Measurement of Asymmetries in the B meson system

$q\bar{b}$

Mesonen

$B^+ = \left\lvert u\bar{b} \right\rangle$	$B^- = \left\lvert \bar{u}b \right\rangle$	$\tau_{B^0} \approx 1.5$ ps
$B^0 = \left\lvert d\bar{b} \right\rangle$	$\bar{B}^0 = \left\lvert \bar{d}b \right\rangle$	$m_B \approx 5.28$ GeV/c^2
$B_s^0 = \left\lvert s\bar{b} \right\rangle$	$\bar{B}_s^0 = \left\lvert \bar{s}b \right\rangle$	$m_B \approx 5.37$ GeV/c^2

Anti-Mesonen

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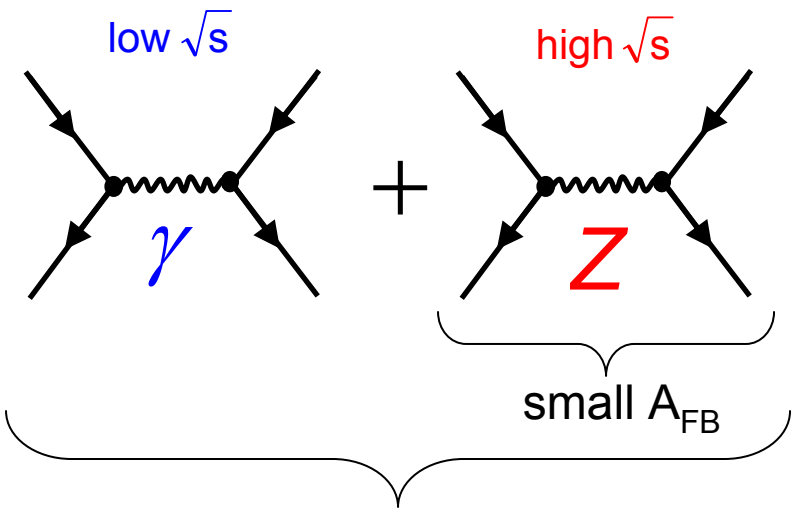
Neckarzimmern 2009

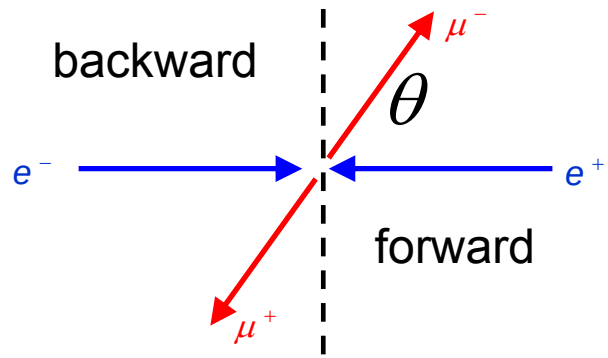
Asymmetries

Asymmetries very often give access to interference effects and offer the possibility to measure phases.

Historical example



Interference → A_{FB} also at low $\sqrt{s}$



$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

$A_{FB}(e^+e^- \to \mu^+\mu^-)$

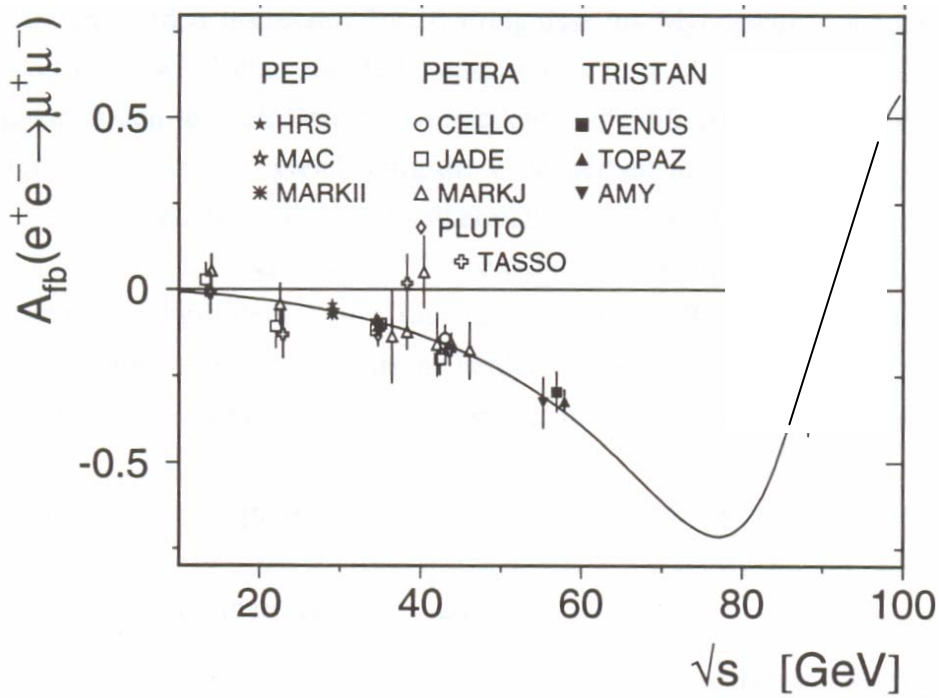
PETRA (1980s):

Clear interference of Z boson seen

LEP (1990s):

Measurement of the Z coupling,
At Z pole: no interference,
very small A_{FB} from Z couplings (~1%)

$$A_{FB} \sim g_A^e \underline{g_V^e} g_A^f \underline{g_V^f}$$



$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Systematic effects:

- Luminosity
- Time dependent detector effciciencies
- Acceptance, selection efficiencies

} Cancel in 1st order !

Typ. systematic error: +/- 0.1% !!!!!!

Mixing Phenomenology

Flavor eigenstates

$$\left|B_q^0\right\rangle = \left|\bar{b}q\right\rangle \qquad \left|\bar{B}_q^0\right\rangle = \left|b\bar{q}\right\rangle$$

Production =
pure flavor states

$$i\frac{d}{dt}\begin{pmatrix}\left|B_q^0(t)\right\rangle \\ \left|\bar{B}_q^0(t)\right\rangle\end{pmatrix} = \left(\underline{\underline{M_q}} - \frac{i}{2}\underline{\underline{\Gamma_q}}\right)\begin{pmatrix}\left|B_q^0(t)\right\rangle \\ \left|\bar{B}_q^0(t)\right\rangle\end{pmatrix}$$

Mass eigenstates

$$\left|B_L\right\rangle = p\left|B^0\right\rangle + q\left|\overline{B^0}\right\rangle \quad \text{with } m_{L,}\Gamma_L$$

$$\left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\overline{B^0}\right\rangle \quad \text{with } m_{H,}\Gamma_H$$

$$|p|^2 + |q|^2 = 1$$

$$\left|B_{H,L}(t)\right\rangle = \left|B_{H,L}(0)\right\rangle \cdot \underbrace{e^{-im_{H,L}t} \cdot e^{-\frac{1}{2}\Gamma_{H,L}t}}_{b_{H,L}(t)}$$

Mixing Observables

Mass difference and decay width difference

$$\Delta m_q = m_H - m_L$$

$$\Delta\Gamma_q = \Gamma_L - \Gamma_H$$

can be linked to eigen-values of mixing matrix

$$\Phi_{M/\Gamma} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$$\Delta\Gamma_q = 2\left|\Gamma_{12}\right|\cos\Phi_{M/\Gamma}$$

$$\Delta m_q = 2\left|M_{12}\right|$$

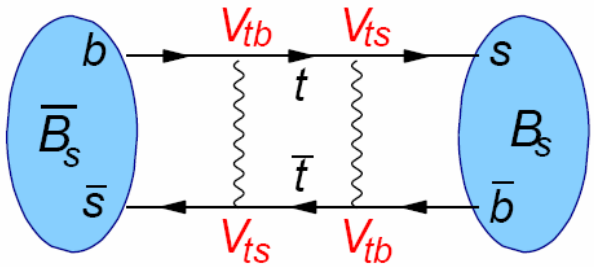
$$\neq \Phi_M = \arg\left(-M_{12}\right)$$

$$a_{fs}^q = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right) = \frac{\left|\Gamma_{12}^q\right|}{\left|M_{12}^q\right|}\sin\Phi_{M/\Gamma} = \frac{\Delta\Gamma}{\Delta M}\tan\Phi_{M/\Gamma}$$

$$\begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12}^* - \frac{i}{2}\Gamma_{12}^* \\ M_{12} - \frac{i}{2}\Gamma_{12} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

$$B_s \quad \begin{array}{l} \Phi_{M/\Gamma}^{SM} = 3.4 \times 10^{-3} \\ \Phi_M^{SM} = 3.7 \times 10^{-2} \end{array}$$

Oscillation



$$\left|B^0(t)\right\rangle = \frac{\left|B_L(t)\right\rangle + \left|B_H(t)\right\rangle}{2p} = \frac{1}{2p}\left(b_L(t)\cdot\left(p\left|B^0\right\rangle + q\left|\overline{B^0}\right\rangle\right) + b_H(t)\cdot\left(p\left|B^0\right\rangle - q\left|\overline{B^0}\right\rangle\right)\right)$$

Ignoring $\Delta\Gamma$ and assuming q/p=1 (no CP in mixing):

Non-mixed $\quad P(B^0 \to B^0) = \frac{\Gamma}{2} e^{-\Gamma t}\left[1 + \cos(\Delta m t)\right]$

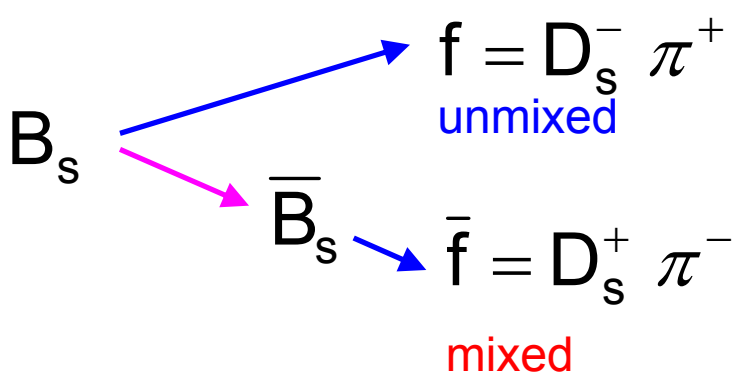
$P(\overline{B^0} \to \overline{B^0})$

mixed $\quad P(B^0 \to \overline{B^0}) = \frac{\Gamma}{2} e^{-\Gamma t}\left[1 - \cos(\Delta m t)\right]$

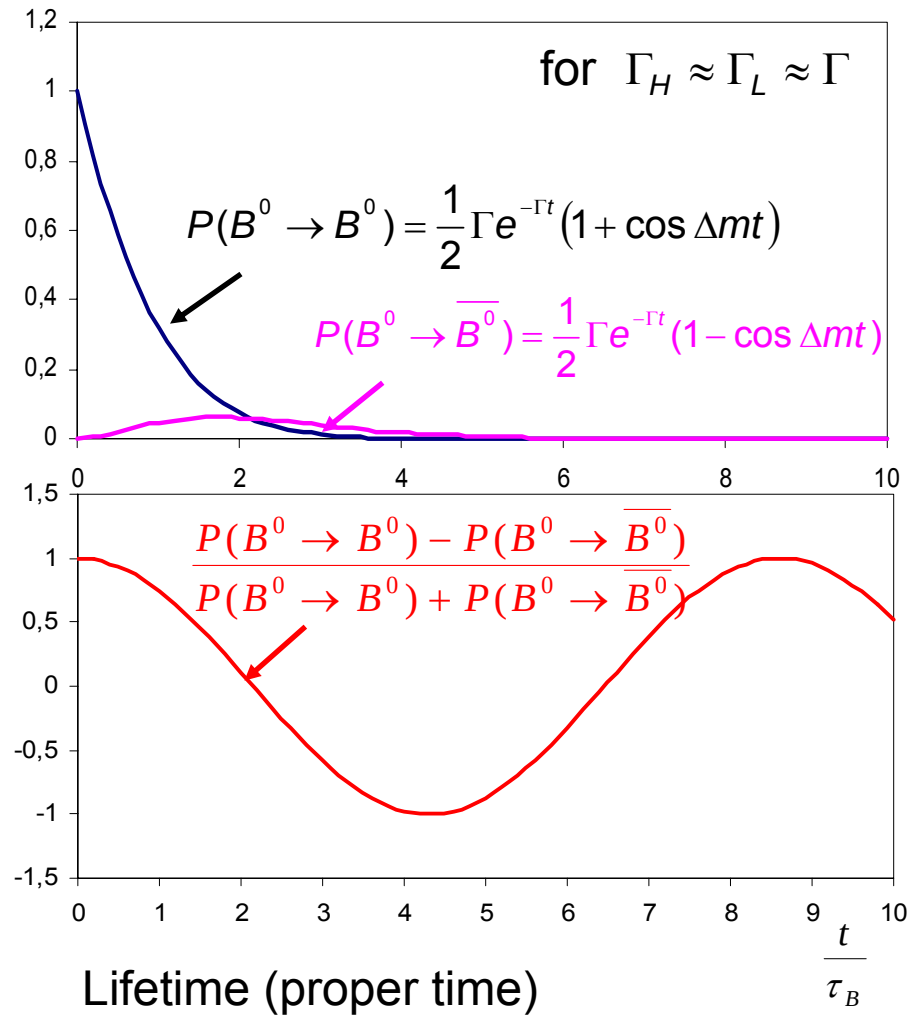
$P(\overline{B^0} \to B^0)$

Mixing Asymmetry

Mixing probability:



$$A(t) = \frac{unmixed(t) - mixed(t)}{unmixed(t) + mixed(t)} = \cos(\Delta m t)$$



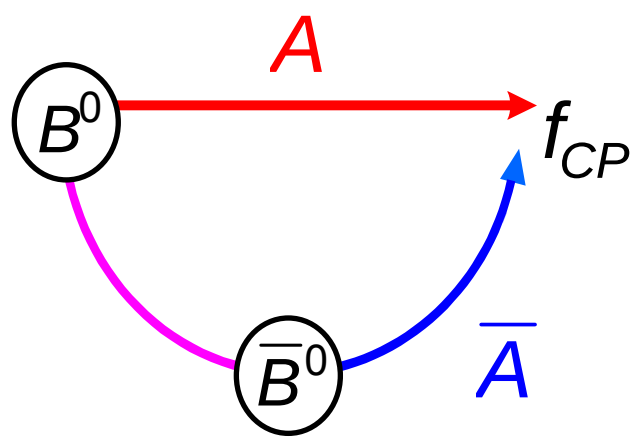
Lifetime (proper time)

CP Asymmetry

$$A_{CP}(t) = \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{\Gamma(\overline{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\overline{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

$$\frac{q}{p} = e^{-i\Phi_M}$$

$$\Phi_M = \arg(-M_{12})$$



$$\mathrm{CP}\left|\mathrm{f_{CP}}\right\rangle = \eta_f \left|\mathrm{f_{CP}}\right\rangle$$

$$\frac{\overline{A}_f}{A_f} = \eta_f e^{-i2\Phi_f}$$

$\frac{q}{p} \neq 1$ CP Violation in mixing

$\frac{\overline{A}_f}{A_f} \neq 1$ CP Violation in decay

CP Asymmetry

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad \Im(\lambda_f) = -\eta_f \sin[2(\Phi_M + \Phi_f)]$$

$$A_{CP}(t) = \frac{\Gamma(\overline{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\overline{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

B^0

$\Delta\Gamma \approx 0$

$\Phi_M = 2\beta$

$$= \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos(\Delta m t)}_{\text{Direct CP violation}} - \underbrace{\frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\sin(\Delta m t)}_{\text{CP violation through interference}}$$

B_s

$\Phi_M = 2\beta_s$

$$= \frac{\eta_f \sin[2(\Phi_M + \Phi_f)]\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) - \eta_f \cos[2(\Phi_M + \Phi_f)]\sinh(\Delta\Gamma t/2)}$$

ignore direct CP violation

Flavor specific asymmetry

$$A_{fs}^{q}(t) = \frac{\Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{f}\right) - \Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{\bar{f}}\right)}{\Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{f}\right) + \Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{\bar{f}}\right)}$$

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

$$B_s^0 \to D_s^- \mu^+ \nu_\mu X^0$$

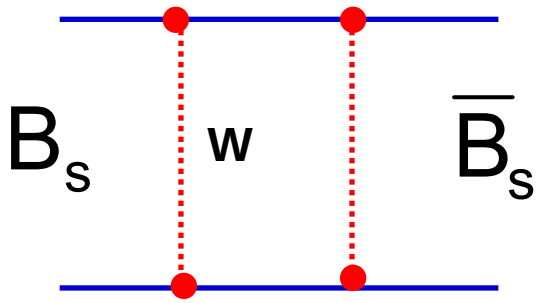
$$= \frac{a_{fs}^q}{2} - \frac{a_{fs}^q}{2} \frac{\cos\left(\Delta m_q t\right)}{\cosh\left(\Delta\Gamma_q t / 2\right)}$$

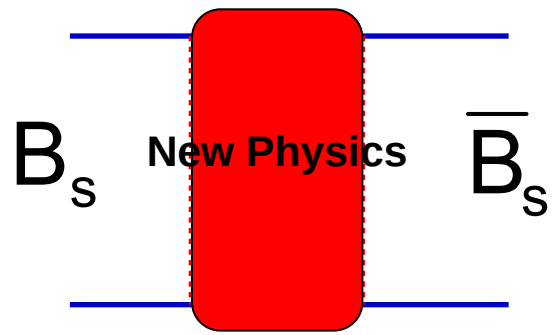
$$\left(a_{fs}^{d}\right)^{SM} = -\left(5.0 \pm 1.1\right) \times 10^{-4}$$

$$\left(a_{fs}^{s}\right)^{SM} = \left(2.1 \pm 0.4\right) \times 10^{-5}$$

$$a_{fs}^q = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right) = \frac{\left|\Gamma_{12}^q\right|}{\left|M_{12}^q\right|} \sin\Phi_{M/\Gamma} = \frac{\Delta\Gamma}{\Delta M} \tan\Phi_{M/\Gamma}$$

New Physics Sensitivity





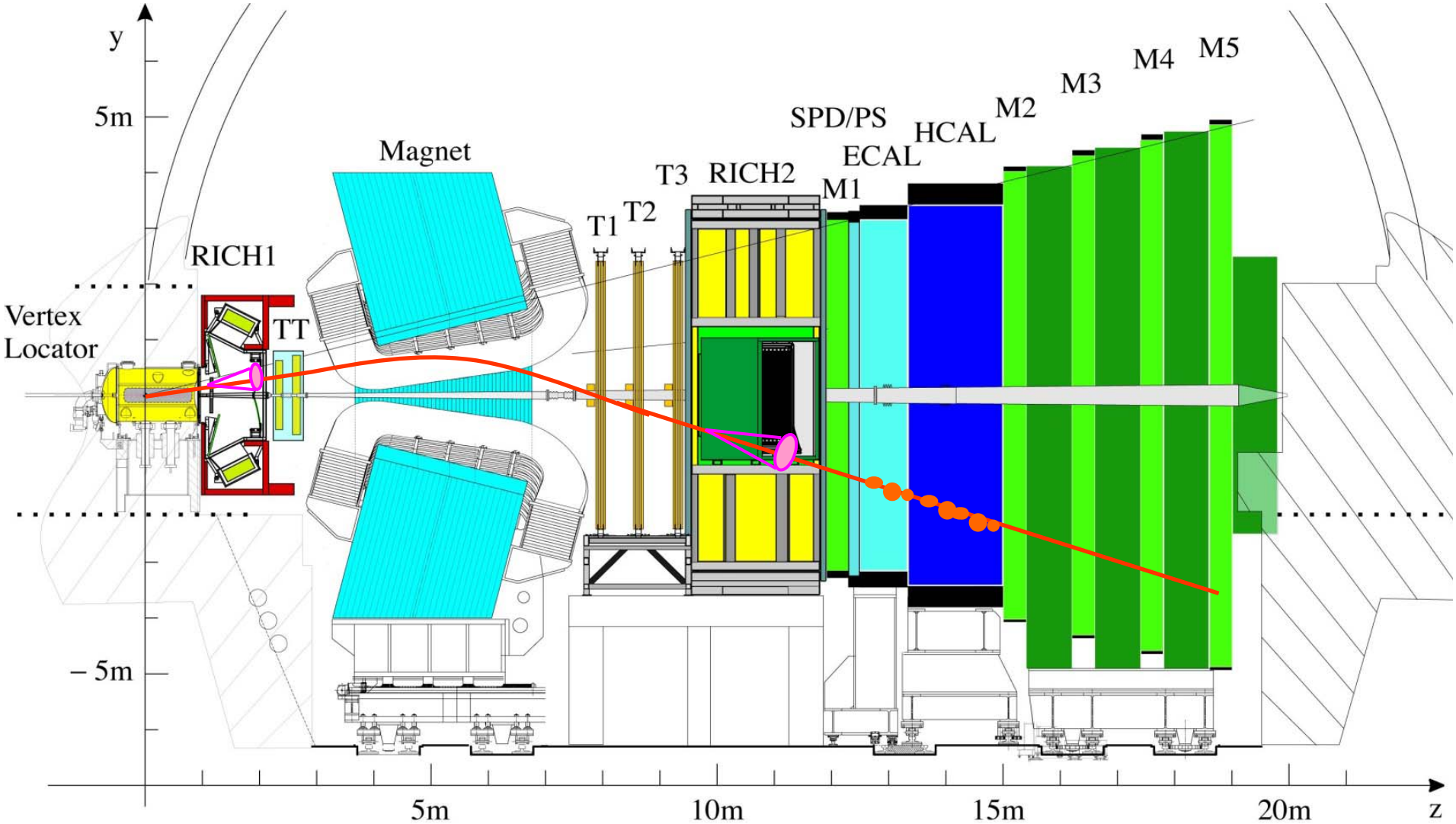
New Physics should effect mostly M_{12} (not Γ_{12}):

$$M_{12} \rightarrow M_{12}^{SM} \cdot \Delta_s = M_{12}^{SM} \cdot \left|\Delta_{NP}\right| \exp(i\phi^{NP})$$

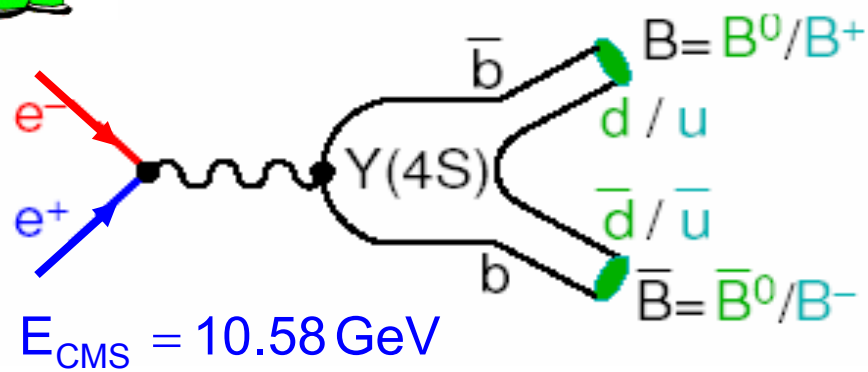
$$\Phi_M \rightarrow \Phi_M^{SM} + \phi^{NP} \qquad \Phi_M^{SM} = -2\beta_s = 0.037$$

$$\Delta\Gamma^{meas} = 2\left|\Gamma_{12}^{SM}\right| \cos\left(\Phi_{M/\Gamma} + \phi^{NP}\right) \qquad a_{fs}^{meas} = \frac{\left|\Gamma_{12}^{SM}\right|}{\left|M_{12}^{SM}\right|} \frac{\sin\left(\Phi_{M/\Gamma} + \phi^{NP}\right)}{\left|\Delta_{NP}\right|}$$

Experiment

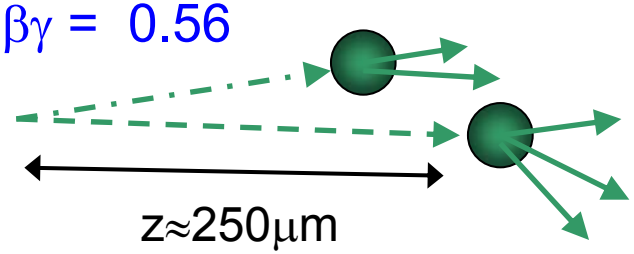

y
5m
– 5m
Vertex
Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

Production of B Mesons

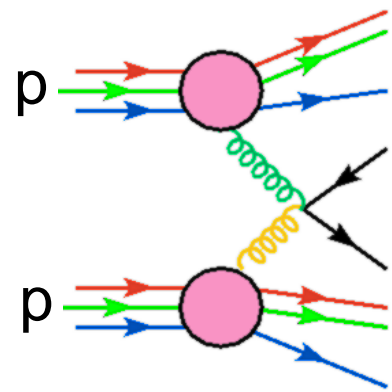


$\sigma_{bb} = 1\,\text{nb}$ ➡ 10 Hz

Boost $\beta\gamma$ = 0.56



Easy to trigger and to record
background level ~ x(3…4)



E_{pp}= 14 TeV

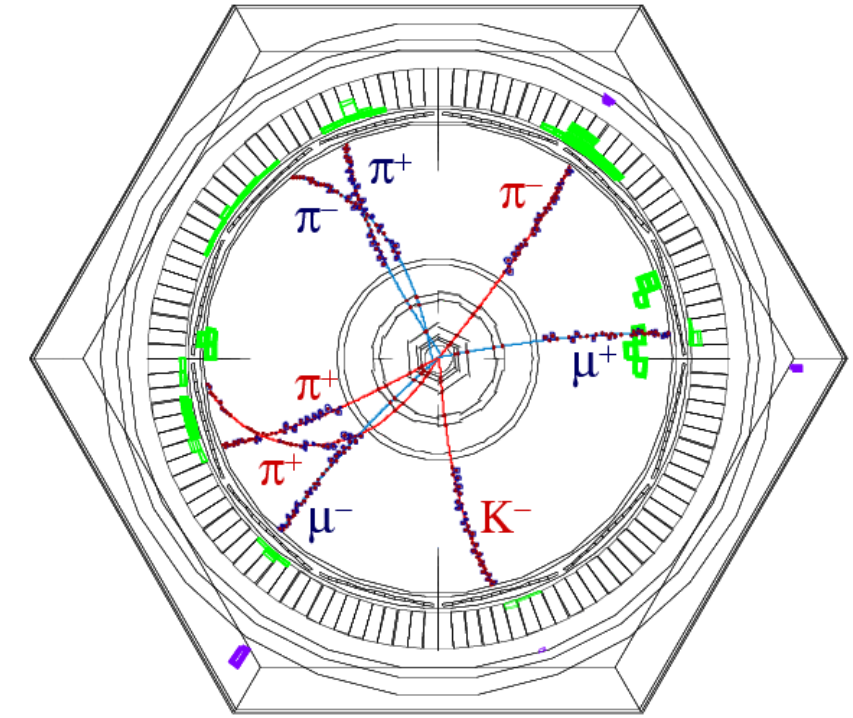
$\sigma_{bb} = 500\ \mu\text{b}$ ➡ 50 kHz

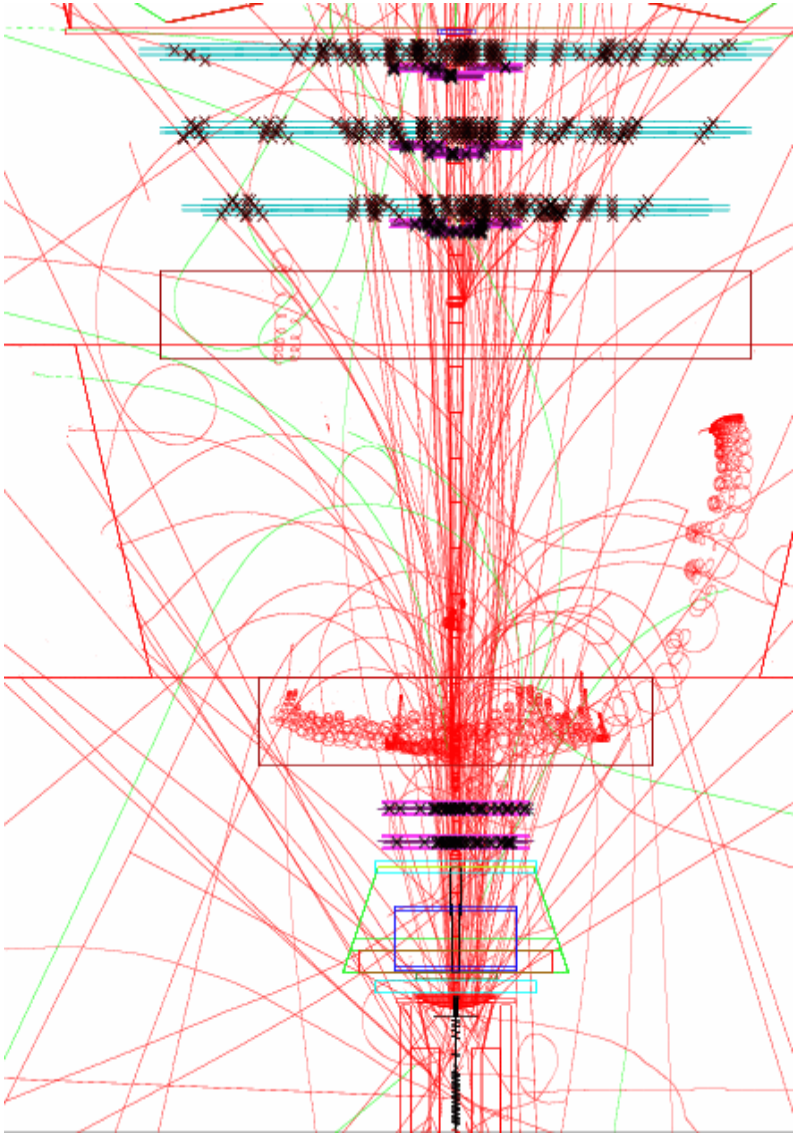
Boost $\beta\gamma$ = 15 … 30

z≈ 7 … 15 mm

Signal looks pretty much like
background (~ x 200)

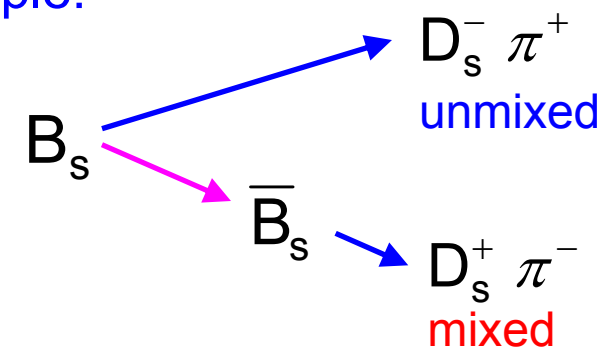
B Events



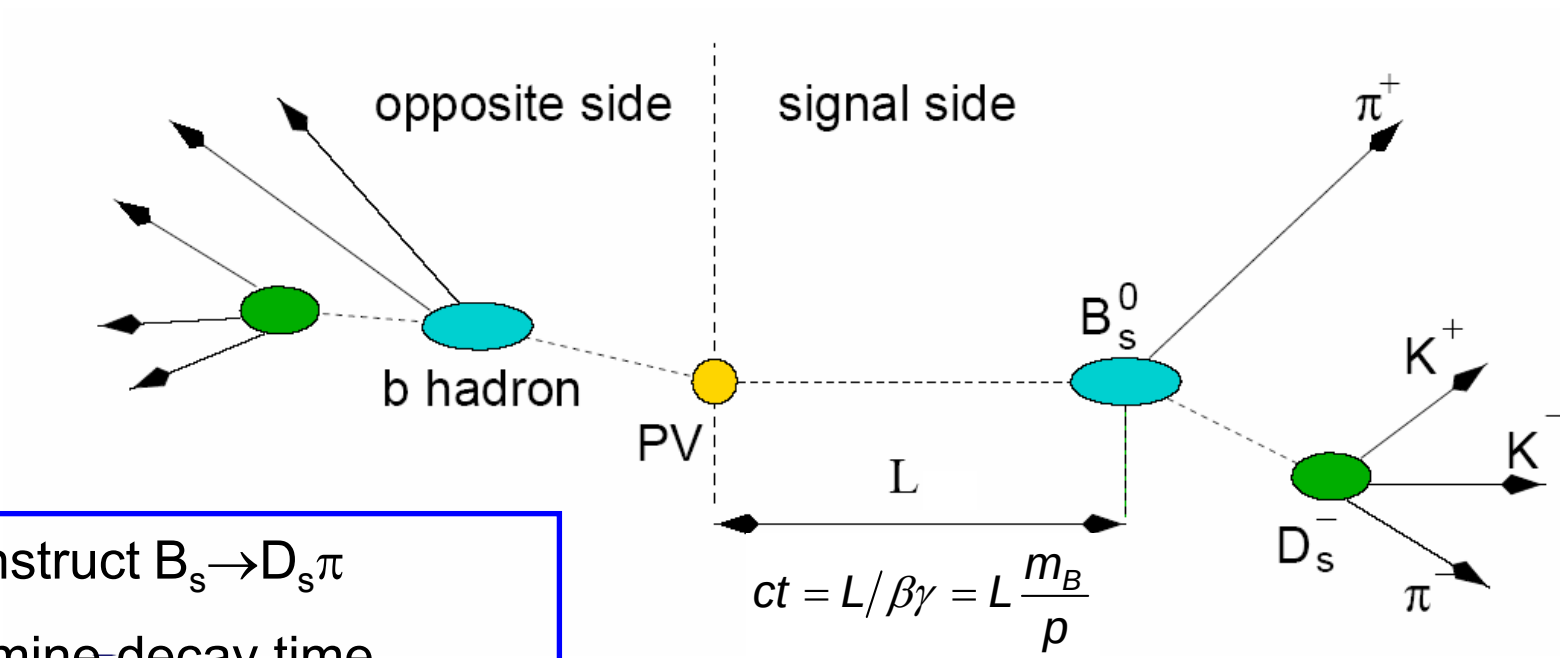


Measuring B_s Mixing

Principle:



$$A(t) = \frac{unmixed(t) - mixed(t)}{unmixed(t) + mixed(t)} = \cos(\Delta m t)$$

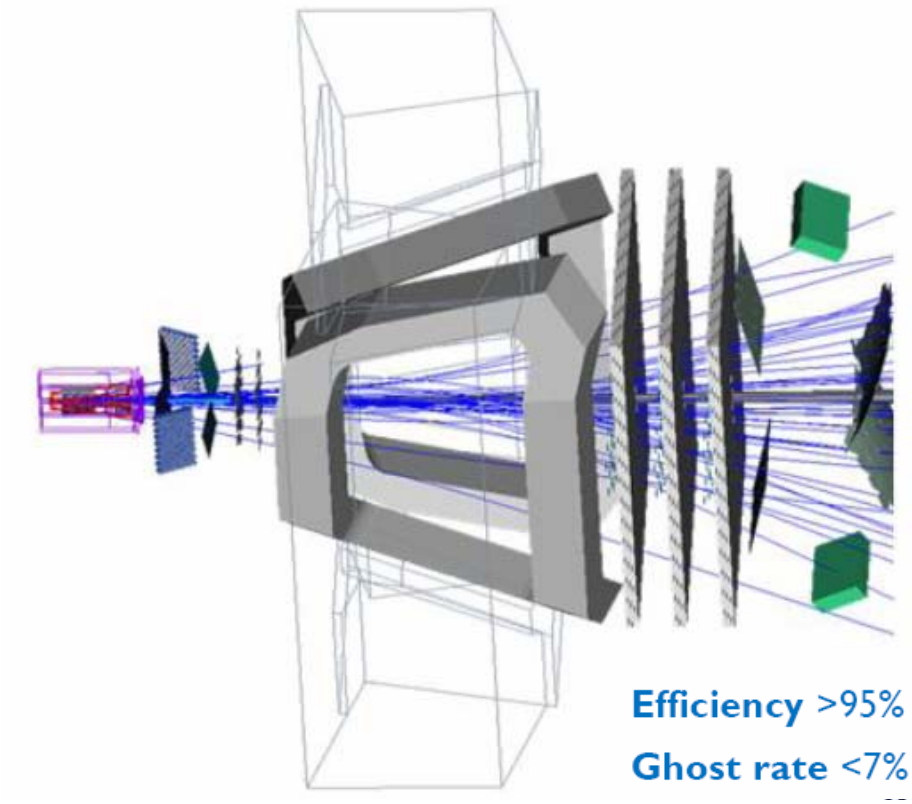


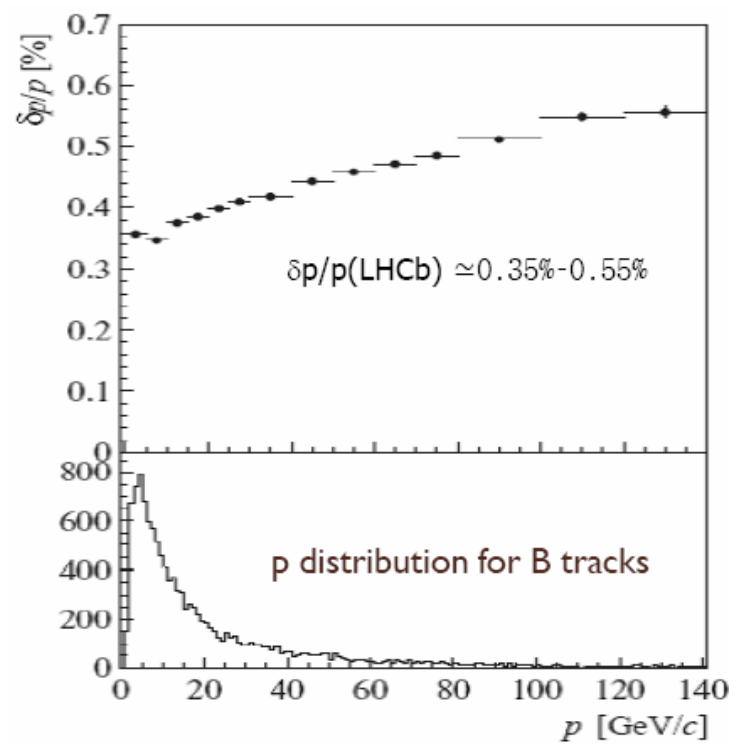
Reconstruct $B_s \rightarrow D_s \pi$

Determine decay time

Determine production flavor

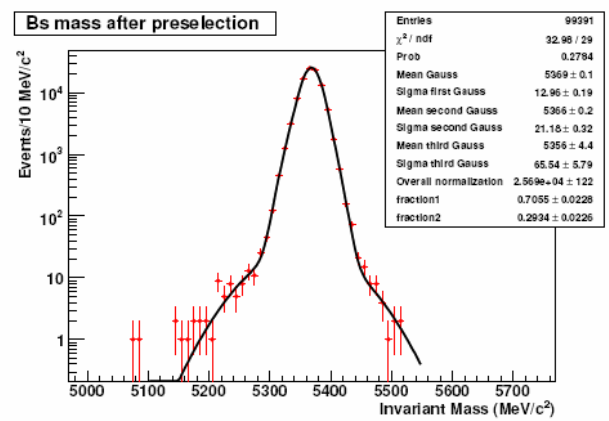
Event Reconstruction: Tracking





Mass Resolution in MeV/c²

	ATLAS	CMS	LHCb
$B_s \to \mu\mu$	80	46	18
$B_s \to D_s \pi$	46	–	14
$B_s \to J/\psi\ \phi$	38	32	16
$B_s \to J/\psi\ \phi$	17	13	8

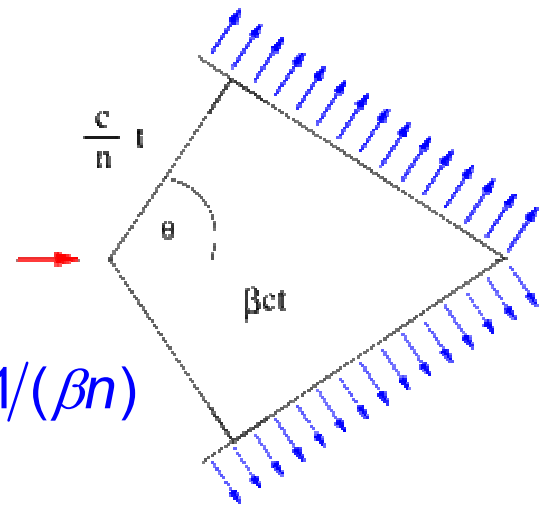


Event Reconstruction: K/π ID

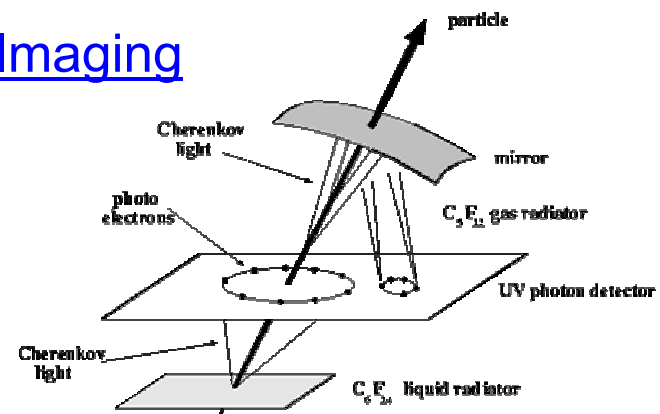
Cherenkov Radiation

if $\beta > \frac{c}{n}$

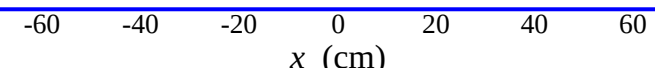
$\cos\theta_c = 1/(\beta n)$



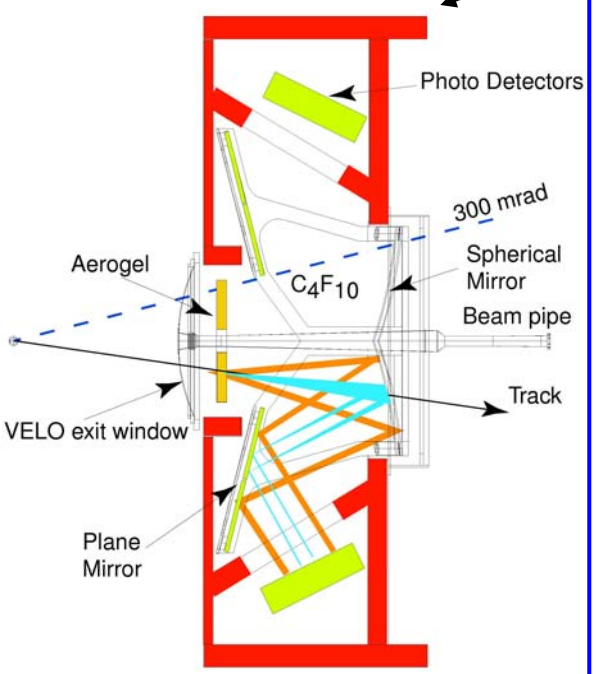
Ring Imaging



Ring radius → θ_c → β

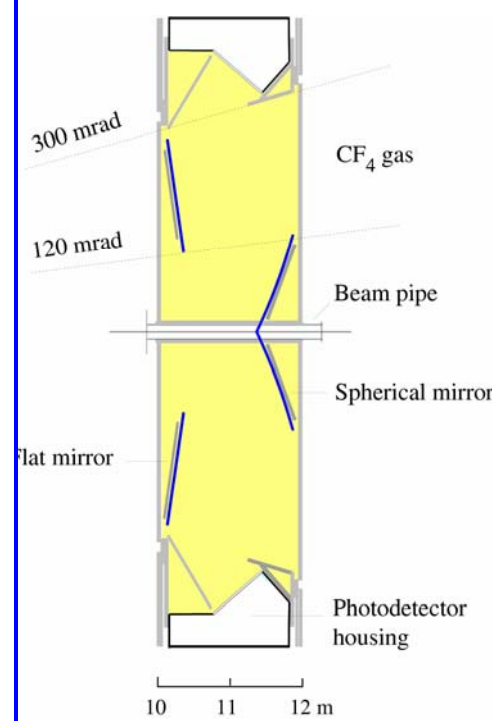


RICH 1



Radiator:
Aerogel n=1.03
C_4F_{10} n=1.0014

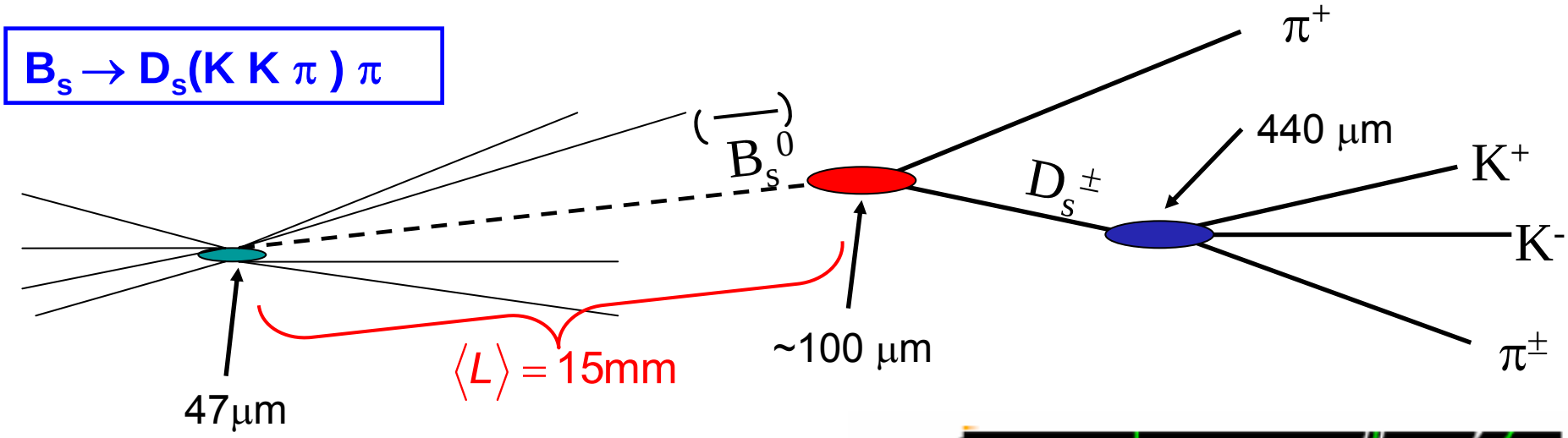
RICH 2



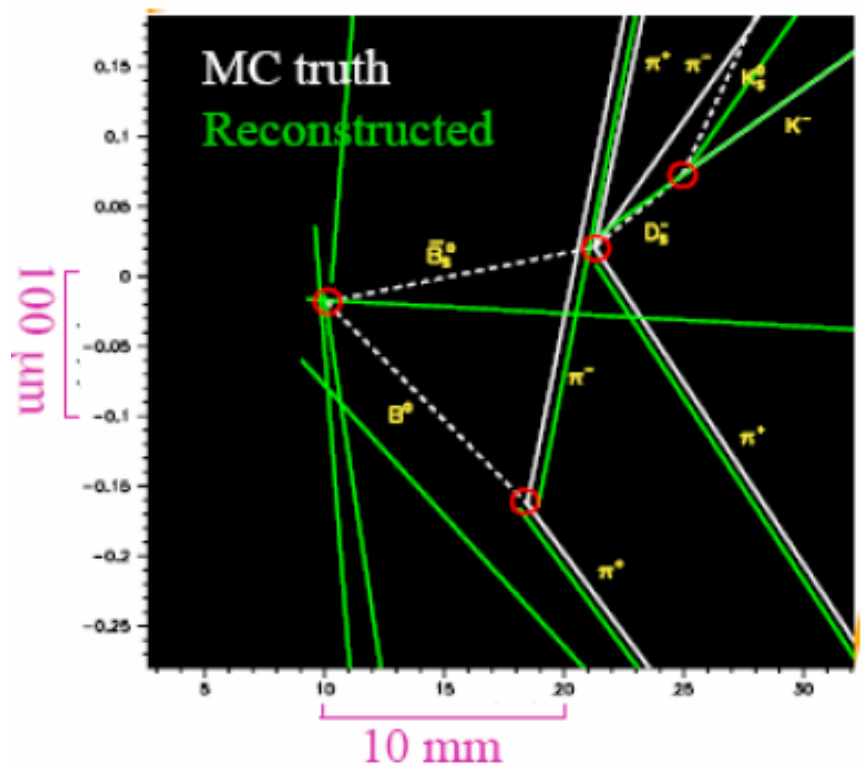
Radiator: CF_4
n=1.0005

Proper Time Measurement

$B_s \rightarrow D_s(K\,K\,\pi)\,\pi$



$$L = c\beta\gamma\, t$$



Proper time resolution

$$ct = \frac{LM_B}{p}$$

$$\sigma_{ct} = \sqrt{(\frac{M_B}{p} * \sigma_L)^2 + (\frac{LM_B}{p^2} * \sigma_p)^2}$$

$$\frac{\sigma_{ct}}{ct} = \sqrt{(\frac{\sigma_L}{L})^2 + (\frac{\sigma_p}{p})^2}$$

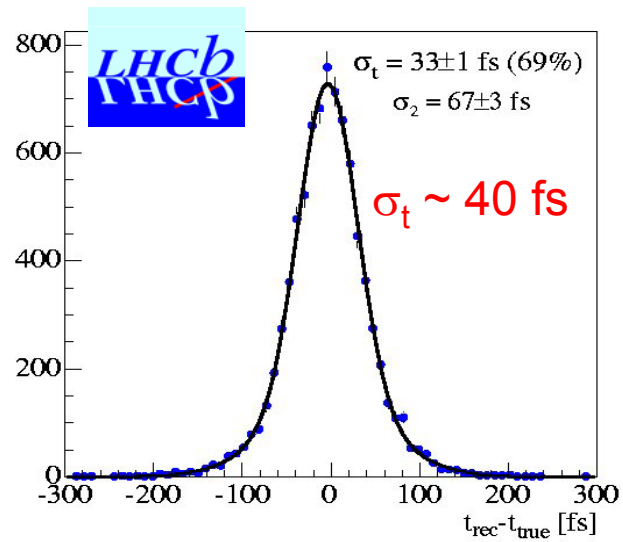
For fully reconstructed B decays:

Relative momentum error < 0.1%

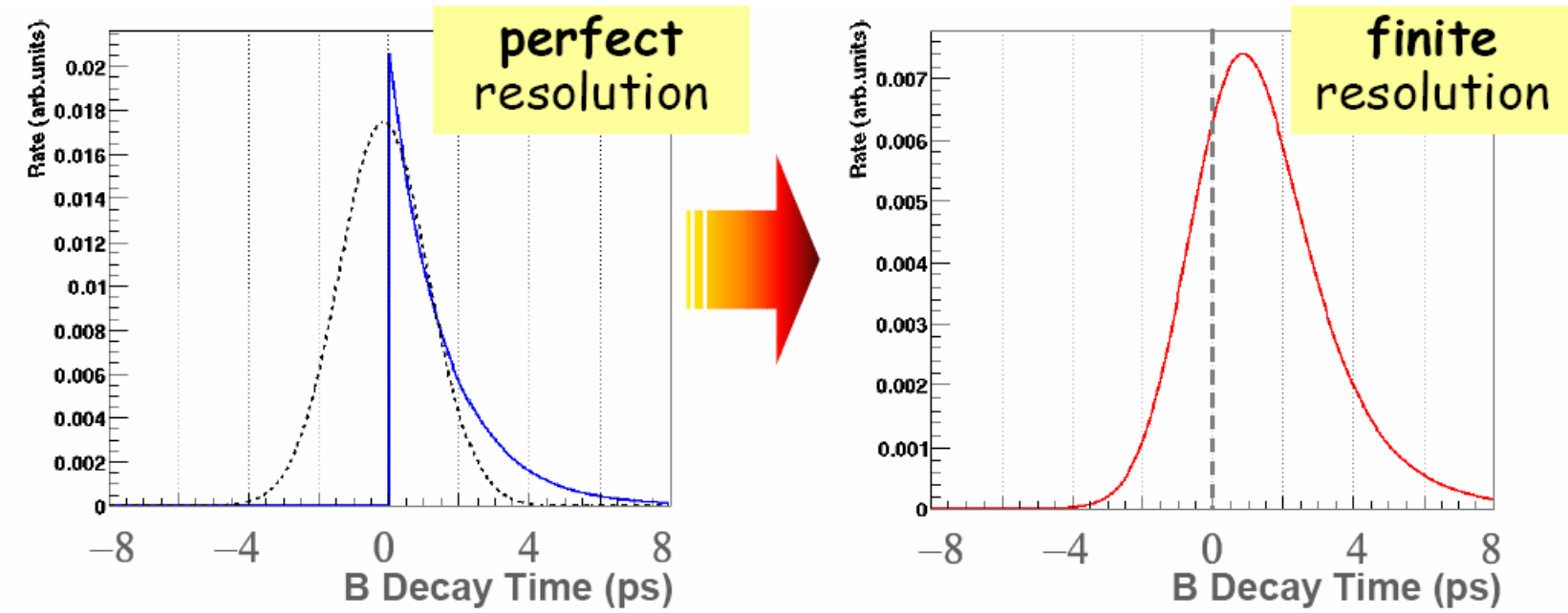
Error dominated by vertex resolution

	<p(B)>	<L>	σ_L	σ_{ct}
CDF	p_T = 12 GeV	L_T = 1.5 mm	25 μm	100 fs
Babar	$p \approx p_z$ = 3 GeV	L_z = 0.25 mm	150 μm	2000 fs
LHCb	$p \approx p_z$ = 50 GeV	L_z = 15 mm	100 μm	40 fs

	ATLAS	CMS
σ_τ [fs]	83	77



Finite Proper Time Resolution



$$e^{-t'/\tau} \otimes G(t,t',\sigma_t) \quad = \quad P(t)$$

also effects the seen asymmetry (see below)

Measurement of Proper Time Resolution

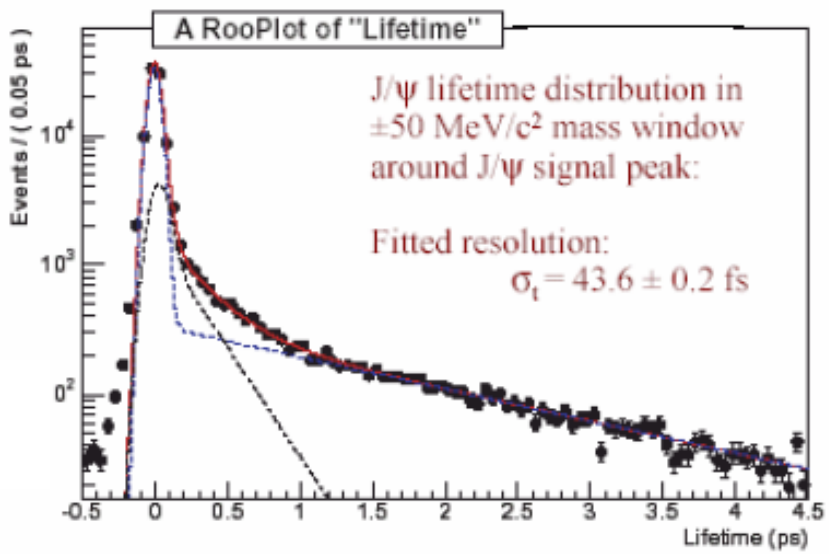
High-rate dimuon trigger provides valuable calibration calibration tool:

- Trigger on distinct $\mu\mu$ mass peaks: J/ψ, Υ and Z
- Sample independent on lifetime
- Dominated by prompt J/ψ

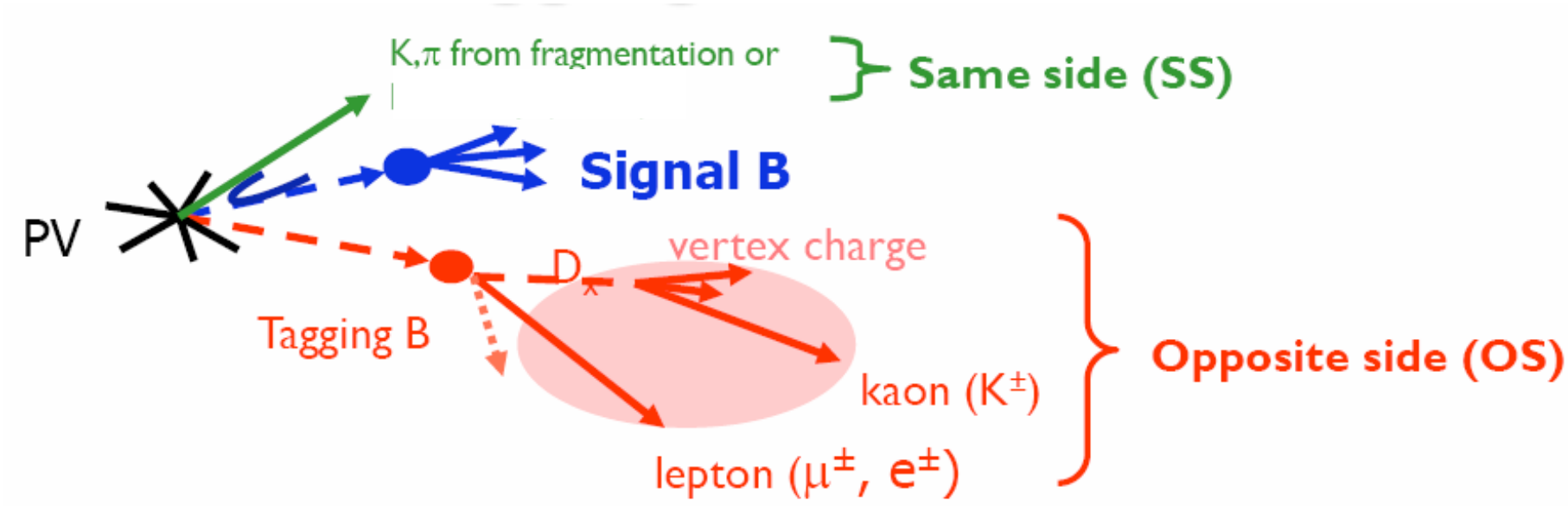
Ratio of $b\bar{b}$: $c\bar{c}$ events in pp collisions: 1:10

Ratio of J/ψ out of B decays and J/ψ out of $c\bar{c}$ decays: 1:100

$\rightarrow \Delta\sigma_t/\sigma_t < 1\%$!



Production Flavor = 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:

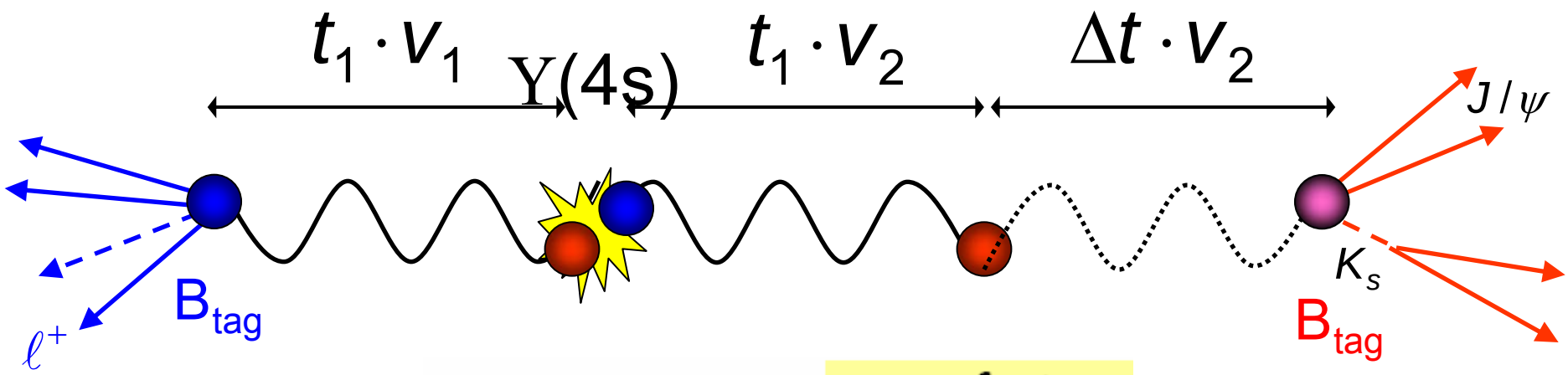
ε_{tag} = tagging effi.

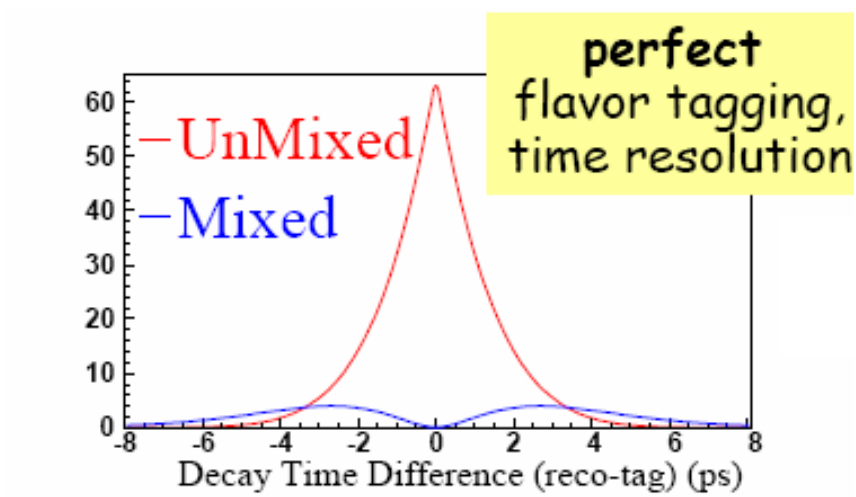
ω = wrong tag fraction

➡ Advantage of e+e- B-factories

Interlude: $\Upsilon(4S) \rightarrow B^0\bar{B}^0$

$$\Upsilon(4S) \rightarrow \left|B^0\overline{B}^0\right\rangle + \left|\overline{B}^0 B^0\right\rangle$$





Effect on Asymmetry

$$A(t) = \frac{N(B)(t) - N(\overline{B})(t)}{N(B)(t) + N(\overline{B})(t)}$$

Observed asymmetry w/ wrong tag fraction ω

$$A_{meas}(t) = \frac{N'(B)(t) - N'(\overline{B})(t)}{N'(B)(t) + N'(\overline{B})(t)}$$

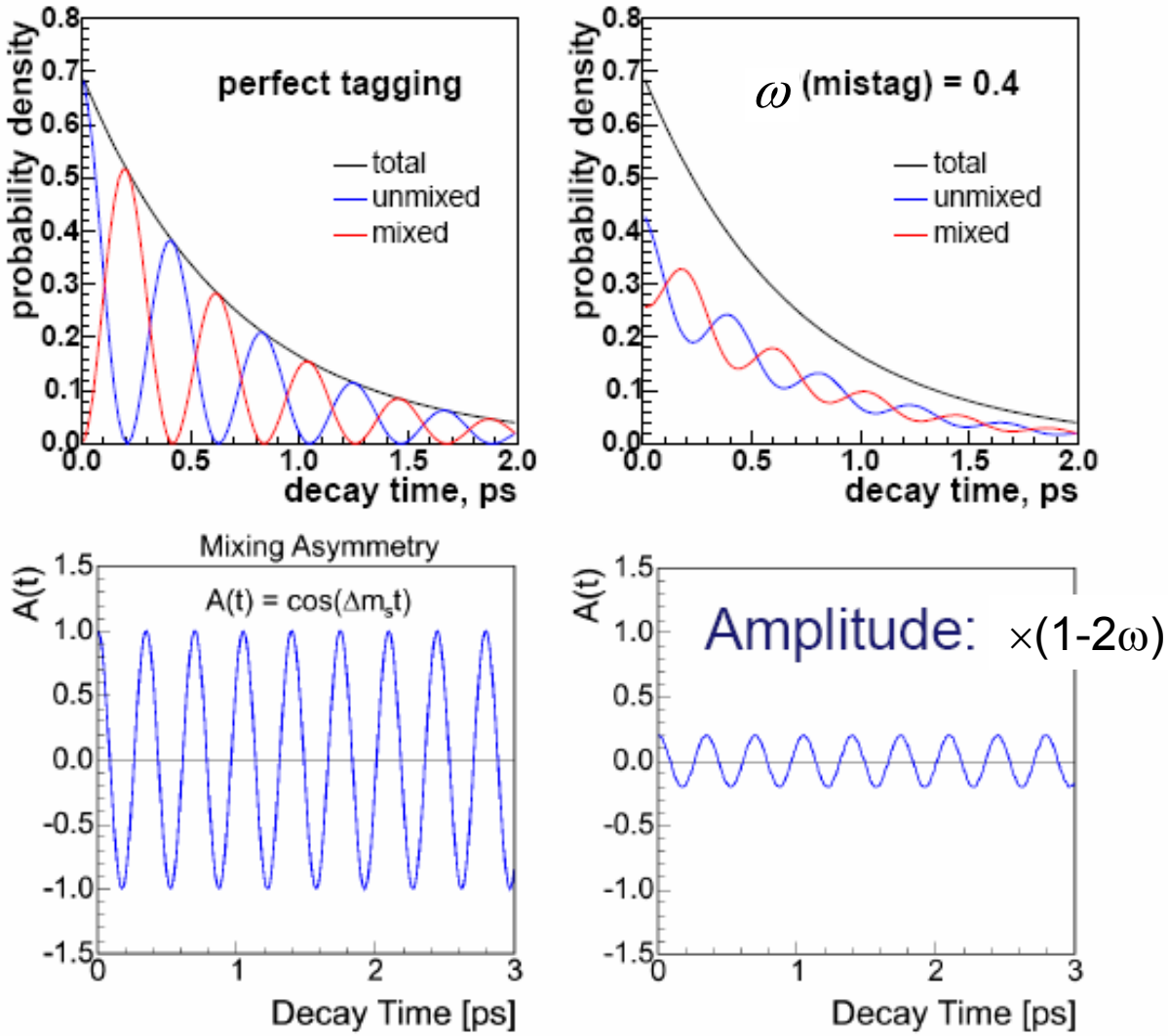
$$= \frac{N(B)(t)(1-\omega) + N(\overline{B})(t)\omega - N(\overline{B})(t)(1-\omega) - N(B)(t)\omega}{N(B)(t)(1-\omega) + N(\overline{B})(t)\omega + N(\overline{B})(t)(1-\omega) + N(B)(t)\omega}$$

$$= (1-2\omega)\frac{N(B)(t) - N(\overline{B})(t)}{N(B)(t) - N(\overline{B})(t)} = (1-2\omega)A(t) = D\,A(t)$$

$N'(B), N'(\overline{B})$ Observed number of events of given flavor

$D = (1-2\omega)$ Tagging "dilution": ω=50% $\rightarrow$ D=0
no measurement possible

Dilution


perfect tagging
total
unmixed
mixed
probability density
decay time, ps
ω (mistag) = 0.4
total
unmixed
mixed
probability density
decay time, ps
Mixing Asymmetry
A(t) = cos(Δm_s t)
A(t)
Decay Time [ps]
Amplitude: ×(1-2ω)
A(t)
Decay Time [ps]

Sensitivity and Tagging Power

Statistical error of asymmetry

$$A = \frac{N(B) - N(\overline{B})}{N(B) + N(\overline{B})}$$

$$N_B = qN,$$
$$N_{\overline{B}} = (1-q)N = pN$$
$$\langle q \rangle = \frac{N_B}{N}$$
$$\sigma(qN)^2 = N(1-q)q$$

Total event number $N = N(B) + N(\overline{B})$ fixed

Statistical error calculated according binominal distribution (A or notA):

$$\Delta A = \frac{1}{\sqrt{N}}(1-A^2)^{1/2}$$

Tagging efficiency: $N \rightarrow N' = \varepsilon N$

$$\Delta A_{meas} = \frac{1}{\sqrt{\varepsilon N}}(1-(A_{meas})^2)^{1/2}$$

Wrong tag fraction: $A_{meas} = D\,A$

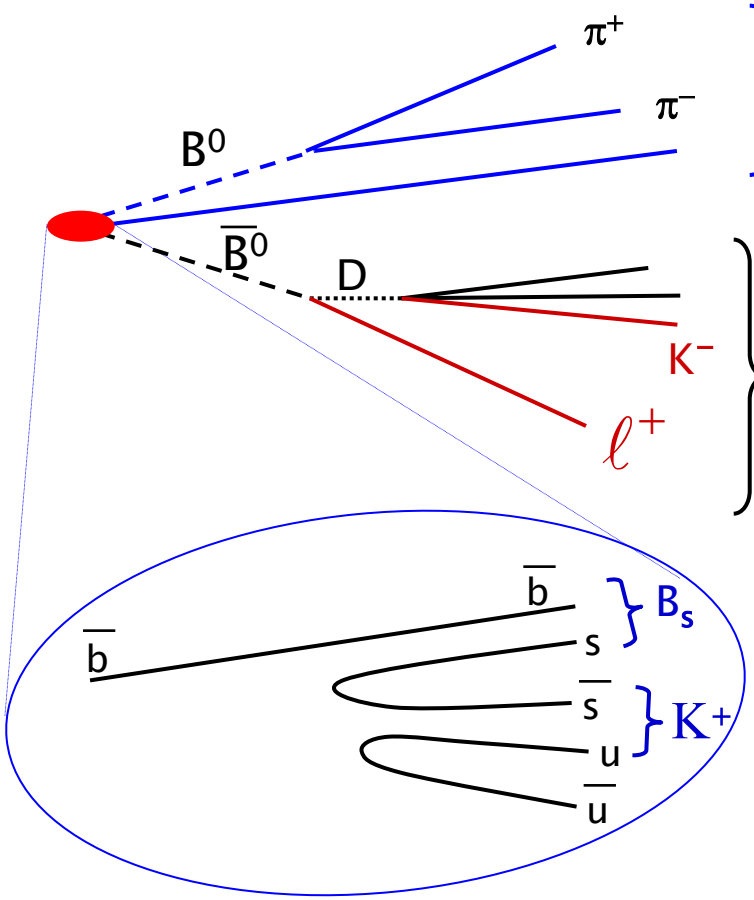
We are interested in A and therefore also in the error of A

$$\Delta A = \frac{1}{D}\Delta A_{meas}$$

$$\Delta A_{stat} \sim \frac{1}{\sqrt{\varepsilon D^2 N}}$$

= effective tagging power

Flavor Tagging at LHCb



Same Side Tagging

- fragmentation pion/kaon near B

Opposite Side Tagging

- lepton
- kaon
- vertex charge

Dilution form oscillation if B^0

tag	ϵ_{tag}[%]	ω[%]	ϵ_{eff}[%]
muon	11	35	1.0
electron	5	36	0.4
kaon	17	31	2.4
vertex charge	24	40	1.0
frag. kaon (B_s)	18	33	2.1
Σ			~ 6

Dilution $D=(1-2w)$

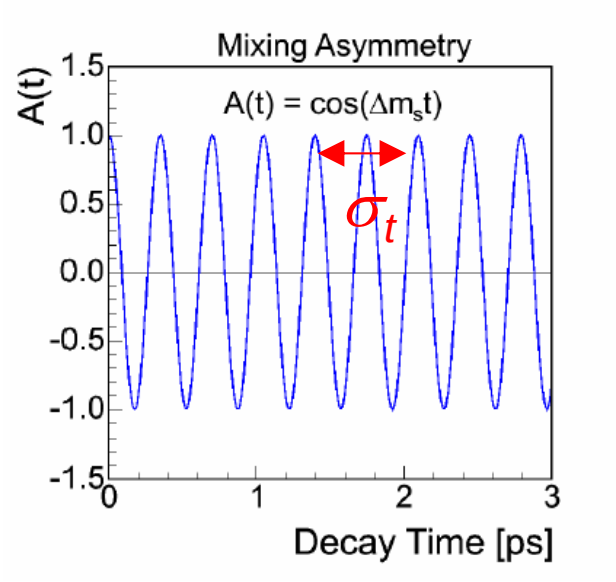
Effective Tagging Power $\varepsilon_{eff}=\varepsilon_{Tag}D^2$

Effective Tagging Power

$$N_{eff} = N\,\varepsilon\,D^2$$

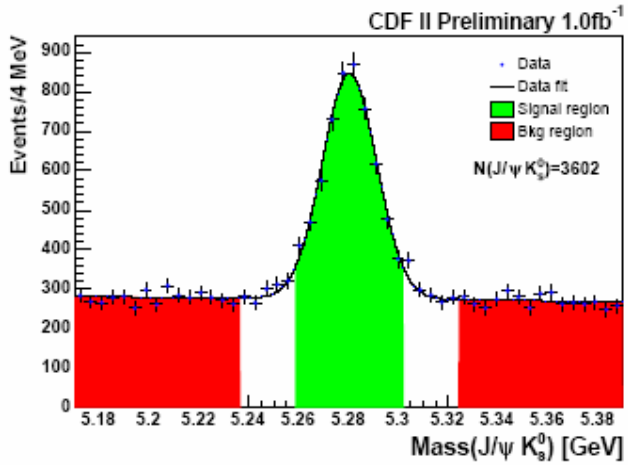
[%]	ϵD^2	Reduction of data set
D0/CDF	2.5 - 5.0	$\times$ 20-50
BABAR/BELLE	$\approx$ 30	$\times$ 3-4
LHCb (MC study)	$\approx$ 6%	$\times$ 17

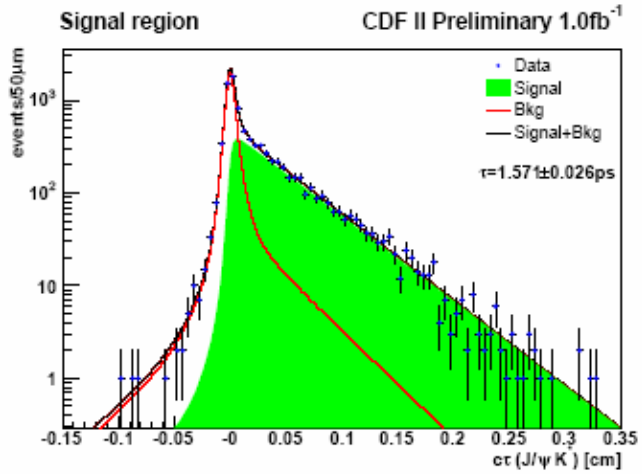
Statistical Significance



Until now ignored: Proper time resolution

➡ Dilution: $D_{\sigma_{ct}} \sim \exp\left[-\frac{(\Delta m_s \sigma_{ct})^2}{2}\right]$





Background: shape and level from side-bands

$\sigma_{stat} \sim 1/\sqrt{S}$

$\rightarrow \sigma_{stat} \sim \frac{1}{\sqrt{S}}\left(\frac{S+B}{S}\right)^{\frac{1}{2}}$

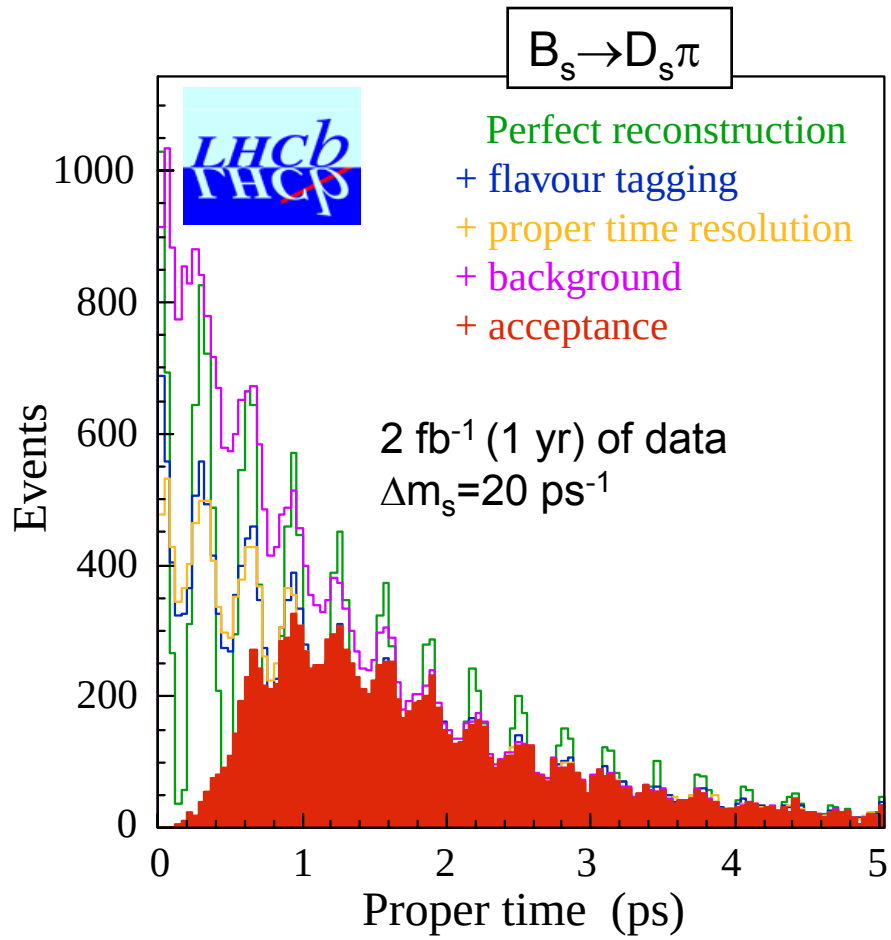
Summary of different effects on mixing

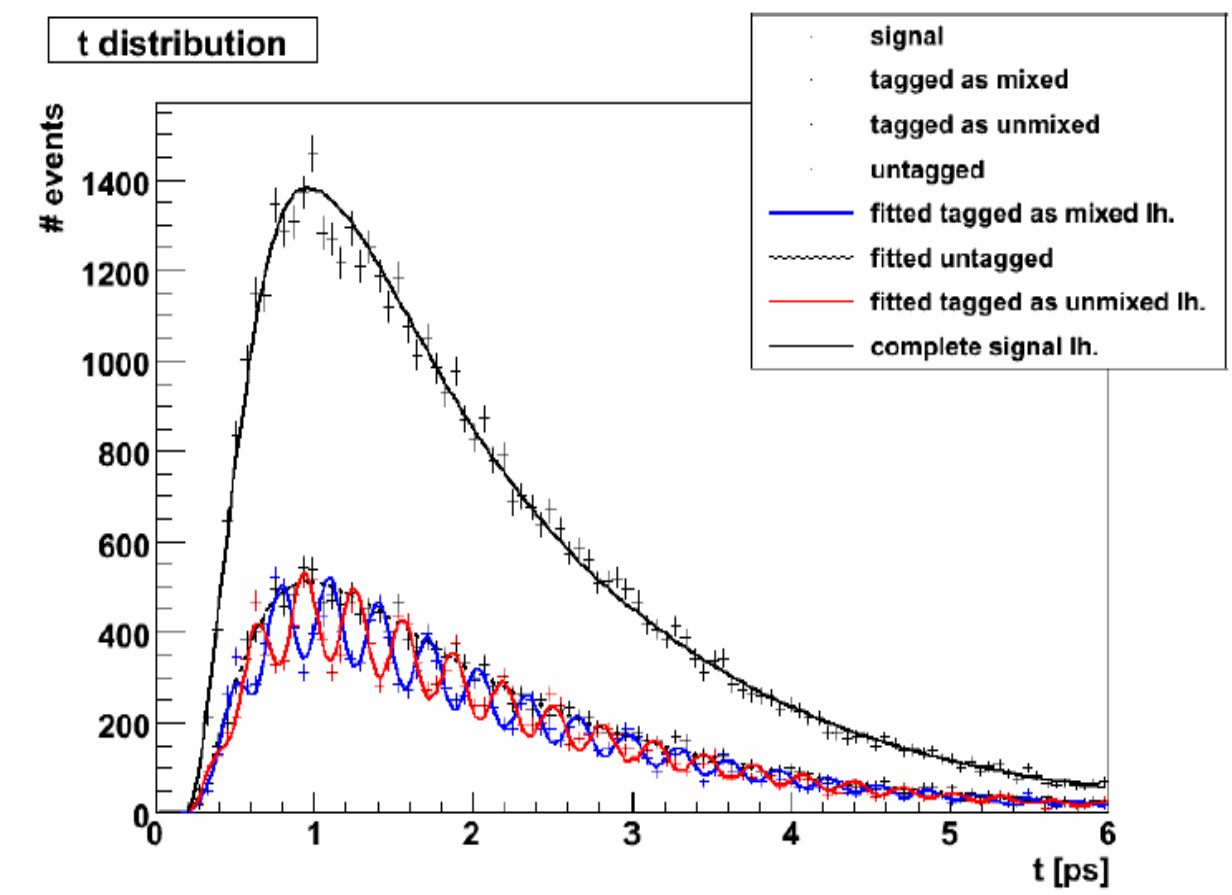
Expectation for 2 fb^{-1} (1 yr):

150 $B_s \to D_s \pi$ events, untagged

ε_{tag}~60%, B/S~1 (mostly short lived)

$$\sigma_{stat}(A) = \sqrt{\frac{2}{S\varepsilon_{tag}D^2}}\left(\frac{S+B}{S}\right)^{\frac{1}{2}} \exp\left(\frac{(\Delta m \sigma_{ct})^2}{2}\right)$$





Expected statistical resolution on Δm_s: $\sigma(\Delta m_s)$ = 0.007ps^{-1}

remember Δm_s = 17.7 ps^{-1}; $\rightarrow \Delta m_s/m_s$ = 0.04%

CP Asymmetry in $B^0 \to J/\psi K_s$

$$A_{CP}(t) = \frac{\Gamma(\overline{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\overline{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

B^0

$\Delta\Gamma \approx 0$

$\Phi_M = 2\beta$

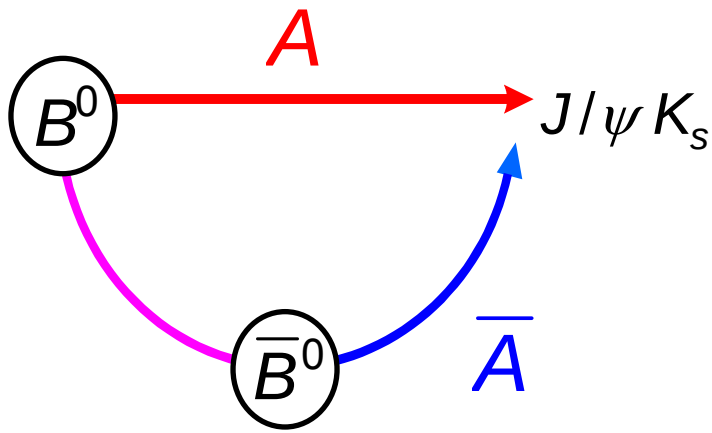
$$= \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos(\Delta m t)}_{\text{Direct CP violation}} - \underbrace{\frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\sin(\Delta m t)}_{\text{CP violation through interference}}$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad \Im(\lambda_f) = -\eta_f \sin[2(\Phi_M + \Phi_f)]$$

$B^0 \to J/\psi K_s$

$$\frac{q}{p} = e^{-i\Phi_M}$$

$$\Phi_M = \arg(-M_{12})$$



$$\frac{\overline{A}_f}{A_f} = \eta_f e^{-i2\Phi_f}$$

1.) CP eigenvalue

B_d : $J^P = 0^{-1}$ (Pseudoskalar)

J/ψ: : $J^{CP} = 1^{-1-1}$ (Vector)

K_s: : $J^{CP} = 0^{-1-1}$ (Pseudoskalar)

Angular momentum conservation:

0 = J $(J/\psi\phi) = |\vec{S} + \vec{L}|; \to$ L = 1

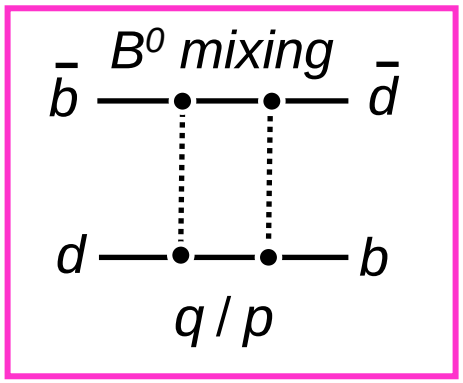
$$CP(J/\psi\phi) = CP(J/\psi) * CP(\phi) * (-1)^L$$

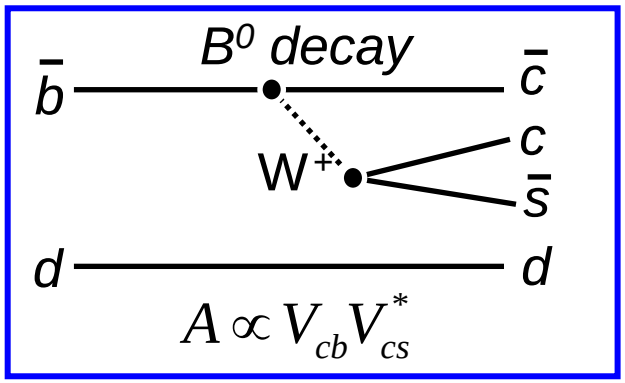
$$\eta_f = -1$$

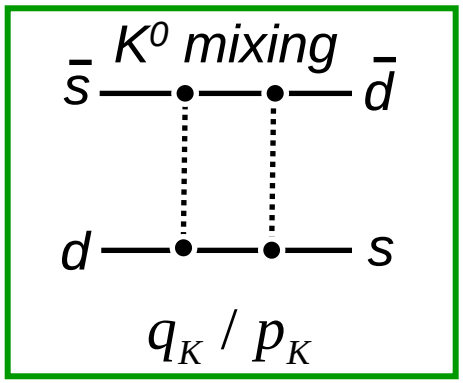
$B^0 \to J/\psi K_s$

$$\Phi_M = \arg\left(V_{td} V_{tb}^*\right) = 2\beta$$

$$\Phi_{J/\psi K} = \arg\left(\left(V_{cb} V_{cs}^*\right)\left(V_{cs} V_{cd}^*\right)\right) = 0$$

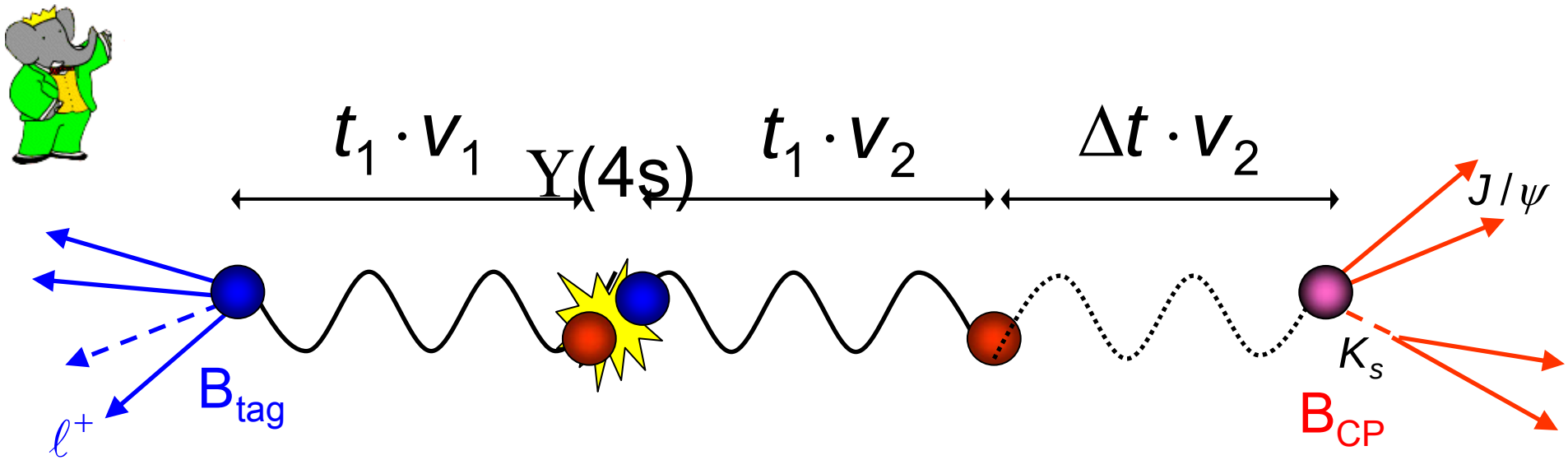


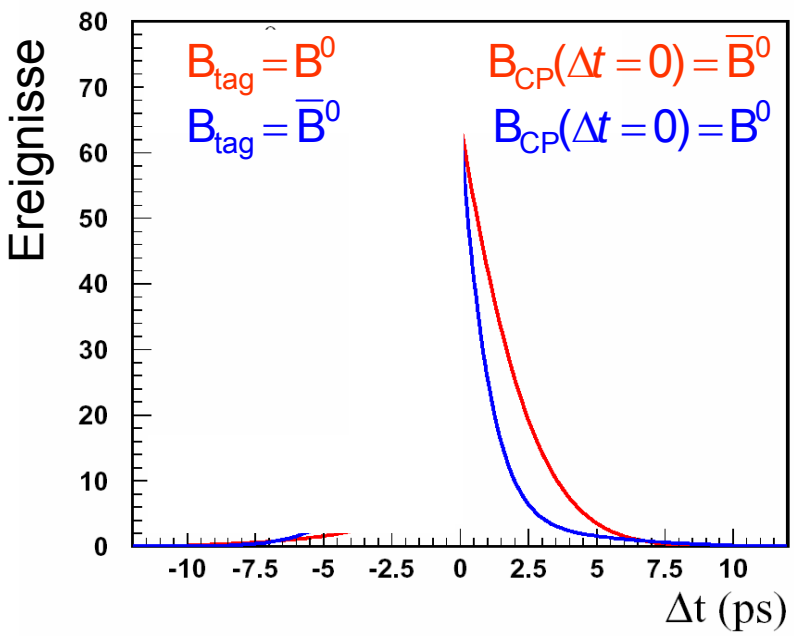


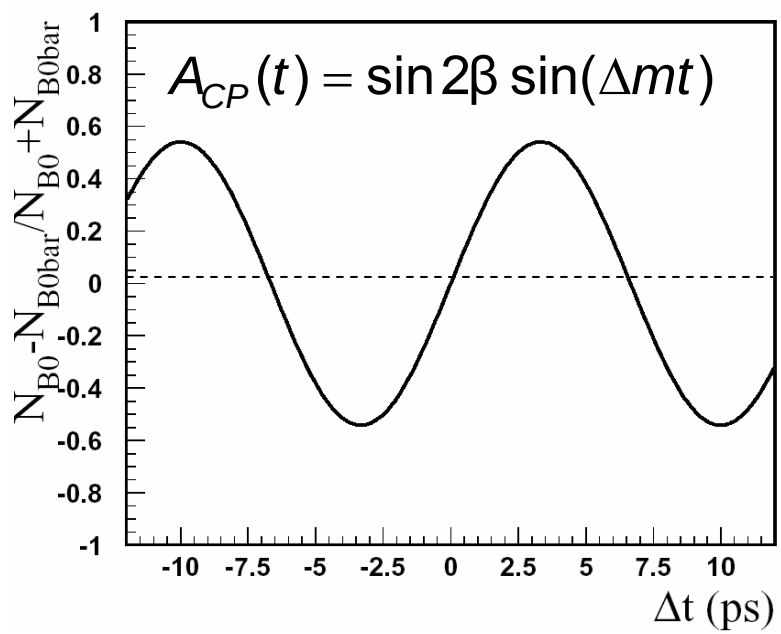


$$A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$$

Measurement of sin2β

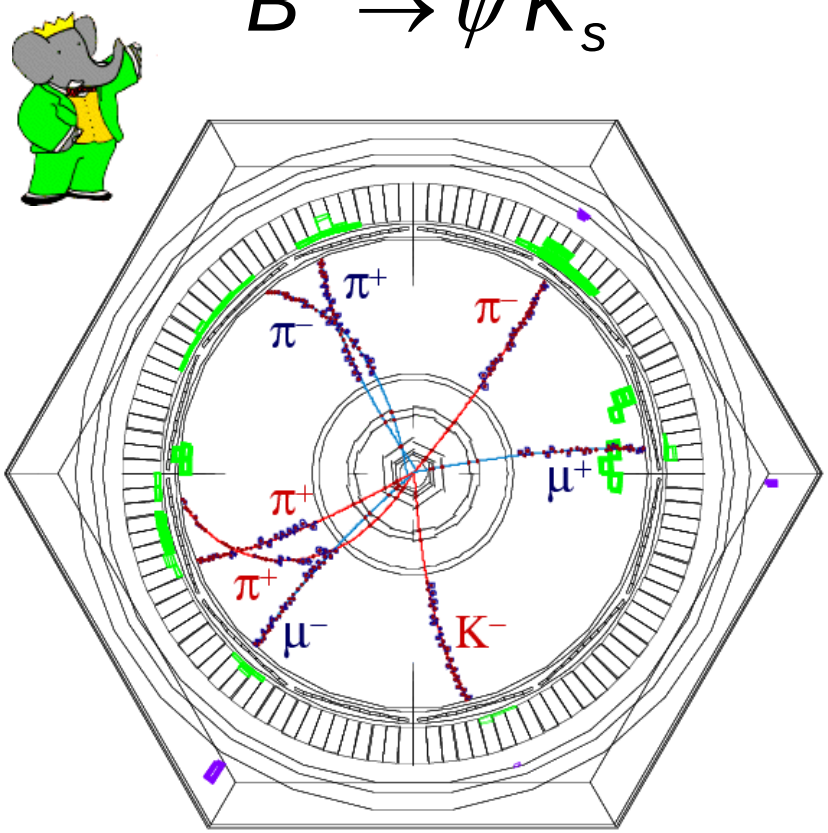






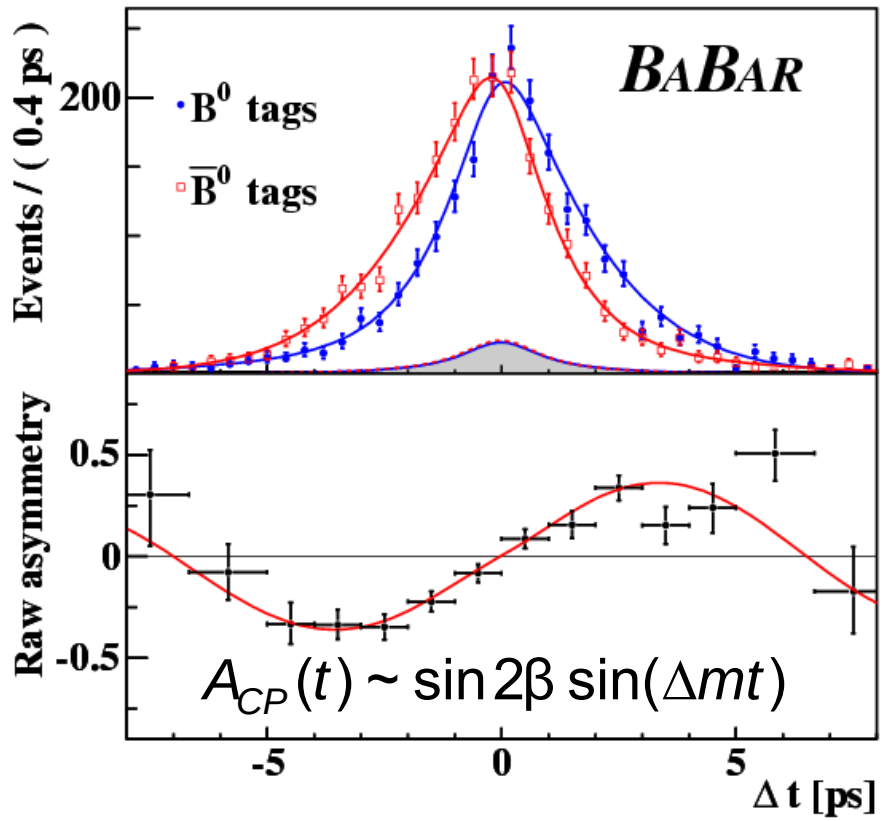
sin2β

$$B^0 \rightarrow \psi K_s$$



PRL 94, 161803.

227 Mio $B\bar{B}$

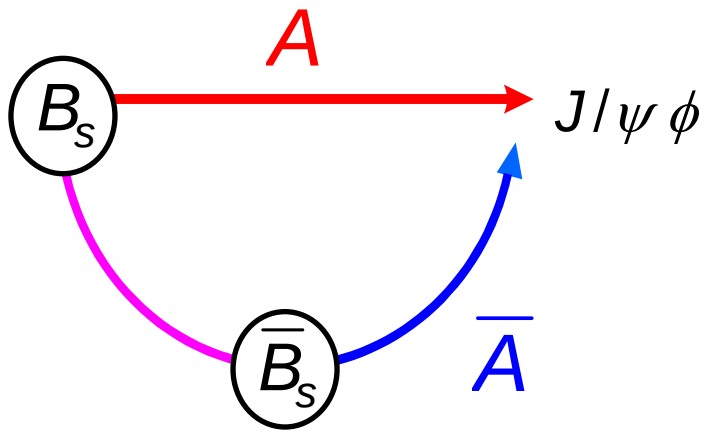


$$\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$$

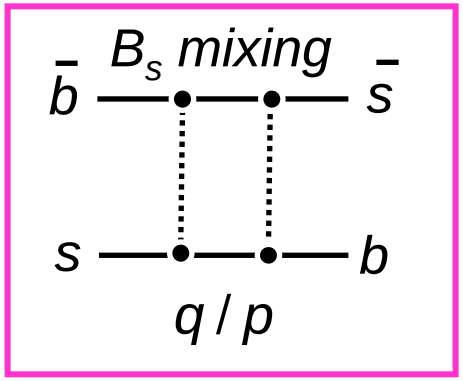
CP Asymmetry in $B_s \to J/\psi\phi$

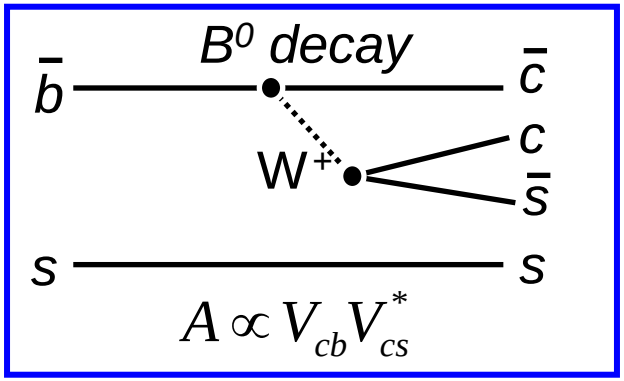
$$\frac{q}{p} = e^{-i\Phi_M}$$

$$\Phi_M = \arg(-M_{12})$$



$$\frac{\overline{A}_f}{A_f} = \eta_f e^{-i2\Phi_f}$$





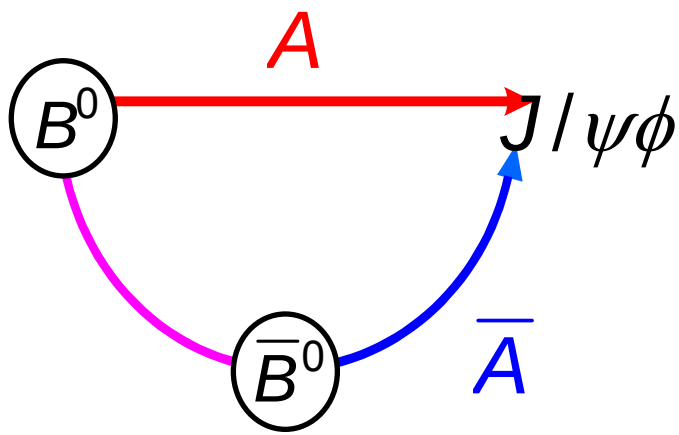
$$\Phi_M = \arg\left(V_{ts}V_{tb}^*\right) = -2\beta_s$$

$$\Phi_{J/\psi\phi} = \arg\left(V_{cb}V_{cs}^*\right) = 0$$

CP Asymmetry $B_s \to J/\psi\phi$

$$\frac{q}{p} = e^{-i\Phi_M}$$

$$\Phi_M = \arg(-M_{12})$$



$$\mathrm{CP}\left|J/\psi\phi\right\rangle = \pm\left|J/\psi\phi\right\rangle$$

$$\frac{\overline{A}_f}{A_f} = \eta_f e^{-i2\Phi_f}$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad \Im(\lambda_f) = -\eta_f \sin[2(\Phi_M + \Phi_f)]$$

$$A_{CP}(t) = \frac{\Gamma(\overline{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\overline{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

$$= \frac{\eta_f \sin[2(\Phi_M + \Phi_f)]\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) - \eta_f \cos[2(\Phi_M + \Phi_f)]\sinh(\Delta\Gamma t/2)}$$

$B_s \to J/\psi\phi$

$B_s \to J/\psi \; \phi$

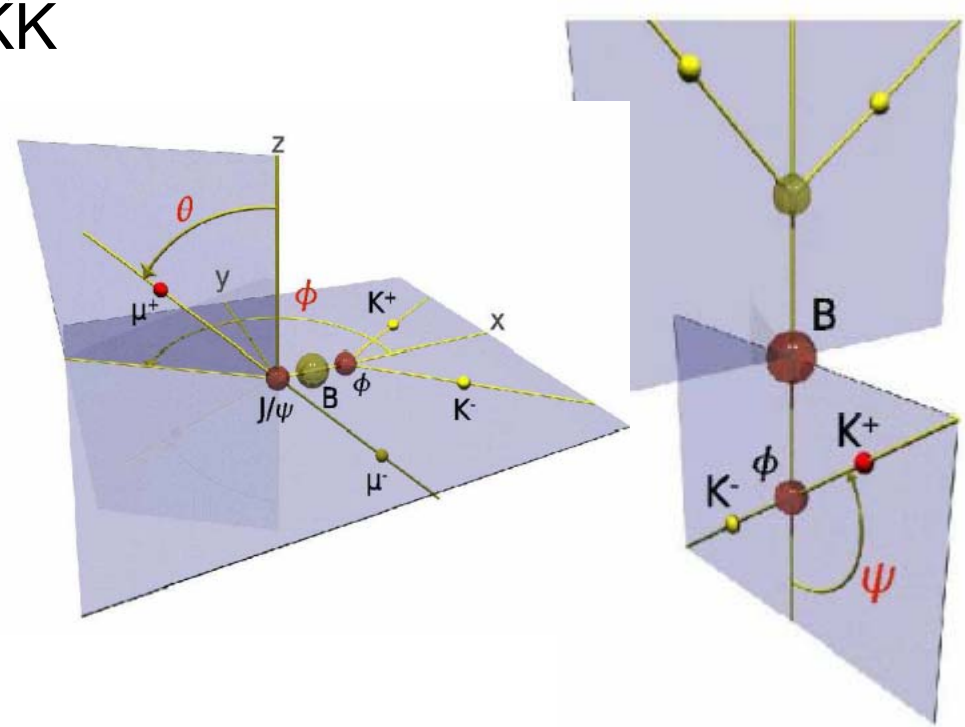
$J/\psi \to \mu\mu$, $\phi \to KK$

Vector mesons w/ $J^{PC}=1^{--}$

$J/\psi\phi$ is admixture of CP states:

L = 0,2 CP = + 1
L = 1 CP = - 1

$$\eta_{CP} = (-1)^L$$



Angular analysis to separate CP +/-1 states

Polarization Amplitudes

- In the Transversity basis the vector meson polarization w.r.t the direction of motion is:

✓ Longitudinal $\Rightarrow A_0$ [CP even]
✓ Transverse and parallel to each other $\Rightarrow A_{||}$ [CP even]
✓ Transverse and perpendicular to each other $\Rightarrow A_{\perp}$ [CP odd]

- Strong phases:

✓ $\delta_{||} \equiv \arg(A_{||}^{*} A_0)$
✓ $\delta_{\perp} \equiv \arg(A_{\perp}^{*} A_0)$

Physics parameters: $m_s, \Gamma_s, \Delta m_s, \Delta\Gamma_s, \phi_s$
$A_0, A_{II}, A_{\perp}, \delta_{II}, \delta_{\perp}$

Angles in transv. basis: θ, ψ, ϕ

Extraction of CP Asymmetry

Signal PDF

$$
\begin{aligned}
s\left(t, \cos\Theta, \phi, \cos\Psi\right) &= \frac{1+\xi D}{2} p\left(t, \cos\Theta, \phi, \cos\Psi\right) \\
&\quad + \frac{1-\xi D}{2} \bar{p}\left(t, \cos\Theta, \phi, \cos\Psi\right) \\
&= \frac{1+\xi \boxed{D}}{2} \sum_{i=1}^{6} A_i\left(t\right) \cdot f_i\left(\cos\Theta, \phi, \cos\Psi\right) \\
&\quad + \frac{1-\xi \boxed{D}}{2} \sum_{i=1}^{6} \bar{A}_i\left(t\right) \cdot f_i\left(\cos\Theta, \phi, \cos\Psi\right)
\end{aligned}
$$

$$\xi = +1 \text{ for a } B_s, \ \xi = -1 \text{ for a } \bar{B}_s$$

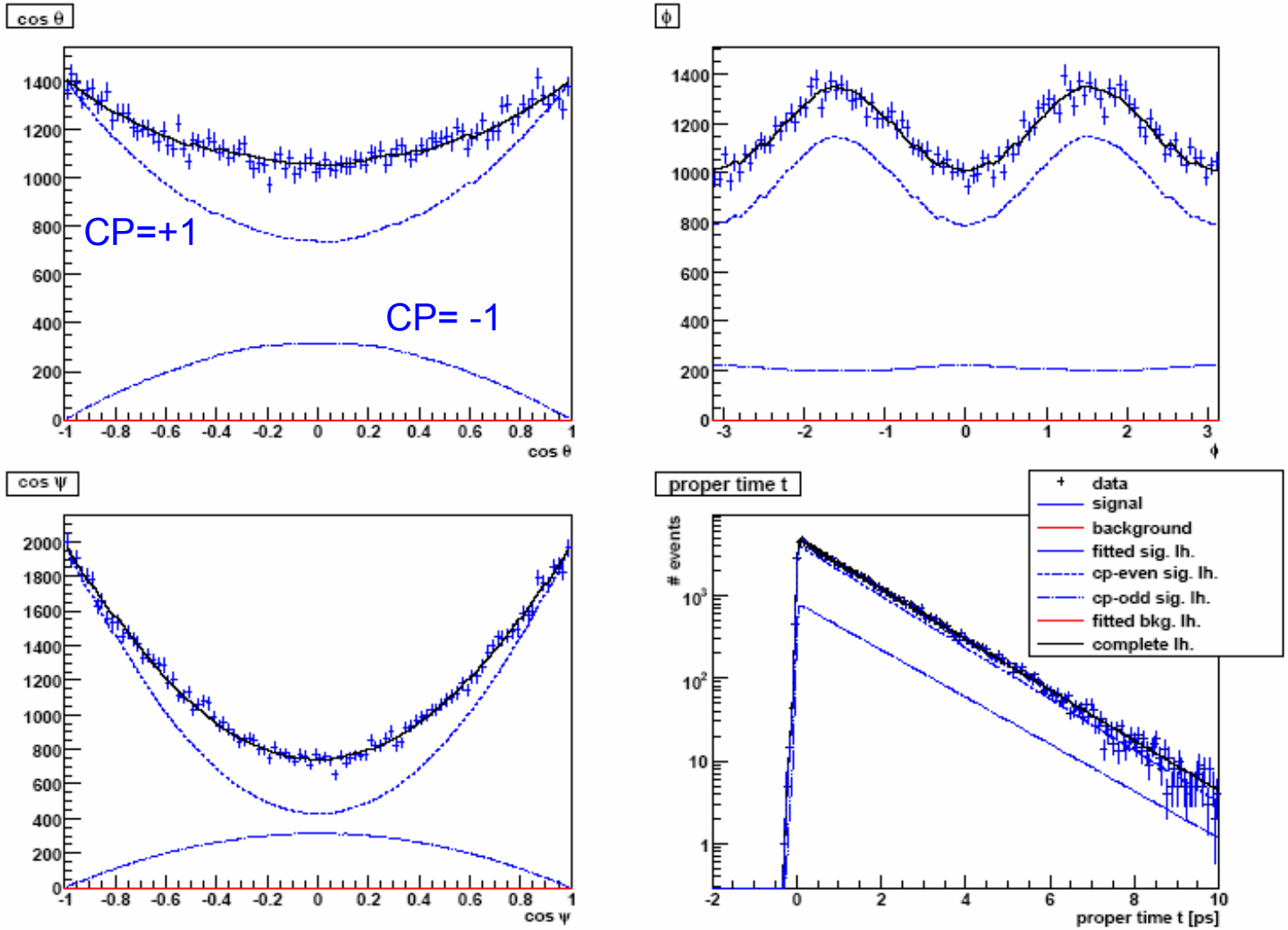
Dilution reduces the observable CP asymmetry: we need to know the dilution to extract the correct CP asymmetry and thus $\sin\phi_s$.

Angular Distributions

k	$A_i(t)$	$\bar{A}_i(t)$	$f_i(\cos\Theta, \phi, \cos\Psi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert\bar{A}_0(t)\rvert^2$	$\frac{9}{32\pi} 2\cos^2\psi\left(1-\sin^2\Theta\cos^2\phi\right)$
2	$\lvert A_\parallel(t)\rvert^2$	$\lvert\bar{A}_\parallel(t)\rvert^2$	$\frac{9}{32\pi}\sin^2\psi\left(1-\sin^2\Theta\sin^2\phi\right)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert\bar{A}_\perp(t)\rvert^2$	$\frac{9}{32\pi}\sin^2\psi\sin^2\Theta$
4	$Im(A_\parallel^*(t)A_\perp(t))$	$Im(\bar{A}_\parallel^*(t)\bar{A}_\perp(t))$	$-\frac{9}{32\pi}\sin^2\psi\sin 2\Theta\sin\phi$
5	$Re(A_0^*(t)A_\parallel(t))$	$Re(\bar{A}_0^*(t)\bar{A}_\parallel(t))$	$\frac{9}{32\pi\sqrt{2}}\sin 2\psi\sin^2\Theta\sin 2\phi$
6	$Im(A_0^*(t)A_\perp(t))$	$Im(\bar{A}_0^*(t)\bar{A}_\perp(t))$	$\frac{9}{32\pi\sqrt{2}}\sin 2\psi\sin 2\Theta\cos\phi$

$$
\begin{aligned}
|A_0(t)|^2 &= \frac{|A_0(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t}+(1-\cos\Phi_s)e^{-\Gamma_H t}-2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]\\
|A_\parallel(t)|^2 &= \frac{|A_\parallel(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t}+(1-\cos\Phi_s)e^{-\Gamma_H t}-2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]\\
|A_\perp(t)|^2 &= \frac{|A_\perp(0)|^2}{2}\left[(1-\cos\Phi_s)e^{-\Gamma_L t}+(1+\cos\Phi_s)e^{-\Gamma_H t}+2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]\\
|\overline{A}_0(t)|^2 &= \frac{|A_0(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t}+(1-\cos\Phi_s)e^{-\Gamma_H t}+2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]\\
|\overline{A}_\parallel(t)|^2 &= \frac{|A_\parallel(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t}+(1-\cos\Phi_s)e^{-\Gamma_H t}+2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]\\
|\overline{A}_\perp(t)|^2 &= \frac{|A_\perp(0)|^2}{2}\left[(1-\cos\Phi_s)e^{-\Gamma_L t}+(1+\cos\Phi_s)e^{-\Gamma_H t}-2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]
\end{aligned}
$$

Angular and proper time distribution



Expectation

2 fb^{-1}

117k $B_s \to J/\psi\phi$ signal events

Prompt background B/S=1.8

Long-lived backgr. B/S=0.5

ε_{tag}=0.56, ω=0.33 $\to$ D=6.1%

parameter	Sensitivity
$\lvert A_\perp(0)\rvert^2$	0.0044 ± 0.0002
$\lvert A_0(0)\rvert^2$	0.0033 ± 0.0001
Γ_s	0.0034 ± 0.0002
$\Delta\Gamma$	0.0105 ± 0.0005
$2\beta_s$	0.030 ± 0.001
$\delta_\perp$	0.081 ± 0.004
$\delta_\parallel$	0.092 ± 0.004

Standard model prediction: $-2\beta_s = -0.0368 \pm 0.0017$

Tagging Calibration

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

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

aim

$\Delta\omega/\omega < 2\%$

- 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

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%

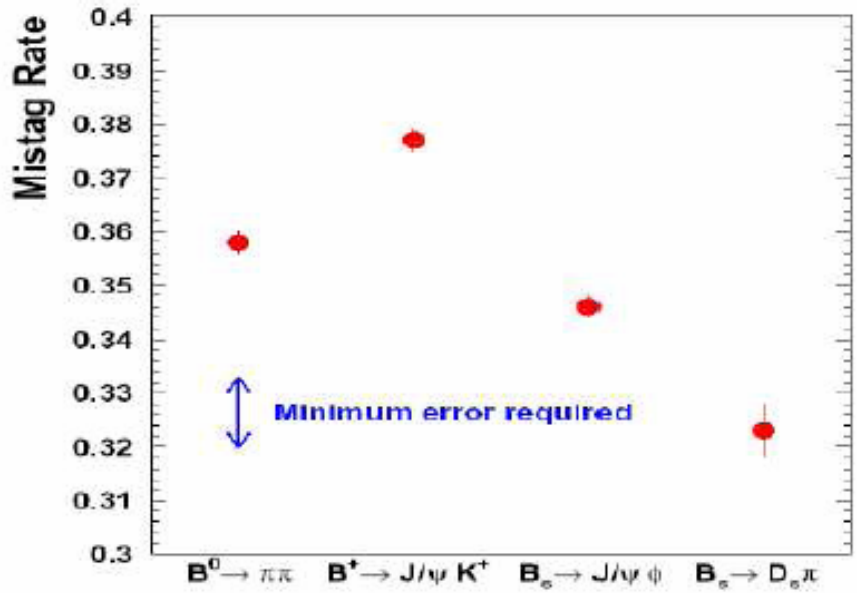
B/S~0.2–0.8

Tagging in Control Channels

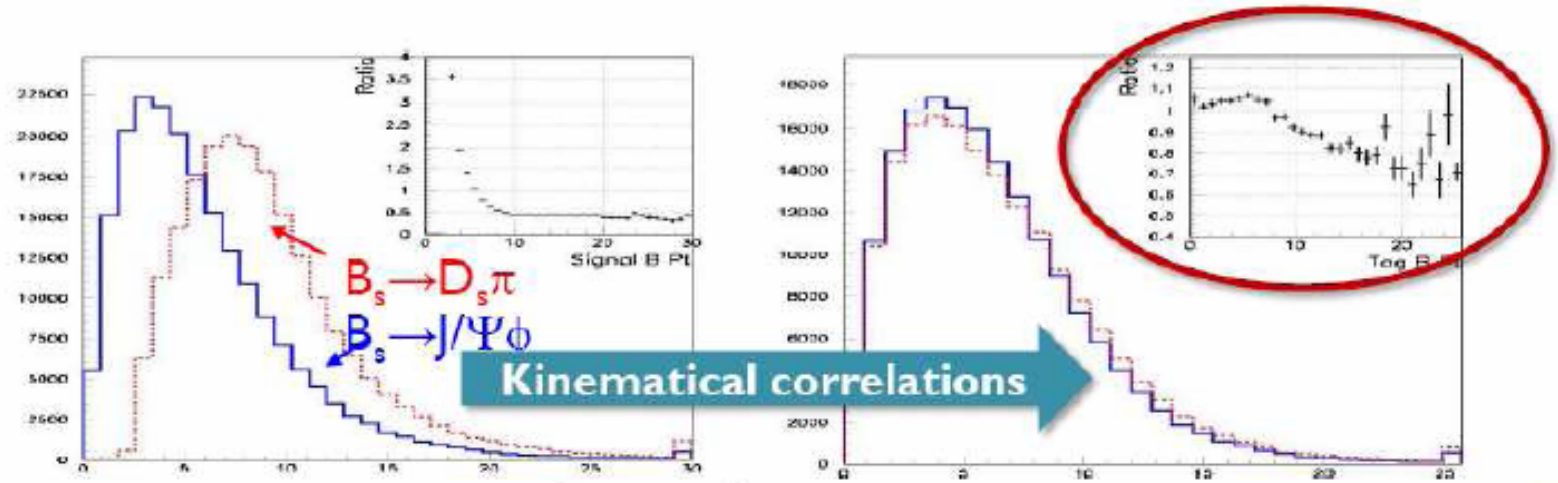
However, the mistag rate is different between different channels, up to ~15%, while the requirement is to know $\Delta\omega/\omega <$ 2% with 2 fb^{-1}

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

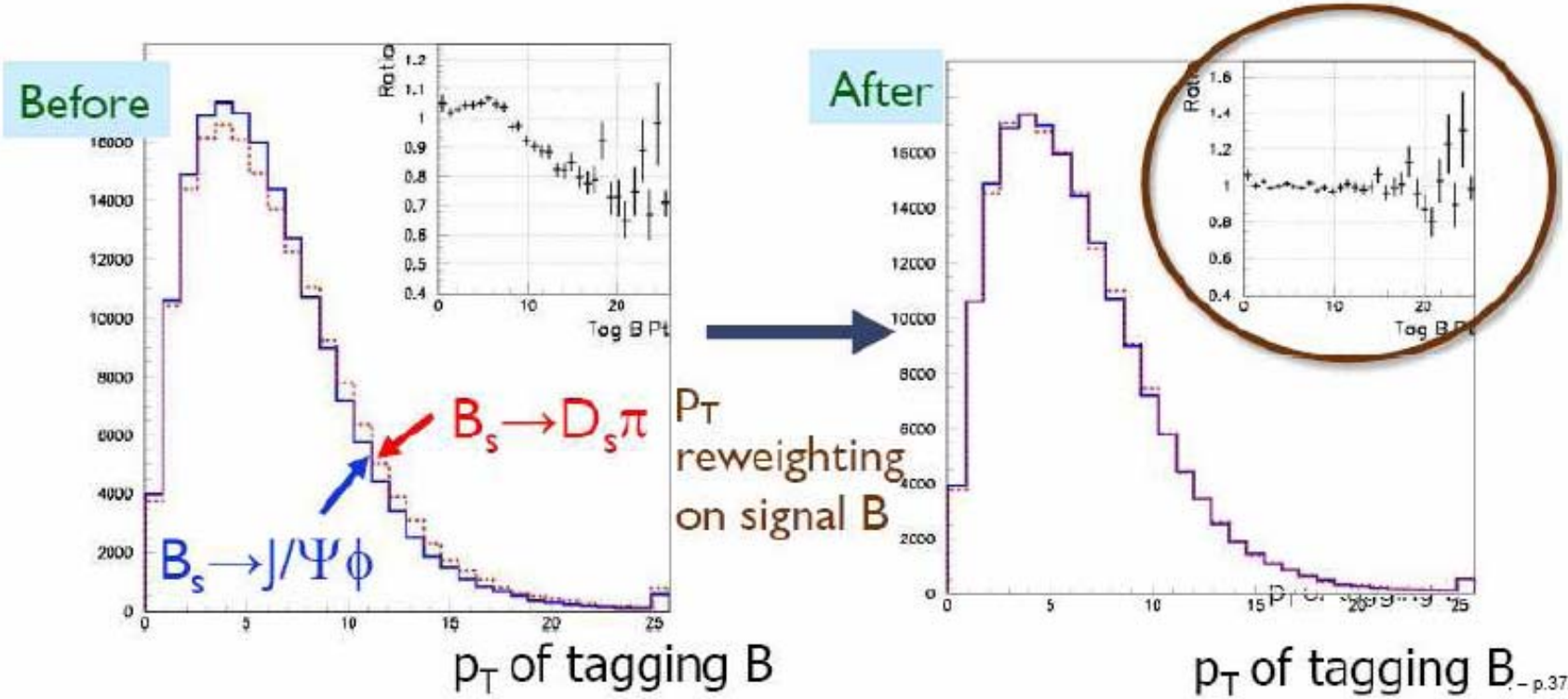


p_T of signal B

p_T of tagging B

Tagging in Control Channels

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!



Flavor specific asymmetry

$$A_{fs}^{q}(t) = \frac{\Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{f}\right) - \Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{\bar{f}}\right)}{\Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{f}\right) + \Gamma\left(B_q^0 \,/\, \overline{B}_q^0 \to \boxed{\bar{f}}\right)}$$

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

$$B_s^0 \to D_s^- \mu^+ \nu_\mu X^0$$

$$= \frac{a_{fs}^q}{2} - \frac{a_{fs}^q}{2} \frac{\cos\left(\Delta m_q t\right)}{\cosh\left(\Delta\Gamma_q t / 2\right)}$$

$$\left(a_{fs}^{d}\right)^{SM} = -\left(5.0 \pm 1.1\right) \times 10^{-4}$$

$$\left(a_{fs}^{s}\right)^{SM} = \left(2.1 \pm 0.4\right) \times 10^{-5}$$

Up to 10^{-3} with NP

$$a_{fs}^q = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right) = \frac{\left|\Gamma_{12}^q\right|}{\left|M_{12}^q\right|} \sin\Phi_{M/\Gamma} = \frac{\Delta\Gamma}{\Delta M} \tan\Phi_{M/\Gamma}$$

Many Asymmetries

- Untagged, time-dependent measurement

$$A_{fs}^{q}(t) = \frac{a_{fs}^{q}}{2} - \frac{\delta_c^q}{2} - \left(\frac{a_{fs}^{q}}{2} + \frac{\delta_p^q}{2} \right) \frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)} + \frac{\delta_b^q}{2} \left(\frac{B}{S} \right)^q$$

- Extra constant and time-dependent terms
  - Detector asymmetry δ_c
  - Production asymmetry δ_p
  - Background asymmetry δ_b

$$\delta_c = \frac{\varepsilon(\bar{f}_i)}{\varepsilon(f_i)} - 1$$

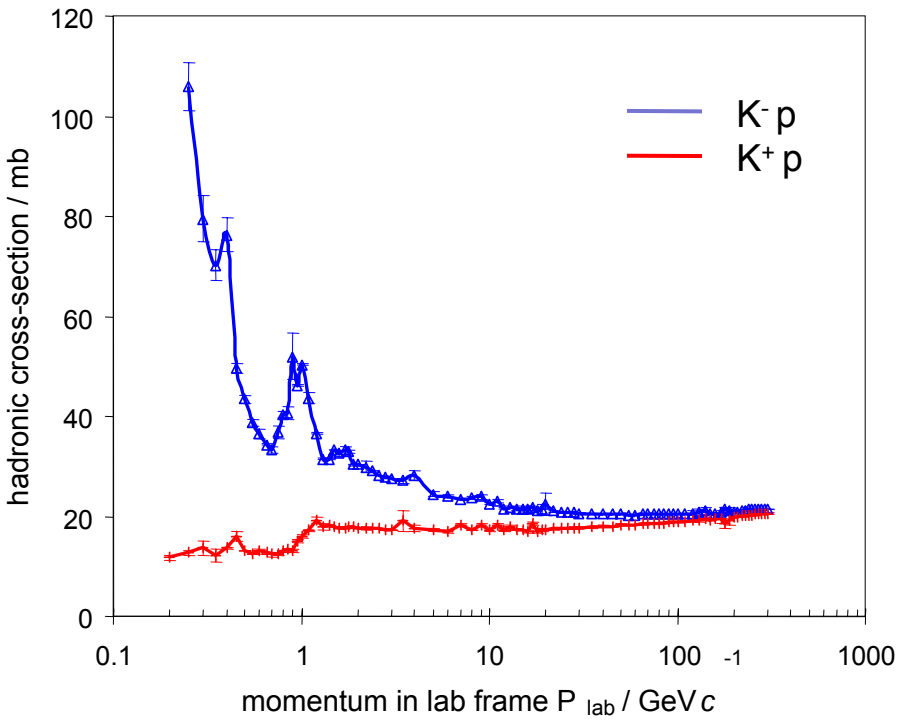
$$\delta_p = \frac{N(\overline{B}_q^0)}{N(B_q^0)} - 1$$

$$\delta_b = \frac{\overline{B}}{B} - 1$$

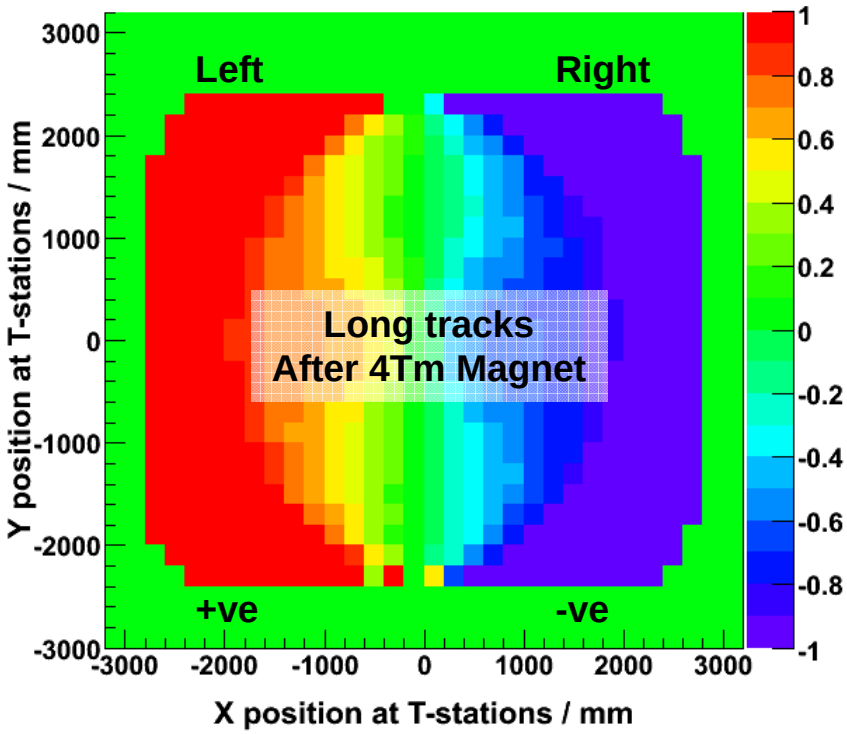
Detection Asymmetries

- Matter detector → hadronic interactions are asymmetric
- Magnet divides +/- charge, allowing +/- asymmetry

Kaon interaction cross-section



Charge distribution from MC



Production Asymmetries

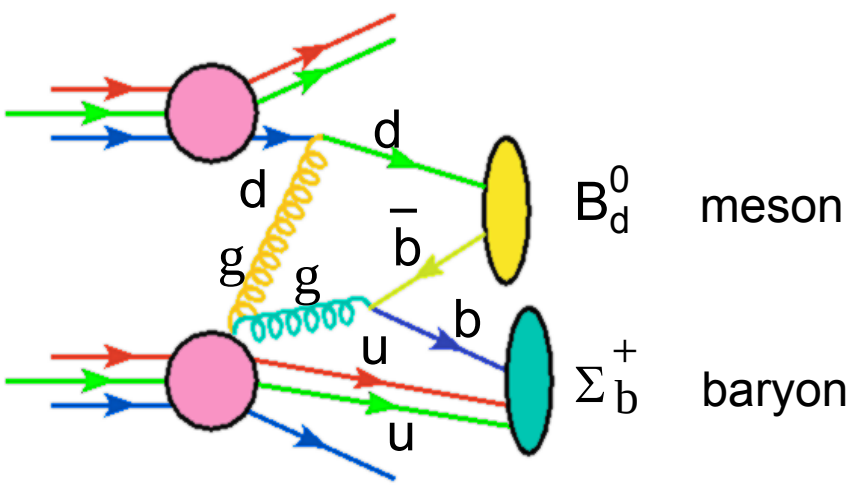
As the **LHC** collides protons with protons, events are **not CP-symmetric**.

$$\frac{\text{produced antiparticles } \overline{P}}{\text{produced particles P}} = \frac{N(\overline{P})}{N(P)} = 1 + \delta_p$$

Production asymmetry is effect of competing processes:

Cluster Collapse

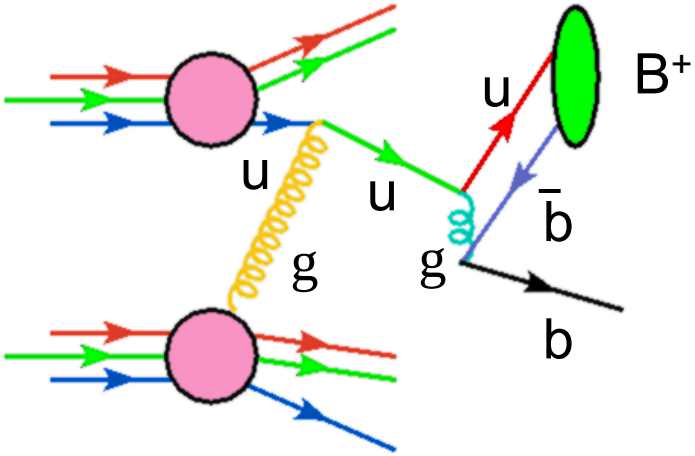
Enhances the production of species containing beam remnants at low transverse momentum (pt)



Production Asymmetries

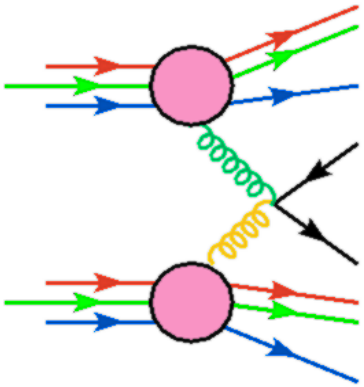
Valence-Quark Scattering

Enhances production of high energy species containing beam constituents

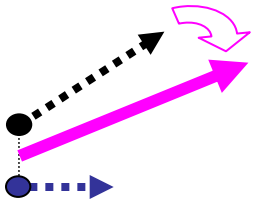


Beam Drag

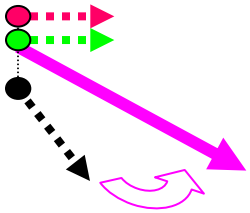
Redistributes particle-antiparticle content as a function of transverse momentum (pt) and rapidity (direction)



Color connections with quark remnants 'drag' antiquarks toward the beam



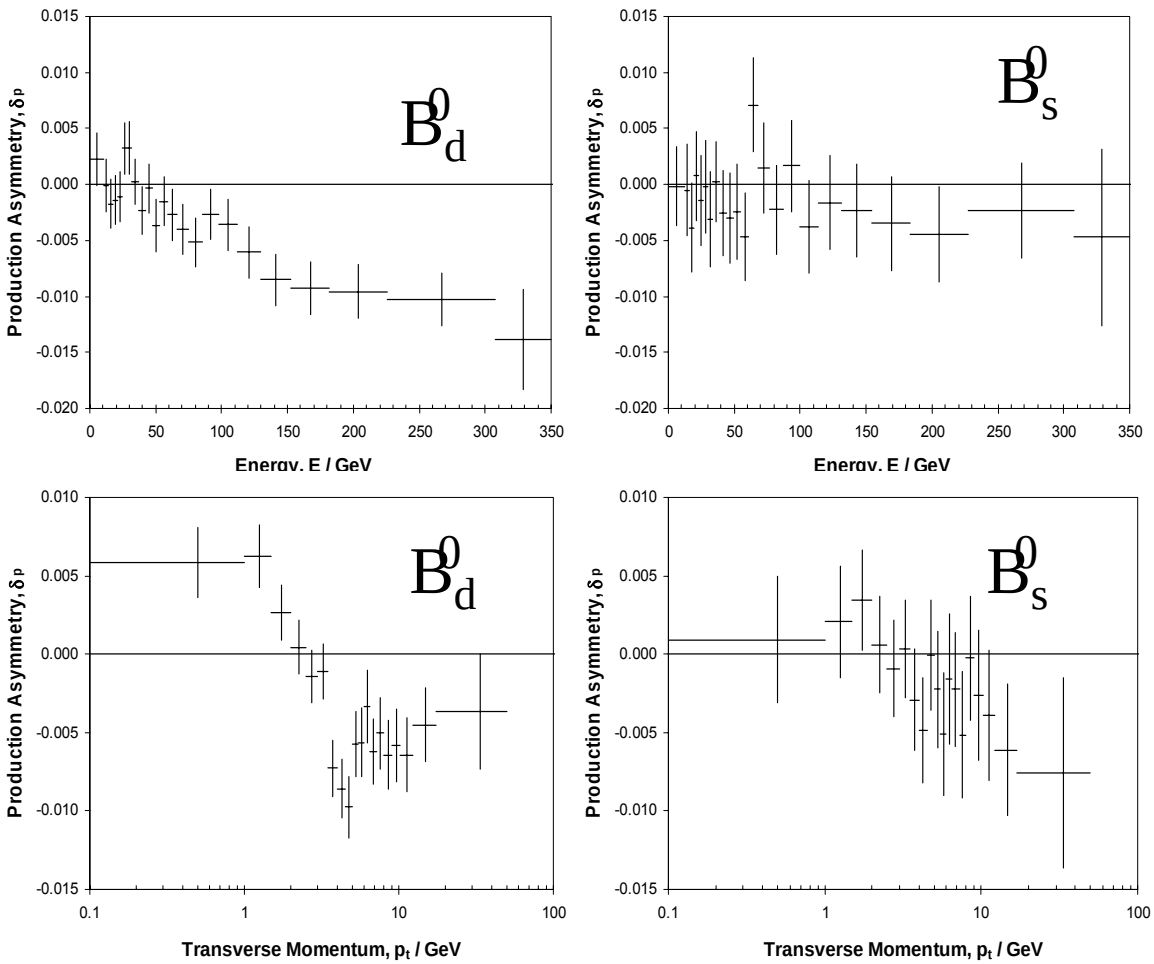
Color connections with di-quark remnants 'drag' quarks toward the beam



Production Asymmetrie

production asymmetry

$$\frac{\overline{B}}{B}$$



20M events with tuned **PYTHIA**

B_d : δ_p = **-(3.2**±0.5) x10^{-3}

B_s : δ_p = **-(1.5**±0.8) x10^{-3}

Subtraction method

$$\Delta A_{fs}^{s,d} \approx A_{fs}^{s} - A_{fs}^{d}$$

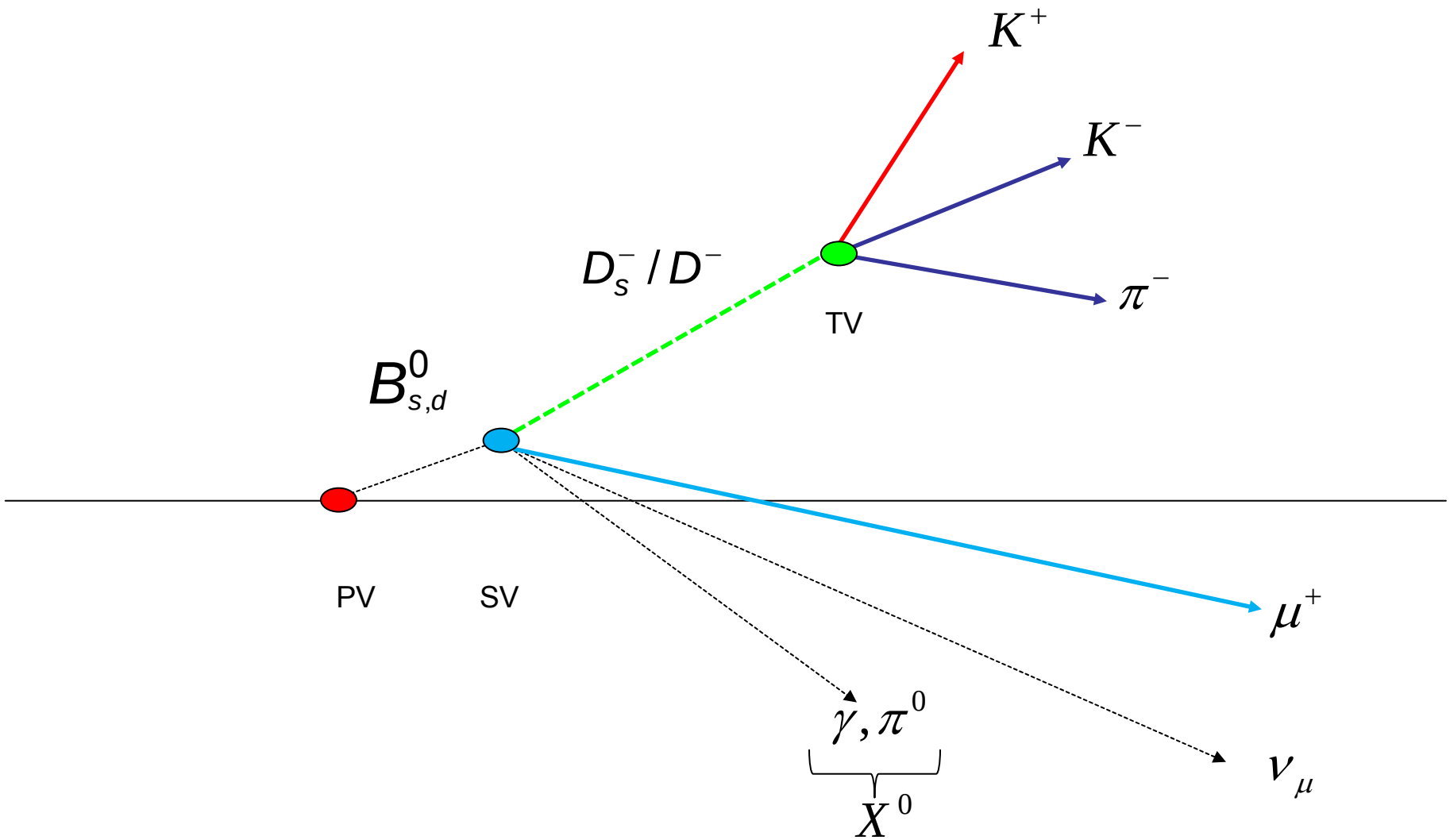
- Examine decays in different channels to the same final state:
  - detector asymmetries should be equal:

$$A_{fs}^{s} \approx \frac{\delta_c}{2} + \frac{a_{fs}^{s}}{2} \qquad A_{fs}^{d} \approx \frac{\delta_c}{2} + \frac{a_{fs}^{d}}{2}$$

  - Measure $\Delta A_{fs}^{s,d}$ instead of a_{fs}^{q} :

$$\Delta A_{fs}^{s,d} \rightarrow \frac{a_{fs}^{s}}{2} - \frac{a_{fs}^{d}}{2} \rightarrow A_{fs}^{s} - A_{fs}^{d}$$

  - Independent of detector asymmetry


K^+
K^-
D_s^- / D^-
π^-
TV
$B_{s,d}^0$
PV
SV
μ^+
γ, π^0
X^0
ν_μ

- High statistics of B_d and B_s.

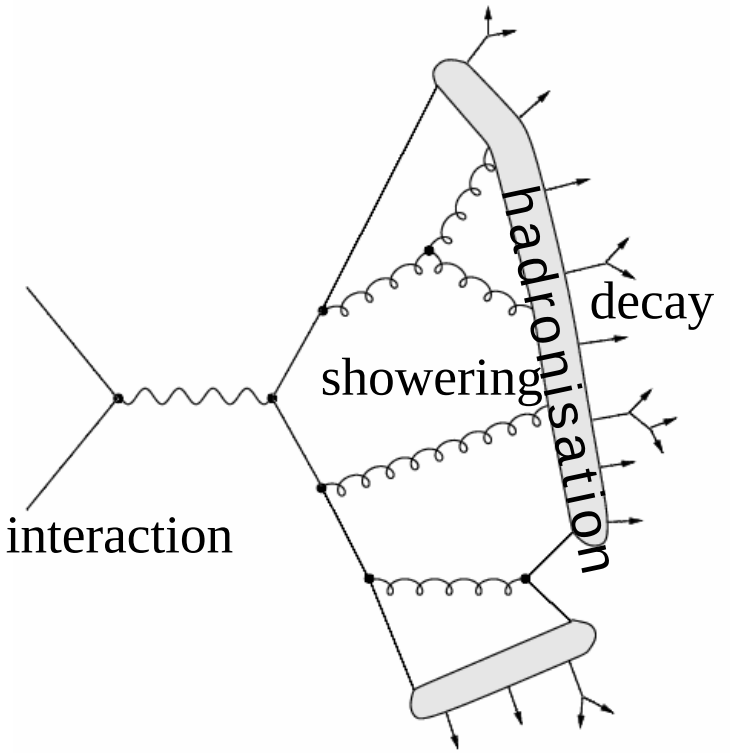
- Trigger sensitive to final states with leptons and only hadrons.

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

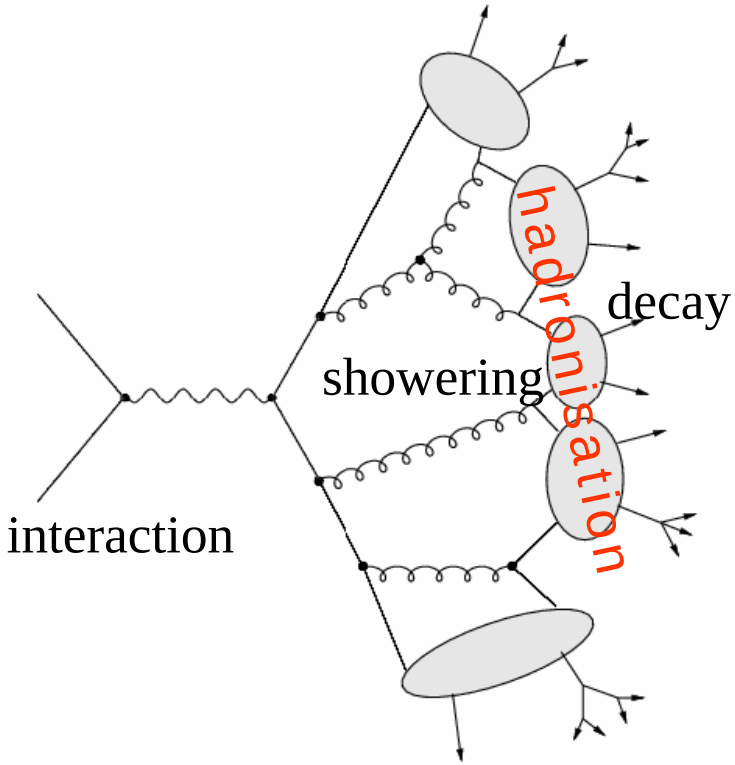
- Good $\pi/K/\mu/e$ separation to reduce the combinatorial background and other B meson decays. K-id is also very useful for flavour tagging.

- Good momentum and vertex resolution to reduce background

Different hadronization models



PYTHIA *uses Lund String hadronization.*



HERWIG *uses clustering hadronization.*