Photon polarization in $B \to K\pi\pi\gamma$
Theory vs experiment

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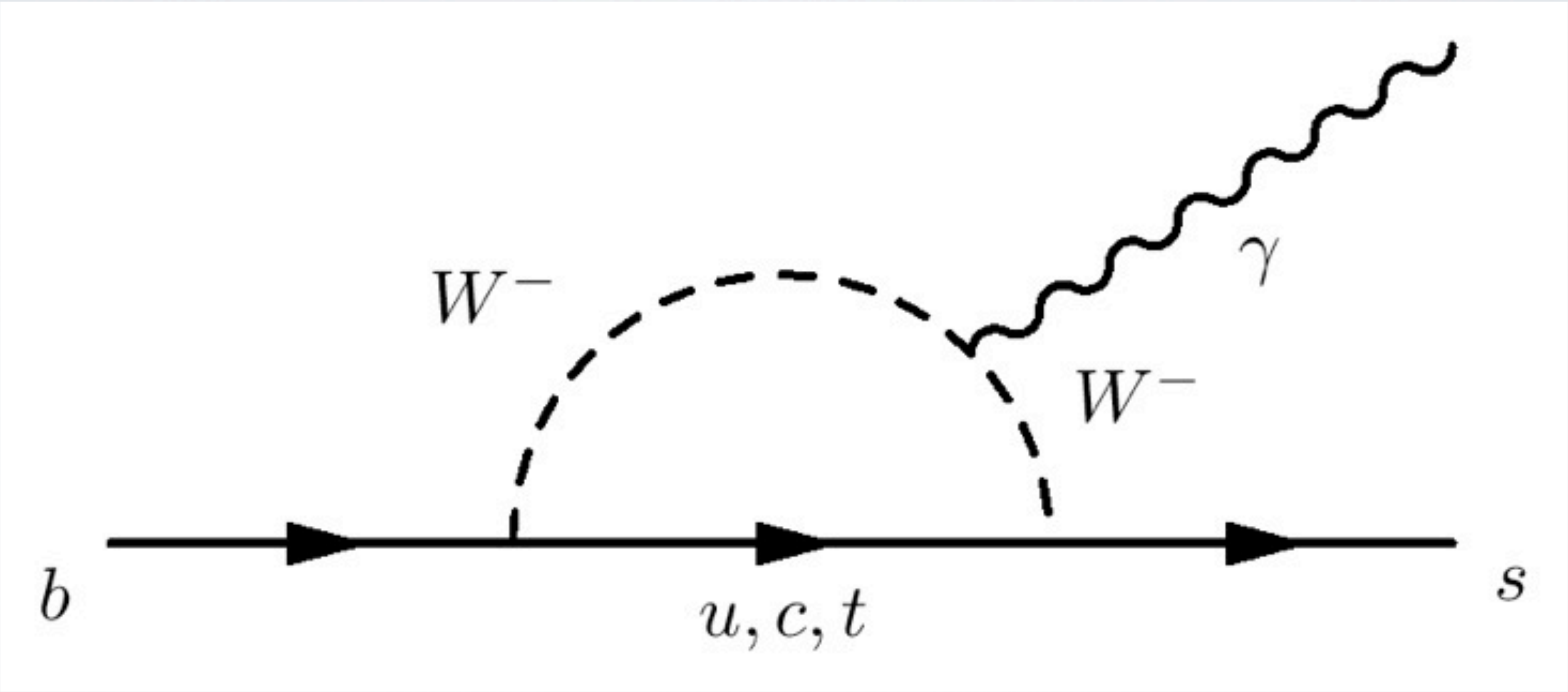
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$b \to s\gamma$



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}

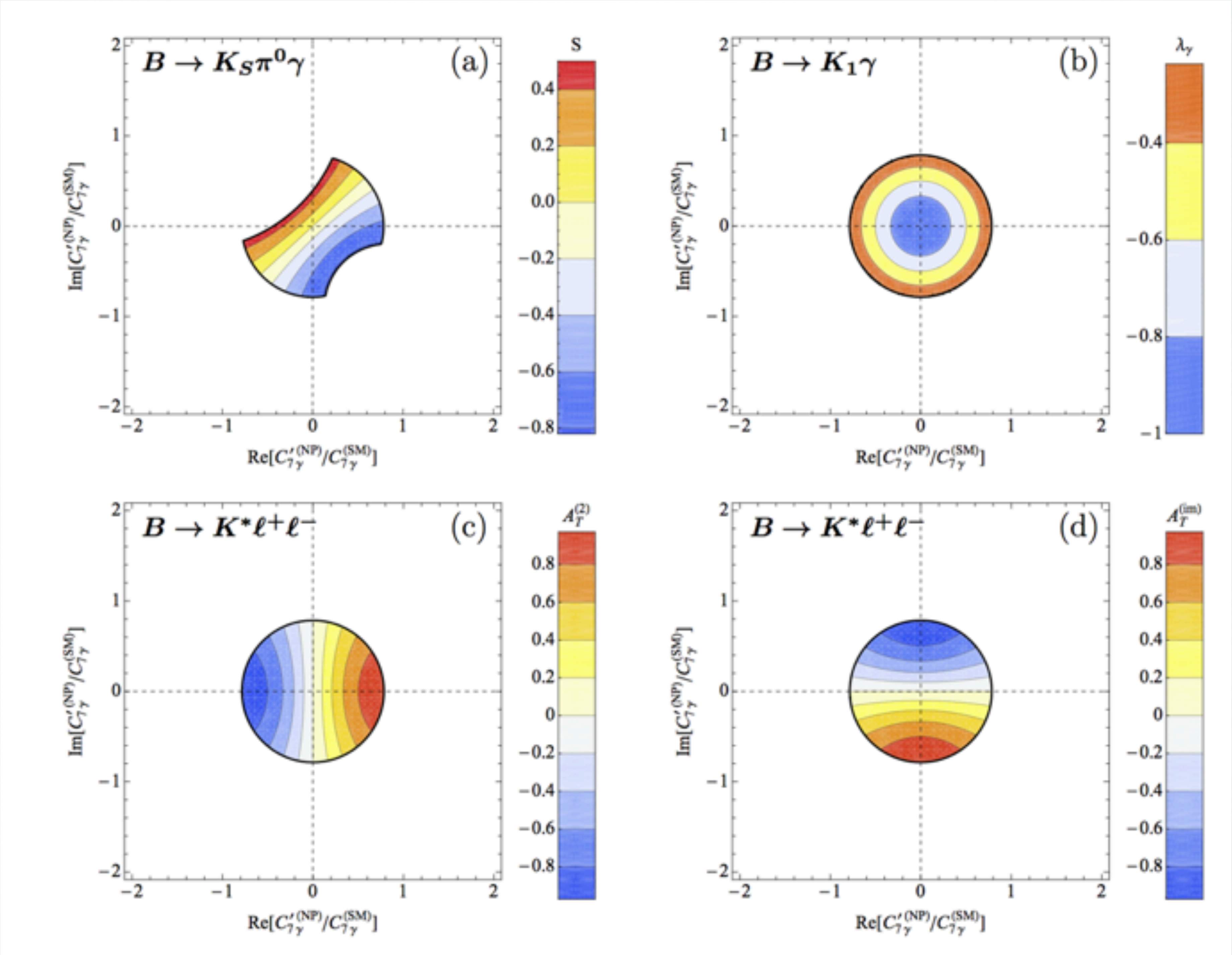
314	$K^{*0}\gamma$	-0.16 ± 0.23	$-0.16 \pm 0.22 \pm 0.07$	$0.008 \pm 0.017 \pm 0.009$	0.007 ± 0.019

Measuring the 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 $B^0 \to K^* l^+ l^-$ (pollution from C_9 and C_{10})
- Angular distribution of radiative decays with 3 charged tracks in the final state, *e.g.*, $B \to K\pi\pi\gamma$
- *b*-baryons: $\Lambda_b \to \Lambda^{(*)}\gamma$, $\Xi_b \to \Xi^{(*)}\gamma$

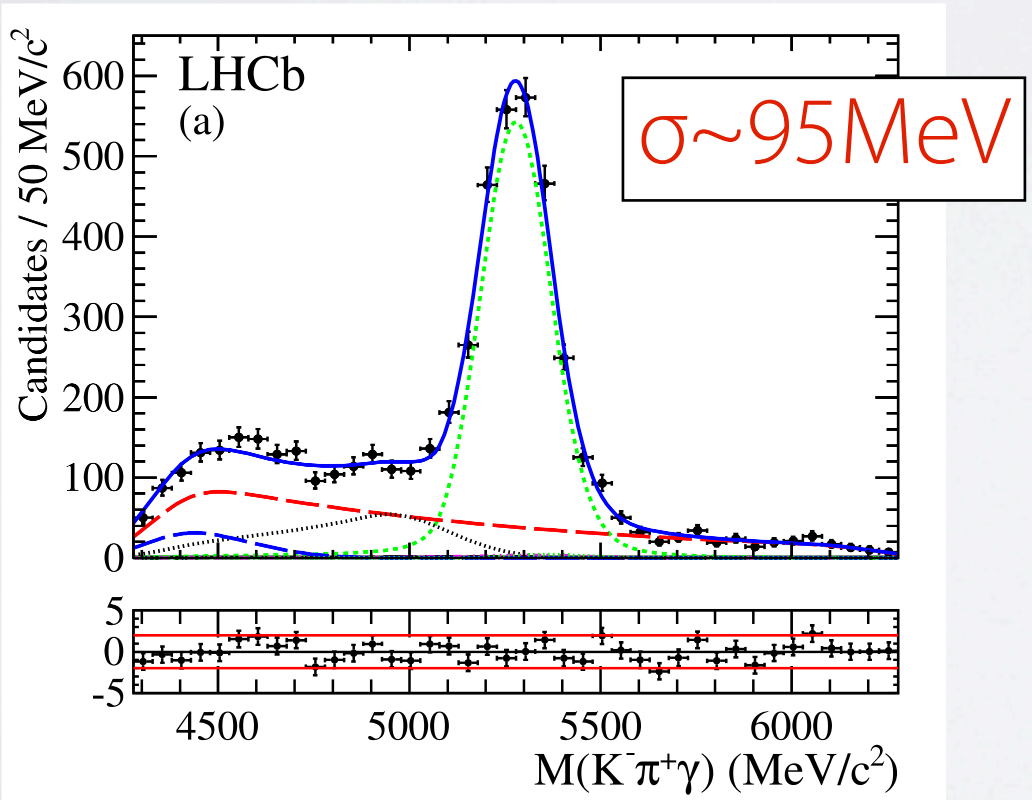
Complementary approaches

[Bečirević et al]

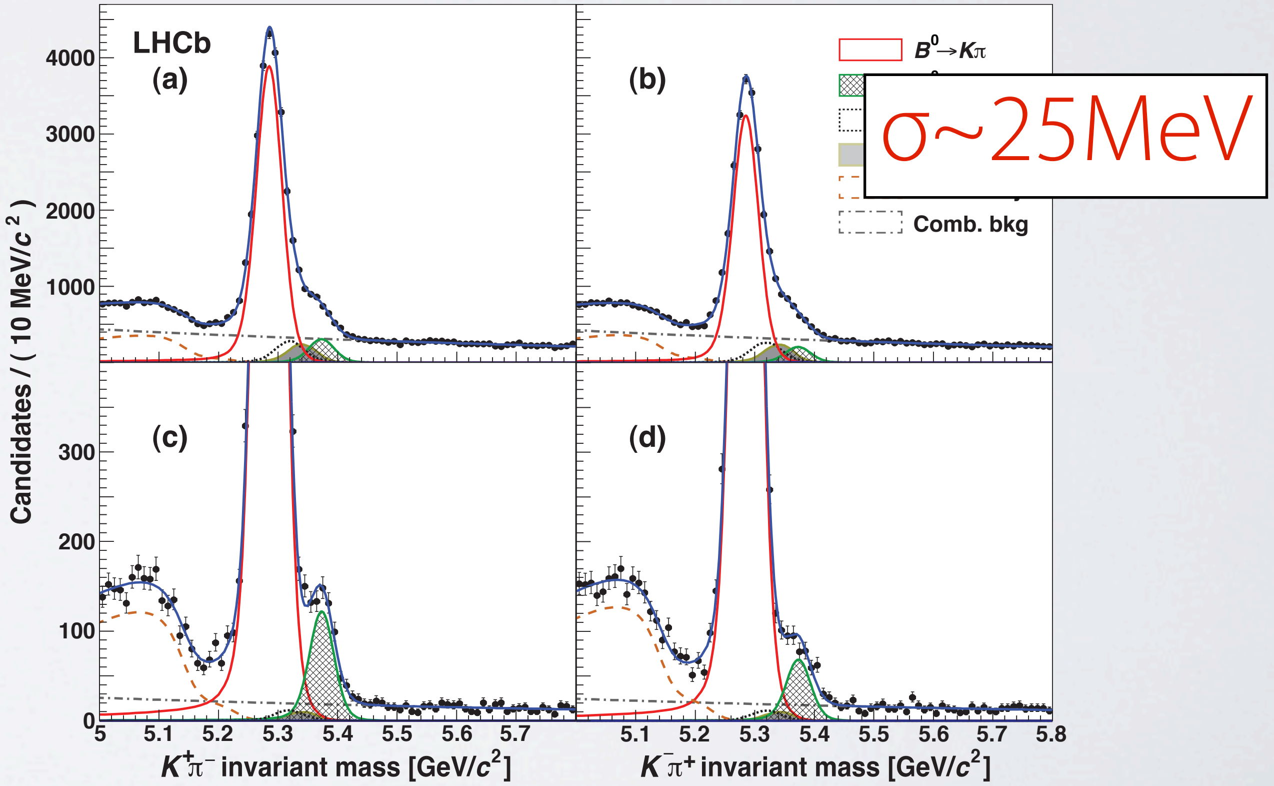


Challenges for radiative decays

- 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]

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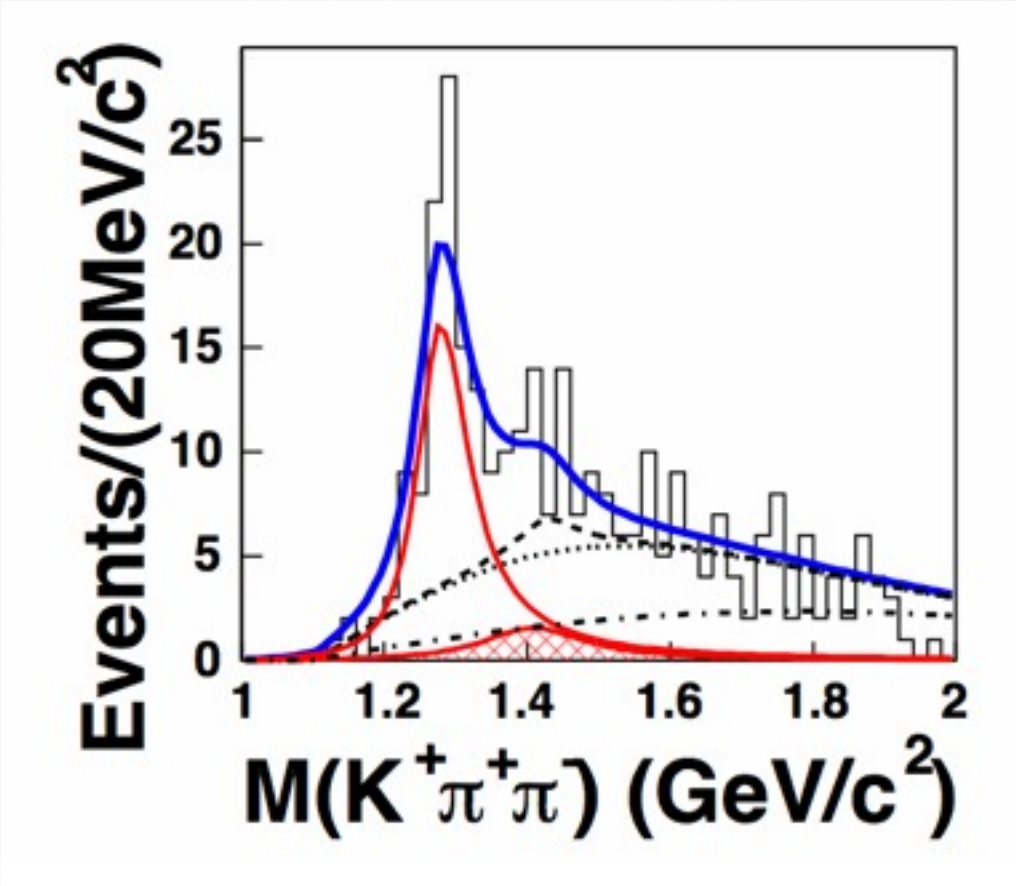
$B \to K\pi\pi\gamma$ in Belle and BaBar

- 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 $B \to K_{res}\gamma$

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

$$c_{L(R)}^{(i)} \equiv A(B \to K_{\rm res}^{(i)}\gamma_{L(R)})$$

weak amplitudes

$$\lambda_\gamma^{(i)} = \frac{|c_R^{(i)}|^2 - |c_L^{(i)}|^2}{|c_R^{(i)}|^2 + |c_L^{(i)}|^2}$$

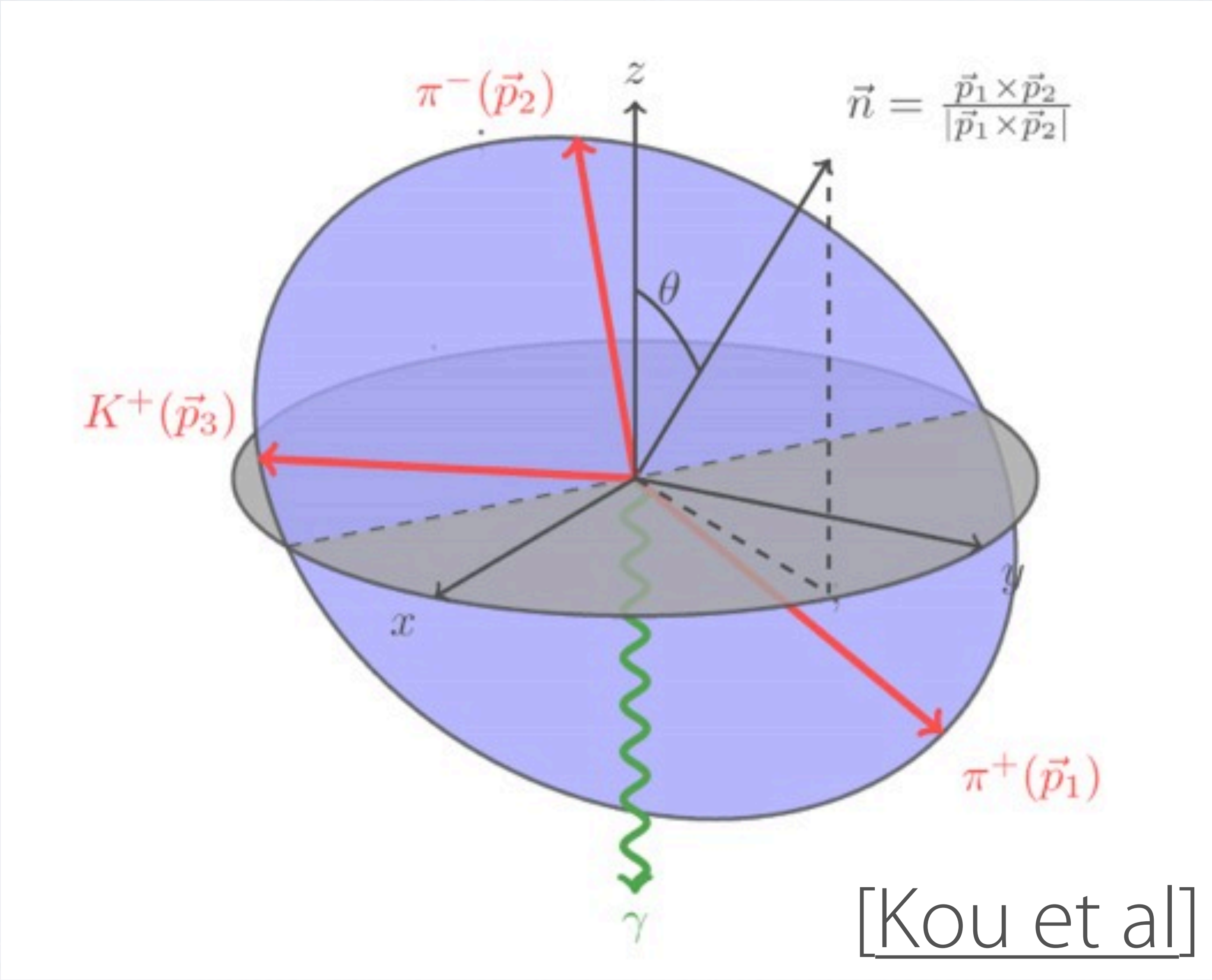
- It can be shown that photon polarization is independent of the *K* resonance and can be expressed as [Gronau et al]

$$\frac{|c_R^{(i)}|}{|c_L^{(i)}|} = \frac{|C_{7R}|}{|C_{7L}|} \Rightarrow \lambda_\gamma^{(i)} = \boxed{\frac{|C_{7R}|^2 - |C_{7L}|^2}{|C_{7R}|^2 + |C_{7L}|^2} \equiv \lambda_\gamma}$$

+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*



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 Dalitz 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

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

and therefore [Kou et al] [Gronau et al]

interference!

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

But life is not so beautiful

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

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

need to know *J* and *K*!

- But λ_γ goes with odd powers of $\cos\theta$

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

Up-down asymmetry

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

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

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

- This asymmetry is expected to be ~$0.3\lambda_\gamma$ in isolated neutral K_1 decays and ~$0.1\lambda_\gamma$ in charged ones

$B^{\pm}\to K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$ 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 in the full data set recorded by LHCb in 2011 and 2012, corresponding to 3/fb
- Preliminary conference note inclusing only 2012 data and with simple counting approach was shown at EPS 2013 [LHCb-CONF-2013-009]

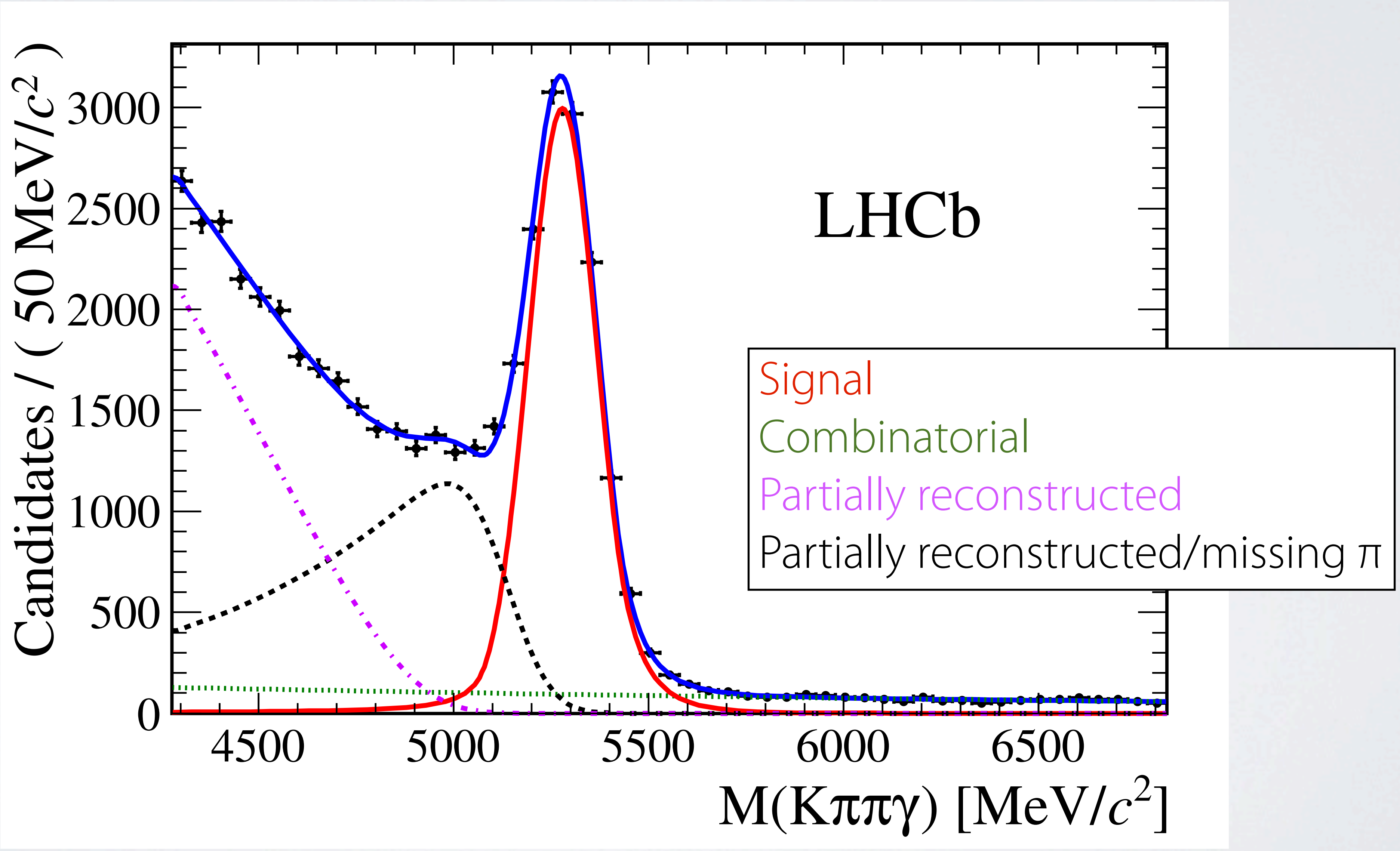
Analysis strategy

PRL 112, 161801 (2014)

- *B* candidates mass fit
- Assessment of the $K\pi\pi$ mass spectrum
- Angular study
  - Provide angular distribution to help theory calculations
- Determination of up-down asymmetry
  - Obtain significance with respect to the no-polarization scenario

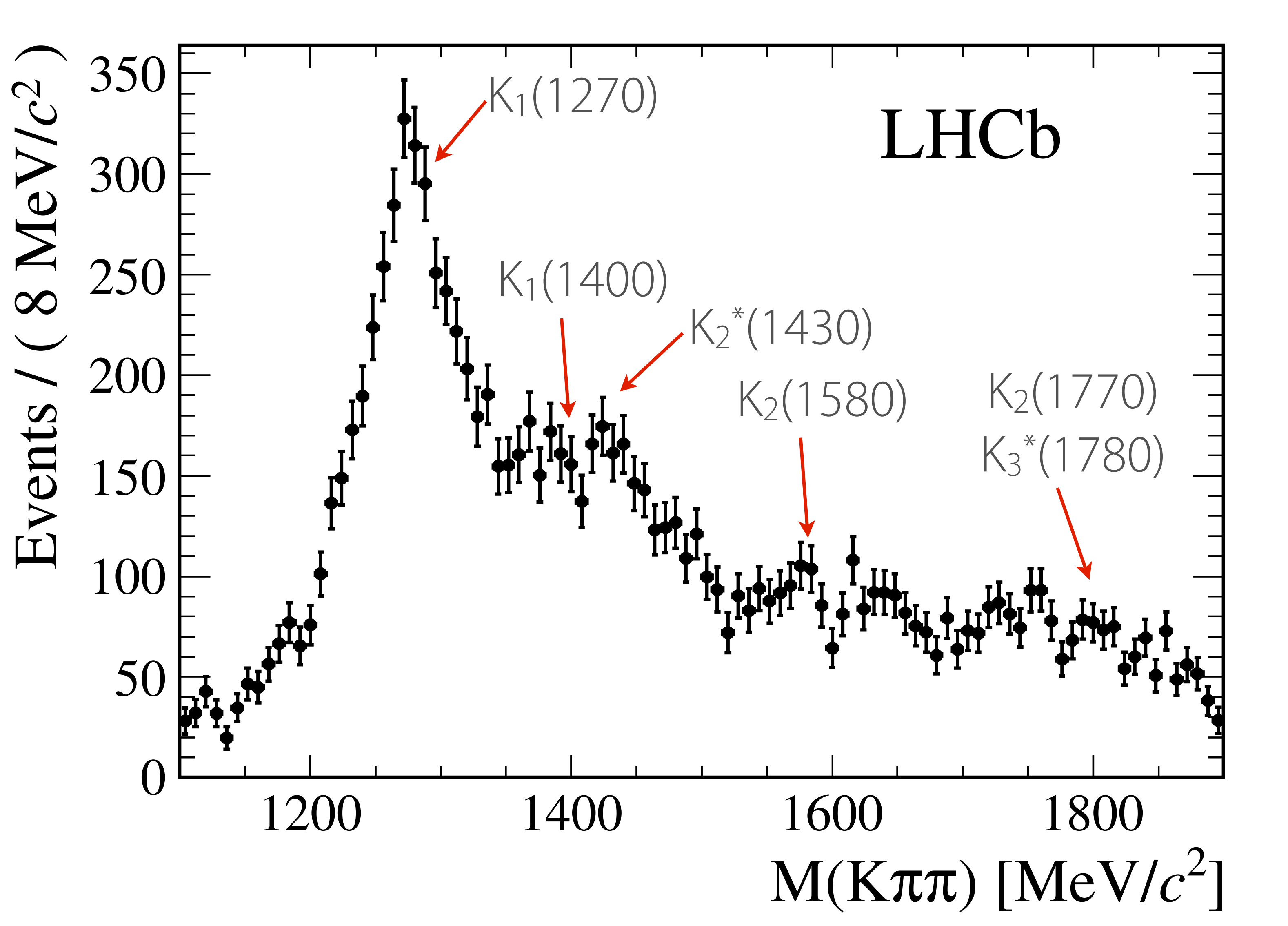
Mass distribution

- Observe ~14000 signal events in the [1.1,1.9] GeV/c^2 $K\pi\pi$ mass region



Background-subtracted $K\pi\pi$ mass spectrum

- Many (unclear) contributions in the $K\pi\pi$ mass spectrum
  - Impossible to separate the resonances without full Dalitz analysis



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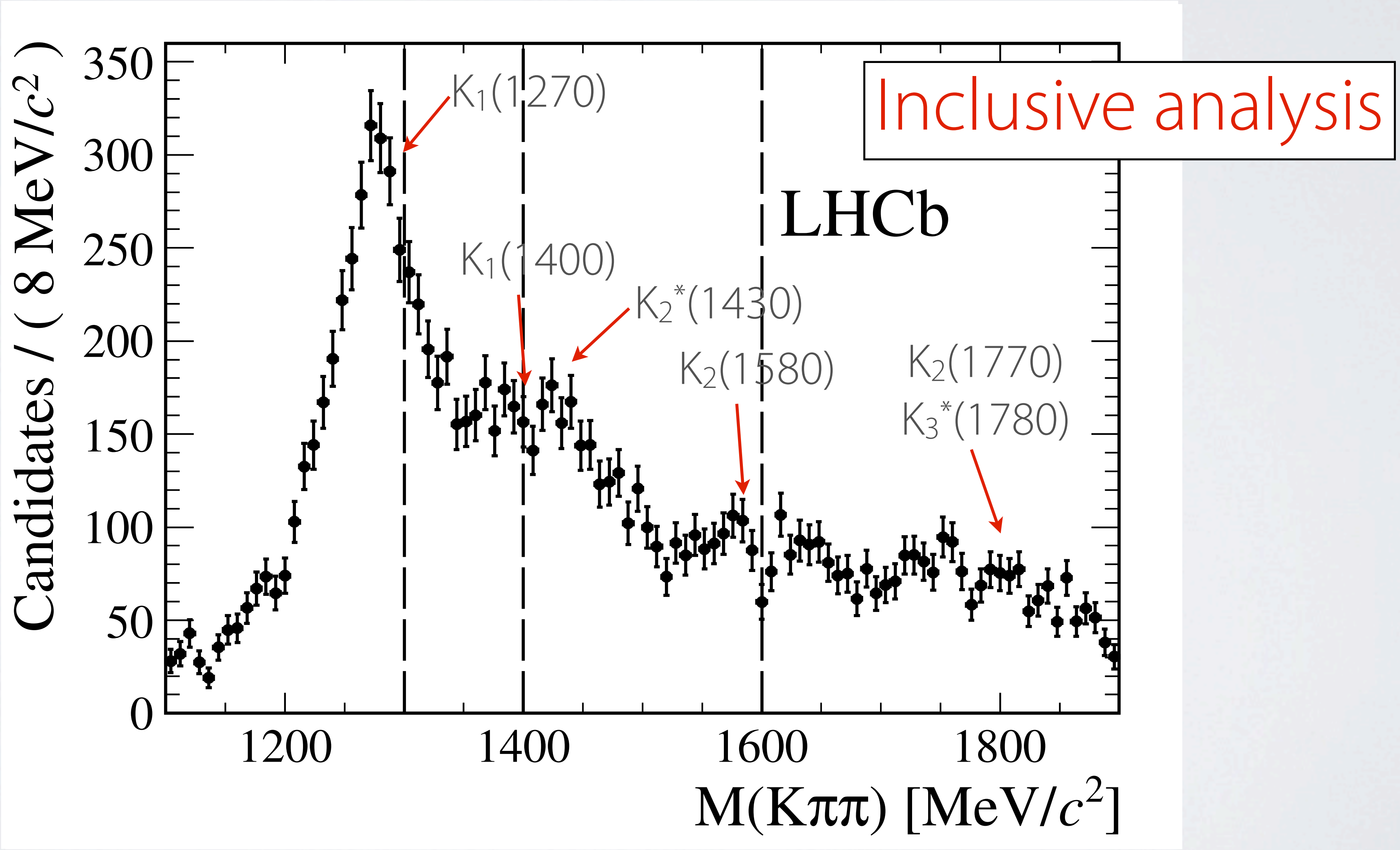
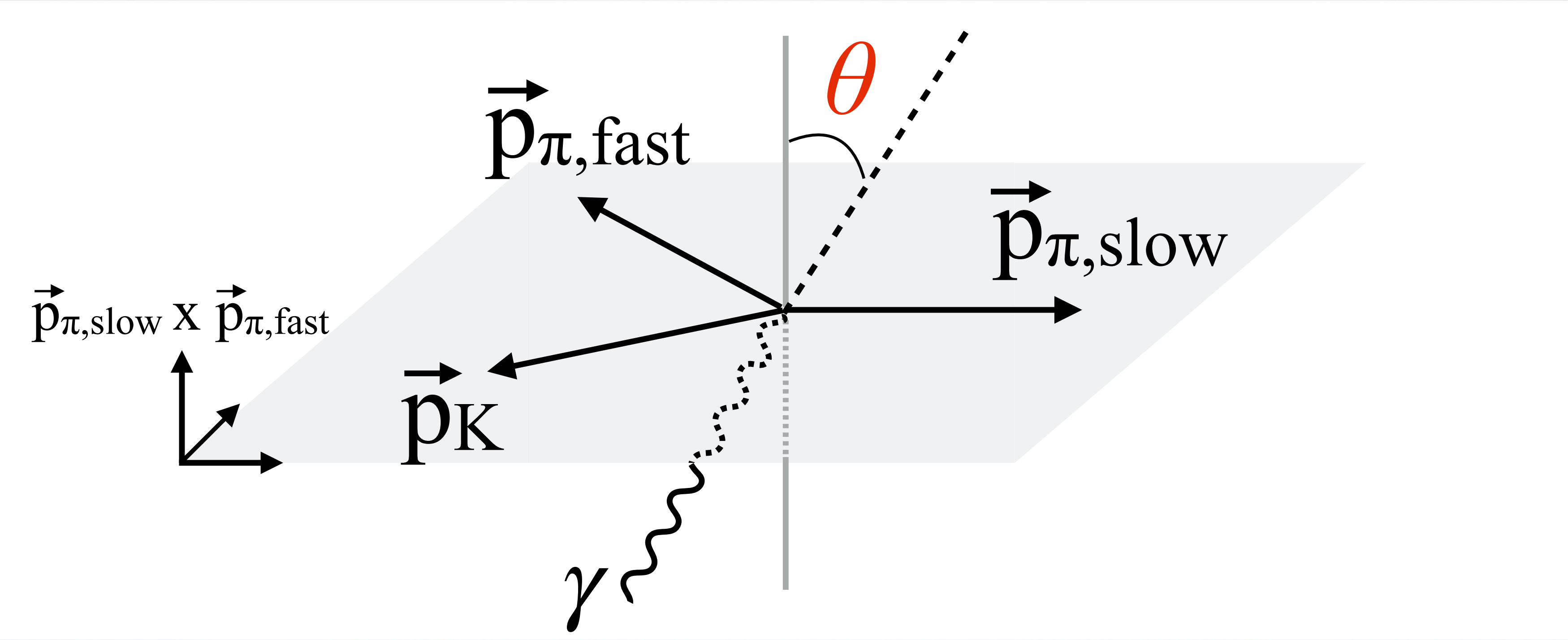


Angle definition

- In order to avoid cancellations due to symmetries, neutral $K\pi\pi$ combinations requiere a change of the sign of $\cos\theta$ according to s_{12} and s_{13}

$$\vec{n} = \vec{p}_{\pi,\mathrm{slow}} \times \vec{p}_{\pi,\mathrm{fast}}$$

- The same convention is used for consistency



Angular fit

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

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

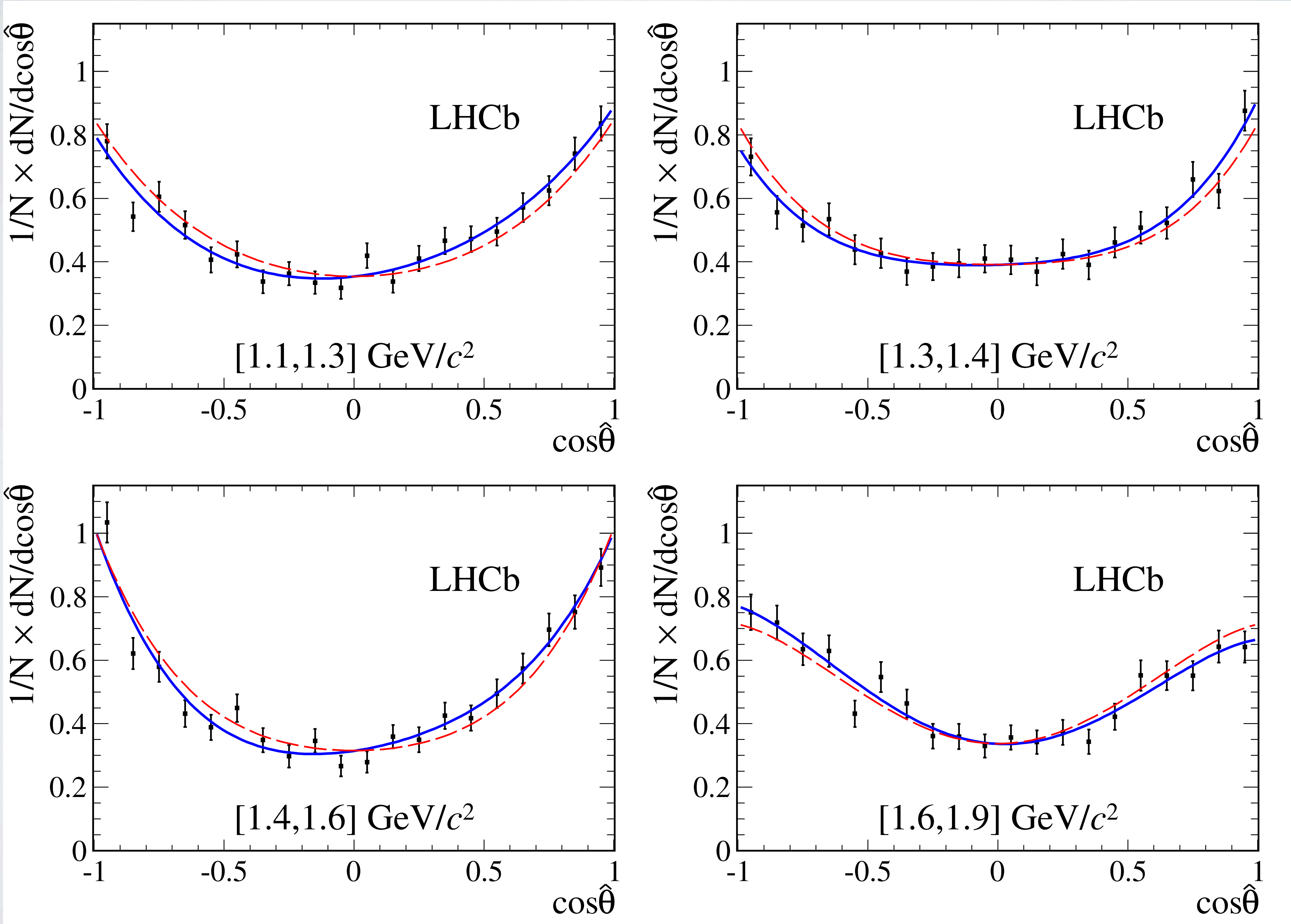
- A χ^2 fit is performed taking into account the full statistical and systematic covariance matrices

- 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

Angular fit results



Angular fit coefficients

- The coefficients of the angular fit are obtained for each of the four $K\pi\pi$ mass regions

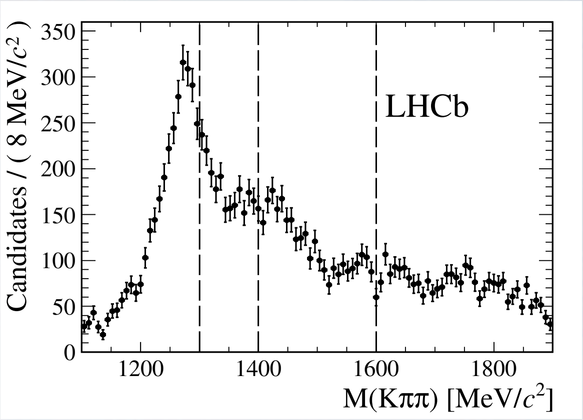
(x10^{-2})

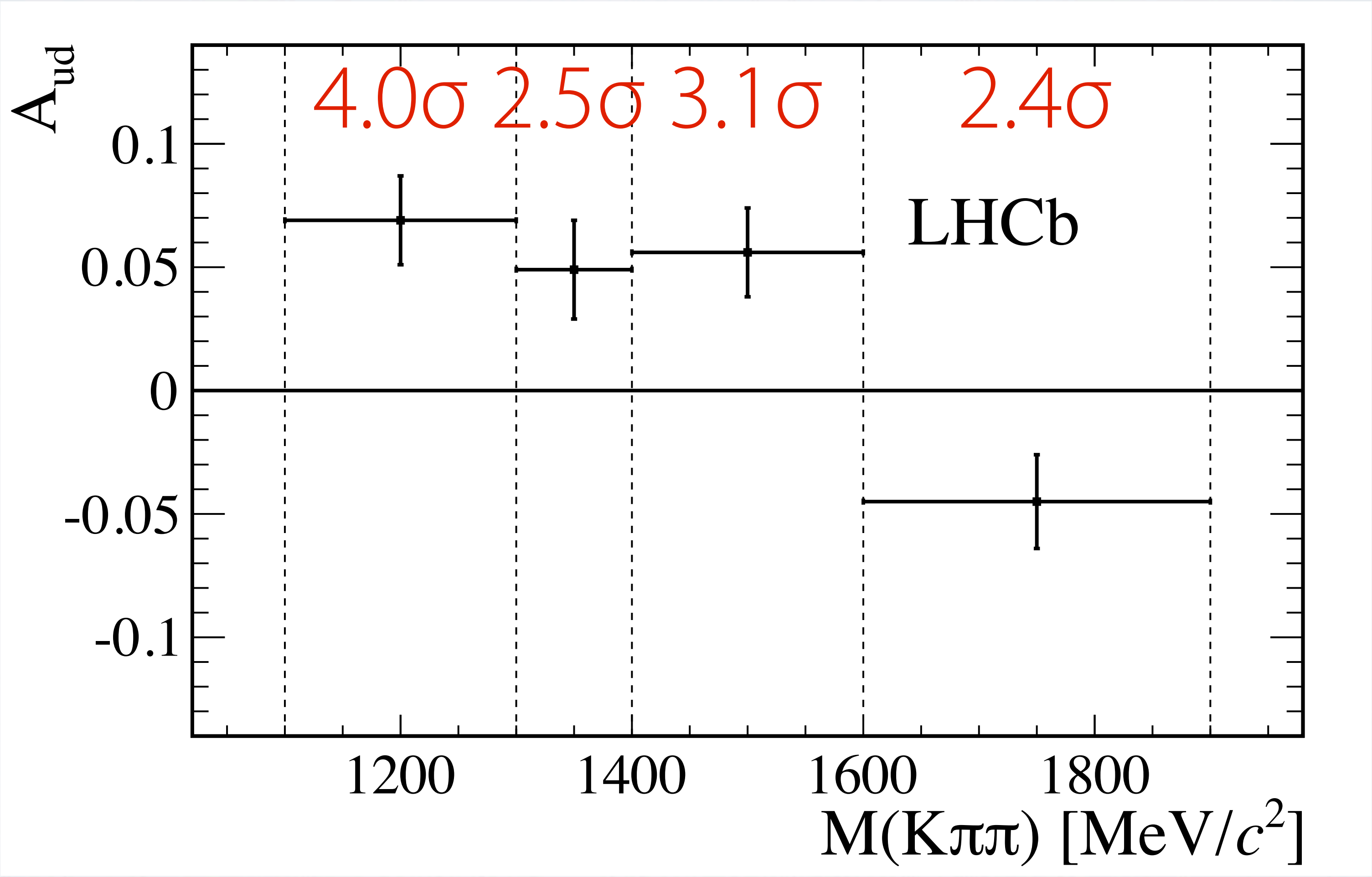
	$[1.1, 1.3]$	$[1.3, 1.4]$	$[1.4, 1.6]$	$[1.6, 1.9]$
c_1	6.3 ± 1.7	5.4 ± 2.0	4.3 ± 1.9	-4.6 ± 1.8
c_2	31.6 ± 2.2	27.0 ± 2.6	43.1 ± 2.3	28.0 ± 2.3
c_3	-2.1 ± 2.6	2.0 ± 3.1	-5.2 ± 2.8	-0.6 ± 2.7
c_4	3.0 ± 3.0	6.8 ± 3.6	8.1 ± 3.1	-6.2 ± 3.2
$\mathcal{A}_{\rm UD}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ± 1.9

- We expect that these results prove to be a useful input for theorists (are they?)

Up-down asymmetry results

- Four independent up-down asymmetries are obtained





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 so far

- 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
  - Impossible to 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

Photon polarization from A_{UD}?

- The up-down asymmetry is proportional to λ_γ

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

- But what is the proportionality constant?

- Right now it looks like it's not possible to translate a measurement of A_{UD} into a measurement of λ_γ

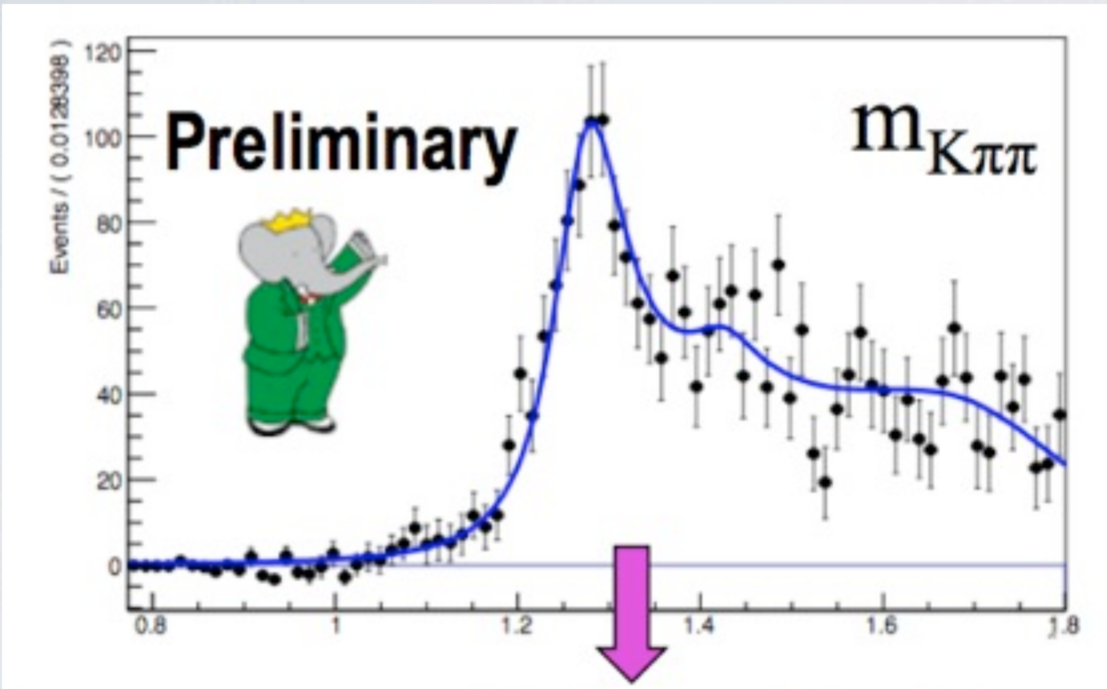
Interlude: theory vs experiment

- Combined work between theory and experiment is needed
  - Need to take into account what experimental data can tell us
  - Need to measure things that are theoretically interesting
- In the case of $K\pi\pi\gamma$, theory papers don't give any prediction or formula we can use, and experiment is probably not measuring things that are interesting to theorists

Interlude: theory vs experiment

- Combined w… …t is needed
  - Need to tak… …can tell us
  - Need to me… …sting
- In the case o… …prediction or formula we … …not measuring t… …s

News on $B \to K\pi\pi\gamma$ from BaBar



Eli Ben-Haim

Moriond EW (March 16th 2014)

Preliminary

$K_{res} \to K^+\pi^-\pi^+$

Mode	$\mathcal{B}(B^+ \to \text{Mode})\times$ $\mathcal{B}(K_{res} \to K^+\pi^+\pi^-) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	PDG values ($\times 10^{-6}$)
Inclusive $B^+ \to K^+\pi^+\pi^-\gamma$	$\cdots$	$27.2 \pm 1.0^{+1.1}_{-1.3}$	27.6 ± 2.2
$K_1(1270)^+\gamma$	$14.5^{+2.0+1.1}_{-1.3-1.2}$	$44.0^{+6.0+3.5}_{-4.0-3.7} \pm 4.6$	43 ± 13
$K_1(1400)^+\gamma$	$4.1^{+1.9+1.3}_{-1.2-0.8}$	$9.7^{+4.6+3.1}_{-2.9-1.8} \pm 0.6$	< 15 CL$=90\%$
$K^*(1410)^+\gamma$	$9.7^{+2.1+2.4}_{-1.9-0.7}$	$23.8^{+5.2+5.9}_{-4.6-1.4} \pm 2.4$	$\emptyset$
$K_2^*(1430)^+\gamma$	$1.5^{+1.2+0.9}_{-1.0-1.4}$	$10.4^{+8.7+6.3}_{-7.0-9.9} \pm 0.5$	14 ± 4
$K^*(1680)^+\gamma$	$17.0^{+1.7+3.5}_{-1.4-3.0}$	$71.7^{+7.2+15}_{-5.7-13} \pm 5.8$	< 1900 CL$=90\%$

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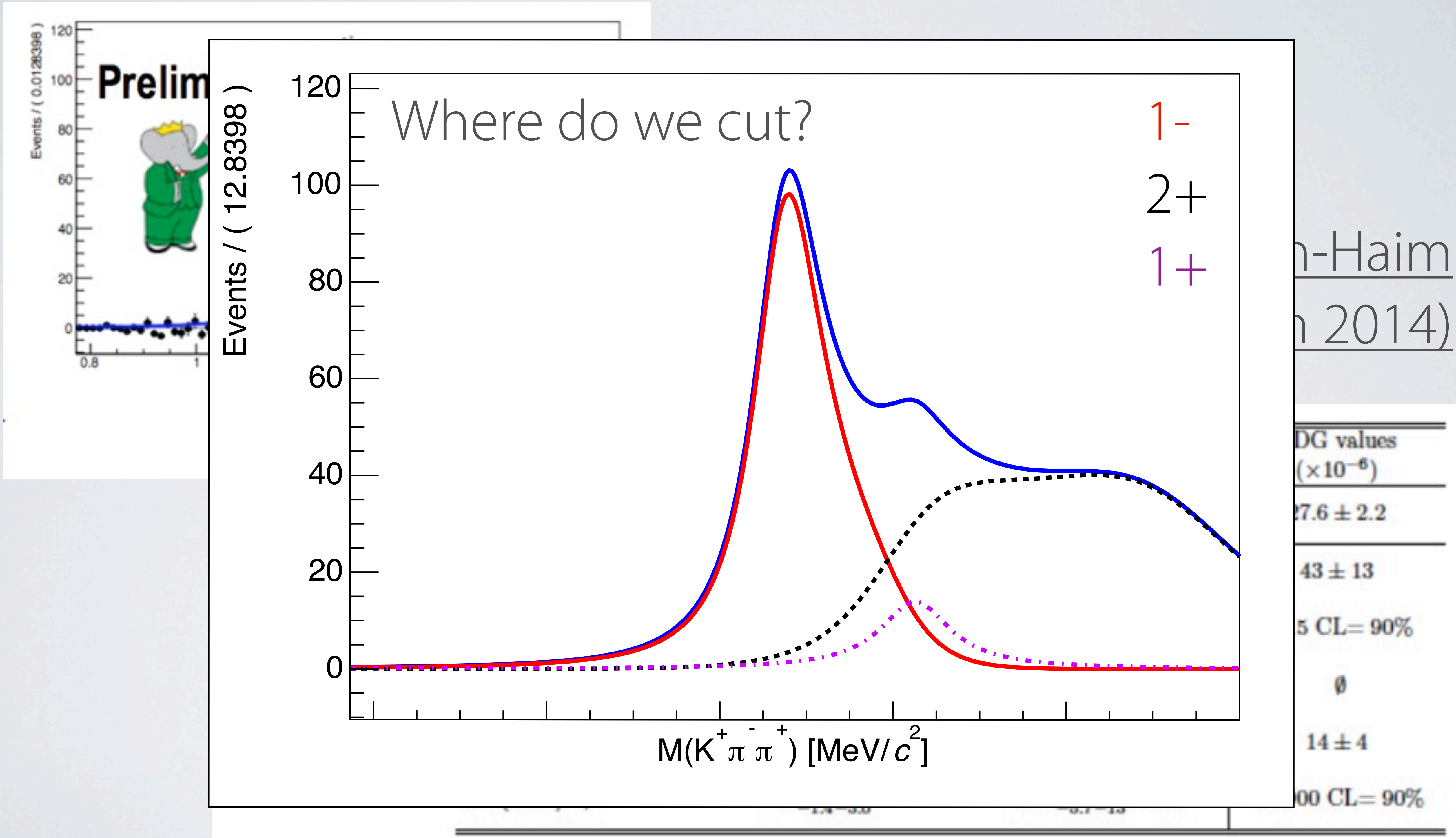

What can we do with $K\pi\pi$?

- Fit mass distribution and split by spin-parity and calculate up-down asymmetry
  - Still, predictions are needed for the up-down asymmetry in spin-parity pairs (how to do it without BR measurements?)
  - Can we anyway fit he mass distribution?
- Get an idea of the mass distribution and cut the $K_1(1270)$ off
  - Still, no prediction for this resonance
  - How to evaluate systematics?

What can we do with $K\pi\pi$?

- Add another variable (an angle) to the mass fit
  - I honestly don't know which
- Another solution is to study the Dalitz plot similarly to what Belle did with the J/ψ mode [Phys. Rev. D83 (2011) 032005]
  - Factor 3 less data (14k vs 40k)
  - Less allowed amplitudes due to the photon (less parameters to fit)
  - Less clean
  - Need to parametrize detection efficiency over the Dalitz plane

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We can do more things in LHCb!

- Angular distribution of radiative decays with 3 charged tracks in the final state, *e.g.*, $B \to K\pi\pi\gamma$
- *b*-baryons: $\Lambda_b \to \Lambda^{(*)}\gamma$, $\Xi_b \to \Xi^{(*)}\gamma$

Ideas that need theory

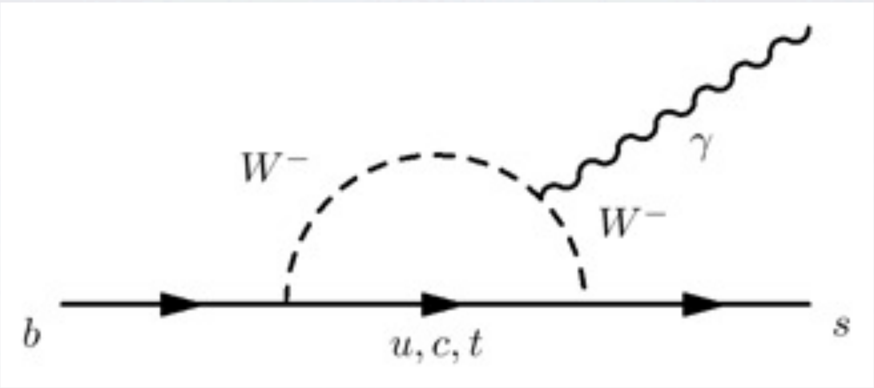
- Angular distributions in $B^+ \to \varphi K^+ \gamma$
  - Some theory papers, nothing conclusive
- Unobserved $B \to VV\gamma$ transitions ($V = \varphi, K^*$) could be observed with the current LHCb dataset
  - Is there anything we can extract from angular distributions?
- Please, think out of the box: if it is interesting, we can try to do it!
  - I leave you my email: albert.puig@cern.ch

Thank you

Backup

Radiative *B* decays

- Access to possible NP through the virtual loop (2HDM, SUSY...)
  - Transitions especially sensitive to NP in the $C_{7\gamma}$ coefficient



electromagnetic penguin operator

- Exclusive decays difficult from the theoretical point of view due to form factor
  - Find form-factor free observables, such as *CP* and isospin asymmetries

- Photon polarization as test of the SM

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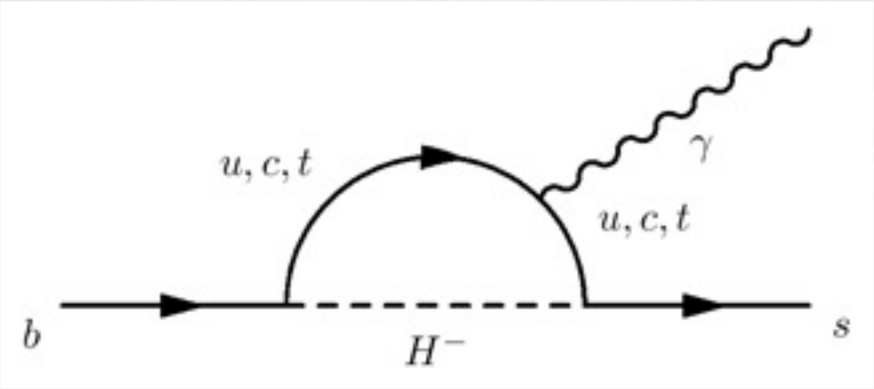

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Photon polarization in the SM

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

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

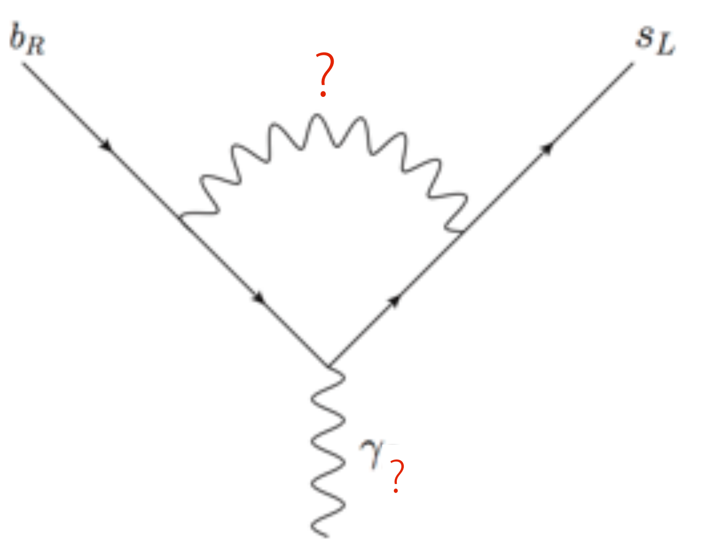
$$b \to s\gamma_L$$
$$\bar{b} \to \bar{s}\gamma_R$$

  - Never confirmed to high precision!

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

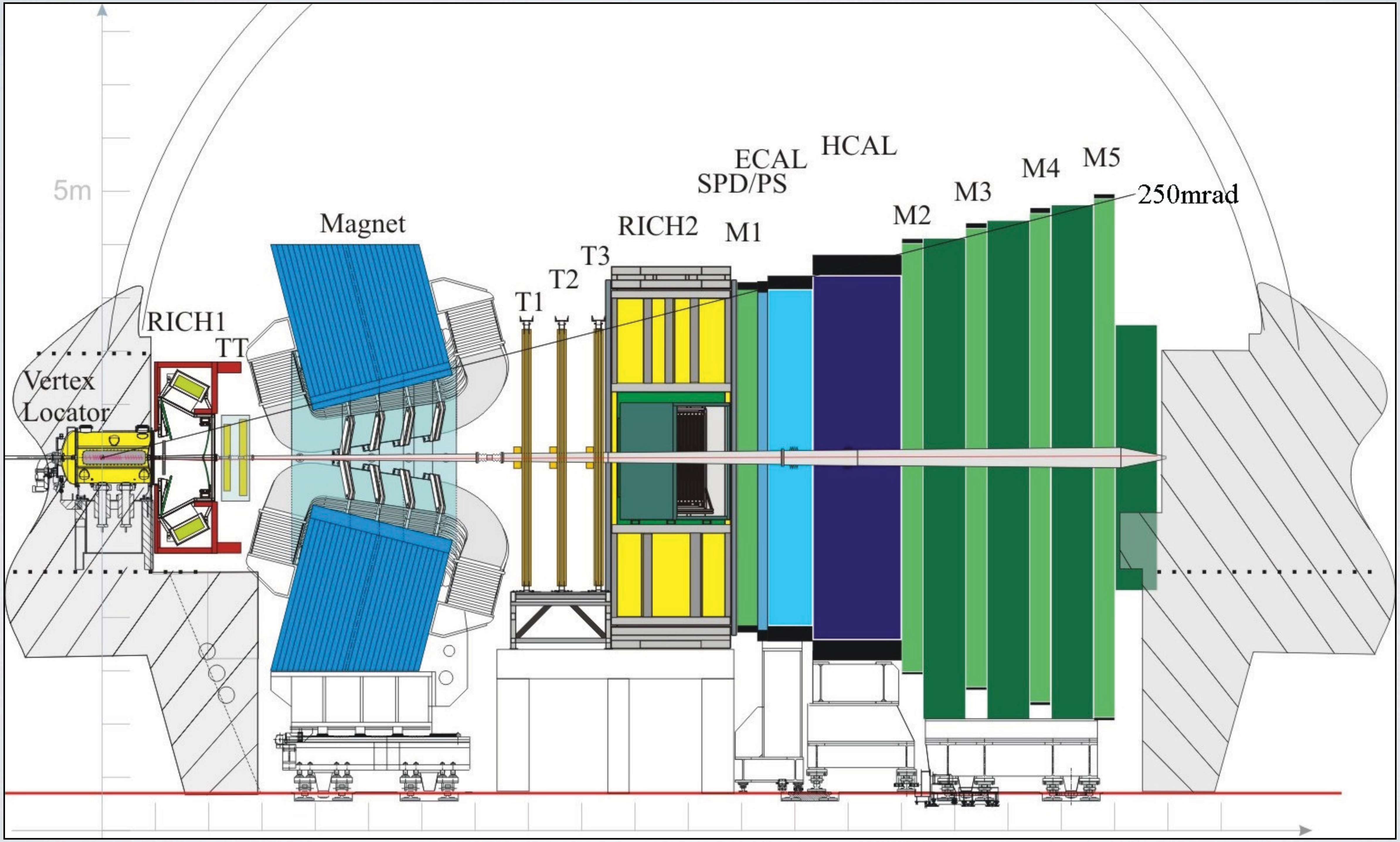
And beyond the SM?

- 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]

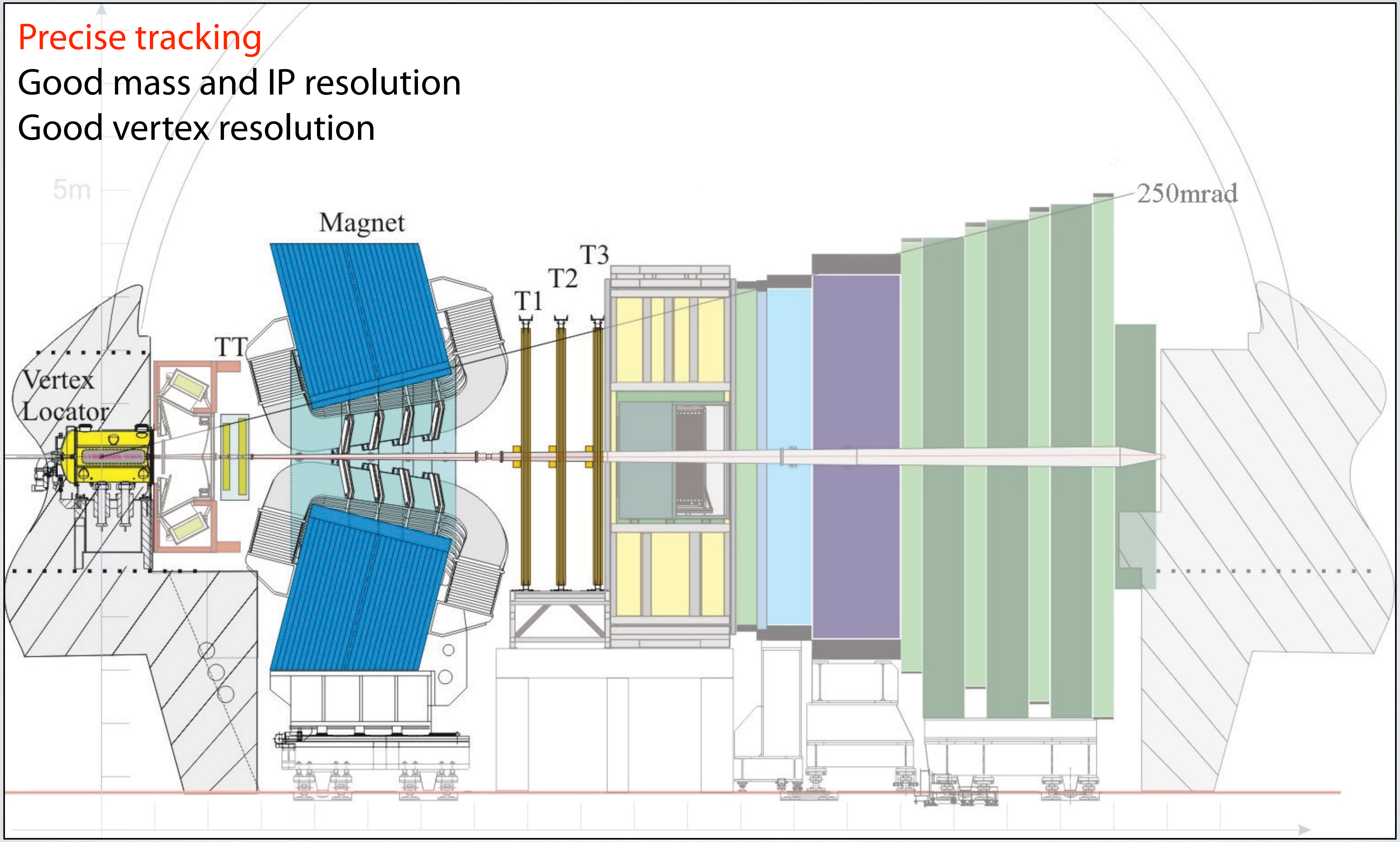


- Still "large" room for NP despite the constraints coming from B_s oscillation parameters, $B_s \to \mu\mu$...
  - New penguins around the corner?

The LHCb experiment



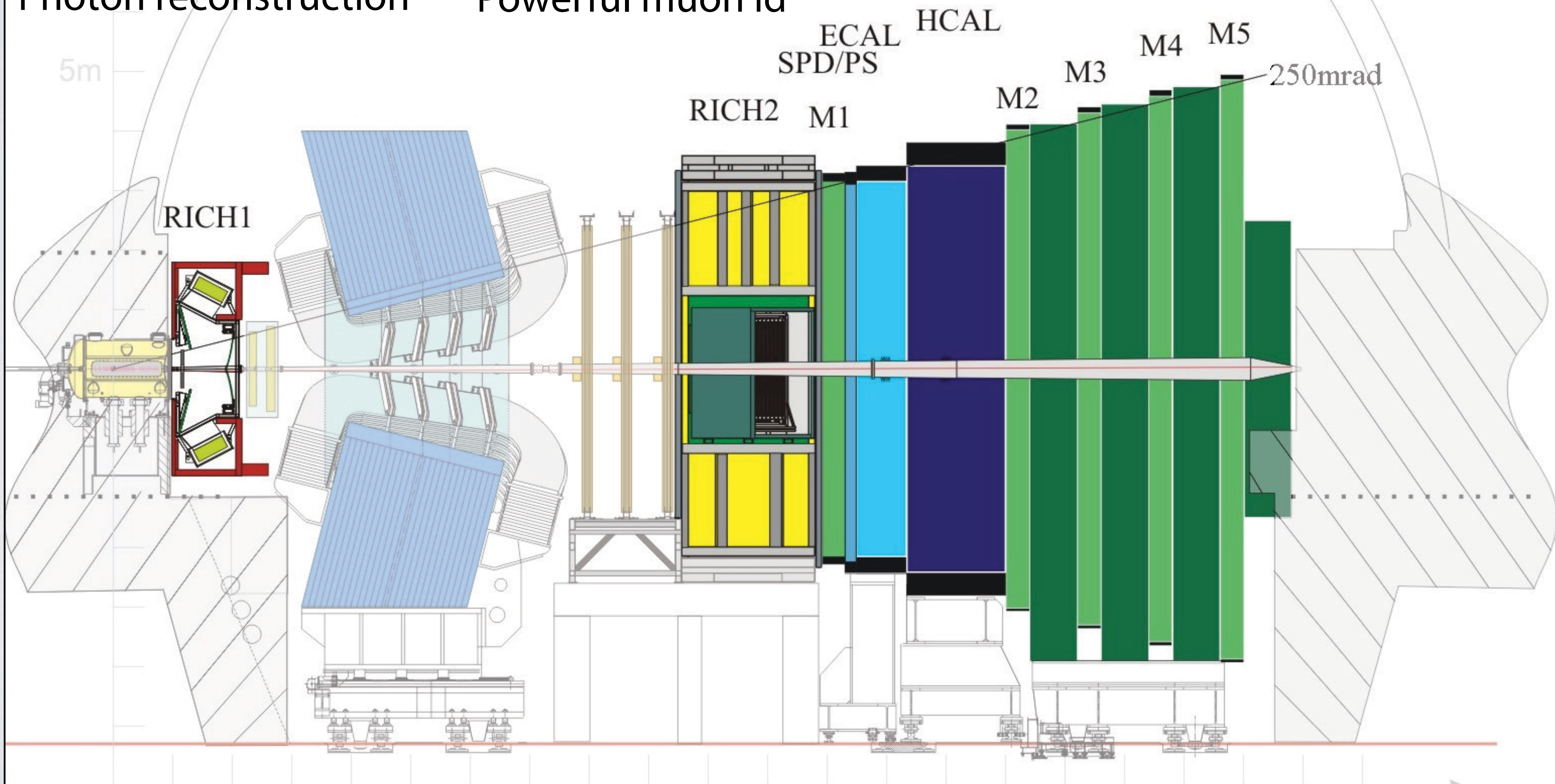
The LHCb experiment



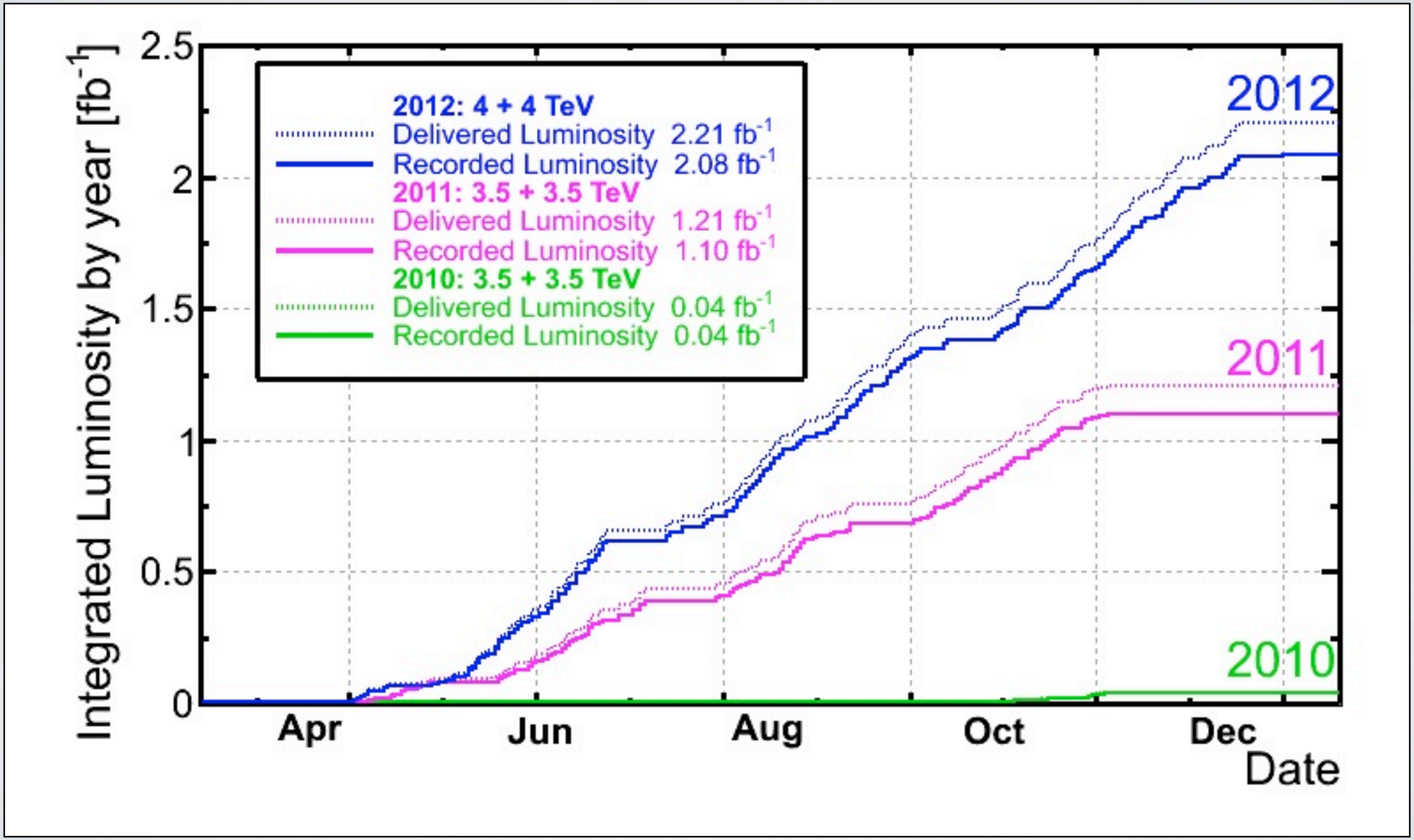
The LHCb experiment

Calorimeter system
Trigger
Photon reconstruction

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



LHCb Run-I summary



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

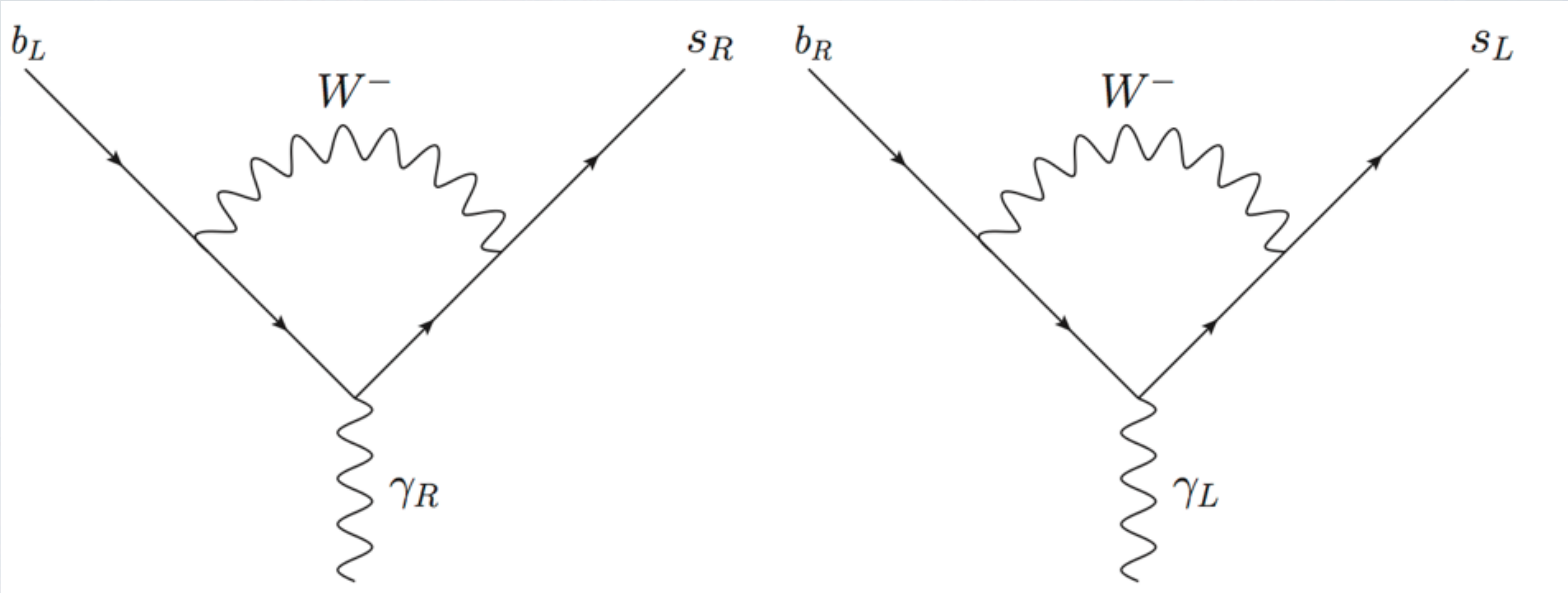
Photon polarization in the SM

- The $b \to s\gamma$ process has a particular structure in the SM

$$\bar{s}\Gamma(b \to s\gamma)_\mu b = \frac{e}{(4\pi)^2}\frac{g^2}{2M_W^2}V_{ts}^* V_{tb} F_2 \bar{s} i\sigma_{\mu\nu} q^\nu \left(m_b \frac{1+\gamma_5}{2} + m_s \frac{1-\gamma_5}{2} \right) b$$

- The W boson couples only left-handedly
- The requirement of a chirality flip leads to left-handed photon dominance

Photon polarization in the SM



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

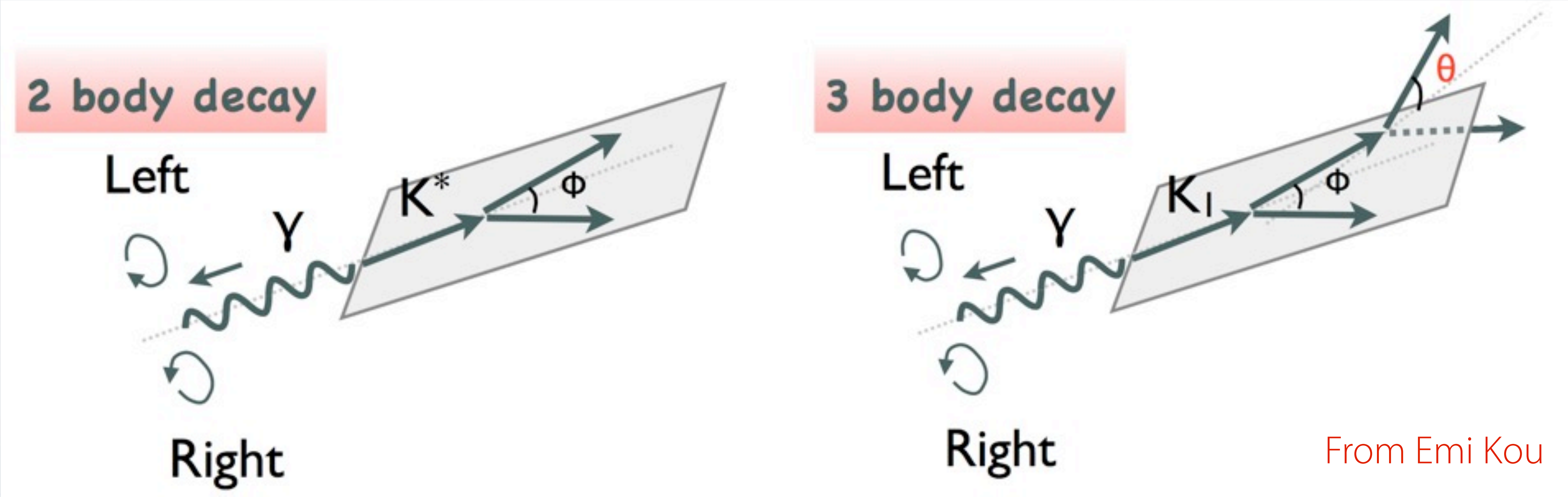
$$\frac{m_s}{m_b} \approx 0.02 \ll 1$$

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



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

strong decay amplitudes of the K_{res}

- In the case of overlapping resonances

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

so (introducing the expression of the weak amplitudes)

$$\mathrm{d}\Gamma(B \to K\pi\pi\gamma) \propto (|\mathcal{A}_R|^2 + |\mathcal{A}_L|^2) + \lambda_\gamma(|\mathcal{A}_R|^2 - |\mathcal{A}_L|^2)$$

- It's interesting to note that

$$P_\gamma = \frac{\mathrm{d}\Gamma(B \to K\pi\pi\gamma_R) - \mathrm{d}\Gamma(B \to K\pi\pi\gamma_L)}{\mathrm{d}\Gamma(B \to K\pi\pi\gamma_R) + \mathrm{d}\Gamma(B \to K\pi\pi\gamma_L)}$$

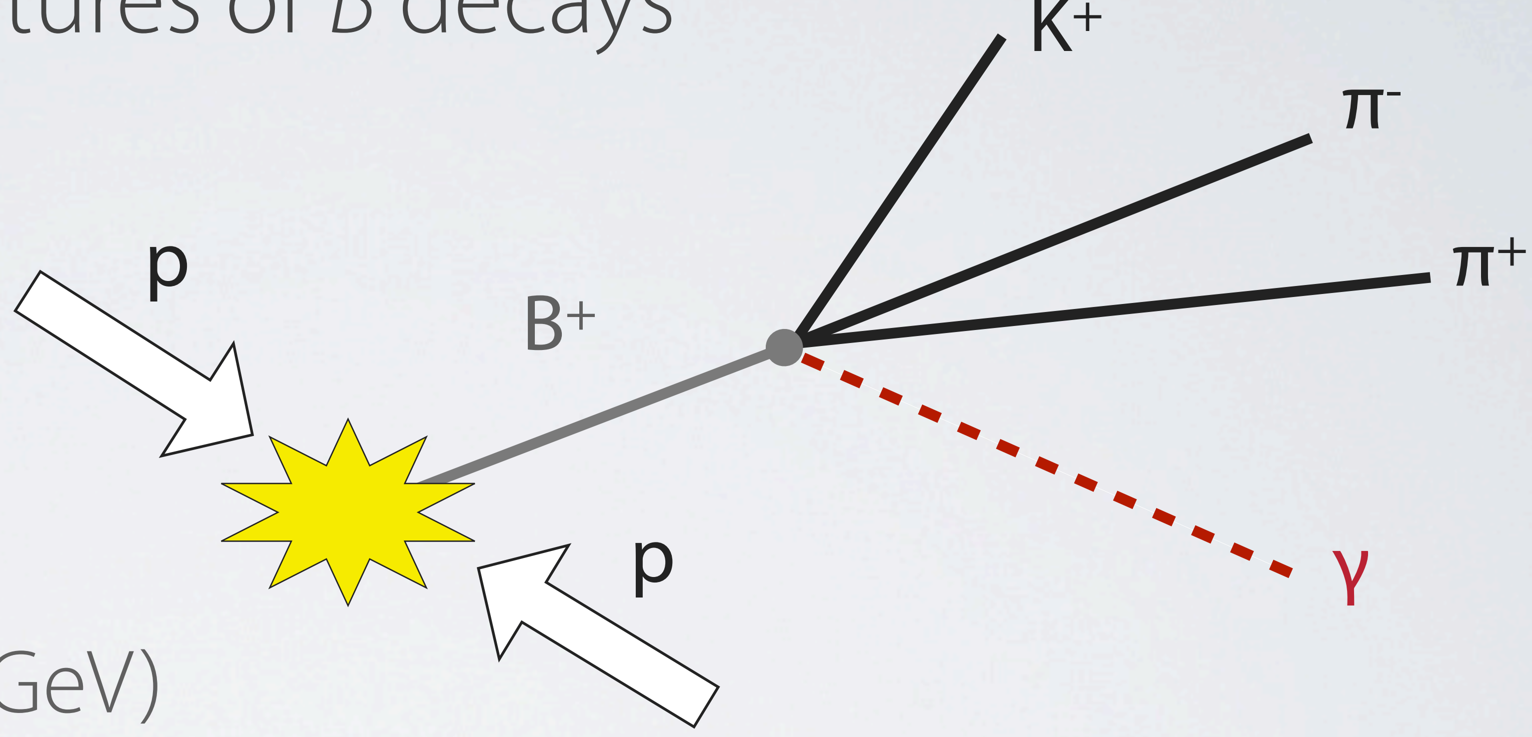
is only equal to λ_γ in the case of one resonance

Interference needed!

- The decay amplitude is required to have a non trivial phase due to final state interactions in order to preserve *T*
  - Knowledge of this phase is required to interpret measurements in terms of photon polarization ⚠
- In the case of *Kππ* final states, this means
  - Interference between two intermediate *K*π* states with different charges (isospin-related amplitudes) ← only for final states with neutrals
  - Interference between intermediate *K*π* and *ρK* amplitudes
  - Interference between different partial waves into *K*π* or *ρK*

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

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

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

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

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

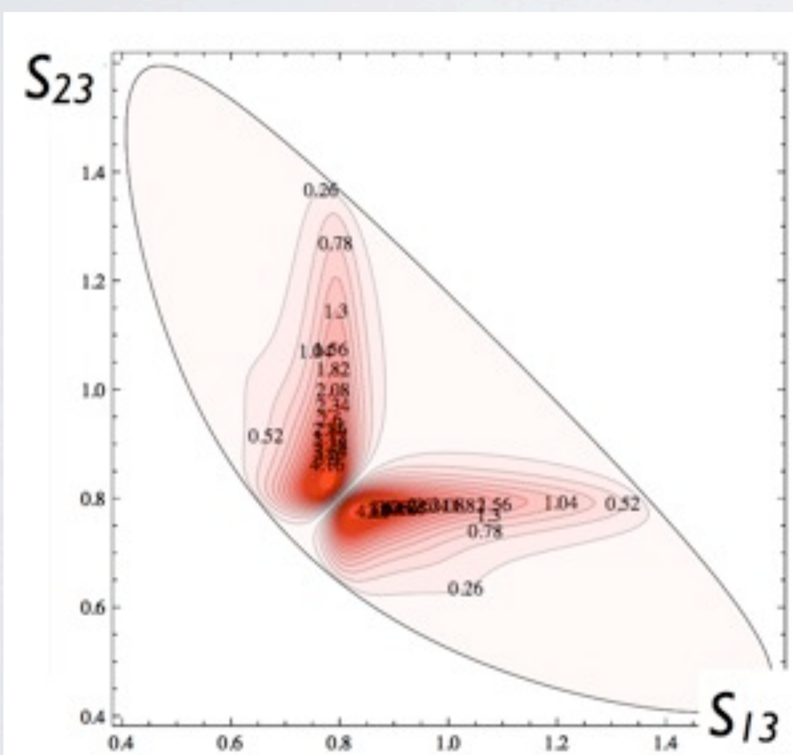
Strong correlations between bins

Cross checks

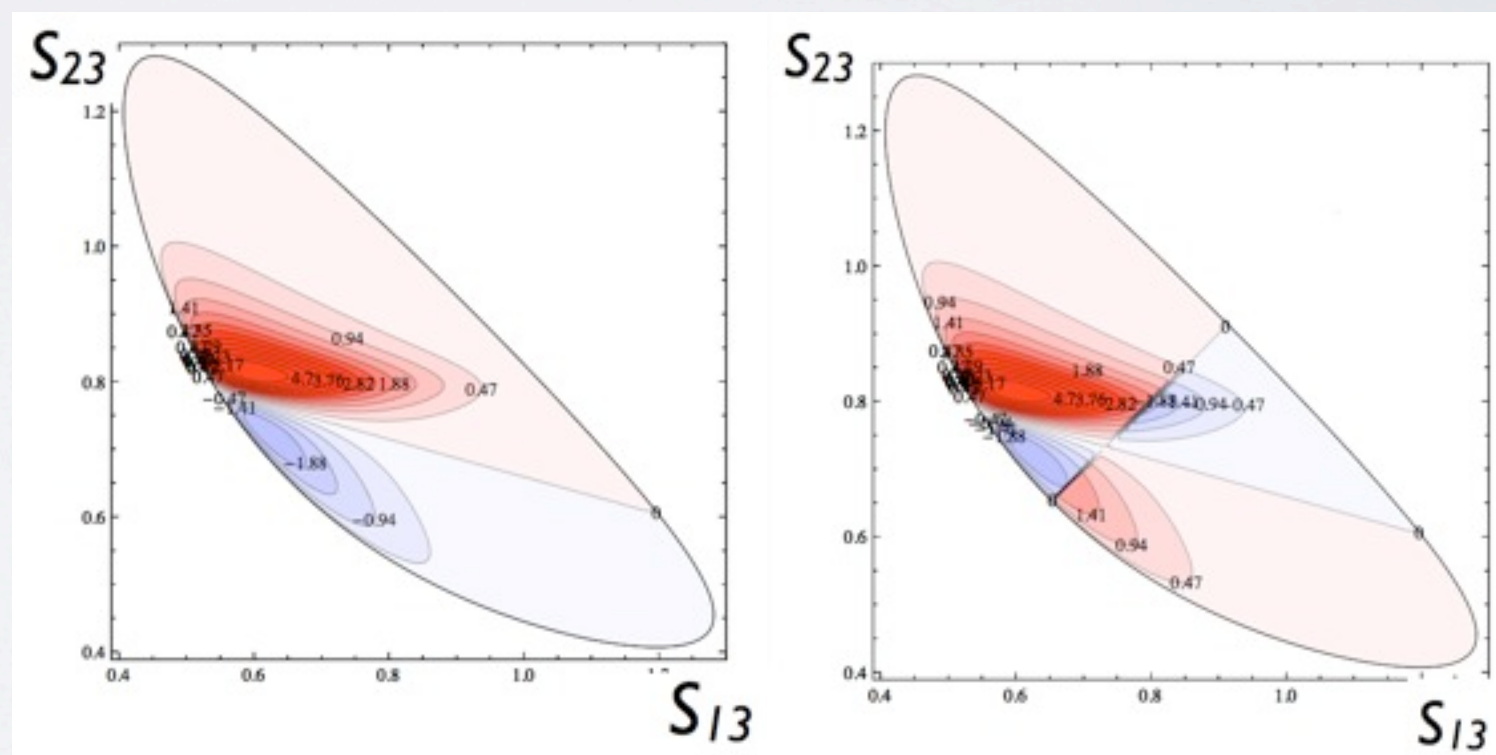
- Adding further orders in Legendre polynomials does not add information (extra parameters ~ 0)
  - Significance unchanged
- Further cross checks performed with counting experiment
  - Up-down asymmetries compatible
  - Lower significance (5.0σ)
  - Difference in significances with respect to the angular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

Angle convention

- In neutral decays, it is necessary to redefine the angle θ in order to avoid cancellations due to the symmetries of J with respect to the exchange of the two π
  - Not necessary in charged decays, but kept for consistency



$K_1(1400)^0$



$K_1(1270)^+$

From E. Kou
(LHCb Implications Workshop)