Measurement of the photon polarisation in $b \to s\,\gamma$ transitions with $B_s \to \phi ee$ (& co)

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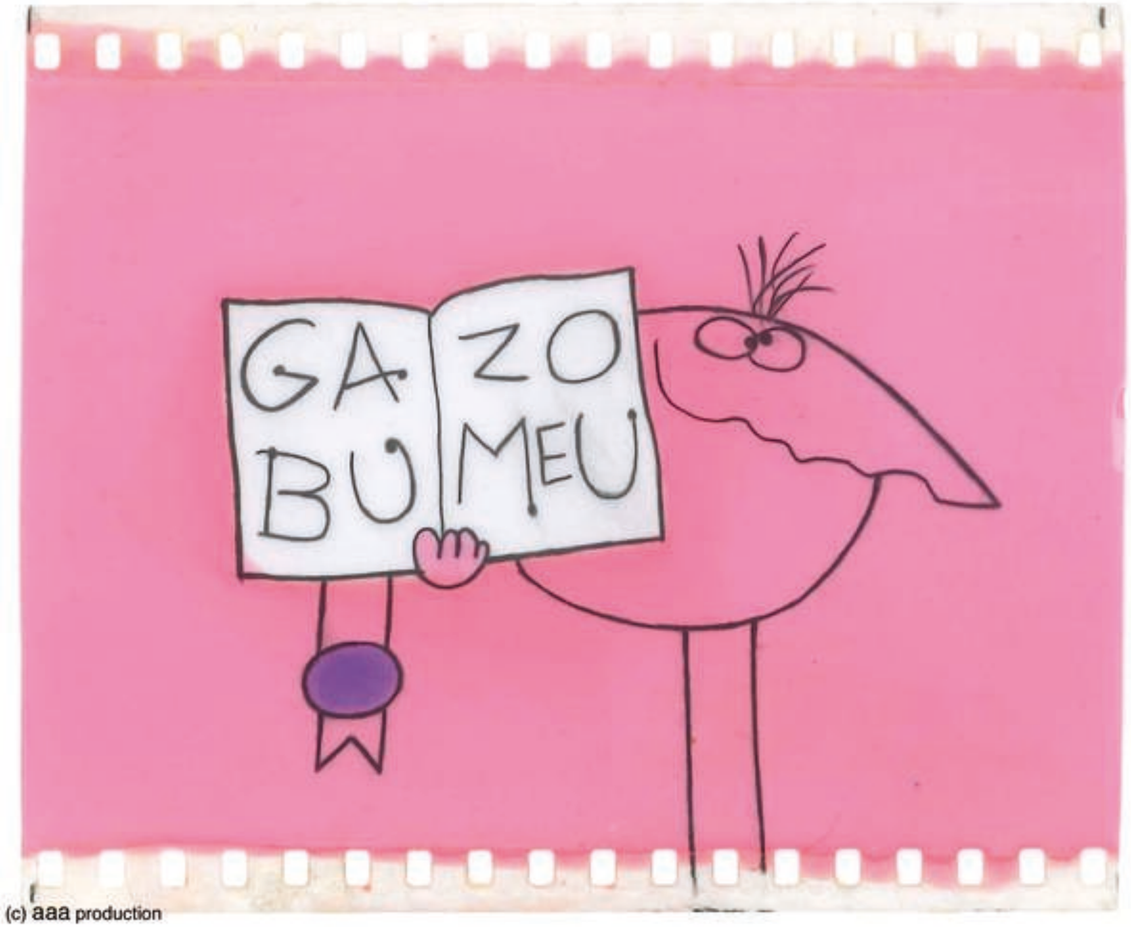
erc European Research Council Established by the European Commission

CHIARO SCURO

- Setting up the scene
- $B_s \to \phi ee$ analysis: the PhD work of Gaëlle Khreich
- Other recent experimental results and overall knowledge

Setting up the scene



Photon polarisation in b→$s\gamma$: SM case

1

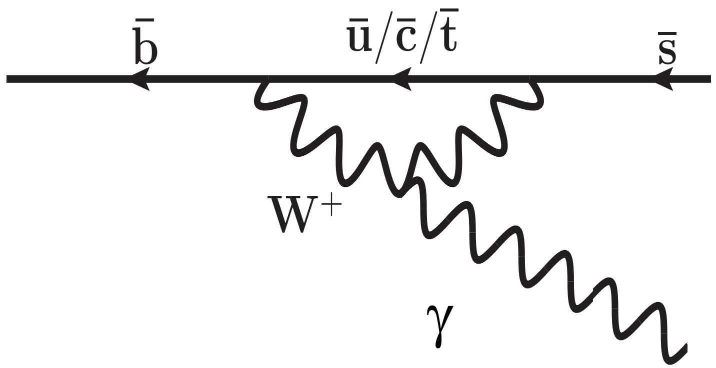
Helicity conservation :

$$b_L \to s_R \gamma_R$$

$$b_R \to s_L \gamma_L$$

2

In the SM W couples to left-handed fermions:



3

⇒ Helicity flip on one of the legs.
Easier for heavier quarks (prop. to m_q)

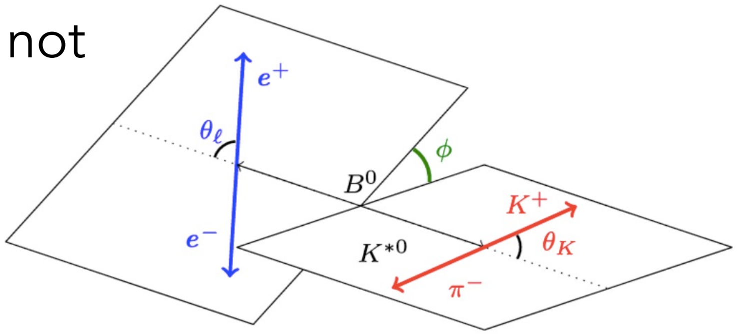
4

Fraction of right-handed photon in $b \to s\gamma \propto \frac{m_s}{m_b}$

Which decays ?

- Mixing-induced CP asymmetries in $B^0 \rightarrow K^{*0}$ ($\rightarrow K^0\, \pi^0$) γ and $B_s \rightarrow \Phi\gamma$
  - Challenging final state and/or time dependent measurement with tagging

- $B \rightarrow K^*$ ($\rightarrow K^+\, \pi^-$) γ or $B_s \rightarrow \Phi\gamma$ untagged & time-integrated : information not accessible
  $\Rightarrow$ use virtual photons: access to the polarisation via the angle ϕ

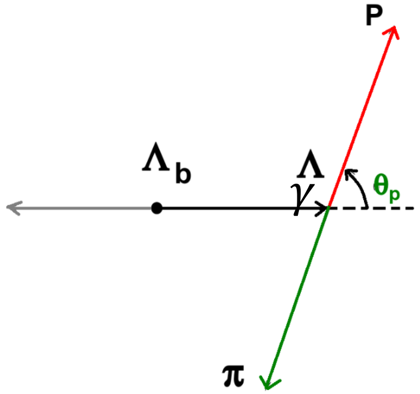


- $B \rightarrow K^{**}$ ($\rightarrow K\pi\pi$) γ : challenging experimentally & theoretically

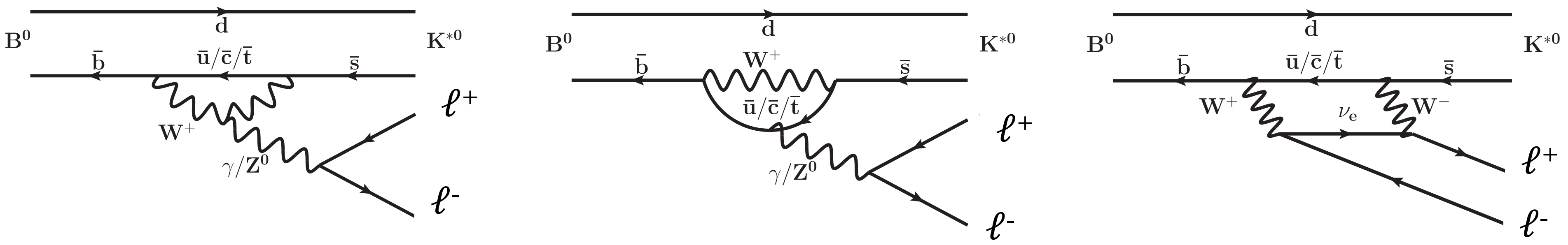
- Unique case of the $\Lambda_b \rightarrow \Lambda\gamma$ decay + Λ weak decay

$$\Gamma_{\Lambda_b} = \frac{1}{4}\left(1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p\right)$$

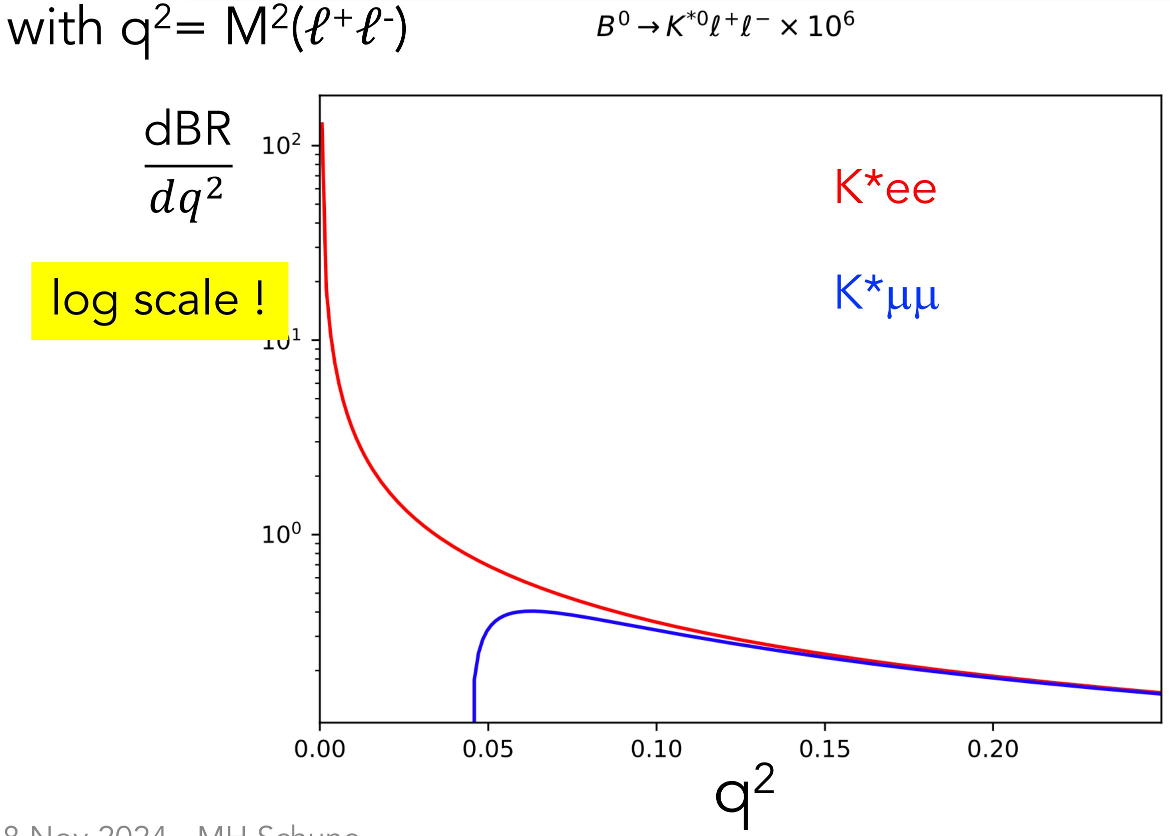
$\alpha_\Lambda = 0.754 \pm 0.004$ [BESIII]



The B→Vℓℓ case



Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$

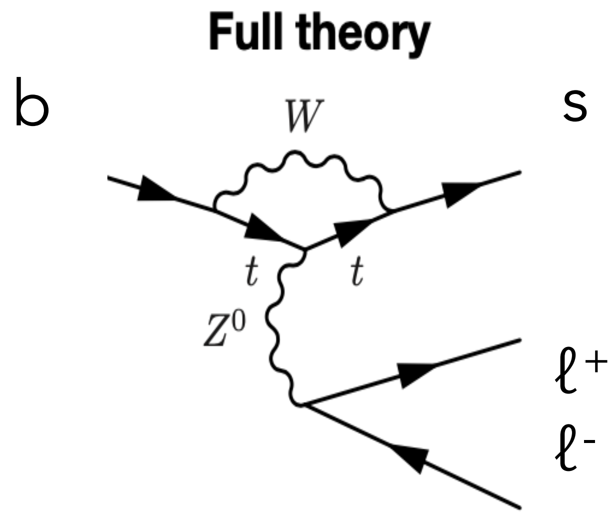


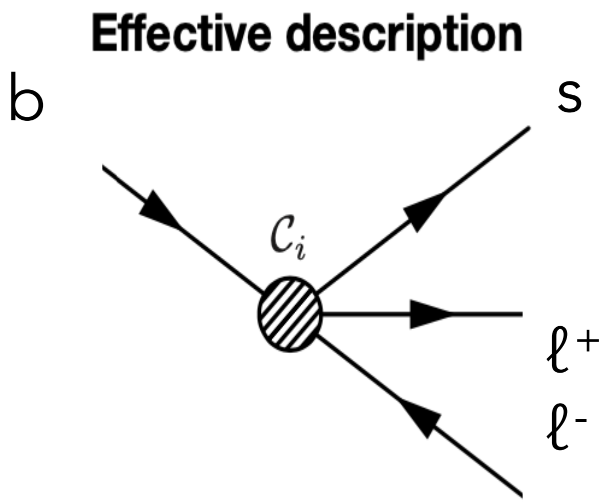
Virtual photon:

⇒ go for q^2 as low as possible :

⇒ use electrons

Weak Effective Theory





W, Z, top, …
integrated out

$$\mathcal{L}_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

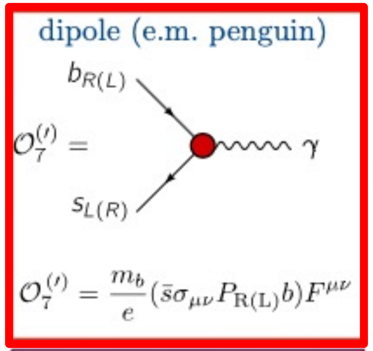
$C_i^{(')} = C_i^{SM\,(')} + C_i^{NP\,(')}$

perturbative, contains the short distance physics. q^2 independent.
Heavy NP

$O_i^{(')}$

non-perturbative, Lorentz structure, long distance physics..
q^2 dependent.

$$O_7^{(')} \propto (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$



Only interested in photon polarisation ? Let's make it simpler !

Full angular distribution

$$= \frac{9}{32\pi}\{J_{1s}\sin^2\theta_k + J_{1c}\cos^2\theta_k + J_{2s}\sin^2\theta_k\cos 2\theta_l$$
$$+ J_{2c}\cos^2\theta_k\cos 2\theta_l + J_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_k\sin 2\theta_l\cos\phi$$
$$+ J_5\sin 2\theta_K\sin\theta_l\cos\phi + J_{6s}\sin^2\theta_K\cos\theta_l + J_{6c}\cos^2\theta_K\cos\theta_l$$
$$+ J_7\sin 2\theta_k\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+ J_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\}$$

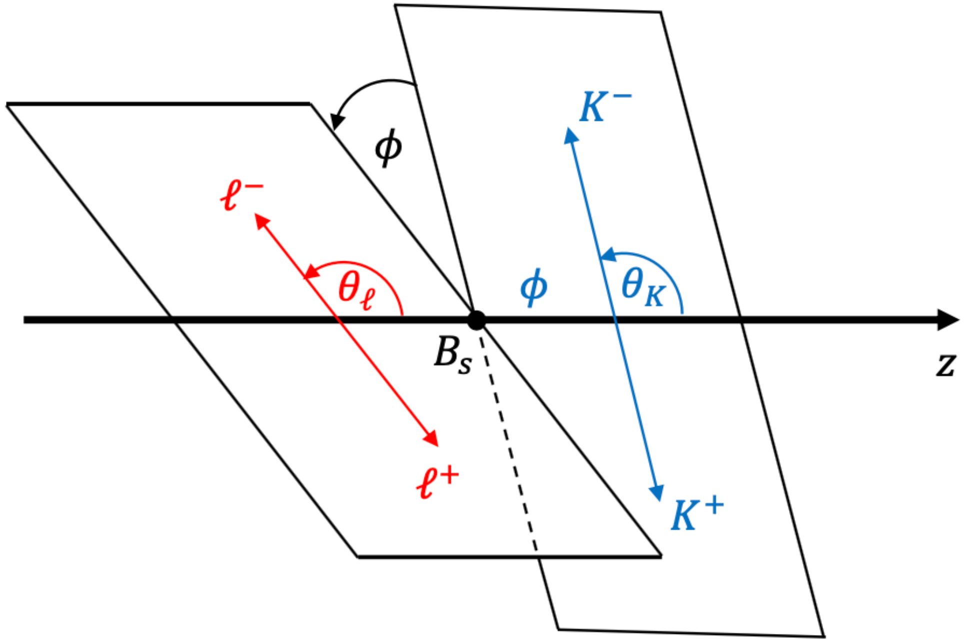
$J_i(q^2)$: combinations of amplitudes $A^{L,R}_{0,\perp,\parallel}$

(11 long formulae)

Each amplitude can be written with C_7, C_9, C_{10} + the ' coefficients

Only J_3 and J_9 are sensitive to the photon polarization

3 angles to describe the decay (valid for all q^2) :



+ some folding:

$$\tilde{\phi} = \phi \text{ if } \phi > 0, \text{ and } \tilde{\phi} = \phi + \pi \text{ if } \phi < 0$$

$$\frac{1}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}} \frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_l d\cos\theta_k d\tilde{\phi}^1}$$

$$= \frac{9}{32\pi} \left\{ \frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k \right.$$
$$+ \left[\frac{1}{4}(1-F_L)\sin^2\theta_k - F_L\cos^2\theta_k\right]\cos 2\theta_l$$
$$+ \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_k\sin^2\theta_l\cos 2\tilde{\phi}$$
$$+ (1-F_L)A_T^{ReCP}\sin^2\theta_k\cos\theta_l$$
$$\left. + \frac{1}{2}(1-F_L)A_T^{ImCP}\sin^2\theta_k\sin^2\theta_l\sin 2\tilde{\phi} \right\}$$

$$F_L = \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2},$$

$$A_T^{(2)} = \frac{|A_\perp|^2-|A_\parallel|^2}{|A_\perp|^2+|A_\parallel|^2},$$

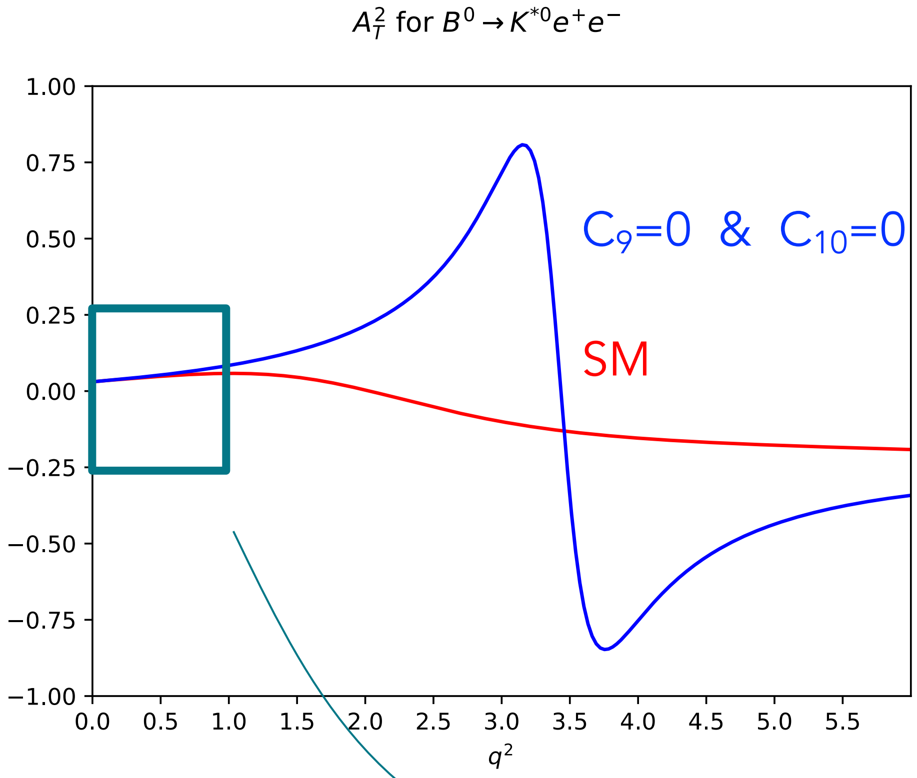
$$A_T^{Im} = \frac{2\mathcal{I}m(A_\parallel^L A_\perp^{L*} + A_\parallel^R A_\perp^{R*})}{|A_\perp|^2+|A_\parallel|^2}.$$

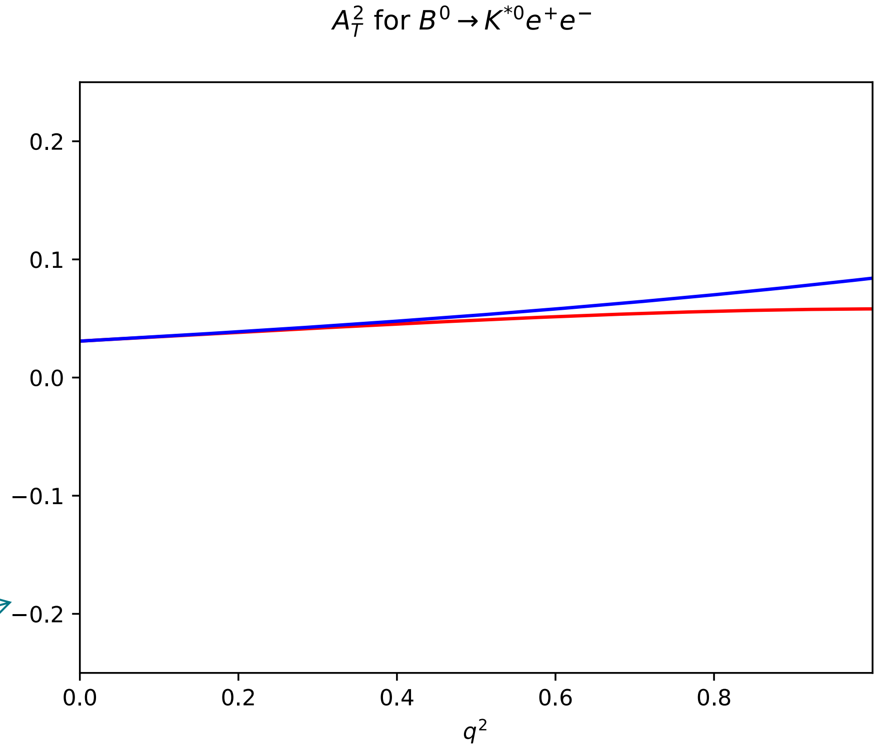
Sensitive to C'_7/C_7

$$A_{\perp L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\text{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} + C_7^{\text{eff}\prime}) \right] \xi_\perp(E_{K^*}),$$

$$A_{\parallel L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\text{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7^{\text{eff}\prime}) \right] \xi_\perp(E_{K^*})$$

Dominating in the very-low q^2 region





F_L is the longitudinal polarisation of the hadronic resonance
⇒ small as the quasi-real photon is transversely polarised

Standard Model predictions

JHEP02(2023)096

$$\langle A_T^{(2)}\rangle_{\rm inc} \sim \frac{2}{(\mathrm{Re}[\mathcal{C}_7])^2 + (\mathrm{Im}[\mathcal{C}_7])^2} \times \left[\mathrm{Re}[\mathcal{C}_7]\mathrm{Re}[\mathcal{C}_{7'}] + \mathrm{Im}[\mathcal{C}_7]\mathrm{Im}[\mathcal{C}_{7'}] + \frac{y}{2}[(\mathrm{Re}[\mathcal{C}_7])^2 - (\mathrm{Im}[\mathcal{C}_7])^2]\right],$$

$$y \equiv \Delta\Gamma_s/(2\Gamma_s)$$

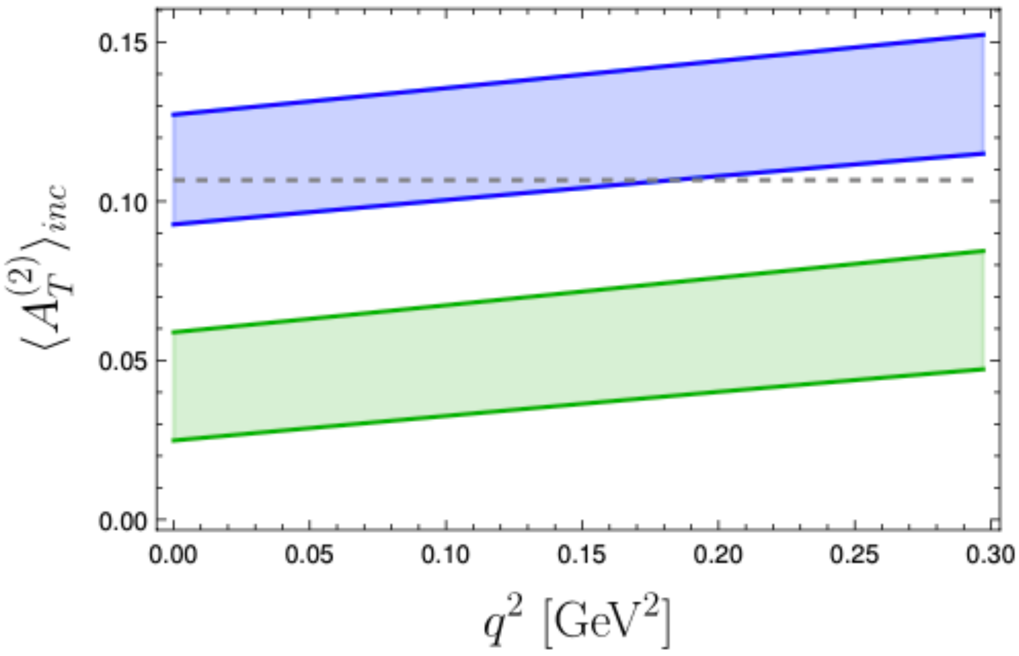
$$\langle A_T^{(\mathrm{Im});CP}\rangle_{\rm inc} \sim \frac{2}{(\mathrm{Re}[\mathcal{C}_7])^2 + (\mathrm{Im}[\mathcal{C}_7])^2} \times \left[\mathrm{Re}[\mathcal{C}_7]\mathrm{Im}[\mathcal{C}_{7'}] - \mathrm{Re}[\mathcal{C}_{7'}]\mathrm{Im}[\mathcal{C}_7] - y\mathrm{Re}[\mathcal{C}_7]\mathrm{Im}[\mathcal{C}_7]\right].$$

- $A_T^{(2)}(q^2 \to 0) = \frac{2Re(C_7 C_7'^*)}{|C_7|^2+|C_7'|^2} + {\Delta_1}^2$
- $A_T^{ImCP}(q^2 \to 0) = \frac{2Im(C_7 C_7'^*)}{|C_7|^2+|C_7'|^2} + {\Delta_2}^2$

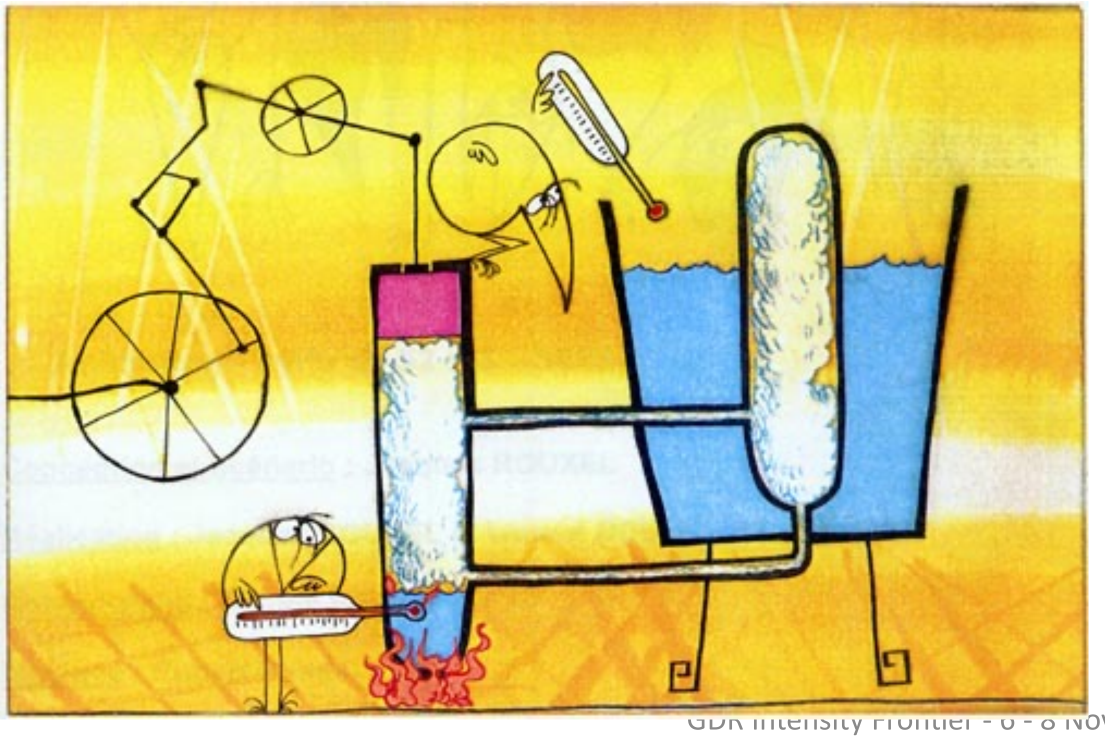
NB : for B^0 $\Delta_i \sim 0$

ϕ^*ee

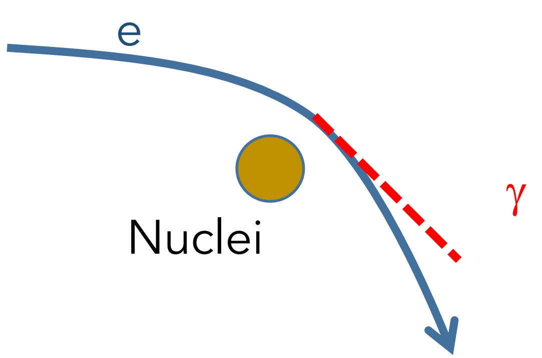
K^*ee

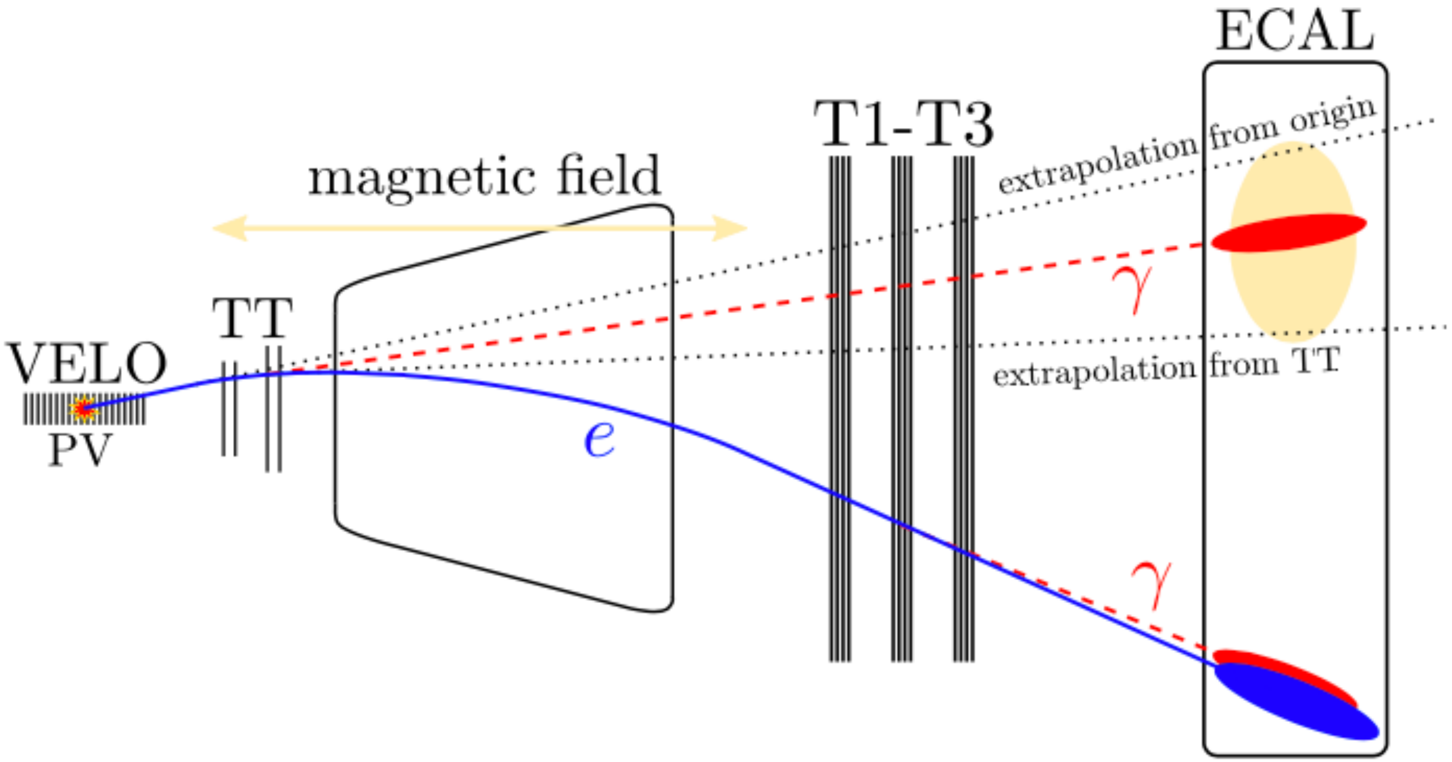


$B_s \rightarrow \phi ee$ angular analysis at very low-q^2



Electrons emit Bremsstrahlung





Before the magnet

- electron can be swept out (=lost !)
- kinematics are "wrong"

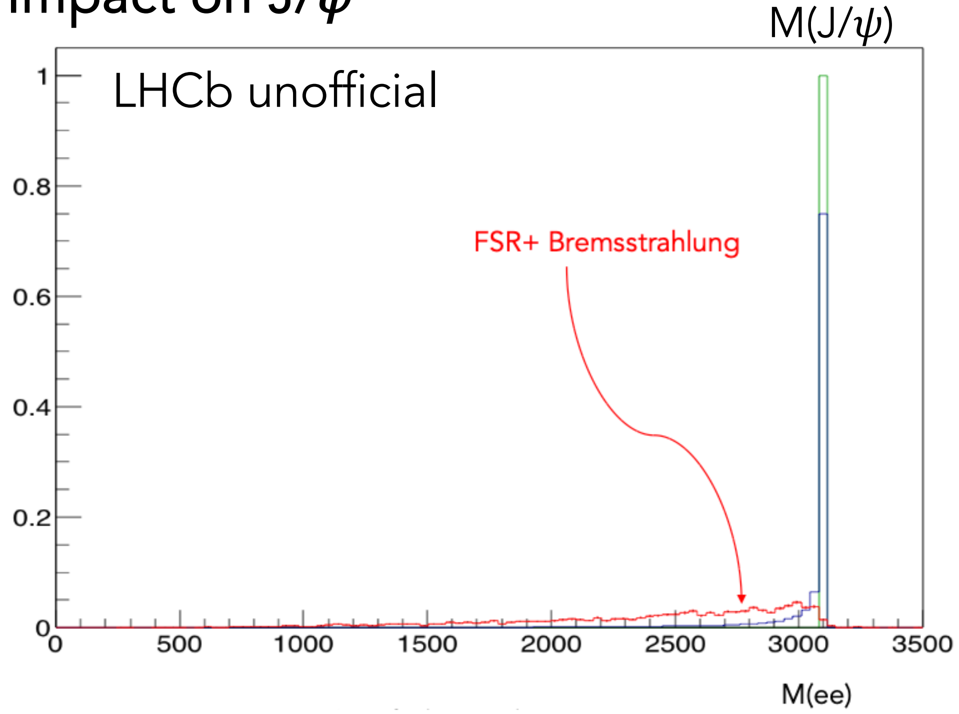
After the magnet

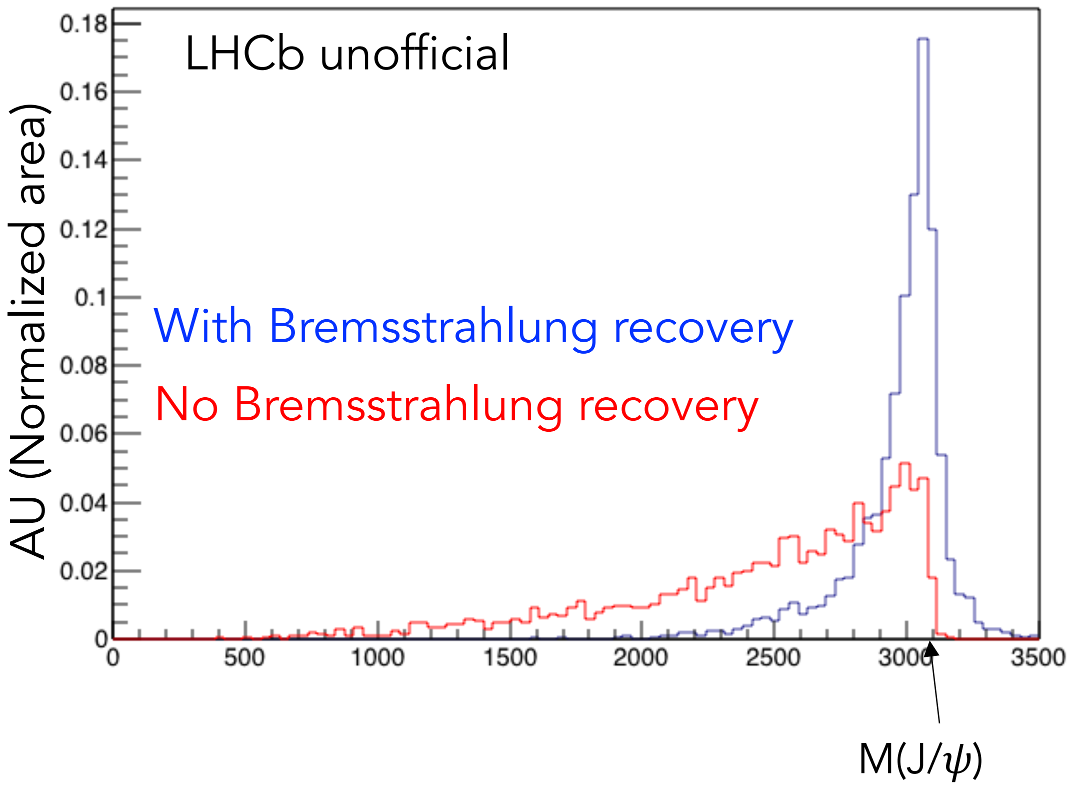
- not an issue

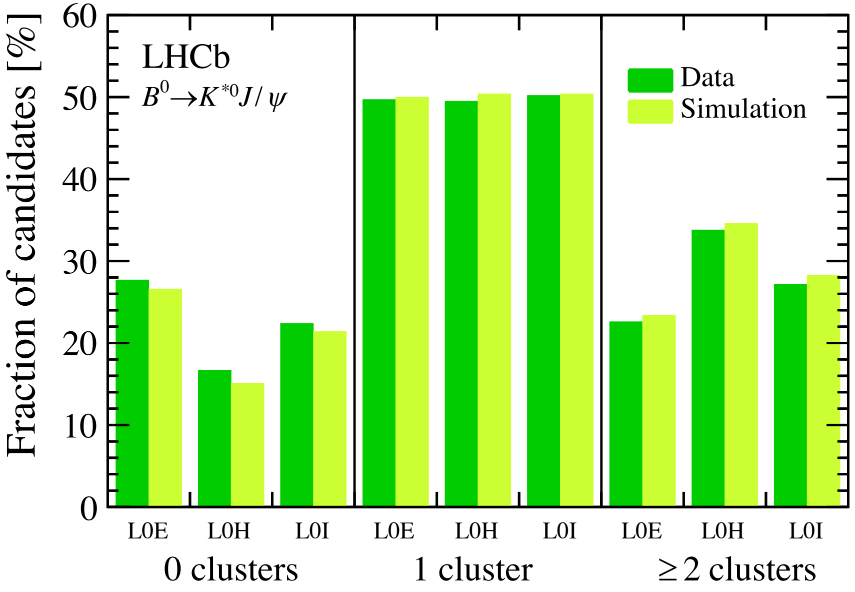
Energy loss ∝ E_e
Energy loss ∝ material

In both cases E/p is correct

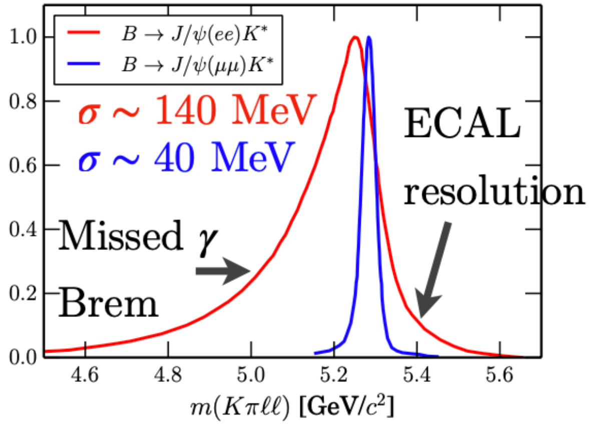
Impact on J/ψ





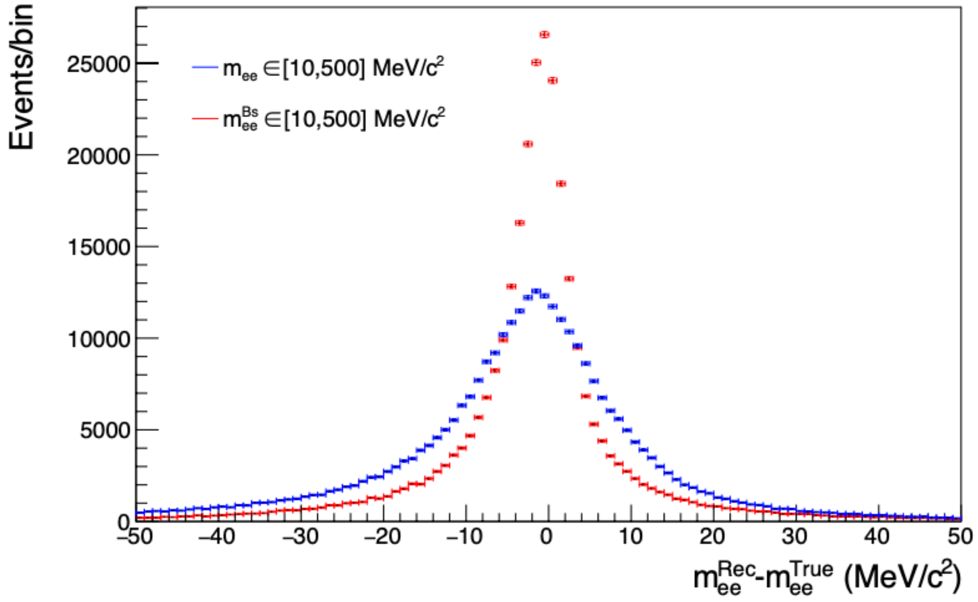


Bremsstrahlung recovery algorithm is ~ 50% efficient
Well described in simulation

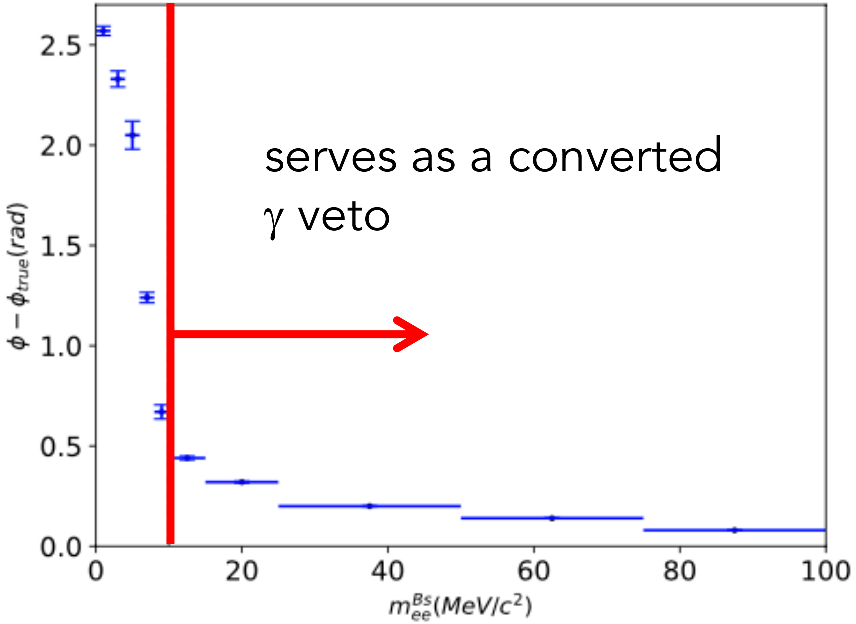


On the q^2 region choice : 10 MeV< m_{ee} <500 MeV

- Compute q^2 imposing a B_s mass constraint



- In principle can go to the threshold (M(ee) = $2m_e$) but bad resolution on φ



- Upper bound : q^2<.25 GeV² (minor contributions from non-γ diagrams) and avoids backgrounds from (eg) $\rho \rightarrow ee$

Two main backgrounds

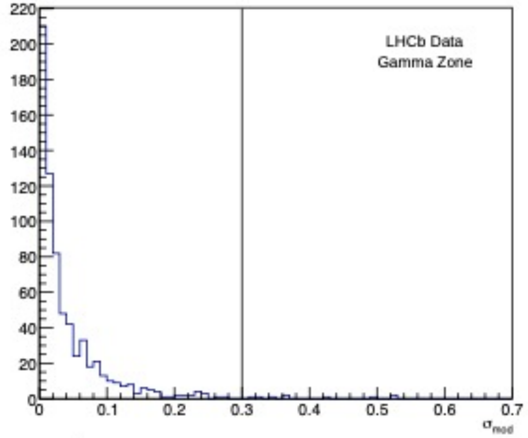
- $B_s \to \phi(\to K^+K^-)\gamma_{ee}$

$M^{Bs}(ee) > 10$ MeV and rejection of pair with a vertex compatible with VELO material (RF Foil)

$$\sigma_{mod} = \sqrt{\left(\frac{\delta_x}{\sigma_x}\right)^2 + \left(\frac{\delta_y}{\sigma_y}\right)^2 + \left(\frac{\delta_z}{\sigma_z}\right)^2}$$

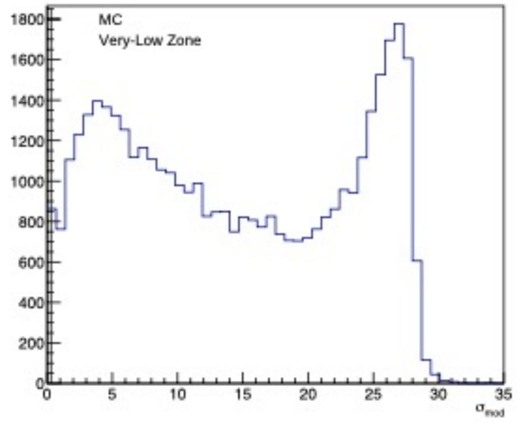
where:

$B_s \to \phi\gamma(\to ee)$



$B_s \to \phi ee$

$\epsilon_{sig} = 97\%$



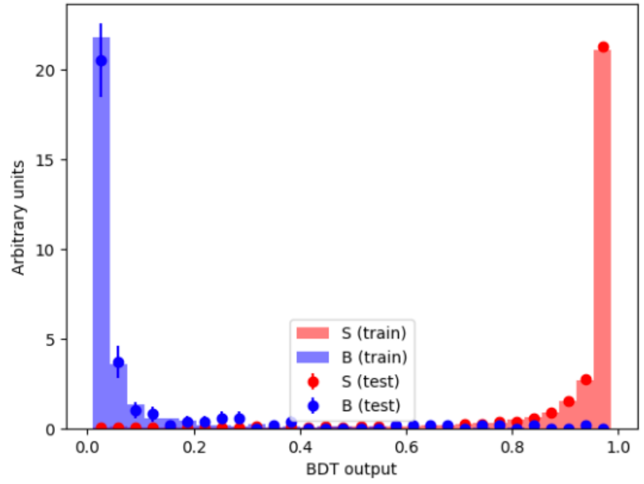
Contamination: $C_\gamma \sim 2.5\% \to$ modelled in the fit

- Combinatorial background

- Signal Proxy: MC Signal of $B_s^0 \to \phi ee$
- Background Proxy: Data corresponding to the upper sideband mass ($m_{Bs} > 5700$ MeV)

⋆ BDT input invariables:

Particle	Variable
B_s	p_T χ^2_{FD} χ^2_{DTF}/ndf log(1 - B_s_DIRA)
ϕ	log χ^2_{IP}
$K^\pm$	min (log χ^2_{IP})
$e^\pm$	min (log χ^2_{IP})
e^+e^-	min (log χ^2_{IP})

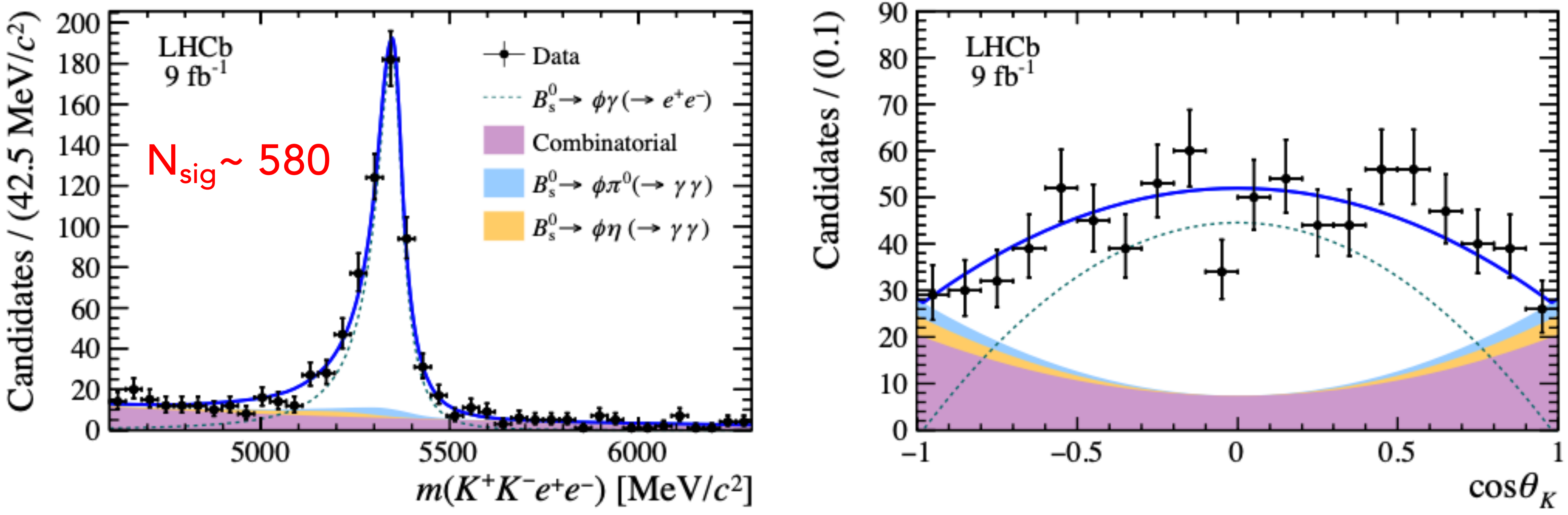


- k-folding technique (k=10)

$B_s \to \phi(\to K^+K^-)\gamma_{ee}$ control channel

[LHCb-PAPER-2024-030, in preparation]

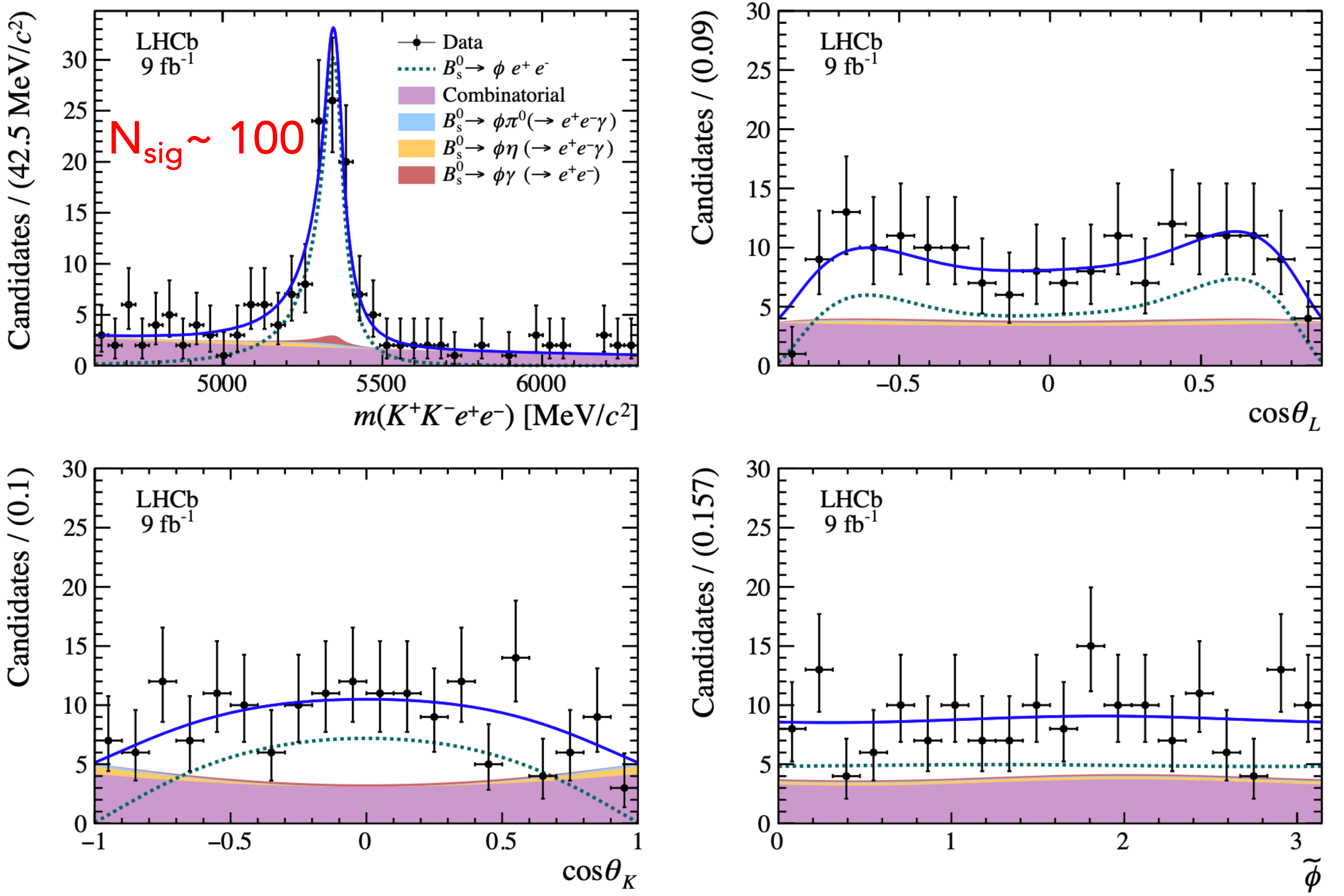
M(ee) < 10 MeV and converted gamma veto removed



$$F_L = -0.01 \pm 0.02 \quad \text{(stat)}$$

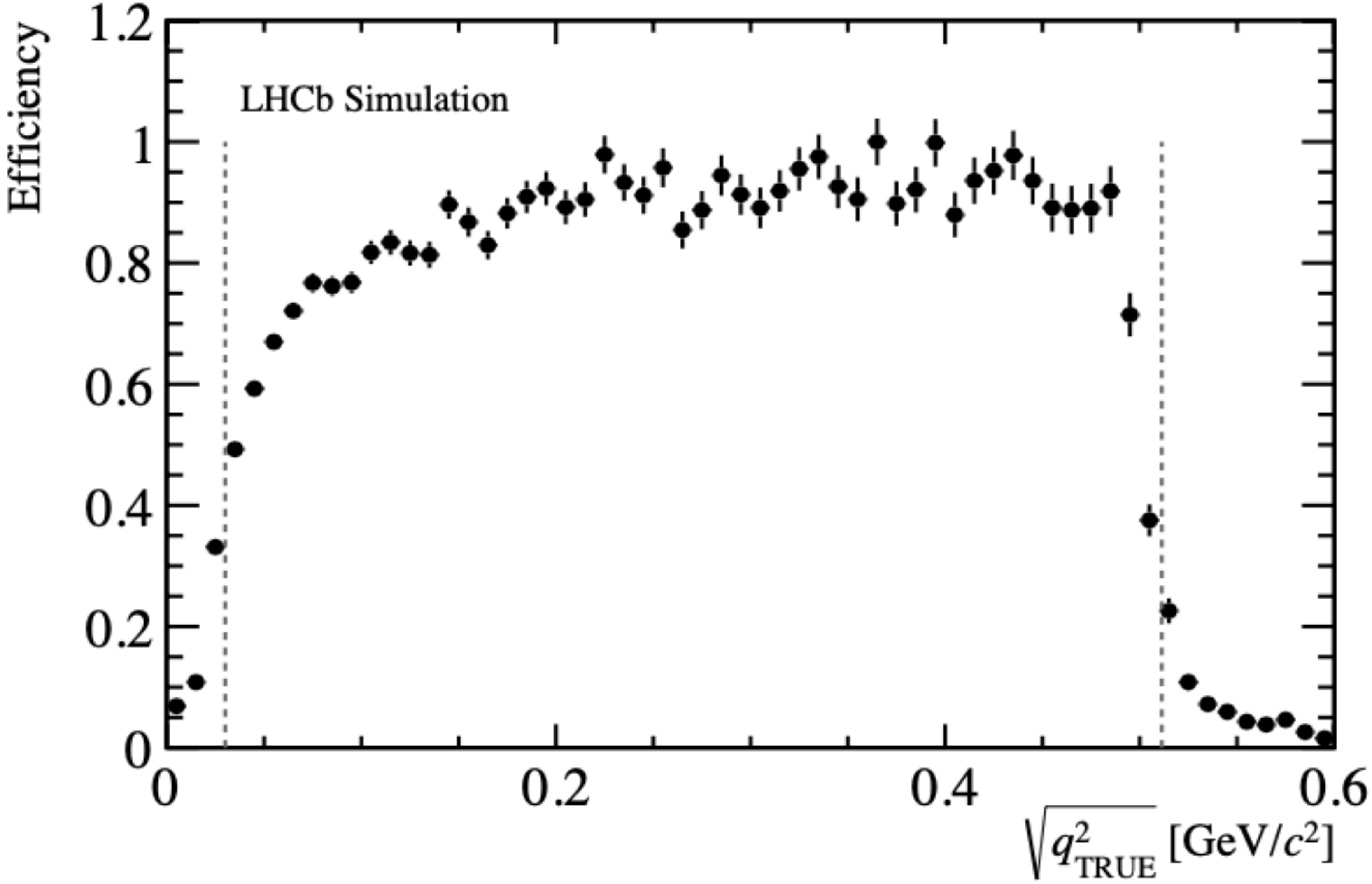
4D fit : m(KKee), $\cos\theta_K$, $\cos\theta_\ell$ $\tilde{\phi}$

[LHCb-PAPER-2024-030, in preparation]



Effective q^2 region

$0.0009 < q^2 < 0.2615$ GeV^2/c^4



Results in good agreement with the SM:

$$A_{\rm T}^{(2)} = -0.045 \pm 0.235 \pm 0.014\,,$$
$$A_{\rm T}^{\mathcal{I}mCP} = 0.002 \pm 0.247 \pm 0.016\,,$$
$$A_{\rm T}^{\mathcal{R}eCP} = 0.116 \pm 0.155 \pm 0.006\,,$$
$$F_{\rm L} = (0.4 \pm 5.6 \pm 1.2)\%\,,$$

Corrected (- 0.025) for the non-flat efficiency in decay time

F_L < 11.5 % (13.7%) @ 90 (05) % CL

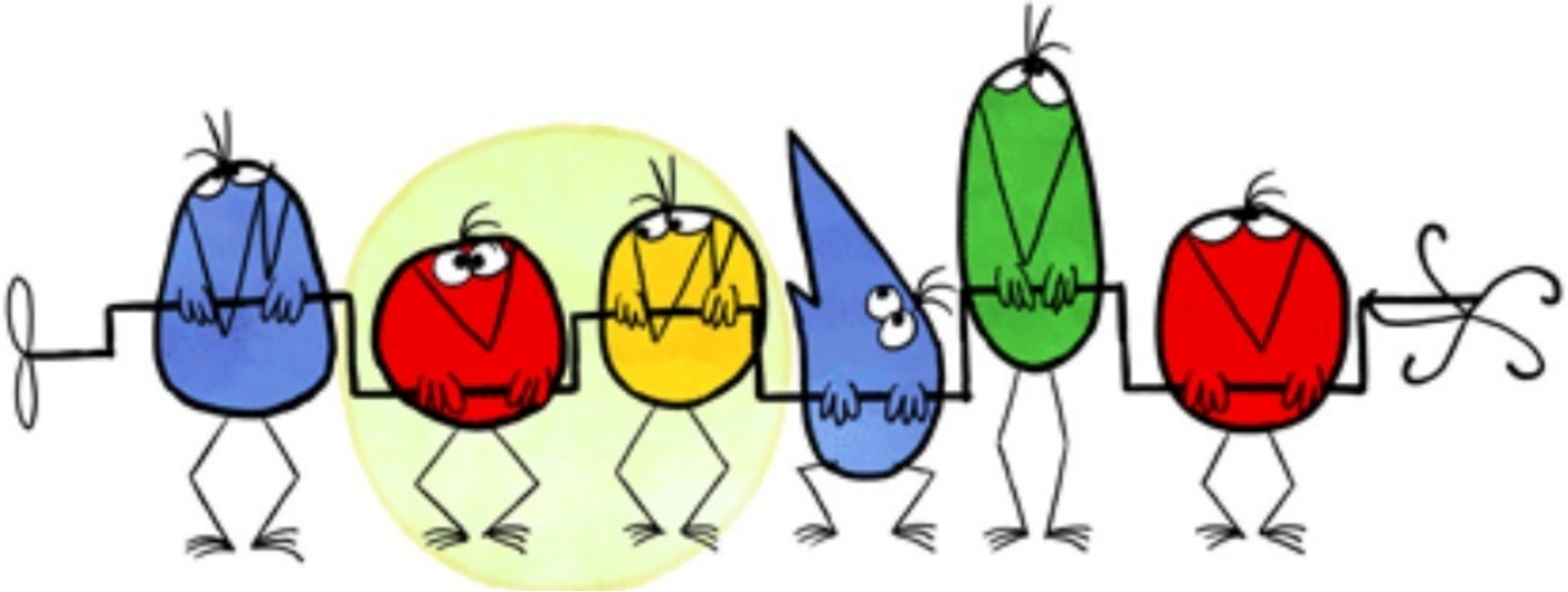
JHEP02(2023)096

Decay mode	$B_s \to \phi ee$			
q^2-bin [GeV^2]	$\langle \text{Br} \rangle_{\text{inc}} \times 10^7$	$\langle F_L \rangle_{\text{inc}}$	$\langle A_T^{(2)} \rangle_{\text{inc}}$	$\langle A_T^{(\text{Im})} \rangle_{\text{inc}}$
[0.0008, 0.257]	2.76(26)	0.106(19)	0.111(20)	0.0369(2)

Flavio (arXiv:1810.08132.)

F_L	0.068
$A_T^{(2)}$	0.094
A_T^{ImCP}	0.000
A_T^{ReCP}	0.000

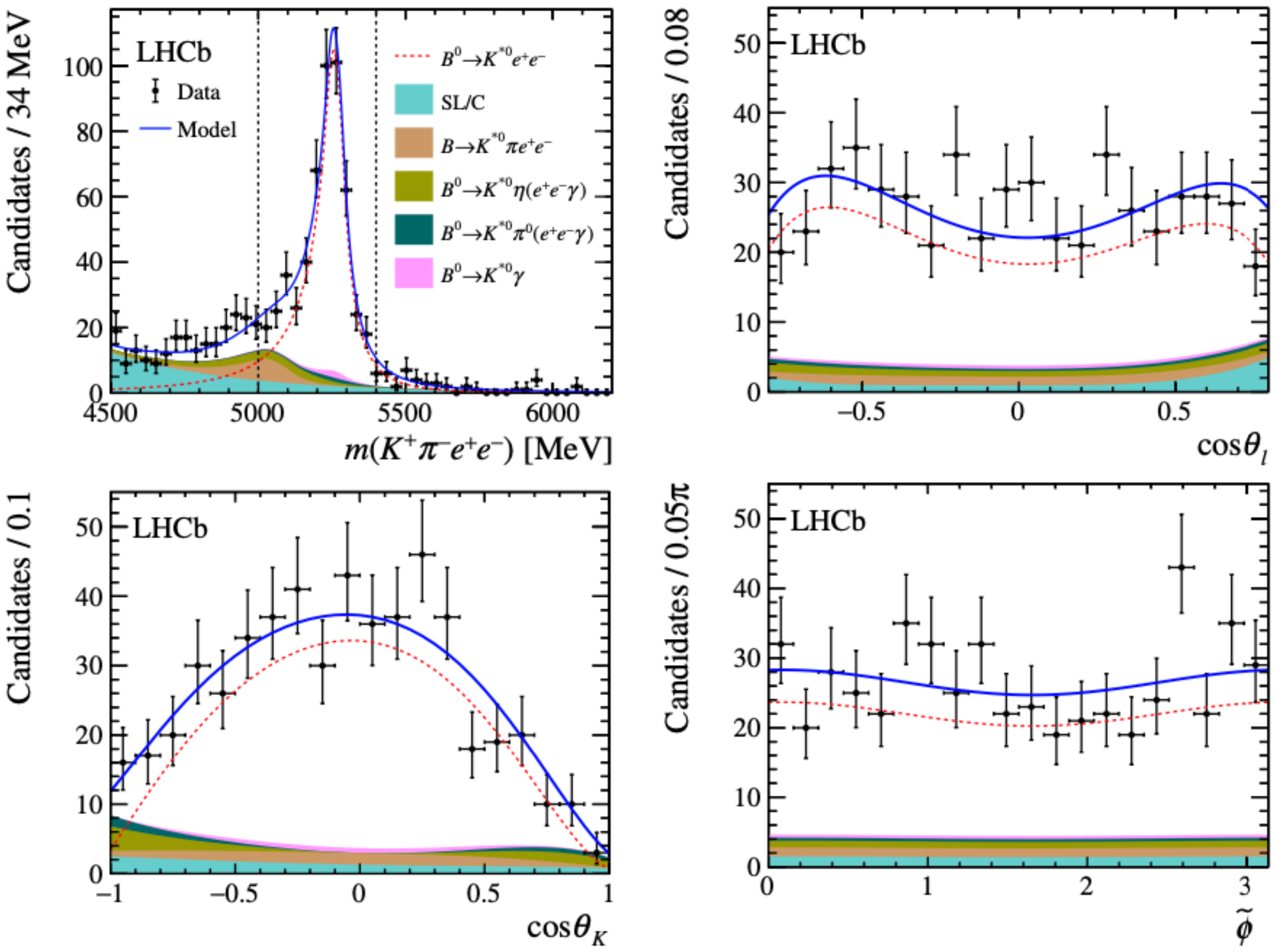
Other recent experimental results and overall knowledge



Another player in the game: $B^0 \to K^*(\to K\pi)ee$

JHEP 12 (2020) 081

$N_{sig} \sim 450$



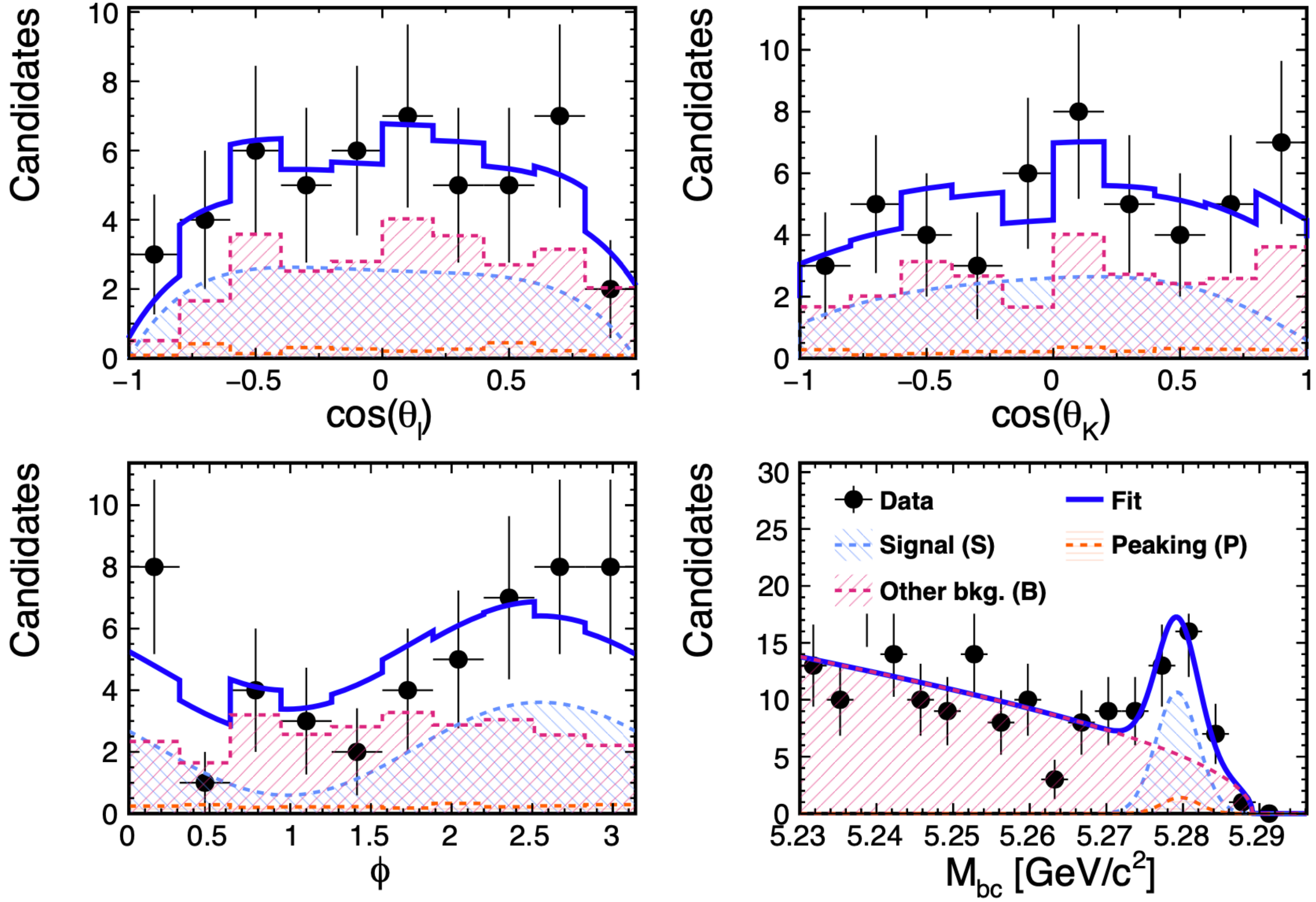
$$F_L = 0.044 \pm 0.026 \pm 0.014,$$
$$A_T^{Re} = -0.06 \pm 0.08 \pm 0.02,$$
$$A_T^{(2)} = +0.11 \pm 0.10 \pm 0.02,$$
$$A_T^{Im} = +0.02 \pm 0.10 \pm 0.01,$$

More than x2 more precise

$B^0 \to K^{0*}(\to K\pi)ee$ and $B^+ \to K^{+*}(\to K_S\,\pi)ee$

$0.0008<q^2<1.12$ GeV^2 K* ± 150 MeV

arXiv:2404.00201]



Limited fit : F_L and A_T^{Re} fixed to SM values

$$A_T^{(2)} = 0.52 \pm 0.53 \pm 0.11,$$
$$A_T^{\rm Im} = -1.27 \pm 0.52 \pm 0.12,$$

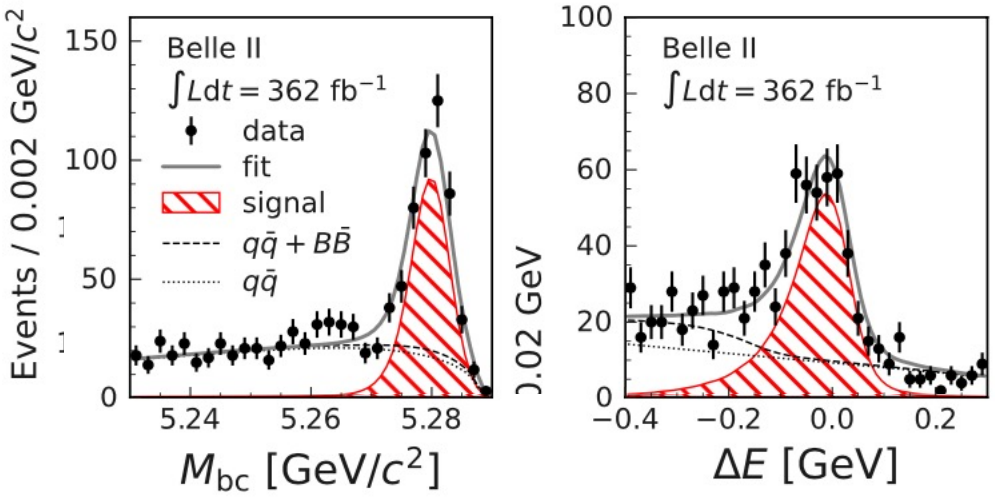
$N_s = 21 \pm 6$

Another player in the game: Mixing-induced CP asymmetries in $B^0 \to K^{*0} (\to K^0 \pi^0) \gamma$

Belle II (362 fb^{-1}) arXiv:2407.09139

$$\mathcal{P}_{\rm TD}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q\cdot[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)]\},$$

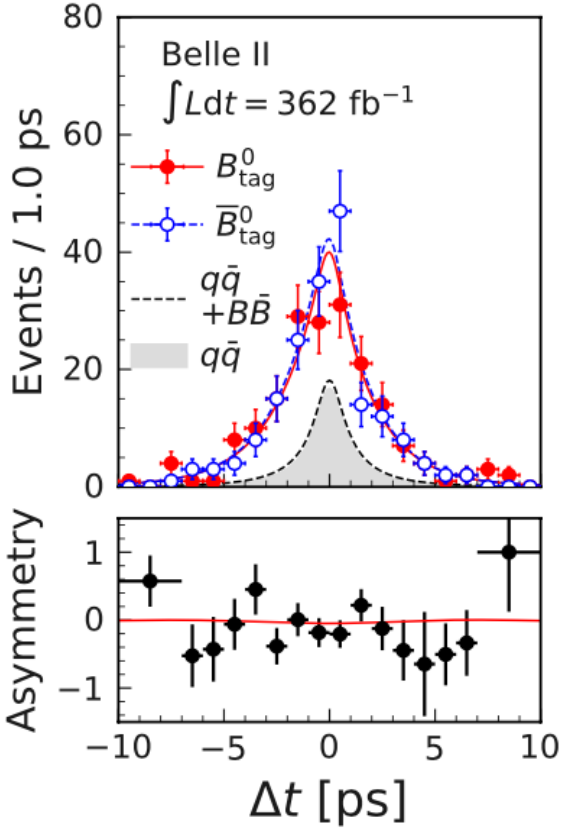
q=+1 (-1) B^0 ($\bar{B}^0$)



$$S = 0.00^{+0.27}_{-0.26} \pm 0.03,$$

$$C = 0.10 \pm 0.13 \pm 0.04$$

$$\mathcal{S} \approx \xi \frac{2\mathcal{I}m[e^{-i\phi_q}\, \mathcal{C}_7 \mathcal{C}_7'|}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$



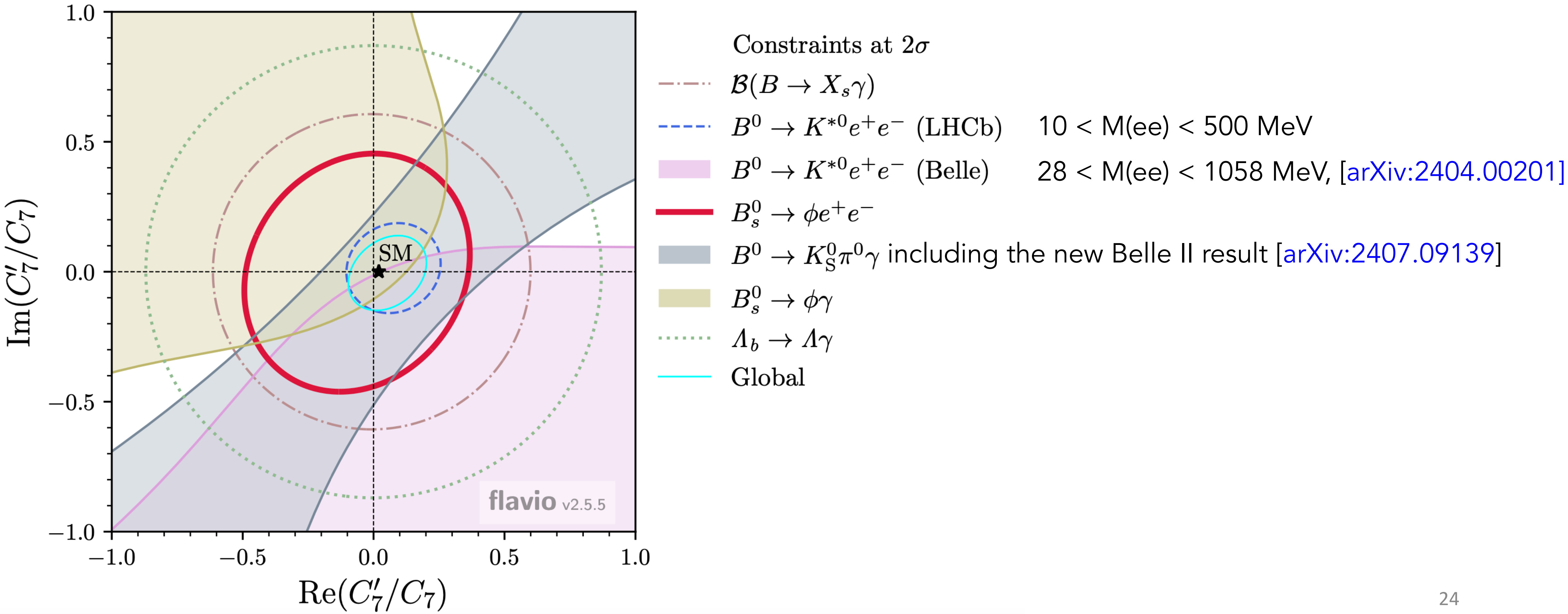
$\mathcal{E}_{eff} = (31.69 \pm 0.35)\%$

HFLAV average was :
-0.16 ± 0.22

The photon polarisation in b → sγ transitions is known with a precision of ~ 4%

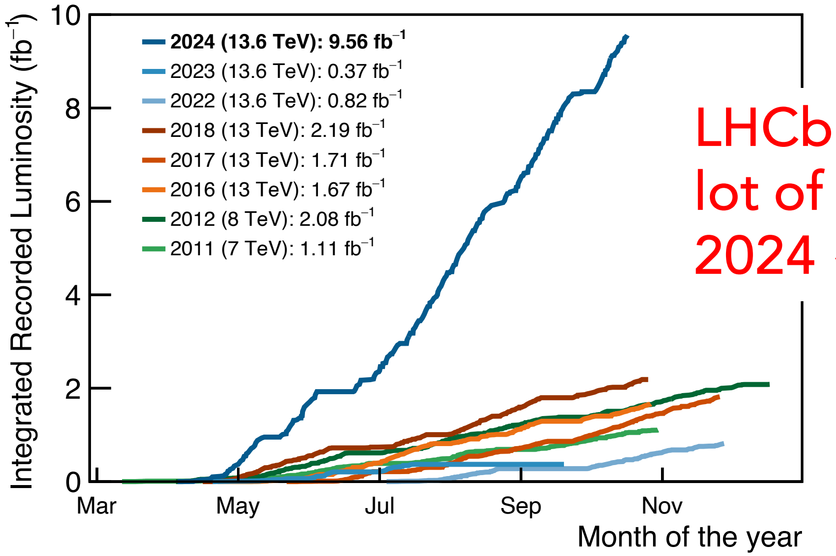
All measurements are in good agreement

[LHCb-PAPER-2024-030, in preparation]



Conclusion

- New result from LHCb $B_s \to \phi ee$ angular analysis in the very-low q2 region
- Precision on the photon polarization ~ 4% dominated by K*ee
- Nice recent result from Belle-II
- Many results dominated by statistical uncertainties

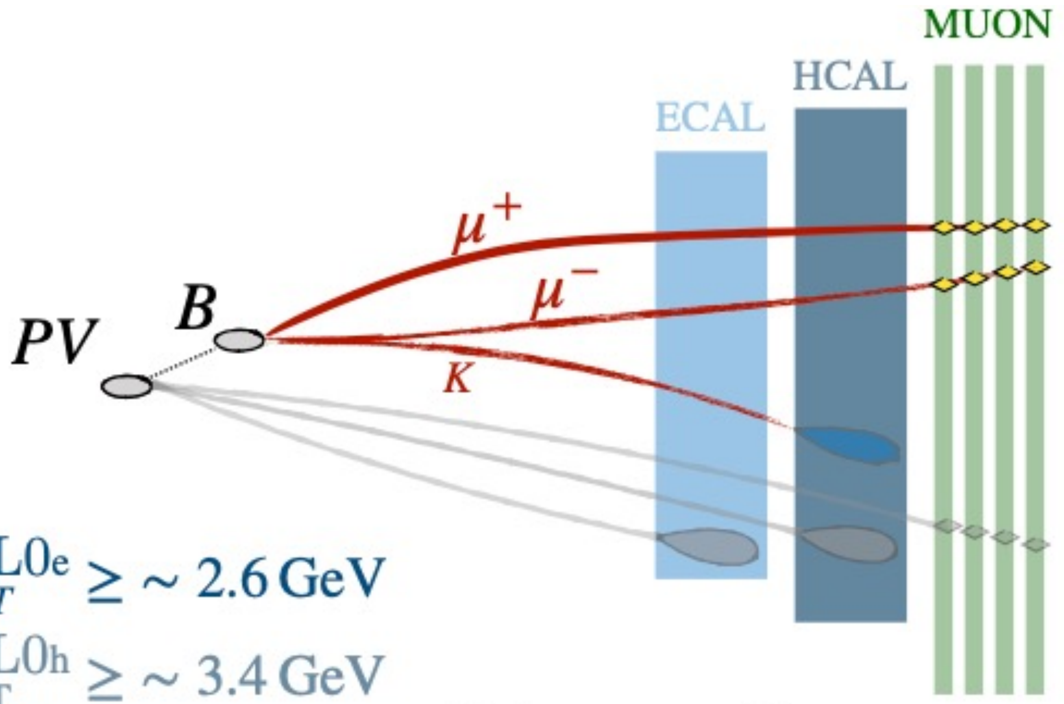


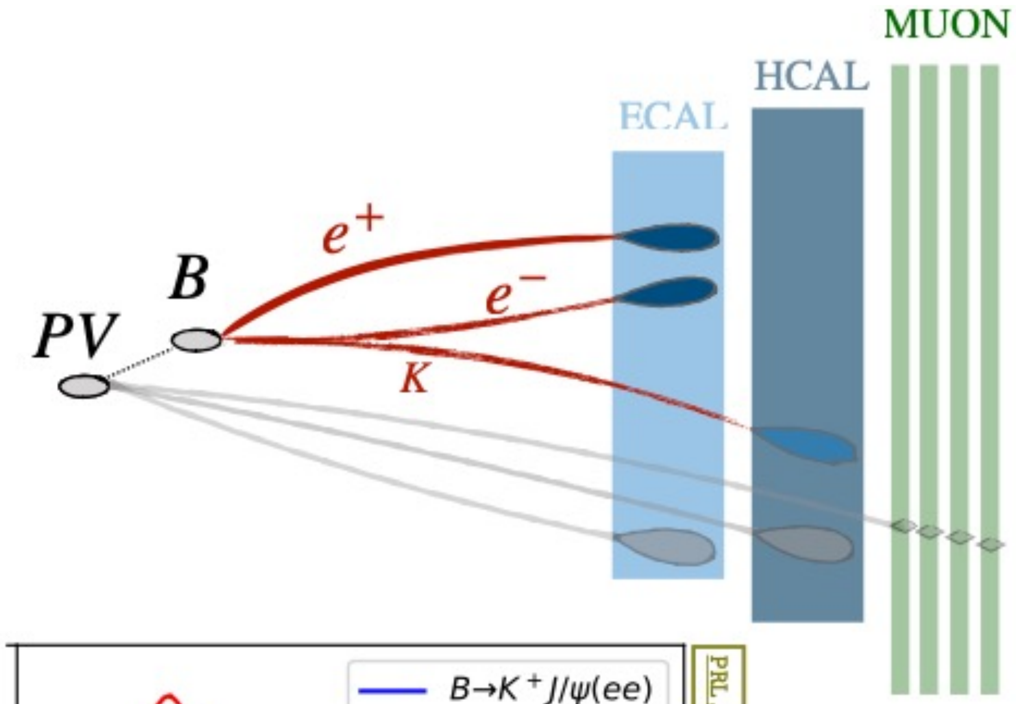
LHCb has recorded a lot of new data in 2024 ~ (Run1 + Run2)

Back up slides

Background	Contamination [4] (Very-Low)	Mass and angular modeling
Combinatorial	Given by fit	$B_s \to \phi e^+ e^-$ data: Mass $B_s \to \phi e \mu$ data: Angles
$B_s^0 \to \phi\eta(\to e^+e^-\gamma)$	L0E: 4.2 ± 0.6 % L0I: 5.1 ± 0.7 %	$\mathrm{B}_s^0 \to \phi\eta(\to e^+e^-\gamma)$ MC
$B_s^0 \to \phi\pi^0(\to e^+e^-\gamma)$	L0E: 1.1 ± 0.2 % L0I: 2.5 ± 0.5 %	$B_s^0 \to \phi\pi^0(\to e^+e^-\gamma)$ MC
$B_s^0 \to \phi\gamma(\to e^+e^-)$	L0E: 2.4 ± 0.3 % L0I: 1.9 ± 0.3 %	$B_s^0 \to \phi e^+e^-$ γ-bin Data and MC

Hardware trigger is very different for electrons and muons





$E_T^{L0e} \geq \sim 2.6\,\text{GeV}$

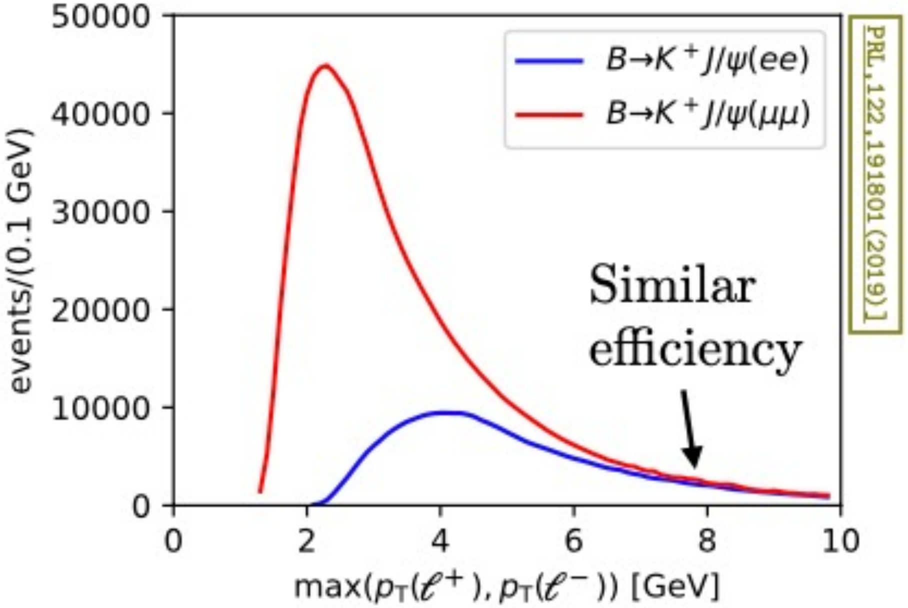
$E_T^{L0h} \geq \sim 3.4\,\text{GeV}$

$p_T^{L0\mu} \geq \sim 1.4\,\text{GeV}$

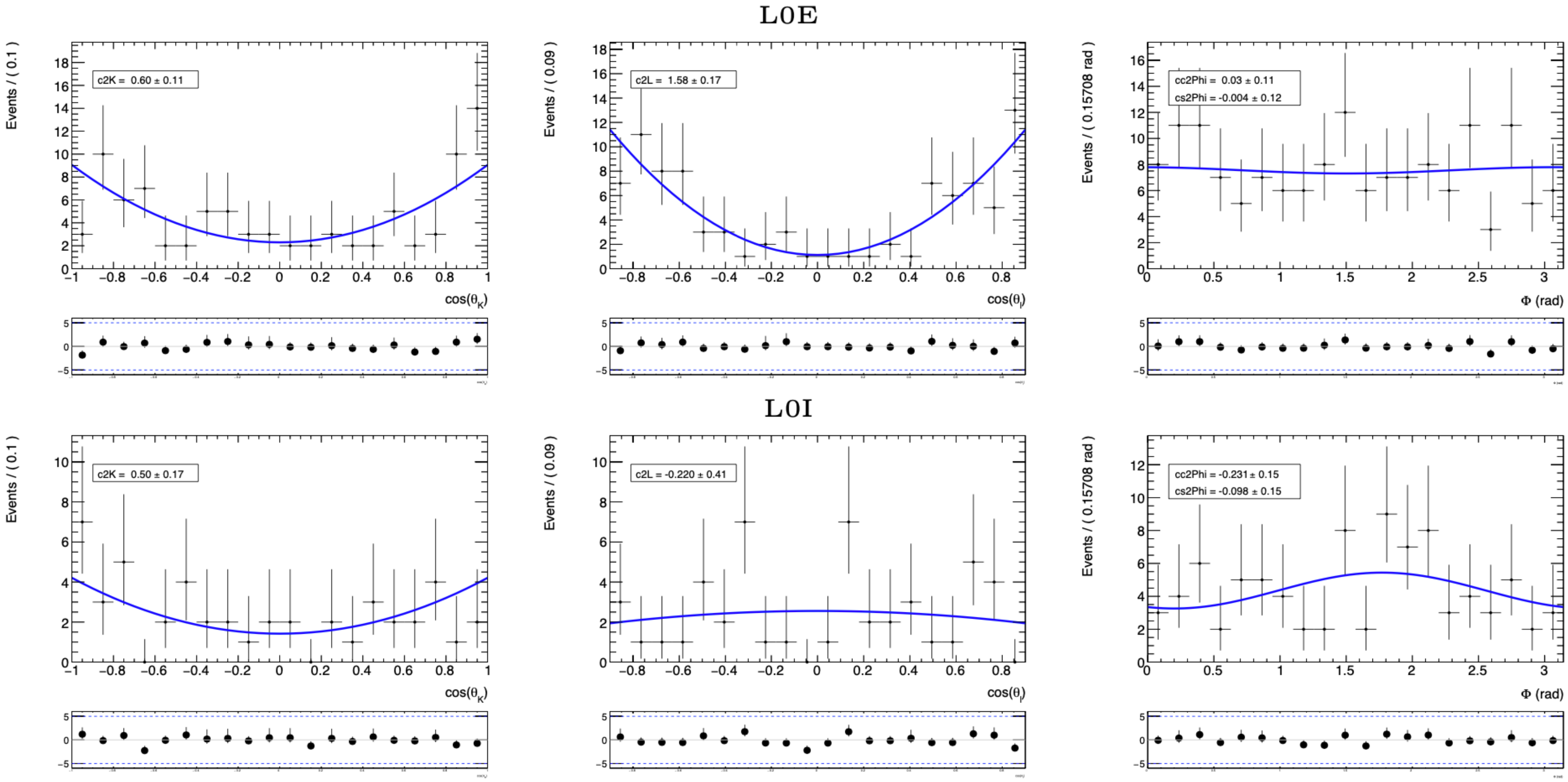
Selection effect

from L0e vs L0μ

$$\sim \frac{1}{3}$$

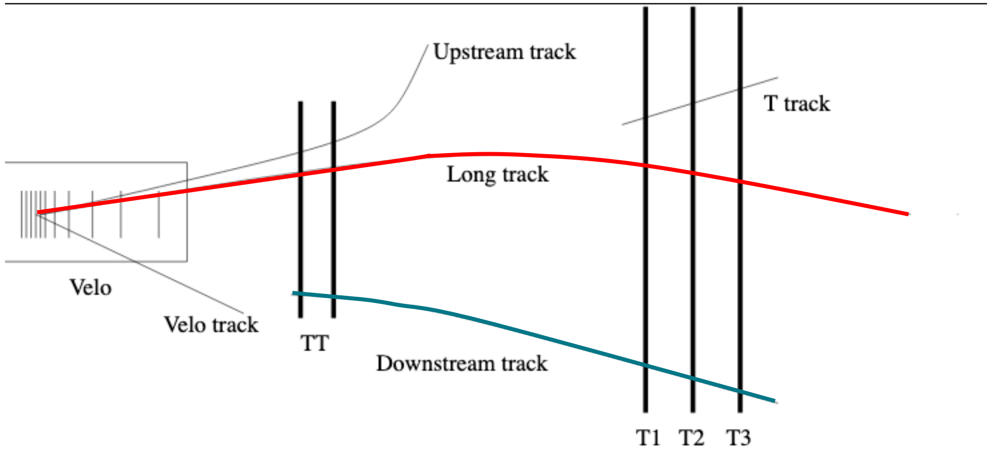


Combinatorial background constrained using by ϕ e μ



and what about converted photons ?

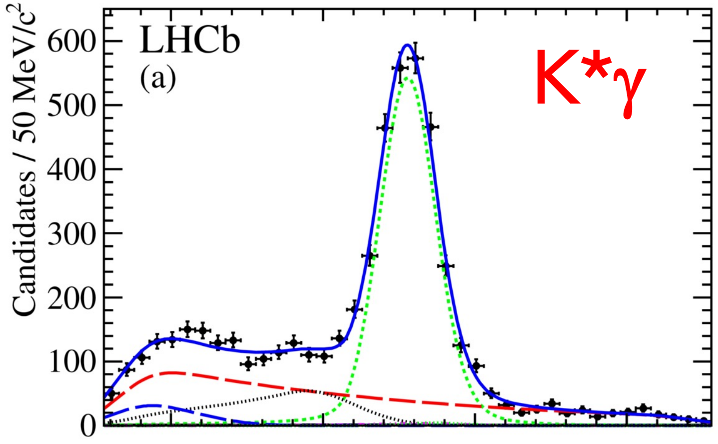
In LHCb ~ 4% of the photons are converting such as they can be reconstructed as LL track pairs

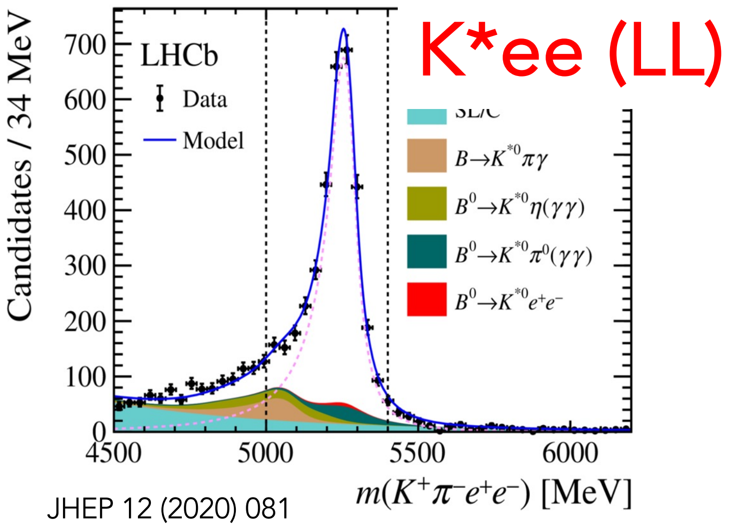


Roughly 30% more DD than LL (and cleaner?)

High quality tracks with excellent properties measurements (but bremsstrahlung …)

Phys. Rev. D85 (2012) 112013





JHEP 12 (2020) 081

Converted photons and photon polarization measurement

Weizacker Williams approximation

In the cm of the ee pair :

$$d\sigma = \left(\frac{\beta r_0^2}{2x^2}\right)\{(1-\beta^2\cos^2\theta)^{-1} - \frac{1}{2} + 2\beta^2(1-\beta^2)(1-\beta^2\cos^2\theta)^{-2}\sin^2\theta\cos^2\phi\}\sin\theta d\theta d\phi.$$

x : photon energy in units of m_e

θ_ℓ

e velocity

G. C. Wick, Phys. Rev. 81 (Feb, 1951) 467- 468.

$$M(ee) = \frac{2m_e}{\sqrt{1-\beta^2}}$$

Work done with J. Lefrancois in the context of Martino Borsato PhD (2015)

The polarization is visible through the ϕ distribution

$$d\sigma = \left(\frac{\beta r_0^2}{2x^2}\right)\{(1-\beta^2\cos^2\theta)^{-1} - \frac{1}{2} + \cancel{2\beta^2(1-\beta^2)(1-\beta^2\cos^2\theta)^{-2}\sin^2\theta\cos^2\phi}\}\sin\theta d\theta d\phi.$$

$\beta \to 1$

'large' M(ee)

In short : sensitivity at very low M(ee) (< 5 – 10 MeV) where we cannot measure ϕ …

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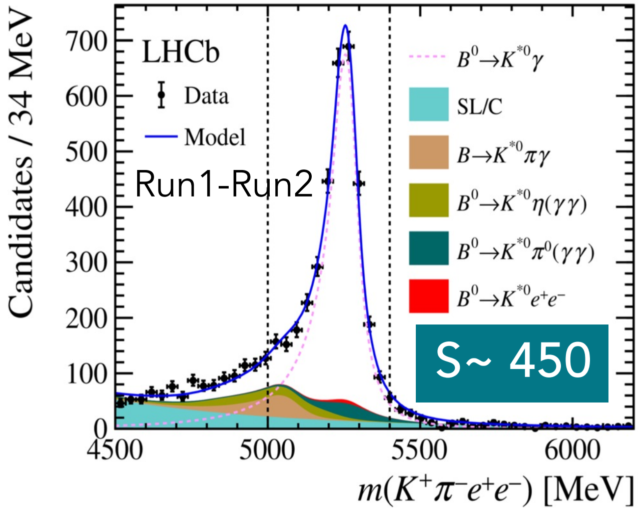
Probing the photon polarization in $B \to K^*\gamma$ with conversion

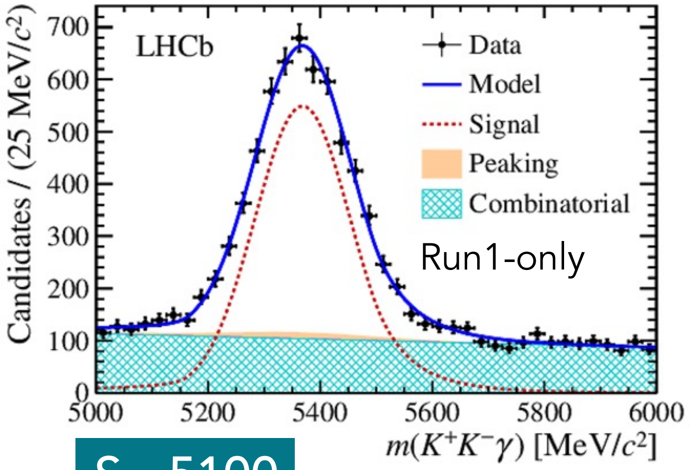
Fady Bishara[a,b] and Dean J. Robinson[c,d]

$$B \to (K^* \to K^+\pi^-)(\gamma \overset{\mathrm{BH}}{\to} e^+e^-)$$

$$re^{i(\phi+\delta)} \equiv \frac{\mathcal{A}(B \to K^*\gamma_L)}{\mathcal{A}(B \to K^*\gamma_R)}$$

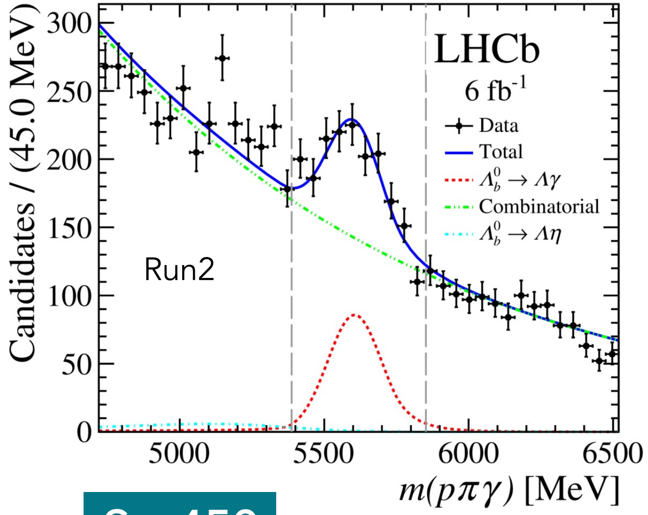


Phys. Rev. Lett. 123 (2019) 081802



S~ 5100

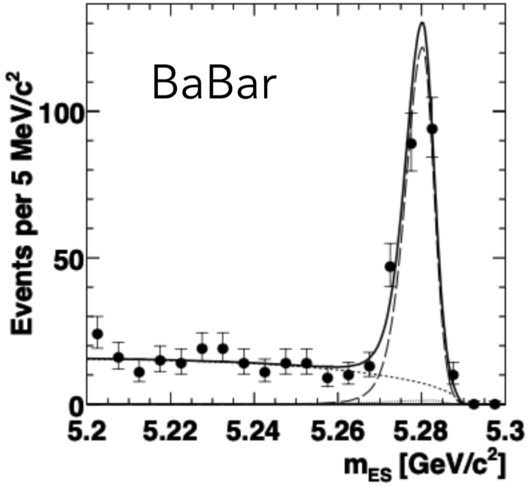
Phys. Rev. D105 (2022) L051104



S~ 450

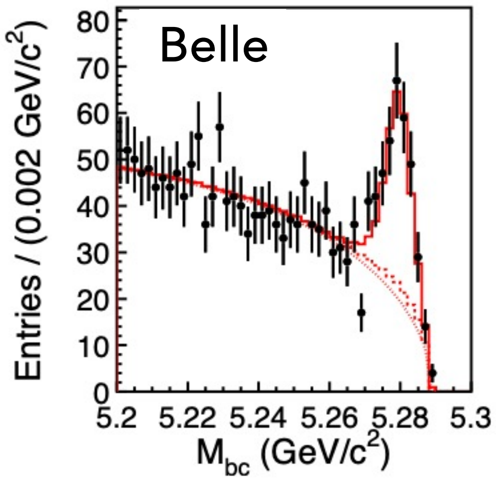
S~ 130 (K*0 region)

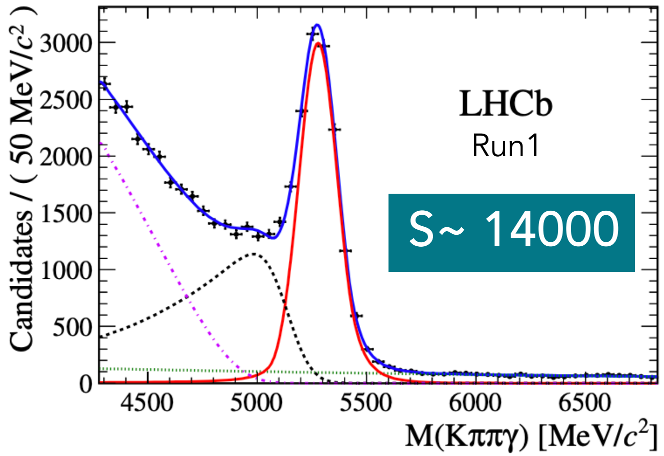
Phys.Rev.D78:071102,2008



S ~ 110 (K*0 region)

Phys.Rev.D74:111104,2006





In the massless lepton limit, we have

$$A_T^{(2)} = \frac{|A_\perp^L|^2 + |A_\perp^R|^2 - |A_{||}^L|^2 - |A_{||}^R|^2 + (A \leftrightarrow \bar{A})}{|A_\perp^L|^2 + |A_\perp^R|^2 + |A_{||}^L|^2 + |A_{||}^R|^2 + (A \leftrightarrow \bar{A})},$$

$$A_T^{(\mathrm{Re});CP} = \frac{2\,\mathrm{Re}\left[(A_{||}^L A_\perp^{L*} - A_{||}^R A_\perp^{R*}) - (A \leftrightarrow \bar{A})\right]}{|A_\perp^L|^2 + |A_\perp^R|^2 + |A_{||}^L|^2 + |A_{||}^R|^2 + (A \leftrightarrow \bar{A})},$$

$$A_T^{(\mathrm{Im});CP} = -\frac{2\,\mathrm{Im}\left[(A_{||}^L A_\perp^{L*} + A_{||}^R A_\perp^{R*}) - (A \leftrightarrow \bar{A})\right]}{|A_\perp^L|^2 + |A_\perp^R|^2 + |A_{||}^L|^2 + |A_{||}^R|^2 + (A \leftrightarrow \bar{A})}$$

$$A_{\perp L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\mathrm{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\mathrm{eff}} + C_7^{\mathrm{eff}\prime}) \right] \xi_\perp(E_{K^*}),$$

$$A_{\| L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(C_9^{\mathrm{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\mathrm{eff}} - C_7^{\mathrm{eff}\prime}) \right] \xi_\perp(E_{K^*})$$