Lepton flavour universality tests and related measurements at LHCb

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on behalf of the LHCb collaboration

17^{th} May 2023

Rencontres de Blois

Lepton Flavour Universality (LFU) & b decays

SM couplings of leptons ($\ell \in \{e, \mu, \tau\}$) to vector bosons are flavour-independent.

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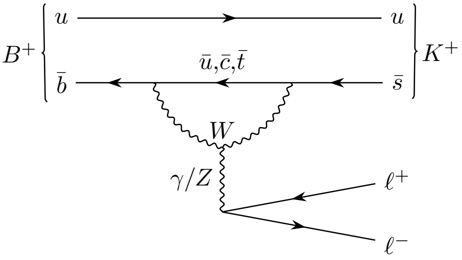

$b \to s\ell^+\ell^-$ 🐧

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- NP can enter at tree-level
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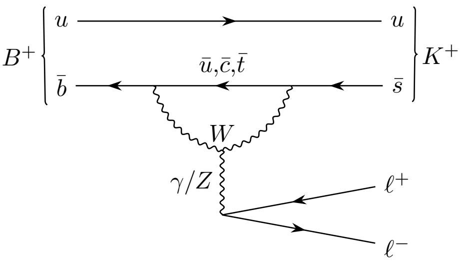

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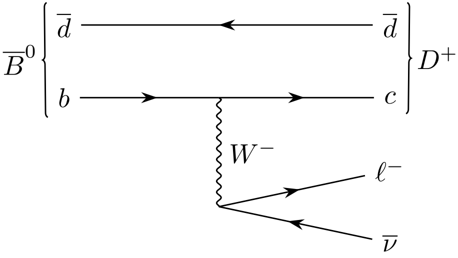


$b \to c\ell^-\overline{\nu}_\ell$

- flavour-changing neutral current (FCNC)
- NP can enter at tree-level
  $\Rightarrow$ enhancement w.r.t. SM

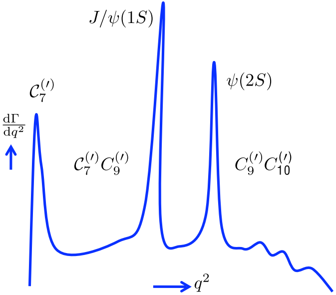
- tree-level $\Rightarrow$ enhanced $\mathcal{B}$
- different process $\Rightarrow$ complementary NP sensitivity

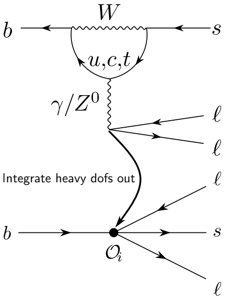
The bigger picture

If NP is at high mass scales, effect on b-decays is short-distance

$\Rightarrow$ describe using $\mathcal{H}_{\text{eff}} \propto -\sum_i C_i \mathcal{O}_i$.

- local operators relevant in different $q^2 \equiv m_{\ell\ell}^2$ regions
- "effective coupling" coefficients may be affected by NP
  - LFU-violating? [M. Ciuchini *et al.*]
  - with universal component? [A. Greljo *et al.*]
  - CP-violating? [R. Fleischer *et al.*]
  - what about the Cabibbo anomaly? [A. Crivellin *et al.*]
- fits to C_i used to inform model building
  - leptoquark, charged Higgs, Z', ...





LFU probes: ratios of branching fractions

$$R_{H_s} = \frac{\mathcal{B}(H_b \to H_s \ell_1^+ \ell_1^-)}{\mathcal{B}(H_b \to H_s \ell_2^+ \ell_2^-)} \qquad R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \ell_1 \nu_1)}{\mathcal{B}(H_b \to H_c \ell_2 \nu_2)}$$

✓ theoretically clean: cancellation of hadronic uncertainties

- $1 + \mathcal{O}(\%)$ EM correction[1] + ℓ_1/ℓ_2 mass effect

✓ experimentally clean: cancellation of common systematics

✗ leptons are similar theoretically, but not in LHCb data

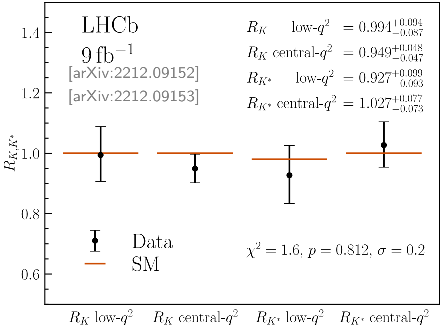
$\Rightarrow$ each flavour has specific experimental challenges

[1] [JHEP 06 (2016) 092] [JHEP 07 (2007) 040] [EPJC 76 (2016) 440] [PRD 69 (2004) 074020] [PRD 68 (2003) 094016] [EOS] [flavio]

Ratios of branching fractions at LHCb

$$R_{K,K^*}^{q_1^2,q_2^2} = \frac{\int_{q_1^2}^{q_2^2} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}(B^{(+,0)}\to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q_1^2}^{q_2^2} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}(B^{(+,0)}\to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}}$$

Example $b \to s\ell^+\ell^-$ ratios: R_K and $R_{K^{*0}}$



Compatible with SM, individual BFs in tension

(see C. Langenbruch's plenary talk)

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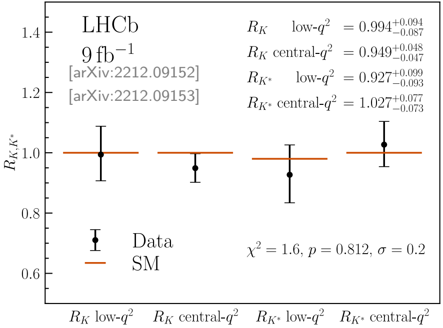
Example $b \to s\ell^+\ell^-$ ratios: R_K and $R_{K^{*0}}$

$$R_{D^0,D^*} = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}$$

Example $b \to c\ell^-\overline{\nu}_\ell$ ratios: R_{D^0} and R_{D^*}



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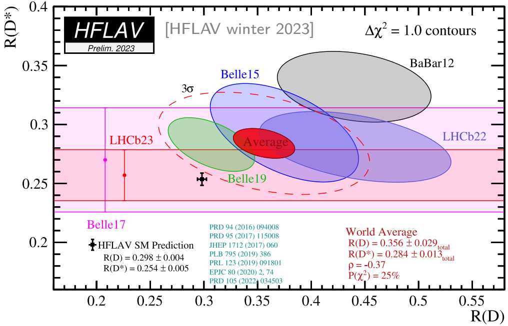
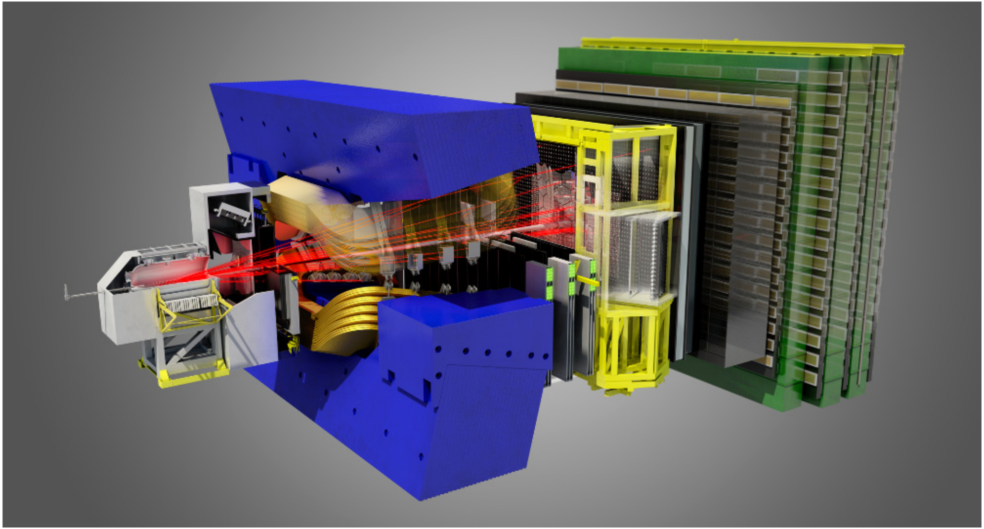


World average $\sim 3\,\sigma$ from SM
(LHCb tension within $1.9\,\sigma$)

The LHCb detector



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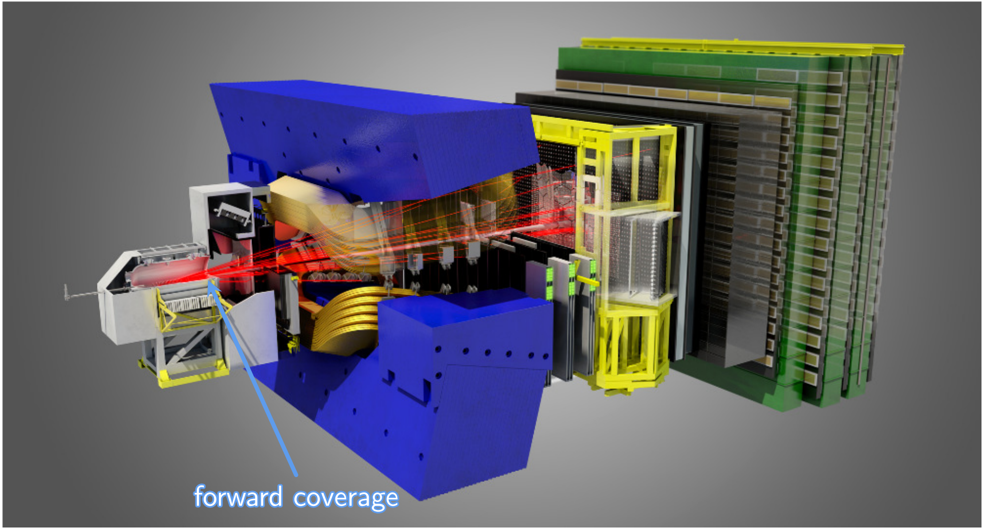
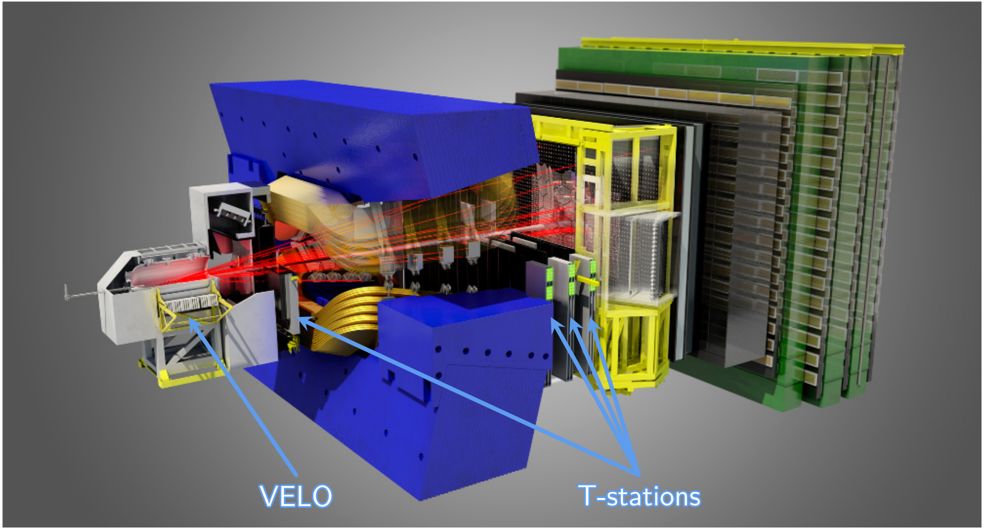


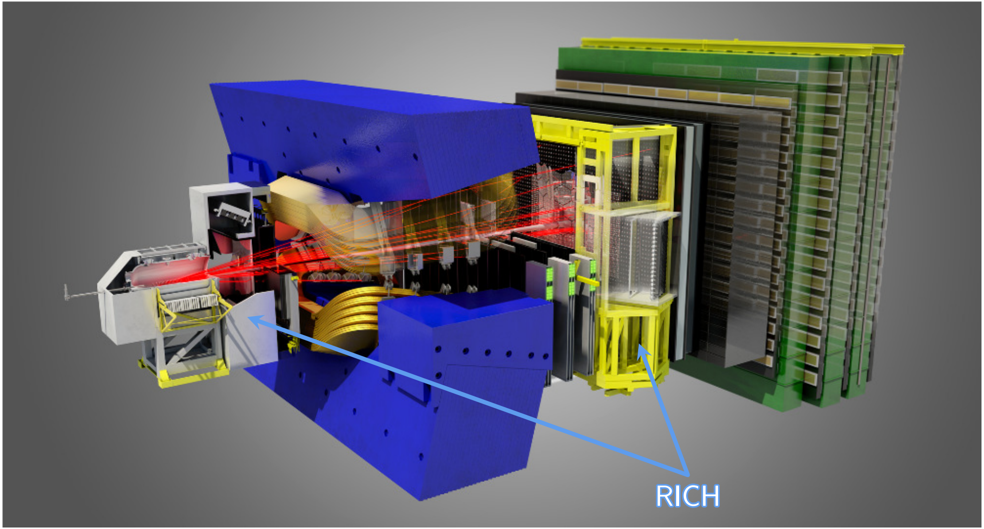
$\sigma_{b\bar{b}}$ up to ~ 500 µb

The LHCb detector



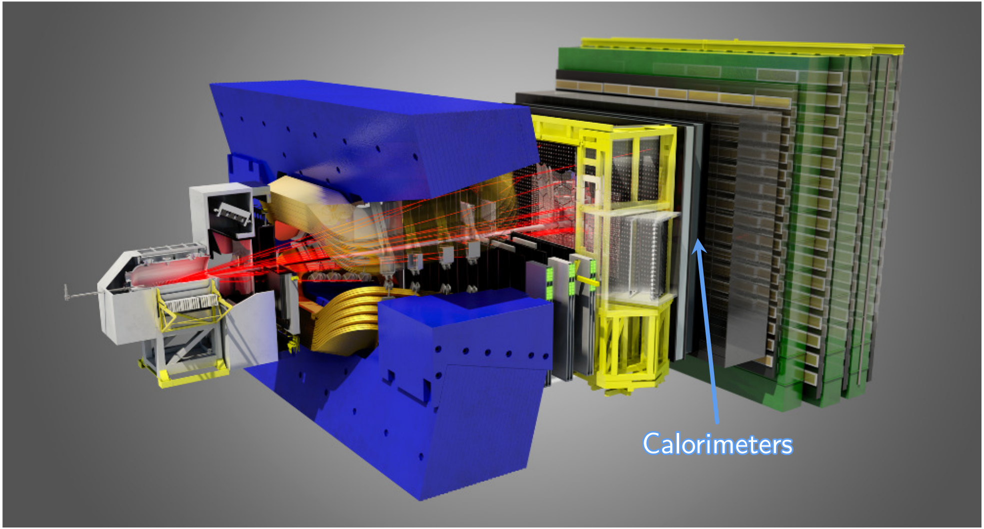
$$\sigma_{\mathrm{IP}} = (15 \pm 29/p_{\mathrm{T}})\ \mu\mathrm{m} \qquad \sigma_p/p \in [0.5\%,\ 1\%]$$

The LHCb detector



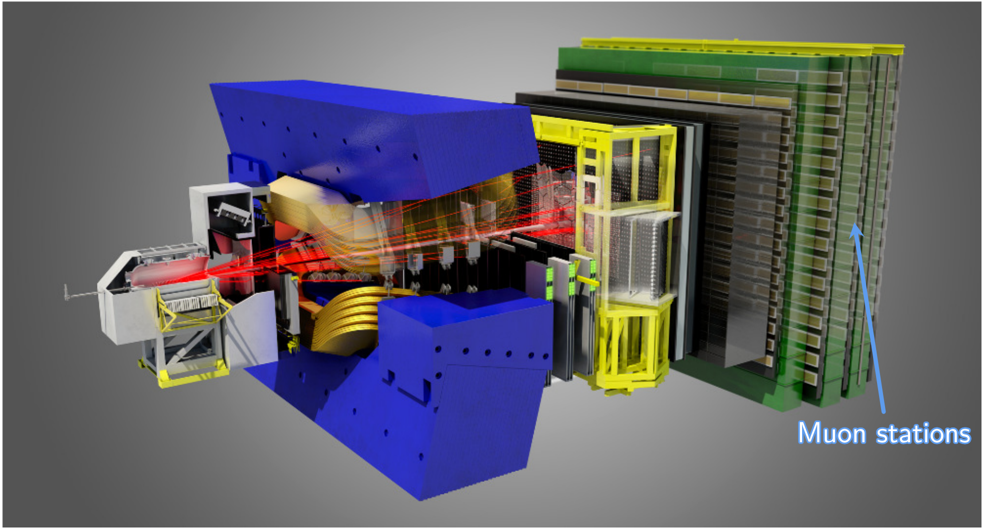
$$\varepsilon_{K\to K} \sim 95\%,\ \varepsilon_{\pi\to K} \sim 5\%$$

The LHCb detector



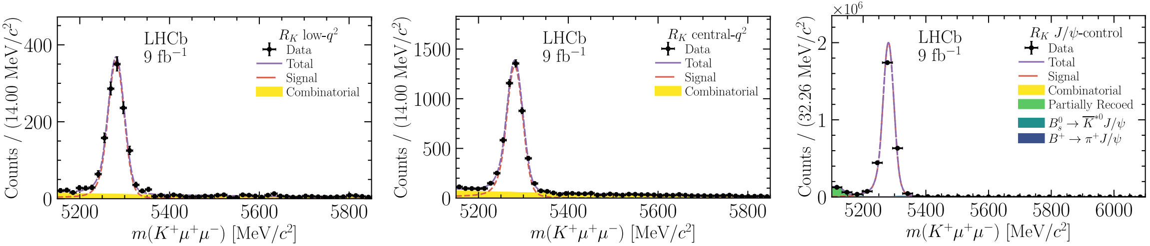
$$\sigma_E/E = 1\% + 10\%/\sqrt{E}$$

The LHCb detector

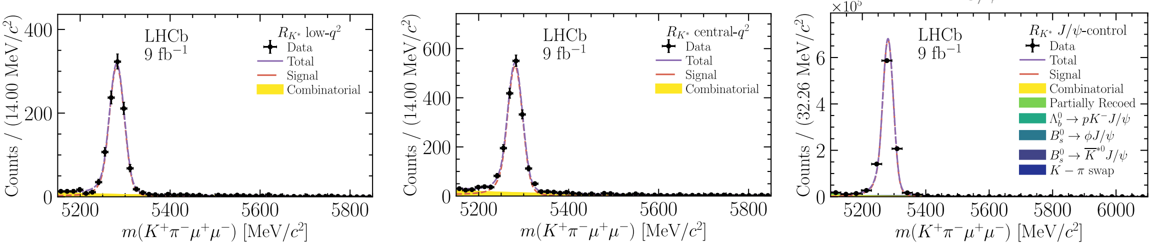


$$\varepsilon_{\mu\to\mu} \sim 97\%,\ \varepsilon_{\pi\to\mu} \sim 1-3\%$$

Muons at LHCb

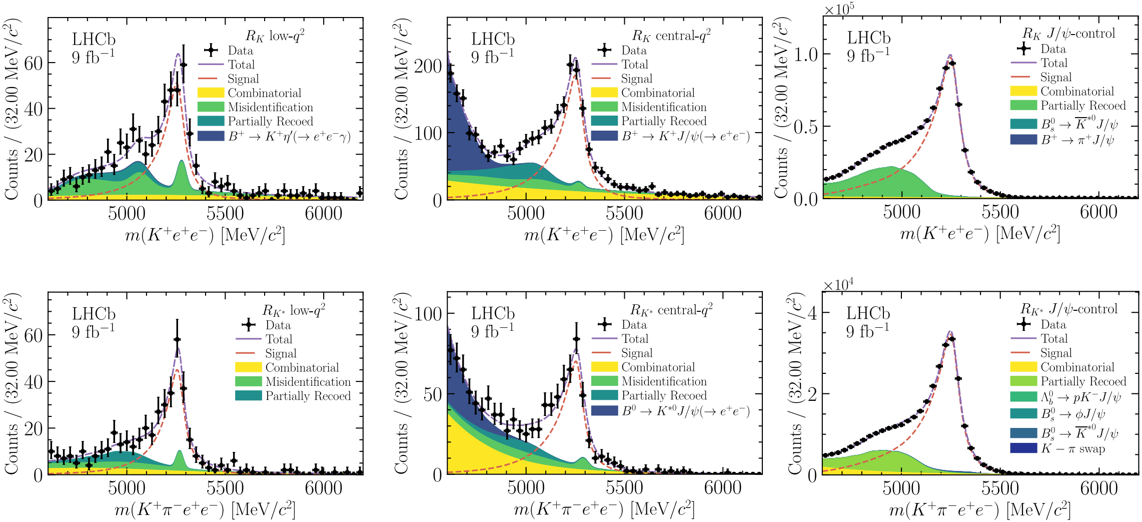


$q^2 \in [0.1,\ 1.1]$ GeV $\quad$ $q^2 \in [1.1,\ 6.0]$ GeV $\quad$ $|m_{\mu\mu} - m_{J/\psi}^{\text{PDG}}| < 0.1$ GeV



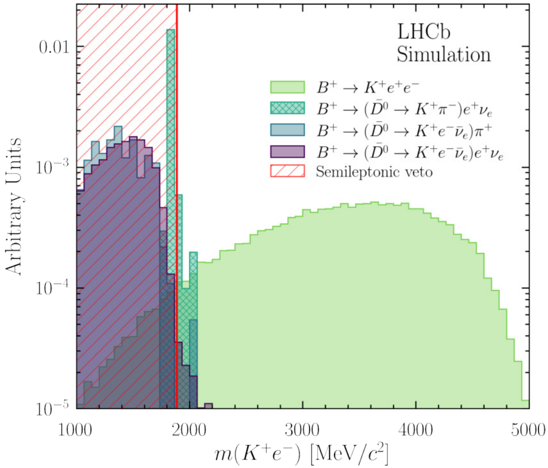
Well-defined very clean $\mu^+\mu^-$ peaks

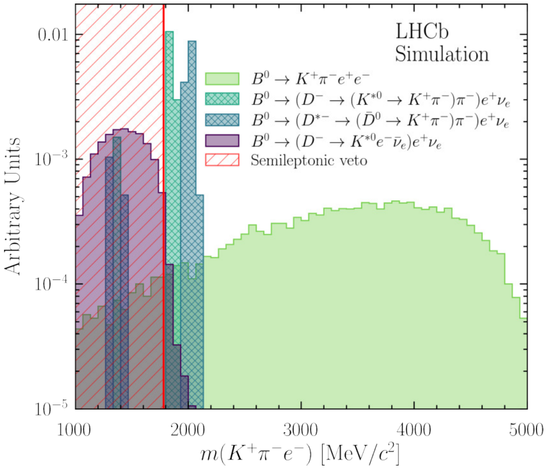
Electrons at LHCb



Diminished resolution of e^+e^- peaks, non-negligible background, challenging trigger, reco, PID

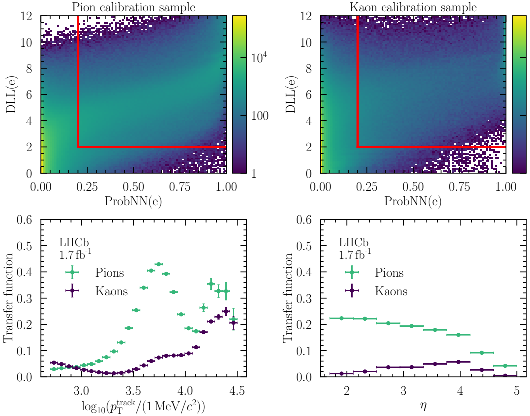
Background treatment in electron data (I)

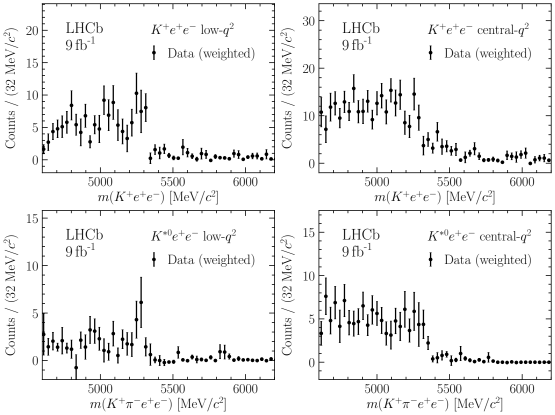




Semileptonic “cascades” and particle swaps removed using PID critera & specific vetoes

Background treatment in electron data (II)

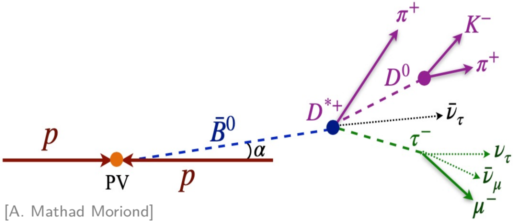




Control samples from inverted PID used to predict hadronic misID contamination & shape

- includes but not limited to: $B \to K\pi\pi$, $B \to KKK$, $B \to KK\pi\pi$, ...

Taus at LHCb



[A. Mathad Moriond]

Leptonic τ decays ($\mathcal{B} \sim 17\%$)

- main backgrounds:
  $B \to D^{**}\mu\nu$, $B \to D^{(*)}DX$
- muon mode can be used as normalisation
  - ✓ no need for external $\mathcal{B}$ input
- today: R_{D^0,D^*} 3 fb^{-1} [arXiv:2302.02886]
  - $R_{D^*} = 0.281 \pm 0.018 \pm 0.024$
  - $R_{D^0} = 0.441 \pm 0.060 \pm 0.066$

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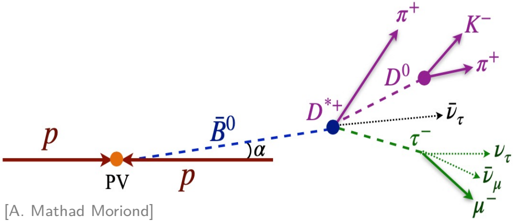

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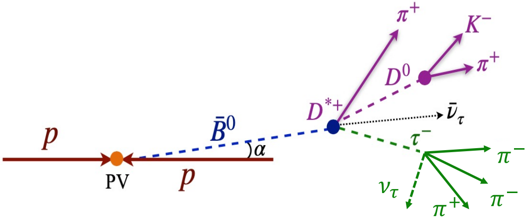

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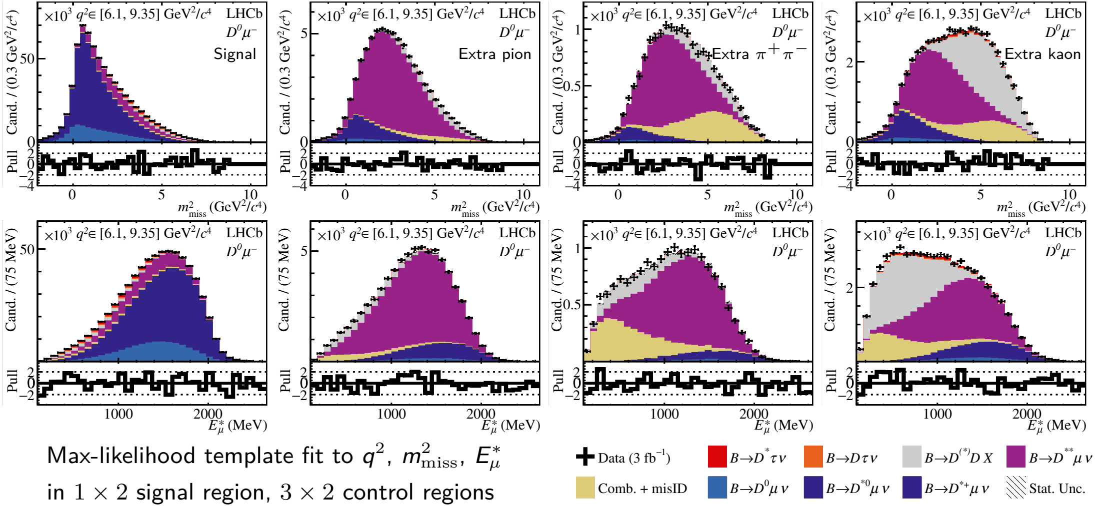
Hadronic τ decays ($\mathcal{B} \sim 14\%$)

- main backgrounds:
  $B \to D^*\pi\pi\pi X$, $B \to D^*DX$
- can reconstruct tau decay vertex
  - ✓ can discriminate using *e.g.* lifetime
- today: R_{D^*} 2 fb^{-1} [arXiv:2305.01463]
  - $R_{D^*} = 0.247 \pm 0.015 \pm 0.015 \pm 0.012$

Background treatment in muonic tau data [arXiv:2302.02886]



Max-likelihood template fit to q^2, $m^2_{\rm miss}$, E^*_μ

in 1×2 signal region, 3×2 control regions

Invert isolation cuts to access background-enriched samples, fit simultaneously with signal

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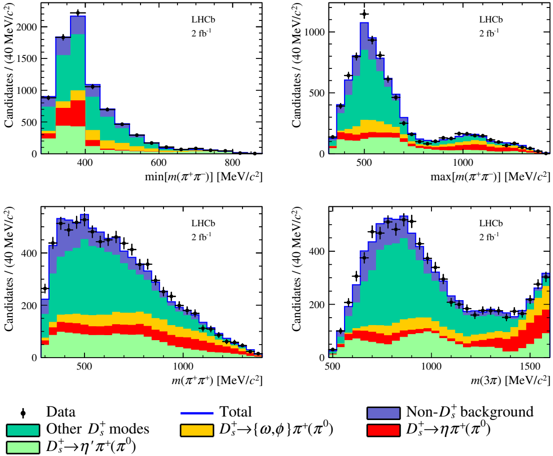

Correct simulated D_s^+ branching fractions using D_s^+-enriched sample

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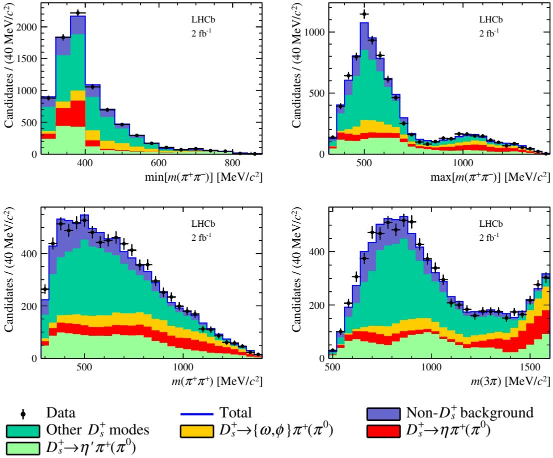
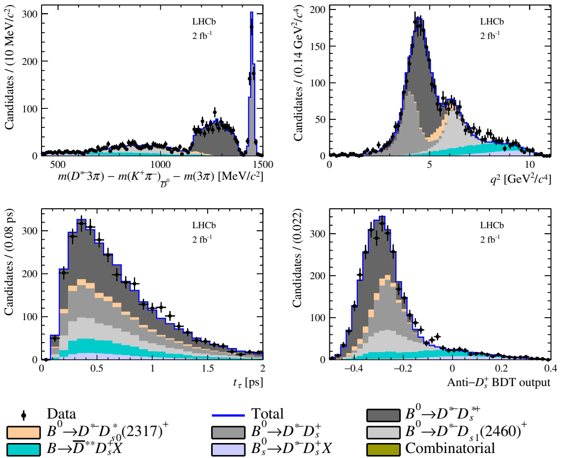




Correct simulated D_s^+ branching fractions using D_s^+-enriched sample

Constrain fit using relative abundance of D_s^+ production modes determined in control data

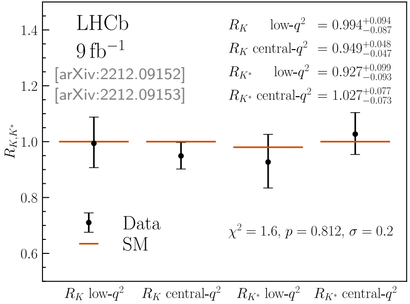
Summary

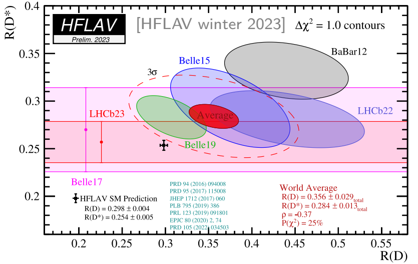
Rich LFU programme at LHCb

- branching-fraction ratios clean both theoretically and experimentally
- $b \to s\ell^+\ell^-$ R-values compatible with SM, persistent tensions in BFs
- $b \to c\ell^-\overline{\nu}_\ell$ R-values in up to $1.9\,\sigma$ tension (world average $3\,\sigma$)

Tree-level and loop-level observables highly complementary

- different physics processes $\Rightarrow$ constrain NP in different ways





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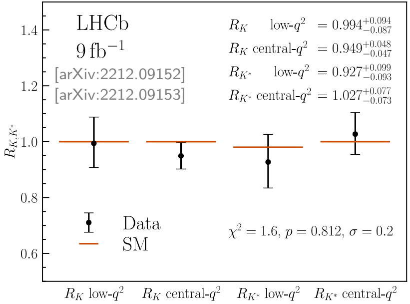

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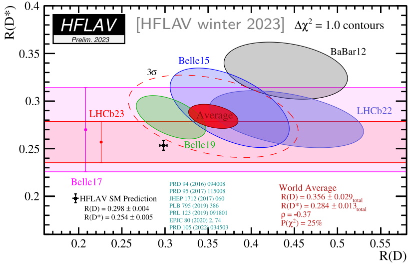
LHCb leptons are nearly the same in theory and barely the same in practice.

- electrons: diminished resolution, misID & part-reco backgrounds
- muons: clean in pairs, non-trivial with neutrinos
- taus: challenging to reconstruct
- these challenges add up in *e.g.* $\tau^+\tau^-$, $e^-\overline{\nu}_e$



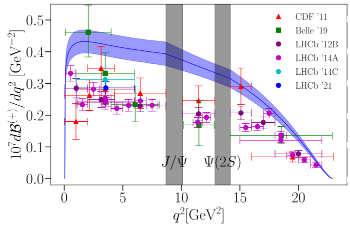
BACKUP

Anomalous $b \to s\ell^+\ell^-$ observables

A pattern of interlinked anomalies has emerged in studies of $b \to s\ell^+\ell^-$ processes.

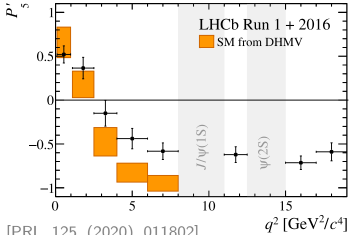
- branching fractions of *e.g.* $B^+ \to K^+\ell^+\ell^-$ consistently below SM
- angular observables in *e.g.* $B^0 \to K^{*0}\mu^+\mu^-$ consistently above SM
- ratios of branching fractions, such as R_{pK} compatible with but consistently below SM

form factors $c\bar{c}$ loops



[PRD 107 (2023) 014511]

~~form factors~~ $c\bar{c}$ loops



[PRL 125 (2020) 011802]

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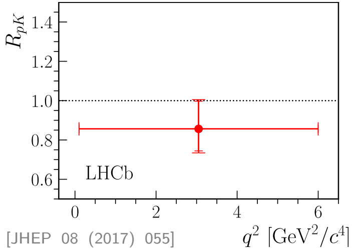
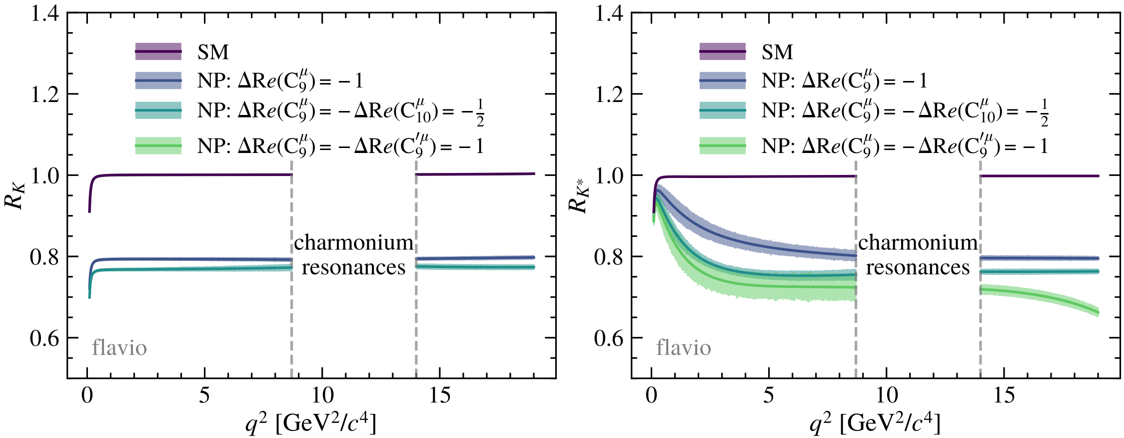


[JHEP 08 (2017) 055]

Effective operators

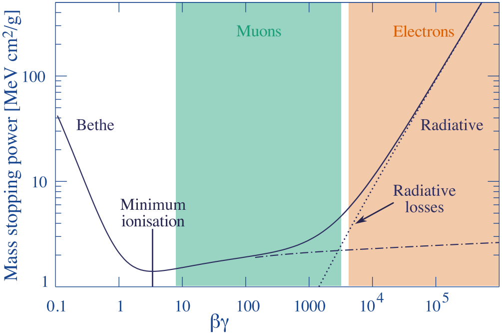
Photon penguin	$\mathcal{O}_7$	$=$	$\frac{m_b}{g_e}(\bar{s}\sigma^{\mu\nu} b_R)F_{\mu\nu}$	$\mathcal{O}_7'$	$=$	$\frac{m_b}{g_e}(\bar{s}\sigma^{\mu\nu} b_L)F_{\mu\nu}$
Vector penguin	$\mathcal{O}_9$	$=$	$(\bar{s}\gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$	$\mathcal{O}_9'$	$=$	$(\bar{s}\gamma_\mu b_R)(\bar{\ell}\gamma^\mu \ell)$
Axial vector penguin	$\mathcal{O}_{10}$	$=$	$(\bar{s}\gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	$\mathcal{O}_{10}'$	$=$	$(\bar{s}\gamma_\mu b_R)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$
Scalar	$\mathcal{O}_S$	$=$	$(\bar{s} b_R)(\bar{\ell}\ell)$	$\mathcal{O}_S'$	$=$	$(\bar{s} b_L)(\bar{\ell}\ell)$
Pseudoscalar	$\mathcal{O}_P$	$=$	$(\bar{s} b_R)(\bar{\ell}\gamma_5 \ell)$	$\mathcal{O}_P'$	$=$	$(\bar{s} b_L)(\bar{\ell}\gamma_5 \ell)$

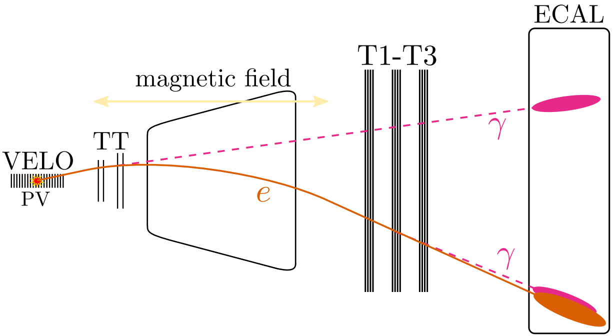
Different NP scenarios



Example (preferred) NP scenarios that lead to downwards shift in R_{K,K^*} (incl. trends)

Electrons at LHCb





Radiative losses induce muon-electron detection differences (reco, trigger, PID, etc.).

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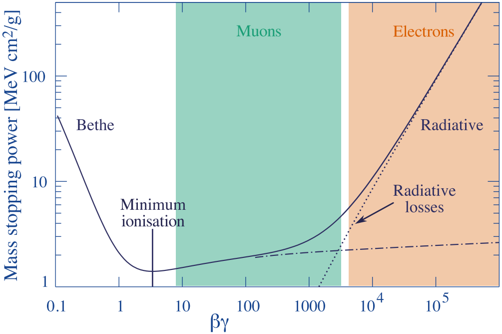

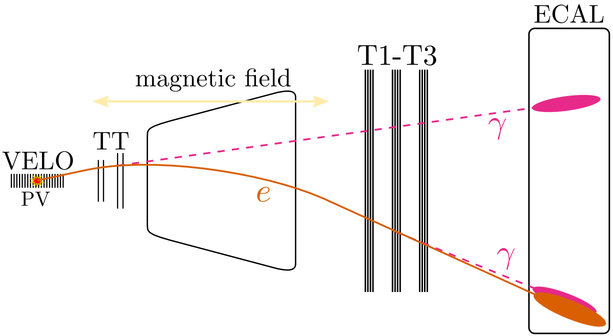

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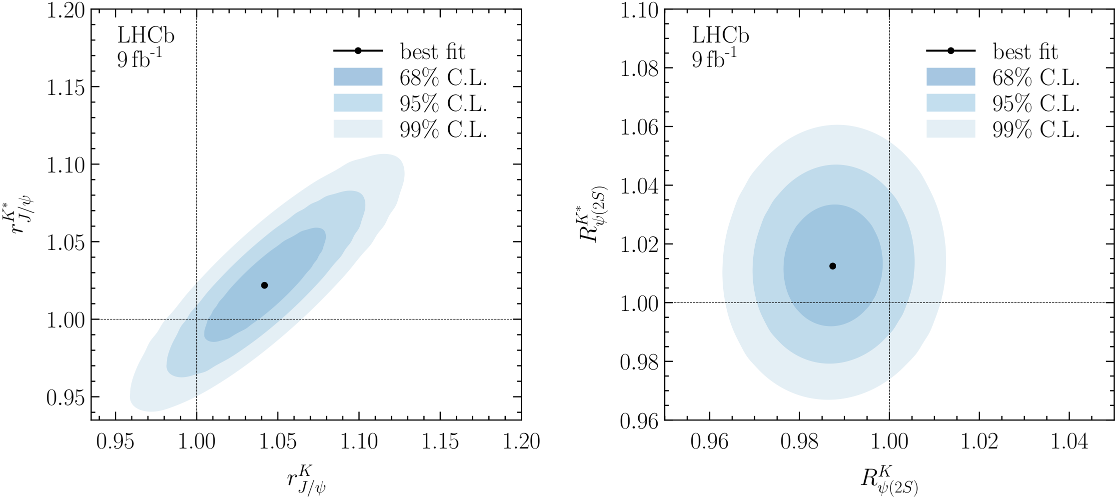
$$R_{K,K^*} = \left(\frac{N^{\mu\mu}_{\text{rare}}}{\varepsilon^{\mu\mu}_{\text{rare}}} \Big/ \frac{N^{ee}_{\text{rare}}}{\varepsilon^{ee}_{\text{rare}}}\right) \Bigg/ \underbrace{\left(\frac{N^{\mu\mu}_{J/\psi}}{\varepsilon^{\mu\mu}_{J/\psi}} \Big/ \frac{N^{ee}_{J/\psi}}{\varepsilon^{ee}_{J/\psi}}\right)}_{r_{J/\psi}} = \left(\frac{N^{\mu\mu}_{\text{rare}}}{N^{\mu\mu}_{J/\psi}} \Big/ \frac{\varepsilon^{\mu\mu}_{\text{rare}}}{\varepsilon^{\mu\mu}_{J/\psi}}\right) \Bigg/ \left(\frac{N^{ee}_{\text{rare}}}{N^{ee}_{J/\psi}} \Big/ \frac{\varepsilon^{ee}_{\text{rare}}}{\varepsilon^{ee}_{J/\psi}}\right)$$

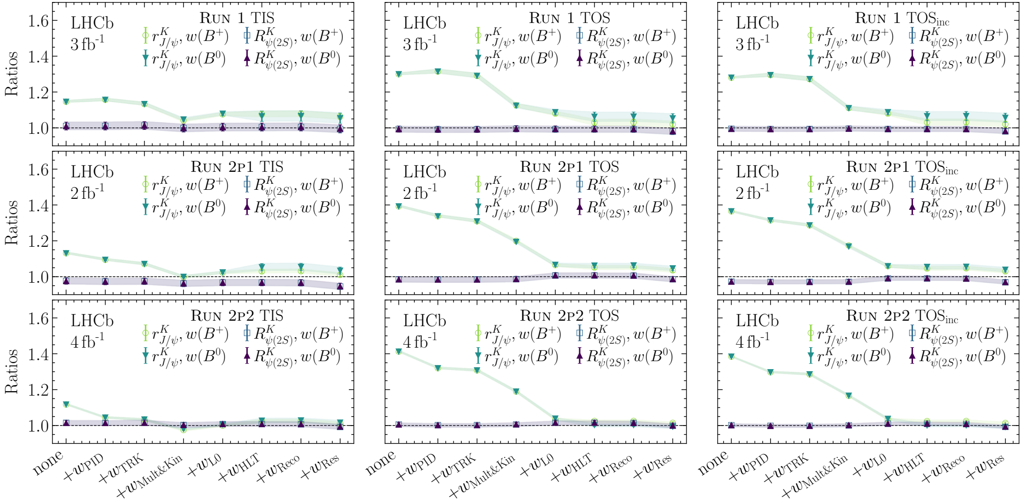
Double-ratio formalism employed to cancel most muon-electron differences, conduct cross-checks.

Cross-checks: ratios



Single ratio probes electron-muon agreement (stringent), double ratio checks stability outside nominal q^2 region.

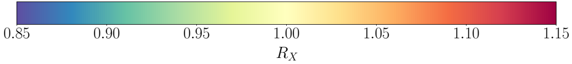
Simulation correction chain



Corrections applied sequentially to calibrate: PID, tracking, multiplicity, kinematics, trigger, reconstruction, mass resolution

Electron PID scans

LHCb



R_K low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	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) > 5	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) > 2	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

ProbNN(e)

R_K central-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	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) > 5	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) > 2	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

ProbNN(e)

R_{K^*} low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	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) > 5	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) > 2	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

ProbNN(e)

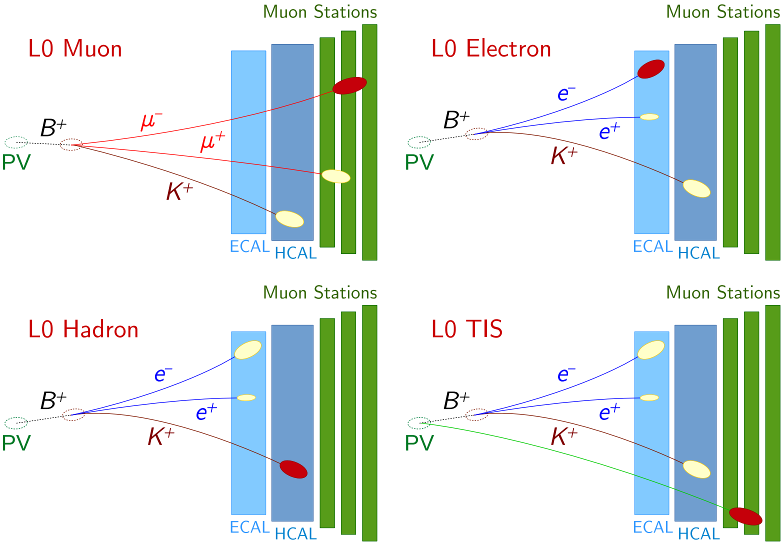
R_{K^*} central-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	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) > 5	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) > 2	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

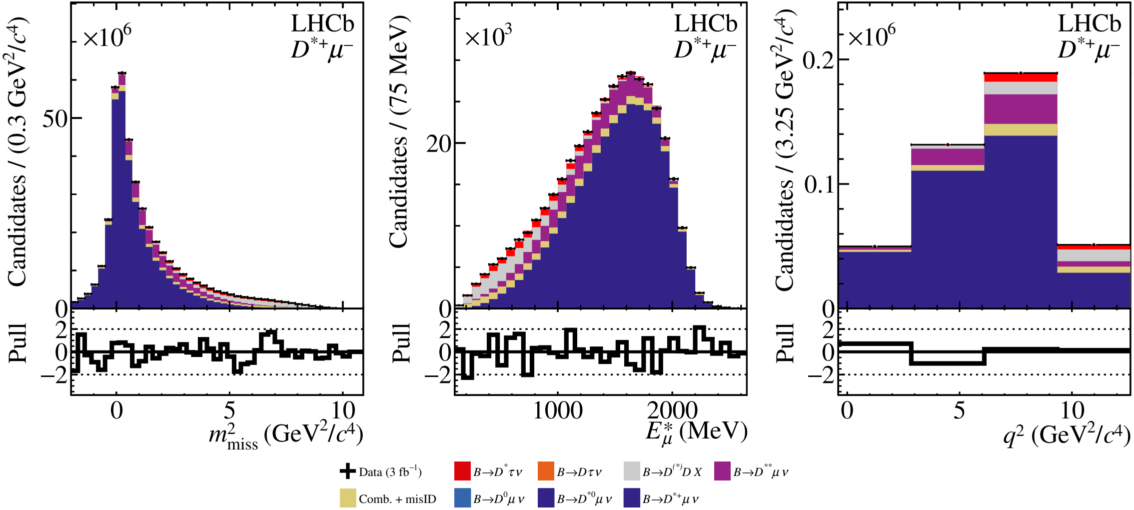
ProbNN(e)

Coherent pattern found when tightening electron PID requirements

Trigger strategy

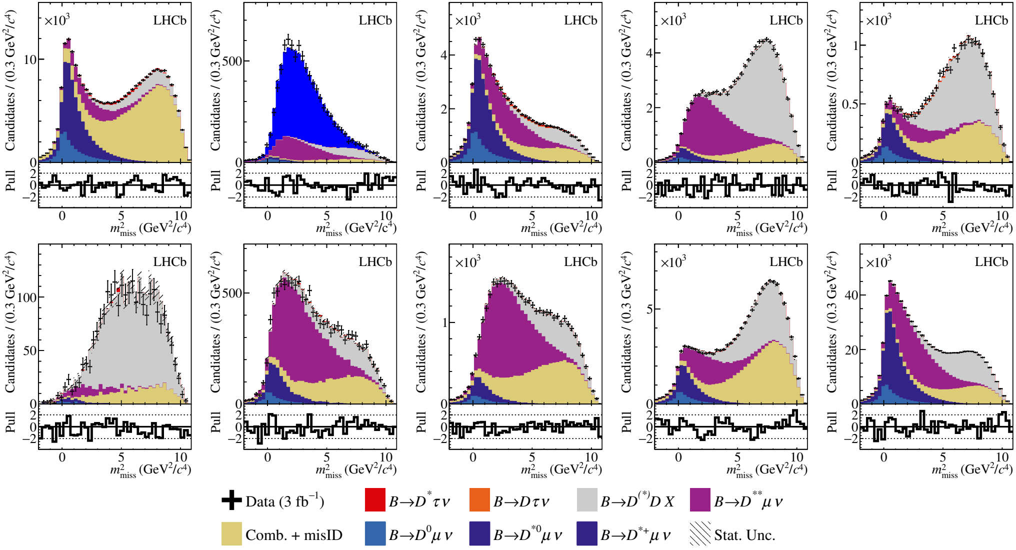


Semileptonic tau decays: muonic signal

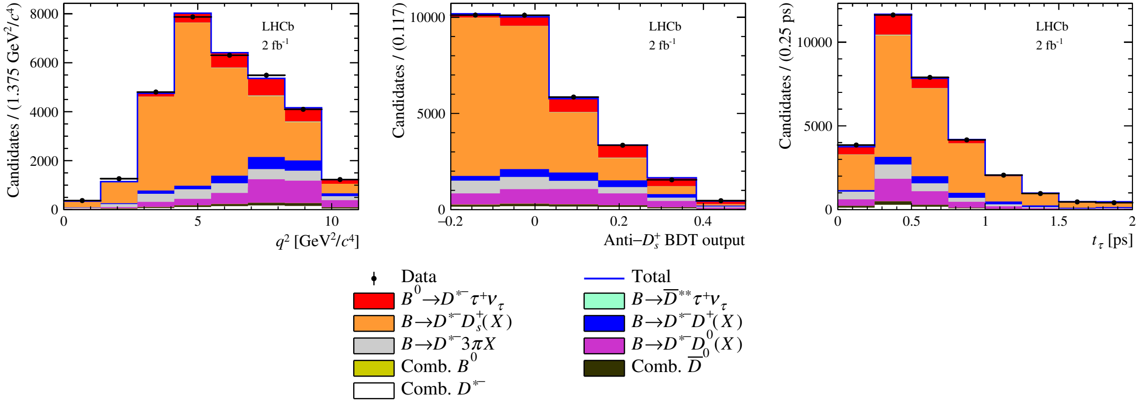


$D^*\tau\nu$ typically has larger missing mass & q^2, lower E^*_μ *cf.* $D^*\mu\nu$

Validation regions for muonic tau data



Semileptonic tau decays: hadronic signal



Signal found predominantly at high-q^2 and $t_\tau \sim 0.3\,\text{ps}$; $D_s^+ \to 3\pi X$ suppressed via BDT.