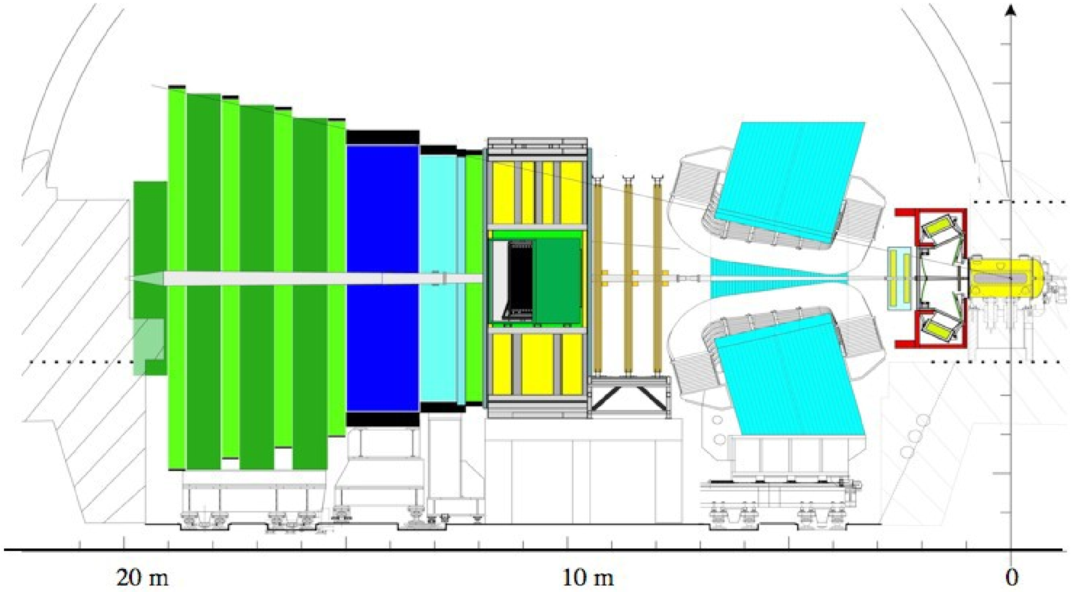
Prospects for CPV in $B_s \rightarrow J/\Psi\phi$ and $A_{FB}(B \rightarrow K^*\mu\mu)$ at LHCb

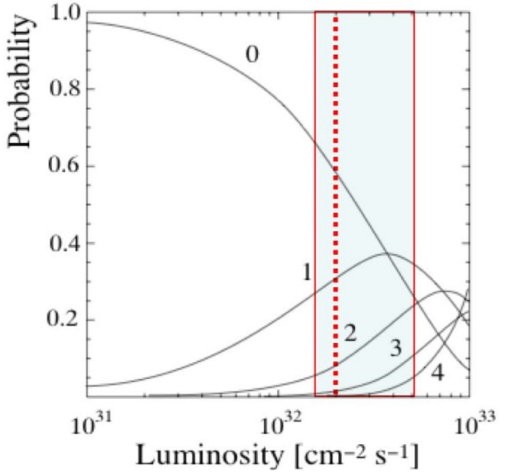


Marco Musy – Universitat de Barcelona,

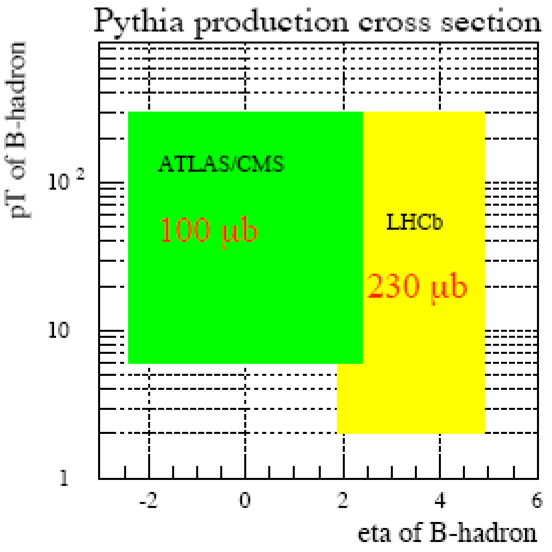
Taipei, 15th January 2010

B production at LHCb

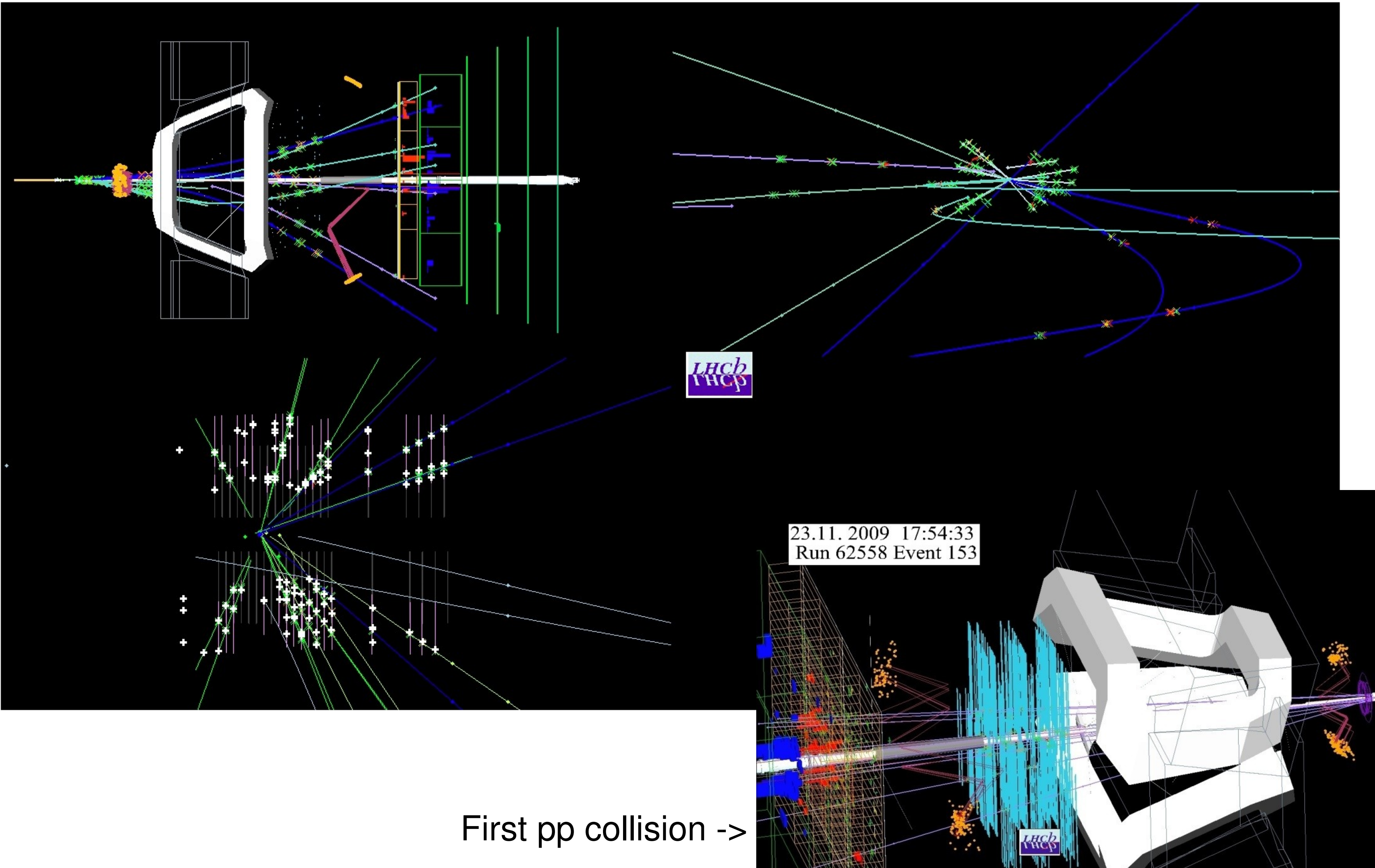
- LHCb limits luminosity to few 10^{32} $cm^{-2}s^{-1}$ by not focusing the beam as much as ATLAS and CMS
  - LHCb luminosity from start
  - Optimize for single pp-collision
  - 10^7 s LHC = 1 year = 2/fb



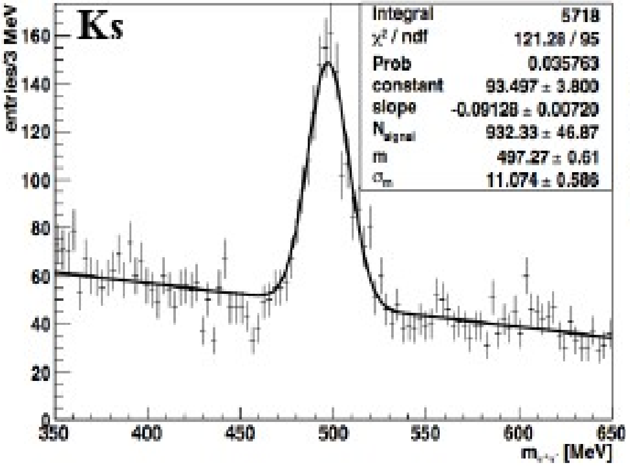
- High bb cross section, σ_{bb}(14 TeV)= 500µb
  - Exploit about 45% of this xsec
  - At 7 TeV a factor ~2 less
  - Access to all b-hadrons and b-baryons
  - In 2010 about 200/pb luminosity at 7 TeV

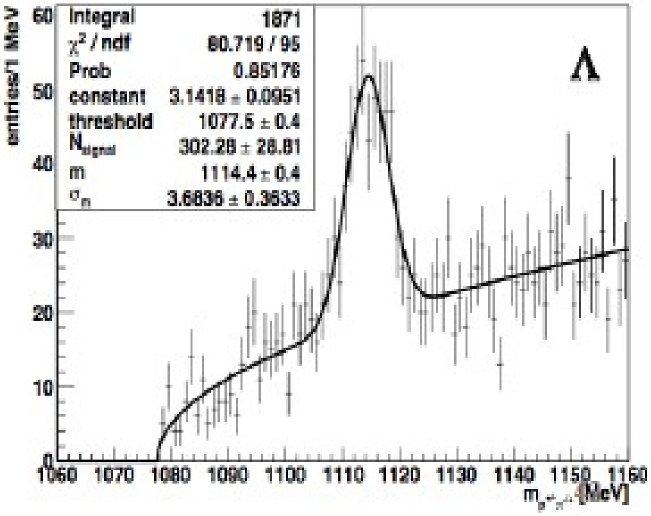


The LHCb detector at work

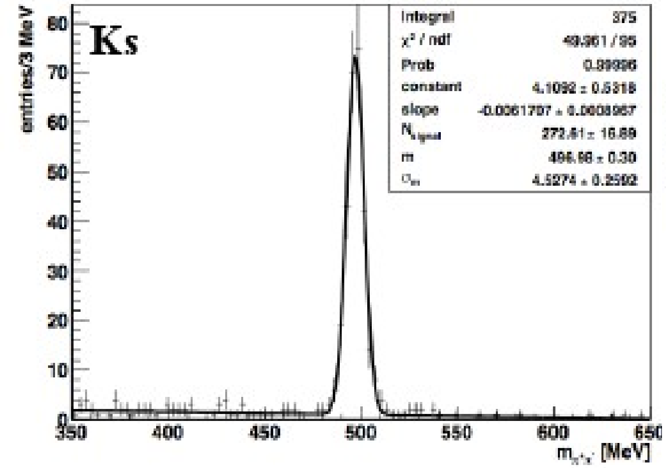


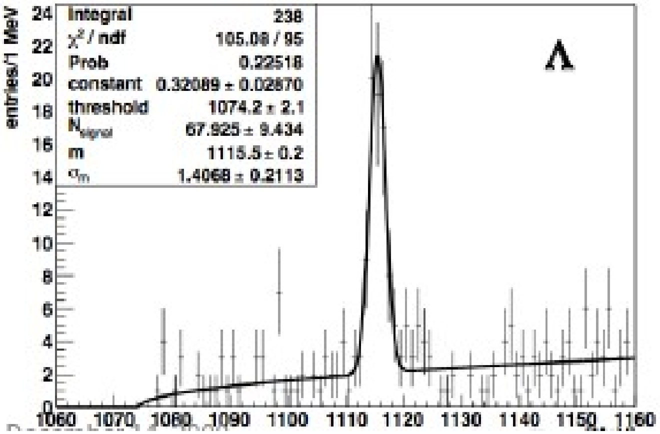
First pp collision ->

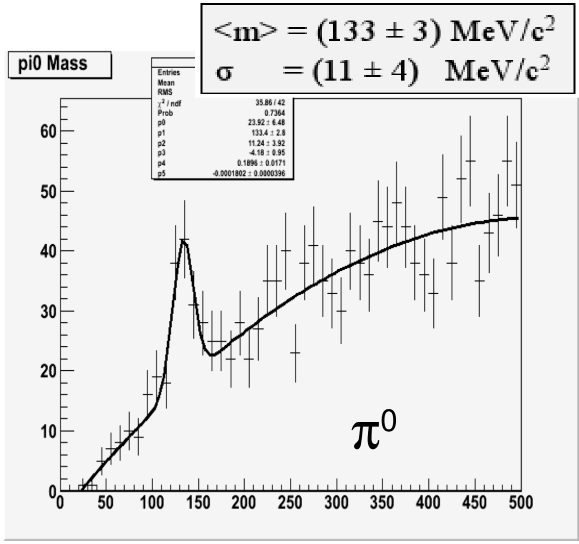

Ks
entries/3 MeV
Integral 5718
χ² / ndf 121.28 / 95
Prob 0.035763
constant 93.497 ± 3.800
slope -0.09128 ± 0.00720
N_signal 932.33 ± 46.87
m 497.27 ± 0.61
σ_m 11.074 ± 0.586
0
20
40
60
80
100
120
140
160
350
400
450
500
550
600
650
m_π+π- [MeV]


Λ
entries/1 MeV
Integral 1871
χ² / ndf 80.719 / 95
Prob 0.85176
constant 3.1418 ± 0.0951
threshold 1077.5 ± 0.4
N_signal 302.28 ± 28.81
m 1114.4 ± 0.4
σ_m 3.6836 ± 0.3633
0
10
20
30
40
50
60
1060
1070
1080
1090
1100
1110
1120
1130
1140
1150
1160
m_p+π- [MeV]

Adding VELO information



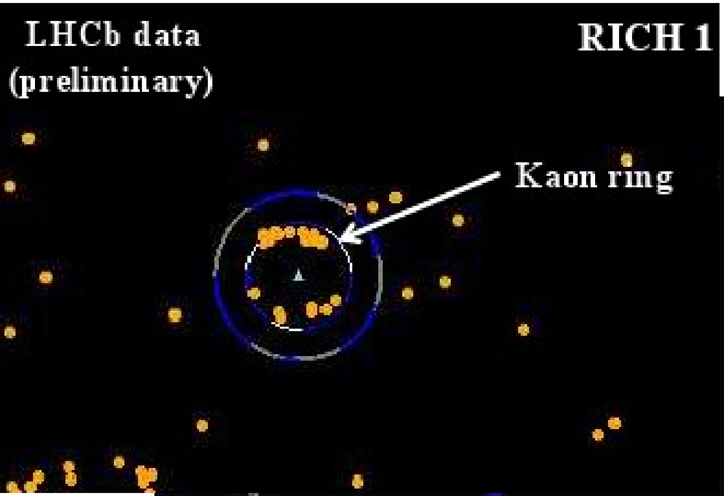




<m> = (133 ± 3) MeV/c²

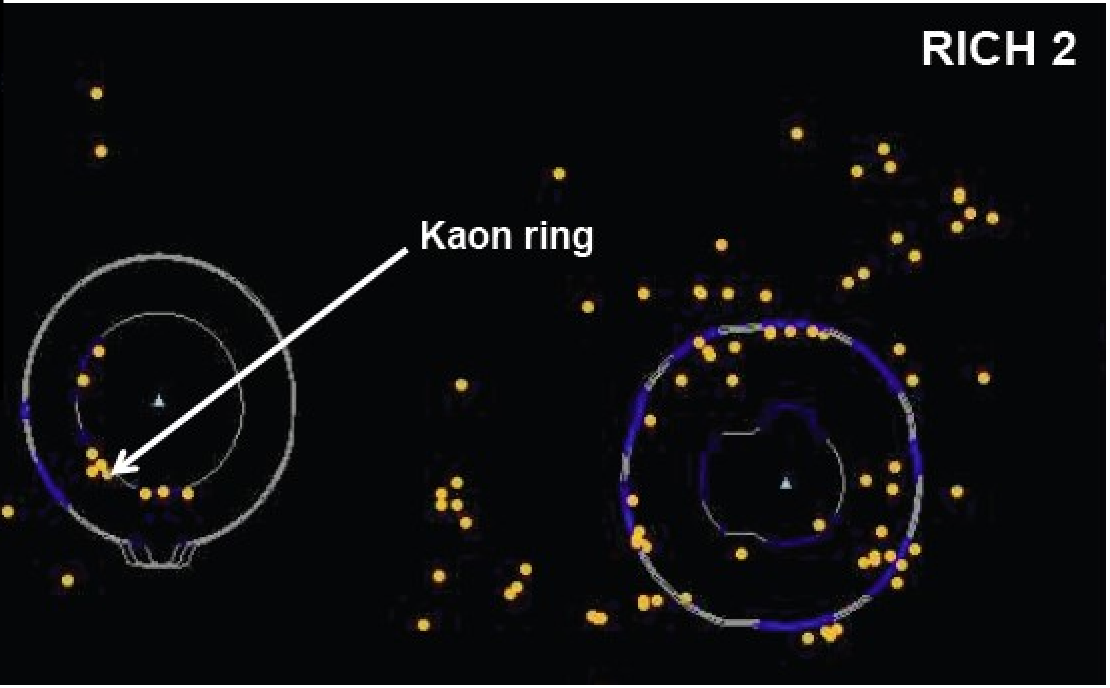
σ = (11 ± 4) MeV/c²

π^0



LHCb data (preliminary)

RICH 1



RICH 2

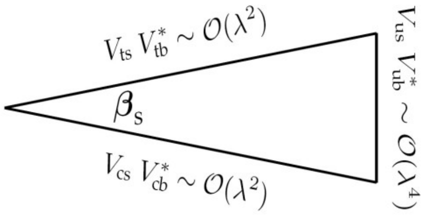
The CPV phase ϕ_s

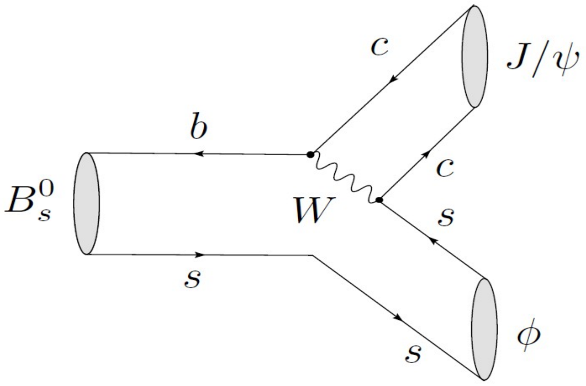
- The interference between B_s decay to J/ψφ either directly or via mixing gives rise to a CP violating phase Φ

$$\begin{tikzcd} B_s \arrow[rr, "-\Phi_D"] \arrow[dr, "\Phi_M"'] & & f = J/\psi\phi \\ & \overline{B}_s \arrow[ur, "\Phi_D"'] & \end{tikzcd}$$

$$\Phi_{J/\psi\phi} \equiv \Phi \equiv -\arg(\eta_f \lambda_f) = \Phi_M - 2\Phi_D$$

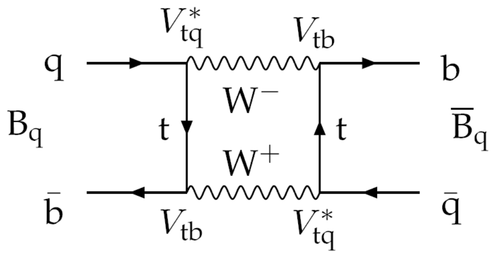
$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

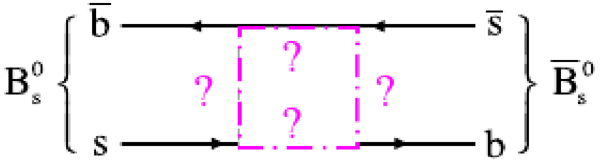




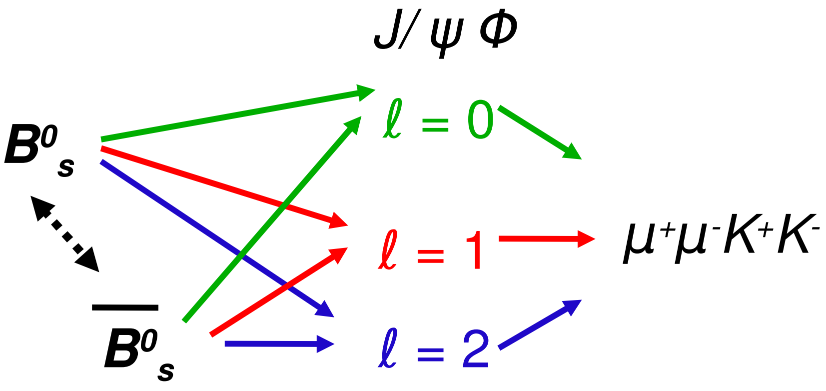
Φ is a sensitive probe of New Physics because:

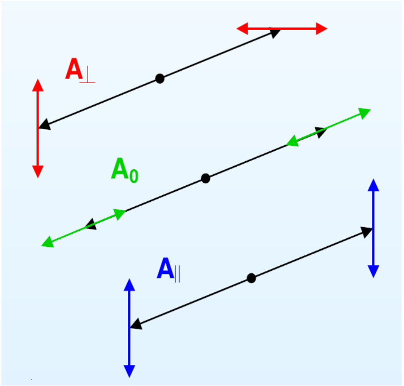
- It is well predicted in the SM: $\Phi^{SM} = -2\beta_s + \delta P = (-0.037 \pm 0.002 + \delta P)$ rad
- New particles can contribute to the B_s-B_s box diagrams and significantly modify the SM prediction





Since $CP|J/\psi\ \phi\rangle = (-1)\ell\ |J/\psi\phi\rangle$, final state is mixture of CP even (ℓ=0,2) and CP odd (ℓ=1)



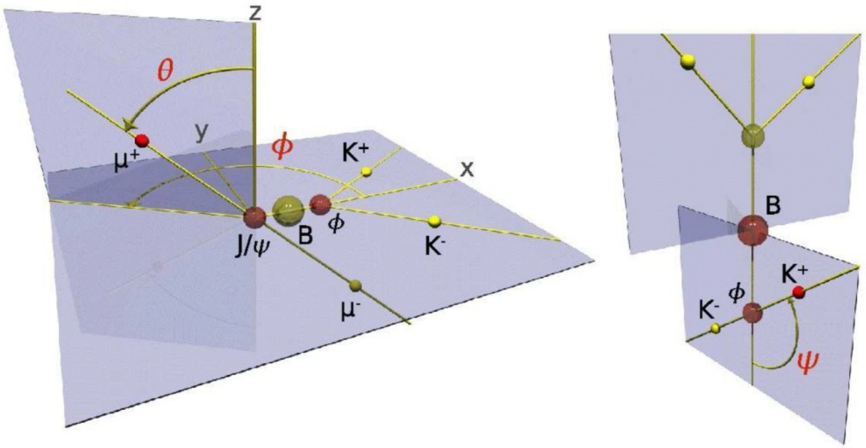


Depend on 8 physics params:

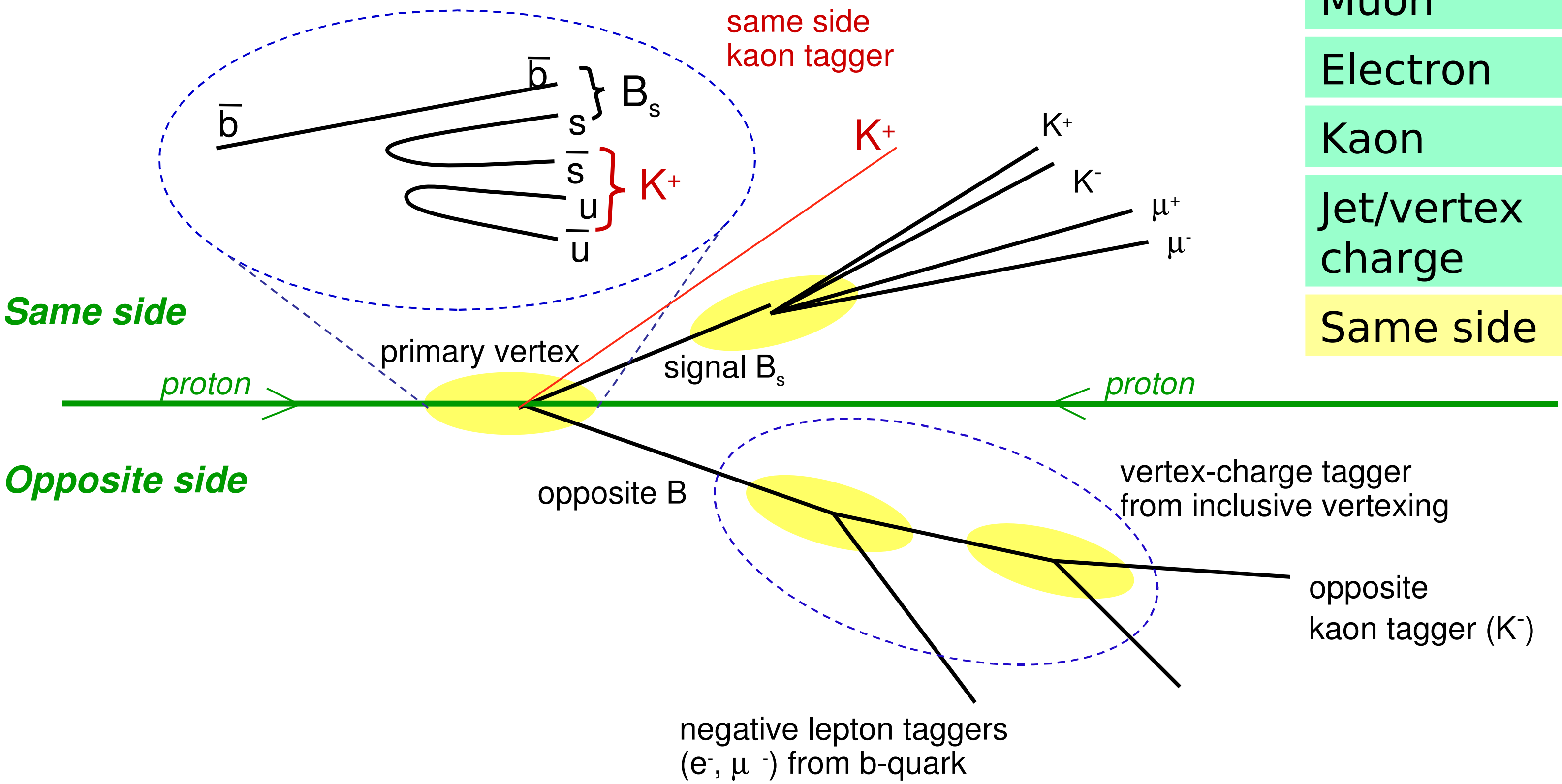
Φ, Γ_s, $\Delta\Gamma_s$, Δm_s, $R_\perp$, $R_{||}$, $\delta_\perp$, $\delta_{||}$

- **6 observables: 3 angles θ, ϕ, ψ describe directions of final decay products $J/\Psi\rightarrow\mu\mu$ and $\phi\rightarrow K^+K^-$, tag state, proper time and mass**

  Angles allow to separate *statistically* the 3 decay amplitudes



How to tag the flavour



Tagging power	εD^2 (%)
Muon	0.9
Electron	0.4
Kaon	1.3
Jet/vertex charge	1.1
Same side	2.4

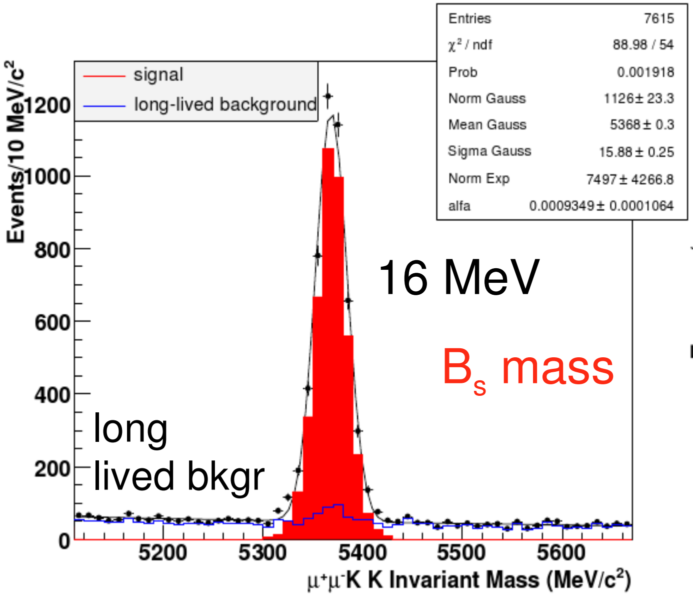
On $B_s \rightarrow J/\Psi\phi$:

global efficiency $\varepsilon \sim 55.7\%$, mistag rate $\omega \sim 33.3\%$, $\varepsilon D^2 = \varepsilon(1-2\omega)^2 \sim 6.2\%$

- Signal: $B_s \to J/\Psi\phi$ (117k in 2/fb, B/S~2.3)

- Main control channels
  - $B^+ \to J/\Psi K^+$, $B^0 \to J/\Psi K^*$ for OS taggers
    (940k) (490k)

- Unified selection makes opposite-side mistag compatible among $B \to J/\Psi X$ channels



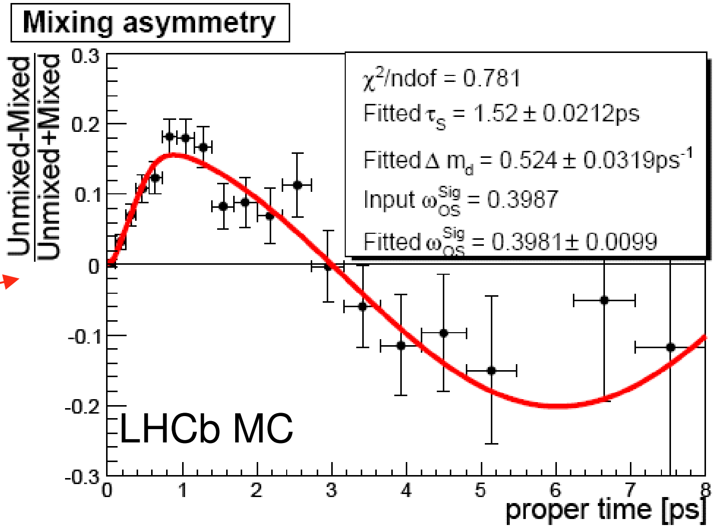
16 MeV

B_s mass

long
lived bkgr

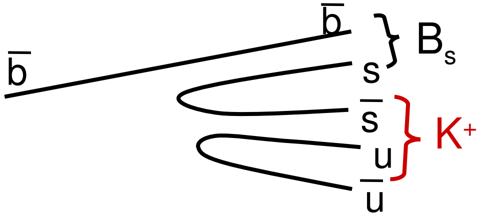
	Combined ω_{OS}	Combined OS $\varepsilon(1-2\omega)^2$(%)
$B_s \to J/\Psi\phi$	36.51± 0.24	3.32± 0.11
$B_d \to J/\Psi K^*$	36.15± 0.20	3.35± 0.09
$B^+ \to J/\Psi K^+$	36.00± 0.21	3.45± 0.10

also used to validate the fit procedure



$\sigma(\omega_{OS})/\omega_{OS}$~0.3% with 2/fb

Same Side

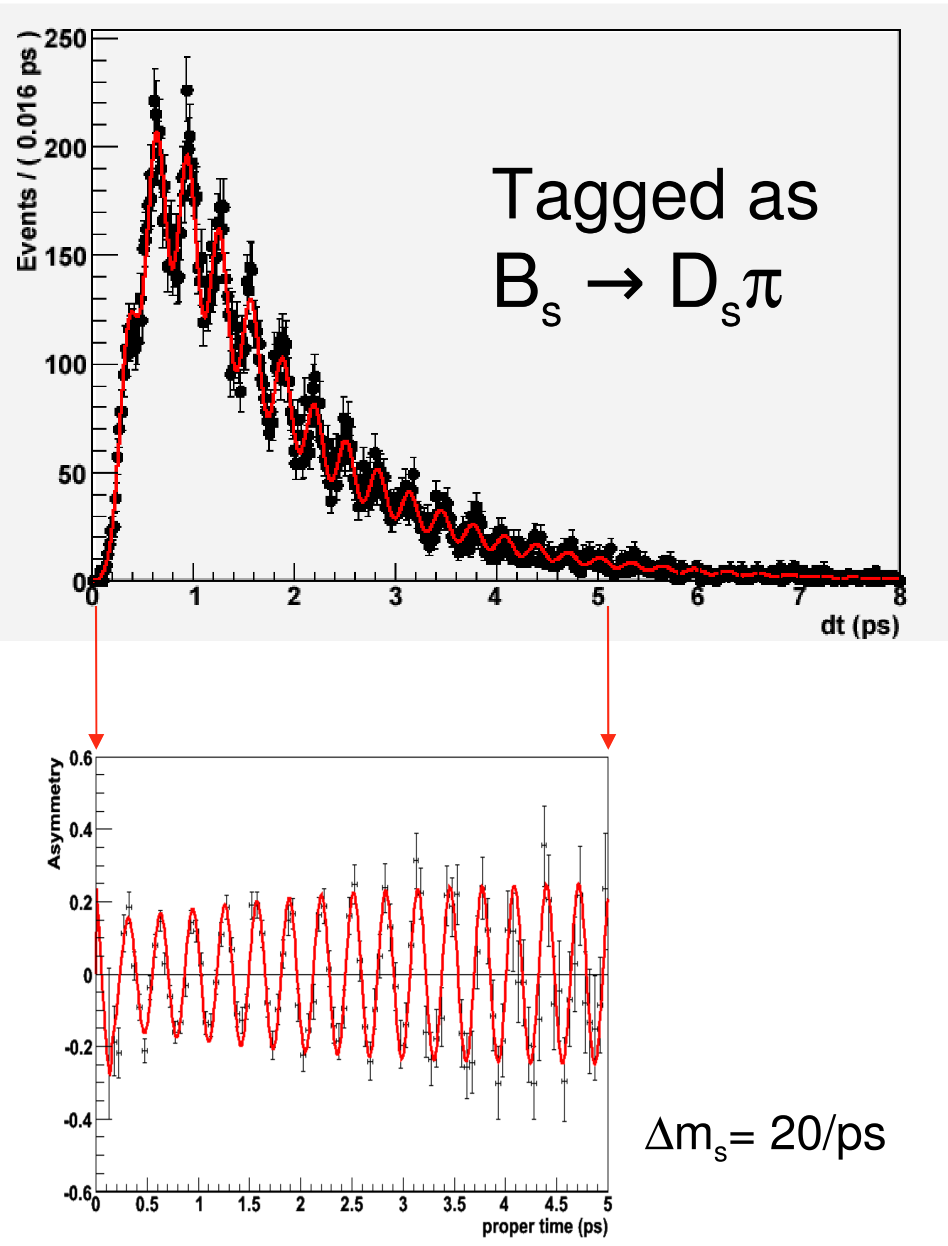


- $B_s \rightarrow D_s\pi$ events can eventually be used to extract mistag parameters (and fit Δm_s at the same time).

- Annual yield is 175k evts in 2/fb with a B/S = 0.4

- A precision of ±0.005 on ω_{SS} = 0.309 can be obtained in a fit to the asymmetry.

- Combination with SS kaon tagging almost doubles the effective tagging power! ε_{eff} of SSk alone is 3.8%



Tagged as $B_s \rightarrow D_s\pi$

Δm_s= 20/ps

$\sigma(\omega_{SS})/\omega_{SS}$~1.6% with 2/fb

Differential decay rates

$$\frac{d^4\Gamma(\mathrm{B}^0_s \to f)}{dt\; d\Omega} \propto \sum_{k=1}^{6} h_k(t)\, g_k(\Omega)$$

$$\frac{d^4\Gamma(\overline{\mathrm{B}}^0_s \to f)}{dt\; d\Omega} \propto \sum_{k=1}^{6} \bar{h}_k(t)\, g_k(\Omega)$$

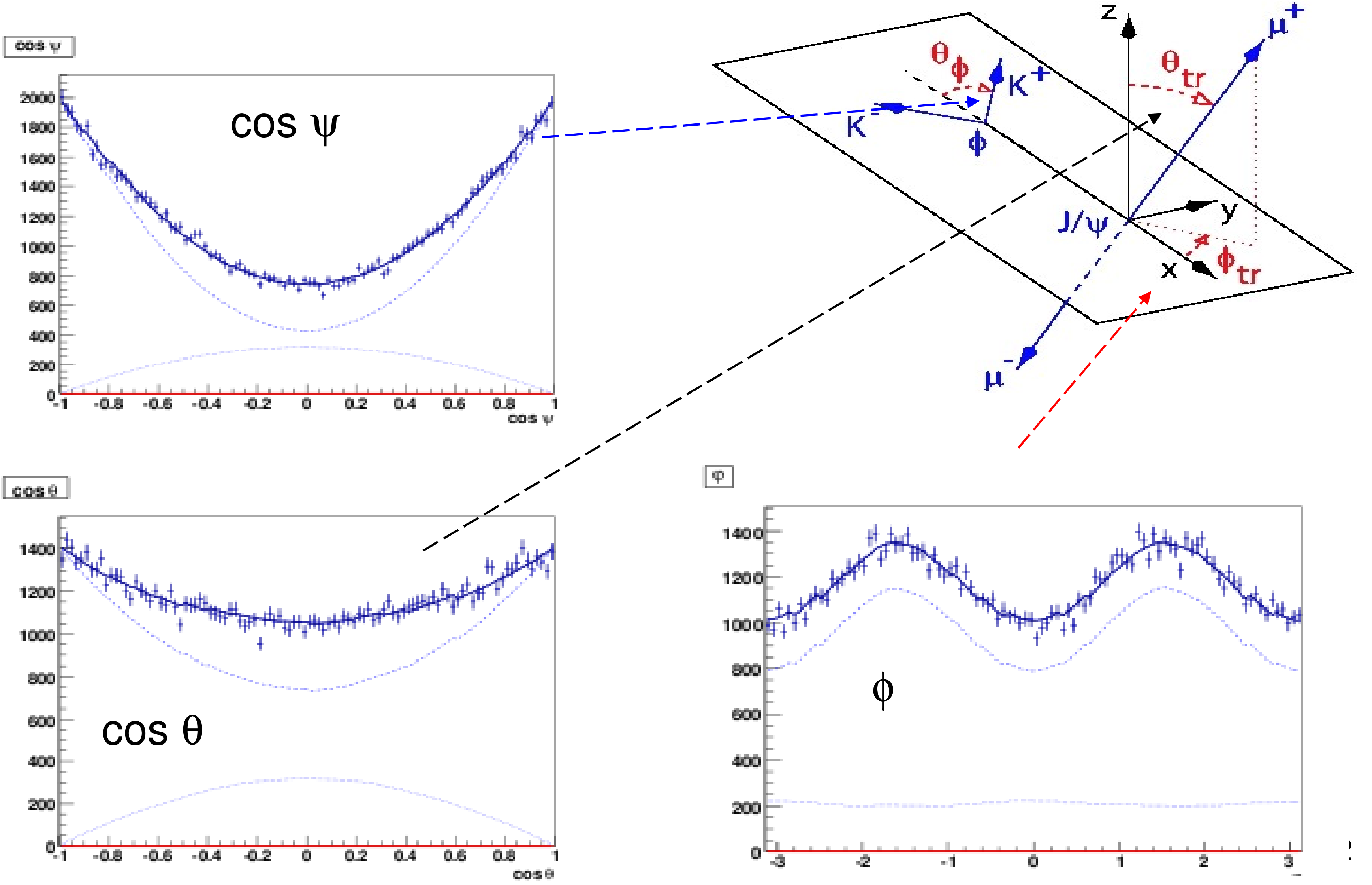
$(f = \mathrm{J}/\psi\phi \;\; \text{or} \;\; \phi\phi)$

Time-dependent part

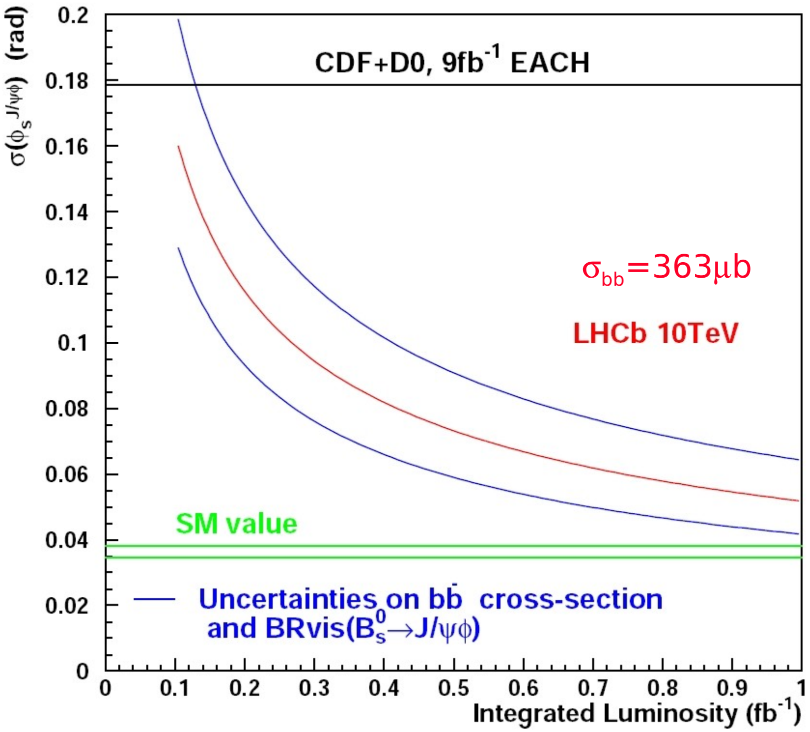
Angular-dependent part

k	$h(t)$	$g_{\mathrm{J}/\psi\phi}(\theta,\psi,\varphi)$	$g_{\phi\phi}(\theta_1,\theta_2,\varphi)$
1	$\|A_0(t)\|^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\|A_{\|\|}(t)\|^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\varphi)$
3	$\|A_\perp(t)\|^2$	$\sin^2\psi\sin^2\theta$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\varphi)$
4	$\mathrm{Re}\{A_0^*(t)A_{\|\|}(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\varphi$
5	$\mathrm{Im}\{A_{\|\|}^*(t)A_\perp(t)\}$	- $\sin^2\psi\sin 2\theta\sin\varphi$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\varphi$
6	$\mathrm{Im}\{A_0^*(t)A_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\varphi$

- Simultaneous likelihood analysis in time, mass, full 3d-angular distribution
- Include mass sidebands to model proper time spectrum and bkg distributions

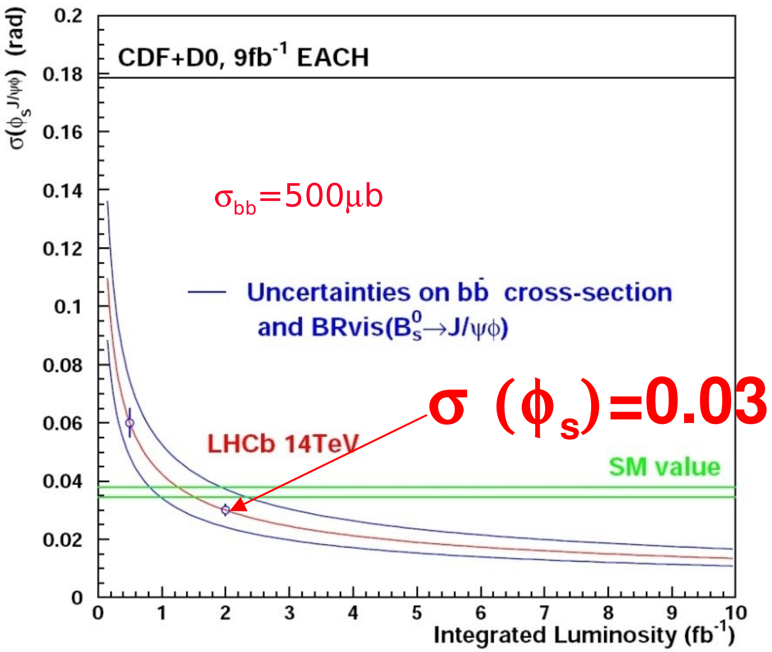


Sensitivity: $\sigma(\phi_s)$



0.2 fb^{-1} (10 TeV):

$\sigma_{LHCb}(\phi_s) < \sigma_{TeVatron}(\phi_s)$



$\sigma(\phi_s)=0.03$

2 fb^{-1} (14 TeV)

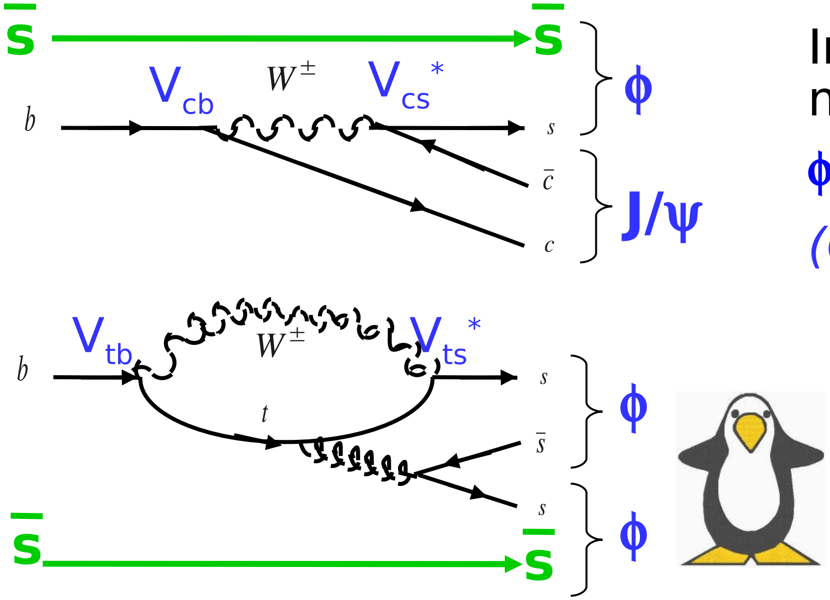
σ(LHCb) ~ ϕ(SM)

If $\phi_{TeVatron} = \phi_{true}$

LHCb 5σ discovery!

For 200/pb integrated luminosity at 7 TeV → 5.3k events, $\sigma_{stat}(\phi_s)\sim 0.12$

b → s$\bar{s}$s hadronic penguin decays



In the SM penguin, cancellation of the mixing and decay phases:

$\phi^{\phi\phi} = 2\arg(V_{ts}^{*}V_{tb}) - \arg(V_{tb}V_{ts}^{*}/V_{tb}^{*}V_{ts}) \approx 0$

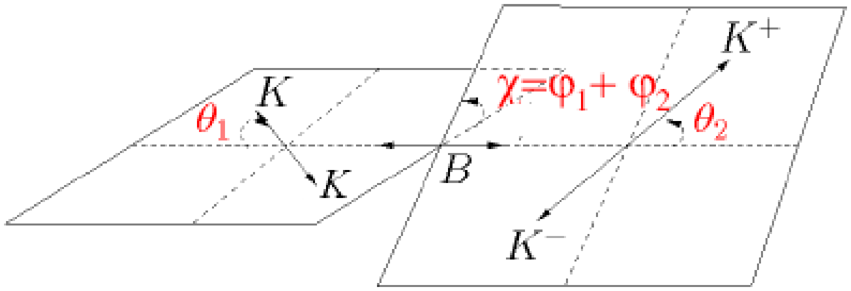
(CP violation in SM < 1%)

$$\phi_s^{J/\psi\phi} = -2\beta_s + \Phi_M^{NP}$$

$$\phi^{\phi\phi} = \Phi_M^{NP} + \Phi_D^{NP}\,.$$

⇒ **good ground to search for New Physics!**

Angular analysis of decay to two vector particles ⇒ time-dependent CP asym.



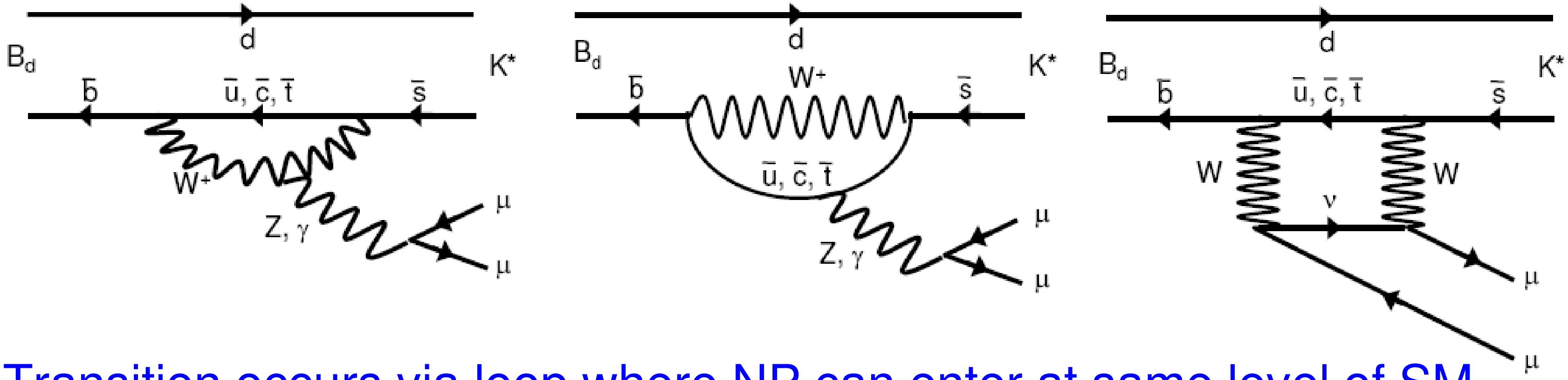
$$\frac{d\Gamma(t)}{d\cos\theta_1\, d\cos\theta_2\, d\varphi_1\, d\varphi_2} \propto \left| \sum_{h=0,\pm1} H_h(t) D^{1*}_{h,0}(\varphi_1,\theta_1,0) D^{1*}_{h,0}(\varphi_2,\theta_2,0) \right|^2$$

Expect 6.2k events/year
B/S < 0.8 at 90% CL
Proper time resolution: 43 fs
Tagging ε D^2 ~ 9.6%

Sensitivity
σ($\phi^{\phi\phi}$) ~ 0.08 for 2/fb
σ($\phi^{\phi\phi}$) ~ 0.03 for 10/fb

FCNC Rare Decays: $B^0 \rightarrow K^*\mu\mu$

- SM amplidudes small wrt to possible contributions of NP models
- theory error small wrt variations among models
- difference in various models large wrt statistical accuracy achievable from data



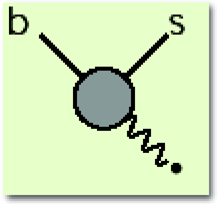
Transition occurs via loop where NP can enter at same level of SM

Treat with Operator Product Expansion, model independent approach

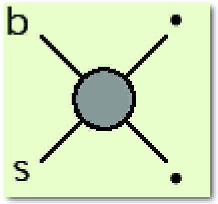
$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \left[C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)\right]$$

Wilson Coefficients parametrising short distance effect

right handed operators suppressed in SM



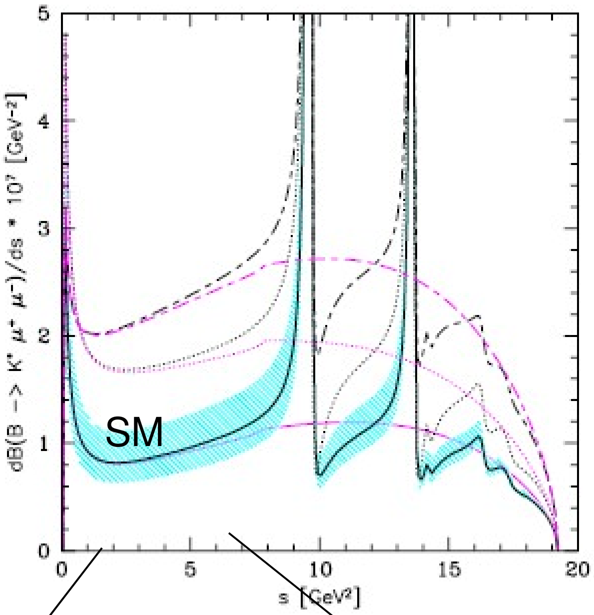
$O_{7\gamma}$

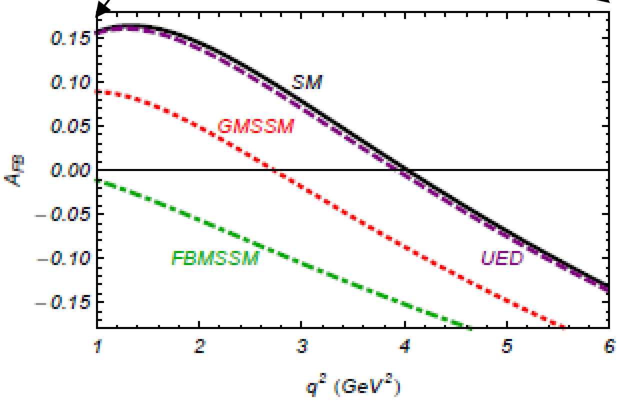


$O_{9,10}$

- The forward-backward asymmetry arises from the interference between γ and Z^0 contributions

$$A_{FB}\left(s=m^2_{\mu\mu}\right)=-C_{10}\,\xi\left(s\right)\left[\mathrm{Re}\left(C_9\right)F_1+\frac{1}{s}C_7F_2\right]$$





- The zero crossing point is most theoretically clean as the form factors cancel out at LO

$$s_0^{SM}=4.36^{+0.33}_{-0.31}\,\mathrm{GeV}^2$$

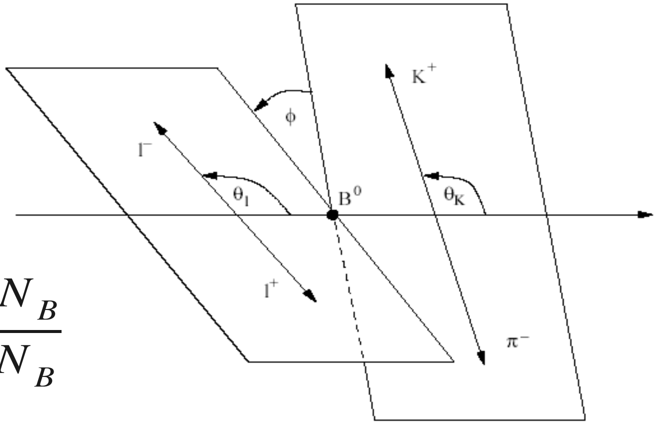
Beneke et al; EPJC41 (2005) 173

Gives access to the Wilson's coefficients ratio C_7/C_9

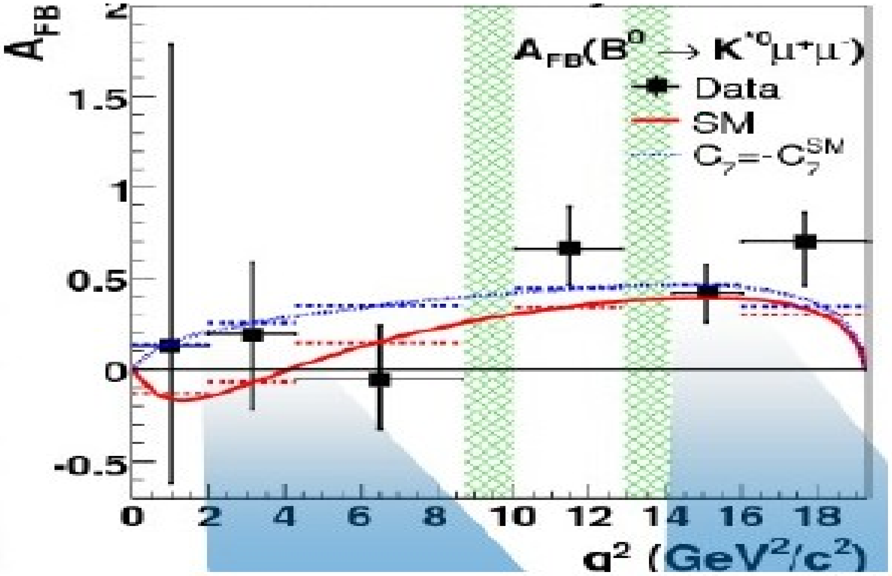
A_{FB} in B → K*μμ

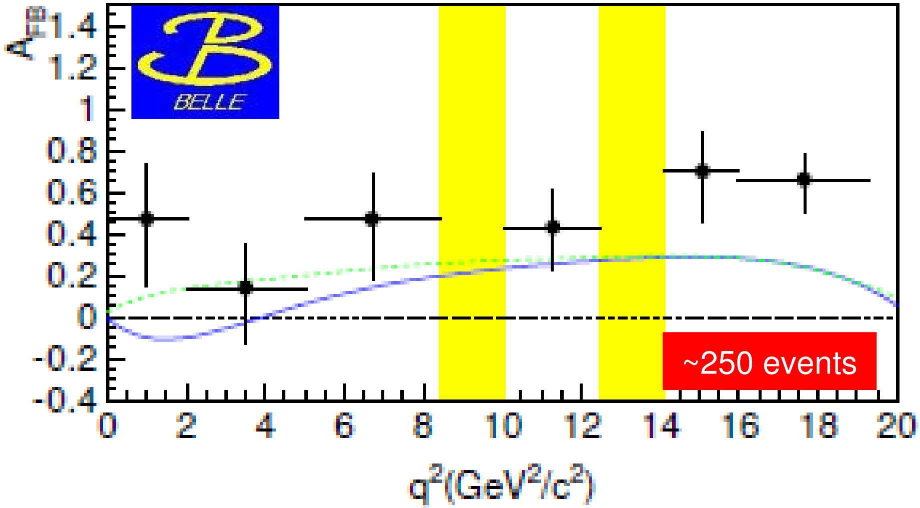
Decay first observed at Belle
BR = 1.1 10^{-6} with 25% error

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



Recent results on A_{FB} show interesting behaviour





Data tend to stay above the SM curve. Is the sign of C_7 wrong ?

Results from Babar show similar trend..

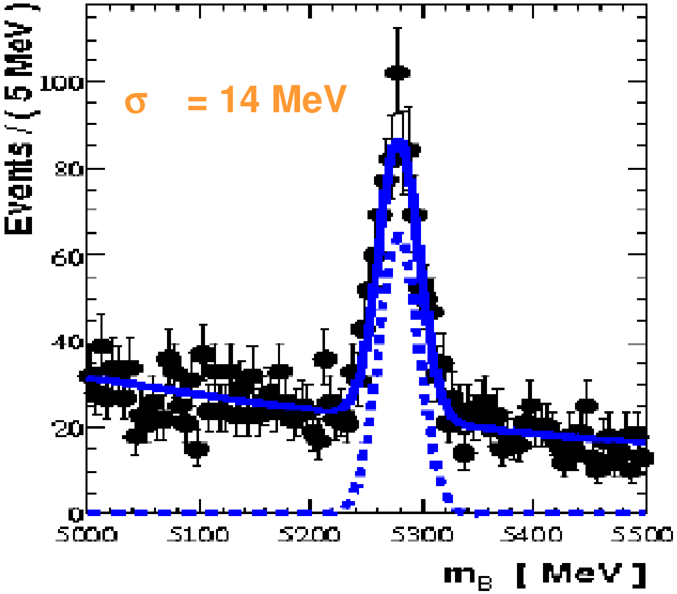
(LHCb will need ~30/pb data to get equivalent sample to CDF)

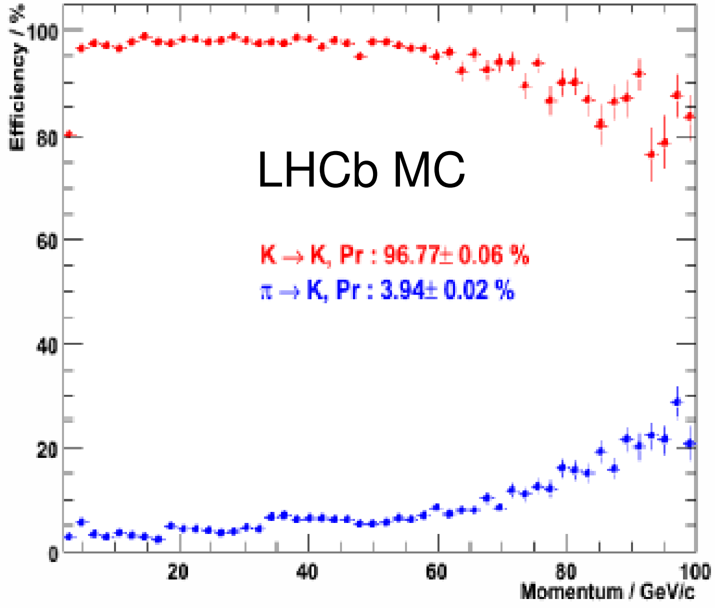
Signal selection

- Selection uses B_d vertex and daughter 4-momenta to fully reconstruct the decay

- B_d vertex resolution ~130μm
- Track momentum Δp/p~0.5%
- μ ID performance important
  Mis-ID = 2% with ID ε= 94%
  π/K separation from RICH's
  – Suppresses comb. background

- Cut-based and multivariate selection have been considered:
In 2/fb expect 6.2±1.5 k events
$S/\sqrt{(S+B)} = 70\pm10$





A_{FB}, counting experiment

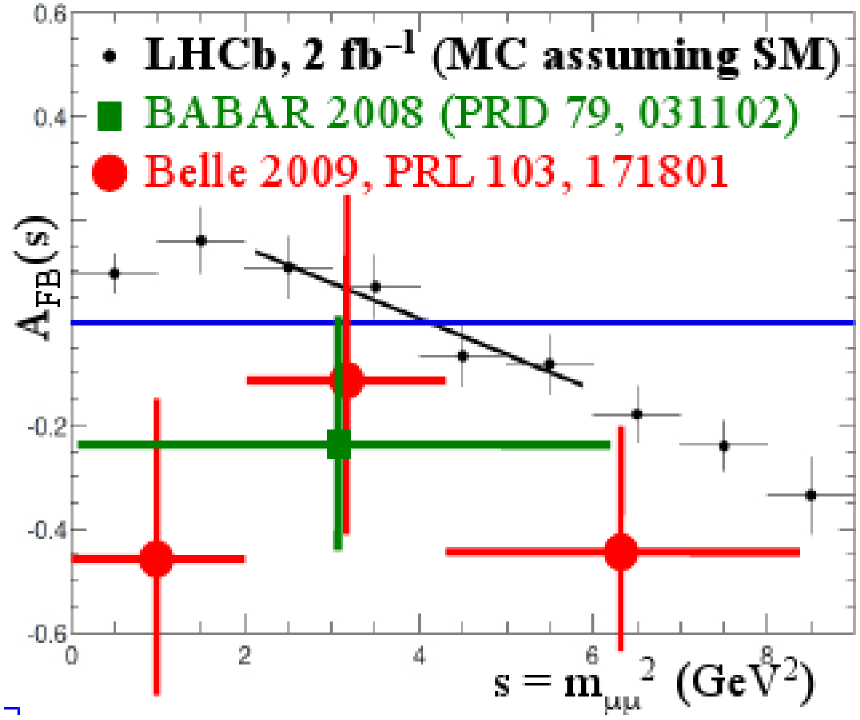
- It is possible to extract A_{FB} by just counting forward and backward muons
  - relatively simple procedure
  - works already at low statistics, **0.5 – 2 /fb**

Allows zero-crossing extraction

- precision is proportional to slope
- σ (s_0) ~ 0.8 GeV^2 for 0.5/pb
- σ (s_0) ~ 0.5 GeV^2 for 2/pb

Background with intrinsic FB asymmetry (such as cascade decays) can bias the zero point measurement

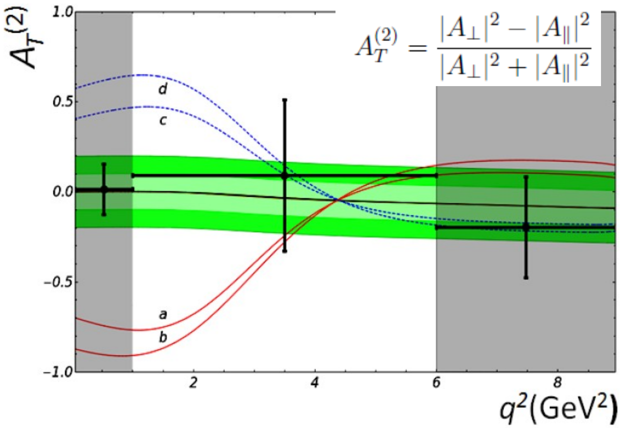
→ Will use mass sidebands and control channels like B → J/ΨK*



Projection and full angular fits

- Use shape of the distributions to constrain more, will need **2 – 4 /fb**

$$\begin{aligned}
\frac{d\Gamma'}{d\phi} &= \frac{\Gamma'}{2\pi}\left(1+\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{Im}\sin 2\phi\right)\\
\frac{d\Gamma'}{d\theta_l} &= \Gamma'\left(\frac{3}{4}F_L\sin^2\theta_l+\frac{3}{8}(1-F_L)(1+\cos^2\theta_l)+A_{\rm FB}\cos\theta_l\right)\sin\theta_l\\
\frac{d\Gamma'}{d\theta_K} &= \frac{3\Gamma'}{4}\sin\theta_k\left(2F_L\cos^2\theta_K+(1-F_L)\sin^2\theta_K\right)\ .
\end{aligned}$$

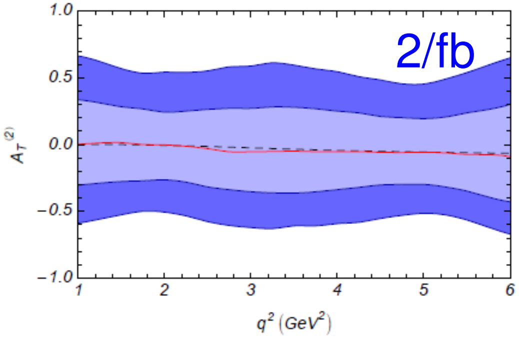


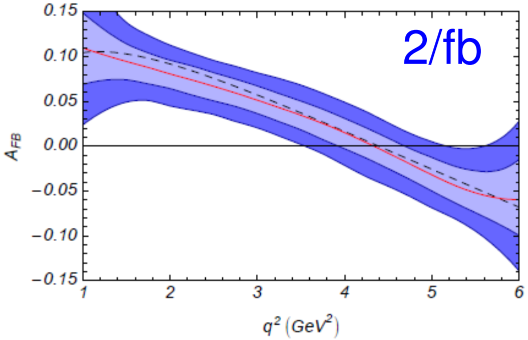
make simultaneous fit in q^2 bins improves A_{FB} precision by a factor 2, also gives access to $A_T^{(2)}$ albeit weakened by large F_L value

- Full angular fit has also been studied

$$\frac{d^4\Gamma_{\overline{B}_d}}{dq^2\,d\theta_l\,d\theta_K\,d\phi} = \frac{9}{32\pi}I(q^2,\theta_l,\theta_K,\phi)\sin\theta_l\sin\theta_K$$

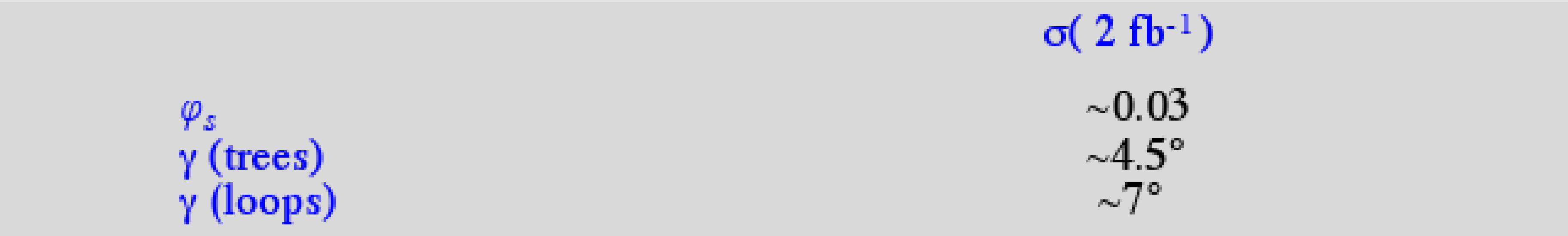
  - parametrized in term of transv. amplitudes can form any observables
  - will be feasible with larger statistics, **3 – 10 /fb**
  - improves precision on A_{FB} by about 30% wrt projection fits





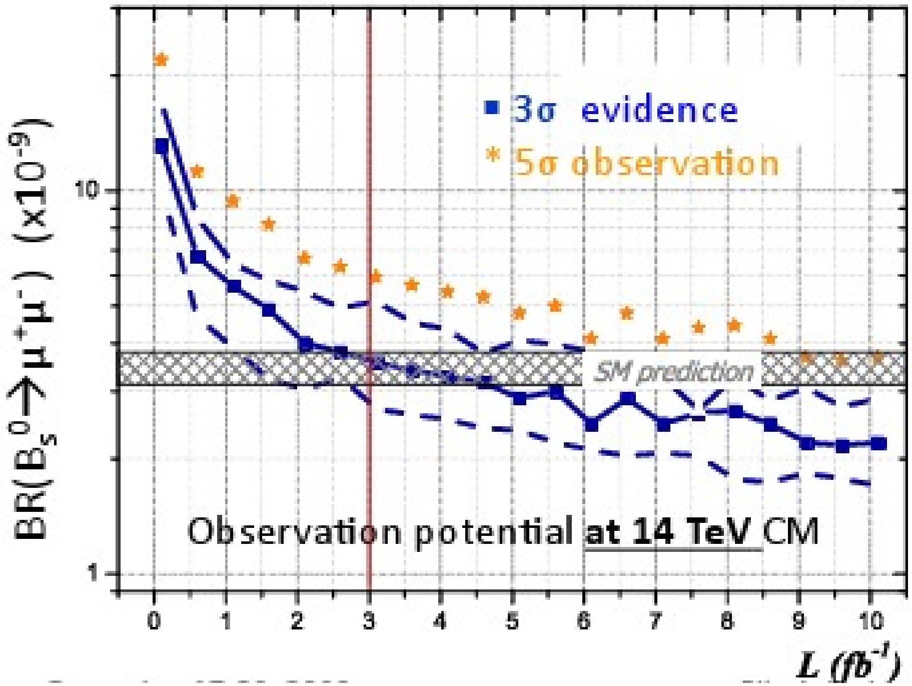
Key measurements at LHCb

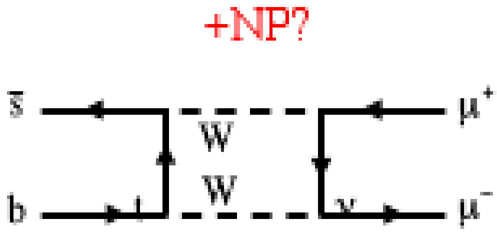
In two year time LHCb will get unprecedented precision in B_d and B_s measurements

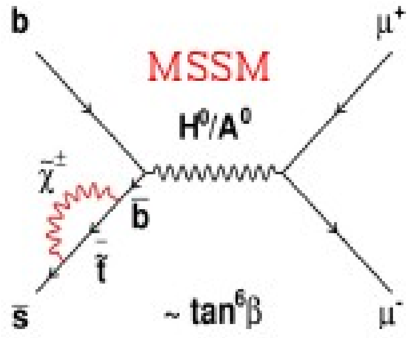


	$\sigma(2\ \mathrm{fb}^{-1})$
φ_s	~0.03
γ (trees)	~4.5°
γ (loops)	~7°

$Br(B_s \to \mu^+\mu^-)$	3σ measurement (SM)
$B_d \to K^{*0}\mu^+\mu^-$	$\sigma(s_0)=0.5\ \mathrm{GeV}^2$
γ polarization in radiative Penguin decays	$\sigma_{stat}(A_R/A_L) = 0.1$ (in $B_S \to \phi\gamma$) $\sigma_{stat}(A_R/A_L) = 0.1$ (in $B_d \to K^* e^+ e^-$)

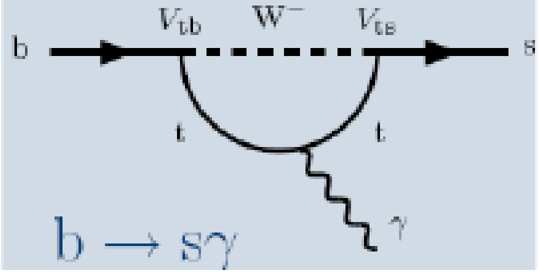






In LHCb using the $B_s \to \varphi\gamma$ decay measurements
time-dependent analysis of 11k signal events for 2 fb^{-1},
(B/S < 0.9; m resolution ~ 100 MeV/c^2; τ resolution ~ 90 fs

$\sigma_{stat}(A_R / A_L) \sim 0.11$



- Most numbers in this talk are taken from arXiv:0912.4179 [hep-ex]

  “Road map for selected key measurements from LHCb”

Conclusion

- **$B_s \rightarrow J/\Psi(\mu\mu)\phi$ hot topic and promising way to discover NP at LHCb**
  But no question, one of the most demanding !

- **Tevatron expects $\sigma(2\beta_s) \sim$ 0.13 by end 2010**
  LHCb with next year data → **$\sigma(2\beta_s) \sim$ 0.12**
  In one nominal year data → **$\sigma(2\beta_s) \sim$ 0.03**

- **Excellent prospects for NP in $B \rightarrow K^*\mu\mu$**
  expect O(6k) signal events per year over q^2
  already with 0.07/fb same precision as
  Babar and Belle on A_{FB}

Exciting and long term physics programme!