

# Measurements of $R_K$ and $R_{K^*}$ with the LHCb Run1+ Run2 dataset

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- Why are we interested in  $b \rightarrow s \ell \ell$  transitions ?
- Electrons and muons in LHCb
- The  $R_X$  analysis

# Why are we interested in $b \rightarrow sl\ell$ transitions ?



FCNC are forbidden at tree level in the SM

# How to find cracks in the SM fortress ?



**Direct** evidence for new particles

**Indirect** evidence through precision measurements sensitive to the presence of virtual states present in the decay of SM particles

# Flavour Changing Neutral Currents were successful in the past

CP violation and FCNC : sensitive probes of short distance physics

Many tests limited by statistics not by systematics nor theory

1964  $K_L \rightarrow \pi\pi$  : CP violation  
3 families

1987  $B_d$  mixing  $\sqrt{s}=10$  GeV (ARGUS)

$$\Delta m_d \sim 0.00002 \times \left( \frac{m_t}{\text{GeV}/c^2} \right)^2 \text{ ps}^{-1} \sim 0.5 \text{ ps}^{-1}$$

$$\Rightarrow m_t > 50 \text{ GeV}$$

PLB 192 (1987)

## OBSERVATION OF $B^0$ - $\bar{B}^0$ MIXING

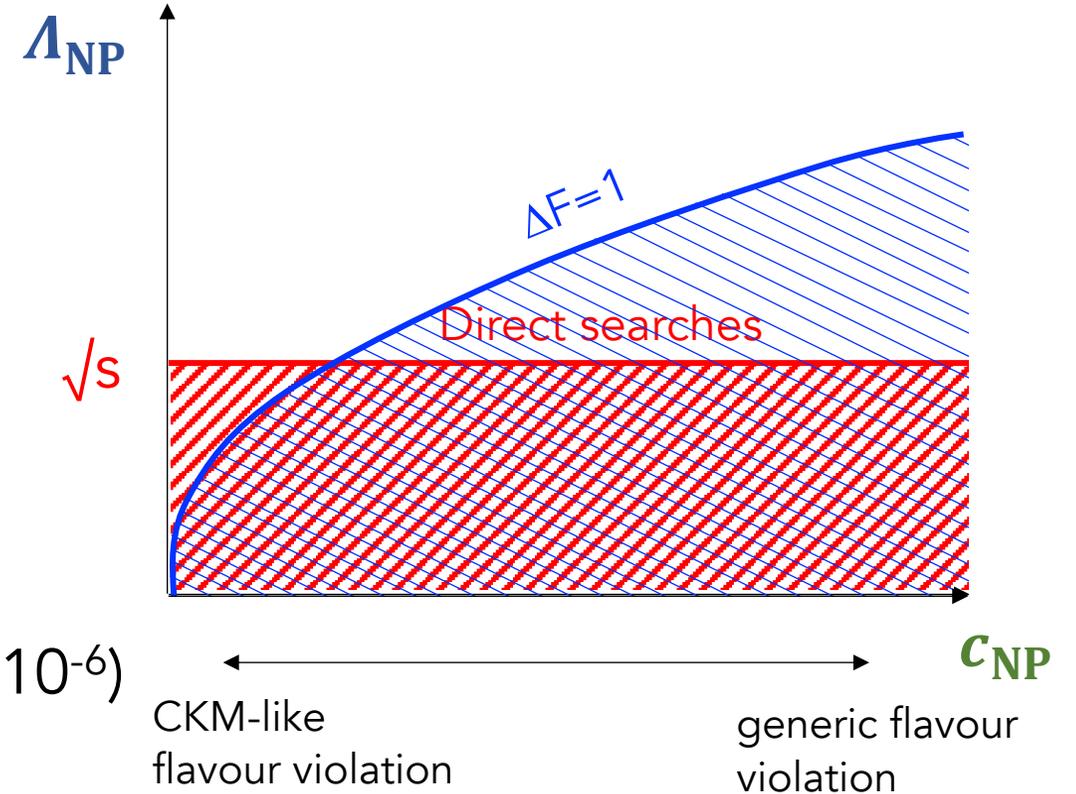
ARGUS Collaboration

In summary, the combined evidence of the investigation of  $B^0$  meson pairs, lepton pairs and  $B^0$  meson-lepton events on the  $\Upsilon(4S)$  leads to the conclusion that  $B^0$ - $\bar{B}^0$  mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_{\pi} < 160 \text{ MeV}$	B meson ( $\approx$ pion) decay constant
$m_b < 5 \text{ GeV}/c^2$	b-quark mass
$\tau < 1.4 \times 10^{-12} \text{ s}$	B meson lifetime
$ V_{ub}  < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{\text{QCD}} < 0.86$	QCD correction factor <sup>a)</sup>
$m_t > 50 \text{ GeV}/c^2$	t quark mass

$$A(\psi_i \rightarrow \psi_j + X) = A_0 \left( \frac{c_{\text{SM}}}{v^2} + \frac{c_{\text{NP}}}{\Lambda_{\text{NP}}^2} \right)$$

NP **scale** and **coupling**

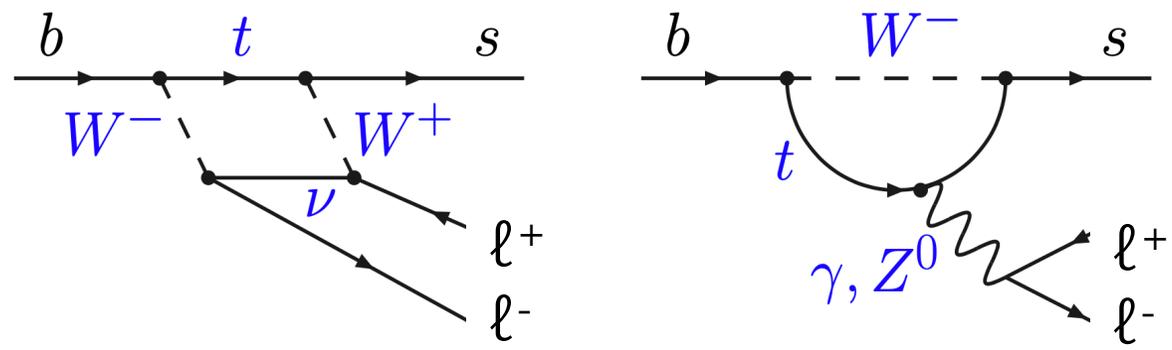


Branching fractions suppressed at tree level ( $< 10^{-6}$ )

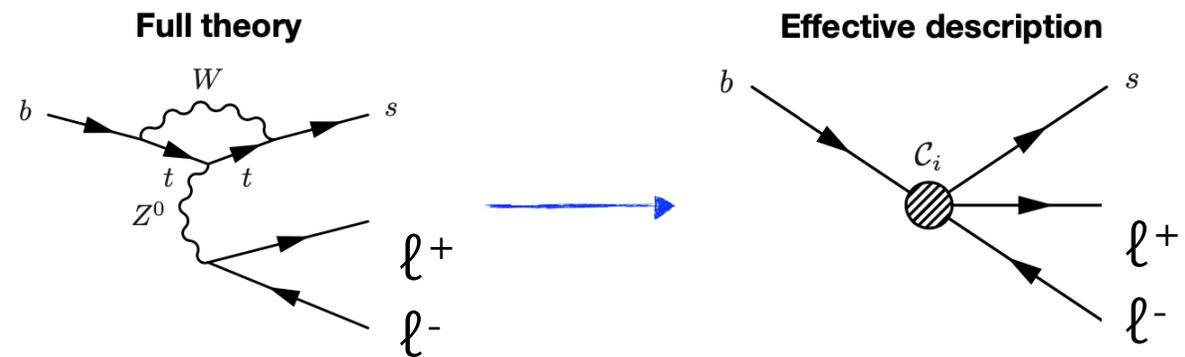
Highly sensitive to New Physics (NP)

NP can affect decay rates and angular distributions

In the SM:



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



~ Fermi's description of the neutron decay

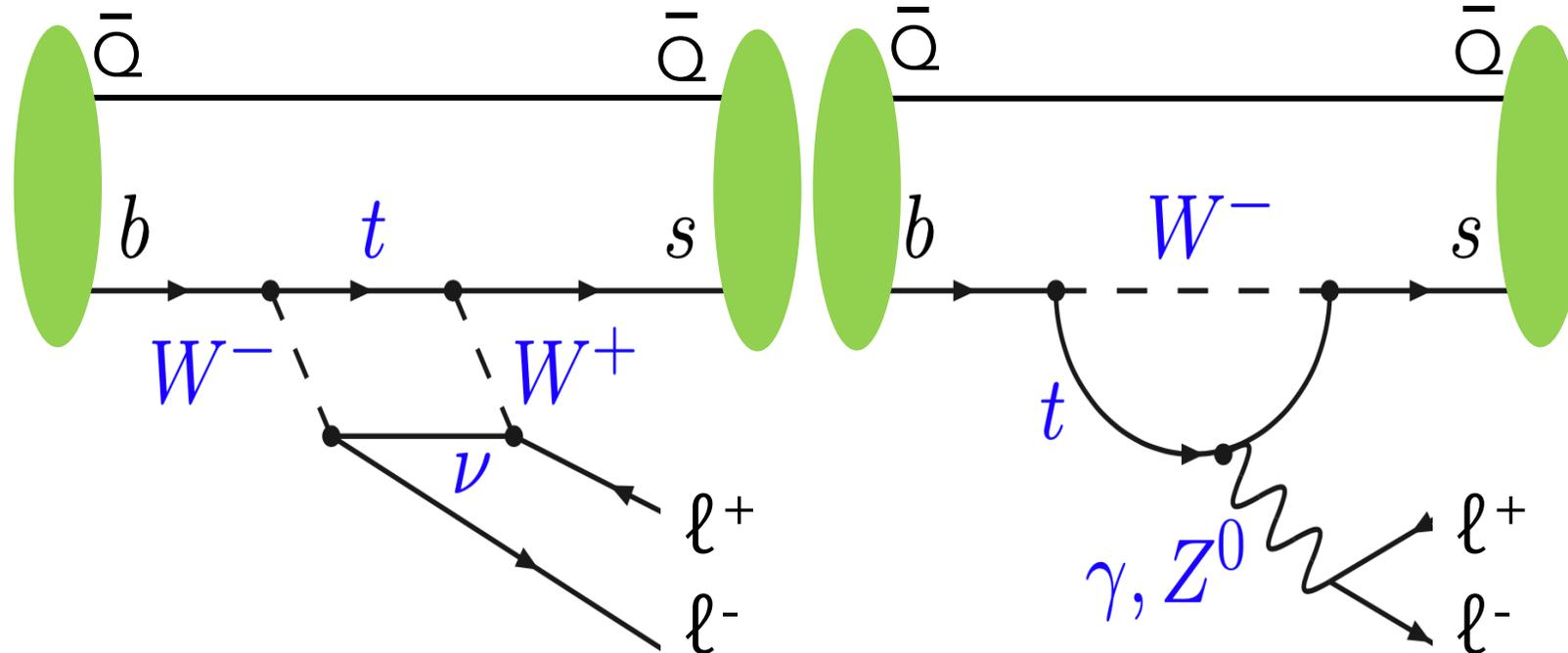
Effective-Hamiltonian approach

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

NP enters here  $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$       Operator encoding Lorentz structure

<p>V-A (EW penguin)</p> <p><math>O_{9,10}^{(r)}</math></p> <p><math>O_9^{(r)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)</math></p> <p><math>O_{10}^{(r)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)</math></p>	<p>dipole (e.m. penguin)</p> <p><math>O_7^{(r)}</math></p> <p><math>O_7^{(r)} = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}</math></p>
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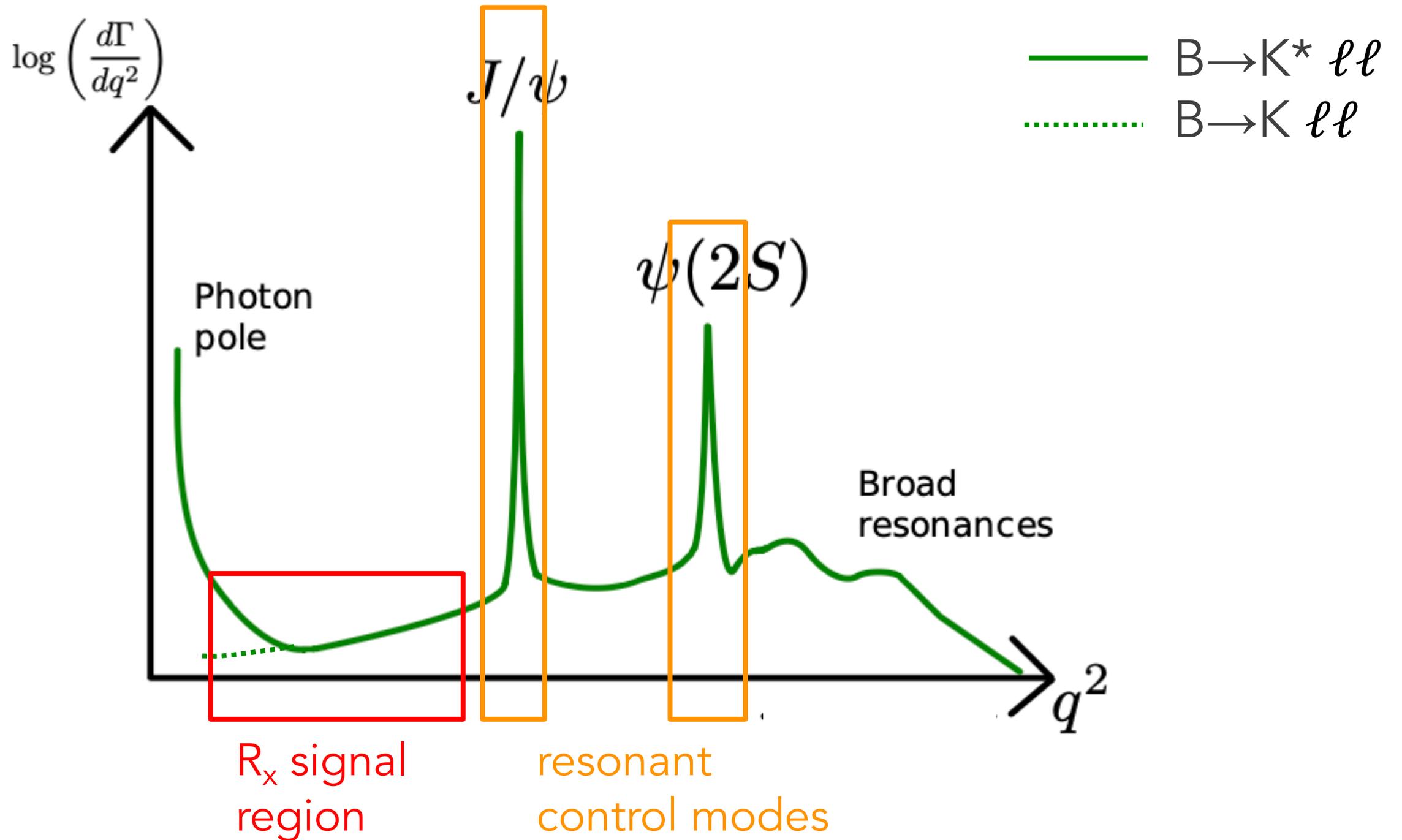
But we are using hadrons ....



Q=u	Q=d	Q=s
$B^- \rightarrow K^- \ell \ell$	$B^0 \rightarrow K_s \ell \ell$	$B_s \rightarrow \phi \ell \ell$
$B^- \rightarrow K^{*-} \ell \ell$	$B^0 \rightarrow K^{*0} \ell \ell$	

+ b-baryons ....

(and  $B_c$ )

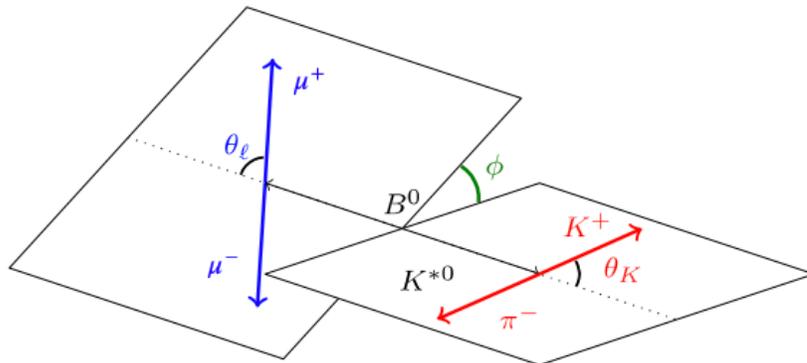


## Rich phenomenology:

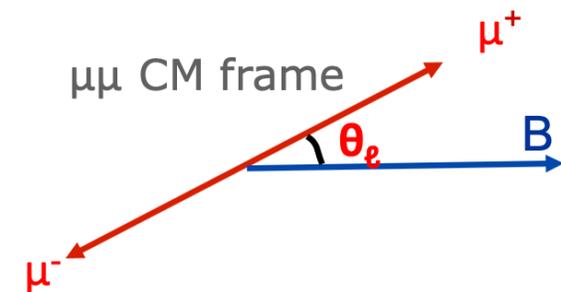
- Branching Ratios (but large theoretical uncertainties due to non-perturbative QCD)
- Angular observables



Described by 3 angles and  $q^2$



Described by one angle and  $q^2$



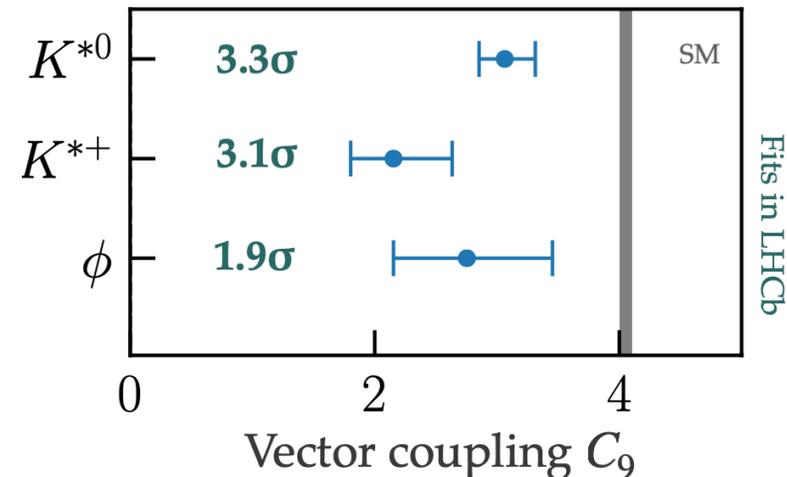
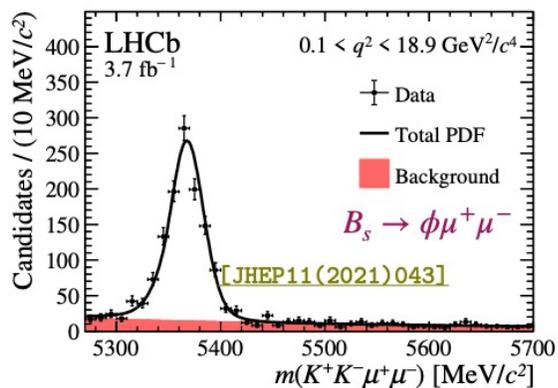
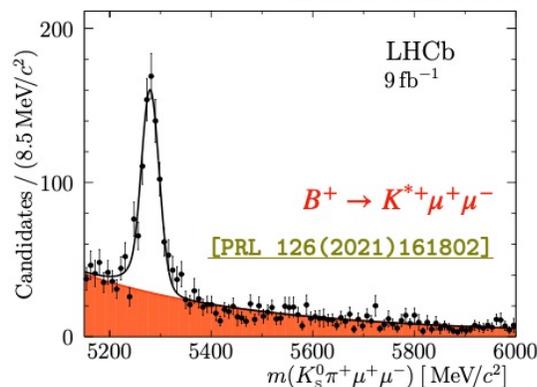
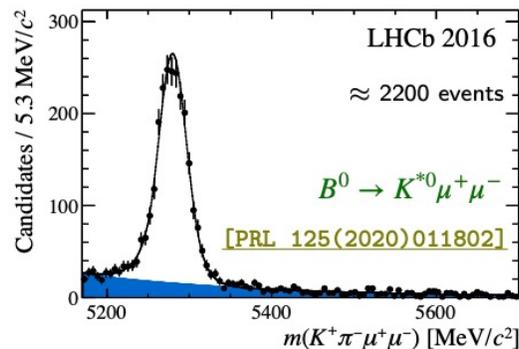
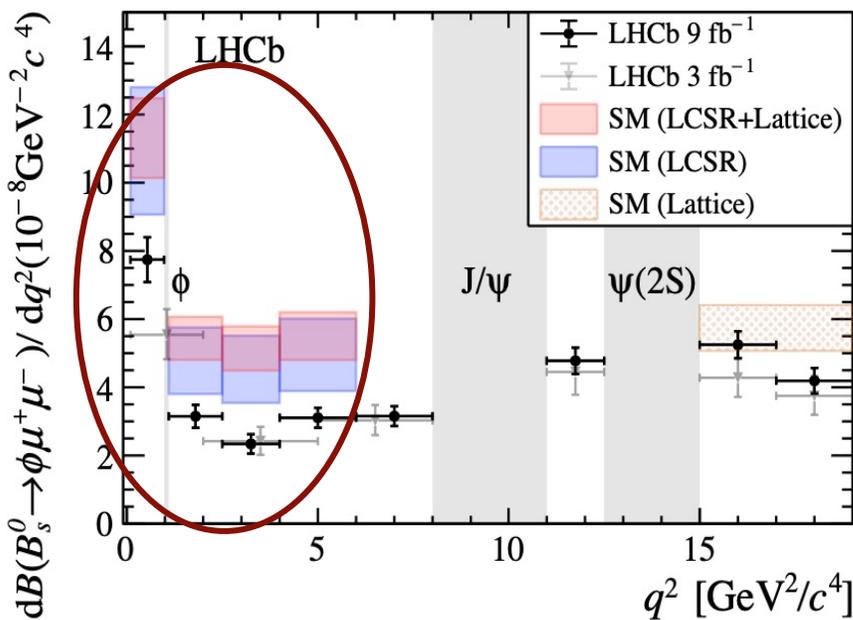
# A set of anomalies in $b \rightarrow s \mu\mu$ transitions

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$  with  $6 \text{ fb}^{-1}$  ( $\sim 4600$  evts.)

$B^+ \rightarrow K^{*+} \mu^+ \mu^-$  with  $9 \text{ fb}^{-1}$  ( $\sim 700$  evts.)

$B_s \rightarrow \phi \mu^+ \mu^-$  with  $9 \text{ fb}^{-1}$  ( $\sim 1900$  evts.)

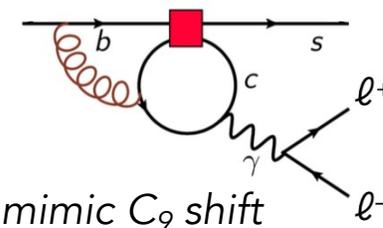
PRL 127 (2021) 151801



Global Wilson coefficients fit seems to indicate a pattern: different observables give a coherent picture

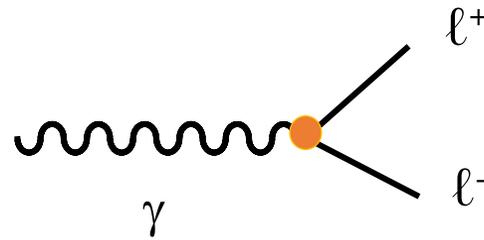
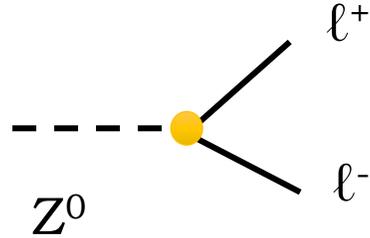
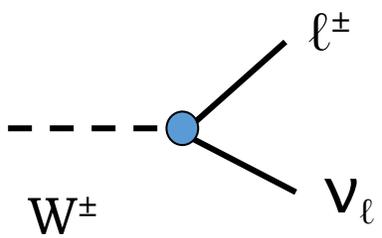
but

theoretical debate about  $c\bar{c}$  loop impact



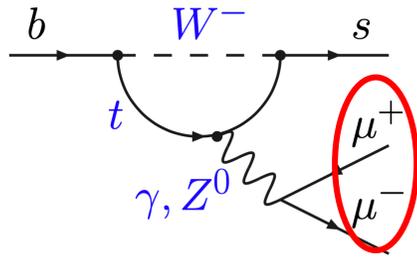
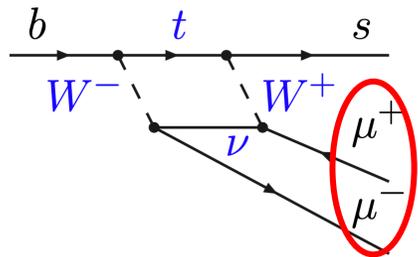
They can mimic  $C_9$  shift

# Lepton Flavour Universality tests in $b \rightarrow s \ell \ell$ transitions



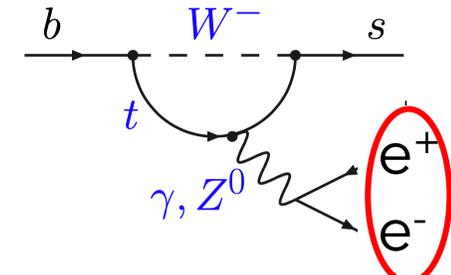
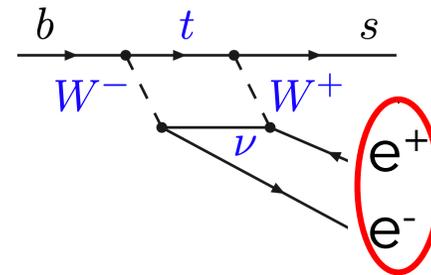
$\ell = e, \mu$  or  $\tau$

Only difference : kinematics  
(lepton masses)



SM

=



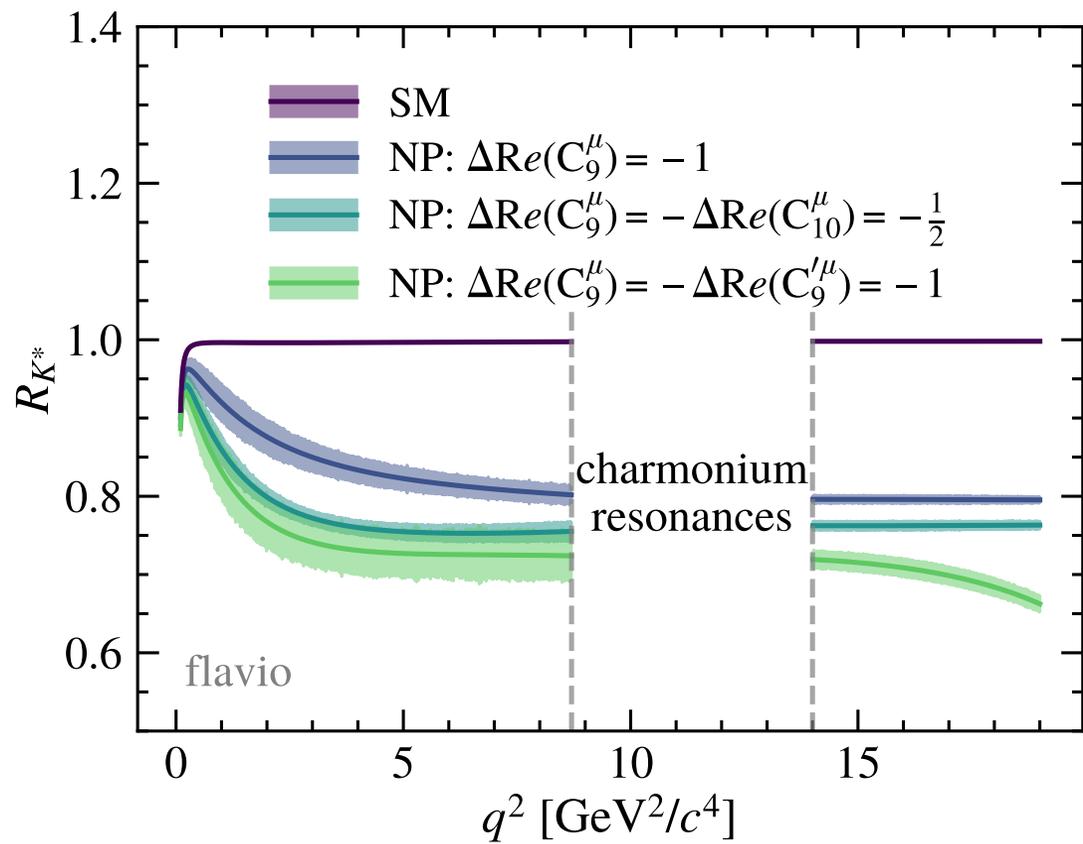
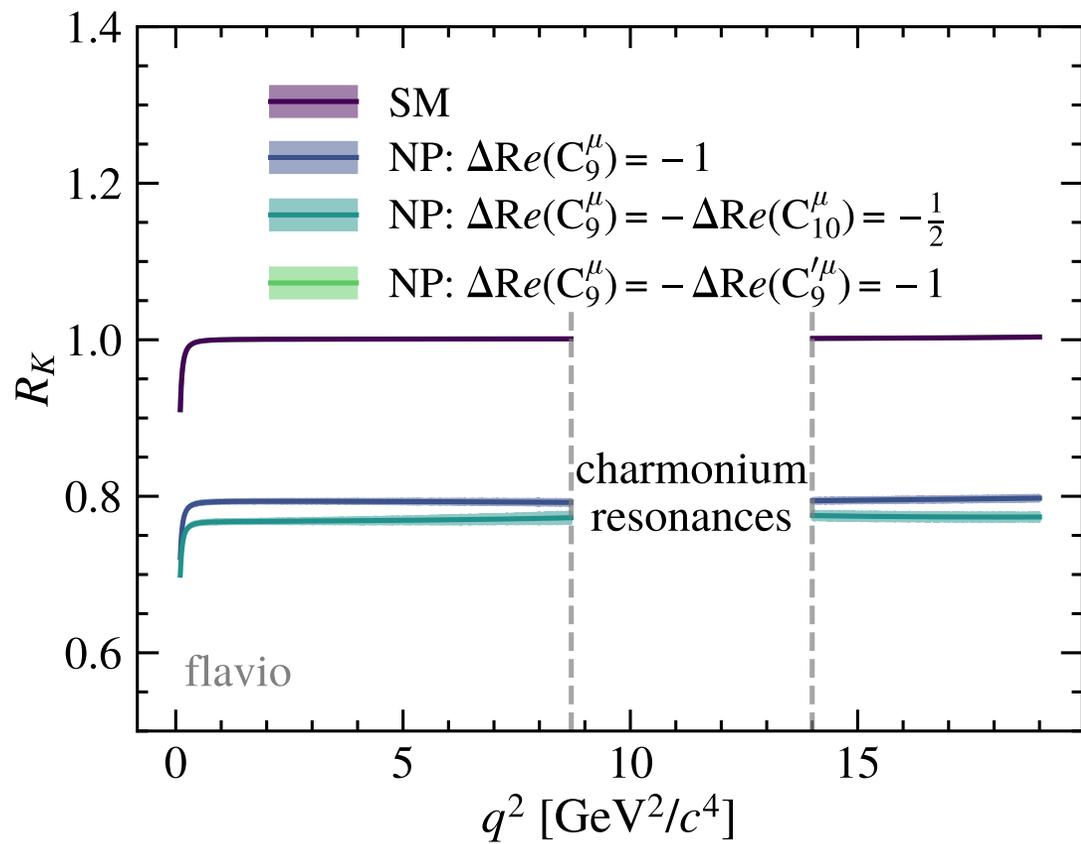
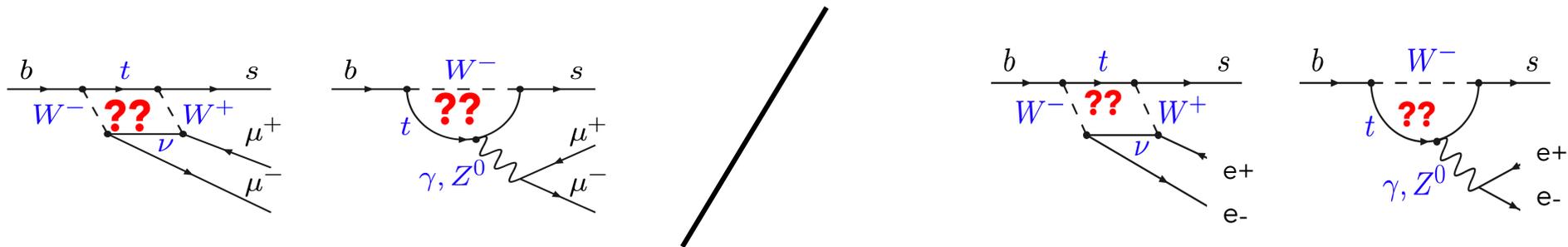
$B^{+,0}, B_s, \Lambda_b$

$K, K^*, \phi, \rho K \dots$

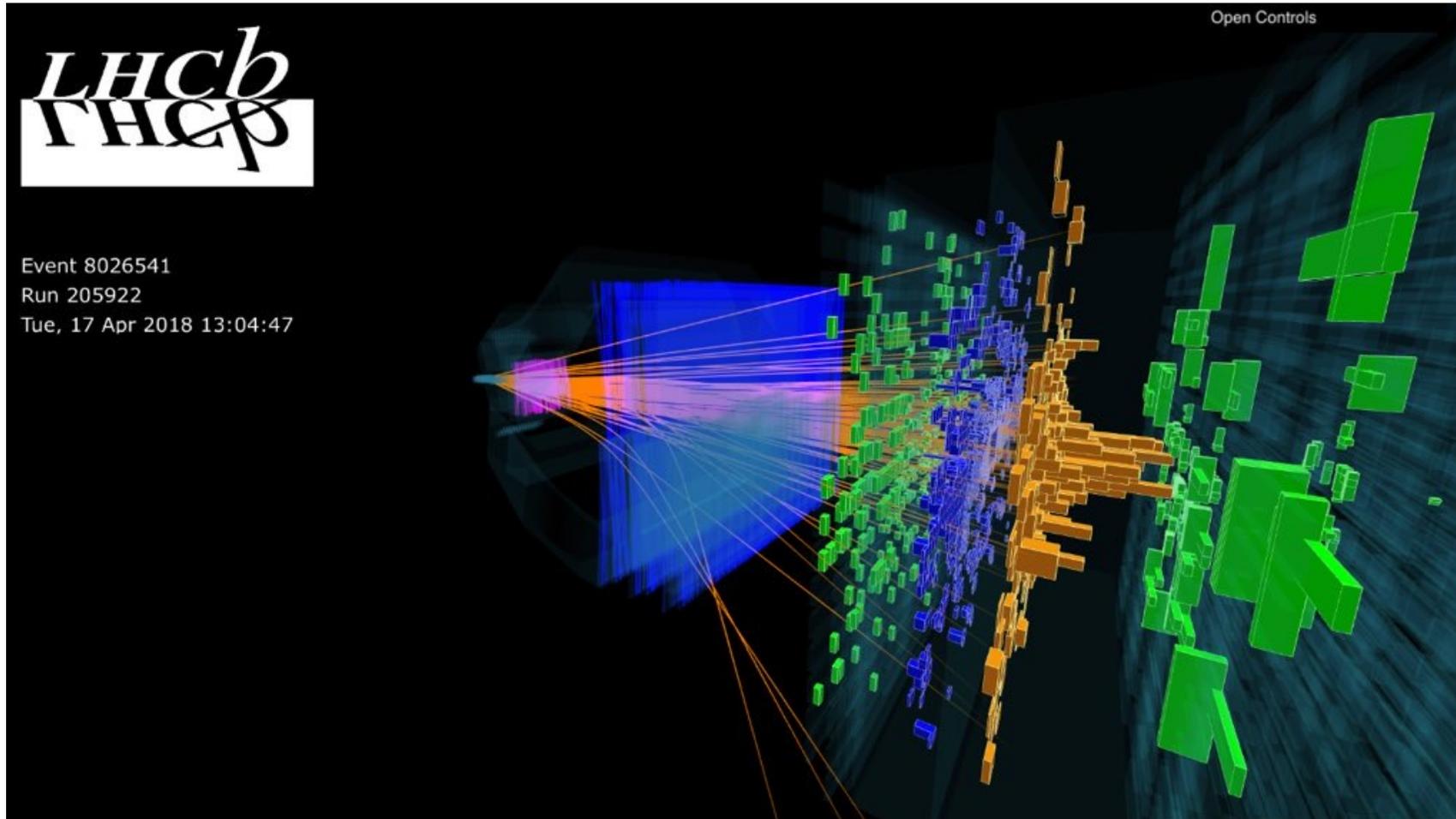
Any ratio of observables in principle

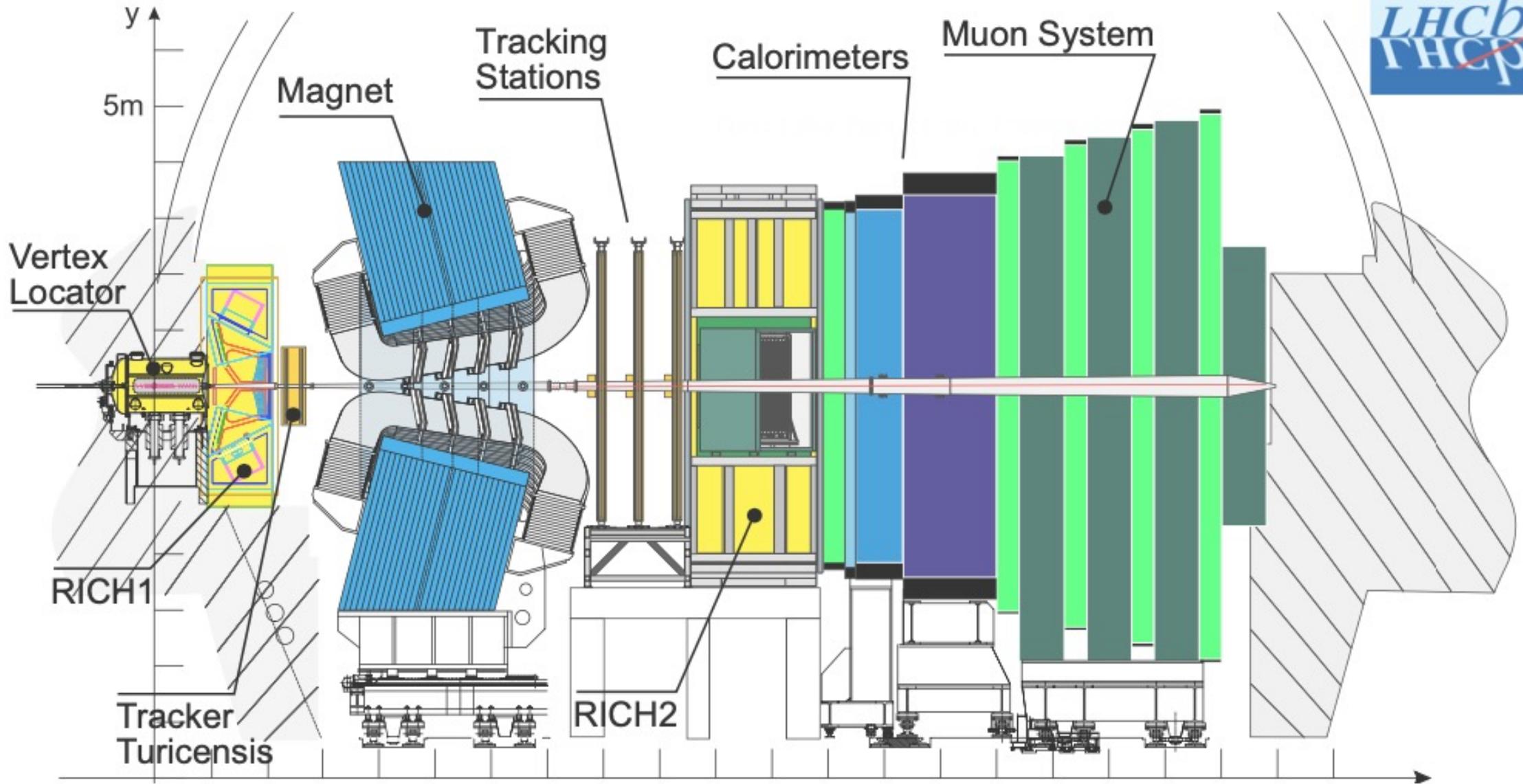
Start with the simplest (?) one: ratio of branching fractions

$$R_{H_s} = \frac{\int \frac{d\Gamma(B \rightarrow H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \rightarrow H_s e^+ e^-)}{dq^2} dq^2} \stackrel{SM}{\approx} 1$$



# Electrons and muons in LHCb





# Muons:

Negligible bremsstrahlung losses at LHCb

Muon stations occupancy much lower than ECAL

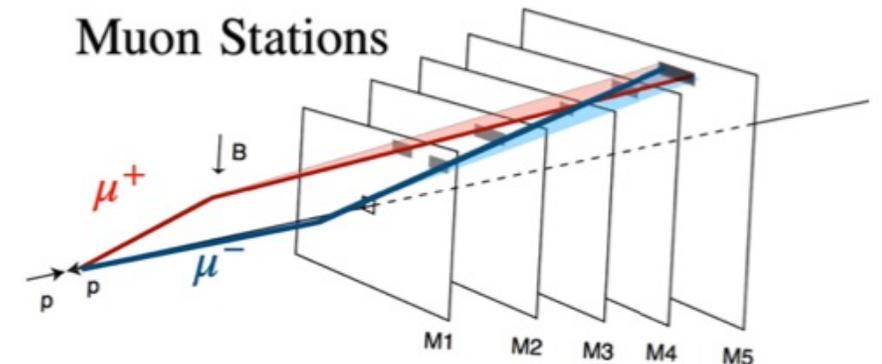
⇒ excellent **MuonID** and  $\mu/h$  already with muon station coincidence

⇒ lower trigger threshold

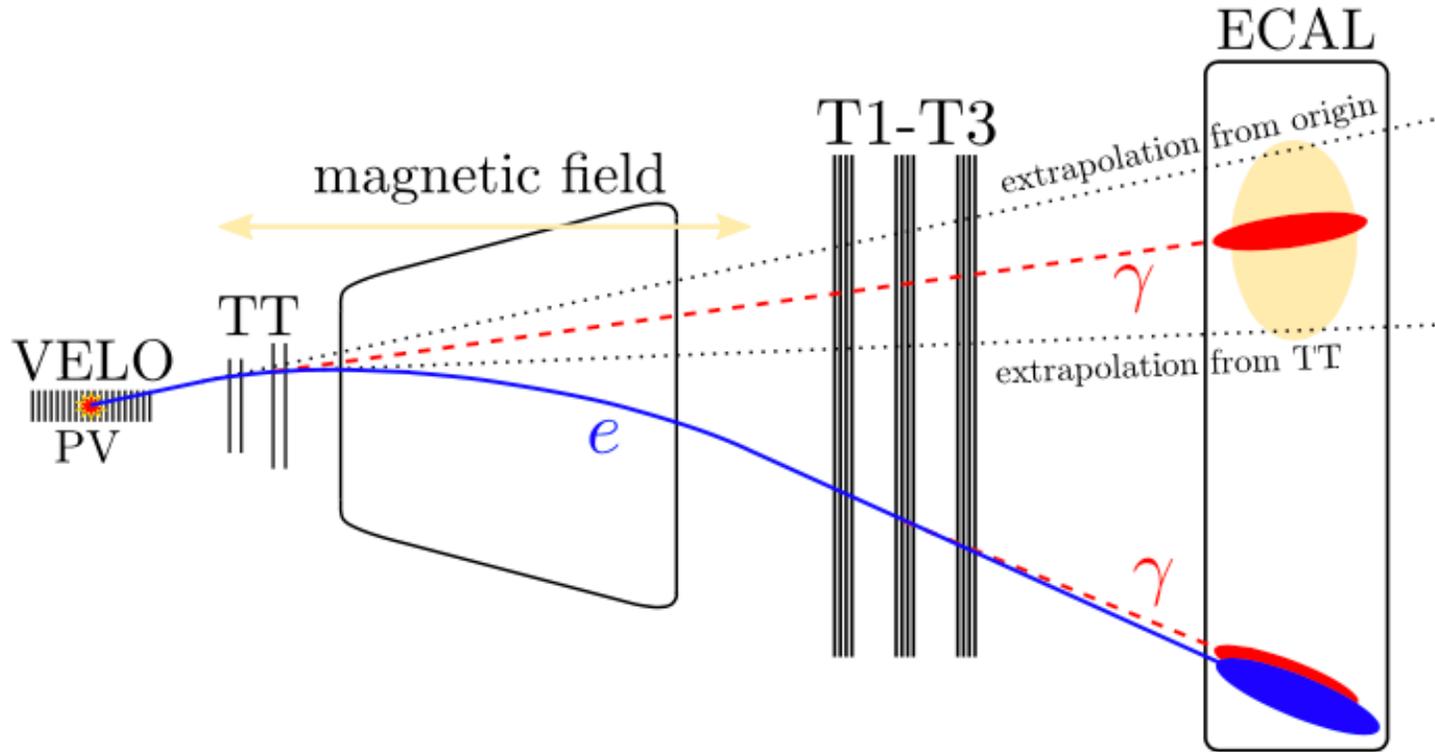
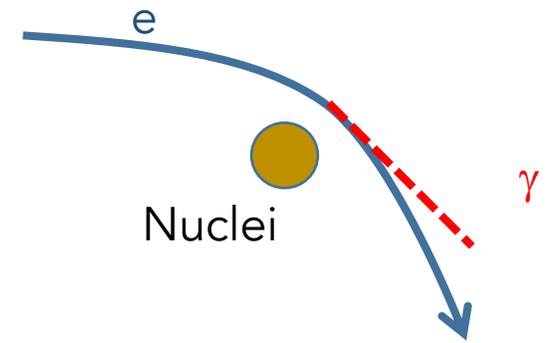
LHCb-PUB-2014-046

Typical L0 thresholds used in Run I

	$p_T$ or $E_T$		SPD
	2011	2012	2011 and 2012
single muon	1.48 GeV/c	1.76 GeV/c	600
dimuon $p_{T1} \times p_{T2}$	$(1.30 \text{ GeV}/c)^2$	$(1.60 \text{ GeV}/c)^2$	900
hadron	3.50 GeV	3.70 GeV	600
electron	2.50 GeV	3.00 GeV	600
photon	2.50 GeV	3.00 GeV	600



# Electrons emit Bremsstrahlung



## Before the magnet

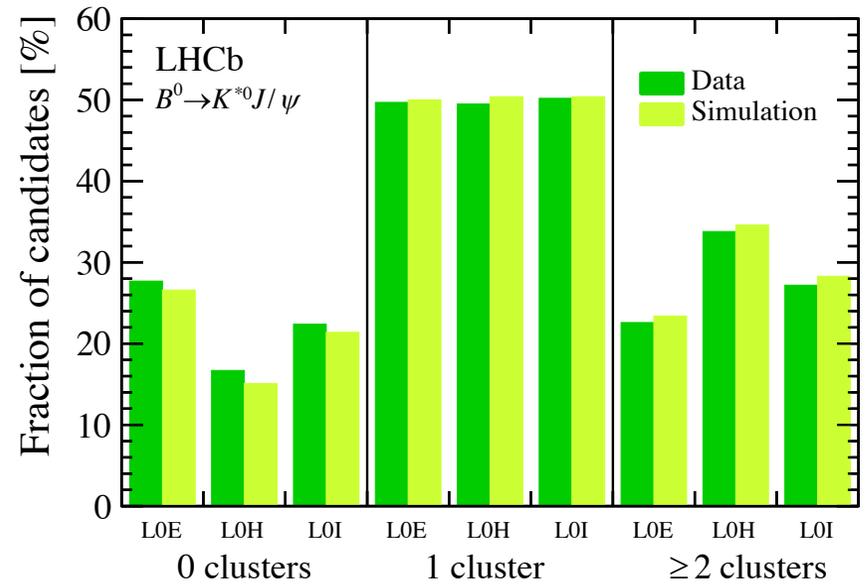
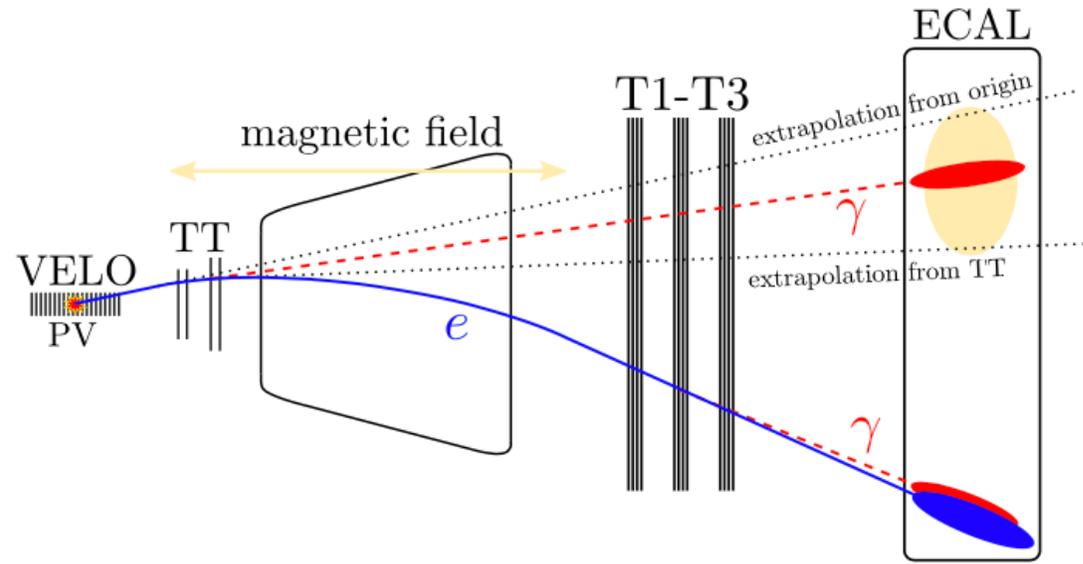
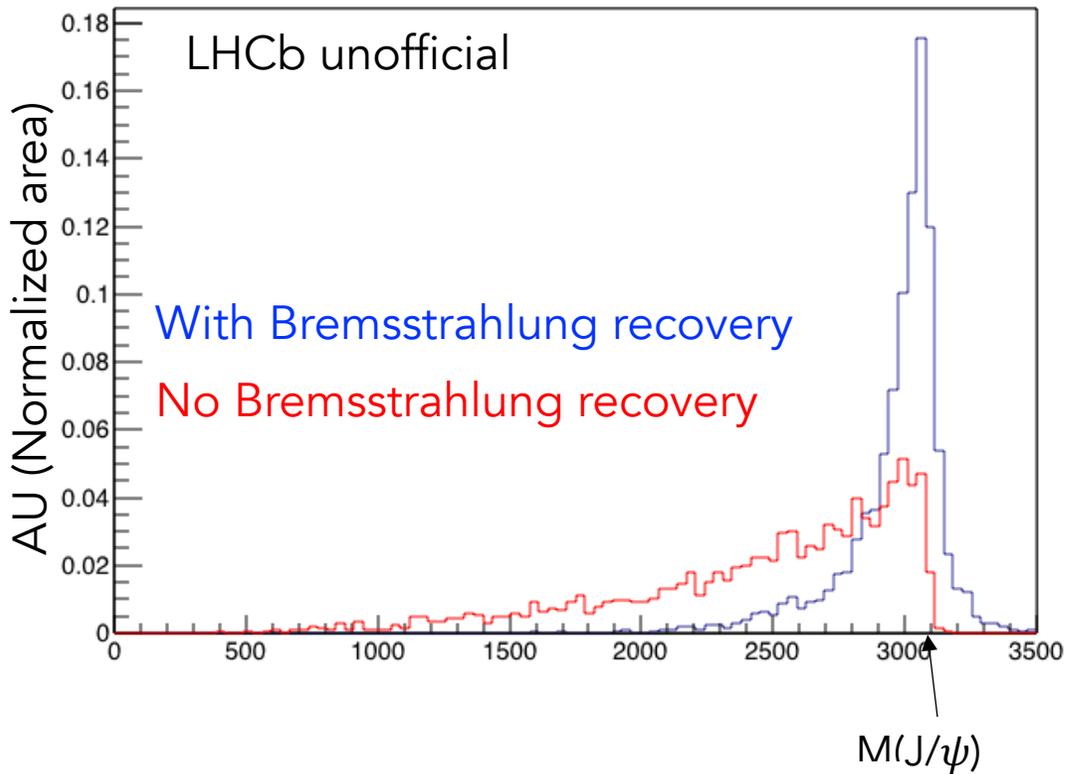
- electron can be swept out (=lost !)
- kinematics are "wrong"

## After the magnet

- not an issue

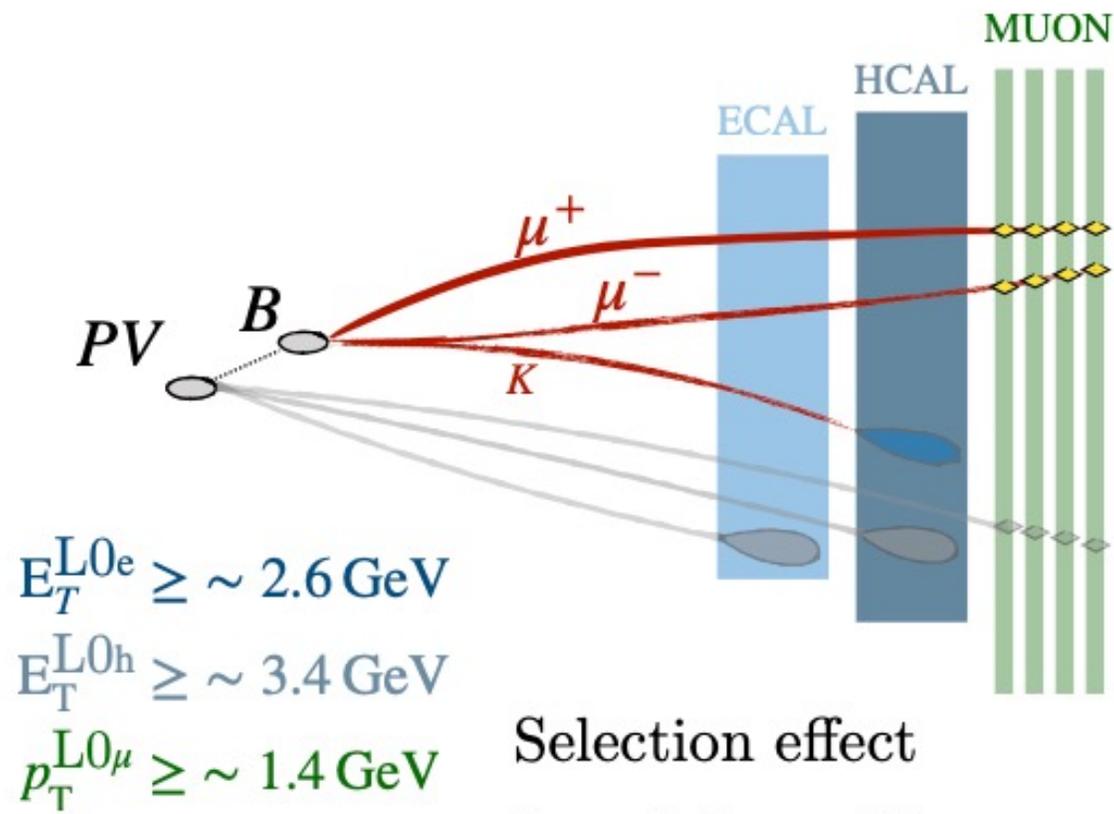
Energy loss  $\propto E_e$   
 Energy loss  $\propto$  material

*In both cases  $E/p$  is correct*



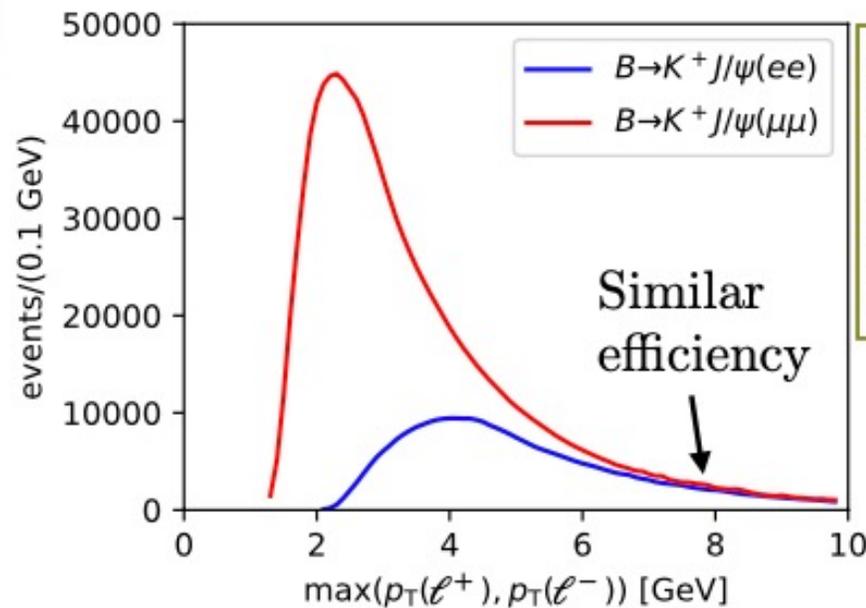
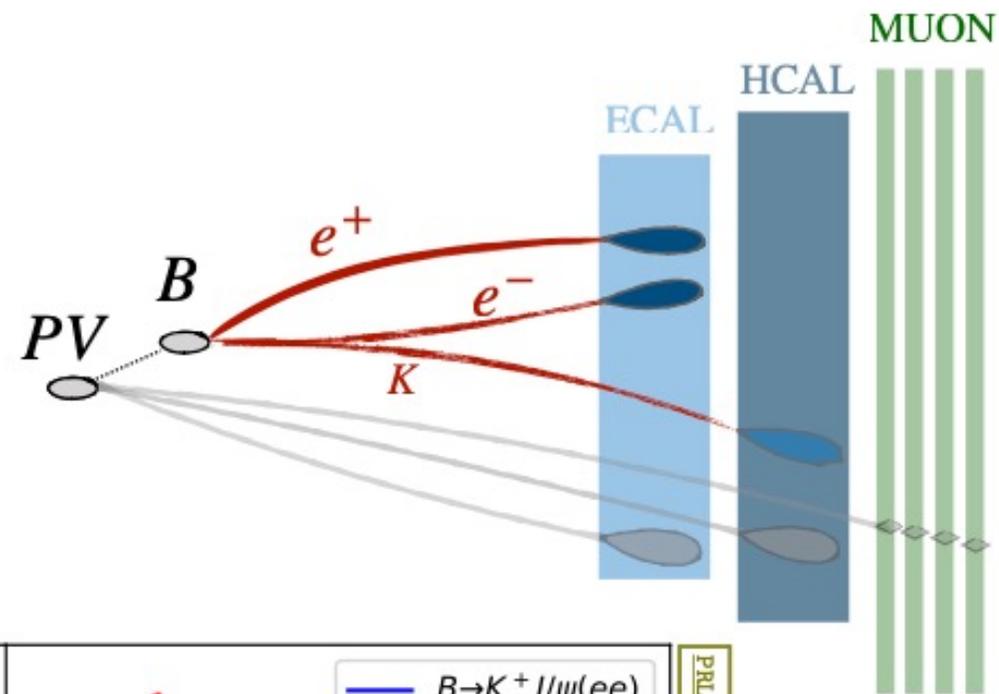
Bremsstrahlung recovery algorithm is  $\sim 50\%$  efficient  
 Well described in simulation

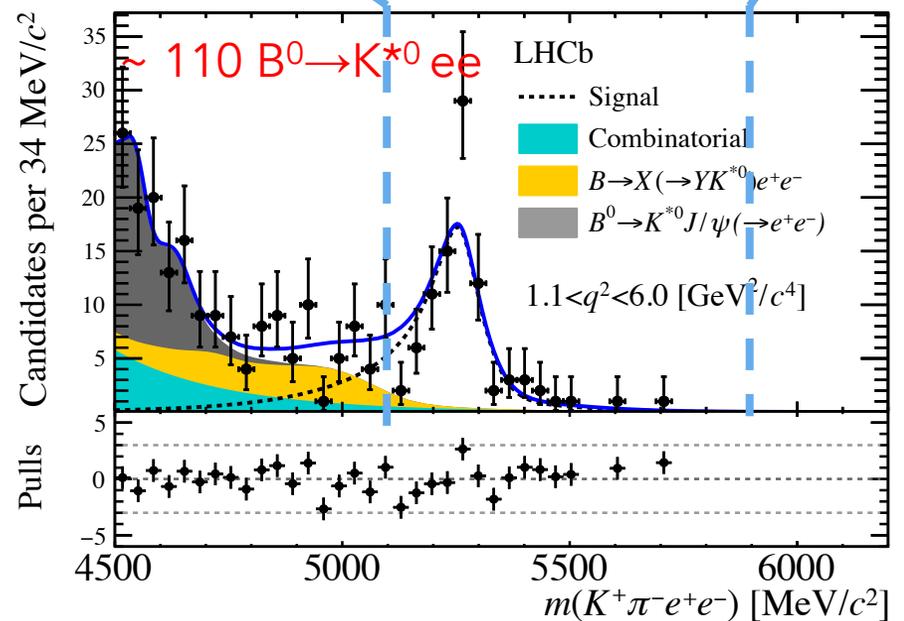
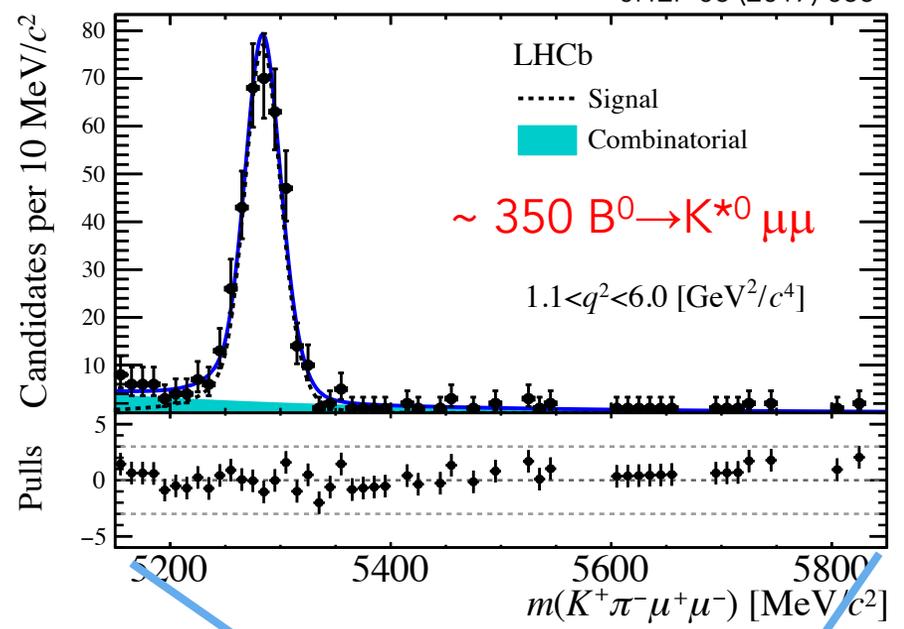
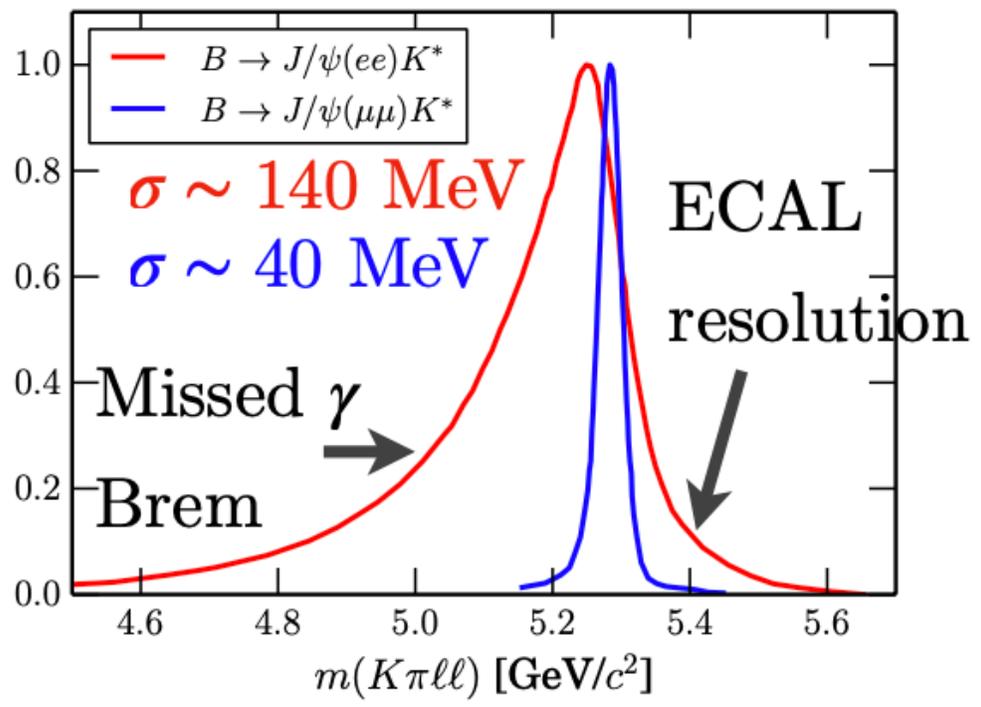
# Hardware trigger is very different for electrons and muons



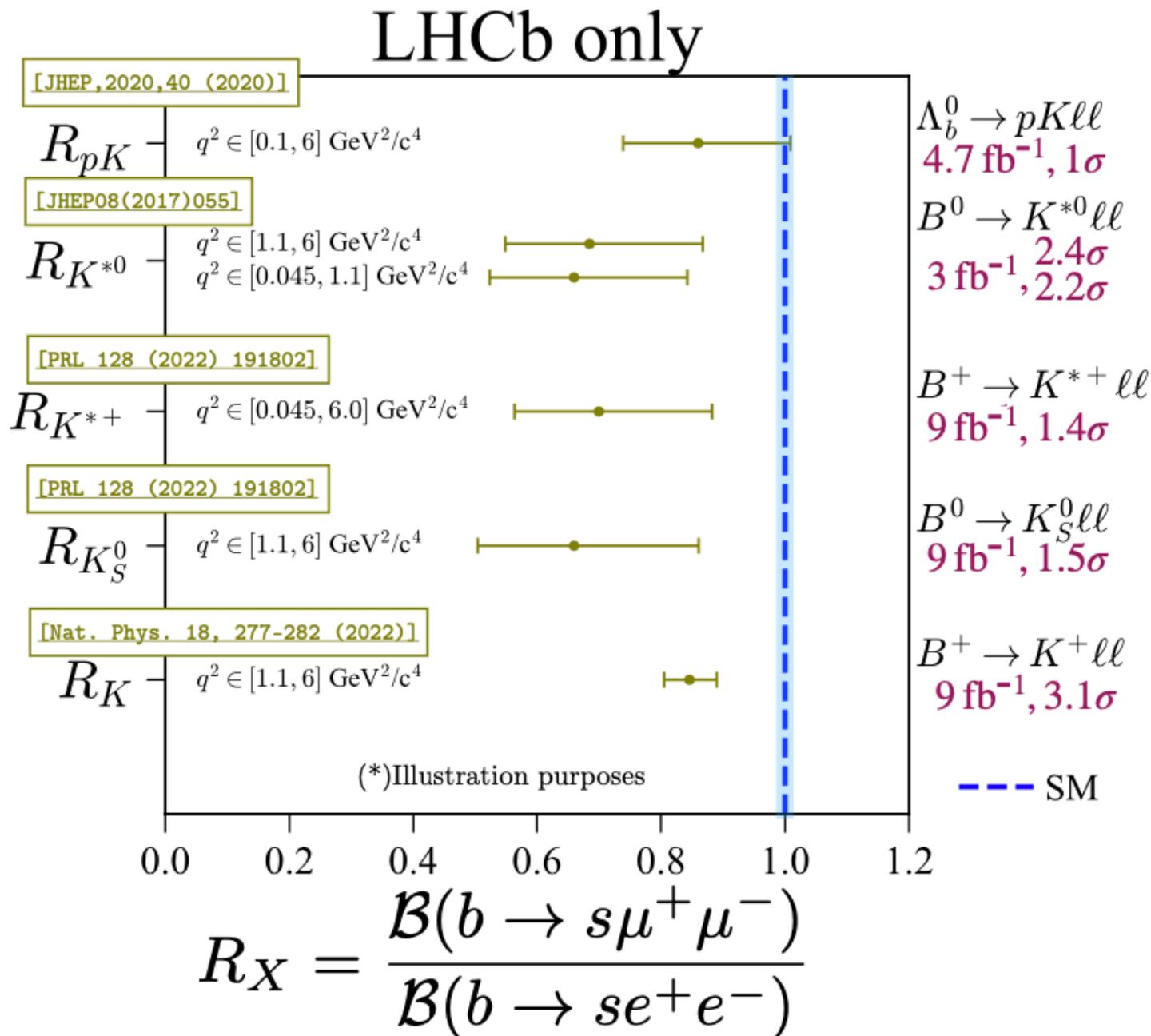
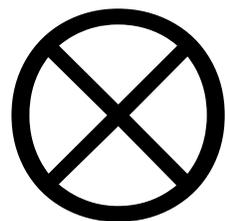
Selection effect  
from L0e vs L0μ

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

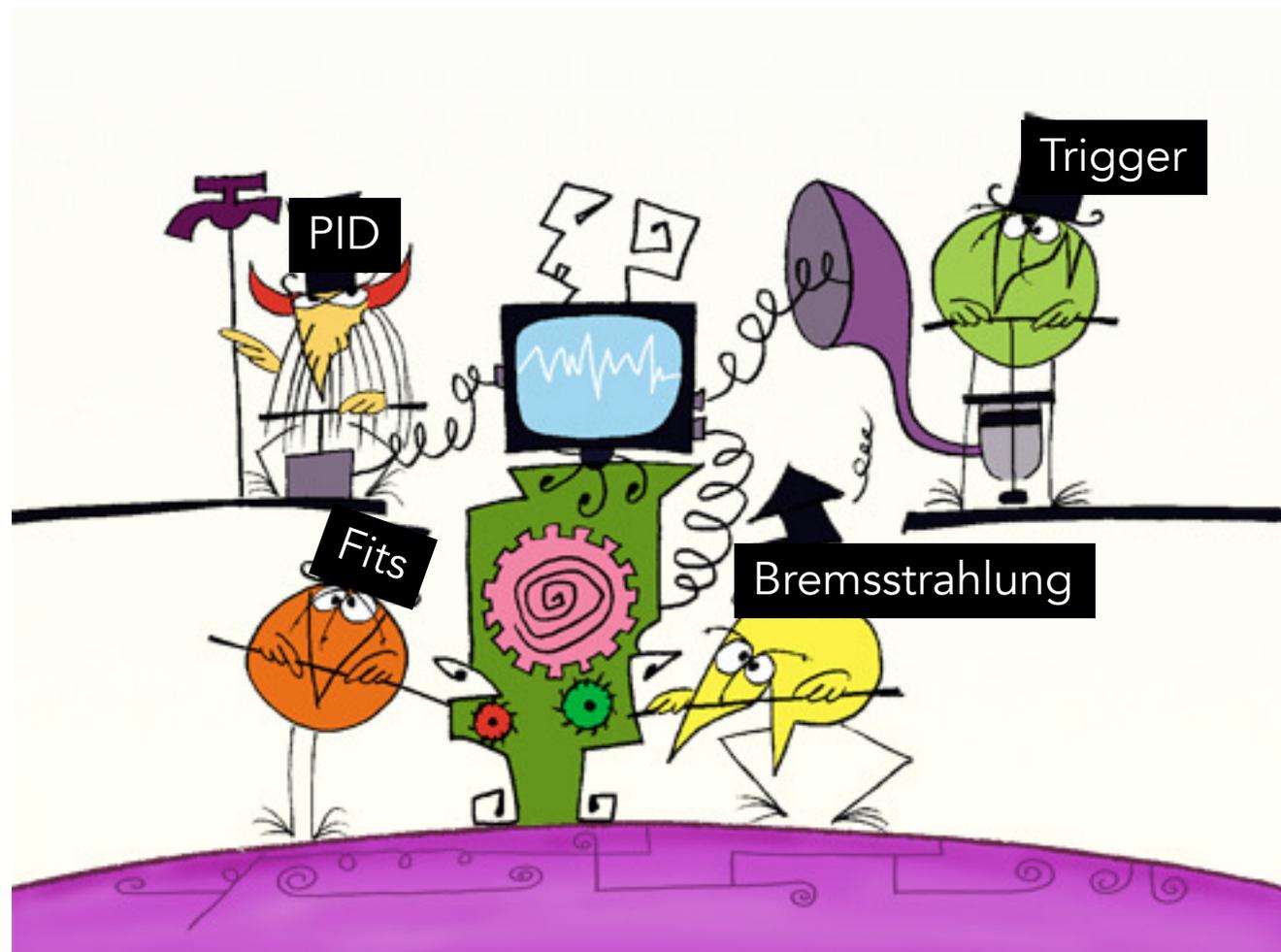




Experimental context



# ⇒ the $R_x$ analysis



# Simultaneous fit of two decay modes and two kinematical regions

Full LHCb dataset ( $9 \text{ fb}^{-1}$ )

$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \rightarrow K^{(+,*0)} \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \rightarrow K^{(+,*0)} e^+ e^-)}{dq^2} dq^2}$$

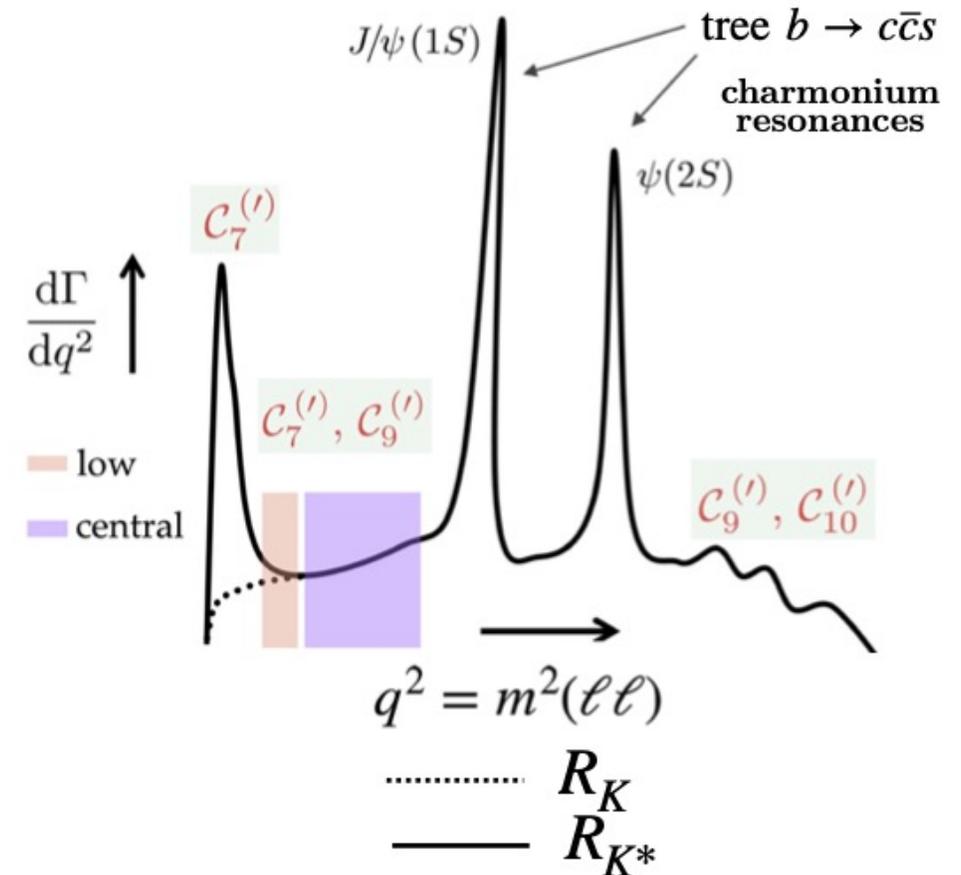
## ◆ $q^2$ ranges:

▶ low- $q^2$  :  $q^2 \in [0.1, 1.1] \text{ GeV}^2/c^4$

▶ central- $q^2$  :  $q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$

## ◆ For $R_{K^*}$

$K^{*0}$  :  $m(K^+ \pi^-) \in [792, 992] \text{ MeV}/c^2$



Rare modes :  $\sim 1.1 - 1.3 \cdot 10^{-7}$  in the central  $q^2$  range

# General analysis strategy

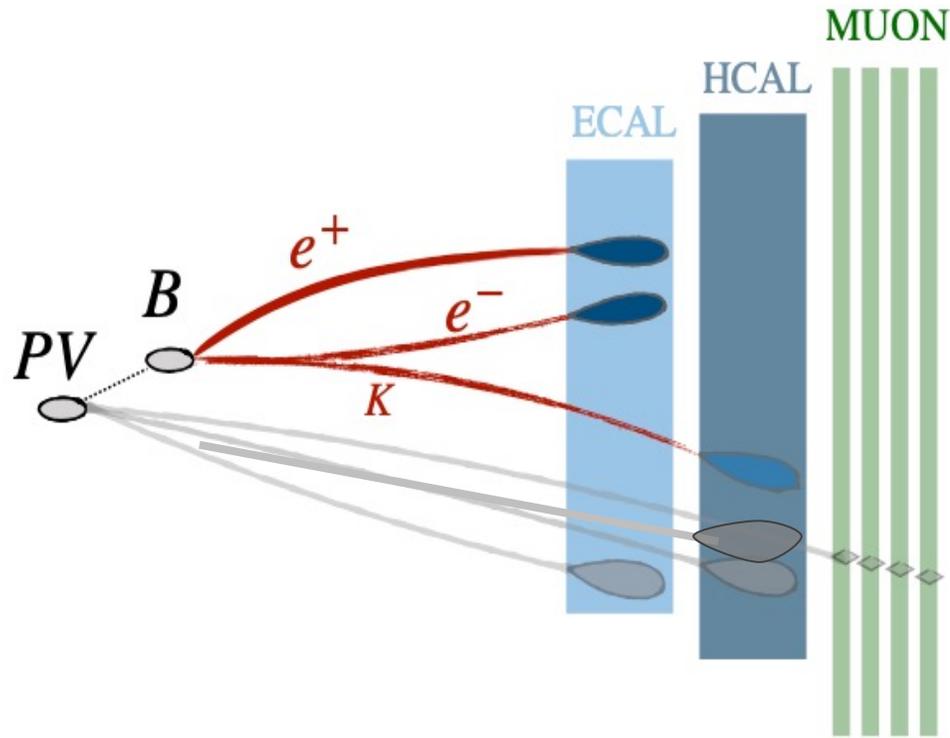
$$R_{(K,K^*)} \equiv \frac{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} \mu^+ \mu^-)}{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow \mu^+ \mu^-))} / \frac{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} e^+ e^-)}{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow e^+ e^-))}$$

$$\frac{\Gamma(J/\psi \rightarrow e^+ e^-)}{\Gamma(J/\psi \rightarrow \mu^+ \mu^-)} \quad \text{measured to be} = 1 \quad \text{[PDG]}$$

- Double ratio using the resonant channels  $\Rightarrow$  cancel out most of the systematics due to e/ $\mu$  differences
- Yields obtained from mass fits
- Efficiencies obtained from corrected MC using data-driven techniques

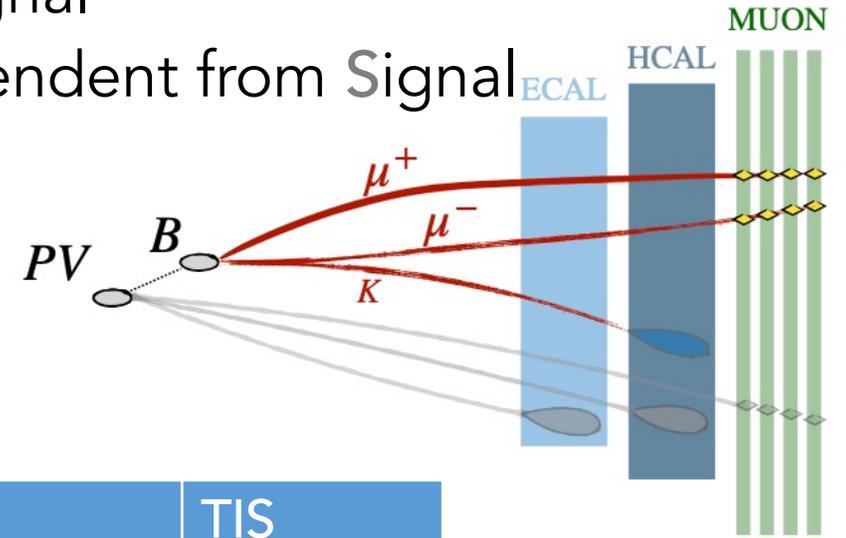
Use  $r_{J/\psi}^{K,K^*} \equiv \frac{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow \mu^+ \mu^-))}{\frac{\mathcal{N}}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow e^+ e^-))}$  to check the corrections

# Trigger strategy



Trigger **O**n **S**ignal

Trigger Independent from Signal



Mode	TOS	TIS
$\mu\mu$	~90%	~25%
ee	~60%	~50%

R ratios computed from

$$\frac{(N/\epsilon)_{\mu\mu} - L_{TIS}}{(N/\epsilon)_{ee} - L_{TIS}} \frac{(N/\epsilon)_{\mu\mu} - L_{\text{MuonTOS}}}{(N/\epsilon)_{ee} - L_{\text{ElectronTOS}}}$$

balance of statistics

less difference in efficiencies due to triggering

# Selection 1/3

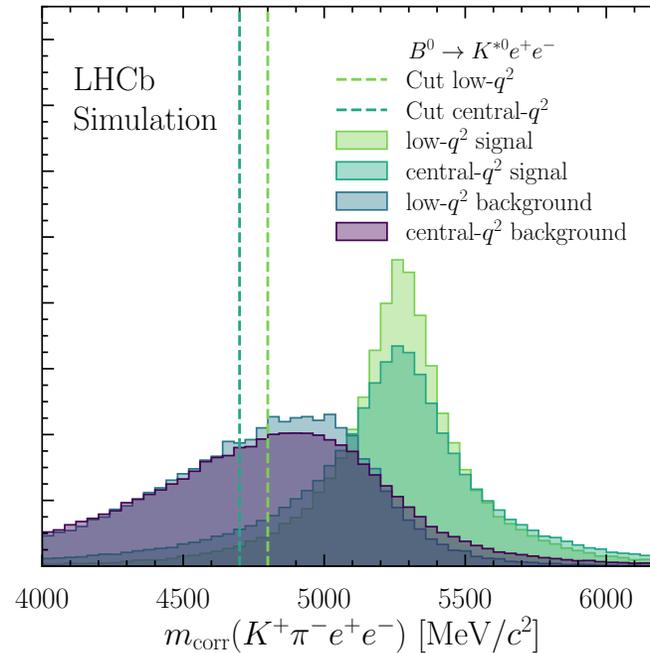
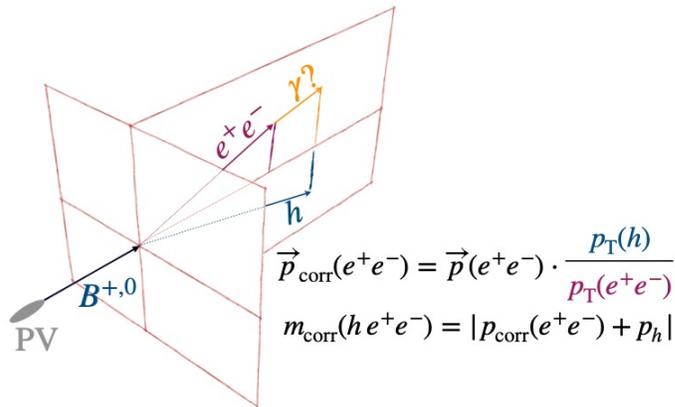
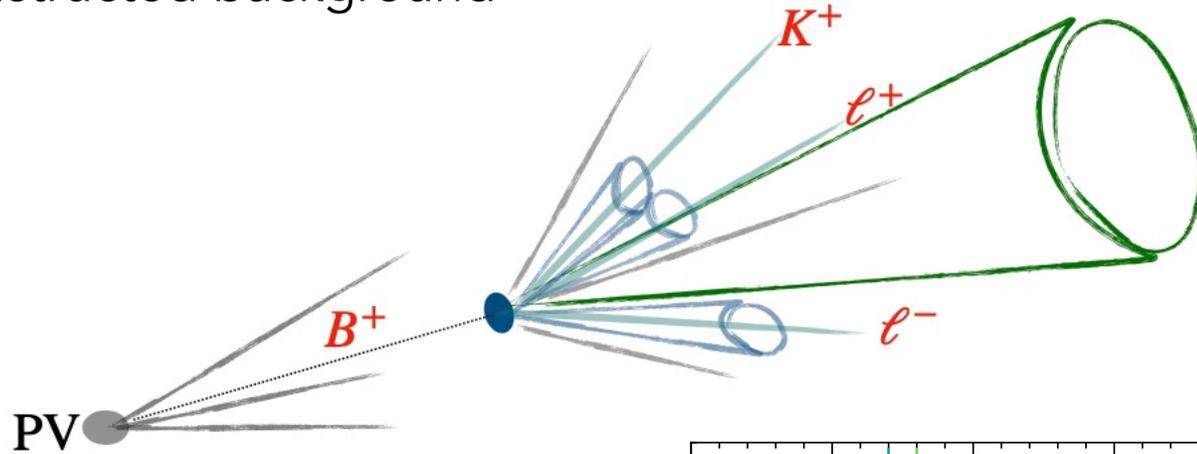
For a given decay mode:

- Stringent lepton PID cuts
- Hadron PID cut
- One multivariate classifier using kinematic and vertex quality information to reject the combinatorial background
- Cut optimized on  $S/\sqrt{S+B}$  separately for each decay mode,  $q^2$  region, run period

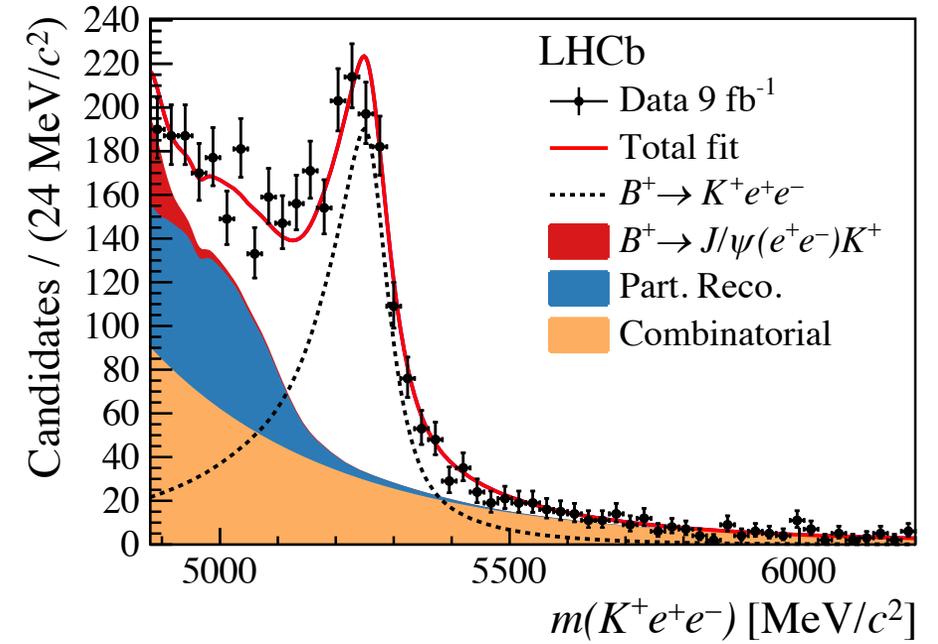
**+ specific treatment of the  $K^{(*)}ee$  decay modes (next slides)**

# Selection 2/3

Remove as much as possible the partially reconstructed background



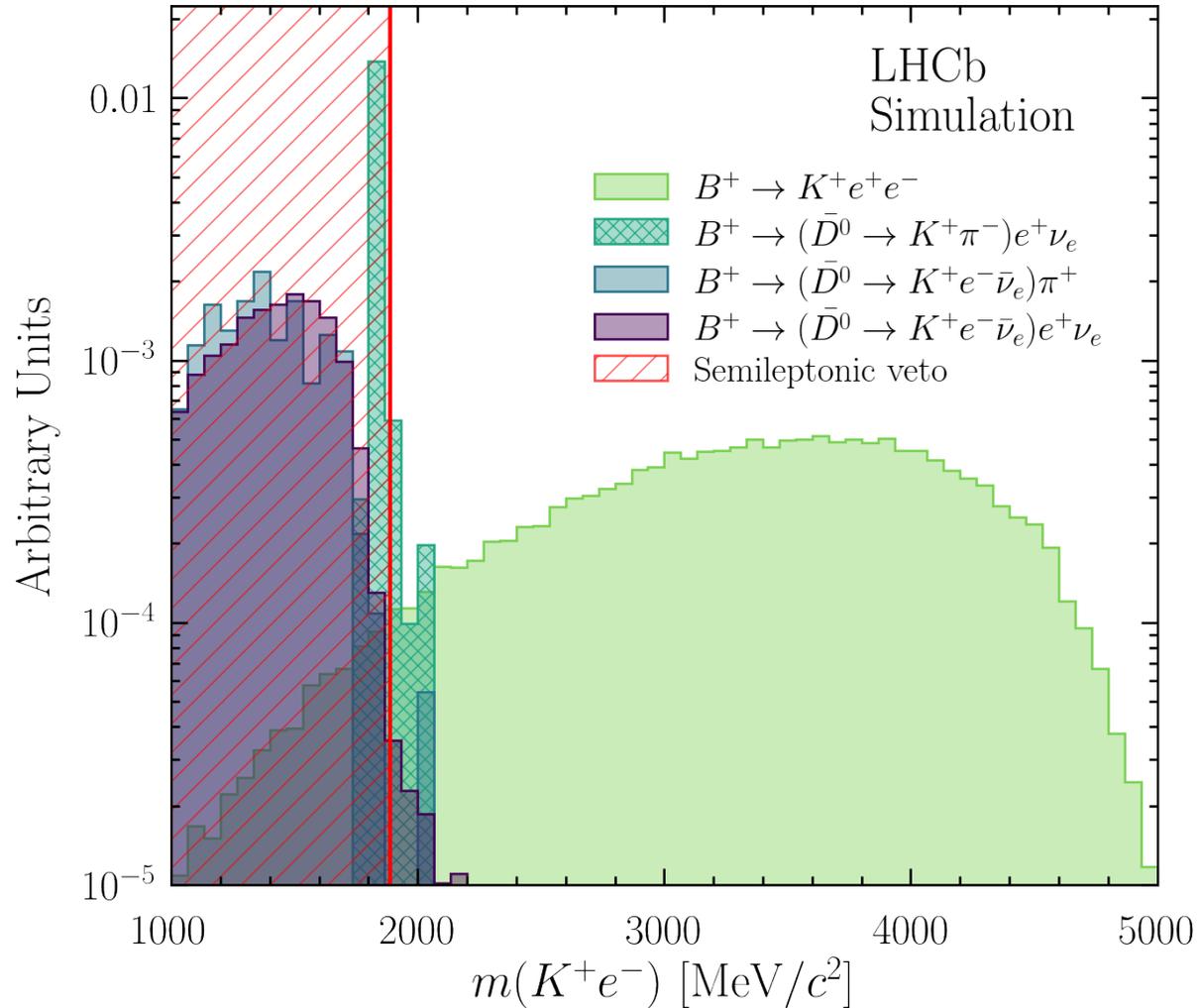
Nature Physics 18, (2022) 277-282



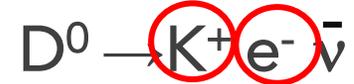
+ a specific multi-classifier

# Selection 3/3

## Veto specific backgrounds



## Semileptonic decays



BF > 100 x signal

Does not peak in B invariant mass  
present in the Bremsstrahlung tail

+ Specific vetoes under electron  
mis-ID hypothesis on  $D^0 \rightarrow K^+ \pi^-$

Potential remaining backgrounds:

$$B^+ \rightarrow K^+ \pi^- (\pi^0, \gamma) X$$

$$B^0 \rightarrow K^{*0} \pi^- (\pi^0, \gamma) X$$

different for  
 $B^0$  and  $B^+$   
low- $q^2$  and central- $q^2$

Tighter PID cuts on the electron candidates than in previous publications.  
small impact on efficiencies (Run1 ~ no loss, Run2 10% loss)

Sample	$\pi \rightarrow e$	$K \rightarrow e$
RUN 1	1.78 (1.70) %	0.69 (1.24) %
RUN 2P1	0.83 (1.51) %	0.18 (1.25) %
RUN 2P2	0.80 (1.50) %	0.16 (1.23) %

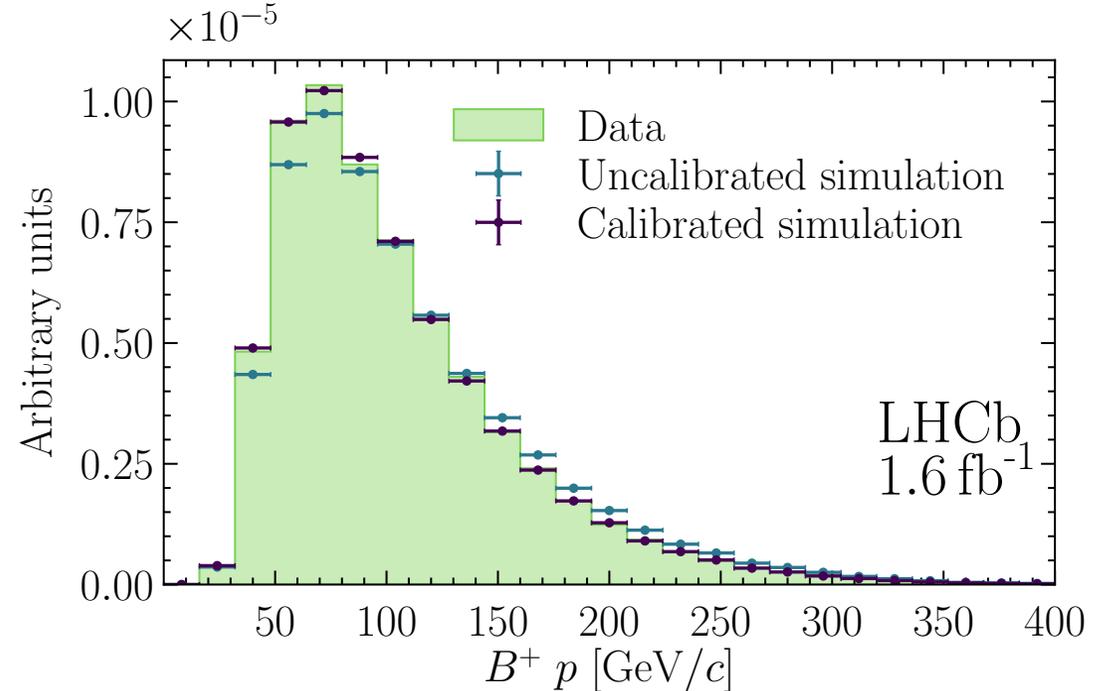
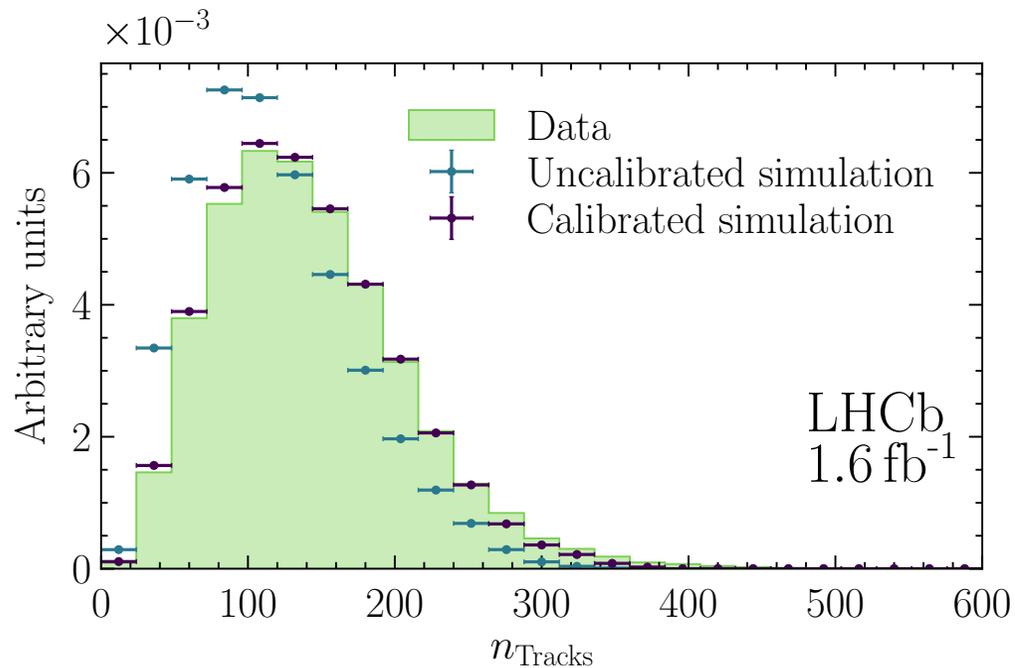
# Efficiencies determination

Hadron collider: MC out of the box is not fully reliable

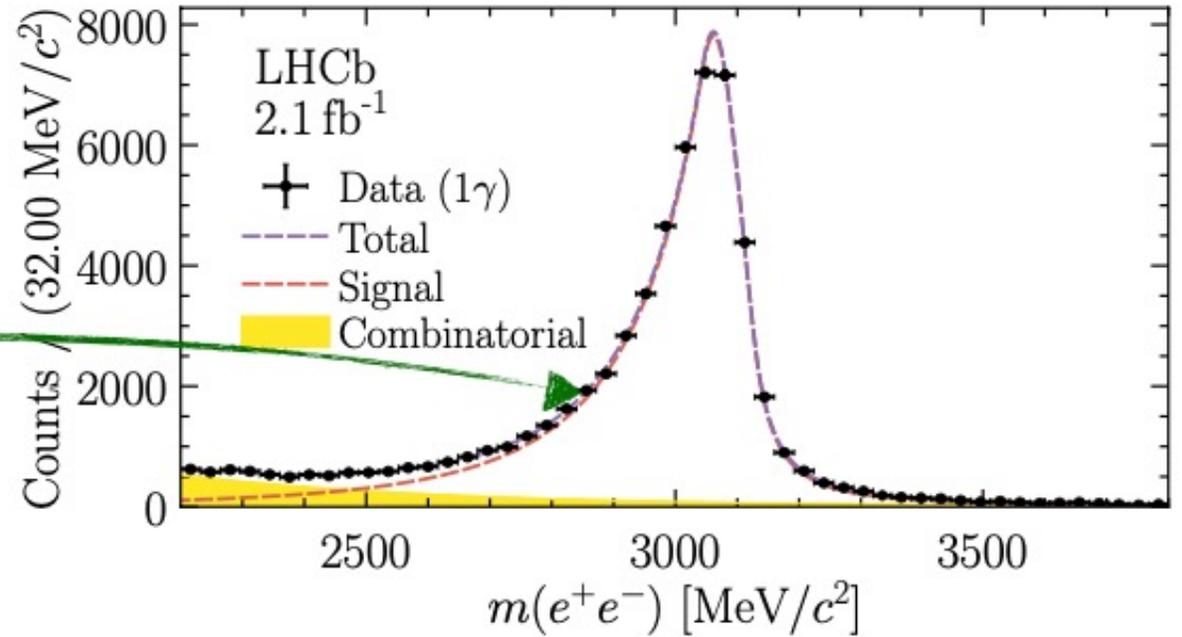
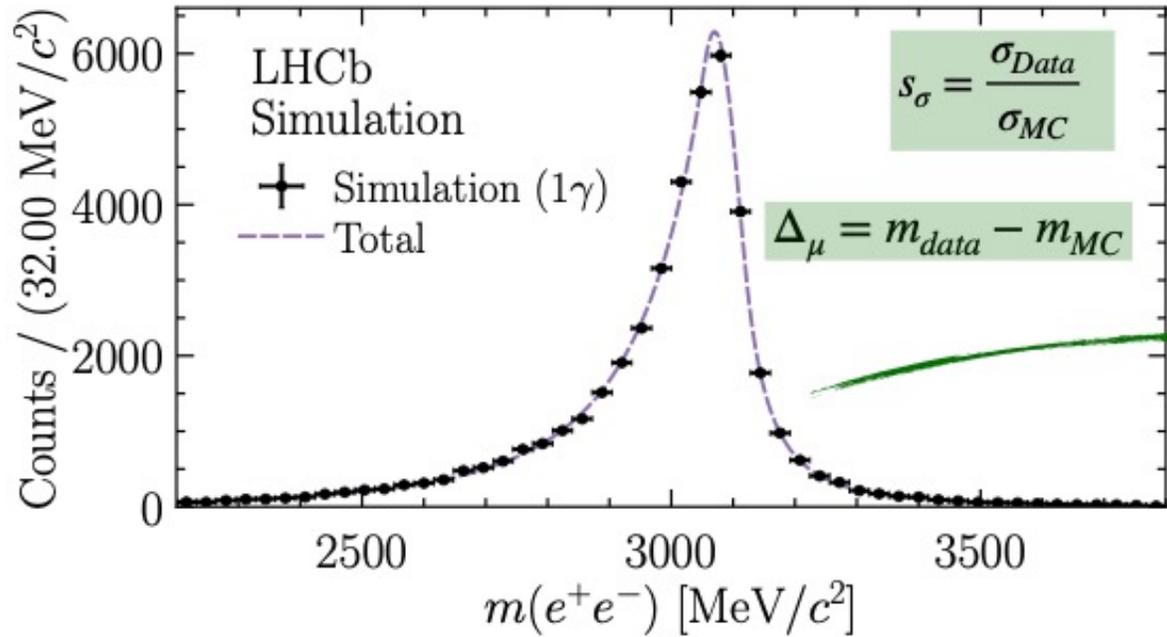
Correct the simulation for

- B kinematics and global event properties (tracks multiplicity)
- Tracking efficiency
- PID efficiency
- Detector response for the trigger (L0 mostly)
- $q^2$  resolution and bin migration (M(ee) in MC & data)

Intensive use of data control samples



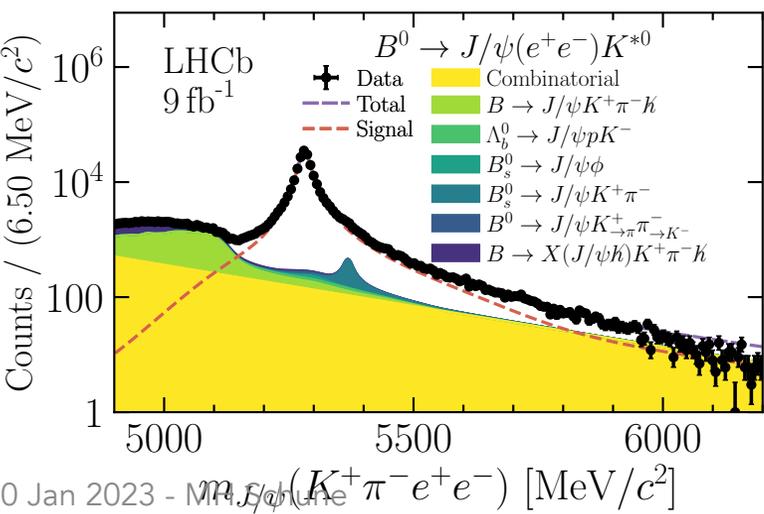
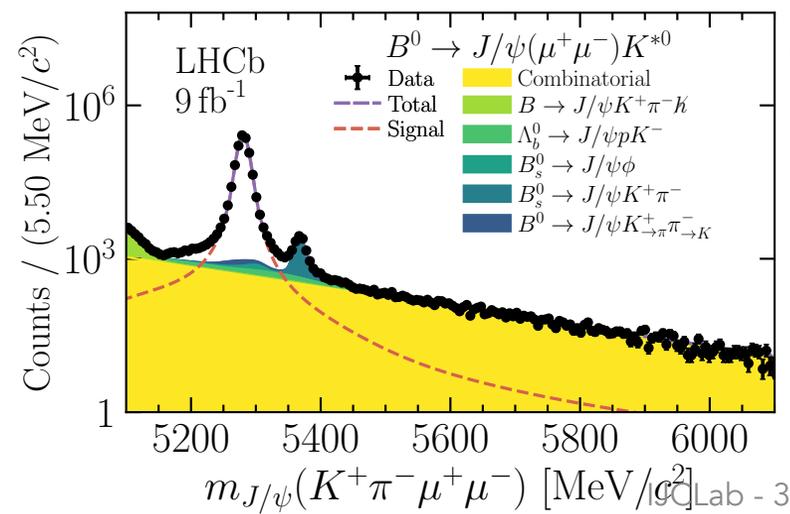
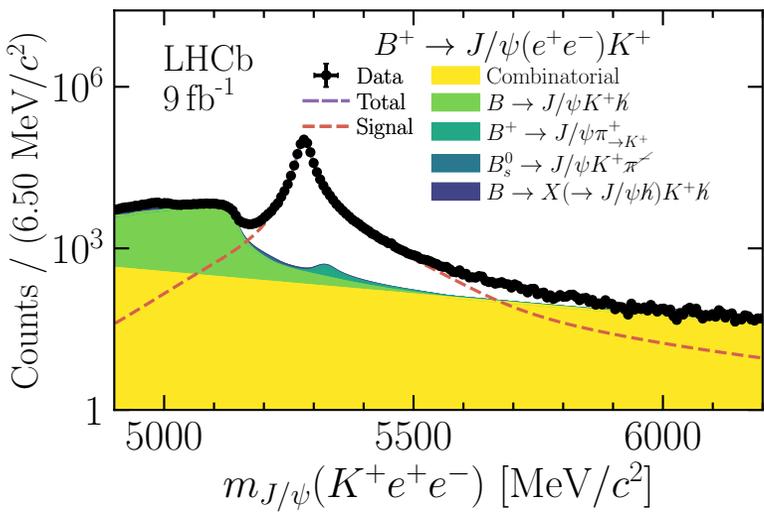
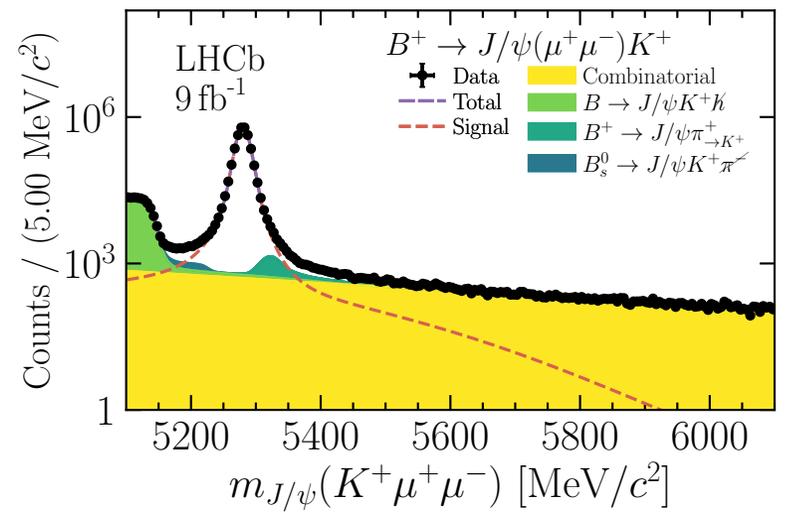
# $q^2$ resolution and bin migration (M(ee) in MC & data)



$$m^{\text{smearred}} = m^{\text{true}} + s_\sigma \cdot (m^{\text{reco}} - m^{\text{true}}) + \Delta\mu + (1 - s_\sigma) \cdot (\mu^{\text{MC}} - M_{J/\psi}^{\text{PDG}}).$$

....and test it on the (challenging) single ratio:

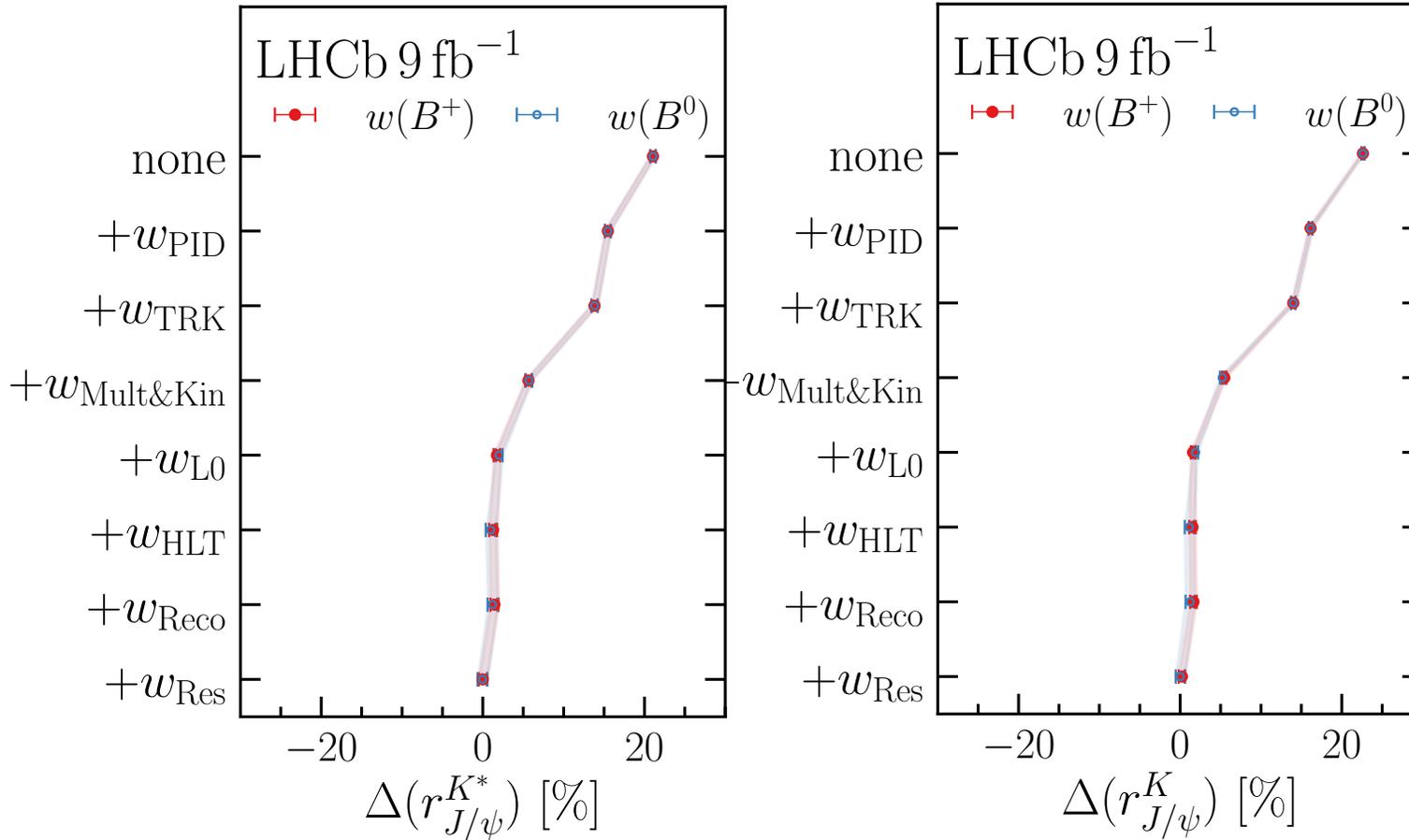
$$r_{J/\psi}^{K, K^*} \equiv \frac{\frac{N}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow \mu^+ \mu^-))}{\frac{N}{\epsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow e^+ e^-))}$$



$$r_{J/\psi}^K = 1.047 \pm 0.024 \text{ and } r_{J/\psi}^{K^*} = 1.028 \pm 0.024$$

(syst dominated)

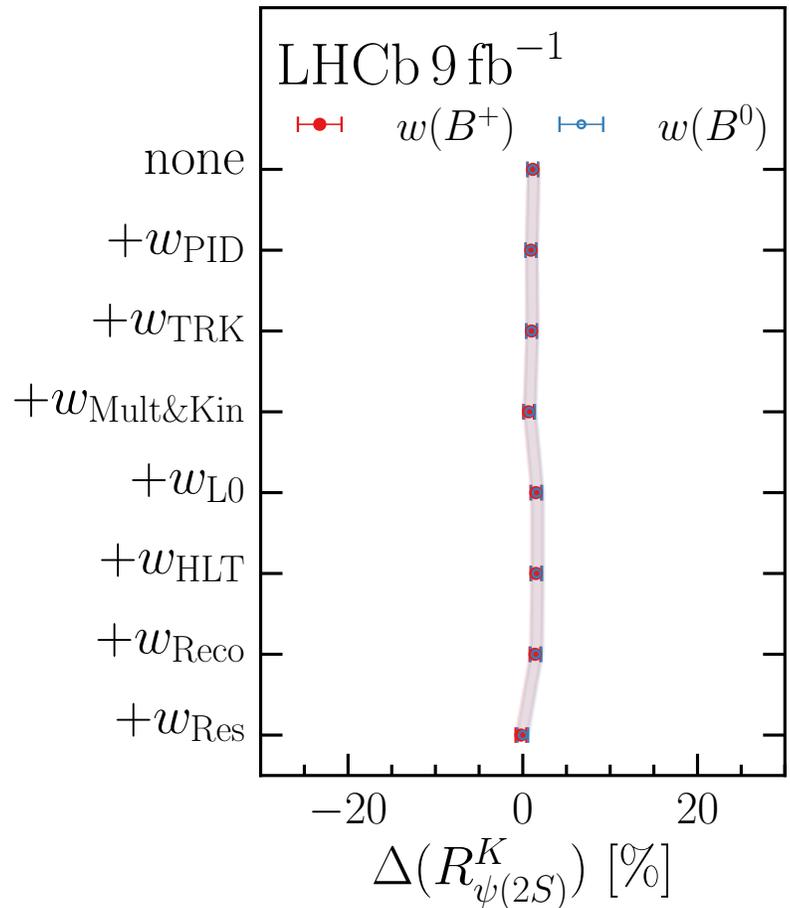
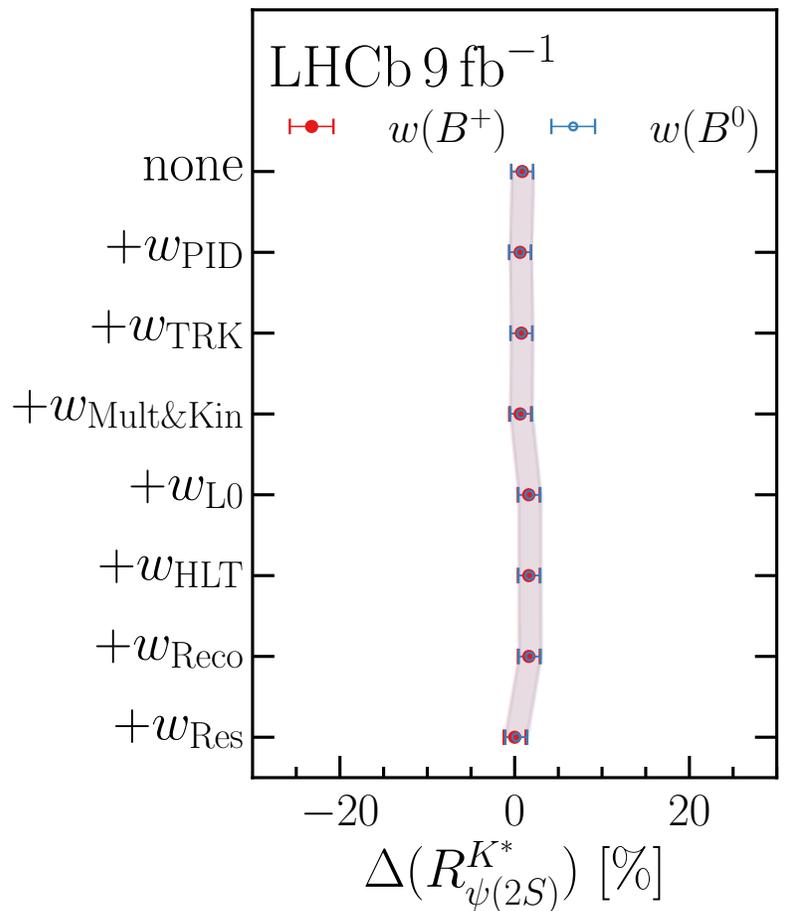
## single ratio



correction impact ~ 25%

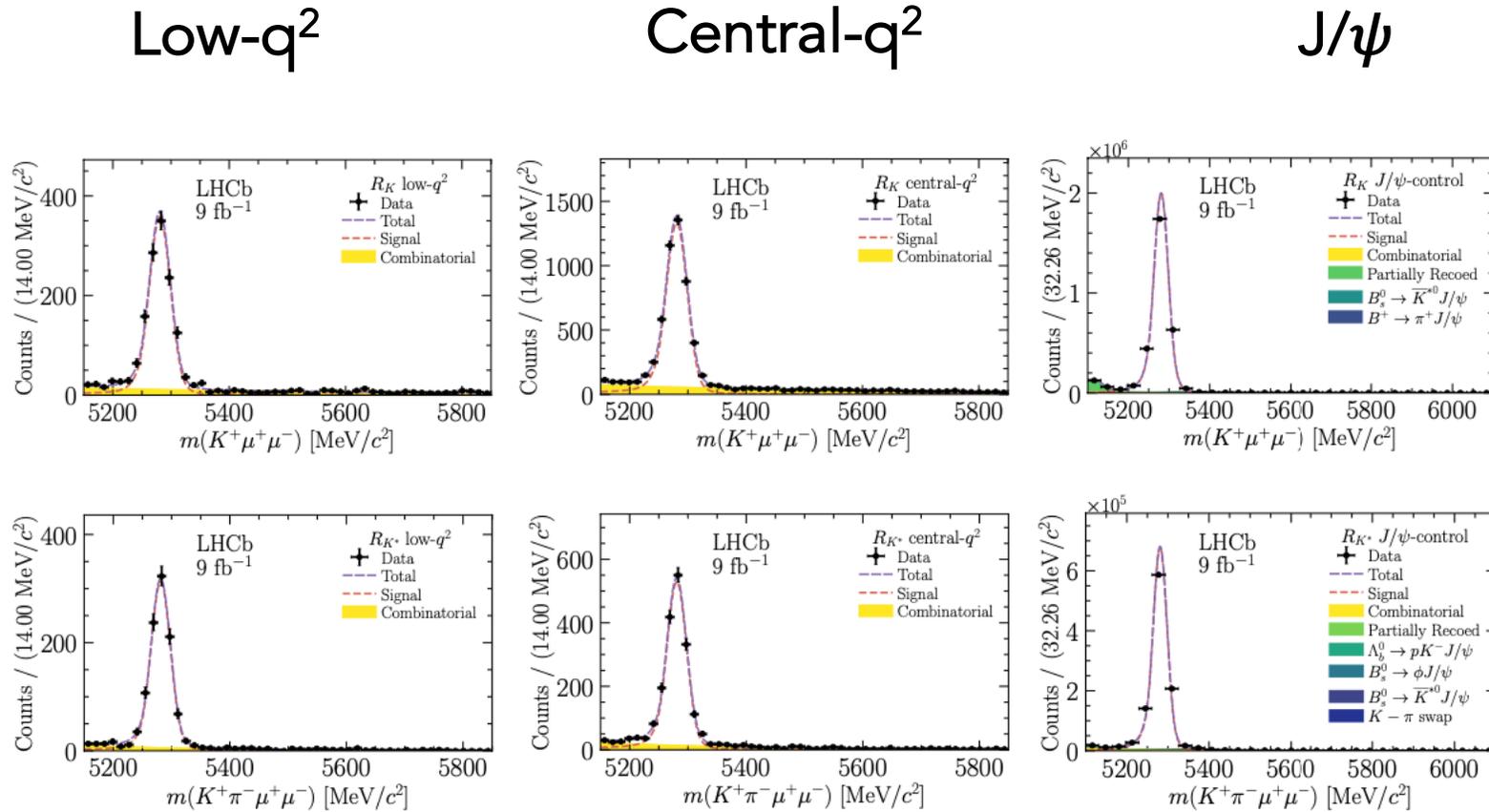
but, as expected, on **double ratio**, the effect is much less important:

$$R_{(K,K^*)}^{\psi(2S)} \equiv \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} \psi(2S)(\rightarrow \mu\mu))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow \mu^+ \mu^-))} / \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} \psi(2S)(\rightarrow ee))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \rightarrow K^{(+,*0)} J/\psi(\rightarrow e^+ e^-))}$$



correction impact < 5%

# Fitter schematics: muon modes

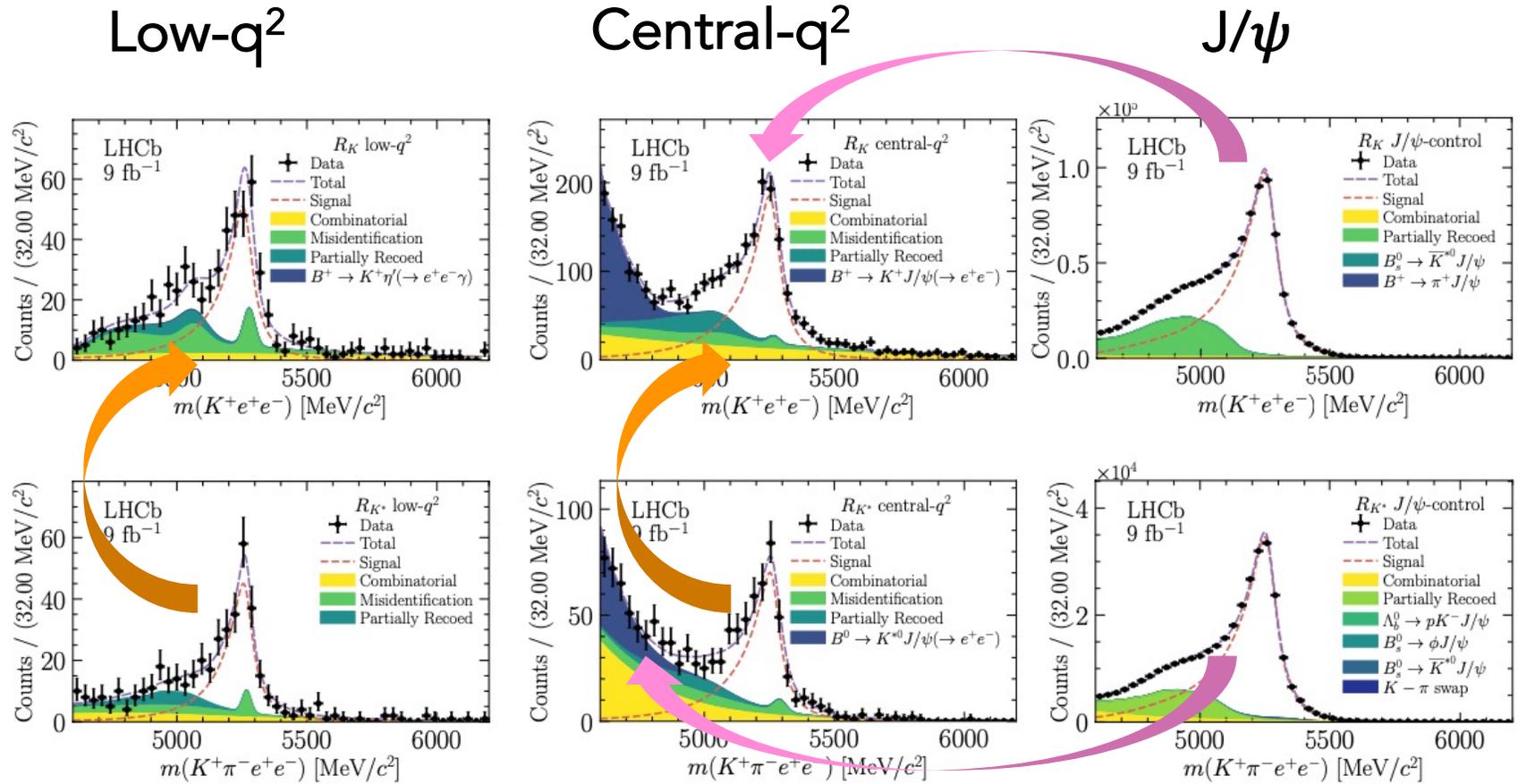


x 3 runs periods (Run1 – Run2p1 – Run2p2)  
x 2 trigger types (TOS or TIS)

# Fitter schematics: electrons modes

$B^+ \rightarrow K^+ ee$

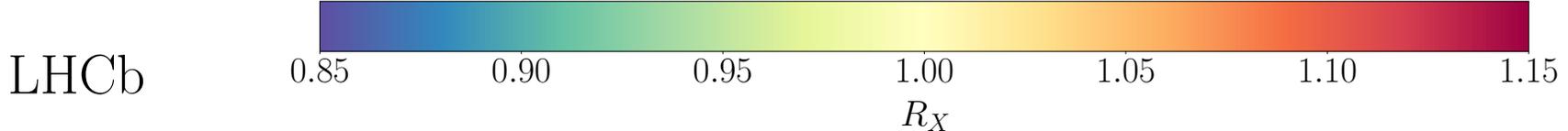
$B^0 \rightarrow K^{*0} ee$



x 3 runs periods (Run1 – Run2p1 – Run2p2)

x 2 trigger types (TOS or TIS)

# Effect of various electron PID cuts on $R_X$ results without treatment of misID background



LHCb

$R_K$  low- $q^2$

	0.960 ± 0.097	0.971 ± 0.099	0.988 ± 0.102	0.997 ± 0.102	0.982 ± 0.100	0.973 ± 0.099	0.967 ± 0.099	0.967 ± 0.099	0.977 ± 0.102
DLL(e) > 7									
	0.961 ± 0.086	0.964 ± 0.086	0.969 ± 0.088	0.983 ± 0.090	0.973 ± 0.089	0.981 ± 0.091	0.979 ± 0.092	0.961 ± 0.090	0.985 ± 0.095
DLL(e) > 5									
	0.873 ± 0.073	0.904 ± 0.078	0.908 ± 0.079	0.958 ± 0.087	0.950 ± 0.086	0.954 ± 0.087	0.938 ± 0.086	0.940 ± 0.087	0.969 ± 0.093
DLL(e) > 2									
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
	ProbNN(e)								

$R_K$  central- $q^2$

	0.948 ± 0.051	0.944 ± 0.051	0.944 ± 0.051	0.939 ± 0.051	0.939 ± 0.051	0.941 ± 0.051	0.934 ± 0.051	0.935 ± 0.051	0.937 ± 0.052
DLL(e) > 7									
	0.941 ± 0.044	0.938 ± 0.044	0.942 ± 0.044	0.933 ± 0.044	0.939 ± 0.045	0.951 ± 0.046	0.946 ± 0.046	0.953 ± 0.047	0.949 ± 0.048
DLL(e) > 5									
	0.906 ± 0.040	0.902 ± 0.040	0.907 ± 0.040	0.895 ± 0.040	0.904 ± 0.041	0.916 ± 0.042	0.920 ± 0.043	0.925 ± 0.044	0.919 ± 0.044
DLL(e) > 2									
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
	ProbNN(e)								

$R_{K^*}$  low- $q^2$

	0.985 ± 0.112	0.982 ± 0.112	0.966 ± 0.109	0.952 ± 0.107	0.971 ± 0.111	0.975 ± 0.112	0.984 ± 0.114	0.970 ± 0.112	0.960 ± 0.111
DLL(e) > 7									
	0.980 ± 0.097	0.993 ± 0.100	0.978 ± 0.099	0.979 ± 0.100	1.007 ± 0.103	1.014 ± 0.105	1.010 ± 0.106	1.010 ± 0.108	1.019 ± 0.110
DLL(e) > 5									
	0.855 ± 0.080	0.848 ± 0.079	0.830 ± 0.076	0.847 ± 0.080	0.883 ± 0.086	0.901 ± 0.088	0.915 ± 0.089	0.925 ± 0.092	0.934 ± 0.117
DLL(e) > 2									
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
	ProbNN(e)								

$R_{K^*}$  central- $q^2$

	1.127 ± 0.100	1.119 ± 0.099	1.116 ± 0.099	1.103 ± 0.098	1.097 ± 0.097	1.083 ± 0.095	1.097 ± 0.099	1.113 ± 0.101	1.119 ± 0.103
DLL(e) > 7									
	1.021 ± 0.074	1.016 ± 0.074	1.016 ± 0.075	0.997 ± 0.073	1.016 ± 0.076	1.001 ± 0.075	1.012 ± 0.077	1.035 ± 0.081	1.049 ± 0.084
DLL(e) > 5									
	0.965 ± 0.066	0.990 ± 0.069	0.986 ± 0.069	0.993 ± 0.071	1.024 ± 0.075	1.006 ± 0.073	1.014 ± 0.075	1.038 ± 0.079	1.039 ± 0.081
DLL(e) > 2									
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
	ProbNN(e)								

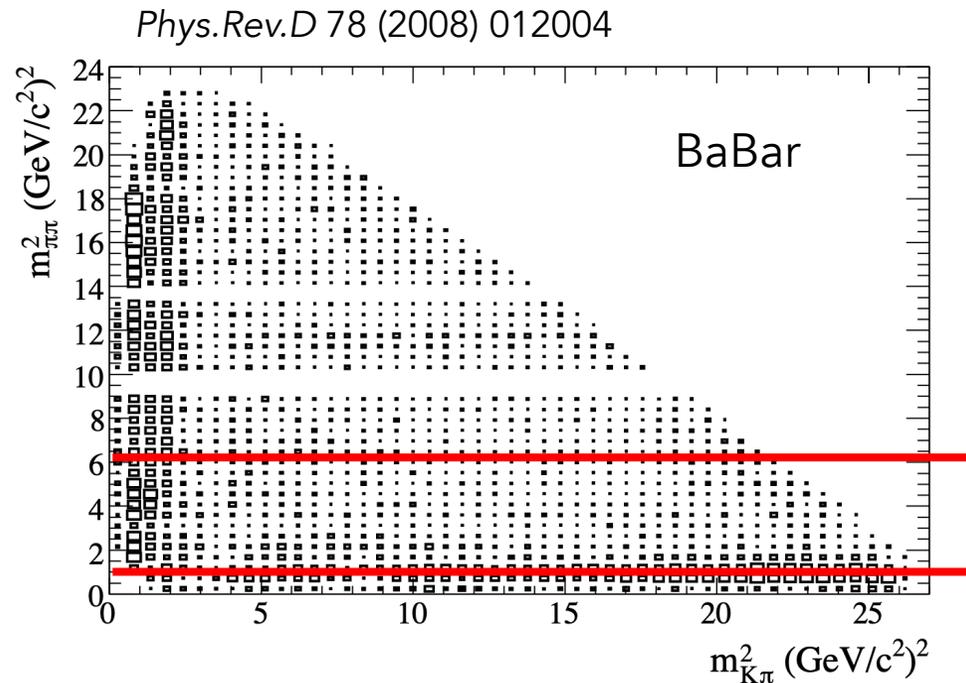
a coherent pattern ...

A simple example:  $B^+ \rightarrow K^+ \pi\pi$

$BR(B^+ \rightarrow K^+ \pi\pi) = 5.1 \cdot 10^{-5}$  to be compared to  $BR(B^+ \rightarrow K^+ ee) = 1.3 \cdot 10^{-7}$  in the central- $q^2$  region

Using a  $\pi$  misld value of 1% and an electron PID pessimistic efficiency of 80% :  $S/B \sim 16$

in addition not all the decay is selected:

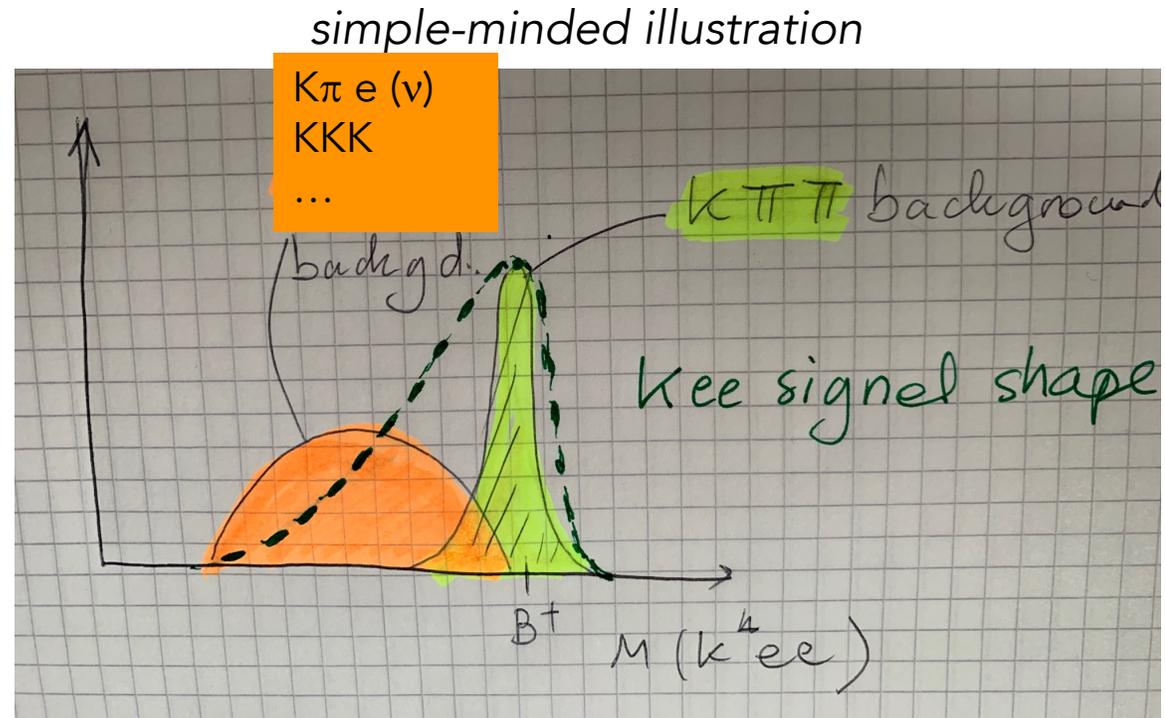


This background is coming from many different sources, many of them not being measured (eg  $B \rightarrow K^* \pi\pi$  Dalitz distribution unknown)

A representative subset of these backgrounds have been studied on MC  $\Rightarrow$  small

But all of them ?

+ Nasty potential interplay:



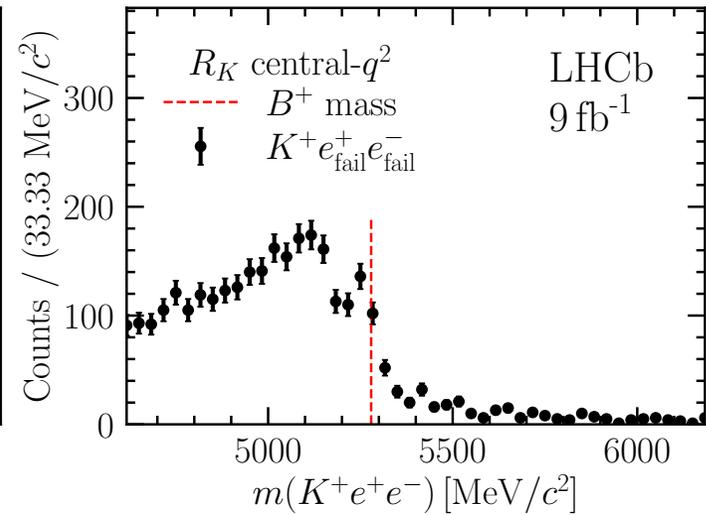
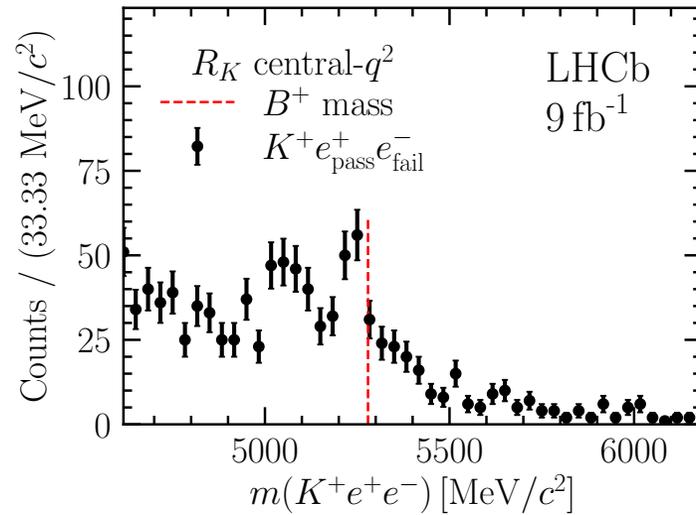
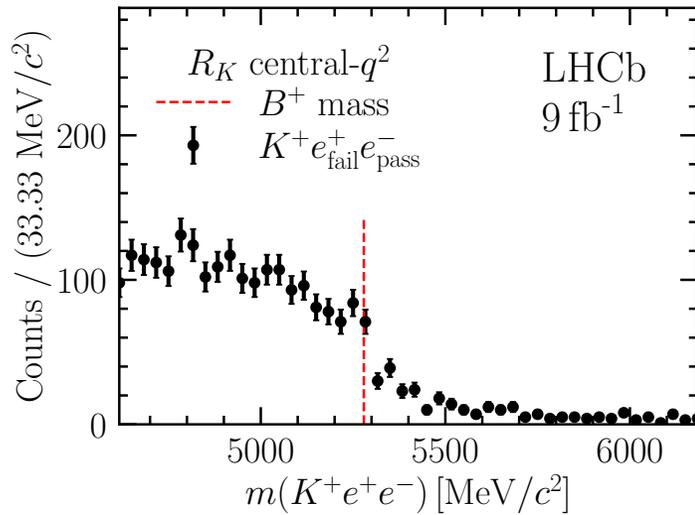
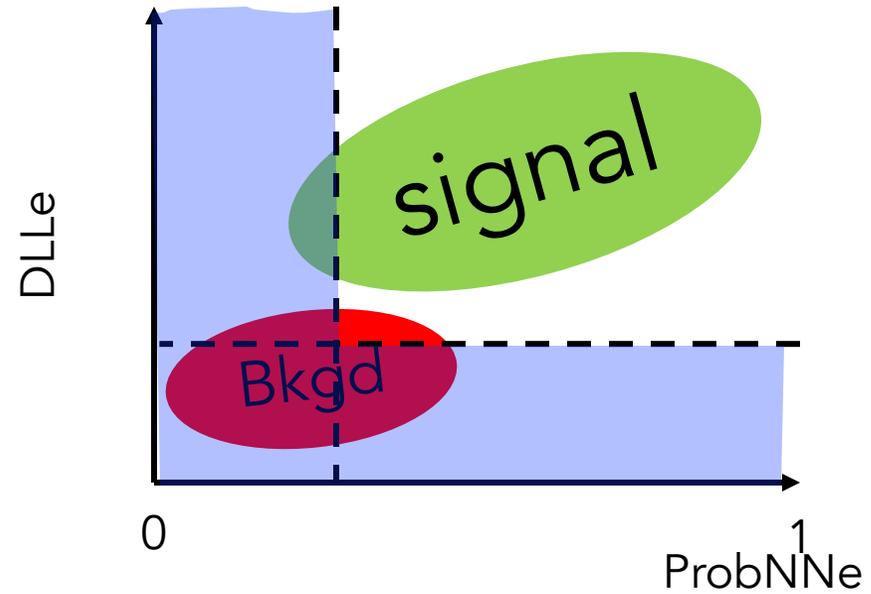
$\Rightarrow$  Extract its shape directly from data

Define a **control** region for the electron identification

Invert PID requirements on one or two electrons after the full selection

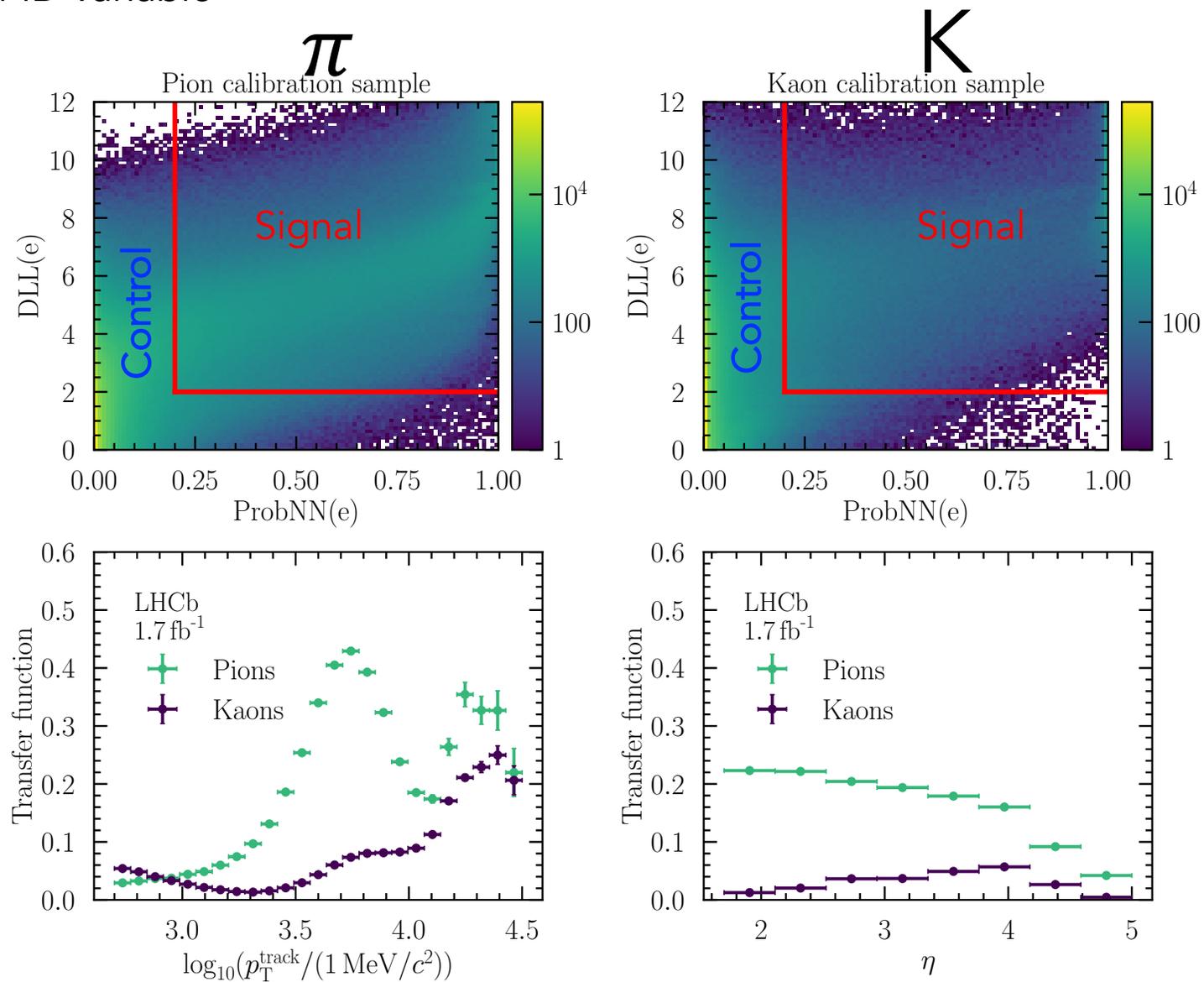
Subtract the remaining signal events in the **control** region

⇒ Invariant mass distribution for the **control** region:

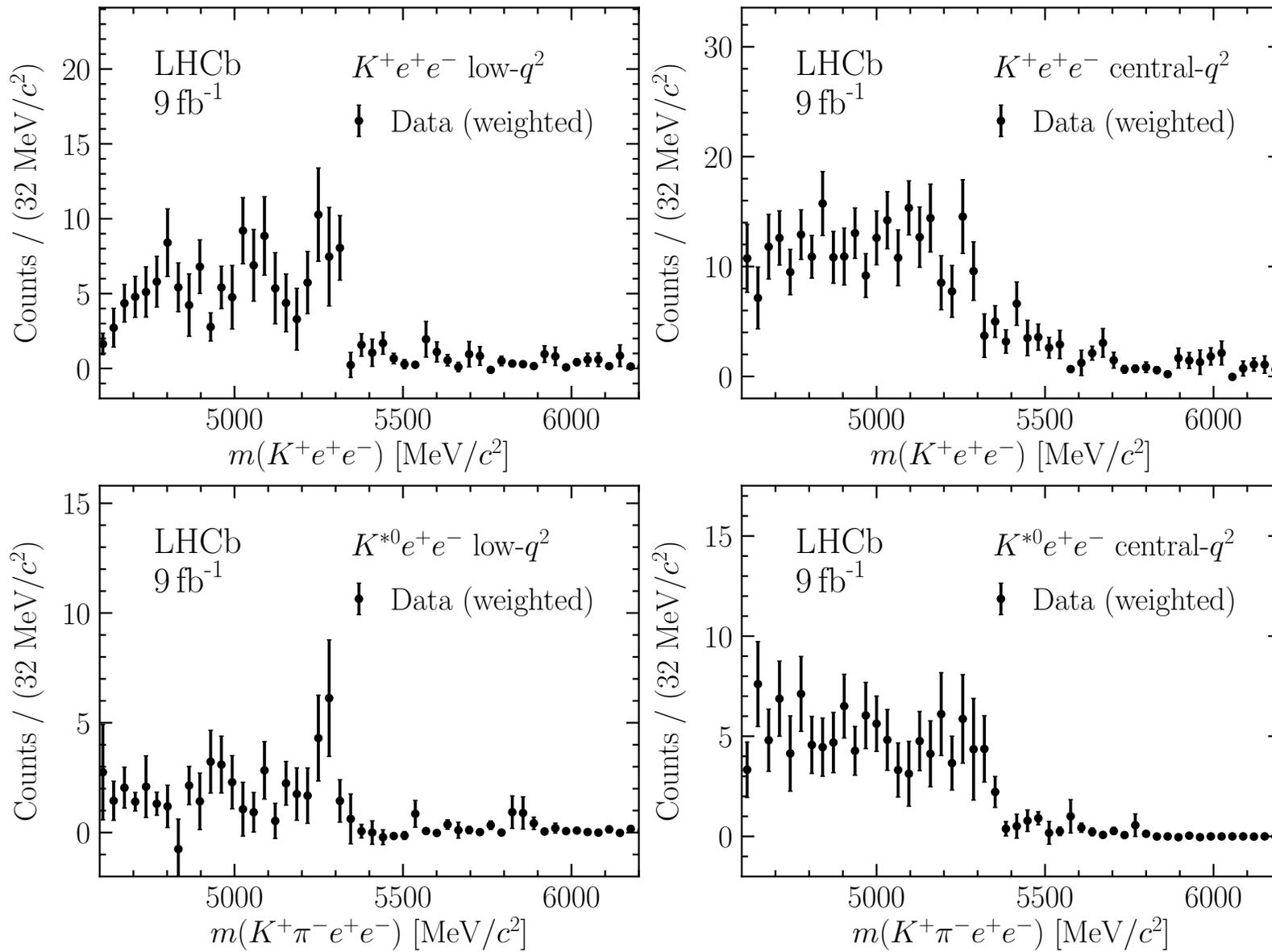


Mis-identified hadron can be Pions or Kaons (leading to different background shapes) which have different probabilities to be mis-identified as electrons

⇒ categorize them using the NN Kaon-ID variable



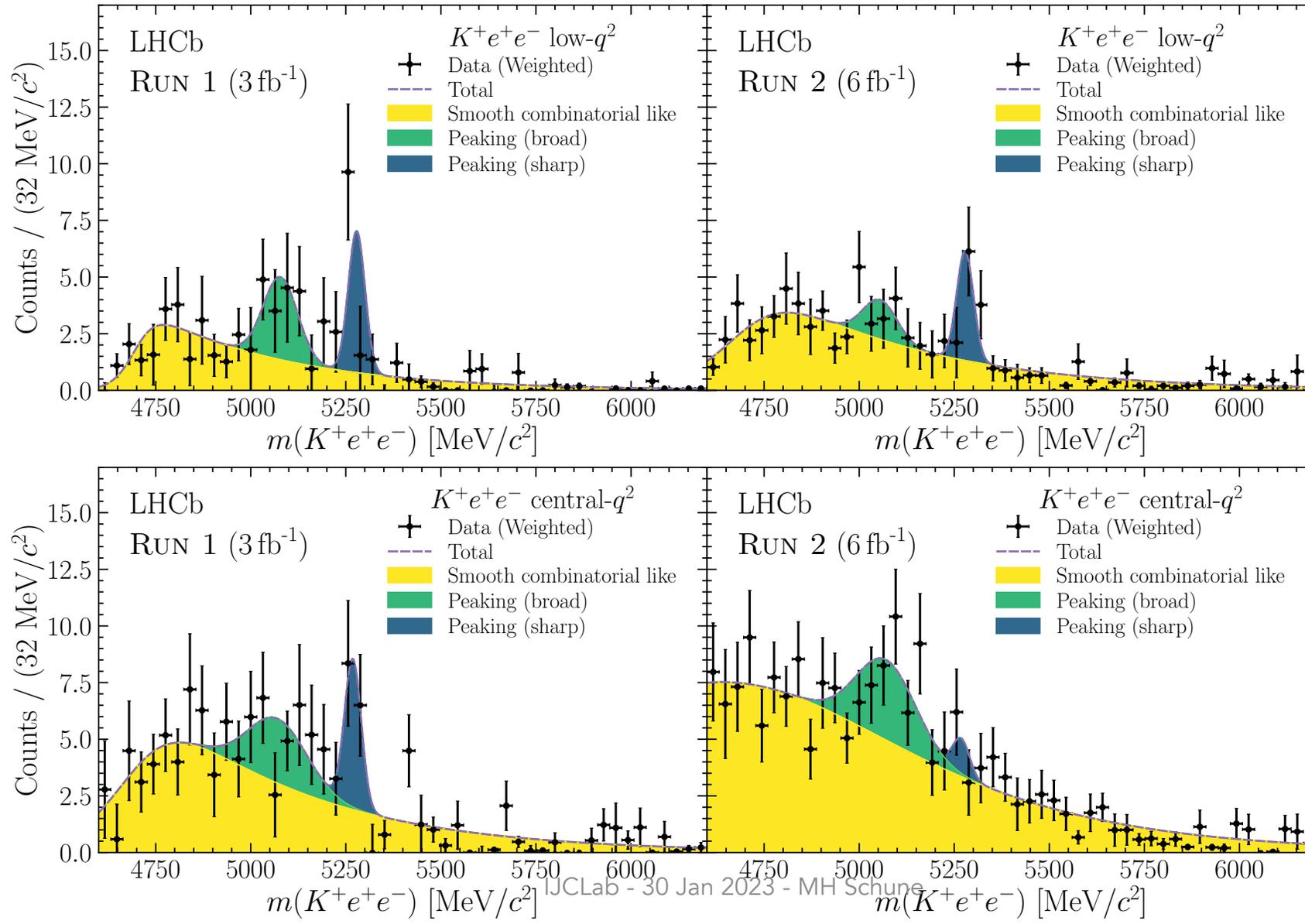
Transfer function  
 $K/\pi \rightarrow e$  : **control** → **signal**  
 obtained from  $D^* \rightarrow D^0(\rightarrow K\pi)\pi$



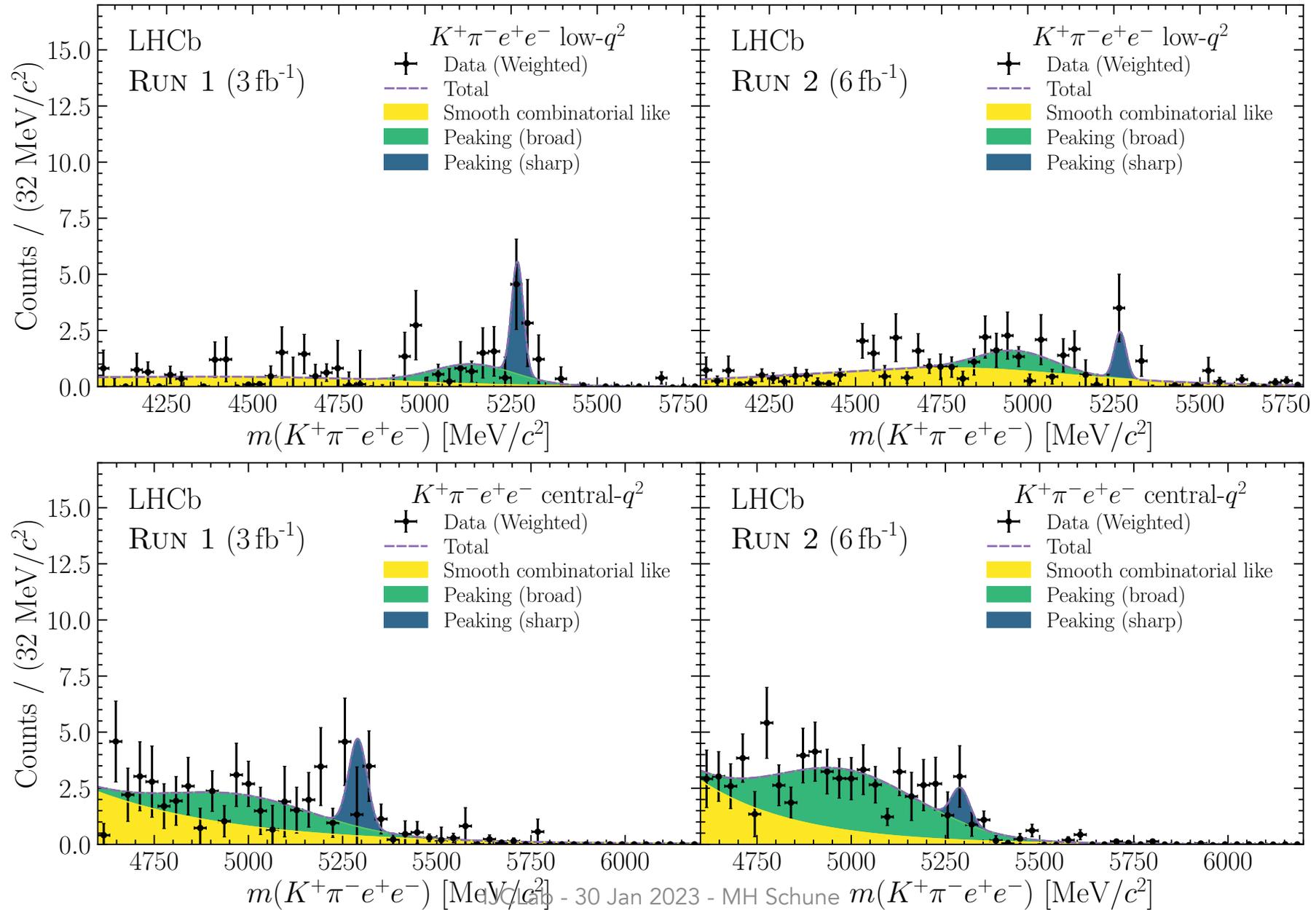
Larger peaking backgrounds in the low- $q^2$  regions due to the presence of hadronic resonances

Those shapes and contaminations are used as constraints in the nominal fit

# Misidentified backgrounds in $R_K$

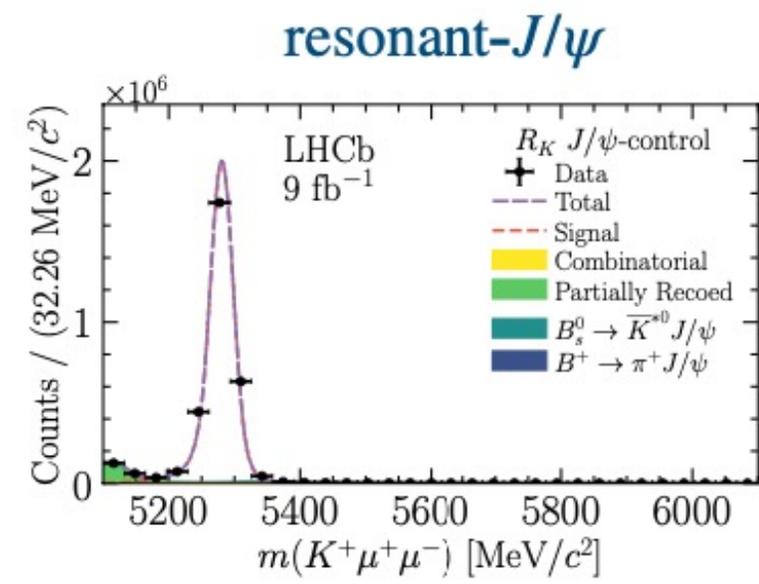
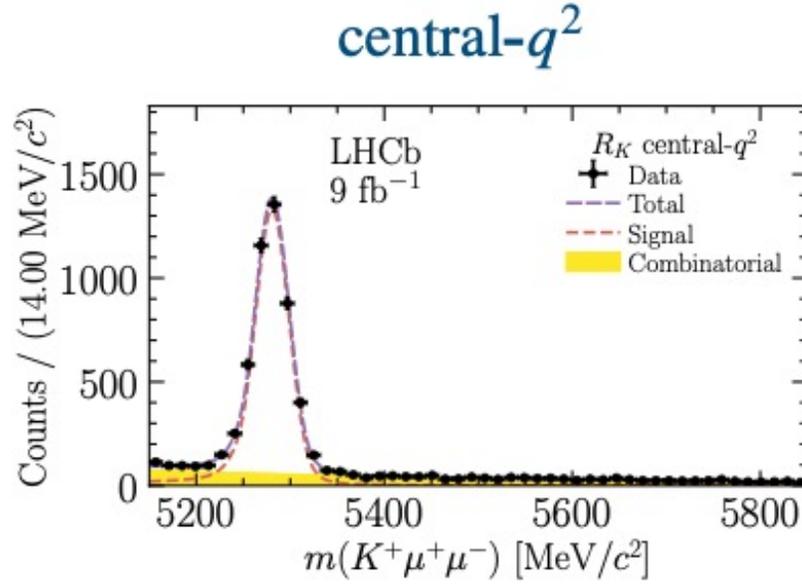
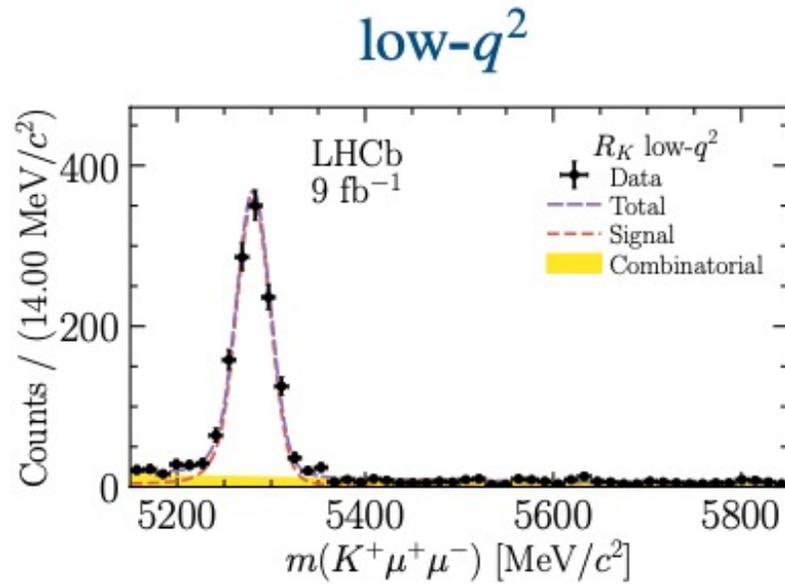


# Misidentified backgrounds in $R_{K^*}$

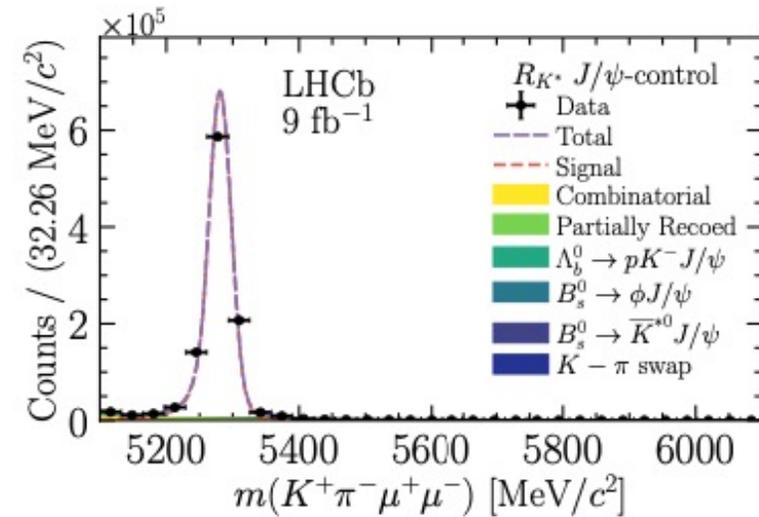
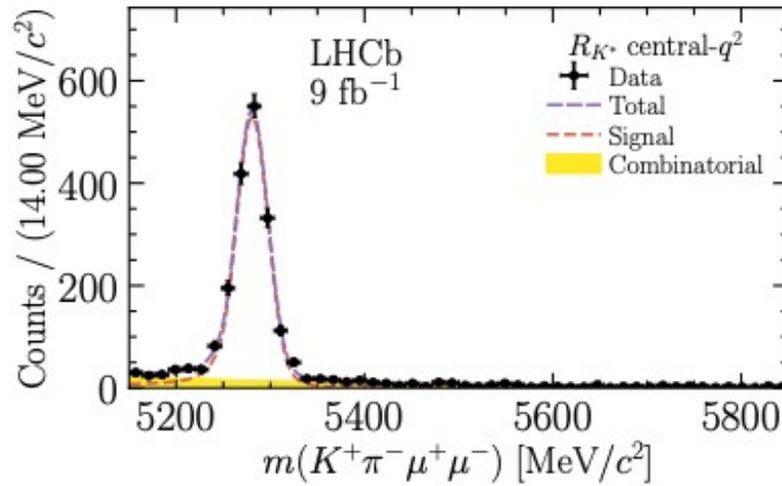
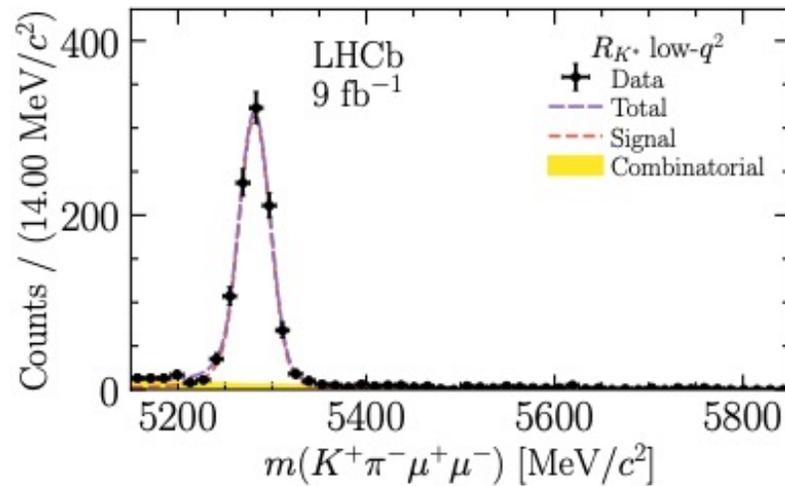


# Simultaneous fit for $R_x$ extraction: muon modes

$B^+$

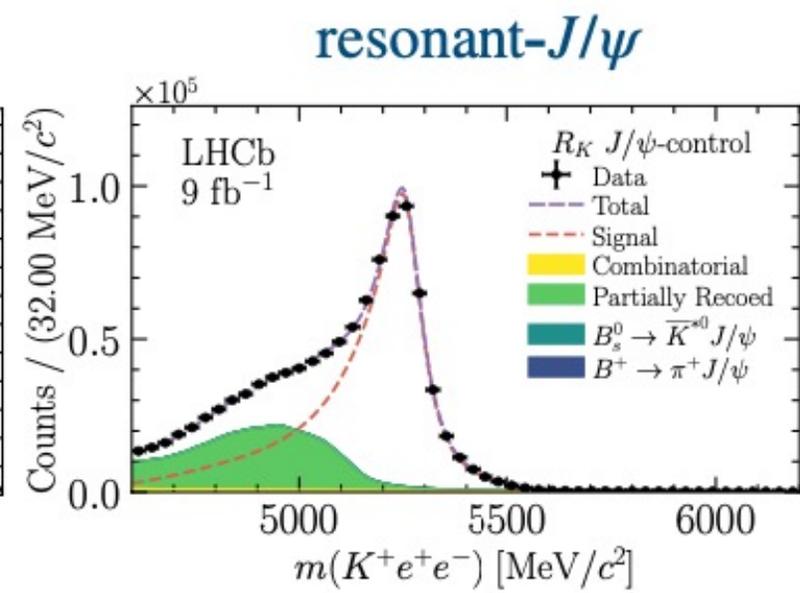
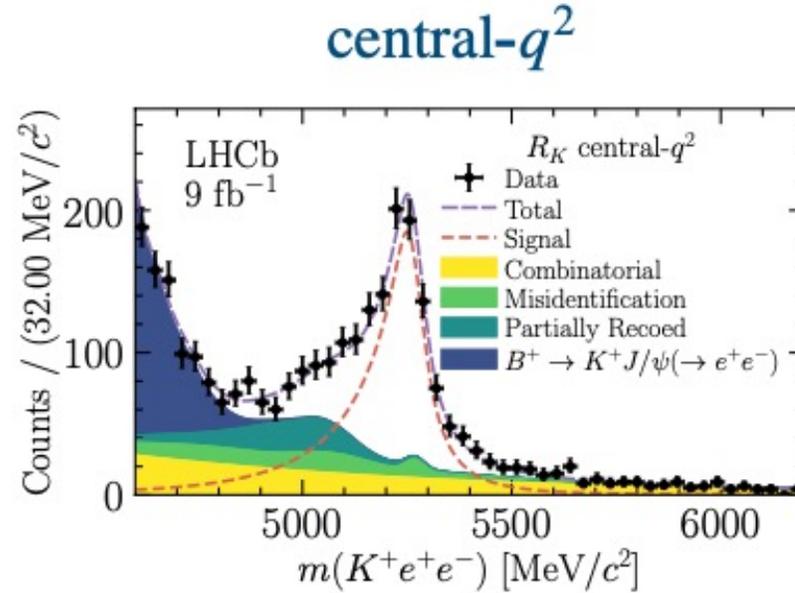
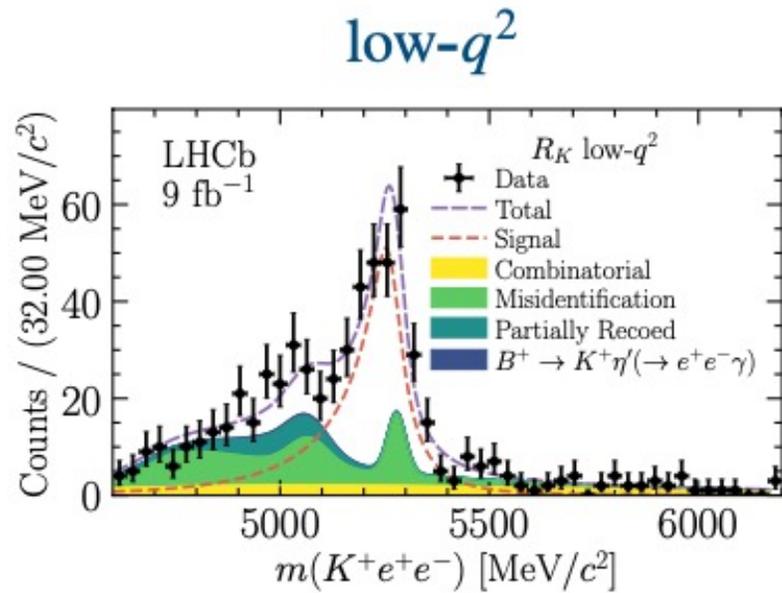


$B^0$

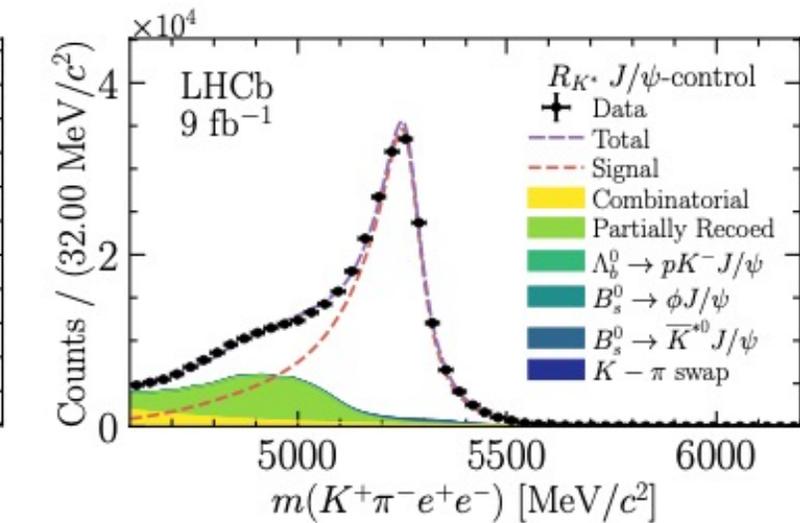
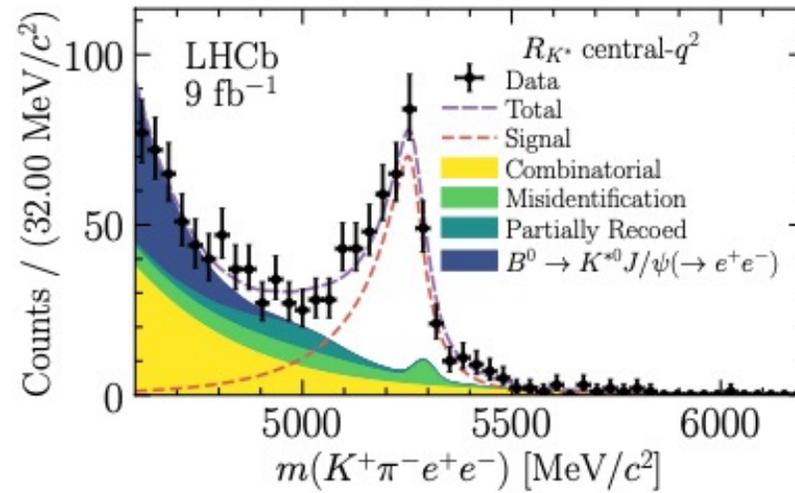
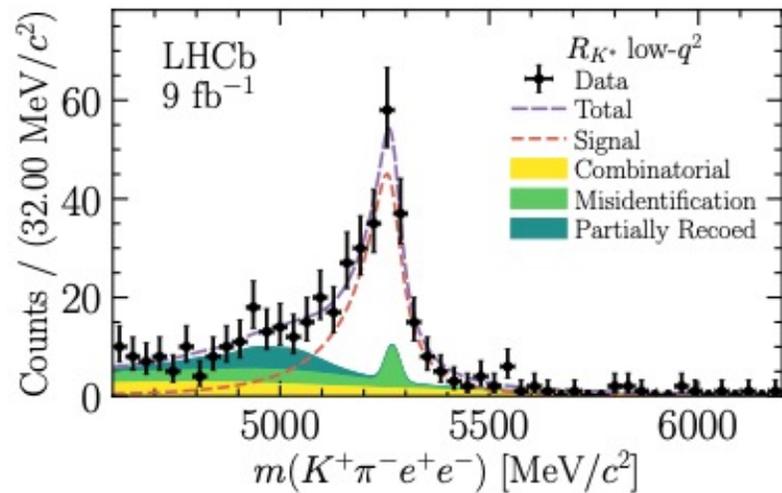


# Simultaneous fit for $R_x$ extraction: electron modes

$B^+$



$B^0$

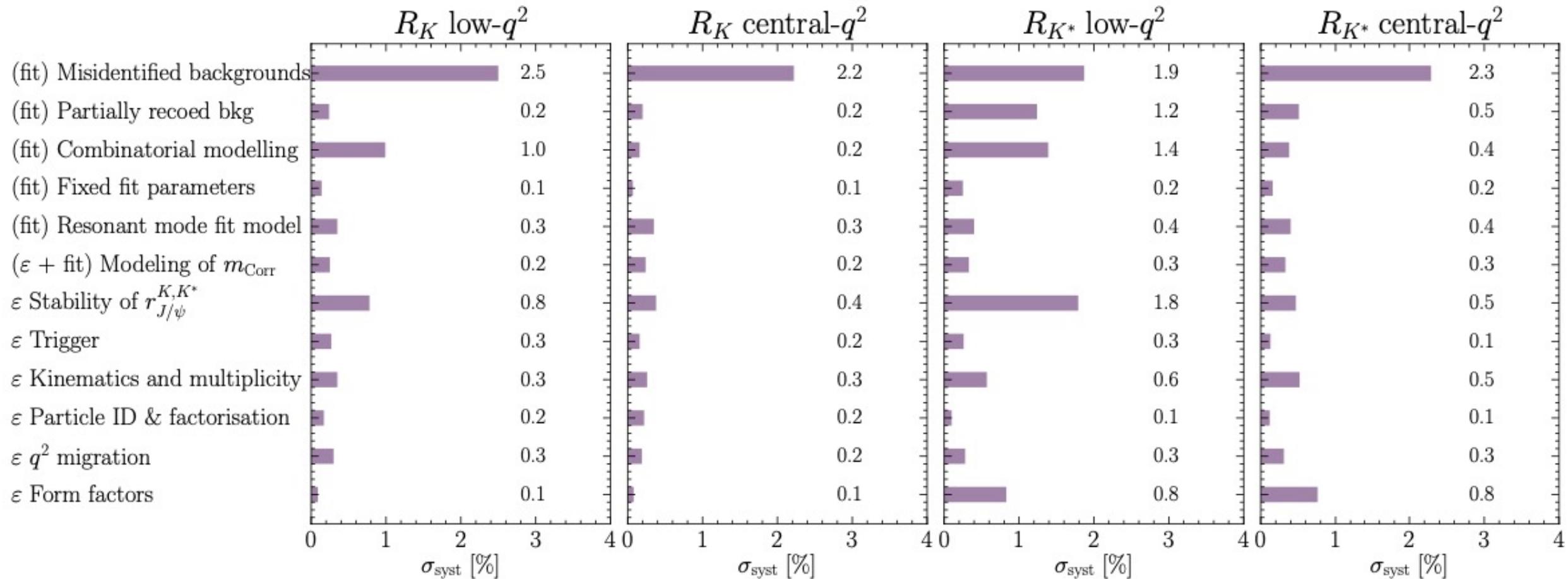


A factor  $\sim 4$  in yields between electron and muon modes

*Measured yields from simultaneous fit to  $R_X$*

LU observable	Muon ( $\times 10^3$ )	Electron ( $\times 10^3$ )
low- $q^2$ $R_K$	$1.25 \pm 0.04$	$0.305 \pm 0.024$
low- $q^2$ $R_{K^*}$	$1.001 \pm 0.034$	$0.247 \pm 0.022$
central- $q^2$ $R_K$	$4.69 \pm 0.08$	$1.19 \pm 0.05$
central- $q^2$ $R_{K^*}$	$1.74 \pm 0.05$	$0.443 \pm 0.028$
$J/\psi$ $R_K$	$(2.964 \pm 0.002) \times 10^3$	$(7.189 \pm 0.015) \times 10^2$
$J/\psi$ $R_{K^*}$	$(9.733 \pm 0.010) \times 10^2$	$(2.517 \pm 0.009) \times 10^2$

# Systematic uncertainties



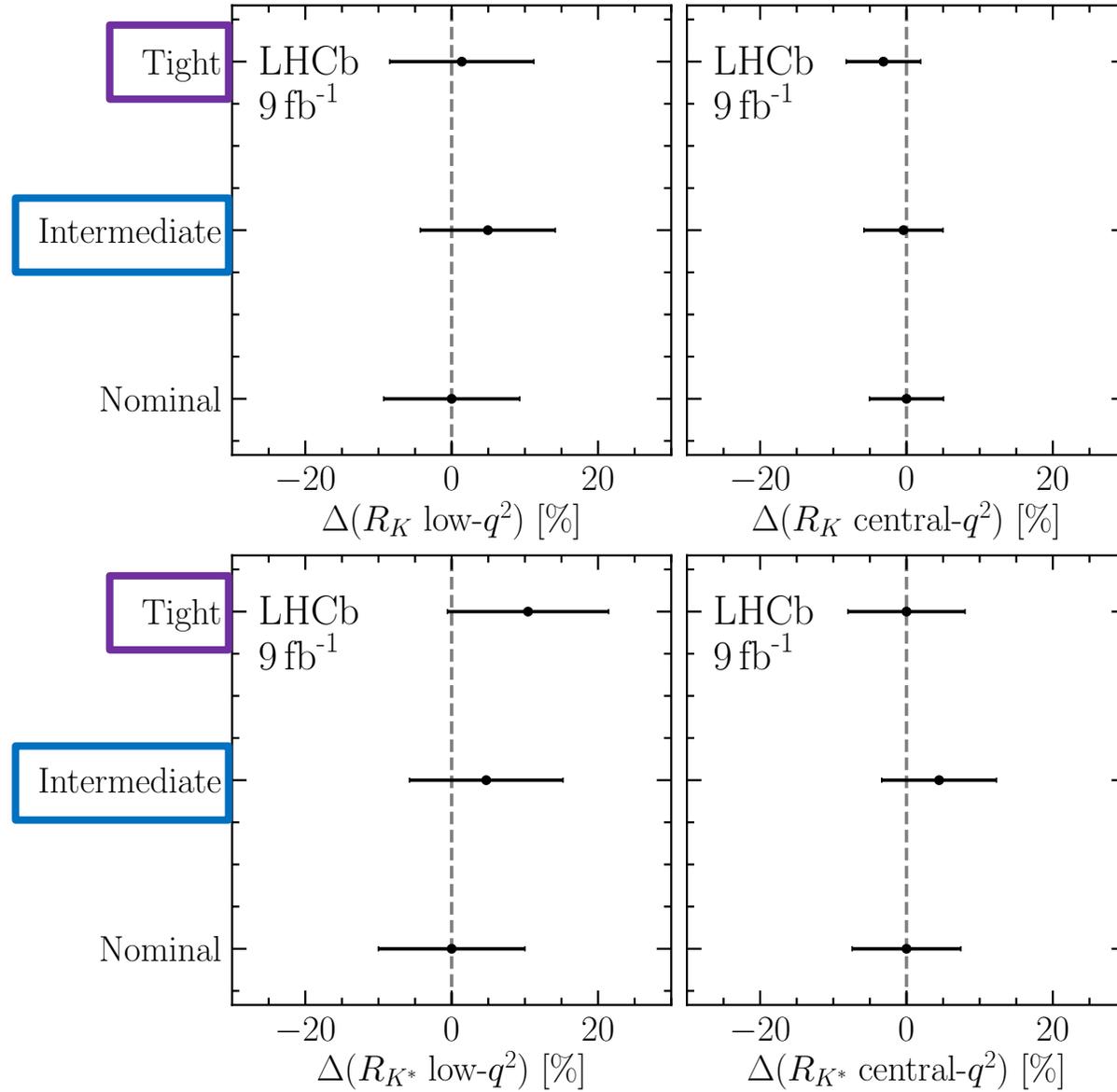
Main ones from misidentified backgrounds

# Tight

80% misID suppression  
50-60% signal loss

# Intermediate

50% misID suppression  
20-30% signal loss



Stability of the results when using tighter PID working points

# Results

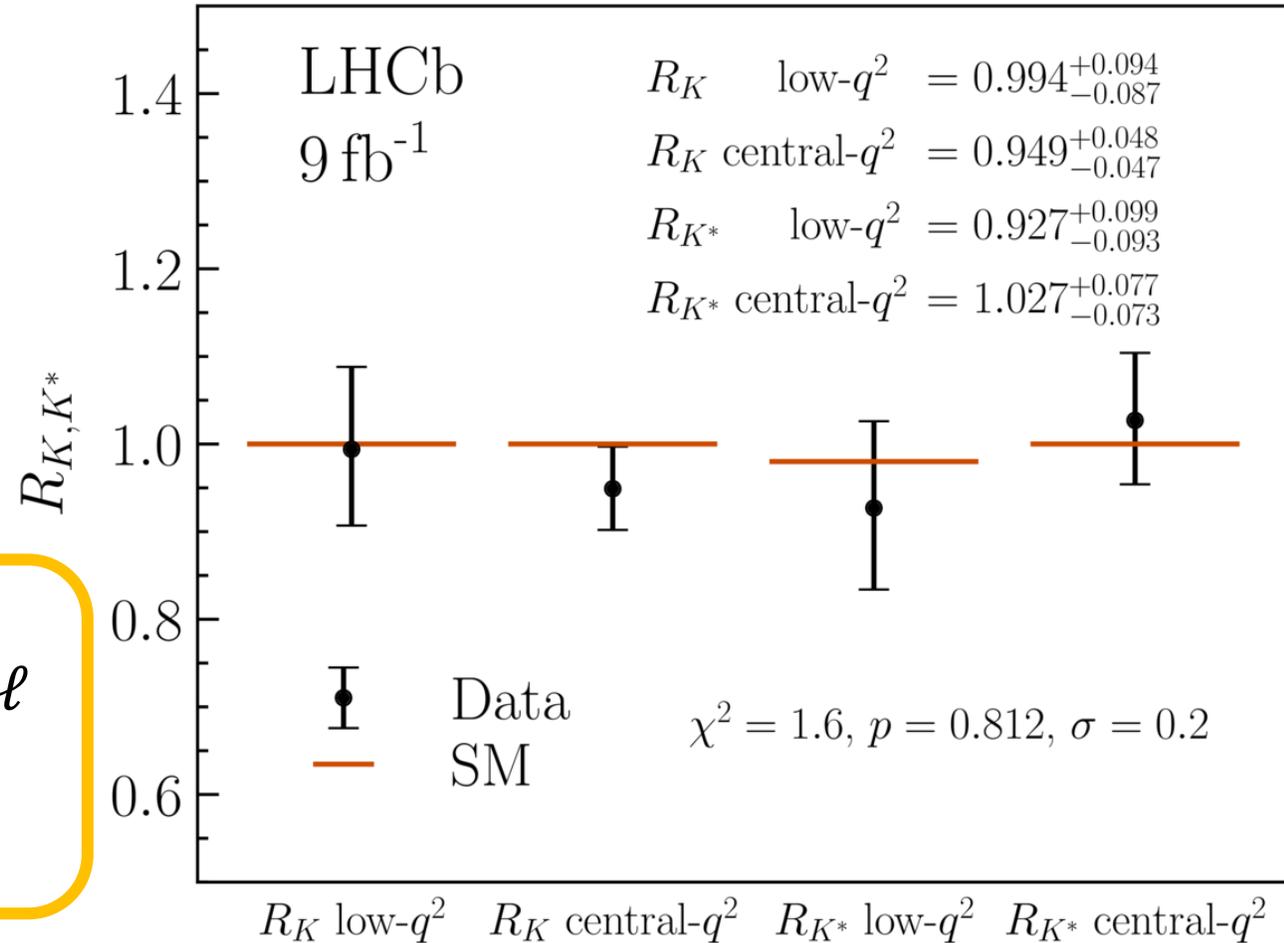


$$\text{low-}q^2 \begin{cases} R_K & = 0.994^{+0.090}_{-0.082} (\text{stat})^{+0.029}_{-0.027} (\text{syst}), \\ R_{K^*} & = 0.927^{+0.093}_{-0.087} (\text{stat})^{+0.036}_{-0.035} (\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K & = 0.949^{+0.042}_{-0.041} (\text{stat})^{+0.022}_{-0.022} (\text{syst}), \\ R_{K^*} & = 1.027^{+0.072}_{-0.068} (\text{stat})^{+0.027}_{-0.026} (\text{syst}), \end{cases}$$

First or most precise test of LFU in  $b \rightarrow s \ell \ell$

Compatible with the SM at  $0.2 \sigma$



# Conclusion

## Simultaneous fit of two decay modes and two kinematical regions

→ In depth revision and understanding of electron misidentification

→

$$\begin{array}{l} \text{low-}q^2 \\ \text{central-}q^2 \end{array} \left\{ \begin{array}{l} R_K = 0.994 \begin{array}{l} +0.090 \\ -0.082 \end{array} (\text{stat}) \begin{array}{l} +0.029 \\ -0.027 \end{array} (\text{syst}), \\ R_{K^*} = 0.927 \begin{array}{l} +0.093 \\ -0.087 \end{array} (\text{stat}) \begin{array}{l} +0.036 \\ -0.035 \end{array} (\text{syst}), \\ R_K = 0.949 \begin{array}{l} +0.042 \\ -0.041 \end{array} (\text{stat}) \begin{array}{l} +0.022 \\ -0.022 \end{array} (\text{syst}), \\ R_{K^*} = 1.027 \begin{array}{l} +0.072 \\ -0.068 \end{array} (\text{stat}) \begin{array}{l} +0.027 \\ -0.026 \end{array} (\text{syst}), \end{array} \right. \begin{array}{l} \bullet \text{ 5 to 10\% precision (stat dominated)} \\ \bullet \text{ Compatible with the SM at } 0.2 \sigma \end{array}$$

$b \rightarrow s\ell\ell$  has a rich phenomenology (= a lot of possible measurements)

- Branching Ratios (but large theoretical uncertainties due to non-perturbative QCD)
- Study of the angular distributions of the decay products
- Ratios of BF (test of Lepton Universality): conceptually very simple, experimentally very challenging



$$\text{low-}q^2 \begin{cases} R_K & = 0.994^{+0.090}_{-0.082} \text{ (stat)} \ ^{+0.029}_{-0.027} \text{ (syst)}, \\ R_{K^*} & = 0.927^{+0.093}_{-0.087} \text{ (stat)} \ ^{+0.036}_{-0.035} \text{ (syst)}, \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K & = 0.949^{+0.042}_{-0.041} \text{ (stat)} \ ^{+0.022}_{-0.022} \text{ (syst)}, \\ R_{K^*} & = 1.027^{+0.072}_{-0.068} \text{ (stat)} \ ^{+0.027}_{-0.026} \text{ (syst)}, \end{cases}$$

- 5 to 10% precision (stat dominated)
- Compatible with the SM at  $0.2 \sigma$



?

$$\text{low-}q^2 \begin{cases} R_K & = 0.994^{+0.090}_{-0.082} \text{ (stat)} \ ^{+0.029}_{-0.027} \text{ (syst)}, \\ R_{K^*} & = 0.927^{+0.093}_{-0.087} \text{ (stat)} \ ^{+0.036}_{-0.035} \text{ (syst)}, \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K & = 0.949^{+0.042}_{-0.041} \text{ (stat)} \ ^{+0.022}_{-0.022} \text{ (syst)}, \\ R_{K^*} & = 1.027^{+0.072}_{-0.068} \text{ (stat)} \ ^{+0.027}_{-0.026} \text{ (syst)}, \end{cases}$$

- 5 to 10% precision (stat dominated)
- Compatible with the SM at  $0.2 \sigma$



## Looking back in the mirror

VOLUME 6, NUMBER 10

PHYSICAL REVIEW LETTERS

MAY 15, 1961

### DECAY PROPERTIES OF $K_2^0$ MESONS\*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov

Joint Institute of Nuclear Research, Moscow, U. S. S. R.

(Received April 20, 1961)

**1961**

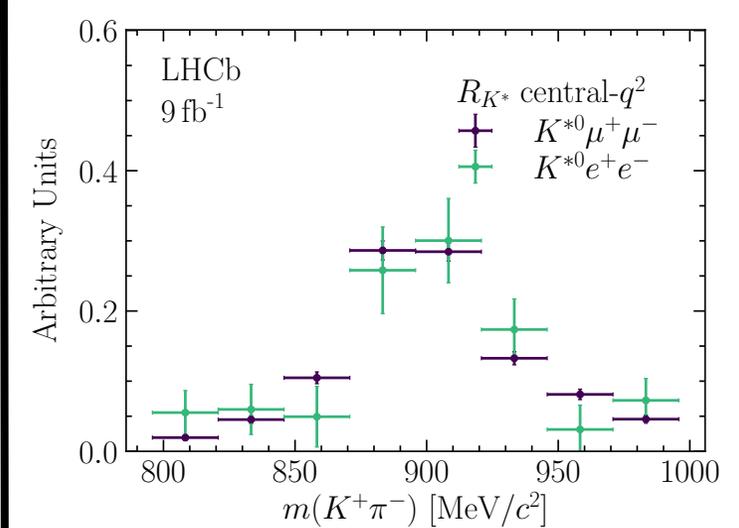
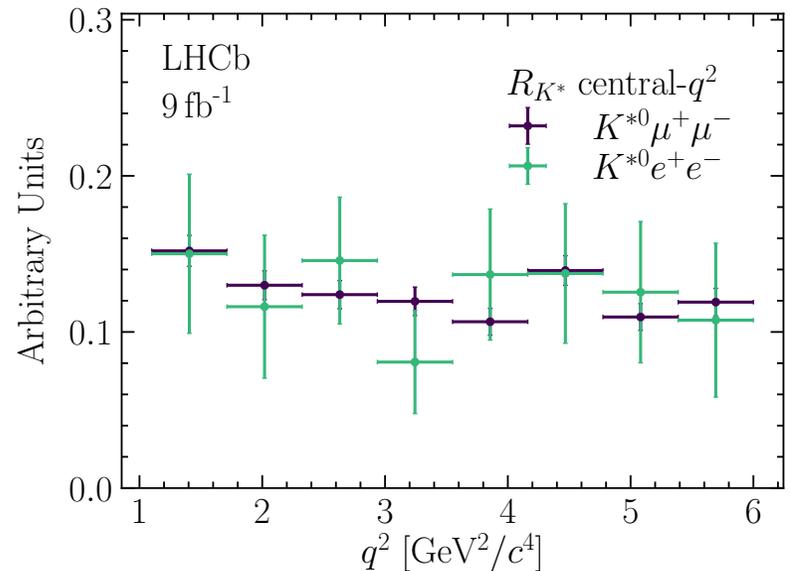
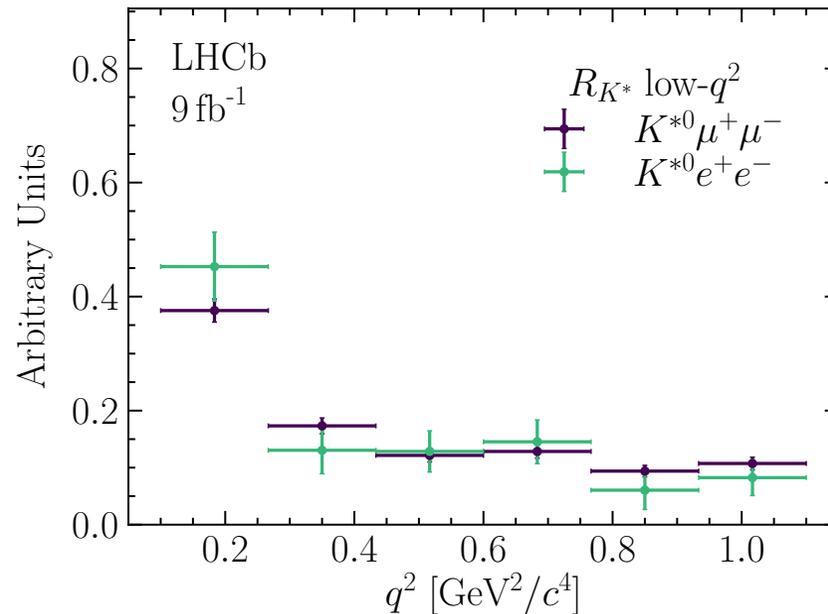
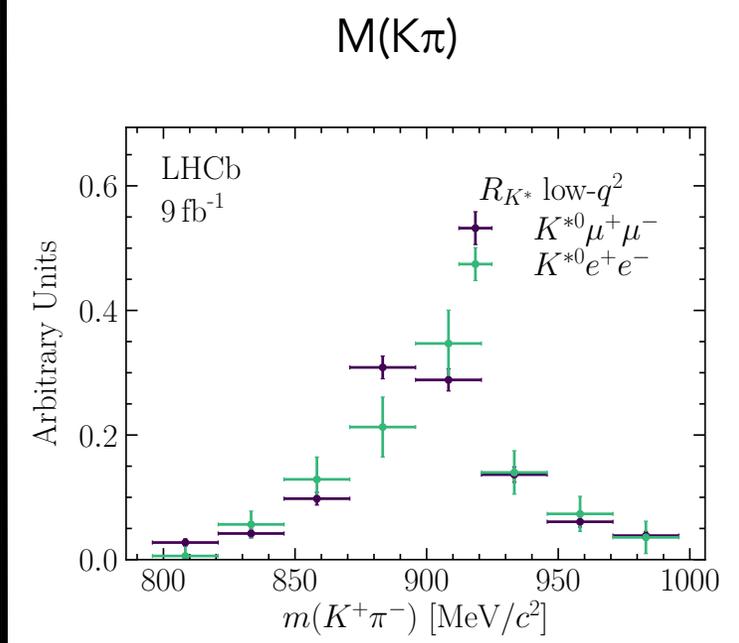
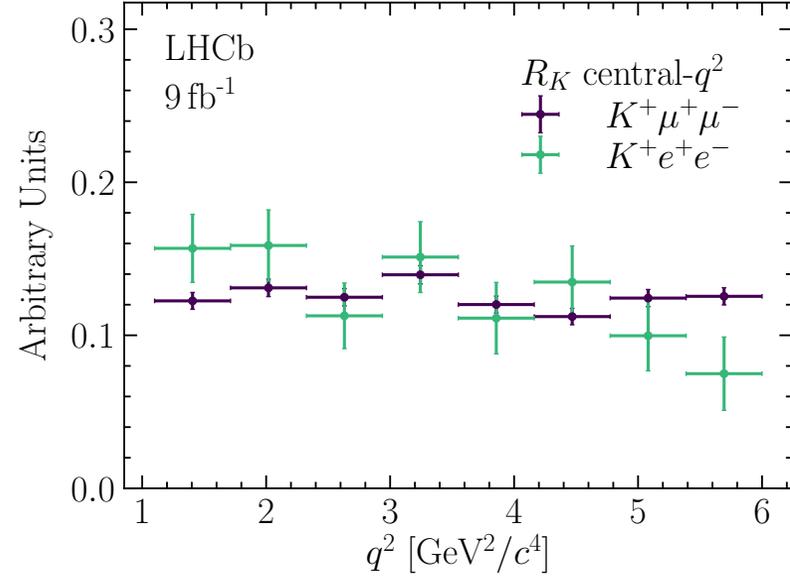
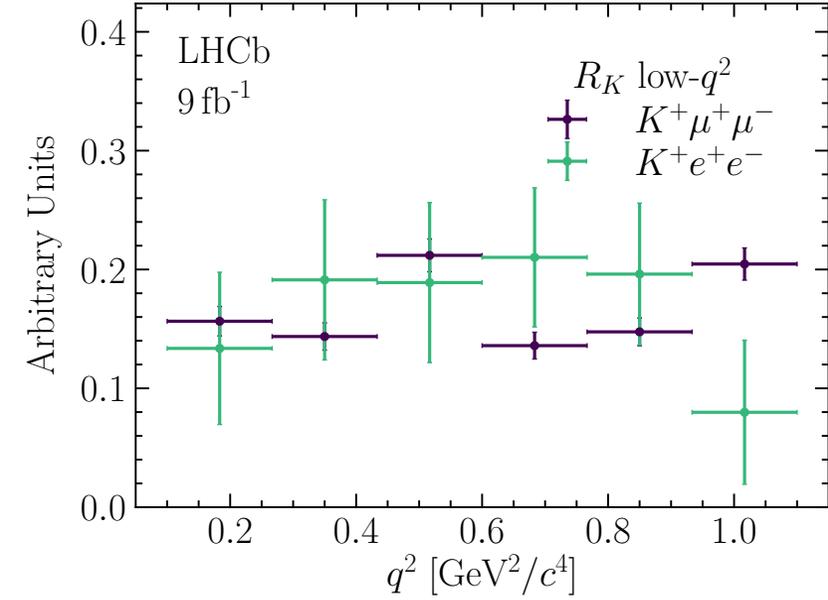
Combining our data with those obtained in reference 7, we set an upper limit of 0.3% for the relative probability of the decay  $K_2^0 \rightarrow \pi^- + \pi^+$ . Our results on the charge ratio and the degree of the  $2\pi$ -decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in  $K^0$  decay.

Experiment stopped by funding agencies

In 1964 CP violation discovery:  
 $(2.0 \pm 0.4) 10^{-3}$

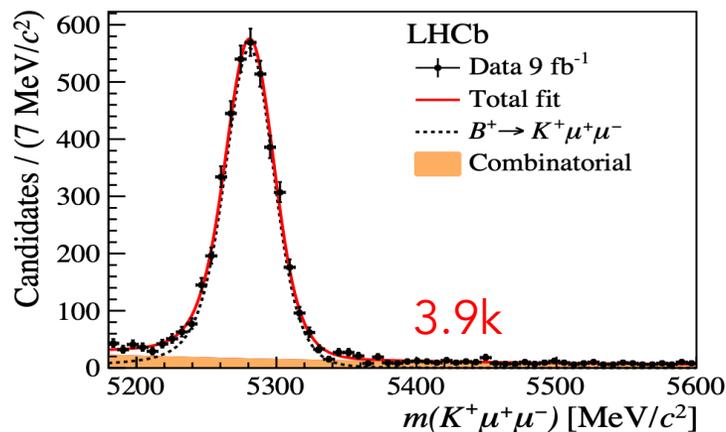
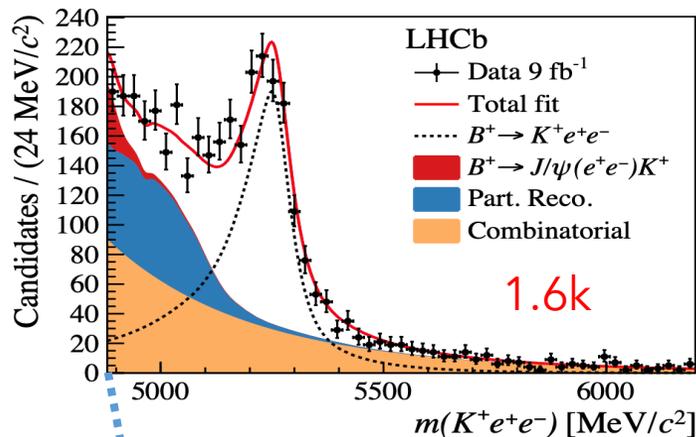
# Back-up slides

# Background subtracted distributions (using sPlots)



# Comparison with previous measurement

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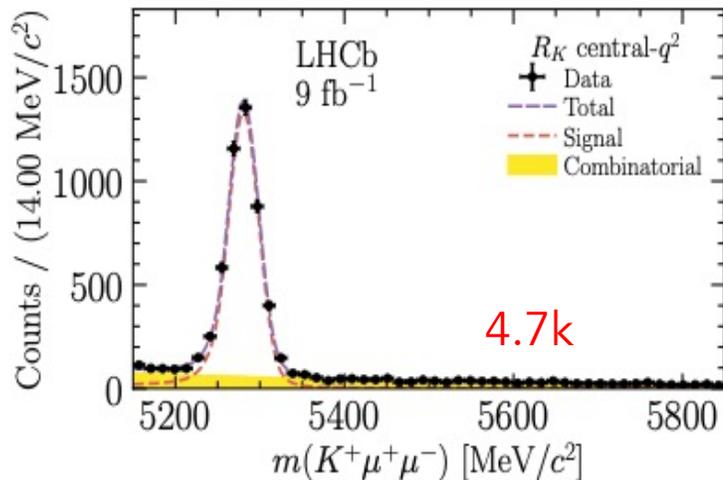
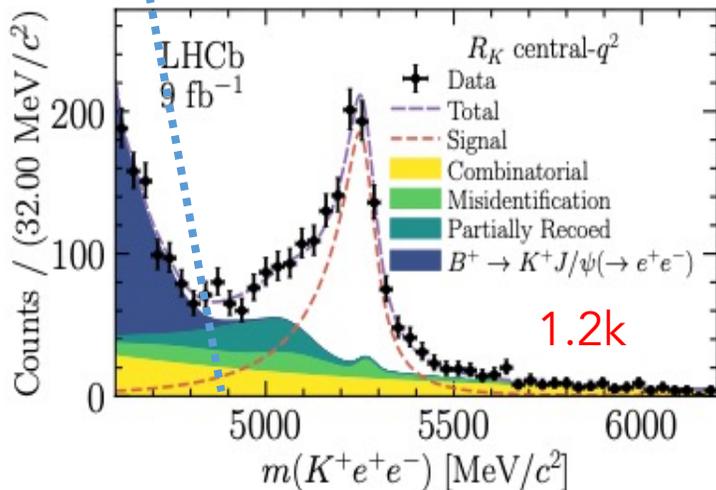
$$R_K = 0.846^{+0.044}_{-0.041}$$

Different selection :  $\pm 0.033$  statistical scattering allowed

Shift due to contamination at looser working point: + 0.064

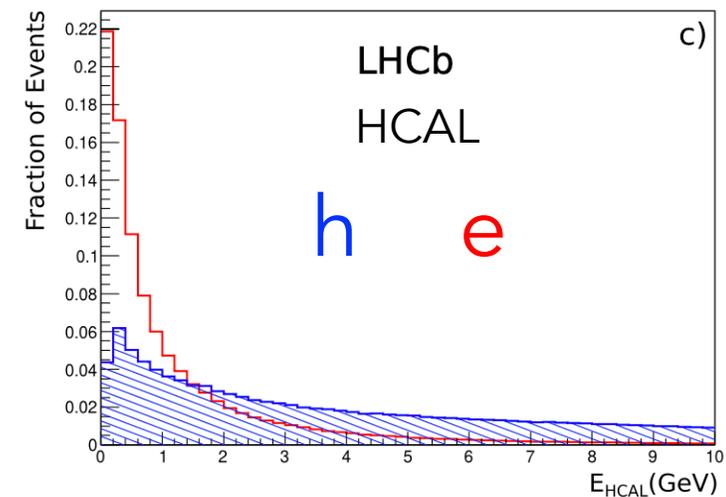
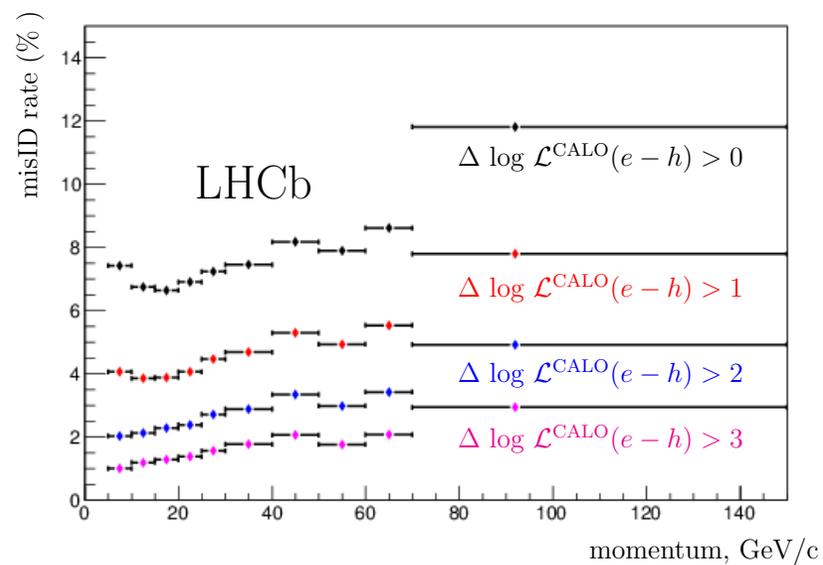
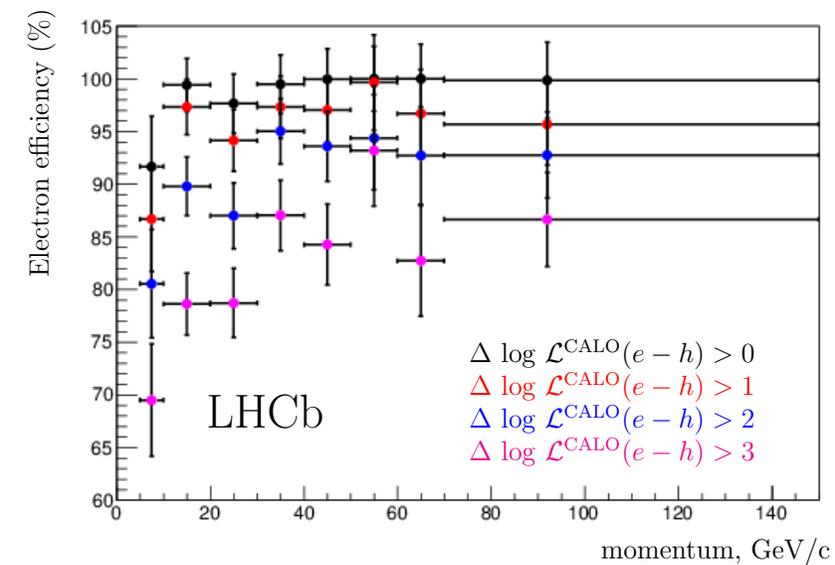
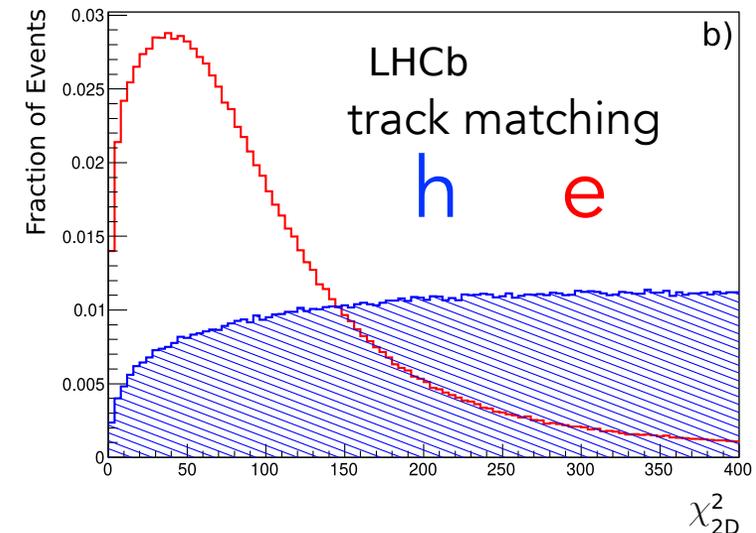
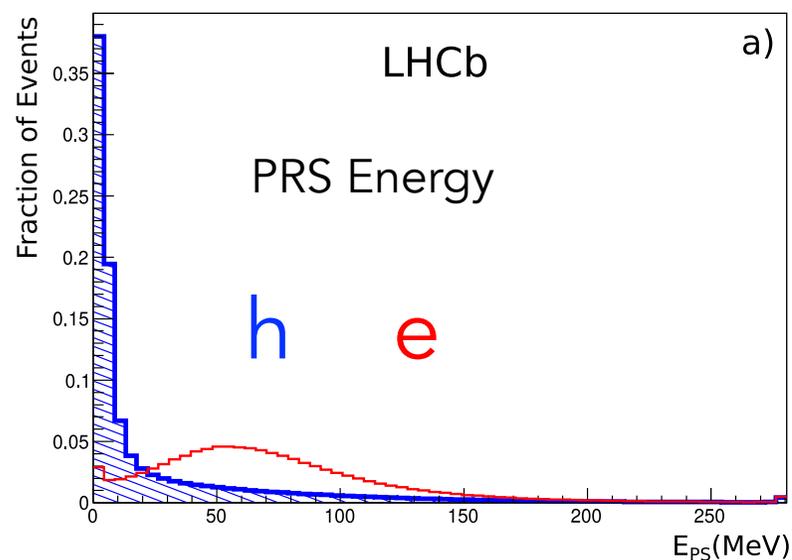
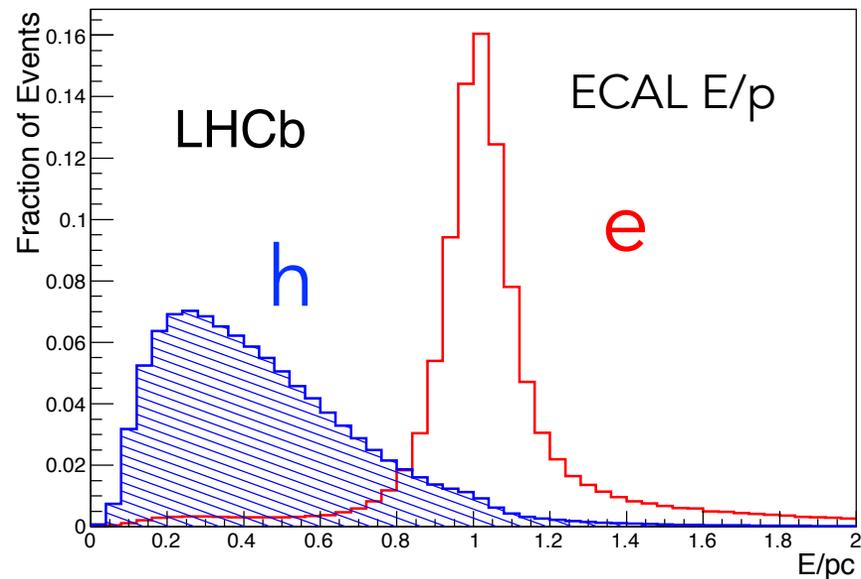
Shift due to non inclusion of the misID backgrounds in the fit: + 0.038

adds linearly



$$R_K = 0.949^{+0.042}_{-0.041} \text{ (stat)}^{+0.022}_{-0.022} \text{ (syst)}$$

# Calorimeter information

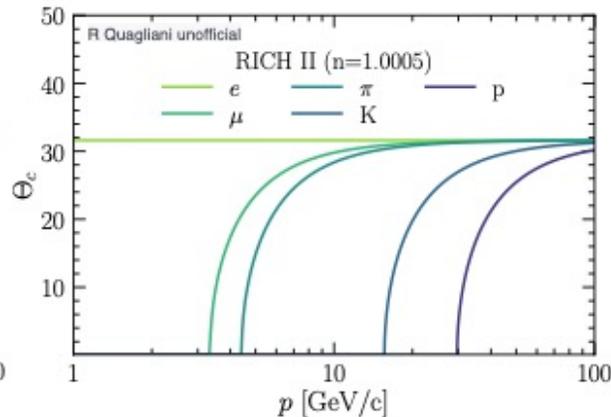
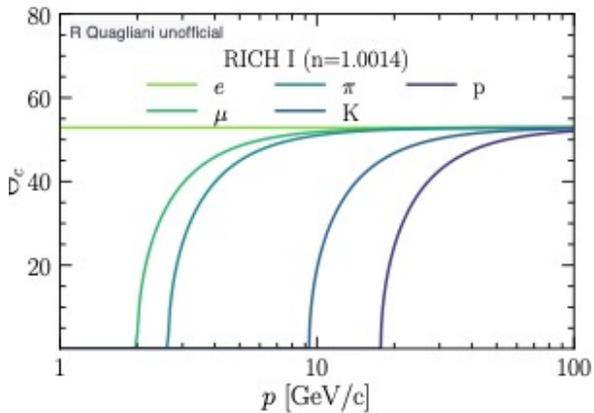
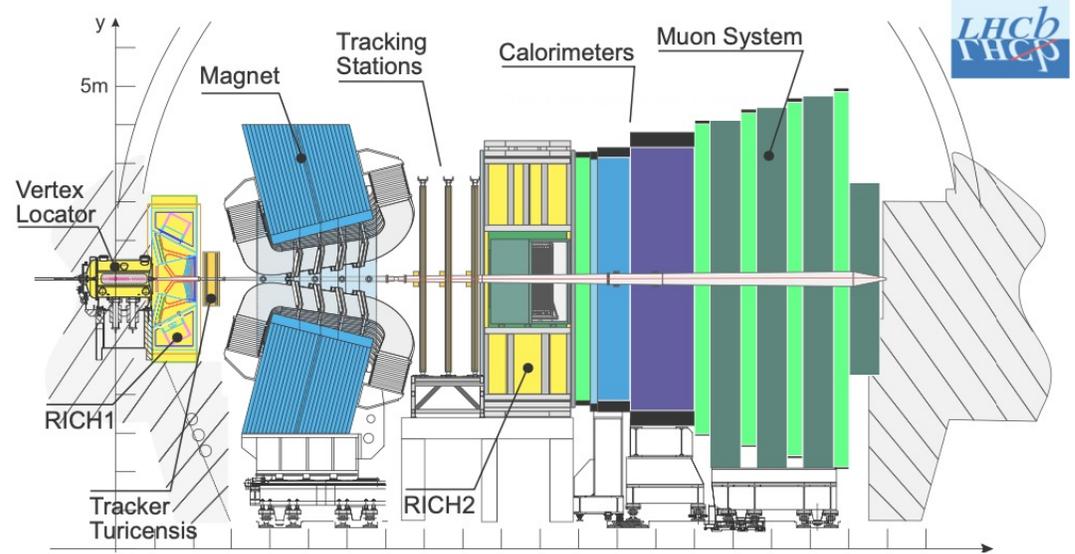
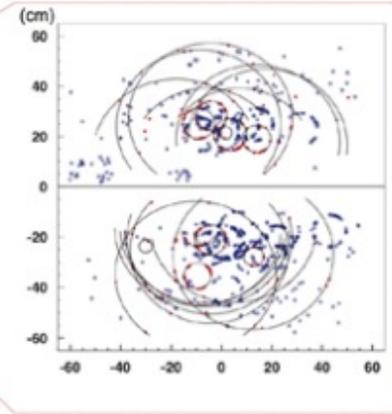
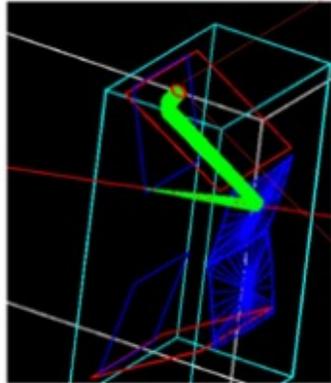


# But also the RICH information !

From RICH I (upstream) and RICH II (downstream) detector

$$m = \frac{p}{c\beta\gamma} \quad \text{from tracking} \quad \cos\theta_C = \frac{1}{n\beta}$$

Ring Radius



$$\blacklozenge \text{DLL}(e) = \sum_{\text{ECAL,HCAL,RICH,MUON}} \Delta \log \mathcal{L}(e - \pi)$$

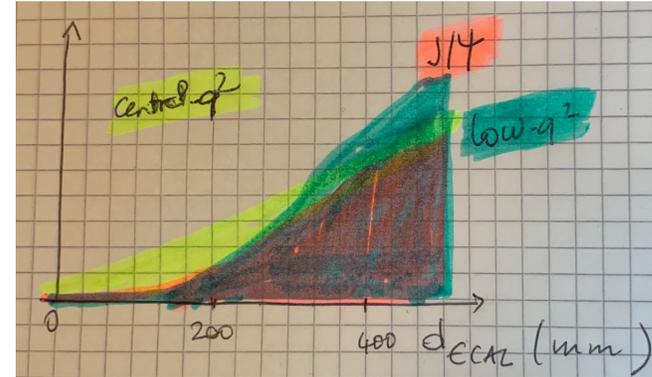
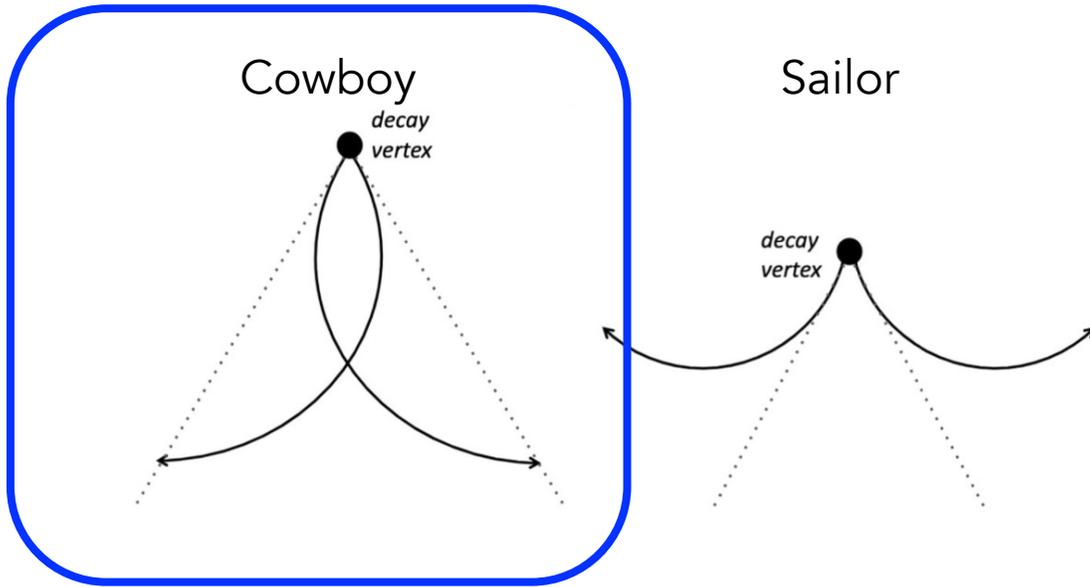
**ProbNNe** = Neural Net using tracking + PID of each detectors: *e/h* separation from simple sub-detectors greatly improved.

Clusters overlap: depends on di-lepton opening angle and momenta

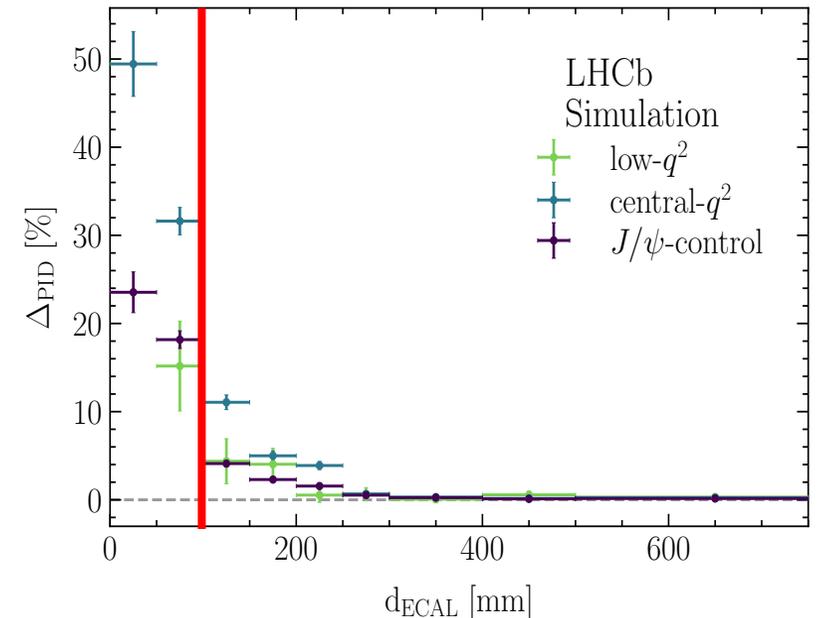
⇒ the effect depends on  $q^2$

It has impact on electron PID and the  $J/\psi$  control region has a different behaviour from the central- $q^2$  one

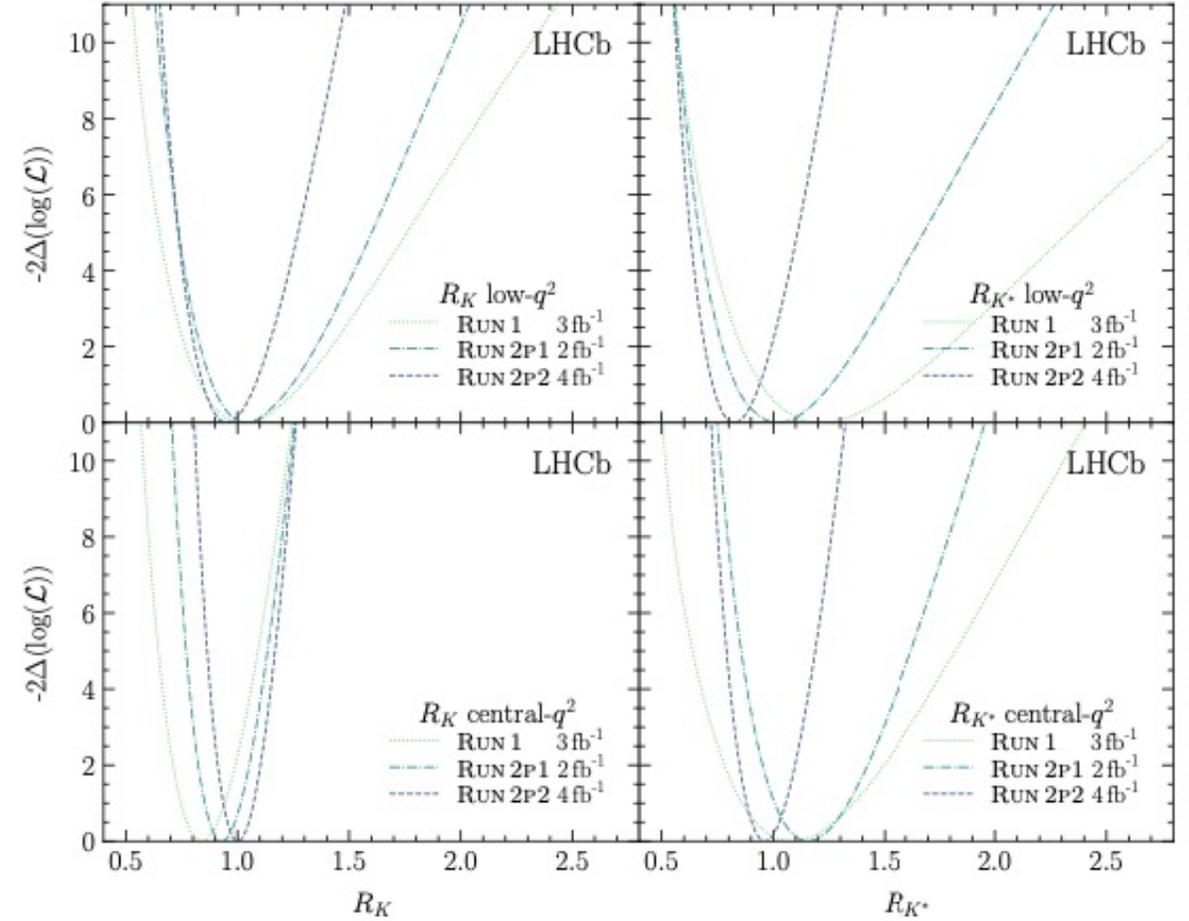
⇒ additional **cut** (few % signal loss only in central- $q^2$ )

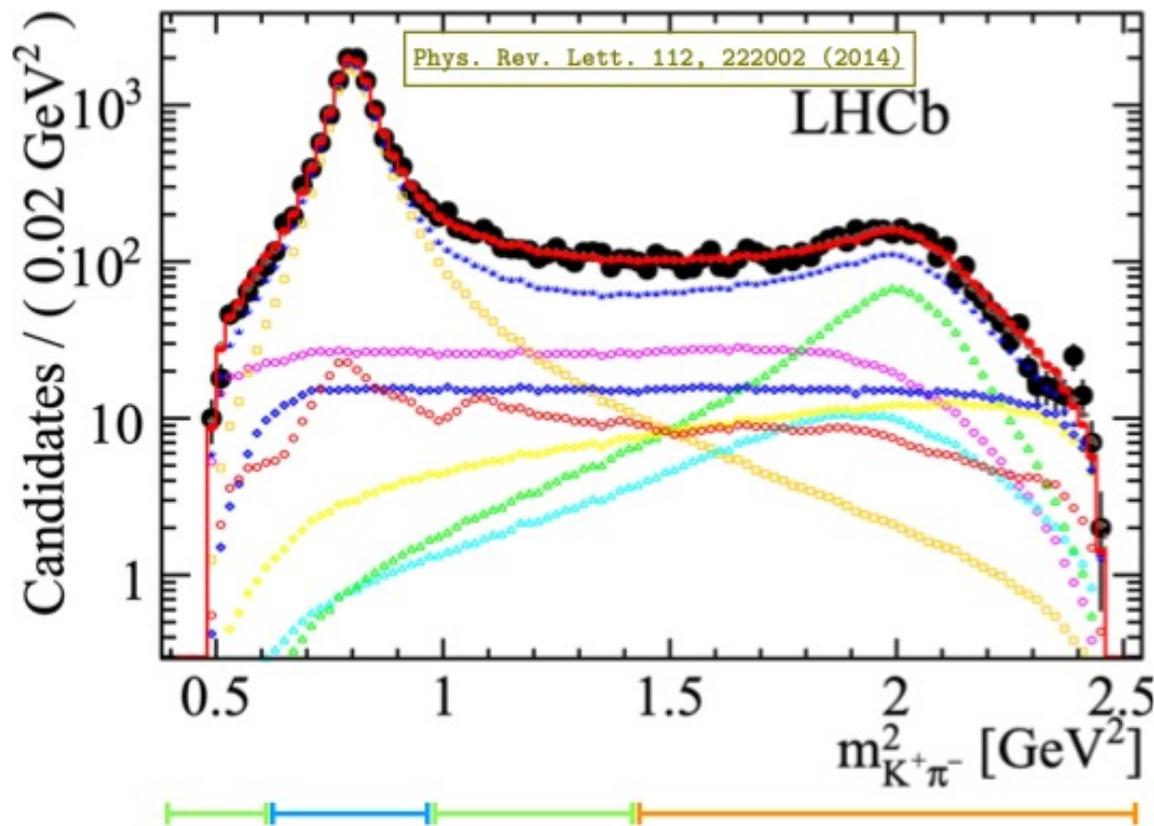
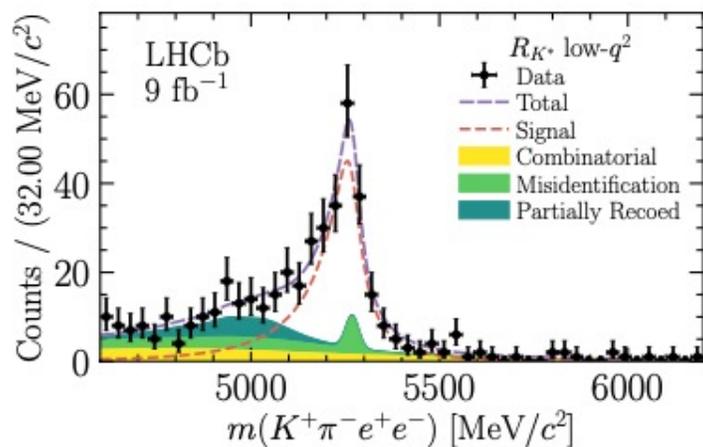
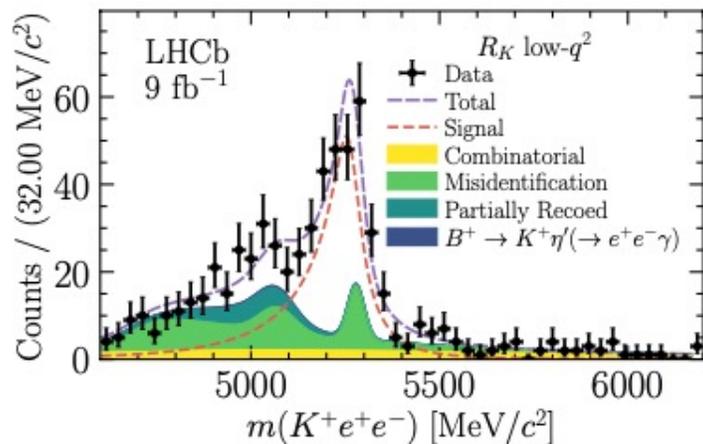


Calorimeter cell sizes: from 4x4 cm<sup>2</sup> to 12x12 cm<sup>2</sup>



LU observable	RUN 1	RUN 2P1	RUN 2P2
$R_K$ low- $q^2$	1.027 $^{+0.243+0.092}_{-0.180-0.073}$	1.039 $^{+0.203+0.027}_{-0.149-0.027}$	0.953 $^{+0.123+0.029}_{-0.104-0.026}$
$R_{K^*}$ low- $q^2$	1.212 $^{+0.344+0.149}_{-0.240-0.114}$	1.021 $^{+0.234+0.036}_{-0.187-0.027}$	0.825 $^{+0.108+0.036}_{-0.091-0.031}$
$R_K$ central- $q^2$	0.839 $^{+0.083+0.062}_{-0.073-0.056}$	0.929 $^{+0.082+0.023}_{-0.073-0.020}$	1.001 $^{+0.066+0.024}_{-0.061-0.022}$
$R_{K^*}$ central- $q^2$	1.082 $^{+0.214+0.176}_{-0.165-0.148}$	1.154 $^{+0.179+0.027}_{-0.147-0.023}$	0.962 $^{+0.091+0.020}_{-0.080-0.018}$
	2011 + 2012 3 fb $^{-1}$	2015 + 2016 2 fb $^{-1}$	2017 + 2018 4 fb $^{-1}$





$K^*$   
 $S$ -wave  
 $K^*(1410)$   
 $K^*(1680)$   
 $K_2^*(1430)$   
 bkg

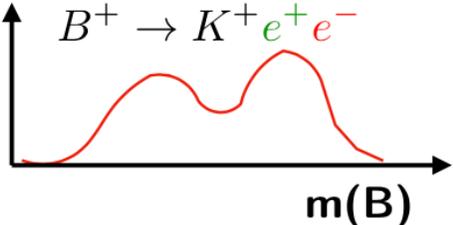
— Directly from  $K^{*0} e^+ e^-$

— Use  $F_S$  measurement in [JHEP 11 \(2016\) 047](#) and Breit-Wigner tails

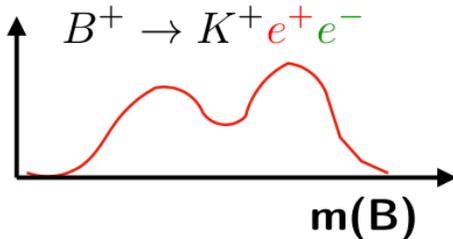
— Extrapolation factors / full amplitude from  $K^* J/\psi$  [Phys. Rev. Lett. 112, 222002 \(2014\)](#)  
 $K^+ \pi^0$  accounting for isospin factors and  $\epsilon$  corrections

# Data-driven approach: Pass-Fail method

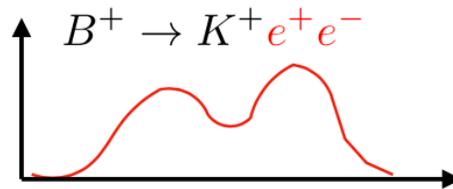
**PassFail (PF)**



**FailPass (FP)**

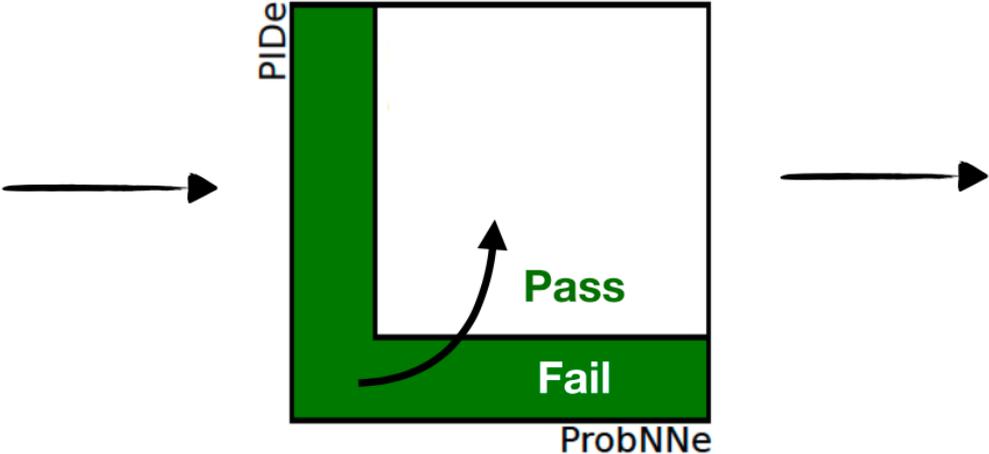


**FailFail (FF)**

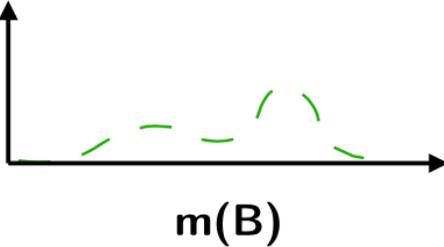


**Transfer Function**  
(From PIDCalib  $\pi/K$  samples)

$$w_{fake}(e) = \frac{\epsilon_{pass}}{\epsilon_{fail}}$$



**PassPass**

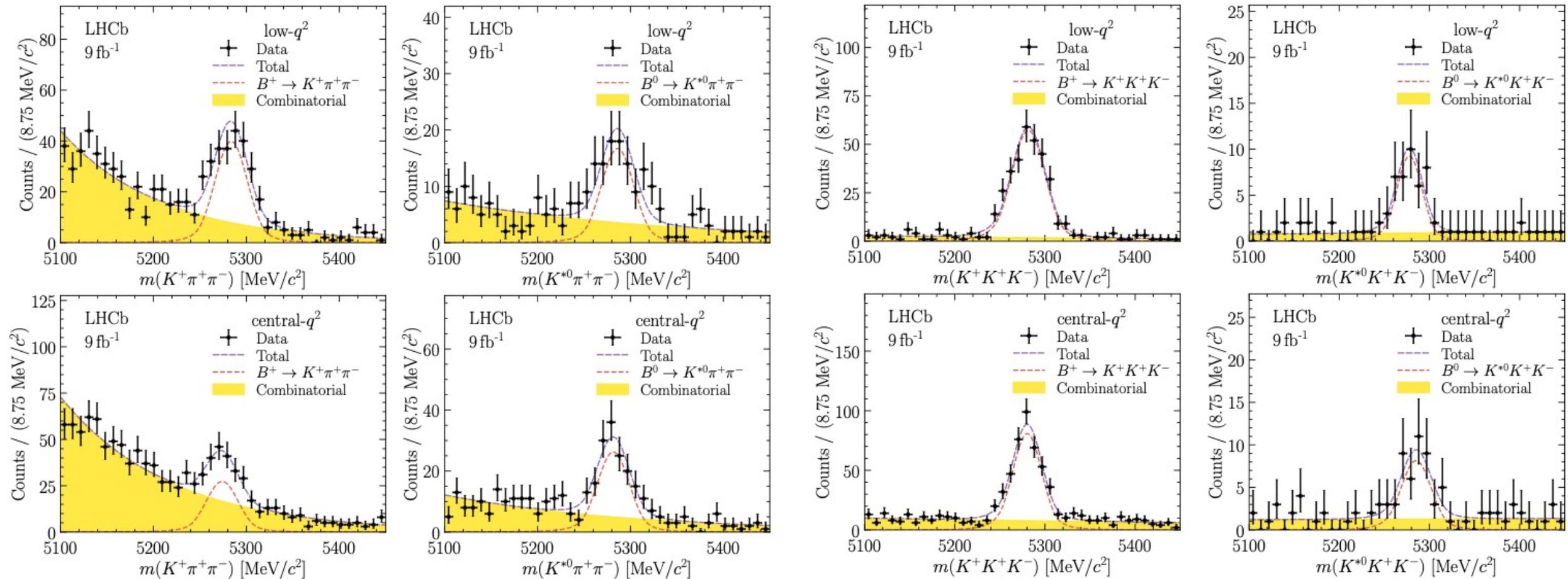


Prediction + Shape

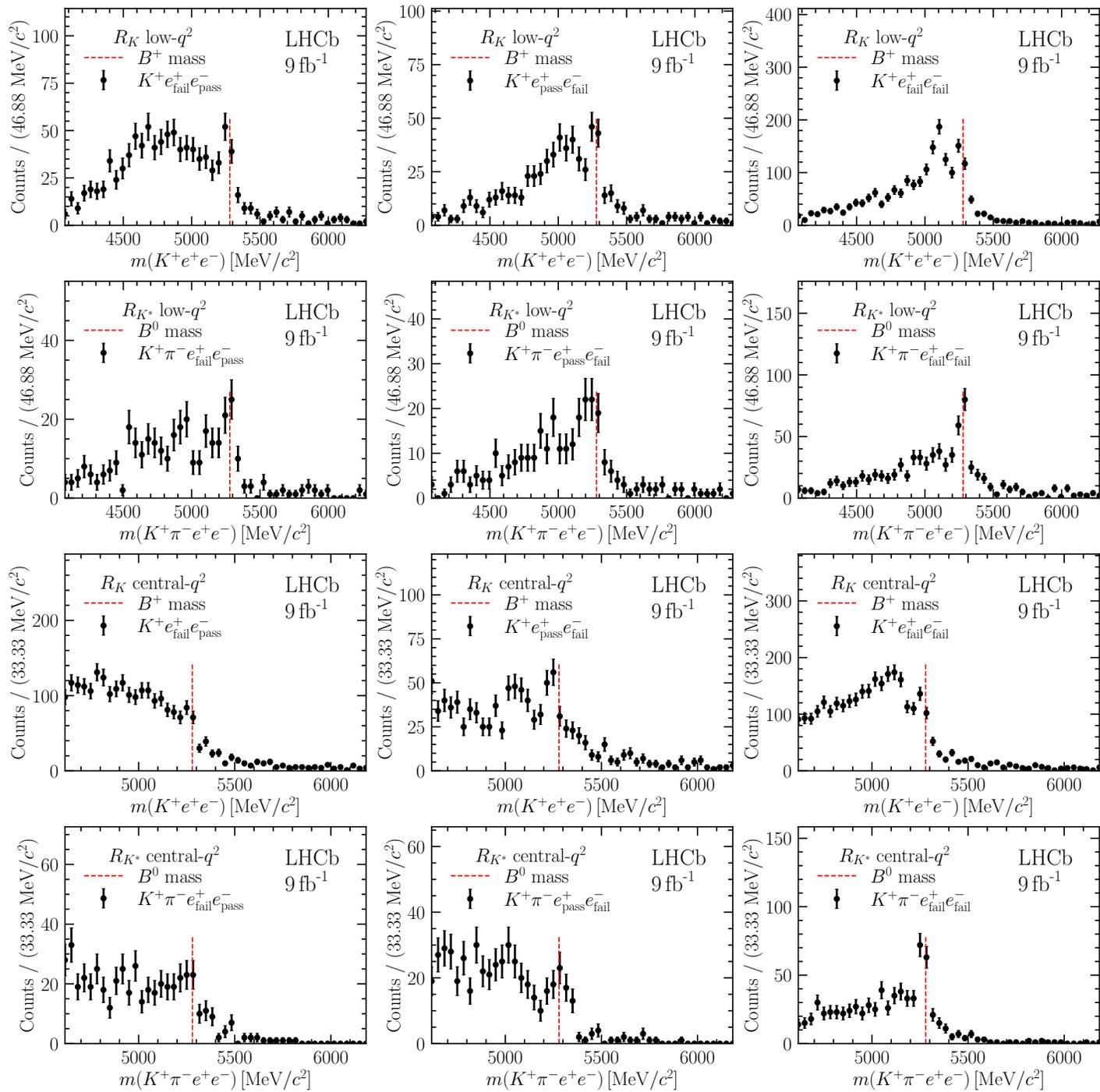
[R. Quagliani]

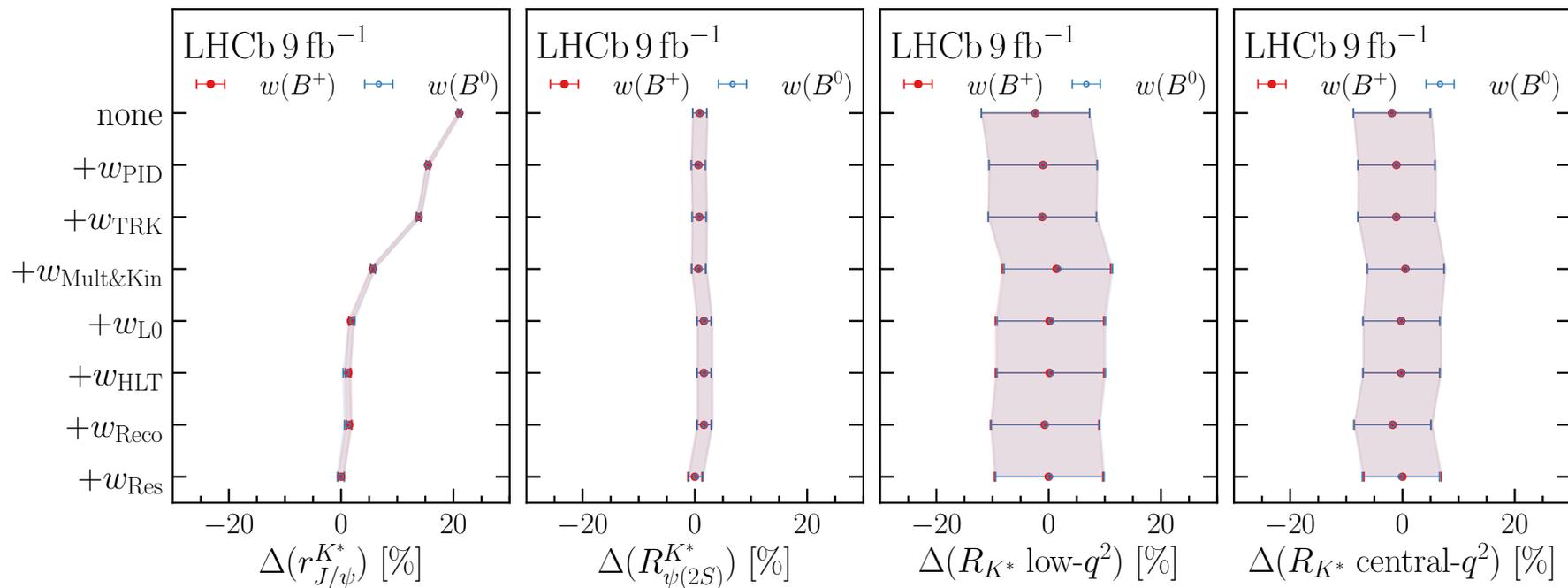
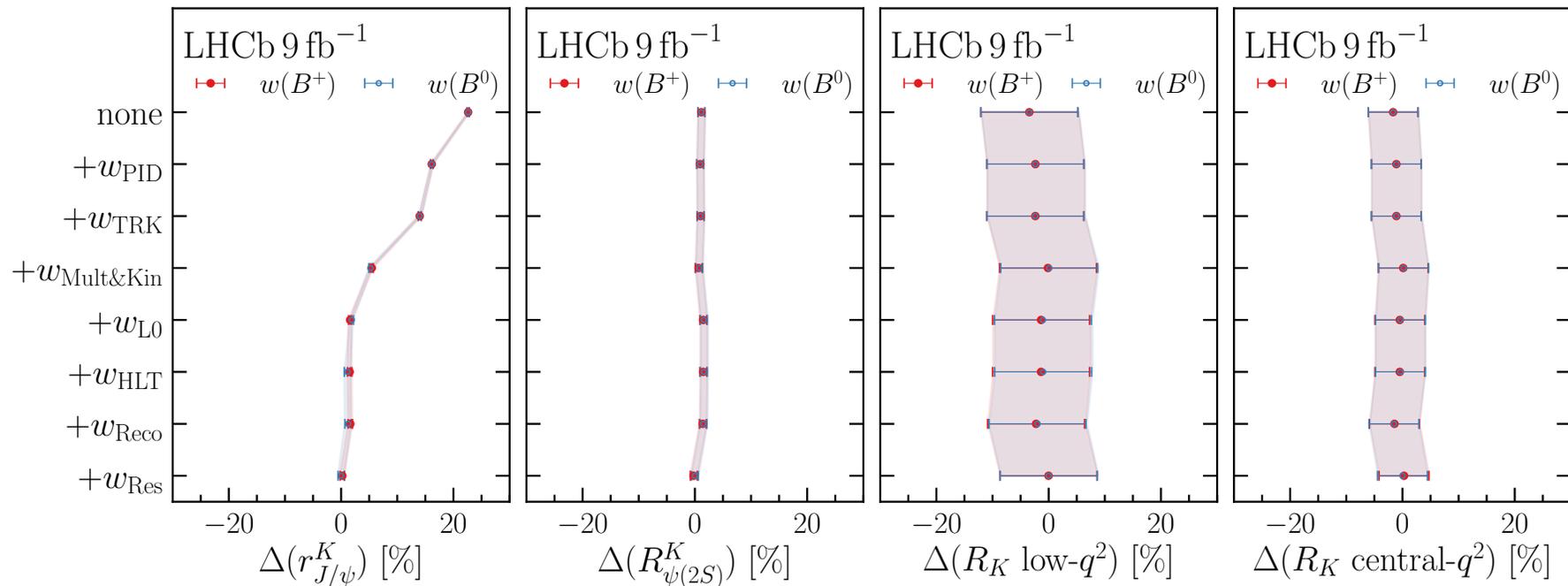
◆ Simple backgrounds from double-misidentification can be isolated inverting PID criteria

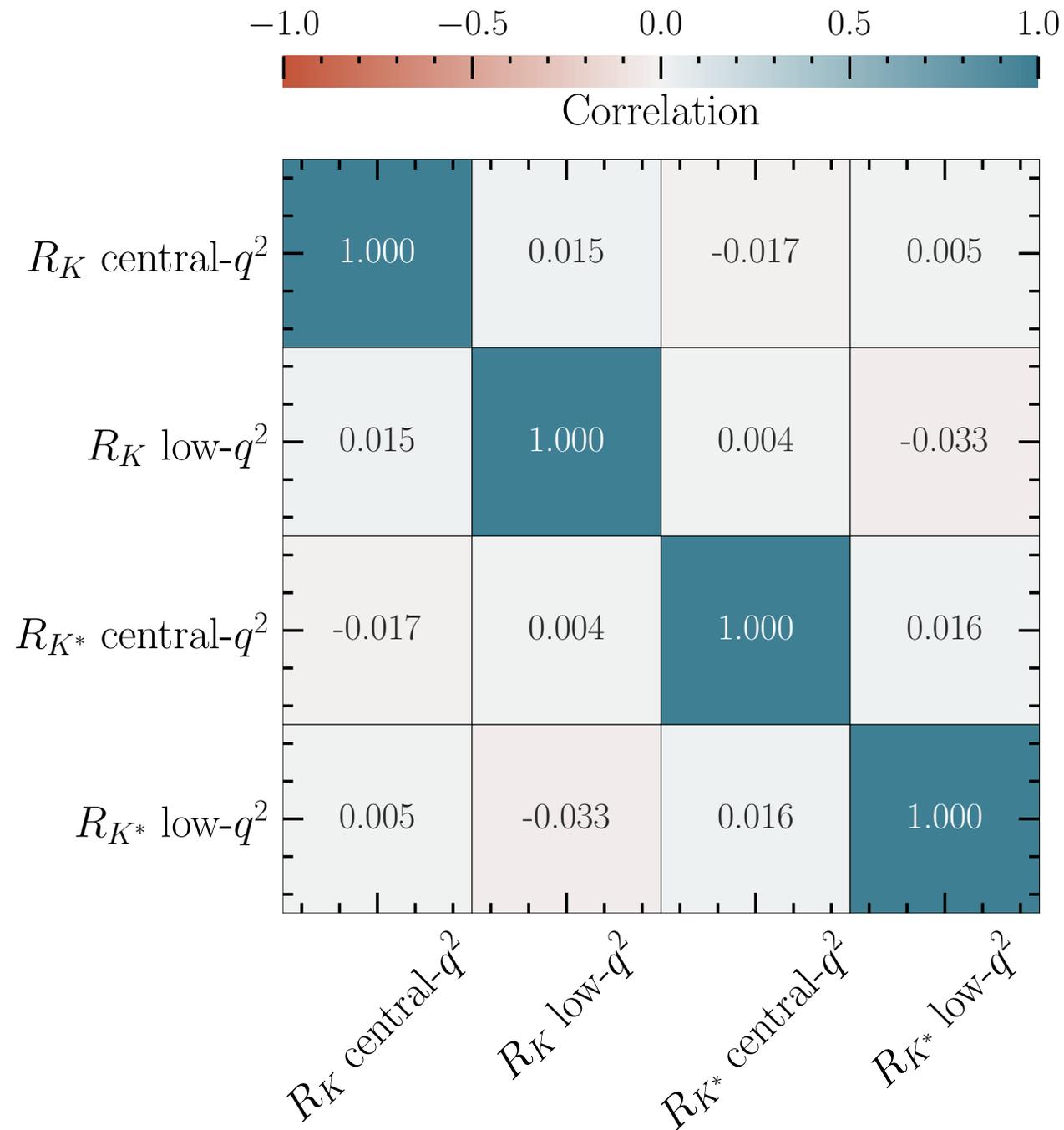
(close to nominal selection) after full selection (i.e  $K^{+,*0}h^+h^-$ ) on electron mode



The rate for misidentifying two hadrons as electrons in the nominal dataset  
 $\sim 2\%$  of that in the control dataset







# Rare decay $b \rightarrow s$

dipole (e.m. penguin)

$\mathcal{O}_7^{(\prime)}$  =

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

V-A (EW penguin)

$\mathcal{O}_{9,10}^{(\prime)}$  =

$$\mathcal{O}_9^{(\prime)} = (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \ell)$$

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

scalar, pseudo-scalar

$\mathcal{O}_{S,P}^{(\prime)}$  =

$$\mathcal{O}_S^{(\prime)} = \bar{s} P_{R(L)} b \bar{\ell} \ell$$

$$\mathcal{O}_P^{(\prime)} = \bar{s} P_{R(L)} b \bar{\ell} \gamma_5 \ell$$

## Goal(s):

- ▶ Test Left/Right handed components modifiers  $C/C'$
- ▶ Test lepton families dependent modifiers  $C_\ell^{(\prime)}/C_{\ell'}^{(\prime)}$

Coupling	Radiative $b \rightarrow s \gamma$	Leptonic $B \rightarrow \mu \mu$	Semileptonic $b \rightarrow s \ell \ell$
$C_7^{(\prime)}$	✓		✓
$C_9^{(\prime)}$			✓
$C_{10}^{(\prime)}$		✓	✓
$C_S^{(\prime)}$		✓	
$C_P^{(\prime)}$		✓	