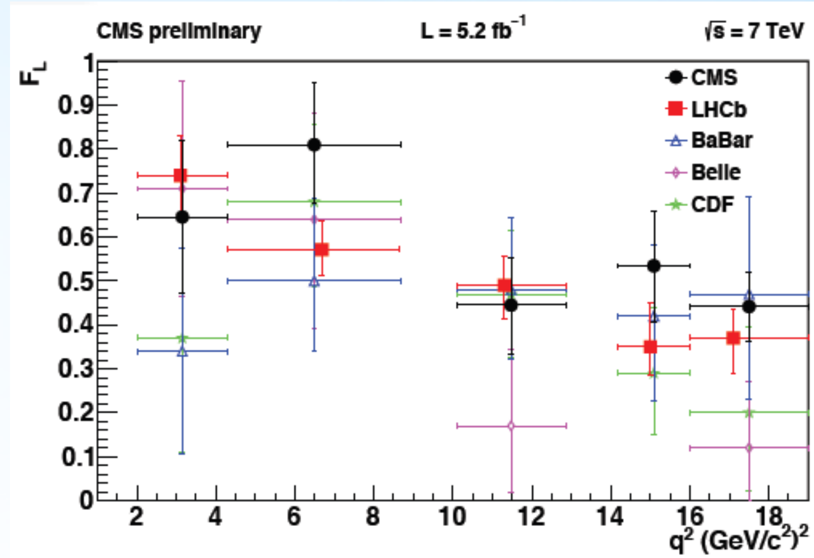
Other theoretical clean observables are available with larger statistics.

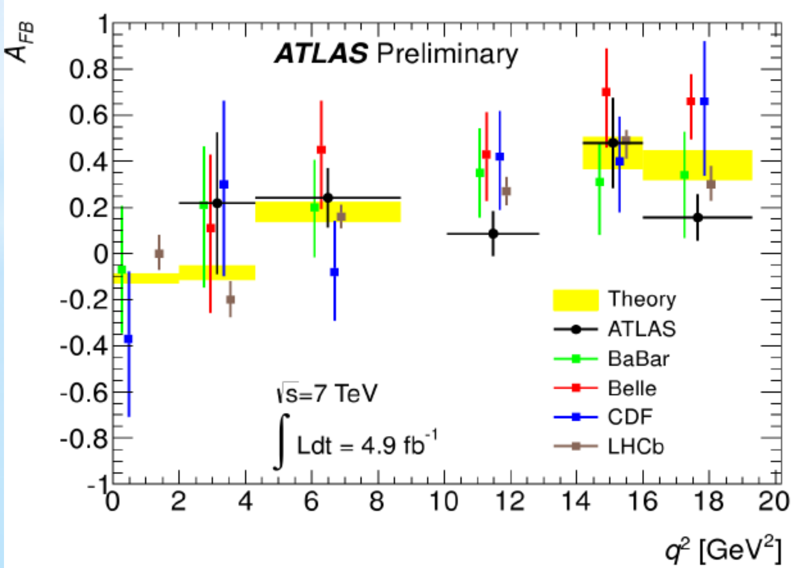


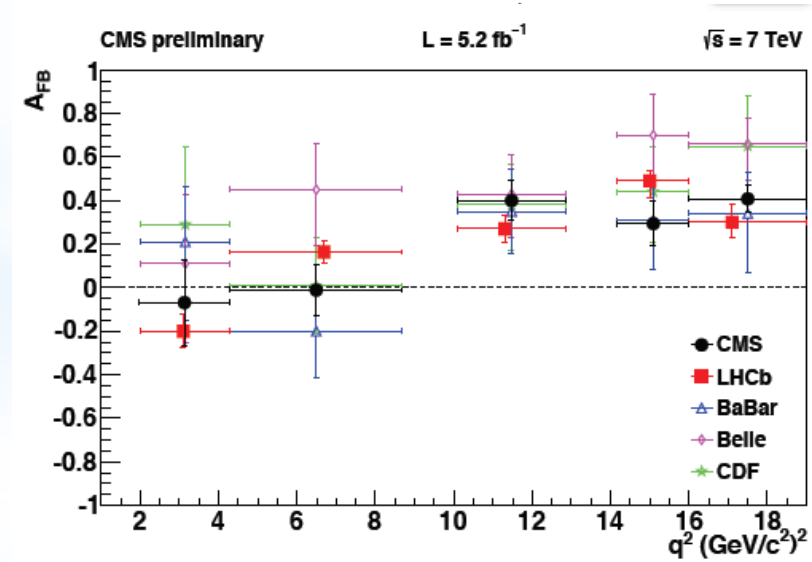
ATLAS, CMS B→K* μ μ angular analysis

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









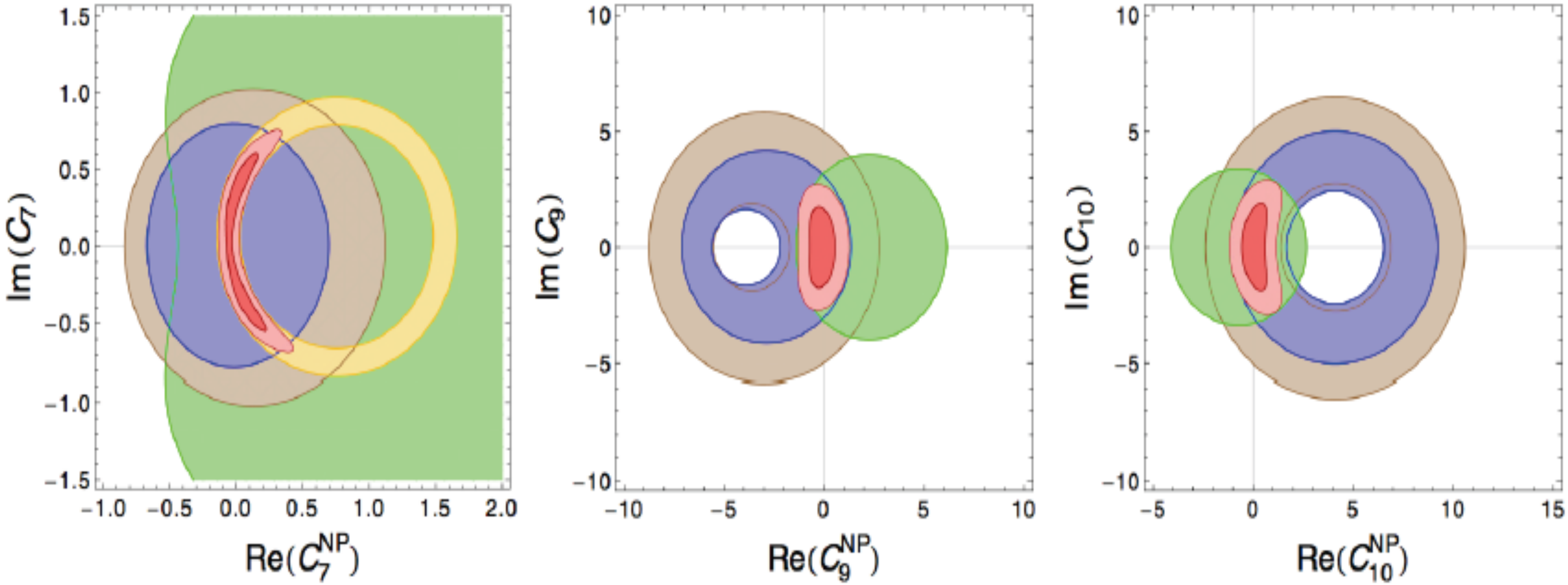
Δ F=1 EW penguins in b→s transitions: Implications

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\, a},$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell),$$

$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell), \qquad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell),$$

arXiv:1111.1257



BR($B \to X_s \ell^+\ell^-$) BR($B \to X_s\gamma$) BR($B \to K^*\mu^+\mu^-$) A_{FB}($B \to K^*\mu^+\mu^-$)

Complementarity of observables allow full scan of NP models.

The vector(-axial) operators (O_9, O_{10}) are very much constrained by $B \to K^* \mu\ \mu$.

Radiative decays are good at constraining O_7 and O_8.

$B_{(s)} \to \mu\ \mu$ is very effective to constrain O_S and O_P.

Agreement with SM implies (as in $\Delta F=2$ processes) strong limits:

Either the scale of NP is in the range >15 TeV for couplings O(1) or if the couplings are loop suppressed the scale of NP is constrained to be typically >0.3 TeV in a model independent approach.

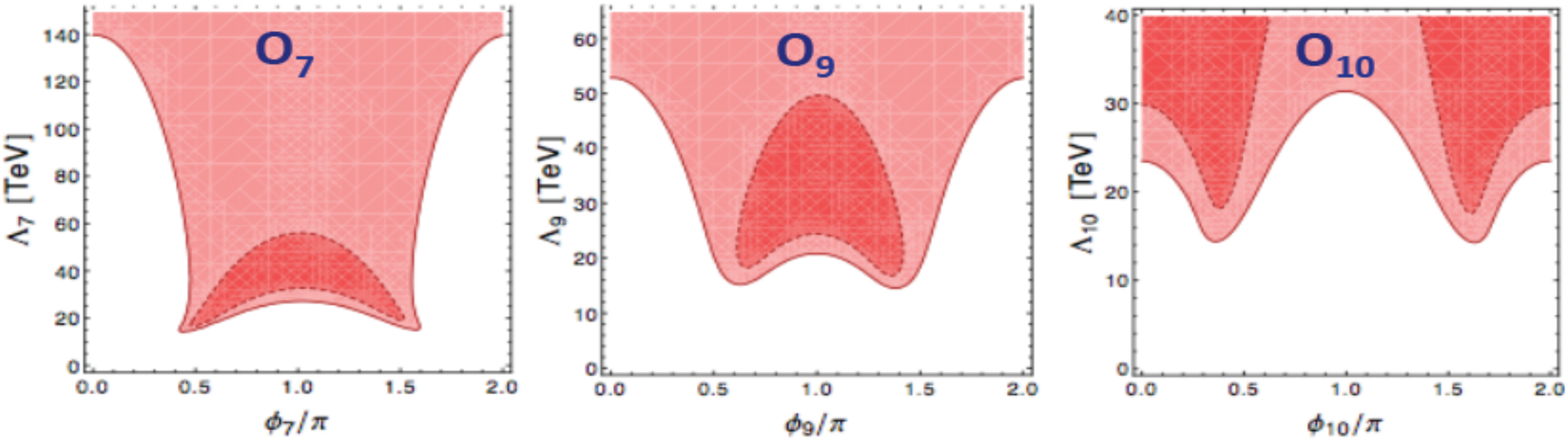
Within a given model, like SUSY scenarios, correlations between observables may push the scale of NP further away.

Δ F=1 EW penguins in b→s transitions: Implications

Tree level flavour violation

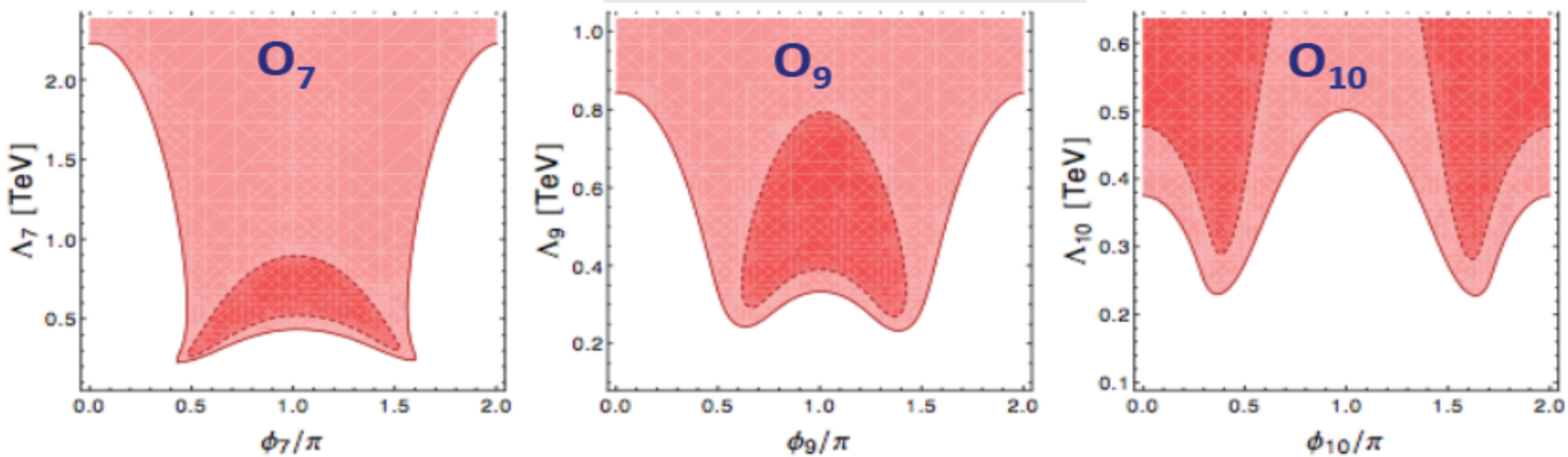
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2}\mathcal{O}_j$$

D. Straub, arXiv:1111.1257, JHEP 1202:106



Loop level CKM-like flavour violation

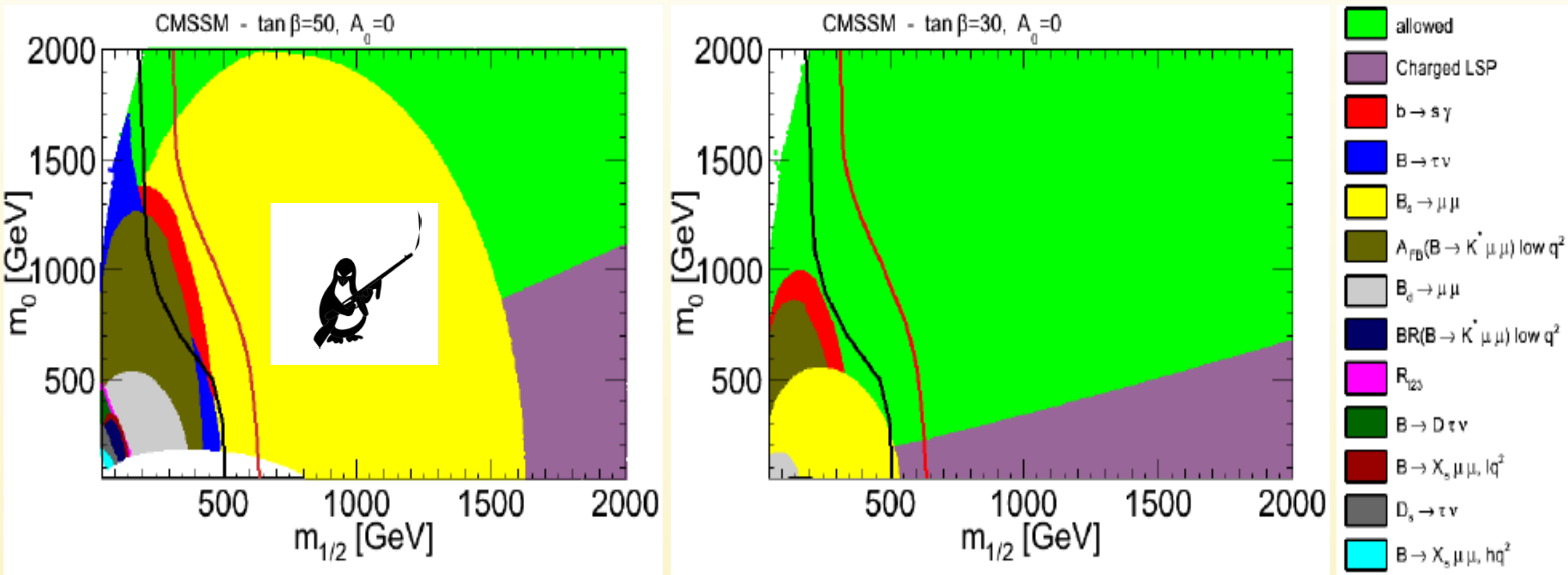
$$\mathscr{L} = \mathscr{L}_{\rm SM} - \sum_{j=7,9,10} \frac{V_{tb}V_{ts}^*}{16\pi^2}\frac{e^{i\phi_j}}{\Lambda_j^2}\mathcal{O}_j$$



B→K* μ μ implications within CMSSM

Take the example of CMSSM… B→K* μ μ implies similar constrains as from the inclusive b→s γ with as yet only 1/fb of data analyzed at LHCb.

N. Mahmoudi, arXiv:1205.3099

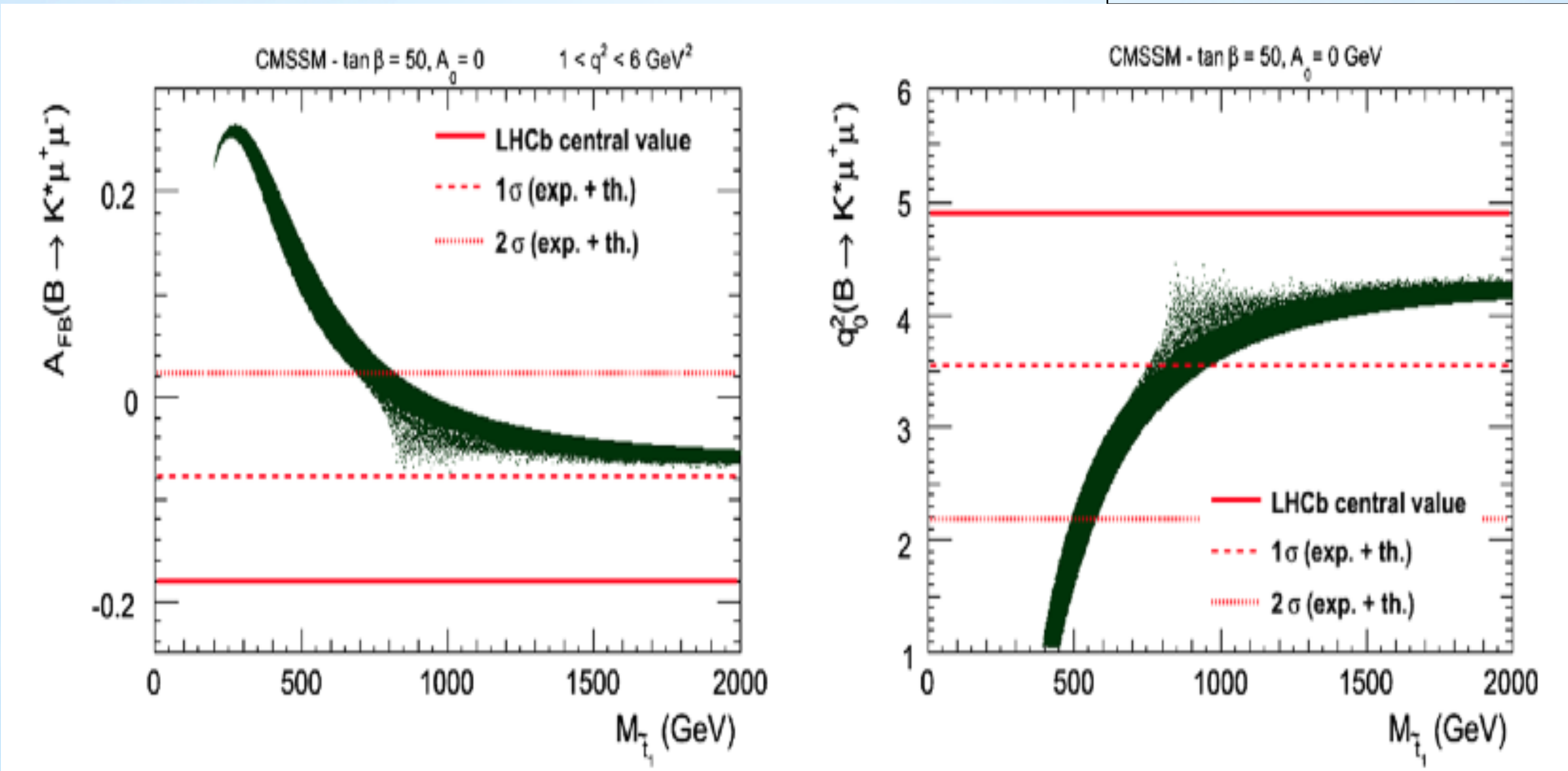


Black line: CMS exclusion limit with 1.1 fb^{-1} data

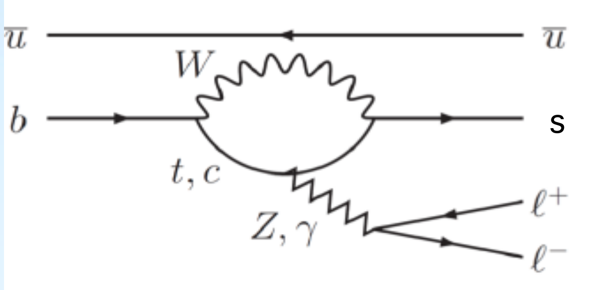
Red line: CMS exclusion limit with 4.4 fb^{-1} data

Take the example of CMSSM…

N. Mahmoudi, arXiv:1205.3099



ΔF=1 EW penguins in b→s transitions: $B^{\pm}\rightarrow K^{\pm}\mu\mu$



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

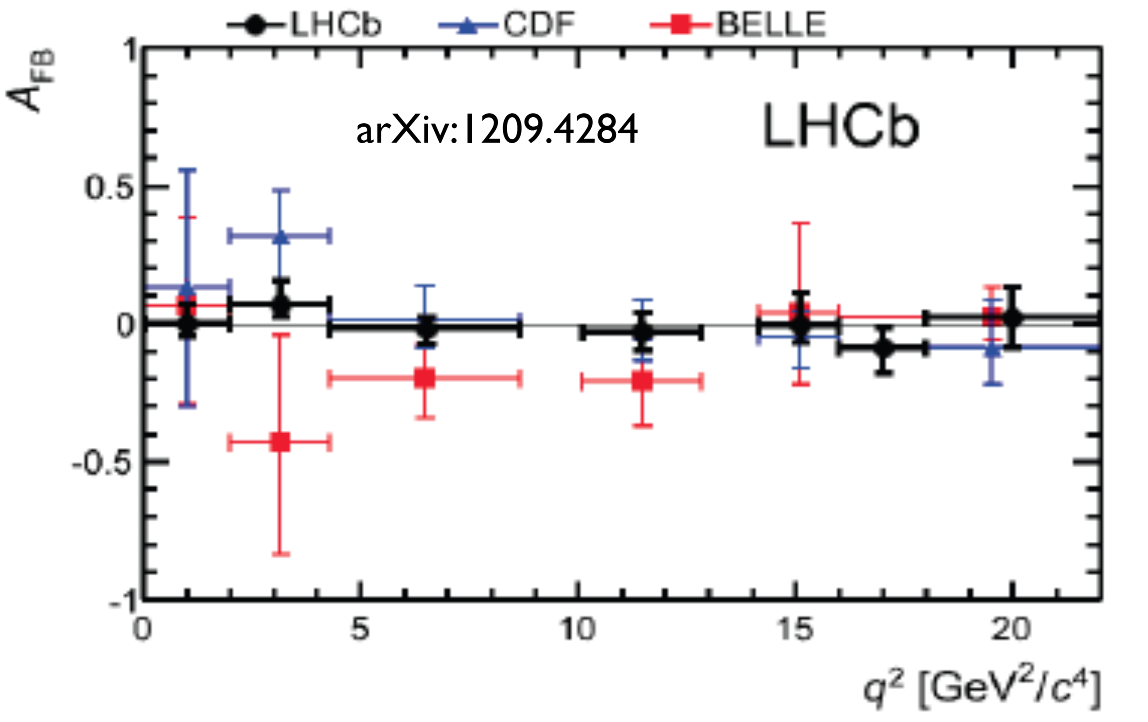
The decay $B^{\pm}\rightarrow K^{\pm}\mu\mu$ is complementary to $B\rightarrow K^{*}\mu\mu$, as the spin of $K^{\pm}$ implies much larger sensitivity to new scalar and tensor contributions.

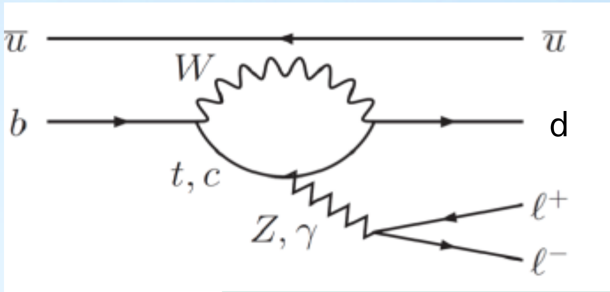
Angular analysis only depends on one angle, and A_{FB} is expected to be very close to zero in the SM.

LHCb measurement:

BR($B^{\pm}\rightarrow K^{\pm}\mu\mu$)= $(4.36\pm0.15\pm0.18)\times10^{-7}$

compared with previous W.A. $(4.8\pm0.4)\times10^{-7}$





$b \to d$ ($|V_{tb}V_{td}| \alpha \lambda^3$)

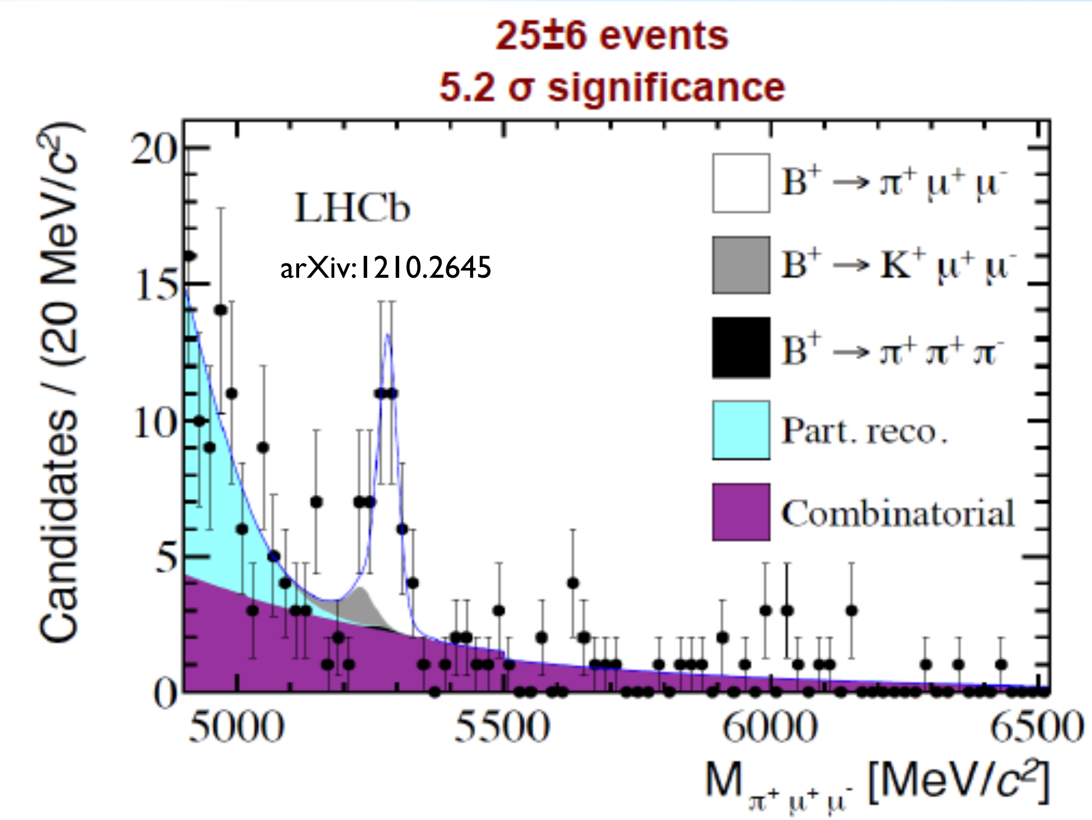
The decay $B^\pm \to \pi^\pm \mu\mu$ is suppressed by $|V_{td}|/|V_{ts}|$.

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

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

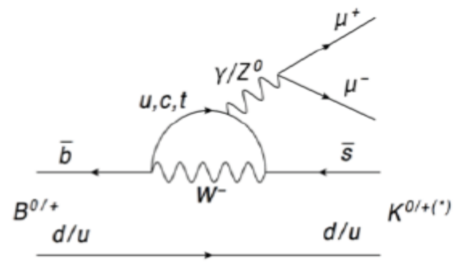
in agreement with SM expectations.

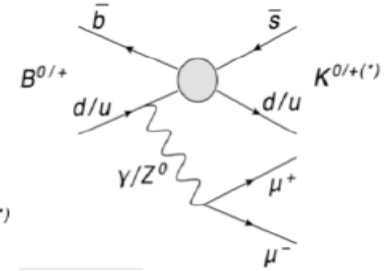
The rarest B decay ever observed, as we wait for $B_s \to \mu\mu$ to reach 5σ.



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

# of evts	BaBar 2012 471 M $B\bar{B}$	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

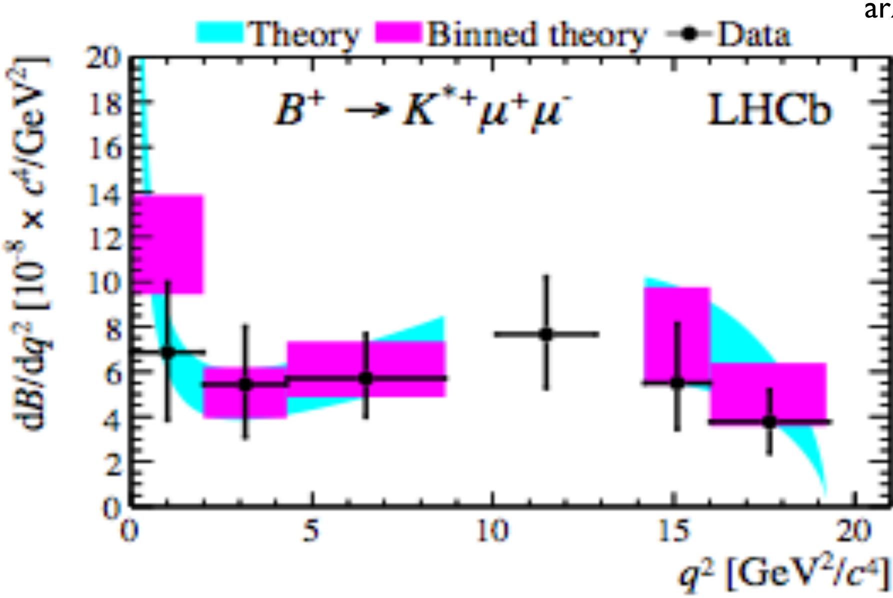


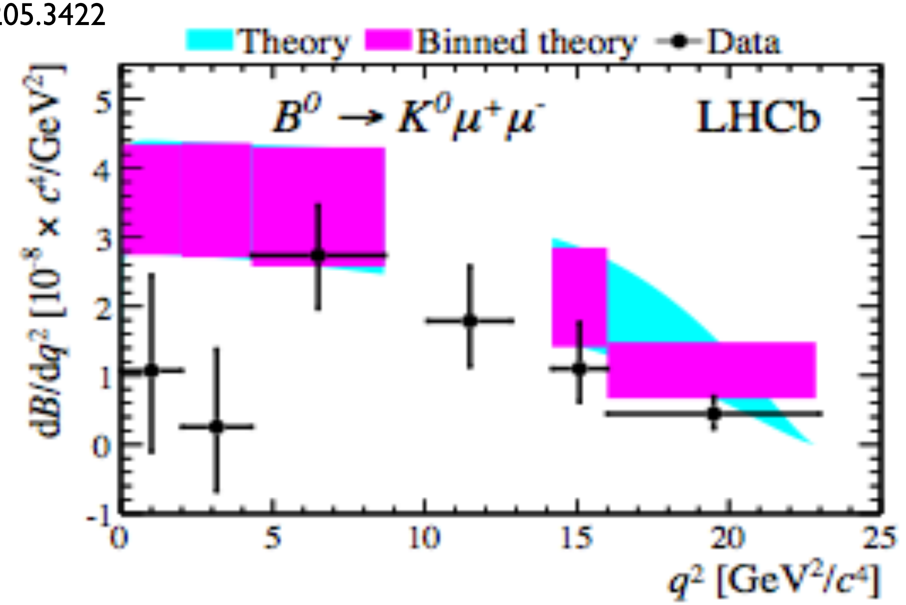


$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

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 q^2) → A$_I$(B→K* γ)=0.07±0.03.

arXiv:1205.3422

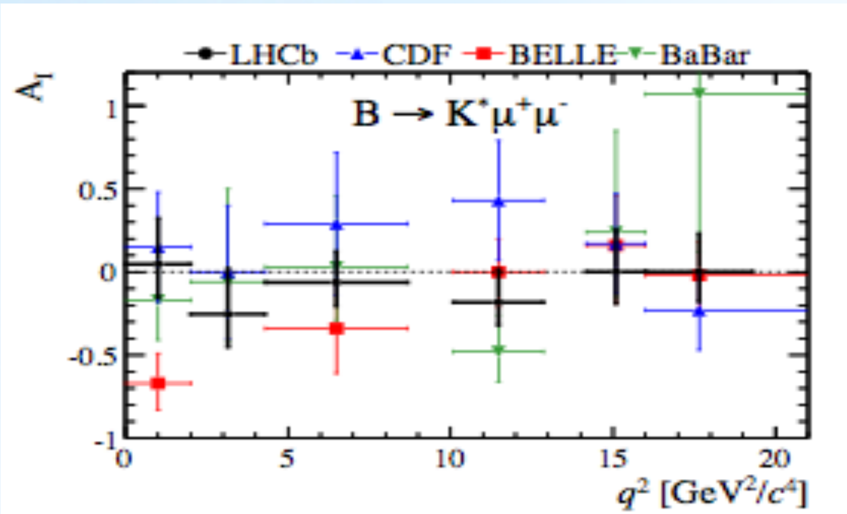


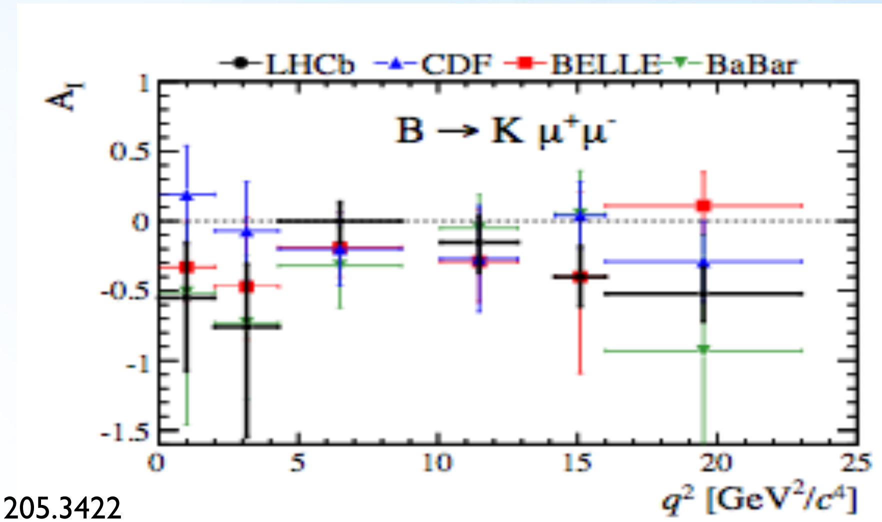


ΔF=1EW penguins in b→s transitions: B→K(*)$\mu\ \mu$ Isospin analysis

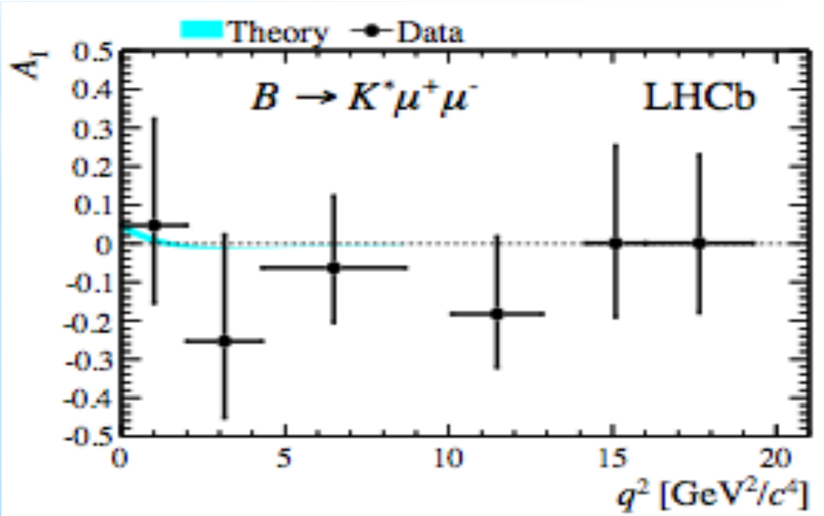
While this is indeed what is observed for **B→K*$\mu\ \mu$** and **B⁺→K*⁺$\mu\ \mu$**, **recent LHCb results** seem to confirm previous less precise measurements of the isospin asymmetry in **B→K$\mu\ \mu$** and **B⁺→K⁺$\mu\ \mu$** decays to be significantly negative (>4σ).

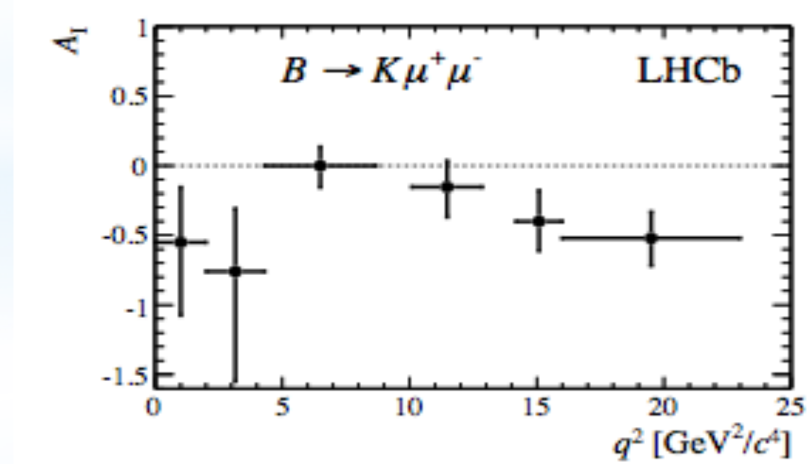
No physics model can explain this results… looking forward to the analysis of 3/fb at LHCb.





arXiv:1205.3422





$\Delta F=1$ EW penguins in b→s transitions: Personal recap.

Both the experimental and theory precision in EW penguins in b→s transitions **allow to look for NP beyond the TeV scale.**

This search is completely generic, independent of the flavour structure of NP it should be visible at some level of precision.

In the next decade expect an order of magnitude improvement.

But for now, let's move to a very special and interesting particular class of EW penguins, so called Higgs penguins!

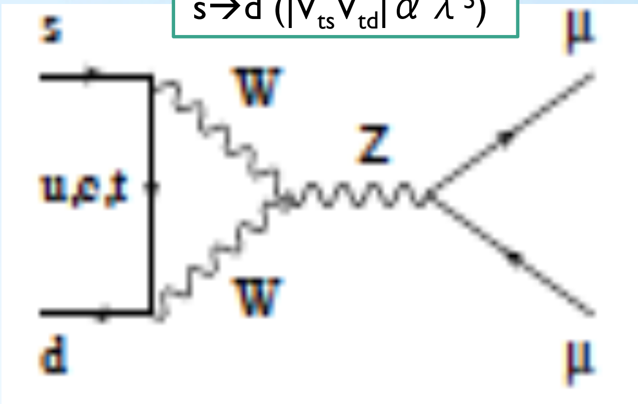
$\Delta F=1$ Higgs Penguins

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

The pure leptonic decays of **K,D and B** mesons are a particular interesting case of EW penguin.

The **helicity suppression** of the vector(-axial) terms, makes these decays particularly sensitive to new (pseudo-)scalar interactions →**Higgs penguins!**

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



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

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

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

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

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

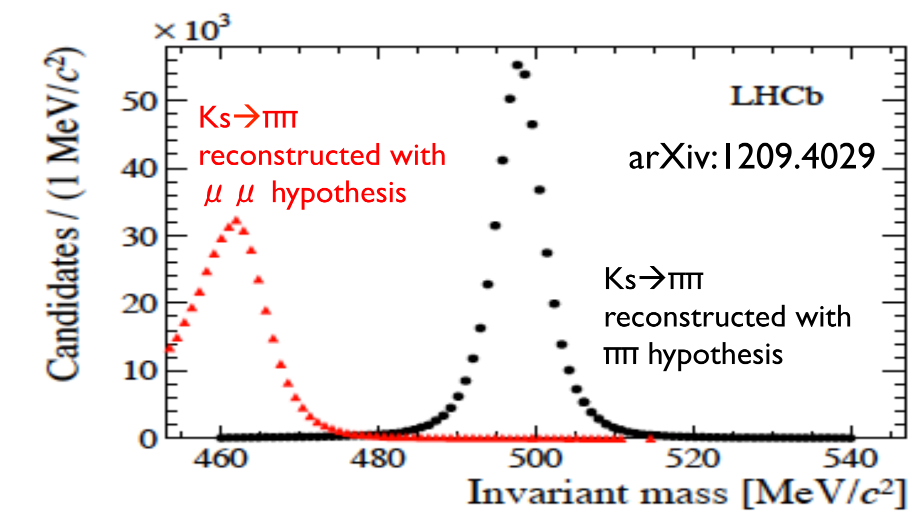
LHC produces 10^{13} K_s/fb in the LHCb acceptance. Trigger was not optimized for this search in 2011 (it is for the 2012 data taking period).

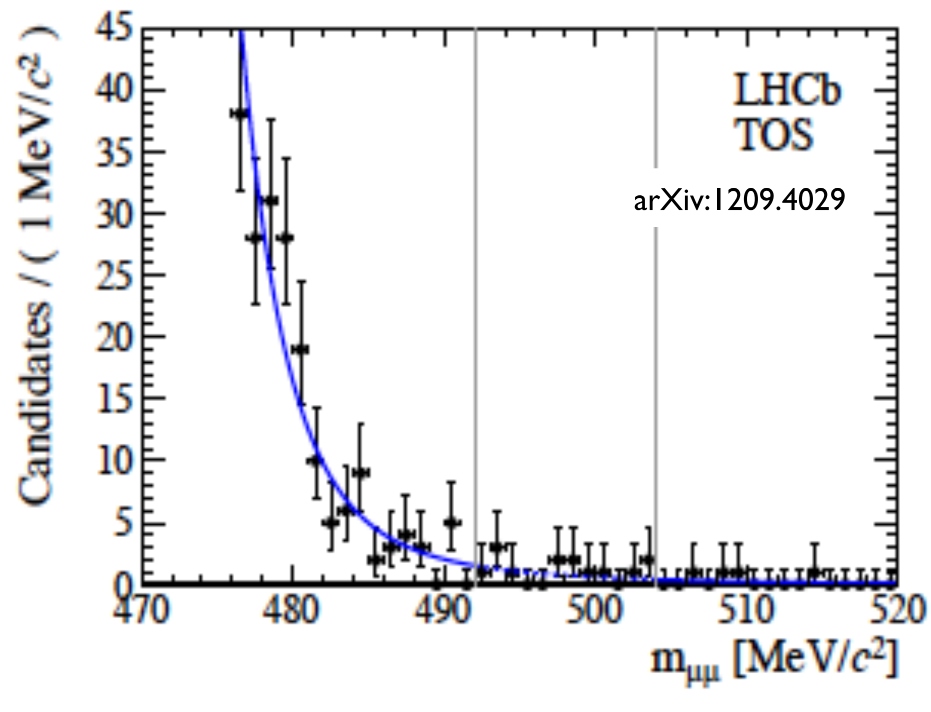
Excellent LHCb invariant mass resolution critical to reduce peaking bkg.

Mass distribution compatible with bkg hypothesis:

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

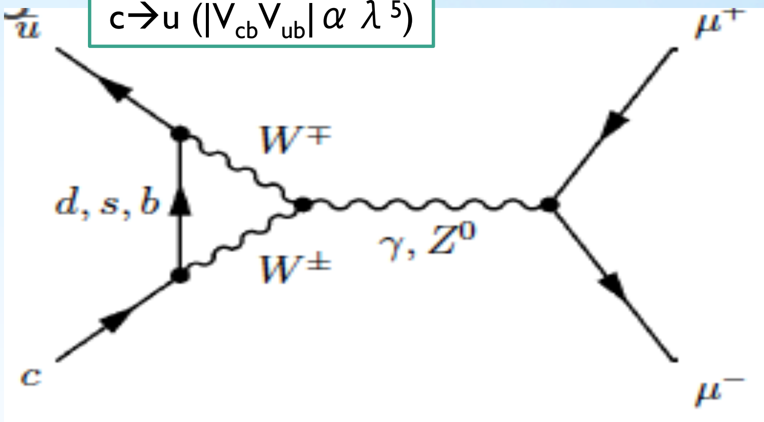
Excellent prospects to reach the interesting region ~10^{-11} with the LHCb upgrade.





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

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



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

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

Long distance contributions could be indeed much larger, but they are limited to be **below 6×10^{-11}** from the existing **limits on D→$\gamma\ \gamma$**:

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

BABAR result BR(D→$\gamma\ \gamma$<2.2×10^{-6} @90% C.L.) Phys. Rev. D85 (2012) 091107

Charm decays complement K and B mesons decays.

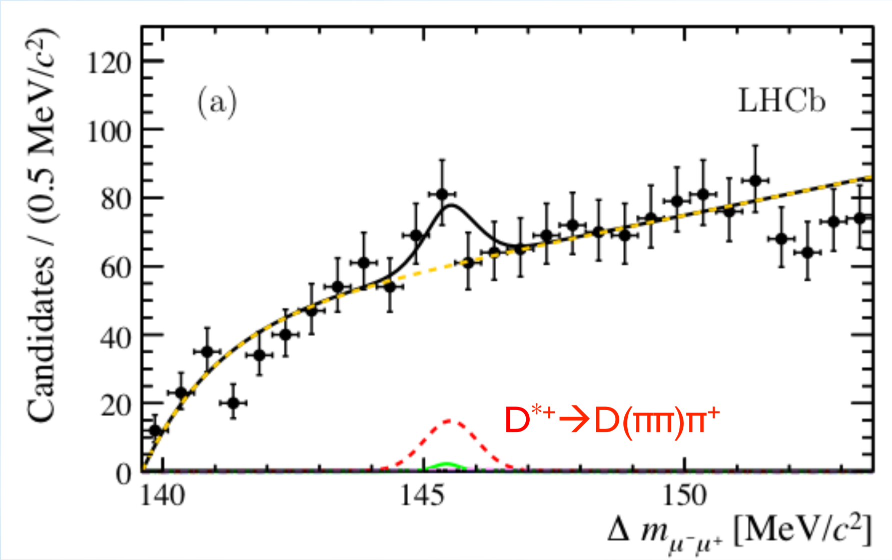
ΔF=1 Higgs penguins in c→u transitions: Charm decays

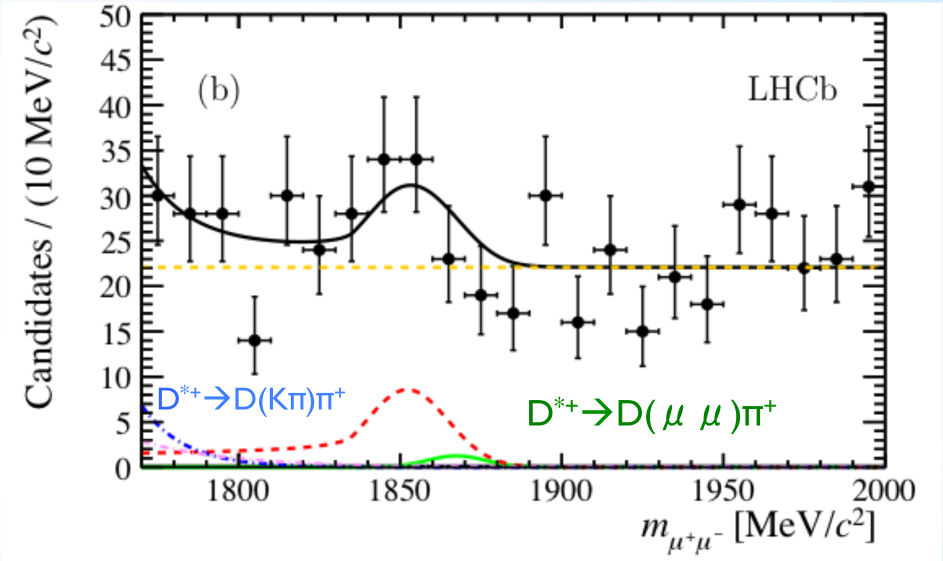
Experimental control of the peaking background is crucial (D→ππ).
Best existing limit before spring 2012 was from **Belle, <1.4x10^{-7}@90%C.L.**

LHCb-PAPER-2013-013

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

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

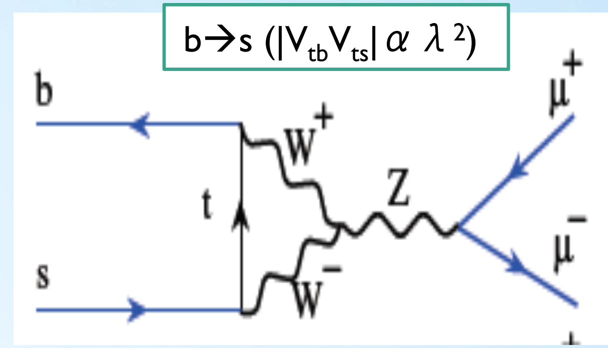




BABAR, arXiv:1206.5419 ,update for summer 2012 show a slight excess of candidates (8 observed, 3.9±0.6 bkg) which was interpreted as a **two-sided 90% C.L. limit, [6,81]x10^{-8}, in tension with LHCb results.**

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

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

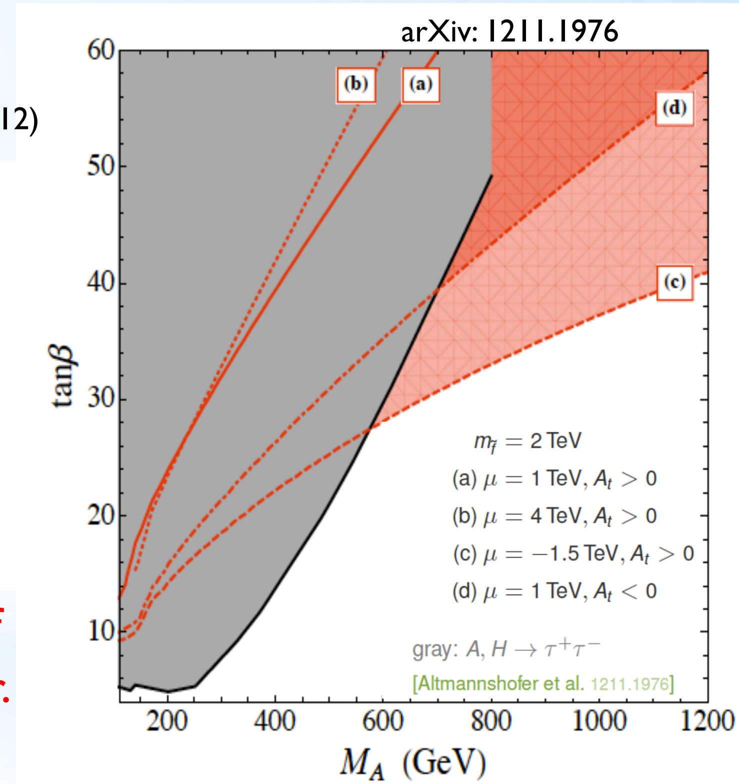


These decays are well predicted theoretically, and experimentally are exceptionally clean. Within the SM,

BR$_{SM}$(B$_s$→ μ μ) (t=0) = (3.6±0.5)x10^{-9}
(CKMfitter using tree level measurements), when comparing with time integrated measurement correct by ~1.1)

BR$_{SM}$(B → μ μ) (t=0) = (1.0±0.1)x10^{-10} PRD 86, 014027 (2012)

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



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

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

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

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

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

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

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

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

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

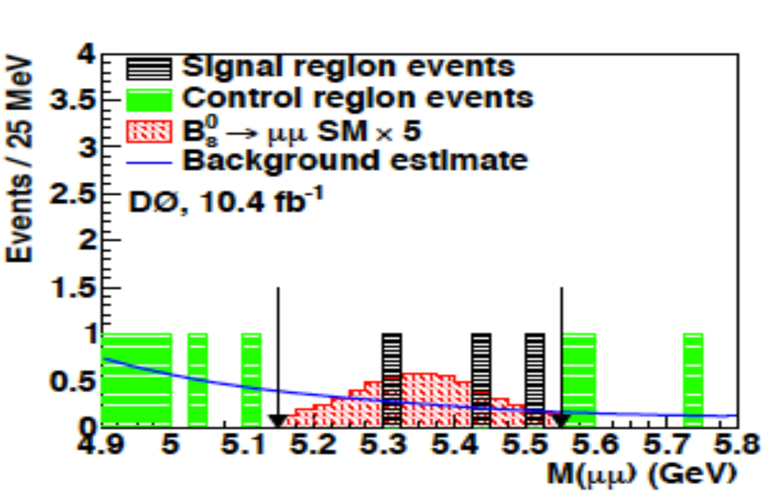
Therefore, for equal analyses strategies:

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

ΔF=1 Higgs penguins in b→d,s transitions: Tevatron Results

D0: 10.4 fb^{-1} [arXiv:1301.4507]

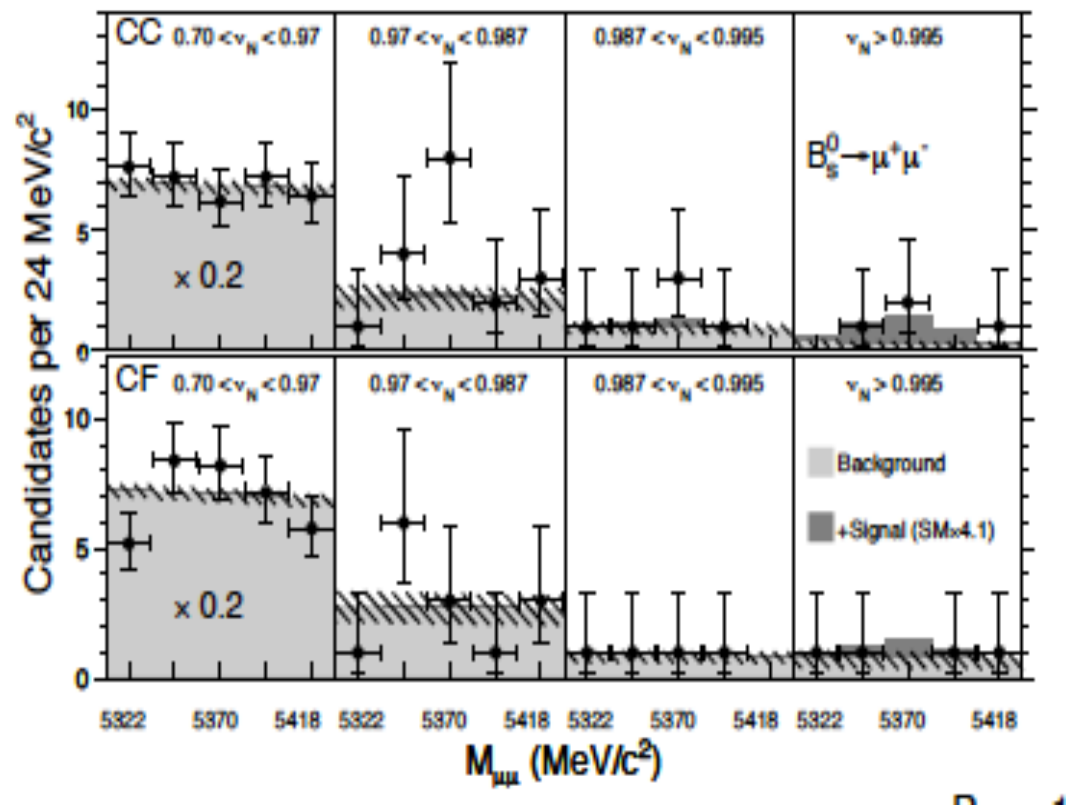
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 15 \cdot 10^{-9} \text{ @ 95 \% C.L.}$$



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

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

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



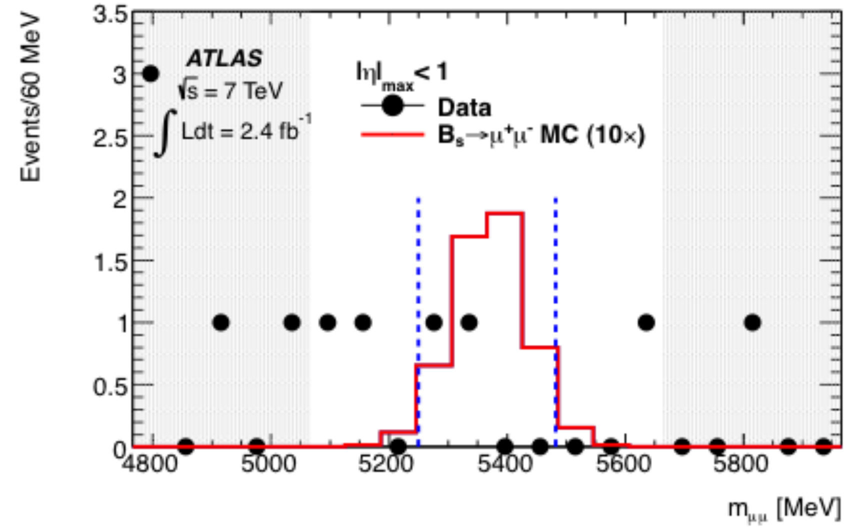
$\Delta F=1$ Higgs penguins in b→d,s transitions: ATLAS/CMS Results

Both ATLAS and CMS divide the data sample in bins of η to take into account the invariant mass resolution dependence.

ATLAS arXiv:12040735

$\|\eta\|_{\max}$ Range	0–1.0	1.0–1.5	1.5–2.5
SES$= (\epsilon\epsilon_i)^{-1}$ $[10^{-8}]$	0.71	1.6	1.4
sideband count $N^{\mathrm{bkg}}_{\mathrm{obs},i}$ (even numbered events)	5	0	2
expected resonant bkg. $N_i^{B\to hh}$	0.10	0.06	0.08
search region count N_i^{obs}	2	1	0

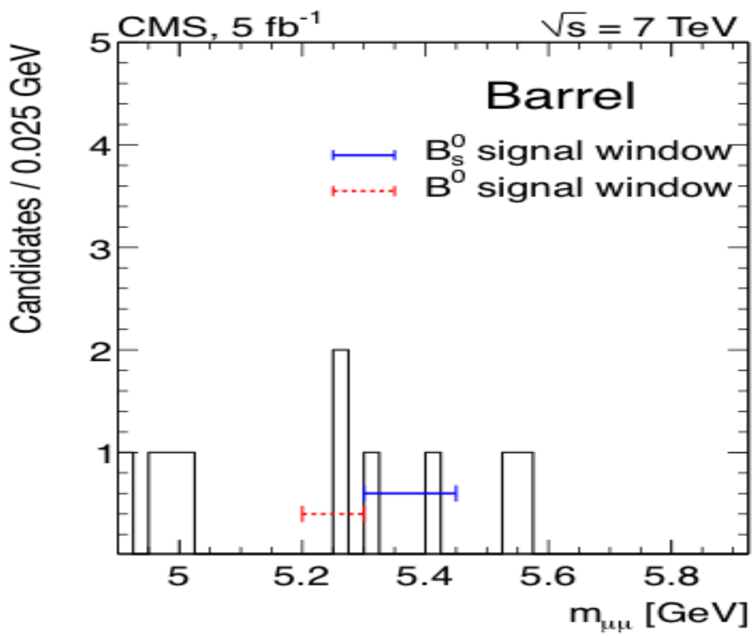
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) < 22 \cdot 10^{-9} \text{ @ 95 \% C.L.}$$



CMS arXiv:12033976

Variable	$B^0\to\mu^+\mu^-$ Barrel	$B^0_s\to\mu^+\mu^-$ Barrel	$B^0\to\mu^+\mu^-$ Endcap	$B^0_s\to\mu^+\mu^-$ Endcap
$\varepsilon_{\mathrm{tot}}$	0.0029 ± 0.0002	0.0029 ± 0.0002	0.0016 ± 0.0002	0.0016 ± 0.0002
$N^{\mathrm{exp}}_{\mathrm{signal}}$	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
$N^{\mathrm{exp}}_{\mathrm{peak}}$	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
$N^{\mathrm{exp}}_{\mathrm{comb}}$	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
$N^{\mathrm{exp}}_{\mathrm{total}}$	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
N_{obs}	2	2	0	4

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) < 7.7 \cdot 10^{-9} \text{ @ 95 \% C.L.}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.8 \cdot 10^{-9} \text{ @ 95 \% C.L.}$$



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

Combined LHCb analysis of 1/fb (7TeV) and 1.1/fb (8TeV), with improved treatment of the exclusive backgrounds in the mass sidebands.

Upper limit @95% CL:

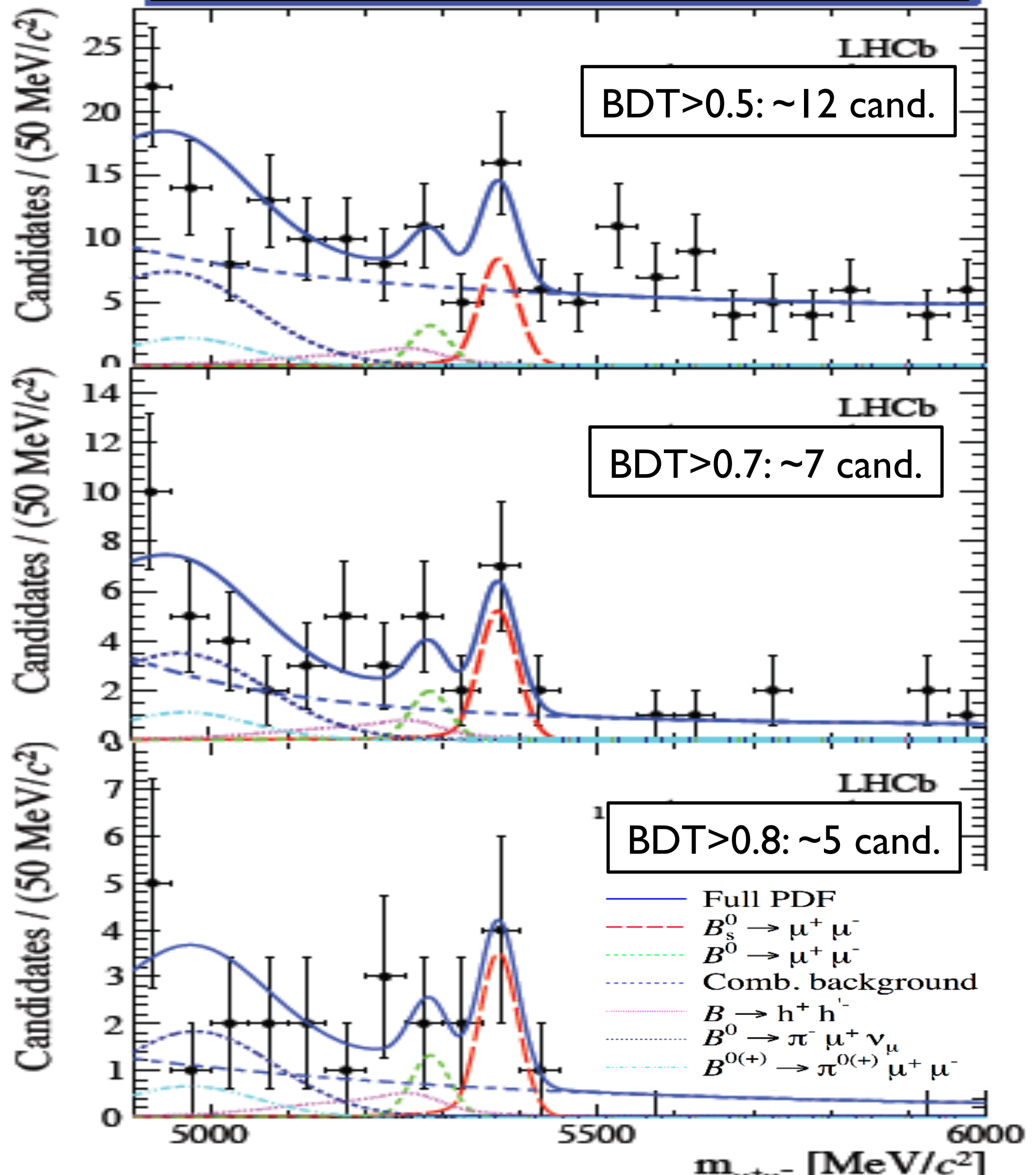
BR(B→$\mu^+\mu^-$)< $9.4\text{x}10^{-10}$

which is worlds best single experiment limit (p-value of bkg-only hypothesis is 11%)

Excess of B_s→$\mu^+\mu^-$ candidates w.r.t. background only hypothesis that corresponds to a signal significance of **3.5σ**!

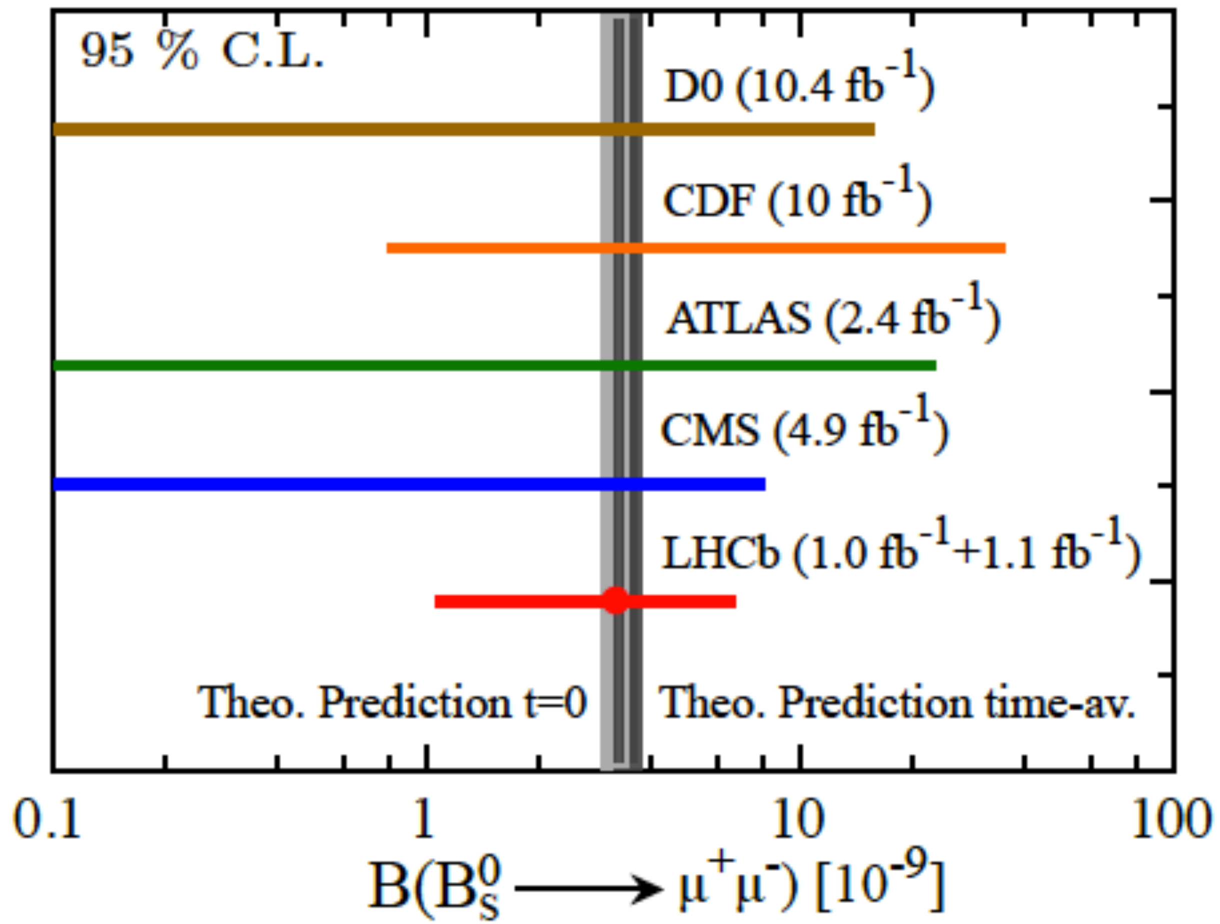
BR(B_s→$\mu^+\mu^-$)= $(3.2^{+1.5}_{-1.2})\text{x}10^{-9}$

LHCb arXiv:12112674

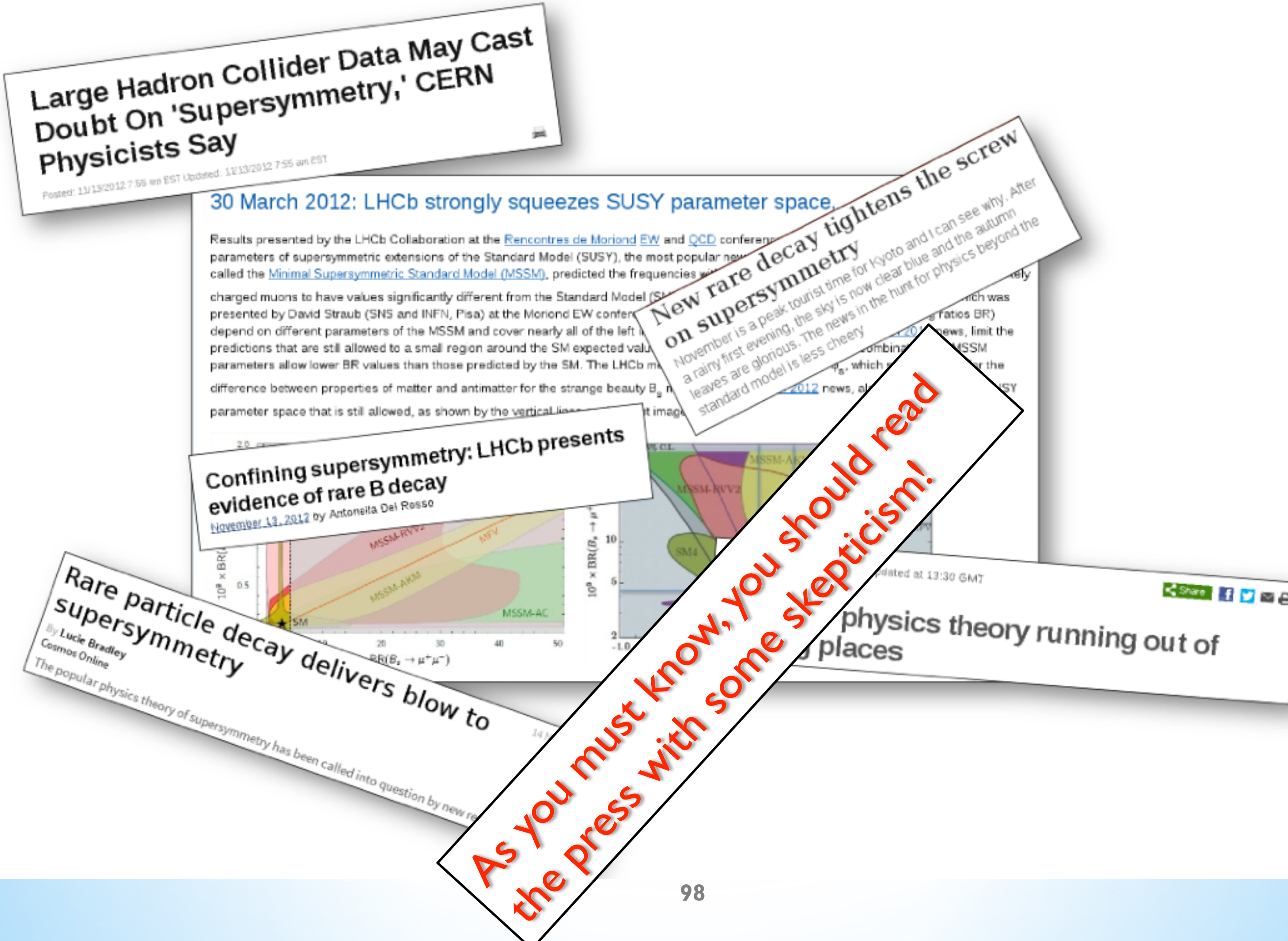


$\Delta F=1$ Higgs penguins in b→s transitions: Results

Current Status of $B_s^0 \to \mu^+\mu^-$



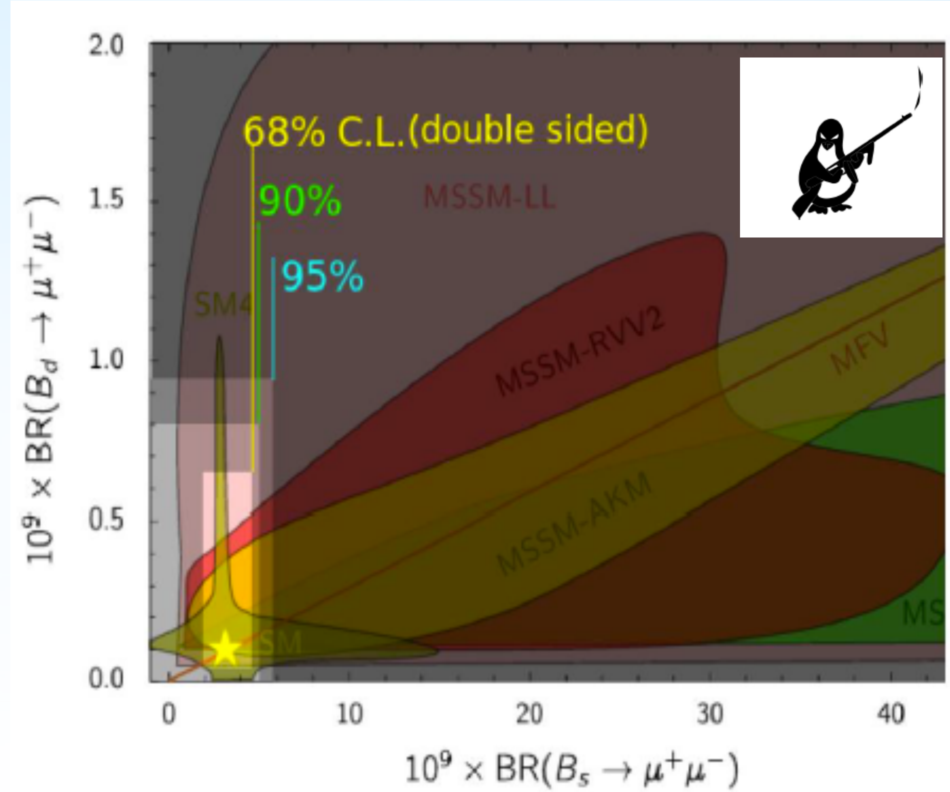
ΔF=1 Higgs penguins in b→d,s transitions: B decays



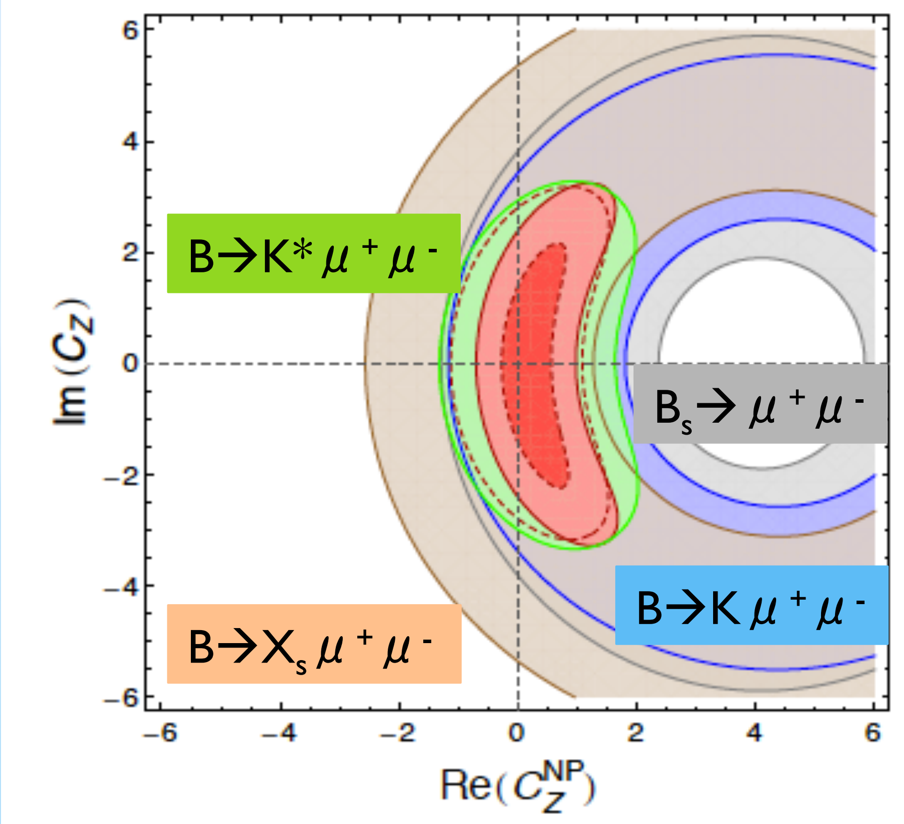
As you must know, you should read the press with some skepticism!

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

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



arXiv:1206.0273

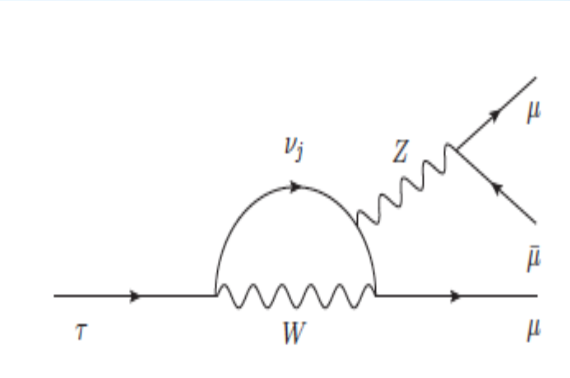


The precision achieved now is such that $B_{(s)} \to \mu^+ \mu^-$ sensitivity to (Z, γ) penguin starts to compete with the golden mode $B \to K^* \mu^+ \mu^-$.

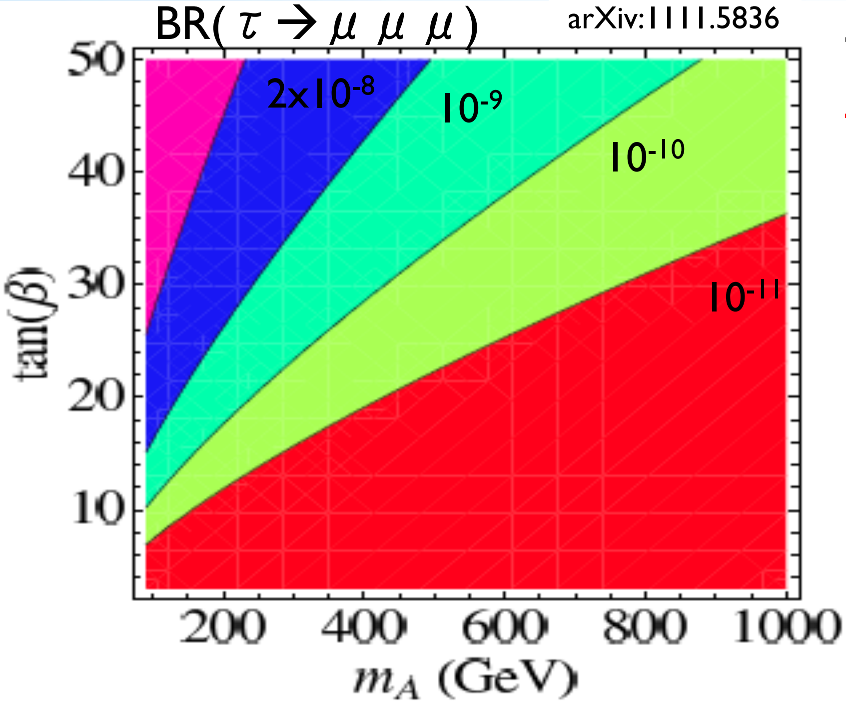
LFV

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

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



Taus are **copiously produced** both at flavour-factories and at LHC (mainly from charm decays, $D_s \rightarrow \tau\ \nu$, ~$8\times10^{10}$ taus produced within the LHCb acceptance).

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

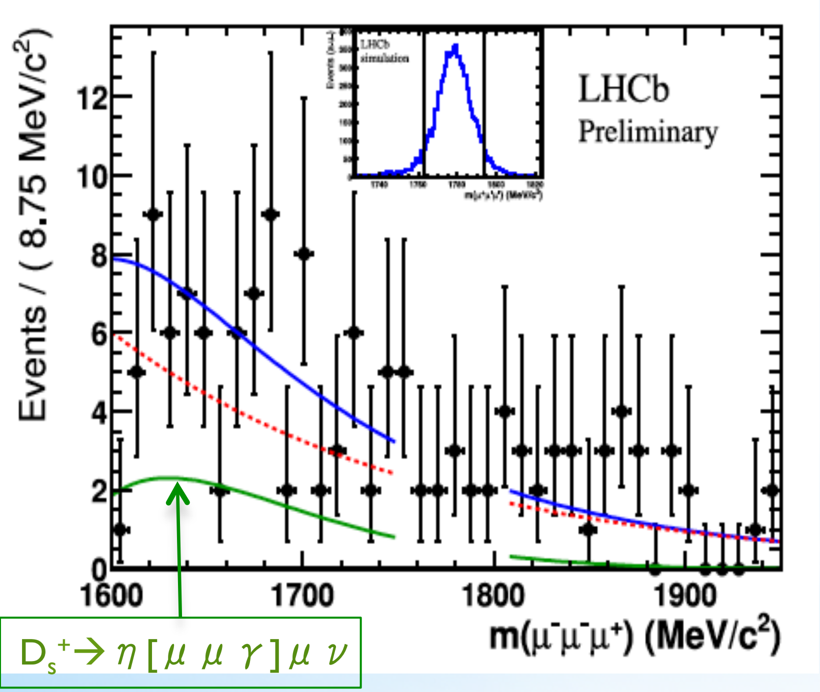
	BR($\tau \rightarrow \mu\ \gamma$)		BR($\tau \rightarrow \mu\ \mu\ \mu$)
BELLE:	4.5×10^{-8}	arXiv:1001.3221	2.1×10^{-8}
BABAR:	4.4×10^{-8}	arXiv:1002.4550	3.3×10^{-8}

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

LHCb has performed for the first time at hadron colliders a search for $\tau \to \mu\ \mu\ \mu$ in 1/fb at $\sqrt{s}$=7 TeV.

Number of candidates is normalized to the number of $D_s \to \phi[\mu\ \mu]\pi$, the measured bb and cc cross-section at LHCb, and the fractions of B$\to \tau$ and D$\to \tau$ from LEP/B-factories.

LHCb-CONF-2012-015



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

BR($\tau \to \mu\ \mu\ \mu$)<7.8(6.3)x10^{-8} at 95(90)% CL.

Preliminary result subject to improvements in the rejection of the main background in the sensitive bins ($D_s^+ \to \eta[\mu\ \mu\ \gamma]\mu\ \nu$).

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

Into the Future…

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

Isidori, Martinez-Santos (Open Symposium ESPG)

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

Conclusions

Conclusions

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

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

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

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

LHCb upgrade plans to collect ~50/fb with a factor ~2 increase in bb cross-section. **ATLAS/CMS** plan to collect ~300/fb by 2022. **Belle-II** plans to collect ~50/ab by 2022.

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

Backup

Yields at LHCb and B-factories

Decay	LHCb		Belle		Ratio
$B_u \to J/\psi K$	10049	34 pb^{-1}	41315	711 fb^{-1}	5.1
$B_u \to D^0{}_{\mathrm{CP}}\pi$	1270	34 pb^{-1}	2163	250 fb^{-1}	4.3
$B_d \to K\pi$	838	35 pb^{-1}	4000	480 fb^{-1}	2.9
$B_u \to K\ell\ell$	35	35 pb^{-1}	161	605 fb^{-1}	2.6
$B_d \to K^*\ell\ell$	144	165 pb^{-1}	230	605 fb^{-1}	2.3
$B_d \to J/\psi K^0_S$	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