Flavor Physics with LHCb

<u>Outline:</u>

- Flavor Physics
- Flavor production at the LHC & LHCb
- Neutral Meson Mixing and CP Violation
- Direct CPV and precision CKM metrology (γ)
- Rare decays
- Future

Ulrich Uwer • Physikalisches Institut • Universität Heidelberg

What is Flavor Physics?

Fundamental matter comes in three generations carrying the same charges under the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)$:

Leptons			Quarks		
e	μ	τ	uuu	ccc	ttt
ν_e	ν_μ	ν_τ	ddd	sss	bbb

Heavy mesons:

D^0 ($c\bar{u}$), D^+ ($c\bar{d}$)

B^0 ($\bar{b}d$), B^+ ($\bar{b}u$), B_s ($\bar{b}s$)

Flavor is **the feature** that distinguishes the generations.

Flavor physics studies the complex phenomenology:

- masses ranging over 12 orders of magnitude (sub-eV neutrino - 173 GeV top)
- flavor transitions (mixing)
- CP Violation

Flavor within the Standard Model

Yukawa interaction couples fermions to Higgs. For the quarks:

$$\mathcal{L}_{\mathrm{Y}}^{\mathrm{quarks}} = -\frac{v}{\sqrt{2}}\left(\overline{d}_{\mathrm{L}}\, Y_d\, d_{\mathrm{R}} + \overline{u}_{\mathrm{L}}\, Y_u\, u_{\mathrm{R}}\right) + \mathrm{h.c}$$

After electroweak symmetry breaking

Y_d, Y_u are 3×3 complex matrices in generation space

not diagonal $\rightarrow$ flavor structure

Mass eigenstates of the quarks obtained by unitary transformations:

$\tilde{q}_A = V_{A,q} q_A$ for $q = u, d$ and $A = L, R$ where $V_{A,q} V_{A,q}^{\dagger} = 1$

$V_{A,q}$ are determined by requiring that the matrices $M_{d,u}$ are diagonal:

$$M_d = \mathrm{diag}(m_d, m_s, m_b) = \frac{v}{\sqrt{2}} V_{\mathrm{L},d}\, Y_d\, V_{\mathrm{R},d}^{\dagger}$$

Quark masses

After this transformation quark masses appear as usual Dirac terms:

$$\mathcal{L}_{\mathrm{Y}}^{\mathrm{quarks}} = -\overline{\tilde{d}}_{\mathrm{L}} M_d \tilde{d}_{\mathrm{R}} - \overline{\tilde{u}}_{\mathrm{L}} M_u \tilde{u}_{\mathrm{R}} + \mathrm{h.c.}$$

Up-type and down-type quarks cannot be diagonalized by the same matrix, i.e. $V_{\mathrm{A},d} \neq V_{\mathrm{A},u}$ $\rightarrow$ net effect on flavor structure of charged current.

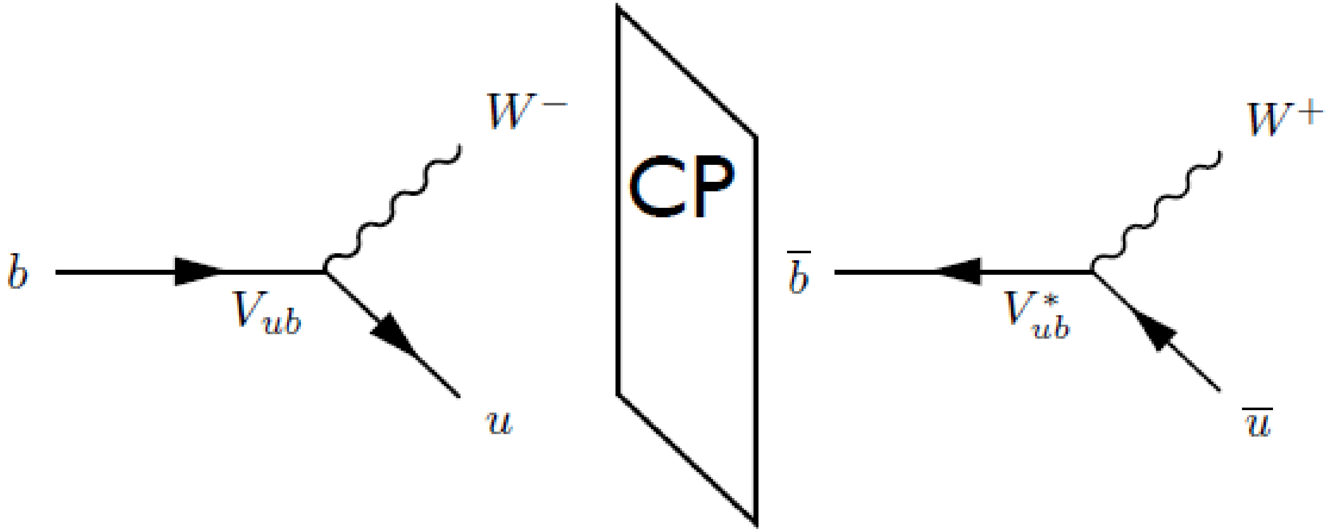
$$\mathcal{L}_{\mathrm{CC}} = -\frac{g_2}{\sqrt{2}} \left(\overline{\tilde{u}}_{\mathrm{L}} \gamma^{\mu} W_{\mu}^{+} V_{\mathrm{CKM}} \tilde{d}_{\mathrm{L}} + \overline{\tilde{d}}_{\mathrm{L}} \gamma^{\mu} W_{\mu}^{-} V_{\mathrm{CKM}}^{\dagger} \tilde{u}_{\mathrm{L}} \right)$$

with $V_{\mathrm{CKM}} = V_{\mathrm{L},u} V_{\mathrm{L},d}^{\dagger}$ (must be unitary)

Violates CP if $\boldsymbol{V_{CKM}}$ is complex:

$$\mathcal{L}_{\mathrm{CC}}^{\mathrm{CP}} = -\frac{g_2}{\sqrt{2}} \left(\overline{\tilde{d}}_{\mathrm{L}} \gamma^{\mu} W_{\mu}^{-} V_{\mathrm{CKM}}^{\mathrm{T}} \tilde{u}_{\mathrm{L}} + \overline{\tilde{u}}_{\mathrm{L}} \gamma^{\mu} W_{\mu}^{+} V_{\mathrm{CKM}}^{*} \tilde{d}_{\mathrm{L}} \right) .$$

CP violation for pedestrians



CP (T) violation possible if $V_{ji} \neq V_{ji}^*$

CKM Matrix

Complex and unitary 3×3 matrix:

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

Complex 3×3 matrix: 18 parameters
+ unitarity condition (9 parameters)
+ removal of 5 unobservable phases results into
$\rightarrow$ 4 free parameter:

3 Euler angles and one phase δ:

Parametrization

$$s_{ij} \equiv \sin\theta_{ij} \text{ and } c_{ij} \equiv \cos\theta_{ij}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} = 2.38±0.06°,

θ_{13} = 0.201±0.011°,
δ_{13} = 1.20±0.08 rad.

θ_{12} = 13.04±0.05°

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

from PDG

Wolfenstein Parametrization

Reflects the hierarchical structure of the CMK matrix

λ, A, ρ, η with $\lambda = 0.22$

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

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

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

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

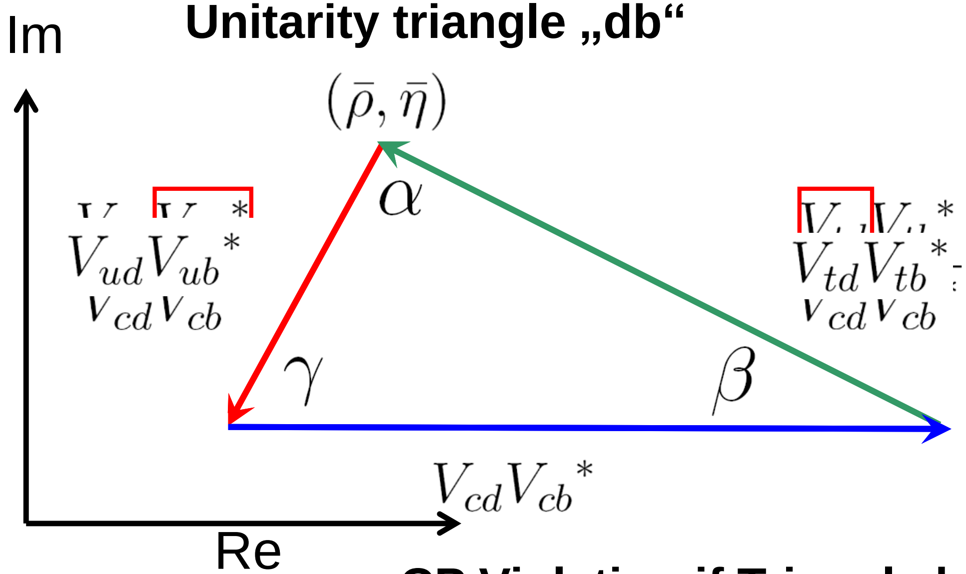
$|V_{ts}| \times e^{i\beta_s}$

Unitarity of CKM Matrix $V_{CKM}^{\dagger} V_{CKM} = 1$

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

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

Unitarity triangle „db“



CKM Phases **b→u**

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

t→d

CP Violation if Triangle has finite area !

More Triangles …

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

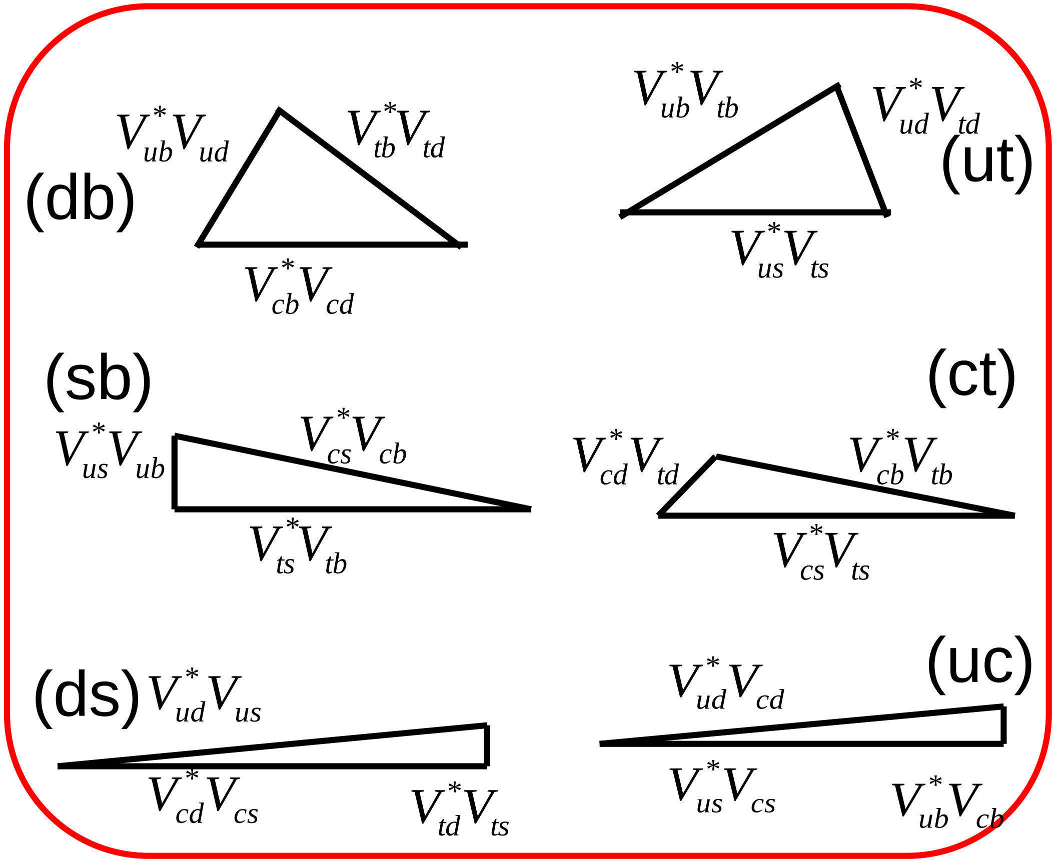
$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0 \text{ (sb)}$$

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

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

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

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

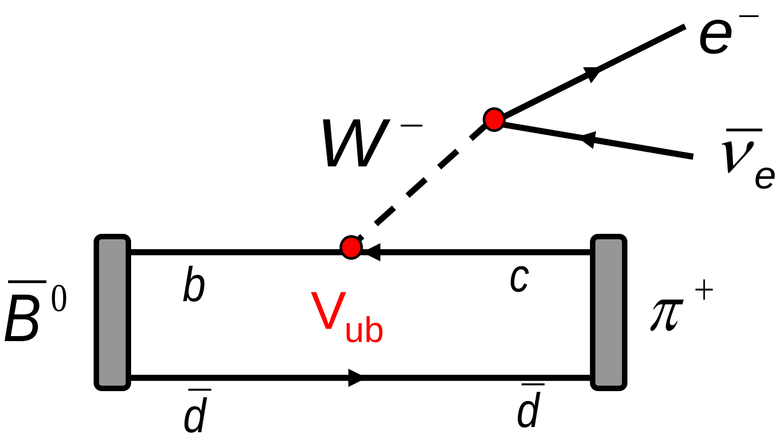


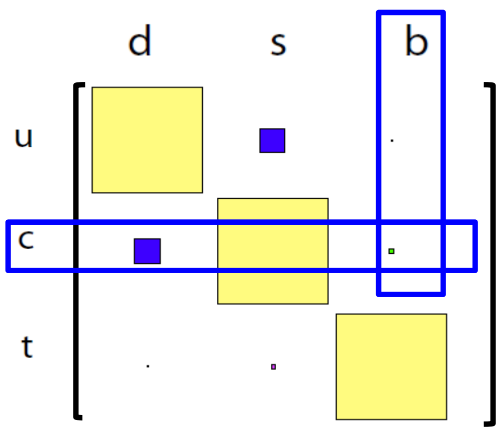
All 6 triangles have the same area: $J_{CP}/2$

J_{CP} is called Jarlskog invariant, it is a measure of CPV in Standard Model.

$$J_{CP} = \mathcal{Im}\left(V_{ij}\, V_{kl}\, V_{il}^{*} V_{kj}^{*}\right) \approx 3 \cdot 10^{-5}$$

Weak b Hadron Decays

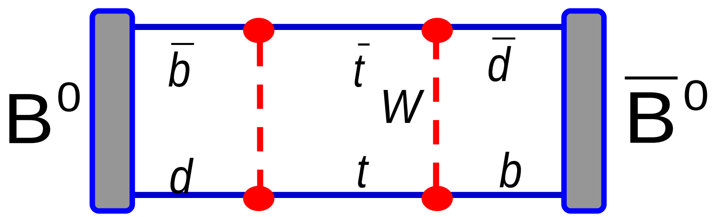


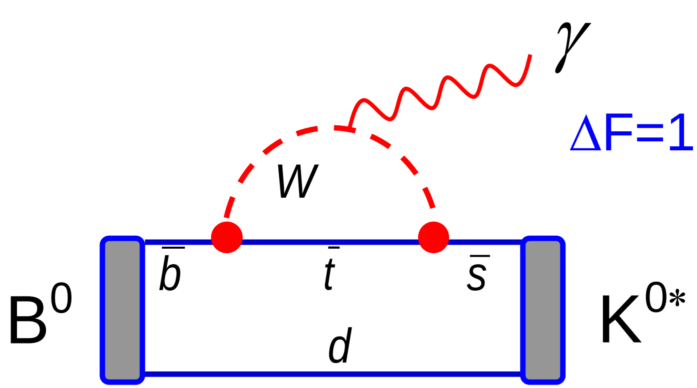


b cannot decay into top quark

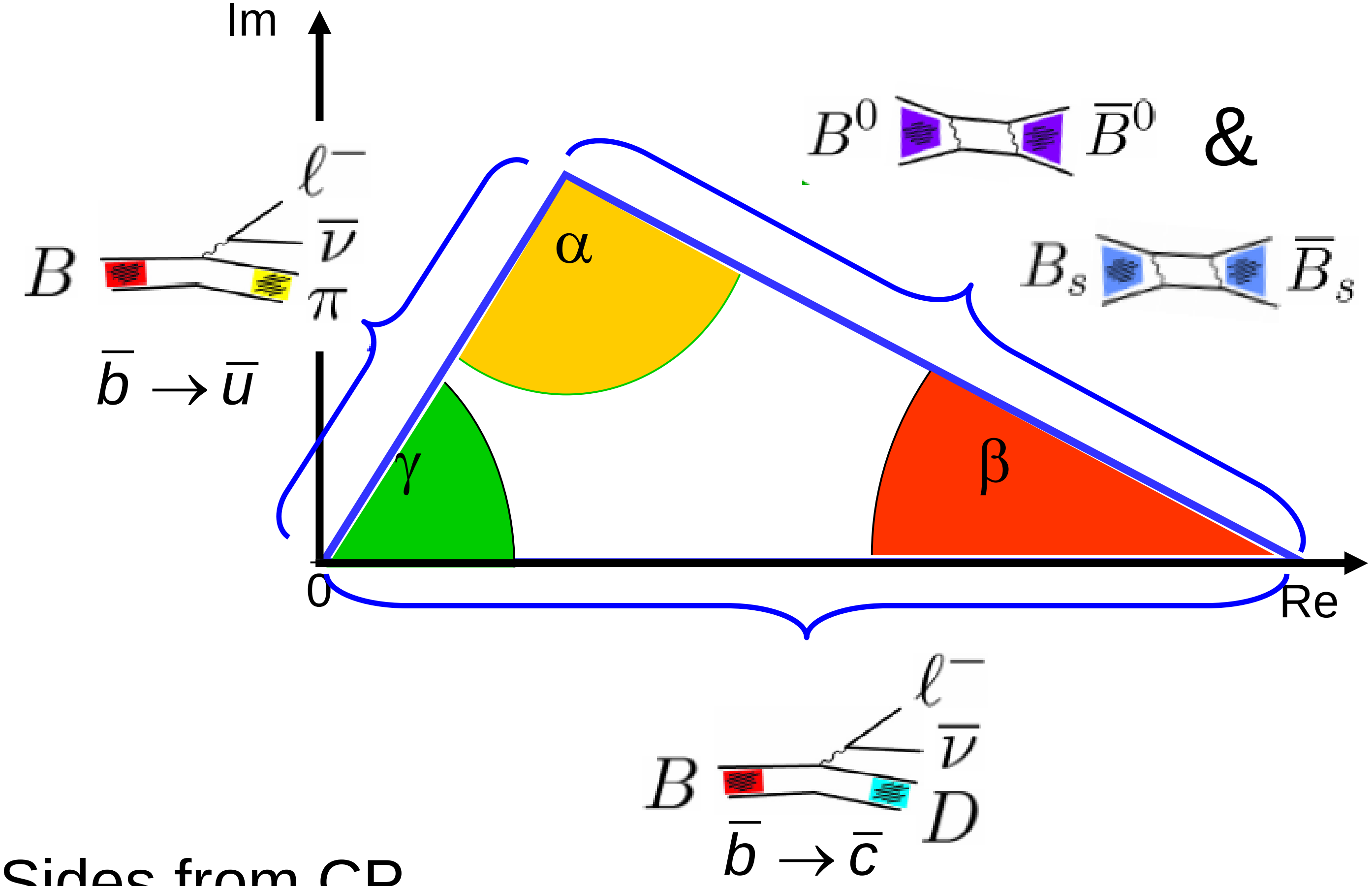
Tree decays “CKM” suppressed:
→ Loop corrections important.

Flavor Changing Neutral Current (FCNC) Processes:





Unitarity Triangle from B Decays

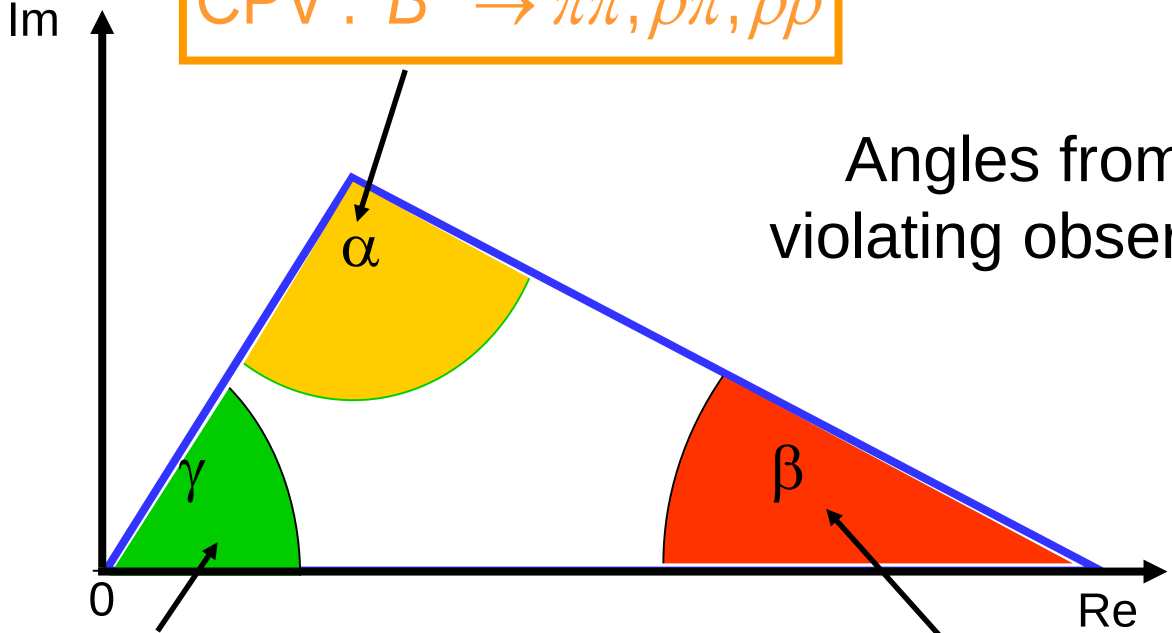


Sides from CP conserving observables

Unitarity Triangle from B Decays

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

Angles from CP violating observables

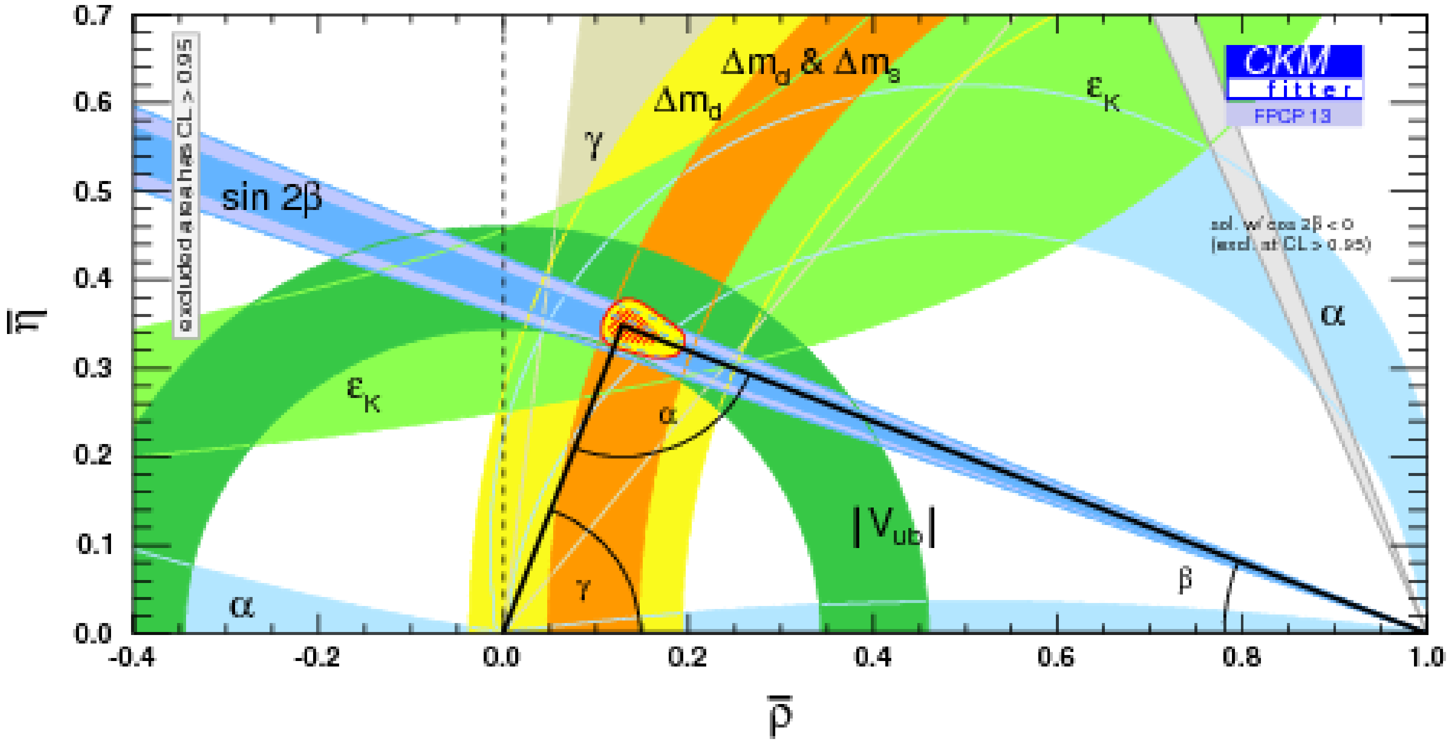


CPV : $B^0 \to DK^{(*)}, DK_S^0, K\pi, D^*\pi$

$B_s^0 \to D_s K, KK$

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

Status of CKM Metrology



CKM mechanism is primary source of observed CPV in quark sector.
Physics Beyond Standard Model → corrections to Standard Model.

<u>New physics constraints from quark flavor sector:</u> *(Z.Ligeti)*

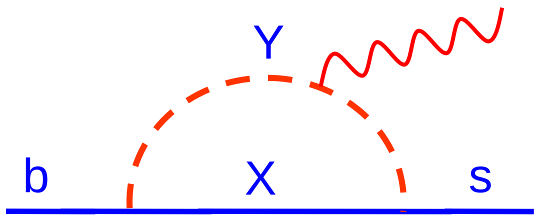
$\text{NP} \lesssim (\text{few} \times \text{SM}) \rightarrow \text{NP} \lesssim (0.3 \times \text{SM}) \rightarrow \text{NP} \lesssim (0.05 \times \text{SM})$

(2003) (2013) (2023)

Searching for New Physics

- If energy is high enough we can discover NP detecting the production of “real” new heavy particles

- If the precision of the measurements is high enough we can discover NP due to effect of “virtual” new particles in loops also at low scales



Why do we think we are sensitive?

Slide from Z.Ligeti

- All flavor changing processes depend only on a few parameters in the SM
  $\Rightarrow$ correlations between large number of s, c, b, t decays

- The SM flavor structure is very special:
  - Single source of CP violation in CC interactions
  - Suppressions due to hierarchy of CKM elements
  - Suppression of FCNC processes (loops)
  - Suppression of FCNC chirality flips by quark masses (e.g., $B \to K^*\gamma$)

  Many suppressions that NP might not respect $\Rightarrow$ probe very high scales

- It is interesting and possible to look for NP contributions with better sensitivity

"Ancient" history: 3-quark model and $K^0 \to \mu\mu$

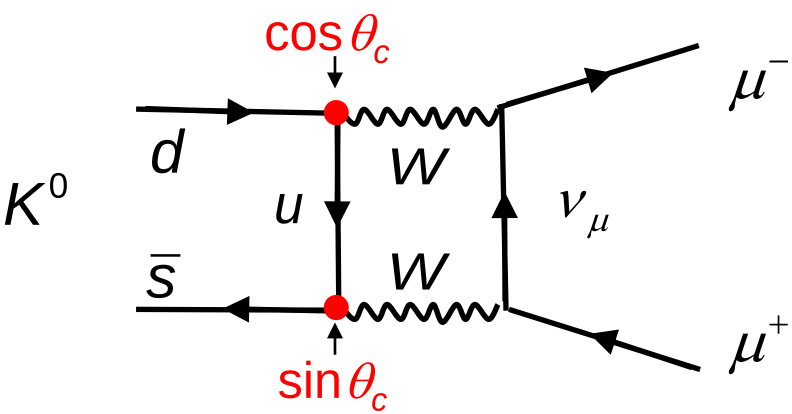
3-quark model and strange decays:

$$\begin{pmatrix} |u\rangle \\ |d'\rangle \end{pmatrix} = \begin{pmatrix} |u\rangle \\ \underbrace{\cos\theta_C}_{=\mathbf{V}_{ud}} |d\rangle + \underbrace{\sin\theta_C}_{=\mathbf{V}_{us}} |s\rangle \end{pmatrix}$$

Suppression of ΔS=1 decays:

Cabibbo mixing angle $\theta_C \approx 13°$ leads to additional factor of $\sin^2\theta_C = 0.05$ for $s \to u$ decays

Problem: $K^0 \to \mu^+\mu^-$



$$\mathcal{A} \sim \sin\theta_c \cos\theta_c$$

Observation:

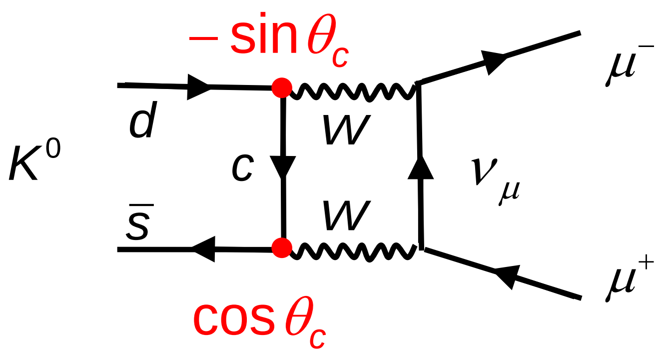
$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

4^{th} quark and GIM Mechanism

New up-type quark $\rightarrow$ 2^{nd} quark generation

$$\begin{pmatrix} u \\ d' \end{pmatrix} \qquad \begin{pmatrix} c \\ s' \end{pmatrix} \qquad \text{where} \qquad \begin{pmatrix} |d'\rangle \\ |s'\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_c \cdot |d\rangle + \sin\theta_c \cdot |s\rangle \\ -\sin\theta_c \cdot |d\rangle + \cos\theta_c \cdot |s\rangle \end{pmatrix}$$

Additional amplitude:



$$\mathcal{A} \sim -\sin\theta_c \cos\theta_c$$

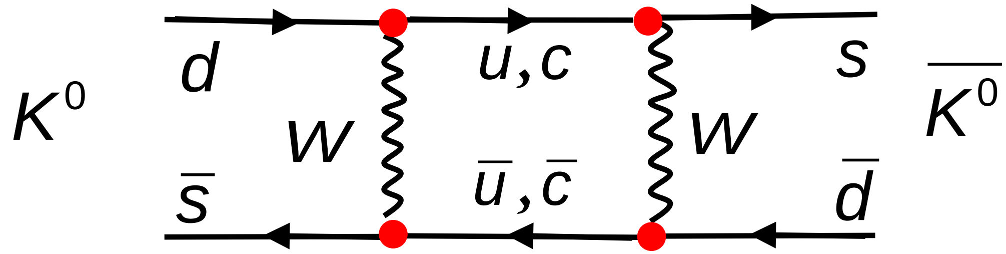
In cases of equal d-type quark masses the two amplitudes cancel each other: No FCNCs.

Glashow, Iliopoulos, Maiani,
Phys. Rev. D 2 (1970) 1285.

GIM Mechanism

Phys. Rev. D 2 (1970) 1285.

K^0 Mixing:



Mixing frequency:

$$\Delta m_{SM} \propto G_F^2 (\cos^2\theta \sin^2\theta\, f(m_u) - \cos^2\theta \sin^2\theta\, f(m_c)) \approx G_F^2 m_c^2 \cos^2\theta \sin^2\theta$$

From the GIM paper:

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

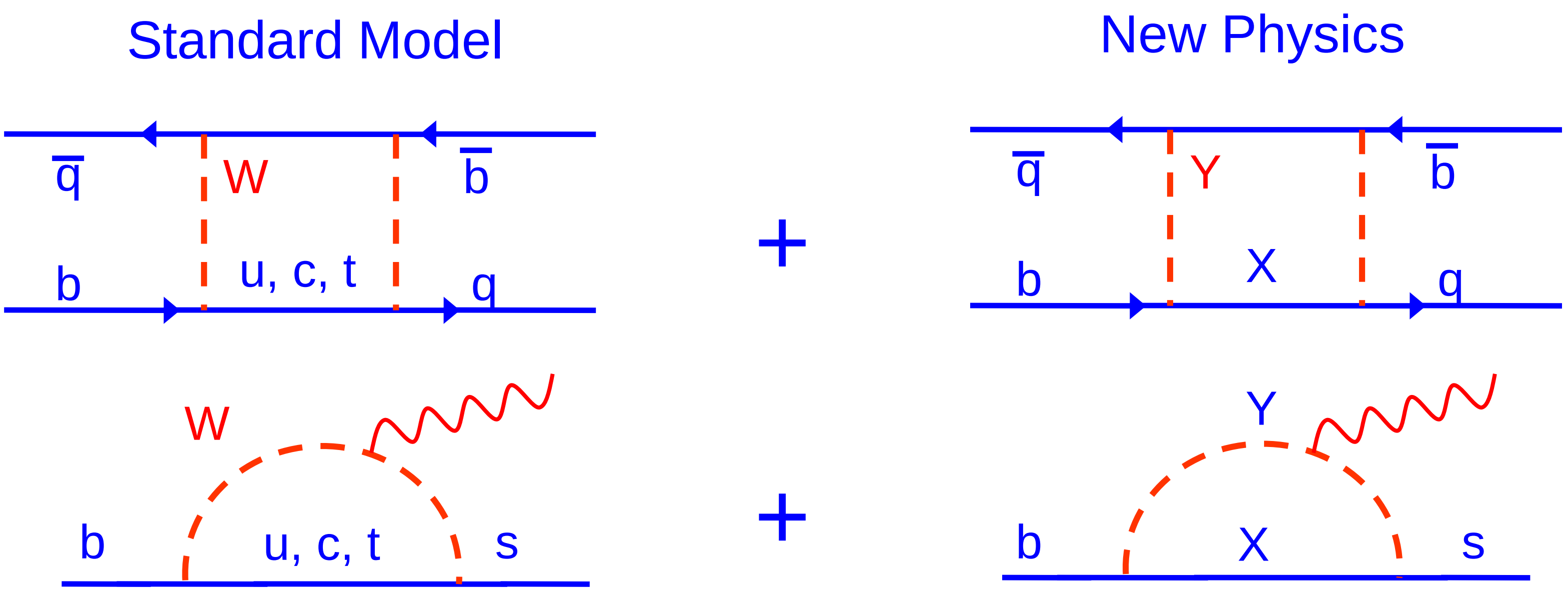
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

… and from the observed $K_1 K_2$ mass difference we now conclude that Δ must be not larger than 3–4 GeV.

New Physics in Quantum Loops

New Physics are corrections to Standard Model processes:



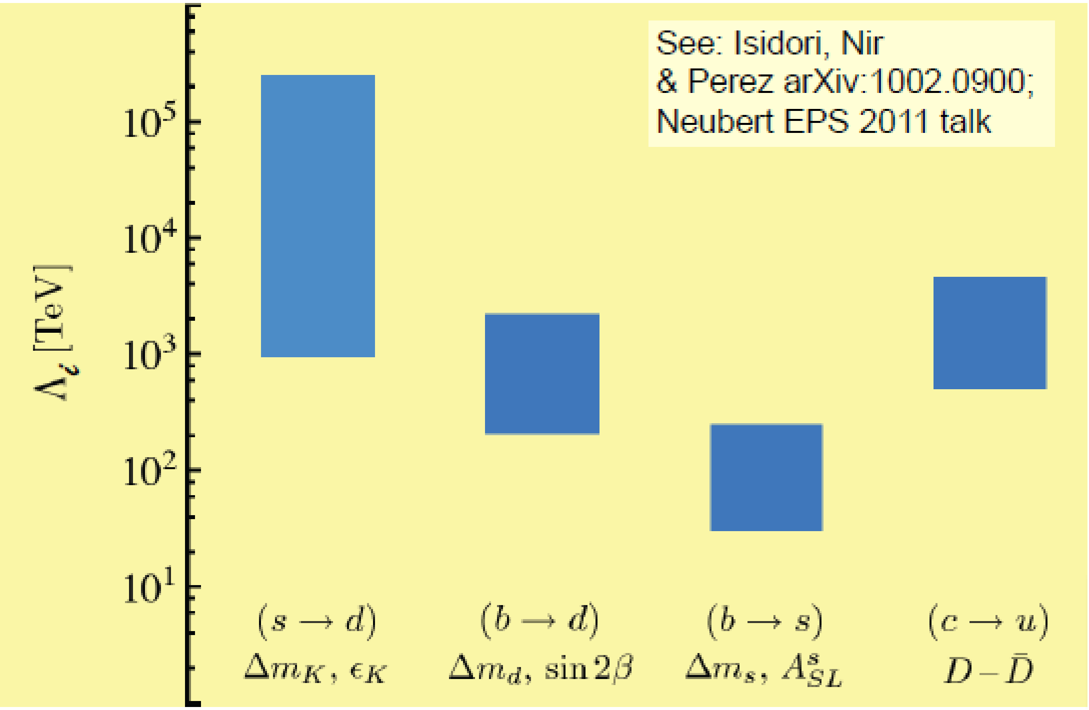
$$\mathcal{A}_{SM} + \mathcal{A}_{NP}$$

$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda_{NP}^2}} \right)$$

What is the scale of Λ_{NP} ? Size of C_{NP} and alignment w/r to C_{SM} ?

The Flavor Problem

excluded NP scales
for generic flavor
models C_{NP}=1



Possible scenarios:
- new particles indeed have very large masses.
- new particles have degenerated masses
- mixing angles in new flavor sector are small, similar to SM

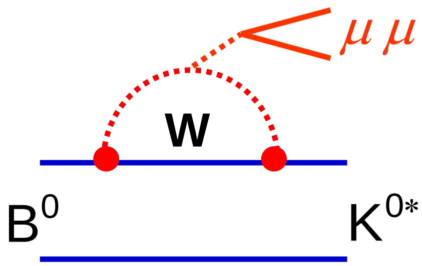
Flavor Problem: Absence of NP effects in flavor physics implies non-natural "fine tuning" if NP at TeV scale exists: Minimal flavor violation (MFV)

LHCb Search Strategies for NP

Adapted from U.Egede

Explore FCNC transitions with large sensitivity to NP, especially $b \to s$ transitions (poorly constrained by earlier experiments)

- B_s mixing phase ϕ_s
- Penguin and rare decays:
  $B_s \to \phi\gamma$, $B^0 \to K^* \mu\mu$, $B_s \to \mu\mu$
- but also CP violation in D decays



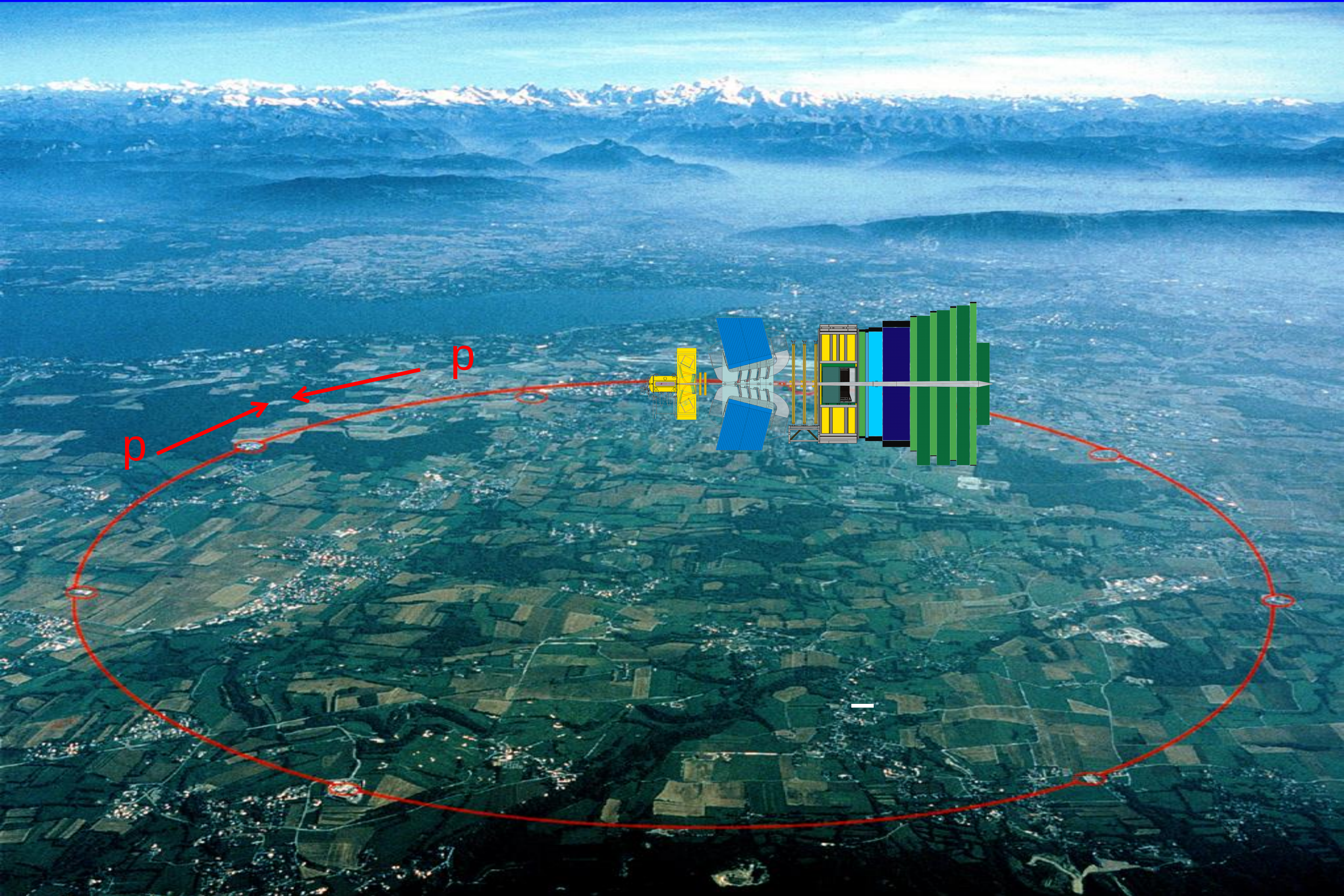
measurements w/ NP discovery potential

Improve CKM elements and challenge the SM by over- constraints:

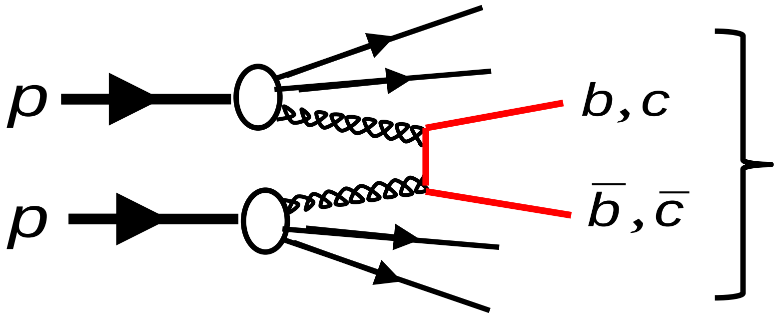
- Precise determination of angle γ
- Compare tree versus loop results

Precision CKM metrology

LHC and the LHCb Experiment



Heavy flavor production at LHC



$B^{\pm}$	40%
B^0	40%
B_s	10%
b-baryons	10%

Predictions at $\sqrt{s}$ = 7 TeV:

$\sigma_{b\bar{b}}$ ~ **250 μb**

200 kHz / 2 MHz (LHCb / CMS)

Every 400th collision with $b\bar{b}$

$\sigma_{c\bar{c}} \approx$ **20**× $\sigma_{b\bar{b}}$

@ 8 TeV → + 15% $b\bar{b}$
@ 14 TeV → + 100% $b\bar{b}$

LHCb Measuremens at $\sqrt{s}$ = 7 TeV:

$$\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\ \mu b$$

Eur. Phys. J. C 71 (2011) 1645.

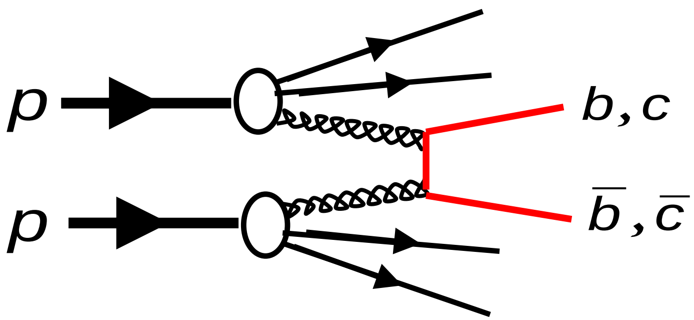
$$f_s/f_d = 0.256 \pm 0.020$$

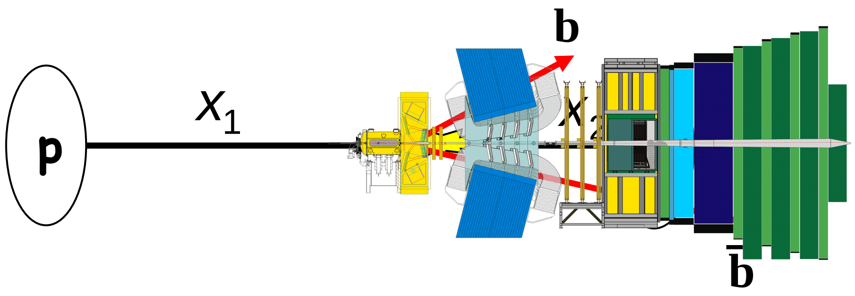
JHEP. 04 (2013) 001

$$\sigma(pp \to c\bar{c}X) = 6.10 \pm 0.93 mb$$

LHCb-CONF-2010-013

Heavy flavor production at LHCb

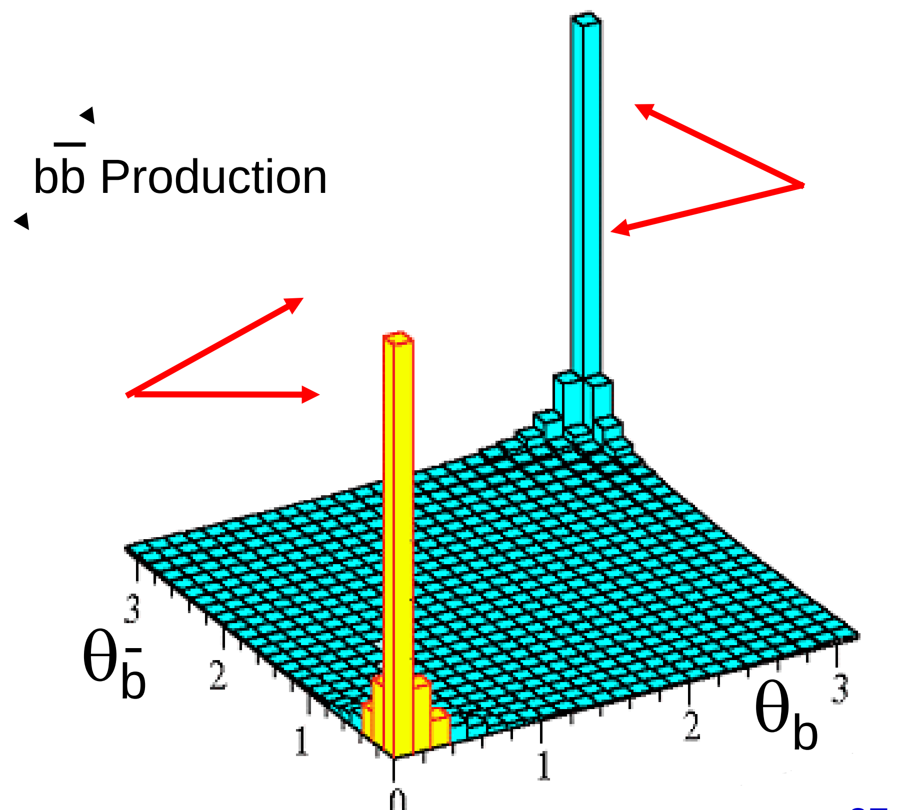




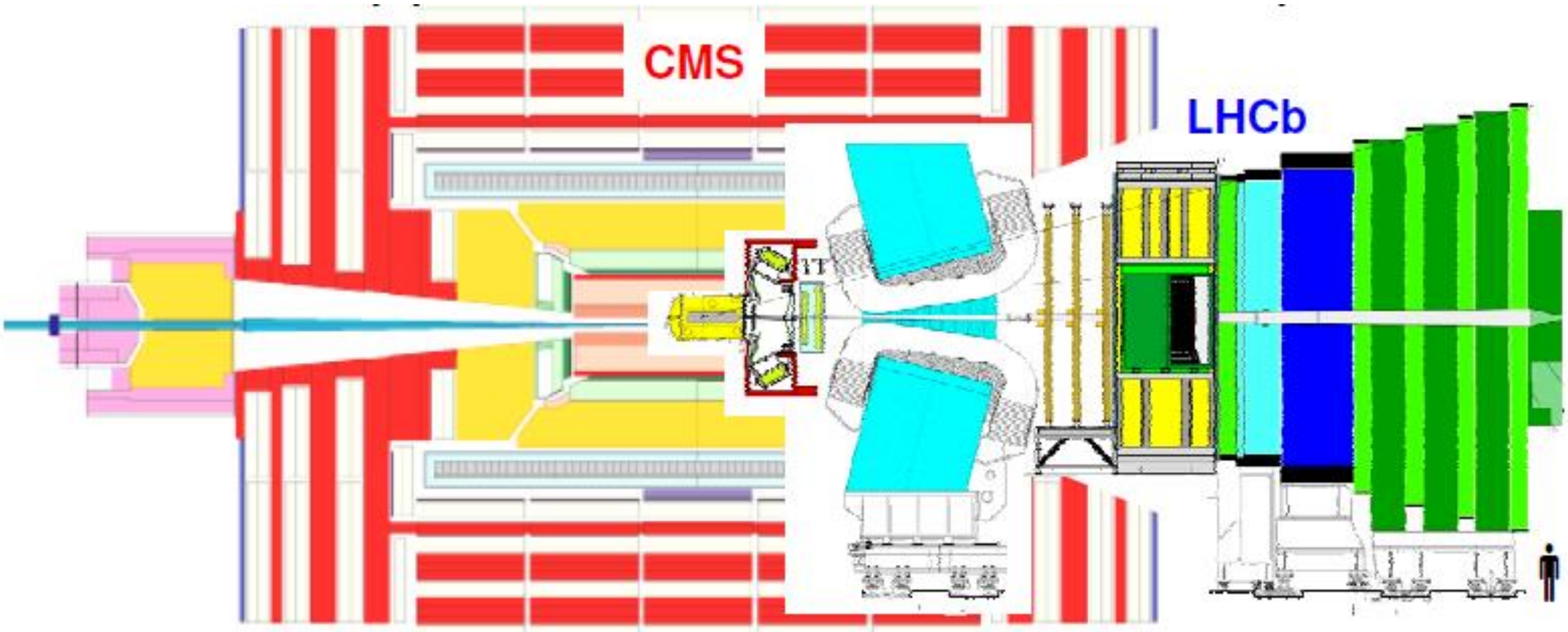
Fraction of cross section in LHCb acceptance (including pt constraints): ~1/4

⇩

50 kHz of bb events at L=2×10[32]

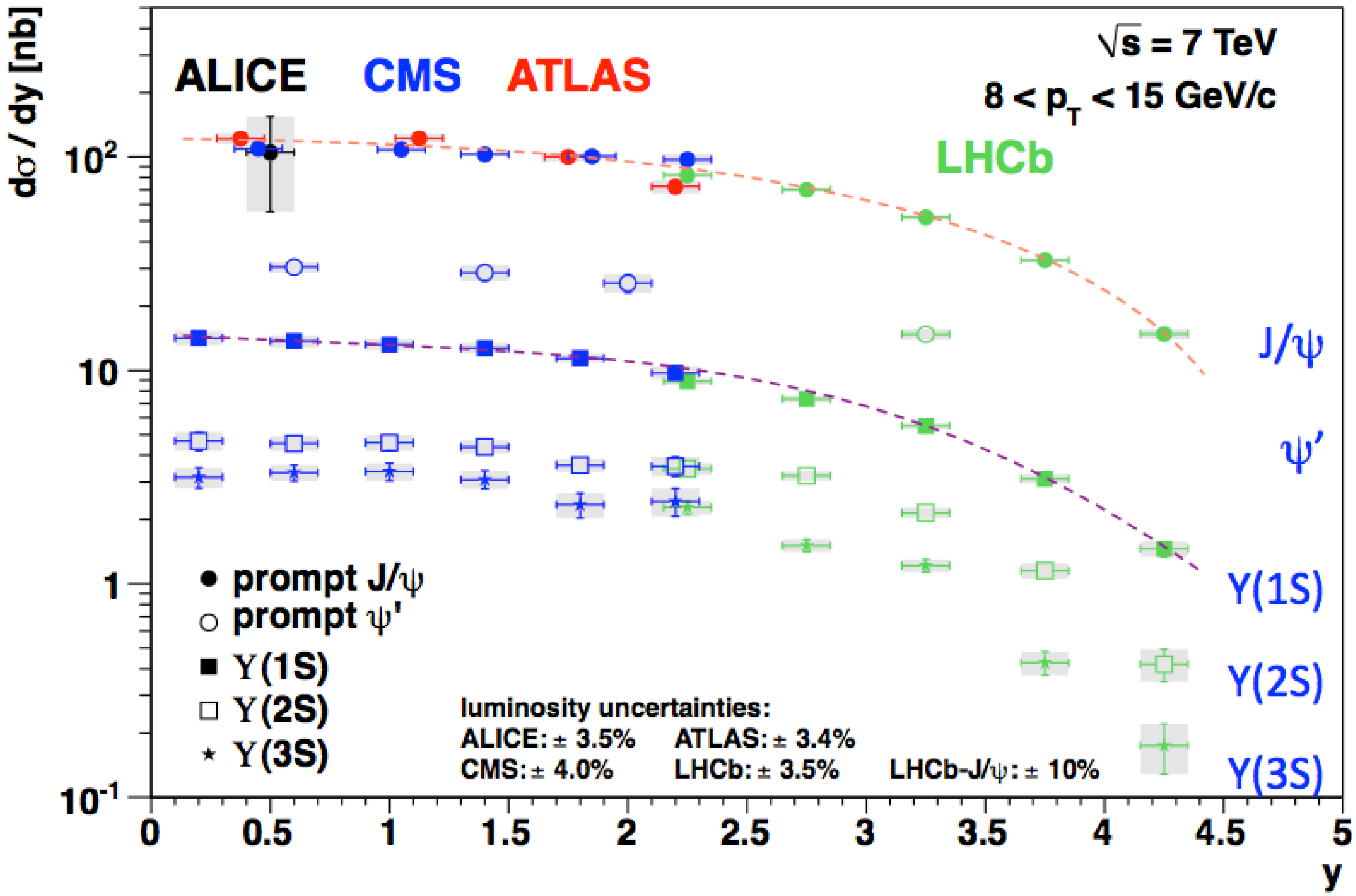


Forward Geometry



Forward geometry allows complementary measurements in non-flavor physics areas: e.g. ψ, Υ, $W^{\pm}$, Z production, even pA physics

Quarkonium Production

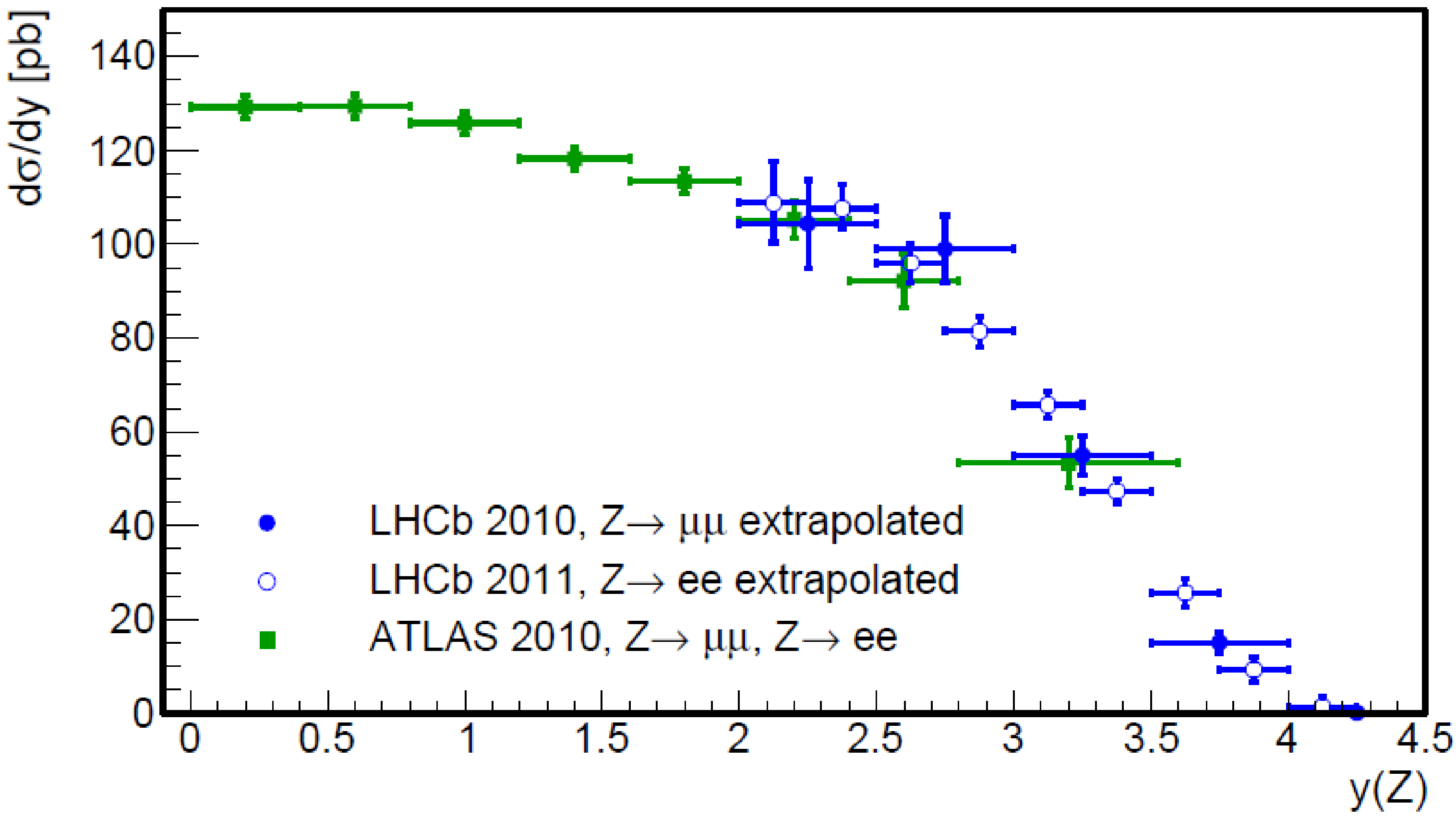


ALICE : 5.6 nb^{-1}
ATLAS : 2.2 pb^{-1}
CMS : 37, 36 pb^{-1}
LHCb : 5.2, 36, 25 pb^{-1}

Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

ALICE: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC71 (2011) 1645
LHCb: arXiv:1204.1258
CMS: BPH-11-001
LHCb: EPJC72 (2012) 2025

Z production



B Production Asymmetries

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

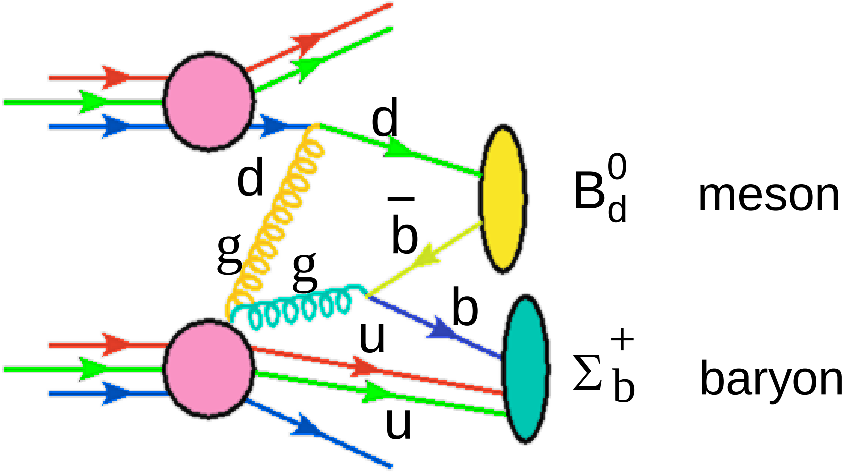
$$\frac{\text{produced antiparticles } \bar{P}}{\text{produced particles P}} = \frac{N(\bar{P})}{N(P)} = 1 + \delta_p$$

i.e. $N(B^0) \neq N(\bar{B}^0)$, $N(B^+) \neq N(B^-)$, etc. – function of p_t

Production asymmetry is effect of competing processes:

Cluster Collapse

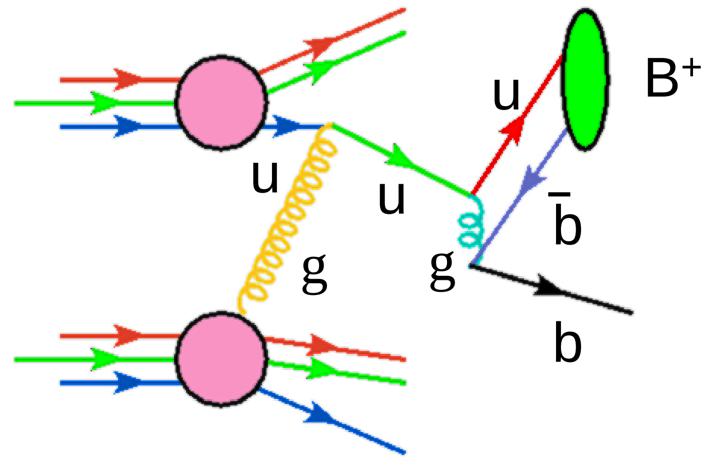
Enhances the production of species containing beam remnants at low transverse momentum (pt)



Production Asymmetries

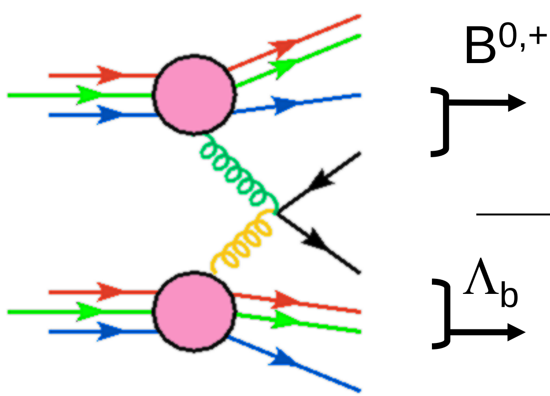
Valence-Quark Scattering

Enhances production of high energy species containing beam constituents



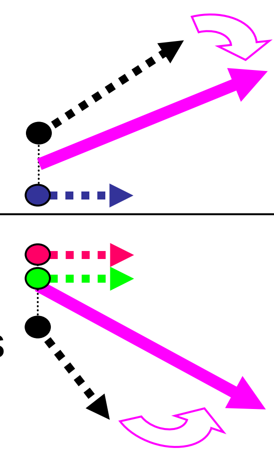
Beam Drag

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



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

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

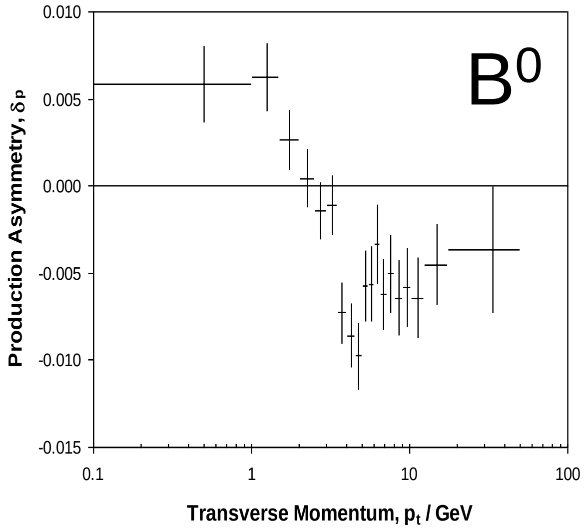


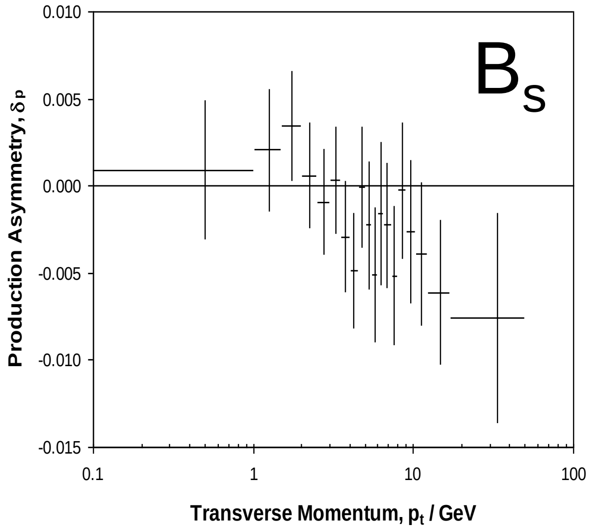
Production Asymmetrie

PHYTIA Simulation

$$A_P = \frac{\overline{B} - B}{\overline{B} + B} = \frac{\delta_P}{2}$$

$O(10^{-3} \ldots 10^{-2})$





LHCb measurements

$B^0{}_{(s)} \rightarrow D^-{}_{(s)} \pi^+$, $B^0 \rightarrow J/\psi K^*$

$A_P(B^0) = (0.1 \pm 1.0)\%$ $\rightarrow \pm 0.7\%$

$A_P(B_s) = (4 \pm 8)\%$. $\rightarrow \pm 2.5\%$

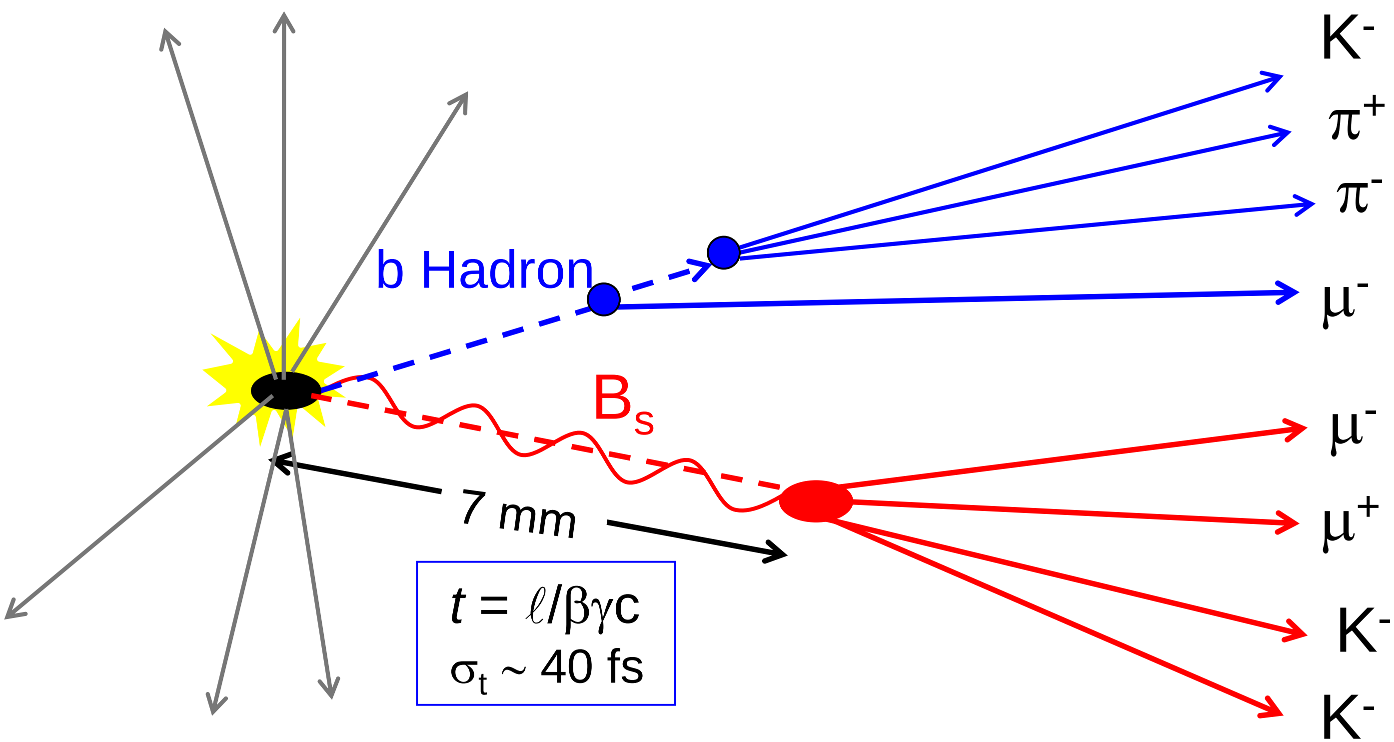
Phys. Rev. Lett. 110 (2013) 221601

$B^+ \rightarrow J/\psi K^+$ (+CPV from D0)

$A_P(B^\pm) = (-0.8 \pm 0.6)\%$

Phys. Rev. D 85, 091105(R) (2012)
+ recent D0 measurement

A typical b event

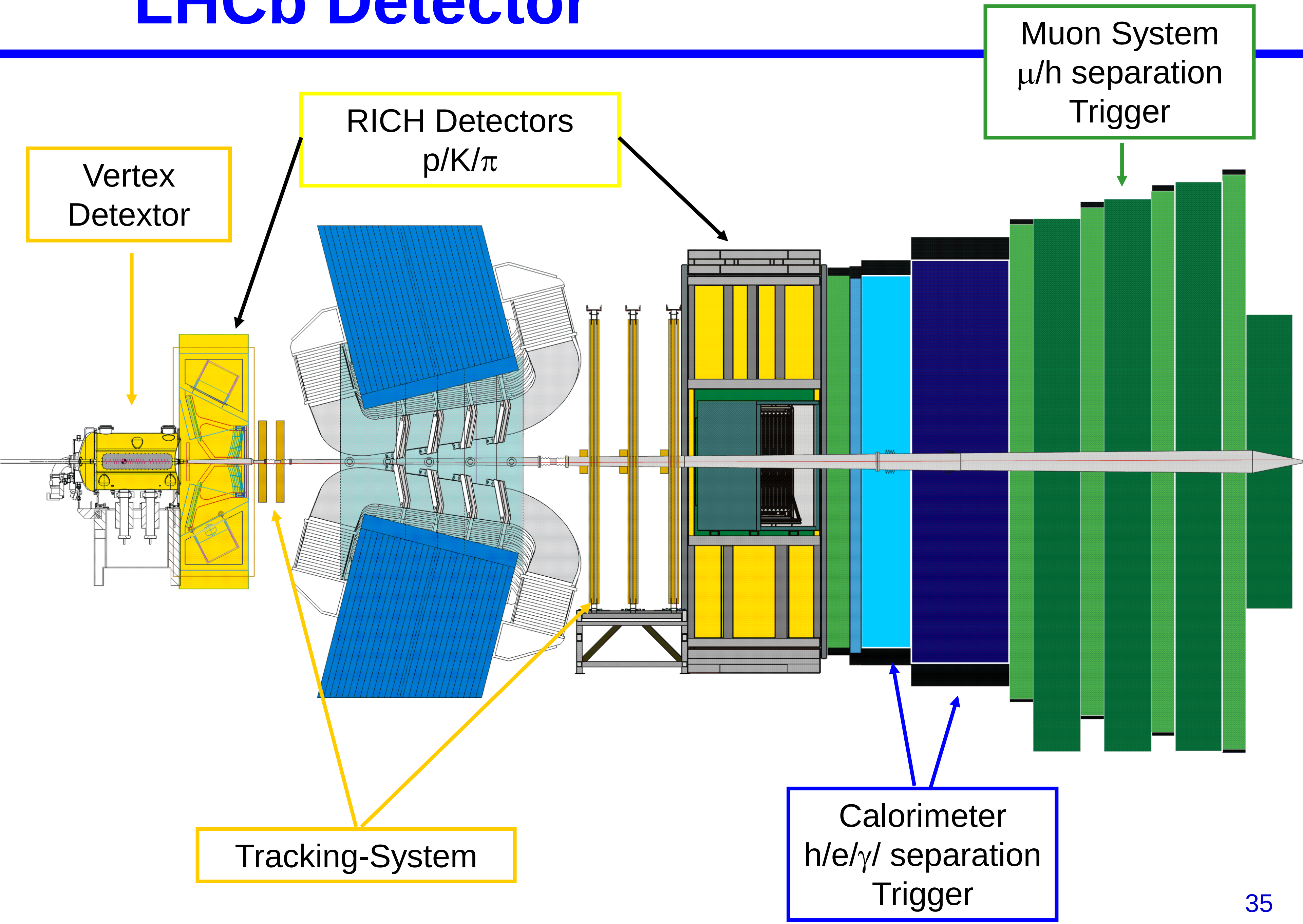


Good vertex resolution: to resolve fast B_s oscillation.

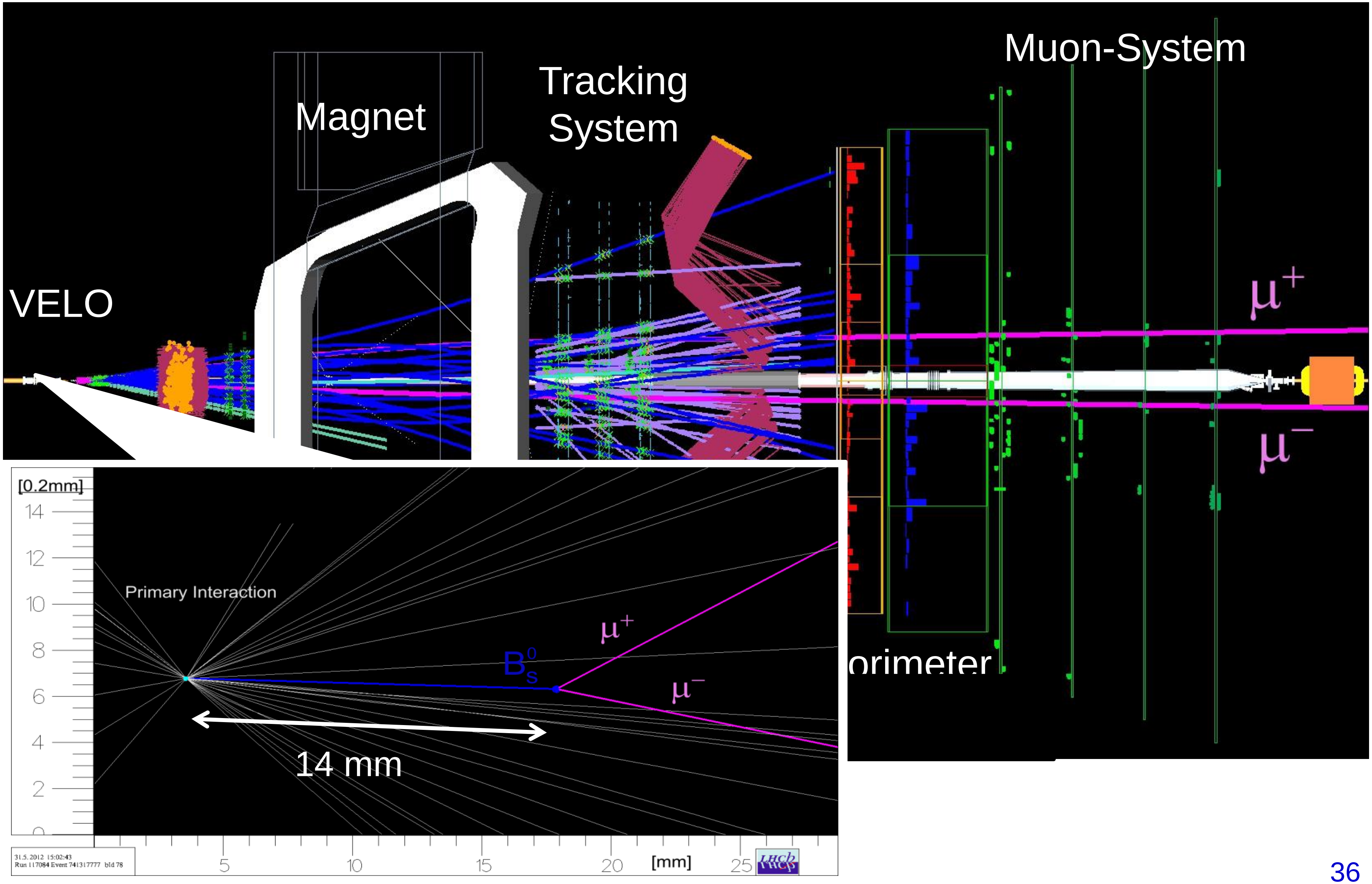
Background reduction: Very good mass resolution
Good particle identification (K/π)

High statistics: Efficient trigger for hadronic and leptonic states

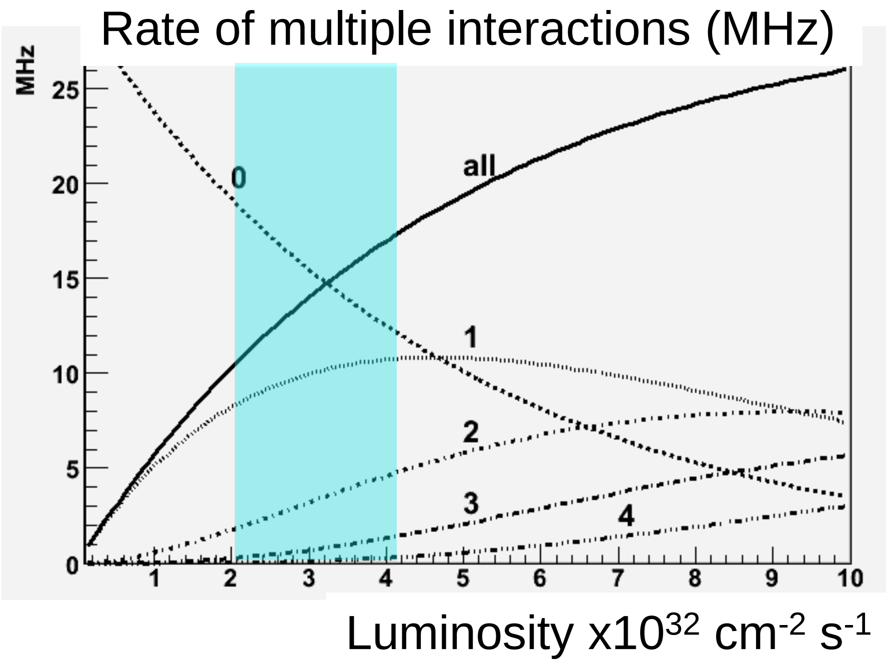
LHCb Detector

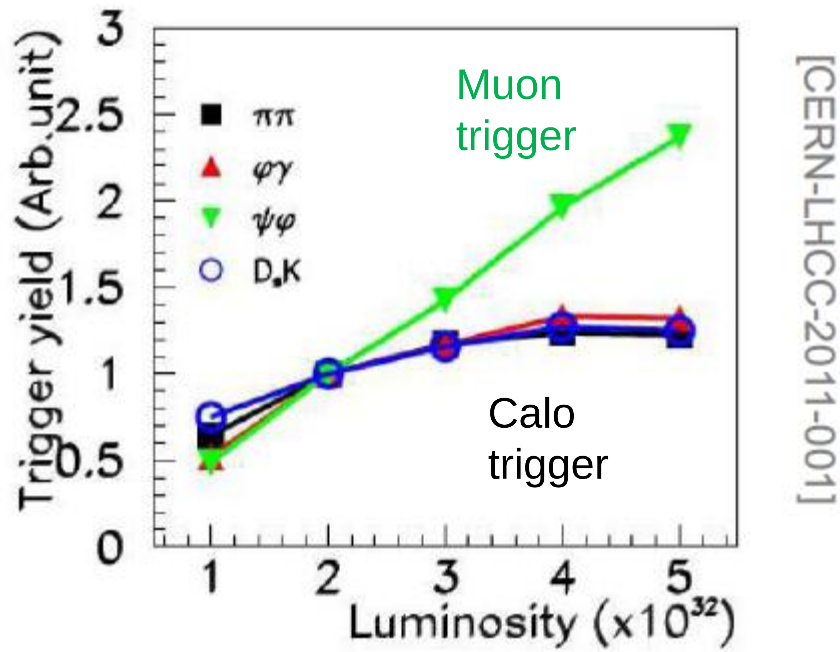


B-decay in LHCb



Optimal luminosity





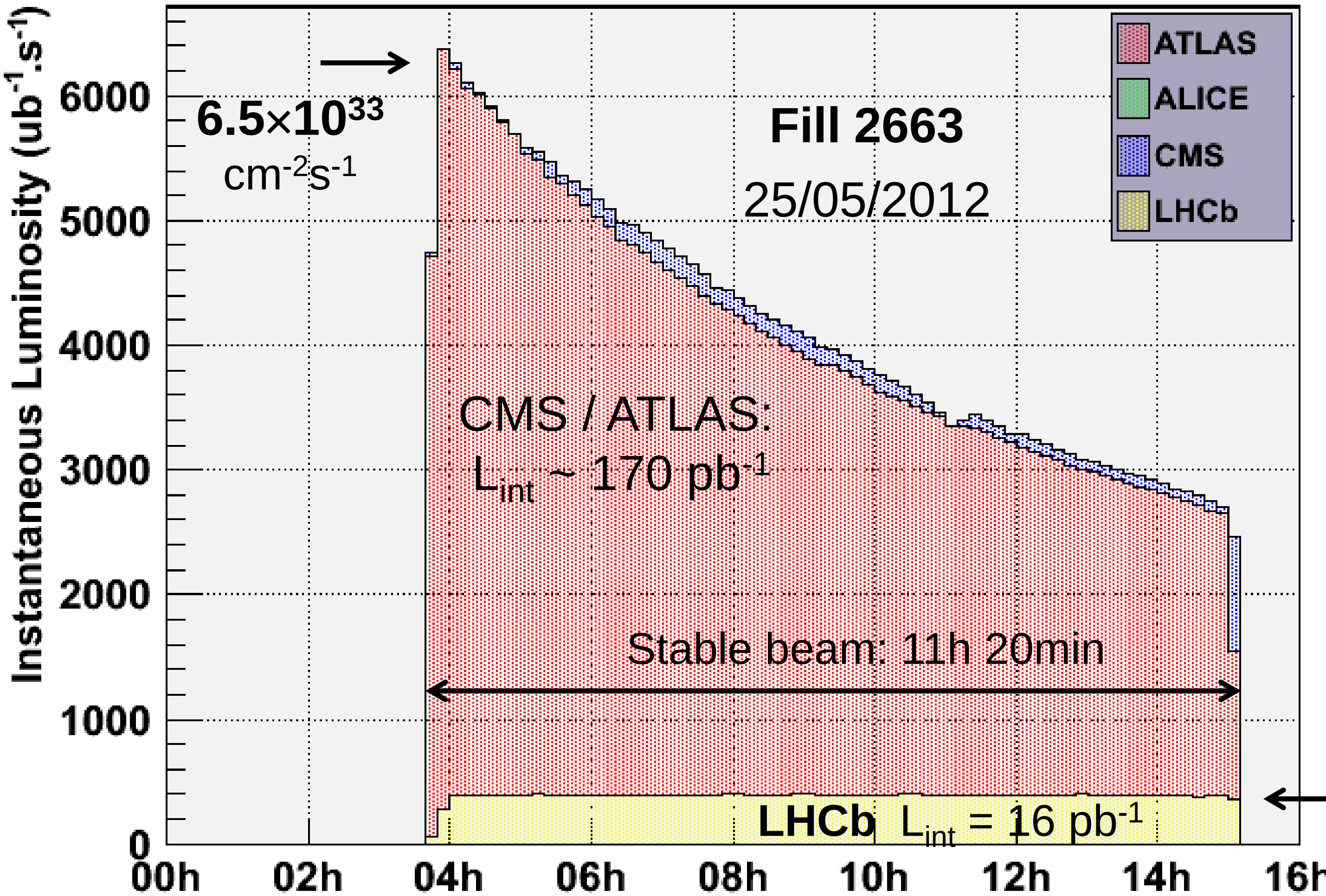
Design: 2×10^{32} $s^{-1}cm^{-2}$
n = 0.5 IA/crossing

Running: no performance loss seen at higher IA rates

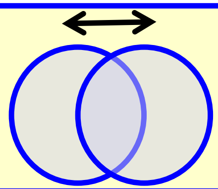
With current trigger, yields of hadronic channels saturate at 4×10^{32} $s^{-1}cm^{-2}$

Luminosity of 4×10^{32} $cm^{-2}s^{-1}$ optimizes data-taking.

Luminosity Leveling



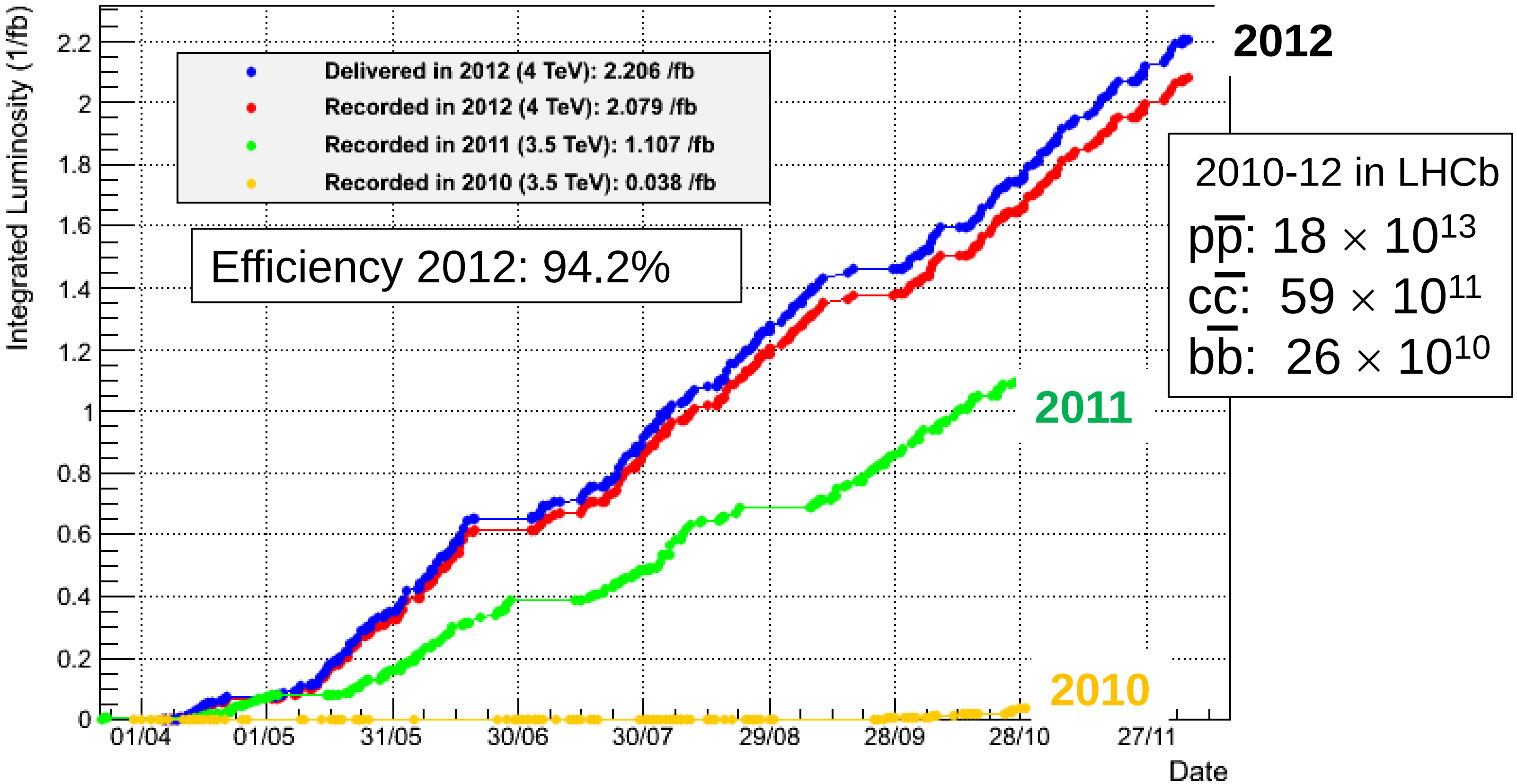
4.1× 10^{32}
= 2x design



LHCb: Displacement of beams to optimize luminosity

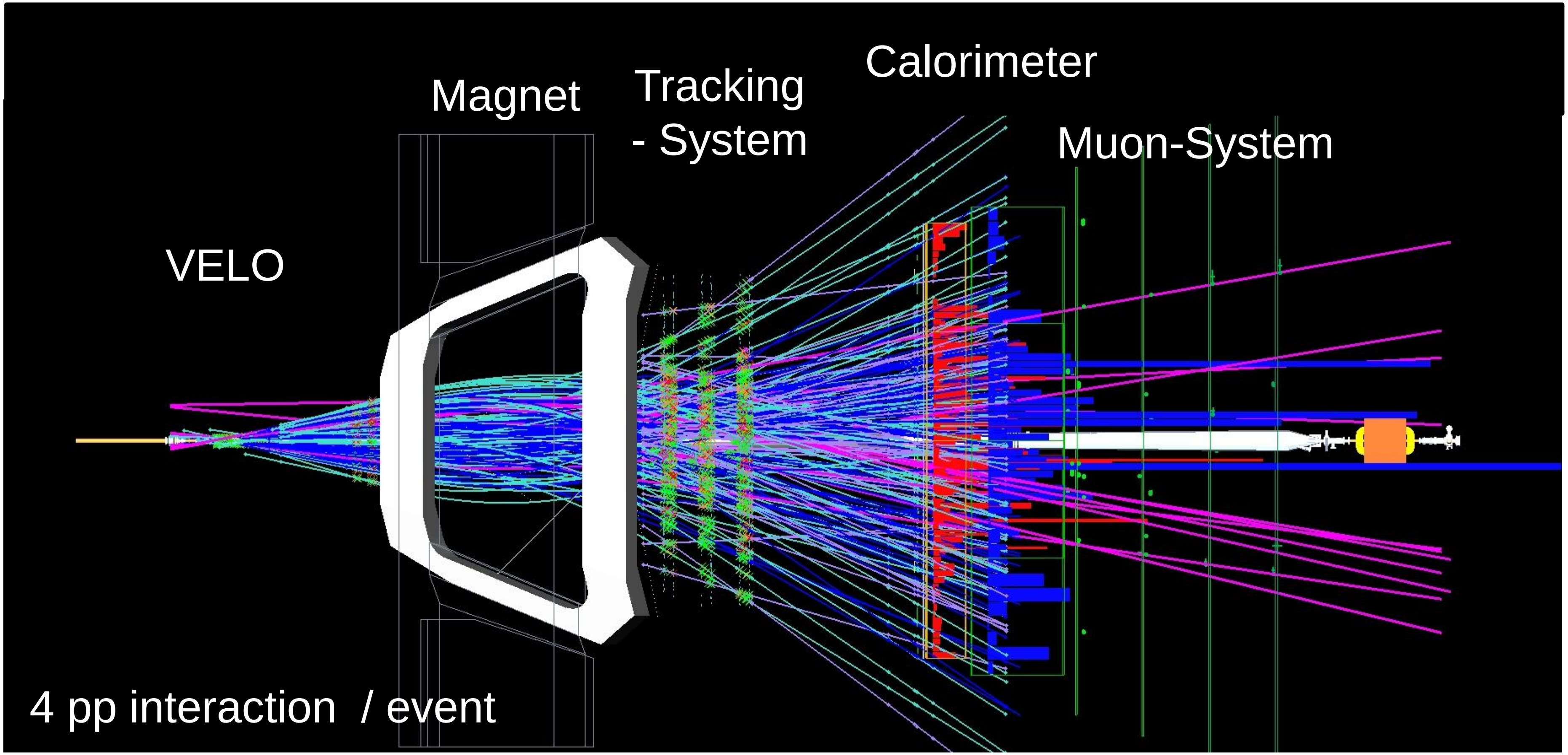
1.8 IA / Crossing
Design: 0.5

Data Taking



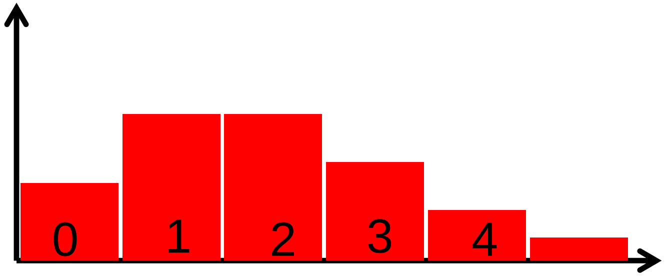
ATLAS / CMS in 2012 about 10× higher integrated luminosity.

“High-rate” event



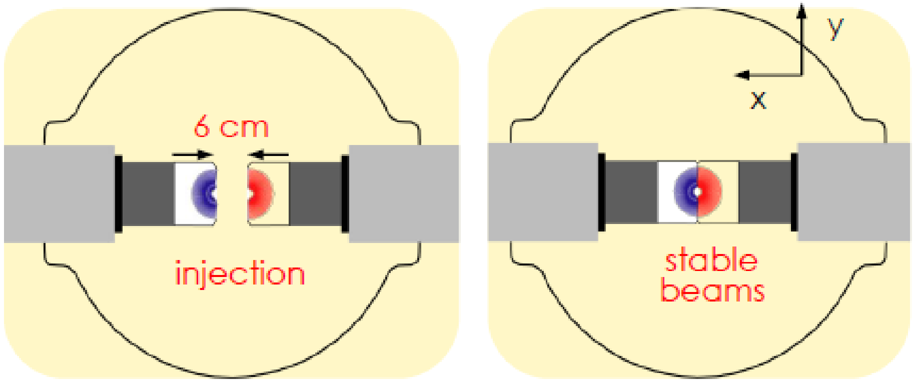
Number of interaction / event:

Poisson distribution with μ=2:
14% of events w/ ≥4 IA/event

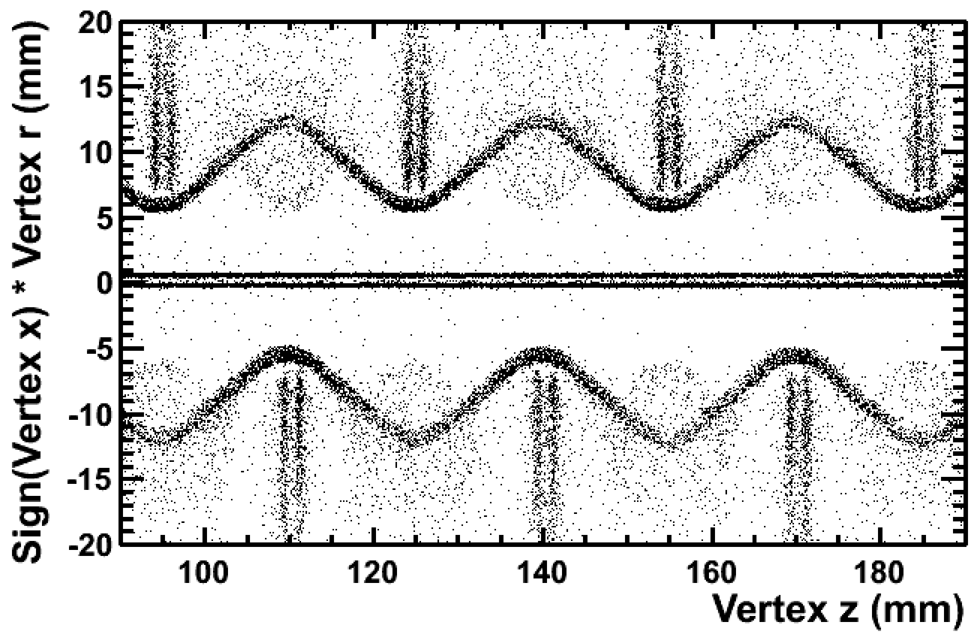


Vertex Detector & Performance

2 retractable detector halves



LHCb VELO Preliminary

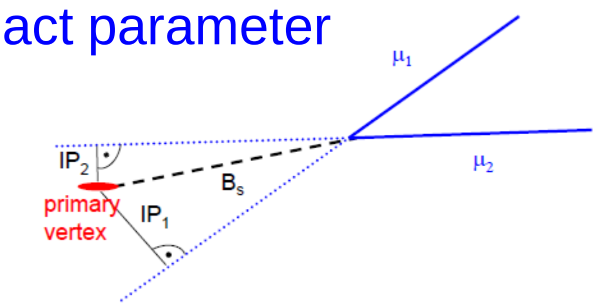


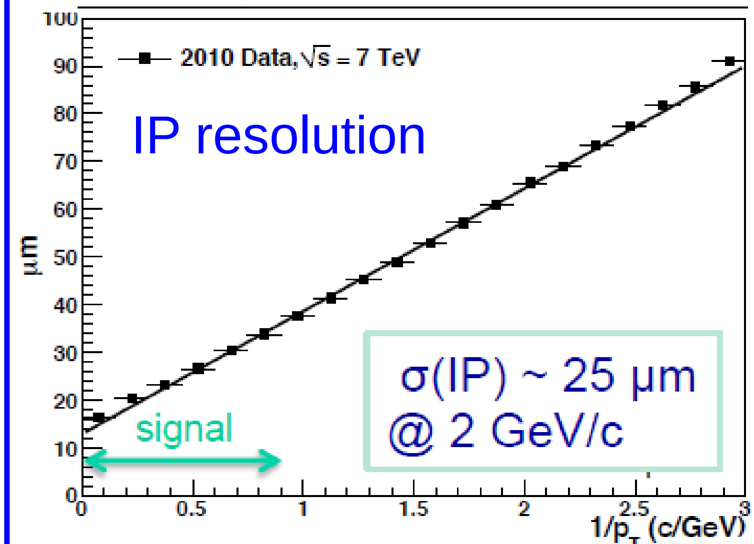
Single sided Silicon strip sensors:

2 × 21 (r and ϕ sensors)

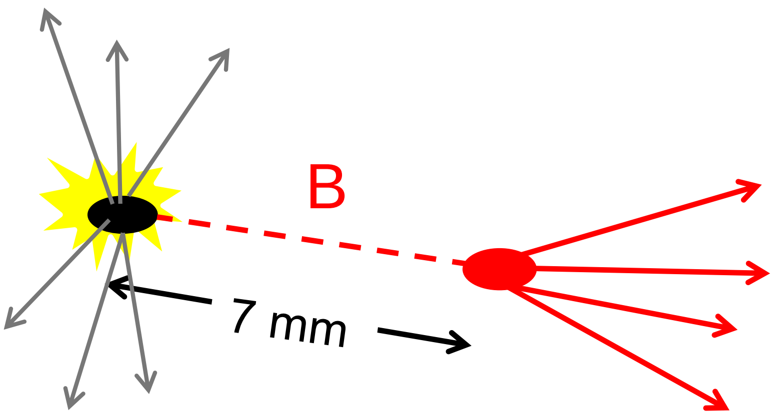
300 μm n^+-on- n strip sensors

Impact parameter

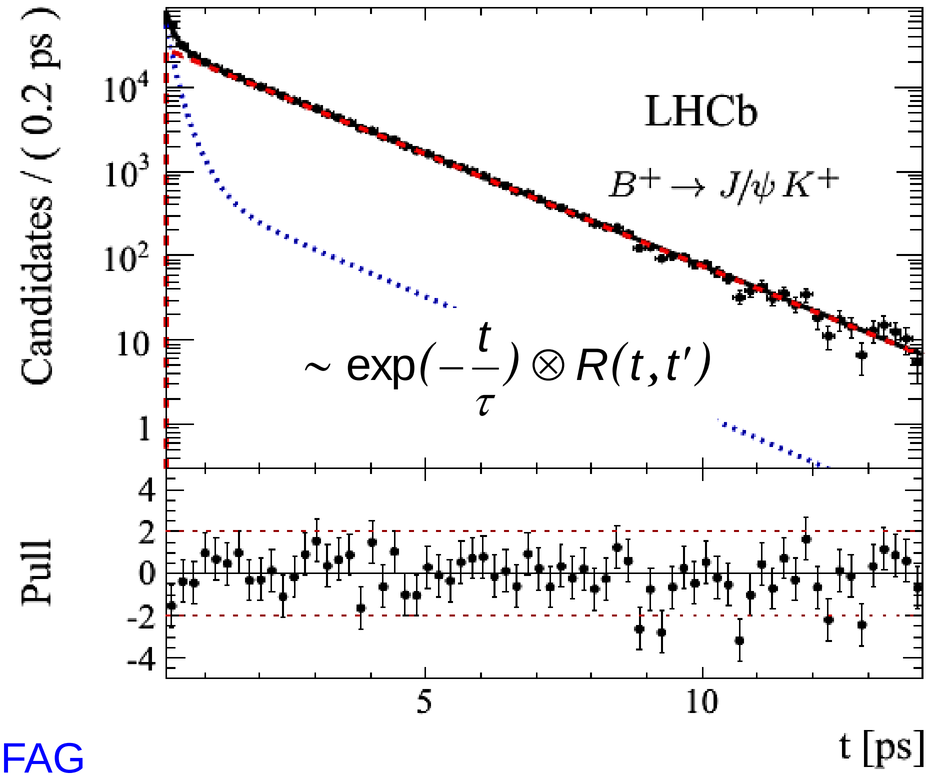




B Lifetime measurements



Proper time $t = \ell/\beta\gamma c$



Lifetime	Value [ps]	HFAG
τ_{B^+}	$1.637 \pm 0.004 \pm 0.003$	± 0.008
$\tau_{B^0 \to J/\psi K^{*0}}$	$1.524 \pm 0.006 \pm 0.004$	± 0.007
$\tau_{B^0 \to J/\psi K_S}$	$1.499 \pm 0.013 \pm 0.005$	
$\tau_{B_s^0 \to J/\psi \phi}$	$1.480 \pm 0.011 \pm 0.005$	± 0.012
$\tau_{\Lambda_b^0}$	$1.415 \pm 0.027 \pm 0.006$	

arXiv:1402.2554

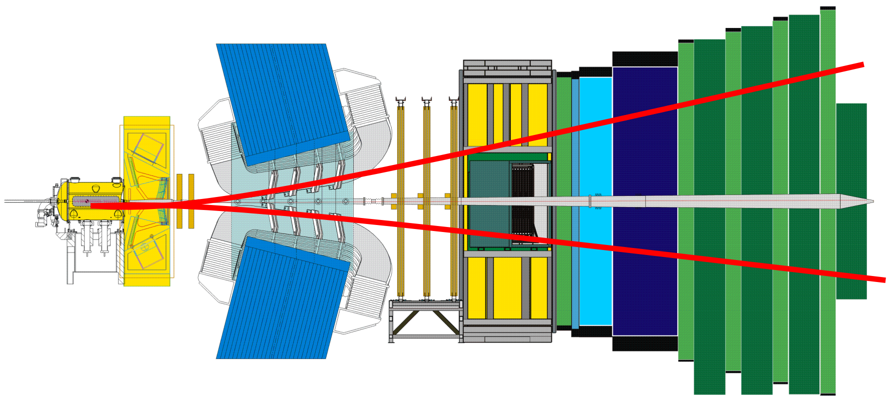
$$\frac{\tau_{\Lambda_b^0 \to J/\Psi p K^-}}{\tau_{B^0 \to J/\Psi \pi^+ K^-}} = 0.974 \pm 0.006 \pm 0.004$$

arXiv:1402.6242

$$\tau_{\Lambda_b^0} = 1.468 \pm 0.009 \pm 0.008 \text{ ps}$$

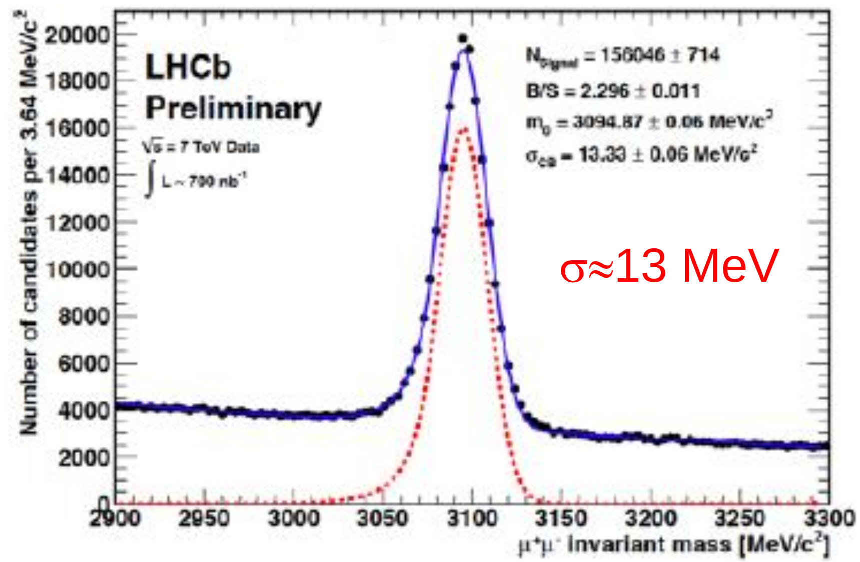
ATLAS: $1.449 \pm 0.036_{stat} \pm 0.017_{syst}$

Momentum & Mass Resolution



$$M(\mu\mu)=\sqrt{(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2}$$

$J/\psi\ (c\bar{c}) \rightarrow \mu^+\mu^-$



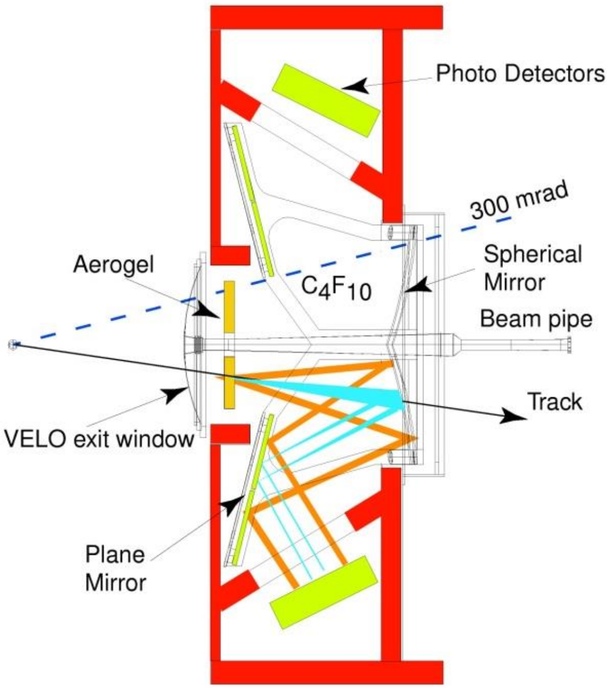
	$\delta p/p$	$\delta m(J/\psi \rightarrow \mu\mu)$
LHCb	0.4-0.6 %	13 MeV

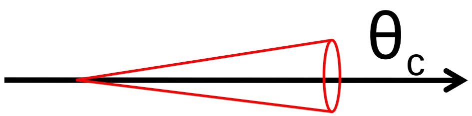
←

CMS 40 MeV
ATLAS 70 MeV

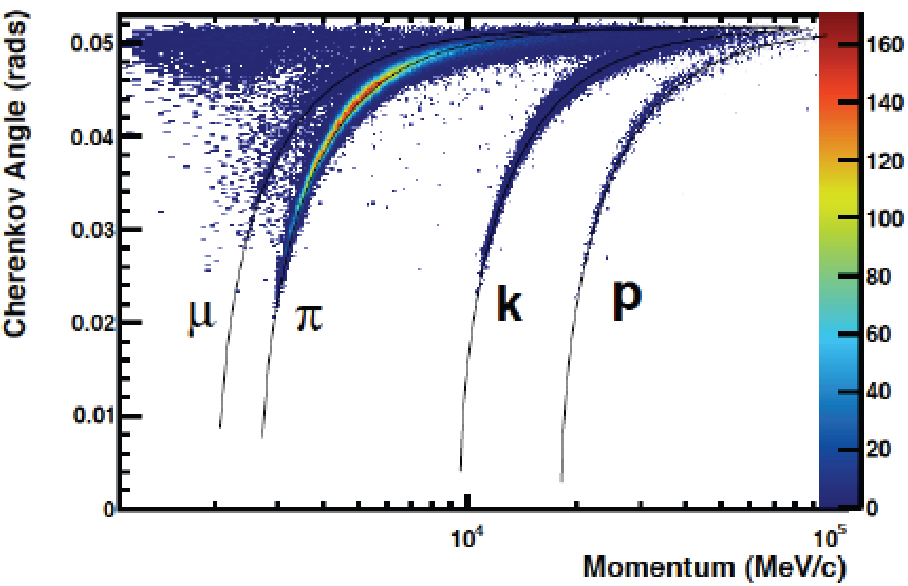
B mass resolution for $B \rightarrow J/\psi X$: 7…13 MeV

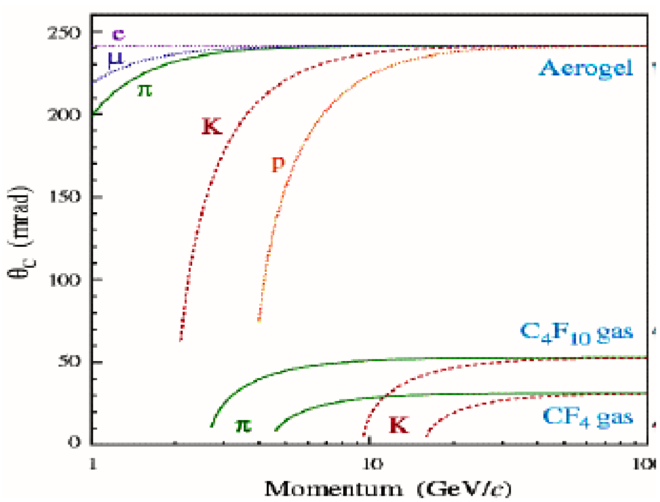
Particle Identification with RICH





$$\cos\theta_c = \frac{1}{\beta n}$$





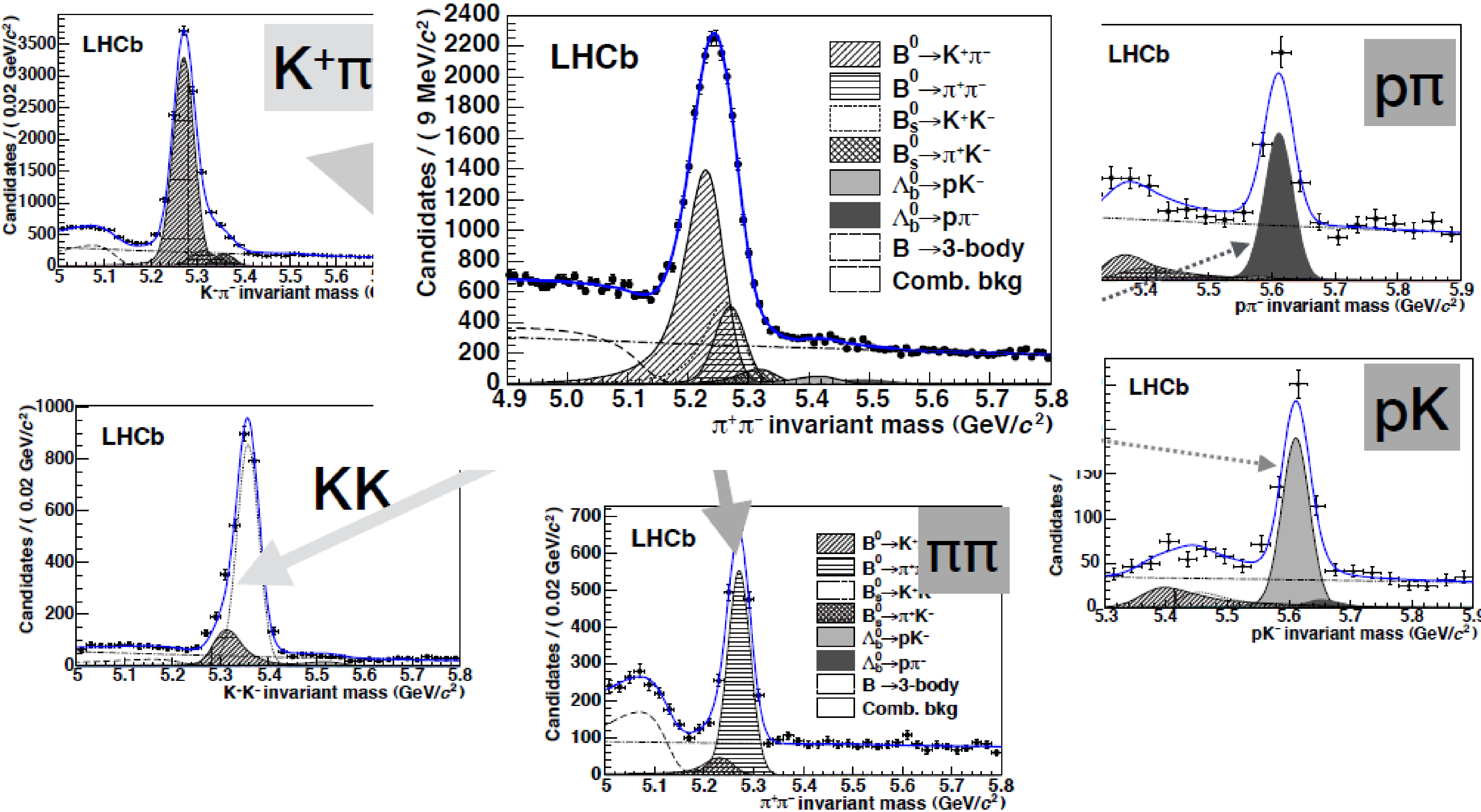
2 RICH detectors with 3 different radiators ensures good PID over full momentum range.

Kaon PiD: 95% efficiency @ 5% mis-ID

Particle ID in $H_b \rightarrow h^+h^-$

JHEP 1210 (2012) 037

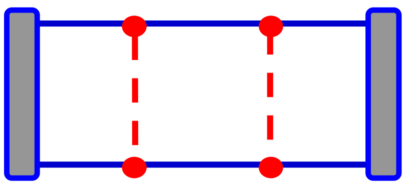
Slide by J.Rademackers



LHCb – Key Measurements

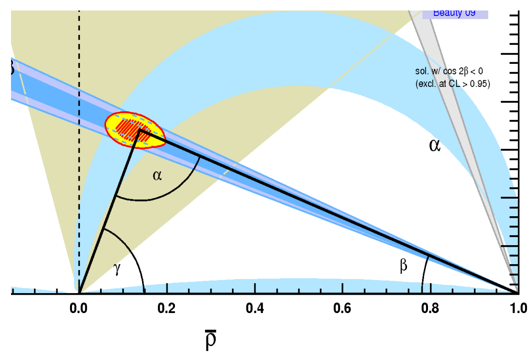
B / D Mixing

$$A_{mix} = \left|A_{mix}\right| e^{-i\phi_{mix}}$$

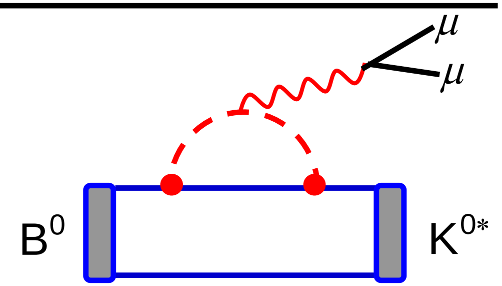


~~CP~~ to get mixing phase

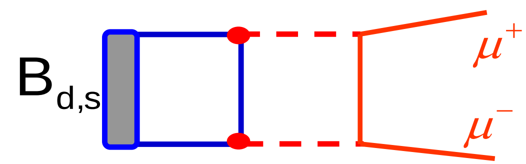
CKM Metrology: γ



Rare decays



angular distribution



Rates

3. Neutral Meson Mixing

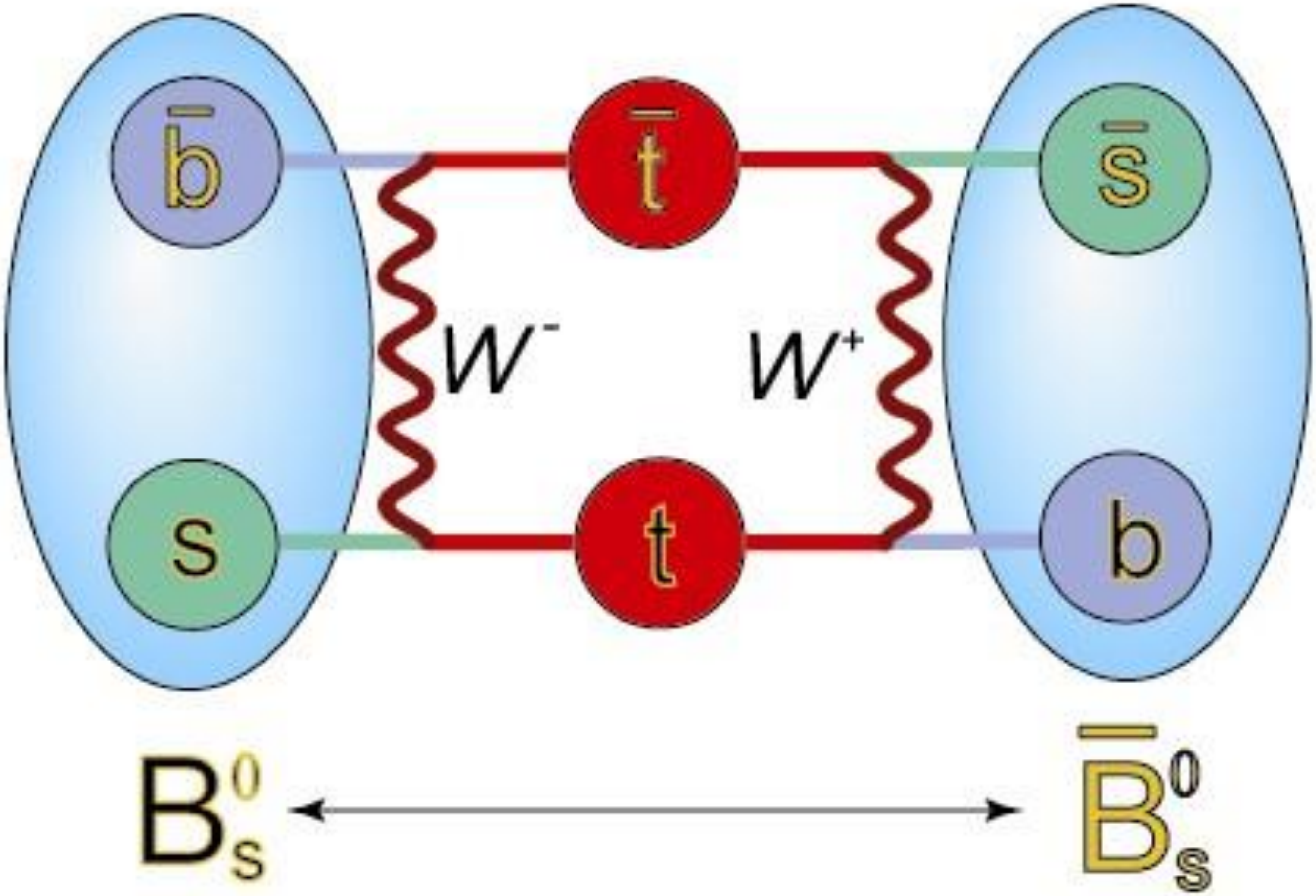
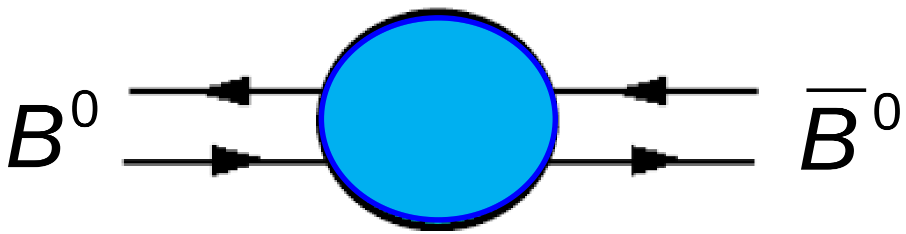


Figure from http://www.gridpp.ac.uk/news/?p=205

Mixing Phenomenology



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

No mass eigenstates

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

CPT

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

M and **Γ** hermitian:

$$m_{21} = m_{12}^*$$
$$\Gamma_{21} = \Gamma_{12}^*$$

Off – diagonal elements describe the mixing.

Mass Eigenstates

Diagonalization: Mass eigenstates:

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

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

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

Time evolution:

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

$$m_{H,L} = m \pm \frac{1}{2}\Delta m \qquad \Gamma_{H,L} = \Gamma \mp \frac{1}{2}\Delta\Gamma$$

Mixing Parameter

$$\Delta m = M_H - M_L \approx 2|M_{12}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_{12}$$ where $$\phi_{12} = \arg\left(\frac{M_{12}}{\Gamma_{12}}\right)$$

$$\phi_M = \arg(M_{12}) = \arg\left(\frac{q}{p}\right)$$ (mixing phase, CP violating)

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

Time evolution of B^0

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\overline{B}^0\rangle$$

$$|\overline{B}^0(t)\rangle = g_-(t)\frac{p}{q}|B^0\rangle + g_+(t)|\overline{B}^0\rangle$$

CP vioaltion in mixing if $\left|\frac{q}{p}\right|^2 \neq 1$

$$g_+(t) = e^{-i(m-i\frac{\Gamma}{2})t}\left[+\cosh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta m t}{2} - i\sinh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta m t}{2}\right]$$

$$g_-(t) = e^{-i(m-i\frac{\Gamma}{2})t}\left[-\sinh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta m t}{2} + i\cosh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta m t}{2}\right]$$

B_d^0 Oscillations

For B_d^0 : $\Delta\Gamma \approx 0$

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}(1 \pm \cos(\Delta m t))$$

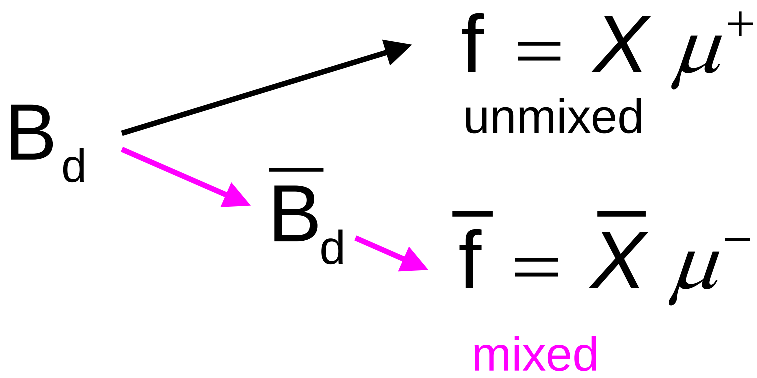
Mixed/ unmixed probability:

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

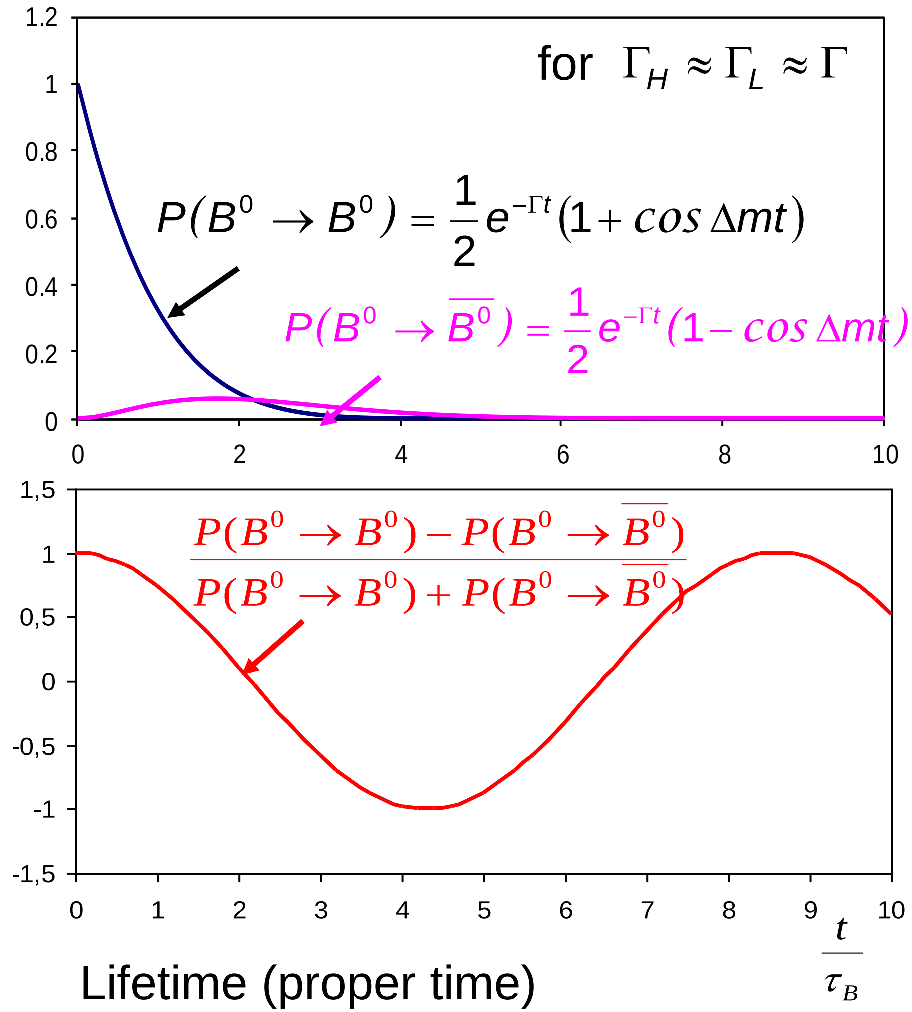
$$\mathcal{P}(B^0 \to \bar{B}^0, t) = \left|\left\langle B^0 | \bar{B}^0(t) \right\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}\left|\frac{q}{p}\right|^2(1 - \cos(\Delta m t))$$

Mixing Asymmetry ($\Delta\Gamma \approx 0$)

<u>Mixing probability:</u>

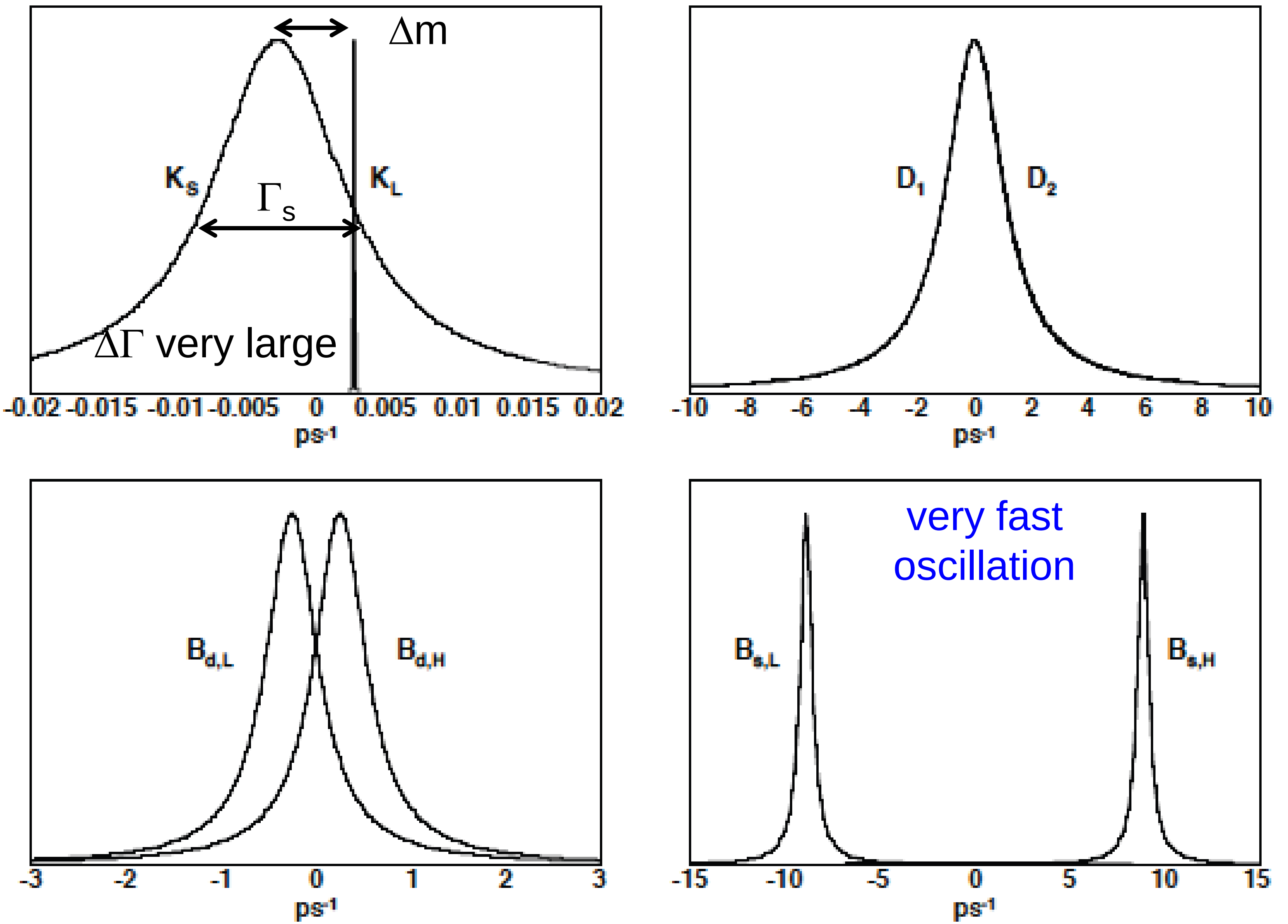


$$A(t) = \frac{unmixed(t) - mixed(t)}{unmixed(t) + mixed(t)} = \cos(\Delta m t)$$



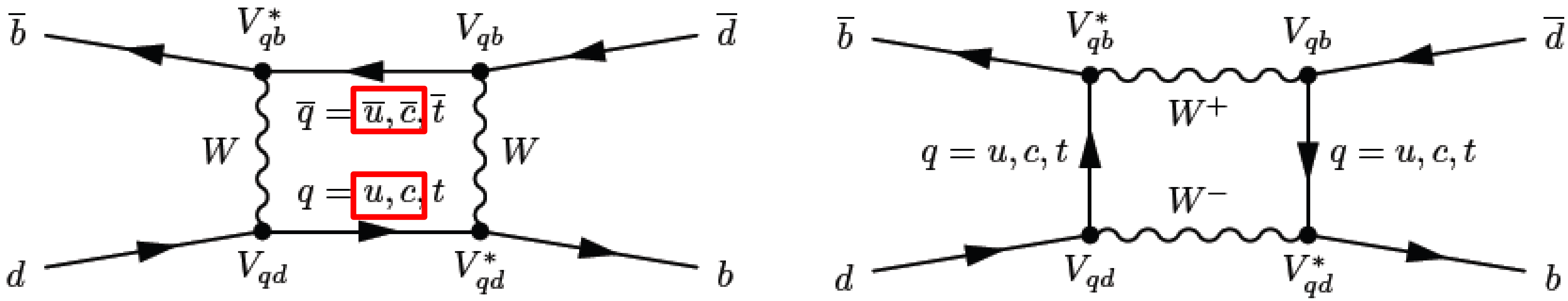
Meson Mixing – Overview

Slide from M. Gersabeck



Standard Model Prediction

Real intermediate states: Γ_{12}



Main contribution from top quark:

$$\Delta m \approx 2\left|M_{12}\right|$$

$$M_{12,q} = \frac{G_F^2}{12\pi^2}(V_{tq}^* V_{tb})^2 M_W^2 S_0(x_t) B_{B_q} f_{B_q}^2 M_{B_q} \hat{\eta}_B$$

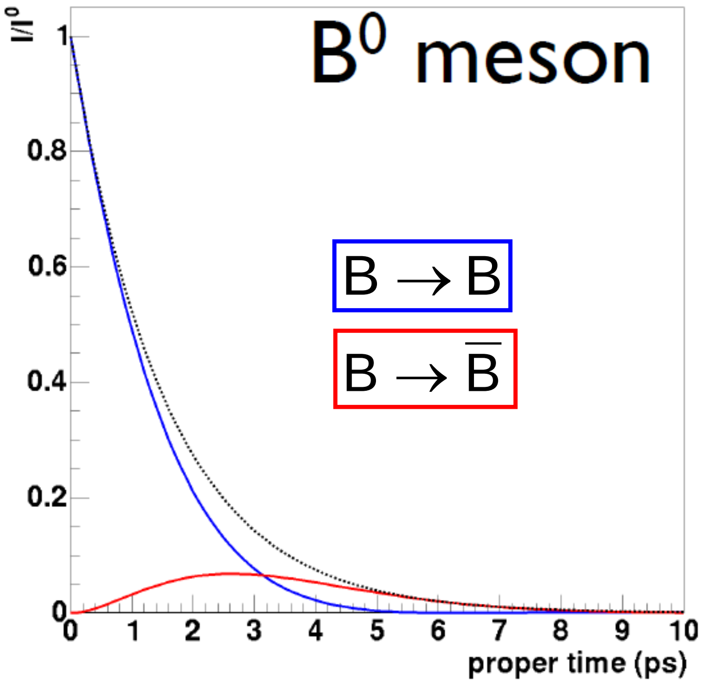
Inami- Lim function for box diagram $S_0\left(m_t^2/m_W^2\right)$

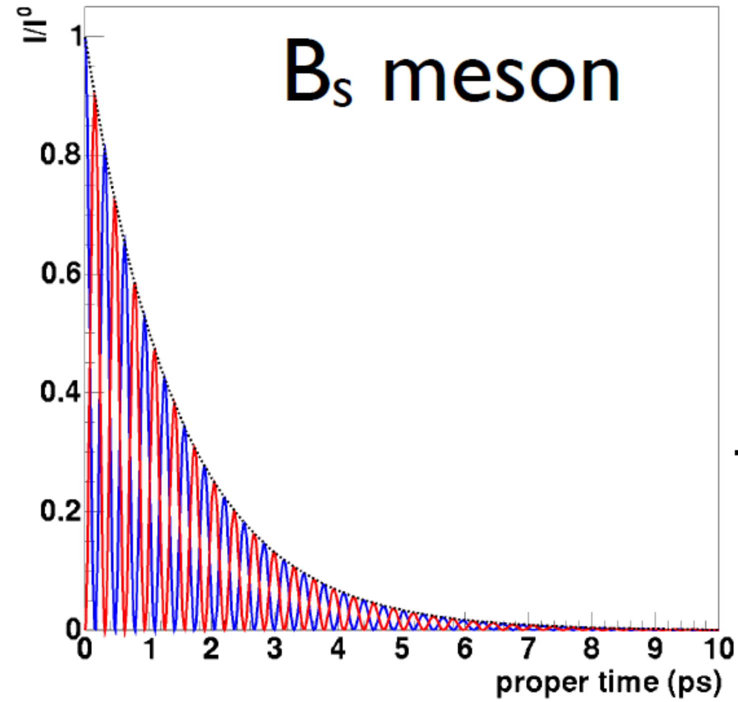
B_B = bag factor, f_B = form factor, η_B = *QCD corrections*

Unitarity of V_{CKM}:

- if u, c, t, have same mass all amplitudes cancel by construction (GIM)
- large top mass $\rightarrow$ deactivation of GIM mechanism

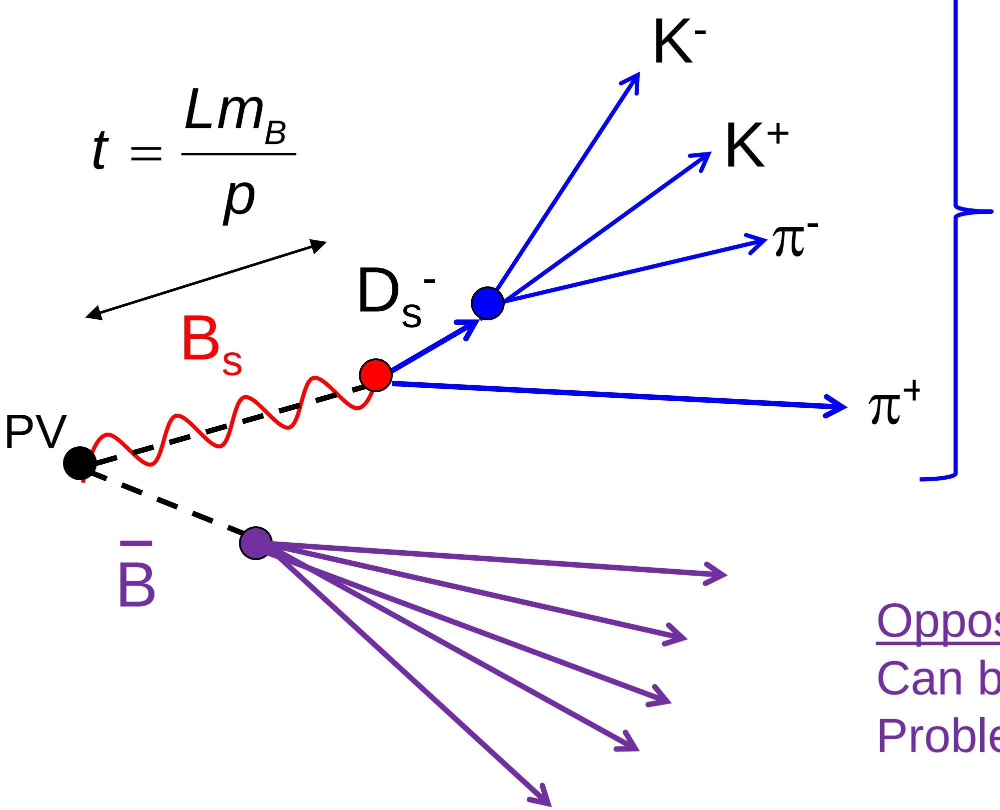
B meson mixing



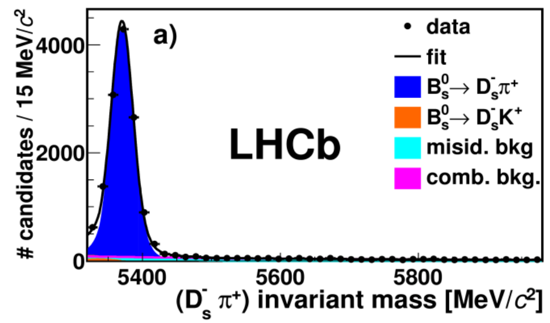


$$\frac{\Delta m_d}{\Delta m_s} \approx \frac{|V_{td}|^2}{|V_{ts}|^2} \approx \frac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04$$

B_s Mixing Measurement



Signal B
(flavor specific decay)



Need production flavor

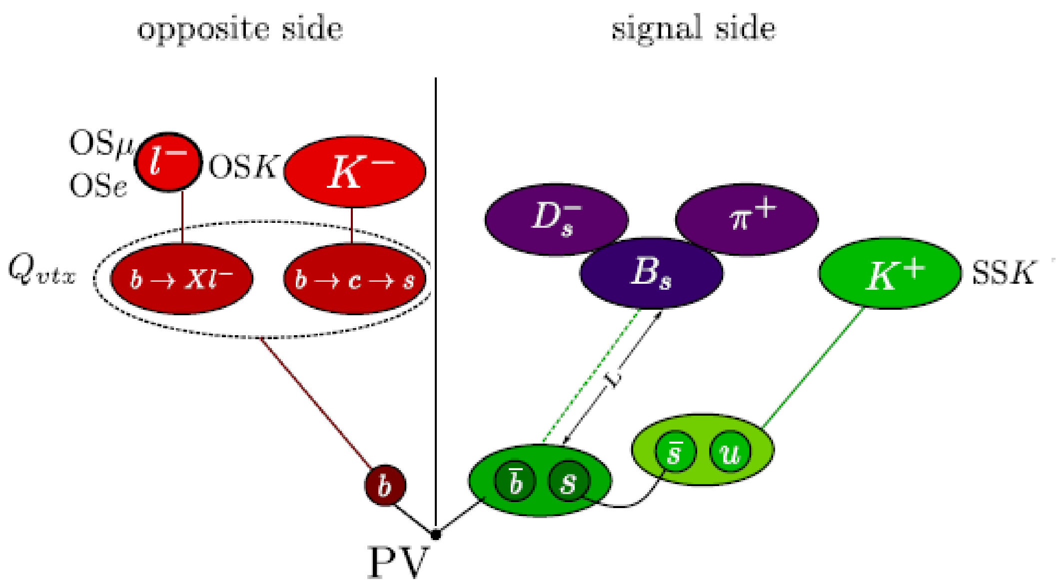
<u>Opposite B</u>
Can be used for flavor tagging
Problem w/ neutral B's (→mixing)

$$PDF \propto \left[e^{-\Gamma t} \cdot \left(\cosh\left(\frac{\Delta\Gamma}{2} t \right) \pm D \cdot \cos(\Delta m \cdot t) \right) \right] \otimes R(\sigma_t)$$

Production flavour from tagging algorithms

resolution

Flavor Tagging



OS

SS

Opposite taggers: use 2nd B

- the two B's are not entangled: neutral tagging B oscillates
- high track multiplicity

→ high mistag probability: 30 – 40 %

Same side taggers: exploit fragmentation:

- high track multiplicity
- depend strongly on signal (B / B_s)

→ high mistag probability: ~35 %

Flavor Tagging

	efficiency	mistag	tagging power
tagger	$\varepsilon_{\rm tag}(\%)$	$\omega(\%)$	$\varepsilon_{\rm tag} D^2(\%)$
OSμ	5.20 $\pm$ 0.04	30.8 $\pm$ 0.4	0.77 $\pm$ 0.04
OSe	2.46 $\pm$ 0.03	30.9 $\pm$ 0.6	0.36 $\pm$ 0.03
OSK	17.67 $\pm$ 0.08	39.33 $\pm$ 0.24	0.81 $\pm$ 0.04
Q_{vtx}	18.46 $\pm$ 0.08	40.31 $\pm$ 0.24	0.70 $\pm$ 0.04
SSK	16.3 $\pm$ 0.4	35.3 $\pm$ 2.1	1.4 $\pm$ 0.4

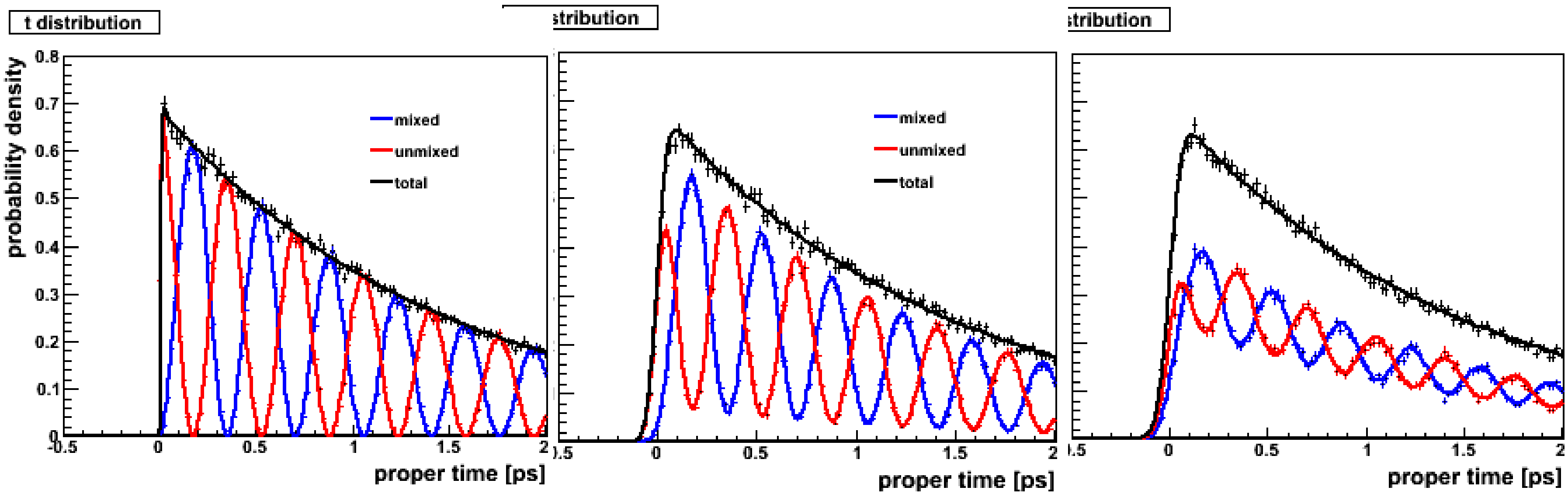
$D = (1 - 2\omega)$

SSK: Compared to CDF higher track multiplicity in forward region

Tagging power $\Leftrightarrow$ fraction of correctly tagged events
typically ~3.5% for the sum of taggers!

Eur. Phys. J. C (2012) 72:2022, LHCb-CONF-2012-026, LHCb-CONF-2012-033

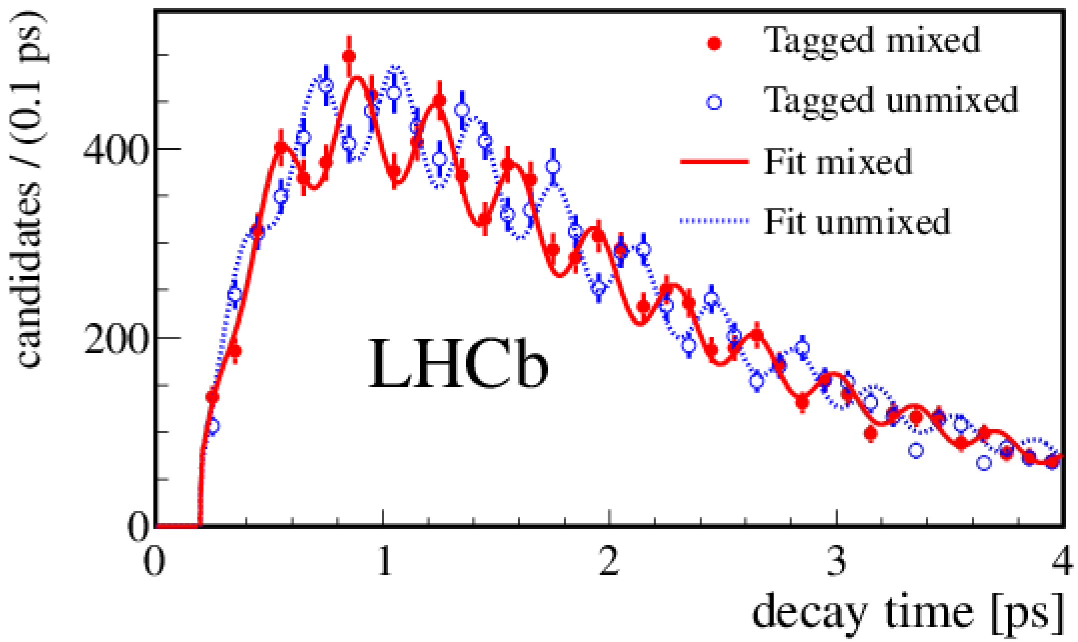
Detector effects on B_s oscillation



Finite time resolution: 44 fs

Realistic tagging

LHCb's B_s Mixing Measurement



34k signal evts
(5 decay channel)

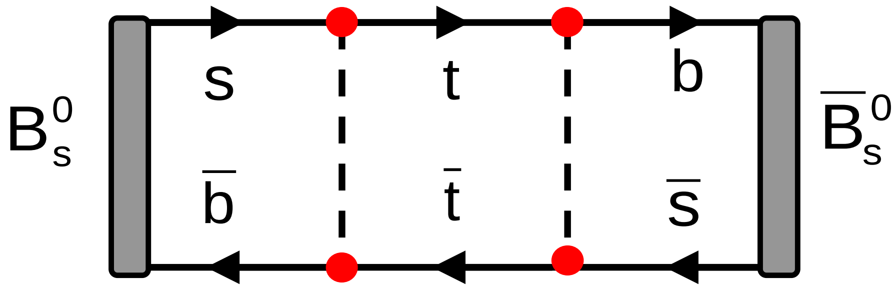
$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ ps^{-1}$

New J. Phys. 15 (2013) 053021
Most precise measurement

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$

PRL 97 062003 (2006).

B_s mixing Phase ϕ_s



$$B_s^0 \xrightarrow{\;\frac{q}{p}\;} \overline{B}_s^0$$

Mixing phase:

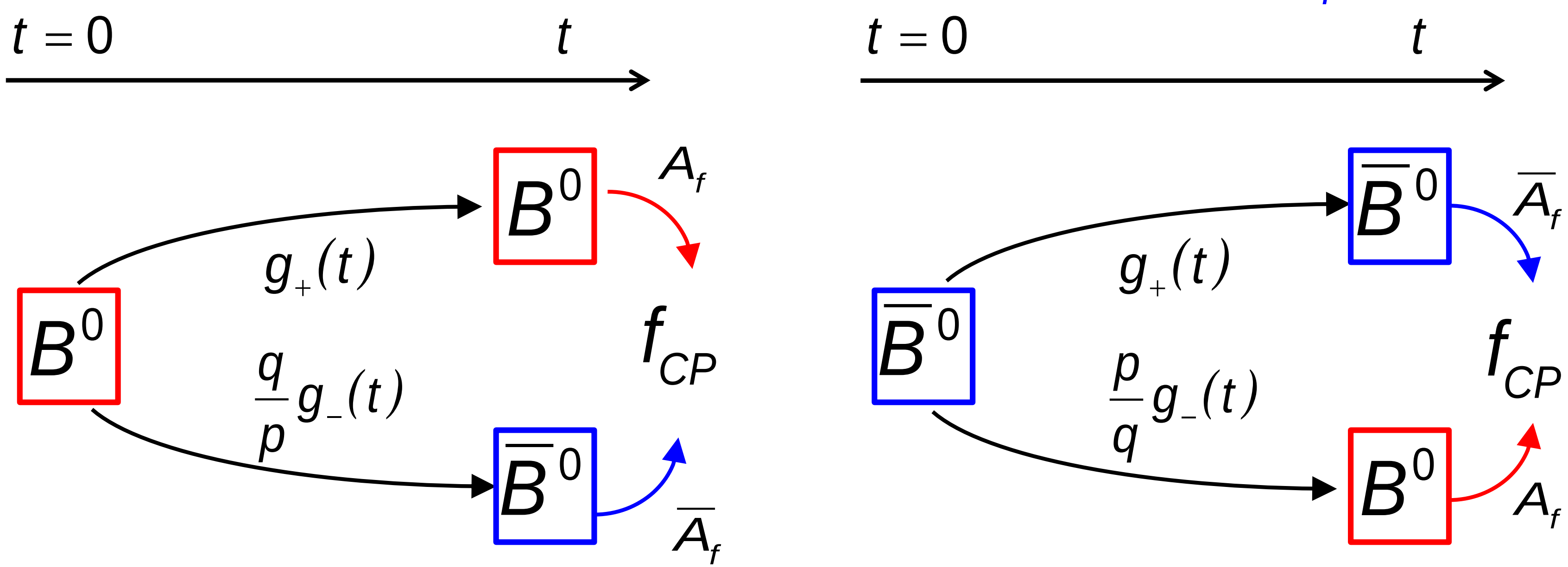
$$\phi_M = \arg\left(\frac{q}{p}\right) = \arg\left(M_{12}\right)$$

New Physics can alter the phase ϕ_M from the Standard Model.

Need an interference experiment to measure phase differences.

Interference between Mixing and Decay

adapted from G. Raven



$$g_+(t)A_f + \frac{q}{p}\,g_-(t)\overline{A}_f \qquad\qquad g_+(t)\overline{A}_f + \frac{p}{q}\,g_-(t)A_f$$

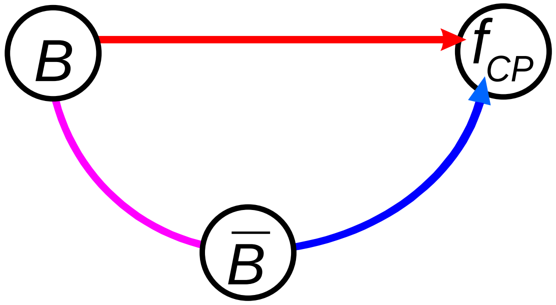
Time-dependent CP-Asymmetry

adapted from G. Raven

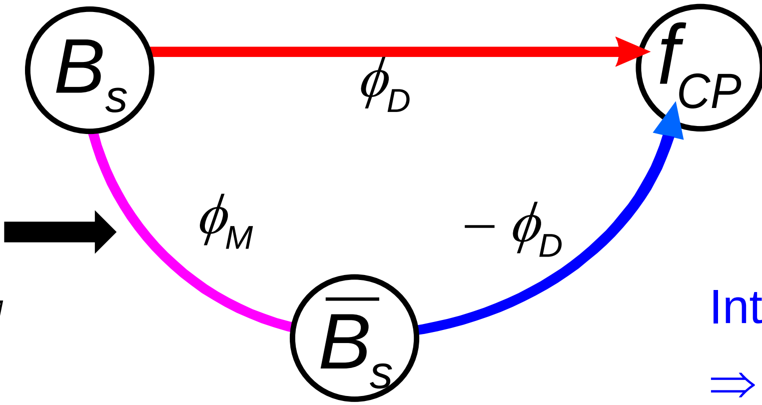
$t=0$	t	Rate
$B^0 \longrightarrow$	f_{CP}	$\propto e^{-\Gamma t}\,[1+\sin(\phi_{\text{weak}})\sin(\Delta m t)]$
$\overline{B^0} \longrightarrow$	f_{CP}	$\propto e^{-\Gamma t}\,[1-\sin(\phi_{\text{weak}})\sin(\Delta m t)]$

$$\mathcal{A}_{CP}(t) \equiv \frac{\Gamma(\overline{B^0}\to f_{CP})-\Gamma(B^0\to f_{CP})}{\Gamma(\overline{B^0}\to f_{CP})+\Gamma(B^0\to f_{CP})} = -\sin\phi_{\text{weak}}\sin(\Delta m t)$$

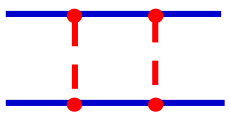
Measurement of time dependent CP asymmetry of a process $B^0 \to f_{CP}$ measures the phase difference ϕ_{weak} between the two path:



Measuring the B_s mixing phase



$B_s \to J/\psi\ \phi(KK)$

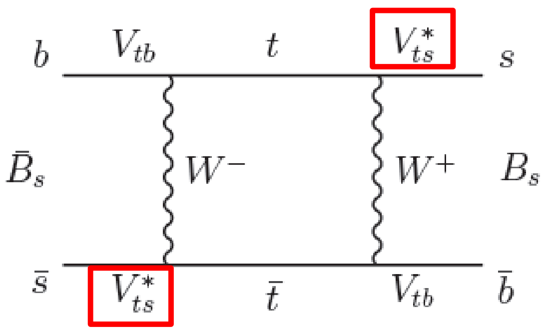


$$A_{mix} = |A_{mix}| e^{i\phi_M}$$

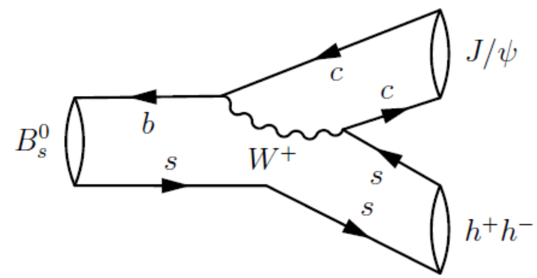
Interference of mixing & decay:

$$\Rightarrow \quad \phi_{weak} = \phi_M - 2\phi_D \equiv \phi_s$$

Standard Model:



$$\phi_M \approx -2\arg(V_{ts}) \approx -2\beta_s$$



+ small penguin pollution

$$\phi_D^{SM} = -2\arg(V_{cs}V_{cb}^*) \approx 0$$

$$V_{ts} = |V_{ts}| e^{i\beta_s}$$

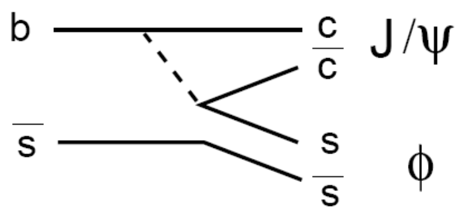
$$\phi_s^{SM} = -0.0364 \pm 0.0016 \text{ rad}$$ *(CKMFitter)*

$\rightarrow$ very small CPV

$B_s \to J/\psi\,(\mu\mu)\,\phi(KK)$

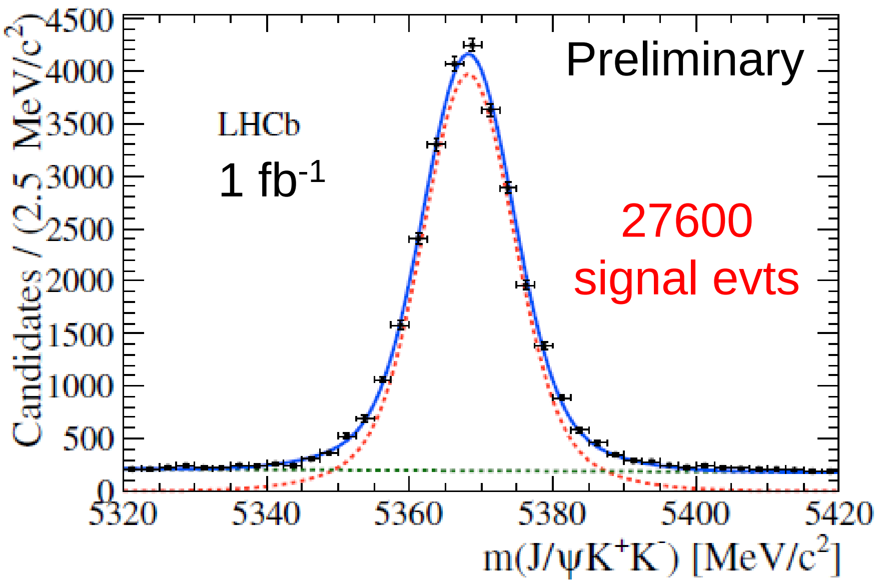
arXiv:1304.2600
Phys. Rev. D 87, 112010 (2013)

- experimentally clean
- VV final state:



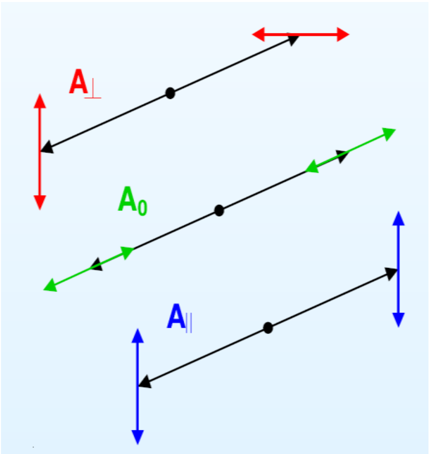
$J^{PC} = 1^{--}$

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



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

(L = 0, 1,2 = relative orbital momentum)



3 different polarization amplitudes with different relative orbital momentum:

CP-odd $(\ell = 1)$: $A_\perp$

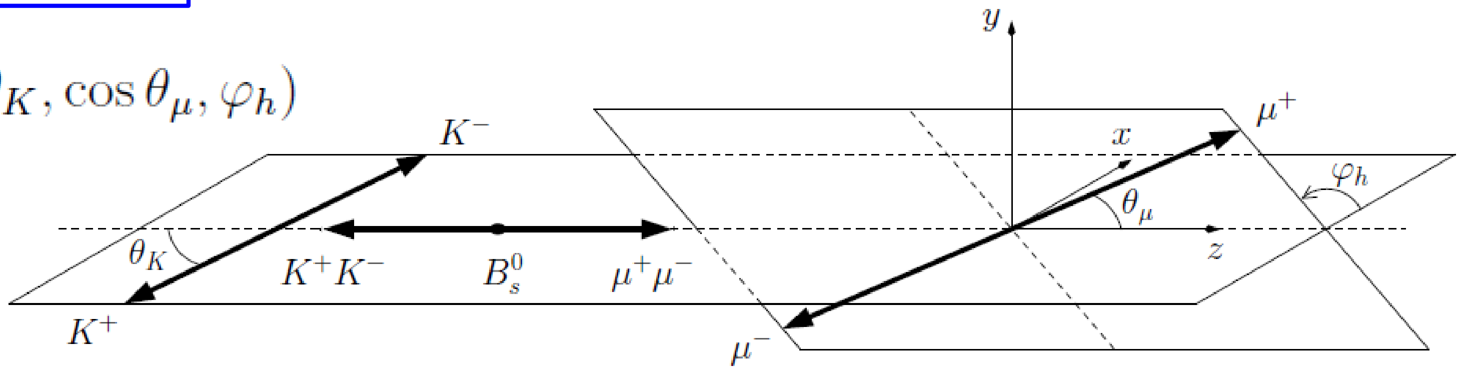
CP-even $(\ell = 0, 2)$: $A_0,\ A_{||}$

angular analysis to disentangle CP even/odd state

Angular dependent t distributions

Helicity angles

$$\Omega = (\cos\theta_K, \cos\theta_\mu, \varphi_h)$$



B_s

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{\mathrm{d}t\,\mathrm{d}\Omega} \propto \sum^{10} h_k(t)\, f_k(\Omega)$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

a_k, b_k c_k, d_k, contain ϕ_s and complex polarization amplitudes.

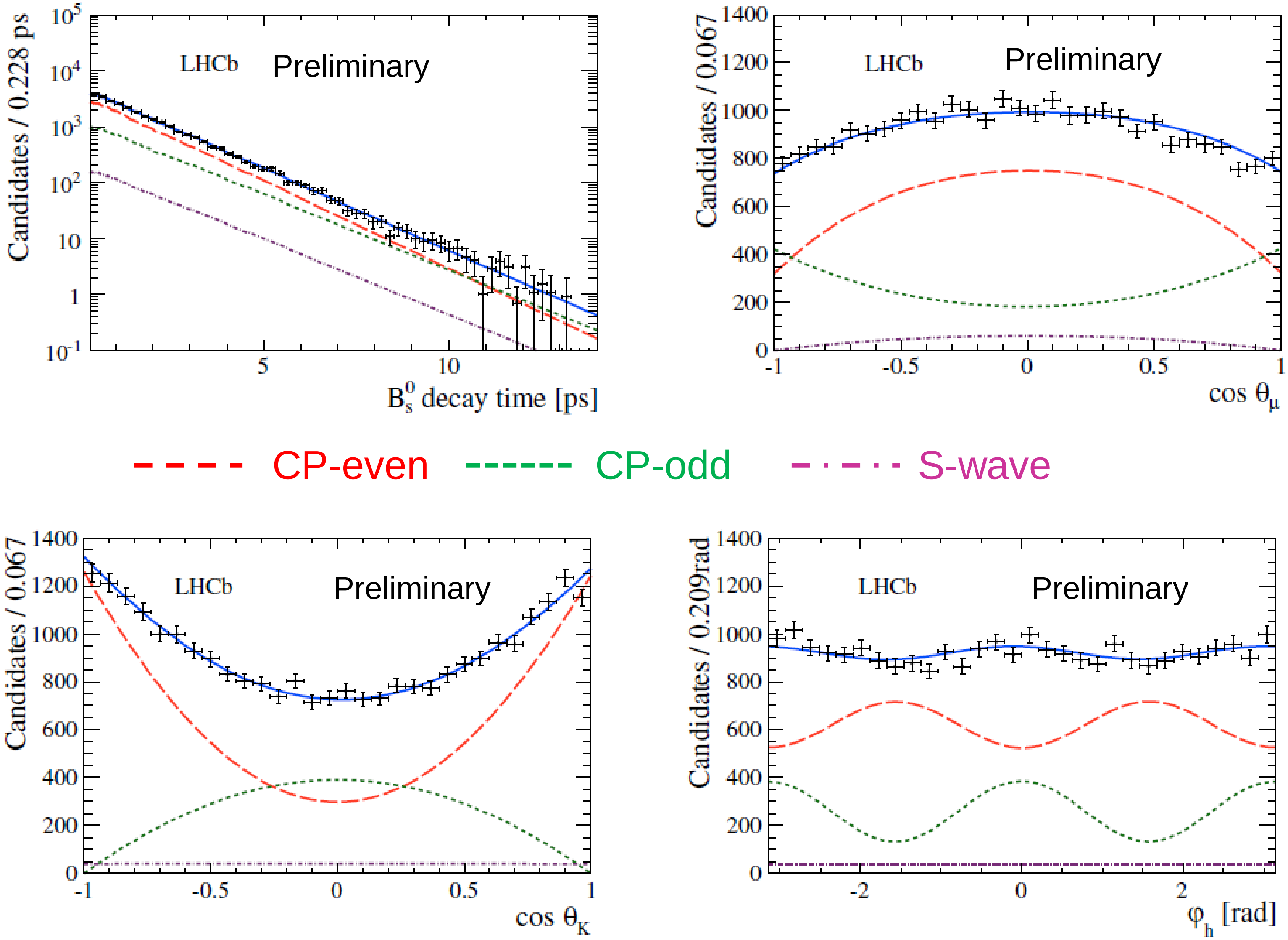
$\overline{B}_s$

$$\frac{\mathrm{d}^4\Gamma(\overline{B}_s^0 \to J/\psi K^+K^-)}{\mathrm{d}t\,\mathrm{d}\Omega} \propto \sum_{k=1}^{10} \overline{h}_k(t)\, \overline{f}_k(\Omega)$$

Fitting procedure

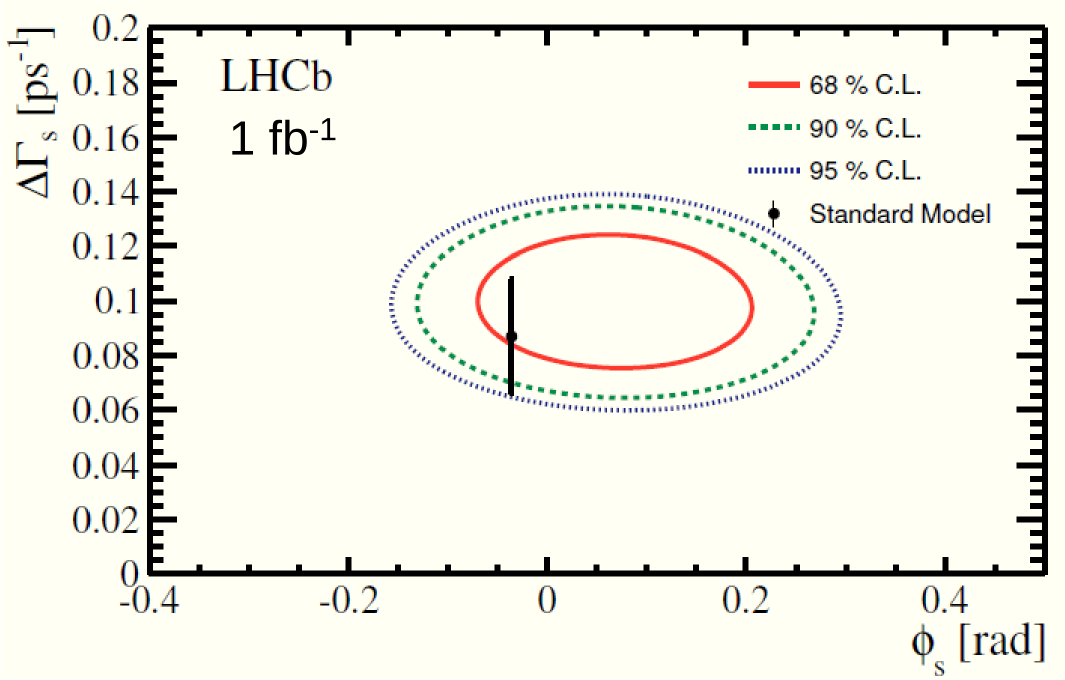
LHCb-Paper-2013-002

No CP violation seen!



Mixing Phase ϕ_s

LHCb-Paper-2013-002



(stat. error only)

$$\phi_s = 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad},$$
$$\Gamma_s = 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$
$$\Delta\Gamma_s = 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst) ps}^{-1}$$

$|\lambda| = 0.94 \pm 0.03 \pm 0.02$ (compatible w/ no CPV in decay)

Systematics - ϕ_s : Angular accept. ; $\Delta\Gamma$: Bckg + t accept.

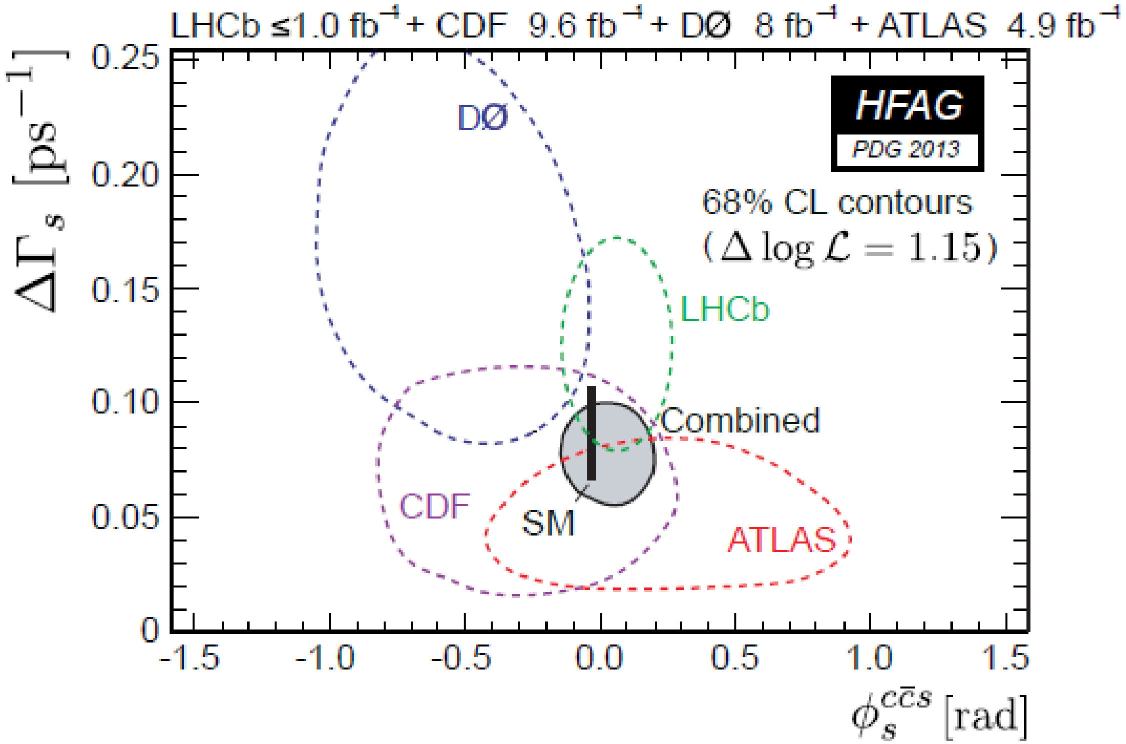
Experimental Status of $\Delta\Gamma_s$ and ϕ_s

Including $B_s \to J/\psi\pi\pi$ (pure CP odd) ⇨

ϕ_s = 0.01 ± 0.07 ± 0.01 rad

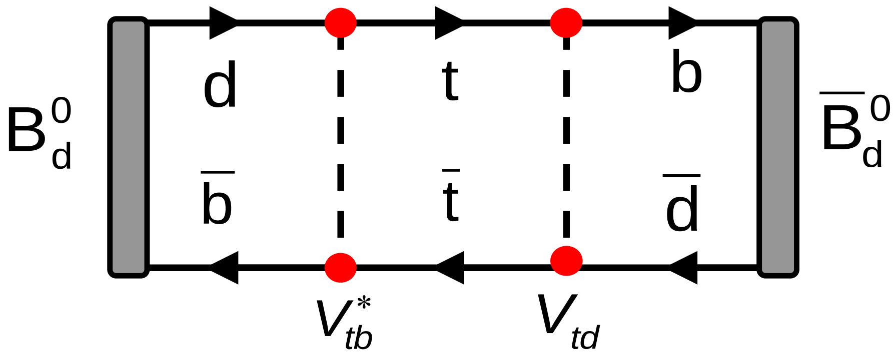
$\Delta\Gamma_s$ = 0.106 ± 0.011 ± 0.007 ps^{-1}

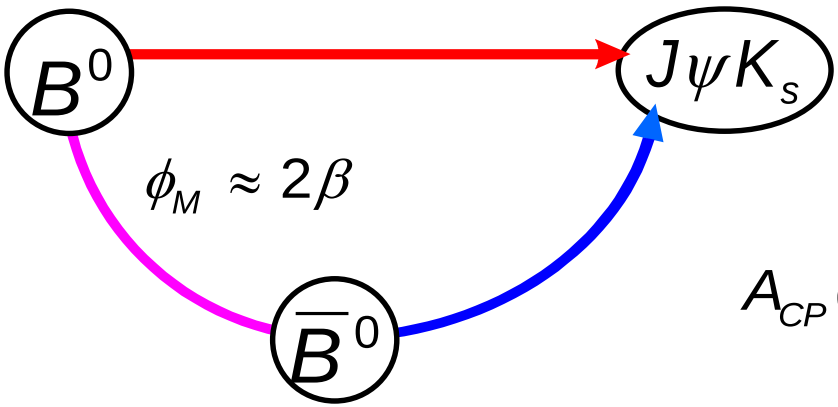
Γ_s = 0.661 ± 0.004 ± 0.006 ps^{-1}



CDF and D0 have pioneered the measurement of ϕ_s

B^0 Mixing and CPV in $B^0 \rightarrow J/\psi K_s$



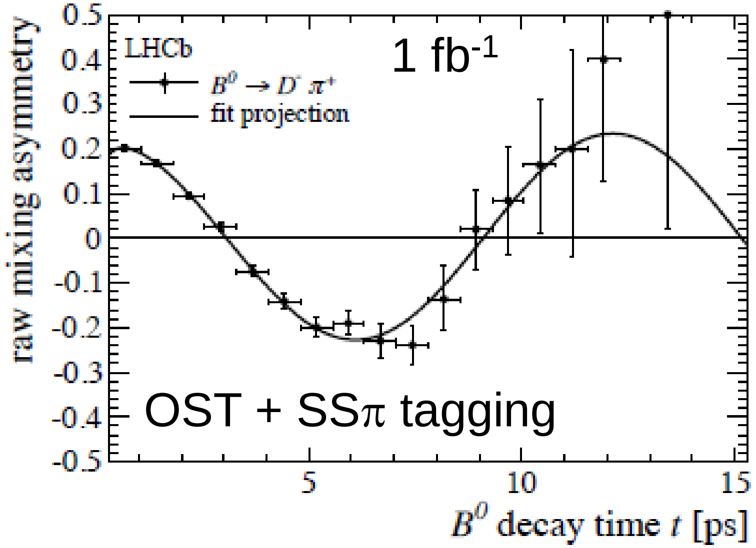


$$A_{CP}(t, B^0 \rightarrow J\psi K_s) \propto \sin(2\beta)$$

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

B^0 mixing and t-dependent CPV

LHCb-PAPER-2012-032

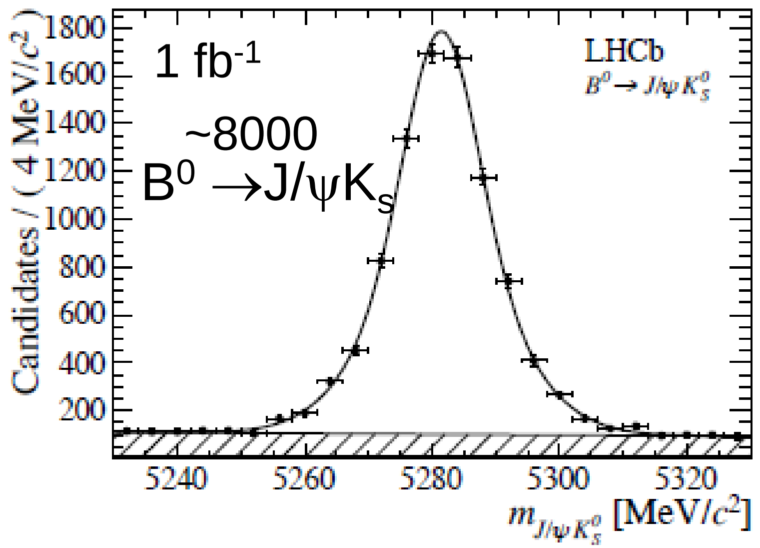


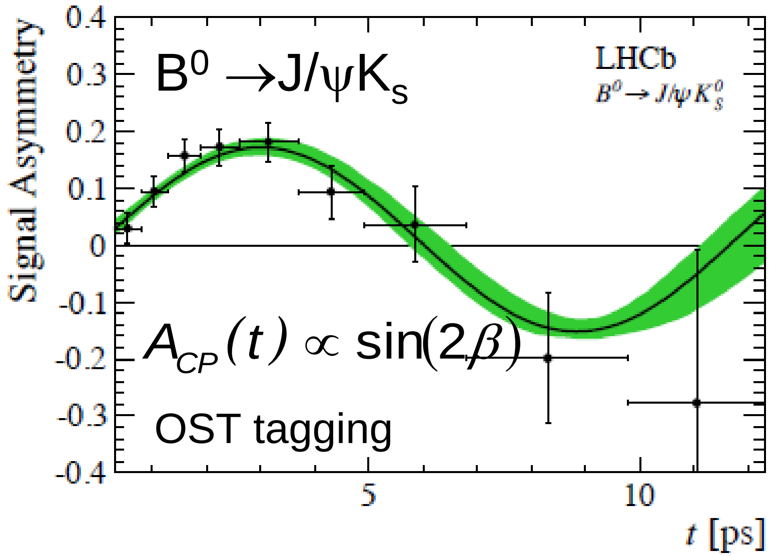
Combination of $B^0 \to D\pi$ & $B^0 \to J/\psi K^*$

$\Delta m_d = 0.516 \pm 0.005 \pm 0.003\ \mathrm{ps}^{-1}$

Single best measurement by BELLE
$\Delta m_d = 0.511 \pm 0.005 \pm 0.006\,\mathrm{ps}^{-1}$

LHCb-PAPER-2012-035





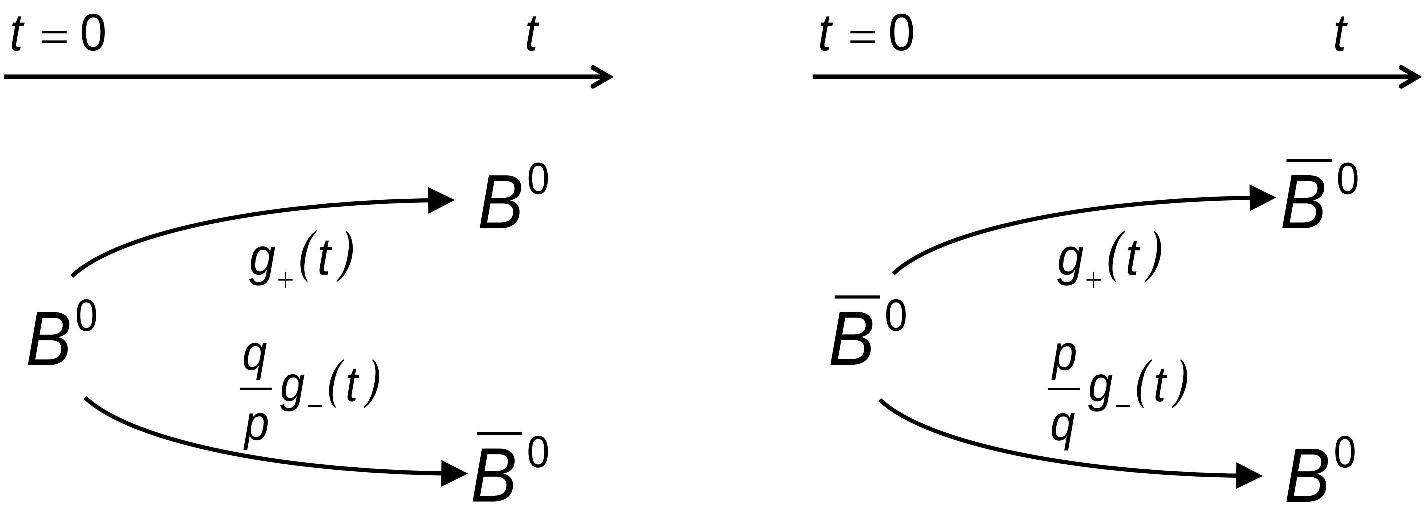
LHCb-PAPER-2012-035

$$\sin(2\beta) = 0.73 \pm 0.07_{stat} \pm 0.04_{syst}$$

HFAG average: ±0.02

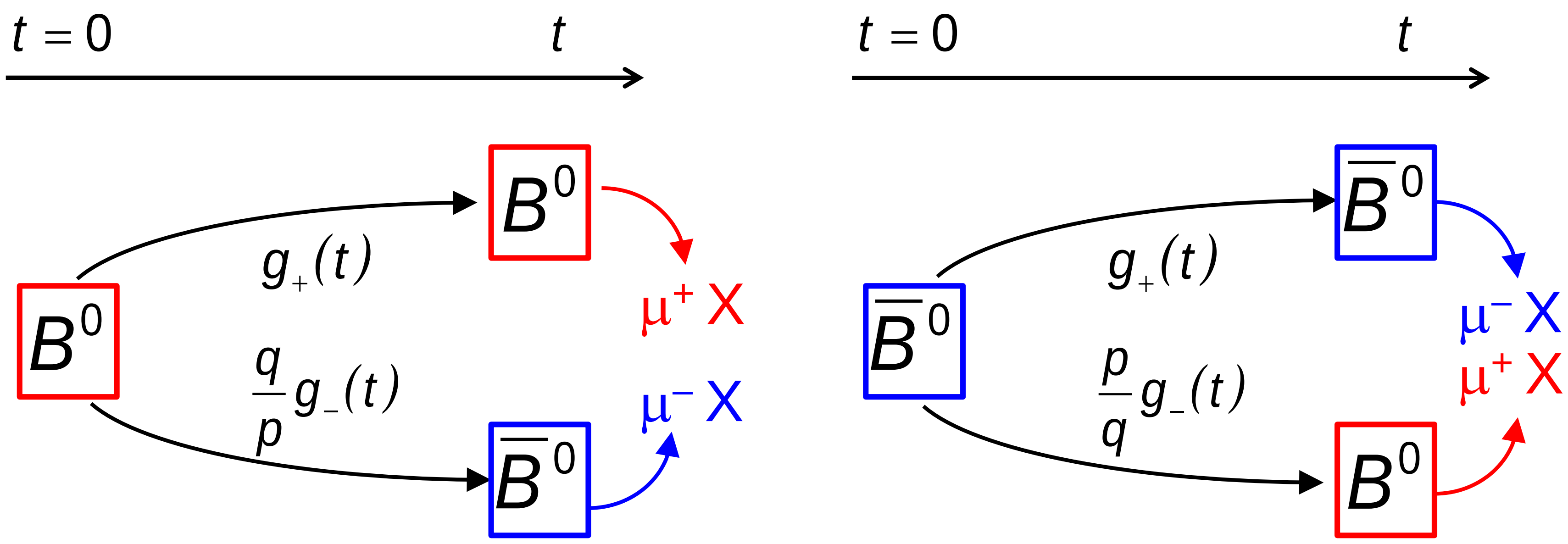
CP Violation in B mixing

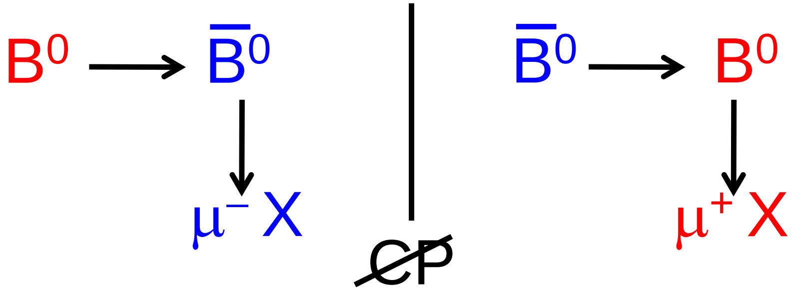
$$P(B^0_{d,s} \rightarrow \overline{B^0_{d,s}}) \neq P(\overline{B^0_{d,s}} \rightarrow B^0_{d,s})$$



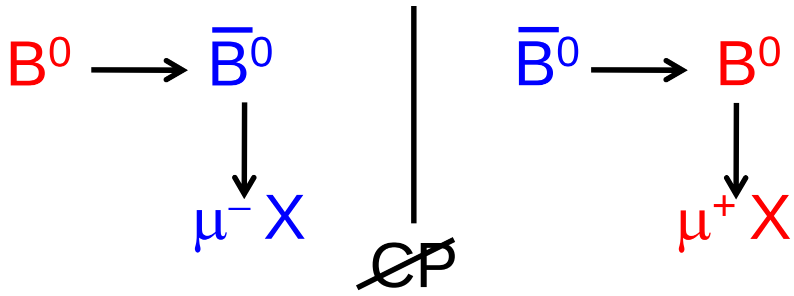
CP violation if $\left|\frac{q}{p}\right| \neq 1$

Semi-leptonic CP asymmetry





Time integrated asymmetry



$$a_{sl}^{q} \equiv \frac{\Gamma(\overline{B}_q^0 \to B_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \overline{B}_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to B_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \overline{B}_q^0 \to \mu^- X)}, \quad q = d, s$$

$$= \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_{12}$$

$$a_{fs}^{d,\mathrm{SM}} = (-4.5 \pm 0.8) \cdot 10^{-4} \qquad a_{fs}^{s,\mathrm{SM}} = (2.11 \pm 0.36) \cdot 10^{-5}$$

A.Lenz and U.Nierste

The D0 experiment have used like sign muon pairs to measure a_{SL} and observed significant deviations from zero.

LHCb measurement of a_{SL}

- Tagging of the initial state reduces the statistical power drastically

- A untagged analysis is possible, reduction of stat. power only by factor 2. However this requires an excellent knowledge of the production asym.

$$A_P = \frac{\mathcal{P}(B^0) - \mathcal{P}(\overline{B}^0)}{\mathcal{P}(B^0) + \mathcal{P}(\overline{B}^0)}$$

- Moreover one needs to know the detection asymmetry for the final state

$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

- Knowing the detection asymmetry, the production and semi-leptonic asymmetries can be determined in a time dependent analysis:

$$A_{\text{meas}}(t) = \frac{N(f,t) - N(\overline{f},t)}{N(f,t) + N(\overline{f},t)} \approx A_D + \frac{a_{sl}^d}{2} + \left(A_P - \frac{a_{sl}^d}{2}\right)\cos(\Delta m_d t)$$

Semi-leptonic asymmetry for B_d

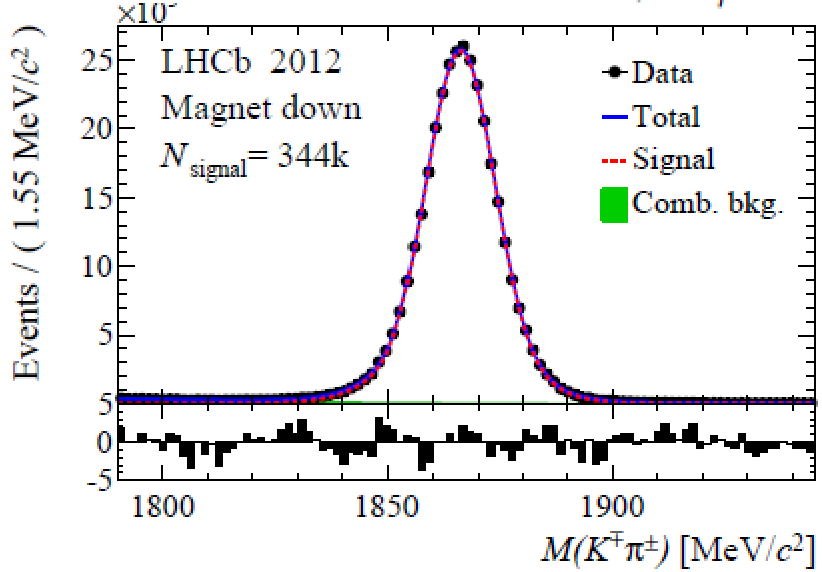
Reconstructing of the D / D* meson for

$$B^0 \to D^- \mu^+ \nu_\mu X$$

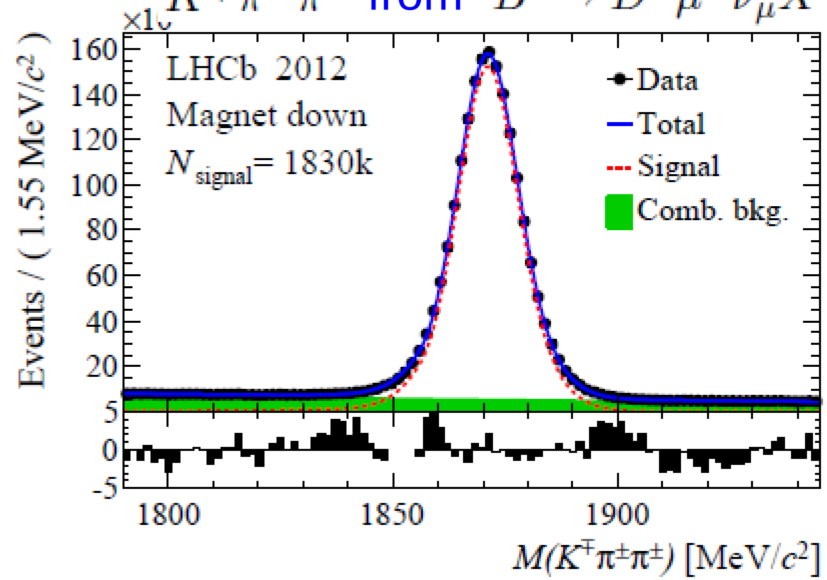
$$B^0 \to D^{*-} \mu^+ \nu_\mu X$$

→semi-leptonic events from **B^0** decays: missing neutrino complicates time reconstruction (k-factor).

$K^\mp \pi^\pm$ from $B^0 \to D^{*-} \mu^+ \nu_\mu X$



$K^\mp \pi^\pm \pi^\pm$ from $B^0 \to D^- \mu^+ \nu_\mu X$



➡ Analysis is on-going

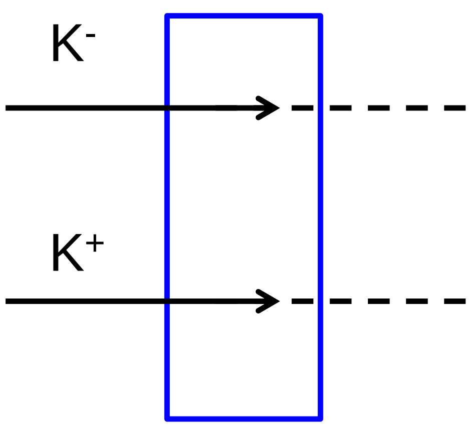
expect $\Delta a_{SL} \approx \pm 0.3\%_{syst}$ for B^0 mixing

Detection asymmetry A_D

- Difference in tracking efficiency for positively/negatively charged tracks: Mostly related to acceptance problems.

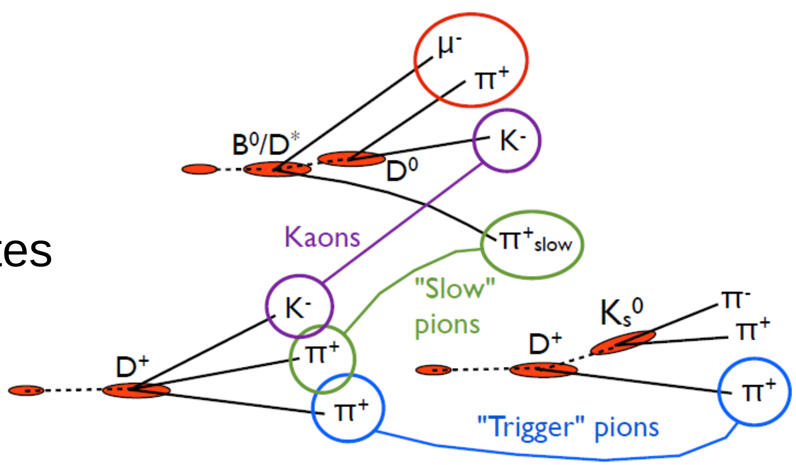
  $\rightarrow$ invert magnetic field of spectrometer

- Different material interaction: most prominent for $K^{\pm}$



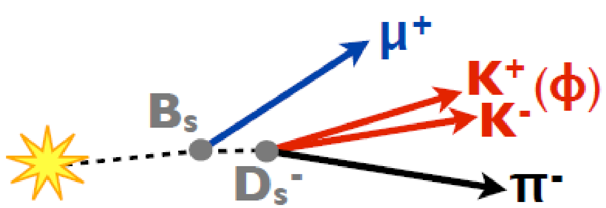
$K^- (s\bar{u}) + N \rightarrow \Lambda + \ldots.$

Use similar final states to measure A_D



Semi-leptonic asymmetry for B_s

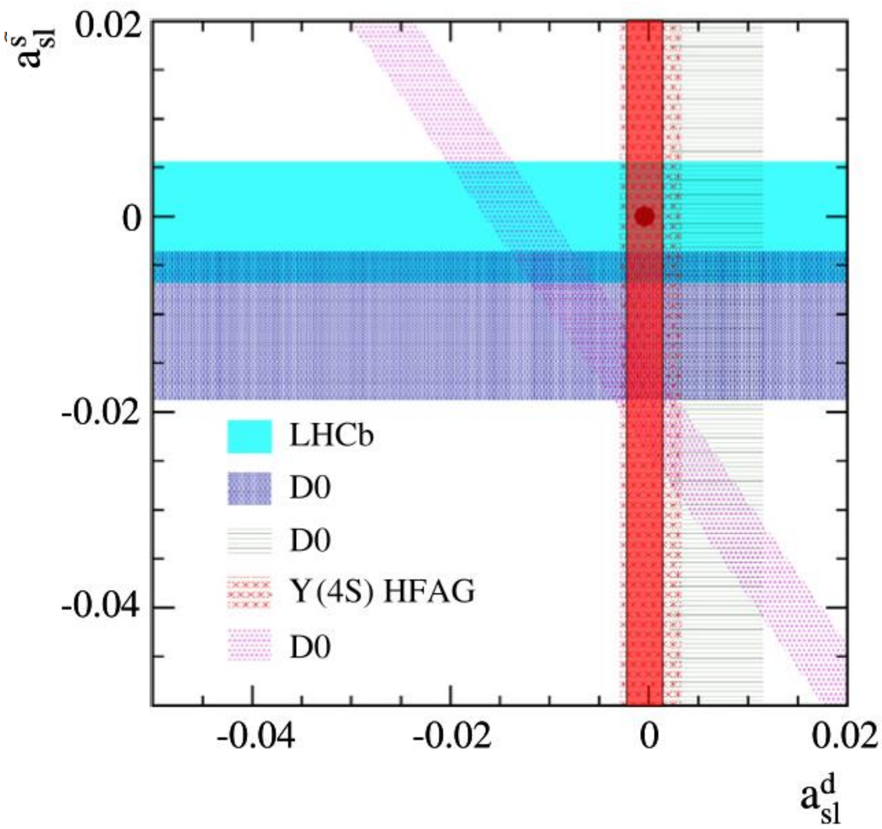
- Due to the fast oscillation, the production asymmetry for B_s mesons is washed out and no time dependent measurement is necessary.
- Use $B_s \to D_s \mu \nu$ decays:



$$\frac{a^s_{sl}}{2} \approx \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)}$$

Asymmetry of μ detection from tag-and-probe $J/\psi \to \mu\mu$:

$$A^c_\mu = (+0.04 \pm 0.25)\%$$

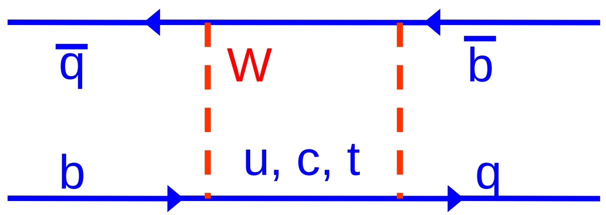


$$a^s_{sl} = (-0.06 \pm 0.50 \pm 0.36)\%$$

consistent with Standard Model

arXiv:1308.1048

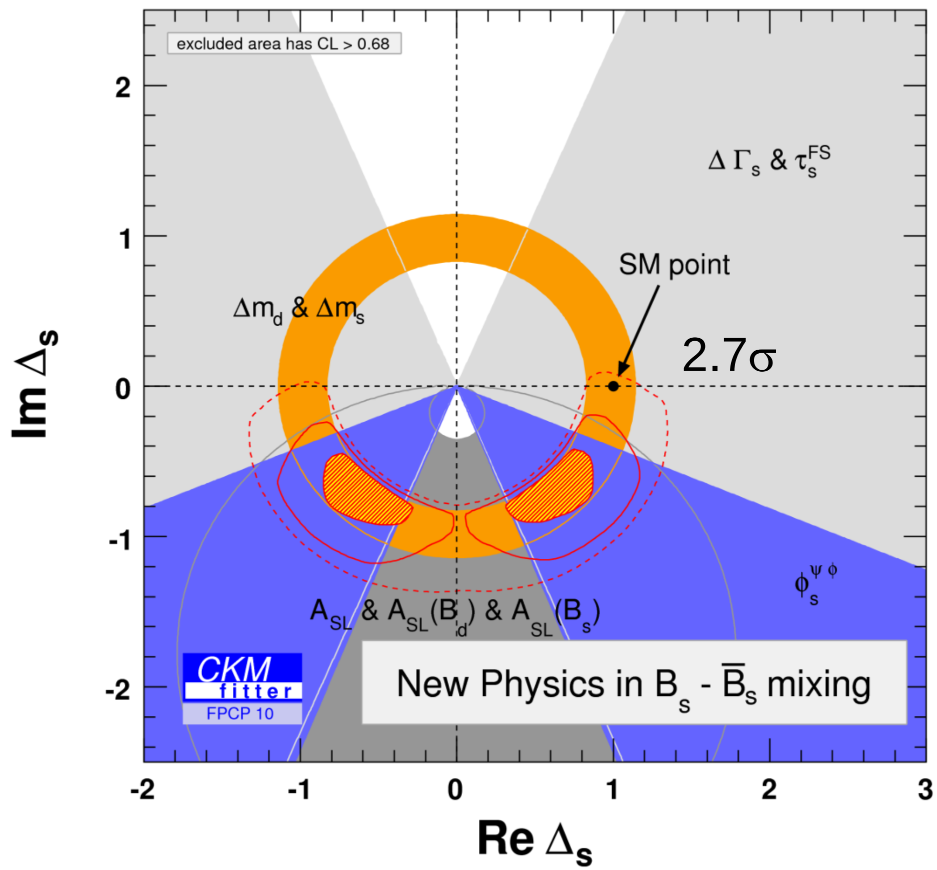
New Physics in B_s Mixing



$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP} = \mathcal{A}_{mix}^{SM} \times \Delta$$

$$\Delta_s = |\Delta_s| e^{i\phi_s^{NP}}$$

Status FPCP 2010



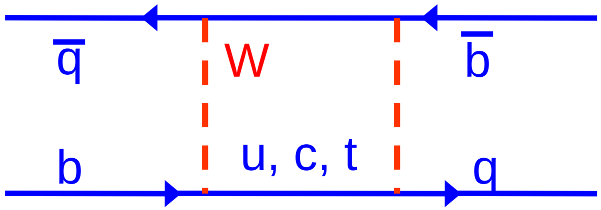
A. Lenz , U. Nierste & CKM Fitter

↓

H. Lacker

SM hypothesis $\Delta_s = 1$, $\Delta_d = 1$
disfavored by 3.6σ

New Physics in B_s Mixing



$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP} = \mathcal{A}_{mix}^{SM} \times \Delta$$

$$\Delta_s = |\Delta_s| e^{i\phi_s^{NP}}$$

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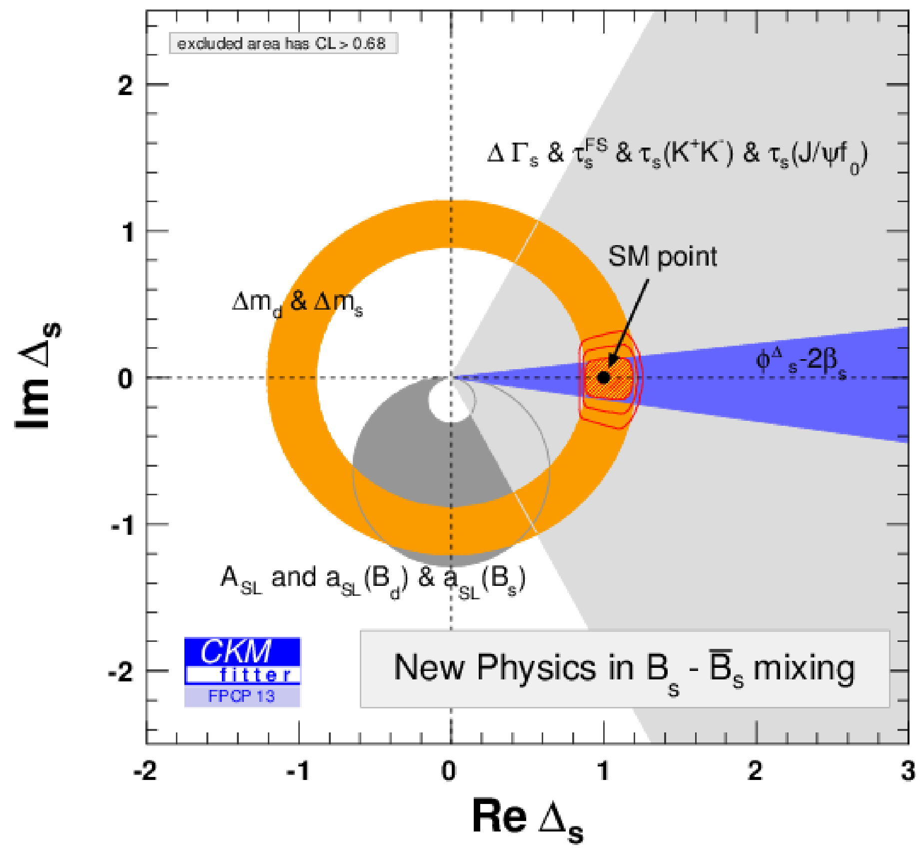
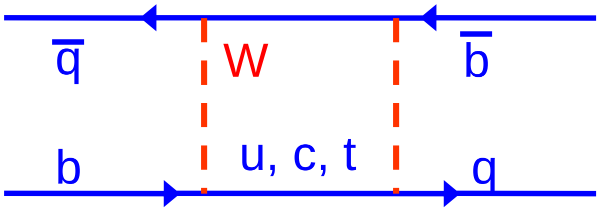
Status FPCP 2013



Agreement with Standard Model, but still room for New Physics (20%)

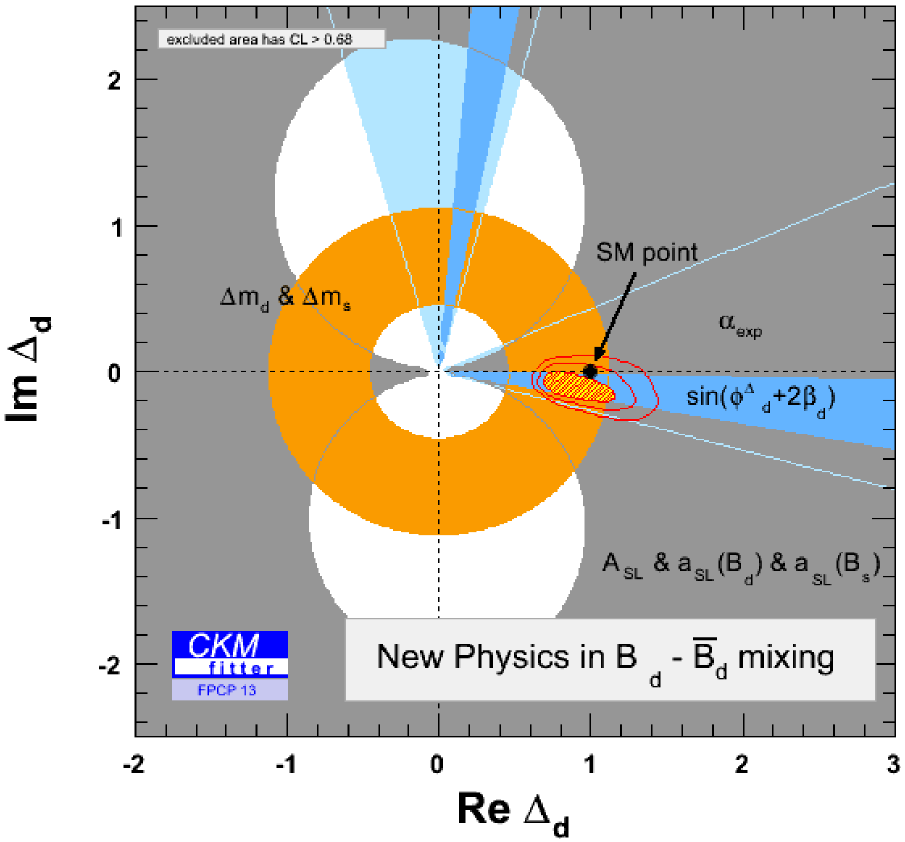
New Physics in B_d Mixing



$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP} = \mathcal{A}_{mix}^{SM} \times \Delta$$

$$\Delta_d = |\Delta_d| e^{i\phi_d^{NP}}$$

Status FPCP 2013



Room for New Physics (10-20%)

A. Lenz , U. Nierste & CKM Fitter

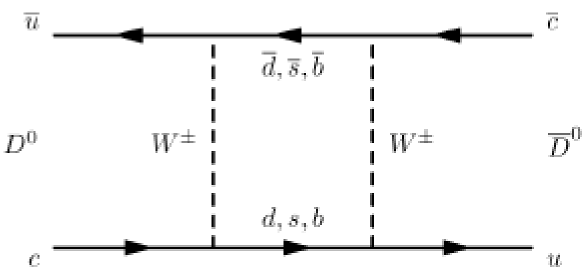
Charm Mixing and CP Violation

http://www.zazzle.de/standardmodell_charme_quark_kaffeetasse

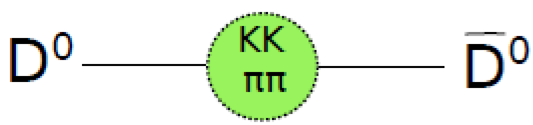
Charm Mixing

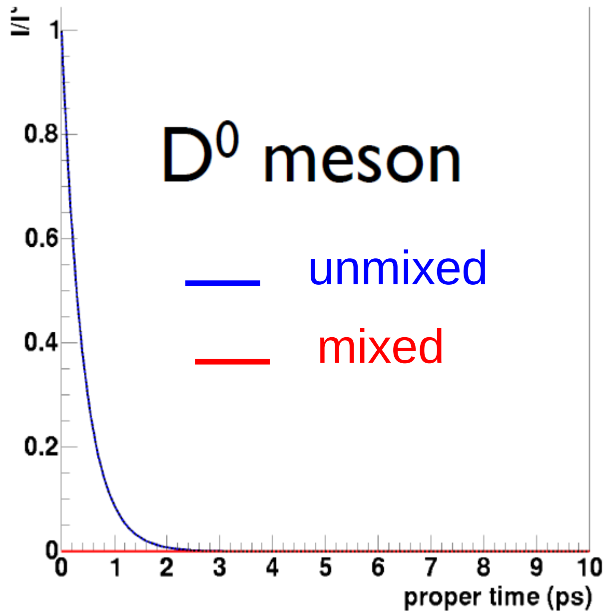
D^0-D^0 mixing is expected to be very small

- Quark loops are second order and GIM suppressed. Why?



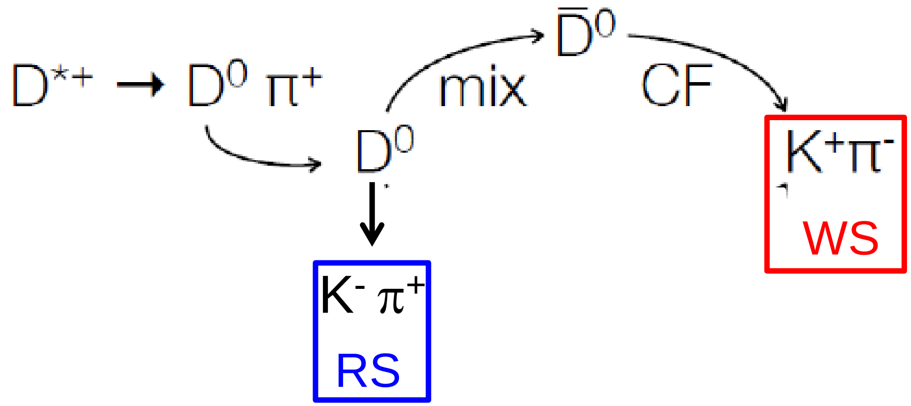
- Long distance effects are tricky to calculate. arxiv:0311371





$D^0 - \bar{D}^0$ Mixing

PRL 111, 251801 (2013)



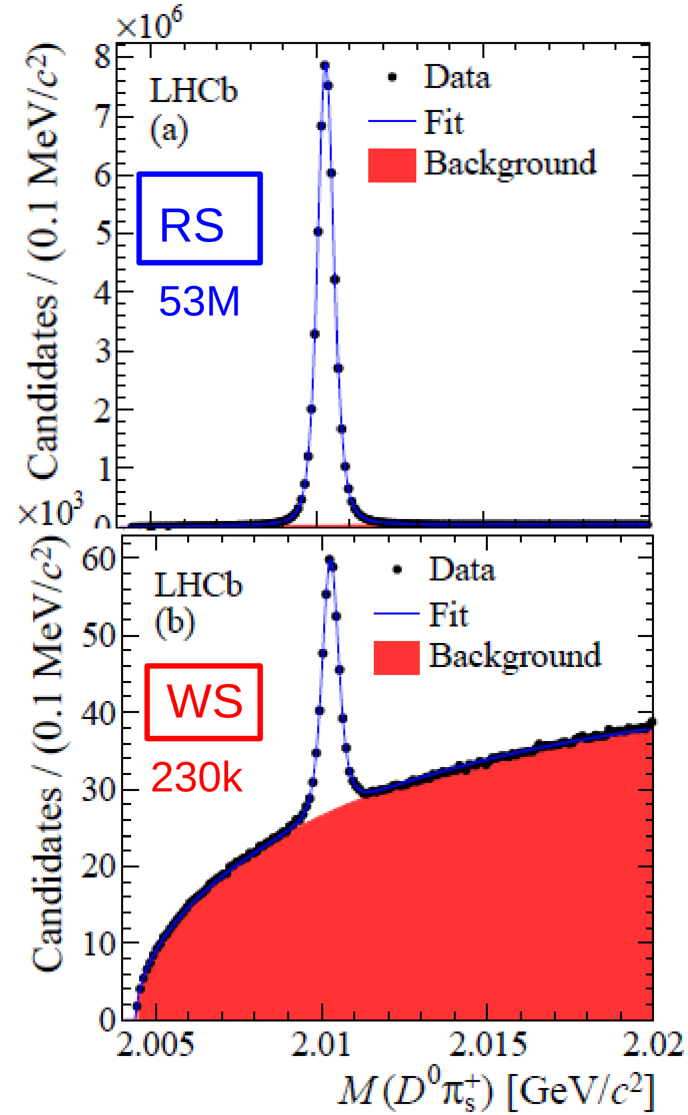
DCS CF

$$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\bar{D}^0 \to K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}$$

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

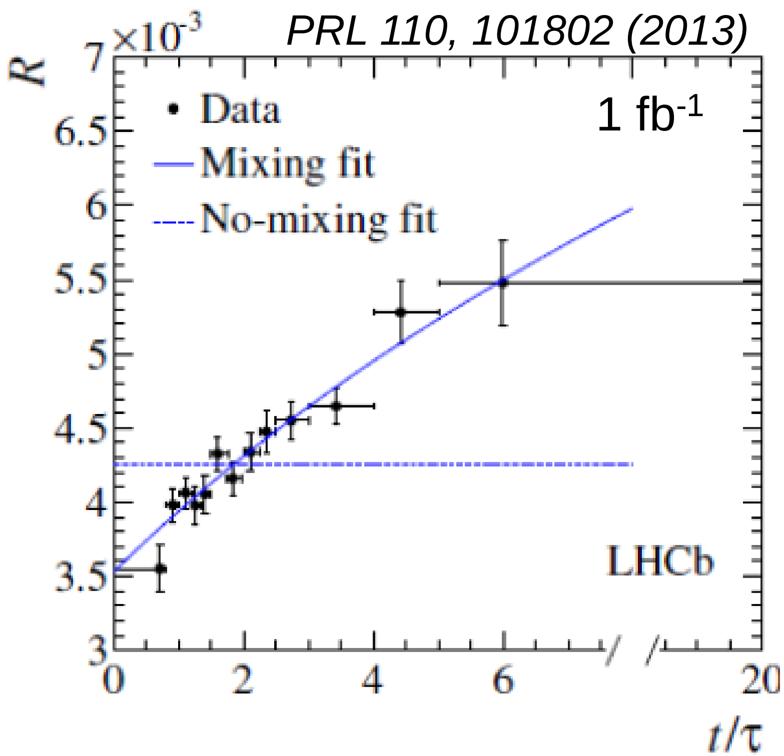
$$x' = x\cos\delta + y\sin\delta \qquad y' = -x\sin\delta + y\cos\delta$$

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



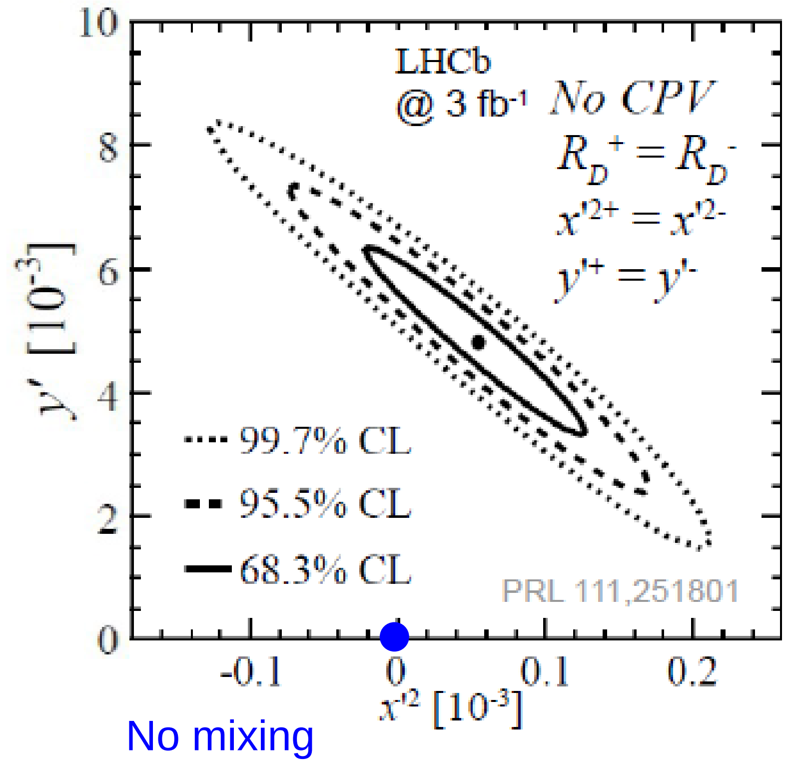
$D^0 - \bar{D}^0$ Mixing

PRL 111, 251801 (2013)



$$R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

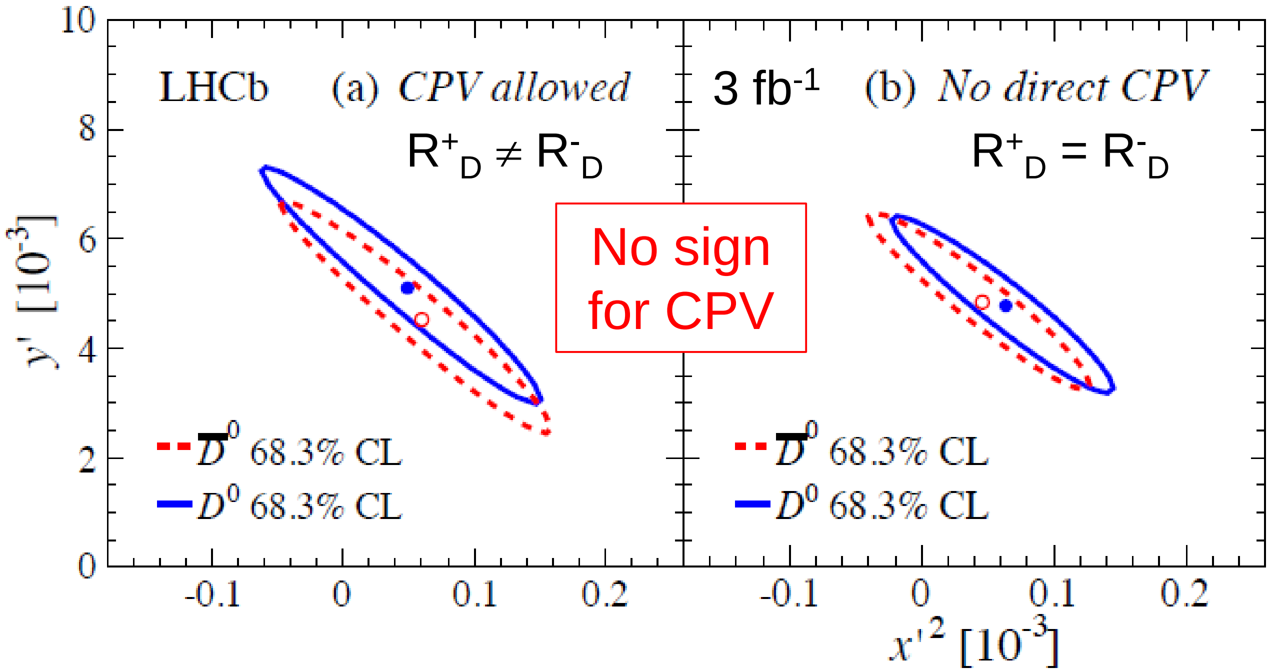
Theoretical interpretation requires the knowledge of strong phase δ.



R_D	$[10^{-3}]$	3.568 ± 0.066
y'	$[10^{-3}]$	4.81 ± 1.00
x'^2	$[10^{-5}]$	5.5 ± 4.9
χ^2/ndf		$86.41/101$

CPV in D-Mixing

PRL 111, 251801 (2013)



Test for CP violation:

- Direct CP violation: $R^+_D \neq R^-_D$?

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-1.3 \pm 1.9)\%$$

- CPV in mixing ($|q/p| \neq 1$) ?

$$0.75 < \left|\frac{q}{p}\right| < 1.24 \text{ at } 68.3\%$$

Direct CP Violation in Charm

- CP Violation in charm difficult to predict, but small (reason: Cabibbo part of CKM matrix is essentially real)

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

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

CP eigenstate f :

$\pi^+ \pi^-$, $K^+ K^-$

Theoretical expectation: A_{CP} is very small, $\leq 10^{-3}$.

Measurement of small CP Violation

$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}) + A_{\rm P}(D^{*+})$$

- Physical CP asymmetry, expected of up to $O(10^{-3})$
- Detection asymmetry, cancels for $D^0 \to \pi\pi$, KK decays
- Detection asymmetry for slow $\pi^{\pm}$
- Production asymmetry

(last two:) Can be large O(1%)

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

LHCb 2011 ($0.6\ fb^{-1}$) *PRL 108 (2012) 111602.*

$$\Delta A_{CP} = [\, -0.82 \pm 0.21_{stat} \pm 0.11_{syst}\,]\ \%$$

Direct CP Violation in Charm?

2.2σ

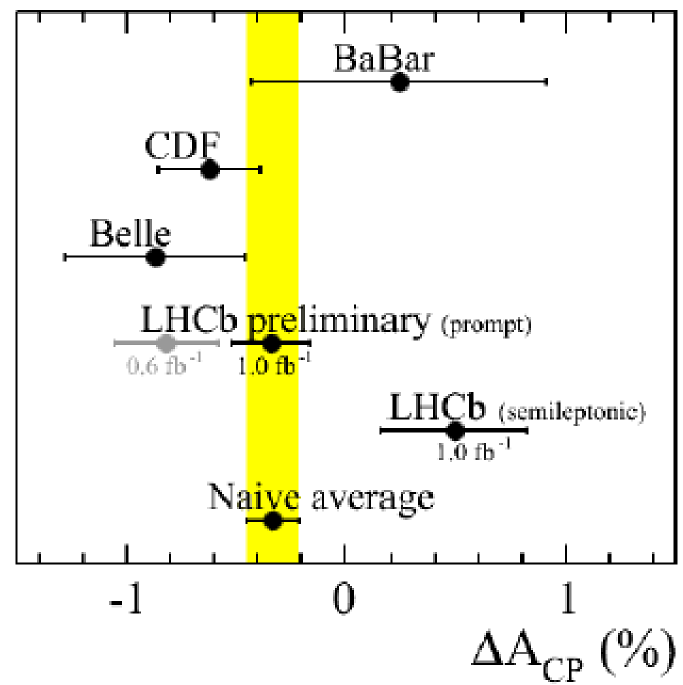
Prompt D *(preliminary: LHCb-Conf-2013-003)*

$\Delta A_{CP} = [\,-0.34 \pm 0.15_{stat} \pm 0.10_{syst}\,]\ \%$

Semileptonic B decays

(LHCb-Paper-2013-003, arXiv:1303.2614)

$\Delta A_{CP} = [\,+0.49 \pm 0.30_{stat} \pm 0.14_{syst}\,]\ \%$

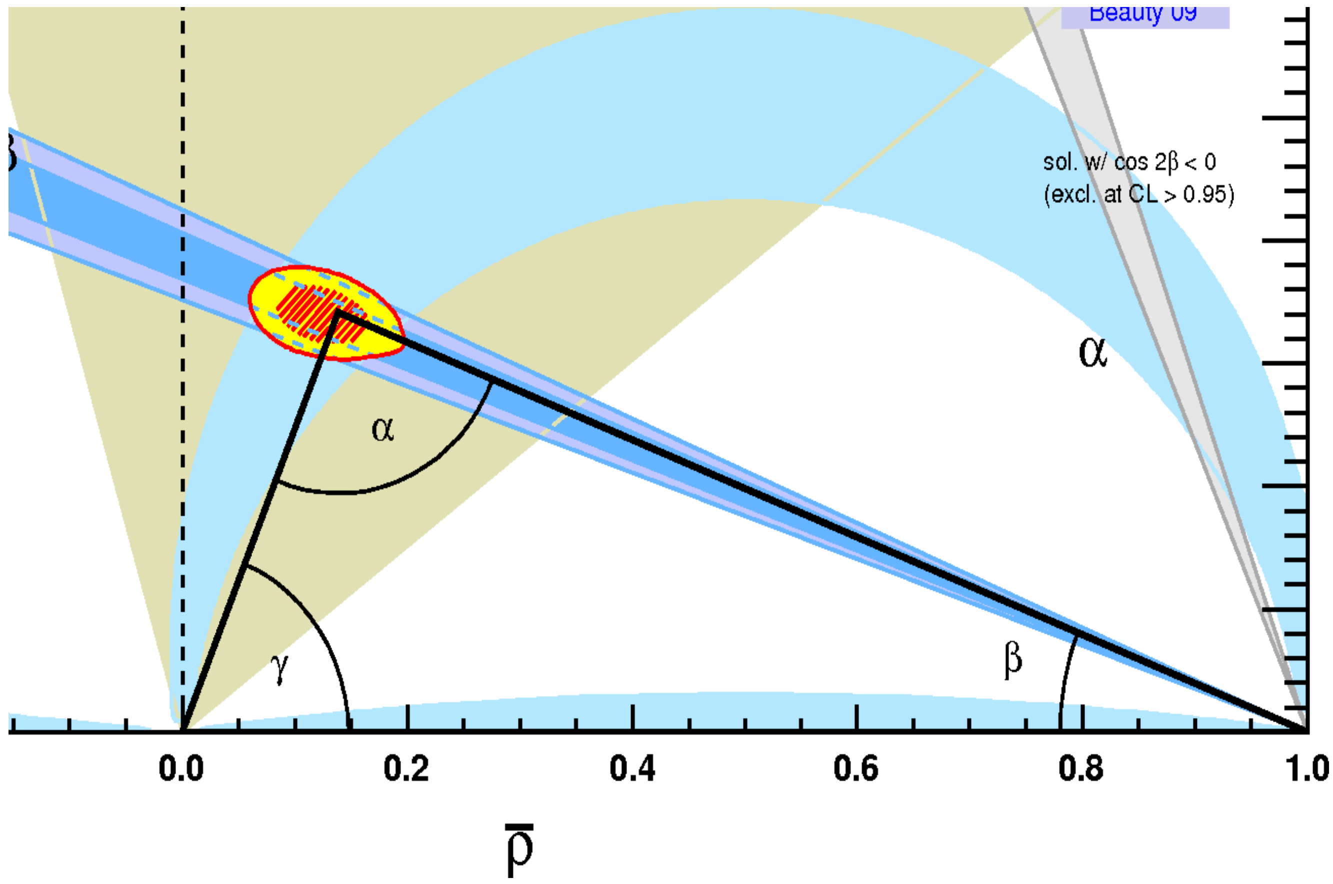


simple average

$\Delta A_{CP} = [\,-0.15 \pm 0.16]\ \%$ (χ^2=4.85 ⇔ P=3%)

New results do not confirm evidence for CPV in charm decays.

Direct CP Violation & CKM angle γ

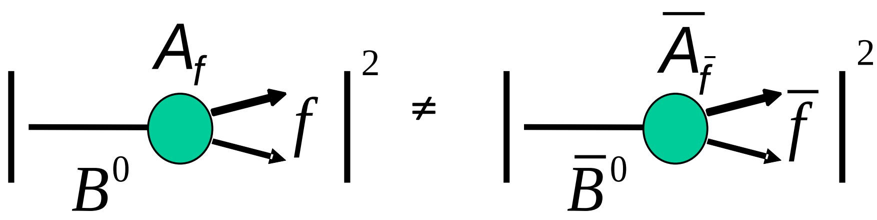


Direct CP Violation & CKM angle γ

- CP Violation in mixing
- CP Violation through interference between decay and mixing

Indirect CPV

- CP violation in decay



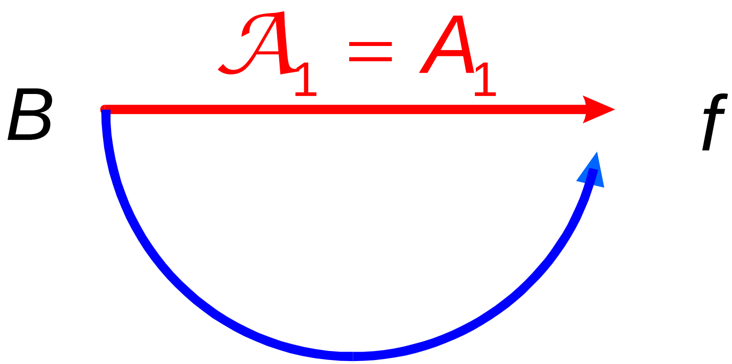
direct CPV

$$P(B \to f) \neq P(\bar{B} \to \bar{f})$$

(time integrated)

Direct CP Violation

$B \rightarrow f$

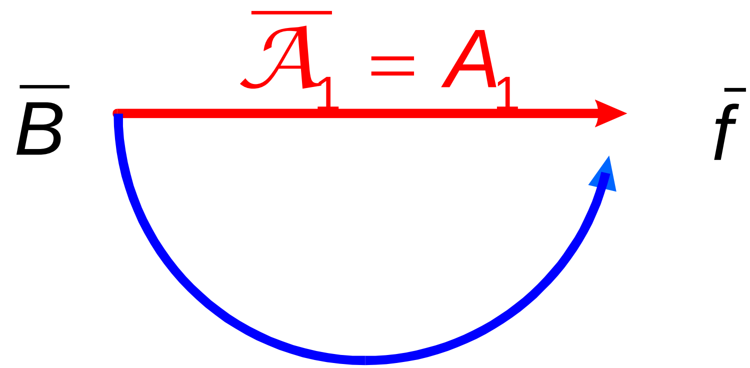


$$\mathcal{A}_2 = A_2\, e^{i\phi_{CP}} e^{i\delta}$$

Weak and strong CP invariant phase difference

CP

$\bar{B} \rightarrow \bar{f}$



$$\overline{\mathcal{A}_2} = A_2\, e^{-i\phi_{CP}} e^{i\delta}$$

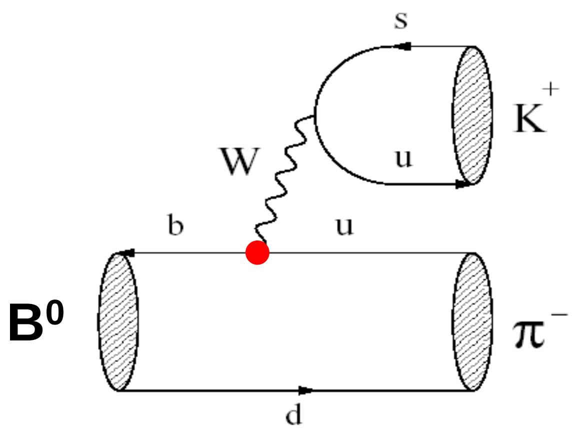
$$|\mathcal{A}|^2 = |\mathcal{A}_1 + \mathcal{A}_2|^2$$
$$= A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} + \delta)$$

$$|\overline{\mathcal{A}}|^2 = |\overline{\mathcal{A}_1} + \overline{\mathcal{A}_2}|^2$$
$$= A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} - \delta)$$

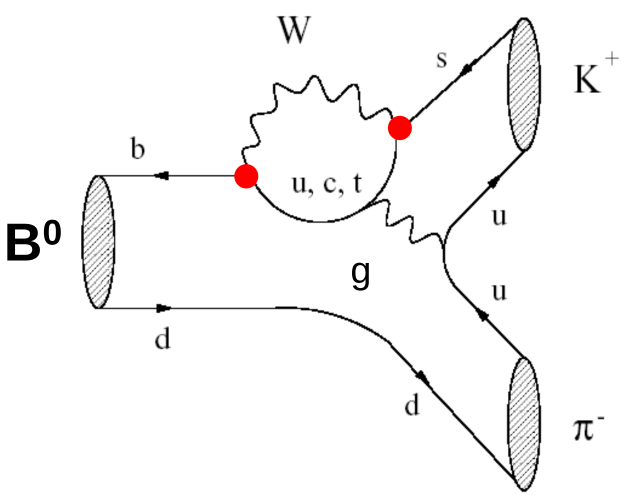
$$|\overline{A}|^2 - |A|^2 = 4A_1A_2\sin(\phi_{CP})\sin(\delta)$$

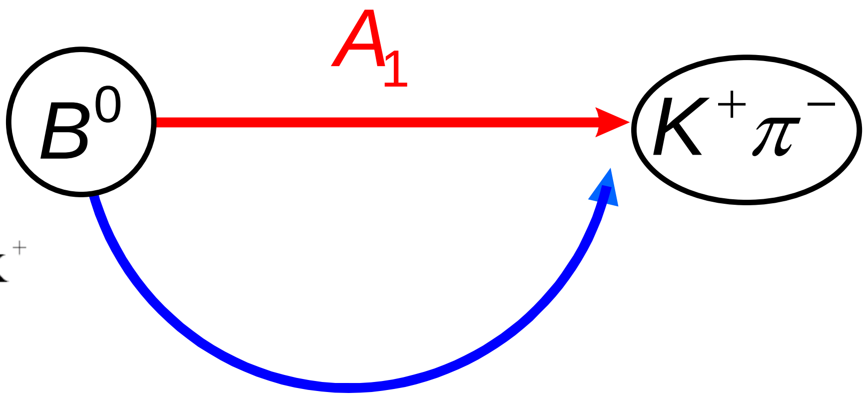
Direct CP Violation in B→Kπ

Tree



Penguin





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

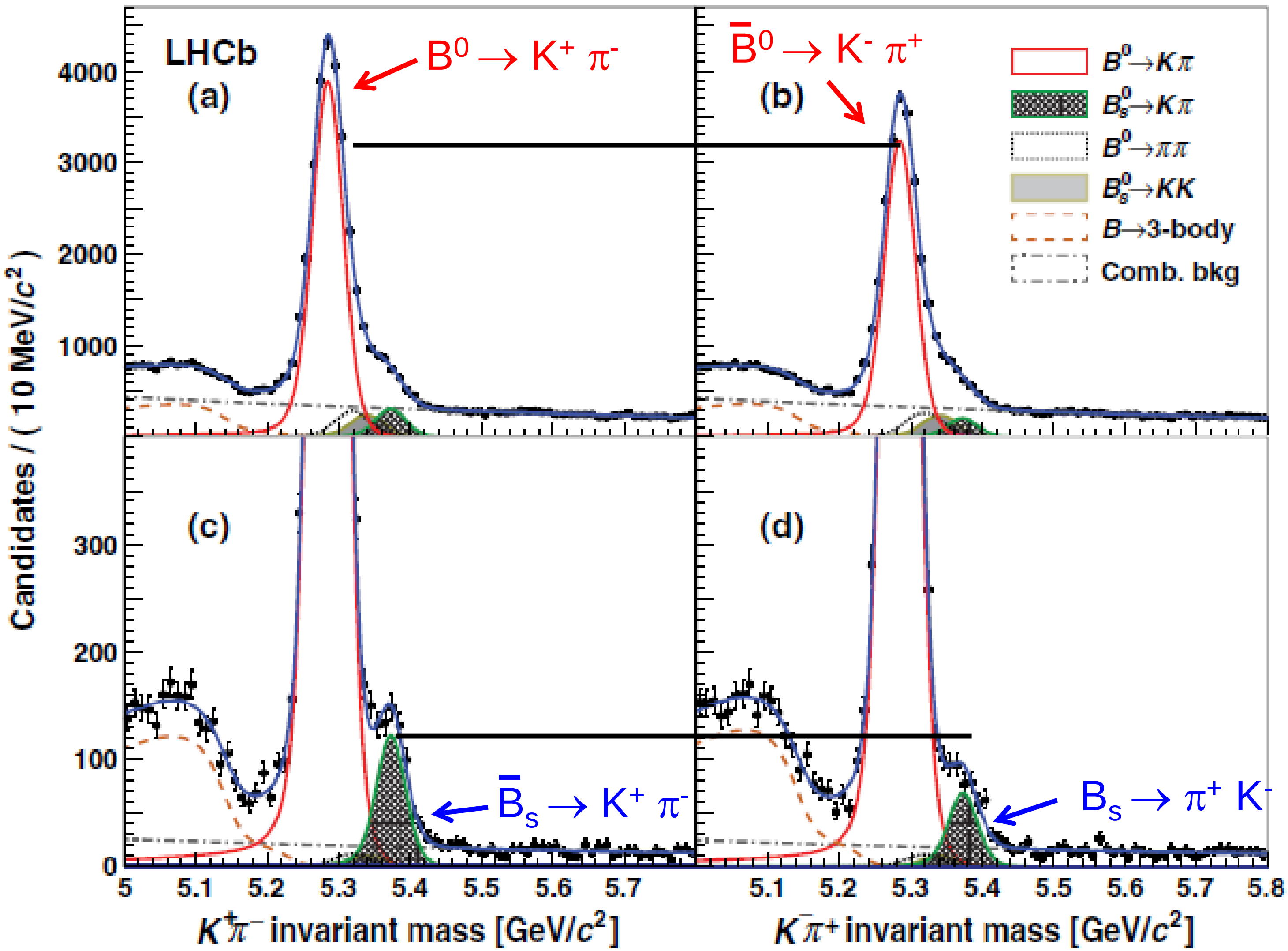
Strong phase difference
difficult to predict

CP Asymmetrie

$$\left|\bar{A}\right|^2 - \left|A\right|^2 = 4\left|A_1\right|\left|A_2\right|\sin\phi\,\boxed{\sin\delta}$$

Direct CP asymmetries for $B^0_{d,s} \to K\pi$

PRL 110, 221601 (2013)



CP Observables

PRL 110, 221601 (2013)

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

Correction for detection / production asymmetry

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst}) \quad [10.5\sigma]$$

$$A_{CP}(B^0_s \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}). \quad [6.5\sigma]$$

Standard Model relation: *[J.Lipkin Phys. Lett. B621 (2005) 126.] *)*

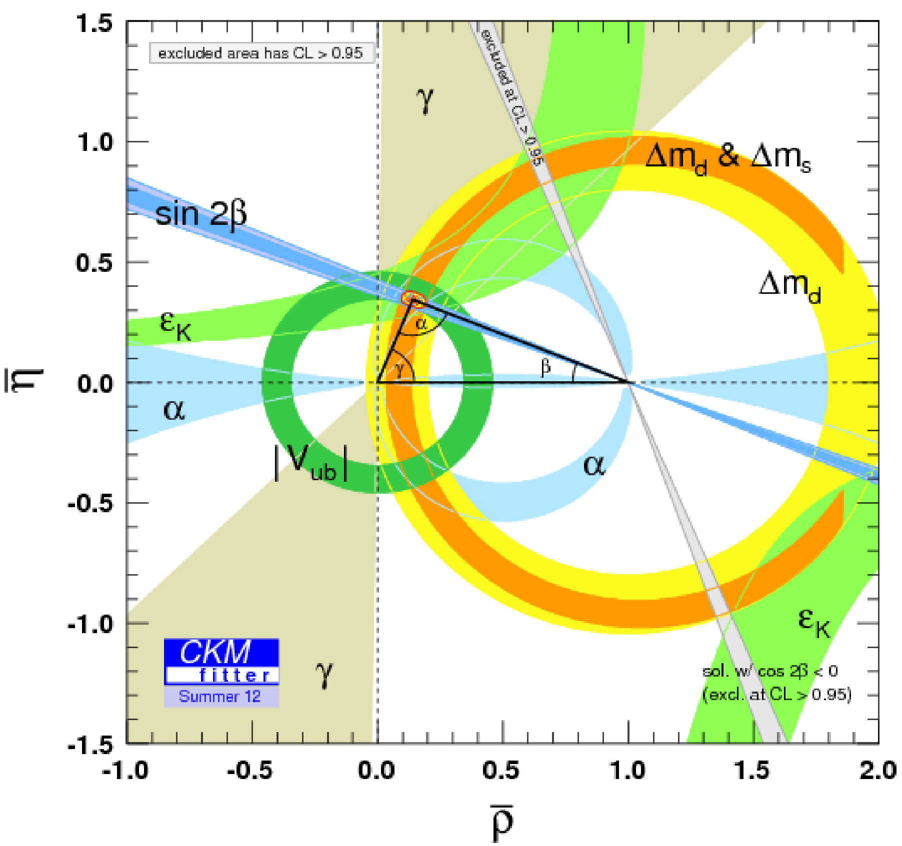
$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B^0_s \to K^-\pi^+)} + \frac{\mathcal{B}(B^0_s \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0,$$

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

Direct CPV in $B \to K\pi$ fully consistent with SM.

.*) …but in the standard model a miracle occurs …

CKM Angle γ



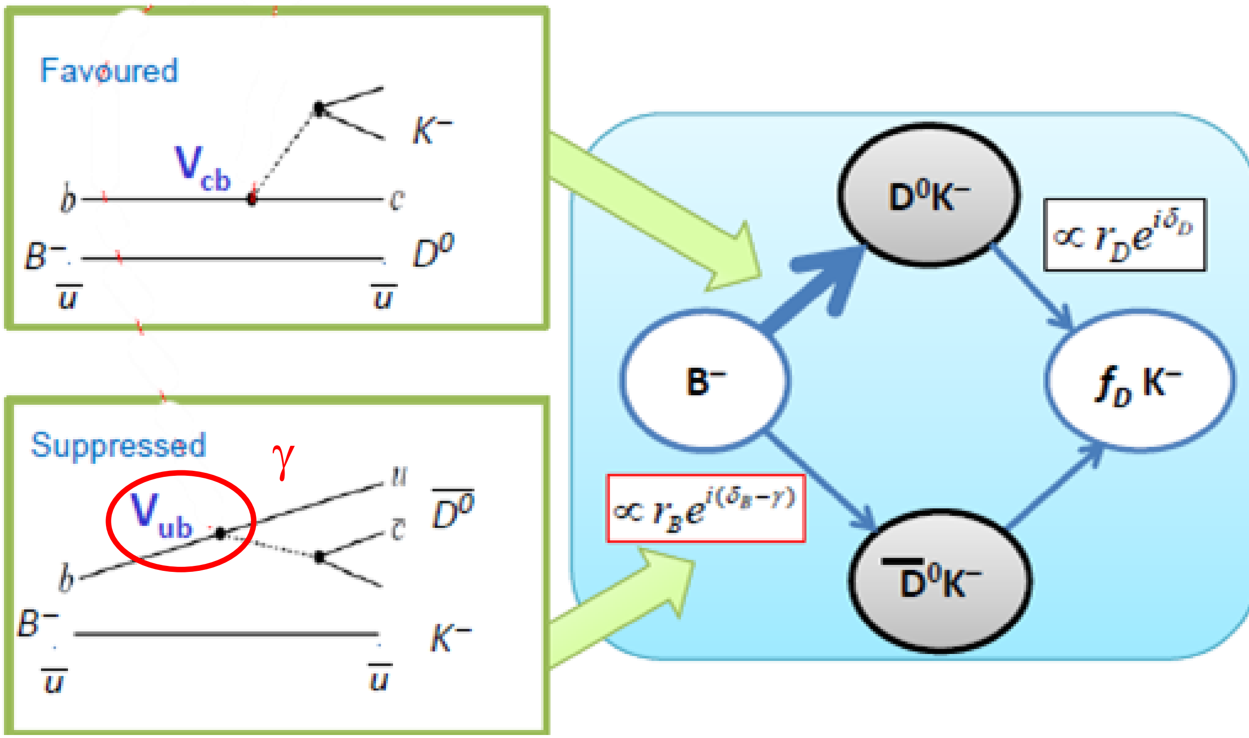
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

⇩

Exploit direct CPV in B→DK decays

Sensitivity of B→DK decays to γ

Adapted from S. Ricciardi



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

$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\bar{D}^0 \to f_D)}$$

All unknowns from data
⇒ No hadronic uncertainties

Gronau, London, Wyler (GLW)
f_D = KK, ππ (CP state)

Atwood, Dunietz, Soni (ADS)
$f_D = K^+\pi^-$ and π^+K^-

Giri, Grossman, Soffer, Zupan (GGSZ)
Self conjugated Dalitz modes

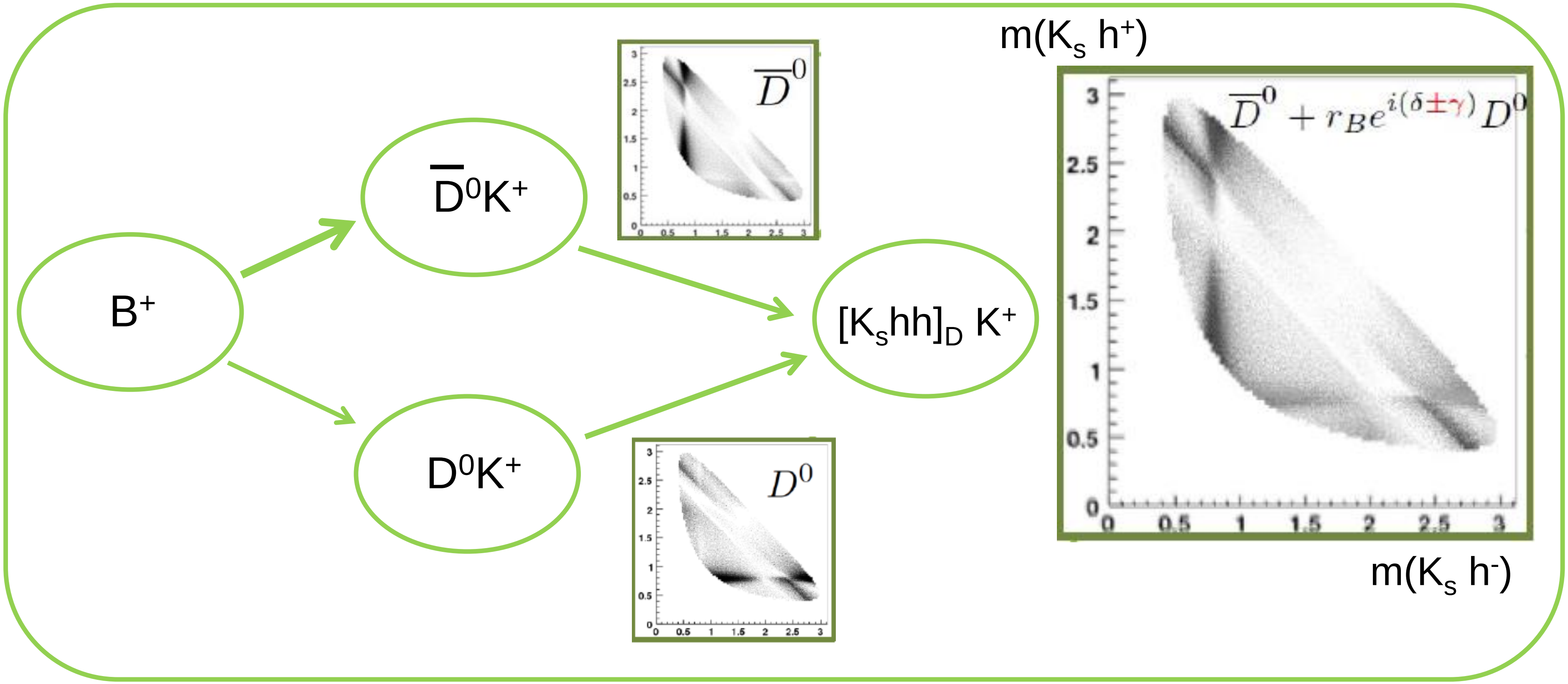
LHCb:
- $B^\pm \to D(KK)\, K^\pm$
- $B^\pm \to D(\pi\pi)\, K^\pm$
- $B^\pm \to D(KK)\, \pi^\pm$
- $B^\pm \to D(\pi\pi)\, \pi^\pm$

LHCb:
- $B^\pm \to D(\pi^+K^-)\, K^\pm$
- $B^\pm \to D(\pi^+K^-)\, \pi^\pm$
- $B^\pm \to D(K_s\, K^+\pi^-)\, \pi^\pm$
- $B^\pm \to D(K_s\, K^+\pi^-)\, K^\pm$

GGSZ Method with $B^+\to[K_s h^+ h^-]_D K^+$

Idea: Exploit interference between $D^0\to \bar{K}^0 h^+ h^-$ and $\bar{D}^0\to K^0 h^- h^+$ across the Dalitz plane

K_s



Different interference structure for B^+ and B^- $\to \gamma$

Powerful method – dominates the precision of γ at B factories.

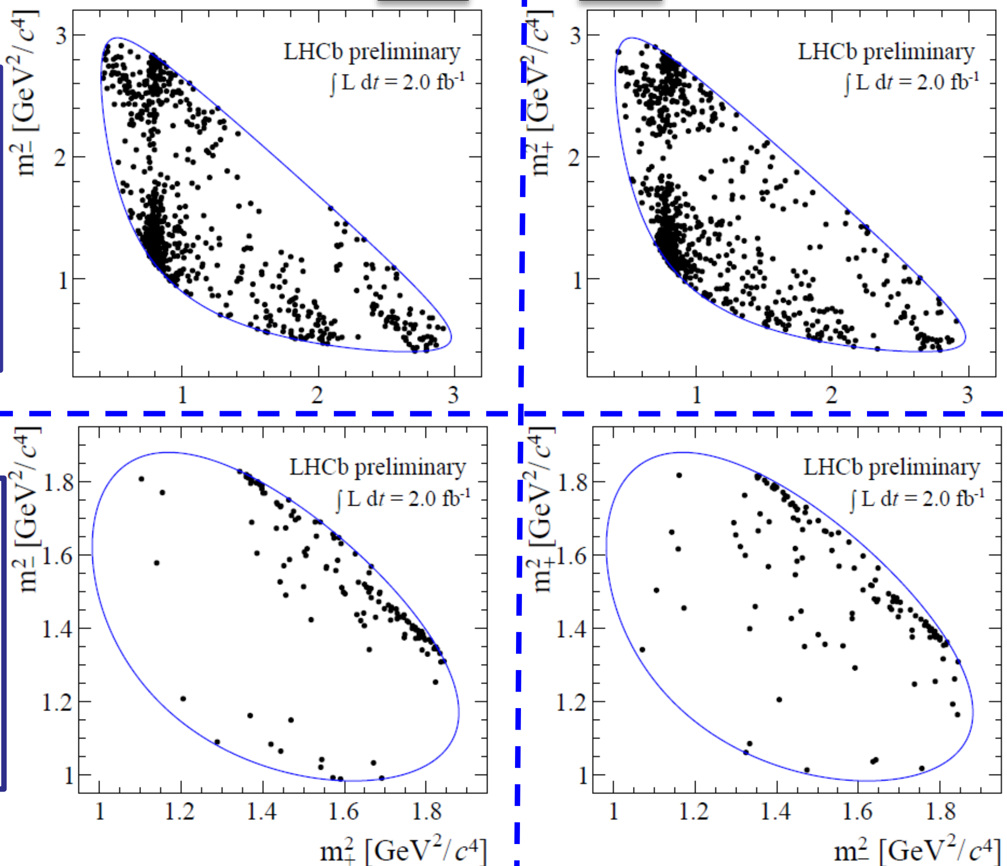
Daltiz Plots for $B^+ \to [K_s h^+ h^-]_D K^+$

$m_\pm = m(K_S h^\pm)$

B+ B-

$D \to K_S\pi^+\pi^-$ 690 signal events

$D \to K_S K^+ K^-$ 110 signal events



>85% purity

Extraction of γ requires information on the $D \to K_s hh$ decay amplitude variation over Dalitz plot: both amplitude and phase δ_D

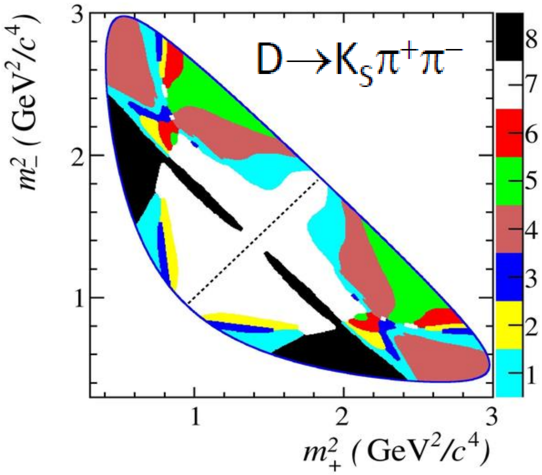
1. model of decay amplitude or
2. external measurements (model independent approach)

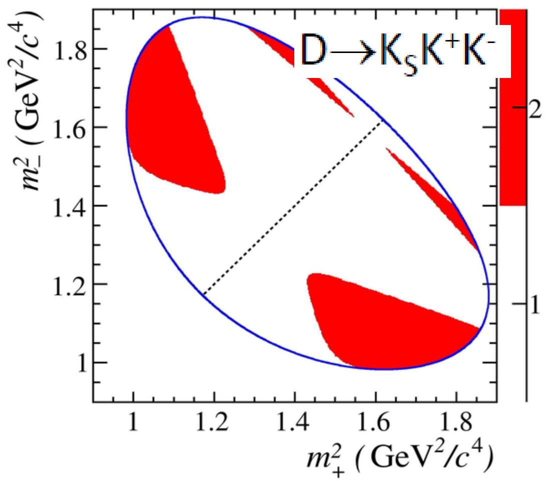
$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\overline{D}^0 \to f_D)}$$

One can see by eye CPV differences between $B^\pm$

Model independent approach

Divide Dalitz plane in bins: CLEO binning





Number of $B^\pm$ events in bin i:

$$N(B^\pm)_{+i} = K_{\mp i} + (x_\pm^2 + y_\pm^2)K_{\pm i} + 2\sqrt{K_i K_{-i}}\{x_\pm c_i \mp y_\pm s_i\}$$

$$x_\pm = r_B\cos(\delta_B \pm \gamma) \qquad c_i = \langle \cos(\delta_d)\rangle_i$$

$$y_\pm = r_B\sin(\delta_B \pm \gamma) \qquad s_i = \langle \sin(\delta_d)\rangle_i$$

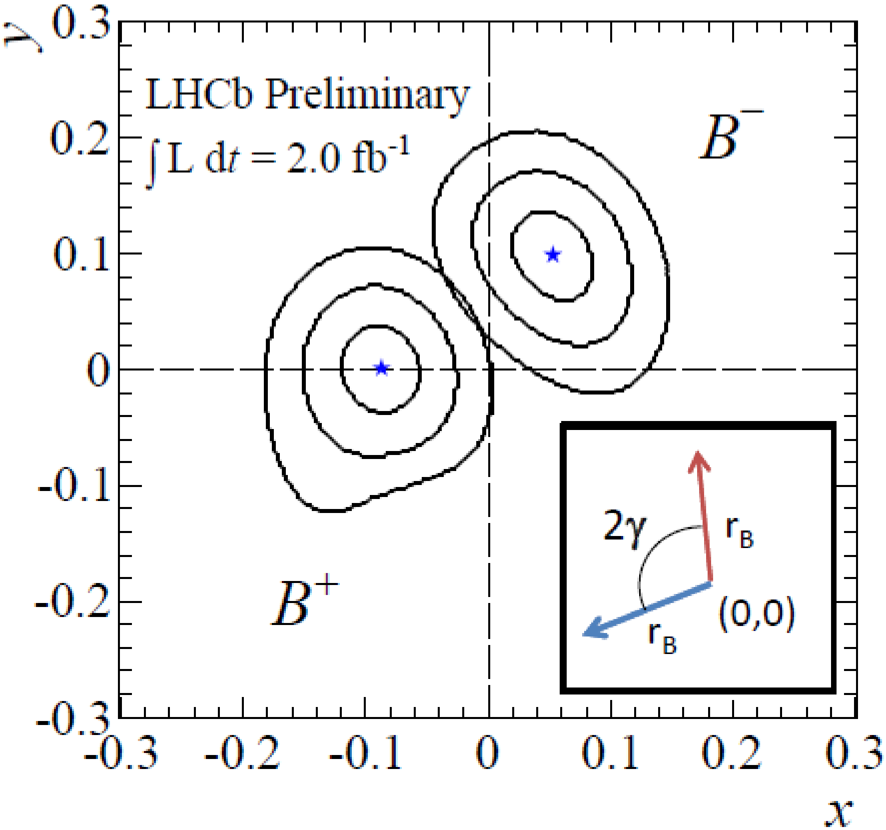
} from CLEO

$K_i = \int_i |A_D(m_+^2, m_-^2)|^2\, dm_+^2 dm_-^2$ from $B^\pm \to D\pi^\pm$

Gamma from GGSZ Method

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$

$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$



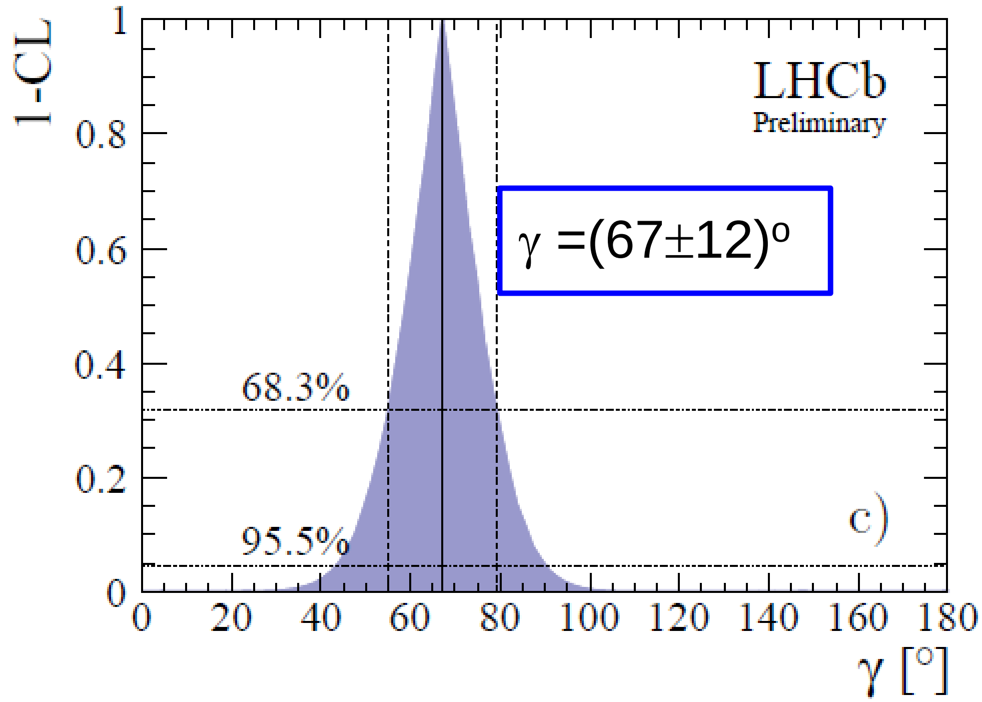
2011+2012 data (3 fb^{-1})	$\gamma = (57 \pm 16)^o$ $r_B = 0.09 \pm 0.02$

Gamma Combination

LHCb-Conf-2013-006

<u>Data:</u> ADS/GLW: 1 fb^{-1} (2011) GGSZ: 1 + 2 fb^{-1} (2011+2012)

quantity	$DK^{\pm}$ combination
γ	$67.2°$
68% CL	$[55.1, 79.1]°$
95% CL	$[43.9, 89.5]°$
δ_B^K	$114.3°$
68% CL	$[101.3, 126.3]°$
95% CL	$[\ 88.7, 136.3]°$
r_B^K	0.0923
68% CL	$[0.0843, 0.1001]$
95% CL	$[0.0762, 0.1075]$

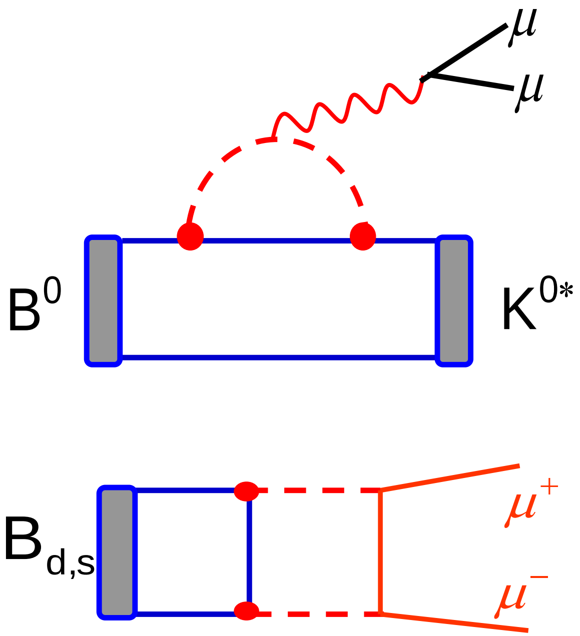


<u>For comparision:</u>

BaBar : $\langle\gamma\rangle = 69\ ^{+17}_{-16}$ (°)
Belle : $\langle\gamma\rangle = 68\ ^{+15}_{-14}$ (°)

Rare B Decays

FCNC*) decays:

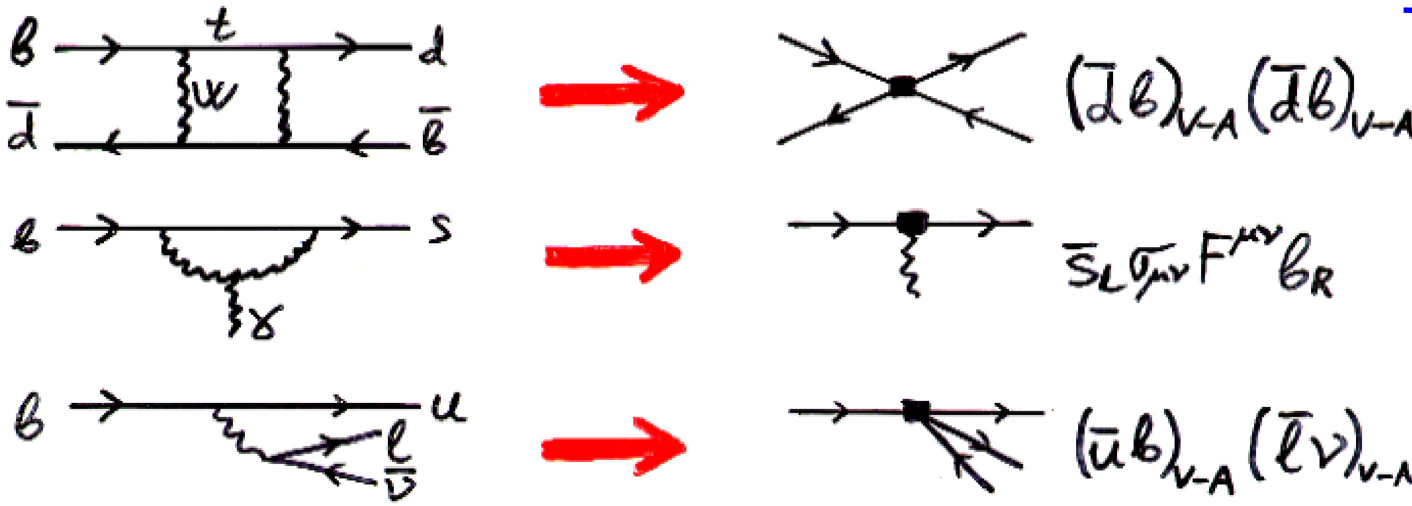


*) Flavor Changing Neutral Currents

Effective Theory & OPE

Z.Ligeti

Electroweak / NP scale Scale of B meson



Effective (local) operators O_i

(absorb long range effects)

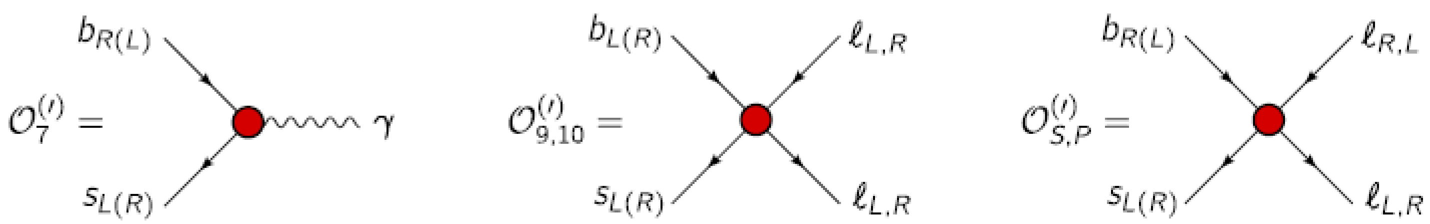
Operator Product Expansion

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

Wilson coefficients describe short range physics: SM + NP

FCNC decay $b \to s\,\mu\mu$

Figure from D.Straub

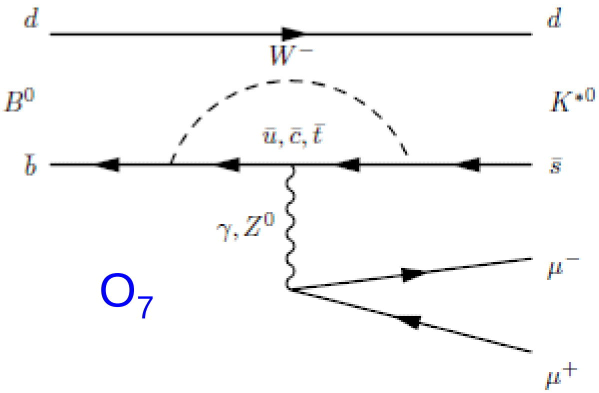


$\mathcal{O}_7^{(\prime)} \propto \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$ $\quad$ $\mathcal{O}_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell)$ $\quad$ $\mathcal{O}_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$

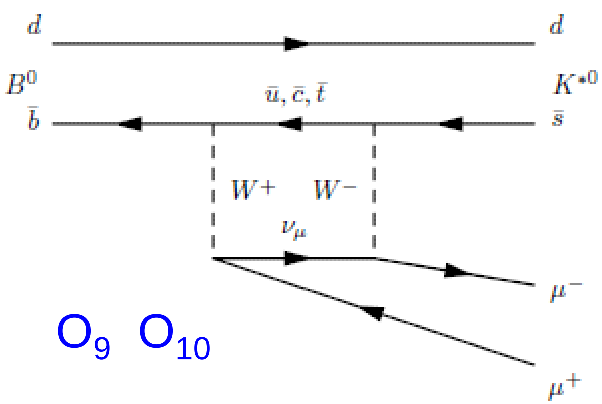
New Physics can lead to new operators with new Lorentz structure or can modify the Wilson coefficients $\rightarrow$ modifies the angular distribution

$$H = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum (C_i^{SM} + \underline{C_i^{NP}}) O_i^{SM} + \sum \frac{c}{\Lambda_{NP}} \underline{O_{NP}}$$

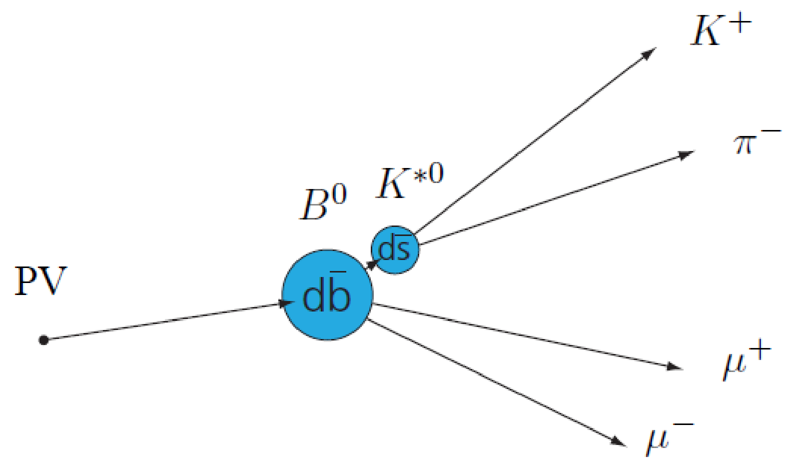
FCNC decay $B^0 \to K^* \mu\mu$



O_7



O_9 O_{10}



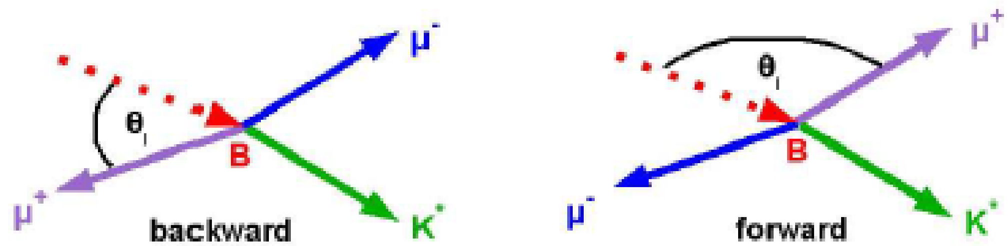
$\mathcal{B} = (1.05^{+0.16}_{-0.13}) \times 10^{-6}$ [PDG]

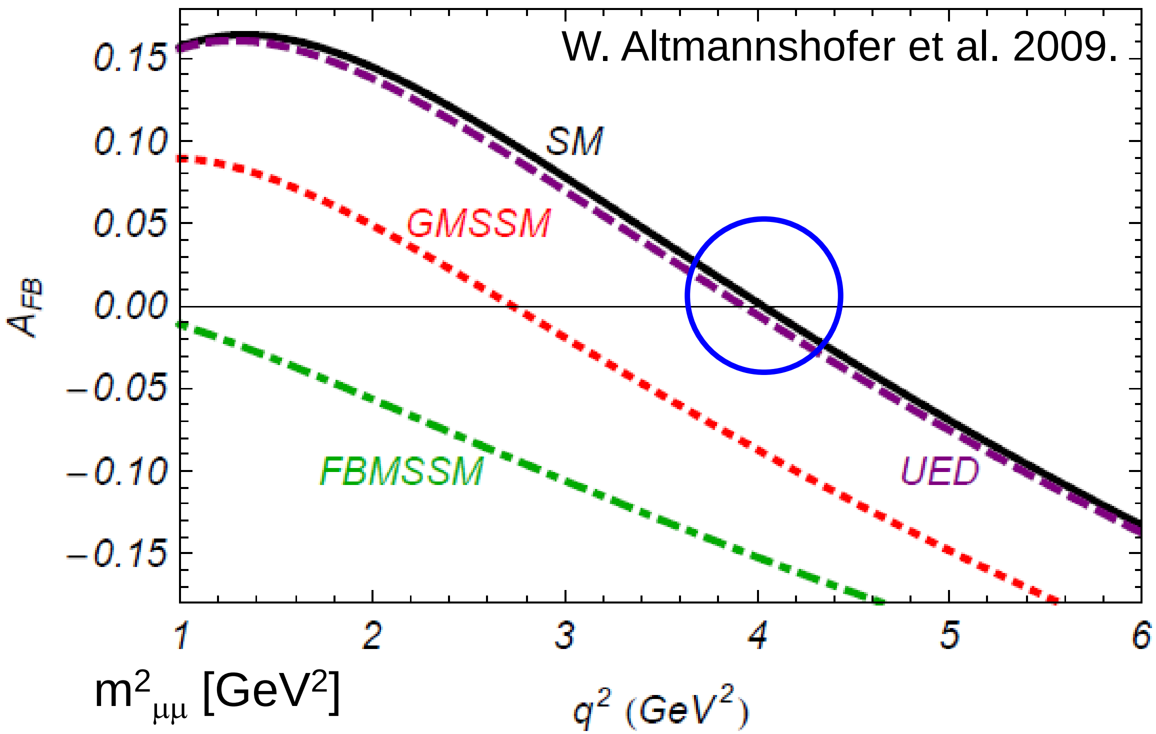
- In Standard Model only O_7, O_9 and O_{10}
- Pseudo-scalar to vector-vector decay $\to$ plenty of angular observables

Forward-Backward Asymmetry

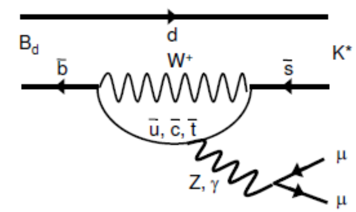
Simplest angular analysis:

$$A_{FB}(q^2) = \frac{N_F - N_B}{N_F + N_B}$$





$m^2_{\mu\mu}$ [GeV^2]

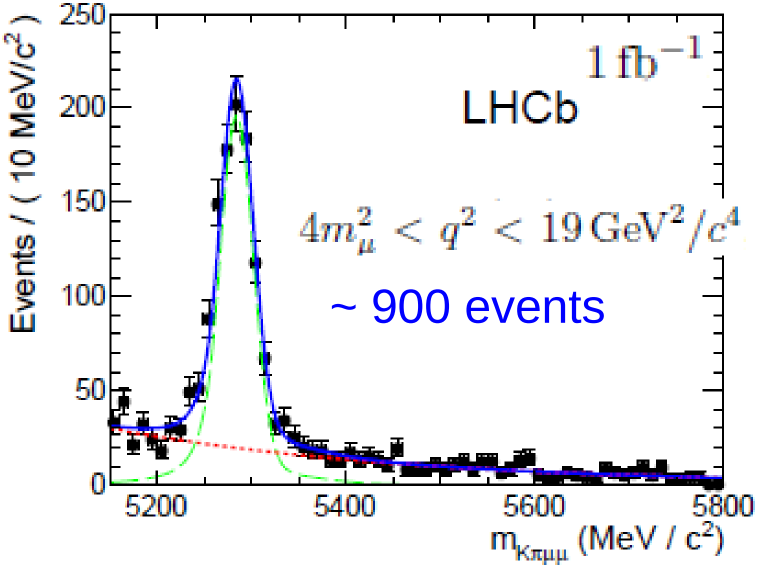


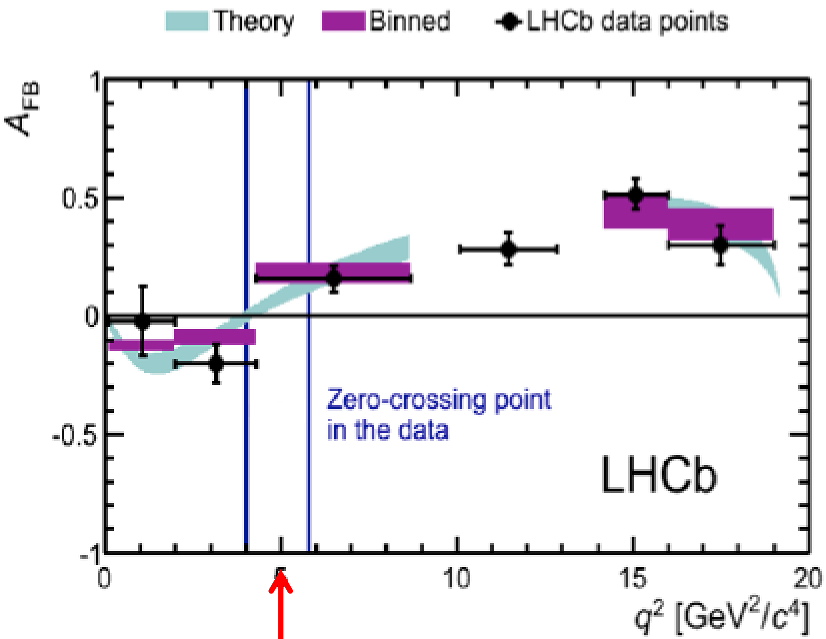
$q^2 = m_{\mu\mu}$

FBMSSM	Flavor Blind MSSM
GMSSM:	MFV MSSM
UED:	One universal extra dimension

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

arXiv:1304.6325





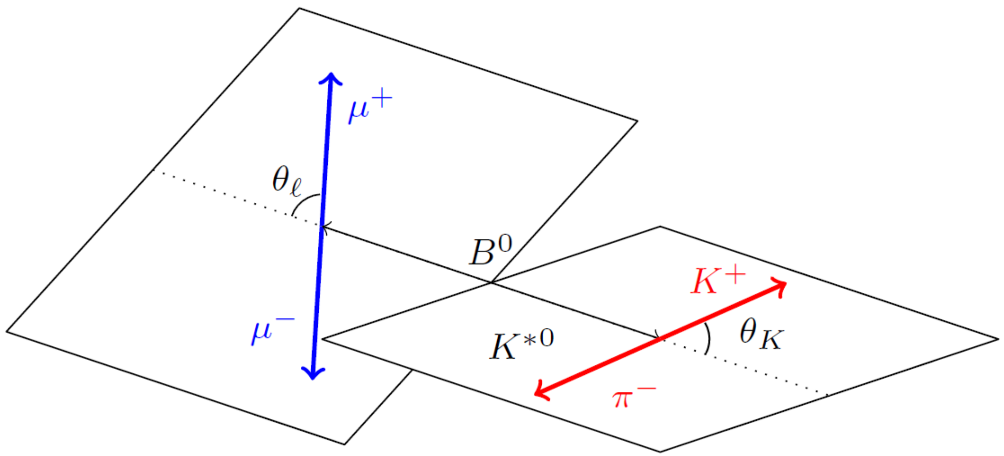
BABAR+BELLE+CDF: ~600

Zero crossing:
$q_0^2 = 4.9 \pm 0.9$ GeV^2

M. Neubert (EPS 2011): Textbook confirmation of Standard Model

Full angular analysis

$B^0 \rightarrow K^* (K\pi)\ \mu\mu$

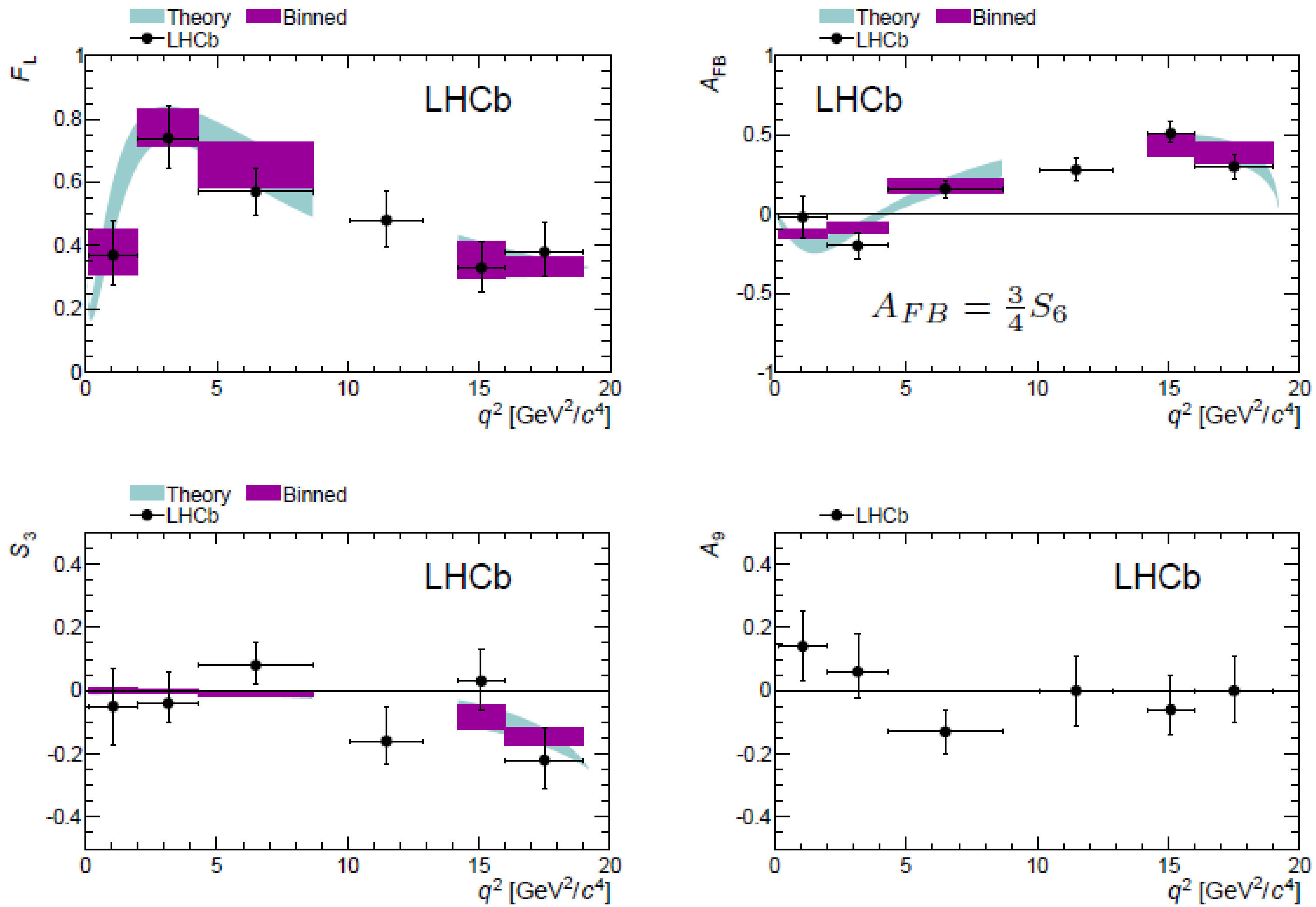


$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos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

$$S_6^s = \frac{3}{4}A_{FB}$$

- Observables F_L and S_i are functions of Wilson coefficients.
- Folding: $\phi \rightarrow \phi + \pi$ for $\phi < 0$ $\rightarrow$ only "blue" terms

Full angular analysis & folding



Different Parametrisation

Different set of observables with reduced dependence on form-factor uncertainty has been proposed by several authors:

$$A_{\mathrm{T}}^{(2)} = \frac{2S_3}{(1-F_L)}$$

$$A_{\mathrm{T}}^{Re} = \frac{S_6}{(1-F_L)}$$

$$P_4' = \frac{S_4}{\sqrt{(1-F_L)F_L}} \qquad P_6' = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$

$$P_5' = \frac{S_5}{\sqrt{(1-F_L)F_L}} \qquad P_8' = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

Kruger-Matias (2005), Matias et al. (2012), Egede-Matias-Hurth-Ramon-Reece (2008), Bobeth-Hiller-Van Dyk (2010-11), Beciveric-Schneider (2012)

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell \,\mathrm{d}\cos\theta_K \,\mathrm{d}\phi} =$$

$$\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$

$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$

$$\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$

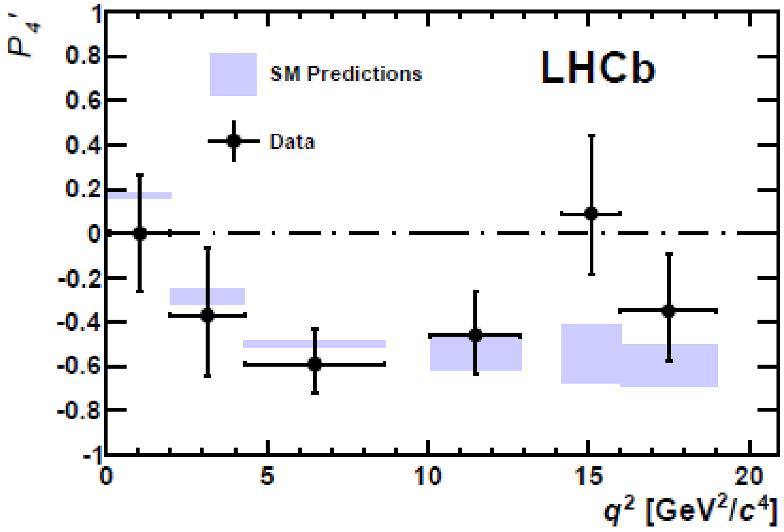
$$(1-F_{\mathrm{L}})A_{Re}^{\mathrm{T}}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$

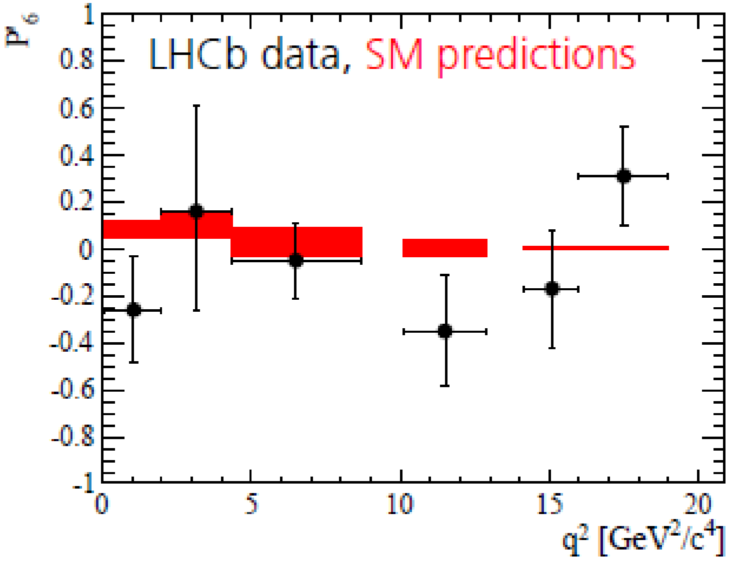
$$\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

P'_4 , P'_5 , P'_6 and P'_8

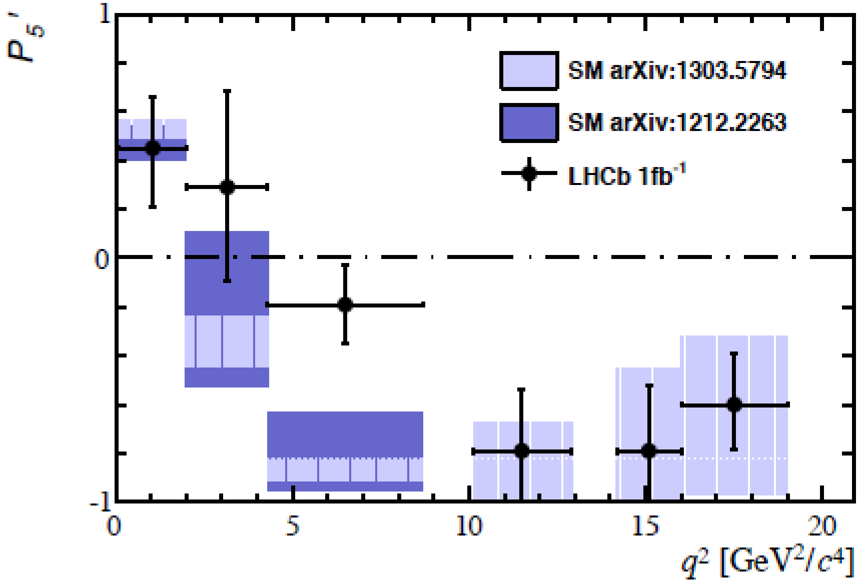
arXiv:1308:1707

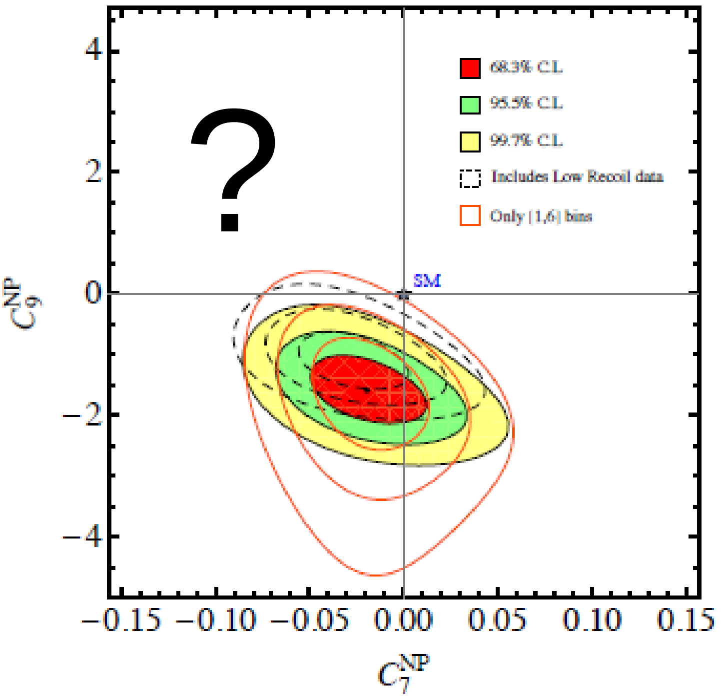
In general data well described by SM prediction





Deviation for observable P_5'

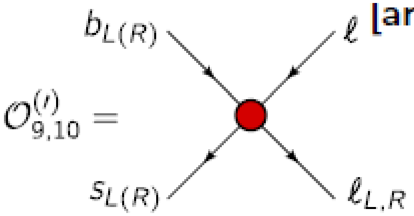




- P_5' shows deviation of 3.7σ from SM ($4.3 < q^2 < 8.68$ GeV^2/c^4)
- 2.5σ for $1 < q^2 < 6$ GeV^2/c^4 (theoretically favored region)

→ Possible interpretation: deviation in di-lepton vector operator C_9

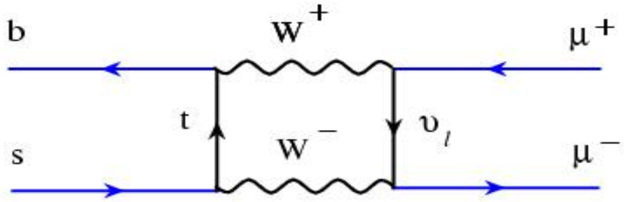
Descote-Genon et al. [arXiv:1307.5683]]

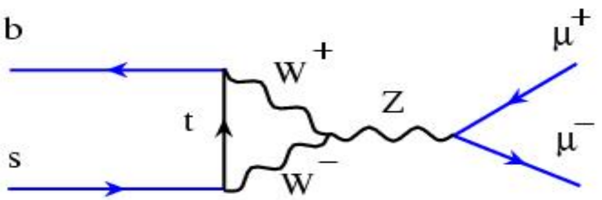


But: + only 1 / 24 bins (0.5% probability)
+ theory error underestimated

Very rare FCNC decay $B_{s,d} \to \mu^+\mu^-$

Standardmodell





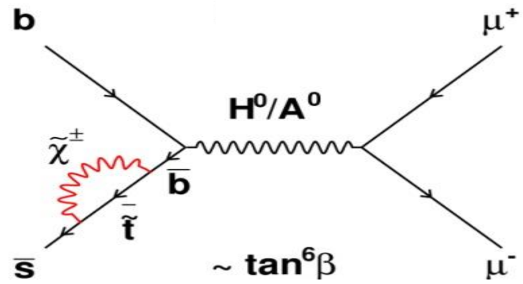
Helicity suppressed

$BR(B_s \to \mu^+\mu^-) = (3.25 \pm 0.17) \times 10^{-9}$

$BR(B_d \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$

Buras et al, arXiv: 1303.3820

NP contributions: SUSY Higgs sector



Sensitive to additional scalar and pseudo-scalar contributions

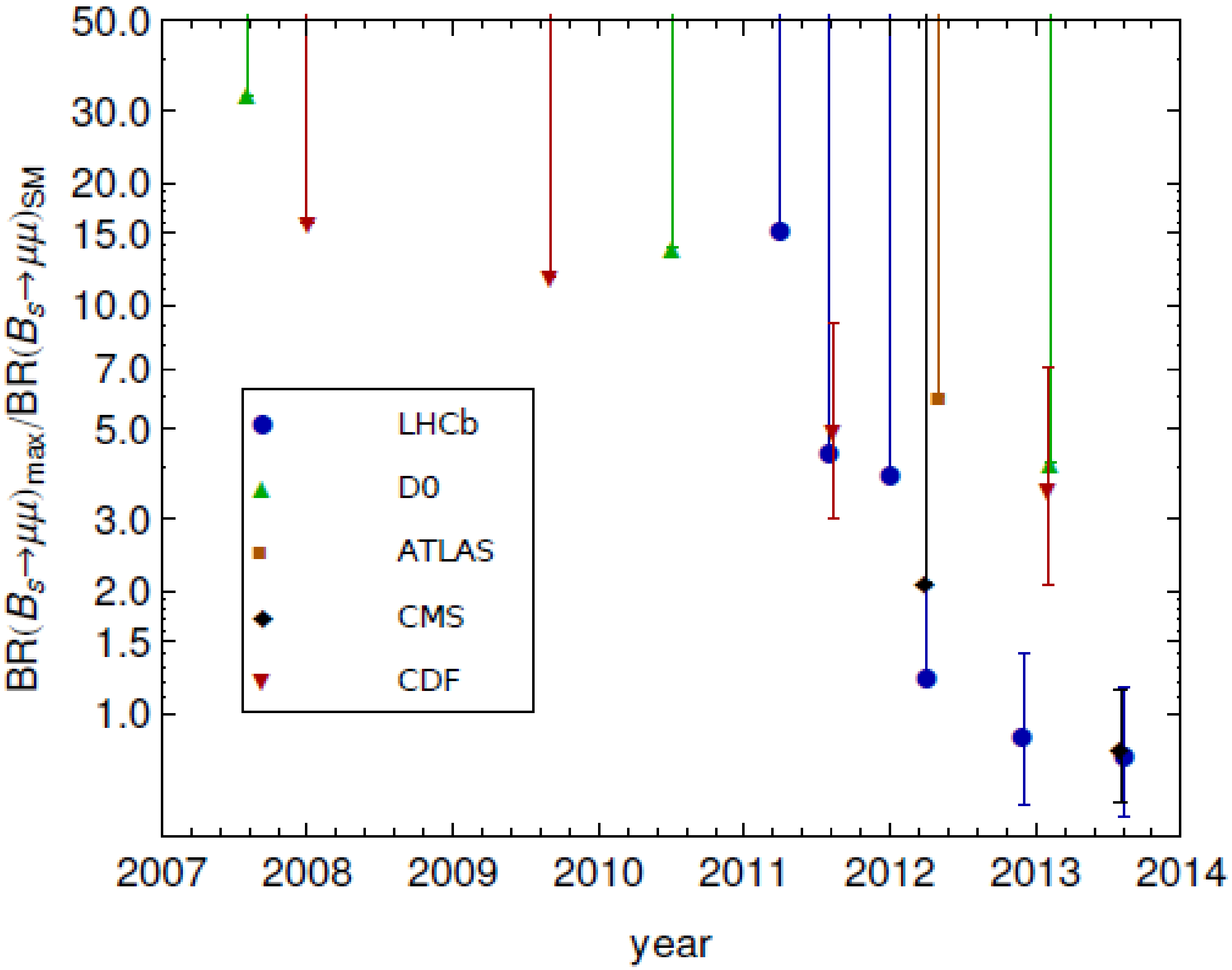
⇨ Correction due to finite $\Delta\Gamma_s$

$BR(B_s \to \mu^+\mu^-) = (3.56 \pm 0.18) \times 10^{-9}$

De Bruyn et al. PRD 86, 014027 (2012)

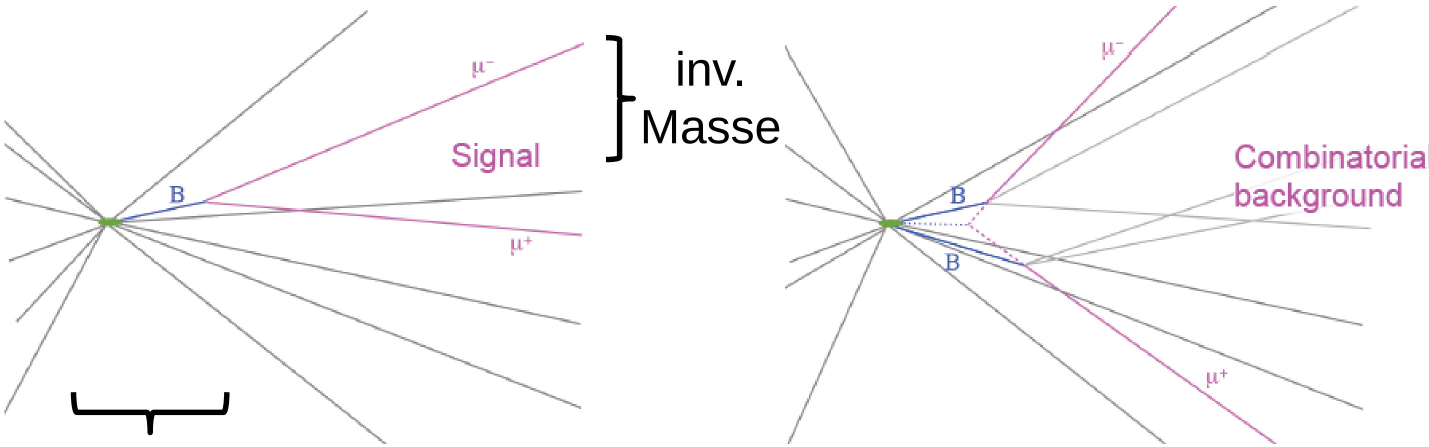
History of $B_s \to \mu\mu$ search

Figure from D. Straub



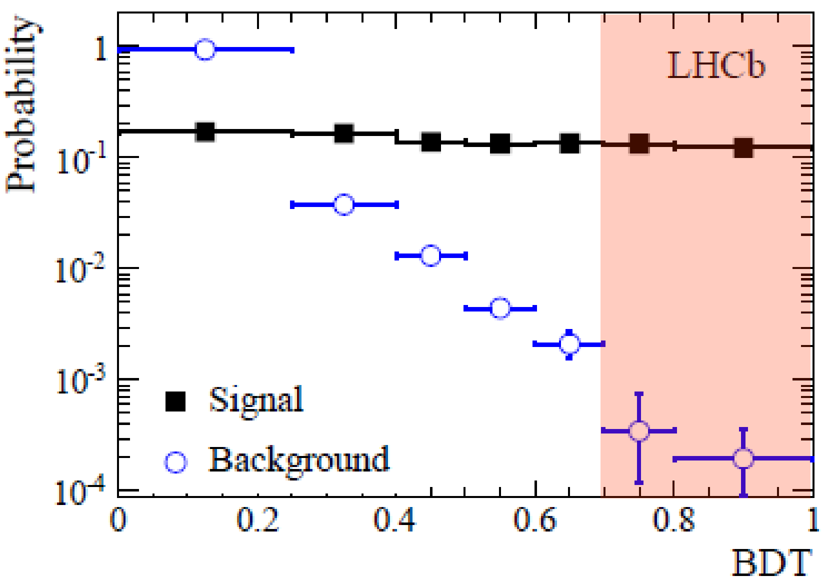
(there are more measurements, not listed)

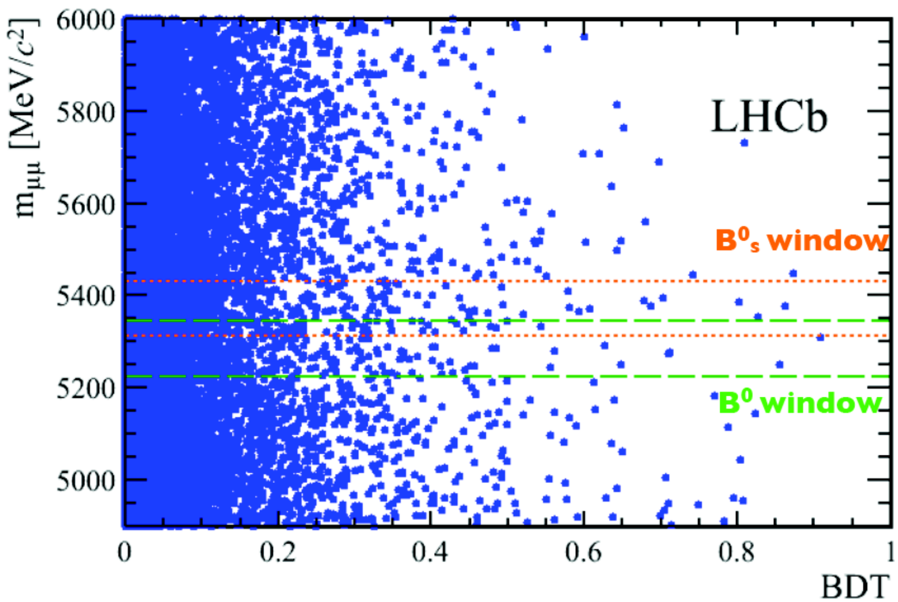
Experimental challenge



inv. Masse

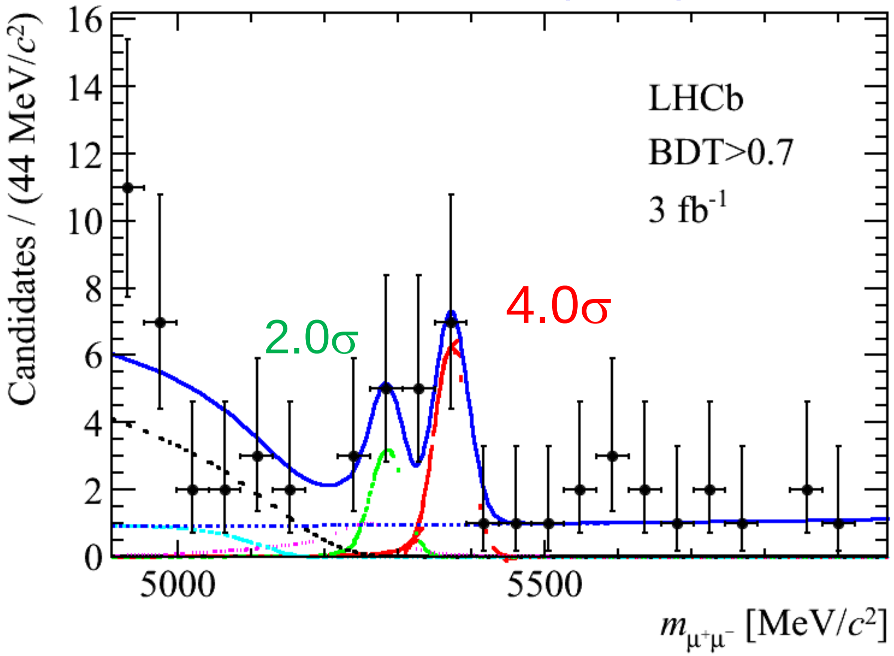
Topologie (BDT)



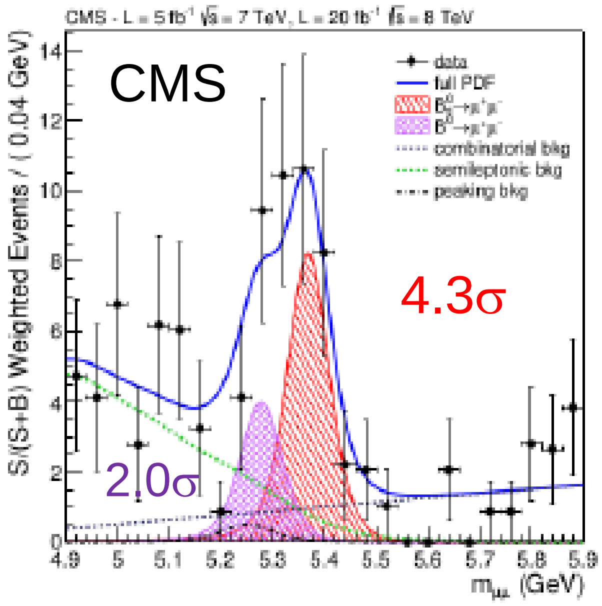


Observation of $B_s \to \mu\mu$

PRL 111 (2013) 101805



arXiv:1307.5025



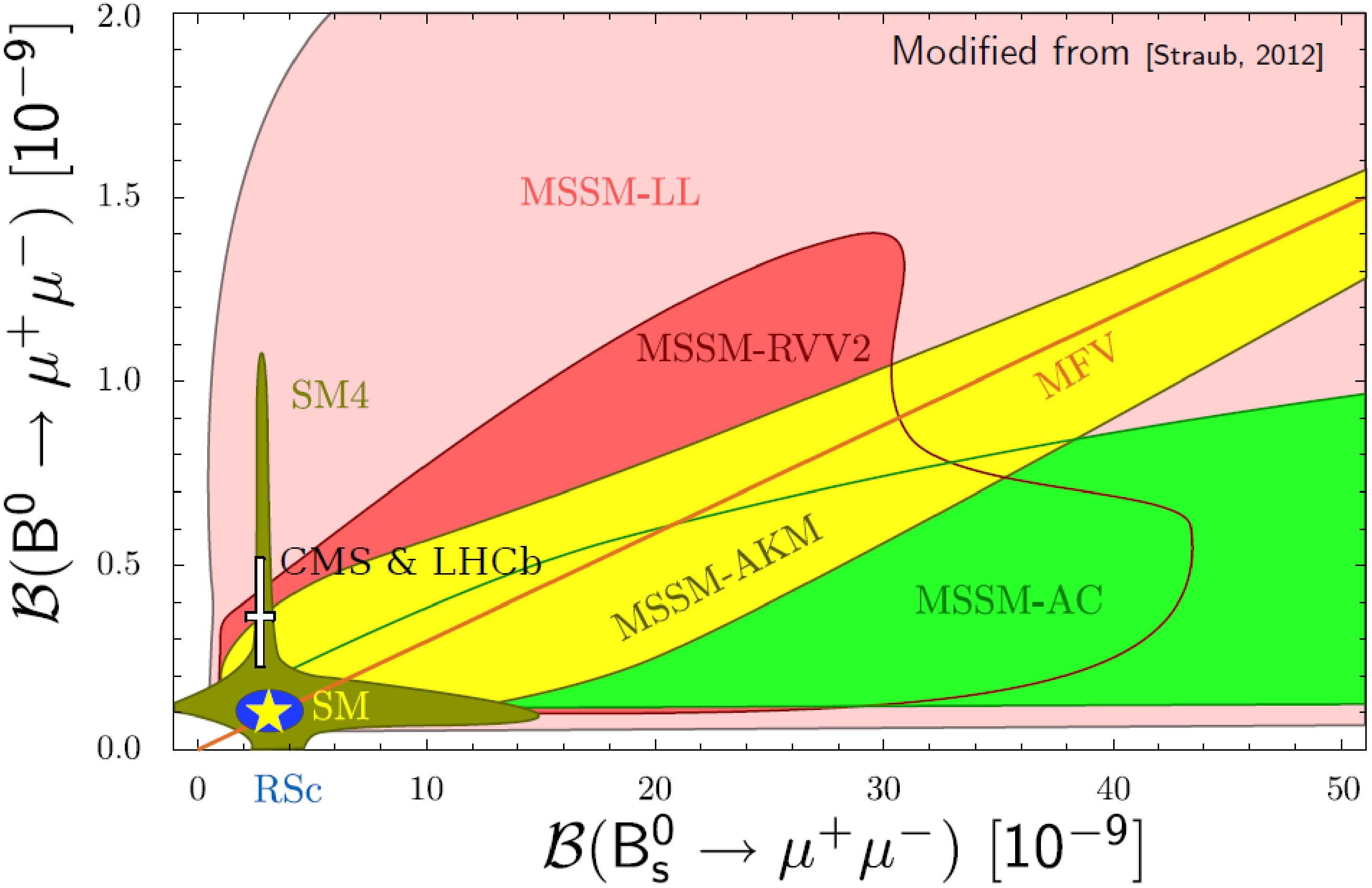
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}$$ $< 7.4\times10^{-10}$ @ 95 CL

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$ significance > 5.0

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$ CMS + LHCb

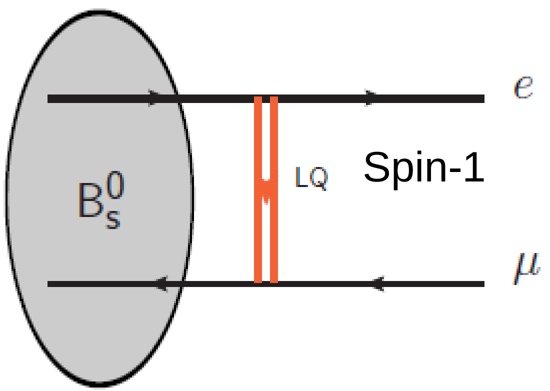
Implications for New Physics



Search for Lepton-Flavor Violation in B decays

- Lepton Flavor Violation forbidden in SM
- Possible LFV extensions of SM:
  - SUSY [Diaz et al., 2005]
  - Heavy singlet Dirac neutrino [Ilakovac, 2000]
  - Pati-Salam lepto-quarks [Pati & Salam, 1974]

$B_s \rightarrow e\mu$

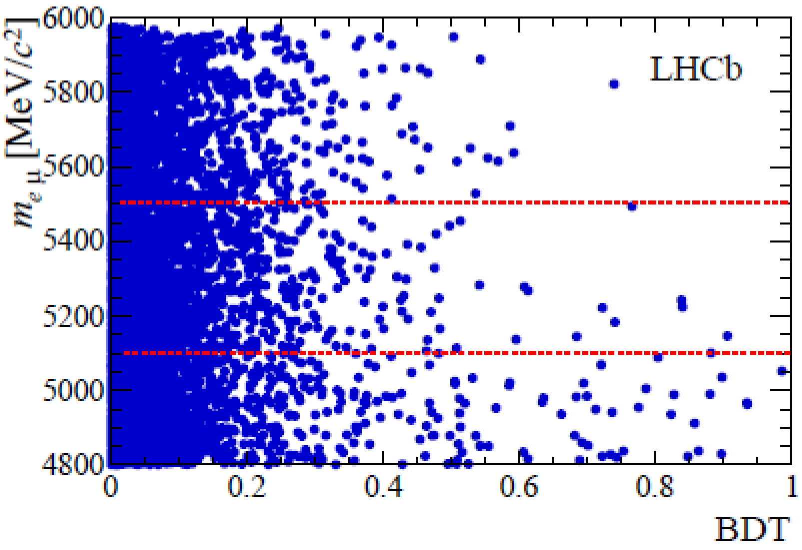


LHCb search for $B_{d,s} \rightarrow e\mu$ follows the $B_{d,s} \rightarrow \mu\mu$ search

LHCb

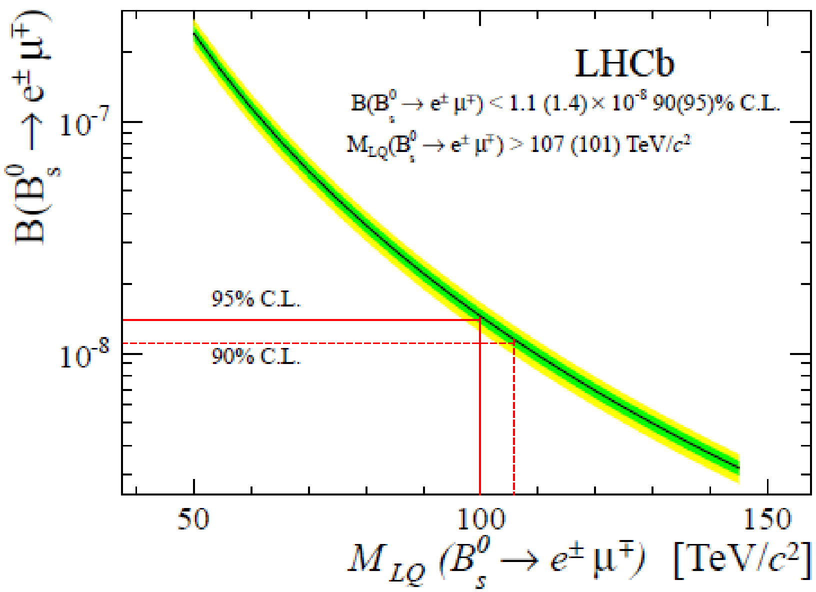
$$\mathcal{B}(B_s^0 \rightarrow e^+\mu^-) < 14 \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow e^+\mu^-) < 3.7 \times 10^{-9}$$

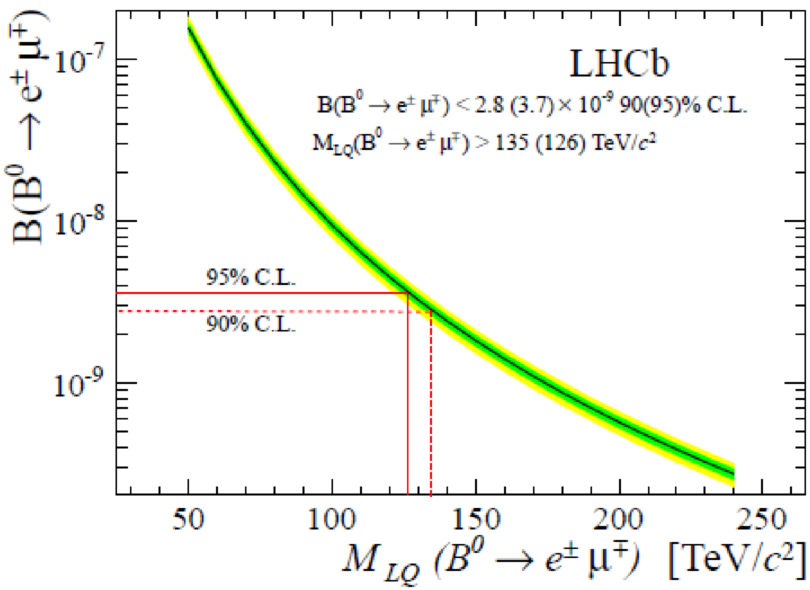
@ 95% CL



Limits on leptoquarks

Convert upper limit on BR into bound on leptoquarks:



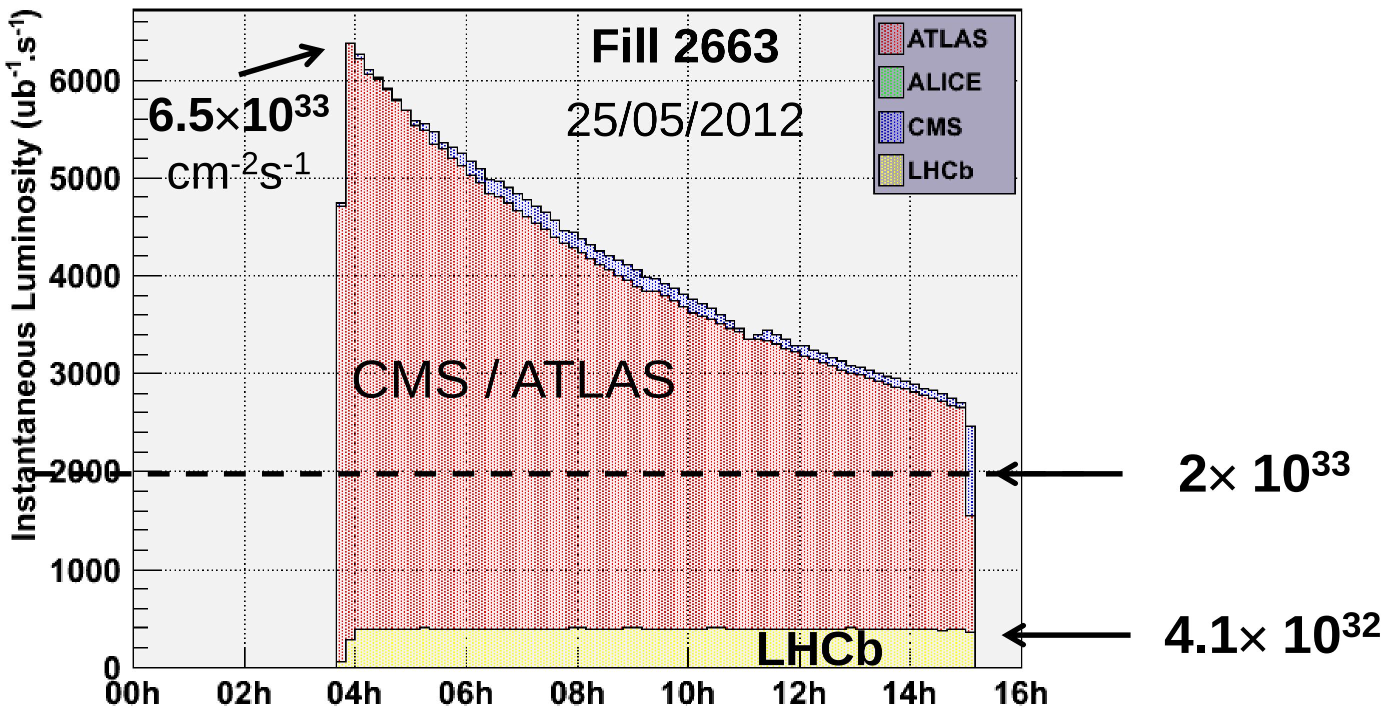


		LHCb	Current ([CDF, 2009])
$m_{LQ}(B_s^0 \to e^+\mu^-)$	$>$	101 TeV	44.9 TeV
$m_{LQ}(B^0 \to e^+\mu^-)$	$>$	126 TeV	53.6 TeV

Nice example to illustrate the power of indirect searches.


FUTURE

Upgrade to increase luminosity



- Detector-Upgrade in 2018: Lumi increase 2×10^{33} $cm^{-2}s^{-1}$

  $\Rightarrow$ triggerless 40-MHz readout

  $\Rightarrow$ new vertex detector, and tracking detector: Fiber Tracker

Physics Reach

Obervable	LHCb 2017 (7 fb^{-1})	Upgrade (+ 50 fb^{-1})	Theory Uncertainty
B_s Mixing phase ϕ_s	0.025	0.008	~0.003
$BR(B_s \to \mu\mu)$ $BR(B_d \to \mu\mu)$ / $BR\ B_s \to \mu\mu$	0.5×10^{-9} ~100%	0.15×10^{-9} ~35%	0.3×10^{-9} ~5%
CKM angle γ	4^o	0.9^o	small
CPV in D (ΔA_{CP})	0.7×10^{-3}	0.1×10^{-3}	

At the End

- High-precision quark flavor physics is an excellent tool to search for effects of New Physics beyond the TeV scale.
- With LHCb a new era of precision B & D physics has started
- So far we have not observed any significant difference from the Standard Model.
- In the coming years LHCb / BELLE II will push the room for New Physics from O(20%) to O(2%).

Historical Note

Copied from J. Rademacker

- A historical note (from L. B. Okun: "Spacetime and vacuum as seen from Moscow", Int.J.Mod.Phys. A17S1 (2002) 105-118):

> A special search at Dubna was carried out by E. Okonov and his group. They have not found a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays of K_L^0 into charged particles [13] (Anikina et al., JETP, 1962). At that stage the search was terminated by administration of the Lab. The group was unlucky.
>
> Approximately at the level 1/350 the effect was discovered by J.Christensen, J.Cronin, V.Fitch and R.Turlay [14] at Brookhaven in 1964 in an experiment[...]

- Don't give up if you have excluded new physics at O(few %) level!