Measurements with final-state photons at LHCb

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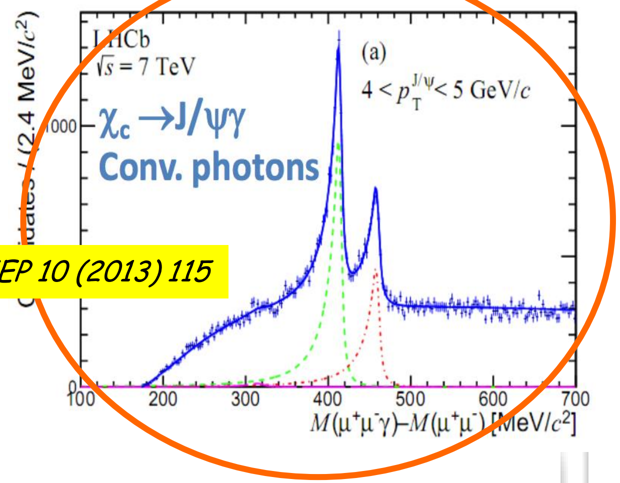
(On behalf of the LHCb collaboration)

Preamble

LHCb has a wide analysis program of decays with final-states neutrals

This talk mostly focuses on radiative decays



JHEP 10 (2013) 115

Observation of the $B_s^0 \to \eta'\eta'$ decay

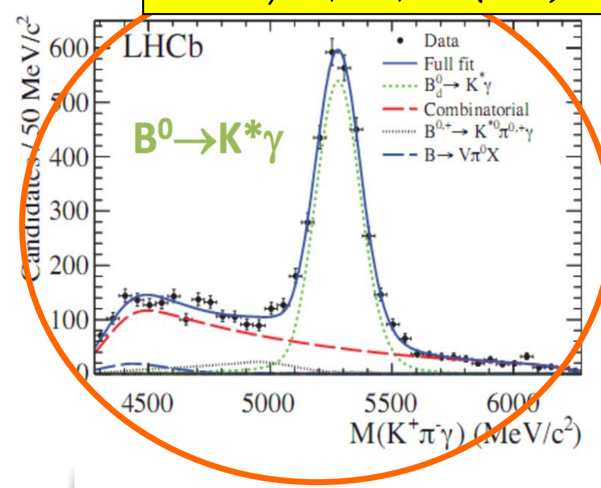
arXiv:1503.07483, (submitted to PRL)

Abstract

The first observation of the $B_s^0 \to \eta'\eta'$ decay is reported. The study is based on a sample of proton-proton collisions corresponding to $3.0\,fb^{-1}$ of integrated luminosity collected with the LHCb detector. The significance of the signal is 6.4 standard deviations. The branching fraction is measured to be $[3.31 \pm 0.64\,(stat) \pm 0.28\,(syst) \pm 0.12\,(norm)] \times 10^{-5}$, where the third uncertainty comes from the $B^\pm \to \eta' K^\pm$ branching fraction that is used as a normalisation. In addition, the charge asymmetries of $B^\pm \to \eta' K^\pm$ and $B^\pm \to \phi K^\pm$, which are control channels, are measured to be $(-0.2 \pm 1.3)\%$ and $(+1.7 \pm 1.3)\%$, respectively. All results are consistent with theoretical expectations.

Submitted to Phys. Rev. Lett.

Nucl. Phys. B, 867, 1-18 (2013)



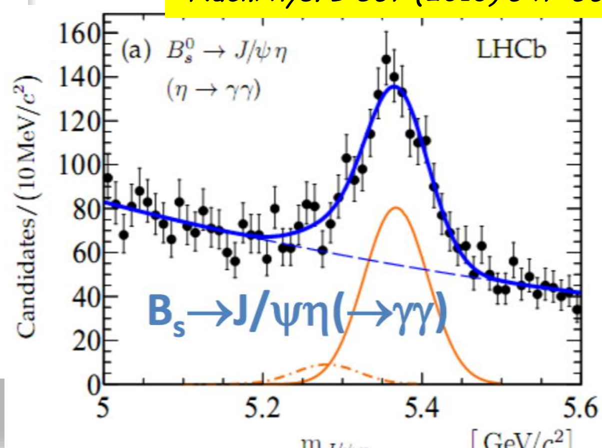
Measurement of the fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays in pp collisions at $\sqrt{s} = 7$ TeV

JHEP 1211 (2012) 031

The LHCb collaboration

ABSTRACT: The production of $\chi_b(1P)$ mesons in pp collisions at a centre-of-mass energy of 7 TeV is studied using 32 pb^{-1} of data collected with the LHCb detector. The $\chi_b(1P)$ mesons are reconstructed in the decay mode $\chi_b(1P) \to \Upsilon(1S)\gamma \to \mu^+\mu^-\gamma$. The fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays in the $\Upsilon(1S)$ transverse momentum range $2 < p_T^{\Upsilon(1S)} < 15$ GeV/c and rapidity range $2.0 < y^{\Upsilon(1S)} < 4.5$ is measured to be $(20.7 \pm 5.7 \pm 2.1^{+2.7}_{-5.4})\%$, where the first uncertainty is statistical, the second is systematic and the last gives the range of the result due to the unknown $\Upsilon(1S)$ and $\chi_b(1P)$ polarizations.

Nucl.Phys. B 867 (2013) 547-566



A study of CP violation in $B^\mp \to Dh^\mp$ ($h = K, \pi$) with the modes $D \to K^\mp\pi^\pm\pi^0$, $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$

arXiv:1504.05442, (submitted to PRD)

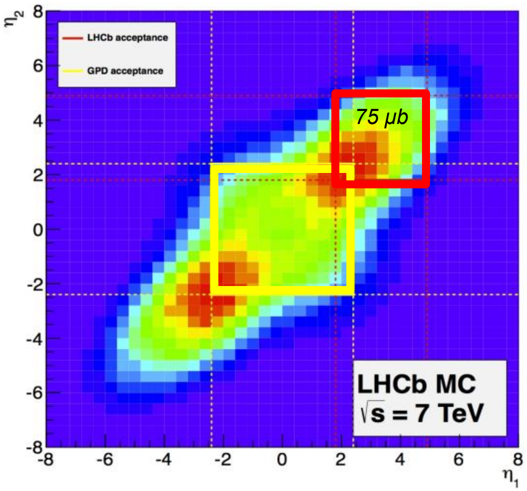
llaboration[†]

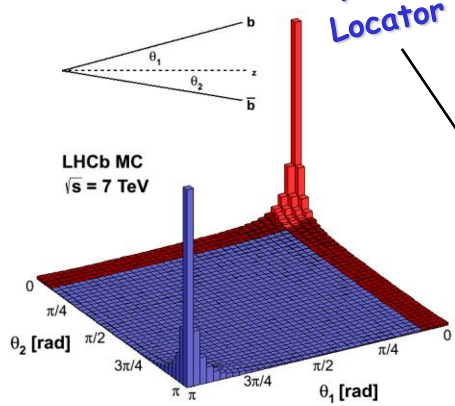
Abstract

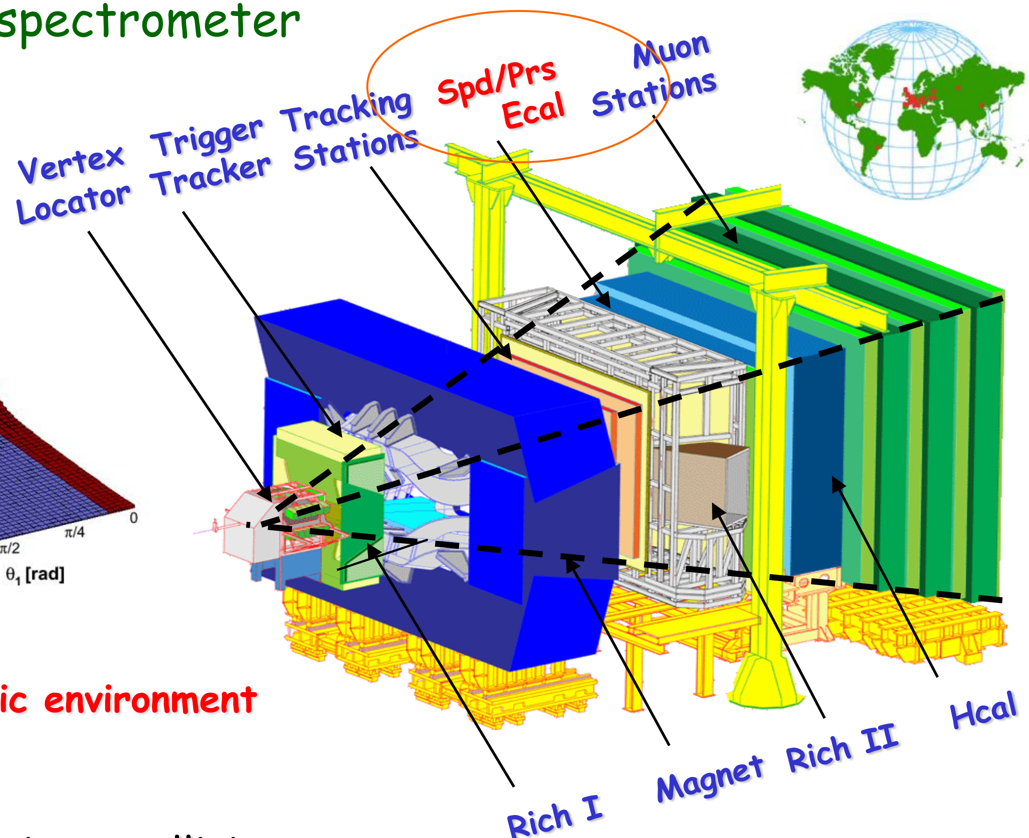
An analysis of the decays of $B^\mp \to DK^\mp$ and $B^\mp \to D\pi^\mp$ is presented in which the D meson is reconstructed in the three-body final states $K^\mp\pi^\pm\pi^0$, $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$. Using data from LHCb corresponding to an integrated luminosity of 3.0 fb^{-1} of pp collisions, measurements of several CP observables are performed. First observations are obtained of the suppressed ADS decay $B^\mp \to [\pi^\mp K^\pm\pi^0]_D\pi^\mp$ and the quasi-GLW decay $B^\mp \to [K^+K^-\pi^0]_D\pi^\mp$. The results are interpreted in the context of the unitarity triangle angle γ and related parameters.

The LHCb experiment

- LHCb detector : single-arm forward spectrometer
  - $2 < \eta < 5$







- Main challenge :
  - Perform precision measurements in hadronic environment

- Large multiplicities
- Large background from high inelastic pp collisions
- Small Branching Ratio for radiative B meson decay

… but …

- 30 kHz $b\bar{b}$ rate
- Access to all b species : B_d, B_u, B_s, B_c, Λ_b, Ξ_b…

This also means we have to fight against many unknown backgrounds !!

Converted photons

- Calorimetric photons: unconverted photons or conversion after magnet
  => from calorimeters deposit
- di-electron photons : conversion before magnet
  => from tracking system

Photon combinatorial background

- Photon combinatorial is huge (~10 calorimetric photon/events)
- Large calorimeter occupancy => large background
  => neutralID to separate neutral EM showers from hadronic deposits & $e^{\pm}$
- Above pT ~2.5 GeV/c π^0 likely produced a single Ecal cluster
  => photon/pi0 separation with multivariate analysis

Radiative B decays at LHCb

Nucl. Phys. B, 867, 1-18 (2013)

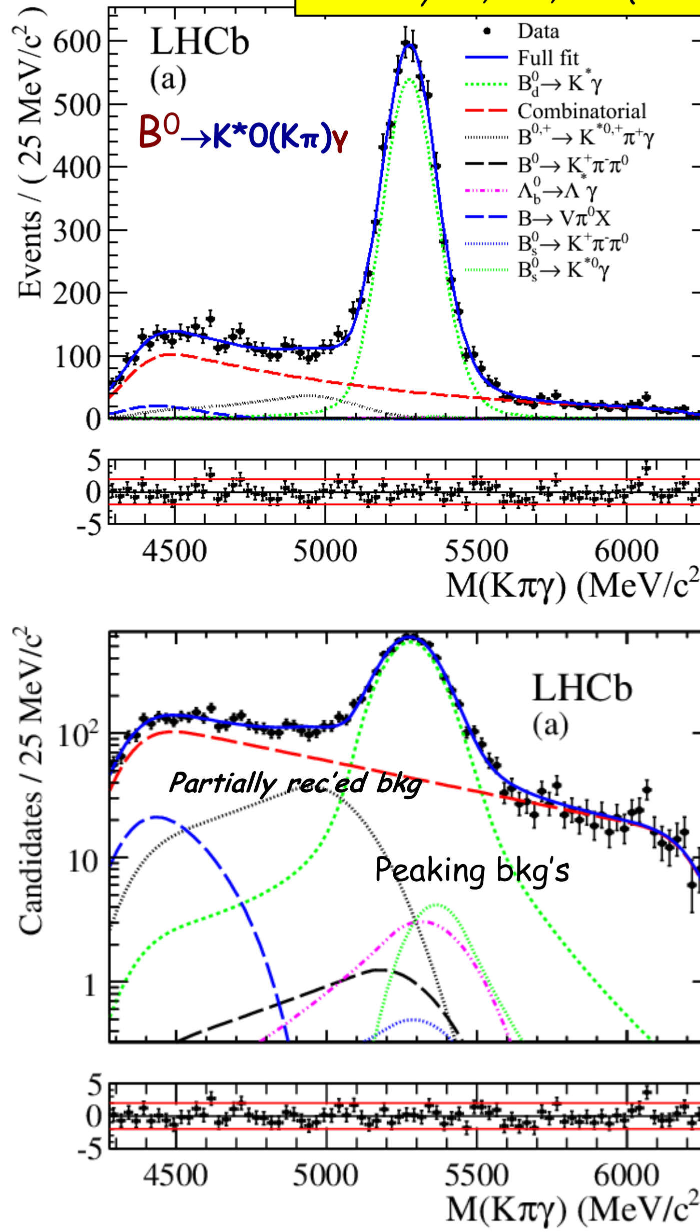
Radiative decays reconstruction

- Due to trigger rate constraint and large combinatorial, the radiative decays at LHCb mostly rely on high pT photons :
  - **L0 threshold in 2011(2012) : $E_T(\gamma)$ > 2.5 (3.0) GeV**
  - **Typical L0+HLT trigger efficiency on rad. ~ 30-40%**
  - **For comparison : (di)muon channel ε_{trg}~80-90%**

- Mass resolution driven by calorimeter resolution :
  - **$\sigma_M(B\rightarrow X\gamma)$ ~ 90 MeV/c²**
  - **For comparison :**
    - **$\sigma_M(B\rightarrow hh)$ ~ 25 MeV/c²**
    - **$\sigma_M(B\rightarrow J/\psi X)$ ≤ 10 MeV/c²**

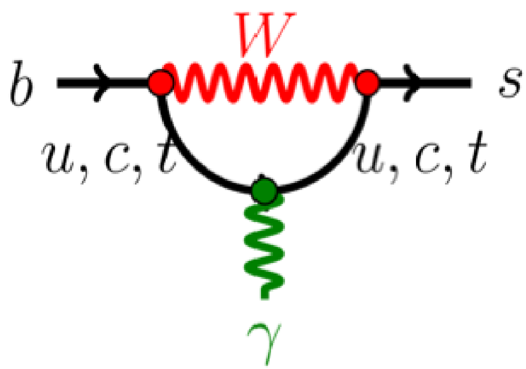
- No constraint on vertexing from γ + large photon multiplicity + limited mass resolution :
  - Large combinatorial background
  - partially rec'ed and peaking backgrounds

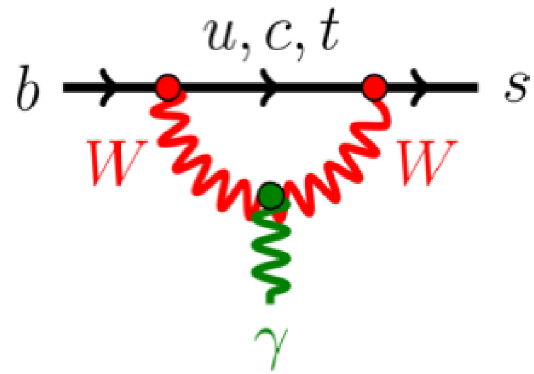
→Tight selections are applied



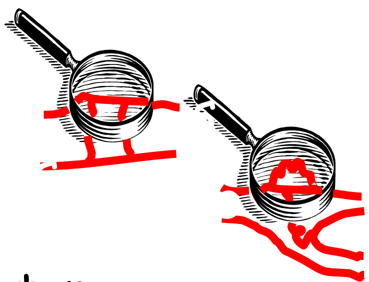
b→q transitions

- Radiative b→qγ (q=d,s) transition : FCNC electro-magnetic penguin





New physics affects the transition dynamics



BR, A_{CP}, Isospin asymmetry, helicity structure of the photon

Radiative decays : $B_d \to V\gamma$

Relative BR of $B_d \to K^*\gamma$ and $B_s \to \varphi\gamma$

- Branching fractions :

[HFAG, 2010]

$BR(B^0 \to K^{*0}\gamma) = (4.33 \pm 0.15) \times 10^{-5}$

$BR(B_s \to \varphi\gamma) = (5.7^{+2.1}_{-1.8}) \times 10^{-5}$

- SM-predictions have large hadronic uncertainty mostly canceling in the ratio :

$R = BR(K^{*0}\gamma)/BR(\varphi\gamma) = 1.0 \pm 0.2$ [Ali, Pecjak, Greub, 2008]

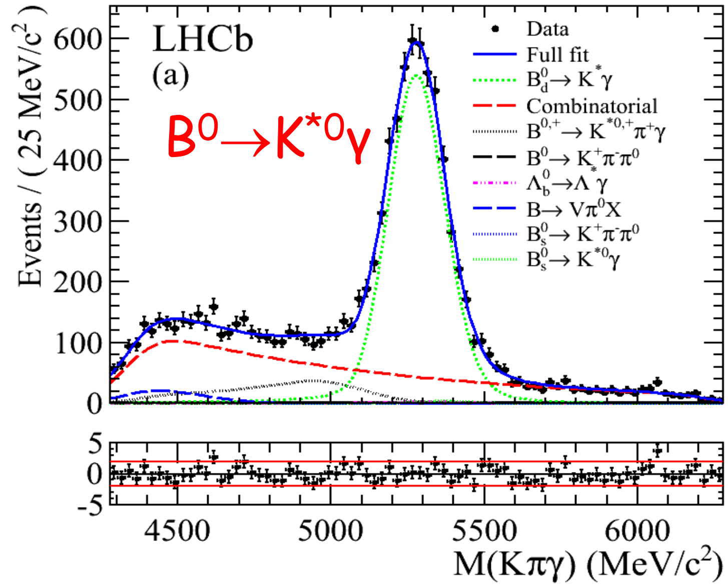
- LHCb result (1.0 fb^{-1} - 2011 data)

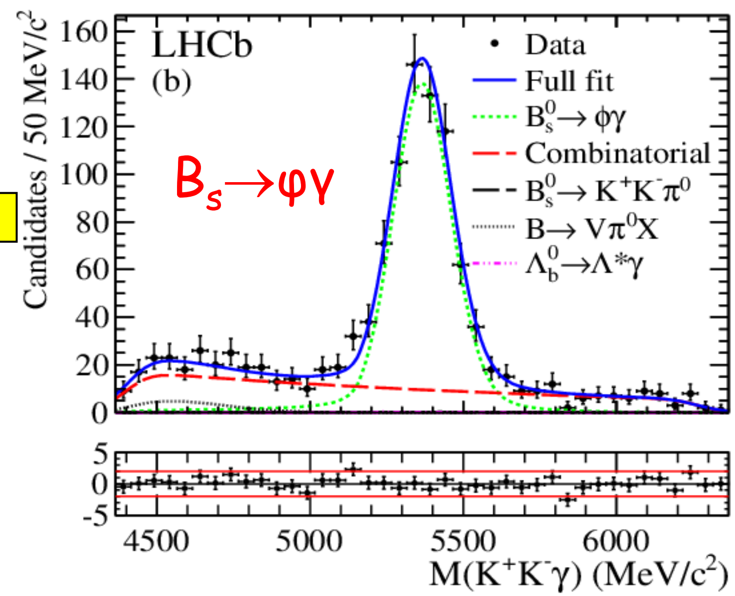
[Nuclear Physics B, 867, 1-18 (2013)]

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B^0_s \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$

$$\mathcal{B}(B^0_s \to \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5}$$

Results on 0.37 fb^{-1} published in Phys. Rev. D 85, 112013 (2012)





Radiative decays : $A_{CP}(B^0 \to K^{*0}\gamma)$

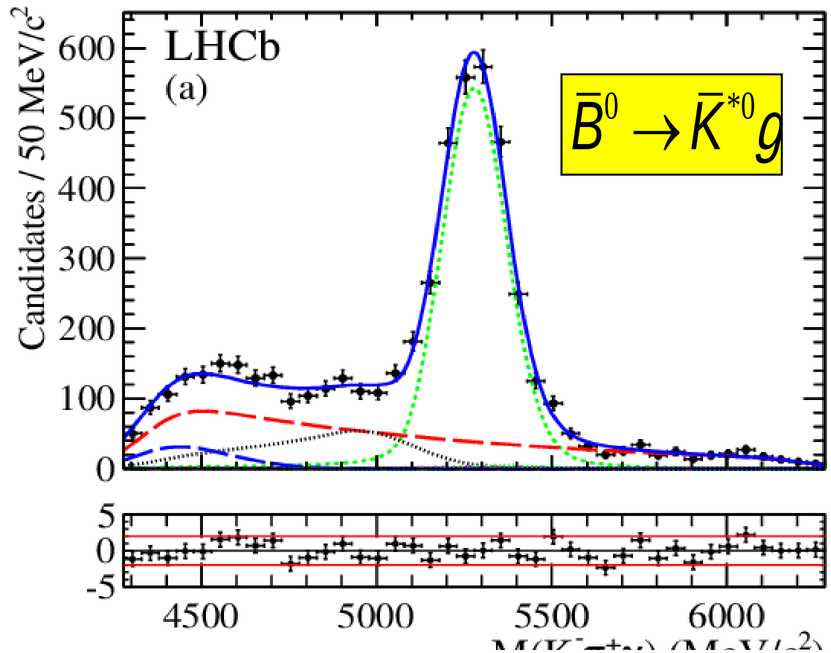
Direct CP asymmetry in $B^0 \to K^{*0}\gamma$

SM-prediction :

Phys. Rev. D72 (2005) 014013

$A_{CP} = -0.0061 \pm 0.0043$

A_{CP} enhanced in NP scenarii



Previous best measurement :

BABAR, Phys. Rev. Lett. 84, 5283-5287

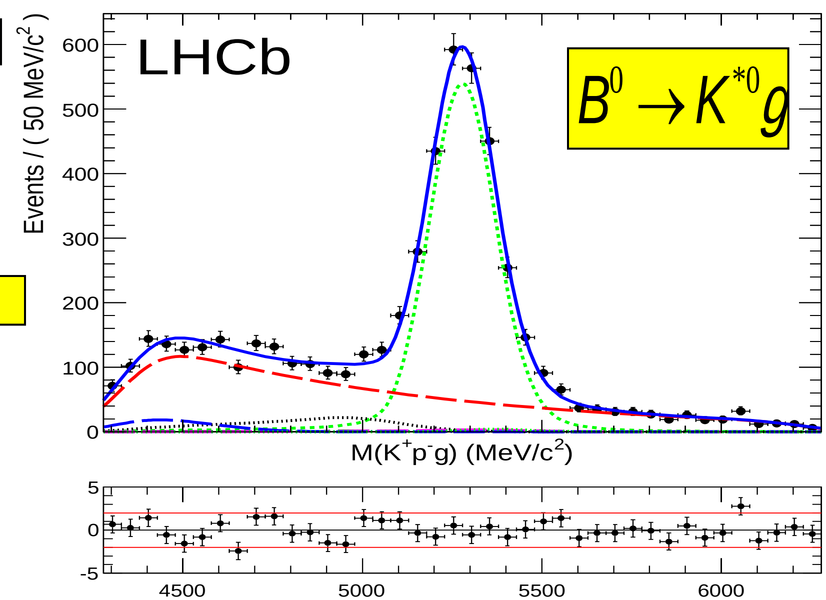
$A_{CP} = -0.016 \pm 0.022 \pm 0.007$

- LHCb result (1.0 fb^{-1} - 2011 data) :

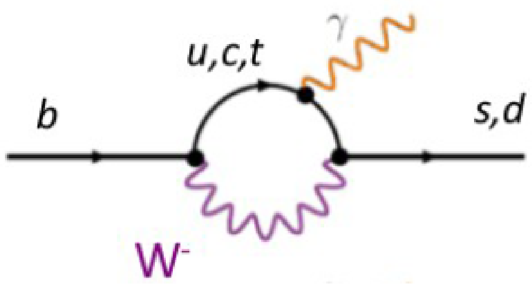
[Nuclear Physics B, 867, 1-18 (2013)]

$$N_{B^0} + N_{\bar{B}^0} = 5300 \pm 100$$

$$A_{CP}(B^0 \to K^{*0}\gamma) = 0.008 \pm 0.017\,(\text{stat}) \pm 0.009\,(\text{syst})$$



Photon polarisation in b→qγ transitions

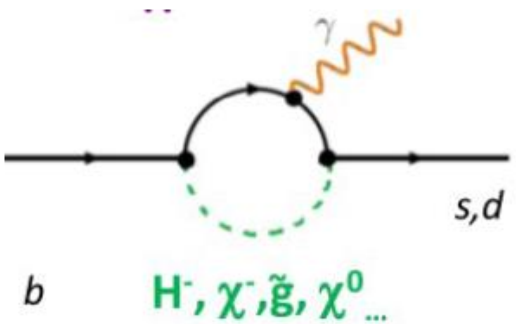


- Since the *W* couples to left-handed quarks, the photon emitted in *b→sγ* is left-handed in the SM (up to corrections of order m_s/m_b)

Leading (em dipole) operator in effective Hamiltonian :

$$O_7 \propto m_b \bar{s} \sigma^{\mu\nu} F_{\mu\nu} (1+\gamma_5) b + m_s \bar{s} \sigma^{\mu\nu} F_{\mu\nu} (1-\gamma_5) b$$

$$\tan\psi = \left| A_L(b_L \to s_R \gamma_R) \right| / \left| A_R(b_R \to s_L \gamma_L) \right| \approx m_s / m_b$$

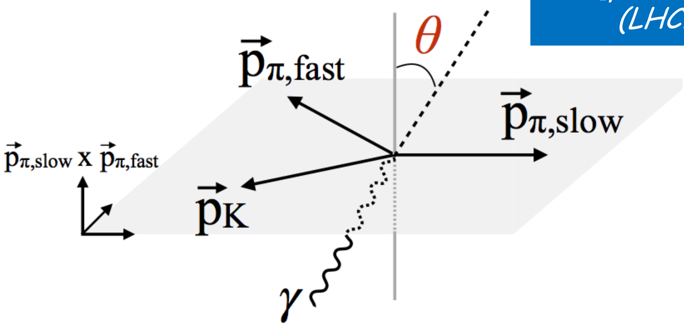


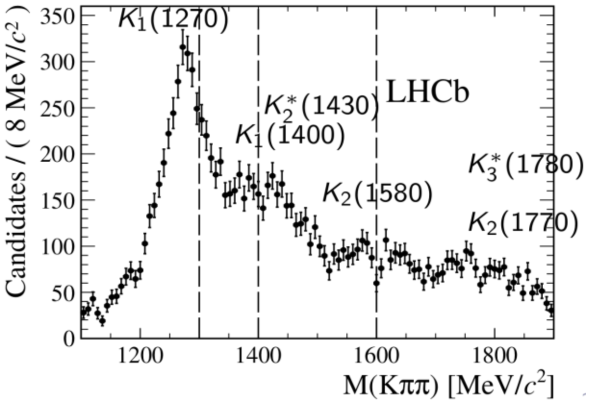
- Right-handed component could be enhanced in NP models

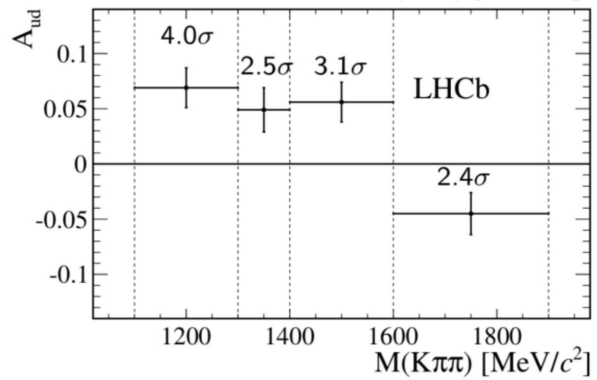
Photon polarisation in $B^+ \to (K\pi\pi)^+\gamma$

$B^+ \to (K\pi\pi)\gamma$

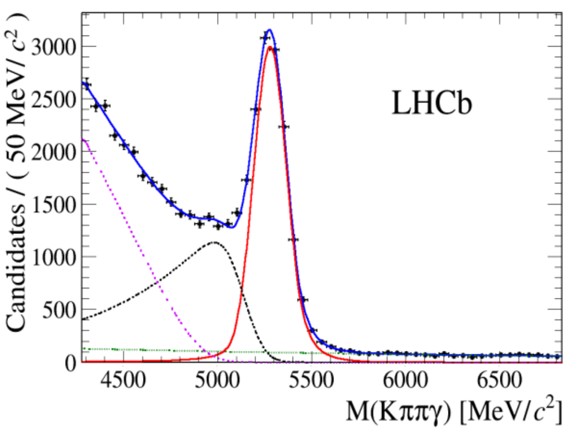
[plots from Zhirui Xu's talk (LHCb-TALK-2014-212)]

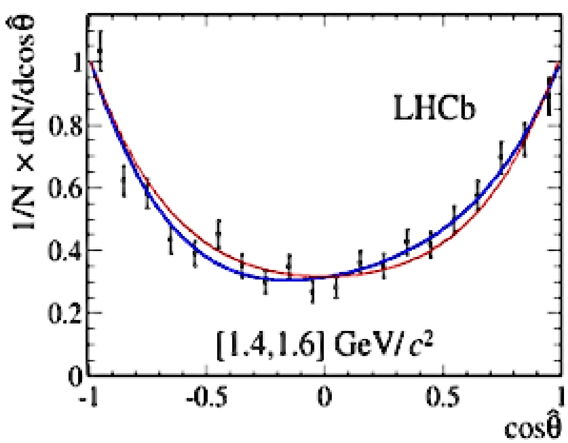






Up-down asymmetry is proportional to the photon polarisation λ_γ





Full angular analysis is in progress

[Phys. Rev. Lett. 112, 161801 (2014)]

Photons from radiative decays are polarized @ 5.2σ significance
First direct observation of photon polarization in $b \to s\gamma$ transition

Photon polarization in $B_s \to \varphi\gamma$

- Untagged decay time in $B_s \to \varphi\gamma$:

$$\Gamma_{B_s}(t) \sim |A|^2 e^{-\Gamma_s t}\left[\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta} \sinh(\Delta\Gamma_s t/2)\right],$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.107 \pm 0.065$$

- The photon polarization is carried by $\mathcal{A}^{\Delta}$

$$\mathcal{A}^{\Delta} = \sin 2\psi \cos \varphi_s, \qquad \tan\psi = \frac{B \to f_{CP}\gamma_L}{B \to f_{CP}\gamma_R}$$

Fraction of photon helicities

- SM expectation: $\mathcal{A}^{\Delta} = 0.047 \pm 0.025 \pm 0.015$ [Muheim, Xie, Zwicky, PLB664(08)174]
- Left-Right Symmetric model: $\mathcal{A}^{\Delta} \sim 0.7$

Analysis of run I data (~3x10[3] reconstructed $B_s \to \varphi\gamma$) in progress
Expected $\mathcal{A}^{\Delta}$ sensitivity of ~0.3 (statistically limited)

Radiative decays of X(3872)

- Evidence for the $X(3872) \to \psi(2S)\gamma$

  - **Mass of X(3872) and quantum numbers $J^{PC}=1^{++}$ has been measured.**
  - **But nature is still not clear: $c\bar{c}$, $D\bar{D}^*$, tetraquark?**
  - Branching fractions ratio

$R_{\psi\gamma}$=BR(X(3872)→J/ψ γ)/BR(X(3872)→ψ(2S) γ)

is dependent on nature of the X(3872):

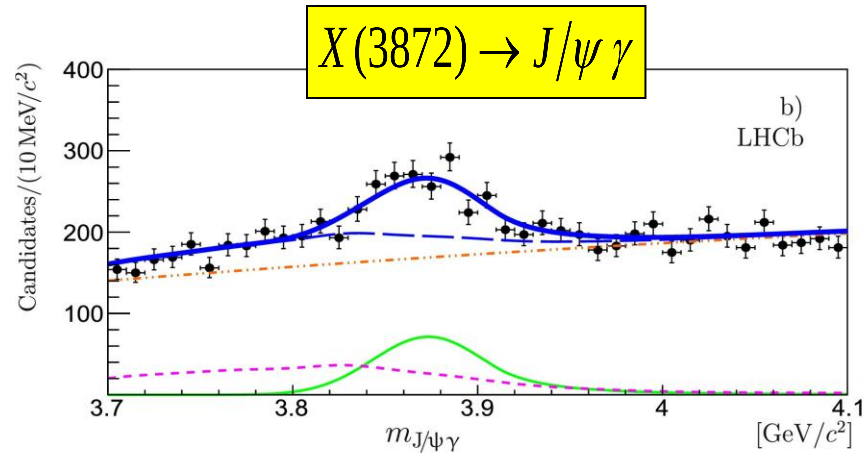
- $R_{\psi\gamma} \approx 1.2 - 15$ for pure charmonium $c\bar{c}$
- $R_{\psi\gamma} \approx (3 \div 4) \times 10^{-3}$ for $D\bar{D}^*$ molecule
- $R_{\psi\gamma} \approx 0.5 - 5$ for $c\bar{c}$-$D\bar{D}^*$ admixture

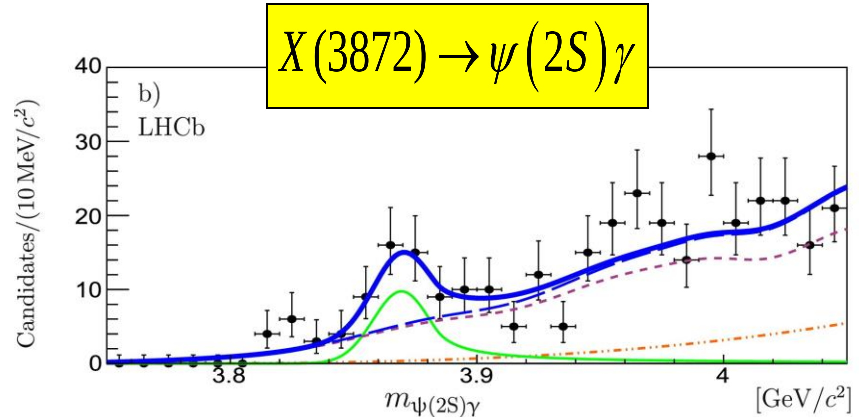
X(3872) is reconstructed in $B^+ \to X(3872)K^+$

3 fb^{-1} analysis, Nucl. Phys. B 886 (2014) 665-680

Rψγ=(2.46±0.64±0.29)

- **4.4σ evidence**
- **Does not support pure $D\bar{D}^*$ interpretation**



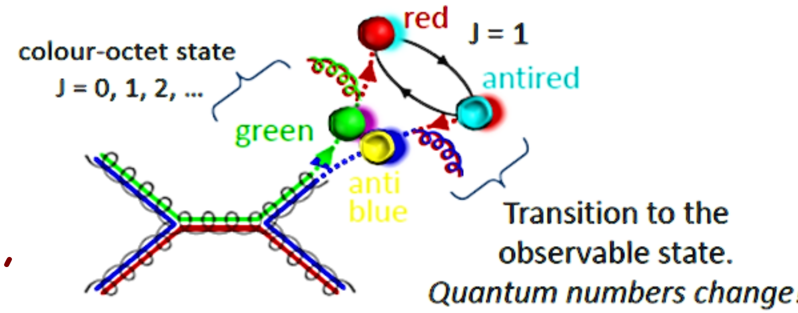


Relative prompt production rate of $\chi_{\{c,b\}}$

- χ_c (χ_b) are reconstructed in the $J/\psi\,\gamma$, $J/\psi \to \mu^+\mu^-$($\Upsilon(\mathrm{nS})\gamma$, $\Upsilon(\mathrm{nS}) \to \mu^+\mu^-$) final state

Motivation

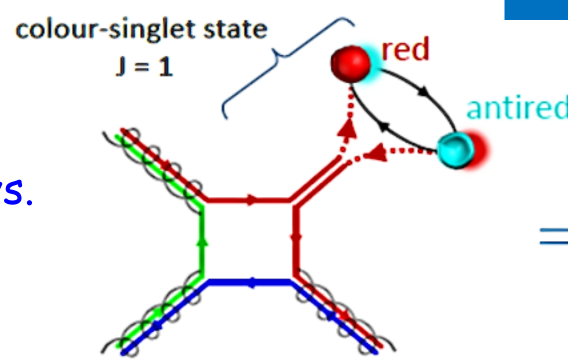
- **Test of QCD models for quarkonia production (color-singlet, color-octet processes, etc.);**
- **Impact on the J/ψ and $\Upsilon(nS)$ polarization measurement (fraction of feed-down from χ_q).**



$\Rightarrow$ NRQCD model (CS + CO processes)

[plots from Edwige Tournefier's talk (LHCb-TALK-2013-165)]

- Background from $B \to \chi_c X$ decays.

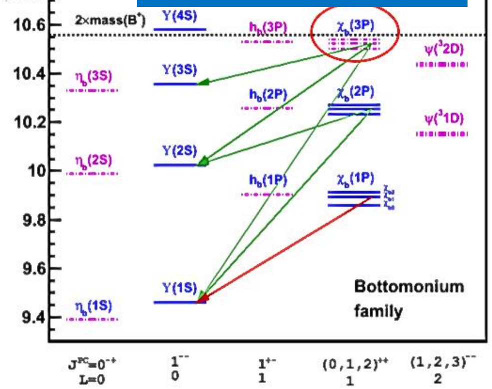


$\Rightarrow$ Color Singlet Model (CSM)

Radiative transitions of quarkonia

Study of χ_b meson production

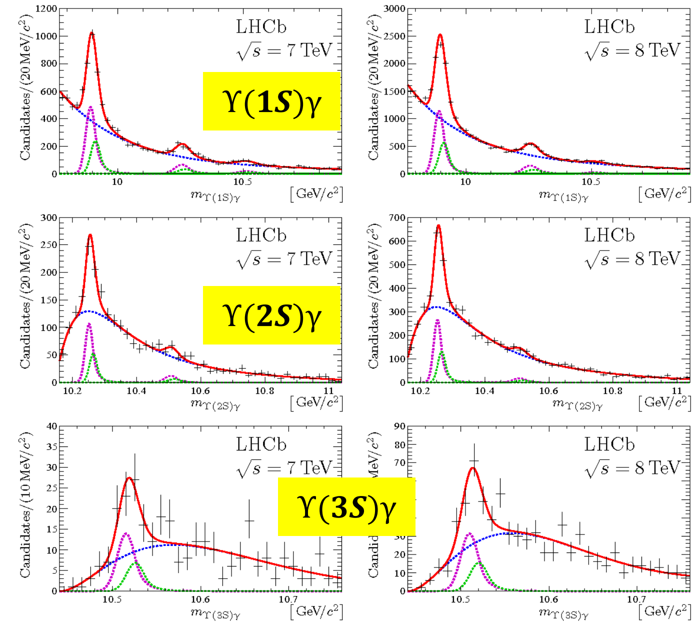
[plot from Sasha Mazurov's Ph.D talk]



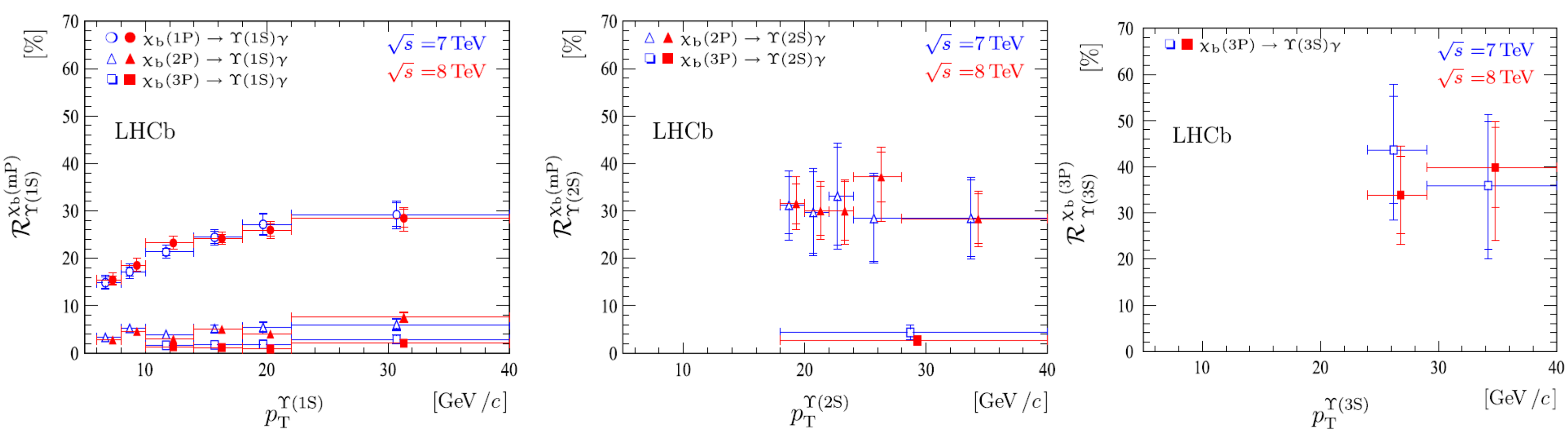
$\chi_b(3P) \to \Upsilon(3S)\gamma$ **is observed for the first time**

$$m_{\chi_b(3P)} = (10511.3 \pm 1.7 \pm 2.5)\ MeV/c^2$$

Fraction of $\Upsilon(nS)$ originating from χ_b decays is measured as a function of Υ transverse momentum



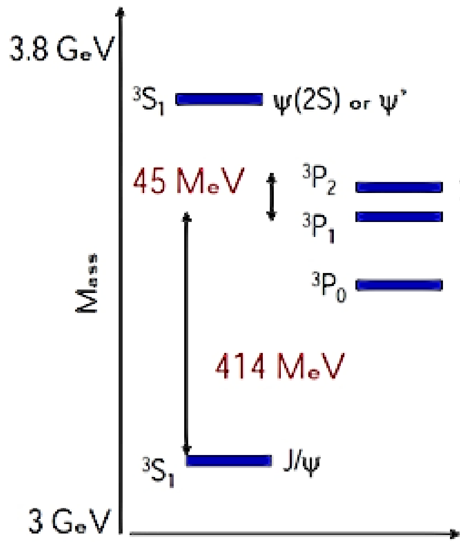
3 fb⁻¹ analysis, Eur. Phys. J. C (2014) 74:3092



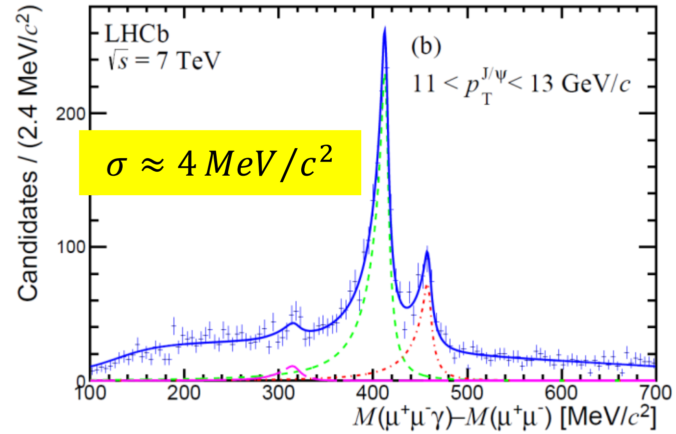
Study of relative prompt χ_{cJ} production rate using converted photons

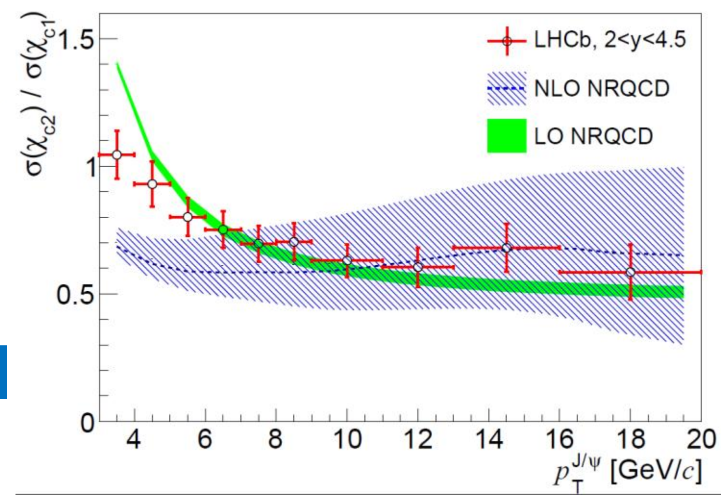
1 fb^{-1} analysis, JHEP 10 (2013) 115

- **Usage of converted photons allows to improve energy resolution and to resolve χ_{c1} and χ_{c2} peaks.**
- **First evidence (4.3σ) for χ_{c0} production at a high-energy hadron collider is obtained.**
- **The results are obtained assuming χ_c mesons are produced unpolarized.**



[plot from L. Li Gioi's talk]



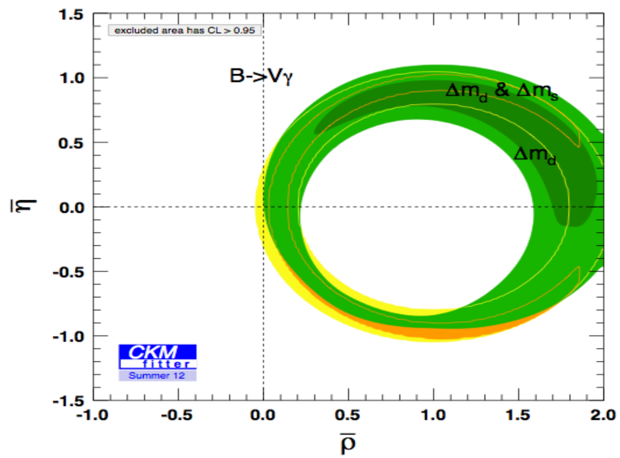


Integrated over $p_T{}^{J/\psi}$ ratio:

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27(stat) \pm 0.29(syst) \pm 0.16(p_T\ model) \pm 0.09(Br)$$

Run II prospects

- Explore the V_{td} suppressed $b \to d\gamma$ penguin



Branching ratio & asymmetry of exclusive $b \to (d + s)\gamma$ modes provide a direct constraint on UT

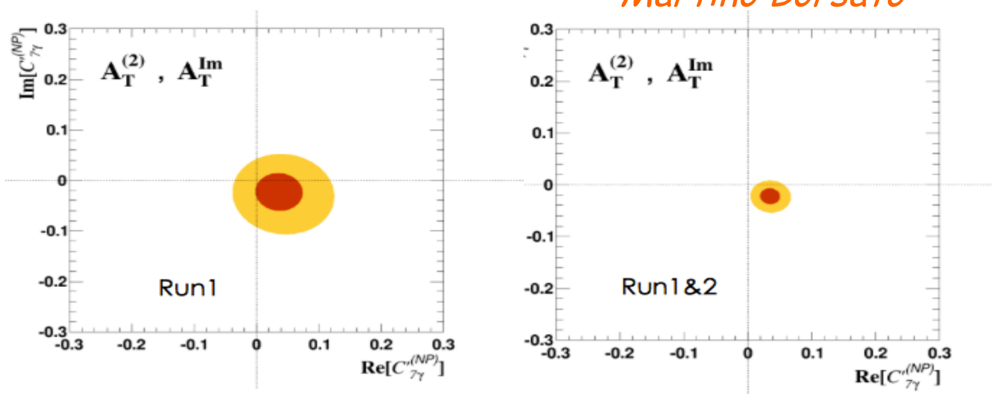
Such transition could be accessible in LHCb via
$B^0 \to \rho/\omega\,\gamma$, $B^+ \to a_1^+\,\gamma$

Could separate the $b \to d\gamma$ transition $B_s \to K^*\gamma$ from B_d using converted photons

- Reach < 10 % resolution on photon polarisation

$$\text{scenario } II\text{: } C_{7\gamma}^{(\mathrm{NP})} = 0,\ C_{7\gamma}^{\prime(\mathrm{NP})} \in \mathbb{C}$$

Martino Borsato



Prospective from K*ee angular analysis

Conclusions

LHCb provides a unique laboratory for precise measurements in radiative decay

Great harvest of results with 2011-2012 RunI
World best measurements in radiative Vγ decays …

… consistent with SM expectation

Many updated or new results expected soon
runII will allow to explore rarest radiative decays

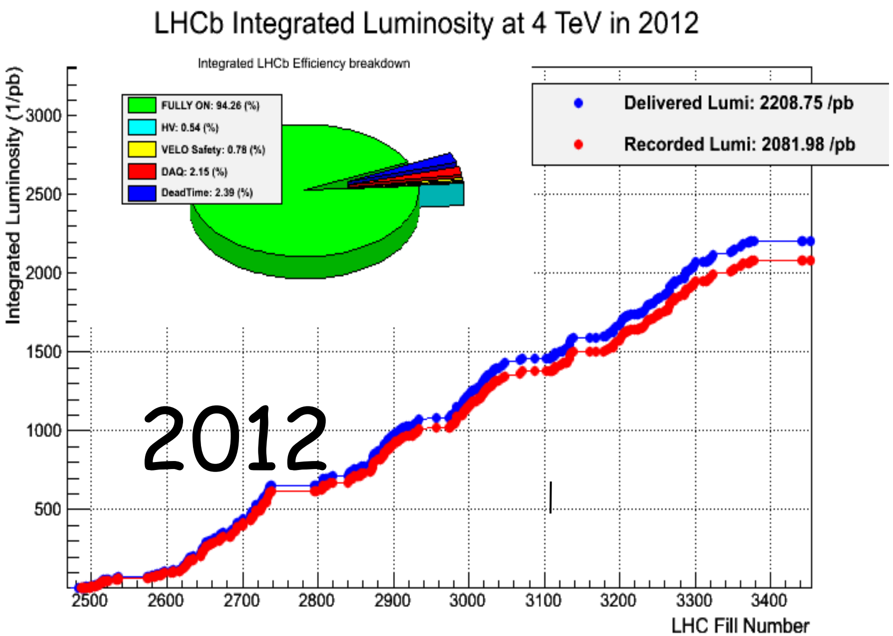
Spares

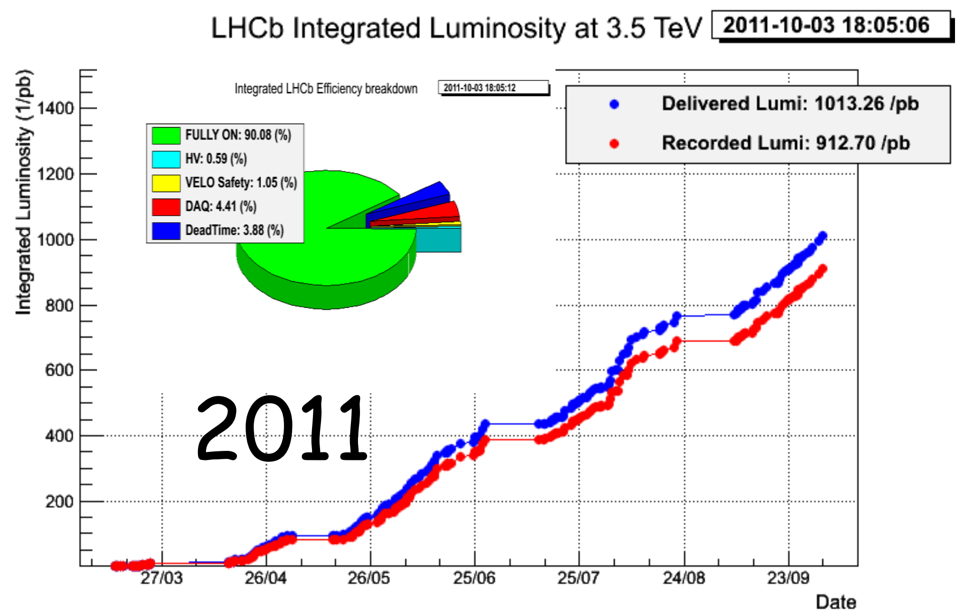
LHC operations (run I)

LHC delivered √s=7 TeV pp collisions in 2010-2011 and √s=8 TeV in 2012

Instantaneous luminosity : **4×10^{32} cm^{-2}s^{-1}** factor 2 beyond the design

visible pp interaction per bunch crossing of O(1.5) factor 4 beyond the design





LHCb collected 0.037 fb^{-1} in 2010 -> ~2.5×10^{9} $b\bar{b}$ in the LHCb acceptance

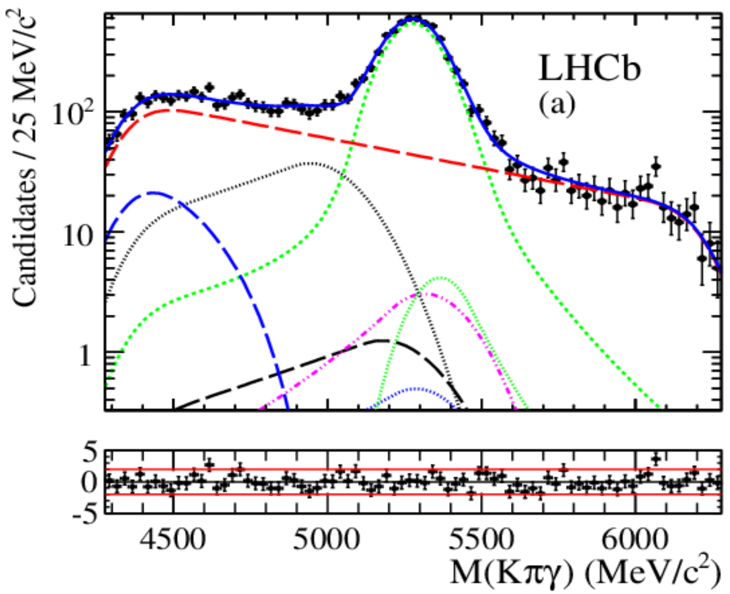
+ 1.0 fb^{-1} in 2011 -> ~8.0×10^{10} $b\bar{b}$

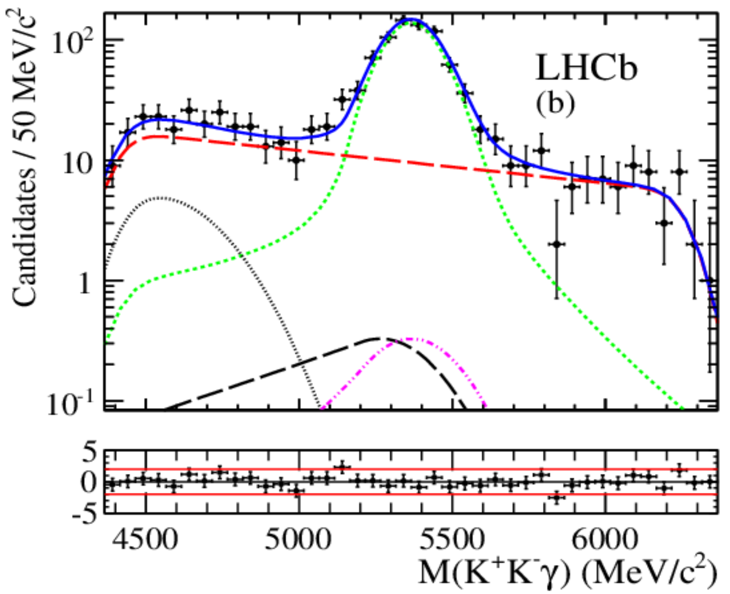
+ 2.0 fb^{-1} in 2012 -> ~2×10^{11} $b\bar{b}$

$B \to V\gamma$ branching fractions: backgrounds

- Generic background contamination :
  - Combinatorial background
  - Partially reconstructed $b \to s\gamma$ decays
  - Partially reconstructed $b \to c$ ($X+hh\pi^0$)
- Specific peaking backgrounds :
  - b-baryons $\Lambda_b \to \Lambda^*(K^-p)\gamma$
  - Charmless $B_{d,s} \to h^+h^-\pi^0$
  - Irreducible $b \to d\gamma$: $B_s \to K^{*0}\gamma$
- No trivial side-bands shape
  - Threshold effect due to different mass resolution in trigger and offline analysis

	Branching fraction ($\times 10^6$)	Relative contamination to $B^0 \to K^{*0}\gamma$	$B^0_s \to \phi\gamma$
$\Lambda^0_b \to \Lambda^*\gamma$	unknown	$(1.0 \pm 0.3)\%$	$(0.4 \pm 0.3)\%$
$B^0_s \to K^{*0}\gamma$	1.26 ± 0.31 (theo. [20])	$(0.8 \pm 0.2)\%$	$\mathcal{O}(10^{-4})$
$B^0 \to K^+\pi^-\pi^0$	$35.9^{+2.8}_{-2.4}$ (exp. [4])	$(0.5 \pm 0.1)\%$	$\mathcal{O}(10^{-4})$
$B^0_s \to K^+\pi^-\pi^0$	unknown	$(0.2 \pm 0.2)\%$	$\mathcal{O}(10^{-4})$
$B^0_s \to K^+K^-\pi^0$	unknown	$\mathcal{O}(10^{-4})$	$(0.5 \pm 0.5)\%$
$B^+ \to K^{*0}\pi^+\gamma$	20^{+7}_{-6} (exp. [4])	$(3.3 \pm 1.1)\%$	$< 6 \times 10^{-4}$
$B^0 \to K^+\pi^-\pi^0\gamma$	41 ± 4 (exp. [4])	$(4.5 \pm 1.7)\%$	$\mathcal{O}(10^{-4})$
$B^+ \to \phi K^+\gamma$	3.5 ± 0.6 (exp. [4])	3×10^{-4}	$(1.8 \pm 0.3)\%$
$B \to K^{*0}(\phi)\pi^0X$	$\mathcal{O}(10\%)$ [4]	few%	few%





$B \to V\gamma$ branching fractions: systematics

- Systematic uncertainty dominated by f_s/f_d (±8%)

[Phys. Rev. D 85 (2012) 032008]

$$f_s/f_d = 0.267^{+0.021}_{-0.020}$$

from semi-leptonic $B_{u,d,s} \to D_{(s)}\mu\nu X$ and hadronic $B_{u,d,s,} \to D_{(s)}h$

- Background model (±2%)

Contamination level and shape

- Reconstruction and selection (±2%)

Trigger and selection efficiencies, Particle reconstruction & identification

Update with whole $3fb^{-1}$ sample ongoing
both statistical and systematical uncertainty will improve
(more precise fs/fd, improved background model …)

$A_{CP}(B^0 \to K^{*0}\gamma)$: systematics

- $K^+\pi^-/K^-\pi^+$ detection asymmetry

  From charm $D^0 \to K\pi$ large control sample

$$A_D(K\pi) = \frac{\varepsilon(K^-\pi^+) - \varepsilon(K^+\pi^-)}{\varepsilon(K^-\pi^+) + \varepsilon(K^+\pi^-)} = (-1.0 \pm 0.2)\%$$

LHCb-CONF-2011-042.

- B production asymmetry

  From large $B \to J/\psi K^*$ sample

$$A_P(B) = \frac{R(\bar{B}) - R(B)}{R(\bar{B}) + R(B)} = (1.0 \pm 1.3)\%$$

- Background model $\Delta A_{CP} = (-0.2 \pm 0.7)\%$

  Contamination level, shape & CP asymmetry in various background components
  Dominated by the unknown asymmetry from the misidentified $\Lambda_b \to (pK)\gamma$ contamination

- Detector non-uniformity $\Delta A_{CP} = (+0.1 \pm 0.2)\%$

  Possible detector bias strongly reduced by switching regularly the magnet polarity

Update with whole $3\,fb^{-1}$ sample ongoing

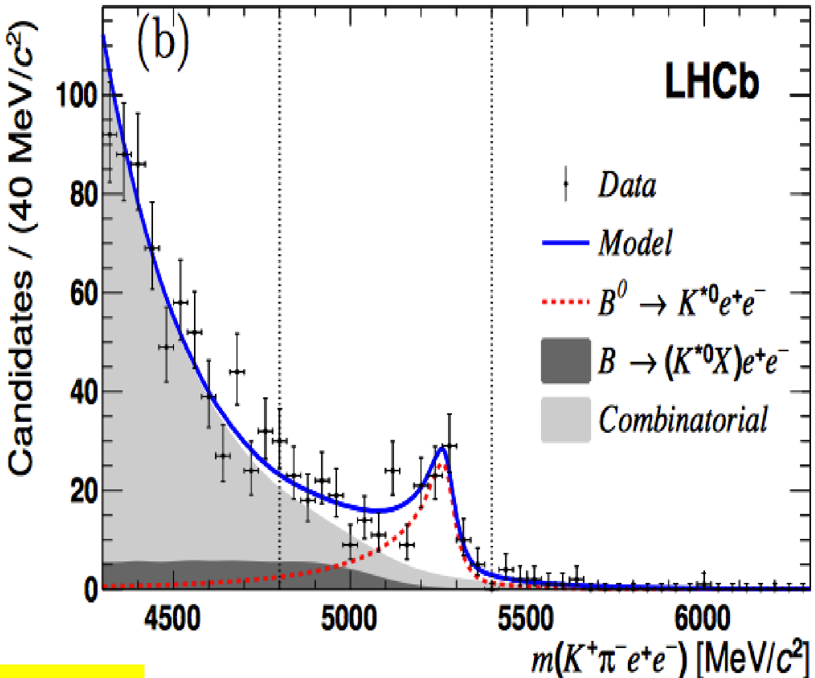
both statistical and systematical uncertainty will improve :
more precise detection and production asymmetry,
CP asymmetry from background in particular $\Lambda_b \to (pK)\gamma$

Virtual photon : $B^0 \to K^{*0} e^+ e^-$

- $B^0 \to K^* \gamma^* (\to ee)$ in the low q^2

Branching fraction in [30 ; 1000]MeV/c^2
(1.0 fb^{-1} - 2011 data) : *J. High Energy Phys.* 05 (2013) 159

$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\,\mathrm{MeV}/c^2} = (3.1\,^{+0.9}_{-0.8}\,^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$$



Full angular analysis in [20; 1120]MeV/c^2
(3.0 fb^{-1} – 2011+2012 data) : *J. High Energy Phys.* 04(2015) 064

$$F_L = 0.16 \pm 0.06 \pm 0.03$$

$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$

$$A_T^{Im} = +0.14 \pm 0.22 \pm 0.05$$

Related to photon polarisation

$$A_T^{Re} = +0.10 \pm 0.18 \pm 0.05,$$

Radiative decays of X(3872)

- Evidence for the X(3872)→ $\psi(2S)\gamma$
  - **Mass of X(3872) and quantum numbers $J^{PC}=1^{++}$ has been measured.**
  - **But nature is still not clear: $c\bar{c}$, $D\bar{D}^*$, tetraquark?**
  - Branching fractions ratio

$R_{\psi\gamma}$=BR(X(3872)→J/ψ γ)/BR(X(3872)→ψ(2S) γ)

is dependent on the nature of the X(3872):

- $R_{\psi\gamma} \approx 1.2 - 15$ for pure charmonium $c\bar{c}$
- $R_{\psi\gamma} \approx (3 \div 4) \times 10^{-3}$ for $D\bar{D}^*$ molecule
- $R_{\psi\gamma} \approx 0.5 - 5$ for $c\bar{c}$-$D\bar{D}^*$ admixture

X(3872) is reconstructed in $B^+ \to X(3872)K^+$

3 fb⁻¹ analysis, Nucl. Phys. B 886 (2014) 665-680

$R_{\psi\gamma}$=(2.46±0.64 ±0.29)

- **4.4σ evidence**
- **Does not support pure $D\bar{D}^*$ interpretation**