Rare charm and strange decays

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On behalf of the LHCb collaboration

CERN, Geneva
Implications workshop 2024
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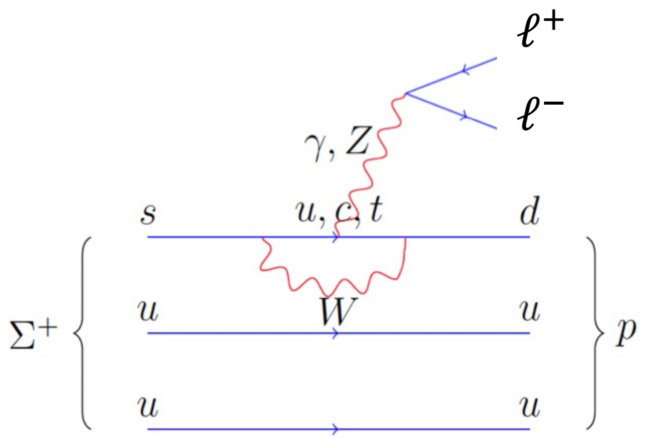
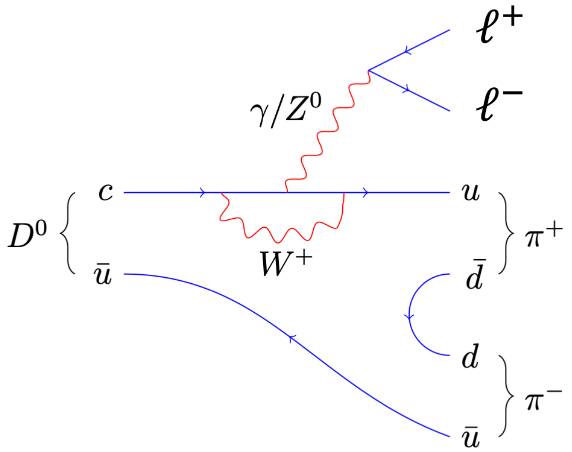
technische universität dortmund

Why study rare charm and strange decays?

- Receive contributions from flavor-changing neutral-current (FCNC) processes
- FCNC cannot proceed at tree level in the SM, but only through highly suppressed loops which makes them ideal probes for New Physics (NP)
  - Rare strange $s \to d\ell\ell$ transitions are complementary to B-sector in down-type quark couplings
  - Rare charm c $\to u\ell\ell$ transitions uniquely probe up-type quarks coupling with bound systems

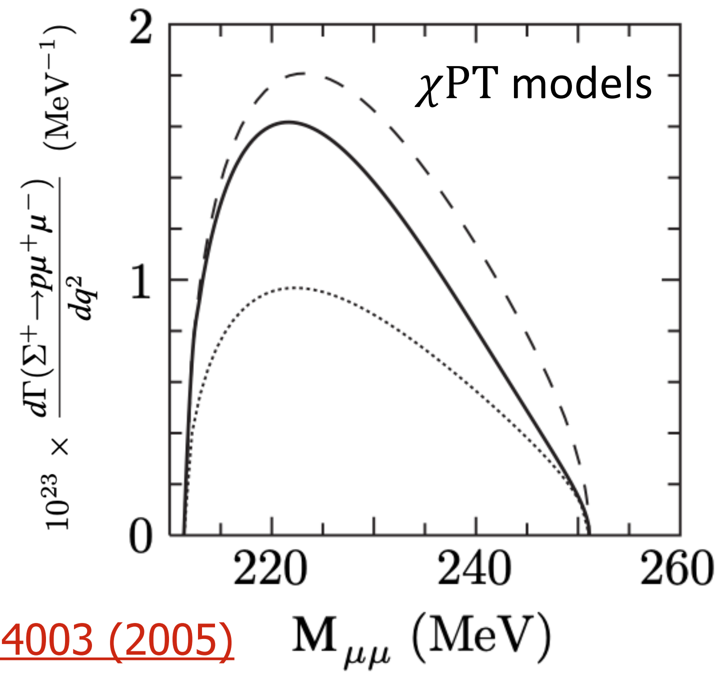




Challenges

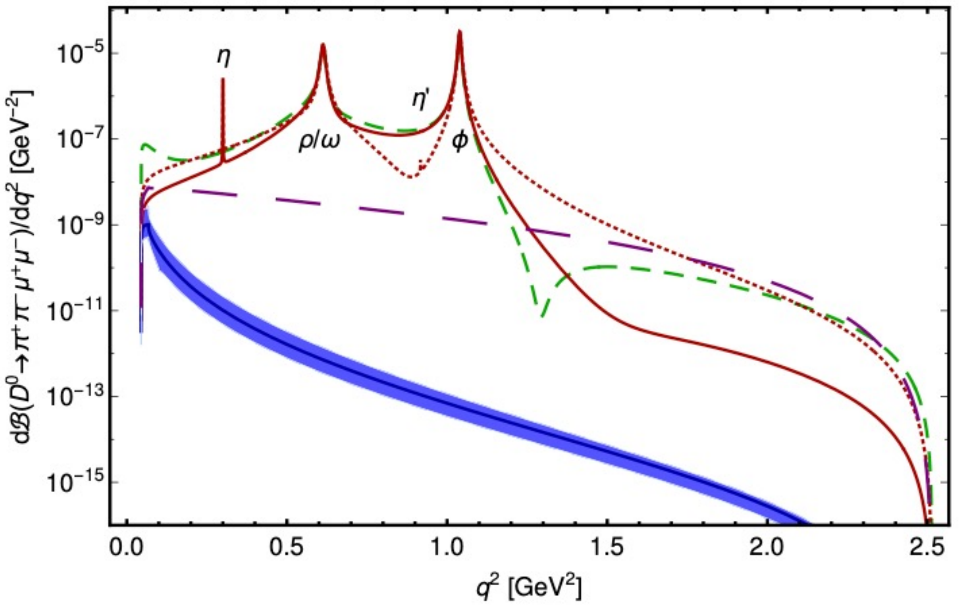
- Both rare charm and strange decays are dominated by the long distance (LD) contribution with tree-level dynamics
- Precise theoretical predictions are difficult on LD component

$\Sigma^+ \to p\,\mu^+\mu^-$



[PRD 72, 074003 (2005)]

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



FCNC component

LD component

LD different model

NP model (dashed)

[PRD 98, 035041 (2018)]

NP searches

How to look for New Physics?

1. Measurements of branching fraction as function q^2
2. CPV and angular analysis
3. Lepton flavour universality

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

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- LHCb is providing a major contributions in the rare charm and strange decays field
- 19 LHCb publications in rare charm and strange sector up to now

Rare charm review:
Mod. Phys. Lett. A 36 (2021) 2130002

NP searches

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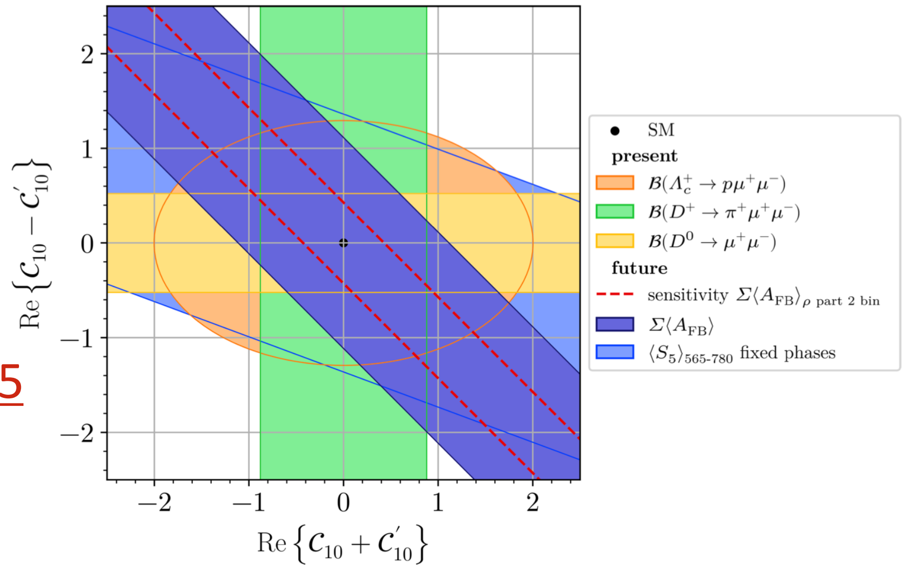
- LHCb is providing a major contributions in the rare charm and strange decays field
- Also from the theory side:
  - study trying to combine all accessible observables in rare charm decays arXiv 2410.00115
  - exclusive study on 3-body rare charm decays See Anshika's talk



NP searches at LHCb

How to look for New Physics?

Measurements of rare modes:

1. Search for $\Sigma^+ \to p\,\mu^+\mu^-$ decays — LHCb-CONF-2024-002
2. Search for $\Lambda_c^+ \to p\,\mu^+\mu^-$ decays — *PRD* 110 (2024) 5, 052007
3. Search for $D^0 \to h^+h^-e^+e^-$ decays — LHCb-PAPER-2024-047, in preparation

NEW!

Rare strange

Rare charm

Rare strange

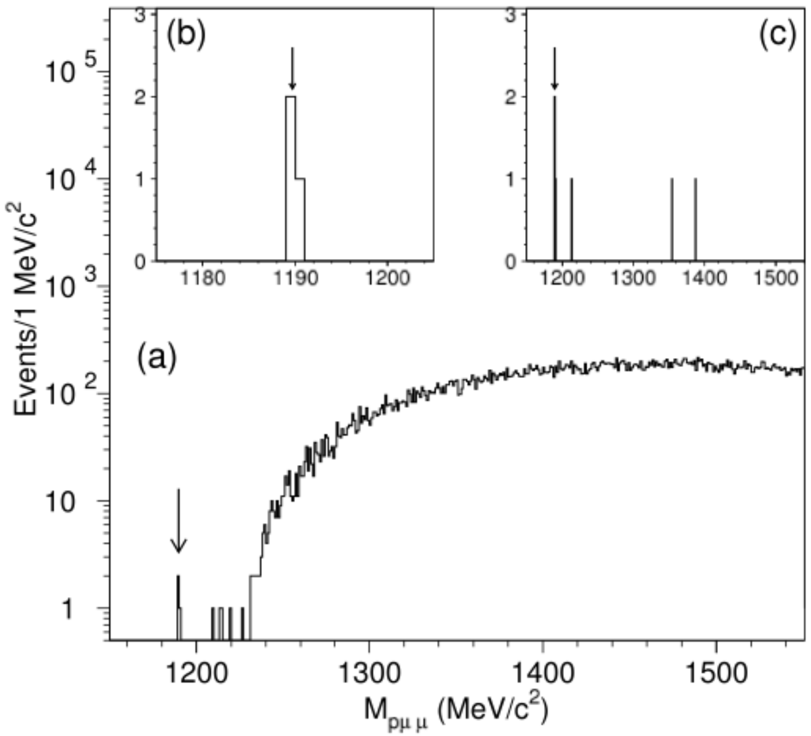
Search for $\Sigma^+ \to p\,\mu^+\mu^-$ decays

LHCb-CONF-2024-002

Search for $\Sigma^+ \to p\,\mu^+\mu^-$ decays

- Evidence found by HyperCP experiment with 3 events in absence of background

$$B(\Sigma^+ \to p\,\mu^+\mu^-) = \left[8.6^{+6.6}_{-5.4} \pm 5.5\right]\times 10^{-8}$$



PRL 94:021801,2005

Search for $\Sigma^+ \rightarrow p\,\mu^+\mu^-$ decays

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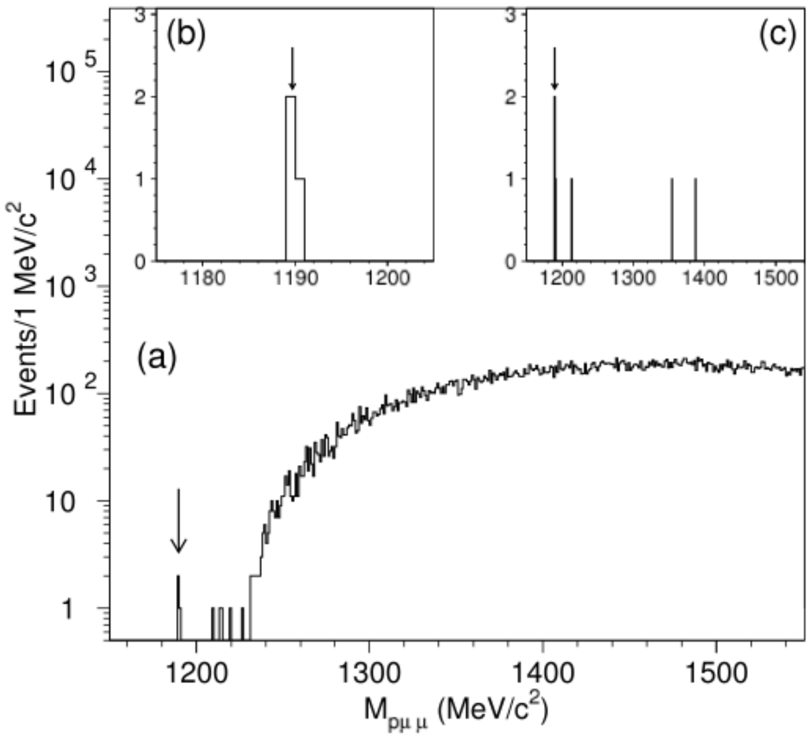
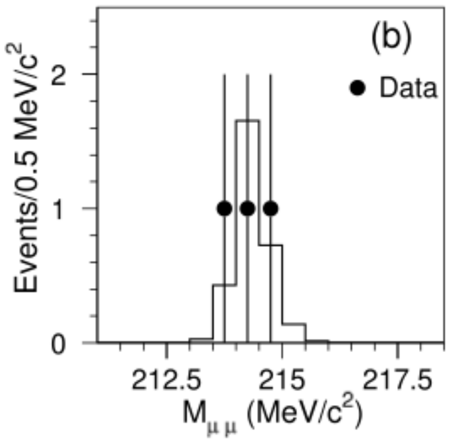
- The 3 events have same dilepton invariant mass pointing towards a decay $\Sigma^+ \rightarrow \mathrm{p}\,P^0(\rightarrow \mu^+\mu^-)$ with $m_{P^0} = 214.3\ \pm 0.5\,MeV$

$$B(\Sigma^+ \rightarrow \mathrm{p}P^0(\rightarrow \mu^+\mu^-)) = [3.1^{+2.4}_{-1.9} \pm 1.5]\times 10^{-8}$$





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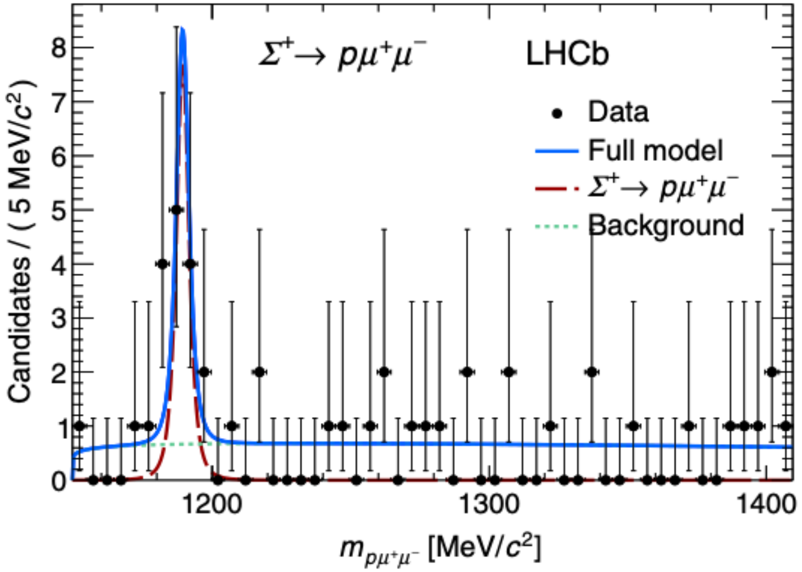
$$B(\Sigma^+ \to pP^0(\to \mu^+\mu^-)) = [3.1^{+2.4}_{-1.9} \pm 1.5]\times 10^{-8}$$

- LHCb performed the analysis with Run1 data with an evidence at 4.1σ:

$$B(\Sigma^+ \to p\,\mu^+\mu^-) = [2.2^{+0.9}_{-0.8}{}^{+1.5}_{-1.1}]\times 10^{-8}$$

But no dimuon structure found

PRL120,221803 (2018)



Search for $\Sigma^+ \to p\,\mu^+\mu^-$ decays

- Analysis repeated by LHCb with Run2 data with $5.4\ \mathrm{fb}^{-1}$
- 10-fold increased trigger efficiency compared to Run1 thanks to dedicated selections and improved PID

LHCb-PUB-2017-023

Channel	ϵ (without new lines)	ϵ (with new lines)
$K^0_S \to \mu^+\mu^-$	0.0290 ± 0.0015	0.250 ± 0.004
$K^0_S \to \pi^0\mu^+\mu^-$	0.026 ± 0.003	0.238 ± 0.008
$\Sigma^+ \to p\mu^+\mu^-$	0.0083 ± 0.0013	0.111 ± 0.004

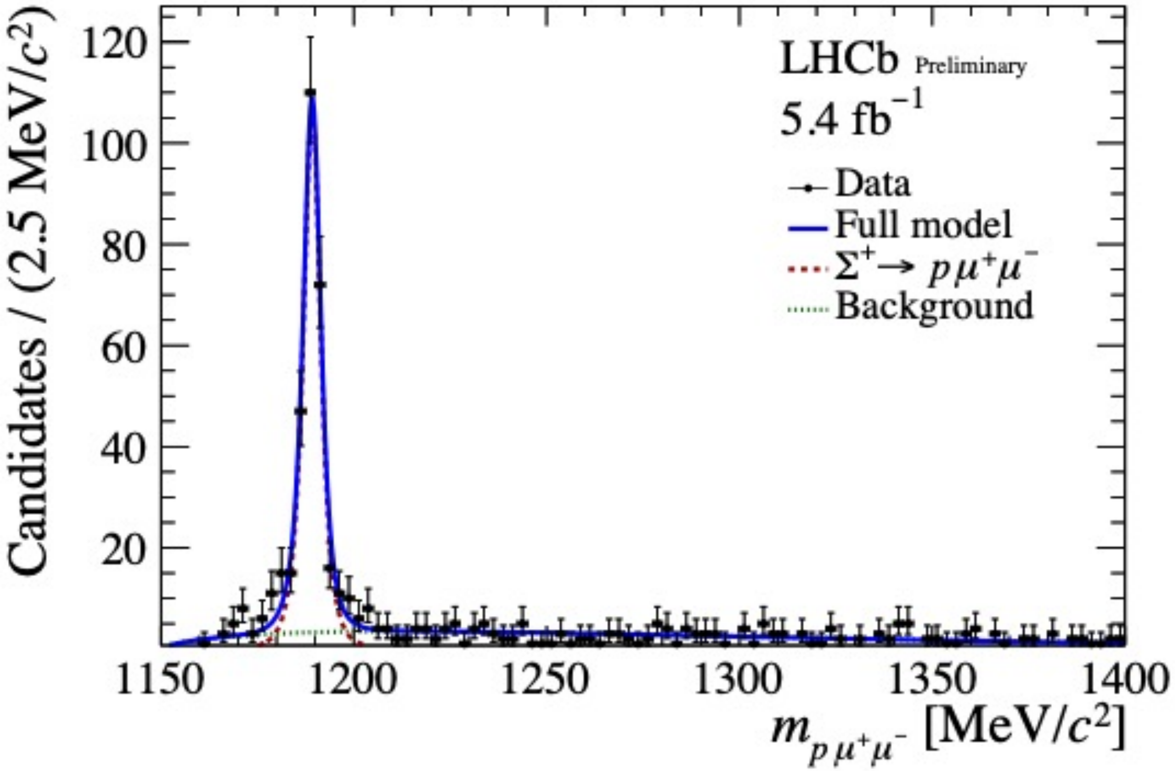
LHCb-CONF-2024-002

Search for $\Sigma^+ \to p\,\mu^+\mu^-$ decays

- Analysis repeated by LHCb with Run2 data with $5.4\ \mathrm{fb}^{-1}$
- 10-fold increased trigger efficiency compared to Run1 thanks to dedicated selections and improved PID
- First observation with a signal yield:

$$N_{\Sigma^+ \to p\,\mu^+\mu^-} = 279\ \pm 19$$

- Rarest hyperon decay ever observed with a significance above 5σ
- Work ongoing on measurement of integrated BF



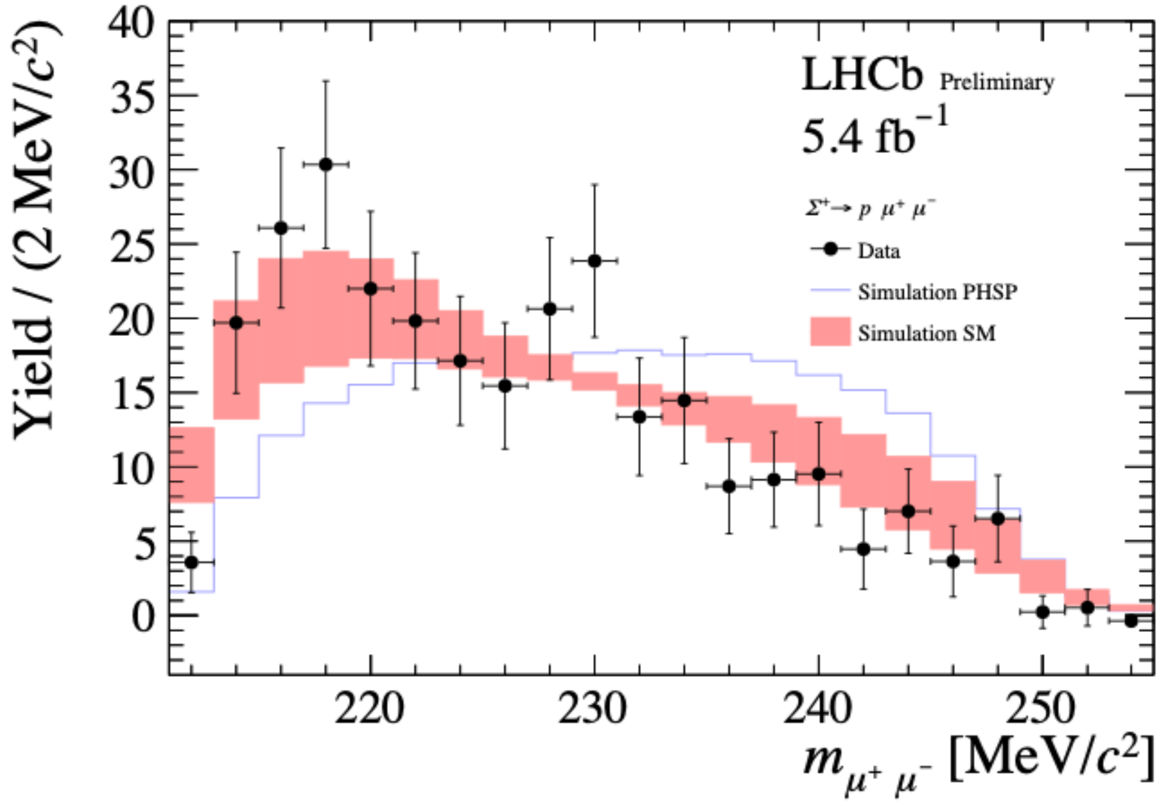
LHCb-CONF-2024-002

Search for $\Sigma^+ \rightarrow p\,\mu^+\mu^-$ decays

- Search for resonances in dimuon invariant mass distribution
- Distribution compatible with SM prediction

  JHEP 10 (2018) 040, hep–ph/2404.15268

- Scan made in the dimuon invariant mass searching for resonant structures but no significant structure found



LHCb-CONF-2024-002

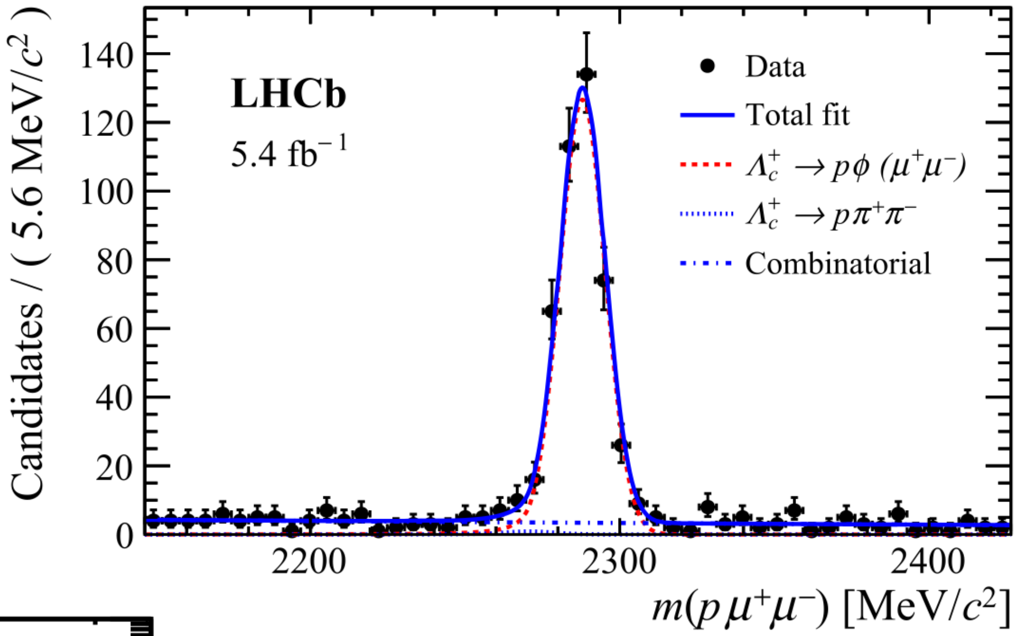
Rare charm

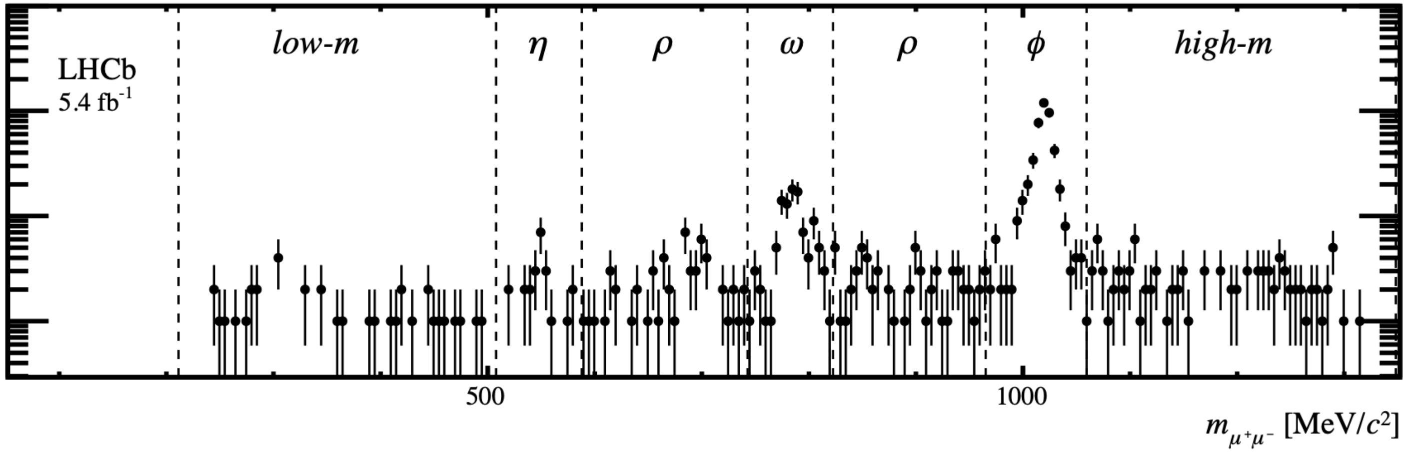
Search for $\Lambda_c^+ \to p\,\mu^+\mu^-$ decays

PRD 110 (2024) 5, 052007

Search for $\Lambda_c^+ \to p\,\mu^+\mu^-$ decays

- Study in both resonant and non-resonant dimuon regions using $5.4\ \text{fb}^{-1}$ dataset
- Not attempting any amplitude analysis
- Normalised to ϕ region: $\Lambda_c^+ \to p\,\phi(\to \mu^+\mu^-)$





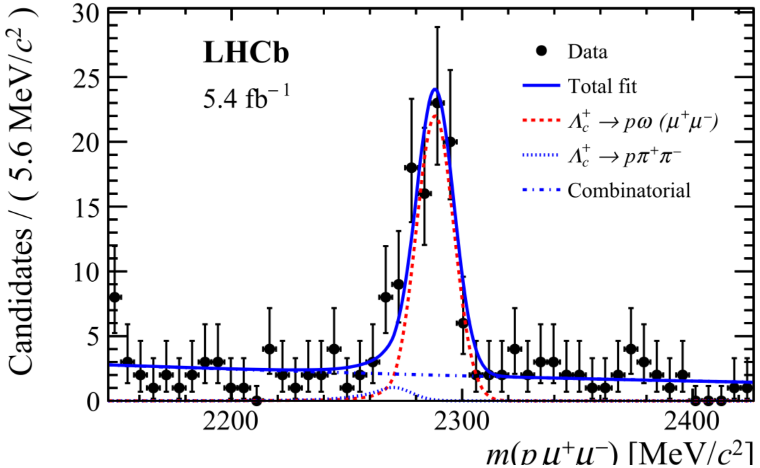
PRD 110 (2024) 5, 052007

Search for $\Lambda_c^+ \to p\,\mu^+\mu^-$ decays

- Evaluating branching fraction in the resonant part

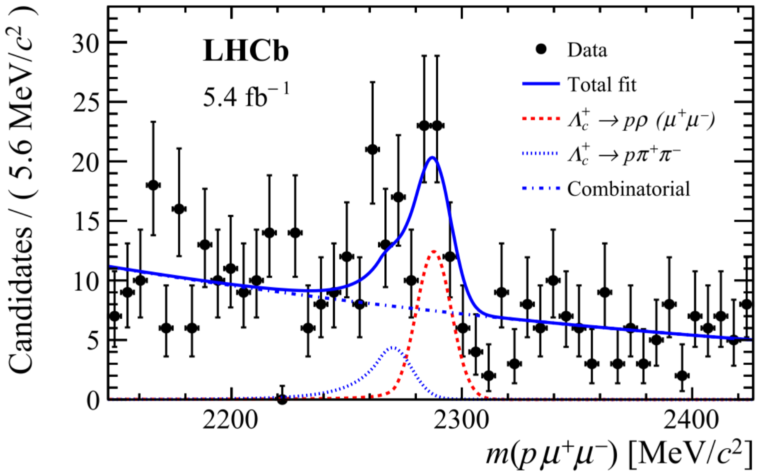
$> 7\sigma$

$\Lambda_c^+ \to p\,\rho(\to \mu^+\mu^-)$



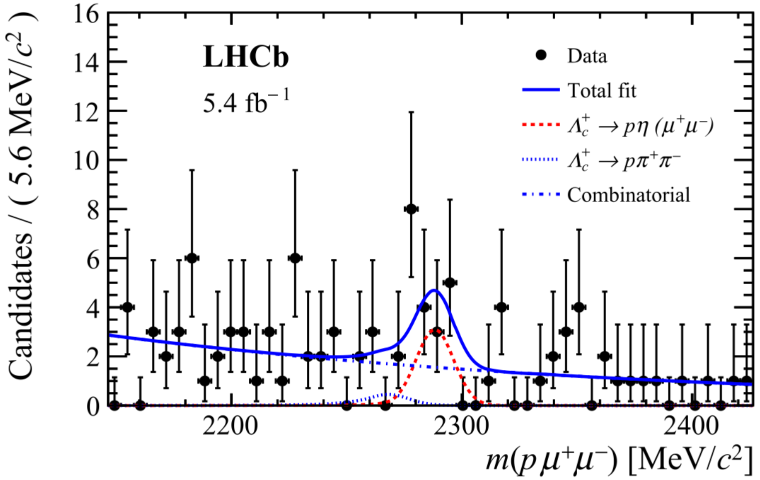
5.6σ

$\Lambda_c^+ \to p\,\omega(\to \mu^+\mu^-)$



3.0σ

$\Lambda_c^+ \to p\,\eta(\to \mu^+\mu^-)$



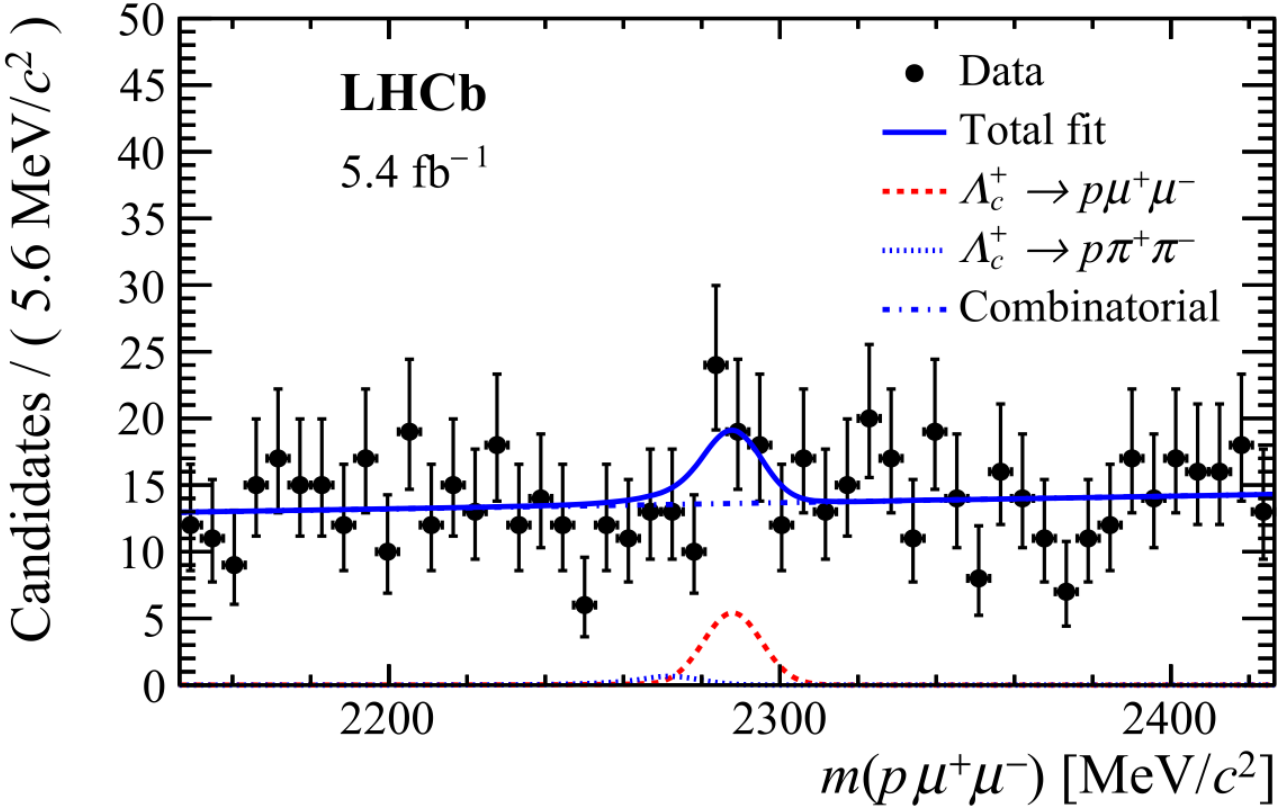
$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23(\text{stat}) \pm 0.73(\text{syst}) \pm 2.79(\text{ext})) \times 10^{-4},$$

$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34(\text{stat}) \pm 0.14(\text{syst}) \pm 0.24(\text{ext})) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69(\text{stat}) \pm 0.23(\text{syst}) \pm 0.34(\text{ext})) \times 10^{-3},$$

PRD 110 (2024) 5, 052007

Search for $\Lambda_c^+ \to p\,\mu^+\mu^-$ (non-resonant) decays



$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9(3.2) \times 10^{-8} \text{ at } 90\%(95\%) \text{ CL.}$$

PRD 110 (2024) 5, 052007

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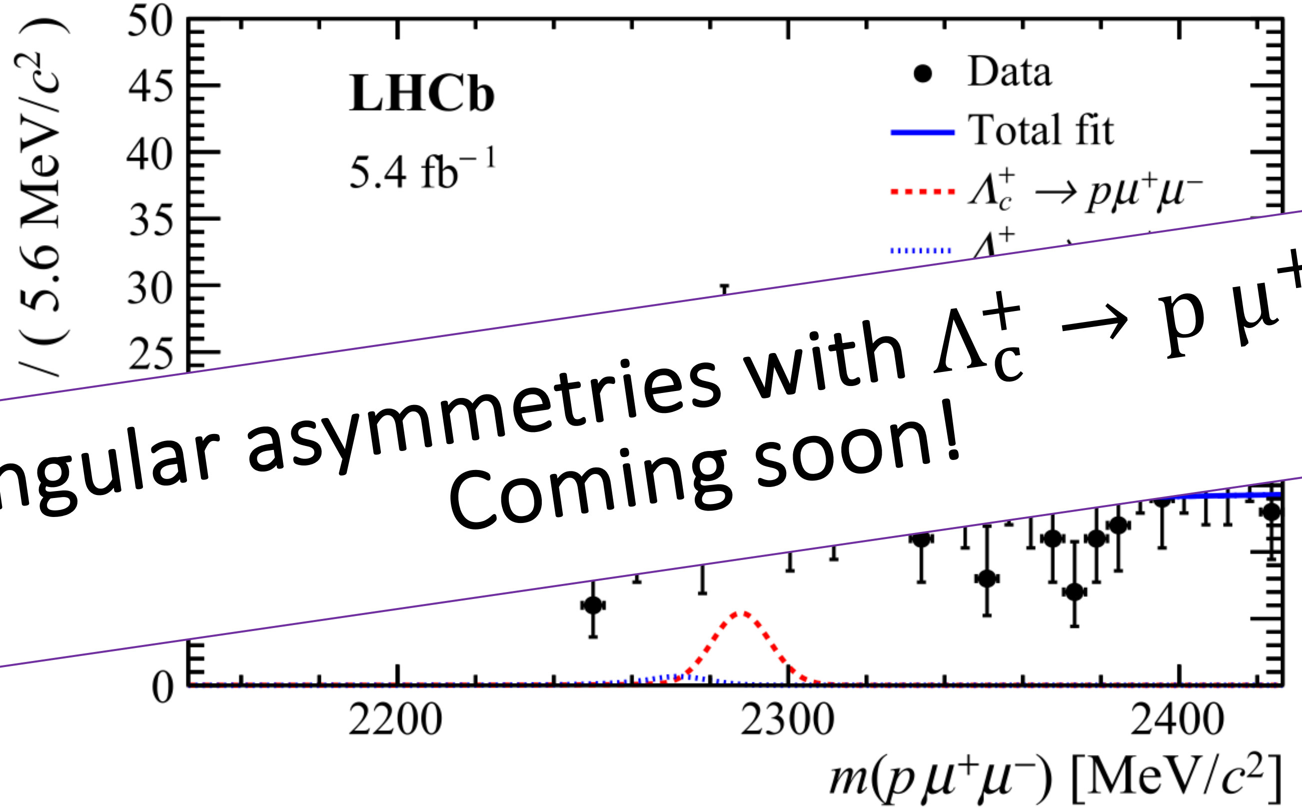

CP and angular asymmetries with $\Lambda_c^+ \to p\,\mu^+\mu^-$ decays:
Coming soon!

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9(3.2) \times 10^{-8} \text{ at } 90\%(95\%) \text{ CL.}$$

PRD 110 (2024) 5, 052007

Rare charm

NEW!

Search for $D^0 \to h^+h^-e^+e^-$ decays

LHCb-PAPER-2024-047, in preparation

Search for $D^0 \to h^+h^-e^+e^-$ decays

NEW!

- First LHCb study on $D^0 \to h^+h^-e^+e^-$ rare charm decays ($h = \pi, K$)

LHCb-PAPER-2024-047, in preparation

- Experimental status:

	$D^0 \to \pi^+\pi^-e^+e^-$	$D^0 \to K^+K^-e^+e^-$	
BESIII	$< 7 \times 10^{-6}$	$< 1.1 \times 10^{-5}$	PRD 97, (2018) 072015
Belle	$< [3.1, 7.2] \times 10^{-7}$	$< [2.3, 7.7] \times 10^{-7}$	Moriond 2024 presentation

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PRD 97, (2018) 072015

Moriond 2024 presentation

- Muon modes $D^0 \to h^+h^-\mu^+\mu^-$ already studied by LHCb with observation in both modes

Channel	Total $[\times 10^{-8}]$	low mass $[\times 10^{-8}]$	η $[\times 10^{-8}]$	ρ/ω $[\times 10^{-8}]$	ϕ $[\times 10^{-8}]$	high mass $[\times 10^{-8}]$
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	96.4 ± 12	7.8 ± 2.1	< 2.4 at 90 % CL	40.6 ± 5.7	45.4 ± 5.9	< 2.8 at 90 % CL
$D^0 \to K^+K^-\mu^+\mu^-$	15.4 ± 3.2	2.6 ± 1.3	< 0.7 at 90 % CL	12.0 ± 2.7		

PRL 119 (2017) 181805

Analysis strategy

- Search for the $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ decays using 6 fb^{-1} dataset
- BF measurement relative to the normalization channel $D^0 \to K^-\pi^+e^+e^-$:

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

- Ratio of yields from likelihood fit to data

LHCb-PAPER-2024-047, in preparation

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- Ratio of yields from likelihood fit to data
- Ratio of efficiencies from simulated samples and corrected for data/simulation differences
- Profiting from partial cancellation of systematic uncertainties in both ratios

LHCb-PAPER-2024-047, in preparation

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- Search for the $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ decays using 6 fb^{-1} dataset
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BaBar measurement

$(4.0 \pm 0.5) \times 10^{-6}$

in ρ/ω region

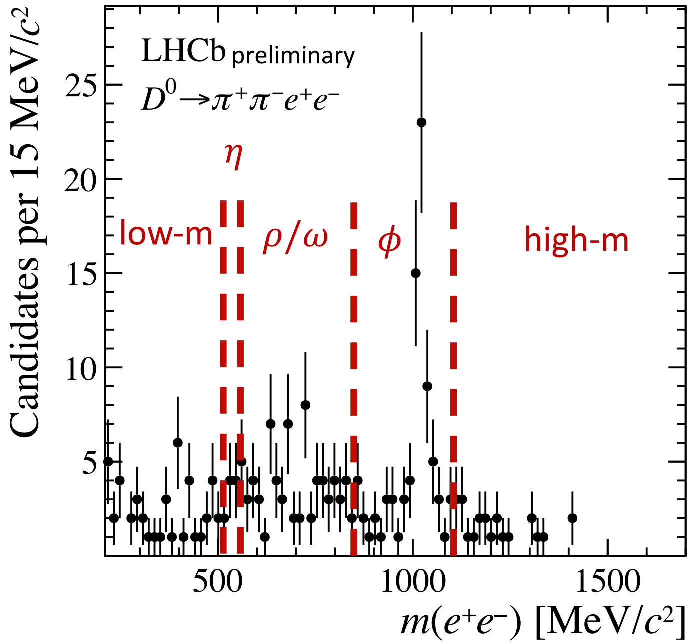
PRL 122, (2019) 081802

- Ratio of yields from likelihood fit to data
- Ratio of efficiencies from simulated samples and corrected for data/simulation differences
- Profiting from partial cancellation of systematic uncertainties in both ratios

LHCb-PAPER-2024-047, in preparation

Analysis strategy

- Measurement integrated and in dilepton mass bins (same as muon mode analysis)
- If significance $< 3\sigma$, calculate upper limits with CLs method [J.Phys.G 28 (2002) 2693-2704]



LHCb-PAPER-2024-047, in preparation

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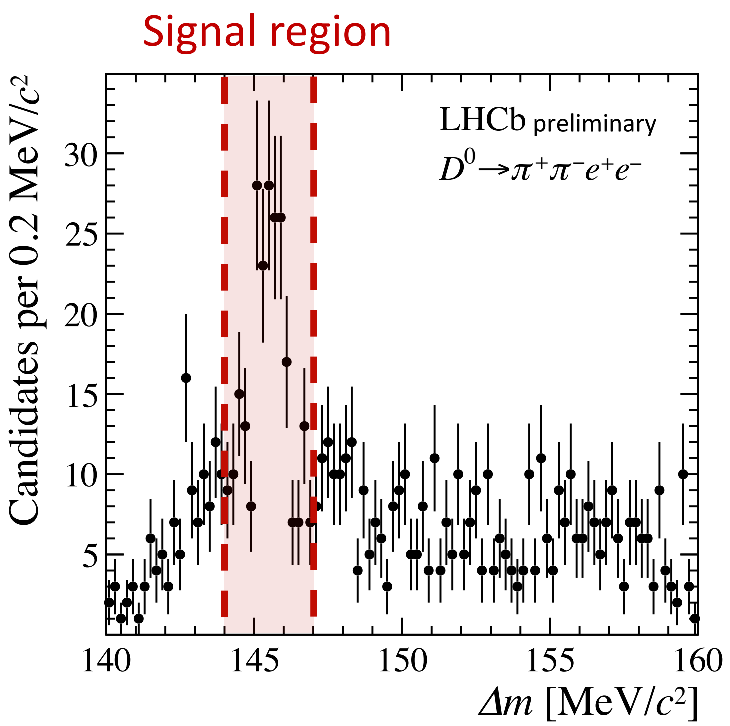
- If significance $< 3\sigma$, calculate upper limits with CLs method [J.Phys.G 28 (2002) 2693-2704](#)
- D^0 candidates from $D^{*+} \to D^0\,\pi^+$ decays for background suppression
- Selection around signal peak in $\Delta m = m(D^{*+}) - m(D^0)$

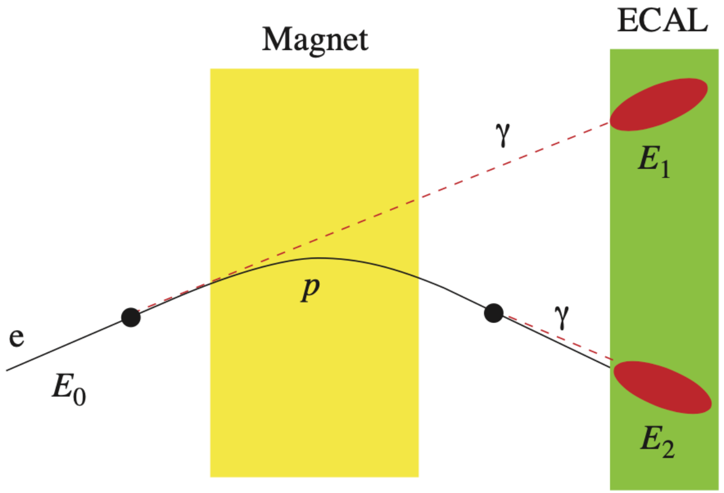


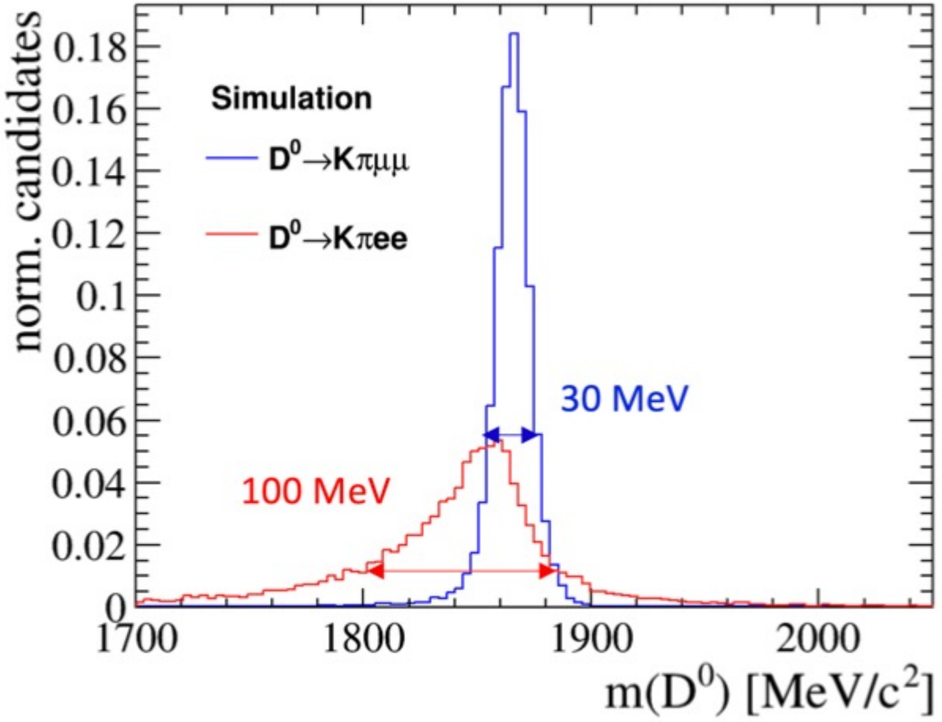
LHCb-PAPER-2024-047, in preparation

Electrons at LHCb

1. Lower trigger efficiency compared to muon modes: high occupancy in calorimeters
2. Bremsstrahlung effects: electrons-detector material interaction

- Candidates split in no-brem (0γ) and with-brem ($\geq 1\gamma$) categories to control different types of background





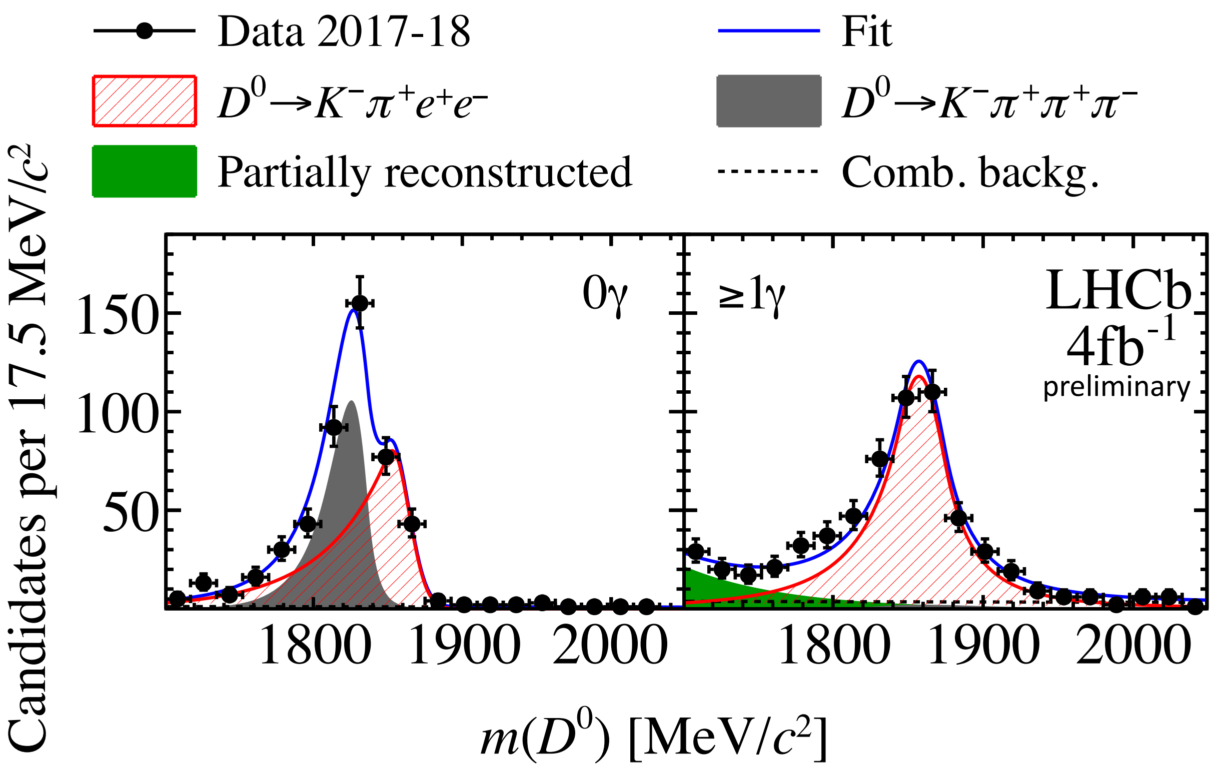
A. Scarabotto, PhD thesis, 04323454 (2023)

LHCb-PAPER-2024-047, in preparation

Background studies and $D^0 \to K^-\pi^+e^+e^-$ fit

- Main backgrounds:
  - Combinatorial
  - $D^0 \to K^-\pi^+\pi^+\pi^-$ with pions mis-id as electrons
  - Partially reconstructed: more prominent in with-brem category with wrongly attached photons

$N_{D^0\to K^-\pi^+e^+e^-} = 820 \pm 39$
in ρ/ω dilepton mass region



LHCb-PAPER-2024-047, in preparation

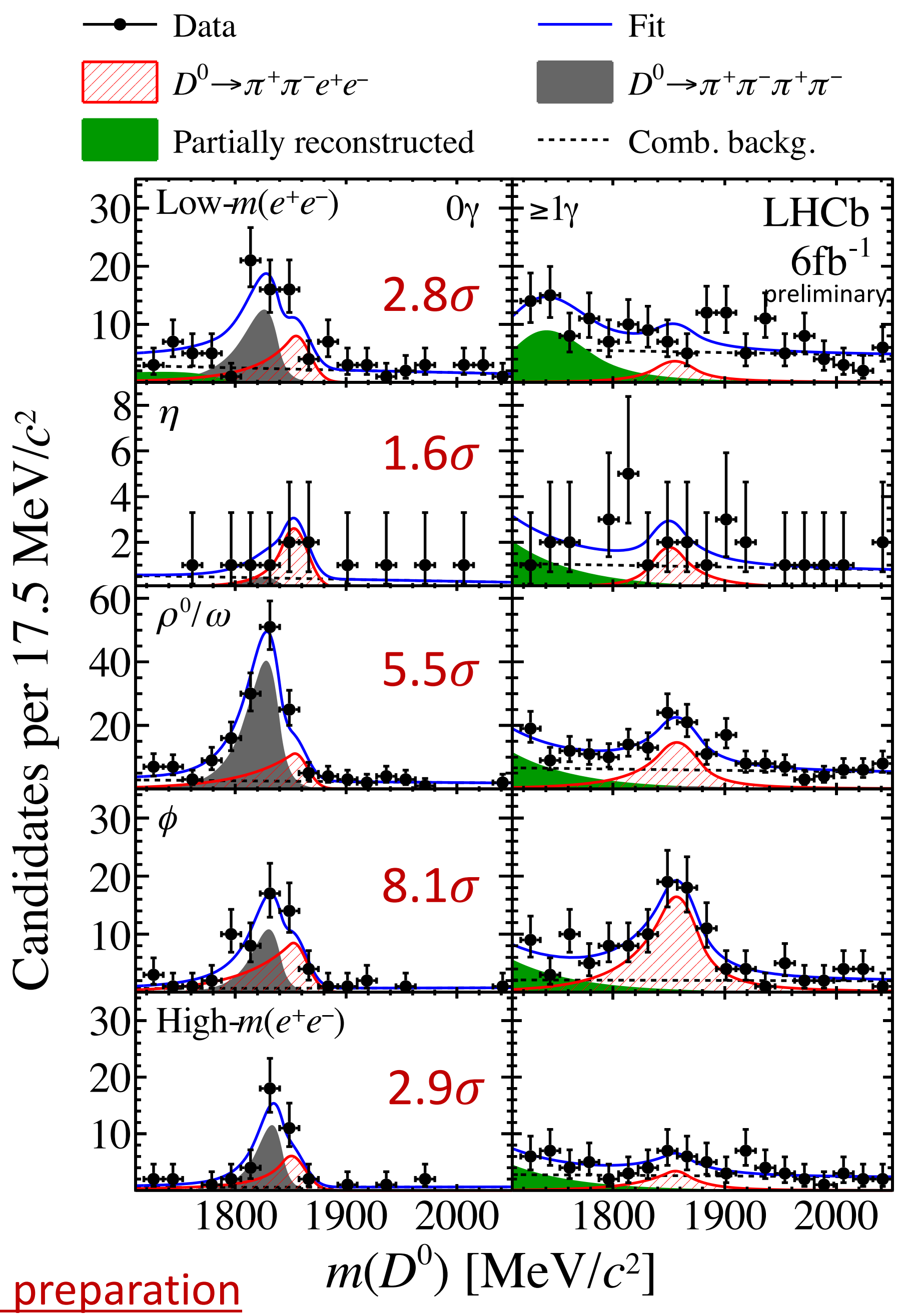
$D^0 \to \pi^+\pi^-e^+e^-$

- First observation of $D^0 \to \pi^+\pi^-e^+e^-$ in ρ/ω and φ dilepton mass regions
- World's best upper limits in other regions

$D^0 \to \pi^+\pi^-e^+e^-$			
$m(e^+e^-)$ region	$[\text{MeV}/c^2]$	$\mathcal{B}\ [10^{-7}]$	
Low mass	211–525	$< 4.81\ (5.39)$	
η	525–565	$< 2.27\ (2.74)$	
ρ^0/ω	565–950	$4.53 \pm 1.00 \pm 0.72 \pm 0.62$	*
ϕ	950–1100	$3.84 \pm 0.70 \pm 0.39 \pm 0.53$	*
High mass	> 1100	$< 2.00\ (2.17)$	

First observation!

* Statistical, systematic and uncertainties related to norm. BF

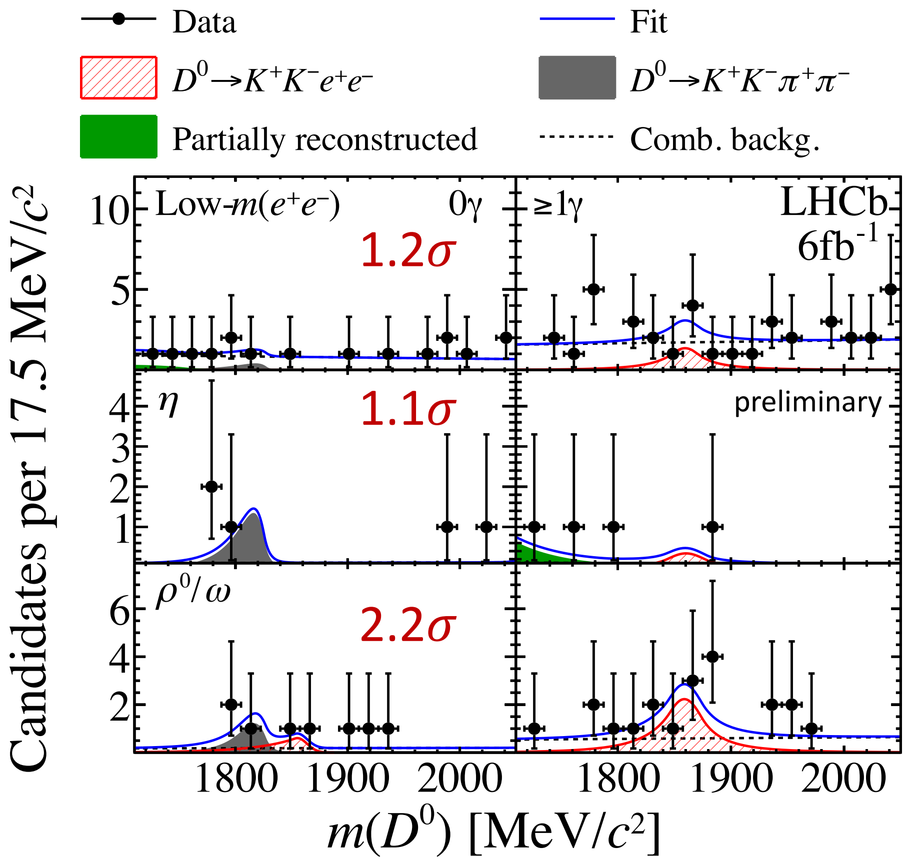


LHCb-PAPER-2024-047, in preparation

$D^0 \to K^+K^-e^+e^-$

- No evidence with current precision
- World's best upper limits reported in all dilepton mass bins

$m(e^+e^-)$ region	$D^0 \to K^+K^-e^+e^-$ [MeV/c^2]	$\mathcal{B}$ [10^{-7}]
Low mass	211–525	$< 0.97\,(1.05)$
η	525–565	$< 0.44\,(0.54)$
ρ^0/ω	> 565	$< 2.15\,(2.47)$



LHCb-PAPER-2024-047, in preparation

Comparison with muon modes

- Integrating over the dielectron mass ranges considered for $D^0 \to \pi^+\pi^-e^+e^-$ decays and accounting for correlations *:

$$\mathcal{B}(D^0 \to \pi^+\pi^-e^+e^-) = (13.3 \pm 1.7 \pm 1.7 \pm 1.8) \times 10^{-7}$$

where uncertainties are statistical, systematic and due to normalization BF

- Compatible with muon modes within 1.3σ:

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) \quad = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

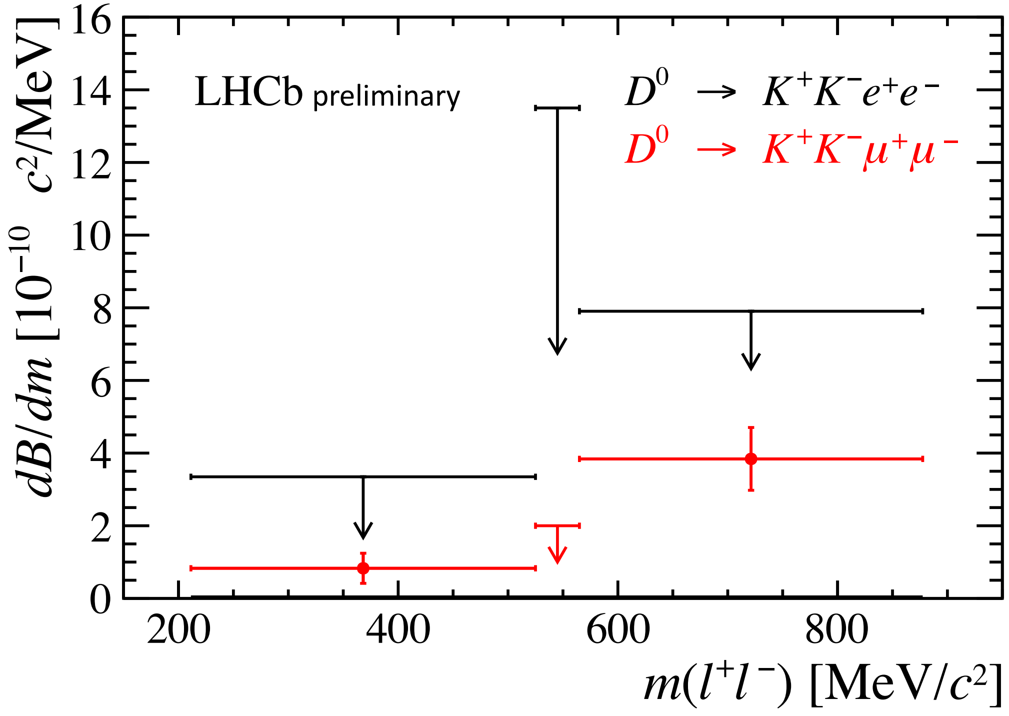
- What about in each dilepton mass region?

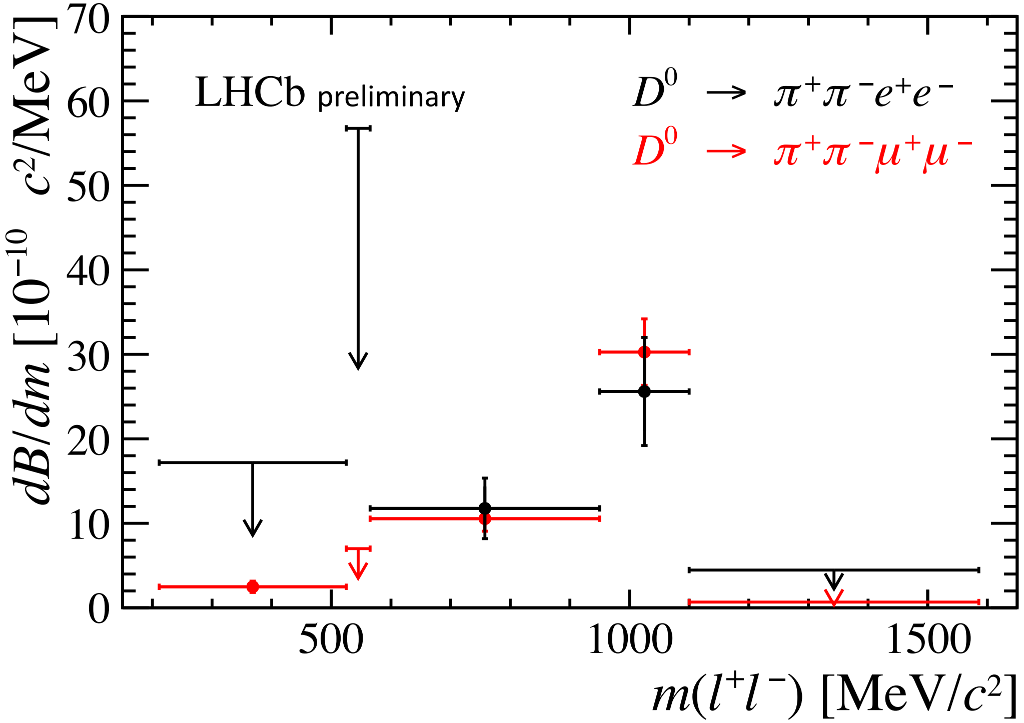
* See backup

LHCb-PAPER-2024-047, in preparation

Comparison with muon modes

- Results compatible with muonic modes confirming lepton universality at the current level of precision ($D^0 \rightarrow \pi^+\pi^-e^+e^-$ in ρ/ω and φ dilepton mass regions)





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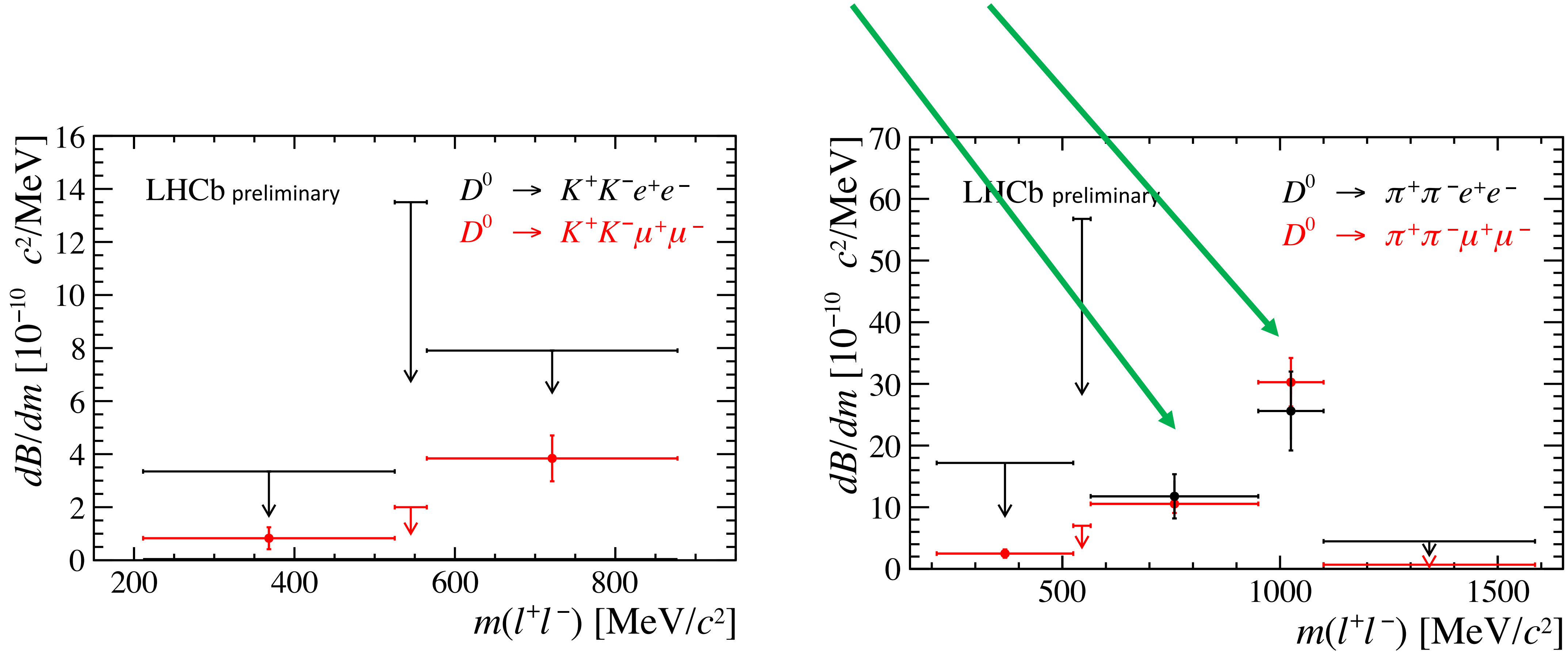
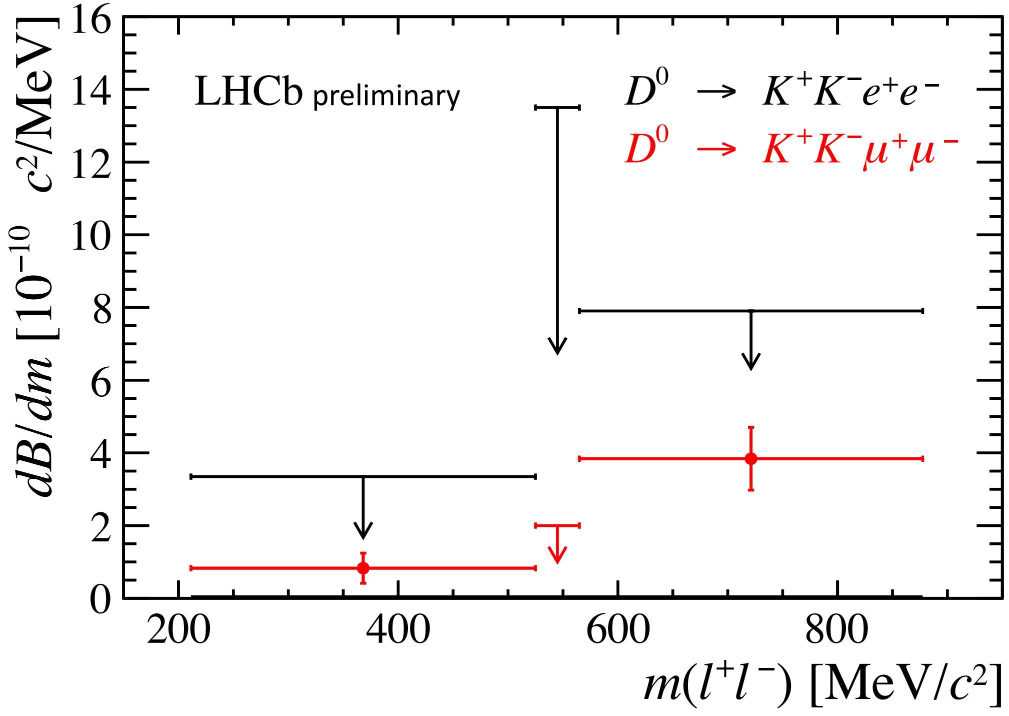
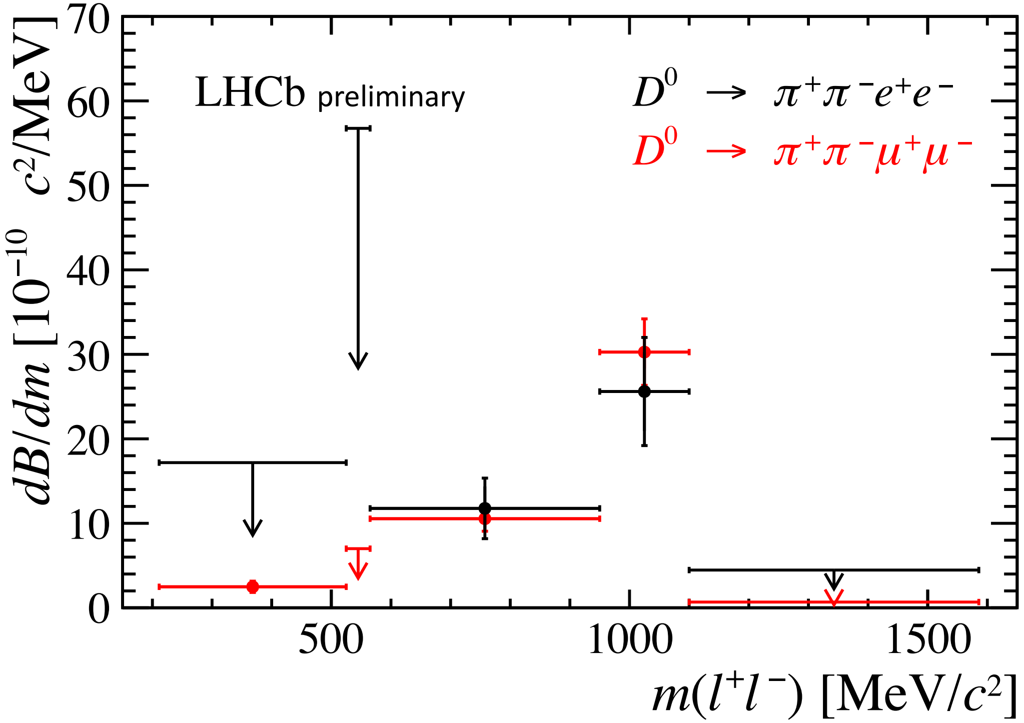


LHCb-PAPER-2024-047, in preparation

Comparison with muon modes

- Results compatible with muonic modes confirming lepton universality at the current level of precision ($D^0 \to \pi^+\pi^-e^+e^-$ in ρ/ω and φ dilepton mass regions)
- Less stringent upper limits in all other dilepton mass regions compared to muon modes





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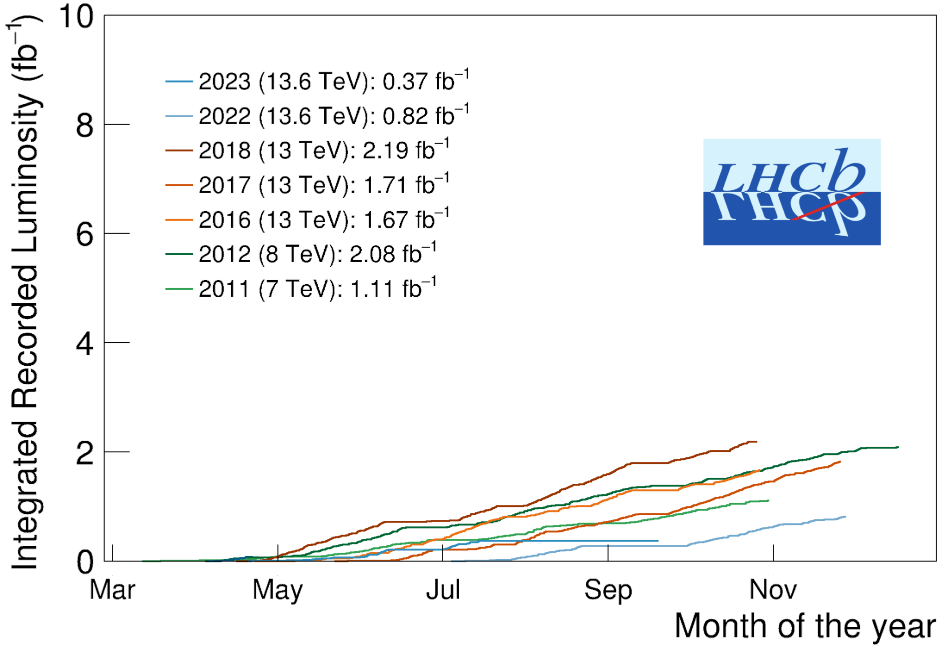
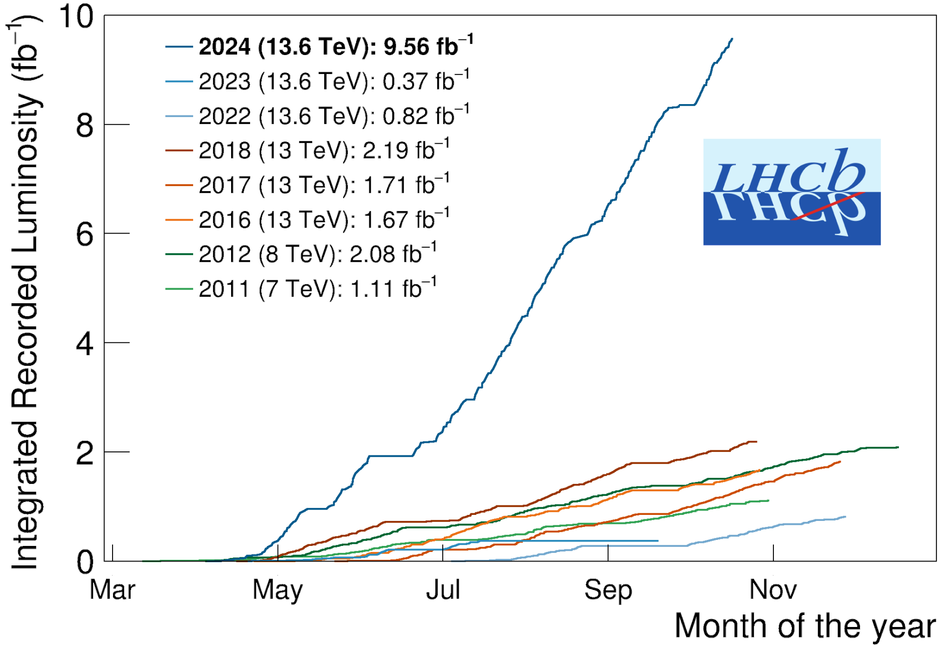
Prospects

- LHCb will continue to exploit the Run2 dataset:
  - $\Sigma^+ \to p\,\mu^+\mu^-$ integrated BF, CPV and angular asymmetries
  - Search for $K^0_S \to \pi^+\pi^-\mu^+\mu^-$ decays
  - $\Lambda_c^+ \to p\,\mu^+\mu^-$ and $D^+_{(s)} \to \pi^+\mu^+\mu^-$ CPV and angular analysis
  - Lepton flavour violating decays
  - Radiative decays
  - …



Prospects

- But … more than 9 fb^{-1} collected in Run3 just with 2024 data-taking year
- Exploit the improved trigger efficiency and our knowledge on rare decays to improve data analysis methods
- Plans for Run3:
  - $\Sigma^+ \to p\,\mu^+\mu^-$ CPV and angular analysis
  - $D^0 \to h^+h^-\ell^+\ell^-$ LFU test
  - $D^0 \to \mu^+\mu^-$ update
  - …



Conclusions

- Rare charm and strange decays constitute a unique environment to look for New Physics, complementary to B-sector
- LHCb is giving a major contribution in the field:
  - $\Sigma^+ \to p\,\mu^+\mu^-$: first observation of rarest hyperon decay — LHCb-CONF-2024-002
  - $\Lambda_c^+ \to p\,\mu^+\mu^-$: world's best upper limit in non-resonant region — *PRD* 110 (2024) 5, 052007
  - $D^0 \to h^+h^-e^+e^-$: first observation in $D^0 \to \pi^+\pi^-e^+e^-$ and world's best upper limit in $D^0 \to h^+h^-e^+e^-$ decays — NEW! LHCb-PAPER-2024-047 in preparation
- Future prospects:
  - Electron mode measurement paving the path for future LFU tests
  - Particular interest in angular and CP asymmetries ($\Lambda_c^+ \to p\,\mu^+\mu^-$ analysis with Run2 dataset coming very soon!)
  - Exploiting larger Run3 dataset with improved trigger efficiency

Backup

$D^0 \to \pi^+\pi^-e^+e^-$ correlations

- Integrating over the dielectron mass ranges considered for $D^0 \to \pi^+\pi^-e^+e^-$ decays and accounting for correlations:

$$\mathcal{B}(D^0 \to \pi^+\pi^-e^+e^-) = (13.3 \pm 1.7 \pm 1.7 \pm 1.8) \times 10^{-7}$$

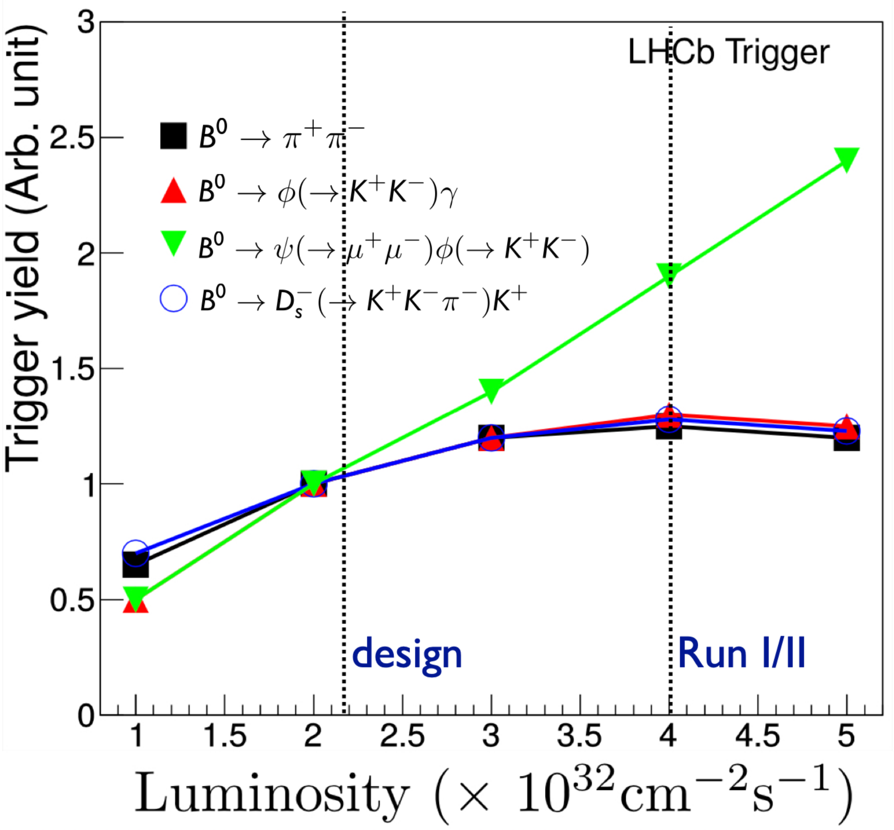
where uncertainties are statistical, systematic and due to normalization BF

$D^0 \to \pi^+\pi^-e^+e^-$		
m(e^+e^-) region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]
Low mass	211–525	$2.81^{+1.00}_{-0.90} \pm 0.43 \pm 0.38$
η	525–565	$1.03^{+0.70}_{-0.50} \pm 0.21 \pm 0.14$
ρ^0/ω	565–950	$4.53 \pm 1.00 \pm 0.72 \pm 0.62$
ϕ	950–1100	$3.84 \pm 0.70 \pm 0.39 \pm 0.53$
High mass	> 1100	$1.05 \pm 0.40 \pm 0.18 \pm 0.14$

Table S3: Correlation coefficients related to the statistical and systematic uncertainties of the branching fractions of $D^0 \to \pi^+\pi^-e^+e^-$ decays in different dilepton mass regions. The matrix reported does not include uncertainties related the normalization mode branching fraction.

$D^0 \to \pi^+\pi^-e^+e^-$					
[MeV/c^2]	211-525	525-565	565-950	950-1100	>1100
211-525	1.00	0.07	0.20	0.17	0.12
525-565		1.00	0.18	0.16	0.11
565-950			1.00	0.37	0.26
950-1100				1.00	0.23
>1100					1.00

Electron trigger efficiency improvements in Run3



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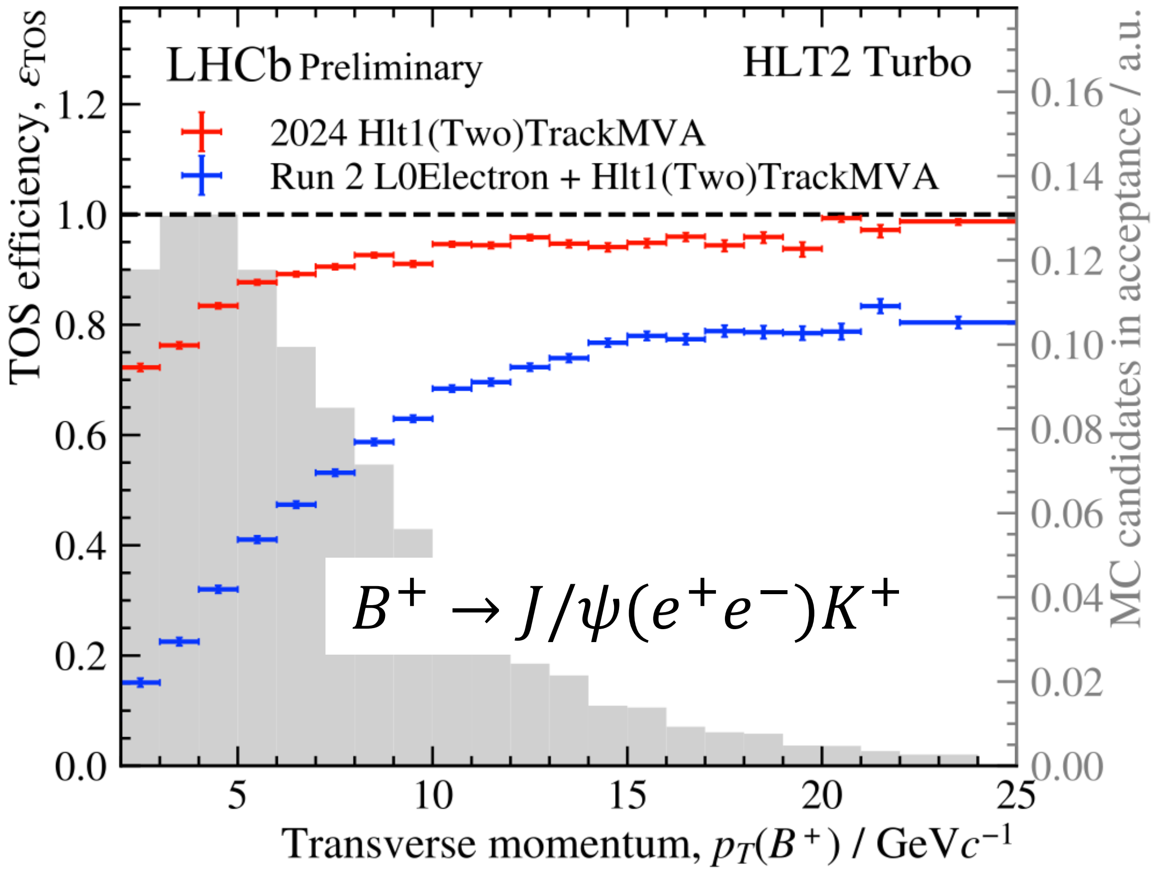

LHCB-FIGURE-2024-030

LFU in charm

Phys. Rev. D 98, 035041 (2018)

While data on muons [17] and electrons [18] exist for $D^0 \to \pi^+\pi^- l^+ l^-$ and $D^0 \to K^+K^- l^+ l^-$ decays, see table I, unfortunately, this does not permit to compute the respective clean LNU-ratios (40) due to incompatible q^2-cuts employed by the two experiments. In particular, BESIII included q^2-regions not accessible with dimuons and vetoed the $\phi \to e^+e^-$ region. We recommend to give dielectron results for q^2 values above the dimuon threshold to allow for a measurement of $R^D_{P_1 P_2}$

$$R^D_{P_1 P_2} = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} d\mathcal{B}/dq^2 (D \to P_1 P_2 \mu^+ \mu^-)}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} d\mathcal{B}/dq^2 (D \to P_1 P_2 e^+ e^-)}$$ with same cuts $q^2_{\text{min}} \geq 4m^2_\mu$

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

Gudrun's talk at IW 2018