Rare Charm decays at LHCb

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LPNHE (Paris)

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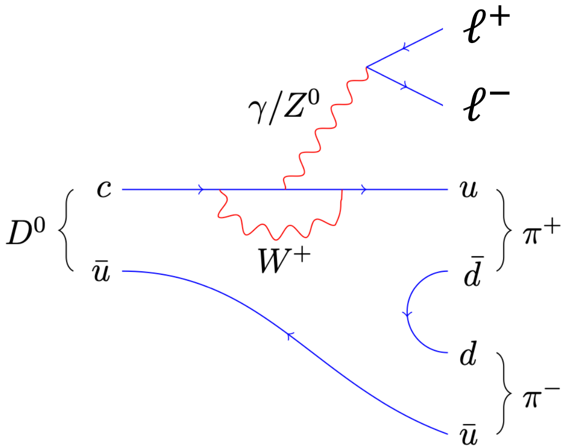
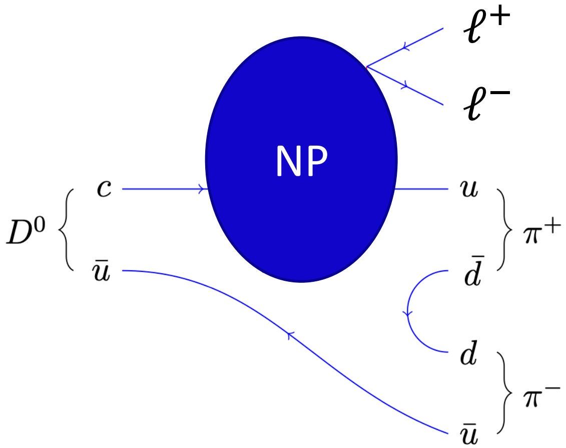
Why study Rare Charm decays?

- Rare Charm decays receive contributions from flavor-changing neutral-current (FCNC) $c \to u\ell\ell$ processes
- Decays containing the charm quark are a unique up-type quark probe for these processes (complementary to the down-type quark studies in the K and B sectors)
- The FCNC transitions at tree level are forbidden in the SM, CKM and GIM suppressed (tiny SM prediction of $\mathcal{B} < 10^{-9}$) [J. High Energ. Phys. 2013, 135 (2013)]
- Some New Physics (NP) models predict large enhancement in rates and CP and angular asymmetries
- Lepton Flavour Universality (LFU) in charm decays is still a relatively unexplored area:

$$R^{D}_{P_1 P_2} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2 (D \to P_1 P_2 \mu^+ \mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2 (D \to P_1 P_2 e^+ e^-)}$$

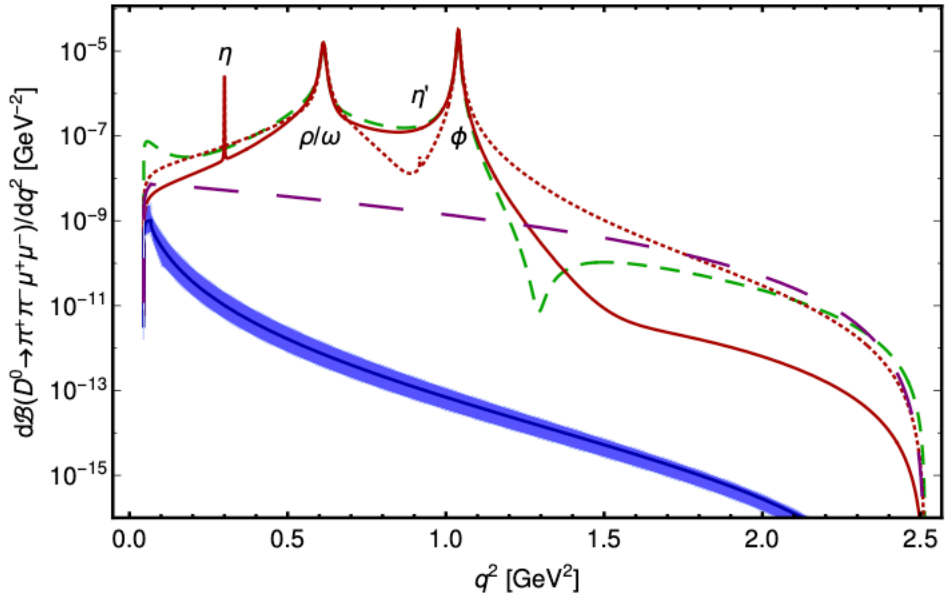




Challenges

- Rare Charm decays are dominated by Long Distance (LD) interactions (resonant component) with tree-level dynamics
- Precise theoretical predictions are difficult on the branching fractions (the resonances contribution are dominated by QCD effects at very low energy and are evaluated with non-perturbative methods with high uncertainty)

[PRD 98 035041 (2018)]



$D^0 \to \pi^+\pi^-\mu^+\mu^-$

non-resonant component

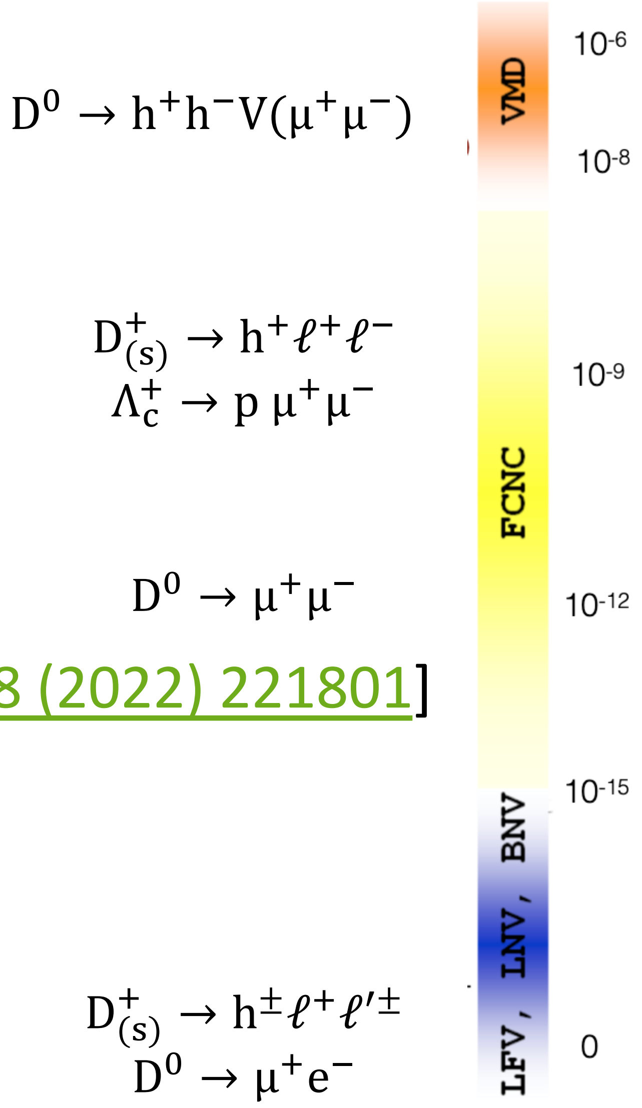
resonant component

LD different model

BSM model (dashed)

Rare Charm decays at LHCb

- Branching fractions:
  - Search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)]
  - Search for $\Lambda_c^+ \to p\,\mu^+\mu^-$ [PRD 97 091101 (2018)]
  - Observation $D^0 \to h^+h^-V(\mu^+\mu^-)$ [PRL 119 (2017) 181805]
- SM null tests (Lepton Flavor Violation and Asymmetries):
  - Search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
  - Search for $D_{(s)}^+ \to h^\pm\ell^+\ell'^\pm$ [JHEP06(2021)044]
  - Asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ [PRL 121 (2018) 091801]
  - Angular analysis and CP violation in $D^0 \to h^+h^-\mu^+\mu^-$ [PRL 128 (2022) 221801]



My ongoing analysis:
Search for $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$

Search for $\mathbf{D^0 \to h^+h^-}\boldsymbol{e^+e^-}$ decays

Goal: First observation of $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$

Channel	Total BF	BF: 675<m(ee)<875 MeV/c^2	BF: 1005<m(ee)<1035 MeV/c^2
$D^0 \to K^-\pi^+e^+e^-$	$< 4.1 \times 10^{-5}$ [1]	$(4.0 \pm 0.5) \times 10^{-6}$ [2]	$< 5.0 \times 10^{-7}$ [2]
$D^0 \to \pi^+\pi^-e^+e^-$	$< 7 \times 10^{-6}$ [1]	/	/
$D^0 \to K^+K^-e^+e^-$	$< 1.1 \times 10^{-5}$ [1]	/	/

[1] Phys. Rev. D **97**, 072015, Apr 2018 (BESIII)
[2] Phys. Rev. Lett. **122**, 081802, Feb 2019 (BABAR)

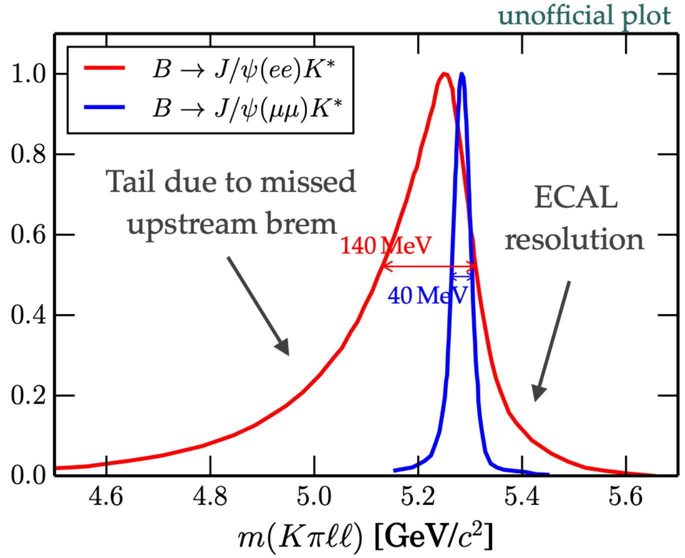
Comparing to measured muon modes BFs

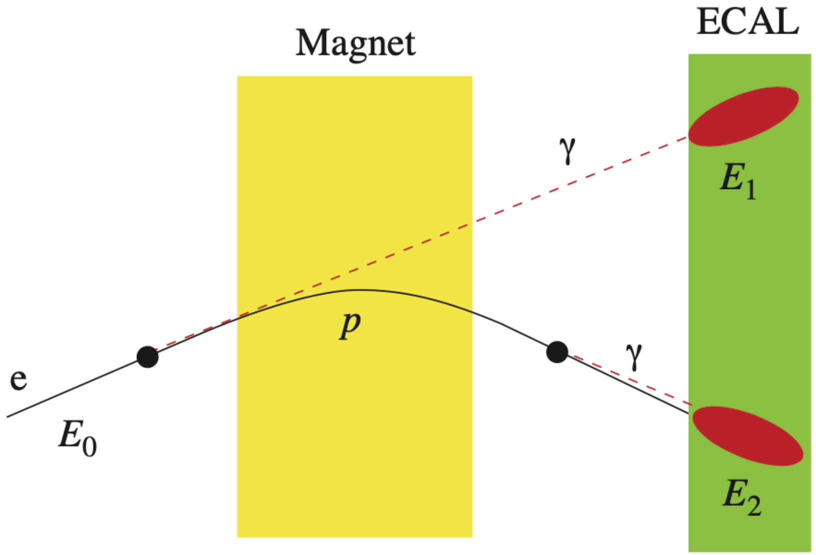
Channel	Branching fraction
$D^0 \to K^-\pi^+\mu^+\mu^-$	$(4.2 \pm 0.4) \times 10^{-6}$ in dimuon range 675-875 MeV/$\boldsymbol{c^2}$ [3]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$(9.6 \pm 1.2)\times 10^{-7}$[4]
$D^0 \to K^+K^-\mu^+\mu^-$	$(1.54 \pm 0.32)\times 10^{-7}$ [4]

[3] Phys.Lett.B 757 (2016), 558-567 (LHCb)
[4] Phys. Rev. Lett. **119**, 181805, Oct 2017(LHCb)

Challenges with electrons

- The main challenge with electrons at LHCb is the bremsstrahlung effects due to the interactions of the electrons with the detector material
- Compared to muons, decays involving electrons show tails in their mass distributions due to the missed brem photon energy
- The Brem recovery procedure has a 50% efficiency on photons emitted before the magnet *Electron reconstruction at LHCb and Belle II - presentation*





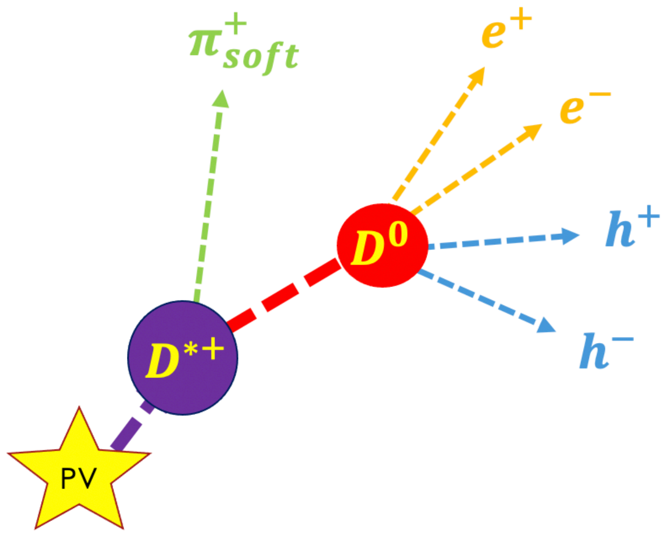
Analysis strategy

- Search for the decays and possible BF measurement relative to the $D^0 \to K^-\pi^+e^+e^-$ decay:

$$BF(D^0 \to h^+h^-e^+e^-) = \frac{N(D^0 \to h^+h^-e^+e^-)}{N(D^0 \to K^-\pi^+e^+e^-)} \frac{\epsilon(D^0 \to K^-\pi^+e^+e^-)}{\epsilon(D^0 \to h^+h^-e^+e^-)} \times \boxed{BF(D^0 \to K^-\pi^+e^+e^-)}$$

input from BaBar measurement with 13 % relative uncertainty

- Data sample: Run2 (2015 to 2018)
- Selecting $\boldsymbol{D}^*$-tagged decays: $\boldsymbol{D}^{*+} \to D^0(\to h^+h^-e^+e^-)\pi^+_{soft}$
- Blind analysis: data removed in the signal D^0 mass range [1700-1900] MeV/$\boldsymbol{c}^2$
- Samples split into decays with and without brem photons attached to the electrons (brem categories)



bin m(e^+e^-) [MeV/c^2]	very low (only e^+e^-) < 211.32	low mass 211.32 - 525	η 525 - 565	ρ/ω 565 - 950	ϕ 950 - 1100	high mass > 1100
$D^0 \to \pi^+\pi^-e^+e^-$	[✓]	✓	✓	✓	✓	✓
$D^0 \to K^+K^-e^+e^-$	[✓]	✓	✓	✓		

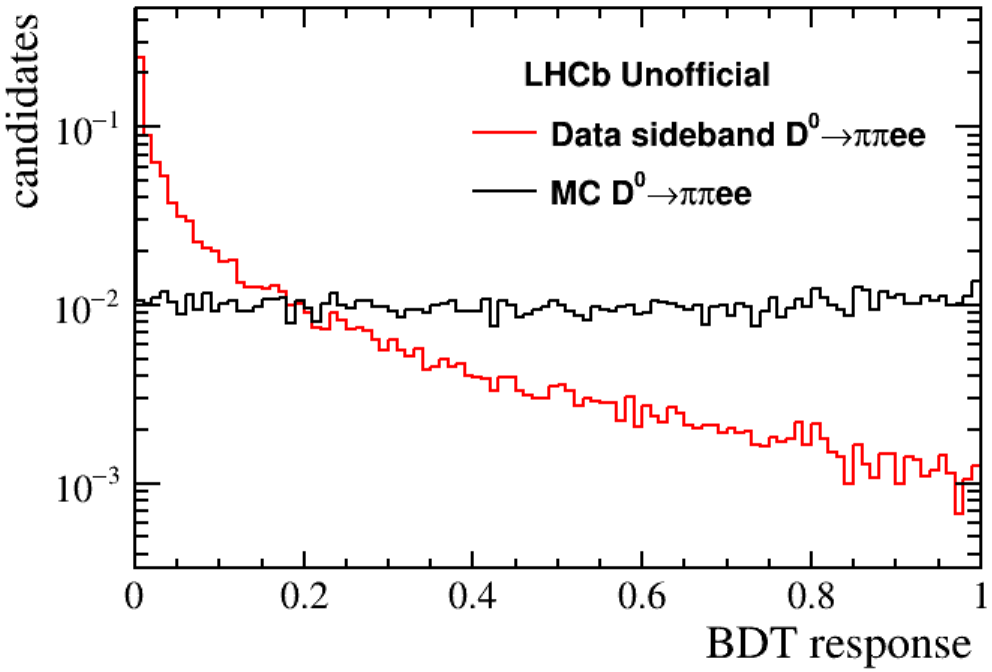
Background studies

- There are two main backgrounds:
  - Combinatorial background, reduced with a multivariate analysis
  - Mis-identified backgrounds, reduced using particle identification (PID) variables:
    - Probability of mis-id two π as two e is on the order of 10^{-4}
- Partially reconstructed $D^0 \to h^+h^-\eta$ with $\eta \to ee\gamma$:
  - Only relevant in low mass dilepton bin

Signal and mis-id bkg	Branching fraction
$D^0 \to K^-\pi^+e^+e^-$	4×10^{-6}
$D^0 \to \pi^+\pi^-e^+e^-$	$\sim 10^{-6}$
$D^0 \to K^+K^-e^+e^-$	$\sim 10^{-7}$
$D^0 \to K^-\pi^+\pi^+\pi^-$	8×10^{-2}
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	8×10^{-3}
$D^0 \to K^+K^-\pi^+\pi^-$	2×10^{-3}
Eta backgrounds	**Branching fraction**
$D^0 \to K^-\pi^+\eta(\to ee\gamma)$	1.4×10^{-4}
$D^0 \to \pi^+\pi^-\eta(\to ee\gamma)$	7×10^{-6}
$D^0 \to K^+K^-\eta(\to ee\gamma)$	4.2×10^{-7}

Multivariate discriminator

- Boosted Decision Tree (BDT) implemented to reject the combinatorial background
- Input: kinematic and topological variables of particle candidates
- Signal proxy: simulation signal sample
- Background proxy: data in the D^0 high mass region



Selection optimization

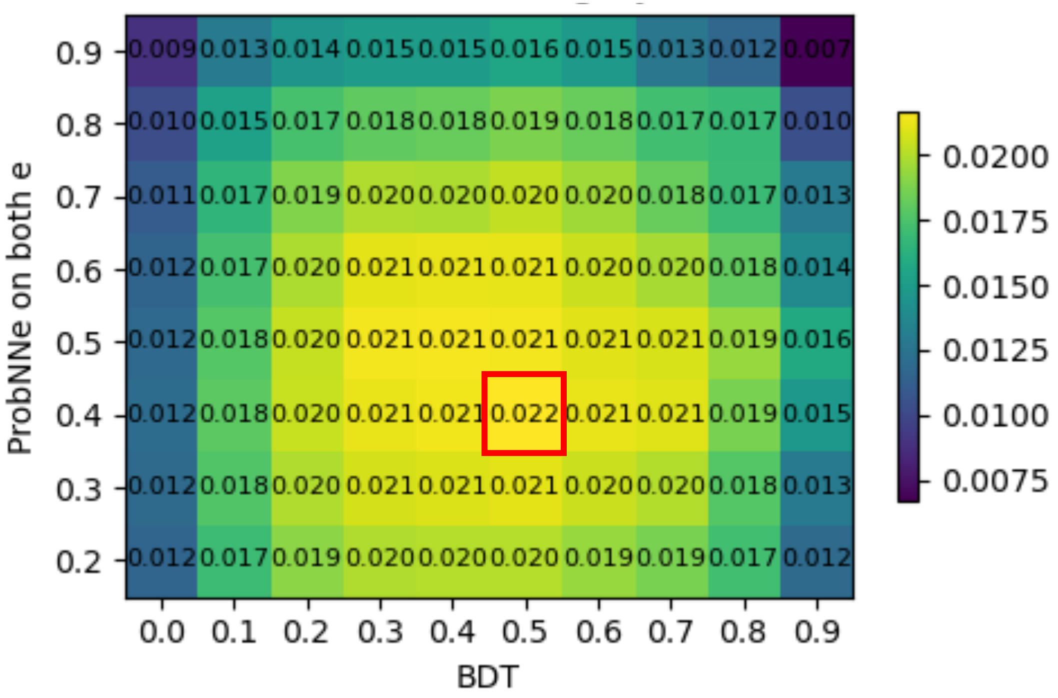
- The PID and BDT selection can be optimized maximizing the Punzi figure of merit:

$$FoM = \frac{\epsilon_{signal}}{\frac{5}{2} + \sqrt{N_{bkg}}}$$

[eConf C030908 (2003), MODT002]

  - ϵ_{signal}: selection signal efficiency from simulation
  - N_{bkg}: background yield in the signal region

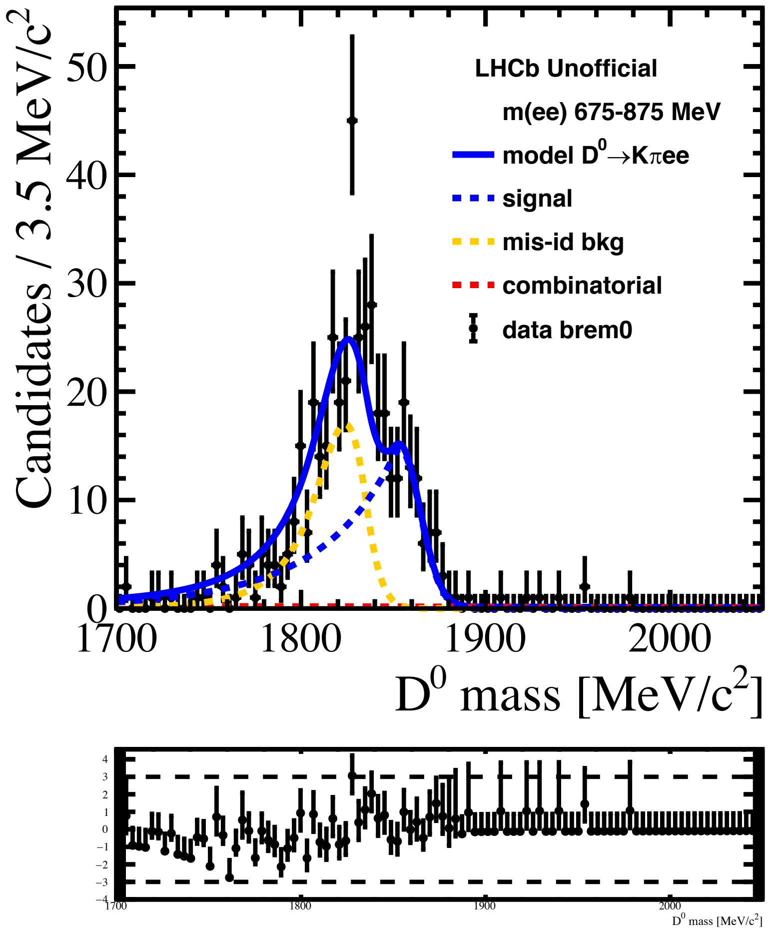
- Background yield composed of:
  - Combinatorial: extrapolated from the D^0 *high-mass* region
  - Mis-id: estimated from normalization channel

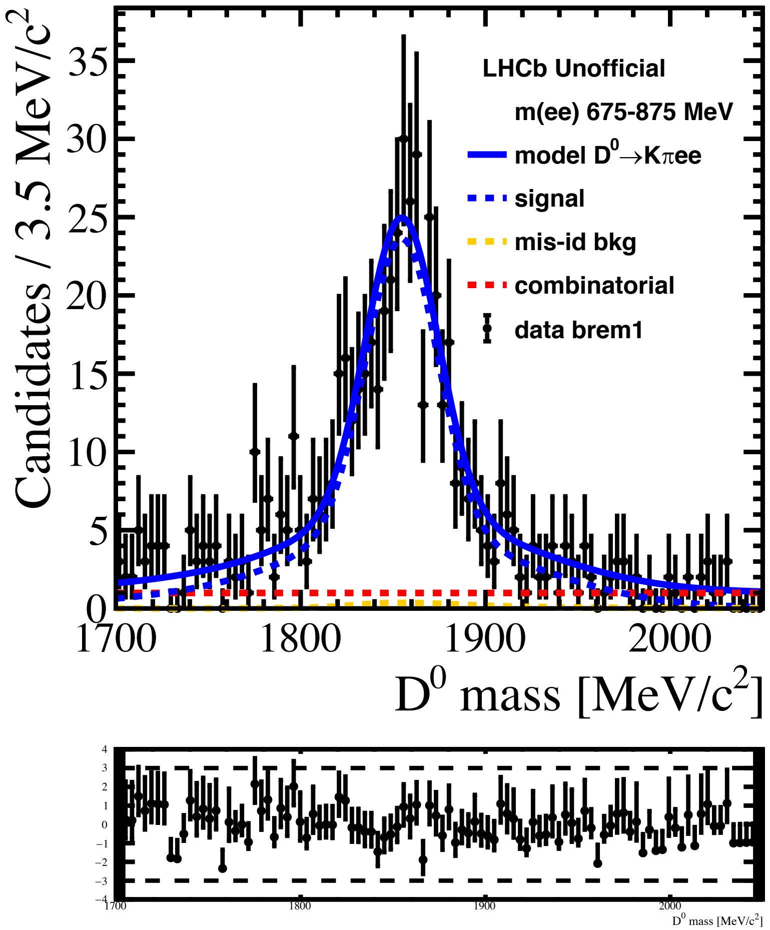


BDT vs PID FoM optimization

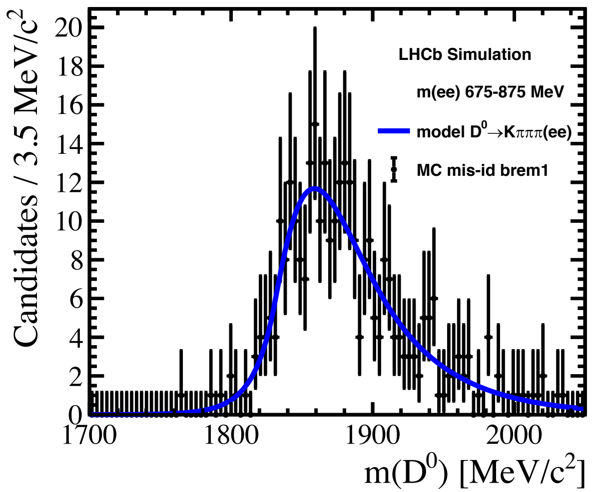
Fit on the normalization decay

Fit on $D^0 \to K^-\pi^+e^+e^-$ after selection optimized on the signal



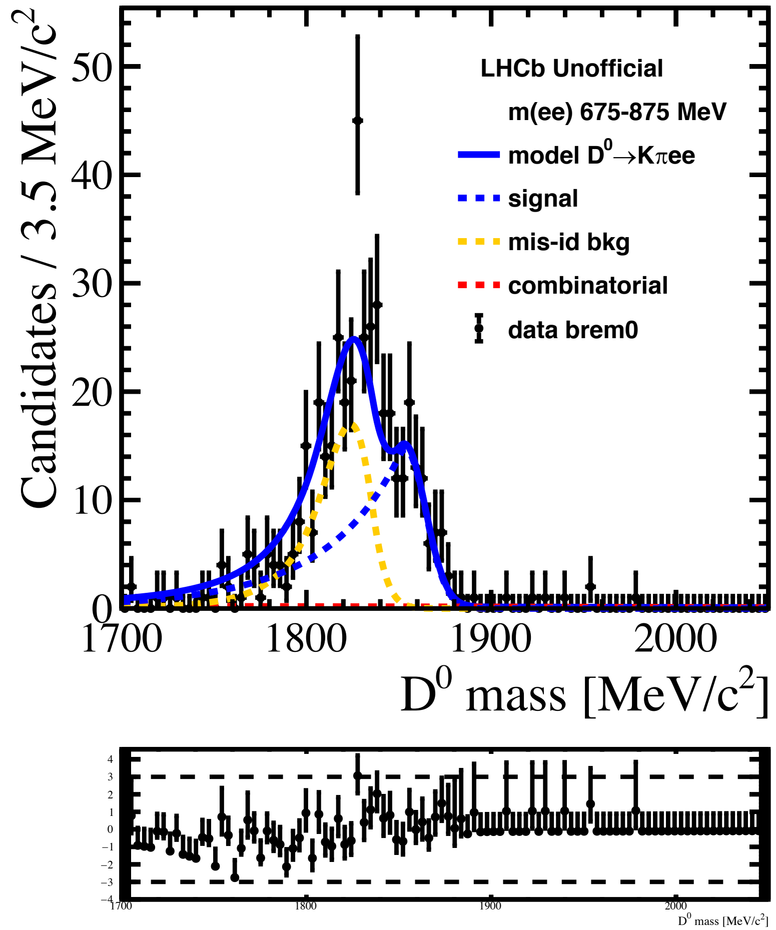


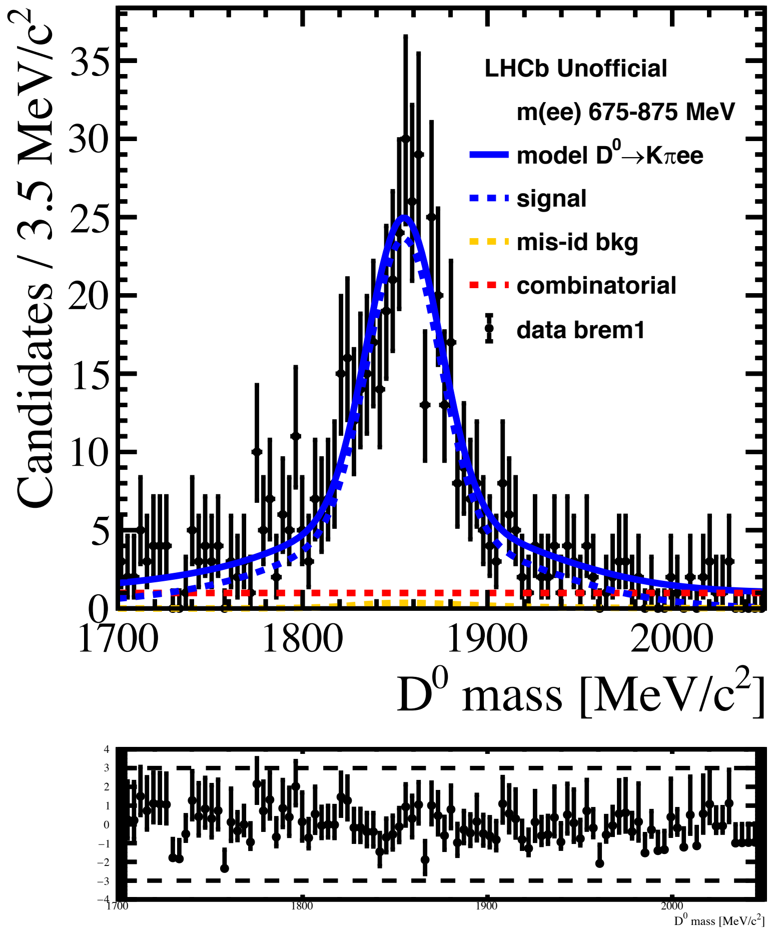
- The fit model:
  - **Signal** model from MC
  - **Mis-id** model from MC $D^0 \to K^-\pi^+\pi^+\pi^-$
  - **Combinatorial** from Data dM sideband
- Mis-id brem1 peaking under signal



Fit on the normalization decay

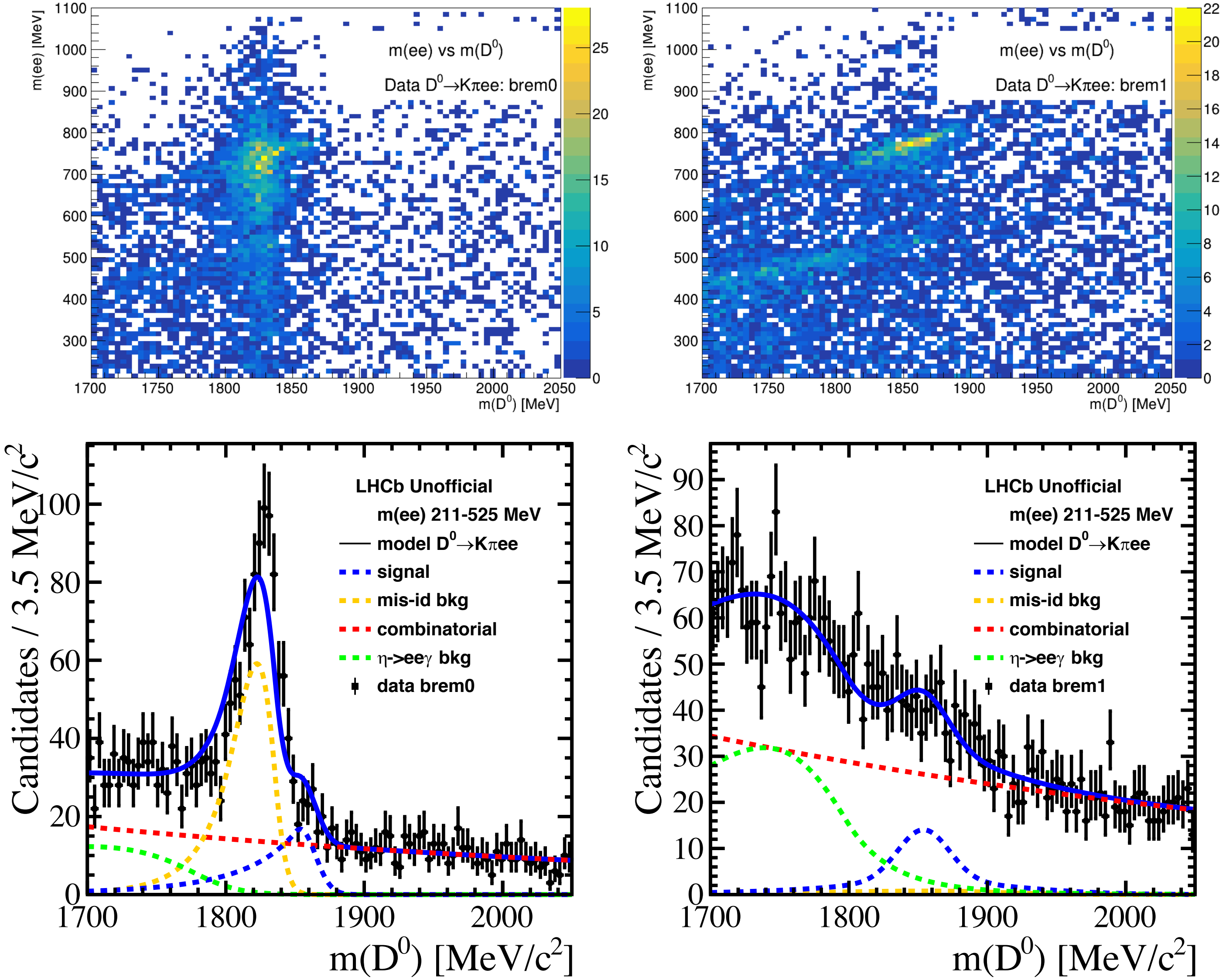
Fit on $D^0 \to K^-\pi^+e^+e^-$ after selection optimized on the signal





- The fit model:
  - **Signal** model from MC
  - **Mis-id** model from MC $D^0 \to K^-\pi^+\pi^+\pi^-$
  - **Combinatorial** from Data dM sideband
- Fixing all parameters apart from yields
- Mis-id yield in brem1 fixed at 5% of mis-id yield in brem0 from MC
- Norm. yields at q^2 range 675-875 MeV/$\boldsymbol{c}^2$: ~ 750 events

“Low mass” bin eta background



- $\mathrm{m}(ee)$ vs $\mathrm{m}(D^0)$ shows a structure around the η dilepton mass and lower $\mathrm{m}(D^0)$
- $D^0 \to K^-\pi^+\eta(\to ee\gamma)$ partially reconstructed background
- Fixed shape from simulation
- Fit on $D^0 \to K^-\pi^+e^+e^-$ with $\mathrm{m}(ee)$ 211-525 MeV/$\boldsymbol{c^2}$

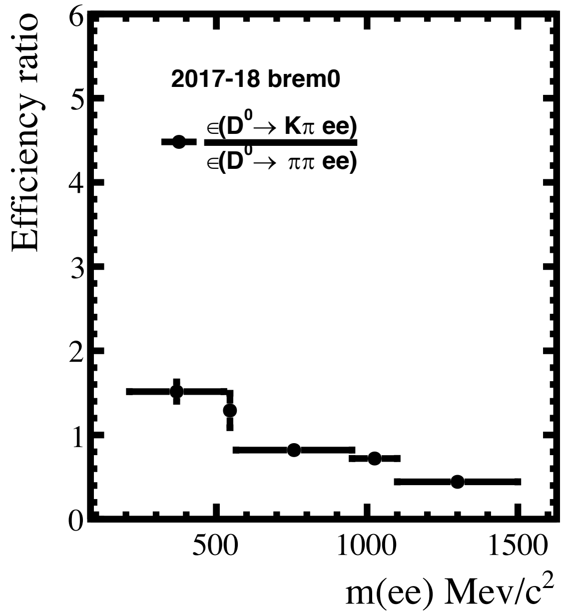
Efficiencies evaluation

- Evaluating the efficiency ratio for the BF measurement:

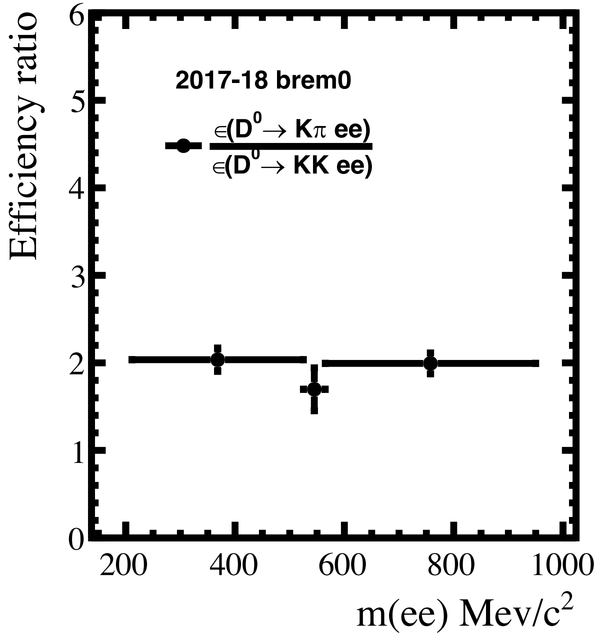
$$BF(D^0 \to h^+h^-e^+e^-) = \frac{N(D^0 \to h^+h^-e^+e^-)}{N(D^0 \to K^-\pi^+e^+e^-)} \frac{\boldsymbol{\epsilon(D^0 \to K^-\pi^+e^+e^-)}}{\boldsymbol{\epsilon(D^0 \to h^+h^-e^+e^-)}} \times BF(D^0 \to K^-\pi^+e^+e^-)$$

- Evaluated from MC and corrected for data/simulation differences:
  - tracking, particle identification and trigger

$$\frac{\epsilon(D^0 \to K^-\pi^+e^+e^-)}{\epsilon(D^0 \to \pi^+\pi^-e^+e^-)}$$



$$\frac{\epsilon(D^0 \to K^-\pi^+e^+e^-)}{\epsilon(D^0 \to K^+K^-e^+e^-)}$$



Systematics

- List of systematics:
  - Normalization channel BF
  - Normalization yields
  - Fit model:
    - Signal PDF
    - Mis-id model and brem0-brem1 fraction
    - Combinatorial shape
  - Efficiency ratio:
    - Tracking, PID and trigger corrections
    - Signal resonances MC model
    - Kinematics reweighting

Normalization channel BF → 13.7 %

\+

Systematic relative uncertainty

Remaining systematics → < 7 %

(few % lower than statistical uncertainty from preliminary studies)

Blind signal fit

- The fit model composed of signal, hadronic mis-id and combinatorial with all fixed parameters
- Simultaneous fit of brem0 and brem1 categories with signal BF as common fitting parameter:

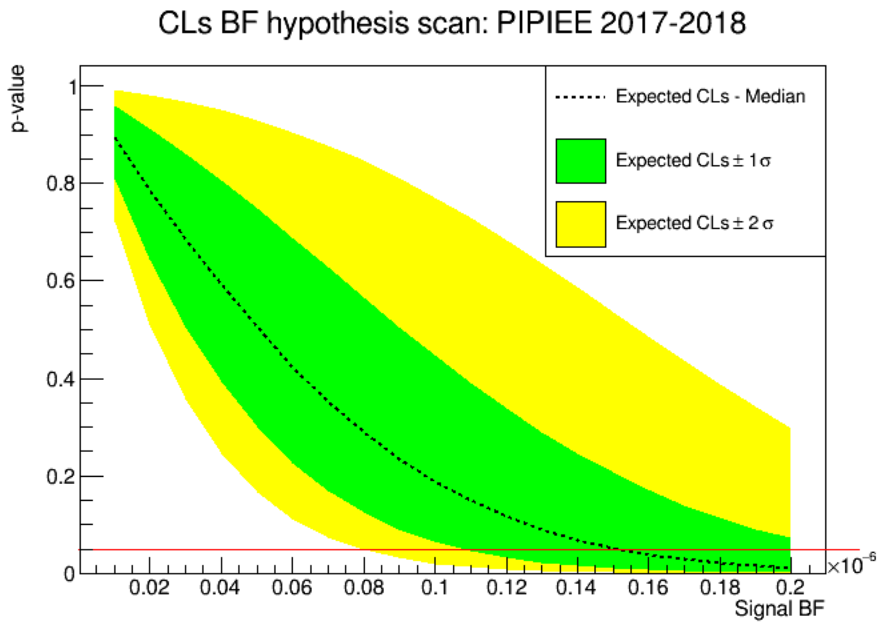
$$N_{sig,brem0} = N_{norm,brem0} \cdot \frac{\epsilon_{sig,brem0}}{\epsilon_{norm,brem0}} \cdot \frac{BF_{sig}}{BF_{norm}}$$

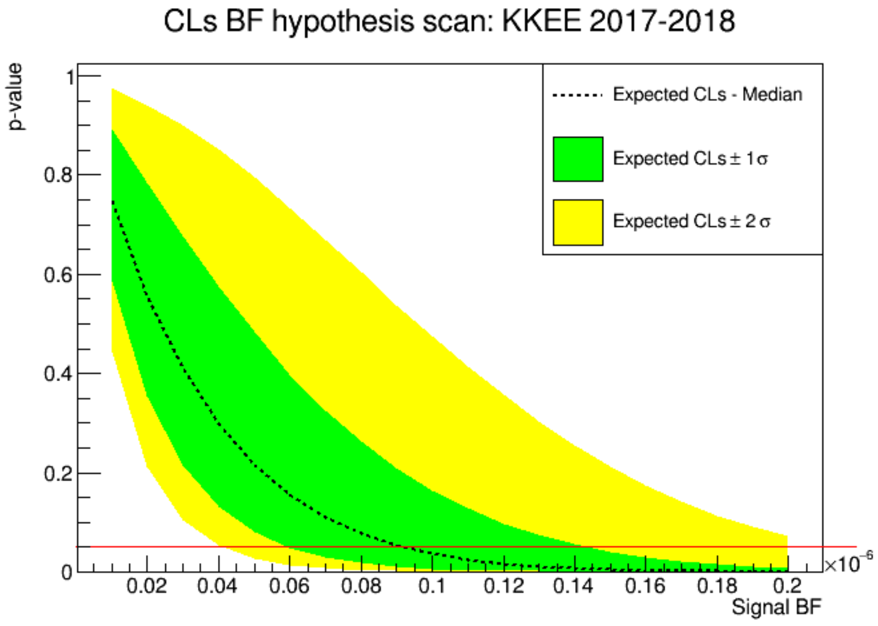
$$N_{sig,brem1} = N_{norm,brem1} \cdot \frac{\epsilon_{sig,brem1}}{\epsilon_{norm,brem1}} \cdot \frac{BF_{sig}}{BF_{norm}}$$

- Results blinded by hiding the data in the signal window and shifting the BF value by a random value

Setting upper limit

- If no significant signal is observed, we will set an upper limit using the CLs method
- Producing only bkg toys and evaluating the ratio of likelihoods of s+b and only bkg hypothesis
- Preliminary expected upper limits: ~ 10^{-7}





Conclusion and prospects

- Rare Charm decays constitutes a unique environment to look for New Physics, either with BF measurements or as SM null tests
- First LHCb study on the $D^0 \to h^+h^-e^+e^-$ decays
- Expecting to observe $D^0 \to \pi^+\pi^-e^+e^-$ and observe/set limit for $D^0 \to K^+K^-e^+e^-$
- Analysis sensitivity: ~ 10^{-7}
- Started internal LHCb WG review

For the future:

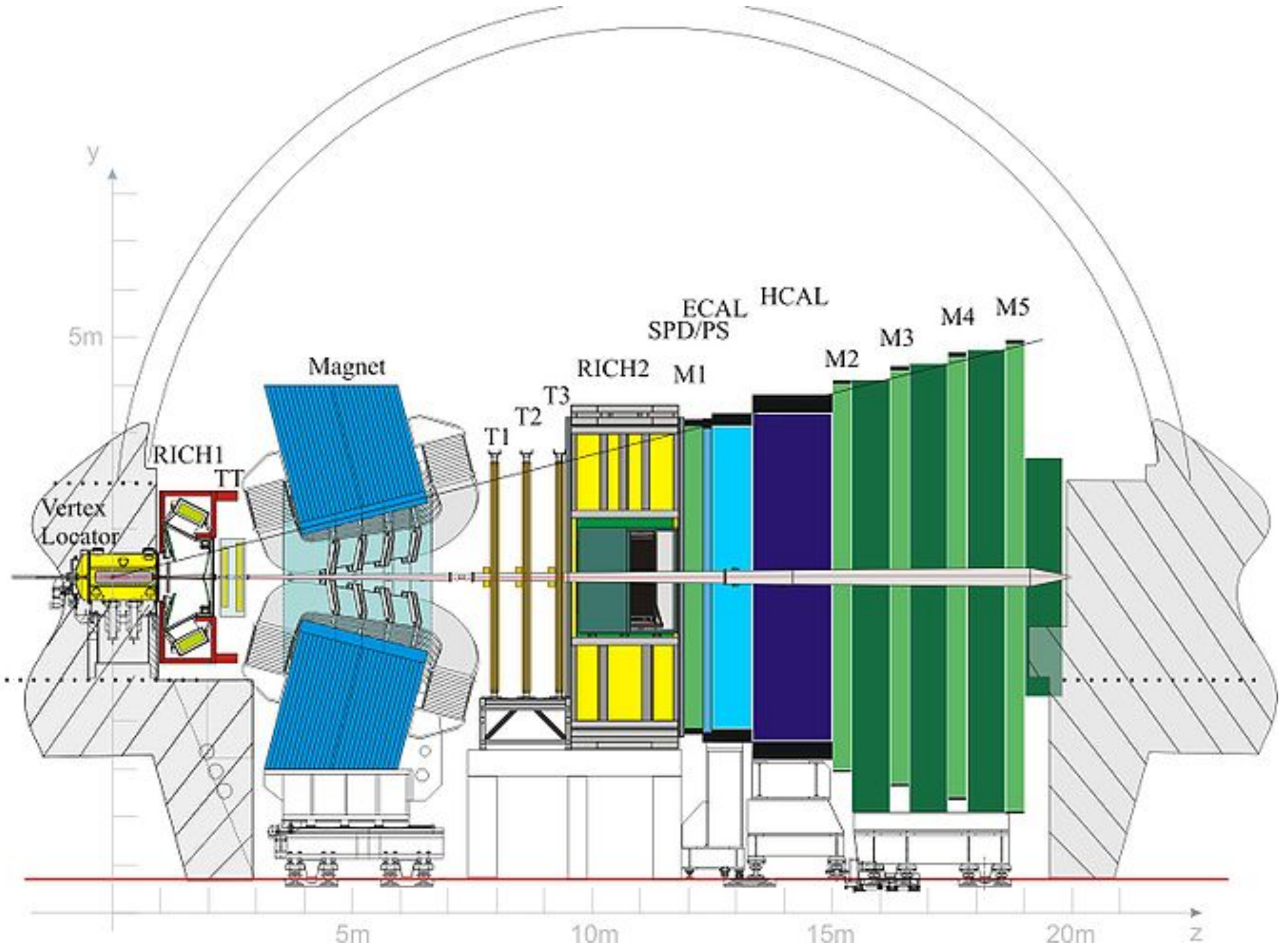
- Study of LFU ratio with muon modes
- CP and angular asymmetries

Backup

The LHCb experiment

- LHCb is a single arm forward spectrometer optimized for b and c physics
- Good vertex/momentum resolution and excellent particle identification
- LHCb has the world's largest sample of charm decays
- $\sigma\ (pp \rightarrow c\bar{c}) \sim O(\text{mb})$
  → $\sim 10^{13}$ pairs produced up to now

[Int. J. Mod. Phys. A 30, 1530022 (2015)]



PID and Mis-id efficiencies

Ring Imaging Cherenkov (RICH) detectors

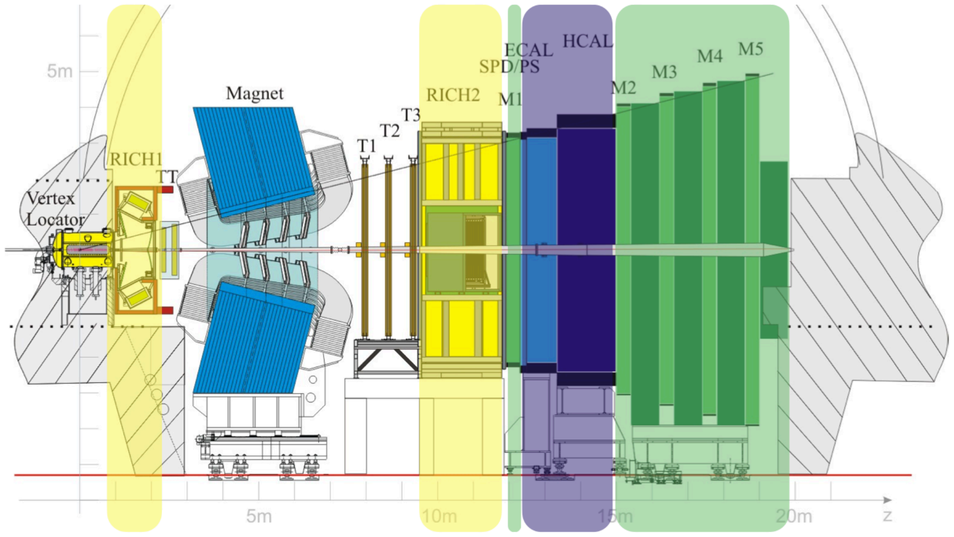
RICH 1 and RICH 2 with PID for kaons, pions, protons, and low-momentum leptons

Muon stations

Five muon stations (M1-M5) with high purity PID for muons

Calorimeters

Scintillating Pad Detector (SPD), Pre-Shower detector (PS), Electromagnetic Calorimeter (ECAL) and Hadronic Calorimeter (HCAL) with PID for electrons, photons and neutral pions



[LHCb-PHO-GENE-2008-002]

The PID varaibles are built as:

1. log likelihood difference particle hypotheses of X and π as reference: $\mathcal{L} = \mathcal{L}_{RICH} \cdot \mathcal{L}_{MUON} \cdot \mathcal{L}_{CALO}$
2. Neural network output, trained on simulation with info from the sub-detectors and tracking

For example, the π to electron mis-id efficiency for different cuts on PID variables:

- ProbNNe > 0.2 → 0.7 %
- ProbNNe > 0.5 → 0.3 %
- ProbNNe > 0.9 → 0.04%

PID performance in Run 2 at LHCb

Prospects for the LHCb Upgrades

Physics Case Upgrade2

- Limits on BFs for Run3-4 (Upgrade1 2022-2030) and Run5 (Upgrade2 2030-…):

Mode	Run1-2 (1-6 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^0 \to \mu^+\mu^-$	6.2×10^{-9}	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	6.7×10^{-8}	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	2.6×10^{-8}	10^{-8}	3×10^{-9}
$\Lambda_c^+ \to p\mu^+\mu^-$	9.6×10^{-8}	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e^\pm\mu^\mp$	1.3×10^{-8}	10^{-9}	4.1×10^{-9}

- Statistical precision on asymmetries:

Mode	Run1-2 (1-6 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^+ \to \pi^+\mu^+\mu^-$		0.2 %	0.08 %
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	3.8 %	1 %	0.4 %
$D^0 \to K^-\pi^+\mu^+\mu^-$		0.3 %	0.13 %
$D^0 \to K^+\pi^-\mu^+\mu^-$		12 %	5 %
$D^0 \to K^+K^-\mu^+\mu^-$	11 %	4 %	1.7 %

A. Contu - Towards ultimate precision in Flavor Physics, Durham (2-4 April 2019)

LFU in Rare Charm decays

- Why these decays are interesting:
  - **Search for New Physics**: contributions from FCNC processes that can be sensitive to new and unknown particles and interactions
  - **Promising channels to test LFU in $c \to u\ell\ell$ transitions** :

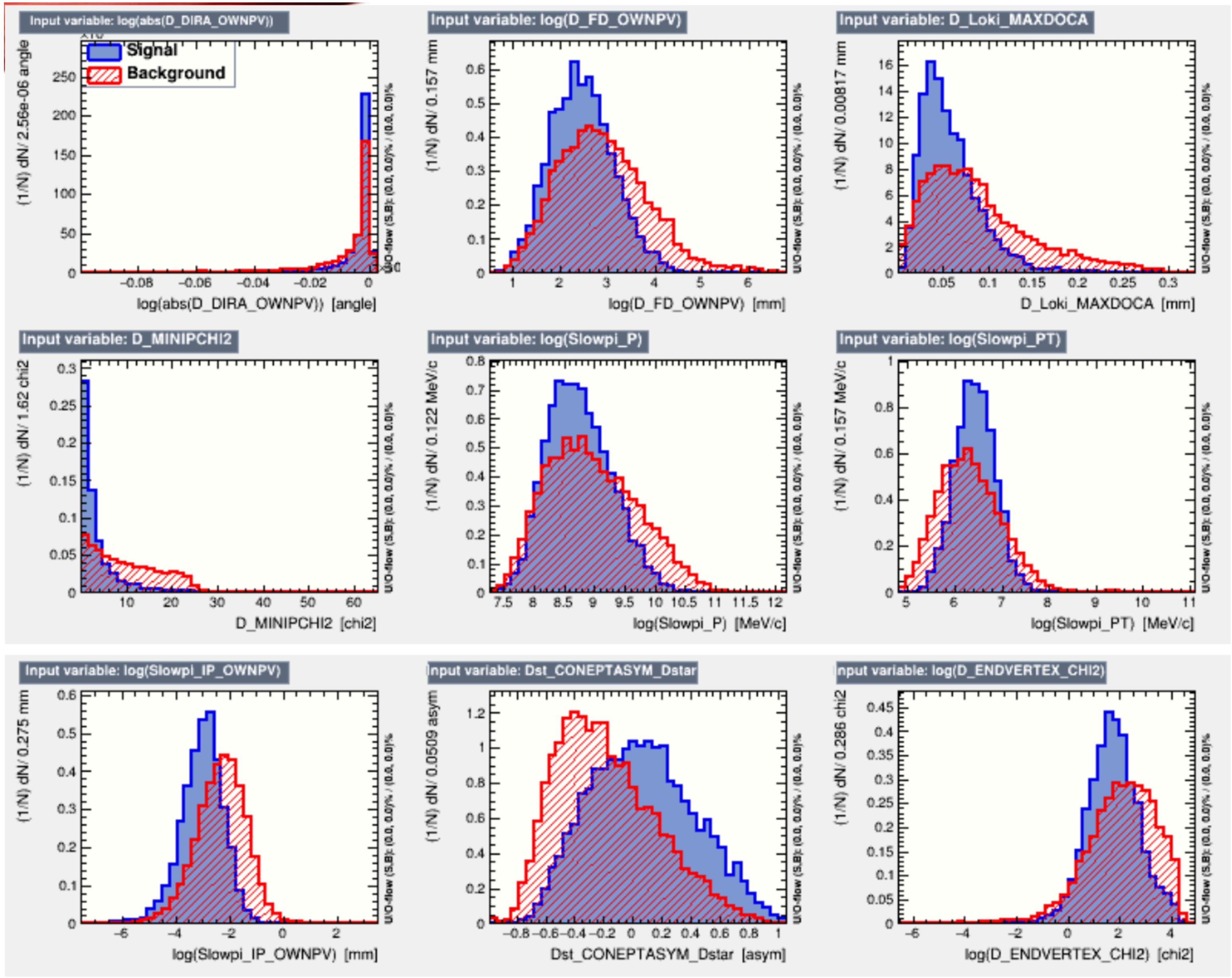
$$R^D_{P_1P_2} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2(D \to P_1 P_2 \mu^+\mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2(D \to P_1 P_2 e^+ e^-)}$$

BSM effects can be seen even in the full q^2 region and soon within the reach of LHCb

full q^2	SM	BSM	LQ	hi q^2 SM	LQs	lo q^2 SM	BSM
$R^D_{\pi\pi}$	$1.00 \pm \mathcal{O}(\%)$	0.85 ...0.99	SM-like	$1.00 \pm \mathcal{O}(\%)$	0.7 ...4.4		
R^D_{KK}	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	NA	NA	$0.83 \pm \mathcal{O}(\%)$	0.60..0.87

(**Angular distributions of semi-leptonic D decays,** Gudrun Hiller, Implications Workshop LHCb, Oct. 2018)

BDT input variables



- D0 flight direction angle
- D0 flight distance from PV
- D0 daughters distance of local approach (DOCA)
- D0 impact parameter from PV
- Soft pion P and PT
- Soft pion impact parameter from PV
- PT asymettry around Dst direction of flight
- D0 vertex chi2