Search for New Physics in the B-sector at the LHC

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on behalf of the LHCb collaboration

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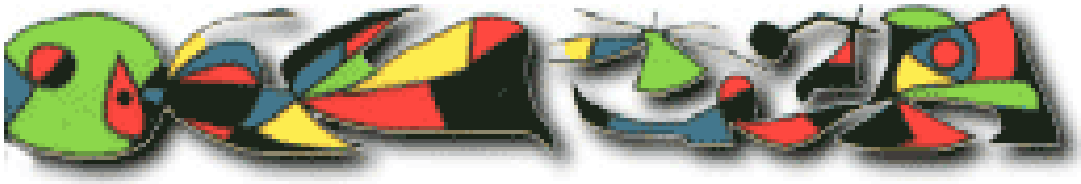
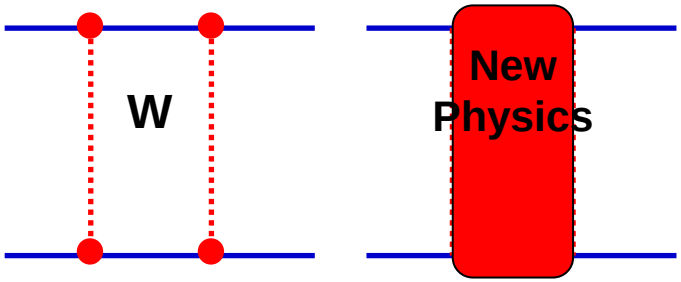


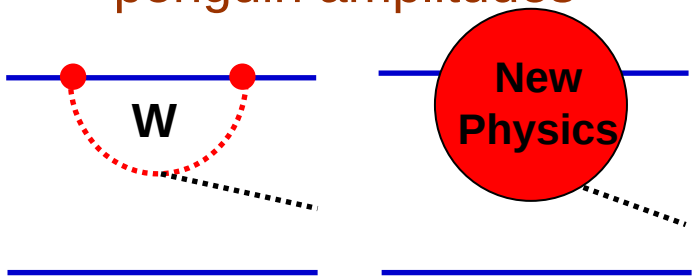
Search for New Physics in the B sector

…precision test of the SM at loop level

box diagrams



penguin amplitudes



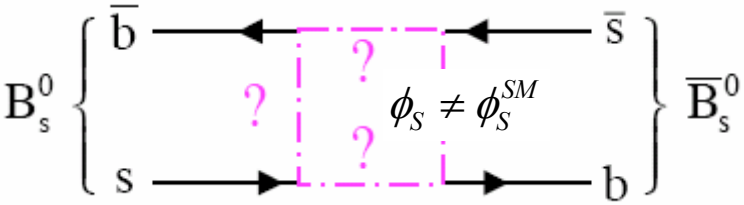
Deviations from Standard Model:
absolute rates and CP asymmetries

- Best probes: processes suppressed in SM
  - New Physics have large impact
  - measurement of CP violation and CKM phases as tools
- LHC as B-factory (e.g., 10^{12} b-quarks/ yr produced in LHCb)

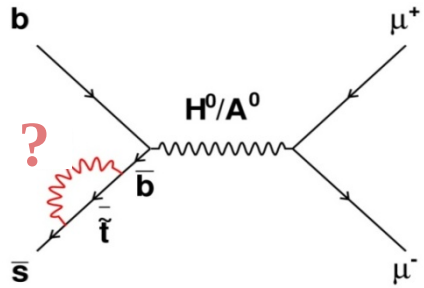
Key Channels for New Physics searches

- Search for New Physics in:
  - CP violation in the B_s system:
    - **"golden decay" $B_s \rightarrow J/\psi\ \phi$**
    - penguin decay $B_s \rightarrow \phi\ \phi$
  - rare flavor changing neutral current decays
    - **$B_s \rightarrow \mu\mu$**
    - **angular asymmetries $B_d \rightarrow K^* \mu\mu$**
    - photon polarization $B_s \rightarrow \phi\ \gamma$
  - CKM angle γ

see also K. Toms:
"Heavy flavor decays in ATLAS"



B_s oscillation "box diagram"



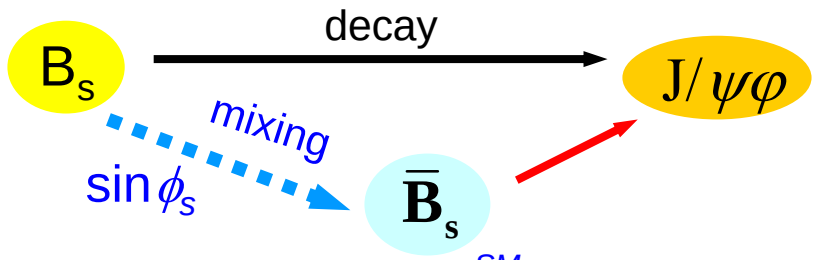
$B_s \rightarrow \mu^+\mu^-$ Higgs "Penguin"

$$\begin{array}{c|ccc} & d & s & b \\ \hline u & 1 & 1 & \boxed{e^{-i\gamma}} \\ c & 1 & 1 & 1 \\ t & e^{-i\beta} & \boxed{-e^{-i\phi_s/2}} & 1 \end{array}$$

CKM phases to order λ^4

CP Violation in the B_s System

ϕ_s from $B_s \rightarrow J/\psi\phi$



$$\phi_s^{SM} = -2\beta_s \approx -0.04$$

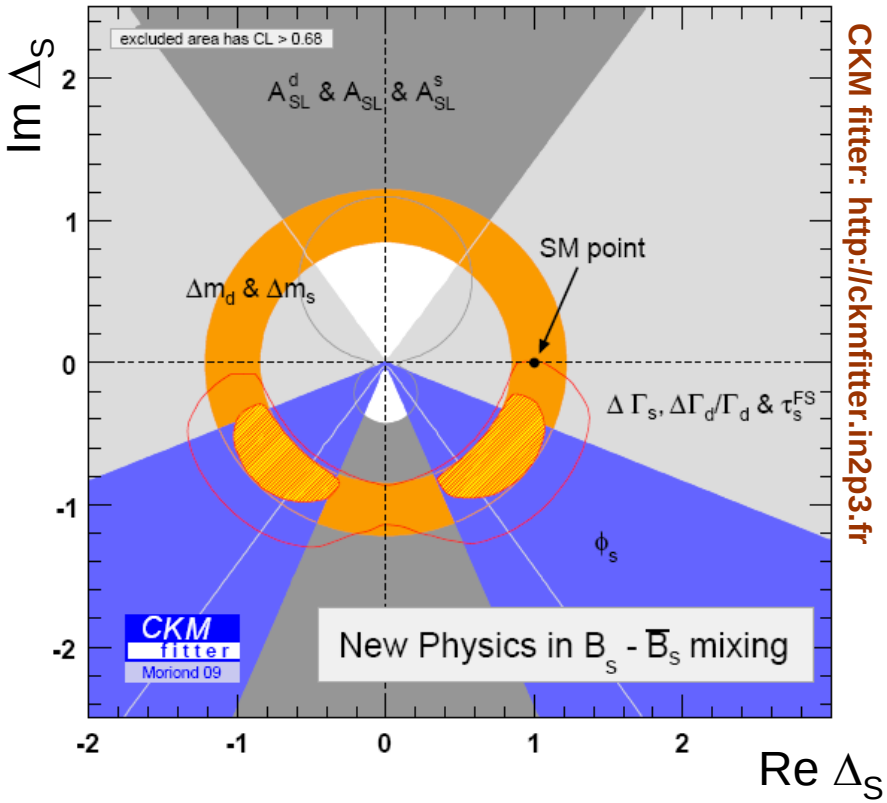
$$A_{CP}(t) = \frac{\Gamma(\overline{B_S^0}(t) \rightarrow f) - \Gamma(B_S^0(t) \rightarrow f)}{\Gamma(\overline{B_S^0}(t) \rightarrow f) + \Gamma(B_S^0(t) \rightarrow f)}$$

$$\frac{\left\langle B_S^0 \middle| H_{eff}^{\mathrm{SM+NP}} \middle| \overline{B_S^0} \right\rangle}{\left\langle B_S^0 \middle| H_{eff}^{\mathrm{SM}} \middle| \overline{B_S^0} \right\rangle} = \mathrm{Re}(\Delta_S^{\mathrm{NP}}) + i\,\mathrm{Im}(\Delta_S^{\mathrm{NP}})$$

$$SM: \ \mathrm{Re}(\Delta_S^{\mathrm{NP}}) = 1, \ \mathrm{Im}(\Delta_S^{\mathrm{NP}}) = 0$$

A.Lenz, U.Nierste

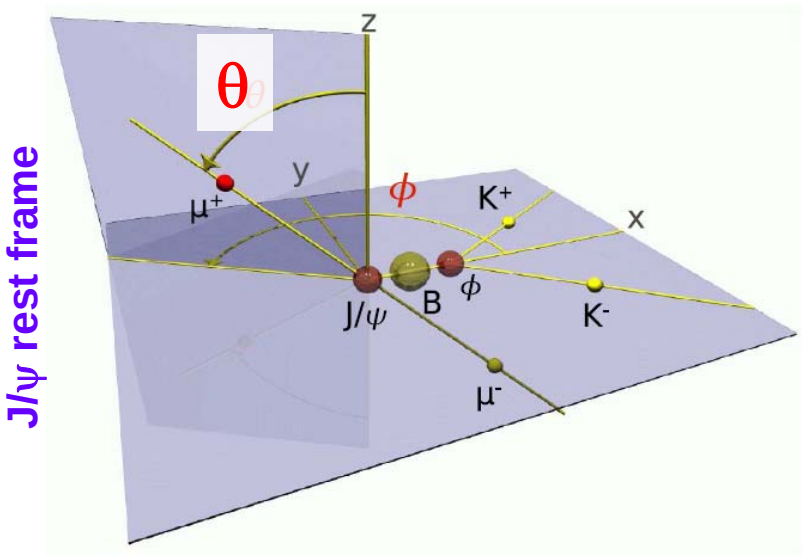
New Physics in B_s mixing

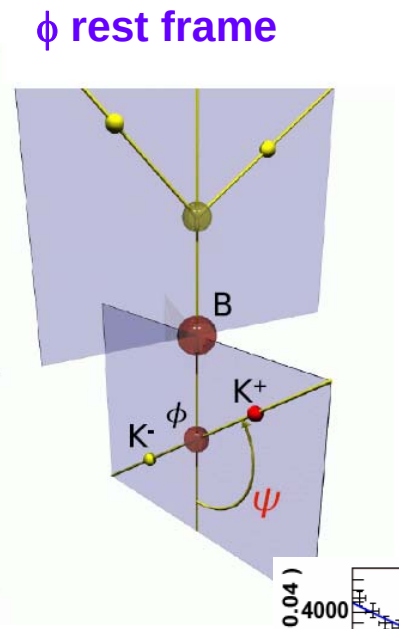


Tevatron measurement:
~2σ discrepancy from SM

$B_s \rightarrow J/\psi\ \phi$ - analysis

Transversity basis:

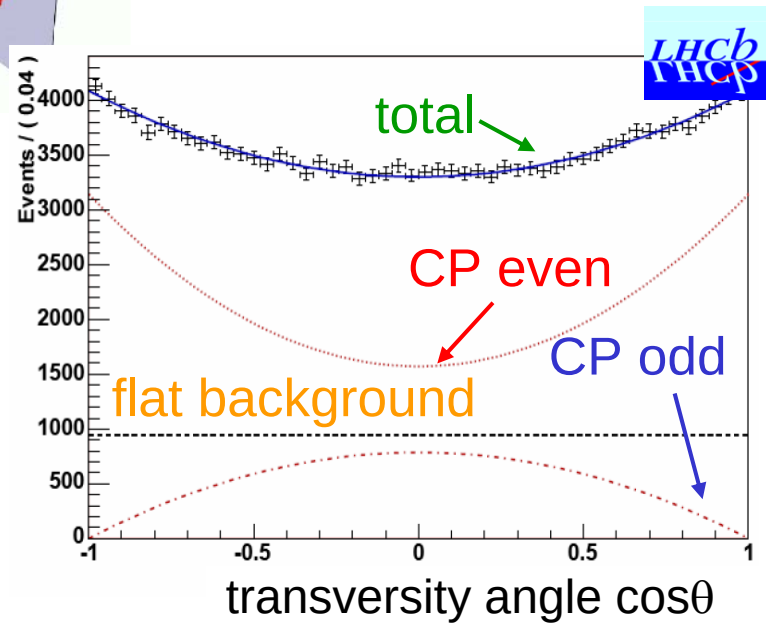




$B_s \rightarrow J/\psi\phi$ is vector- vector state:

L=0, 2 → CP-even

L=1 → CP-odd



Experimental challenge:

Simultaneous fit to time and angular distributions to distinguish between CP-odd and CP-even components.

ϕ_s Sensitivity

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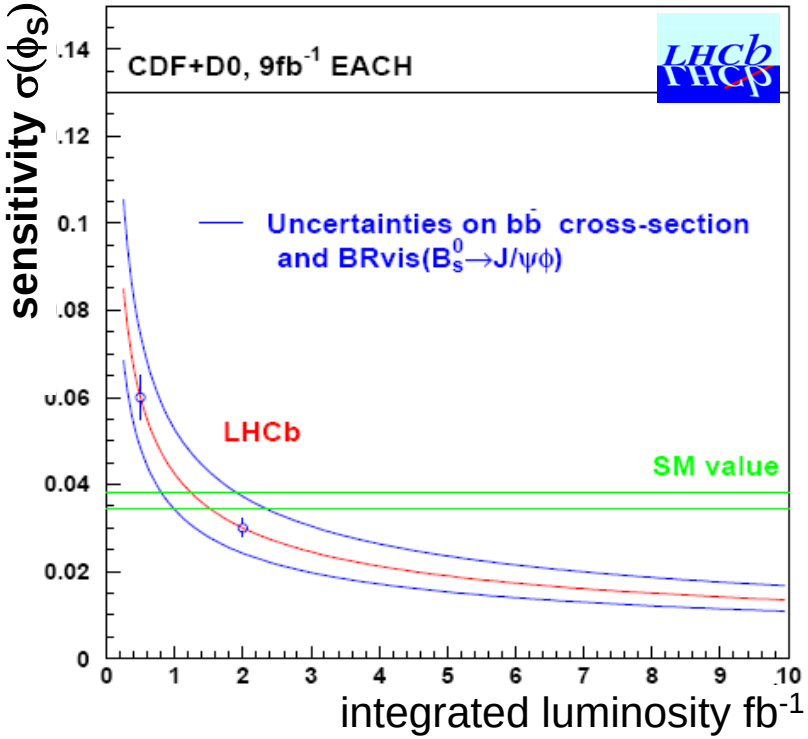
LHCb sensitivity to ϕ_s



Pure CP eigenstates: small yield, large bkg.

CP eigenstates

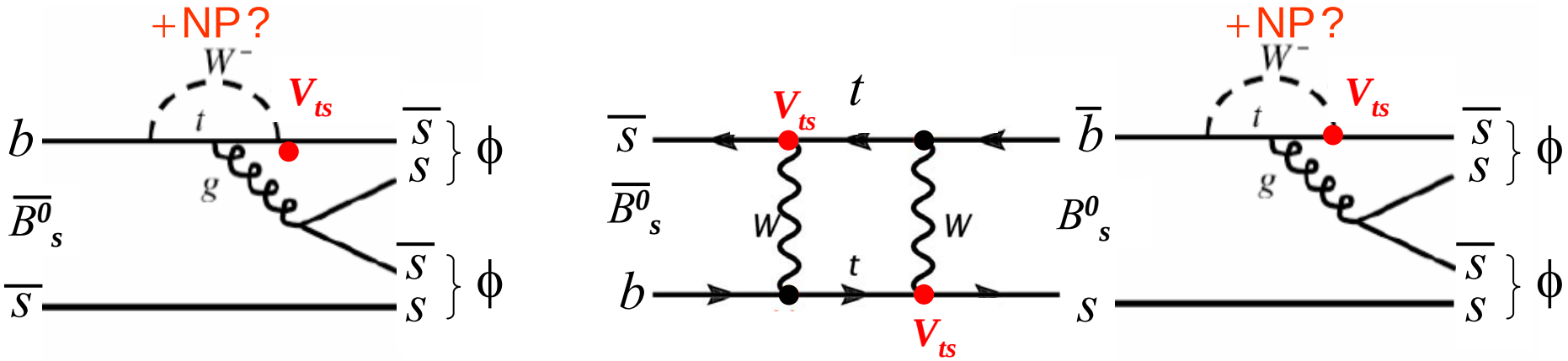
Decay	Yield (2 fb^{-1})	$\sigma(\phi_s)$
$J/\psi\ \eta_{\gamma\gamma}$	8.5 k	0.109
$J/\psi \eta_{\pi\pi\pi}$	3 k	0.142
$J/\psi\ \eta'_{\pi\pi\eta}$	2.2 k	0.154
$J/\psi\ \eta'_{\rho\gamma}$	4.2 k	0.08
$\eta_c\ \phi$	3 k	0.108
$D_s^+ D_s^-$	4k	0.133
All CP eig	-	0.046
$J/\psi\ \phi$	***117k***	***0.030***

ATLAS : $\sigma(\phi_S)$ = 0.16 (2.5fb-1)*

CMS: $\sigma(\phi_S)$ = 0.18 (2.5fb^{-1})*

*O. Leroy: "NP search in Bs → J/ψφ and Bs → φφ (includes ATLAS and CMS sensitivities)", talk at "Flavor as a window to NP at the LHC", May 2008

ϕ_s in Penguin decays: $B_s \to \phi\phi$



- V_{ts} both in mixing and decay: phases cancel
  $\phi_{Bs \to \phi\phi} = \phi_s - \phi_{decay} = 0 \quad \Rightarrow$ **zero CP asymmetry**

- Angular analysis similar to $B_s \to J/\psi\phi$

•Yield (2 fb-1): 3100 evts, B/S <0.8

2 fb^{-1} (10 fb^{-1})

$$\sigma(\phi_{B_s \to \varphi\varphi}) \approx 0.11 \ \ (0.05)$$

Effective Hamiltonian

- Operator Product Expansion: effective Hamiltonian

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{CKM} \sum_{i=1}^{10} C_i \times O_i$$

SM:

i=1,2	tree
i=3-6,8	g penguin
i=7	γ penguin
i=9,10	EW penguin

Wilson coefficients: short distance calculated pertubatively in SM an beyond

Local Operator: Long-distance/non-pert.

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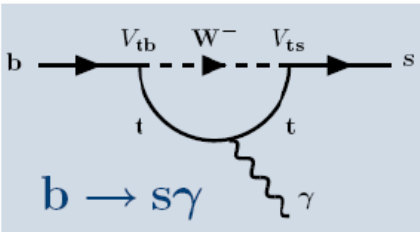
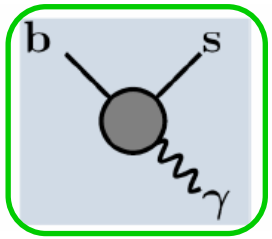
Wilson coefficients: short distance calculated pertubatively in SM an beyond

Local Operator: Long-distance/non-pert.

- Example: main contribution to b → s γ



$$\sim V_{tb}V_{ts}^* \times C_7(m_B) \times$$



$$O_7 \sim m_b(\overline{s_L}\sigma^{\mu\nu}b_R)F_{\mu\nu}$$

- New Physics as modified coefficients C_i
  - modified: branching ratios, angular asymmetries, polarizations

Rare decays: $B_s \to \mu^+\mu^-$

- Bs → μμ: very rare loop decay, sensitive to New Phyisics
  - **BR~(3.37±0.31) x 10^{-9} in SM**
  - can be strongly enhanced in SUSY

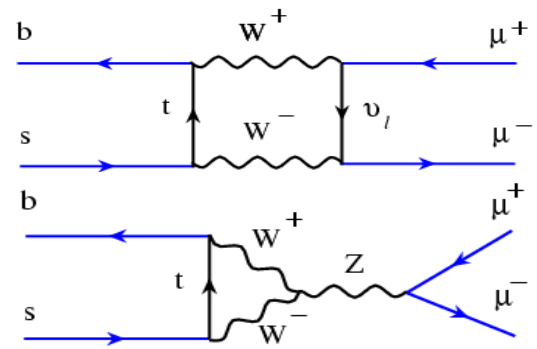
$$BR^{MSSM}(B_q \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

(hep-ph/707.3954)

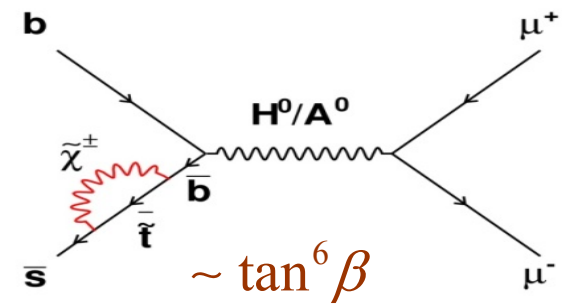
- Main issue: background rejection
  - events in LHCb / 2fb^{-1}:
    b→μ,$\bar{b}$→μ: 5 x 10^9 (also b→c→μ)
    Bs → μμ 240 (SM)

- Selection variables
  - muon ID
  - di-μ mass ($\sigma(m_{\mu\mu})$ ~ 18MeV)
  - B-vertex topology

Standard Model:



SUSY (MSSM):



2 fb^{-1}

BR($B_s \to \mu^+\mu^-$) < 4.7x10^{-8} (90% CL) **(PRL 100.101202)**

$B_s \to \mu^+\mu^-$: LHC*b* Prospects

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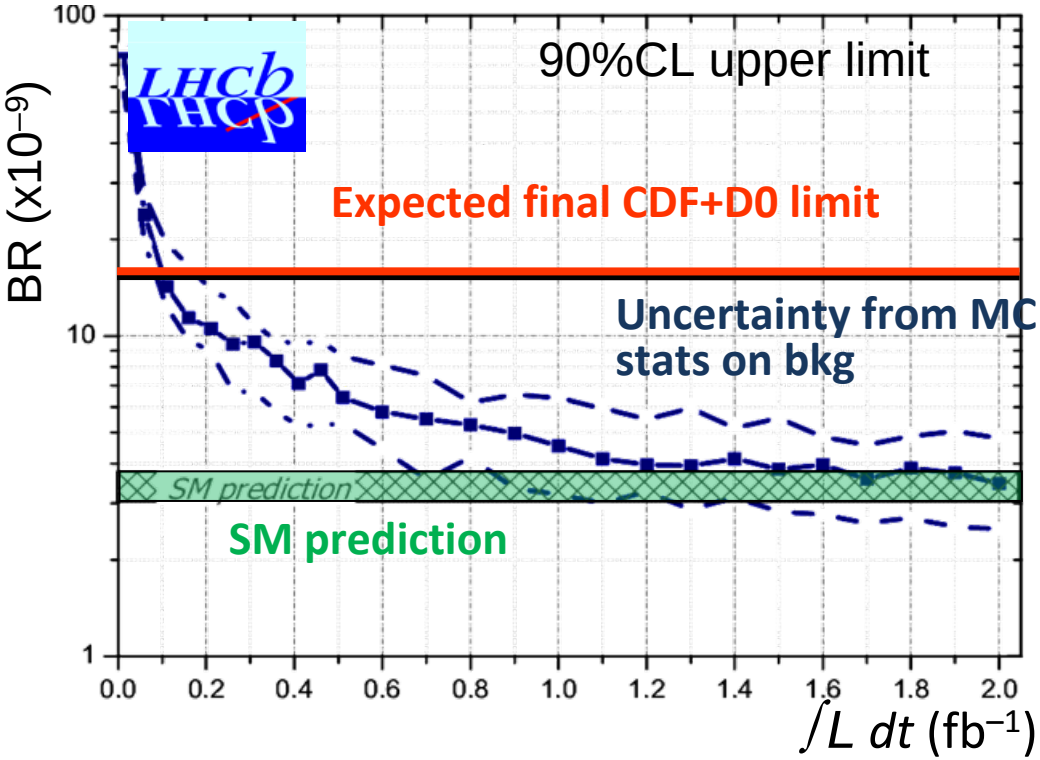
Exclusion



Exclusion @ 90% CL

- reach SM prediction: $2\,fb^{-1}$

Observation:

- Evidence (3σ): $3\,fb^{-1}$
- Discovery (5σ): $10\,fb^{-1}$

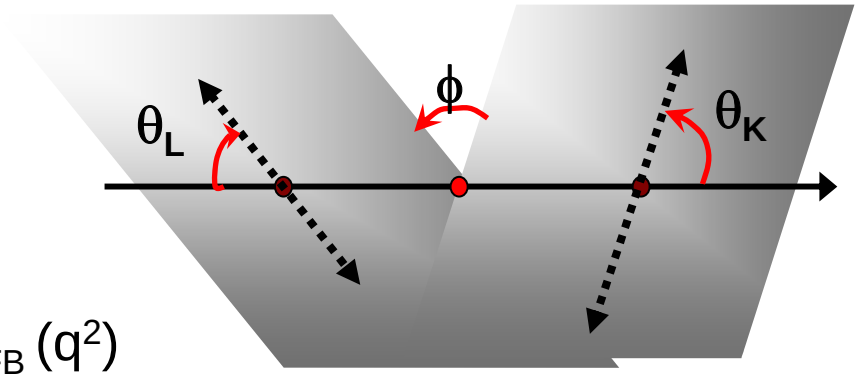
ATLAS	$< 10^{-8}$	$(2\ fb^{-1})$*
CMS	$< 1.4 \times 10^{-8}$	$(10\ fb^{-1})$**

*S. Ben-Ami: "B-Physics in ATLAS, an overview", talk at "Flavor as a window to NP at the LHC", May 2008
** K. Ulmer: Prospects for Measurements of Rare B Decays and Other Heavy Flavour Physics at CMS, roceedings of the BEACH2008 conference

Angular observables in $B^0 \to K^*\mu\mu$

- Decay distribution parameterized by
  - three transversity angles θ_k , θ_L , ϕ
  - dimuon invariant mass $s=m^2_{\mu\mu}$

Transversity basis:



- Experimental observables (sensitive to C_7, C_9,C_{10})
  - forward backward asymmetry A_{FB} (q^2)
    - theoretically clean: A_{FB} zero crossing point S_0
  - fraction of longitudinal K* polarization F_L

- Analysis:
  - **binned counting**: robust, only A_{FB} accessible (and S_0)
  - **fit to angular distribution** (needs knowledge of acceptances)
    - opens window to many angular observables

$B^0 \to K^*\mu\mu$ - LHC*b* prospects

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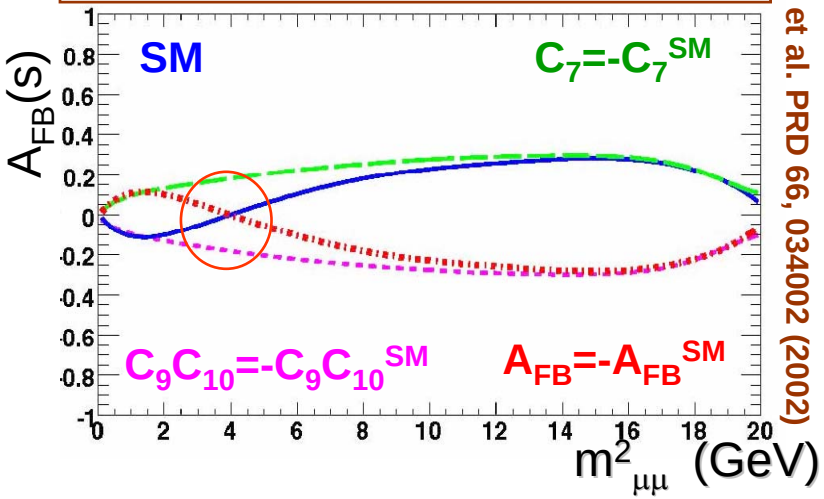
Channel	Yield (2 fb^{-1})	B/S
$B_s \to K^*\mu^+\mu^-$	7200	~0.5

Forward-backward asymmetry



Ali et al. PRD 66, 034002 (2002)

$B^0 \to K^*\mu\mu$ - LHC*b* prospects

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$B_s \to K^*\mu^+\mu^-$	7200	~0.5

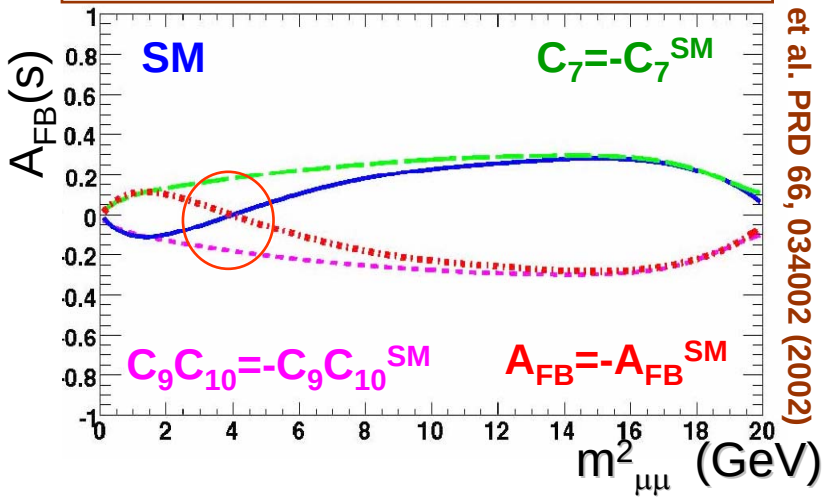
Sensitivity: 2fb^{-1} 10fb^{-1}

A_{FB}: $\sigma(S_0)$ = 0.5GeV^2 (0.28GeV^2)

ATLAS: 4.8% on A_{FB} (30fb^{-1})*

*C. Adorisio:"Rare B decays", talk at "Flavor as a window to NP at the LHC", May 2008

Forward-backward asymmetry



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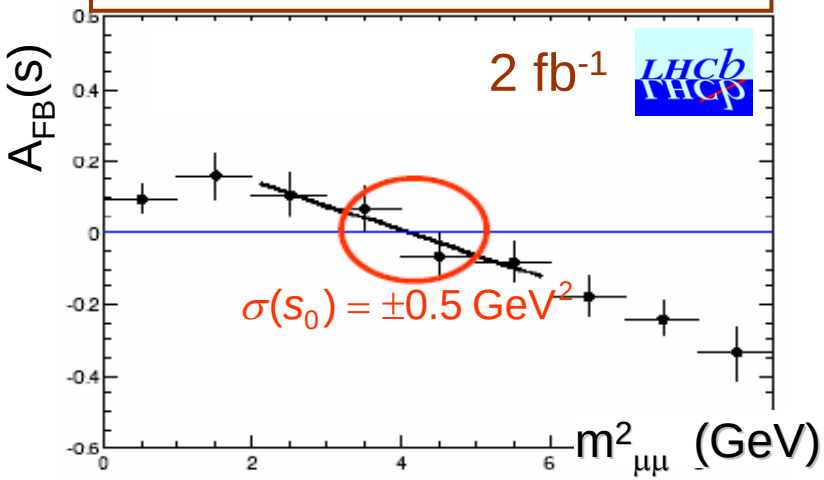
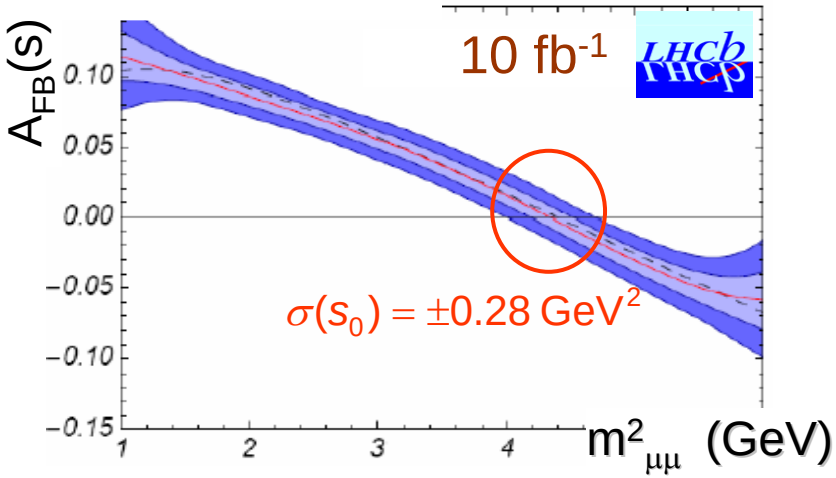
Counting analysis



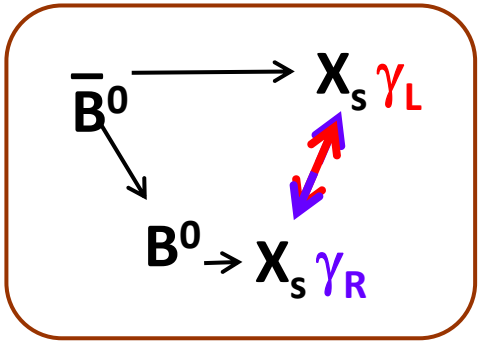
Full angular fit



Radiative $b \to s\gamma$ penguins

- Magnitude C_7 well constrained by $BR(b \to s\gamma)$ (BABAR, Belle)
- Photon polarization accessible with time dependent CP asymmetry:
  $C_7 = C_{7L} + C_{7R}$
  - SM dominated by $\mathbf{C_{7R}}$: $B^0 \to s\,\gamma_R$
    wrong helicity $\mathbf{C_{7L}}$: $B^0 \to s\,\gamma_L$
  - naively in SM: $C_{7L}/C_{7R} \sim m_s/m_b \sim 0.02$
    (additional corrections small)
    (hep-ph/0612081)

<u>Time dependent CP asymmetry:</u>



only interference between states with **same γ polarization**
→ suppressed by
$r = C_{7L} / C_{7R}$

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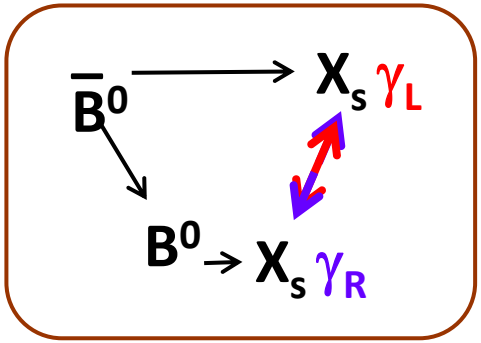

only interference between states with **same γ polarization**
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$r = C_{7L} / C_{7R}$

Time dependent CP asymmetry to determine photon polarization

$$A_{CP}(t) = -\frac{A^{dir}\cos(\Delta m_q\, t) + A^{mix}\sin(\Delta m_q\, t)}{A^{\Delta}\sinh(\Delta\Gamma_q\, t/2) + \cosh(\Delta\Gamma_q\, t/2)}$$

$B_s \to \phi\gamma$

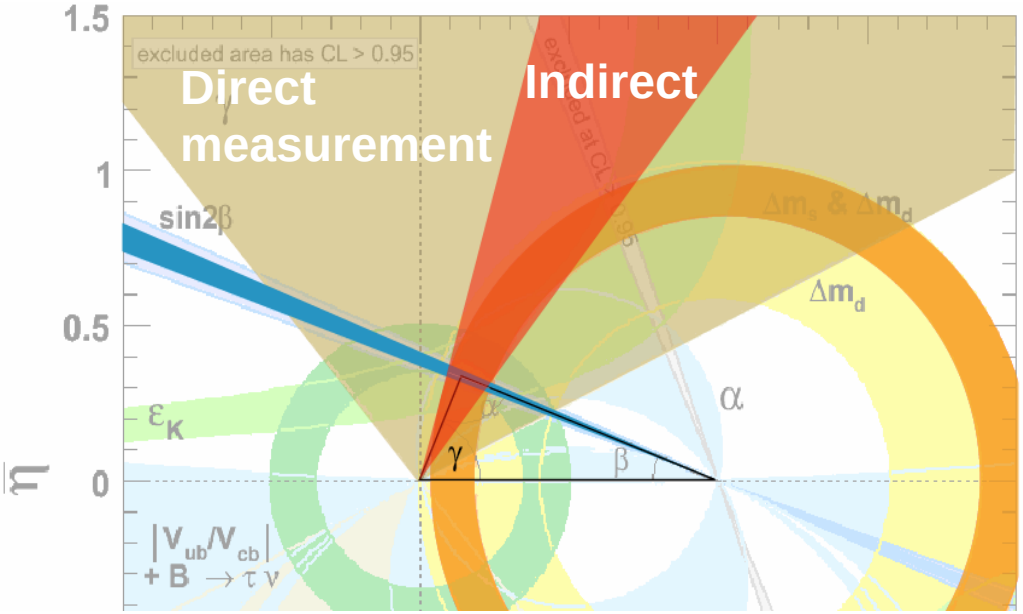
SM: $A^{dir} = 0$ (no direct CPV)
$A^{mix} = \sin 2\psi \sin\phi \sim 0$
$A^{\Delta} = \sin 2\psi \cos\phi \sim 0$

➡ $\tan\psi = |A(b \to s\gamma_R)| \,/\, |A(b \to s\gamma_L)|$

2 fb^{-1}: $\sigma(A^{\Delta}) = 0.22$ $\sigma(A^{dir,mix}) = 0.11$

$\sigma(\psi) \approx 0.11$ Fraction of "wrongly" polarized photons

CKM Angle γ



analysis: CKM fitter (http://ckmfitter.in2p3.fr)

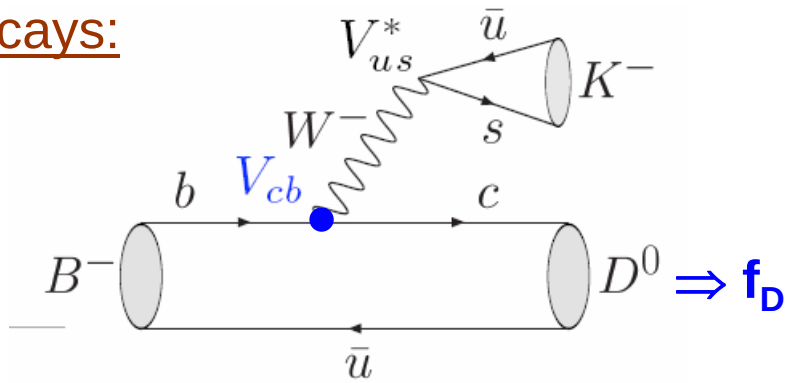
$$\begin{array}{c c} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1 & 1 & \boxed{e^{-i\gamma}} \\ 1 & 1 & 1 \\ e^{-i\beta} & -e^{-i\phi_s/2} & 1 \end{pmatrix} \end{array}$$

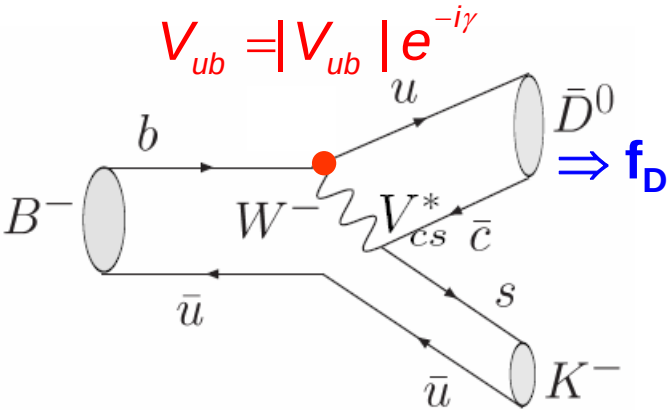
CKM phases to order λ^4

- A lot of pioneering work from B factories
- No significant constraints from direct measurements yet
  → measure γ in tree and loop decays

γ from B $\rightarrow$ DK Tree Decays

Tree decays:





$$\frac{A(B^- \rightarrow \overline{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)} = r_B e^{i\delta_B} e^{-i\gamma}$$

ADS (*Atwood,Dunietz,Soni*) method:

Common flavour state $f_D = (K^+ \pi^-)$

Note: $D^0 \rightarrow K^+\pi^-$ doubly Cabibbo suppr.

GLW (*Gronau,London,Wyler*) method:

f_D is a CP eigenstate, $f_D = K^+K^-, \pi^+\pi^-$

GGSZ (*Giri, Grossman, Soffer, Zupan*)

Use Dalitz decays $D^0 \rightarrow K_s \pi^+ \pi^-$

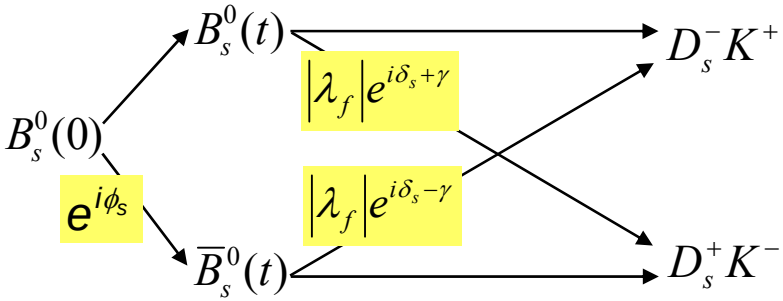
2 fb^{-1}

sensitivity each: σ_γ = 11° – 13°

combined: σ_γ = 4.3° – 6.1°

γ from Time Dependent Asymmetries

Tree b->c & b->u decays interfere through B_s mixing



Time dependent CP asymmetry: $\phi_s + \gamma$

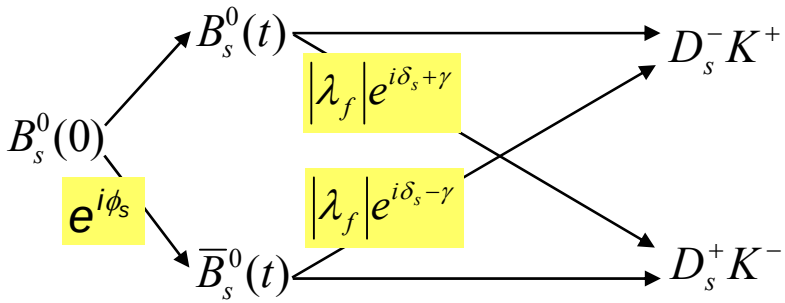
2 fb^{-1}

Use $B_s \to D_s \pi$ to determine tagging dilution simultaneously

$\phi_s + \gamma$	9°-12°
Δm_s	0.007 ps^{-1}

γ from Time Dependent Asymmetries

Tree b->c & b->u decays interfere through B_s mixing



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$\phi_s + \gamma$	9°-12°
Δm_s	0.007 ps^{-1}

Tree Level Processes

LHCb-Roadmap document in preparation

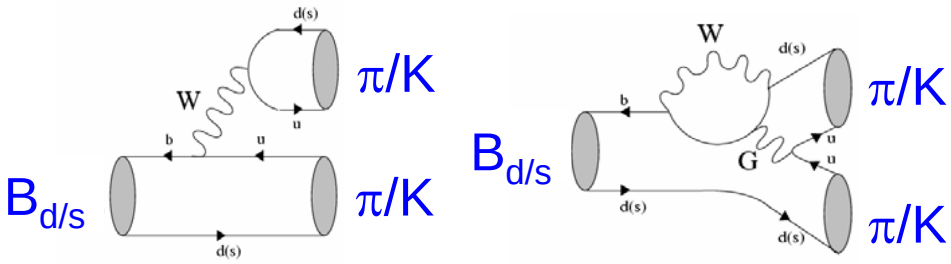
Combination of all tree level methods:
(sensitivity depends on δ_B)

	0.5 fb^{-1}	2 fb^{-1}	10 fb^{-1}
$\sigma(\gamma)$ (°)	7.8 – 10.1	3.9 – 5.1	1.9 – 2.7

2 – 3° reachable after 5 yr

γ from B → h^+h^- Loop Decays

Loop Processes



γ from interference between mixing tree (**T**) and penguin (**P**) amplitudes

Measure time dependent CP asymmetries (direct, mixing) in $B_d \to \pi\pi$ and $B_s \to KK$.

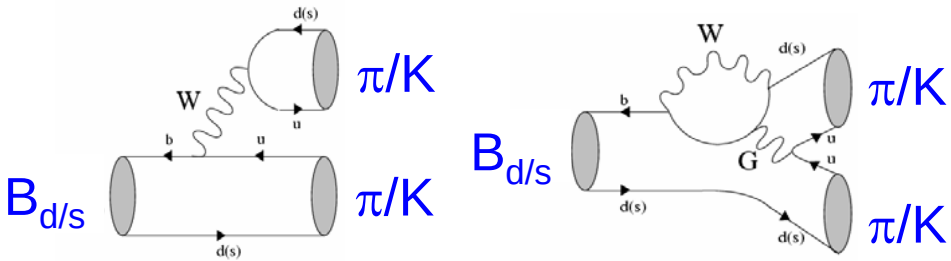
Crucial: **P**/**T** ratio

Uspin constraint: 7 – 10° (2fb^{-1})

$d_{\pi\pi} = d_{KK} \pm 20\%$ ~5° (10 fb^{-1})

γ from B → h^+h^- Loop Decays

Loop Processes



γ from interference between mixing tree (**T**) and penguin (**P**) amplitudes

Measure time dependent CP asymmetries (direct, mixing) in $B_d \to \pi\pi$ and $B_s \to KK$.

Crucial: **P**/**T** ratio

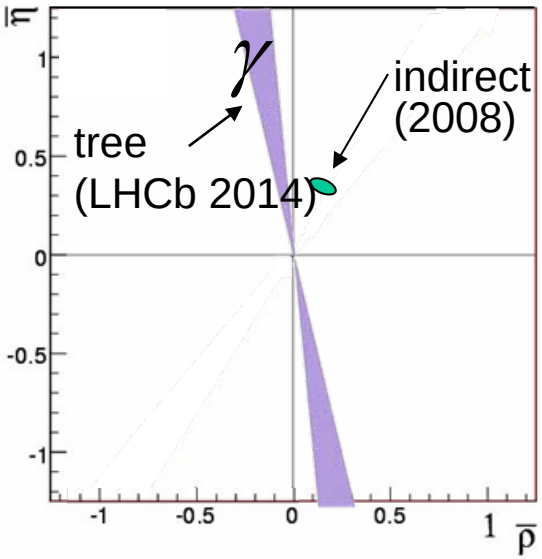
Uspin constraint: $d_{\pi\pi} = d_{KK} \pm 20\%$

7 – 10° (2fb^{-1})

~5° (10 fb^{-1})

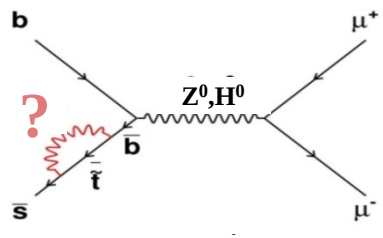
Possible scenario after 5 years (10fb^{-1}) of LHC running

→ **γ from Trees comparable to loops**



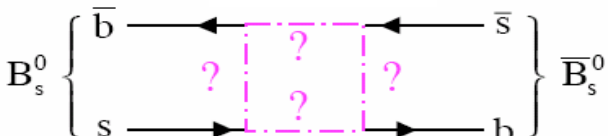
Conclusion

- There is room for sizeable effects of New Physics:



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

$$\phi_S \neq \phi_S^{SM}$$



B_s oscillation "box diagram"

- LHC*b* will try to map-out effects of New Physics
  - ATLAS, CMS also have competitive B-Physics programs

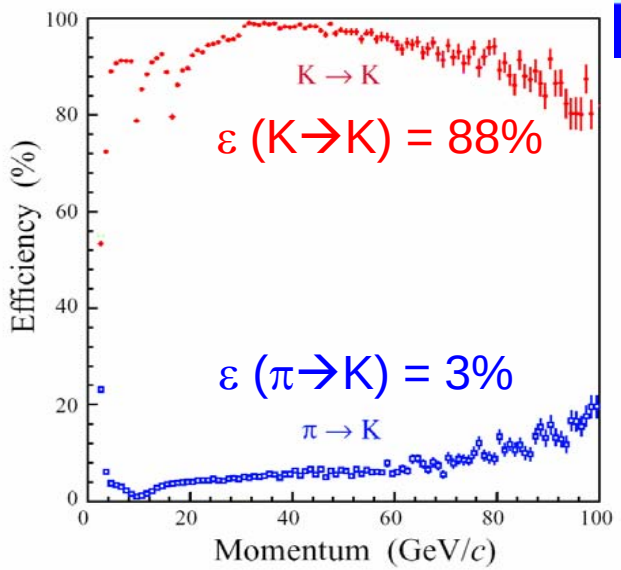
- Interesting results can come early (0.5 fb^{-1})
  - ϕ_s ($B_s \rightarrow J/\psi\phi$) w/ precision of 0.06
  - Limit for BR($B_s \rightarrow \mu\mu$) < 10^{-8}
  - γ from trees w/ precision 8 – 10°

Backup Slides

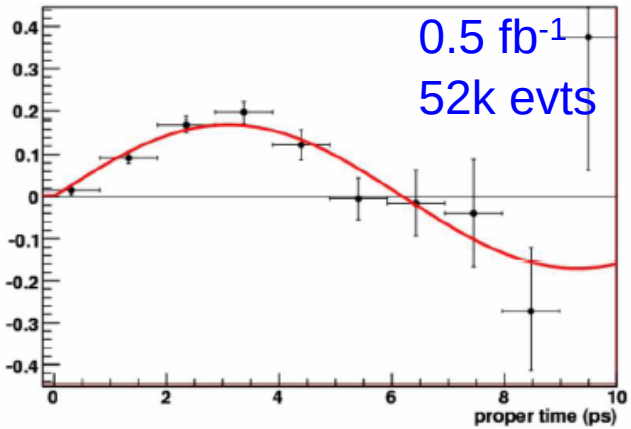
LHC*b* – Key Properties

- High statistics
  - L ~ 2 x 10^{32} cm^{-2} s^{-1}
  - ~ 10^{12} bb events / year (2 fb^{-1})
  - 50 kHz bb-events
  - $B^{\pm}$, B^0, B_s, B_c, Λ_b ...
- Tracking & Vertexing
  - B Mass resolution: ~ 15...20 MeV
  - Proper time resolution: ~ 40 fs
- Particle identification
  - π/K separation over 2 GeV < p < 100 GeV
- Trigger (2 kHz to tape)
  - "High p_T" lepton, photon & hadron 1st level trigger w/ 1 MHz:

    μ/e/h/γ: 1.1/2.8/3.6/2.6 GeV



Example: sin2β($B^0 \to J/\psi K_s$)



σ(sin2β)=0.020 (2 fb^{-1})
σ(sin2β)=0.023 (today)

Outlook – LHC*b* beyond 10 fb^{-1}

LHCb upgrade

- Run at 10× design luminosity: 2×10^{33}
- Needs detector and trigger upgrade
- Increase trigger efficiency for hadrons by at least a factor 2
- Accumulate data sample of 100 fb^{-1}

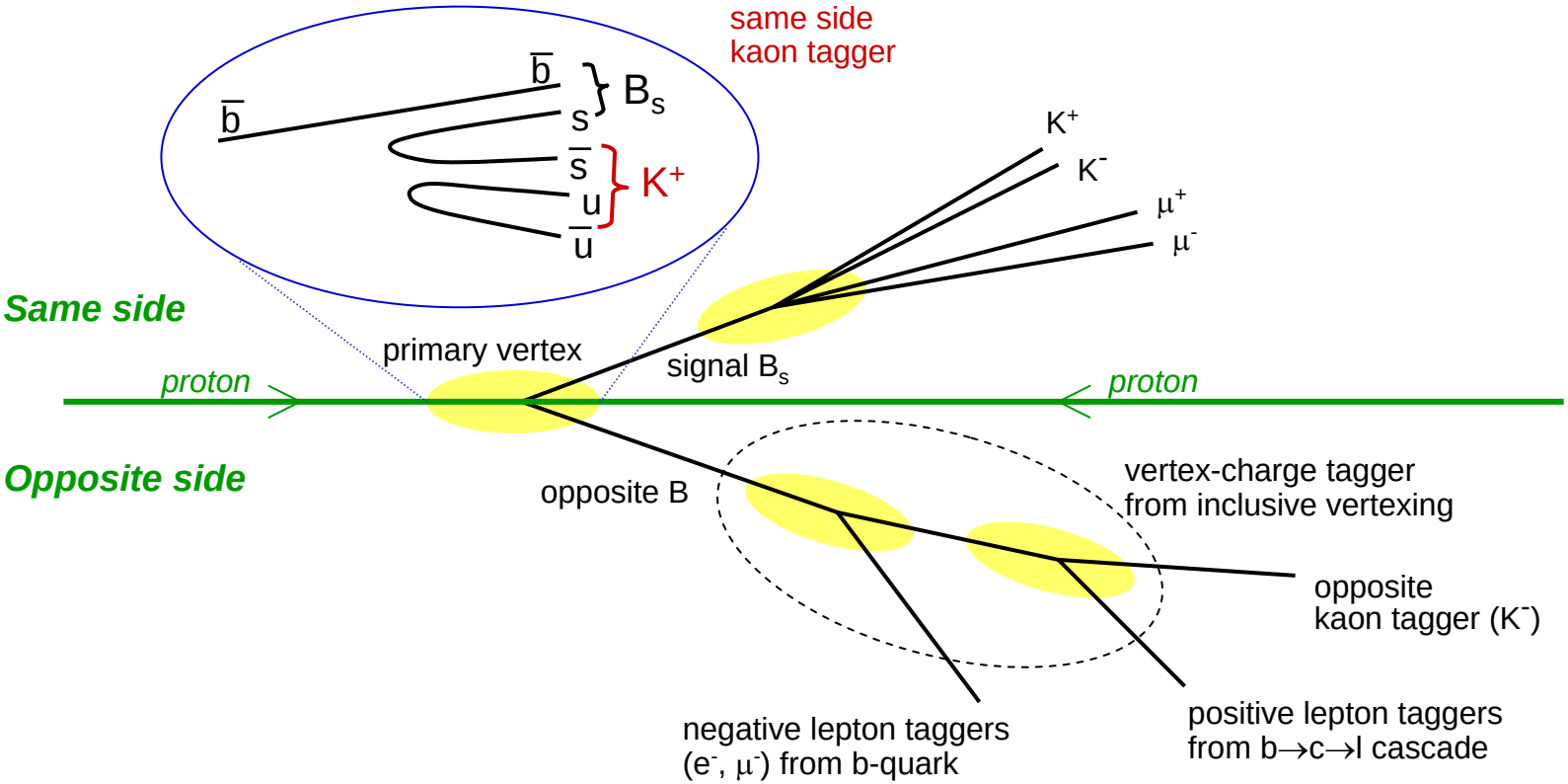
Physics case

- CPV in B_s mixing (tree and penguins)
- CKM angle γ with ~1° precision
- Chiral structure of b→s decays
- Lepton flavor violation in $\tau\to\mu\mu\mu$

→ **100 fb^{-1}**

Observable	100 fb^{-1}	Sensitivity
$S(B_s \to \phi\phi)$		$0.01 - 0.02$
$S(B_d \to \phi K_S^0)$		$0.025 - 0.035$
$\phi_s\ (J/\psi\phi)$		0.003
$\sin(2\beta)\ (J/\psi K_S^0)$		$0.003 - 0.010$
$\gamma\ (B \to D^{(*)}K^{(*)})$		$< 1^\circ$
$\gamma\ (B_s \to D_s K)$		$1 - 2^\circ$
$\mathcal{B}(B_s \to \mu^+\mu^-)$		$5 - 10\%$
$\mathcal{B}(B_d \to \mu^+\mu^-)$		3σ
$A_T^{(2)}(B \to K^{*0}\mu^+\mu^-)$		$0.05 - 0.06$
$A_{\rm FB}(B \to K^{*0}\mu^+\mu^-)\ s_0$		$0.07\ \mathrm{GeV}^2$
$S(B_s \to \phi\gamma)$		$0.016 - 0.025$
$A^{\Delta\Gamma_s}(B_s \to \phi\gamma)$		$0.030 - 0.050$
charm x'^2		2×10^{-5}
mixing y'		2.8×10^{-4}
CP y_{CP}		1.5×10^{-4}

Flavour tagging at LHCb (1)



$B_s \to J/\psi\phi$: efficiency ε~ 55.7%, mistag rate ω~33.3%, $\varepsilon(1-2\omega)^2$~6.2%

	Combined w_{OS} (%)	Combined OS $\varepsilon(1-2w)^2$ (%)
$B_s \to J/\psi\phi$	36.51±0.24	3.32±0.11
$B_d \to J/\psi K^*$	36.15±0.20	3.35±0.09
$B^+ \to J/\psi K^+$	36.00±0.21	3.45±0.10

True performance (MC truth) after L0