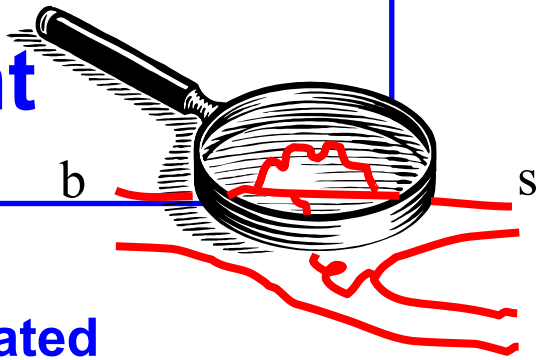
Large Hadron Collider
beauty Experiment



Precision measurements of loop-dominated B decays as possible probes for New Physics

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Content:

Motivation

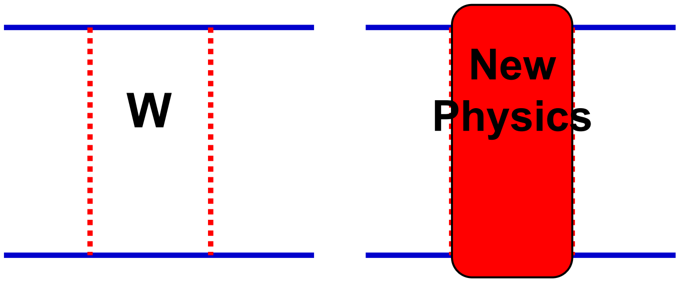
Theoretical Introduction

LHCb Experiment

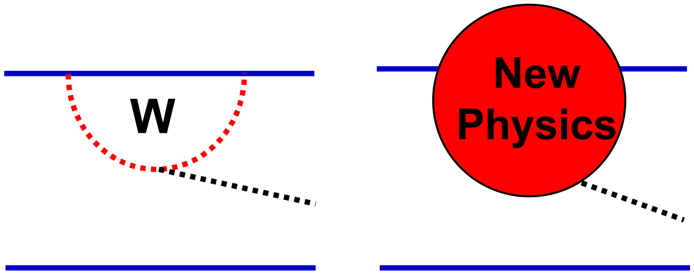
LHCb Measurements and expected performance

Motivation

Precision B Meson Physics as Probe for New Physics in Loop-Processes:



Box Diagrams (Oscillation)



Penguin Decays

Popular New Physics Scenarios: SUSY, Little Higgs Models

➡ Deviations from Standard Model predictions

Complementary to direct New Physics searches by ATLAS and CMS

Examples from the past

GIM Mechanism

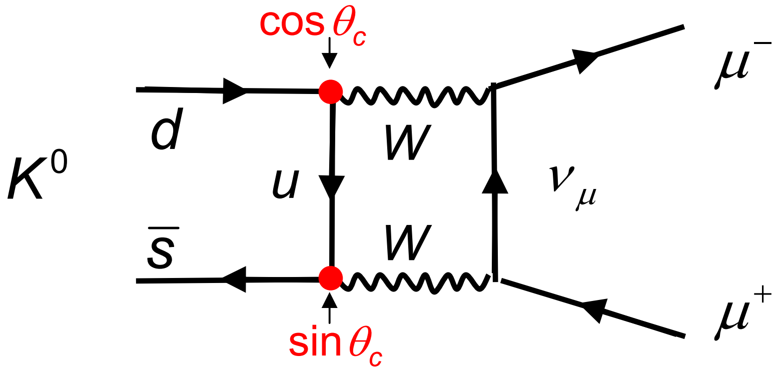
Observed branching ratio $K^0 \to \mu\mu$

$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

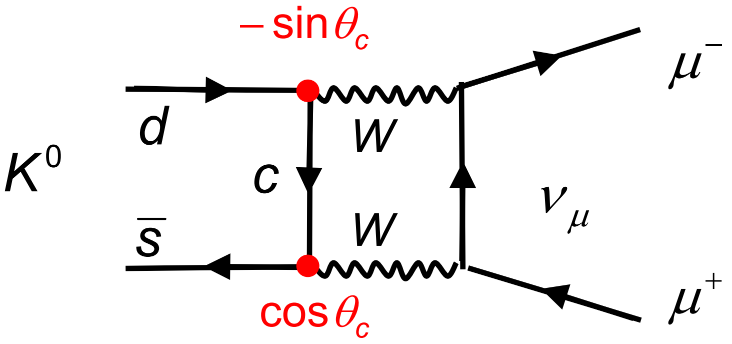
In contradiction with theoretical expectation in the 3-Quark Model

Glashow, Iliopolus, Maiani (1970):

Prediction of a 2nd up-type quark, additional Feynman graph cancels the “u box graph”.



$$M \sim \sin\theta_c \cos\theta_c$$

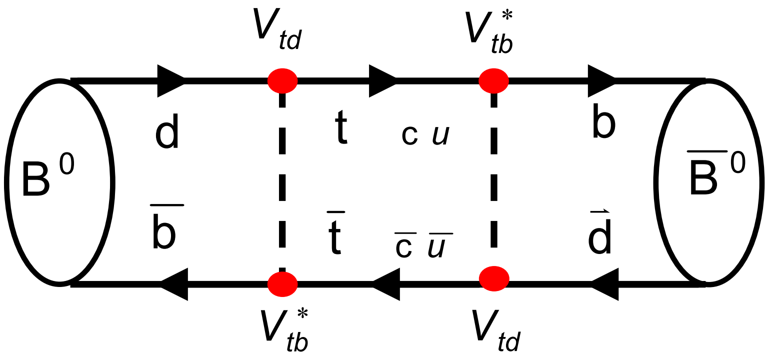


$$M \sim -\sin\theta_c \cos\theta_c$$

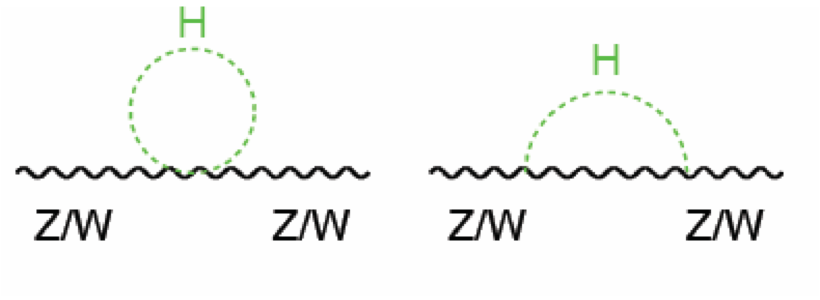
More Examples

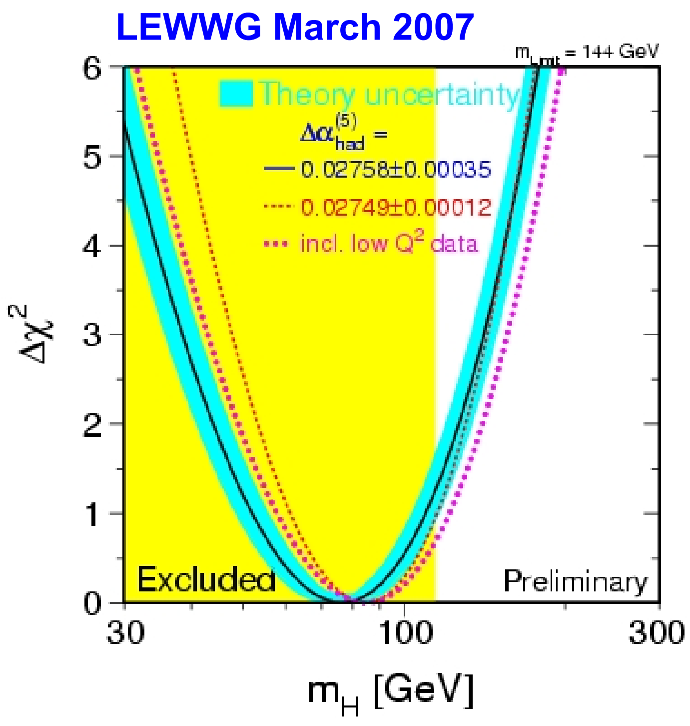
ARGUS Experiment, 1987:

Observation of B^0-B^0 Oscillation → $m_t > 50$ GeV



Precision electro-weak Physics at the Z →





$m_H < 144$ GeV (95% C.L)

Pros and Cons

1. Interpretation of precision measurements (CP asymmetries, charge asymmetries, branching ratios) requires good understanding of the "old physics" (Standard Model).
2. Nobel Prizes are generally not awarded for "dubious" conclusions from precision measurements.

Go to ATLAS and CMS ? But are all questions solvable ?

3. New particles / signatures found with ATLAS and CMS must interact with existing particles: What is the flavor structure of NP ? What are the coupling of NP ?
4. Particles at ~1 TeV scale are difficult to be directly observed

Wait for new collider ? Exploit the B Physics Potential of LHC !

Theoretical Introduction

- Quark Mixing and CKM matrix
- Mixing phenomenon
- C, P and CP Violation
- CP Violation in the Standard Model
- Standard Model and Baryon Asymmetry in the Universe
- Measurement of CP Violation
- CKM Metrology
- Rare (Penguin) decays

Quark Mixing in Standard Model

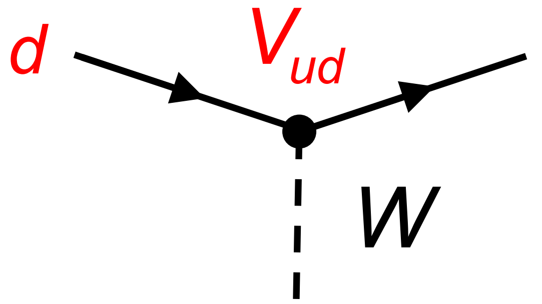
Standard Model Lagrangian:

Yukawa coupling between fermions and the Higgs field

Spontaneous symmetry breaking ➡

- Massive fermions $m_f \sim Y_f \cdot \upsilon / \sqrt{2}$
- For quarks: mass eigenstates different from weak eigenstates

$$\underset{\textbf{weak}}{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}} = \underset{\textbf{CKM matrix}}{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \underset{\textbf{mass}}{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}$$



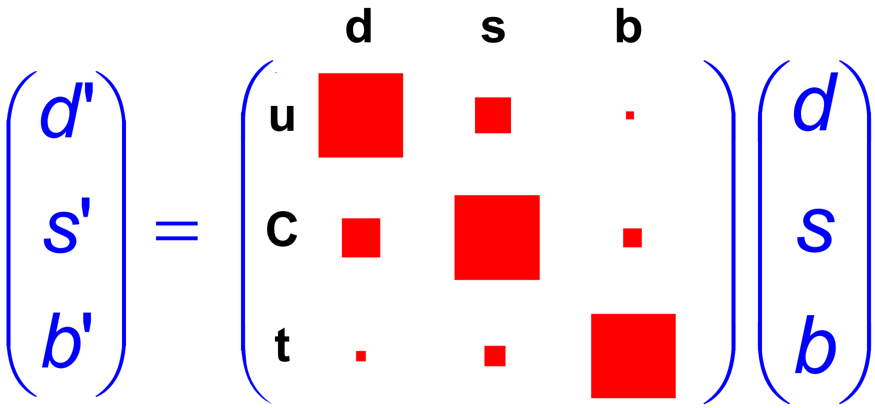
Charged currents:

$$J_\mu^+ \propto (\bar{u}, \bar{c}, \bar{t})(1-\gamma_5)\,\gamma_\mu \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

$$\propto (\bar{u}, \bar{c}, \bar{t})(1-\gamma_5)\,\gamma_\mu \mathbf{V}_{\mathbf{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM Matrix

complex, unitary 3x3 matrix:



4 real Parameter = 3 Euler-angles und 1 Phase

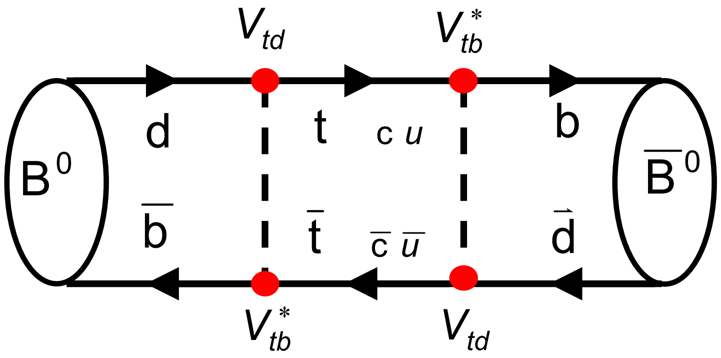
Wolfenstein Parametrization

λ, A, ρ, η

$\lambda = \sin\theta_c \approx 0.22$

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Quark Mixing and Flavor Oscillation



Flavor states B^0 and $\bar{B}^0$

$\neq$

Mass eigenstates B_H and B_L

Mixing phenomenology decribed by

$$i\frac{d}{dt}\begin{pmatrix}B^0\\ \bar{B}^0\end{pmatrix} = \mathbf{H}\begin{pmatrix}B^0\\ \bar{B}^0\end{pmatrix} = \begin{pmatrix}H_{11} & H_{21}\\ H_{12} & H_{22}\end{pmatrix}\begin{pmatrix}B^0\\ \bar{B}^0\end{pmatrix} = \left(\mathbf{M}-\frac{i}{2}\Gamma\right)\begin{pmatrix}B^0\\ \bar{B}^0\end{pmatrix} = \begin{pmatrix}m_{11}-\frac{i}{2}\Gamma_{11} & m_{12}^*-\frac{i}{2}\Gamma_{12}^*\\ m_{12}-\frac{i}{2}\Gamma_{12} & m_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}B^0\\ \bar{B}^0\end{pmatrix}$$

Diagonal elements: $\left|\psi(t)\right\rangle = \left|\psi_0\right\rangle \cdot e^{-imt} \cdot e^{-\frac{1}{2}\Gamma t}$

$$H_{11} = H_{22} = H$$

CPT $\Rightarrow$ $m_{11} = m_{22} = m$

$$\Gamma_{11} = \Gamma_{22} = \Gamma$$

Off-diag elements: mixing

M and $\mathbf{\Gamma}$ hermitian: $m_{21} = m_{12}^*$, $\Gamma_{21} = \Gamma_{12}^*$

Mixing phase ϕ= arg(m_{12})

Flavor and Mass Eigenstates

⇒ **Diagonalizing Hamitonian:**

Mass eigenstates

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

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

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

⇓

Flavor states

$$|B^0\rangle = \frac{1}{2p}(|B_L\rangle + |B_H\rangle)$$

$$|\overline{B}^0\rangle = \frac{1}{2q}(|B_L\rangle - |B_H\rangle)$$

Parameters of the mass states

$$m_{H,L} = m \pm \mathrm{Re}\sqrt{H_{12}H_{21}}$$

$$\Gamma_{H,L} = \Gamma \mp 2\,\mathrm{Im}\sqrt{H_{12}H_{21}}$$

$$\Delta m = m_H - m_L = 2\,\mathrm{Re}\sqrt{H_{12}H_{21}}$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L = -4\,\mathrm{Im}\sqrt{H_{12}H_{21}}$$

$$x \equiv \frac{\Delta m}{\Gamma} \quad \text{und} \quad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

Neutral B mesons

$$\Delta m_d = 0.502 \pm 0.007 \text{ ps}^{-1} \text{ (PDG)}$$

$$\Delta m_s = 17.78 \pm 0.12 \text{ ps}^{-1} \text{ (CDF)}$$

$$\Delta\Gamma / \Gamma < 0.07 \ (90\%\ CL)$$

$$\Delta\Gamma_s / \Gamma_s = 0.09 \pm 0.64 \text{ (Moriond07)}$$

Mixing of neutral mesons

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

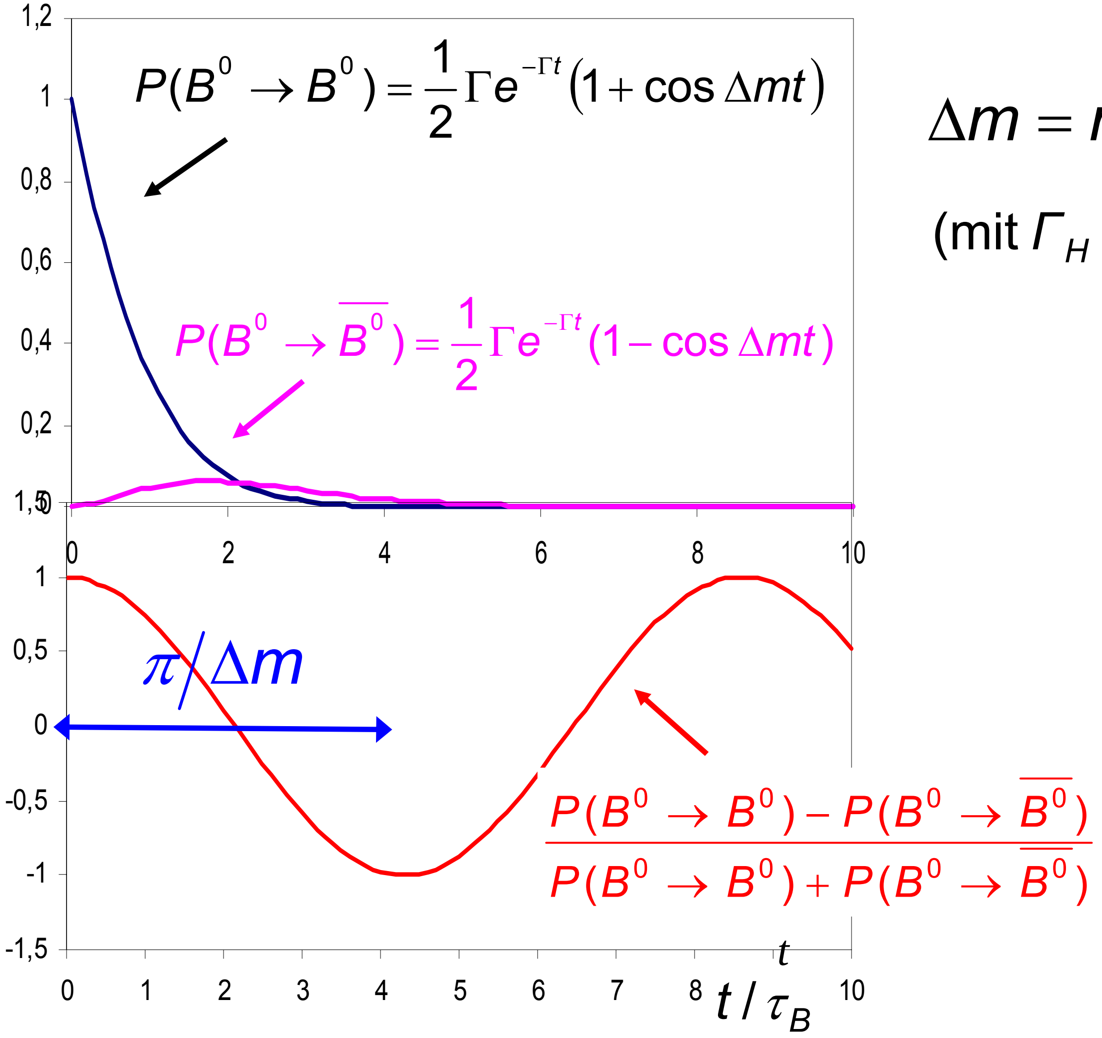
$$P(B^0 \to \overline{B^0}) = \frac{1}{4}\left|\frac{q}{p}\right|^2\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right] \qquad \Delta m = m_H - m_L$$

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

CP, T- violation in mixing:

$$P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0) \Rightarrow \left|\frac{q}{p}\right| \neq 1$$

B^0-$\overline{B^0}$ Mixing



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

$$P(B^0 \to \overline{B^0}) = \frac{1}{2}\Gamma e^{-\Gamma t}(1-\cos\Delta m t)$$

$\pi / \Delta m$

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

t / τ_B

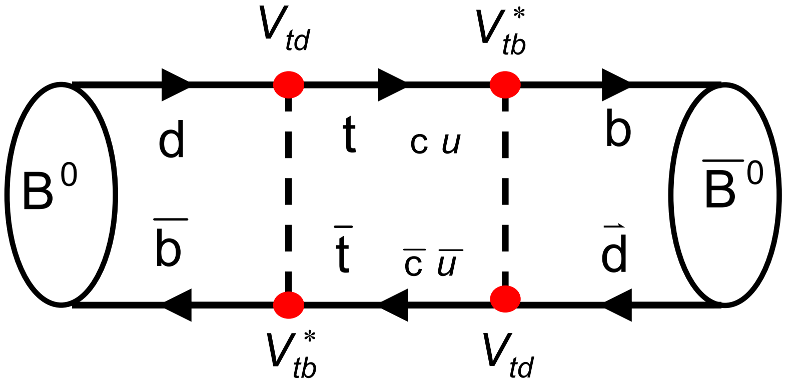
$$\Delta m = m_H - m_L$$

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

Oscillation Frequency

Standard Model Prediction

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



$\eta_B = 0.55 \pm 0.01$

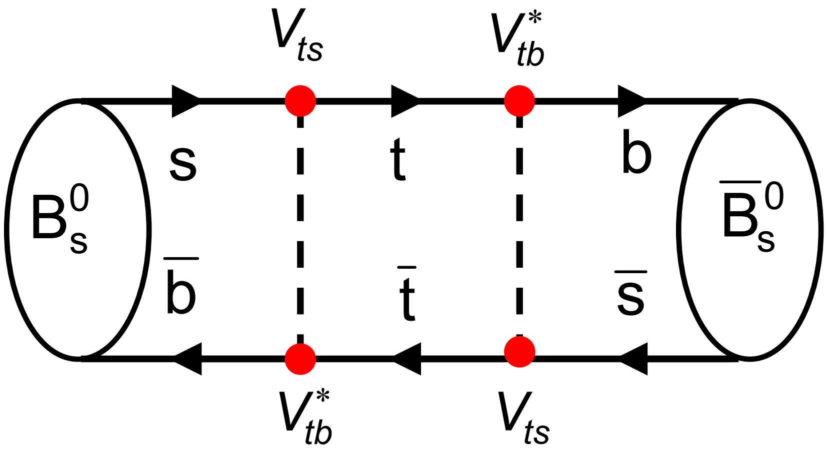
NLO QCD

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_B f_B^2 B_B (V_{td}^* V_{tb})^2 m_W^2 \, \eta_B \, F\left(\frac{m_t^2}{m_W^2}\right)$$

← e.w. correction

$f_B^2 B_B = (235 \pm 33 \pm 12)^2 \, MeV^2$ from lattice QCD

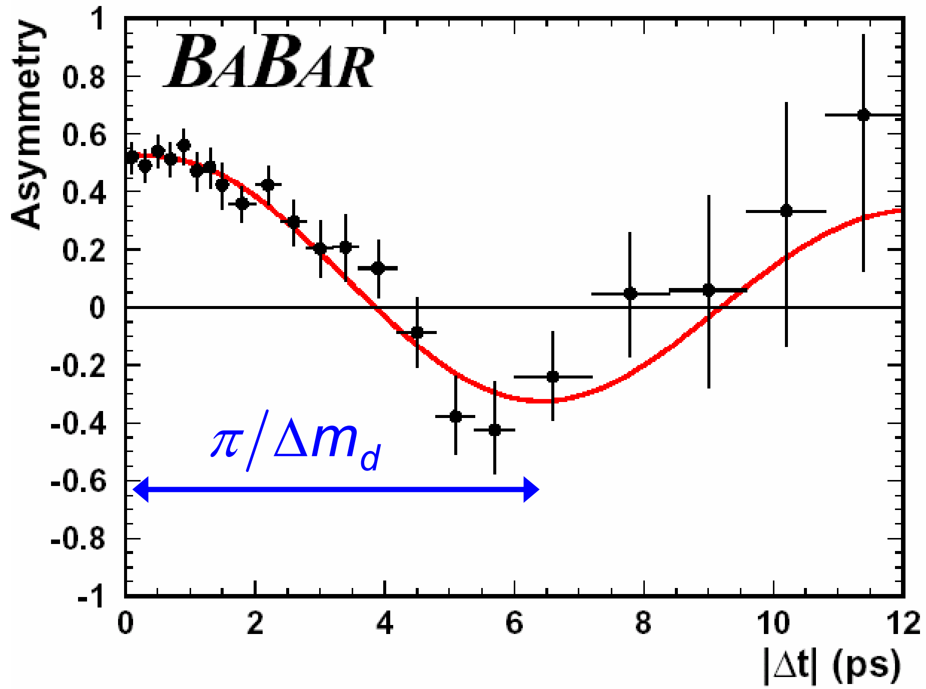
$B_s^0 - \overline{B}_s^0$



$$\Delta m_s \sim (V_{ts}^* V_{tb})^2$$

B^0 Oscillation

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



$$\Delta m_d = 0.506 \pm 0.006 \pm 0.004\ \mathrm{ps}^{-1} \approx \frac{0.774}{\tau_\mathrm{B}}$$

(BABAR mean value March 2006)

$B_s^0 - \overline{B}_s^0$

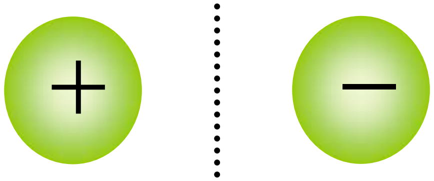
$$\Delta m_s = 17.77 \pm 0.10\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.})\ \mathrm{ps}^{-1} \approx \frac{26}{\tau_\mathrm{B}}$$

(CDF Collaboration, September 2006)

Discrete Symmetries

Charge conjugation C

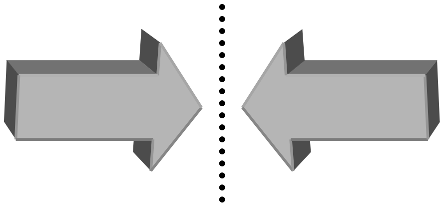
Particle ⇔ Anti-particle



$$e^- \to e^+$$

$$\gamma \to \gamma$$

Parity P

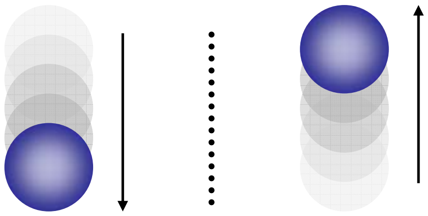


$$\vec{r} \to -\vec{r}$$

$$\vec{p} \to -\vec{p}$$

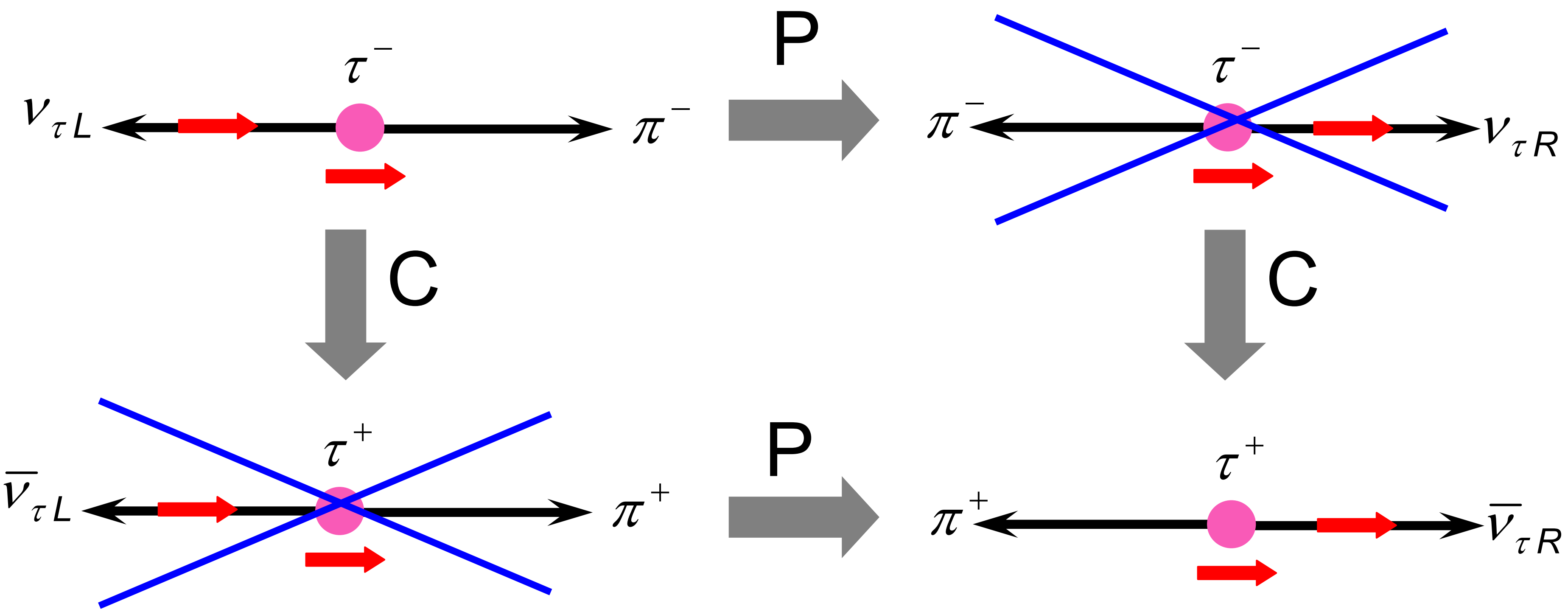
$$\vec{L} \to \vec{L}$$

Time inversion T



$$t \to -t$$

Weak Interaction: P, C and CP Symmetry



While the weak interaction violates C and P maximally, CP was thought to be a good symmetry until 1964, when CPV was observed in K decays:

Small (10^{-3}) effect !

CP Violation in B Meson Decays

Summer 2001

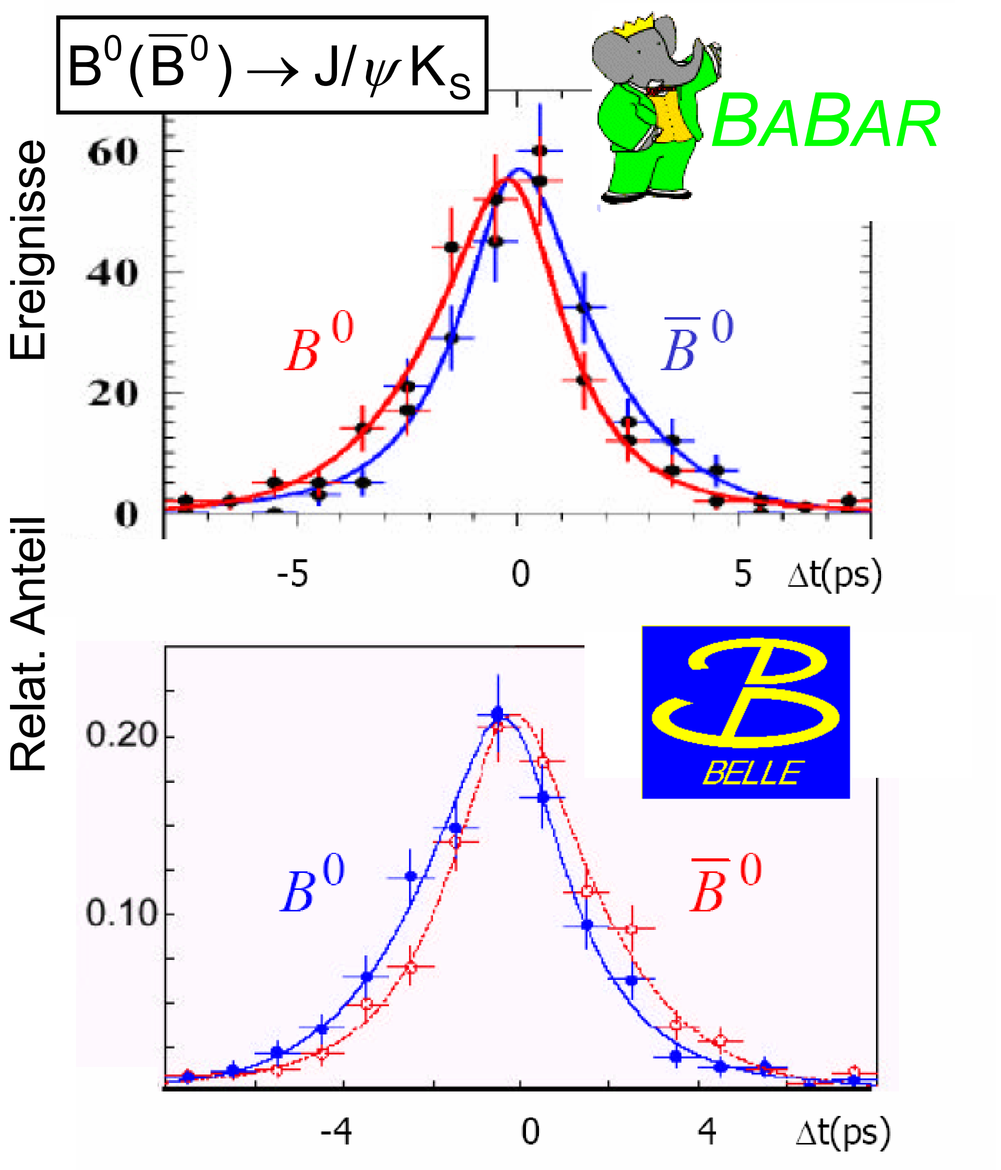
CP Violation in B decays:

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

CP Asymmetry „70 % effect“

BR ~ 4×10^{-4}

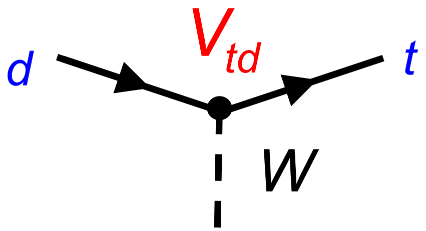
CP violation is observed in many B decays with loop-contributions but also in tree-dominated decays.



CP Violation in the Standard Model

Quarks

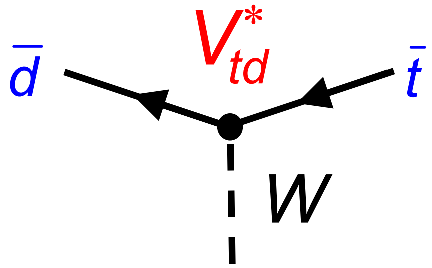
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



CP

Anti-quarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



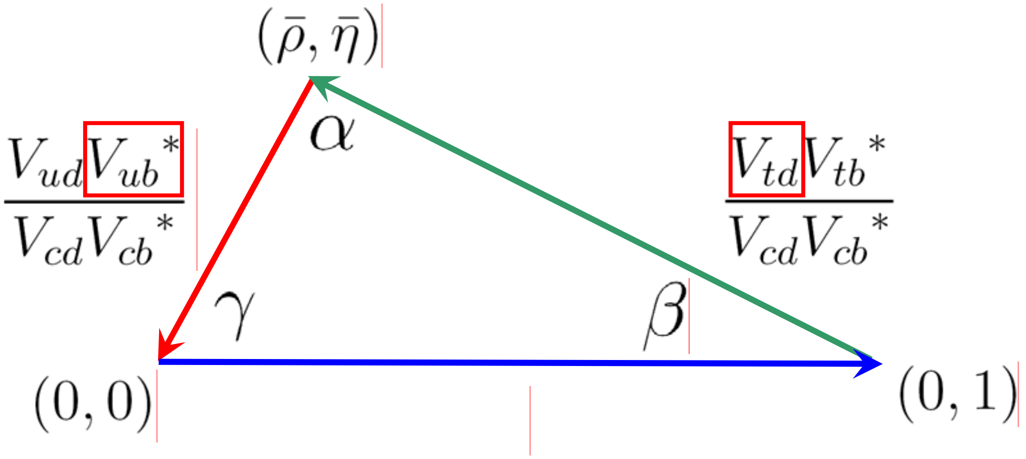
CP Violation ⇔ **complex matrix elements**

Unitarity Triangle

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td}} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Rightarrow V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

Unitarity triangle „bd“



CKM Phases

$$\begin{pmatrix} 1 & 1 & \overset{b\to u}{\overset{\downarrow}{e^{-i\gamma}}} \\ 1 & 1 & 1 \\ \underset{t\to d}{\underset{\uparrow}{e^{-i\beta}}} & 1 & 1 \end{pmatrix} + O(\lambda^4)$$

CP Violation if Triangle has finite area !

Standard Model & Baryon-Asymmetry

Explains the Standard Model the Baryon-Asymmetry of the Universe ?

Sacharow Conditions:

- Baryon number violation
- C und CP violation **No**
- Deviation from thermal equilibr **No**

- CP Violation in quark sector by faktor ~10^{10} too small.
- For M_{Higgs}> 114 GeV: Symmetry breaking = 2nd order phase transition

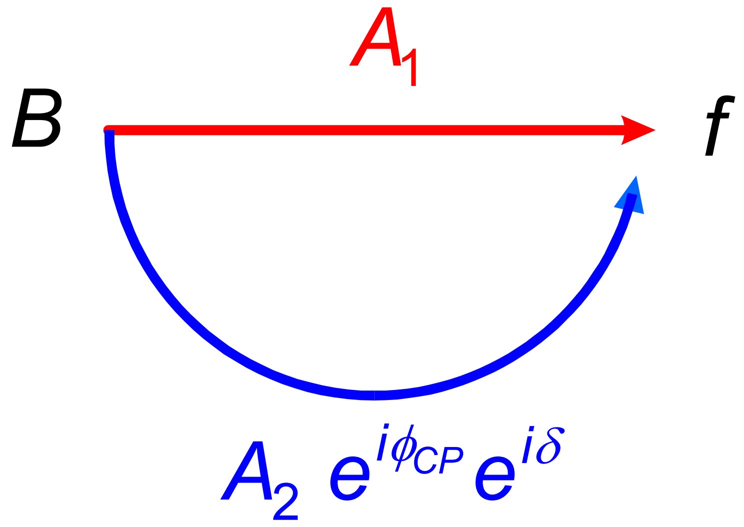
Attractive: SUSY extensions of the Standard Model

- Additional CP Violation
- extended Higgs-Sector→ strong phase transition

Alternatives: Lepto-Baryogenesis

Measurement of CP violating Phases

$\boxed{B \to f}$



A_1

B

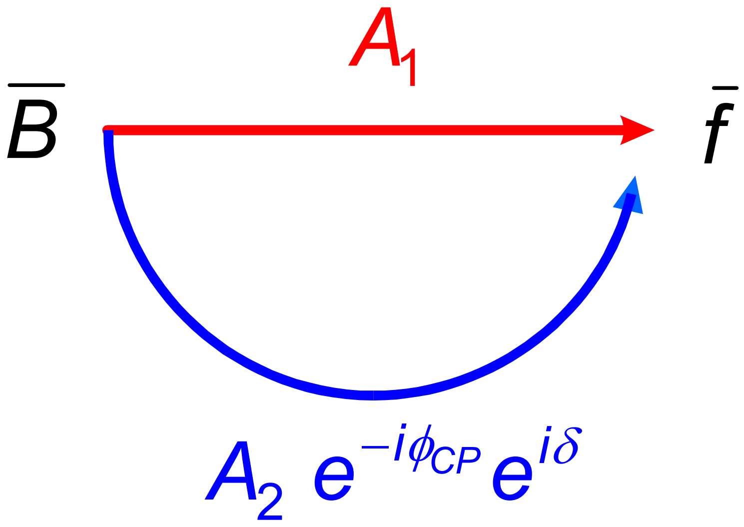
f

$A_2\, e^{i\phi_{CP}} e^{i\delta}$

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

CP

$\boxed{\overline{B} \to \bar{f}}$



A_1

$\overline{B}$

$\bar{f}$

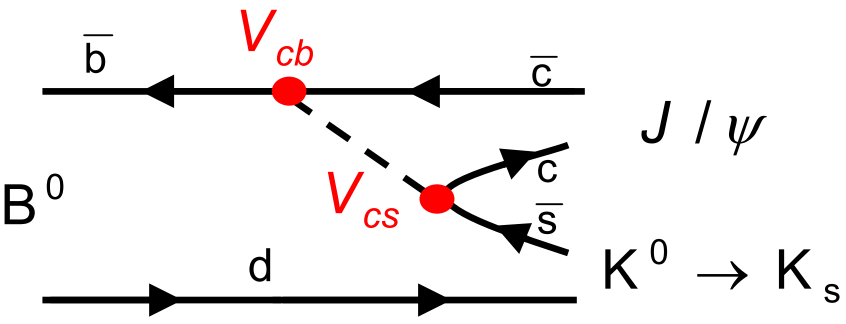
$A_2\, e^{-i\phi_{CP}} e^{i\delta}$

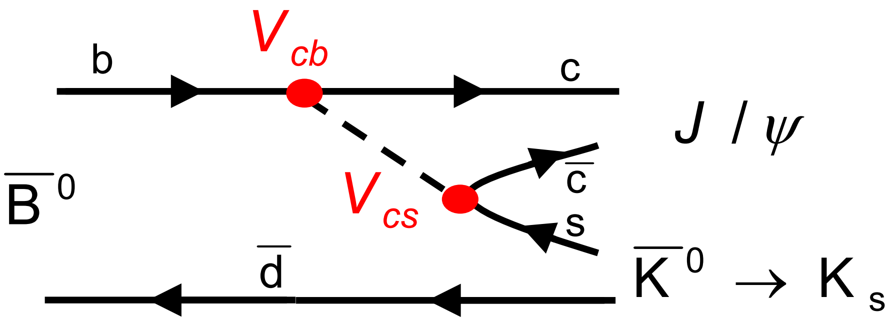
$$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP}-\delta)$$

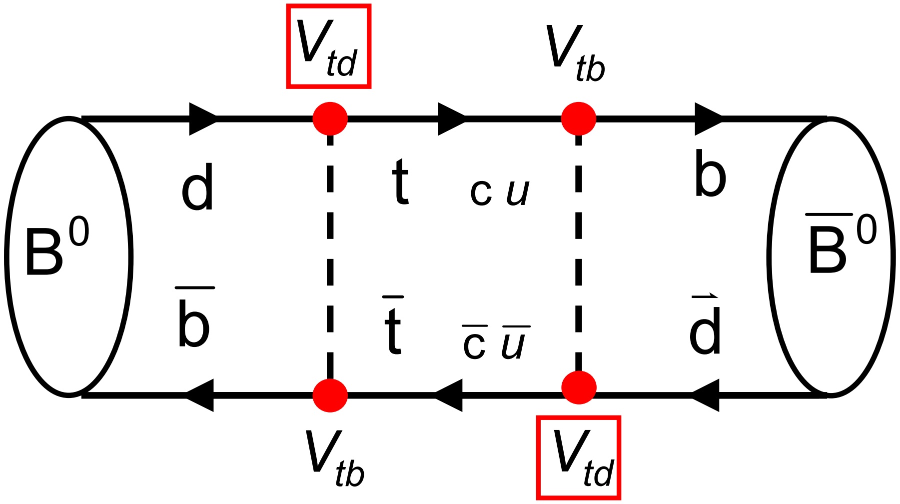
„Golden“ Decay $B^0 \to J/\psi K_s$

$B^0 \to J/\psi K_s$ CP $\overline{B}^0 \to J/\psi K_s$

$\eta_{CP}=-1$







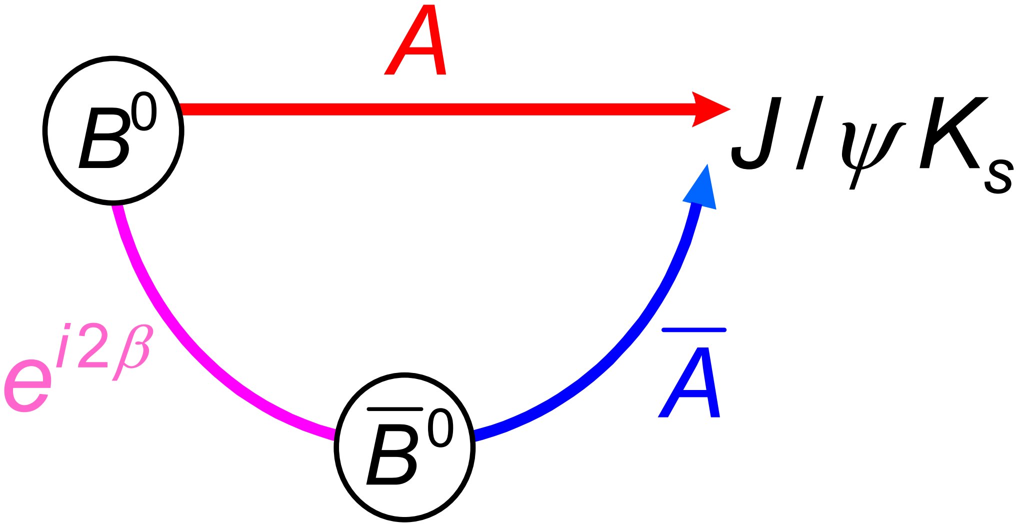
Mixing Phase:

$$e^{i\phi_d} = e^{i2\beta}$$

„Golden“ Decay $B^0 \to J/\psi K_s$

$\boxed{B^0 \to J/\psi K_s}$ $\xrightarrow{\text{CP}}$ $\boxed{\overline{B}^0 \to J/\psi K_s}$

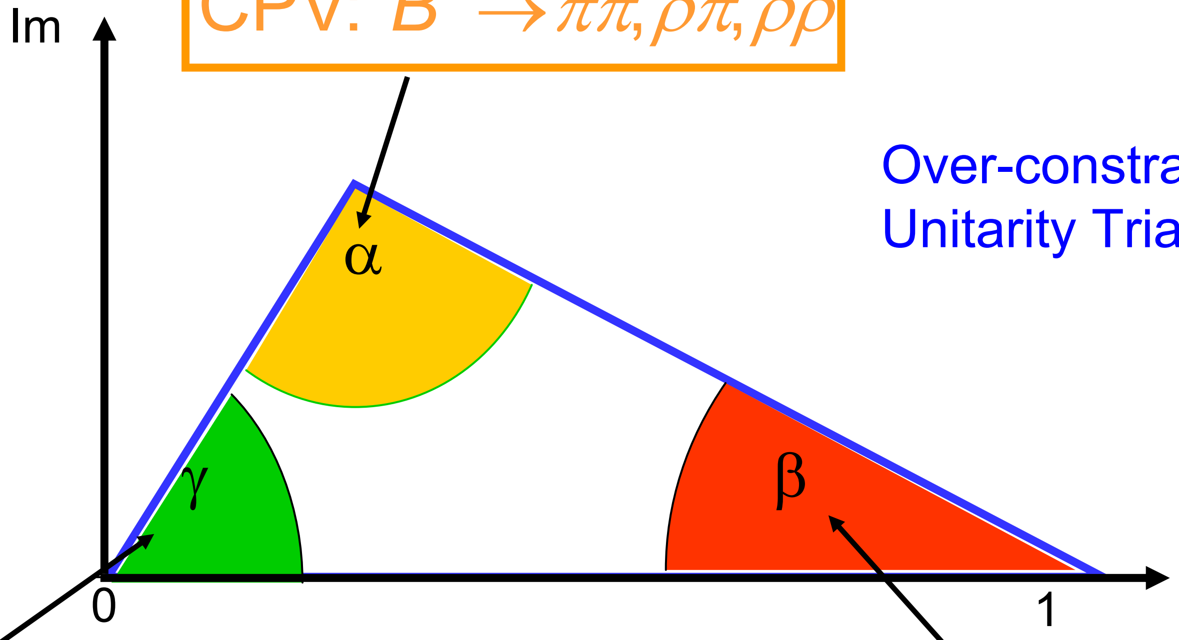
$\eta_{CP}=-1$



$$\Gamma(B^0 \to J/\psi K_s)(t) \neq \Gamma(\overline{B}^0 \to J/\psi K_s)(t)$$

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

CKM Phases from CPV in B Decays



CPV: $B^0 \rightarrow \pi\pi, \rho\pi, \rho\rho$

Over-constrain the
Unitarity Triangle !

CPV: $B^0 \rightarrow DK^{(*)}, DK_s^0, K\pi, D^*\pi$

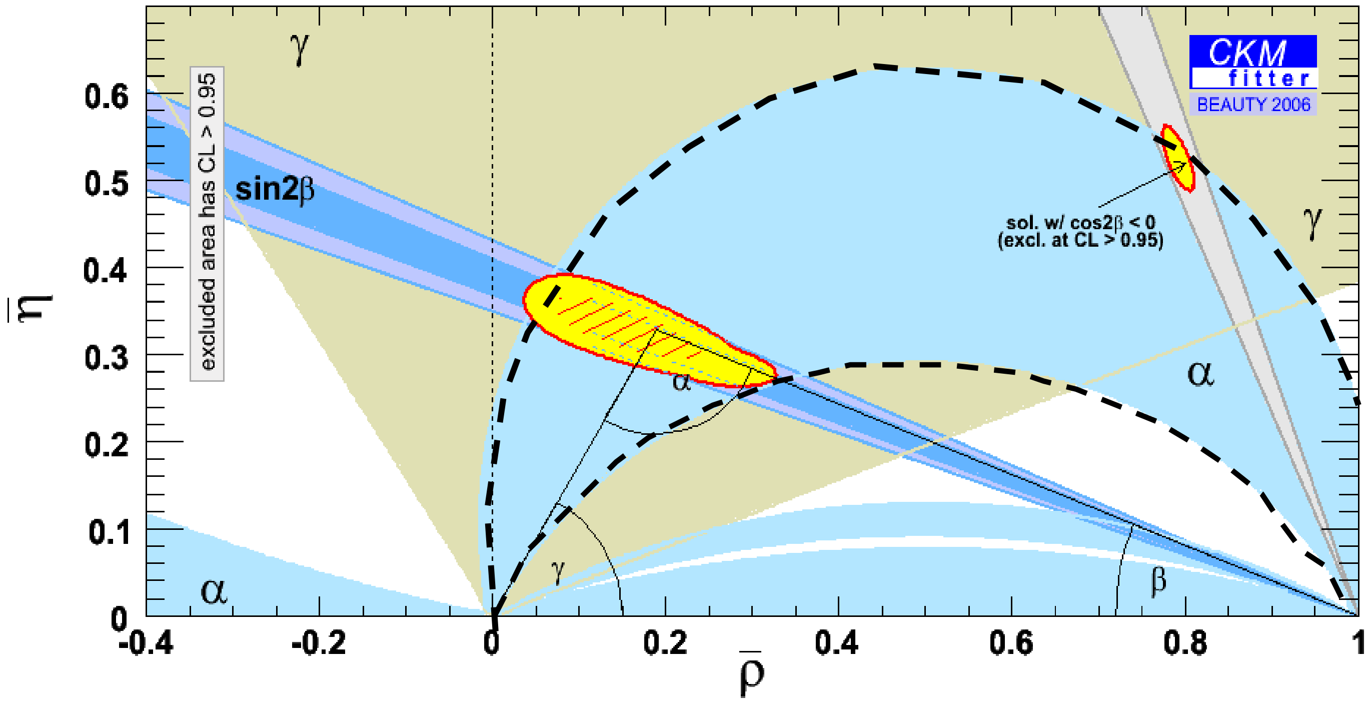
$B_s^0 \rightarrow D_s K, KK$

CPV: $B^0 \rightarrow J/\psi K_S^0$

„Golden channel“

Very rare decays → several 10^9 B mesons necessary

CKM Metrology



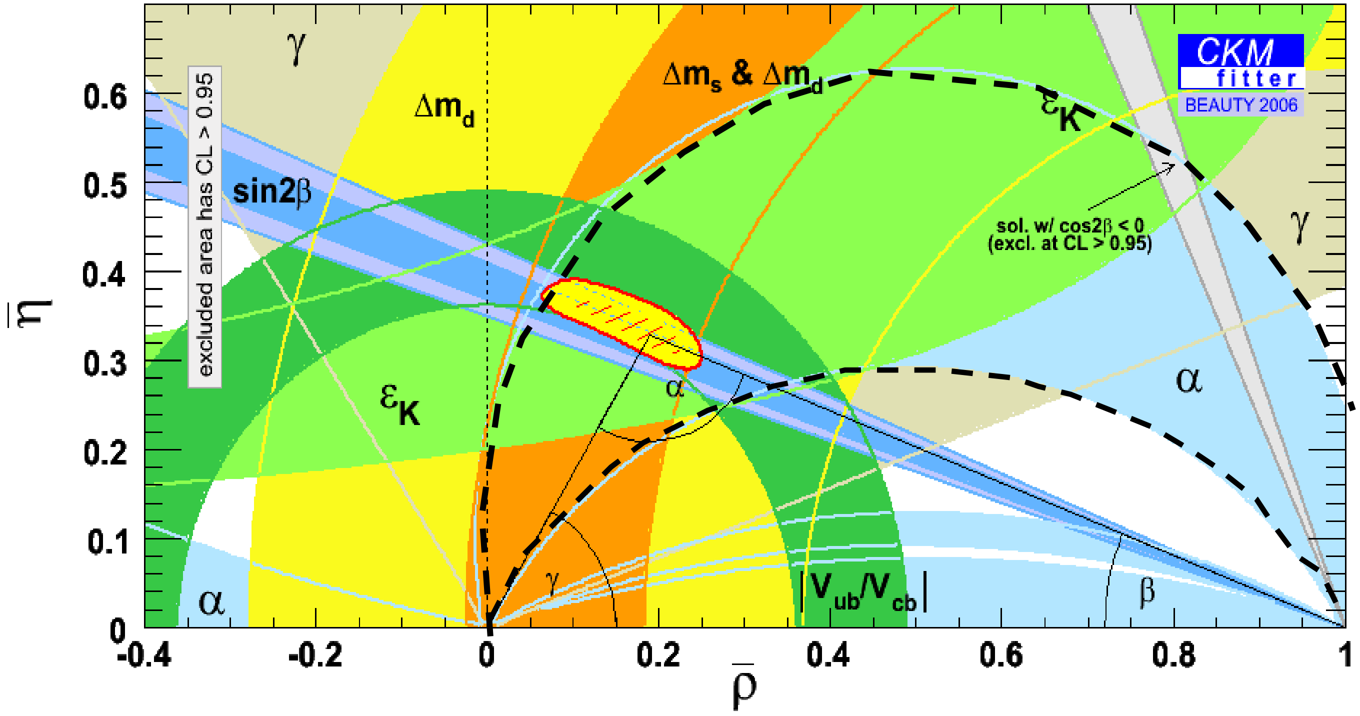
β $\beta = 21.3^o \pm 1.0^o \quad \sin 2\beta = 0.674 \pm 0.026 \quad (\pm 4\%)$

α $\alpha = 93^o \pm 10^o$

World Average

γ With BABAR/BELLE difficult: $\gamma = 60^o \pm^{38^o}_{24^o}$

CKM Metrology



CKM Mechanism is primary source of CP violation in quark sector.
Test of New Physics needs high precision measurements of α,β γ.

Further New Physics Searches

CPV in Penguin suppressed decays:

$B^0(\overline{B}^0) \to \phi K_s$

$B_s^0(\overline{B}_s^0) \to \phi\phi$ $\quad BR \sim 10^{-6}$ (visible)

B_s mixing diagrams (non SM phases):

$B_s^0(\overline{B}_s^0) \to J/\psi\,\phi$

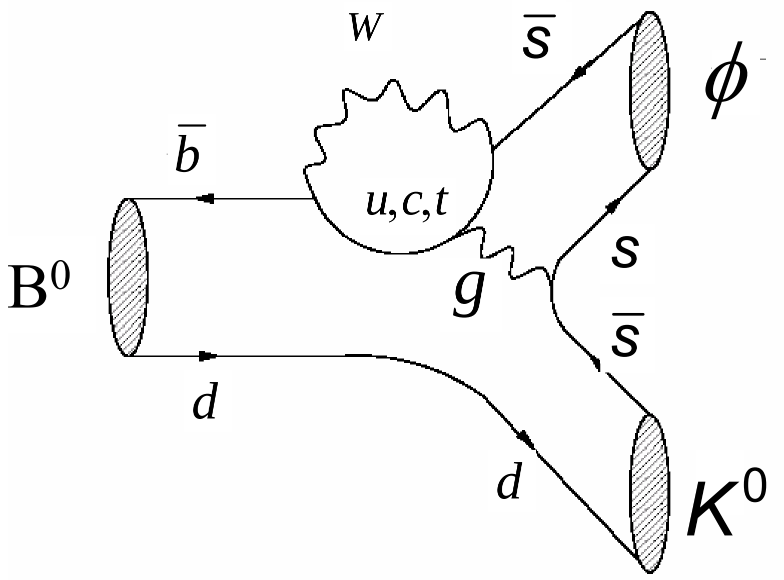
$BR \sim 3 \times 10^{-5}$ (visible)

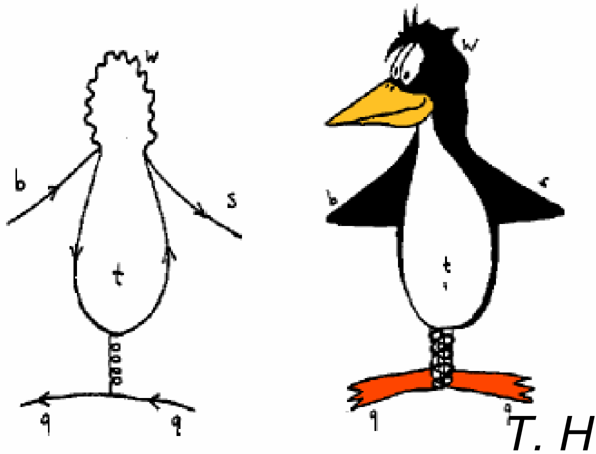
Rates of rare decays:

$B^0 \to K^{(*)}\ell\ell$

$B_{(s)}^0 \to \mu\mu$ $\quad BR \sim 10^{-9}$

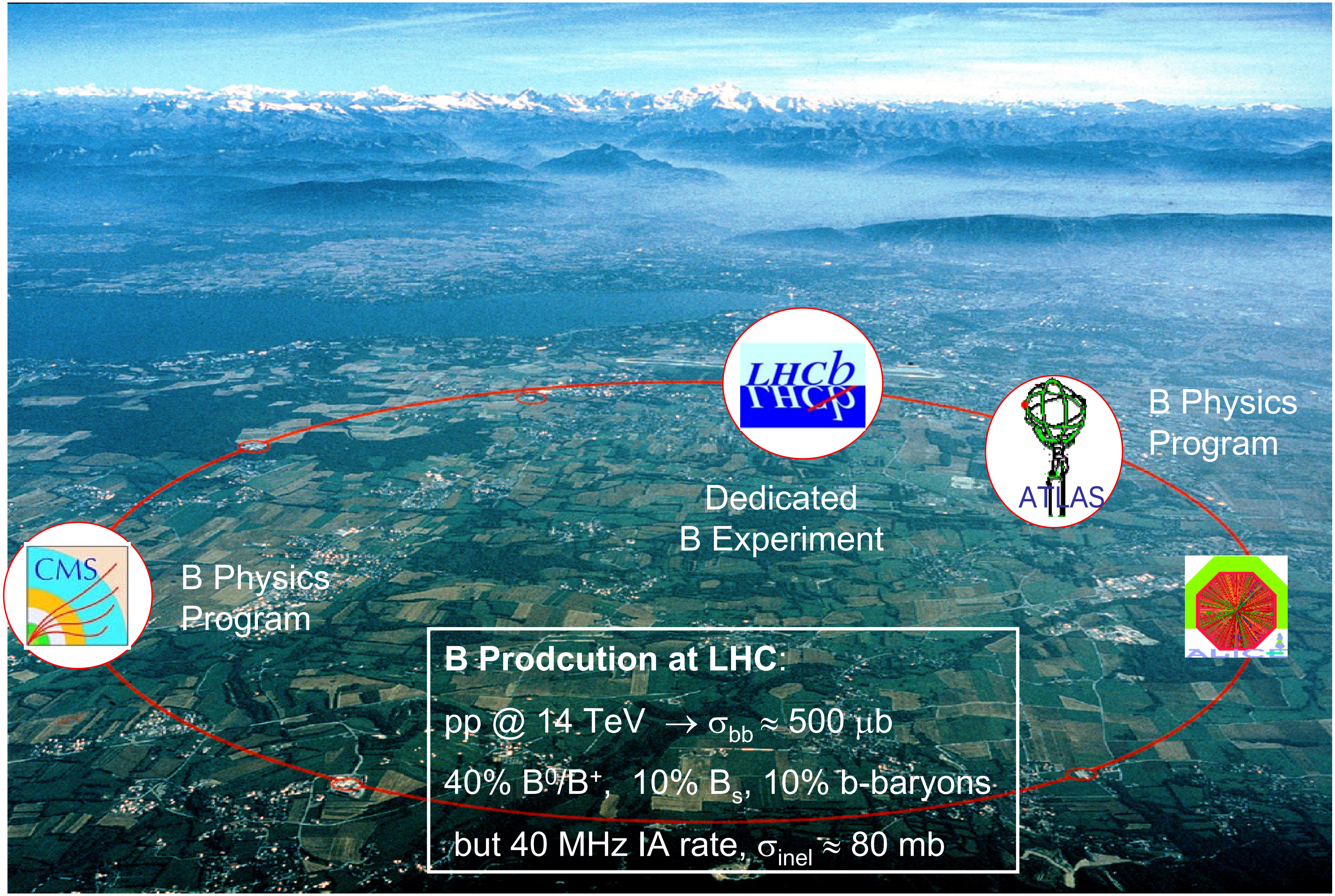
Pinguin-Graphen





T. Hurth

B Physics at the LHC



B Physics
Program

Dedicated
B Experiment

B Physics
Program

B Prodcution at LHC:

pp @ 14 TeV $\rightarrow \sigma_{bb} \approx 500\ \mu b$

40% B^0/B^+, 10% B_s, 10% b-baryons

but 40 MHz IA rate, $\sigma_{inel} \approx 80$ mb

B Production at LHC

LHC

- pp collisions at √s = 14 TeV

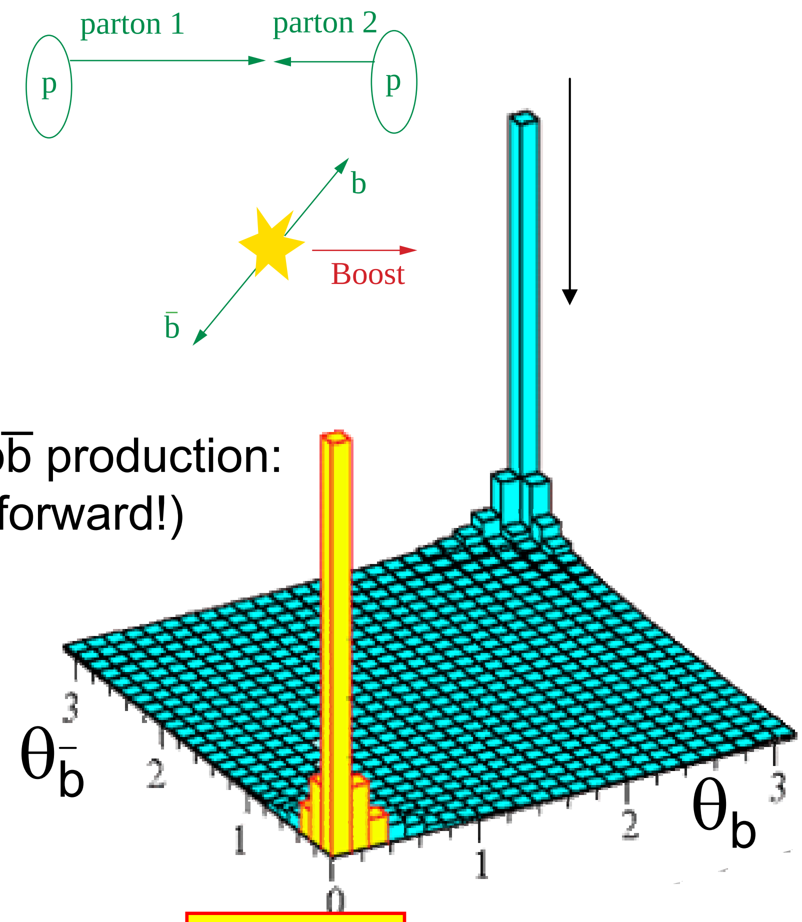
$$\begin{cases} \sigma_{inel} \sim 80 \text{ mb} \\ \sigma_{bb} \sim 500\ \mu\text{b} \end{cases}$$

- Forward production of bb, correlated
- for $L \sim 2 \times 10^{32}$ cm^{-2}s^{-1} (defocused beams at LHCb IP)

~10^{12} b $\bar{\text{b}}$ events/yr produced

LHCb

- Single arm forward spectrometer 12 mrad < θ < 300 mrad(1.8<η<4.9)



b$\bar{\text{b}}$ production: (forward!)

~ 35 %

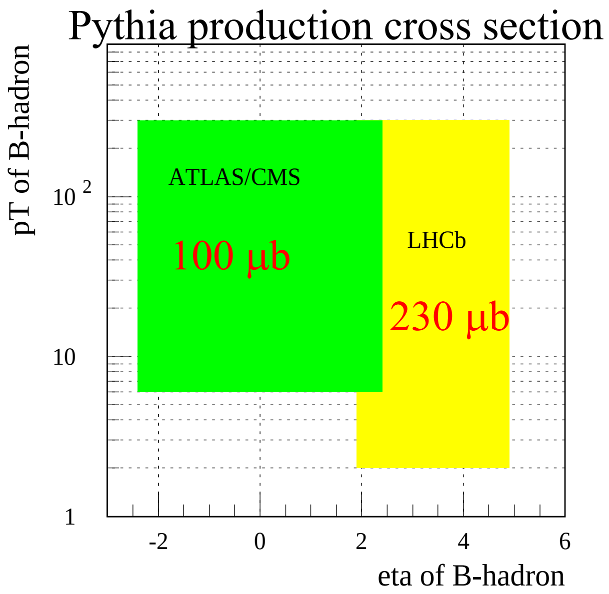
B Physics & LHC Detectors

ATLAS/CMS:

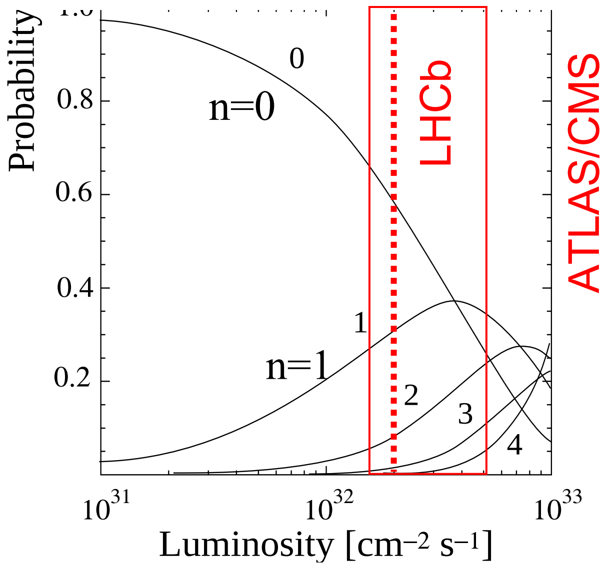
- optimized for high-pT discovery physics
- central detectors, $|\eta|<2.5$
- B physics using high-pT muon triggers, Purely hadronic modes triggered by "opposite" tagging muon
- aim for highest possible luminosities: expect $L<2\times10^{33}$ $cm^{-2}s^{-1}$ for first 3 yr → n=5 (afterwards L~ 10^{33} $cm^{-2}s^{-1}$ → n=25)

LHCb:

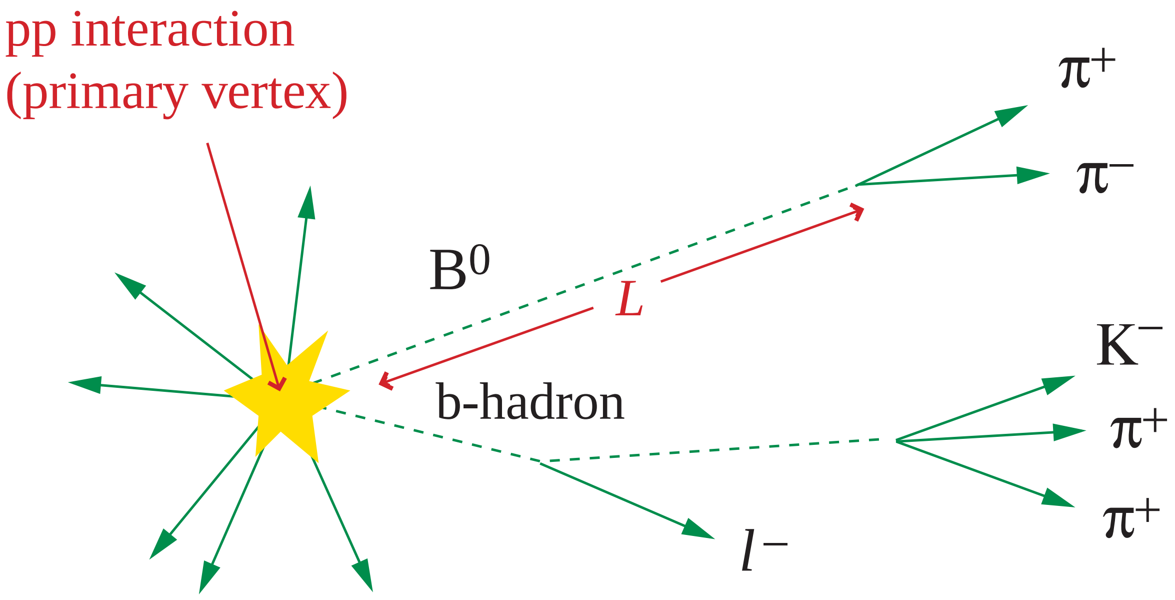
- designed to maximize B acceptance
- Forward, single arm spectrometer, $1.9 < \eta < 4.9$ (bb pairs correlated, mainly forward)
- Excellent vertexing and particle ID (K/π separation)
- "lower" pT triggers, including purely hadronic modes, very flexible
- Luminosity tuneable by adjusting beam focus: run at L ~ 2×10^{32} $cm^{-2}s^{-1}$ → $n\approx0.5$



n = # of pp interactions/crossing

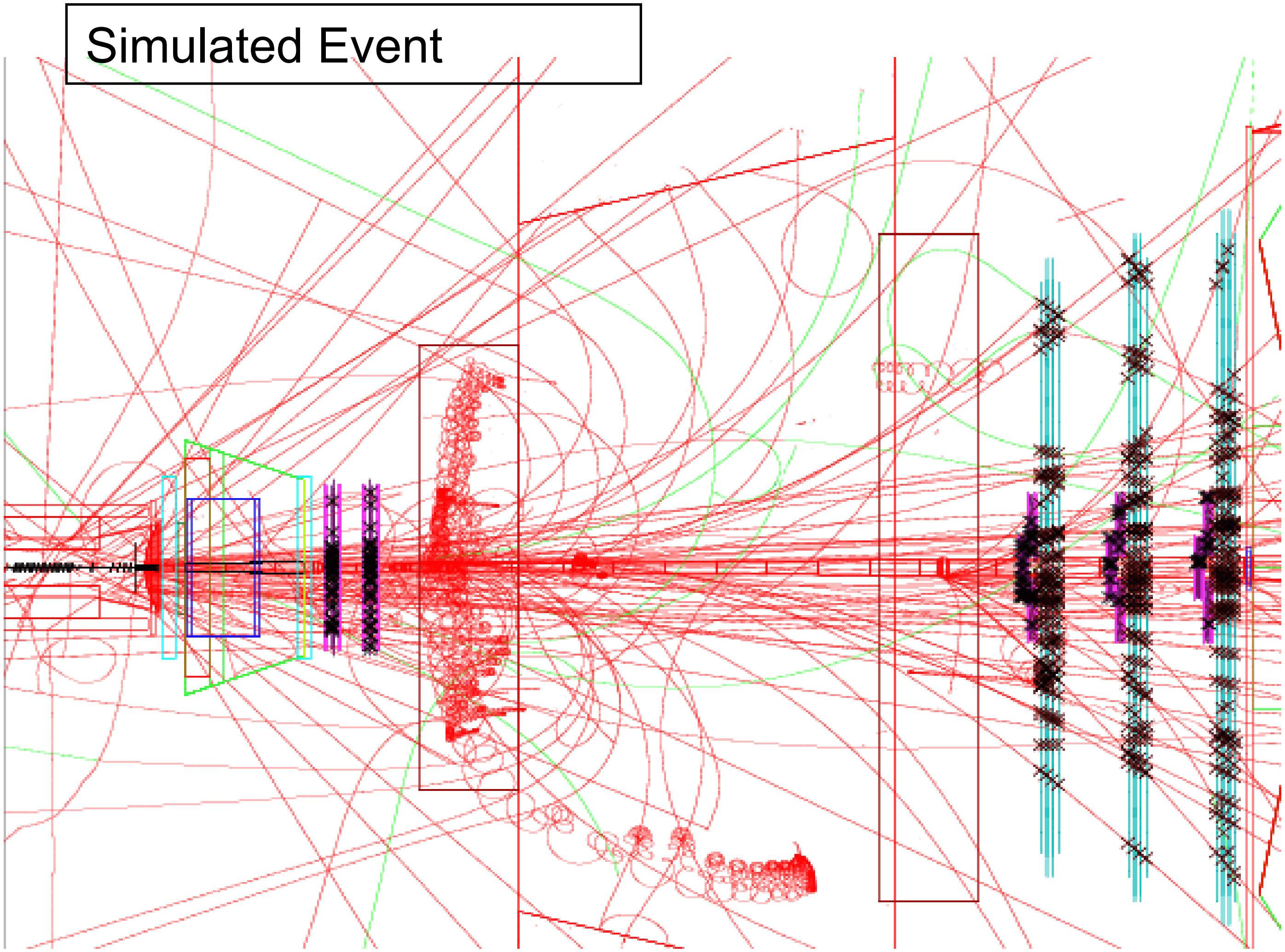


Typical Event



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

Typical Event

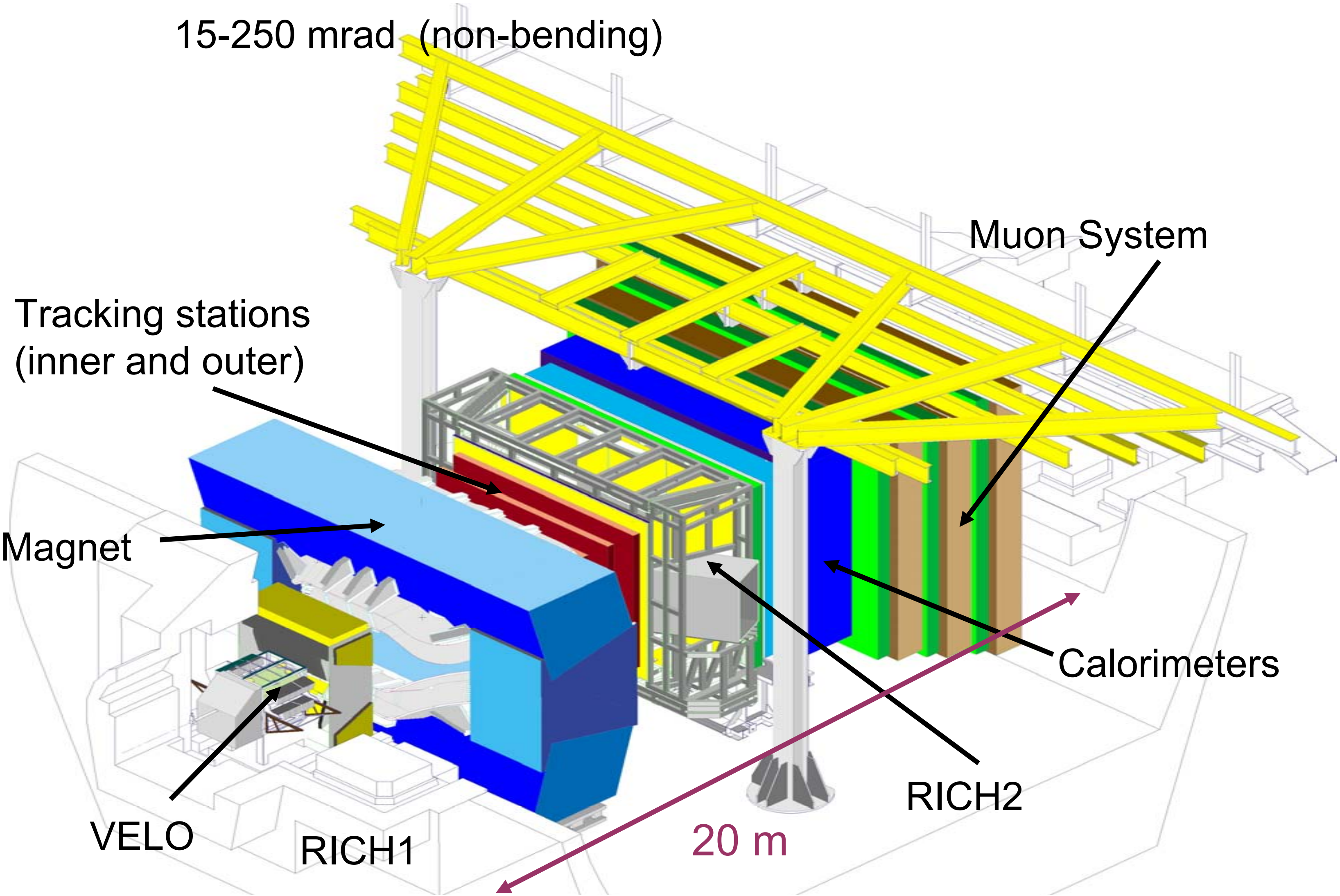

Simulated Event

all 25 ns

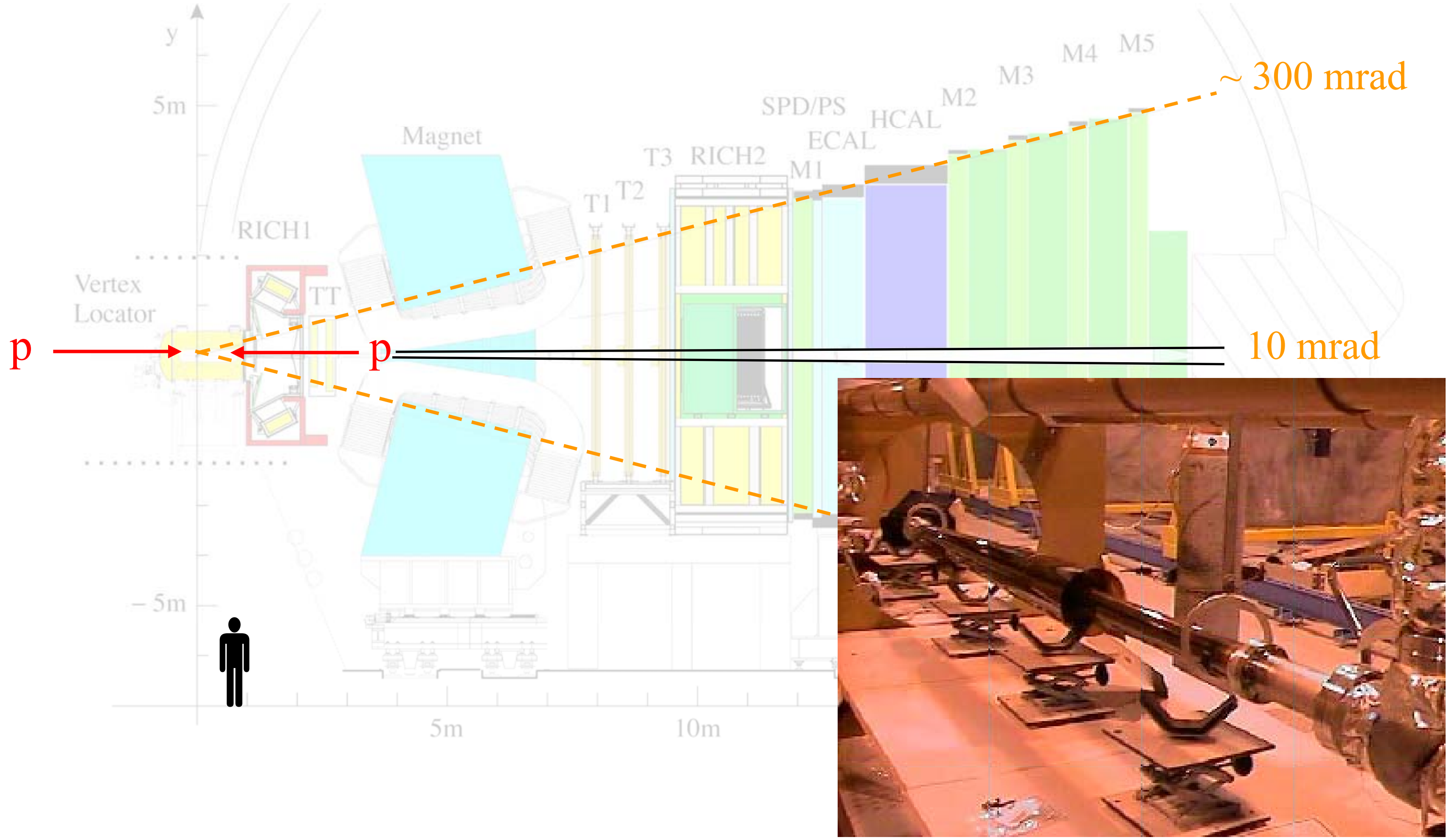
LHCb Detector

Acceptance: 15-300 mrad (bending)

15-250 mrad (non-bending)

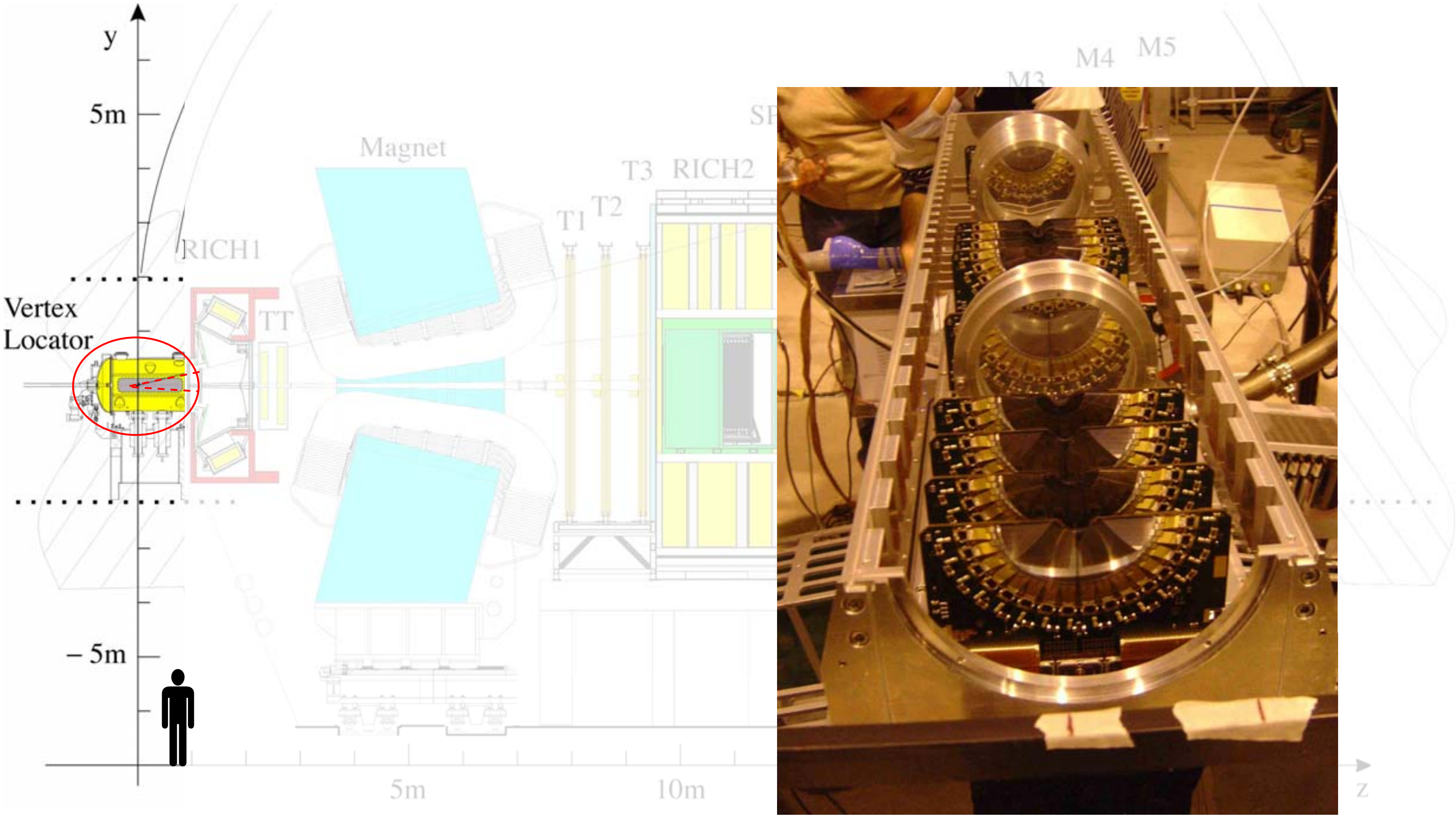


LHCb detector



Forward spectrometer (running in pp collider mode)
Inner acceptance 10 mrad from conical beryllium **beam pipe**

LHCb detector

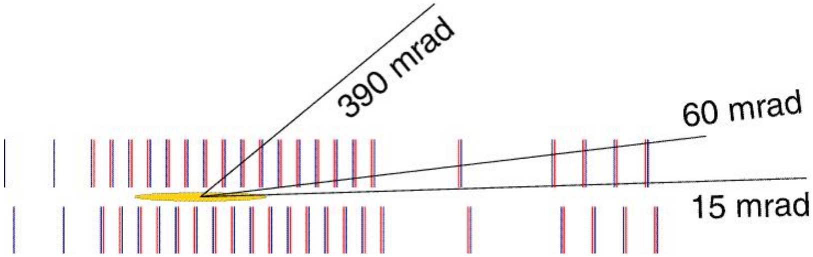


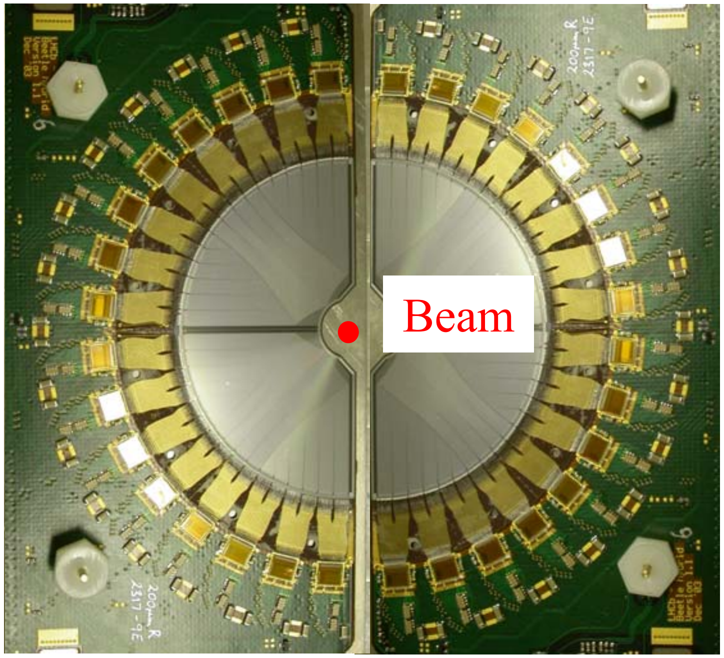
Vertex locator around the interaction region

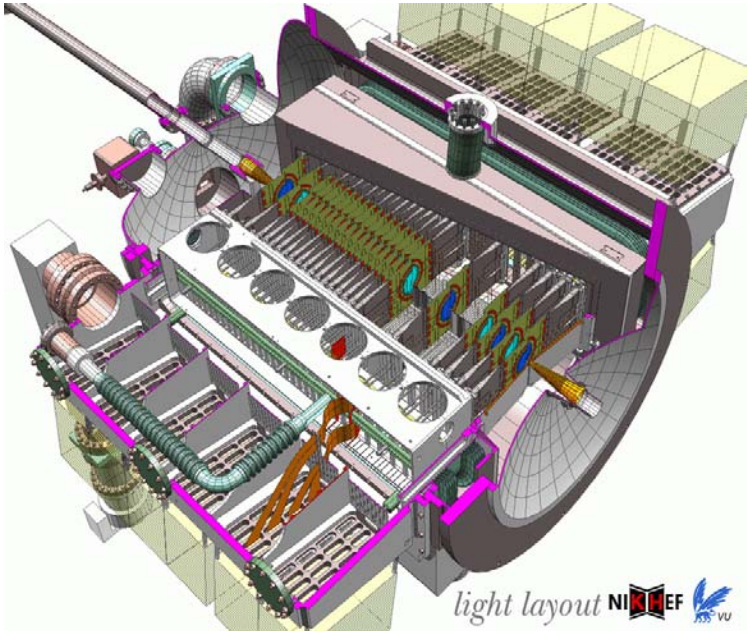
Silicon strip detector with ~ 30 μm impact-parameter resolution

Vertex detector

- 21 stations w/ double sided silicon sensors
- micro-strip sensors with $r\phi$ geometry,
- approach to 8 mm from beam
  (inside complex secondary vacuum system)

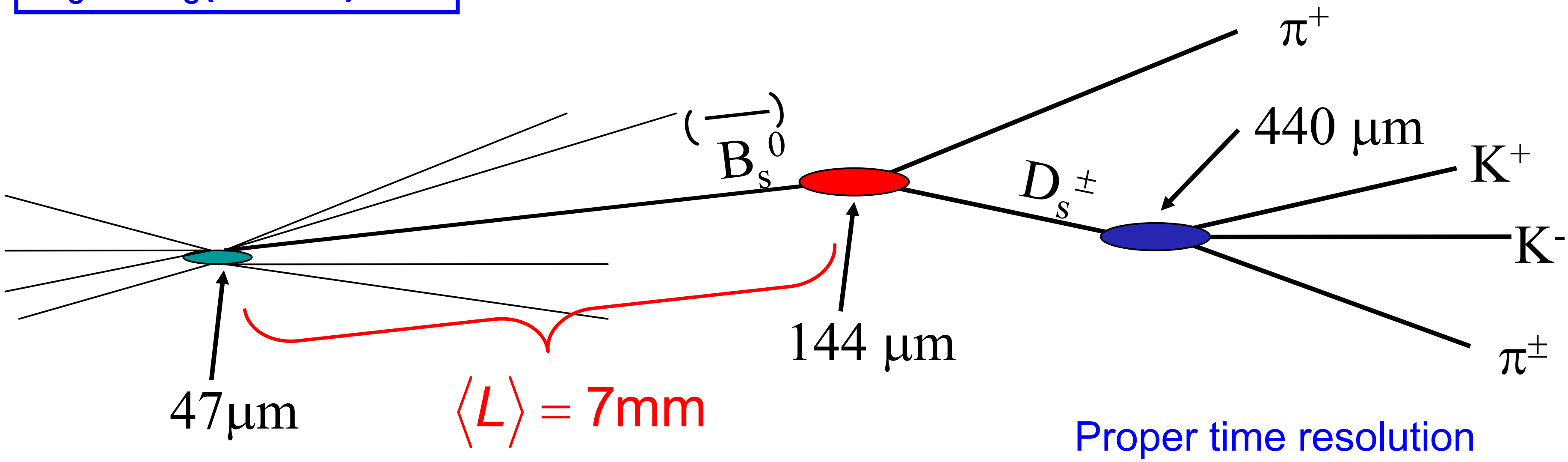






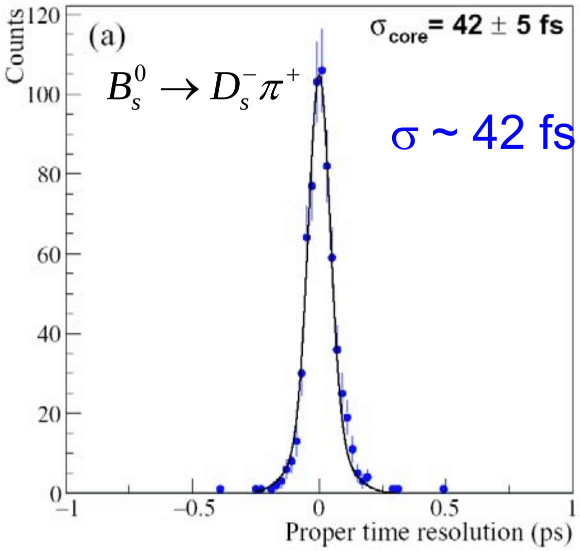
Vertex Reconstruction

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



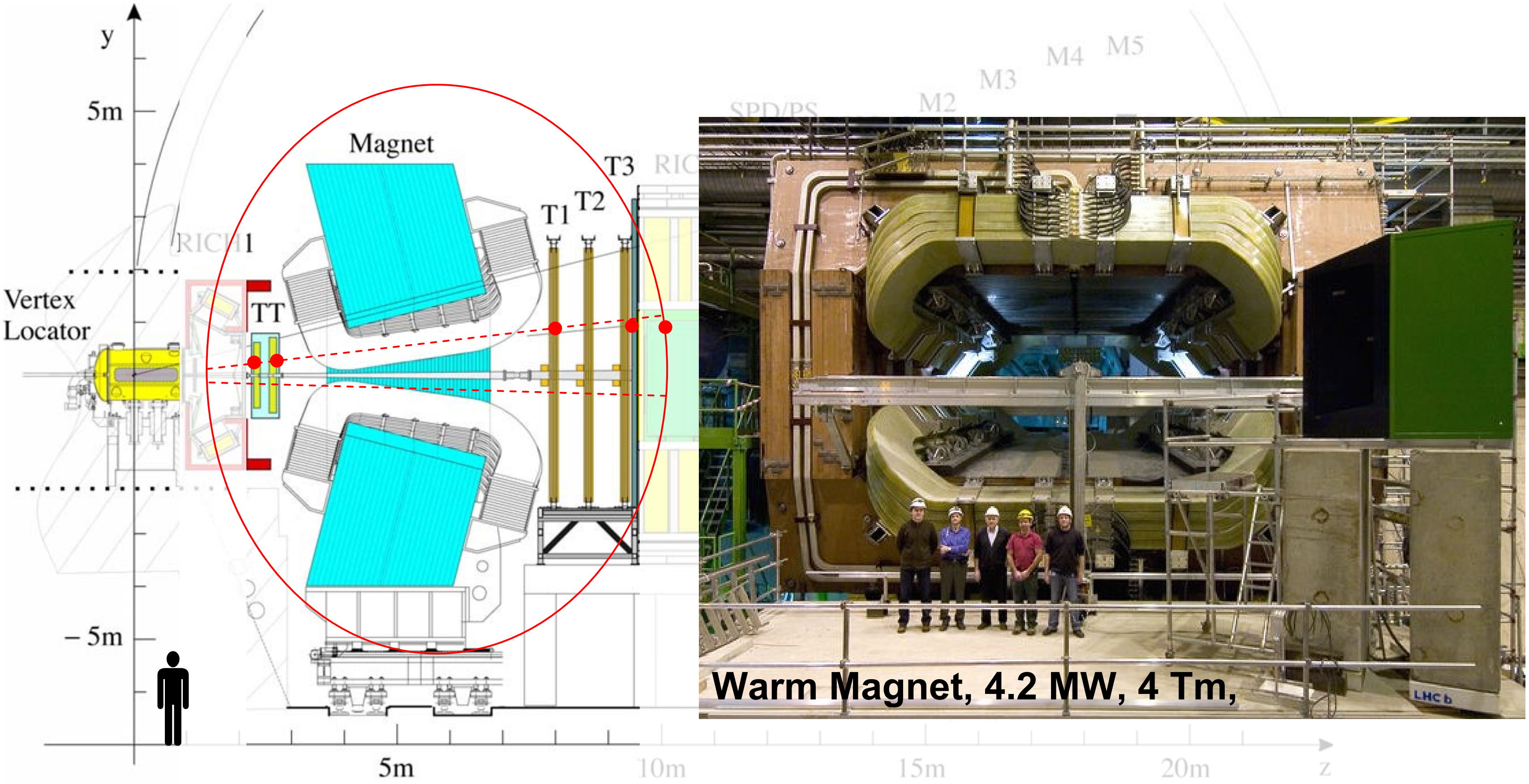
$$L = c\beta\gamma \boxed{t}$$

Proper time resolution



Life time information is used in the trigger !

LHCb detector

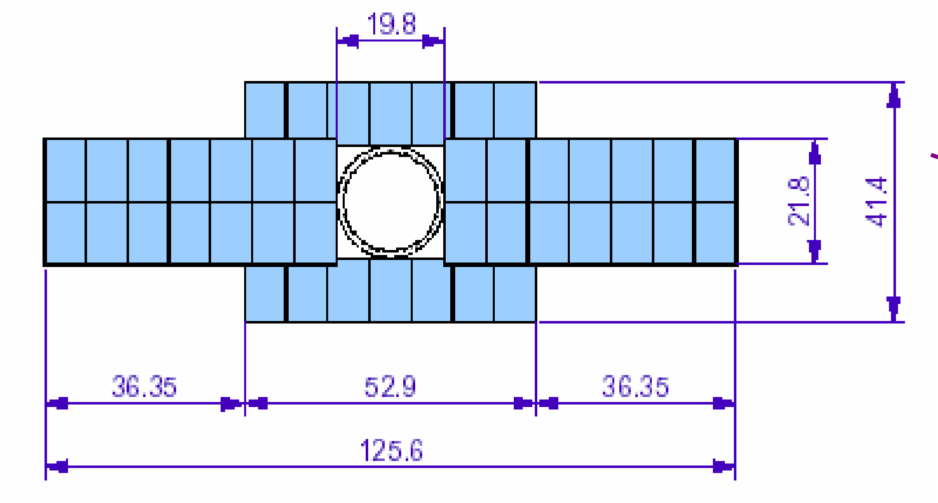


Tracking system and dipole magnet to measure angles and momenta

$\Delta p/p \sim 0.4$ %, mass resolution ~ 14 MeV (for $B_s \to D_s K$)

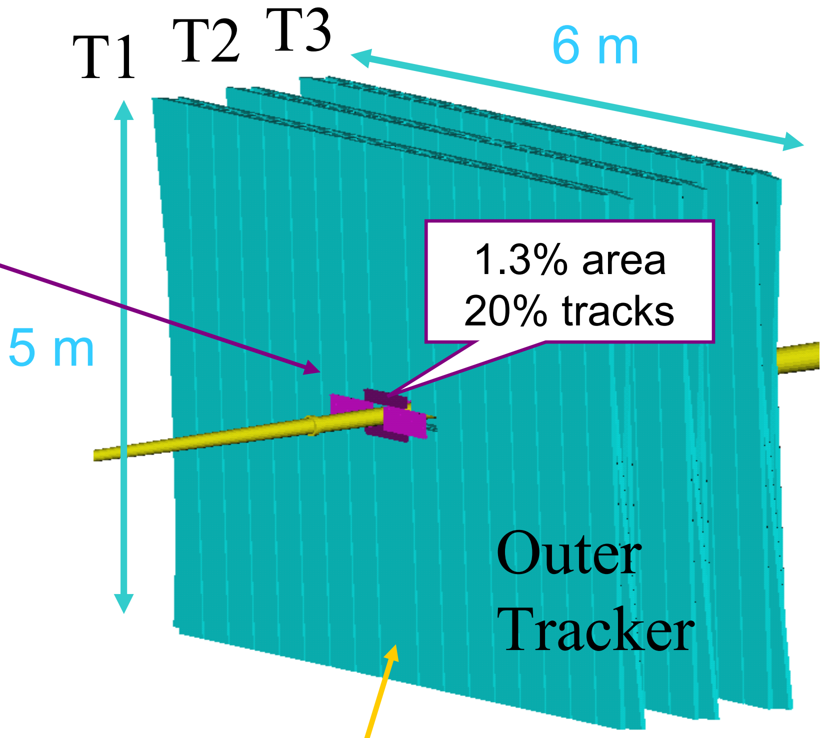
Main Tracking Stations

Inner Tracker: Silicon sensors

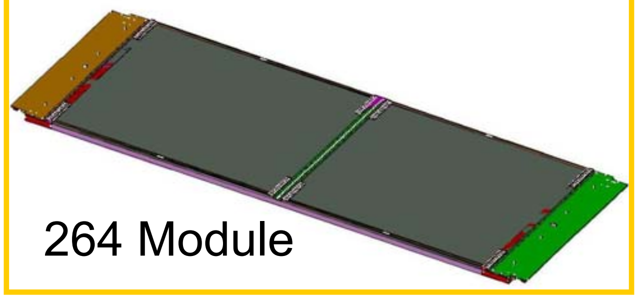


Cross to optimize occupancy for OT

	OT occupancy
average	4.3 %
top	5.4 %
corner	6.6 %
side	6.3 %



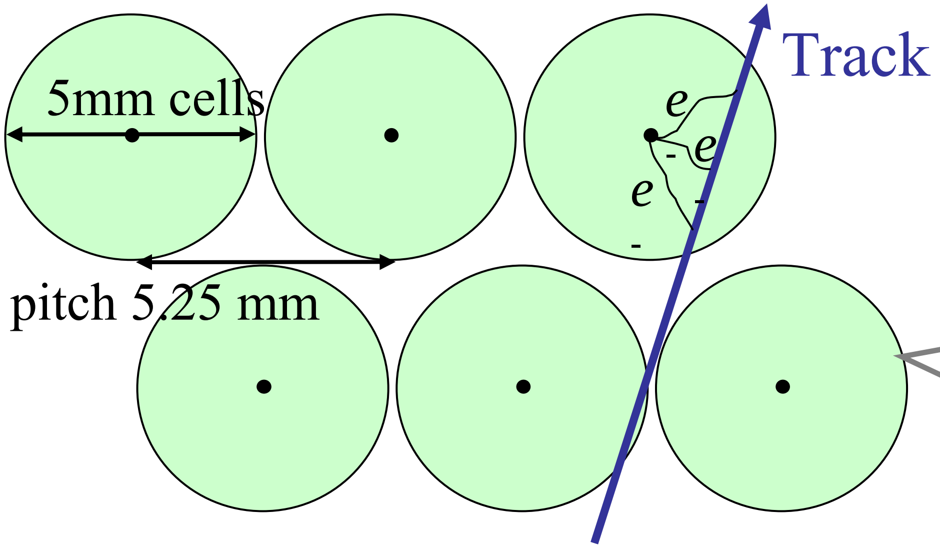
1.3% area
20% tracks

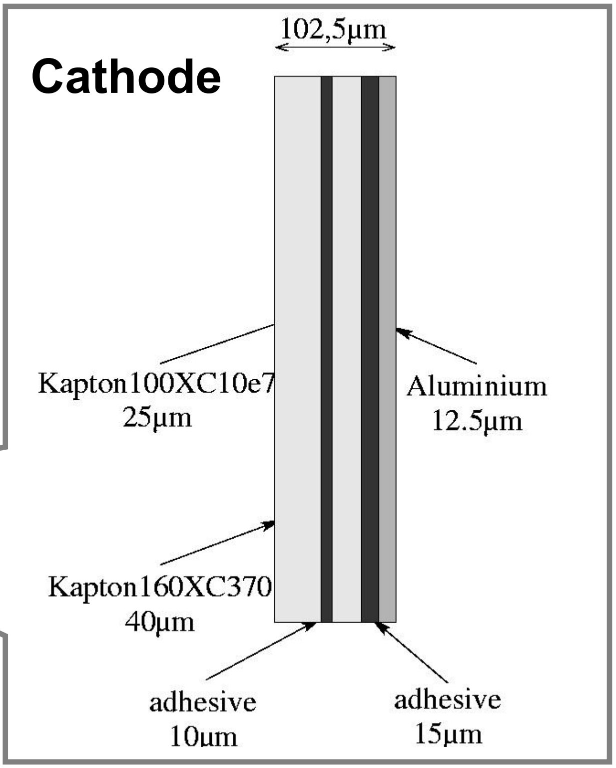


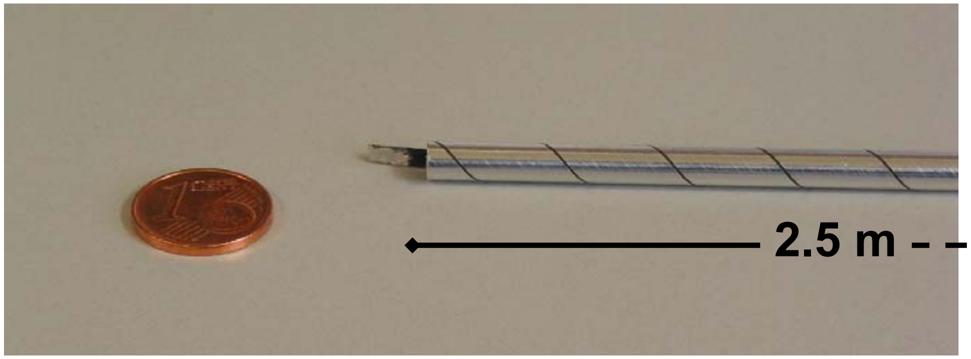
264 Module

Outer Tracker

Straw tube drift chamber modules





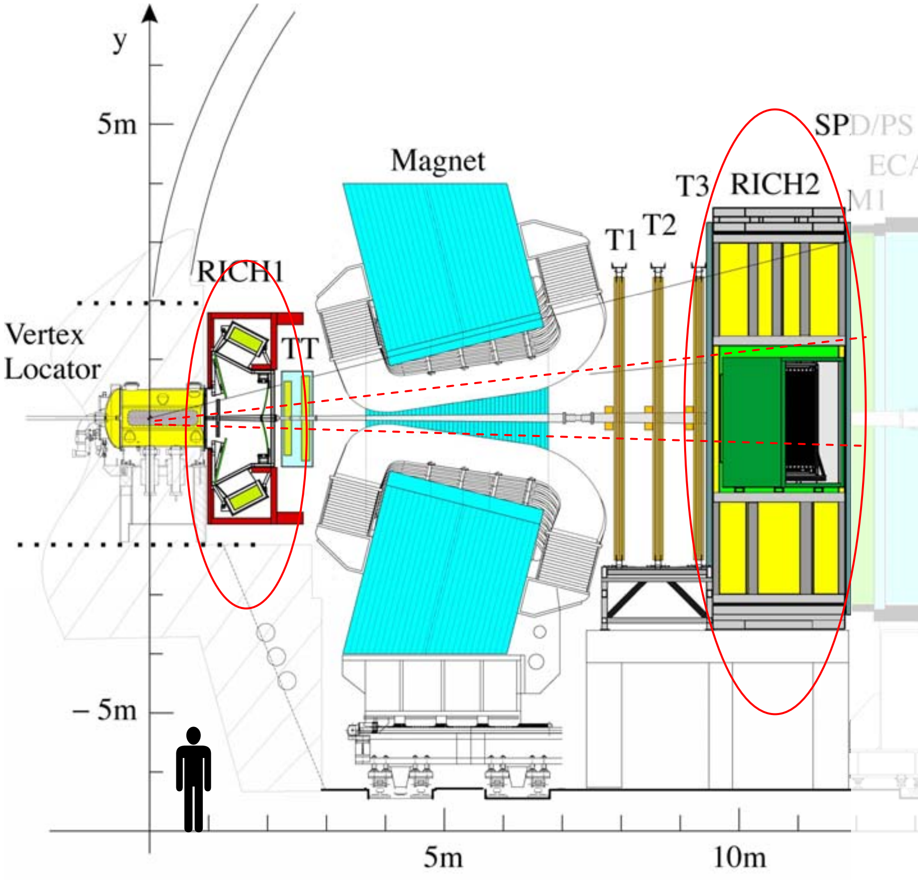


Straw tube winding:

Lamina Dielectrics Ltd.

Outer Tracker

LHCb detector



Two **RICH** detectors for charged hadron identification

RICH = Ring Imaging CHerenkov Detector

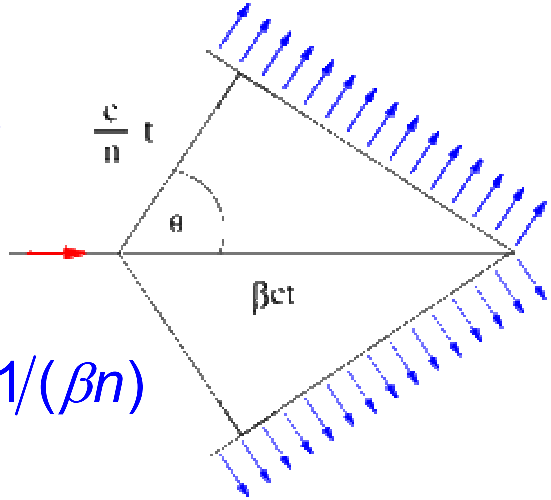
RICH detectors are the specialized detectors to allow charged hadron (π, K, p) identification.

Important for B physics, as there are many hadronic decay modes e.g.: $B_s \to D_s^- K^+ \to (K^+ K^- \pi^-) K^+$

Since ~7× more π than K are produced in pp events, making the mass combinations would give rise to large ***combinatorial background*** unless K and π tracks can be separated

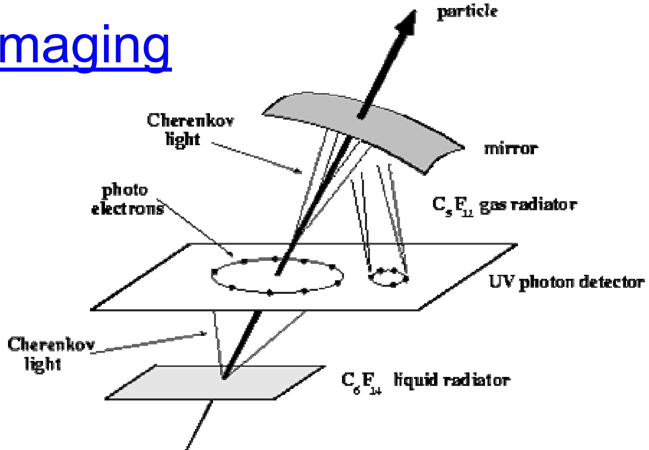
Cherenkov Radiation

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



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

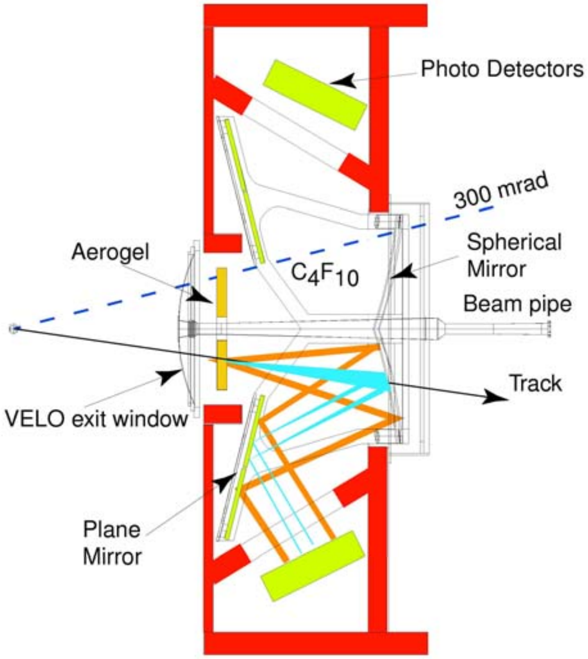
Ring Imaging

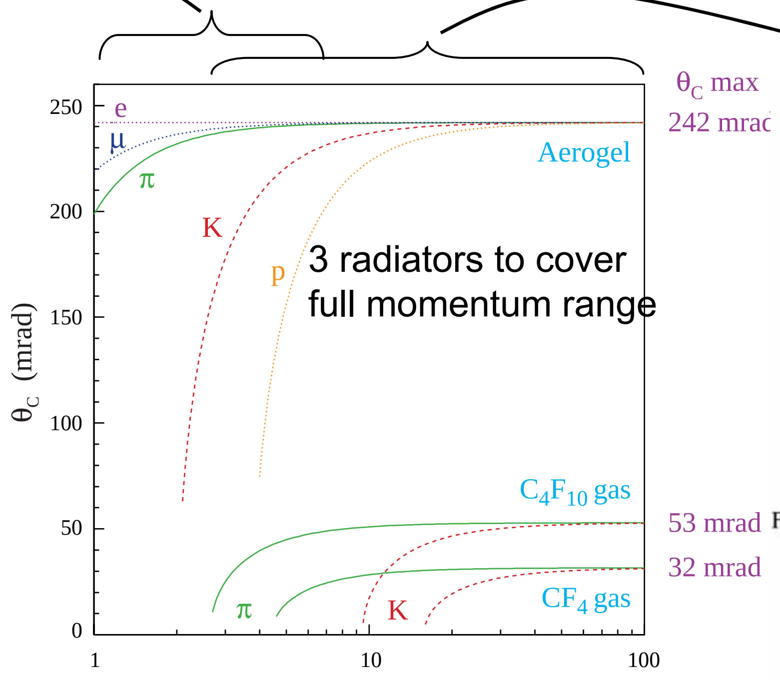


Ring radius $\to \theta_c \to \beta$

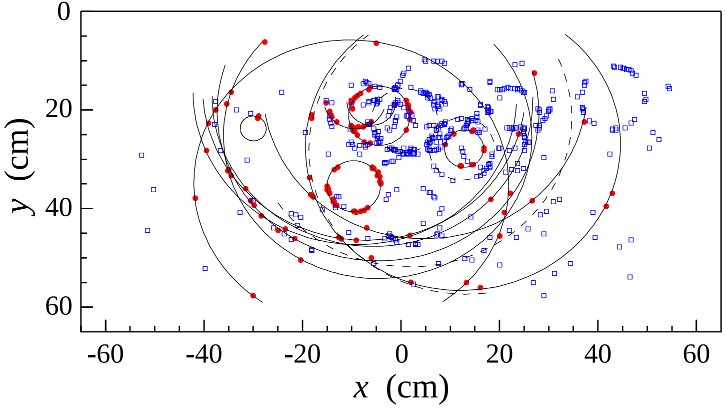
Particle Identification

RICH 1

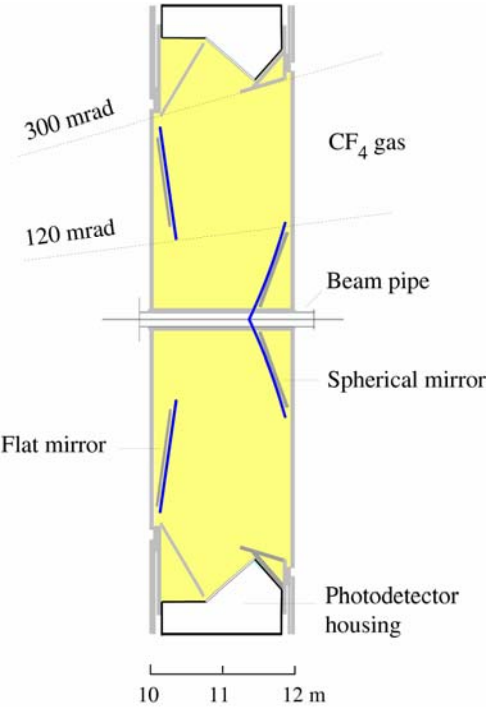




3 radiators to cover full momentum range



RICH 2



Radiator:

Aerogel **n=1.03**

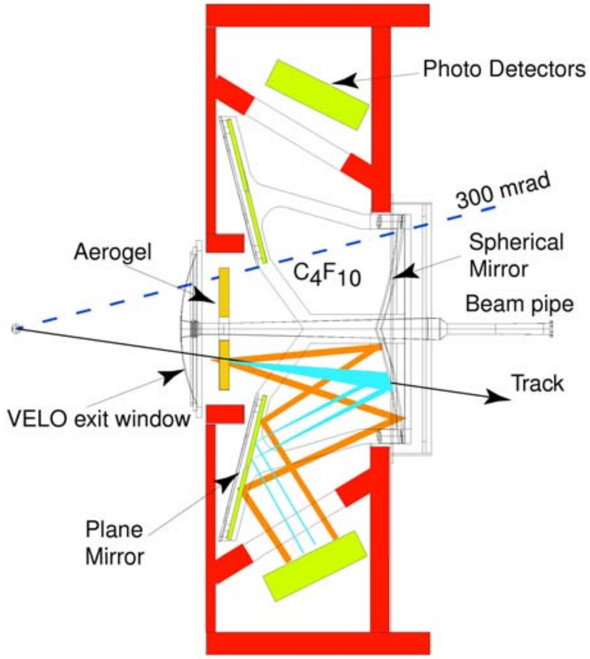
C_4F_{10} **n=1.0014**

Radiator: CF_4

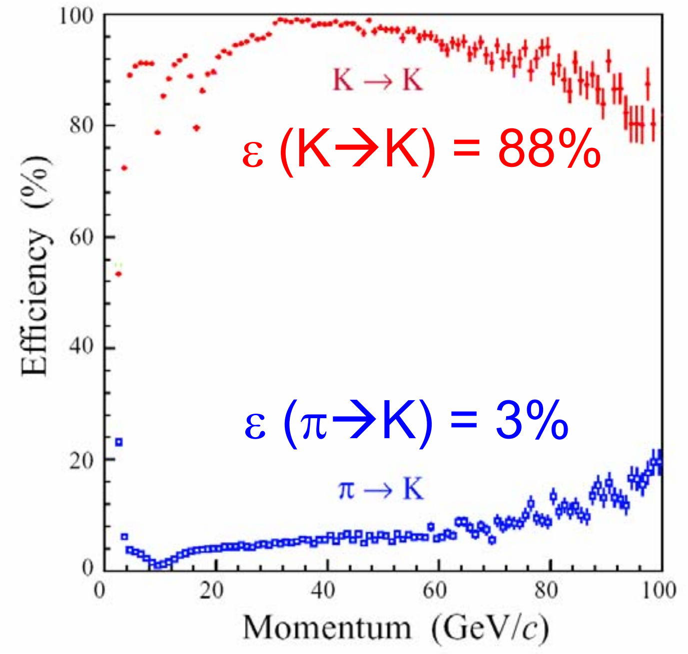
n=1.0005

Particle Identification

RICH 1



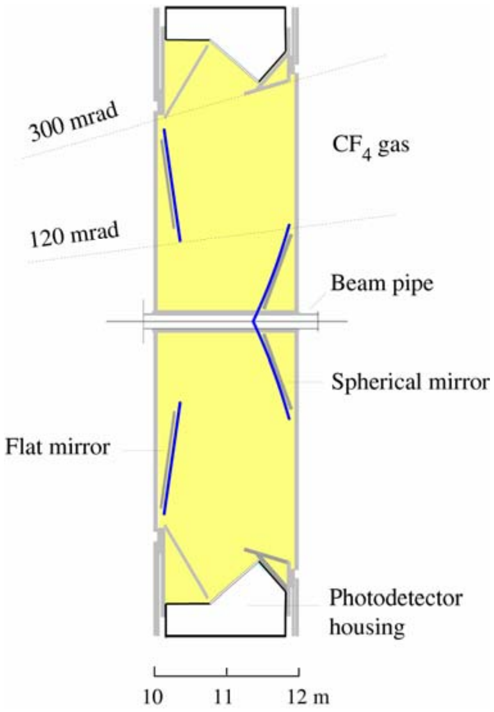
Radiator:
Aerogel n=1.03
C_4F_{10} n=1.0014



ε (K→K) = 88%

ε (π→K) = 3%

RICH 2



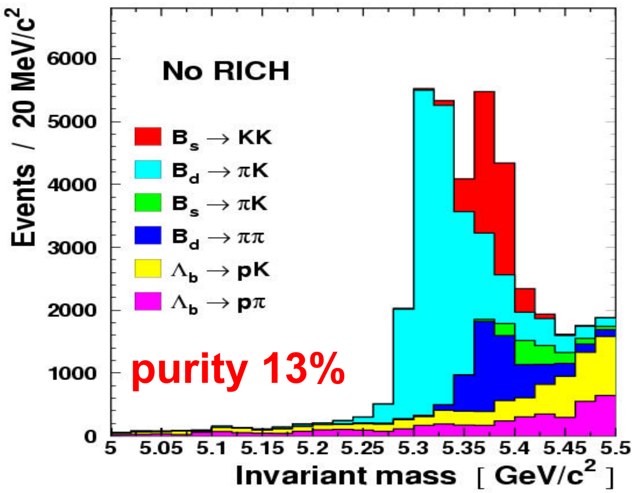
Radiator: CF_4
n=1.0005

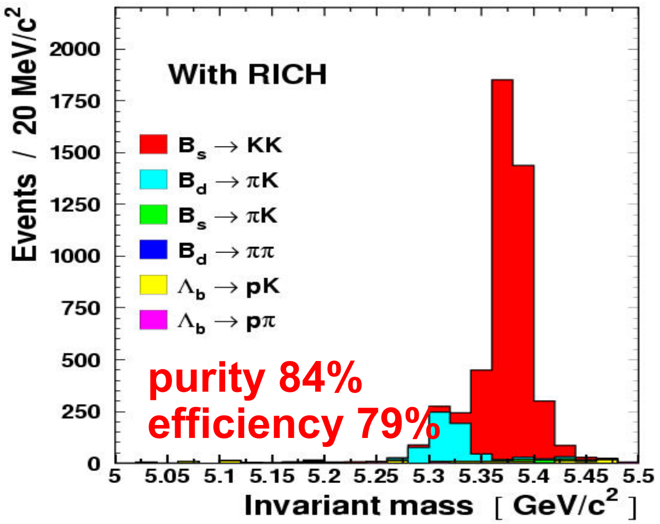
Background suppression with PID

No RICH

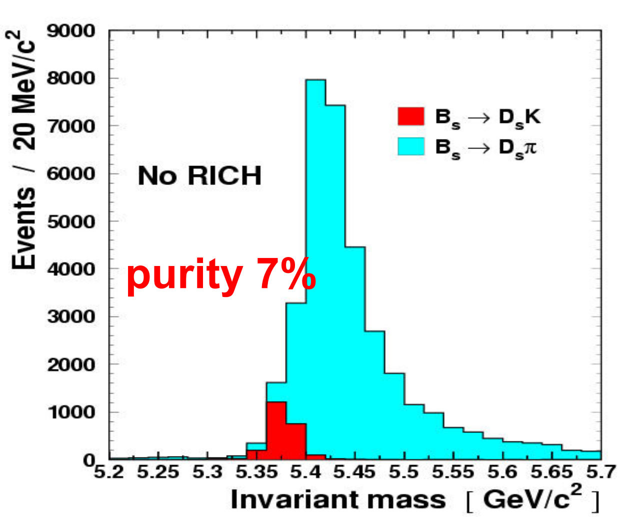
With RICH

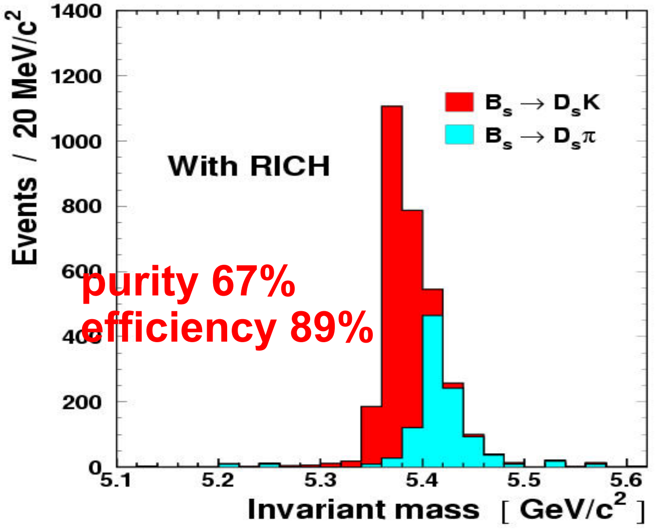
$B_s \rightarrow KK$



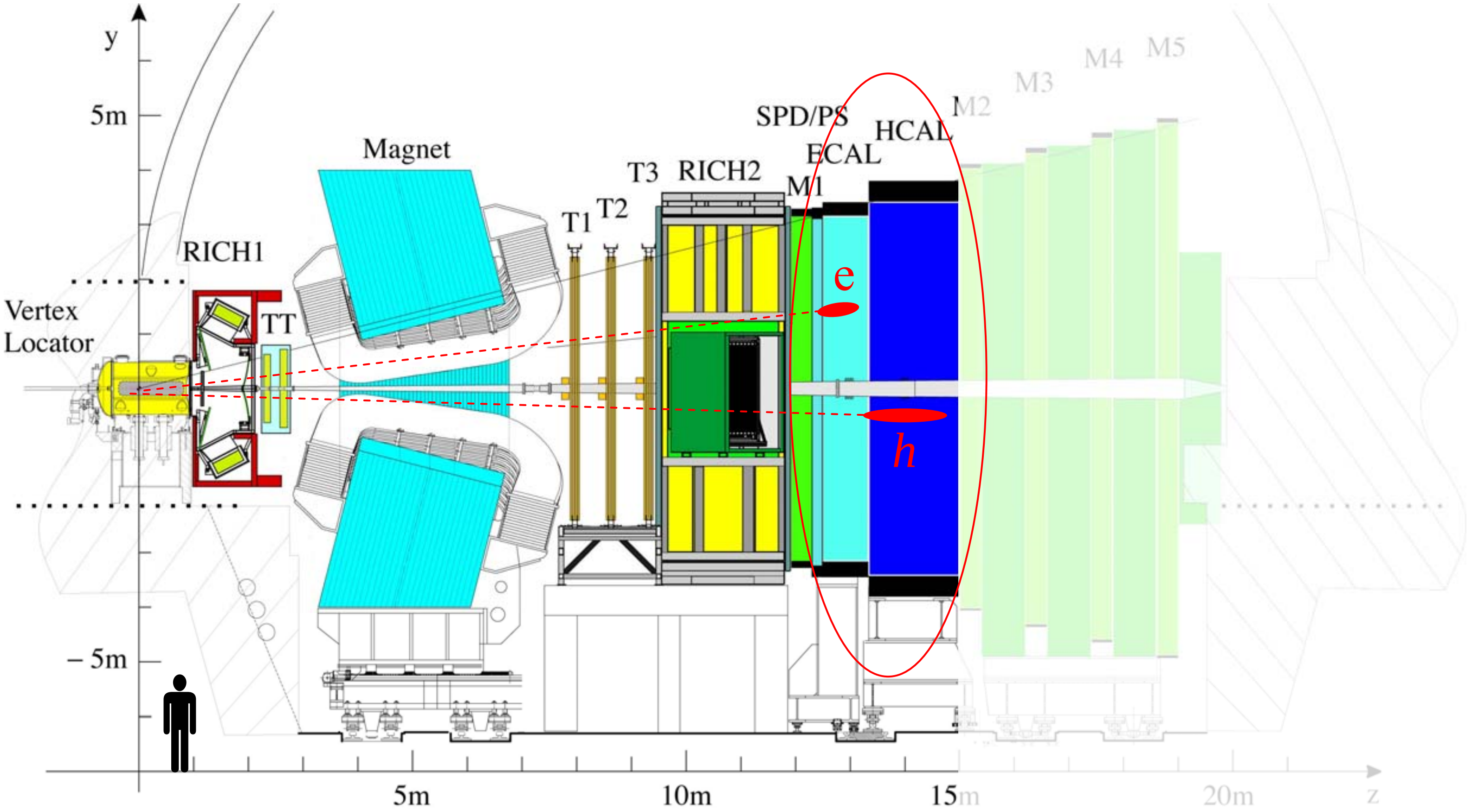


$B_s \rightarrow D_s K$





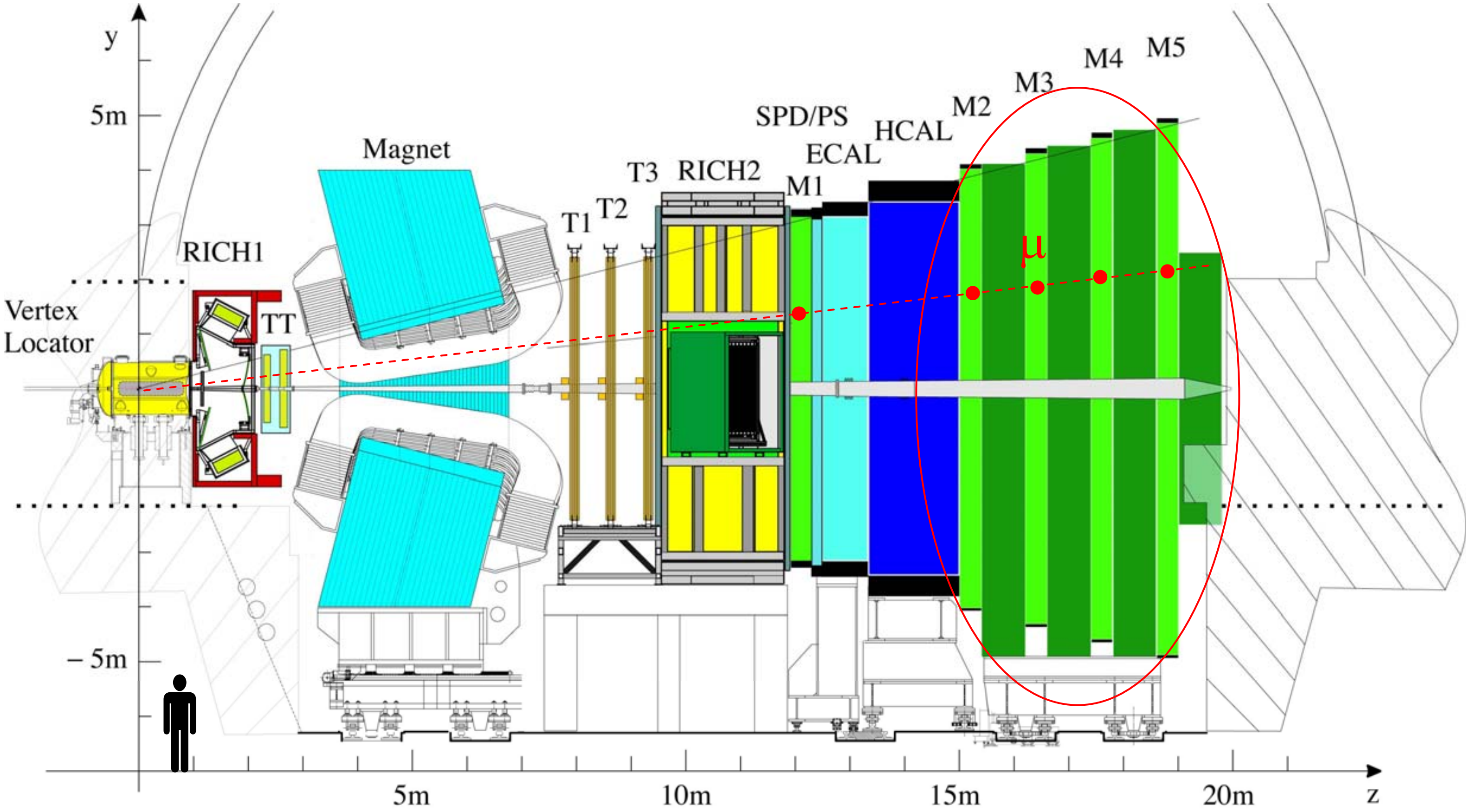
LHCb detector



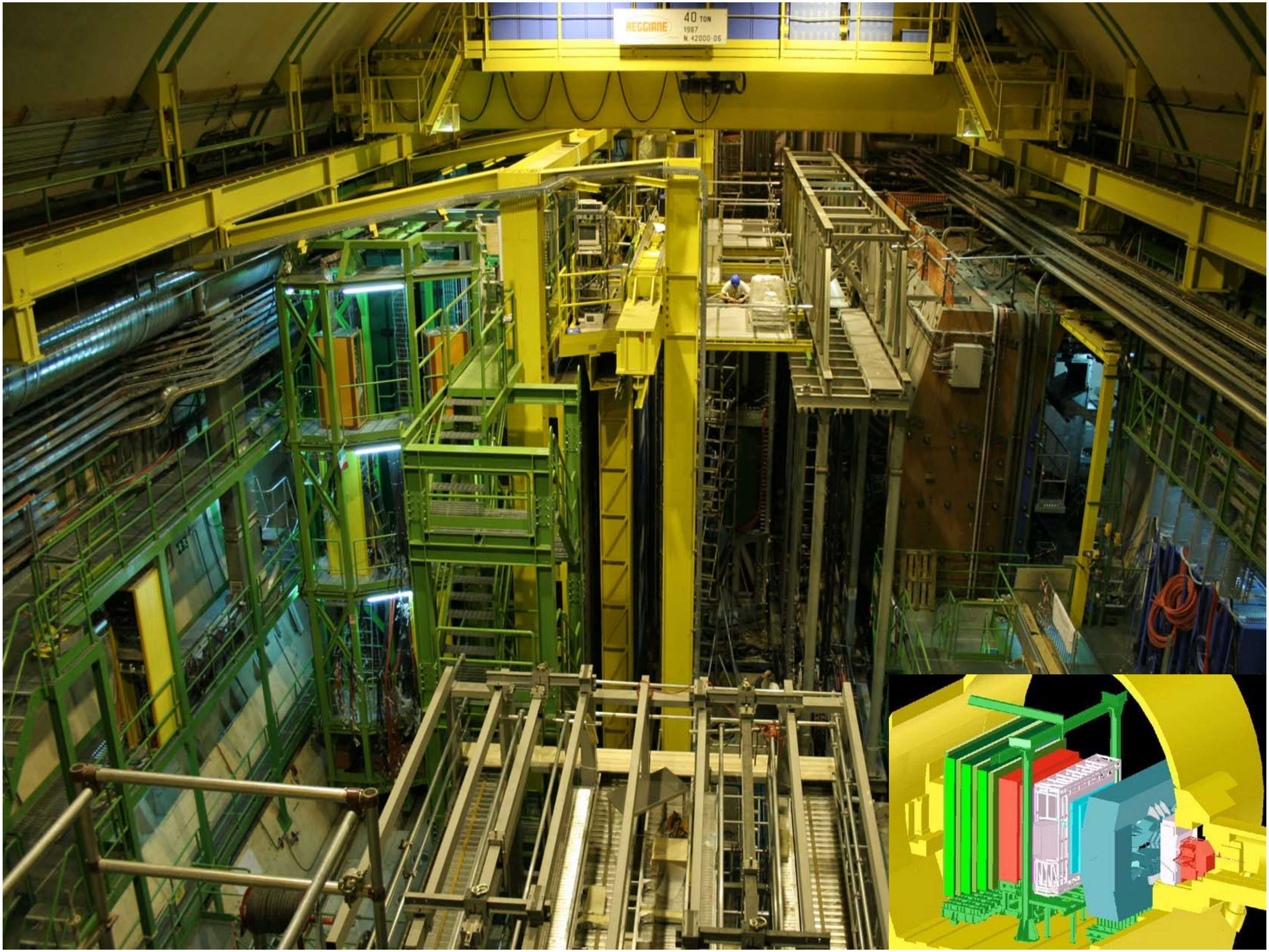
Calorimeter system to identify electrons, hadrons and neutrals

Important for the first level (Level 0) of the trigger.

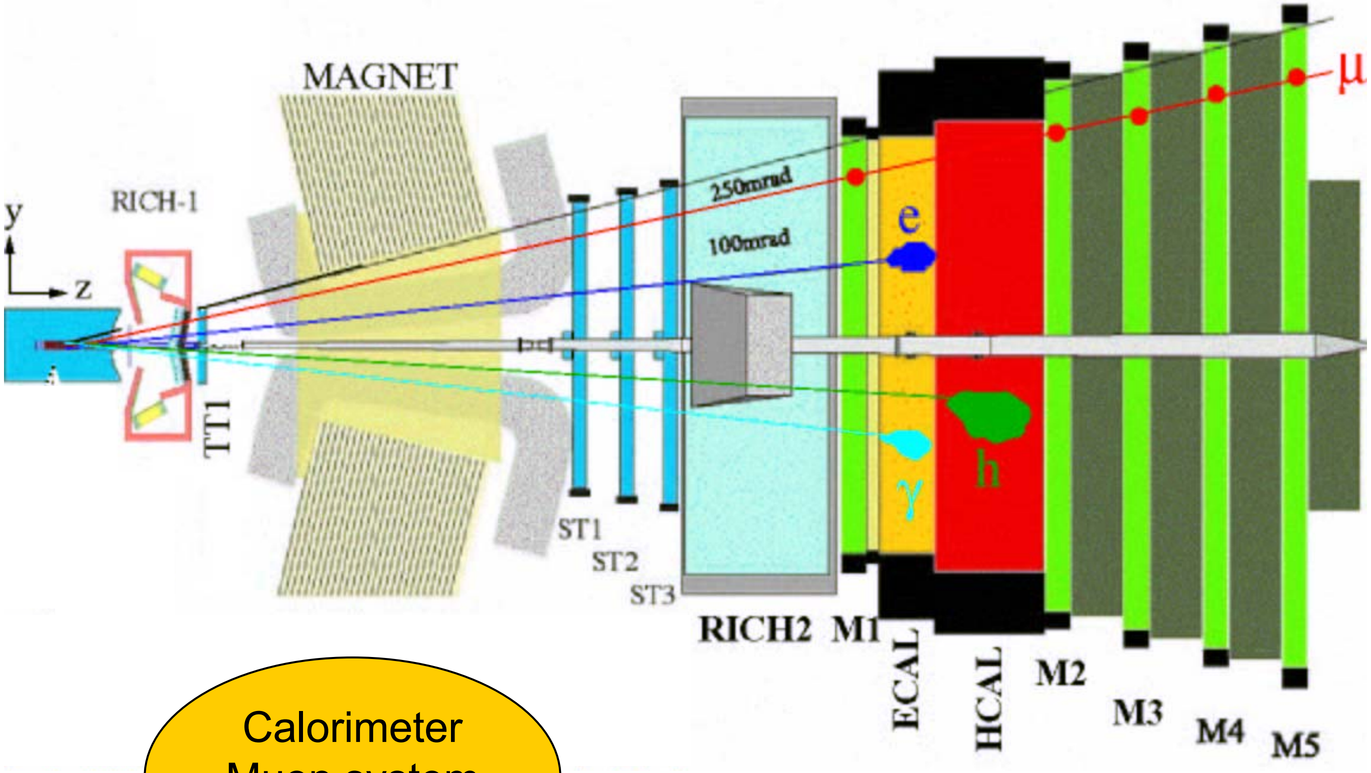
LHCb detector



Muon system to identify muons, also used in first level (L0) of the trigger


REGGIANE
40 TON
1987
N 42000-06

Trigger Level-0



Calorimeter
Muon system
Pile-up system

40 MHz

<u>Level-0 Hardware</u>: (4μs)
High p_T μ, e, h, γ signatures
1.1, 2.8, 3.6, 2.6 GeV

1 MHz

<u>PC Farm:</u>

Higher Level Trigger
(full event info)

Higher Level Trigger

1 MHz

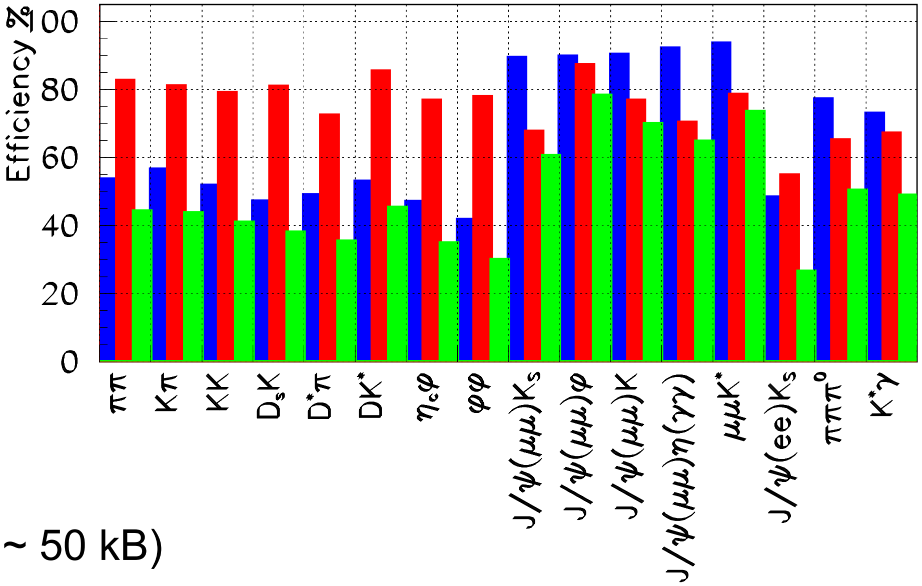
Higher Level Trigger (Software)

Stepwise event reconstruction:

- Confirmation of trigger signature using tracking chambers
- Secondary vertex reconstruction
- Full event reconstruction

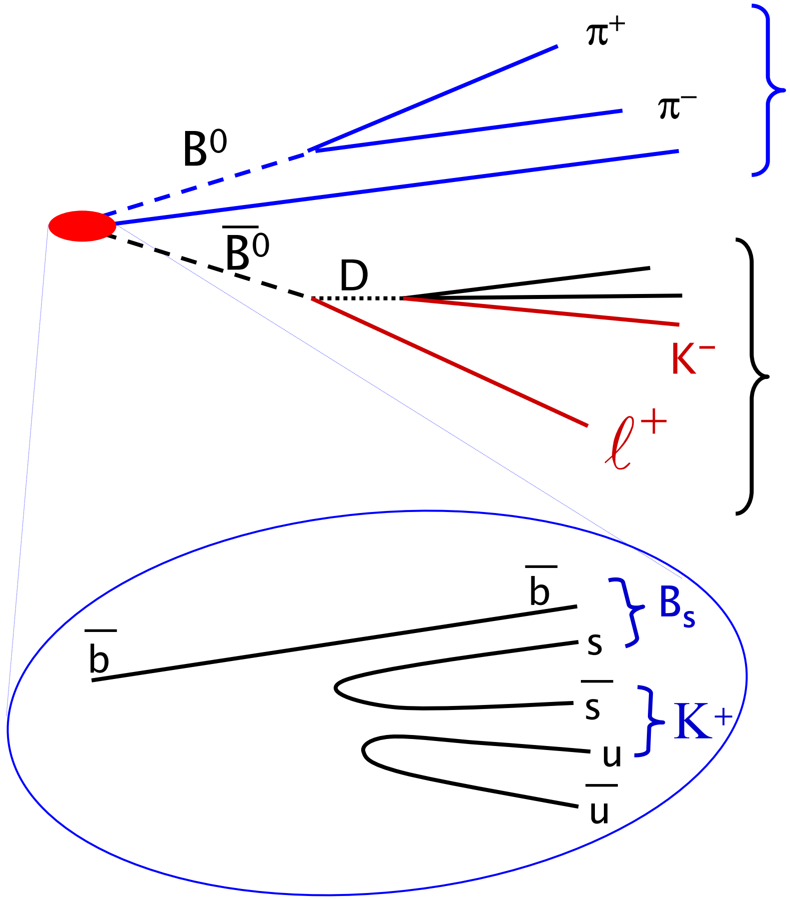
2 KHz Storage (event size ~ 50 kB)

L0, HLT and L0×HLT efficiency



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

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

Mistag rate ↓

Tag	ε_{Tag} (%)	w (%)	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**
Combined B^0 (decay dependent:			**~4**
Combined B_s trigger + select.)			**~6**

Dilution D=(1-2w)

Effective Tagging Power

$\varepsilon_{eff}=\varepsilon_{Tag}D^2$

LHCb - Expected Physics Performance

- $\sin(2\beta)$ - the reference measurement
- B_s – mixing
  - Δm_s with $B_s^0 \to D_s\pi$
  - ϕ_s and $\Delta\Gamma_s$ with $B^0_s \to J/\psi\phi\ (\eta)$
- Measurement of γ
- Rare decays
  - $B_s^0 \to \mu^+\mu^-$
  - Exclusive $b \to s\ \mu^+\mu^-$

$\sin(2\beta)$ in $B^0 \rightarrow J/\psi K_s$

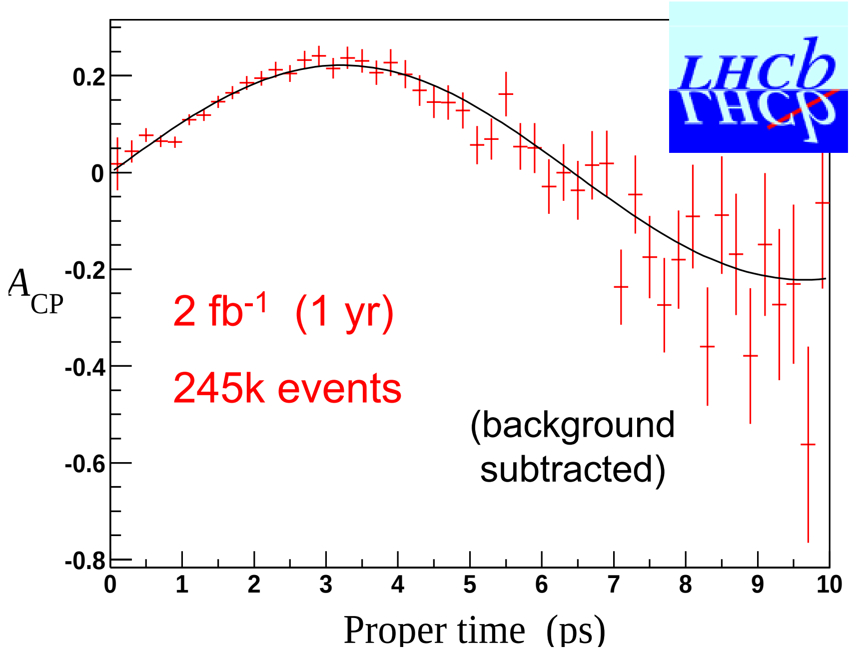
- $\sin(2\beta)$ will be measured very precisely at e^+e^- B factories.
  Expect. for 2008: $\sigma(\sin 2\beta) \sim 0.02$
- Not a primary goal for LHCb. Measurement will serve as reference:

$$A_{CP}(t) =$$

$$\frac{N(\overline{B}^0 \rightarrow J/\psi K_s)(t) - N(B^0 \rightarrow J/\psi K_s)(t)}{N(\overline{B}^0 \rightarrow J/\psi K_s)(t) + N(B^0 \rightarrow J/\psi K_s)(t)}$$

$$= \sin(\phi_d + \phi_{J/\psi K}) \sin(\Delta m t)$$

$$= \sin 2\beta \sin(\Delta m t)$$



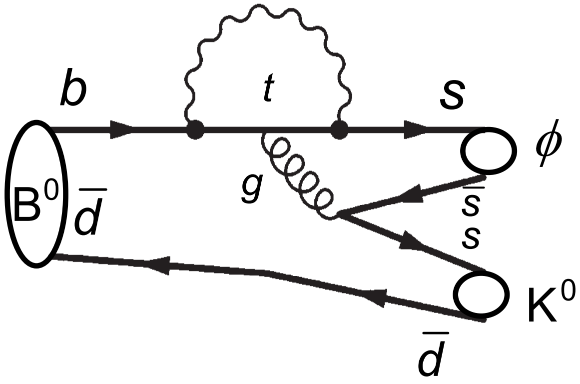
$\Rightarrow \sigma_{stat}(\sin 2\beta) \sim 0.02$

(for 2 fb^{-1}, 1 yr)

sin(2β) in Penguin Decays

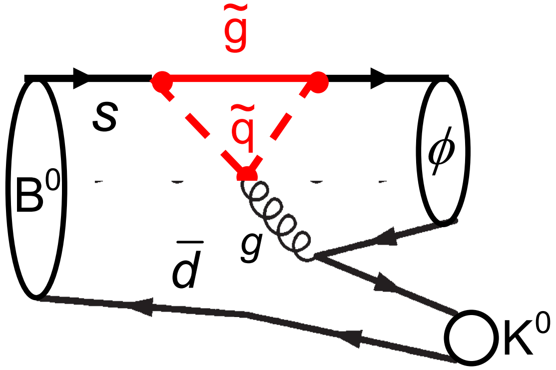
$$B^0(\overline{B}^0) \to \phi K^0$$

Standard Model



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

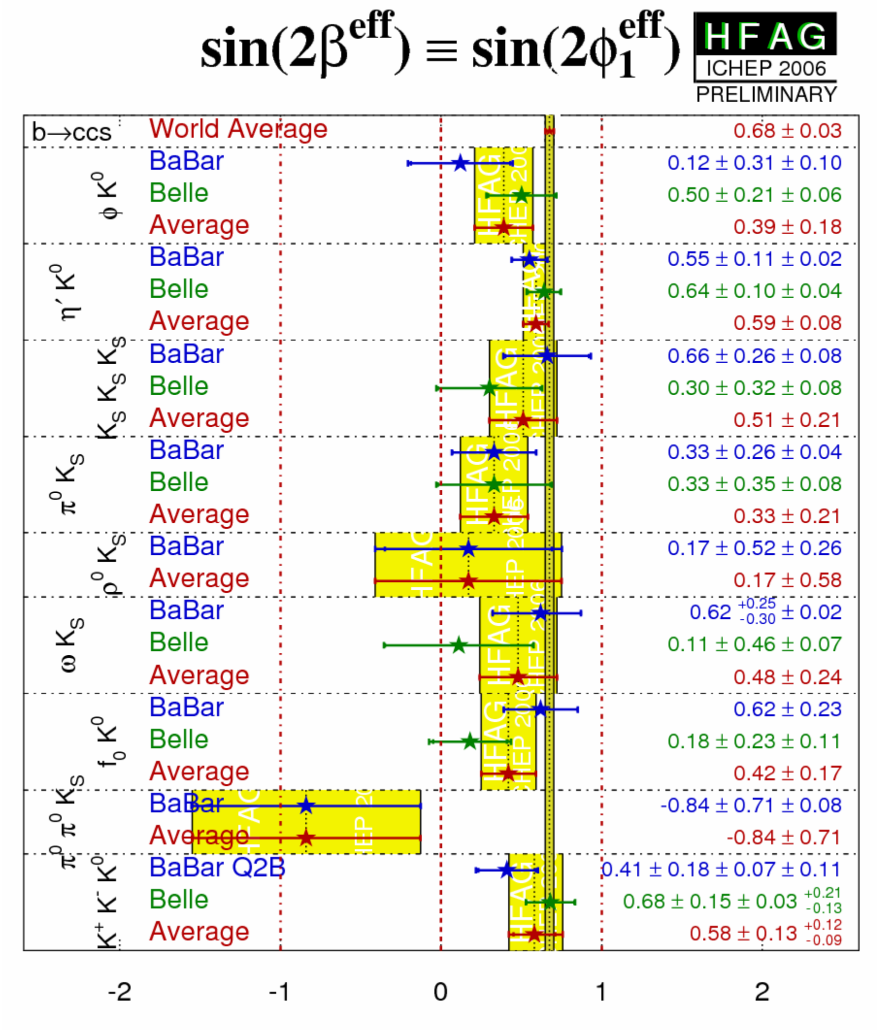
SUSY contributions



$$A_{CP}(t) = \sin 2\beta_{\text{eff}} \sin(\Delta m t)$$

$$= \sin 2\beta(J/\psi\, K_s) \neq \sin 2\beta_{\text{eff}}$$

LHCb Measurement of Penguin Decays



Experimental status (2006)

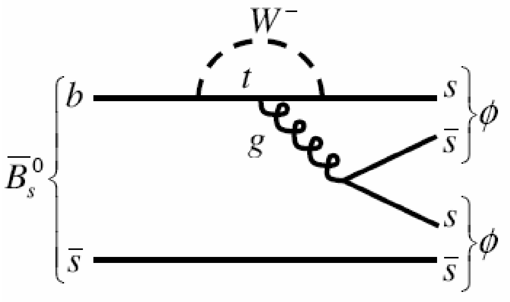
- sin(2β) in penguin decays always lower than sin(2β) in $B^0 \to J/\psi K_s$
- Statistics ? Need more data !

LHCb:

$\sigma_{stat}(\sin 2\beta) = 0.12\ldots0.18$

(10 fb^{-1}, 5 yr) ~4000 evts

Similar:



$A_{CP}(B_s \to \phi\phi)$:

$\sigma_{stat} \approx \pm 0.04$

Second triangle accessible at LHCb

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

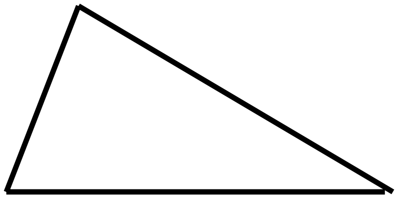
„bd“

$$\left.\begin{aligned} & V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0 \\ & A\lambda^3(\rho + i\eta) - A\lambda^3 + A\lambda^3(1-\rho-i\eta) = 0 \end{aligned}\right.$$

„tu“

$$\left.\begin{aligned} & V_{ud}^{*}V_{td} + V_{us}^{*}V_{ts} + V_{ub}^{*}V_{tb} = 0 \\ & A\lambda^3(1-\rho-i\eta) - A\lambda^3 + A\lambda^3(\rho + i\eta) = 0 \end{aligned}\right\}$$

$O(\lambda^3)$



Same triangle !

Different in O(λ^5)

„bd“

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

$$A\lambda^3(\rho+i\eta) - A\lambda^3 + A\lambda^3(1-\rho-i\eta) = 0$$

$$-\frac{1}{2}A\lambda^5(\rho+i\eta) \qquad +\frac{1}{2}A\lambda^5(\rho+i\eta)$$

$$+O(\lambda^7)$$

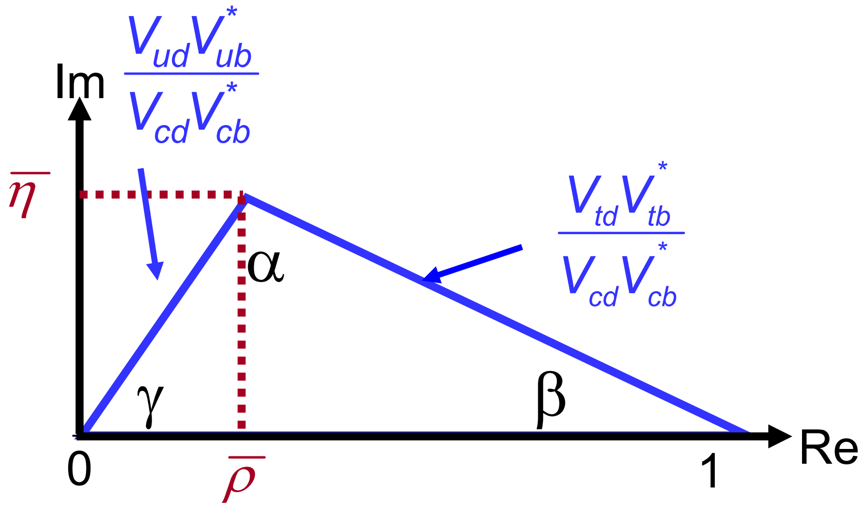
„tu“

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

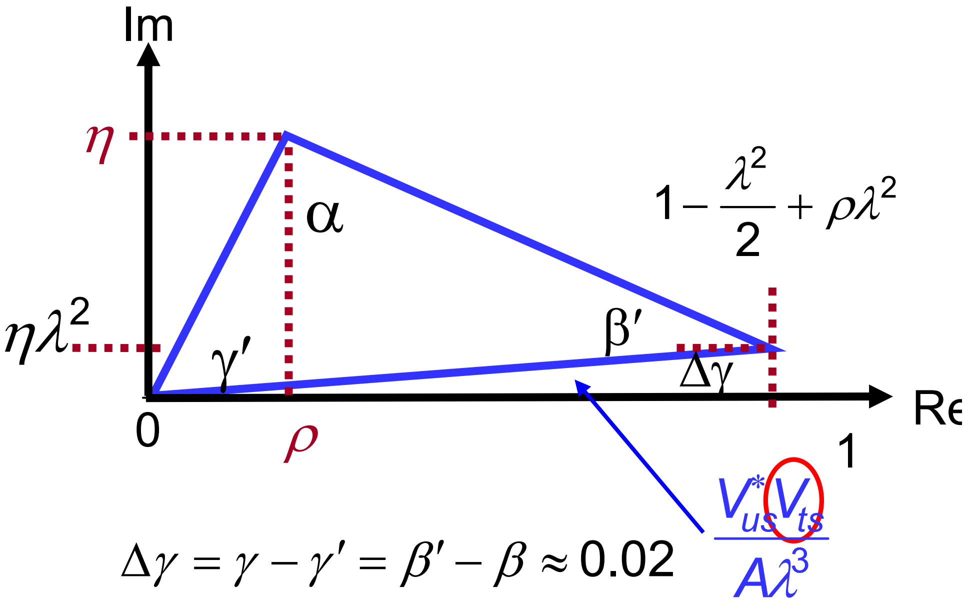
$$A\lambda^3(1-\rho-i\eta) - A\lambda^3 + A\lambda^3(\rho+i\eta) = 0$$

$$-A\lambda^5\left(\frac{1}{2}-(\rho+i\eta)\right) \qquad +A\lambda^5\left(\frac{1}{2}-(\rho+i\eta)\right)$$

$$+O(\lambda^7)$$



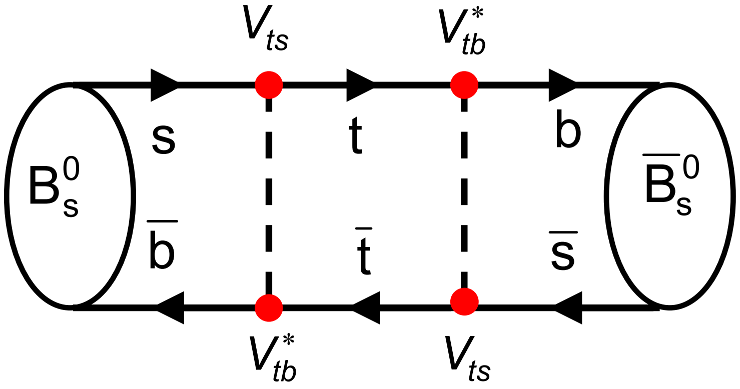
$$\bar{\eta} = \eta\cdot\left(1-\frac{\lambda^2}{2}\right) \qquad \bar{\rho} = \rho\cdot\left(1-\frac{\lambda^2}{2}\right)$$



$$\Delta\gamma = \gamma - \gamma' = \beta' - \beta \approx 0.02$$

Very small in SM

B_s Mixing



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

$$\Delta m = m_H - m_L$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L$$

$$\left|\frac{q}{p}\right| = 1 \quad \text{or} \quad \frac{q}{p} = e^{-i\phi_s}$$

(if CPV in mixing is ignored)

$$\mathbf{H} = \begin{pmatrix} m - \frac{i}{2}\Gamma & -e^{+i\phi_s}\frac{\Delta m - i\Delta\Gamma/2}{2} \\ -e^{-i\phi_s}\frac{\Delta m - i\Delta\Gamma/2}{2} & m - \frac{i}{2}\Gamma \end{pmatrix}$$

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

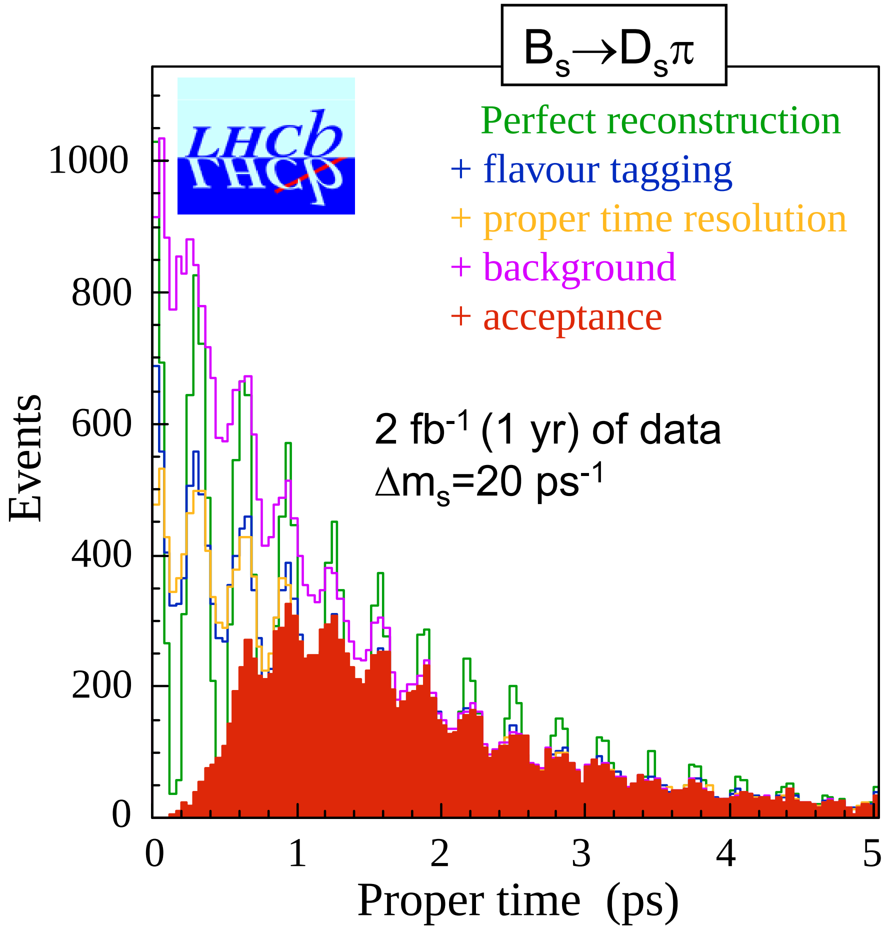
⬅ In SM small: 0.04

Measurement of B_s Mixing

B_s oscillates about 26 times until it decays: need excellent proper time resolution to resolve the mixing. LHCb: 44 fs

B_s mixing has been observed at Tevatro

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



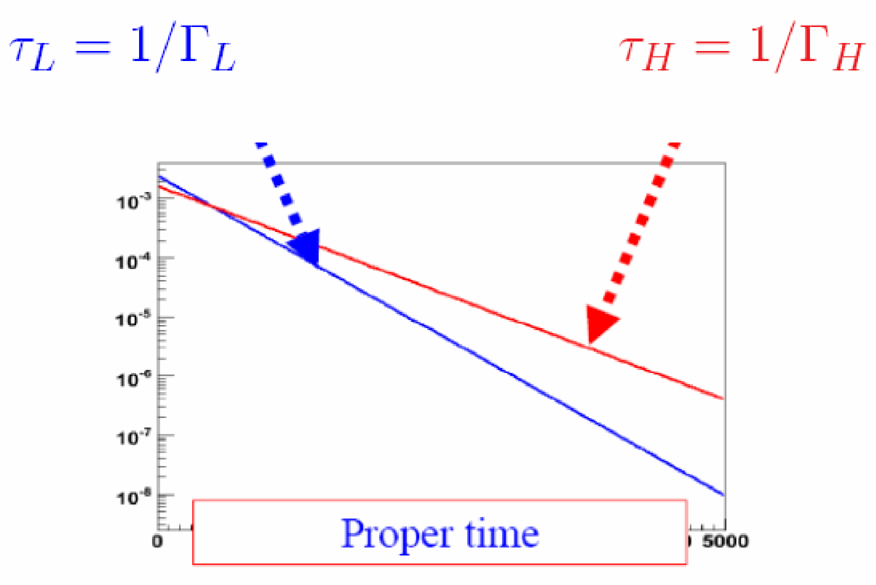
LHCb expects 80k $B_s \to D_s \pi$ events in 1 yr

5σ measurement w/ less than 1 month of good data possible !

$\Delta\Gamma_s$ and $B_s \to J/\psi\phi$

As ϕ_s is small in the SM (0.04):

Mass eigenstates are CP eigenstates



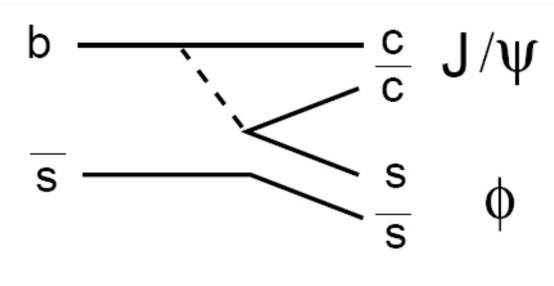
$$\mathrm{CP}(|B_H\rangle) = -|B_H\rangle \quad \text{(CP odd)}$$

$$\mathrm{CP}(|B_L\rangle) = +|B_L\rangle \quad \text{(CP even)}$$

$$\Gamma_H = \Gamma_{odd}$$

$$\Gamma_L = \Gamma_{even}$$

$$B_s(\overline{B}_s) \to J/\psi\phi$$



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

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

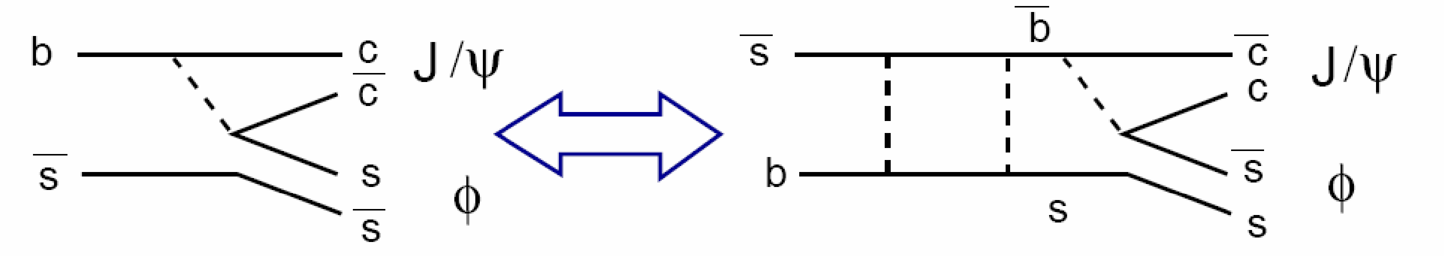
$$\mathrm{CP}(J/\psi\phi) = \mathrm{CP}(J/\psi)\mathrm{CP}(\phi)(-1)^L$$

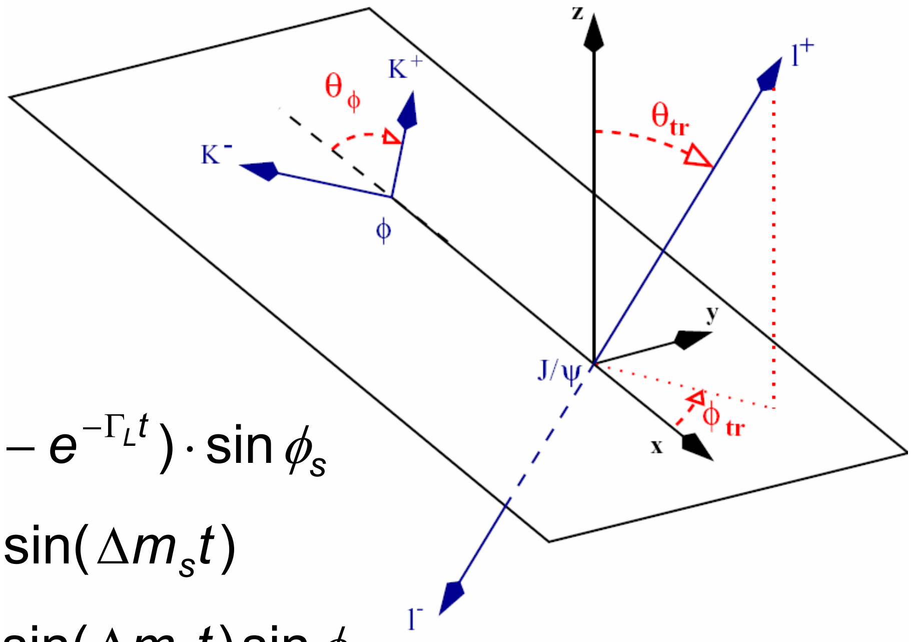
L=0,2 → CP even

L=1 → CP odd

Final state is mixture of CP even/odd.

Interference between Mixing and Decay





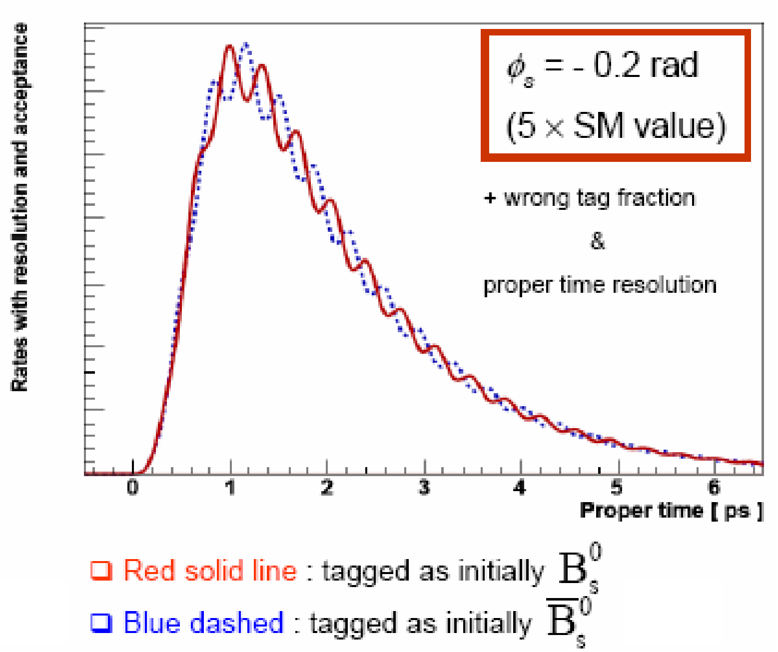
$$
\begin{aligned}
\Gamma(B_s/\overline{B}_s \to J/\psi\phi) = {} & f_1(\theta_{tr},\phi_{tr},\theta_\phi)\cdot e^{-\Gamma_L t} \\
& + f_2(\theta_{tr},\phi_{tr},\theta_\phi)\cdot e^{-\Gamma_H t} \\
& + f_3(\theta_{tr},\phi_{tr},\theta_\phi)\cdot(e^{-\Gamma_H t} - e^{-\Gamma_L t})\cdot \sin\phi_s \\
& \pm f_4(\theta_{tr},\phi_{tr},\theta_\phi)\cdot e^{-\Gamma_L t}\cdot \sin(\Delta m_s t) \\
& \pm f_5(\theta_{tr},\phi_{tr},\theta_\phi)\cdot e^{-\Gamma_L t}\cdot \sin(\Delta m_s t)\sin\phi_s
\end{aligned}
$$

Simultaneous determination of $\Delta\Gamma$ and ϕ_s

Measurement possible as tagged and untagged analysis!

Expected Constraints for ϕ_s

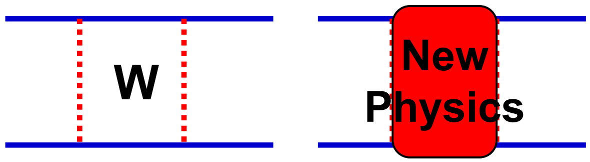
Expect 130k recon. $B_s \to J/\psi\phi$ events/yr
ε_{tot}=1.6%, B/S<0.1, σ_{ct}=37 fs, εD^2=5.5%



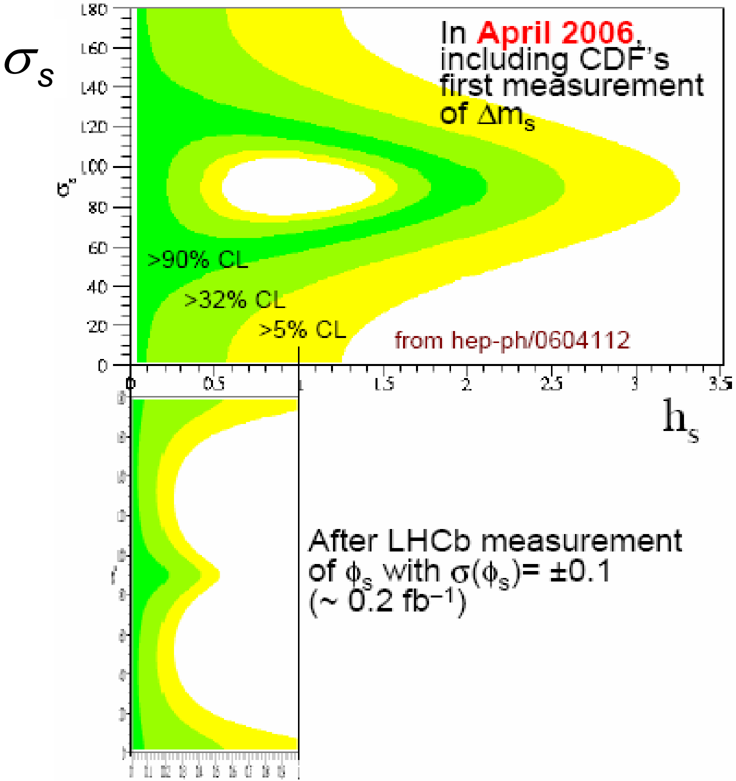
Expectation: $\sigma_{stat}(\sin\phi_s) = 0.02 - 0.06$

$\sigma_{stat}(\Delta\Gamma/\Gamma) = 2\%$

Constraints on new physics



$$\Delta m_s = (1+\boxed{h_s \exp(2i\sigma_s)})\,\Delta m_s^{SM}$$



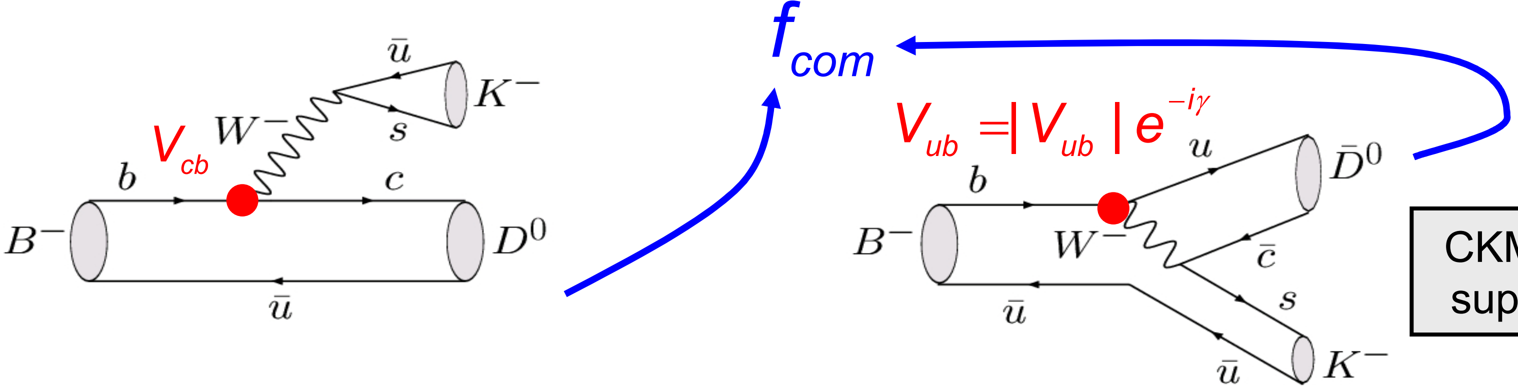
In **April 2006**, including CDF's first measurement of Δm_s

from hep-ph/0604112

After LHCb measurement of ϕ_s with $\sigma(\phi_s)$= ±0.1 (~ 0.2 fb^{-1})

Measurement of γ with $B \to DK$ decays

Gronau and Wyler



CKM +Color suppressed

Interference ⇒ direct CPV (i.e. in decay) ⇒ γ

In lowest order, there is no loop diagram !!

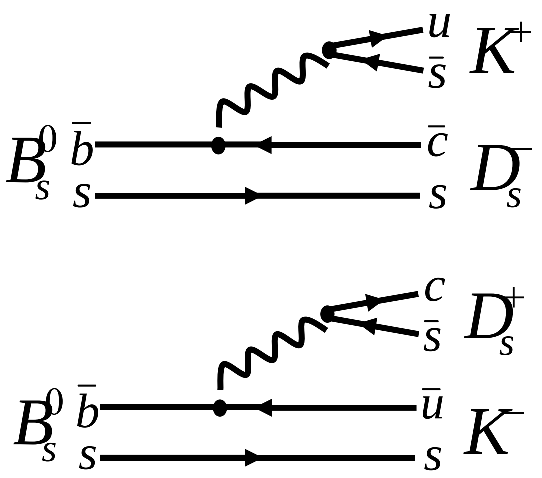
	LHCb (2fb^{-1})
ADS Method (Atwood,Dunietz,Soni) $B^\pm \to D^0 K^\pm$ w/ $D^0 \to [K^+\pi^-]$ & $D^0 \to [K^-\pi^+]$	$\sigma(\gamma) \approx 5^o$
Dalitz Method (Giri,Grossman,Soffer,Zupan) $B^\pm \to D^0 K^\pm$ w/ $D^0 \to [K^0_s \pi^+\pi^-]$	Studies ongoing: $\sigma(\gamma) \approx 8^o$?
Dunietz+GW Method (Gronau,Wyler,Dunietz) $B^0 \to D^0_{CP} K^{*0}$ w/ $D^0_{CP} \to K^+K^-$	$\sigma(\gamma) \approx 8^o$
	$\sigma(\gamma) \approx 5^o$

2007

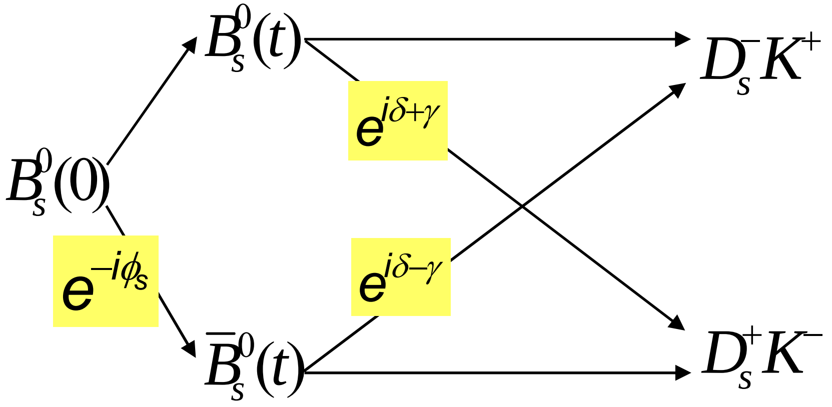
$\sigma(\gamma) \approx 20^o$

Measurements of γ with B_s decays

Feynman tree diagrams



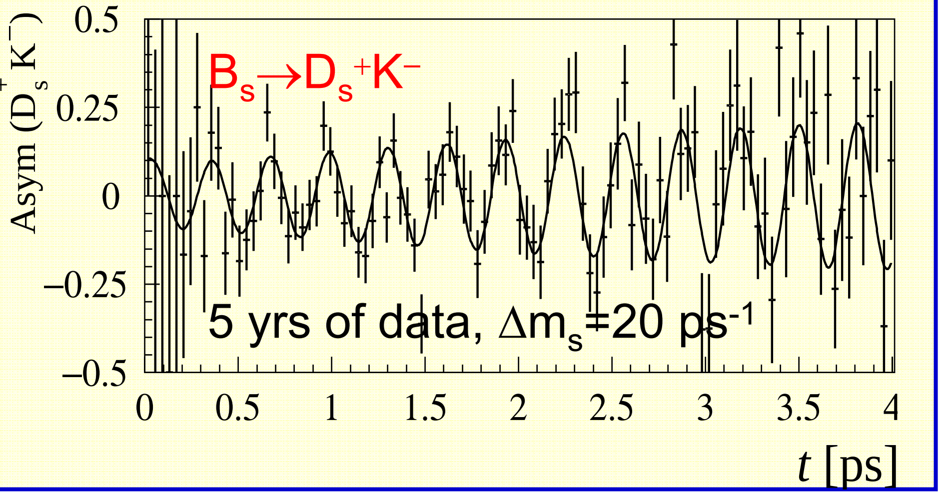
Interference between direct decay and decay after oscillation



Time dependent CP asymmetries in $B_s \to D_s K$

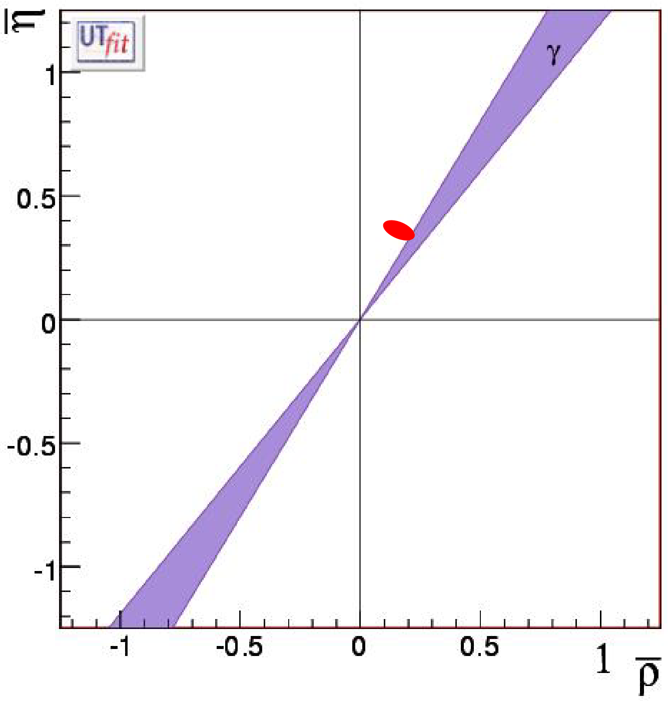
- Measure $\gamma + \phi_s$ from 4 time-dependent rates: $B_s \to D_s^- K^+$ and $B_s \to D_s^+ K^-$ (+ CP-conjugates) → strong phase difference δ
- Use ϕ_s from $B_s \to J/\psi\phi$

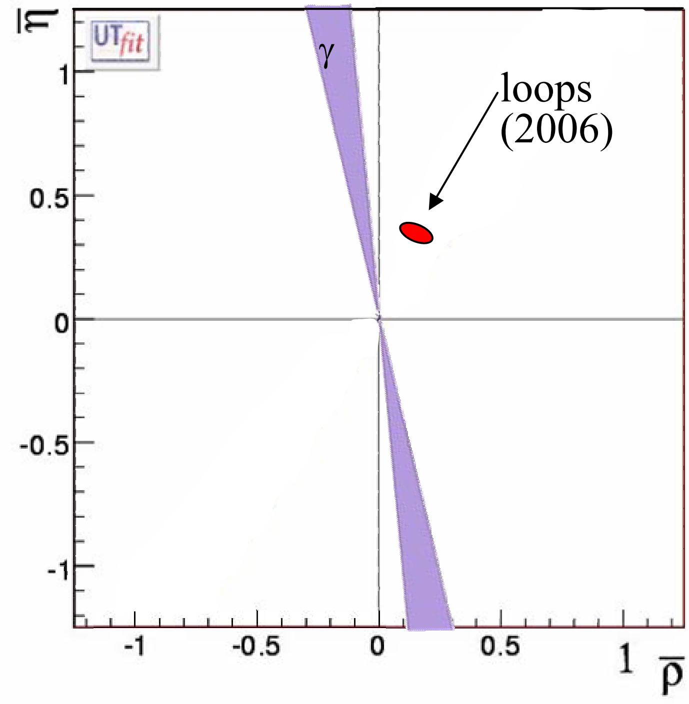
➡ $\sigma(\gamma) \sim 13^\circ$ (2fb^{-1} 1yr)



LHCb Measurement of CKM Angle γ

γ from $B \to DK$ at LHCb (10 fb^{-1})



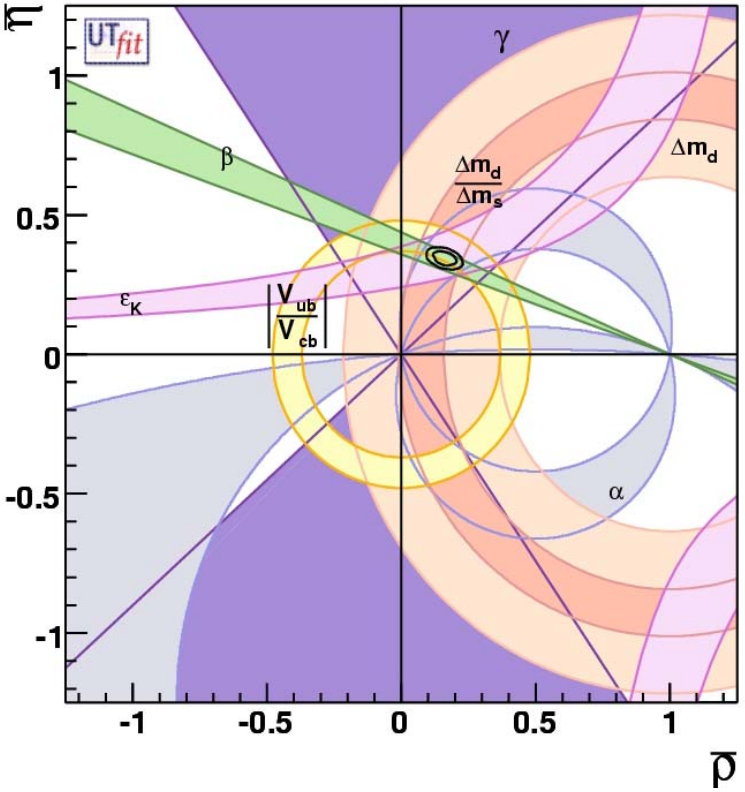


loops (2006)

Two possible scenarios

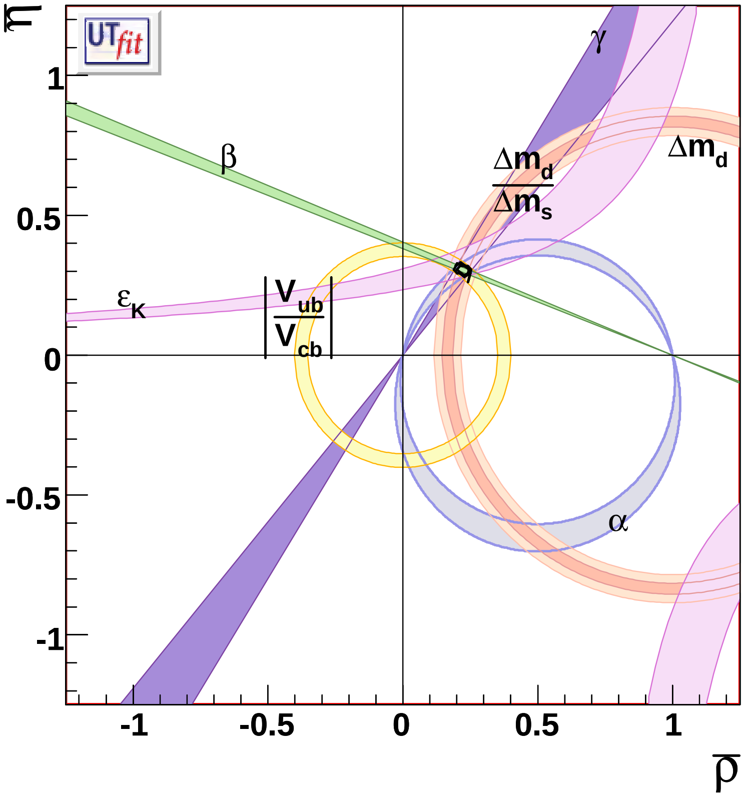
CKM Metrology and LHCb

Summer 2006



$$\sigma(\bar{\rho})/\bar{\rho} = 17\%$$
$$\sigma(\bar{\eta})/\bar{\eta} = 4.7\%$$

LHCb at L=10fb^{-1}



$$\sigma(\bar{\rho})/\bar{\rho} = 3.5\%$$
$$\sigma(\bar{\eta})/\bar{\eta} = 1.7\%$$

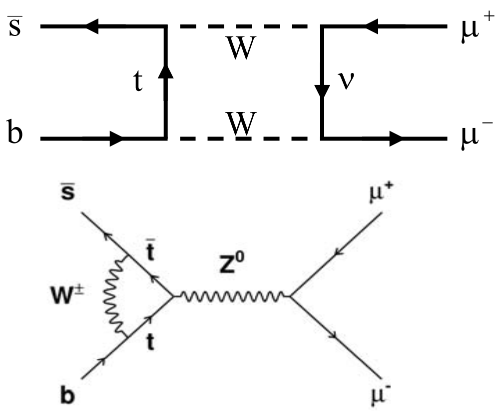
Rare B Decays $B_{s,d}\to\mu\mu$

SM Branching ratio:

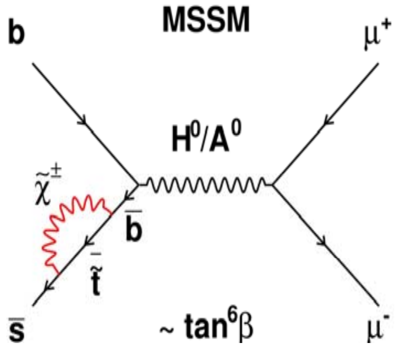
$BR(B_s\to\mu^+\mu^-) = (3.5 \pm 0.9)\times10^{-9}$

$BR(B_d\to\mu^+\mu^-) = (1.0 \pm 0.5)\times10^{-10}$

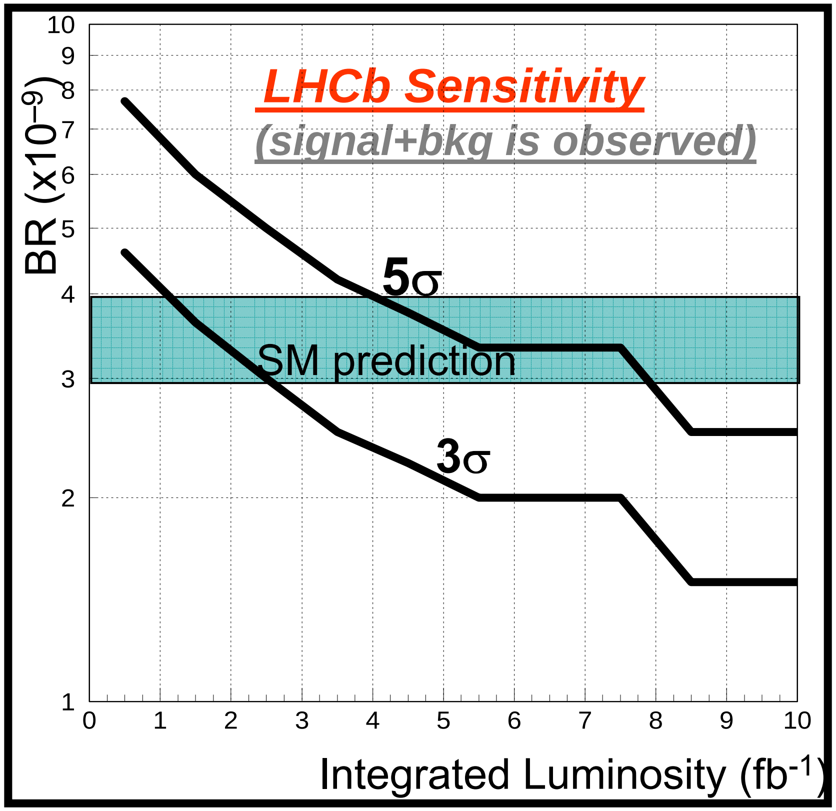
Limits from CDF+D0: $BR \sim 1\times10^{-7}$



Large contribution from SUSY

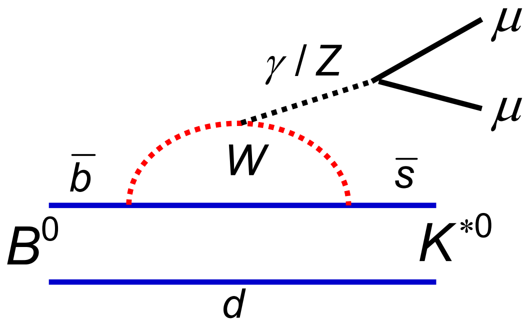


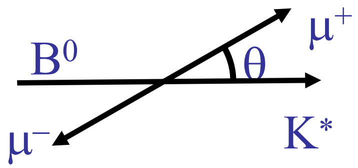
LHCb Mass resolution $\Delta m_{\mu\mu}\approx18$ MeV



2 fb−1 ⇒ 3σ evidence of SM signal
10 fb−1 ⇒ >5σ observation of SM signal

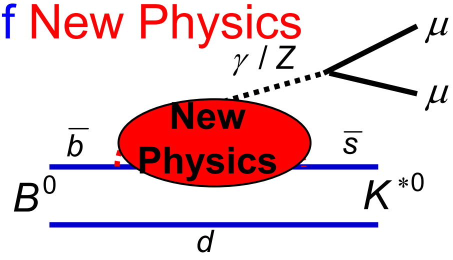
Rare $B^0 \to K^{*0}\mu^+\mu^-$ decays

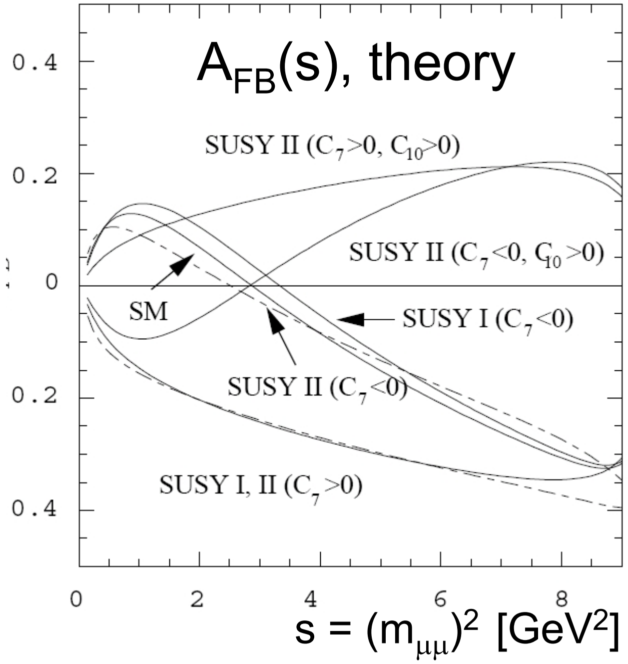


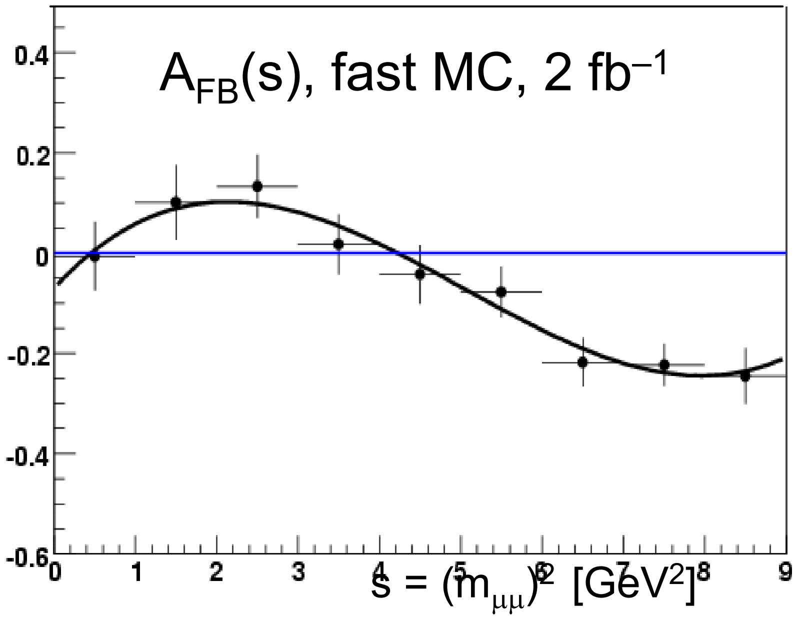


In Standard Model:
Suppressed by loop decay: BR ~1.2×10^{-6}

Forward-backward asymmetry $A_{FB}(s)$
In the $\mu\mu$ rest-frame is sensitive
probe of New Physics







LHCb - Conclusion

LHCb is a dedicated experiment to exploit the enormous B production rate at LHC: excellent vertexing and PID, good tracking, flexible trigger.

Precision measurement of loop-suppressed B decays at LHC opens a window to look for New Physics.

This approach is complementary to the direct searches of New Physics at ATLAS and CMS.

Numbers

	Channel	**Yield**	**B/S**	**Precision**
γ	$B_s \rightarrow D_s^{\mp} K^{\pm}$	5.4k	< 1.0	$\sigma(\gamma) \sim 14^{\circ}$
	$B_d \rightarrow \pi^+ \pi^-$	36k	0.46	$\sigma(\gamma) \sim 4^{\circ}$
	$B_s \rightarrow K^+ K^-$	36k	< 0.06	
	$B_d \rightarrow D^0\ (K\pi, KK)\ K^{*0}$	3.4 k, 0.5 k, 0.6 k	<0.3, <1.7, < 1.4	$\sigma(\gamma) \sim 7^{\circ} - 10^{\circ}$
	$B^- \rightarrow D^0\ (K^-\pi^+, K^+\pi^-)\ K^-$	28k, 0.5k	0.6, 4.3	$\sigma(\gamma) \sim 5^{\circ} - 15^{\circ}$
	$B^- \rightarrow D^0\ (K^+K^-, \pi^+\pi^-)\ K^-$	4.3 k	2.0	
	$B^- \rightarrow D^0\ (K_S\pi^+\pi^-)\ K^-$	1.5 - 5k	< 0.7	$\sigma(\gamma) \sim 8^{\circ} - 16^{\circ}$
α	$B_d \rightarrow \pi^+ \pi^- \pi^0$	14k	< 0.8	$\sigma(\alpha) \sim 10^{\circ}$
	$B \rightarrow \rho^+\rho^0, \rho^+\rho^-, \rho^0\rho^0$	9k, 2k, 1k	1, <5, < 4	
β	$B_d \rightarrow J/\psi(\mu\mu)K_S$	216k	0.8	$\sigma(\sin 2\beta) \sim 0.022$
Δm_s	$B_s \rightarrow D_s^- \pi^+$	80k	0.3	$\sigma(\Delta m_s) \sim 0.01\ \mathrm{ps}^{-1}$
ϕ_s	$B_s \rightarrow J/\psi(\mu\mu)\phi$	131k	0.12	$\sigma(\phi_s) \sim 1.3^{\circ}$
Rare decays	$B_s \rightarrow \mu^+\mu^-$	17	< 5.7	
	$B_d \rightarrow K^{*0} \mu^+\mu^-$	7.7 k	0.4	$\sigma(C_7^{eff}/C_9^{eff}) \sim 0.13$
	$B_d \rightarrow K^{*0} \gamma$	35k	< 0.7	$\sigma(A_{CP}) \sim 0.01$
	$B_s \rightarrow \phi\gamma$	9.3 k	< 2.4	
charm	$D^{*+} \rightarrow D^0\ (K^-\pi^+)\ \pi^+$	100 M		