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Radiative B meson decays at LHCb

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Introduction

- Radiative $b \rightarrow s\gamma$ decays proceed via an effective FCNC (loop penguin diagrams)
  - Sensitive probe of physics at high mass scales
    - Good testing ground in search of new physics
- FCNC processes are described by an effective Hamiltonian in the form of Operator Product Expansion :

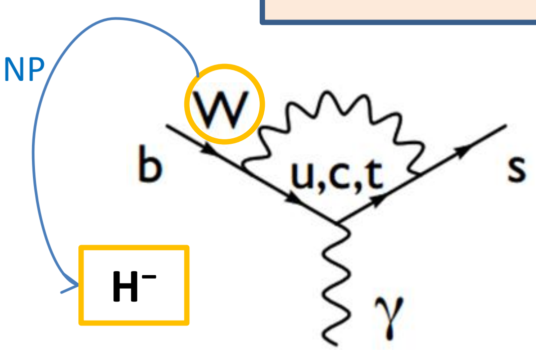
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big] + \sum \frac{c}{\Lambda_{NP}^2} O_{NP}$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

Introduction

- NP can modify the Wilson coefficients (C_i) affecting observable quantities as (in case of radiative decays) photon polarization (C'_7)
  - Observation of the photon polarization in $B^+ \to K^+\pi^-\pi^+\gamma$ decays
  - Measurement of the photon polarization in $B_s \to \phi\gamma$ decays
- The left-handed nature of the weak interactions $SU(2)_L$ predicts:

W boson couples to left handed quarks ⟺ The photon is left handedly polarized



$b \to s\,\gamma_L$ (left-handed polarization)

$\bar{b} \to \bar{s}\,\gamma_R$ (right-handed polarization)

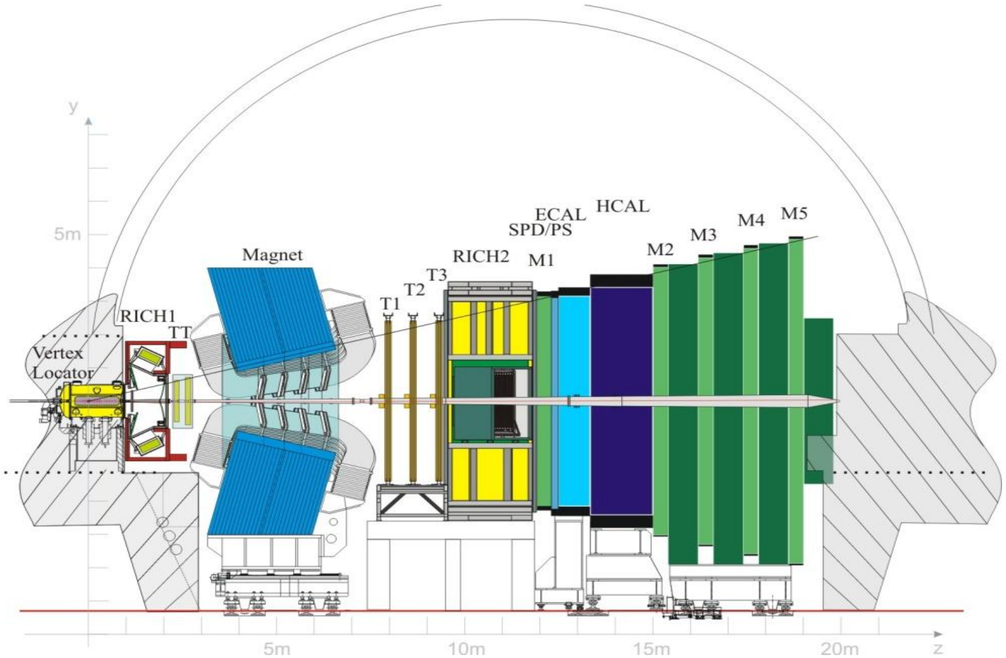
The opposite polarization is suppresed by m_s/m_b

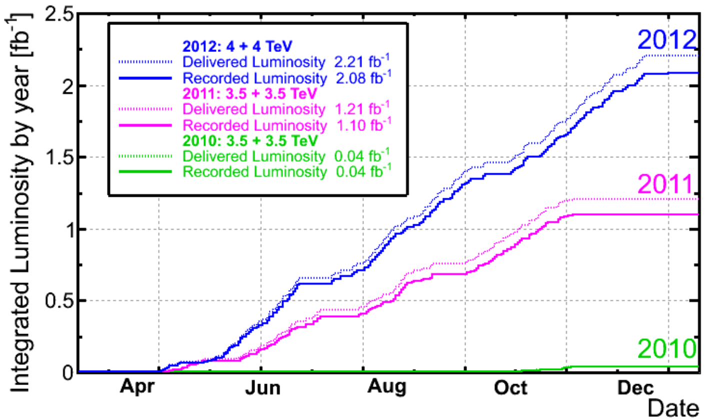
The LHCb detector

- Single-arm forward spectrometer ($2<\eta<5$)
- Vast program of heavy flavor studies
- Challenge:
  - Precision measurements in a hadronic environment

    On top of
  - High background level from large multiplicities
    - 30 particles for hard PP collision

    But with
  - High statistics from 30 KHz rate
    - Access to all b species:
      - Bd, Bu, Bs, Λb, Ξb, …..
- Excellent performance:
  - $\sigma(m)$~10-25 MeV/c² (except for radiative ~90 MeV/c²)
  - $\Delta p/p$~0.4-0.6 %(5-100 GeV/c)
  - High proper time resolution $\sigma(t)$=60 fs
  - $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
  - ε(K→K)~95% for ε(π→K)~5%





Rad. Decays at LHCb: $B^0 \to K^*\gamma$ and $B_s \to \phi\gamma$

2011 Data [Nucl. Phys. B 867(2012) 1-18]

- Mass resolution ~90 MeV/c² dominated by LHCb Electromagnetic CALorimeter (ECAL) resolution.
- Many background contributions

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

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

HFAG 2010

- World best measurement of the ratio of branching fractions

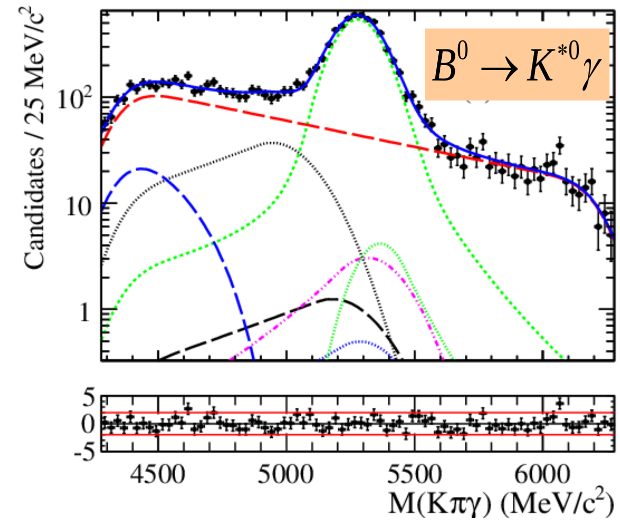
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B^0_s \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$

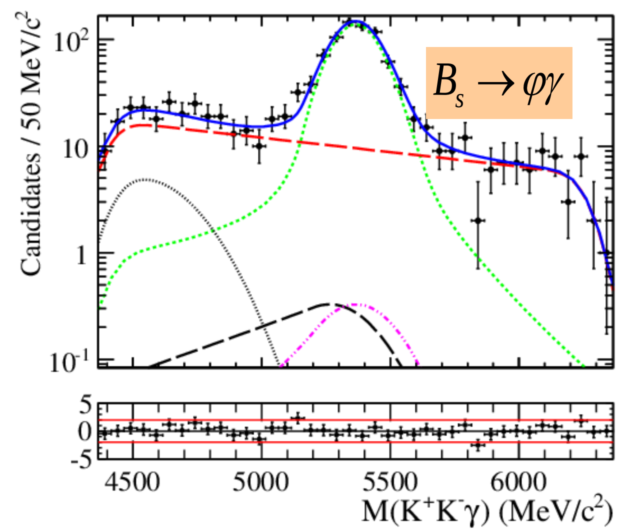
Theory predictions:

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B^0_s \to \phi\gamma)} = 1.0 \pm 0.2$$

- And $BR(B_s \to \phi\gamma)$

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



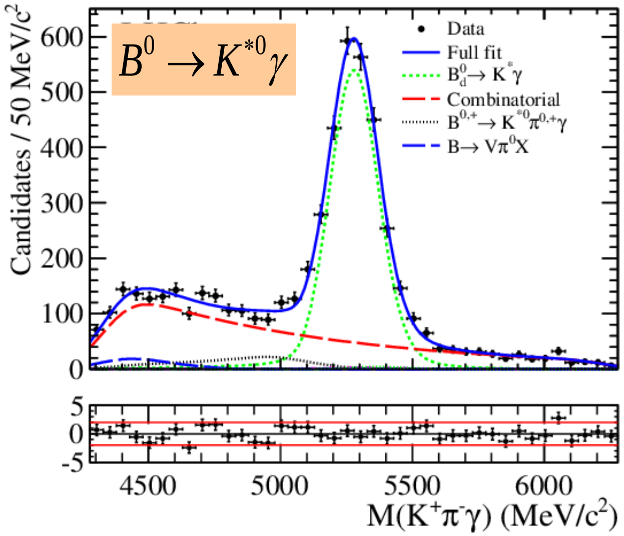


Rad. Decays at LHCb: $B^o \to K^*\gamma$

2011 Data [Nucl. Phys. B 867(2012) 1-18]

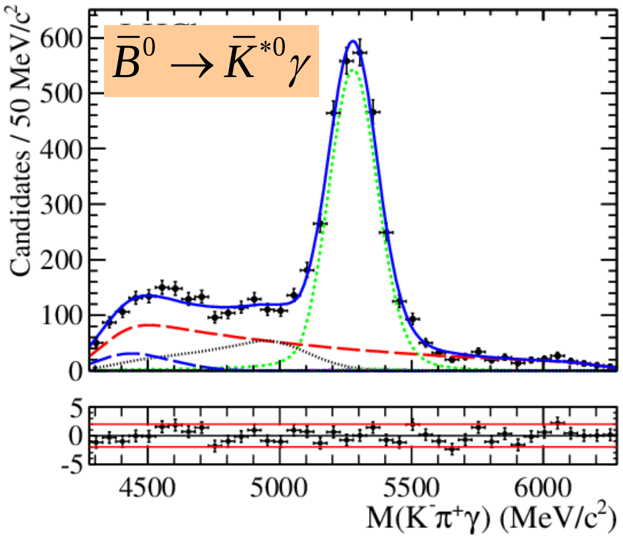
- $B^o \to K^*\gamma$

$$N_{B_0} + N_{\bar{B}_0} = 5300 \pm 100$$



- World best measurement of the direct CP asymmetry in $B_0 \to K^*\gamma$

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.}))\%$$



Theory predictions:

$$\mathcal{A}_{CP} = -0.0061 \pm 0.0043$$

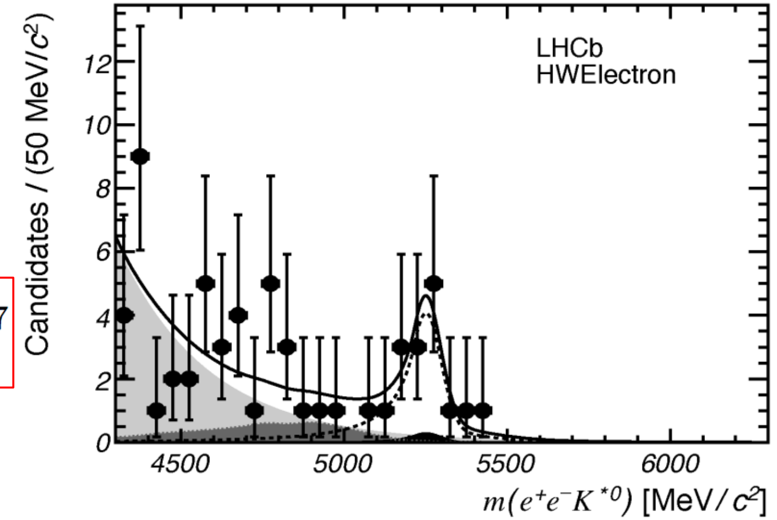
RD at LHCb: $B^0 \to K^* \gamma^* (e^+e^-)$

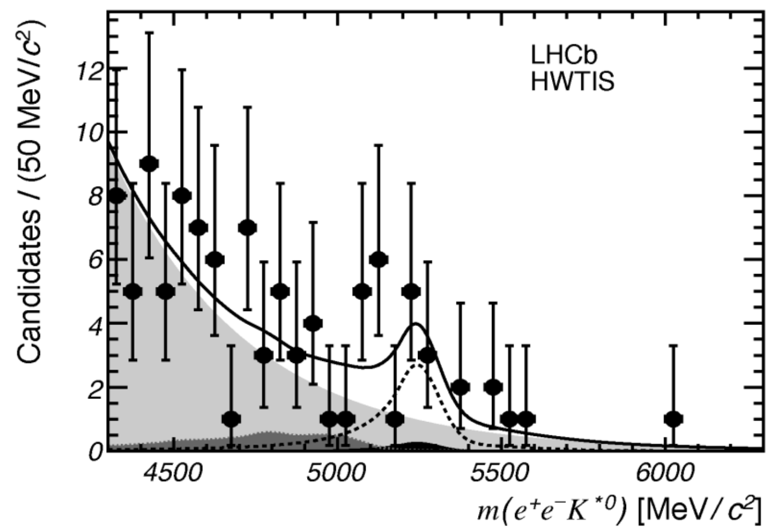
2011 Data [J. High Energy Phys. 05 (2013) 159]

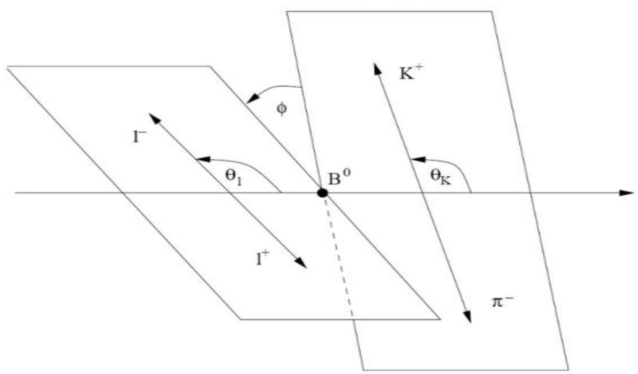
- The world best measurement of the BR of $B^0 \to K^* e^+ e^-$

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

- An update with 2012 data is ongoing
  - Perform an angular analysis to extract a virtual photon polarization







Photon polarization from $B \to K\pi\pi\gamma$

- The main goal is to extract photon polarization from $B \to K_{res}\gamma$ where $K_{res} \to K\pi\pi$
- The decay amplitude is given by

$$|A(B \to K_{res}\gamma \to P_1 P_2 P_3 \gamma)|^2 = |c_R|^2 |\mathcal{M}_R|^2 + |c_L|^2 |\mathcal{M}_L|^2$$

- The photon polarization

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

- With $\lambda\gamma$=-1 for B^- decays and +1 for B^+ decays
- This 3-body decay allow to access the γ polarization through the up-down asymmetry defined by the γ direction w.r.t the plane defined by the daughters of the kaon resonance

Photon polarization from B→Kππγ

Kou et al, PRD83 (2011) 094007

Gronau et al, PRL88 (2002) 051802

- The differential decay rate, for a given intermediate resonance is given as:

$$\frac{d\Gamma(B\to K_{res}\gamma\to P_1P_2P_3\gamma)}{ds ds_{13} ds_{23} d\cos\theta} \propto |\vec{\mathcal{J}}|^2(1+\cos^2\theta) + \lambda_\gamma 2\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)\right]\cos\theta$$

Helicity amplitude

Photon direction

- And for multiple intermediate resonances, we have

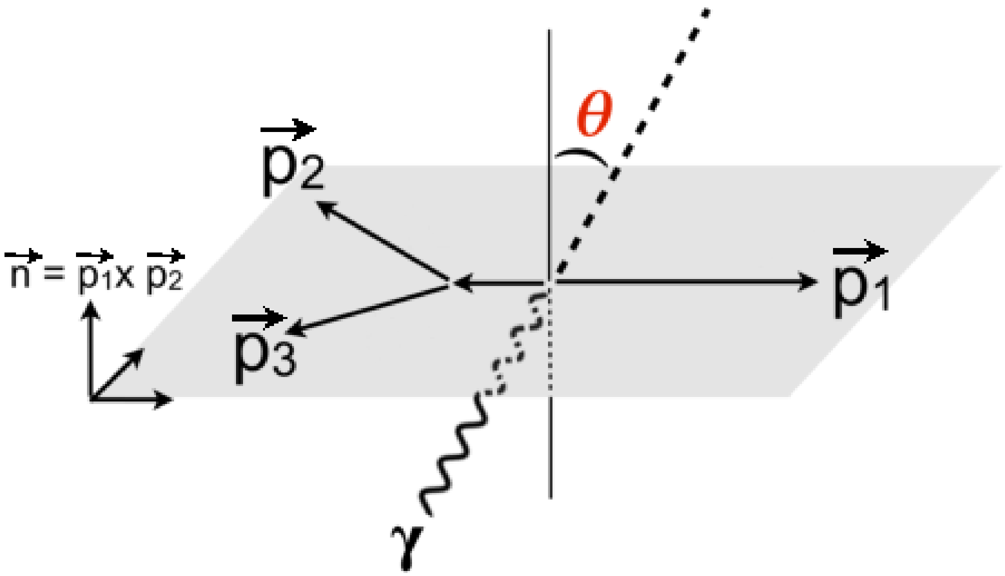
$$\frac{d\Gamma(\sum B\to K_{res,i}\gamma\to P_1P_2P_3\gamma)}{ds ds_{13} ds_{23} d\cos\theta} \propto \sum_{j=0,\mathrm{even}}^{4} a_j(s_{13},s_{23})\cos^j\theta + \sum_{j=1,\mathrm{odd}}^{3} \lambda_\gamma a_j(s_{13},s_{23})\cos^j\theta$$

Eq. 1

- To extract an up-down asymmetry, the photon direction should be well defined

Photon polarization

The photon direction



- We define:

$$\cos\theta \equiv -\frac{\vec{p}_\gamma}{|\vec{p}_\gamma|} \cdot \hat{n}$$

- With:

$$\hat{n} \equiv \frac{\vec{p}_1 \times \vec{p}_2}{|\vec{p}_1 \times \vec{p}_2|}$$

The up-down asymmetry: formalism

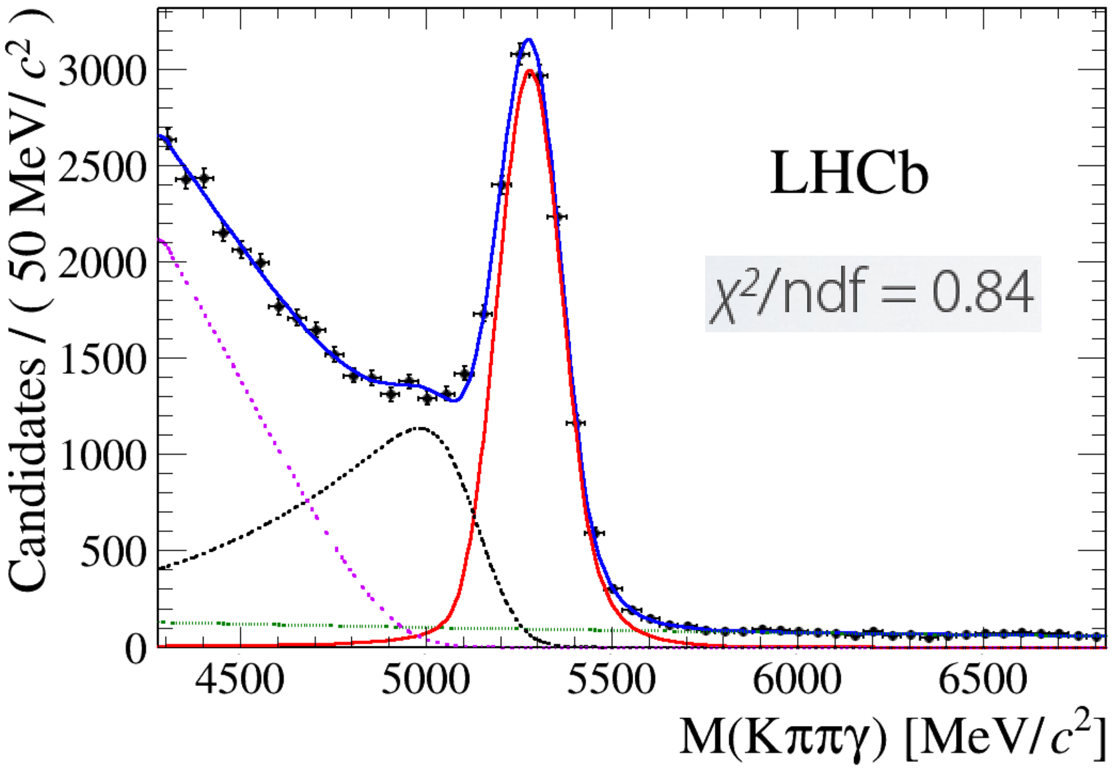
- The up-down asymmetry:
  - The number of events having the photon above the plane defined by the daughter of the Kaon resonance subtracted from those with the photon below the plane

$$\mathcal{A}_{UD} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} \overset{\text{single resonance}}{=} \frac{3}{4}\lambda_\gamma \frac{\int ds\, ds_{13}\, ds_{23} \operatorname{Im}\left[\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)\right]}{\int ds\, ds_{13}\, ds_{23} |\mathcal{J}|^2}$$

- A_{UD} is proportional to $\lambda\gamma$
- If J is known, i.e. A_{UD} is known for a single resonance, the up-down asymmetry would allow to compute the photon polarization $\lambda\gamma$

The B→Kππγ invariant mass spectrum

2011+2012 Data [Phys. Rev. Lett. **112**, 161801**]**

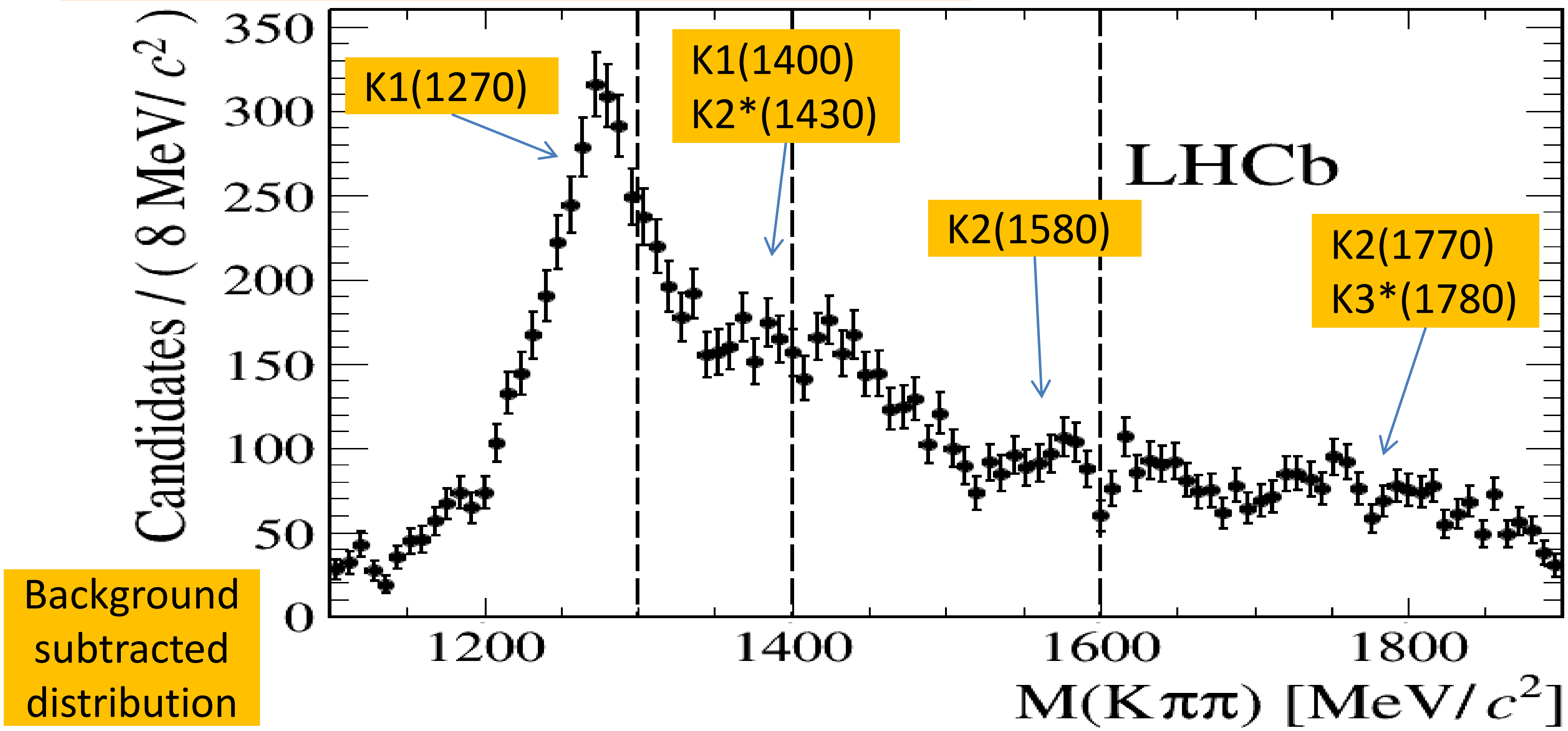


- Fit components:

  Signal
  Combinatorial
  Part' reco' Missing π
  Partially reconstructed

The Kππ invariant mass Spectrum

2011+2012 Data [Phys. Rev. Lett. **112**, 161801]



- Can't isolate individual components without amplitude analysis
  - Asymmetry measurement need to be inclusive
- Up-down asymmetry can't be converted to photon polarization, only a significance w.r.t no-polarization is extracted (in each mass region)

The up-down asymmetry: measurement

- A background-subtracted cos (θ) distribution is extracted from each Kππ invariant mass bin

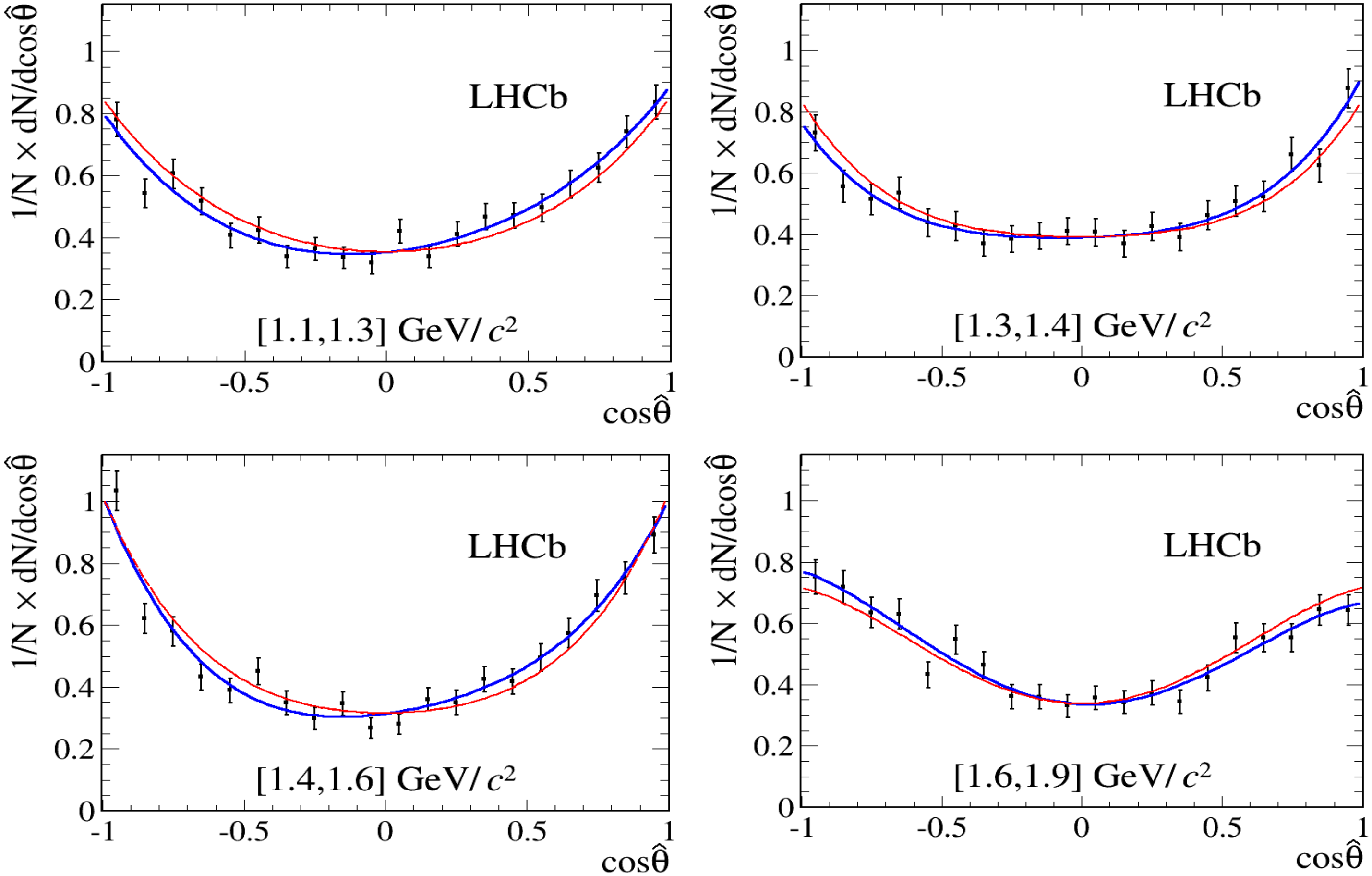
- cos (θ) distribution is fitted (unbinned ML fit) with 4-th order polynomial normalized to unit area

$$f(\cos\theta; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos\theta)$$

Eq. 2

cos (θ) distribution

2011+2012 Data [Phys. Rev. Lett. **112**, 161801**]**



-Odd terms are put to zero: assume no photon polarization
-Fit of odd and even components

5.2 σ significance: taking into account correlations between errors

Up-down asymmetry: results

2011+2012 Data [Phys. Rev. Lett. **112**, 161801**]**

- The asymmetry is then given by: [from Eq. 1(slide 9) and Eq. 2 (slide 14)]

$$A_{UD} = c_1 - \frac{c_3}{4}$$

Obtained from the odd terms of the poly. fit

	$[1.1, 1.3]$	$[1.3, 1.4]$	$[1.4, 1.6]$	$[1.6, 1.9]$
c_1	6.3 ± 1.7	5.4 ± 2.0	4.3 ± 1.9	-4.6 ± 1.8
c_2	31.6 ± 2.2	27.0 ± 2.6	43.1 ± 2.3	28.0 ± 2.3
c_3	-2.1 ± 2.6	2.0 ± 3.1	-5.2 ± 2.8	-0.6 ± 2.7
c_4	3.0 ± 3.0	6.8 ± 3.6	8.1 ± 3.1	-6.2 ± 3.2
$\mathcal{A}_{\text{ud}}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ± 1.9

- The quoted uncertainties contain systematic and statistical contributions

Conclusions I

- Radiative decays at LHCb: many important results
    - Direct CP asymmetry in $B^0 \to K^* \gamma$
    - Ratio of BR of $B^0 \to K^* \gamma$ / $B_s \to \phi \gamma$
    - The BR of $B^0 \to K^* e^+ e^-$

– Observation of photon polarization in $B \to K \pi \pi \gamma$
    - Up-down asymmetry

- And more to come..

Conclusions II

- LHCb has, for the first time, an evidence of the polarization of the photon with a 5.2σ significance
  - A dedicated amplitude analysis will help to translate this result to a value for the photon polarization

Or

- Input from theory is needed to translate this result into a value of the photon polarization λ_γ
  - How to derive the polarization over all the mass range

- Constrain effects of physics beyond the SM in $b \to s\gamma$ sector

Perspectives

- $B_s \to \phi\gamma$ time dependent analysis:
- In the time dependent decay rate, the photon polarization appears through two parameters, S and $\mathcal{A}^{\Delta}$

$$\Gamma_B(t) \propto |A|^2 e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma t/2) \pm C\cos(\Delta m t) \mp S\sin(\Delta m t)\right]$$

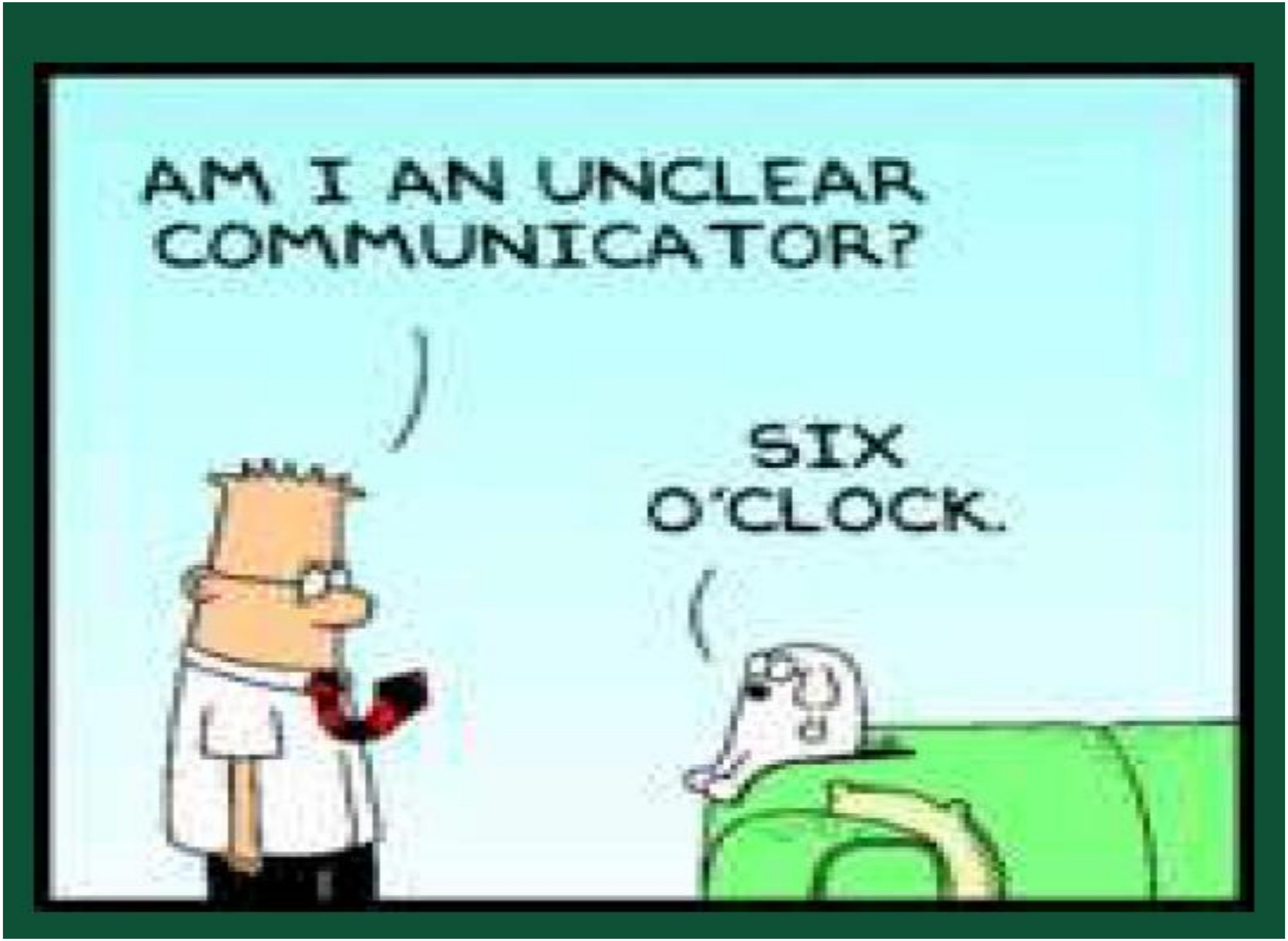
Defining:

$$\tan\psi = \frac{\overline{B} \to f^{CP}\gamma_R}{\overline{B} \to f^{CP}\gamma_L}$$

$$\mathcal{A}^{\Delta} = \sin(2\psi)\cos\phi \qquad S = \sin(2\psi)\sin\phi$$

Where ϕ is the B mixing phase

- Which channels?
- $B_d \to K^*(K_s\pi^0)\gamma$
    - $\Delta\Gamma \sim 0$ → the sinh term cancels and we have only acces to S
    - Done at Babar but not possible at LHCb S= $0.9 \pm 1.0 \pm 0.2$ (Babar, $1.1\,\mathrm{GeV} < m_{K_S\pi^0} < 1.8\,\mathrm{GeV}$)
- $B_s \to \phi(K^+K^-)\gamma$
    - $\Delta\Gamma_s$ is not negligible → the dominant term is the sinh → $\mathcal{A}^{\Delta}$ can be measured
    - Work in progress: untagged time dependent analysis to extract $\mathcal{A}^{\Delta}$


AM I AN UNCLEAR COMMUNICATOR?
SIX O'CLOCK.

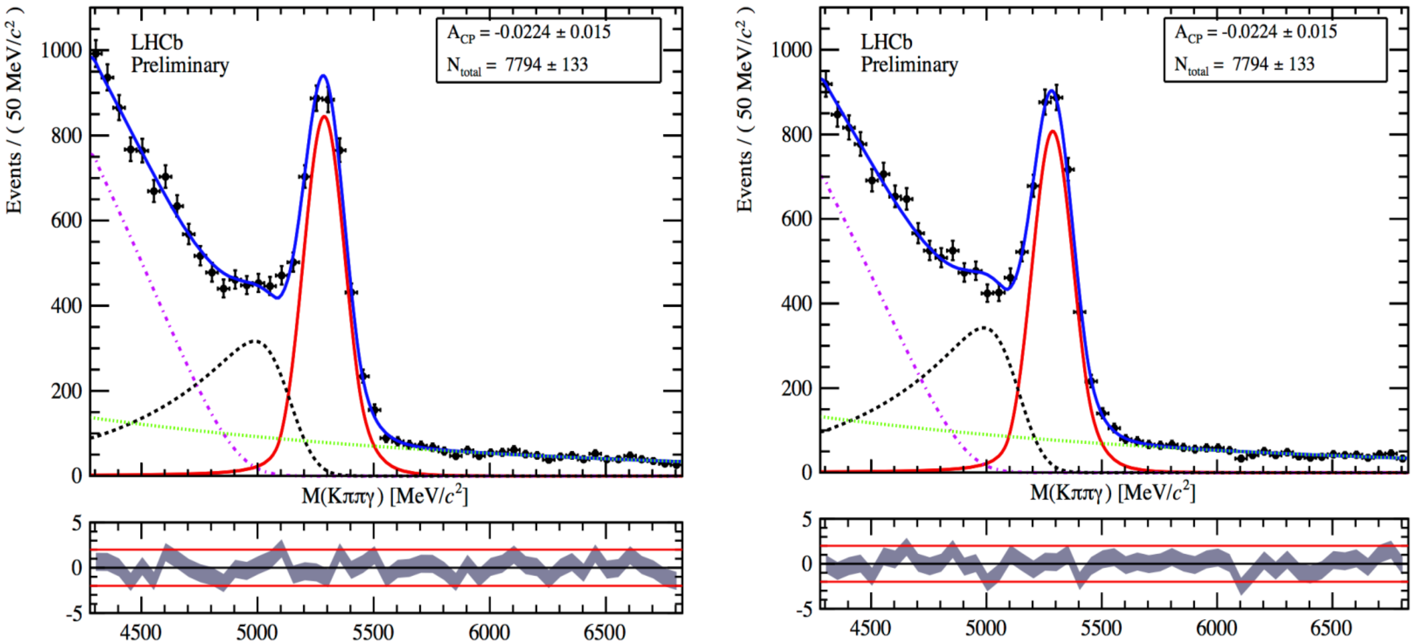
spares

CP asymmetry in B→Kππγ

2011+2012 Data [LHCb-PAPER-2014-001]

- A CP asymmetry measurement can also be conducted:

$$\mathcal{A}_{CP}^{\text{raw}} = -0.022 \pm 0.015$$



CP asymmetry in B→Kππγ

- A CP asymmetry measurement can also be conducted:

$$\mathcal{A}_{CP}^{\text{raw}} = -0.022 \pm 0.015$$

- The raw ACP obtained from the fit is corrected to obtain the physical CP asymmetry
  - Charged B meson production asymmetry
  - Particle interaction with matter (cross-section) asymmetry (K+ vs K–)
  - Geometrical detection asymmetries

- Corrections are extracted from control channels and from data corresponding to different magnet polarities

CP asymmetry in B→K_{res}γ: resluts

2011+2012 Data [LHCb-PAPER-2014-001]

- B→Kππγ has been observed by LHCb: world largest sample

$$N = 13876 \pm 153$$ events

- CP asymmetry (consistent with 0) has been measured for the first time in B→ Kππγ

$$A_{CP} = -0.007 \pm 0.0155(stat.)^{+0.012}_{-0.011}(syst.)$$