Perspectives with radiative penguins at LHCb

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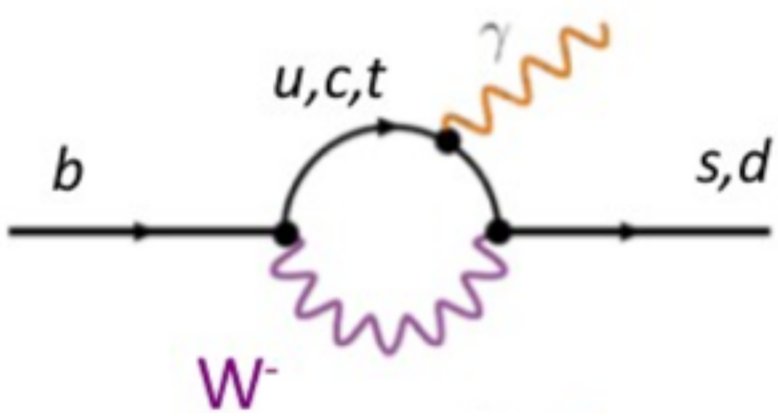
on behalf of the LHCb Collaboration

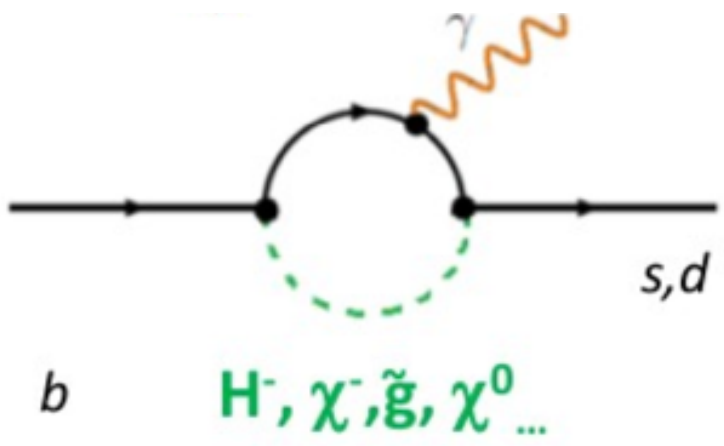
Beyond the LHCb Phase-1 Upgrade workshop

May 28-31, 2017

MOTIVATION

- b→s/dγ transitions are flavour-changing neutral current (FCNC) transitions, forbidden at tree level in the Standard Model





- New physics (NP) effects can show up in these electroweak penguin loops
- Measurements of various observable quantities - branching ratios, CP and isospin asymmetries, photon polarisation- could provide hints of physics beyond the SM

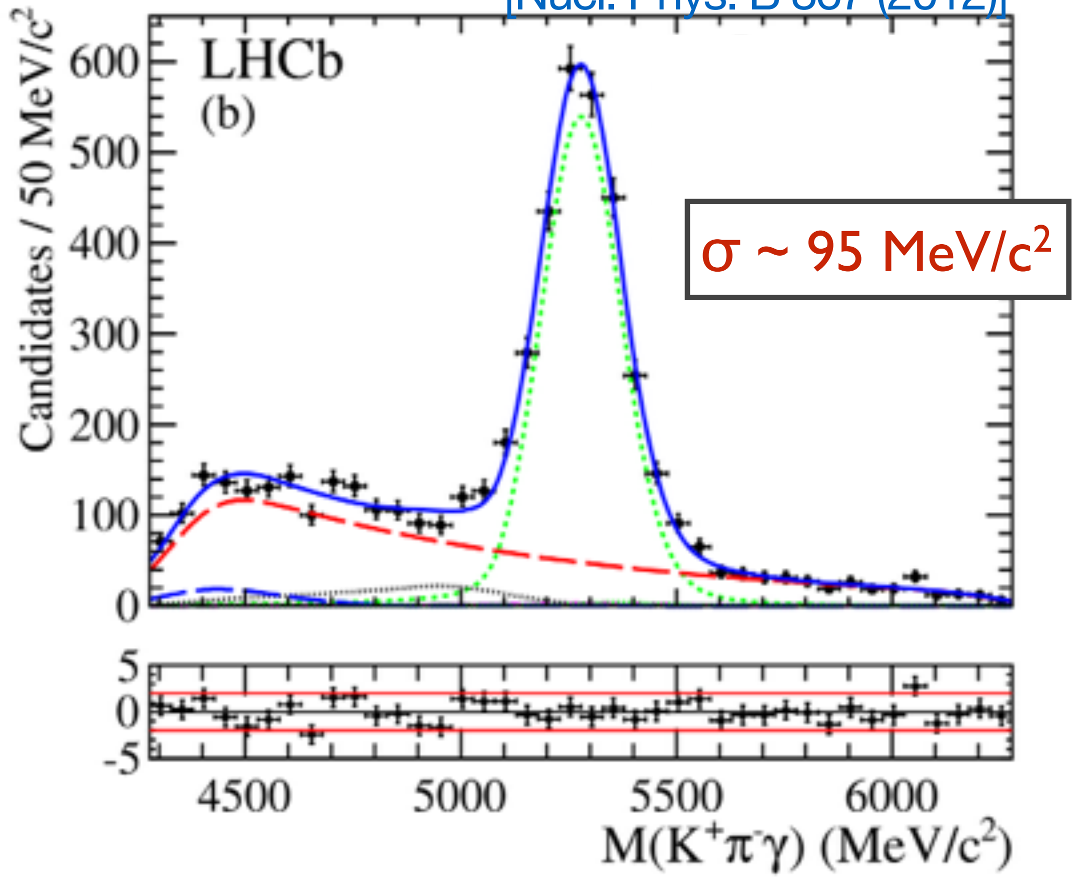
RADIATIVE DECAYS AT LHCb

- Branching fraction measurements
- Direct CP asymmetries
- Isospin asymmetry in $B \to K^{*}\gamma$ decays
- Measurements of the photon polarization:
  - Time-dependent analysis of $B \to f_{cp}\gamma$ decays
  - Angular analysis of radiative decays with three charged final state particles
  - Angular distributions of radiative b-baryon decays
  - Transverse asymmetry in $B^0 \to K^{*}e^{+}e^{-}$ decays

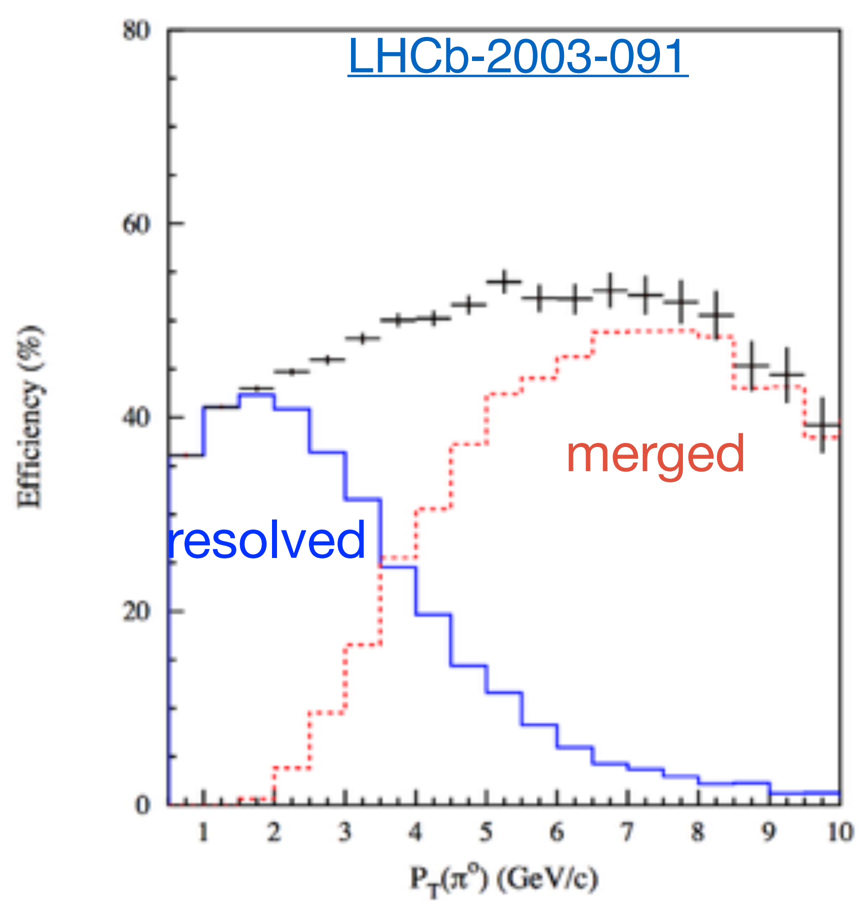
Experimental Challenges

- Mass resolution dominated by photon reconstruction
  - **σ~95 MeV/c²** for B→K*γ decays, compared to ~25 MeV/c² for B→Kπ decays.
- Backgrounds:
  - Above transverse energies of 4 GeV, $\pi^0 \rightarrow \gamma\gamma$ reconstructed as a single cluster in the calorimeter
  - Combinatorial: *O*(10) reconstructed photons per event

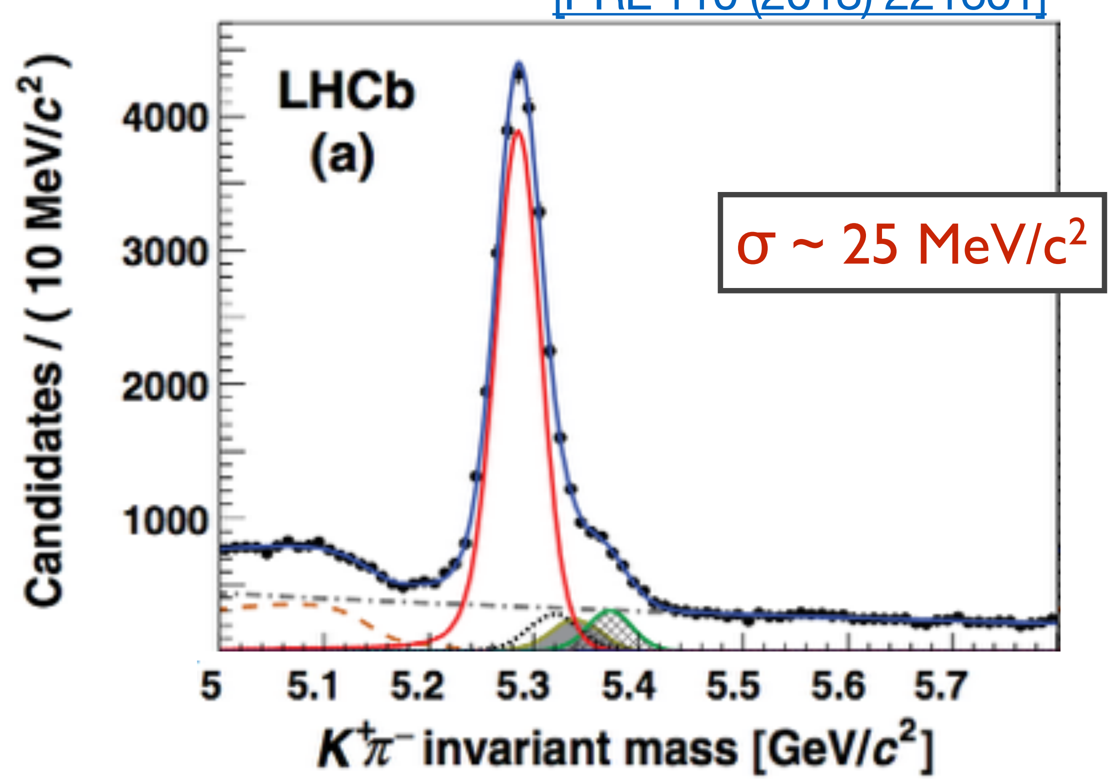
[Nucl. Phys. B 867 (2012)]



LHCb-2003-091



[PRL 110 (2013) 221601]



Experimental Challenges - II

Without analysis improvements, many analyses would be systematics-limited by Run 5

Primary known/expected sources of systematic uncertainty:

- Partially reconstructed background, due to large invariant mass resolution
  - Correlation between decay time and reconstructed mass in $B_s \to \phi\gamma$ decays
  - Uncertainty in background modeling in A_{cp} and branching fraction measurements
  - Effects on angular distributions in $K\pi\pi\gamma$ decays
- Detector effects
  - Decay time resolution for C,S measurements in tagged $B_s \to \Phi\gamma$ analysis
  - Detection asymmetry in A_{cp} measurement
- Modeling of acceptances
  - Main source of uncertainty for $\Lambda_b \to \Lambda^0\gamma$ angular analysis

Radiative Decays at LHCb - Run 5

- Increased calorimeter resolution would improve invariant mass resolution for radiative decays
  - Since many analyses will not be statistically limited, important to reduce systematic uncertainties from background effects
  - Improved π^0 reconstruction would also allow for the study of modes with neutral pions
- Fast-timing calorimeter information
  - Would lead to significant reduction in background rate from pile-up in HL-LHC environment
- Analyses will also benefit from improvements to trigger and downstream track reconstruction
  - L0 trigger is currently the main limiting factor ($E_T(\gamma) > 3$ GeV)
  - Must reduce timing in order to run reconstruction at lower energies
- 300 fb^{-1} of data expected by the end of Run 5
  - Some analyses (radiative b-baryons, analyses with converted photons) will still be statistically limited after Run 2

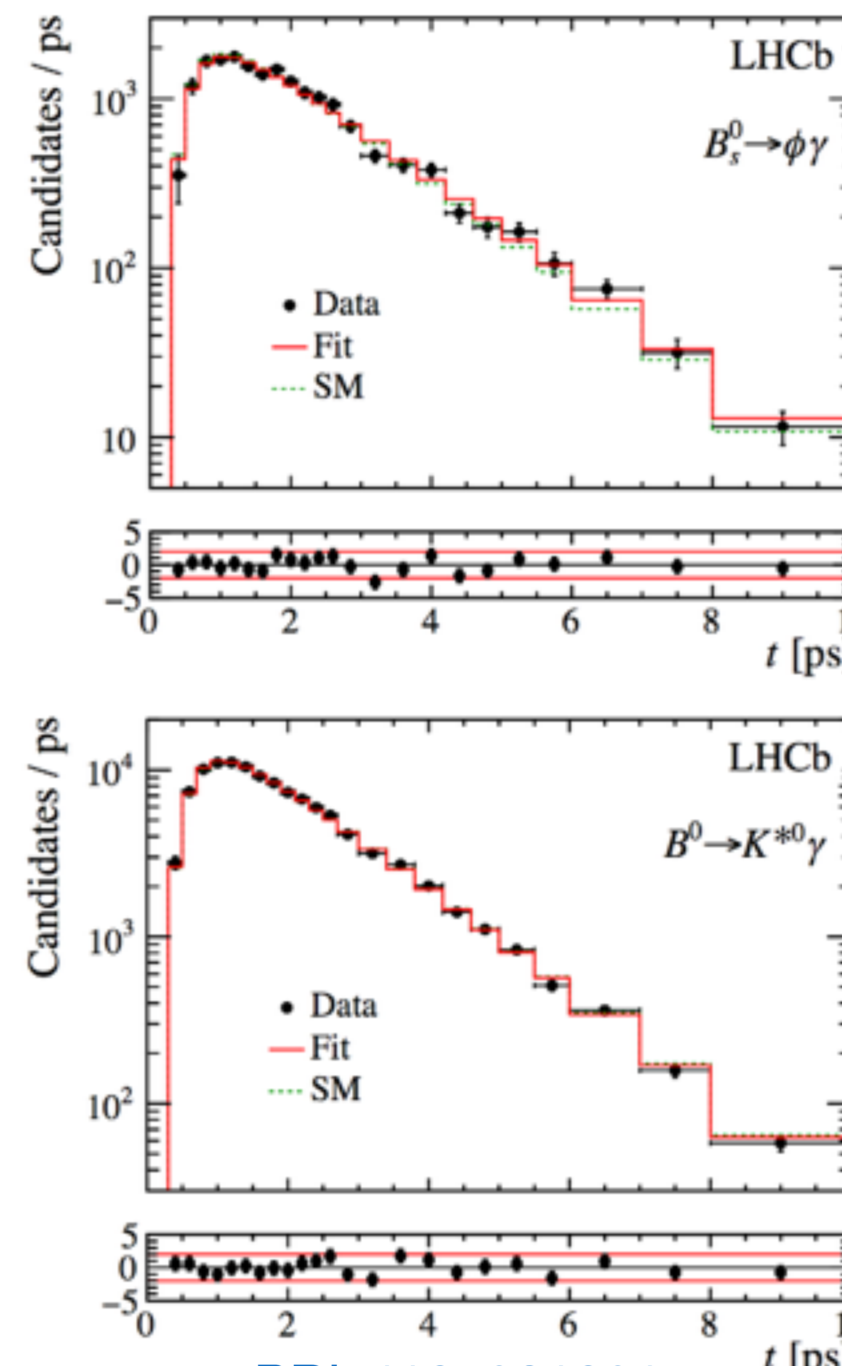
$B_s \to \phi\gamma$

Access photon polarization via time-dependent decay rate of $B_s \to \phi\gamma$ decays

$$\Gamma(B^0_{(s)} \to f^{CP}\gamma) \sim e^{-\Gamma_{(s)}t}\Big\{\cosh\frac{\Delta\Gamma_{(s)}t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_{(s)}t}{2} \pm \mathcal{C}\cos\Delta m_{(s)}t \mp \mathcal{S}\sin\Delta m_{(s)}t\Big\}.$$

Run 1 - untagged analysis:

- Access to photon polarisation through A^{Δ}
- Simultaneous fit of $B_s \to \phi\gamma$ and $B^0 \to K^*\gamma$ decay time distributions
- Dominant systematic uncertainty from background subtraction (mass - decay time correlations)



$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$

Compatible with SM within 2σ

PRL 118, 021801

$B_s \to \phi\gamma$

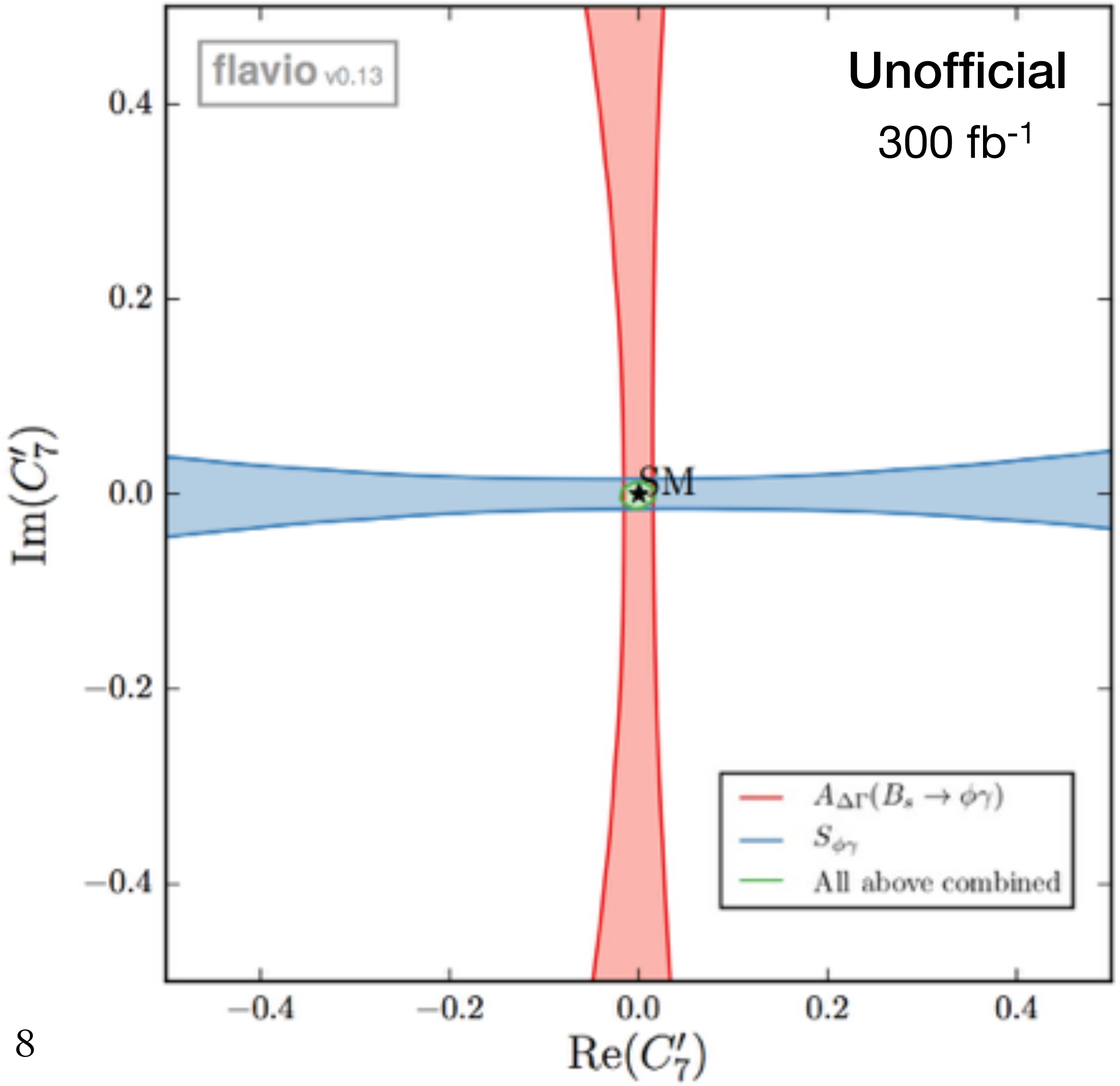
Tagged analysis ongoing for Run 2:

$$\Gamma(B^0_{(s)} \to f^{CP}\gamma) \sim e^{-\Gamma_{(s)}t}\left\{ \cosh\frac{\Delta\Gamma_{(s)}t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_{(s)}t}{2} \pm \mathcal{C}\cos\Delta m_{(s)}t \mp \mathcal{S}\sin\Delta m_{(s)}t \right\}.$$

- CP parameter C and mixing parameter S can also be extracted
- A^{Δ} and S are sensitive to the photon polarisation
- With a flavour-tagging efficiency of ~ 5%, the combined $\sigma(A^{\Delta})$, $\sigma(S)$ is expected to be ~0.3 (including systematic uncertainties)

With 300 fb^{-1}, expect O(80,000) $B_s \to \phi\gamma$ events

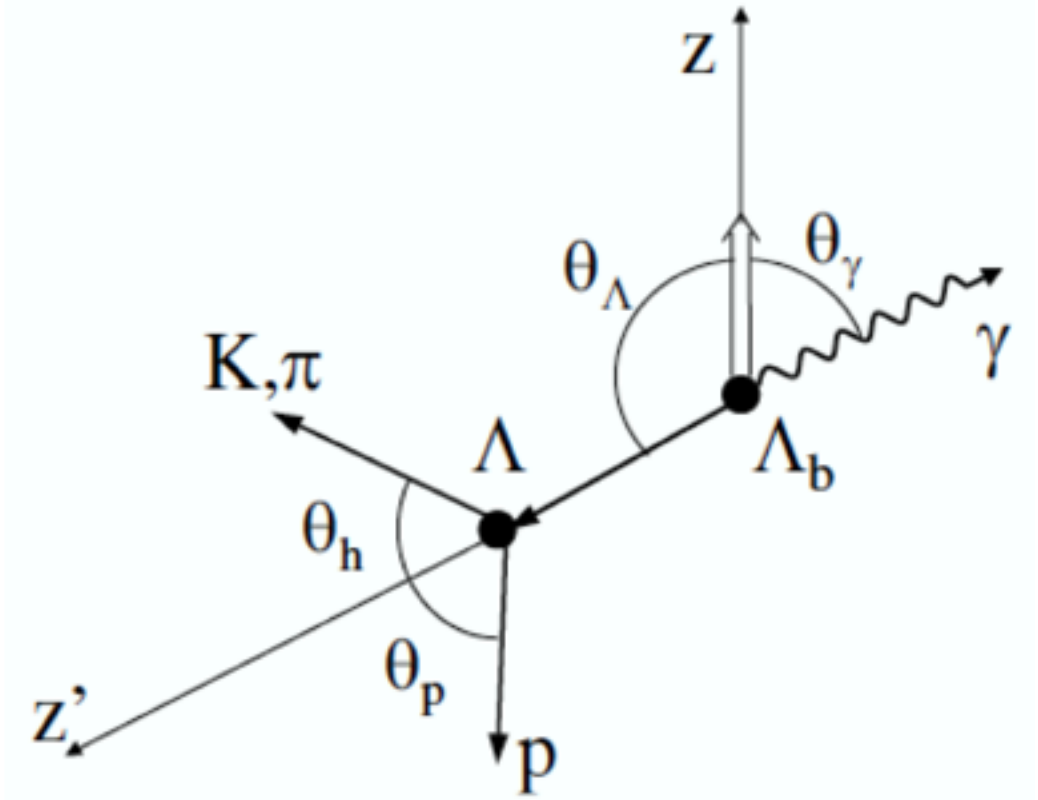
- $\sigma(A^{\Delta})$ ~ 0.02 (statistical only)
- Need to work on reducing systematics from lifetime acceptance
- Uncertainties on C,S dominated by proper time resolution (80fs in Run 1)



RADIATIVE b-BARYON DECAYS

Angular distributions of radiative b-baryon decays expected to be sensitive to the photon polarisation parameter:

$$\alpha_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)}$$



At LO in the SM:

$$\alpha_\gamma^{LO} = \frac{1-|r|^2}{1+|r|^2} \qquad r = \frac{C'_7}{C_7} \sim \frac{m_s}{m_b}$$

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos\theta_p$$

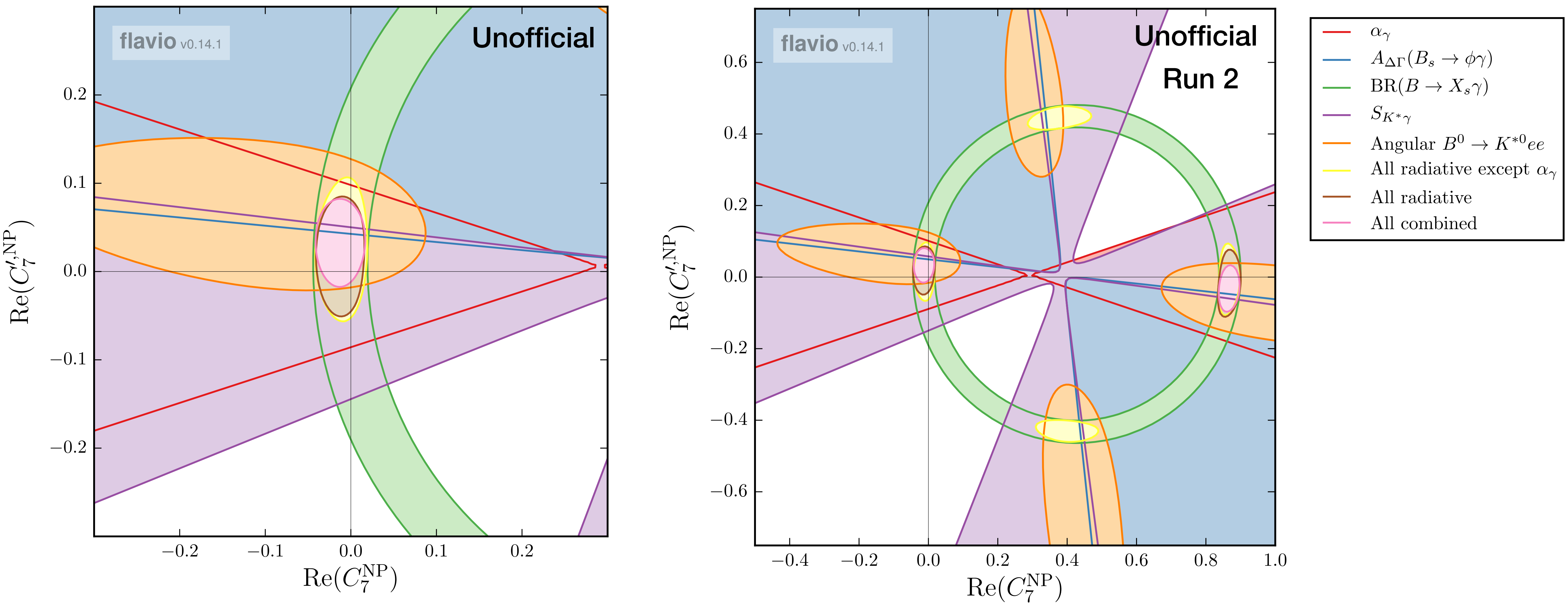
Study of $\Lambda_b \rightarrow \Lambda^0\gamma$ decays:

- Challenges: No Λ_b vertex, long-lived Λ^0
- Simultaneous fit of $\cos\theta_p$ and $\cos\theta_\gamma$
- Gaussian constrain $\alpha_{p,1/2}$=(0.642±0.013) and P_{Λ_b}=(0.06±0.07)

RADIATIVE b-BARYON DECAYS

Analysis ongoing with Run 2 (2015+2016) data:

- Dedicated HLT2 line developed for Run 2; uses long tracks only
- 770 signal events expected with 2 fb^{-1} (assuming a BR of 4.5 x 10^{-5}); expected sensitivity $\sigma(\alpha_\gamma)$ ~ 0.9



With 300fb^{-1}, should obtain O(10,000) signal events

- Uncertainty on α_γ (stat.) ~ 0.01
- Dominant uncertainty would be modeling of acceptance
- Yield could be improved with upgrade trigger + downstream track reconstruction

Radiative b-baryon Decays

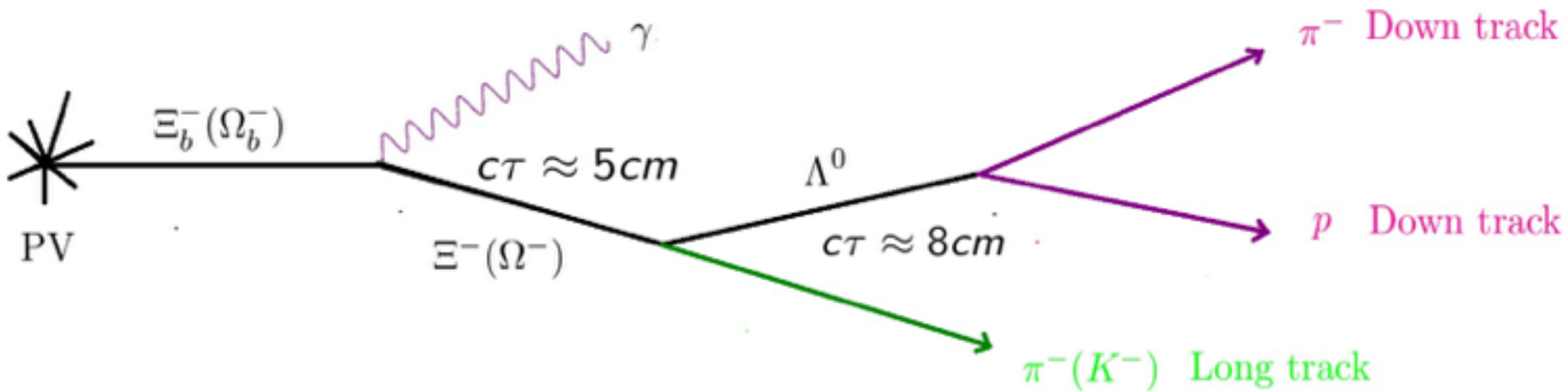
- Can also study $\Xi_b^- \to \Xi^- \gamma$ and $\Omega_b^- \to \Omega^- \gamma$ decays
- Rich angular distribution:

$$\Gamma_{\Xi_b}(\theta_\Lambda, \theta_p) = \frac{1}{4}\left(1 - \alpha_\gamma \alpha_\Xi \cos\theta_\Lambda + \alpha_\Lambda \cos\theta_p \left(\alpha_\Xi - \alpha_\gamma \cos\theta_\Lambda\right)\right)$$

- Reconstruction aided by presence of additional charged tracks (Ξ^-, π^-)
- Limitations: Low reconstruction efficiency, smaller decay parameter (with respect to Λ_b decays)

Run 2 (and beyond):

- Dedicated HLT2 line (from 2016)
- ~100 events expected in Run 2 (trigger+stripping)
- Will benefit from increase in statistics for Run 5, improvements in trigger and reconstruction
- Expected sensitivity similar to $\Lambda_b \to \Lambda^0 \gamma$ mode

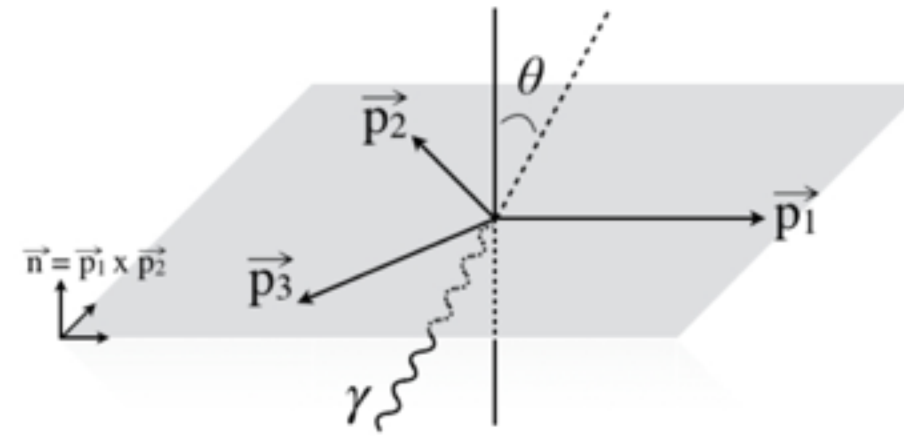


PHOTON POLARISATION IN $B^+ \to K^+\pi^-\pi^+\gamma$ DECAYS

Can measure the photon polarisation using the recoil hadron distribution:

- Photon helicity is odd under parity
- Need three tracks in the final state; can form a parity-odd triple product from final-state particle momenta

$$\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)$$

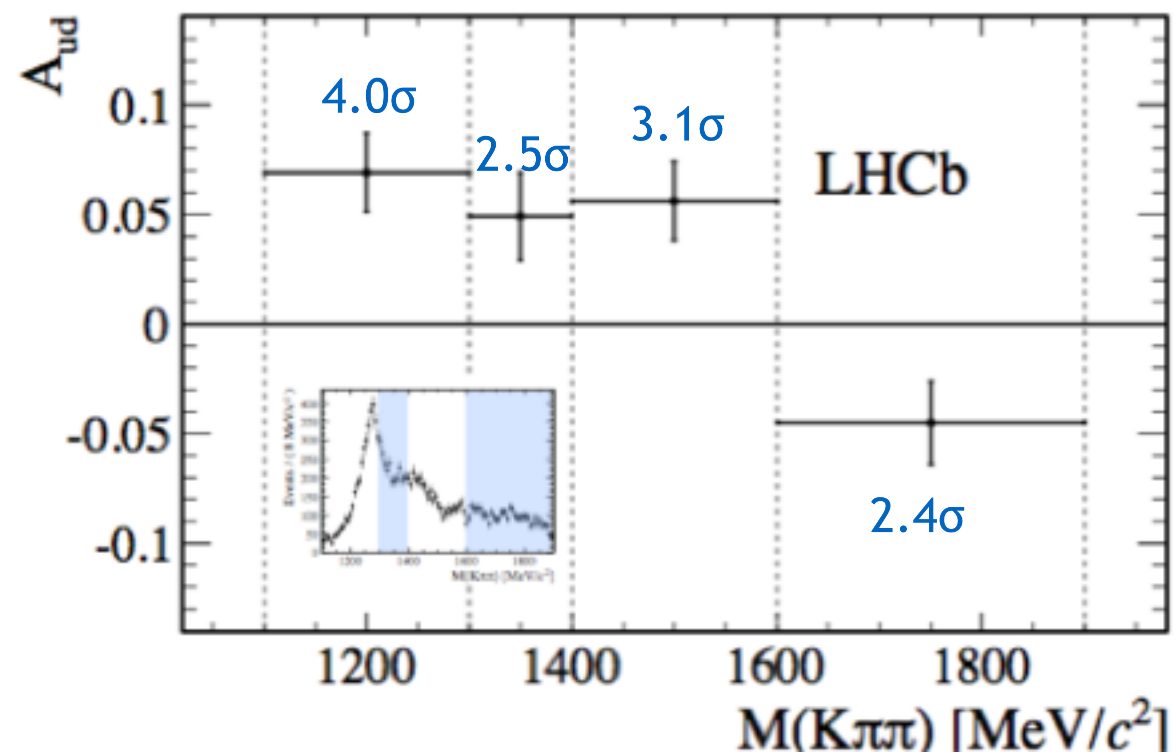


Gronau et. al:
PRL 88, 051802
PRD 66, 054008

Define up-down asymmetry, proportional to the photon polarization parameter λ_γ

$$\mathcal{A}_{ud} \equiv \frac{\int_0^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} - \int_{-1}^0 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}}{\int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}} = C\lambda_\gamma$$

First observation of a non-zero photon polarisation in $b \to s\gamma$ transitions (**5.2σ** significance)

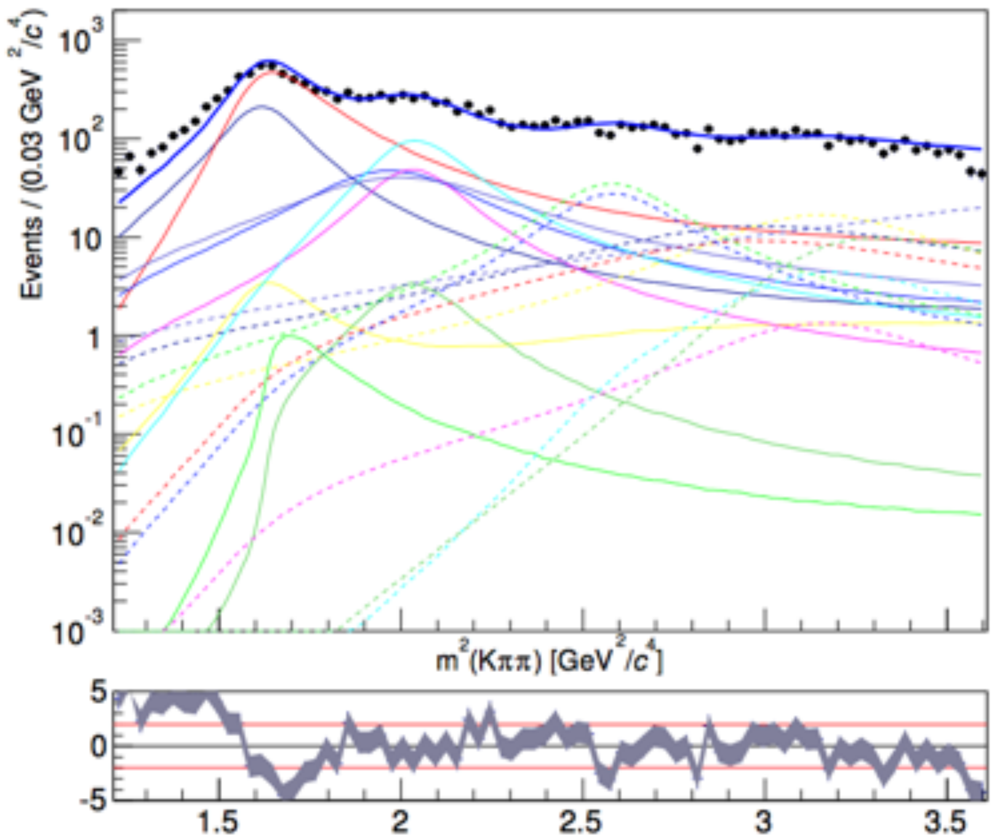


PRL 112, 161801

Photon Polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ Decays

Full five-dimensional amplitude analysis needed:

CERN-THESIS-2015-287



- Access to λ_γ through interferences between decay modes
- Use three invariant masses ($m^2(K\pi\pi)$, $m^2(K\pi)$ and $m^2(\pi\pi)$), and two angular variables of the photon (χ and θ) to describe the $K\pi\pi\gamma$ system

Sensitivity study ongoing for Runs1+2

- ~14,000 signal B candidates in Run 1
- O(300,000) events expected with 300 fb^{-1}
- Expected dominant systematic uncertainty - effect of partially reconstructed background on angular distributions

$$\mathrm{d}\Gamma(B^+ \to K^+\pi^-\pi^+\gamma) = \left|\sum_i \frac{c_R^{(i)} A_R^{(i)}}{s - M_i^2 - iM_i\Gamma_i}\right|^2 + \left|\sum_i \frac{c_L^{(i)} A_L^{(i)}}{s - M_i^2 - iM_i\Gamma_i}\right|^2$$

$c_{R,L}$ - weak decay amplitudes
$A_{R,L}$ - strong decay amplitudes
B_i - Breit Wigner propagator for resonance (i)

$$d\Gamma(B^+ \to K_{\mathrm{res}}^{+(i)}\gamma \to K^+\pi^-\pi^+\gamma) \propto (|\mathcal{M}_\mathrm{R}|^2 + |\mathcal{M}_\mathrm{L}|^2) + \lambda_\gamma(|\mathcal{M}_\mathrm{R}|^2 - |\mathcal{M}_\mathrm{L}|^2)$$

Prospects for $B \to K\pi\pi\gamma$ Decays

- Neutral Kππ modes ($B^0 \to K_S \pi^- \pi^+ \gamma$, $B^0 \to K^+ \pi^- \pi^0 \gamma$) are expected to have larger up-down asymmetry due to additional interferences between isospin-related amplitudes (Gronau, PRD 66, 054008)
- Photon polarization depends on B^0 flavour ⇒ require flavour-tagging
- With a FT efficiency of 5%, could expect O(10,000) events with $300 fb^{-1}$
- Other decay modes?
  - $B^+ \to K_S \pi^+ \pi^0 \gamma$? Very difficult due to Ks and π^0 reconstruction

Branching Fractions and A_{CP}

- Ratio of $B^0 \to K^*\gamma$ and $B^0 \to \phi\gamma$ branching fractions with 1fb $^{-1}$

  1.23 ± 0.06 (stat.) ± 0.04 (syst.) ± 0.10 (f_S/f_d)

- Update with full Run 1 dataset soon!
  - Includes $\Lambda_b \to \Lambda(\to pK)\gamma$ decay
- Limited by hadronic form factors; also nearing systematics-dominated regime
- Run2: Study higher hadronic resonance states of $B \to (Kh)\gamma$

Nucl. Phys. B867

	$B^0 \to K^{*0}\gamma$ ($\times 10^{-5}$)	$B_s^0 \to \phi\gamma$ ($\times 10^{-5}$)
Theory	4.3 ± 1.4	4.3 ± 1.4
CLEO	$4.55^{+0.72}_{-0.68} \pm 0.34$	-
BaBar	$4.47 \pm 0.10 \pm 0.16$	-
Belle	$4.01 \pm 0.21 \pm 0.17$	$5.7^{+1.8+1.2}_{-1.5-1.1}$
LHCb	-	3.5 ± 0.4

- A_{cp} in $B^0 \to K^*\gamma$ decays also measured with 1fb $^{-1}$
- Main systematic due to A_{cp} from background (will be improved with inclusion of $\Lambda_b \to pK\gamma$ decay mode in the fit model)
- Could be systematics-dominated by the end of Run 2
- A_{cp} in $b \to d\gamma$ transitions is expected to be larger (around 10%, compared to 1% for $b \to s\gamma$)

	$\mathcal{A}^{CP}$ ($B^0 \to K^{*0}\gamma$)
Theory	$-(0.61 \pm 0.46)\%$
CLEO	$(8 \pm 13 \pm 3)\%$
BaBar	$(-1.6 \pm 2.2 \pm 0.7)\%$
Belle	$(-1.5 \pm 4.4 \pm 1.2)\%$
LHCb	$(0.8 \pm 1.7 \pm 0.9)\%$

$b \to d\gamma$ TRANSITIONS

- Allows access to $|V_{td}/V_{ts}|$ via a measurement of $BR(B^0 \to \rho^0\gamma)/BR(B^0 \to K^*\gamma)$
- A_{cp} expected to be larger than for $b \to s\gamma$ transitions
- Highly suppressed, so large statistics are needed
- Need to control background from decay modes with neutral pions
- Currently studying $B^0 \to \rho^0\gamma$ decays with Run 1 data
    - A few hundred signal events expected

Looking ahead:

- Could add in study of $B \to \omega(\to \pi^+\pi^-\pi^0)\gamma$ decays
- Challenging! Currently expect ~5% reconstruction efficiency compared to $\rho\gamma$ mode
- Will benefit from increased statistics, and partial reconstruction of the ω decay vertex
- More decay modes: $B \to \pi\pi\pi\gamma$, $B \to p p \pi\gamma$, …

ISOSPIN ASYMMETRY IN $B \to K^* \gamma$

- Isospin asymmetry in $B \to K^*\gamma$ decays has a small theoretical uncertainty, interesting to measure:

$$\Delta_{0-} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

- Current best measurement by the BABAR collaboration [PRL 103, 211802]:

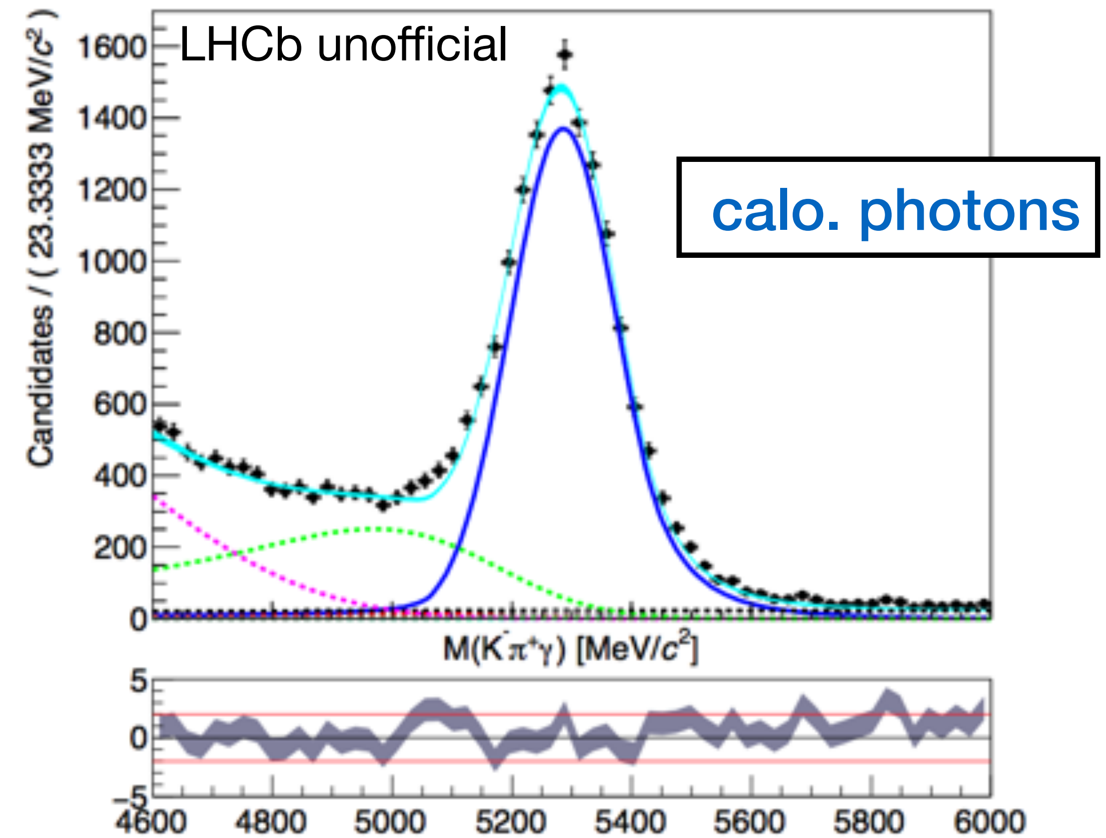
$0.017 < \Delta_{0-} < 0.116$ at 90% C.L

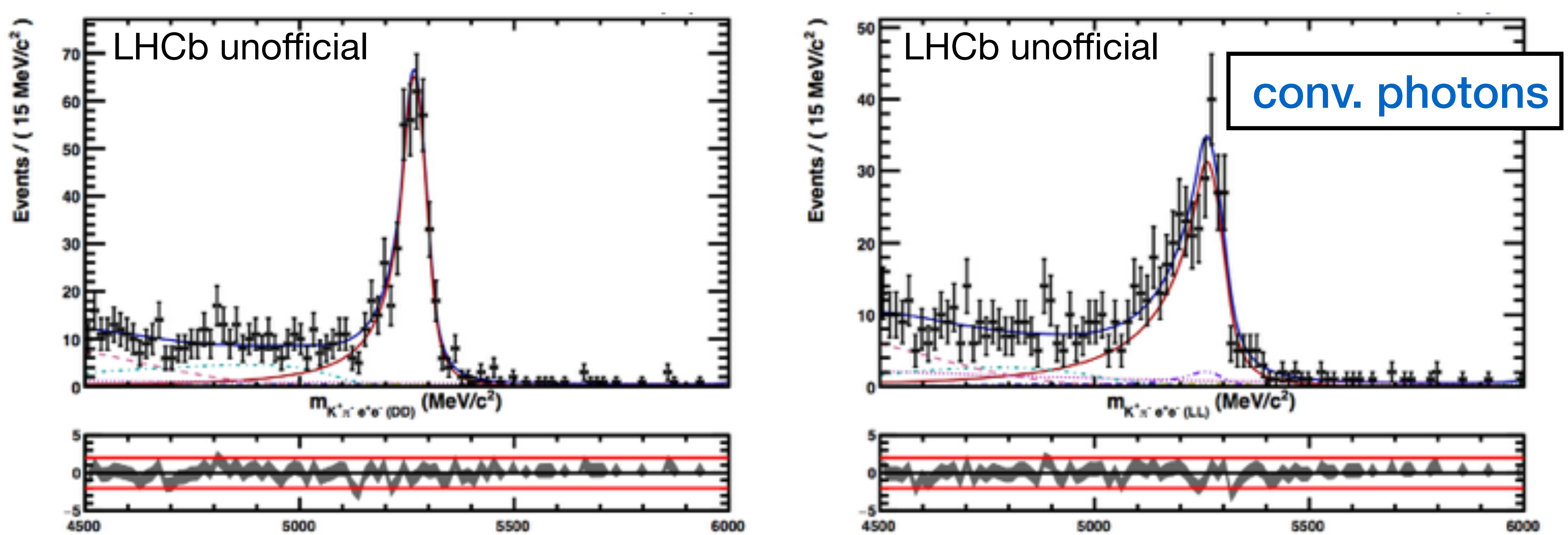
Can LHCb have a competitive measurement?

- Need to reach a statistical uncertainty of ~3%
- Limitations: Low efficiency for $B^+ \to K^{*+}(\to K_S \pi^+)\gamma$ decays (due to low K_S reconstruction efficiency)
- Initial studies with Run1 + 2015 data show that we need ~ 3 times the statistics

Converted Photons

- B invariant mass resolution is improved with photon conversions
- However, have to contend with lower statistics (10-20% compared to yield obtained with calo. photon analyses)
- Run 1 branching fraction and A_{cp} measurements done
  - Limited compared to calo photon analysis
- Included $B_s \rightarrow K^*\gamma$ contribution, set a limit on $B_s \rightarrow K^*\gamma$ decay branching fraction

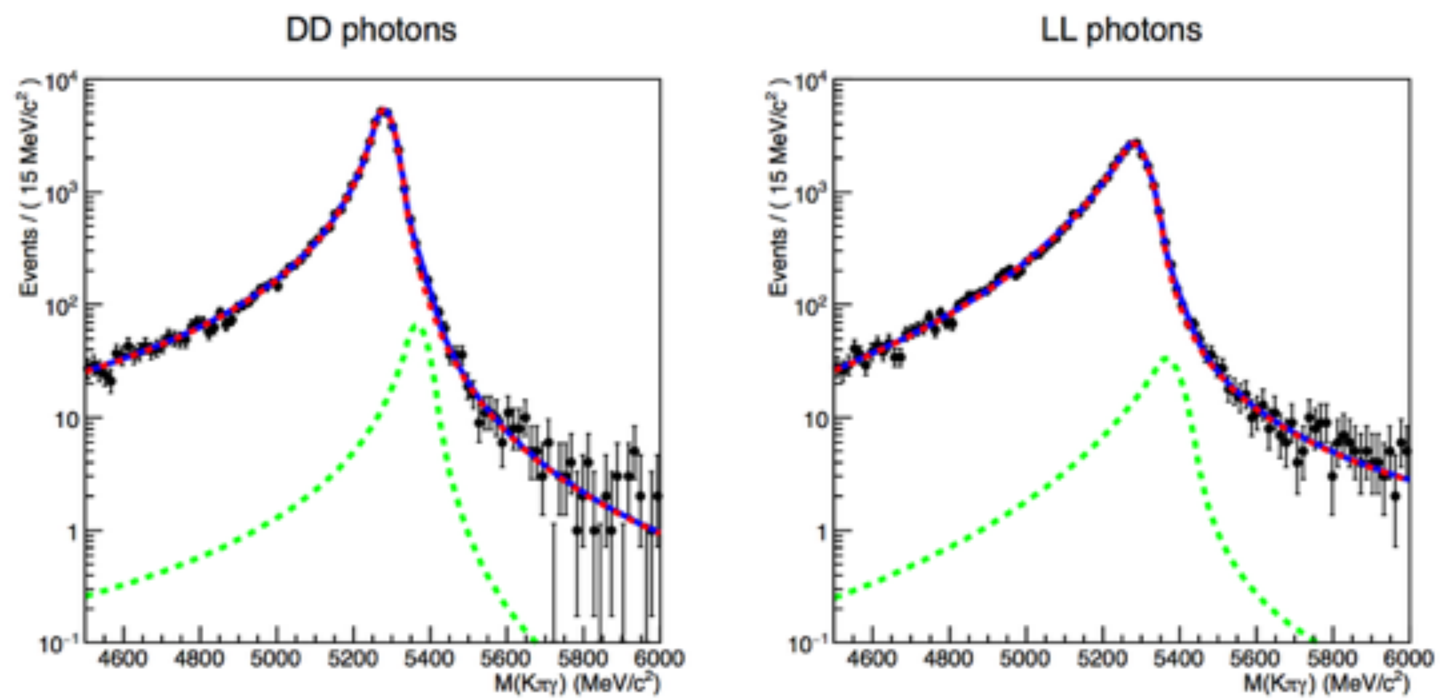




Converted Photons

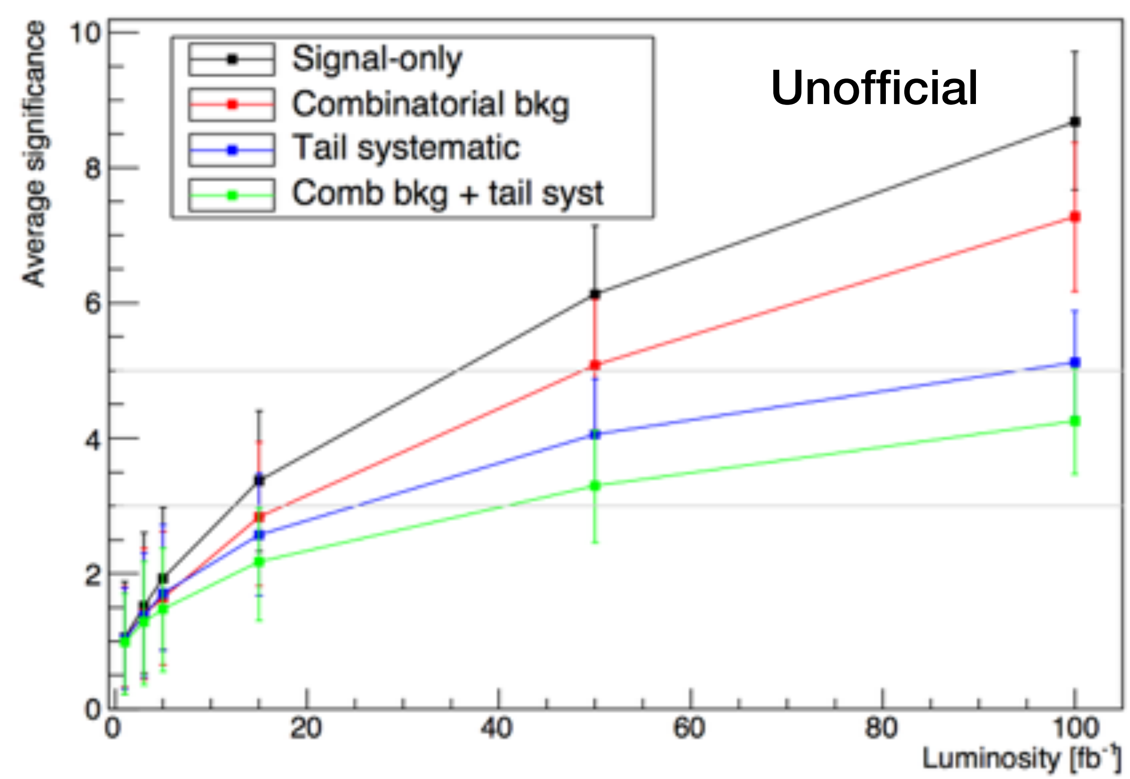
Finding the $B_s \rightarrow K^*\gamma$ needle in a $B^0 \rightarrow K^*\gamma$ haystack:

- Decay mode is highly suppressed
- $\Delta m(Bs,B)$ is around the typical invariant mass resolution
- Better resolution of B^0 mass peak with converted photons, so is interesting to search here



Sensitivity study:

- Use shapes from Run 1 analysis to model $B_s \rightarrow K^*\gamma$ (signal) and $B^0 \rightarrow K^*\gamma$ (background)
- Fit with simultaneous PDF, calculate log(L) between S+B and B only hypotheses
- Obtain signficances using Wilks' theorem
- Can also include combinatorial background, and a systematic from incorrect knowledge of the right $B^0 \rightarrow K^*\gamma$ tail

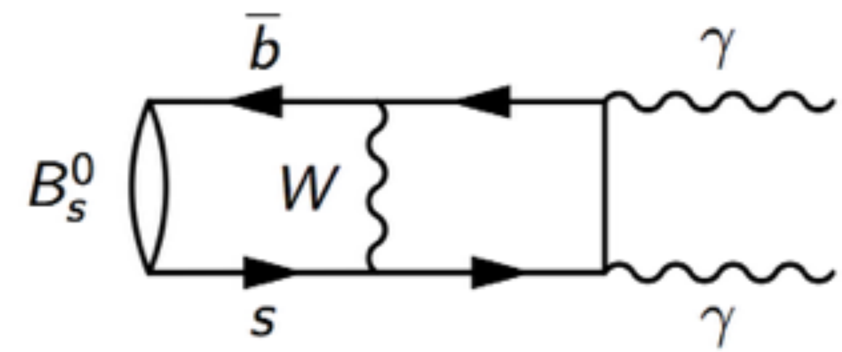


High statistics + reduction in background (and systematics effects) needed for observation

CAN WE DO MORE?

$B \to \gamma\gamma$ decays

- Expected to be very sensitive to New Physics (from SUSY, extended Higgs models, etc.)



- Challenging analysis for LHCb
- Three detector final states:
  - Two calo photons (very difficult to construct, but largest yield)
  - One calo photon, one conversion (cleaner detector signal, but lower statistics)
  - Two conversions (can reconstruct B vertex, very low statistics)

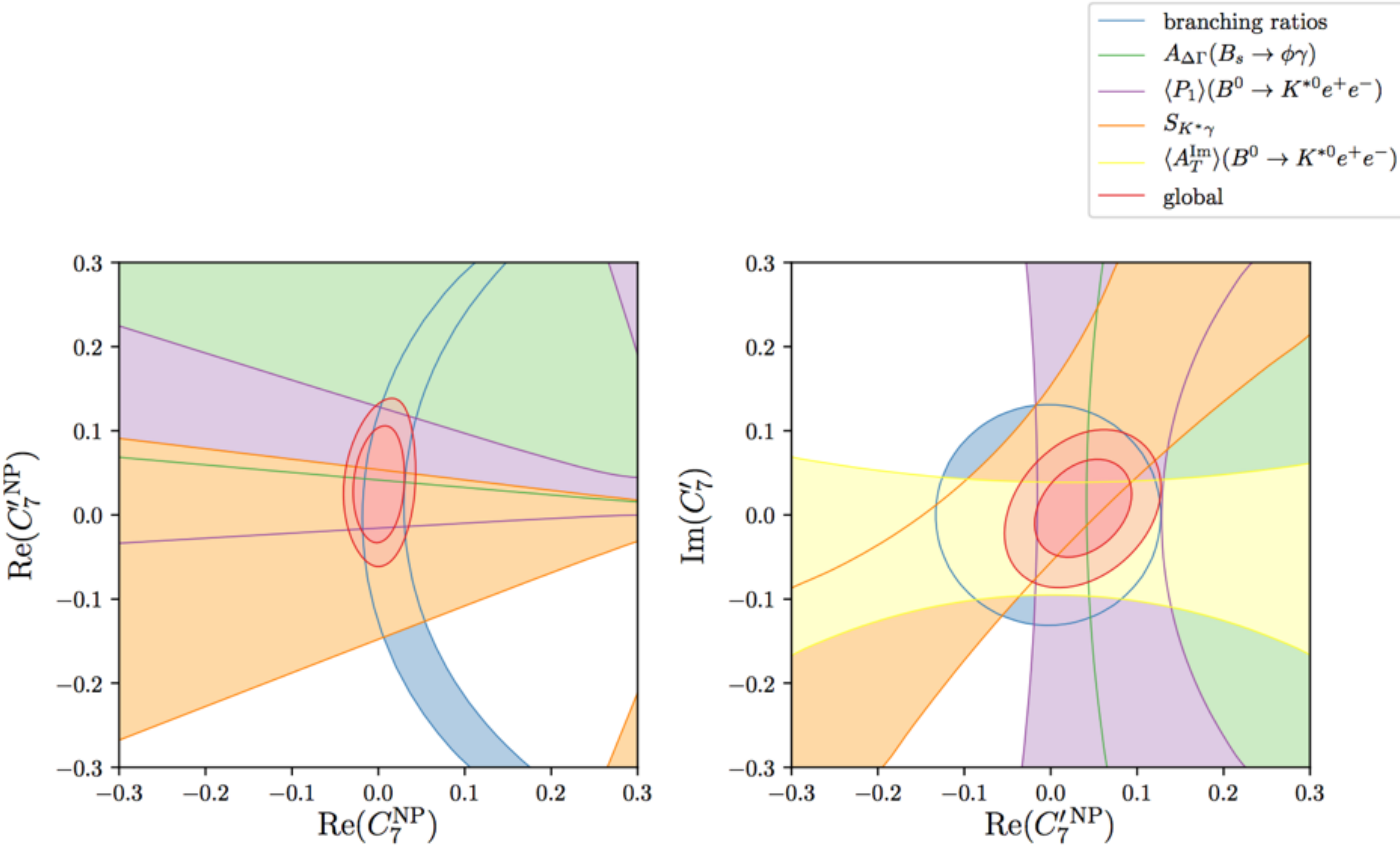
- Would greatly benefit from high statistics dataset and improved calorimeter

Summary

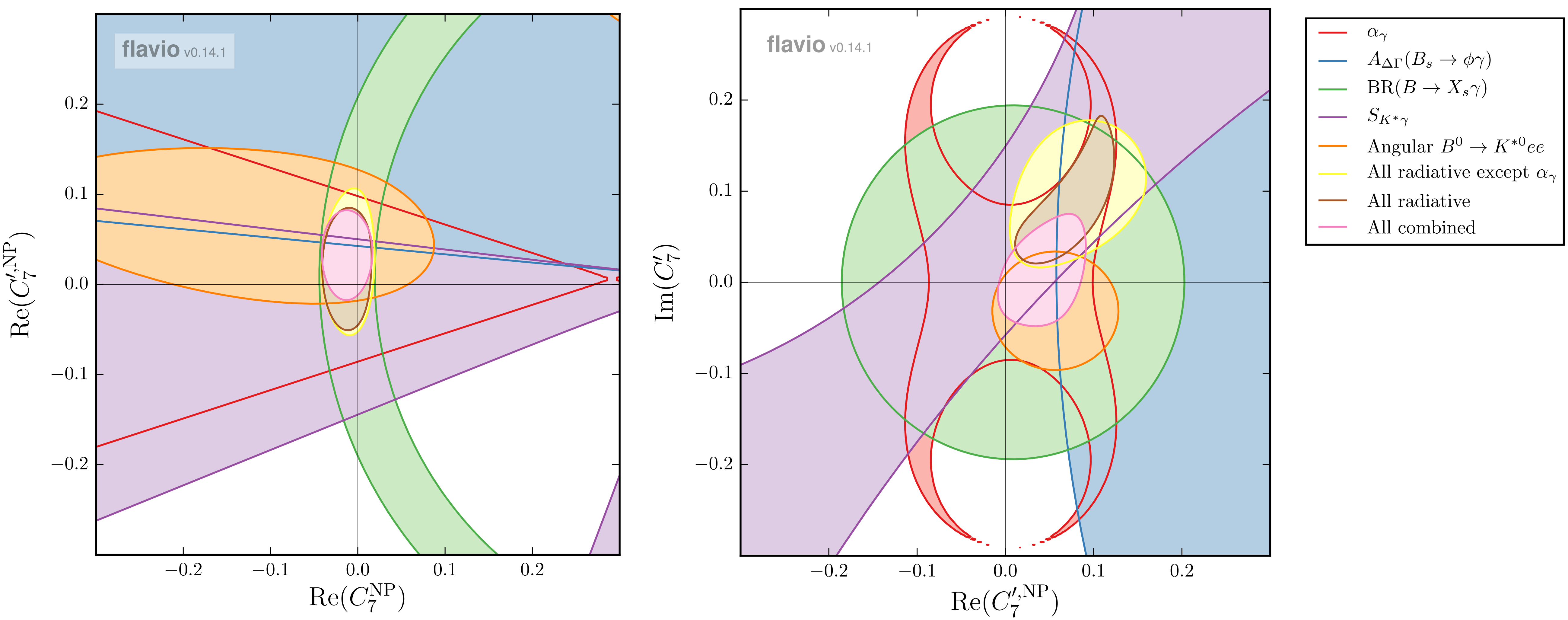
- Studying new radiative decay modes, performing more complex analyses with Run 2 data
  - However, many analyses will be systematics-limited by the start of Run 5
- Calorimeter upgrade will be important for reduction of systematic uncertainties
  - Improved resolution will decrease the (currently dominant) effect of partially reconstructed background
  - Addition of time-of-flight information will help reduce backgrounds further
- The 300fb^{-1} dataset will enable the study of highly suppressed decay modes
- Will be able to test Standard Model hypotheses in multiple channels

Backup

CONSTRAINTS ON C7/C7' - CURRENT PICTURE



Constraints on C7/C7' - Λ_b Decays



Belle II Prospects

- Summarized from this talk at CKM 2016
- Inclusive $B \to X_q \gamma$ branching fraction
  - With 50ab^{-1}, an uncertainty of 3.9% is foreseen for $E_\gamma > 1.6$ GeV
  - Comparable to theoretical uncertainties from non-perturbative effects
- A_{cp}, $\Delta(A_{cp})$:
  - $B \to X_s \gamma$ A_{cp} expected to have an uncertainty of 0.61% (i.e. 3.4σ if central value from previous result stays the same).
  - $\Delta(A_{cp})$ uncertainty Is expected to be 0.34%
- Time-dependent CP asymmetry in $B^0 \to K_s \pi^0 \gamma$ decays
  - Significant improvements expected over previous result
  - Measure symmetry parameter S in this channel (and in $B^0 \to \rho^0 \gamma$ decays)