Heavy flavour physics

Lecture 3

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Lecture 3

- Measurement of CKM angle γ
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Measurements of CKM angles

3rd CKM measurement: γ

Extract γ with $B \to D^{(*)}K^{(*)}$ final states using:

- GLW: Use CP eigenstates of D^0
- ADS: Interference between favoured and doubly suppressed decays
- GGSZ: Use the Dalitz structure of $D \to K_s h^+h^-$ decays

$b \to c$ interfering with $b \to u$

$B \to D^{(*)}K^{(*)}$

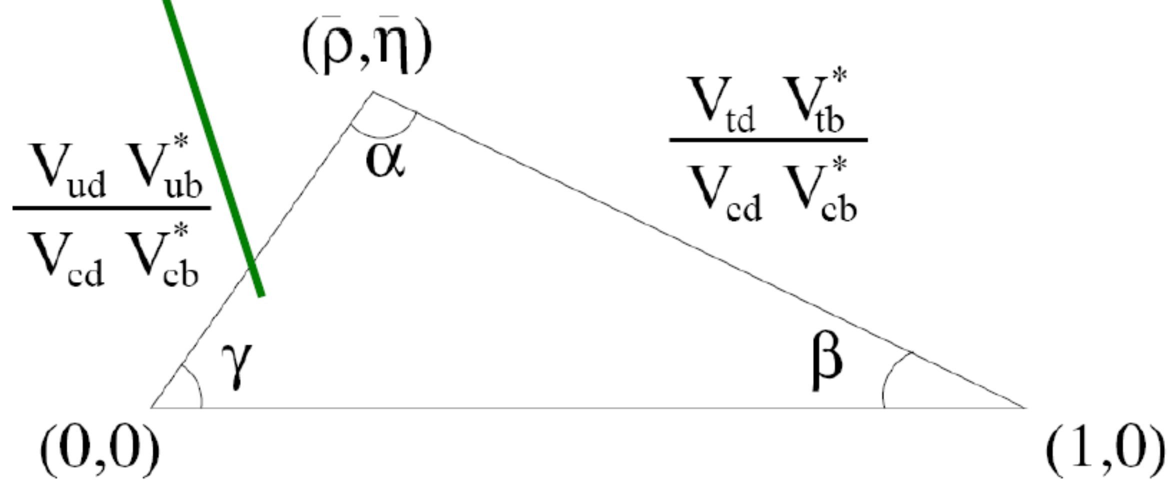
$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)}\pi$

$B^0 \to D^{(*)}\rho$

+ *charmless*

$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$$



Measurement of γ

- Charmless B decays, eg. $B^0 \rightarrow K^+\pi^-$
  - $\rightarrow$ contributions from
    - P : $b \rightarrow s\bar{u}u$ penguin
    - T : $b \rightarrow us\bar{u}$ tree
  - $\rightarrow$ relative weak (CP violating) phase is γ
  - $\rightarrow$ relative strong (CP conserving) phase δ

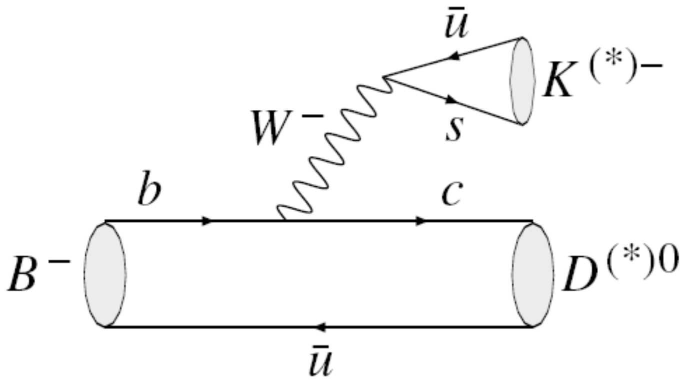
$$A_{CP} = 2|P||T|\sin(\gamma)\sin(\delta)/\{|P|^2+|T|^2+2|P||T|\cos(\gamma)\cos(\delta)\}$$

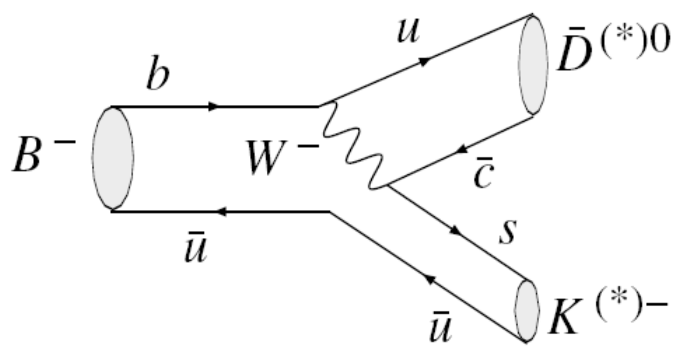
- Hadronic uncertainties:
  - $\rightarrow$ even if we observe $A_{CP} \neq 0$, cannot easily extract γ
  - $\rightarrow$ other processes also contribute

- A theoretically clean measurement of γ can be made using $B \rightarrow DK$ decays
- Reconstruct D mesons in states accessible to both D^0 and $\bar{D}^0$
  - $\rightarrow$ interference between $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$
  - $\rightarrow$ relative weak phase is γ
  - $\rightarrow$ various different D decays utilized
  - $\rightarrow$ large statistical errors at present

The idea of measurement

- Two possible diagrams for $B^- \to DK^-$





$\propto V_{cb} V^{*}_{us}$

- colour allowed
- final state contains *D^0*

$\propto V_{ub} V^{*}_{cs}$

- colour suppressed
- final state contains *D^0(bar)*

- Relative magnitude of suppressed amplitude is $\boldsymbol{r_B}$
- Relative weak phase is $\boldsymbol{-\gamma}$, relative strong phase is $\boldsymbol{\delta_B}$
- Need *D^0* and *D^0(bar)* to decay to common final state

Three ways to make DK interfere

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

more sensitive to r_B

uses the CP eigenstates $D^{(*)0}_{CP}$ with final states:

K^+K^-, $\pi^+\pi^-$ (CP-even), $K_s\pi^0$ (ω,ϕ) (CP-odd)

$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B \qquad A_{CP\pm} = \frac{\pm 2r_B \sin\gamma \sin\delta_B}{1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B}$$

ADS(*Atwood, Dunietz, Soni*) method: B^0 and $\bar{B}^0$ in the same final state with $D^0 \to K^+\pi^-$ (suppr.) and $\bar{D}^0 \to K^+\pi^-$ (fav.)

$$R_{ADS} = r_B^2 + r_{DCS}^2 + 2r_B r_{DCS} \cos\gamma \cos(\delta_B + \delta_D)$$

the most sensitive way to γ

D^0 Dalitz plot with the decays $B^- \to D^{(*)0}[K_S\pi^+\pi^-]\,K^-$

3 free parameters to extract: γ , r_B and δ_B

Constraint from γ

Best constraint from combining all available results

- B→DK, B→D(*)K, B→DK(*)
- Different D decays

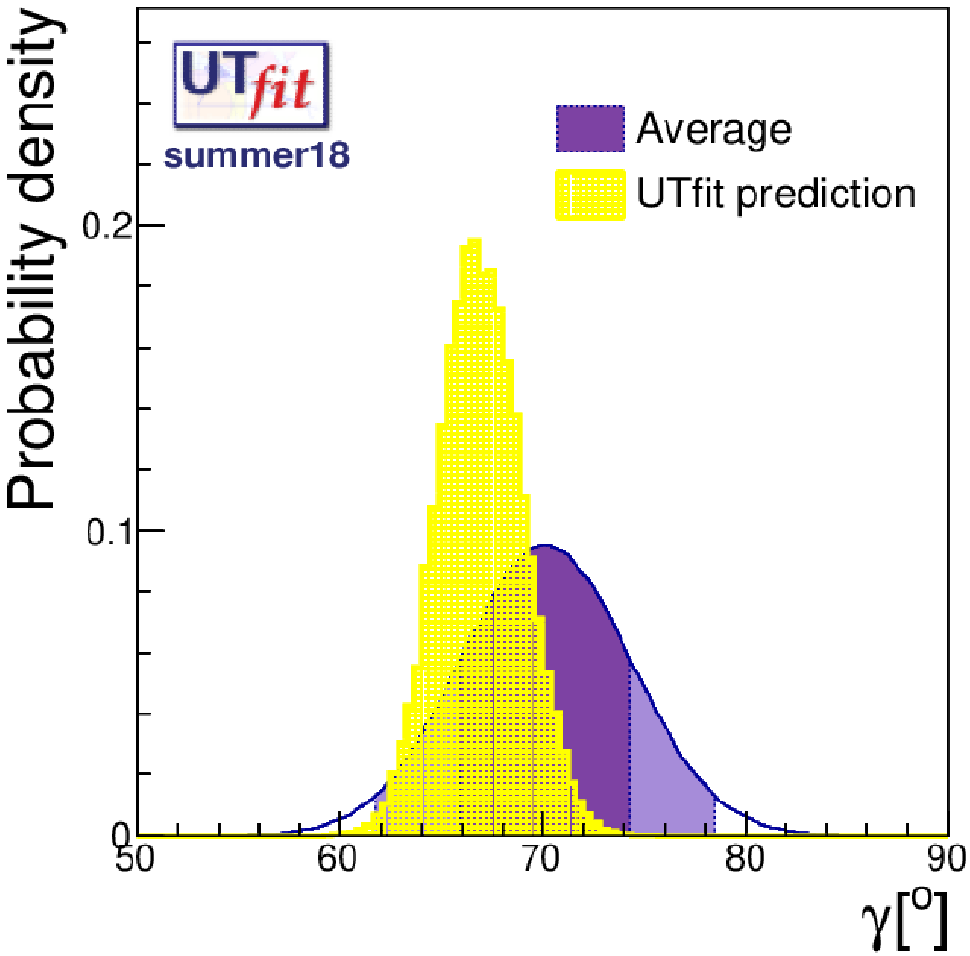
→ D → CP eigenstates

→ D → suppressed states

- (eg. $K\pi$)

→ D → multibody states

- (eg. $K_S \pi^+\pi^-$)



γ from B into DK decays:

combined: (73.4 ± 4.4)°

UTfit prediction: (65.8 ± 2.2)°

CKM matrix - magnitudes

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

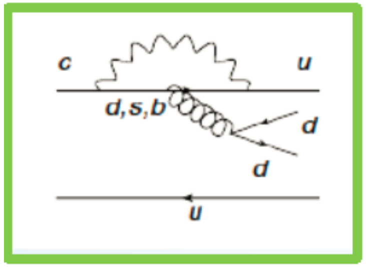
$$\begin{pmatrix} 0.97425 \pm 0.00022 & 0.2252 \pm 0.0009 & (4.15 \pm 0.49) \times 10^{-3} \\ 0.230 \pm 0.011 & 1.006 \pm 0.023 & (40.9 \pm 1.1) \times 10^{-3} \\ (8.4 \pm 0.6) \times 10^{-3} & (42.9 \pm 2.6) \times 10^{-3} & 0.89 \pm 0.07 \end{pmatrix}$$

- V_{ud}: superallowed $0^+ \to 0^+$ β decays
- V_{us}: semileptonic / leptonic kaon decay; hadronic tau decays
- V_{ub}: semileptonic / leptonic B decays
- V_{cd}: semileptonic charm decays; charm production in neutrino beams
- V_{cs}: semileptonic / leptonic charm decays
- V_{cb}: semileptonic B decays
- V_{td}: B_d oscillations
- V_{ts}: B_s oscillations
- V_{tb}: single top production

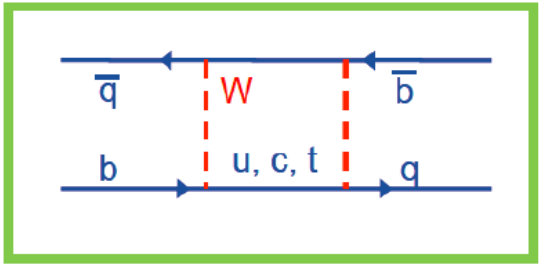
significant progress in many of these over the last few years
(including some new results not yet in the PDG compilation)

FCNC loops in the SM

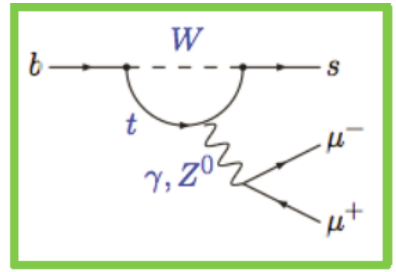
Map of flavour transitions and types of loop processes



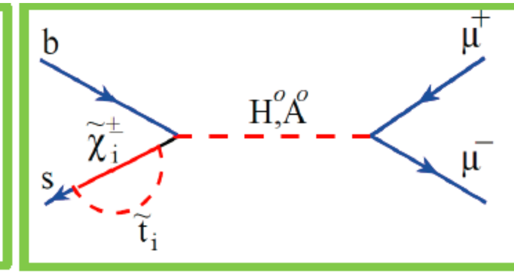
QCD penguin



ΔF=2 box



EW penguin



Higgs penguin

	b→s	b→d	c→u	s→d
QCD penguin	$A_{CP}(B_s \to hhh)$	$A_{CP}(B^0 \to hhh)$	**$\Delta a_{CP}(D \to hh)$**	$K \to \pi^0 ll$ ε'/ε
ΔF=2 box	**ΔM_{Bs}** **$A_{CP}(B_s \to J/\psi\varphi)$**	ΔM_{Bd} $A_{CP}(B^0 \to J/\psi K_s)$	x,y, q/p	ΔM_K ε_K
EW penguin	**$B \to K^{(*)}\mu\mu$** $B \to X_s\gamma$	$B \to \pi\mu\mu$ $B \to X\gamma$	$D \to X_u l\, l$	$K \to \pi^0 ll$ $K \to \pi^{\pm} \nu\nu$
Higgs penguin	**$B_s \to \mu\mu$**	**$B^0 \to \mu\mu$**	$D \to \mu\mu$	$K^0 \to \mu\mu$

QCD penguins

Search for CP violation in charm decays

Charm physics

- Neutral D meson offers the only chance to study $\Delta F = 2$ (mixing) phenomena among up-type quarks

- FCNC in decays can also be studied

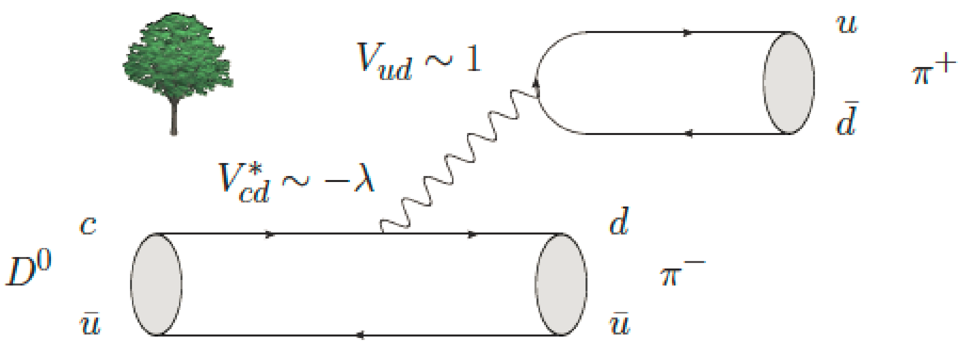
- CP violation in the D system is tiny in the SM, and hence its study probes New Physics

  $\rightarrow$ precise measurements needed to test realistic NP models

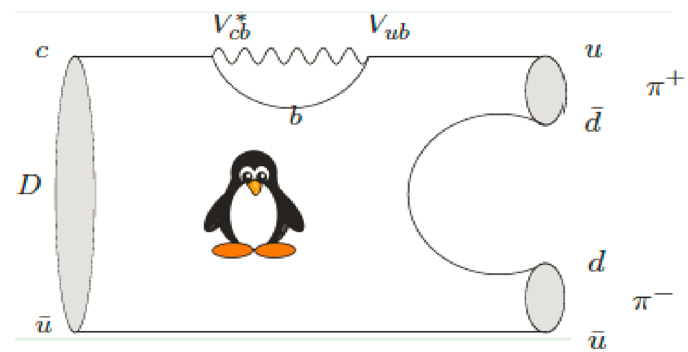
CP violation in charm

- Charm:
  - → direct CP violation (in decay) in SM is small
  - → could there be large **direct CP violation** in charm **penguin decays**?
  - → CP violation O(1%) would be „clear sign for NP”

$(|V_{cd}V_{ud}| \alpha \lambda)$



$(|V_{cb}V_{ub}| \alpha \lambda^5)$



Time integrated A_{CP} has both direct and indirect components

CP violation in charm: ΔA_{CP}

$$A_{\text{raw}}(f) = \boxed{A_{CP}(f)} + \boxed{A_{\text{D}}(f)} + \boxed{A_{\text{P}}(D^{*+})}$$

- Physical CP asymmetry (very small)
- Detection asymmetry, cancels for $D^0 \rightarrow \pi\pi$, KK
- Production asymmetry

large O(1%)

$$\Delta A_{CP} = A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

w/ U-spin symmetry: $A_{CP}(K^-K^+) = -A_{CP}(\pi^-\pi^+)$

CP violation in charm: ΔA_{CP}

- ΔA_{CP} cancels detector and production asymmetries to first order
- The SM, and most NP models, predict opposite sign for KK and ππ
- Use of U-spin and QCD factorization leads to:

$$\Delta A_{CP} \sim 4\ \text{penguin/tree} \sim 0.04\%$$

Analysis:

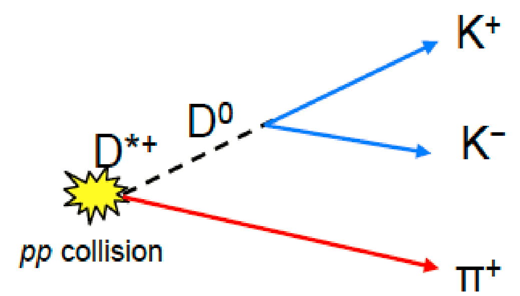
- LHCb performed two (experimentally orthogonal) measurements
- **$D^{*\pm} \to D^0\ [h^+h^-]\ \pi^\pm$** pion's charge determines the flavour of D^0
- Alternatively, using **$B \to D\ \mu\nu$** decays the muon's charge determines the flavour.
- Most of the systematics cancel in the subtraction, and are controlled by swapping the magnetic field

Measure CP violation: $D^{*+} \rightarrow D^0\pi^+$

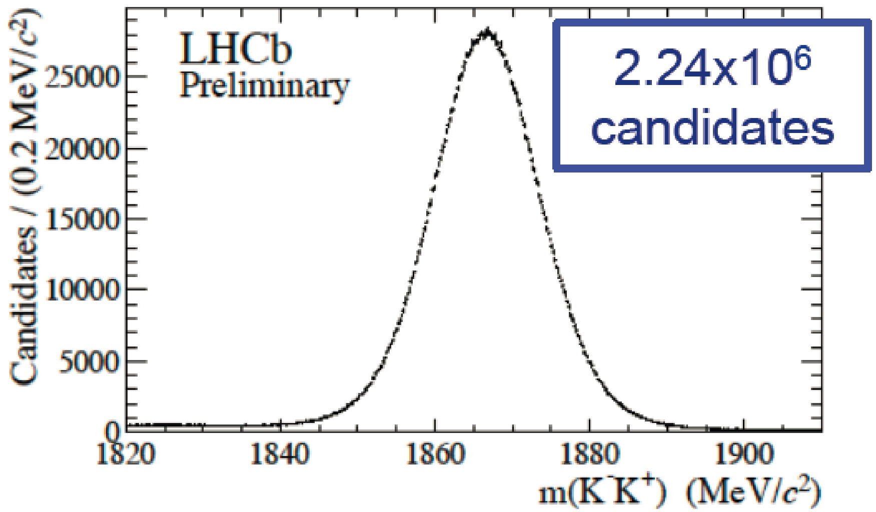
- LHCb performed two independent measurements

  → „D^* tagged": $D^{*\pm} \rightarrow D^0 (\rightarrow K^+K^- \text{ or } \pi^+\pi^-) \pi^\pm$

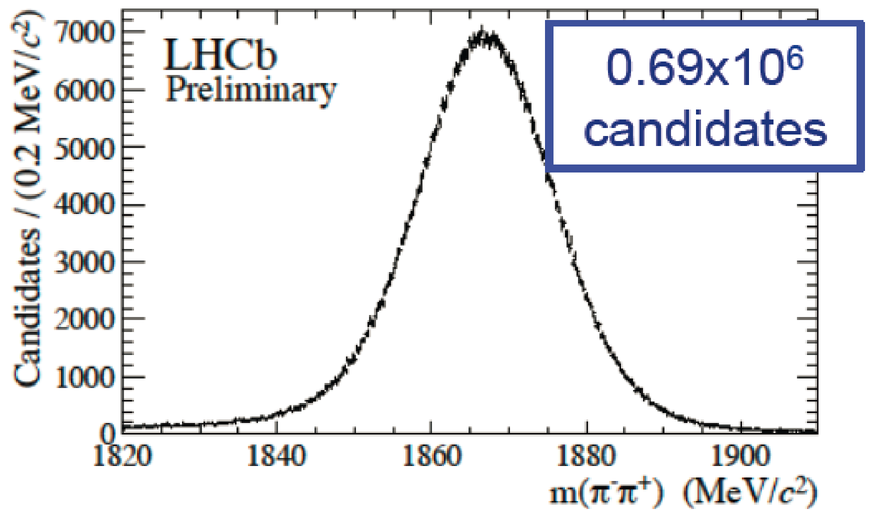
  - pion charge determines D^0 production flavour



$D^0 \rightarrow K^+K^-$

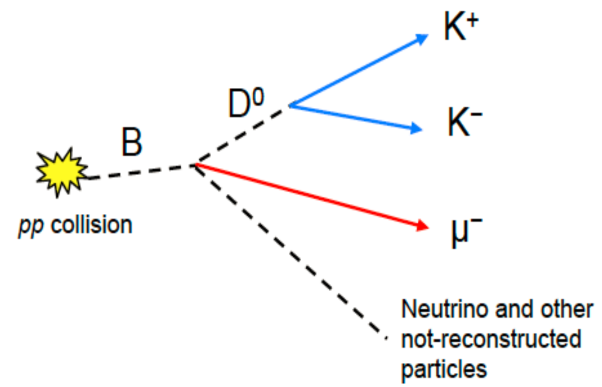


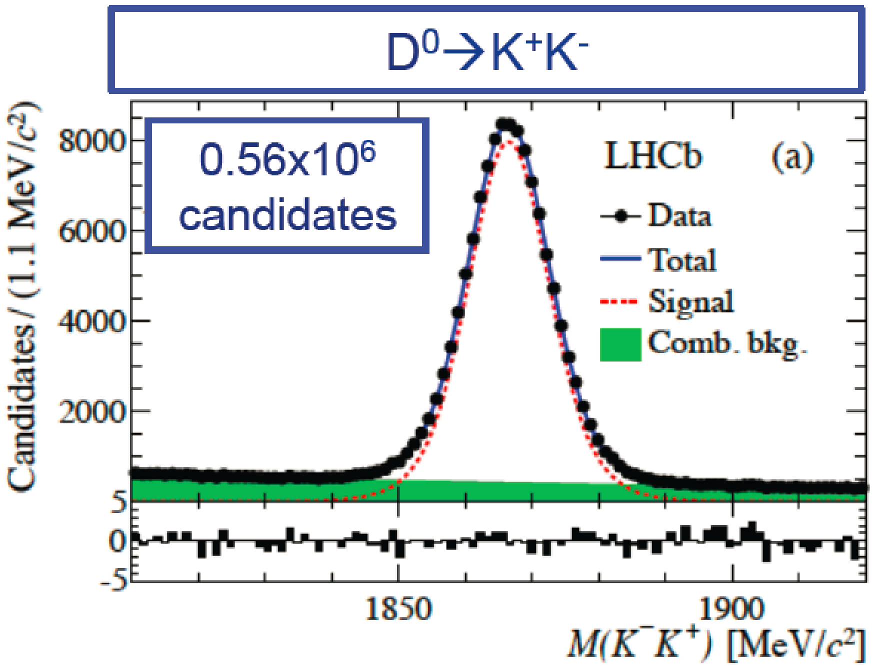
$D^0 \rightarrow \pi^+\pi^-$

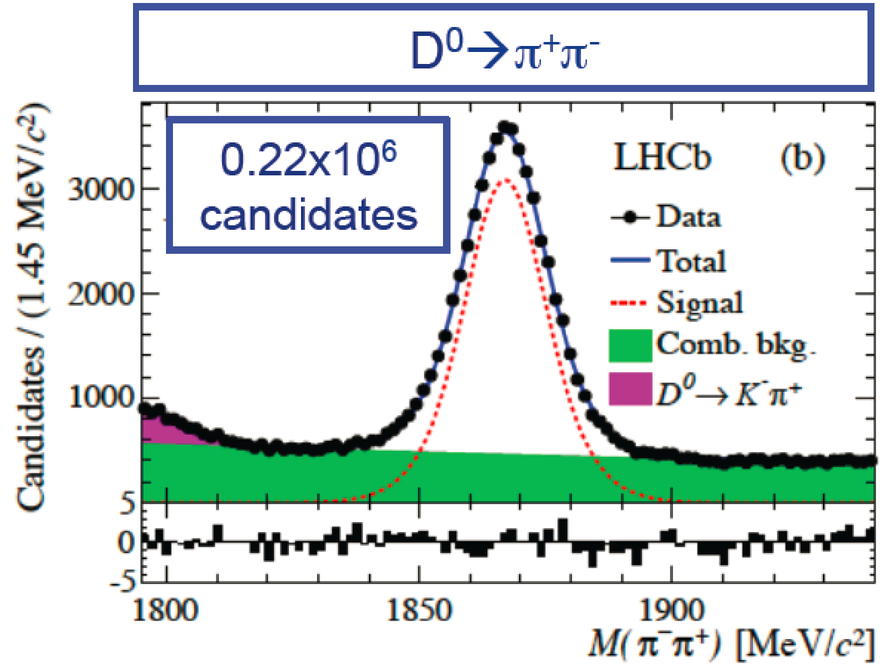


Measure CP violation: $D^{*+} \rightarrow D^0\pi^+$

- LHCb performed two (experimentally orthogonal) measurements
  - → "Muon tagged": $B^\pm \rightarrow D^0 (\rightarrow K^+K^- \text{ or } \pi^+\pi^-)\ \mu^\pm\ \nu\ X$
    - muon charge determines D^0 production flavour

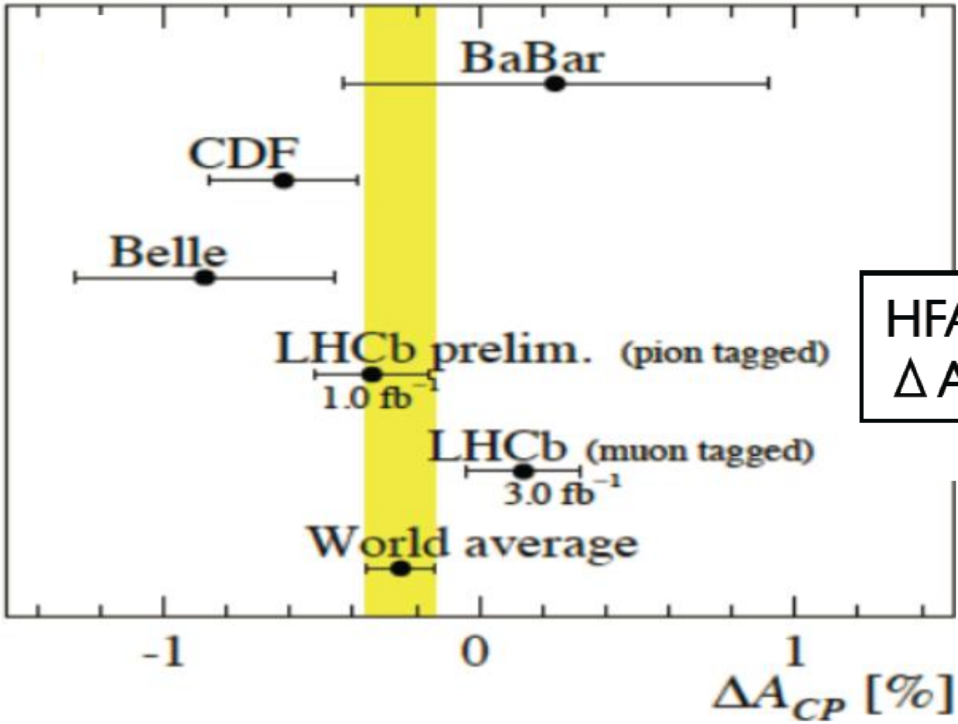






Measure CP violation: $D^{*+} \to D^0\pi^+$

ΔA_{CP}: world average



HFAG:
$\Delta A_{CP}=(-0.253\pm0.104)\%$

No significant evidence for CP violation
Effects O(%) are out of the game

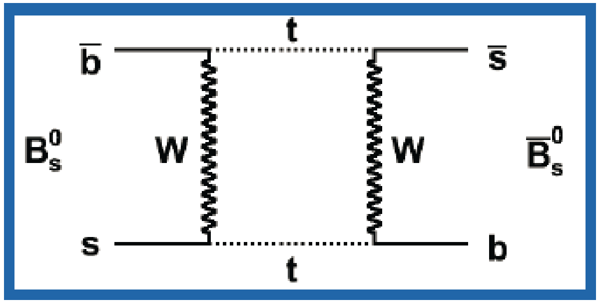
ΔF=2 boxes: B_s mixing

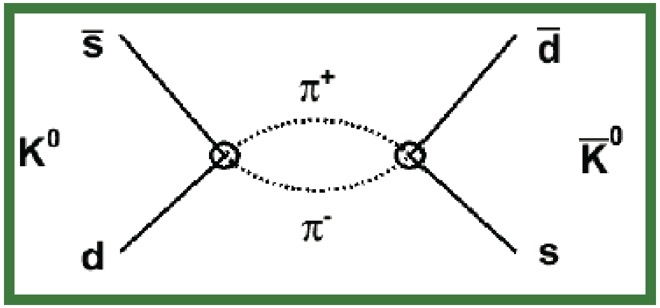
Neutral meson mixing

The eigenstates of flavour M^0, anti-M^0, degenerated in pure QCD, mix under weak interactions:

M^0 : K^0 (anti-s d), D^0(c anti-u), B^0(anti-b d), B_s^0(anti-b s)

Mixing can occur via **short distance** or **long distance** processes:





Time-dependent Schrödinger equation

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = H \begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma \right) \begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix}$$

H is Hamiltonian; **M** and **Γ** are 2x2 Hermitian matrices

CPT theorem: $M_{11} = M_{22}$ & $\Gamma_{11} = \Gamma_{22}$

→ particle and antiparticle have equal masses and lifetimes

Mixing formalism

Time evolution of B^0 or B^0(bar) can be described by an *effective* Hamiltonian

Hamiltonian

$$\mathcal{H} = M - \frac{i}{2}\Gamma = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\text{hermitian}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\text{hermitian}}$$

Mass term: "dispersive"

Decay term: "absorptive"

Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix} = \mathcal{H}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}$$

Define the mass eigenstates (physical states): $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$

p & q complex coefficients that satisfy $|p|^2 + |q|^2 = 1$

Heavy and light mass eigenstates have time dependence: $|B_{H,L}(t)\rangle = e^{-(im_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}(0)\rangle$

Diagonalising → the mass and decay width difference

$$\begin{aligned} \Delta m &= m_{B_H} - m_{B_L} = 2\,|M_{12}| \\ \Delta\Gamma &= \Gamma_L - \Gamma_H = 2\,|\Gamma_{12}|\cos\phi \end{aligned} \qquad \phi = \arg\left(-M_{12}/\Gamma_{12}\right)$$

S,L (short-, long-) or L,H (light, heavy) depending on values of Δm & ΔΓ (1,2 usually for CP eigenstates)

Mixing formalism

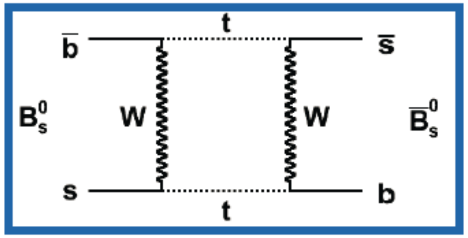
Solving the Schrödinger equation gives:

$$\frac{q}{p} = -\sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}$$

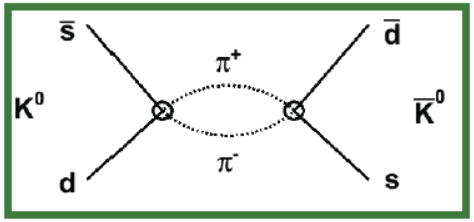
$$\Delta m = 2\,\mathrm{Re}\sqrt{\left(M_{12} - i\Gamma_{12}/2\right)\left(M_{12}^* - i\Gamma_{12}^*/2\right)}$$

$$\Delta\Gamma = 2\,\mathrm{Im}\sqrt{\left(M_{12} - i\Gamma_{12}/2\right)\left(M_{12}^* - i\Gamma_{12}^*/2\right)}$$

- Δm: value depends on rate of mixing diagram
  - → short distance, virtual (off shell)



- $\Delta\Gamma$: value depends on widths of decays into common final states (CP-eigenstates)
  - → long distance, on shell states
  - → large for K^0, small for D^0 & B^0

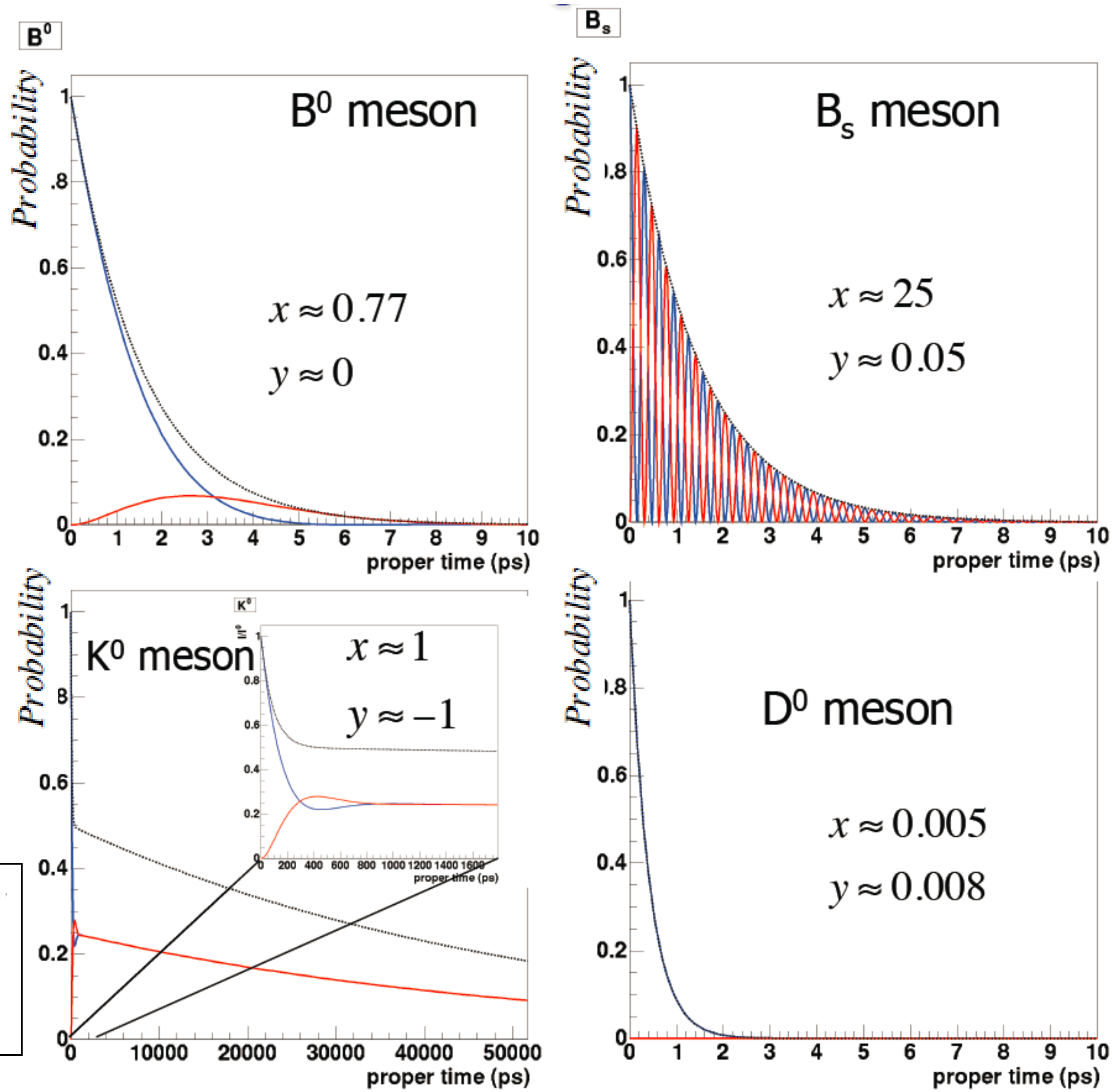


- $q/p \approx 1$ if $\arg(\Gamma_{12}/M_{12}) \approx 0$ ($|q/p| \approx 1$ if $M_{12} << \Gamma_{12}$ or $M_{12} >> \Gamma_{12}$)
  - → CP conserved if physical states = CP eigenstates ($|q/p| = 1$)
  - → CP violation in mixing when mass eigenstates ≠ CP eigenstates $|q/p| \neq 1$

Mixing of neutral mesons

4 different neutral meson systems have very different mixing properties:

- B_s system
  - → very fast mixing
- Kaon system
  - → large decay time difference
- Charm system
  - → very slow mixing



x: the average number of oscillations before decay	$x \equiv \frac{\Delta m}{\Gamma}$
y: the relative decay width difference	$y \equiv \frac{\Delta\Gamma}{2\Gamma}$

Kaon and charm mixing

- **Kaon mixing**

→ CPLEAR experiment

- tag strangeness of initial kaon using charge of associated kaon from production pp(bar) → K^+K^0(bar)π^- / $K^-K^0\pi^+$

- **Charm mixing**

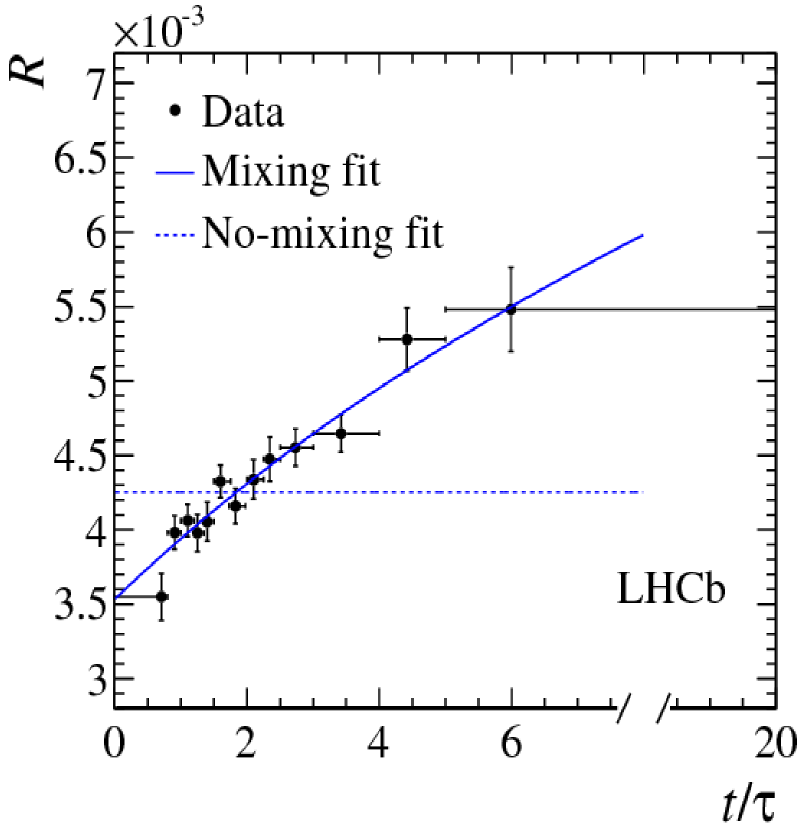
→ evidence (3σ) for charm mixing in 2007 from BaBar & Belle

→ followed by further evidence from CDF

→ combined significance of mixing overwhelming, but no single 5σ measurement until LHCb

→ time-dependence of ratio of wrong-sign (WS) to right-sign (RS) $D^0 \to K\pi$ decays

- WS/RS known by $D^{*+} \to D^0\pi$ tag



B^0-B^0(bar) oscillations

ARGUS experiment (1987)

First evidence

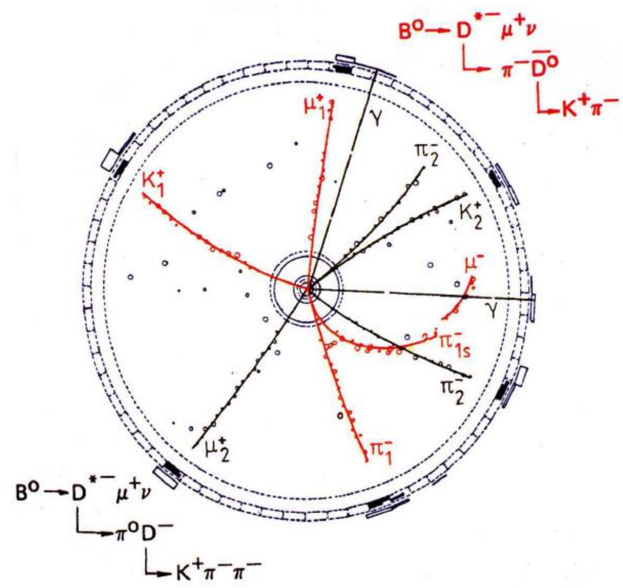
- Same sign leptons

  → same flavour B mesons

- Mixing probability is large

  → top quark is heavy

- Mixing probability: r = 0.21 ± 0.08
- PDG 2006: r = 0.188 ± 0.003
- From 103/pb of data

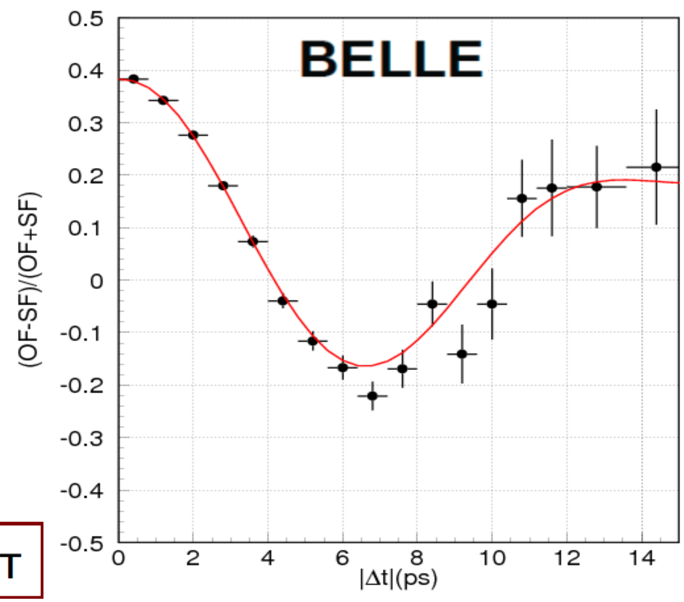


B mixing with current data sets

- Belle experiment (2005)

  $\Delta m = (0.511 \pm 0.005 \pm 0.006)\ ps^{-1}$

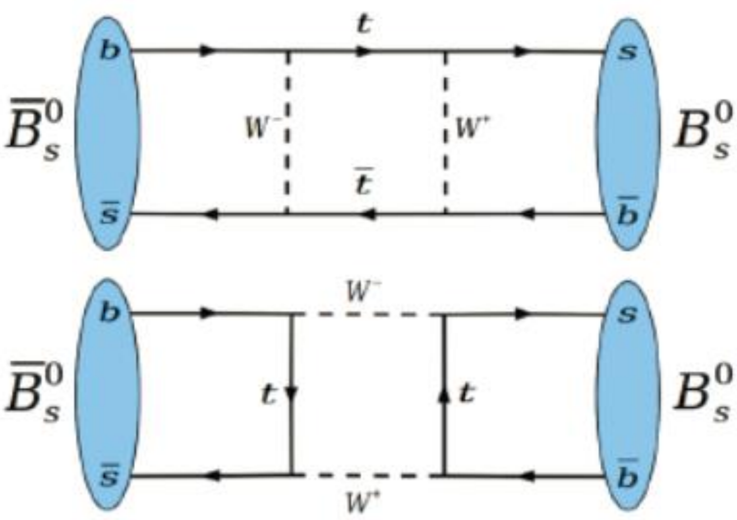
- From 140/fb of data



$$P(\Delta t) = (1 \pm \cos(\Delta m \Delta t))e^{-|\Delta t|}/2\tau$$

B_s-B_s(bar) oscillations

Dominant Feynman diagrams (Standard Model)



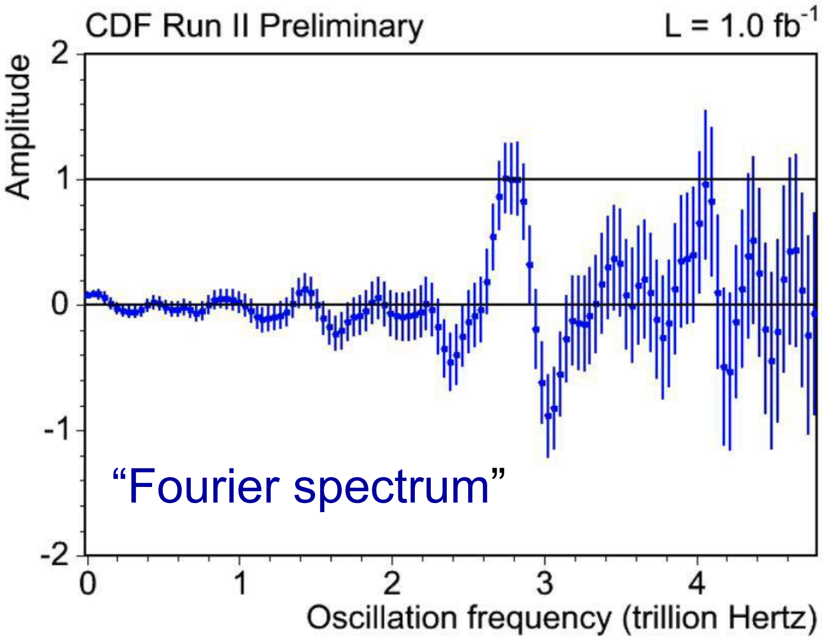
$$\Delta m_s = m_H - m_L = 2|M_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$\phi_M = \arg(M_{12})$$

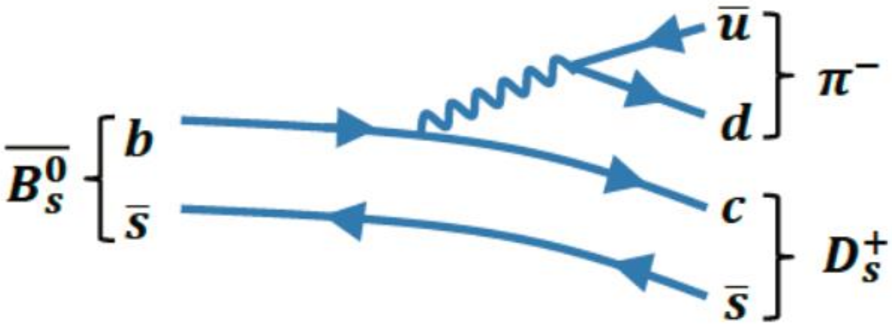
These oscillations were first observed at the Tevatron in 2006:

Δm_s=17.77 ± 0.10(stat) ± 0.07 (sys) ps^{-1}



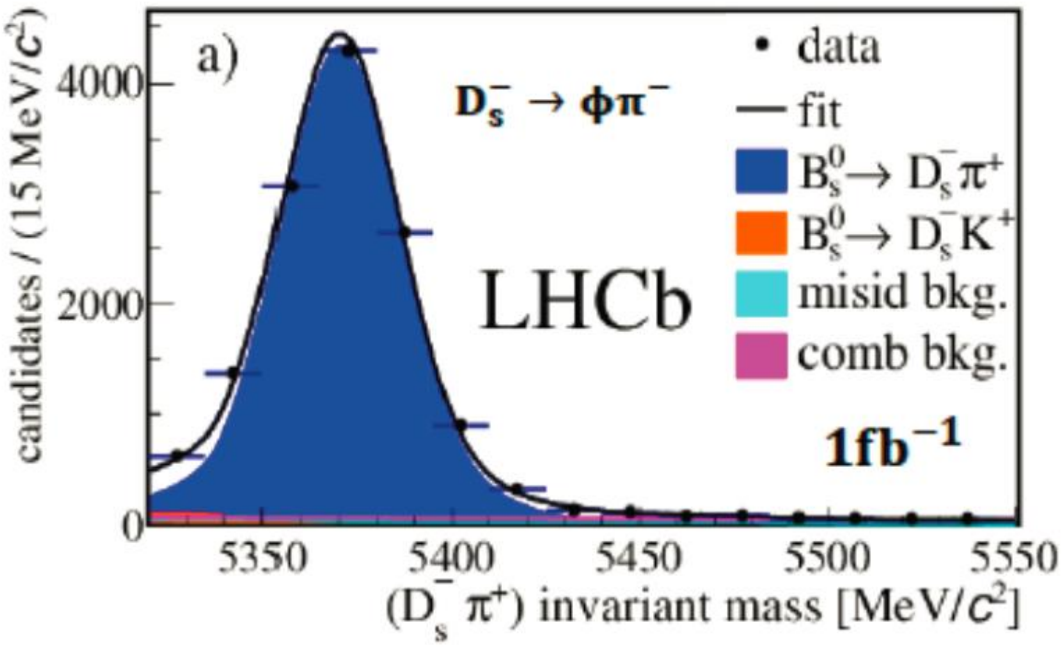
Now this measurement has been repeated with much better precision by LHCb

LHCb: Δm_s from $B_s \to D_s\pi$



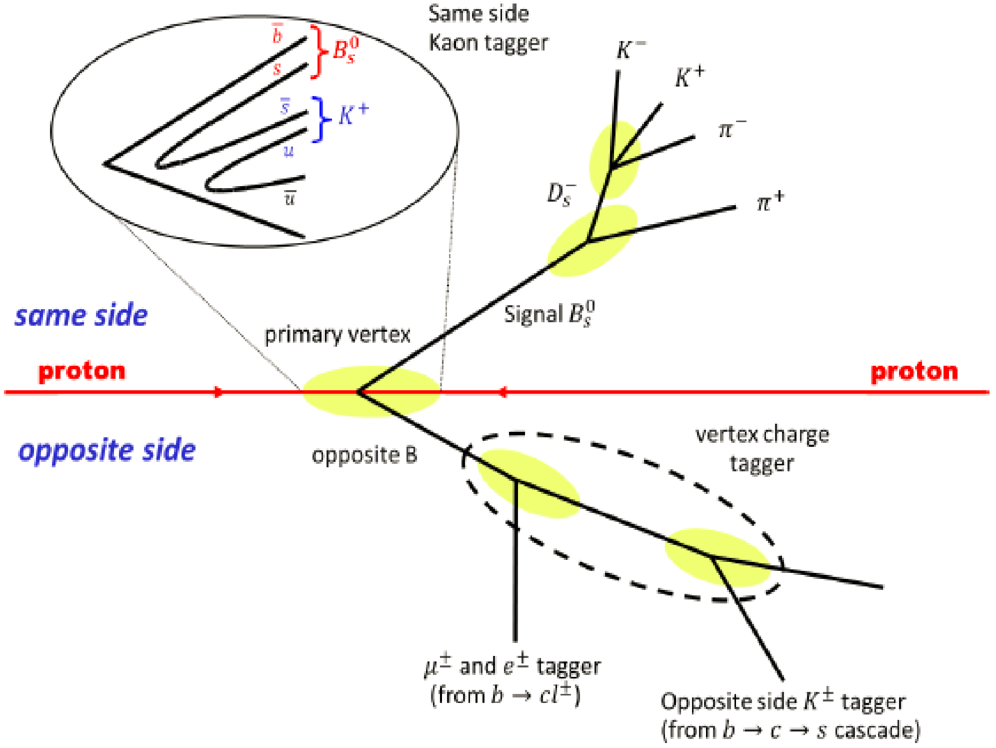
- Very high statistics
- Low background level
- Can resolve B_s mixing frequency due to high boost

Use flavour tagging to determine flavour at production, pion charge for flavour at decay



Flavour tagging at hadron colliders

Tagging efficiency	Mistag probability	Dilution
$\varepsilon = \frac{\#\,tagged\ candidates}{\#\,all\ candidates}$	$\omega = \frac{\#\,tagged\ wrong}{\#\,tagged}$	$D = (1 - 2\omega)$



- Opposite side taggers
  - exploits $b\bar{b}$ pair production by partially reconstructing the second B-hadron in the event
- Same side kaon tagger
  - exploits hadronization of signal B_s-meson
- Combined tagging power (in $B_s^0 \to D_s^- \pi^+$)
  - $\varepsilon D^2 = 3.5 \pm 0.5\%$

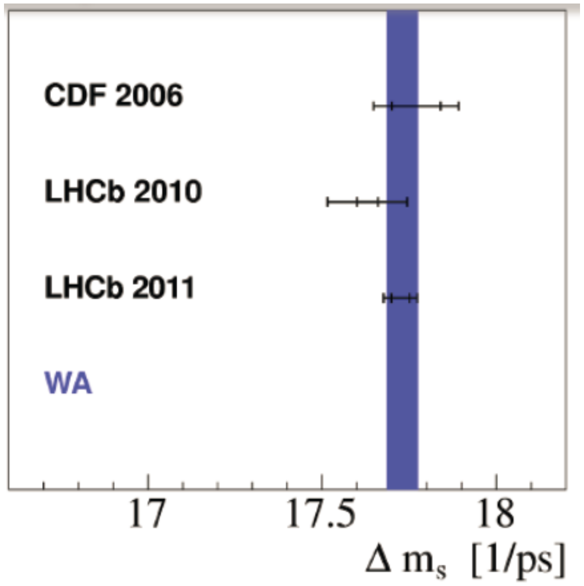
Compare this to e$^+$e$^-$ colliders:
$\varepsilon D^2 \sim 30\%$

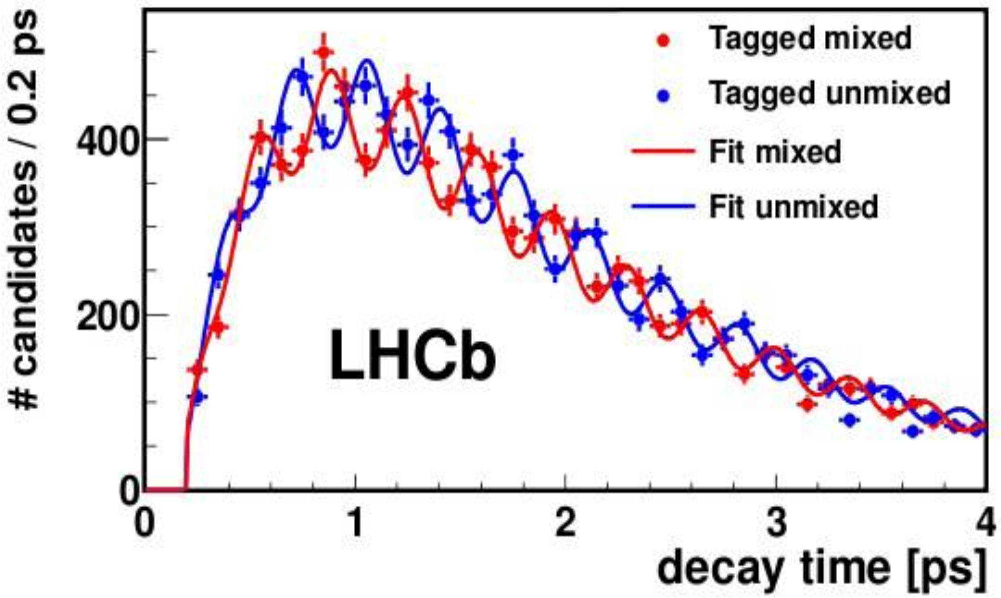
LHCb: Δm_s from $B_s \rightarrow D_s\pi$

What is needed to measure Δm_s ?

- Resolve the fast B_s oscillations (→ average decay time resolution ~45 fs)
- Decays into flavour specific final state: $B_s \rightarrow D_s\pi$ (→ high BR ~ 0.3%)
- Tag the B_s flavour at production
  - → high efficiency and low mistag rate
  - → tagging power: ~4%

Most precise measurement of Δm_s



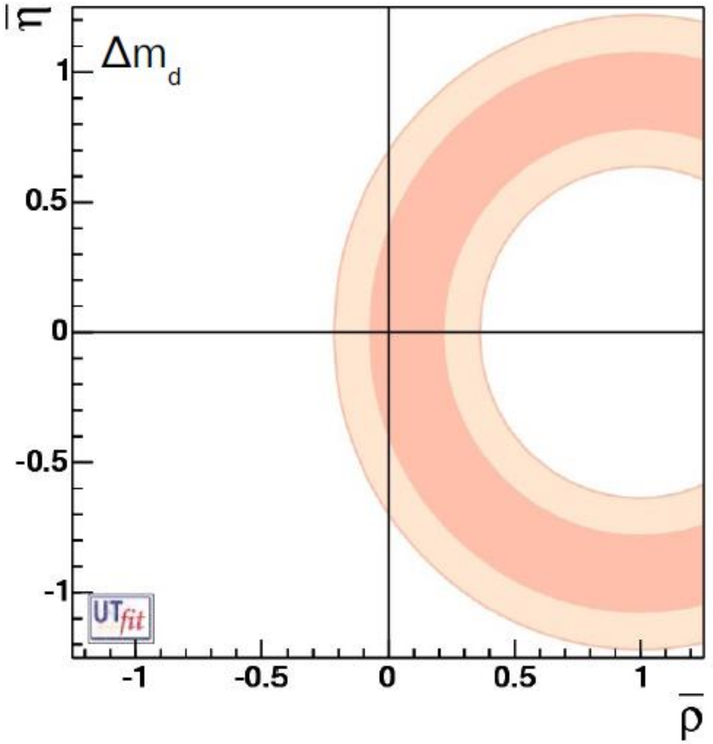


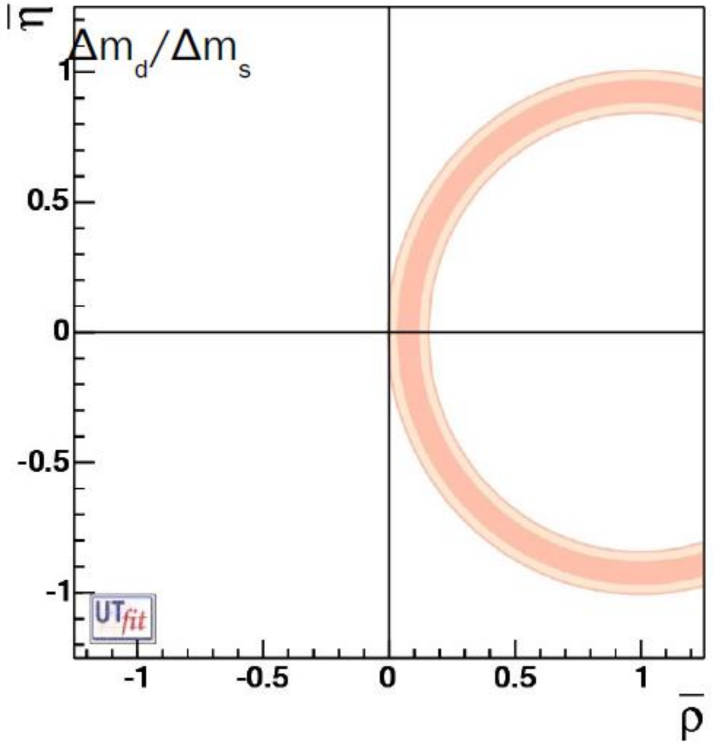
$$\Delta m_s = 17.768 \pm 0.023(stat) \pm 0.006(syst)\ ps^{-1}$$

Constraints from mixing

- Δm_d contains information on $|V_{td}|$
- Δm_d / Δm_s preferred since theoretically cleaner

  → constraint on $R_t = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right|$





$\Delta F=1$:
Electroweak penguins

$b \to s$ transitions

- $b \to s\, l^+l^-$ processes also governed by FCNCs

  → rates and asymmetries of many exclusive processes sensitive to NP

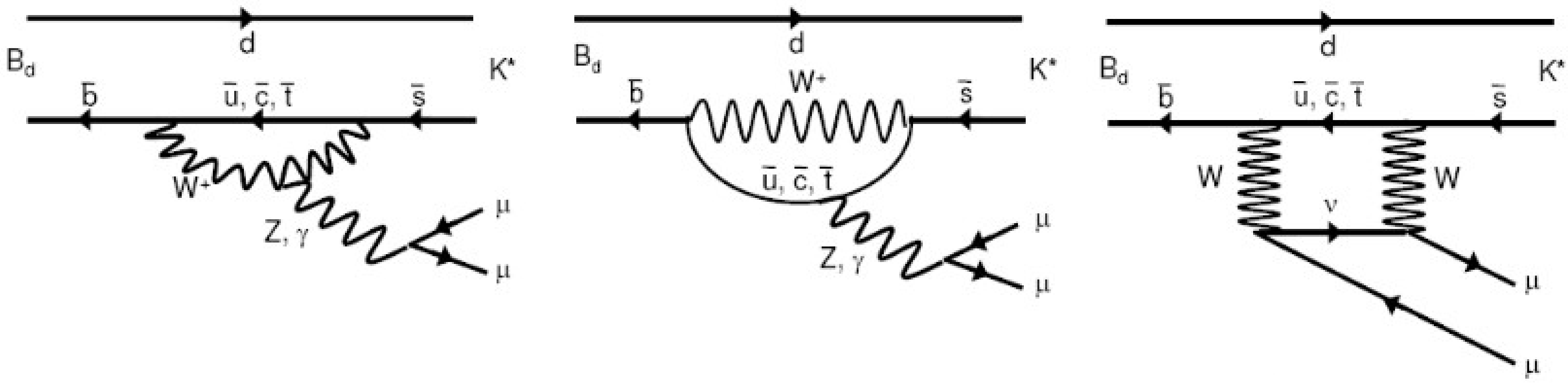
- Golden $\Delta F=1$ EW penguin decay: $B_d \to K^{*0}\mu^+\mu^-$

  → superb laboratory for NP tests

  → experimentally clean signature

  → many kinematic variables …

  → with clean theoretical predictions (at least at low q^2)



b → s transitions: theoretical framework

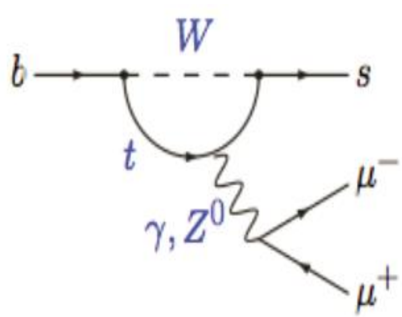
Describe b → s transitions by an effective Hamiltonian

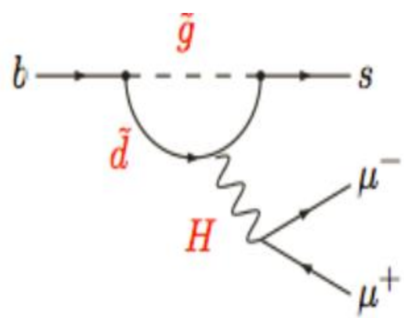
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

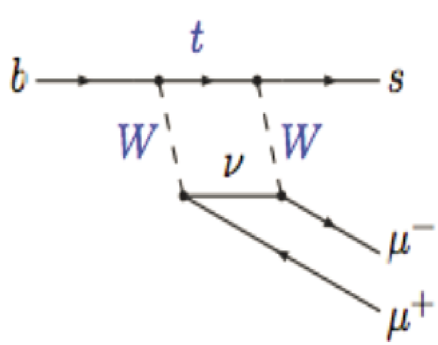
$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

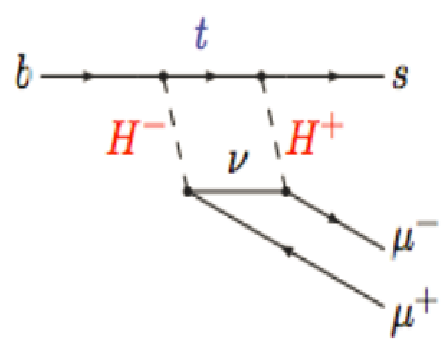
- long distance effects absorbed in the definition of the operators O_i
- interesting short distance can be computed perturbatively in Wilson coefficients C_i

b → s transitions are sensitive to: O_7(‘), O_9(‘), O_{10}(‘)



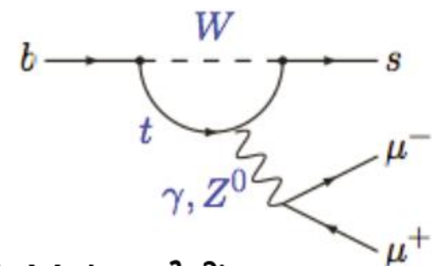






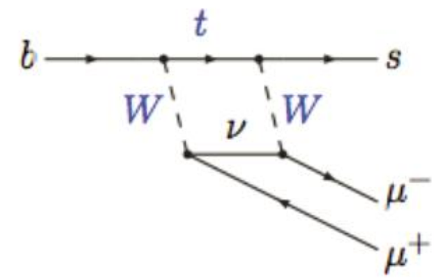
- $B^0 \rightarrow K^* \mu^+\mu^-$ is the most prominent channel (large statistics & flavour specific)
- Studies with rarer $B_s \rightarrow \varphi\, \mu^+\mu^-$, $\Lambda^0_b \rightarrow \Lambda\, \mu^+\mu^-$, … have started

$B^0 \rightarrow K^*\mu^+\mu^-$ - angular analysis



- $B^0 \rightarrow K^*\mu^+\mu^-$ is the golden mode to test new vector(-axial) couplings in $b \rightarrow s$ transitions

b→s ($|V_{tb}V_{ts}| \alpha \lambda^2$)



- $K^* \rightarrow K\pi$ is self tagged, hence angular analysis ideal to test helicity structure

- Sensitivity to O_7, O_9 and O_{10} and their primed counterparts:

$$Q_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu} b \quad \text{[real or soft photon]}$$

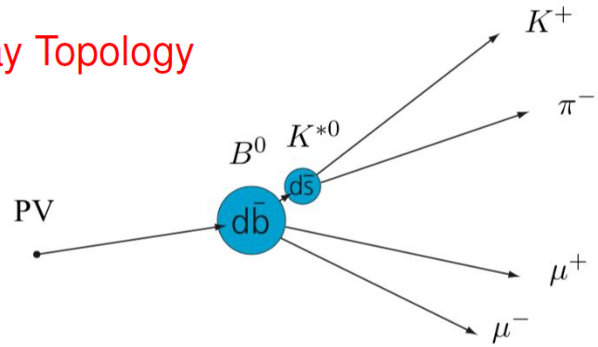
$$Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu \ell \quad [b \rightarrow s\mu\mu \text{ via } Z/\text{hard } \gamma]$$

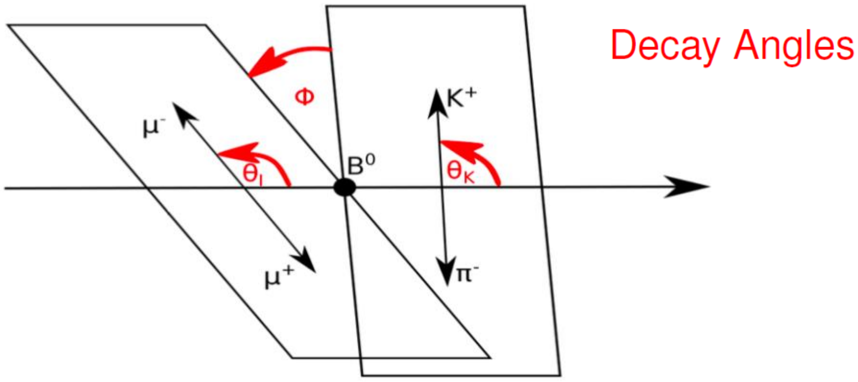
$$Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\gamma_5 \ell \quad [b \rightarrow s\mu\mu \text{ via } Z]$$

Right-handed currents: $1-\gamma_5 \rightarrow 1+\gamma_5$

Decay topology

Decay Topology





$B^0 \to K^*\mu^+\mu^-$ - angular analysis

$B^0 \to K^*\mu^+\mu^-$ full decay rate is given as differential decay distribution

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\ \Big]$$

- Experiments typically measure sub-set of these observables by integrating out some parts
- Classical observable measured for the FIRST time by LHCb
- Results from **B-factories and CDF** very much limited by the statistical uncertainty

$B^0 \to K^*\mu^+\mu^-$ - angular analysis

Folding technique ($\phi \to \phi + \pi$) for $\phi < 0$, reduces the nr of parameters to fit to four

By exploiting symmetries: this form can be reduced to …

$$\hat{\phi} = \begin{cases} \phi + \pi & \text{if } \phi < 0 \\ \phi & \text{otherwise} \end{cases}$$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} = \frac{9}{16\pi}\Big[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) - F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$

fraction of longitudinal polarisation of the K^* (F_L)

forward-backward asymmetry of the dilepton system (A_FB)

Simpler expression remains, sensitive to: F_L, **A_{FB}**, S_3, A_9

$\to$ lost sensitivity to terms 4, 5 ,7 and 8

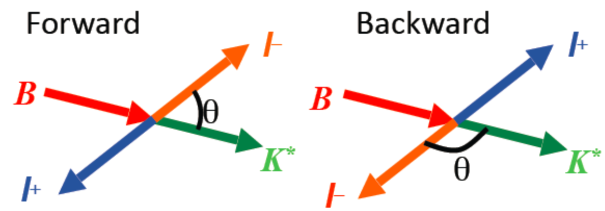
$B^0 \to K^*\mu^+\mu^-$ - Forward-Backward asymmetry

Hadronic uncertainties under reasonable control for:

→ **F_L**: Fraction of K^* longitudinal polarization

→ **A_{FB}**: Forward-Backward asymmetry of lepton

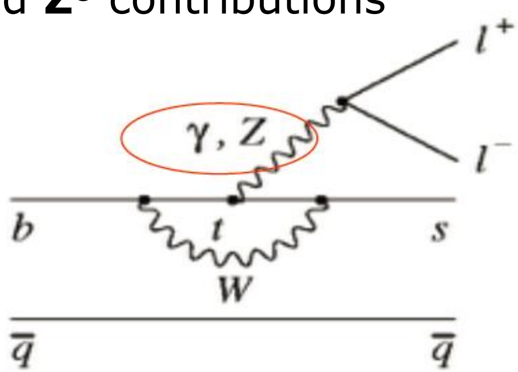
→ **$S_3 \sim A_T^2\,(1-F_L)$**: Asymmetry in K^* transverse polarization

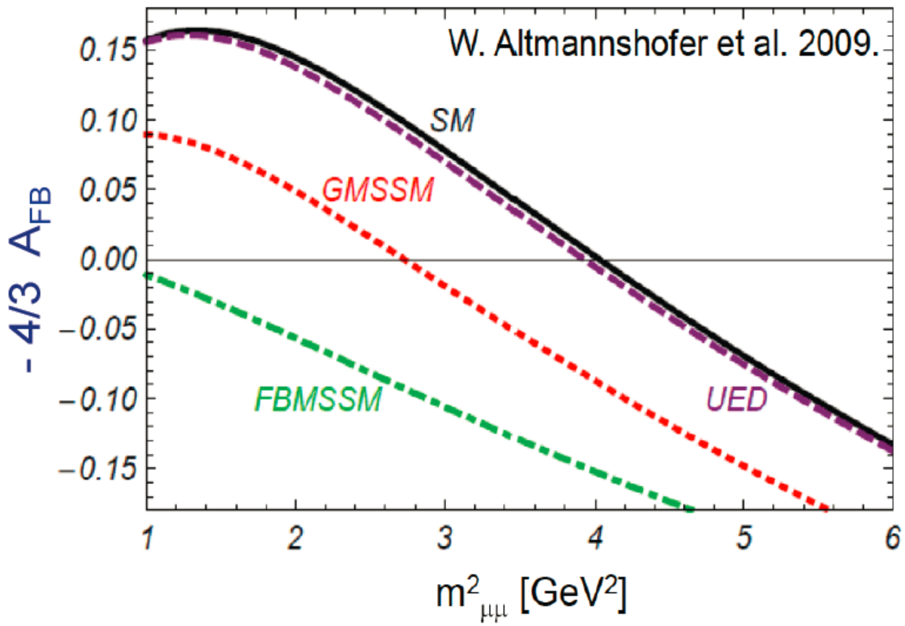


A_{FB} zero crossing point particularly well predicted within the SM

$$A_{FB} \propto -Re[(2C_7^{eff} + \frac{q^2}{m_b^2}C_9^{eff})C_{10}]$$

The SM forward-backward asymmetry in $b \to s\, l^+l^-$ arises from **interference** between ***γ*** and **Z^0** contributions

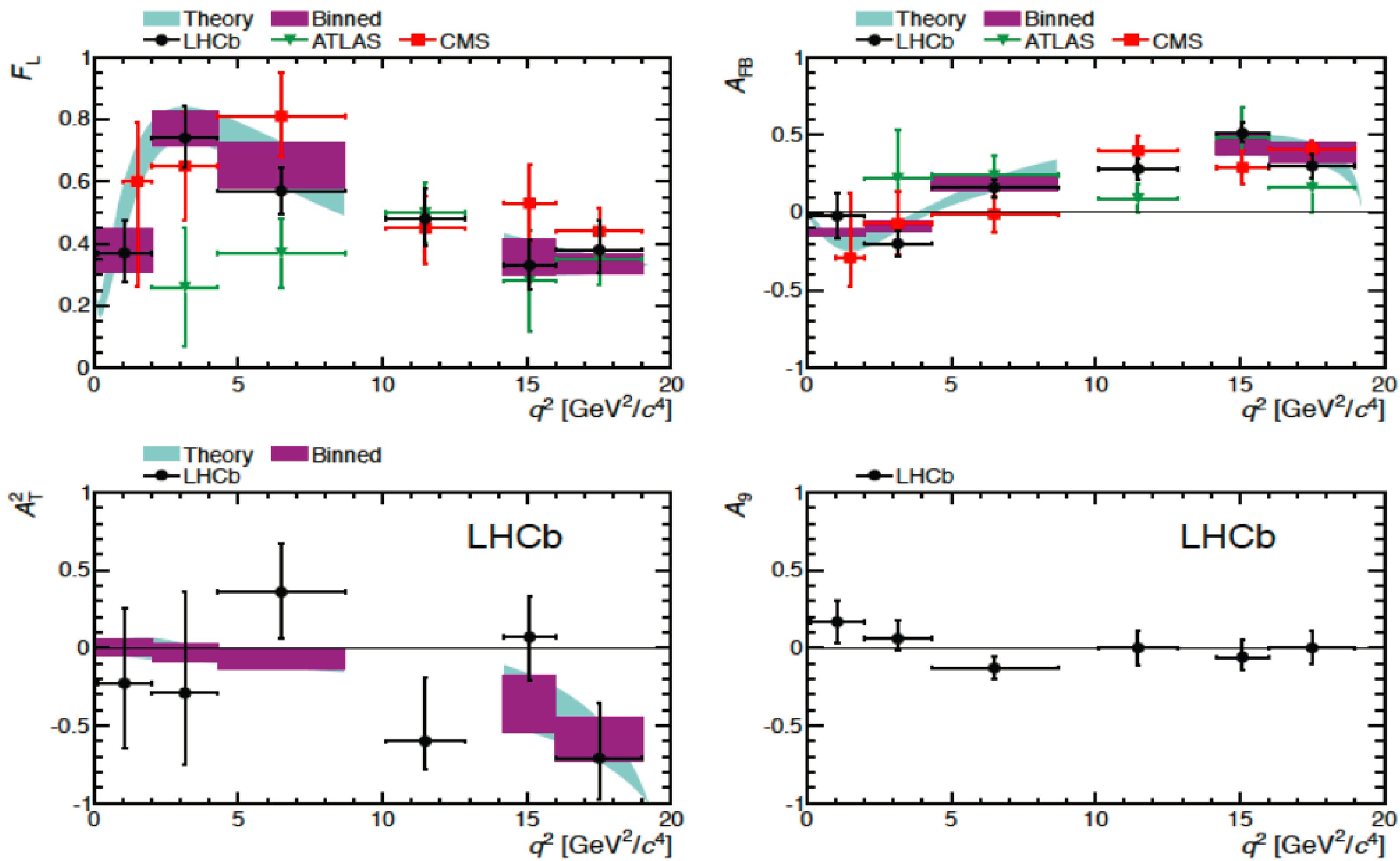




FBMSSM	Flavor Blind MSSM
GMSSM:	Non Minimal Flavor Violating MSSM
UED:	One universal extra dimension

$B^0 \to K^*\mu^+\mu^-$ - angular analysis results

Generally very good agreement with SM in the observables F_L, A_{FB}, S_3, A_9



LHCb 2012: First measurement of A_{FB} zero-crossing point: q_0=4.9±0.9 GeV^2/c^4

$B^0 \to K^*\mu^+\mu^-$ - angular analysis results

- Earlier we lost sensitivity to 4 terms to simplify the fit
- Now: extract the observables relater to those terms!

Other folding techniques, applying different transforms, can give access to the rest of observables:

S - standard observables

P - theoretically cleaner observables

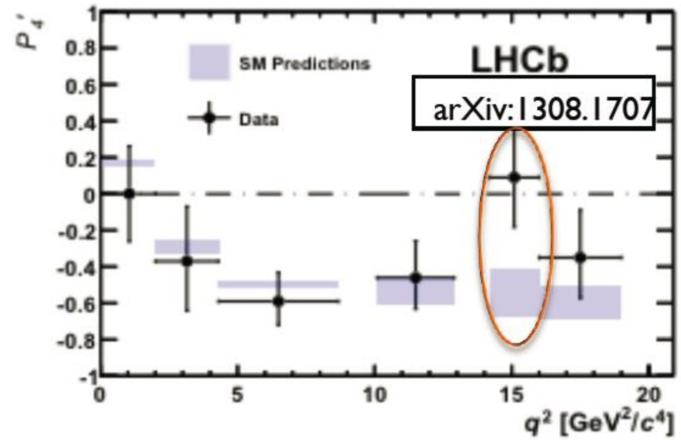
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

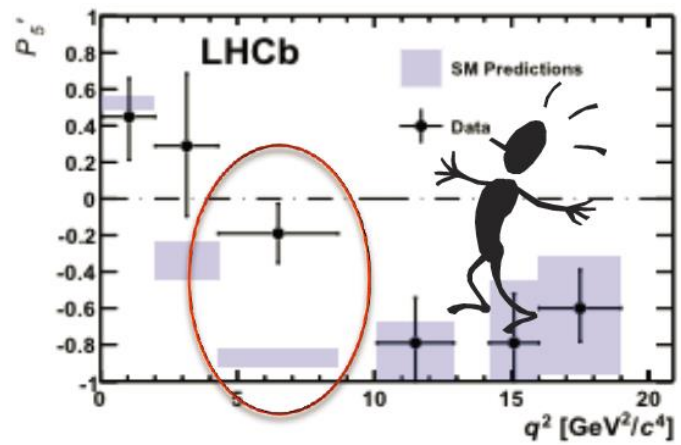
$$P'_4, S_4: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_5, S_5: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_6, S_7: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_8, S_8: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \to \pi - \theta_K & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases}$$



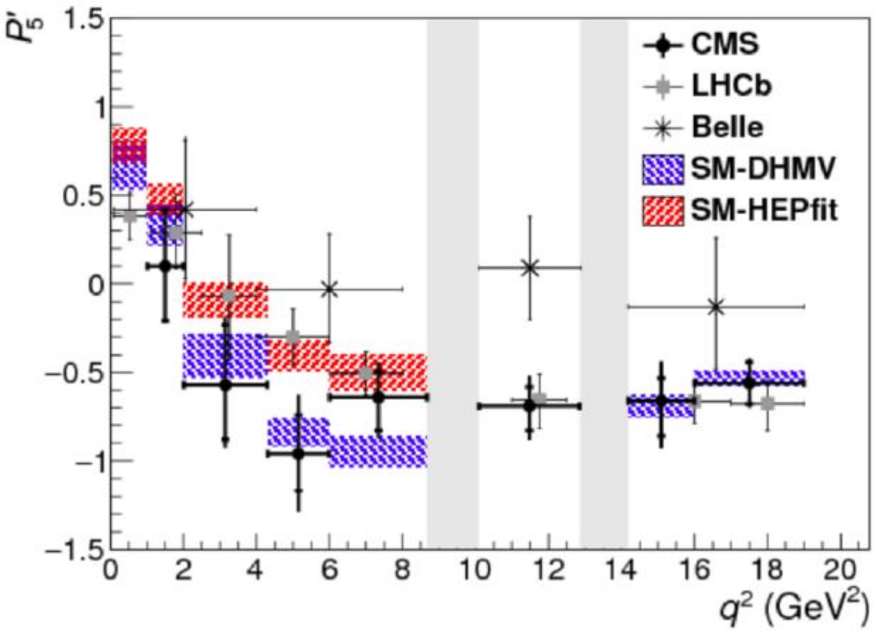


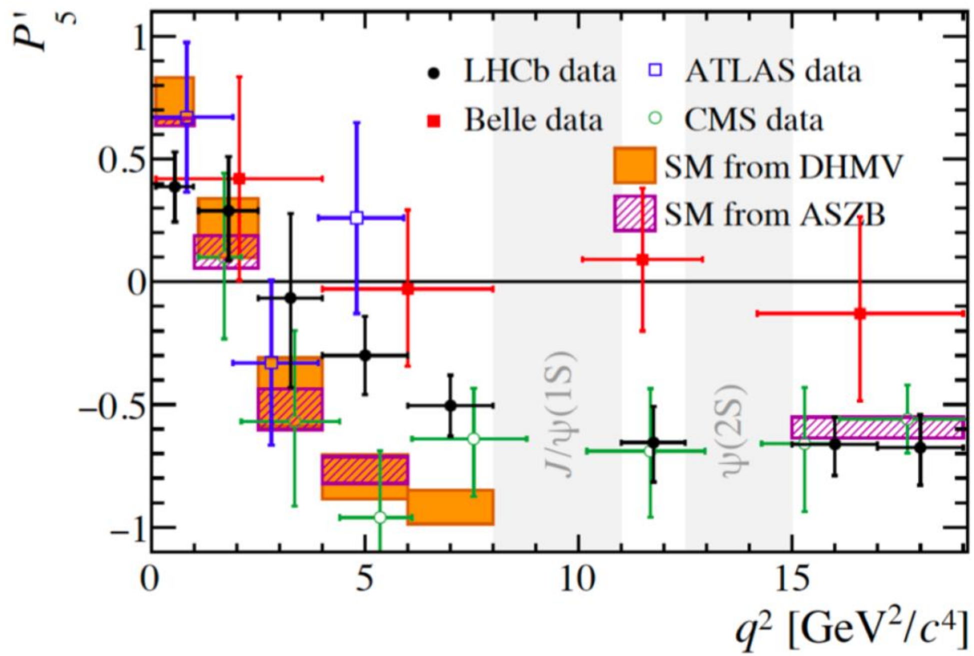
Local fluctuation in $P_5' > 3\sigma$ from the SM prediction has been observed

$B^0 \to K^*\mu^+\mu^-$ - angular analysis results

- LHCb performed first full angular analysis in 2016
  - → extracted full set of CP-averaged angular terms and correlations
  - → determined full set of CP-asymmetries

$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

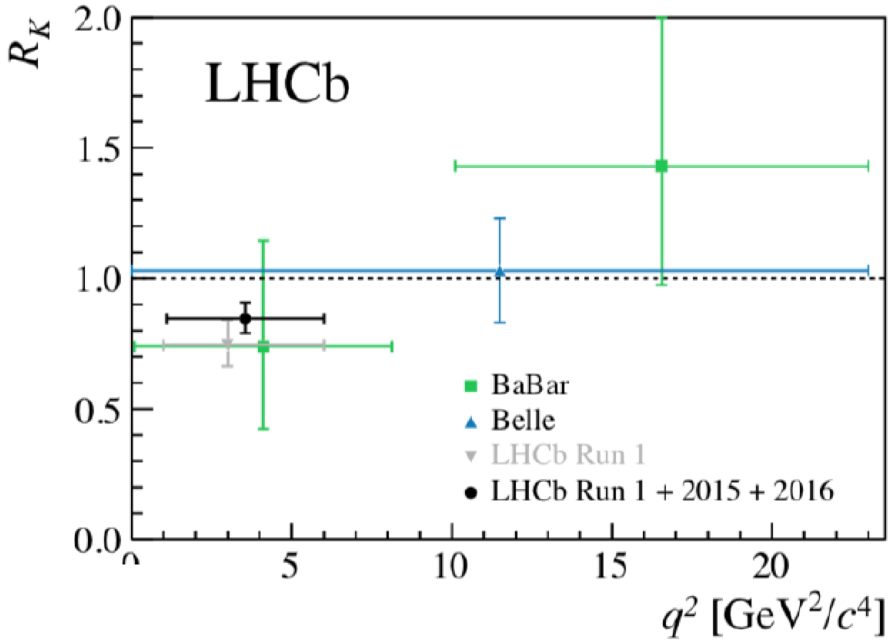


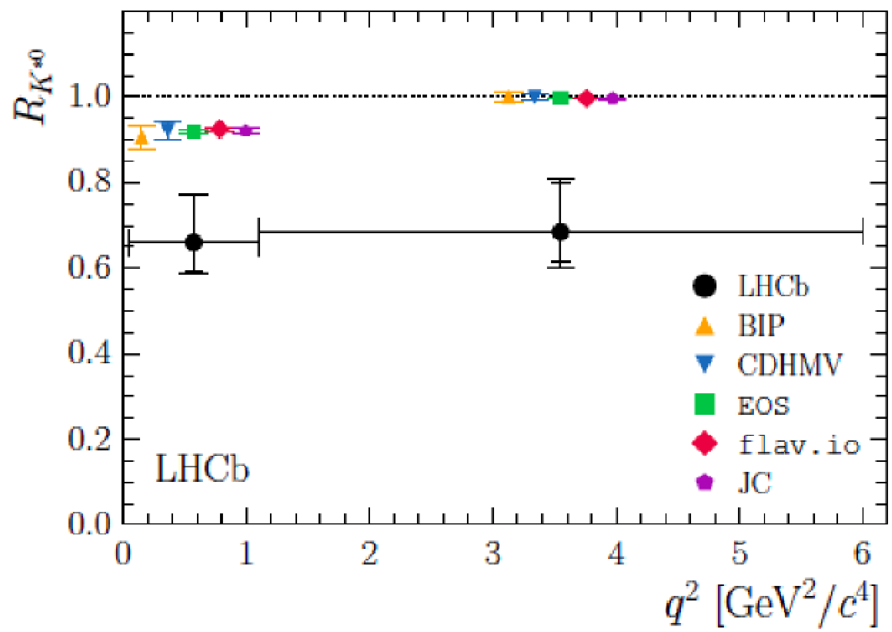


Differences with predictions based on the Standard Model at the level of 3.4 standard deviations

Lepton flavour universality tests

- In SM couplings of the gauge bosons to leptons are independent of lepton flavour
- Ratios of the form: $R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \overset{\text{SM}}{\cong} 1$
- Free from QCD uncertainties that affect other observables
  - $\to$ hadronic effects cancel, error is $O(10^{-4})$
  - $\to$ QED corrections can be $O(10^{-2})$





SM compatibility:

~2.5σ in $1.1 < q^2 < 6.0$ GeV^2

SM compatibility:

~2.2σ in low q^2, **~2.5σ** in central q^2

Interpretation of the anomaly

- Most of measurements in good agreement with SM predictions

  → only a hint of disagreement in P_5' at low q^2

- But, anyway: interesting local discrepancy in P_5'

  → few others tensions less significant in other observables

- Possibly due to:

  → statistical fluctuation

  → SM theoretical prediction not fully correct
  (QCD effects not fully understood…)

- New Physics:

→ different value for some Wilson coefficients, e.g. C_9, or C_9 and C_9', including the possibility of Z' particle with a mass around few TeV

$\Delta F=1$:
Higgs penguins

$B_s \to \mu^+\mu^-$

- Decay well predicted theoretically, and experimentally is exceptionally clean
- Within the SM, the time-integrated predicted value is very small:

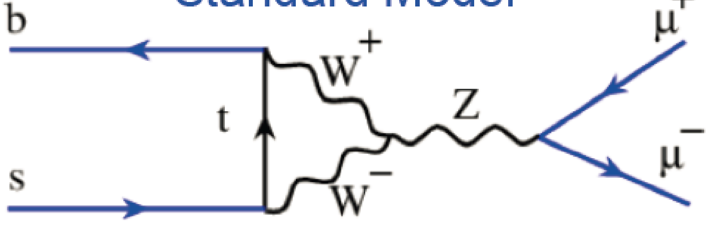
$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9}$$

- Huge NP enhancement ($\tan\beta$ = ratio of Higgs vevs)

$$BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

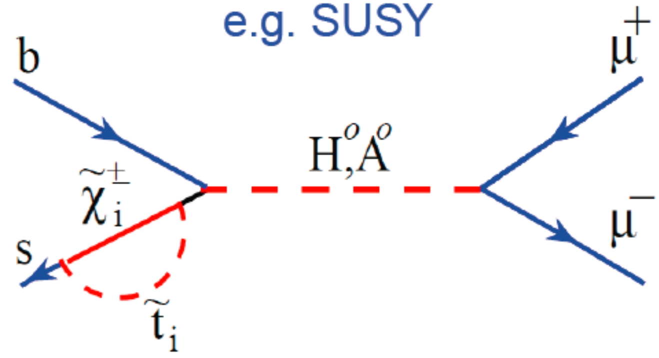
- Very **sensitive to an extended scalar sector** (e.g. extended Higgs, SUSY, etc.)
- Clean experimental signature

Standard Model



Left handed couplings
→ helicity suppressed

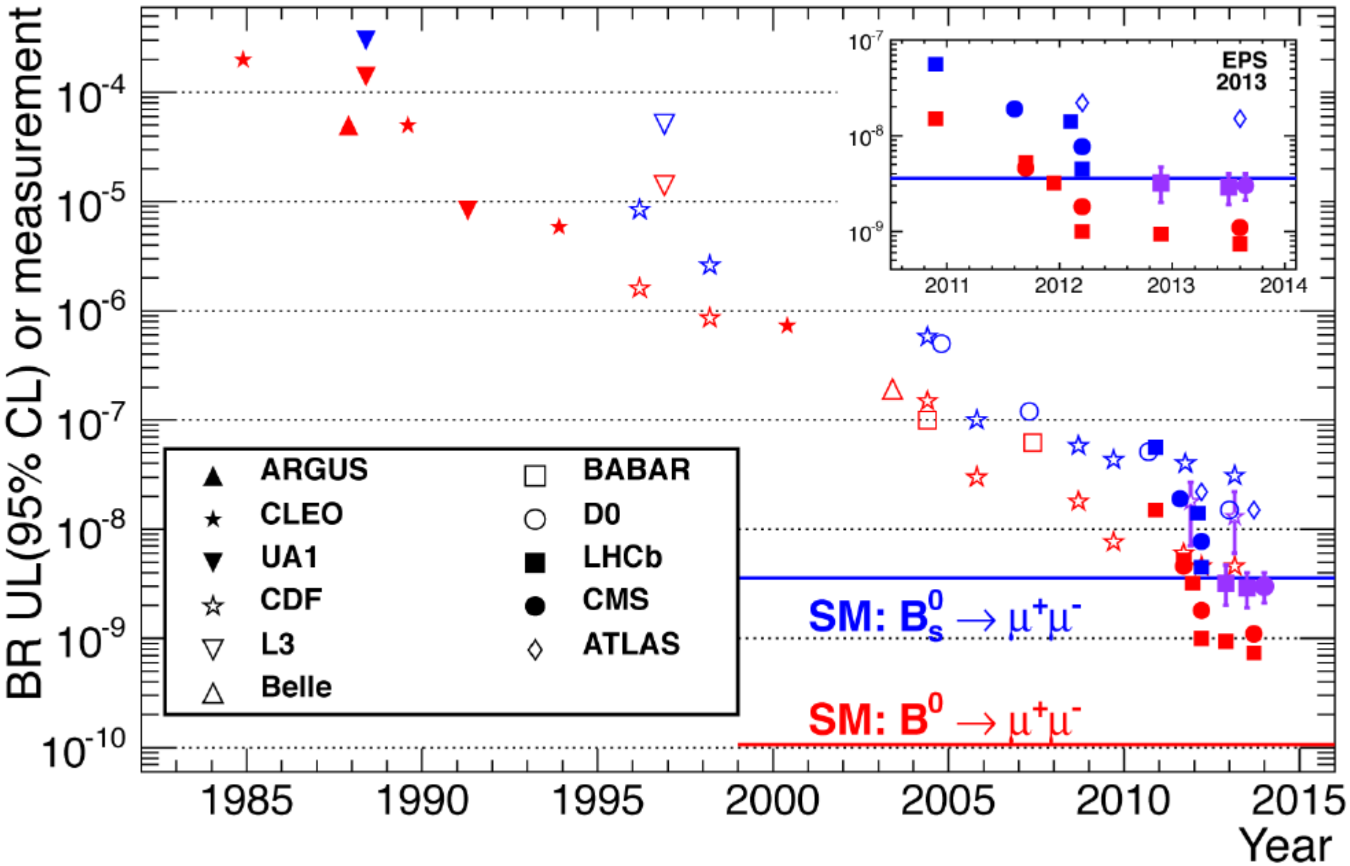
e.g. SUSY



Killer for new physics discovery!

$B^0_{(s)} \rightarrow \mu^+\mu^-$

- It was considered one of the hottest channels for early NP discovery at LHC ($B_d \rightarrow \mu^+\mu^-$ also interesting...)



Searches over 30 years

$B^0_{(s)} \to \mu^+\mu^-$: analysis ingredients

- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background

  → excellent vertex resolution (identify displaced vertex)

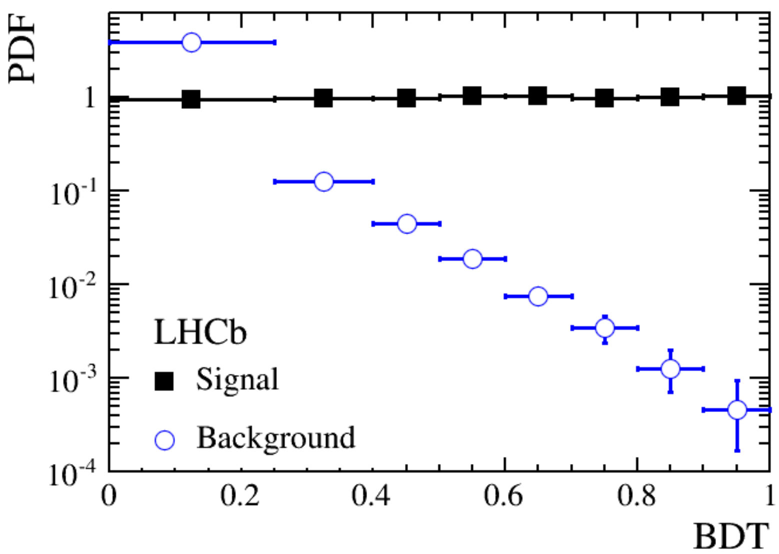
  → excellent mass resolution (identify B peak)

  - also essential to resolve B^0 from B_s^0 decays

  → powerful muon identification (reject background from B decays with misidentified pions)

  → typical to combine various discriminating variables into a multivariate classifier

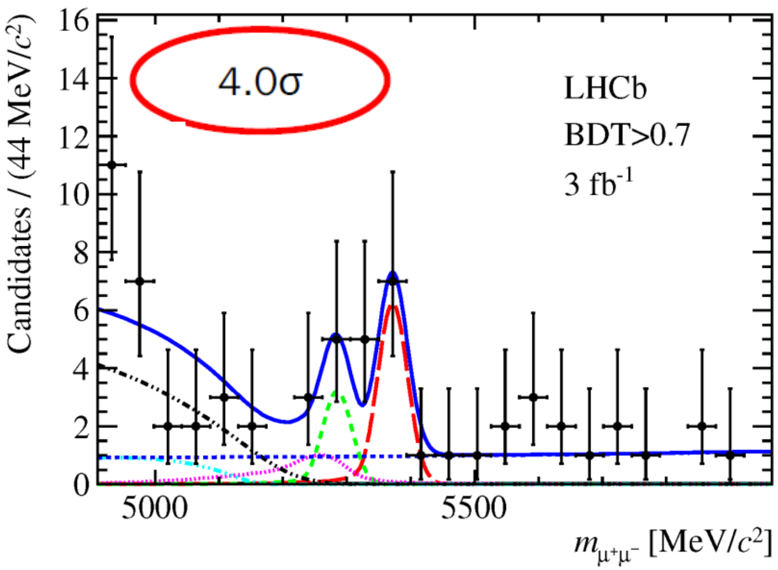
  - e.g. Boosted Decision Trees algorithm



$B_s \to \mu^+\mu^-$: latest results from CMS & LHCb

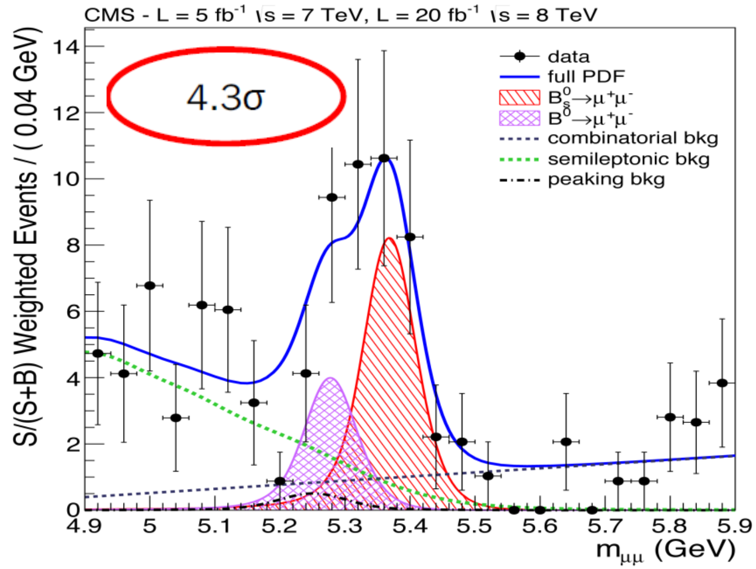
Nov 2012: LHCb found the first evidence for $B_s \to \mu^+\mu^-$ using 2.1 fb^{-1}

- Update: full dataset: 3 fb^{-1}
  - improved BDT
  - expected sensitivity: 5.0σ



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}) \times 10^{-10}$$

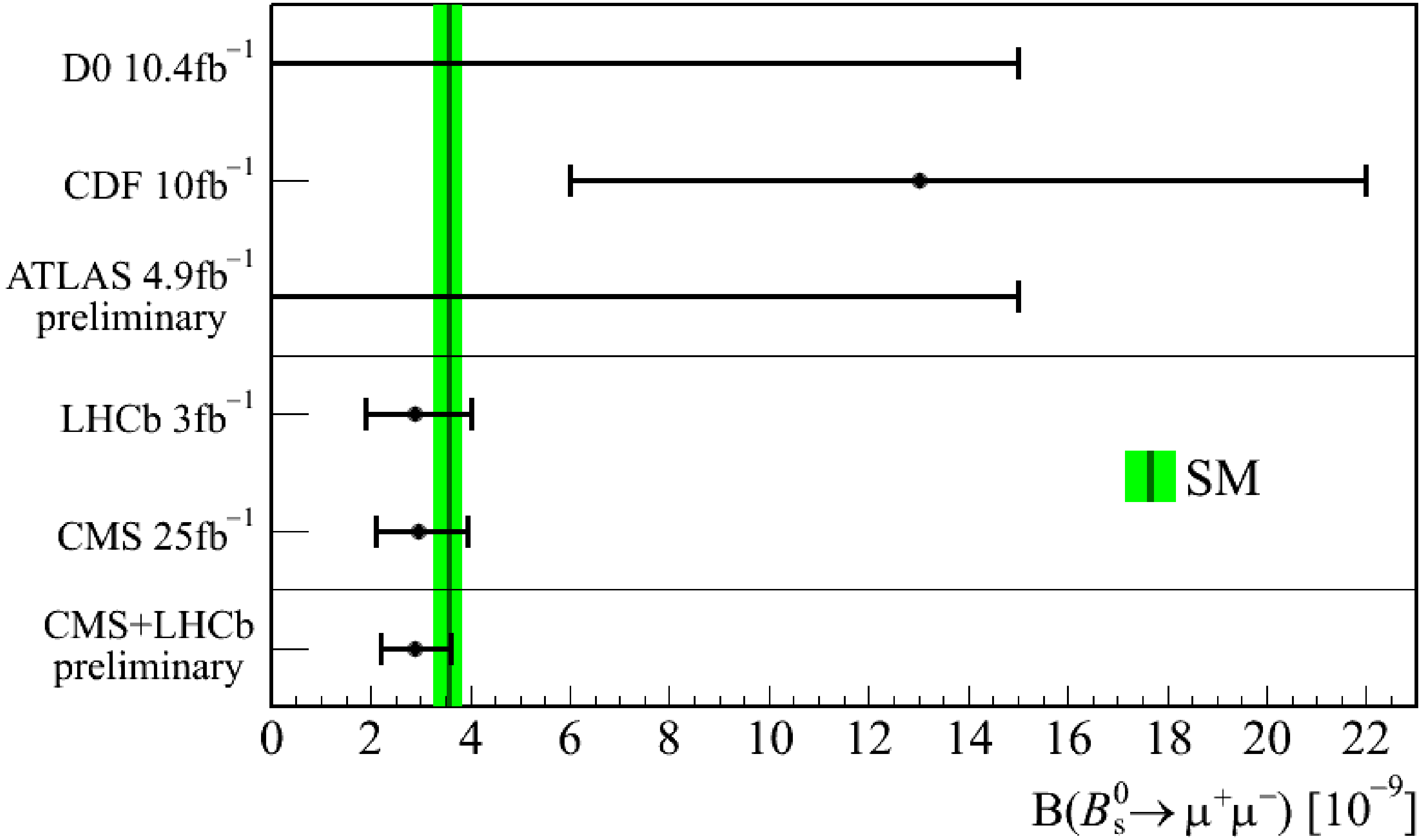
- Update to 25 fb^{-1}
  - cut based → BDT based
  - improved variables
  - expected sensitivity: 4.8σ



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5\,^{+2.1}_{-1.8}) \times 10^{-10}$$

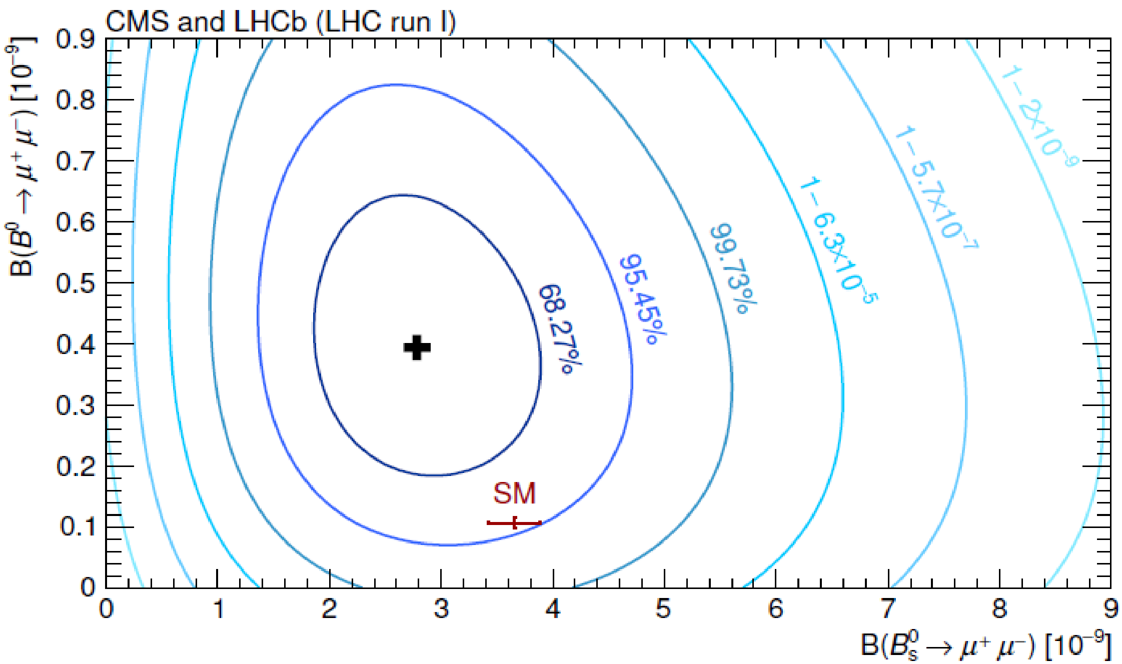
$B_s \to \mu^+\mu^-$: combined LHCb + CMS result

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$



Implications of $B_s \to \mu^+\mu^-$

The measured BR is compatible with the SM prediction



Strong constraints on many New Physics models

→ together with direct searches:

constrained MSSM models (almost) excluded

Important key measurements:

- ratio of decay rates of $B^0 \to \mu^+\mu^-$ / $B_s \to \mu^+\mu^-$

  → allows e.g. to test of „Minimal Flavour Violation" hypothesis

- lifetime of $B_s \to \mu^+\mu^-$

  → new, theoretically clean observable that is largely unconstrained