Recent results from LHCb

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on behalf of LHCb Collaboration

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Outline

I. Why Flavour Physics?

II. Three ways of CPV

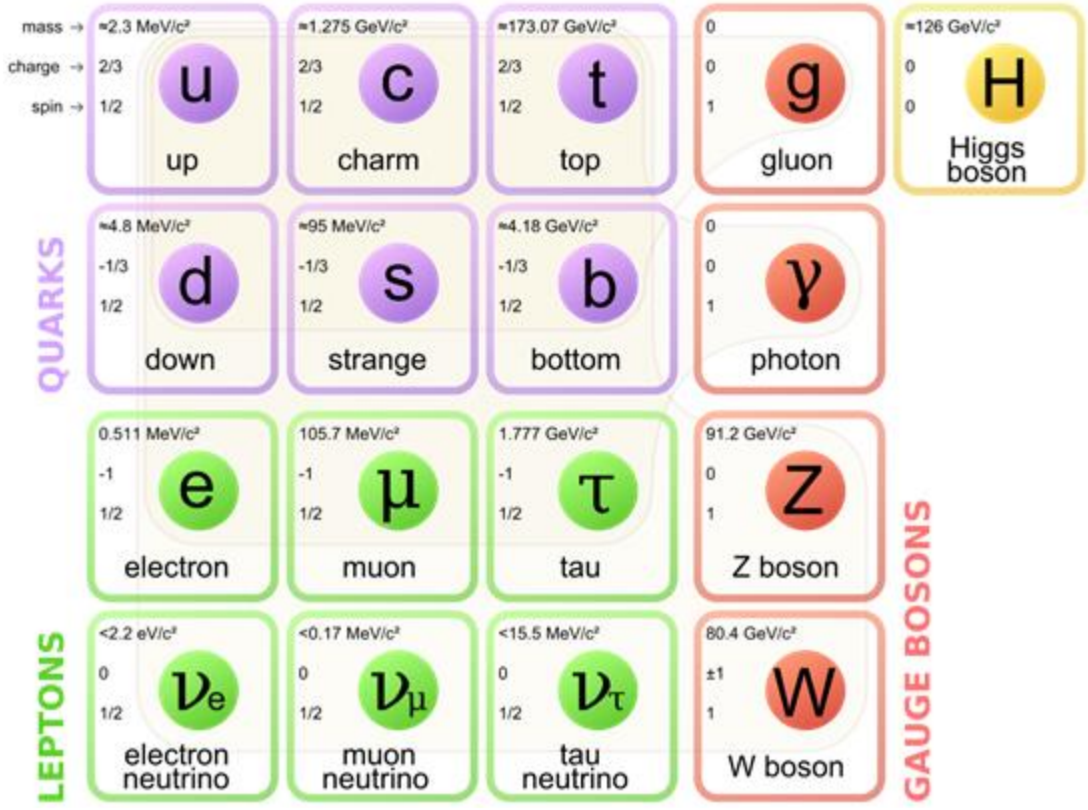
III. Selected results from LHCb:

- CP Violation
- Weak phase ϕ_S
- CKM γ angle
- Rare decays
- Exotic states

IV. Summary

V. Prospects for measurements in Run II and Upgrade

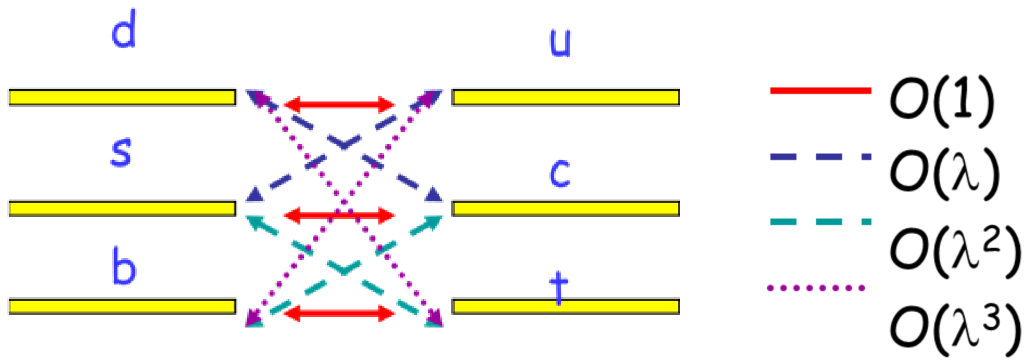
Standard Model



I Why Flavour Physics?

1. To constrain Standard Model
2. To find a reason for only three generations.
3. To search for CP violation in both quark and neutrino sector

All three generations of -1/3e quarks (d,s,b) are mixed



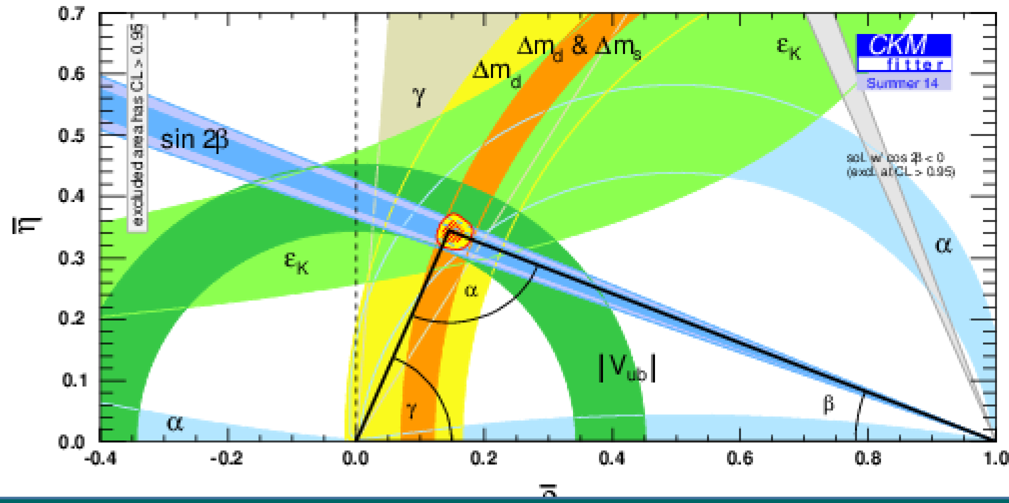
weak eigenstates

mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

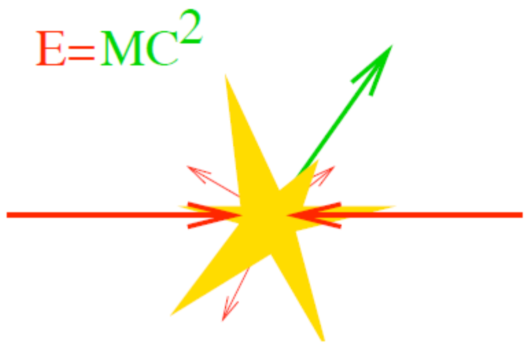
$$= \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The parameters of mixing (V_{CKM} matrix) are fundamental constants of Nature in the SM

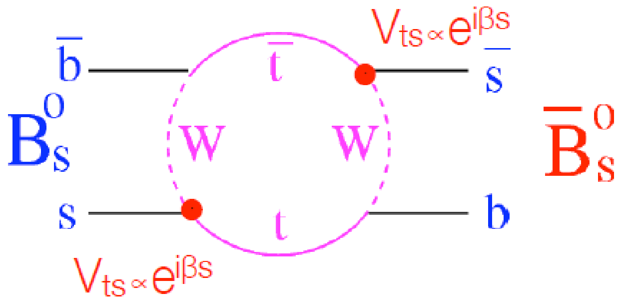


I Two roads to New Physics

1. **Direct** searches for production of new objects (higher and higher energies, luminosities – ATLAS, CMS)
2. **Indirect** searches (a low energy „window” for discoveries) – LHCb
   a) test the SM with very precision measurements, especially processes which are very well predicted and calculated.
   b) if disagreements are found – this is a sign of the existence of new objects via indirect method
   c) very successful in the past (charm and top quarks predictions)



3. Of a special interest are:
   a) **CP violation in B and D decays** (CPV in SM is too small to explain the observed domination of matter over the antimatter)
   b) Very rare decays of B and D mesons



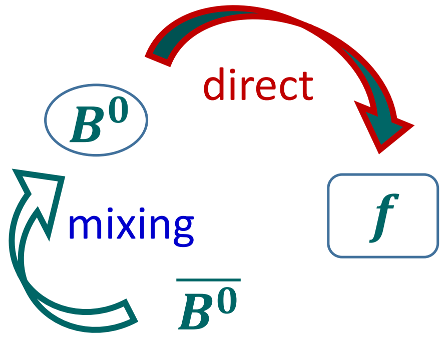
Three ways of CPV – selected results

1. Direct – in decay amplitudes; when two amplitudes with different phases interfere:

$$B^{\pm} \to h^{+}h^{-}h^{\pm}$$

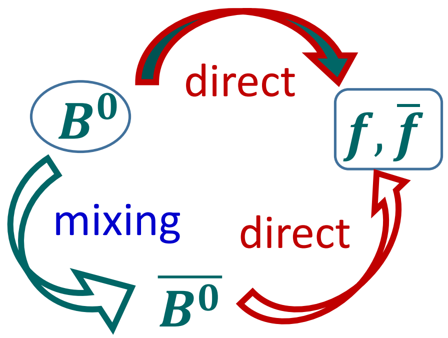
2. Indirect – in mixing; if $B^0 \to f$ decay then but $\overline{B^0} \to f$ only possible after mixing

$$B_S \to D_S^{\pm}\pi^{\mp}$$



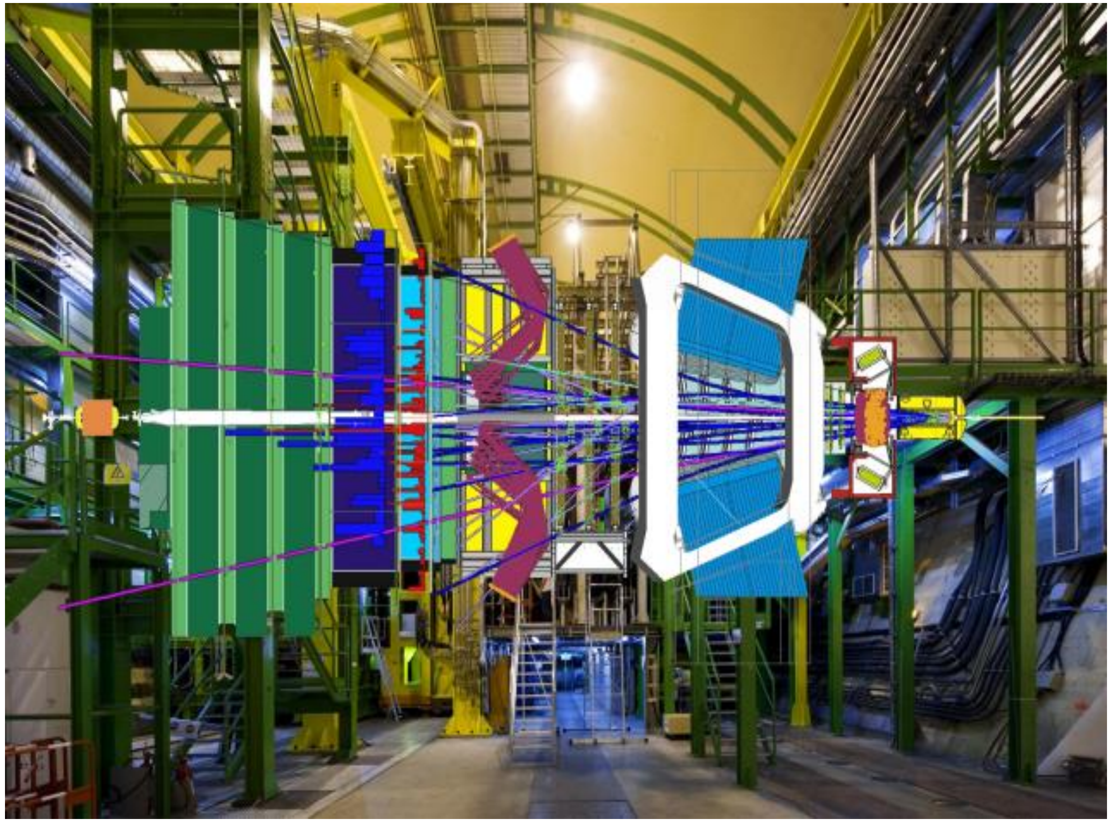
3. Indirect – in interference between direct decays $B^0 \to f$ and decays after mixing, $B^0 \to \overline{B^0_{d,s}} \to f$, both final states $f, \bar{f}$ are possible (although one is usually suppressed)

$$B^0 \to J/\psi X \qquad B_S \to D_S^{\pm}K^{\mp}$$



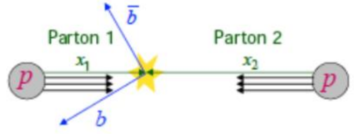
III LHCb Spectrometer

The detector dedicated for studying flavour physics at LHC.
Especially CP violation and rare decays of beauty and charm mesons.



Physics program:

- CP Violation ,
- Rare B decays,
- B decays to charmonium and open charm,
- Charmless B decays,
- Semileptonic B decays,
- Charm physics
- B hadron and quarkonia
- QCD, electroweak, exotica …



$$\sigma_{b\bar{b}} = (75.3 \pm 14.1)\ \mu b$$
$$\sigma_{c\bar{c}} = (1419 \pm 133)\ \mu b$$

$\sqrt{s}$= 7 TeV

Excellent performance:

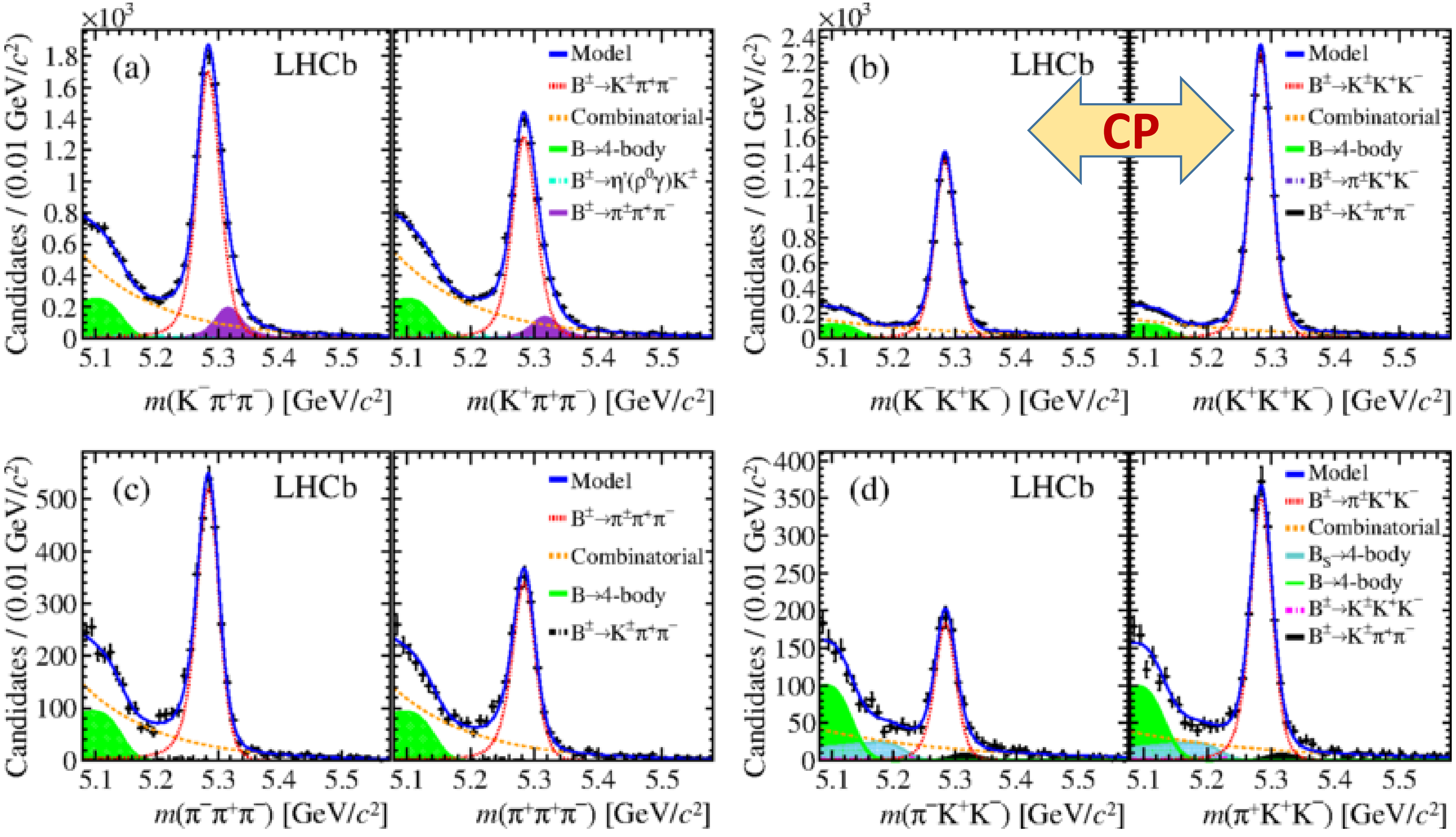
3fb^{-1} accumulated in RUN I
Excellent Vertex Resolution
Precise tracking: $\delta p/p \sim 0.4 - 0.6\%$
Particle identification 2-100 GeV/c

III Direct CP violation

$B^+ \rightarrow K^- K^+ K^+$

Huge direct **CP** violation in decay amplitudes seen in B$^-$/B$^+$ decays

$B^- \rightarrow K^- K^+ K^-$



Phys.Rev.D90(2014)112004,
3.0 fb^{-1}

LHCb results – CP violation

$B^0 \to J/\psi K^0_S$

Asymmetry:

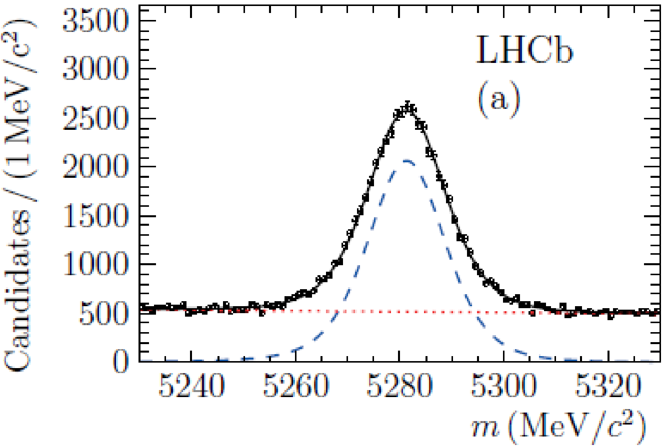
$$A_{CP}(t) = \frac{\Gamma\{\overline{B} \to f\} - \Gamma\{B \to f\}}{\Gamma\{\overline{B} \to f\} + \Gamma\{B \to f\}}$$

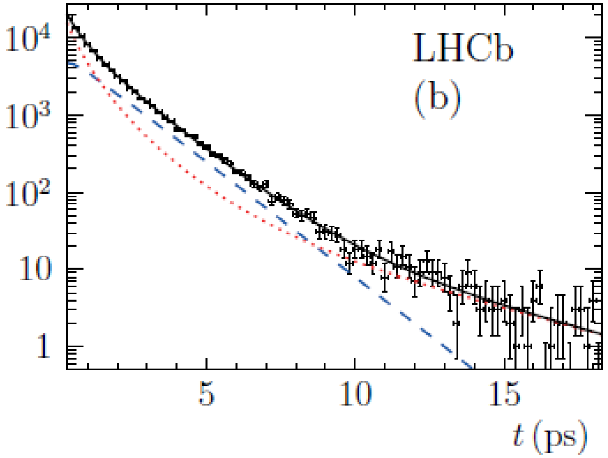
For $B^0 \leftrightarrow \overline{B^0}$ systems:

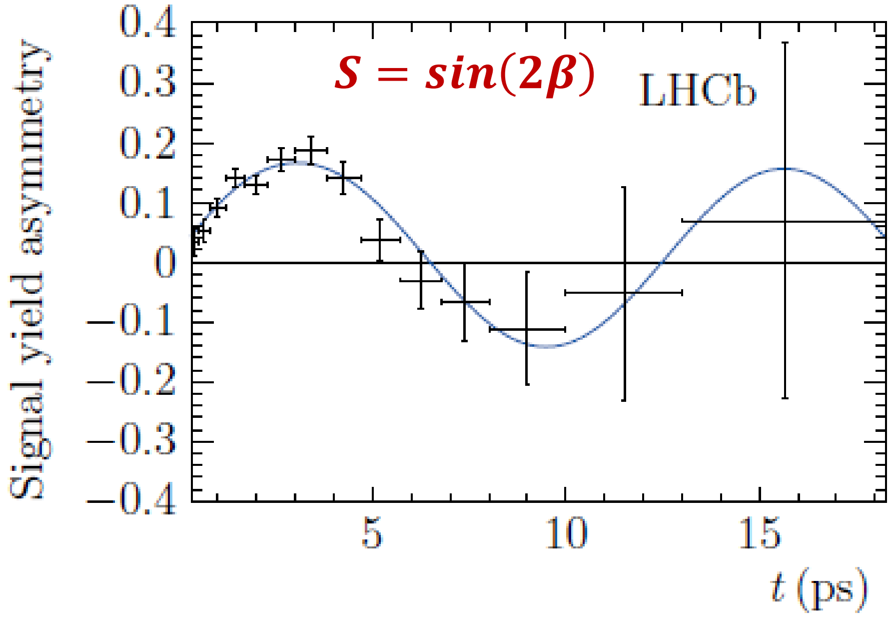
$$A_{CP}(t) \sim S\, \sin(\Delta m t)$$

B^0, $\overline{B^0}$ $\Rightarrow$ $J/\psi K^0_S$

Both B^0 and $\overline{B^0}$ can decay to this final state -
Interference between B^0 and $\overline{B^0}$ amplitudes,







$$S = 0.731 \pm 0.035(stat) \pm 0.020(syst)$$

The values are consistent with the current world averages and with the Standard Model expectations.
The most precise time-dependent CP violation measurement at hadron colliders.

arXiv:1503.07089 (3.0 fb^{-1} 2015)

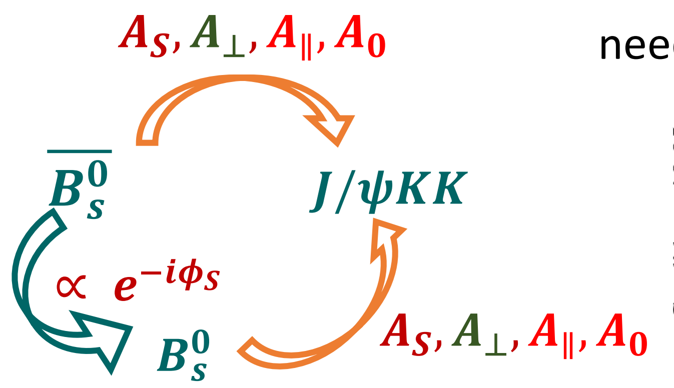
III LHCb results: weak phase ϕ_s

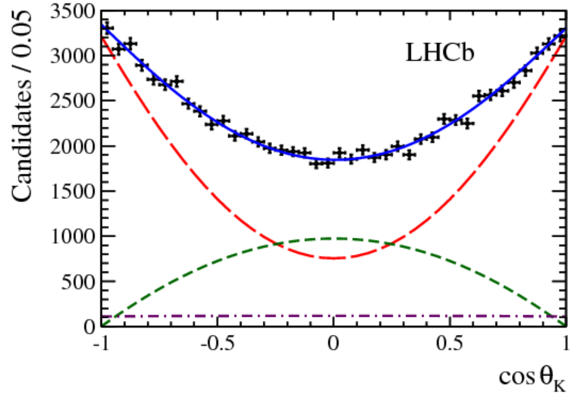
$B_s^0 \to J/\psi KK(\phi)$

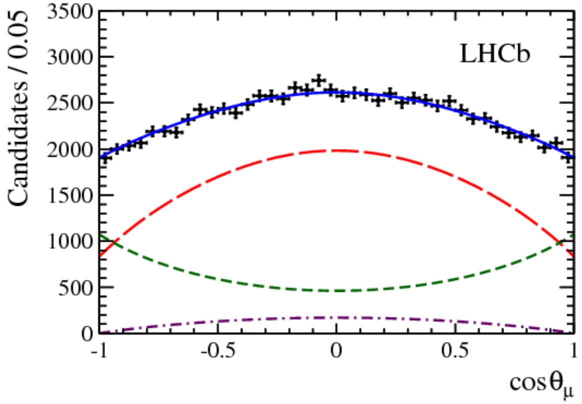
Orbital angular momentum of the final state is mixture of CP-even and CP-odd components:

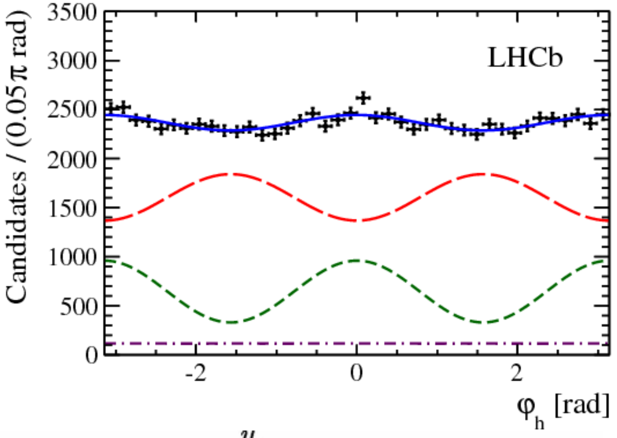
$$L = 0, 1, 2$$

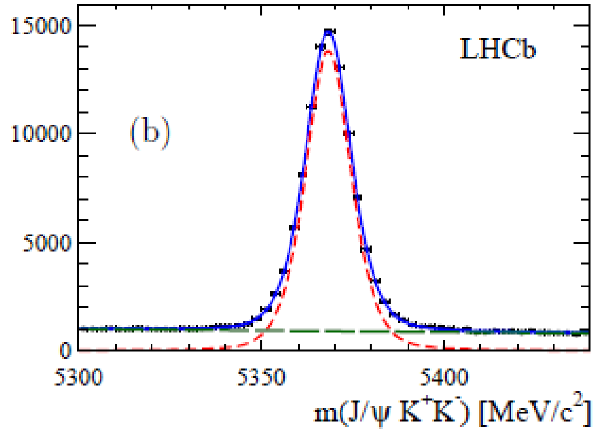
need to disentagle **CP even** and **CP odd** amplitudes via time-dependent angular analysis

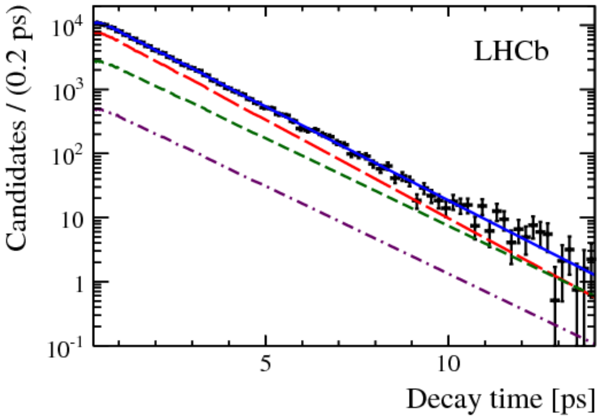


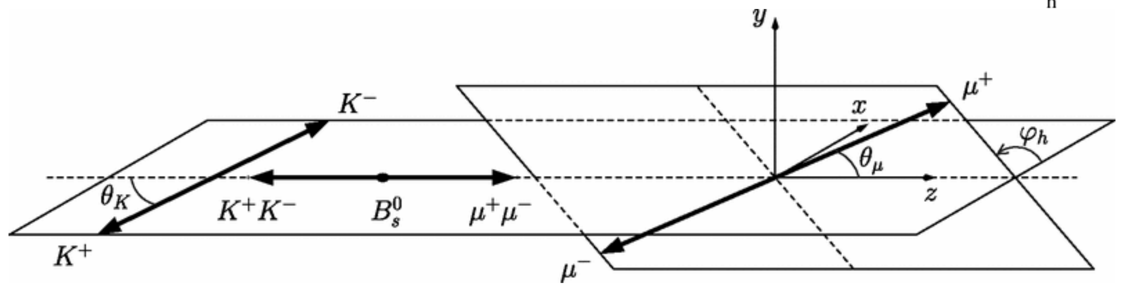










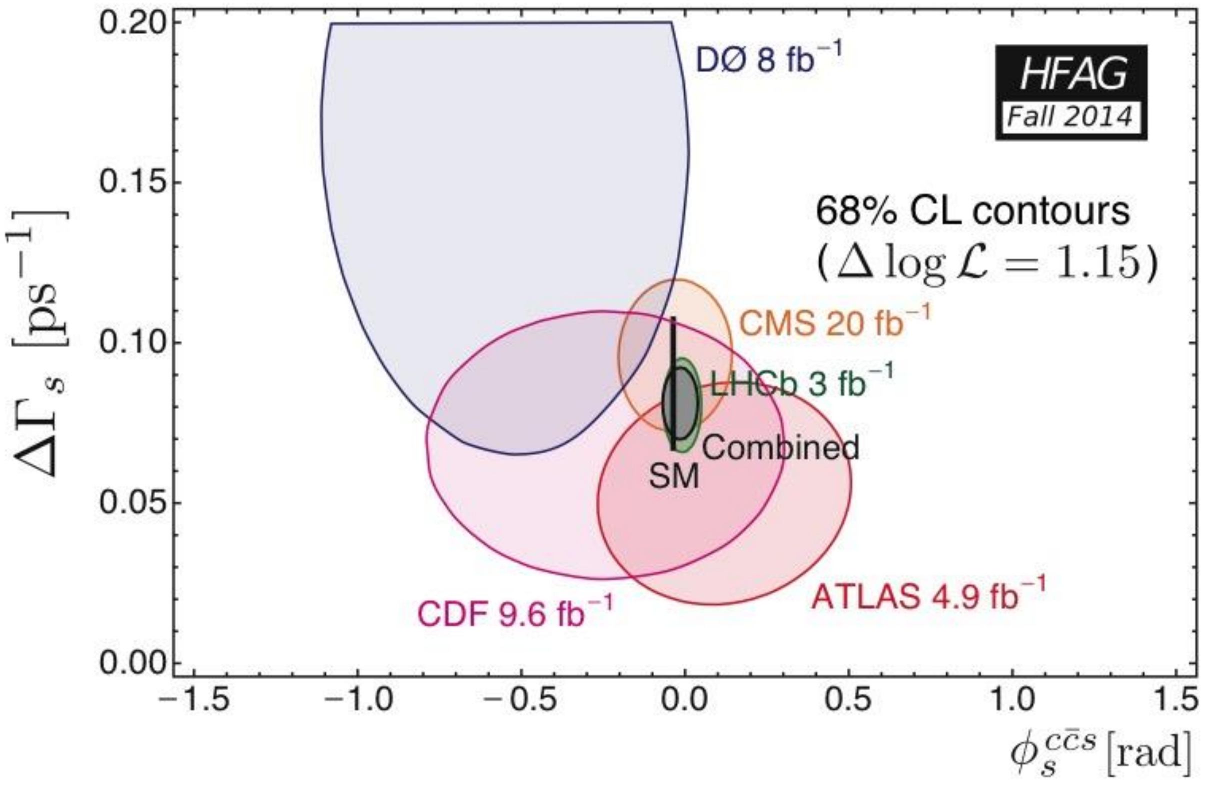


$$\phi_s = -0.058 \pm 0.049(stat) \pm 0.006(syst)$$

Phys.Rev.Lett. 114 041801 (2015) (3.0 fb^{-1})

III Weak phase ϕ_S (combined results)

ϕ_S is very sensitive to New Physics, but no NP effects have been seen, yet…



SM:	$\phi_S^{SM} = -0.0363^{+0.0014}_{-0.0012}$
HFAG:	$\phi_S^{exp} = -0.015 \pm 0.035$

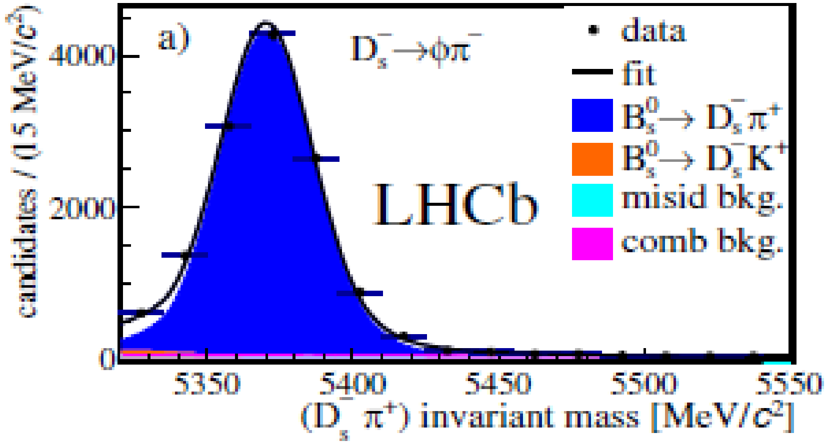
Great progress but still plenty of possibilities for NP

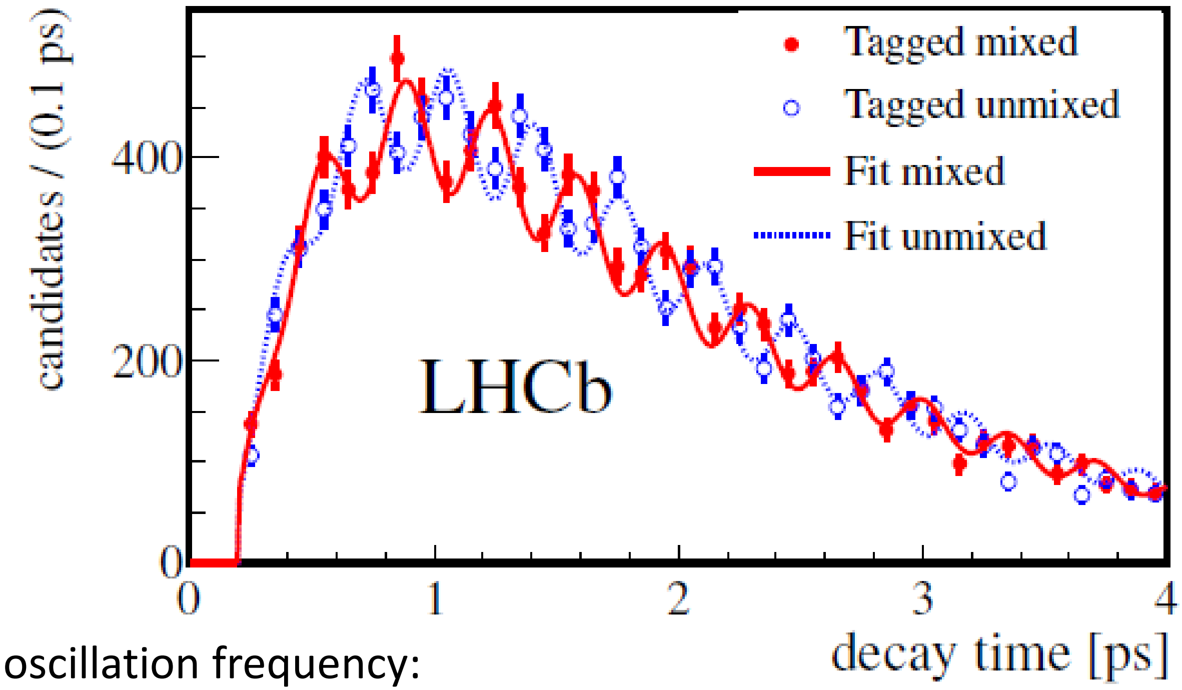
Mixing of neutral mesons

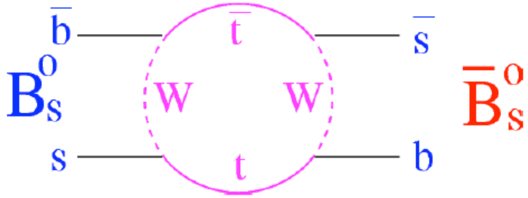
$B_s^0 \to D_s^- \pi^+$

$B_s^0 \leftrightarrow \overline{B_s^0}$ oscillation in flavour specific mode $D_s^- \pi^+$

$$A(t) = D \frac{\cos(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s t}{2}\right)}$$







The oscillation frequency:

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

Most precise measurement to date

New J.Phys. 15(2013)053021

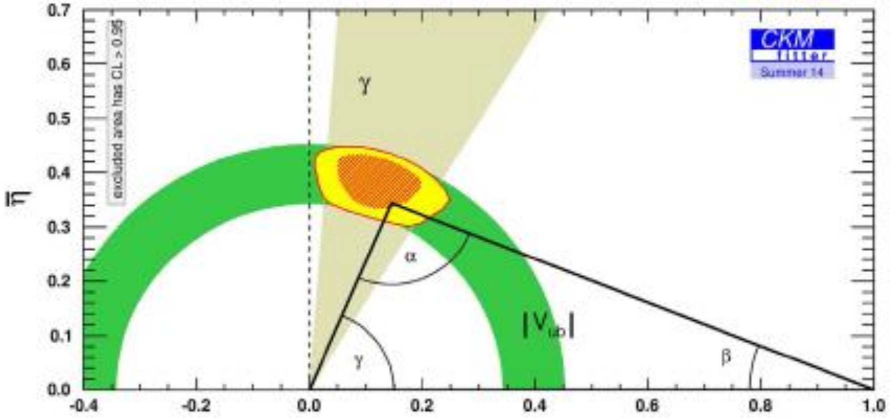
agrees with world av. 17.69 ± 0.08 ps^{-1}

CKM γ angle

1. $\boldsymbol{\gamma}$ angle is the only one that can be determined from tree only processes,
2. Theoretically clean: $\delta\gamma/\gamma \leq \mathcal{O}(10^{-7})$
3. So far has the worst precision:
   a) direct measurements: BaBar: $\gamma = (69 \pm 17)^{\circ}$, Belle: $\gamma = (68 \pm 15)^{\circ}$
   b) indirect measurements (dominated by loops): $(66.9^{+1.0}_{-3.7})^{\circ}$

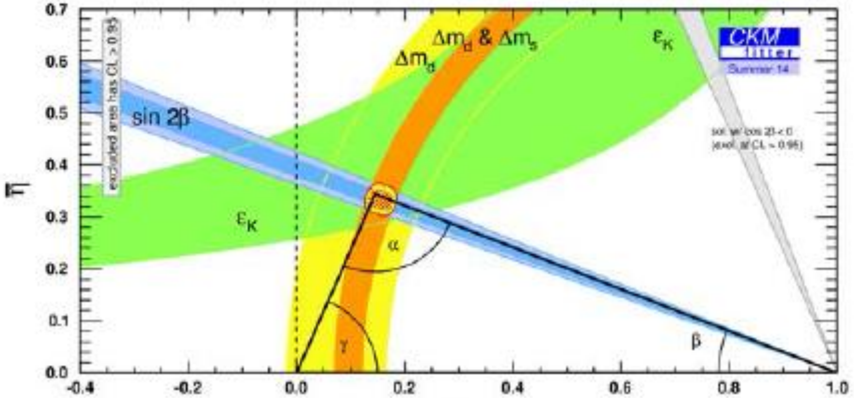
$$\boldsymbol{\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)}$$

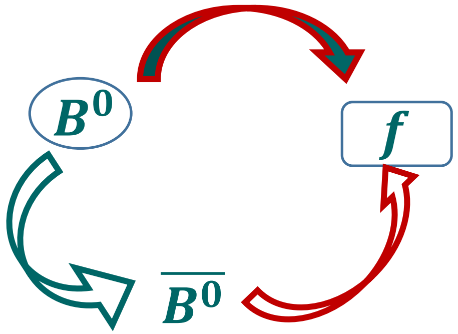
trees - direct



some tension between direct and indirect methods- need better precision from trees measurements

no trees - indirect



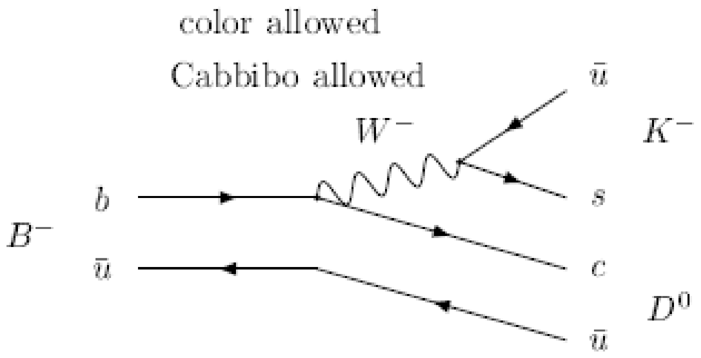


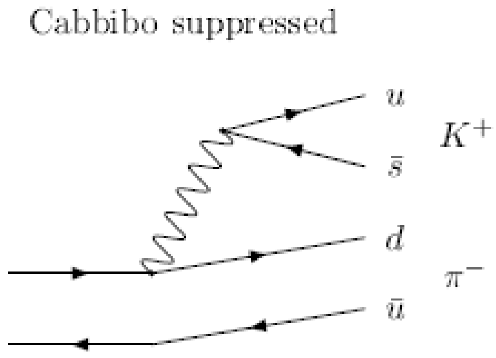
III CKM γ angle

$B^{\pm 0} \to D^0 K^{\pm * 0}$

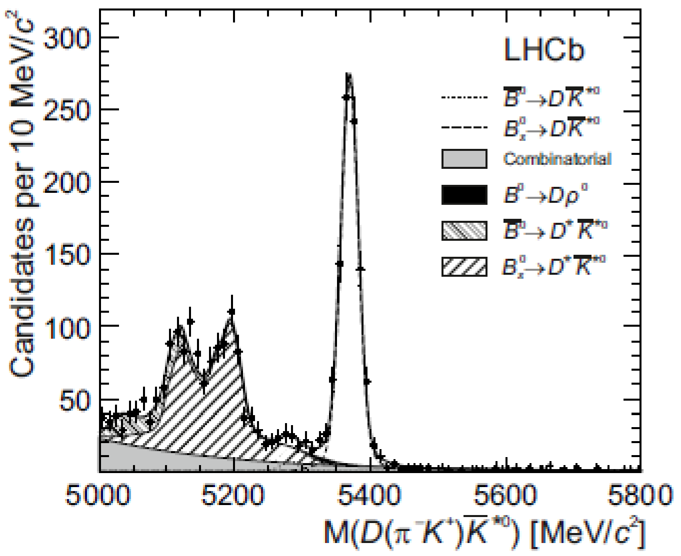
Time integrated measurement

1. Sensitive to γ when D^0 and $\overline{D^0}$ decay to the same final state.
2. Interference of the two amplitudes dependent on relative magnitudes of amplitudes - one of them is usually suppressed.
3. Different experimental techniques (GLW, ADS, GGSZ).



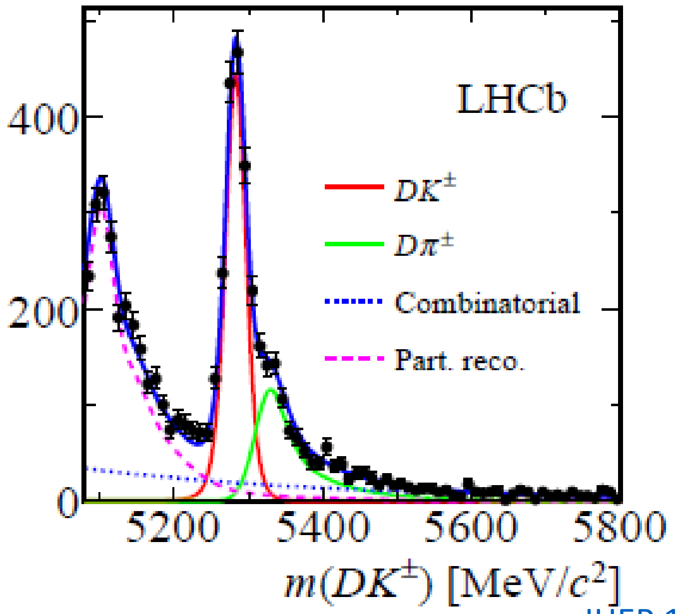


$B^0 \to D^0 K^{*0}$ $(D^0 \to K^- \pi^+)$



Phys.Rev. D90 (2014) 112002

$B^{\pm} \to D^0 K^{\pm}$ $(D^0 \to K^0_S K^+ K^-)$



JHEP 10 (2014) 097

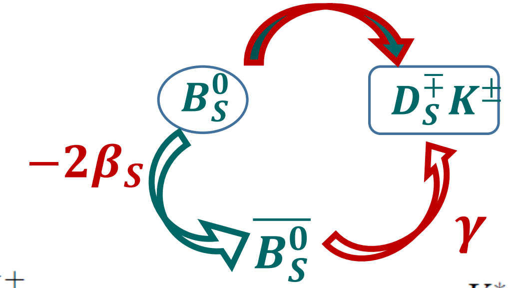
$$\gamma = \left(62^{+15}_{-14}\right)^{\circ}$$

world most precise single γ measurement

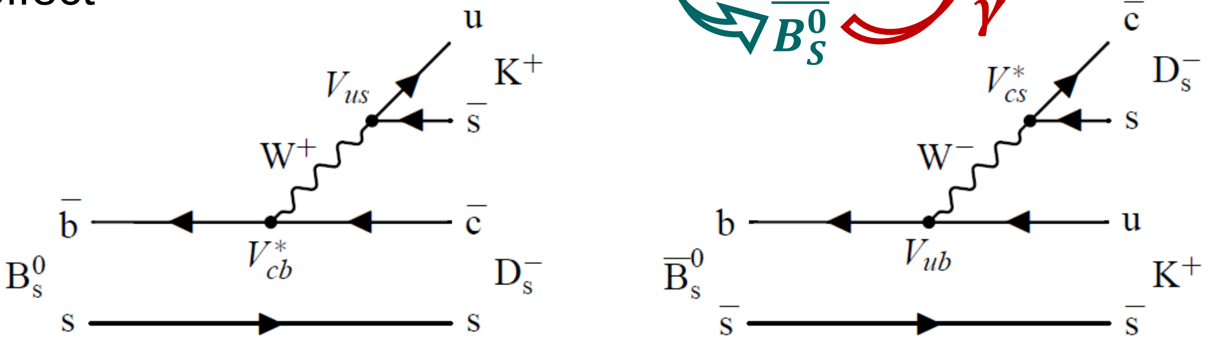
III CKM γ angle

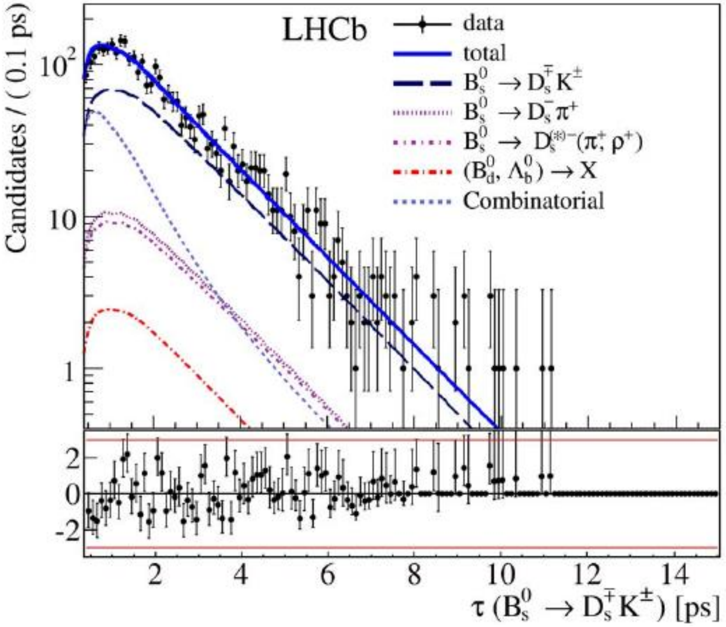
$B_s^0 \to D_s^{\mp} K^{\pm}$

Time dependent



1. Interference between mixing and direct decay, large effect because decays are not colour suppressed,
2. Sensitive to $(\gamma + \phi_s)$, strong phase δ,
3. Need to measure 4 time dependent decay rates





$$\Gamma_{B_s^0 \to f}(t) = |A_f|^2 \left(1 + |\lambda_f|^2\right) \frac{e^{-\Gamma_s t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma_s t}{2} + \boldsymbol{D_f} \sinh\frac{\Delta\Gamma_s t}{2} + C_f \cos\Delta m_s t - \boldsymbol{S_f} \sin\Delta m_s t\right)$$

$$\boldsymbol{D_f \propto cos(\delta - (\gamma - 2\beta_s))}$$

$$\boldsymbol{S_f \propto sin(\delta - (\gamma - 2\beta_s))}$$

First measurement with this technique, 1fb^{-1}

$$\gamma = \left(115^{+28}_{-43}\right)^{\circ}$$

JHEP 11 (2014) 060

III Very rare decay

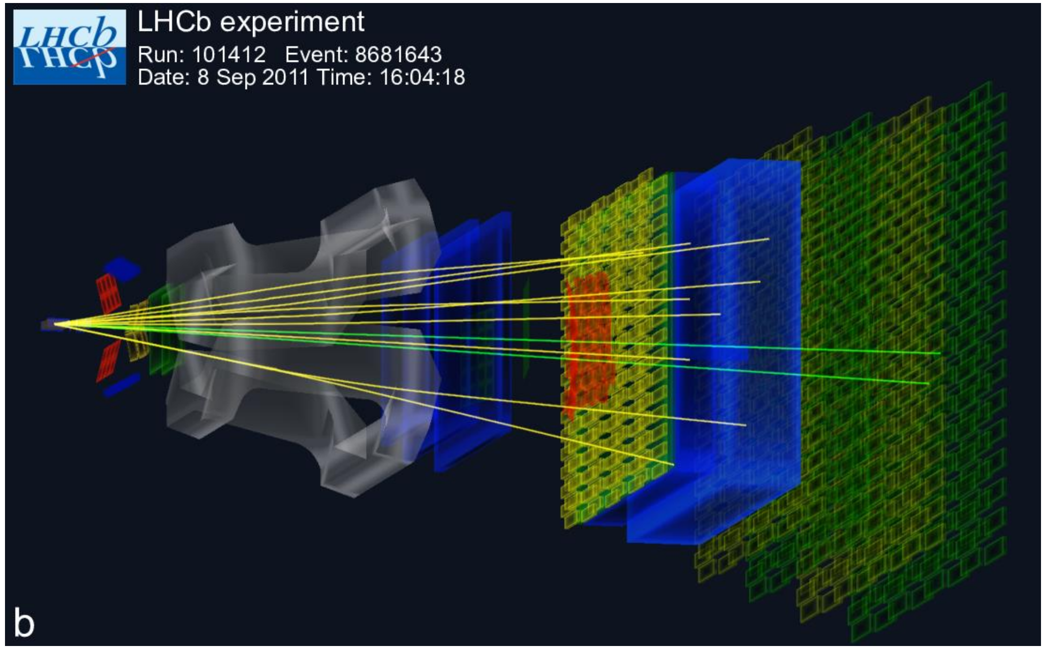
- CMS & LHCb – first observation of the decay $B_S \to \mu\mu$
- Statistical significance above $\boldsymbol{6\sigma}$
- The best measurement of branching fraction to date
- $\boldsymbol{3\sigma}$ evidence for $\boldsymbol{B \to \mu\mu}$

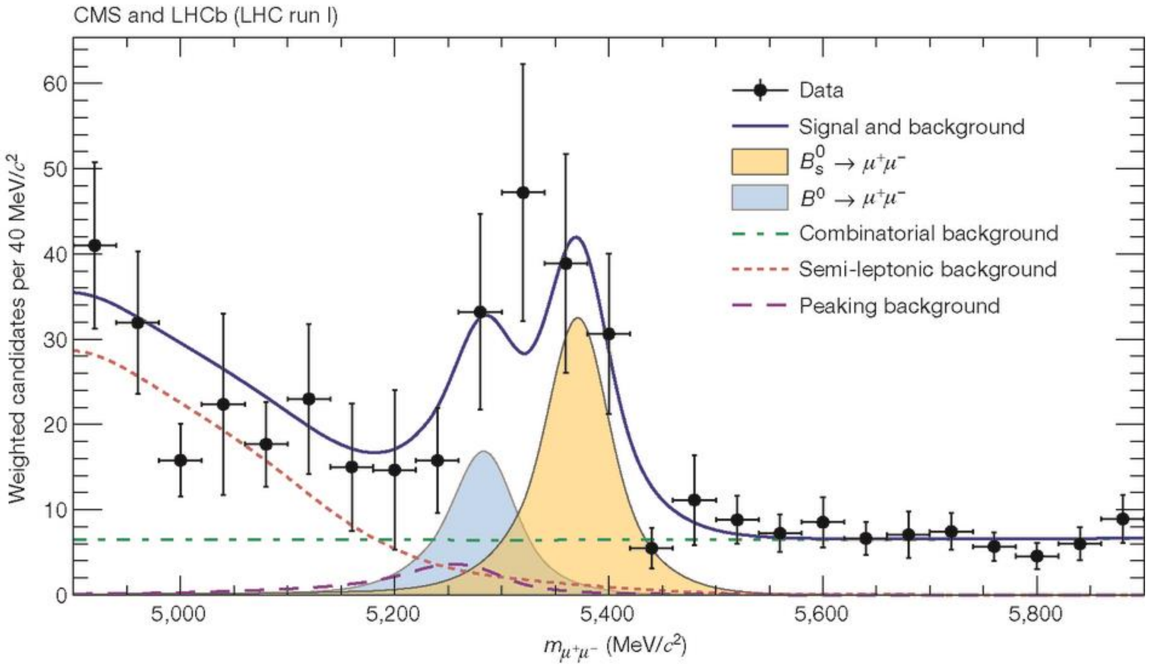
$$\boldsymbol{BR(B_S \to \mu\mu) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}}$$

$$BR(B_S \to \mu\mu)SM = (3.66 \pm 0.23) \times 10^{-9}$$

$$\boldsymbol{BR(B \to \mu\mu) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}}$$

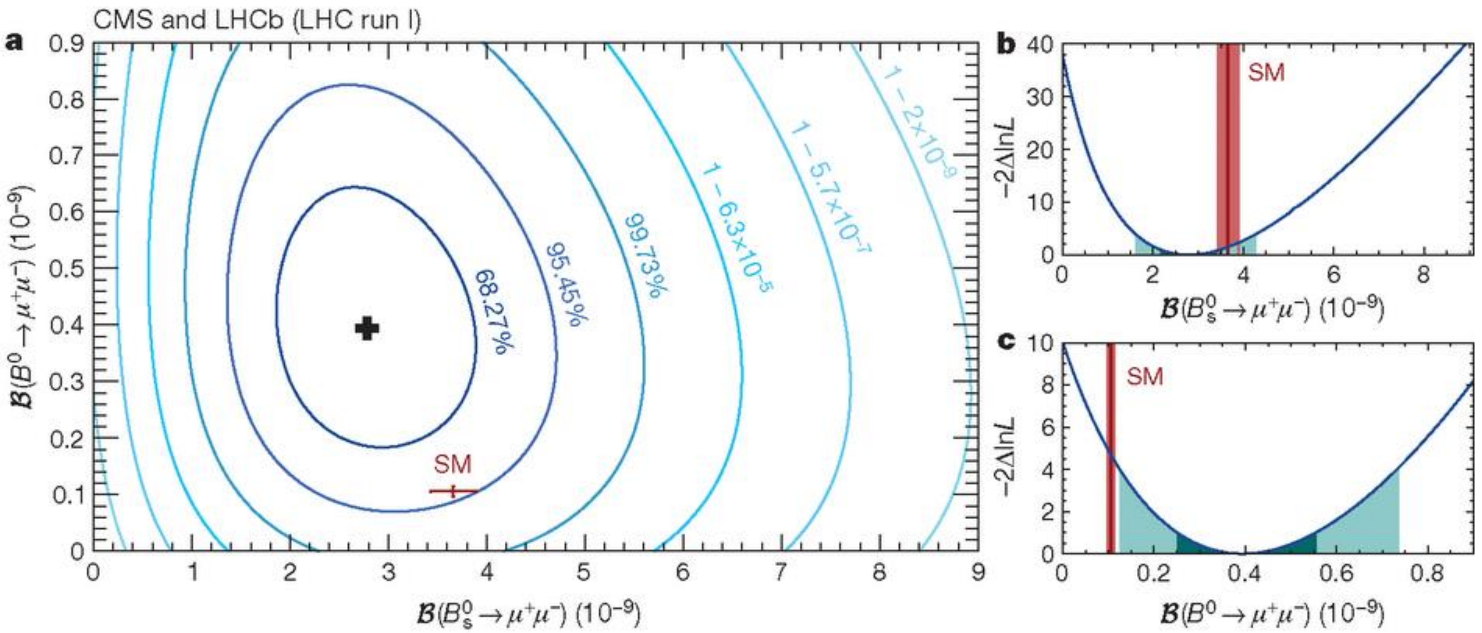
$$BR(B \to \mu\mu)SM = (1.06 \pm 0.09) \times 10^{-10}$$





Nature 13 May 2015 doi:10.1038/nature14474

Very rare decay



- Both results are statistically compatible with Standard Model predictions
- Stringent constraints on theories beyond SM

$$BR(B_S \to \mu\mu) = \left(2.8^{+0.7}_{-0.6}\right) \times 10^{-9}$$

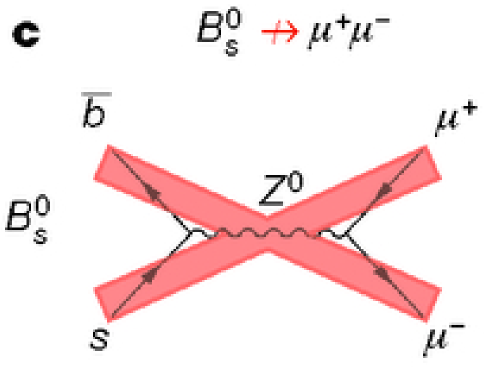
$$BR(B_S \to \mu\mu)SM = (3.66 \pm 0.23) \times 10^{-9}$$

$$BR(B \to \mu\mu) = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}$$

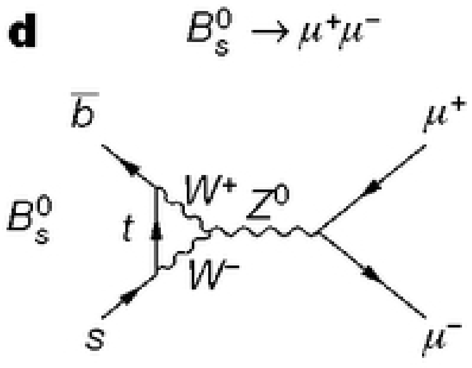
$$BR(B \to \mu\mu)SM = (1.06 \pm 0.09) \times 10^{-10}$$

Nature 13 May 2015 doi:10.1038/nature14474

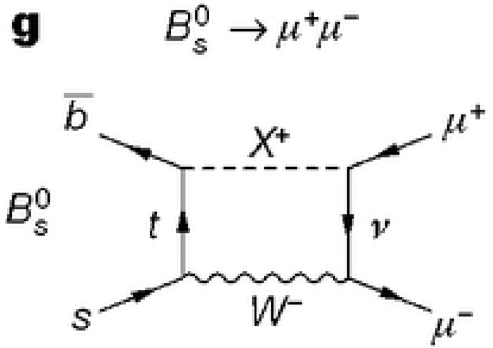
Why so rare?



Forbidden!
No direct Flavour Changing Neutral Currents



Only higher order transitions



New, heavy particles can enter in competing processes and significantly change:

- the branching fraction BR of the decay
- and the angular distribution of the final state particles

$B \rightarrow \mu\mu$ even more suppressed due the transitions from III to I generation

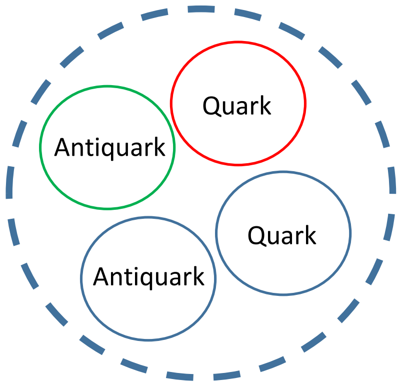
Exotic mesons

Exotic hadrons – have structures more complex than $|q\bar{q}\rangle$ or $|qqq\rangle$

1. In quantum theory one can express a meson as a linear superposition of allowed basis states
   a) This basis spanning $|q\bar{q}q\bar{q}\rangle$, $|q\bar{q}g\rangle$, $|gg\rangle$,….
   b) Respective amplitudes in this linear expansion are govern by the QCD interactions
2. Depending on the dominating component we can classify mesons as quarkonia, hybrids, glueballs, dibarions, tetra-quarks

Diquark – antidiquarks (tetraquarks)

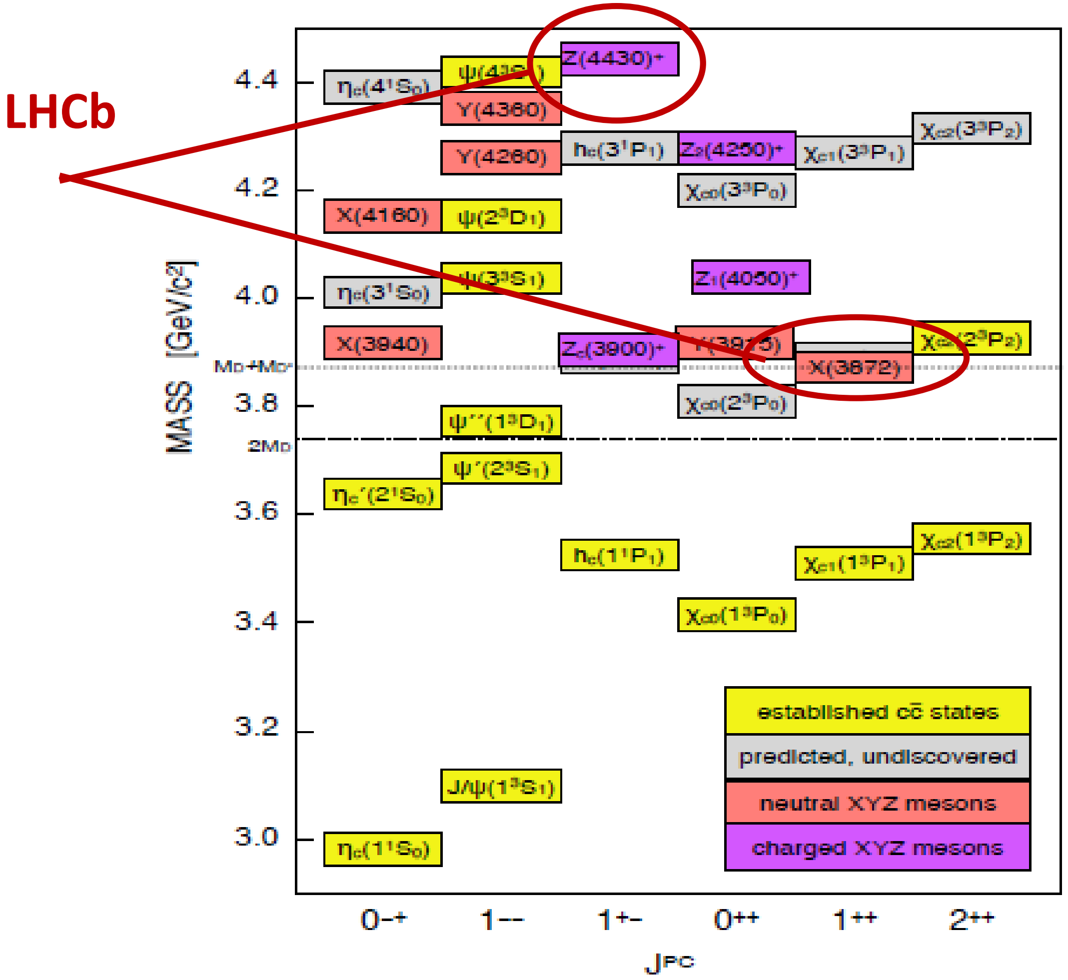
- quark pairs tightly bound in diquarks
- diquarks interact by strong QCD force
- rich spectrum of mass states (not necessary close to the mass threshold) possible
- large number of decay channels with open and hidden charm



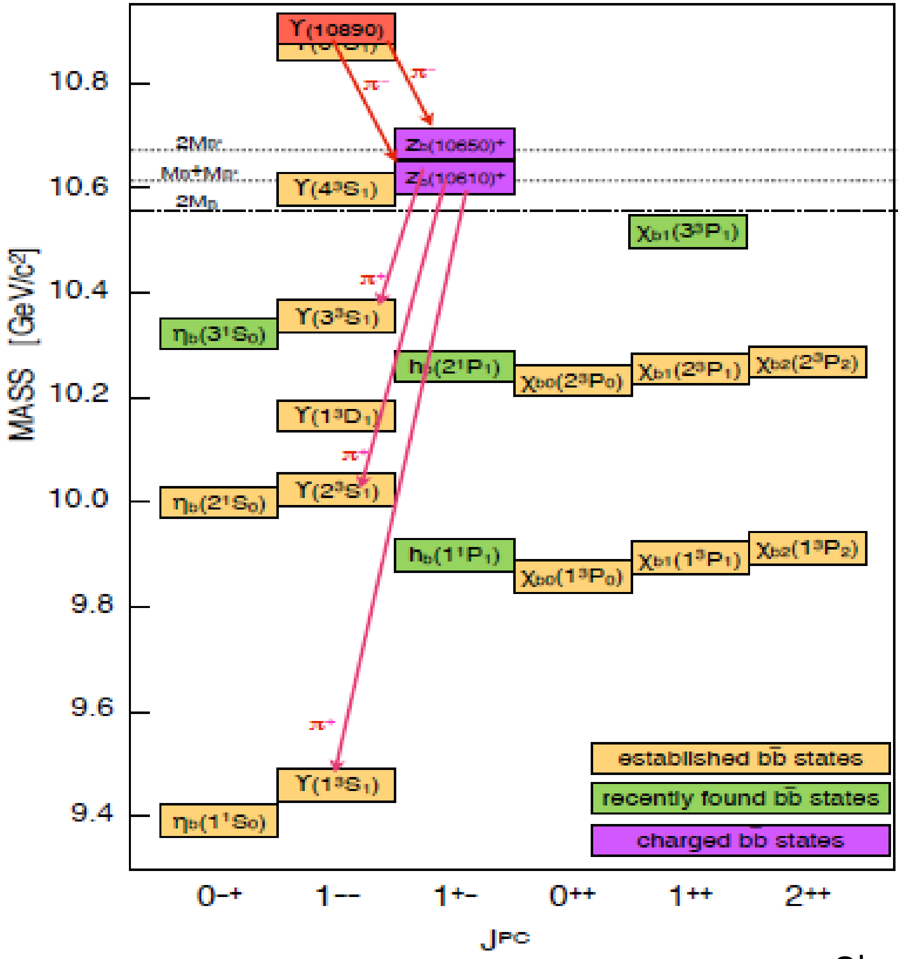
Exotic mesons

XYZ meson are seen to decay to final states with heavy quark and antiquark (c or b) but hardly fit to $q\bar{q}$ spectrum

Charmonium



Bottonium

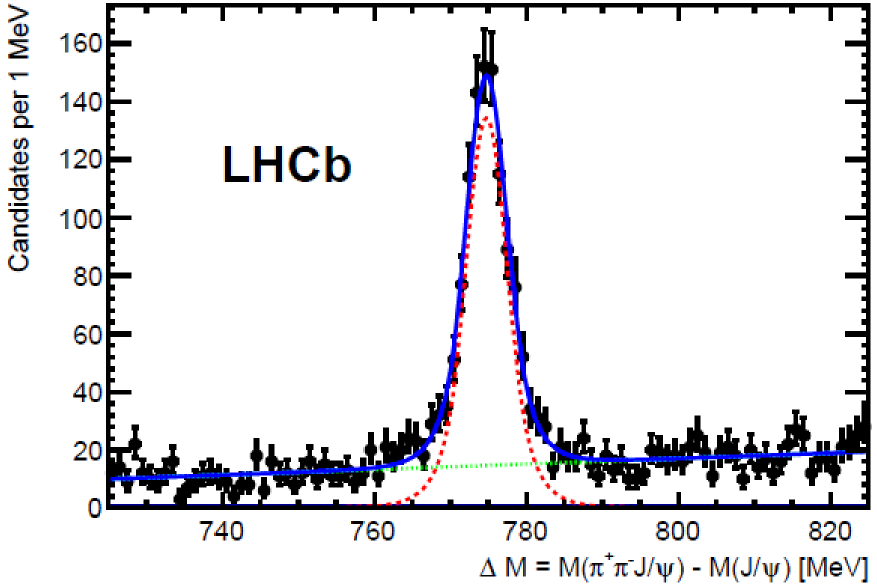


Olsen, arXiv:1403.1254 [hep-ex]

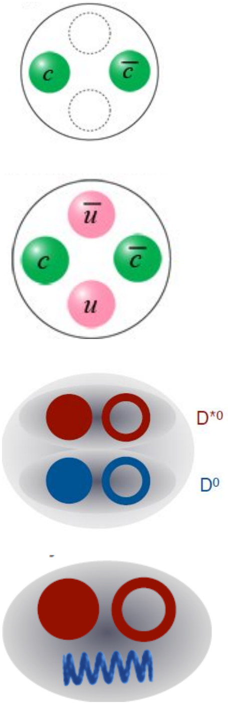
Exotic mesons

$B^+ \to X(3872)K^+$ $X(3872) \to J/\Psi\pi^+\pi^-$

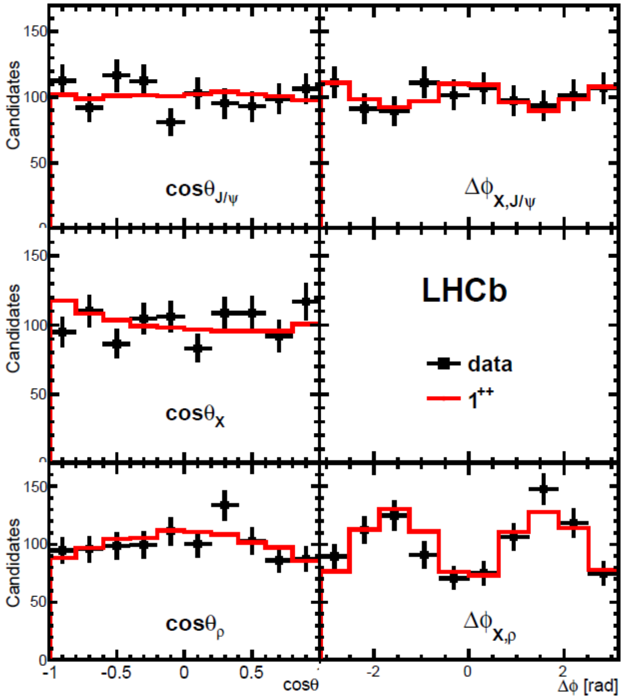
The narrow **X(3872)** was discovered by the Belle experiment, confirmed by several other 6 experiments.
Unlikely to be conventional charmonium
Interpretation as an exotic state: tetraquark $c\bar{c}u\bar{u}$, molecule $D^0D^{*0} = (c\bar{u})(\bar{c}u)$, hybrid $c\bar{c}g$



LHCb 3fb^{-1}, 1011±38 events



Determination of quantum numbers:
- Angular analysis in helicity basic
- No assumptions about orbital momentum L



Data unambiguously prefers: $J^{PC} = 1^{++}$

Consistent with all models….

Phys.Rev.Lett 110 (2013) 222001
NEW! LHCb-PAPER-2015-015

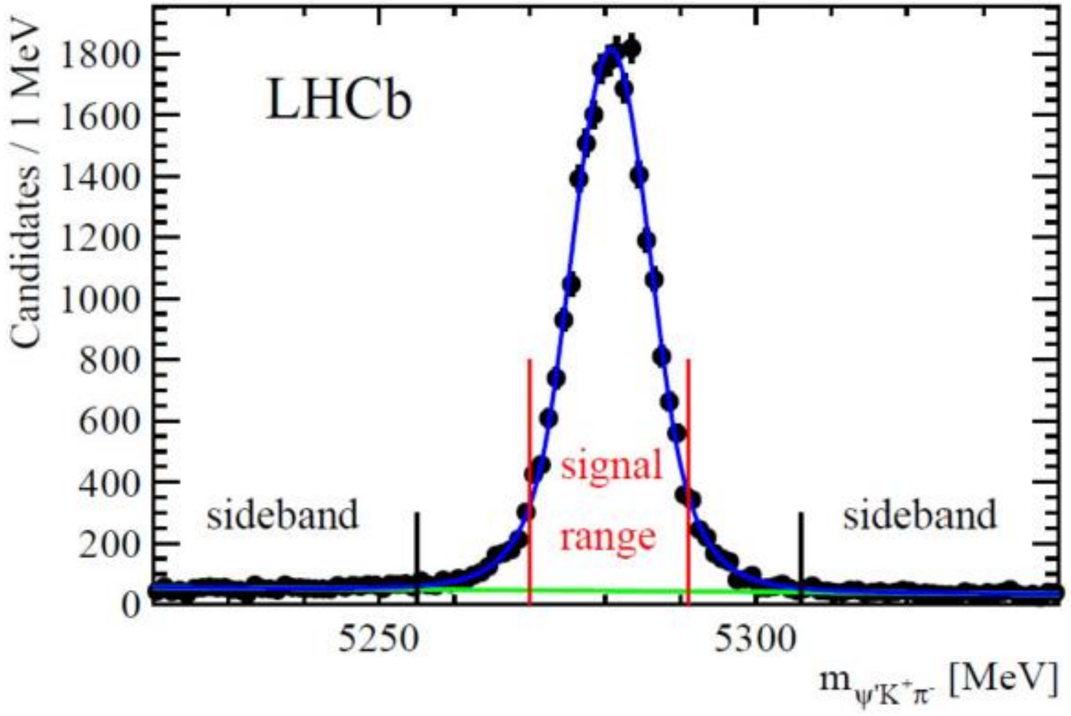
Exotic mesons

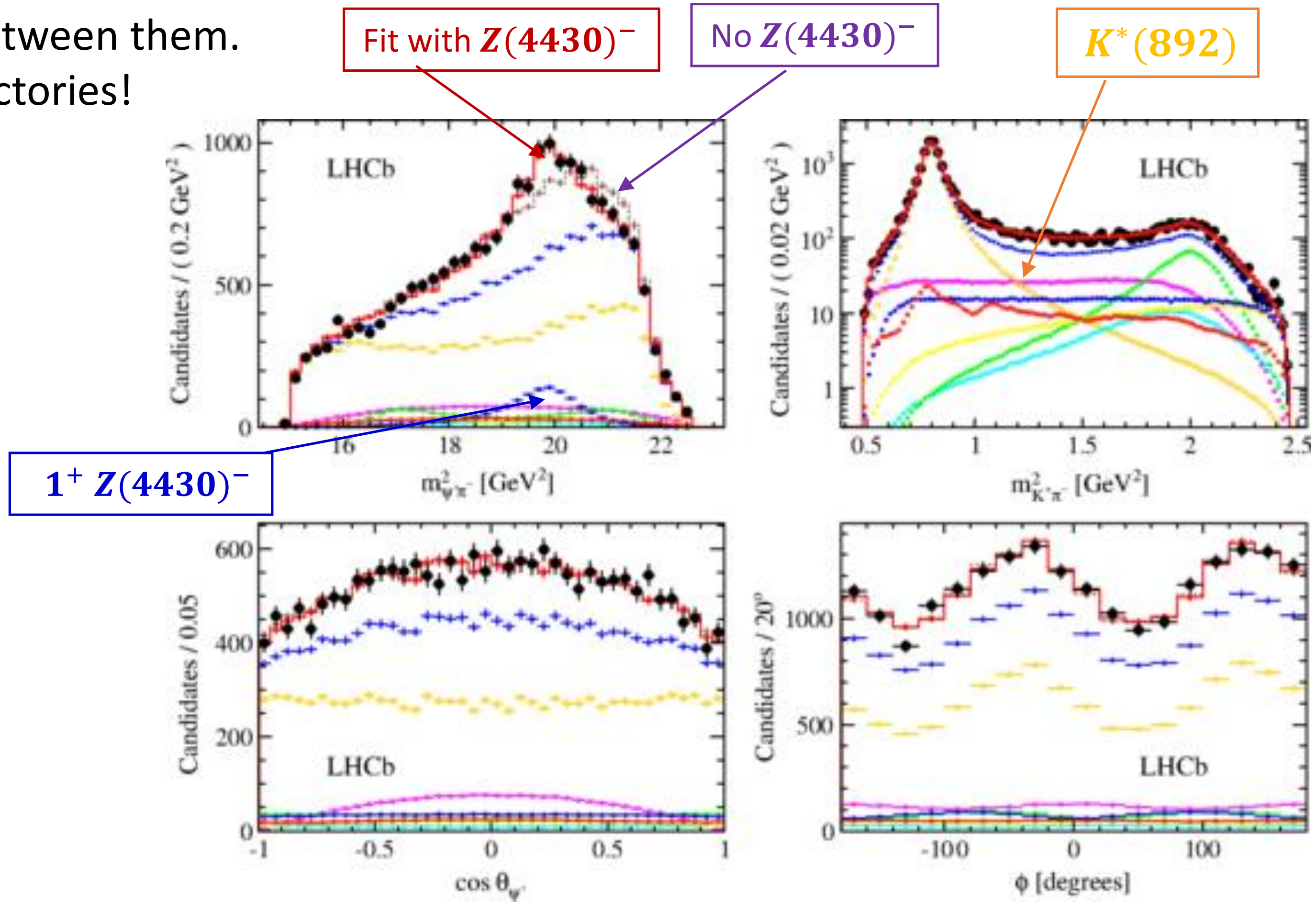
$B^0 \rightarrow \Psi' K^+ \pi^-$

$Z(4430)^- \rightarrow \Psi' \pi^-$

Discovered by Belle, Babar, but with discrepancies between them.
25 000 events in LHCb, smaller background than B factories!

4D fit $\{m^2_{K\pi}, m^2_{\Psi\pi}, cos\theta_{\Psi}, \phi\}$
Full amplitude analysis with K^*resonances up to $J \leq 2$





Phys.Rev.Lett. 112, 222002 (2014)

The data are well described with a $J^P = 1^+ \; Z(4430)^-$ in the fit

Exotic mesons

$Z(4430)^- \rightarrow \Psi'\pi^-$

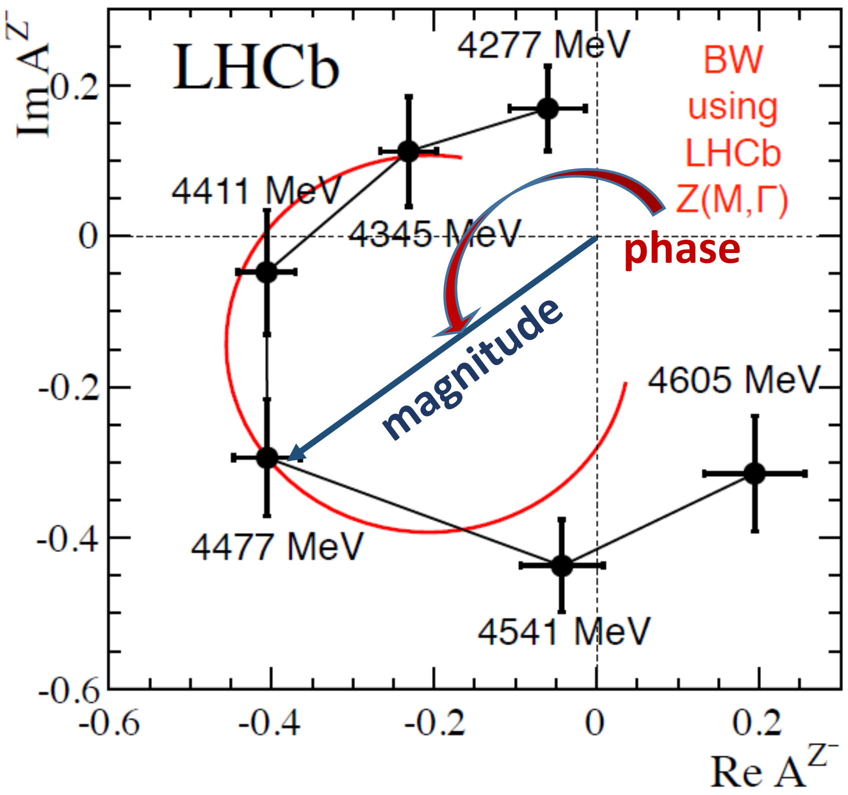
1. Confirmation of Belle results:

$$M_{Z^-} = 4475 \pm 7\ MeV$$
$$\Gamma_{Z^-} = 172 \pm 13\ MeV$$
$$J^{PC} = 1^{++}$$

2. Resonant behaviour?

Model independent Argand diagram technique:

- Replace the BW amplitude by 6 independent complex numbers in 6 bins of $\Psi'\pi^-$ mass near $Z(4430)^-$ mass.
- Only $K\pi$ amplitudes in Z mass shape
- If phase changes rapidly near maximum → resonance!



The diagram shows clearly **resonant behavior** of the **Z(4430)**

Phys.Rev.Lett. 112, 222002 (2014)

IV. Summary

1. LHCb is the experiment to study CP Violation and rare decays:
2. After three years of data taking in data with B decays:
   a) Direct CP Violation
   b) CP Violation in mixing (mixing of neutral mesons, both B^0 and B_S^0
   c) CP Violation in interference between direct decay and decay after mixing
   d) Rare decays
3. In charm sector – mixing is observed, approaching CPV SM limits
4. Exotic states – confirmation of B factories result with more statistic.

very precise measurements of:

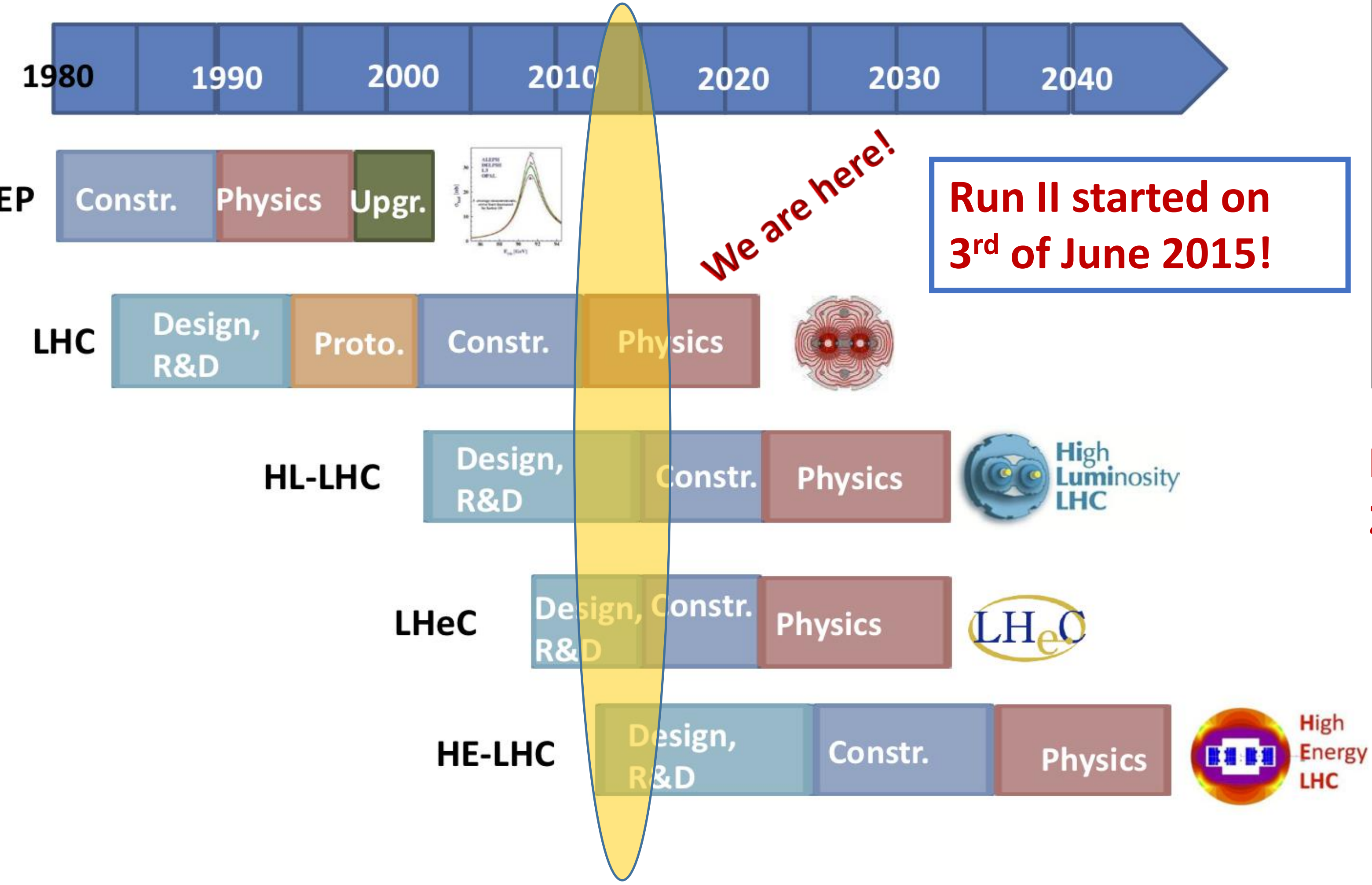
- weak phase ϕ_S
- CKM γ angle

ALL within the Standard Model limits

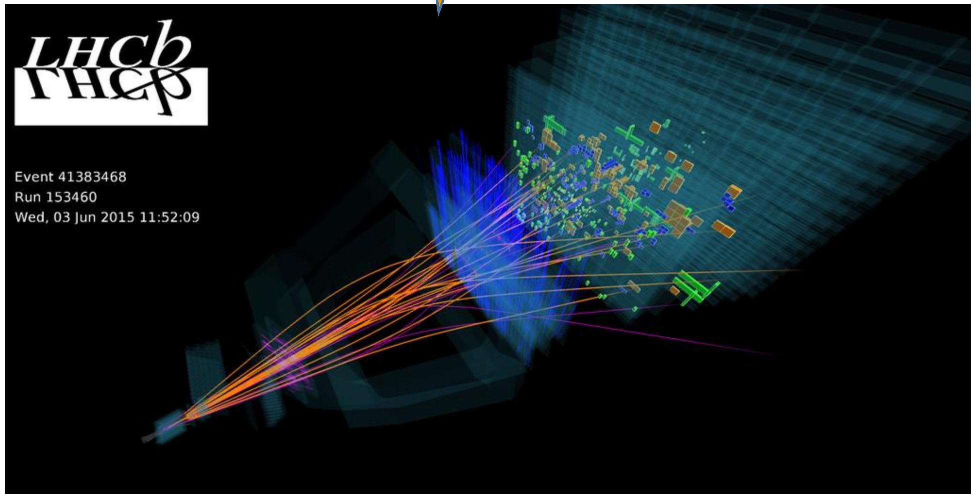
What's next? Run II & Upgrade!

The LHC Run II & Upgrade

HOT !



Run II started on 3rd of June 2015!



Run III of the LHC scheduled to begin in 2020:

- Instantaneous luminosity: $\mathcal{L}_{inst} = 2 \times 10^{33}\, cm^{-2} s^{-1}$ (increase of factor 5),
- LHCb plans to collect 50 fb^{-1} of integrated luminosity @ √s=14 TeV,
- Average number of (visible) interaction ν≈7.6 (μ≈5.2), σ_{vis}=70 mb, $\sigma_{bb} \propto \sqrt{s}$

LHCb Upgrade

Upgraded detector:

Installation is foreseen between 2018-19

- New **tracking system**.
- Full event readout at 40 MHz.
- Upgraded trigger (fully software).
- Increase of the output rate to 20-100 KHz
- New PID system.