Beauty 2014
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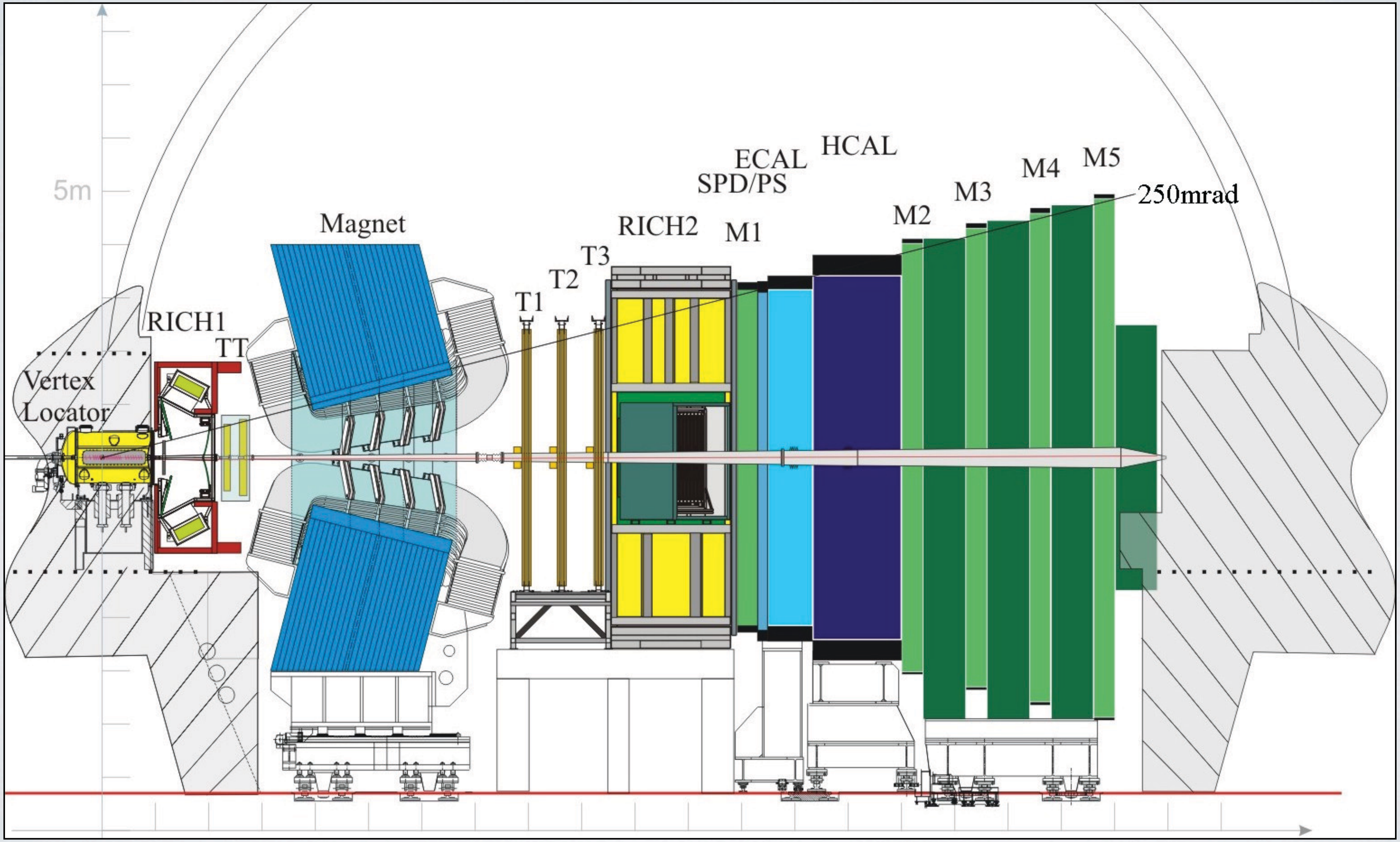
Radiative electroweak penguins at LHCb

Albert Puig (EPFL)
on behalf of the LHCb collaboration

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

The LHCb experiment

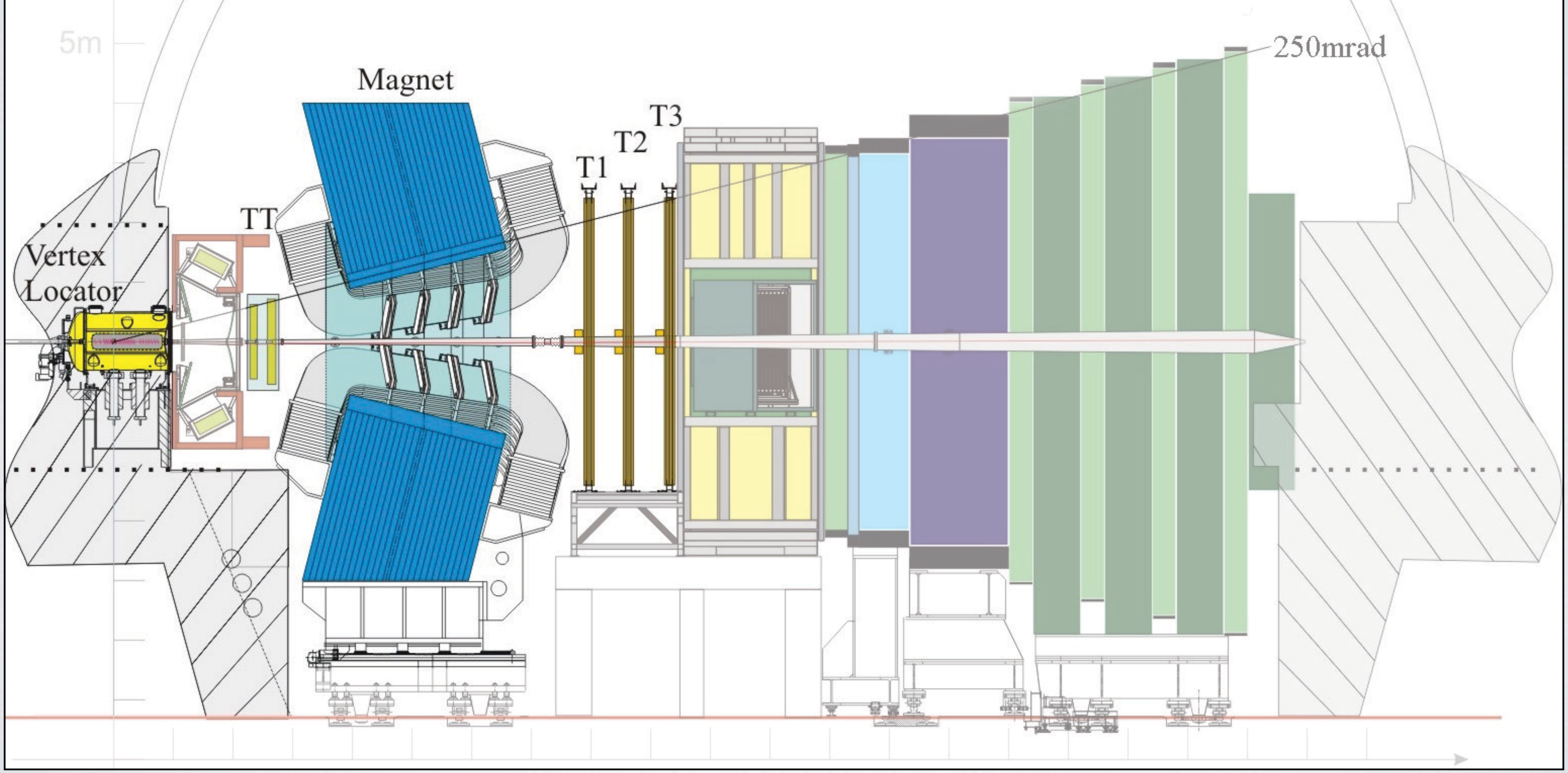


The LHCb experiment

Precise tracking

Good momentum ($\Delta p/p$~0.4% at 5GeV) resolution

Good IP (20μm for high-p_T tracks) and decay time (~45fs) resolution



The LHCb experiment

Excellent particle identification

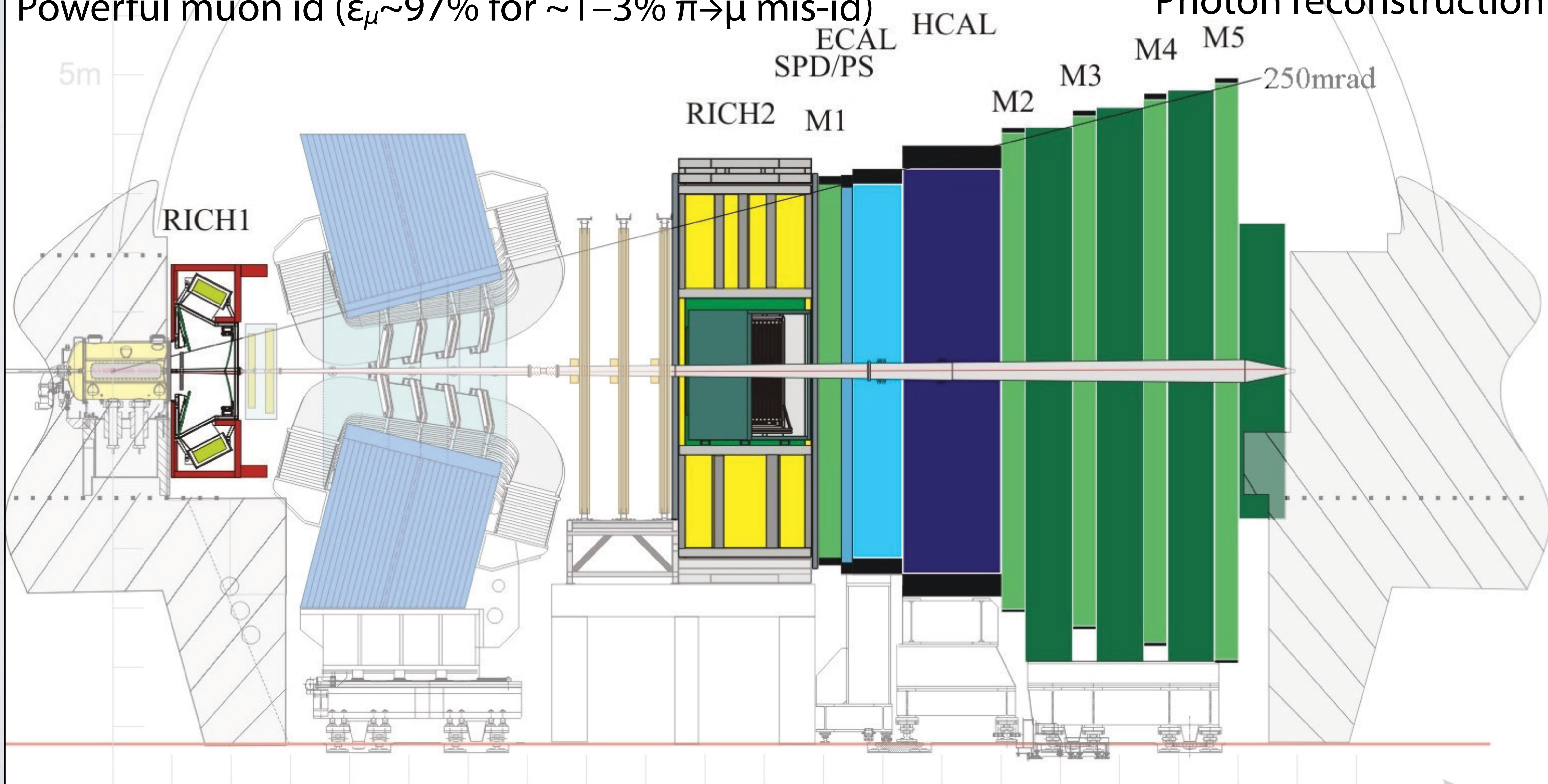
π/K separation over 2-100 GeV (ε_K~90% for ~5% $\pi \rightarrow$K mis-id)

Powerful muon id (ε_μ~97% for ~1–3% $\pi \rightarrow \mu$ mis-id)

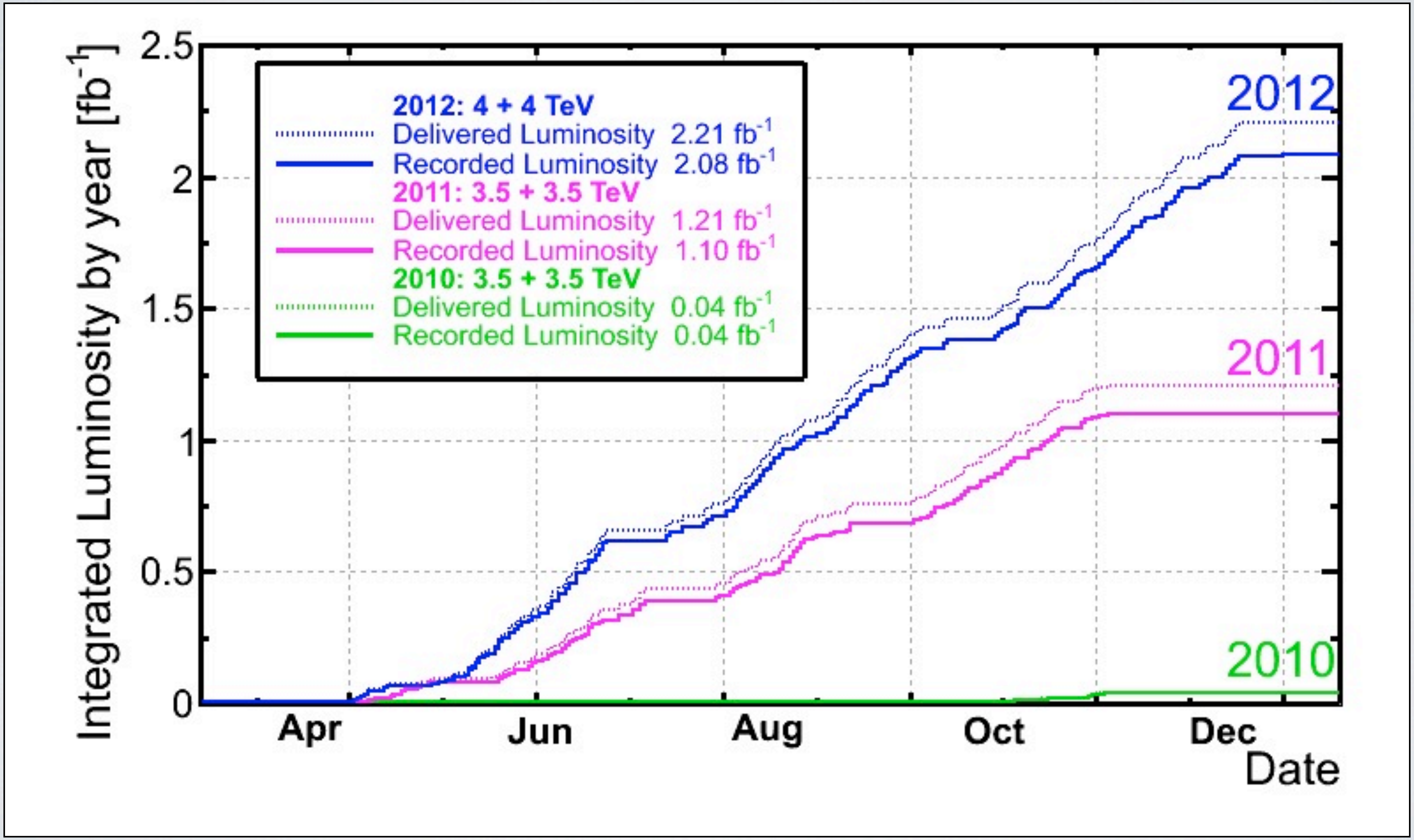
Calorimeter system

Trigger

Photon reconstruction

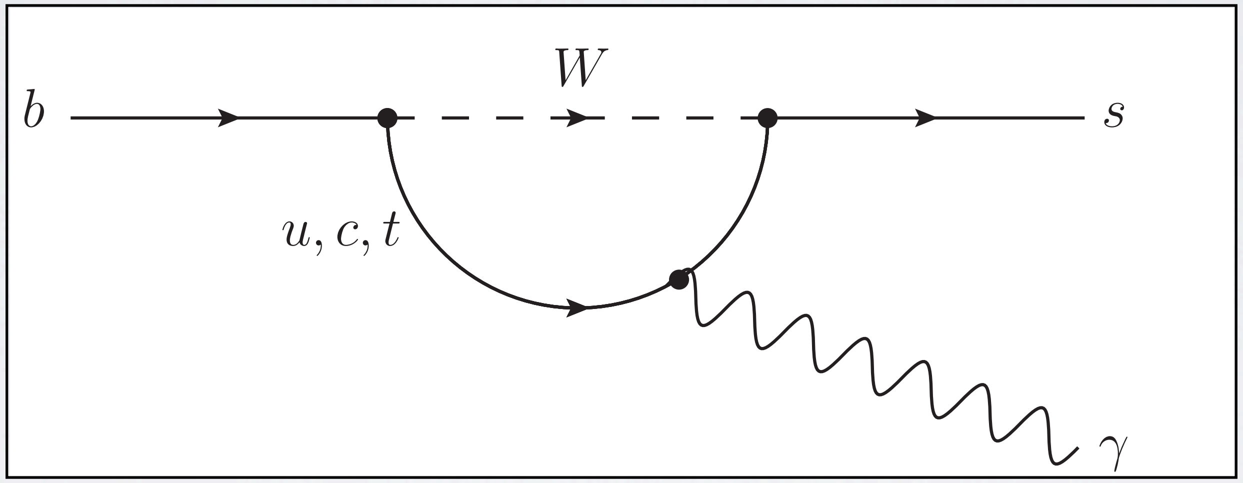


LHCb Run-I summary



Radiative *B* decays

- In the SM, effective FCNC are introduced by penguin (1-loop) diagrams, so they are a sensitive probe to new physics



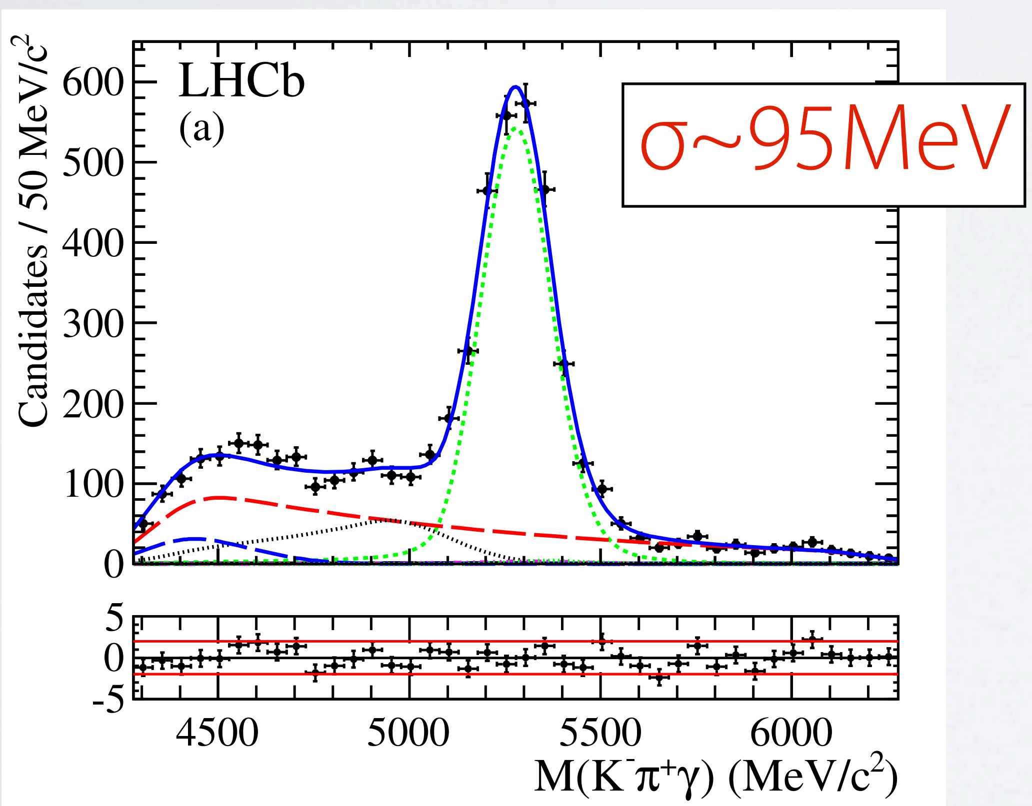
- Exclusive decays have large theoretical uncertainties
  - Find form-factor free observables (*CP* and isospin asymmetries)

- Photon polarization as test of the SM

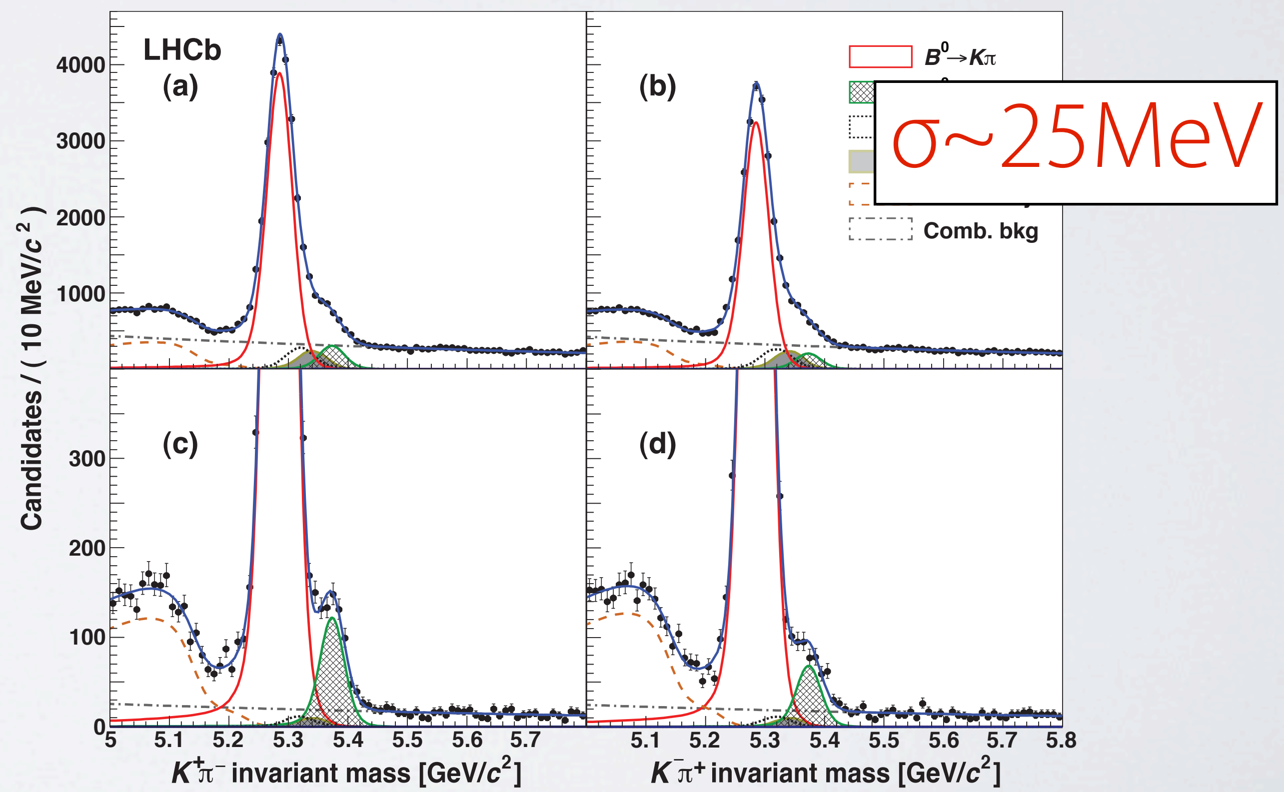
Challenges for radiative decays

- Distinct experimental signature with a high E_T photon
  - Large levels of background are expected in a *pp* machine

- Mass resolution dominated by photon reconstruction



[Nucl. Phys. B 867 (2012)]



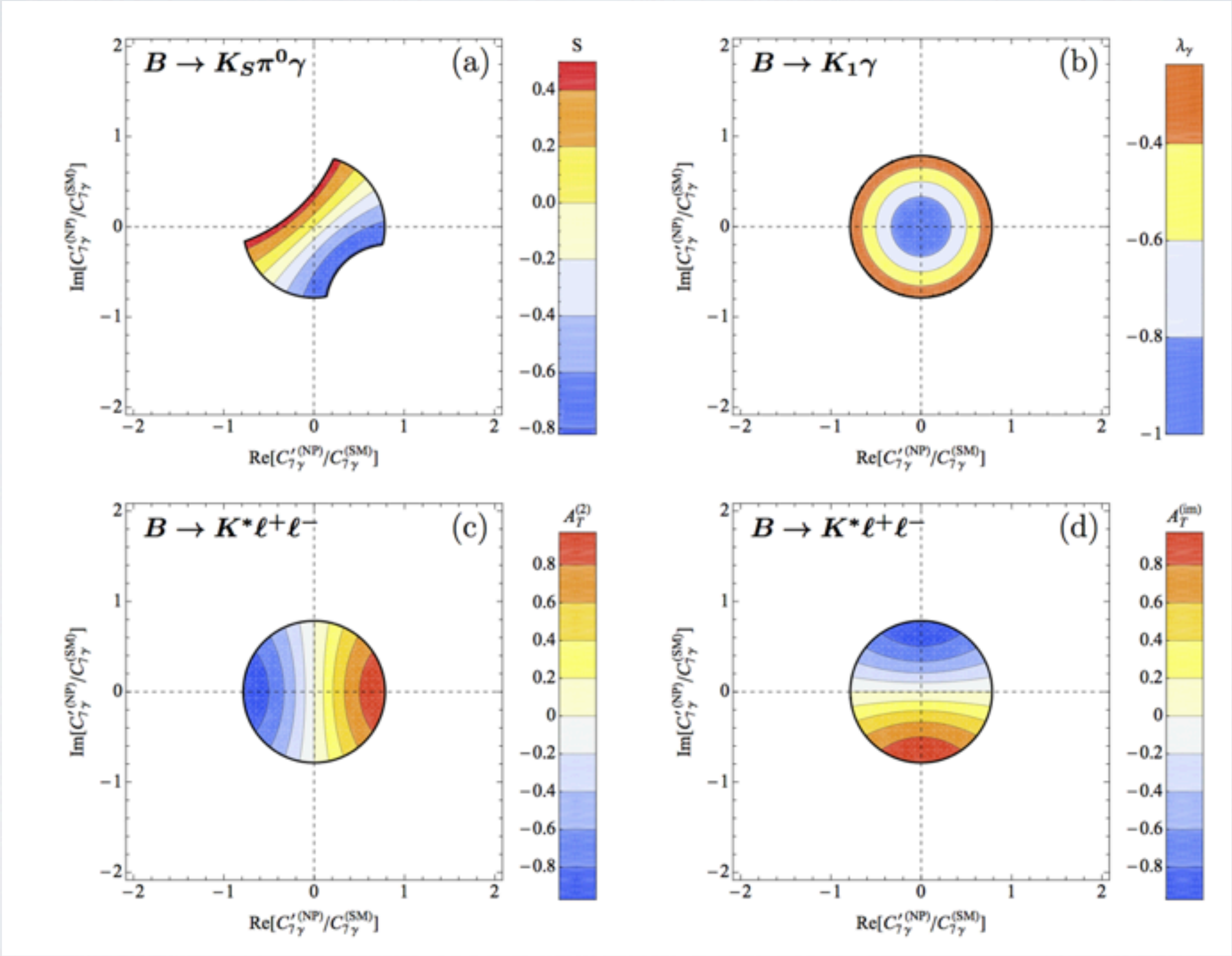
[PRL 110 (2013) 221601]

Measuring the γ polarization

- Time-dependent analyses of $B_{(s)}\to f^{CP}\gamma$, *e.g.*, $B_s\to\varphi\gamma$ and $B^0\to K_S\pi^0\gamma$
- Transverse asymmetry in $B^0\to K^*l^+l^-$ (see C. Langenbruch's talk)
- Angular distribution of radiative decays with 3 charged tracks in the final state, *e.g.*, $B\to K\pi\pi\gamma$
- *b*-baryons: $\Lambda_b\to\Lambda^{(*)}\gamma$, $\Xi_b\to\Xi^{(*)}\gamma$

Complementary approaches

[Bečirević et al (JHEP08 (2012) 090)]



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Photon polarization in $B \to K_{res}\gamma$

- If we consider $B \to K^{(i)}_{\rm res}\gamma$ we can define the **photon polarization** as

$c^{(i)}_{L(R)} \equiv A(B \to K^{(i)}_{\rm res}\gamma_{L(R)})$

weak amplitudes

$$\lambda^{(i)}_\gamma = \frac{|c^{(i)}_R|^2 - |c^{(i)}_L|^2}{|c^{(i)}_R|^2 + |c^{(i)}_L|^2}$$

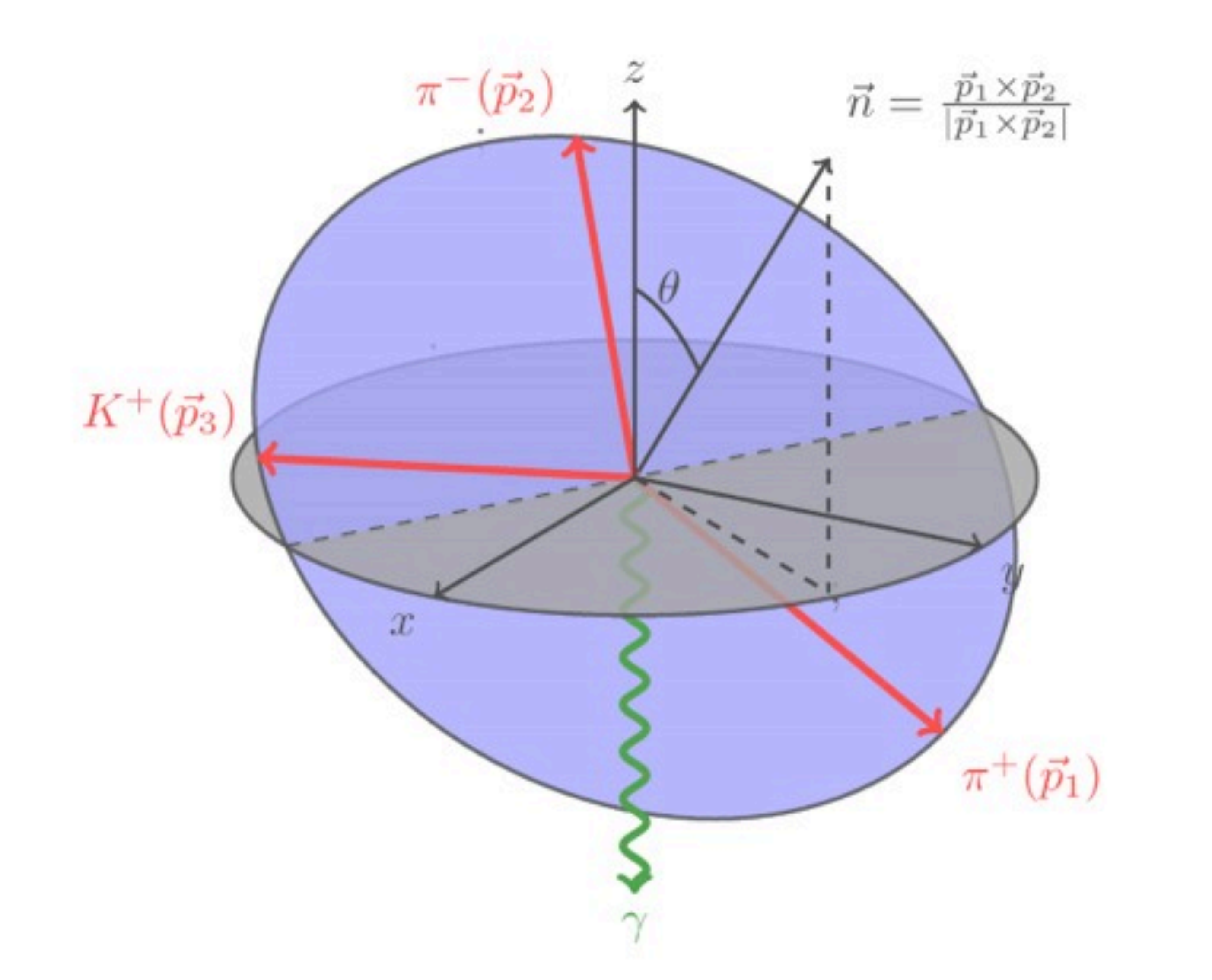
- It can be shown that the photon polarization is independent of the *K* resonance [Gronau et al (PRD 66 054008)]

$$\frac{|c^{(i)}_R|}{|c^{(i)}_L|} = \frac{|C_{7R}|}{|C_{7L}|} \Rightarrow \lambda^{(i)}_\gamma = \frac{|C_{7R}|^2 - |C_{7L}|^2}{|C_{7R}|^2 + |C_{7L}|^2} \equiv \lambda_\gamma$$

+1 for $\bar{b}$ and -1 for b

Angular distribution in *B→Kππγ*

- The photon polarization can be inferred from the polarization of the *K*



[Kou et al (PRD 83 094007)]

Angular distribution in $B \to K\pi\pi\gamma$

- The amplitude of one K resonance decay can be described by the helicity amplitude J_μ

polarization vector

contains all amplitude information

$$A^{(i)}_{L(R)}(s, s_{13}, s_{23}, \cos\theta) = \epsilon^{\mu}_{K,L(R)} \mathcal{J}_\mu$$

- Considering only **one** (1^+) intermediate resonance [Kou et al] [Gronau et al]

$$\frac{\mathrm{d}\Gamma(B \to K_{\mathrm{res}}\gamma \to K\pi\pi\gamma)}{\mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{dcos}\,\theta} \propto \frac{1}{4}|\vec{\mathcal{J}}|^2(1+\cos^2\theta) + \lambda_\gamma \frac{1}{2}\cos\theta\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)\right]$$

But life is not so beautiful

- Interference between 1^+, 1^-, 2^+ resonances [Gronau et al]

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{dcos}\,\theta} = |A|^2\left\{\frac{1}{4}|\vec{\mathcal{J}}|^2(1+\cos^2\theta)+\frac{1}{2}\lambda_\gamma\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)\right]\cos\theta\right\}+$$
$$+|B|^2\left\{\frac{1}{4}|\vec{\mathcal{K}}|^2(\cos^2\theta+\cos^2 2\theta)+\frac{1}{2}\lambda_\gamma\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathcal{K}}\times\vec{\mathcal{K}}^*)\right]\cos\theta\cos 2\theta\right\}+|C|^2\frac{1}{2}\sin^2\theta+$$
$$+\left\{\frac{1}{2}(3\cos^2\theta-1)\mathrm{Im}\left[AB^*\,\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{K}}^*)\right]+\lambda_\gamma\,\mathrm{Re}\left[AB^*\,\vec{n}\cdot(\vec{\mathcal{J}}\cdot\vec{\mathcal{K}}^*)\right]\cos^3\theta\right\}$$

need to know *J* and *K*!

- But λ_γ goes with odd powers of cosθ

$$\frac{\mathrm{d}\Gamma(\sum B\to K_{\mathrm{res}}\gamma\to P_1P_2P_3\gamma)}{\mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{dcos}\,\theta}\propto\sum_{j=\mathrm{even}}a_j(s_{13},s_{23})\,\cos^j\theta+\lambda_\gamma\sum_{j=\mathrm{odd}}a_j(s_{13},s_{23})\,\cos^j\theta$$

Up-down asymmetry

- We can exploit the structure of the decay rate and define the up-down asymmetry

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

where C takes into account the integral over the Dalitz plot and the angular distribution

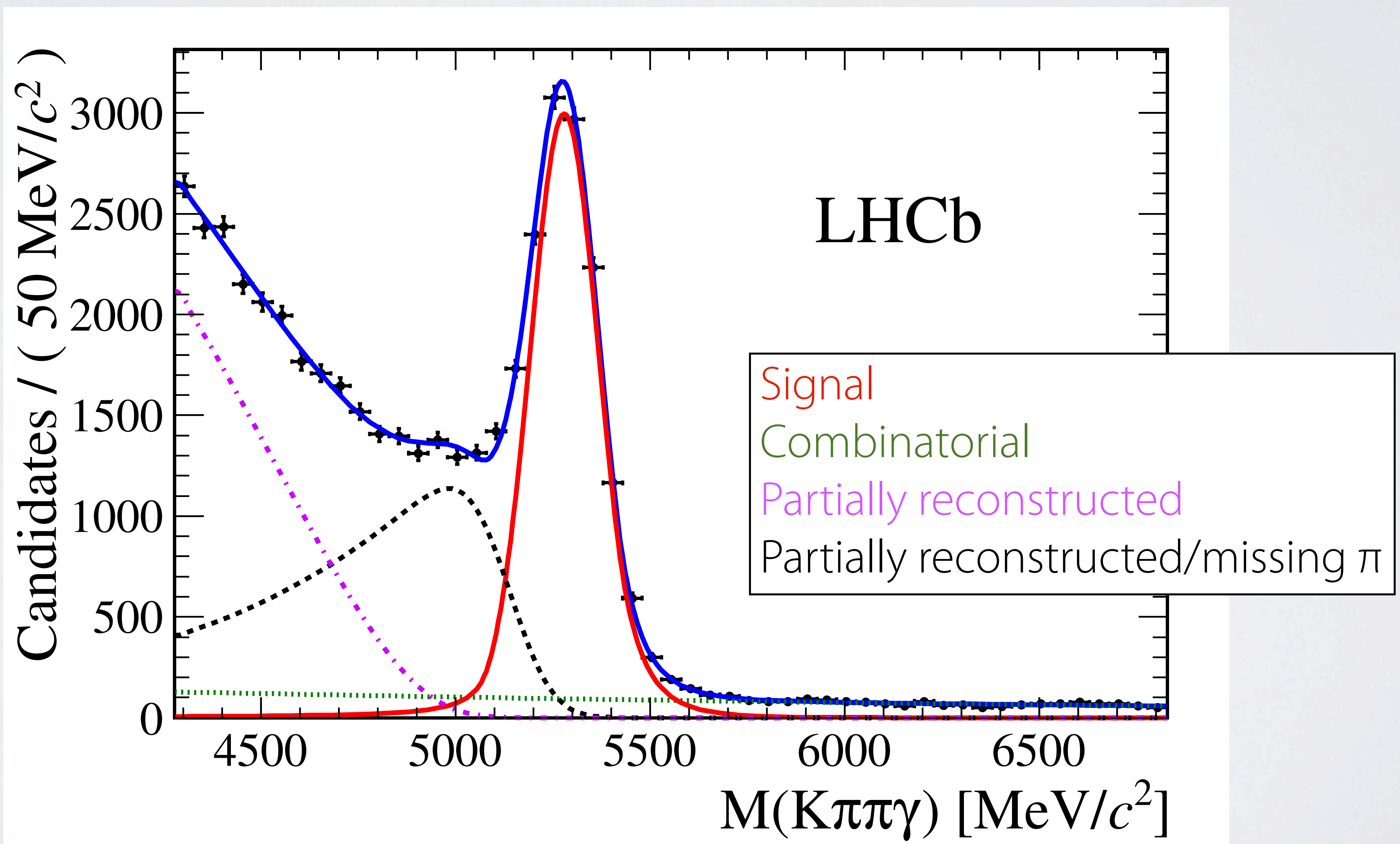
$B^{\pm}\to K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$ at LHCb

- In LHCb we have studied the charged mode $B^{+}\to K^{+}\pi^{-}\pi^{+}\gamma$ (and charge conjugate)
  - Inclusive study with $K\pi\pi$ system mass in the [1.1, 1.9] GeV/c^2 range
- Analysis performed using the full data set recorded by LHCb in 2011 and 2012, corresponding to 3/fb
- Study of angular distributions and determination of up-down asymmetries

PRL 112, 161801 (2014)

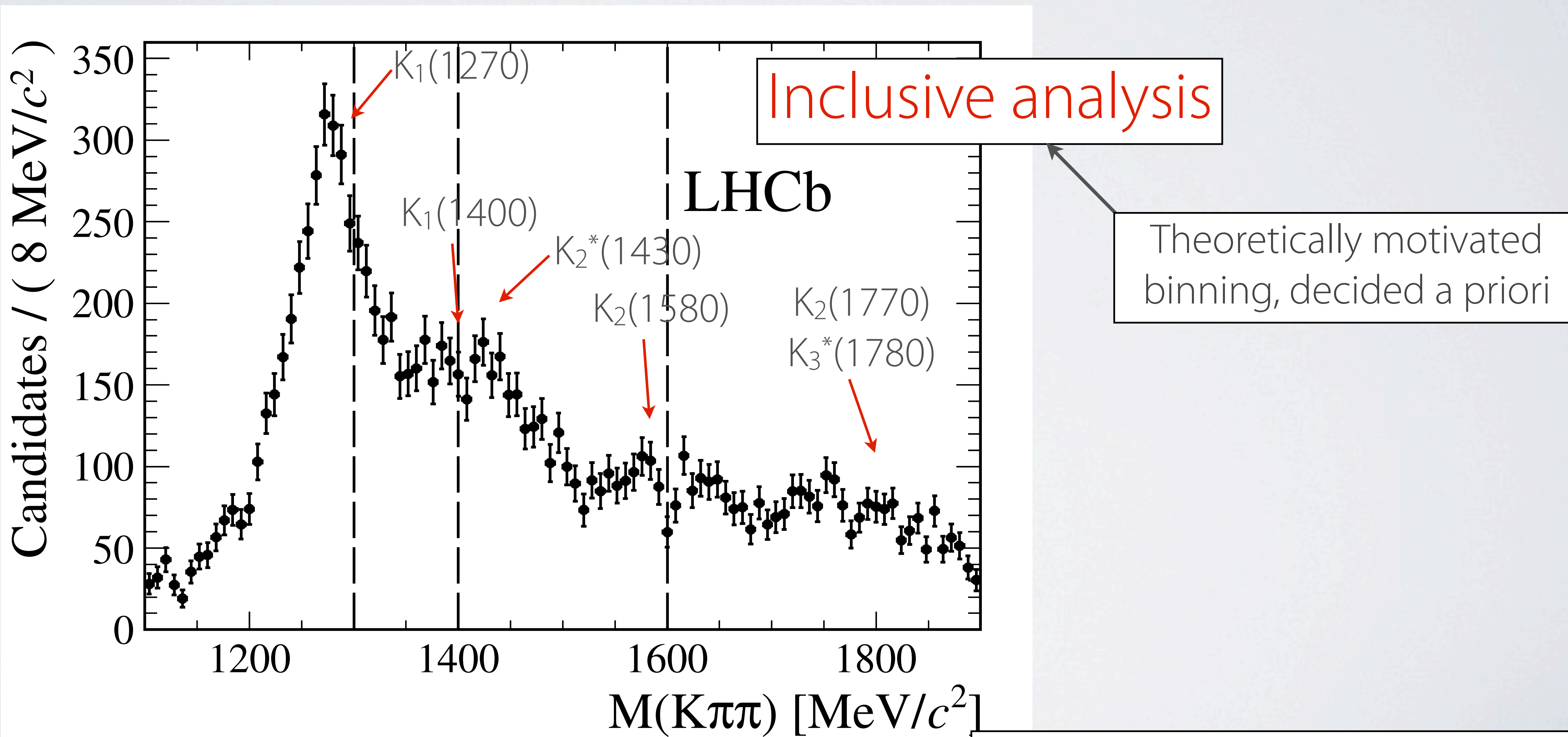
Mass distribution

- Observe 13876±153 signal events in the [1.1,1.9] GeV/c^2 $K\pi\pi$ mass region



Background-subtracted *Kππ* mass spectrum

- Many (unclear) contributions in the *Kππ* mass spectrum, impossible to separate without full amplitude analysis



PRL 112, 161801 (2014)

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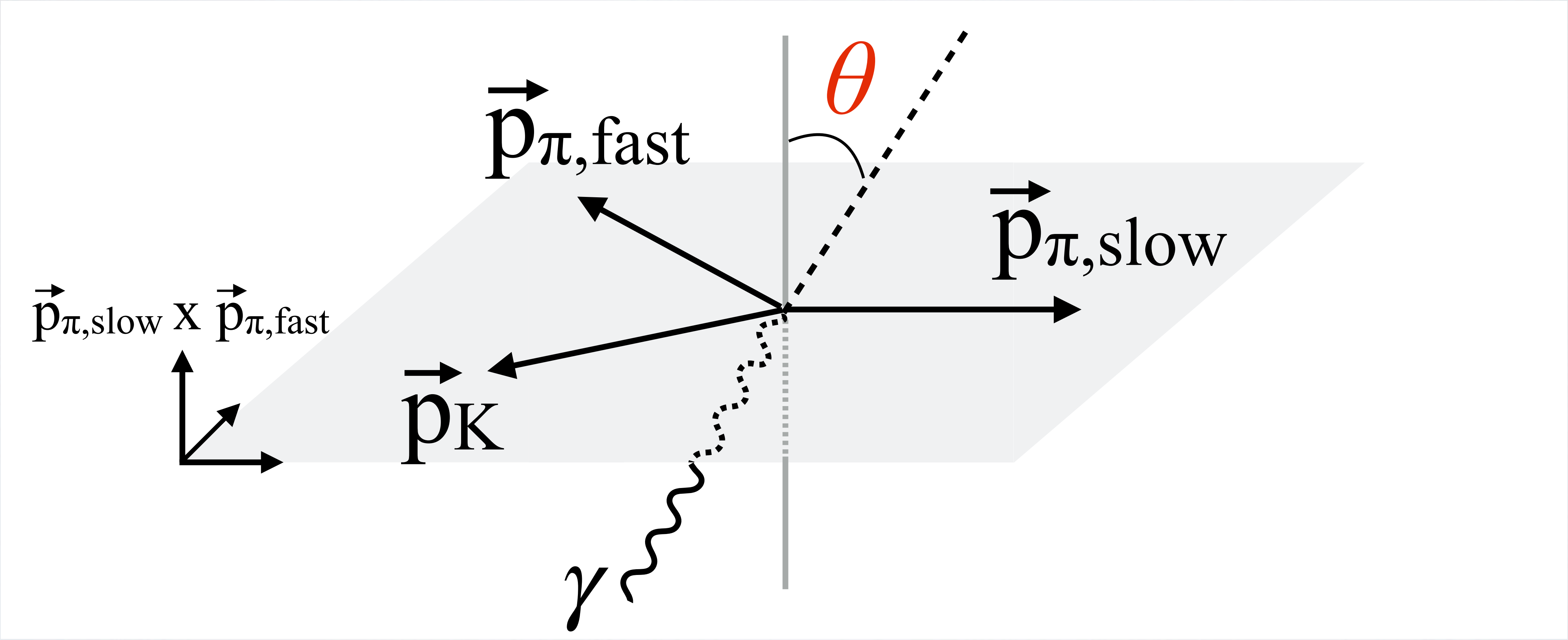
Reminder: angle definition



PRL 112, 161801 (2014)

Angular fit

- Angular distributions for each region are fitted with a combination of Legendre polynomials up to order 4

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

Legendre coefficients

- A χ^2 fit is performed taking into account the full statistical and systematic covariance matrices

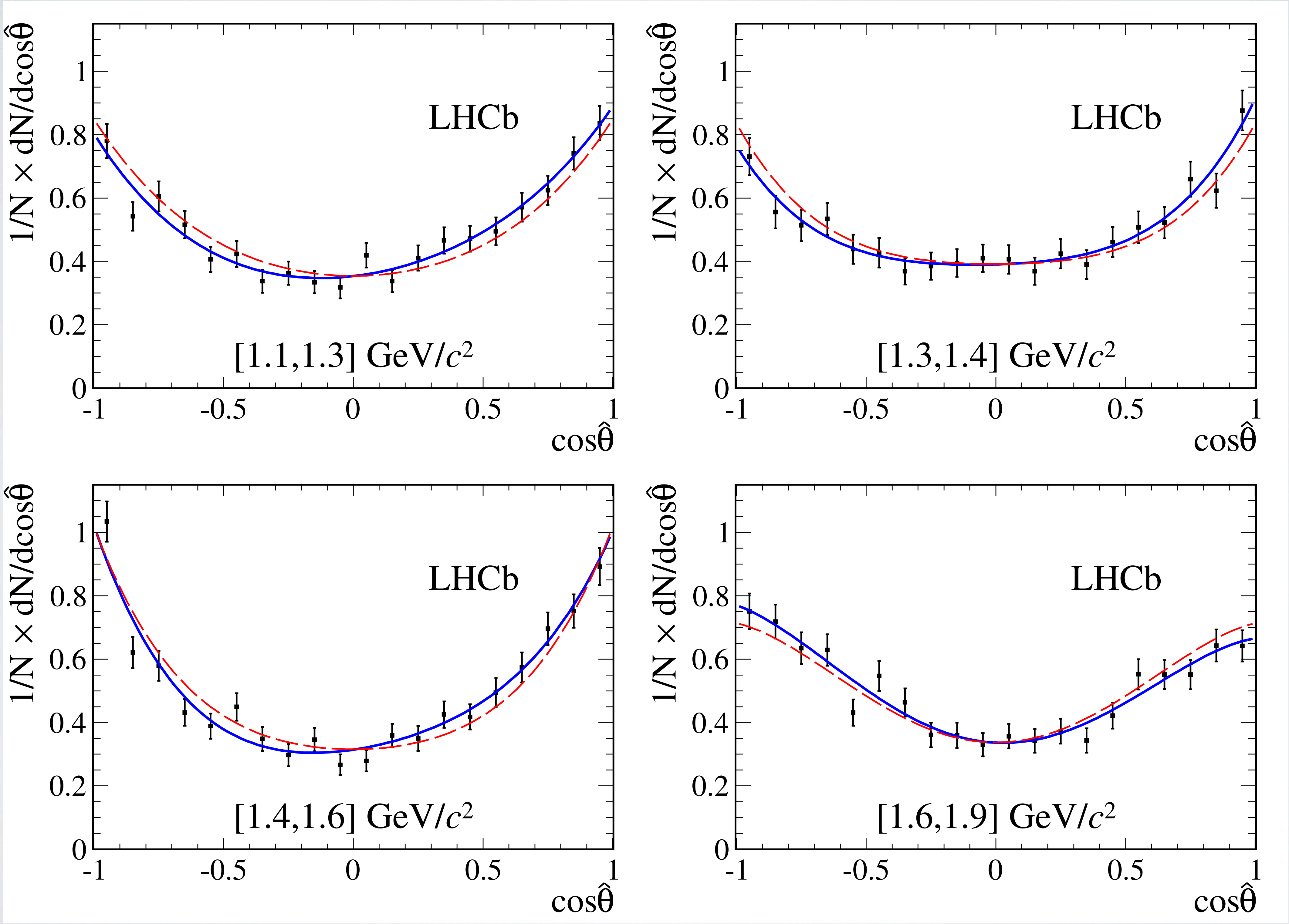
- The up-down asymmetry is determined with the relation

$$\mathcal{A}_{ud} = \frac{c_1 - c_3/4}{2c_0}$$

Nominal fit
No odd components

PRL 112, 161801 (2014)

Angular fit results



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Angular fit coefficients

- The coefficients of the angular fit are obtained for each of the four $K\pi\pi$ mass regions (stat. and syst. uncertainties combined)

(x10[-2])

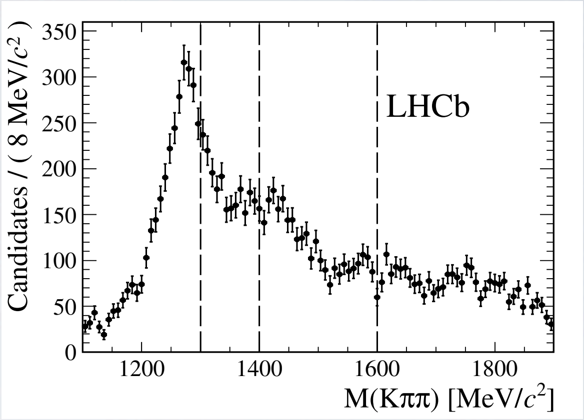
	$[1.1, 1.3]$	$[1.3, 1.4]$	$[1.4, 1.6]$	$[1.6, 1.9]$
c_1	6.3 ± 1.7	5.4 ± 2.0	4.3 ± 1.9	-4.6 ± 1.8
c_2	31.6 ± 2.2	27.0 ± 2.6	43.1 ± 2.3	28.0 ± 2.3
c_3	-2.1 ± 2.6	2.0 ± 3.1	-5.2 ± 2.8	-0.6 ± 2.7
c_4	3.0 ± 3.0	6.8 ± 3.6	8.1 ± 3.1	-6.2 ± 3.2
$\mathcal{A}_{\mathrm{UD}}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ±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

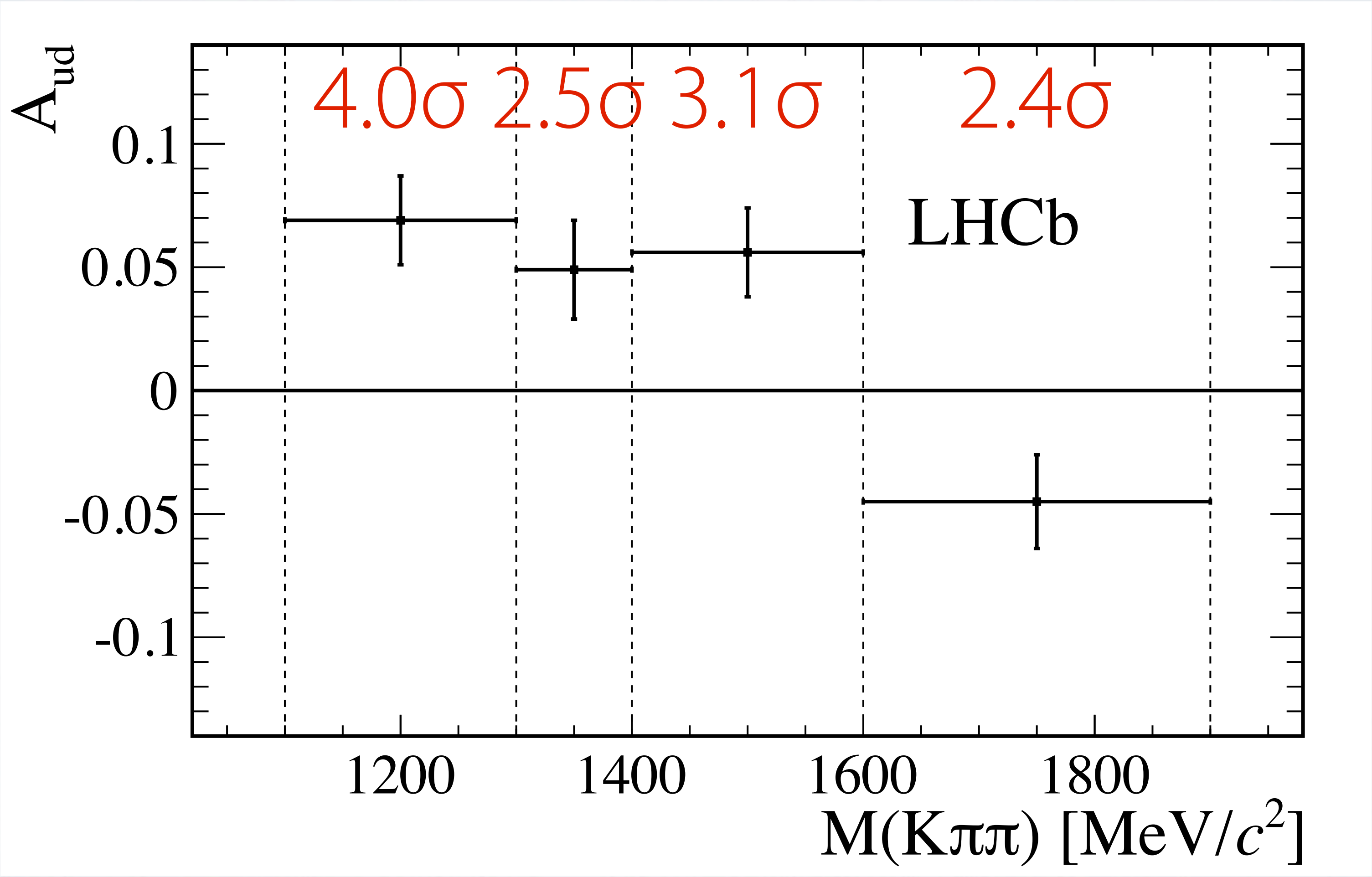
- We expect that these results prove to be a useful input for theorists (also provide correlation matrices)

PRL 112, 161801 (2014)

Up-down asymmetry results

- Four independent up-down asymmetries are obtained (stat. and syst. uncertainties combined)





PRL 112, 161801 (2014)

A_{UD} significance

- Use the four independent up-down asymmetries to extract a combined significance with respect to the no-polarization scenario
- Up-down asymmetry is different from zero at 5.2σ

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First observation of photon polarization in $b \to s\gamma$ transitions!

Conclusions

- LHCb has studied the $B^+ \to K^+\pi^-\pi^+\gamma$ decay with its full available statistics of 3/fb
- The angular distribution of the photon with respect to the plane defined by the final state hadrons has been characterized for different regions of their invariant mass
  - Cannot extract photon polarization without further input
  - Aim to provide a valuable input for theorists
- Photon polarization has been observed for the first time in $b \to s\gamma$ transitions

What about the future?

- LHCb can (and will) continue the study of the photon polarization through other paths
  - Full amplitude analysis of the $B^+ \to K^+\pi^-\pi^+\gamma$ decay
  - Proper time distribution of $B_s \to \varphi\gamma$
  - Angular distribution in $B^0 \to K^*e^+e^-$, already observed by LHCb [JHEP05(2013)159], to be updated soon
  - Angular distribution in $B^+ \to \varphi K^+\gamma$
  - Radiative *b*-baryon decays: $\Lambda_b \to \Lambda^{(*)}\gamma$, $\Xi_b \to \Xi^{(*)}\gamma$

Seen by LHCb! [Nucl. Phys. B 867 (2012)]

And remember, watch out for the penguins!

Thank you

Backup

Rare *B* decays

- FCNC with *ΔF*=1 are forbidden at tree level in the SM, so they proceed through loop (box, penguin) diagrams
  - In extensions of the SM, these loop processes may receive contributions from new virtual particles

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + h.c.$$

NP may modify the Wilson Coefficients

- Rare decays can be used for indirect searches of New Physics
  - Highly suppressed in the SM
  - Highly sensitive to NP effects

Radiative B decays

- Rare penguin FCNC transitions with a final-state (real) photon
- Discovered by CLEO in 1993 (PRL 71.674)

VOLUME 71, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1993

Evidence for Penguin-Diagram Decays: First Observation of $B \to K^*(892)\gamma$

- Studied extensively by CLEO, BaBar, Belle and LHCb

HFAG BRs for B^0

RPP#	Mode	PDG2012 Avg.	BABAR	Belle	CLEO	CDF	LHCb	New Avg.
310	$K^0\eta\gamma$	7.6 ± 1.8	$7.1^{+2.1}_{-2.0} \pm 0.4$	$8.7^{+3.1+1.9}_{-2.7-1.6}$				$7.6^{+1.8}_{-1.7}$
311	$K^0\eta'\gamma$	< 6.4	< 6.6	< 6.4				< 6.4
312	$K^0\phi\gamma$	2.7 ± 0.7	< 2.7	$2.74 \pm 0.60 \pm 0.32$				2.74 ± 0.68
313	$K^+\pi^-\gamma$ §	4.6 ± 1.4		$4.6^{+1.3+0.5}_{-1.2-0.7}$				4.6 ± 1.4
314	$K^{*0}\gamma$	43.3 ± 1.5	$44.7 \pm 1.0 \pm 1.6$	$40.1 \pm 2.1 \pm 1.7$	$45.5^{+7.2}_{-6.8} \pm 3.4$			43.3 ± 1.5
315	$K^*(1410)^0\gamma$	< 130		< 130				< 130
316	$K^+\pi^-\gamma$ (N.R.) §	< 2.6		< 2.6				< 2.6
318	$K^0\pi^+\pi^-\gamma$	19.5 ± 2.2	$18.5 \pm 2.1 \pm 1.2$ †	$24 \pm 4 \pm 3$ ‡				19.5 ± 2.2
319	$K^+\pi^-\pi^0\gamma$	41 ± 4	$40.7 \pm 2.2 \pm 3.1$ †					40.7 ± 3.8
320	$K_1^0(1270)\gamma$	< 58		< 58				< 58
321	$K_1^0(1400)\gamma$	< 12		< 15				< 15
322	$K_2^*(1430)^0\gamma$	12.4 ± 2.4	$12.2 \pm 2.5 \pm 1.0$	$13 \pm 5 \pm 1$				12.4 ± 2.4
324	$K_3^*(1780)^0\gamma$	< 83		< 83				< 83
326	$\rho^0\gamma$	0.86 ± 0.15	$0.97^{+0.24}_{-0.22} \pm 0.06$	$0.78^{+0.17+0.09}_{-0.16-0.10}$	< 17			$0.86^{+0.15}_{-0.14}$
328	$\omega\gamma$	$0.44^{+0.18}_{-0.16}$	$0.50^{+0.27}_{-0.23} \pm 0.09$	$0.40^{+0.19}_{-0.17} \pm 0.13$	< 9.2			$0.44^{+0.18}_{-0.16}$
329	$\phi\gamma$	< 0.85	< 0.85		< 3.3			< 0.85

HFAG A_{CP}

314	$K^{*0}\gamma$	-0.16 ± 0.23	$-0.16 \pm 0.22 \pm 0.07$	$0.008 \pm 0.017 \pm 0.009$	0.007 ± 0.019

Photon polarization in the SM

- The chiral structure of the *b*→*sγ* process and the fact that the *W* couples only left-handedly causes the photons to be (almost completely) circularly polarized

$$\mathcal{O}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$

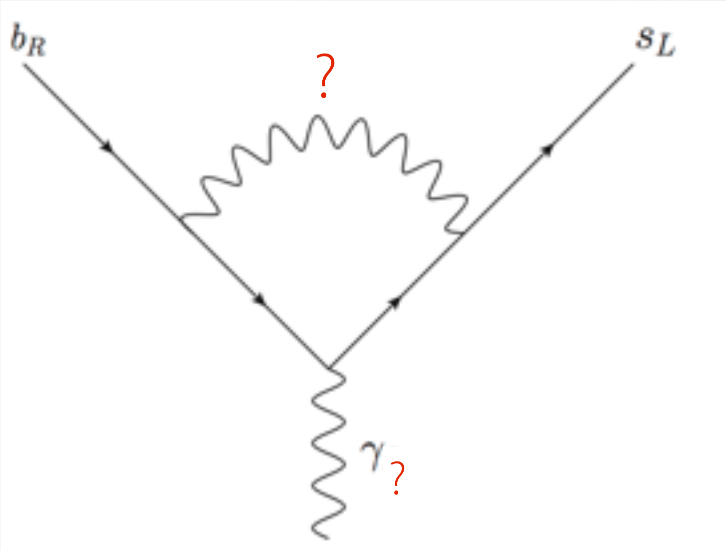
$$b \to s\gamma_L$$
$$\bar{b} \to \bar{s}\gamma_R$$

  - Never confirmed to high precision!

- QCD corrections coming from C_2 are expected to be in the 1-10% range [Bečirević et al]

And beyond the SM?

- Several NP models introduce right-handed currents
- New particles can change the chirality inside the loop, producing chiral enhancement
  - m_t/m_b from LRSM [Babu et al]
  - m_{SUSY}/m_b in SUSY with δ_{RL} mass insertions [Gabbiani et al]



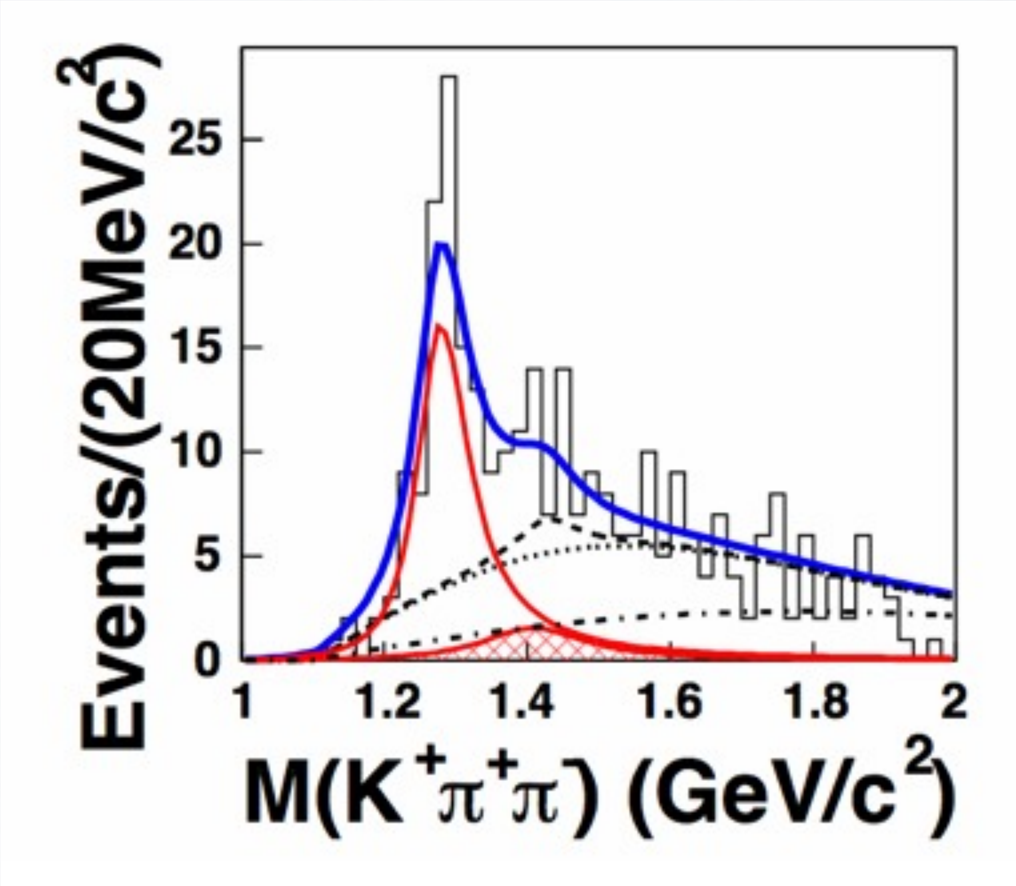
- Still "large" room for NP despite the constraints coming from B_s oscillation parameters, $B_s \to \mu\mu$...
  - New penguins around the corner?

$B \to K\pi\pi\gamma$ in Belle and BaBar

- Belle observed $B \to K_1(1270)^+\gamma$ and BaBar $B \to K_2^*(1430)^+\gamma$

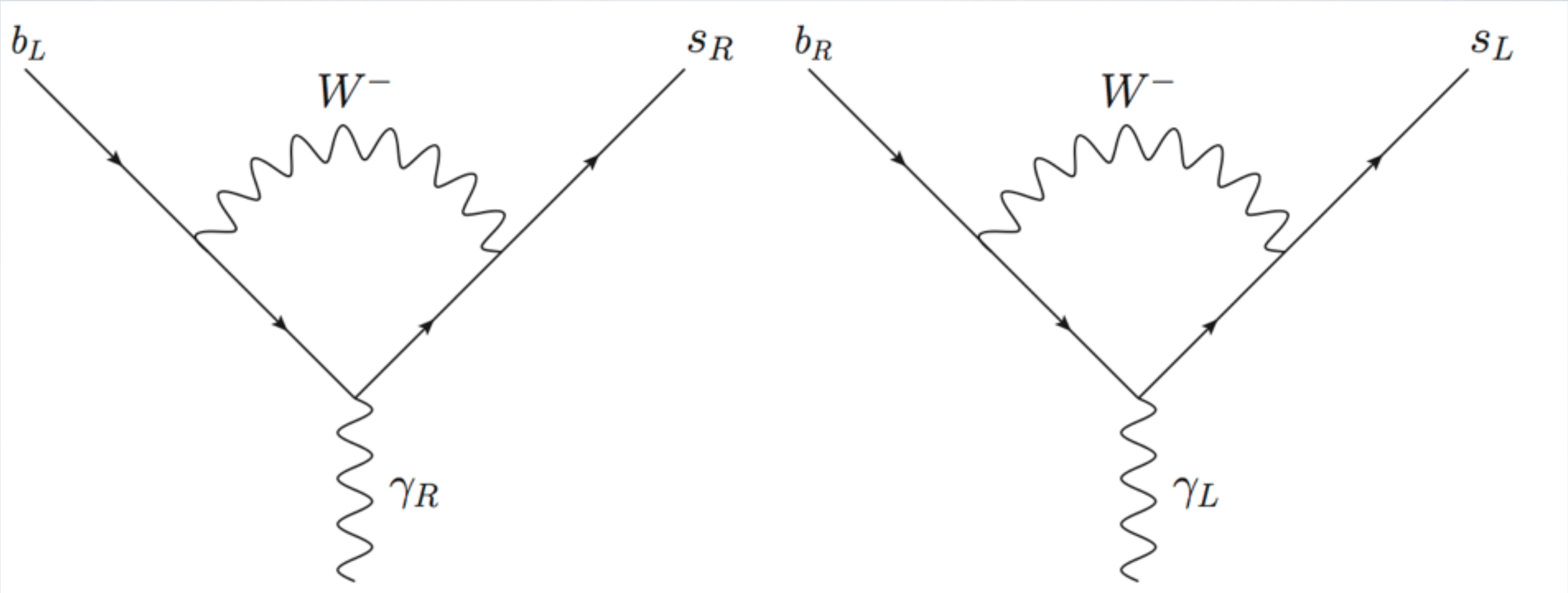
- Both BaBar and Belle have measured the inclusive BR

$K_1(1270)^+\gamma$	$(4.3 \pm 1.2) \times 10^{-5}$
$K_1(1400)^+\gamma$	$< 1.5 \times 10^{-5}$
$K_2^*(1430)^+\gamma$	$(1.45 \pm 0.43) \times 10^{-5}$
$K^+\pi^+\pi^-\gamma$	$(2.76 \pm 0.18) \times 10^{-5}$
$K^0\pi^+\pi^0\gamma$	$(4.5 \pm 0.52) \times 10^{-5}$



Belle, [Nishida et al] (2002)
Belle, [Yang et al] (2005)
BaBar, [Aubert et al] (2007)

Photon polarization in the SM



$m_s \bar{s}_R \sigma_{\mu\nu} q^\nu b_L$ $m_b \bar{s}_L \sigma_{\mu\nu} q^\nu b_R$

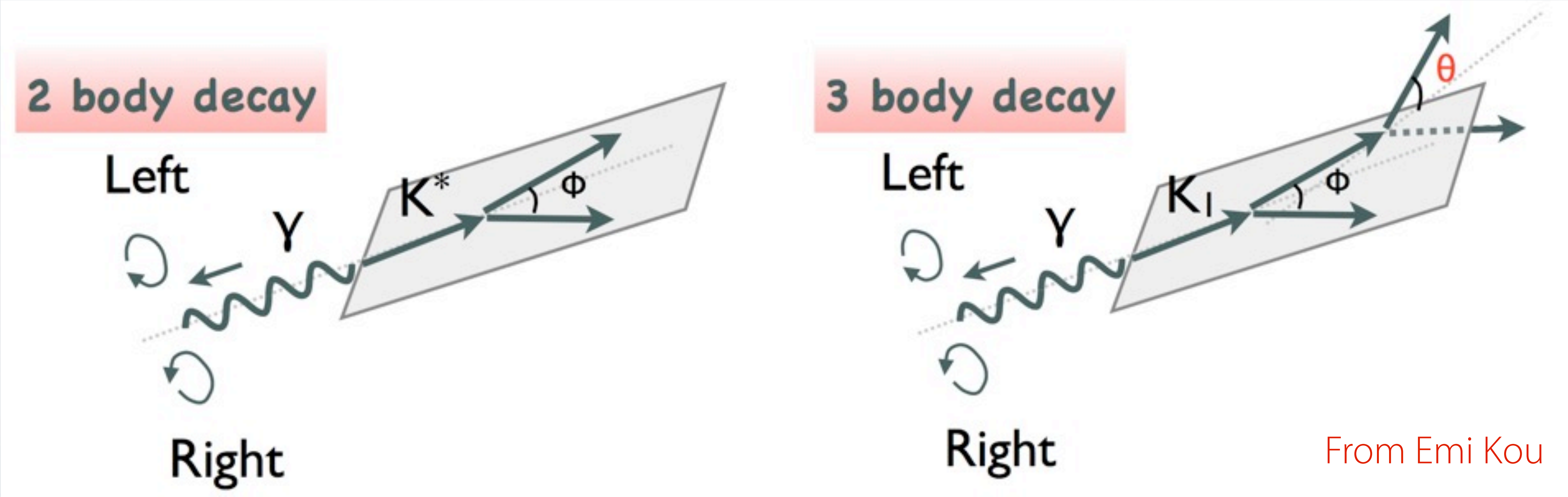
$$\frac{m_s}{m_b} \approx 0.02 \ll 1$$

Why 3 charged particles?

- Three tracks is the minimum needed to build a *P*-odd triple product proportional to the photon polarization using the final state momenta

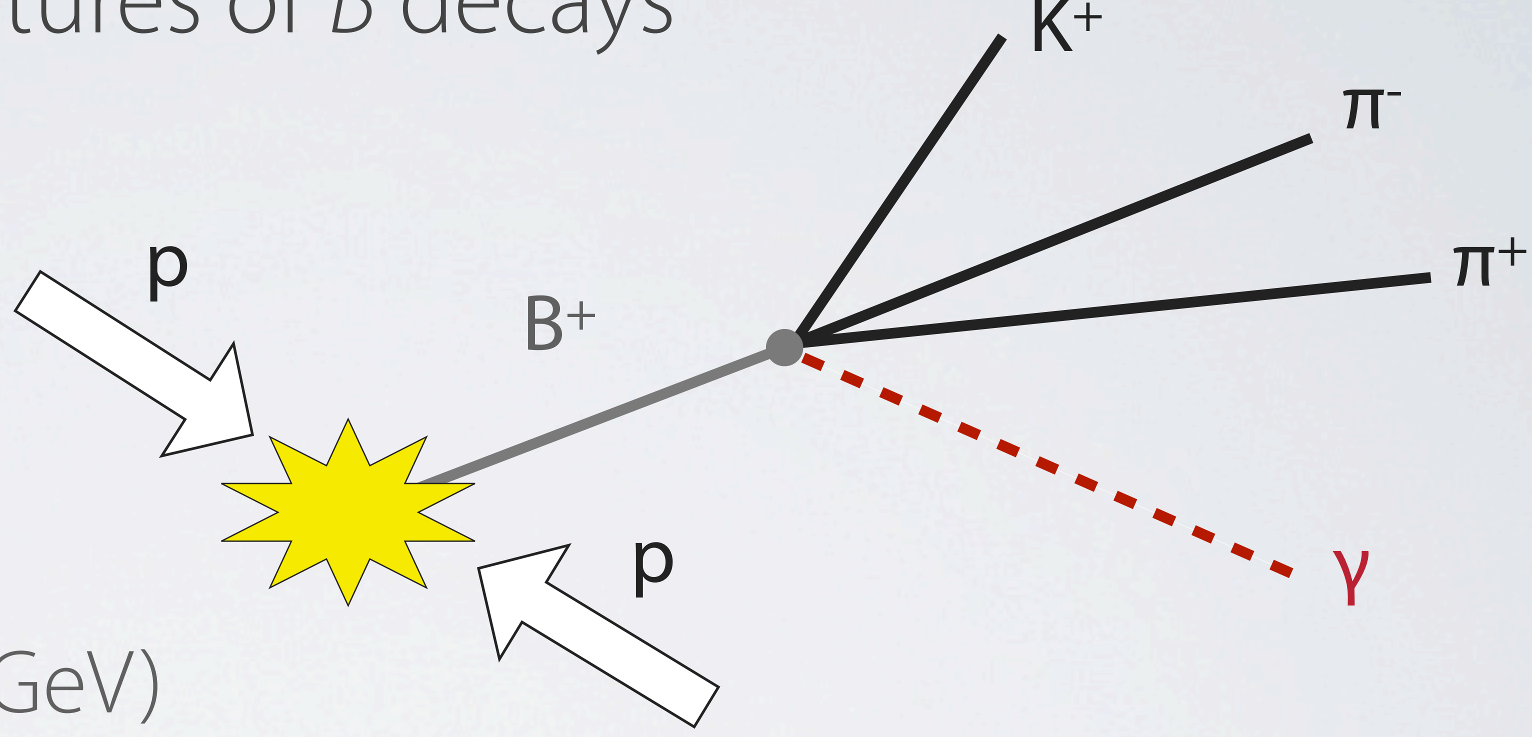
$$\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)$$

changes sign with photon helicity



Event selection

- Exploit the special features of *B* decays



- Selection criteria:
  - High E_T photon (>3.0 GeV)
  - Multivariate tool with kinematical variables
  - Charged particle identification
  - Photon identification (separation from charged e-m particles and other neutral e-m particles)

Backgrounds

- Combinatorial (exponential)
- Partially reconstructed background (Argus ⊗ Gaussian)
  - Missing π, $B \to K\pi\pi\eta(\to\gamma\gamma)$ (negligible) and general partial.
- Peaking backgrounds (suppressed with specific cuts)
  - $B^+ \to \overline{D}^0(\to K^+\pi^-\pi^0)\,\pi^+$, $B^+ \to \overline{D}^{*0}(\overline{D}^0(\to K^+\pi^-)\gamma)\pi^+$ and $B^+ \to K^{*+}(\to K^+\pi^0)\,\pi^+\,\pi^-$
- Contamination from neutral $B^0 \to K_1(1270)^0\gamma$ (negligible)
- Crossfeed from $B^+ \to \pi\pi\pi\gamma$ (suppressed with PID)

Backgrounds

included in mass fit

- Combinatorial (exponential)
- Partially reconstructed background (Argus ⊗ Gaussian)
  - Missing π, $B \to K\pi\pi\eta(\to\gamma\gamma)$ (negligible) and general partial.
- Peaking backgrounds (suppressed with specific cuts)
  - $B^+ \to \overline{D}^0(\to K^+\pi^-\pi^0)\,\pi^+$, $B^+ \to \overline{D}^{*0}(\overline{D}^0(\to K^+\pi^-)\gamma)\pi^+$ and $B^+ \to K^{*+}(\to K^+\pi^0)\,\pi^+\,\pi^-$
- Contamination from neutral $B^0 \to K_1(1270)^0\gamma$ (negligible)
- Crossfeed from $B^+ \to \pi\pi\pi\gamma$ (suppressed with PID)

negligible in mass fit

Mass fit

- Unbinned maximum likelihood fit to the invariant mass of the *B* candidates
- Simultaneously fit 2011 and 2012 to account for slightly different calorimeter performance
  - Share shape parameters except for the *B* mass resolution
  - Different background contamination
- Signal shape fixed from MC
- Background shapes partially fixed from MC
  - Free combinatorial and partially reconstructed background tail

Angle definition

- The sign of the λ_γ parameter changes with the charge of the *B* meson (positive for B^- and negative for B^+)

- When putting together the data, take the change of sign by taking into account the sign of the charge of the *B* candidate

$$\cos\hat{\theta} = \mathrm{sign}(\mathrm{charge}\, B^{\pm})\cos\theta$$

Angular distribution

- Angular distributions for each region of $K\pi\pi$ mass are obtained as a simultaneous fit of the mass of the B candidates in bins of $\cos\hat{\theta}$
  - Used 20 bins in the angular variable
  - All fit parameters shared
- Yields for each bin are corrected with the selection acceptance and then normalized to the total yield

Systematic uncertainties

- Effect of bin migration, evaluated with pseudo experiments
  - Use angle-dependent resolution
  - Determined as a covariance matrix between bins
- Fit model, evaluated by testing alternative modelizations
- Parameters fixed from simulation, including acceptance, evaluated using simulated pseudo experiments

Systematic uncertainties

Largest systematic

- Effect of bin migration, evaluated with pseudo experiments
  - Use angle-dependent resolution
  - Determined as a covariance matrix between bins
- Fit model, evaluated by testing alternative modelizations
- Parameters fixed from simulation, including acceptance, evaluated using simulated pseudo experiments

Strong correlations between bins

Cross checks

- Adding further orders in Legendre polynomials does not add information (extra parameters ~ 0)
    - Significance unchanged
- Further cross checks performed with counting experiment
    - Up-down asymmetries compatible
    - Lower significance (5.0σ)
    - Difference in significances with respect to the angular fit match expectations from pseudo experiments