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Flavour Physics potential of LHCb

Data samples:

- ***10fb^{-1} in a few years of data taking***
  → current LHCb physics program

- ***100fb^{-1} → plans for LHCb upgrade → SuperLHCb***

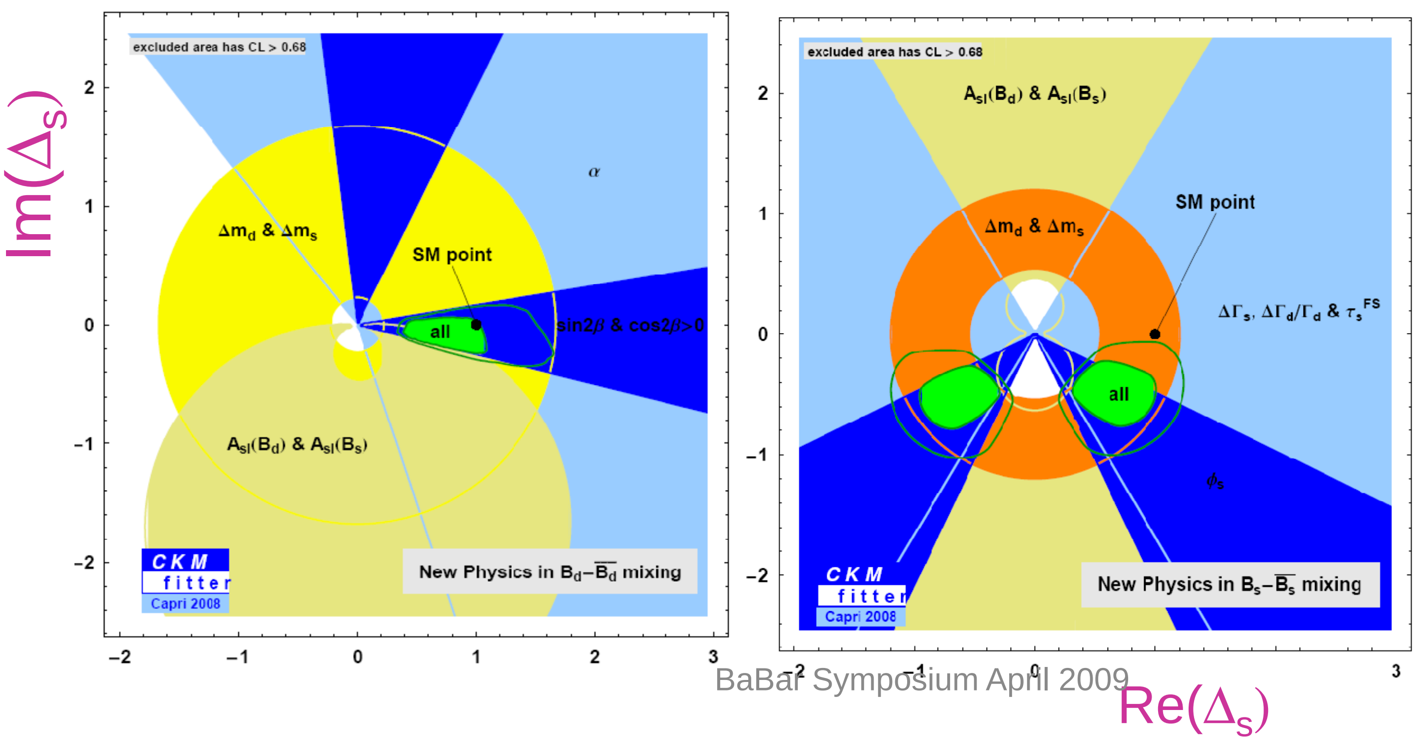
Search & Study of New Physics at LHC

are the main objectives of the LHCb physics program

Thanks to B-factories and CDF/D0 the CKM mechanism of CP violation is proven to be the leading one

Extend the parameterization to include possible New Physics contributions to B-$\bar{B}$ oscillations

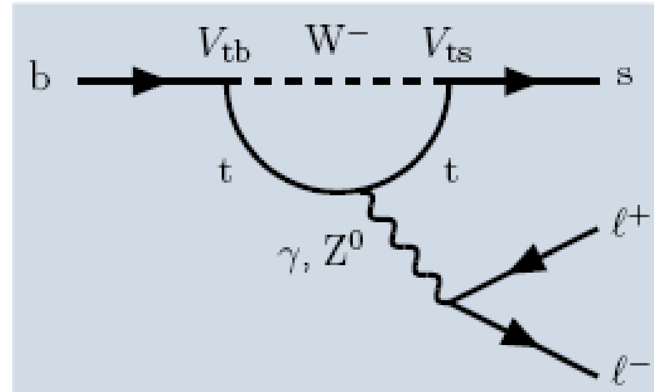
$$\mathrm{Re}(\Delta_q)+i\mathrm{Im}(\Delta_q)=\frac{\langle B^o|H^{full}|\bar{B}^o\rangle}{\langle B^o|H^{SM}|\bar{B}^o\rangle}$$



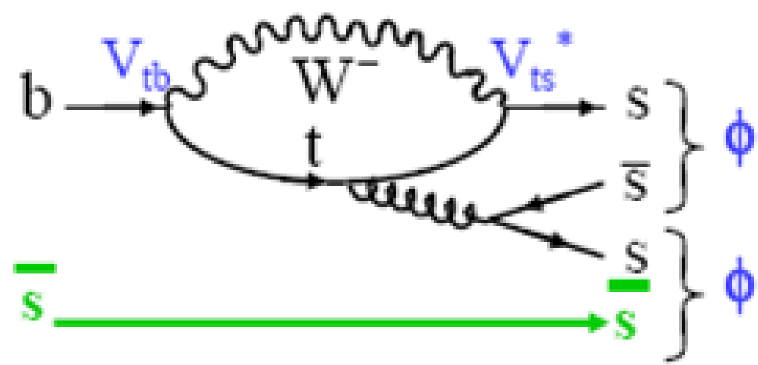
Large range of NP allowed !

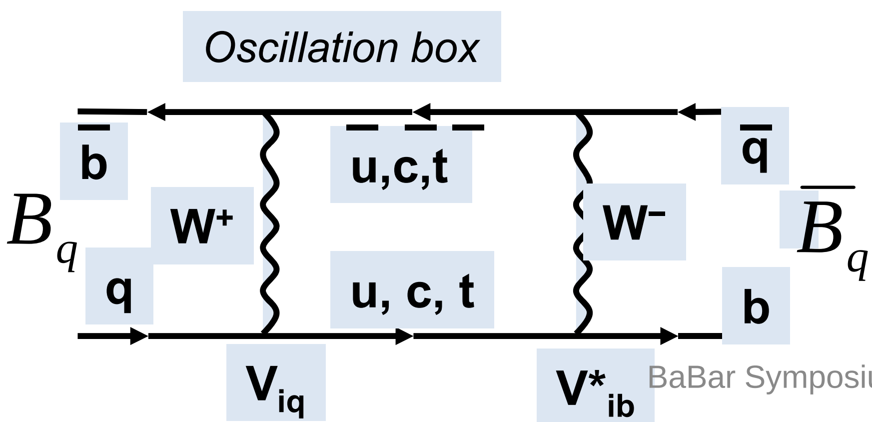
LHCb strategy

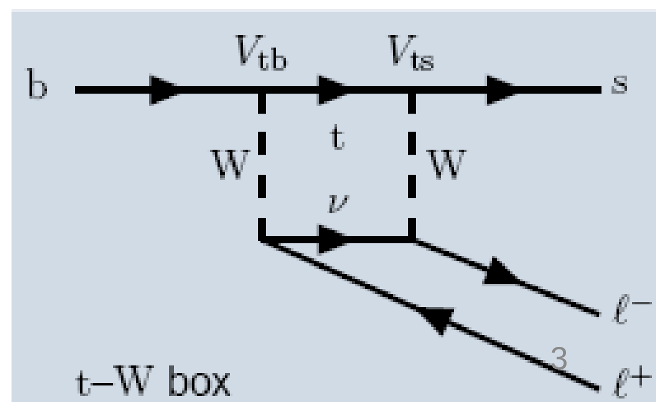
Measure experimental observables sensitive to New Particles through their interference effects with well studied objects, b-quarks, in the processes mediated by the loop diagrams:



- ❑ *$B_{d,s}$ oscillations: box diagram*
- ❑ *Penguin diagrams:*
  - ➢ *Radiative penguin: $B_s \rightarrow \phi\gamma$*
  - ➢ *Electroweak penguin: $B \rightarrow K^*\mu\mu$*
  - ➢ *Strong penguin: $B \rightarrow \pi\pi$, $B_s \rightarrow \phi\phi$*

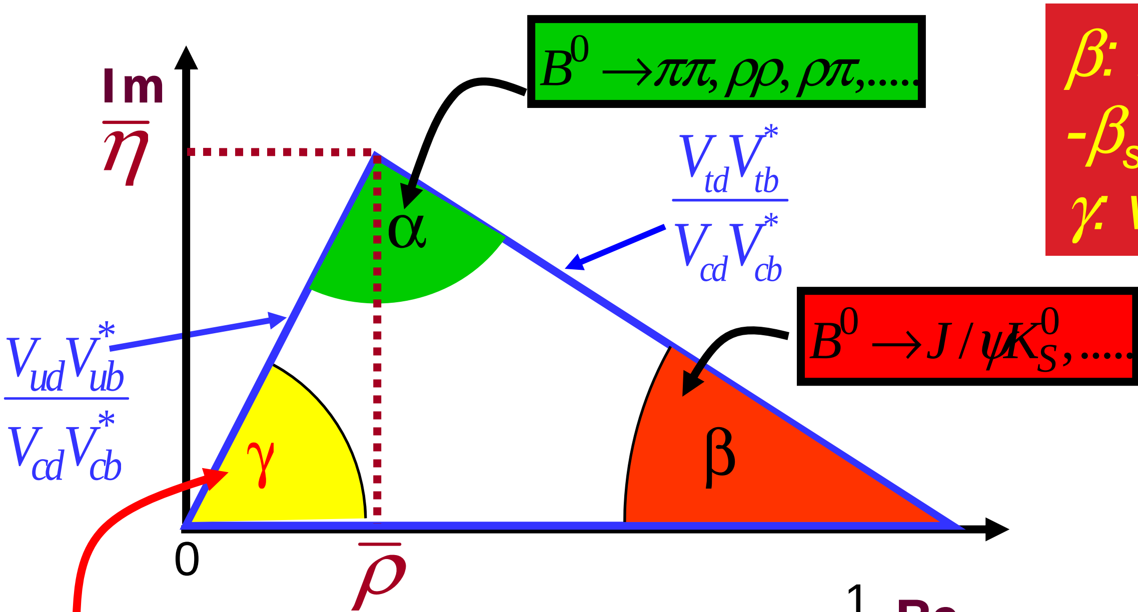






The Unitarity Triangle

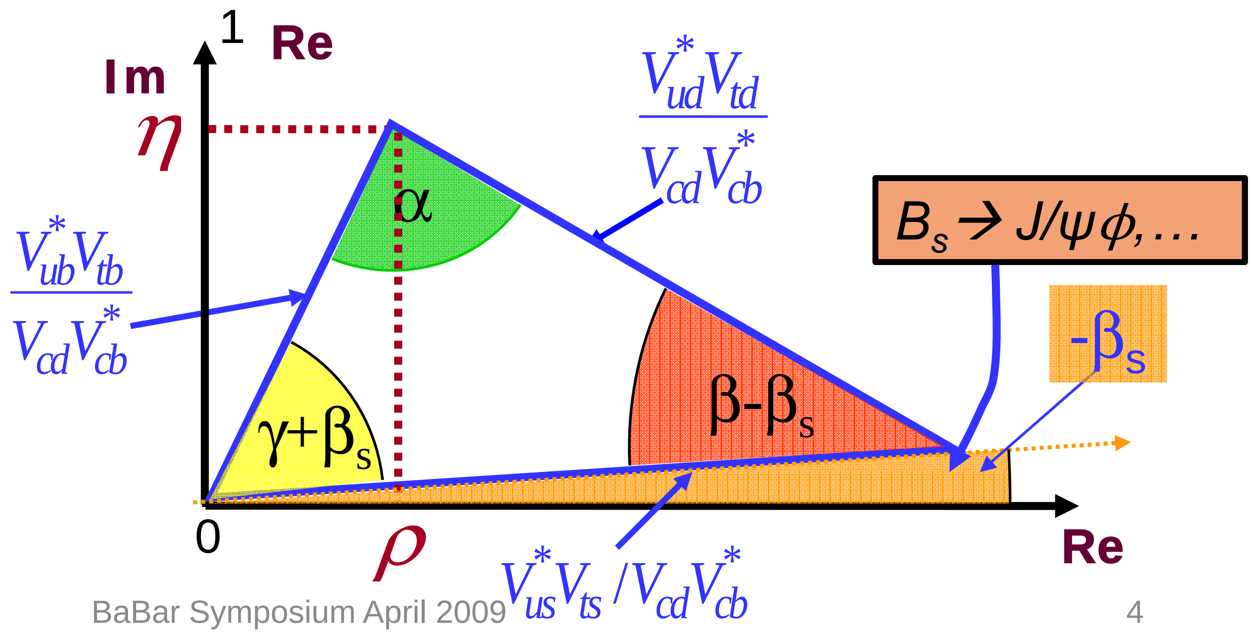
β: B_d mixing phase
$-\beta_s$: B_s mixing phase
γ: weak decay phase



$B_d \rightarrow DK, DK^*$

$B_s \rightarrow D_s K \qquad (\gamma + \phi_s$

$B_d \rightarrow D^*\pi \qquad (\gamma + 2\beta)$



The Unitarity Triangle

Main experimental observables:

- **|Vub/Vcb|** *side in trees (exclusive and inclusive semileptonic b-decays)*

- $\Delta m_d / \Delta m_s$ *side in the ratio of s- and d-boxes*
  (or s- and d- penguins in $B \rightarrow K^*\gamma$ and $B \rightarrow \rho\gamma$)

- β *angle in the d-box: $B \rightarrow J/\psi K^0$ (d-box + s-penguin in $B \rightarrow \phi K^0$)*

- β_s *angle in the s-box: $B_s \rightarrow J/\psi\phi$ (s-box + s-penguin in $B_s \rightarrow \phi\phi$)*

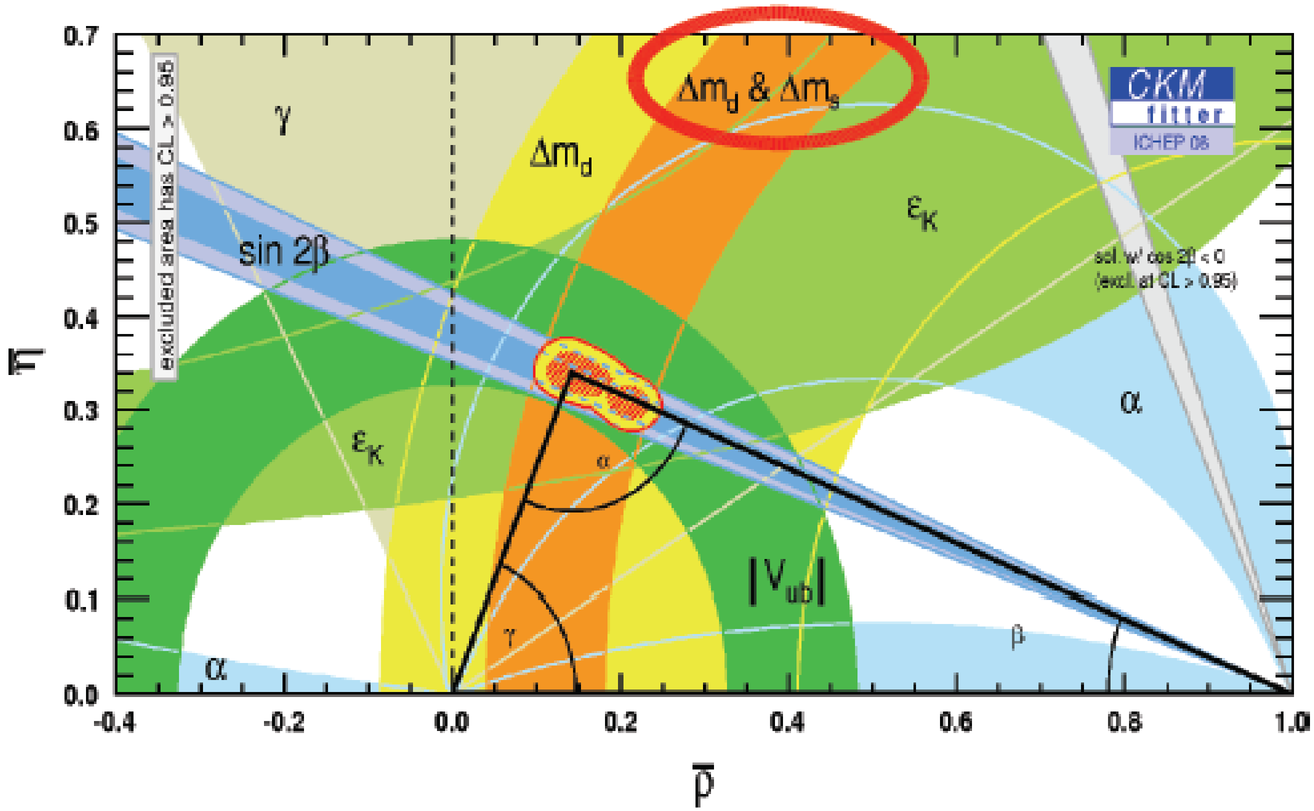
- γ *angle in trees (many possibilities in $B \rightarrow DX$ decays)*

- α *angle in trees + penguins in $B \rightarrow \pi\pi, \rho\pi, \rho\rho$*
  (reduced sensitivity to penguins)

Accuracy of sides is limited by theory:

- *Extraction of |Vub|*
- *Lattice calculation of*

$$\xi^2 = \frac{\hat{B}_{B_s} f_{B_s}^2}{\hat{B}_{B_d} f_{B_d}^2}$$



Accuracy of angles is limited by experiment

α= ± 5° (???)
β = ± 1°
γ = ± 20°

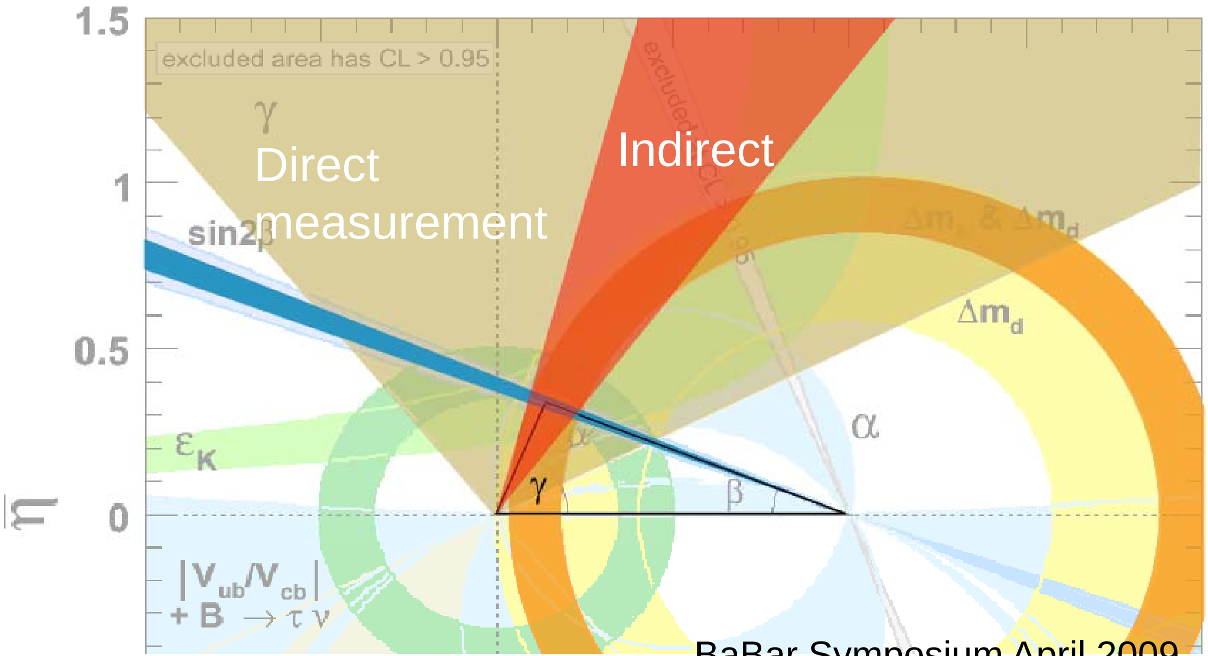
β_s is not measured accurately
Hint for a large value (beyond the SM) from CDF/D0

Search for New Physics in CPV measurements

- ## *In box diagrams*

*β **vs $|V_{ub}$ / $V_{cb}|$** is largely limited by theory (~10% precision in $|V_{ub}|$)* *(d-box)*
Note a discrepancy in $|V_{ub}|$ determined in inclusive and exclusive measurements : $|V_{ub}|$ incl ~ $(4.0\text{-}4.9)\times 10^{-3}$ and $|V_{ub}|$ excl ~ $(3.3\text{-}3.6)\times 10^{-3}$

*γ **vs $\Delta m_d / \Delta m_s$** is limited by experiment: γ is poorly measured (± 20°)*



BaBar Symposium April 2009

Indirectly γ is determined to be $\gamma = (68 \pm 5)^{\circ}$ from the processes involving loops

LHCb will measure γ directly in trees:

$\sigma(\gamma)$ ~ 2-3° (10 fb^{-1} sample)

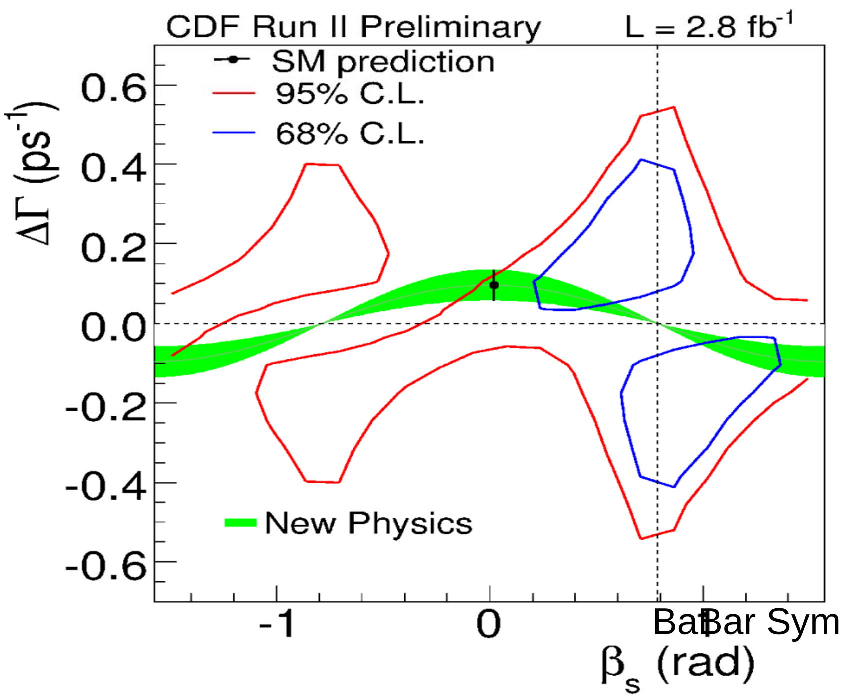
Search for New Physics in CPV measurements

- **In box diagrams**

$\phi_S = -2\beta_S$ is the counterpart of $\phi_d = 2\beta$

β_s not measured accurately (indication of large value from CDF/D0) **(s-box)**
Theoretical uncertainty is much smaller than for β
$\phi_S (J/\psi\phi)[SM] = 0.0368\pm0.0017$ (CKMfitter 2007)

Consistency with SM at 1.8σ level



By the end of Run 2, assuming 9 fb^{-1}
For both D0 and CDF, combined
Tevatron sensitivity $\sigma(\phi_s)\approx0.13$

LHCb prospects (10 fb^{-1} sample)

Expected yield 660k $B\rightarrow J/\psi\phi$ events

$\sigma(\phi_s)$ ~ 0.01

Search for New Physics in CPV measurements

- ***In penguin diagrams:***

$\delta\beta(NP) = \beta(B \rightarrow \phi Ks) - \beta(B \rightarrow J/\psi Ks) \neq 0$

$\delta\beta_s(NP) \approx \beta_s(B_s \rightarrow \phi\phi) - \beta_s(B_s \rightarrow J/\psi\phi)$

$\sigma(\delta\beta(NP)) \sim 10°$ *(s-penguin)*

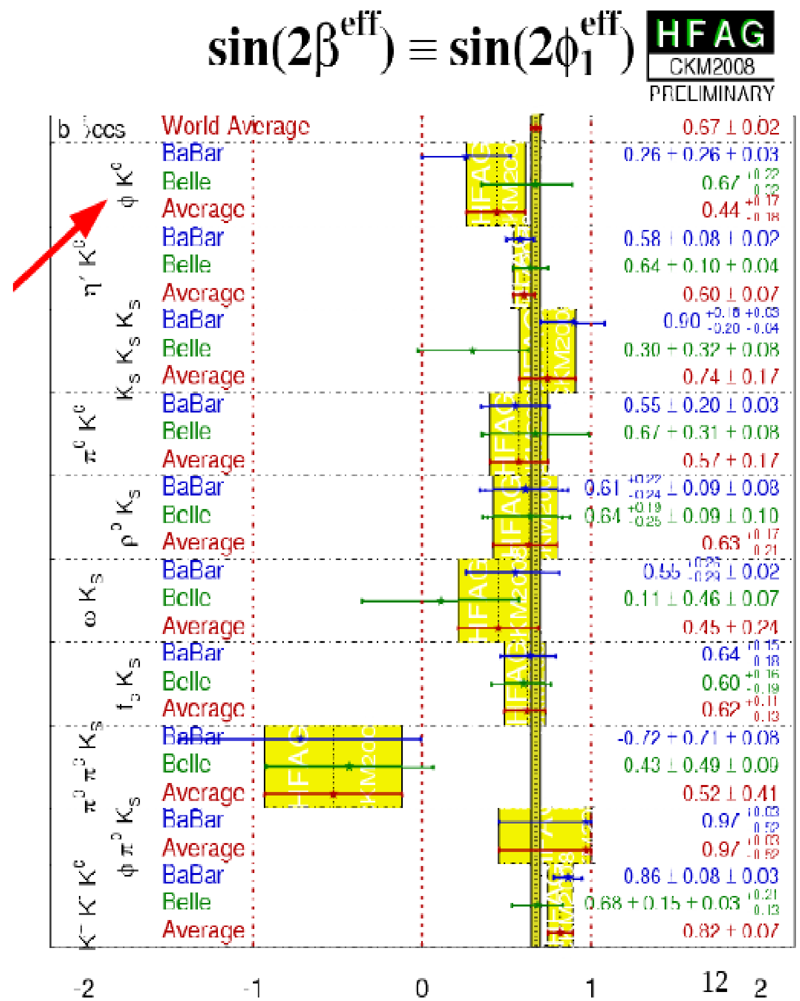
$\sigma(\delta\beta_s(NP))$ *not measured* *(s-penguin)*

PS $\delta\beta(NP) \approx \delta\beta_s(NP)$

LHCb prospects (10 fb^{-1} sample):

$\sigma(\delta\beta_s) \sim 2°$

$\sigma(\delta\beta) \sim 4°$



Search for New Physics in Rare Decays

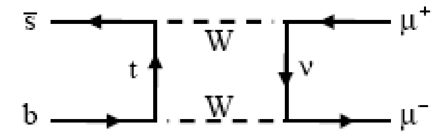
(combination of various box and penguin diagrams)

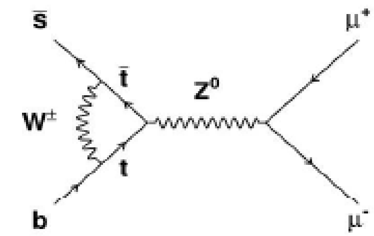
Experiments are just reaching an interesting level of sensitivity in exclusive decays:

- *BR* ($B_s \rightarrow \mu\mu$) (CDF /D0)
  BR ($B_d \rightarrow \mu\mu$)
- *Photon polarization in* $B \rightarrow K^*\gamma$ (BELLE/BaBar)
- A_{FB} *in* $B \rightarrow K^*\mu\mu$ (BELLE/BaBar)
- *BR* ($D^0 \rightarrow \mu\mu$) (CDF)
- *Lepton Flavor Violation in* τ *decays* (BELLE/BaBar)

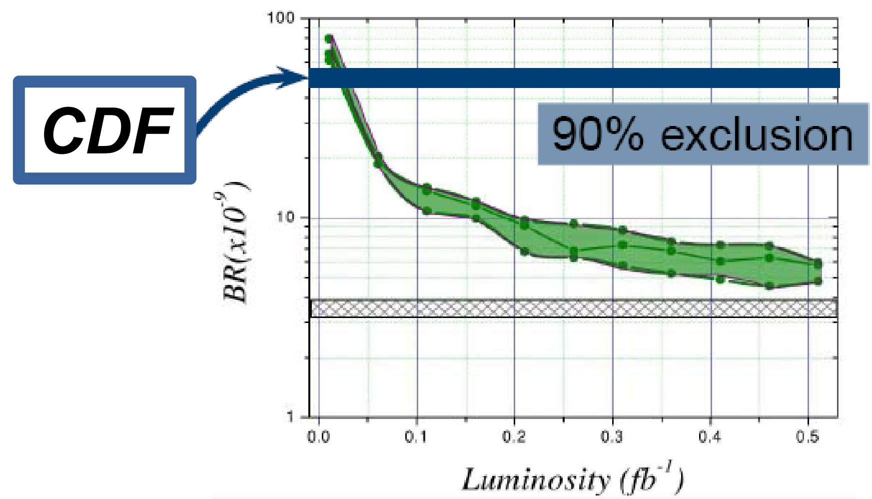
Contribution from LHCb is extremely important !!!

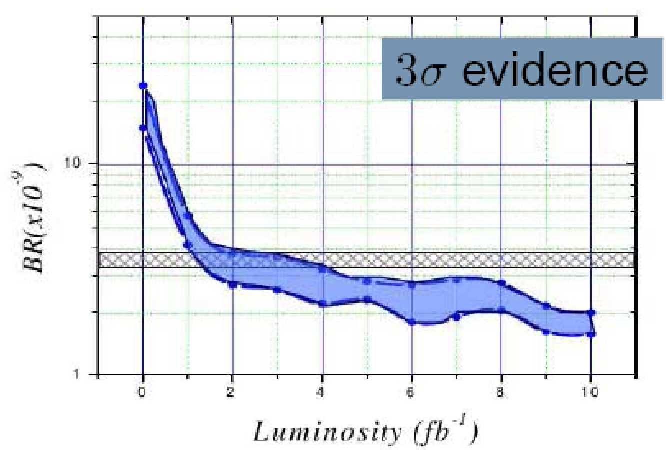
$B_s \rightarrow \mu\mu$



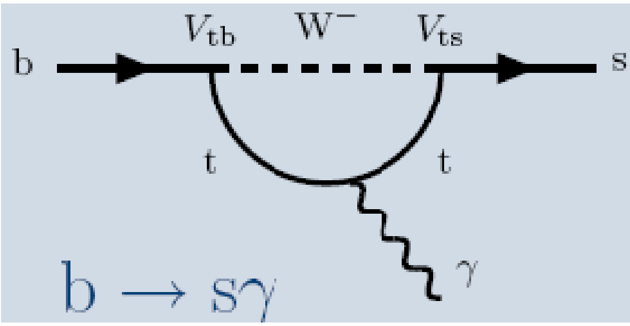


- *Super rare decay in SM with well predicted $BR(B_s \rightarrow \mu\mu) = (3.55 \pm 0.33) \times 10^{-9}$*
- *Sensitive to NP in MSSM* $BR \propto \tan^6\beta / M^4_A$
- *Best present limit is from CDF:* $BR(B_s \rightarrow \mu\mu) < 4.7 \times 10^{-8}$ *@ 90% CL*
- *For the SM prediction LHCb expects 8 signal and 12 background events in the most sensitive bin in 2 fb^{-1} . Background is dominated by semileptonic decays of different b quarks*
- *3σ evidence with 2 fb^{-1}*
  5σ observation with 6fb^{-1}





Measurement of the photon polarization in $B_s \rightarrow \phi\gamma$ decay



$b \rightarrow \gamma(L) + (m_s/m_b) \times \gamma(R)$

$\phi\gamma$ produced in B_s and $\overline{B}_s$ decays do not interfere in SM $\rightarrow$ corresponding $A_{CP} = 0$

$$\Gamma(\mathrm{B}_q(\bar{\mathrm{B}}_q) \to f^{CP}\gamma) \propto e^{-\Gamma_q t}\left(\cosh\frac{\Delta\Gamma_q t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_q t}{2} \pm \pm\mathcal{C}\cos\Delta m_q t \mp \mathcal{S}\sin\Delta m_q t\right)$$

SM:

- *C = 0 direct CP-violation*
- *S = **sin2ψ** sinϕ*
- *A^{Δ} = **sin2ψ** cosϕ*

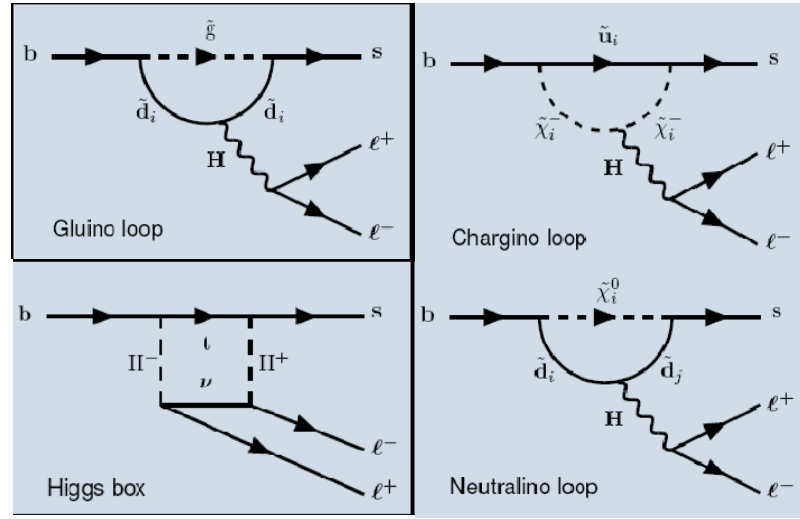
$$\tan\psi \equiv \left|\frac{A(\bar{\mathrm{B}}\to f^{CP}\gamma_R)}{A(\bar{\mathrm{B}}\to f^{CP}\gamma_L)}\right|$$

- *Expected signal yield is 11k for 2 fb^{-1}*

Sensitivity: σ (A (B$\rightarrow f^{CP}\gamma_R$) / A (B$\rightarrow f^{CP}\gamma_L$) = 0.11 for 2$fb^{-1}$

$B \to K^*\mu\mu$

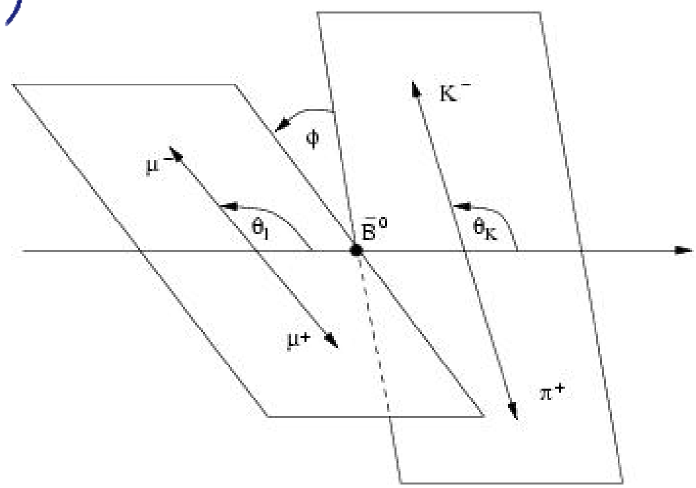
In SM this b→s penguin decay contains right-handed calculable contribution but this could be added to by NP resulting in modified angular distributions



$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi}\left(1 + \frac{1}{2}(1 - F_L)A_T^{(2)}\cos 2\phi + A_{Im}\sin 2\phi\right)$$

$$\frac{d\Gamma'}{d\cos\theta_l} = \Gamma'\left(\frac{3}{4}F_L\sin^2\theta_l + \frac{3}{8}(1 - F_L)(1 + \cos^2\theta_l) + A_{FB}\cos\theta_l\right)$$

$$\frac{d\Gamma'}{d\cos\theta_K} = \frac{3\Gamma'}{4}\left(2F_L\cos^2\theta_K + (1 - F_L)\sin^2\theta_K\right)$$

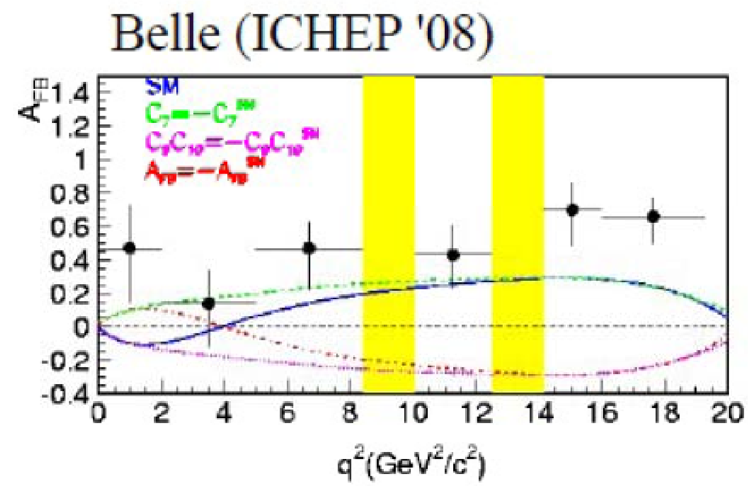


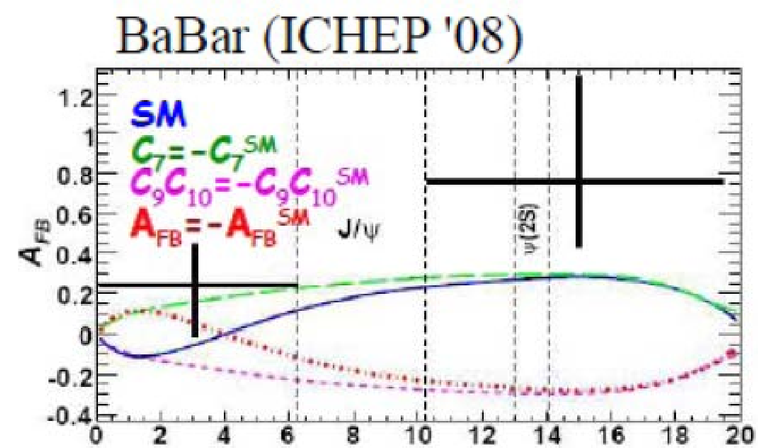
- *Described by three angles (θ_l, ϕ, θ_K) and di-μ invariant mass q^2*
- *Forward-backward asymmetry A_{FB} of θ_l distribution of particular interest:*
  - *Varies between different NP models →*
  - *At zero-point, dominant theor. uncert. from hadronic form-factors cancels at LO*

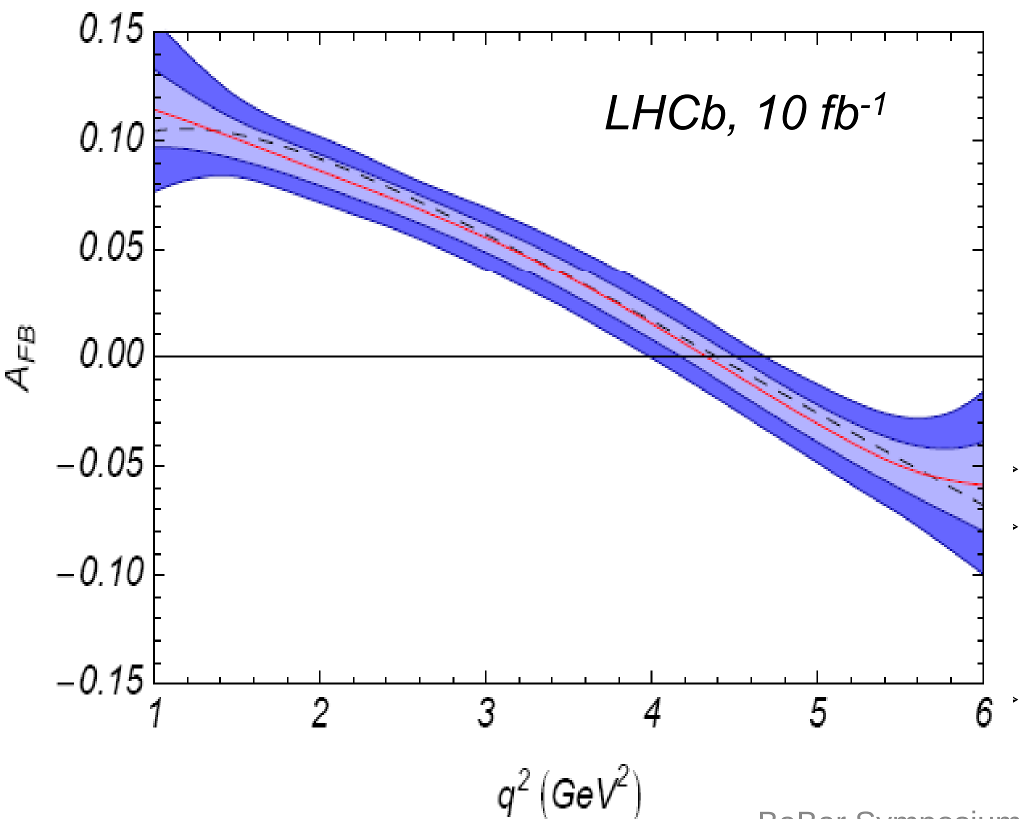
$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$

$B \rightarrow K^*\mu\mu$

- Forward-backward asymmetry A_{FB} (s) in $\mu\mu$-rest frame is a sensitive NP probe
- Predicted zero of A_{FB} (s) depends on Wilson coefficients C_7^{eff} / C_9^{eff}







- ~7k events / 2fb^{-1} with B/S ~ 0.2
- After 10 fb^{-1} zero of A_{FB} located to ±0.28 GeV^2 (0.5 GeV^2 after 2 fb^{-1}) providing 7% stat. error on C_7^{eff} / C_9^{eff}
- Full angular analysis gives better discrimination between models.

$B_d \to K^{*0}e^+e^-$ is as powerful as $B_s \to \phi\gamma$ to measure the photon polarization

Contribution not coming from virtual photons is very small at low $q^2 < (1\ \mathrm{GeV})^2$

$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi}\left(1 + \frac{1}{2}(1 - F_L)A_T^{(2)}\cos 2\phi + A_{Im}\sin 2\phi\right)$$

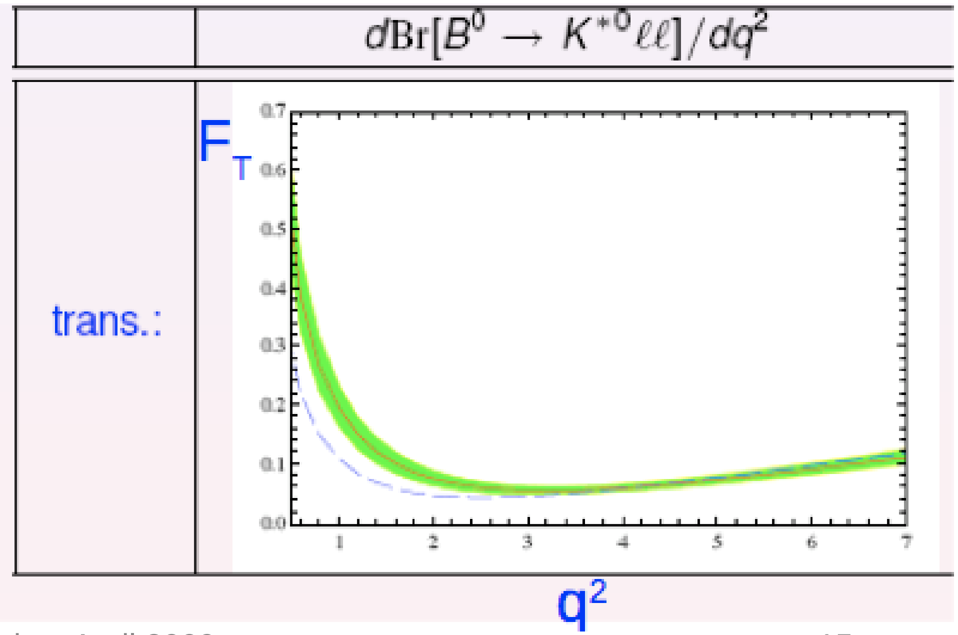
- *In SM limit $A_T^{(2)} \approx -2\mathrm{Re}\,|H_{+1}/H_{-1}|$*
  → the fraction of right-handed photons in the amplitude

- *$A_T^{(2)}$ can be extracted from the fit to the distribution of ϕ – angle Between di-lepton and K* planes*

- *Current estimate of resolution with 2 fb^{-1}*

$\sigma(A(B \to f^{CP}\gamma_R)/A(B \to f^{CP}\gamma_L)) \approx 0.1$

Feldmann CKM08



Charm Physics

Charm has unique sensitivity to NP since loop diagrams involve down-type quarks

- ***Precision measurements of x & y****, mixing parameters in the charm system (factor of 5 improvement wrt current accuracy)*

  - ***Wrong Sign ($D^0 \rightarrow \pi^- K^+$) mixing analysis***

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

    with 10 fb^{-1} N(ws) = 232500

    $x'^2 \pm 0.064$ (stat.) ($\times 10^{-3}$) & $y' \pm 0.87$ (stat.) ($\times 10^{-3}$)

  - ***Singly Cabibbo Suppressed 2-body lifetime ratio measurement of y_{CP}: $D^0 \rightarrow K^- K^+, \pi^- \pi^+$***

    $$y_{CP} \equiv \frac{\tau(D^0 \to K^- \pi^+)}{\tau(D^0 \to (K^+ K^-, \pi^+ \pi^-)} - 1 = y \cos\phi - x \sin\phi \left[\frac{R_m^2 - 1}{2}\right]$$

    with 10 fb^{-1} N($D^0 \rightarrow K^- K^+$ from secondary D^{*+}) ~ 8 $\times 10^6$

    $y_{CP} \pm 0.0005$ (stat.)

Charm Physics

- CP Violation in the charm sector is extremely small in SM
  CP asymmetries possible in mixing (A^M) or in between mixing and decay(A^I)

$$A^M \propto -y/2(|q/p| - |p/q|)\times\cos(\phi) \quad \& \quad A^I \propto x/2(|q/p| + |p/q|)\times\sin(\phi)$$

- Both ϕ and (|q/p| - 1) are negligibly small in SM
  Existing limits:
  $|q/p| = 0.87 \pm^{0.18}_{0.15}$ & $\phi = -9.1 \pm^{8.1}_{7.8}$ degree

- Higher sensitivity will come as mixing analyses improve precision
  → Sensitivity to many NP models

Example: CPV in Singly Cabibbo Suppressed decays (NP in penguins)
$D^0 \to KK, \pi\pi$

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

With 10 fb^{-1} statistical sensitivity on Acp will reach 10^{-3} level
May be observable !

If NP is discovered by LHCb with 10 fb^{-1} the NP models should be studied

Plan for LHCb upgrade to collect ~100 fb^{-1}

There are many observables where we are not limited by theoretical uncertainties

CPV measurements

	Sensitivity with 10 fb^{-1}	Do we need 100 fb^{-1}?
NP in boxes:		
❑ ϕ_s is the most sensitive measurement	$\sigma(\phi_s) \sim 0.01$	**Yes** (theor. uncert. 0.002)
NP in penguins:		
❑ Probably the best sensitivity: β_s in $B_s \to J/\psi\phi$ & $B_s \to \phi\phi$	$\sigma(\delta\beta_s) \sim 2°$	**Yes**
or β in $B \to J/\psi Ks$ & $B \to \phi Ks$	$\sigma(\delta\beta) \sim 4°$	**Yes**

Rare Decays

	Sensitivity with 10 fb^{-1}	Do we need 100 fb^{-1} ?
NP in penguins:		
❑ *Photon polarization in $B_s \rightarrow \phi\gamma$ decay:*	$\sigma(H_R/H_L) = 0.04$	**Yes** (theor. uncert. ~0.01)
NP in a mixture of loop diagrams:		
❑ $B \rightarrow K^*\mu\mu$	$\sigma(s0) \sim 0.3\ GeV^2$	**Yes** (assuming theor. progress)
❑ $B_s \rightarrow \mu\mu$ ($B_d \rightarrow \mu\mu$)	$>5\sigma$ observation if SM	**Yes**

Charm Physics

Measured CP asymmetries

approach SM prediction

LVF in τ decays

$BR(\tau \rightarrow 3\mu) < 10^{-8}$

using τ from $D_s \rightarrow \tau\nu$

There could be great possibilities To be explored !

LHCb sensitivities for integrated lumi of 100 fb^{-1}

Observable	Sensitivity
$S(B_s \to \phi\phi)$	$0.01 - 0.02$
$S(B_d \to \phi K^0_S)$	$0.025 - 0.035$
$\phi_s\ (J/\psi\phi)$	0.003
$\sin(2\beta)\ (J/\psi K^0_S)$	$0.003 - 0.010$
$\gamma\ (B \to D^{(*)}K^{(*)})$	$< 1^\circ$
$\gamma\ (B_s \to D_s K)$	$1 - 2^\circ$
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$5 - 10\%$
$\mathcal{B}(B_d \to \mu^+\mu^-)$	3σ
$A_T^{(2)}(B \to K^{*0}\mu^+\mu^-)$	$0.05 - 0.06$
$A_{\rm FB}(B \to K^{*0}\mu^+\mu^-)\ s_0$	$0.07\ {\rm GeV}^2$
$S(B_s \to \phi\gamma)$	$0.016 - 0.025$
$A^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	$0.030 - 0.050$
charm x'^2	2×10^{-5}
mixing y'	2.8×10^{-4}
CP y_{CP}	1.5×10^{-4}

Also studying Lepton Flavour Violation in $\tau \to \mu\mu\mu$

Physics: main objectives

Search for New Physics in CP-violation and Rare Decays

Key Measurements	Accuracy in 1 nominal year (2 fb^{-1})
❑ In CP – violation	
✓ ϕ_s	**0.023**
✓ γ in trees	$4.5°$
✓ γ in loops	$10°$
❑ In Rare Decays	
✓ $B \rightarrow K^*\mu\mu$	$\sigma(s0) = 0.5\ GeV^2$
✓ $B_s \rightarrow \mu\mu$	**3σ measurement down to SM prediction**
✓ Polarization of photon in radiative penguin decays	$\sigma(H_R/H_L) = 0.1$ (in $B_s \rightarrow \phi\gamma$) $\sigma(H_R/H_L) = 0.1$ (in $B_d \rightarrow K^*e^+e^-$

Conclusion

- ***LHCb has many opportunities to discover NP in flavour sector within a few years of data taking (10 fb^{-1} sample); complementary to direct search by ATLAS & CMS***

- ***Preparing the LHCb upgrade to collect 100fb^{-1} is very important to study NP models***

  - ✓ *Since the luminosity is limited for the first phase of LHCb the time to double statistical precision will become long, after a few years of stable operation*

Various Scenarios to happen in the next few years

No space left for the 4th possibility

ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

Even if 4th possibility → LHCb, and superB, measurements of virtual effects may be the only way to set scale of BSM physics