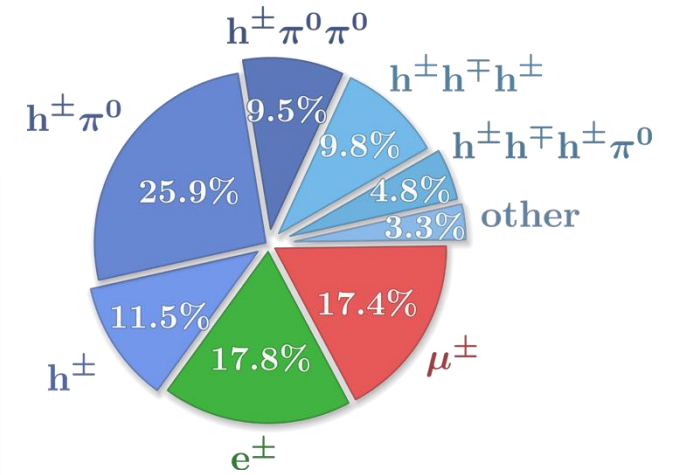


$b \rightarrow s \tau \tau$



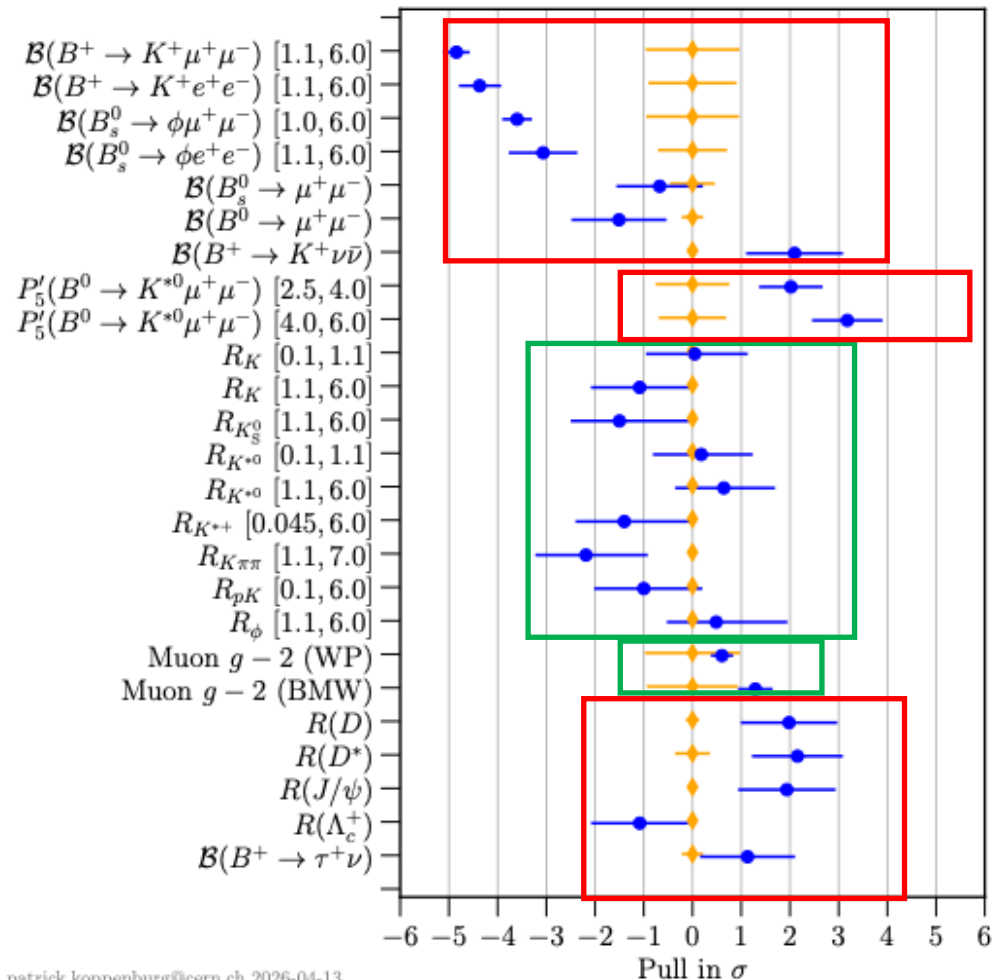
Lesya Shchutska

EPFL

FPBM 2026

Observables under spotlight

Orange: theory unc.; blue: experiment



$b \rightarrow s \ell \ell$ rates

$b \rightarrow s \mu \mu$ angular

$b \rightarrow s \ell \ell$ ratios
(back to SM)

$g-2$ (back to SM)

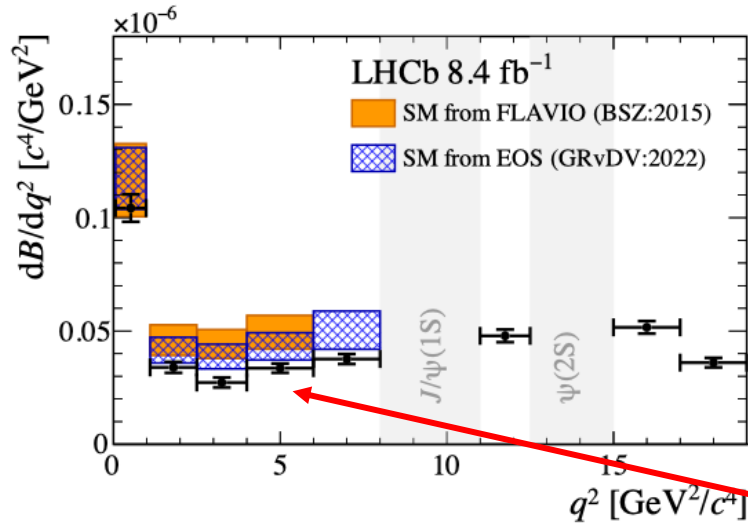
$b \rightarrow c \tau \nu$

- $b \rightarrow s \ell \ell$ ratios for $\ell = e, \mu$ are back to SM

- other observables in the $b \rightarrow s \ell \ell$ transitions exhibit tensions with the SM:
 - rates and angular observables

- some enhancement of $b \rightarrow c \tau \nu$ decays vs. $b \rightarrow c \mu \nu$

A comprehensive $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ analysis

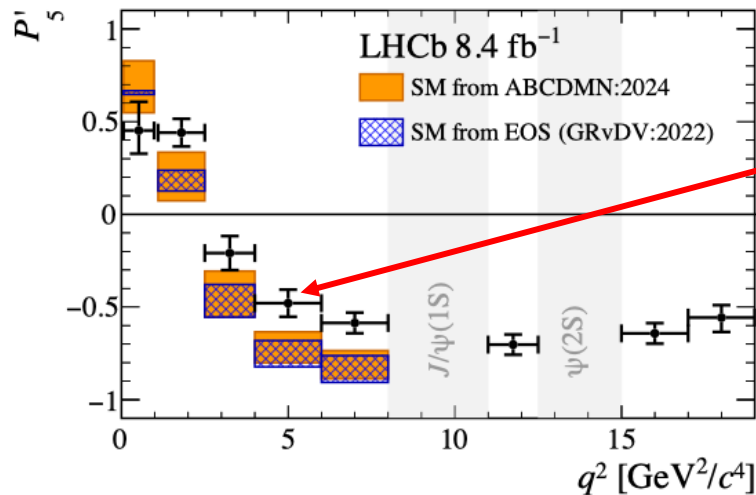


Legacy Run 1+ Run 2 analysis with a new approach:

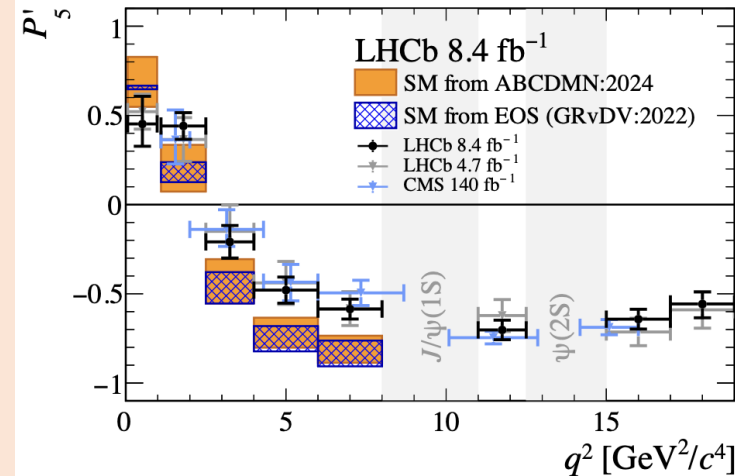
- fit simultaneously differential BF and angular observables
- take into account lepton masses (important at low q^2)
- include CP-averaged observables in full basis of CP-asymmetries
- use all S-wave and P-/S-wave interference observables
- go to finer binning scheme

- differential BF consistently below theory prediction (large theory uncertainties!)

- tension between theory and experiment in P'_5 increases:
 - in $4.0 < q^2 < 6.0 \text{ GeV}^2$ is now 2.7σ
- no significant CP-asymmetry observed



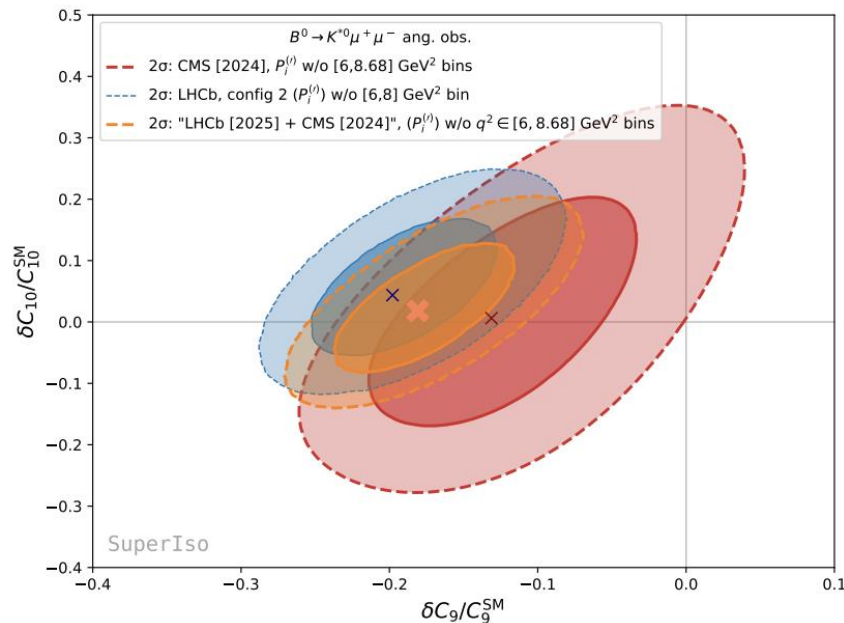
Good agreement with CMS



Interpretations from theory

The 1 and 2σ C.L. of the $\{C_9, C_{10}\}$, **without** $[6, 8]$ and $[6., 8.68]$ GeV^2 bins

Combining LHCb and CMS results



Red: CMS (pull_{SM} : 2σ)

Blue: LHCb 2025 (pull_{SM} : 5σ)

Orange: LHCb+CMS (pull_{SM} : 4.9σ)

Wilson coefficients parameterize short-distance contributions:

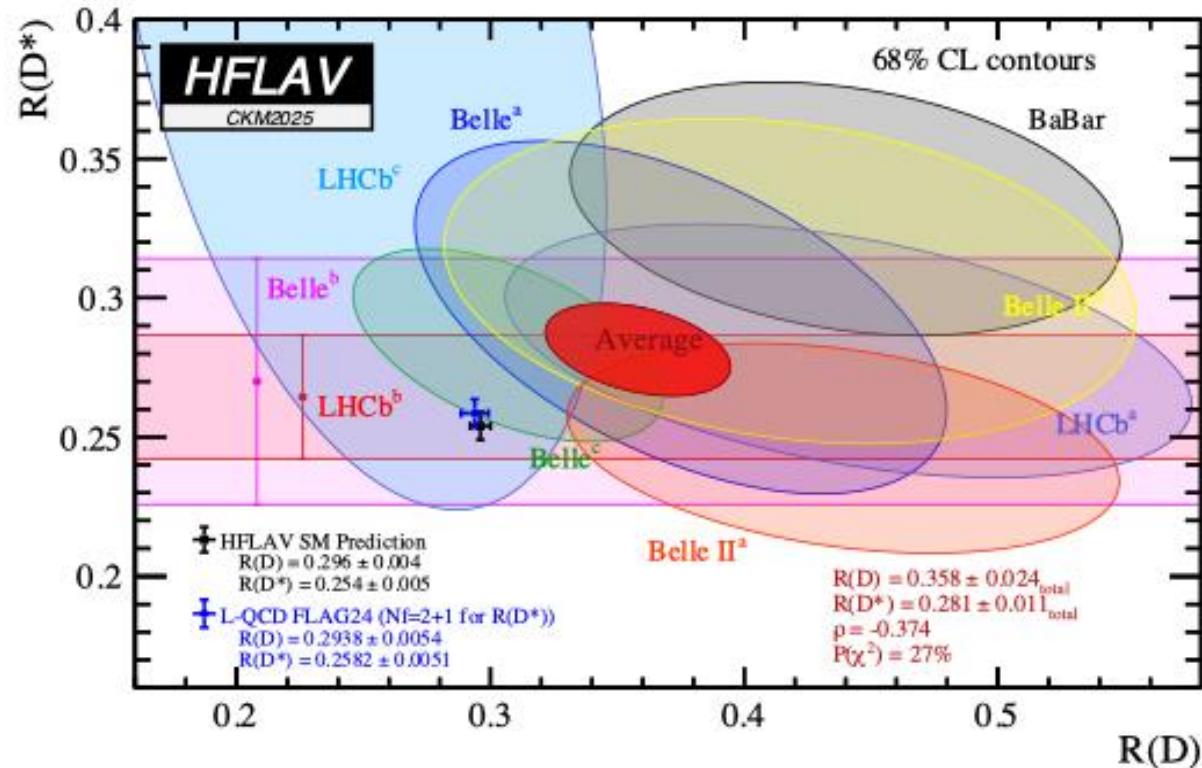
- C_9 – vector
- C_{10} – axial-vector

Here, C_9 can incorporate most NP effects

NP is favored to be universal (LFU)

General wish: measure inclusive modes!

Semileptonic decays: $R(D^{(*)})$



Note:

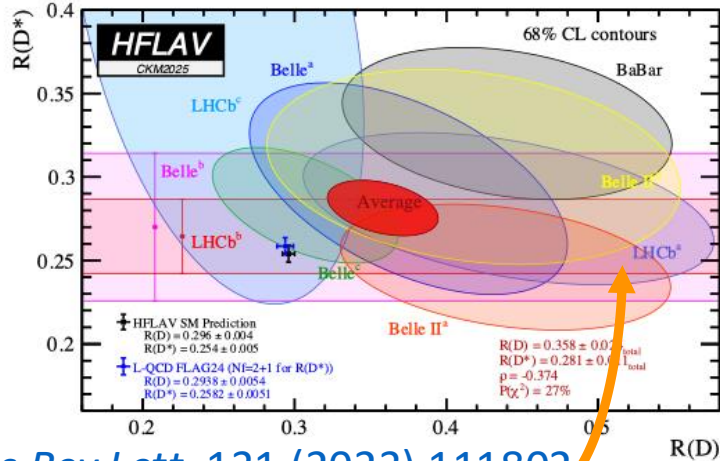
- very preliminary BaBar $R(D)$ – $R(D^*)$ (SL tag, $\tau^+ \rightarrow \ell^+ \nu_\ell \bar{\nu}_\tau$) not included;
- compatible with the SM
- [David Hitlin at VFSB'25](#)

Abundant tree-level decays:

- very difficult measurements;
- high backgrounds, especially for taus;
- feed-downs from higher D^{**} modes can be important
- results are available with Run 1 data only due to analysis complexity

Tension with the SM about 3.8σ

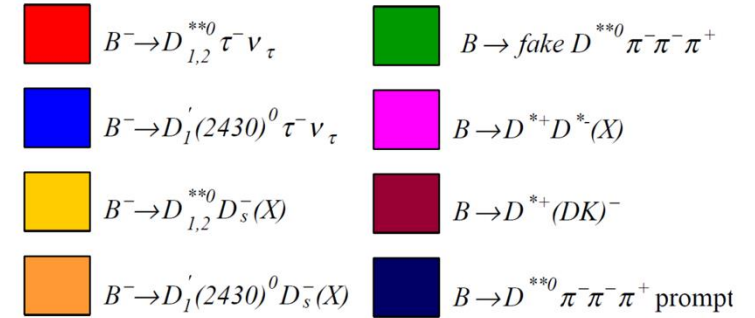
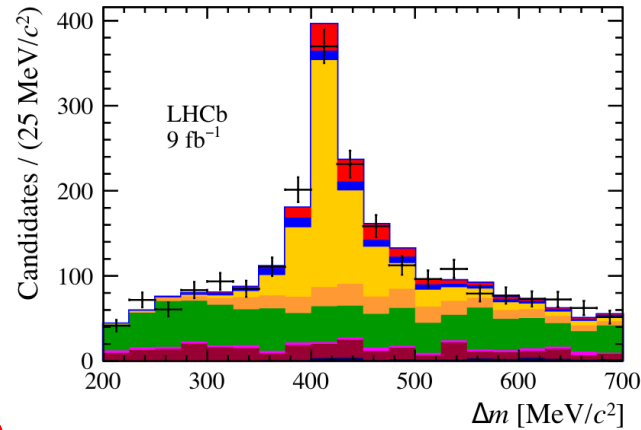
Glimpse into D^{**} modes



First evidence for $B^- \rightarrow D^{**0} \tau^- \bar{\nu}_\tau$ at 3.5σ level

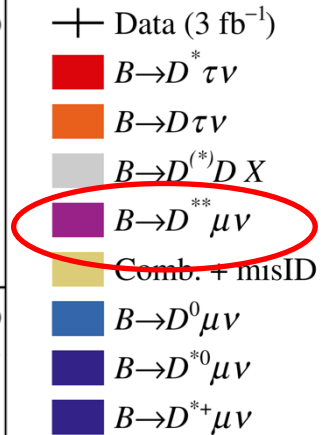
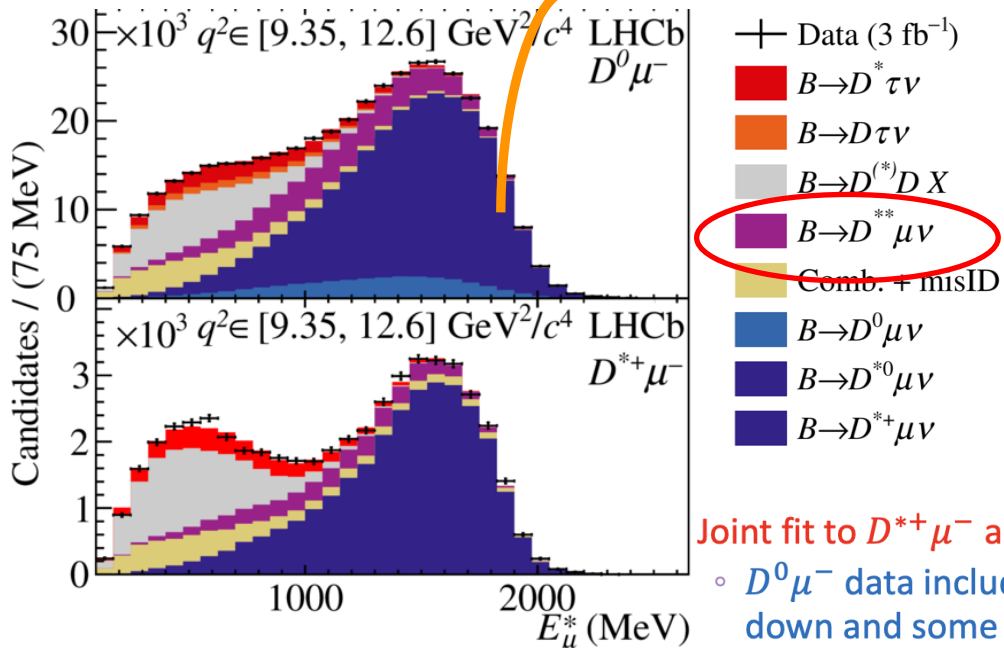
$$\mathcal{R}(D_{1,2}^{**0}) = 0.13 \pm 0.03 \text{ (stat)} \pm 0.01 \text{ (syst)} \pm 0.02 \text{ (ext)}$$

SM prediction is 0.09 ± 0.02



The measurement agrees with the SM prediction and is in line with the assumptions used in the R(D) analyses!
 Feed-down rate is of the order of 10%

[Phys.Rev.Lett. 131 \(2023\) 111802](https://arxiv.org/abs/2208.02180)



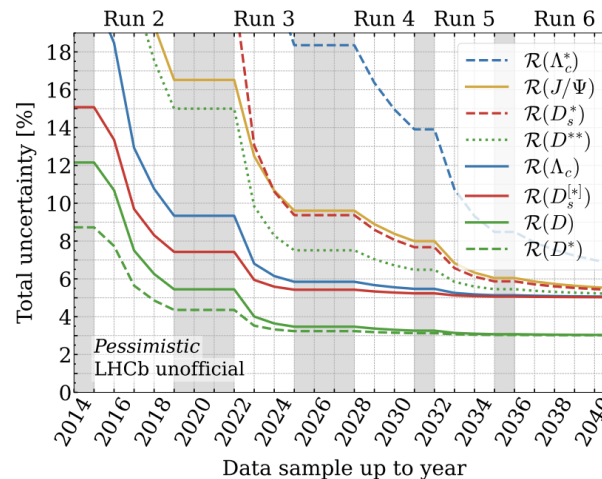
Joint fit to $D^{*+} \mu^-$ and $D^0 \mu^-$ datasets
 ◦ $D^0 \mu^-$ data includes large D^{*0} feed-down and some D^{*+}

[Phys.Rev.Lett. 135 \(2025\) 2, 021802](https://arxiv.org/abs/2402.02180)

NP or not NP: alternative paths

0. $b \rightarrow c\tau\nu$

- very challenging experimentally
- prognoses exist, but no breakthrough in methods?



[e.g. Rev.Mod.Phys. 94 \(2022\) 1, 015003](#)

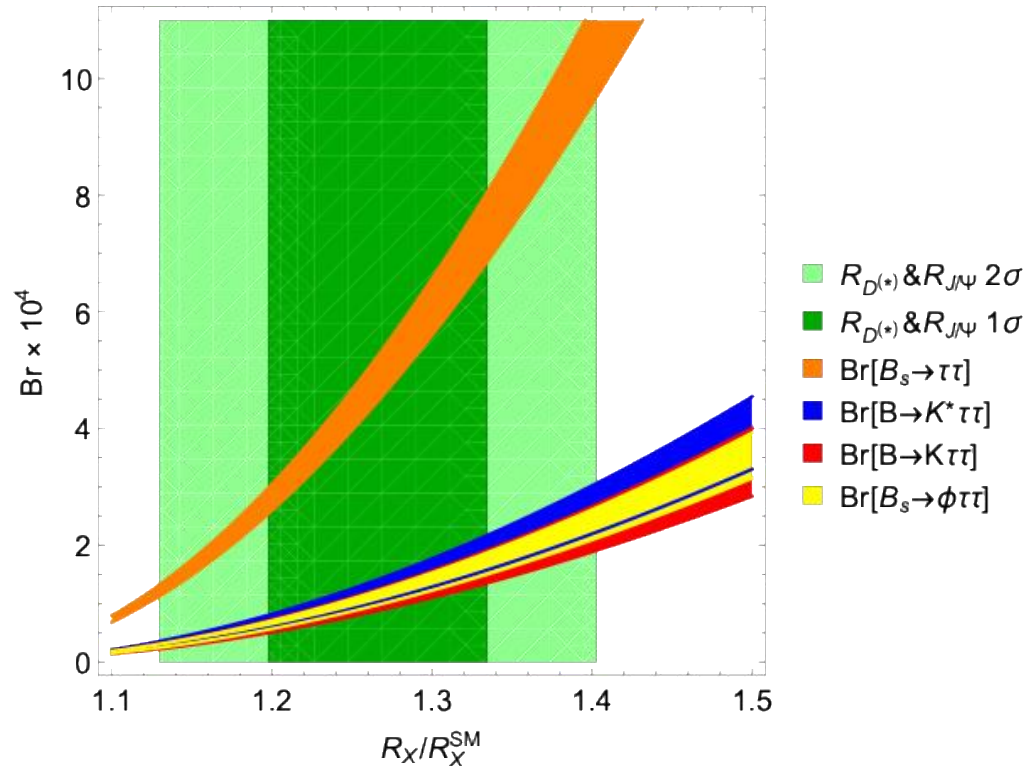
1. $bc \rightarrow \tau\nu$

- thought to be an FCC-ee target
 - emerging ideas in the LHCb era
 - **can be within reach!**
- see Guy's talk

2. $b \rightarrow s\tau\tau$

- a smoking gun for new physics
- large enhancements predicted, if tree-level $R(D)$ anomaly is due to NP
- **can we get there?**

Another angle on R(D): $b \rightarrow s\tau\tau$



[Phys.Rev.Lett. 120 \(2018\) 181802](#)

New physics in tree-level $b \rightarrow c\tau\nu$ can significantly enhance loop $b \rightarrow s\tau\tau$ transitions: predictions of up to 10^4 enhancement

Such decays are relatively unexplored
SM expectation: $\mathcal{B} \sim \mathcal{O}(10^{-7})$

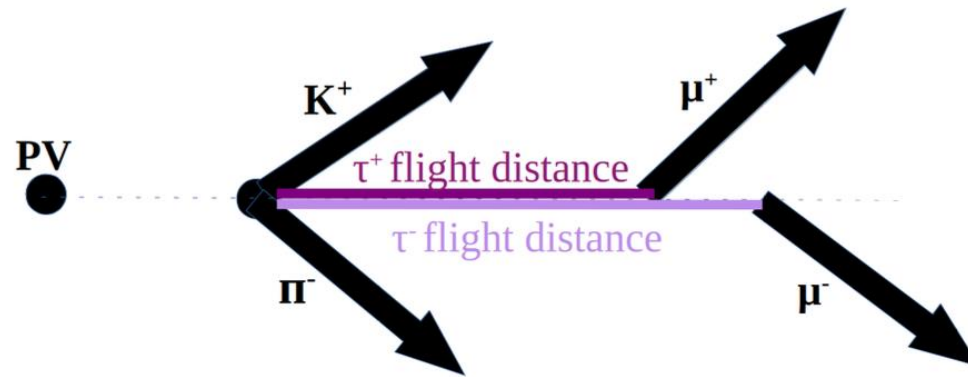
LHCb searched for $B_s^0 \rightarrow \tau\tau$ with $\tau \rightarrow 3\pi^\pm\nu$
BF $< 6.8 \times 10^{-3}$ at 95% CL
([PRL 118 \(2017\) 251802](#))

$$B^0 \rightarrow K^+ \pi^- \tau^+ \tau^- \text{ and } B_S^0 \rightarrow K^+ K^- \tau^+ \tau^-$$

□ LHCb Collaboration, “Searches for $B^0 \rightarrow K^+ \pi^- \tau^+ \tau^-$ and $B_S^0 \rightarrow K^+ K^- \tau^+ \tau^-$ decays”, [Phys.Rev.Lett. 136 \(2026\) 18, 181802](#)

$$B^0 \rightarrow K^+ \pi^- \tau^+ \tau^- \text{ and } B_S^0 \rightarrow K^+ K^- \tau^+ \tau^-$$

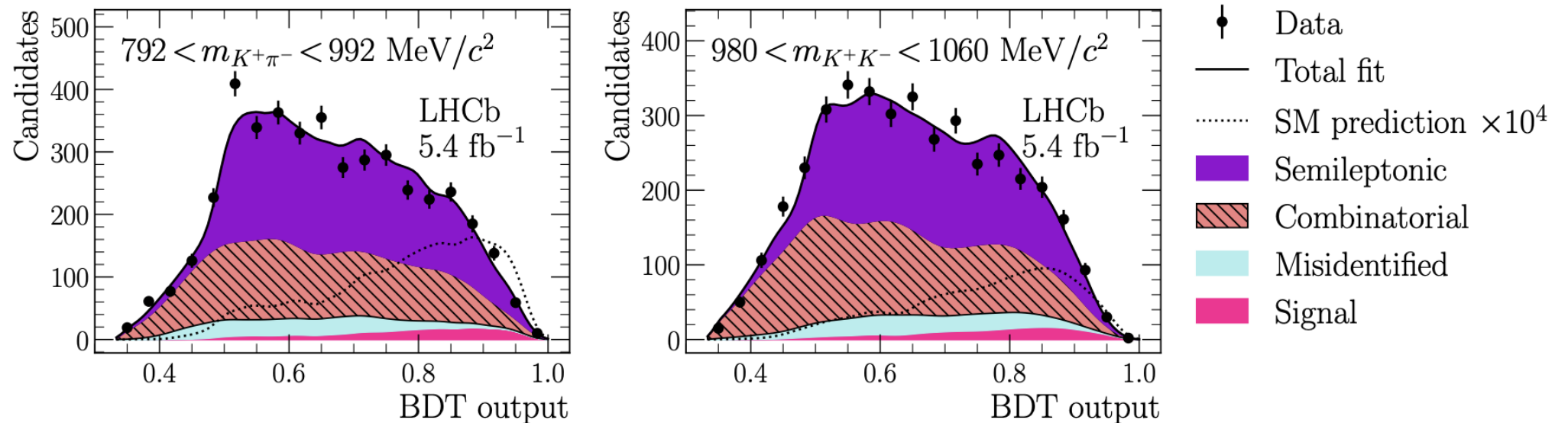
- use muonic decays of taus
- assume taus fly in B direction
- use estimated tau flight distance



NB: muons do not have to form a vertex

$$B^0 \rightarrow K^+ \pi^- \tau^+ \tau^- \text{ and } B_S^0 \rightarrow K^+ K^- \tau^+ \tau^-$$

Signal extracted from the fit to the BDT shape:
 BDT templates derived in simulation and control samples in data
 misID yields constrained, others – determined from the fit



$$B^0 \rightarrow K^+ \pi^- \tau^+ \tau^- \text{ and } B_s^0 \rightarrow K^+ K^- \tau^+ \tau^-$$

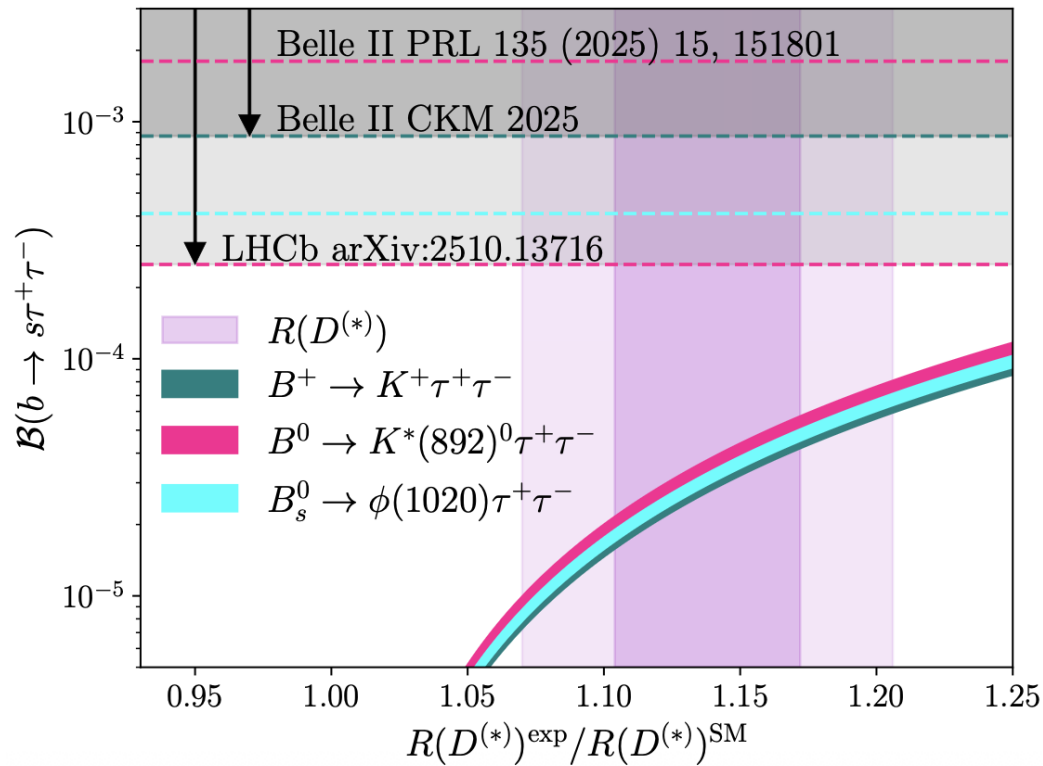
Results presented in hadronic system mass bins

Confidence level	Upper limit on $\mathcal{B}(B^0 \rightarrow K^+ \pi^- \tau^+ \tau^-)$			
	$m_{K^+ \pi^-}$ (MeV/ c^2)	[792, 992]	[992, 1330]	[1330, 1530]
90%	1.4×10^{-4}	2.7×10^{-5}	1.0×10^{-5}	2.7×10^{-6}
95%	1.6×10^{-4}	3.4×10^{-5}	1.1×10^{-5}	3.3×10^{-6}

The smaller phase-space for ditau system – the more stringent limits!

Interpretation for K^{*0} and ϕ

Courtesy of LHCb-Imperial group



based on [Phys.Rev.Lett. 120 \(2018\) 181802](#)

- K^{*0} mode improved by an order of magnitude wrt Belle II ([PRL 135 \(2025\) 151801](#))
- first result for the ϕ decay mode

$$\mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \tau^-) < 2.8 \times 10^{-4} \quad (2.5 \times 10^{-4}) \text{ at 95\% (90\%) CL,}$$

$$\mathcal{B}(B_s^0 \rightarrow \phi \tau^+ \tau^-) < 4.7 \times 10^{-4} \quad (4.1 \times 10^{-4}) \text{ at 95\% (90\%) CL.}$$

About an order of magnitude away from predicted enhancements:
with adding more τ decay modes and new data can start probing new physics scenarios favored by $R(D^{(*)})$

Other tau decay modes?

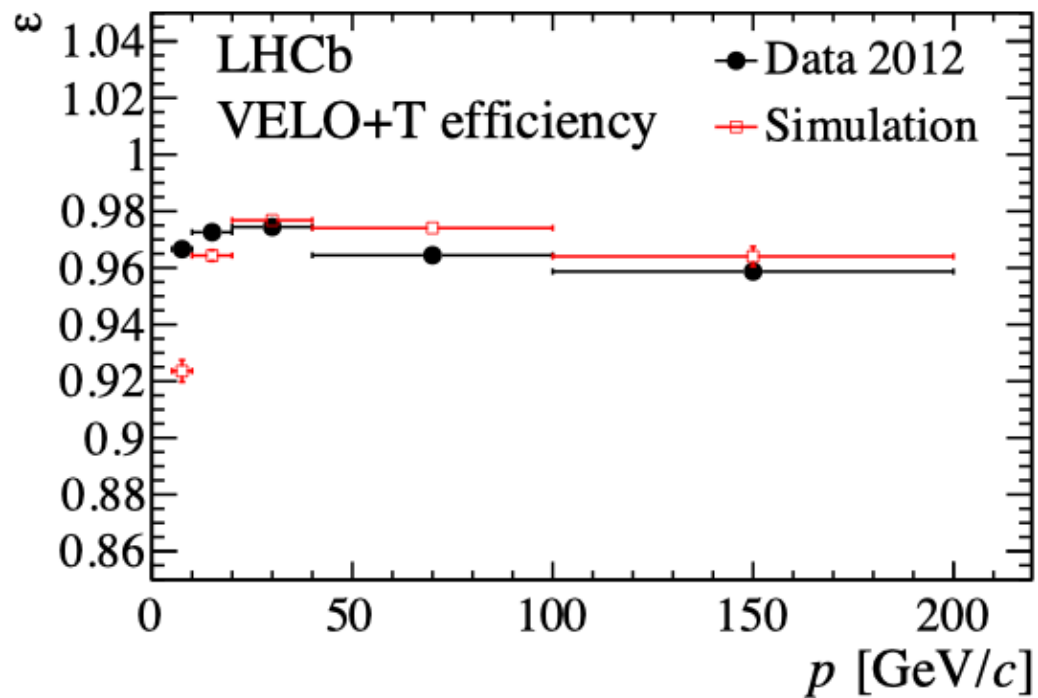
$\tau\tau$ decays: branching fractions

%	μ	e	$\pi^\pm(\pi^0)$	$3\pi^\pm(\pi^0)$	rest
one τ	17.4	17.9	36.3	13.5	14.9
μ	3.0				
e	6.2	3.2			
$\pi^\pm(\pi^0)$	12.6	13.0	13.2		
$3\pi^\pm(\pi^0)$	4.7	4.8	9.8	1.8	
rest	5.2	5.3	10.8	4.0	2.2

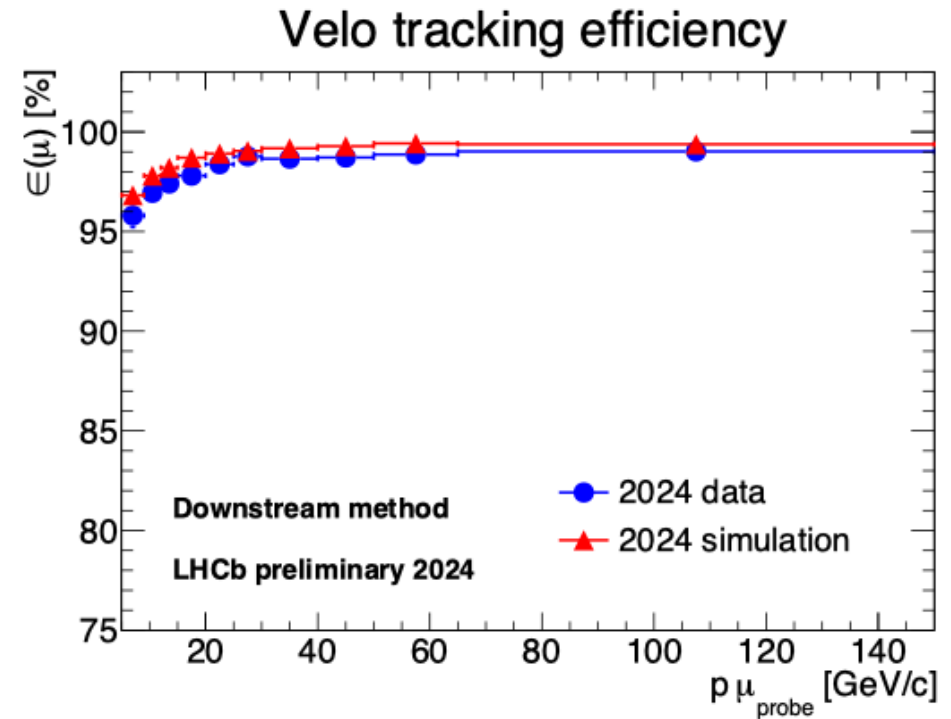
- multiple options to consider to maximize the sensitivity
- traditionally, 6π final state was pursued (e.g. $B_S^0 \rightarrow \tau\tau$)
- now, $\mu\mu$ and $3\pi\ell$ states are also included
- electrons are still often neglected

Track efficiencies at LHCb

- Typical tracking efficiencies go from 95% to 98%



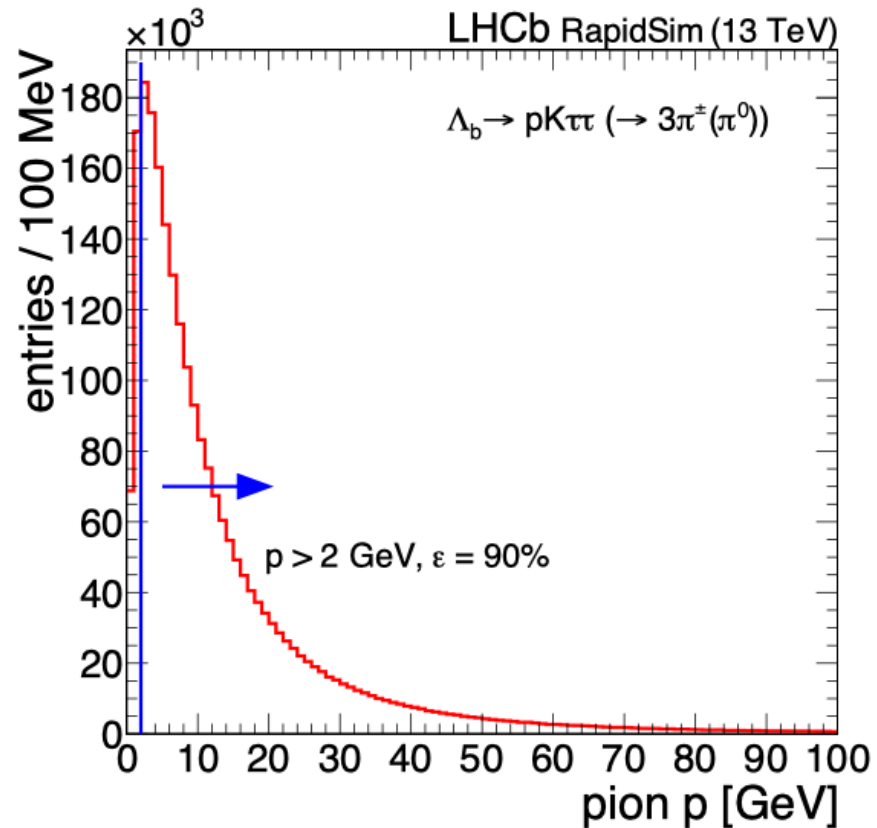
[JINST 10 \(2015\) 02, P02007](#)



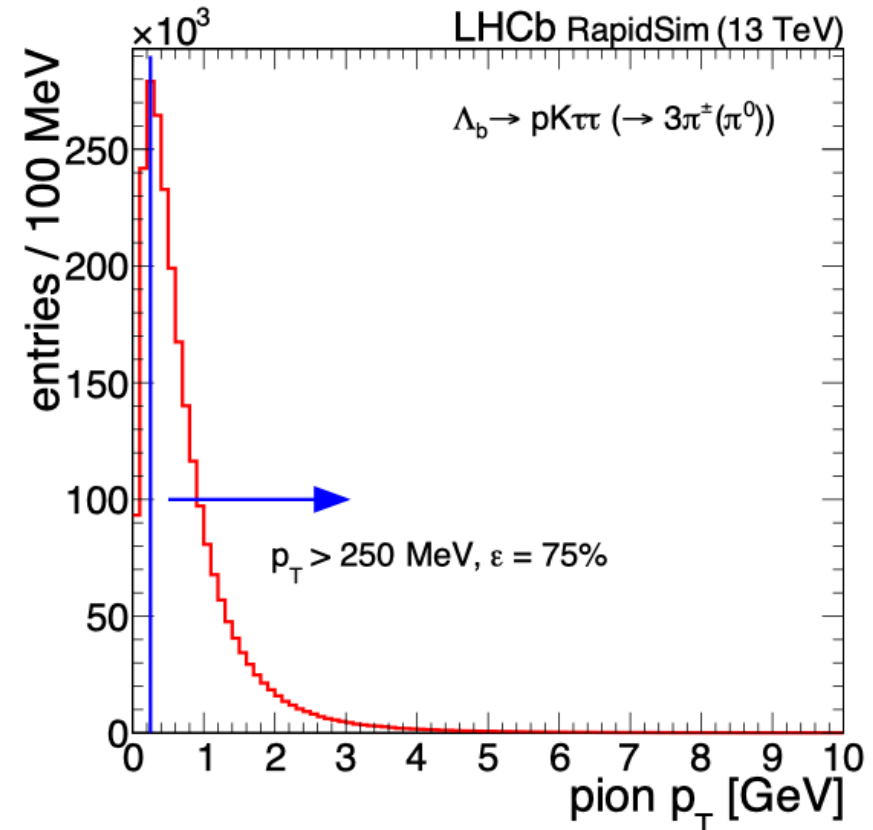
[LHCb-FIGURE-2024-032](#)

Real efficiency per track

- Typical pion track selection:
 - $p > 2 \text{ GeV}$ ($\varepsilon = 90\%$)



- $p_T > 250 \text{ MeV}$ ($\varepsilon = 75\%$)



Total efficiency per track

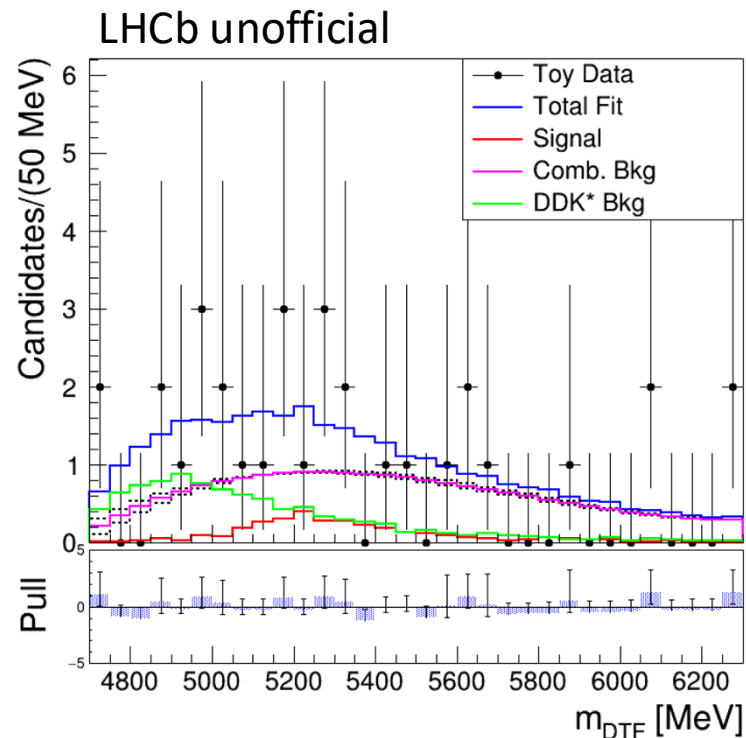
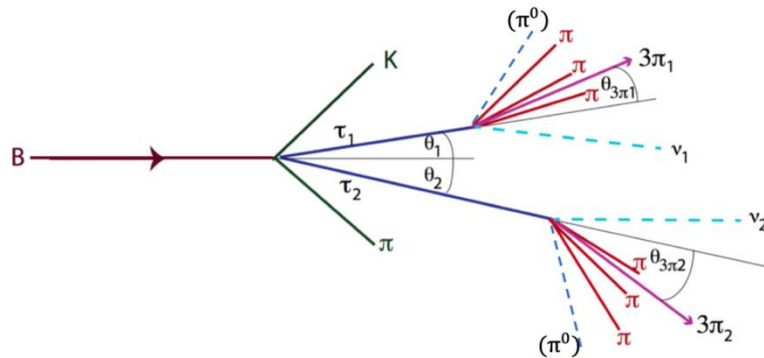
- Total efficiency per track:
 - $95\% \times 75\% = 71\%$ (even **lower** if take into account cuts on impact parameter!)
- Impact on the branching table:
 - 2μ : 3.0% \rightarrow 1.5%
 - $\mu + 3\pi$: 4.7% \rightarrow 1.1%
 - 6π : 1.8% \rightarrow 0.2%
- In 6π , factor 6 loss of efficiency compared to the mixed mode:
 - to compensate (*think S/\sqrt{B}*), need at least **factor 40** suppression of background with 3π compared to μ
- We learnt it a hard way that 6π is not competitive with $\ell + 3\pi$:
 - ran full analysis, and got an expected limit $\times 10$ worse

B^0 decays:

PhD theses with Run 2 data

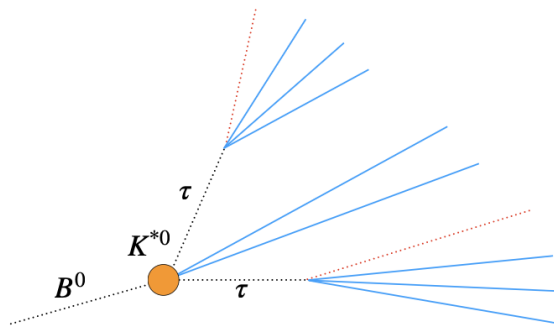
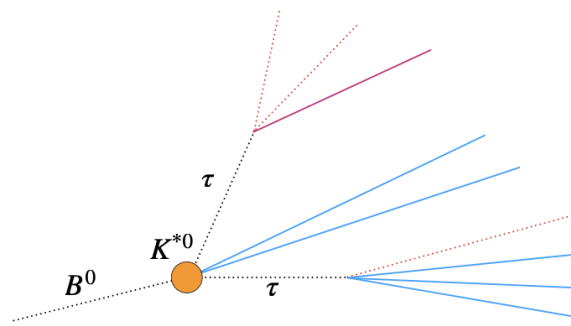
- ❑ Jacopo Cerasoli, “Search for the rare $B^0 \rightarrow K^{*0} \tau^+ \tau^-$ decay at the LHCb experiment”, [CERN-THESIS-2022-017](#) (2021)
- ❑ Arvind Venkateswaran, “Probing lepton flavour universality with $B^0 \rightarrow K^{*0} \tau^+ \tau^-$ ”, [CERN-THESIS-2022-124](#) (2022)

Arvind's thesis

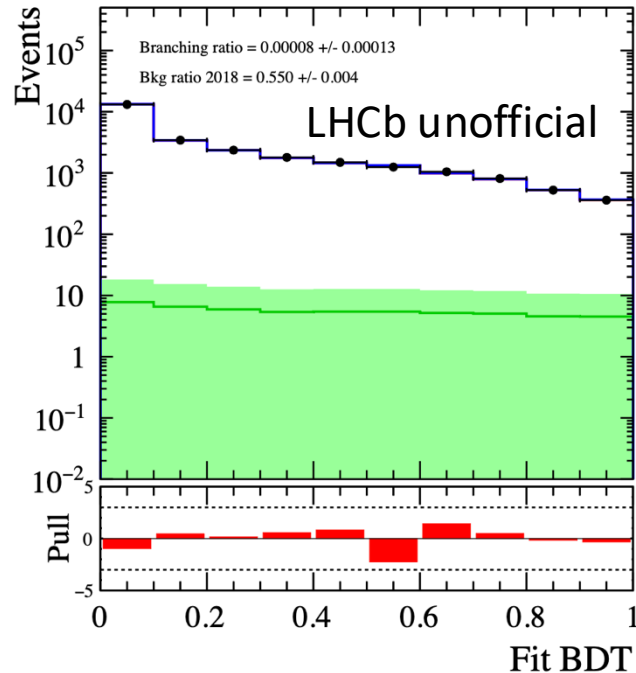
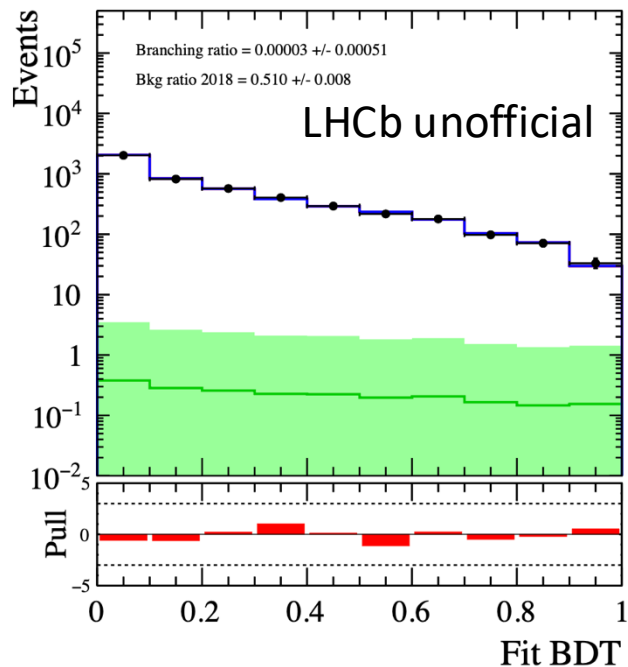


- one channel: 6π
- modified decay tree fitter (DTF) to account for missing neutrinos
- dedicated BDT to suppress bkg
- fit the DTF mass distribution
 - combinatorial background
 - physics background (DDK*) with Gaussian constraints
- analysis in the low-bkg regime
- expected UL 1.5×10^{-3} @ 95% CL

Jacopo's thesis

(a) $3\pi 3\pi$ final state(b) $3\pi\mu$ final state

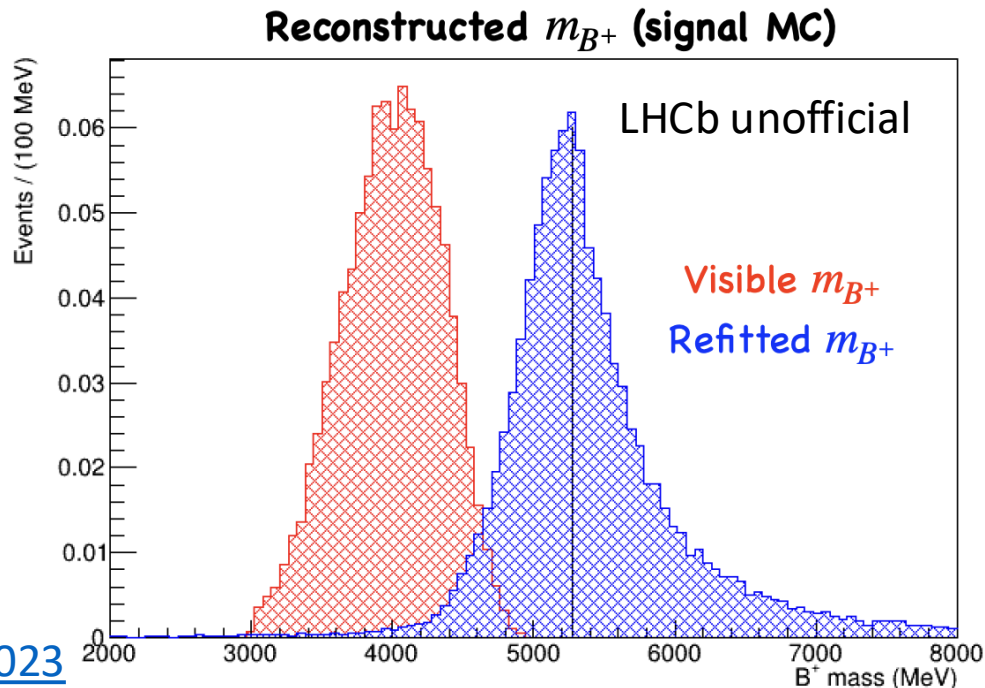
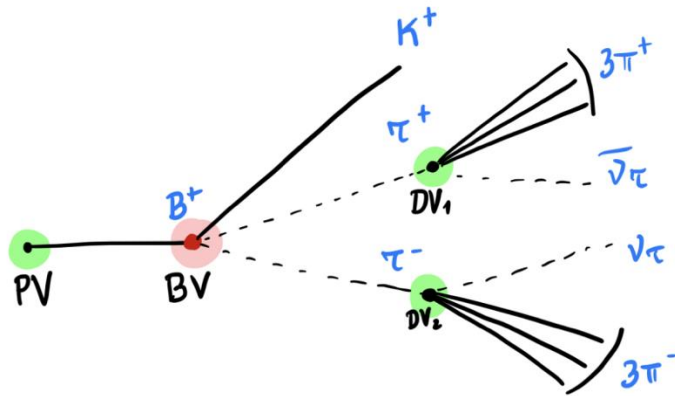
- two channels: $3\pi\mu$ and 6π
- signal extraction from a fit to a BDT output:
 - combinatorial bkg
 - signal contamination in the control region
- expected UL 3.2×10^{-4} @ 95% CL:
 - 1.3×10^{-3} for the 6π channel
 - 3.3×10^{-4} for the $3\pi\mu$ channel
- mixed mode dominates the sensitivity



$$B^+ \rightarrow K^+ \tau^+ \tau^- \text{ with } 6\pi^\pm$$

□ Maria Faria, “Search for the rare $B^+ \rightarrow K^+ \tau^+ \tau^-$ decay with the LHCb experiment” (2026)

Mass peak reconstruction improvements

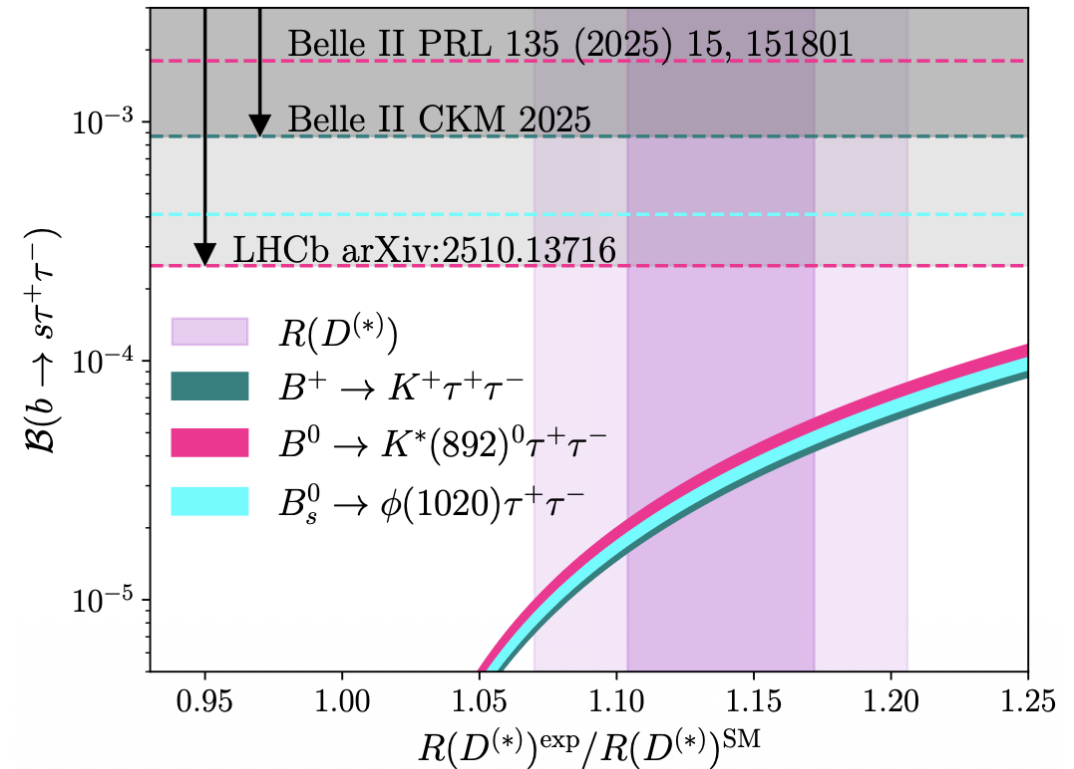


- using information on decay vertices and tau mass, can significantly improve mass fit:
 - **23 unknown** parameters, **24 constraints**
- mass resolution of **100 MeV** reached for a large fraction of events
- sensitivity of the 6π channel becomes comparable to the mixed mode:
 - **$< 4.5 \times 10^{-4}$ @ 90 %CL (Run 2, expected)**
- **having both taus reconstructed enables angular analysis in case of observation**

Putting it together: $B^0 \rightarrow K^{*0} \tau^+ \tau^-$

- 2μ channel: $< 2.8 \times 10^{-4}$
 - can gain a **factor 2** by adding $2e$ and $e\mu$ channels – from $\nu(\times 4)$
- $3\pi\mu$ channel: $< 3.2 \times 10^{-4}$ expected (thesis, could be optimistic)
 - can gain about 40% by adding $3\pi e$ channel
- $6\pi^\pm$ channel can be brought to a similar level with new developments
- \Rightarrow about 10^{-4} is within reach with Run 2
- If no advances in analysis strategy, to get to 10^{-5} need $\times 100$ more data
- LHCb Upgrade II gives $\times 40 \Rightarrow 1.5 \times 10^{-5}$
 - can get there in mid-2040s

Courtesy of LHCb-Imperial group



$\Lambda_b \rightarrow pK\tau\tau$:
master's thesis with Run 2 data

□ Kai Kang, “Search for rare decay $\Lambda_b^0 \rightarrow pK^-\tau^+\tau^-$ ”, [CERN-THESIS-2024-116](#) (2024)

$\Lambda_b \rightarrow pK\tau\tau$: master's thesis

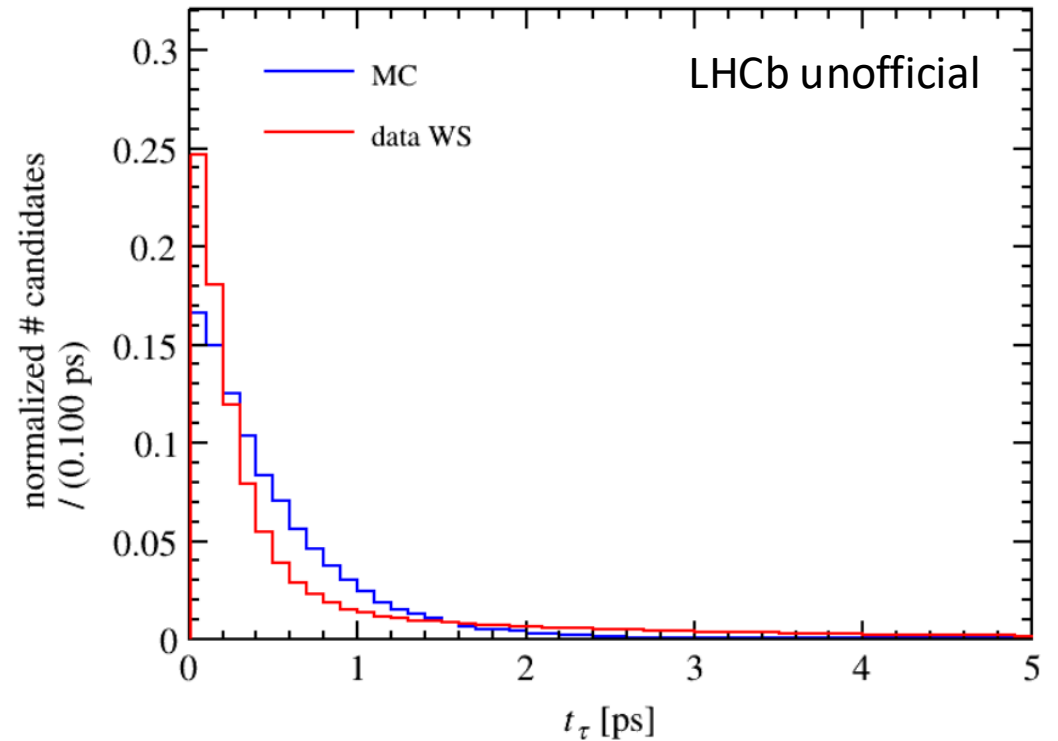
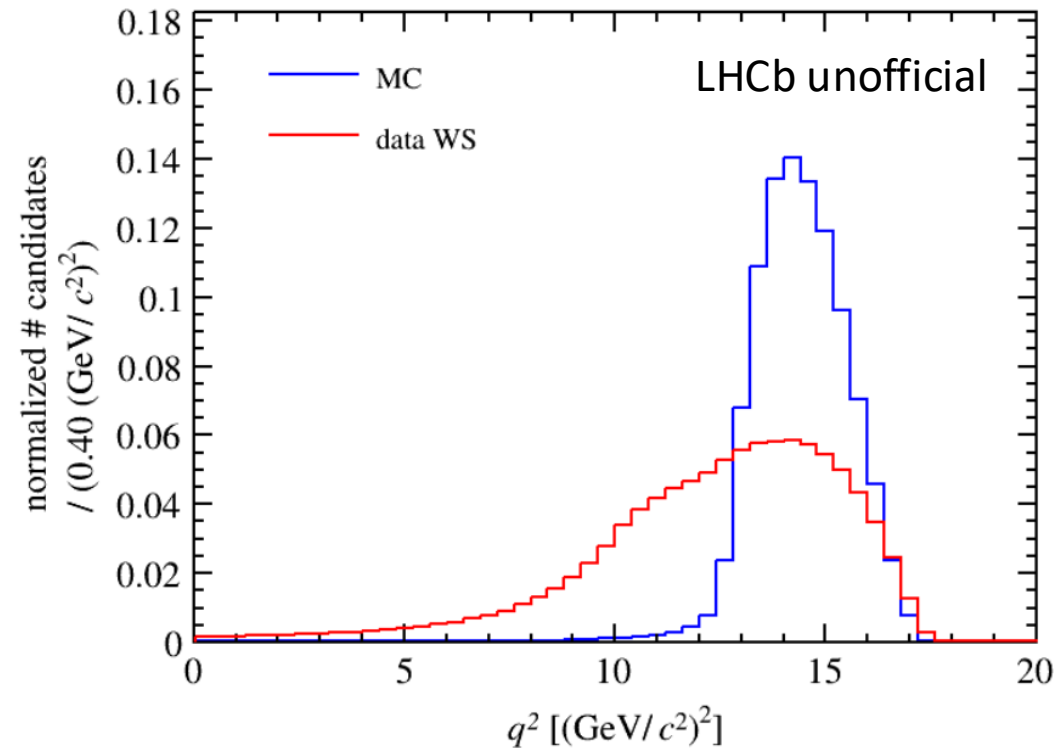
(NB: expected sensitivity blinded by an unknown MC filtering efficiency 😊)

- Strategy:

- Maximize signal efficiency by using both $\mu+3\pi$ and $e+3\pi$ modes
 - electrons are not liked in LHCb due to poor momentum and hence mass resolution
 - but here mass resolution is irrelevant as it is already not usable due to neutrinos
 - electrons serve to “tag” the event with a presence of lepton and suppress bkg
 - 3π side of the event is used to infer a presence of the τ
- use $q^2(\tau\tau)$ and $\tau(\rightarrow 3\pi)$ lifetime shapes fit for signal extraction
- a set of mass vetos to reject physics background
- a BDT to reject combinatorial background
 - take special care that wrong-sign/right-sign distributions stay the same
- use wrong-sign shape in data as a bkg shape in the fit

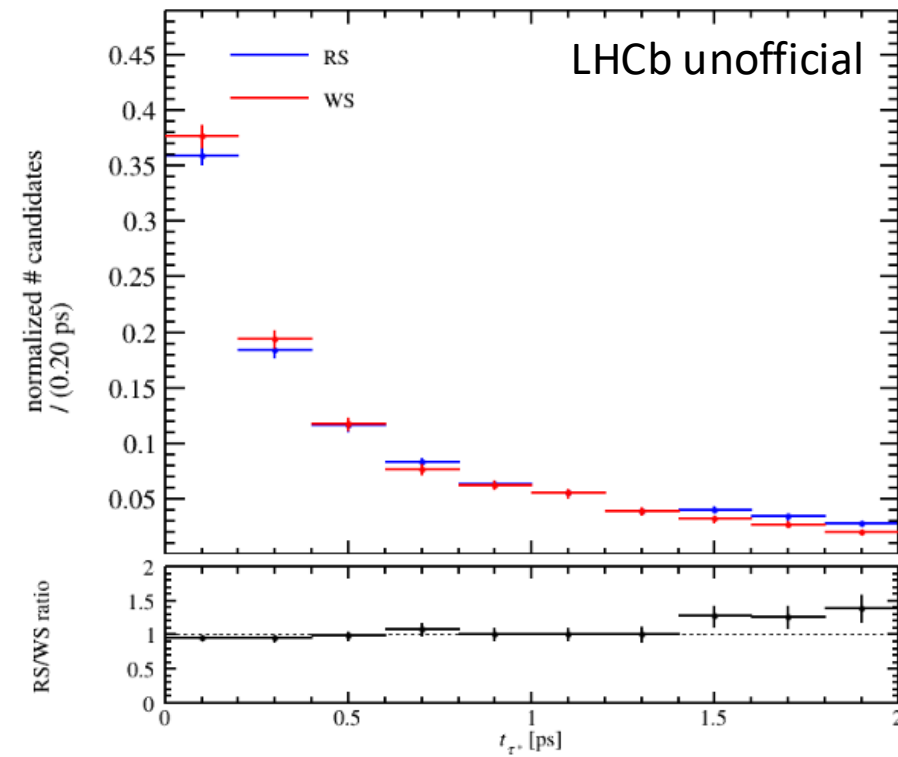
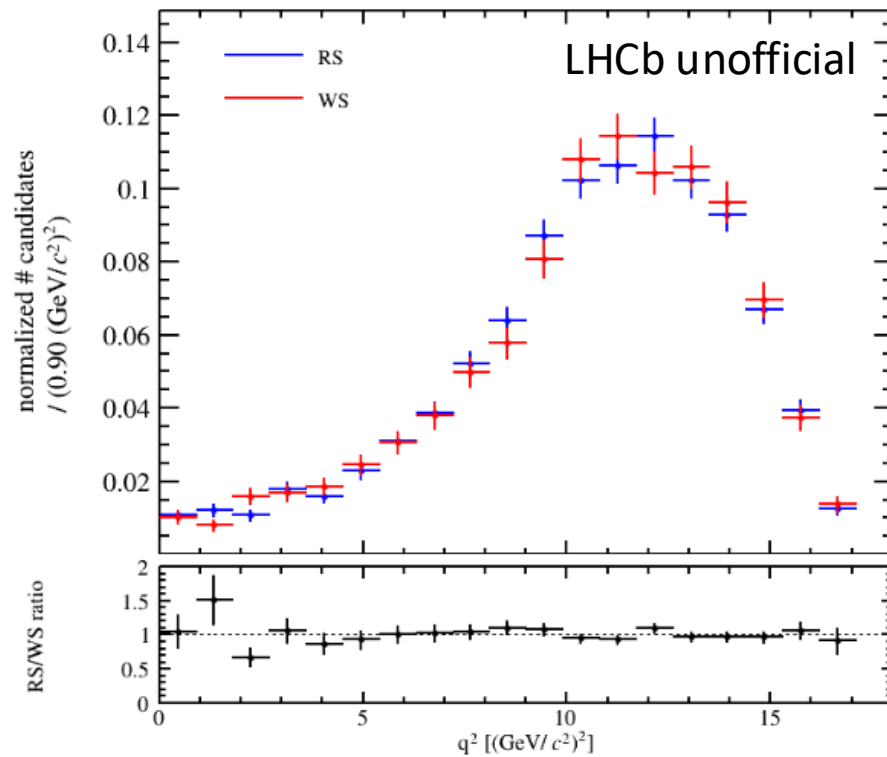
Fit variables in the $3\pi\mu$ channel: signal

- $q^2(\tau\tau)$ computed from Λ_b^0 PV and SV (pK vertex) and pK momenta
- $\tau(\rightarrow 3\pi)$ lifetime computed from visible products: largely follows the exponential



Fit variables in the $3\pi e$ channel: background

- distributions after the BDT selection:
 - wrong-sign taus wrt right-sign taus in a control region



Sensitivity for $\Lambda_b \rightarrow pK\tau\tau$ in the mixed channel

- The numbers in the thesis are too optimistic
 - sensitivity is weaker due to missing signal efficiency factor, $O(10^{-4})$
- Conclusions about $3\pi\mu$ and $3\pi e$ channels:
 - $3\pi\mu$ leads the sensitivity
 - $3\pi e$ adds 15% improvement
- In Run 2, electron mode power is limited by the hardware trigger:
 - harder p_T selection on an electron than on a muon
- In Run 3, electrons will be more important:
 - kinematic selections can be more aligned, softer electron and larger signal acceptance

Extrapolating from the muonic B^0 result

- $m(\Lambda_b) - m(p) - m(K^\pm) = 5620 - 938 - 494 - 4188 \text{ MeV}$
- $m(2\tau) = 3554 \text{ MeV}$

\Rightarrow available energy is 634 MeV

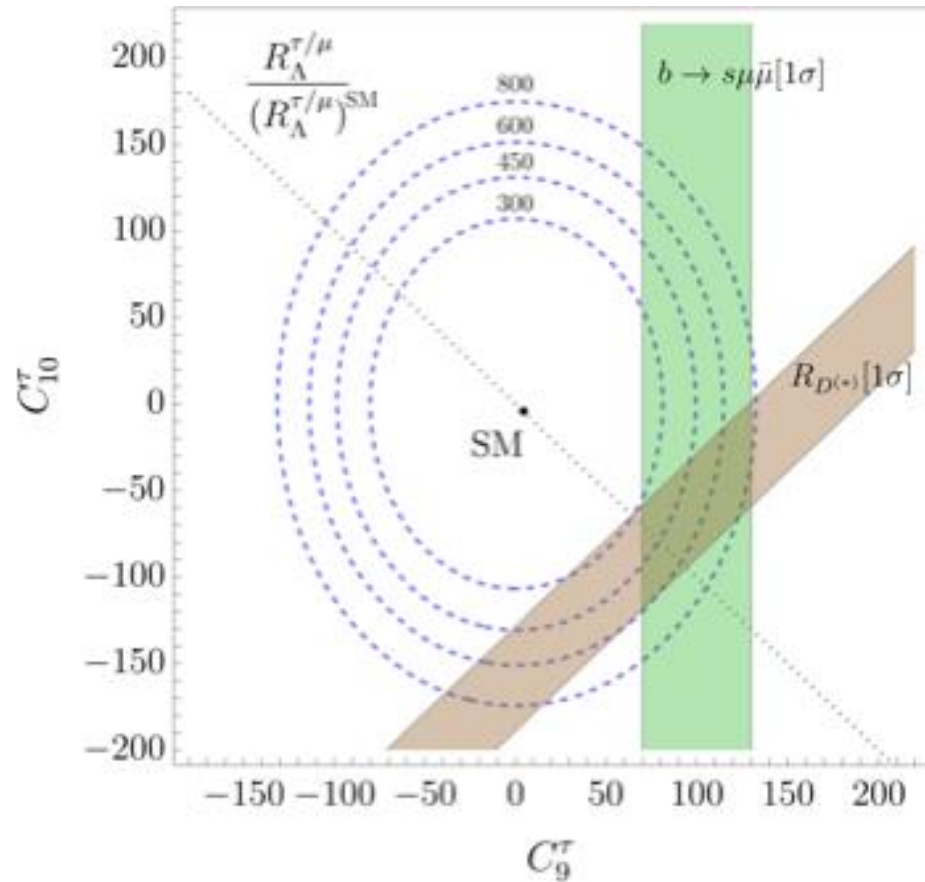
\Rightarrow approximation of taus produced at rest works very well!

Kinematic regime in Λ_b decay is equivalent to the **second bin** of the dimuon analysis

\Rightarrow might achieve sensitivity of the order of $\text{few} \times 10^{-5}$!

Confidence level	Upper limit on $\mathcal{B}(B^0 \rightarrow K^+\pi^-\tau^+\tau^-)$			
$m_{K^+\pi^-}$ (MeV/ c^2)	[792, 992]	[992, 1330]	[1330, 1530]	[1530, 1726]
90%	1.4×10^{-4}	2.7×10^{-5}	1.0×10^{-5}	2.7×10^{-6}
95%	1.6×10^{-4}	3.4×10^{-5}	1.1×10^{-5}	3.3×10^{-6}

Which Λ_b sensitivity is interesting



future. Our analysis demonstrates that, even in the absence of a direct observation, upper bounds below 10^{-4} would already provide useful constraints on motivated models. The framework we have presented can also be extended to related baryonic channels, in particular to the $\Lambda_b \rightarrow pK\tau^+\tau^-$ decay,

- below 10^{-4} is around the corner!
- more precise predictions for the pK decay mode are wanted!

Summary

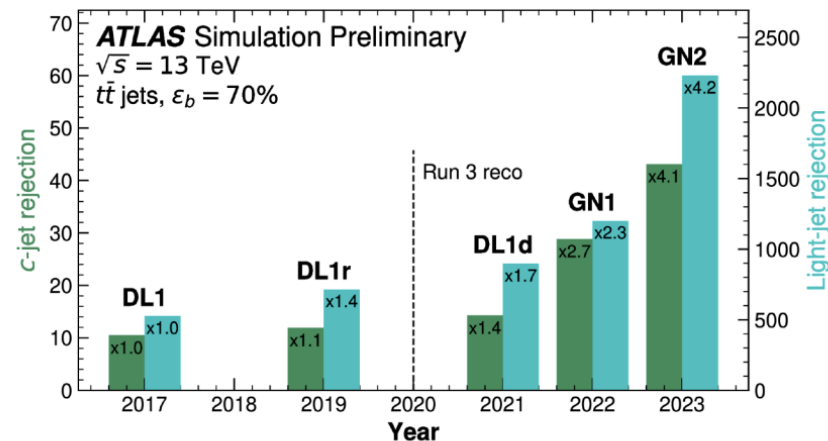
- LHCb Run 2 sensitivity reaches 10^{-4} for typical $b \rightarrow s\tau\tau$ transitions
 - but potentially can start probing 10^{-5} for Λ_b decays already!
- if no improvement in data analysis techniques, can get to 10^{-5} in meson decays after full exploitation of the LHCb Upgrade II
- current LHCb Upgrade allows to operate at lower p_T thresholds for tracks
 - potential impact on the sensitivity is not investigated yet
 - can gain another factor of 2-3: e.g. $(90\%/70\%)^4$ for $3\pi\ell$ final state
- There is room for innovative ideas to progress more:
 - inclusive reconstruction for one of the taus?
 - ML methods for efficient b hadron/tau pattern recognition?
 - full event information usage?
 - **Various R&D is ongoing!**

Recent progress beyond lumi scaling (1)

Di-Higgs 5σ observation at HL-LHC can be possible with new jet tagging tools!

4 times better background rejection-> these algorithms are not yet used for the published analyses! They will be available for run 3 analyses.

small r-jet tagging Jet Flavour Tagging With GN1 and DL1d



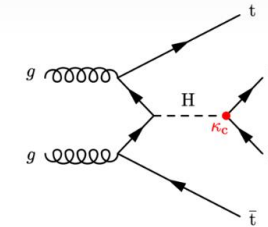
- Boosted b-tagging: new algorithm, GN2X for large-radius jets: discriminating boosted H(bb) jets and H(cc) jets.
- GN2X benefits from recent advances in flavour tagging of small-radius jets using Graph Neural Networks (GNNs) and transformer architectures

Recent progress beyond lumi scaling (2)

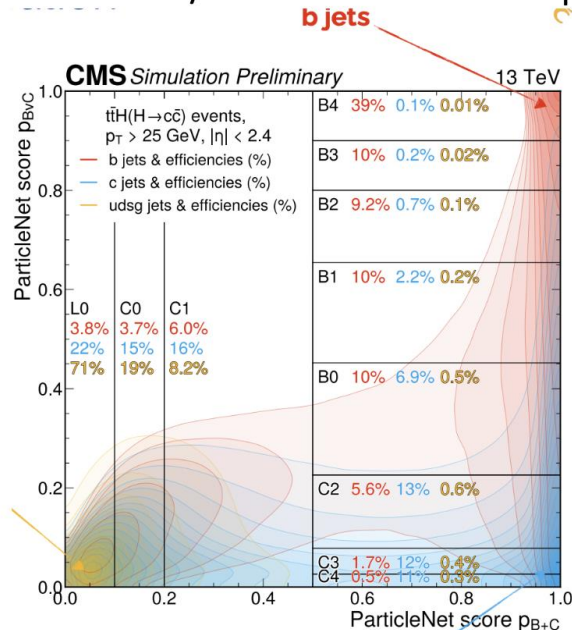
CMS gets to HL-LHC projected sensitivity to Higgs-charm coupling already in Run 2!

S. Wuchterl

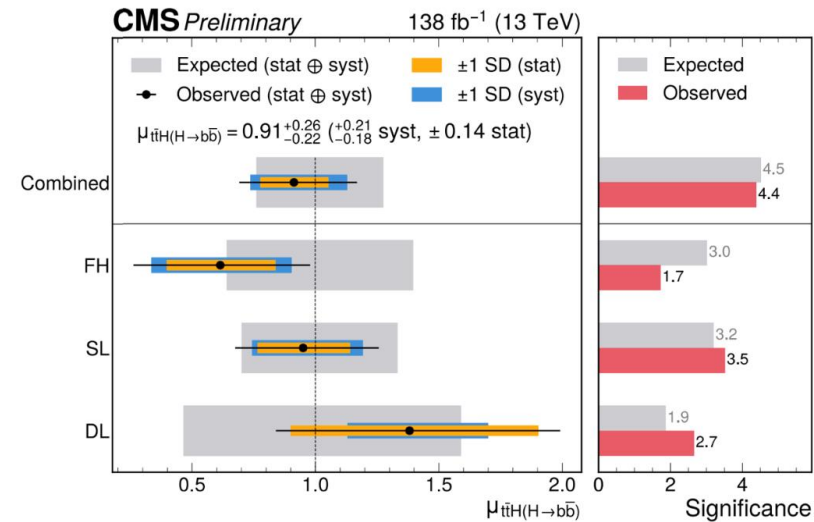
Higgs boson: coupling to charm in ttH



Simultaneous treatment of b, c, light jets
 Simultaneous measurement of ttH(cc/bb), ttZ(bb/cc)
 Lessons from ttbb/ttcc measurements incorporated



Impact of the full-hadronic channel is the same as semileptonic and better than double-lepton!



- ttH(bb) signal strength is compatible with 1
- ttH(cc) $|\kappa_c| \lesssim 3.0$: reached HL-LHC projection!
- "18 years of progress in 3 years"

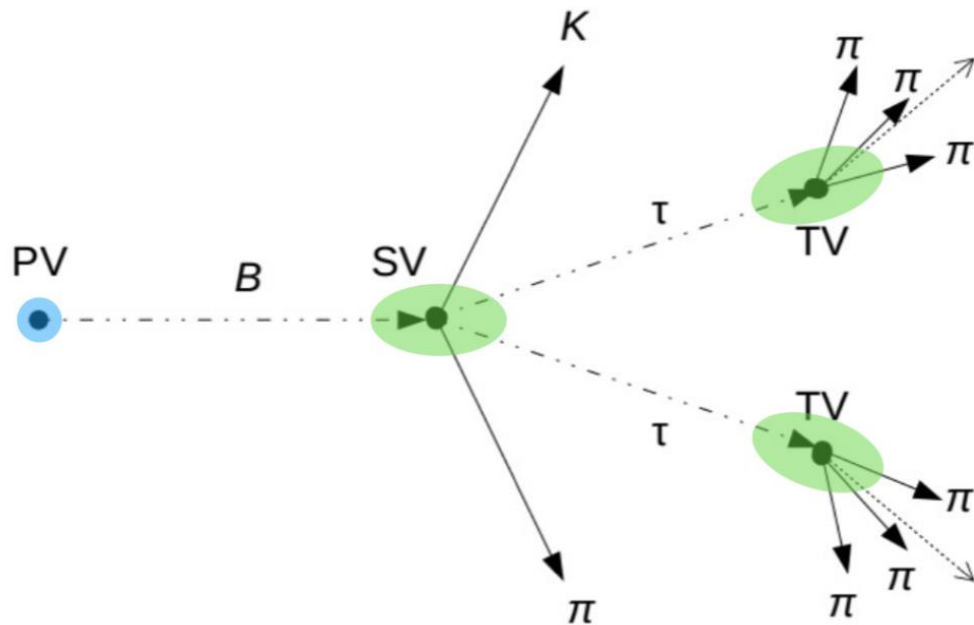


**Bonus
slides**

LFV searches: similar techniques

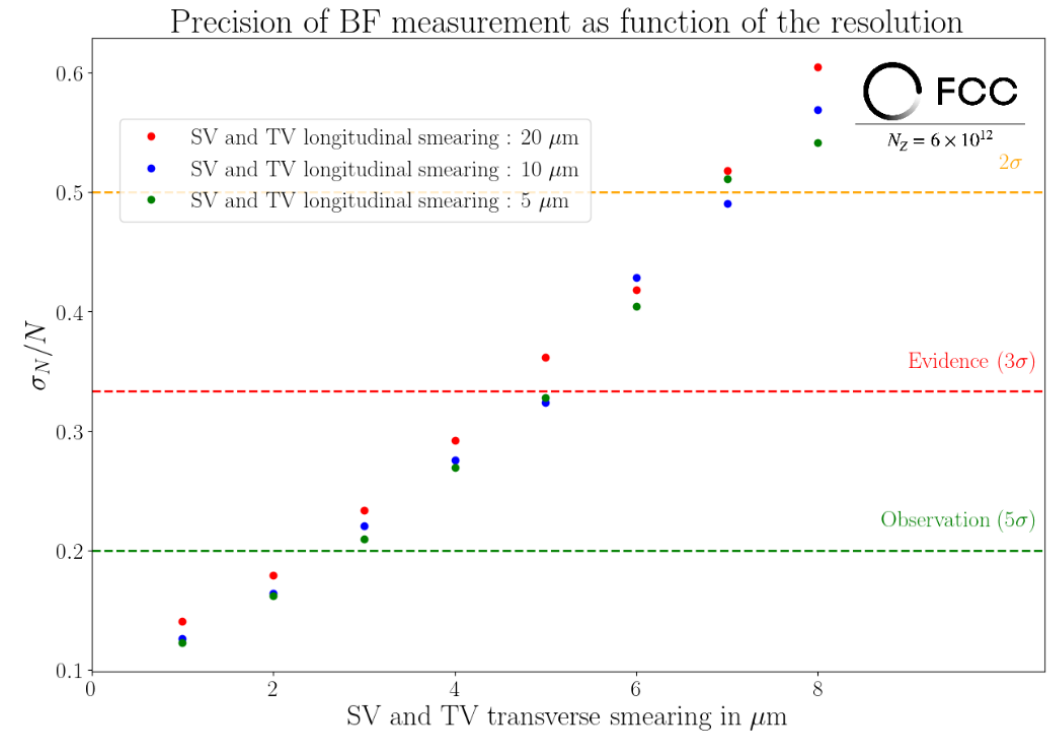
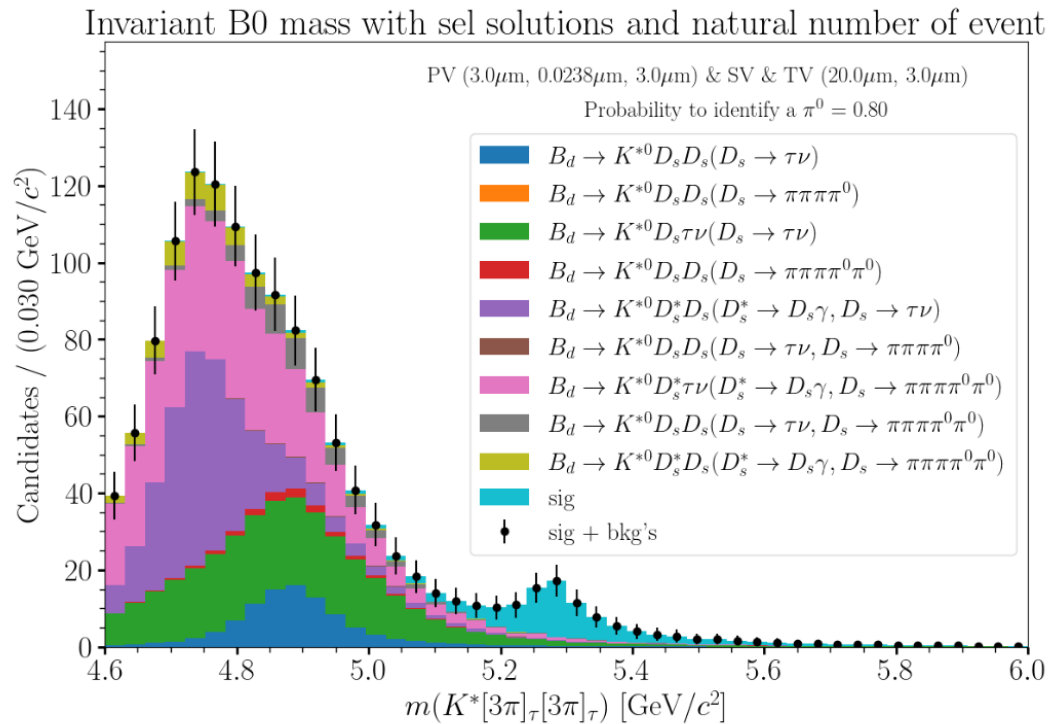
- Rich range of results using $\tau \rightarrow 3\pi^\pm(\pi^0)$ decay mode to tag taus:
 - $B^0 \rightarrow K^{*0}\tau^\pm\mu^\mp$: $< 1.0 \times 10^{-5}$ ([arXiv:2209.09846](#), *JHEP* 06 (2023) 143)
 - $B_S^0 \rightarrow \phi\tau^\pm\mu^\mp$: $< 1.1 \times 10^{-5}$ ([arXiv:2405.13103](#), *Phys.Rev.D* 110 (2024) 7)
 - $B^0 \rightarrow K^{*0}\tau^\pm e^\mp$: $< 0.6 \times 10^{-5}$ ([arXiv:2506.15347](#), *JHEP* 11 (2025) 172)
 - **NB: electron channel almost $\times 2$ better than muon one \Rightarrow analysis improvements!**
- One result using missing mass handle to infer tau lepton presence:
 - $B^+ \rightarrow K^+\tau^+\mu^-$: $< 4.5 \times 10^{-5}$ ([arXiv:2003.04352](#), *JHEP* 06 (2020) 129)
- To put these numbers into context:
 - $B_S^0 \rightarrow \tau^+\tau^-$: $< 6.8 \times 10^{-3}$ ([arXiv:1703.02508](#), *Phys.Rev.Lett.* 118 (2017) 25, 251802)
 - $B_S^0 \rightarrow \tau^+\mu^-$: $< 4.2 \times 10^{-5}$ ([arXiv:1905.06614](#), *Phys.Rev.Lett.* 123 (2019) 21, 211801)
 - \Rightarrow having $\tau \rightarrow 3\pi^\pm(\pi^0)$ instead of ℓ costs two orders of magnitude in sensitivity

FCC-ee projections for $B^0 \rightarrow K^{*0} \tau^+ \tau^-$



- target: SM value of $O(10^{-7})$
- sensitivity is studied in the 6π channel
- special attention to the vertexing performance:
 - green ovals show studied smearing to vertex precision
 - discovery potential obtained as a function of vertex resolution

FCC-ee projections for $B^0 \rightarrow K^{*0} \tau^+ \tau^-$



- 10^{-7} is achievable with micron precision in vertex measurement
- two orders or magnitude jump over rule-of-thumb LHCb projections