Challenges & opportunities in the quark flavour sector

Yuehong Xie
CCNU

清华大学工物学术论坛
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About the speaker

Recently joined CCNU.
2003-2013: School of Physics, University of Edinburgh, which boasts Peter Higgs!

Outlines

- Successes of SM in quark flavour sector
- Challenges in the sector: requirement of higher precision and wider scope
- Turn challenges into opportunities: some personal experience
- Conclusions

Status ...

Physics frontiers at LHC

Energy frontier: ATLAS and CMS

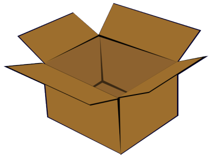
Search for direct production of TeV level new particles

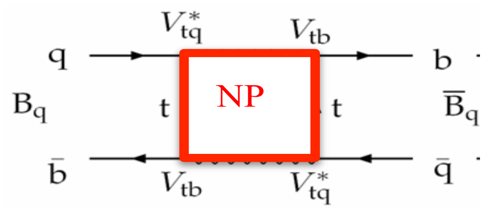
Quantum frontier: LHCb

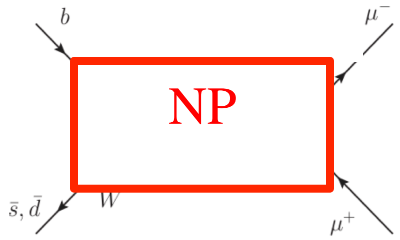
Test CKM and search for new sources of CP violation

Explore physics up to 100 TeV

Study flavour changing processes and seek footprints of new particles in the quantum loops







Quark flavour physics

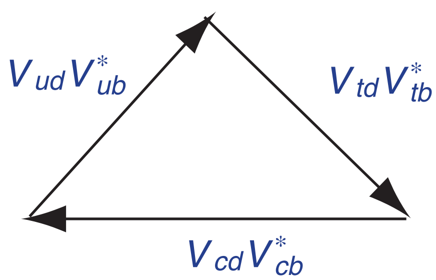
- Flavour and CP violation in Standard Model (SM)

CKM matrix links mass eigenstates and weak eigenstates

CKM matrix — Wolfenstein parameterization:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP Violation is possible in the Standard Model only if V_{CKM} is complex ⇔ $\eta \neq 0$ ⇔ Unitarity Triangle is not flat



- New sources of CP violation needed to explain the matter-antimatter asymmetry in the Universe

Where to look for surprises

- Observables that are well understood in the SM but sensitive to new physics (NP) contributions
  - ✧ Rate of rare decays
  - ✧ Angular distributions in FCNC decays
  - ✧ CP violation
  - ✧ …

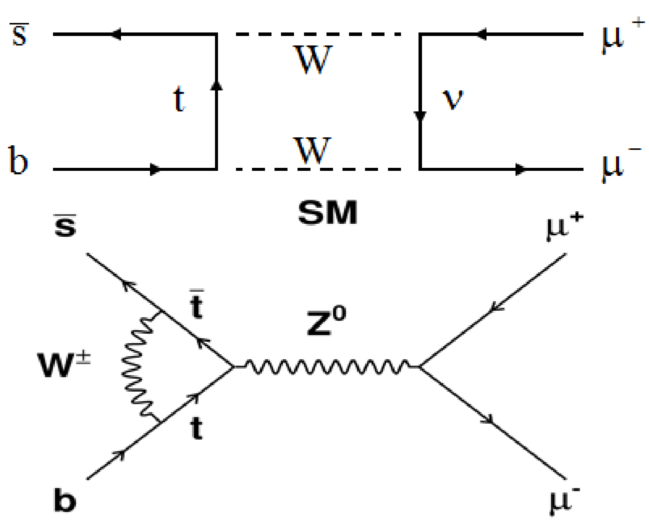
Example:

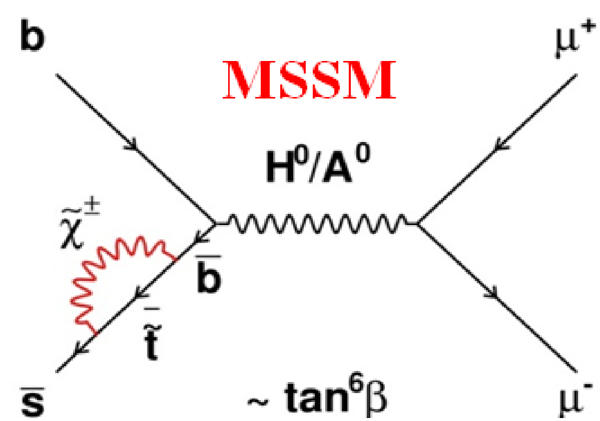
rate of $B_{(s)}^{0} \longrightarrow \mu^{+}\mu^{-}$

Search for $B_{(s)}^0 \to \mu^+\mu^-$

- Strongly suppressed in SM
  - helicity suppression
  - loop suppression

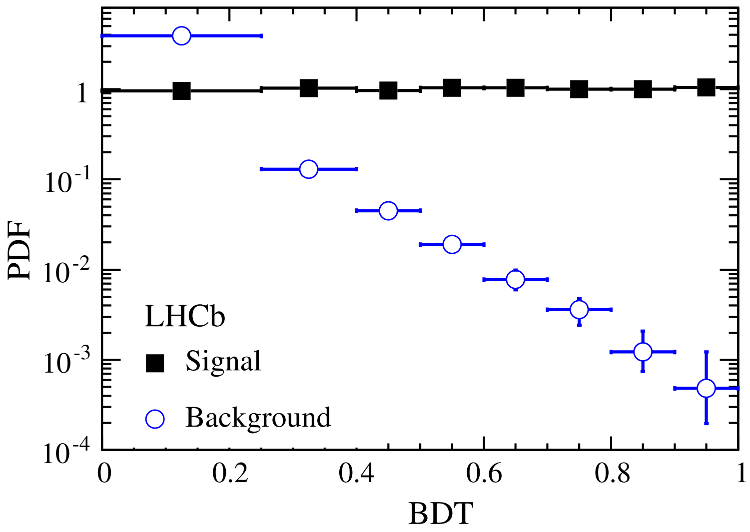
- Golden mode to probe new scalar interactions

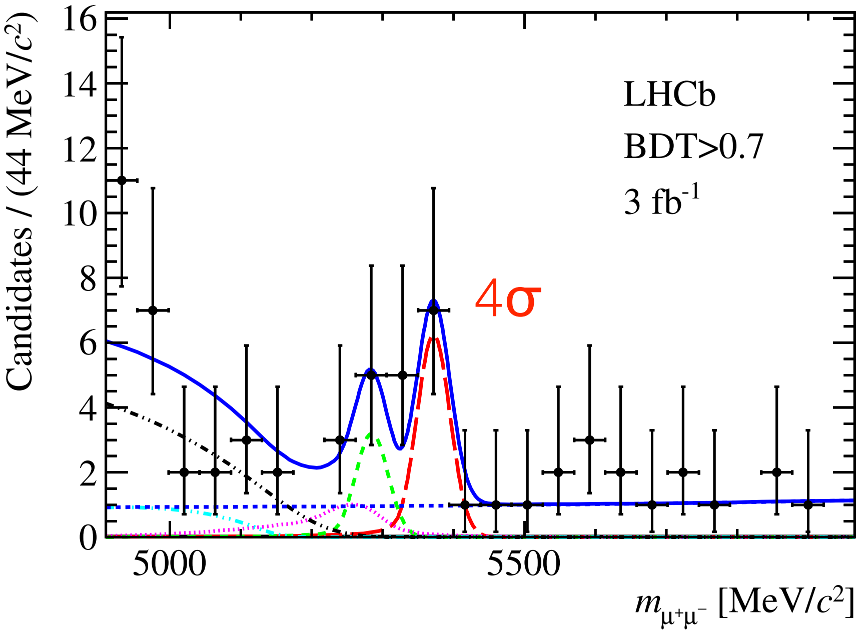




LHCb analysis

- Discriminate signal and background using
  - output of Boosted Decision Tree (BDT) built on kinematic and topological variables
  - invariant mass of $\mu^+\mu^-$





LHCb run I result

PRL 111 (2013) 101805

LHCb result

In good agreement with the SM predictions within current uncertainties

LHCb+CMS results

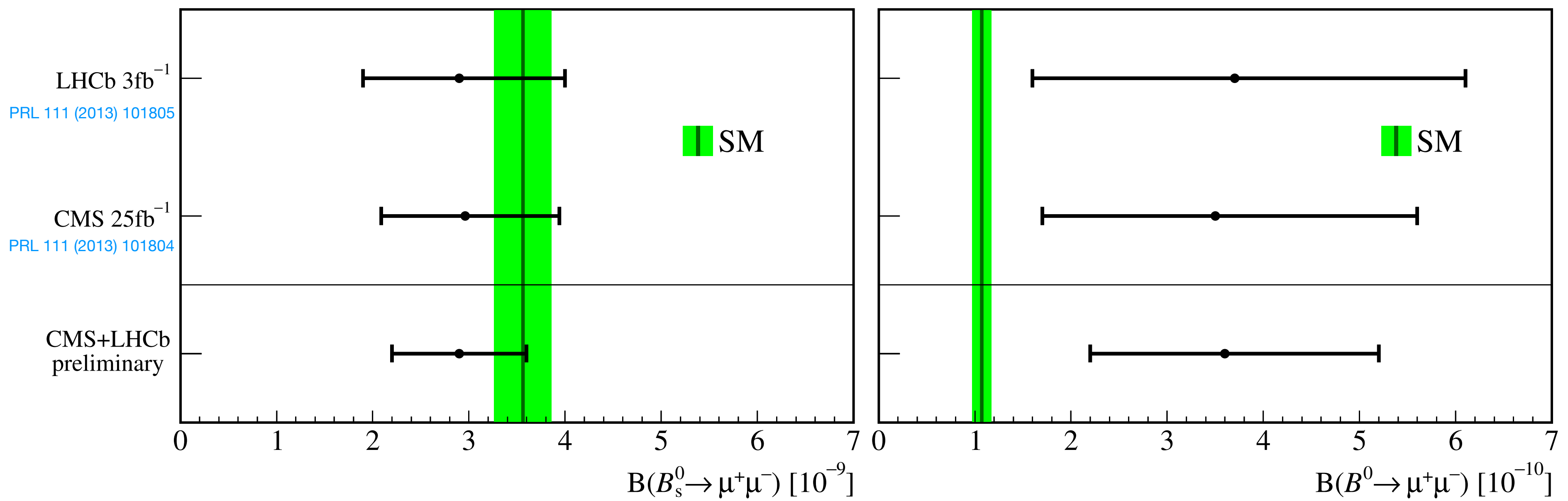
CMS-PAS-BPH-13-007
LHCb-CONF-2013-012

Observation

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

$>5\sigma$

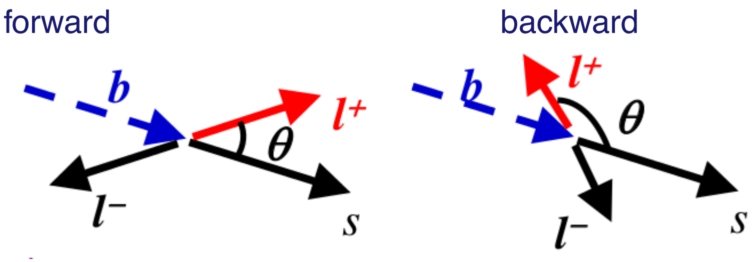
$$B(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$



Example:
Angular distributions in $B^0 \to K^* \mu^+ \mu^-$

Observables in $B^0 \to K^* \mu^+ \mu^-$

Forward backward asymmetry F_{BA}



Longitudinal fraction F_L

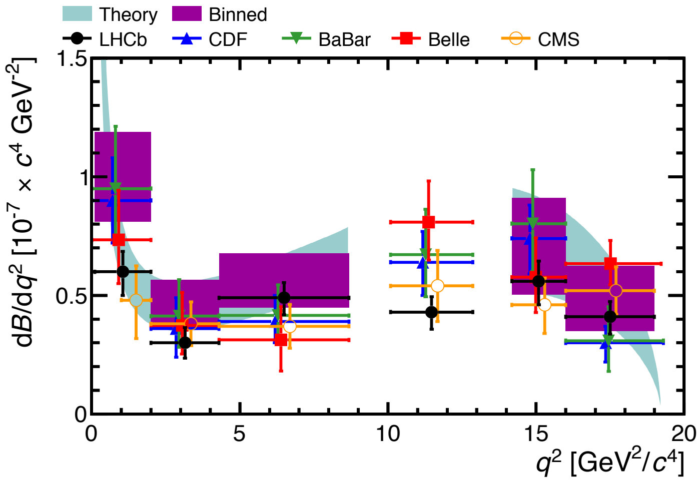
Other angular variables insensitive to hadronic form factors

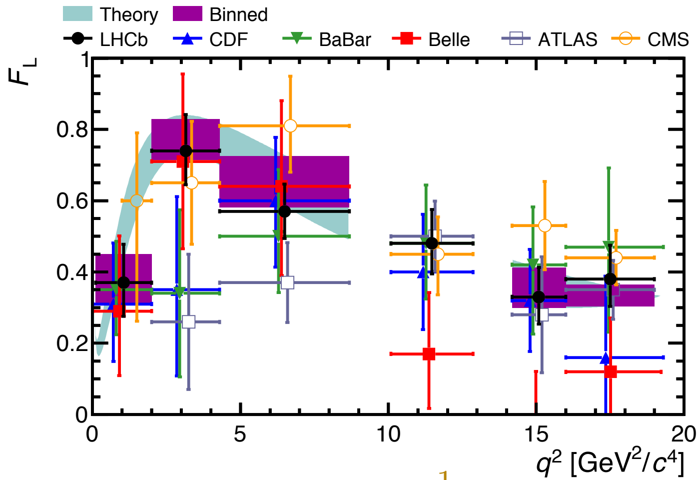
P_4', P_5', P_6', P_8'

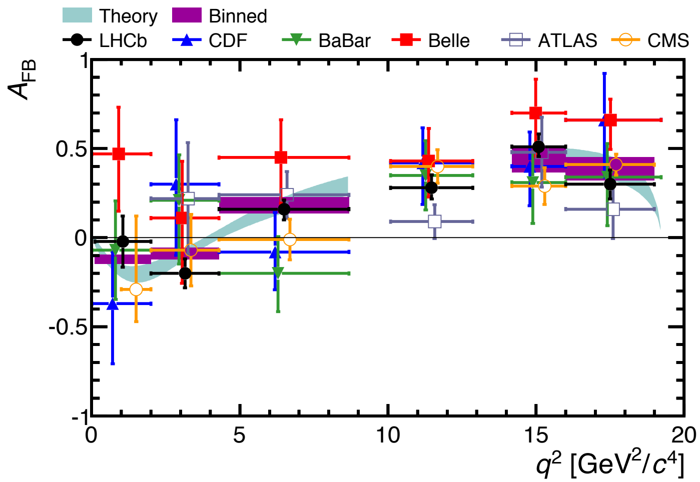
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_\mathrm{L})A_{Re}^\mathrm{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Measure their dependency on $q^2 = m^2(\mu\mu)$

Results of A_{FB} and F_L







CMS: CMS-PAS-BPH-11-009 (5.2 fb^{-1})

ATLAS: ATLAS-CONF-2013-038 (4.9 fb^{-1})

BELLE: Phys. Rev. Lett. 103 (2009) 171801 (605 fb^{-1})

BABAR: Phys. Rev. D73 (2006) 092001 (208 fb^{-1})

CDF: Phys. Rev. Lett 108 (2012) 081807 (6.8 fb^{-1})

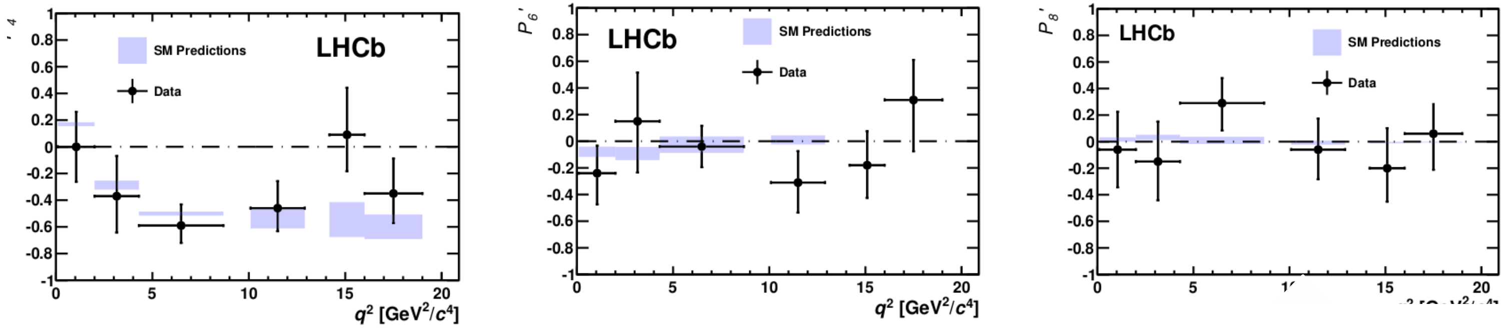
(results from CDF Public Note 10894 (9.6 fb^{-1}) not included)

LHCb: arXiv:1304.6325 (1 fb^{-1})

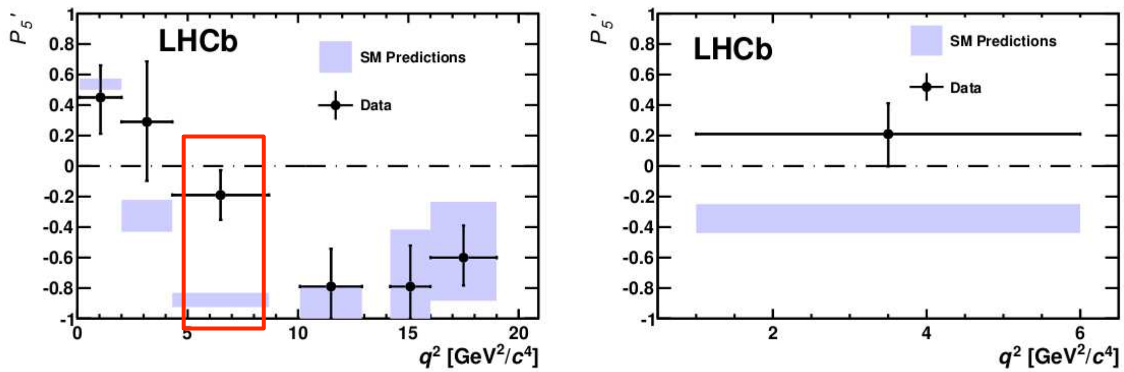
Results of P_4', P_5', P_6' and P_8'

LHCb-PAPER-2013-037

Very good agreement in P_4', P_6', P_8'



some tension in P_5' (3.7 σ):



0.5% probability to see such a deviation with 24 independent measurements.

Waiting for increased sensitivity with 2011+2012 data

Examples:
CP violation in B_s^0, B^0, D^0 , K^0 systems

(some details for my favourite topic)

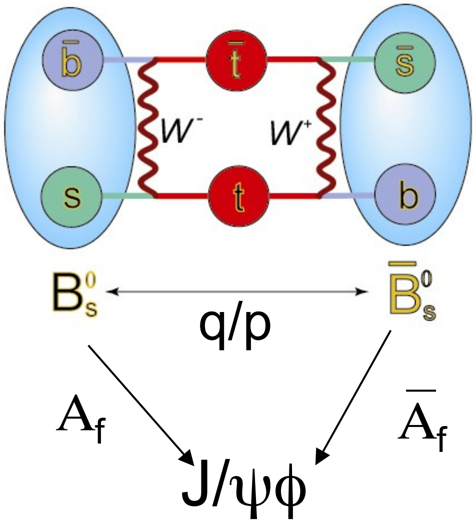
CP violation in $B_s \to J/\psi\phi$

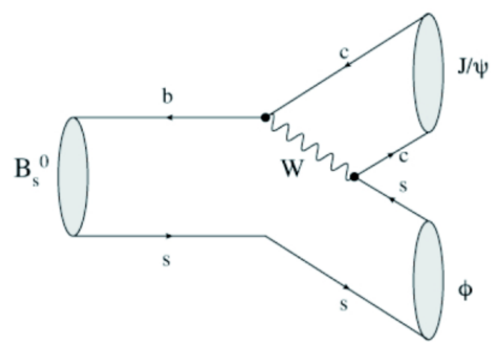
- Time-dependent CP violation characterized by phase difference between $B \to f$ and $B \to \overline{B} \to f$, ϕ_s
- Theoretically clean

  $$\phi_s^{SM} = -0.036 \pm 0.002 \text{ (rad)}$$

- Sensitive to NP in B_s mixing

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



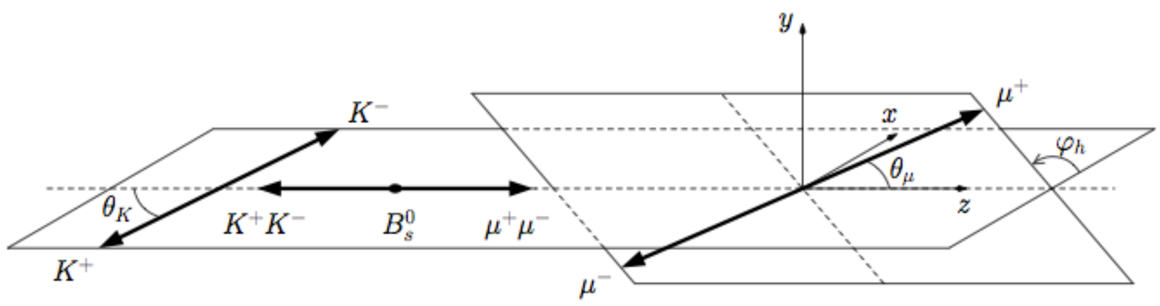


Angular analysis

- Angular analysis needed to separate CP even and odd

  K^+K^- in P wave: 0 (CP even), || (CP even), $\perp$(CP odd)

  Helicity angles: $\Omega=(\theta_\mu, \theta_K, \phi_h)$



- A small CP odd K^+K^- S-wave contribution accounted for

Time-dependent angular PDF

k	$f_k(\Omega)$	$h_k(t)$
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\|A_0\|^2(t)$
2	$\sin^2\theta_K (1-\sin^2\theta_\mu \cos^2\phi_h)$	$\|A_{\|\|}\|^2(t)$
3	$\sin^2\theta_K (1-\sin^2\theta_\mu \sin^2\phi_h)$	$\|A_\perp\|^2(t)$
4	$\sin^2\theta_K \sin^2\theta_\mu \sin 2\phi_h$	$\mathrm{Im}\{A_{\|\|}^*(t) A_\perp(t)\}$
5	$(\sqrt{2}/2)\sin 2\theta_K \sin 2\theta_\mu \cos\phi_h$	$\mathrm{Re}\{A_0^*(t) A_{\|\|}(t)\}$
6	$-(\sqrt{2}/2)\sin 2\theta_K \sin 2\theta_\mu \sin\phi_h$	$\mathrm{Im}\{A_0^*(t) A_\perp(t)\}$
7	$(2/3)\sin^2\theta_\mu$	$\|A_S\|^2(t)$
8	$(\sqrt{6}/3)\sin\theta_K \sin 2\theta_\mu \cos\phi_h$	$\mathrm{Re}\{A_S^*(t) A_{\|\|}(t)\}$
9	$-(\sqrt{6}/3)\sin\theta_K \sin 2\theta_\mu \sin\phi_h$	$\mathrm{Im}\{A_S^*(t) A_\perp(t)\}$
10	$(4\sqrt{3}/3)\cos\theta_K \sin^2\theta_\mu$	$\mathrm{Re}\{A_S^*(t) A_0(t)\}$

- Depending on ϕ_s, $\Delta\Gamma_s$, polarization fractions, strong phases …

Key ingredients

- Theoretical time-dependent CP asymmetry

$$A_{\mathrm{CP}} \equiv \frac{\Gamma\left(\overline{B}_s^0 \to f\right) - \Gamma\left(B_s^0 \to f\right)}{\Gamma\left(\overline{B}_s^0 \to f\right) + \Gamma\left(B_s^0 \to f\right)} = \eta_f \sin\phi_s \sin(\Delta m_s t)$$

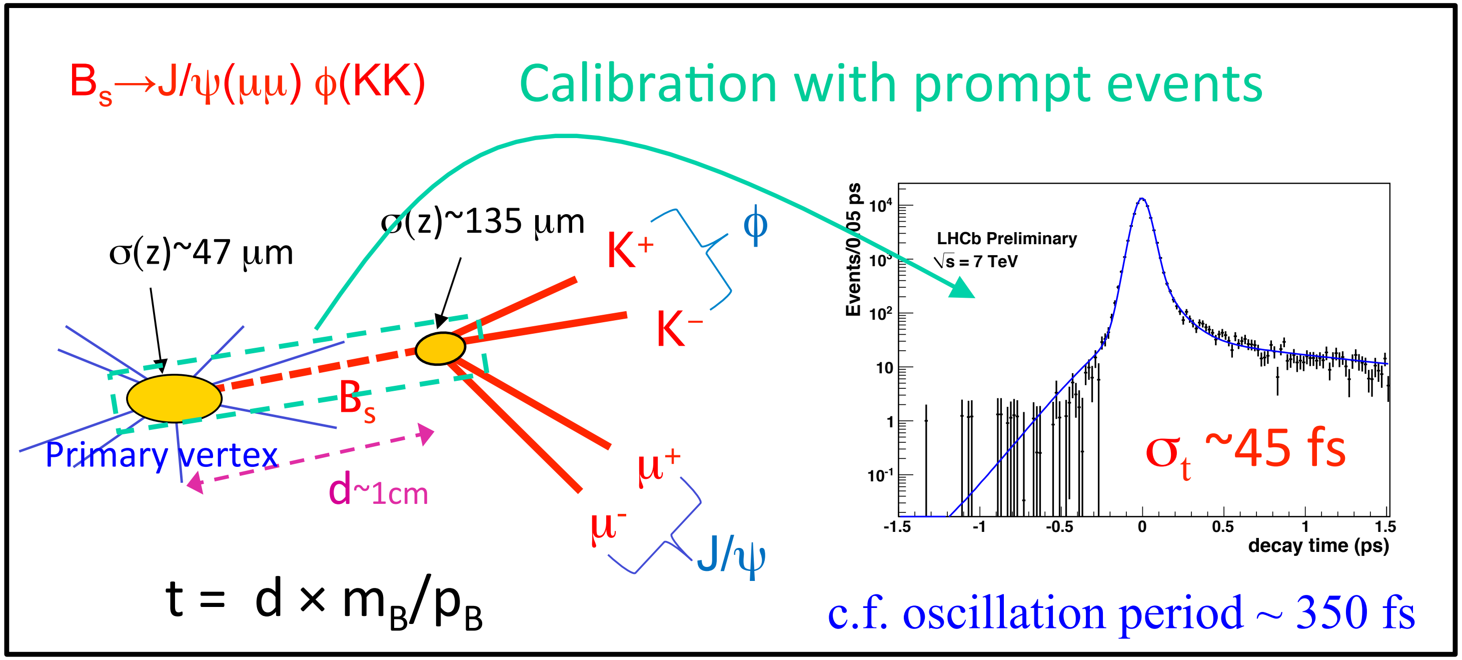
- From flavour tagged time-dependent angular analysis

$$A_{\mathrm{CP}} \approx (1-2w) e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \eta_f \sin\phi_s \sin(\Delta m_s t)$$

  - ω Probability of getting the initial flavour wrong
  - σ_t Decay time resolution
  - η_f CP eigenvalue $\longrightarrow$ angular analysis

Essential ingredients: excellent decay time resolution, good flavour tagging performance, precise knowledge of time resolution, mistag rate and Δm_s

Decay time resolution



Impact of decay time resolution, $\Delta m_s \approx 17.7\ \text{ps}^{-1}$

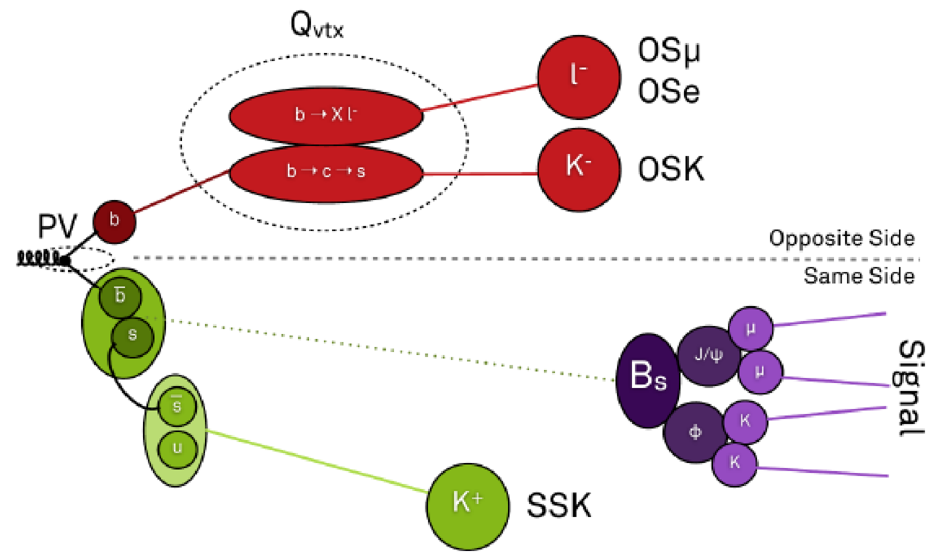
- If $\sigma_t = 45$ fs, dilution factor $\exp(-\Delta m_s^2 \sigma_t^2/2) \approx 0.73$
- If $\sigma_t = 90$ fs, dilution factor $\exp(-\Delta m_s^2 \sigma_t^2/2) \approx 0.28$

Flavour tagging

- Use charge of leptons or hadrons from the decay of the other B meson: opposite-side tagging

- Use charge of kaon produced in the fragmentation: same-side tagging

- Analysis requires precise knowledge of
  - Mistag rate: ω

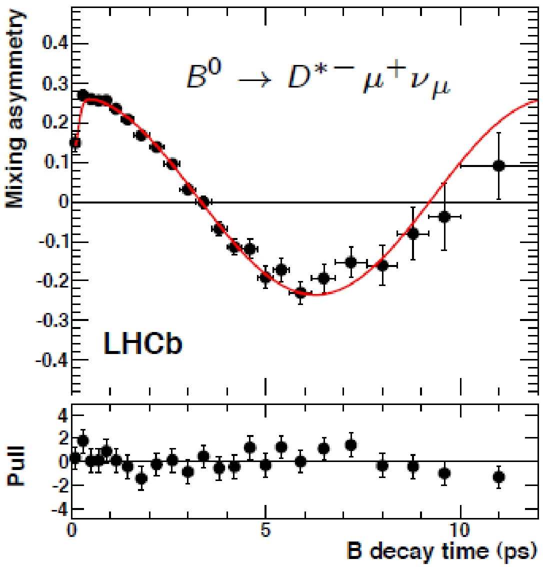


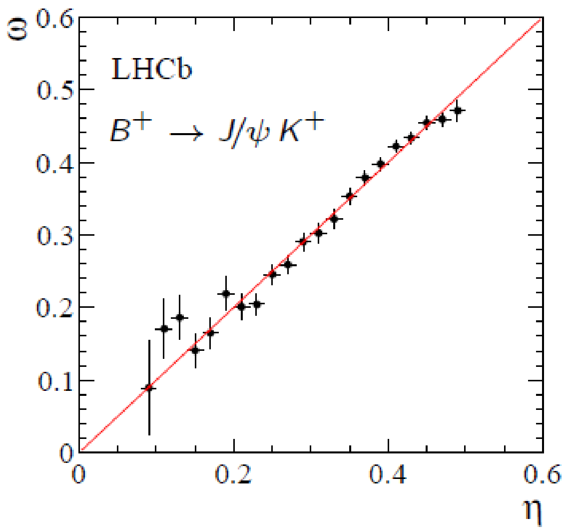
Opposite side performance

- Use control channels for calibration
- Opposite-side tagging:
  - Fit time evolution in flavour specific $B^0 \to D^{*-} \mu^+ \nu_\mu$
  - Count correctly/mis-tagged events in self tagging $B^+ \to J/\psi\, K^+$
- OS tagging optimized on MC and calibrated on data

algorithm	$\varepsilon(1-2\omega)^2$ [%]
OS	2.29 ± 0.06

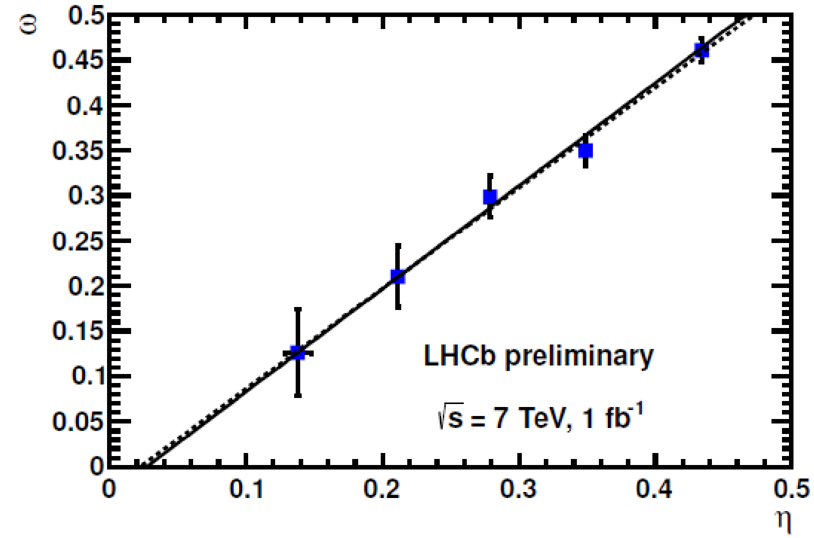
[EPJC 72 (2012) 2022, arXiv: 1202.4979]





Same side performance

- Use flavour specific control channels to calibrate tagging
- Same-side tagging:
  - Fit time evolution in $B_s \rightarrow D_s^- \pi^+$



$B_s \rightarrow D_s^- \pi^+$

- SS tagging optimized on MC and calibrated on data

algorithm	$\varepsilon(1\text{-}2\omega)^2$ [%]
SSK	0.89 ±0.17
OS	2.29 ± 0.06
OS + SSK	3.13±0.12

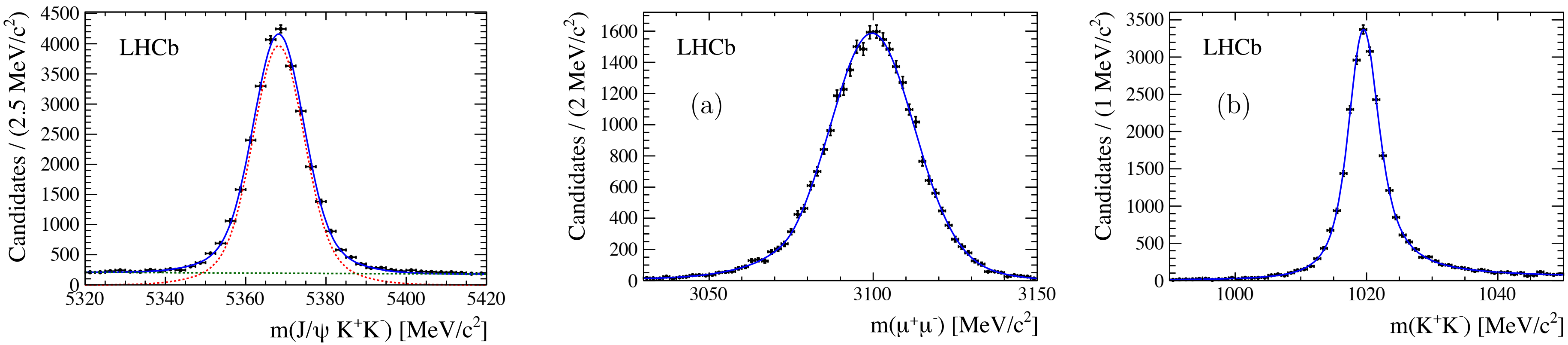
[LHCb-CONF-2012-033]

Event selection

Very clean sample obtained by exploiting

- Excellent muon and kaon identification
- Precise tracking and vertexing
- Powerful trigger provided by the muon detector
- A requirement of t>0.3 ps to remove prompt background

27.6 ± 0.1 k signals



Background subtraction

Developed the sFit method to optimally subtract combinatorial background in maximum likelihood fit

- Avoid parameterization in multiple dimension

[Y. Xie, arXiv: 0905.0724]

$$-\ln L(\theta) = -\alpha \sum_{e=1}^{N_s+N_b} w_e \cdot \ln P_s(x_e;\theta)$$

θ fit parameters

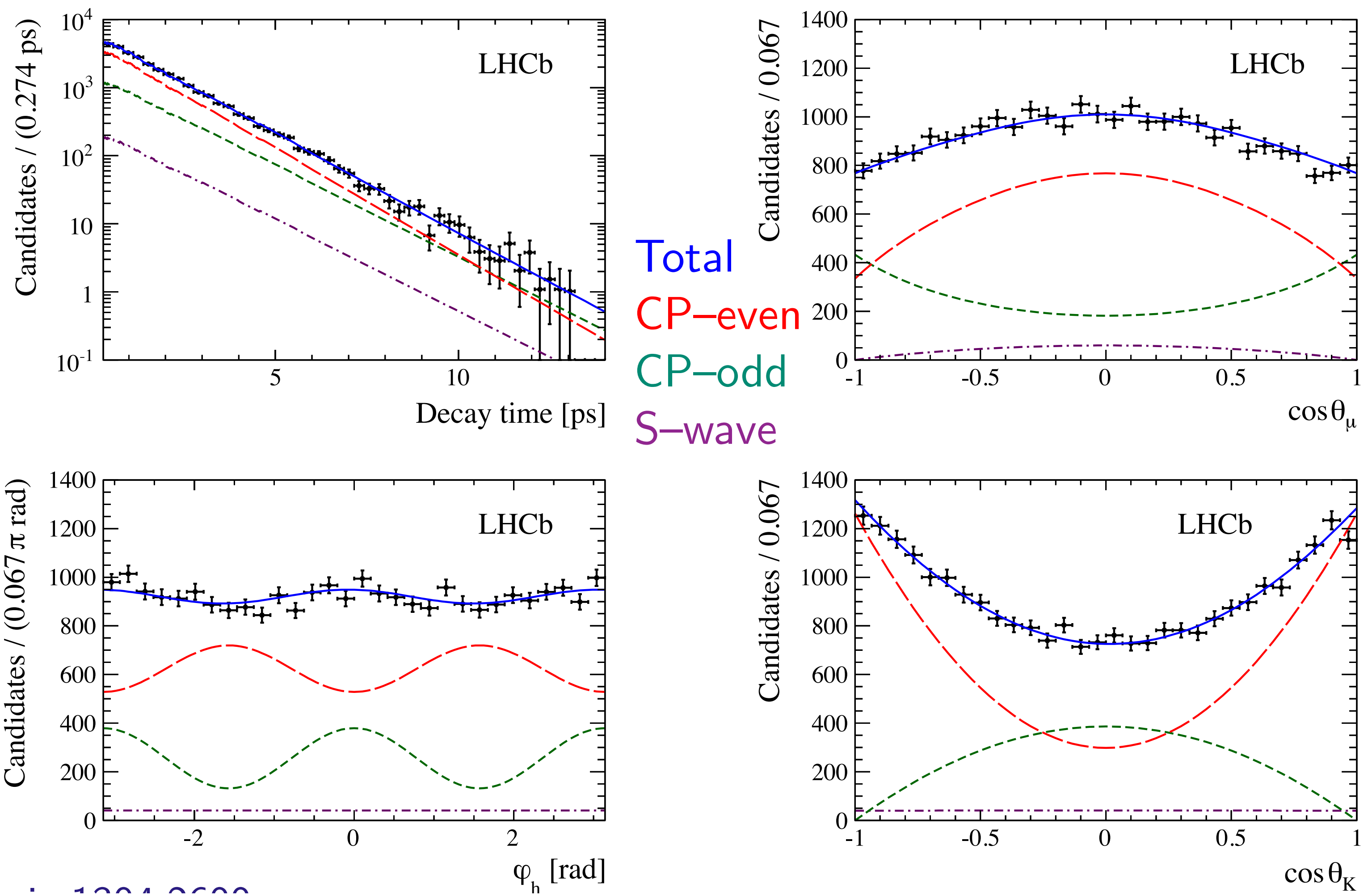
x t, Ω, σ_t, η

$P_s(x)$ signal PDF

w signal weight calculated using $J/\psi KK$ mass as discriminating variable, such that $\sum_{e=1}^{N_b} w_e = 0$

[M. Pivk, F. R. Le Diberder, NIMA 555 (2005) 356]

Projections



LHCb result of ϕ_s (2011 data)

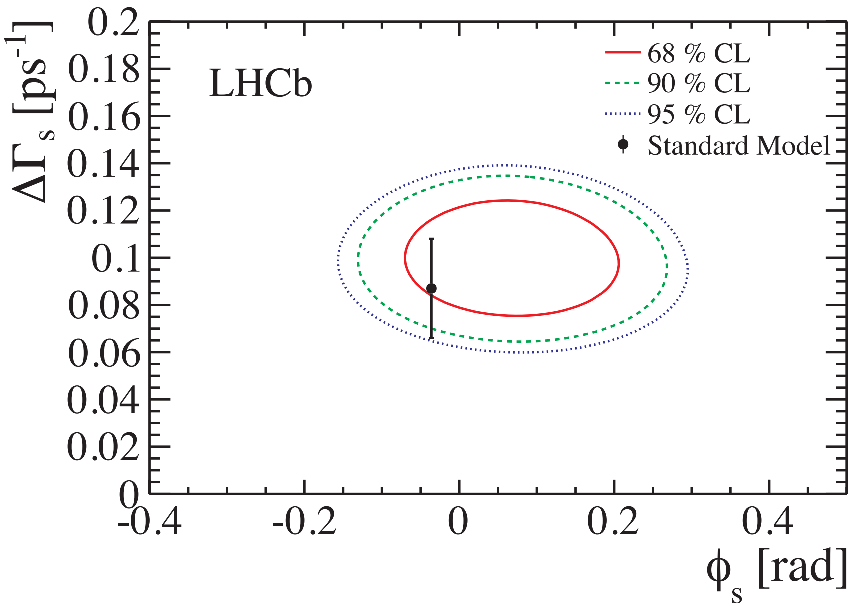
PRD 87 (2013) 112010

$\phi_s = 0.07 \pm 0.09\ (\text{stat}) \pm 0.01(\text{syst})\ \text{rad}$

$\Delta\Gamma_s = 0.100 \pm 0.016\ (\text{stat}) \pm 0.003\ (\text{syst})\ \text{ps}^{-1}$

SM: $\phi_s = -\ 0.036 \pm 0.002\ \ \text{rad}$, $\Delta\Gamma_s = 0.087 \pm 0.021\ \text{ps}^{-1}$

[J. Charles *et. al*, PRD 84 (2011) 033005] [A. Lenz, U. Nierste, arXiv: 1102.4274



In good agreement with the SM expectation.

No surprise yet!

CP violation in $D^0 \to hh$

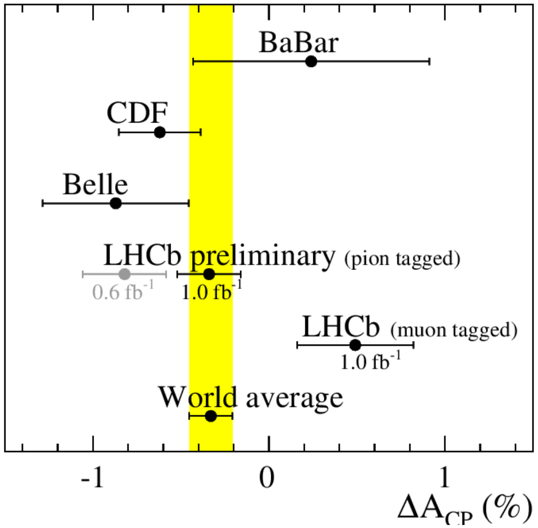
- Highly suppressed in the SM, probing NP that couples to the up quark sector

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

- Two tagging methods

soft pion tag: $D^{*+} \to D^0\pi^+$

muon tag: $B^- \to D^0\mu^- X$



- D^* tagged sample [LHCB-CONF-2013-003]

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(stat) \pm 0.10\,(sys))\,\%$$

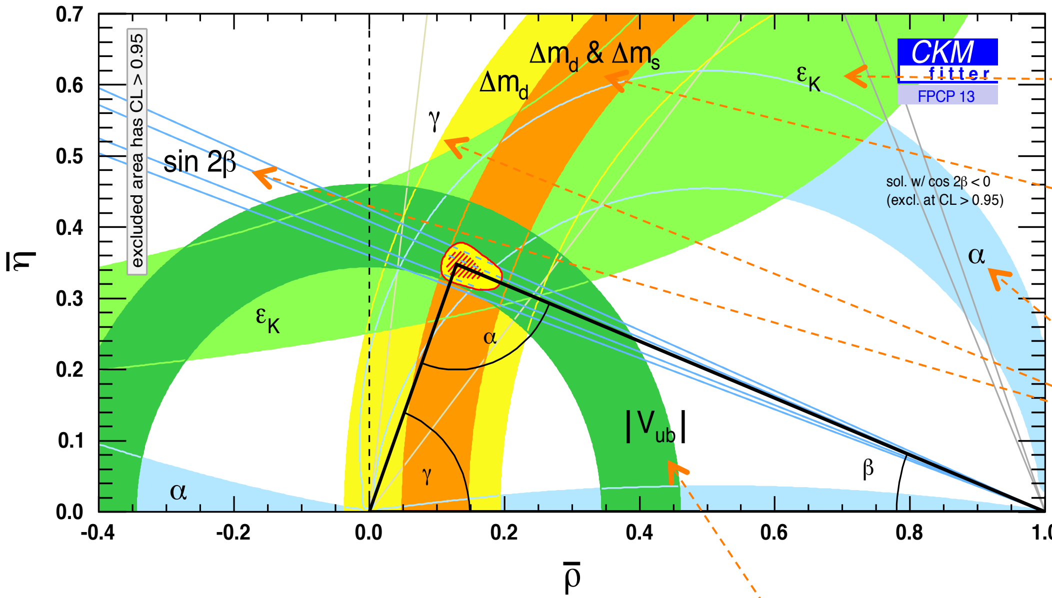
- μ tagged sample [PLB 723 (2013) 33]

$$\Delta A_{CP} = (+0.49 \pm 0.30\,(stat) \pm 0.14\,(sys))\,\%$$

Consistent with no CP violation hypothesis

CKM global fit in (ρ, η) plane

- ρ and η are precisely determined
- Good consistency between various measurements in K^0, B^0 and B_s systems



CPV in K^0

$B_{(s)}{}^0$ mixing

CPV in B^0

Rate of $b \to u l \nu$ decays

Overall picture

- **Flavour sector**
  measurements generally agree with SM at current precision
  - ✧ NP has similar flavour structure as SM (Minimal flavour violation)? Unnecessary!
  - ✧ And/or NP energy scale far above 1 TeV?

- **Direct search for NP, which must exist**
  no hint of any new phenomenon yet, except the SM-like Higgs (and a Nobel prize!)
  - ✧ NP energy scale likely to be pushed above 1 TeV

A plausible scenario

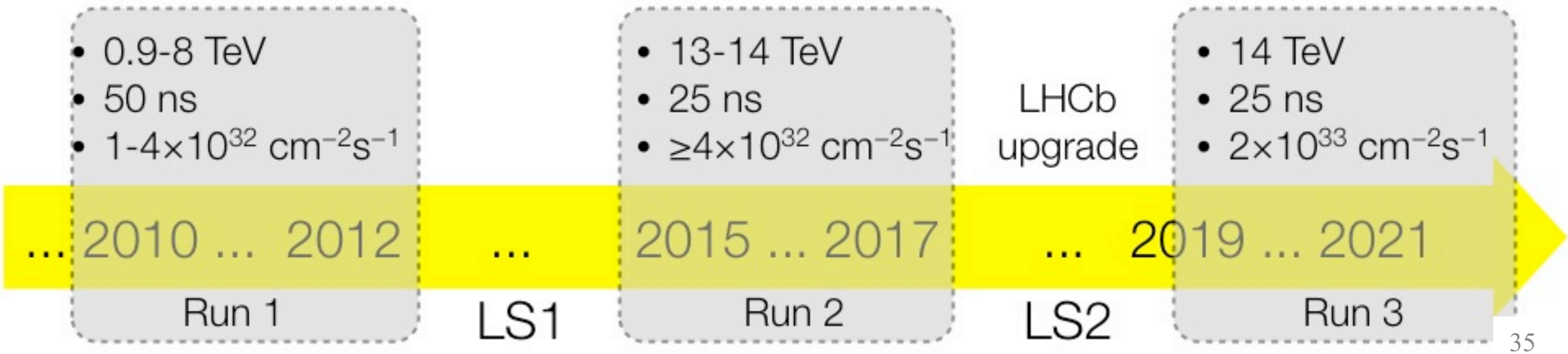
- NP occurs at quite high energy scale
  - Beyond reach of direct search at the LHC
- NP has flavour structure different from the SM
  - Flavour measurements in principle have chances to explore effects of very heavy particles (up to 100 TeV) in loops
- LHCb upgrade fits into this picture perfectly
  - Expect 10 times higher precision in key measurements

Challenges …

Challenges: detector upgrade

- High demands on detectors and trigger to face increases in
  - Energy & luminosity
  - Radiation
  - Occupancy
  - Output event rate and event size

Not the main topic of this talk



Challenges: physics exploitation

- We have no idea where exactly loop effects of NP will be seen and how big they should be
  - Critical to perform searches in as high precision and as wide scope as possible
- Innovation in high demands
  - New ideas in physics
  - New experimental techniques
  - New decay modes to study
  - New observables in explored modes
  - New initiatives to solve known problems

Opportunities …

In every challenge
there lies great opportunity

Turn challenges into opportunities

Requires physicists to be innovative, intuitive, open-minded and collaborative

Some personal experience in exploring new ideas at LHCb experiment

- 与实验研究者：共同探讨，交流经验，开拓思路
- 对理论研究者：抛砖引玉，激发灵感，促进合作

Resolving discrete ambiguity in ϕ_s in $B_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ analysis

An example to show how a good sense of physics helps to identify opportunities

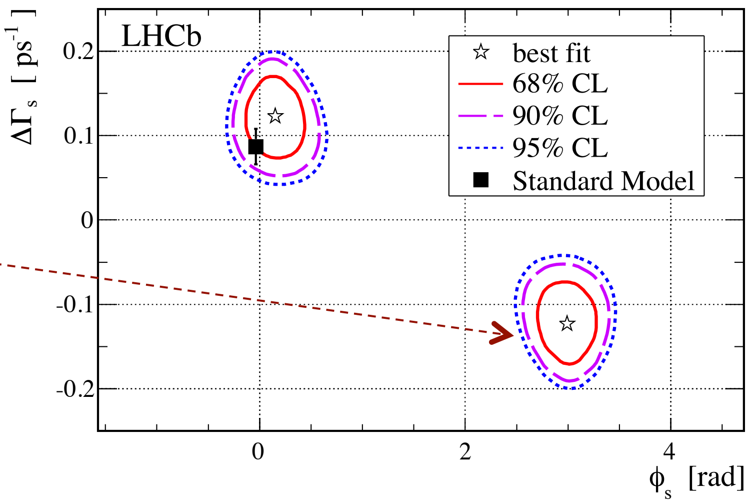
The notorious 2-fold ambiguity

- Two "indistinguishable" solutions in $B_s \to J/\psi\phi$ analysis

$(\Delta\Gamma_S \equiv \Gamma_L - \Gamma_H)$

$$(\phi_s, \Delta\Gamma_s) \longleftrightarrow (\pi - \phi_s, -\Delta\Gamma_s)$$

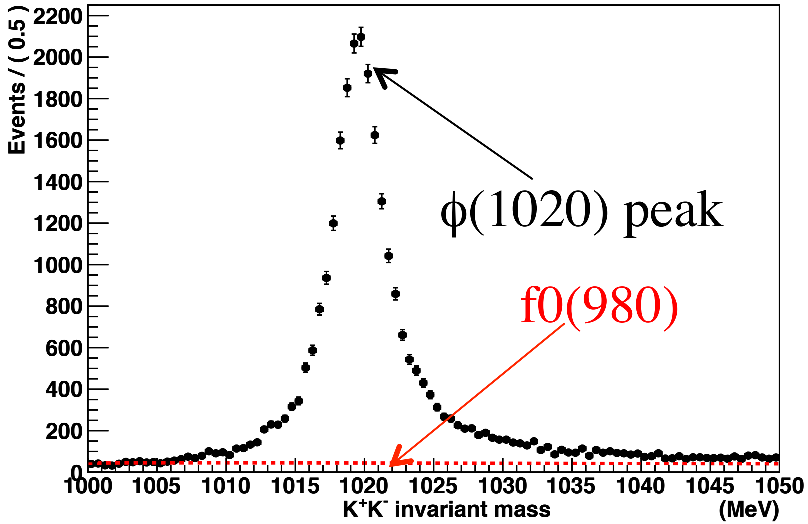
If we were very (un)lucky, NP hiding here could have escaped our attention …



PRL 108 (2012) 101803

Nuisance or opportunity?

- A tiny K^+K^- S-wave contribution (f0(980) or non-resonance) interferes with $\phi(1020)$



- Normally this "pollution" is considered to be an annoying nuisance

- Needs some physics insight to recognize it as an opportunity …

Including S wave in analysis

- There are four decay amplitudes corresponding to different polarization
  - ✧ KK in P wave: A_0, $A_{||}$, A_{perp}
  - ✧ KK in S wave: A_S

  δ_i: phase of A_i

- Each of the two ambiguous solutions in (ϕ_s, $\Delta\Gamma_s$) corresponds to different solution in strong phase differences

$$(\varphi_s, \Delta\Gamma_s, \delta_{||} - \delta_0, \delta_\perp - \delta_0, \delta_s - \delta_\perp) \longleftrightarrow$$

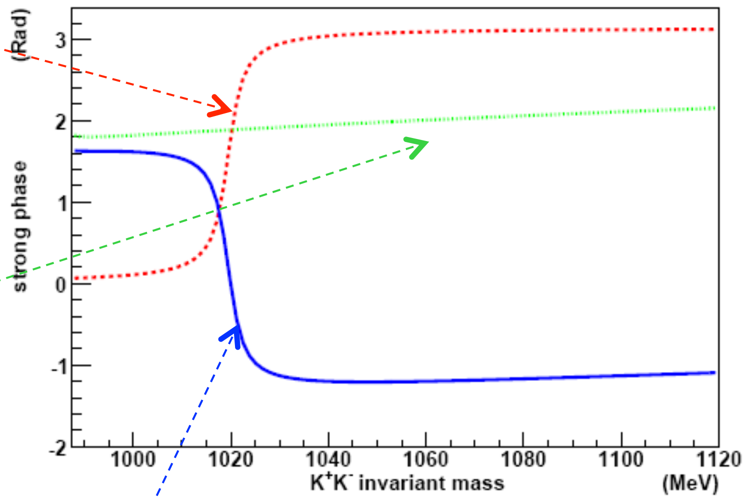
$$(\pi - \varphi_s, -\Delta\Gamma_s, -(\delta_{||} - \delta_0), \pi - (\delta_\perp - \delta_0), \pi - (\delta_S - \delta_\perp))$$

Method to resolve the ambiguity

Y. Xie, P. Clarke, G. Cowan, F. Muheim, JHEP 09 (2009) 074

K^+K^- P-wave:
Phase of Breit-Wigner amplitude increases rapidly across $\phi(1020)$ mass region

$$BW(m_{KK}) = \frac{F_r F_D}{m_\phi^2 - m_{KK}^2 - i m_\phi \Gamma(m_{KK})}$$



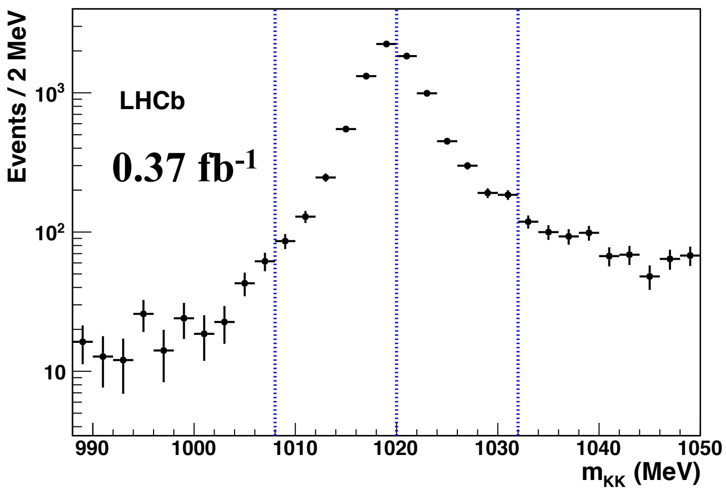
K^+K^- S-wave:
Phase of Flatté amplitude for $f_0(980)$ relatively flat (similar for non-resonance)

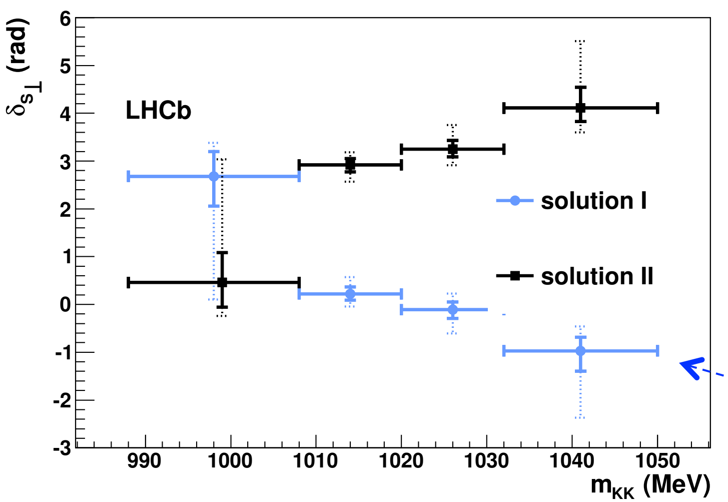
Phase difference between S- and P-wave amplitudes
Decreases rapidly across $\phi(1020)$ mass region

Resolution method: choose the solution with decreasing trend of $\delta_s - \delta_P$ vs m_{KK} in the $\phi(1020)$ mass region

Application of the method

PRL 108 (2012) 241801





CERN COURIER

Mar 27, 2012

The heavier B_s meson state lives longer

The LHCb collaboration has determined the sign of the width difference in the B_s system, $\Delta\Gamma_s$, through the influence of quantum-mechanical interference. This shows for the first time that the heavier of the two B_s meson states has the longer lifetime, a result that is in agreement with the Standard Model expectation and similar to the situation in the kaon system.

Also top news at LHCb public page
http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#phis-2

$\Delta\Gamma_s < 0$ and $\phi_s \sim \pi$ excluded at 4.7σ CL

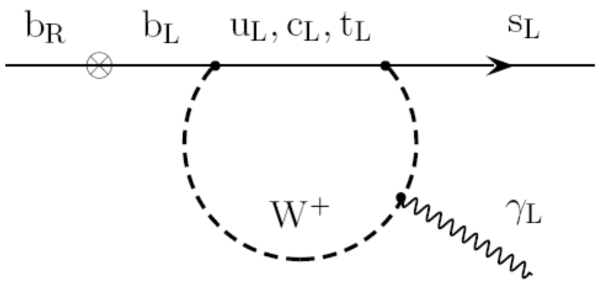
True solution: $\Delta\Gamma_s > 0$ and $\phi_s \sim 0$.

SM wins so far.

Exploiting the large B_s decay width difference in $B_s \to \phi\gamma$

An example to show how a new idea of an experimentalist led to fruitful collaboration with theorists

Interests in b→sγ



- SM: photons from b → sγ are predominantly left-handed due to V-A structure in weak interactions

- Golden channel in B factories: mixing induced CP asymmetry in $B^0 \to K^{*0}(K_S\pi^0)\gamma$, $S(K^{*0}\gamma)$
- SM value

$$S(K^{*0}\gamma) \approx C_7' / C_7 \sin 2\beta \to 0$$

could be enhanced due to new right-handed currents that leads to sizeable C_7'/C_7

Can LHCb do the same?

- $B^0 \rightarrow K^{*0}(K_S\pi^0)\gamma$ is difficult to detect at LHCb due to K_s and π^0 in the final state

- $B_s \rightarrow \phi(KK)\gamma$ is also a $b \rightarrow s\gamma$ process

$$S(\phi\gamma) \approx {C_7^{'}}\big/{C_7} \sin\phi_s$$

which is ~ 0 due to smallness of the B_s mixing angle ϕ_s

- S($\phi\gamma$) is insensitive to C_7'/C_7 !

Any way out?

- New observable proposed (Y. Xie, 25/1/2007, LHCb internal talk)
  - ✧ $A_\Delta(\phi\gamma)$ in decay time distribution without flavour

$$R(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\Delta\Gamma_s t/2\right) + A_\Delta \sinh\left(\Delta\Gamma_s t/2\right)\right]$$

$$A_\Delta(\phi\gamma) \approx {C_7^{'}}\big/{C_7} \cos\phi_s$$

- $A_\Delta(\phi\gamma)$ is sensitive to C_7'/C_7 since $\cos\phi_s \sim 1$
- Measurement of $A_\Delta(\phi\gamma)$ is facilitated by the sizeable value of B_s decay width difference $\Delta\Gamma_s$

Collaboration with theorists

- Seek theorist's help to make quantitative prediction of the SM values

F. Muheim, R. Zwicky, Y. Xie, PLB 664 (2009) 175

$$S(\phi\gamma) = 0 \pm 0.002$$

$$A_\Delta(\phi\gamma) = 0.047 \pm 0.025^{+0.015}$$

- Establish the measurement of $A_\Delta(\phi\gamma)$ as a key physics goal for LHCb upgrade

LHCb, EPJC 73 (2013) 2373

Conclusions

- Status: almost all flavour measurements agree with the SM
- Challenges: require higher precision and wider scope in heavy flavour experiments
- Let's turn challenges into opportunities!

Yes, we can!

Wishes to young friends

Dream big
Free your thoughts
Fly high

Being afraid of making mistake
is the biggest mistake in a life