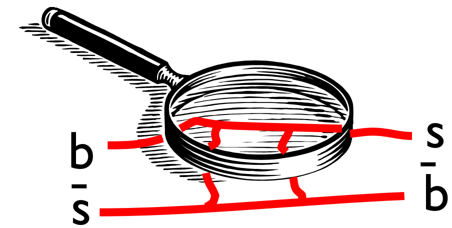
B Physics at LHC



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CERN - FERMILAB
HADRON COLLIDER PHYSICS SUMMER SCHOOL
2007

CERN, Geneva, Switzerland
June 6-15, 2007

Outline

Many transparencies from the recent CERN Workshop:
"Flavour in the era of LHC"
http://mlm.home.cern.ch/mlm/FlavLHC.html

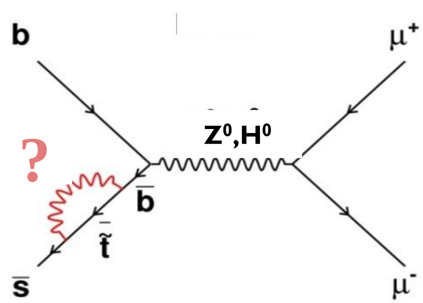
- **Introduction:**
  - B Physics as an indirect probe for New Physics
  - CKM picture of CP violation
  - What measurements are sensitive to New Physics?
- **LHC experimental conditions:**
  - LHC as a B factory
  - Detector requirements
- **Detectors:**
  - Triggers, Vertex, Particle Id.
- **LHC B-Physics potential (examples):**
  - Flavour Tagging
  - B_s mixing phase: ϕ_s ; penguin: $B_s \rightarrow \phi\ \phi$
  - γ at tree level ; measurement of α
  - (Very) rare decays
- **Control Channels and Calibration:**
  - Proper time and PID Calibration
  - Tagging Calibration
  - Control Measurements
- **Outlook and Conclusions.**

Friday 8/6/2007

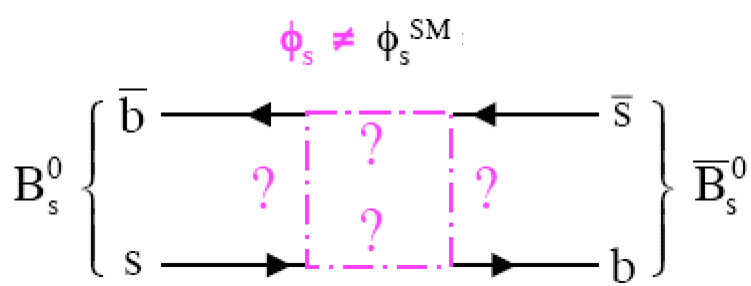
Saturday 9/6/2007

B Physics as an indirect probe for New Physics

- **SM cannot be the ultimate theory**
  - must be a low-energy effective theory of a more fundamental theory at a higher energy scale, expected to be in the TeV region (accessible at LHC !)
- **How can New Physics (NP) be discovered and studied ?**
  - NP models introduce new particles, dynamics and/or symmetries at a higher energy scale. These new particles could
    - be produced and observed as real particles at energy frontier machines (e.g LHC)
    - **appear as virtual particles (in loop processes), leading to observable deviations from the pure SM expectations in flavour physics and CP violation.**



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



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

Strengths of indirect approach

- **Can in principle access higher scales and therefore see effect earlier:**
  - Third quark family inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured in kaon mixing (1964), but only directly observed in 1977 (b) and1995 (t)
  - Neutral currents (ν+N$\rightarrow$ ν+N) discovered in 1973, but real Z discovered in 1983
- **Can in principle also access the phases of the new couplings:**
  - NP at TeV scale needs to have a "flavour structure" to provide the suppression mechanism for already observed FCNC processes $\rightarrow$ once NP is discovered, it is important to measure this structure, including new phases
- **Complementary to the "direct" approach:**
  - If NP found in direct searches at LHC, B (as well as D, K) physics measurements will help understanding its nature and flavour structure

Why bother with B mesons?

- **In many New Physics scenarios, large effects are seen in third family:**
  - Looking at new physics through radiative corrections many times imply factors $\propto \Delta m^2$
  - Moreover, the long lifetime of the b-quark helps experimentalists.
- **CP violation is a "strange" phenomena in the SM:**
  - It does not seem to explain the asymmetry between matter and antimatter observed in the Univers.
  - Why we do not see CP violation in the strong interactions and we do see a very small effect in the EW sector?

The B-meson provides a laboratory where theoretical predictions can be precisely compared with experimental results

When does one have CP violation?

when $\Gamma(a \to b + c) \neq \Gamma(\overline{a} \to \overline{b + c})$ ($\overline{x}$ = CP conjugate state)

How can this happen in the SM?

1. Get two amplitudes to interfere.
2. Get two relative phases between the two amplitudes.
3. Get one relative phase to change when going to the CP conjugate state, while the other does not change.

$$\Gamma(a \to b + c) = \left|A_1\right|^2 + \left|A_2\right|^2 + 2\Re(A_1 A_2^*)$$

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

In the SM for any process we have, $|A_k| = |\overline{A_k}|$ $\Longrightarrow$ $\Re(A_1 A_2^*) \neq \Re(\overline{A_1}\,\overline{A_2^*})$

In the SM, **only weak** interactions do this.

It does it **via the quark flavor mixing** mechanism.

Hence, it is a **consequence of the quark mass generation** mechanism

CKM picture of CP violation

up quarks: $m_{j,k} = Y_{j,k}\, v/\sqrt{2}$

down quarks: $m'_{j,k} = Y'_{j,k}\, v/\sqrt{2}$

m is a matrix of complex numbers, in general not diagonal

After diagonalization, still a new rotation is needed as the quark fields used in the weak interactions are not the mass eigenstates

B-decays

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ \boxed{V_{td}} & \boxed{V_{ts}} & \boxed{V_{tb}} \end{pmatrix}$$

B-mixing+loops

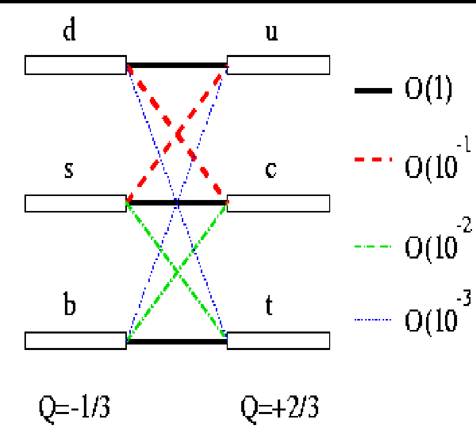
After diagonalization, using the convention $u \equiv u^{phys}$, and

$$d^{phys} \equiv \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

1) Neutral currents unchanged

2) Charged currents are modified

$$|V_{CKM}| = \begin{pmatrix} 0.974 & 0.227\pm0.001 & 0.004 \\ 0.227\pm0.001 & 0.973 & 0.042\pm0.001 \\ 0.008\pm0.001 & 0.042\pm0.001 & 0.999 \end{pmatrix}$$



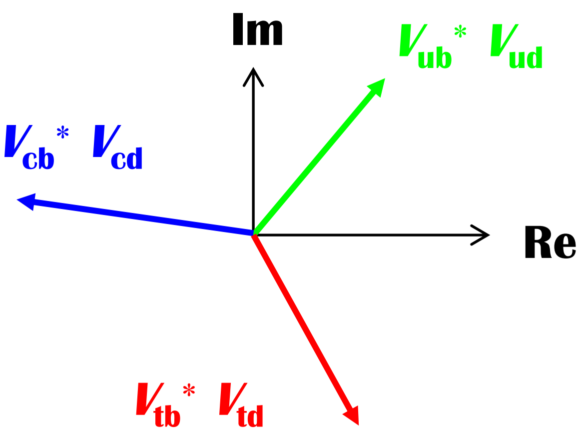
CKM picture of CP violation

Unitarity: $V^{\dagger}V = 1$

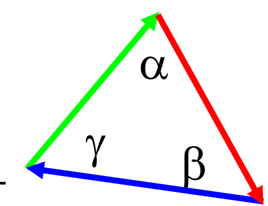
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

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



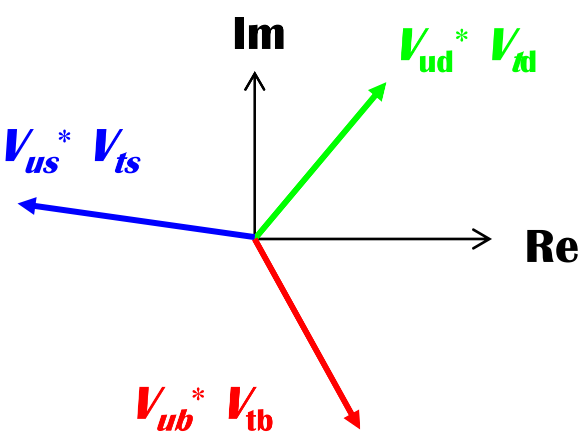
Unitarity requires



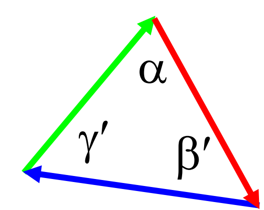
$$\alpha \equiv \phi_2 = \arg \frac{-V_{tb}^{*}V_{td}}{V_{ub}^{*}V_{ud}}$$

$$\gamma \equiv \phi_3 = \arg \frac{-V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}}$$

$$\beta \equiv \phi_1 = \arg \frac{-V_{cb}^{*}V_{cd}}{V_{tb}^{*}V_{td}}$$



Unitarity requires



$$\gamma' = \gamma - \delta\gamma$$

$$\delta\gamma = \gamma - \arg \frac{-V_{ud}^{*}V_{td}}{V_{us}^{*}V_{ts}}$$

$$\beta' = \beta + \delta\gamma$$

CKM picture of CP violation

Using the Wolfenstein parameterisation (λ, A, ρ, η)

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

$\arg V_{td} = -\beta$
$\arg V_{ub} = -\gamma$
$\arg V_{ts} = \delta\gamma+\pi$

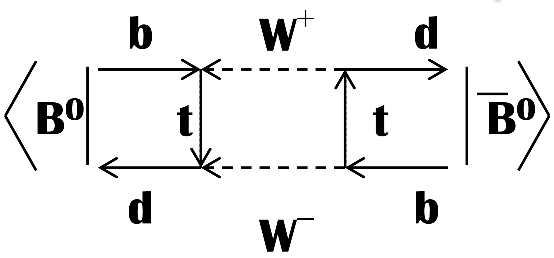
$$\tan\beta \approx \frac{\eta}{1-\rho}\left(1-\frac{\lambda^2}{2(1-\rho)}\right) \approx \tan(23.6°)$$

$$\tan\gamma \approx \frac{\eta}{\rho} \approx \tan(57°)$$

$$\delta\gamma \approx \eta\lambda^2 \approx 1°$$

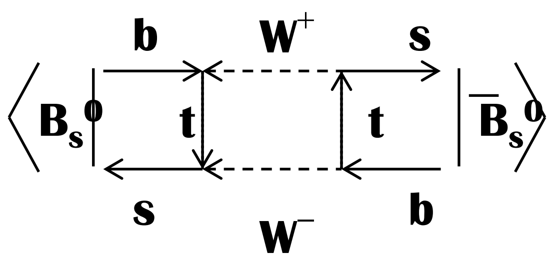
B-mixing and complex phases

B-$\bar{B}$ oscillation dispersive part: M_{12}



$$\Delta m = 2|M_{12}| \propto B_d f_d^2 |V_{td}|^2\, |V_{tb}|^2$$

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

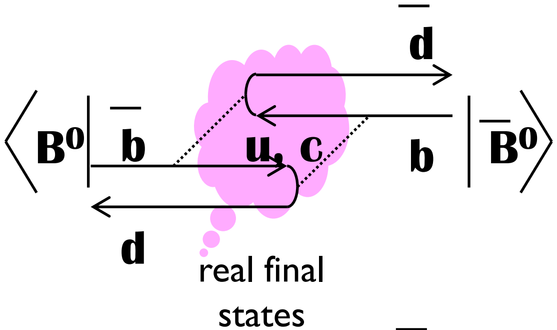


$$\Delta m_s = 2|M_{12}| \propto B_s f_s^2 |V_{ts}|^2\, |V_{tb}|^2$$

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

B-$\bar{B}$ oscillation absorptive part: Γ_{12}

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

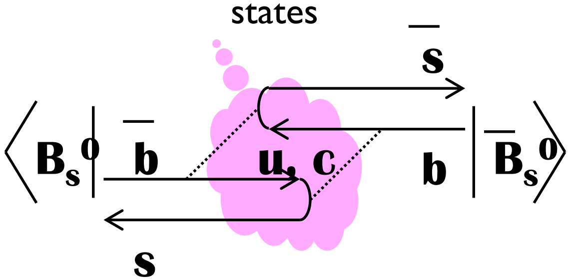


$\Delta\Gamma \propto 0.004 \mathrm{x} \Gamma$

$\arg (M_{12}/\Gamma_{12}) \cong \pi - 10^{-1}$

$\Delta\Gamma \propto 0.1 \mathrm{x} \Gamma$

$\arg (M_{12}/\Gamma_{12}) \cong \pi + 5\mathrm{x}10^{-3}$



CP violation in oscillation: $\Im\left(\frac{\Gamma_{12}}{M_{12}}\right) = \frac{-\Delta\Gamma}{\Delta m} \sin(\arg \frac{M_{12}}{\Gamma_{12}})$

How do we measure these phases?

$$A_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \to f] - \Gamma[B_s(t) \to f]}{\Gamma[\overline{B}_s(t) \to f] + \Gamma[B_s(t) \to f]}$$

$\overline{B^0} \longrightarrow \overline{B^0}$

$\overline{B^0} \longrightarrow B^0$

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

$\overline{B^0} \to J/\psi\, K_S$, $B^0 \to J/\psi\, K_S$

$M_{12} \propto e^{2i\,\beta}$

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

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

$\overline{B^0} \longrightarrow \overline{B^0}$

$\overline{B^0} \longrightarrow B^0$

$b \to c + \overline{u}d$: $V_{cb} V_{cd}^* \propto e^{i0}$

$$r_b \approx \frac{A\lambda^2}{A\lambda^4 \sqrt{\rho^2 + \eta^2}} \approx 1/0.02$$

$\overline{B^0} \to D^{(*)+}\, \pi^-$, $B^0 \to D^{(*)+}\, \pi^-$ ☹

$M_{12} \propto e^{2i\,\beta}$

$\overline{b} \to \overline{u} + c\overline{d}$: $V_{ub}^*\, V_{cd} \propto e^{i\gamma}$

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

Theoretically Very Clean

How do we measure these phases?

$$A_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \to f] - \Gamma[B_s(t) \to f]}{\Gamma[\overline{B}_s(t) \to f] + \Gamma[B_s(t) \to f]}$$

$$\begin{array}{ccccc} \overline{B}_s^0 & \longrightarrow & \overline{B}_s^0 & & \\ & \searrow & & \searrow & \\ & & & & J/\psi\ \phi(\eta) \\ & & & \nearrow & \\ & & B_s^0 & & \end{array}$$

$b \to c + \overline{c}s$: $V_{cb} V_{cs}^* \propto e^{i0}$

$M_{12} \propto e^{-2i\delta\gamma}$

$\overline{b} \to \overline{c} + c\overline{s}$: $V_{cb}^* V_{cs} \propto e^{i0}$

$A_{CP}(t) \propto \sin 2\delta\gamma \times \sin \Delta m t$

$$\begin{array}{ccccc} \overline{B}_s^0 & \longrightarrow & \overline{B}_s^0 & & \\ & \searrow & & \searrow & \\ & & & & D_s^+ K^- \\ & & & \nearrow & \\ & & B_s^0 & & \end{array}$$

☺

$b \to c + \overline{u}s$: $V_{cb} V_{us}^* \propto e^{i0}$

$r_b \approx \dfrac{A\lambda^3}{A\lambda^3 \sqrt{\rho^2 + \eta^2}} \approx 0.4$

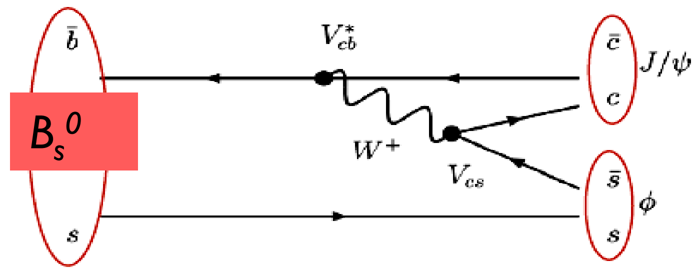
$M_{12} \propto e^{-2i\delta\gamma}$

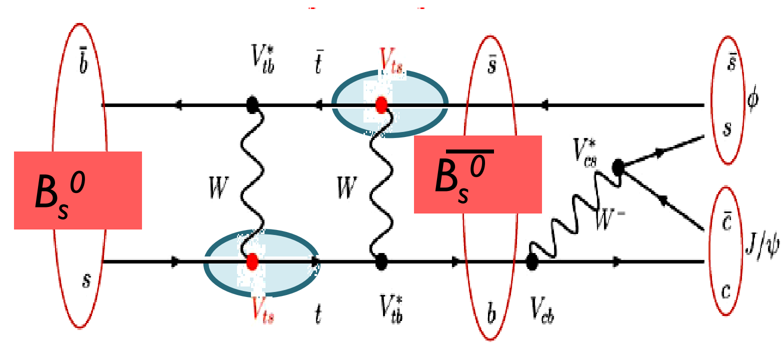
$\overline{b} \to \overline{u} + c\overline{s}$: $V_{ub}^* V_{cs} \propto e^{i\gamma}$

$A_{CP}(t) \propto \sin (2\delta\gamma - \gamma) \times \sin \Delta m t$

Theoretically Very Clean

How do we measure these phases?

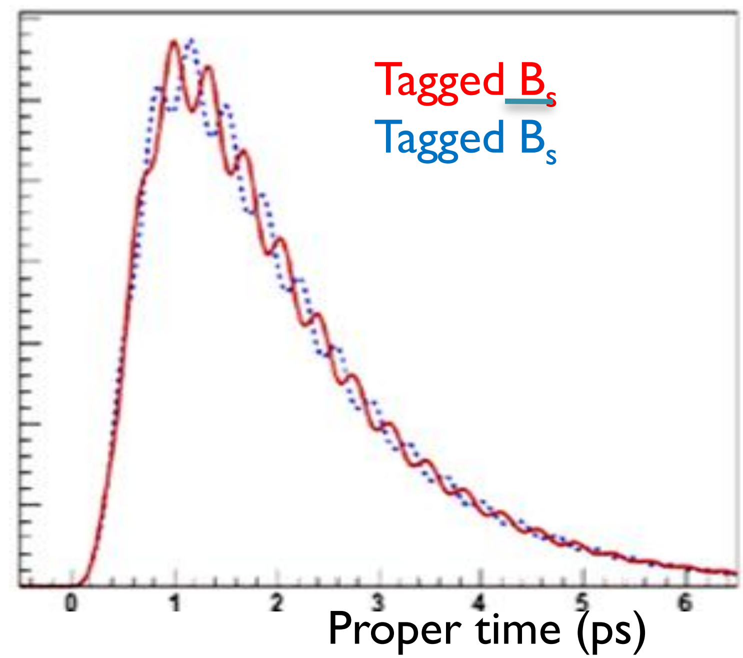




- Lifetime distributions of events with a B_s ($\overline{B_s}$) at production show oscillation pattern
- The frequency of these oscillations is Δm_s while the amplitude of the oscillation is proportional to $\sin\phi_s$
- If we take the asymmetry of the two distributions (A_{CP}) many factors cancel out and we are left with:

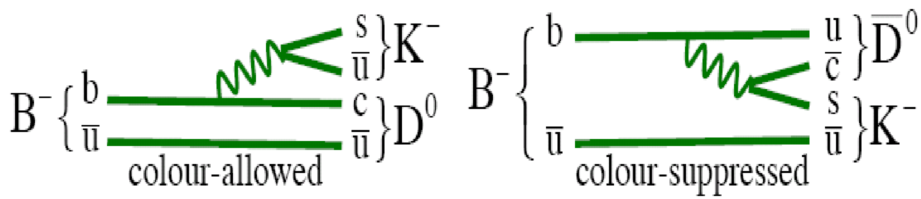
$$A_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \to f] - \Gamma[B_s(t) \to f]}{\Gamma[\overline{B}_s(t) \to f] + \Gamma[B_s(t) \to f]}$$

$$A_{CP}(t) = \frac{\eta_f sin\phi_s sin(\Delta m_s)t}{cosh(\Delta\Gamma_s t/2) - \eta_f cos\phi_s sinh(\Delta\Gamma_s t/2)}$$



Alternative ways to measure γ

γ from $B^{\pm} \rightarrow D\,K^{\pm}$:



Weak phase difference = γ
Magnitude ratio = $r_B \sim 0.15$

ADS (Atwood, Dunietz, Sony) method to measure γ without time dependent analysis of tagged B candidates:

Measure the relative rates of $B^+ \rightarrow DK^+$ and $B^- \rightarrow DK^-$ with neutrals D's observed in finals states such as: $K^{\pm}\pi^{\mp}$, $K^{\pm}\pi^{\mp}\pi^+\pi^-$, K^+K^-.

These depend on:

Relative magnitude, strong phase and weak phase between $B^- \rightarrow DK^-$ and $B^- \rightarrow \bar{D}K^-$
Relative magnitudes (known) and strong phases between $D \rightarrow K\pi$ and $\bar{D} \rightarrow K\pi$.

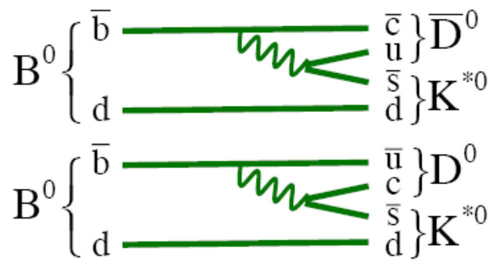
Can solve for all unknowns, including the weak phase γ.

Alternative ways to measure γ

γ from $B^0 \rightarrow D\,K^*$:

Dunietz variant of Gronau-Wyler method

Two colour suppressed diagrams with $|A_2|/|A_1| \cong 0.4$ interfering via D^0 mixing



$A_1 = A(B^0 \rightarrow \bar{D}^0K^{*0})$: $b \rightarrow c$ transition, phase 0

$A_2 = A(B^0 \rightarrow D^0K^{*0})$: $b \rightarrow u$ transition, phase $\Delta+\gamma$

$A_3 = \sqrt{2}\, A(B^0 \rightarrow D_{CP}K^{*0}) = A_1+A_2$, because $D_{CP}=(\bar{D}^0+D^0)/\sqrt{2}$

γ from $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$:

For each mode, measure time-dependent CP asymmetry:

$$A_{CP}(t) = A_{dir}\cos(\Delta m t) + A_{mix}\sin(\Delta m t)$$

A_{dir} and A_{mix} depend on mixing phase, angle γ, and ratio of penguin to tree amplitudes = $de^{i\theta}$

Exploit U-spin symmetry (Fleischer):

Assume $d_{\pi\pi} = d_{KK}$ and $\theta_{\pi\pi} = \theta_{KK}$

4 measurements and 3 unknowns (taking mixing phases from other modes) $\rightarrow$ can solve for γ

Or even possibilities to measure $\alpha = \pi-\beta-\gamma$

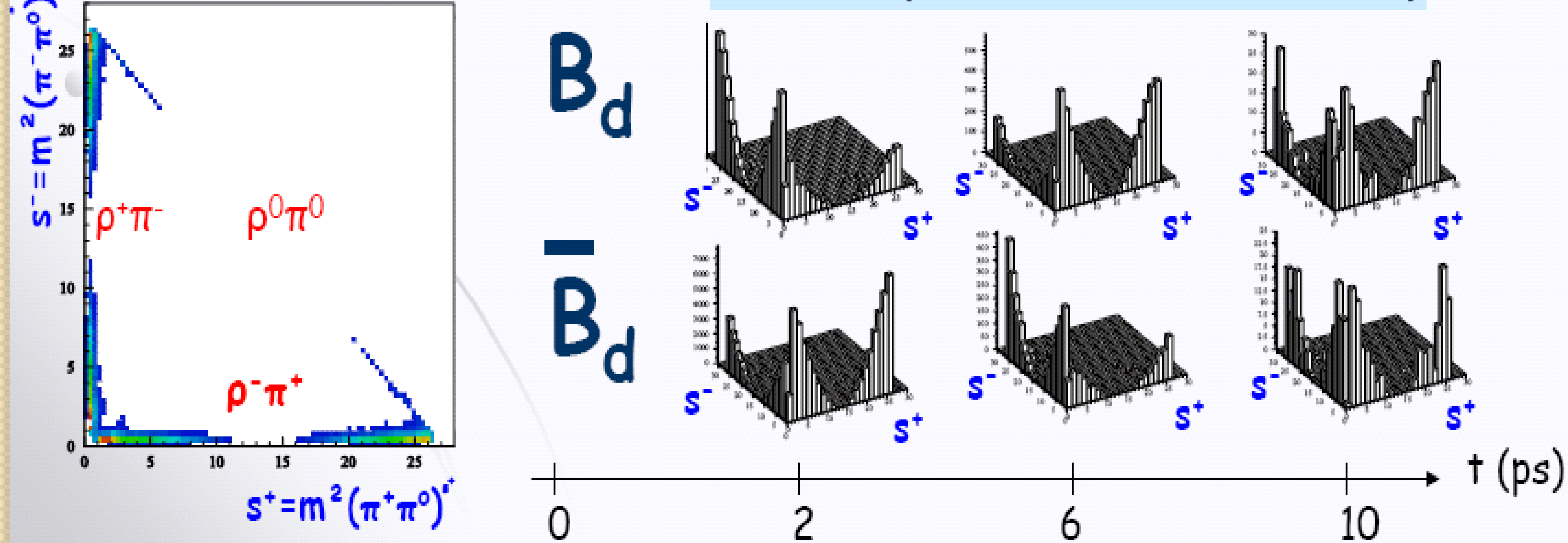
α from $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$:

(Snyder, Quinn) method to measure α from the interference between the tree and penguin amplitudes:

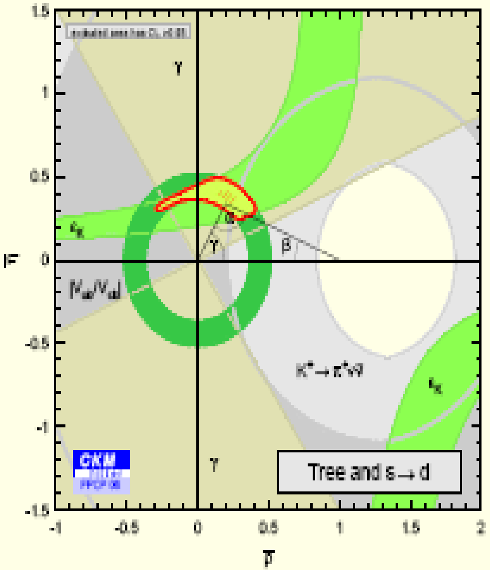
Measure the time dependence of the tagged Dalitz plot distribution:

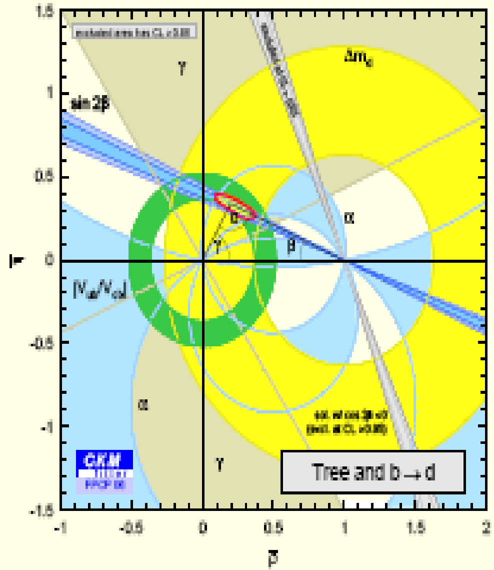
$F(s^+, s^-, B_{tag}; t)$

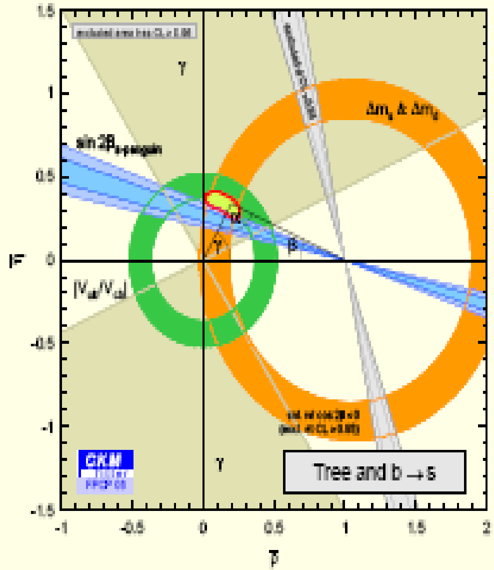
$$M^{\pm}(s^+,s^-,t) = e^{-\frac{\Gamma t}{2}}\left\{\cos\left(\frac{\Delta m}{2}t\right)A^{\pm}(s^+,s^-) + i\left(\frac{q}{p}\right)^{\pm 1}\sin\left(\frac{\Delta m}{2}t\right)A^{\mp}(s^+,s^-)\right\}$$



So… what's the status now?







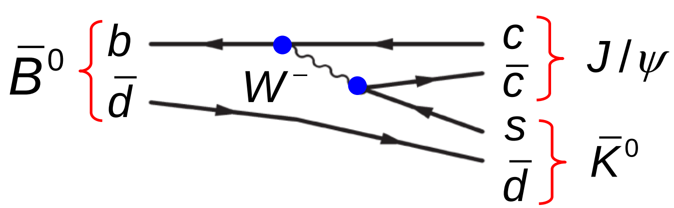
$s \to d$ $\quad$ $b \to d$ $\quad$ $b \to s$

$\varepsilon,\ \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ $\quad$ $\Delta m_{B_d},\ S_{\psi K},\ S_{\rho\rho}$ $\quad$ $\Delta m_{B_s},\ S_{b\to s\bar{s}s}$

Certainly, the CKM mechanism is the dominant source of the CP violation observed so far. However...

Consistency within measurements?

- Almost, but not quite all yet …
  → more sensitivity to unknown heavy fields from loop diagrams



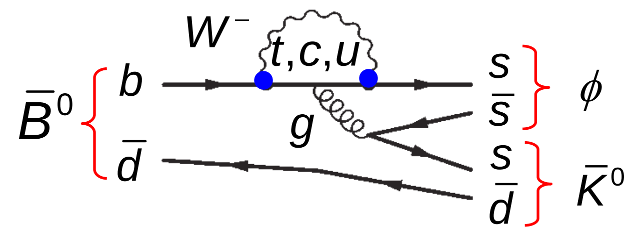
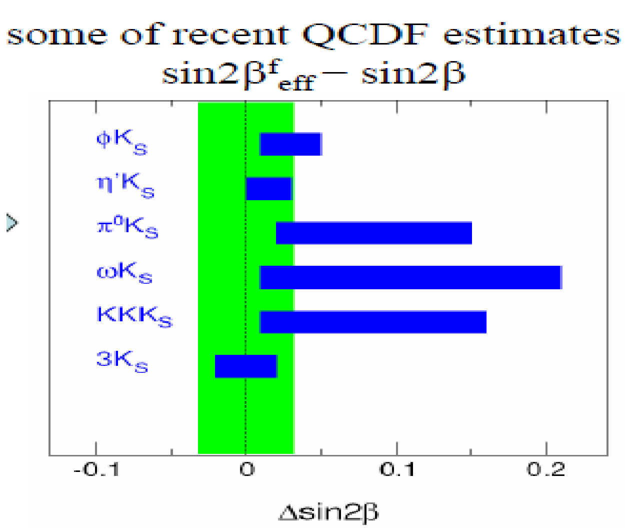
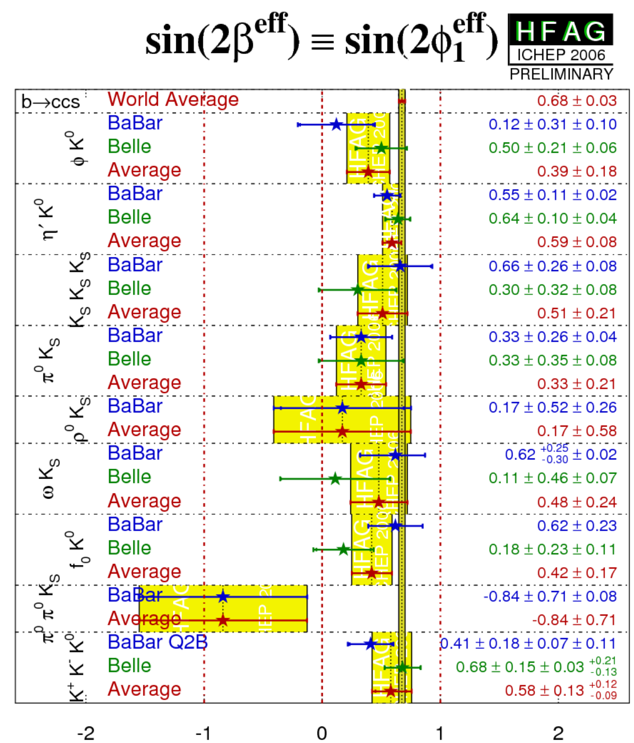


Diagram: Tree | "Penguin"-loop diagram

CP observable: $\sin(2\beta)[J/\psi\ K^0]$ | $\sin(2\beta)[\phi K^0]$

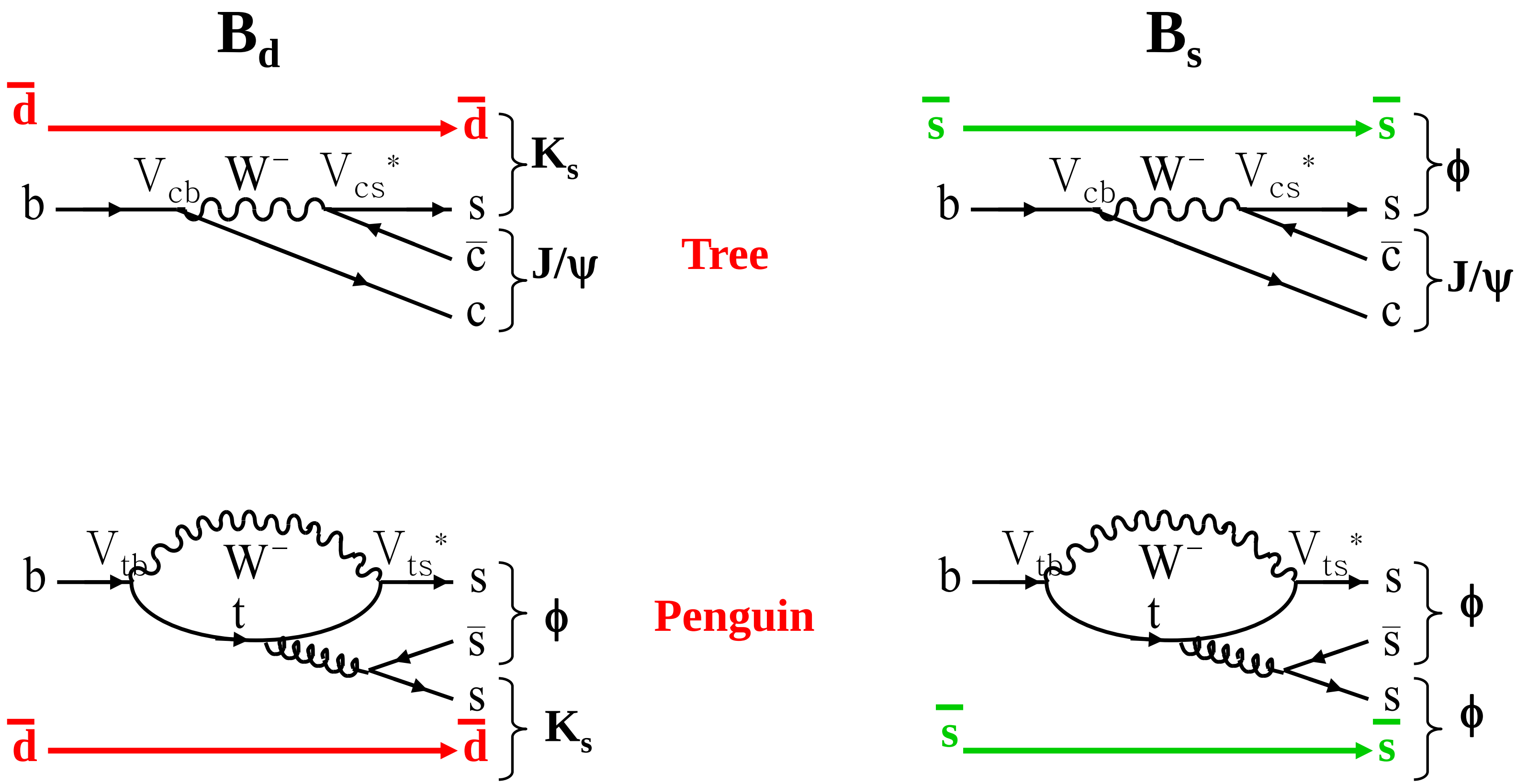




Tantalising, naive average gives 2.6σ... still, it is perhaps more correct to average only 3 cleanest channels,

→ ΦK_S, $\eta' K_S$ and $K_S K_S K_S$: $\delta\beta \sim 0.13 \pm 0.08$

New Physics through Tree-Penguin comparison



β(tree)-β(penguin) = $\delta\beta$**(NP)~20%**

ϕ_s(tree)-ϕ_s(penguin) = $\delta\phi_s$**(NP)**

Same s-penguin diagram contributes to both. If $\delta\beta$ effect persists, we can expect a difference in $\delta\phi_s$

Parameterization of New Physics in mixing

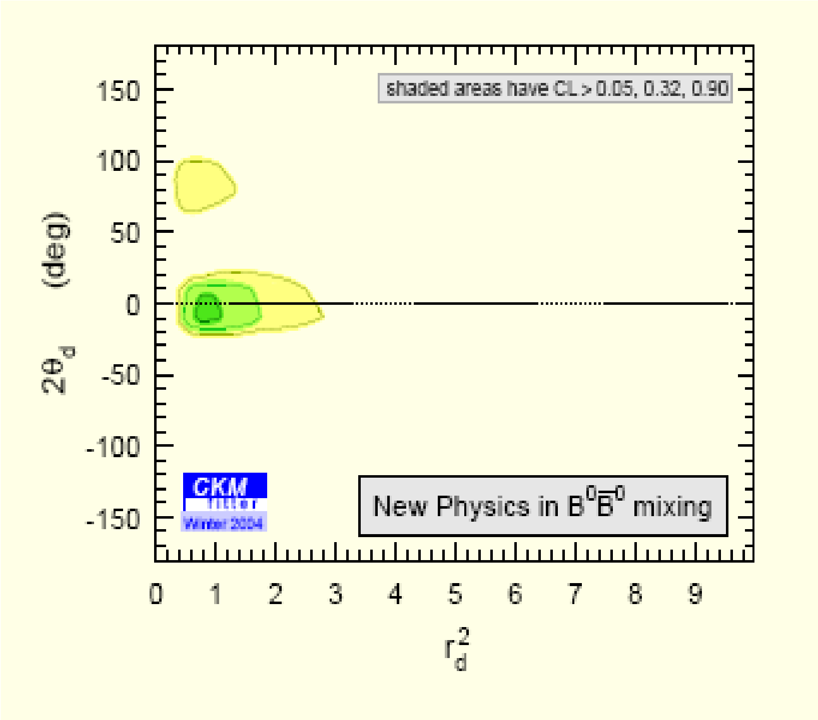
- The effects of New Physics in the oscillation can be parameterized as:

$$M_{12} = r_q^{\,2} e^{(2i\theta q)} M^{SM}{}_{12} = (1 + h_q\, e^{\,2i\sigma_q})\, M^{SM}{}_{12}$$

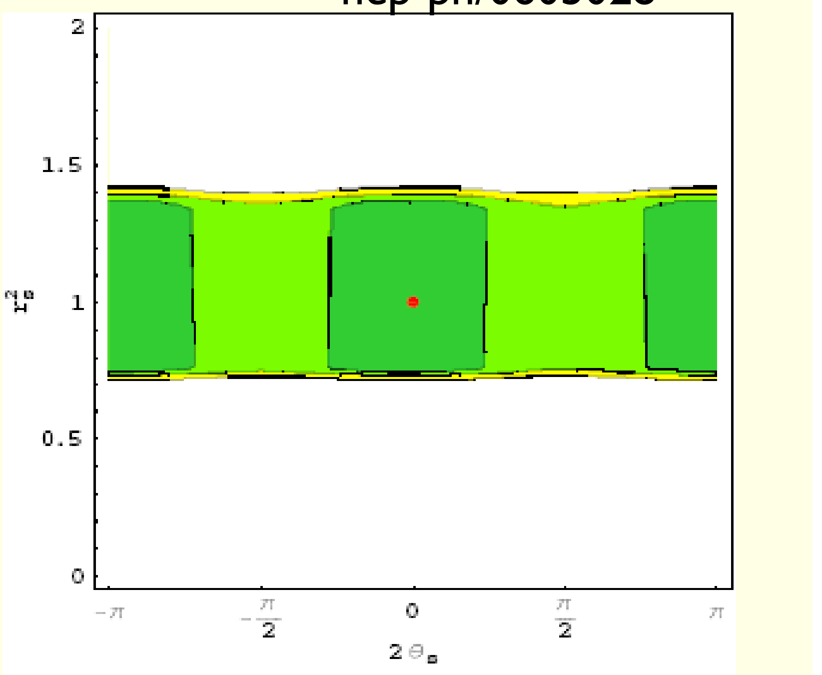
- Then $\mathbf{\Delta m_q}$ and $\boldsymbol{\phi_q}$ can be used to constrain NP in the oscillation:

$$\Delta m_q = r_q^2 \Delta m_q^{SM}$$

$$\Phi_q = \Phi_q^{SM} + \theta_q$$



hep-ph/0605028



Rare decays

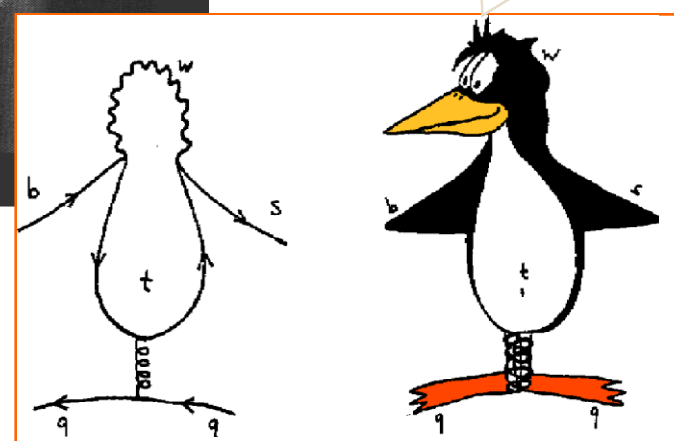
- The penguin diagram prefers heavy virtual fields in the loop; penguin-to-tree ratio:

$$\left|\frac{A^{\text{penguin}}_{Q\text{-heavy}} - A^{\text{penguin}}_{q\text{-light}}}{A^{\text{tree}}}\right| \approx \frac{\alpha_s}{12\pi}\ln\left(\frac{m^2_{Q\text{-heavy}}}{m_b^2}\right)$$

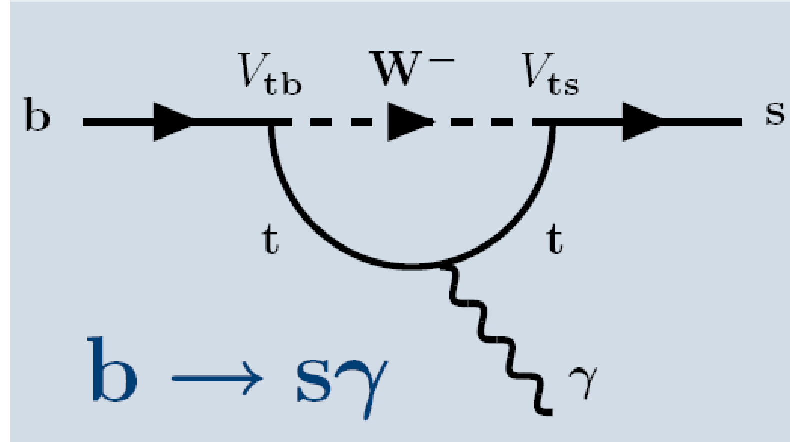
mirror image of Richard Feynman

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** ☺



Radiative decays



The measurements of BR like:

BR(B $\to$ K*γ) = $(4.0\pm0.2)\times10^{-5}$

BR(B $\to$ $\omega(\phi)\gamma$) $<8\times10^{-7}$ @90% C.L.

BR(B_s $\to$ $\phi\gamma$) $<1.2\times10^{-4}$ @90% C.L.

are proportional to V_{ts}

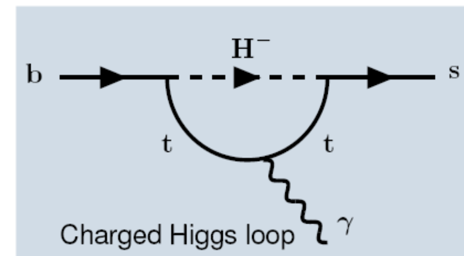
Moreover, the photon polarization could be largely affected by New Physics:

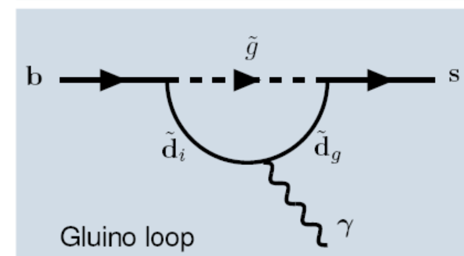
- Time Dependent A_{CP}(K*γ)
- Virtual photons (eg. $b \to s\, \ell^+\ell^-$)

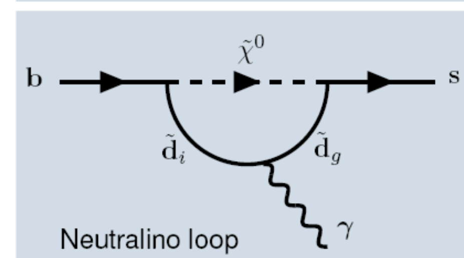
  Melinkov et al., [PLB442 381-389, 1998]
- Converted photons Grossman et al., [JHEP06 29, 2000]
- B$\to$ γK** (K$\pi\pi$) Gronau & Pirjol, [PRD66 054008, 2002],

  Gronau et al., [PRL88 051802, 2002]

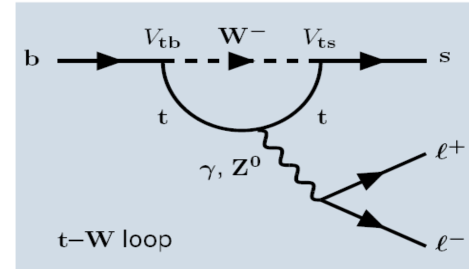
Λ_b baryons Hiller & Kagan , [PRD65 074038, 2002]

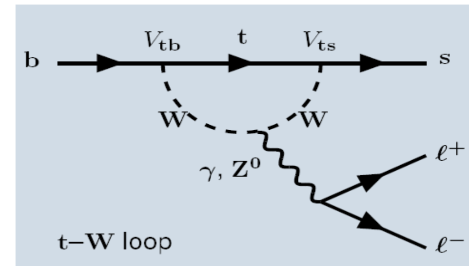






Rare semi-leptonic decays





In this case the suppression factor is α_{EM} :

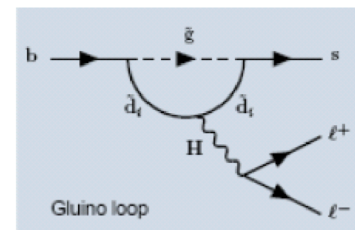
BR($b \longrightarrow sl^+l^-$) $= (4.5\pm1.0)\times10^{-6}$

BR($B^+ \longrightarrow sl^+l^-$) $= (0.5\pm0.1)\times10^{-6}$

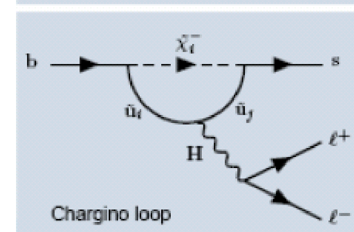
Currently the rarest observed B decay!

Inclusive decays well described by theory

- Shape of dilepton mass distribution sensitive to NP
- SM branching ratio $(1.36\pm0.08)\times10^{-6}$ (NNLL) for $s = q^2/m_b^2 < 0.25$



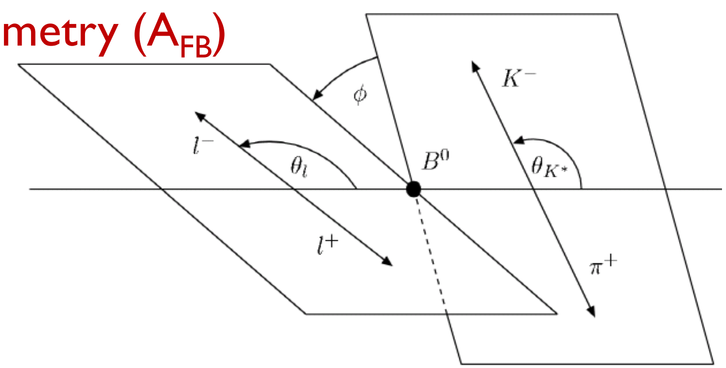
… but hard to analyze experimentally (impossible at hadron colliders?)

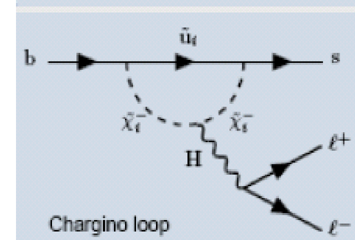


Exclusive decays *much* easier for experiment

Use ratios to cancel hadronic uncertainties

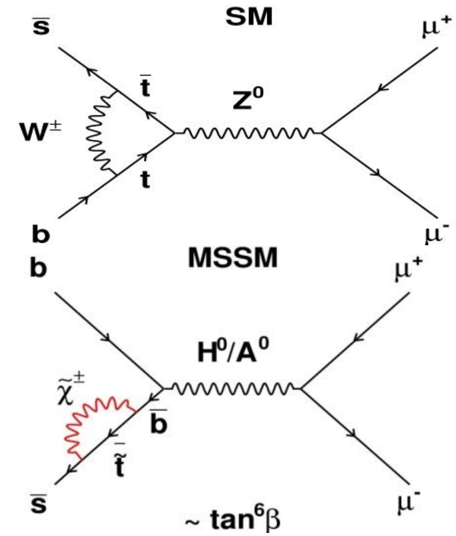
- Forward-Backward asymmetry (A_{FB})
- Transverse asymmetries
- CP asymmetry
- CP asymmetry in A_{FB}
- Ratio of e^+e^- to $\mu^+\mu^-$





Very rare leptonic decays: $B_s \to \mu^+\mu^-$

- Within the SM the dominant contribution stems from the "Z-penguin" diagram. The "box" diagram is suppressed by a factor $(M_W/m_t)^2$
  - Small BR in SM: **$(3.55 \pm 0.33) \times 10^{-9}$**

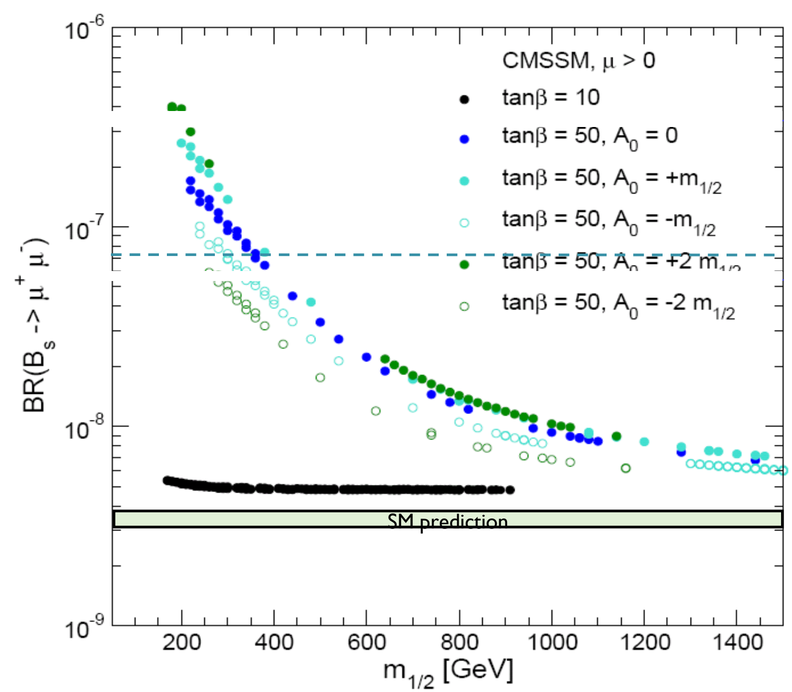


- It is very sensitive to New Physics with new scalar or pseudoscalar interactions. Highly interesting to probe models with extended Higgs sector!

- For instance, in the MSSM the branching ratio scales as

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

- Limit from TeVatron at 90% CL:
  - Current (~2 fb^{-1}) **< 75×10^{-9}**
  - Expected final (8 fb^{-1}): **< 20×10^{-9}**
    - ~ 6 times higher than SM!



Map of Flavour Physics and EW structure

th. error $\lesssim 10\%$
● = exp. error $\lesssim 10\%$
○ = exp. error $\sim 30\%$

Table from G. Isidori

FLAVOUR COUPLING:

ELECTROWEAK STRUCTURE	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
$\Delta F=2$ box	ΔM_{B_s}, $A_{CP}(B_s \to \psi\phi)$	ΔM_{B_d}, $A_{CP}(B_d \to \psi K)$	ΔM_K, ε_K
$\Delta F=1$ 4-quark box	$B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to \pi\pi$, $B_d \to \rho\pi$, ...	ε'/ε, $K \to 3\pi$, ...
gluon penguin	$B_d \to X_s \gamma$, $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d \gamma$, $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 \ell^+\ell^-$, ...
γ penguin	$B_d \to X_s \ell^+\ell^-$, $B_d \to X_s \gamma$, $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d \ell^+\ell^-$, $B_d \to X_d \gamma$, $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 \ell^+\ell^-$, ...
Z^0 penguin	$B_d \to X_s \ell^+\ell^-$, $B_s \to \mu\mu$, $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d \ell^+\ell^-$, $B_d \to \mu\mu$, $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 \ell^+\ell^-$, $K \to \pi\nu\nu$, $K \to \mu\mu$, ...
H^0 penguin	$B_s \to \mu\mu$	$B_d \to \mu\mu$	$K_{L,S} \to \mu\mu$

Still a lot of room for B physics contributions from LHC !

Search strategies for NP

- **Measure FCNC transitions where NP may show up as a relatively large contribution, especially in $b \to s$ transitions which are poorly constrained by existing data:**
  - B_s mixing phase ($\boldsymbol{\phi_s \equiv -2\delta\gamma}$)
  - $b \to s\gamma$, $b \to sl^+l^-$, $B_{(s)} \to \mu\mu$
  - Also: rare K and D decays, D^0 mixing

Single measurements with NP discovery potential

- **Improve measurement precision of CKM elements**
  - Compare two measurements of the same quantity, one which is insensitive and another one which is sensitive to NP:
    - $\sin(2\beta)$ from $B^0 \to J/\psi K_S$ and $\sin(2\beta)$ from $B^0 \to \phi K_S$
    - γ from $B_{(s)} \to D_{(s)}K$ and γ from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$
  - Measure all angles and sides in many different ways
    - any inconsistency will be a sign of new physics

Precision CKMology, including NP-free determinations of angle γ

So... what do we need to fulfil this program?

- High statistics of B_d and B_s.

- Trigger sensitive to final states with leptons and only hadrons.

- Excellent proper time resolution to measure the CP violating oscillation amplitudes of the Bs system.

- Good π/K/μ/e separation to reduce the combinatorial background and other B meson decays. K-id is also very useful for flavour tagging.

- Good momentum and vertex resolution to reduce background

LHC experimental conditions

B-Physics at LHC: (dis)advantages

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEPII, KEKB	$pp \to b\bar{b}X$ ($\sqrt{s}$ = 14 TeV, Δt_{bunch}=25 ns) LHC (LHCb–ATLAS/CMS)
Production σ_{bb}	1 nb	~500 μb
Typical $b\bar{b}$ rate	10 Hz	100–1000 kHz
$b\bar{b}$ purity	~1/4	$\sigma_{bb}/\sigma_{inel}$ = 0.6% Trigger is a major issue !
Pileup	0	0.5–5
b-hadron types	B^+B^- (50%) $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s (10%) B_c (< 0.1%), b-baryons (10%)
b-hadron boost	Small	Large (decay vertexes well separated)
Production vertex	Not reconstructed	Reconstructed (many tracks)
Neutral B mixing	Coherent $B^0\bar{B}^0$ pair mixing	Incoherent B^0 and B_s mixing (extra flavour-tagging dilution)
Event structure	$B\bar{B}$ pair alone	Many particles not associated with the two b hadrons

B-Physics at LHC: (dis)advantages

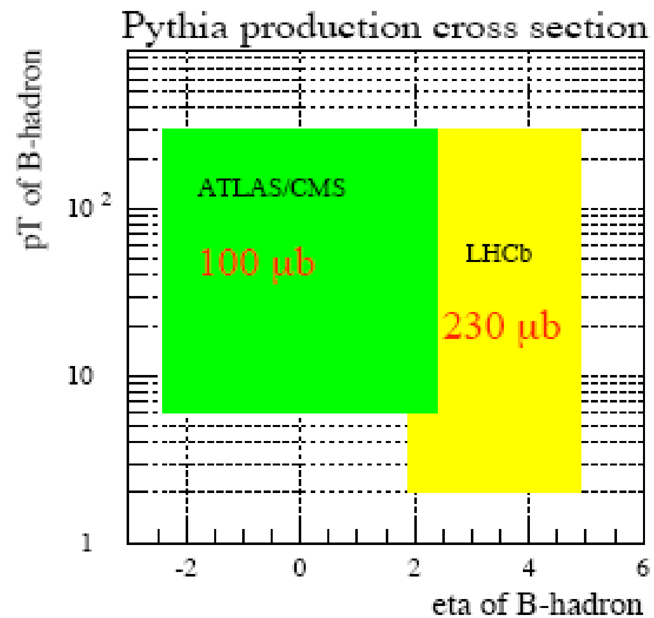
	Tevatron	LHC
	proton−antiproton	proton−proton
$\sqrt{s}$	2 TeV	14 TeV
σ_{Bb}	100 μb	500 μb
σ_{Cc}	1mb	3.5 mb
$\sigma_{Inelastic}$	60 mb	80 mb
σ_{Total}	75 mb	100 mb
$\omega_{bunch\ crossing}$	7.6 MHz	40 MHz
Δt_{bunch}	132 ns	25 ns
$\sigma_{z\ (luminous\ region)}$	30 cm	5.3 cm

Cross sections not measured yet: large uncertainties

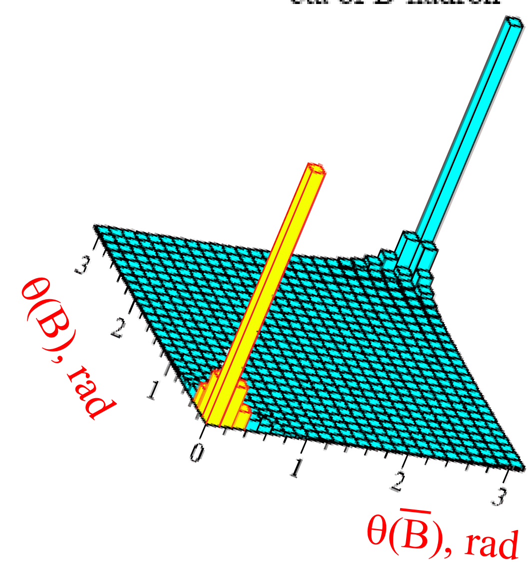
	Tevatron	LHC @LHCb	LHC @ATLAS/CMS
L [cm^{-2}s^{-1}]	2×10^{32}	2×10^{32}	$10^{33}(10^{34})$
$\langle n_{inelastic\ pp\ interactions} / bx\rangle$	1.6	0.5	~2 (25)

B Acceptance

- ATLAS/CMS
  - •Central detectors, |η|<2.5
  - •Will do B-physics using high Pt muon triggers, mostly with modes involving di-muons.
    - •Purely hadronic modes triggered by the tagging muon.



- •LHCb
  - •Designed to maximize B-acceptance (within cost and space constraints)
  - •Forward spectrometer, 1.9<η<4.9
    - •More b-hadrons produced at low angles.
    - •Single arm is OK as b-quarks are correlated.
  - •Rely on much softer, lower Pt triggers, efficient also for purely hadronic decays.



Luminosity and Pileup

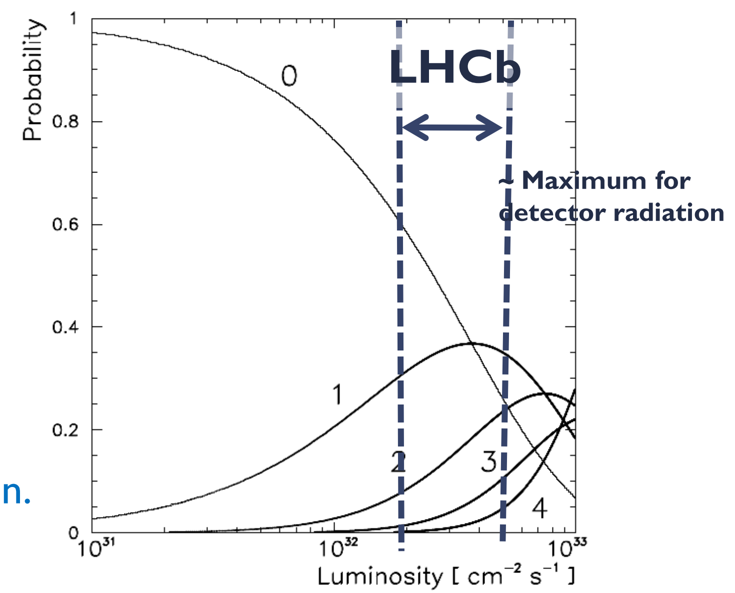
- Pileup
  - Number of inelastic pp interactions in a bunch crossing is Poisson distributed with mean:

$$n = \frac{L\sigma_{inel}}{f}$$

L = instantaneous luminosity
f = non-empty bunch crossing rate
$\sigma_{inel} = 80$ mb

- ATLAS/CMS (f=32 MHz)
  - Want to run at highest luminosity available
  - Expect $L<2\times10^{33}$ cm^{-2} s^{-1} (n<5) for first 3 years.
  - At L= 10^{34} cm^{-2} s^{-1} (n=25) only $B_s \rightarrow \mu\mu$ still possible

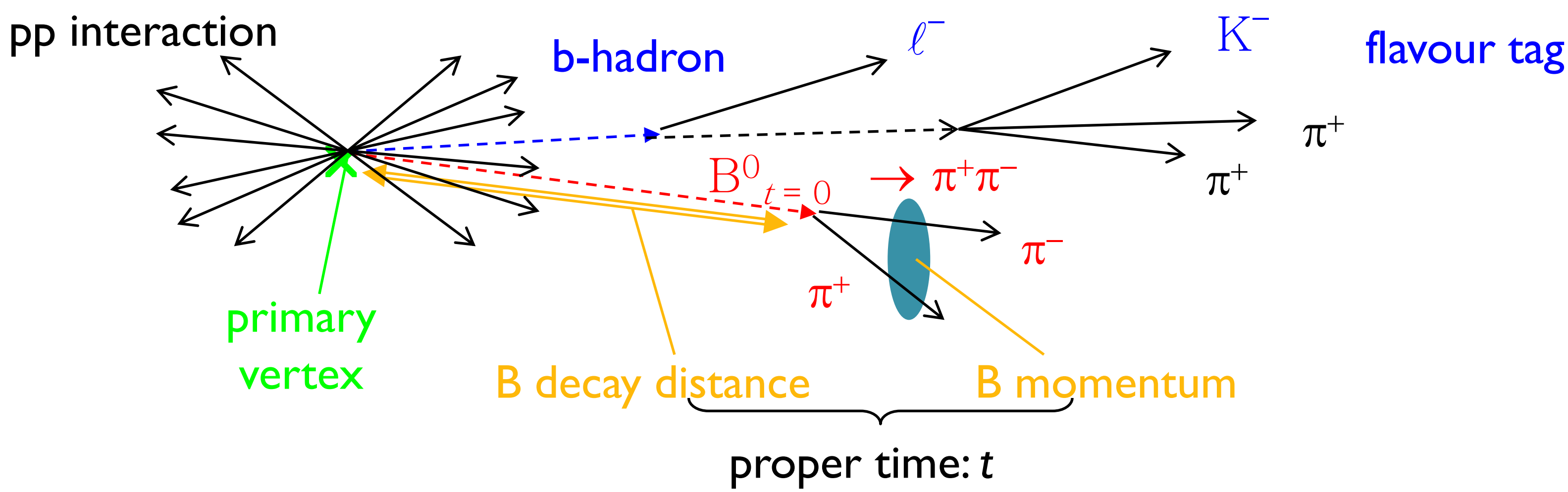
10 fb^{-1} per 10^7 s
~30 fb^{-1} at low lumi



- LHCb (f=30 MHz)
  - L tuneable by defocusing the beams.
  - Choose to run at $L<5\times10^{32}$ cm^{-2} s^{-1} (n<1.2)
  - Clean environment: easier event reconstruction.
  - Less radiation damage: LHCb is only 8 mm from beam

2 fb^{-1} per 10^7 s
10 fb^{-1} in ~5 years

Detector requirements

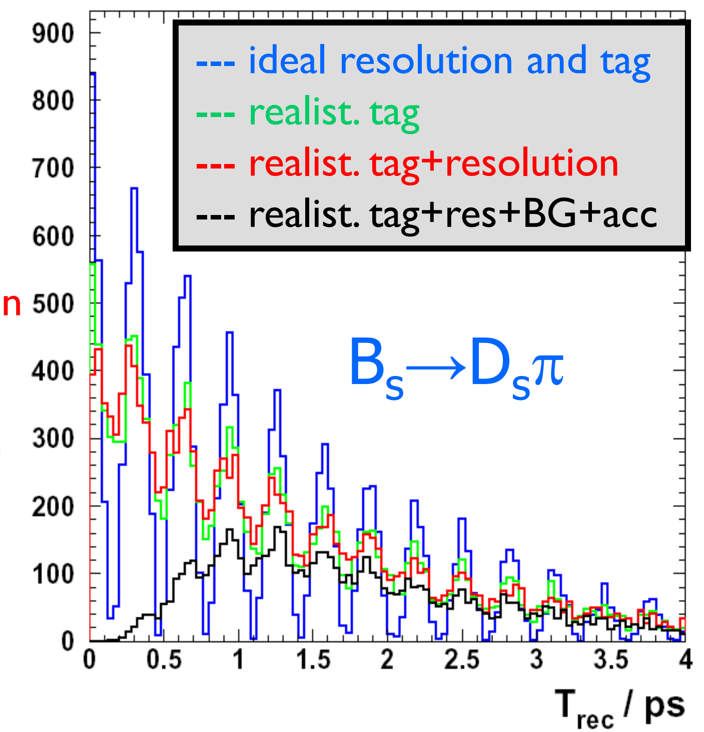


CP violating oscillation amplitudes are damped by

proper time resolution → good decay vertex resolution, good momentum resolution

wrong flavour tag → good particle identification

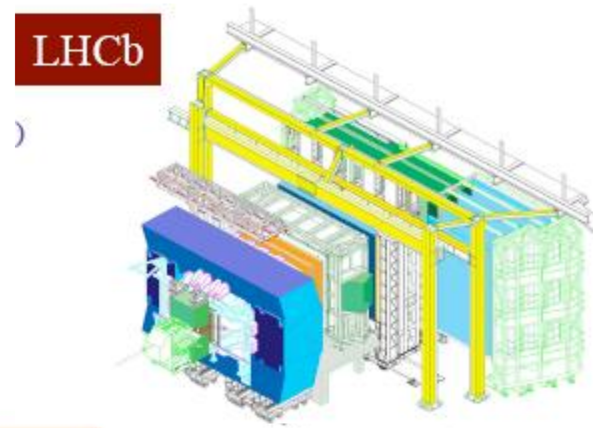
background → good decay vertex resolution, good momentum resolution, good particle identification

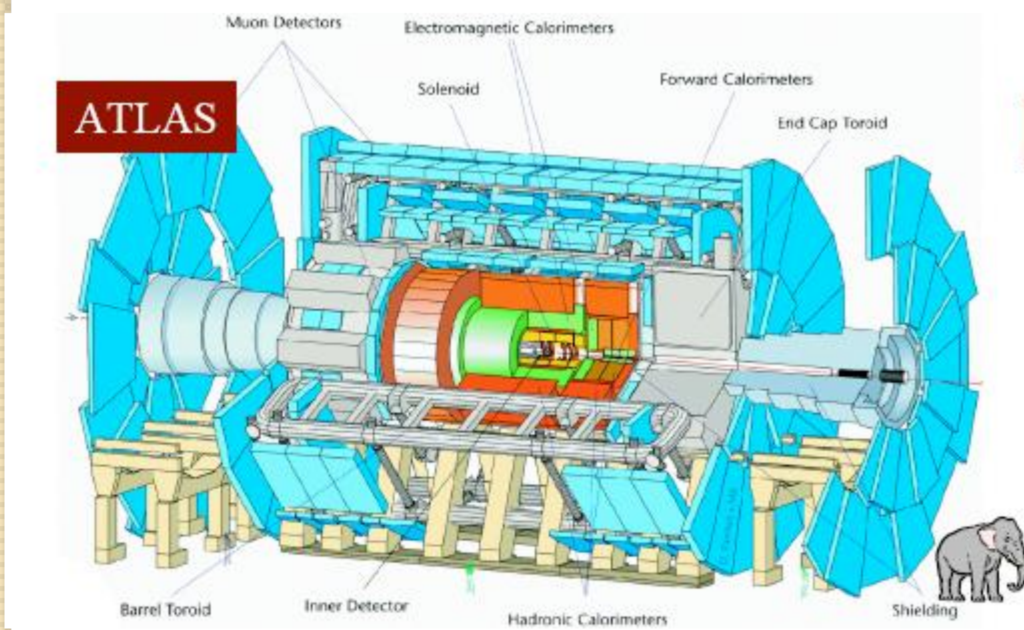


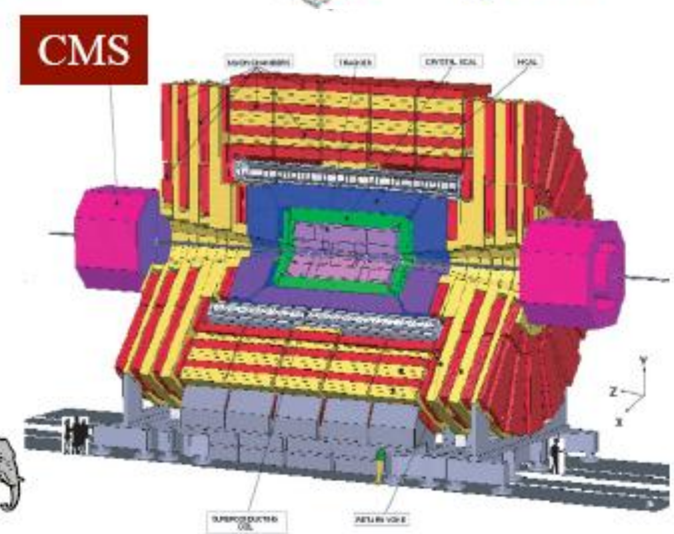
LHC Detectors

LHC detectors doing B-Physics

- ATLAS/CMS
  - General purpose experiments optimized for high Pt Physics at 10^{34} cm^{-2} s^{-1}
- LHCb
  - Dedicated B-Physics experiment







LHCb detector

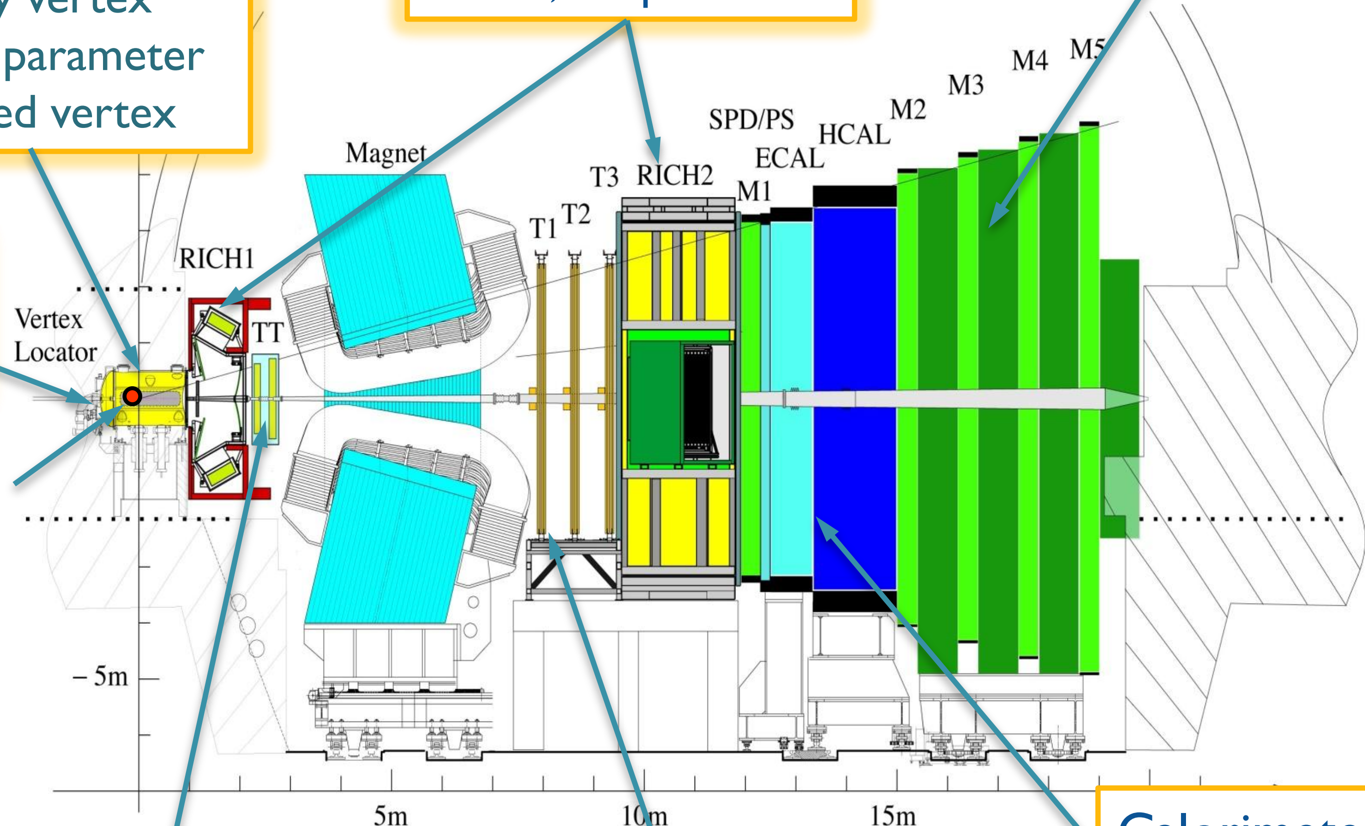
VELO:
primary vertex
impact parameter
displaced vertex

RICHES:
PID: K,π separation

Muon System

PileUp
System

Interaction region



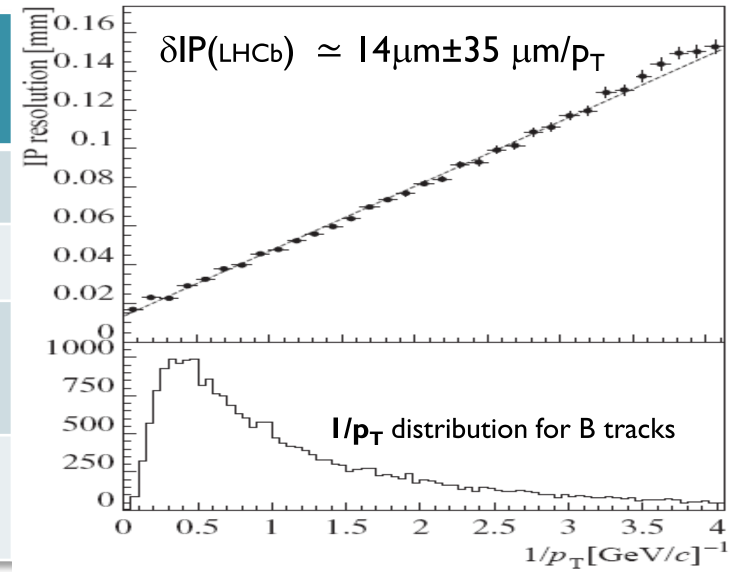
Trigger Tracker: p for trigger and K_s reco

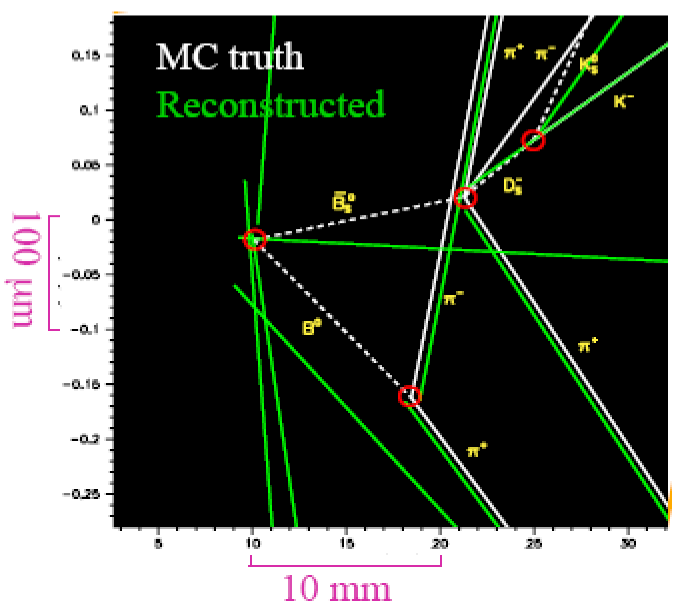
Tracking Stations:
p of charged particles

Calorimeters:
PID: e,γ, π^0

Tracking performance: Proper time resolution

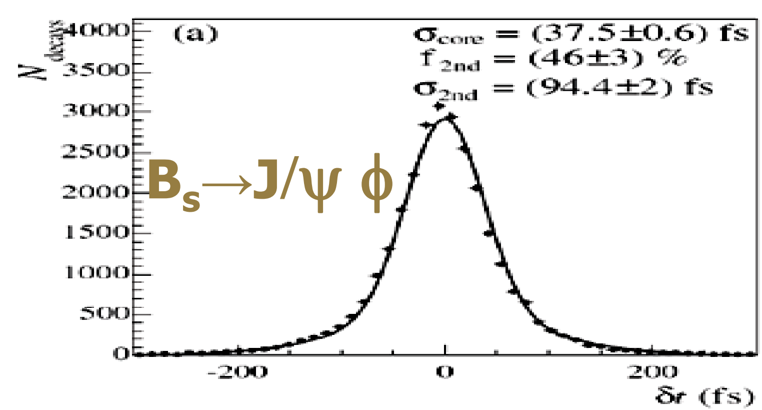
	ATLAS Si Tracker	CMS Si Tracker	LHCb VELO
Surface	65 m^2	210 m^2	0.23 m^2
N channels	6 M	10 M	170 k
Size	50x400 µm (pixel)	150x150 µm (pixel)	40 µm (strip)
Distance to beam	5 cm	4 cm	0.8 cm



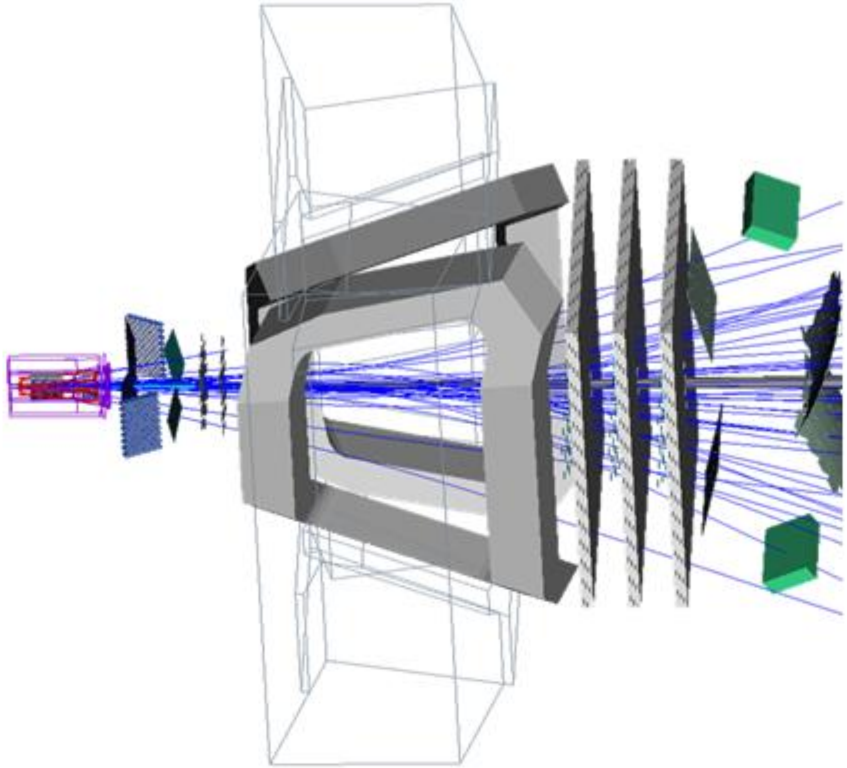


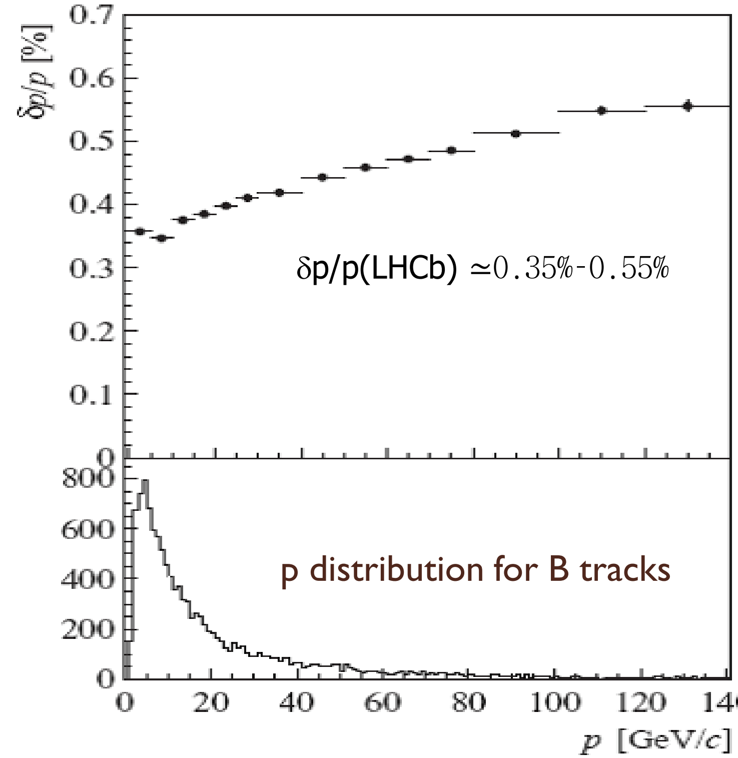
B lifetime:

- LHCb: **36 fs**, ATLAS: **83 fs**, CMS: **77 fs** ($2\pi \cdot \Delta m_s^{-1} \sim$ **350 fs**)
- CDF ~ 87 fs fully reco decays PRL 242003 (2006)



Tracking performance: Momentum resolution





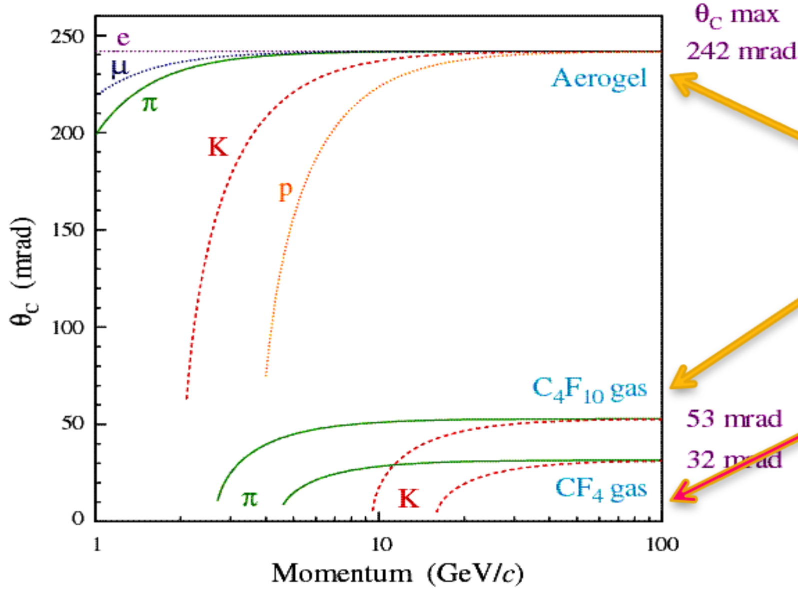
Resolution dominated by multiple scattering (over detector resolution) up to 80 GeV

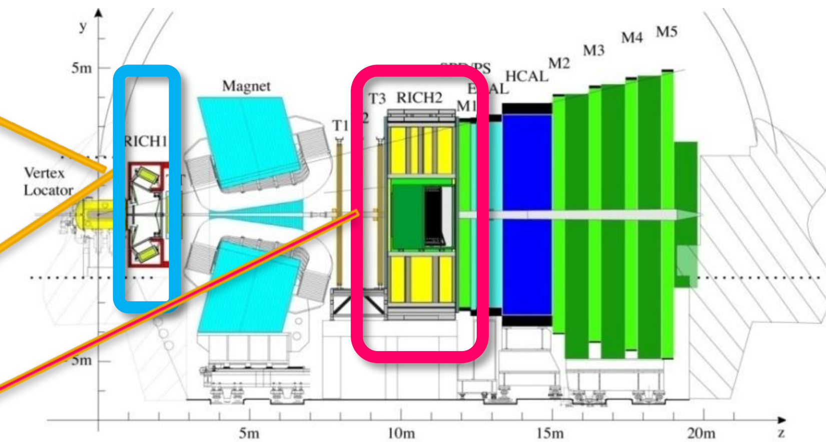
Mass Resolution in MeV/c^2

	ATLAS	CMS	LHCb	
$B_s \rightarrow \mu\mu$	80	46	18	
$B_s \rightarrow D_s \pi$	46	–	14	
$B_s \rightarrow J/\psi\ \phi$	38	32	16	without J/ψ mass constraint
$B_s \rightarrow J/\psi\ \phi$	17	13	8	with J/ψ mass constraint

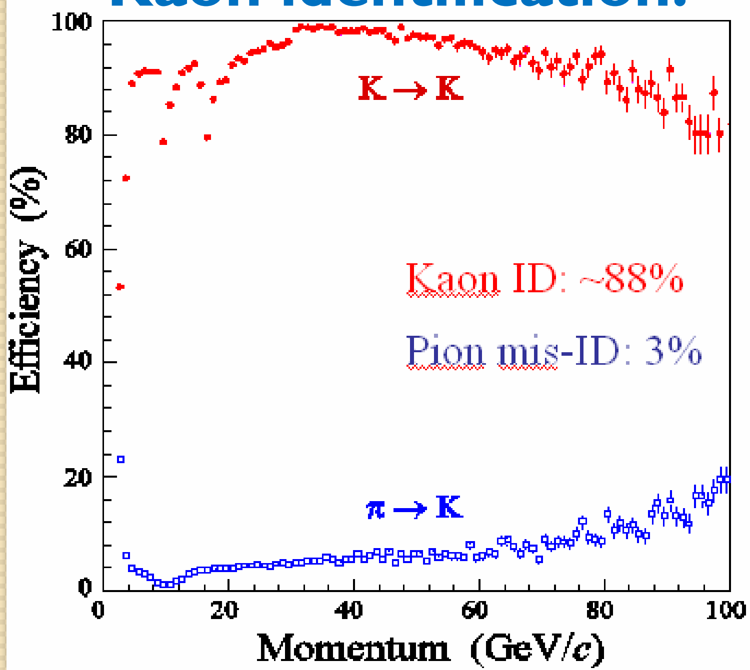
- **Typical B track in LHCb** (p>12 GeV):
  - **20-50 hits:** 98.7% correctly assigned
  - **Efficiency >95%**
  - **Ghost rate <7%**

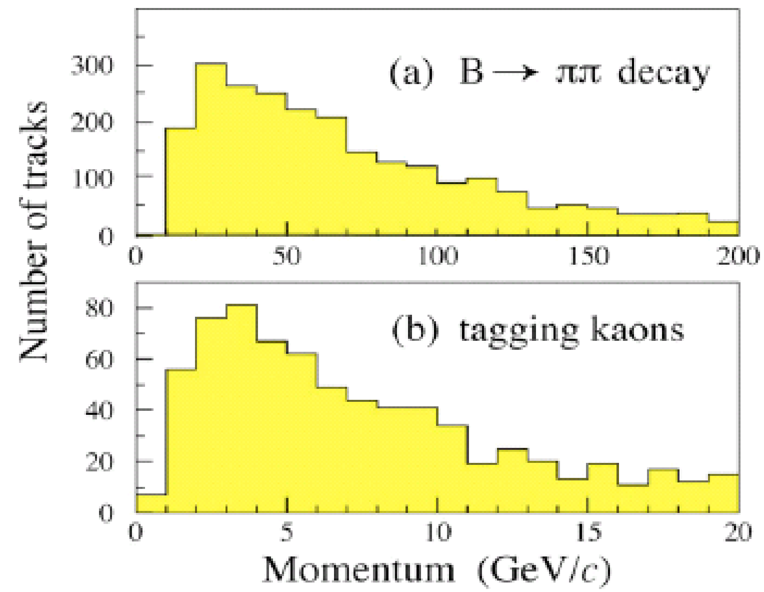
LHCb Particle Identification





Kaon identification:



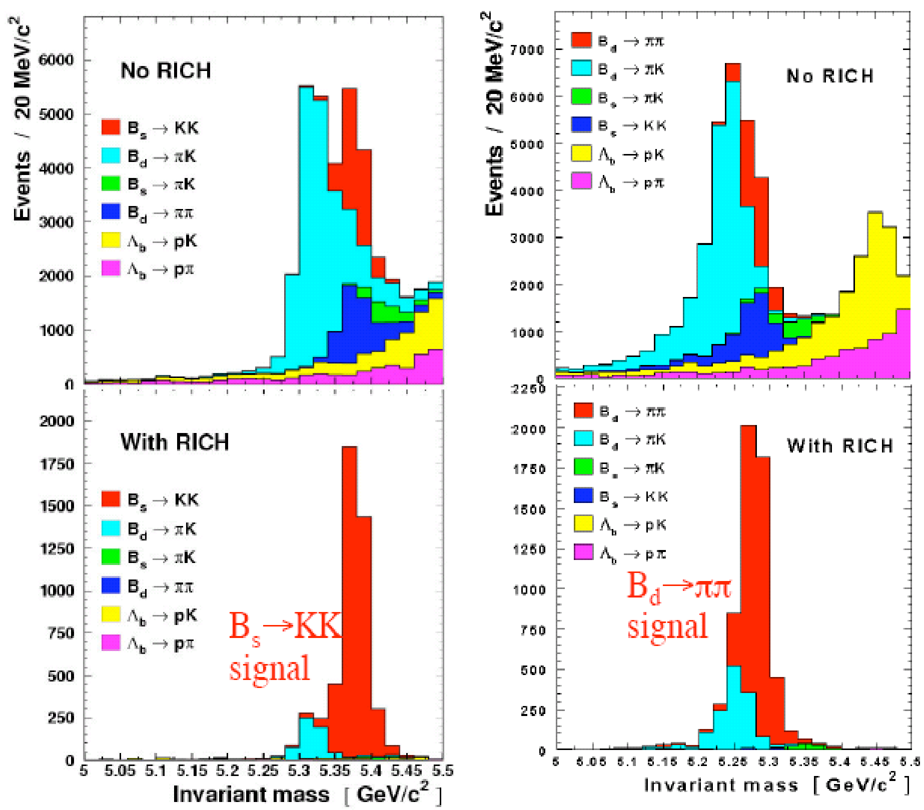


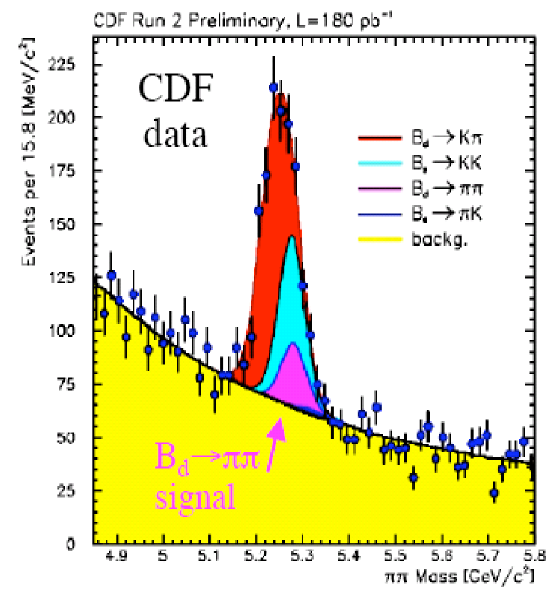
Good K-π separation between 2-100 GeV/c

LHCb Particle Identification

Clean separation of different $B_{(s)} \rightarrow hh$ modes: a unique feature of LHCb at hadron colliders.

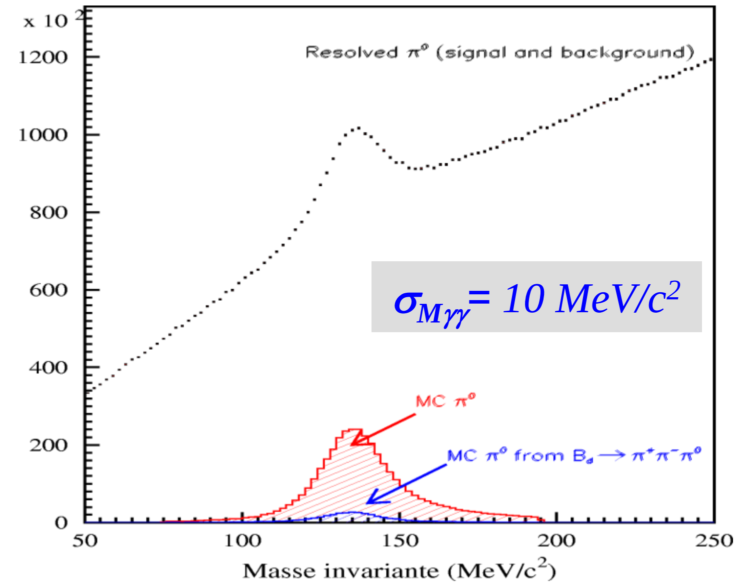
LHCb full simulation

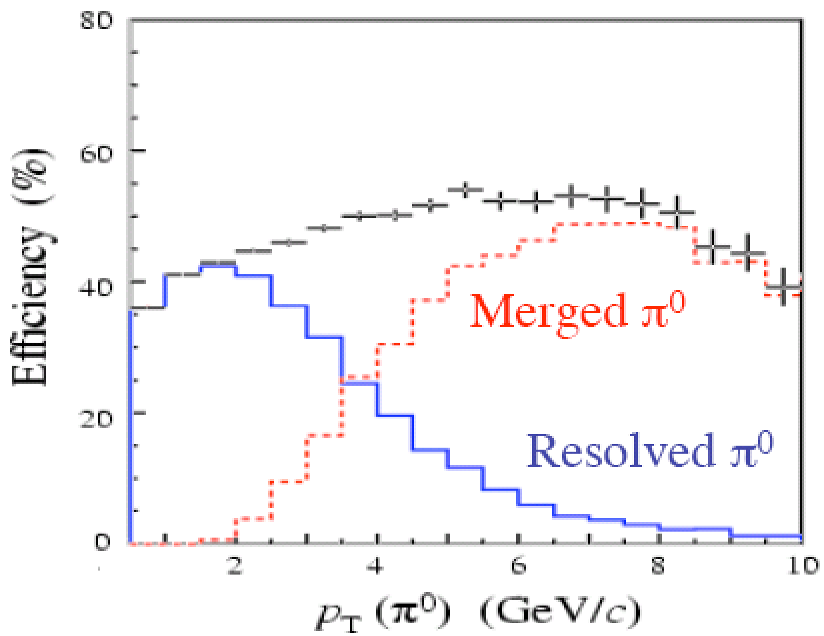


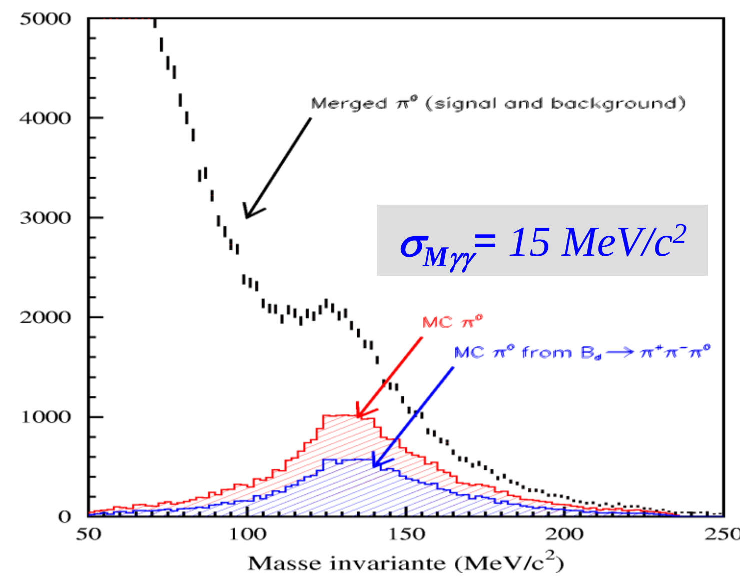


Reconstruction of neutrals at LHCb

- **Neutral π reconstruction:**
  - Use calorimeter clusters unassociated to charged tracks
  - Reconstruct π^0 as two separate (resolved) clusters or a single (merged) cluster.
- **LHCb can also reconstruct $\eta \to \gamma\gamma$:**
  - However it would be challenging to use modes with several neutrals (π^0,η,Ks)







ATLAS B-Physics Trigger

- **ATLAS full trigger:**
  - **L1:** hardware, coarse detector granularity: 2μs buffer
  - **L2:** full granularity, L1confirmation + partial reconstruction: <10ms> processing.
  - **EF (Event Filter):** full event access, "offline" algorithms: <1sec> processing.

Trigger level	Total output rate	Output rate for B physics
LVL1	75 kHz	10–15 kHz
LVL2	2 kHz	1–1.5 kHz
EF	200 Hz	10–15 Hz

- **Strategy for B-Physics Trigger:**
  - High luminosity (> 2×10^{33} cm^{-2} s^{-1}):
    - L1: dimuon with Pt>6 GeV/c each.
  - Low luminosity (or end of) fills:
    - L1: add single muon with Pt>6-8 GeV/c
    - L2: look for objects around the muon:
      - 2[nd] muon with lower treshold around RoI
      - Single e/γ or e+e- pair in EM RoI
      - Hadronic b decay products in Jet RoI

CMS B-Physics Trigger

- **CMS full trigger:**
  - **L1:** hardware, coarse detector granularity: 3.2μs buffer
    - Output rate: 100KHz (nominal)
  - **HLT(High Level Trigger):** full event access, "offline" algorithms: 1sec buffer, <40ms> processing.
    - Output rate: 100 Hz (nominal)
- **Strategy for B-Physics Trigger:**
  - L1: dimuon with Pt>3 GeV/c each and single muon with Pt>14 GeV/c .
  - HLT :Limited time budget: Restrict B reconstruction to RoI around the muon

    Restrict to a reduced number of hits/track.

Trigger level	Total output rate (at startup)	Output rate relevant for B physics
Level 1	50 kHz	14 kHz (1μ) 0.9 kHz (2μ)
HLT	100 Hz	~ 5 Hz of incl. b,c→μ+jet + O(1 Hz) for each excl. B mode

LHCb Trigger

Relevant rates:

– LHC: **40 MHz**, 2 bunches full: **30 MHz**

– At least 2 tracks in acceptance **10 MHz**

– bb: **100 KHz**

  - Decay of one B in acceptance: **15 KHz**

    - relevant decays **BR ~10^{-4} – 10^{-9}**

– cc: **600 KHz**

10 MHz

L0: hight p_T + not too busy

- On custom boards
- Fully synchr. (40 MHz), 4μs latency

1 MHz

High Level Trigger (HLT)

In PC farm with ~1800 CPUs

Refine p_T measurement + IP cuts

Reconstruct in(ex)clusive decays

Full detector available (full flexibility) (**but** no time to process everything for every event) Average latency: 2 ms

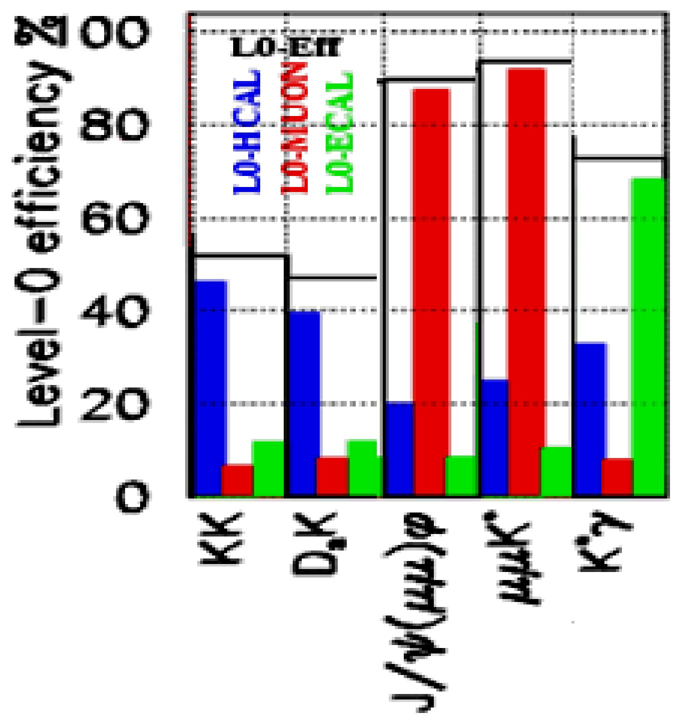
~2KHz, ~35Kb/evt

LHCb L0 Trigger

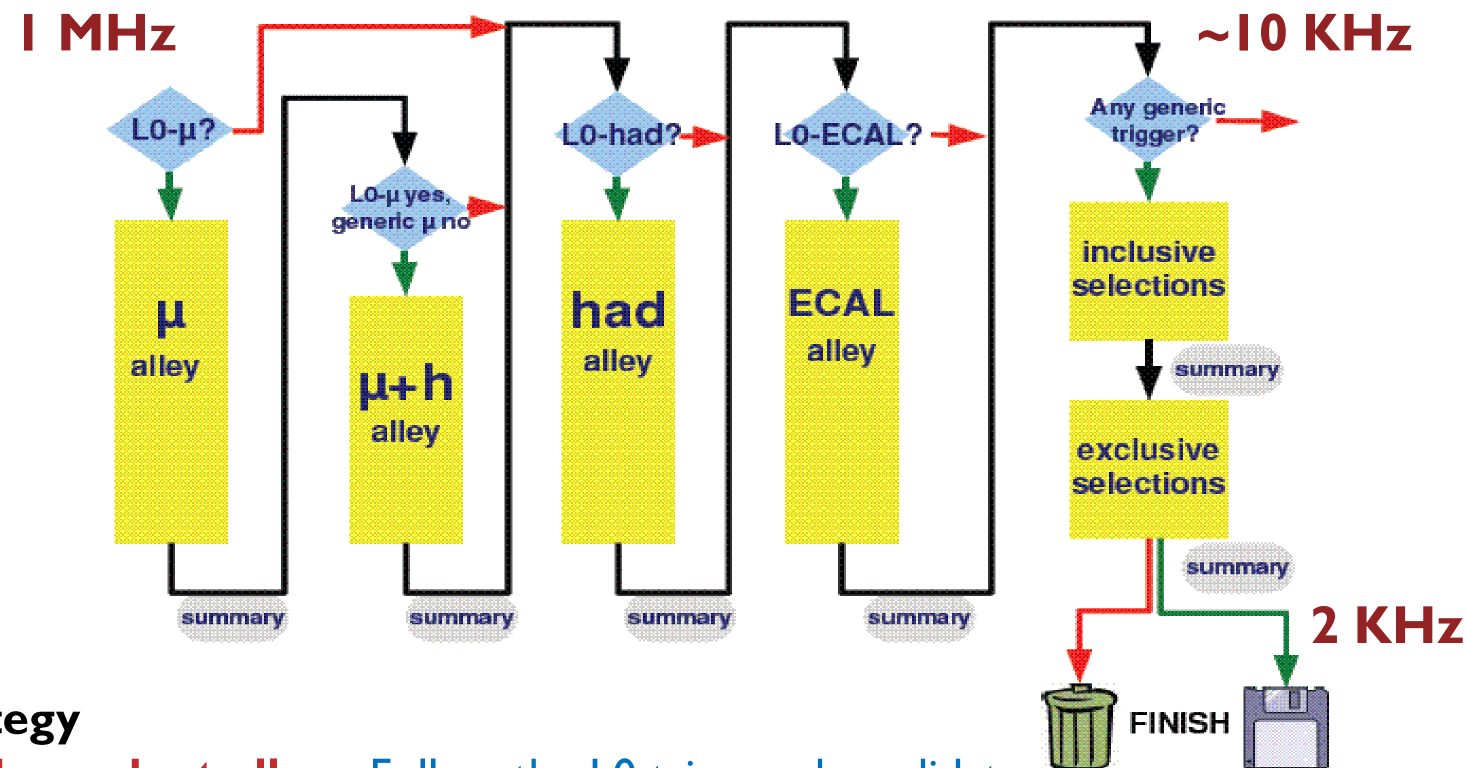
Bandwidth share:

Type	Thresh (GeV)	Rate
Hadron	3.6	700 KHz
Electron	2.8	200 KHz
Photon	2.6	
π^0 local/ global	4/4.5	
Muon	1.1	200 KHz
Di-muon Σp_T^{μ}	1.3	

Efficiency (**off-line selected evts**):



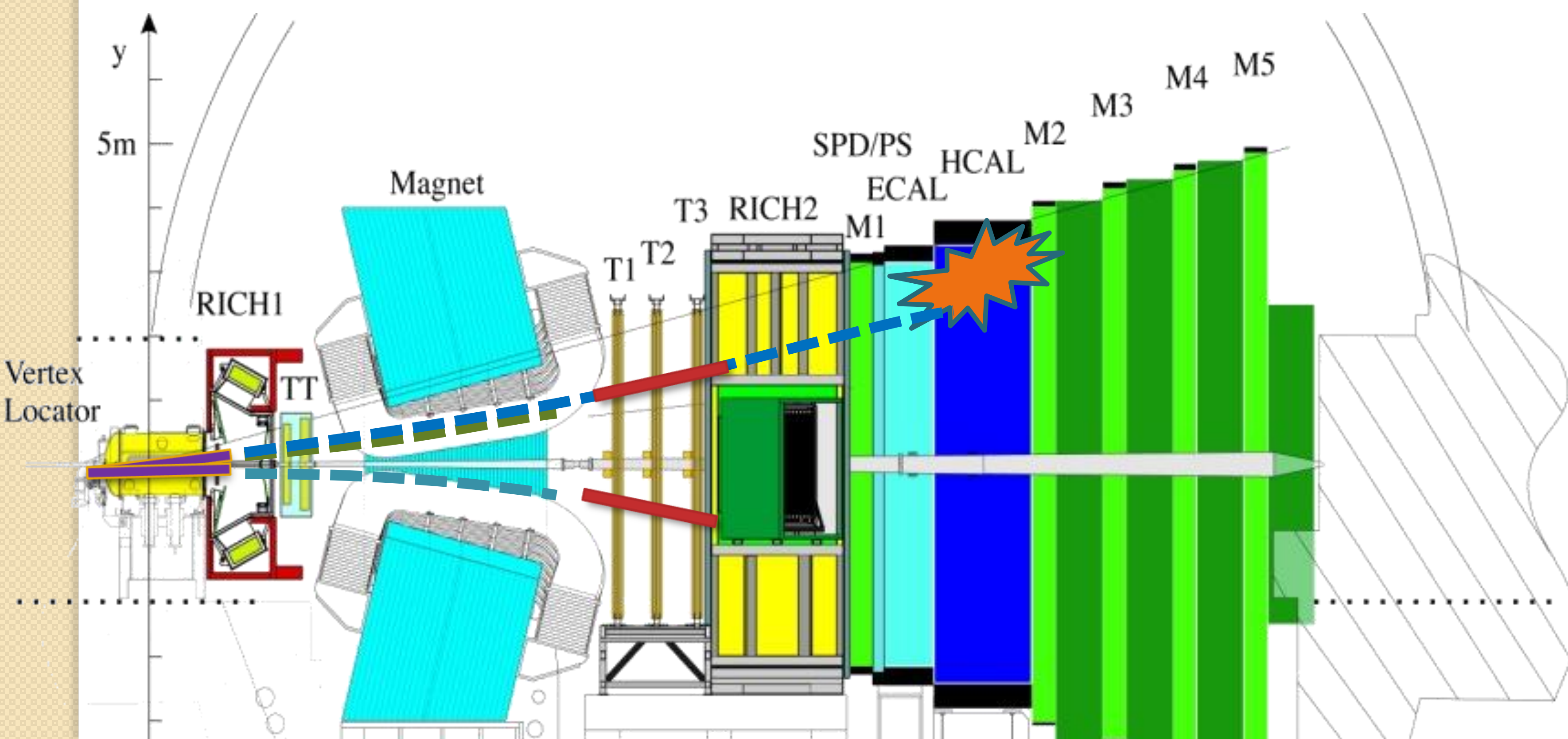
LHCb HLT



- **Strategy**
  - **Independent alleys**: Follow the L0 triggered candidate:
    - Muon, Muon+Hadron, Hadron, ECal
  - ***Partial Reconstruction***:
    - Select few tracks per alley, full reconstruction is done at the end of the alleys
  - **Produce a summary:**
    - With all the information needed to understand how the event has been triggered.

Example: di-hadron alley

- **L0 hadron: 700 KHz**
- **Reconstruct Velo**, match to L0 object, IP cut (~75μm): **250 kHz** (~2 cands.)
- **Reconstruct T tracker**, match VELO track, p_T>2GeV: **40 kHz** (~1.2 cands.)
- Select VELO tracks with IP forming good vertex with 1st candidate
- Match them to T stations and cut at p_T>1 GeV: **5 kHz** (~1 cand. vertex)
- **Then enter ex(in)clusive selections (rate reduced by a factor 100)**



LHCb Trigger bandwidth share

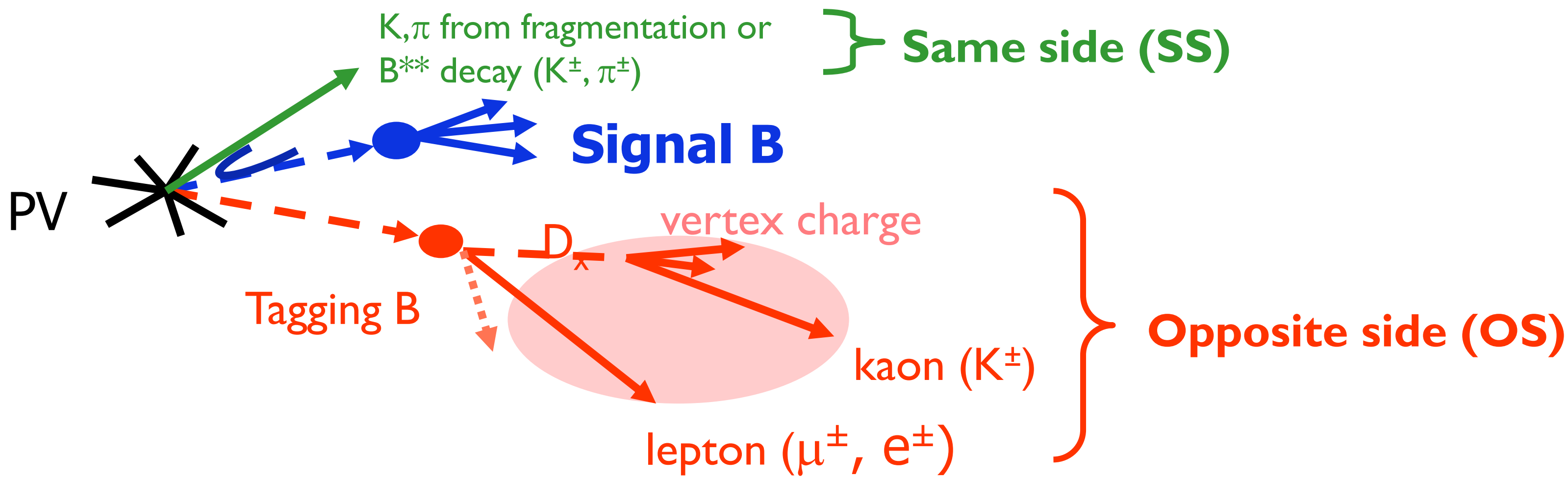
Line	Rate	Cuts	Use
Di-muon	**600 Hz**	Di-μ with: • High mass or • Moderate mass and IP	• All J/ψ channels • Calibration of lifetime
D*	**300 Hz**	$D^0(hh)+\pi$, no Pid used	• Charm physics • Calibration of Pid
In(ex)clu-sive B	**200 Hz**	Dedicated cuts aiming for specific decays	•Core physics channels •Control channels
Generic B	**900 Hz**	Single μ with • very high IP, P_T or • only high and accompanying hadron	Trigger-unbiased B sample. Useful for: • Difficult decays • Trigger studies • Calibration of tagging

- **Overall efficiencies** (on offline selected events)

Type	Example	Efficiency
Hadronic	$B \to h^+h^-$	**25 – 35 %**
Radiative	$B \to K^*\gamma$	**30 – 40%**
Dimuon	$B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	**60 – 70 %**

LHC B-Physics Potential (Examples)

Flavour Tagging

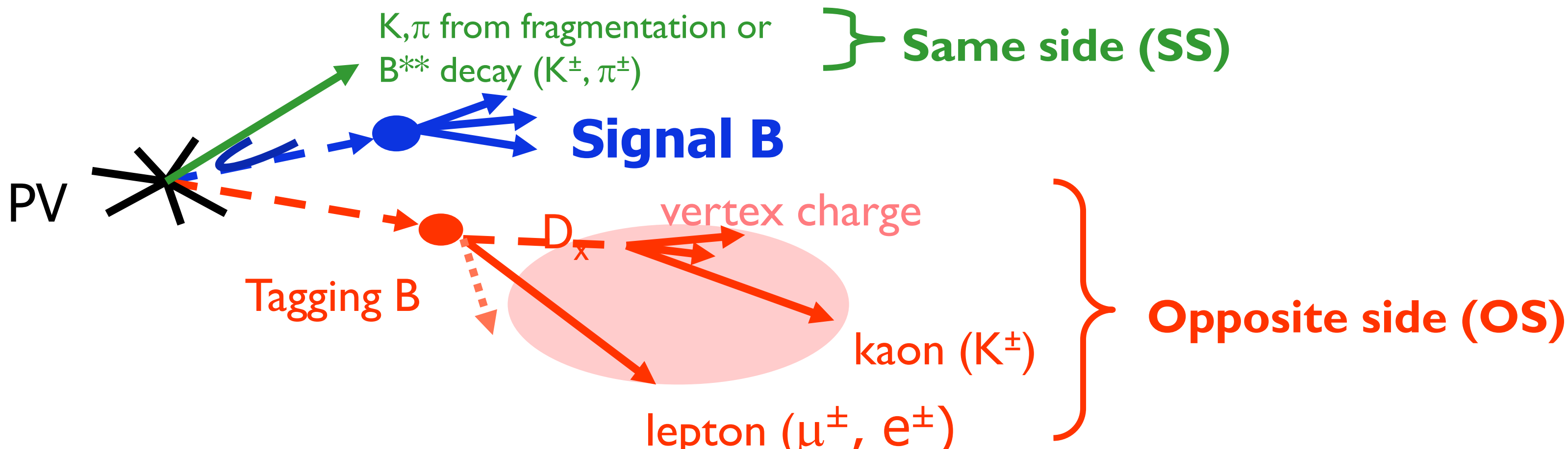


- **Flavour tagging algorithms are not perfect!**
  - Backgrounds in tagger selections
  - The *tagging B* can oscillate incoherently (unlike in B-factories):
    - **40% $B^{\pm}$, 10% baryons :** no oscillation ☺
    - **40% B_d:** $\Delta m_d \sim \Gamma_d \Rightarrow$ oscillated 17.5% ☺
    - **10% 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/D0 ε_{eff} ~4% for B_s
BABAR/BELLE ε_{eff} ~30% for B_d

Details on LHCb flavour tagging performance



Flavour tagging performance depends on the B meson type and on how the event has been selected: online and offline:

$\varepsilon_{\mathrm{eff}} = \varepsilon_{\mathrm{tag}}(1 - 2w_{\mathrm{wrong}})^2$

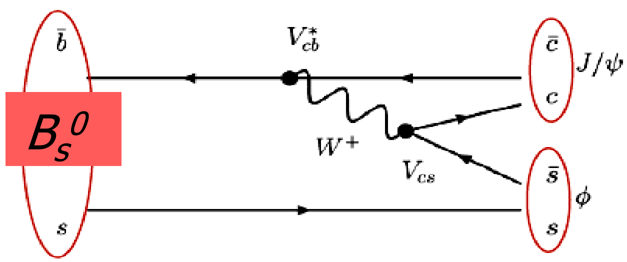
		B^0 ($B^0 \to \pi^+\pi^-$)			B_s ($B_s \to D_sK$)		
		ε^{tag} (%)	ω (%)	ε^{eff} (%)	ε^{tag} (%)	ω (%)	ε^{eff}(%)
OS	**μ±**	8.7	32	**1.14 ± 0.07**	13	33	**1.47 ± 0.12**
	e±	3.6	33	**0.39 ± 0.04**	4.2	30	**0.69 ± 0.08**
	K±	28	36	**2.09 ± 0.73**	27	36	**2.27± 0.15**
	Vertex	22	39	**1.01 ± 0.07**	25	40	**0.97± 0.10**
SS	**K±/π±**	15	39	**0.73 ± 0.06**	33	34	**3.50 ± 0.19**
Total		51	34	**5.05±0.22**	65	31	**9.50 ± 0.42**

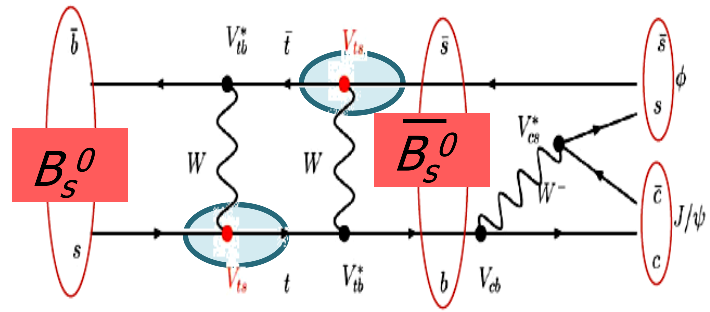
B_s mixing phase: ϕ_s

In the SM $\phi_s^{SM} = -2\lambda^2\eta \sim -0.04$

Direct measurements not very precise: Recent D0: $-0.79 \pm 0.56(\text{stat})\ ^{+0.14}_{-0.01}\ (\text{syst})$

Can access it via $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$





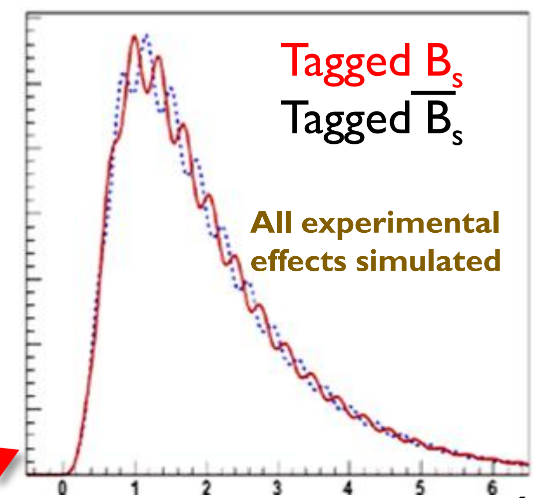
2 arg(V_{ts}) is only weak phase

- Lifetime distributions of events with a B_s ($\overline{B}_s$) at production show oscillation pattern

$$A_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \to f] - \Gamma[B_s(t) \to f]}{\Gamma[\overline{B}_s(t) \to f] + \Gamma[B_s(t) \to f]}$$

$$A_{CP}(t) = \frac{\eta_f \sin\phi_s \sin(\Delta m_s)t}{\cosh(\Delta\Gamma_s t/2) - \eta_f \cos\phi_s \sinh(\Delta\Gamma_s t/2)}$$

$\eta_f = +, -$ 1 CP eigenstates



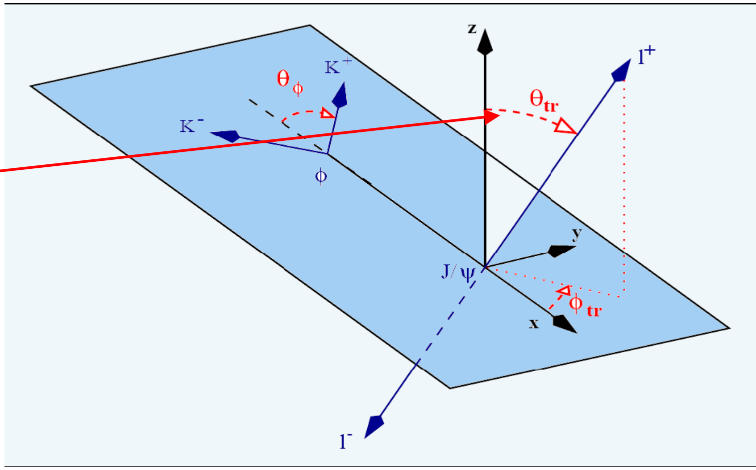
Proper time (ps)

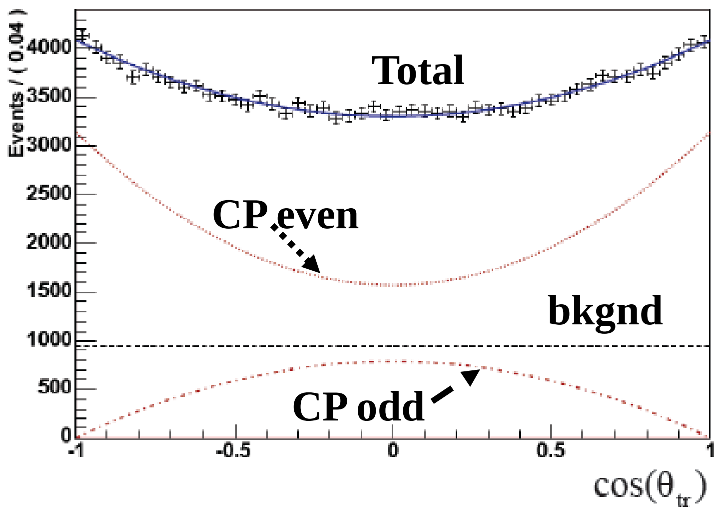
Need flavour tagging

Proper time resolution:
ATLAS 83 fs, CMS 77 fs, LHCb 36 fs

B_s mixing phase: ϕ_s

- Because the final state contains two vector particles, it is a mixture of CP odd and CP even
- Use θ_{tr} angle between μ^+ and **normal** to ϕ decay plane to do an angular analysis to identify the states.





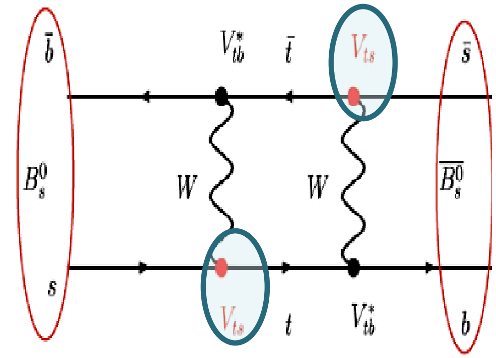
Simultaneous fit to **Time** and **Angular** Distributions

LHCb expects to measure $\sigma(\phi_s)$= 0.02 with 2 fb^{-1} from this channel. Adding also pure CP modes such as $J/\psi\eta$, $J/\psi\eta'$, $\eta_c\phi$ there is a small improvement,. The final precision is $\sigma(\phi_s)$= 0.009 with 10 fb^{-1}

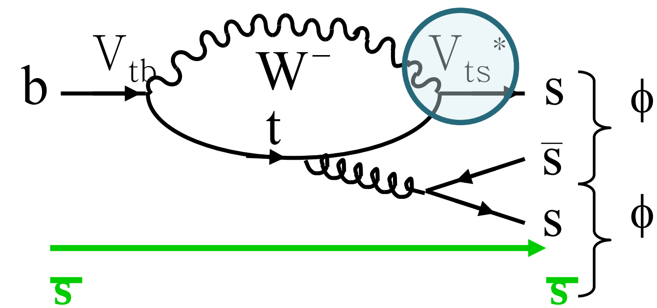
ATLAS/CMS expect to measure $\sigma(\phi_s)$= 0.04 with 30 fb^{-1} , i.e. by the end of the low luminosity LHC running.

We should know by the Physics Conferences in 2009 if $\phi_s \neq \phi_{SM}$

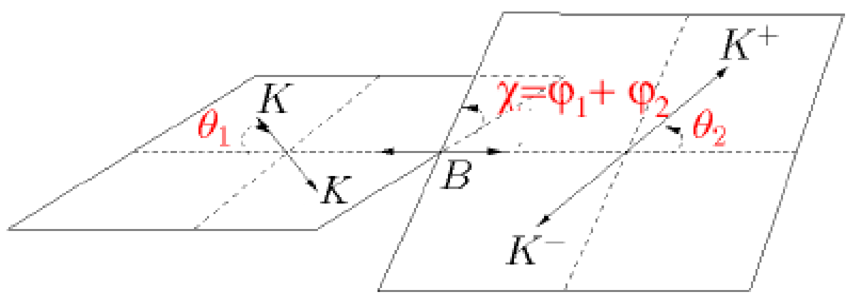
Tree vs Penguin: $B_s \rightarrow \phi\phi$



- FCNC gluonic penguin, can also proceed via mixing
- V_{ts} in both decay and mixing.
- In the SM the CP asymmetry is ~0



- Decay to two vector particles requires an angular analysis to extract CP asymmetries.



Remember present discrepancy seen in B-factories, $\delta\beta$~20%

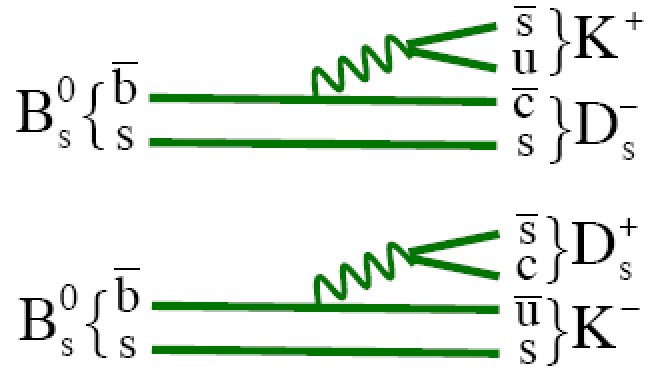
LHCb prospects:

Expect ~20k signal events in $10 fb^{-1}$. Proper time resolution: 42 fs. Sensitivity $\delta\phi_s$ ~6% which can give some hint about the present discrepancy seen in the B factories. It may be a good argument to continue with Super-LHCb ($100 fb^{-1}$): $\delta\phi_s$ ~2%

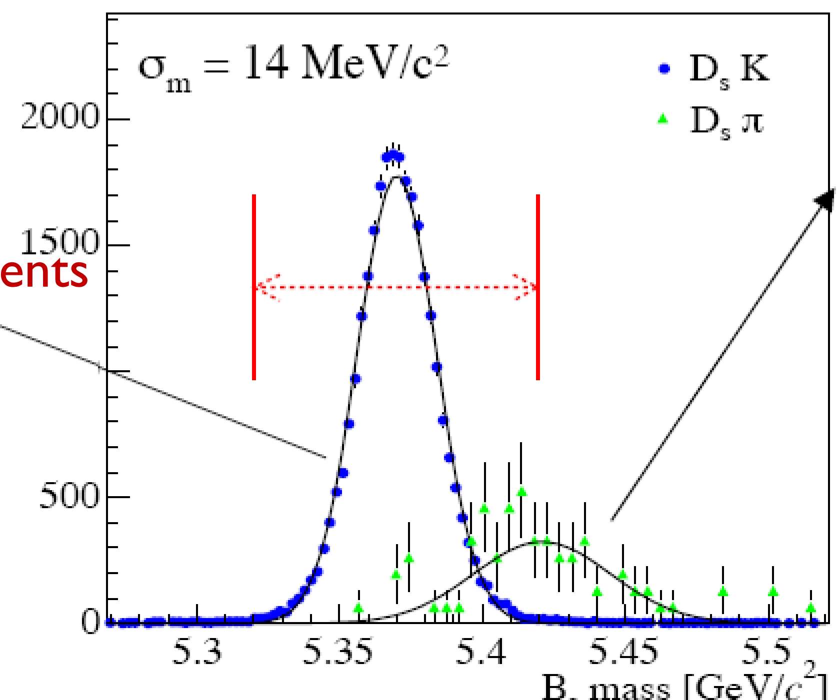
LHCb: γ at tree level

γ from $B_s \rightarrow$ Ds K : crucial hadron trigger and K/π separation

Two tree decays (b→c) and (b→u) that interfere via B_s mixing. Can determine $\phi_s+\gamma$ in the same way than $2\beta+\gamma$ using $B \rightarrow D^*\pi$ done at the B-factories. However in this case, both amplitudes are similar ($\sim\lambda^3$) and their ratio can be extracted from data!



Expect 27k events with 10 fb^{-1}



$B_s \rightarrow$ Ds π background (with 12x larger Br) suppressed using PID: residual contamination ~10%

LHCb: γ at tree level

Four decay time distributions $\longrightarrow$ **two** asymmetries

Strong phase difference

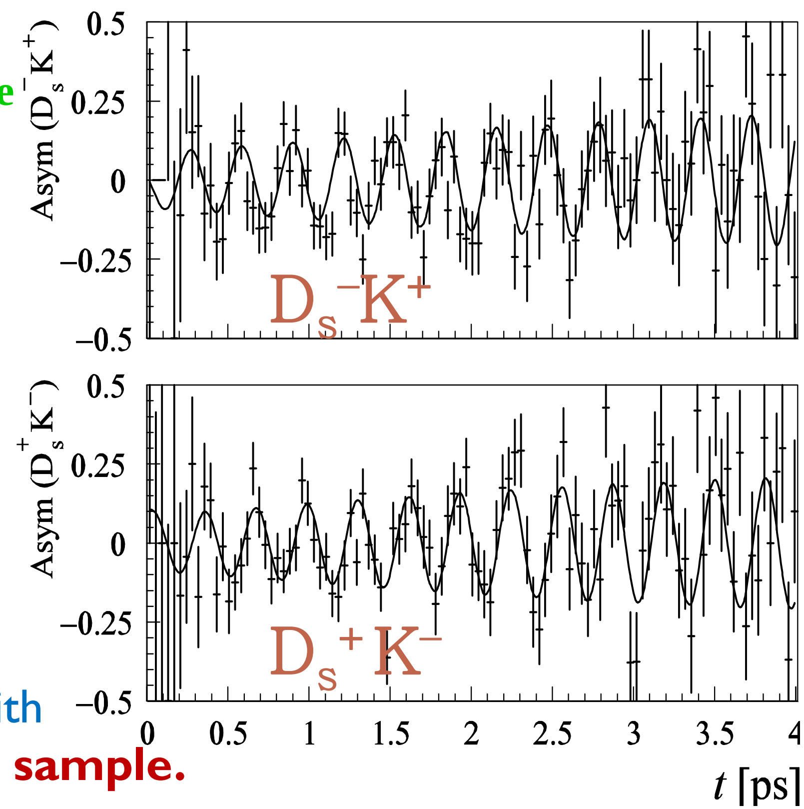
$$D_s^- K^+ \propto \left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right) e^{i\delta\Delta} \left(\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}}\right) \propto e^{-i(\delta\Delta + (\gamma + \phi_s))}$$

Mixing

Decay

$$D_s^+ K^- \propto \left(\frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}}\right) e^{i\delta\Delta} \left(\frac{V_{ub}^* V_{cs}}{V_{cb} V_{us}^*}\right) \propto e^{-i(\delta\Delta - (\gamma + \phi_s))}$$

Both D_sK asymmetries 10 fb^{-1}, Δm_s = 20 ps^{-1})



Fit **D_sK** time distributions, simultaneously with 10 x more abundant **$D_{s\pi}$**, and the **untagged sample.**

This allows simultaneous extraction of :

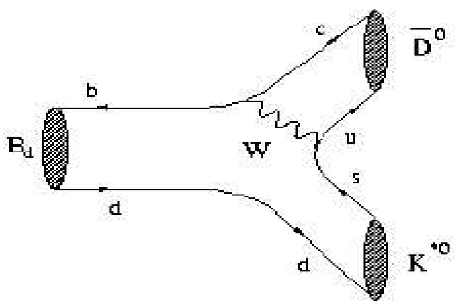
- Δm_s, $\Delta\Gamma_s$
- ω the wrong tag rate
- strong phase difference $\delta\Delta$,
- $\phi_s + \gamma$

Using ϕ_s obtained from B_s to $J/\psi\phi$,

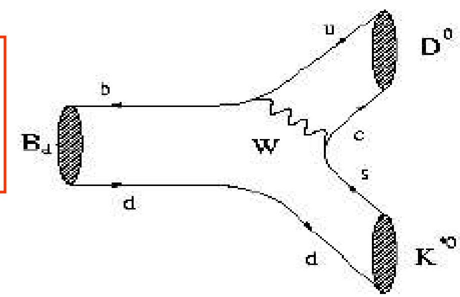
$\sigma(\gamma) = 4.5^o$ with 10 fb^{-1}

LHCb: γ at tree level

γ from B → D K* : crucial hadron trigger and K/π separation



Both colour suppressed
→ Same magnitude
Good for large interference.



$D_1 = (\overline{D}_0 + D_0)/\sqrt{2}$

- Observe $B^0 \rightarrow D^0 K^{*o}$, $B^0 \rightarrow D^0 K^{*0}$, $B^0 \rightarrow D_1 K^{*0}$ and the 3 charge conjugate reactions.
- The D^0 and the K^* are observed in their $K^{+-}\pi^{-+}$ decay modes. The D_1 in $\pi^+\pi^-$ or K^+K^-
- The flavour of the B is identified by the charge of the K in K* decay.
- The flavour of the D by the charge of the K in D decay → **Self tagging.**

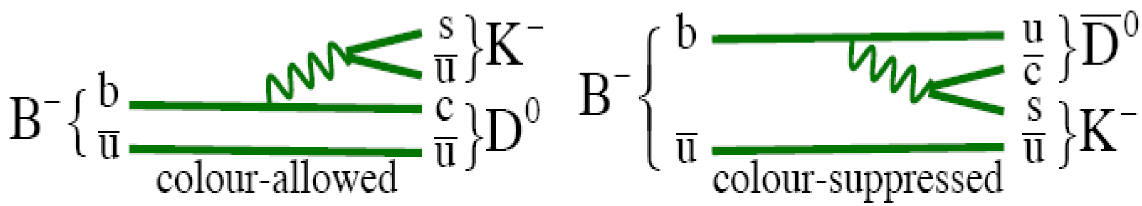
Mode	Yield / $2fb^{-1}$	B/S
favoured $B^0 \rightarrow (K^+\pi^-)_D K^{*0}$ + c.c.	3400	< 0.3
suppressed $B^0 \rightarrow (K^-\pi^+)_D K^{*0}$ + c.c.	500	< 1.7
$B^0 \rightarrow (K^+K^-/\pi^+\pi^-)_D K^{*0}$ + c.c.	600	< 1.4

With r_B=0.4,

$\sigma(\gamma) = 3.6^o$ with 10 fb^{-1}

LHCb: γ at tree level

γ from $B^{\pm} \rightarrow D K^{\pm}$: crucial hadron trigger and K/π separation



Weak phase difference = γ

Magnitude ratio = $r_B \sim 0.15$

- Challenge is to find the suppressed $K\pi$, $K\pi\pi\pi$ modes (Br ~ 10^{-7})

$K\pi$ modes	Yield (summing both modes)	Bckgd / mode
Favoured	57k	20±5 k
Suppressed	300-800	0.8±0.5k

$K\pi\pi$ modes	Yield (summing both modes)	Bckgd / mode
Favoured	61k	20±5 k
Suppressed	300-800	1.2±0.7 k

Background comes from:
- * good D + random bachelor K
- * bad D
- * D π (favoured mode only)

Caveat in the $K\pi\pi\pi$ modes the treatment of intermediate resonances needs to be understood.

With r_B=0.1,

$\sigma(\gamma) = 3.6^o$ with 10 fb^{-1}

LHCb: γ at tree level

γ from $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$: crucial hadron trigger and K/π separation

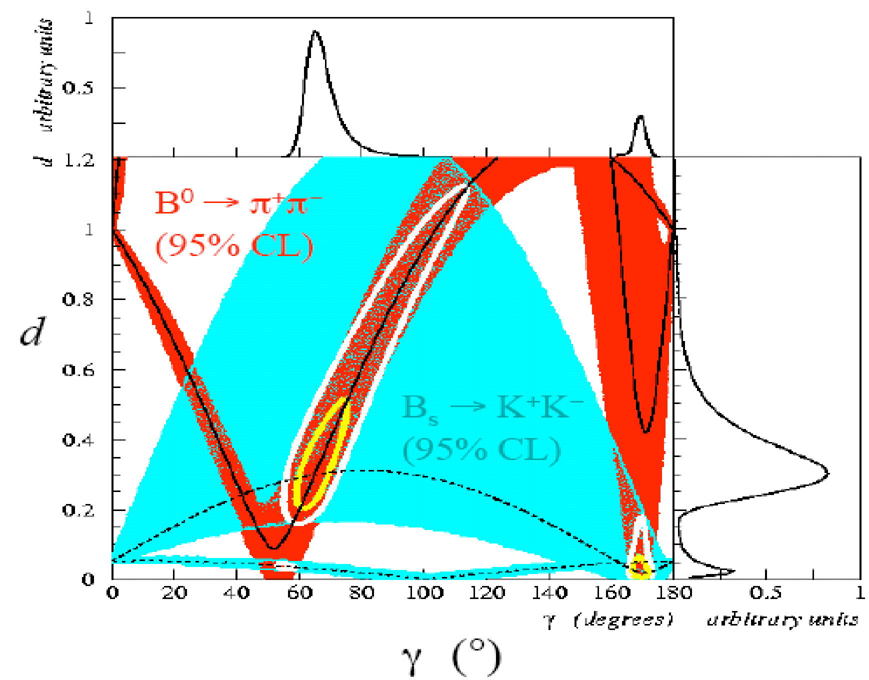
For each mode, measure time-dependent CP asymmetry:

$$A_{CP}(t) = A_{dir}\cos(\Delta mt) + A_{mix}\sin(\Delta mt)$$

A_{dir} and A_{mix} depend on mixing phase, angle γ, and ratio of penguin to tree amplitudes = $de^{i\theta}$

Exploit U-spin symmetry (Fleischer):

Assume $d_{\pi\pi} = d_{KK}$ and $\theta_{\pi\pi} = \theta_{KK}$
4 measurements and 3 unknowns (taking mixing phases from other modes) → can solve for γ



With a weak dependence on U-spin symmetry,

$\sigma(\gamma) = 4^o$ with 10 fb^{-1}

could be affected by New Physics

LHCb: γ at tree level

B mode	D mode	Method	$\sigma(\gamma)$ 10 fb^{-1}
$B_s \rightarrow D_s K$	$KK\pi$	tagged, A(t)	4.5º
$B^0 \rightarrow DK^{*0}$	$K\pi + KK + \pi\pi$	ADS+GLW	3.6º
$B^+ \rightarrow DK^+$	$K\pi + KK/\pi\pi + K3\pi$	ADS+GLW	3.6º
$B^+ \rightarrow DK^+$	$KK\pi\pi$	4-body "Dalitz"	6.7º
$B \rightarrow \pi^+\pi^-, B_s \rightarrow K^+K^-$	---	U-spin symmetry	4º

Not included in the average, as may be affected by New Physics.

LHCb overall precision from tree processes:
$\sigma(\gamma) = 2.4^o$ with 10 fb^{-1}

The impact of LHCb with 10 fb^{-1}

B-factories measurements (tree decays only): γ = (83± 19)°

From global fit (2006) (incl. loop processes!): (64.1 ± 4.6)°

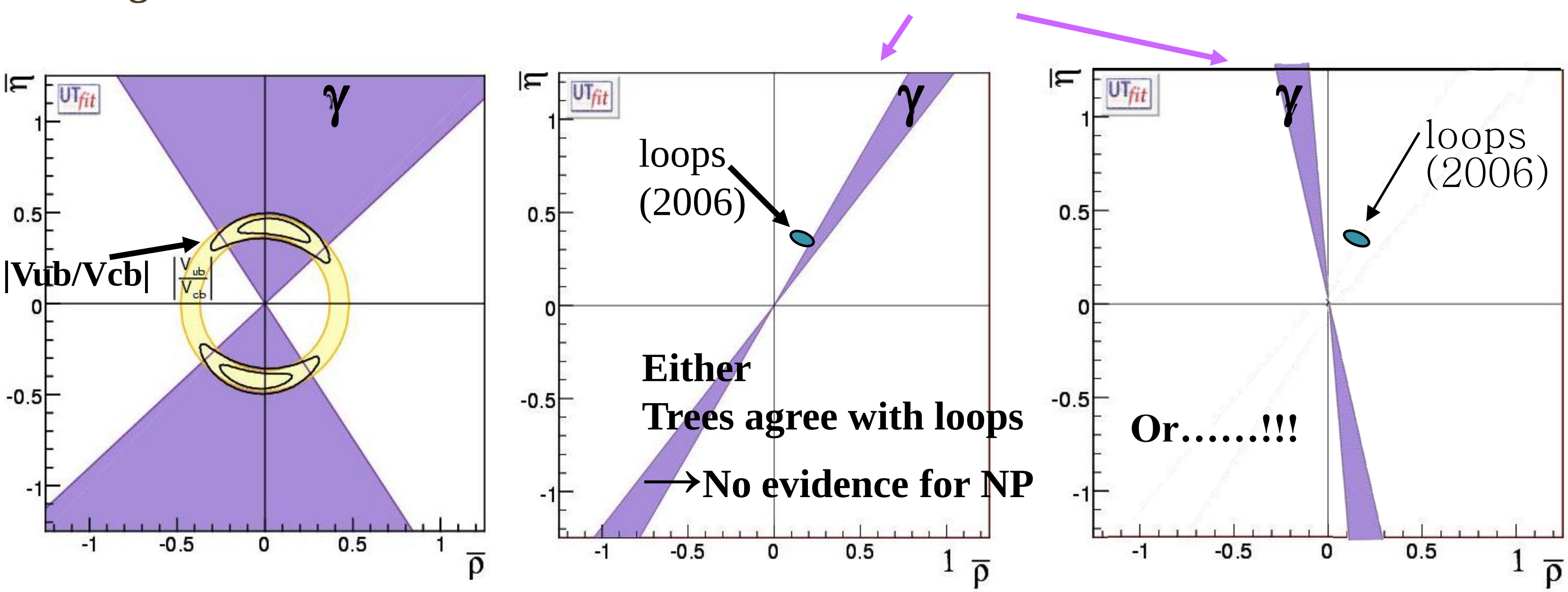
LHCb with 10fb^{-1}

$\sigma(\gamma)$ (tree decays)= 2.4° (~4%)

In few years we should know if γ as measured with tree processes is compatible with loop measurements !

Tree processes only
(No NP contribution)
Large uncertainties

γ from B→DK LHCb 10 fb^{-1}
Tree process (No NP contribution)

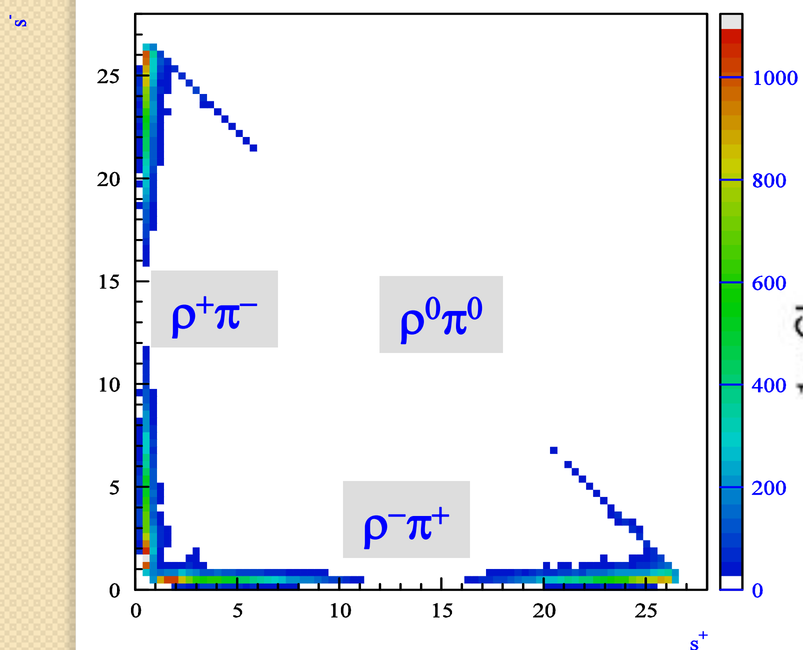


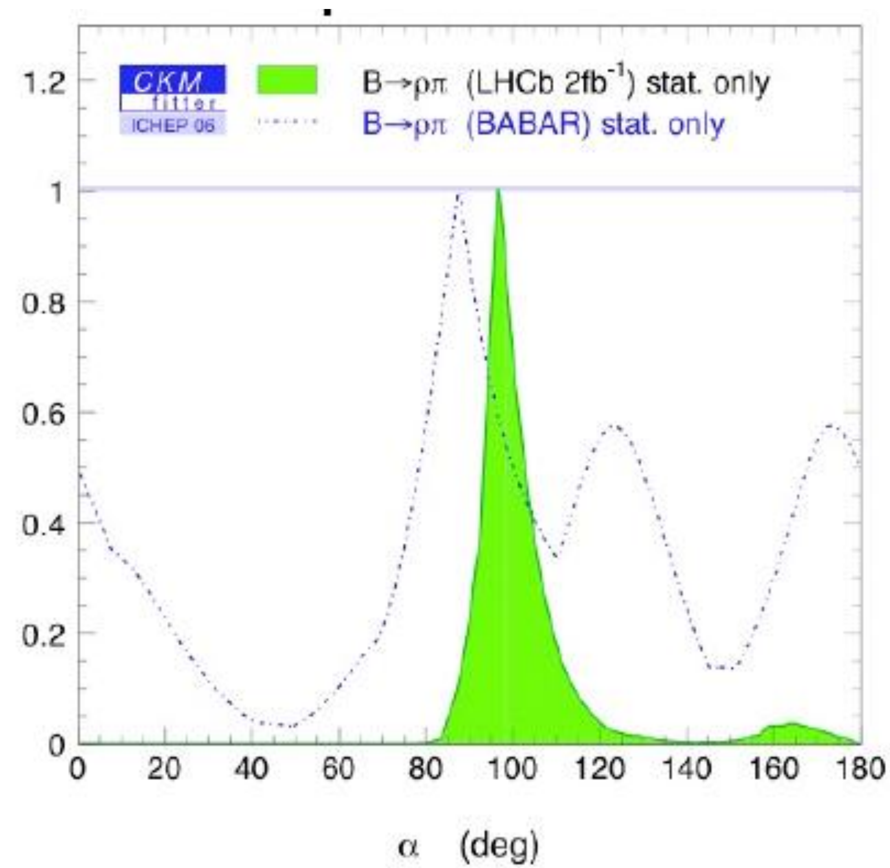
LHCb measurement of α

α from $B^0 \rightarrow (\rho\pi)^0 \rightarrow \pi^+\pi^-\pi^0$: CALO trigger crucial.

LHCb expects 70k $B \rightarrow \pi^+\pi^-\pi^0$ with S/B~1 with 10 fb^{-1}.

•$\sigma(m_B)$ ~ 60 MeV/c^2 , $\sigma(\tau)$ ~ 50 fs , ε_{eff} ~ 5.8%





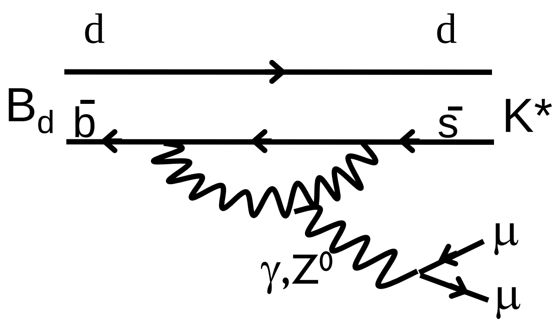
LHCb sensitivity

$\sigma(\alpha) = 4.6^o$ with 10 fb^{-1}

could be affected by New Physics

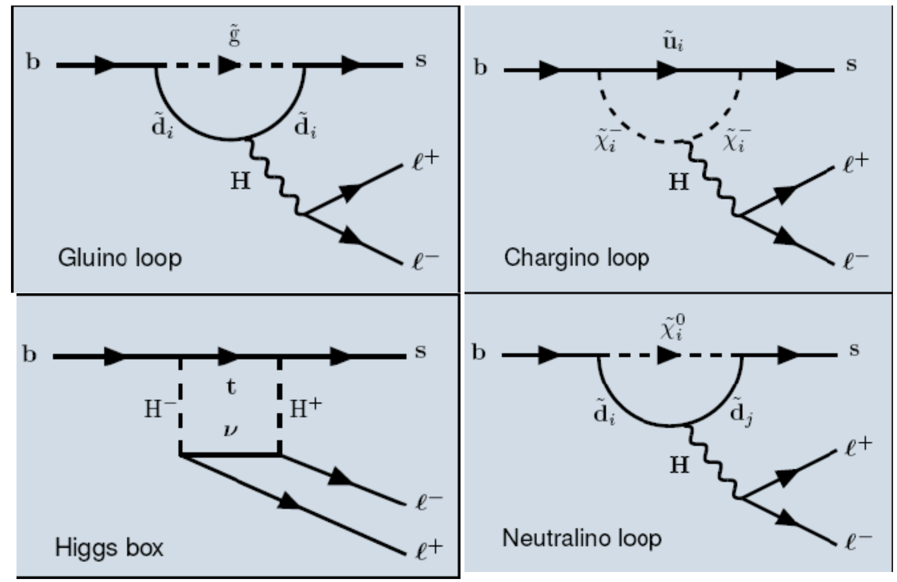
Rare decays: $B_d \rightarrow K^*\mu\mu$

In SM, the decay is a $b \rightarrow s$ penguin diagram



Br: $(1.22^{+0.38}_{-0.32})\ 10^{-6}$

But NP diagrams could also contribute at the same level



•The measured Br agrees within 30% with the SM prediction.

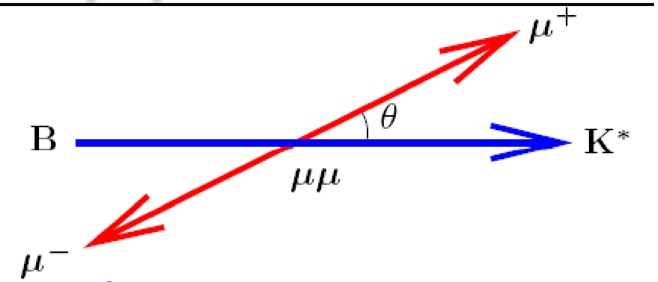
•However, New Physics could **modify the angular distributions** by much more than this!

LHCb $\sigma(m_B)$~14 MeV/c^2 **ATLAS** $\sigma(m_B)$~51 MeV/c^2

For 10 fb^{-1} **LHCb** expects **36k±11k** signal events with **B/S < 0.5** **,(uncertainty mostly due to BR)**

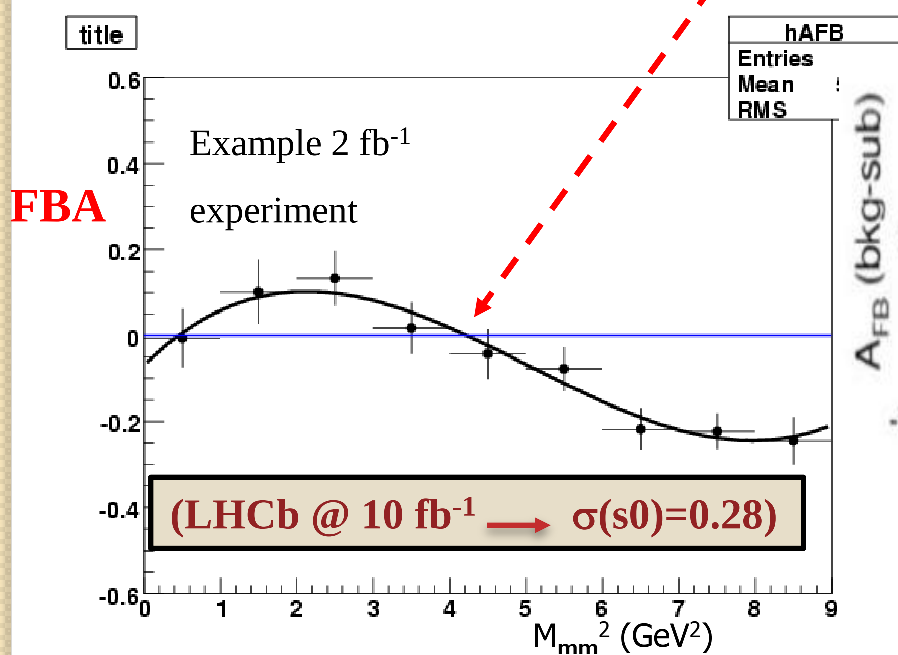
For 30 fb^{-1} **ATLAS** expects **2.4k** signal events with **B/S < 4.8**

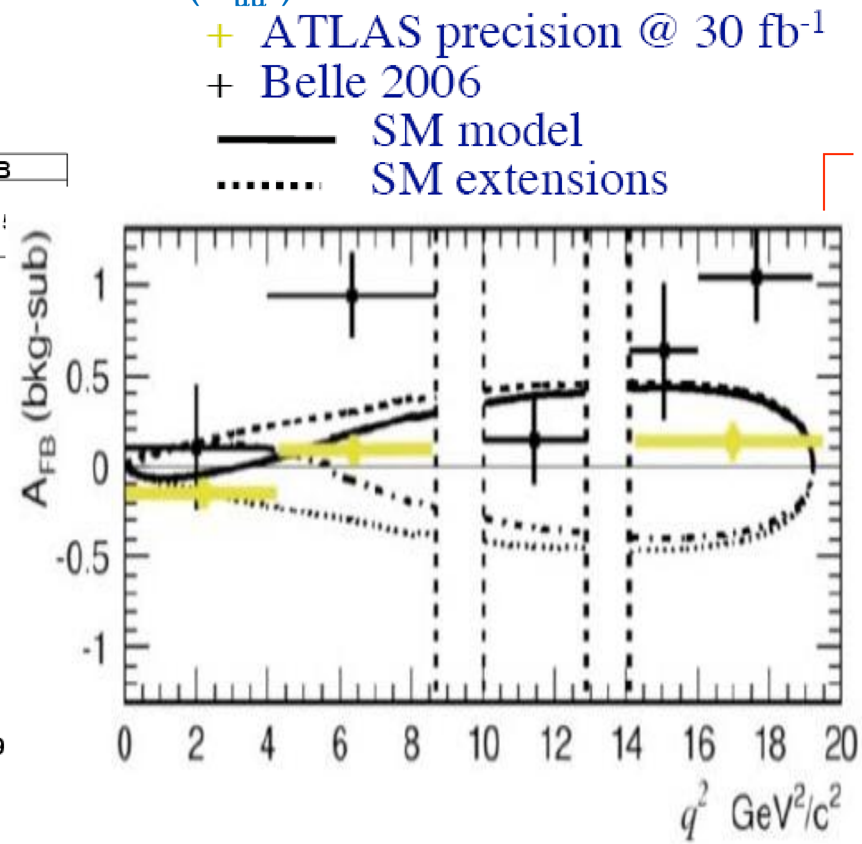
Rare decays: $B_d \rightarrow K^*\mu\mu$



Measure

- the angular distribution of the μ^+ in the $\mu\mu$ rest frame relative to the B direction.
- Measure the Forward – Backward Asymmetry (**FBA**) of this distribution as a function of the $\mu\mu$ invariant mass ($M_{\mu\mu}^2$)
- Determine, $\mathbf{s_0}$, the $M_{\mu\mu}^2$ for which **FBA** = 0.



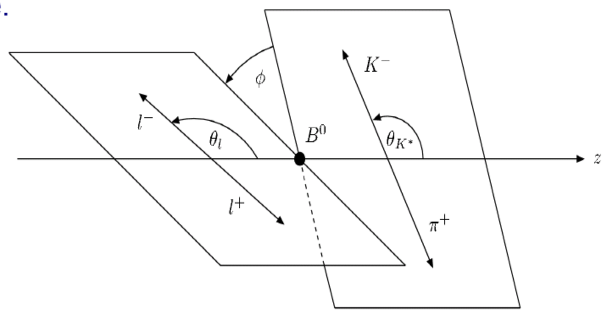


Rare decays: $B_d \to K^*\mu\mu$

Kruger & Matias, Phys. Rev. D 71: 094009, 2500

Kinematic variables in $B \to K^{*0}\mu^+\mu^-$

- q^2 : The invariant mass squared of the dilepton system
- θ_l : The angle of the positive lepton in the dimuon rest frame wrt the B flight direction.
- θ_K : The angle of the Kaon in the $K\pi$ rest frame wrt the B flight direction.
- φ : The angle between the dilepton and the $K\pi$ decay planes in the B rest frame.



Look at decays in terms of transversity amplitudes:

- **Transverse Asymmetries,**(very well known theoretically at low q^2):

$$A_T^{(1)}(s) = \frac{-2\mathrm{Re}(A_\parallel A_\perp^*)}{|A_\perp|^2 + |A_\parallel|^2}, \quad A_T^{(2)}(s) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}.$$

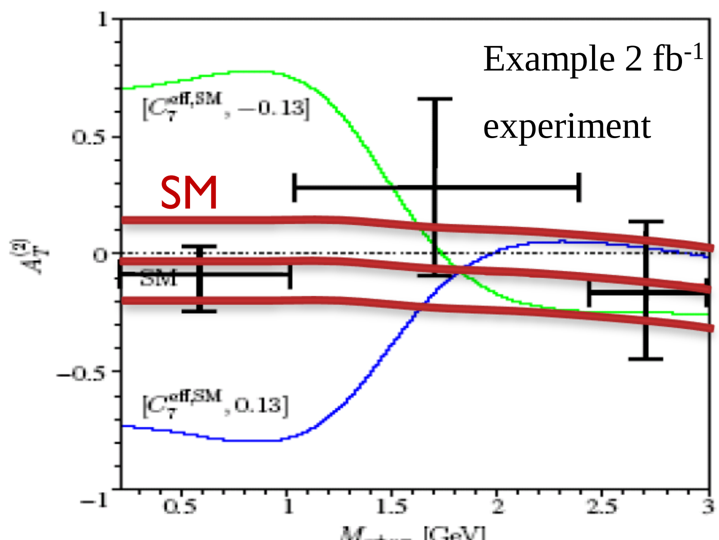
- **Fraction of K* Polarization,(**Theoretical error not negligible):

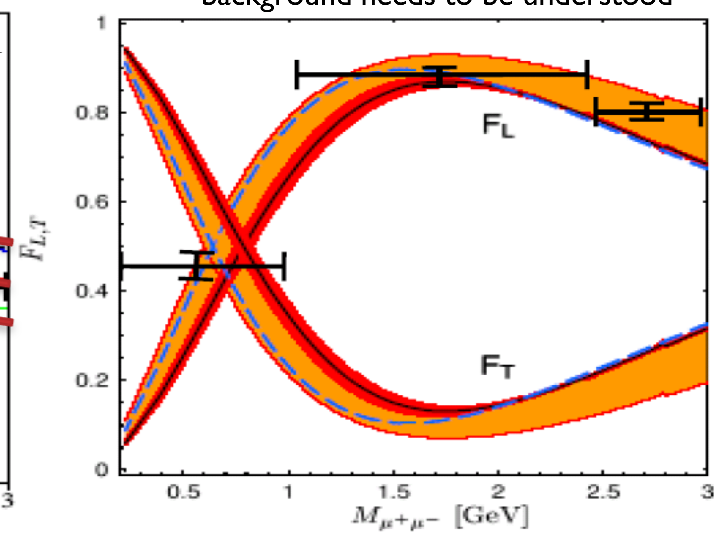
$$F_L(s) = \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2} \qquad F_T(s) = \frac{|A_\perp|^2+|A_\parallel|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$

- **K* Polarization**, (large theoretical uncertainties):

$$\alpha_{K^*}(s) = \frac{2|A_0|^2}{|A_\parallel|^2+|A_\perp|^2} - 1$$

K* is a wide resonance... effect of non resonant $K\pi$ background needs to be understood





Very rare leptonic decays: $B_s \rightarrow \mu^+\mu^-$

Complementarity between B-Physics and High Pt Physics:

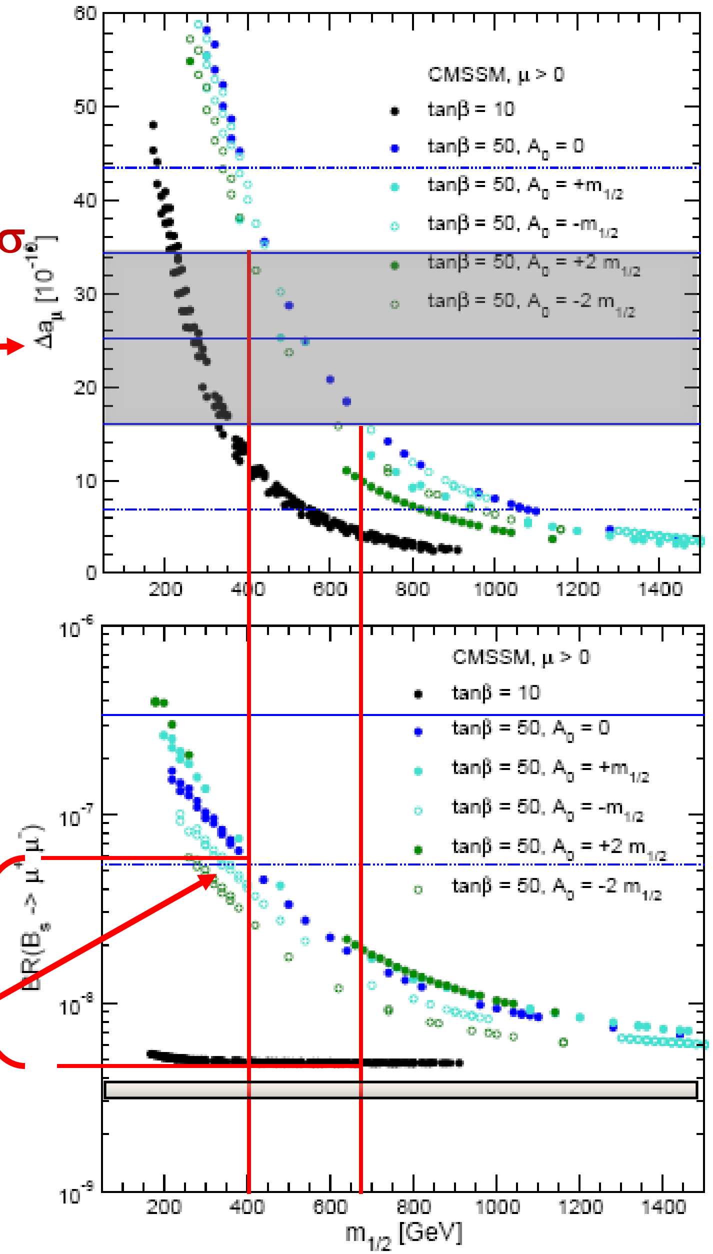
Anomalous magnetic moment of muon: measured at BNL, disagrees with SM at **2.7 σ**

Δa_μ **= (25.2 ±9.2) 10^{-10}**

Within CMSSM,
for different A_0 at large tanβ~50:
400 < $m_{1/2}$ (gaugino mass) < 650 GeV
(within the range of ATLAS/CMS with few fb^{-1})

CMSSM with this **same range** of gaugino mass, predicts **BR ($B_s \rightarrow \mu^+\mu^-$)** could be
~ a few **10^{-9} to few 10^{-8}**

Remember current limit from TeVatron
Br < 75×10^{-9} @90% C.L.



10^{-7}

10^{-8}

10^{-9}

Very rare leptonic decays: $B_s \rightarrow \mu^+\mu^-$

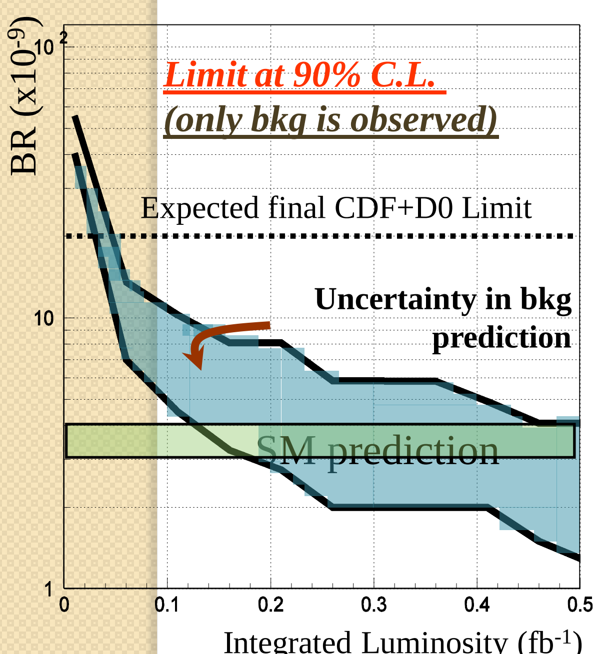
Trigger is "easy" for the three LHC experiments.

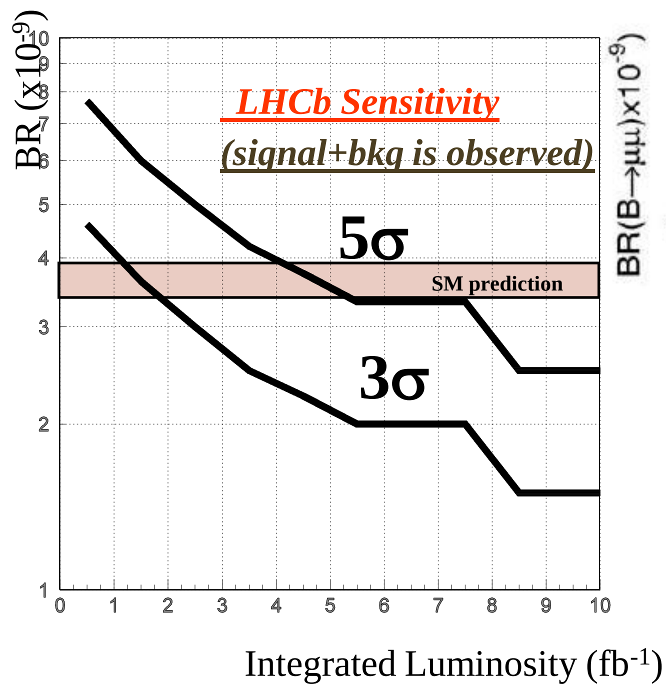
Flavour tag, Proper time are not needed... however, VERY rare decay ~10^{-9}

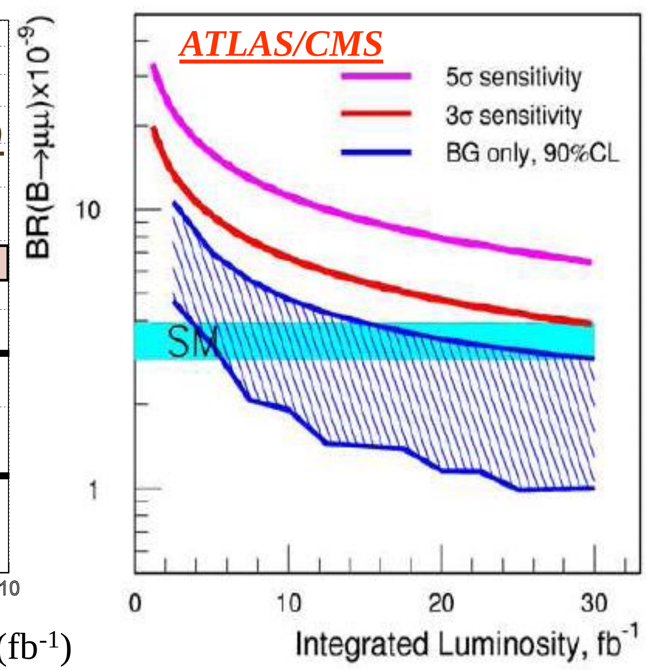
The issue is background:

	LHCb	CMS	ATLAS	
combinatorial $b\rightarrow\mu^- X, \bar{b}\rightarrow\mu^+ X$ need good $\sigma(m_{Bs})$	18	36	84	MeV/c^2
and IP resolution	14-26	30-50	25-70	μm

resonant $B(s)\rightarrow hh$ need good μ-id and $\sigma(m_{Bs})$







We should know by the Physics Conferences in 2009 if $Br(B_s\rightarrow\mu\mu) > 3.5\times10^{-9}$

Control Channels and Calibration

Proper time calibration

Both mistags (ω) & finite proper time resolution (σ_t) dilute CP asymmetries:

$$A^{meas}(t_{rec}) \cong D_{tag}\, D_{res}\, A^{true}(t_{rec})$$

where

$$D_{tag} = (1 - 2\omega)$$
$$D_{res} = \exp\left[-(\Delta m\, \sigma_t)^2 / 2 \right]$$

$\left\{\begin{array}{l}\text{Gaussian approximation} \\ D_{res} \text{ only relevant for } B_s\end{array}\right.$

So both these factors need to be well known to get back A^{true} !

Consider for example $B_s \to D_s K$. LHCb statistical error on $A^{true} \sim 0.10$ with 2 fb^{-1}
Aim for systematic error contributions of < 0.05. For the case $\omega=0.35$,
$\sigma_t = 40$ fs & $\Delta m_s = 18\ ps^{-1}$ (in this sense we are lucky that the measured Δm_s was not larger than SM!). Then, we require $\Delta\omega/\omega < 0.02$ and $\Delta\sigma_t/\sigma_t < 0.06$.

Very demanding ! This for a 'low yield' channel – $J/\Psi\phi$ has 20x more events!

Good control of tagging & proper time resolution crucial in CP measurements.

Proper time calibration

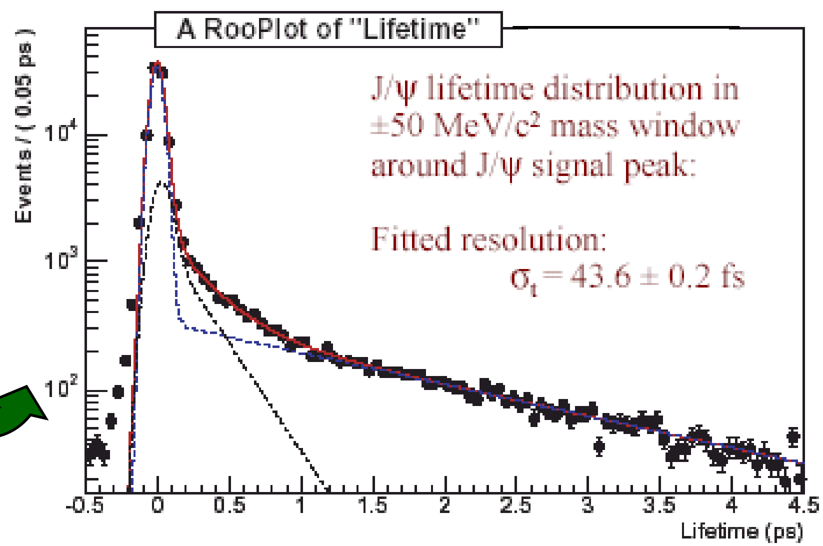
High rate dimuon trigger provides invaluable calibration tool.
Remember, LHCb unbiased dimuon trigger ~ 600 Hz

- Distinctive mass peaks: J/Ψ…, ϒ…, Z…
  → can be used to fix mass scale (muon chambers cover almost full angular and momentum acceptance of LHCb)

- Sample selected ***independent of lifetime*** information will be dominated by prompt J/Ψ and will allow study of IP and proper time resolution in data.

Preliminary study using fully simulated J/Ψ. After offline selection gives ~130 Hz i.e. 10^9 events/$2fb^{-1}$!

$\boxed{\Delta\sigma_t / \sigma_t < 1\%}$



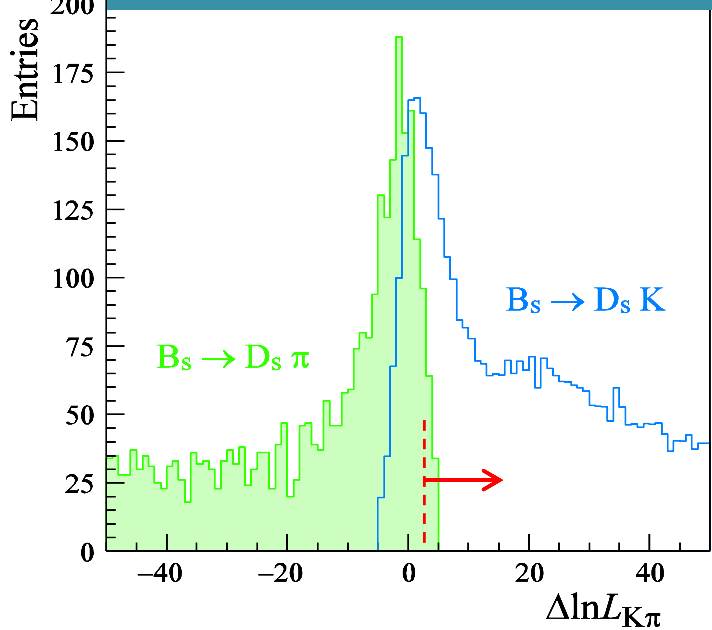
- Overlap with other triggers will allow proper time acceptance to be studied

K/π PID calibration

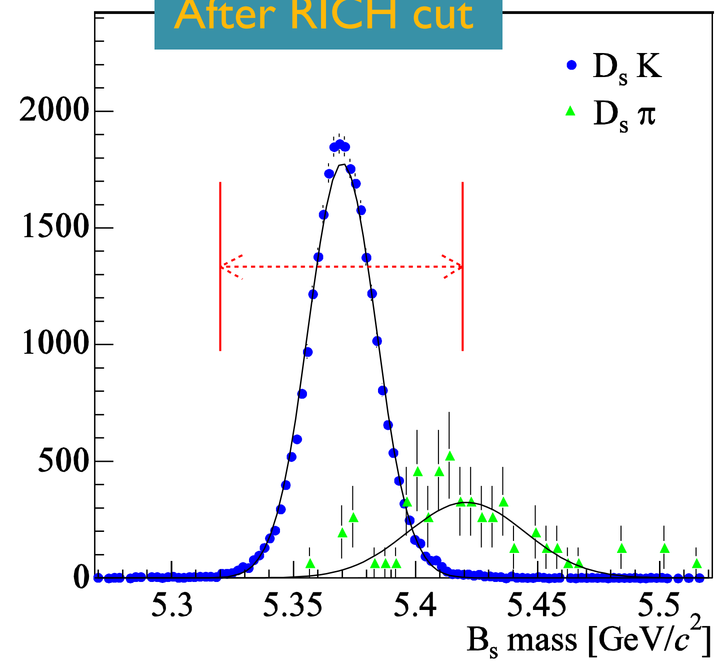
Many rare modes rely on RICH to kill same topology background with $\pi \leftrightarrow K$

Good example: separation of $B_s \to D_s K$ and 10x more abundant $B_s \to D_s \pi$

RICH log likelihood variable



After RICH cut

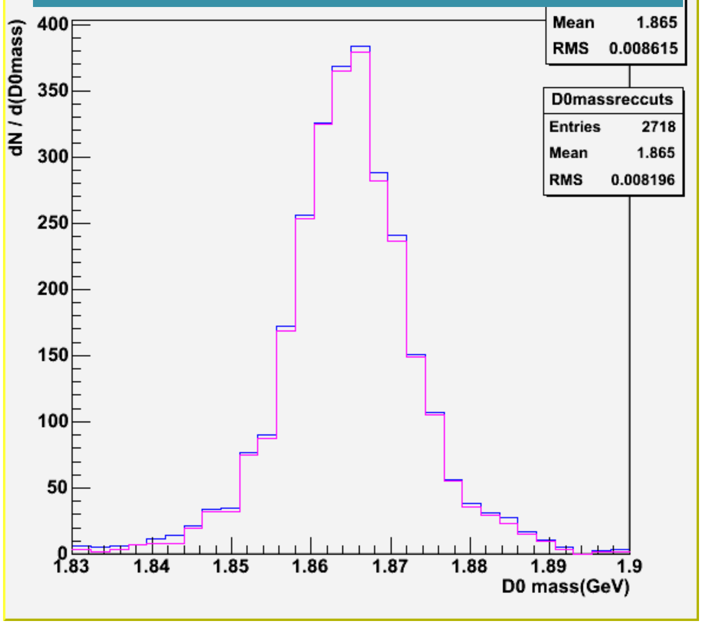


To control residual peaking background, must understand PID very well !

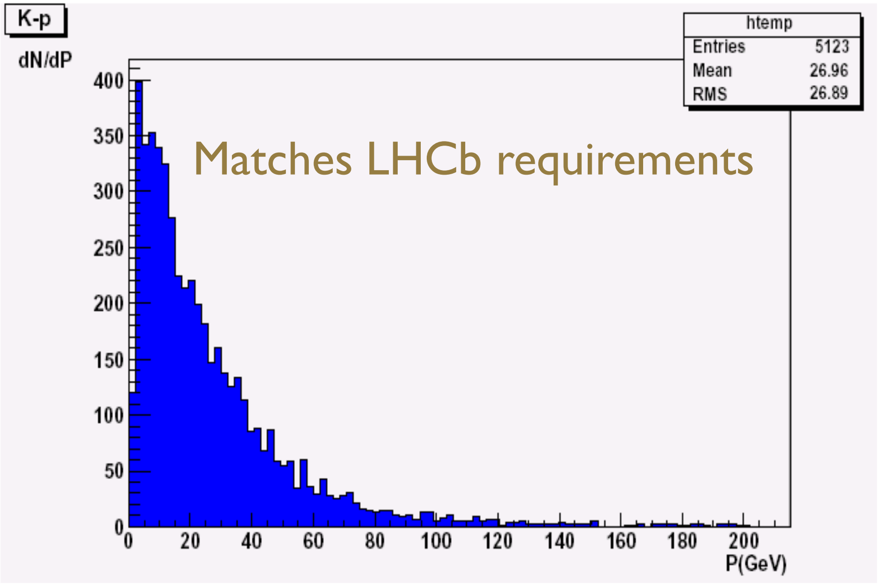
K/π PID calibration

Dedicated D^* selection in LHCb HLT (~300 Hz) will yield very large numbers of D^0 ($K\pi$) events. Possible to achieve very clean samples even without RICH.

D^0 peak in $B \rightarrow D^*\pi$ events



Momentum spectrum of kaons:



Ideal tool for unbiased PID calibration studies with K and π samples. After offline Selection, ~30 Hz, i.e. 300M events/2 fb^{-1}.

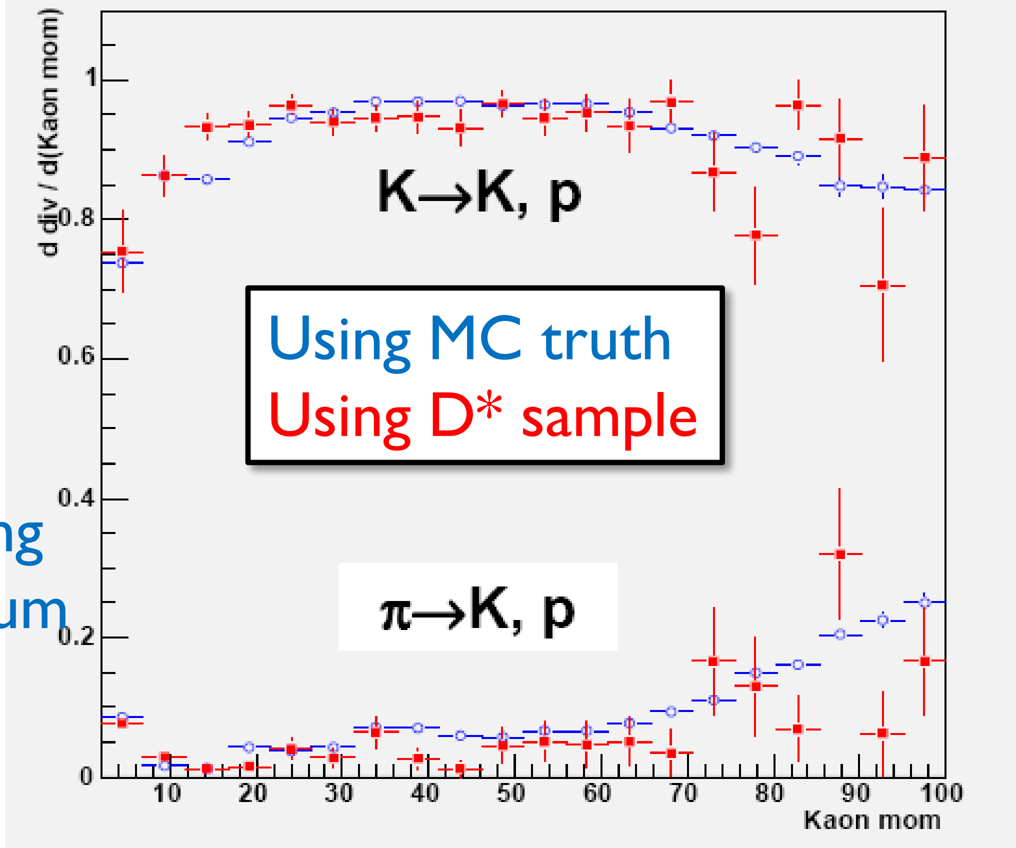
Clean signal peak will also allow for invaluable tracking & vertexing checks.

K/π PID calibration

1M events sufficient to control *global* id/misid scale to 0.1%. 300 M will allow for such understanding in bins of phase-space.

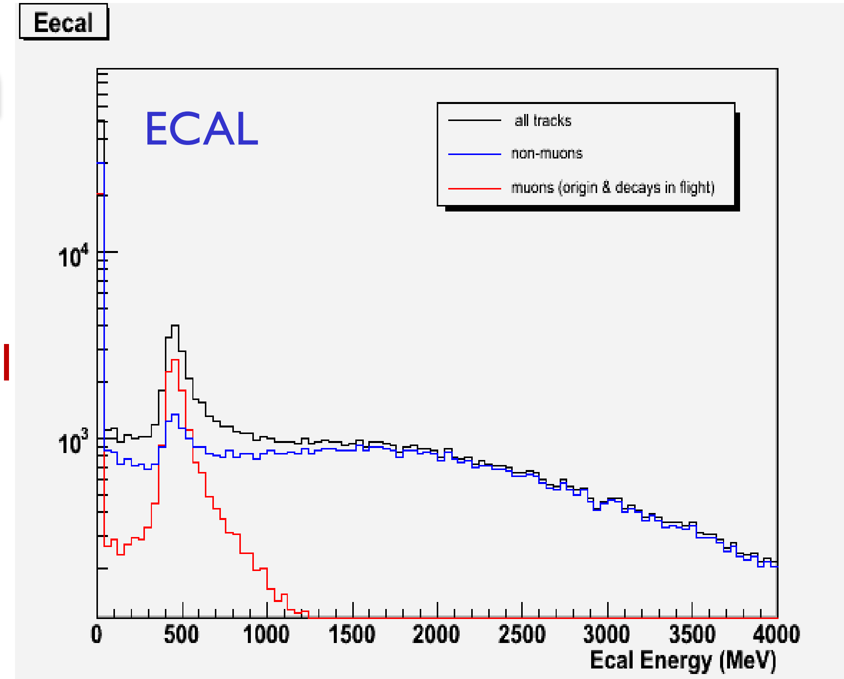
Large statistics allow to map the D* sample into the signal phase space with enough precision.

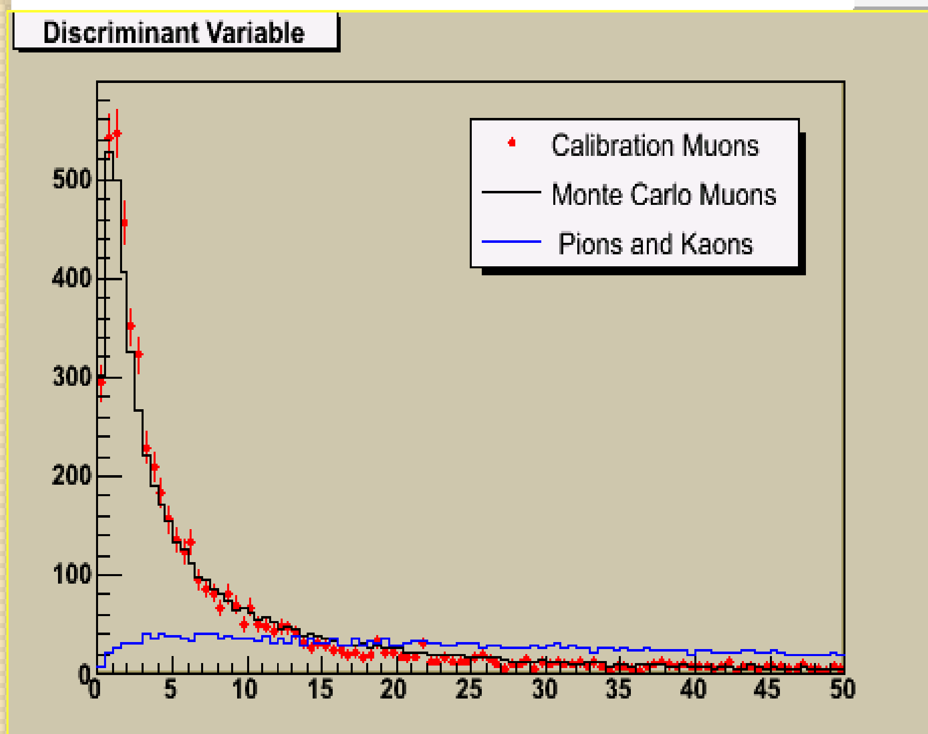
This is important as the PID Probability is a strong function of the momentum and direction of the candidate.



μ PID calibration

Select a pure sample of muons, by selecting MIPs in the Calorimeters + some Kinematic cuts: ~25 Hz of useful tracks for calibration after the LHCb trigger.





The distance of closest hit to track extrapolation (in Pad units) which is used as discriminating variable is well reproduced by calibration muons

Flavour tagging calibration

Knowledge of tagging performance essential ! Mistag rate, ω, enters as first order correction to CP asymmetries: A_{CP} meas = $(1\text{-}2\omega)$ A_{CP} true

Undesirable to use simulation to fix ω. Many things we don't properly know:

- Production mechanisms
  Kinematical correlation between signal and tagging B depends on how $b\bar{b}$ are produced – predictions of relative contribution of various mechanisms (qq, gg, qg…) have significant uncertainties…

- Material effects
  K^+ and K^- interact differently with the material of the detector. This affects tag efficiency and mistag rates.

- Other
  B hadron composition, B decay modelling, PID performance etc etc

Therefore intend to measure performance from data using control channels

Flavour tagging control channels

- **Idea:** accumulate high statistics in flavour-specific modes
- ω can be extracted by:
  - **$B^{\pm}$:** just comparing tagging with observed flavour
  - **B_d and B_s:** fitting known oscillation

	Channel	Yield/ 2 fb^{-1}	$\delta\omega/\omega$ (2fb^{-1})
Similar to signal	$B^+ \to J/\psi(\mu\mu)K^+$	1.7 M	0.4%
	$B^+ \to D^0\pi^+$	0.7 M	0.6%
	$B^0 \to J/\psi(\mu\mu)K^{*0}$	0.7 M	0.6%
	$B_s \to D_s^+ \pi^-$	0.12 M	2%
Semi-leptonics	$B_d^0 \to D^{*-} \mu^+ \nu$	9 M	0.16%
	$B^+ \to D^{0\,(*)} \mu^+ \nu$	3.5 M	0.3%
	$B_s \to D_s^{(*)} \mu^+ \nu$	2 M	1%

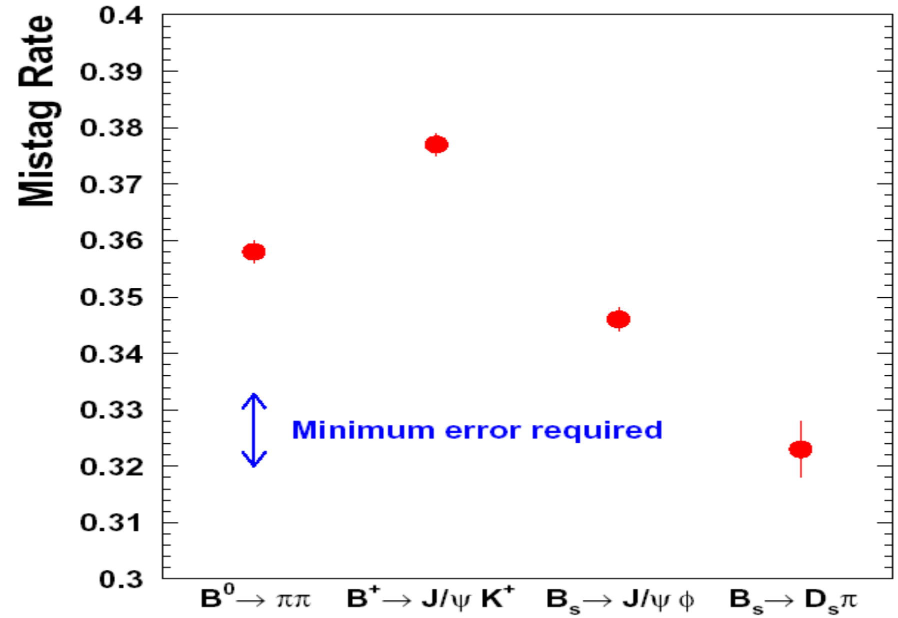
B/S~0.2–0.8

Flavour tagging calibration

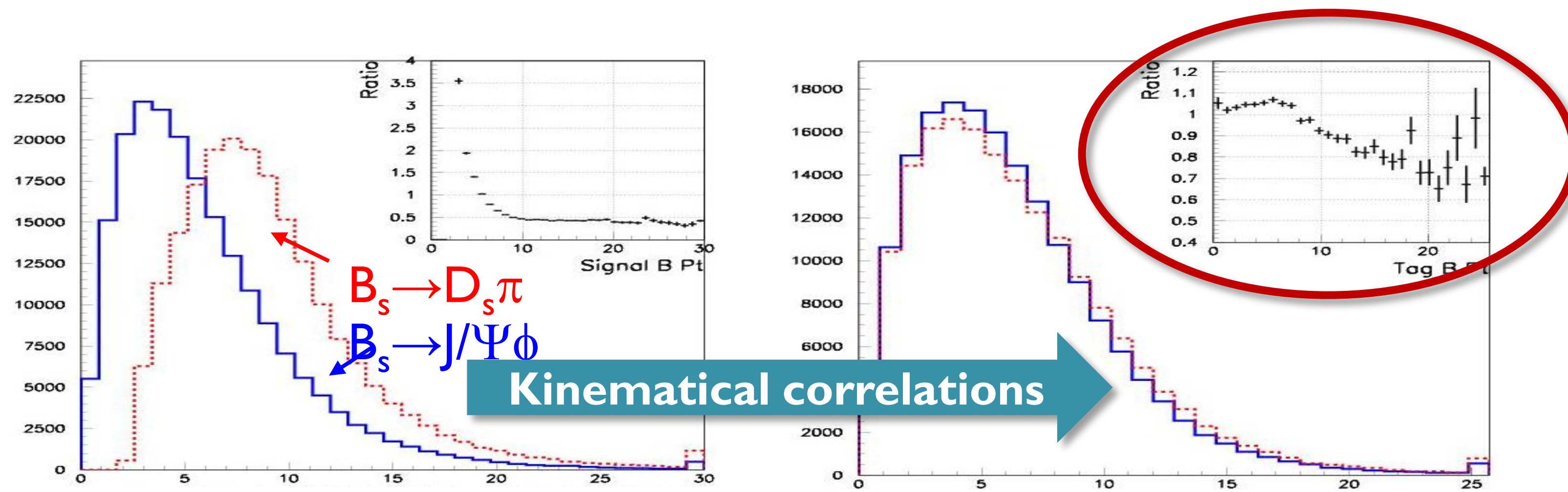
However, the mistag rate is different between different channels, up to ~15%, while the requirement is to know $\Delta\omega/\omega$ < 2% with 2 fb^{-1}

The reason is that trigger and offline selections bias in a different way the phase space of the control and signal channels.

Due to the kinematical correlation between signal B and tagging B this translates into a different tagging power.



In case the trigger object is the tagging B the effect is even more obvious

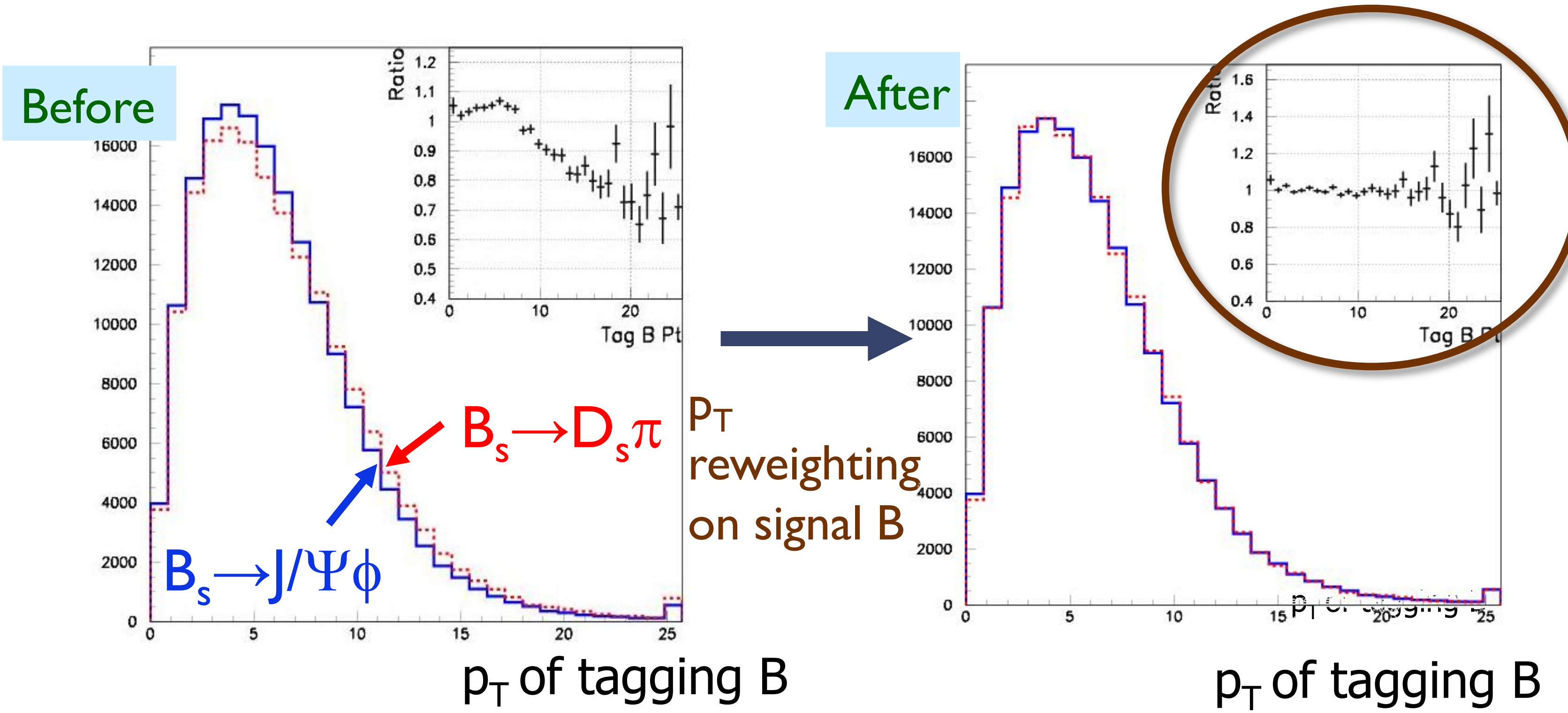


p_T of signal B

p_T of tagging B

Flavour tagging calibration (solution)

1. Split each channel in subsamples according to whether the trigger decision was based on signal or not
2. In each subsample, re-weight the events to get **the same 3-momentum distribution of the signal-B**.
3. Different channels are now comparable!



Control measurements: sin(2β)

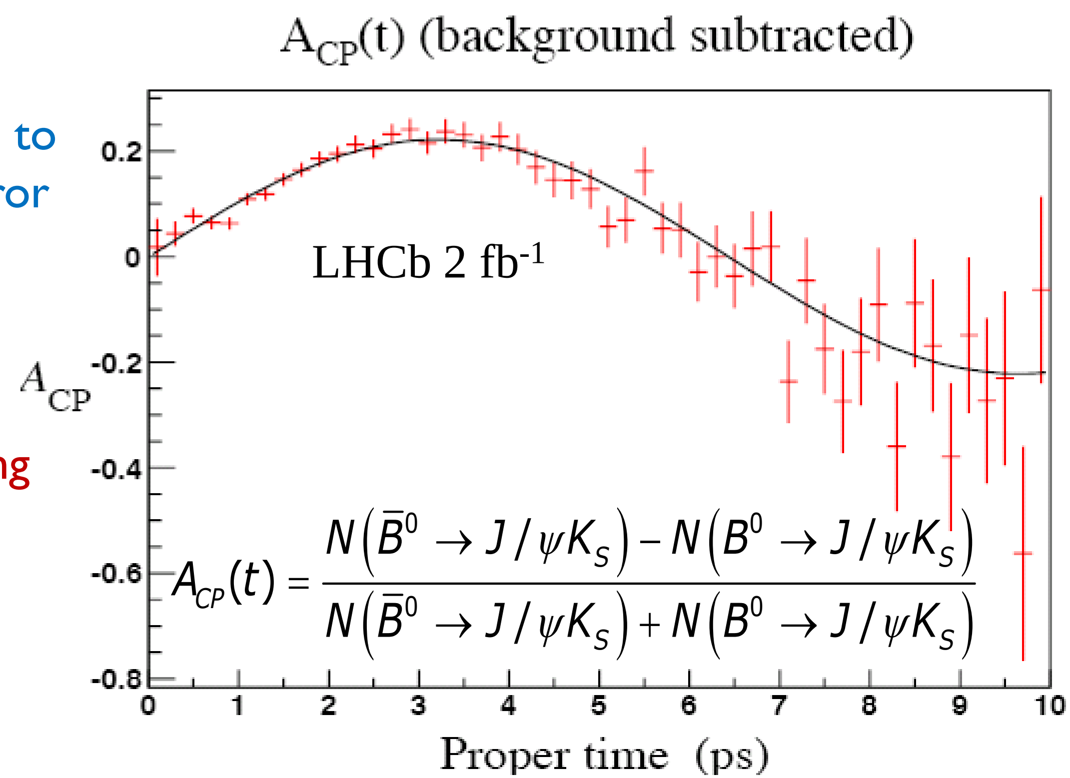
B-factories measurement from $B \to J/\psi\ K_s$: **sin(2β) = 0.67±0.03**

Expected final sensitivity **σ(sin(2β)) = 0.02**

The measurement of sin(2β) in ATLAS/CMS/LHCb will perform a global test of tagging and ability to do CP physics within ~3%.

For instance, LHCb expects to measure sin(2β) with an error of ~0.02 already with 2 fb^{-1}

Can also push further the search for direct CP violating term $\propto \cos(\Delta m_d\ t)$

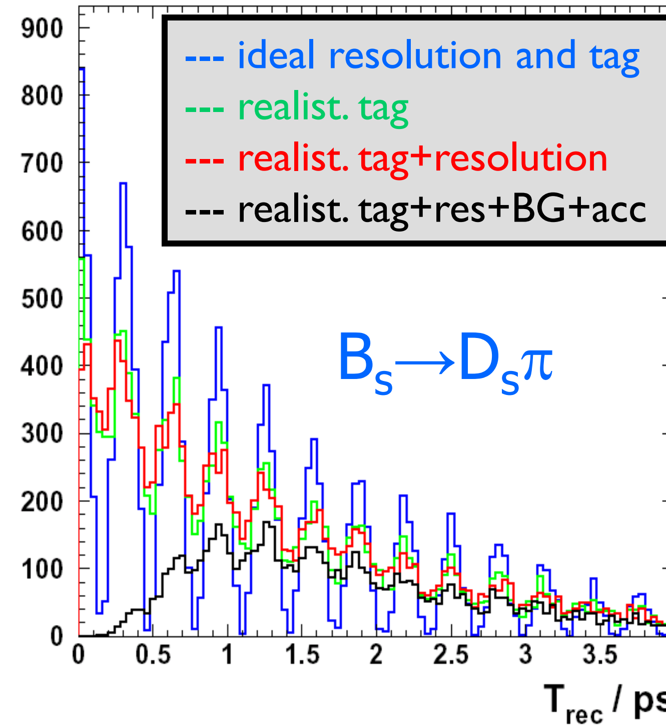


Control measurements: Δm_s

- Measurement of Δm_s:
  - CDF observed B_s oscillations in 2006 : $\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$ compatible with the SM expectation

$B_s \rightarrow D_s\ \pi$

	ATLAS ($10fb^{-1}$)	LHCb ($2\ fb^{-1}$)
$\sigma(\tau)$[fs]	~110	40
$\sigma(M(B_s))$[MeV]	43	14
$N(D_s\pi)$	2.7k	120k
B/S	<1	0.4



LHCb $\sigma_{stat}(\Delta m_s) = \pm\ 0.007\ ps^{-1}$, *i.e.* 0.04% with 2 fb^{-1}

hence, it will test the proper time scale better than from the control channels!

$\Rightarrow$**interesting physics result AND a proof that**

- the tagging of the B production state can be controlled

- a precise proper time measurement can be performed

in the LHC environment

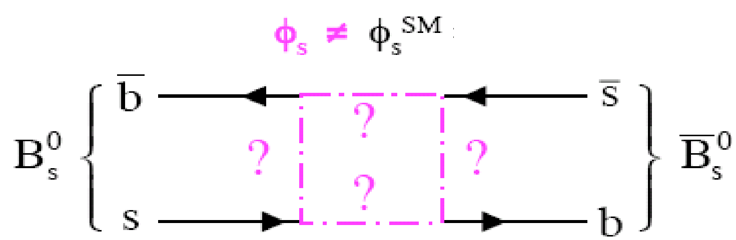
Outlook and Conclusions

Conclusions

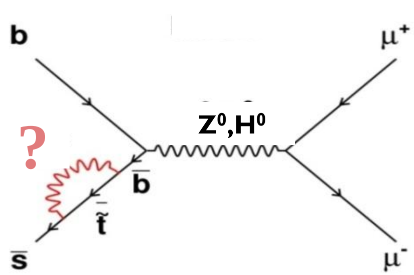
- LHC is a superb B-factory (100-1000 kHz), of all types including Bs, coming online next year.

- The B-physics program will certainly contribute significantly to the overall LHC effort to find and study Physics beyond the SM.

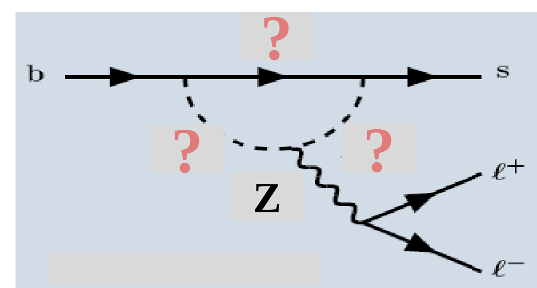
- A few highly-sensitive b→s observables are accessible from the very first data (reserve your place at the Physics Conferences in 2009):



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



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



$B \rightarrow K^*\mu^+\mu^-$ Z "Penguin"

Conclusions

- LHCb will pursue the program and improve precision of CKM angles.
  - Several γ measurements from tree decays only: **$\sigma(\gamma)$~2.4°** may reveal inconsistencies in the CKM picture.

- LHC experiments will soon face reality: background levels may be higher than expected, resolution worse, etc...
  - But once we have data, previous experience has shown that we learn how to deal with difficulties: CESAR, DORIS, LEP. TEVATRON, PEP-II and KEKB they all produced heavy flavour physics results beyond the original expectations.