LHC results on CP Violation

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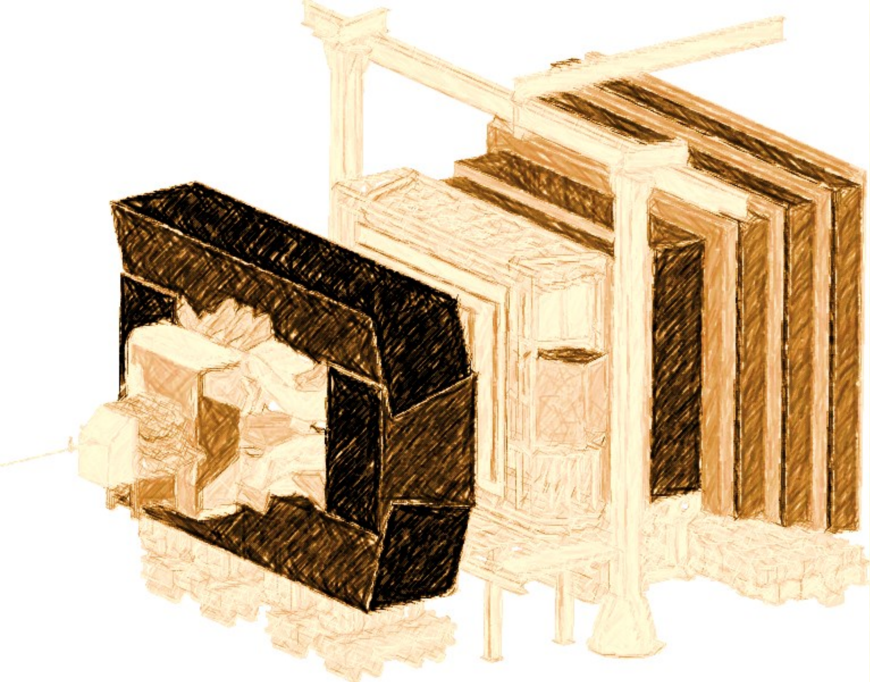
(on behalf of LHCb collaboration)

Rencontres du Vietnam, **Quy Nhơn**,
2016

Introduction

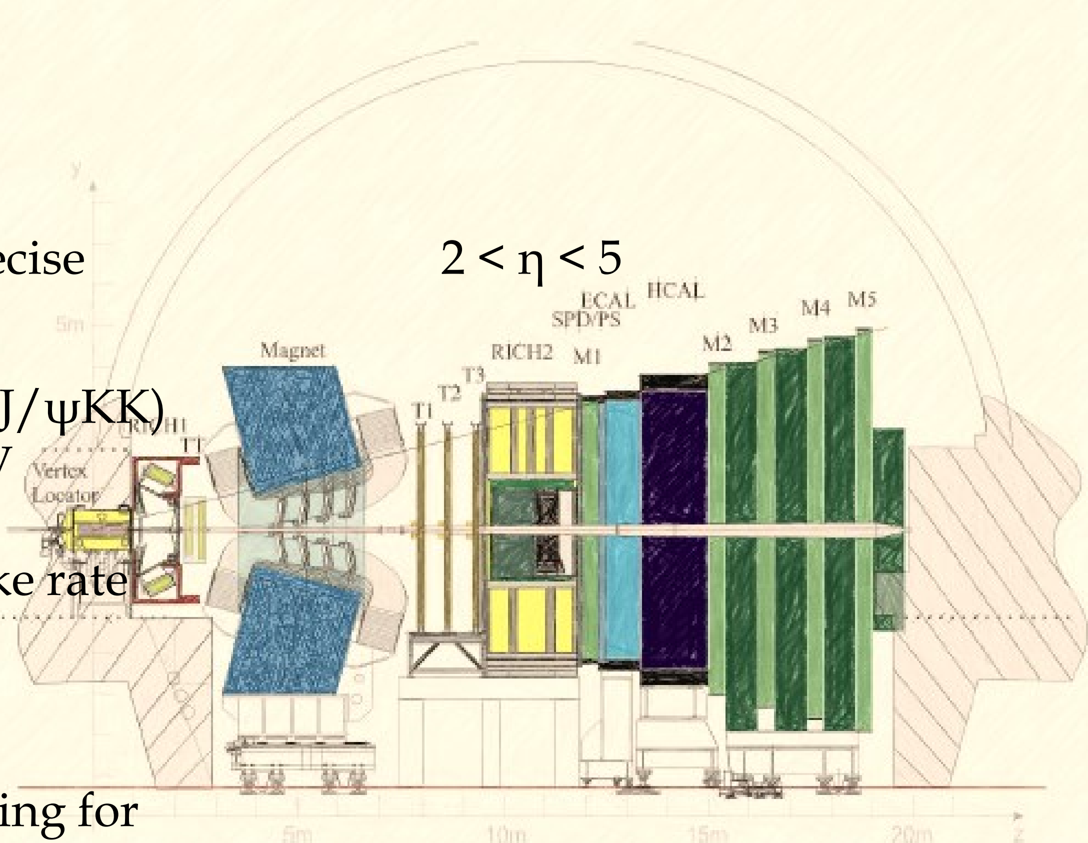
- The LHCb experiment
  - Detector
  - Indirect searches for New Physics
- Measurement of ϕ_s
  - Introduction
  - Results / status
  - Prospects
- Other CPV measurements
  - The CKM angle γ
  - $\phi_s^{\phi\phi}$ from $B_s \to \phi\phi$
  - CPV in B→3h
  - Vub



The LHCb experiment

Forward spectrometer with very precise tracking and PID

- Decay time resolution ~40 fs ($B \rightarrow J/\psi KK$)
- Invariant mass resolution ~8 MeV ($B \rightarrow J/\psi KK$)
- 95% (K-π) ID efficiency for 5% fake rate

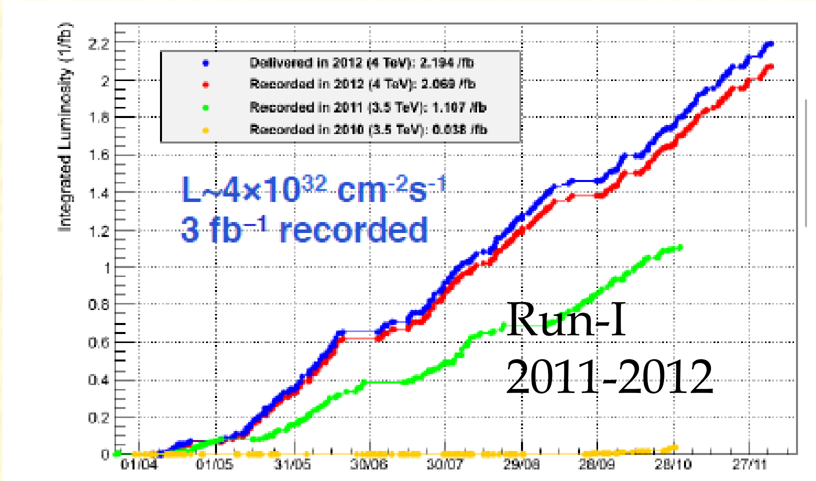


Efficient and flexible trigger

- ε ~80% $B \rightarrow J/\psi X$ decays interesting for physics studies

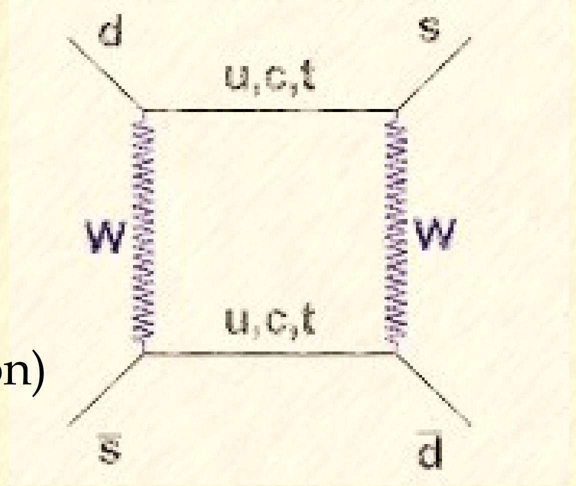
Recorded luminosity: 3 fb^{-1}

1 fb^{-1} at 7 TeV (2011)
2 fb^{-1} at 8 TeV (2012)
>1 fb^{-1} at 13 TeV (2015, 2016)



The LHCb experiment

- The **LHCb physics program** focuses mostly on CP violation and rare decays
- Both correspond to **indirect searches for New Physics** (i.e, new particles),
- Indirect approach has been very successful in the past
  - Neutral Currents
    (Z^0 inferred ten years before direct observation)
  - Kaon mixing
    (top-quark inferred 30 years before direct observation)



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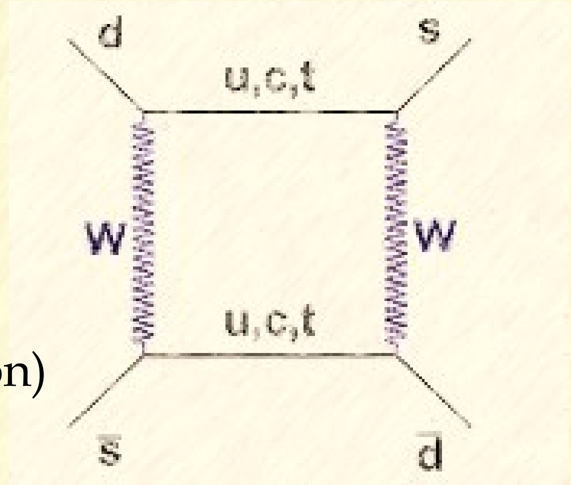
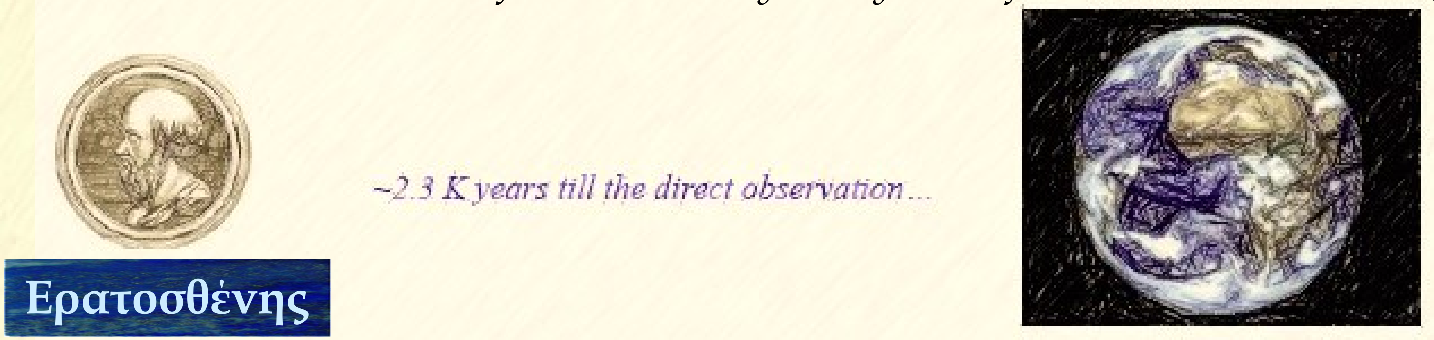
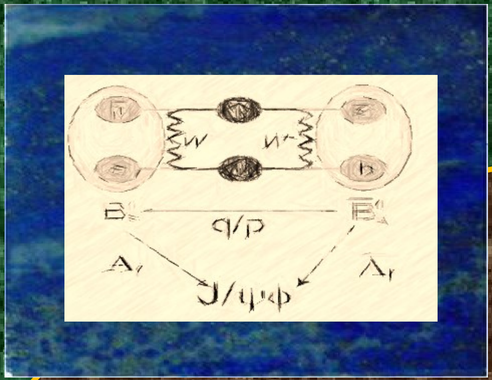
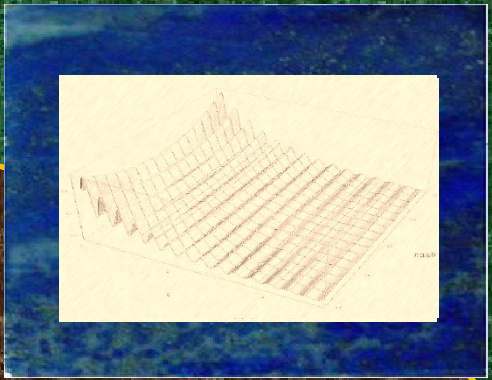


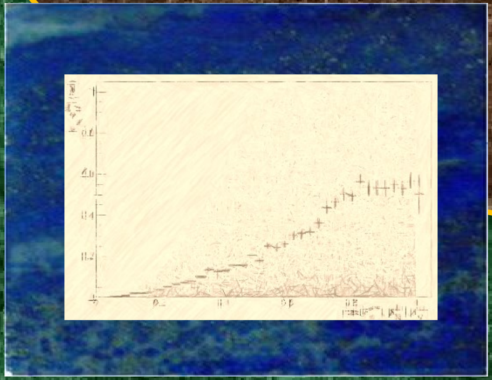
(you may also notice Earth' radius was inferred indirectly 2.3k years before direct observation…)

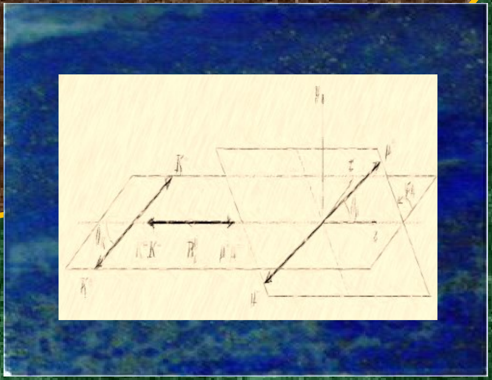




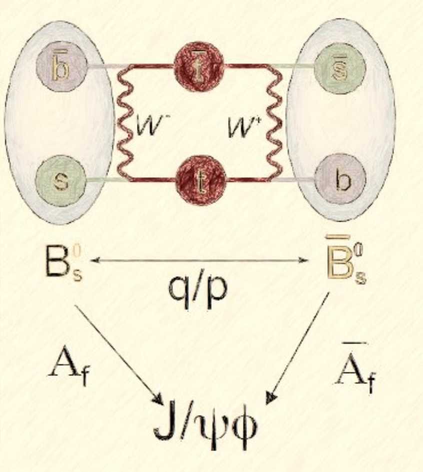


What (and why) Φ_s





Φ_s from $B_s \to J/\psi\ (\rightarrow\mu\mu)\ KK$



B_s mass eigenstates:
$$|B_L^s\rangle = p|B_s\rangle + q|\bar{B}_s\rangle$$
$$|B_H^s\rangle = p|B_s\rangle - q|\bar{B}_s\rangle$$

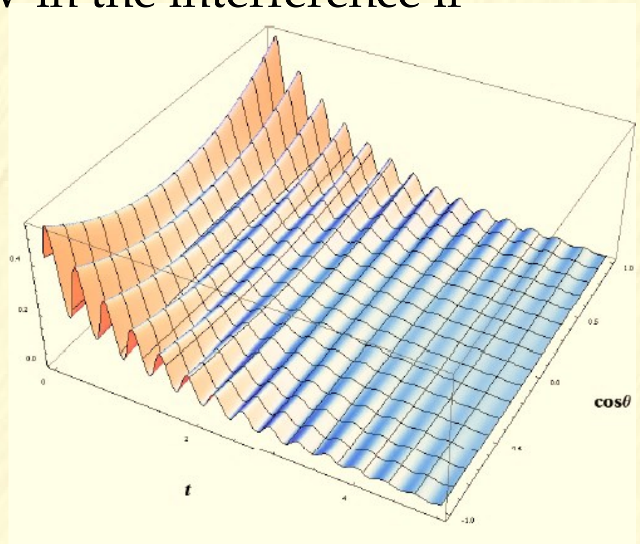
Weak eigenstates (mix via box diagram)

- q/p: complex number. $|q/p| \neq 1 \rightarrow$ CPV in mixing
- $A_f, \overline{A_f}$ complex amplitudes. $|A_f/\overline{A_f}| \neq 1 \rightarrow$ CPV in decay

Even if not CPV in mixing or decay, you can generate CPV in the interference if

$$\sin(\boldsymbol{\phi_s}) \equiv \sin\left(-arg\left(\frac{q}{p}\frac{A_f}{\overline{A_f}}\right)\right) \neq 0$$

Main (but not only) experimental signature of a non-zero $\boldsymbol{\phi_s}$: it generates **wiggles** in the time-dependent angular distribution of the $B_s \rightarrow J/\psi\ \phi \rightarrow \mu\mu KK$ final state particles. The frequency of the (potential) wiggles is known: Δm_s.



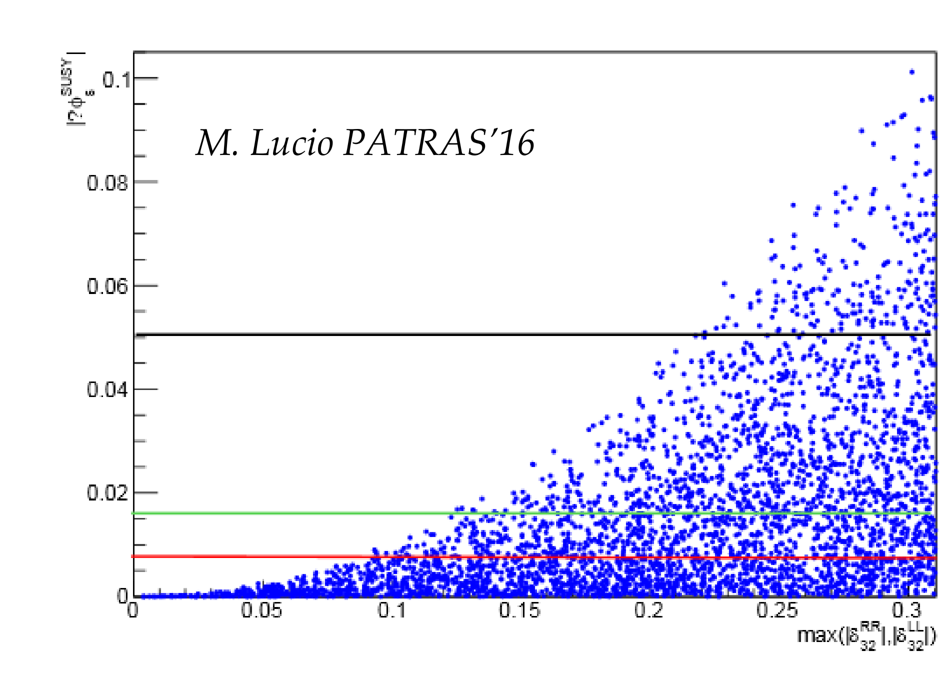
Φ_s : Standard Model and New Physics sensitivity

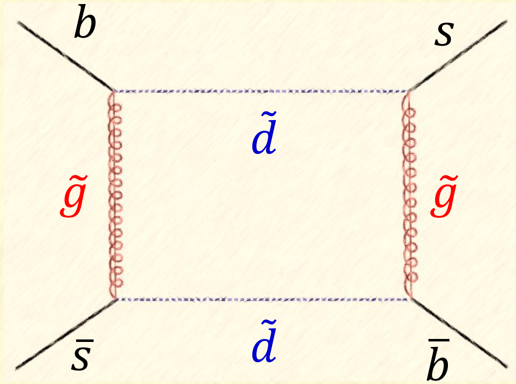
SM prediction: $\Phi s = -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right)$= -0.038±0.001(*)

(*)Neglecting penguin contributions CKMFitter.

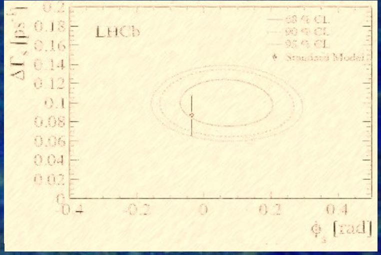
It is very precise, and sensitive to Physics Beyond the SM, specially to non–MFV New physics …. which is accessible even if the NP is at a high scales

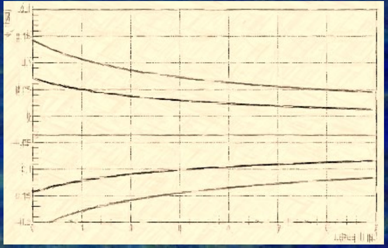
→ Illustrative (brute force) test: calculate non-MFV SUSY contributions setting all particle masses to wino DM mAMSB best fit point



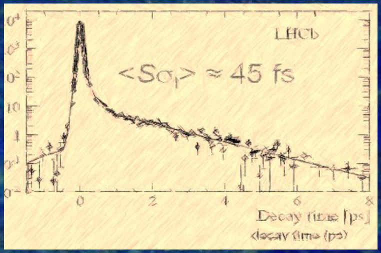


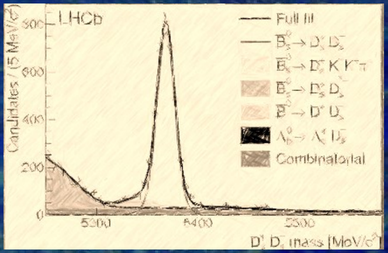
Those potential effects are within reach of current experimental precision!





Results and prospects



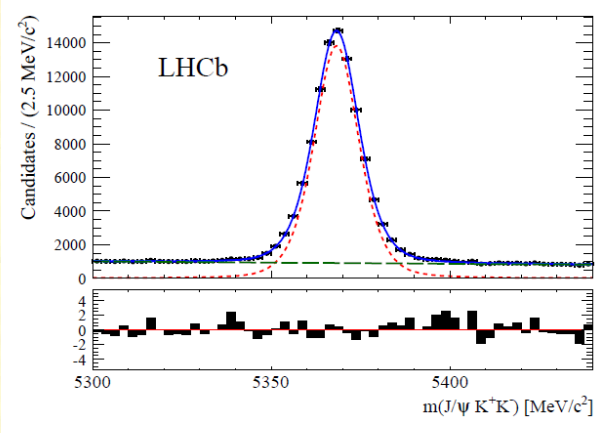


Φ_s from $B_s \rightarrow J/\psi$ (→μμ) KK

Phys. Rev. Lett. 114, 041801 (2015)

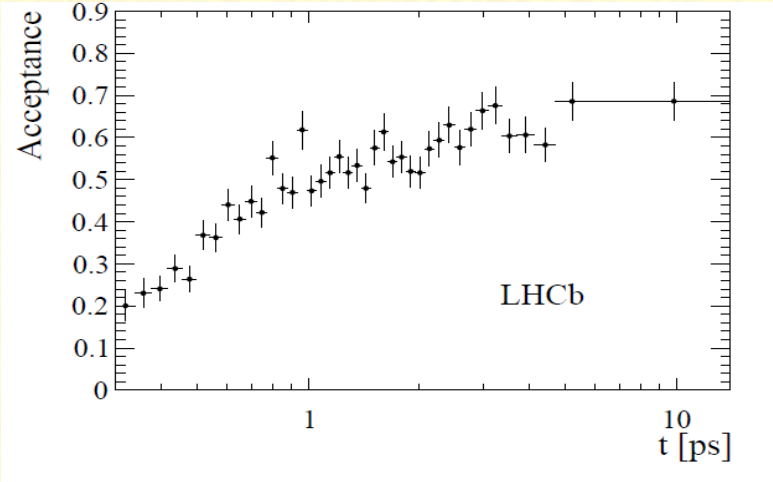
Analysis strategy: Fit the time dependent angular distribution, considering experimental effects:

- **Background**: Events are weighted according to position in J/ψKK mass spectrum



- Angular distributions are distorted on data because of **non-flat angular acceptance**. Simulation (weighted according to kinematics seen on data) is used to correct for this

- **Lifetime acceptance**. Samples from different trigger lines are used to unfold trigger biases. Simulation is used for selection/reconstruction biases

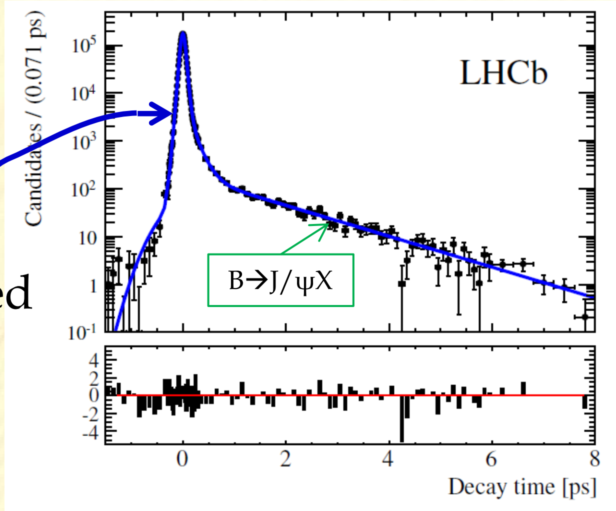


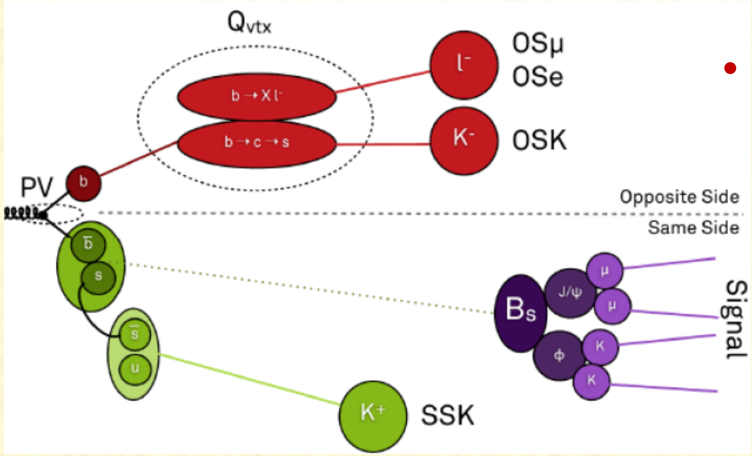
Φ_s from $B_s \rightarrow J/\psi$ ($\rightarrow\mu\mu$) KK

Phys. Rev. Lett. 114, 041801 (2015)

Analysis strategy: Fit the time dependent angular distribution, considering experimental effects:

- **Lifetime resolution**: Non-perfect time resolution (45 fs, still much smaller than oscillation period, 350 fs) convolved with the pdf. Main effect is a ~25% dilution of the amplitude of the wiggles. Measured on data using prompt J/ψ events

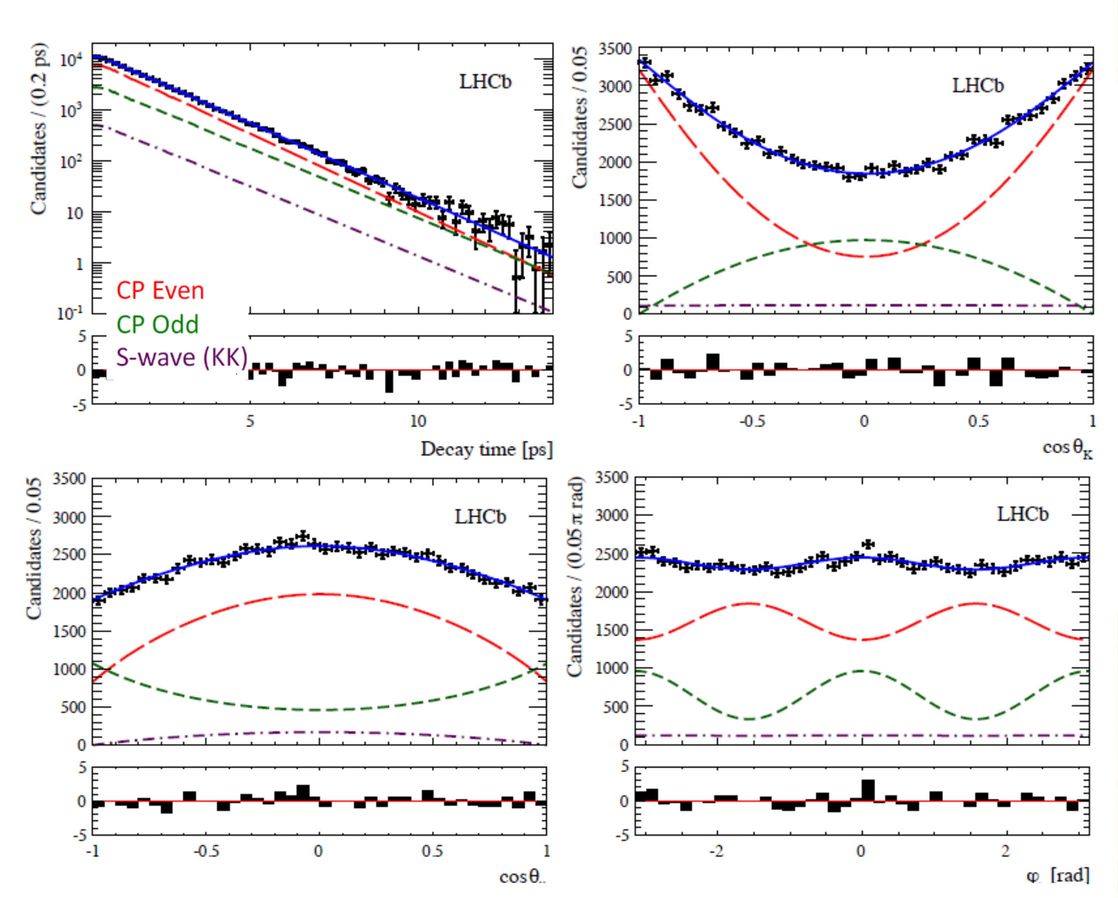


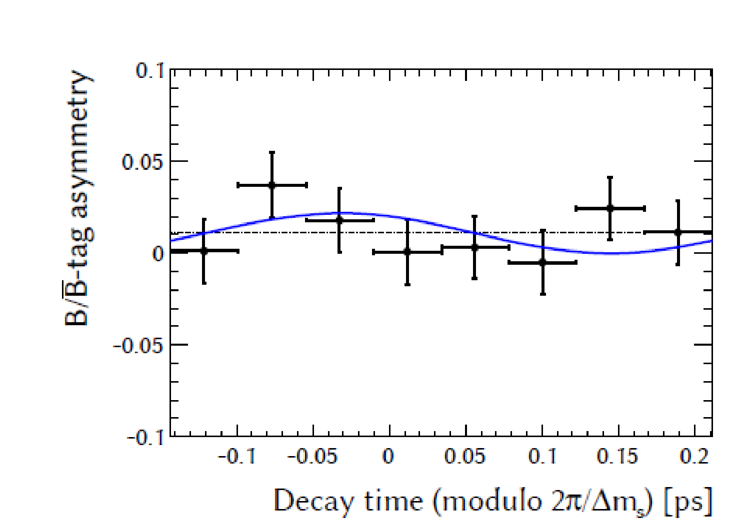


- **Flavour tagging**: The initial flavour of the B_s is determined either by a muon/kaon from the other B, and/or by a kaon from the fragmentation. The performance of these taggers is calibrated with control samples such as $B^+ \rightarrow J/\psi K^+$, $B_d \rightarrow D^{*+}\mu\upsilon$ and $B_s \rightarrow D_s^- \pi^+$

Φ_s from $B_s \rightarrow J/\psi$ ($\rightarrow\mu\mu$) KK

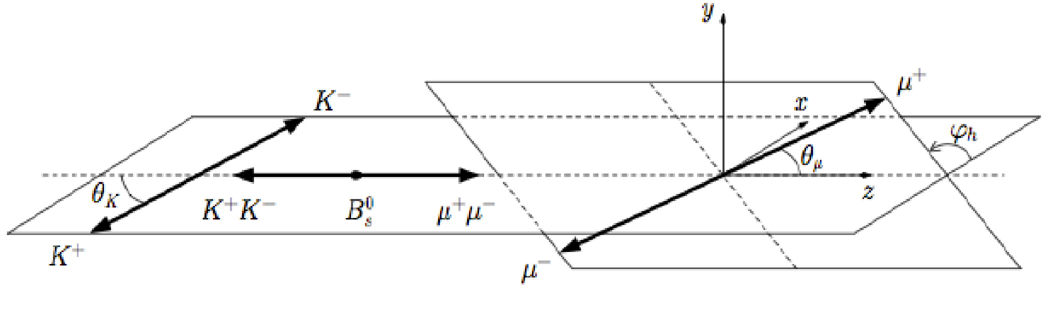
Phys. Rev. Lett. 114, 041801 (2015)





ϕ_s ($B_s \rightarrow J/\psi KK$), 3fb^{-1}

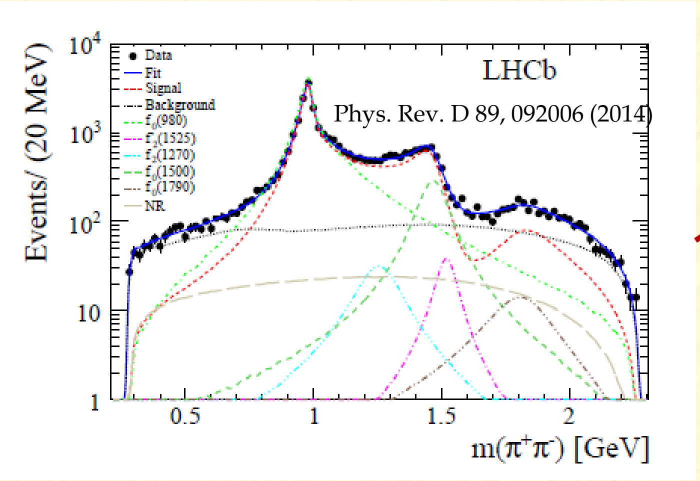
-0.058±0.049±0.006 rad

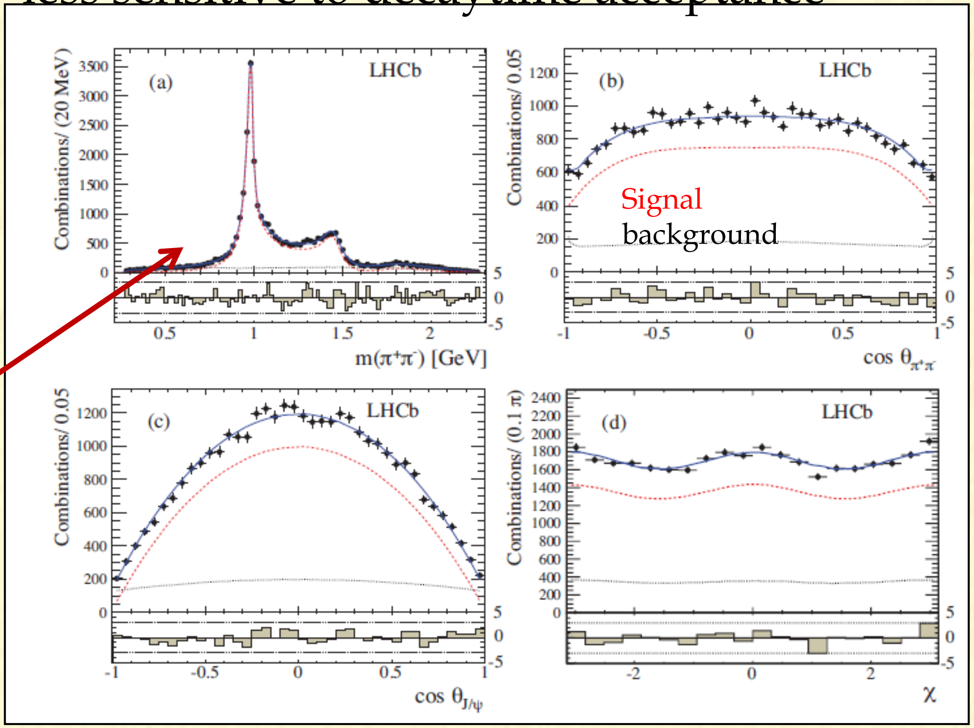


Phys. Rev. D 89, 092006 (2014)

Φ_s from $B_s \to J/\psi\ (\to\mu\mu)\ \pi\pi$

- Similar analysis methodology than $B_s \to J/\psi KK$. Some differences:
  - Deal with several $\pi^+\pi^-$ resonances (implies a time dependent Dalitz analysis)
  - Almost no sensitivity to $\Delta\Gamma_s$ → less sensitive to decaytime acceptance

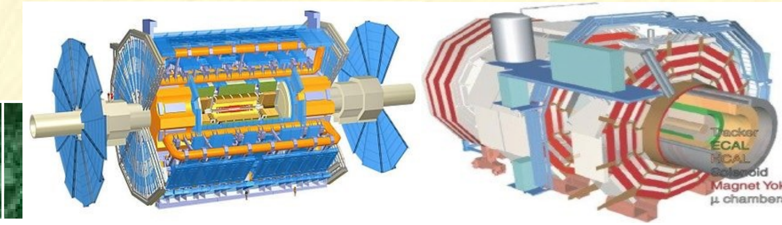




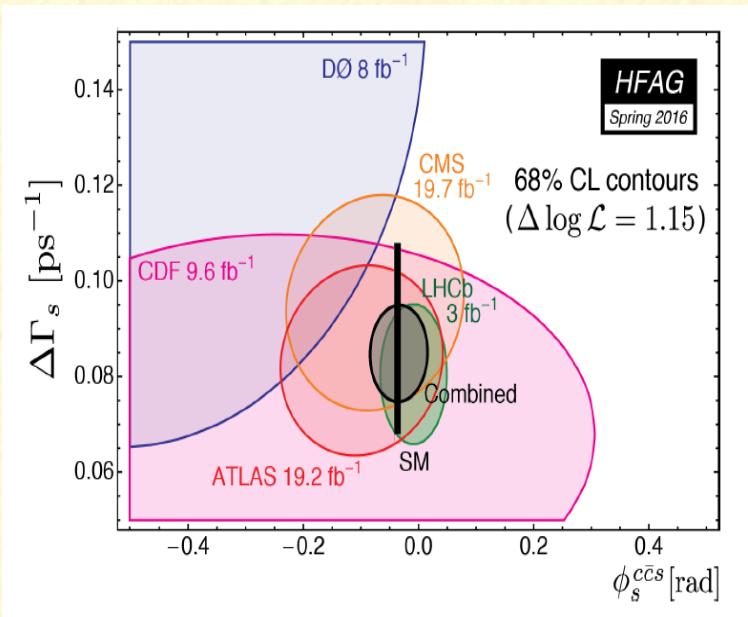
ϕ_s ($B_s \to J/\psi\pi\pi$), $3\,fb^{-1}$ = 0.075±0.067±0.008 rad

Φ_s (ATLAS/CMS)

ATLAS and CMS also study
$B_s \to J/\psi\ \phi \to \mu\mu KK$



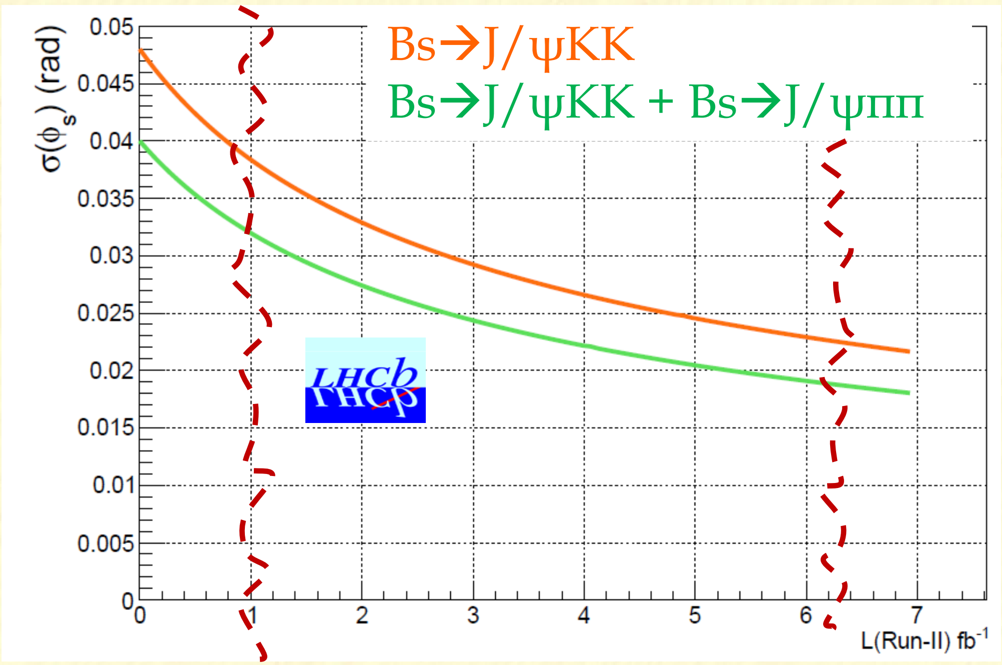
Experiment		
Lumi. (fb^{-1})	14.3	19.7
$\Delta\Gamma_s$ (ps^{-1})	0.085±0.011±0.007	0.095±0.013±0.007
Φ_s	-0.090±0.078±0.041 JHEP 08（2016）147	-0.075±0.097±0.031 PLB 757（2016）97



ϕ_s (World Average) = -0.033±0.033 rad

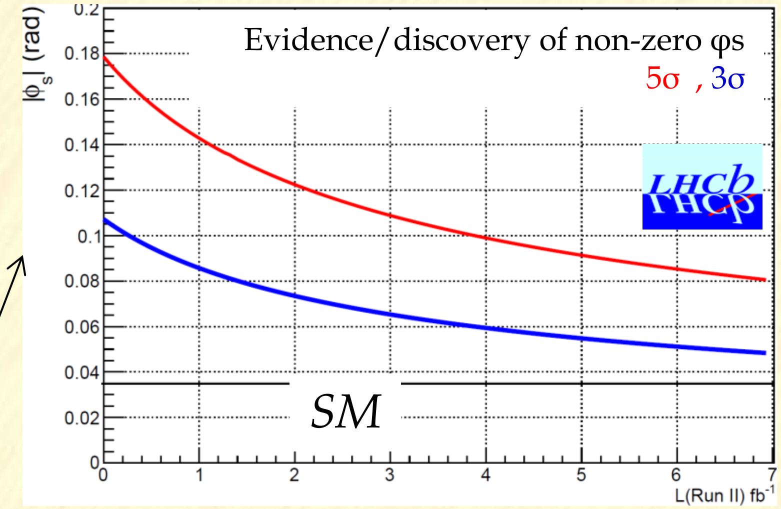
SM prediction: Φs = -0.038±0.001(*)

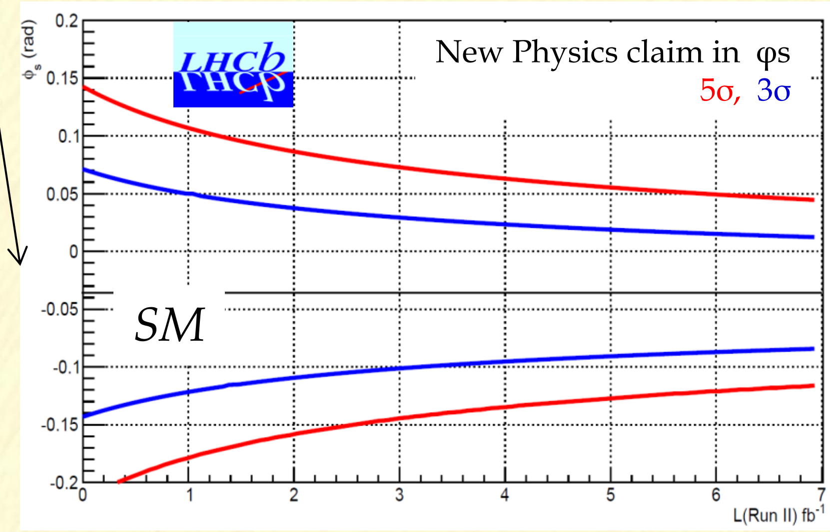
Prospects



~2016

~ end of Run-II



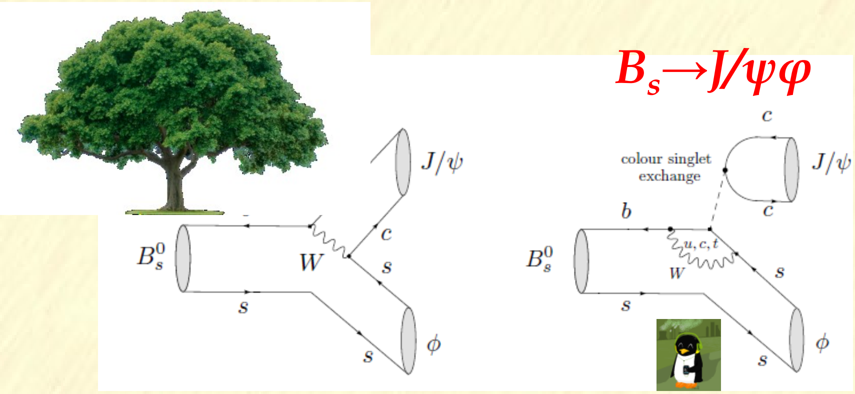


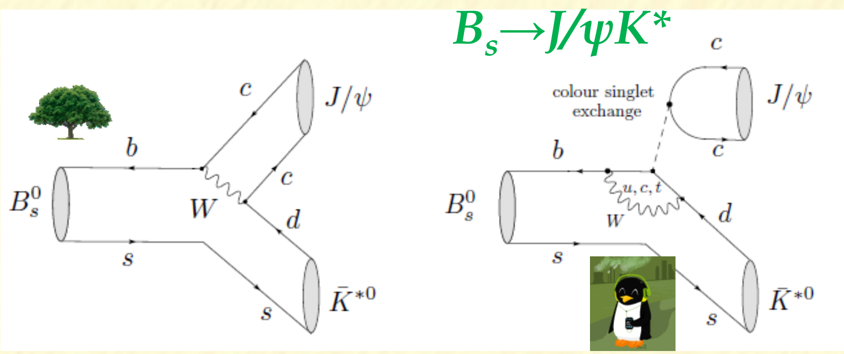
… and with LHCb upgrade the sensitivity can go below 0.01 rad

Penguin pollution

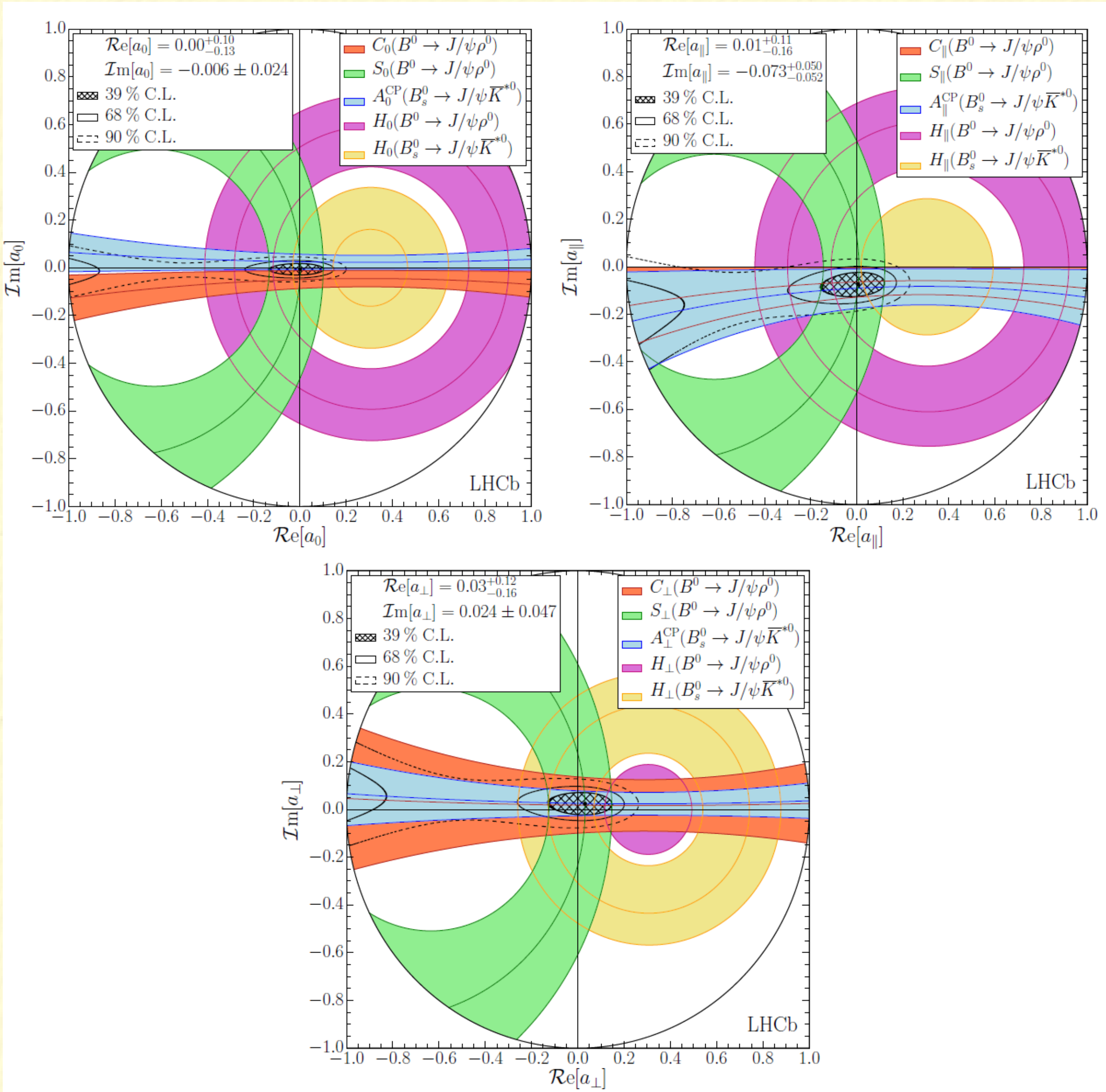
- Penguin contributions to Φ_s , are usually neglected because they are doubly Cabibbo supressed.
- However, these contributions cannot be calculated reliably from QCD
- S. Faller, R. Fleischer, T. Mannel arXiv:0810.4248 [hep-ph] propose a method to calculate the penguin pollution to Φ_s by analyzing Bs → $J/\psi K^*$ and Bd → $J/\psi\rho$ data

Source: google penguin pollution





Penguin pollution



Results dominated by Bd → J/ψρ

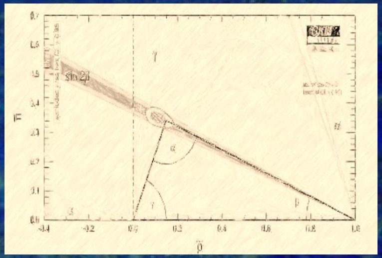
The penguin contribution to ϕ_s is measured to be consistent with zero for all polarization states

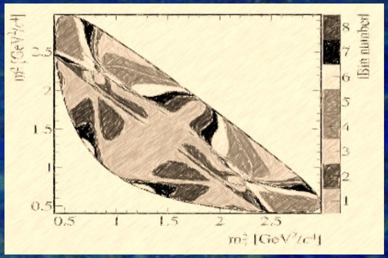
[LHCb, PLB 742 (2015) 38-49] [LHCb, JHEP 11 (2015) 082]

$$\delta_P^0 = 0.000 \;^{+0.009}_{-0.011}\;^{+0.004}_{-0.009}\ \text{rad}$$

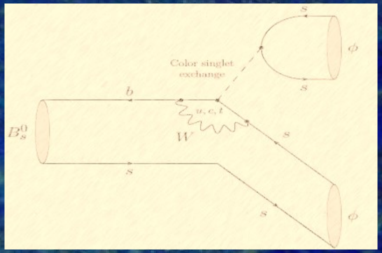
$$\delta_P^\parallel = 0.001 \;^{+0.010}_{-0.014} \pm 0.008\ \text{rad}$$

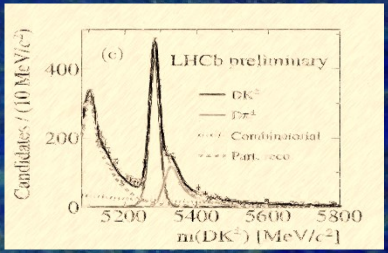
$$\delta_P^\perp = 0.003 \;^{+0.010}_{-0.014} \pm 0.008\ \text{rad}$$





Other CPV measurements





$\phi_s^{\phi\phi}$ *from* $B_s \to \phi\phi$

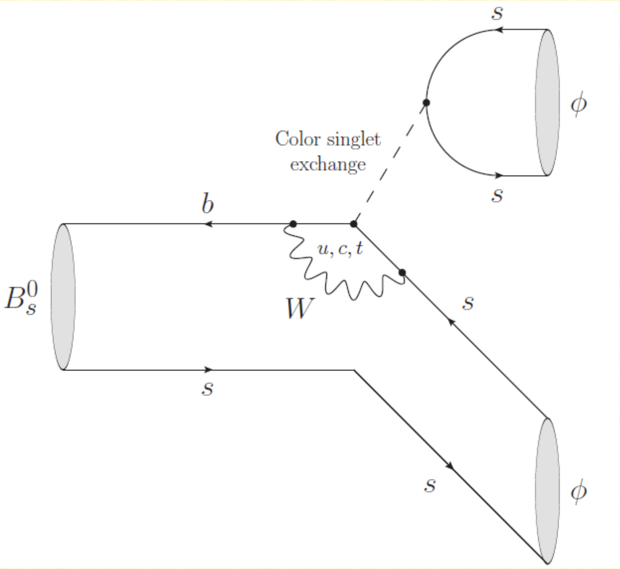
PRD 90 (2014) 052011

$$\phi_s^{\phi\phi} \equiv arg\left(\frac{q}{p}\frac{A\,(\overline{B_s} \to \phi\phi)}{A\,(B_s \to \phi\phi)}\right)$$

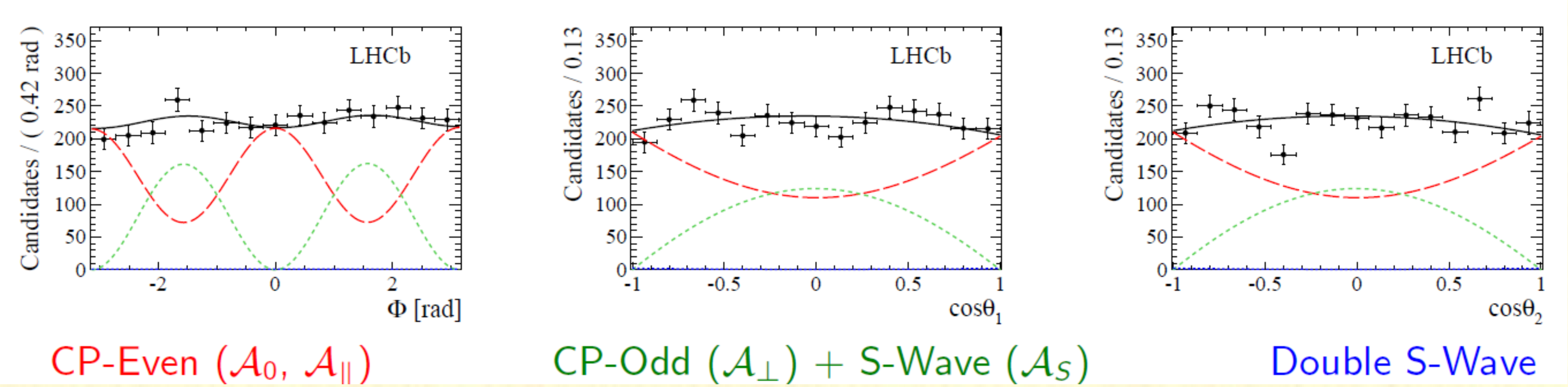
different quantity than the Φs I presented at the beginning of my talk

SM expectation is $\phi_s^{\phi\phi} < 0.02$

arXiv:0810.0249
arXiv:hep-ph/0612290
arXiv:0910.5237



Also measured through time dependent angular analysis. We have analysed the full Run-I dataset:



$$\phi_s^{\phi\phi} = -0.17 \pm 0.15 \pm 0.03$$

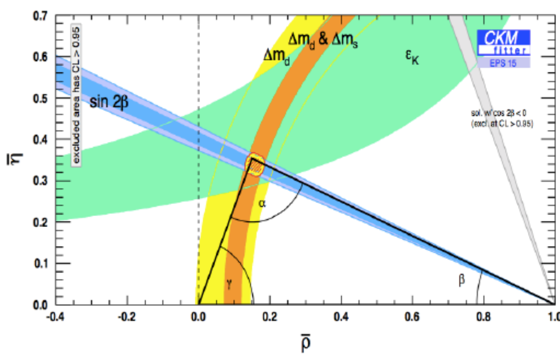
In very good agreement with SM

The CKM angle γ

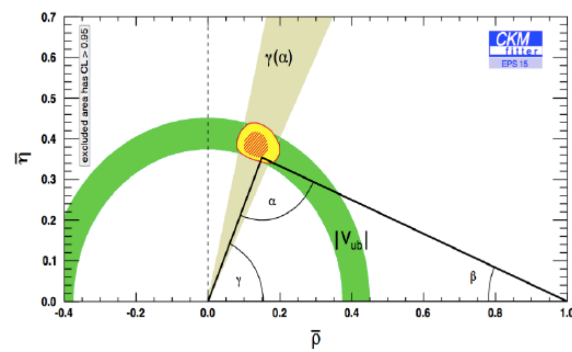
$$
\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}
$$

$$
\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}
$$

Measurements from "loop"



Measurements from "tree"



- The precision of the SM prediction is very high, $\delta\gamma/\gamma \sim 10^{-7}$ (JHEP 1401(2014)051)
- Comparison between different measurements (specially those from tree-level decays with loop-level decays) **can be used to test SM /NP**

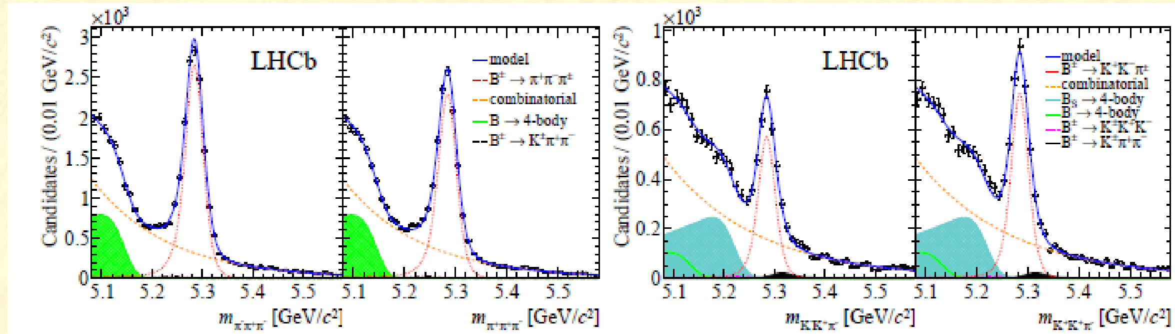
Experiment	ref	γ (degrees)
BaBar	PRD87(2013)05015	70^{+18}_{-17}
Belle	arXiv:1301.2033	73^{+13}_{-15}
LHCb	LHCb-CONF-2016-001	$70.9^{+7.1}_{-8.5}$

CPV in B→3h

Phys. Rev. D 90 (2014) 112004

Study of CP asymmetries across the B→3h Dalitz plane

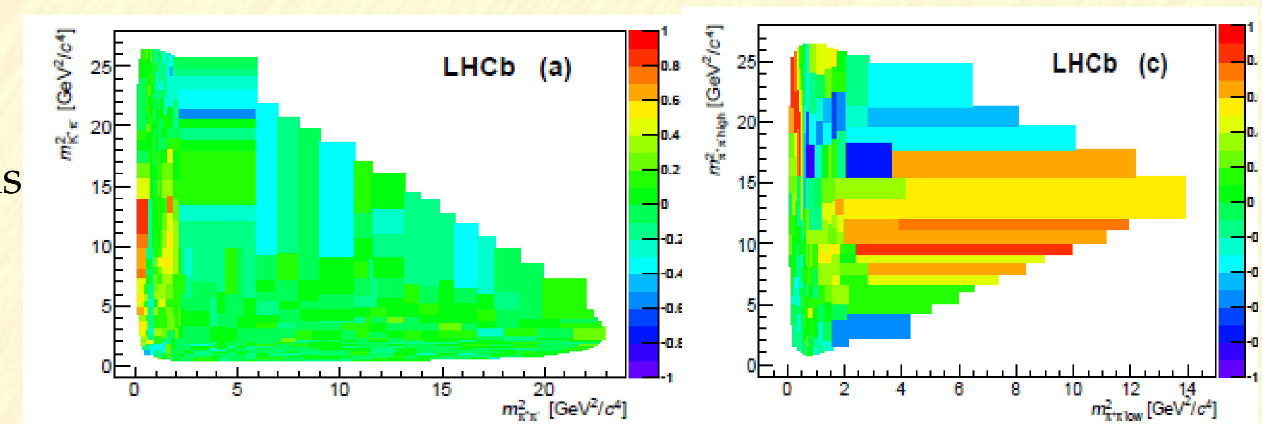
Overall CP asymmetries are found to be significant



$$
\begin{aligned}
A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) &= +0.025 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm})\,,\\
A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) &= -0.036 \pm 0.004\,(\text{stat}) \pm 0.002\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm})\,,\\
A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) &= +0.058 \pm 0.008\,(\text{stat}) \pm 0.009\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm})\,,\\
A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) &= -0.123 \pm 0.017\,(\text{stat}) \pm 0.012\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm})\,,
\end{aligned}
$$

(3 fb^{-1})

On top of that, the asymmetries in some regions of the Dalitz plane are huge



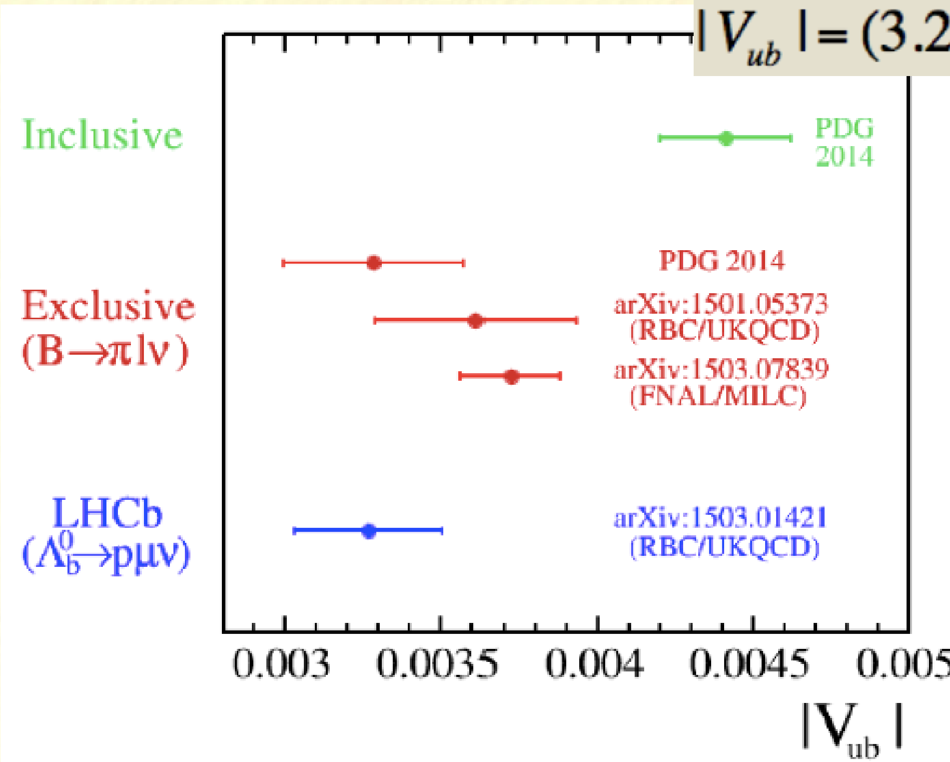
V_{ub} from semilectonic Λ_b decays

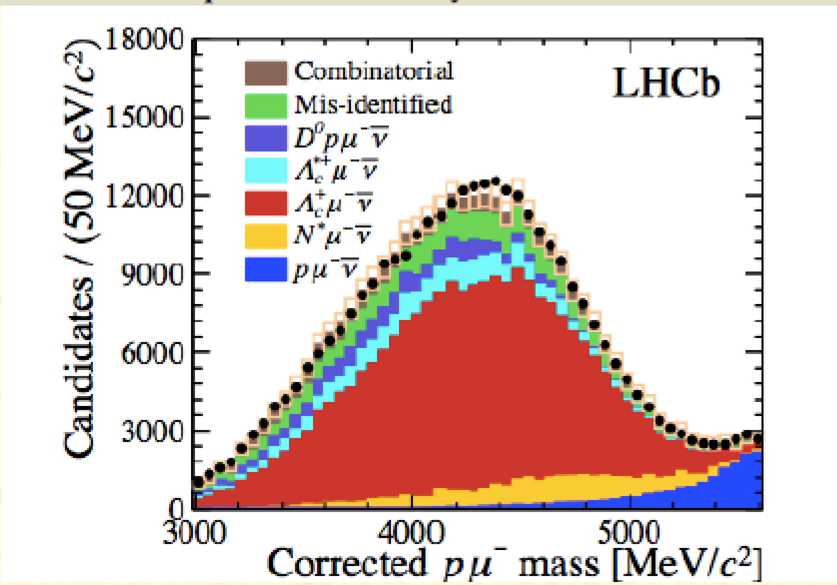
Nature Physics 11 (2015) 743

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\ GeV^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\ GeV^2}} R_{FF}$$

form factor ratio
5% uncertainty
on $|V_{ub}|$

$$|V_{ub}| = (3.27 \pm 0.15_{exp} \pm 0.17_{theory} \pm 0.06_{|Vcb|}) \times 10^{-3}$$



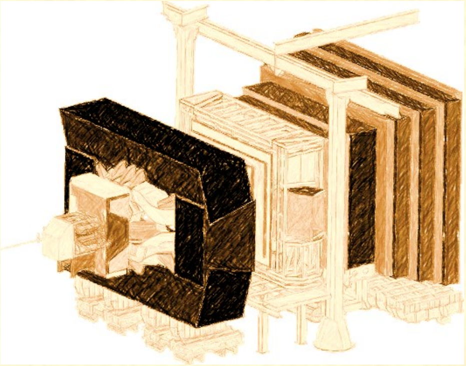


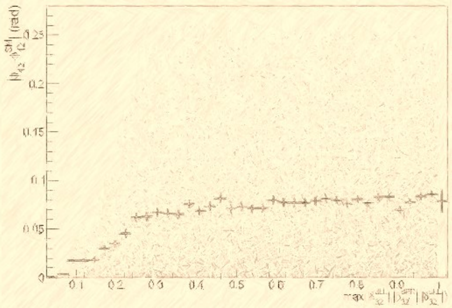
Conclusions

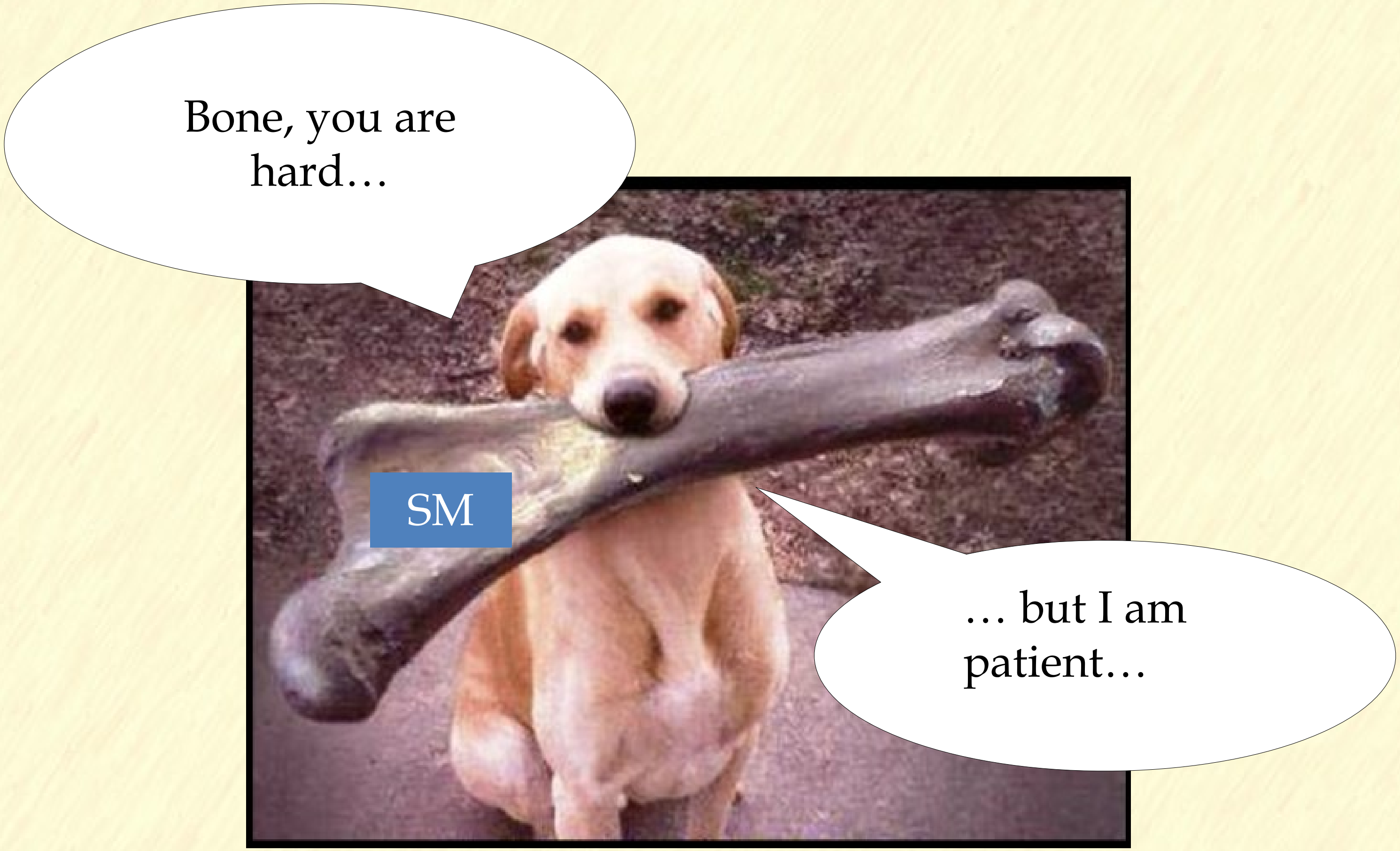
. Different CPV measurements from different types of decays and transitions @ LHC consistent with SM expectations

. V_{ub} LHCb measurements from exclusive Λ_b decays consistent with other exclusive results

. Good prospects for the LHCb upgrade!







source: google osso duro

Penguin pollution

arXiv:0810.4248

Mainly two observables:

$$H_f = \frac{1}{\epsilon}\left|\frac{\mathcal{A}_f}{\mathcal{A}'_f}\right|^2 \frac{\Gamma[f,t=0]'}{\Gamma[f,t=0]} = \frac{1 - 2a'_f\cos\theta'_f\cos\gamma + a'^2_f}{1 + 2\epsilon a_f\cos\theta_f\cos\gamma + \epsilon^2 a_f^2}$$

$F(|V_{us}|)$

CKM angle

penguin stuff

f = polarization state

Experimental input. Basically $\frac{(BR \cdot f_f)_{J/\psi K^*}}{(BR \cdot f_f)_{J/\psi\varphi}}$

(modulo lifetimes)

$$\hat{A}_D^{f'} = \frac{2a'_f\sin\theta'_f\sin\gamma}{1 - 2a'_f\cos\theta'_f\cos\gamma + a'^2_f},$$

Direct CP asymmetry (difference of yields)

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Direct CP asymmetry (difference of yields)

SU(3) → a′ = a, θ′ = θ

…and plug here

$$\tan\Delta\phi_s^f = \frac{2\epsilon a_f\cos\theta_f\sin\gamma+\epsilon^2a_f^2\sin2\gamma}{1+2\epsilon a_f\cos\theta_f\cos\gamma+\epsilon^2a_f^2\cos2\gamma}$$

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penguin stuff

This other stuff are SU(3) breaking effects which are currently poorly known

$$\left|\frac{\mathcal{A}'_0}{\mathcal{A}_0}\right|^2 = 0.42 \pm 0.27\,,$$

$$\left|\frac{\mathcal{A}'_\parallel}{\mathcal{A}_\parallel}\right|^2 = 0.70 \pm 0.29\,,$$

$$\left|\frac{\mathcal{A}'_\perp}{\mathcal{A}_\perp}\right|^2 = 0.38 \pm 0.16\,.$$

Penguin pollution

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Or maybe not so poorly?

arXiv:1309.0313 [hep-ph]

arXiv:0810.4248

$$\left|\frac{\mathcal{A}'_0}{\mathcal{A}_0}\right|^2 = 0.42 \pm 0.27\,, \quad \rightarrow \quad = 0.858^{+0.206}_{-0.196}$$

$$\left|\frac{\mathcal{A}'_\parallel}{\mathcal{A}_\parallel}\right|^2 = 0.70 \pm 0.29\,, \quad \rightarrow \quad = 0.845^{+0.210}_{-0.188}$$

$$\left|\frac{\mathcal{A}'_\perp}{\mathcal{A}_\perp}\right|^2 = 0.38 \pm 0.16\,. \quad \rightarrow \quad = 0.869^{+0.234}_{-0.204}$$

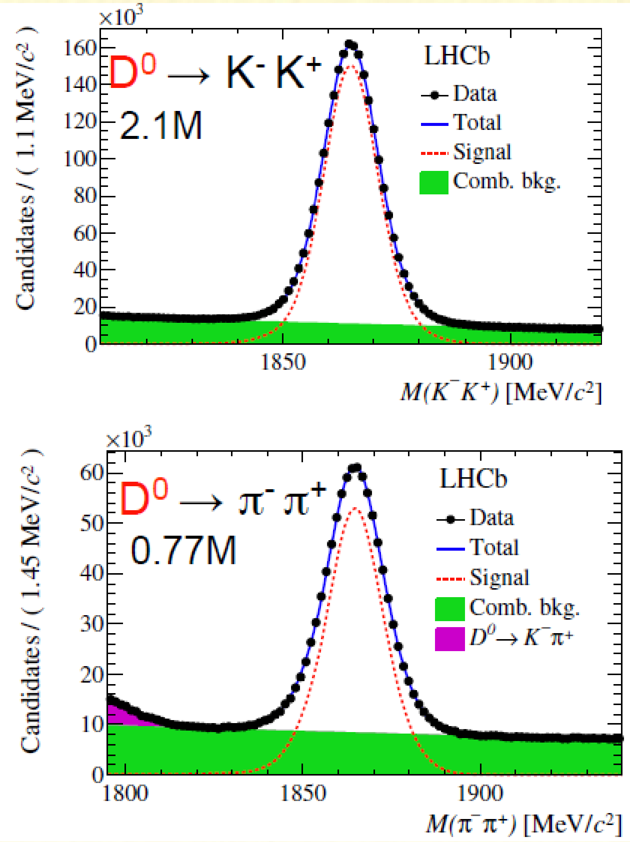
CPV in charm

$$A_{CP} \equiv \frac{N(D^0 \to h^- h^+) - N(\bar{D}^0 \to h^- h^+)}{N(D^0 \to h^- h^+) + N(\bar{D}^0 \to h^- h^+)}$$

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

$$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$$

arxiv:1405.2797

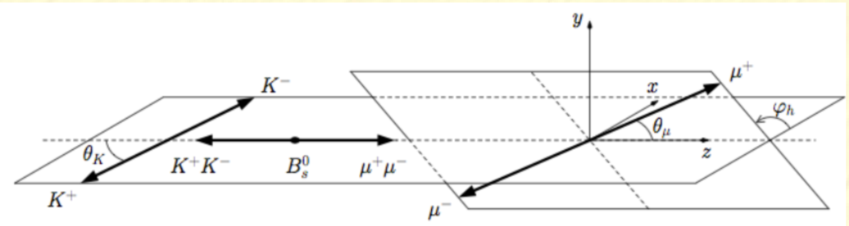


Other recent studies of CPV in charm:

$D_{(s)}^+ \to K_S h^+$ (arXiv: 1406.2624)
$D^+ \to \pi^+\pi^-\pi^+$ PLB 728 (2014) 585
$D^0 \to K^+K^-\pi^+\pi^-$ (LHCb-PAPER-2014-046)

… all consistent for the moment with CP conservation.

Φ_s *from* $B_s \to J/\psi\ (\rightarrow \mu\mu)\ KK$



wiggles

$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right],\\
|A_\parallel(t)|^2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right],\\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right],\\
\Im(A_\parallel(t)\,A_\perp(t)) &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.\\
&\quad \left.- \cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)\right],\\
\Re(A_0(t)\,A_\parallel(t)) &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.\\
&\quad \left.+ \sin\phi_s \sin(\Delta m t)\right],\\
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&\quad \left.- \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)\right],\\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right],\\
\Re(A_s^*(t)A_\parallel(t)) &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\cos\phi_s \sin(\Delta m t)\right.\\
&\quad \left.+ \cos(\delta_\parallel - \delta_s)\cos(\Delta m t)\right],\\
\Im(A_s^*(t)A_\perp(t)) &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.\\
&\quad \left.- \sin\phi_s \sin(\Delta m t)\right],\\
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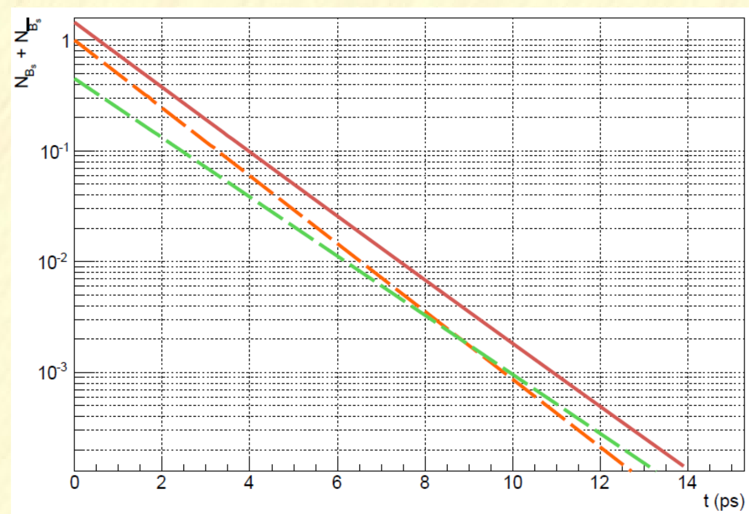
&\quad \left.- \sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)\right].
\end{aligned}
$$

Apart from the wiggles, there are other terms in the pdf that have some sensitivity to Φs:



The CKM angle γ

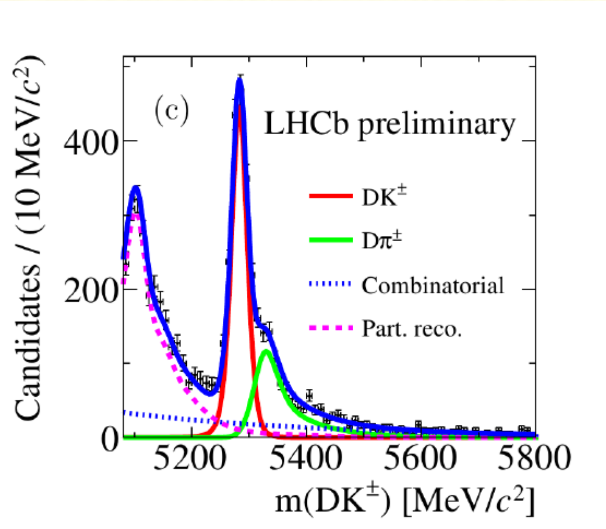
LHCb-PAPER-2014-041

- $B^{\pm} \to DK^{\pm}$, full Run-I dataset

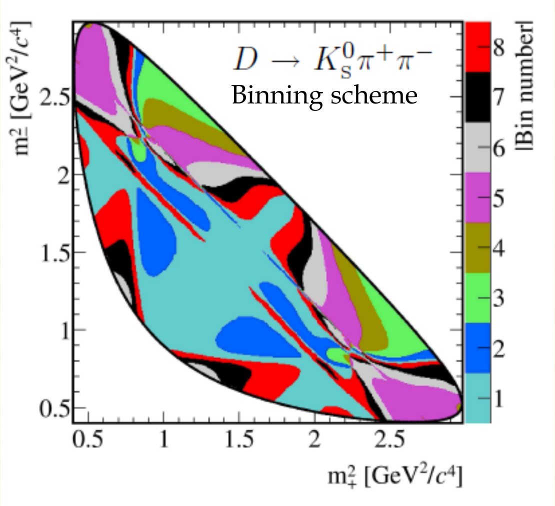
Measured by comparing the Dalitz plot of the D decays between D's from B^+ and D's from B^-.

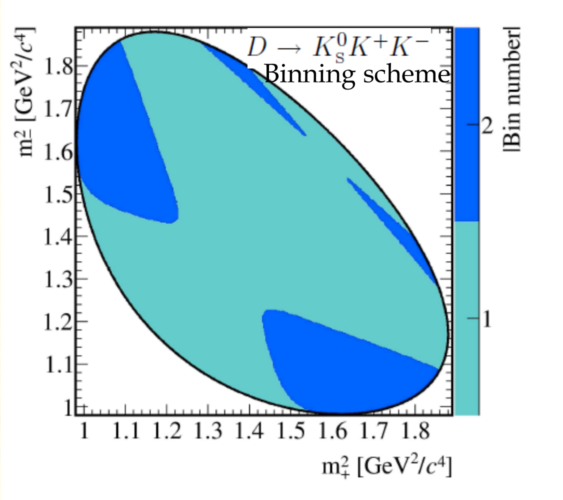
$$A_+(m_+^2, m_-^2) \equiv \bar{A}(m_+^2, m_-^2) + r_B e^{i(\delta+\gamma)} A(m_+^2, m_-^2)$$

$$A_-(m_+^2, m_-^2) \equiv A(m_+^2, m_-^2) + r_B e^{i(\delta-\gamma)} \bar{A}(m_+^2, m_-^2)$$



The (m_+^2, m_-^2) Dalitz planes are binned in a non-trivial way in order to maximize sensitivity to γ





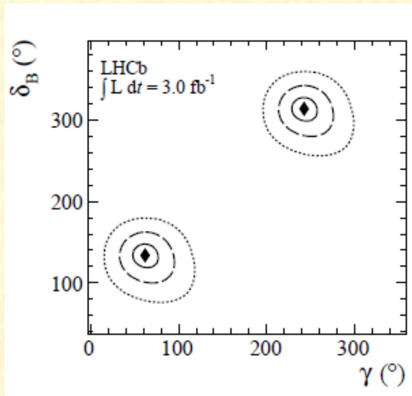
The CKM angle γ

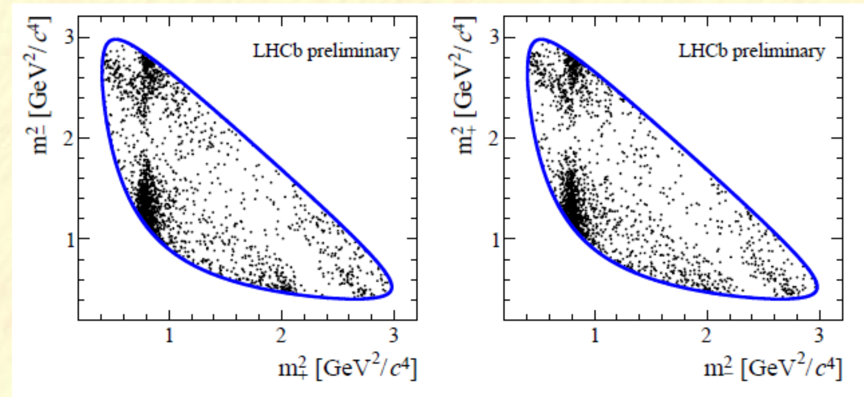
LHCb-PAPER-2014-041

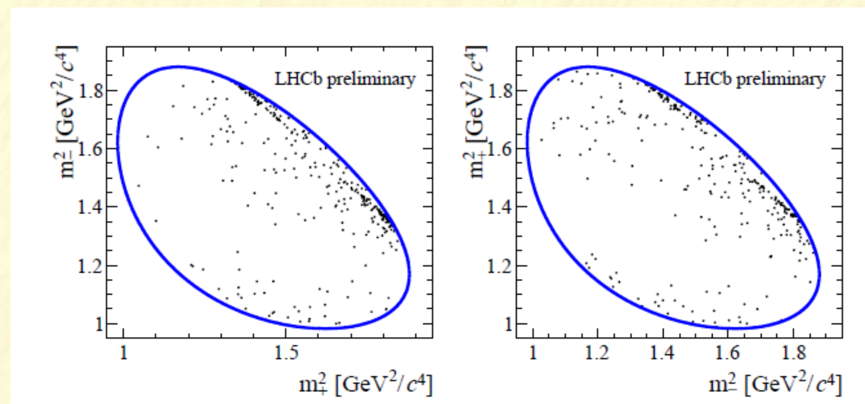
$$A_+(m_+^2, m_-^2) \equiv \overline{A}(m_+^2, m_-^2) + r_B e^{i(\delta+\gamma)} A(m_+^2, m_-^2)$$

$$A_-(m_+^2, m_-^2) \equiv A(m_+^2, m_-^2) + r_B e^{i(\delta-\gamma)} \overline{A}(m_+^2, m_-^2)$$

Detector efficiency modelled with data from B→D*μυ







$$\gamma = (62^{+15}_{-14})^\circ$$

(modulo 180°)