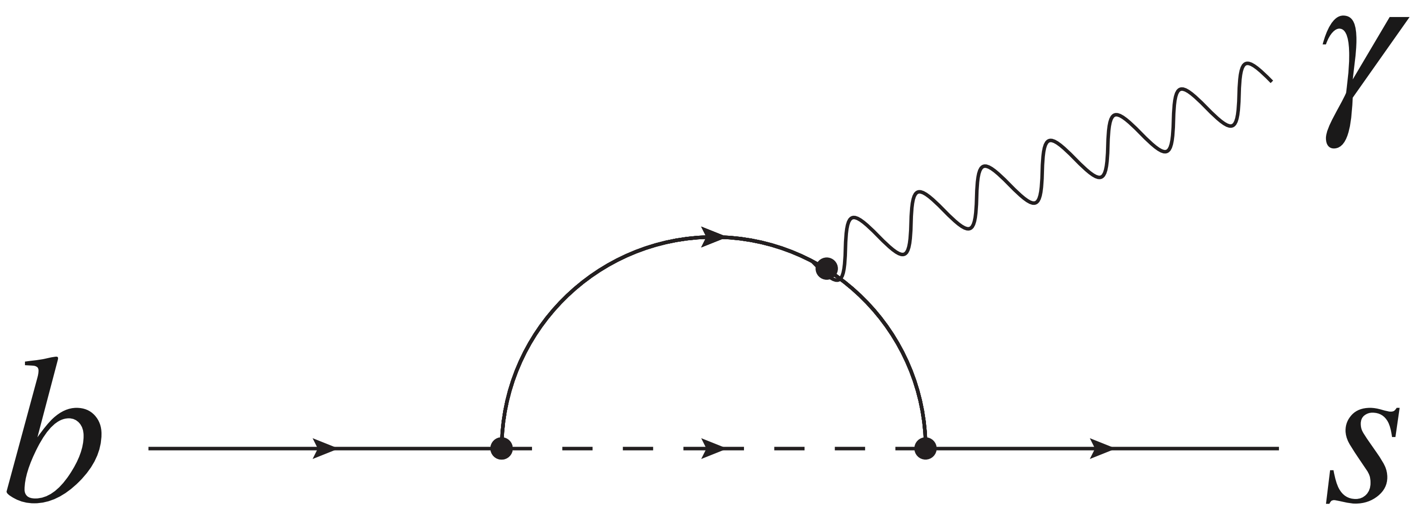
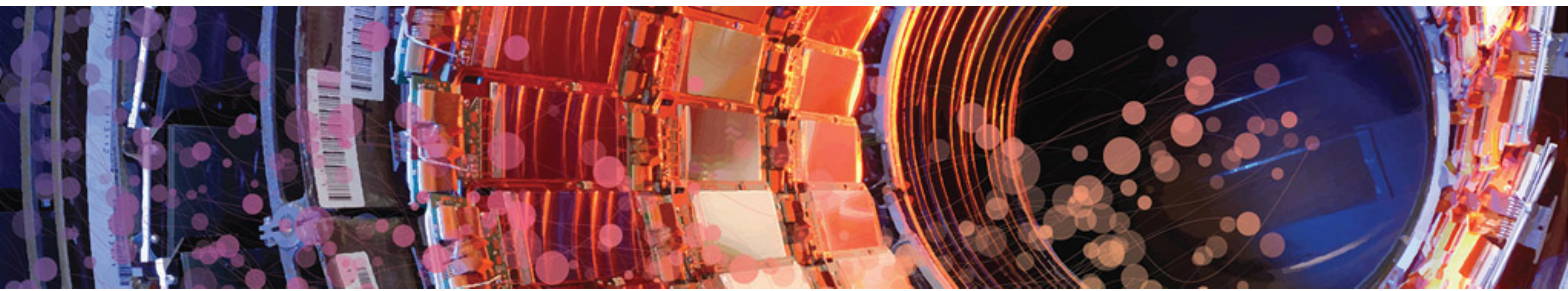


Alexander von Humboldt
Stiftung / Foundation



ICHEP 2020 - ~~Prague~~ virtual

Rare Radiative decays at LHCb

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On behalf of the LHCb Collaboration

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@MartinoBorsato

$b \to s\gamma$

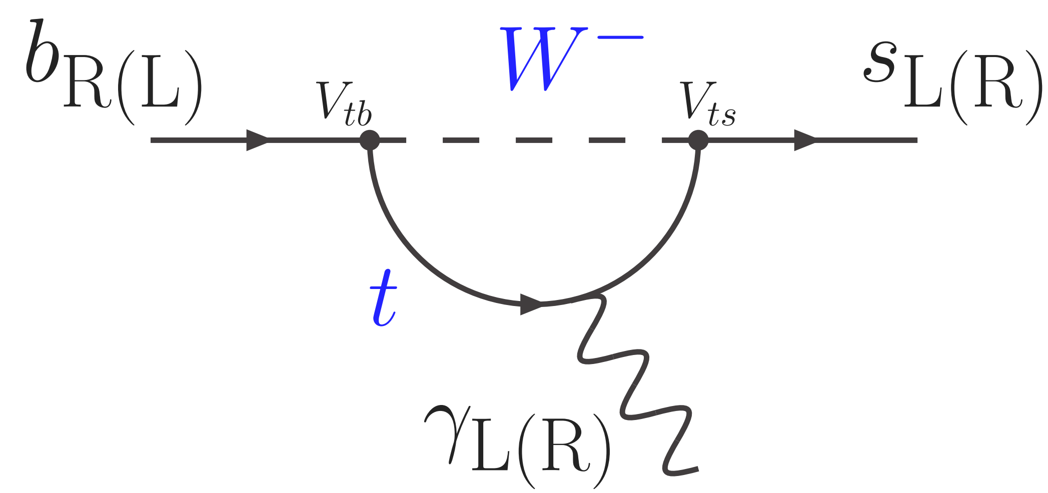
- $b \to s\gamma$ is a golden channel of b physics
  - FCNC mediated by loop with W^- and t
  - Virtual BSM contribution can be large
  - Not so rare! e.g. $\mathcal{B}(B \to X_s\gamma) \simeq (3.32 \pm 0.15) \times 10^{-4}$ HFLAV April 2019

see David's talk

- Effective Hamiltonian description:

$$\mathcal{H}_{\text{eff}} \simeq -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_7 O_7 + C_7' O_7' \right)$$

where $O_7^{(\prime)}$ is the left(right)-handed electromagnetic dipole operator



$$\frac{C_7'}{C_7} \simeq \frac{A_R}{A_L} \simeq \frac{m_s}{m_b} \simeq 0.02$$

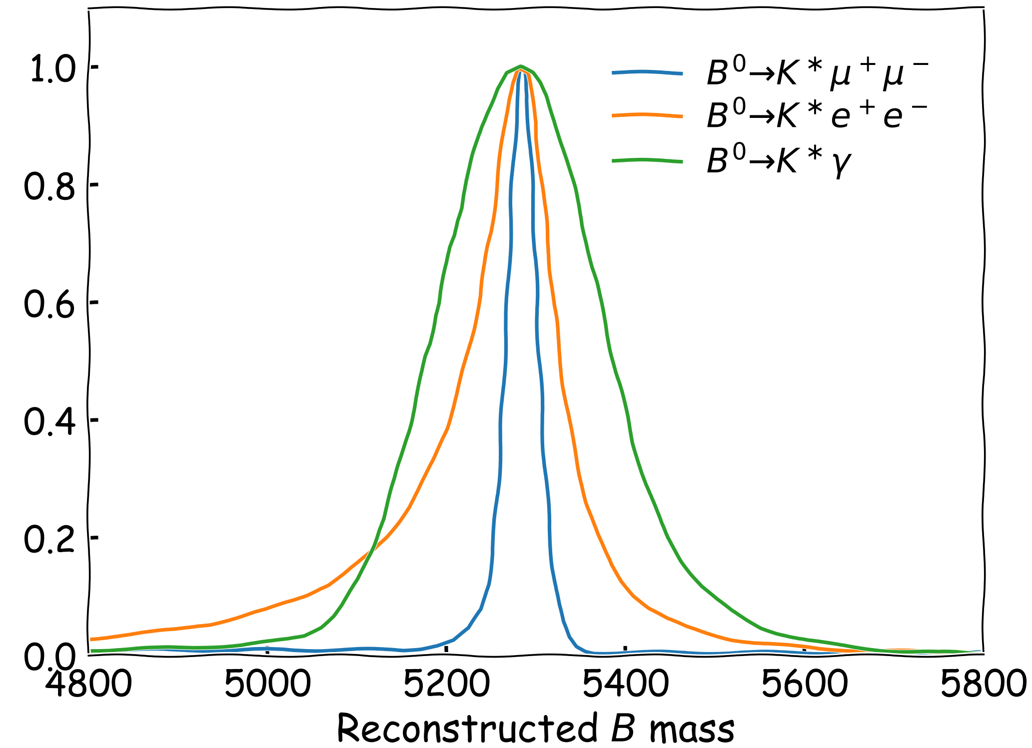
- The γ is mostly left-handed in SM
  - A measurement of the polarisation can reveal tiny BSM right-handed currents e.g. due to heavy vector-like quark masses

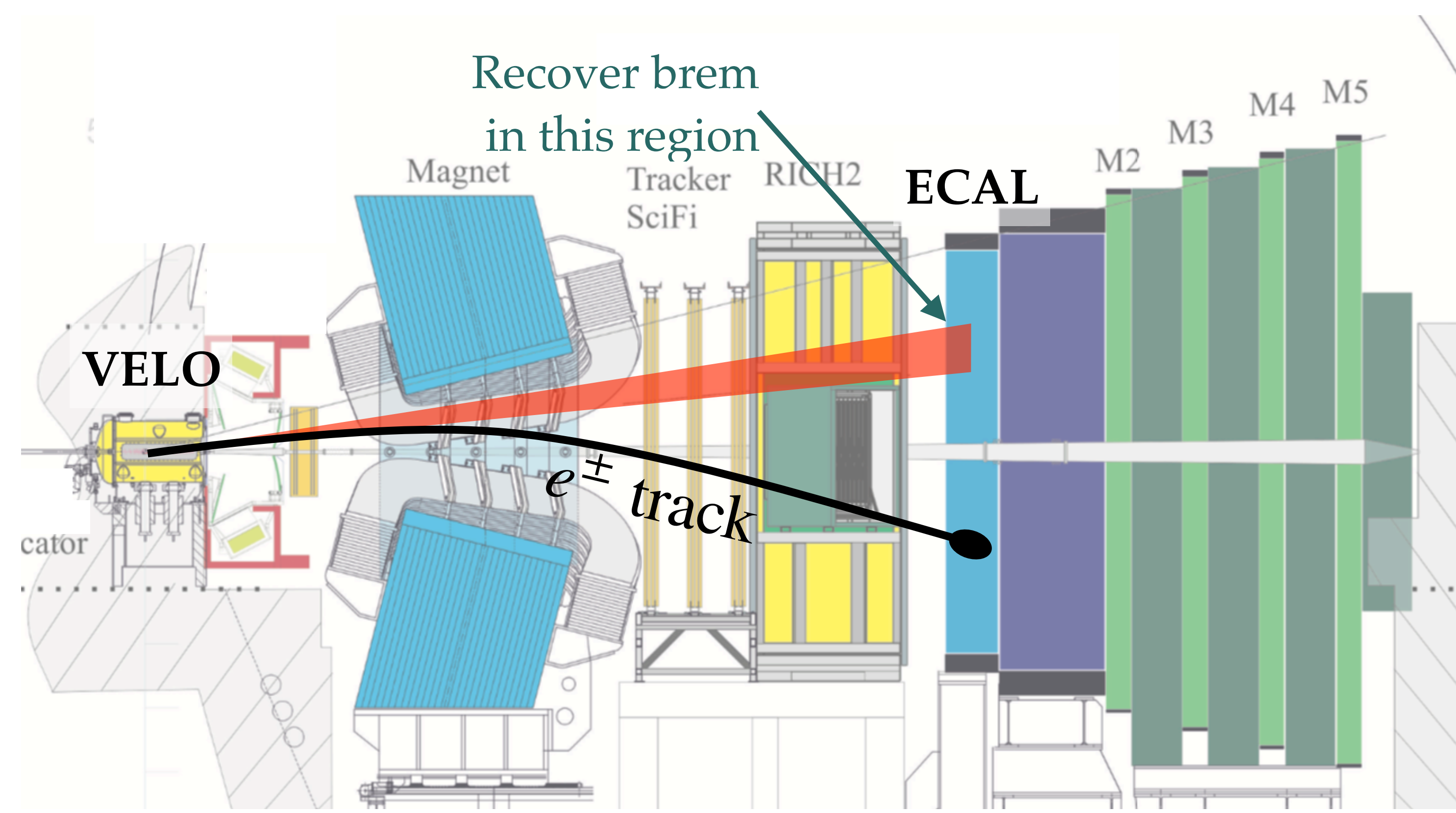
D. Becirevic et al, JHEP 08(2012)090
Fu-Sheng Yu et al, JHEP 12(2013)102
N. Haba et al, JHEP 03(2015)160
A. Paul et al, JHEP 04(2017)027

$b \to s\gamma$ at LHCb

Int.J.Mod.Phys. A 30, 1530022 (2015)

- About 10^{12} $b\bar{b}$ in acceptance in 2012-2018 (Run 1 + Run 2)
  - B_d , B_u , B_s , Λ_b , …
- Best reconstruction with $\mu^{\pm}, \pi^{\pm}, K^{\pm}, p^{\pm}$
  - Price to pay for neutrals γ, π^0, K_S
  - $e^{\pm}$ emit bremsstrahlung before magnet $\to$ brem reco procedure ~50% efficient
- Hardware trigger is key
  - $p_T(\mu^{\pm}) > 1.5 - 1.8$ GeV
  - $E_T(e^{\pm}) > 2.5 - 3.0$ GeV
  - $E_T(\gamma) \;\; > 2.1 - 3.0$ GeV
- Upgraded trigger in software
  - More potential and flexibility
  - See dedicated talk by Federico





$C_7^{(\prime)}$ at LHCb

- **Left handed C_7** measured with $\mathrm{BR} \propto (C_7^{\mathrm{SM}} + C_7^{\mathrm{NP}})^2 + (C_7^{\prime\,\mathrm{NP}})^2$
  - 5% precise prediction only for inclusive BR (quark-level)
    M. Misiak et al JHEP 06(2020)175
  - 5% precise inclusive BR measurement from B-factories
  - Inclusive BR very hard at LHCb
- ImC_7 measured with direct A_{CP}
  - $B \to K_S \pi^0 \gamma$ (et al) at B-factories
  - LHCb uses the **tagged** time-dep. analysis of $B_s \to \phi\gamma$

- **Right handed C_7'** measured with:
  - Mixing induced CP asymmetry in $B \to K_S \pi^0 \gamma$ (et al) at B-factories
  - $\Delta\Gamma_s$ induced rate asymmetry in $B_s \to \phi\gamma$ at LHCb
  - Full amplitude analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ at LHCb
  - Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb
  - Transverse asymmetries in $B^0 \to K^* e^+ e^-$ at LHCb

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  measured with 3/fb

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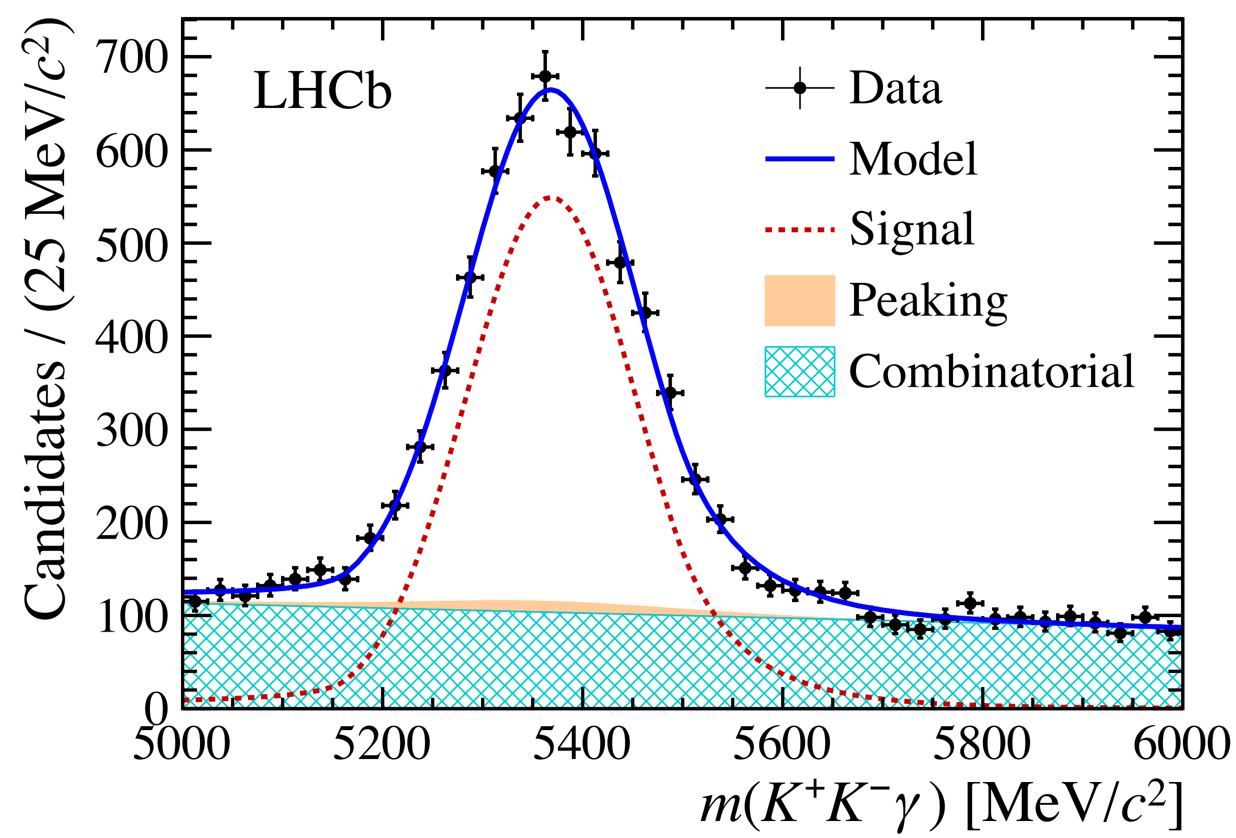
  - $\Delta\Gamma_s$ induced rate asymmetry in $B_s \to \phi\gamma$ at LHCb — measured with 3/fb
  - Full amplitude analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ at LHCb → Future
  - Angular analysis of $\Lambda_b \to \Lambda\gamma$ at LHCb → first observ. Anna's talk
  - Transverse asymmetries in $B^0 \to K^* e^+ e^-$ at LHCb

  New today!
  Measured with 9/fb

$B_s \to \phi\gamma$ at LHCb

Phys.Rev.Lett. 123 (2019) no.8, 081802

- LHCb uniquely placed to study $B_s \to \phi\gamma$
  - Signal yield is ~5000 with 3/fb (Run 1)
  - Large bkg but mostly combinatorial
  - Can use $B^0 \to K^*\gamma$ as calibration channel



- Large $\Delta\Gamma_s$ allows to extract mixing induced A^Δ from untagged sample

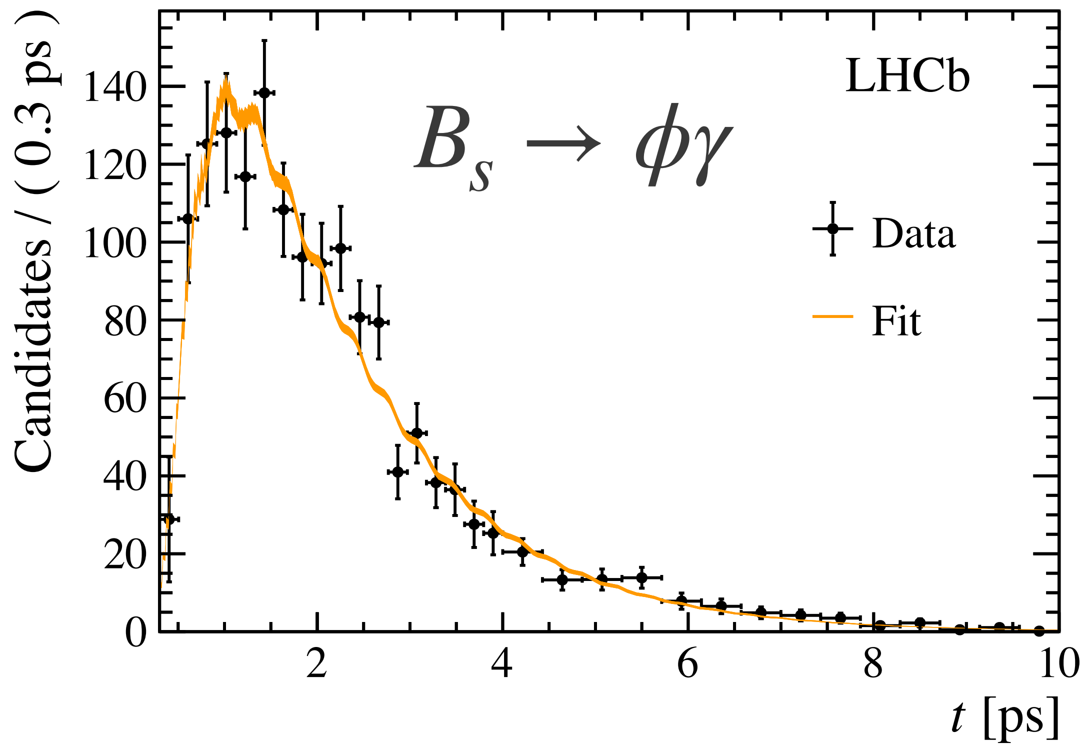
- Can also do flavour tagging!
  - Effective tagging efficiency is 5%
  - Large enough for time-dep. analysis

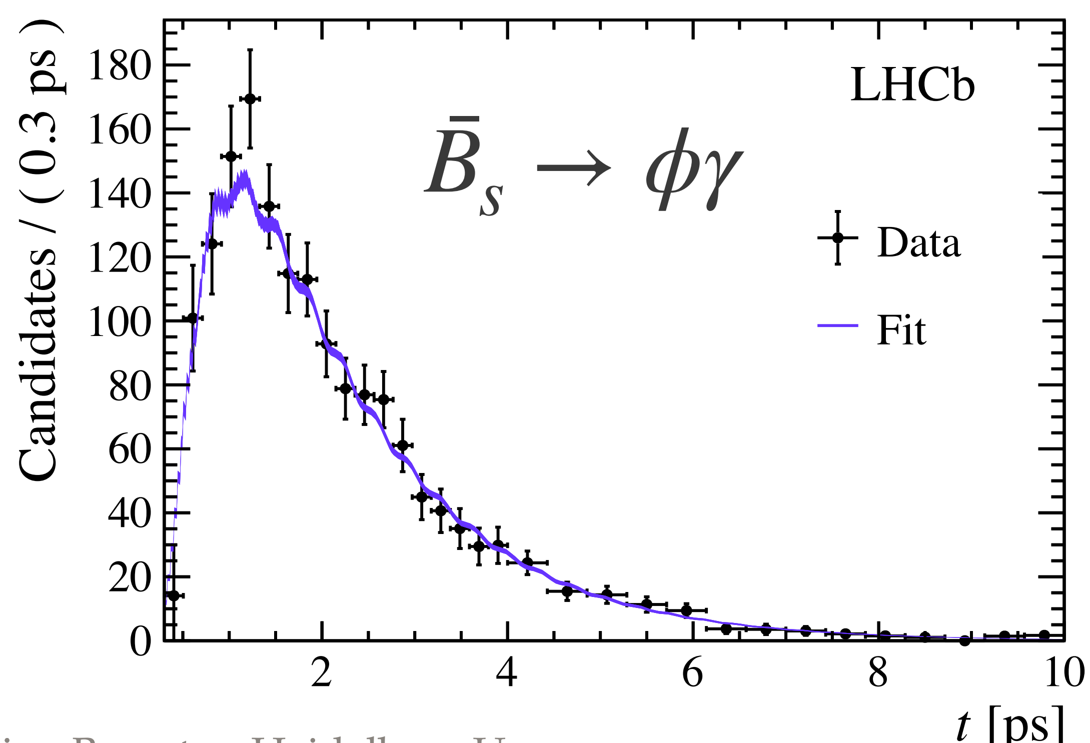
depends on B_s or $\bar{B}_s$

$$\mathscr{P}(t) \propto e^{-\Gamma_s t}\left\{\cosh\left(\Delta\Gamma_s t/2\right) - A^\Delta \sinh\left(\Delta\Gamma_s t/2\right) \pm C_{CP}\cos\left(\Delta m_s t\right) \mp S_{CP}\sin\left(\Delta m_s t\right)\right\}$$

$B_s \to \phi\gamma$ at LHCb

Phys.Rev.Lett. 123 (2019) no.8, 081802





- Results of the 3/fb analysis:

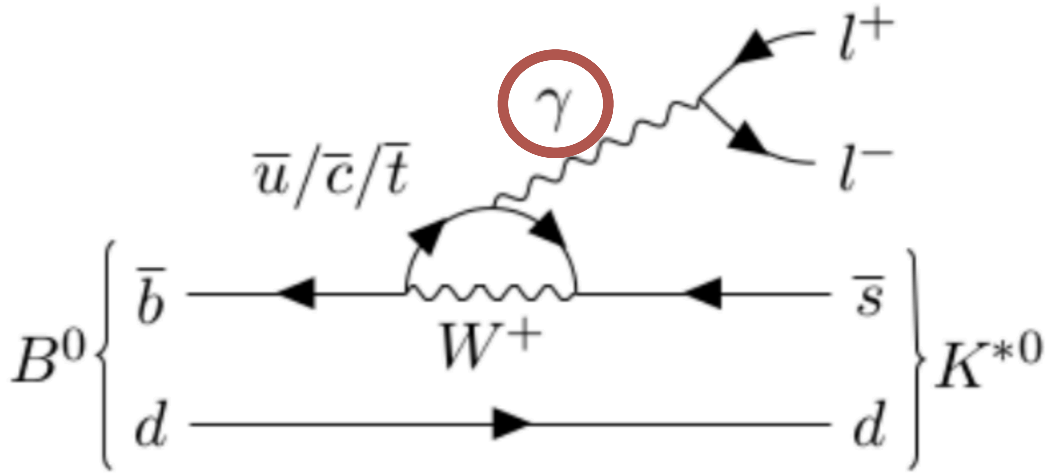
$$A^{\Delta} = -0.67^{+0.37}_{-0.41} \pm 0.17$$
$$S_{CP} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{CP} = 0.11 \pm 0.29 \pm 0.11$$

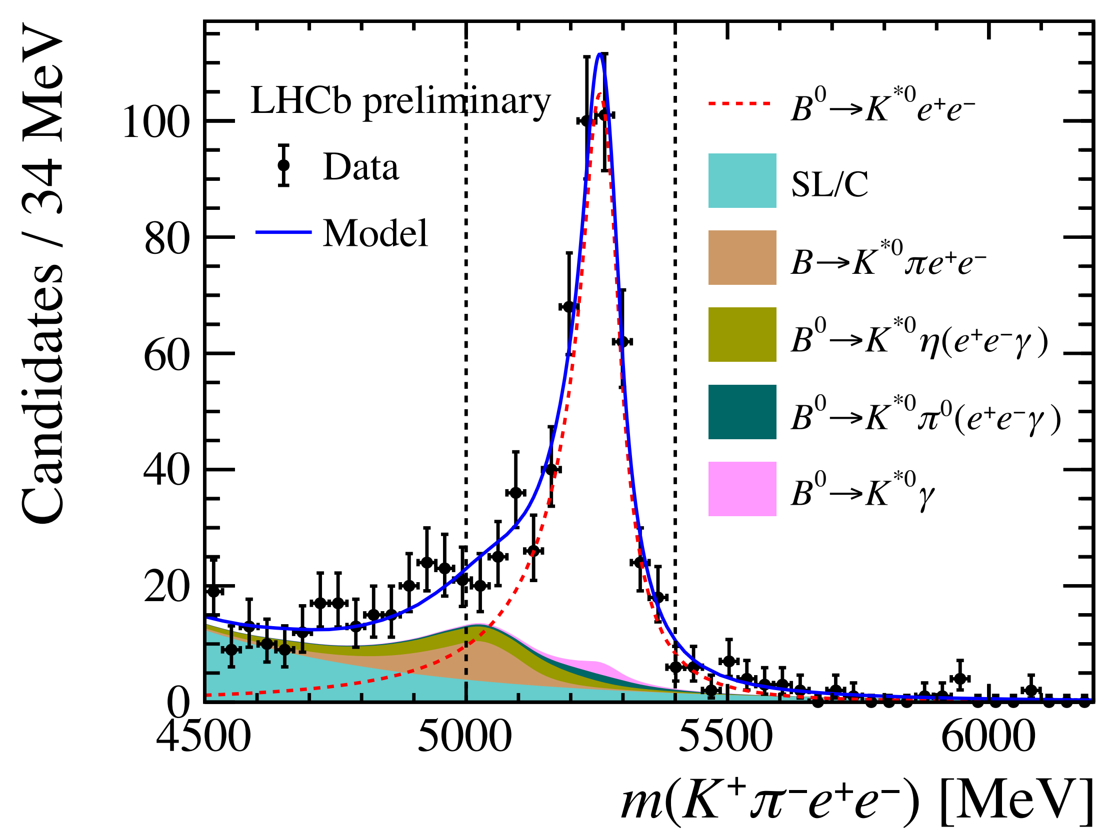
- Systematics mainly from decay-time resolution and tagging efficiency
- Compatible with SM predictions
- Still statistically limited with 3/fb
  - Run 2 analysis on the way!

$B^0 \to K^{*}e^+e^-$ at very low q^2

LHCb-PAPER-2020-020 (in preparation)

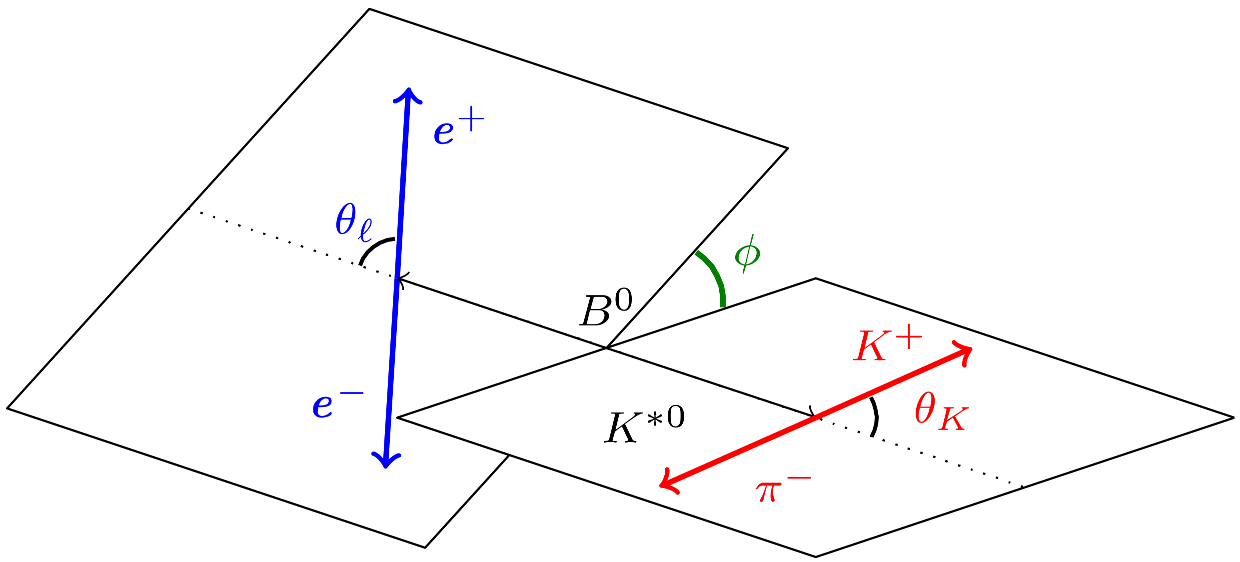
- Rare $B^0 \to K^{*}e^+e^-$ decay dominated by $b \to s\gamma$ pole at very-low q^2
- Select in $q^2 = m(ee)^2$ region between $(28\ \mathrm{MeV})^2$ and 0.257 GeV^2
  - Pollution from (axial-)vector currents is negligible in this region
- SM BR is as small as $\sim 2 \times 10^{-7}$ but:
  - Fully charged final state ($K^* \to K^+\pi^-$)
  - Semileptonic+combinatorial (SL/C) background is phase-space suppressed
- New Run 1+2 (9/fb) analysis with greatly improved selection strategy
  - Allowed even lower q^2 range
  - 530 signal candidates selected with extremely low background





$B^0 \to K^* e^+ e^-$: Angular analysis

LHCb-PAPER-2020-020 (in preparation)



- Folding ϕ angle to simplify the 3D angular expression:

$$\tilde{\phi} \equiv \begin{cases} \phi \text{ if } \phi \geq 0 \\ \phi + \pi \text{ if } \phi < 0 \end{cases}$$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+(1-F_\mathrm{L})A_T^{Re}\sin^2\theta_K\cos\theta_\ell$$
$$+\tfrac{1}{2}(1-F_\mathrm{L})A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi}$$
$$+\tfrac{1}{2}(1-F_\mathrm{L})A_T^{Im}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big].$$

$B^0 \to K^*\gamma$ photon polarisation:

$$A_{\mathrm{R(L)}} \equiv |A_{\mathrm{R(L)}}|\,e^{i\phi_{\mathrm{R(L)}}}, \quad \tan\chi \equiv \left|A_\mathrm{R}/A_\mathrm{L}\right|$$

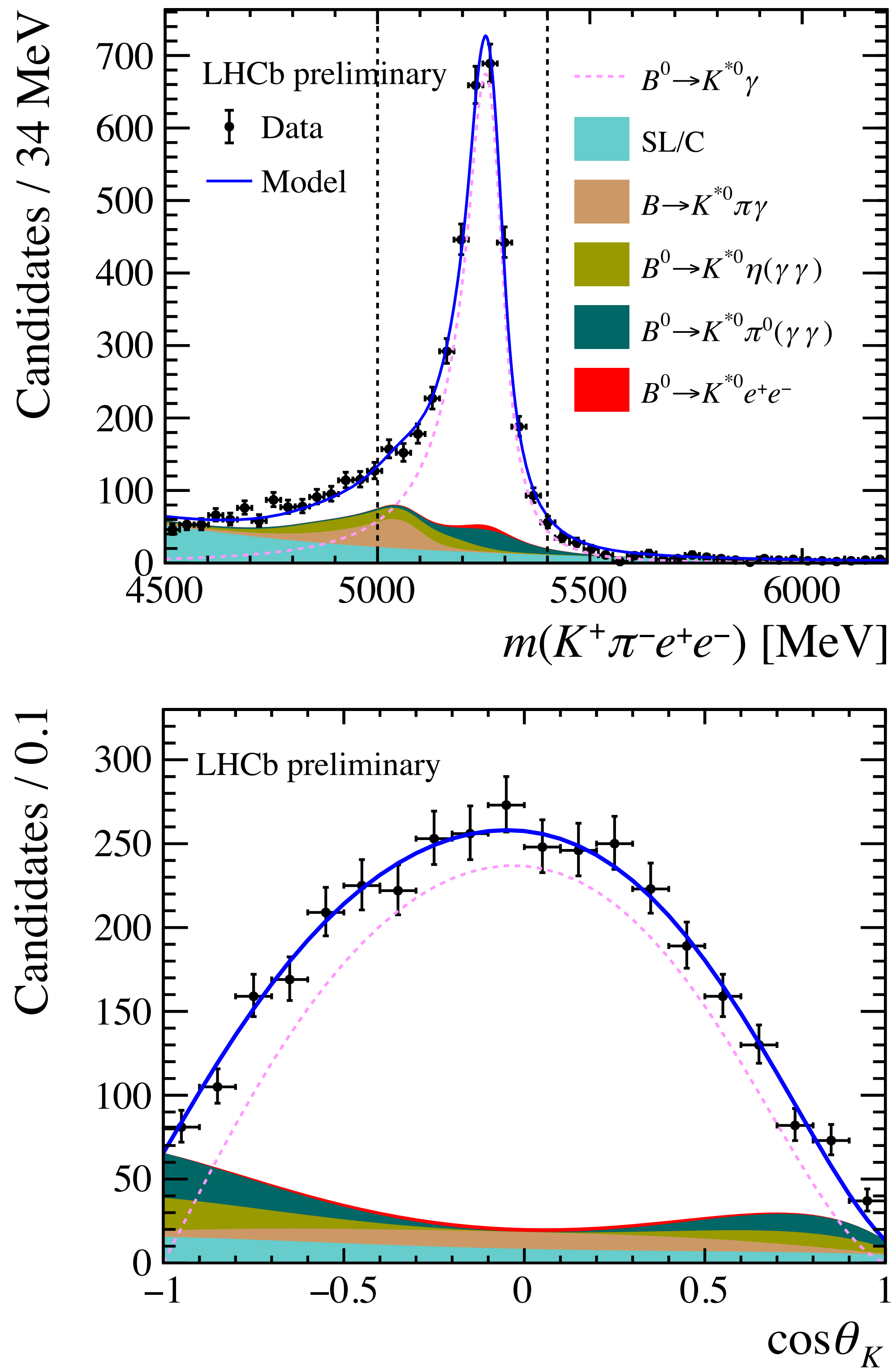
$$A_\mathrm{T}^{(2)} \simeq \sin(2\chi)\cos(\phi_\mathrm{L}-\phi_\mathrm{R}),$$
$$A_\mathrm{T}^{\mathrm{Im}} \simeq \sin(2\chi)\sin(\phi_\mathrm{L}-\phi_\mathrm{R}),$$

$B^0 \to K^* e^+ e^-$: Control channel

NEW

LHCb-PAPER-2020-020 (in preparation)

- $B^0 \to K^*\gamma$ has much larger BR
  - Same final state as $B^0 \to K^* e^+ e^-$ when γ converts to e^+e^- in the material
  - Can be well separated with material veto and cut on $m(e^+e^-) > 10$ MeV
- Use $B^0 \to K^*\gamma$ as control for $B^0 \to K^* e^+ e^-$
  - Very similar signal shape and background composition to signal
  - Fit $m(K^+\pi^- e^+ e^-)$ distribution to validate signal fit (found 2950 $B^0 \to K^*\gamma$ candidates)
  - Fitted F_L to $\cos\theta_K$ found to be compatible with 0 with sub-percent precision
    $\to$ due to real γ, longitudinal polarisation fraction F_L is expected to be zero

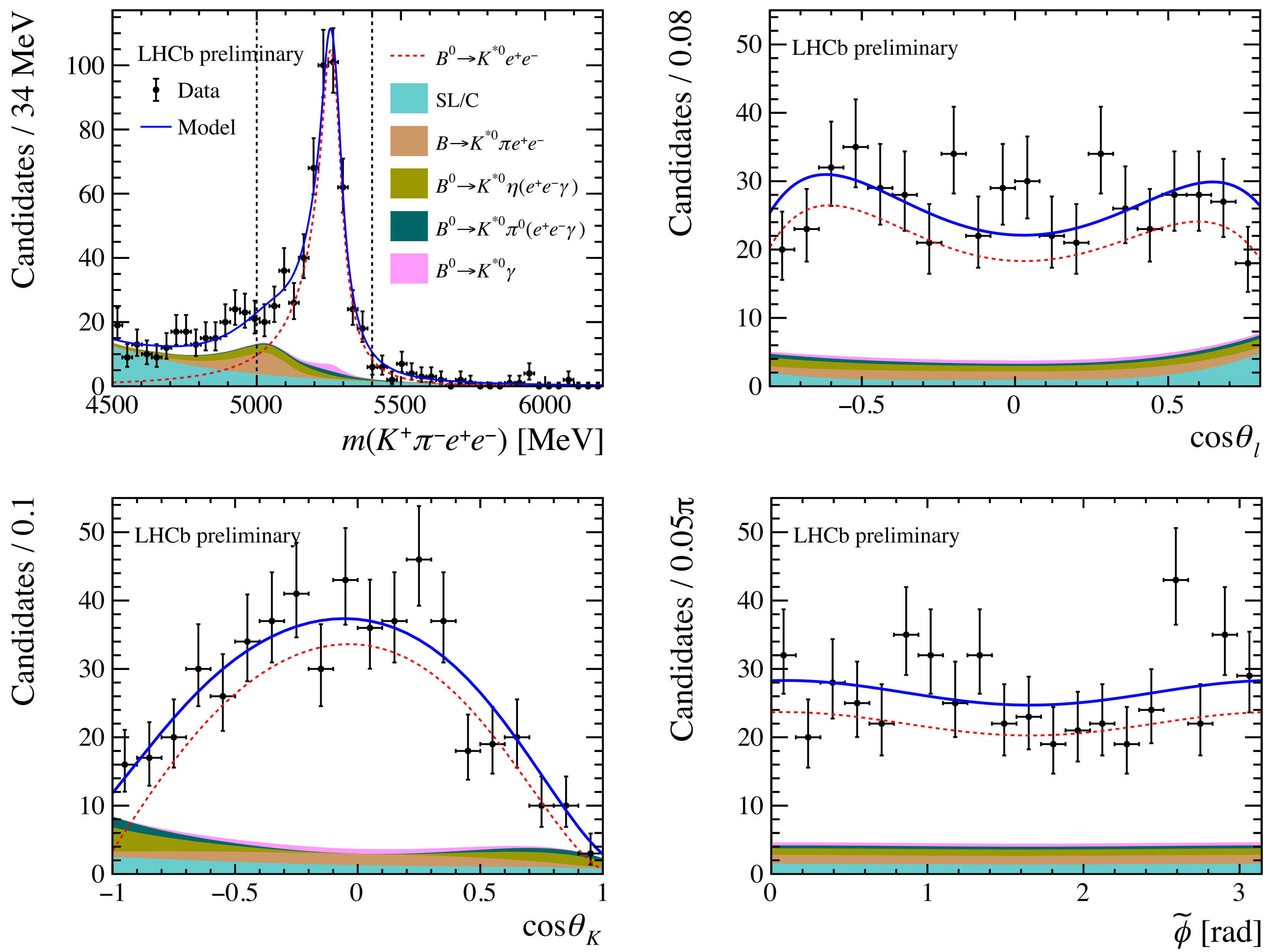


$B^0 \to K^*e^+e^-$: Angular fit

NEW

LHCb-PAPER-2020-020 (in preparation)

- Fit to B mass and angles
  - In reduced mass region
  - Semilept+combinatorial (SL/C) modelled using $B \to K^*\mu^\pm e^\mp$ data candidates
  - Other backgrounds from simulation
  - Fit procedure thoroughly tested with pseudo-experiments



$B^0 \to K^* e^+ e^-$: Results

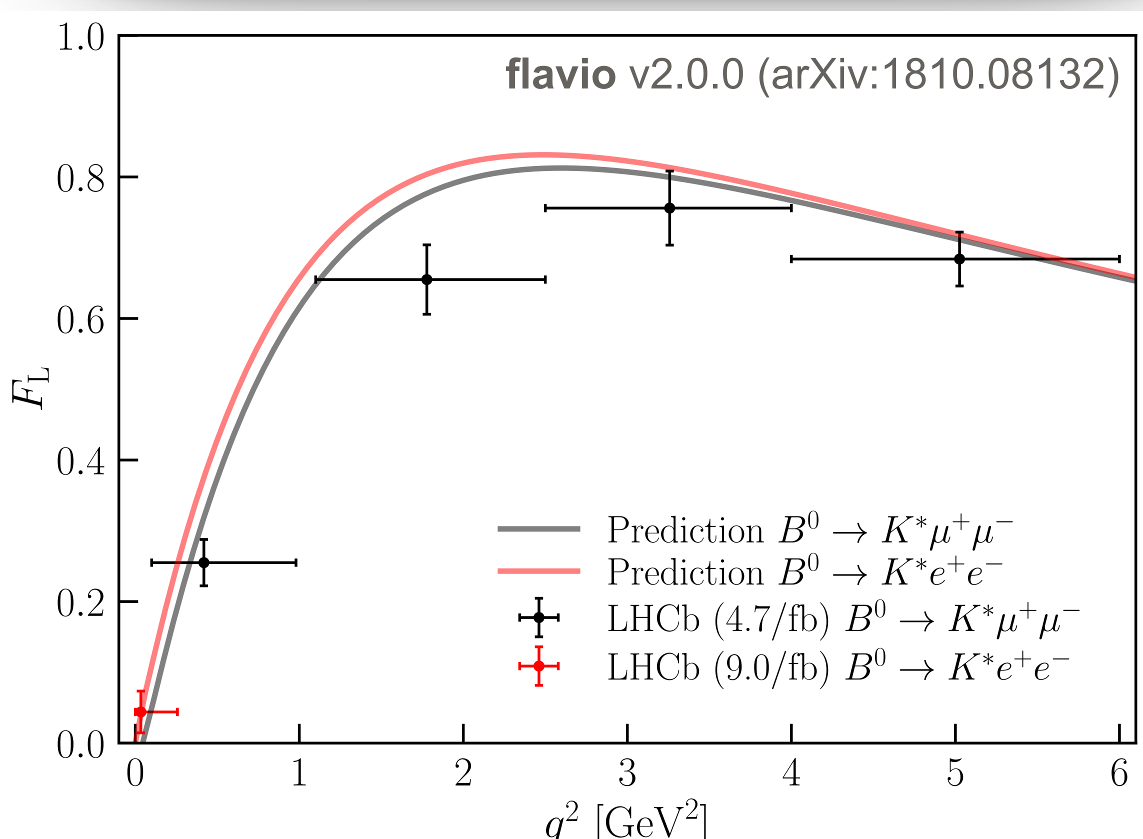
NEW

LHCb-PAPER-2020-020 (in preparation)

$(28\ \text{MeV})^2 < q^2 < 0.257\ \text{GeV}^2$

PRELIMINARY

$$F_L = 0.044 \pm 0.026 \pm 0.014$$
$$A_T^{Re} = -0.064 \pm 0.077 \pm 0.015$$
$$A_T^{(2)} = +0.106 \pm 0.103^{+0.016}_{-0.017}$$
$$A_T^{Im} = +0.015 \pm 0.102 \pm 0.012$$



LHCb, PRL 125(2020)011802
LHCb-PAPER-2020-020 (in preparation)

- Main systematics from signal acceptance and angular background modelling
- Statistical error still dominates
- Measurements of F_L and $A_T^{Re} = \frac{3}{4} A_{FB}(1 - F_L)$ are also interesting in the context of $B^0 \to K^*\mu^+\mu^-$ angular analysis anomalies (see David's talk)

LHCb, PRL 125(2020)011802

- The analysis prepares the ground for lepton universality tests in the angles
- $A_T^{(2)}$ and A_T^{Im} are sensitive to C_7'

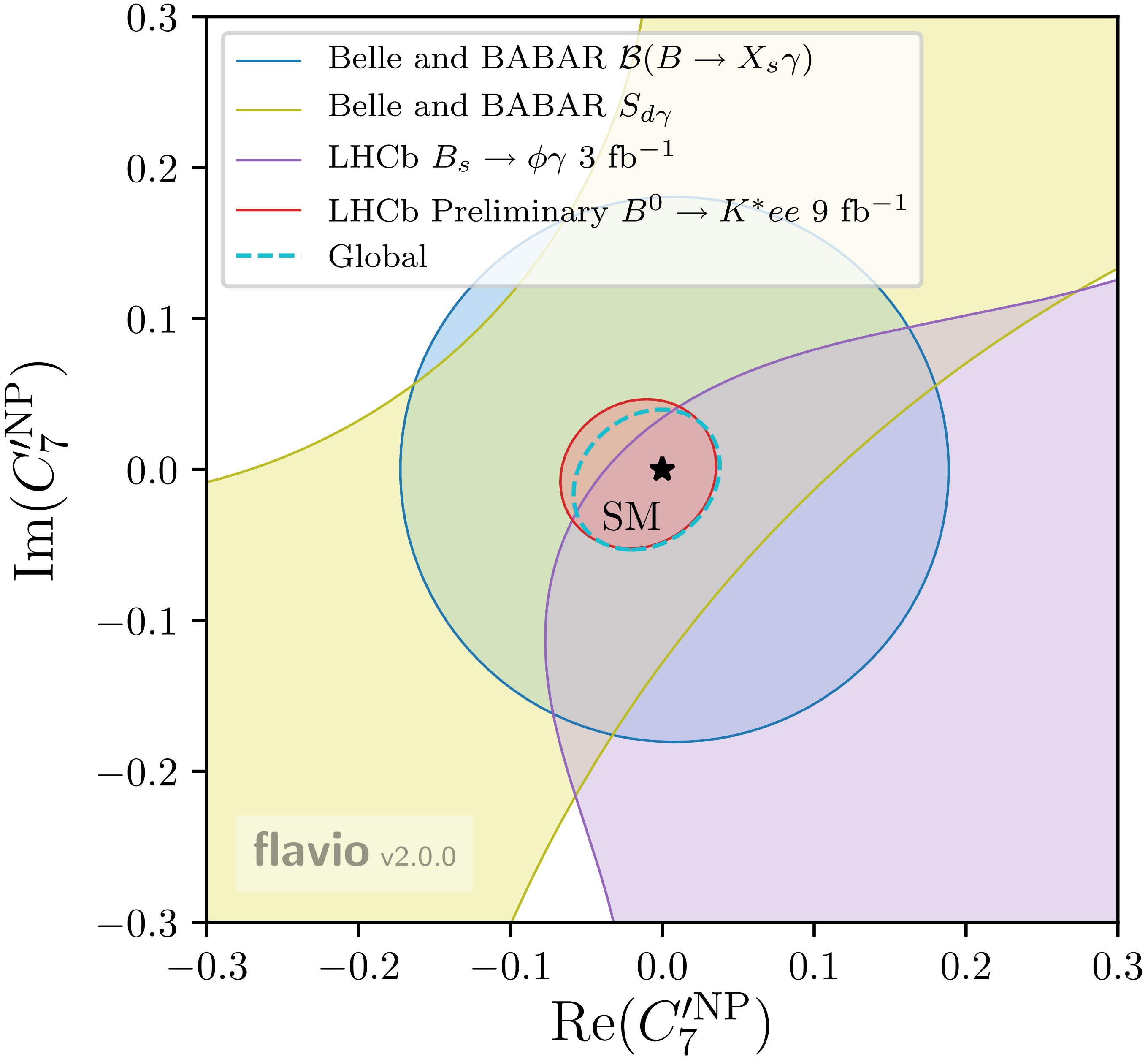
next slide

$B^0 \to K^* e^+ e^-$: Results

NEW

LHCb-PAPER-2020-020 (in preparation)

$b \to s\gamma$ photon polarisation



A. Paul and D. M. Straub, JHEP 04 (2017) 027
D. M. Straub, "flavio", arXiv:1810.08132

- Constraint from $B^0 \to K^* e^+ e^-$ dominating the sensitivity to C_7'
  - Constraining both Re and Im part
  - Better than combination of all previous results
- Statistically limited measurements
  - The constraint will keep improving with more luminosity (upgrade)

Conclusions

- LHCb program of $b \to s\gamma$ studies is flourishing
  - Achieved world-best measurement of photon polarisation
- Methods very different from B-factories:
  - Time-dependent analysis of $B_s \to \phi\gamma$
  - Angular analysis of $B^0 \to K^{*}e^{+}e^{-}$ at very-low q^2 NEW
- Expect more precise results from Run 2 data (on tape) and the upcoming LHCb upgrade

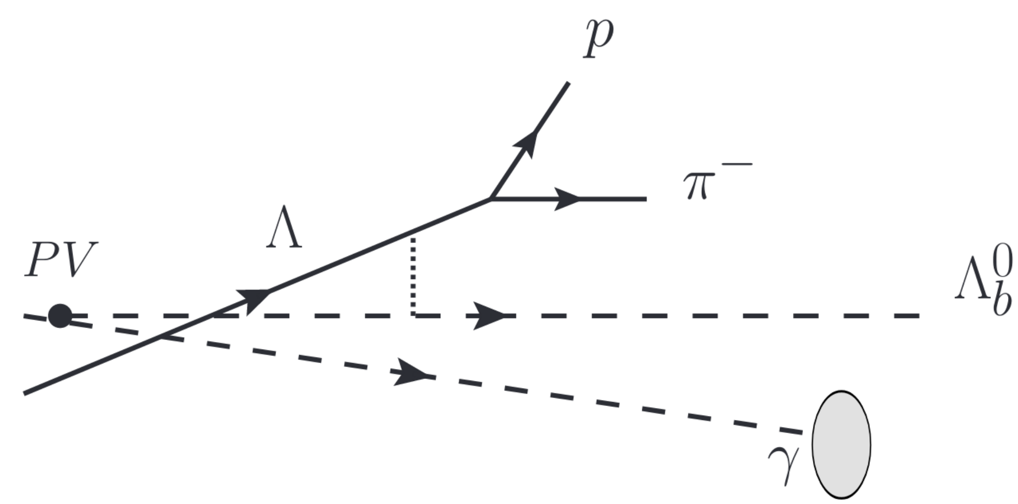
BACKUP

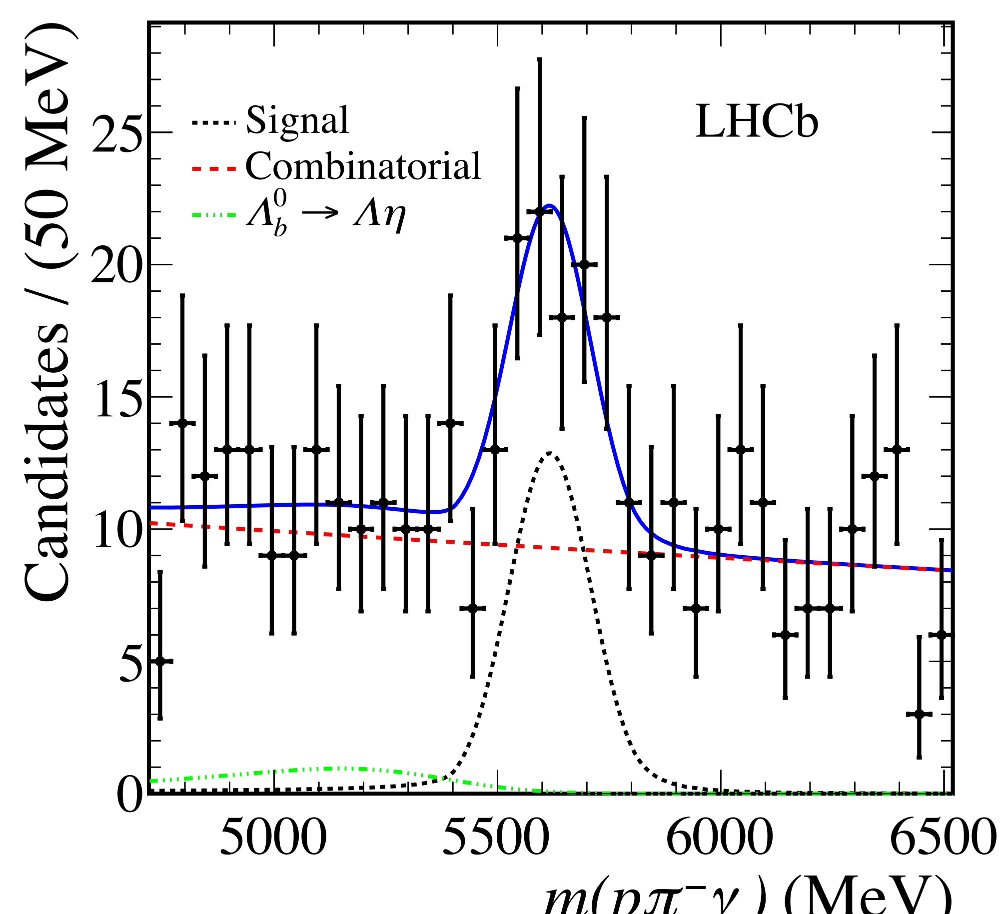
$\Lambda_b \to \Lambda\gamma$ at LHCb

LHCb, Phys. Rev. Lett. 123 (2019) 031801

- LHCb has unique capability to study radiative baryon decays
- First attempt with $\Lambda_b \to \Lambda\gamma$
  - Using only 2016 data (1.7/fb)
  - No γ direction and $c\tau(\Lambda) \simeq 8$ cm
    $\to$ no Λ_b vertex reconstructed
  - Signal classification with BDT is crucial
- Found 65 ± 13 $\Lambda_b \to \Lambda\gamma$ decays
  - **First observation** at 5.6σ significance
  - $\mathrm{BR} = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$
    $\to$ in agreement in with SM predictions
- Possibile to measure photon polarisation
  - To be competitive with B measurements, precision needs to improve by factor ~ 6

Eur.Phys.J.C 79 (2019) 7, 634

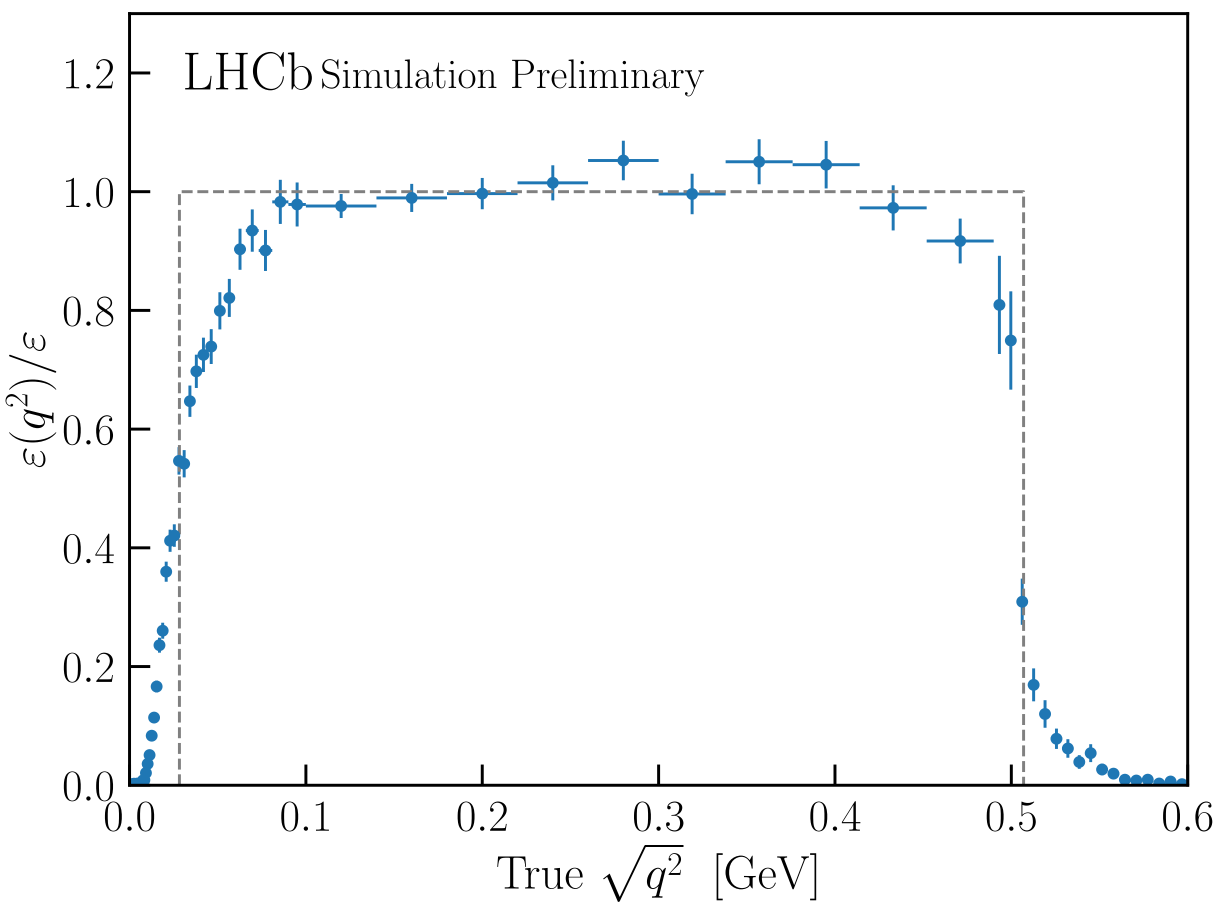




$B^0 \to K^{*}e^+e^-$: effective q^2

LHCb-PAPER-2020-020 (in preparation)

- Analysis performed in bins of reconstructed $m(e^+e^-)$ between 10 and 500 MeV
- The $m(e^+e^-)$ resolution is not negligible and asymmetric
  - Provide efficiency map as a function of true $m(e^+e^-)$
  - For most use cases one can use the effective q^2 range from $(28\ \text{MeV})^2$ to 0.257 GeV^2



$B^0 \to K^* e^+ e^-$: systematics

NEW

LHCb-PAPER-2020-020 (in preparation)

Source of systematic	$\sigma(A_{\mathrm{T}}^{(2)})$	$\sigma(A_{\mathrm{T}}^{\mathrm{Im}})$	$\sigma(A_{\mathrm{T}}^{\mathrm{Re}})$	$\sigma(F_{\mathrm{L}})$
Acceptance sample size	0.007	0.007	0.007	0.003
Acceptance model	0.004	0.001	0.008	0.001
SL/C sample size	0.007	0.007	0.007	0.003
SL/C model	0.012	0.005	0.006	0.005
PR model	0.001	0.003	0.002	0.001
η/π^0 model	0.0004	0.0001	0.002	0.01
ϕ resolution	-0.004	-0.001	-	-
MC corrections	0.003	0.001	0.003	0.007
Signal mass shape	0.002	0.002	0.004	0.001
Fit bias	-	-	-	-0.003
Total systematic uncertainty	$^{+0.016}_{-0.017}$	0.012	0.015	0.014
Statistical uncertainty	0.103	0.102	0.077	0.026

$B^0 \to K^* e^+ e^-$: All results

NEW

LHCb-PAPER-2020-020 (in preparation)

PRELIMINARY

$(28\ \text{MeV})^2 < q^2 < 0.257\ \text{GeV}^2$

$$
\begin{aligned}
F_{\rm L} &= 0.044 \pm 0.026 \pm 0.014 \\
A_{\rm T}^{\rm Re} &= -0.064 \pm 0.077 \pm 0.015 \\
A_{\rm T}^{(2)} &= +0.106 \pm 0.103^{+0.016}_{-0.017} \\
A_{\rm T}^{\rm Im} &= +0.015 \pm 0.102 \pm 0.012,
\end{aligned}
$$

	$F_{\rm L}$	$A_{\rm T}^{\rm Re}$	$A_{\rm T}^{(2)}$	$A_{\rm T}^{\rm Im}$
$F_{\rm L}$	1.00	−0.02	−0.01	0.02
$A_{\rm T}^{\rm Re}$		1.00	0.05	0.02
$A_{\rm T}^{(2)}$			1.00	0.10
$A_{\rm T}^{\rm Im}$				1.00

- Statistically dominated
- Small correlations
- Can determine $B^0 \to K^* \gamma$ photon polarisation

$$
\begin{aligned}
{\rm Re}\,(A_{\rm R}/A_{\rm L}) &= 0.05 \pm 0.05 \\
{\rm Re}\,(A_{\rm R}/A_{\rm L}) &= 0.01 \pm 0.05
\end{aligned}
$$