Towards the Ultimate Precision in Flavour Physics (16–18 April 2018)

Standard Model tests in modes with photons

Albert Puig, *on behalf of the LHCb collaboration*

(With many thanks to D. Straub)

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FNSNF
Fonds national suisse
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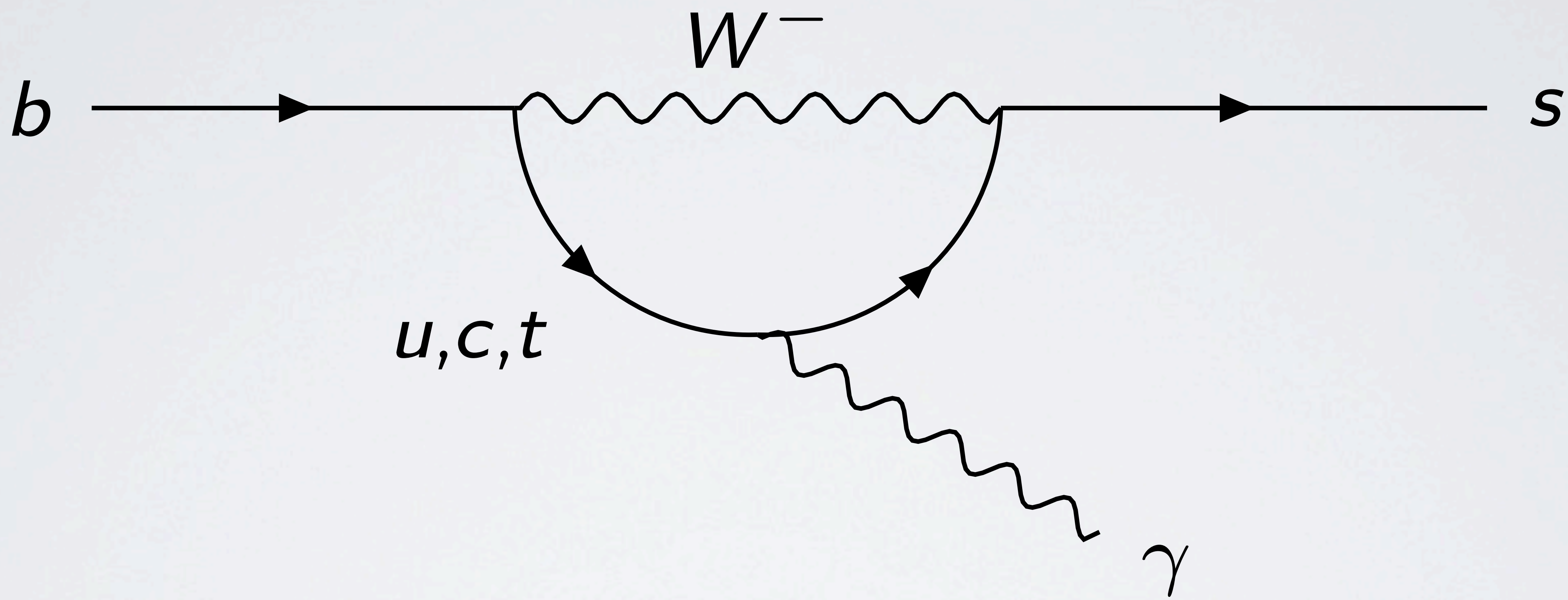
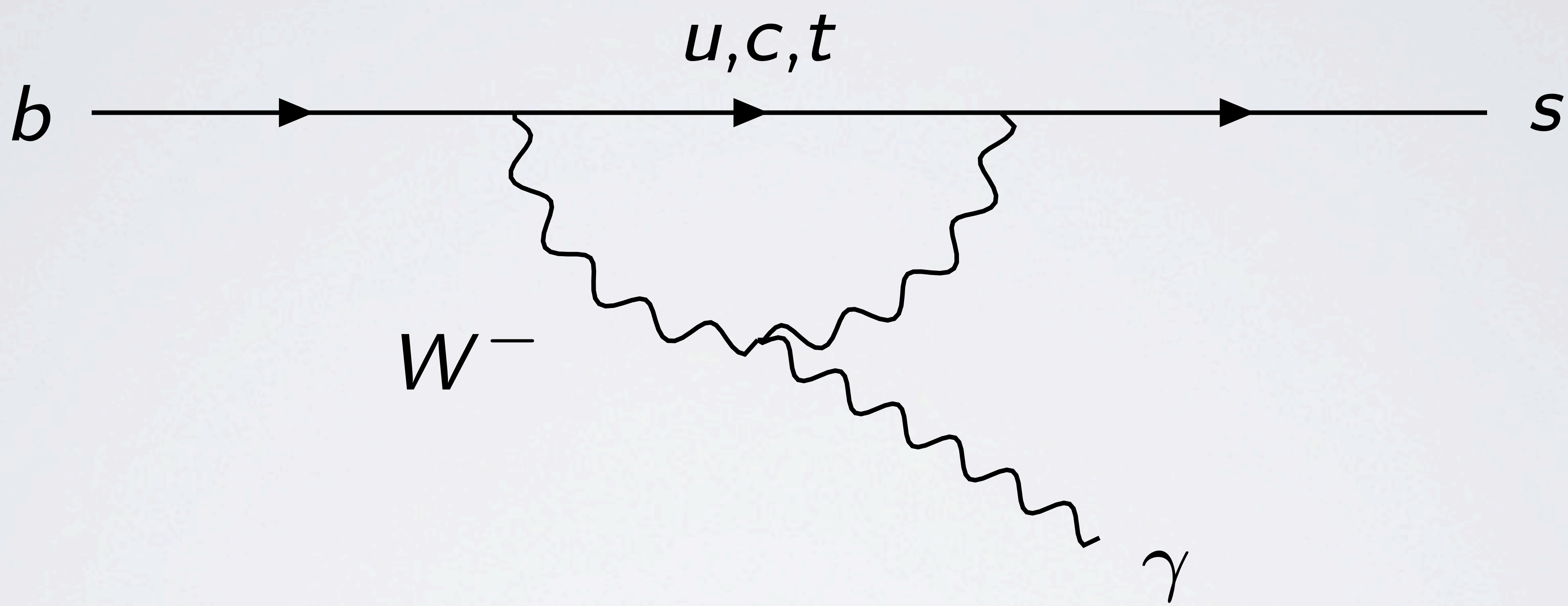

b
W^-
s
u,c,t
γ


u,c,t
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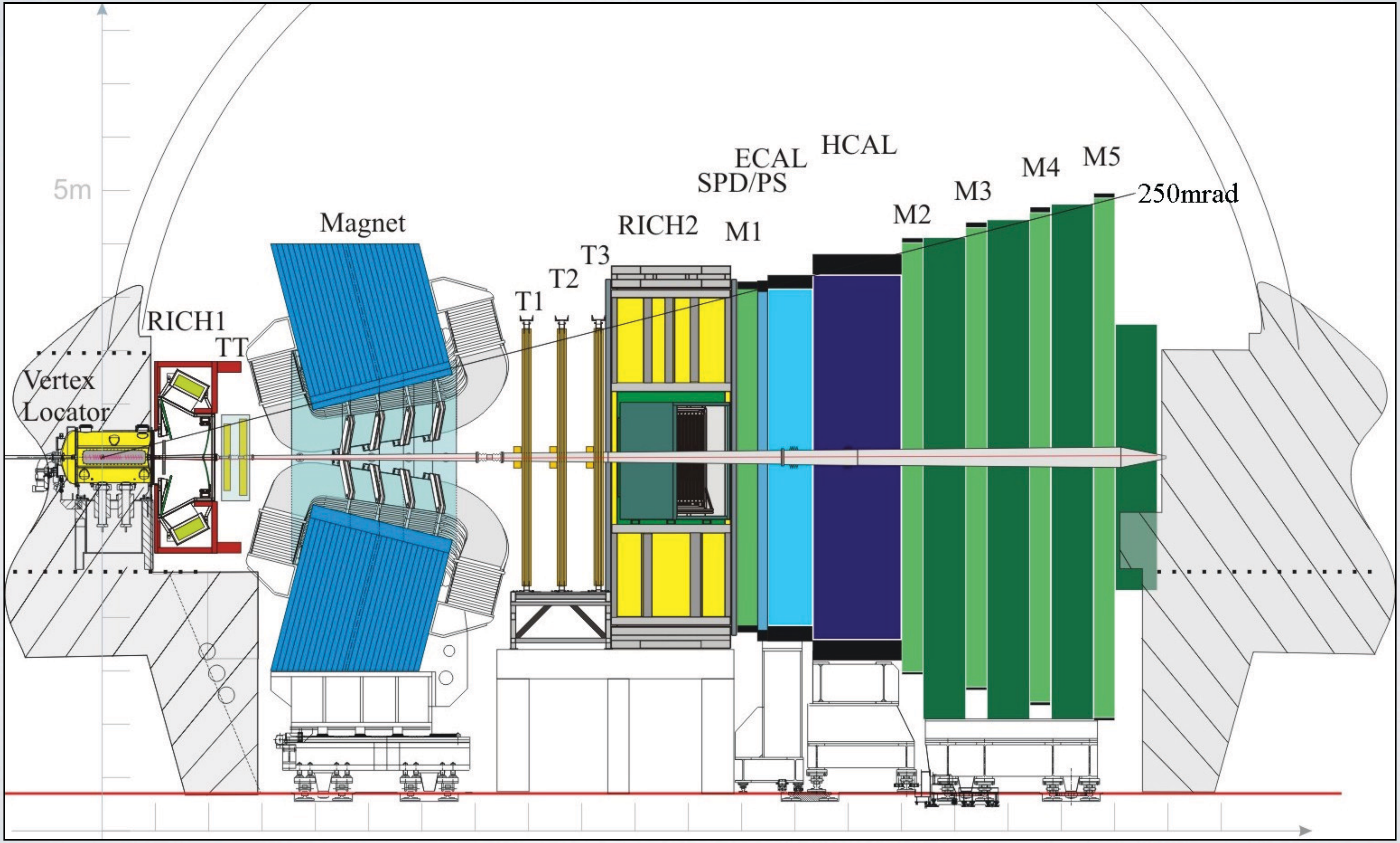
[JINST 3 (2008) S08005]

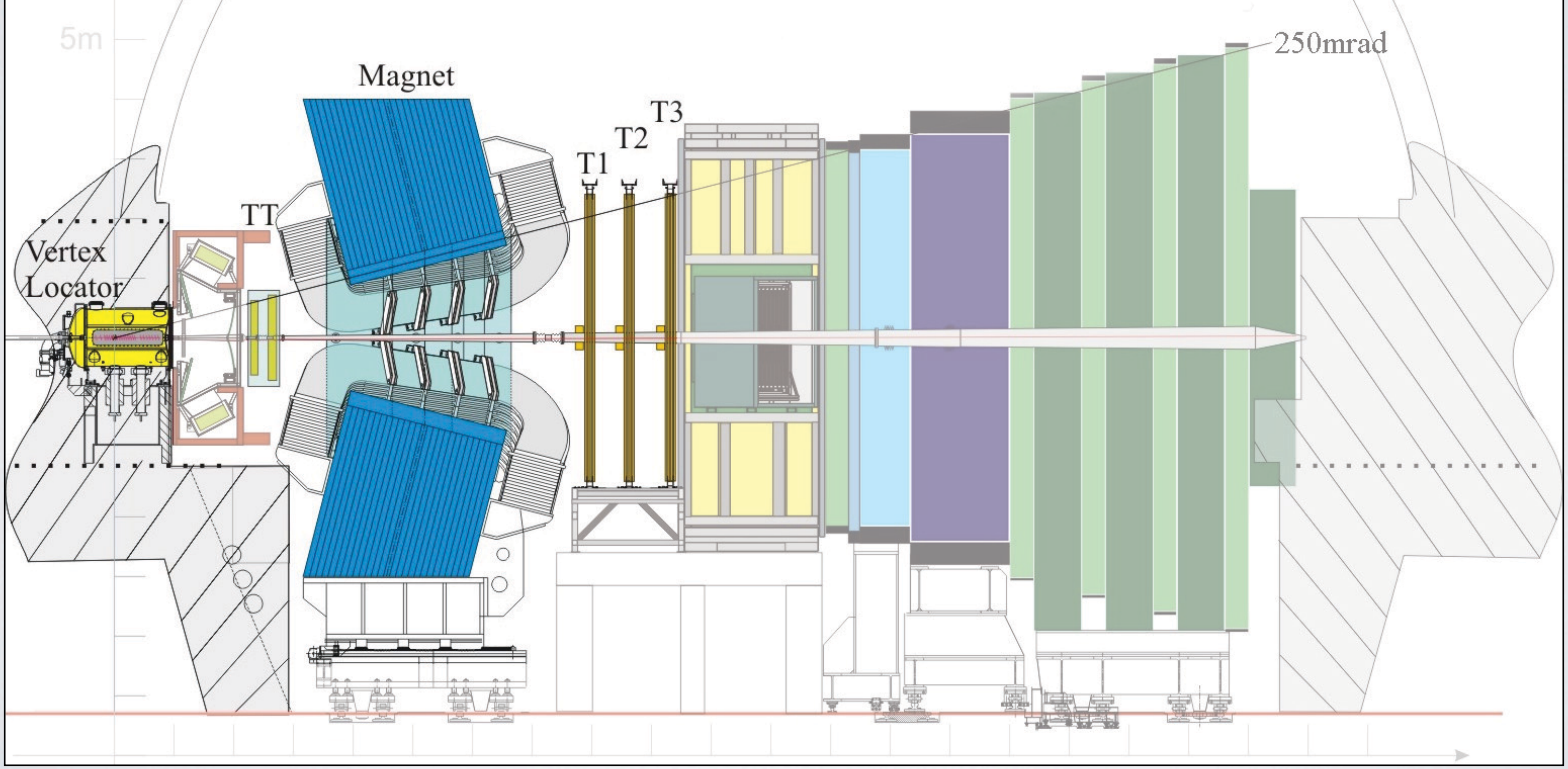
The LHCb experiment



[JINST 3 (2008) S08005]

The LHCb experiment

Precise tracking
Good mass and IP resolution
Good vertex resolution

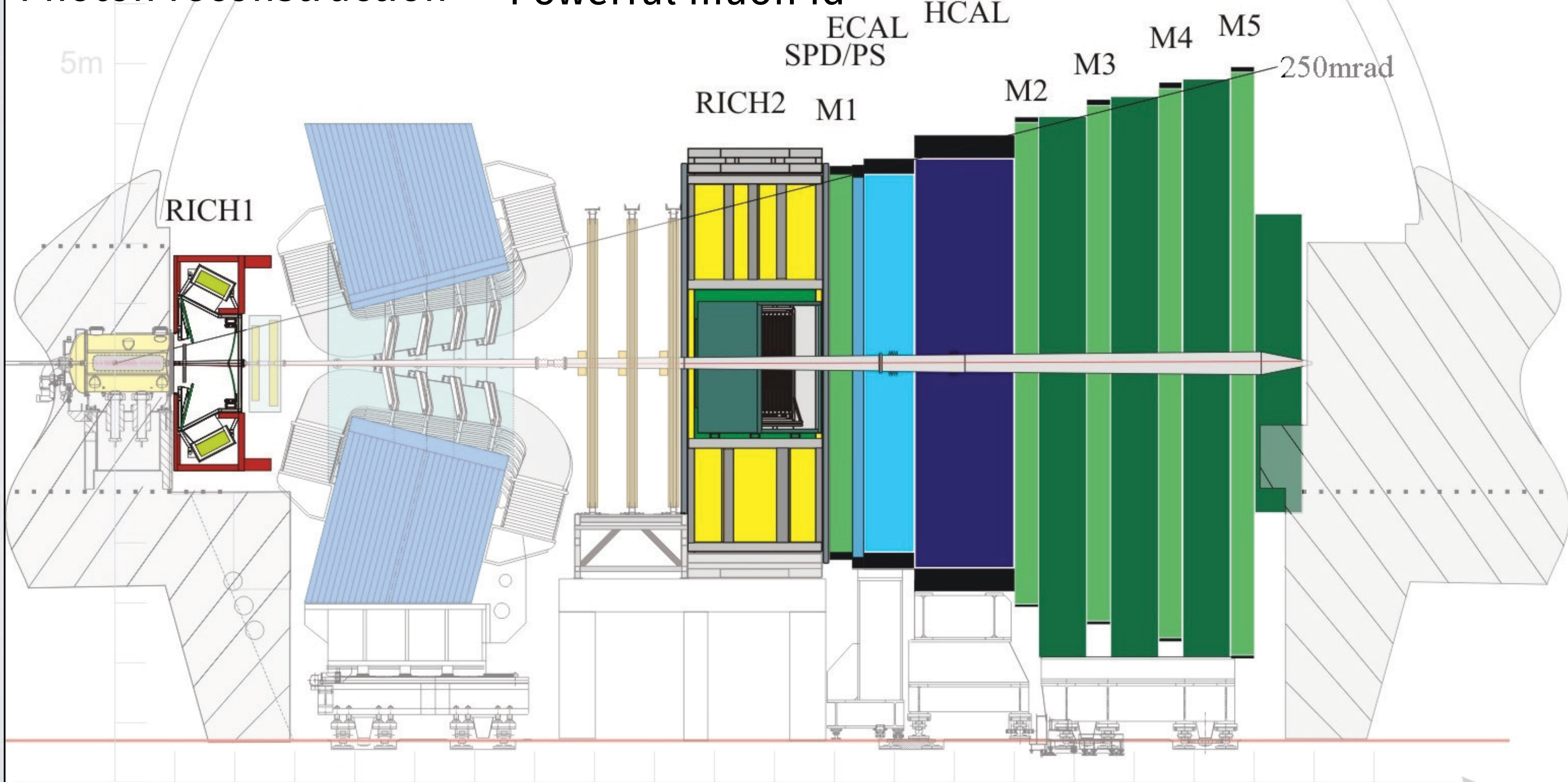


[JINST 3 (2008) S08005]

The LHCb experiment

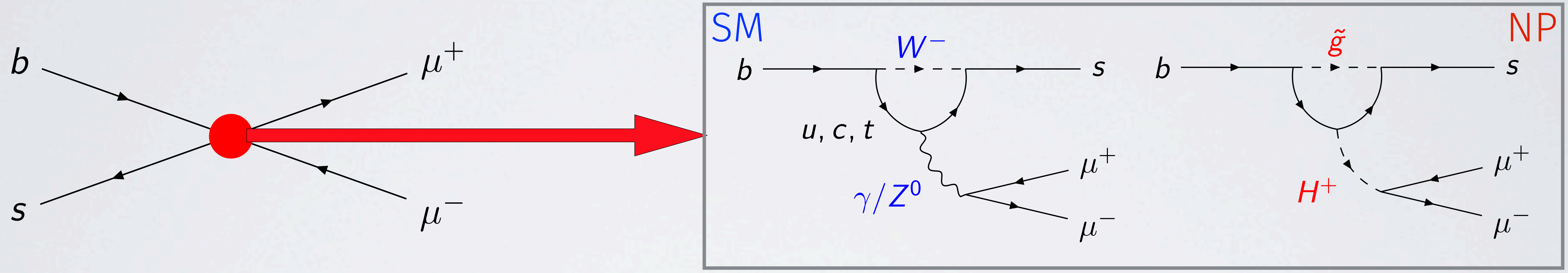
Calorimeter system
Trigger
Photon reconstruction

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



Radiative decays

Rare decays of heavy mesons are FCNC (forbidden at tree level and thus highly suppressed) sensitive to quantum corrections from degrees of freedom at larger scales



Radiative decays are $b \to s\gamma$ FCNC

- Inclusive decays are clean, but hard experimentally
- Exclusive decays have large theoretical uncertainties, so need to find form-factor free observables (CP and isospin asymmetries)
- **Null test of the SM: the photon polarisation**

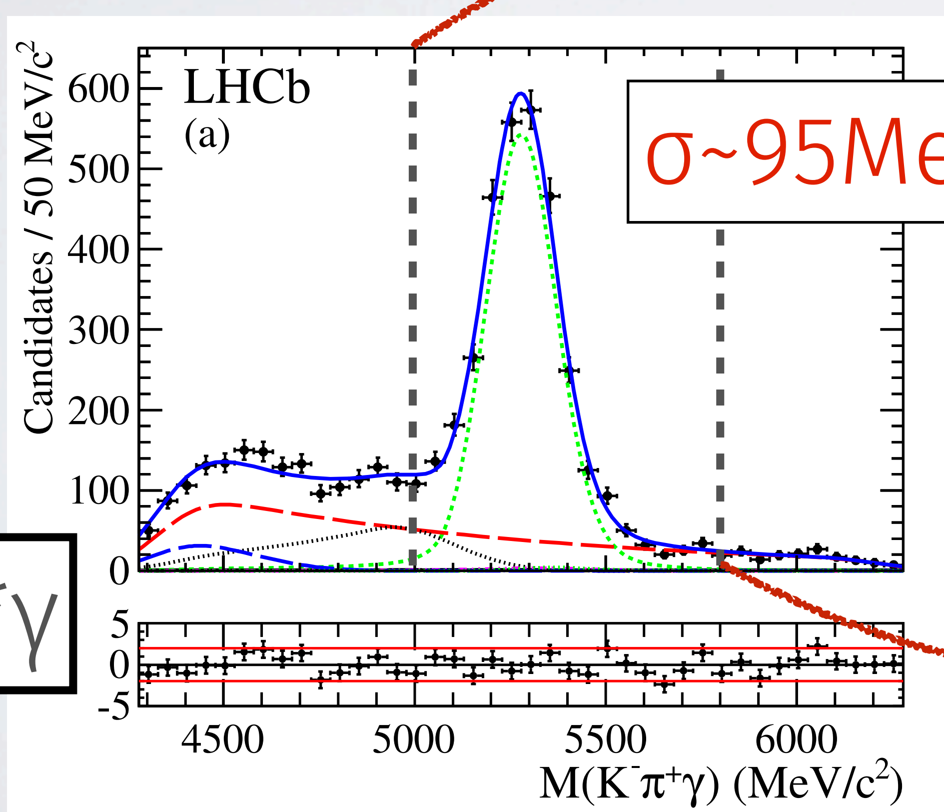
Challenges for radiative decays

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

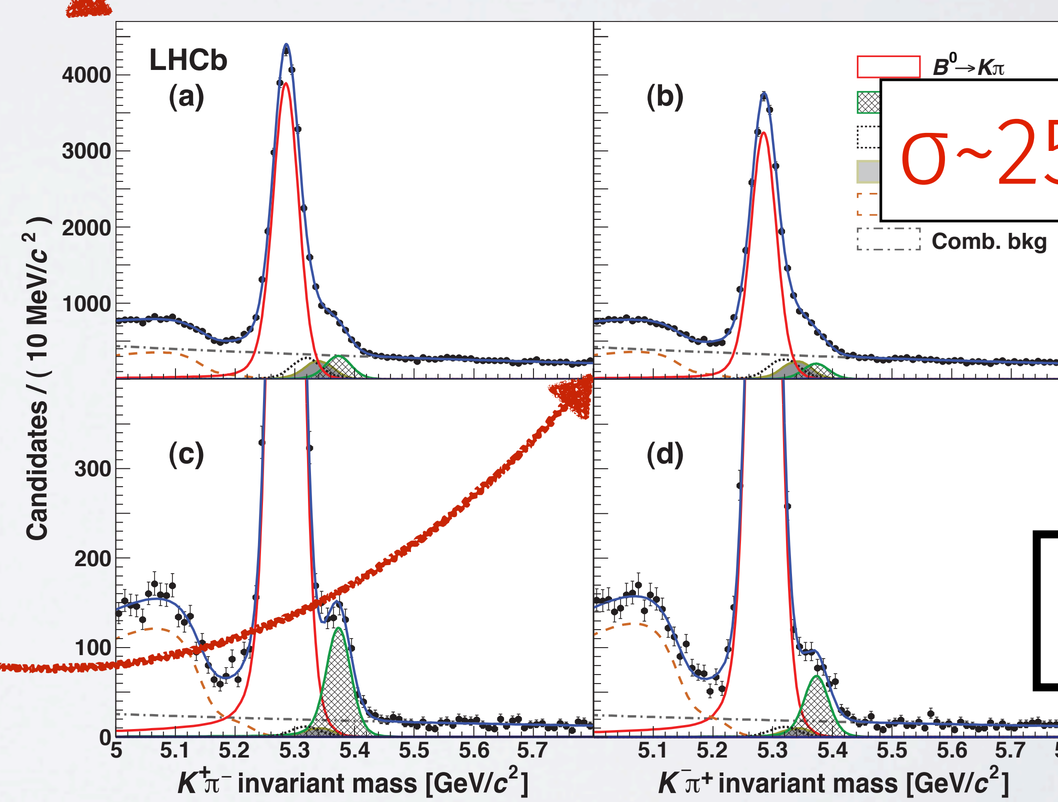
$B \to K^* \gamma$



σ~95MeV

[Nucl. Phys. B 867 (2012)]

σ~25MeV



$B \to K\pi$

[PRL 110 (2013) 221601]

Photon polarisation 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. This, combined with the chiral structure of the $b \to s\gamma$ process causes the photons to be (almost completely) circularly polarised

- The requirement of a chirality flip leads to left-handed photon dominance

Photon polarisation never been measured with precision

Photon polarisation in the SM

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

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Photon polarisation never been measured with precision

Describing FCNC processes

FCNC are described by an effective Hamiltonian in the form of an Operator Product Expansion, which allows to identify the types of operators (O_i) that enter in each transition, along with their corresponding Wilson coefficients (C_i)

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i \Big\{ \underbrace{C_i O_i}_{\text{left-handed}} + \underbrace{C_i' O_i'}_{\substack{\text{right-handed} \\ \text{(suppressed in the SM)}}} \Big\} + \sum_i \underbrace{\frac{C_i^{\text{NP}}}{\Lambda^2} O_i^{\text{NP}}}_{\text{new physics}}$$

Describing FCNC processes

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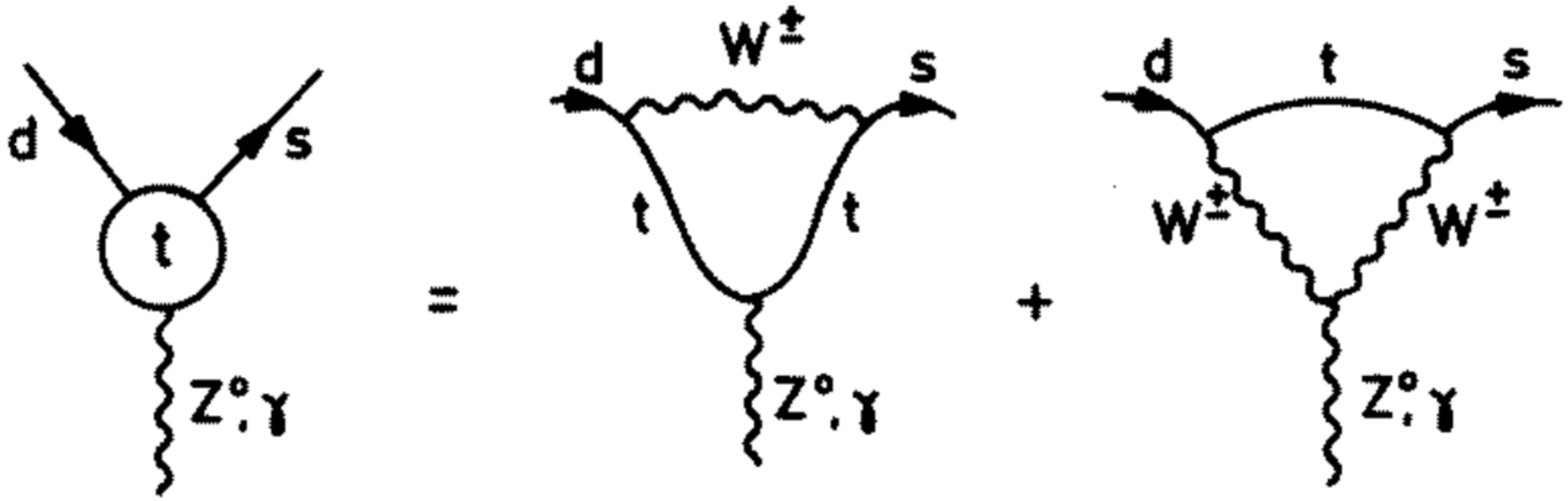
$\mathcal{H}_{\text{eff}}$ … O_i^{NP}

…hysics

Photon polarization mainly concerned with

$$O_{7\gamma} \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$



[Buras, hep-ph/9806471]

$b \to s\gamma$ in practice

$O_{1\ldots6,8}$ also enter as non factorisable contributions

$$C_7 = C_7^{\rm eff} + \Delta C_7$$

$$C_7^{\rm eff,SM}(\mu = m_b) = -0.2915$$

$$C_7^{\prime,\rm SM} = \frac{m_s}{m_b} C_7^{\rm SM}$$

$$\Delta C_7 = \sum_{l=1\cdots6,8} C_i \frac{\langle O_i \rangle}{\langle O_7 \rangle}$$

	$B^0 \to K^*\gamma$	$B^+ \to K^*\gamma$	$B_s \to \phi\gamma$
Vertex corrections	$-(7.8 \pm 1.0) - (1.1 \pm 0.3)i$		
Spectator scattering Q_{1-6}	$-0.7 - 1.3i$	$-0.7 - 1.3i$	$-0.7 - 1.7i$
Spectator scattering Q_8	-0.3	-0.3	-0.4
Weak annihilation	-0.4	$+0.9$	-0.5

[JHEP04 (2017) 027]

b→sγ in practice

$O_{1\ldots6,8}$ also enter as non factorisable contributions

Remaining effects estimated to be <1.5% [PRD 75 (2007) 054004, JHEP 09 (2010)089, PLB 664 (2008)174–179], but need to cross check assumptions on ΔC_7 by measuring several hadronic systems

$C_7^{\mathrm{eff,S}}$

	$B^0 \to K^*\gamma$	$B^+ \to K^*\gamma$	$B_s \to \phi\gamma$
Vertex corrections	$-(7.8 \pm 1.0) - (1.1 \pm 0.3)i$		
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$$\Delta C_7 = \sum_{I=1\cdots6,8} C_i \frac{\langle O_i \rangle}{\langle O_7 \rangle}$$

[JHEP04 (2017) 027]

Measuring $C_7^{(')}$

Inclusive branching fraction measurements

Time-dependent analyses of $B_{(s)} \to f^{CP}\gamma$, *e.g.*, $B_s \to \varphi\gamma$ and $B^0 \to K_S\pi^0\gamma$

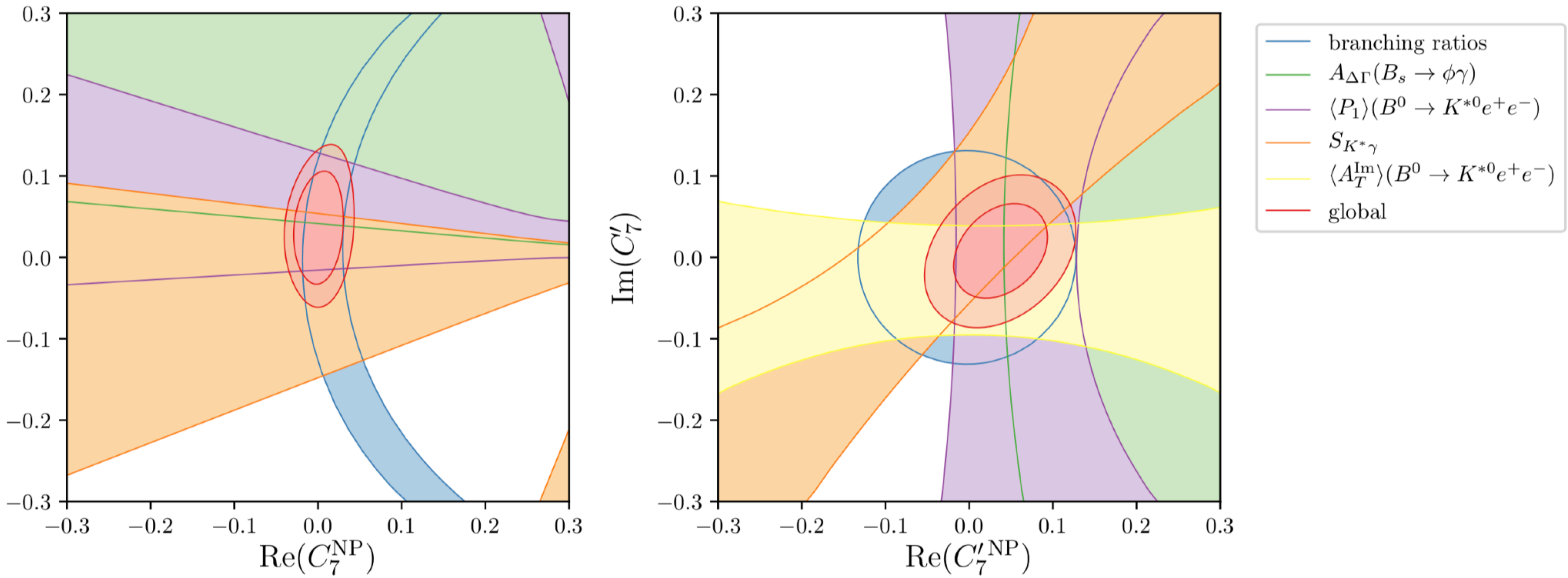
Angular distribution of radiative decays with 3 charged tracks in the final state, *e.g.*, $B \to K\pi\pi\gamma$

b-baryons: $\Lambda_b \to \Lambda^{(*)}\gamma$, $\Xi_b \to \Xi^{(*)}\gamma$

Transverse asymmetry in $B^0 \to K^* l^+ l^-$

[JHEP04 (2017) 027]

Current status



Inclusive BR measurement

$\mathrm{BR}(b \to X_{s(d)}\,\gamma) \propto |C_7^{\mathrm{eff}}|^2 + |C_7'|^2$

- Very precisely measured at the B factories
- Very precise theory prediction

$$BR(B \to X_s\gamma)^{\mathrm{SM}}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.36 \pm 0.23) \times 10^{-4}$$ [PRL 114 221801 (2015)]

$$BR(B \to X_s\gamma)^{\mathrm{exp}}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.32 \pm 0.15) \times 10^{-4}$$ [EPJC77 (2017) 895]

Excellent theory/experiment prediction

- Experimental improvements could come from Belle II, but theory limitations

Time-dependent CP analyses

$$\Gamma(B_q(\bar{B}_q) \to f_{CP}\gamma)(t) \sim e^{-\Gamma_q t}\Big[\cosh\left(\frac{\Delta\Gamma_q}{2}\right) - \mathcal{A}^{\Delta}\sinh\left(\frac{\Delta\Gamma_q}{2}\right) \pm \mathcal{C}\cos(\Delta m_q t) \mp \mathcal{S}\sin(\Delta m_q t)\Big]$$

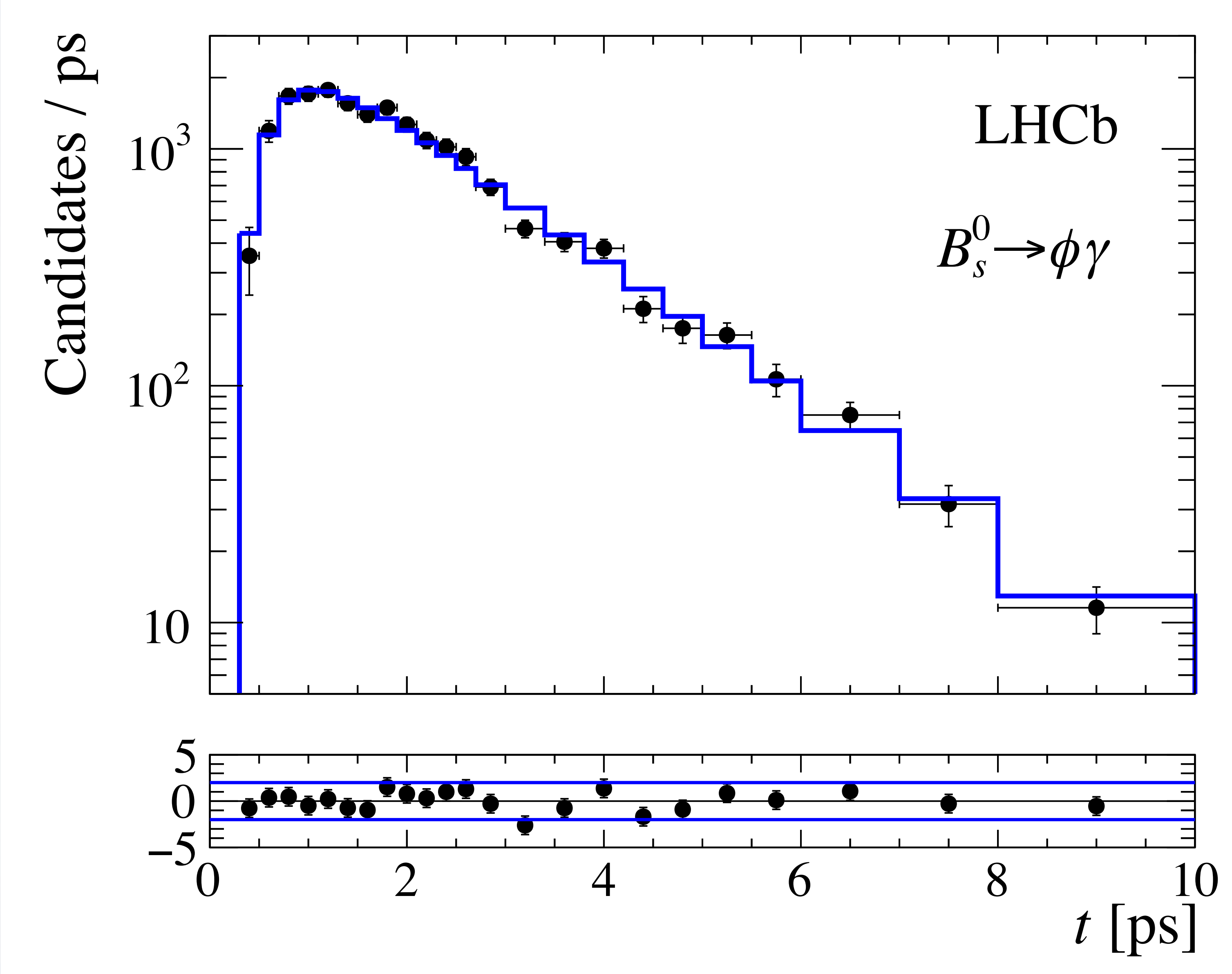
Defining **tanξ = |C_7'/C_7|**, both *S* and A^{Δ} are proportional to sin(2ξ)

- These observables measure the ratio of amplitudes with left- and right-handed photons
- Null test for ξ→0, but in case of sizeable values due to NP, small dependence on strong phases

[PRL 118 (2017) 021801]

$B_s \to \varphi\gamma$ lifetime

Without distinguishing the flavour, LHCb has measured A^{Δ} through the fit of the effective lifetime of the B_s



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

Consistent with SM at 2σ

$S(B^0 \to K^{*0}\gamma)$

Measured at the *B*-factories

$$S_{K^*\gamma} = -0.03 \pm 0.29 \text{ (stat)} \pm 0.03 \text{ (syst)},$$
$$C_{K^*\gamma} = -0.14 \pm 0.16 \text{ (stat)} \pm 0.03 \text{ (syst)},$$

[BaBar, PRD78 (2008) 071102]

$$\mathcal{S}_{K^0_S\pi^0\gamma} = -0.10 \pm 0.31\text{(stat)} \pm 0.07\text{(syst)},$$
$$\mathcal{A}_{K^0_S\pi^0\gamma} = -0.20 \pm 0.20\text{(stat)} \pm 0.06\text{(syst)},$$

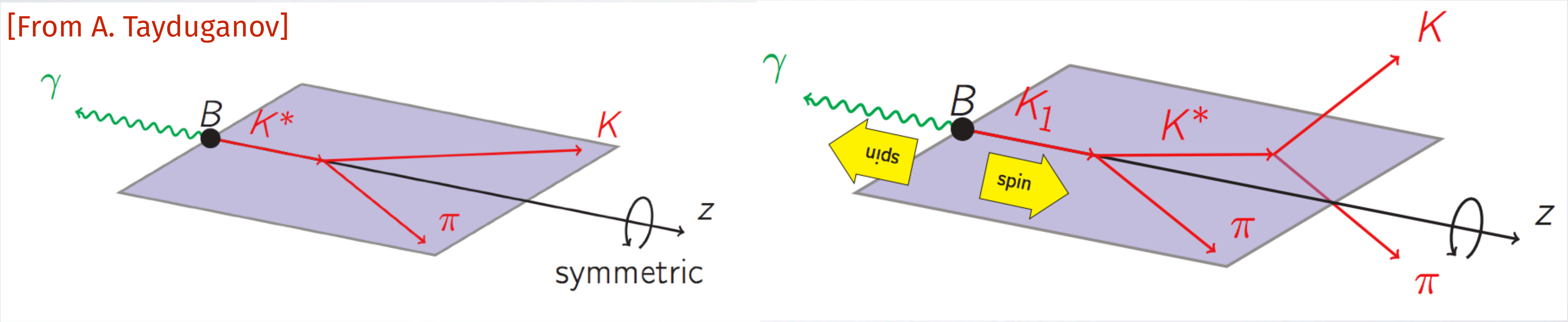
[Belle, PRD 74 (2006) 111104]

Expect 3% precision at Belle II

$B^+ \to K\pi\pi\gamma$ angular analysis

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

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



$B^+ \to K\pi\pi\gamma$ angular analysis

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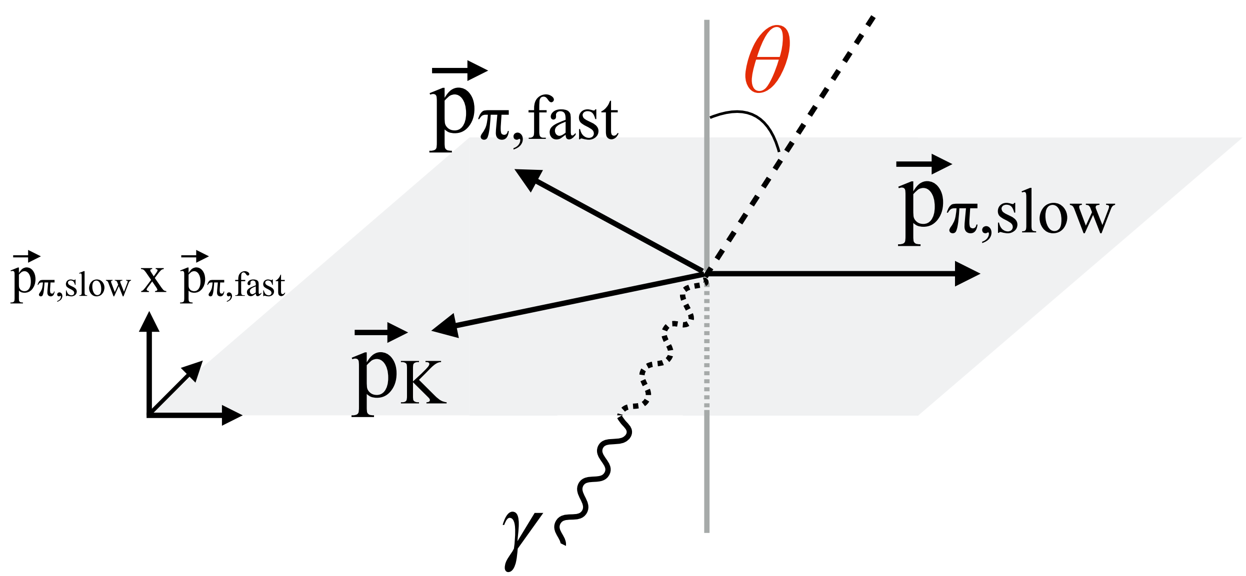
The photon polarisation can be inferred from the polarisation of the *K* resonance



symmetric

[PRL 112 (2014) 161801]

$B^+ \to K\pi\pi\gamma$ angular analysis

For a given $K_{\text{resonance}} \to K\pi\pi$, the decay amplitude is a function of the Dalitz variables and the photon polarisation

The $K_{\text{resonance}}$ spectrum is very complex, so LHCb studied the up-down asymmetry to determine if the photon is polarised or not

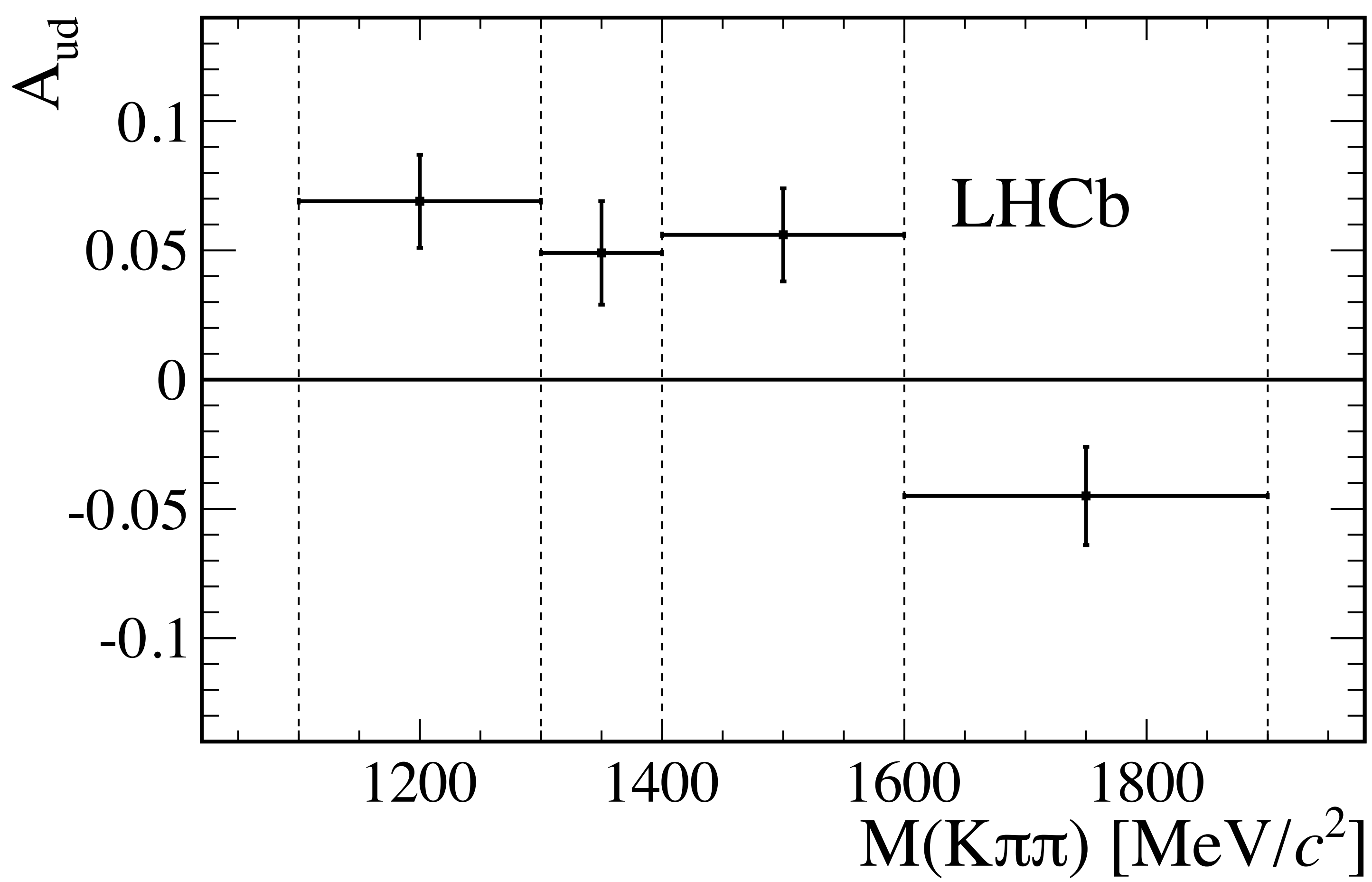
$$\frac{\mathrm{d}\,\Gamma(B^+ \to K_{\text{res}} \to K^+\pi^-\pi^+\gamma)}{\mathrm{d}\,s\,\mathrm{d}\,s_{13}\,\mathrm{d}\,s_{23}\,\mathrm{d}\cos\theta} \propto \sum_{j=\text{even}} a_i(s_{13}, s_{23}) \cos^j\theta + \text{Pol}_\gamma \sum_{j=\text{odd}} a_i(s_{13}, s_{23}) \cos^j\theta$$

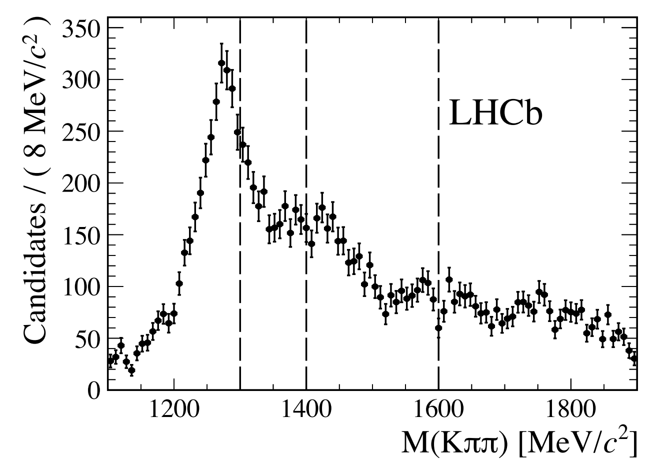
$$\mathcal{A}_{\text{UD}} \equiv \frac{\int_0^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\,\Gamma}{\mathrm{d}\cos\theta} - \int_{-1}^0 \mathrm{d}\cos\theta \frac{\mathrm{d}\,\Gamma}{\mathrm{d}\cos\theta}}{\int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\,\Gamma}{\mathrm{d}\cos\theta}} = C\lambda_\gamma$$

[PRL 112 (2014) 161801]

$B^+ \to K\pi\pi\gamma$ angular analysis

Determination of non-zero polarization at 5.2σ, but theory input and full amplitude analysis are needed to determine the exact value of the polarisation





[PRL 112 (2014) 161801]

$B \to K\pi\pi\gamma$ angular analysis

Without Dalitz information it is not possible to extract the value of the photon polarisation λ

Even with this information, the photon polarisation parameter λ can be expressed as $\cos(2\xi) \sim 1 - 2\xi^2 + O(\xi^4)$

- Require higher relative precision wrt to time-dependent analyses and rich hadronic system plagues measurement with hadronic uncertainties
- Complementary dependence

$B \to K\pi\pi\gamma$ amplitude analysis

Idea: extract λ directly from an amplitude fit to the $B \to K\pi\pi\gamma$ system

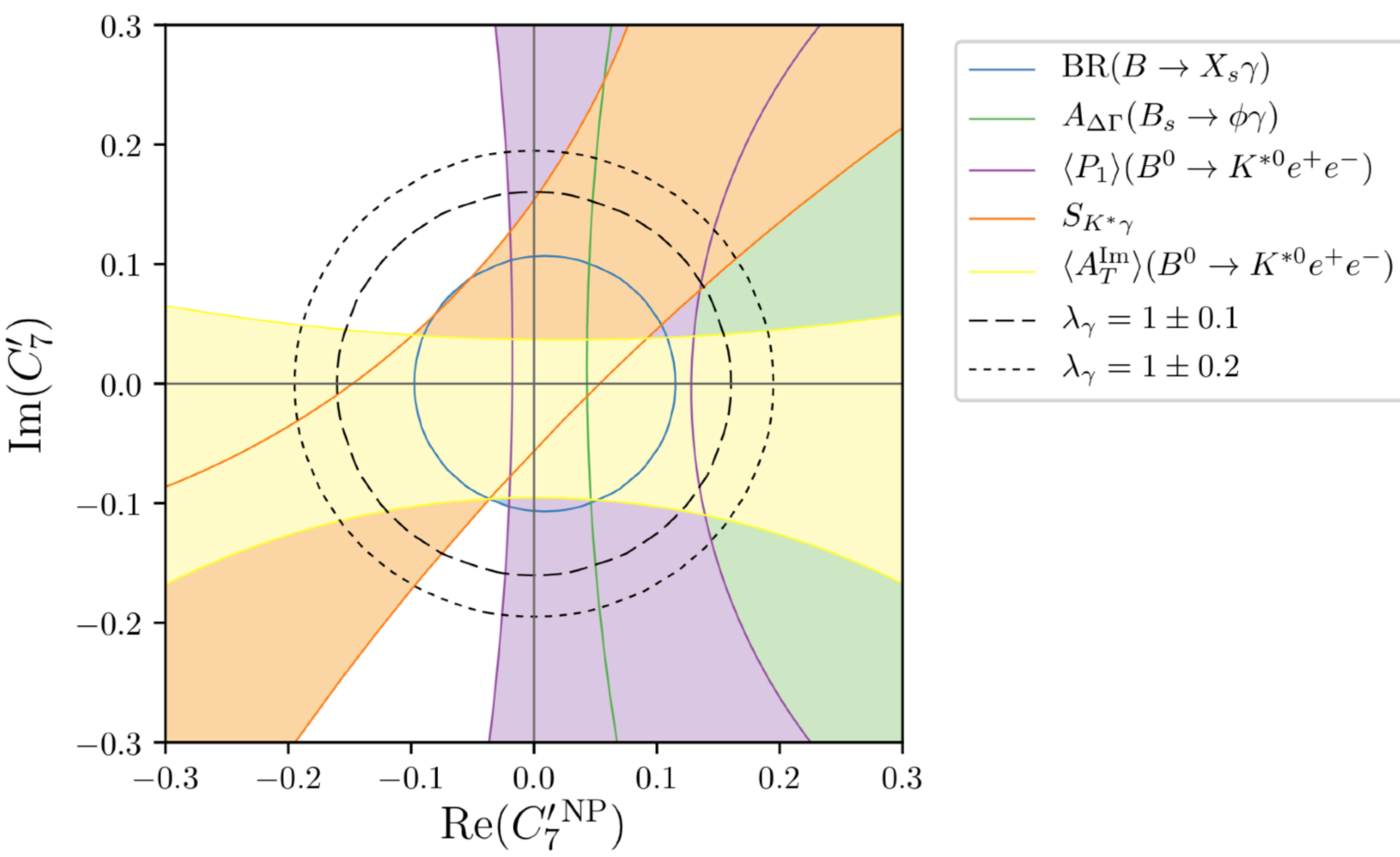
- Keep the same requirements wrt to precision, but drop the hadronic uncertainties

Preliminary studies [Bellée et al, in preparation] show a statistical precision of ~5% with Run 1 statistics, systematics still unclear

- Potentially interesting constraints for model building

$B \to K\pi\pi\gamma$ amplitude analysis

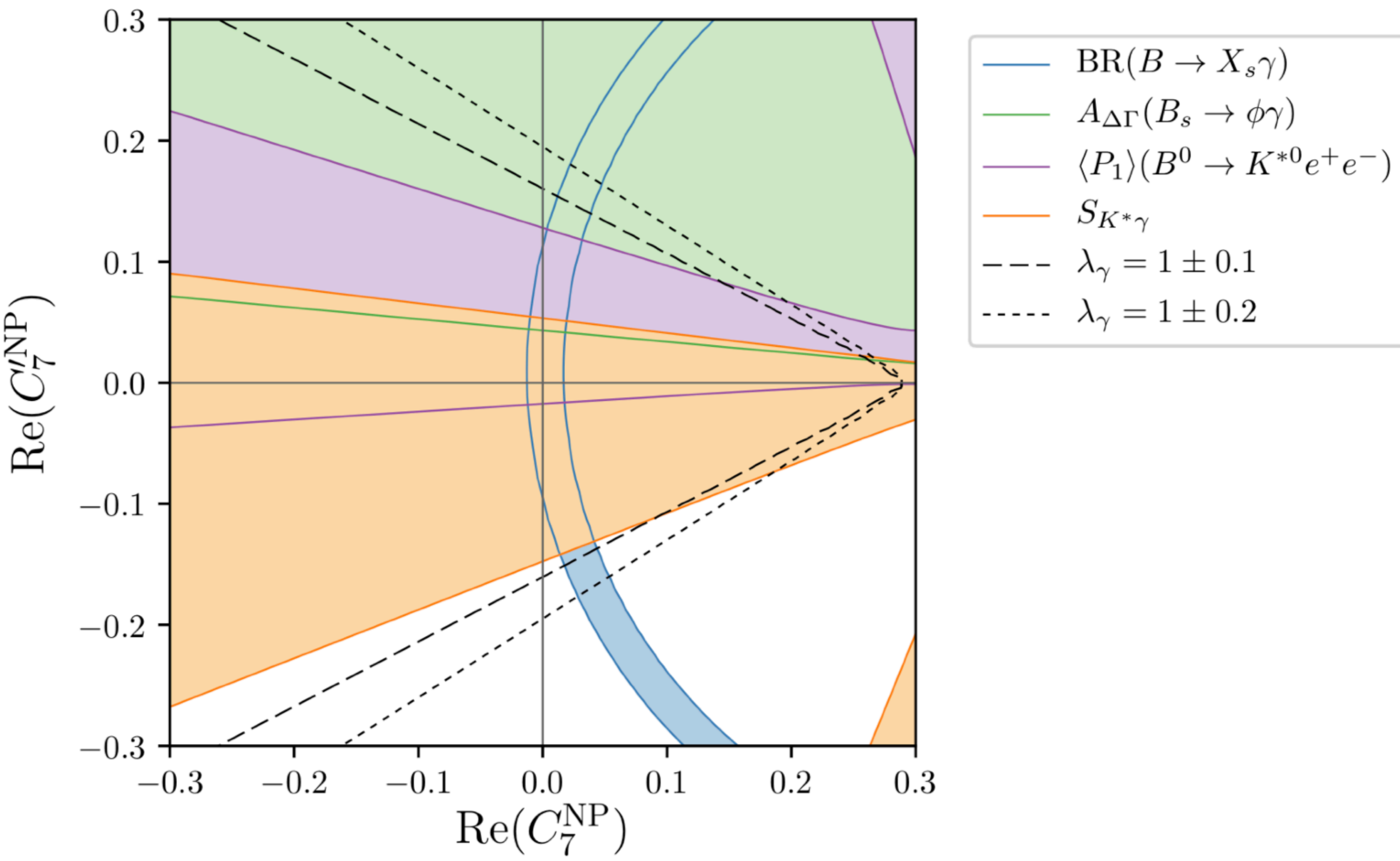
update of Paul and Straub 1608.02556 see also Becirevic et al. 1206.1502 Descotes-Genon et al. 1104.3342



assuming C_7 to be SM-like; neglecting theory uncertainties and ΔC_7 in λ_γ

[D. Straub @ $B \to K\pi\pi\gamma$ workshop]

$B \to K\pi\pi\gamma$ amplitude analysis



assuming $\mathrm{Im}(C_7^{(\prime)}) = 0$; neglecting theory uncertainties and ΔC_7 in λ_γ

[D. Straub @ B→Kππγ workshop]

b-baryon angular analyses

Weak radiative decays of *b*-baryons have not yet been observed, but are sensitive to the photon polarisation through their angular distributions

$$\frac{\mathrm{d}\,\Gamma}{\mathrm{d}\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b^0} \cos\theta_\gamma$$

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

Since α_γ is λ_γ at LO, their dependence on ξ is the same, and thus high precision is required

- Interesting due to different form factors

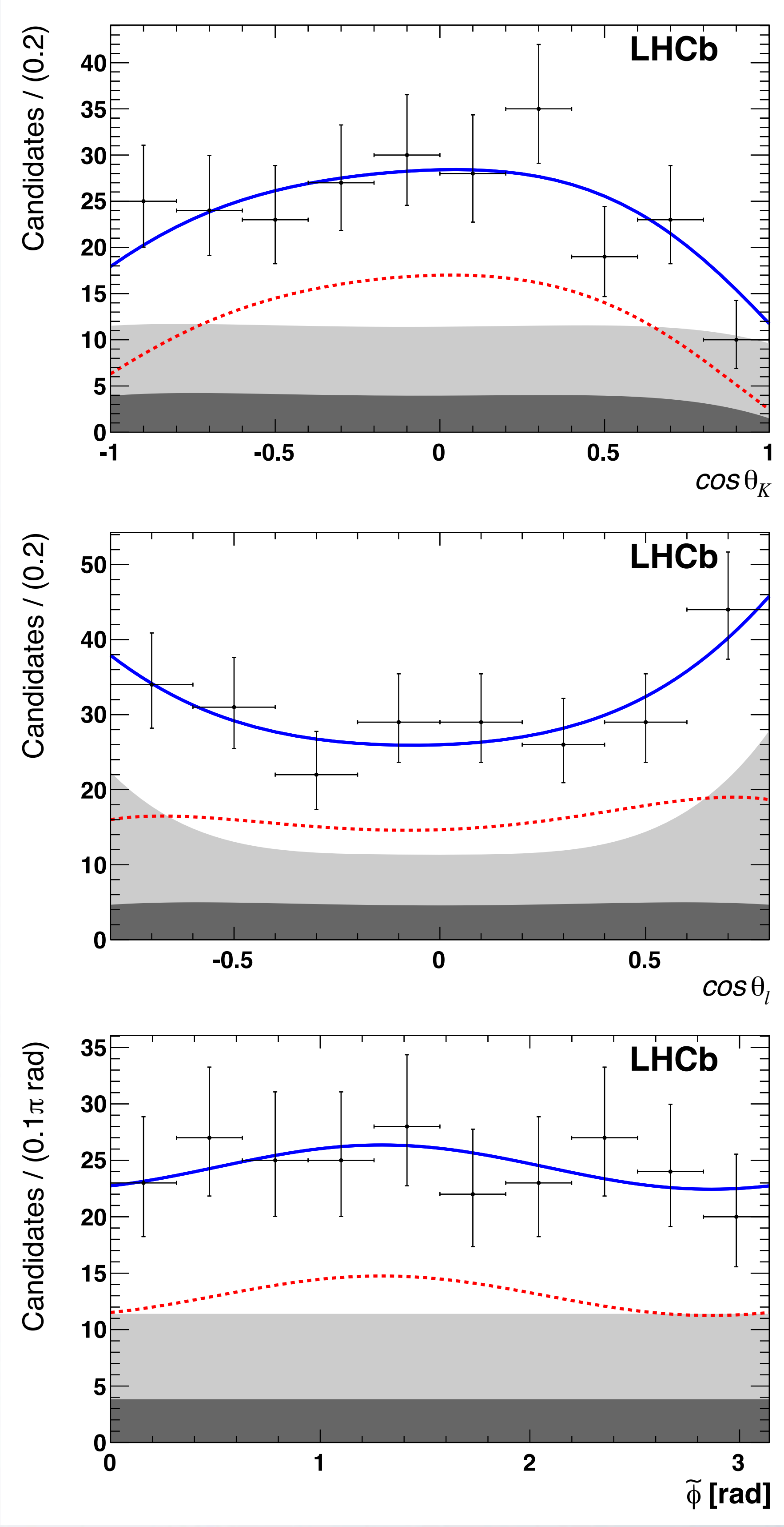
[LHCb, JHEP 04 (2015) 064]

And $B^0 \to K^{*0} e^+ e^-$

Angular analysis at very low $m(e^+e^-)$, sensitive to photon polarisation, using simplified distribution with 4 observables

- $A_T^{(2)}$ and A_T^{Im} only depend on helicity amplitudes with transverse K* (so no pollution from NP in O_9 and O_{10})
- Dependence on C_7' as sin(2ξ)

$$F_L = 0.16 \pm 0.06 \pm 0.03$$
$$A_T^{\mathrm{Re}} = 0.10 \pm 0.18 \pm 0.05$$
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_T^{\mathrm{Im}} = 0.14 \pm 0.22 \pm 0.05$$



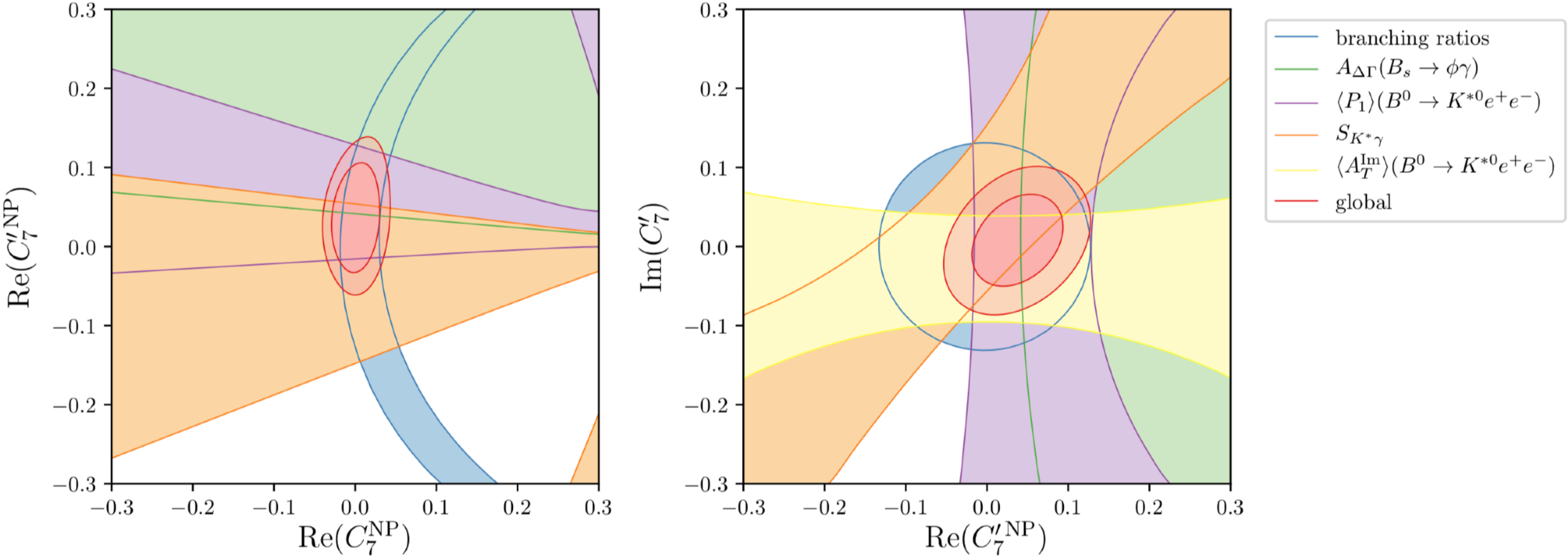
[JHEP04 (2017) 027]

Summary of measurements

Observable	SM prediction		Measurement	
$10^4 \times \mathrm{BR}(B \to X_s\gamma)_{E_\gamma>1.6\,\mathrm{GeV}}$	3.36 ± 0.23	[16]	3.27 ± 0.14	[46]
$10^5 \times \mathrm{BR}(B^+ \to K^*\gamma)$	3.43 ± 0.84		4.21 ± 0.18	[19]
$10^5 \times \mathrm{BR}(B^0 \to K^*\gamma)$	3.48 ± 0.81		4.33 ± 0.15	[19]
$10^5 \times \overline{\mathrm{BR}}(B_s \to \phi\gamma)$	4.31 ± 0.86		3.5 ± 0.4	[47, 48]
$S(B^0 \to K^*\gamma)$	-0.023 ± 0.015		-0.16 ± 0.22	[19]
$A_{\mathrm{CP}}(B^0 \to K^*\gamma)$	0.003 ± 0.001		-0.002 ± 0.015	[19]
$A_{\Delta\Gamma}(B_s \to \phi\gamma)$	0.031 ± 0.021		-1.0 ± 0.5	[4]
$\langle P_1 \rangle(B^0 \to K^*e^+e^-)_{[0.002,1.12]}$	0.04 ± 0.02		-0.23 ± 0.24	[49]
$\langle A_T^{\mathrm{Im}} \rangle(B^0 \to K^*e^+e^-)_{[0.002,1.12]}$	0.0003 ± 0.0002		0.14 ± 0.23	[49]

[JHEP04 (2017) 027]

Current summary (again)



Conclusions

Currently, strong competition in exclusive $B \to V\gamma$ and $B \to Vee$, but different dependence on WCs

Addition of new modes and approaches will add even further complementary dependences

- Some of these new measurements can be extremely competitive!

"In view of hadronic uncertainties, using many different hadronic systems is important to corroborate constraints (or tensions!)" (D. Straub)

Conclusions

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With data from LHCb Upgrade + Belle II, the constraints in global fits will become quite narrow, and tensions coming from treatment of hadronic effects will be highlighted, even if C_7 is SM. This will be very useful in the study of anomalies in $b\to sll$ decays

"In view of hadronic uncertainties, using many different hadronic systems is important to corroborate constraints (or tensions!)" (D. Straub)

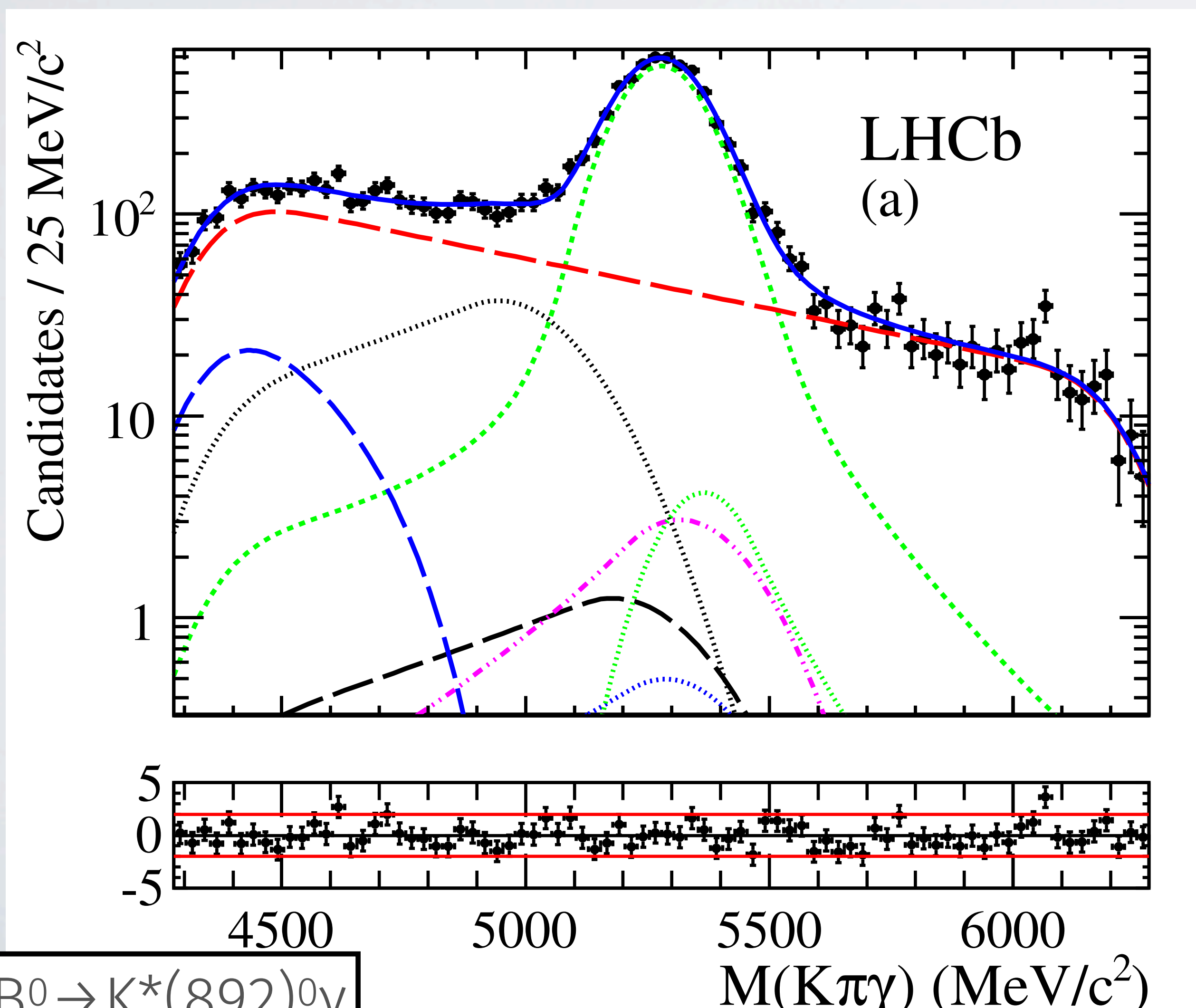
Thank you!

[JHEP 10 (2013) 183]

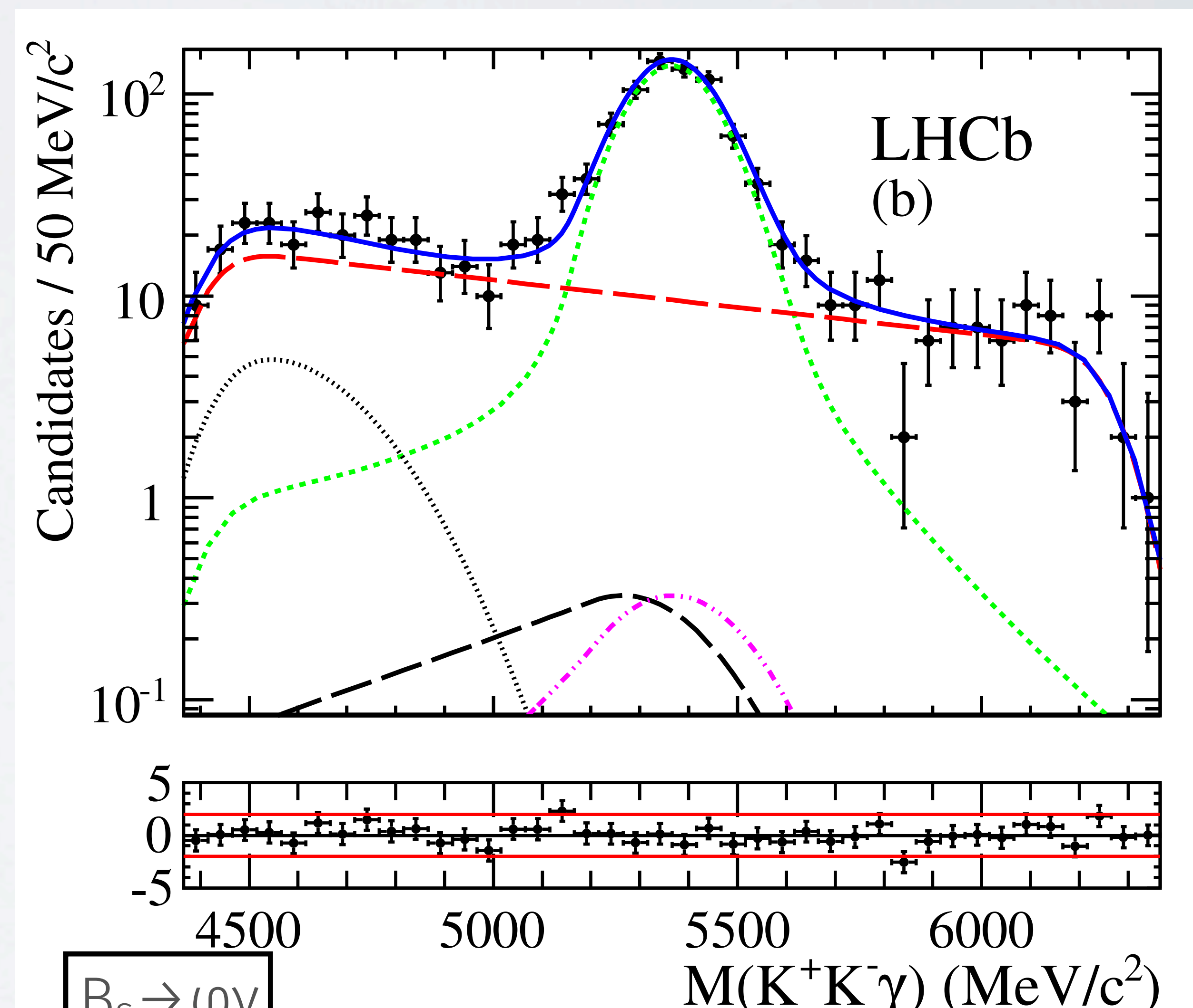
$B^0 \to K^{*0}\gamma$ and $B_s \to \varphi\gamma$ BF

$B^0 \to K^{*0}\gamma$ and $Bs \to \varphi\gamma$ BF ratio measured with 1/fb of data

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



$B^0 \to K^*(892)^0\gamma$



$B_s \to \varphi\gamma$

[JHEP 10 (2013) 183]

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

A_{CP} in $B^0 \to K^{*0}\gamma$ measured with 1/fb of LHCb data

$$A_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst}))\%$$

$$A_{CP}^{SM}(B^0 \to K^{*0}\gamma) = (-0.61 \pm 0.43)\%$$

Main systematic coming from A_{CP} in the background

Update with full Run 1 coming soon (including ratio of BF), getting closer to systematic limitation