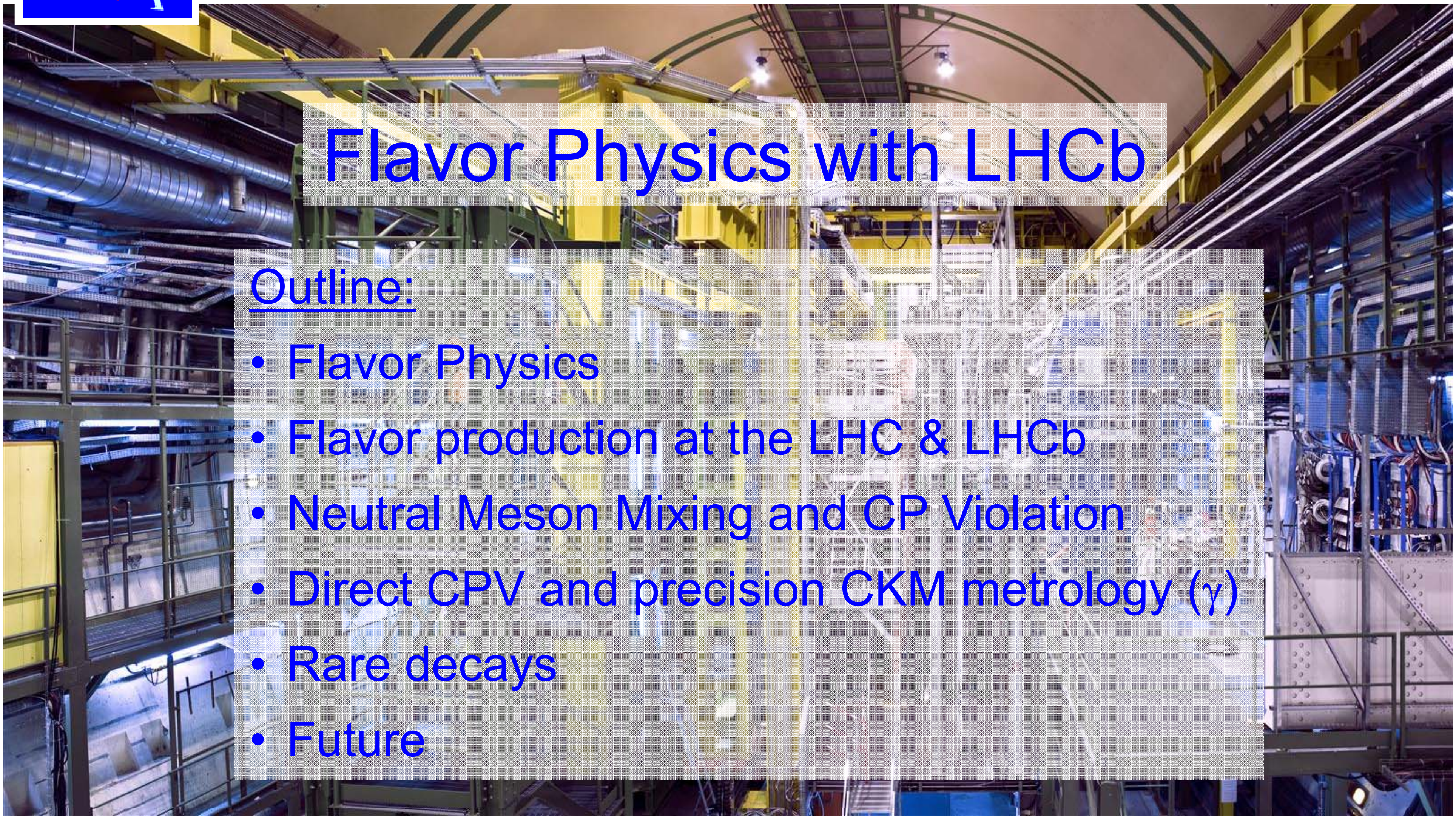


Flavor Physics with LHCb

<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

Flavor Physics

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

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 left 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 → flavor structure

not diagonal!

Mass eigenstates of the quarks obtained by unitary transformations:

$\tilde{q}_A = V_{A,q} q_A$ for $q_A = u, d$ 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:

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

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

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

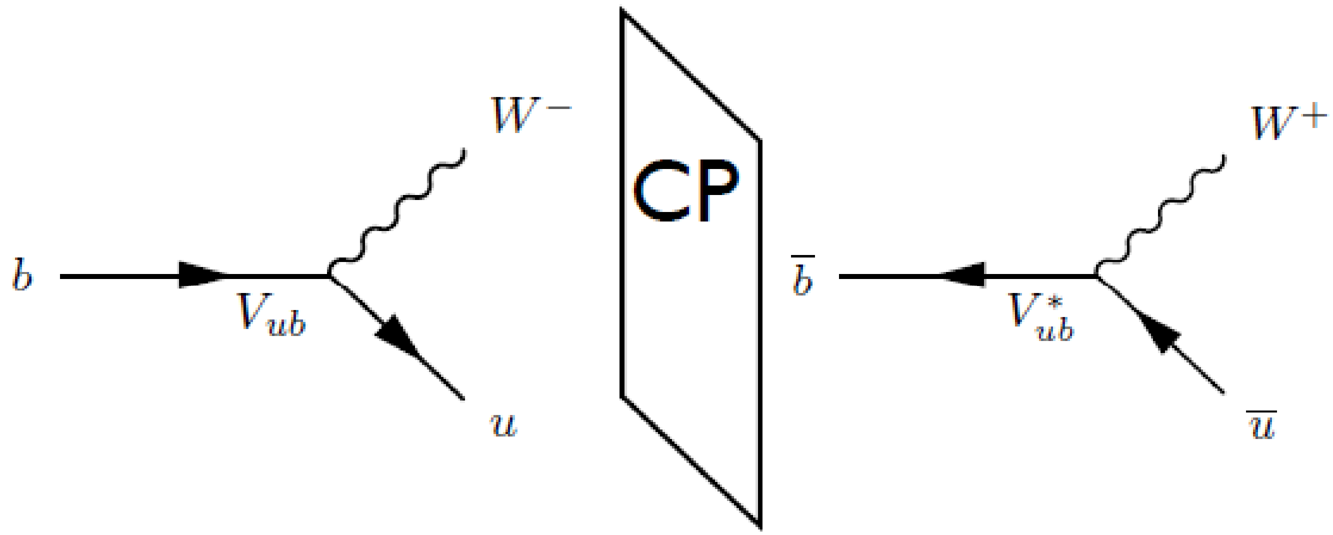
with $V_{\mathrm{CKM}} = V_{\mathrm{L},u} V_{\mathrm{L},d}^{\dagger}$ (must be unitary)

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 for pedestrians

The *T* (and *CP*) operations must be **anti-unitary**, which implies **complex conjugation** !



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

CKM Matrix

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

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

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

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

Complex 3×3 matrix:
Unitarity condition and removal of 5 unobservable phases results into 4 free parameter: 3 Euler angles and one phase δ:

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

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Unobservable Phases

Phases of left-handed fields in J_C are unobservable: possible redefinition

$$u_L \to e^{i\phi(u)} u_L \qquad c_L \to e^{i\phi(c)} c_L \qquad t_L \to e^{i\phi(t)} t_L$$

$$d_L \to e^{i\phi(d)} d_L \qquad s_L \to e^{i\phi(s)} s_L \qquad b_L \to e^{i\phi(b)} b_L$$

Real numbers

Under phase transformation:

$$V \to \begin{pmatrix} e^{-i\phi(u)} & 0 & 0 \\ 0 & e^{-i\phi(c)} & 0 \\ 0 & 0 & e^{-i\phi(t)} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} e^{i\phi(d)} & 0 & 0 \\ 0 & e^{i\phi(s)} & 0 \\ 0 & 0 & e^{i\phi(b)} \end{pmatrix}$$

$$V\alpha j \to \exp[i(\phi(j) - \phi(\alpha))] V\alpha j$$

$L^{phys}(f,G)$ invariant

$L(f,H)$ affected …. rephasing q_R

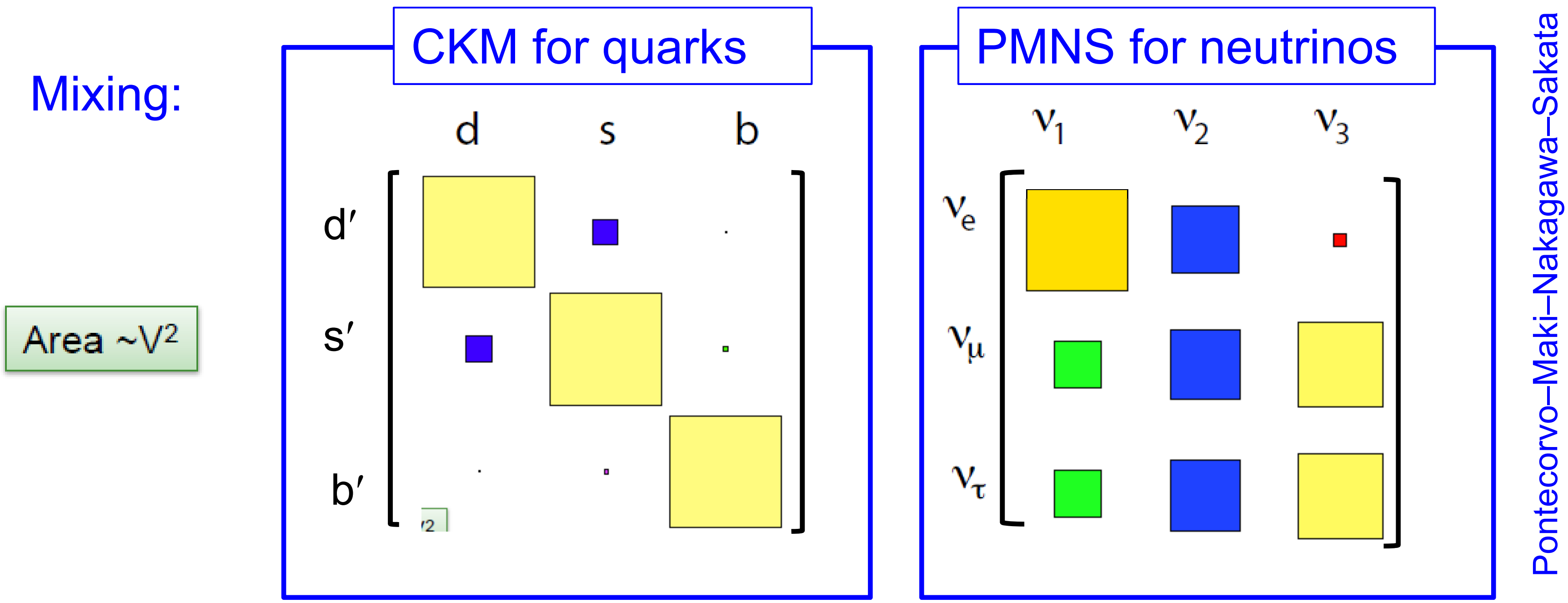
Flavor sector in Standard Model

Flavor parameters:

- 6 quark masses
- 3 quark mixing angles + 1 phase: CKM matrix
- 3 + 3 lepton masses
- 3 lepton mixing angles + 1phase : PMNS matrix

20 parameters

Mixing:



Why these values? Are the two related? Are they related to masses?

Wolfenstein Parametrization for CKM

Reflects well the hierarchical structure of the CMK matrix

λ, A, ρ, η with $\lambda = 0.22$

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

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

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

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

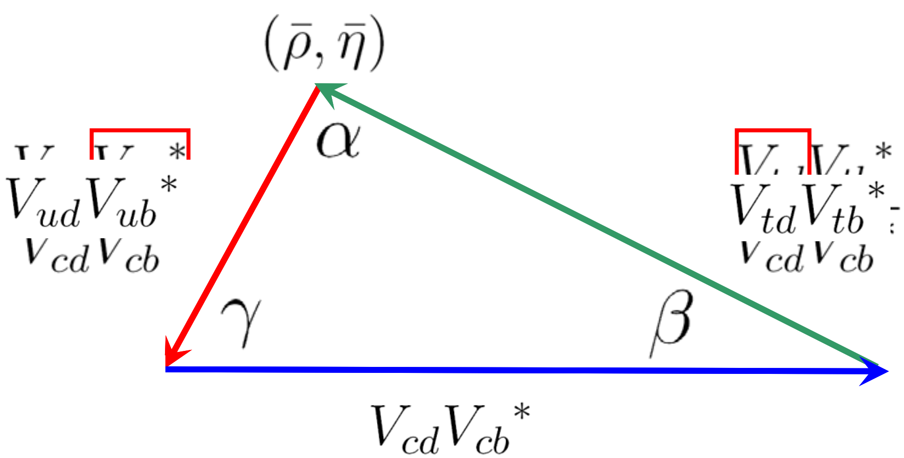
$|V_{ts}| \times e^{+i\beta_s}$

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 …

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

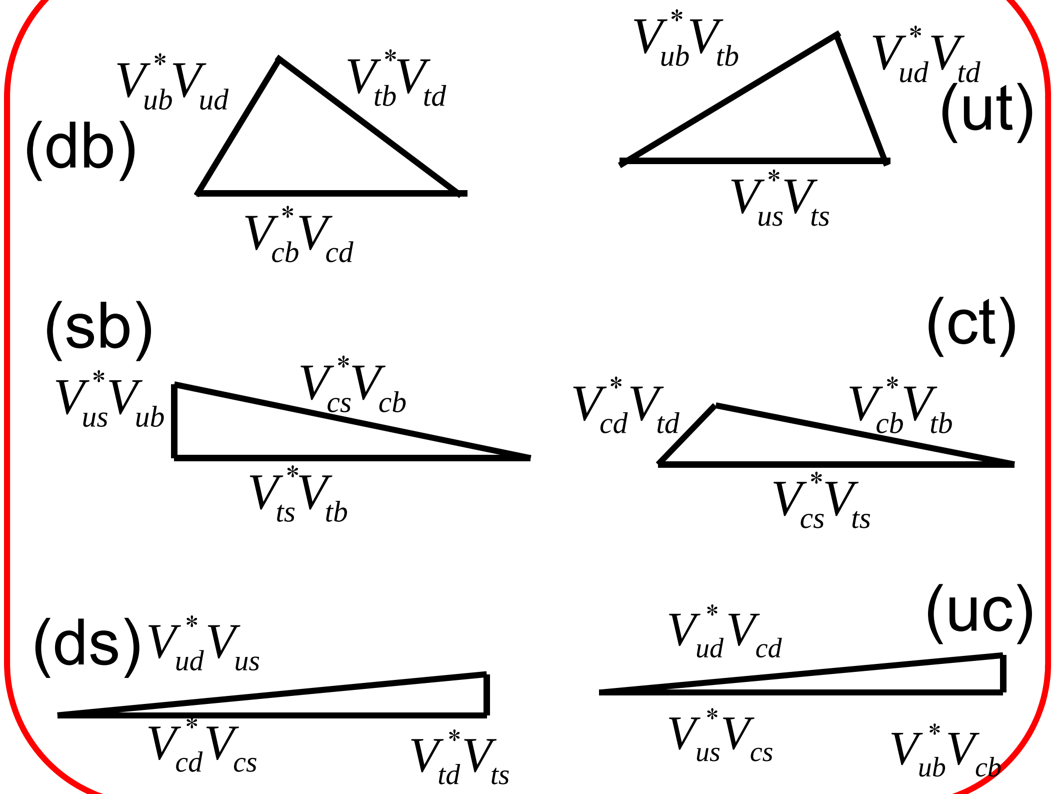
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \text{ (sb)}$$

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

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

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

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

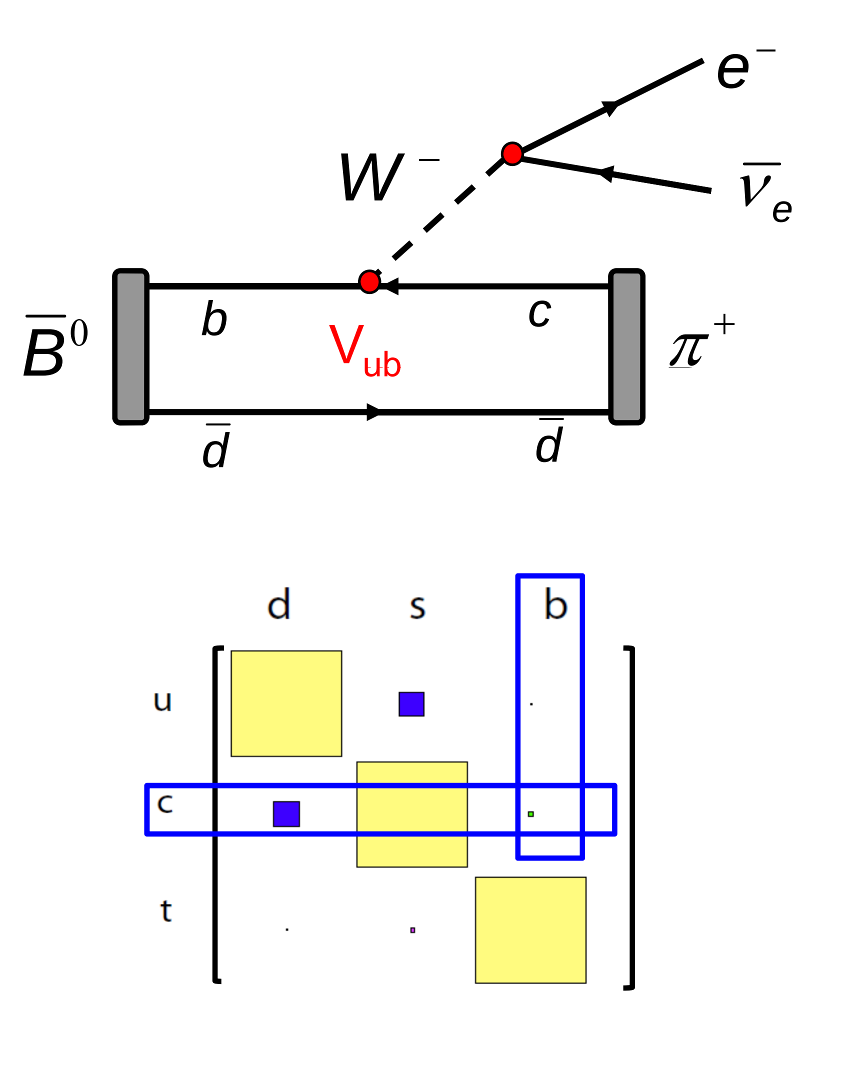


All 6 triangles have the same area: $J_{CP}/2$

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

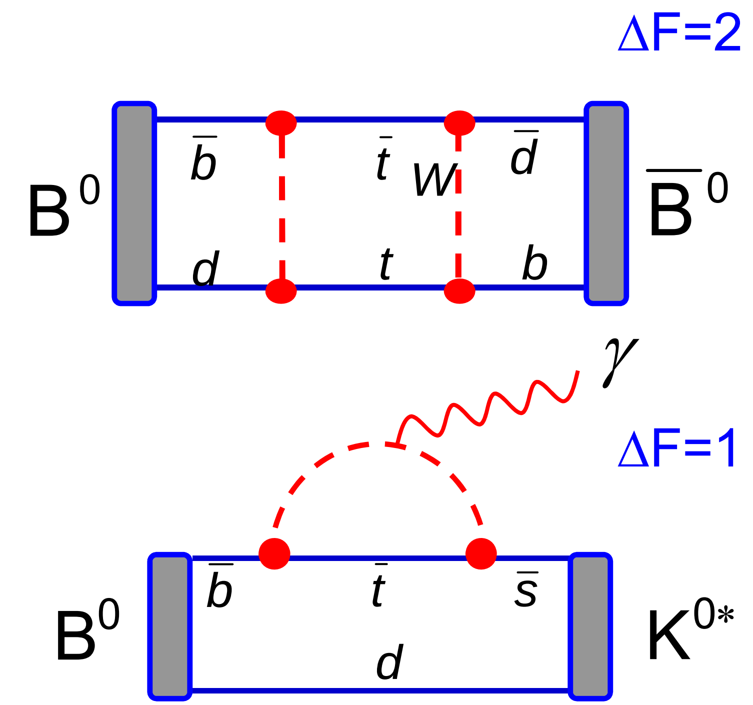
$$J_{CP} = \mathcal{Im}\left(V_{ij}\, V_{kl}\, V_{il}^* V_{kj}^*\right) \approx 3 \cdot 10^{-5}$$

Weak b Hadron Decays

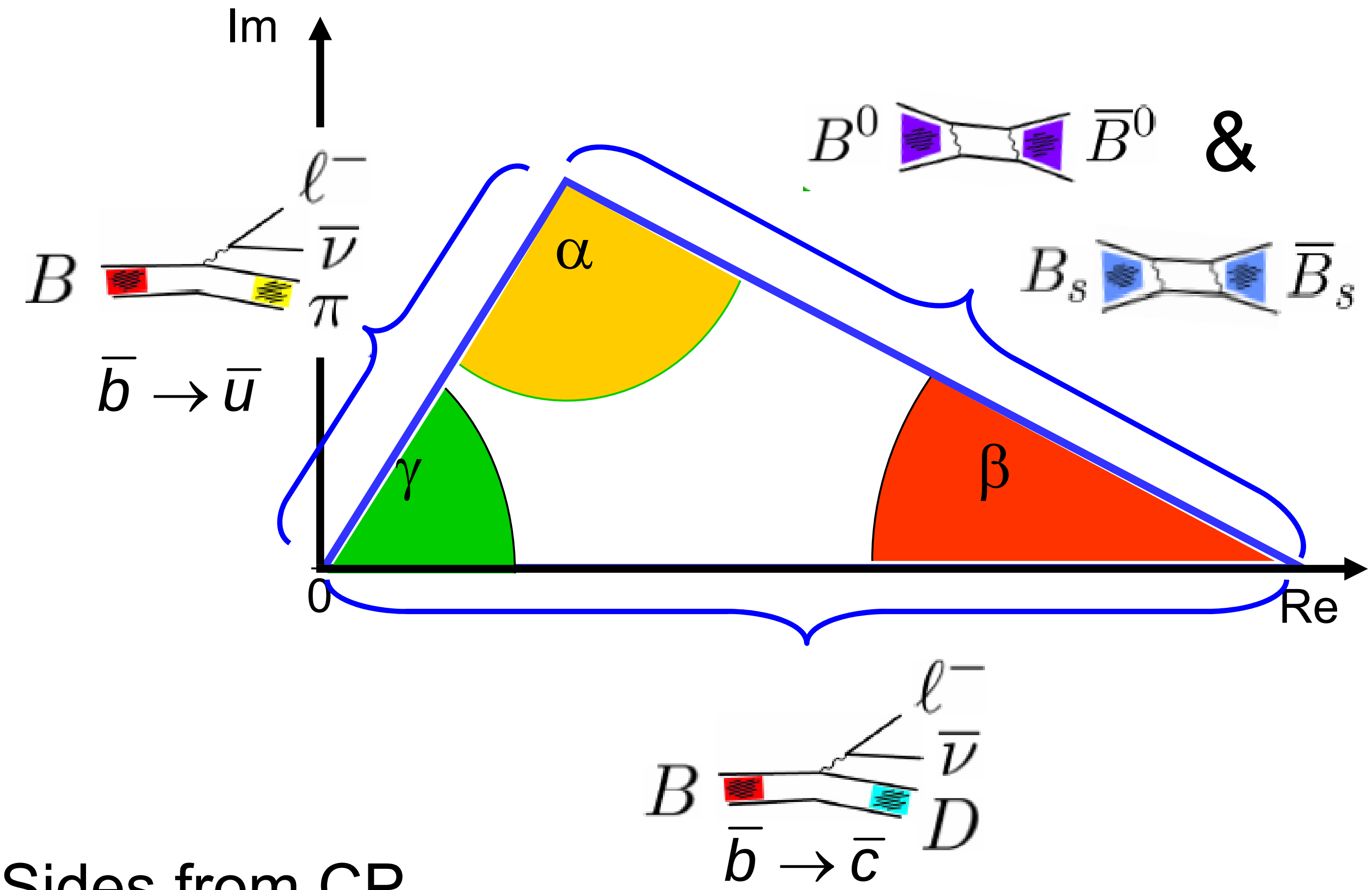


Tree dcays “CKM” suppressed:
→ Loop corrections important.

Flavor Changing Neutral Current (FCNC) Processes:



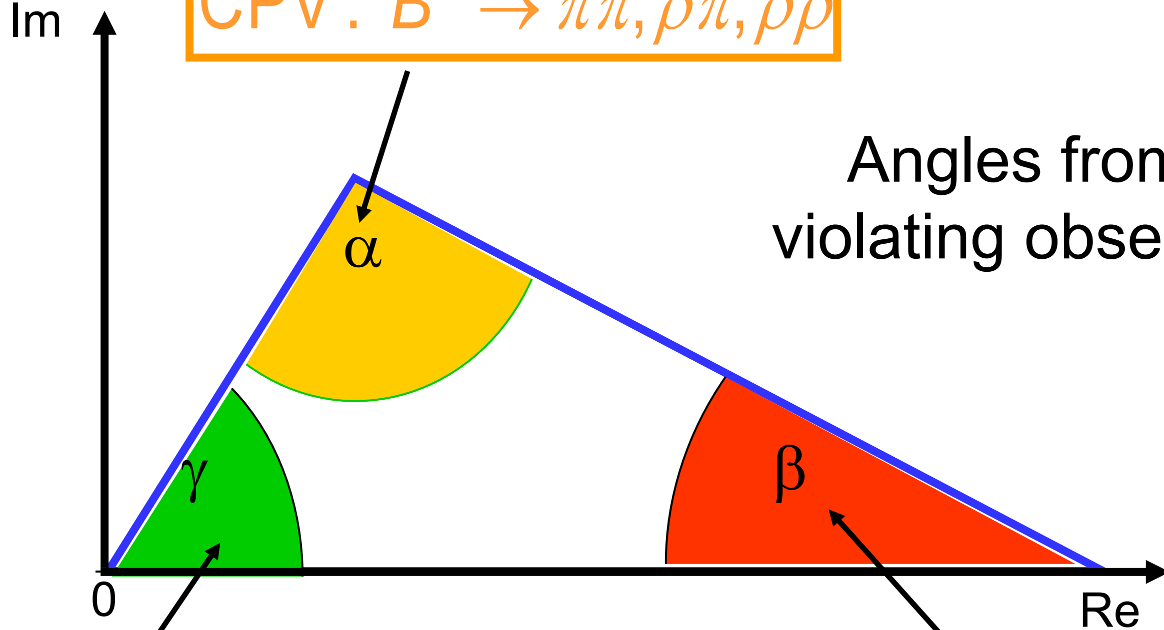
Unitarity Triangle from B Decays



Sides from CP
conserving observables

Unitarity Triangle from B Decays

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



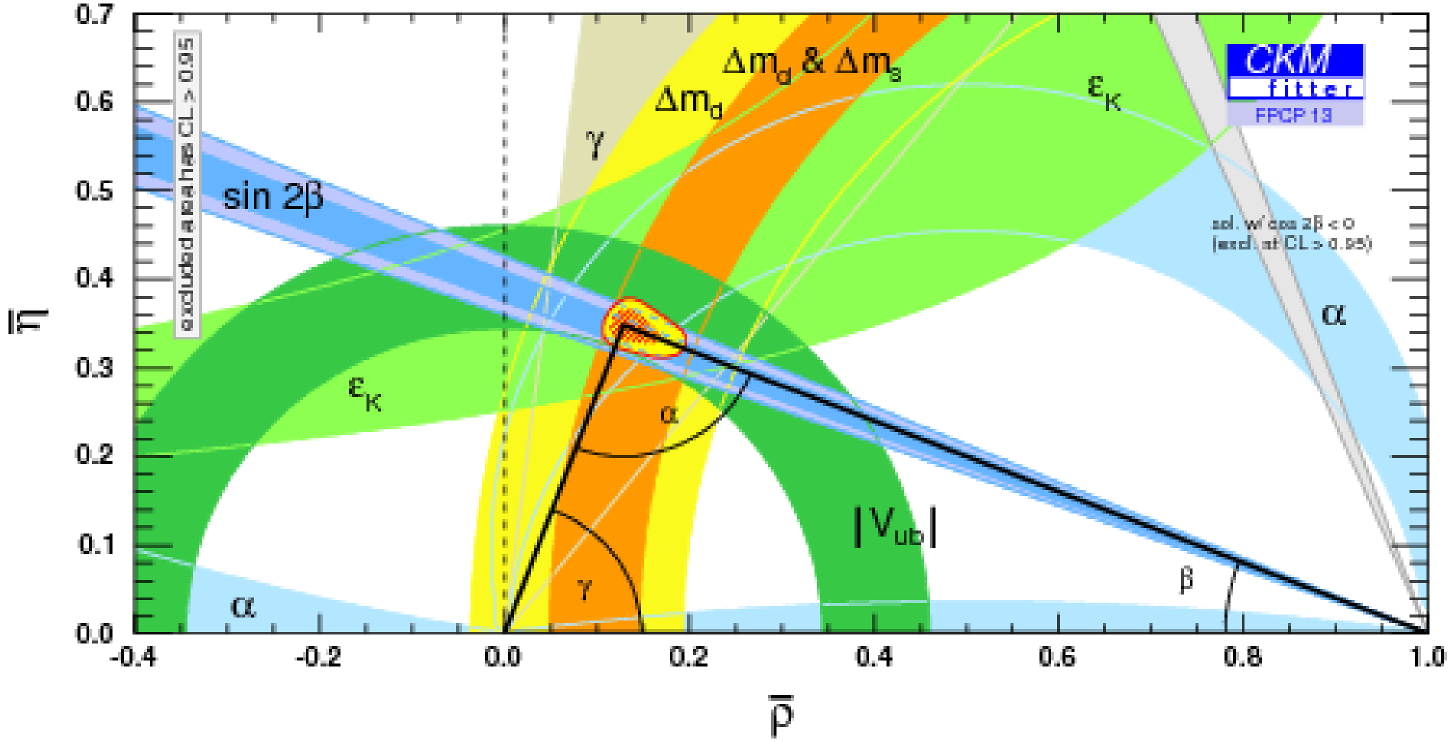
Angles from CP violating observables

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

$B_S^0 \to D_s K, KK$

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

Status of CKM Metrology



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

New physics constraints from quark flavor sector: *(Z.Ligeti)*

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

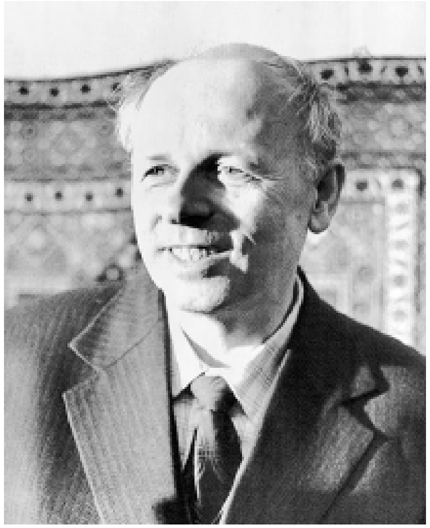
(2003) (2013) (2023)

Baryon Asymmetry in Universe

Slide from Z.Ligeti

Motivation for New Physics: Dark matter, hierarchy problem, BAU

- Sakharov conditions (1967):
  1. baryon number violating interactions
  2. C and CP violation
  3. deviation from thermal equilibrium

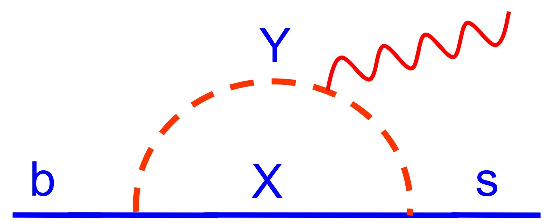


- SM contains 1–3, but:
  - i. CP violation is too small
  - ii. deviation from thermal equilibrium too small at the electroweak phase transition

New TeV-scale physics can enhance both (supersymmetry, etc.) and may have observable CPV effects (possibly only in flavor-diagonal processes, e.g., EDM-s)

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

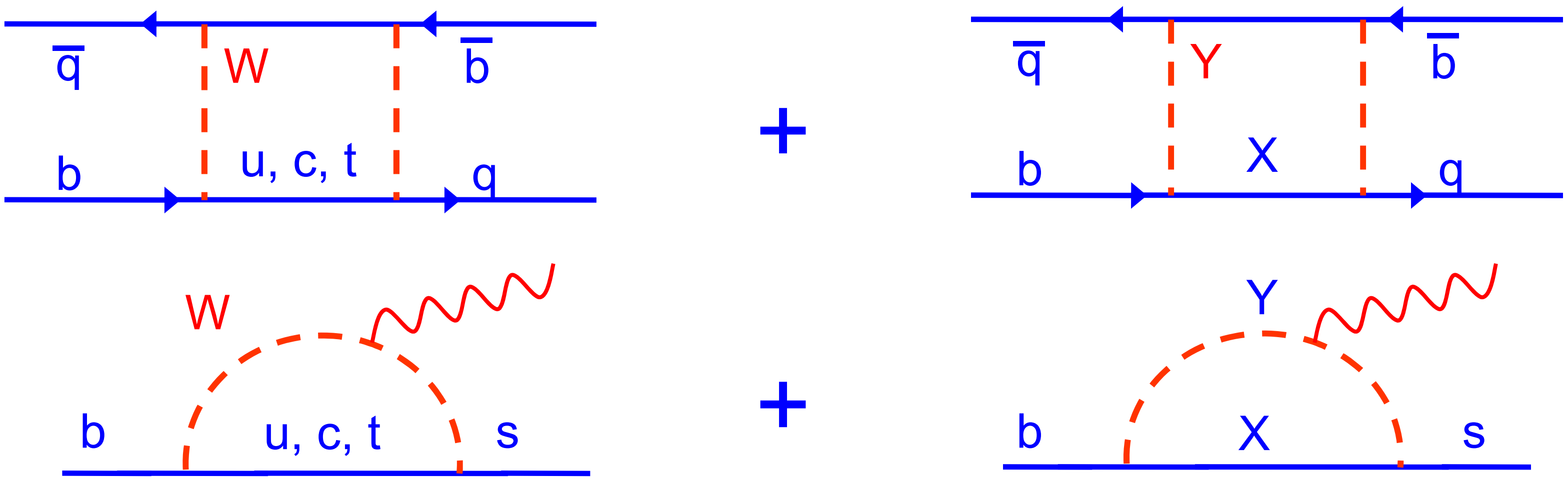
- All flavor changing processes depend only on a few parameters in the SM
  $\Rightarrow$ correlations between large number of s, c, b, t decays
- The SM flavor structure is very special:
  - Single source of CP violation in CC interactions
  - Suppressions due to hierarchy of CKM elements
  - Suppression 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

New Physics in Quantum Loops

New Physics are corrections to Standard Model processes:

Standard Model | New Physics



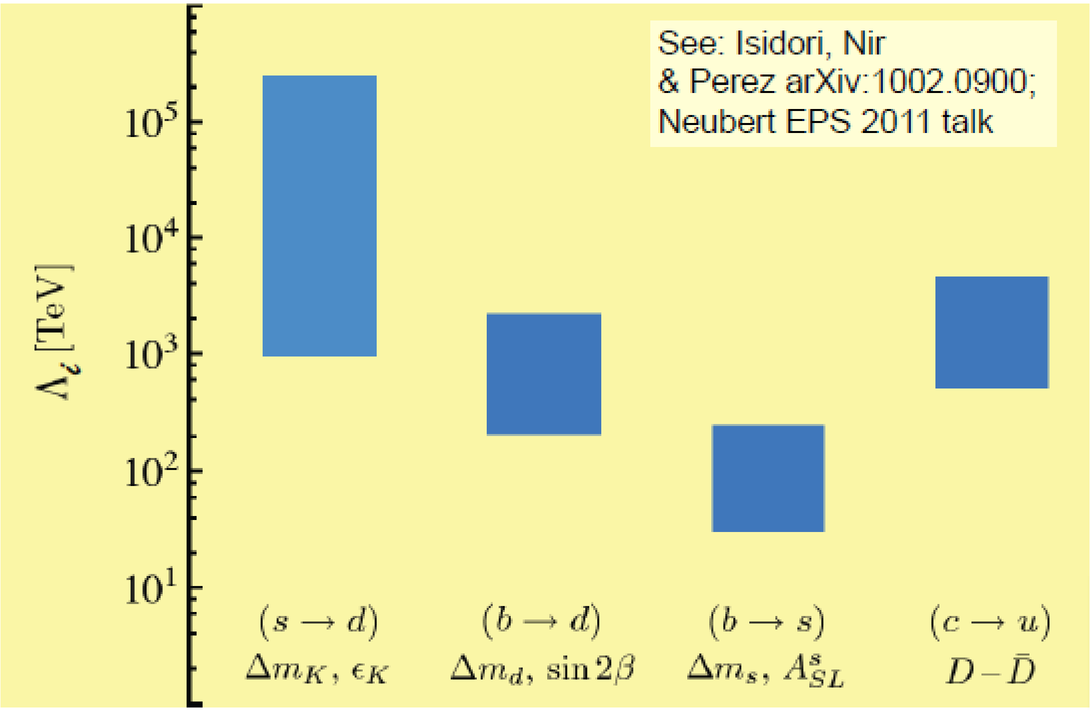
$$\mathcal{A}_{SM} \quad + \quad \mathcal{A}_{NP}$$

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

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)

Naturalness and Flavor Physics

loss of naturalness in Higgs sector

Reduction of flavor problem

N. Arkani-Hamed
Intensity Frontier Workshop, 2011

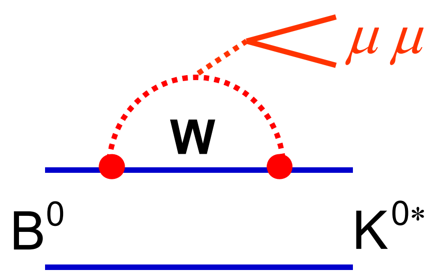
As we push the energy scale of NP higher, the NP FLAVOUR PROBLEM is reduced, hypothesis like MFV look less likely → **chances to see NP in flavour physics have, in fact, increased** when Naturalness (in the Higgs sector) seems to be less plausible!

LHCb Search Strategies for NP

Slide by U.Egede

Explore FCNC transitions with large sensitivity to NP, especially b → s transitions (poorly constrained so far)

- 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



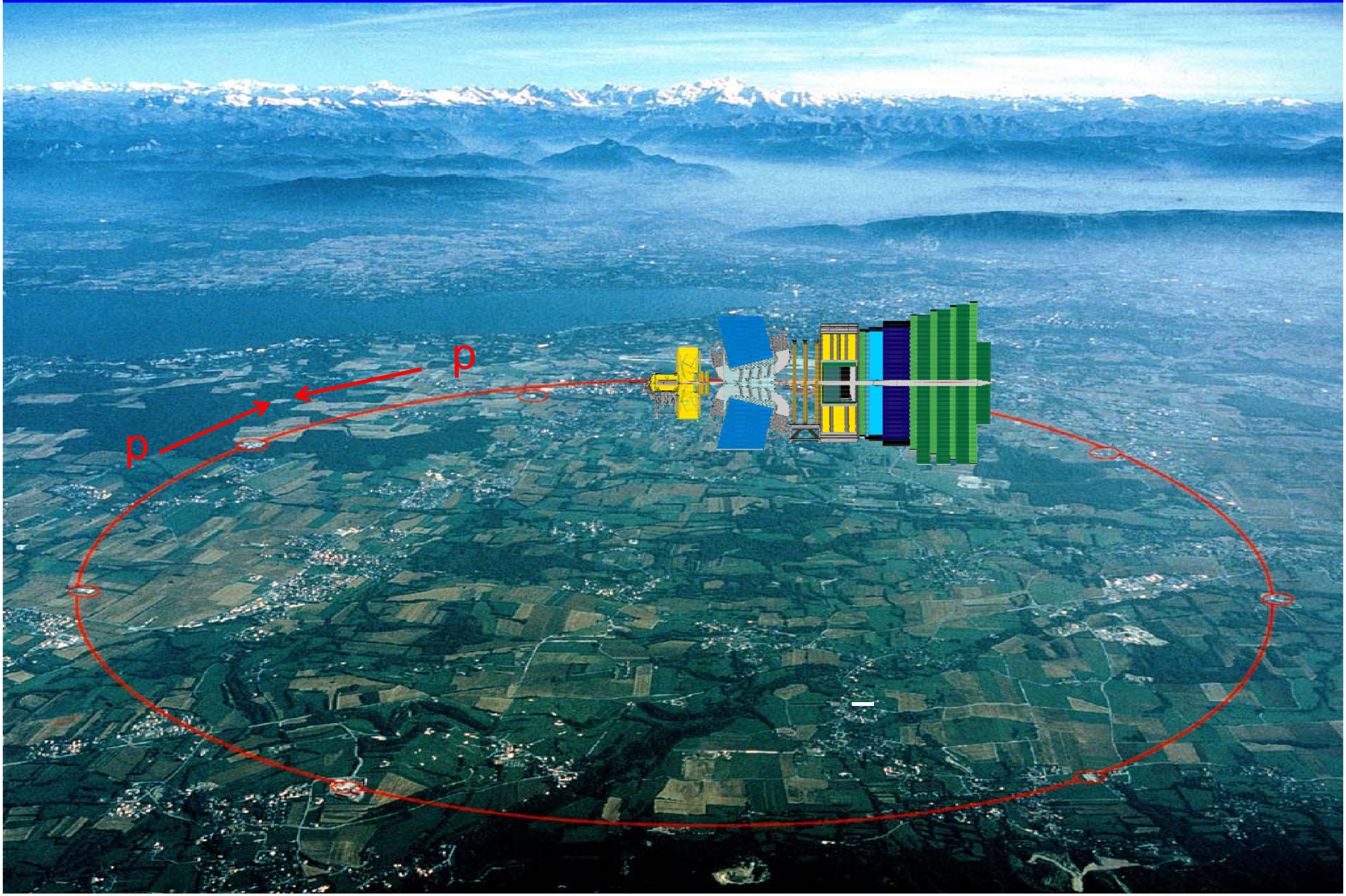
measurements w/ NP discovery potential

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

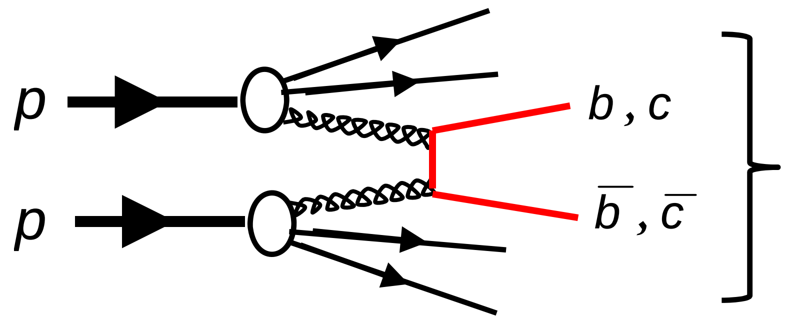
- Precise determination of angle γ
- Compare tree versus loop results

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 √s = 7 TeV:

$\sigma_{b\bar{b}}$ ~ 250 μb

200 kHz / 2 MHz (LHCb / CMS)

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

$\sigma_{c\bar{c}} \approx 20\times\,\sigma_{b\bar{b}}$

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

LHCb Measuremens at √s = 7 TeV:

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

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

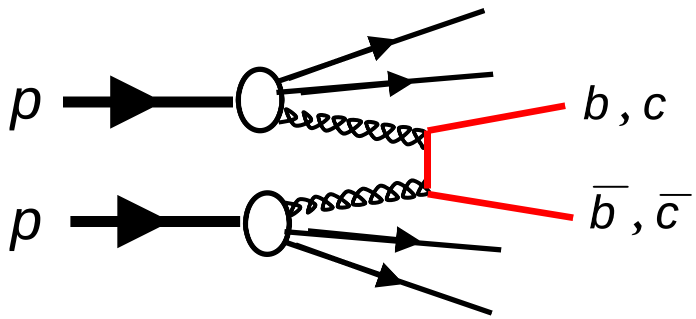
$$f_s/f_d = 0.256 \pm 0.020$$

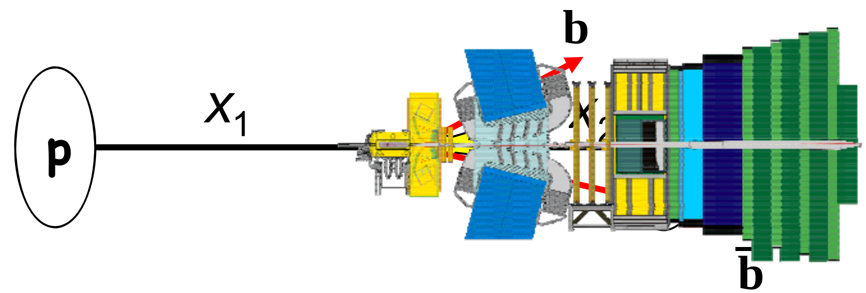
JHEP. 04 (2013) 001

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

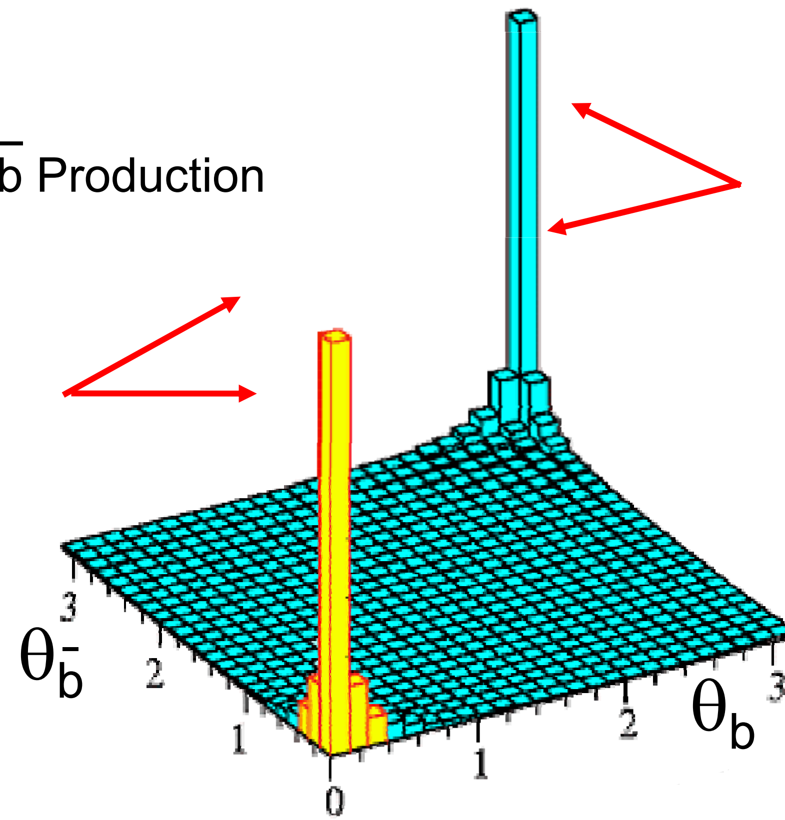
LHCb-CONF-2010-013

Heavy flavor production at LHCb





$b\bar{b}$ Production

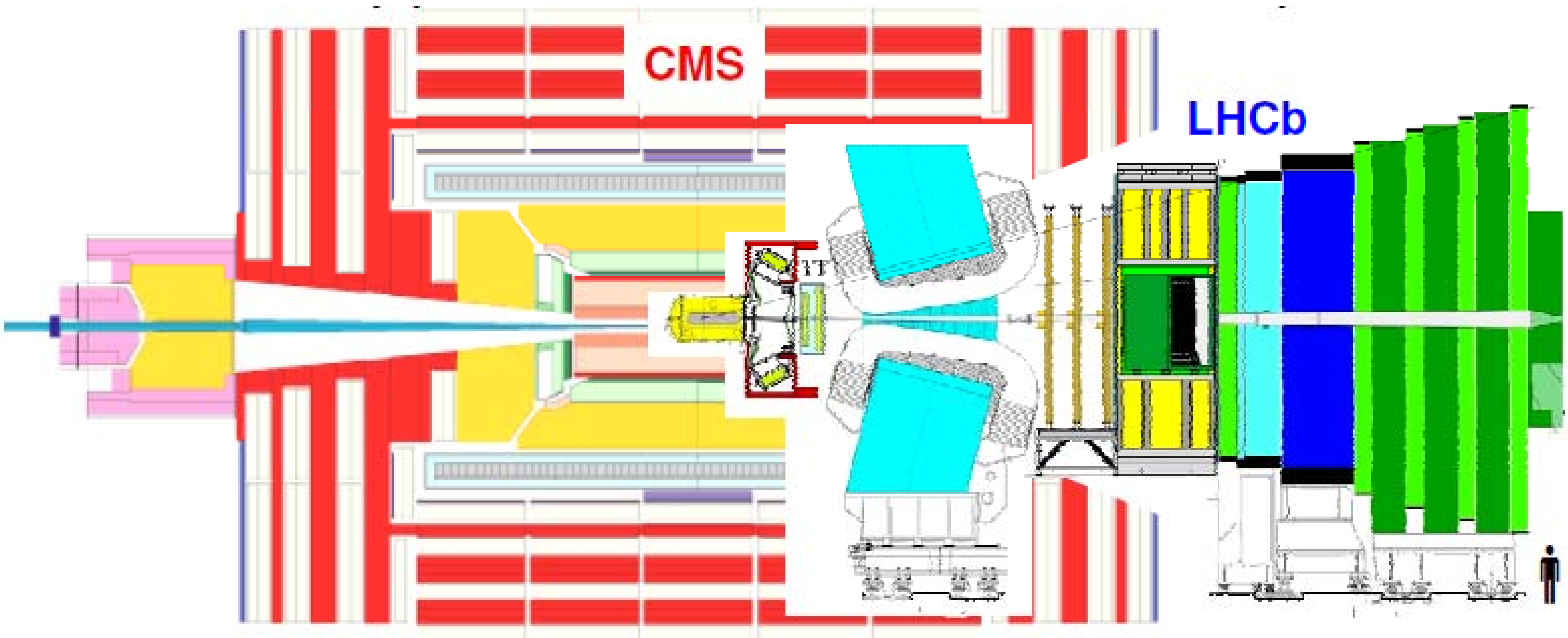


Fraction of cross section in LHCb acceptance (including pt constraints): ~1/4

⇩

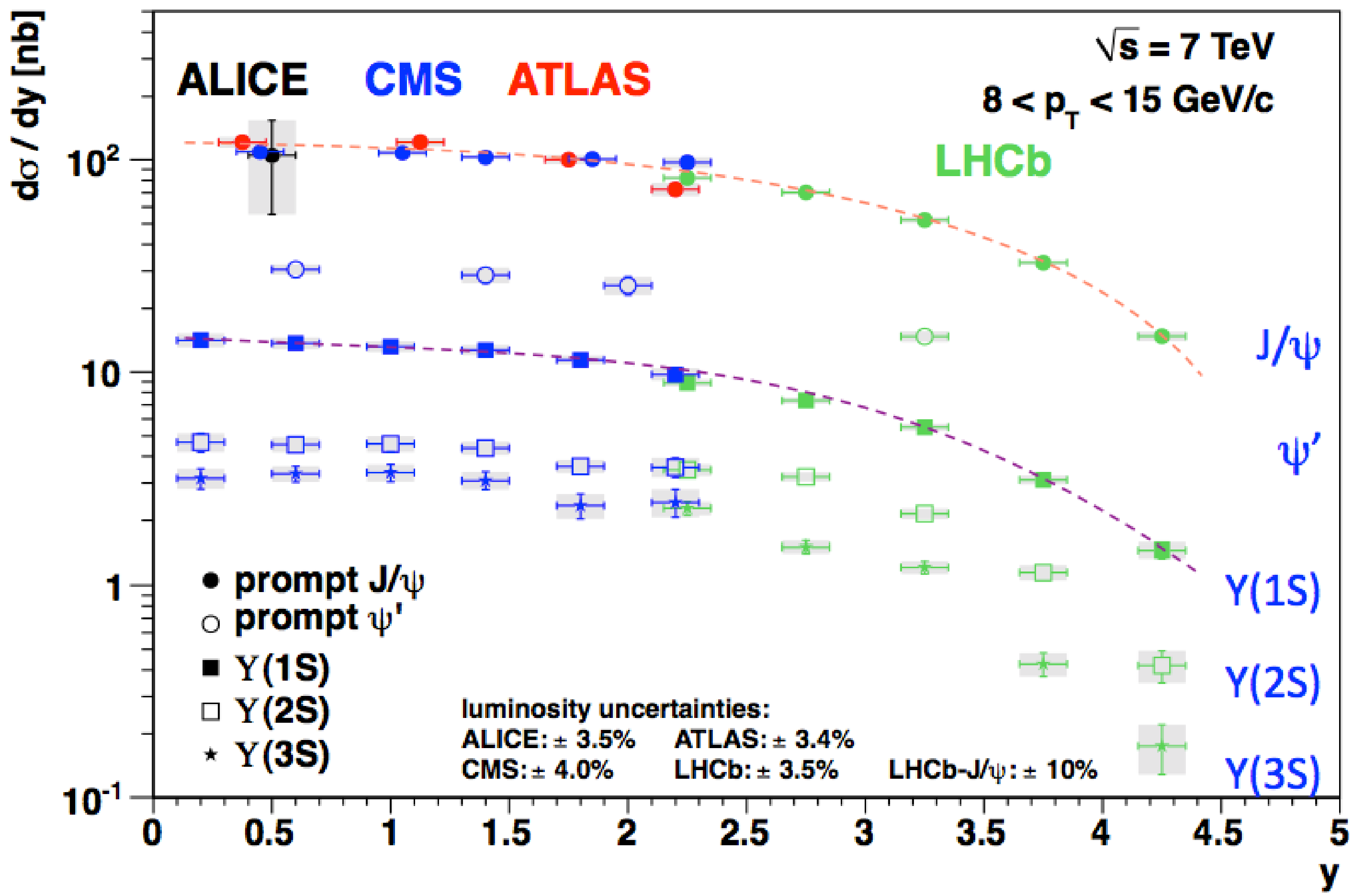
50 kHz of bb events at L=2×10^{32}

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

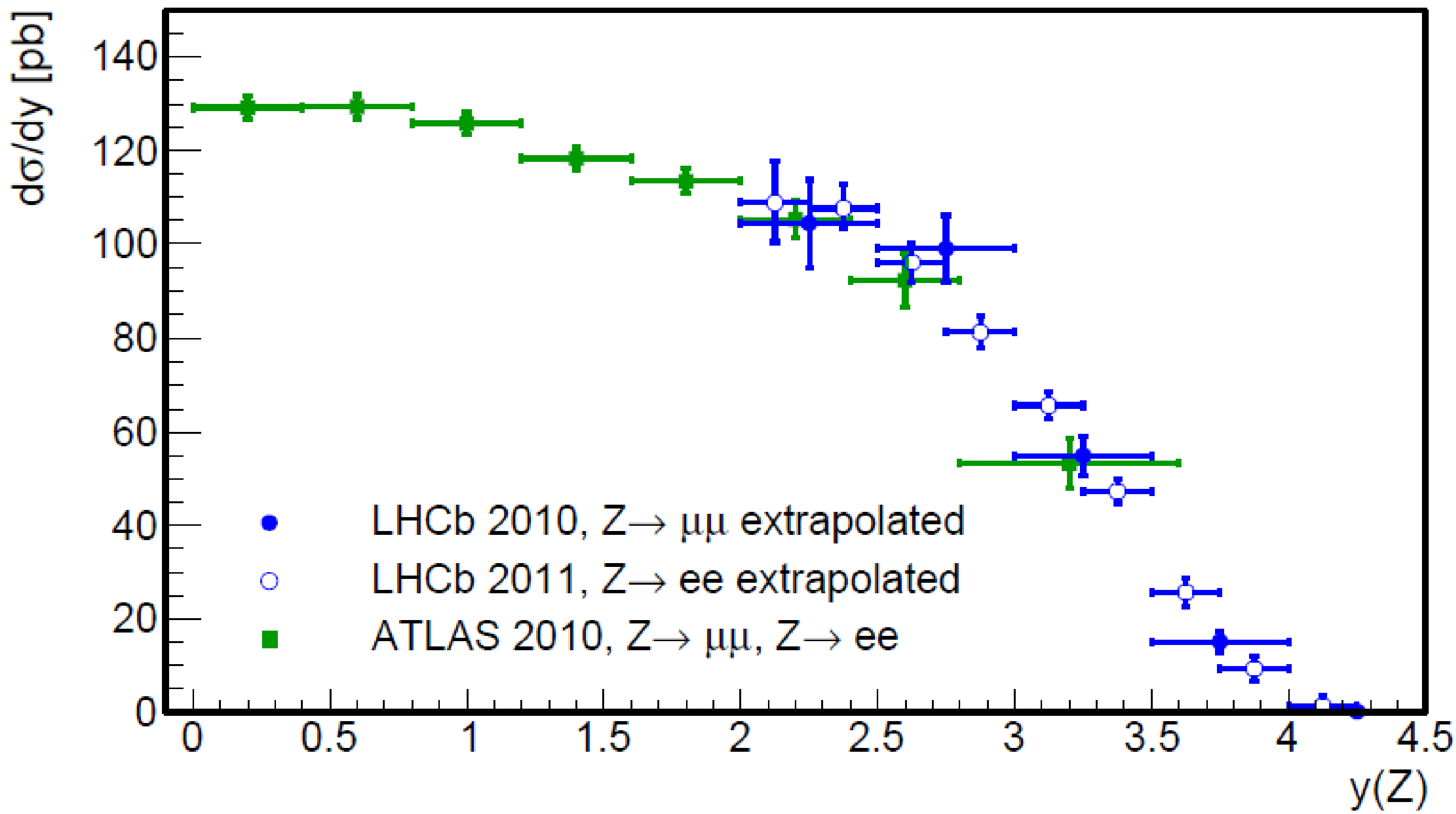


ALICE : 5.6 nb^{-1}
ATLAS : 2.2 pb^{-1}
CMS : 37, 36 pb^{-1}
LHCb : 5.2, 36, 25 pb^{-1}

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**.

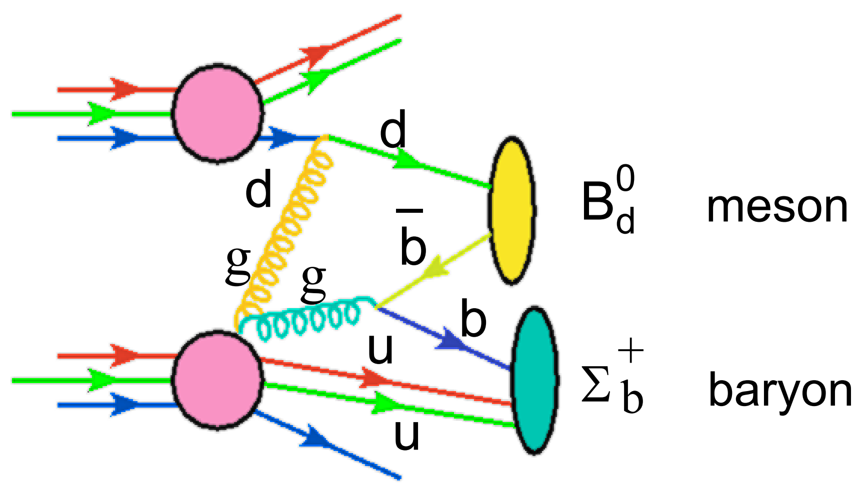
$$\frac{\text{produced antiparticles } \bar{P}}{\text{produced particles P}} = \frac{N(\bar{P})}{N(P)} = 1 + \delta_p$$

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

Production asymmetry is effect of competing processes:

Cluster Collapse

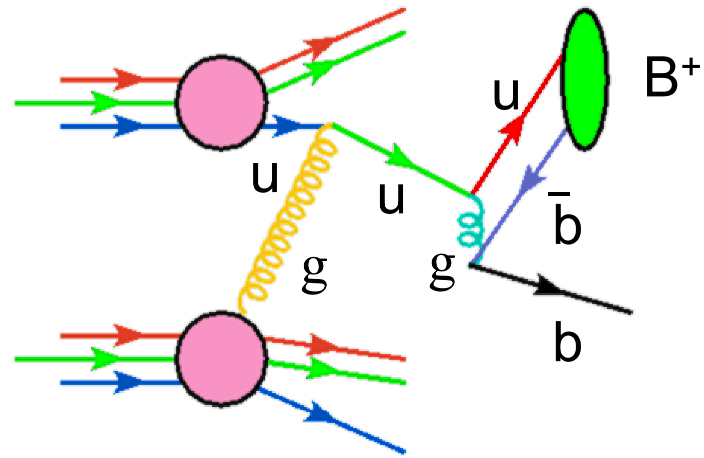
Enhances the production of species containing beam remnants at low transverse momentum (pt)



Production Asymmetries

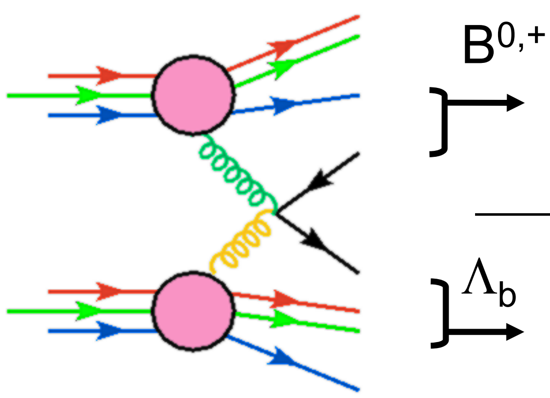
Valence-Quark Scattering

Enhances production of high energy species containing beam constituents



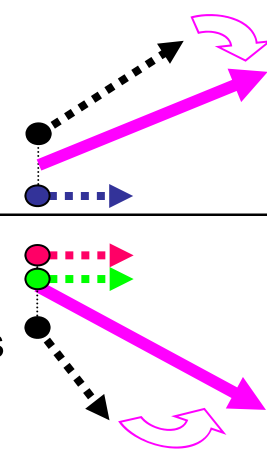
Beam Drag

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



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

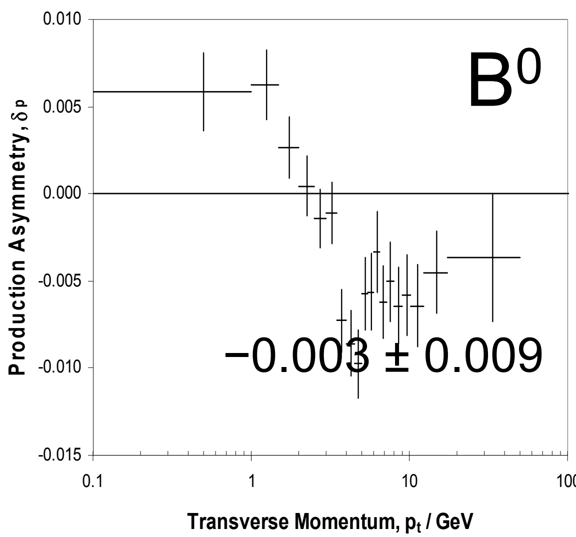
Color connections with di-quark remnants 'drag' quarks toward the beam



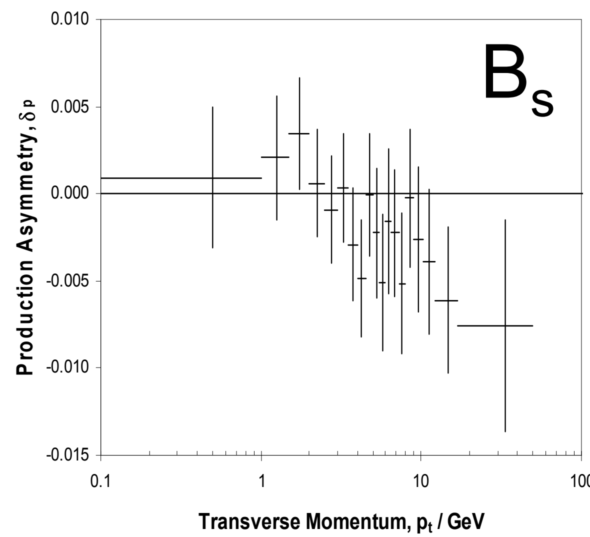
Production Asymmetrie

PHYTIA Simulation

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



δ_p = -(**3.2**±0.5) x10^{-3}



δ_p = -(**1.5**±0.8) x10^{-3}

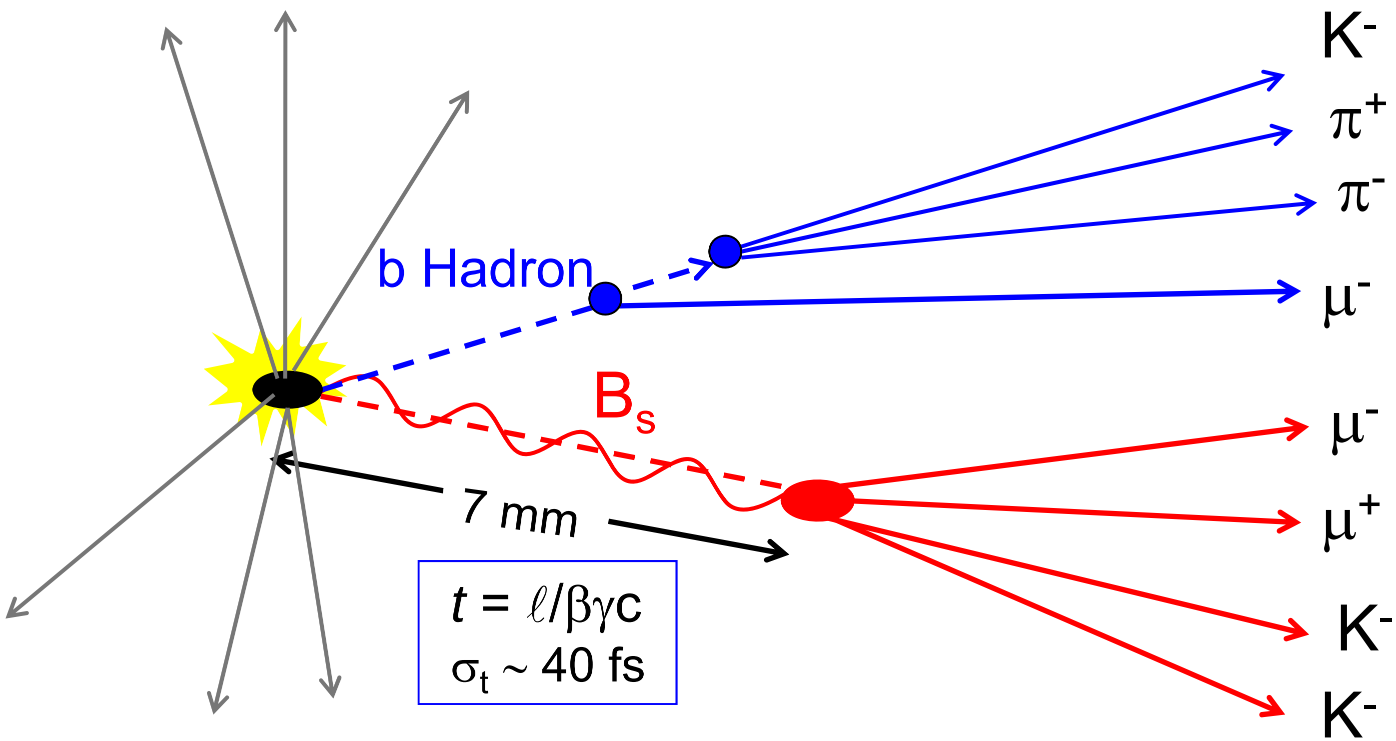
$A_P(B^0)$ = (0.1 ±1.0)%
$A_P(B_s)$ = (4 ±8)%.

Phys. Rev. Lett. 110 (2013) 221601

$A_P(B^{\pm})$ = (-0.3 ± 0.9)%

Phys. Rev. D 85, 091105(R) (2012)

A typical b event

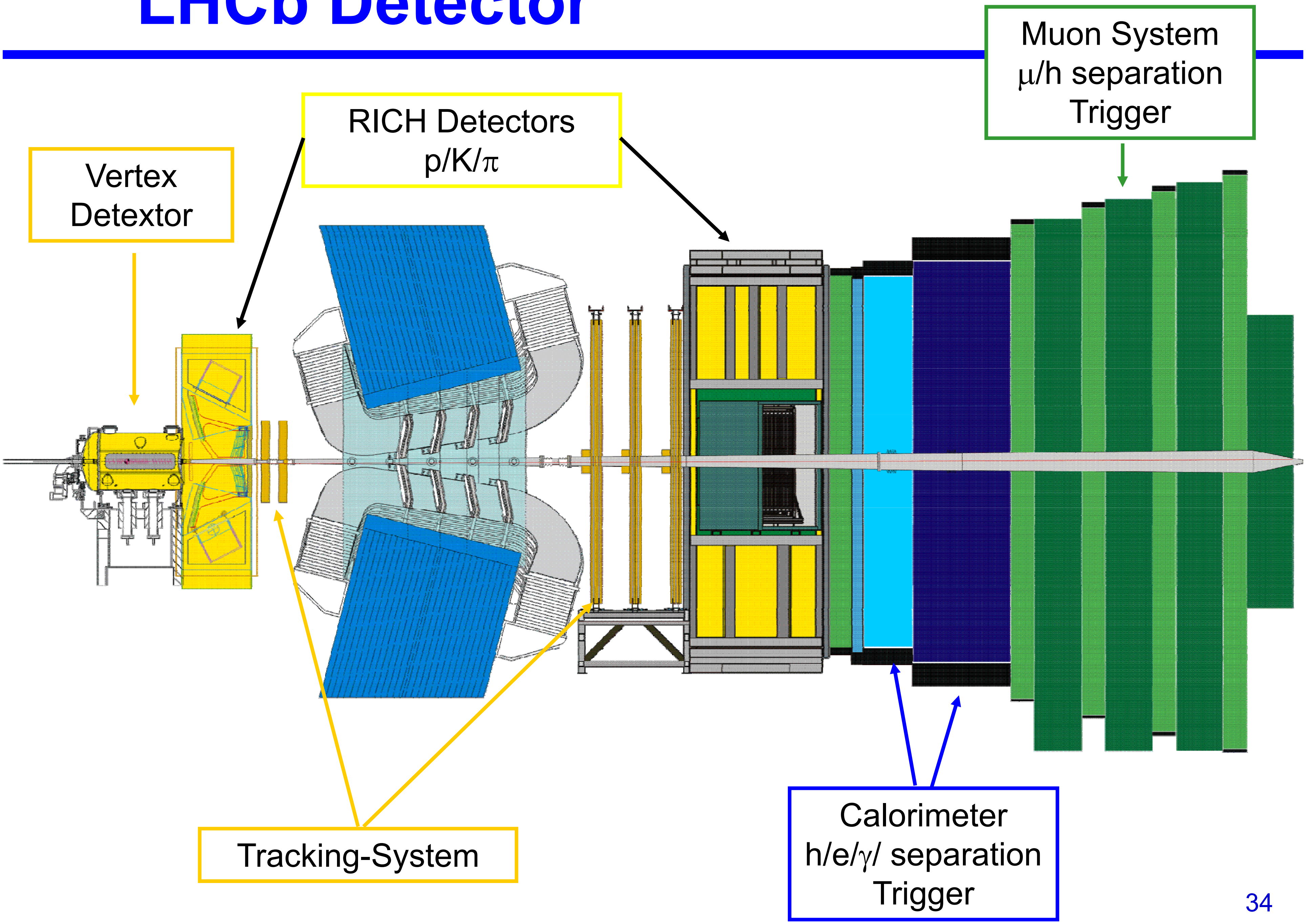


Good vertex resolution: to resolve fast B_s oscillation.

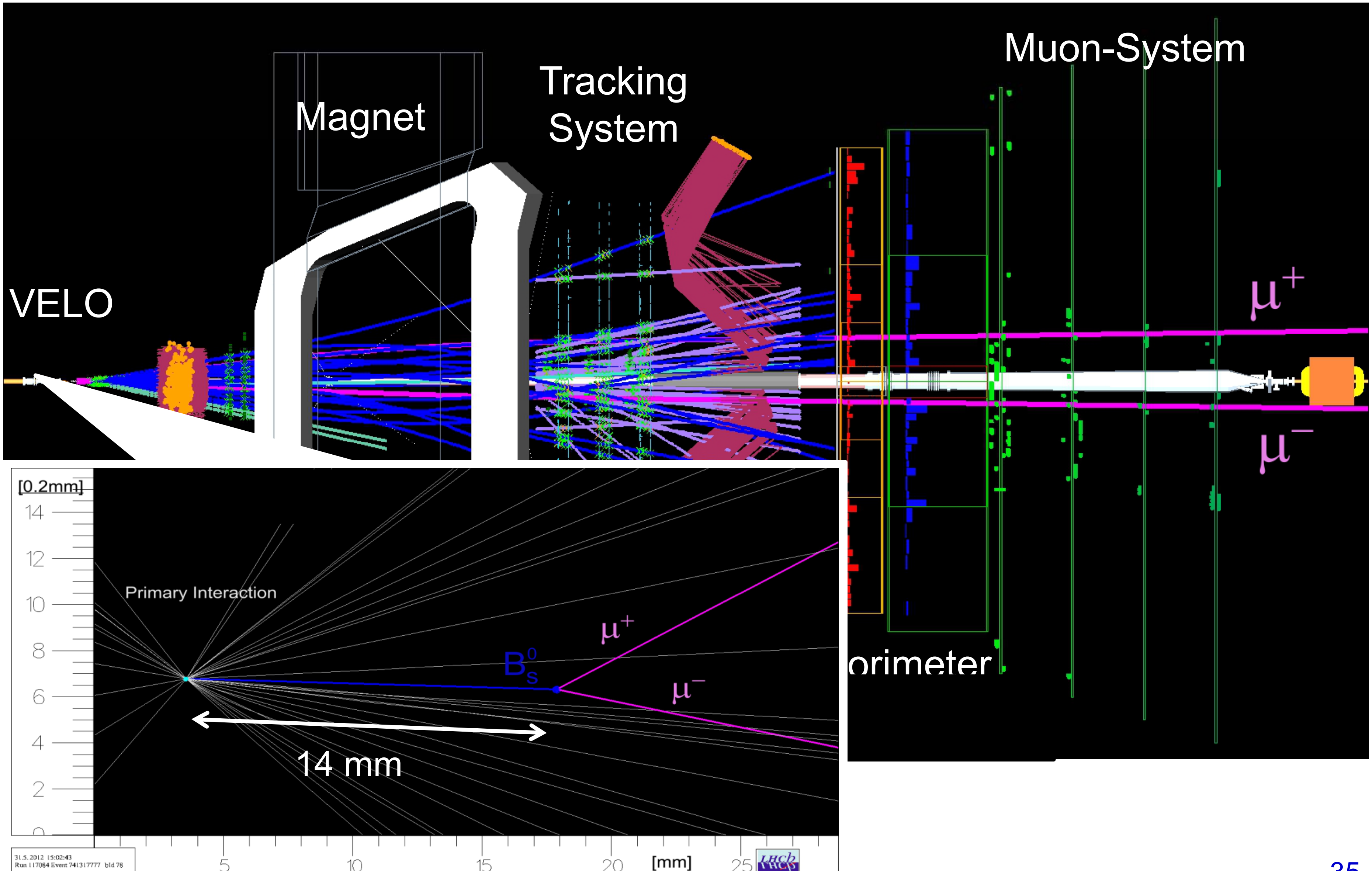
Background reduction: Very good mass resolution
Good particle identification (K/π)

High statistics: Efficient trigger for hadronic and leptonic states

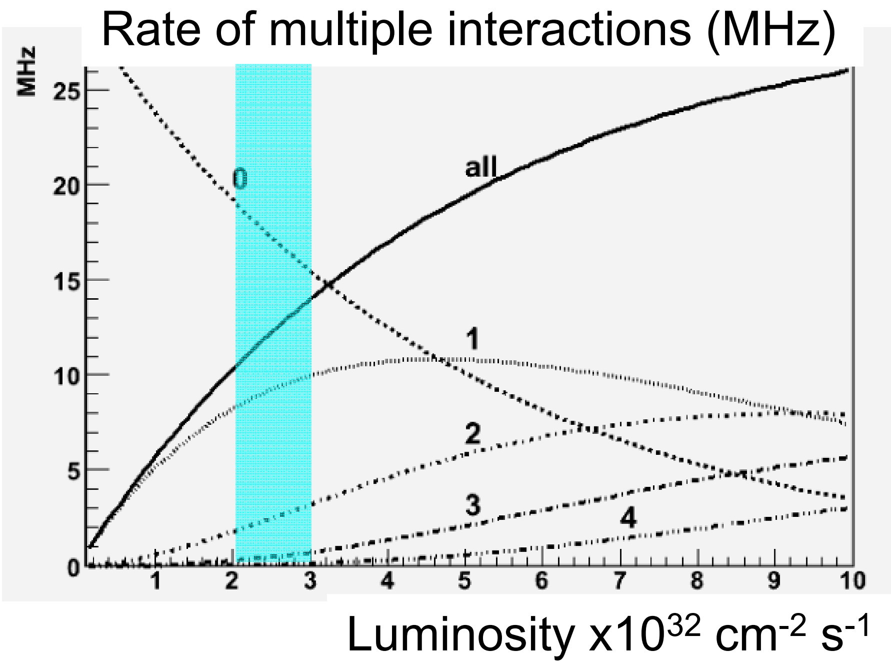
LHCb Detector

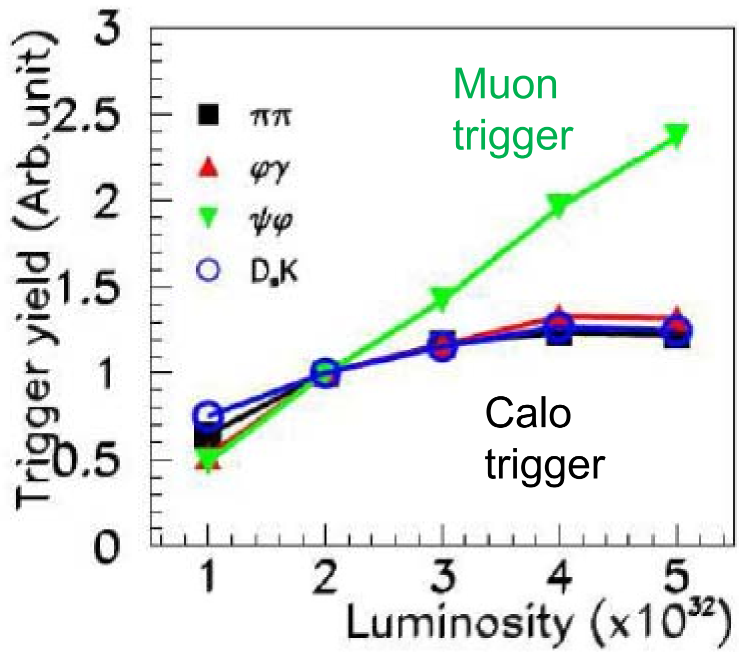


B-decay in LHCb



Optimal luminosity





[CERN-LHCC-2011-001]

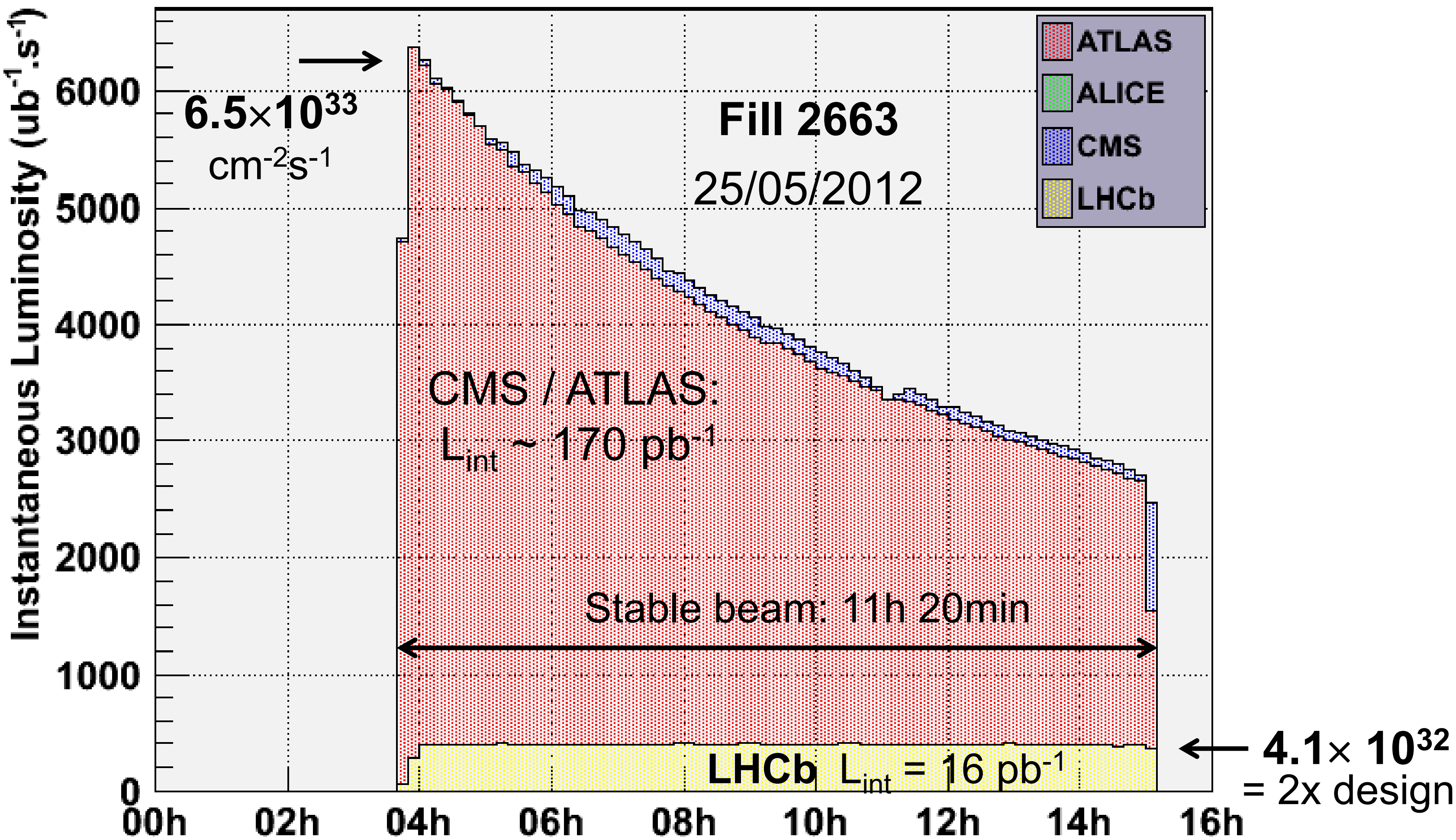
Design: 2×10^{32} s^{-1}cm^{-2}
n = 0.5 IA/crossing

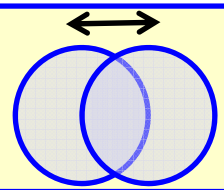
Running: no performance loss seen at higher IA rates

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

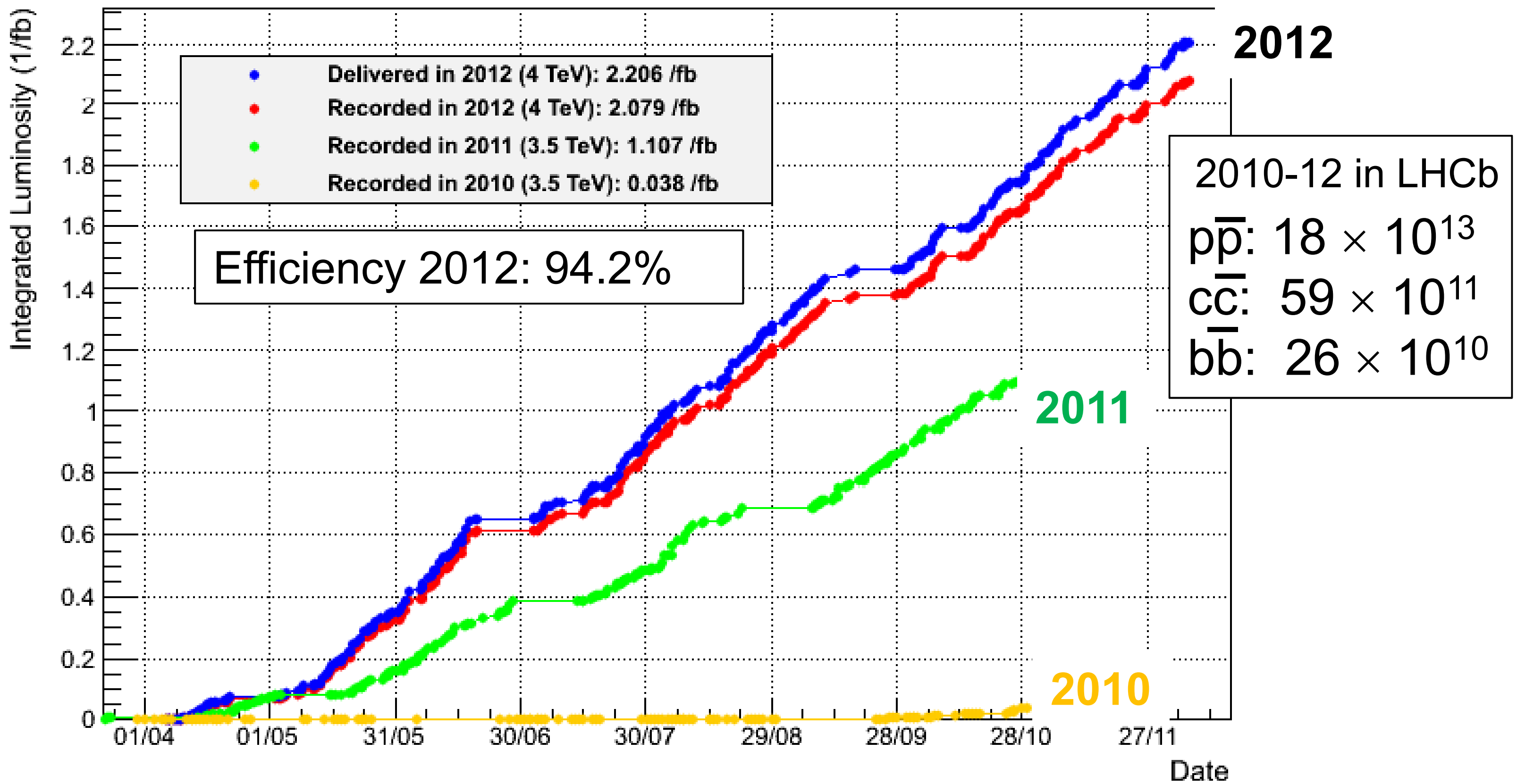




LHCb: Displacement of beams to optimize luminosity

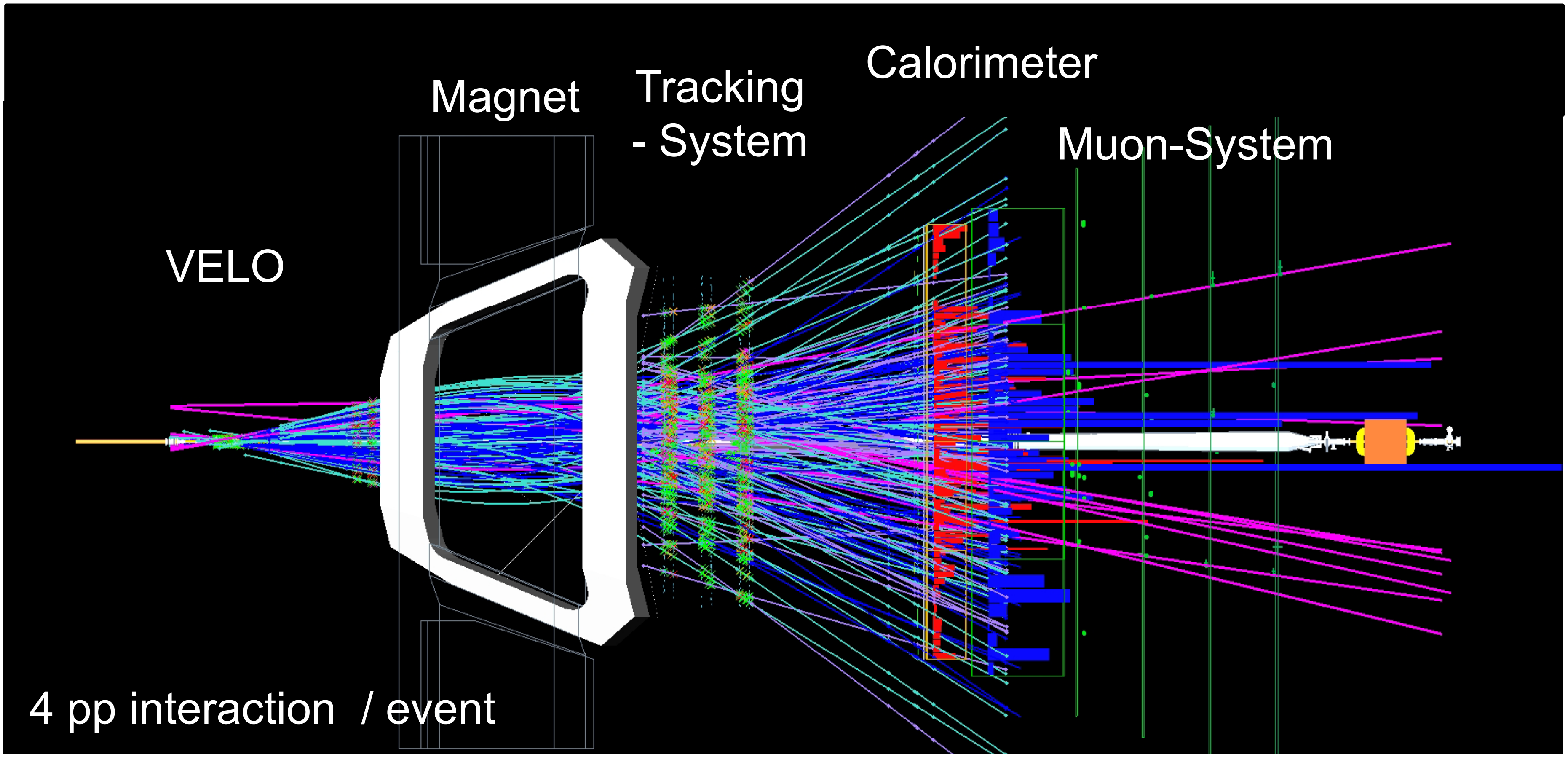
1.8 IA / Crossing
Design: 0.5

Data Taking



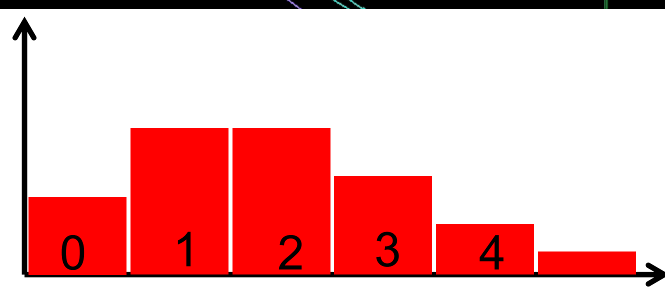
ATLAS / CMS in 2012 about 10× higher integrated luminosity.

"High-rate" event

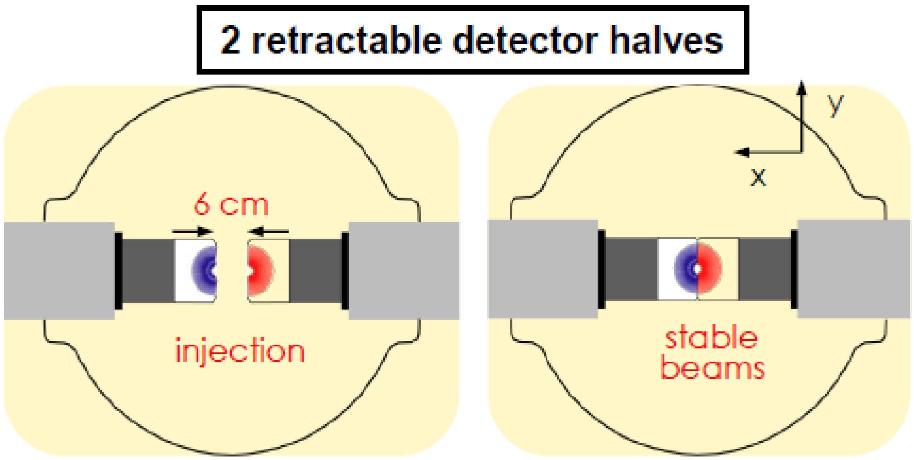


<u>Number of interaction / event</u>:

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



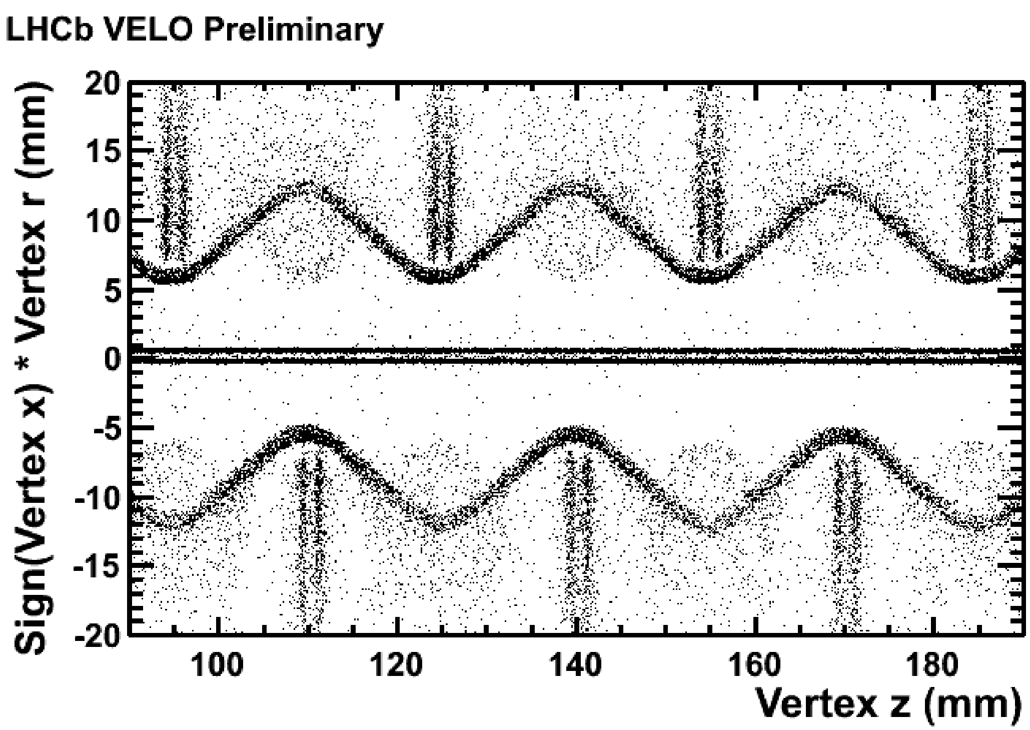
Vertex Detector & Performance

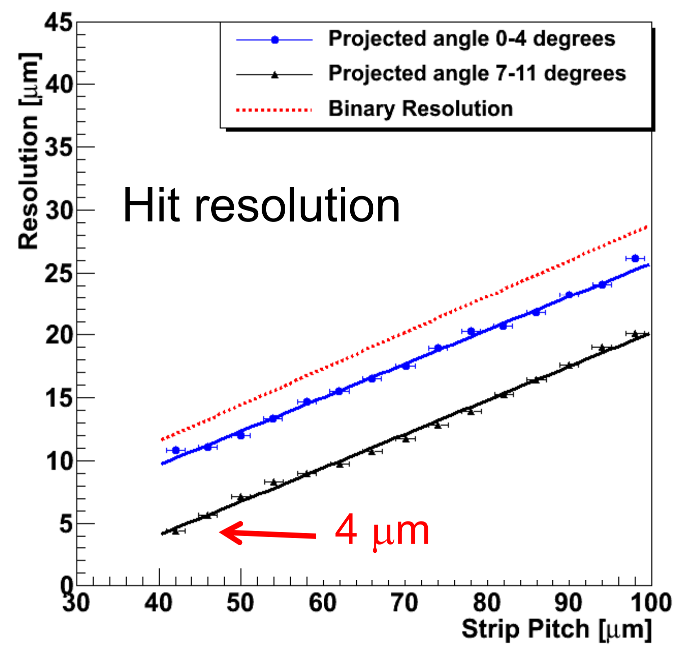


Single sided Silicon strip sensors:

2 × 21 (r and ϕ sensors)

300 μm n^+-on- n strip sensors



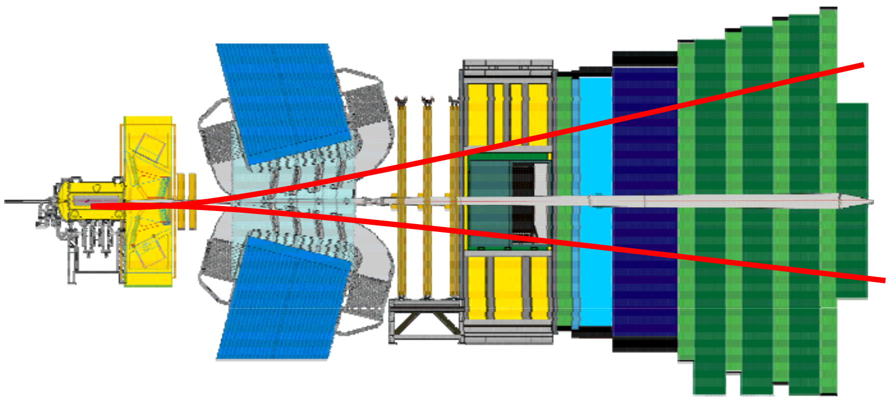


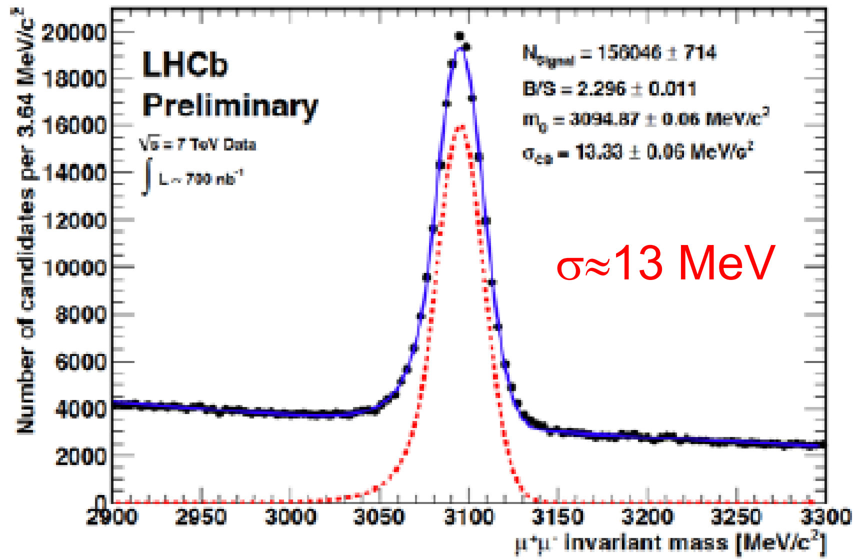
IP resolution:

σ_{IP} =14μm±20 μm/p_T

Momentum & Mass Resolution

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





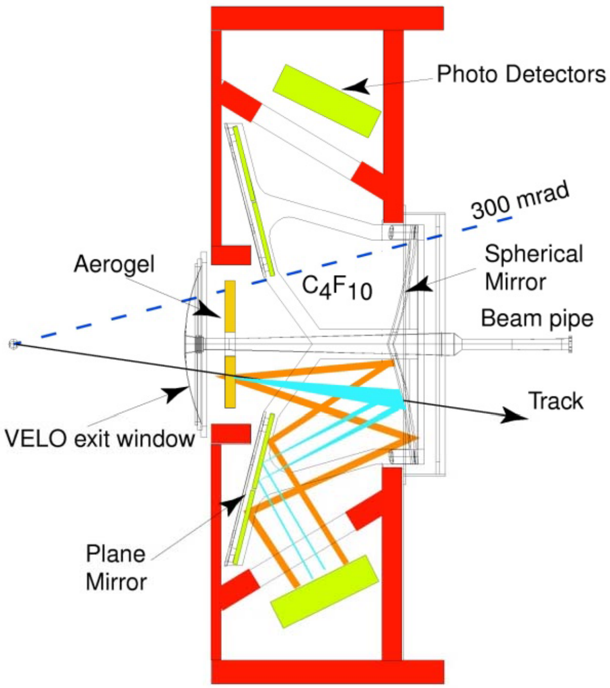
$$M(\mu\mu) = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

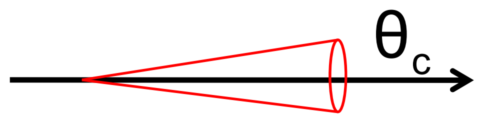
	δp/p	δm(J/ψ→μμ)
LHCb	0.4-0.6 %	13 MeV

← CMS 40 MeV
ATLAS 70 MeV

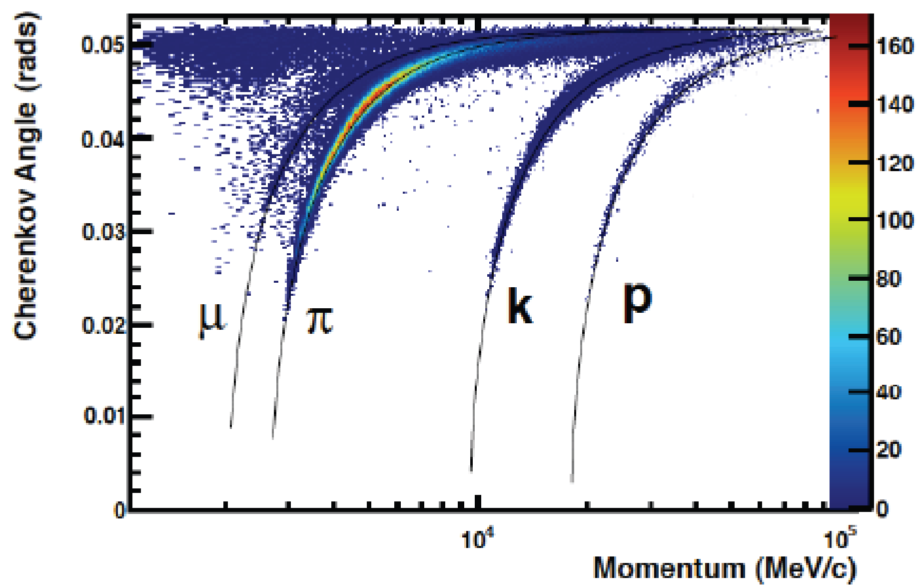
B mass resolution for $B \rightarrow J/\psi X$: 7…13 MeV

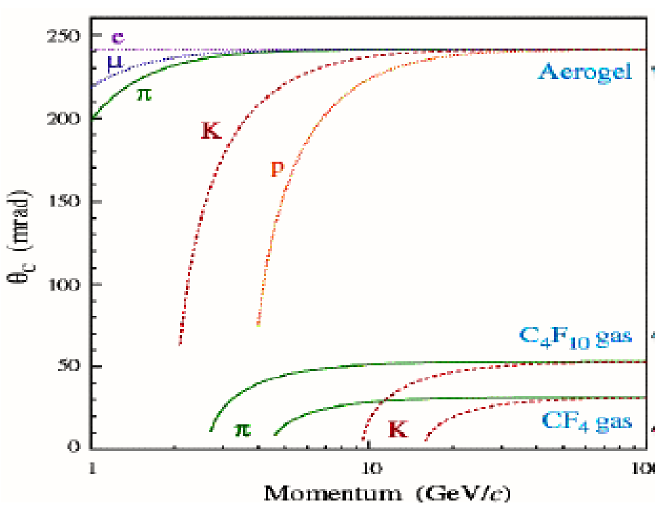
Particle Identification with RICH





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





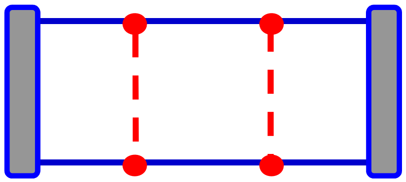
2 RICH detectors with 3 different radiators ensures goof PID over full momentum range.

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

LHCb – Key Measurements

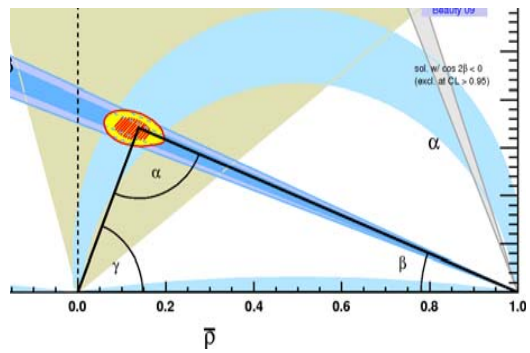
B / D Mixing

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

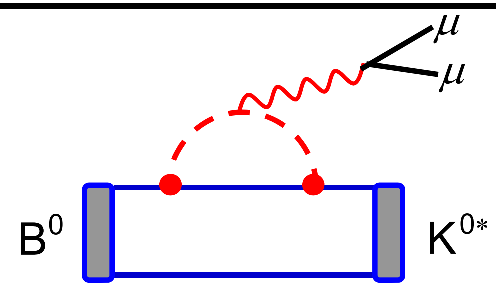


$\not{CP}$ to get mixing phase

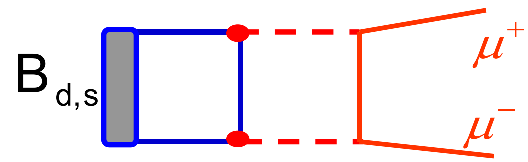
CKM Metrology: γ



Rare decays

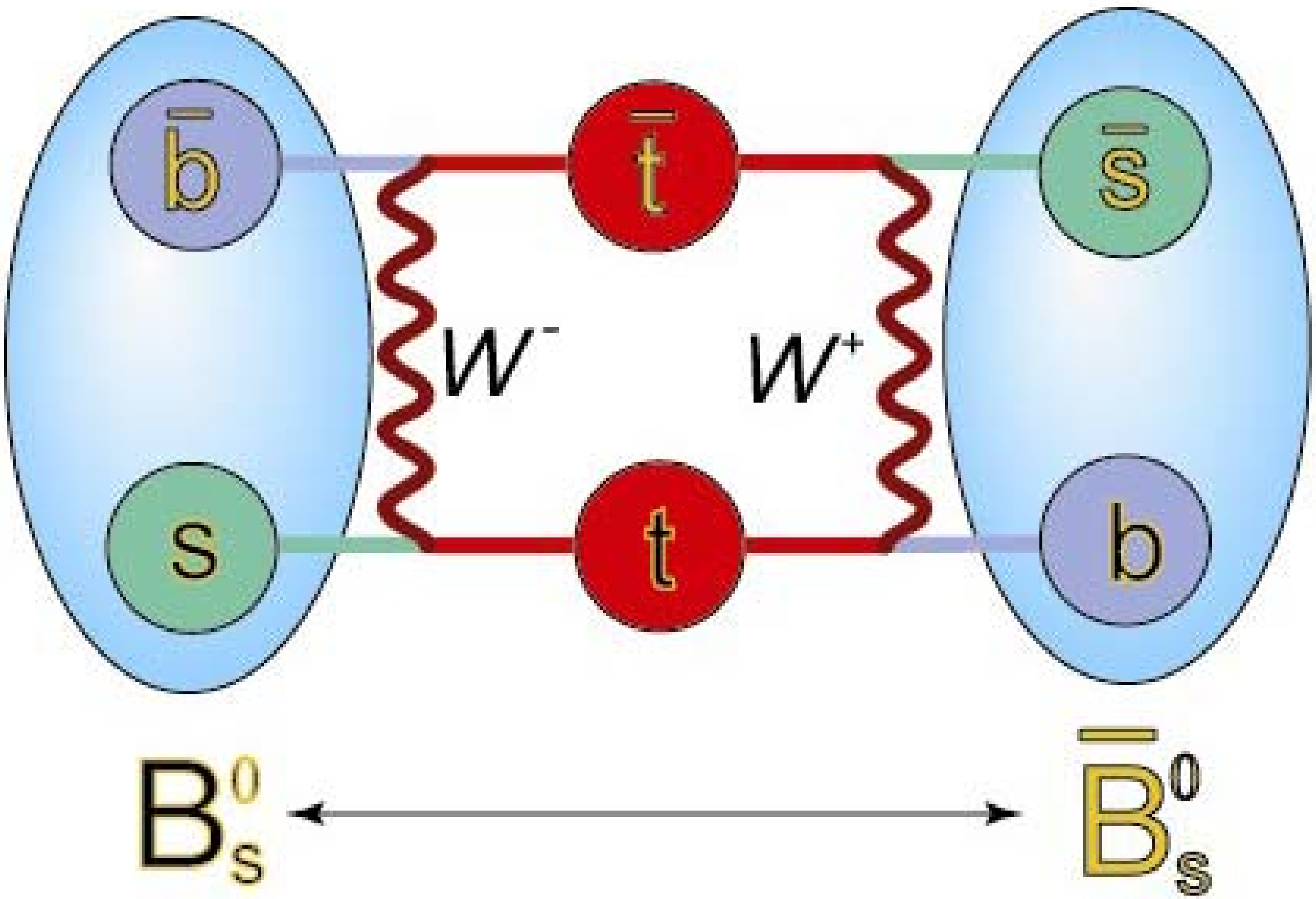


angular distribution

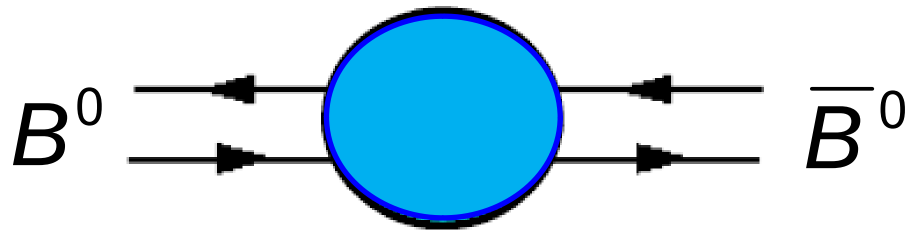


Rates

3. Neutral Meson Mixing



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:

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

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

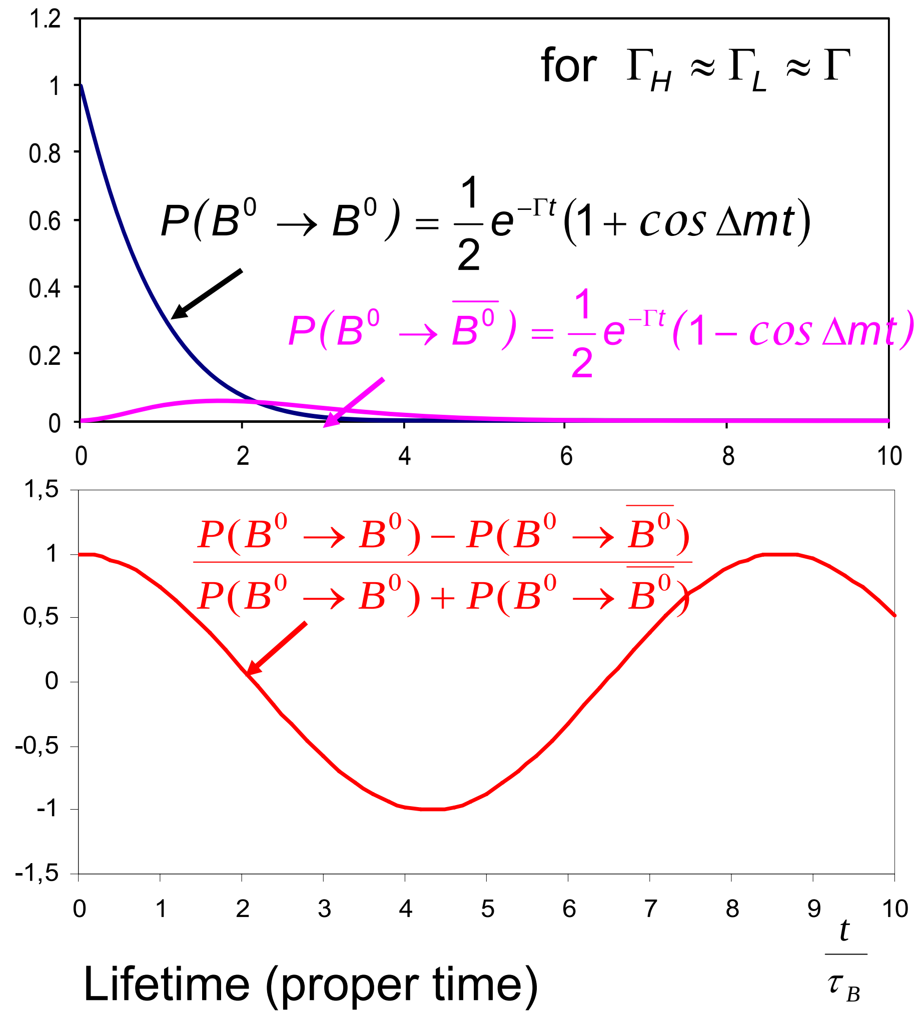
Mixing Asymmetry ($\Delta\Gamma \approx 0$)

<u>Mixing probability:</u>

$B_d \rightarrow f = X\,\mu^+$ unmixed

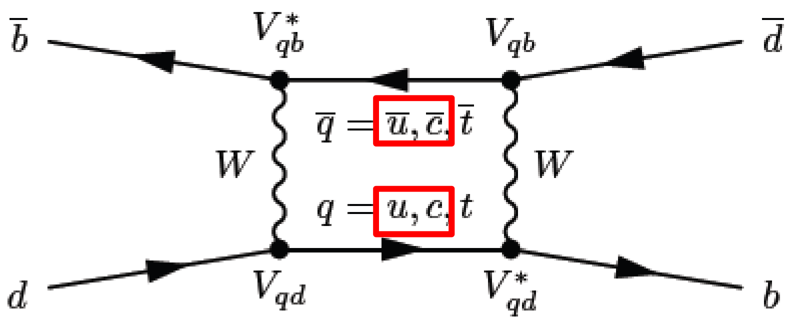
$B_d \rightarrow \overline{B}_d \rightarrow \overline{f} = \overline{X}\,\mu^-$ mixed

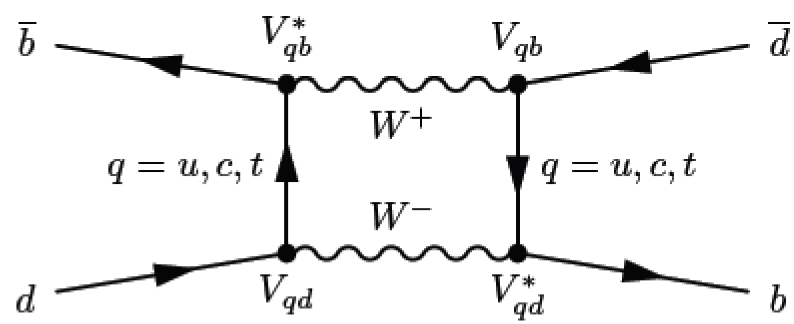
$$A(t) = \frac{unmixed(t) - mixed(t)}{unmixed(t) + mixed(t)} = \cos(\Delta m t)$$



Standard Model prediction

Real intermediate states: Γ_{12}





Main contribution from top quark:

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

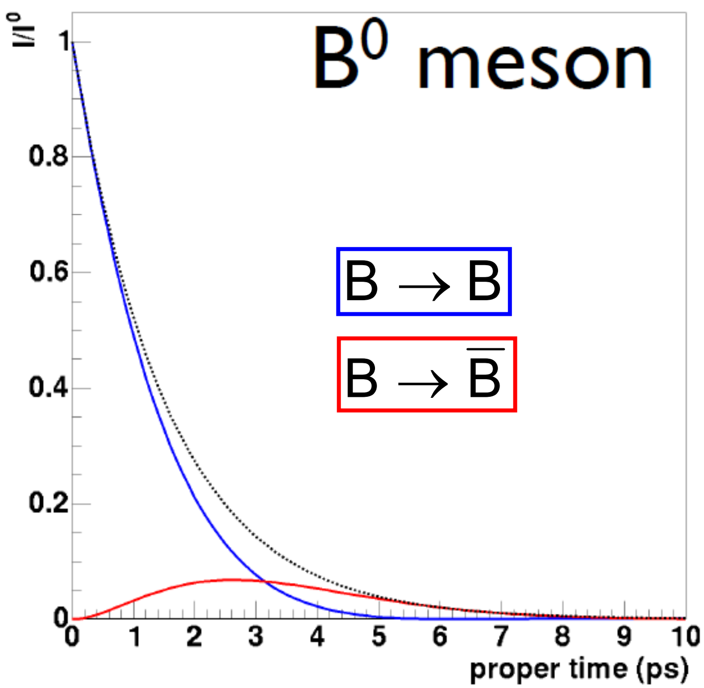
$$M_{12,q} = \frac{G_F^2}{12\pi^2}(V_{tq}^* V_{tb})^2 M_W^2 S_0(x_t) B_{B_q} f_{B_q}^2 M_{B_q} \hat{\eta}_B$$

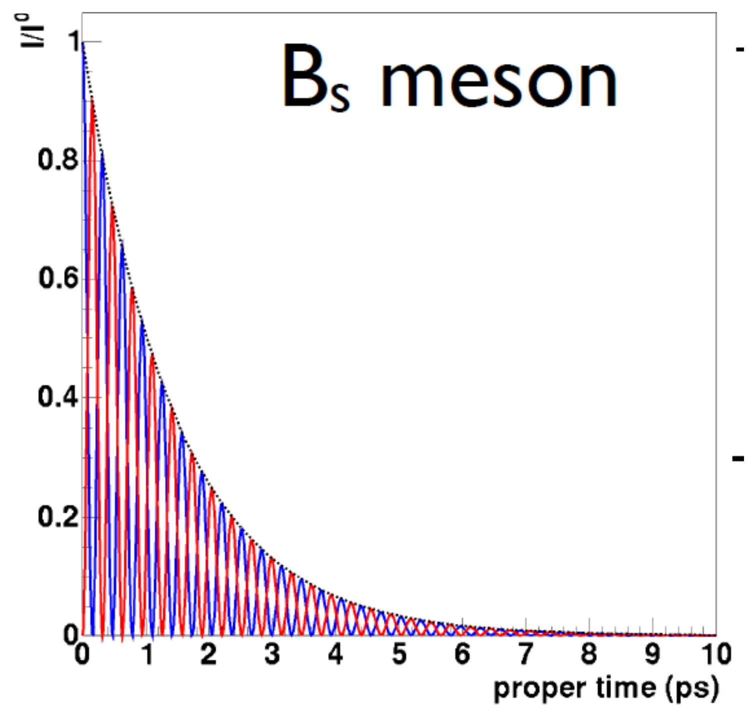
Inami- Lim Funct. for box diagram $S_0(m_t^2/m_W^2)$

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

GIM(V_{CKM} unitarity):
if u,c,t same mass, everything
cancels *by construction*!

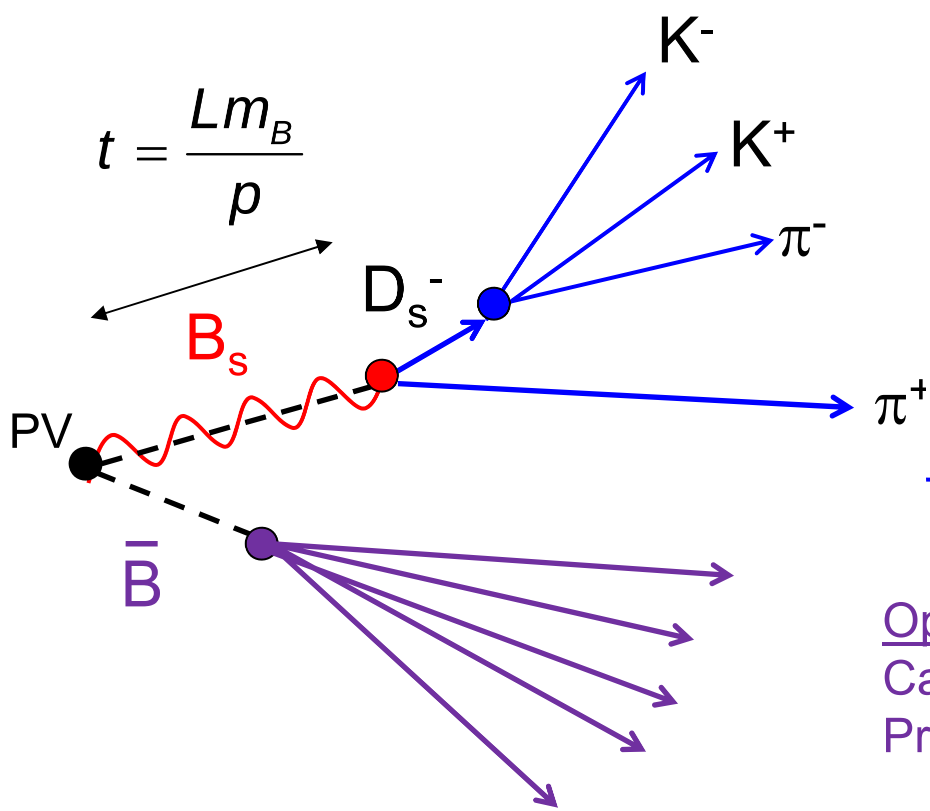
B meson mixing



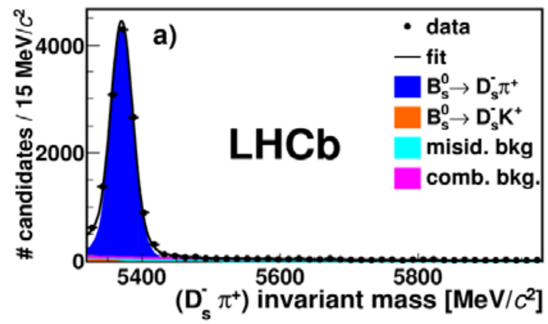


$$\frac{\Delta m_d}{\Delta m_s} \approx \frac{|V_{td}|^2}{|V_{ts}|^2} \approx \frac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04$$

B_s Mixing Measurement



Signal B
(flavor specific decay)



Need production flavor

Opposite B

Can be used for flavor tagging

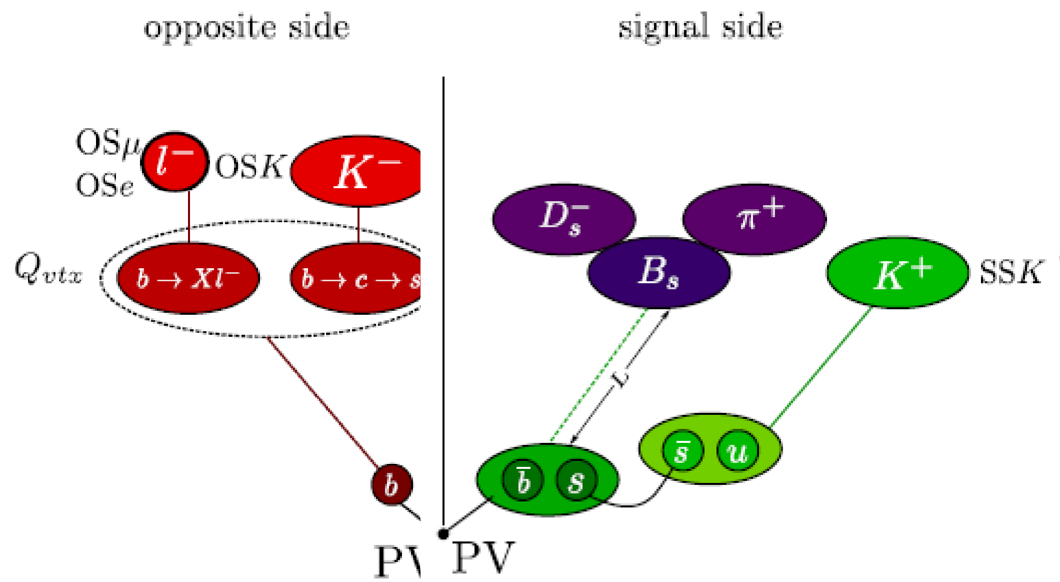
Problem w/ neutral B's ($\to$mixing)

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

Production flavour from tagging algorithms

resolution

Flavor Tagging



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
Difficulties:

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

→ high mistag probability: ~35 %

Flavor Tagging

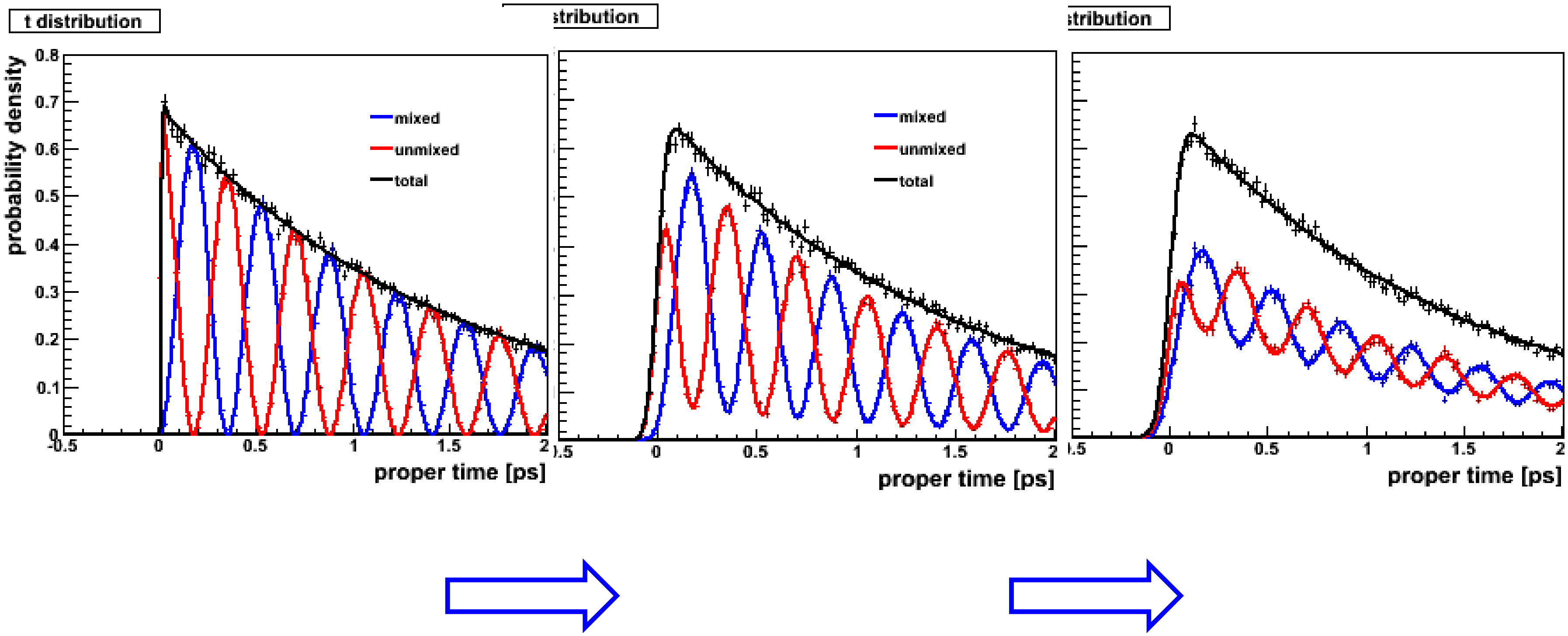
	efficiency	mistag	tagging power
tagger	$\varepsilon_{\rm tag}(\%)$	$\omega(\%)$	$\varepsilon_{\rm tag} D^2(\%)$
OSμ	5.20 ± 0.04	30.8 ± 0.4	0.77 ± 0.04
OSe	2.46 ± 0.03	30.9 ± 0.6	0.36 ± 0.03
OSK	17.67 ± 0.08	39.33 ± 0.24	0.81 ± 0.04
Q_{vtx}	18.46 ± 0.08	40.31 ± 0.24	0.70 ± 0.04
SSK	16.3 ± 0.4	35.3 ± 2.1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

$D = (1 - 2\omega)$

SSK: Compared to CDF higher track multiplicity in forward region

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

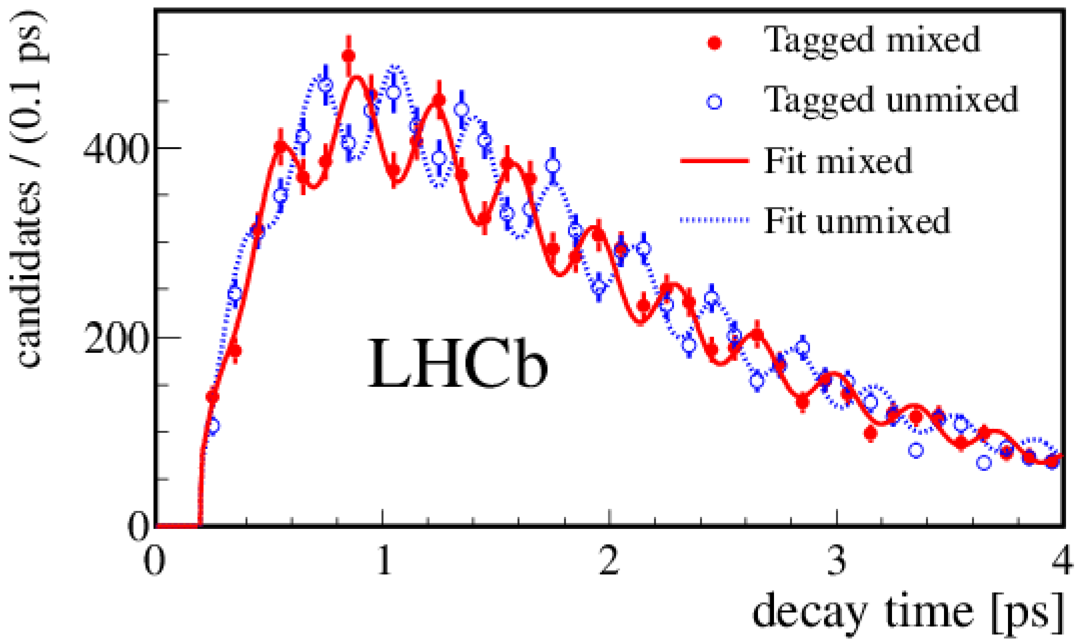
Detector effects on Oscillation



Finite time resolution: 44 fs

Realistic tagging

LHCb's B_s Mixing Measurement



34k signal evts
(5 decay channel)

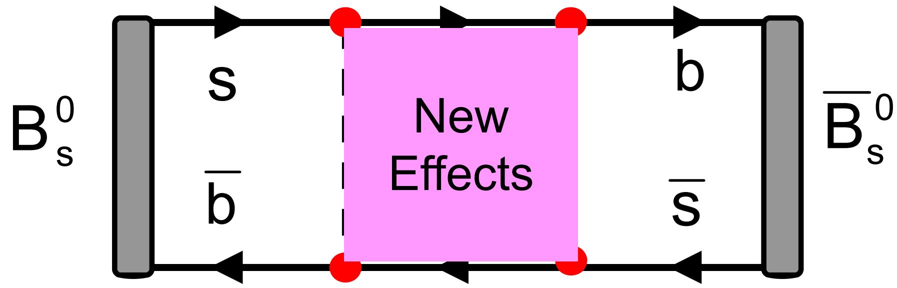
Δm_s = 17.768± 0.023 ± 0.006 ps^{-1}

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

Δm_s = 17.77 ± 0.10 ± 0.07 ps^{-1}

PRL 97 062003 (2006).

B_s mixing Phase ϕ_s



$$B_s^0 \xrightarrow{\quad \frac{q}{p} \quad} \bar{B}_s^0$$

Mixing phase:

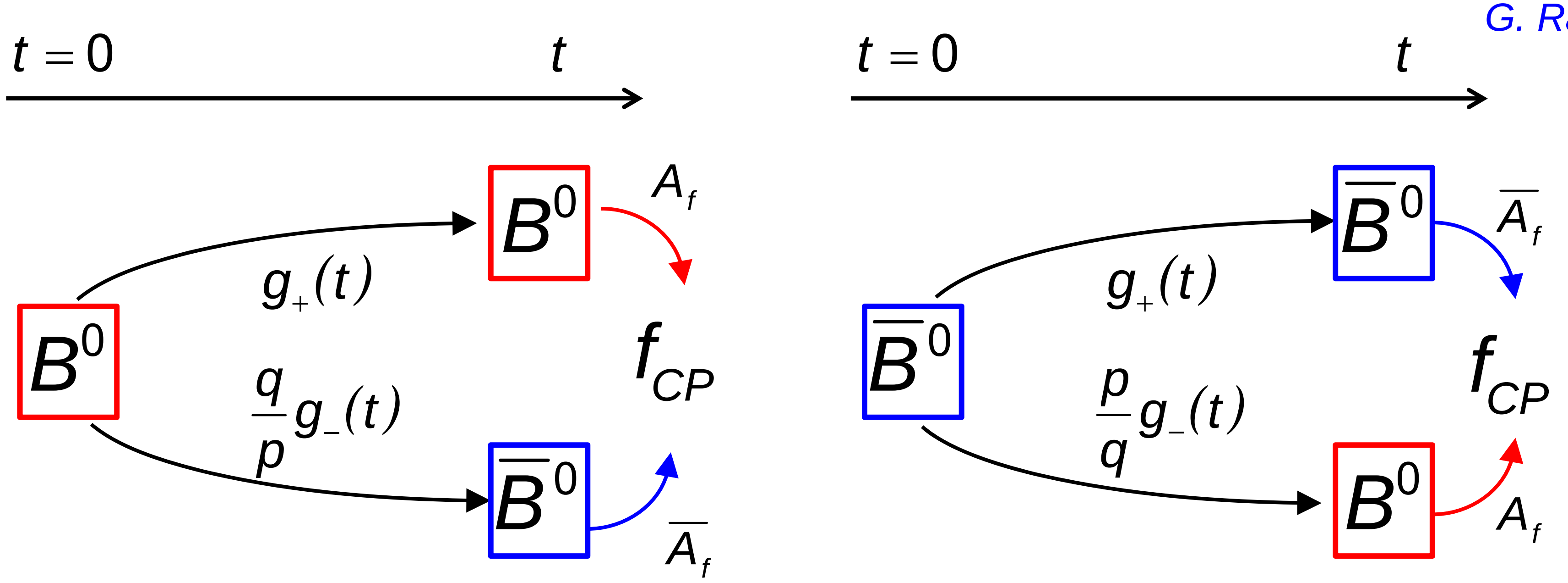
$$\phi_M = \arg\left(\frac{q}{p}\right) = \arg(M_{12})$$

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

Need an interference experiment to measure phases.

Interference between Mixing and Decay

G. Raven



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

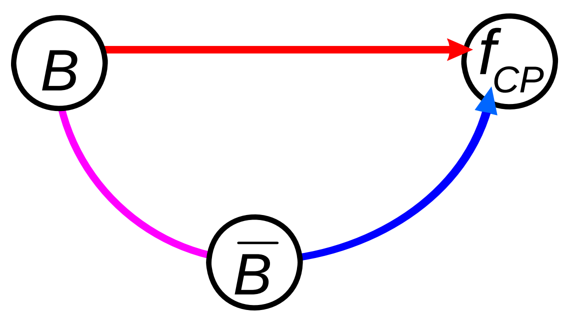
Time-dependent CP-Asymmetry

G. Raven

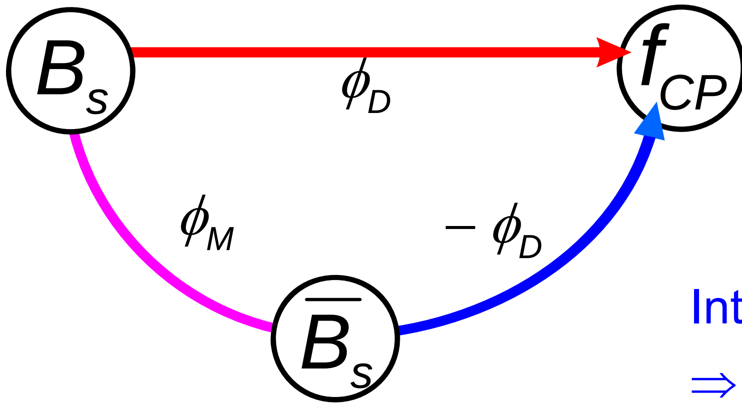
$t=0$	t	Rate
B^0 $\longrightarrow$	f_{CP}	$\propto e^{-\Gamma t}\,[1+\sin(\phi_{\text{weak}})\sin(\Delta m t)]$
$\overline{B^0}$ $\longrightarrow$	f_{CP}	$\propto e^{-\Gamma t}\,[1-\sin(\phi_{\text{weak}})\sin(\Delta m t)]$

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

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

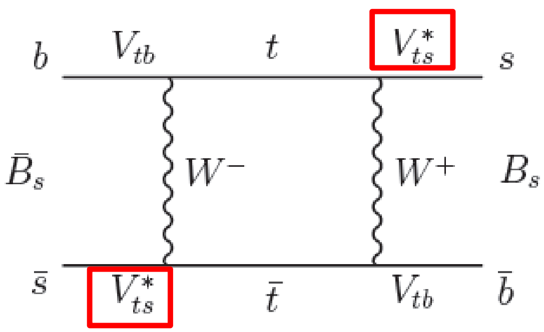


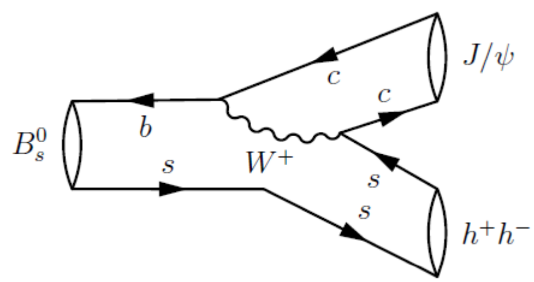
$B_s \to J/\psi\ \phi(KK)$

Interference of mixing & decay:

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

Standard Model:





+ small penguin pollution

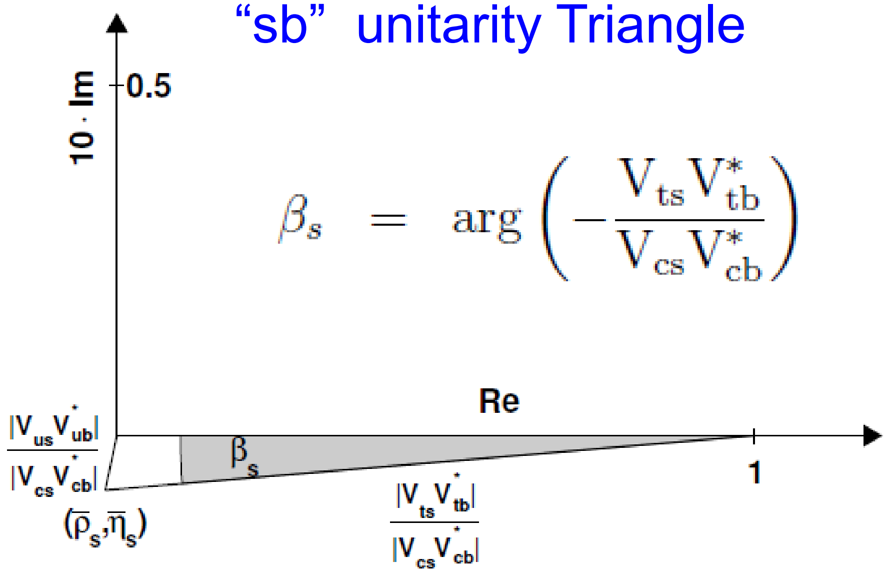
$$\phi_M \approx -2\arg(V_{ts}) \approx -2\beta_s$$

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

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

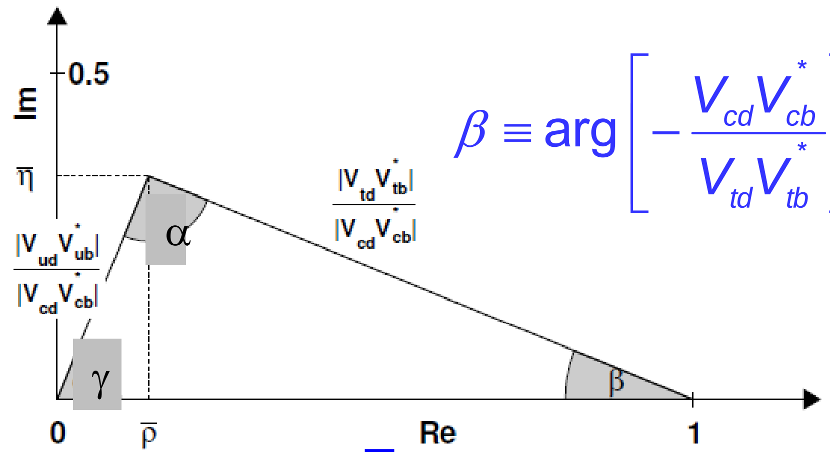
Phase β_s in Standard Model

"sb" unitarity Triangle

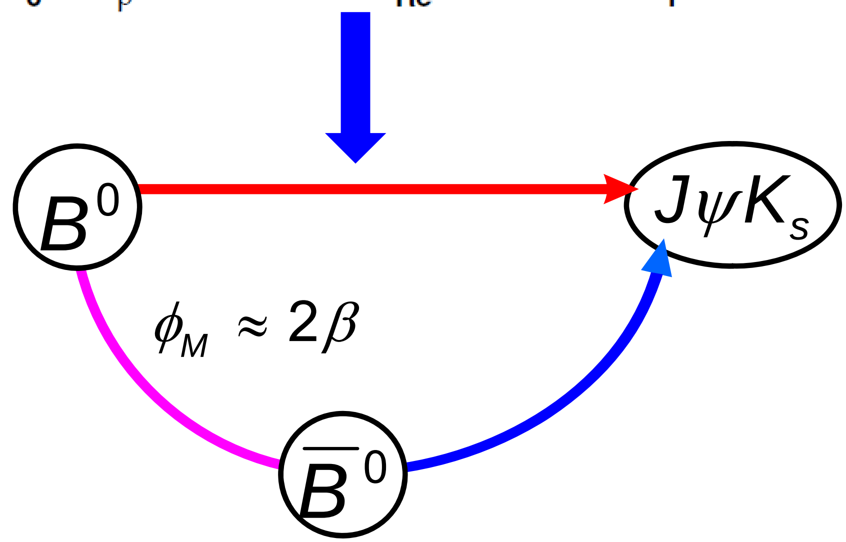


$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

"db" unitarity Triangle



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



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

<u>Standard Model:</u>

$$\phi_s \approx \phi_M \approx -2\beta_s$$

(CKMFitter)

$$\phi_s^{SM} = -0.0364 \pm 0.0016 \text{ rad}$$

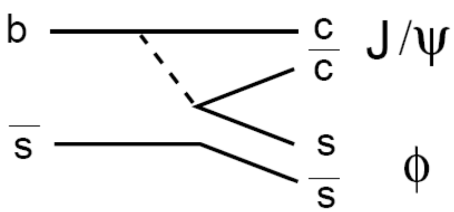
Possible New Physics contribution:

$$\phi_s = \phi_s^{SM} + \Delta\phi_s^{NP}$$

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

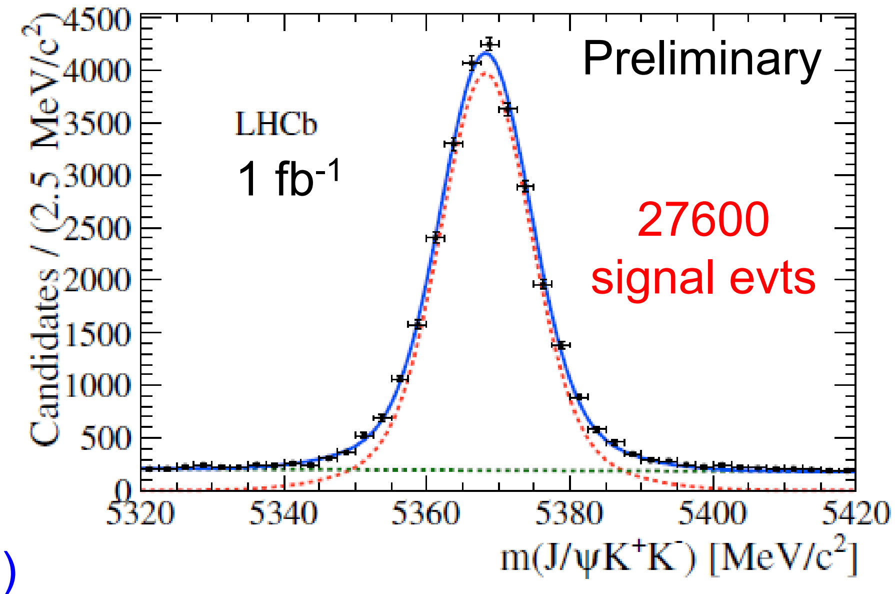
LHCb-Paper-2013-002
to be submitted to PRD

- experimentally clean
- VV final state:



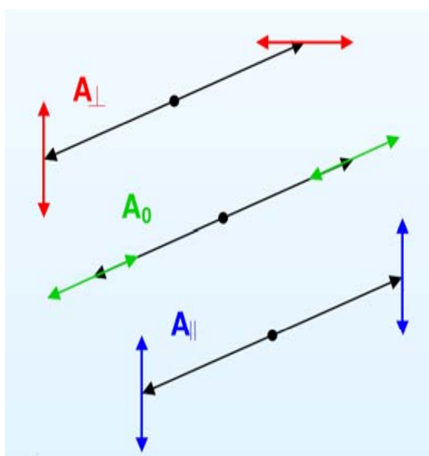
$J^{PC} = 1^{--}$

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



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

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



3 different polarization amplitudes with different relative orbital momentum:

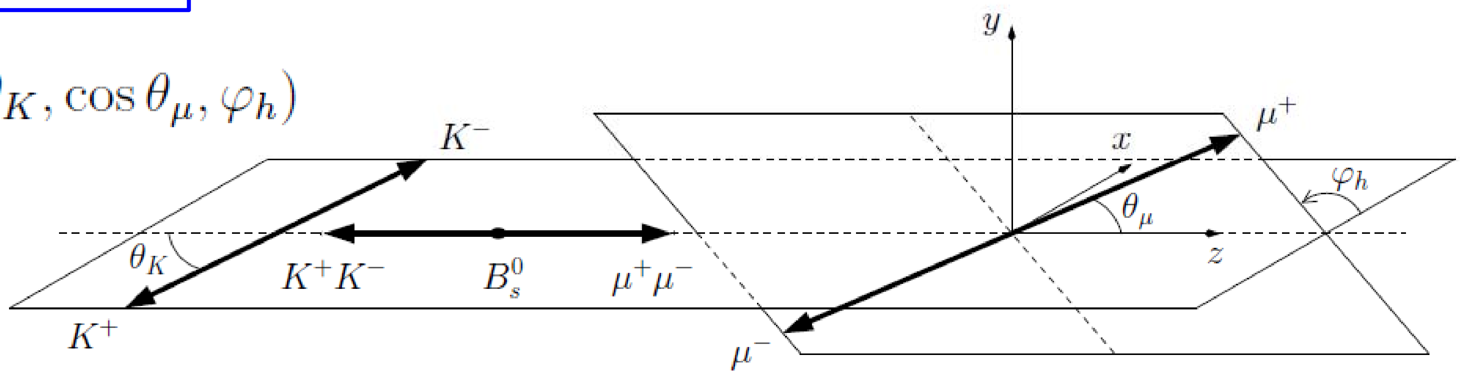
CP-odd ($\ell = 1$): $A_\perp$
CP-even ($\ell = 0, 2$): $A_0,\ A_{||}$

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

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

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

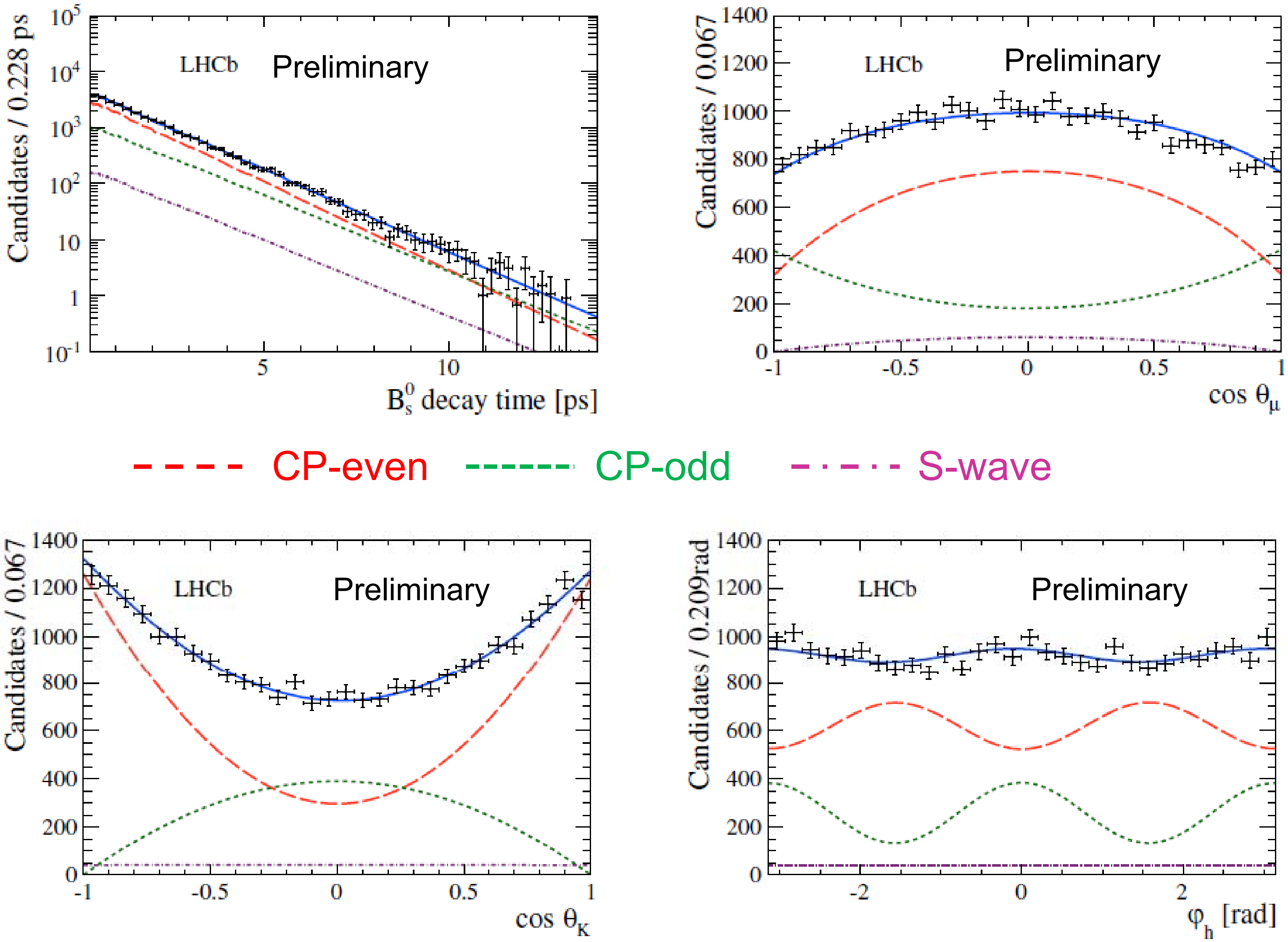
$a_{k,}$ b_k $c_{k,}$ $d_{k,}$ contain ϕ_s and complex polarization amplitudes.

$\overline{B}_s$

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

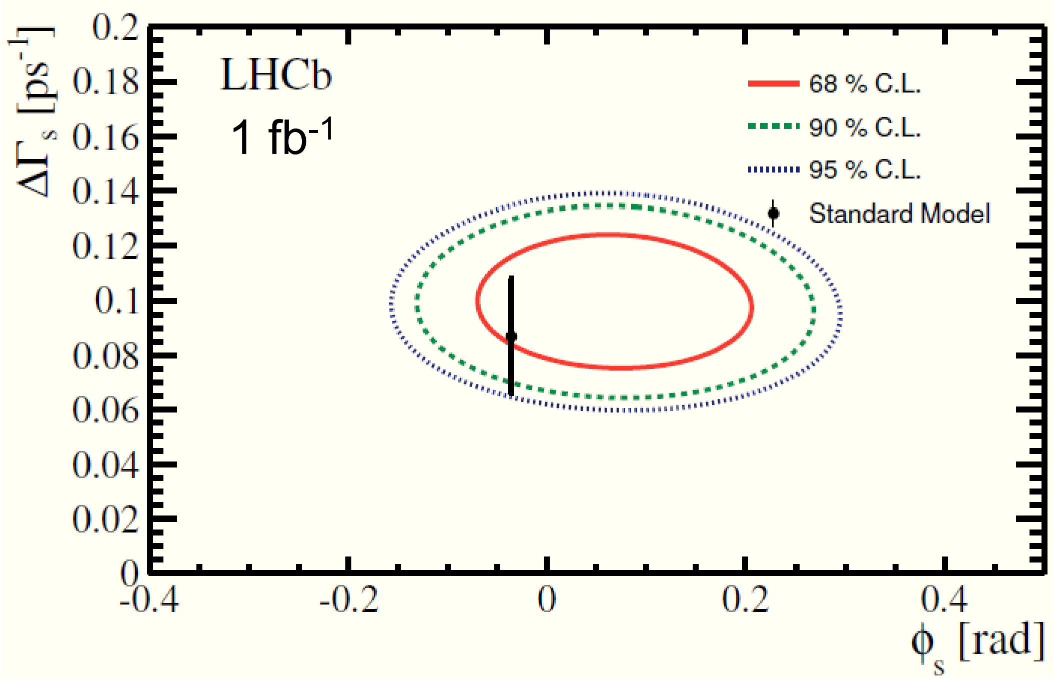
Fitting procedure

LHCb-Paper-2013-002



Mixing Phase ϕ_s

LHCb-Paper-2013-002



(stat. error only)

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

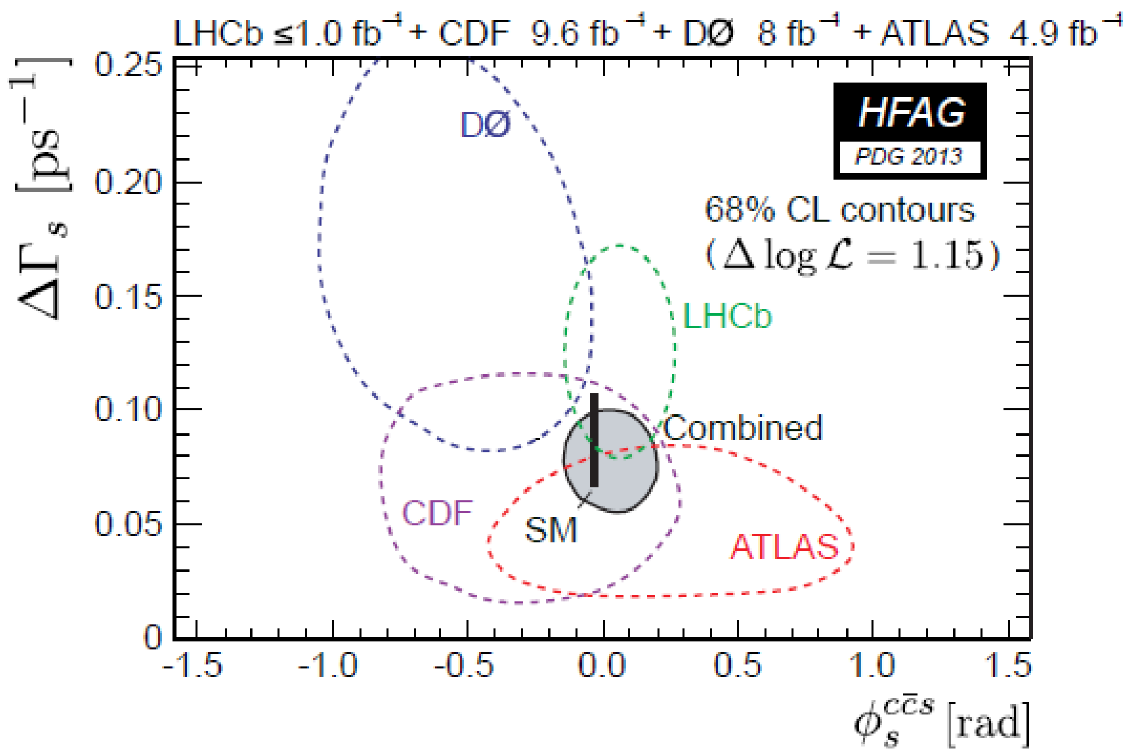
$|\lambda| = 0.94 \pm 0.03 \pm 0.02$ (compatible w/ no CPV in decay)

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) $\Rightarrow$

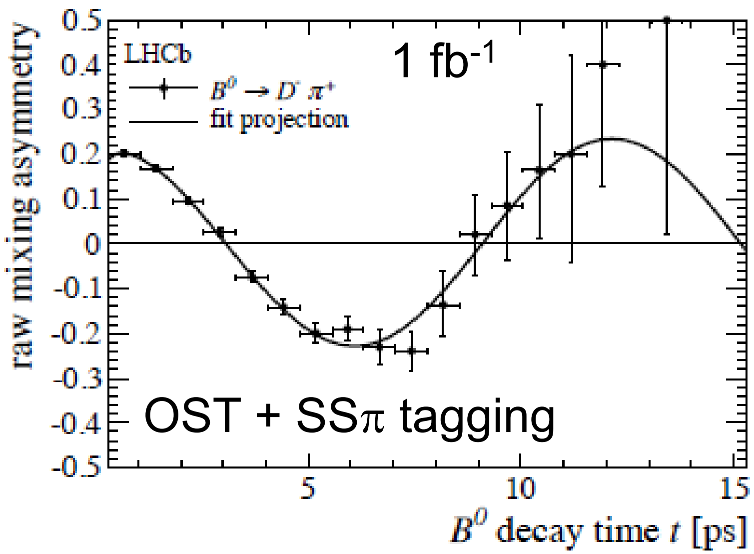
$$\phi_s = 0.01 \pm 0.07 \pm 0.01 \text{ rad}$$
$$\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007 \text{ ps}^{-1}$$
$$\Gamma_s = 0.661 \pm 0.004 \pm 0.006 \text{ ps}^{-1}$$



CDF and D0 have pioneered the measurement of ϕ_s

B^0 mixing and t-dependent CPV

LHCb-PAPER-2012-032

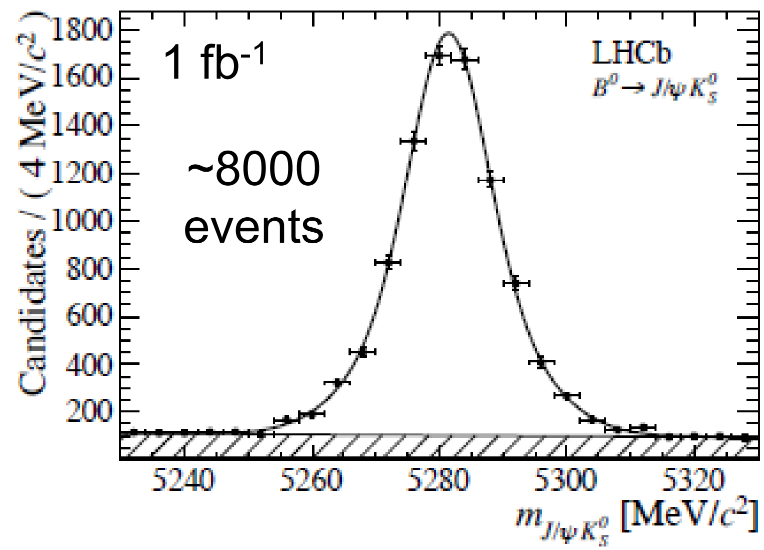


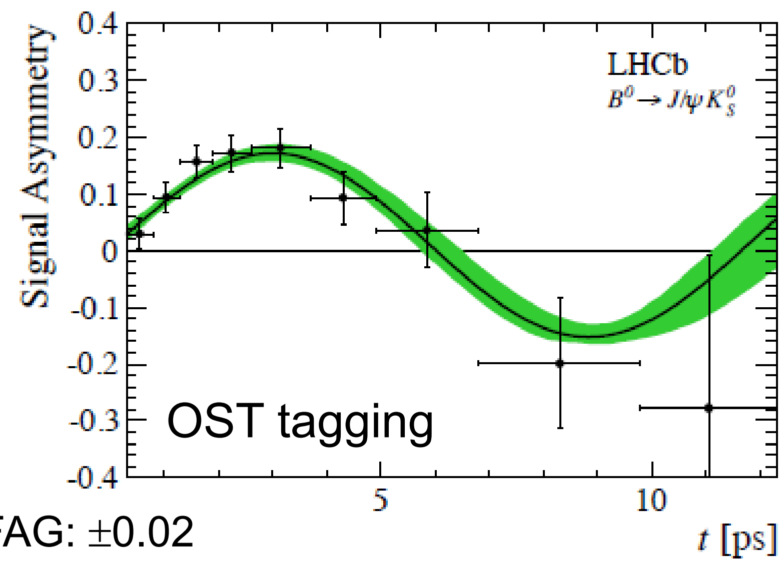
Combination of $B^0 \to D\pi$ & $B^0 \to J/\psi K^*$

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

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

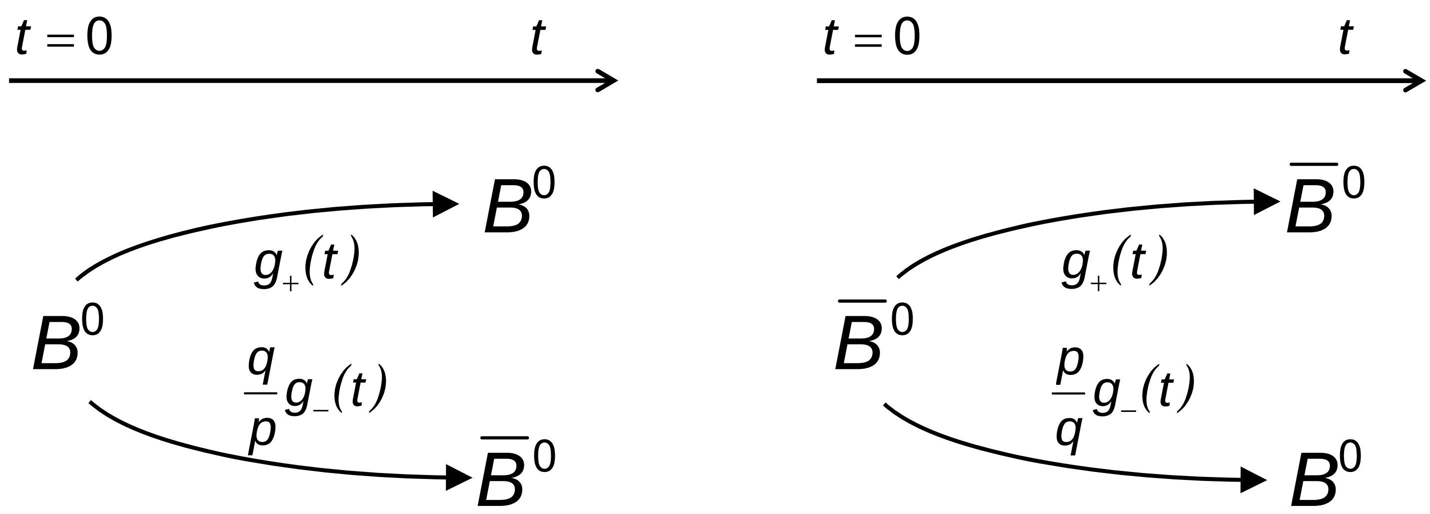
$$S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\mathrm{stat}) \pm 0.04\,(\mathrm{syst}),$$

$$C_{J/\psi K^0_S} = 0.030 \pm {}^{0.089}_{0.091}\,(\mathrm{stat}) \pm 0.012\,(\mathrm{syst}).$$

HFAG: ±0.02

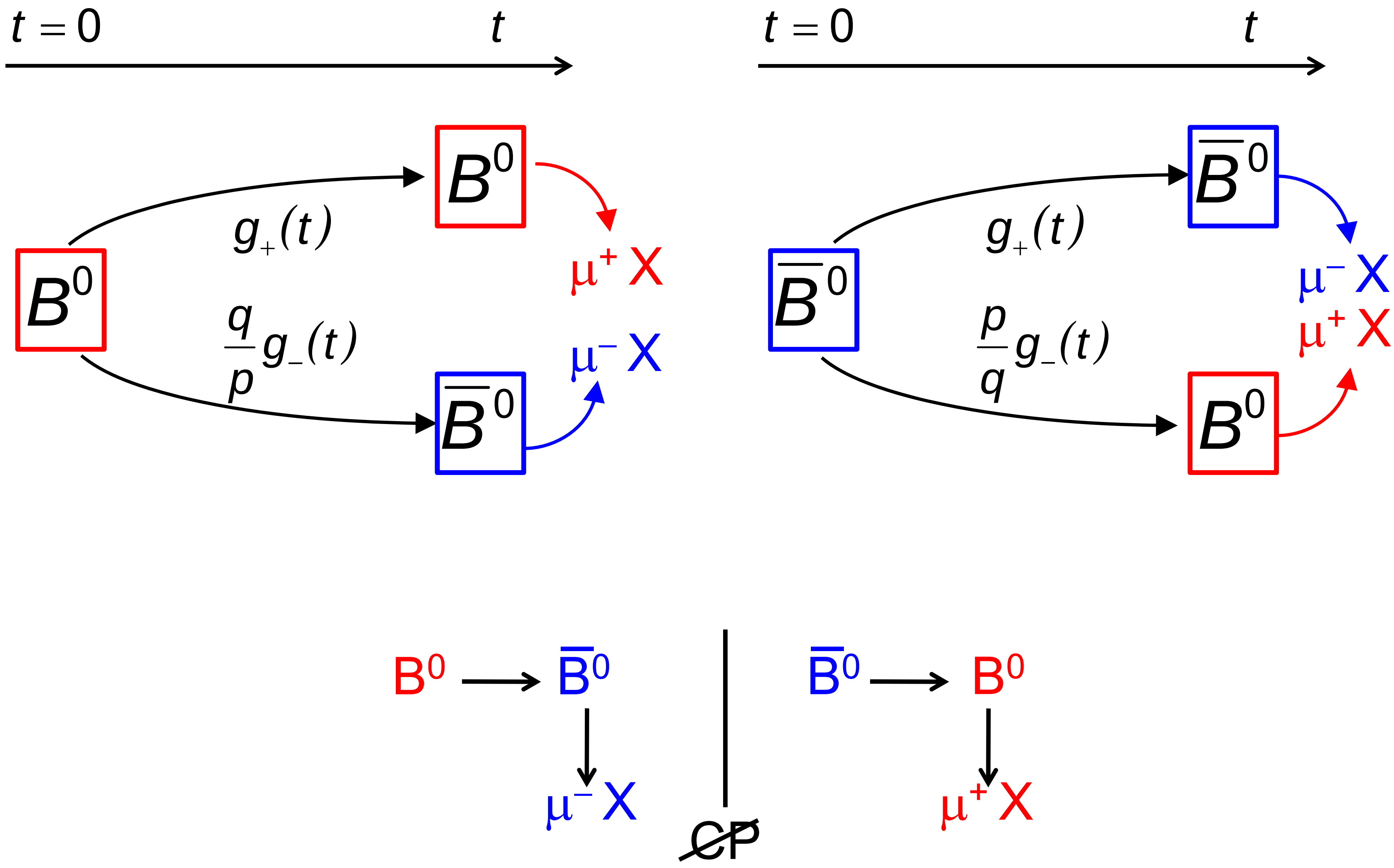
CP Violation in B mixing

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

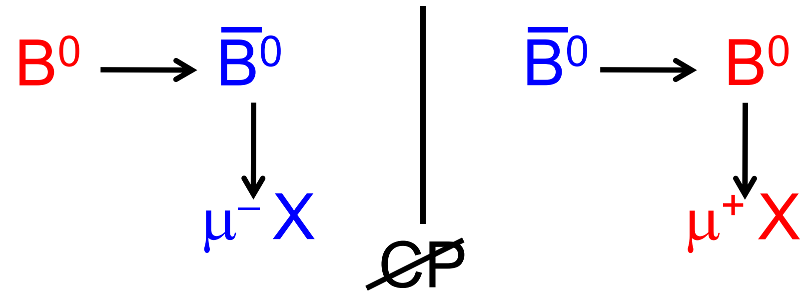


CP violation if $\left|\frac{q}{p}\right| \neq 1$

Semi-leptonic CP asymmetry



Time Integrated asymmetry



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

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

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

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

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

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

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

Semi-leptonic asymmetry for B_d

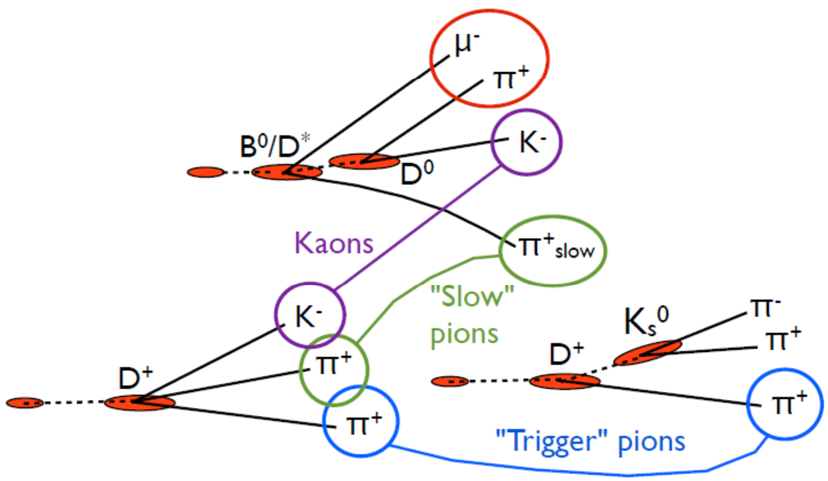
Reconstructing of the D / D* meson for

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

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

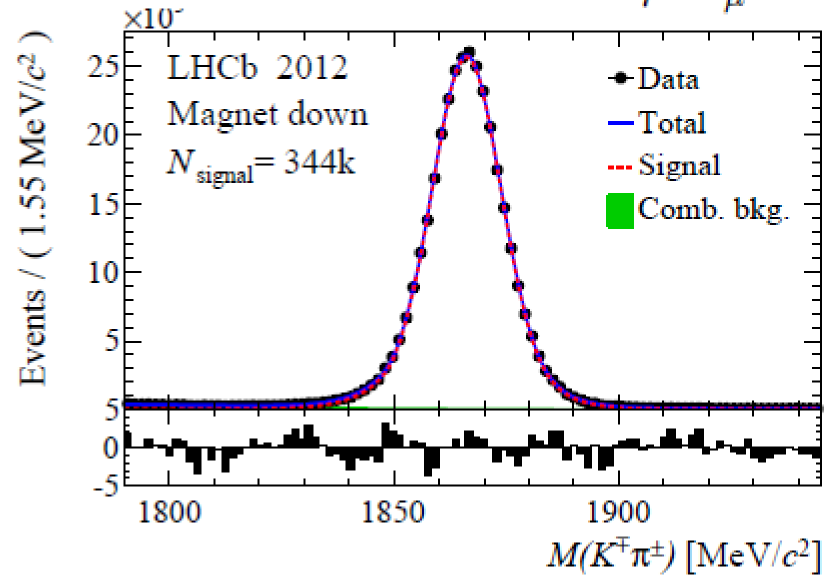
$\rightarrow$semi-leptonic events from $\mathbf{B^0}$ decays.

K detection asymmetry:

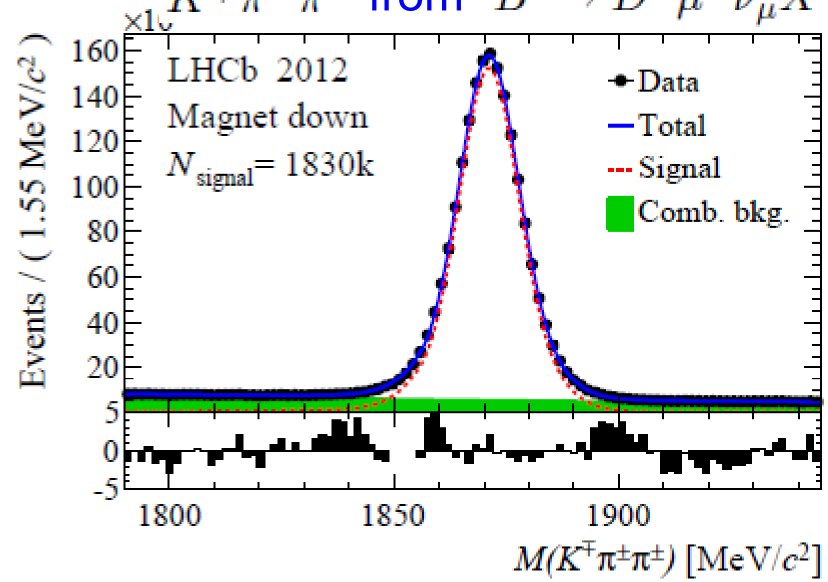


Analysis is on-going

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

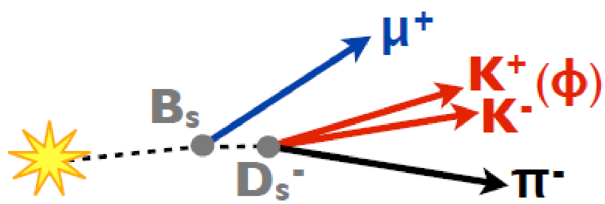


$K^{\mp}\pi^{\pm}\pi^{\pm}$ from $B^0 \to D^-\mu^+\nu_\mu X$



Semi-leptonic asymmetry for B_s

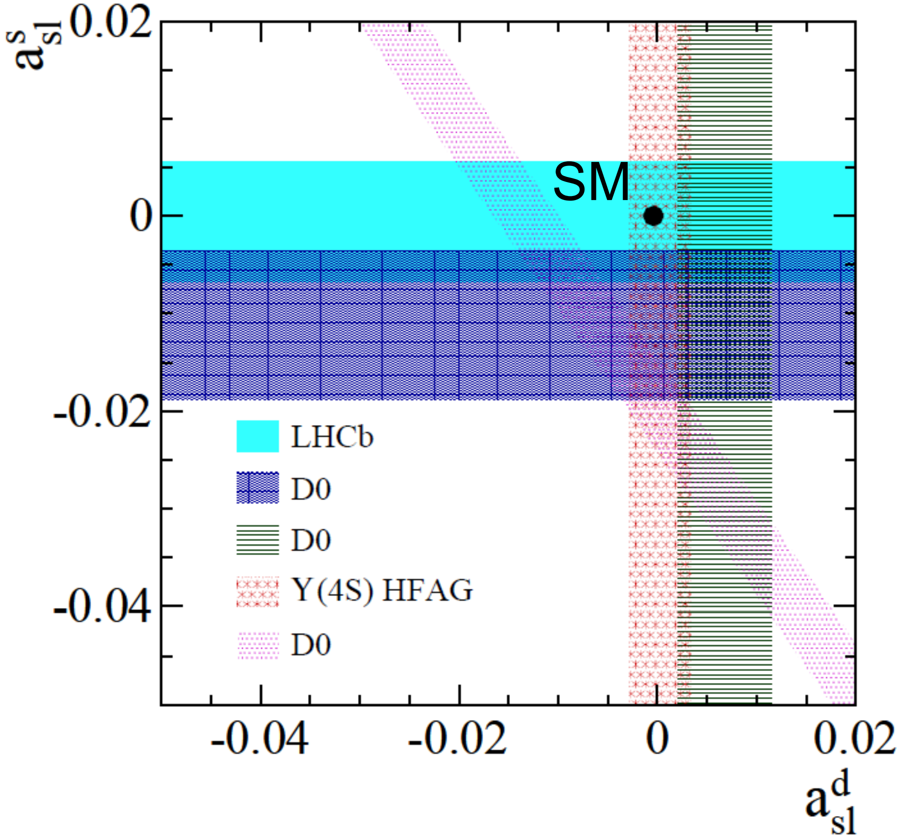
- Due to the fast oscillation, the production asymmetry for B_s mesons is washed out and no time dependent measurement is necessary.
- Use $B_s \to D_s \mu\nu$ decays:



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

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

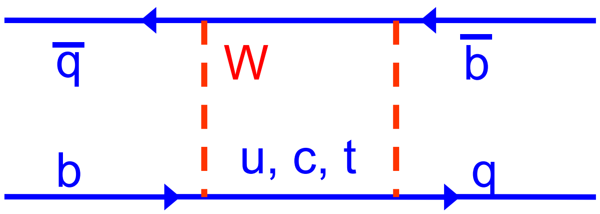
$$A_\mu^c = (+0.04 \pm 0.25)\%$$



$$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%.$$

arXiv:1308.1048

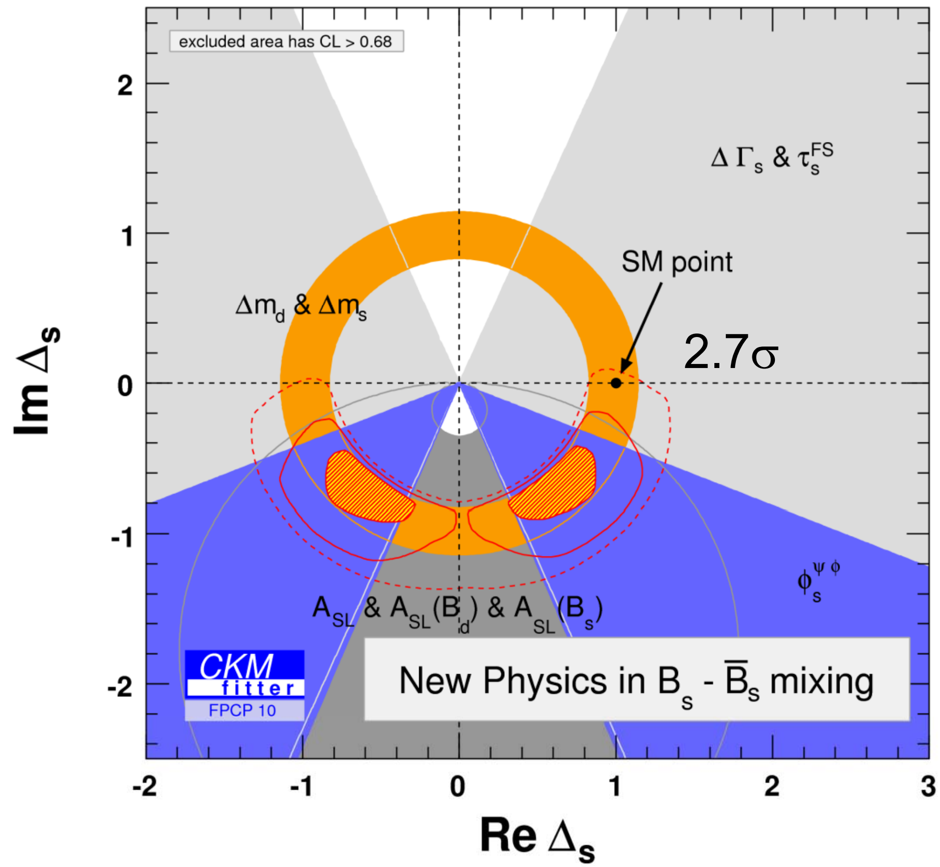
New Physics in B_s Mixing



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

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

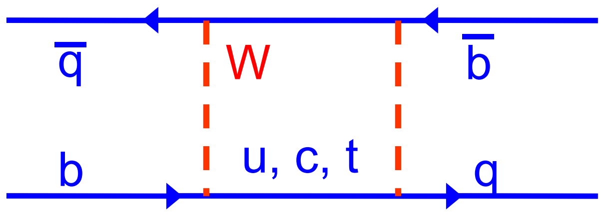
Status FPCP 2010



A. Lenz , U. Nierste & CKM Fitter

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

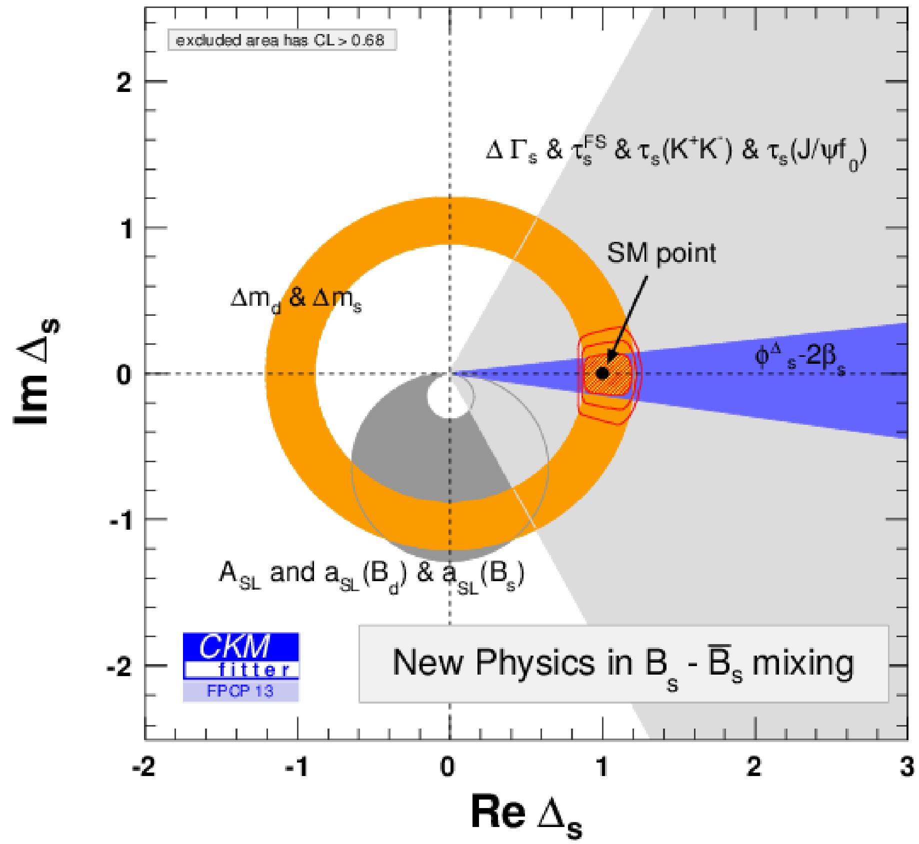
New Physics in B_s Mixing



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

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

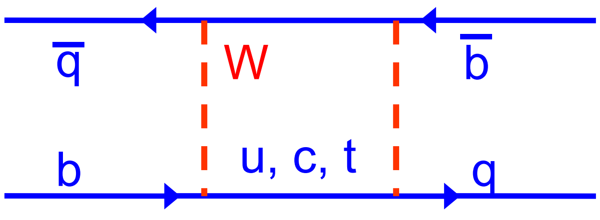
Status FPCP 2013



A. Lenz , U. Nierste & CKM Fitter

Agreement with Standard Model, but still room for New Physics (10-20%)

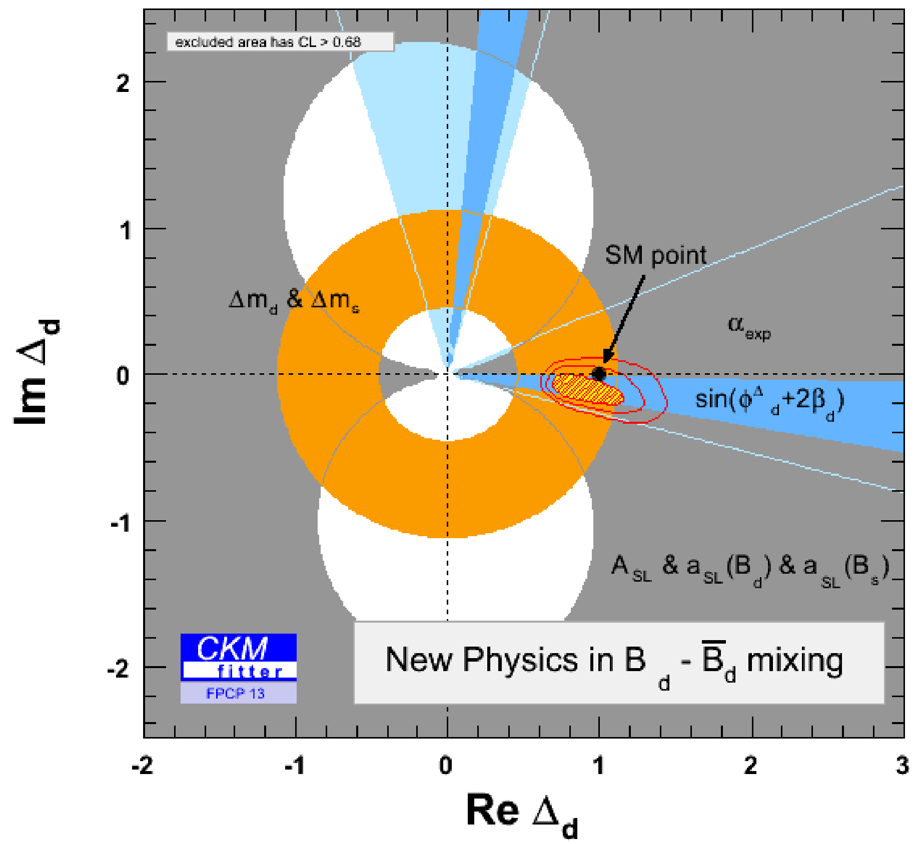
New Physics in B_d Mixing



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

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

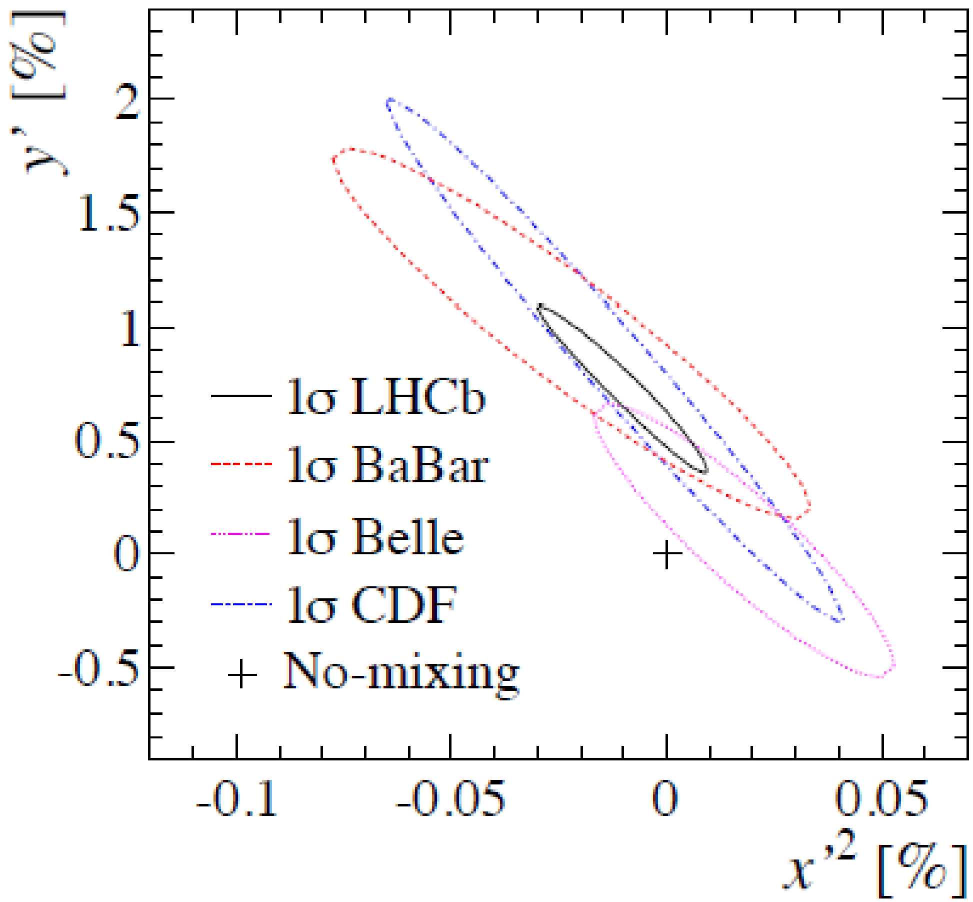
Status FPCP 2013



A. Lenz , U. Nierste & CKM Fitter

Some tension with Standard Model at 10-20% level.

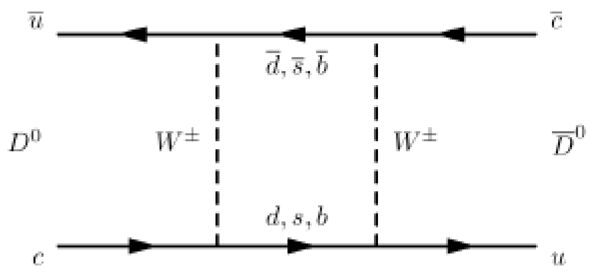
Charm mixing and CP Violation



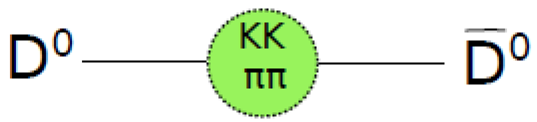
Charm Mixing

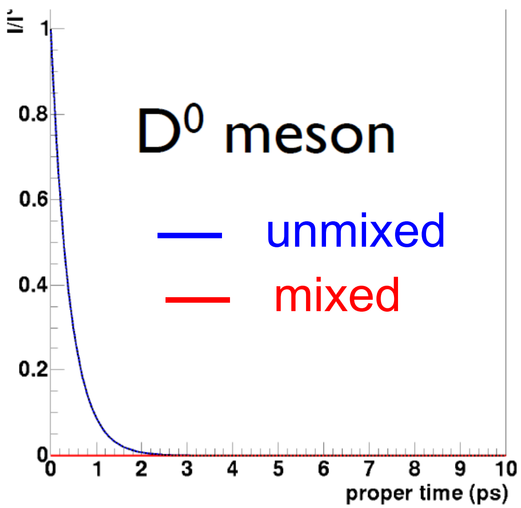
D^0-D^0 mixing is expected to be small

- Quark loops are second order and GIM suppressed.

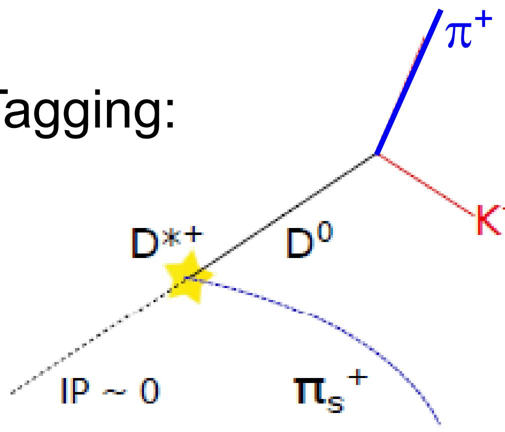


- Long distance effects are tricky to calculate. arxiv:0311371



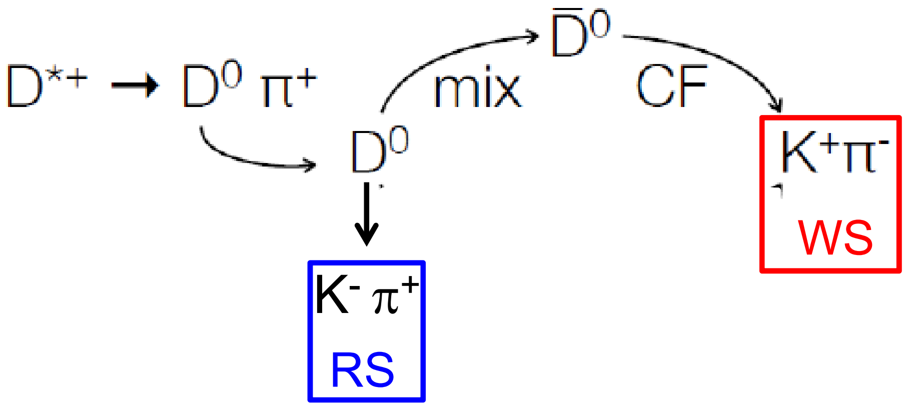


Tagging:



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

LHCb-Paper-2012-038
arXiv:1211.1230



DCS CF

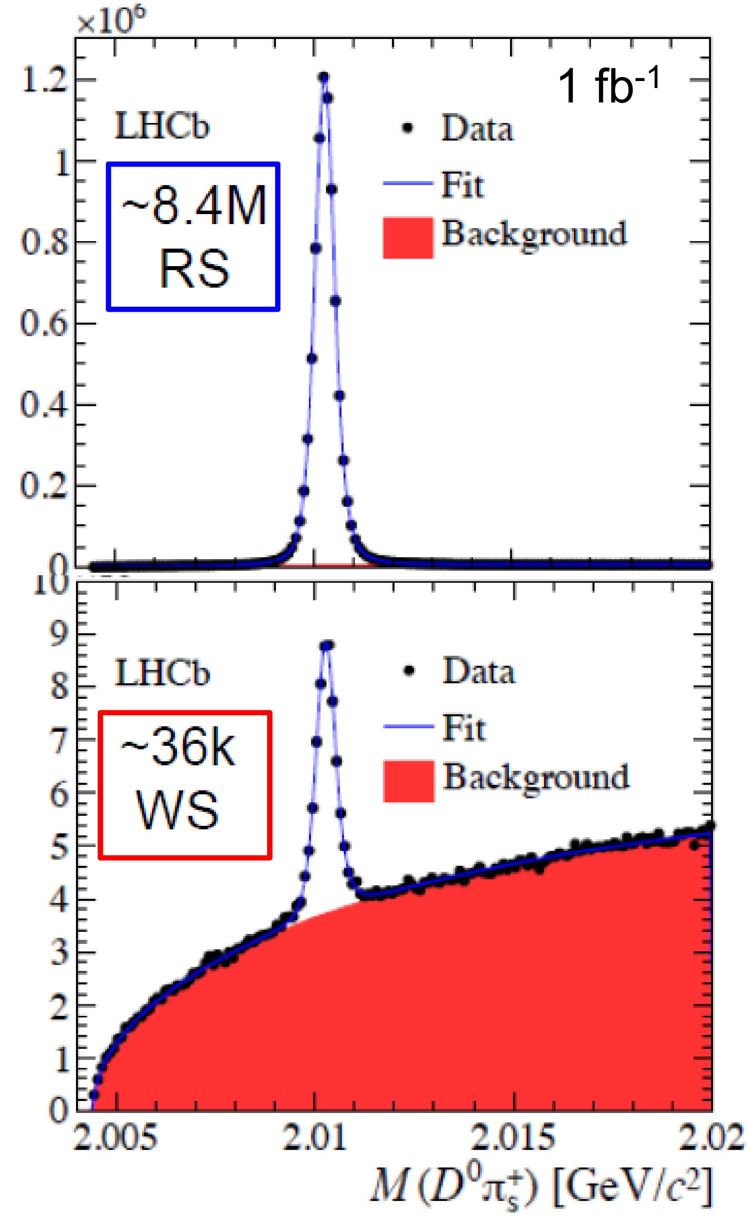
$$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\bar{D}^0 \to K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}$$

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

(no CPV)

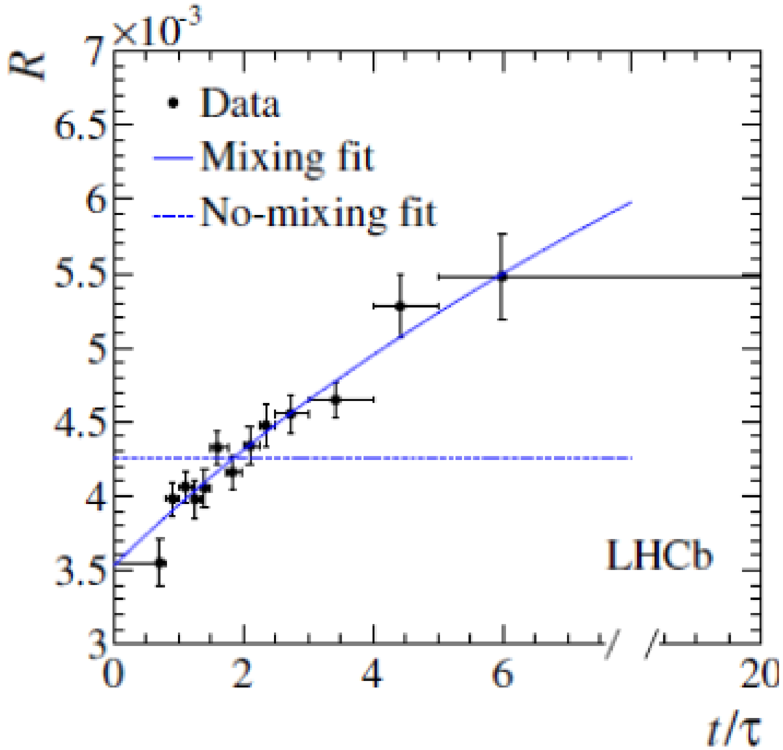
$$x' = x\cos\delta + y\sin\delta \qquad y' = -x\sin\delta + y\cos\delta$$

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



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

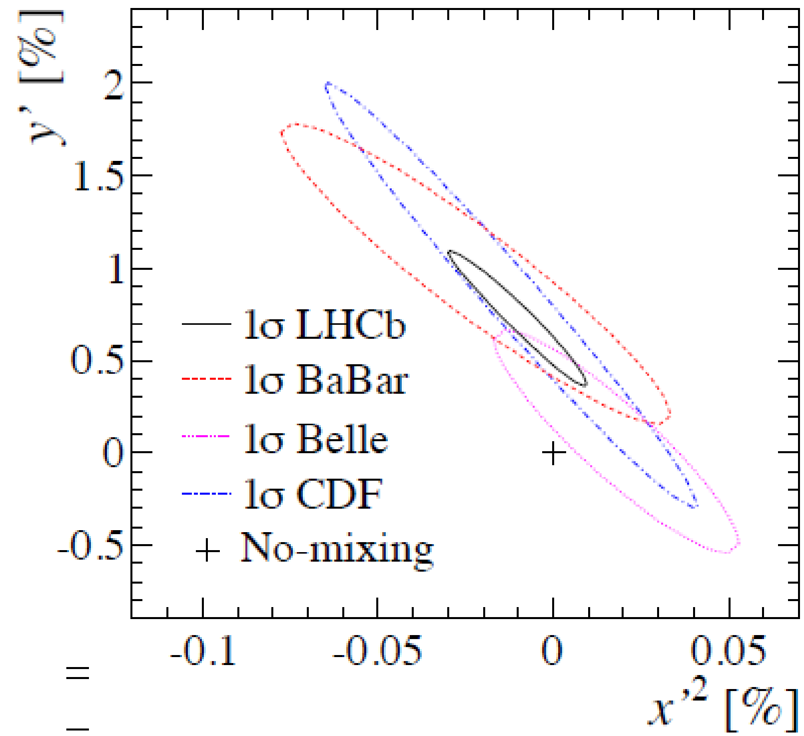
LHCb-Paper-2012-038
arXiv:1211.1230



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

Interpretation requires the knowledge of strong phase δ.
LHCb started to look at $D^0 \rightarrow K_s \pi\pi$.

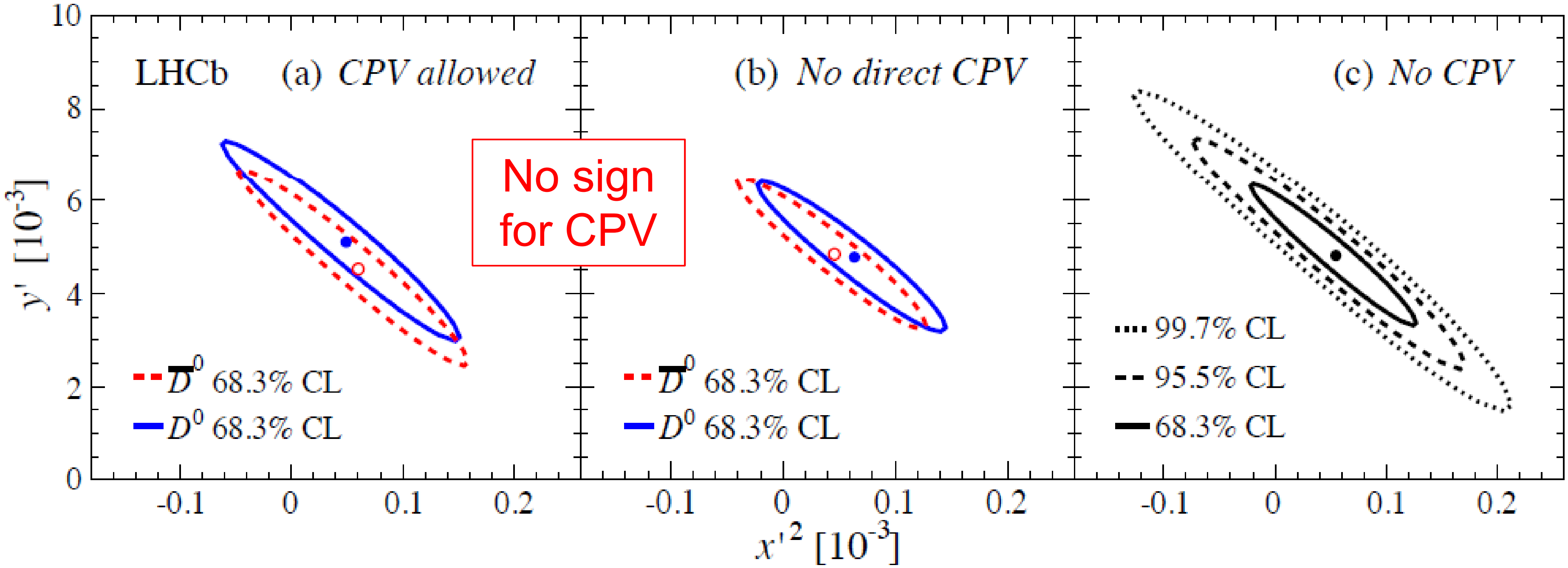
No mixing excluded w/ 9.1σ



Fit type	Parameter	Fit result (10^{-3})
Mixing	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing	R_D	4.25 ± 0.04

Analysis of 3 fb^{-1}

LHCB-PAPER-2013-053



Test for CP violation:

- $R^+_D \neq R^-_D$ (direct CP violation) → $A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-1.3 \pm 1.9)\%$
- CPV in mixing ($|q/p| \neq 1$) or interference mixing & decay → $0.75 < \left|\frac{q}{p}\right| < 1.24$ at 68.3%

Standard Model: no significant CPV.

CP Violation in Charm

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

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

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

CP eigenstate f :
$\pi^+ \pi^-$, $K^+ K^-$

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

Aymmetries of

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

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

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?

Prompt D *(preliminary: LHCb-Conf-2012-003)*

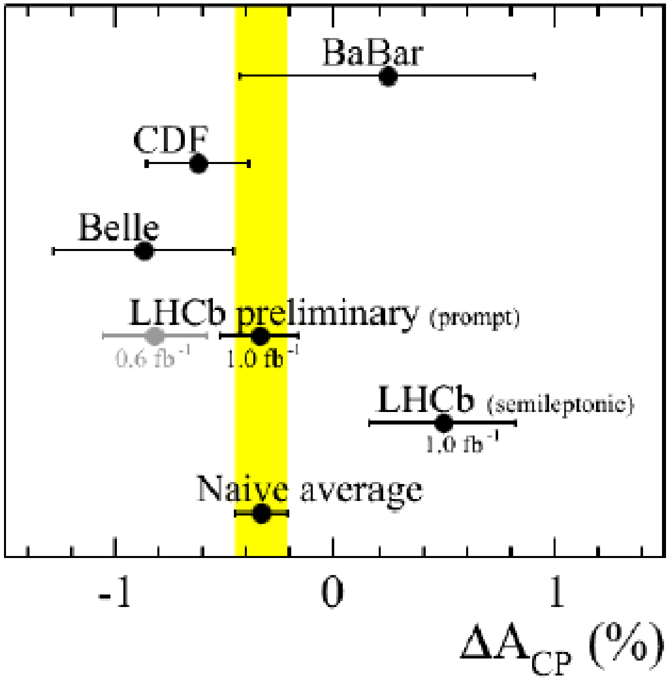
ΔA_{CP} = [- 0.34 $\pm$ 0.15$_{stat}$ $\pm$ 0.10$_{syst}$] %

2.2σ

Semileptonic B decays

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

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



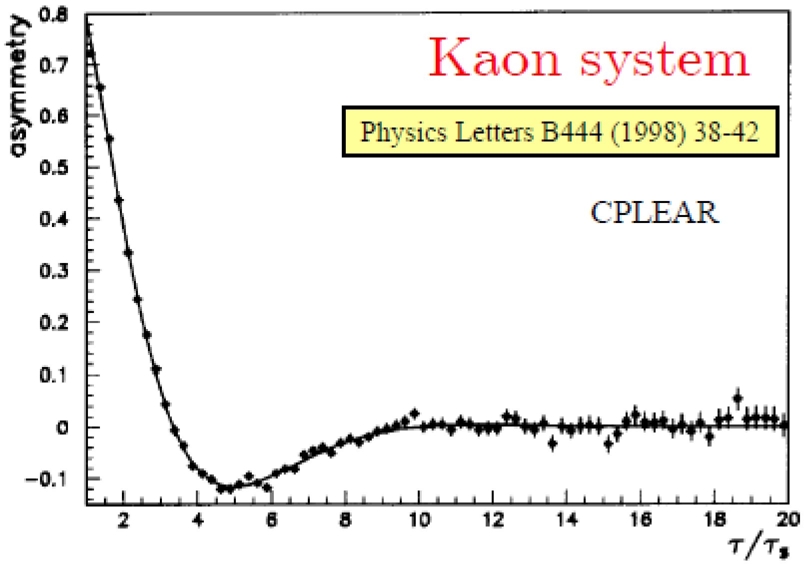
simple average

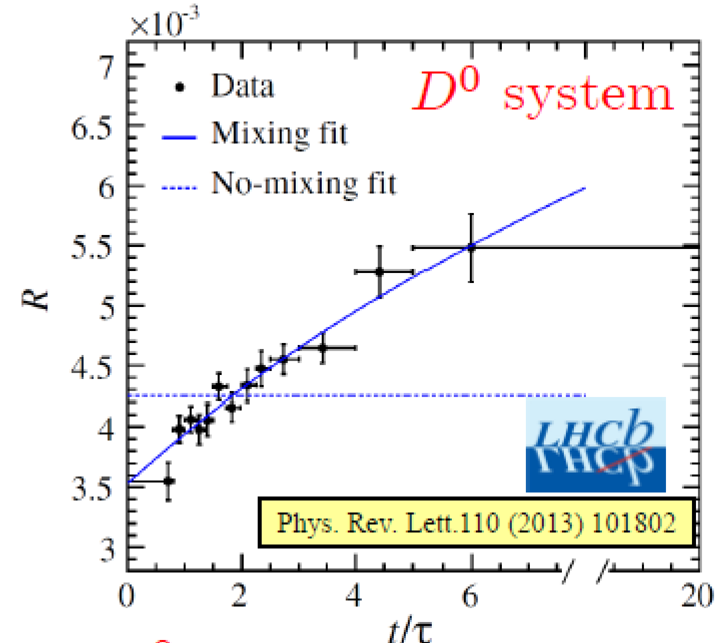
ΔA_{CP} = [- 0.15 $\pm$ 0.16] % (χ^2=4.85 $\Leftrightarrow$ P=3%)

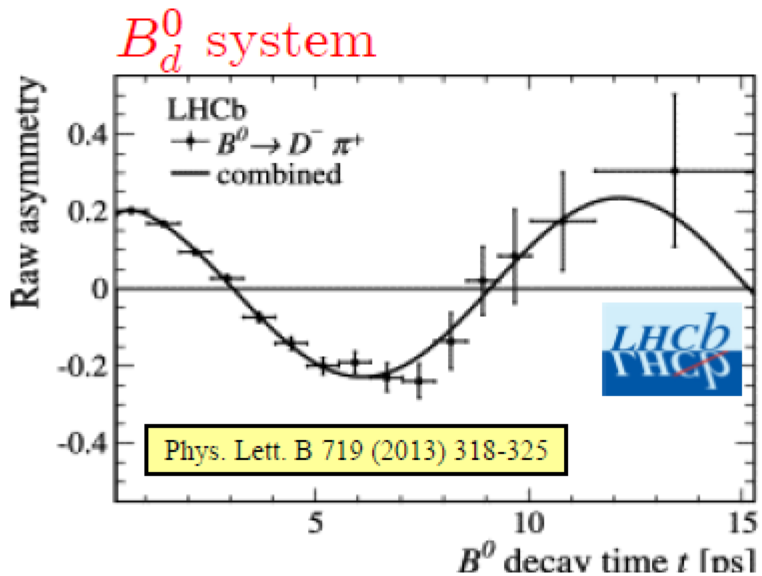
New results do not cannot confirm evidence for CPV in charm decays.

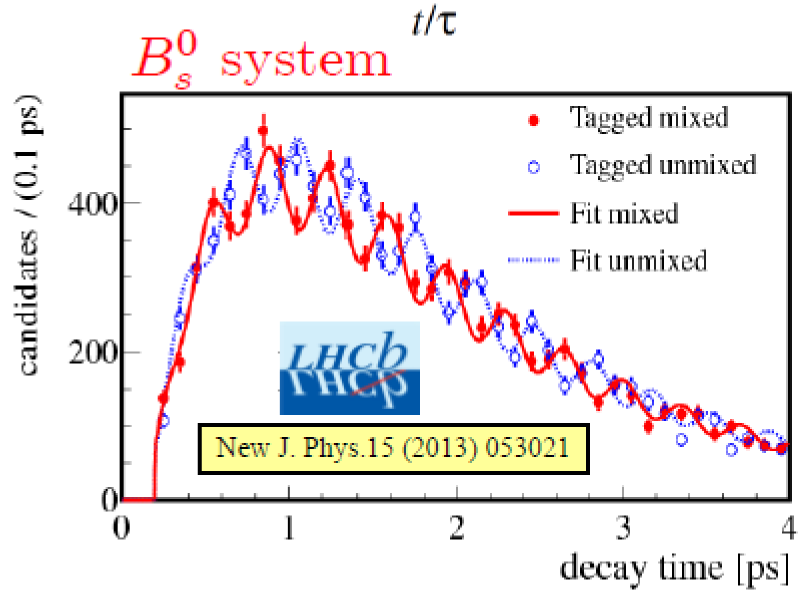
Mixing of Neutral Mesons

Slide S.Bachmann

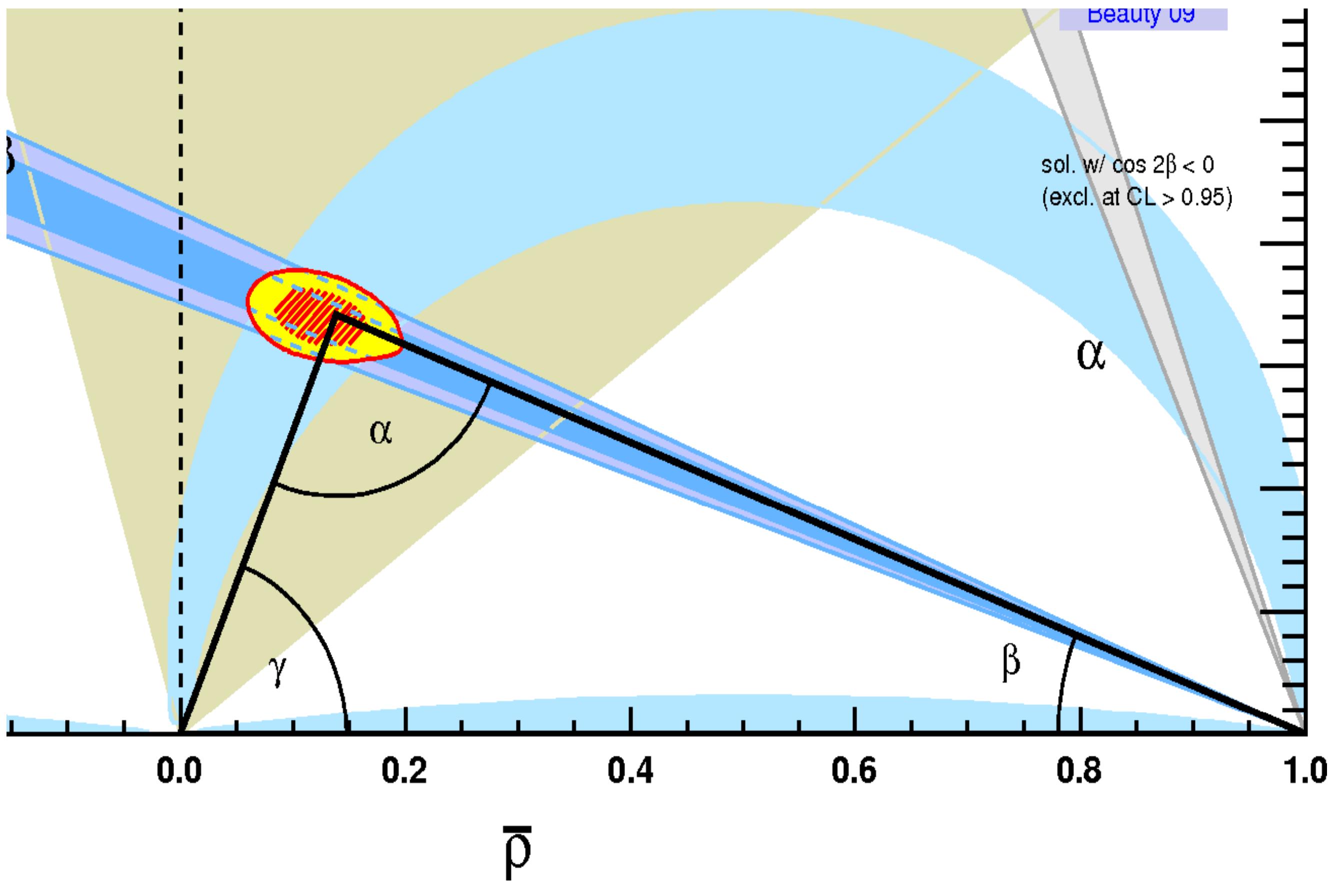








Direct CP Violation & CKM angle γ

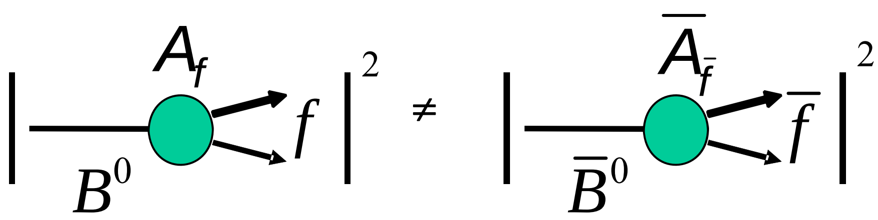


Direct CP Violation & CKM angle γ

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

Indirect CPV

- CP violation in decay



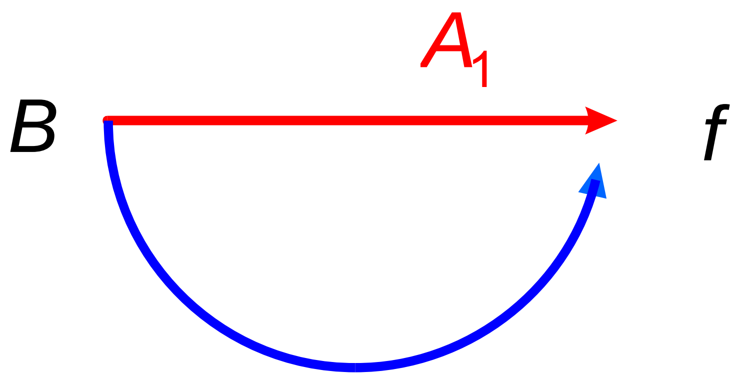
$$P(\overline{B} \to \bar{f}) \neq P(B \to f)$$

(time integrated)

direct CPV

Direct CP Violation

$B \to f$

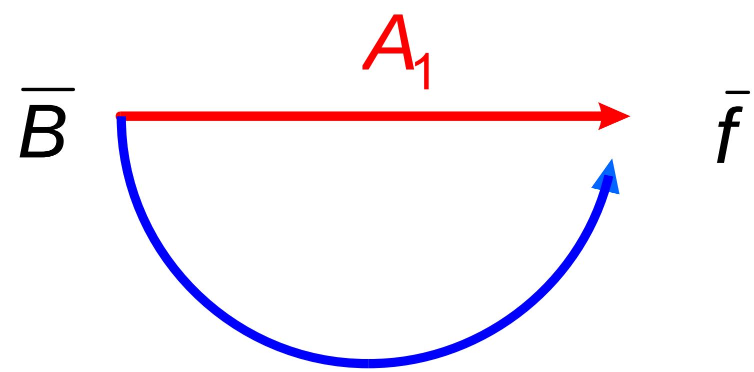


$A_2\, e^{i\phi_{CP}} e^{i\delta}$

Weak and strong CP invariant phase difference

CP

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



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

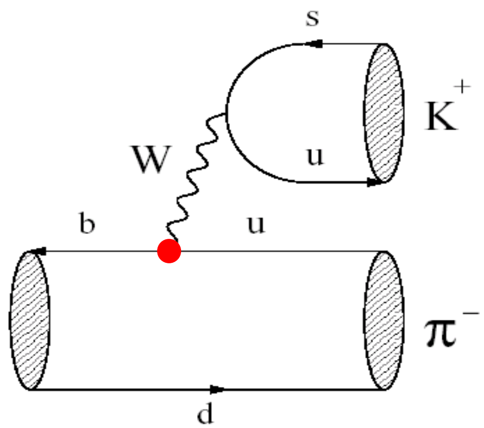
$$|A|^2 = |A_1 + A_2|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} + \delta)$$

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

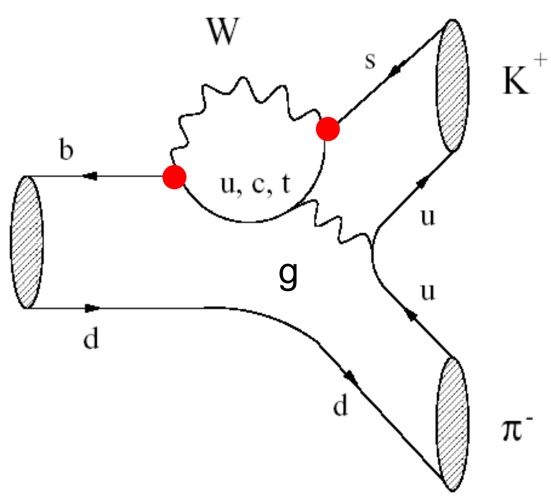
$$|\overline{A}|^2 - |A|^2 = 4A_1A_2\sin(\phi_{CP})\sin(\delta)$$

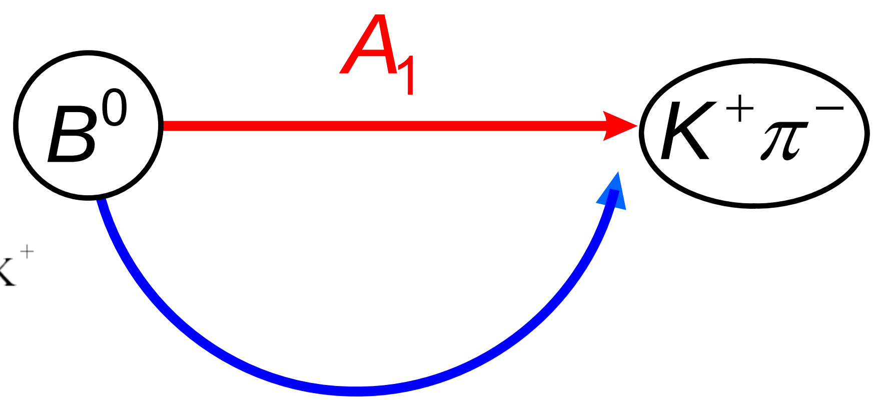
Direct CP Violation in B→Kπ

Tree **B^0**



Penguin **B^0**





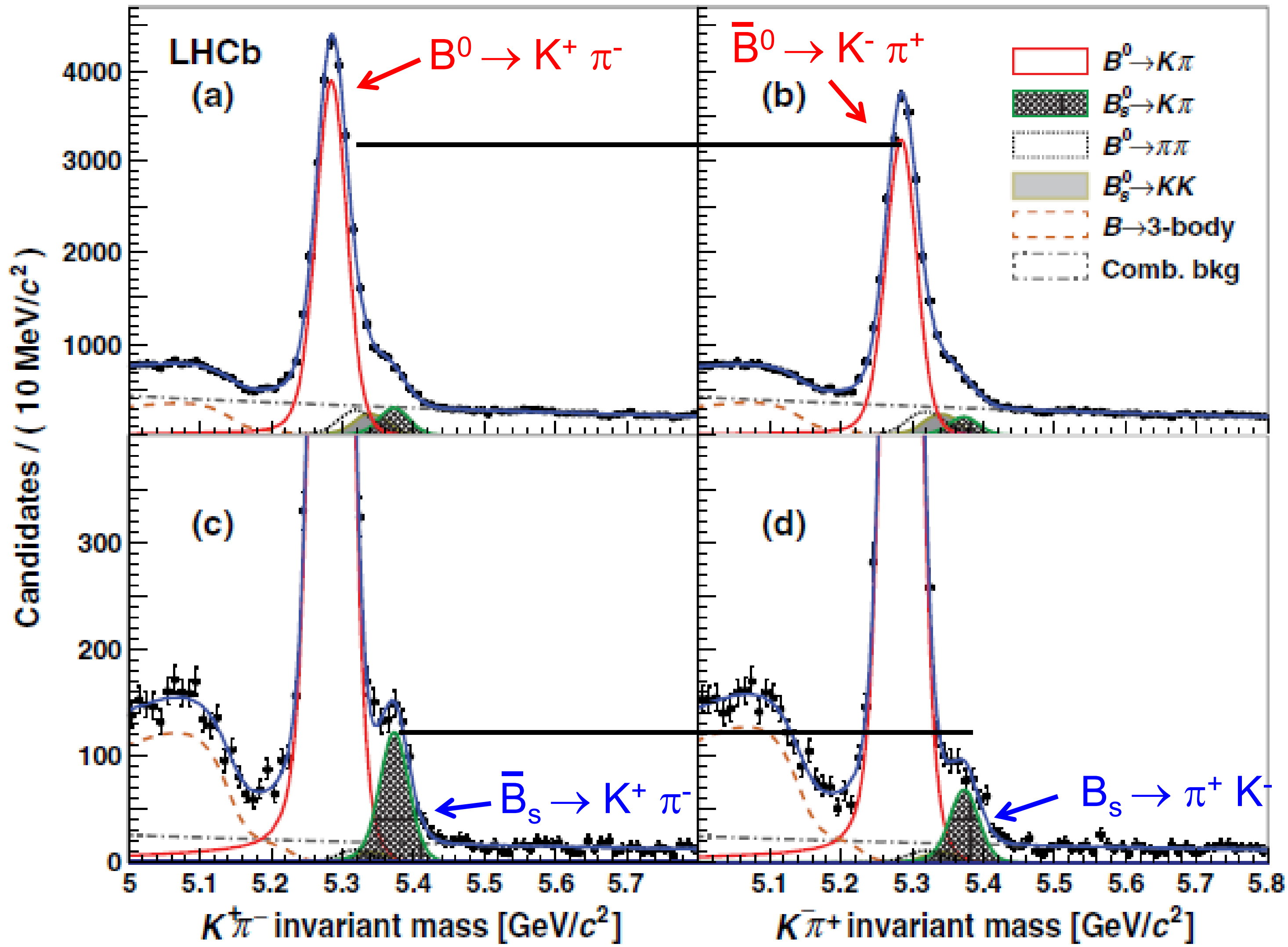
$A_2\, e^{i\phi_{CP}} e^{i\delta}$

Strong phase difference difficult to predict

CP Asymmetrie $\quad |\bar{A}|^2 - |A|^2 = 4|A_1||A_2|\sin\varphi \boxed{\sin\delta}$

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

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

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

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

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

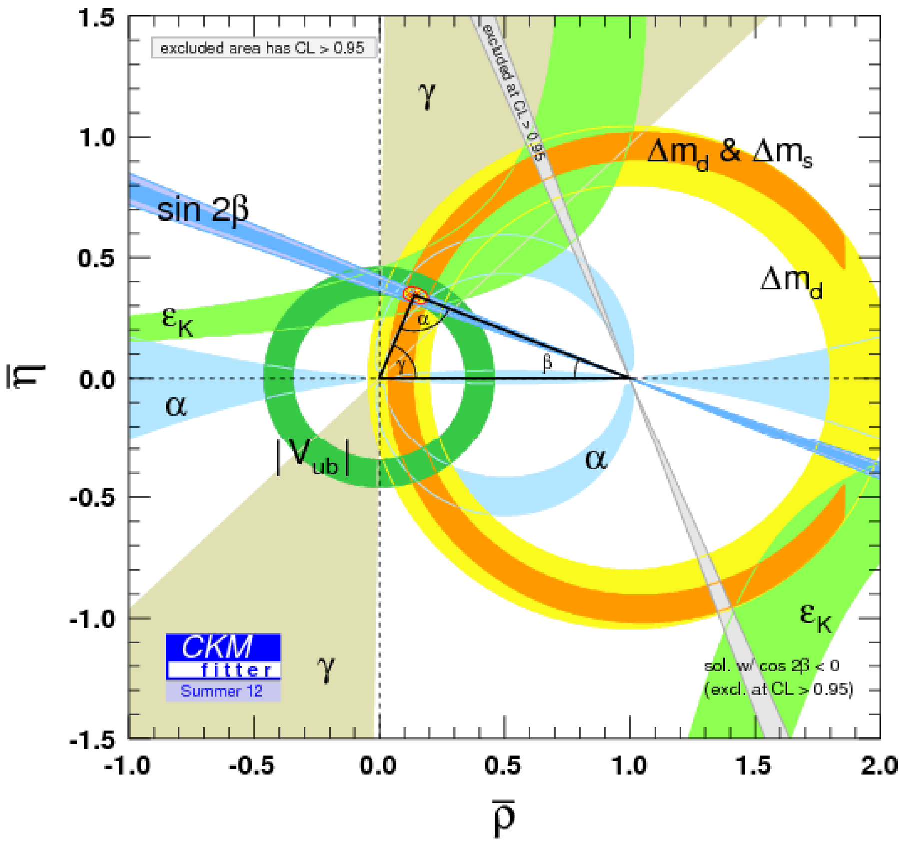
$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0,$$

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

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

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

CKM Angle γ

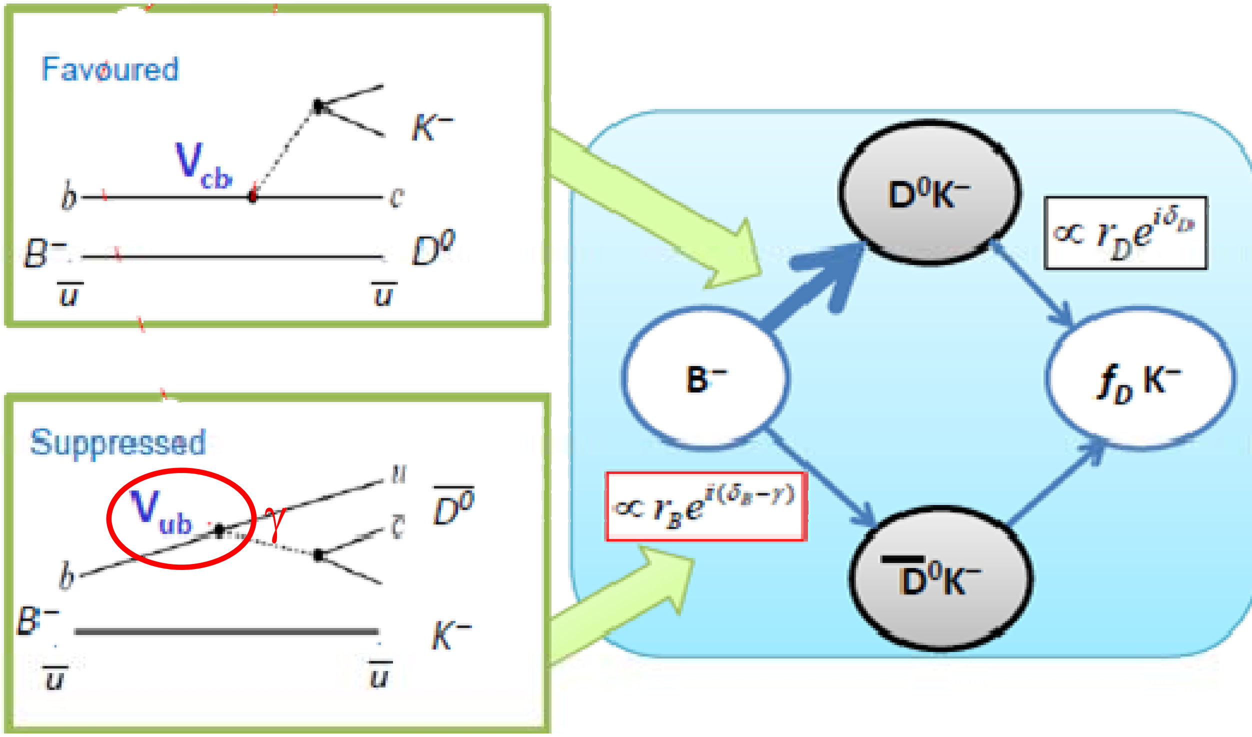


$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

⇩

Exploits direct CPV in $B \rightarrow DK$ decays

Sensitivity of B→DK decays to γ



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

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

All unknowns from data

⇒ No hadronic uncertainties

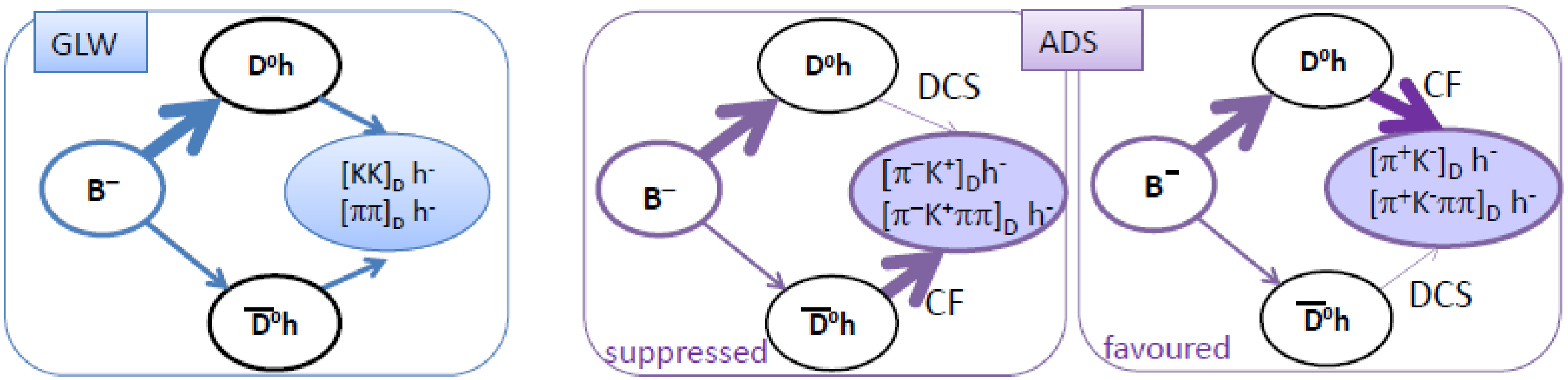
Gronau, London, Wyler (GLW)	Atwood, Dunietz, Soni (ADS)	Giri, Grossman, Soffer, Zupan (GGSZ)
f_D = KK, ππ (CP state)	f_D = Kπ and πK	Self conjugated Dalitz modes

LHCb 1 fb^{-1}:
- $B^\pm \to D(KK)\, K^\pm$
- $B^\pm \to D(\pi\pi)\, K^\pm$
- $B^\pm \to D(KK)\, \pi^\pm$
- $B^\pm \to D(\pi\pi)\, \pi^\pm$

LHCb 1 fb^{-1}:
- $B^\pm \to D(\pi^+K^-)\, K^\pm$
- $B^\pm \to D(K^+\pi^-)\, K^\pm$
- $B^\pm \to D(\pi^+K^-)\, \pi^\pm$
- $B^\pm \to D(K^+\pi^-)\, \pi^\pm$

LHCb 1 fb^{-1} + 2 fb^{-1}

GLW / ADS Observables



GLW / ADS observables are ratios of branching ratios:
$\rightarrow$ many systematic uncertainties cancel in the ratios

ADS/GLW CP asymmetries, f_D = KK, ππ ,Kπ, Kπππ

$$A_h^f \equiv \frac{\Gamma(B^- \to f_D h^-) - \Gamma(B^+ \to f_D h^+)}{\Gamma(B^- \to f_D h^-) + \Gamma(B^+ \to f_D h^+)}$$

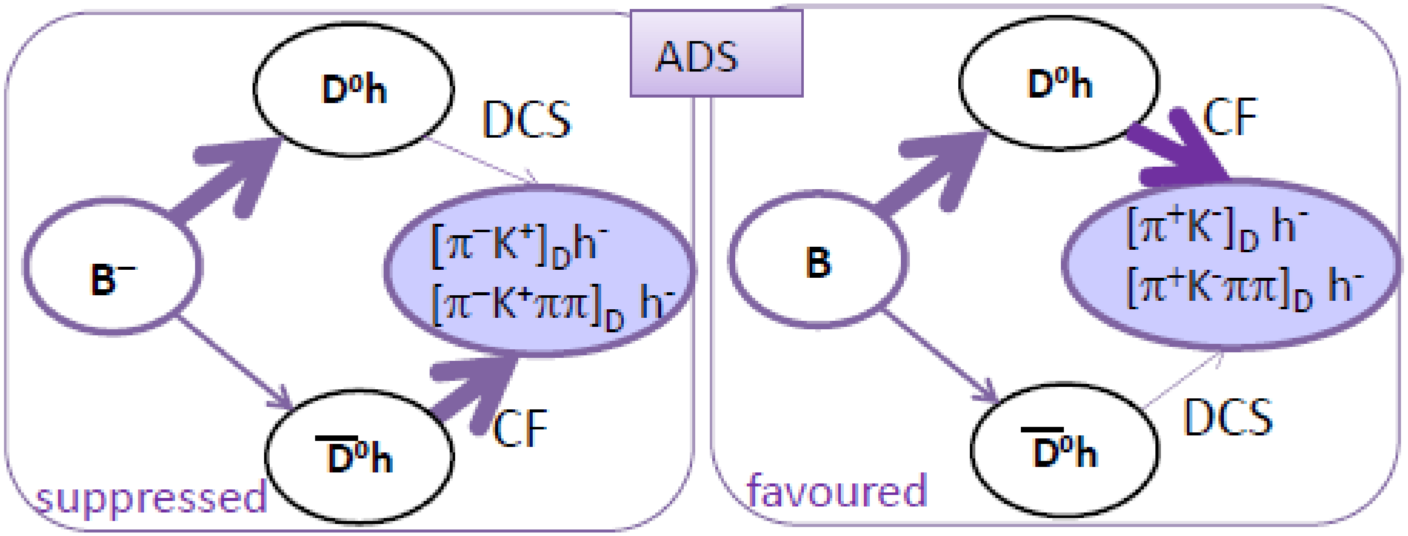
ADS/GLW K/π ratios, f_D = KK, ππ ,Kπ, Kπππ

$$R^f{}_{K/\pi} \equiv \frac{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to f_D K^+)}{\Gamma(B^- \to f_D \pi^-) + \Gamma(B^+ \to f_D \pi^+)}$$

Ratio of ADS suppressed and favoured final states, f_D = Kπ, Kπππ

$$R_h^{f\pm} \equiv \frac{\Gamma(f_D h^\pm)^{sup}}{\Gamma(\bar{f}_D h^\pm)^{fav}}$$

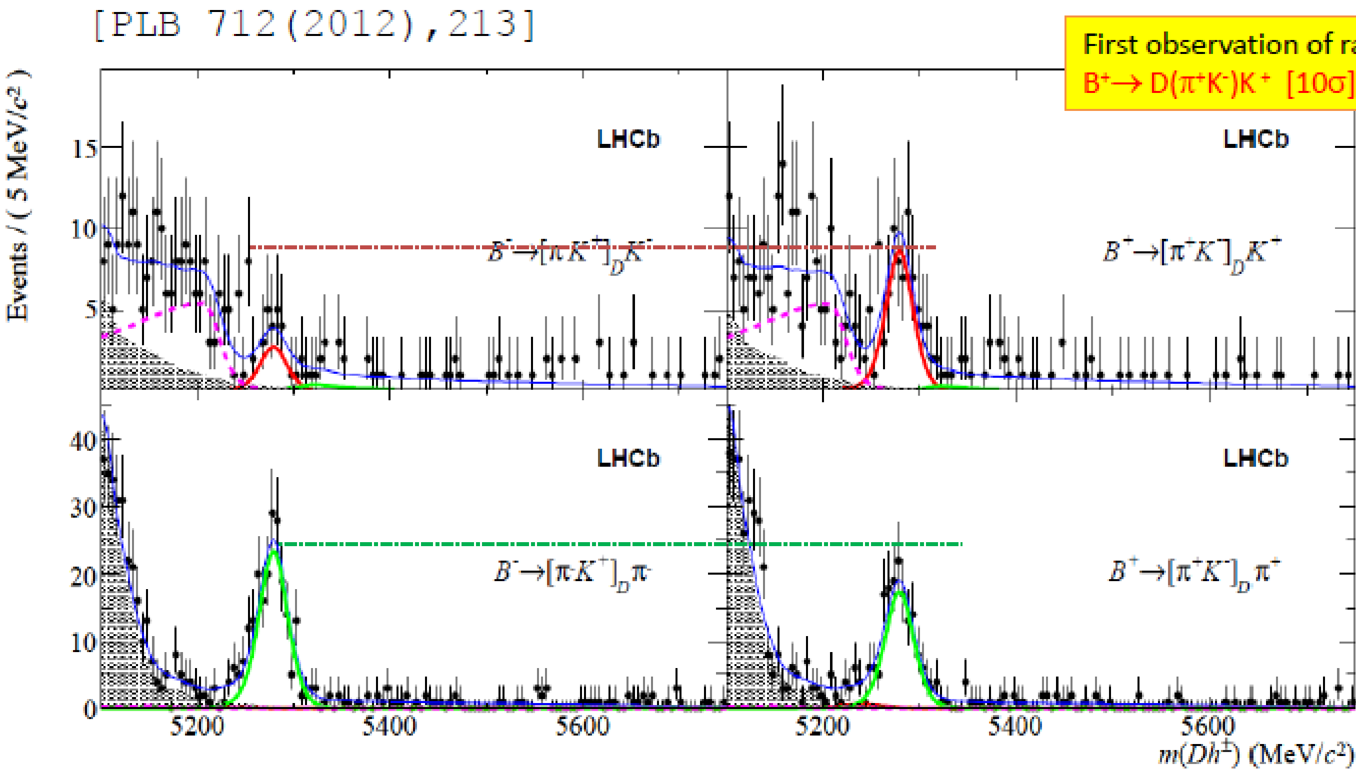
Suppressed ADS Mode $B^- \rightarrow [\pi^- K^+]_D K^-$



$$R_{ADS}^{DK} \equiv \frac{\Gamma([K^+\pi^-]_D K^-) + \Gamma([K^-\pi^+]_D K^+)}{\Gamma([K^-\pi^+]_D K^-) + \Gamma([K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \cos\gamma \cos(\delta_B + \delta_D)$$

$$A_{ADS}^{DK} \equiv \frac{\Gamma([K^+\pi^-]_D K^-) - \Gamma([K^-\pi^+]_D K^+)}{\Gamma([K^+\pi^-]_D K^-) + \Gamma([K^-\pi^+]_D K^+)} = 2 r_B r_D \sin\gamma \sin(\delta_B + \delta_D) / R_{ADS}^{DK}$$

Suppressed ADS Mode $B^- \to [\pi^- K^+]_D K^-$



First observation of rare ADS $B^+ \to D(\pi^+ K^-) K^+$ [10σ]

Large asymmetry in $B \to DK$: $A_{ADS} = (-52 \pm 15 \pm 2)\%$ [4σ]

Hint of asymmetry in $B \to D\pi$: $A_{ADS} = (14.3 \pm 6.2 \pm 1.1)\%$ [2.4σ]

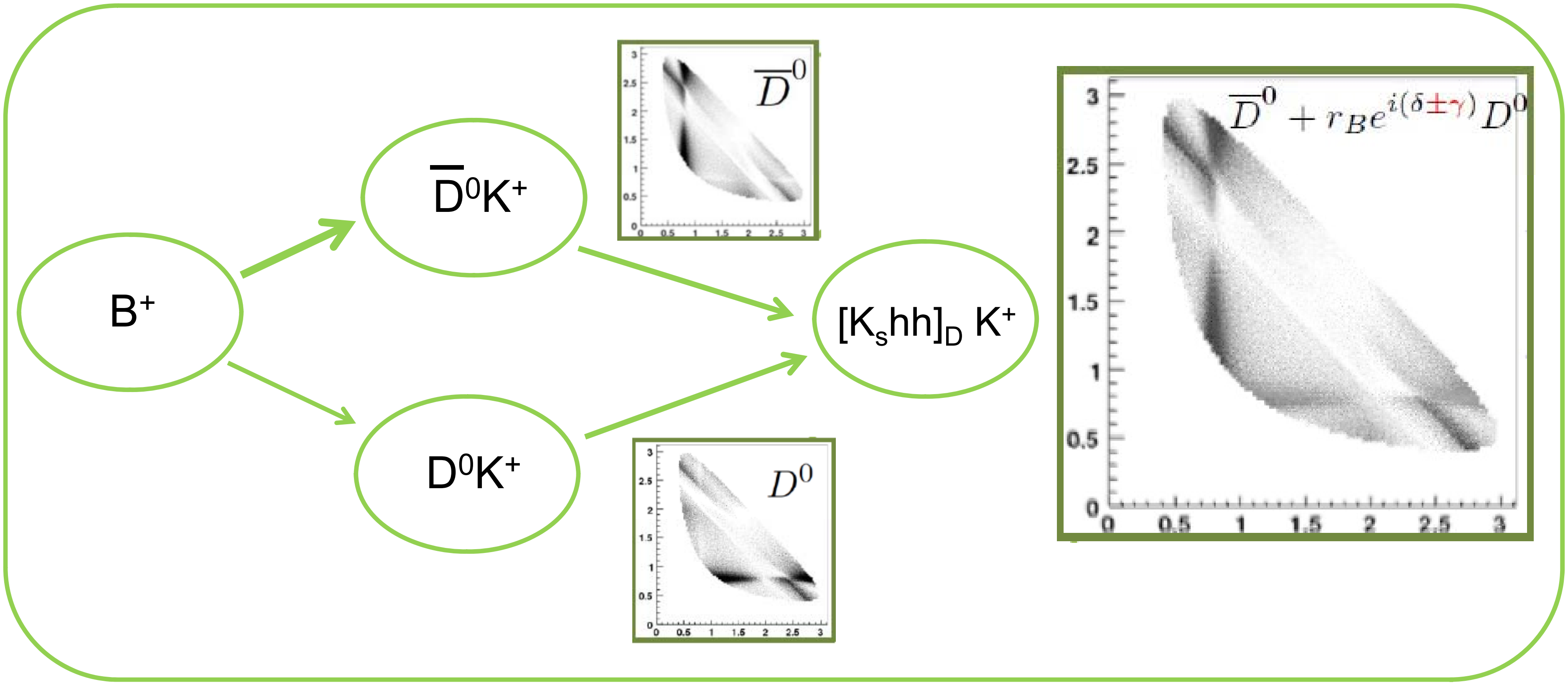
$$R_{ADS}^{DK} \equiv \frac{\Gamma([K^+\pi^-]_D K^-) + \Gamma([K^-\pi^+]_D K^+)}{\Gamma([K^-\pi^+]_D K^-) + \Gamma([K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \cos\gamma \cos(\delta_B + \delta_D)$$

$$A_{ADS}^{DK} \equiv \frac{\Gamma([K^+\pi^-]_D K^-) - \Gamma([K^-\pi^+]_D K^+)}{\Gamma([K^+\pi^-]_D K^-) + \Gamma([K^-\pi^+]_D K^+)} = 2 r_B r_D \sin\gamma \sin(\delta_B + \delta_D) / R_{ADS}^{DK}$$

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

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

K_s

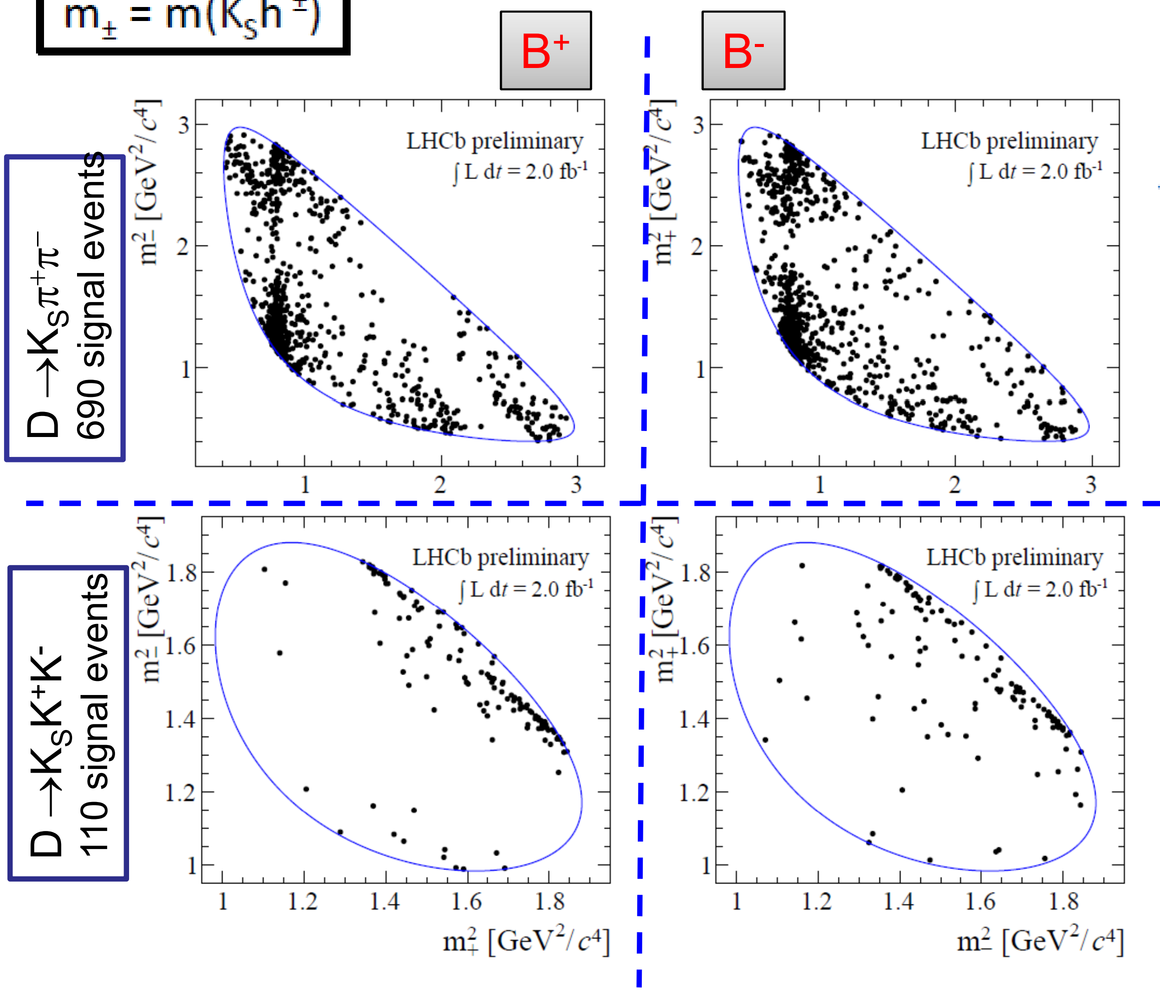


Different interference structure for B^+ and $B^- \to \gamma$

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

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

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



>85% purity

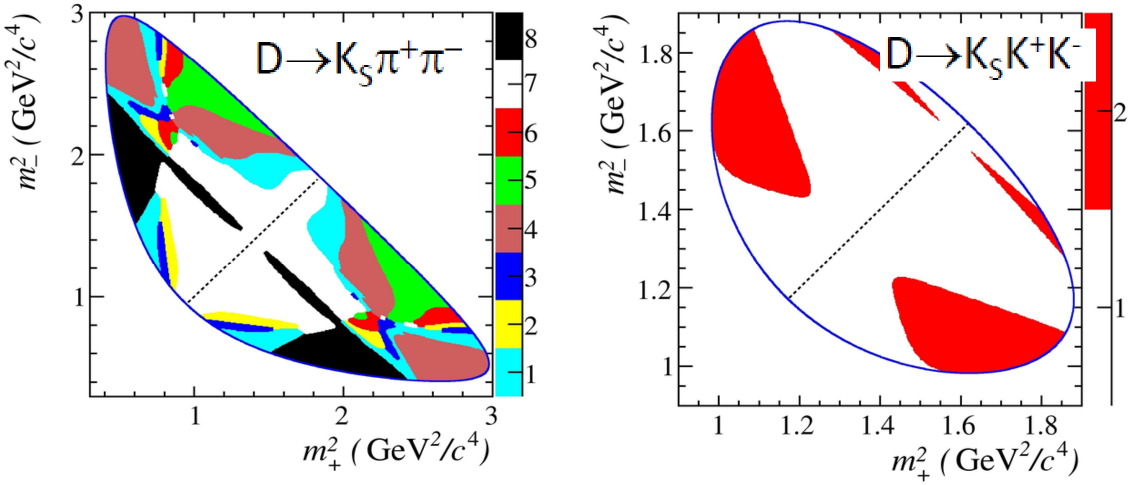
Extraction of γ requires information on the $D \to K_s hh$ decay amplitude variation over Dalitz plot: both amplitude and phase δ_D

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

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:

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

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

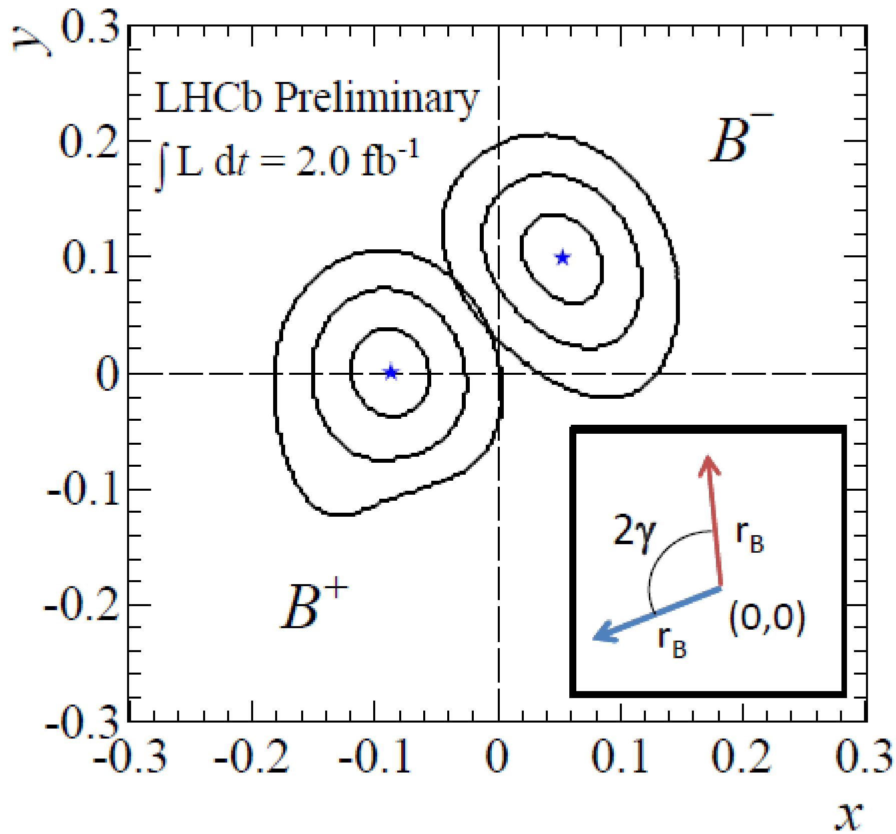
$$y_{\pm} = r_B \sin(\delta_B \pm \gamma) \qquad s_i = \langle \sin(\delta_d) \rangle_i$$

} 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})	$\gamma = (57 \pm 16)^o$ $r_B = 0.09 \pm 0.02$

The LHCb γ combination

Slide by S. Ricciardi

Input	Observables (A_i)
$B^+ \to D(hh)h^+$	A^{KK}_{h}, $R^{KK}_{K/\pi}$, $A^{\pi\pi}_{h}$, $R^{\pi\pi}_{K/\pi}$
	$A^{K\pi}_{h}$, $R^{K\pi}_{K/\pi}$, $R^{\pm K\pi}_{h}$
$B^+ \to D(K\pi\pi\pi)h^+$	$A^{K3\pi}_{h}$, $R^{K3\pi}_{K/\pi}$, $R^{\pm K3\pi}_{h}$
$B^+ \to D(K_s hh)K^+$	$x_\pm$, $y_\pm$
Charm constraints	

Frequentist approach

$$L(\vec{\alpha}) = \prod_i \exp\left(-\tfrac{1}{2}(\vec{A_i}^{obs} - \vec{A_i}(\vec{\alpha_i}))^T V_i^{-1} (\vec{A_i}^{obs} - \vec{A_i}(\vec{\alpha_i}))\right)$$

Charm hadronic parameters are determined from data but constrained by CLEO, HFAG and D-mixing studies at LHCb

Decay	Parameters (α_i)
$B^+ \to Dh^+$	γ
$B^+ \to DK^+$	r_B^K, δ_B^K
$B^+ \to D\pi^+$	r_B^π, δ_B^π
$B^+ \to DK^+ / B^+ \to D\pi^+$	R_{cab}
$D \to K\pi$	$r_{K\pi}$, $\delta_{K\pi}$, $\Gamma(D \to K\pi)$
$D \to K\pi\pi\pi$	$r_{K3\pi}$, $\delta_{K3\pi}$, $\kappa_{K3\pi}$, $\Gamma(D \to K3\pi)$
$D \to KK$	$A^{dir}_{CP}(KK)$
$D \to \pi\pi$	$A^{dir}_{CP}(\pi\pi)$
D^0-D^0bar mixing	x_D, y_D

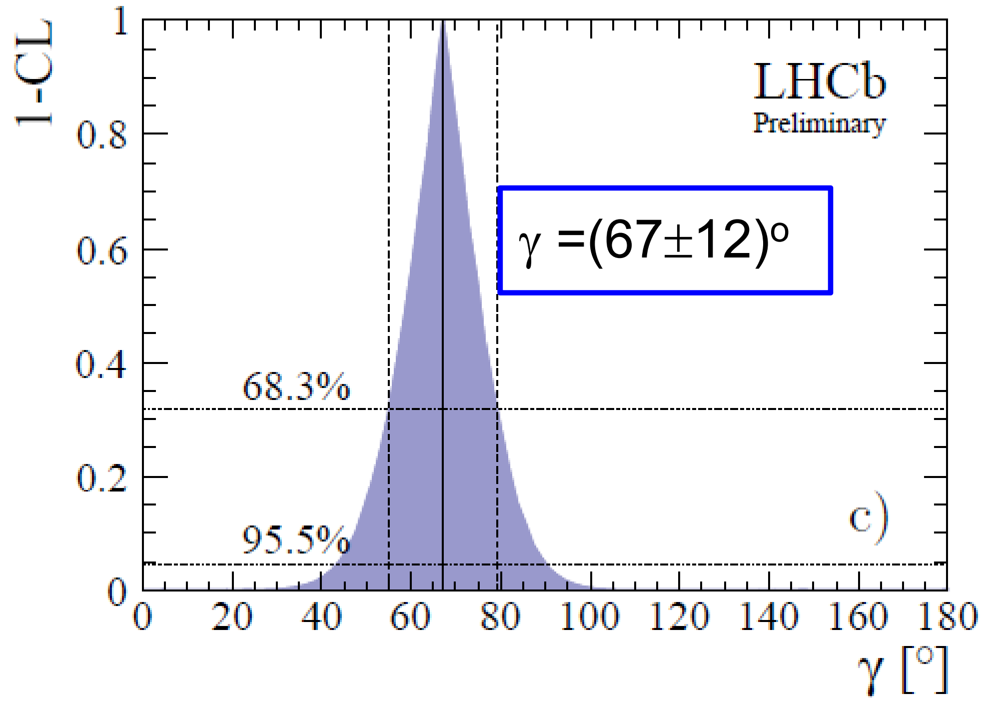
$0 \le \kappa \le 1$ Coherence factor for D decays
=1 for $D \to$ 2-body decays

Gamma Combination

LHCb-Conf-2013-006

Data: 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]

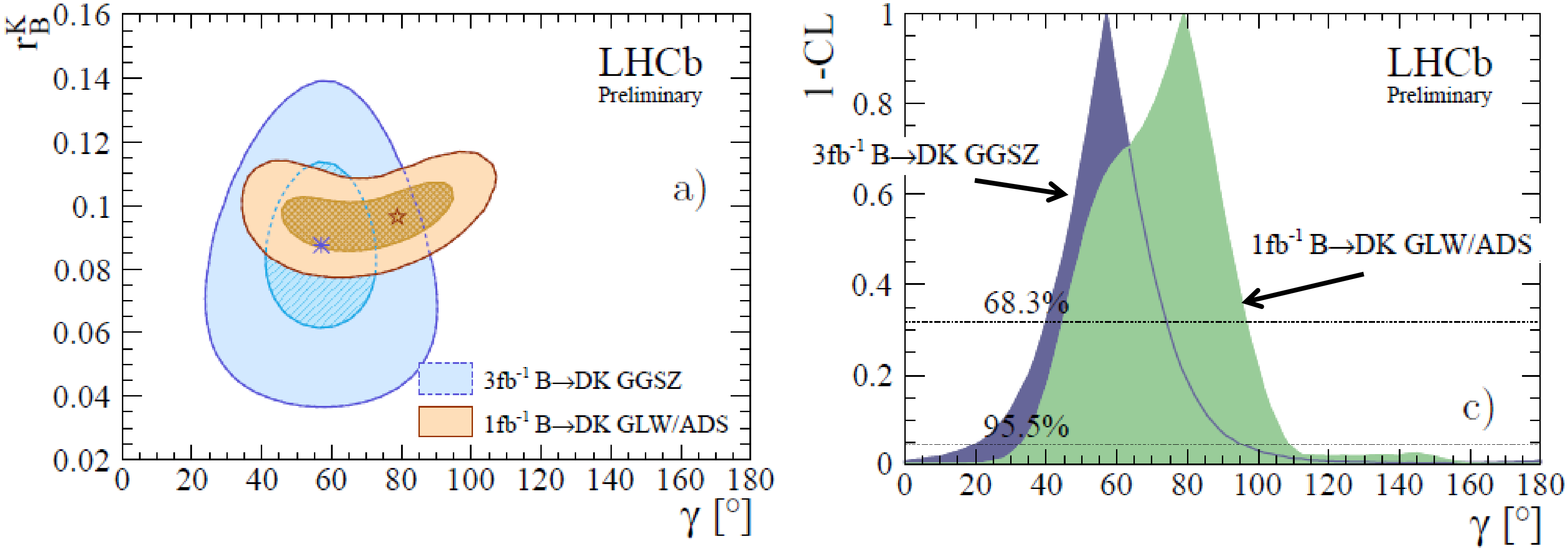


For comparision:

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

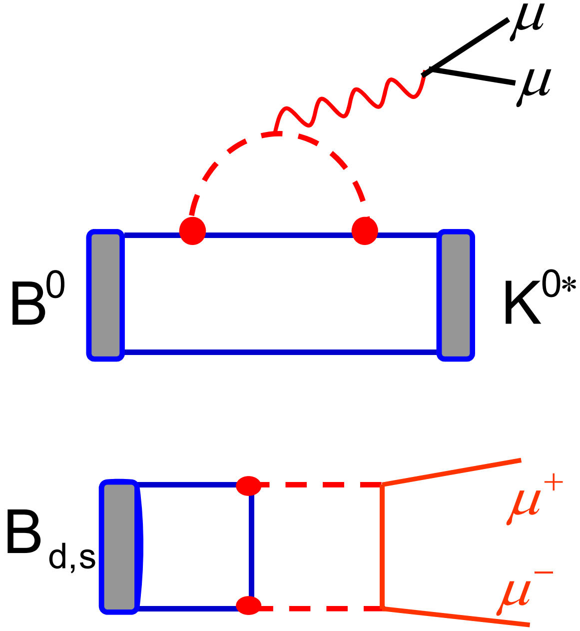
ADS/GLW versus GGSZ

LHCb-Conf-2013-006



Rare B Decays

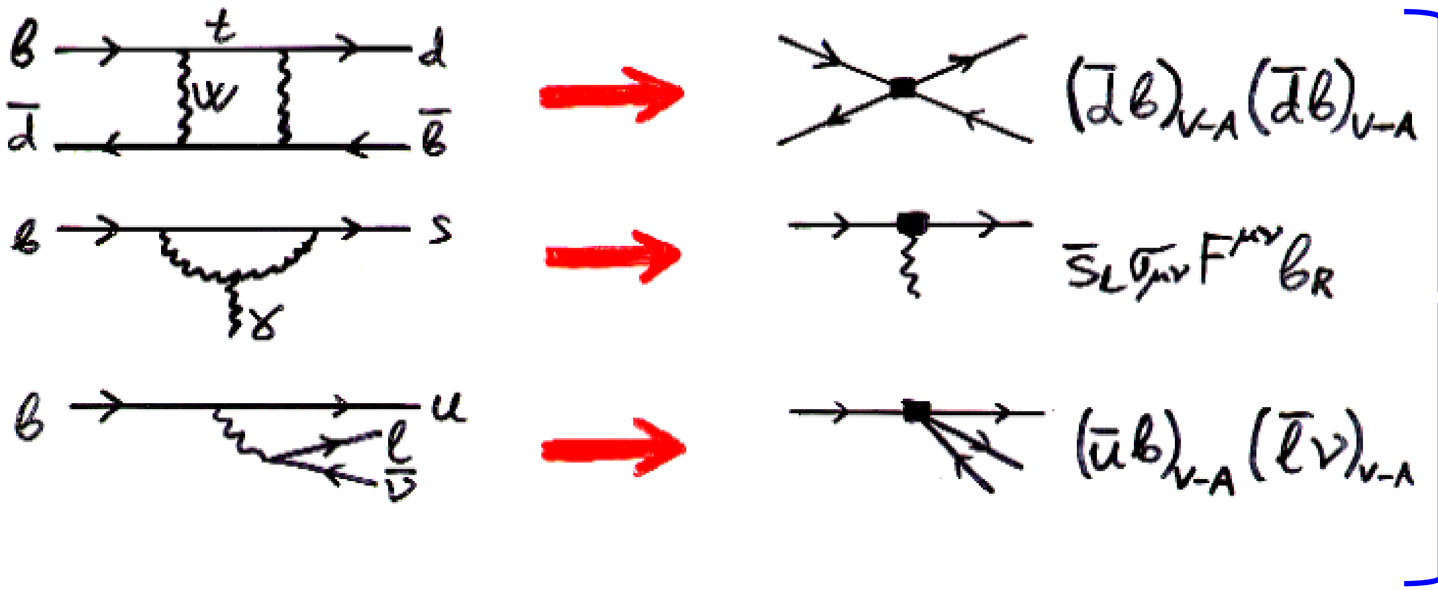
FCNC decays:



Effective Theory & OPE

Electroweak / NP scale

Scale of B meson



Effective (local) operators O_i

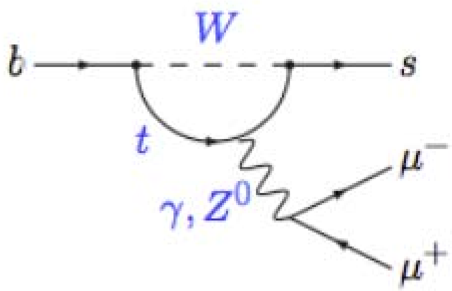
(absorb long range effects)

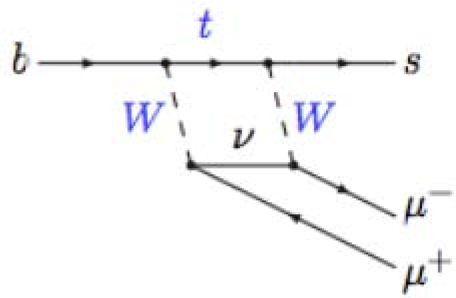
Operator Product Expansion

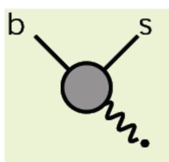
$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^{*}\sum C_i(\mu)O_i(\mu)$$

Wilson coefficients describe short range physics: SM + NP

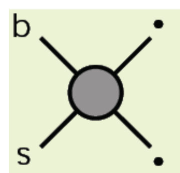
FCNC decay $B^0 \to K^* \mu\mu$







O_7



O_9 O_{10}

Standard Model:

$$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu}$$
$$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$$
$$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$$

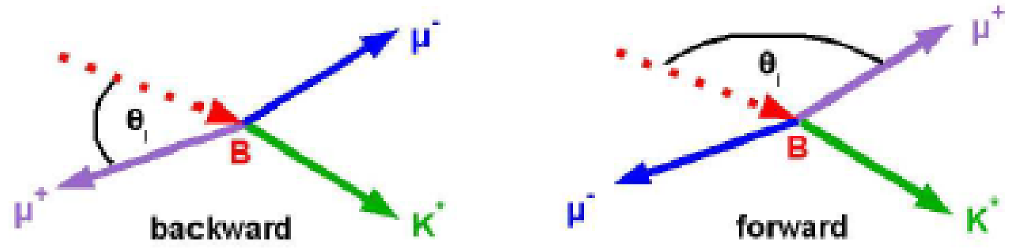
New Physics can lead to new operators with new Lorentz structure or can modify the Wilson coefficients → modifies the angular distribution

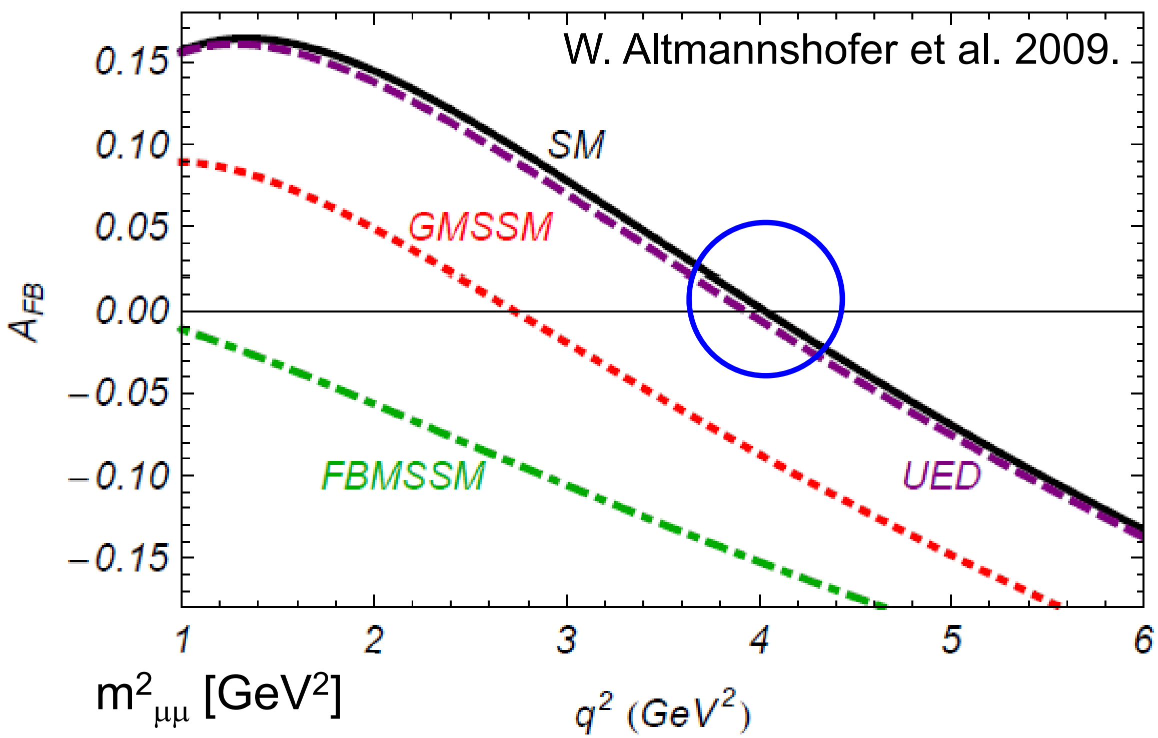
$$H = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i^{SM} + C_i^{NP}) O_i^{SM} + \sum \frac{c}{\Lambda_{NP}} O_{NP}$$

Forward-Backward Aysmmetry

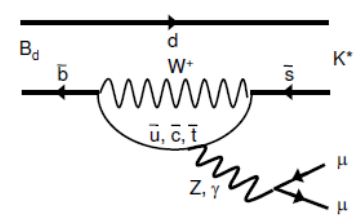
Simplest angular analysis:

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





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

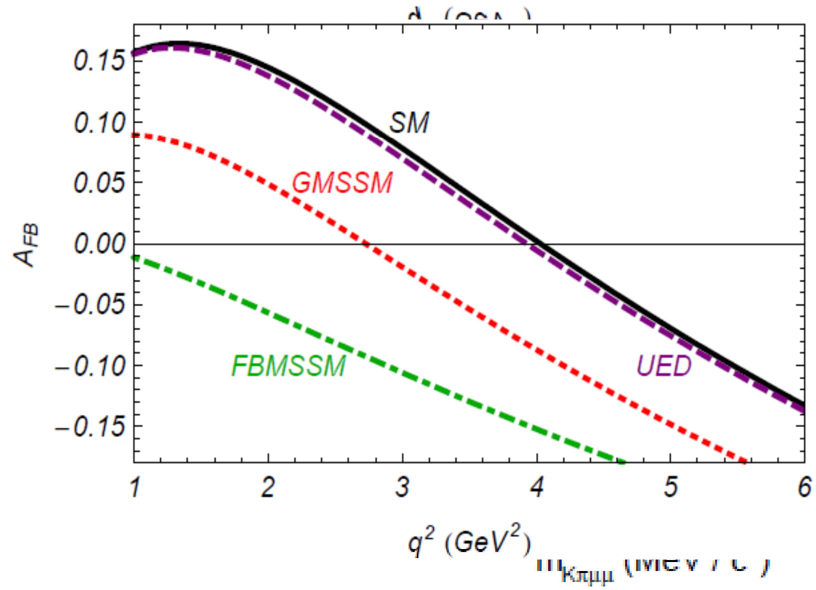


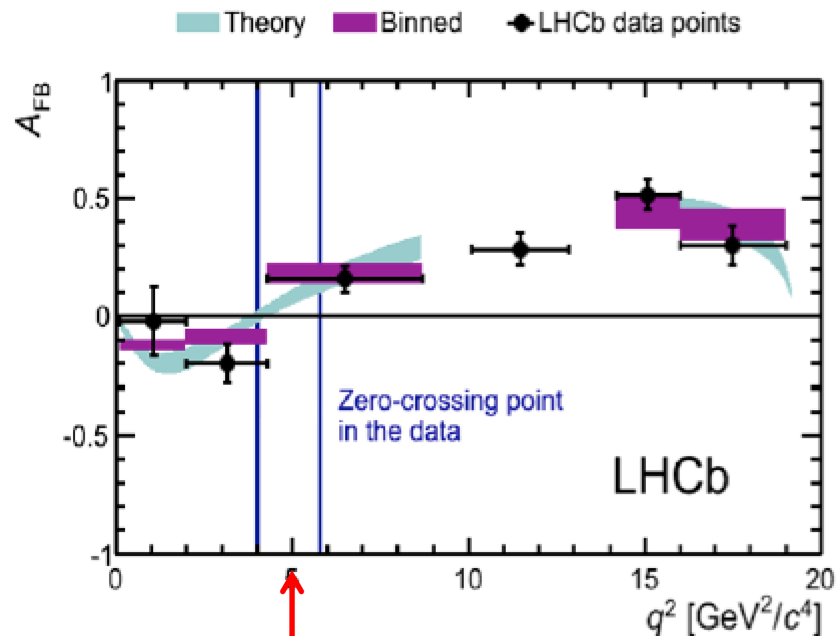
$q^2 = m_{\mu\mu}$

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

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

arXiv:1304.6325





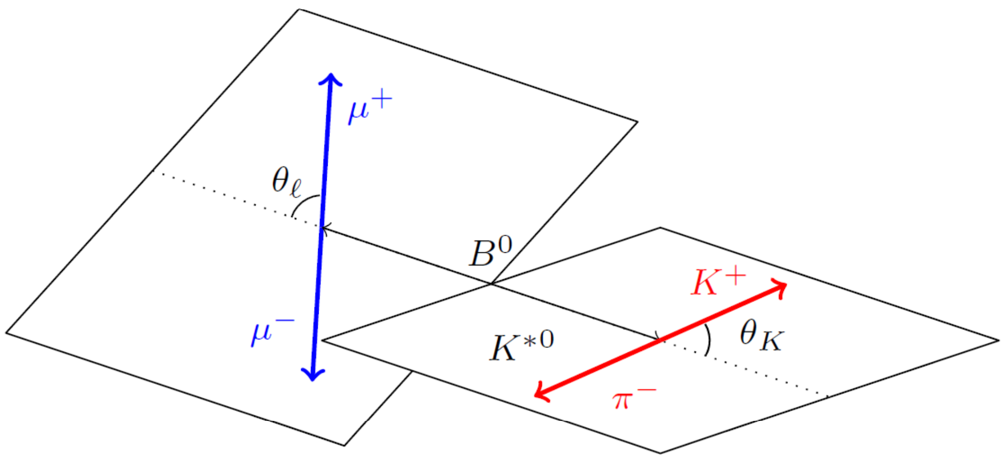
BABAR+BELLE+CDF: ~600

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

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

Full angular analysis

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



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

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

Observables F_L and S_i are functions of Wilson Coefficients.

New Parametrisation

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

$$A_T^{(2)} = \frac{2S_3}{(1-F_L)}$$

$$A_T^{Re} = \frac{S_6}{(1-F_L)}$$

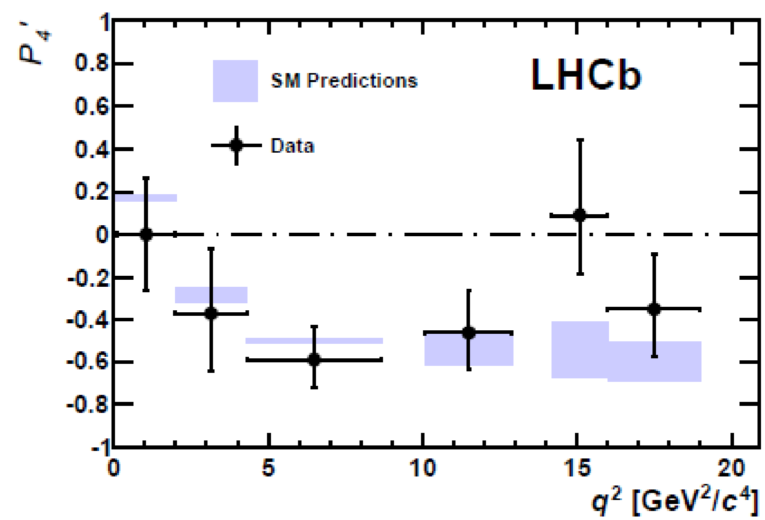
$$P_4' = \frac{S_4}{\sqrt{(1-F_L)F_L}} \qquad P_6' = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$

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

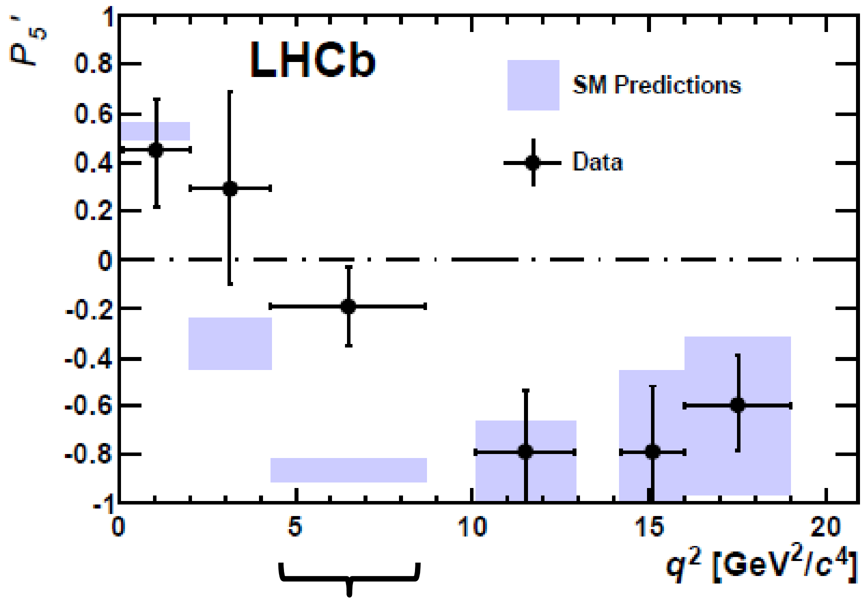
Kruger-Matias (2005), Matias et al. (2012), Egede-Matias-Hurth-Ramon-Reece (2008), Bobeth-Hiller-Van Dyk (2010-11), Beciveric-Schneider (2012)

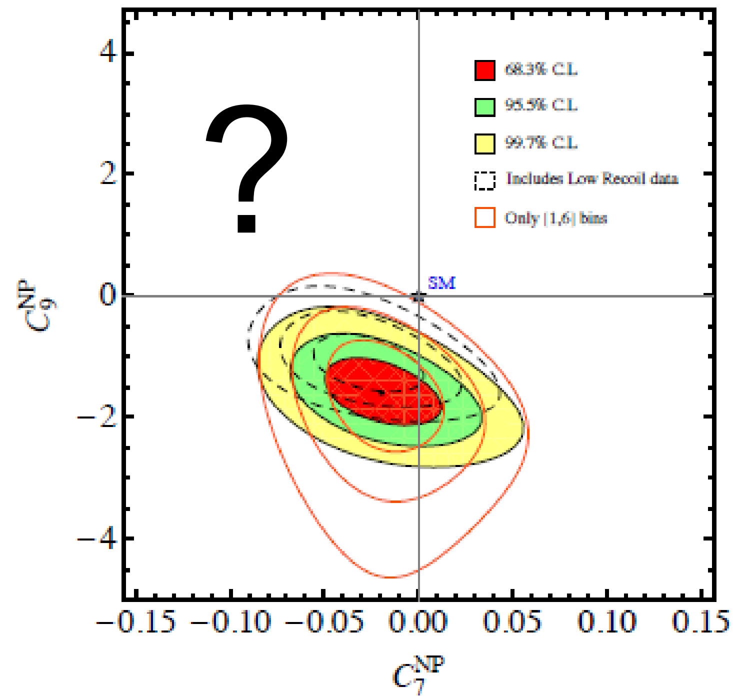
In general data well described by SM prediction

arXiv:1308:1707



Deviation for observable P_5'





- P_5' shows deviation of 3.7σ from SM ($4.3 < q^2 < 8.68$ GeV²/c⁴)
- 2.5σ for $1 < q^2 < 6$ GeV²/c⁴ (theoretically favored region)

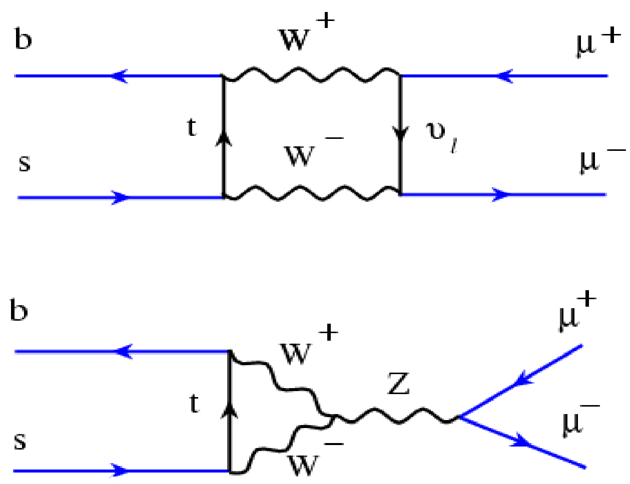
Possible interpretation: deviation in di-lepton vector operator C_9

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

But: only 1 / 24 bins (0.5% probability)

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

Standardmodell



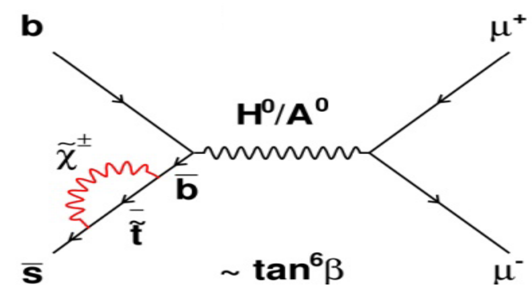
Helicity suppressed

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

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

Buras et al, arXiv: 1303.3820

NP contributions: SUSY Higgs sector



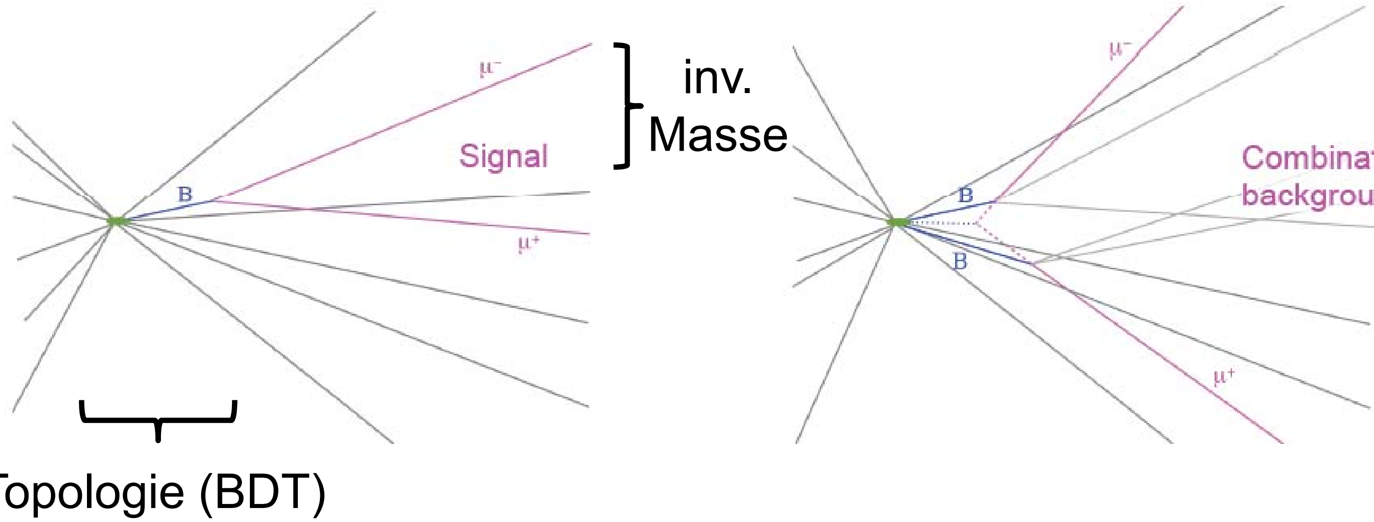
Sensitive to additional scalar and pseudo-scalar contributions

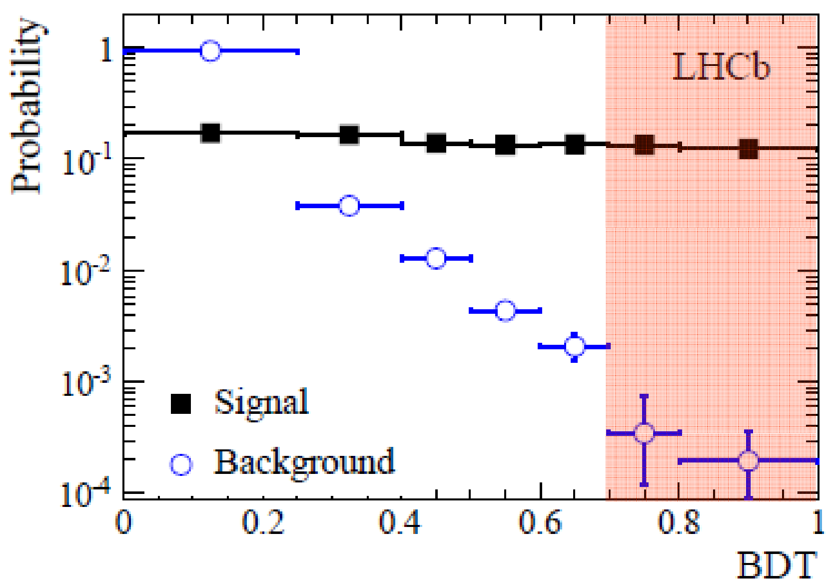
⇨ Correction due to finite $\Delta\Gamma_s$

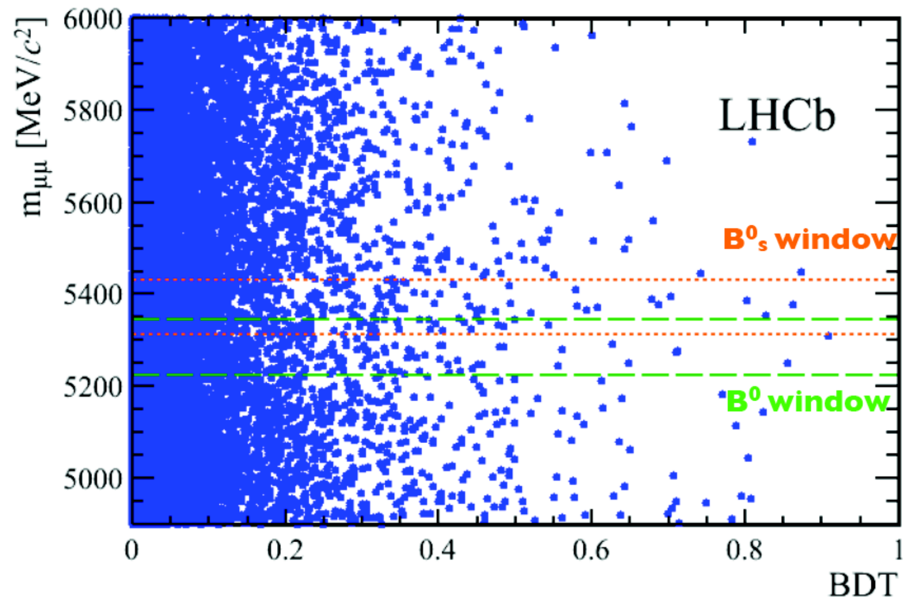
$BR(B_s \to \mu^+\mu^-) = (3.56 \pm 0.18) \times 10^{-9}$

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

Experimental challenge



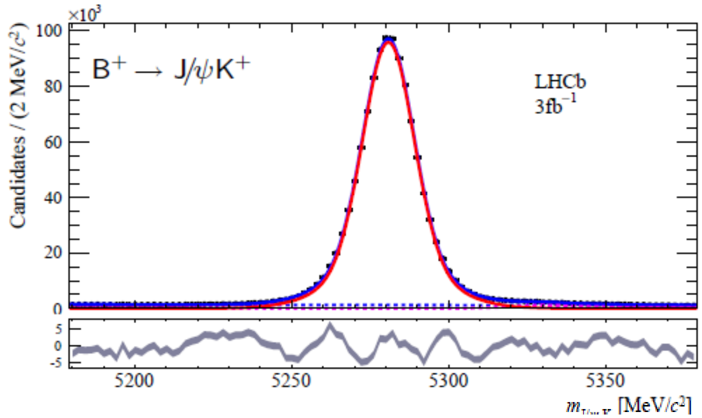




Measure B→μμ w/r reference

Reference channel:

$B^0 \rightarrow K^+\pi^-$ **and** $B^+ \rightarrow J/\psi K^+$



$$f_s/f_{d,u} = N_{B_s^0}/N_{B^{0(+)}}$$

$$\mathcal{B}_{sig} = \mathcal{B}_{cal} \times \frac{\epsilon_{cal}^{rec}\epsilon_{cal}^{sec}}{\epsilon_{sig}^{rec}\epsilon_{sig}^{sel}} \times \frac{\epsilon_{cal}^{trig}}{\epsilon_{sig}^{trig}} \times \frac{f_{cal}}{f_{sig}} \times \frac{N_{sig}}{N_{cal}}$$

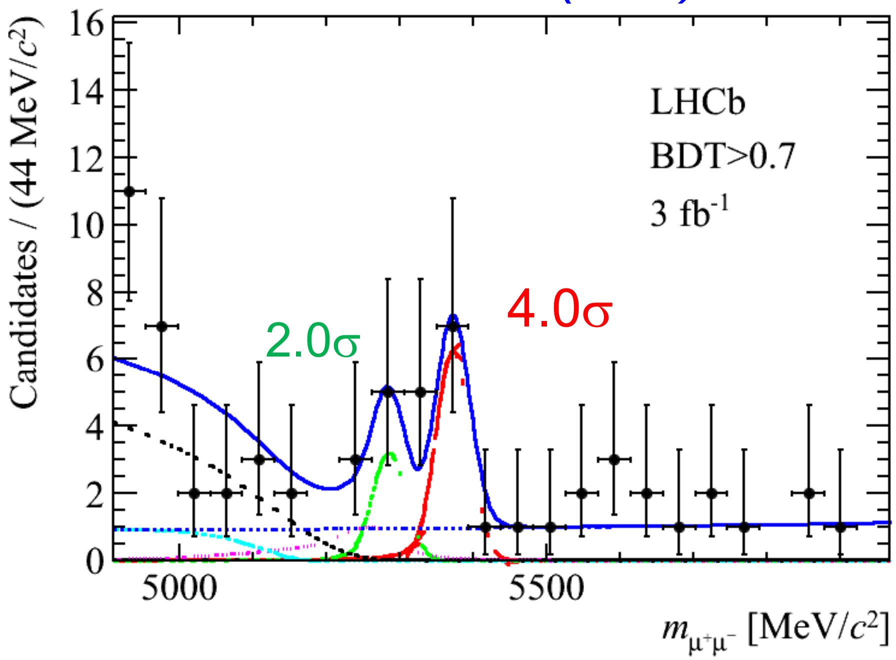
from MC checked on data

from data

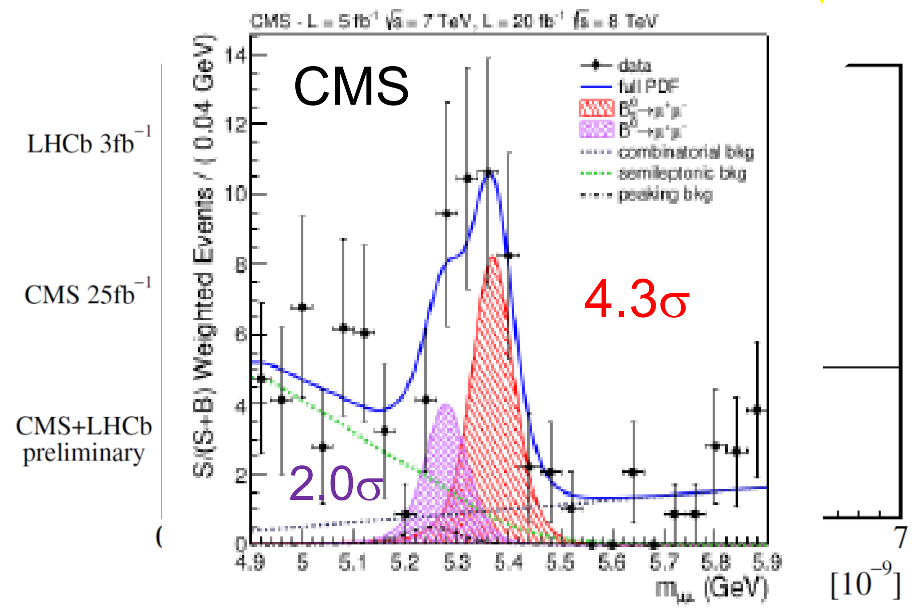
hadronization fraction ratio

Observation of $B_s \to \mu\mu$

PRL 111 (2013) 101805



arXiv:1307.5025



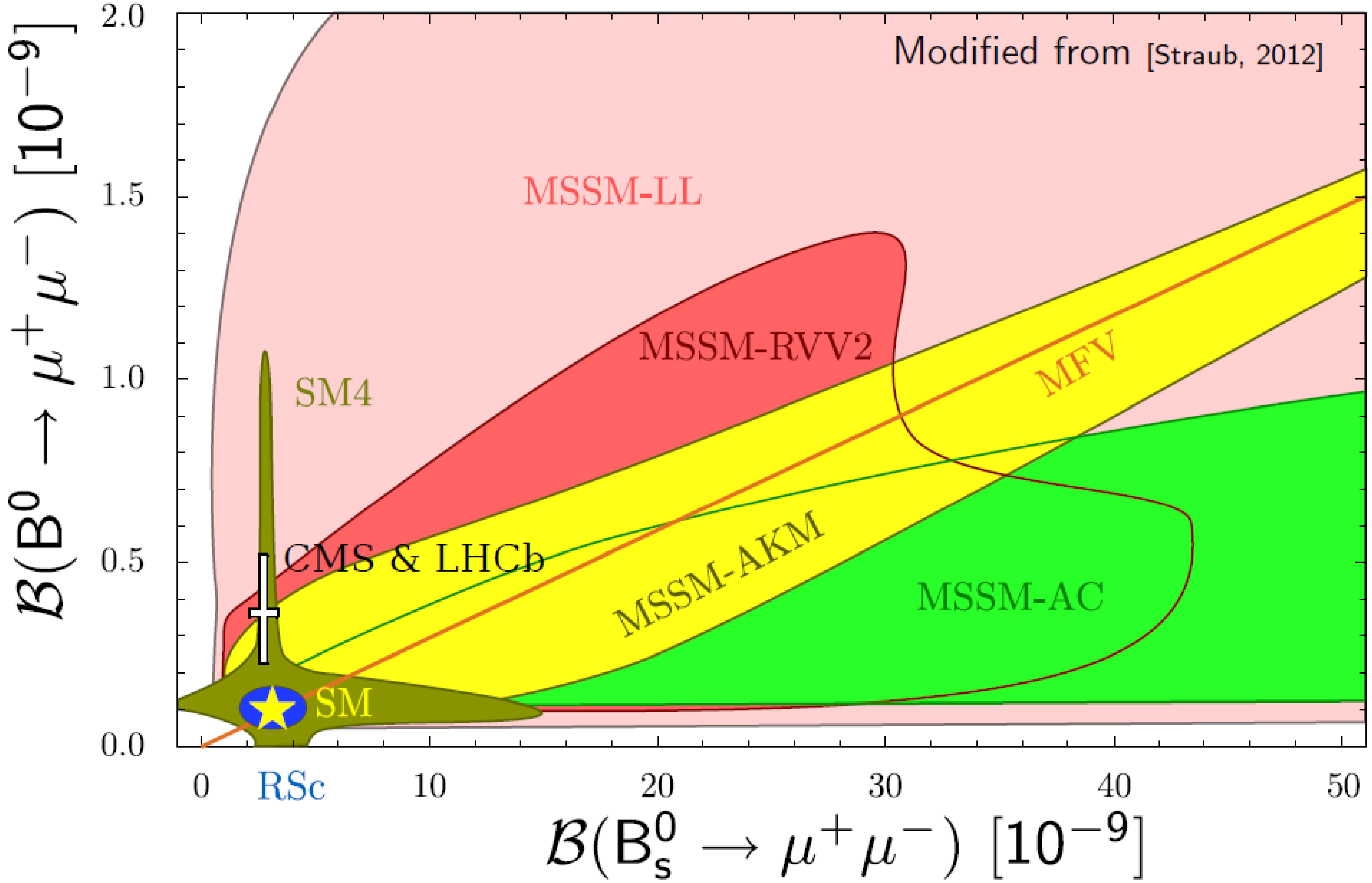
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$$

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

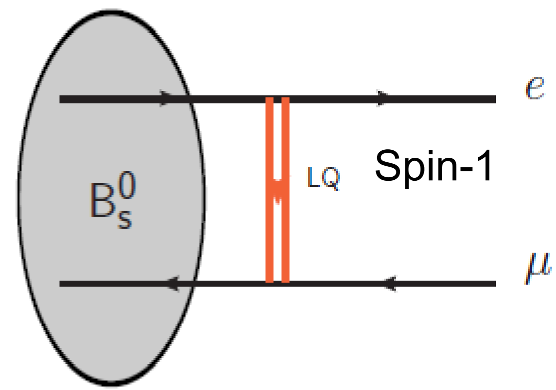
Implications for New Physics



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]

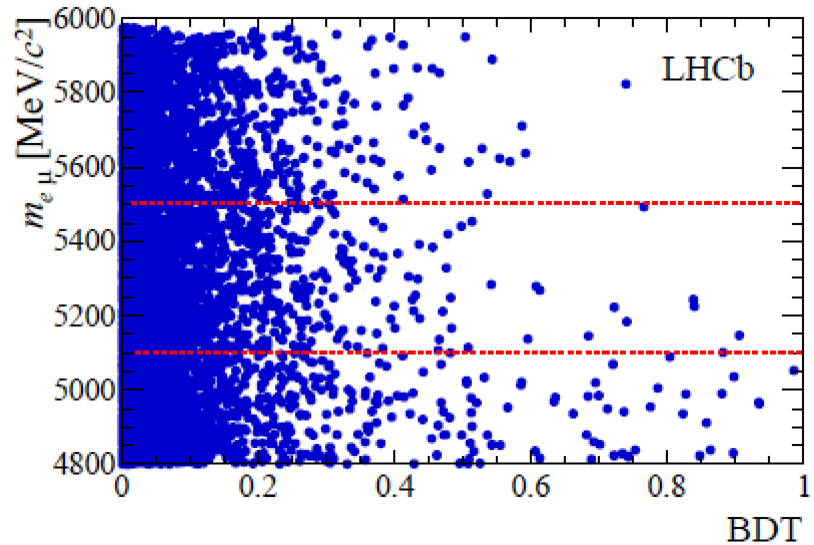
$B_s \to e\mu$



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

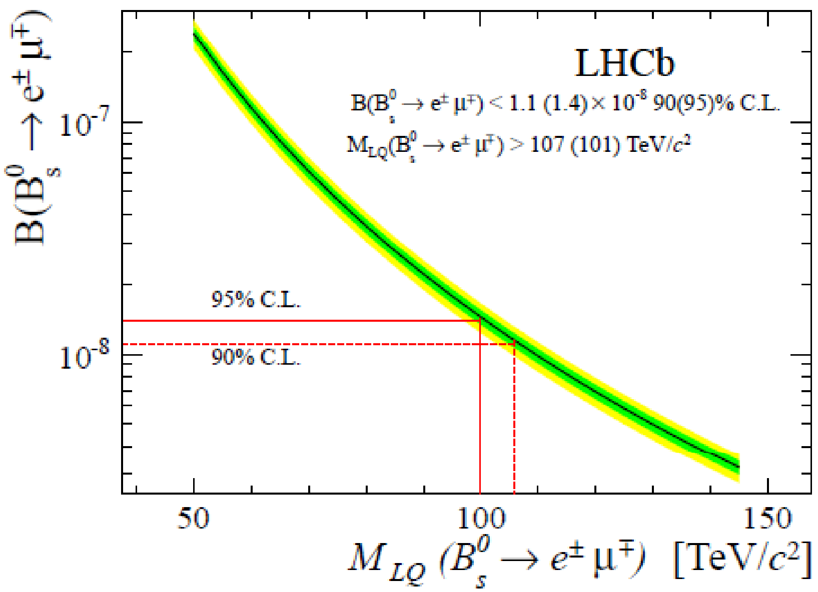
		LHCb
$\mathcal{B}(B_s^0 \to e^+\mu^-)$	$<$	14×10^{-9}
$\mathcal{B}(B^0 \to e^+\mu^-)$	$<$	3.7×10^{-9}

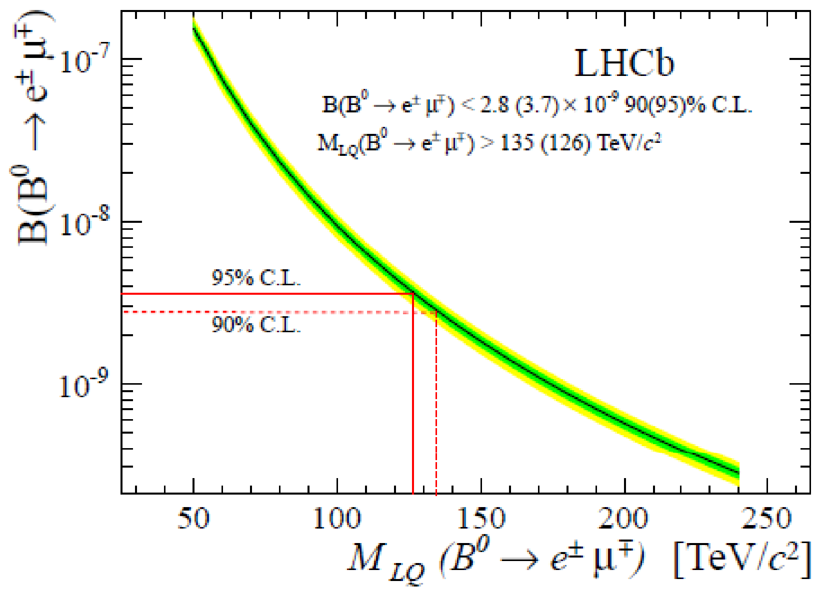
@ 95% CL



Limits on leptoquarks

Convert upper limit on BR into bound on leptoquarks:



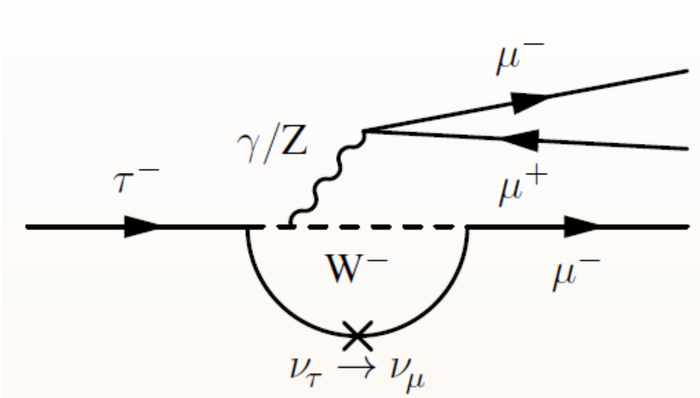


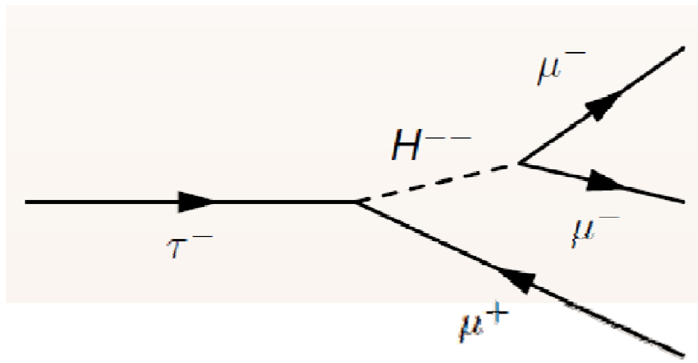
		LHCb	Current ([CDF, 2009])
$m_{LQ}(B_s^0 \to e^+\mu^-)$	$>$	101 TeV	44.9 TeV
$m_{LQ}(B^0 \to e^+\mu^-)$	$>$	126 TeV	53.6 TeV

Nice example to illustrate the power of indirect searches.

Lepton-Flavor Violation in $\tau \rightarrow \mu\ \mu\ \mu$

Standard Model:





Highly suppressed, BR<<10^{-50}

Enhancement in NP models
e.g.: doubly charged Higss

τ Production @ LHCb

- σ_τ = 80±8 μb (in LHCb)
- 8 × 10^{10} τ in 2011 (1 fb^{-1})
- Dominant production: $D_s \rightarrow \tau\nu$ (78%)

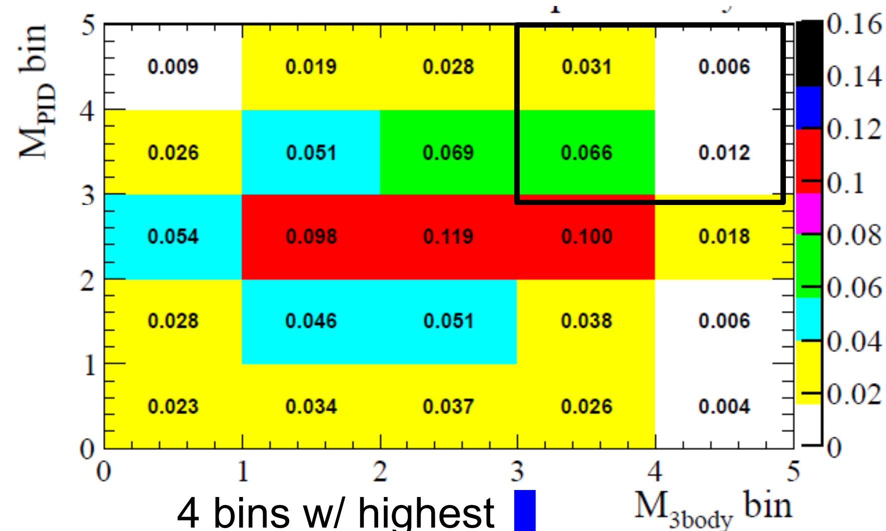
Search for $\tau \to \mu\ \mu\ \mu$

Analysis strategy:

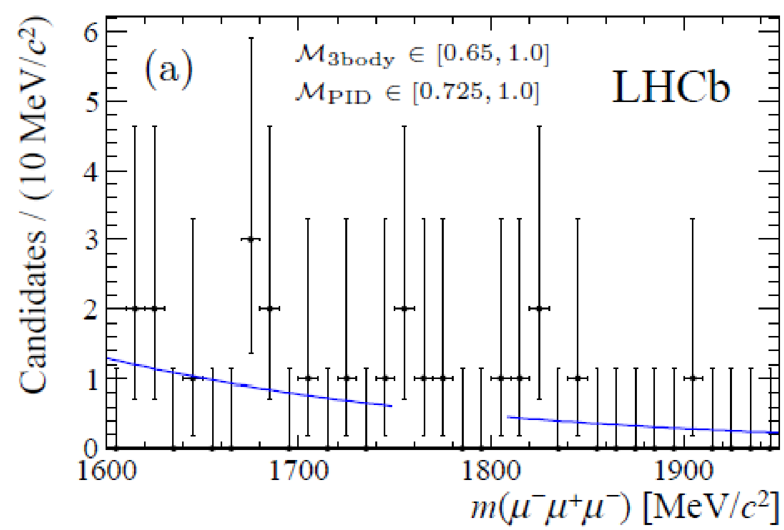
- 3-body likelihood M_{3body}
  μ-PID likelihood M_{PID}
- Normalization/control $D_s \to \phi\ (\mu\mu)\ \pi^-$
- Largest background $D_s \to \eta(\mu\mu\gamma)\ \mu^- \nu$

$BR(\tau \to \mu\mu\mu) < 8 \times 10^{-8}$ @ 90% CL
$< 10 \times 10^{-8}$ @ 95% CL

BELLE:	$< 2.1 \times 10^{-8}$ @ 90% CL
BABAR:	$< 3.3 \times 10^{-8}$ @ 90% CL

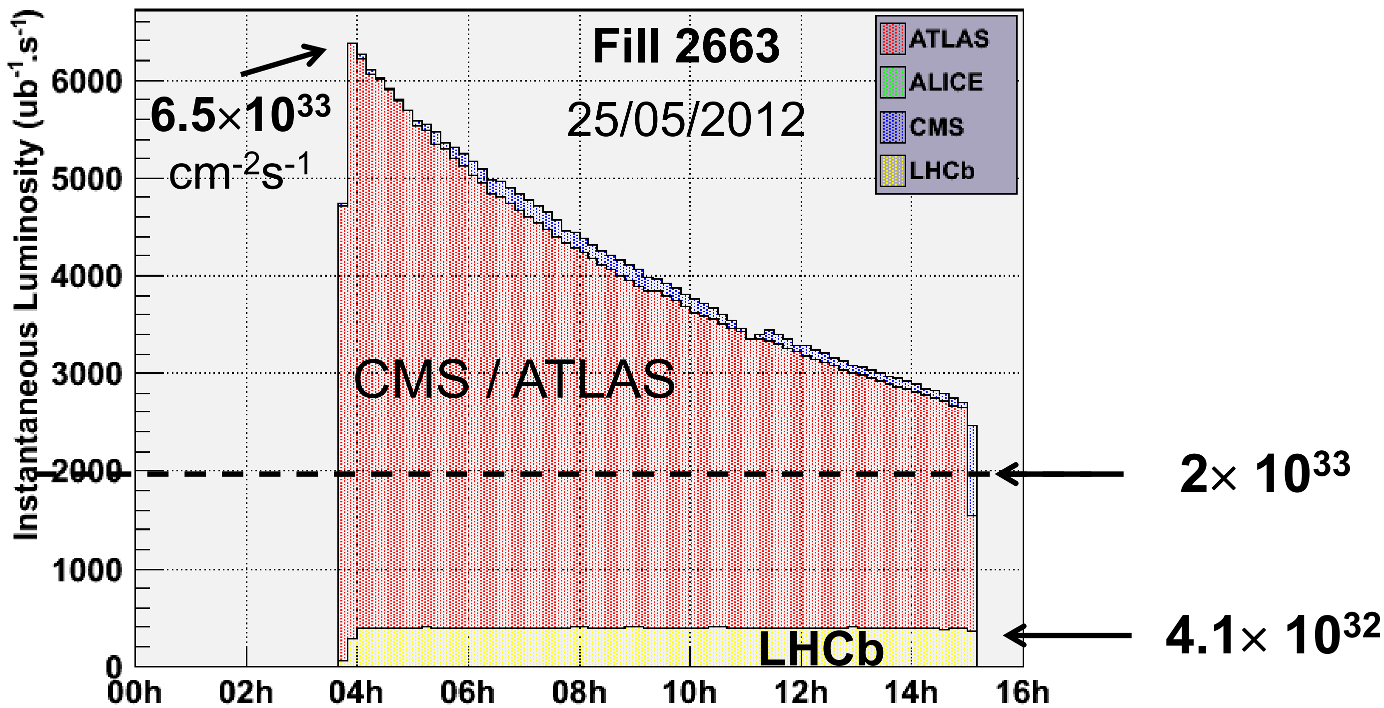


4 bins w/ highest signal probability:




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: Central 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
$BR(B_s \to \mu\mu)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
$BR(B_d \to \mu\mu)$ / $BR\ B_s \to \mu\mu$	~100%	~35%	~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 hast 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(10%) to O(2%).
- We are eagerly awaiting the start-up of BELLE-II: "Konkurrenz belebt das Geschäft."
- It makes a lot of fun!