Prospects for new physics in rare decays, mixing and related CP violation at LHCb

1. Motivation
2. The LHCb detector
3. Selected key measurements on
   - Mixing and CP-violation
   - Rare decays

Symposium on hadron collider physics

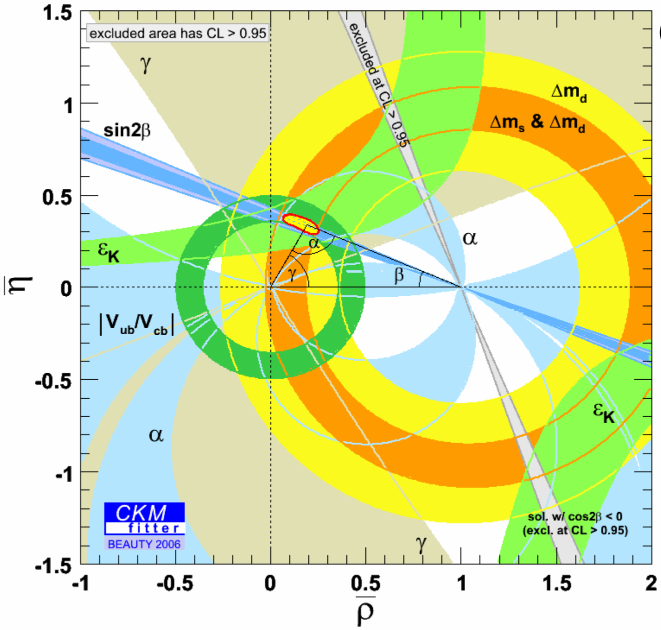
Isola d'Elba, 21-25 May 2007

Sebastian Bachmann

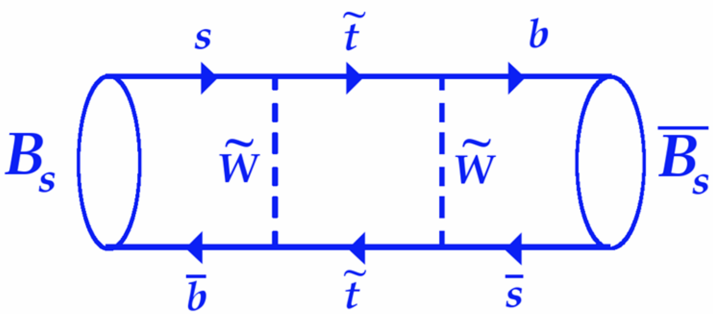
University of Heidelberg/CERN

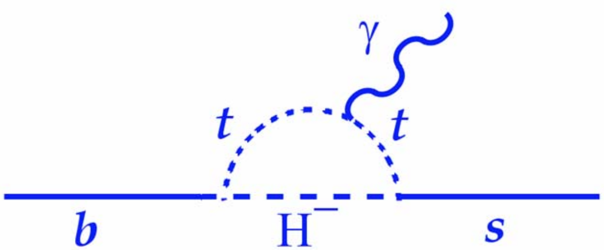
Motivation

A lot of precise measurements are available from B-factories and Tevatron to test the CKM picture of flavour structure and CP violation.



(from CKM-fitter)





However it is expected that New Physics is accessible from box and/or loop diagrams.

LHCb aims to find New Physics contributions in these processes.

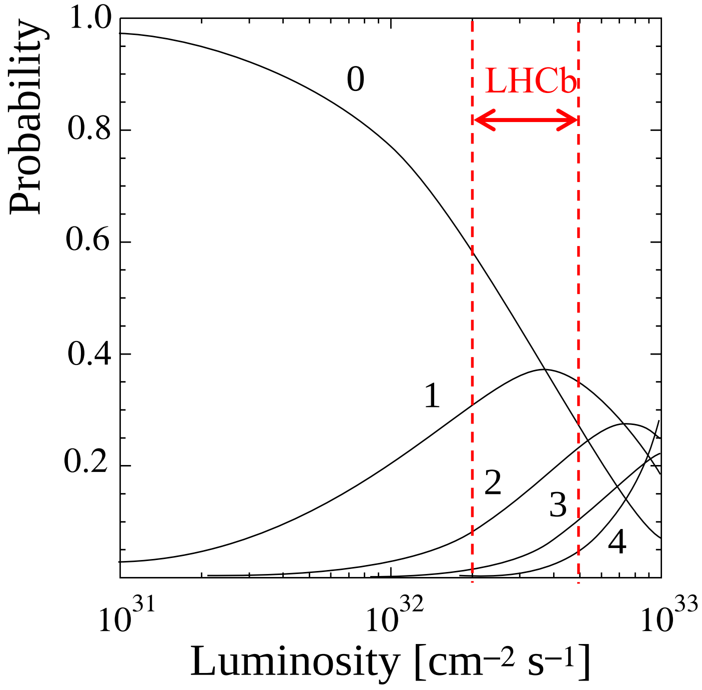
What do we get from LHC?

- bb cross section: 500μb +

  LHCb luminosity ~ 2-5 • 10^{32} cm^{-2} s^{-1}

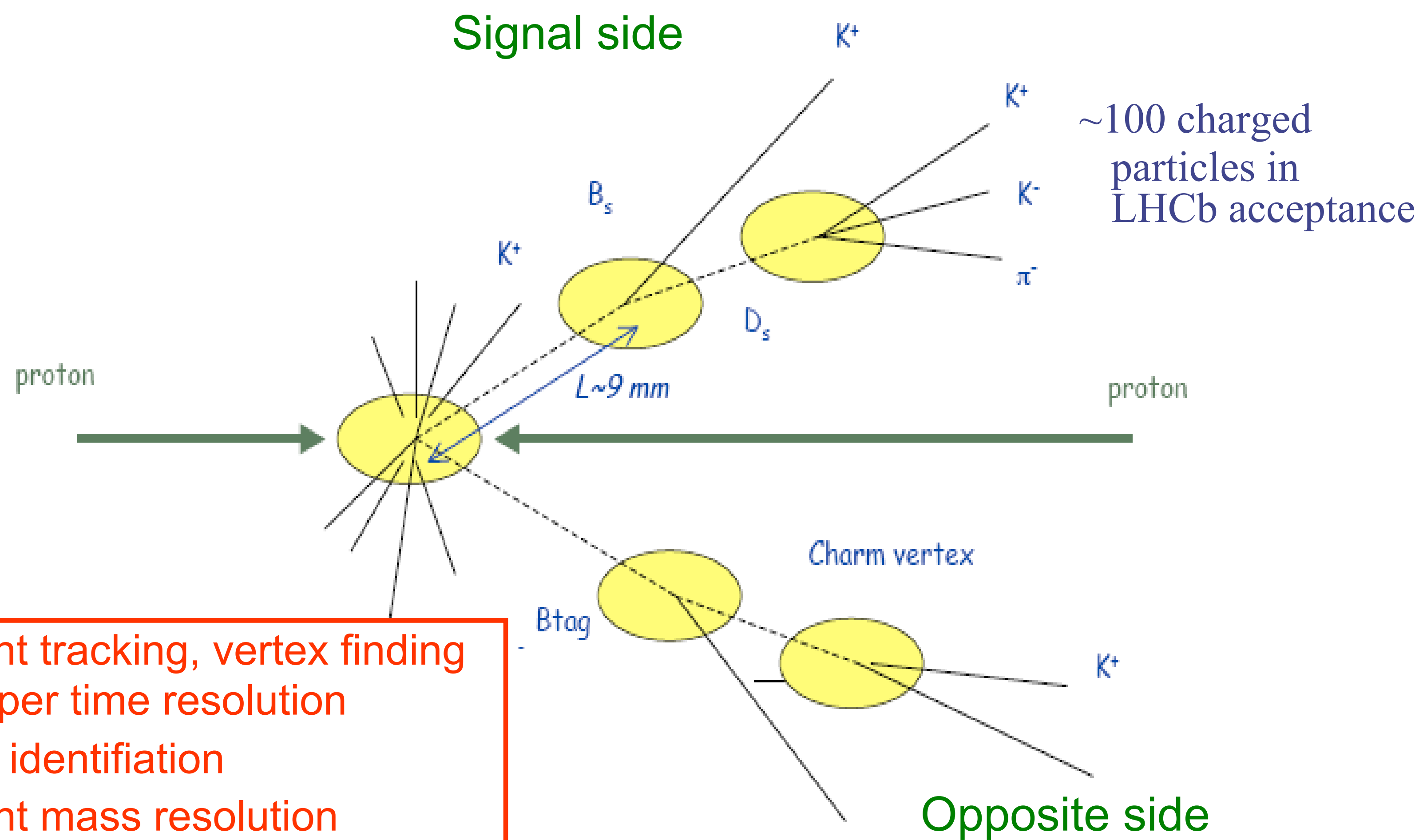
  b-production rate ~100kHz

Inelastic pp collisions/crossing:
For LHCb mainly single interactions



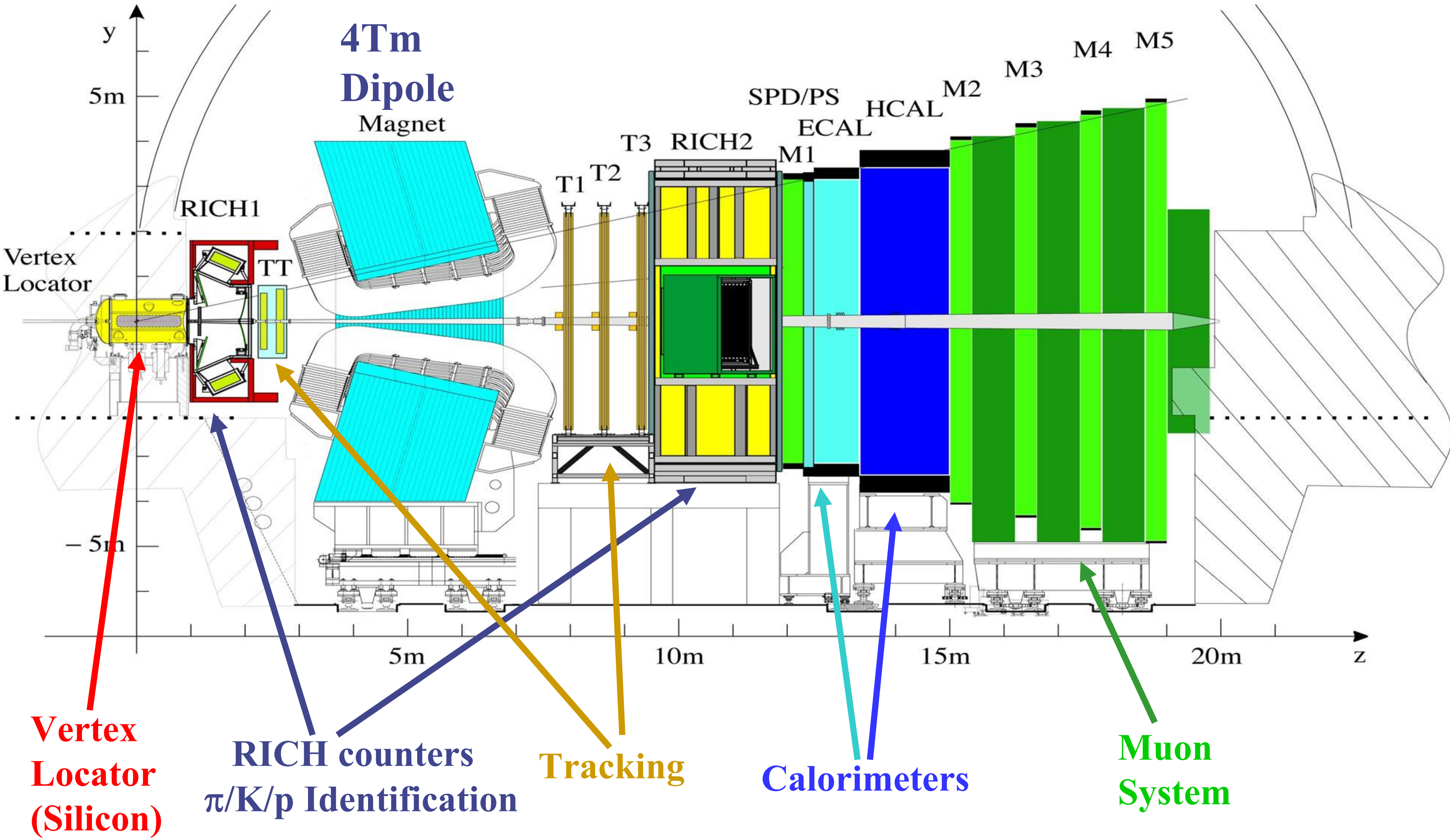
One year of nominal data taking corresponds to 2fb^{-1}

A signal event: $B_s \rightarrow D_s^-(K^+K^-\pi^-)K^+$

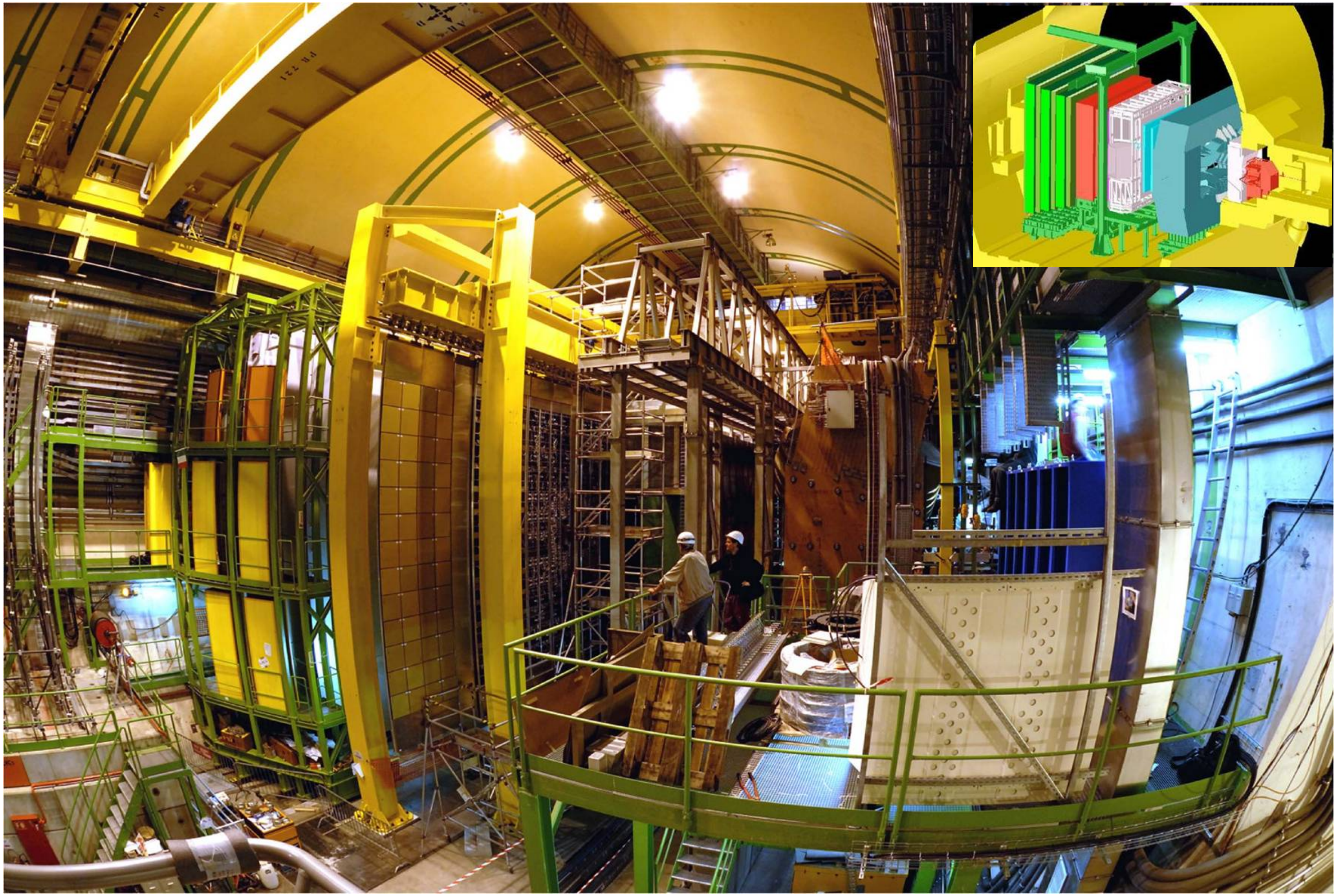


- Excellent tracking, vertex finding and proper time resolution
- Particle identifiation
- Excellent mass resolution
- Trigger including
  - low cuts on p_t
  - fully hadronic trigger
- Flavour tagging

LHCb detector

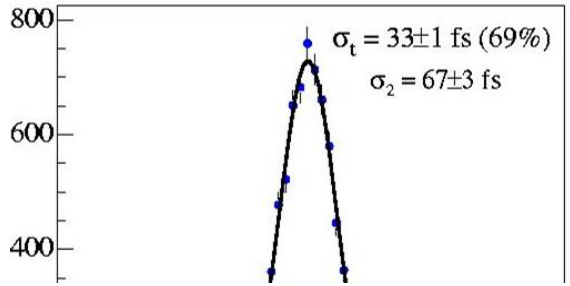


LHCb detector in place



LHCb performance:

Proper time resolution:



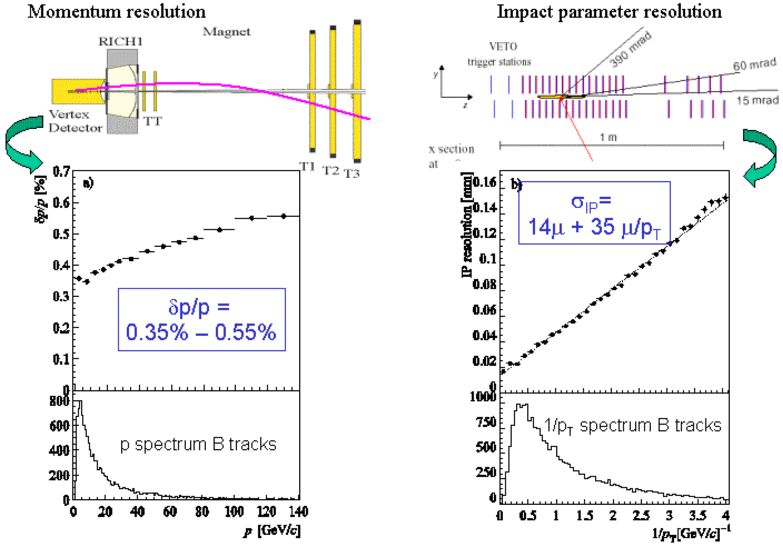
<u>LHCb:</u>

~ 40 fs for ($B_s \to D_s^- \pi^+$)

<u>CDF:</u>

87fs for fully reco decays.

PRL 242003 (200



π-K separation

Momentum resolution:

B_s-mixing

and

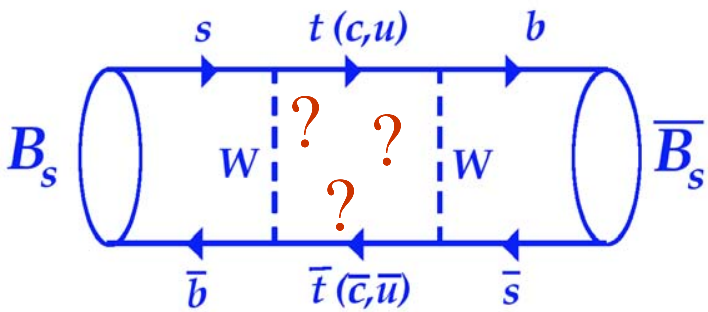
related CP-asymmetries

NP from mixing and CP-asymmetries

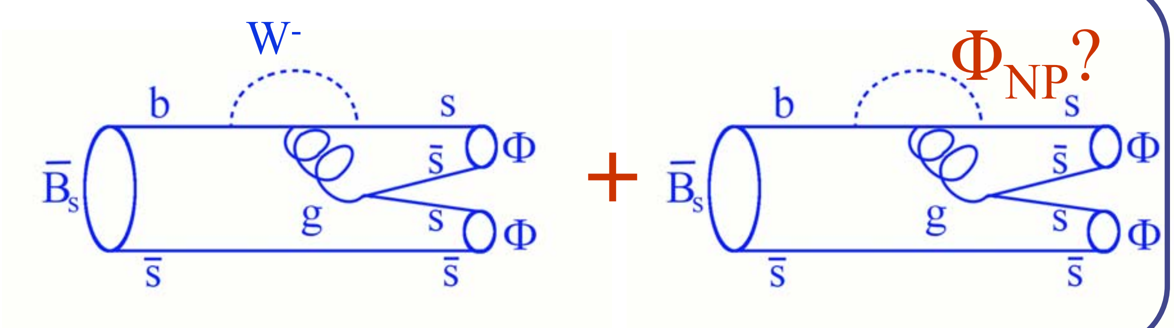
$B_s \to D_s^- \pi^+$:
Precise measurement of Δm_s using $B_s \to D_s^+ \pi^-$.

- CDF: $\Delta m_s = (17.77 \pm 0.1^{stat} \pm 0.07^{syst})\ ps^{-1}$
- LHCb: Observation expected after few month data taking at nominal luminosity

$B_s \to J/\psi\Phi$:
Extract Φ_s and $\Delta\Gamma_s$ in golden mode $B_s \to J/\psi\Phi$.
(NP → contribution to box diagram)

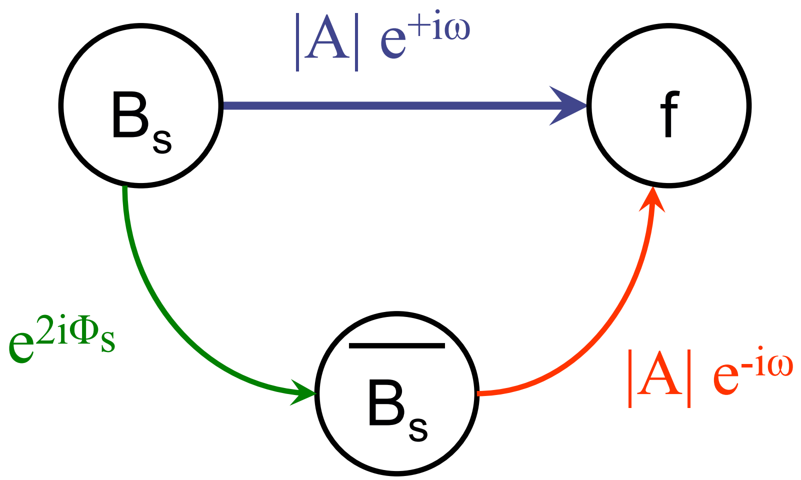


$B_s \to \Phi\Phi$:
Measure hadronic penguin $B_s \to \Phi\Phi$.
(NP → contribution to decay mode?)



CP-violation in the B_s-system

Decay into a final state f
with $CP\, f \rightarrow \eta_f\, f$
(assume only one amplitude contributes to decay)



CP-asymmetry:

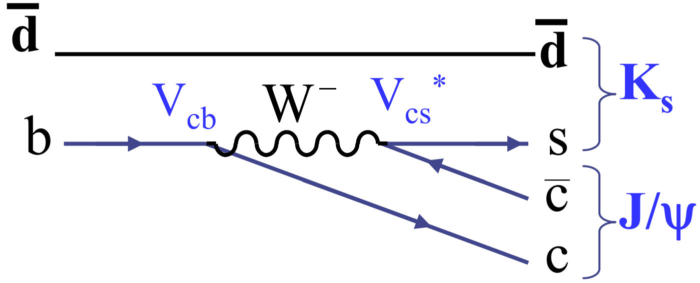
$$A_{CP}(t) = \frac{\Gamma(\overline{B_s^0}(t)\rightarrow f_{CP}) - \Gamma(B_s^0(t)\rightarrow f_{CP})}{\Gamma(\overline{B_s^0}(t)\rightarrow f_{CP}) + \Gamma(B_s^0(t)\rightarrow f_{CP})}$$

$$= -\frac{\eta_f \sin(\phi_s - 2\omega)\sin(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \eta_f \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)}$$

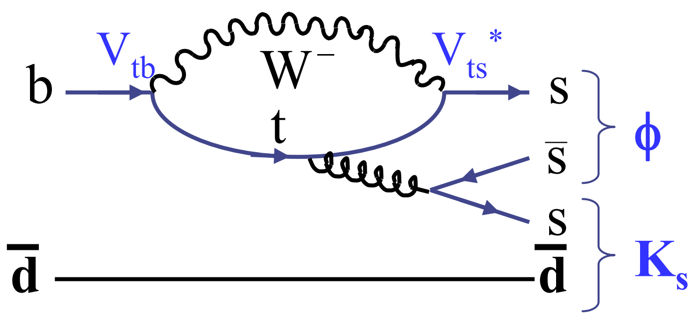
For $B_s \rightarrow J/\psi\phi$:
$\omega \approx 0$

NP by Tree↔Penguin comparison

B_d-system:



Tree



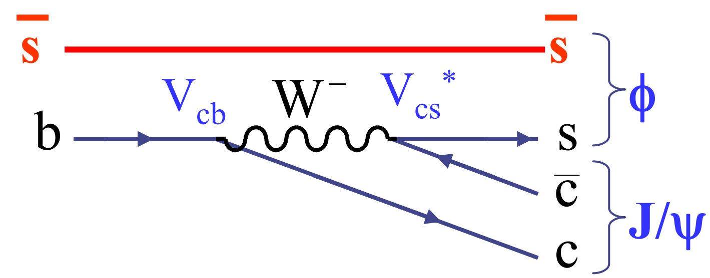
Penguin

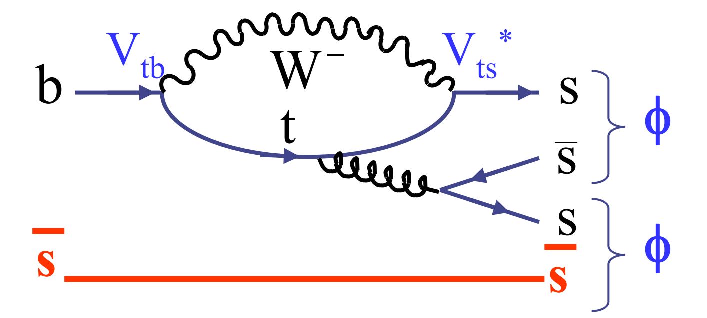
Φ_d(tree)-Φ_d(penguin) = $\boldsymbol{\delta\Phi_d}$**(NP)**

B-factories:

Currently: $\delta\beta = 8^o$ (2.6σ)

B_s-system:





Φ_s(tree)-Φ_s(penguin) = $\boldsymbol{\delta\Phi_s}$**(NP)**

And:

Φ_s(SM) small!

Φ_s and $\Delta\Gamma_s$

In the SM:

$$\phi_s = 2\arg[V_{tb}^{*}V_{ts}] = -0.04\text{rad}$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.12 \pm 0.06$$

Phys.Rev.D63 114015(2001)

If new physics contributes to B_s mixing:

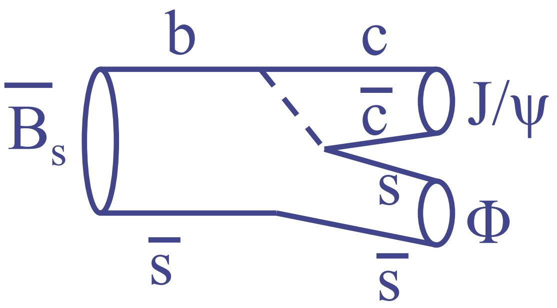
$$\phi_s \rightarrow \phi_s + \phi_{NP}$$

$$\Delta\Gamma_s \rightarrow \Delta\Gamma_s \cos(\phi_s)$$

Any sizeable CP violation in $B_s \rightarrow J/\psi\Phi$ or $B_s \rightarrow \Phi\Phi$ is a clear sign for NP!

$B_s \rightarrow J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$

<u>Advantages:</u> High branching ratio
Good experimental signature



$J^{PC}=1^{--}$

$J^{PC}=1^{--}$

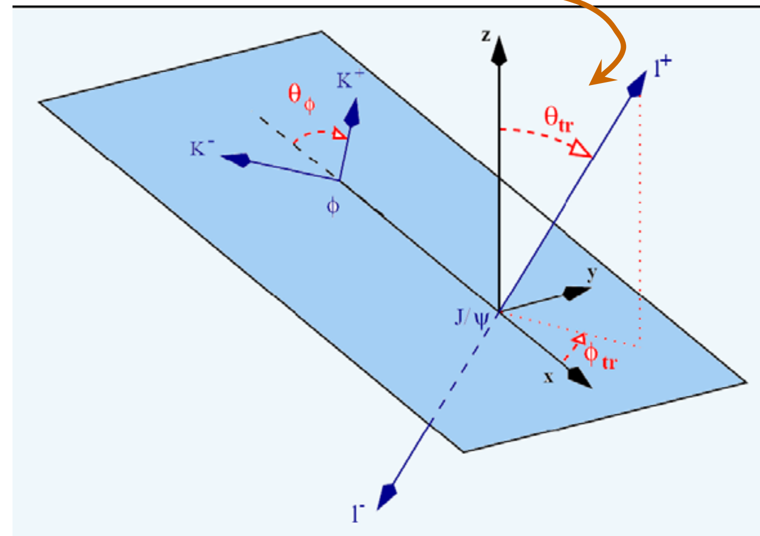
$CP(J/\psi\phi) = CP(J/\psi)\ CP(\phi)\ (-1)^L$

⇨ L=0, 2: CP even
L=1: CP odd
} Final state is a mixture of CP even/odd

⇨ Angular analysis needed to identify CP even and CP odd states!

$B_s \to J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$

Use angle θ_{tr} between μ^+ and normal of ϕ decay plane:



$$\frac{d\Gamma}{d\cos\Theta_{tr}} \propto \left(|A_0(t)|^2 + |A_2(t)|^2\right)\frac{3}{8}\left(1+\cos^2\Theta_{tr}\right) + |A_1(t)|^2\,\frac{3}{4}\sin^2\Theta_{tr}$$

$$|A_{0,2}(t)|^2 = |A_{0,2}(0)|^2\left(e^{\Gamma_L t} - e^{\overline{\Gamma} t}\sin(\Phi_s)\sin(\Delta m_s t)\right)$$

$$|A_1(t)|^2 = |A_1(0)|^2\left(e^{\Gamma_L t} + e^{\overline{\Gamma} t}\sin(\Phi_s)\sin(\Delta m_s t)\right)$$

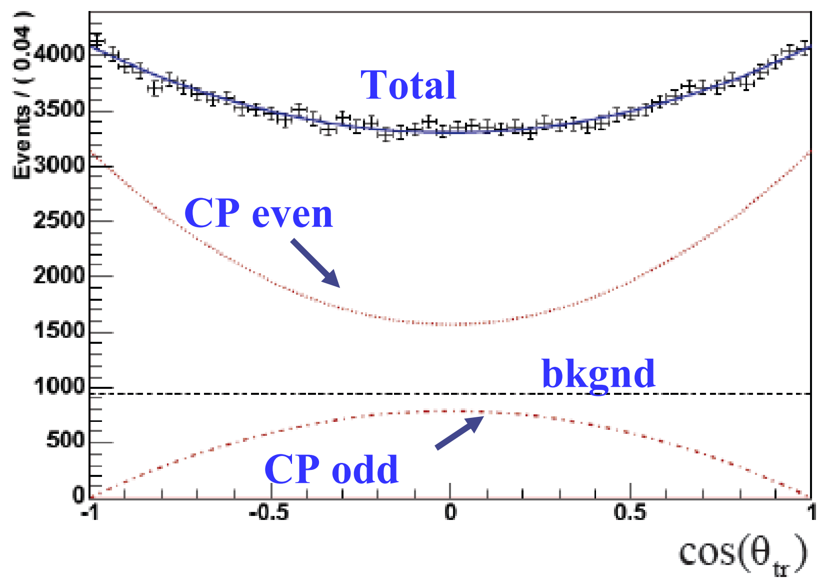
CP-odd fraction:

$$R_T \equiv \frac{|A_\perp(t)|^2}{\sum_{f=0,\|,\perp}|A_f(t)|^2}$$

$R_T(t=0)$ ~20% (CDF, D0)

$R_T = 0 \to$ CP even

$R_T = 0.5 \to$ Maximum dilution

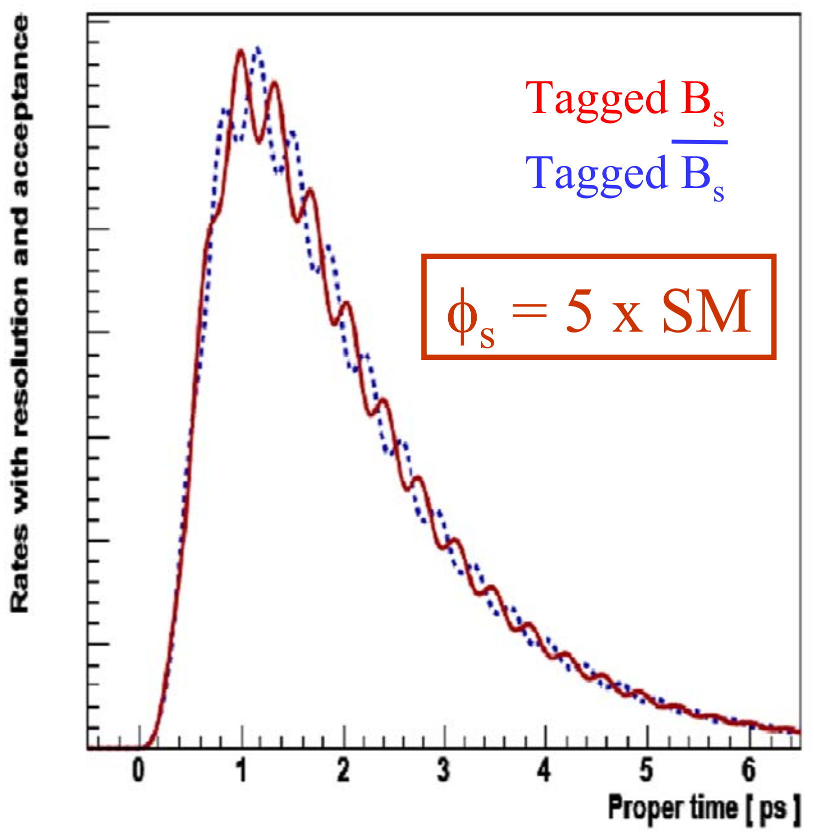


Selection and signal decay rate

- Yield: 130k events per $2fb^{-1}$
- B/S: 0.12
- $<\delta_t>$: 36 fs
- σ_{Mass}: 14 Mev/c^2
- w_{tag}: 33%
- ε_{tag}: 57%

<u>Signal decay rates including:</u>

- Trigger and selection bias on τ
- Background parametrization
- Mass resolution
- Proper time resolution
- Tagging efficiency and dilution
- Transversity angle distribution



Projection for Φ_s and $\Delta\Gamma_s$ with 2fb^{-1}

Parameter	Exp. error	Channel
ϕ_s	0.023 rad	$B_s \rightarrow J/\psi(\mu^+\mu^-)\ \Phi(K^+K^-)$
$\Delta\Gamma/\Gamma$	0.0092	$B_s \rightarrow J/\psi(\mu^+\mu^-)\ \Phi(K^+K^-)$
Δm_s	0.007 ps^{-1}	$B_s \rightarrow D_s^-(K^+K^-\ \pi^-)\pi^+$
w_{tag}	0.0036	$B_s \rightarrow D_s^-(K^+K^-\ \pi^-)\pi^+$

} Control channel only

Sensitivity can be improved by adding more channels.
Using $B_s \rightarrow J/\psi\eta$, $B_s \rightarrow \eta_C\phi$, $B_s \rightarrow D_sD_s$ gives σ_Φ=0.021 rad.

CP-Eigenstates

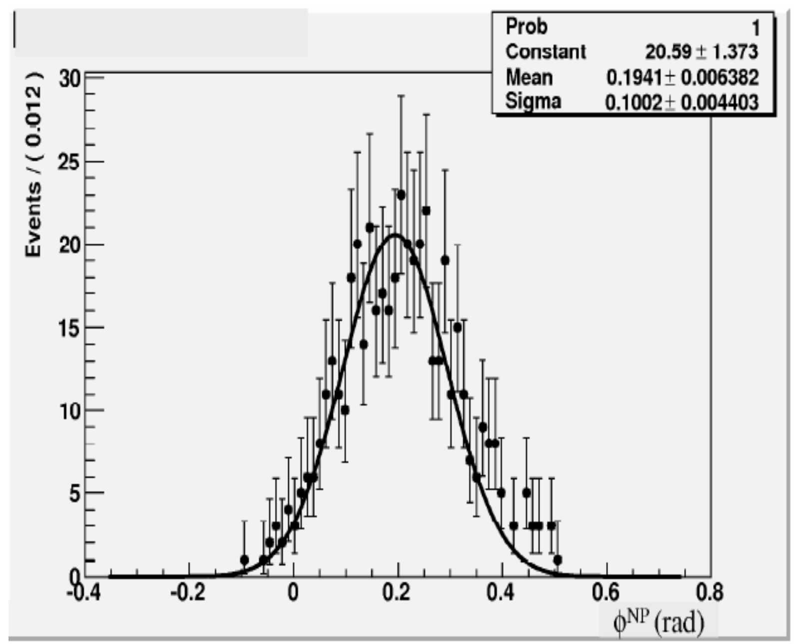
$B_s \to \phi\phi$: Sensitvity to ϕ_s

LHCb profits from excellent PID and hadronic trigger!

- Expected yield: 4000 events per $2fb^{-1}$
- BG estimate limited by MC statistics: 0.4<B/S<2.1 at 90%CL

- Sensitivity to ϕ_s is 0.1rad at 2 fb^{-1}.
- No significant variation as a function of input ϕ_s, R_t and proper time resolution.

Distribution from 500 MC experiments:



Baseline physics inputs (varied for robustness) to sensitivity studies:

$\phi^{NP} = 0.2$	$R_t = \|A_\perp\|^2 / \left(\|A_\perp\|^2 + \|A_0\|^2 + \|A_{//}\|^2\right) = 0.25$
$\delta_{//} = 0, \delta_0 = \pi$	$R_p = \|A_{//}\|^2 / \left(\|A_\perp\|^2 + \|A_0\|^2 + \|A_{//}\|^2\right) = 0.25$
$\Gamma_s = 0.67\ \text{ps}^{-1}, \Delta m_s = 17\ \text{ps}^{-1}$	$R_{p,t}$ values motivated by polarisation
$\Delta\Gamma_s / \Gamma_s = 15\%$	measurements of $B^0 \to \phi K^{*0}$

Rare decays

Decay	Sensitivity to	Example for model
1. $B_{d,s} \rightarrow \mu^+\mu^-$	- large tanβ	CMSSM
2. $B_d \rightarrow K^{*0}\mu\mu$	- small tanβ - right handed currents	non-MFV MSSM MIA MSSM SUGRA
3. $B_u \rightarrow K^+ll$ (in combination with 1.)	- no right handed currents - (pseudo-)scalar couplings	MFV

1. $B_{d,s} \rightarrow \mu^+\mu^-$

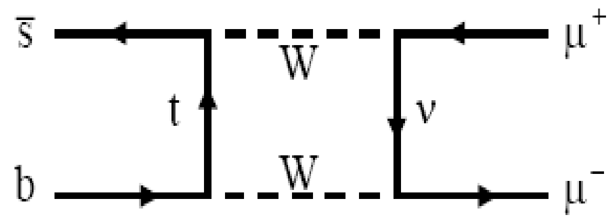
<u>SM expectation:</u>

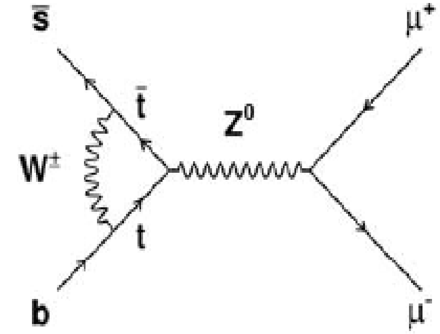
$BR(B_s \rightarrow \mu^+\mu^-) = (3.4 \pm 0.4) \times 10^{-9}$

$BR(B_d \rightarrow \mu^+\mu^-) = (1.0 \pm 0.5) \times 10^{-10}$

World best limit by D0:

$BR(B_s \rightarrow \mu^+\mu^-) < 7.5 \times 10^{-8}$ @90%CL

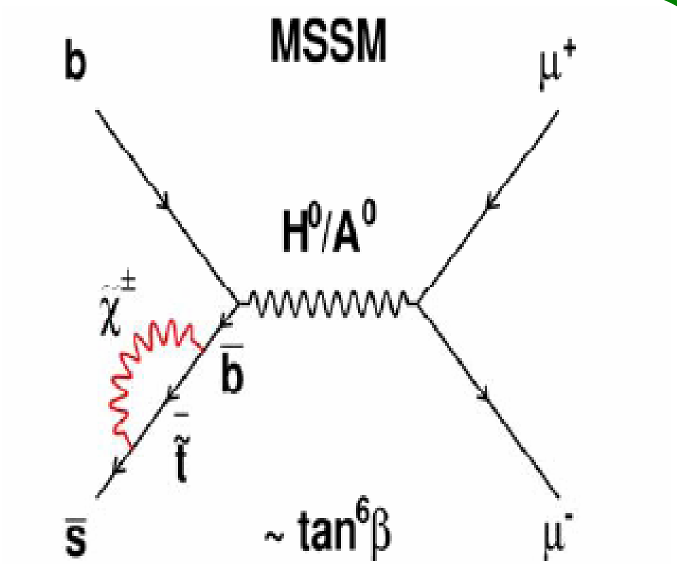




<u>In Supersymmetry:</u>

Large contributions e.g. by Higgs penguins $\sim \tan^6\beta$, i.e.

$BR(B_{d,s} \rightarrow \mu^+\mu^-)$ is very sensitive to high values of $\tan\beta$.

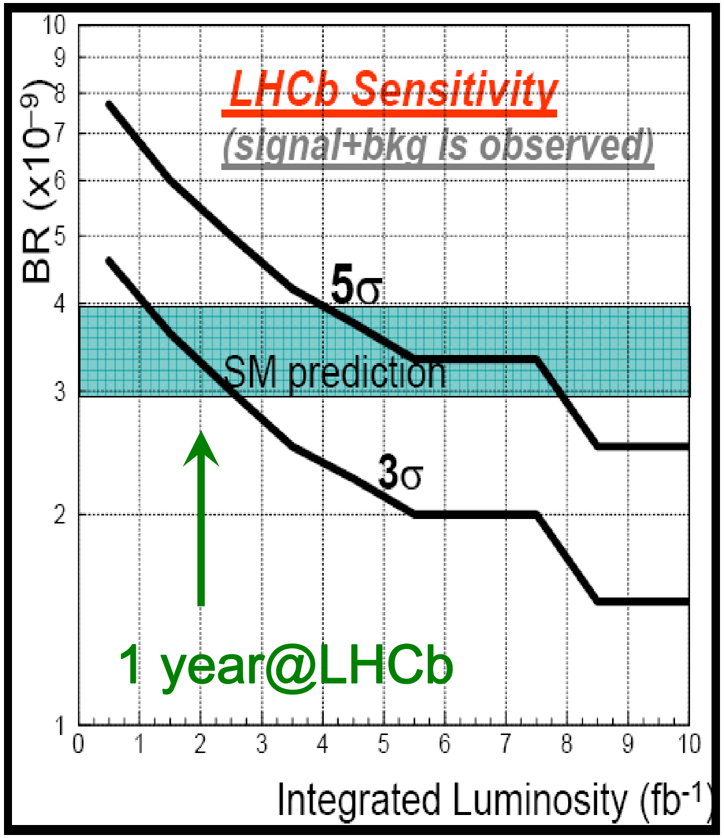


Sensitivity by LHCb

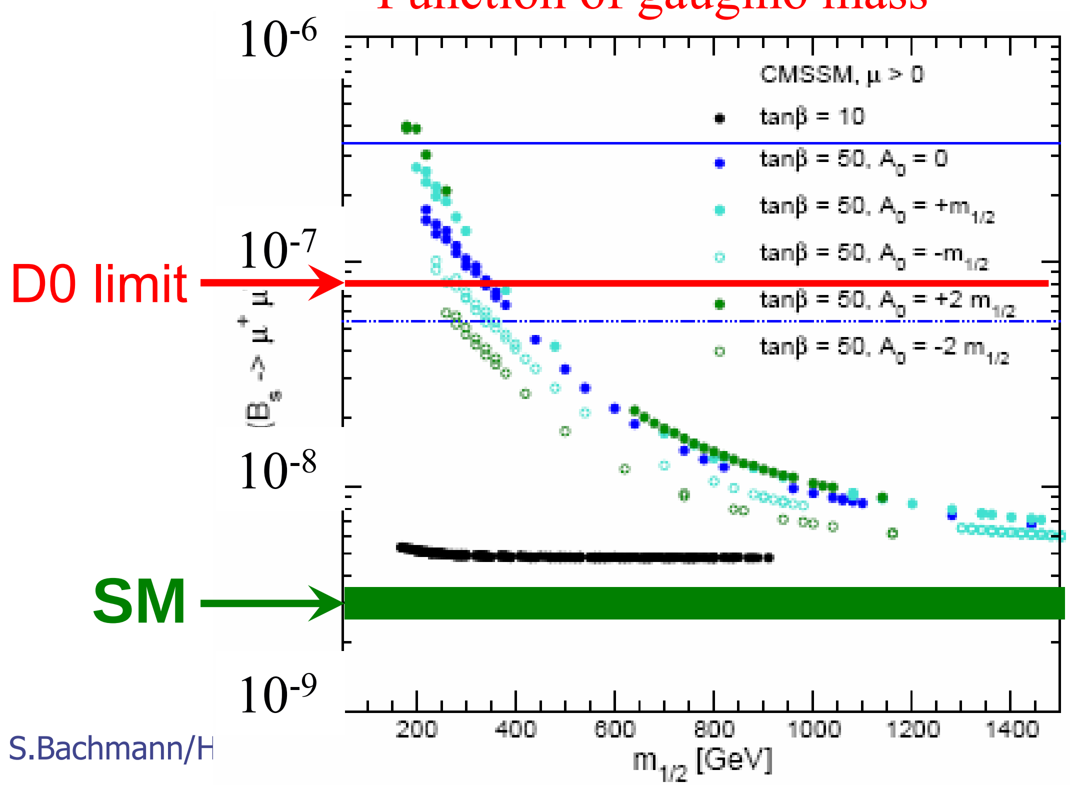
Main background:

- Combinatoric $b\rightarrow\mu$, $b\rightarrow\mu$
- $B_c^{\pm} \rightarrow J/\psi(\mu^+\mu^-)\mu^{\pm}\nu$
- $B_{d,s}\rightarrow h^+h^-$

Adressed by excellent mass resolution (18MeV), vertex resolution and particle ID

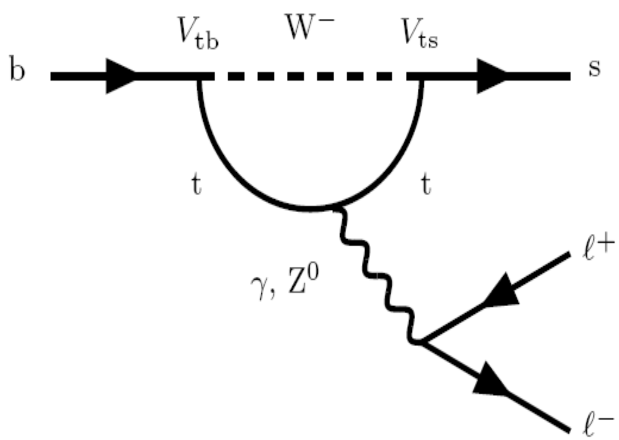


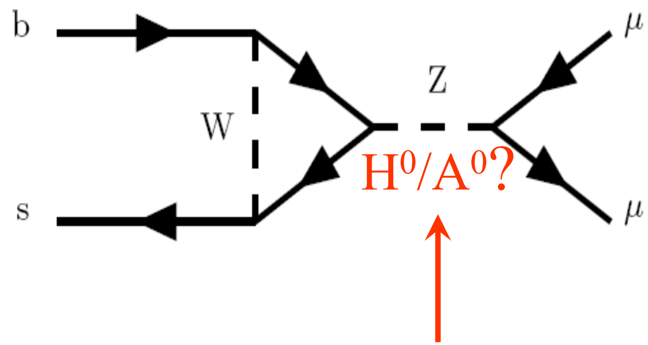
BR($B_s\rightarrow\mu^+\mu^-$) in CMSSM as a Function of gaugino mass



S.Bachmann/H

3.) $B_u^+ \to K^+ ll$





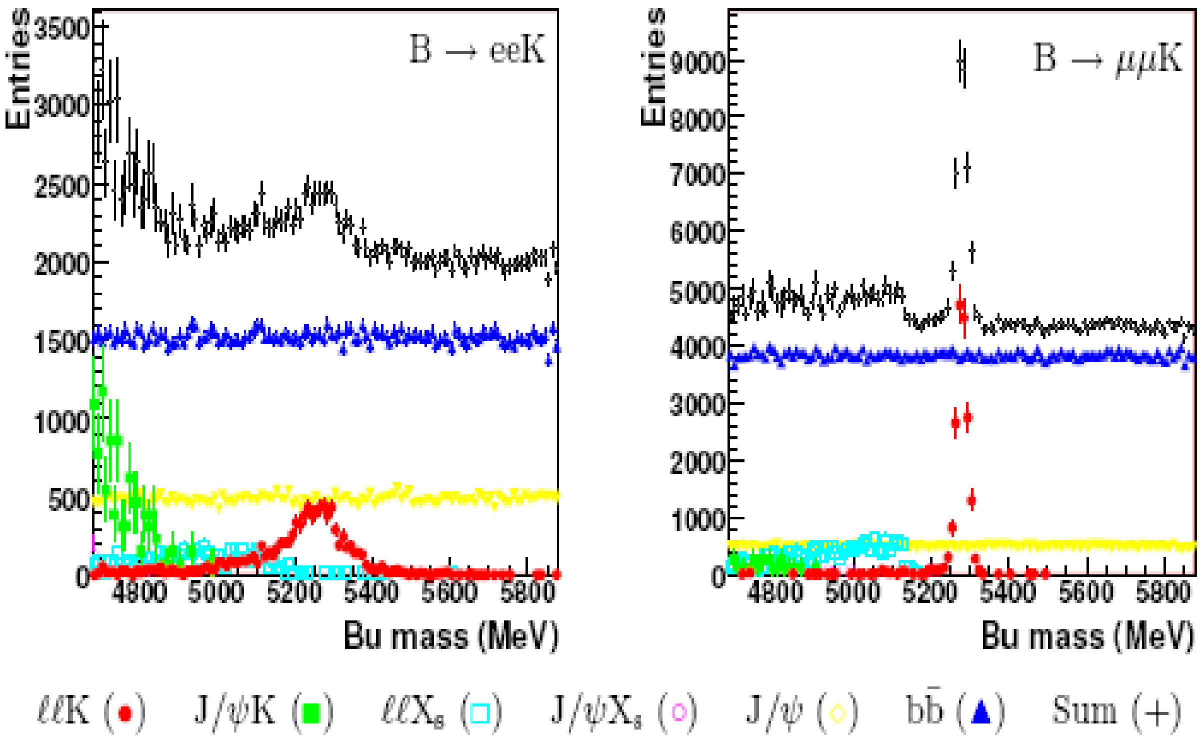
SM prediction can get corrections of ~10% by neutral Higgs boson exchange due to couplings ~ m_l

Use the ratio

$$R_{\mathbf{X}} = \frac{\int_{4m_\mu^2}^{q^2_{\text{max}}} \mathrm{d}s \frac{d\Gamma(\mathbf{B}\to\mathbf{X}\mu^+\mu^-)}{\mathrm{d}s}}{\int_{4m_\mu^2}^{q^2_{\text{max}}} \mathrm{d}s \frac{d\Gamma(\mathbf{B}\to\mathbf{X}\mathrm{e}^+\mathrm{e}^-)}{\mathrm{d}s}} \overset{\text{SM}}{=} \begin{cases} 1.000 \pm 0.001 & \mathbf{X} = \mathbf{K} \\ 0.991 \pm 0.002 & \mathbf{X} = \mathbf{K}^* \end{cases}$$

Hiller & Krüger, PRD69 (2004) 074020)

$B_u^+ \rightarrow K^+ ll$ with $2fb^{-1}$



- Takes into account an inclusive di-lepton trigger
- applies Brems-strahlung corrections

	Signal	Mean	Sigma
eeK	349±34	5245 MeV	74 MeV
μμK	1550±50	5279 MeV	15 MeV

$\sigma_{Rk}(2fb^{-1}) \approx 10\%$

$\sigma_{Rk}(10fb^{-1}) \approx 4\text{-}6\%$

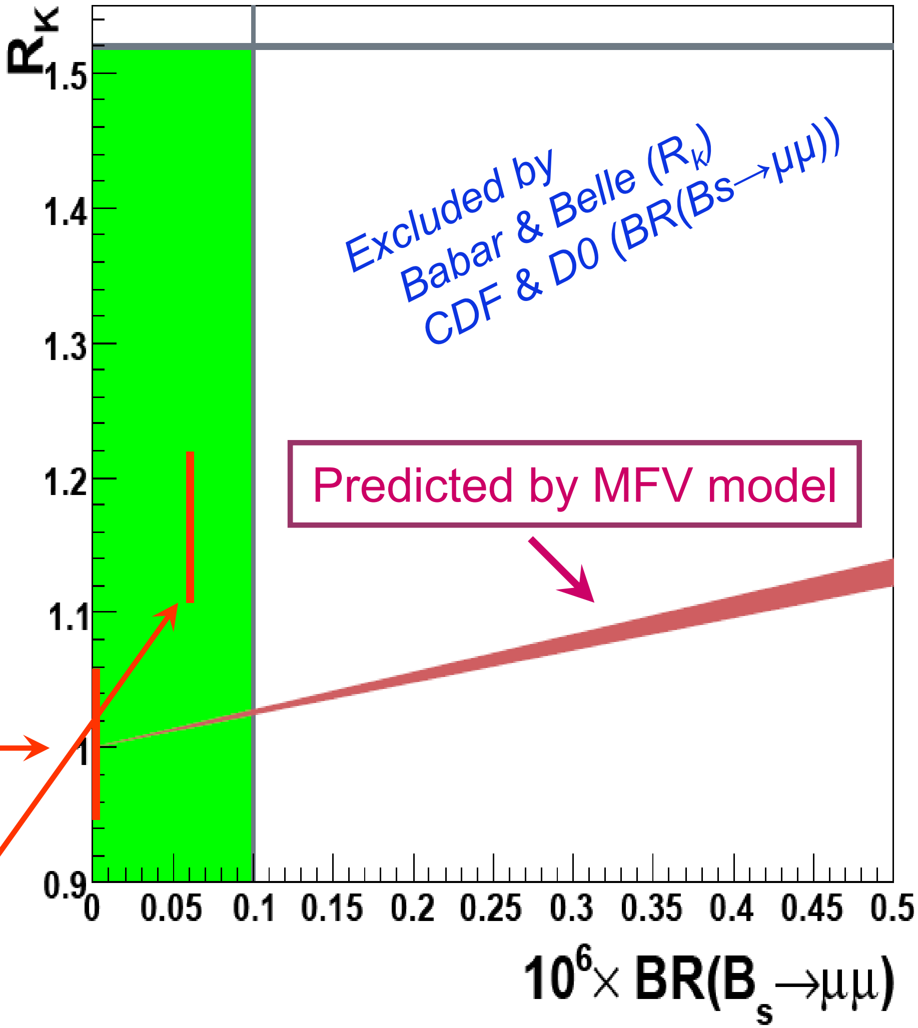
R_k in a MFV model

Assume

- o Right handed currents are negligible.
- o (Pseudo-)scalar couplings lepton masses
- o No CP-phases beyond the SM

$$R_k - 1 \sim BR(B_s \to \mu\mu)$$

Hiller & Krüger, PRD69 (2004) 074020)



LHCb projection if SM is holds

But we hope for something else…

Conclusion

- LHCb is on a good track to take first data soon.
- It has a wide potential to search for New Physics complementary to new particle searches.
- Searches allow to
  - find New Physics in model independent analysis,
    e.g. by measuring B_s-mixing and related CP-asymmetries.
  - pin-down the nature of New Physics e.g. by the study of rare decays.

- The challenge is to achieve that performance with real data!

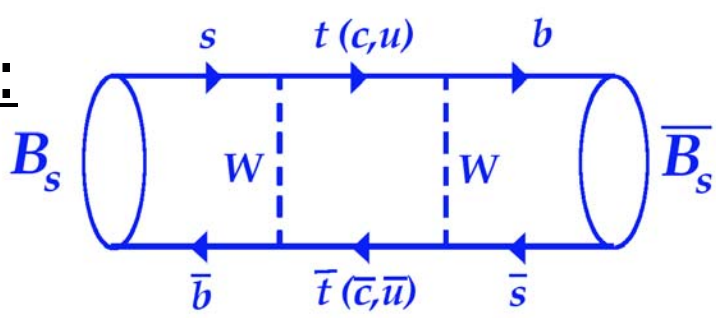
Backup slides

Physics motivation

- A copious number of B-mesons is produced at LHC (10^5Hz @ $2\times10^{32}cm^{-2}s^{-1}$).
- SM contributions to mixing and many decay processes are well understood.
- New Physics may alter SM predictions

LHCb aims to search for New Physics contributions to loop processes, e.g.

B_s-mixing:



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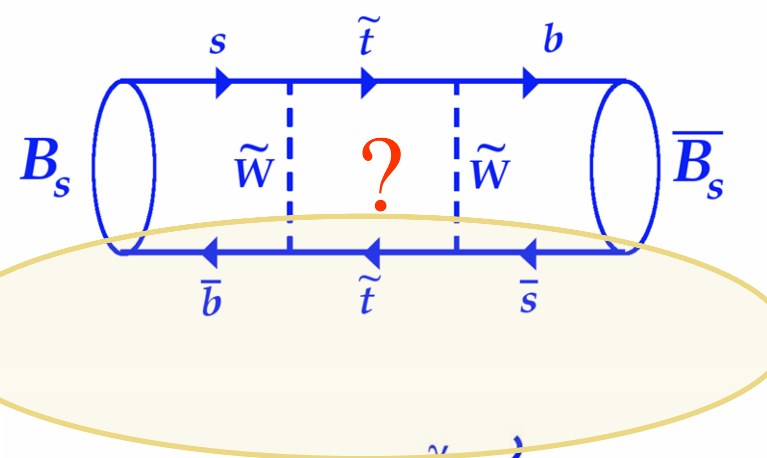
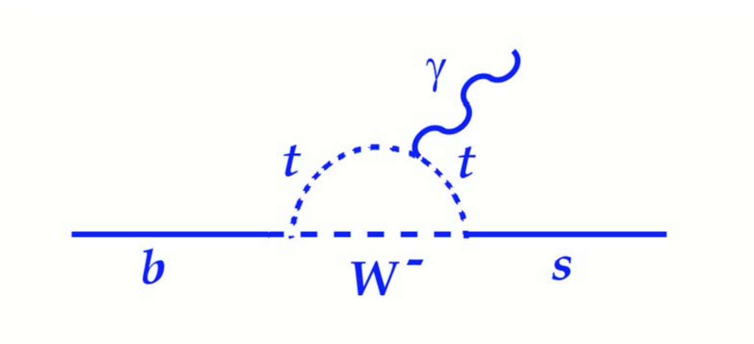


$b \rightarrow s\gamma$:



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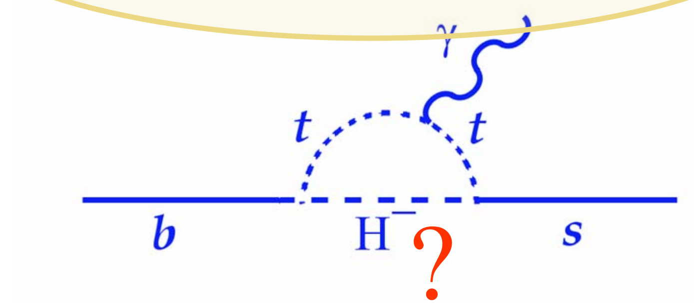
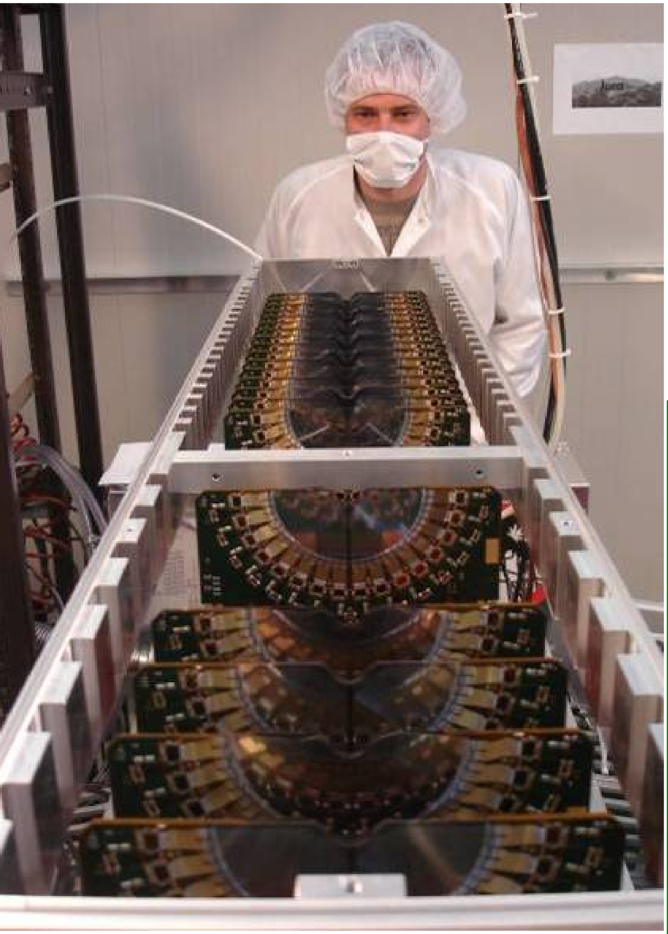
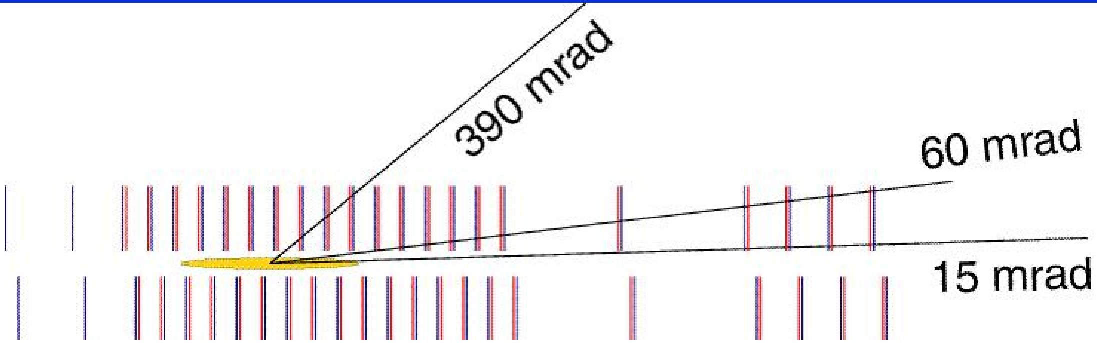


Performance: Vertex locator





Proper time resolution:

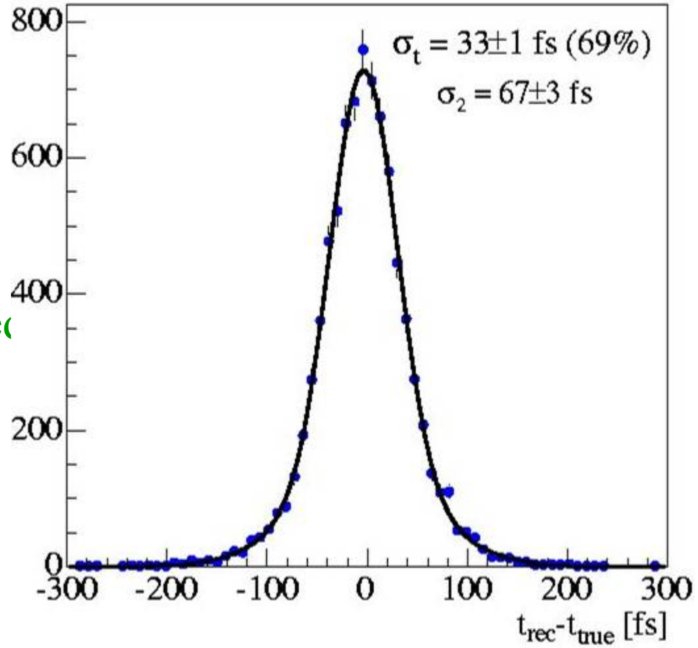
LHCb:

~ 40 fs for ($B_s \to D_s^- \pi^+$)

CDF:

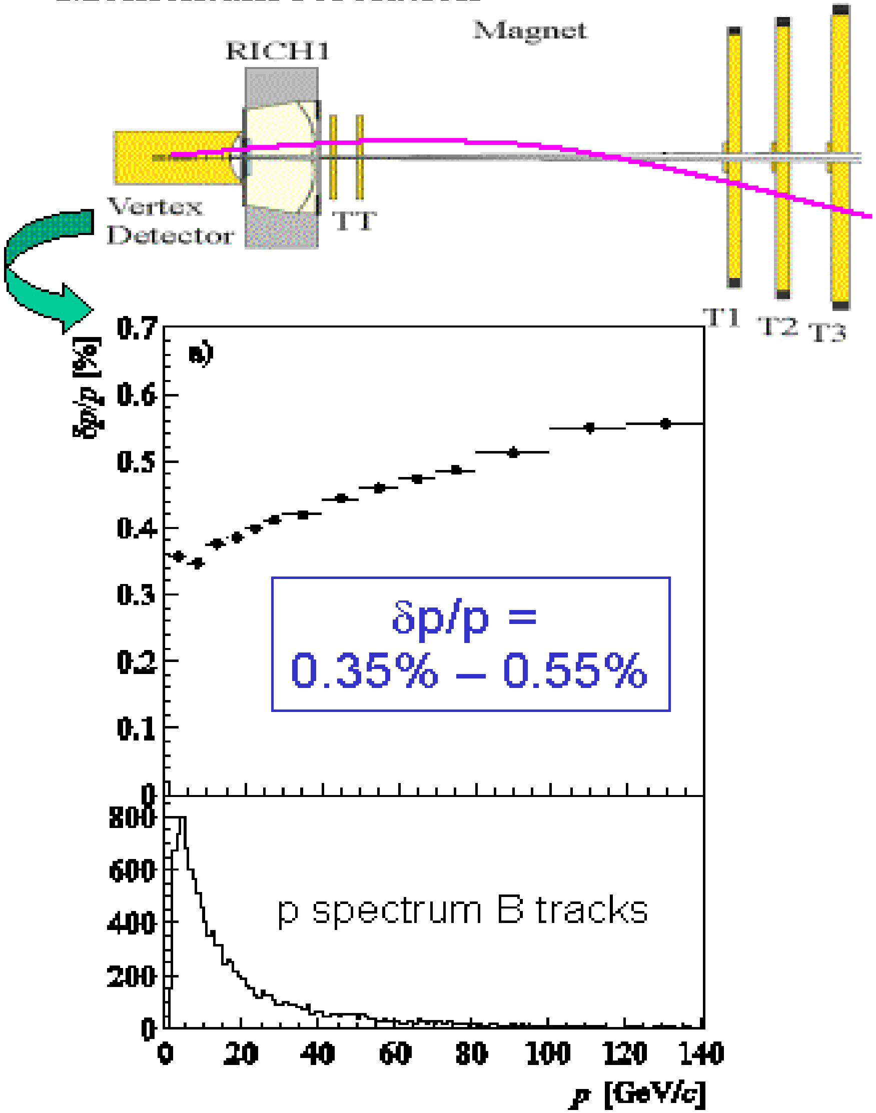
87fs for fully reconstructed decays.

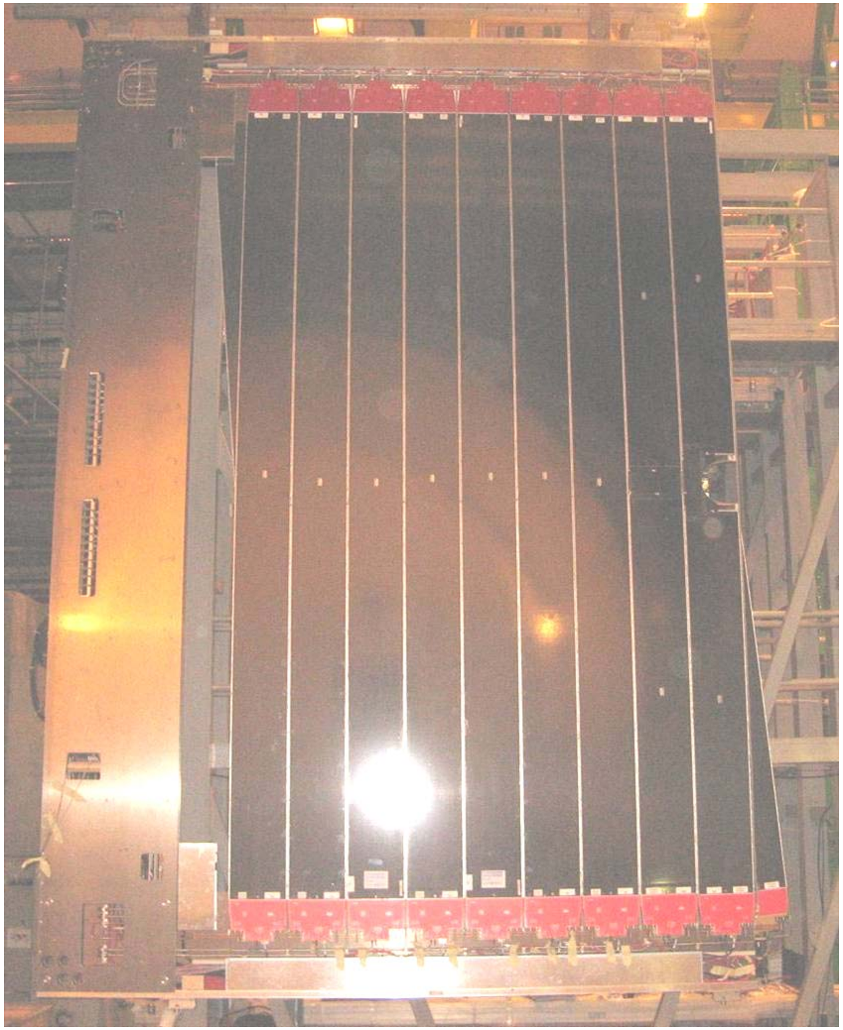
PRL 242003 (2006)



Tracking

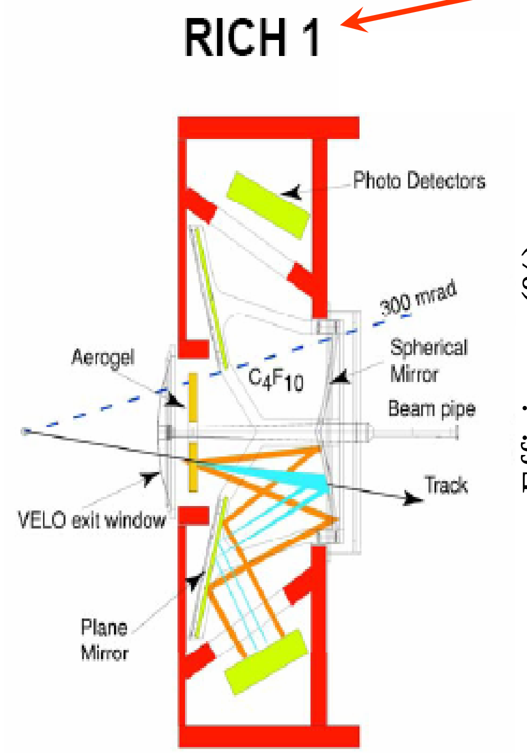
Momentum resolution





Performance: Particle Identification

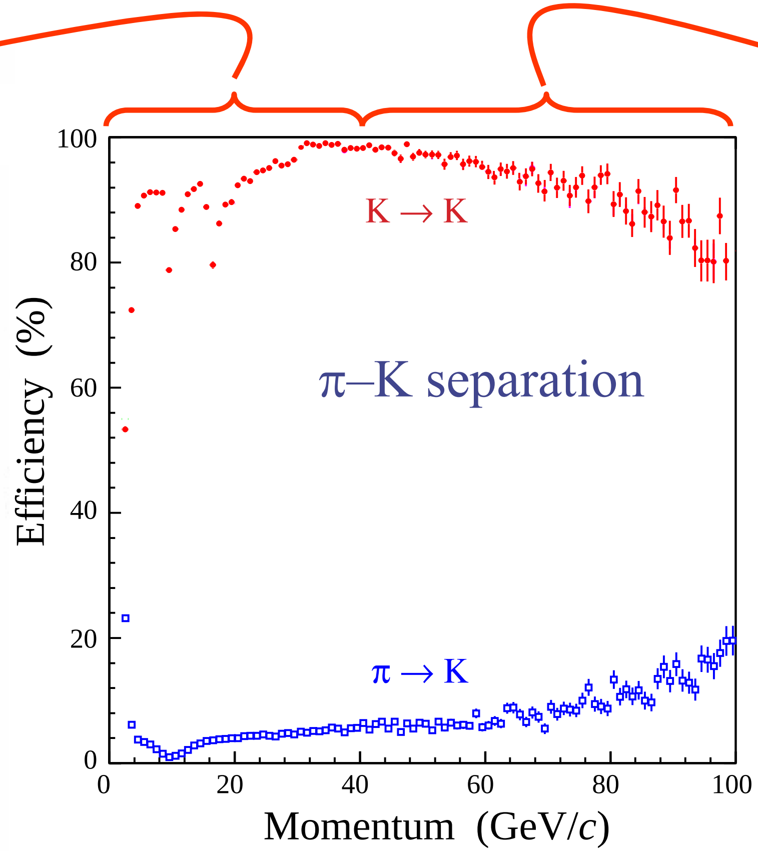
RICH 1



Radiator:

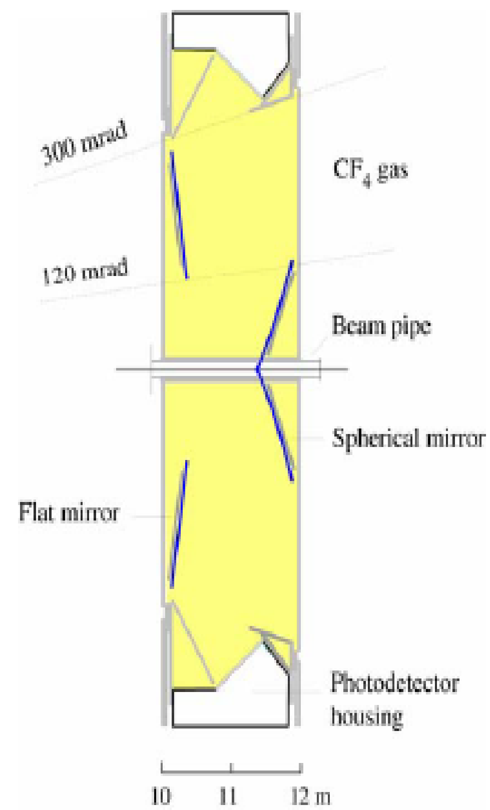
Aerogel n=1.03

C_4F_{10} n=1.0014



Unique feature of LHCb

RICH 2



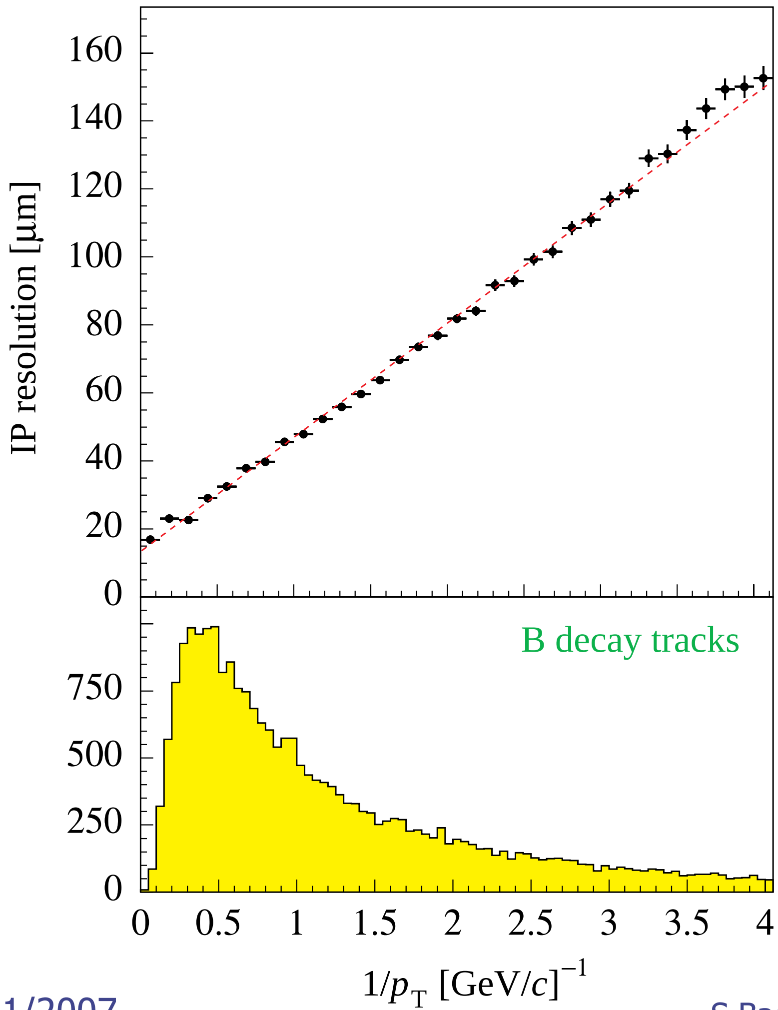
Radiator: CF_4

n=1.0005

Performance of VeLo

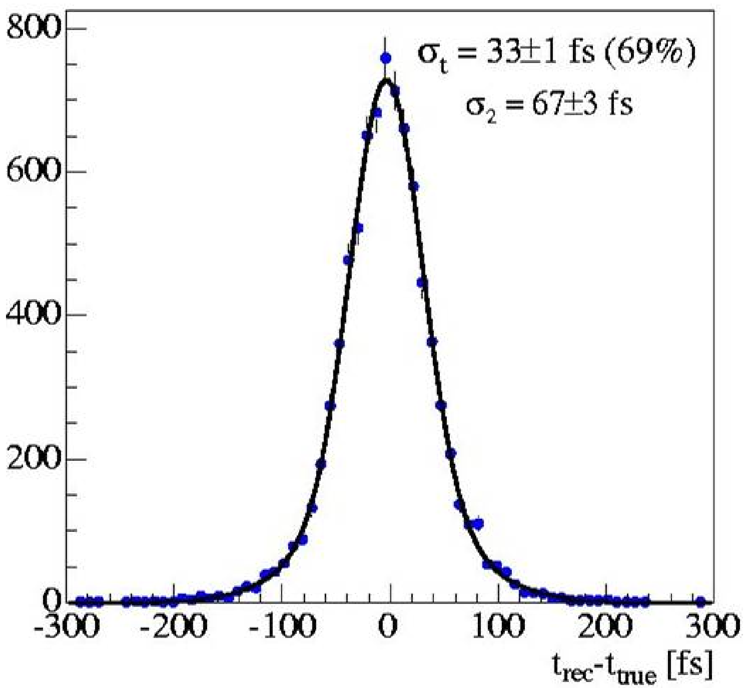
Impact parameter resolution:

$\delta IP = 14\mu m + 35\mu m/p_t$



Proper time resolution:

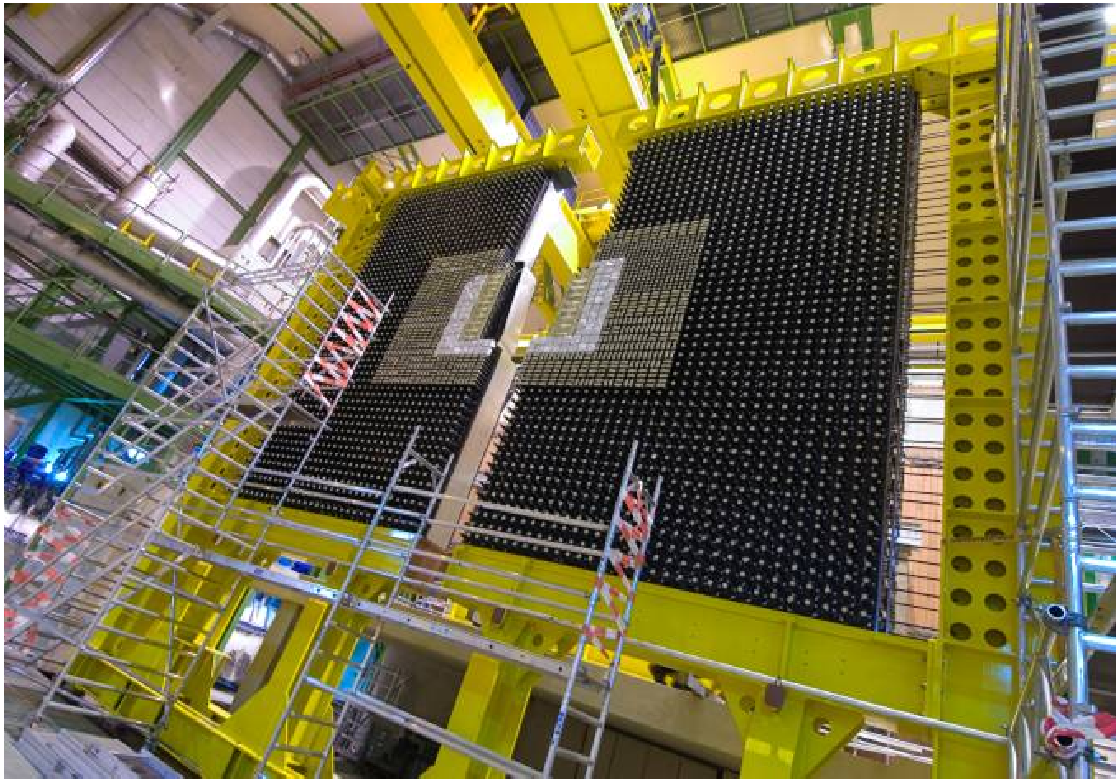
~ 40 fs ($B_s \rightarrow D_s^-\pi^+$)



Calorimeter

Calorimeter system to identify electrons, hadrons and neutrals

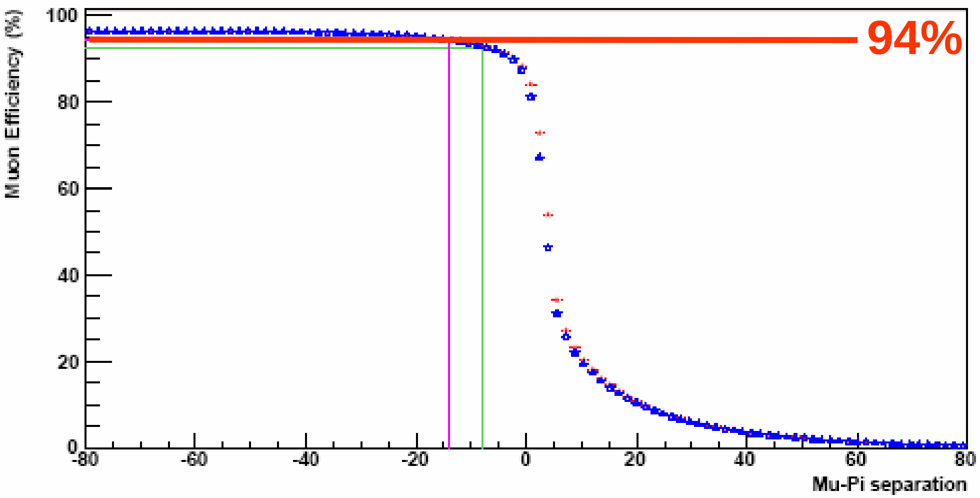
Important for the first level of the trigger



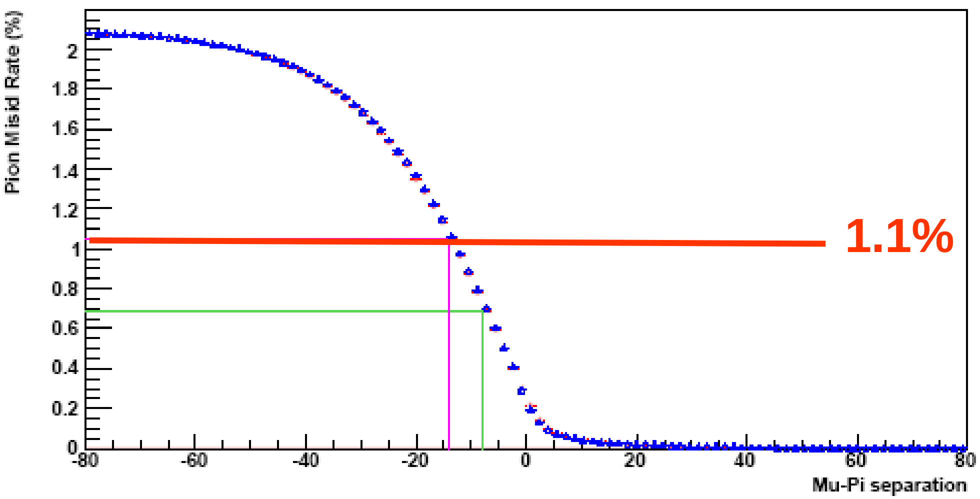
- ***Scintillating Pad Detector / PreShower***
- ***Electromagnetic calorimeter***
- ***Hadron Calorimeter***

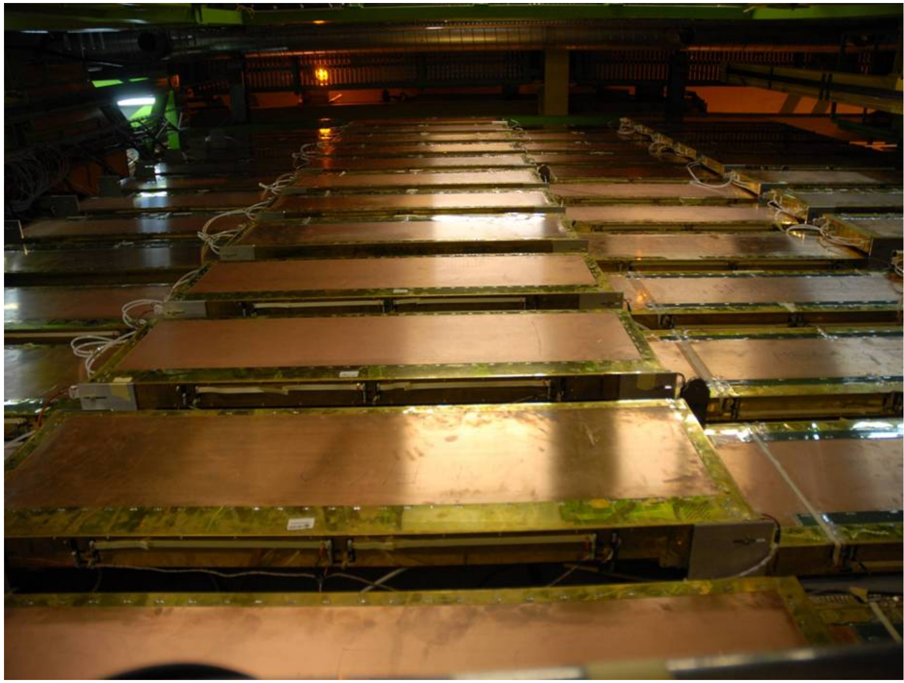
Muon identification

Muon ID efficiency (%) vs μ-π DLL cut



Pion mis ID efficiency (%) vs μ-π DLL cut





Trigger

detector

40 MHz

high p_T (μ,e,γ,h) [hardware, 4 μs latency]

1 MHz

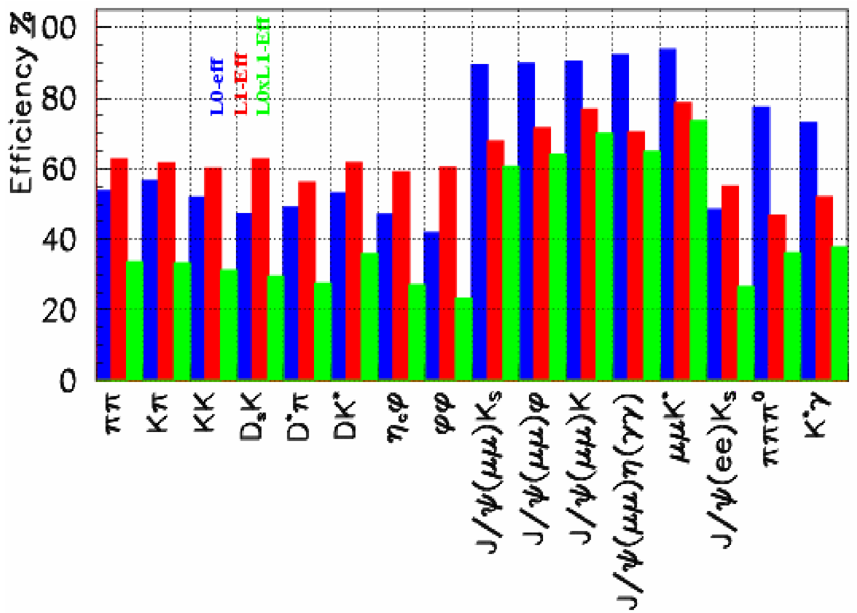
high IP, high p_T tracks [software, 1 ms]

40 kHz

HLT: software using complete event [10 ms]

2 kHz

storage



HLT rate	Event type	Calibration	Physics
200 Hz	Exclusive B candidates	Tagging	B (core program)
600 Hz	High mass di-muons	Tracking	J/ψ, b$\rightarrow$J/ψX (unbiased)
300 Hz	D* candidates	PID	Charm (mixing & CPV)
900 Hz	Inclusive b (e.g. b$\rightarrow\mu$)	Trigger	B (data mining)

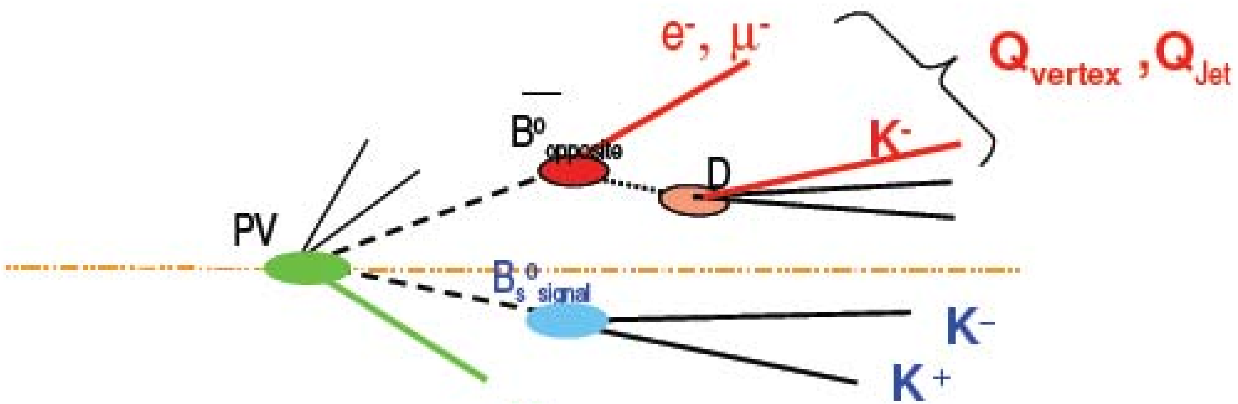
Flavor tagging

- **Opposite side**
  - Charge of the kaon in the b→ c→ s chain
  - Charge of the lepton in semi-leptonic decays
  - Charge of accompanying b jet

- **Same side**
  - Charge of the K accompanying B_s
  - Charge of the π from $B^{**} \rightarrow B^{*}\pi^{\pm}$

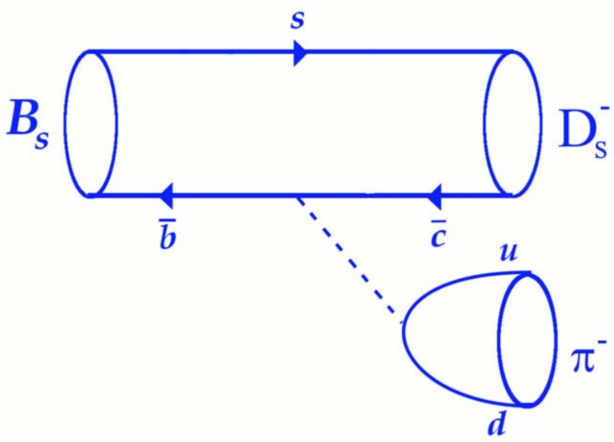
Tagging power in $\varepsilon(1-2\omega)^2$

Tag (%)	B_d	B_s
Muon	1.1	1.5
Electron	0.4	0.7
Kaon opp. side	2.1	2.3
Vertex charge	1.0	1.0
Same side π/k	0.7 (π)	3.5 (K)
Combined (neu.net)	**~ 5.1**	**~ 9.5**



Δm_s from $B_s \rightarrow D_s^-(K^+K^-\pi^-)K^+$

$$B_s^0 \rightarrow D_s^- \pi^+$$



-has a large branching fraction of $(3.4 \pm 0.7) \times 10^{-3}$.

- is flavor specific.

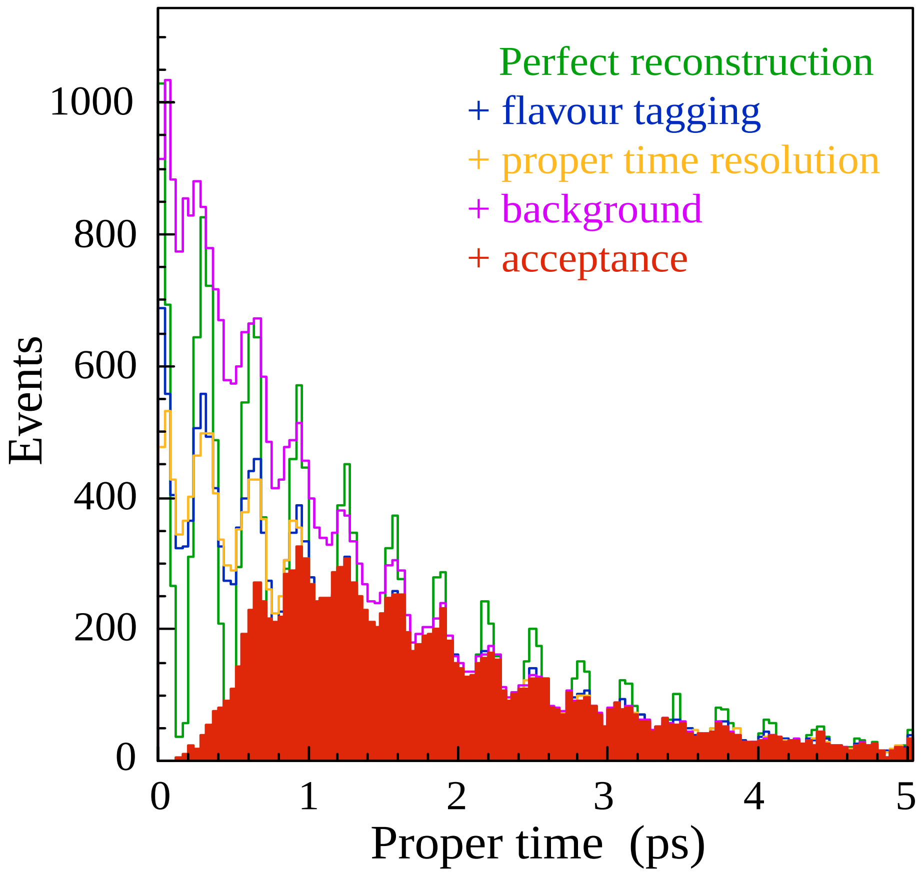
Total efficiency: $\varepsilon_{tot} = 0.39\%$

Signal yield: 140 k ± 0.67 k (stat.) ± 40 k (syst.) (assuming 1 year of nominal running, i.e. 2 fb^{-1})

B/S at 90% CL: [0.014, 0.05] (bb combinatorial)
[0.08, 0.4] (bb specific)

Sensitivity to Δm_s

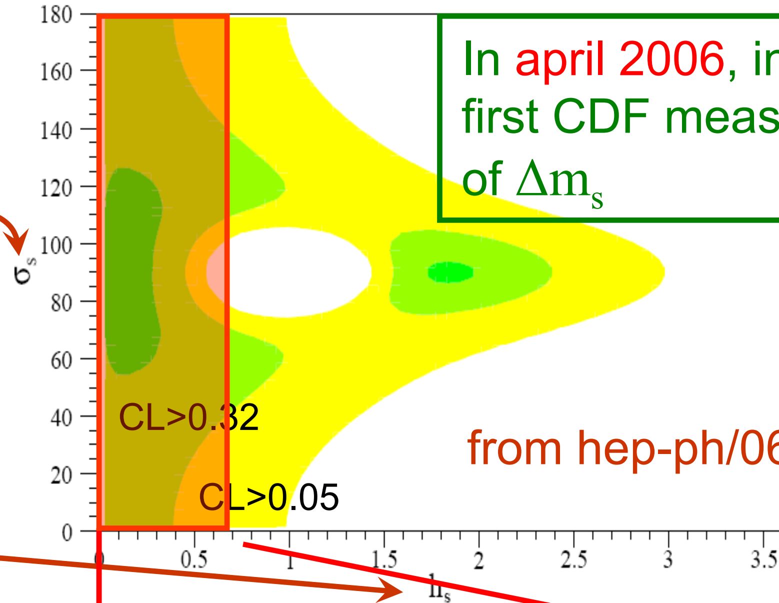
- Plot made for 1 year of data (80k selected events, LHCb) for Δm_s =20 ps^{-1}
- Control of mistag rate, resolution, background and acceptance important
- Expected sensitivity for 2 fb-1 (i.e. year of data)
  $\sigma(\Delta m_s) = \pm 0.007\ ps^{-1}$
  CDF: $\Delta m_s = (17.8 \pm 0.1)\ ps^{-1}$



Sensitivity for New Physics

Model independent parametrization for New Physics:

$$M_{12} = (1 + h_s \exp(2i\sigma_s))M_{12}^{SM}$$

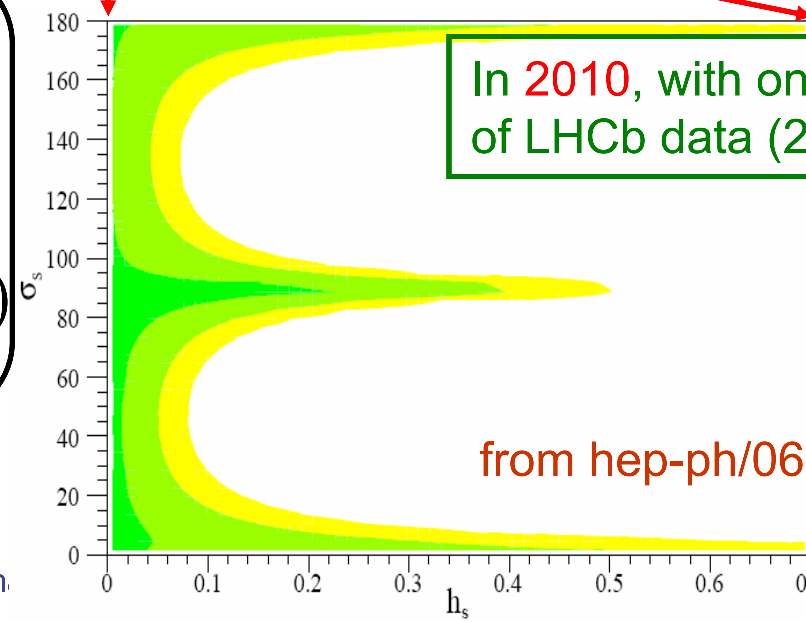


This results in:

$$\Delta m_s = \Delta m_s^{SM} \left|1 + h_s \exp(2i)\sigma_s\right|$$

$$\phi_s = \phi_s^{SM} + \arg(1 + h_s \exp(2i\sigma_s))$$

$$\Delta\Gamma_s = \Delta\Gamma_s^{SM} \cos^2(\arg(1 + h_s \exp(2i\sigma_s)))$$



$B_s \to \Phi(K^+K^-)\ \Phi(K^+K^-)$

- FCNC ($b \to s\bar{s}s$)with SM prediction for CP-asymmetry < 1%. see e.g. M.Raidal, PRL 89,231803(2002)
- Sizeable CP asymmetry is an unambiguous sign for NP.
- Like in $B_s \to J/\psi\phi$ a full angular analysis to extract CP-asymmetry is needed.
- Experimentally demanding, as full hadronic trigger is needed.

<u>Remark:</u>

- In SM $B_s \to J/\psi\phi$ and $B_s \to \phi\phi$ measure both $arg[V_{tb}^* V_{ts}]$.

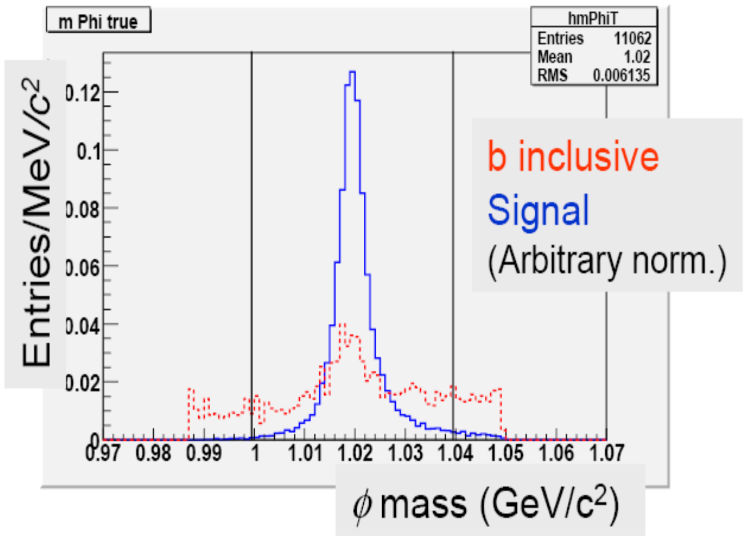
  ↳ Tree ↳ Penguin

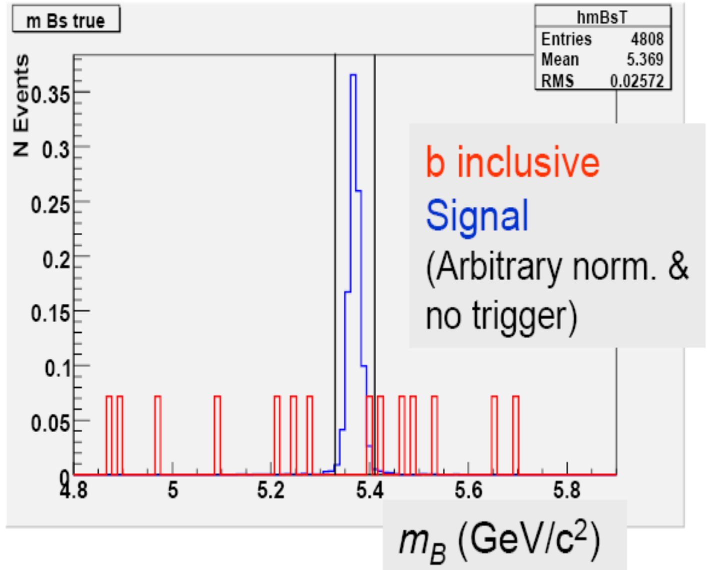
- Deviations point to physics beyond the SM.
- Belle/Babar have 2.7σ deviation when comparing tree and penguin decays of B_d to CP-Eigenstate.

Event selection and sensitivity studies

Selection:

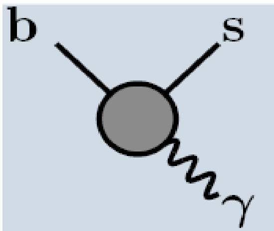
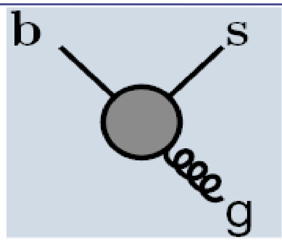
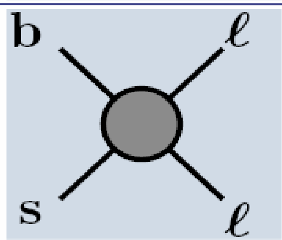
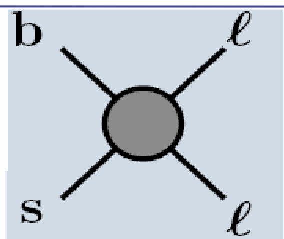
- Reconstruct only $\phi \to K^+K^-$.
- Full detector simulation including trigger bias.
- Reconstruction based on:
  - o RICH $K^\pm$ ID
  - o pt and impact parameter of $K^\pm$ and ϕ candidates.
  - o B_s and ϕ invariant mass.
  - o B_s and ϕ vertex quality.





Sensitivity to ϕ_s studied by toy MC:

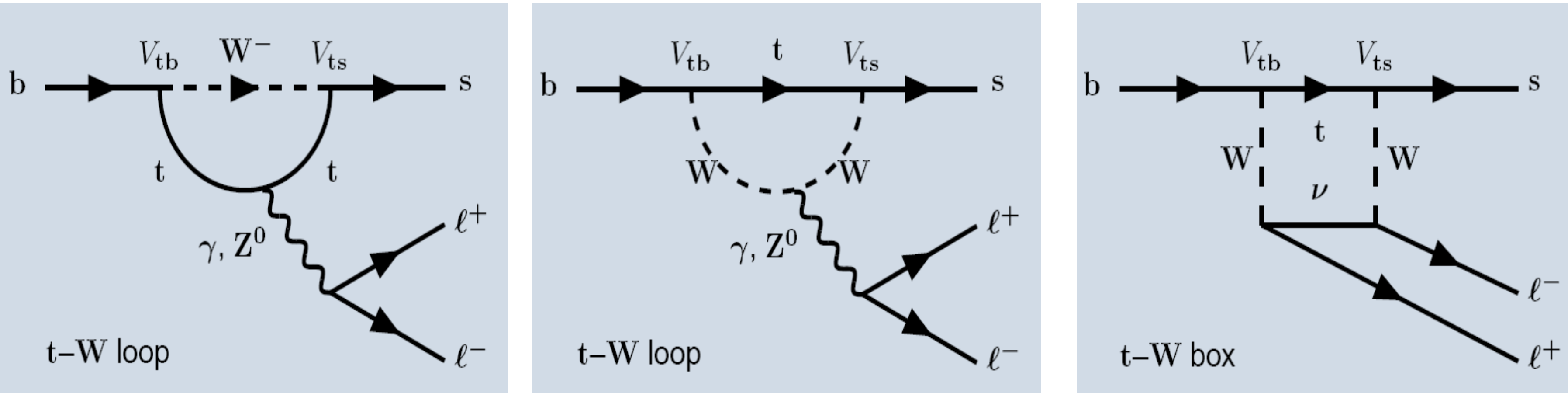
- proper time resolution of 42fs.
- proper time acceptance function.
- flat BG in m_B and transversity angle.
- mistag dilution: $\varepsilon(1\text{-}2\omega) = 9.6\%$
- exponential lifetime distribution for BG

		magnitude	phase	helicity flip $\mathcal{O}'_i$
$\mathcal{O}_{7\gamma}$		$b \to s\gamma$	$a_{CP}(b \to s\gamma)$	$\Lambda_b \to \Lambda\gamma$ $B \to (K^* \to K\pi)\ell^+\ell^-$ $B \to (K^{**} \to K\pi\pi)\gamma$
$\mathcal{O}_{8g}$		$b \to s\gamma$ $B \to \not{X}_c$	$a_{CP}(b \to s\gamma)$ $B \to K\phi$	$\Lambda_b \to \Lambda\phi$ $B \to K^*\phi$
$\mathcal{O}_{9\ell,10\ell}$		$b \to se^+e^-$	$A_{FB}(b \to s\ell^+\ell^-)$	$B \to (K^* \to K\pi)\ell^+\ell^-$
$\mathcal{O}_{S,P}$		$B_{d,s} \to \mu^+\mu^-$	$B_{d,s} \to \tau^+\tau^-$	$b \to s\tau^+\tau^-$

From G. Hiller [hep-ph/0308180]

2.) $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

SM processes contributing to decay:



$BR(B^0 \rightarrow lls) = 4.5x10^{-6}$

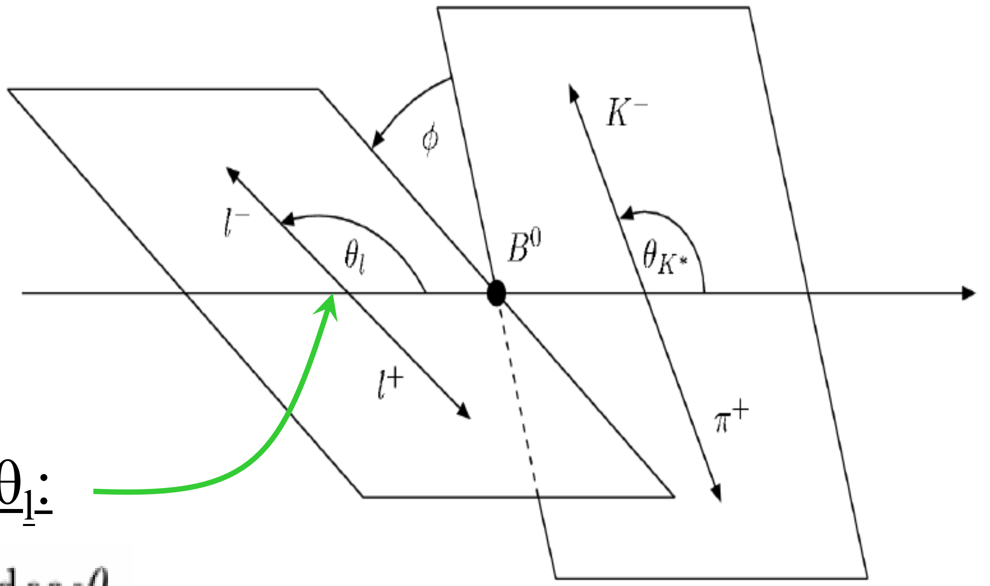
$BR(B^0 \rightarrow llK) = 0.5x10^{-6}$

Decay is very sensitive to extensions of SM, especially to models with right handed currents:

Analysis of angular distributions allow to extract this information about new Physics.

Observables in $B^0 \rightarrow K^{*0}\mu^+\mu^-$

Two observables are of special interest, as they have small theoretical errors and are very sensitive to NP:



Forward-Backward Asymmetry in θ_l:

$$A_{FB}(s) = \frac{\int_0^1 \frac{d^2\Gamma}{dsdcos\theta}dcos\theta - \int_{-1}^0 \frac{d^2\Gamma}{dsdcos\theta}dcos\theta}{\int_0^1 \frac{d^2\Gamma}{dsdcos\theta}dcos\theta + \int_{-1}^0 \frac{d^2\Gamma}{dsdcos\theta}dcos\theta}$$

Transverse Asymmetry:
(asymmetry in the spin amplitude of the K*)

$$A_T^{(2)}(s) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}.$$

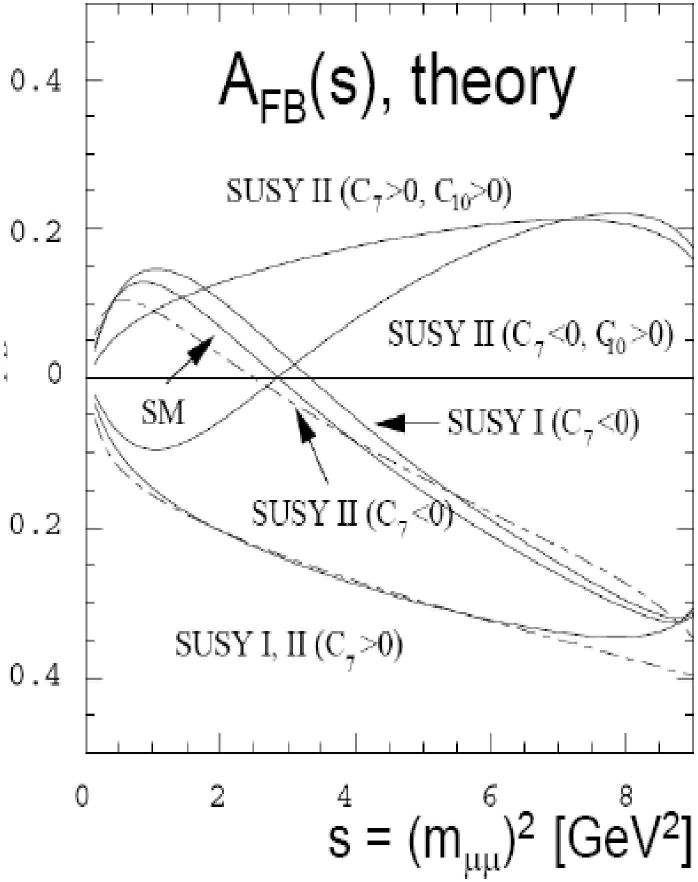
A_{FB} and $A_T^{(2)}$

AFB(s) in SM and different SUSY models:

SUSY I = SUGRA

SUSY II = MIA MSSM

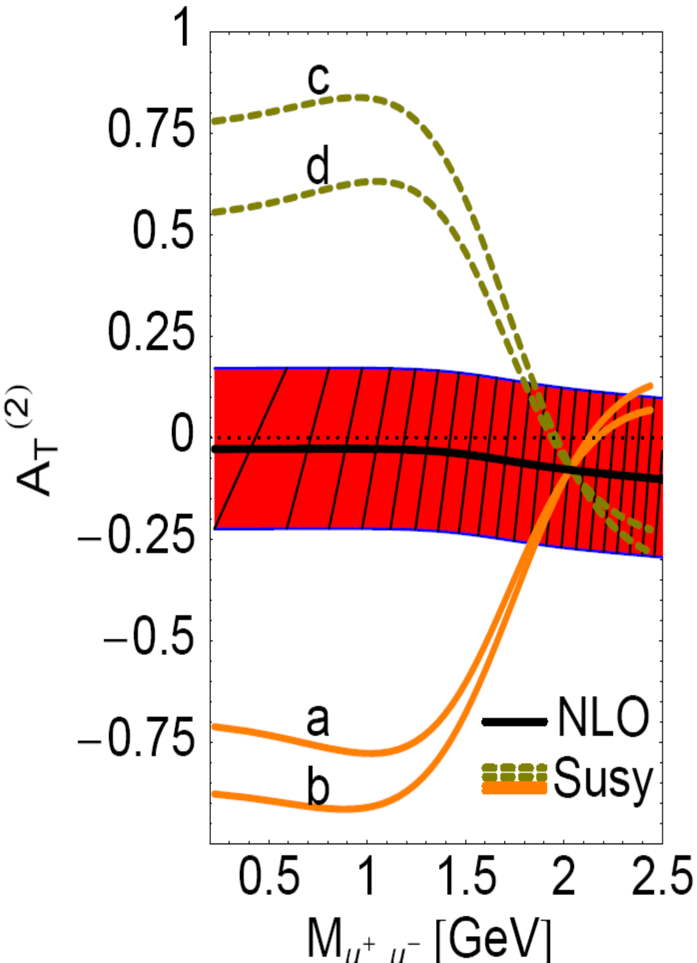
(from Phys.Rev.D61 (2000) 074024)



Non-MFV MSSM with

$\tan(\beta) = 5$

from HEP-ph/0612166

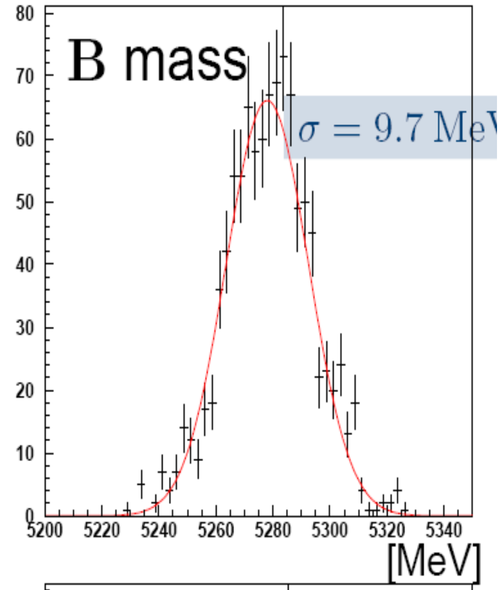


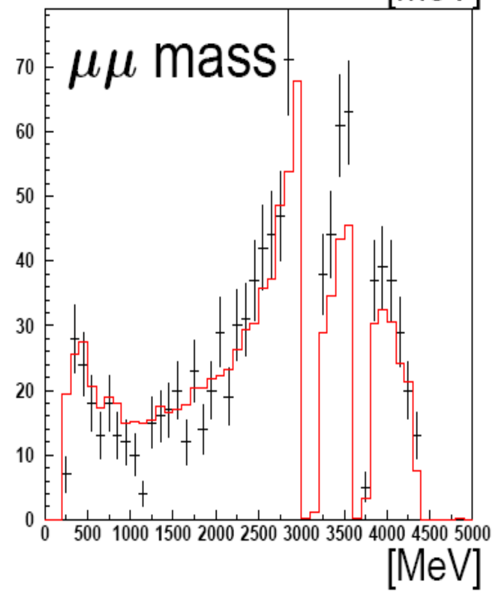
Selection of events: $B^0 \to K^{*0}\mu^+\mu^-$

Expected yield for $2fb^{-1}$:
7200 ± 180(stat.) ± 2200 (BR)

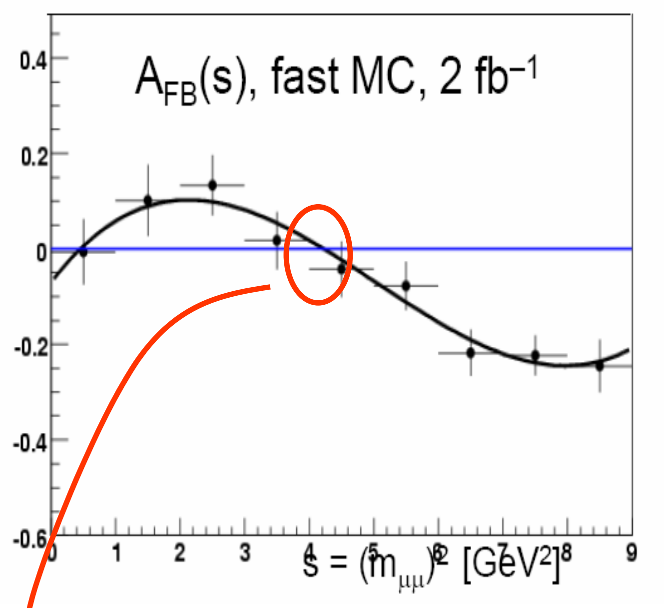
Estimate for Background:

MC sample	No. of events per $2fb^{-1}$
Bd,u→sμμ (no K*)	9 ± 3
b→μ, b→μ	1050±250
b→μ, c→μ	690±180
Total	**1770±310**





A_{FB} and $A_T^{(2)}$ from $B^0 \to K^{*0}\mu\mu$



1 year of data taking, errors expected to be limited by statistics

Zero crossing point is a probe for NP:

$$\sigma_{A_{FB}^{(0)}}(2\text{fb}^{-1}) = 1.2\text{GeV}^2$$

$$\sigma_{A_{FB}^{(0)}}(10\text{fb}^{-1}) = 0.5\text{GeV}^2$$