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Search for the rare decay $D^+ \to \pi^+ e^+ e^-$ with Belle and Belle II detectors

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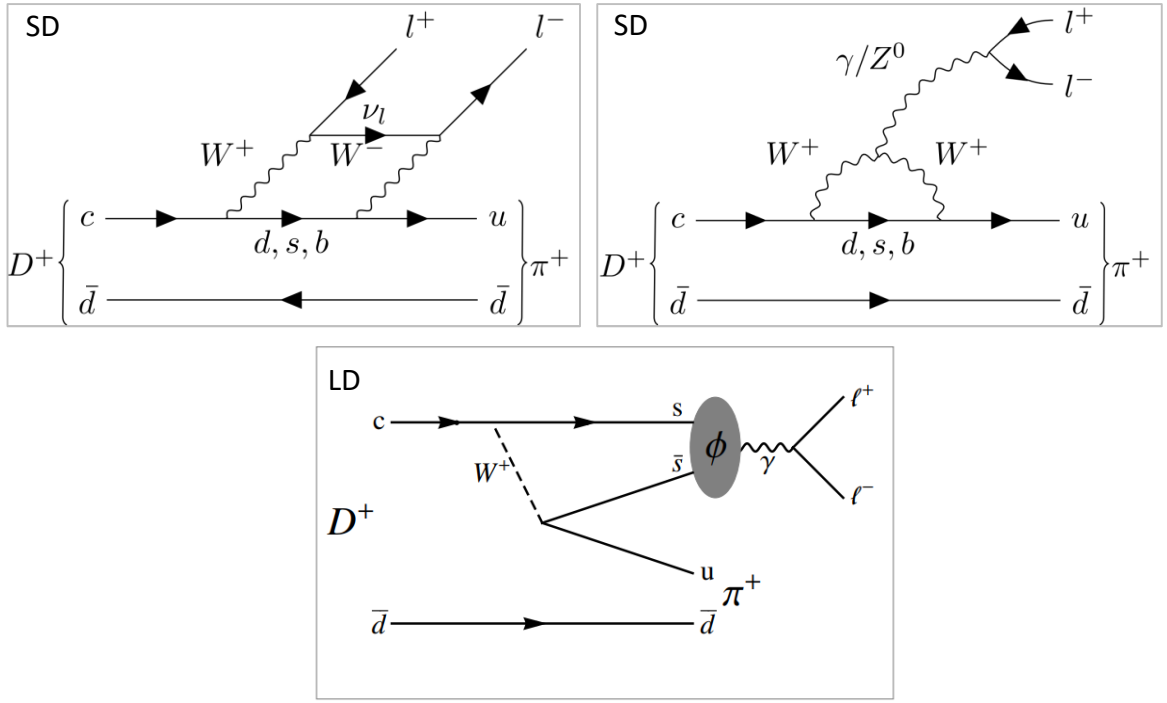
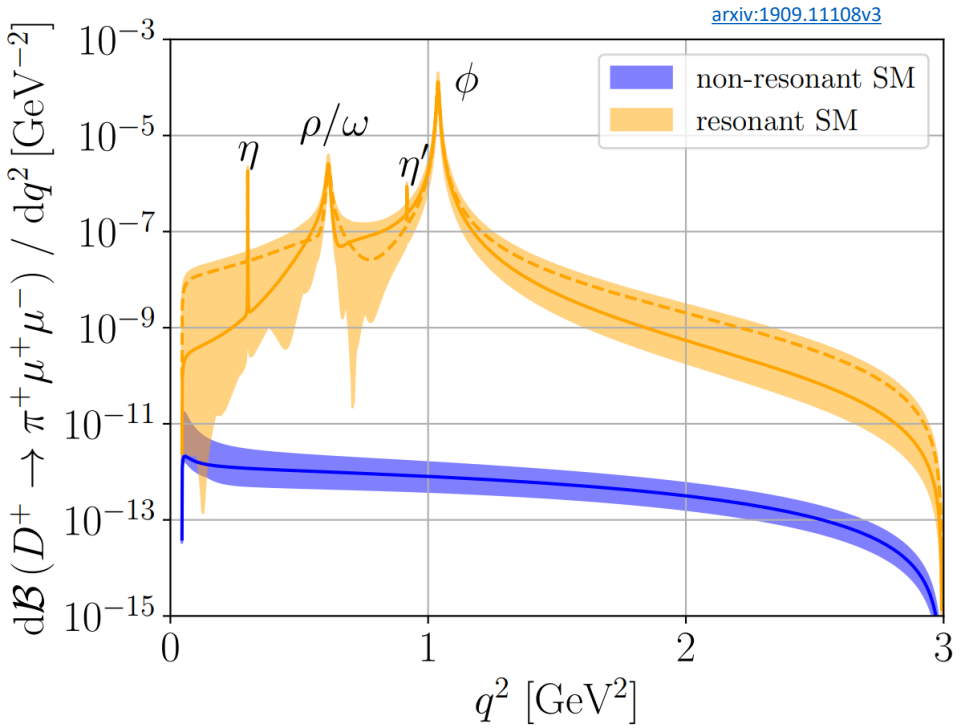
Strateško srečanje

28 – 30 September 2026, Krvavec

Introduction

- Rare decay: flavour changing neutral current (FCNC) are suitable for testing SM and NP models
  - SM: $c \rightarrow u\,\ell^+\ell^-$ transitions do not occur at tree level; proceed only through loops, where further suppressed by GIM mechanism
  - BSM contributions may be comparable far from resonances with short-distance: $\mathcal{B}(SM) \sim \mathcal{O}(10^{-12})$
- The observable rate is dominated by long-distance amplitudes through intermediate vector resonances $(\eta, \omega, \rho, \phi)$ with $\mathcal{B}(SM) \sim \mathcal{O}(10^{-6})$





Experimental status

- $D^+ \to \pi^+ e^+ e^-$
  - LHCb (2021), BABAR (2011), CLEO (2010), E791, E687, MRK2, CLEO
  - Most stringent limit set by BABAR (10.1103/PhysRevD.84.072006)
- $D^+ \to \pi^+ \mu^+ \mu^-$
  - LHCb (2021), BABAR (2011), D0 (2008), FOCS (2003), E791, E687, E653, MRK2, CLEO
  - Most stringent limit set by LHCb (10.1007/JHEP06(2021)044)

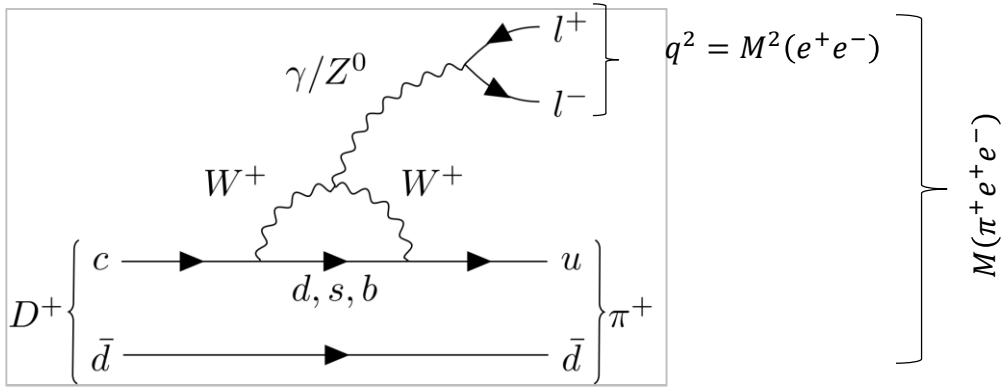
- Goal: improvement of the current upper limits spoiler -> success

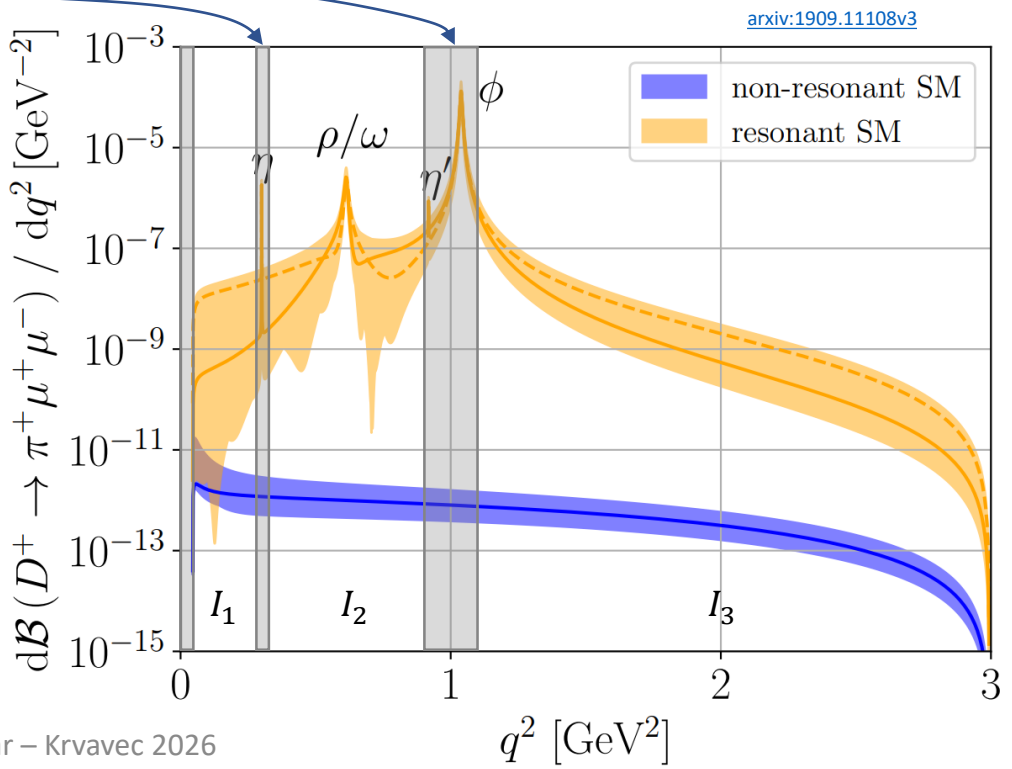
BaBar (2011), 348/fb	LHCb (2021), 1.6/fb	
$\boldsymbol{\mathcal{B}(D^+ \to \pi^+ e^+ e^-) < 1.1 \cdot 10^{-6}}$	$\mathcal{B}(D^+ \to \pi^+ e^+ e^-) < 1.6 \cdot 10^{-6}$	← **focus**
$\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-) < 6.5 \cdot 10^{-6}$	$\boldsymbol{\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-) < 6.7 \cdot 10^{-8}}$	

- First search in bins of $M(e^+e^-)$, usable for constraining Wilson coefficients

Analysis strategy 1/2

- Search for signal events in q^2 bins, away from intermediate vector resonances
- Extract signal yield with simultaneous, unbinned maximum-likelihood fit to $\boldsymbol{M(\pi^+ e^+ e^-)}$
- Bin the $\boldsymbol{M(e^+ e^-)}$: I_1=(0.20, 0.50), I_2 =(0.56, 0.95), I_3 =(1.05-1.75) GeV
  $I_{full} = I_1 \cup I_2 \cup I_3$
- Exclude contributions from $D^+ \to \pi^+ \eta (\to \gamma e^+ e^-)$, $D^+ \to \pi^+ \phi (\to e^+ e^-)$, and low-mass di-leptons





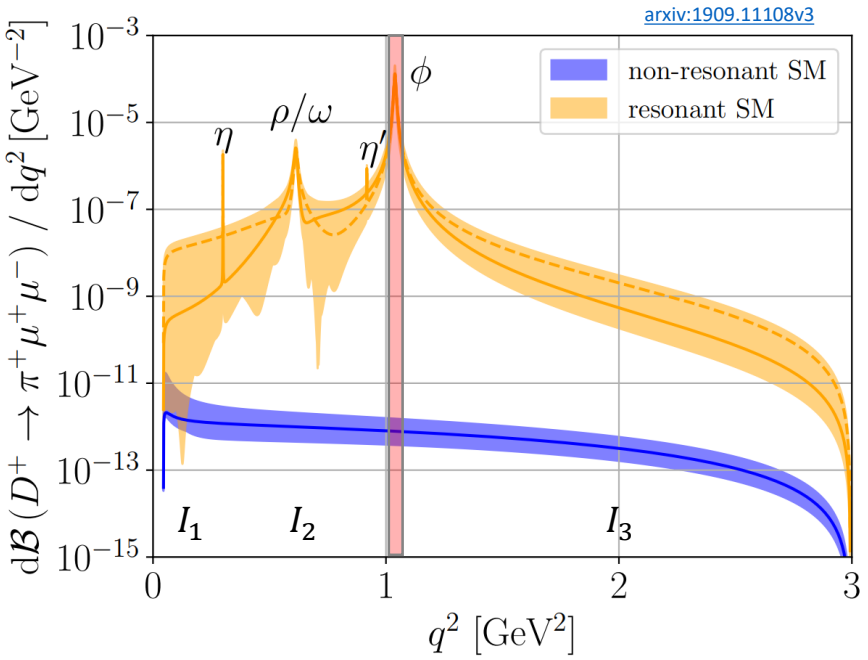
Analysis strategy 2/2

- Determine branching fraction relative to $\mathcal{B}(D^+ \to \pi^+ K^+ K^-) = (9.68 \pm 0.18) \cdot 10^{-3}$, reconstructed near ϕ

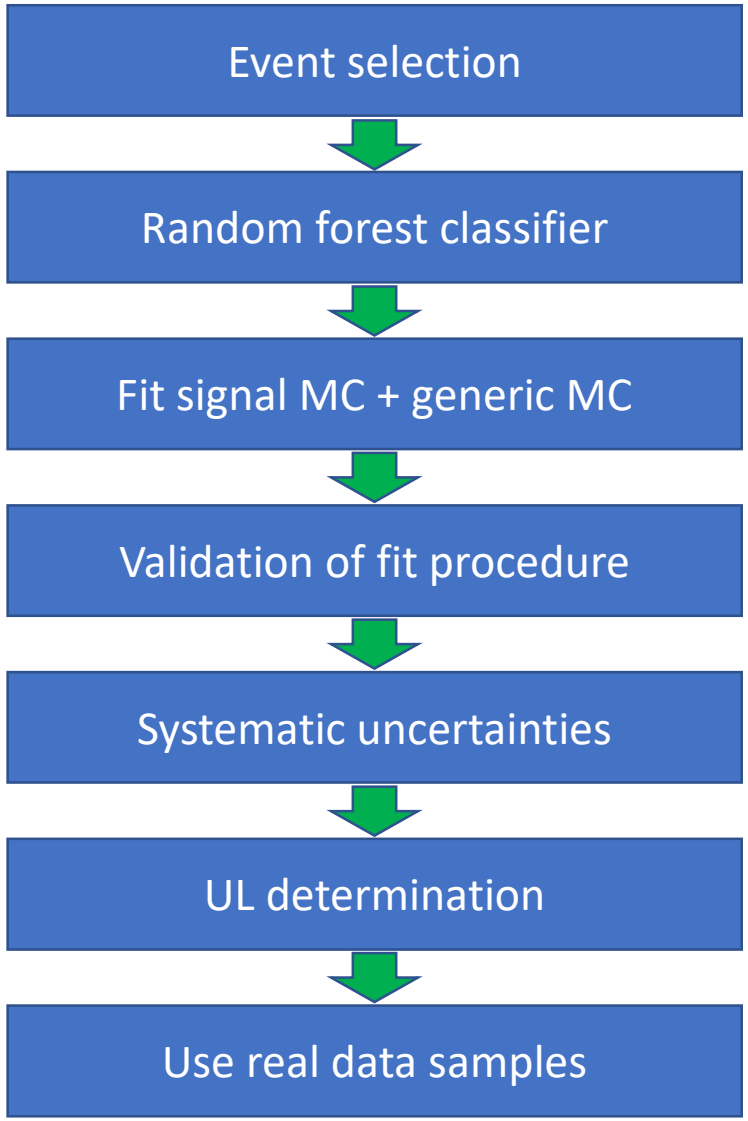
$$\mathcal{B}(D^+ \to \pi^+ e^+ e^-; q^2) = \mathcal{B}(D \to \pi K K) \cdot \frac{N_{\pi ee}(q^2)}{N_{\pi KK}(m_\phi^2)} \cdot \frac{\epsilon_{\pi KK}(m_\phi^2)}{\epsilon_{\pi ee}(q^2)}$$

from PDG | measure | from MC

- Validation channel: $\mathcal{B}\left(D^+ \to \pi^+ \phi(\to e^+ e^-)\right) = 1.7 \cdot 10^{-6}$
  - Use same event selection for cross-validating the analysis
- Data samples: Run 1 Belle II (428/fb) and full Belle (980/fb)



Analysis procedure



Analysis procedure

Event selection

Random forest classifier

Fit signal MC + generic MC

Validation of fit procedure

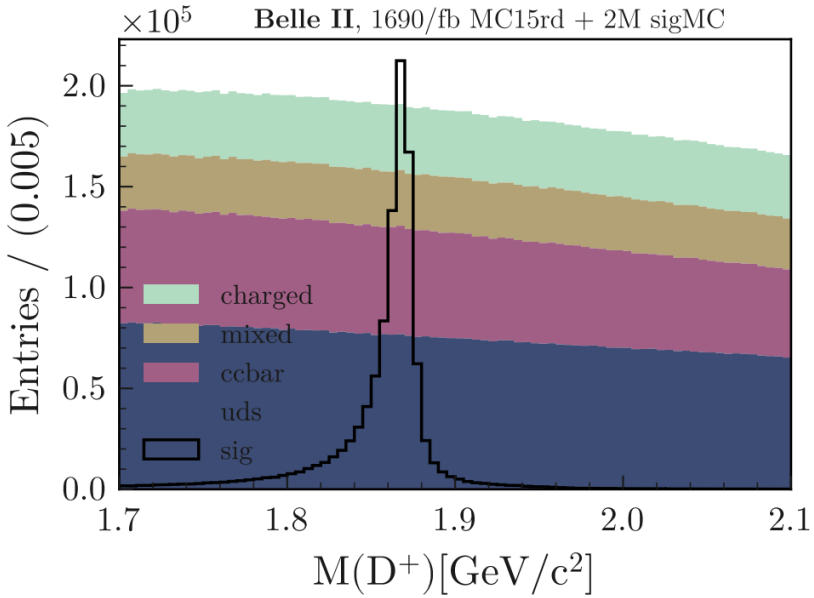
Systematic uncertainties

UL determination

Use real data samples

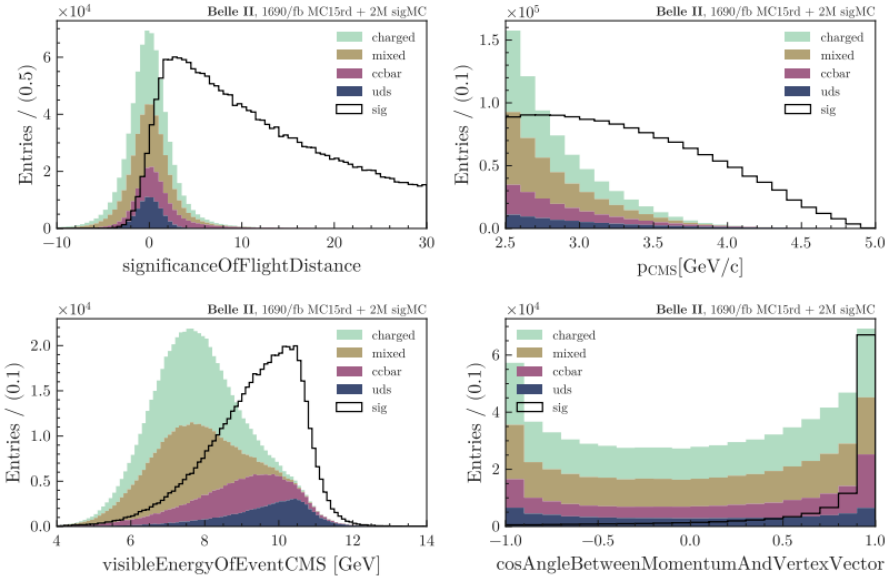
Simple rectangular cuts:

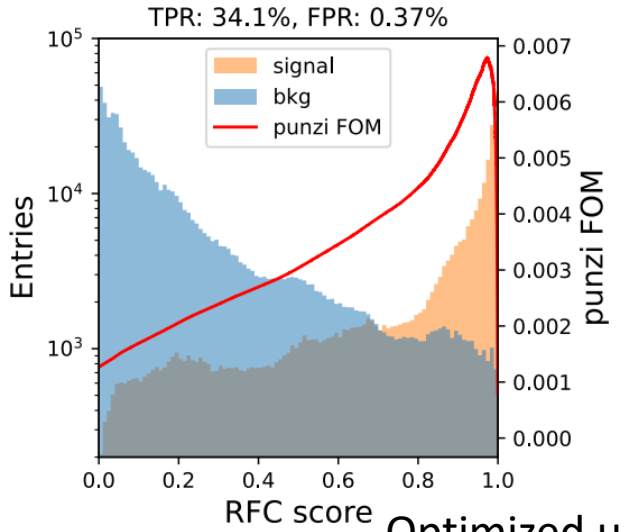
- track quality
- PID selection
- D^+ momentum
- …



Analysis procedure

4 input variables

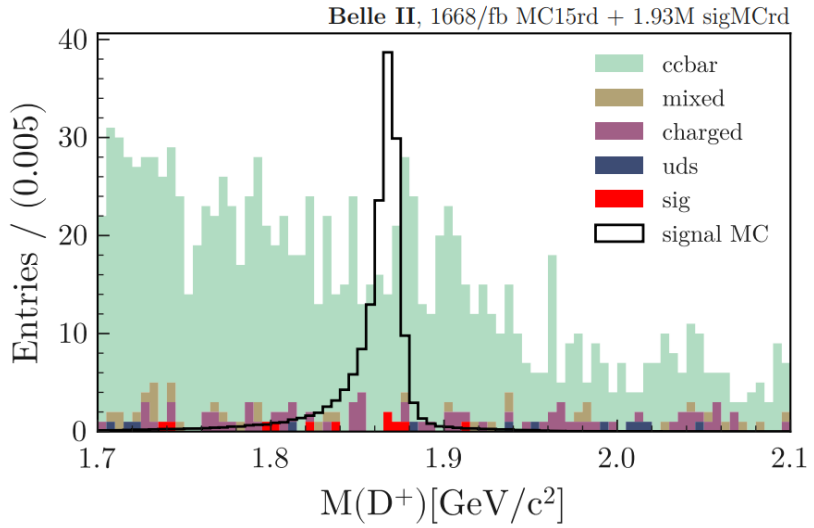




Optimized using Punzi FOM

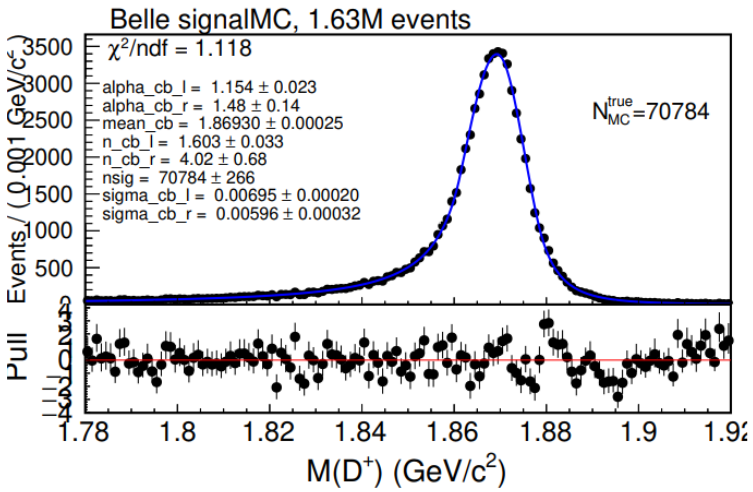
- Event selection
- Random forest classifier
- Fit signal MC + generic MC
- Validation of fit procedure
- Systematic uncertainties
- UL determination
- Use real data samples

Supress most of background



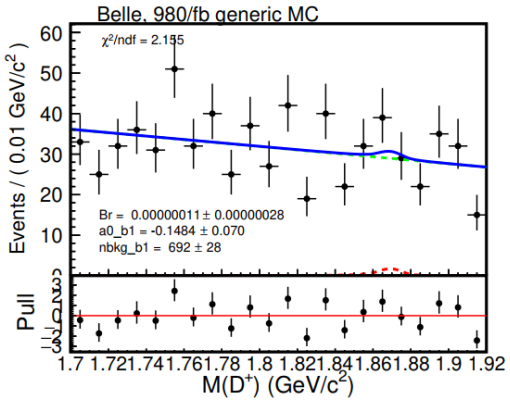
Analysis procedure

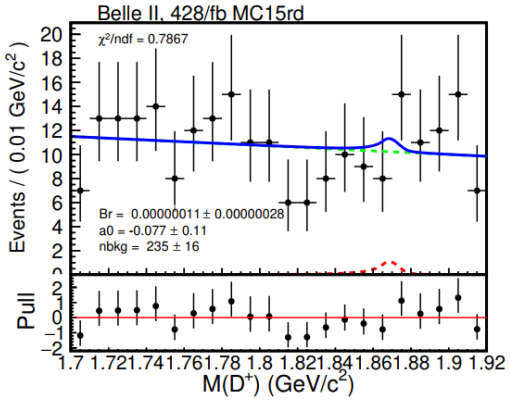
1. Determine signal shapes from signal MC
   - Two-sided Crystal ball
   - Symmetric-core CB
   - Bifurcated Gaussian
   - Cruijff



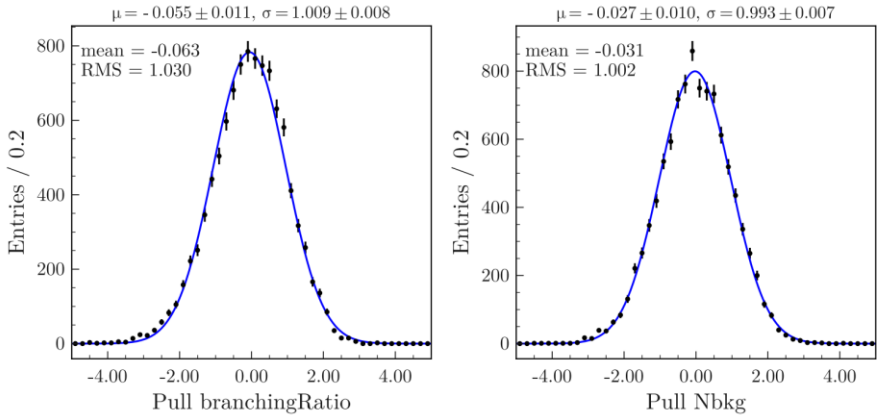
- Event selection
- Random forest classifier
- Fit signal MC + generic MC
- Validation of fit procedure
- Systematic uncertainties
- UL determination
- Use real data samples

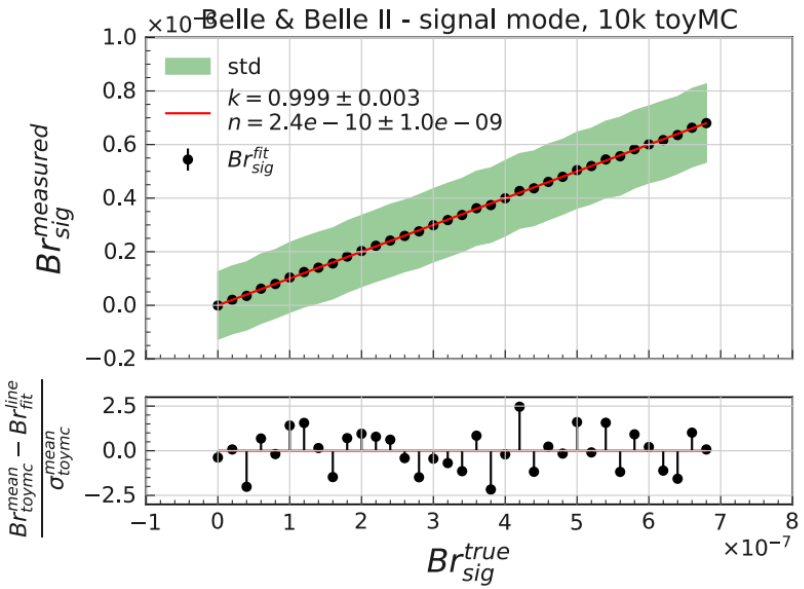
2. Fit generic MC with fixed signal shape
   - Simultaneous unbinned maximum likelihood fit
   - Simultaneous = shared $\mathcal{B}$ between the Belle and Belle II samples





Analysis procedure





Event selection

Random forest classifier

Fit signal MC + generic MC

Validation of fit procedure

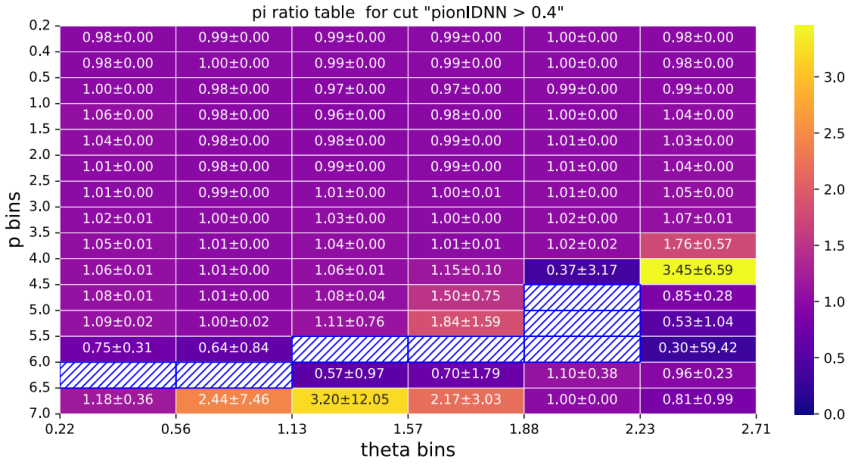
- Toy MC studies
- Linearity studies
- Bootstrapping
- …

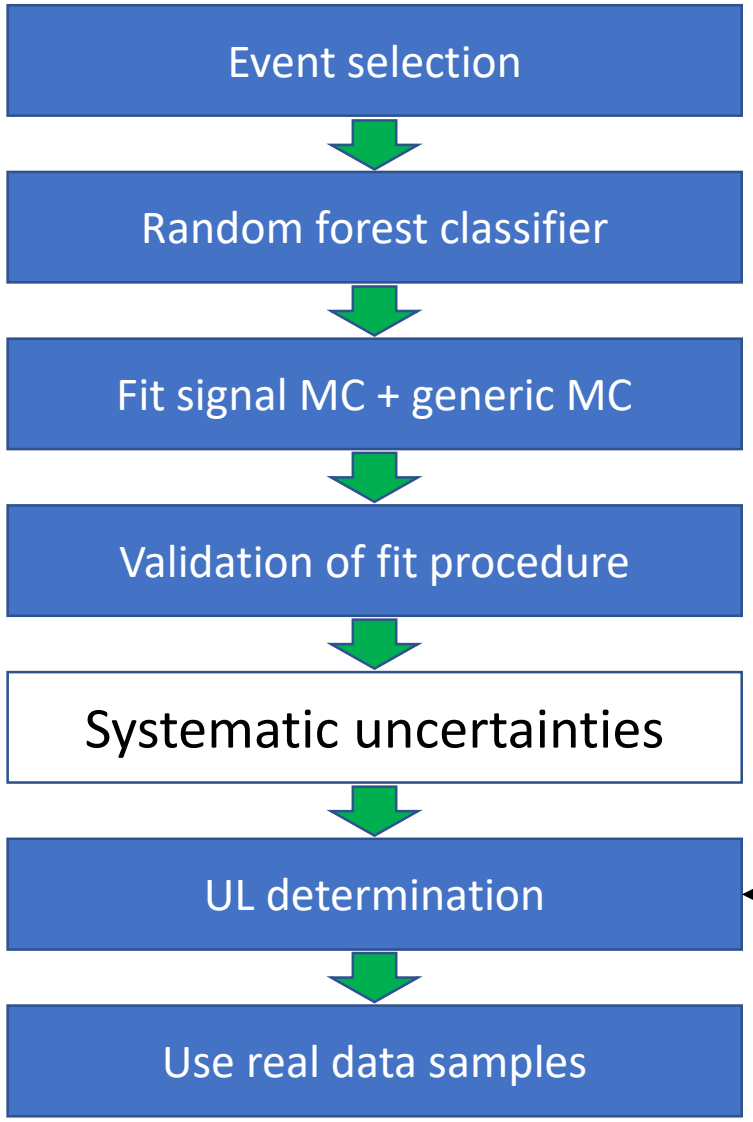
Systematic uncertainties

UL determination

Use real data samples

Analysis procedure





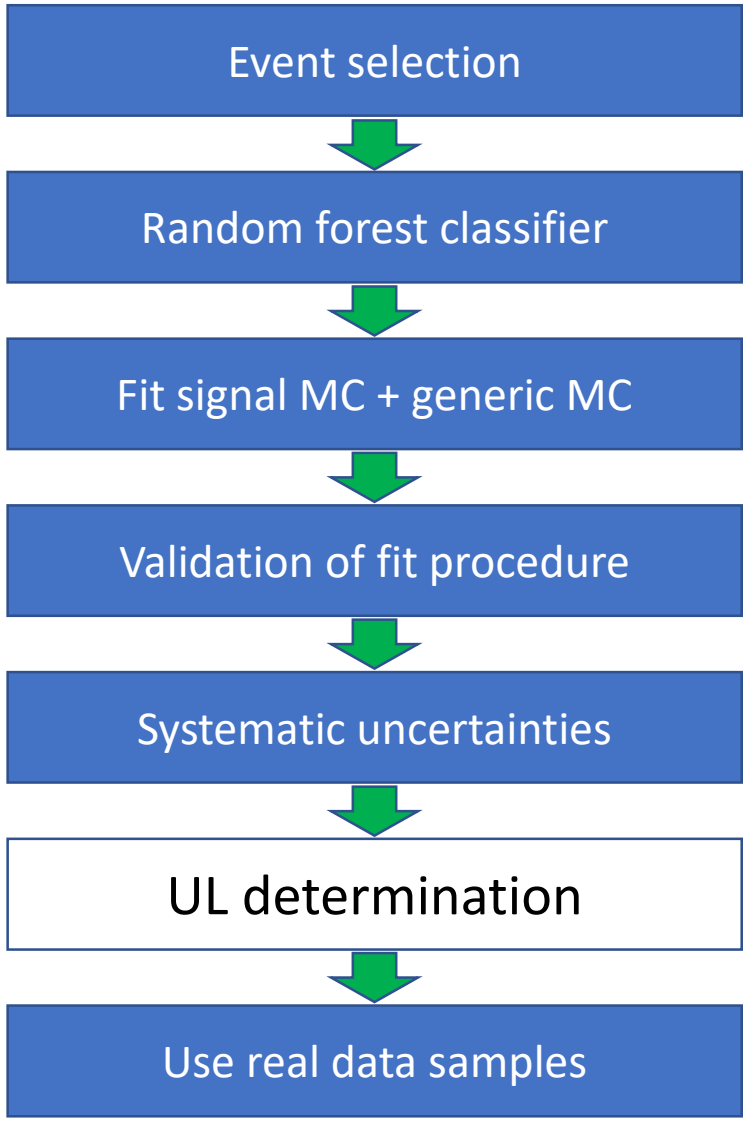
Estimate systematic uncertainties:

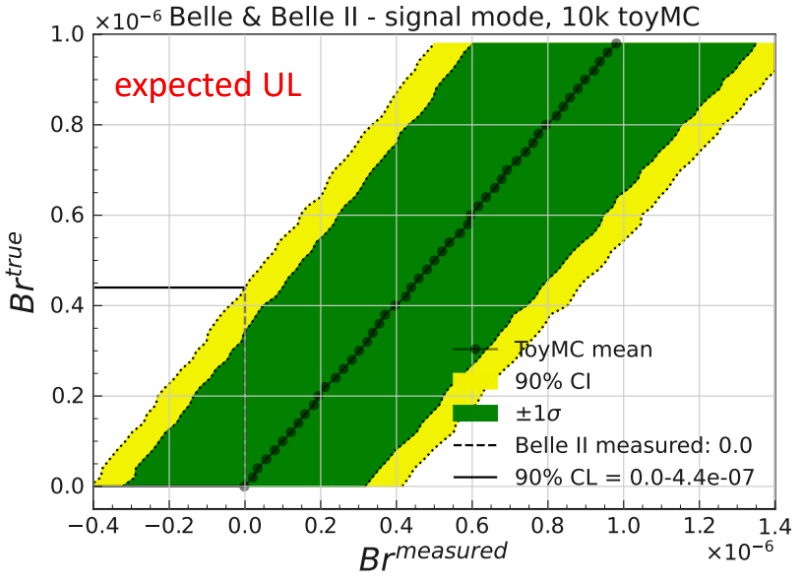
- PID efficiency
- RFC efficiency
- Signal model
- MC/data discrepancies
- PDF mismodeling
- Alternative fit model
- …

Include directly into

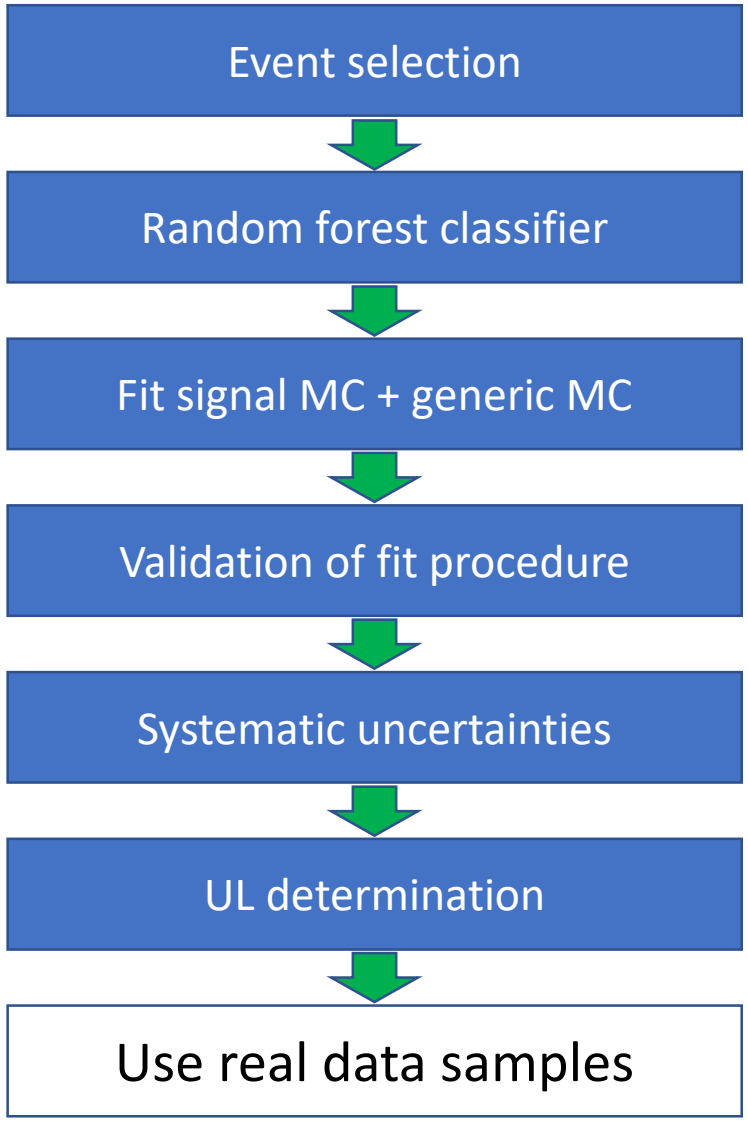
Analysis procedure

- Neyman construction from toy MC samples
- Generate from the fitted PDFs at fixed true $\mathcal{B}$ (nuisance parameters varied within their uncertainties → systematics enter here)
- Fit each toy MC sample with nominal parameters; build the belt from the extracted yields.
- UL = intersection of the 90% CL belt with the observed yield; evaluated at zero if the observed yield is negative.



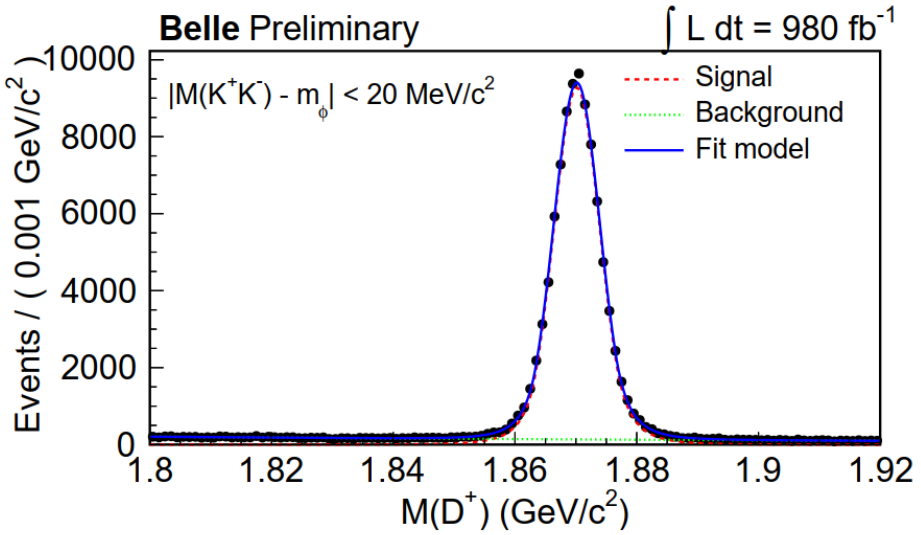


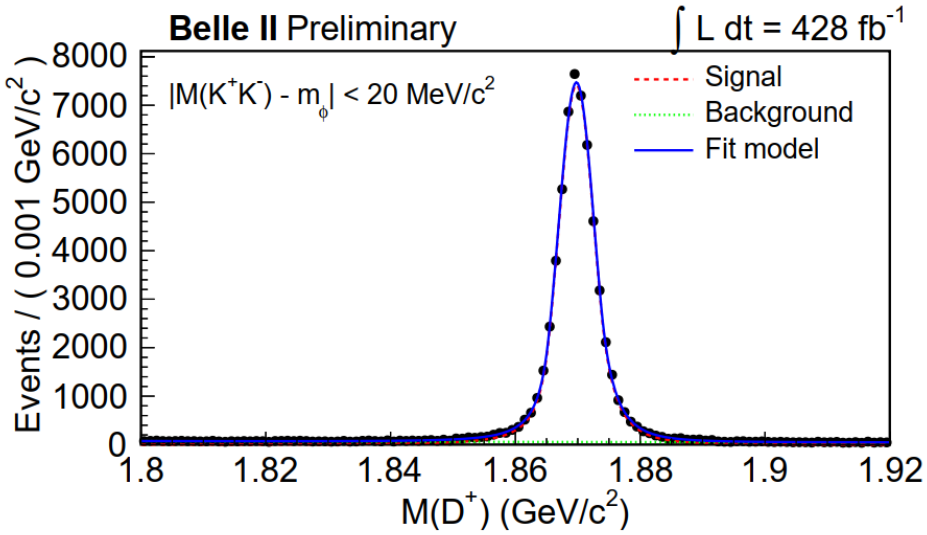
Analysis procedure



Results – normalization mode

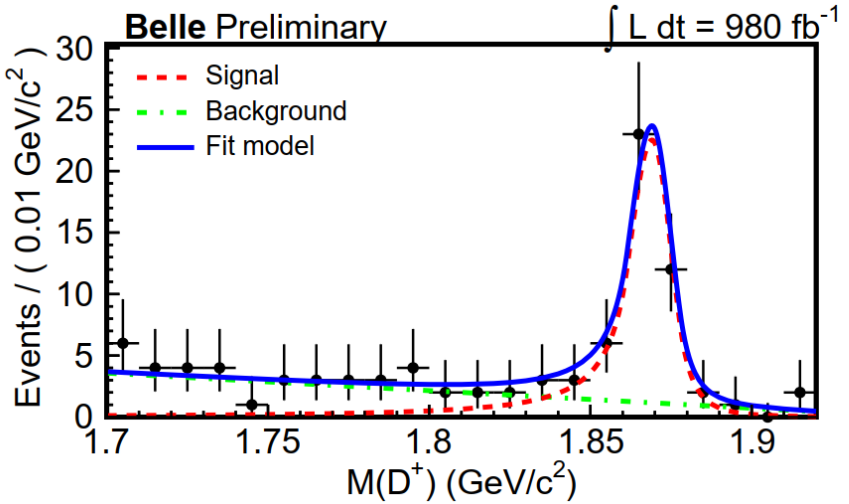
- Comparable yields between Belle and Belle II
- Fits with all parameters free

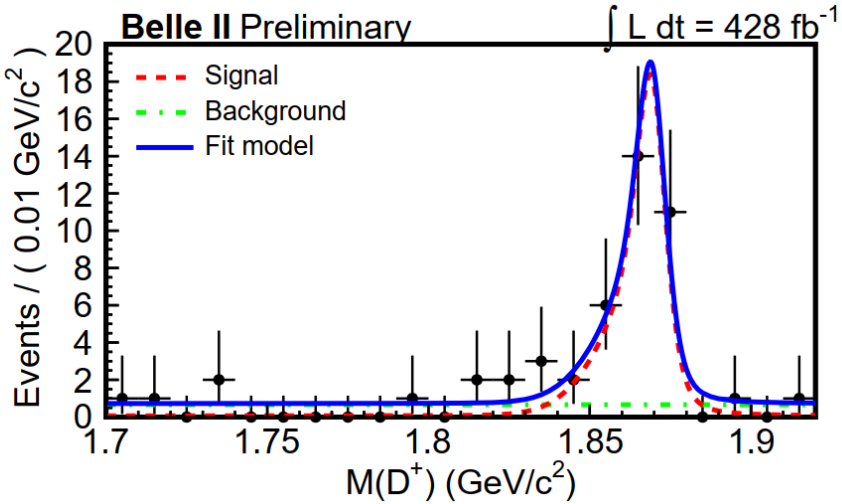




Results – validation mode

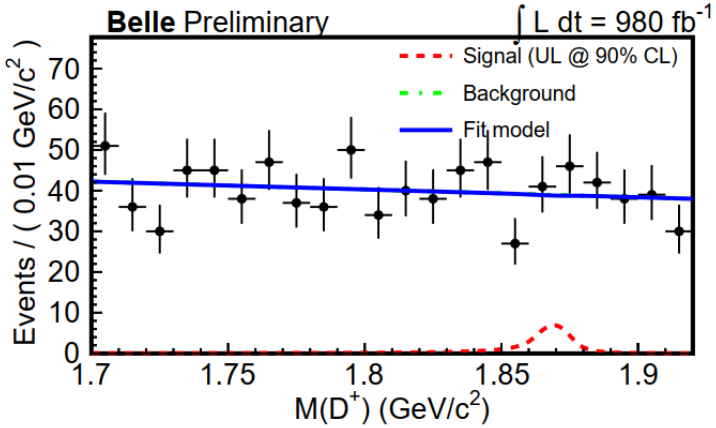
- Validate analysis with measurement near ϕ resonance
  $\mathcal{B}\left(D^+ \to \pi^+(\phi \to e^+e^-)\right) = (1.75 \pm 0.22(stat) \pm 0.12(syst)) \cdot 10^{-6}$
- Consistent results with the PDG values: $\mathcal{B}(D^+ \to \pi^+\phi) \cdot \mathcal{B}(\phi \to e^+e^-) = (1.70 \pm 0.05) \cdot 10^{-6}$
- Most precise measurement of this decay: statistical precision improved by a factor ~5 over CLEO
  CLEO (2010) measurement $(1.7^{+1.4}_{-0.9} \pm 0.1) \cdot 10^{-6}$ 1009.1606

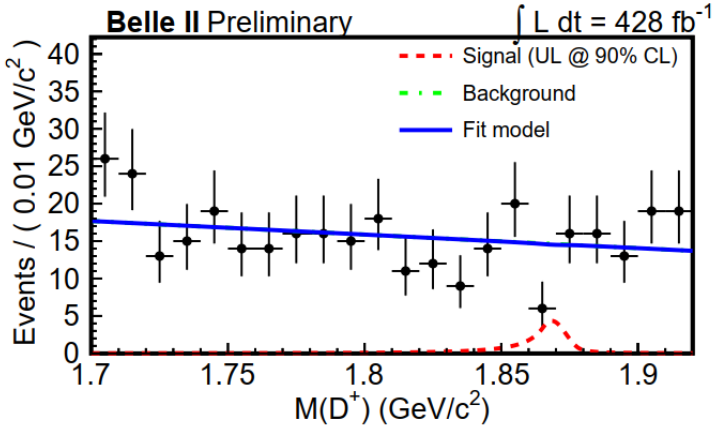




Results – signal mode

- No significant signal
- Upper limits determined for q^2 bins and full mass range
- Improved precision by a factor of >2
- Results presented at ICHEP2026





90% CL

$M(e^+e^-)$ interval	Efficiency (%) Belle	Efficiency (%) Belle II	$N_{\rm sig}$ Belle	$N_{\rm sig}$ Belle II	$\mathcal{B}$ $(\times 10^{-7})$	UL $(\times 10^{-7})$
I_1	3.82 ± 0.04	4.73 ± 0.04	-1.7 ± 5.8	-1.0 ± 3.4	-0.6 ± 2.0	< 2.9
I_2	5.03 ± 0.03	6.14 ± 0.03	0.0 ± 6.0	0.0 ± 3.6	0.0 ± 2.1	< 3.2
I_3	5.94 ± 0.03	7.42 ± 0.03	-2.0 ± 5.8	-1.2 ± 3.4	-0.7 ± 2.0	< 2.9
$I_{\rm full}$	5.29 ± 0.02	6.57 ± 0.02	-0.3 ± 9.6	-0.2 ± 5.7	-0.1 ± 3.3	< 4.7
$I_\phi^{\rm Valid.}$	4.75 ± 0.02	6.13 ± 0.02	$51 \pm 6 \pm 3$	$30 \pm 4 \pm 2$	$17.5 \pm 2.2 \pm 1.2$	-

Summary

- PhD topic: improved upper limit for rare charm decay $D^+ \to \pi^+ e^+ e^-$
  - Thesis finished
  - Paper in final stages of collaboration review

- Other work:
  - Hardware testing: photon detector (LAPPD, MCP-PMT) with PetSys TOF-PET
  - Irradiations at TRIGA, CERN testbeams

- What next:
  - **TOF-PET projects**: joining PetVision and the ARIS-PET project (more in Gašper's presentation)
  - Transitioning **Belle II** → **LHCb**