Looking for New Physics: Precision measurement of B meson decays

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Content:

CKM Matrix and Unitarity Triangle

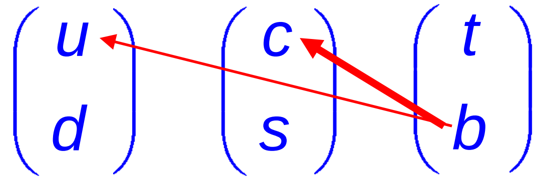
CKM Metrology - Experimental Status

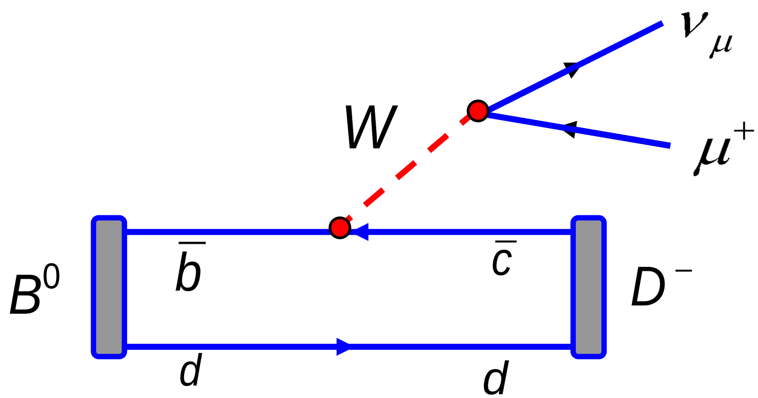
B Physics with LHCb

Why studying B mesons ?

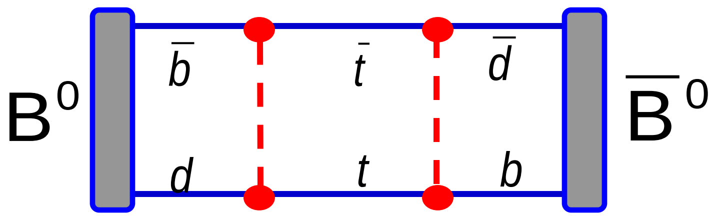
<u>Mesons with b-Quarks:</u>

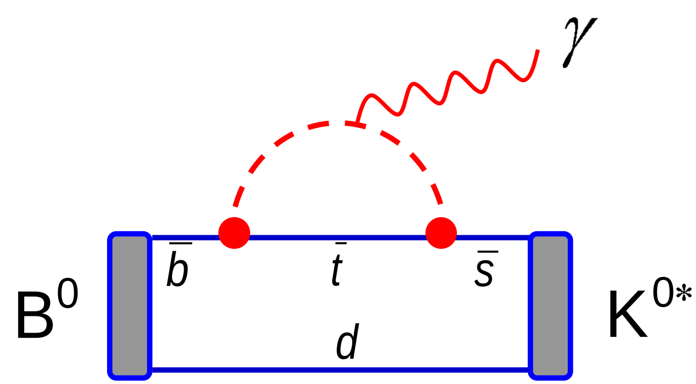
- Heaviest quark that forms hadronic bound states (m~4.7 GeV).
- Must decay outside 3rd family
- All decays are CKM suppressed
- High mass: many accessible final states
- Long lifetime (~1.6 ps): experimentally simple to identify
- Large CP violation expected





Loop corrections are important:





CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Number of independent parameters: →

18 parameter (9 complex elements)

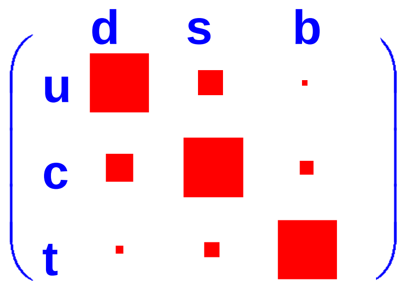
-5 relative quark phases (unobservable)

-9 unitarity conditions

=4 independent parameters: 3 angles + phase

Wolfenstein Parametrization

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} =$$



$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

λ, A, ρ, η with $\lambda = 0.22$

$|V_{ub}| \times e^{-i\gamma}$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$|V_{td}| \times e^{-i\beta}$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5(1/2-\rho-i\eta) & 1-\lambda^2/2-\lambda^4/8\,(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 + A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

$|V_{ts}| \times e^{-i\beta_s}$

Unitarity Triangles

CKM matrix is unitary :

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \text{(db)}$$

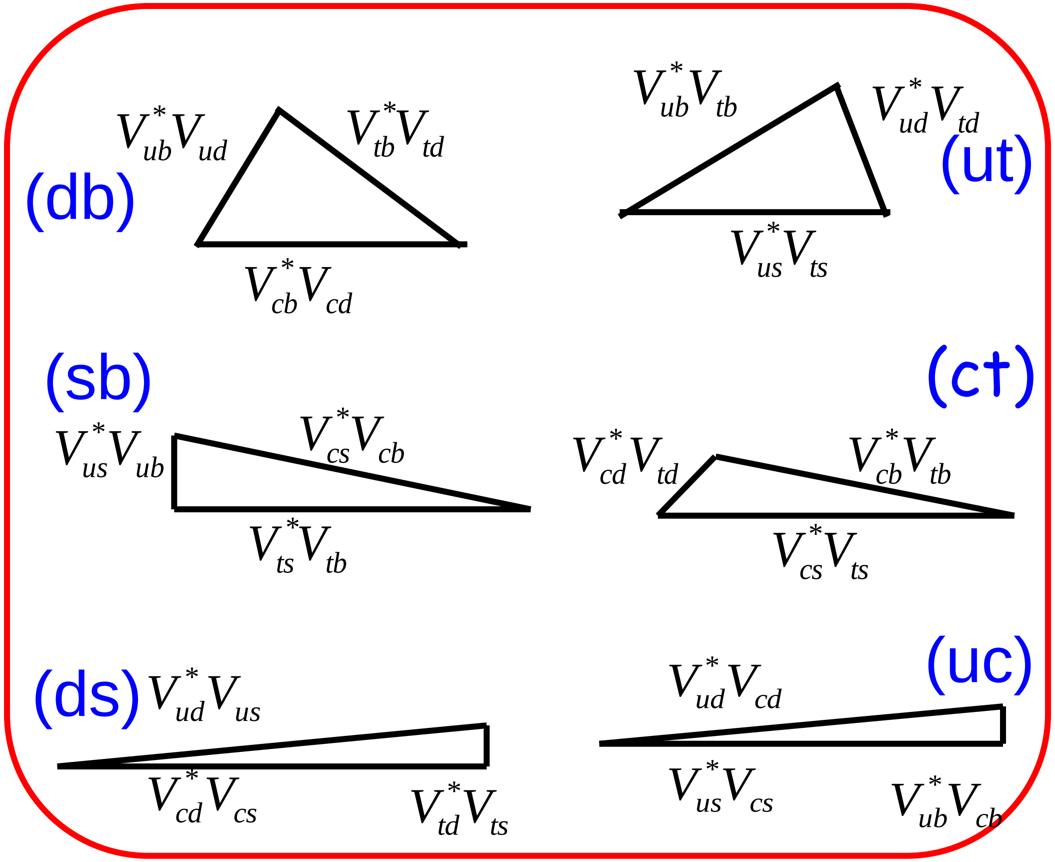
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad \text{(sb)}$$

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad \text{(ds)}$$

$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0 \quad \text{(ut)}$$

$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0 \quad \text{(ct)}$$

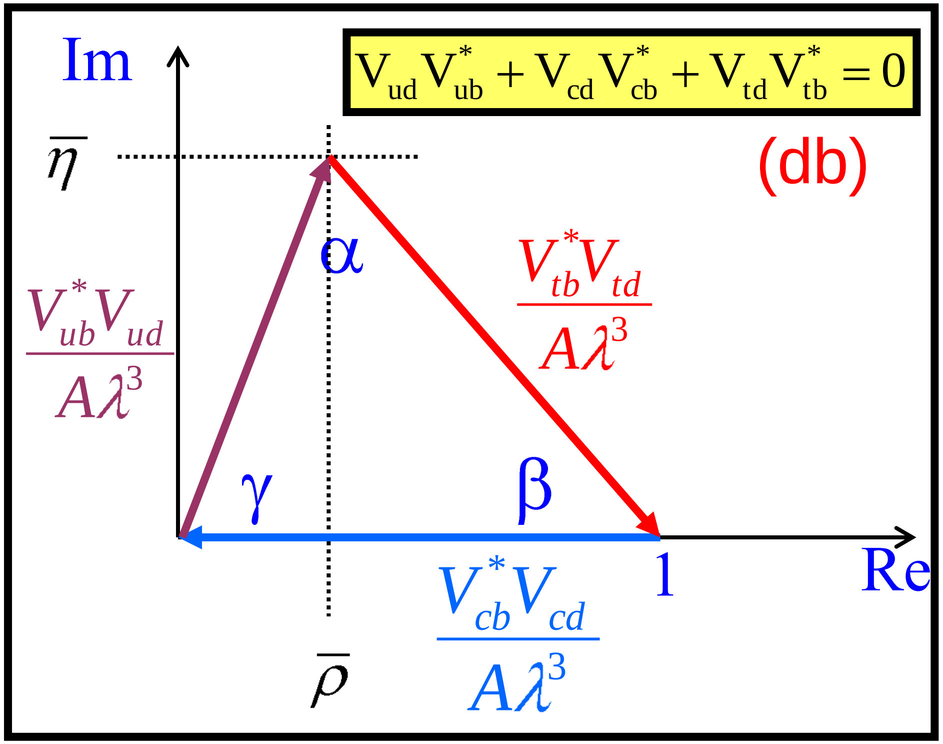
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad \text{(uc)}$$



All 6 triangles have the same area (= $J_{CP}/2$): a measure of CPV in the Standard Model.

Unitarity Triangle

Redraw "unsquashed" Δ's and divide by $V^*_{cb}V_{cd}$



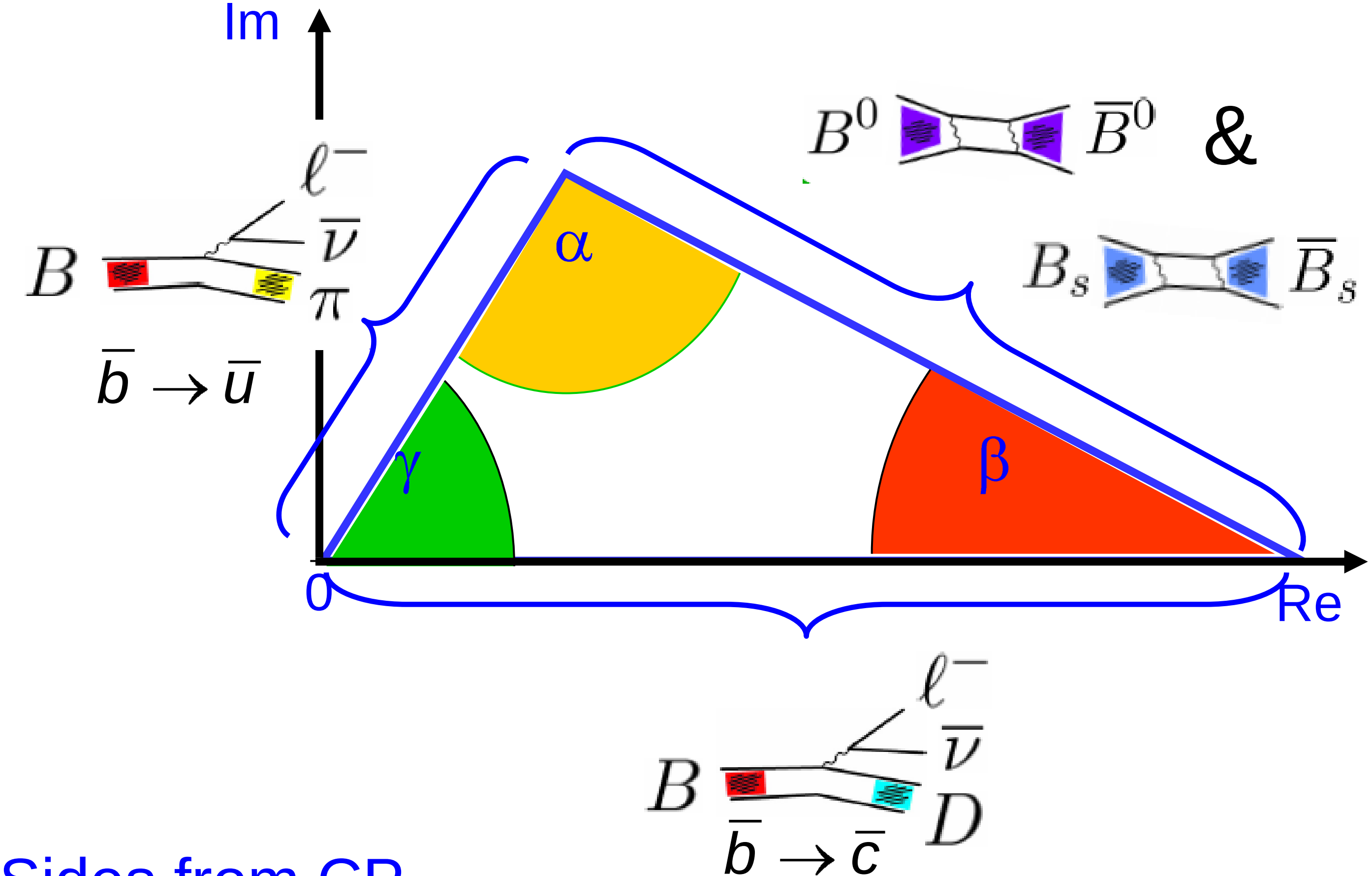
$$(\bar{\rho},\bar{\eta}) \equiv (1-\lambda^2/2)(\rho,\eta)$$

$$\alpha \equiv \pi - \beta - \gamma$$

$$\gamma \equiv \arg\left[-\frac{V^*_{ub}V_{ud}}{V^*_{cb}V_{cd}}\right] = \tan^{-1}\frac{\eta}{\rho} \sim 70^o$$

$$\beta \equiv \arg\left[-\frac{V^*_{cb}V_{cd}}{V^*_{tb}V_{td}}\right] = \tan^{-1}\frac{\bar{\eta}}{1-\bar{\rho}} \sim 21^o$$

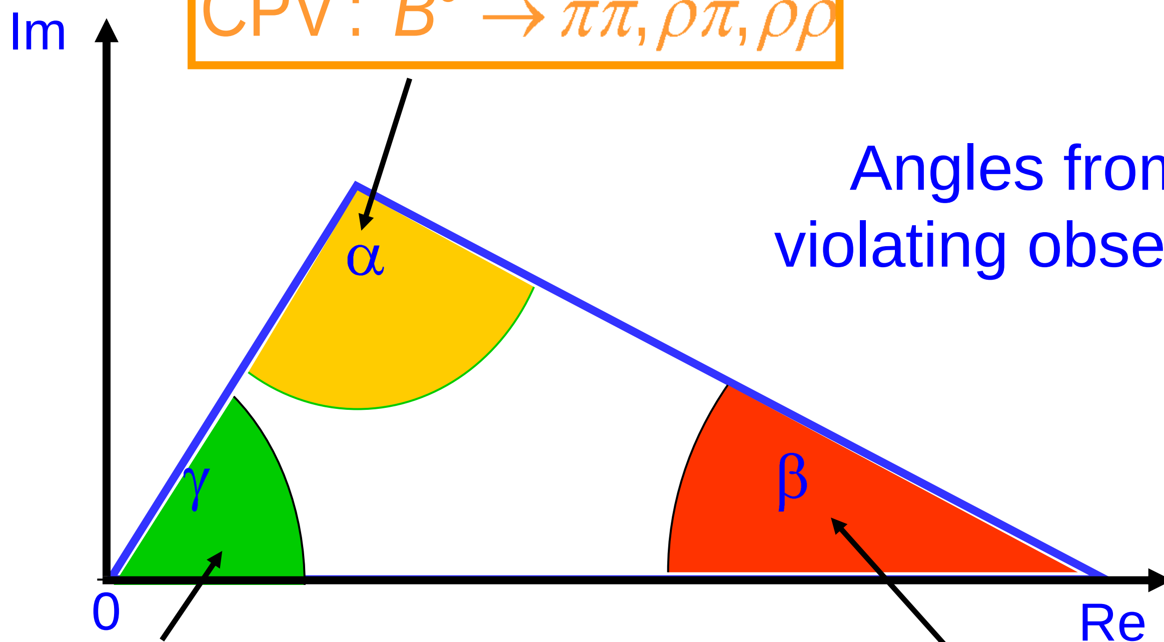
Unitarity Triangle from B Decays



Sides from CP conserving observables

Unitarity Triangle from B Decays

$\mathrm{CPV:}\ B^0 \to \pi\pi, \rho\pi, \rho\rho$



Angles from CP violating observables

$\mathrm{CPV:} B^0 \to DK^{(*)}, DK_S^0, K\pi, D^*\pi$

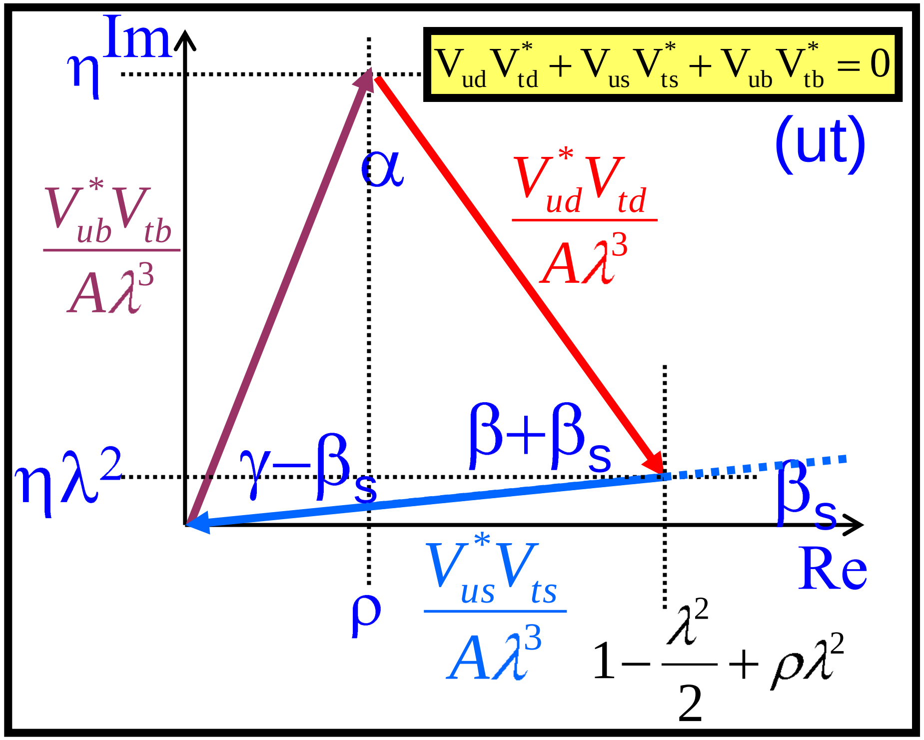
$B_S^0 \to D_S K, KK$

$\mathrm{CPV:}\ B^0 \to J/\psi K_S^0$

„Golden channel"

Very rare decays $\to$ several 10^9 B mesons necessary

The 2nd Unitarity Triangle



$$\beta_s \equiv \arg\left[-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}\right] \sim \eta\lambda^2 \sim 1^o$$

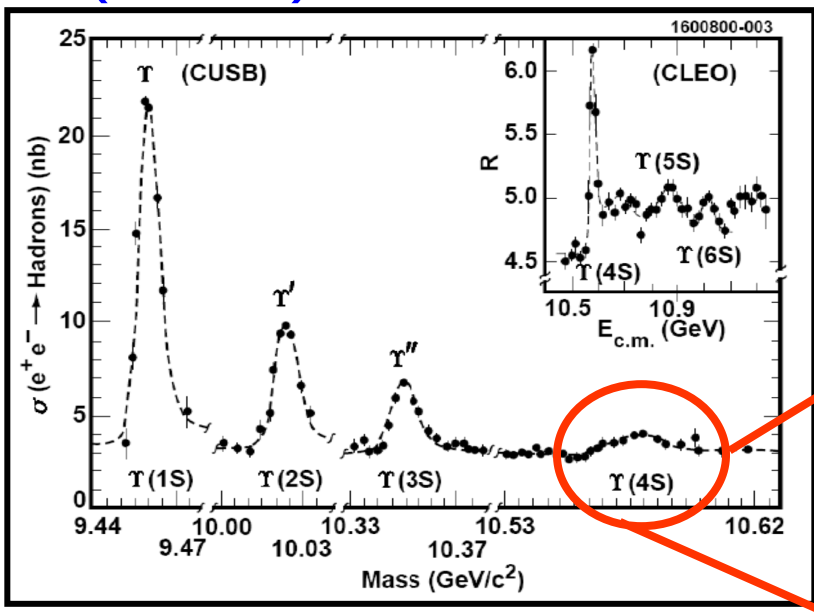
~20 mrad

CKM Metrology - Experimental Status

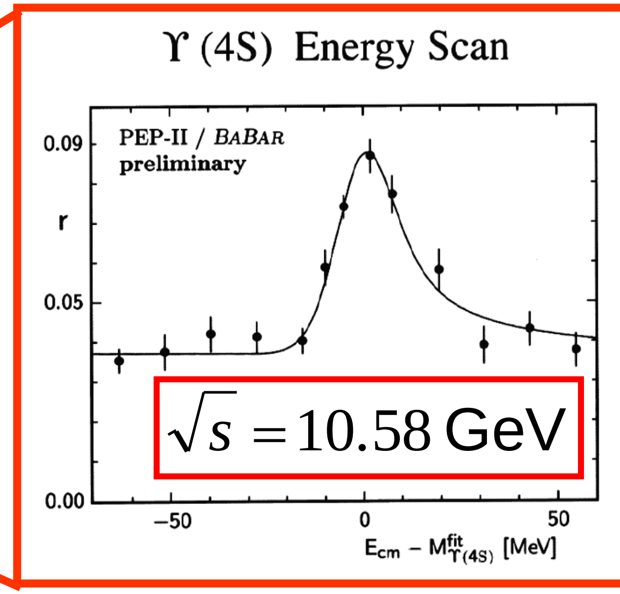
- $e^+ e^-$ B factories
- Measurement $B^0 \overline{B^0}$ oscillation
- Measurement of CP Violation in $B^0 \rightarrow J/\psi K_s$
- UnitarityTriangle

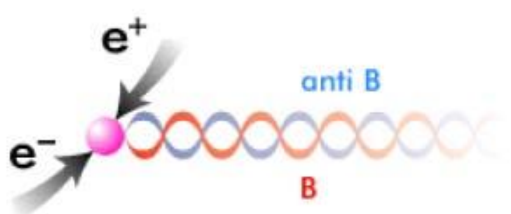
$e^+ e^-$ B factories

$\sigma\ (e^+ e^+)$



$e^+ e^+ \to \Upsilon\ (4s) \to B\ B$





50% / 50%

$B^0\overline{B^0} / B^+B^-$

$\sigma_{b\bar{b}} = 1.1$ nb

Continuum ~ 3 nb

1.1 million / fb^{-1}

$B^0\overline{B^0}$ pair is produced in a coherent L=1 state:

$$|B_1B_2\rangle = \frac{1}{\sqrt{2}}\left(|B^0\rangle|\overline{B}^0\rangle - |\overline{B}^0\rangle|B^0\rangle\right)$$

Asymmetric B factories

PEP-II @ SLAC

Energy: 9.0 GeV e^- + 3.1 GeV e^+

Max. currents: e^+ / e^- ~ 3.2 / 2.3 A

Design luminosity : 3 x 10^{33} $cm^{-2}s^{-1}$

Peak luminosity : 1.207 x 10^{34} cm^{-2} s^{-1}

B mesons: rate ~ 13 Hz, 470 M $B\bar{B}$

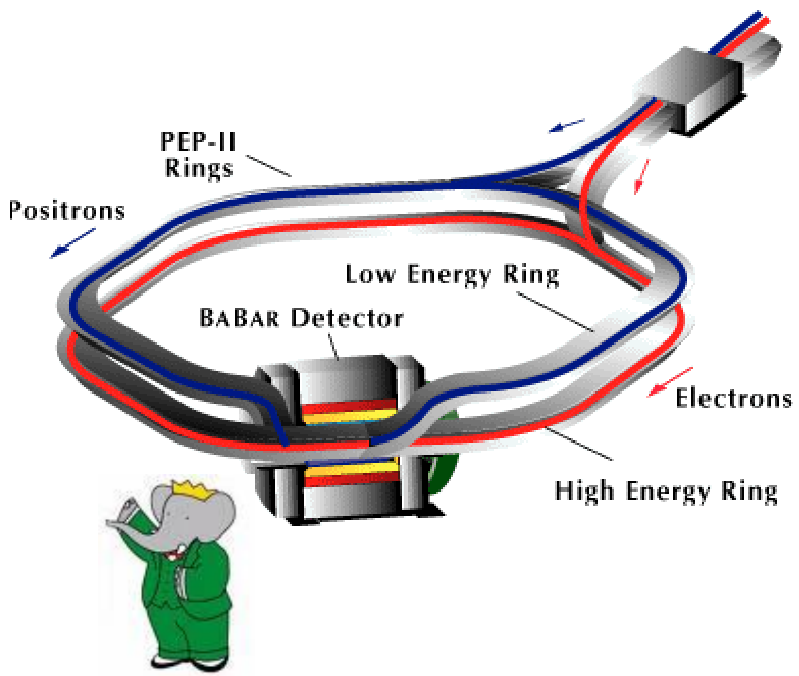
KEK-B @ KEK

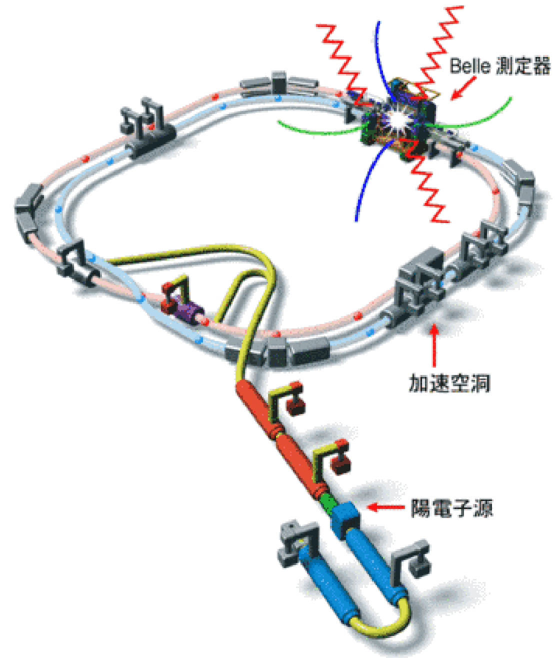
Energy: 8.0 GeV e^- +3.5 GeV e^+

Design luminosity : 1 x 10^{34} $cm^{-2}s^{-1}$

Peak luminosity : 1.71 x 10^{34} cm^{-2} s^{-1}

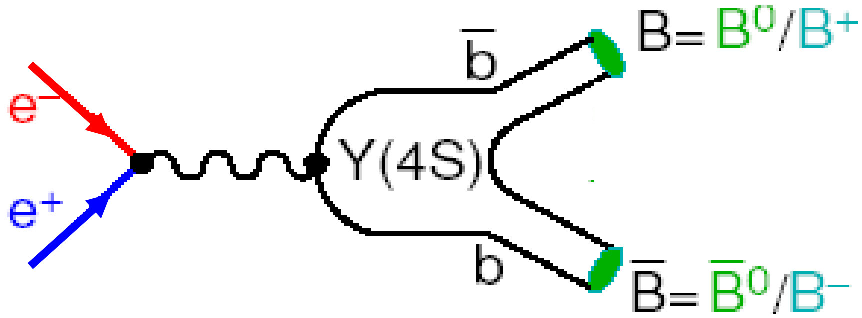
B mesons: rate ~ 19 Hz, 780 M $B\bar{B}$





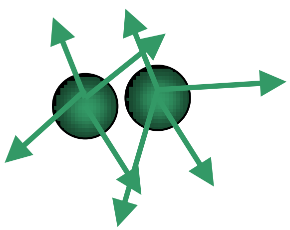
Asymmetric beam energy

$E_{CMS} = 10.58\,\text{GeV}$



Symmetric:

e^- $\xrightarrow{5.3\,\text{GeV}}$ $\xleftarrow{5.3\,\text{GeV}}$ e^+

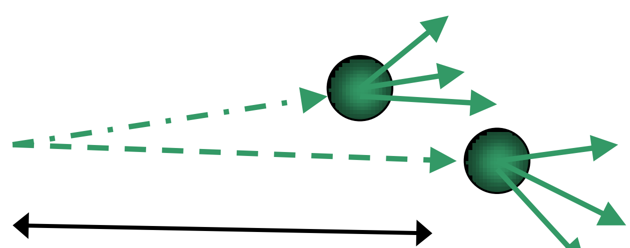


B mesons at rest
→ decay length z≈0

Asymmetric:

e^- $\xrightarrow{9\,\text{GeV}}$ $\xleftarrow{3.1\,\text{GeV}}$ e^+

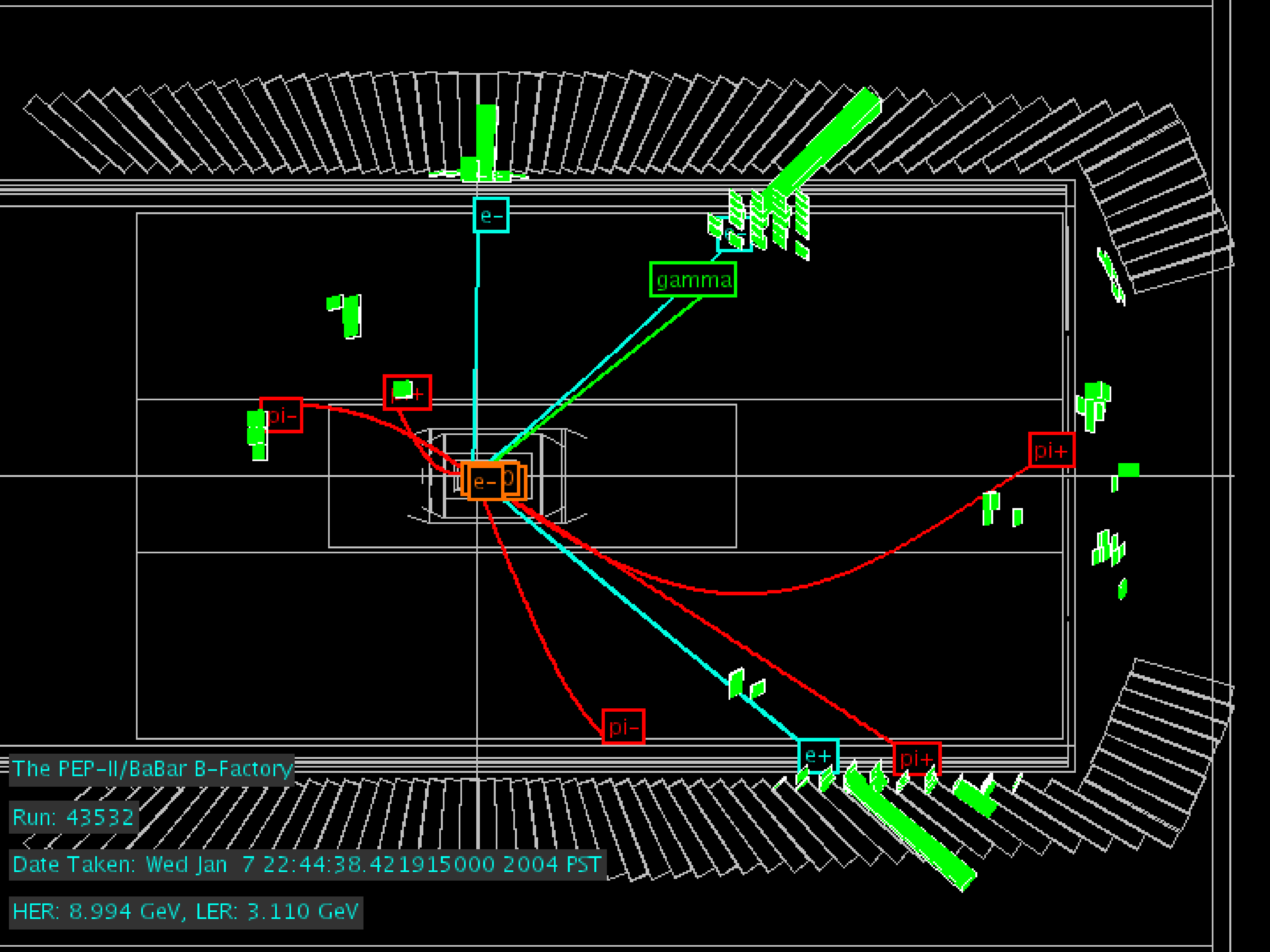
Boost β = 0.56 *(BABAR)*



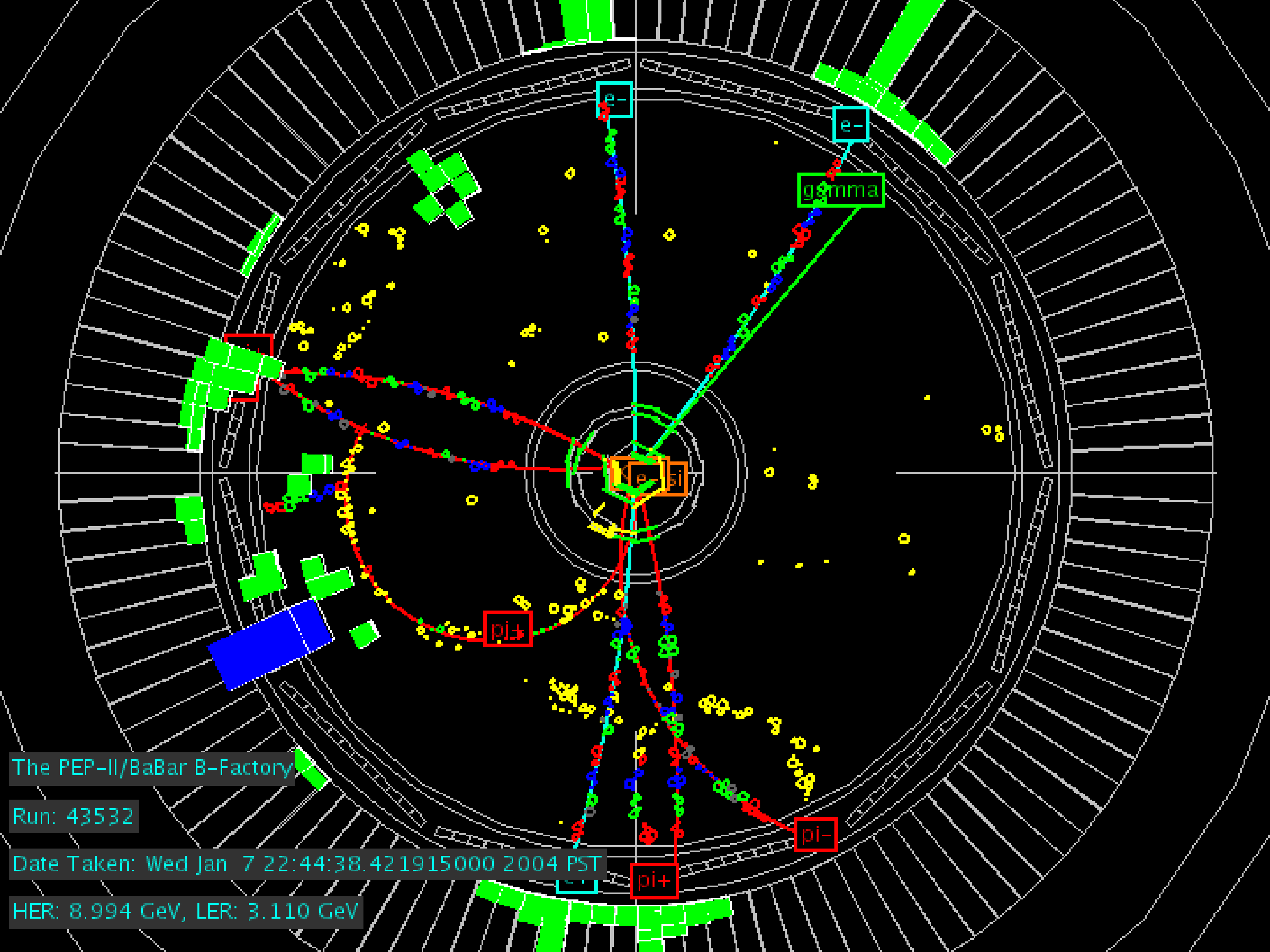
$$z = \beta\gamma\, c\, t$$

decay length

z≈250μm



e-
gamma
pi+
pi-
e-
pi+
pi-
e+
pi+
The PEP-II/BaBar B-Factory
Run: 43532
Date Taken: Wed Jan 7 22:44:38.421915000 2004 PST
HER: 8.994 GeV, LER: 3.110 GeV


e-
e-
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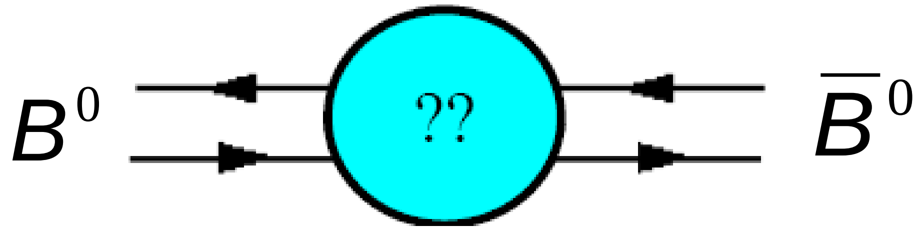
Mixing Phenomenology



$$i\frac{d}{dt}\begin{pmatrix} B^0(t) \\ \overline{B}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix} B^0(t) \\ \overline{B}^0(t) \end{pmatrix}$$

No mass eigenstates

Mass eigenstates: $\left|B_L\right\rangle = p\left|B^0\right\rangle + q\left|\overline{B^0}\right\rangle$ with m_L, Γ_L

$\left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\overline{B^0}\right\rangle$ with m_H, Γ_H

complex coefficients

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

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

Flavor eigenstates: $\left|B^0\right\rangle = \frac{1}{2p}\left(\left|B_L\right\rangle + \left|B_H\right\rangle\right)$ $\quad \left|\overline{B}^0\right\rangle = \frac{1}{2q}\left(\left|B_L\right\rangle - \left|B_H\right\rangle\right)$

Mixing of neutral mesons

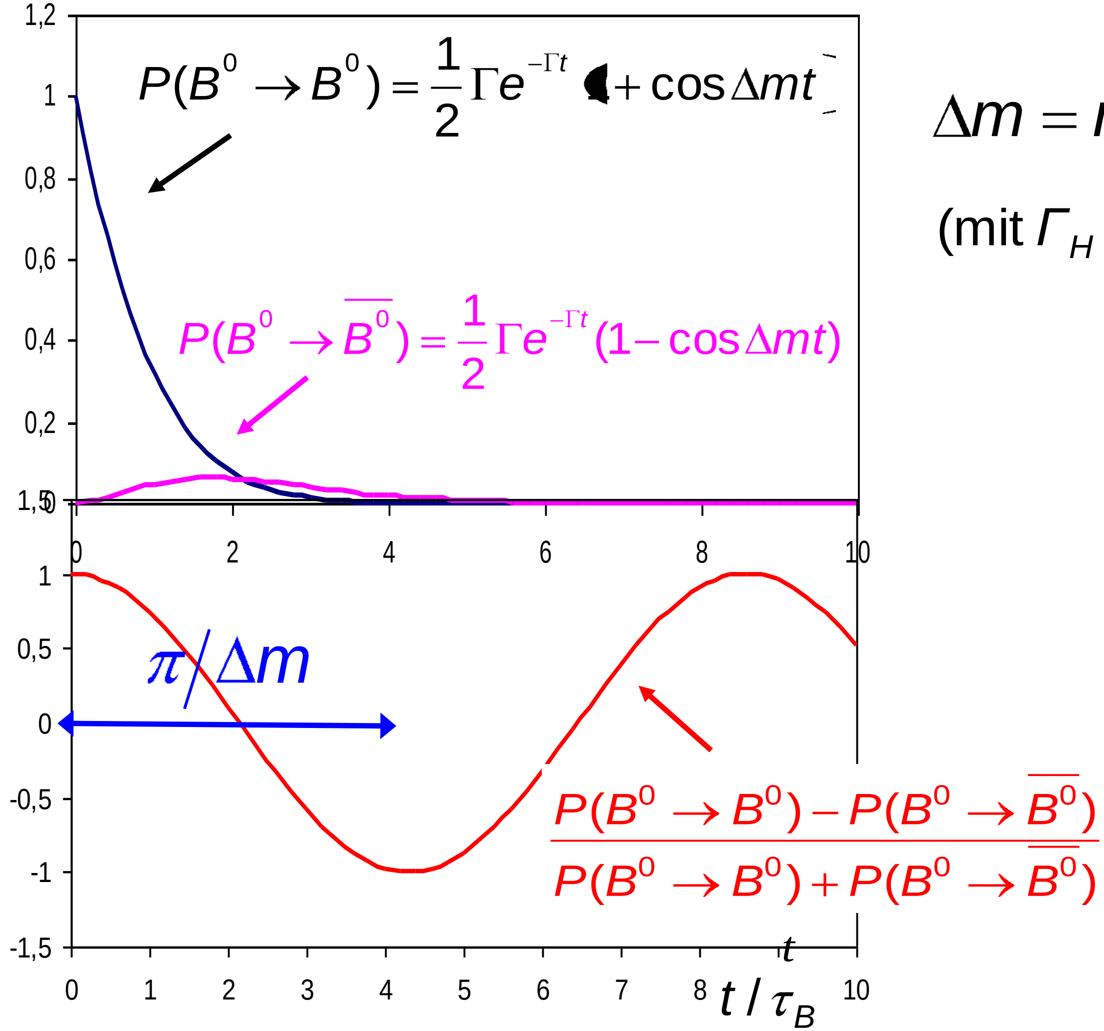
$$\underbrace{P(B^0 \to B^0) = P(\overline{B^0} \to \overline{B^0})}_{\text{CPT}} = \frac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} + 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

$$P(B^0 \to \overline{B^0}) = \frac{1}{4}\left|\frac{q}{p}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

$$\Delta m = m_H - m_L$$

$$P(\overline{B^0} \to B^0) = \frac{1}{4}\left|\frac{p}{q}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

B^0-B^0 Mixing

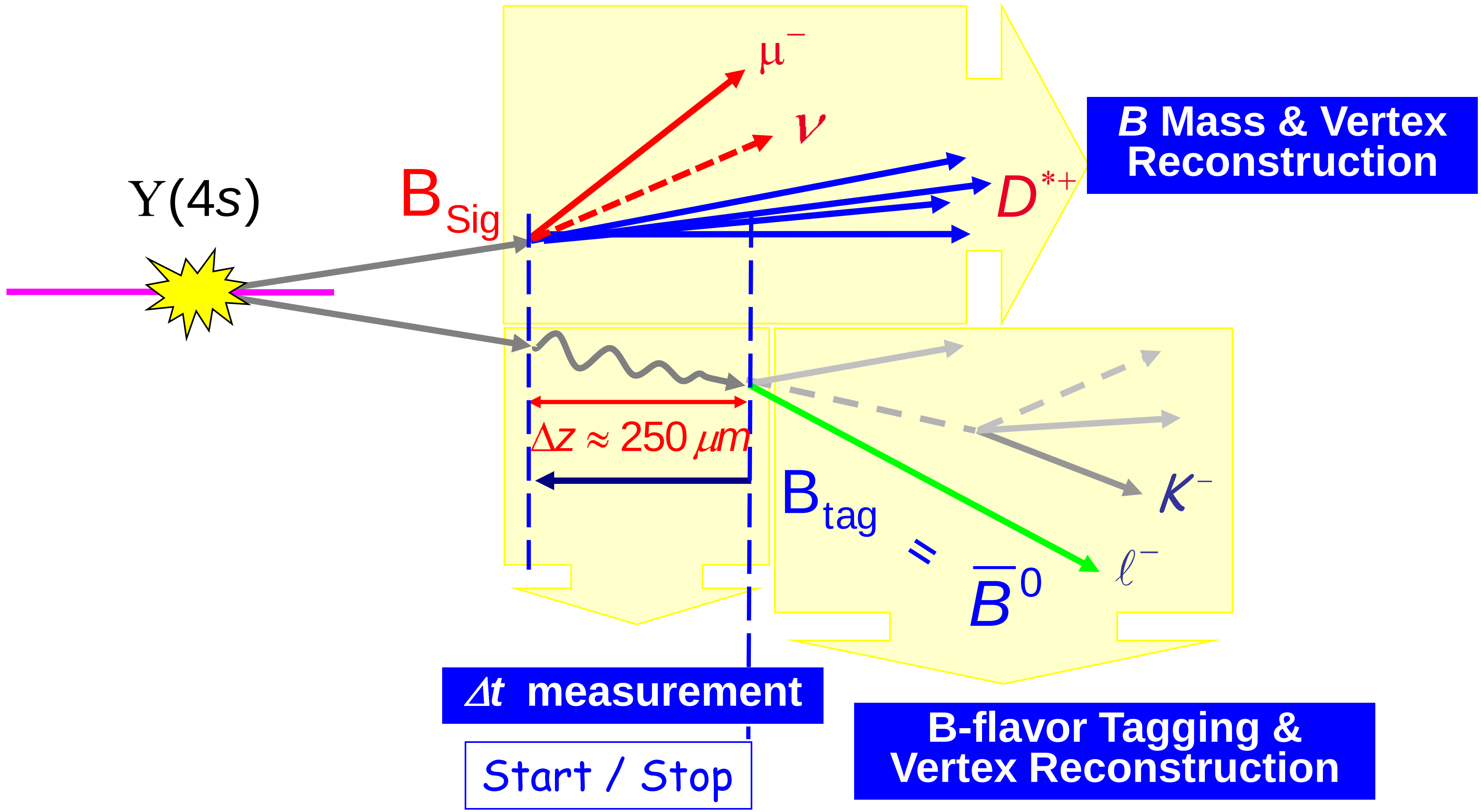


$$\Delta m = m_H - m_L$$

(mit $\Gamma_H \approx \Gamma_L \approx \Gamma$)

Oscillation Frequency

Steps of oscillation measurement



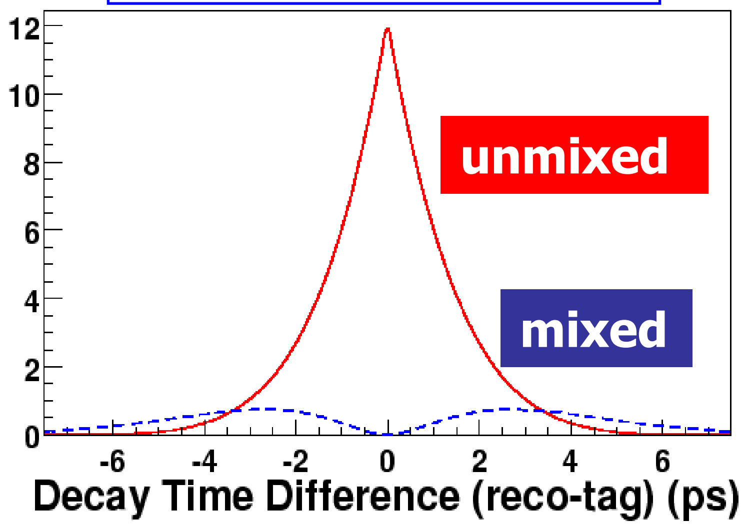
Tagging Quality: Q = 30.5%

B^0 Oscillation

$$A_{mix}(t) = \frac{N(B)_{unmixed}(t) - N(B)_{mixed}(t)}{N(B)_{unmixed}(t) + N(B)_{mixed}(t)} \sim \cos(\Delta m t)$$

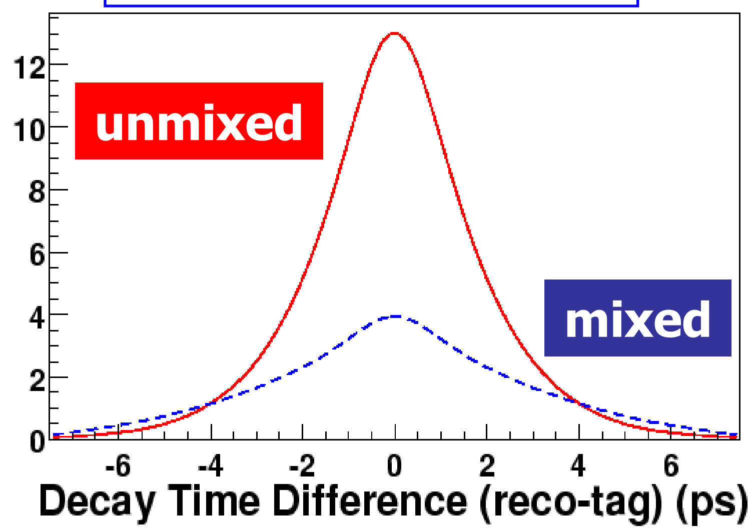
perfect

tagging & Δt resolution



realistic

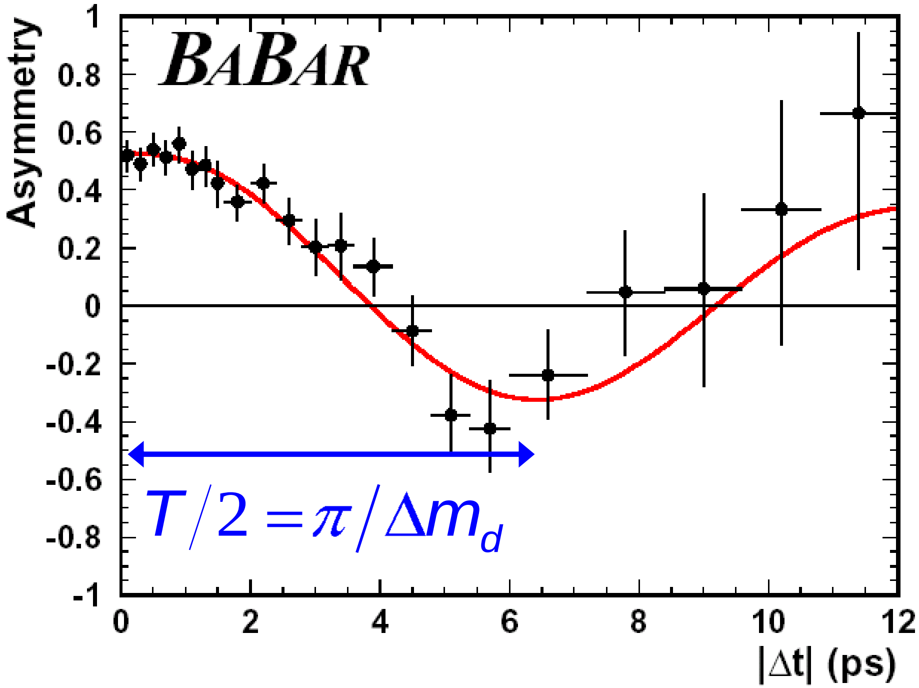
tagging & Δt resolution



Negative Δt:
Signal B decays before tagging B

B^0 Oscillation

$B_d^0 - \overline{B}_d^0$

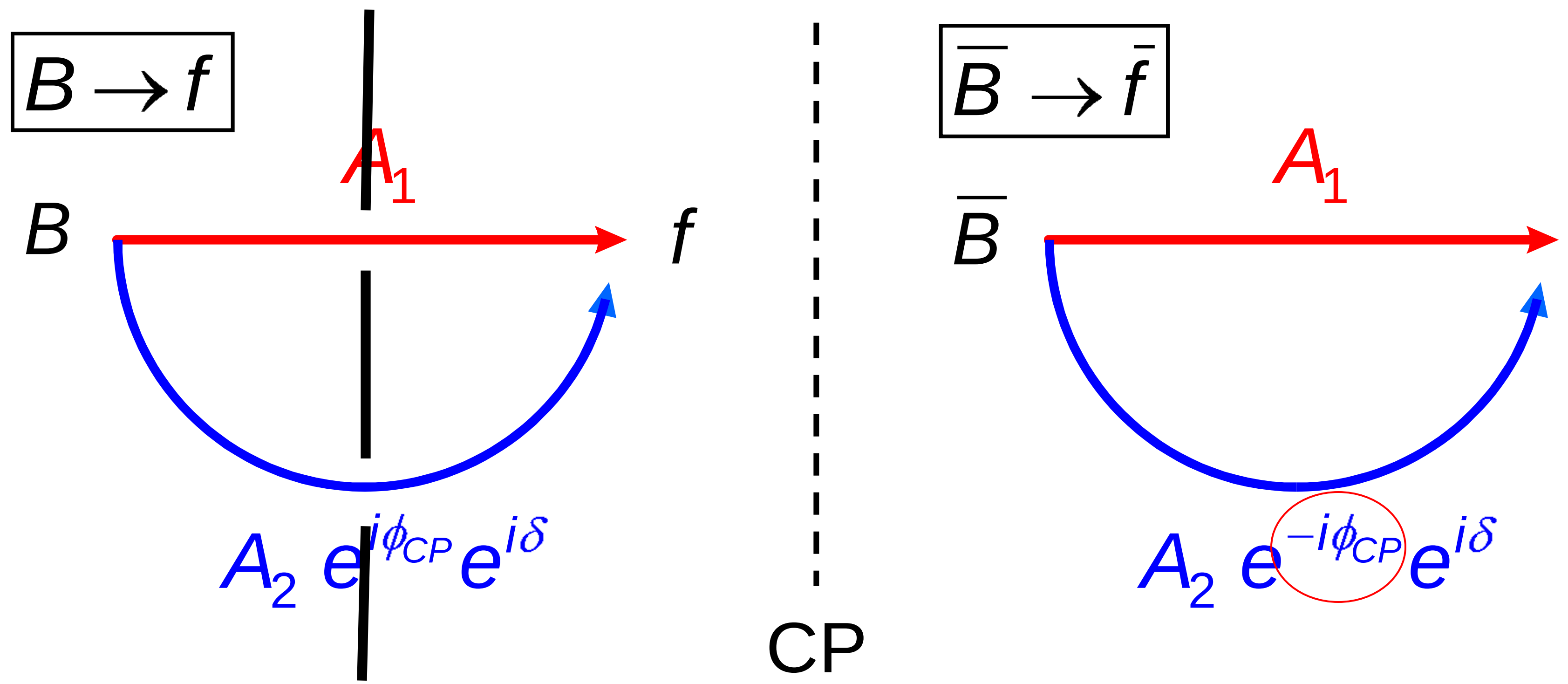


$$\Delta m_d = 0.507 \pm 0.005\ \mathrm{ps}^{-1}$$

(World average, PDG 20098)

Observation of CP violation

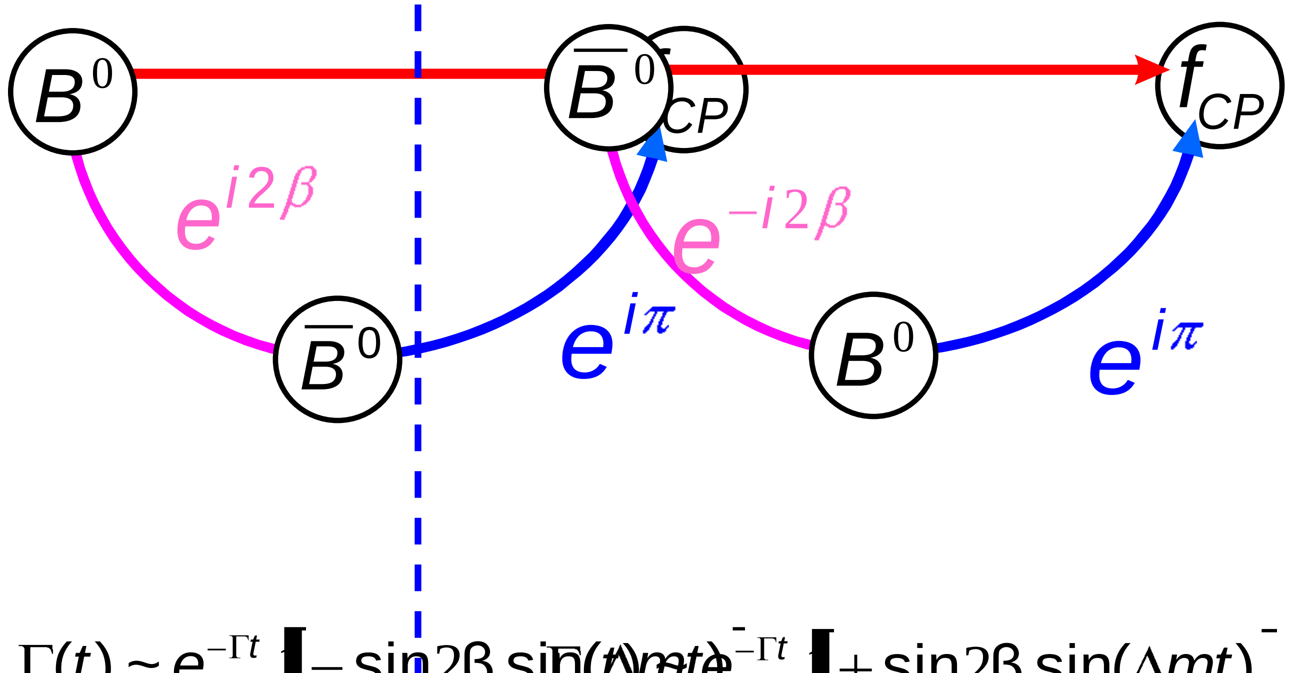
Observation of CP violating phase → Interference effect of 2 amplitudes



$$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} + \delta)$$

$$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} - \delta)$$

CP-Violation through mixing and decay



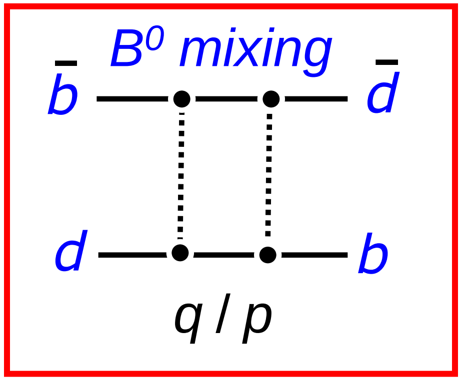
$$\Gamma(t) \sim e^{-\Gamma t}\left[1 - \sin 2\beta \sin(\Delta m t)\right] \qquad \overline{\Gamma}(t) \sim e^{-\Gamma t}\left[1 + \sin 2\beta \sin(\Delta m t)\right]$$

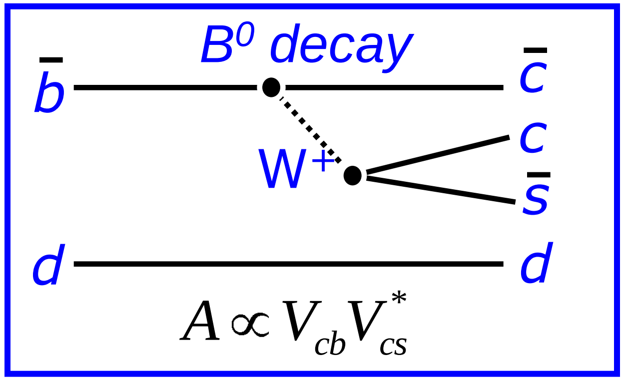
CP

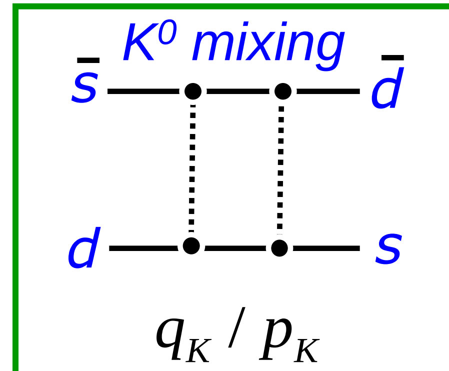
$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0 \to f)(t) - \Gamma(B^0 \to f)(t)}{\Gamma(\overline{B}^0 \to f)(t) + \Gamma(B^0 \to f)(t)} = \sin 2\beta \sin(\Delta m t)$$

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

$$\eta_{CP} = -1$$







Same for all $c\bar{c}K^0$ channels

$$\frac{q}{p} \sim e^{2i\beta}$$

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}} = -e^{-2i\beta}$$

Beside V_{td} all other CKM elements are real

$$V_{td} \approx |V_{td}| e^{-i\beta} \quad \Rightarrow \quad \begin{array}{c} |\lambda_{CP}| = 1 \\ \mathrm{Im}(\lambda_{CP}) = \sin(2\beta) \end{array}$$

no direct CPV, no CPV in mixing

Account for direct CP Violation

$$\Gamma(B^0 \to f_{CP})(t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} - \operatorname{Im}\left(\lambda_{CP}\right)\sin\left(\Delta m_d t\right) + \frac{1-|\lambda_{CP}|^2}{2}\cos\left(\Delta m_d t\right)\right]$$

$$\neq$$

$$\Gamma(\overline{B}^0 \to f_{CP})(t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} + \operatorname{Im}\left(\lambda_{CP}\right)\sin\left(\Delta m_d t\right) - \frac{1-|\lambda_{CP}|^2}{2}\cos\left(\Delta m_d t\right)\right]$$

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} = \ldots$$

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

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

$$B^0 \quad \begin{cases} = \dfrac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos(\Delta m t) - \dfrac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\sin(\Delta m t) \end{cases}$$

Direct CP violation

CP violation through interference

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad \Im(\lambda_f) = -\eta_f \sin 2\beta$$

CP Asymmetry if no direct CPV

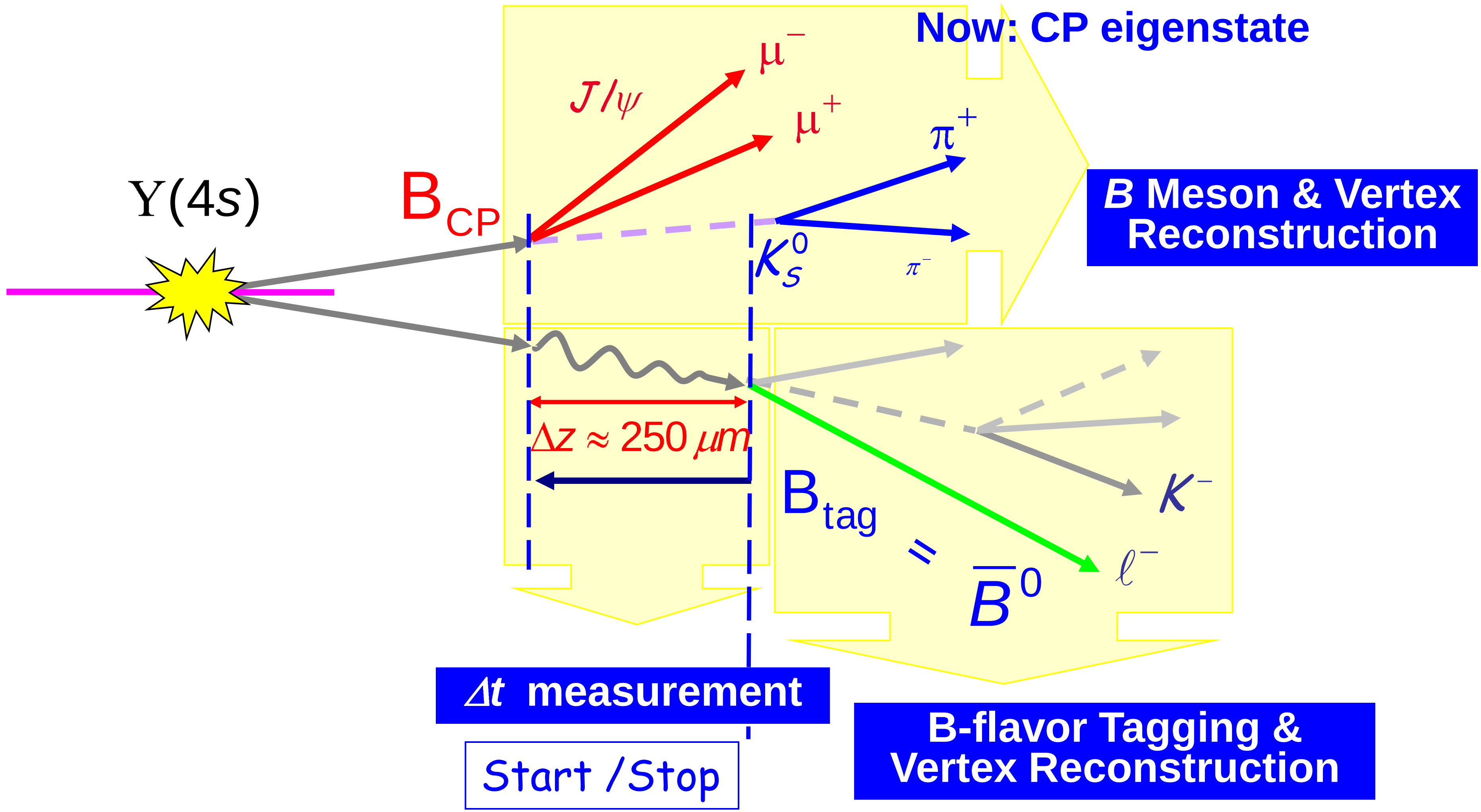
$$\Gamma(B^0 \to f_{CP})(t) \propto e^{-|\Delta t|/\tau_{B^0}} \times \left(1 - \sin 2\beta \sin(\Delta m_d t)\right)$$

$$\neq$$

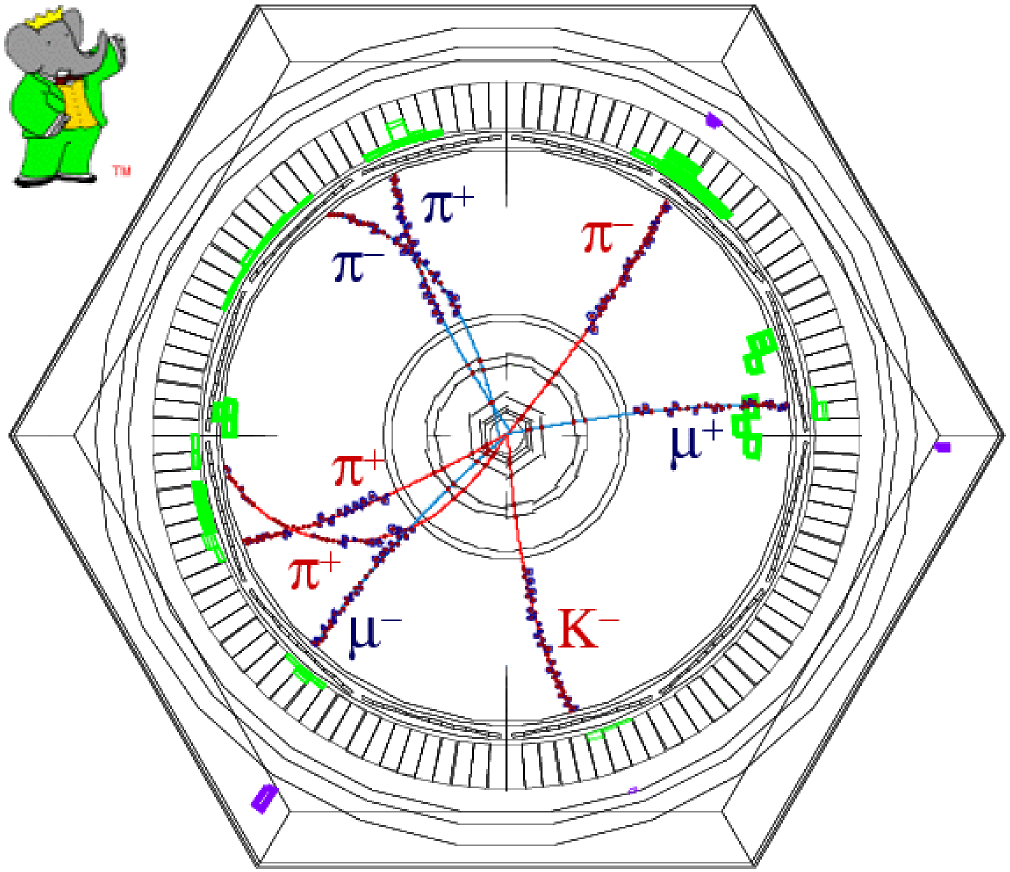
$$\Gamma(\overline{B^0} \to f_{CP})(t) \propto e^{-|\Delta t|/\tau_{B^0}} \times \left(1 + \sin 2\beta \sin(\Delta m_d t)\right)$$

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} = \sin 2\beta \sin(\Delta m_d t)$$

Steps of the CP measurement



Decay $B^0 \rightarrow \psi K_s$



$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\,\overline{B}$

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

$\psi \rightarrow \mu^+\mu^-$, $K_s \rightarrow \pi^+\pi^-$ } B_{CP}

$\overline{B}^0 \rightarrow D^{*+} \; \pi^-_{fast}$

$D^{*+} \rightarrow D^0 \, \pi^+_{soft}$

$D^0 \rightarrow K^-\pi^+$ } B_{tag}

at $\Delta t=0$: $B_{CP} = B^0$

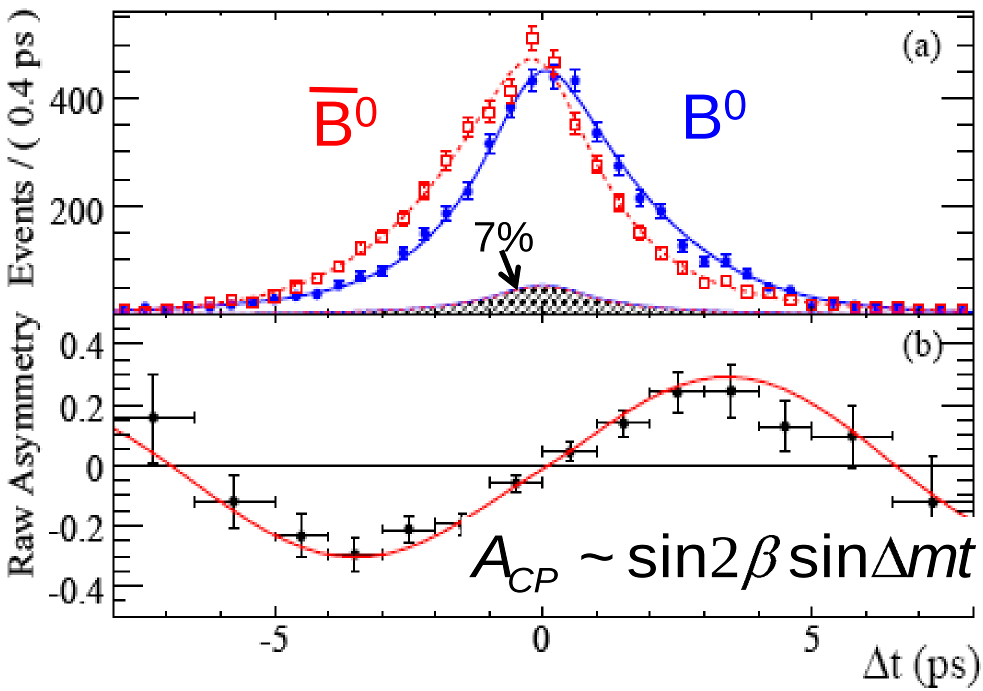
BABAR Experiment (SLAC, USA, 1999-2008)

CP Violation in $B^0 \to \psi K_s$

$B\bar{B}$-rate: 13 Hz

$B\bar{B}$ – events: 470 Mio. $\to$ 6750 B^0 / $\bar{B}^0 \to \psi K_s$

PRD 79, 072009 (2009)



$$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$$

BELLE experiment

(KEK, Japan, 1999-2010)

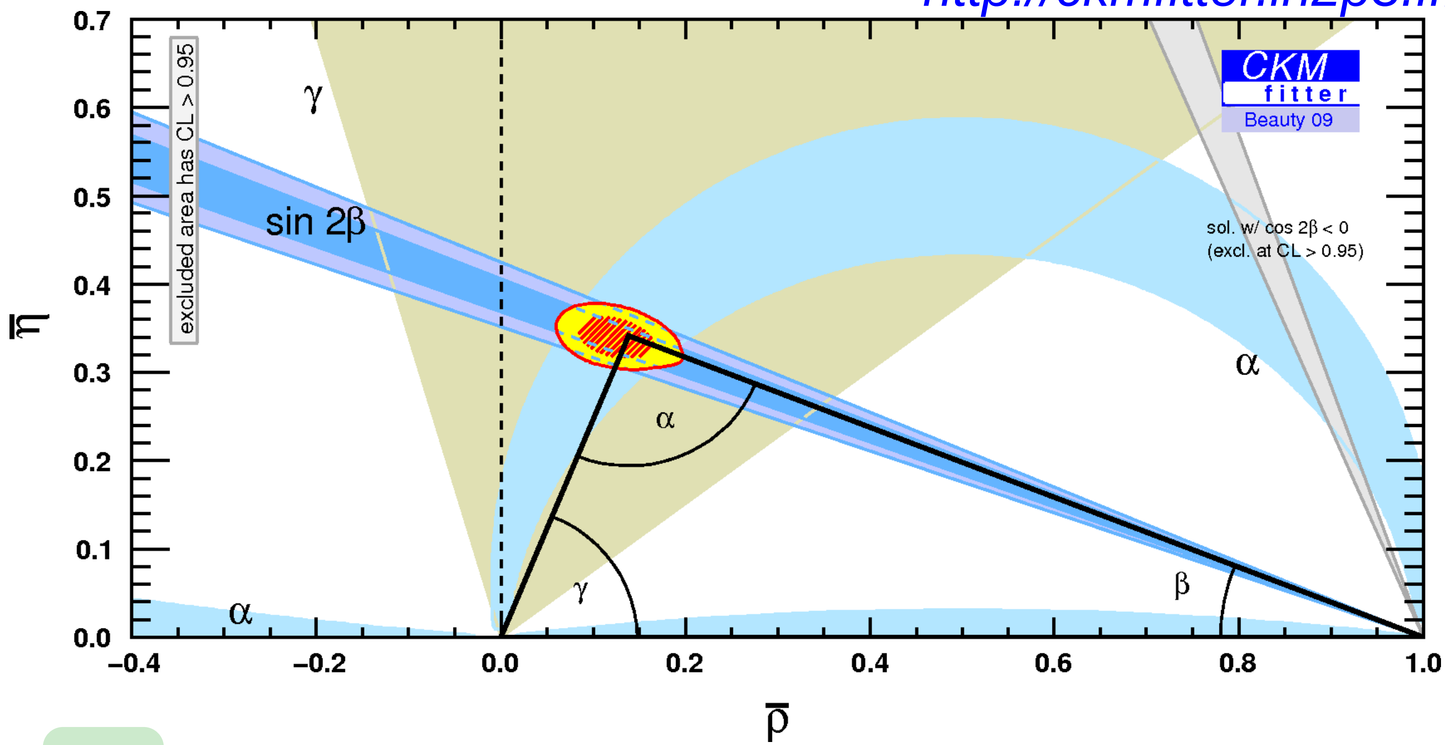
535 Mio. B B

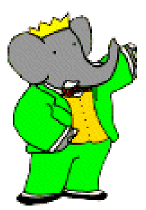
PRL 79, 031802 (2007)

$$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$$

Trigonometrie

http://ckmfitter.in2p3.fr/



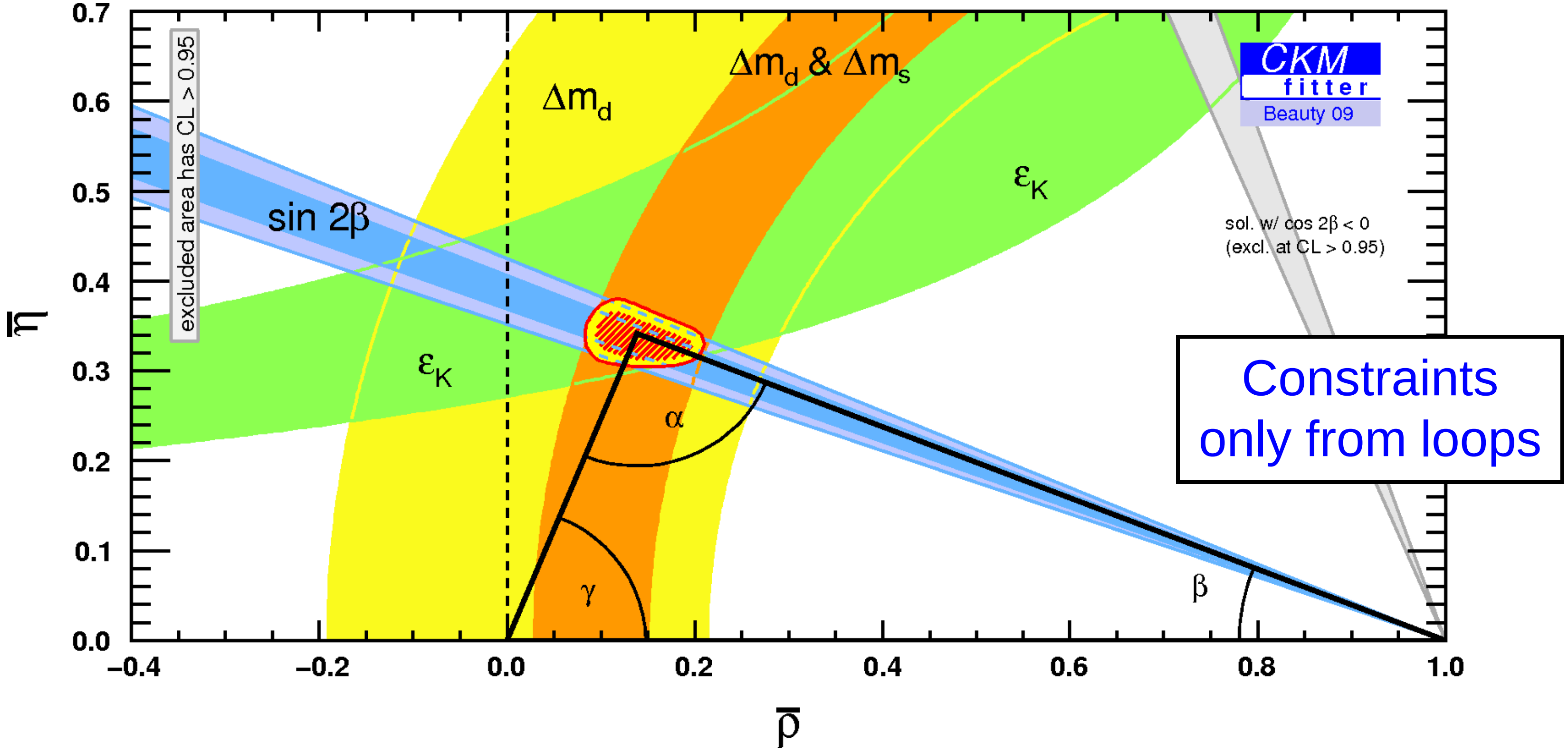


β $\beta = 21.0^o \pm 0.9^o \quad \sin 2\beta = 0.672 \pm 0.023 \quad (\pm 3.5\%)$

α $\alpha = (89^{+4.4}_{-4.2})^o$ World average.

γ With BABAR/BELLE difficult: $\gamma = (73^{+19}_{-24})^o$

Experimental Status



Within uncertainties loop-processes well described by SM.

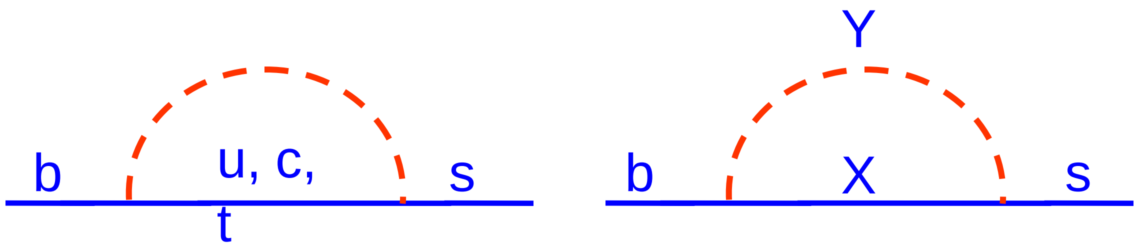
New Physics effects only appear corrections to leading SM terms.

Flavor Violation beyond the SM

Effects of New Physics*) at $\Lambda = O(\Lambda_{EW})$ on B decays can be treated in a low-energy "effective theory" approach (similar to Fermi-theory).

*) electroweak

New Physics in flavor changing amplitudes:



$$\mathcal{A}_{BSM}(b \to q + X) = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \frac{c_{NP}}{\Lambda^2} \right)$$

"CKM" factors

Loop-factors

In most general case NP has generic flavor structure!

Experiments tell us that NP around the EW scale should be MFV.

B Physics with LHCb

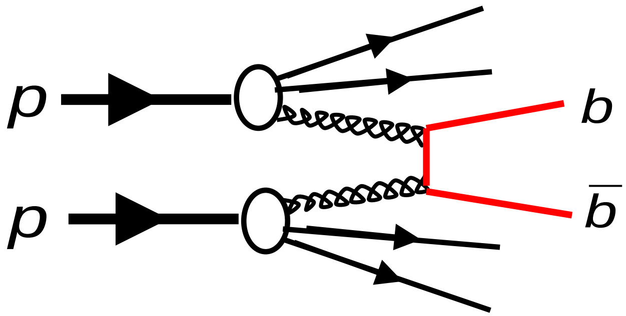
and other future B experiments

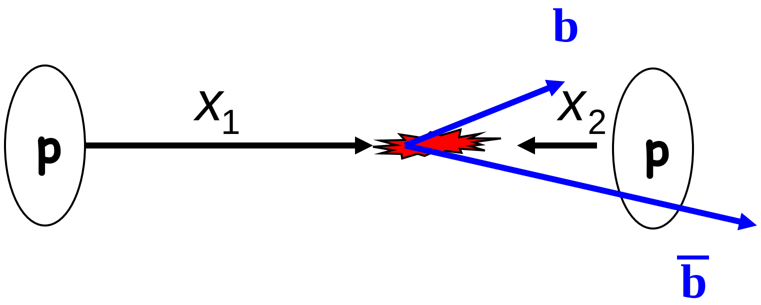
= Looking for corrections to corrections

Contents:

- B production at the LHC
- B event signature
- Detector properties
- Key measurements

B Production at the LHC

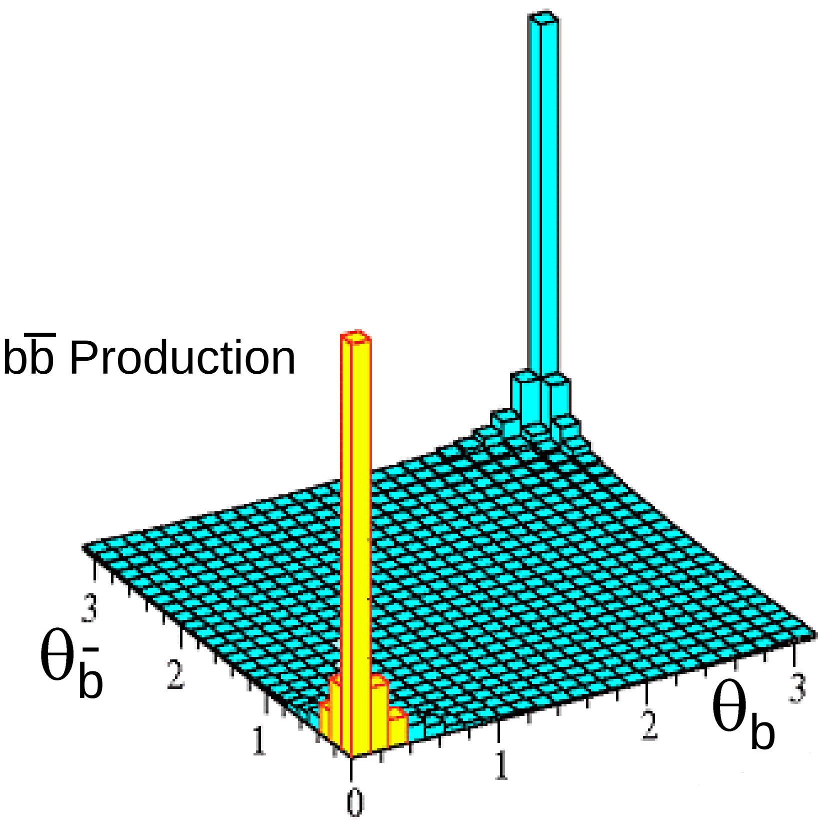




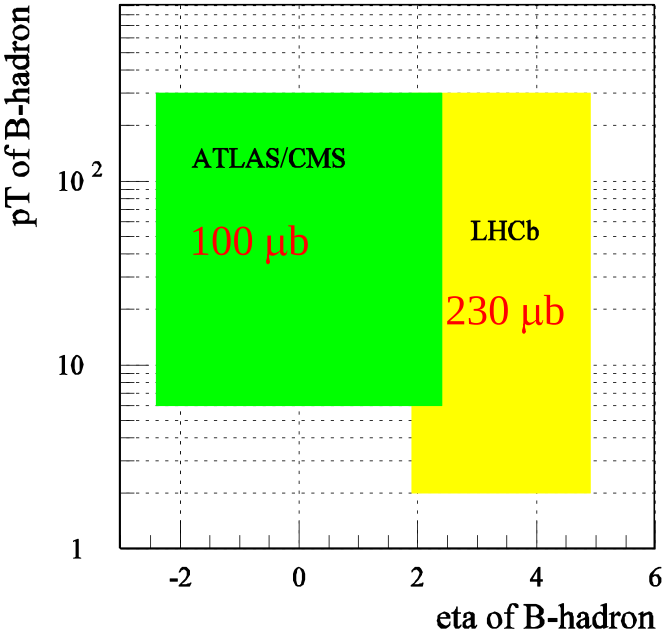
- pp collisions at $\sqrt{s}$ = 7, 10, 14 TeV

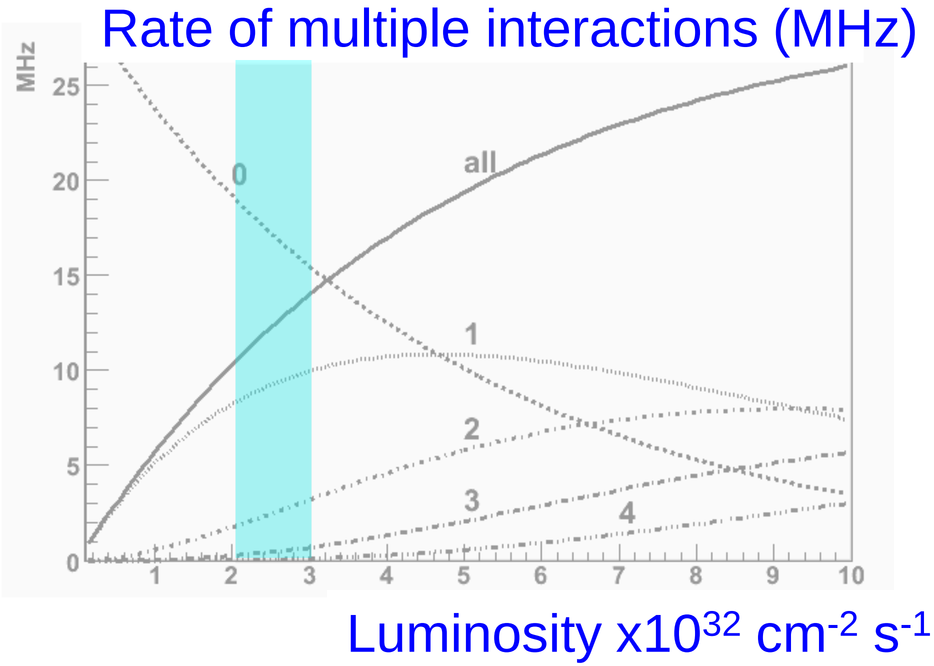
  σ_{inel} ~ (0.89, 0.95, 1) ×100 mb
  σ_{bb} ~ (0.44, 0.67, 1) × 500 μb

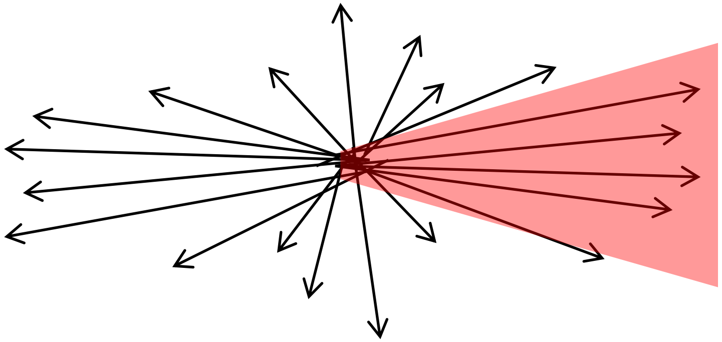
- Correlated forward production of bb
- B , B^0, B_s, B_c, Λ_b ...
- $\mathcal{L}$ ~ 2 x 10^{32} cm^{-2} s^{-1} (tuned at LHCb)
  - ~ 10^{12} bb events / year (2 fb^{-1})
  - 50 kHz bb-events in LHCb
- Charged particle multiplicity ~30 / unit of rapidity



B Physics & LHCb Detector



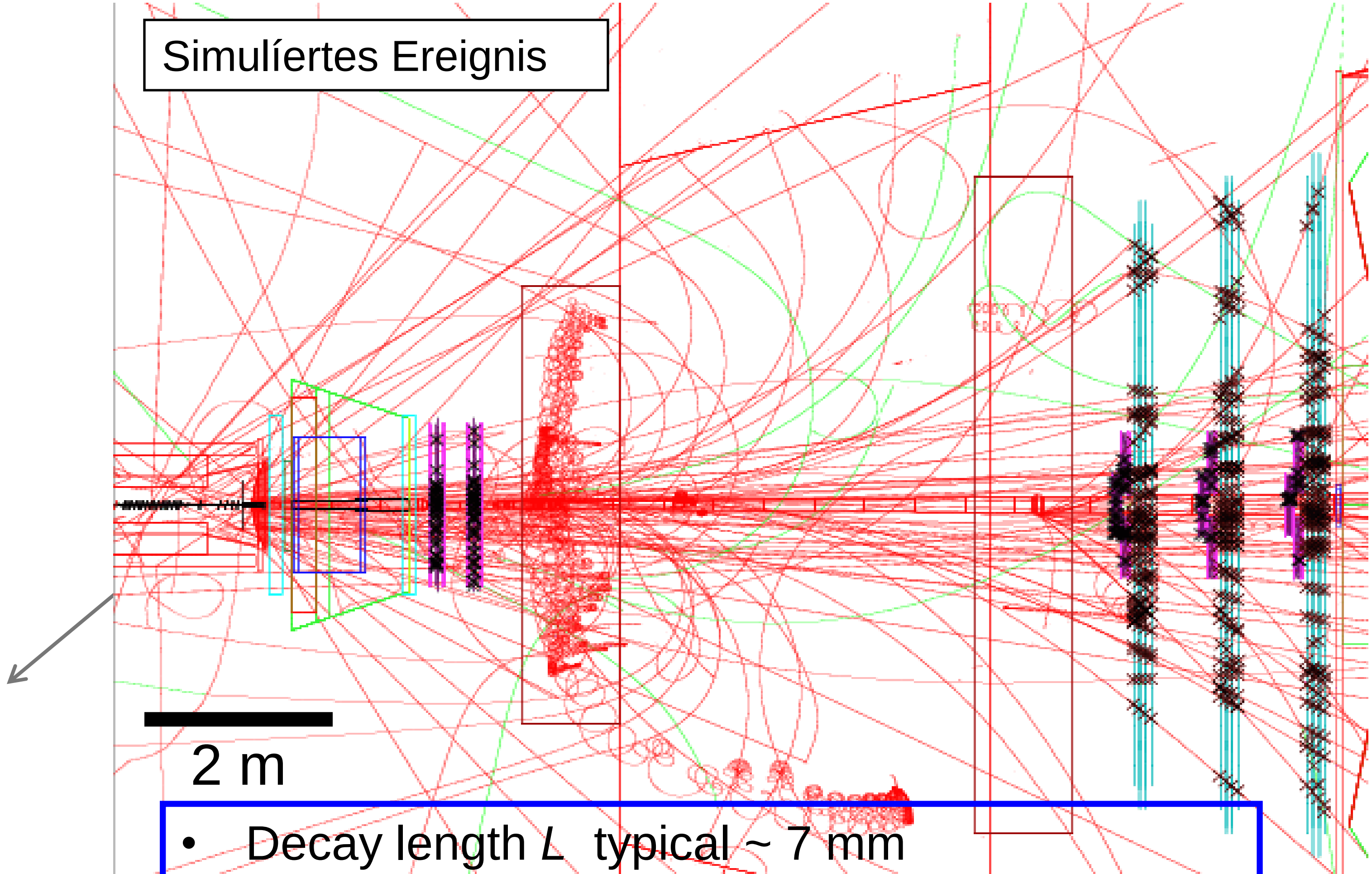




LHCb:

- Forward, single arm spectrometer, $1.9 < \eta < 4.9$ (bb pairs correlated, mainly forward)
- Excellent vertexing and particle ID (K/π separation)
- "high" p_T triggers, including purely hadronic modes, very flexible
- Luminosity tuneable by adjusting beam focus: run at $L \sim 2\times10^{32}\ cm^{-2}s^{-1} \rightarrow n\approx0.5$

Typical Event



- Decay length *L* typical ~ 7 mm
- Decay products with p ~ 1–100 GeV
- K/π Separation
- Trigger on “low p_t” particles (similar to backgr)

B factory versus Hadron Maschines

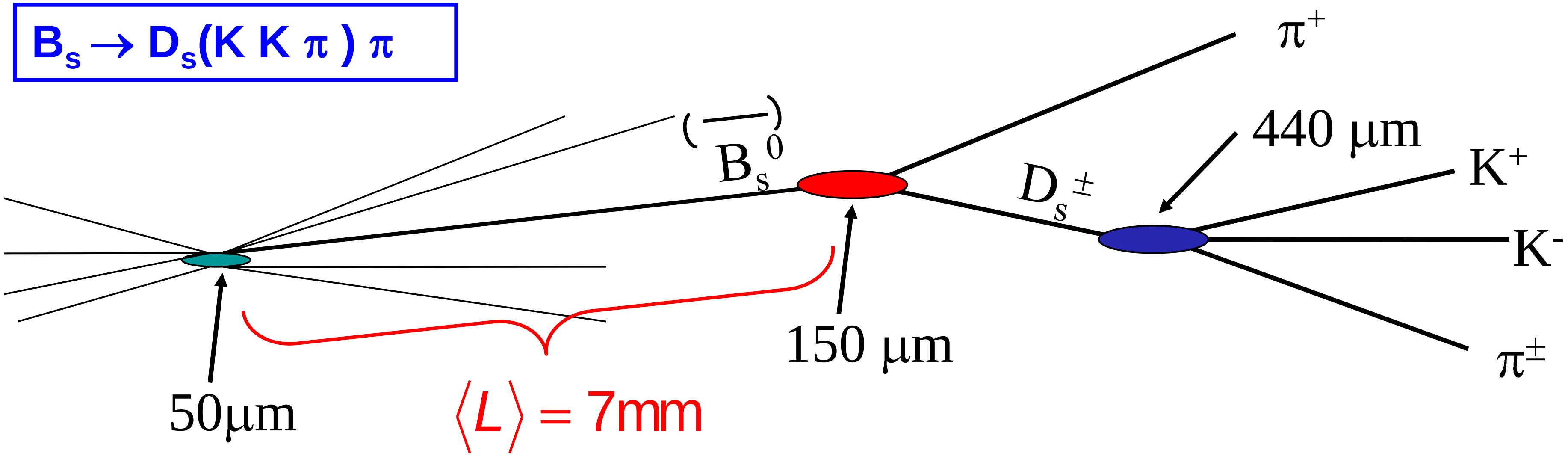
	PEP-II, KEK-B $e^+e^- \to \Upsilon(4S) \to B\bar{B}$	TeVatron $p\bar{p} \to b\bar{b}X \left(\sqrt{s} = 2\text{TeV}\right)$	LHC $pp \to b\bar{b}X \left(\sqrt{s} = 14\text{TeV}\right)$
prod	1 nb	~100 μb	~500 μb
typ. rate	10 Hz	~50 kHz	100…1000 kHz
purity	~1/4	$\sigma_{bb}/\sigma_{inel} \approx 0.2\%$	$\sigma_{bb}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%), B^0\bar{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%), \text{ b-baryons}(10\%)$	
B boost	small, $\beta\gamma$~0.56	large, decay vertices are displaced	
event structure	BB pair alone	many particles non-associated to $b\bar{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
tagging/mixing	coherent	incoherent$\to$ flavour tagging dilution	

LHC / Tevatron = "b" (not only B) factory:

B^0, B^+, B_s, B_c, b-baryons ~ 40 : 40 : 10 : 0.1 : 10 %

Vertex Reconstruction

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



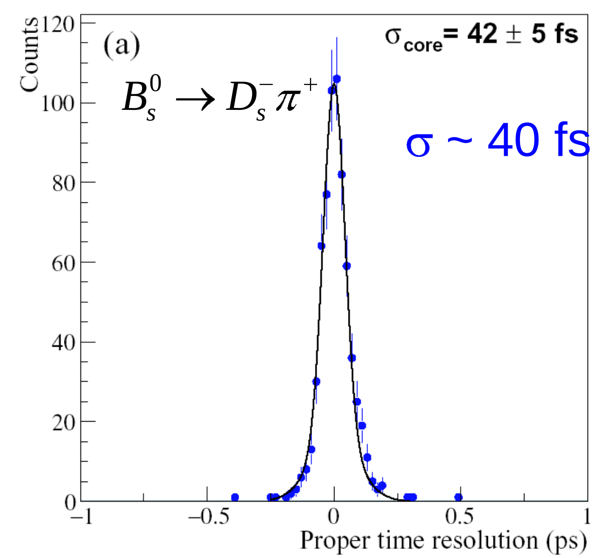
$\sigma_L = 160\,\mu m$ $\quad$ $$L = \beta\gamma ct$$

$\sigma_{ct} = 36\,fs$ $\quad$ $$ct = \frac{M_B}{p}L$$

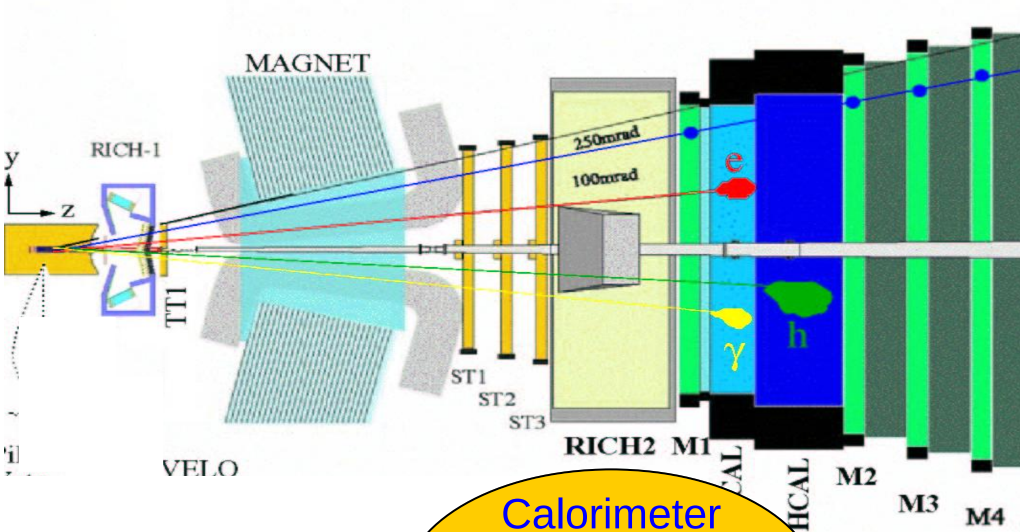
(momentum uncertainty negligible)

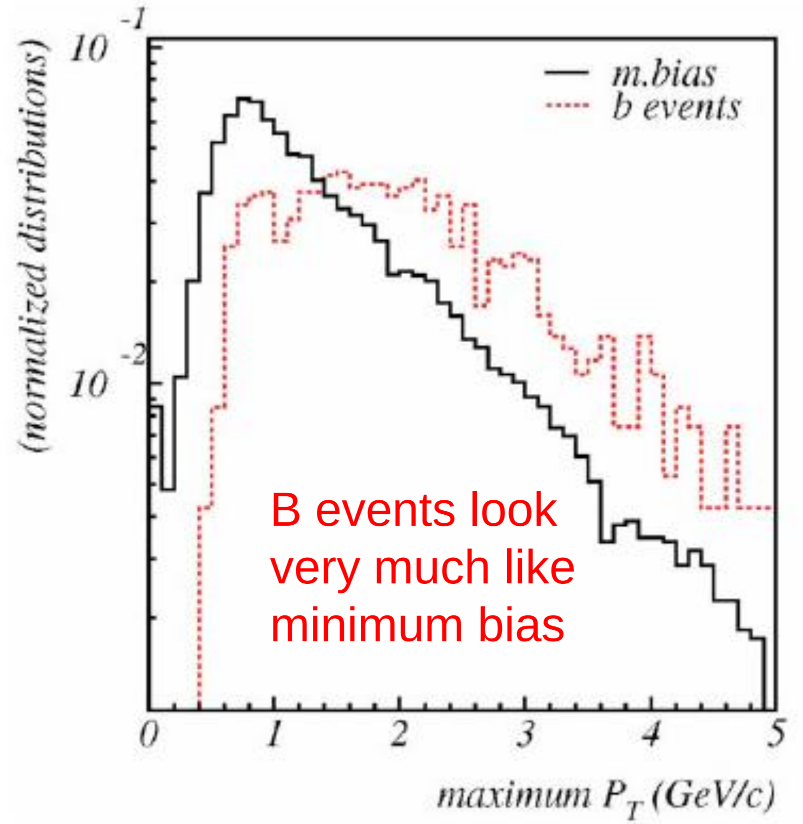
CDF: ~100 fs

Proper time resolution



Trigger





B events look very much like minimum bias

Calorimeter

Muon system

Pile-up system

40 MHz → **Level-0 Hardware: (4μs)**

"High p_T" μ, e, h, γ signatures

1.1, 2.8, 3.6, 2.6 GeV

→ **Readout** **1 MHz** → **PC Farm:**

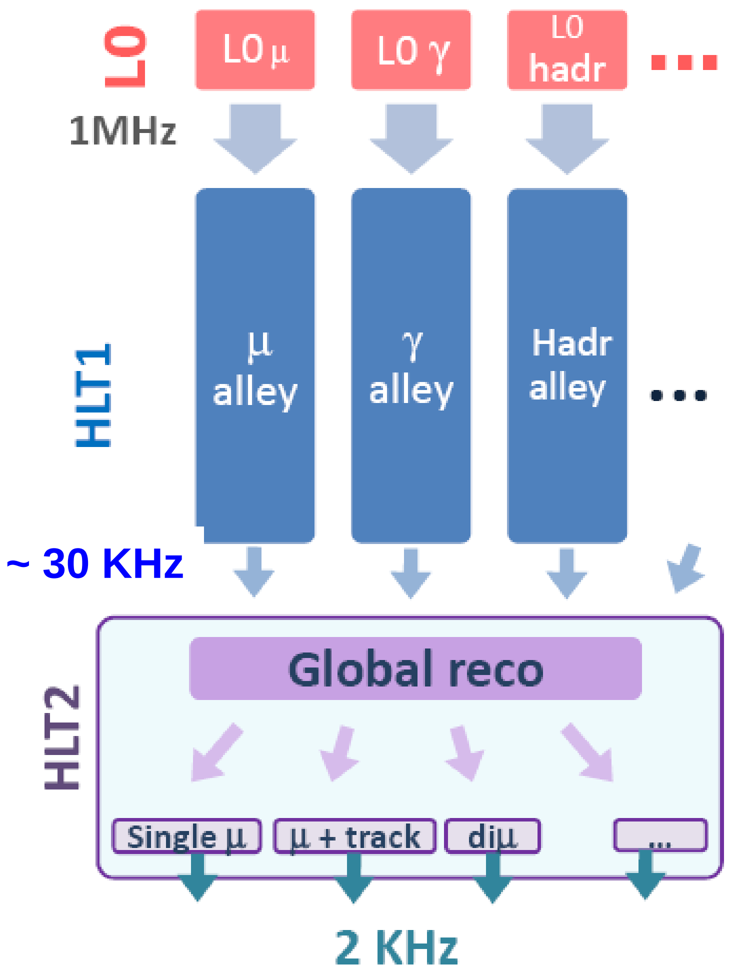
Higher Level Trigger

→ **2 KHz**

Disk

Rather modest p_t values → only modest rate reduction

Higher Level SoftwareTrigger



Storage (event size ~ 35 KB)

Higher Level Trigger (Software)
Computing Fram ~ 10000 CPUs

1. Confirmation of trigger signature using tracking information (1 ms/track)
   + track impact parameter information
   ⇒ ~ **30 KHz**

2. Global event reconstruction: inclusive & exclusive selections

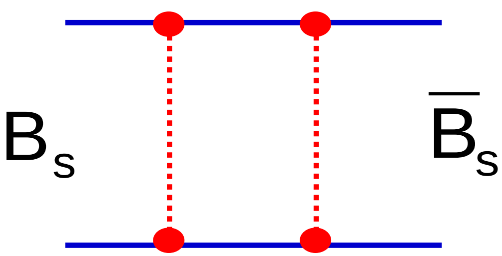
	L0	HLT	Total
$\varepsilon(B_s \to D_s^+\pi^-)$	50%	80%	40%
$\varepsilon(B_s \to J/\psi(\mu\mu)\phi)$	90%	80%	70%
$\varepsilon(B \to K^*\gamma)$	70%	60%	40%

w/r to "offline" selection → $\varepsilon_{tot} \approx 1 \ldots 3\%$

B meson key measurements at the LHC

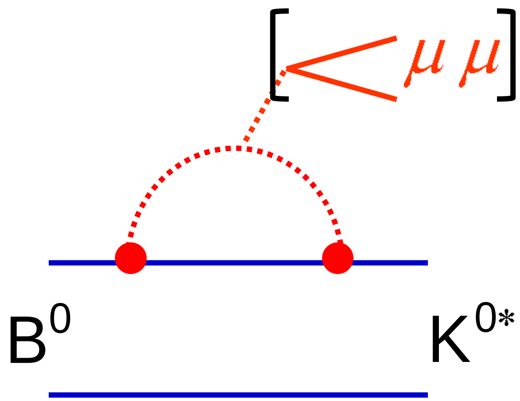
LHCb – Key Measurements

B_s mixing phase ϕ_s



$A_{CP}\,(B_s \rightarrow J/\psi\ \phi)$

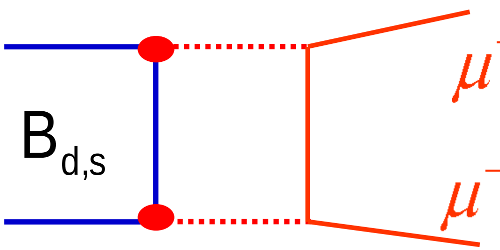
$b \rightarrow s\ \gamma$ penguins



$B_d \rightarrow K^*\gamma$

$B_d \rightarrow K^*\ \mu\mu$

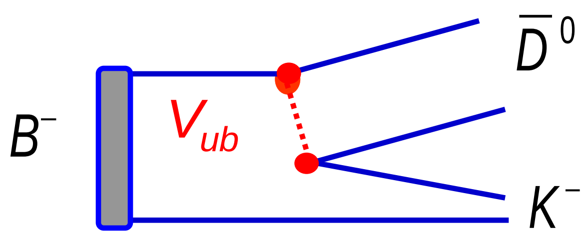
Very rare FCNC proc.



$B_{d,s} \rightarrow \mu\mu$

CKM angle γ

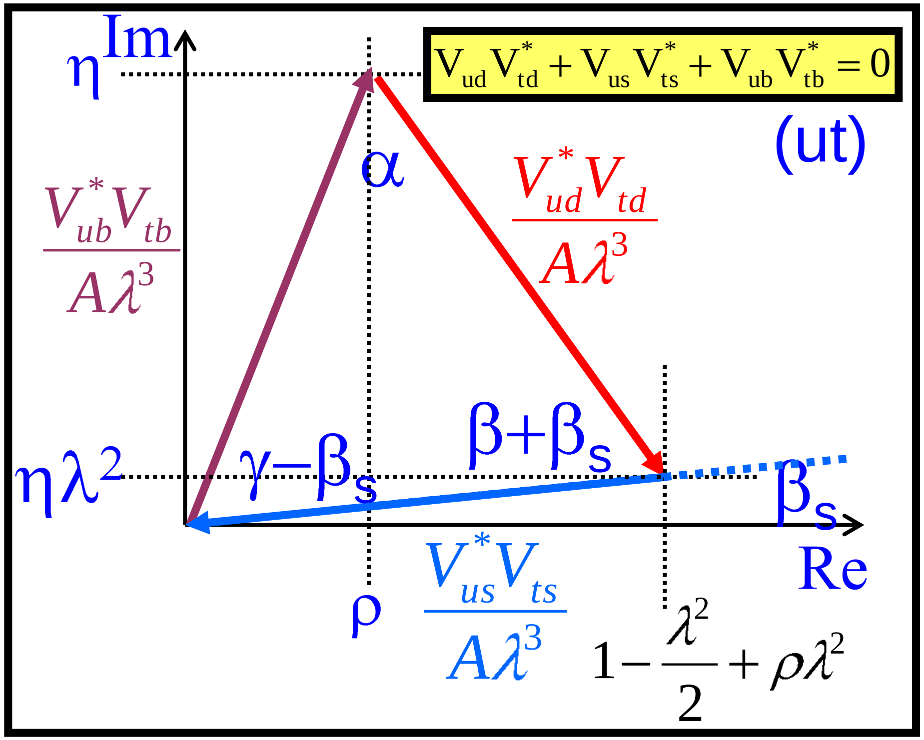
$B \rightarrow DK$



B_s – Mixing: Amplitude and Phase

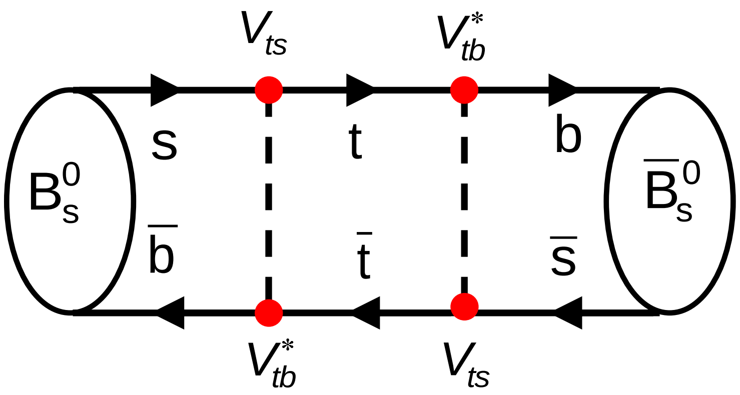
Access to the 2nd

Unitarity Triangle



$$\beta_s \equiv \arg\left[-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}\right] \sim \eta\lambda^2 \sim 1^{o}$$

B_s Mixing Phenomenology

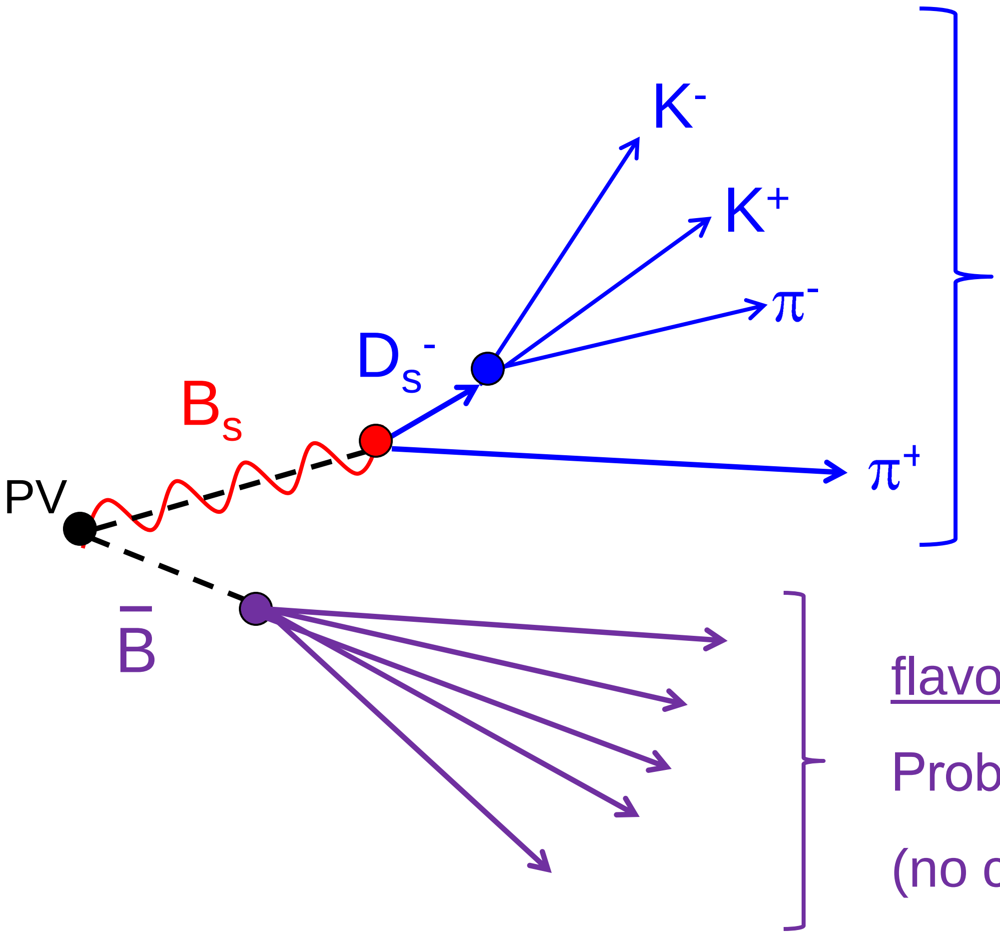


$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \mathbf{H}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} m_{11} - \frac{i}{2}\Gamma_{11} & m_{12}^* - \frac{i}{2}\Gamma_{12}^* \\ m_{12} - \frac{i}{2}\Gamma_{12} & m_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

	B_d	B_s
$\Delta m = m_H - m_L$	0.5 ps^{-1}	17.8 ps^{-1}
$\Delta\Gamma = \Gamma_H - \Gamma_L$	$O(0.01)\cdot\Gamma_d$	$O(0.1)\cdot\Gamma_s$ (*)
$\phi_{s,d}$	$2\arg(V_{tb}V_{td}^*) = 2\beta$	$2\arg(V_{tb}V_{ts}^*) = 2\beta_s$

In SM small: 0.04

B_s Mixing Measurement



Signal B
(flavor specific decay)

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

$\bar{B}_s \rightarrow D_s^+ \pi^-$

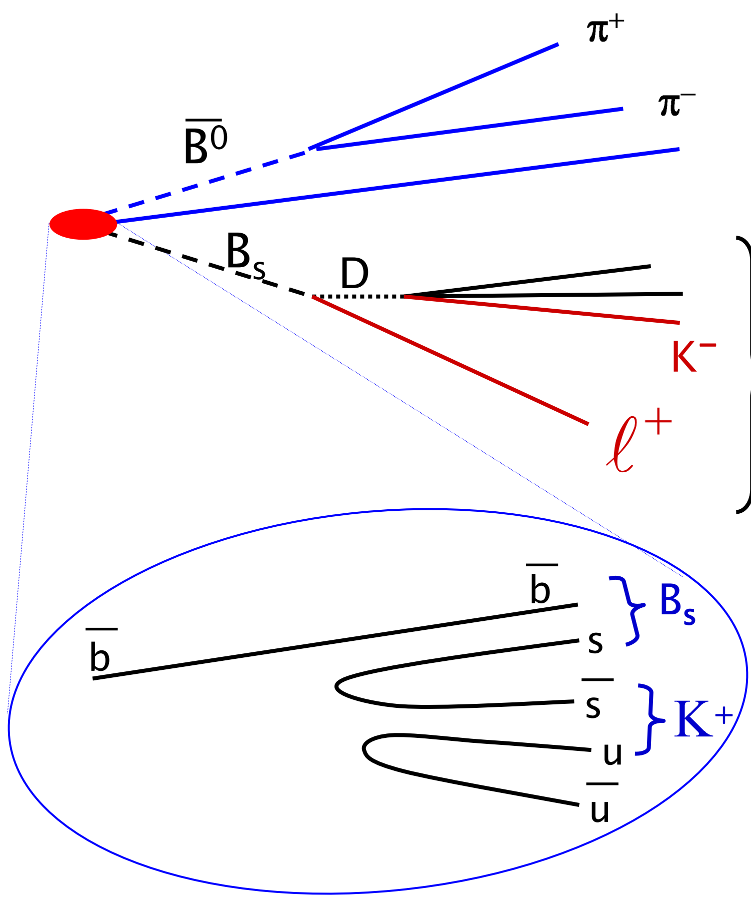
flavor tagging B

Problem w/ neutral B's

(no coherence)

$$A_{mix}(t) = \frac{N(B)_{unmixed}(t) - N(B)_{mixed}(t)}{N(B)_{unmixed}(t) + N(B)_{mixed}(t)} \sim \cos(\Delta m_s t)$$

Necessary Tool: B Flavor Tagging



Signal B (same side tagging)

- Fragmentation kaon near B_s

Tagging B (opposite tagging)

- lepton
- kaon
- Vertex charge

Dilution form oscillation if B^0

Dilution	$D=(1-2w)$
Effective Tagging Power	$\varepsilon_{eff}=\varepsilon_{Tag}D^2$

Mistag rate

Tag	ε_{Tag} (%)	w (%)	ε_{eff} (%)
Muon	6	32	**0.8**
Electron	3	32	**0.4**
$Kaon_{opp}$	15	36	**1.3**
Vertex Charge	44	42	**1.1**
Frag. kaon (B_s)	26	35	**2.4**
Combined B^0 (decay dependent:			**4.2**
Combined B_s trigger + select.)			**6.2**

LHCb-Pub-2009-029

Effect of mistags on mixing

$$A(t) = \frac{N(B)(t) - N(\overline{B})(t)}{N(B)(t) + N(\overline{B})(t)} \qquad B(t=0) = B$$

Observed asymmetry w/ wrong tag fraction ω

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

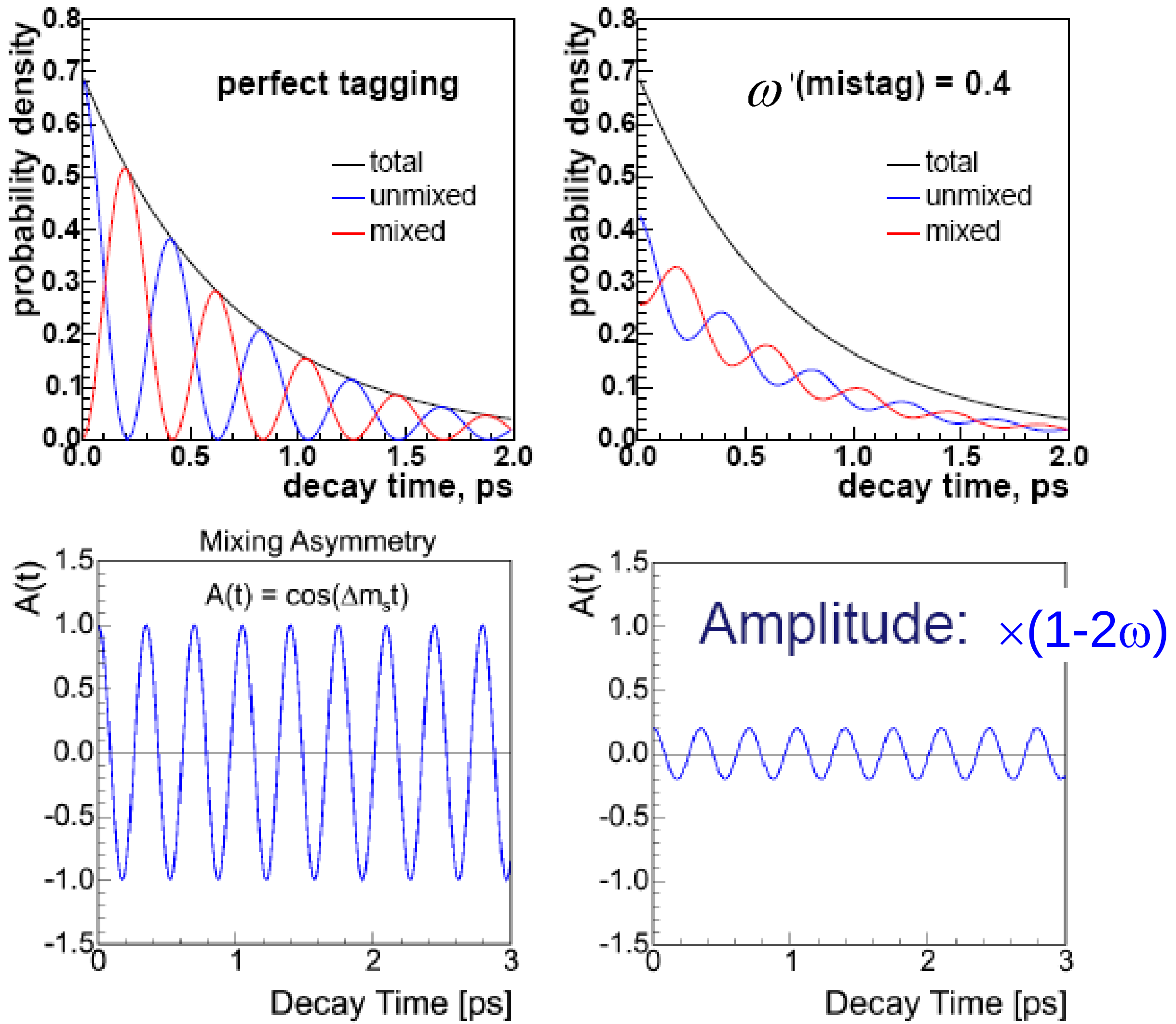
$$= \frac{N(B)(t)(1-\omega) + N(\overline{B})(t)\omega - N(\overline{B})(t)(1-\omega) - N(B)(t)\omega}{N(B)(t)(1-\omega) + N(\overline{B})(t)\omega + N(\overline{B})(t)(1-\omega) + N(B)(t)\omega}$$

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

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

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

Dilution


perfect tagging
probability density
decay time, ps
total
unmixed
mixed
ω'(mistag) = 0.4
Mixing Asymmetry
A(t) = cos(Δm_s t)
A(t)
Decay Time [ps]
Amplitude: ×(1-2ω)

Sensitivity and Tagging Power

$$N_B = qN,$$
$$N_{\bar{B}} = (1-q)N = pN$$
$$\langle q \rangle = \frac{N_B}{N}$$
$$\Delta q = \frac{1}{\sqrt{N}}\sqrt{(1-q)q}$$

Statistical error of asymmetry

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

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

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

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

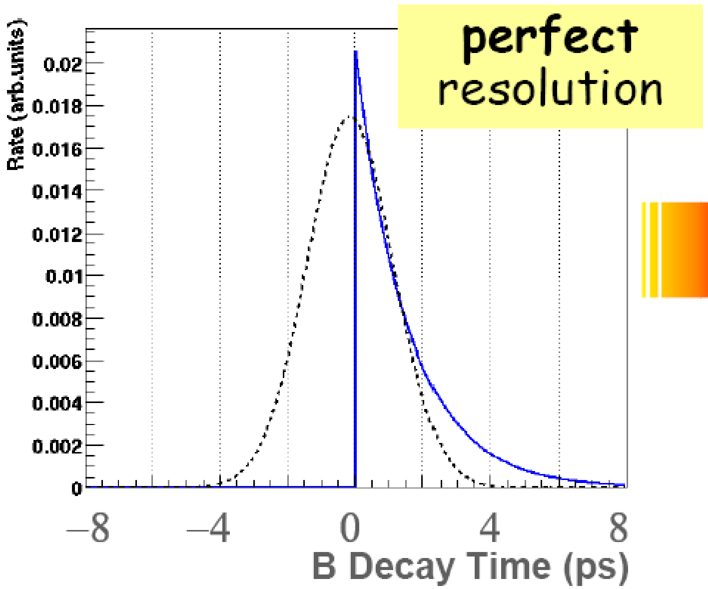
= effective tagging power

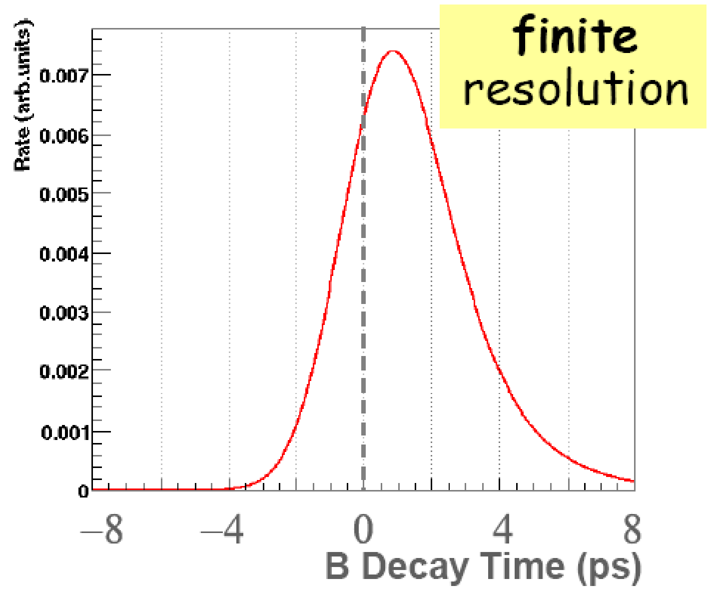
Effective Tagging Power

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

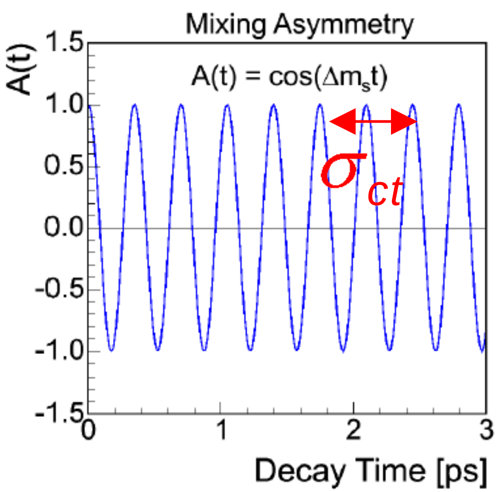
	ϵD^2	Reduction of data set
D0/CDF	2.5 - 5.0%	$\times$ 20-50
BABAR/BELLE	$\approx$ 30 %	$\times$ 3-4
LHCb (MC study)	$\approx$ 6%	$\times$ 17

Finite Proper Time Resolution





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



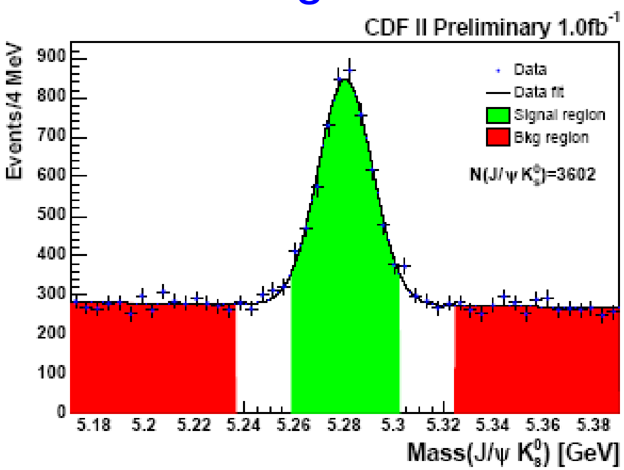
Affects the observed asymmetry: $A_{obs} = D_{ct}\ A$

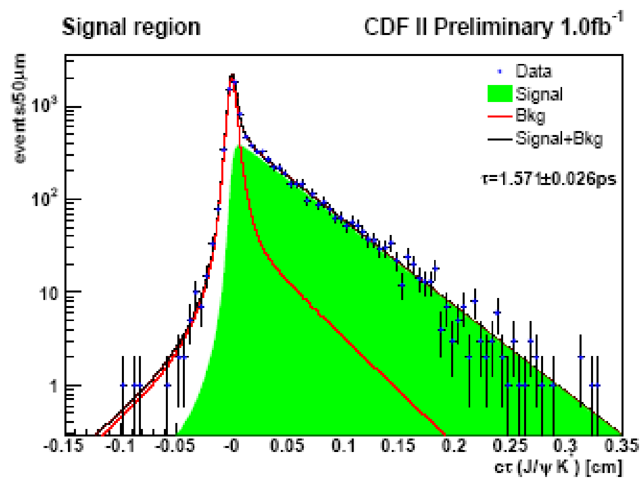
➡ Dilution: $D_{\sigma_{ct}} \sim \exp\left[-\frac{(\Delta m_s\,\sigma_{ct})^2}{2}\right]$

Statistical Significance of Mixing Asymmetry

Only signal: $\sigma_{stat} \sim \dfrac{1}{\sqrt{S}}$

With background:





Background:
shape and level
from side-bands

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

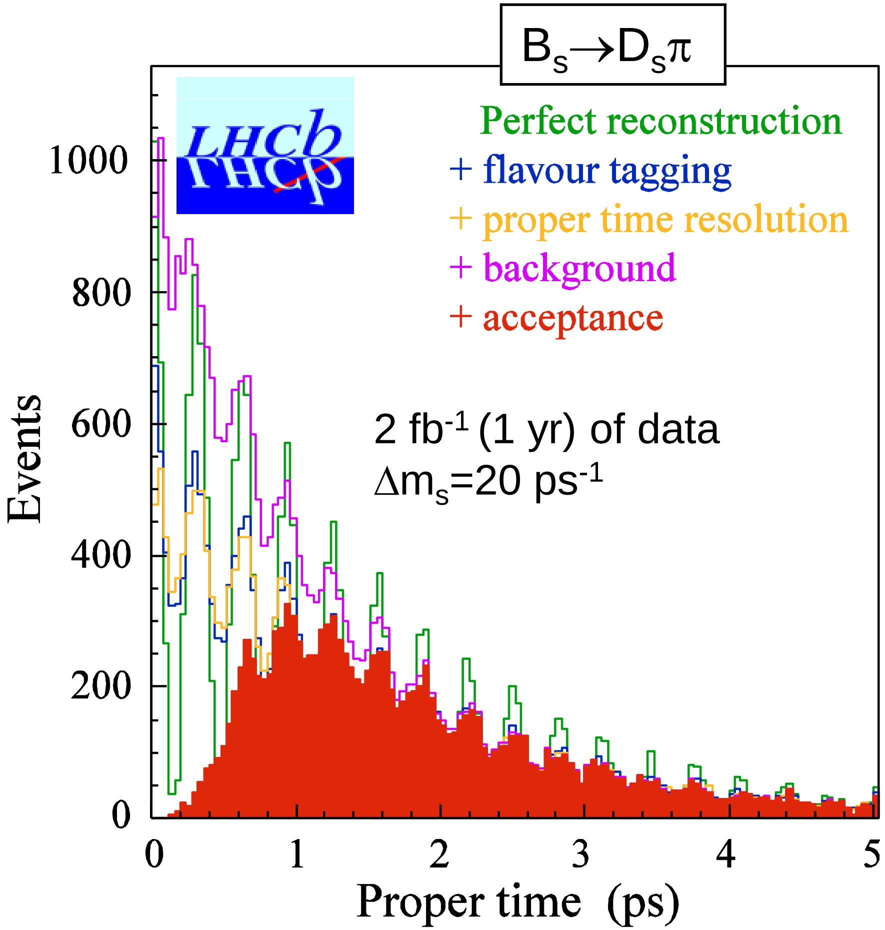
Statistical significance including all tagging/resolution/background:

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

B_s Mixing

B_s changes its flavor about ~9 times until it decays: need an excellent proper time resolution to resolve the mixing (LHCb ~40 fs)

Observation of B_s mixing is basis for time dependent CP asymmetry measurements.



CDF:

$$\sigma(\Delta m_s) = \pm 0.10_{stat} \pm 0.07_{syst} \text{ ps}^{-1}$$

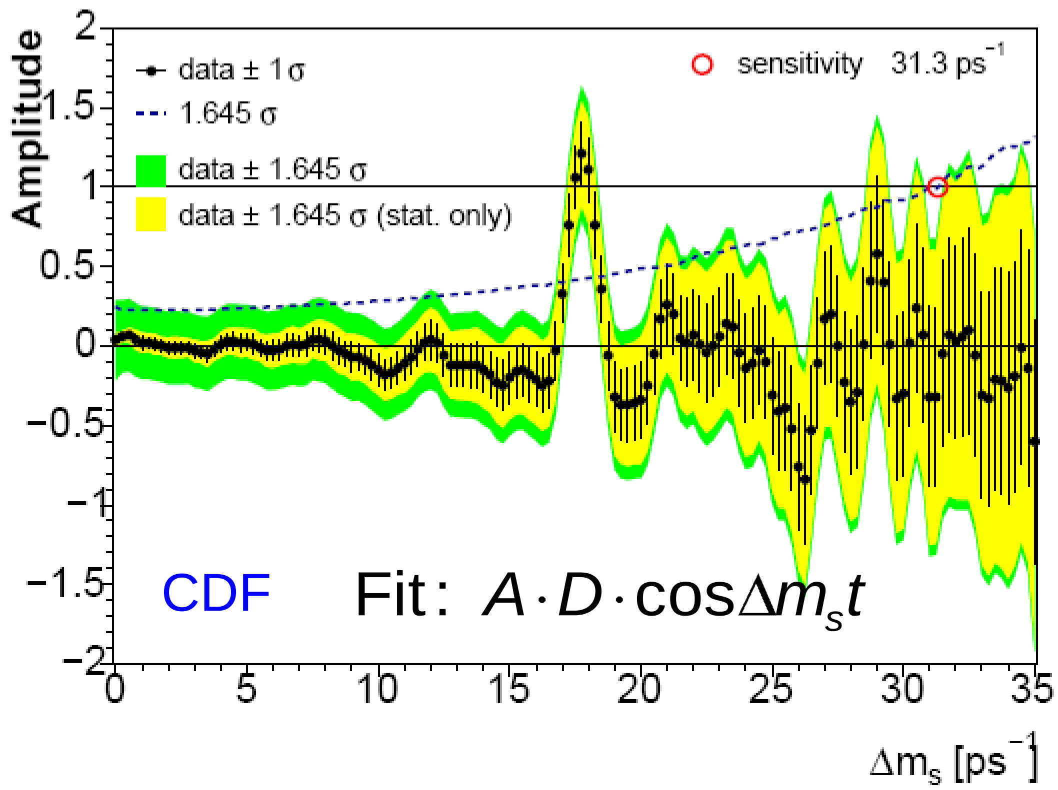
$$\sigma_{ct} \approx 100 \text{ ps}$$

LHCb expects 80k $B_s \to D_s \pi$ events in 1 yr

$$\sigma_{stat}(\Delta m_s) \approx 0.006 \text{ ps}^{-1}$$

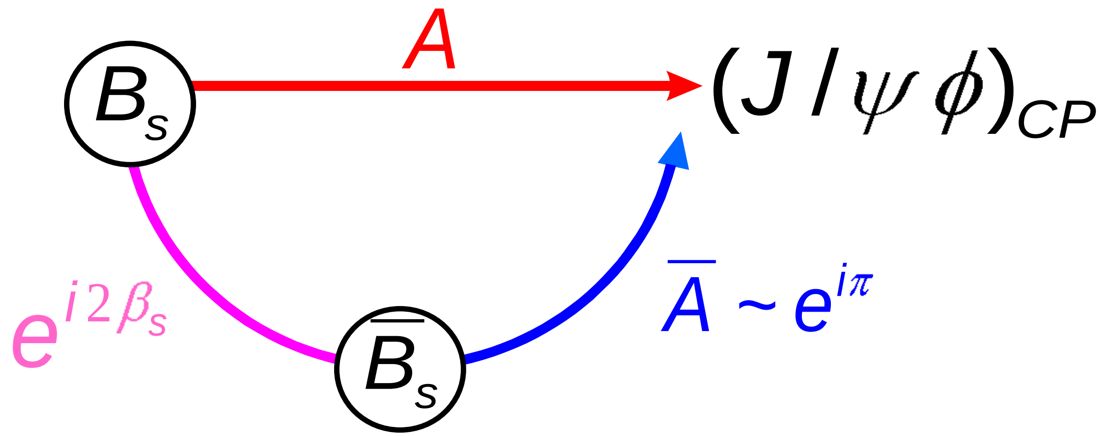
B_s Mixing at Tevatron

$$P_{ct,Signal}(t) = e^{-\Gamma t'} \frac{1 \pm AD\cos(\Delta m_s t')}{2} \otimes G(t-t', \sigma_{ct}) * \epsilon_{ct}(t)$$



$$\Delta m_s = 17.77 \pm 0.10(\text{stat.}) \pm 0.07(\text{syst.})\, \hbar\ \text{ps}^{-1}$$

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



$$A_{CP}(t) = \frac{\Gamma(\overline{B}_s \to [J/\psi\phi]_{CP})(t) - \Gamma(B_s \to [J/\psi\phi]_{CP})(t)}{\Gamma(\overline{B}_s \to [J/\psi\phi]_{CP})(t) + \Gamma(B_s \to [J/\psi\phi]_{CP})(t)}$$

$$= \frac{\eta_f \sin(2\beta_s)\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) - \eta_f \cos 2\beta_s \sinh(\Delta\Gamma t/2)}$$

Problem: $B_s(\overline{B}_s) \to J/\psi\phi$ is not a pure CP state

$B_s \to J/\psi\phi$

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

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

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

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

L = 0,2   CP = + 1

L = 1   CP = - 1

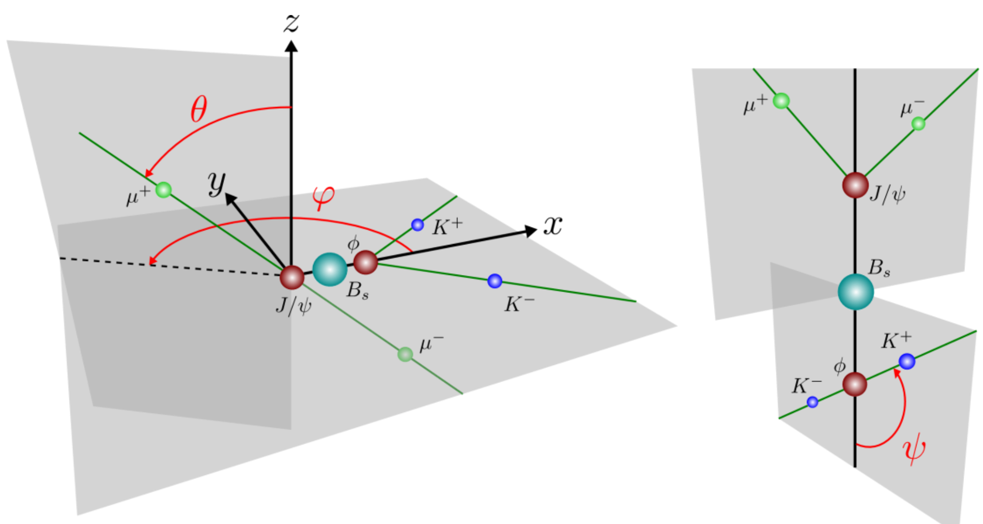
$$\eta_{CP} = (-1)^L$$

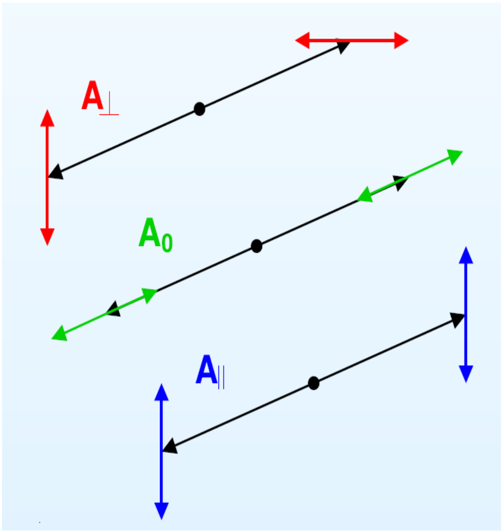
Angular analysis to separate CP +/-1 states:

Decompose decay amplitudes in term of linear polarizations.

Transversity Basis

- Decompose decay amplitudes in term of linear polarization, when J/ψ and ϕ are:
  - A_0: longitudinally polarized (CP-even)
  - $A_\perp$: transversely polarized and $\perp$ to each other (CP-odd)
  - $A_{||}$: transversely polarized and $\|$ to each other (CP-even)
- $\Rightarrow$ 3 angles θ, ϕ, ψ describe directions of final decay products
  $J/\psi \to \mu\mu$, $\phi \to K^+K$





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	$Im(A_0^*(t)A_\perp(t))$	$Im(\bar{A}_0^*(t)\bar{A}_\perp(t))$	$\frac{9}{32\pi\sqrt{2}} \sin 2\psi \sin 2\Theta \cos\phi$

$$|A_0(t)|^2 = \frac{|A_0(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t} + (1-\cos\Phi_s)e^{-\Gamma_H t} - 2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]$$

$$|A_\parallel(t)|^2 = \frac{|A_\parallel(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t} + (1-\cos\Phi_s)e^{-\Gamma_H t} - 2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]$$

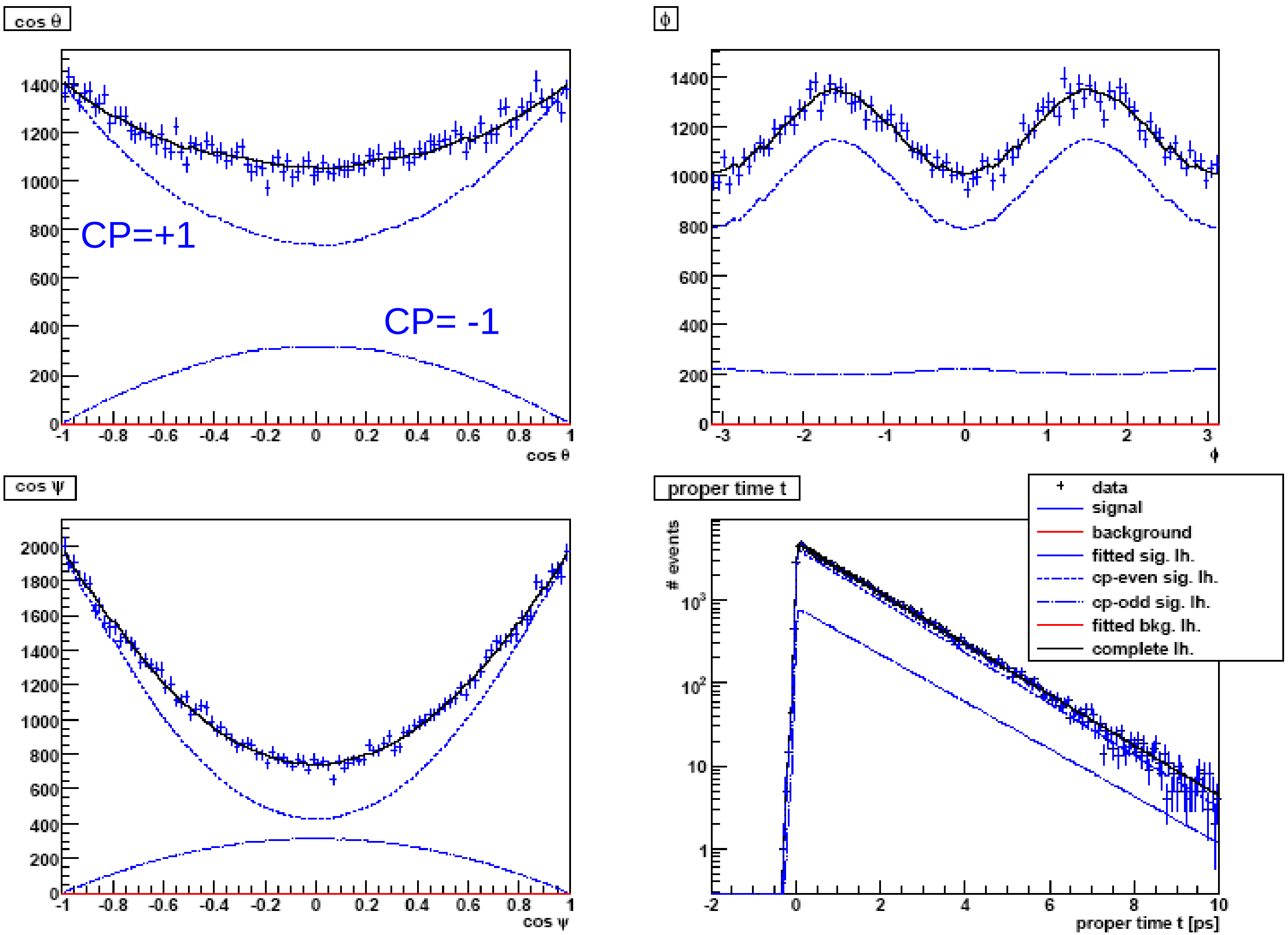
$$|A_\perp(t)|^2 = \frac{|A_\perp(0)|^2}{2}\left[(1-\cos\Phi_s)e^{-\Gamma_L t} + (1+\cos\Phi_s)e^{-\Gamma_H t} + 2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]$$

$$|\bar{A}_0(t)|^2 = \frac{|A_0(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t} + (1-\cos\Phi_s)e^{-\Gamma_H t} + 2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]$$

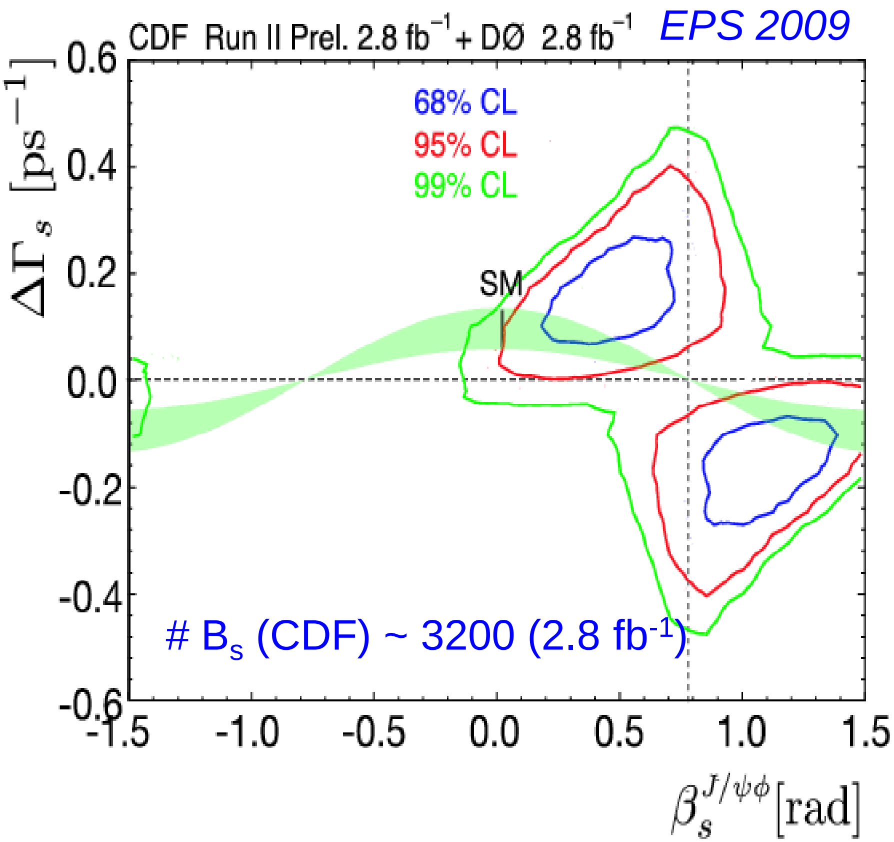
$$|\bar{A}_\parallel(t)|^2 = \frac{|A_\parallel(0)|^2}{2}\left[(1+\cos\Phi_s)e^{-\Gamma_L t} + (1-\cos\Phi_s)e^{-\Gamma_H t} + 2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]$$

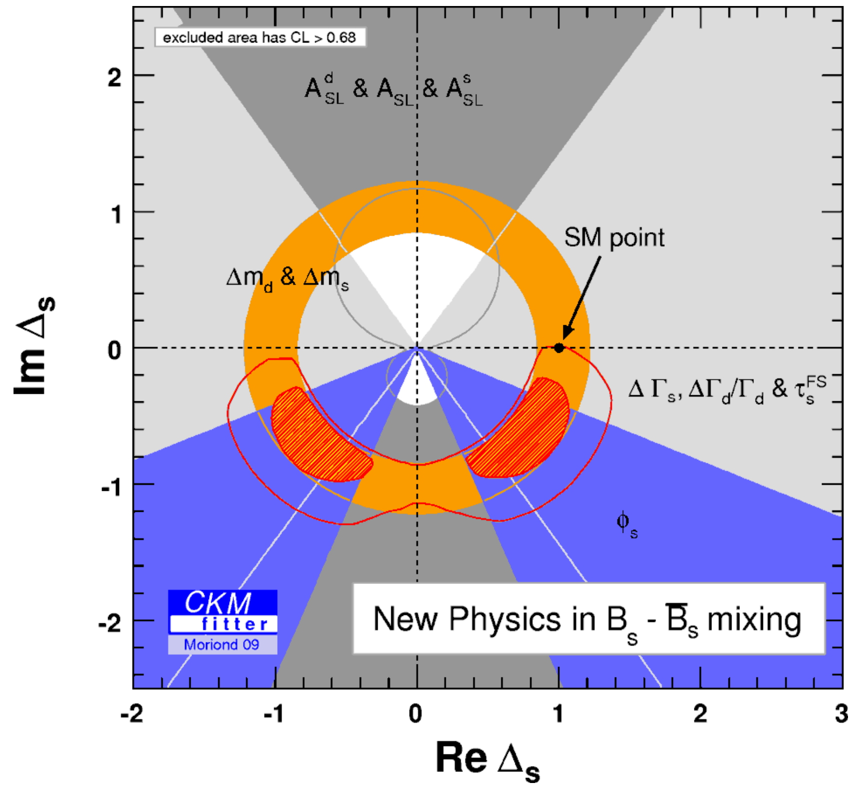
$$|\bar{A}_\perp(t)|^2 = \frac{|A_\perp(0)|^2}{2}\left[(1-\cos\Phi_s)e^{-\Gamma_L t} + (1+\cos\Phi_s)e^{-\Gamma_H t} - 2e^{-\Gamma t}\sin(\Delta m t)\sin\Phi_s\right]$$

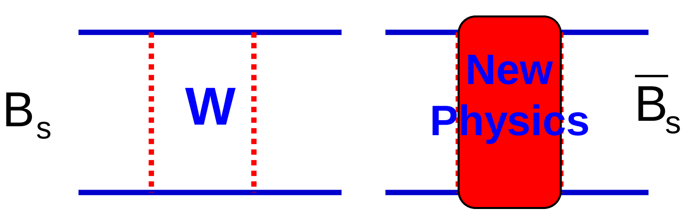
Angular and proper time distribution



Experimental Status (Tevatron)





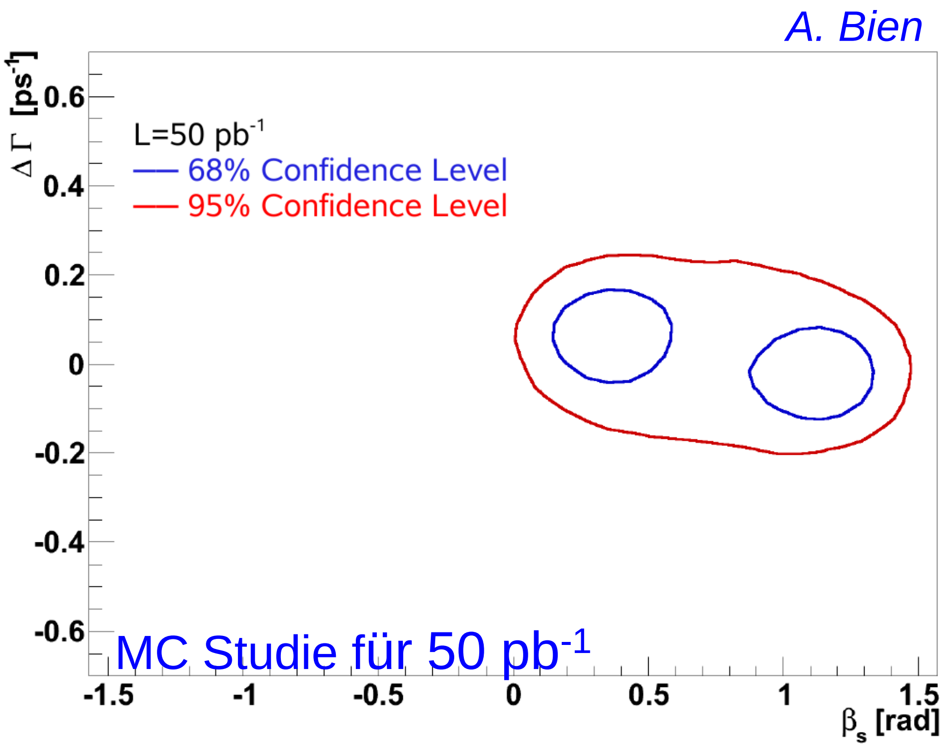


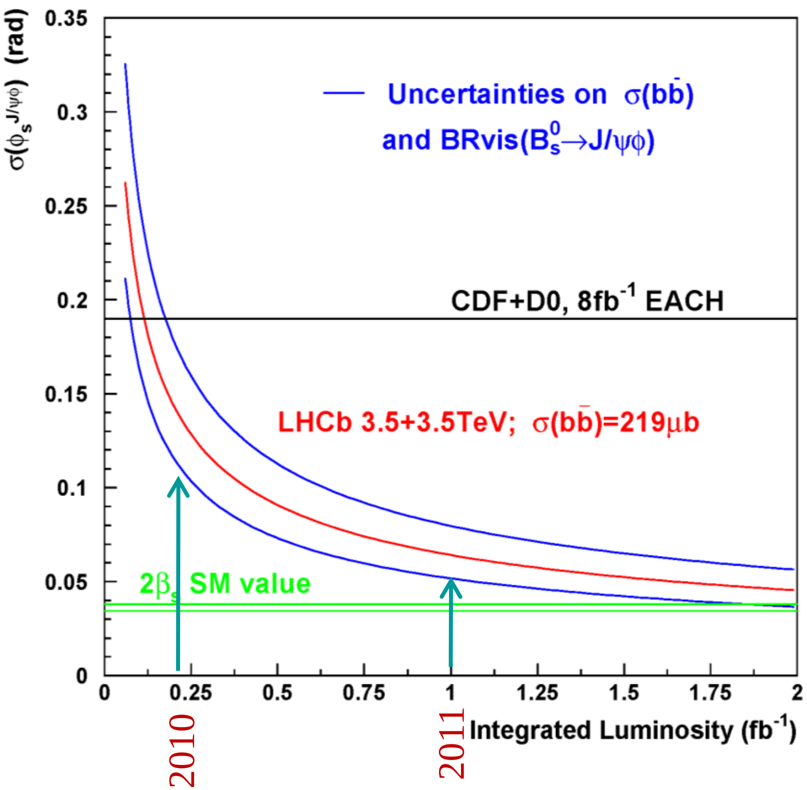
$$\mathcal{A}_{SM+NP} = \mathcal{A}_{SM} \times \left(\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q) \right)$$

A.Lenz, U.Nierste

LHCb Prospects for ϕ_s

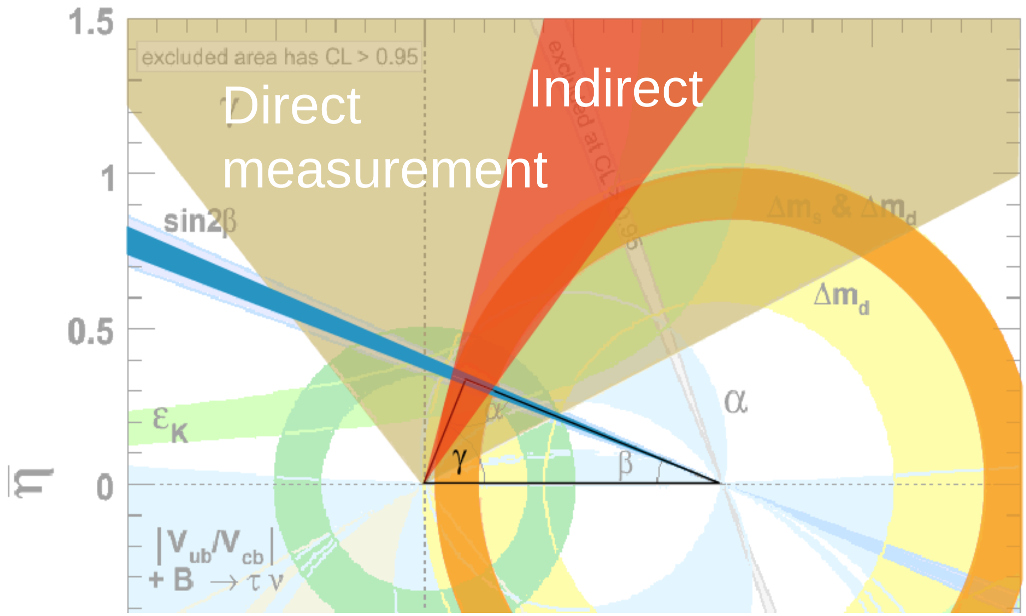
#Evts ($2 fb^{-1}$)	B/S	ε_{tag}(%)
117k	2.0	6.2





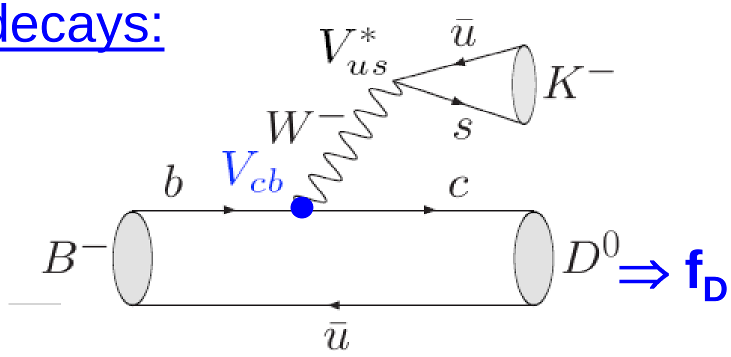
CKM Angle γ

- A lot of pioneering work from B factories
- No significant constraint from direct measurements yet

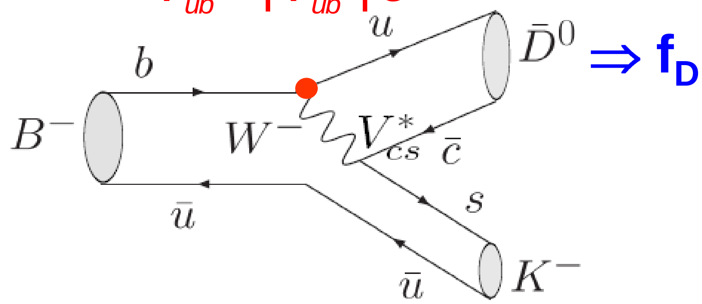


γ from B → DK tree decays

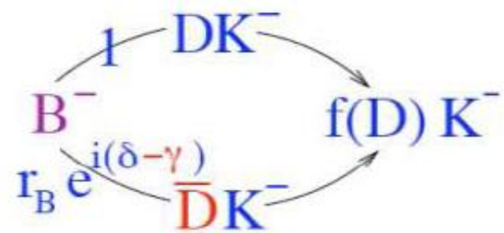
Tree decays:



$V_{ub} = |V_{ub}| e^{-i\gamma}$



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



Principle of the "γ in trees" measurement:

Cabibbo favored and suppressed decay amplitudes of the B$^-$ (B$^+$) can interfere in case that the D^0 and $\overline{D}^0$ decay into the same final state f$_D$.

⇒ Several methods are proposed and have already been explored at the B factories.

γ from $B \to DK$ Tree Decays

Mode	Yield (2 fb^{-1})	B/S
$B^{\pm} \to D(K\pi)K^{\pm}$ (fav.)	84k	0.6
$B^{\pm} \to D(K\pi)K^{\pm}$ (sup.)	1.6k	0.6
$B^{\pm} \to D(KK)K^{\pm}$	8.5k	1.2
$B^{\pm} \to D(\pi\pi)K^{\pm}$	3k	3.2
$B^{\pm} \to D(K_s\pi\pi)K^{\pm}$	6.8k	0.4

ADS/GLW (first four modes)

GGSZ (last mode)

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

Common flavour state $f_D = (K^+ \pi^-)$
Note: $D^0 \to K^+\pi^-$ doubly Cabibbo suppr.

σ_γ = 11 ...13 (2 fb^{-1})

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

Use Dalitz decays $D^0 / \overline{D}^0 \to K_s(\pi\pi)\pi^+\pi^-$

σ_γ = 10 (13°) ampl.model/binned fit

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

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

σ_γ = 11 ...13 (2 fb^{-1})

Combined (2fb^{-1})

δ_B ( )	0	45	90	135	180
$\sigma(\gamma)$	4.6	6.1	5.7	6.0	4.3

LHCb-2008-031

γ from Tree Sensitivity

LHCb-2008-031

Tree Level Processes

<u>Combination:</u>

$B^{\pm} \to D^0 K^{\pm}$

$B^0 \to D^0 K^{*0}$

Time dependent:

$B_s \to D_s K$ $(B^0 \to D\pi)$

δ_{B^0} (°)	0	45	90	135	180
σ_γ for 0.5 fb^{-1} (°)	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 fb^{-1} (°)	4.1	5.1	4.8	5.1	3.9
σ_γ for 10 fb^{-1} (°)	2.0	2.7	2.4	2.6	1.9

2° …3° reachable after 5 yr

CKM Metrology and LHCb

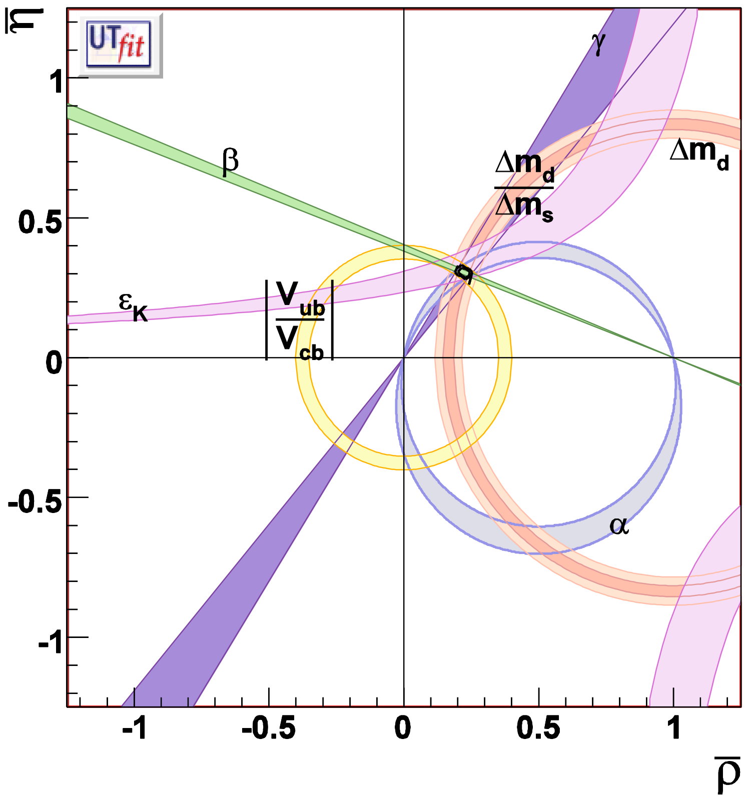
$\delta\gamma_{stat}$ = 2…3° für $\mathcal{L}$ = 10 fb^{-1} (5 J)

$\delta(\sin 2\beta)_{stat} \approx 0.01$

für $\mathcal{L}$ = 10 fb^{-1}

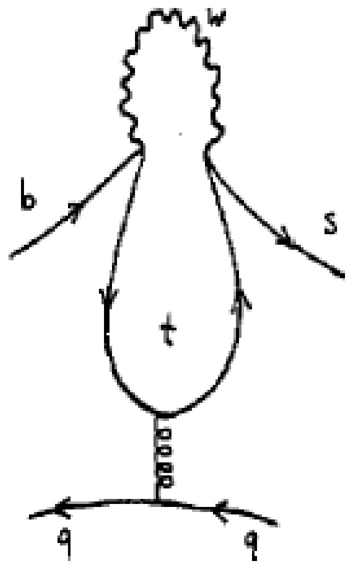
$\delta\alpha_{stat} \approx 4.5$ °

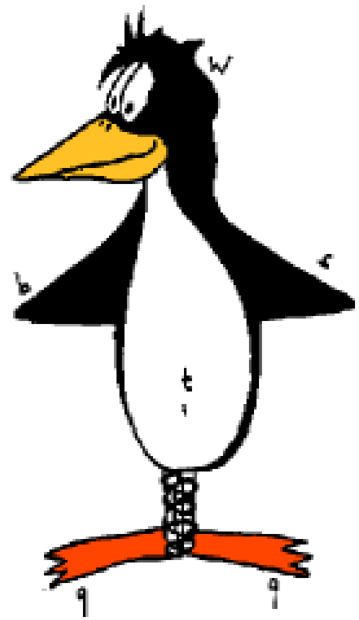
Mit LHCb Daten*) $\mathcal{L}$ = 10 fb^{-1} (5 J)



*) +Verbesserung von Gitterrechnungen.

Penguin

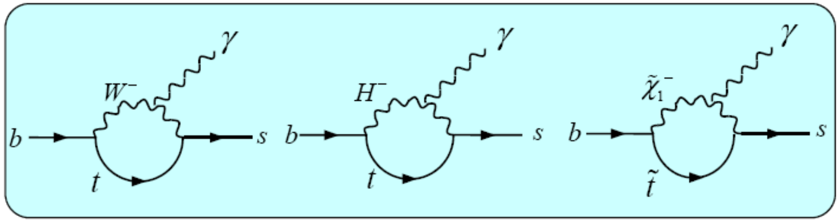




A.Lenz

and very rare decays

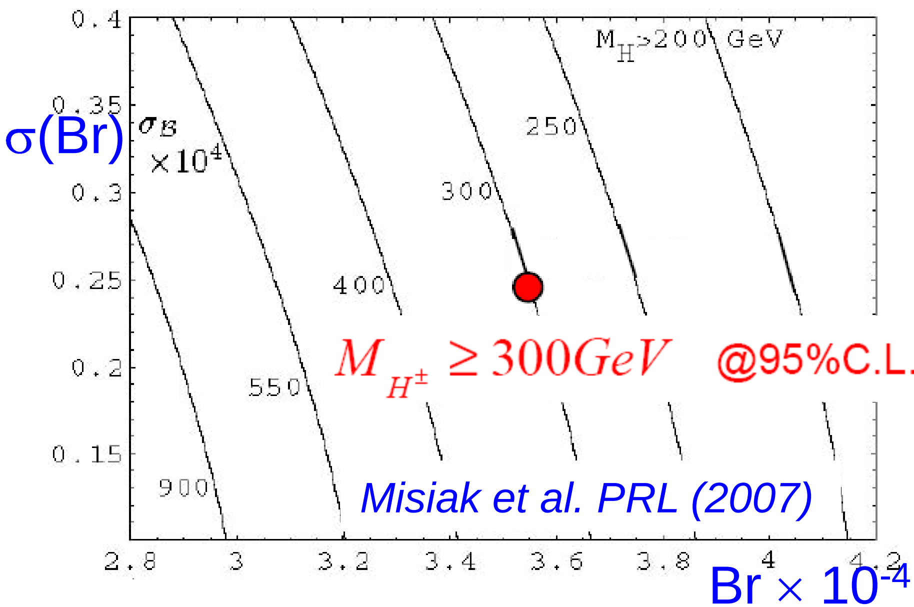
$B \to X_s \gamma$ Challenge for any NP model



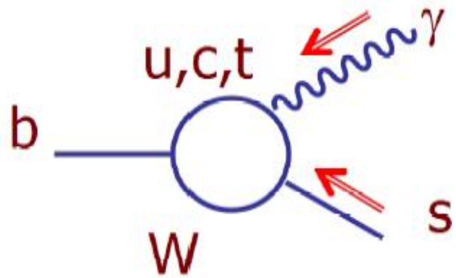
$$Br(B \to X_s \gamma) = (3.57 \pm 0.24) \times 10^{-4}$$

$$Br_{SM}(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

Constraints from observed BR on Type II 2-Higgs Doublett Models:



Probe photon polarization:



$B_s \to \phi\gamma$ events: LHCb: 12k ($2fb^{-1}$)

From time dependent decay rates:

$$\tan\psi \equiv \left| \frac{A(\bar{B} \to f^{CP}\gamma_R)}{A(\bar{B} \to f^{CP}\gamma_L)} \right|$$

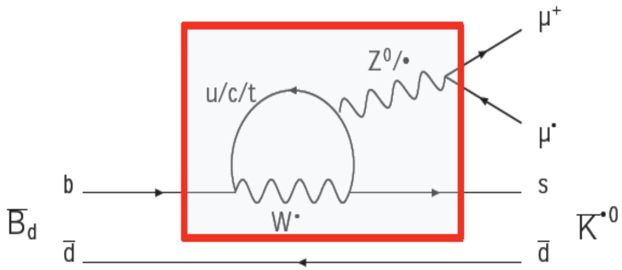
LHCb: $\sigma(\psi) \approx 0.11$

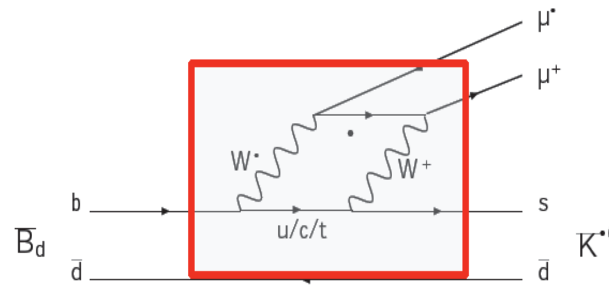
= amount of wrong pol. photons

➡ Test models w/ RH currents

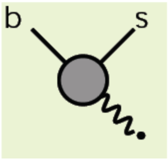
$B^0 \to K^*\mu\mu$

Standard Model

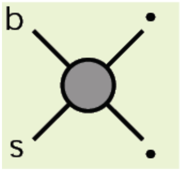




Effective Theory



O_7



O_9 O_{10}

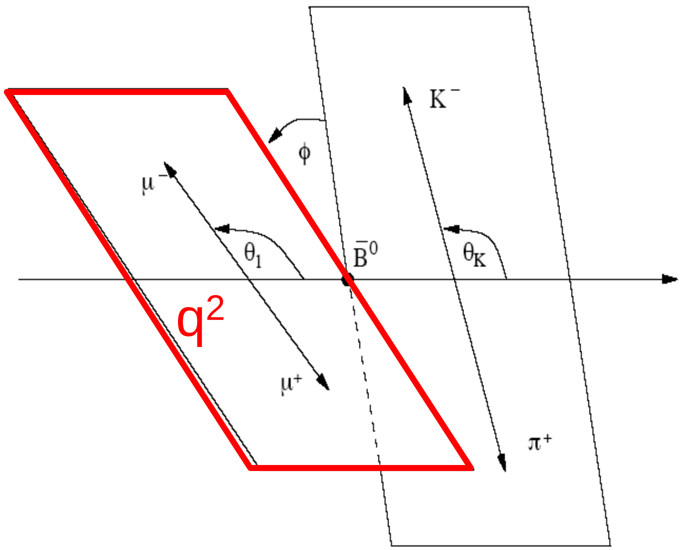
Operator Product Expansion

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum C_i(\mu) O_i(\mu)$$

Corresponding Wilson coefficients C_i describe short-range physics.

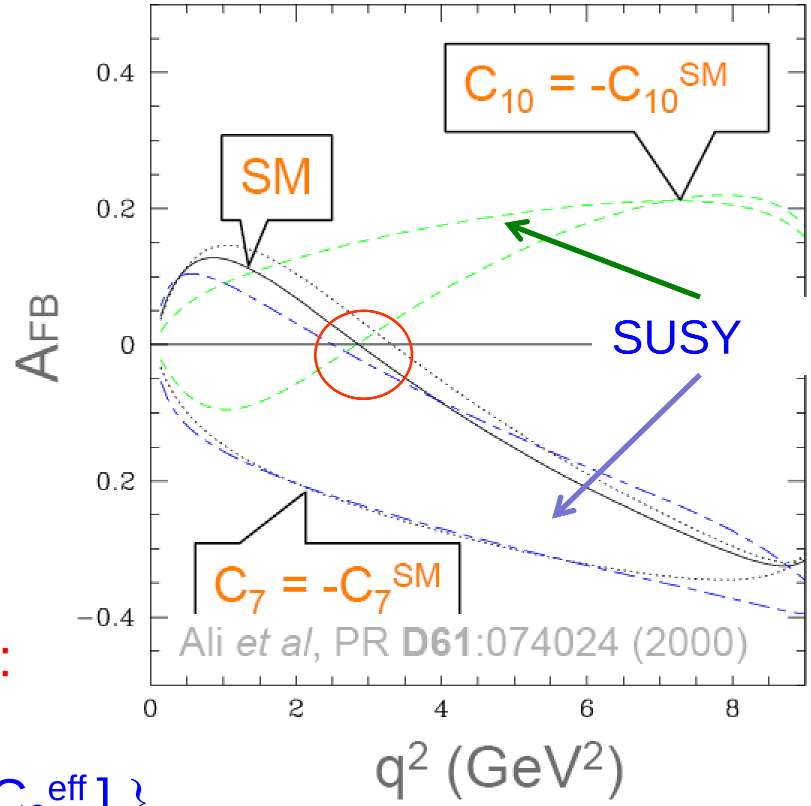
New Physics in Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$ or new operators.

Sensitivity of Angular Observables



Observables: θ_l, θ_K, ϕ, $m^2_{\mu\mu}$

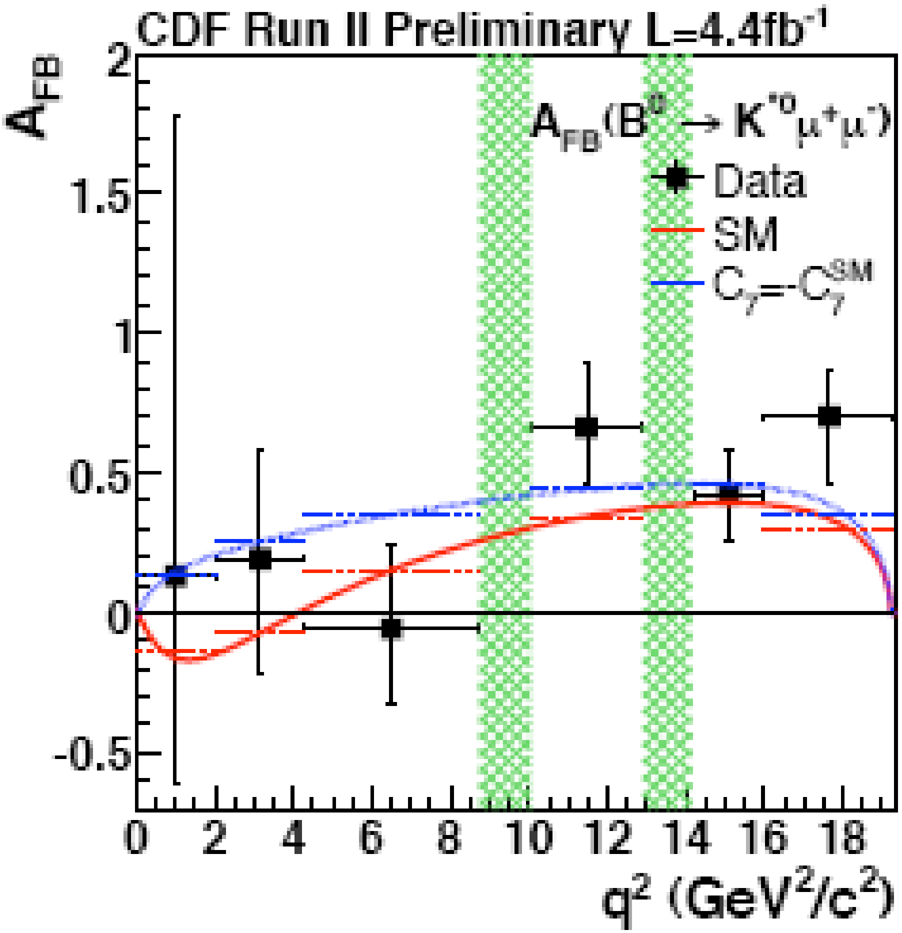
→ μμ forward-backward asymmetry:



$A_{FB}(q^2) \sim -\mathrm{Re}\{ C_{10}^* [C_7^{eff} + \beta(q^2) C_9^{eff}] \}$

Angular observables offer a powerful test bench for any New Physics model

$B^0 \rightarrow K^*\mu\mu$ - Experimental Status



$B^0 \rightarrow K^*\mu\mu$ events:

- Belle: ~250 evts
- Babar: ~100 evts
- CDF: ~100 evts (4.4 fb^{-1})

~450 evts

q²(GeV²/c²)

Poor agreement with SM.
LHCb data will clarify.

LHCb expectation for 2 fb^{-1}

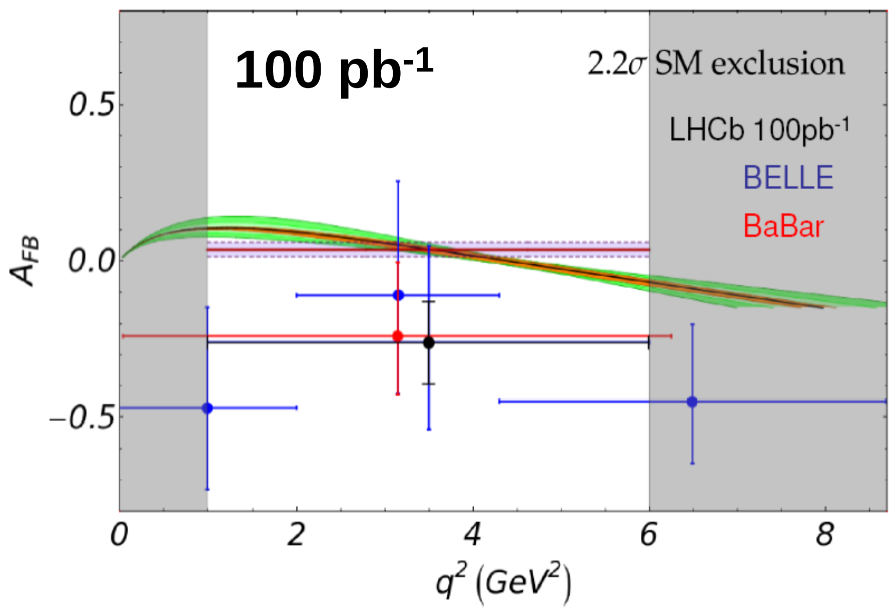
~7000 events w/ B/S~0.25

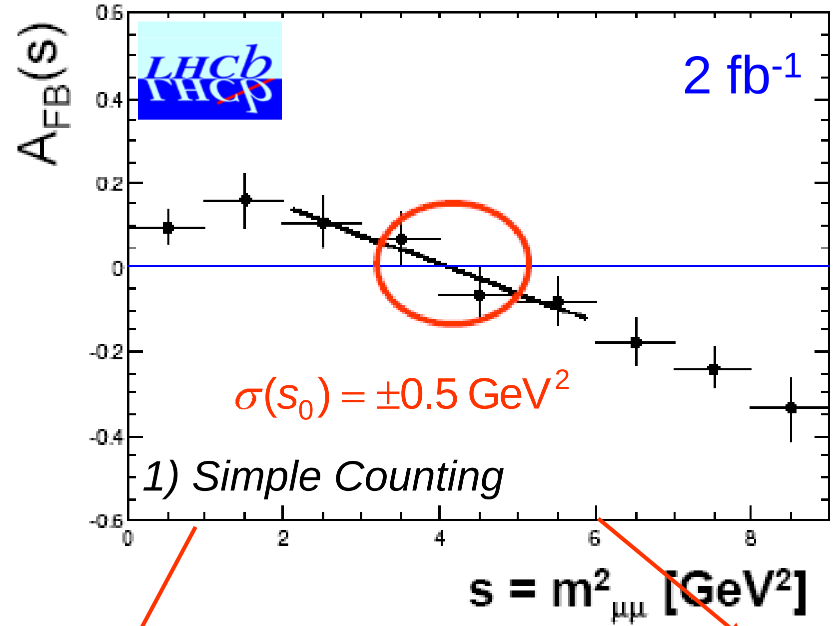
➡ 700 events for 200 pb^{-1}

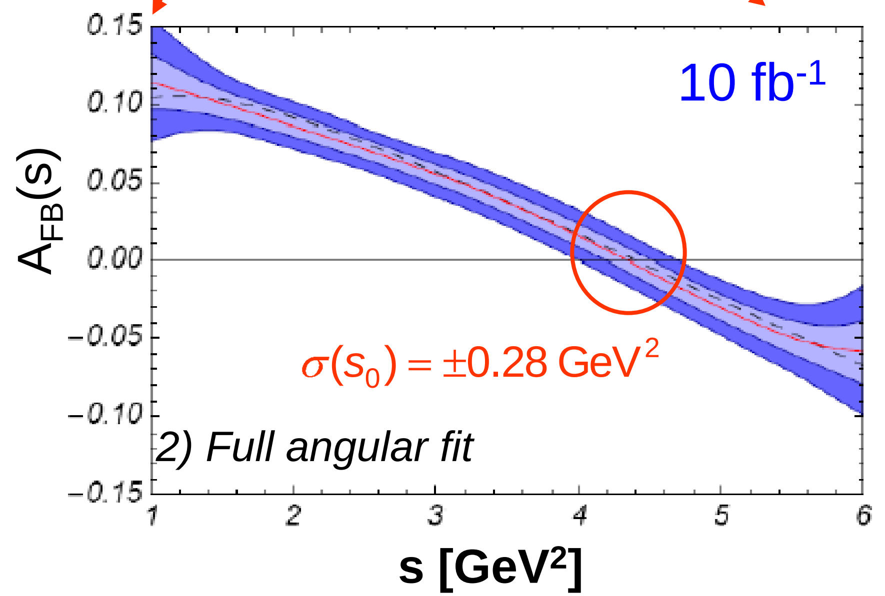
$B^0 \to K^*\mu\mu$ - Prospects

Example:

LHCb sensitivity for early data
(assume BELLE values for A_{FB})

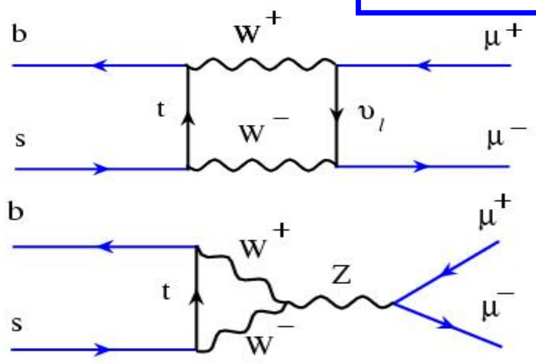






Very Rare Decays - $B_{d,s} \to \mu\mu$

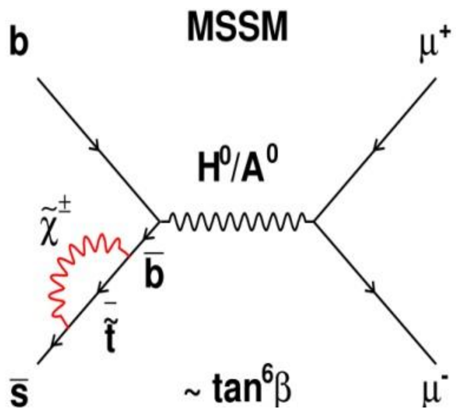
$B_{d,s} \to \mu^+ \mu^-$

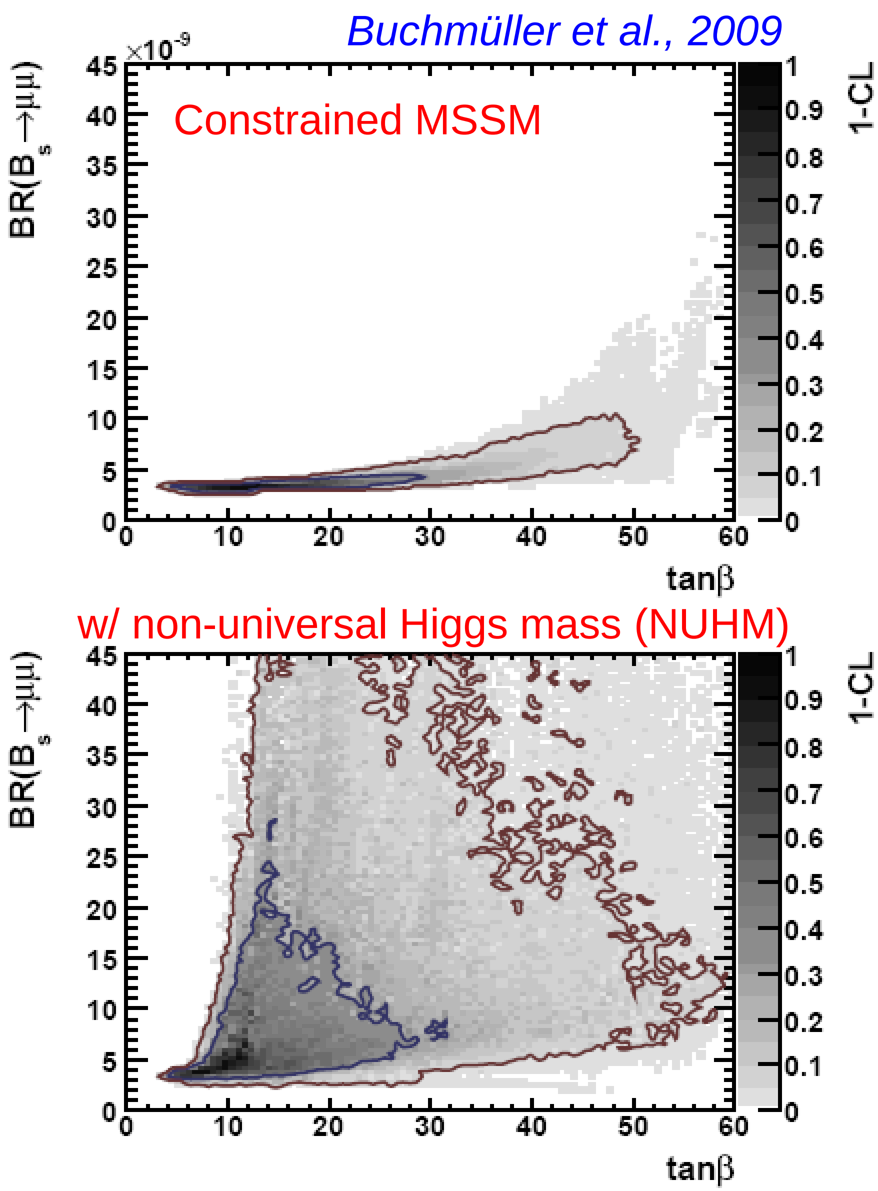


SM: $BR(B_s \to \mu^+\mu^-) = (3.2 \quad 0.2) \times 10^{-9}$

$BR(B_d \to \mu^+\mu^-) = (1.0 \quad 0.1) \times 10^{-10}$

Large SUSY contributions possible





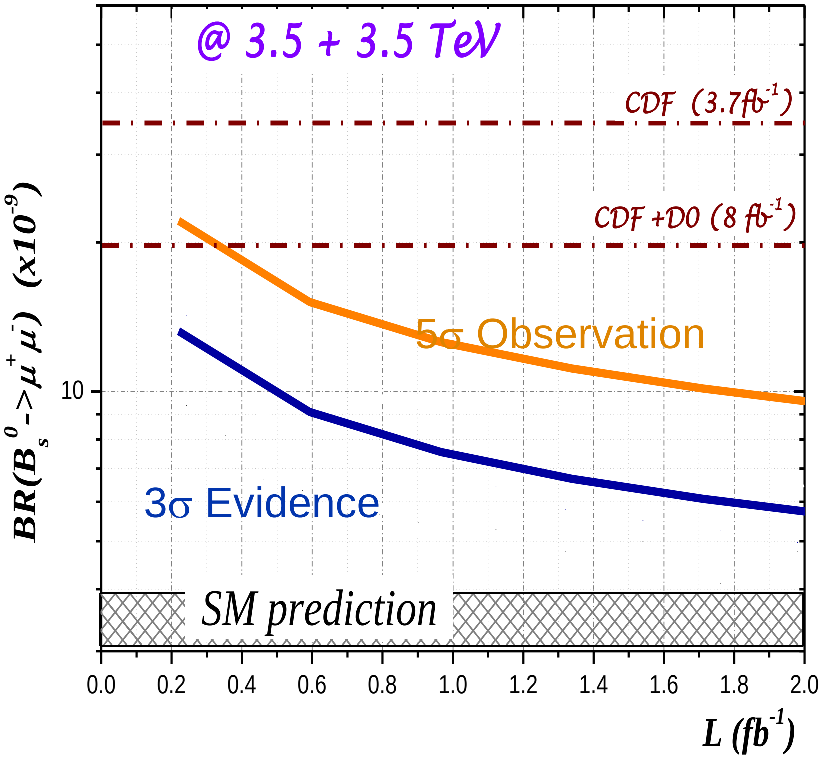
LHCb Prospects for $B_s \to \mu\mu$

<u>Experimental status:</u> *CDF 2009*

$BR(B_s \to \mu^+ \mu^-) < 4.3\times10^{-8}$ 95% CL

$BR(B_d \to \mu^+ \mu^-) < 7.6\times10^{-9}$ 95% CL

For ~150 pb^{-1} LHCb expects to reach the final Tevatron sensitivity.



$$R_{\mu\mu} = \frac{\mathcal{B}(B_s \to \mu\mu)}{\mathcal{B}(B_d \to \mu\mu)} \sim \frac{|V_{ts}|^2}{|V_{td}|^2}\Bigg|_{\text{SM MFV}}$$

Ratio is sensitive test for MFV

Conclusion

"Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

A.Soni