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LHCb Physics Program
On behalf of the LHCb collaboration

- *A spokesperson of any LHC collaboration has to believe that there will be discovery of New Physics at LHC*

- *General Purpose Detectors are designed for direct observation of New Particles*

- *LHCb has a different strategy*

  Experimental observables sensitive to New Particles through the interference effects with well studied objects, b-quarks

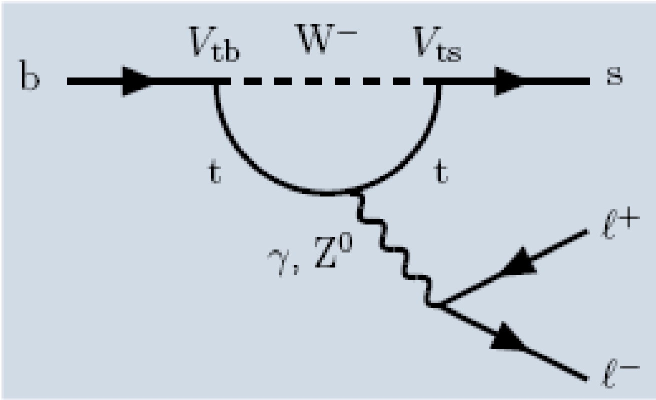
Various Scenarios

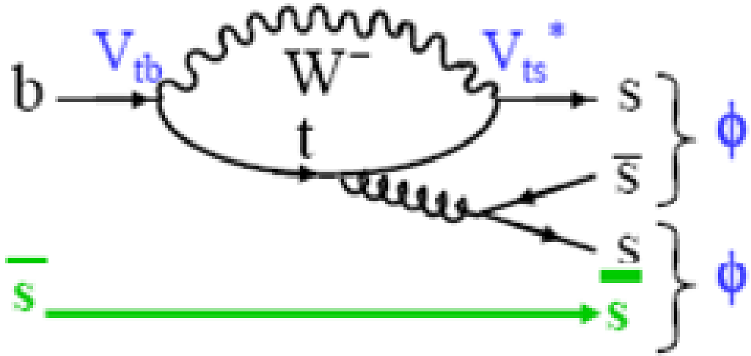
No space left for the 4th possibility

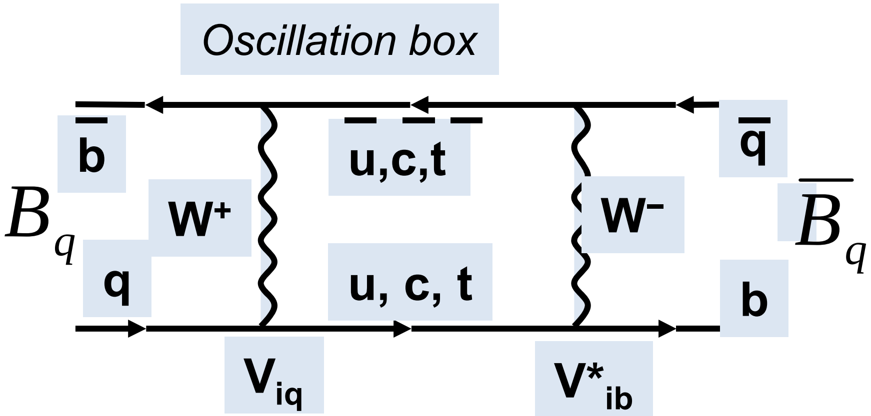
ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

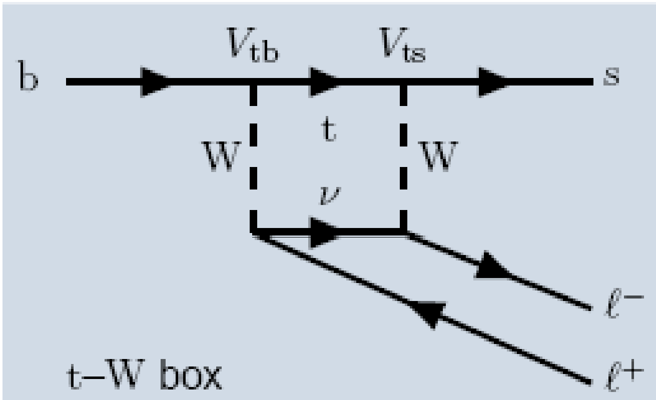
Examples of processes mediated by loop diagrams in b-physics

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





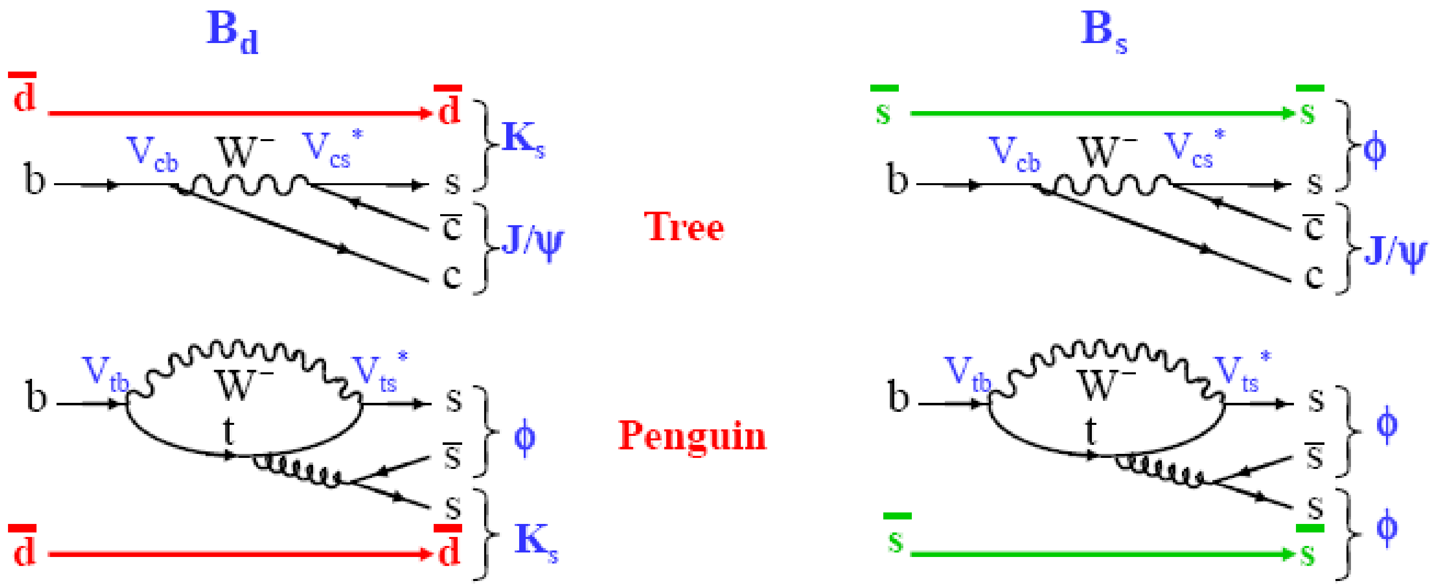




Search for NP in CPV by comparing observables measured in tree and loop topologies

β(tree+box) in $B \rightarrow J/\psi K_s$
γ(tree) in many channels
β_s(tree+box) in $B_s \rightarrow J/\psi\, \phi$

β(peng+box) in $B \rightarrow \phi K_s$
γ(peng+tree) in $B \rightarrow \rho\rho, \rho\pi, \pi\pi$ or $B_s \rightarrow KK$
β_s(peng+box) in $Bs \rightarrow \phi\, \phi$



New heavy particles, which may contribute to d- and s- penguins, could lead to some phase shifts in all three angles:

$\delta\gamma(NP) = \gamma(\text{peng+tree}) - \gamma(\text{tree})$

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

$\delta\beta_s\,(NP) = \beta_s\,(B_S \rightarrow \phi\phi) - \beta_s\,(B_S \rightarrow J/\psi\phi)$

Current sensitivity to New Physics in CPV measurements

- ***In box diagrams***

β vs $|V_{ub} / V_{cb}|$ is limited by theory (~10% precision in $|V_{ub}|$) *(d-box)*
β_s not measured accurately (indication of large value from CDF/D0) *(s-box)*

- ***In penguin diagrams:***

$\sigma(\delta\gamma(NP)) \sim 30°$ *(d-penguin)*
$\sigma(\delta\beta(NP)) \sim 10°$ *(s-penguin)*
$\sigma(\delta\beta_s(NP))$ *not measured* *(s-penguin)*

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

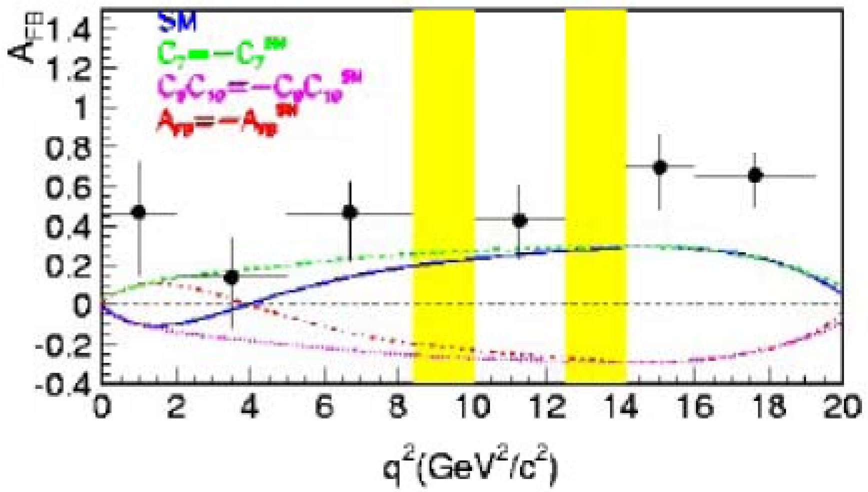
Current sensitivity to New Physics
in Rare Decays *(combination of various box and penguin diagrams)*

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

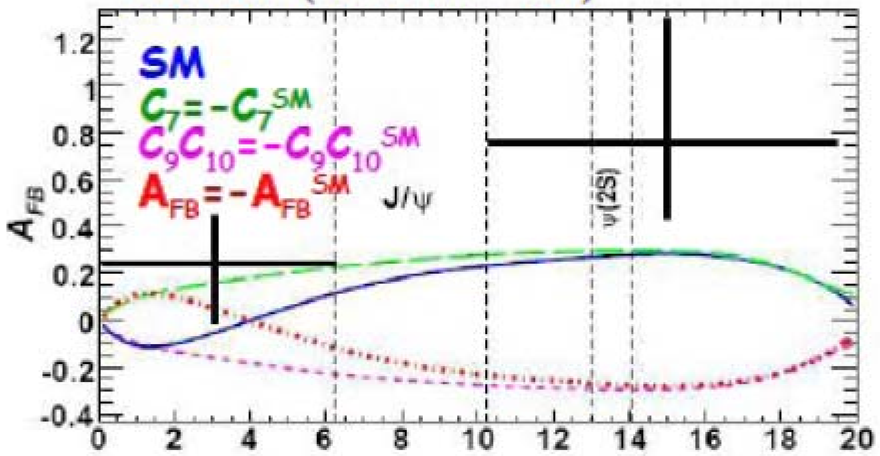
- *A_{FB} in $B \to K^*\mu\mu$ (BELLE/BaBar)*
- *Photon polarization in $B \to K^*\gamma$ (BELLE/BaBar)*
- *BR ($B_s \to \mu\mu$) (CDF /D0)*
- *BR ($D^0 \to \mu\mu$) (CDF)*
- *Lepton Flavor Violation in τ decays (BELLE/BaBar)*

Contribution from LHCb is extremely important !!!
Background suppression is a challenge

Belle (ICHEP '08)



BaBar (ICHEP '08)



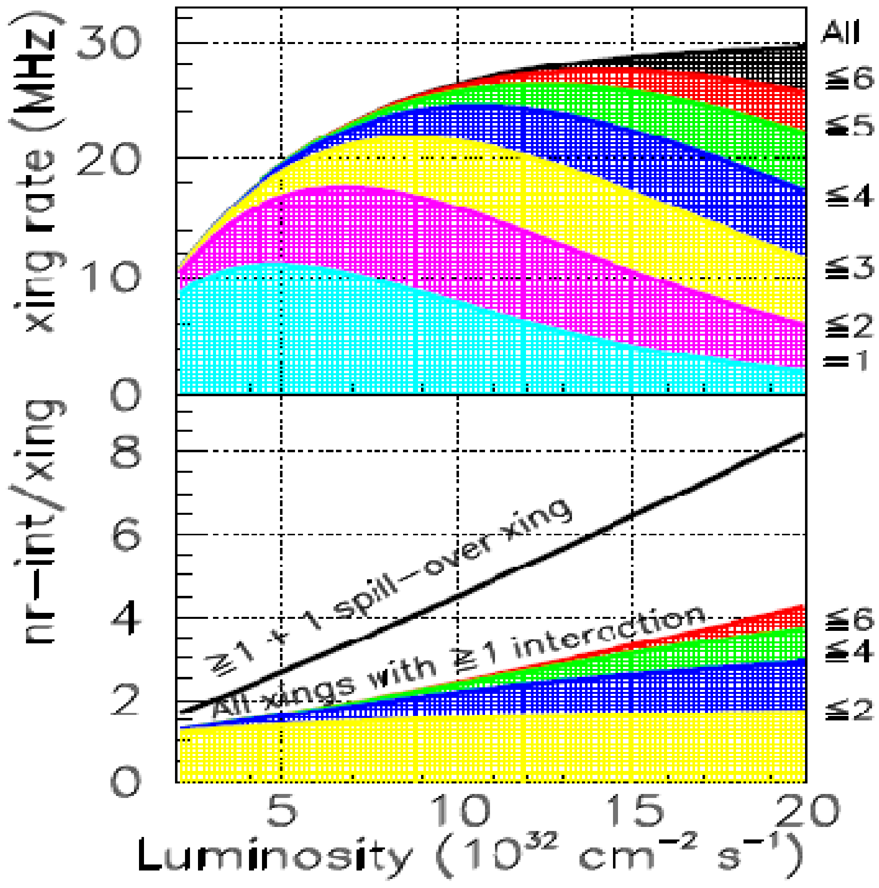
LHCb Running Conditions

- *Bunch crossing frequency: ~ 40 MHz*

- *For LHCb $L \sim 2 \times 10^{32}\ cm^{-2}s^{-1}$*
  (less focusing of the beam locally)
  → multiple interactions are subdominant

- *Prospects for data samples:*
  - *2 fb^{-1} in 1 nominal LHC year*
  - *~10 fb^{-1} in a few years*
  - *~100 fb^{-1} after possible upgrade to run at $L \sim 2 \times 10^{33}\ cm^{-2}s^{-1}$*

Inelastic pp reactions



LHCb key measurements are potentially sensitive to discovery of New Physics

- ❑ ***In CP – violation***

✓ ϕ_s
✓ γ **in trees**
✓ γ **in loop**

- ❑ ***In Rare Decays***

✓ A_{FB} in $B \rightarrow K^*\mu\mu$
✓ BR ($B_s \rightarrow \mu\mu$)
✓ ***Polarization of photon in radiative penguin decays***

&

- ❑ ***Mixing and CP – violation in Charm sector***

- ❑ ***Search for Lepton Flavor Violation in*** $\tau \rightarrow \mu\mu\mu$

LHCb sensitivities for the key measurements

Int. Lumi

- ❑ *For nominal LHC year* — *(2fb^{-1})*
- ❑ *For a few years of running at 2-5 × 10^{32}* — *(10 fb^{-1})*
  Accuracy is limited by statistics
- ❑ *Do we need larger data samples ?* — *(~ 100 fb^{-1})*
  - ➢ *Theoretical uncertainties*
  - ➢ *Study of systematic accuracy is ongoing*

LHCb prospects for β_s

See talk of A. Sarti

- ϕ_S = $-2\beta_S$ *is the counterpart of* ϕ_d = 2β

- ϕ_S *(J/ψφ)[SM] = 0.0368±0.0017 (CKMfitter)*

Most accurate SM prediction → increased sensitivity to New Physics effects in the B_s-B_s system : if NP in the box loop

$$\phi_S = \phi_S(SM) + \phi_S(NP)$$

- *High BR($B_s \to J/\psi\phi$) and trigger eff.*

  LHCb yield in 2 fb^{-1} 115 k

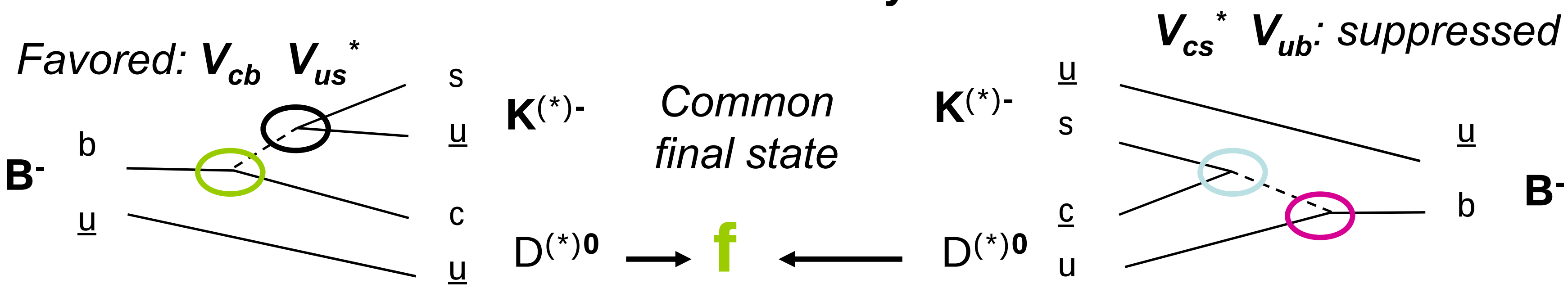
- *$J/\psi\phi$ is not a pure CP-eigenstate;*

  angular analysis is needed to separate odd and even states

Decay	Yield ($2\ fb^{-1}$)	σ (ϕ_s)
$J/\psi\ \eta_{\gamma\gamma}$	8.5 k	0.109
$J/\psi\eta_{\pi\pi\pi}$	3 k	0.142
$J/\psi\ \eta'_{\pi\pi\eta}$	2.2 k	0.154
$J/\psi\ \eta'_{\rho\gamma}$	4.2 k	0.08
$\eta_c\ \phi$	3 k	0.108
$D_s^+\ D_s^-$	4k	0.133
All CP eig	-	0.046
$J/\psi\ \phi$	115 k	0.03
All	-	0.021

LHCb prospects for γ

- ***In trees:***
  - ***Interference between tree-level decays***



$$\frac{A\left(B^- \to \bar{D}^0 K^-\right)}{A\left(B^- \to D^0 K^-\right)} = r_B e^{i\delta_B} e^{-i\gamma}$$

Parameters: γ,
(r_B, δ_B) per mode

Three methods for exploiting interference (choice of D^0 decay modes):

- *(GLW): Use CP eigenstates of $D^{(*)0}$ decay, e.g. $D^0 \to K^+ K^- / \pi^+\pi^-$, $K_s\pi^0$*
- *(ADS): Use doubly Cabibbo-suppressed decays, e.g. $D^0 \to K^+\pi^-$*
- *(Dalitz): Use Dalitz plot analysis of 3-body D^0 decays, e.g. $K_s \pi^+ \pi^-$*

  - ***Mixing induced CPV measurement in $B_s \to D_s K$ decays***
    (Specific for LHCb)

- ***Interference of trees and penguins***

  CP asymmetries of $B^0 \to \pi\pi$ and $B_s \to KK$ events assuming U-spin symmetry

γ with trees

See talk of V. Gibson

- Perform global fit to $B \rightarrow DK$ with common parameters
  Include results from B^0 and B_s time dependent analyses.

δ_{B^0} (°)	0	45	90	135	180
σ_γ for 0.5 fb^{-1} (°)	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 fb^{-1} (°)	4.1	5.1	4.8	5.1	3.9
σ_γ for 10 fb^{-1} (°)	2.0	2.7	2.4	2.6	1.9

γ in penguin loops: $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow KK$

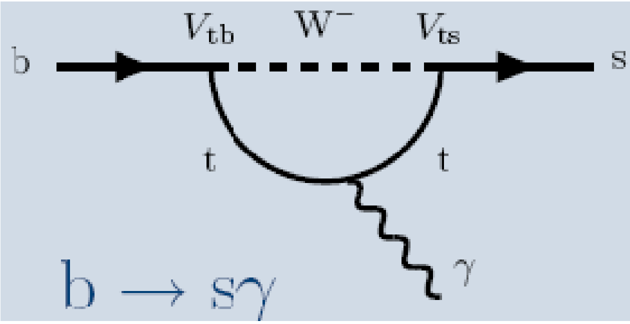
- Fit CP asymmetries of $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow KK$ event
  - 4 observables: $A^{dir}_{\pi\pi}, A^{mix}_{\pi\pi}, A^{dir}_{KK}, A^{mix}_{KK}$
- Parameters: γ, penguin to tree amplitude ratio $d_{\pi\pi} e^{i\Theta_{\pi\pi}}$, $d_{KK} e^{i\Theta_{KK}}$
- Weak U - spin constraint
  - $d_{\pi\pi} = d_{KK} \pm 20\%$, $\Theta_{\pi\pi}$, Θ_{KK} independent

  Measures γ under certain assumptions on U - spin symmetry

Sensitivity	2 fb^{-1}	10 fb^{-1}
σ_γ (°)	10	5
$\sigma_{d_{\pi\pi}}$	0.18	0.09
$\sigma_{\theta_{\pi\pi}}$ (°)	9	5
$\sigma_{\Delta\Theta}$ (°)	17	8

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

See poster of L. Shchutska



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

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

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

SM:

- *C = 0 direct CP-violation*
- *S = **sin2ψ** sinϕ*
- *A^D = **sin2ψ** cosϕ*

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

- ❑ *Expected signal yield is 11k per nominal LHCb year*

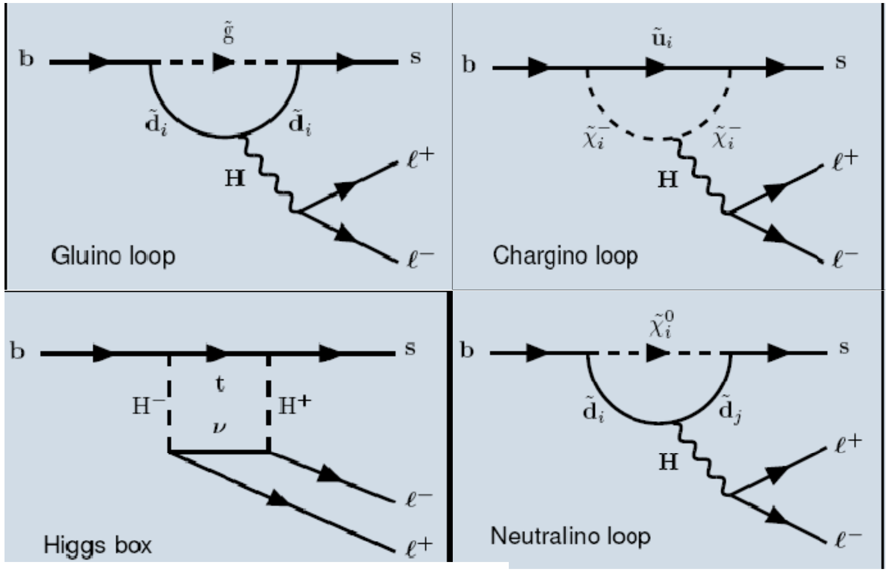
- ❑ *Sensitivity: $\sigma(A^D)=0.22$, $\sigma(S)=\sigma(C)=0.11$ for $2fb^{-1}$*
  $\sigma(A^D)=0.09$ for $10fb^{-1}$

To be compared with current accuracy from B-factories: $\sigma(\sin 2\psi) \sim 0.4$

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

See talk of W. Reece

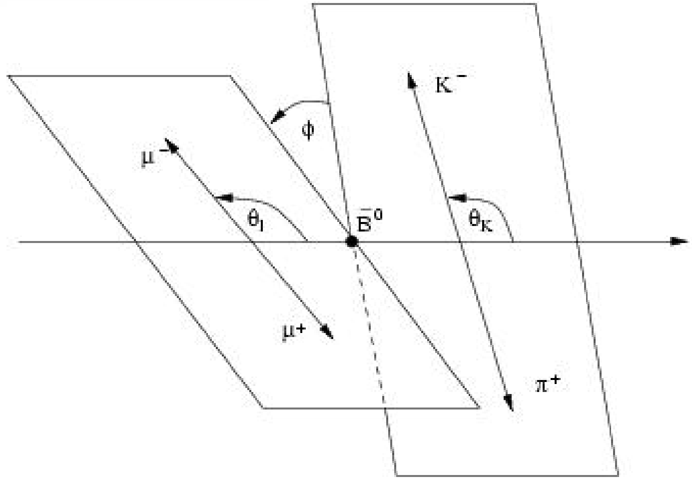
In SM this b→s penguin decay contains right-handed calculable contribution but this could be added to by NP resulting in modified angular distributions



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}F_0\sin^2\theta_\ell + \frac{3}{8}F_T(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$

- *Described by three angles (θ_l, ϕ, θ_K) and di-μ invariant mass q^2*

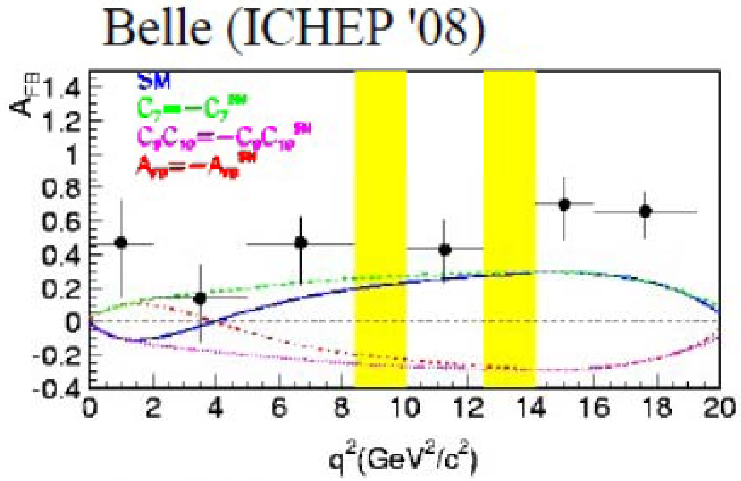
- *Forward-backward asymmetry A_{FB} of θ_l distribution of particular interest:*
  - *Varies between different NP models →*
  - *At zero-point, dominant theor. uncert. from $B_d \rightarrow K^*$ form-factors cancels at LO*

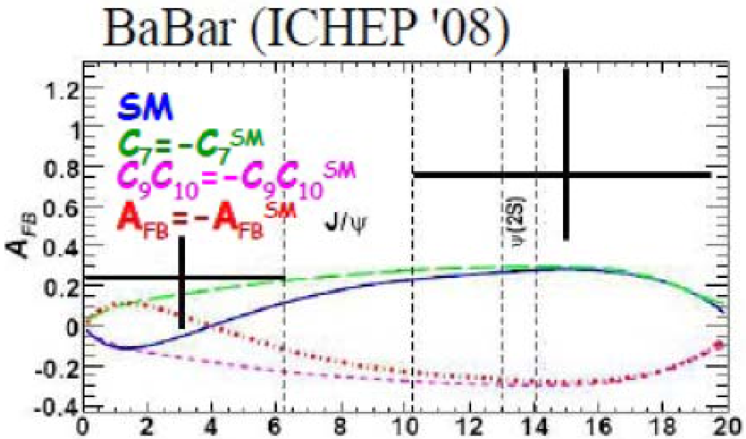


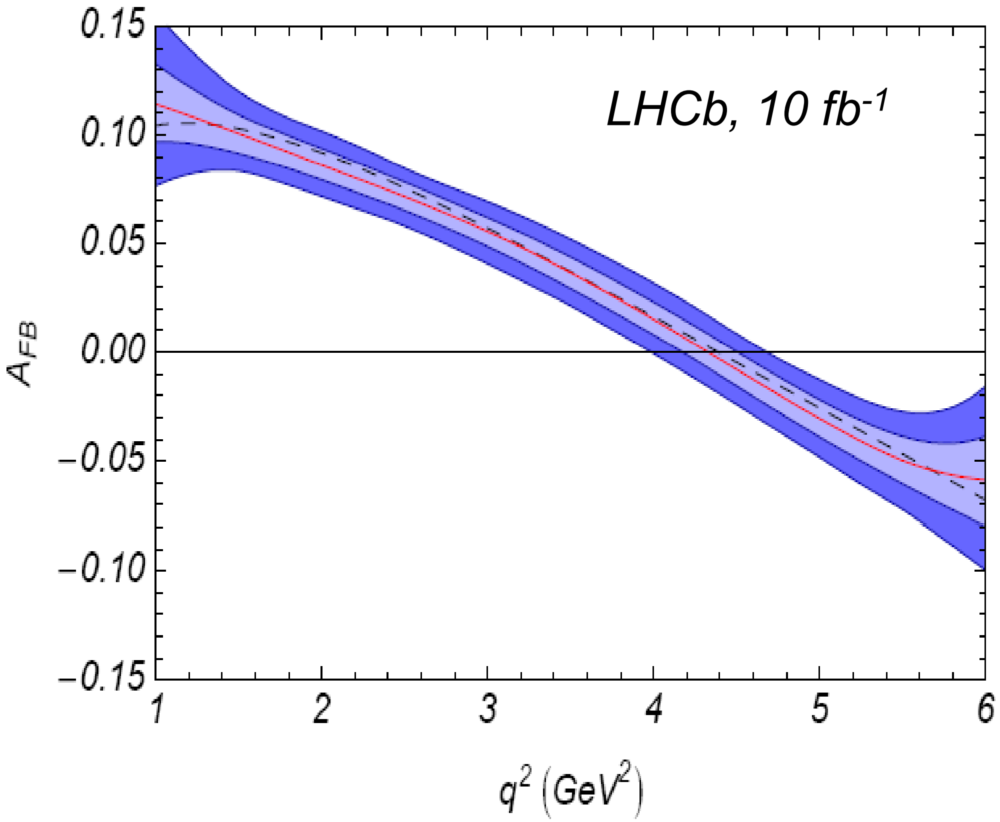
$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$

B → K*μμ

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



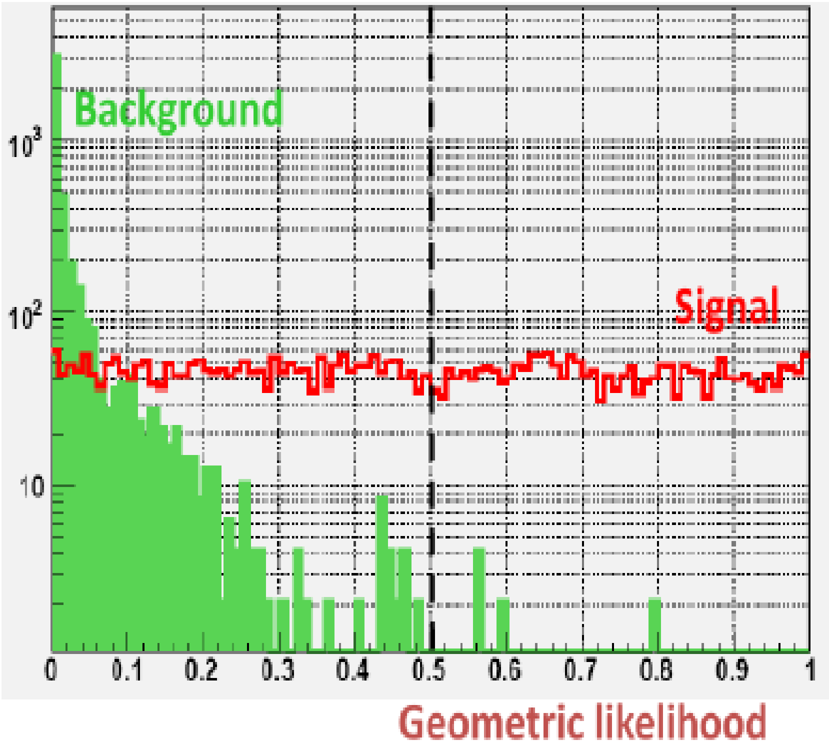




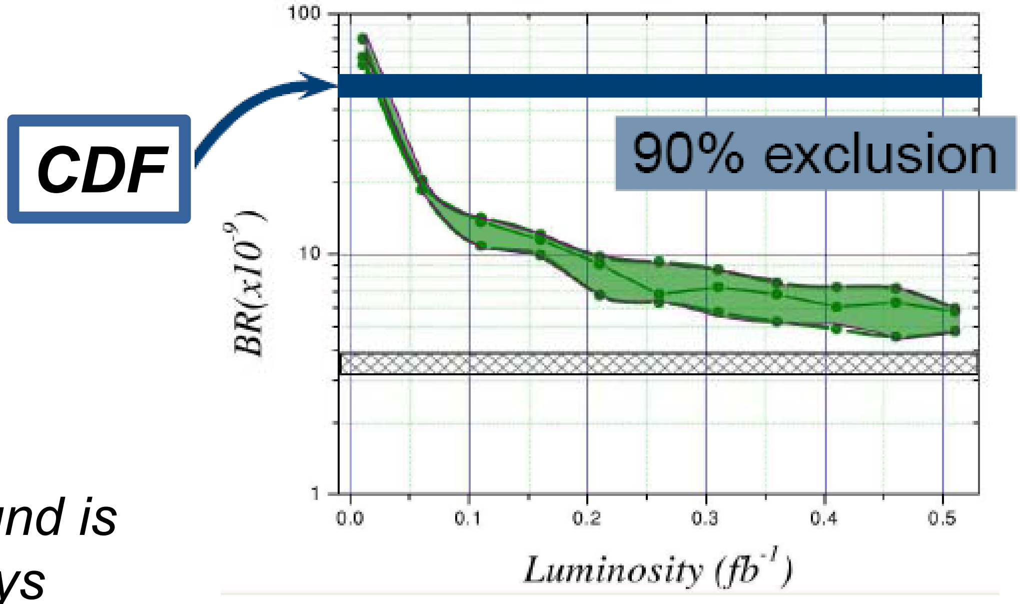
- ~7k events / 2fb^{-1} with B/S ~ 0.2
- After 10 fb^{-1}zero of A_{FB} located to ±0.28 GeV^2 (0.5 GeV^2 after 2 fb^{-1}) providing 7% stat. error on C_7^{eff} / C_9^{eff}
- Full angular analysis gives better discrimination between models. Looks promising

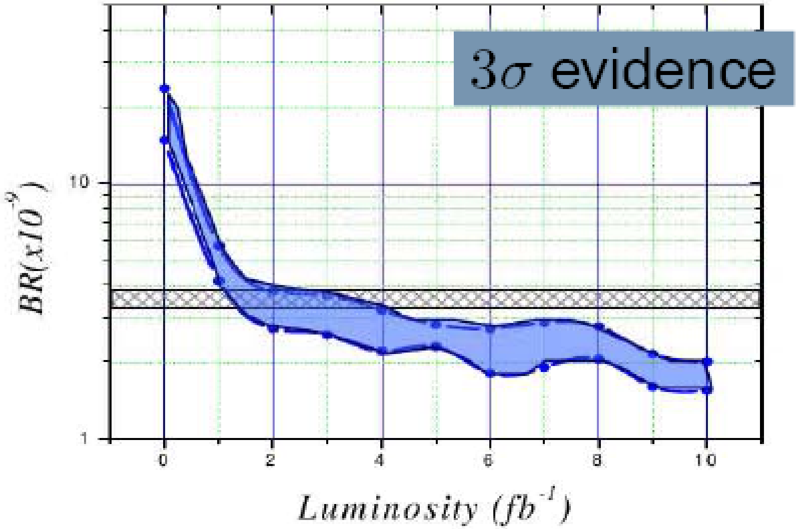
$B_s \to \mu\mu$

- *Super rare decay in SM with well predicted $BR(B_s \to \mu\mu) = (3.55 \pm 0.33) \times 10^{-9}$*
- *Potentially sensitive to NP*
  In MSSM $BR \propto \tan^6\beta / M^4_A$
- *Best present limit is from CDF:*
  $BR(B_s \to \mu\mu) < 4.7 \times 10^{-8}$ @ 90% CL
- *LHCb selects a signal using 3D likelihood of invariant mass, geometrical variables and PID:*
  - *Uncorrelated variables with different control samples*
  - *Invariant mass resolution is ~ 20 MeV/c^2*



$B_s \to \mu\mu$





- *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*

- *3σ evidence with 2 fb^{-1}*
  5σ observation with 6fb^{-1}

  For more precision measurement one needs the absolute normalization Measurements of B_s BR at Y(5S) by BELLE would be welcome

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 ± 0.064 (stat.) (×10^{-3}) & y' ± 0.87 (stat.) (×10^{-3})

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

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

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

    y_{CP} ± 0.05 (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 !

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:		
Very difficult to measure		
❑ γ(tree) vs γ(loop) requires assumption on the U-spin symmetry	$\sigma(\delta\gamma) \sim \sigma(\gamma_{loop}) \sim 5^\circ$	Yes (?)
❑ γ(tree) vs α(loop) α is sensitive to NP contribution in penguins only if SU(2) breaks or large electro-weak penguins	$\sigma(\delta\gamma) \sim \sigma(\alpha) \sim 4^\circ$	Yes (?)
❑ Probably the best sensitivity: β_s in $B_s \to J/\psi\phi$ & $B_s \to \phi\phi$	$\sigma(\delta\beta_s) \sim \sigma(\beta_s) \sim 0.05$	Yes
or β in $B \to J/\psi Ks$ & $B \to \phi Ks$	$\sigma(\delta\beta) \sim \sigma(\beta) \sim 0.1$	Yes

Rare B Decays

Sensitivity with 10 fb^{-1} | **Do we need 100 fb^{-1} ?**

NP in penguins:

- Photon polarization in $B_s \to \phi\gamma$ decay: $\sigma(A^{\Delta})= 0.09$ — Yes (theor. uncert. ~0.01)

NP in a mixture of loop diagrams:

- $B \to K^*\mu\mu$ — $\sigma(s0) \sim 0.3\ GeV^2$ — Yes (assuming theor. progress)
- $B_s \to \mu\mu$ — >5σ observation if SM — Yes (abs. norm. is required)

Charm Physics

Measured CP asymmetries approach SM prediction

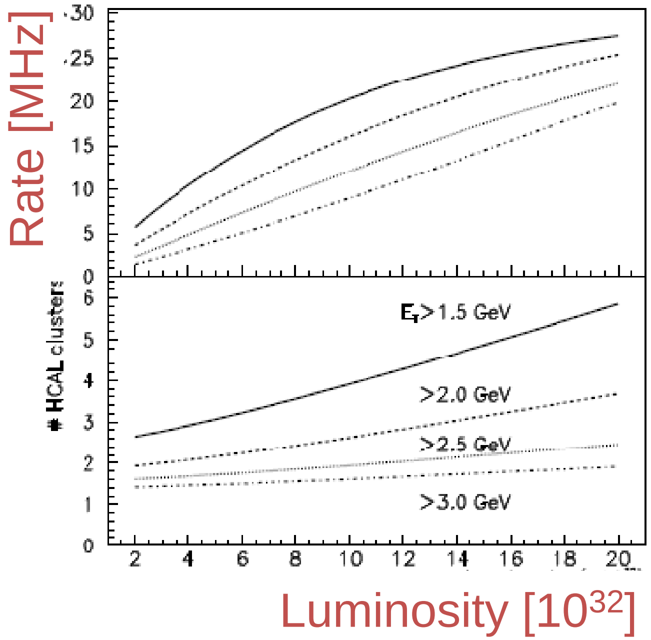
LVF in τ decays

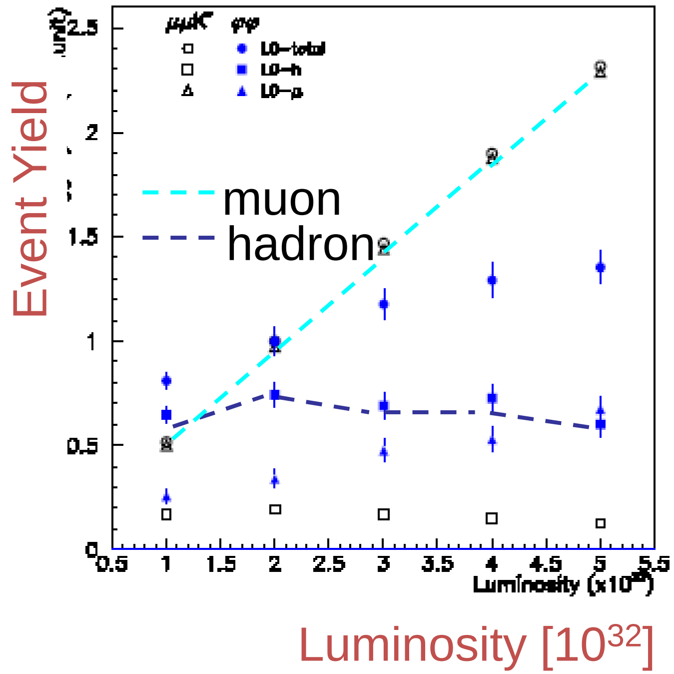
$BR(\tau \to 3\mu) < 10^{-8}$ using τ from $D_s \to \tau\nu$

There could be great possibilities
To be explored !

The LHCb Upgrade

- *L0 hadron trigger*
  - *Is bandwidth limited*
  - *Rate of HCAL triggers with E_T > 2 GeV increases from 4 to 25 MHz when lumi from 2 to 20x 10^{32}*





- ***L0 muon trigger***
  - *~90% efficiency, scales with luminosity*
- ***L0 hadron trigger***
  - *Only ~50% efficient*
  - *does not scale with luminosity*

The LHCb Upgrade

- ***Must change all front end electronics (except muon system) to 40 MHz***
  - *all Si based devices are replaced*
  - *changing RICH photon detectors*
  - *Keep same Vertex Locator geometry for a few years, change to pixels or 3D devices later*
  - *Outer Tracker geometry to be slightly modified to keep occupancies acceptable*
- ***Work on 40 MHz readout chip is starting***

Summary

- *Clean experimental signature of NP is unlikely at currently operating experiments*

- ***LHCb has a lot of opportunities to discover NP in a few years of data taking (with 10 fb^{-1} data sample)***

  - ✓ *Physics program is complementary to that of ATLAS & CMS*

- *Study of NP properties needs much improved precision in b-physics*

  → ***LHCb upgrade to collect 100fb^{-1} is very important***