Radiative B Decays

CPPM Marseille seminar

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Outlook

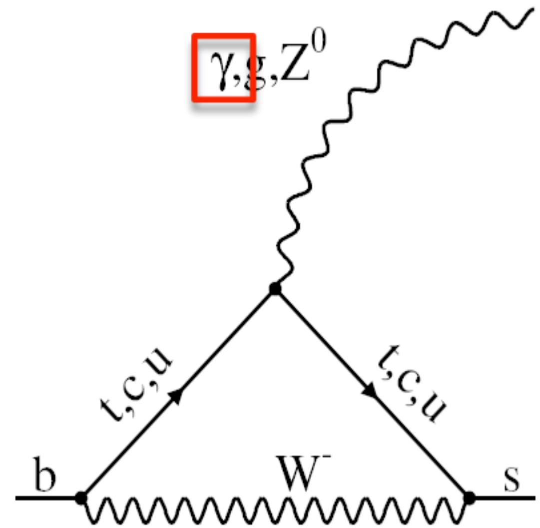
- What are radiative B decays?
- Why are they interesting?
- What can be measured?
- What has been measured in LHCb?
- What is going to be measured in LHCb?

Radiative B decays

Interesting observables

Penguin decays of B mesons

- In the SM, flavor-changing neutral currents (FCNC) ar forbidden
- Effective FCNC are introduced by penguin diagrams.
  - Combinations of CKM matrix elements
  - Sensitive to new physics (NP)



Standard Model predictions

- Predictions on exclusive radiative B decays decays are difficult due to hadronization
- SCET is used to obtain deeper understanding of factorization theorems
  - Perturbative calculations completely known up to NLO, partially up to NNLO
  - Non-perturbative calculations performed with light cone sum rules

Observables

- Branching fractions
- Isospin asymmetry in $B^0 \to K^*\gamma$
- Direct CP asymmetries
- Photon polarization
  - Time dependent CP-asymmetry in $B_s \to \phi\gamma$
  - Angular distributions in radiative baryonic B decays

Branching fractions

- Low predicting power due to hadronization uncertainties

	$B^+ \to K^+\gamma\,(\times 10^{-5})$	$B^0 \to K^{*0}\gamma\,(\times 10^{-5})$	$B_s^0 \to \phi\gamma\,(\times 10^{-5})$
Theory	4.6 ± 1.4	4.3 ± 1.4	4.3 ± 1.4
CLEO	$3.76^{+0.89}_{-0.83} \pm 0.28$	$4.55^{+0.72}_{-0.68} \pm 0.34$	—
BABAR	$4.22 \pm 0.14 \pm 0.16$	$4.47 \pm 0.10 \pm 0.16$	—
Belle	$4.25 \pm 0.31 \pm 0.24$	$4.01 \pm 0.21 \pm 0.17$	$5.7^{+1.8}_{-1.5}{}^{+1.2}_{-1.1}$
HFAG	4.21 ± 0.18	4.33 ± 0.15	$5.7^{+2.1}_{-1.8}$

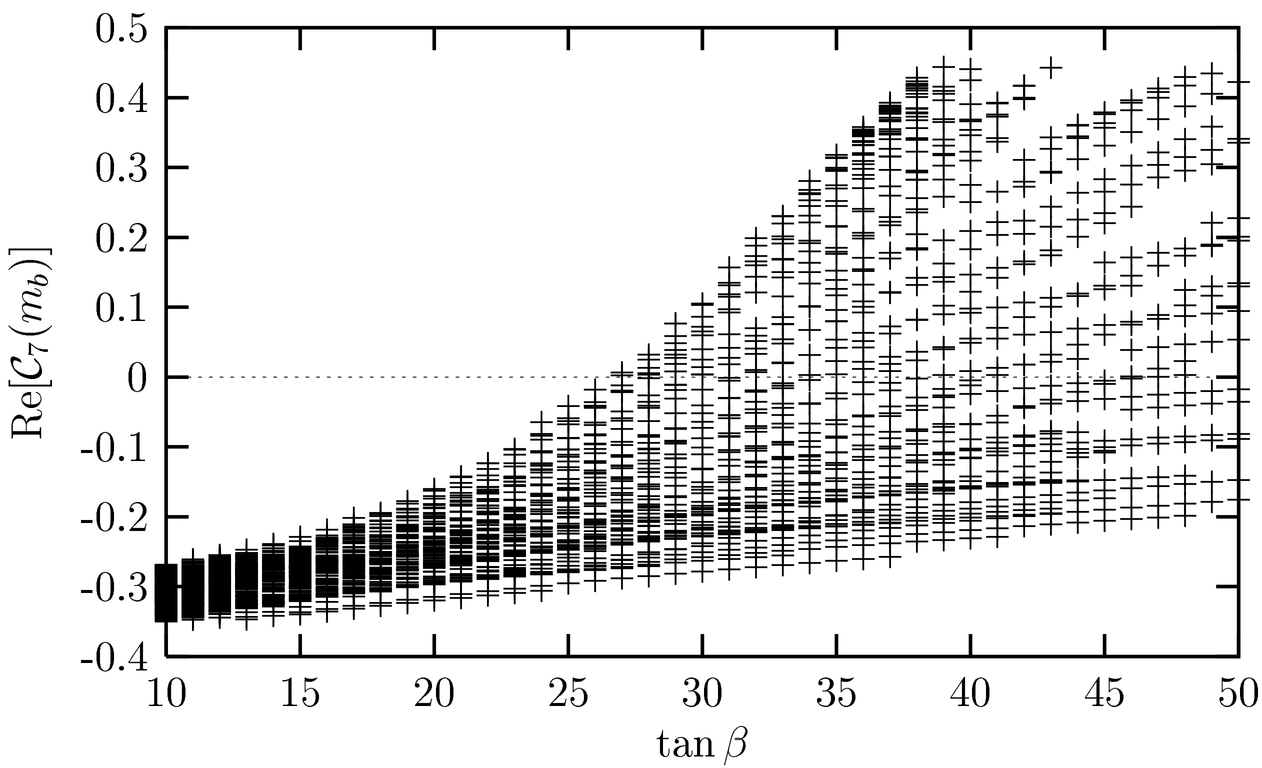
Isospin asymmetry in B → K* γ

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

- Strong sensitivity to NP effects
- Experimental challenges arising from K_S or π^0 in charged K* decay

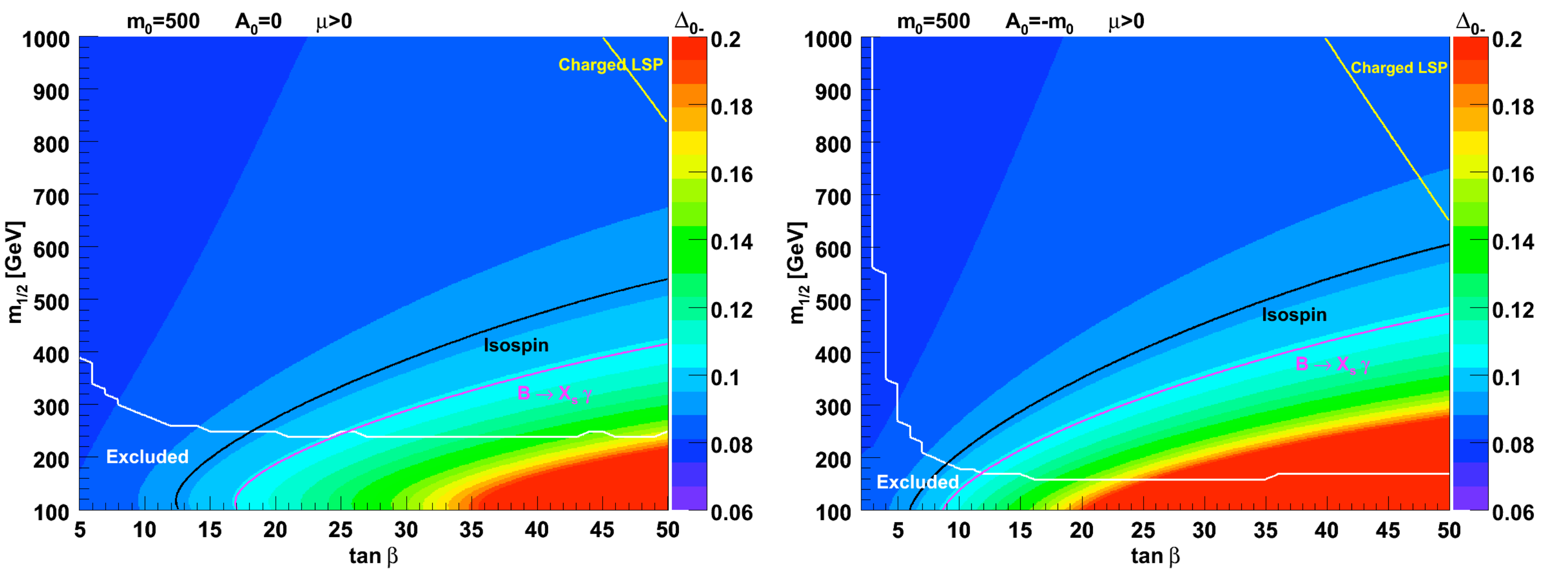
Isospin asymmetry and MSSM

- Positive values of Re(C_7), which flip the sign of Δ_{0-}, become more probable as tanβ increases



Isospin asymmetry and mSUGRA

- Constrain the mSUGRA parameter space
  - Isospin asymmetry is more restrictive than inclusive $B \to X_s \gamma$



arxiv:hep-ph/0610144

Isospin asymmetry status

- Theory predictions

$$\Delta_{0-}(B^0 \to K^{*0}\gamma)_{\mathrm{Kagan}} = (+8.0^{+2.1}_{-3.2})\% \times 0.3/T_1^{B\to K^*}$$

$$(T_1^{B\to K^*} \text{ estimates go from } 0.23 \pm 0.06 \text{ to } 0.38 \pm 0.06)$$

$$\Delta_{0+}(B^0 \to K^{*0}\gamma)_{\mathrm{Matsumori}} = +(2.7 \pm 0.8)\%$$

- Experimental results

$$\Delta_{0+}(B^0 \to K^{*0}\gamma)_{\mathrm{Belle}} = +(1.2 \pm 4.4 \pm 2.6)\%$$

$$\Delta_{0-}(B^0 \to K^{*0}\gamma)_{\mathrm{BaBaR}} = +(6.6 \pm 2.1 \pm 2.2)\%$$

Direct CP asymmetries

- Uncertainties due to form factors largely cancel
- In $B \to K^{*}\gamma$ CP asymmetry is suppressed by $m_{s,d}/m_b$
  - Theoretically, values of O(1%) with uncertainties ~0.5%

$$\mathcal{A}^{0}_{CP} = -(1.6 \pm 2.2 \pm 0.7)\%$$
$$\mathcal{A}^{+}_{CP} = (1.8 \pm 2.8 \pm 0.7)\%$$
$$\mathcal{A}^{\text{combined}}_{CP} = -(0.3 \pm 1.7 \pm 0.7)\%$$

- In $B \to \rho\gamma$, one finds O(10%) predictions in the SM
  - Very challenging experimentally

Photon polarization

$$\lambda_\gamma = \frac{|\mathcal{A}_R|^2 - |\mathcal{A}_L|^2}{|\mathcal{A}_R|^2 + |\mathcal{A}_L|^2}$$

- Admixture of photons with the "wrong" polarization can be large in SM extensions
  - Left Right Symmetric Model (LSRM), unconstrained MSSM, models with non-supersymmetric extra dimensions
- Measure as "null test", since photons are ~100% polarized in the SM

Time-dependent CP asymmetry

- Time evolution of B $\longrightarrow \Phi^{CP}\gamma$

$$\Gamma_{B^0_{(s)}\to\Phi^{CP}\gamma}(t) = |A|^2 e^{-\Gamma_{(s)}t}(\cosh\frac{\Delta\Gamma_{(s)}t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_{(s)}t}{2} + \\ + \mathcal{C}\cos\Delta m_{(s)}t - \mathcal{S}\sin\Delta m_{(s)}t)$$

$$\Gamma_{\bar{B}^0_{(s)}\to\Phi^{CP}\gamma}(t) = |A|^2 e^{-\Gamma_{(s)}t}(\cosh\frac{\Delta\Gamma_{(s)}t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_{(s)}t}{2} - \\ - \mathcal{C}\cos\Delta m_{(s)}t + \mathcal{S}\sin\Delta m_{(s)}t)$$

- Time-dependent CP asymmetry can be used to probe the photon polarization

Time-dependent CP-asymmetry

- In the SM

sum of $B_{(s)}$ mixing phase and CP-odd weak phases for right and left amplitudes

$$\mathcal{C} \approx 0$$

$$\mathcal{S} \approx \sin 2\psi \sin \varphi_{(s)}$$

$$\mathcal{A}^{\Delta} \approx \sin 2\psi \cos \varphi_{(s)}$$

$$\tan\psi \equiv \left| \frac{\mathcal{A}(\bar{B}_{(s)} \to \Phi^{CP}\gamma_R)}{\mathcal{A}(\bar{B}_{(s)} \to \Phi^{CP}\gamma_L)} \right| \longrightarrow \lambda_\gamma = \cos 2\psi$$

- Therefore, $\mathcal{S}$ and $\mathcal{A}^{\Delta}$ directly give access to the fraction of "wrongly"-polarized photons

Photon polarization in B^0

- $\Delta\Gamma/\Gamma$ is negligible, so terms proportional to $\mathcal{A}^\Delta$ vanish

$$\Gamma_{B^0\to\Phi^{CP}\gamma}(t) = |A|^2 e^{-\Gamma t}(1 + \mathcal{C}\cos\Delta m t - \mathcal{S}\sin\Delta m t)$$
$$\Gamma_{\bar{B}^0\to\Phi^{CP}\gamma}(t) = |A|^2 e^{-\Gamma t}(1 - \mathcal{C}\cos\Delta m t + \mathcal{S}\sin\Delta m t)$$

- Also one expects in the SM

CP-odd weak penguin phase

$$\varphi = \sin(2\beta - \phi_p)$$

- Therefore

$$\mathcal{S}_{B^0} = \sin 2\psi \sin 2\beta$$

Photon polarization in B_s

- $\Delta\Gamma/\Gamma$ is not negligible, and

$$\varphi_s = \sin(2\beta_s - \phi_p) \approx 0$$

so the term with S vanishes

$$\Gamma_{B_s^0 \to \Phi^{CP}\gamma}(t) = |A|^2 e^{-\Gamma_s t}(\cosh\frac{\Delta\Gamma_s t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_s t}{2})$$

$$\Gamma_{\bar{B}_s^0 \to \Phi^{CP}\gamma}(t) = \Gamma_{B_s^0 \to \Phi^{CP}\gamma}(t)$$

- Therefore

$$\mathcal{A}^{\Delta}_{B_s^0} \approx \sin 2\psi$$

Photon polarization in Λ_b

- $\Lambda_b \to \Lambda\gamma$ decays also allow to access photon polarization from angular analysis
  - $J(\Lambda_b) = ½$
  - Λ_b are polarized in the LHC
- Two decay topologies
  - $\Lambda_b \to \Lambda^0(\pi p)\gamma$ with $J(\Lambda^0(1115)) = ½$
  - $\Lambda_b \to \Lambda^*(pK)\gamma$

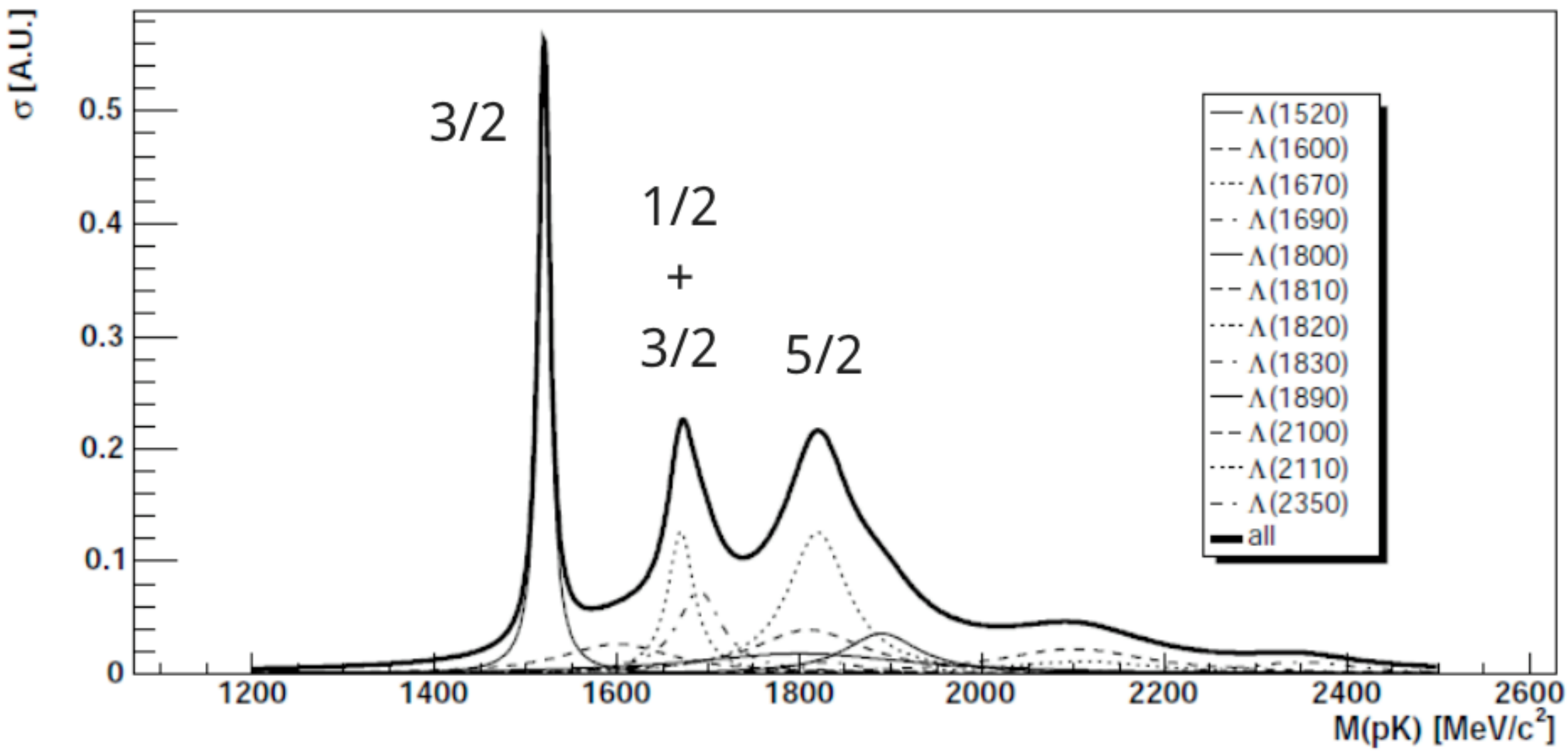
$\Lambda_b \rightarrow \Lambda^0(1115)\gamma$

- Two observables to access photon polarization
  - Photon angular distribution
  - Proton angular distribution
- Topology different than $B^0 \rightarrow K^*\gamma$
  - Λ^0 flies through the detector

$\Lambda_b \to \Lambda^*(X)\gamma$

- Several resonances over the pK threshold
  - Similar topology to $B^0 \to K^*\gamma$
  - Overlapping poorly known states w/different spins
- Two cases
  - J=½ is a strong decay, and thus only one observable for photon polarization: photon distribution
  - J=3/2 is more complex, sensitivity depends on the ratio of the J=1/2 and J=3/2 states

$\Lambda_b \to \Lambda^*(X)\gamma$ cases

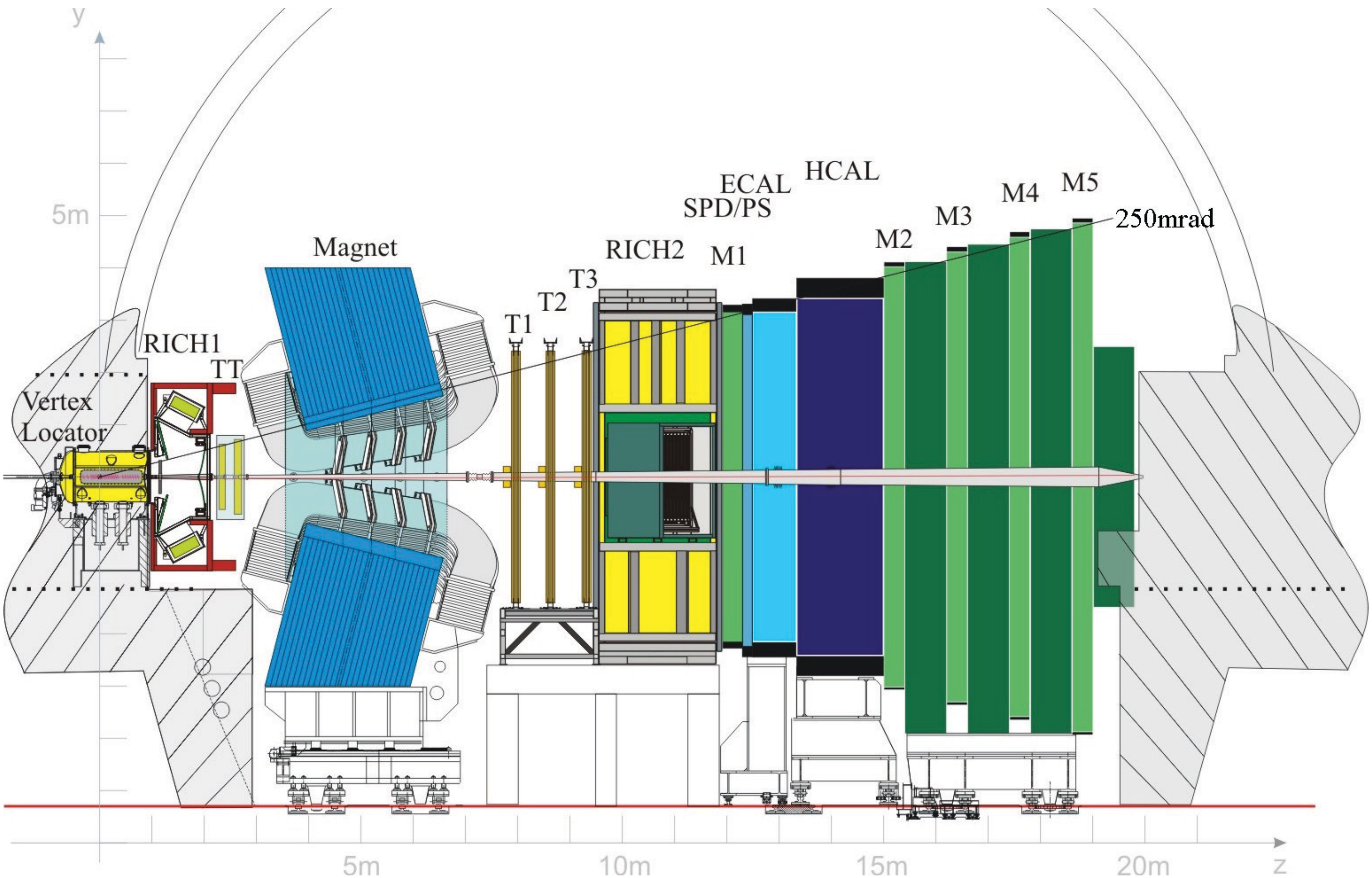


$\Lambda_b \rightarrow \Lambda^*(X)\gamma$ cases

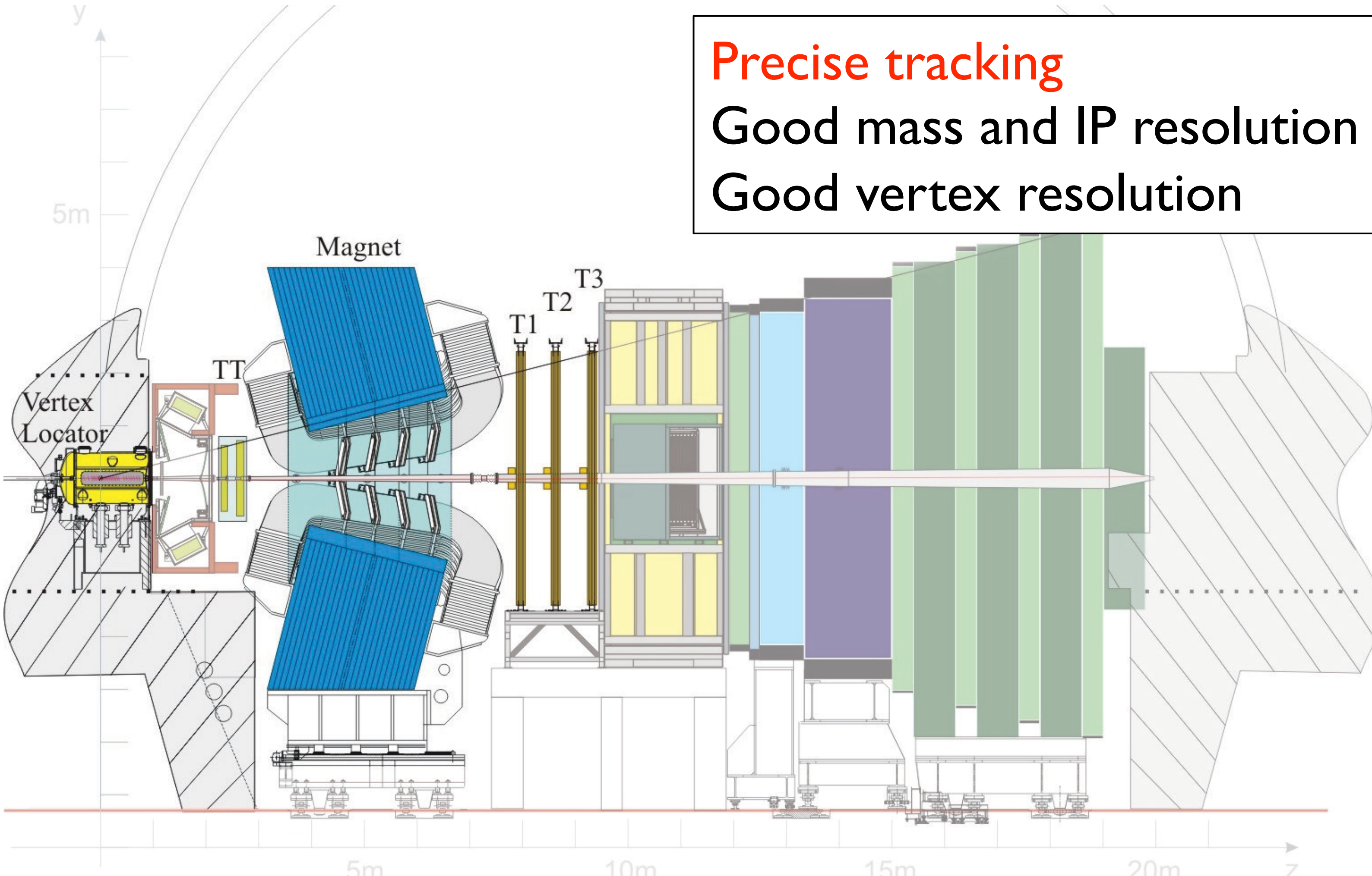
- $\Lambda^*(1520)$ is well stablished
  - J=3/2, so maybe not sensitive to photon polarization
  - Small contamination from poorly known $\Lambda^*(1600)$
- $\Lambda^*(1670)$ and $\Lambda^*(1690)$ are not well known
  - $\Lambda^*(1670)$ is J=1/2 and $\Lambda^*(1690)$ is J=3/2
  - Contamination from other poorly known states
  - Can they be resolved?

The LHCb experiment

The LHCb experiment



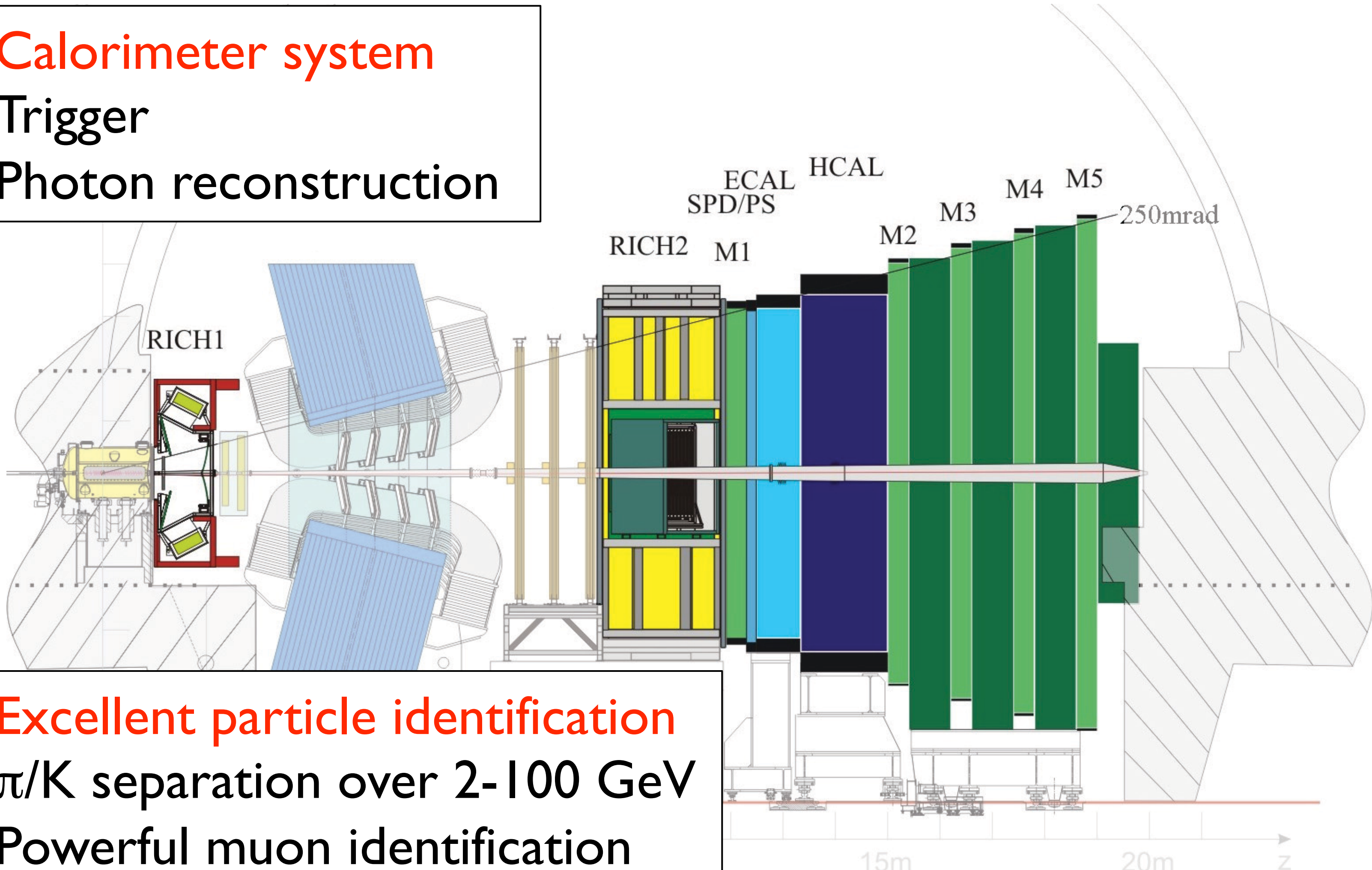
Tracking



Precise tracking
Good mass and IP resolution
Good vertex resolution

Particle identification

Calorimeter system
Trigger
Photon reconstruction



Excellent particle identification
π/K separation over 2-100 GeV
Powerful muon identification

Radiative B decays measurements in LHCb

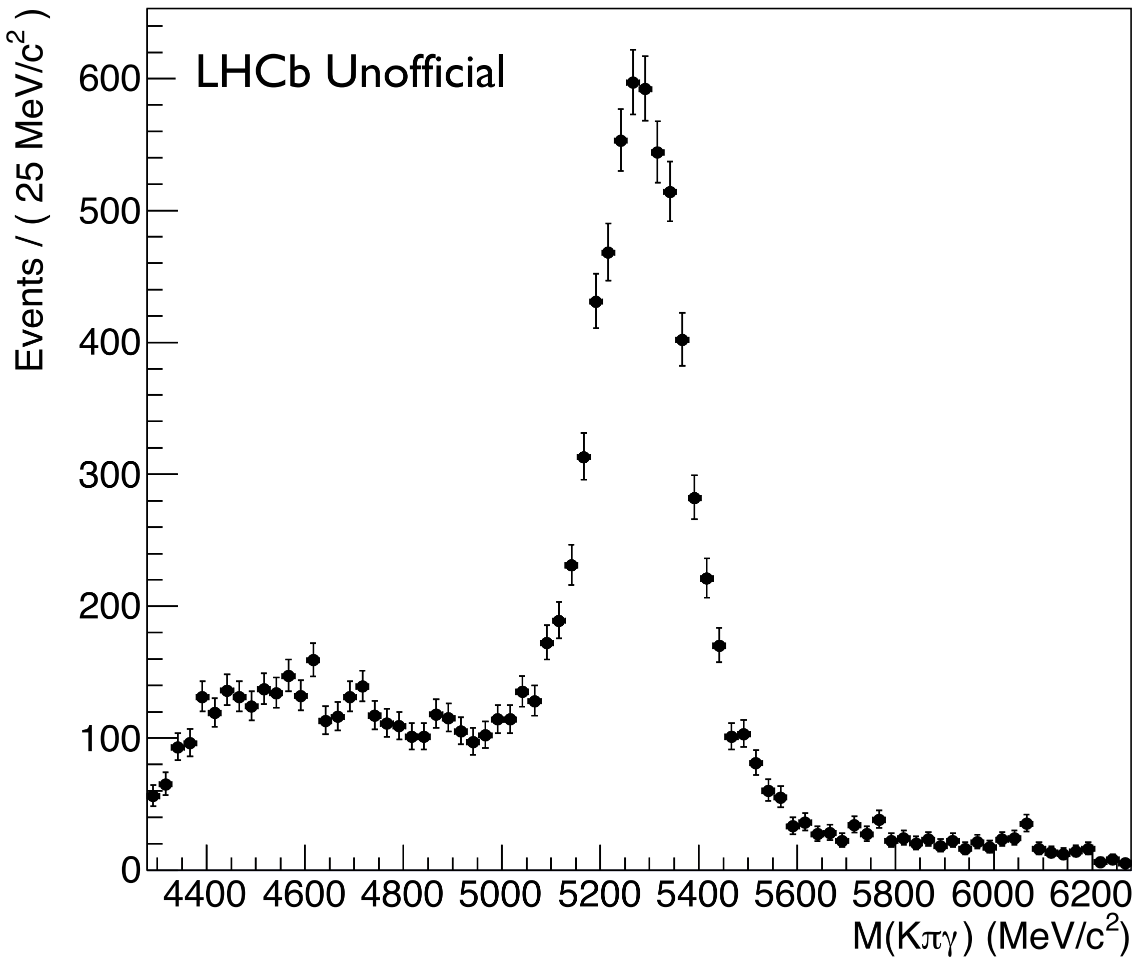
Triggering radiative B decays

- In 2010-2011
  - Exclusive lines for $B^0 \to K^* \gamma$ and $B_s \to \phi\gamma$
  - Inclusive ϕ line
- Since mid-2011
  - Radiative topological lines: topological HLT2 + photon information
  - Similar efficiency, triggers all 2track+photon decays

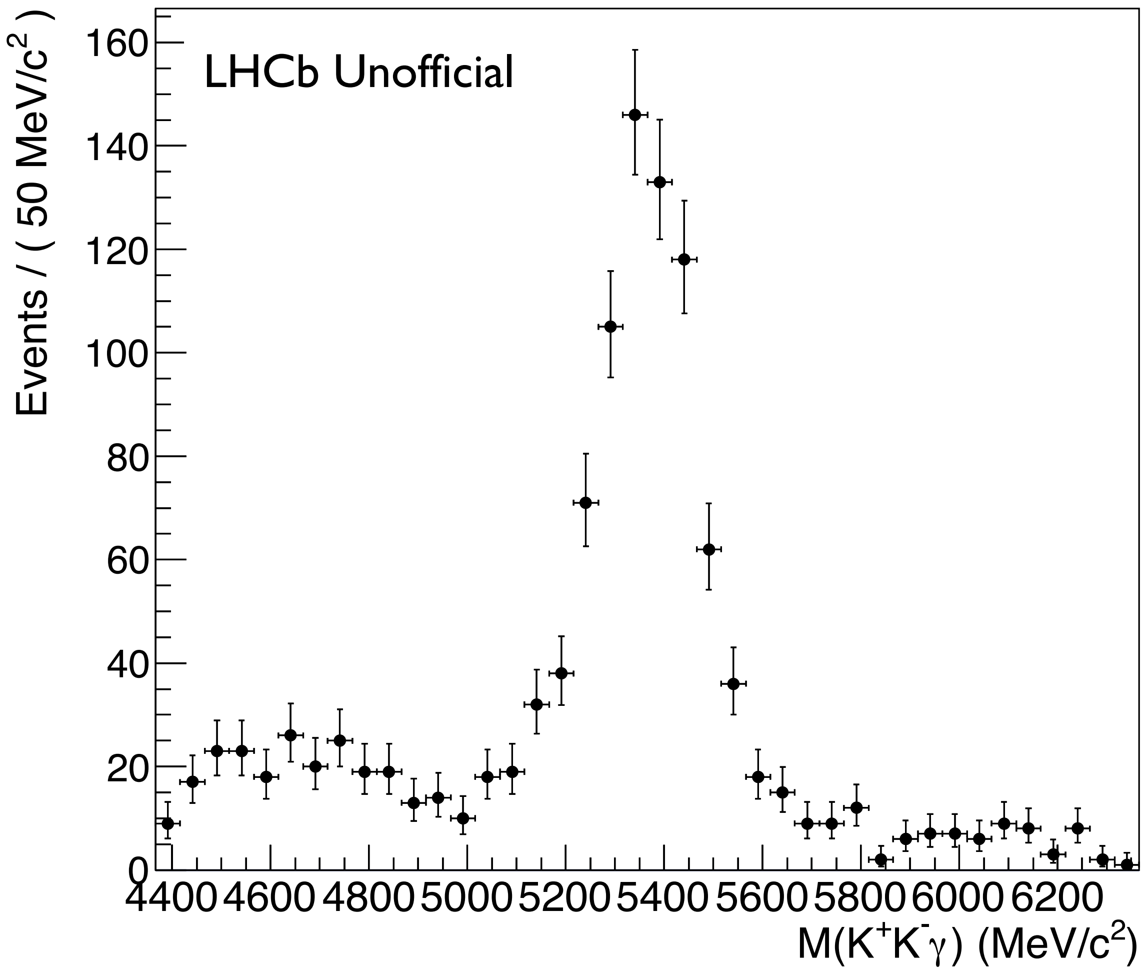
B→Vγ selections

		$B^0 \to K^{*0}\gamma$	$B_s^0 \to \phi\gamma$
Track χ^2		< 5	< 5
Track IP χ^2		> 25	> 25
Track p_{T}	(MeV/c)	> 500	> 500
Max track p_{T}	(MeV/c)	> 1200	> 1200
Kaon $\mathrm{PID}_{K\pi}$		> 5	> 5
Kaon PID_{Kp}		> 2	> 2
Pion $\mathrm{PID}_{K\pi}$		< 0	–
V meson vertex $\Delta\chi^2$		< 9	< 9
V meson ΔM_{PDG}	(MeV/c^2)	< 50	< 9
Photon E_{T}	(MeV)	> 2600	> 2600
Photon CL		> 0.25	> 0.25
π^0/γ separation		> 0.5	> 0.5
B candidate p_{T}	(MeV/c)	> 3000	> 3000
B candidate IP χ^2		< 9	< 9
B candidate DIRA	(mrad)	< 20	< 20
B candidate FD χ^2		> 100	> 100
B candidate ΔM_{PDG}	(MeV/c^2)	< 1000	< 1000
B candidate $\lvert\cos\theta_H\rvert$		< 0.8	< 0.8
B candidate isolation $\Delta\chi^2$		> 2	> 2

$B^0 \to K^{*}\gamma$ in 2011



$B_s \to \phi\gamma$ in 2011



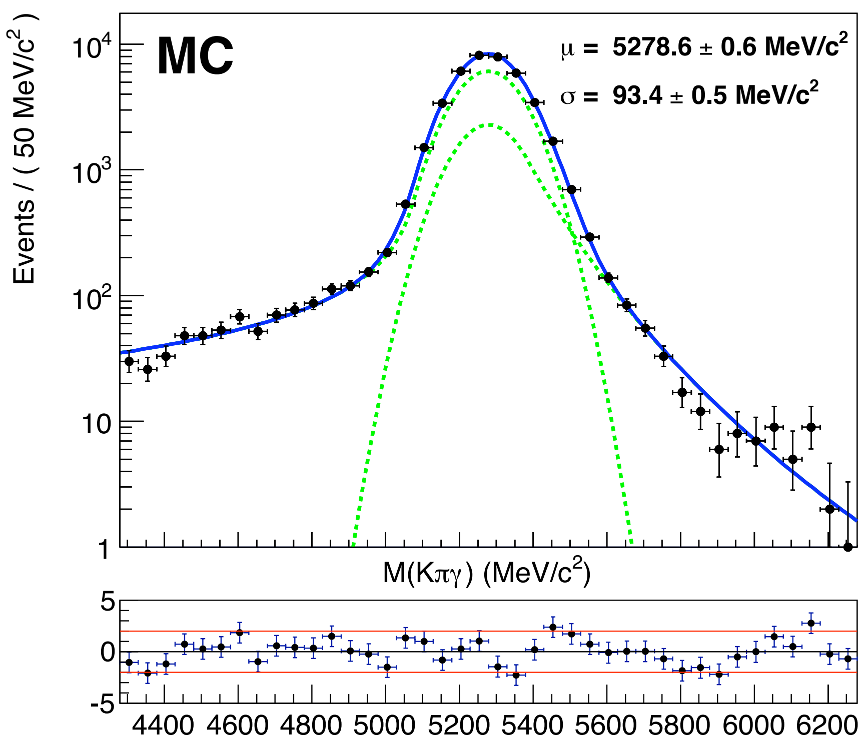
$B^0 \to K^*\gamma$ and $B_s \to \phi\gamma$

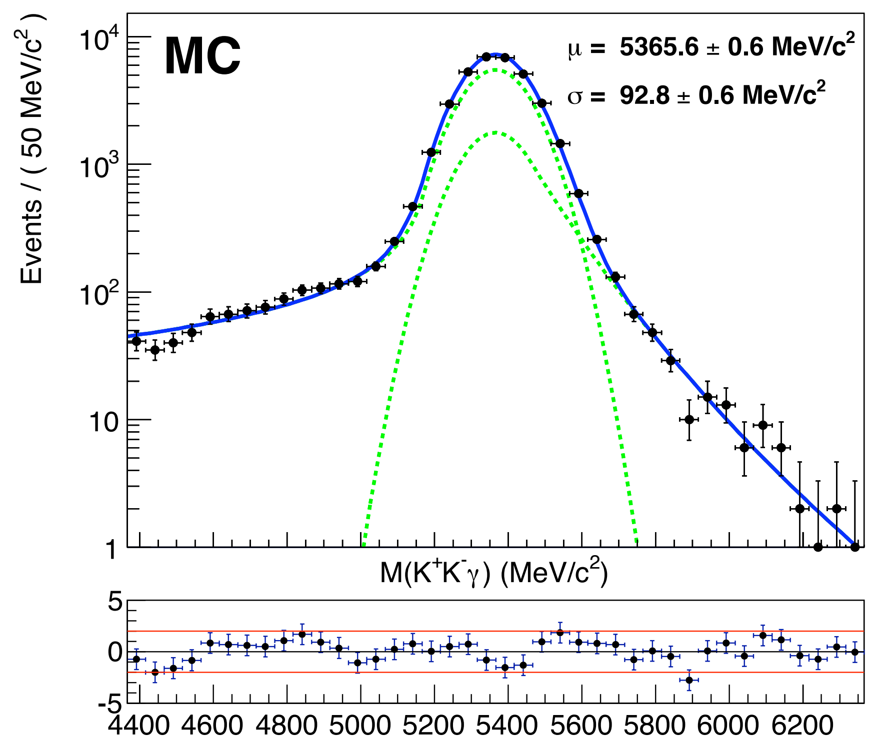
- Before performing measurements, need to characterize invariant mass line shape
  - Signal
  - Background
  - Calorimeter resolution acceptance

Signal shape

- Combination of two Crystal Ball distributions (gaussian + potential tail)
  - Radiative effects at low mass
  - Error distribution of invariant B mass generates a tail at high masses

Signal shape (smeared)





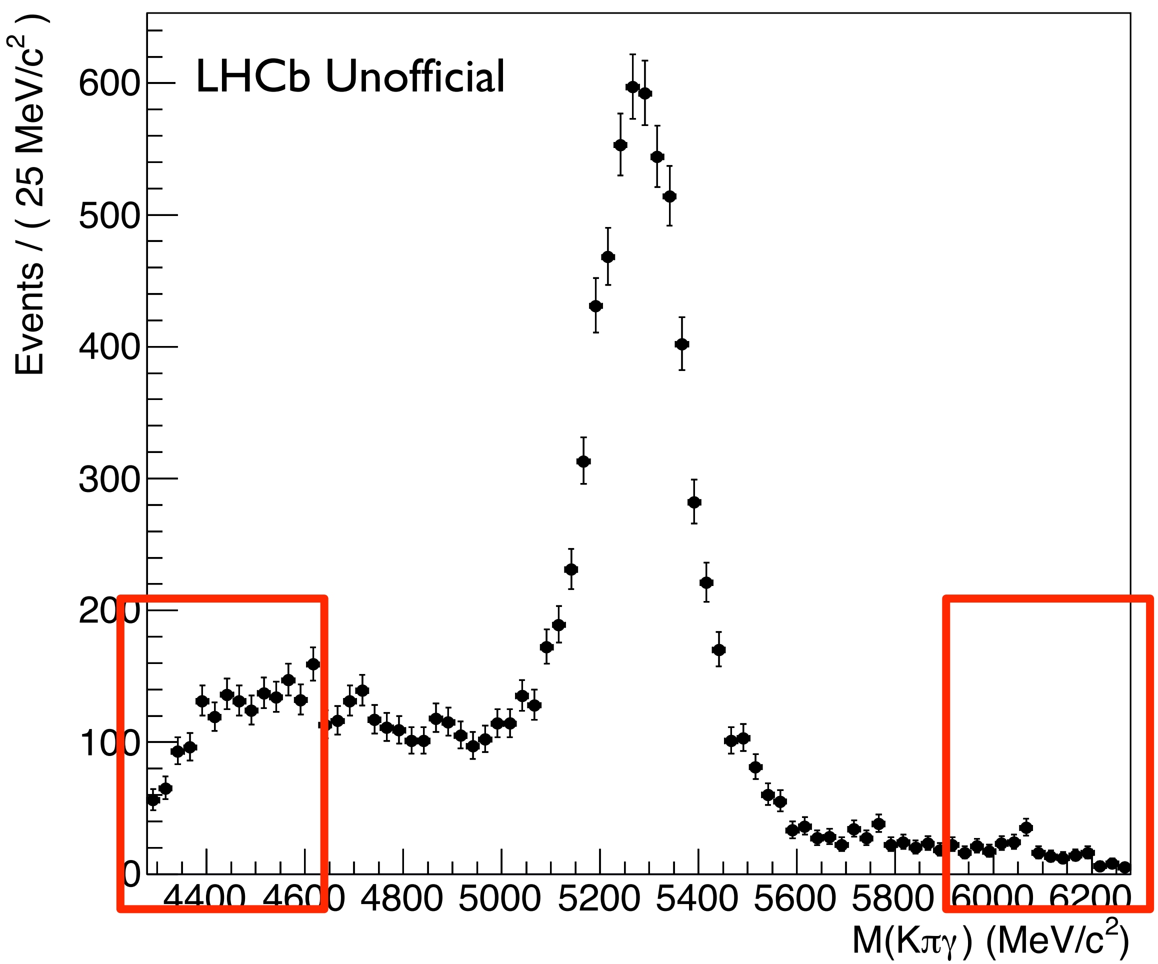
Background sources

- Combinatorial background
- Merged π^0
- Partially reconstructed *B* decays
- Baryonic radiative decays
- Signal cross-feed

Background determination

- Shape of backgrounds fixed from MC
- Contamination of backgrounds
  - Fixed from MC in contaminations under the peak
  - Free in the case of partially reconstructed background

Trigger acceptance



Putting everything together

- First LHCb measurement:

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s \to \phi\gamma)} = \frac{N_{sig}^{B^0 \to K^{*0}\gamma}}{N_{sig}^{B_s \to \phi\gamma}} \frac{\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(K^* \to K^+\pi^-)} \frac{f_s}{f_d} \frac{\epsilon_{B_s \to \phi\gamma}}{\epsilon_{B^0 \to K^{*0}\gamma}}$$

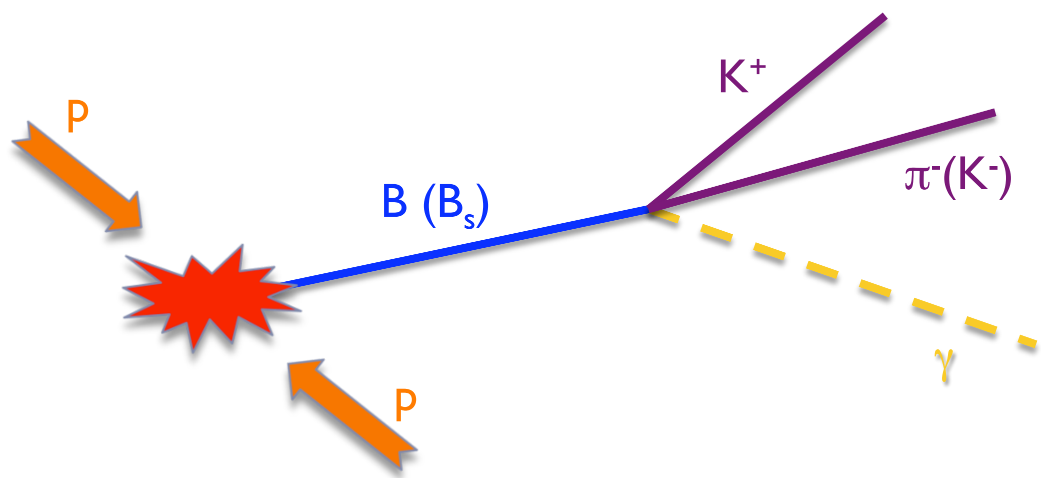
in a way that most systematic effects cancel

- Extract the $B_s \to \phi\gamma$ from the HFAG value of the $B \to K^*\gamma$ branching fraction

$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.3 \pm 0.15) \times 10^{-5}$$

Systematics cancellation

- Achieved through the same candidate reconstruction and selection process:
  1. Build V meson from two oppositely charged tracks
  2. Select high E_T photons
  3. Combine the meson a with photon to build *B*

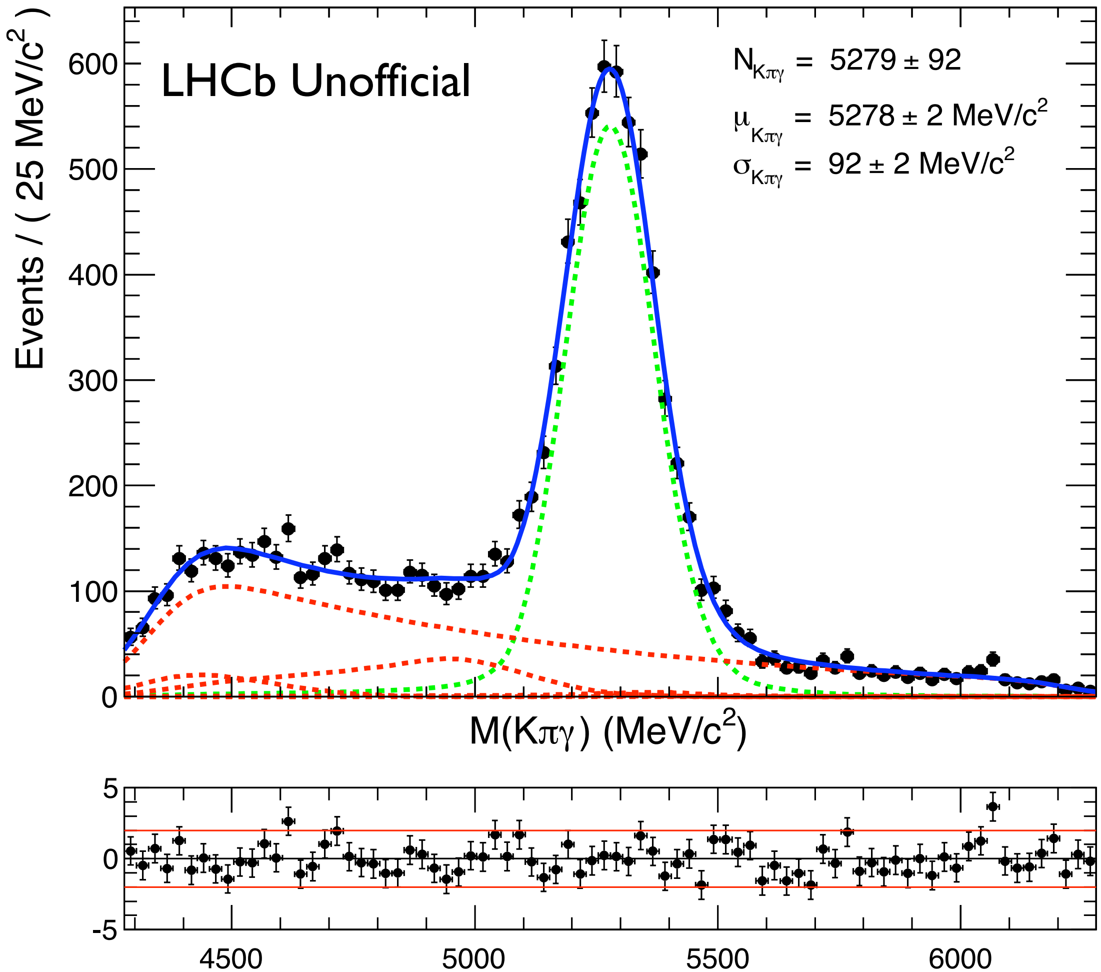


Extraction of the ratio of BRs

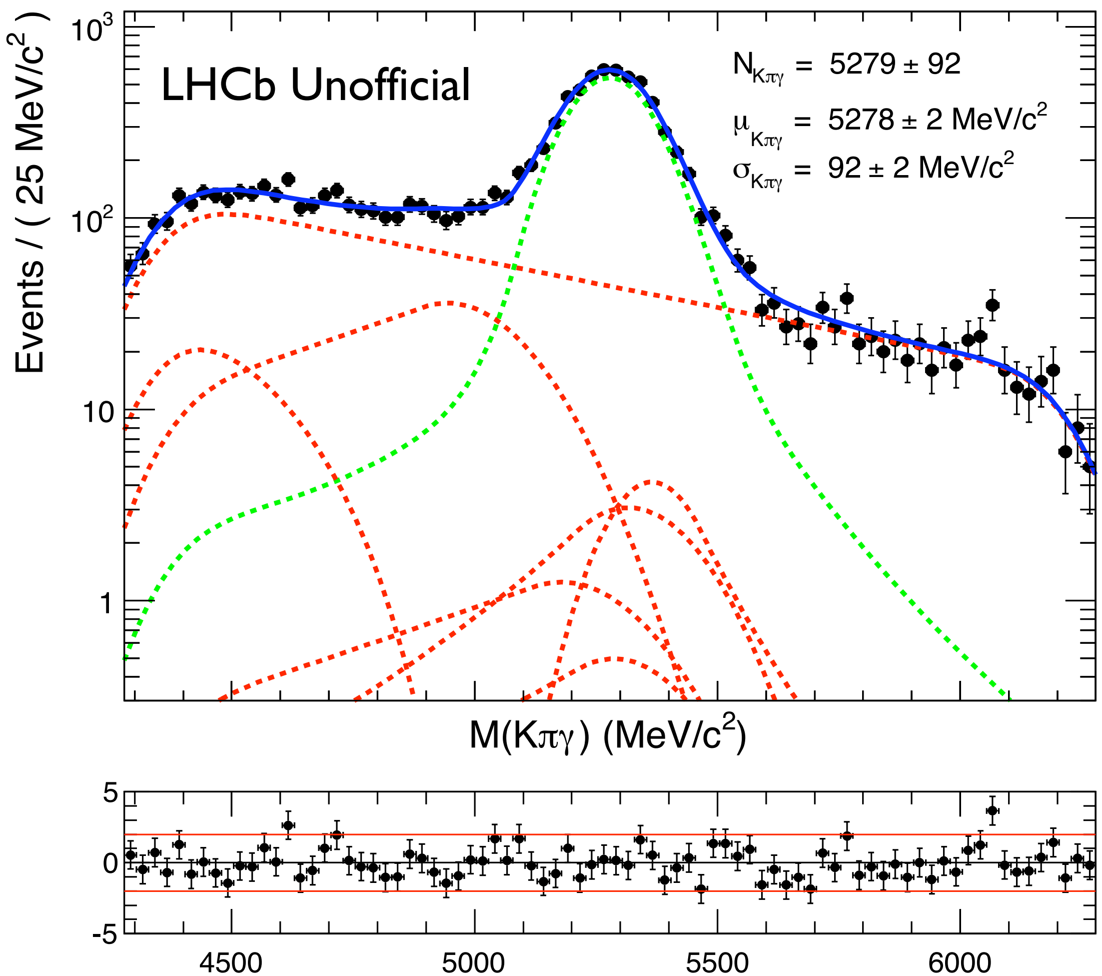
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s \to \phi\gamma)} = \boxed{\frac{N_{sig}^{B^0 \to K^{*0}\gamma}}{N_{sig}^{B_s \to \phi\gamma}}} \boxed{\frac{\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(K^* \to K^+\pi^-)}} \boxed{\frac{f_s}{f_d}} \boxed{\frac{\epsilon_{B_s \to \phi\gamma}}{\epsilon_{B^0 \to K^{*0}\gamma}}}$$

- From fit to the data
- From PDG
- From LHCb measurement (arXiv:hep-ex/1111.2357v1)
- From simulation and data

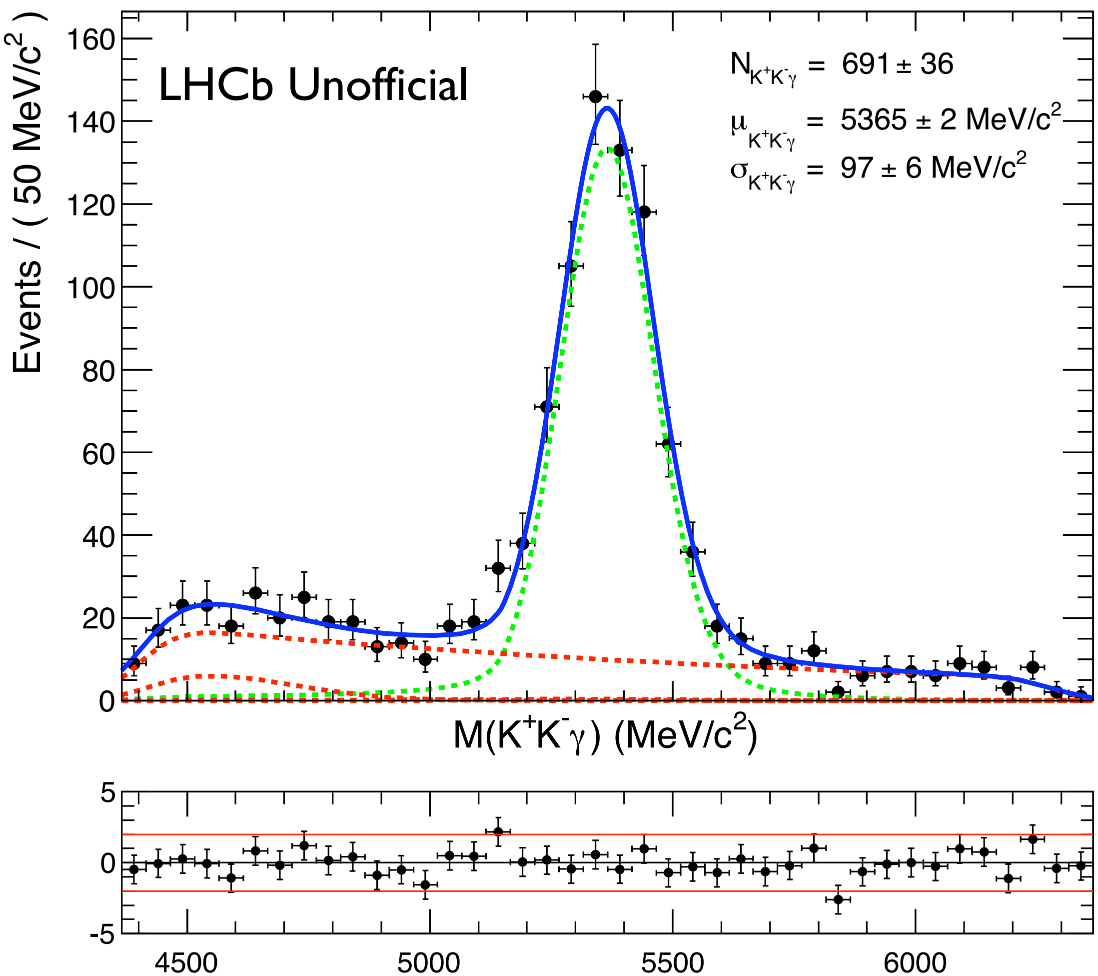
$B \to K^{*}\gamma$ in LHCb (1 fb^{-1})



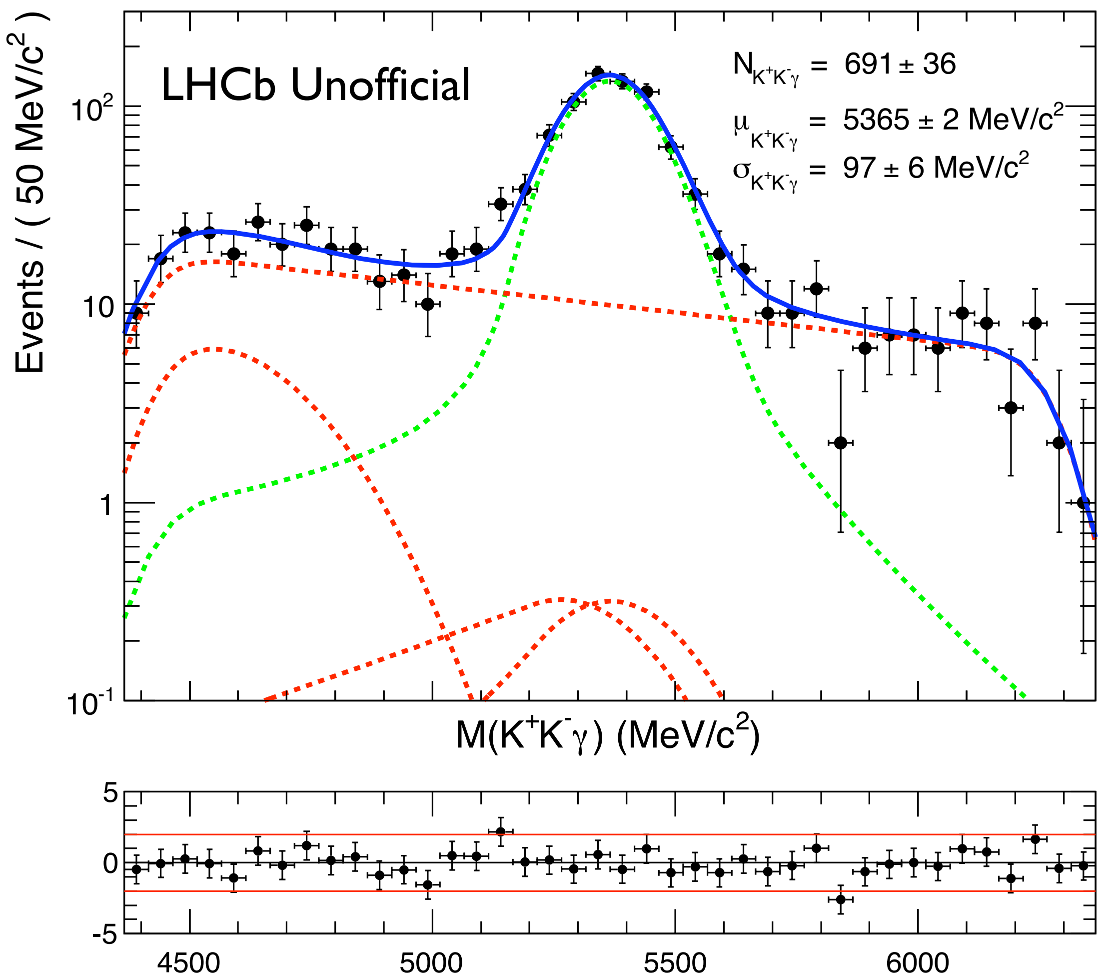
$B \to K^*\gamma$ in LHCb ($1\ fb^{-1}$)



$B_s \to \phi\gamma$ in LHCb (1 fb^{-1})



$B_s \to \phi\gamma$ in LHCb (1 fb^{-1})



Ratio of yields

- Extracted from the fit
- Systematical uncertainties
  - Signal shape parameters
  - Fixed background shapes and contaminations
  - Trigger acceptance function

Ratio of efficiencies

$$\frac{\epsilon^{B_s^0\to\phi\gamma}}{\epsilon^{B^0\to K^{*0}\gamma}} = \boxed{\frac{\epsilon^{B_s^0\to\phi\gamma}_{\mathrm{Trigger}}}{\epsilon^{B^0\to K^{*0}\gamma}_{\mathrm{Trigger}}} \times \frac{\epsilon^{B_s^0\to\phi\gamma}_{\mathrm{Acceptance}}}{\epsilon^{B^0\to K^{*0}\gamma}_{\mathrm{Acceptance}}} \times \frac{\epsilon^{B_s^0\to\phi\gamma}_{\mathrm{Reco\&SelNoPID}}}{\epsilon^{B^0\to K^{*0}\gamma}_{\mathrm{Reco\&SelNoPID}}}} \times \boxed{\frac{\epsilon^{B_s^0\to\phi\gamma}_{\mathrm{PID}}}{\epsilon^{B^0\to K^{*0}\gamma}_{\mathrm{PID}}}}$$

- From MC / data
- Systematics
  - MC sample size
  - Differences between MC/data and the two channels
  - Data-driven PID calibration method

First LHCb measurement

- First measurement

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.31 \pm 0.08\,(\mathrm{stat}) \pm 0.04\,(\mathrm{syst}) \pm 0.10\,(f_s/f_d)$$

$$\mathcal{B}(B_s^0 \to \phi\gamma) = (3.3 \pm 0.3) \times 10^{-5}$$

World best measurement!

- Compatible with previous result from Belle but with lower uncertainty

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

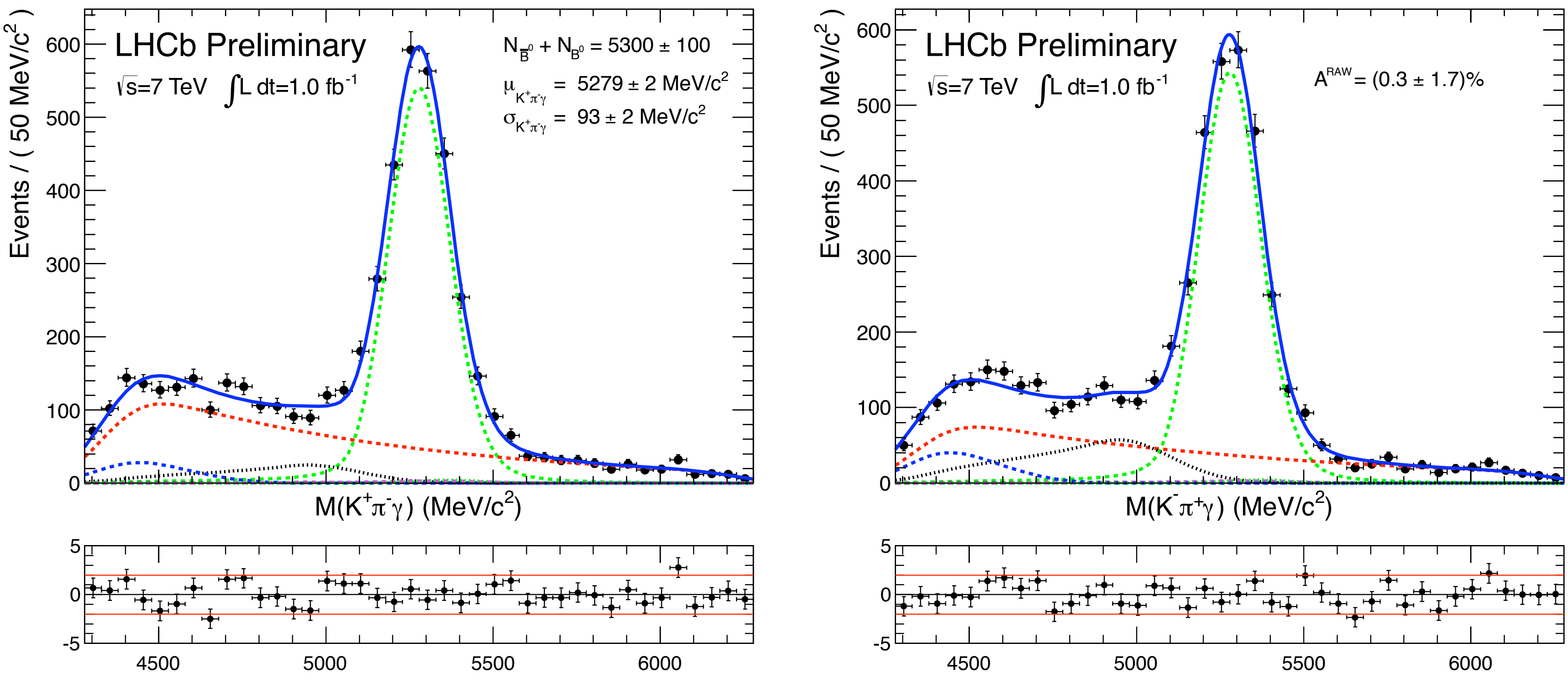
A_{CP} in $B \to K^{*}\gamma$

$$A_{CP} = A^{raw}(B^0 \to K^{*0}\gamma) - A_D(K\pi) - \kappa A_P(B^0)$$

κ: dilution factor due to oscillation

- A^{raw} is extracted from fit
  - Simultaneous fit of the two flavors B^0 and $\bar{B}^0$
  - Observables: sum of yields and CP asymmetry
- A_P and A_D extracted from $B \to hh$
- κ calculated from sPlotted data

Raw asymmetry



$$A_{\mathrm{CP}}^{\mathrm{raw}} = 0.003 \pm 0.017\,(\mathrm{stat})$$

Systematics

- From the fit model
  - Background shape and contamination
  - CP asymmetry of background
- Magnet polarity

A_{CP} in $B \to K^{*}\gamma$

- Putting all the results together we obtain

$$A_{\mathrm{CP}}^{\mathrm{raw}} = 0.003 \pm 0.017\,(\mathrm{stat}) \pm 0.009\,(\mathrm{syst})$$

- This result improves by 18% the most precise measurement up-to-date
- Compatible with the SM prediction

Prospects

- Short-term
  - Direct CP asymmetries
    - $B^+ \to K^{*0}\pi^+\gamma$
    - $B^+ \to \phi K^+\gamma$
  - Lambda baryon observation
- Longer term
  - Photon polarization
  - Isospin asymmetry in $B^0 \to K^{*0}\gamma$

Summary

- Radiative B decays are sensitive probes to NP
- While BRs are difficult to predict theoretically, there is plenty of NP-sensitive observables
- The first results from LHCb have largely improved the previous results
- Many interesting prospects

Exciting times ahead!