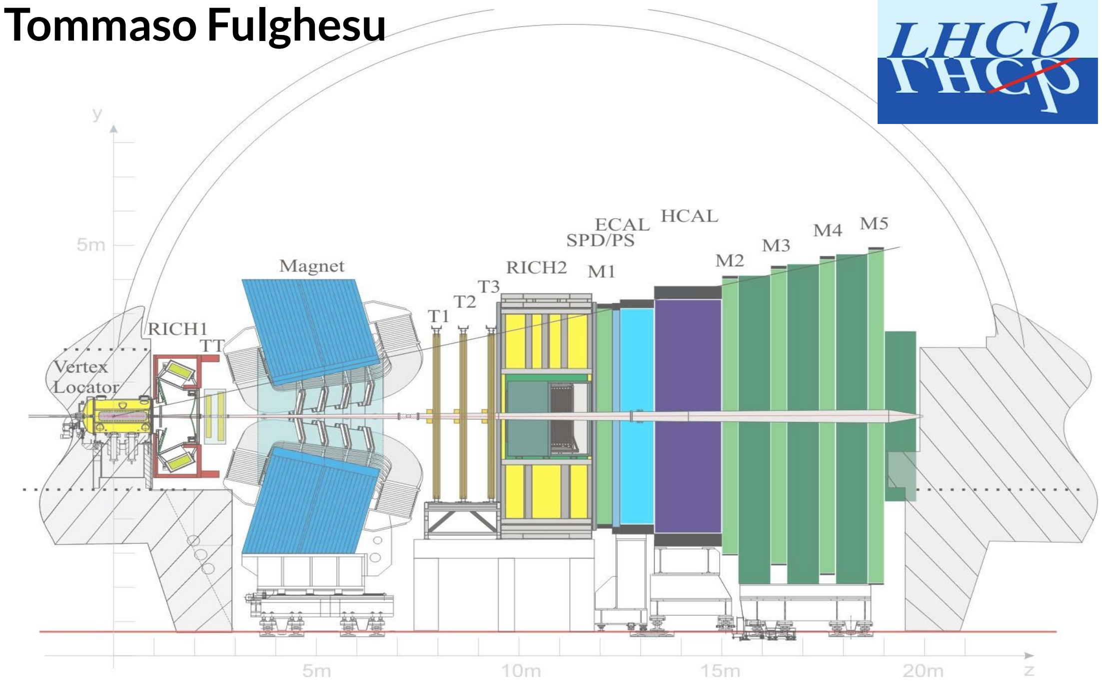
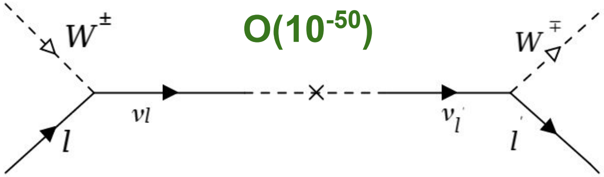
Lepton Flavour Violation Searches in B decays at LHCb

Tommaso Fulghesu

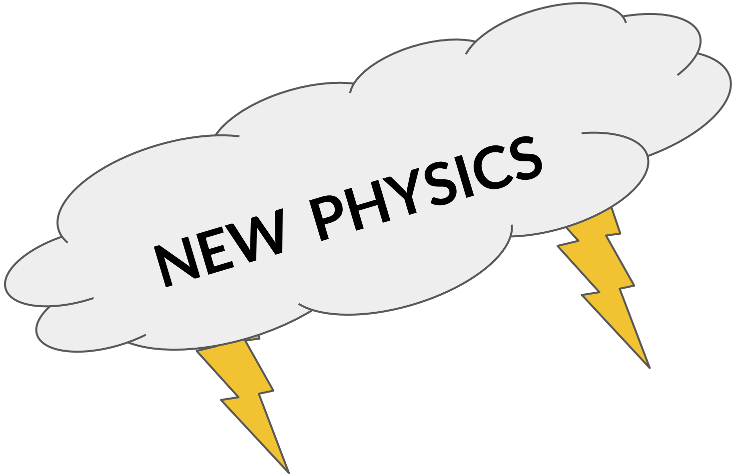


Introduction

- ➜ Standard Model (SM) predicts the lepton universality and the conservation of the lepton flavour.
- ➜ Extending the SM to massive and oscillant neutrinos introduces the possibility of having Flavour Changing Neutral Currents.
- ➜ Charged-lepton flavour violating (cLFV) decays are highly suppressed ($O(10^{-50})$) and their observation will constitute an **unambiguous sign of New Physics** (NP).



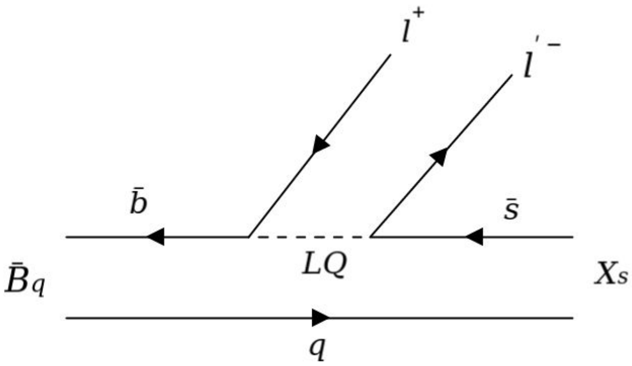
HIGHLY SUPPRESSED



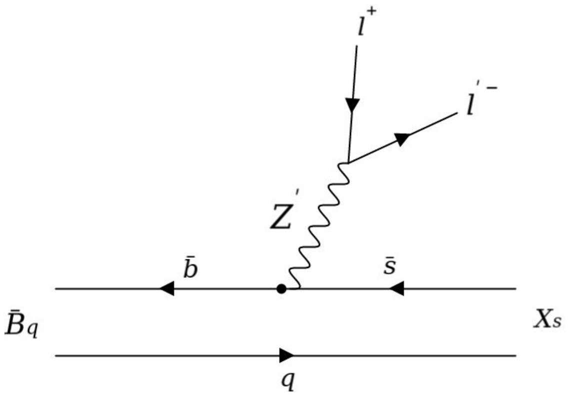
Theoretical models

$$b \to sl^+l'^- \text{ transitions}$$

New Physics scenario with Leptoquark (LQ)



New Physics scenario with Z' mediator



Different interaction strengths, depending on the fermions interacting, are possible

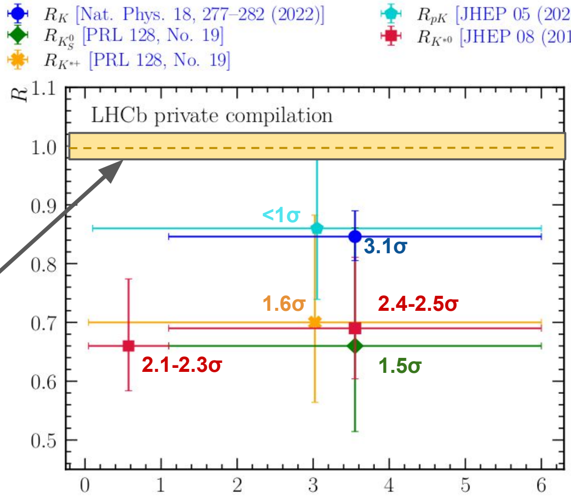
$\to$ interest in studying all possible lepton combination in the final state!

Relation with LFUV

- ➜ LFUV is closely related to LFV
- ➜ Electroweak penguins mediating $b \to sl^+l^-$ transitions showed interesting **tensions with the SM**

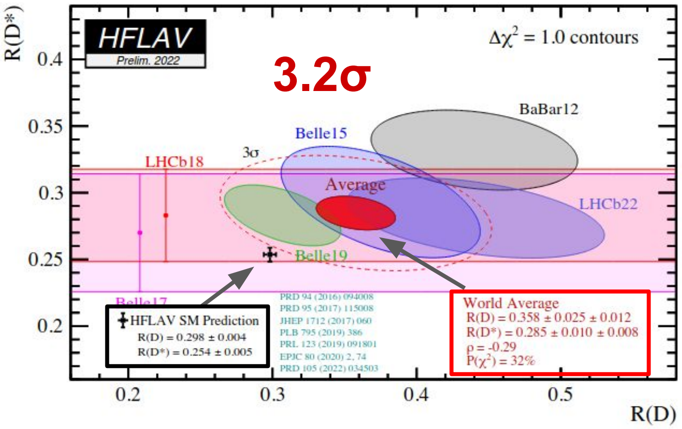
$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{dB(B_q \to X_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{dB(B_q \to X_s e^+ e^-)}{dq^2} dq^2}$$

Predicted from SM:
R = 1 ± *O*(1%)



SOURCE: https://indico.cern.ch/event/1187939/attachments/2530158/4355180/DTaunu_CERNSeminar.pdf

SOURCE: https://arxiv.org/pdf/2207.01851 q^2 [GeV^2/c^4]



- ➜ Also in the $b \to cl^- \bar{\nu}$ decays discrepancies in the lepton-universality ratios were observed

$$R_{D^{(*)}} = \frac{B(\bar{B} \to D^{(*)} \tau^- \bar{\nu})}{B(\bar{B} \to D^{(*)} l^- \bar{\nu})} \quad \text{with} \begin{cases} l = \mu \text{ @ LHCb} \\ l = e/\mu \text{ @ B factories} \end{cases}$$

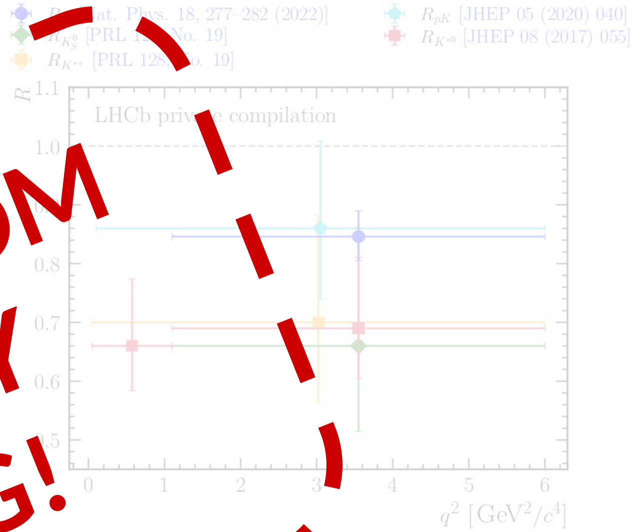
- ➜ Interest from theorists and experimentalists to study and understand these type of **anomalies**

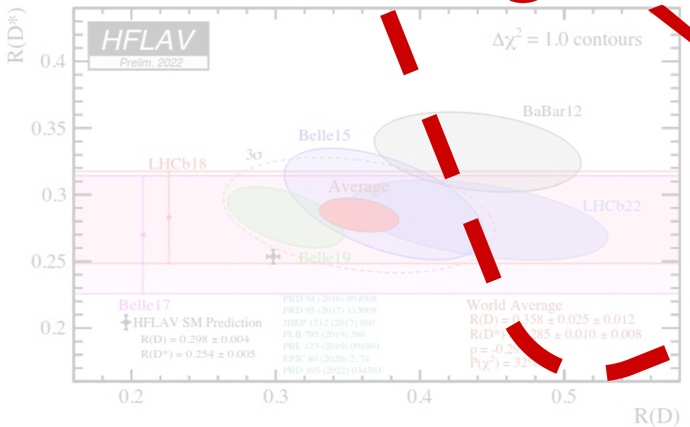
Relation with LFUV

SEE TALKS FROM YESTERDAY MORNING!

- LFUV is closely related to LFV
- Electroweak penguins mediating $b \to s l^+ l^-$ transitions showed interesting **tensions with the SM**

$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{dB(B_q \to X_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{dB(B_q \to X_s e^+ e^-)}{dq^2} dq^2}$$





- Also in the $b \to c l^- \bar{\nu}$ decays discrepancies in the lepton-universality ratios were observed

$$R_{D^{(*)}} = \frac{B(\bar{B} \to D^{(*)} \tau^- \bar{\nu})}{B(\bar{B} \to D^{(*)} l^- \bar{\nu})} \quad \text{with} \begin{cases} l = \mu \text{ @ LHCb} \\ l = e/\mu \text{ @ B factories} \end{cases}$$

- Interest from theorists and experimentalists to study and understand these type of **anomalies**

Latest results @ LHCb

- ➜ LHCb searches for LFV in B decays include final state with $\boldsymbol{e}$ and $\boldsymbol{\mu}$ or with $\boldsymbol{\tau}$ and $\boldsymbol{\mu}$
- ➜ **No signal** observed so far in any search
- ➜ **Upper limits** set using CLs method, constraining theories beyond the SM

Decay	Limit (90% C.L.)	Integrated luminosity
$B^0 \to e\mu$	$1.0 \cdot 10^{-9}$	3 fb^{-1}
$B_s \to e\mu$	$5.4 \cdot 10^{-9}$	3 fb^{-1}
$B^+ \to K^+ e^+ \mu^-$	$7.0 \cdot 10^{-9}$	3 fb^{-1}
$B^+ \to K^+ e^- \mu^+$	$6.4 \cdot 10^{-9}$	3 fb^{-1}
$B^0 \to K^{*0} e^\mp \mu^\pm$	$9.9 \cdot 10^{-9}$	9 fb^{-1}
$B^0 \to K^{*0} e^+ \mu^-$	$6.7 \cdot 10^{-9}$	9 fb^{-1}
$B^0 \to K^{*0} e^- \mu^+$	$5.7 \cdot 10^{-9}$	9 fb^{-1}
$B_s \to \phi e^\mp \mu^\pm$	$1.6 \cdot 10^{-8}$	9 fb^{-1}
$B^0 \to \tau\mu$	$1.2 \cdot 10^{-5}$	3 fb^{-1}
$B_s \to \tau\mu$	$3.4 \cdot 10^{-5}$	3 fb^{-1}
$B^+ \to K^+ \tau\mu$	$3.9 \cdot 10^{-5}$	9 fb^{-1}
$B^0 \to K^{*0} \tau^+ \mu^-$	$1.0 \cdot 10^{-5}$	9 fb^{-1}
$B^0 \to K^{*0} \tau^- \mu^+$	$8.2 \cdot 10^{-6}$	9 fb^{-1}

NEW! [marks the $B^0 \to K^{*0} e\mu$ and $B_s \to \phi e\mu$ rows]

NEW! [marks the $B^0 \to K^{*0} \tau\mu$ rows]

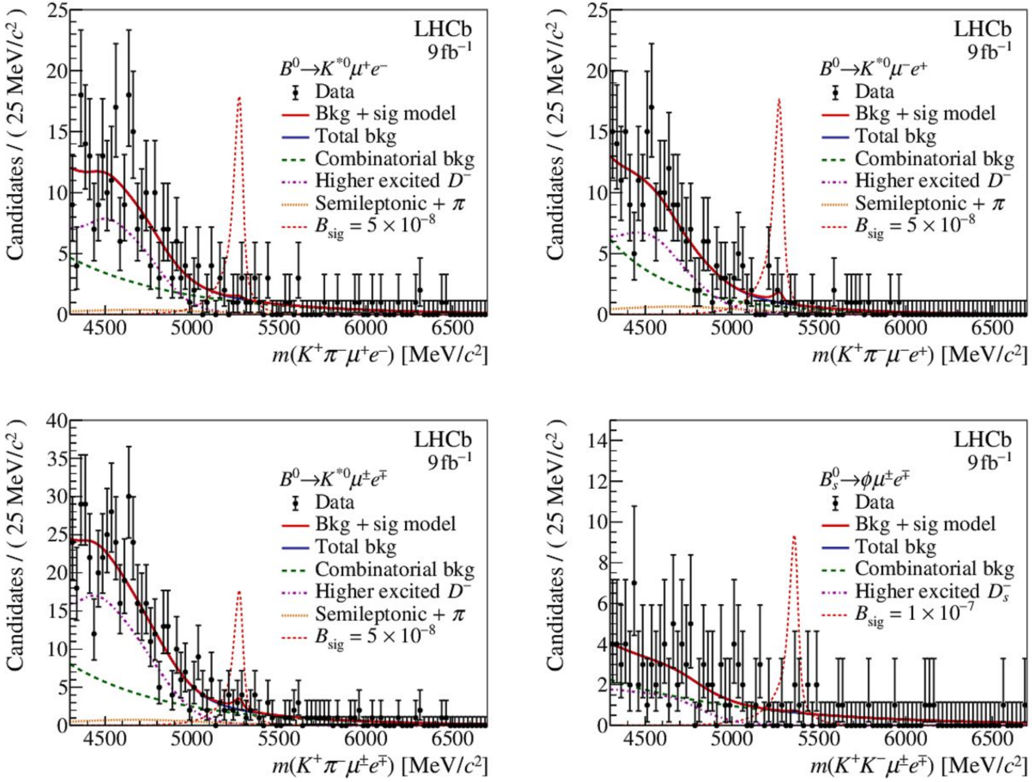
RECENT RESULTS:

Search for lepton flavour violating decays $B^0_s \to K^{*0}\mu^\pm e^\mp$ and $B^0_s \to \phi\mu^\pm e^\mp$ submitted on Arxiv on 08/06/2022

Search for lepton flavour violating decays $B^0 \to K^{*0}\tau^\pm\mu^\mp$ submitted on Arxiv on 20/09/2022

Searches for B→K*eμ and B_s→ϕeμ: Fit

https://arxiv.org/abs/2207.04005

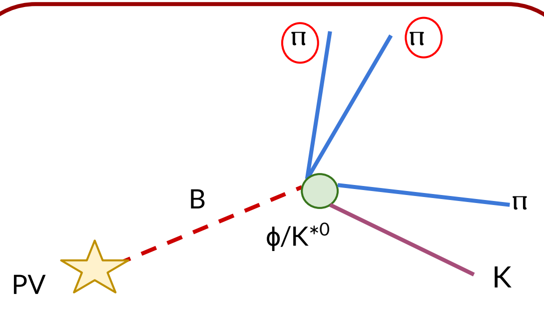


Fit on data of invariant mass distributions

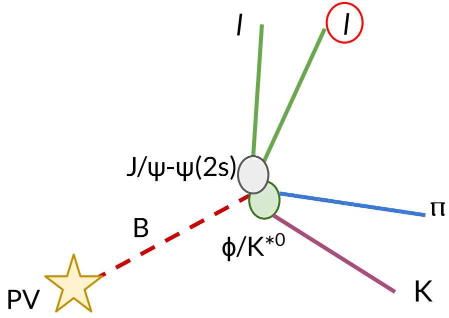
- ➜ Run 1 + Run 2 datasets ($9fb^{-1}$)
- ➜ First result ever for $B^0_s \to \phi\mu^{\pm}e^{\mp}$
- ➜ Using $B \to K^{*0}J/\psi(\to\mu^+\mu^-)$ and $B_s \to \phi J/\psi(\to\mu^+\mu^-)$ as normalization samples
- ➜ *Kμ* charge combinations treated separately

Searches for B→K*eμ and B_s→φeμ: Background examples

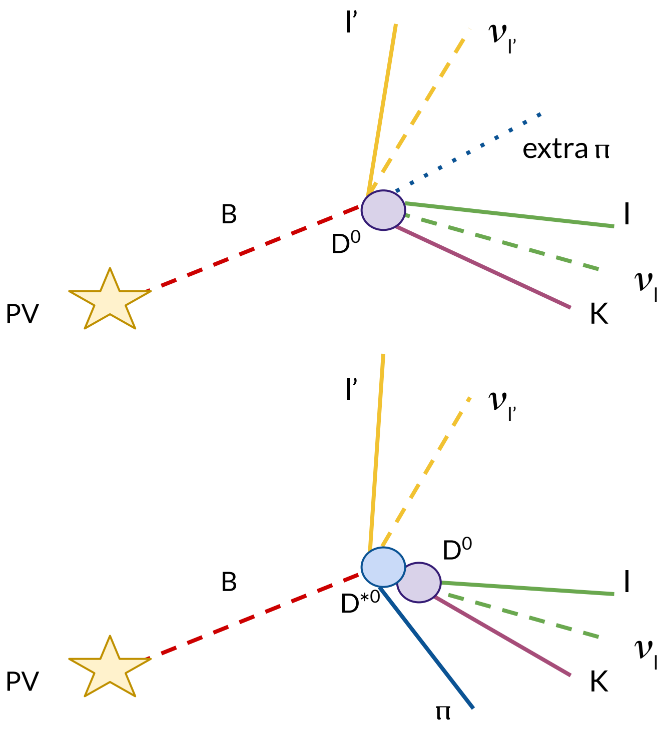
https://arxiv.org/abs/2207.04005



Double mis-ID $B^0_{(s)} \to K^{*0}(\phi)\, \pi^{\pm}\pi^{\mp}$



Lepton mis-ID $B^0_{(s)} \to K^{*0}(\phi)\, J/\psi$ or $B^0_{(s)} \to K^{*0}(\phi)\, \psi(2s)$



$b \to c l \nu_l$ cascades with same final states as signal

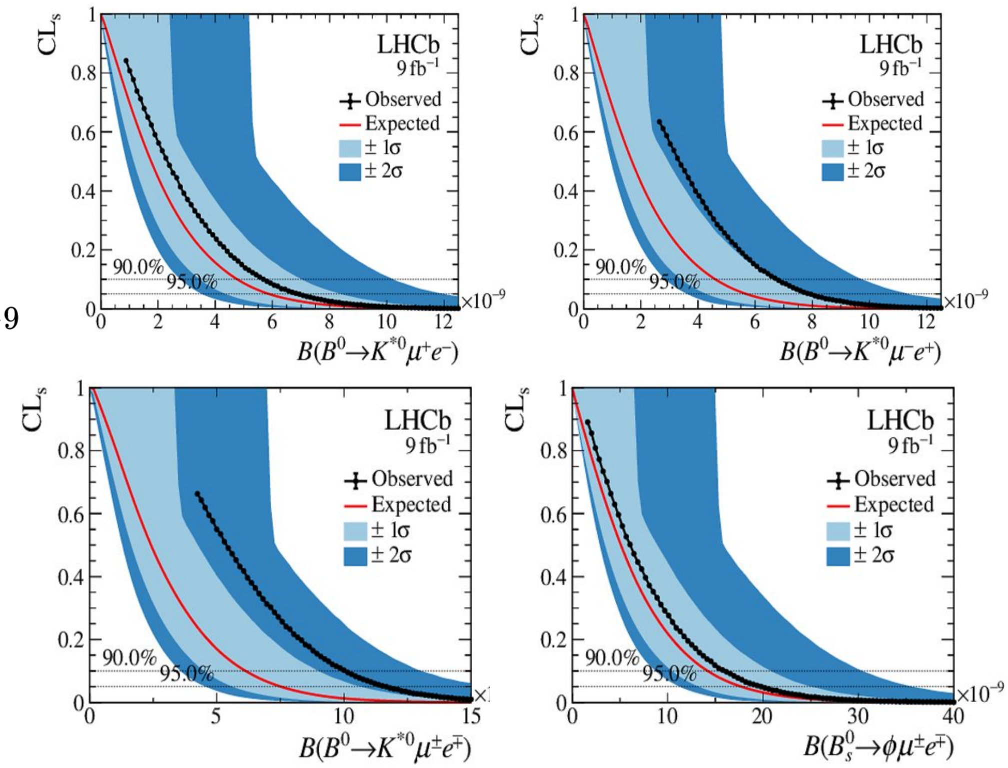
Searches for B→K*eμ and B_s→ϕeμ: Results

https://arxiv.org/abs/2207.04005

- **No significant signal observed**
- Upper limits at 90 (95)% CL

$$\mathcal{B}(B^0 \to K^{\star 0} e^+ \mu^-) < 6.8(7.9) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{\star 0} e^- \mu^+) < 5.7(6.9) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{\star 0} e^\pm \mu^\mp) < 10.1(11.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \phi e^\pm \mu^\mp) < 16.9(19.8) \times 10^{-9}$$

MOST STRINGENT LIMITS



Searches for $B \to K^* e\mu$ and $B_s \to \phi e\mu$: NP models

https://arxiv.org/abs/2207.04005

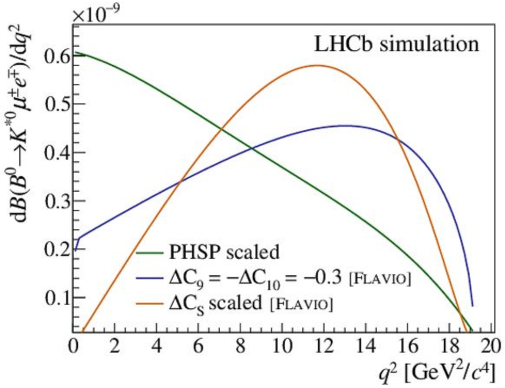
- Limit set assuming **uniform phase space**
- Distributions differs significantly in NP models

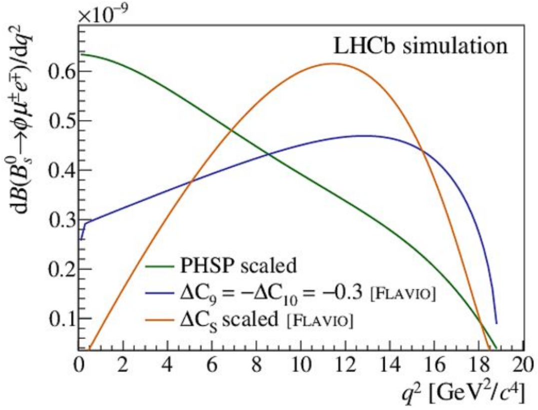
Scalar model $C_9^{\mu e} \neq 0$

$$B(B^0 \to K^{*0} e^+ \mu^-) < 9.9(11.5) \times 10^{-9}$$
$$B(B^0 \to K^{*0} e^- \mu^+) < 8.4(10.2) \times 10^{-9}$$
$$B(B^0 \to K^{*0} e^\pm \mu^\mp) < 14.7(17.0) \times 10^{-9}$$
$$B(B^0 \to \phi e^\pm \mu^\mp) < 18.8(23.1) \times 10^{-9}$$

Left-handed model $C_9^{\mu e} = -C_{10}^{\mu e} \neq 0$

$$B(B^0 \to K^{*0} e^+ \mu^-) < 8.0(9.5) \times 10^{-9}$$
$$B(B^0 \to K^{*0} e^- \mu^+) < 6.7(8.3) \times 10^{-9}$$
$$B(B^0 \to K^{*0} e^\pm \mu^\mp) < 12.0(13.9) \times 10^{-9}$$
$$B(B^0 \to \phi e^\pm \mu^\mp) < 16.5(20.5) \times 10^{-9}$$



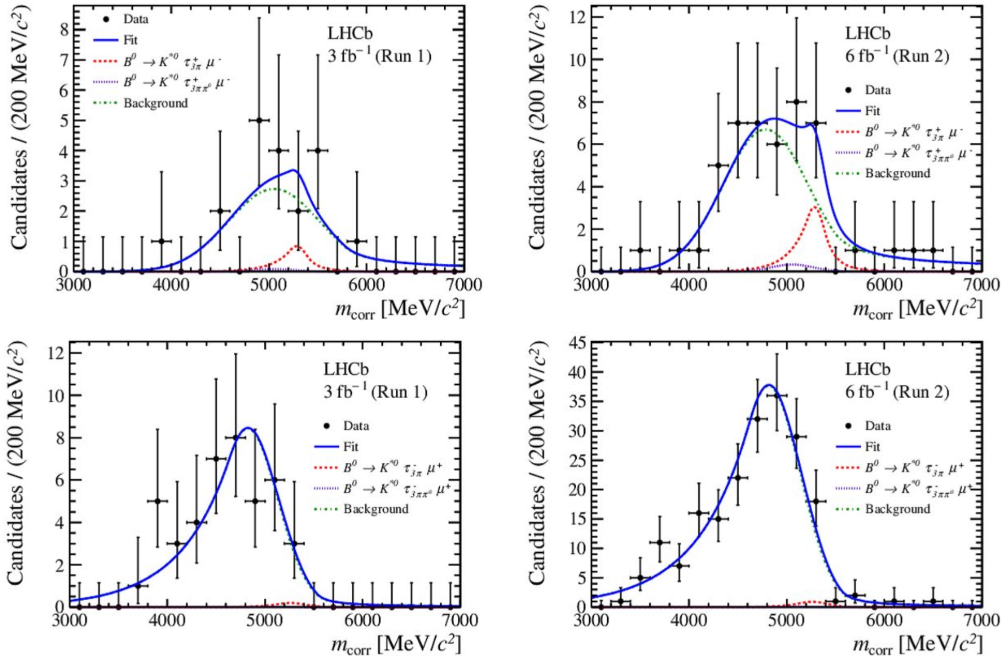


Searches for $B \to K^* \tau\mu$: Fit

https://arxiv.org/abs/2209.09846

$B^0 \to K^{*0}\tau^+\mu^-$

$B^0 \to K^{*0}\tau^-\mu^+$



Fit on data of corrected mass distribution

- Run 1 ($3fb^{-1}$) + Run 2 ($6fb^{-1}$) dataset
- First search for $B^0 \to K^{*0}\tau^\pm\mu^\mp$
- Using $B \to D^-(\to K^+\pi^-\pi^-)D_s^+(\to K^+K^-\pi^+)$ as normalization sample
- $K\mu$ charge combinations treated separately
- Additional challenge given by **missing neutrino momentum** from $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp(\pi^0)\nu$ in the final state

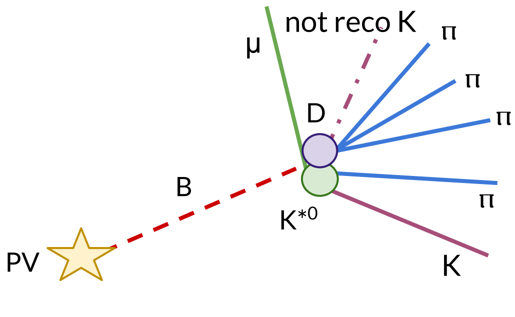
$$m_{corr} = \sqrt{p_T^2 + M^2} + p_T$$

Missing momentum in the transverse plane

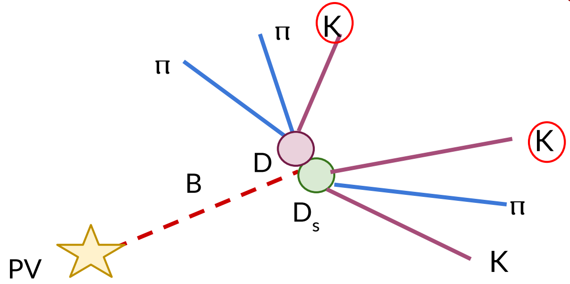
Invariant mass of the final states

Searches for B→K*τμ: Background example

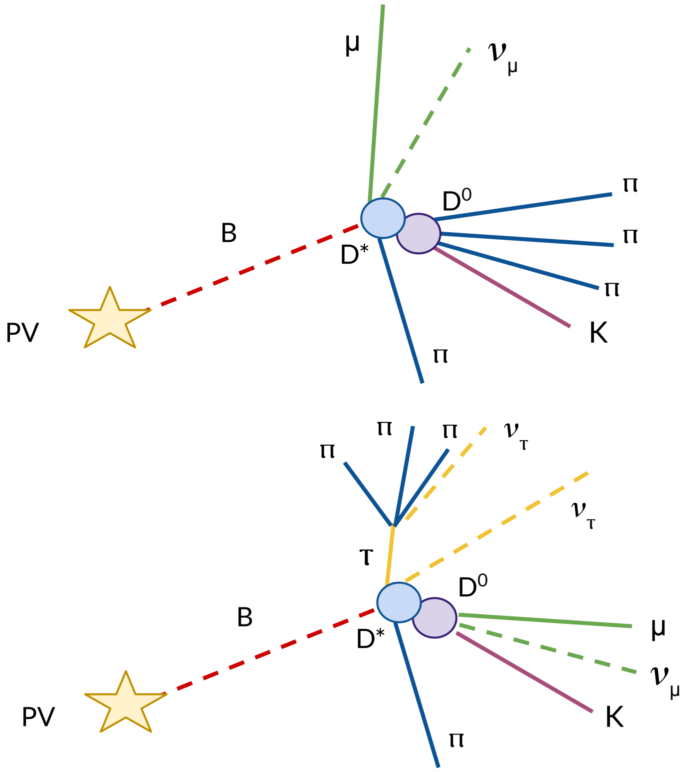
https://arxiv.org/abs/2209.09846



Partial reconstructed decay



Double mis-ID B→D_sD



b→c$l\nu_l$ cascades with same final states as signal

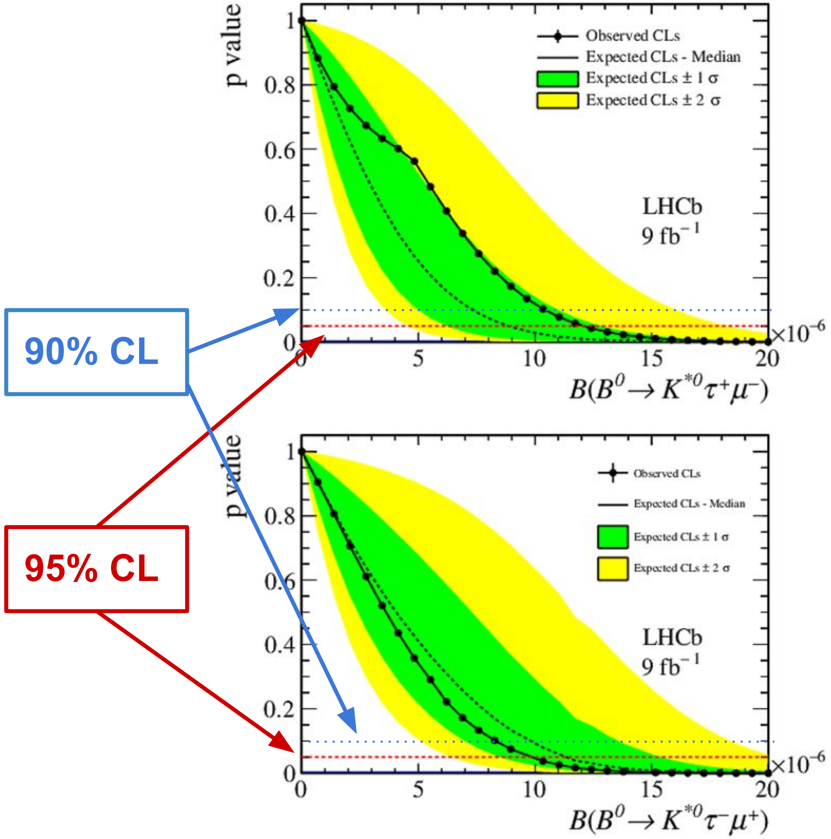
Searches for B→K*τμ: Results

https://arxiv.org/abs/2209.09846

- **No significant signal observed**
- Upper limits at 90 (95)% CL

$$B(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$$
$$B(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8) \times 10^{-6}$$

MOST STRINGENT LIMITS

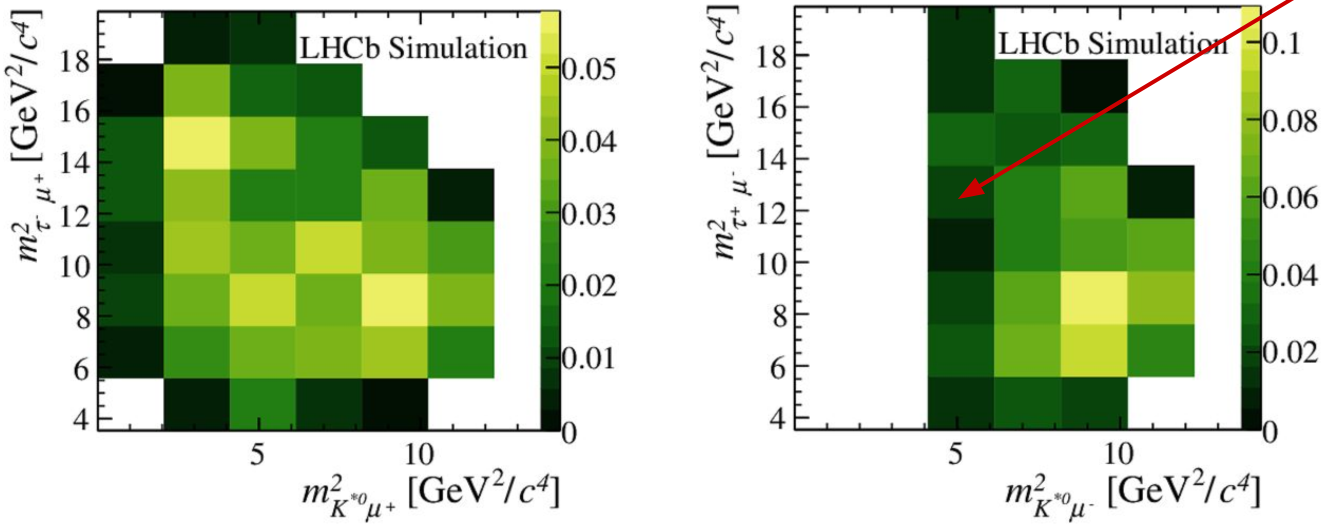


Searches for $B \to K^* \tau\mu$: Efficiencies

https://arxiv.org/abs/2209.09846

- Efficiencies evaluated on MC assuming **uniform phase space**
- Allows to reweight obtained results wrt a specific model

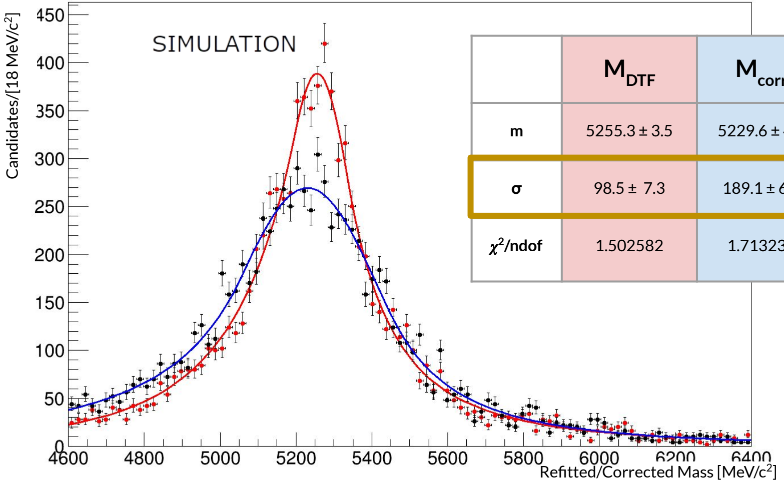
Veto on **$m(K^+\mu^-) > 1885$ MeV/c^2** to reject $B^0 \to D^{(*)-}\tau^+\nu_\tau$ bkg



Why not searching for B→K*τe?

➜ First look at a *τe* final state @ LHCb

New strategy to correct the B mass: **refitting the kinematics using mass constraints**



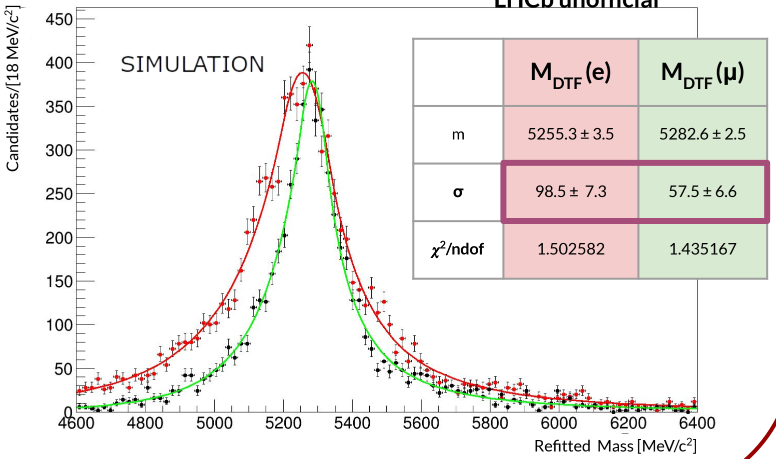
	M_{DTF}	M_{corr}
m	5255.3 ± 3.5	5229.6 ± 4.6
σ	98.5 ± 7.3	189.1 ± 6.7
χ^2/ndof	1.502582	1.713239

➜ **Improvement in mass resolution** 👍

COMPARISON WITH $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

Reasonable mass resolution comparing electron and muon channels

→ Feasibility of the decay search!



	M_{DTF}(e)	M_{DTF}(μ)
m	5255.3 ± 3.5	5282.6 ± 2.5
σ	98.5 ± 7.3	57.5 ± 6.6
χ^2/ndof	1.502582	1.435167

Outlook

FINAL STATES WITH $e\mu$ and $\tau\mu$

Decay	Limit (90% C.L.)	Integrated luminosity
$B^0 \to e\mu$	$1.0 \cdot 10^{-9}$	$3\ \text{fb}^{-1}$
$B_s \to e\mu$	$5.4 \cdot 10^{-9}$	$3\ \text{fb}^{-1}$
$B^+ \to K^+ e^+ \mu^-$	$7.0 \cdot 10^{-9}$	$3\ \text{fb}^{-1}$
$B^+ \to K^+ e^- \mu^+$	$6.4 \cdot 10^{-9}$	$3\ \text{fb}^{-1}$
$B^0 \to K^{*0} e^\mp \mu^\pm$	$9.9 \cdot 10^{-9}$	$9\ \text{fb}^{-1}$
$B^0 \to K^{*0} e^+ \mu^-$	$6.7 \cdot 10^{-9}$	$9\ \text{fb}^{-1}$
$B^0 \to K^{*0} e^- \mu^+$	$5.7 \cdot 10^{-9}$	$9\ \text{fb}^{-1}$
$B_s \to \phi e^\mp \mu^\pm$	$1.6 \cdot 10^{-8}$	$9\ \text{fb}^{-1}$
$B^0 \to \tau\mu$	$1.2 \cdot 10^{-5}$	$3\ \text{fb}^{-1}$
$B_s \to \tau\mu$	$3.4 \cdot 10^{-5}$	$3\ \text{fb}^{-1}$
$B^+ \to K^+ \tau\mu$	$3.9 \cdot 10^{-5}$	$9\ \text{fb}^{-1}$
$B^0 \to K^{*0} \tau^+ \mu^-$	$1.0 \cdot 10^{-5}$	$9\ \text{fb}^{-1}$
$B^0 \to K^{*0} \tau^- \mu^+$	$8.2 \cdot 10^{-6}$	$9\ \text{fb}^{-1}$

DISCUSSED

DISCUSSED

Outlook

FINAL STATES WITH $e\tau$

Decay	Limit (90% C.L.)	Integrated luminosity	Experiment
$B^0 \to e^\pm \tau^\mp$	$1.6 \cdot 10^{-5}$	772M BB (711 fb^{-1})	Belle
$B^+ \to K^+ e^\pm \tau^\mp$	$3.0 \cdot 10^{-5}$	472M BB (426 fb^{-1})	BaBar
$B^+ \to K^+ e^+ \tau^-$	$4.3 \cdot 10^{-5}$	472M BB (426 fb^{-1})	BaBar
$B^+ \to K^+ e^- \tau^+$	$1.5 \cdot 10^{-5}$	472M BB (426 fb^{-1})	BaBar
$B^+ \to \pi^+ e^\pm \tau^\mp$	$7.5 \cdot 10^{-5}$	472M BB (426 fb^{-1})	BaBar
$B^+ \to \pi^+ e^+ \tau^-$	$7.4 \cdot 10^{-5}$	472M BB (426 fb^{-1})	BaBar
$B^+ \to \pi^+ e^- \tau^+$	$2.0 \cdot 10^{-5}$	472M BB (426 fb^{-1})	BaBar
$B^0 \to K^{*0} e^+ \tau^-$	?	1.6 fb^{-1}	LHCb
$B^0 \to K^{*0} e^- \tau^+$	?	1.6 fb^{-1}	LHCb

Wait for my PhD!


thank you
danke
謝謝
ngiyabonga
teşekkür ederim
gracias
спасибо
Баярлалаа
рахмат
mersi
barka
welalin
tack
dank je
misaotra
matondo
paldies
grazzi
mahalo
tapadh leat
хвала
asante
manana
tenki
faafetai lava
kiitos
dankie
blagodaram
vinaka
bedankt
enkosi
nandri
hvala
mauruuru
koszonom
dziękuję
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sulpay
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dekuji
obrigado
mesi
sagolun
sukriya
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arigatō
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trugarez
ありがとう
najis tuke
terima kasih
tanemirt
rahmet
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dhanyavadagalu
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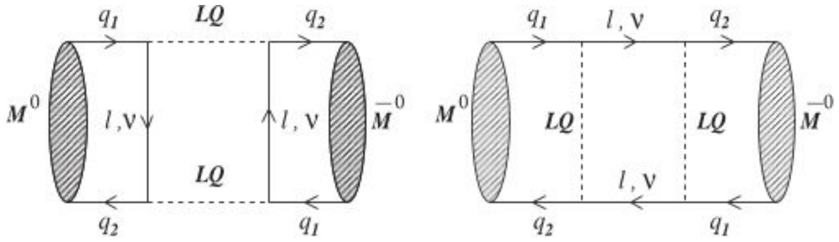
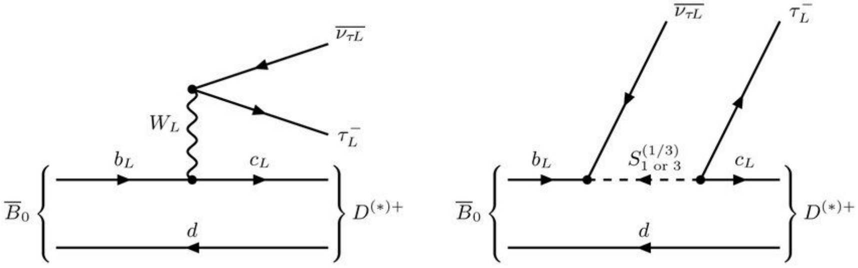
BACKUP

Theoretical models

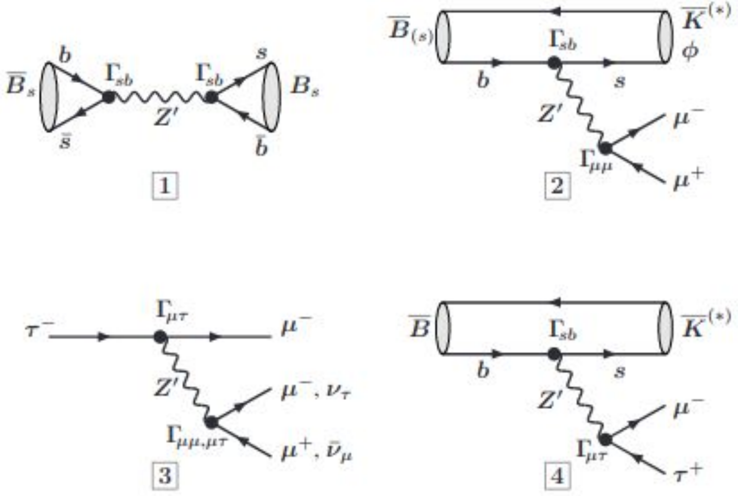
New Physics scenario with Leptoquark (LQ)



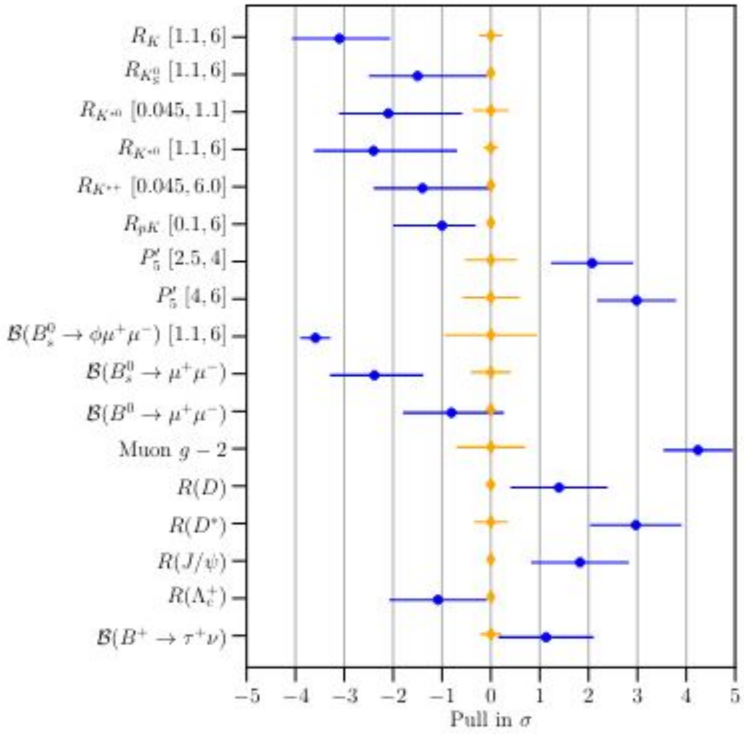


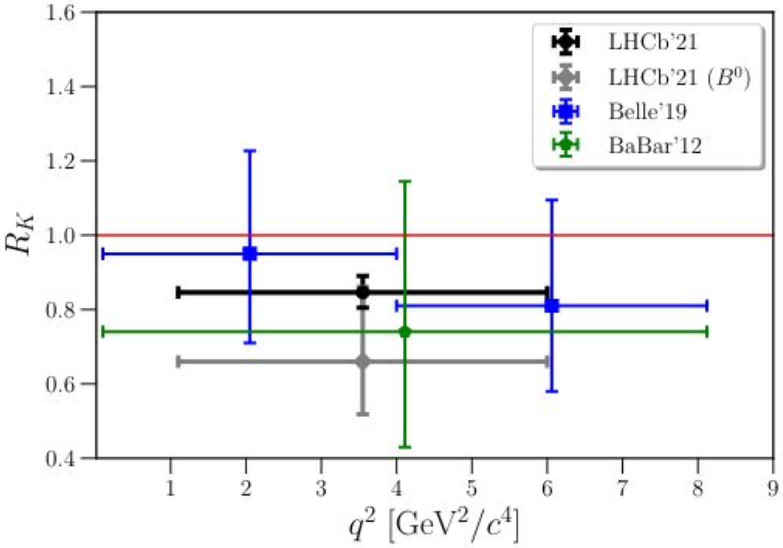
(a) (b)

New Physics scenario with Z' mediator



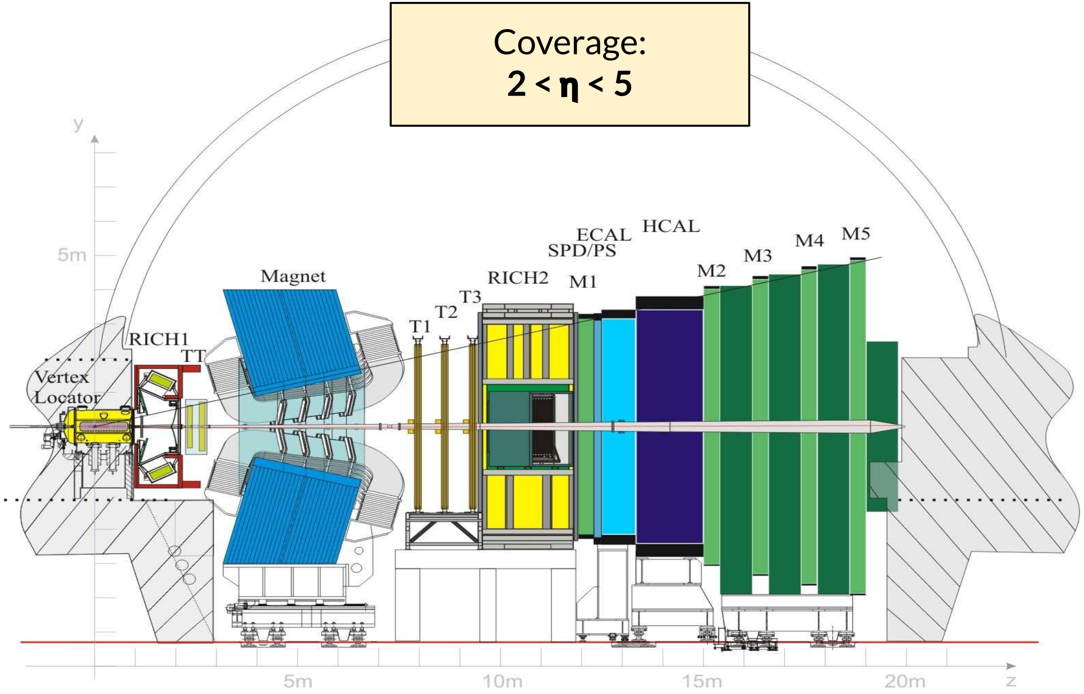
LFUV measurements





R_K measurements for LHCb and B factories experiments

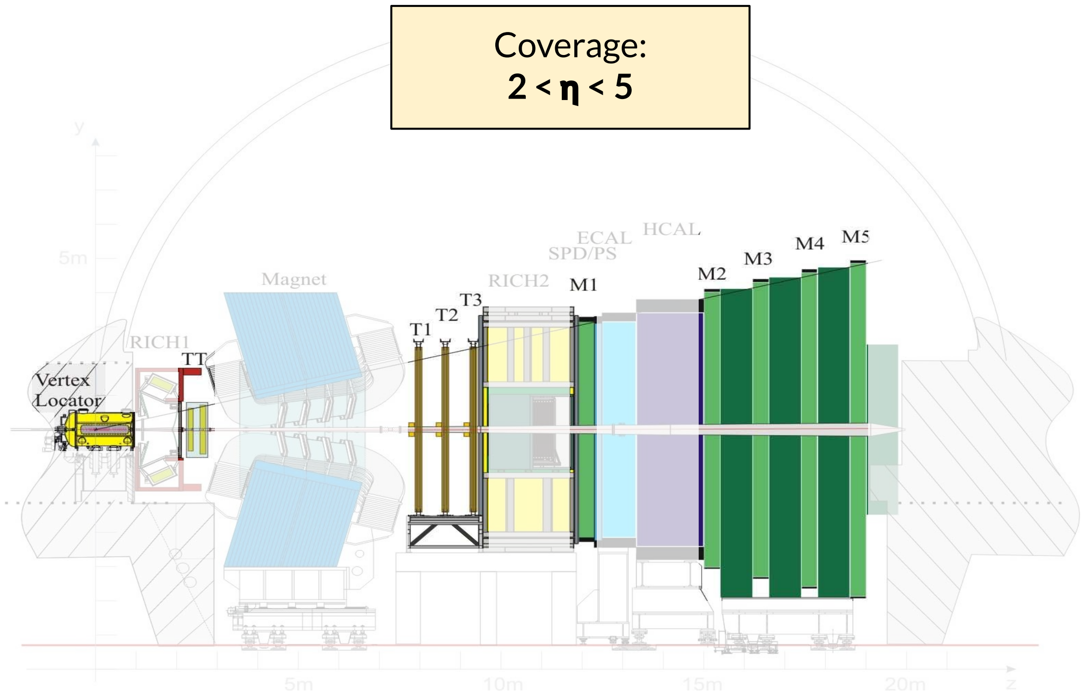
LHCb detector



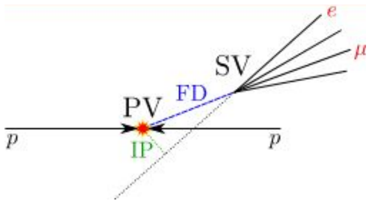
➜ Single arm **forward spectrometer**, designed for **heavy flavour physics**

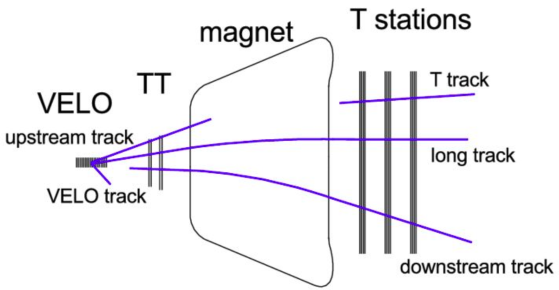
LHCb detector: reconstruction & tracking

➜ Single arm **forward spectrometer**, designed for **heavy flavour physics**



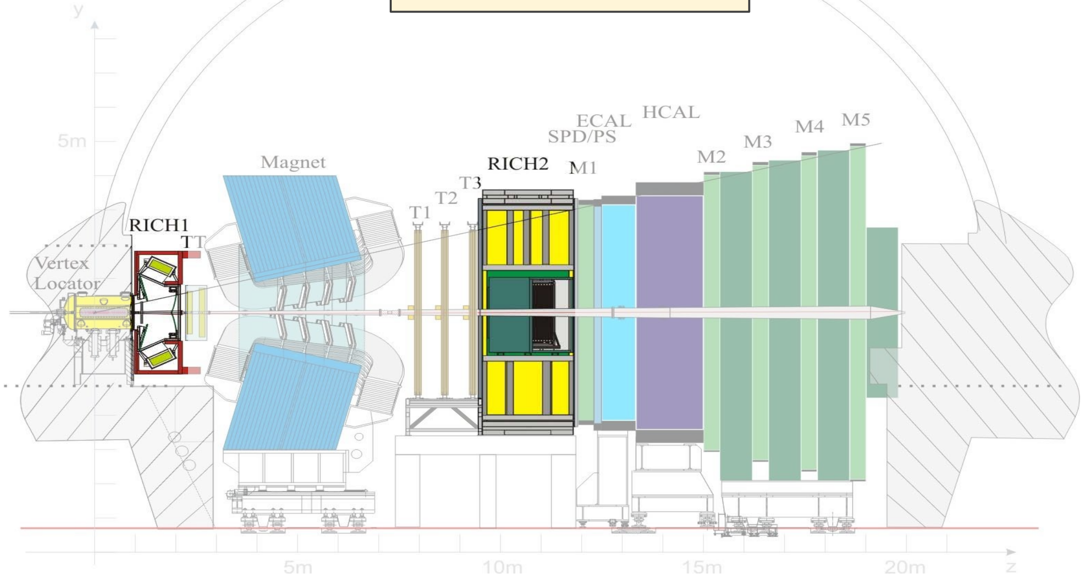
COMPONENTS OF THE DETECTOR





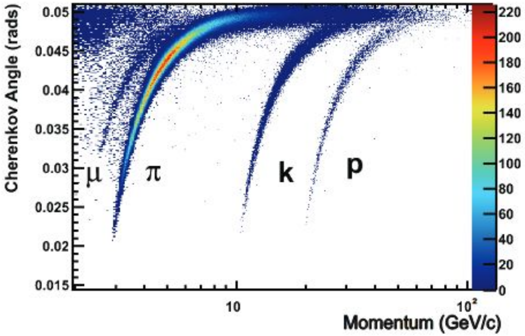
LHCb detector: Particle Identification (PID)

Coverage:
$2 < \eta < 5$



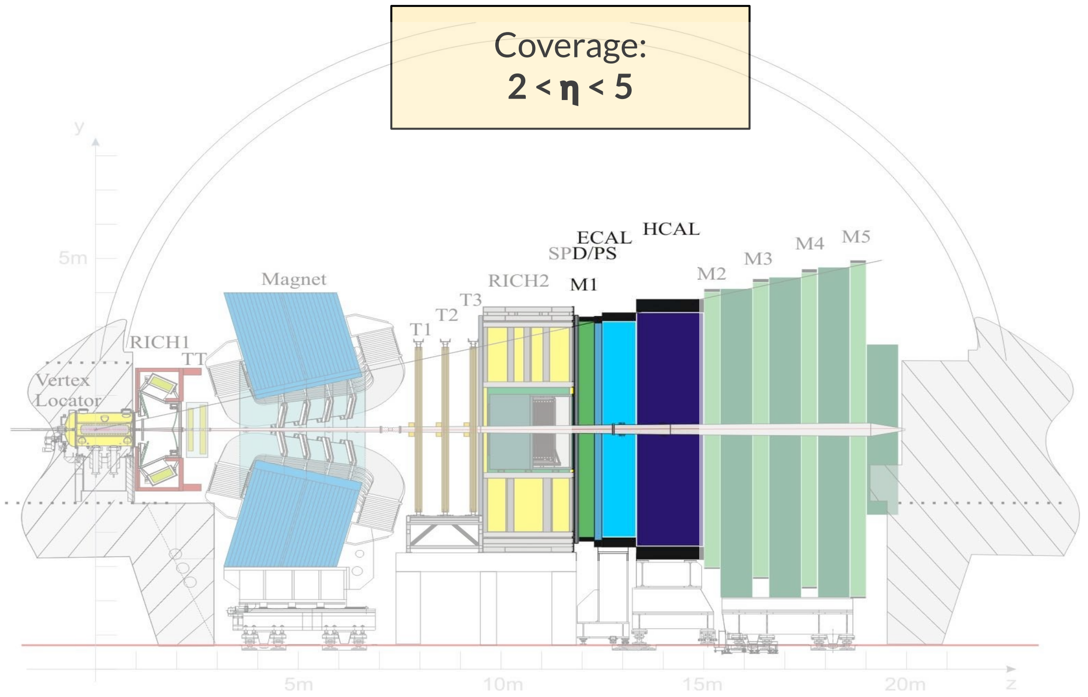
➜ Single arm **forward spectrometer**, designed for **heavy flavour physics**

COMPONENTS OF THE DETECTOR



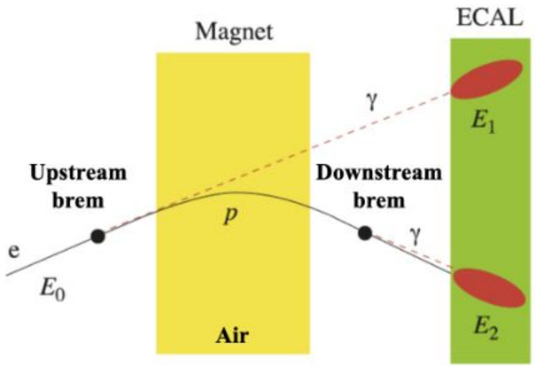
https://arxiv.org/pdf/1211.6759.pdf

LHCb detector: Energy deposit (calorimetry)



➜ Single arm **forward spectrometer**, designed for **heavy flavour physics**

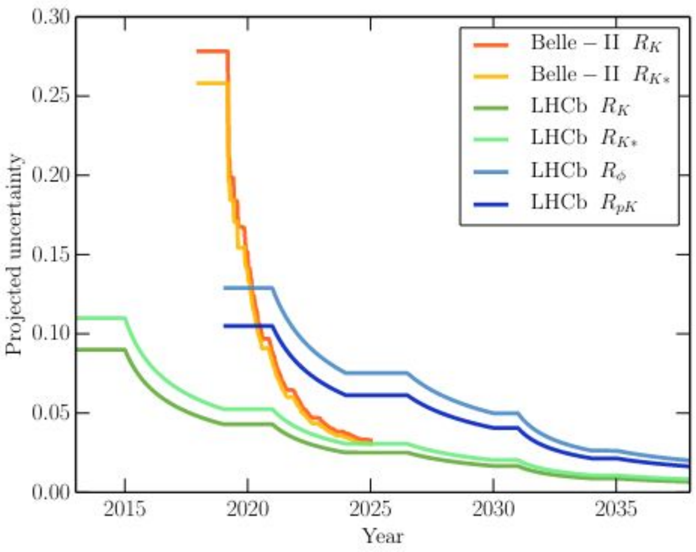
COMPONENTS OF THE DETECTOR



Bremsstrahlung recovery for electrons

Future prospects for LFUV studies

https://arxiv.org/pdf/2207.01851.pdf



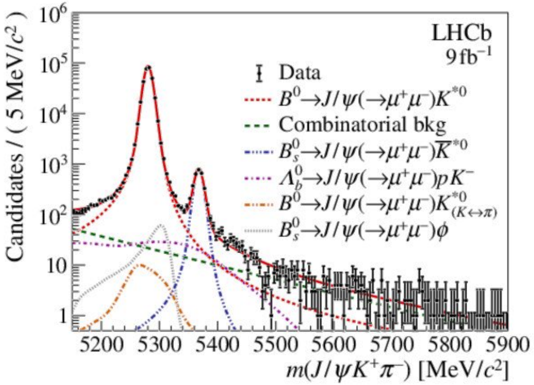
Observable	Current	LHCb U1	Belle II	LHCb UII
$R_K([1,6]\,\mathrm{GeV}^2/c^4)$	0.044 [3]	0.025	0.036	0.007
$R_{K^*}([1,6]\,\mathrm{GeV}^2/c^4)$	0.12 [4]	0.031	0.034	0.009
$R(D^*)$	0.014 [12]	0.007	0.003	0.002
$R(D)$	0.030 [12]		0.004	
$R(J/\psi)$	0.24 [55]	0.07		0.02
$\mu(B^+ \to K^+\nu\overline{\nu})$	0.7 [65]		0.08	
$\mu(B^0 \to K^{*0}\nu\overline{\nu})$	1.8 [67]		0.34	
$\mathcal{B}(B \to K^*\tau^+\tau^-)$	$< 2 \times 10^{-3}$ [68]		$< 5.3 \times 10^{-4}$	
$\mathcal{B}(B^+ \to \mu^+\nu)$	50% [69]		2.5%	
$\mathcal{B}(B^+ \to \tau^+\nu)$	22% [70]		3.0%	

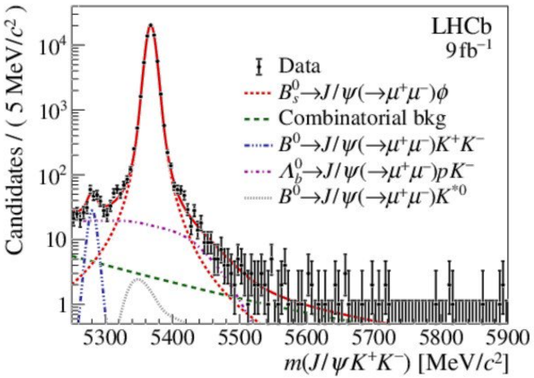
➜ Improvement of measurement uncertainties to get more precise information about these B anomalies

Selection and Normalization for $B\to K^*e\mu$ and $B_s\to\phi e\mu$

https://arxiv.org/abs/2207.04005

- Signal region in **[4300, 6700] MeV/c²**
- PID requirements on final state hadrons and leptons to suppress double mis-ID bkg $B^0_{(s)}\to K^{*0}(\phi)\,\pi^{\pm}\pi^{\mp}$
- Mass window of invariant mass for $K^+\pi^-$ and K^-K^+ with width respectively 100 MeV/c² and 12 MeV/c² for K^{*0} and ϕ and centered on known mass value
- Vetoes for rejecting background for J/ψ and ψ(2s) resonances and semileptonic cascade involving D mesons ($b\to c(\to s l'^+\nu_{l'})l^-\bar{\nu}_l$ decays)
- Separate BDT for each of the two signal decay to remove combinatorial background





$$\mathcal{B}_{\rm sig} = \underbrace{\frac{\mathcal{B}_{\rm norm}}{N_{\rm norm}} \times \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}}_{=\alpha} \times N_{\rm sig},$$

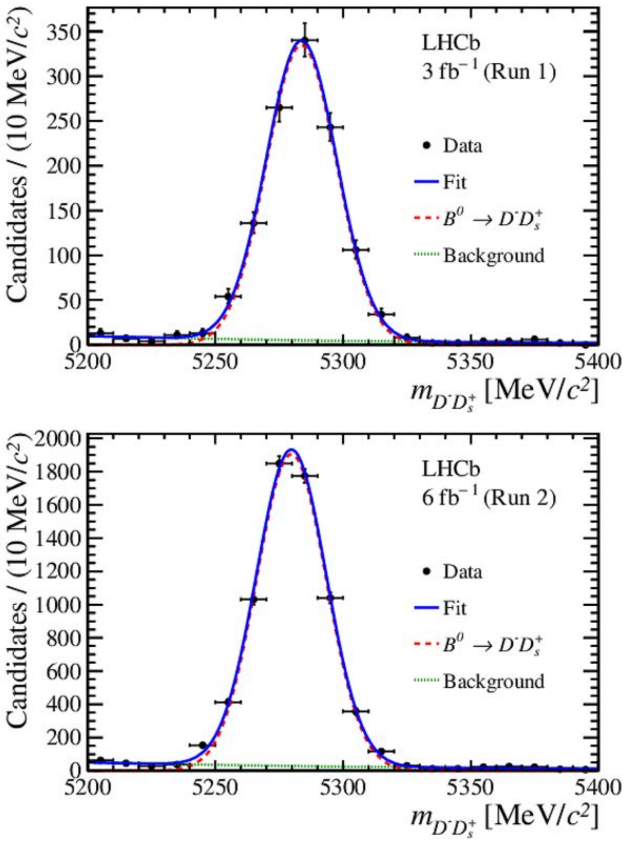
BRANCHING FRACTION FOR THE SIGNAL

Mode	$\alpha \pm (\sigma_{\rm stat} \oplus \sigma_{\rm syst})$ $[10^{-9}]$ 2011–2012	2015–2016	2017–2018
$B^0\to K^{*0}\mu^+e^-$	2.47 ± 0.14	2.38 ± 0.16	1.49 ± 0.09
$B^0\to K^{*0}\mu^-e^+$	2.50 ± 0.15	2.39 ± 0.16	1.49 ± 0.09
$B^0\to K^{*0}\mu^\pm e^\mp$	2.48 ± 0.14	2.39 ± 0.16	1.49 ± 0.09
$B^0_s\to \phi\mu^\pm e^\mp$	9.50 ± 0.70	9.68 ± 0.78	5.09 ± 0.39

Selection, Normalization and Efficiencies for $B \to K^* \tau\mu$

https://arxiv.org/abs/2209.09846

- Signal region in **[4600, 6400] MeV/c^2**
- PID requirements on final state hadrons and leptons
- BDT to suppress combinatorial background
- BDT to suppress charmed meson contribution in τ reconstruction
- Fisher discriminant using isolation information of the candidates to remove partially reconstructed bkg sources
- Specific vetoes for D^0 mesons
- Separate BDT for each of the two signal decay to remove combinatorial background



DecayTreeFitter

Fitting the decay chain using **Kalman filters** (https://arxiv.org/pdf/physics/0503191.pdf)

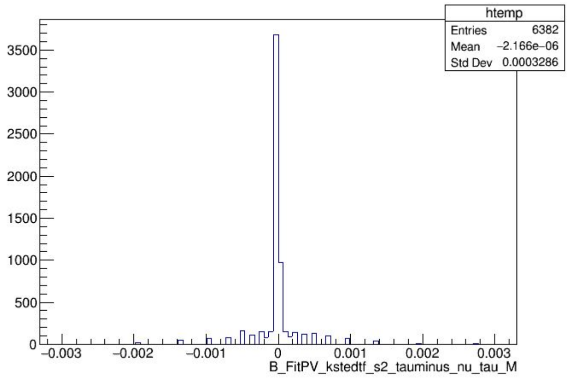
- Extract the optimal set of decay tree parameters (f.e. momentum and energy) by fixing *exact* (without associated uncertainty) and *measured* (with associated uncertainties) constraints and using least square fit

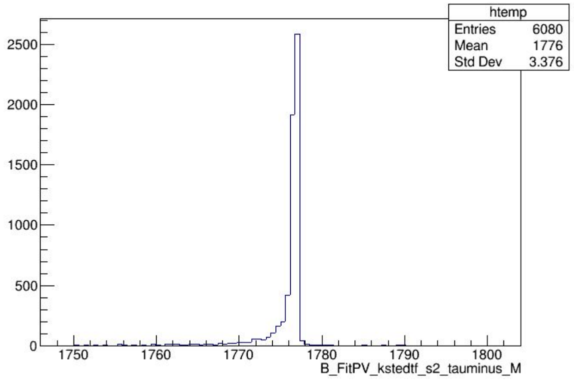
PROBLEM: Missing momentum carried by the neutrino

Solution: B direction deduced from K^*e system and assumption that $\tau_\perp$=-$(K^*e)_\perp$

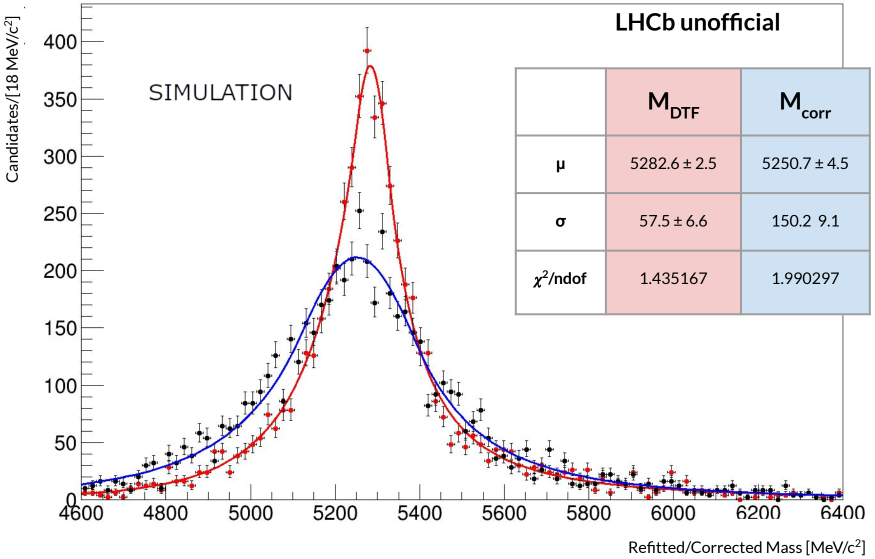
Constraints

B constrain to PV

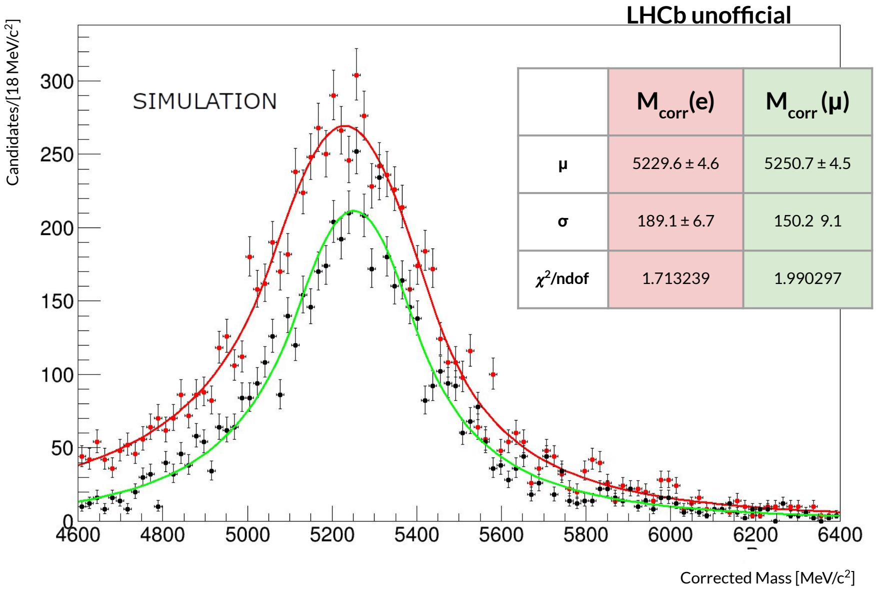




B→K*τe vs B→K*τμ



	M_{DTF}	M_{corr}
μ	5282.6 ± 2.5	5250.7 ± 4.5
σ	57.5 ± 6.6	150.2 9.1
χ^2/ndof	1.435167	1.990297



	$M_{corr}(e)$	$M_{corr}(\mu)$
μ	5229.6 ± 4.6	5250.7 ± 4.5
σ	189.1 ± 6.7	150.2 9.1
χ^2/ndof	1.713239	1.990297