Search for rare four-body charm decays $D^0 \to h^- h^+ e^- e^+$ at LHCb

WIFAI - Bari, November 2025

Alberto Bellavista[1,2], Angelo Carbone[1,2], Fabio Ferrari[1,2], Marianna Fontana[2], Sofia Zalambani[1,2]

[1] University of Bologna, [2] INFN Bologna

Istituto Nazionale di Fisica Nucleare

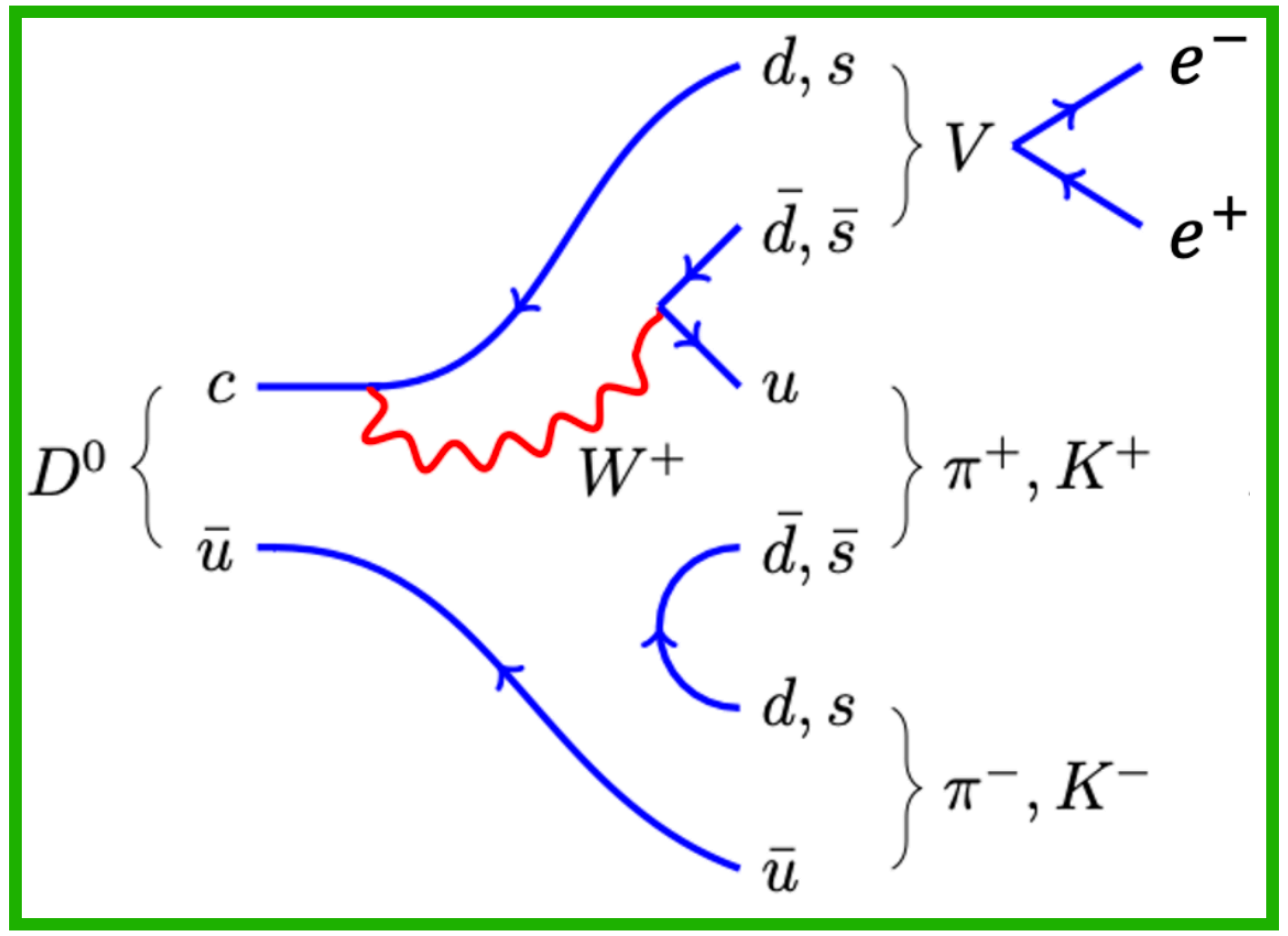
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Outline

- **Introduction and motivation (+ Run 2 results)**
- First look at Run 3 data
  - RapidSim setup
  - Normalization channel
  - First look at $D^0 \to \pi\pi ee$
- Outlook and conclusions

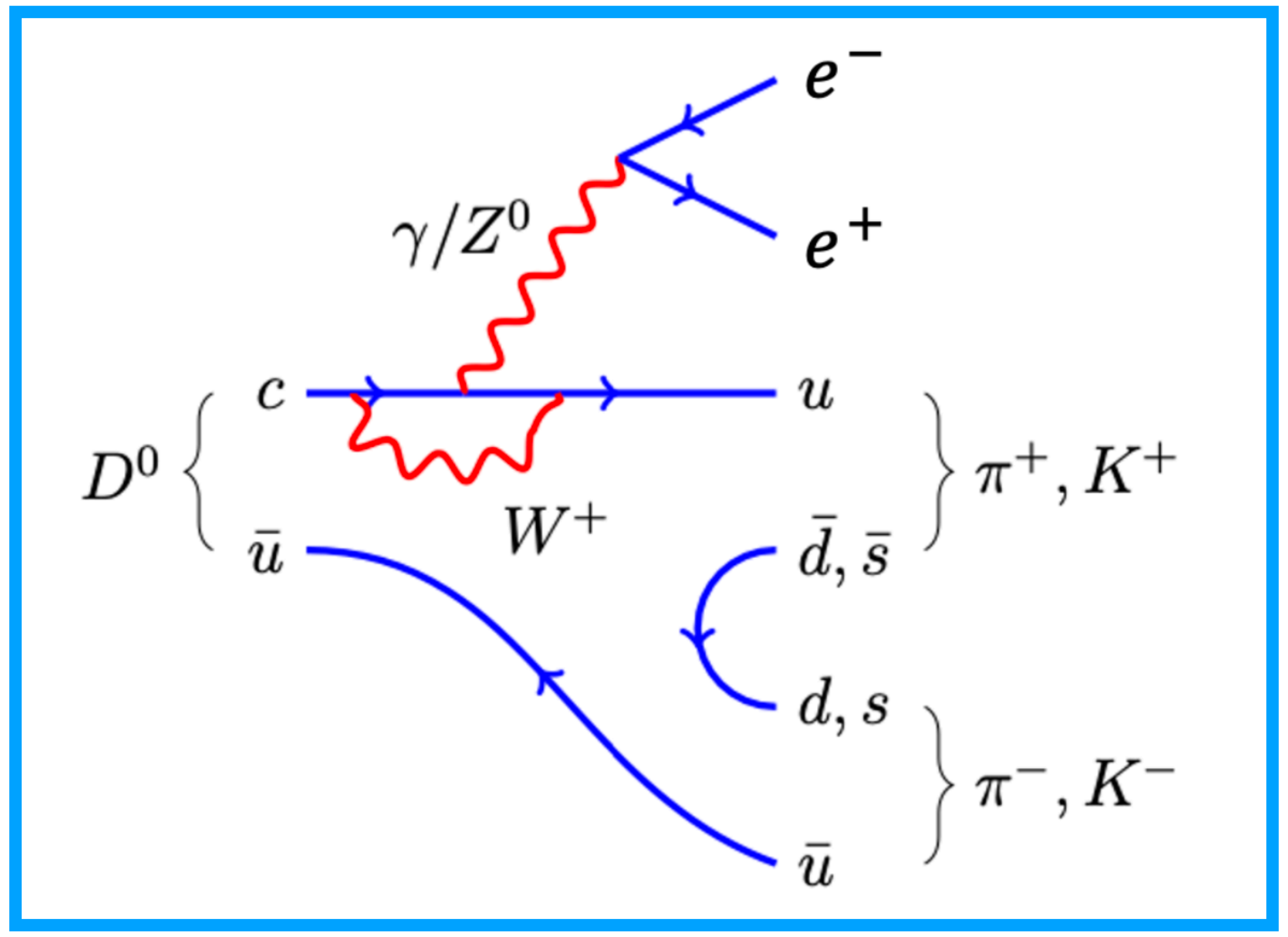
Introduction and motivation

- $D^0 \to h^- h^+ e^- e^+$ decays can proceed in 2 main ways:
  - **Long distance:** intermediate resonance $V \to e^+ e^-$
  - **Short distance:** via FCNC $c \to u$ transitions



- Expected Branching Fractions:
  - $\mathscr{B}(D^0 \to K^- K^+ e^- e^+) \sim 1.1 \times 10^{-7}$
  - $\mathscr{B}(D^0 \to \pi^- \pi^+ e^- e^+) \sim 1.3 \times 10^{-6}$

- Expected short distance contribution is $< 10^{-9}$ [1] …



- … but **New Physics effects can enhance the FCNC mode** [2]

- Tests of Lepton Flavour Universality (**LFU**) can be performed comparing the results to the $D^0 \to h^- h^+ \mu^- \mu^+$ modes

[1] H. Gisbert, M. Golz, and D. S. Mitzel, Theoretical and experimental status of rare charm decays
[2] L. Cappiello, O. Cat`a, and G. D'Ambrosio, Standard model prediction and new physics tests for D0 →h+h−ℓ +ℓ −(h= π,K; ℓ = e,μ)

Method

- Select D^0 candidates coming from $D^{*+} \to D^0\pi^+$
  - ➡ Exploit cut on $\Delta m \equiv m(D^{*+}) - m(D^0) \in [144, 147]$ MeV
- Analysis performed in several **di-electron mass bins**
  - Different resonant contributions
  - Increase sensitivity to BSM effects
  - Compare to the corresponding $D^0 \to h^-h^+\mu^-\mu^+$ *analysis results*

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

Method

- Cabibbo-favoured decay $D^0 \to K^-\pi^+e^-e^+$ expected to be dominated by SM amplitudes
  - ➡ Not sensitive to New Physics
  - ➡ Good normalization mode to cancel out uncertainties

$$\boxed{\frac{\mathcal{B}(D^0 \to h^-h^+e^-e^+)}{\mathcal{B}(D^0 \to K^-\pi^+[e^-e^+]_{\rho^0/\omega})}} = \boxed{\frac{N(D^0 \to h^-h^+e^-e^+)}{N(D^0 \to K^-\pi^+[e^-e^+]_{\rho^0/\omega})}} \times \boxed{\frac{\varepsilon(D^0 \to K^-\pi^+[e^-e^+]_{\rho^0/\omega})}{\varepsilon(D^0 \to h^-h^+e^-e^+)}}$$

Ratio of the Branching Fractions

Measured yields (extracted from $m(D^0)$ fit)

Total efficiencies (trigger, reconstruction, offline selection)

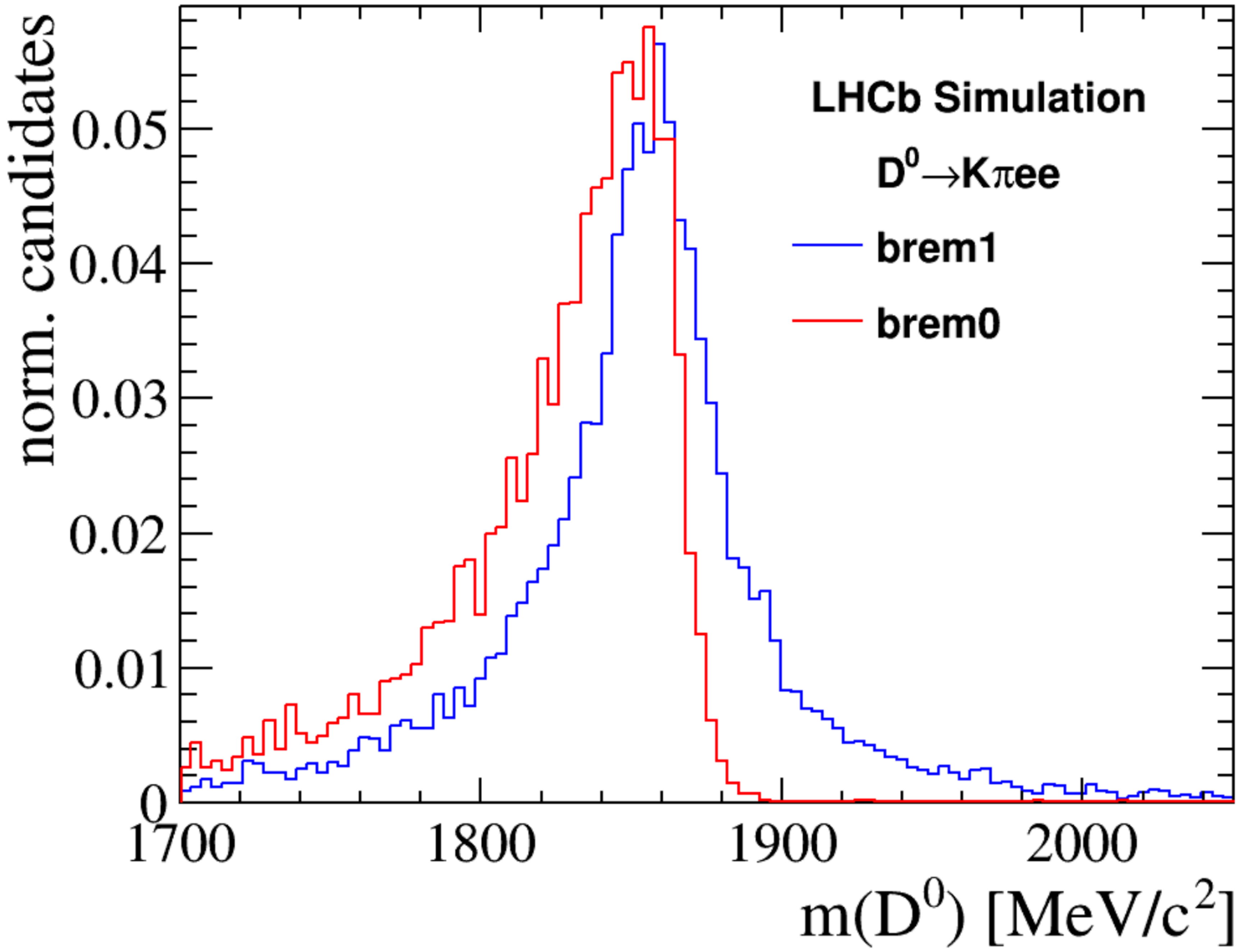
- $\mathcal{B}(D^0 \to K^-\pi^+[e^-e^+]_{\rho^0/\omega}) = (4.0 \pm 0.5(\text{stat}) \pm 0.2(\text{syst}) \pm 0.1(\text{norm BF})) \times 10^{-6}$ taken as external input (measurement by BaBar *here*)
  - ➡ $\Delta\mathcal{B}_{norm}/\mathcal{B}_{norm} = 13.7\,\%$

Brem categories

- Due to different background levels and shapes, the analysis will be performed dividing the dataset based on the "brem category":
  - **Brem 0: no bremsstrahlung** emission associated to e^+ and e^-
  - **Brem 1: at least one bremsstrahlung** γ associated to one of the electrons

- Brem 0: large tail on the left due to non-reconstructed bremsstrahlung photons

- Brem 1: tail on the right due to wrong photon-to-electron association (limits due to the calorimeter resolution and brem recovery algorithms)

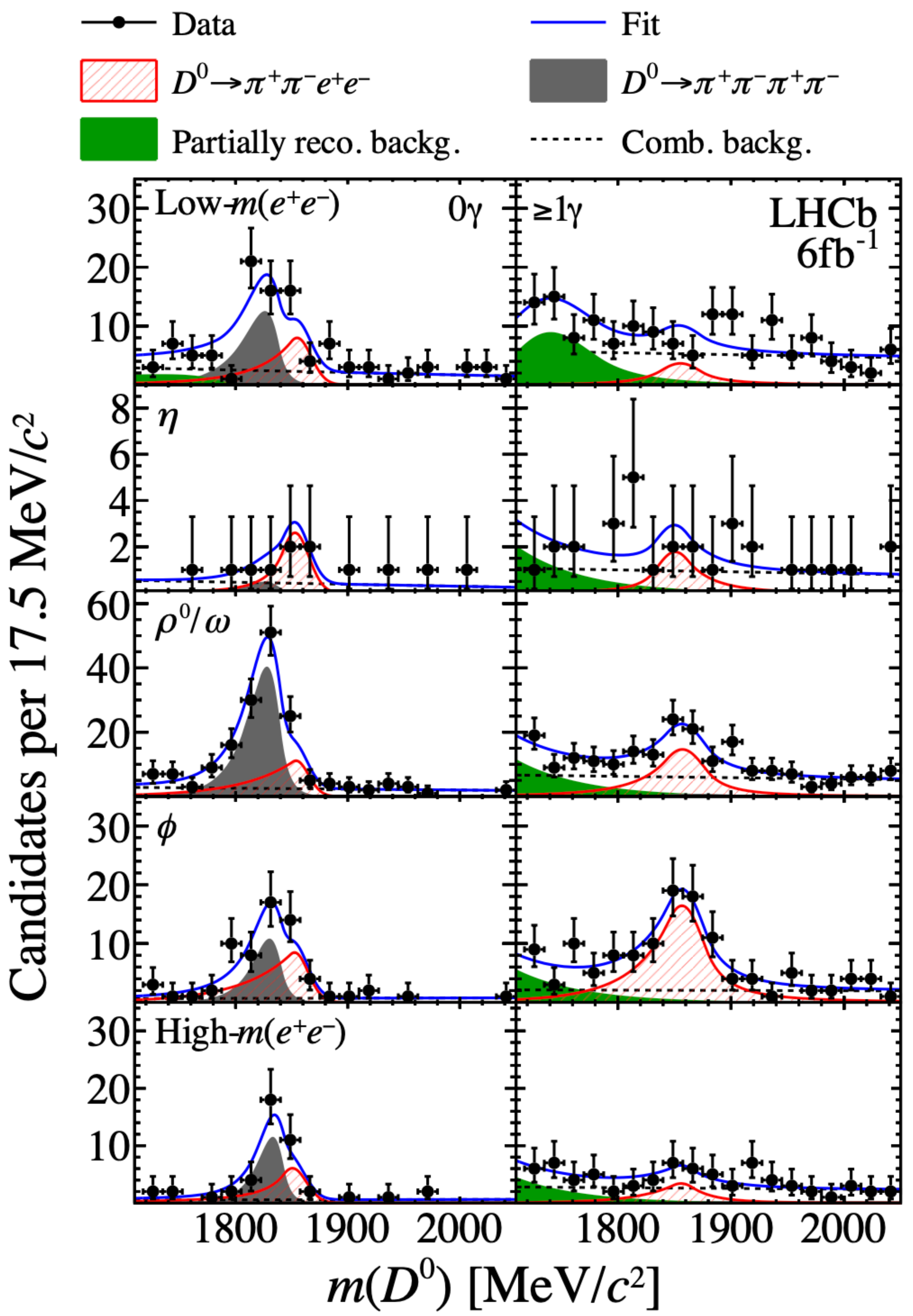


Run 2 analysis results

- Results of the *Run 2 analysis*:
  - ✓ No hints for LFU violation
  - ✓ First observation of $D^0 \to \pi^-\pi^+e^-e^+$ in the ρ^0/ω and ϕ bins
  - ✶ No observation of the kaons channel: **limited by the statistics**

$m(e^+e^-)$ region	[MeV/c^2]	Yield	$\mathcal{S}$
	$D^0 \to \pi^+\pi^-e^+e^-$		
Low mass	$2m_\mu$–525	37 ± 13	2.8σ
η	525–565	10 ± 7	1.6σ
ρ^0/ω	565–950	97 ± 21	5.5σ
ϕ	950–1100	100 ± 18	8.1σ
High mass	> 1100	30 ± 11	2.9σ
	$D^0 \to K^+K^-e^+e^-$		
Low mass	$2m_\mu$–525	4 ± 8	1.2σ
η	525–565	1 ± 2	1.1σ
ρ^0/ω	> 565	12 ± 7	2.2σ

$m(e^+e^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]
	$D^0 \to \pi^+\pi^-e^+e^-$	
Low mass	$2m_\mu$–525	$< 4.8\,(5.4)$
η	525–565	$< 2.3\,(2.7)$
ρ^0/ω	565–950	$4.5 \pm 1.0 \pm 0.7 \pm 0.6$
ϕ	950–1100	$3.8 \pm 0.7 \pm 0.4 \pm 0.5$
High mass	> 1100	$< 2.0\,(2.2)$
	$D^0 \to K^+K^-e^+e^-$	
Low mass	$2m_\mu$–525	$< 1.0\,(1.1)$
η	525–565	$< 0.4\,(0.5)$
ρ^0/ω	> 565	$< 2.2\,(2.5)$



Outline

- Introduction and motivation (+ Run 2 results)
- **First look at Run 3 data**
  - **RapidSim setup**
  - **Normalization channel**
  - **First look at $D^0 \to \pi\pi ee$**
- Outlook and conclusions

Run 3 - Normalization channel

- First look at **2024 data**
- **Electrons mass resolution is worse than in Run 2**
  - Brem recovery strongly depends on the **occupancy** of the detector
  - Higher **material budget** in Run 3

Run 3 luminosity is 5x Run 2

- Rough estimation of expected signal $D^0 \to \pi\pi ee$ and $D^0 \to KKee$ events

➡ Dataset split into 3 HLT1 selections —> different background levels and shapes

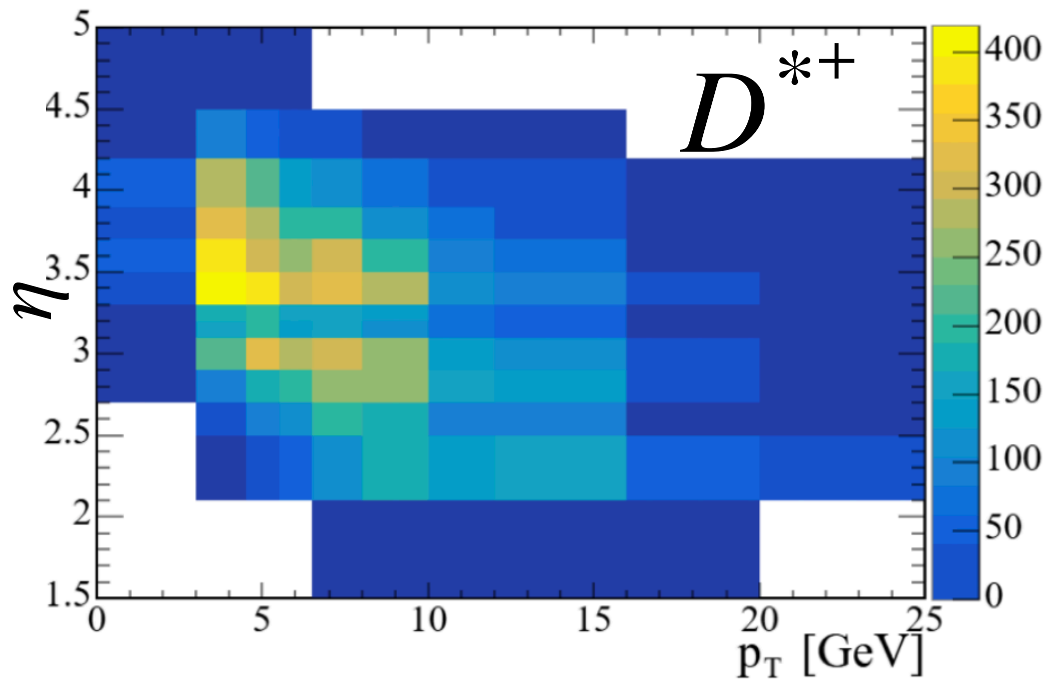
- **Only** TrackMVA lines: select particles with MVA based on p_T and IP requirements
- **Only** Electrons lines: similar to TrackMVA, adding PID information, or look for a pair of displaced electrons
- TrackMVAs **AND** Electron lines: require both

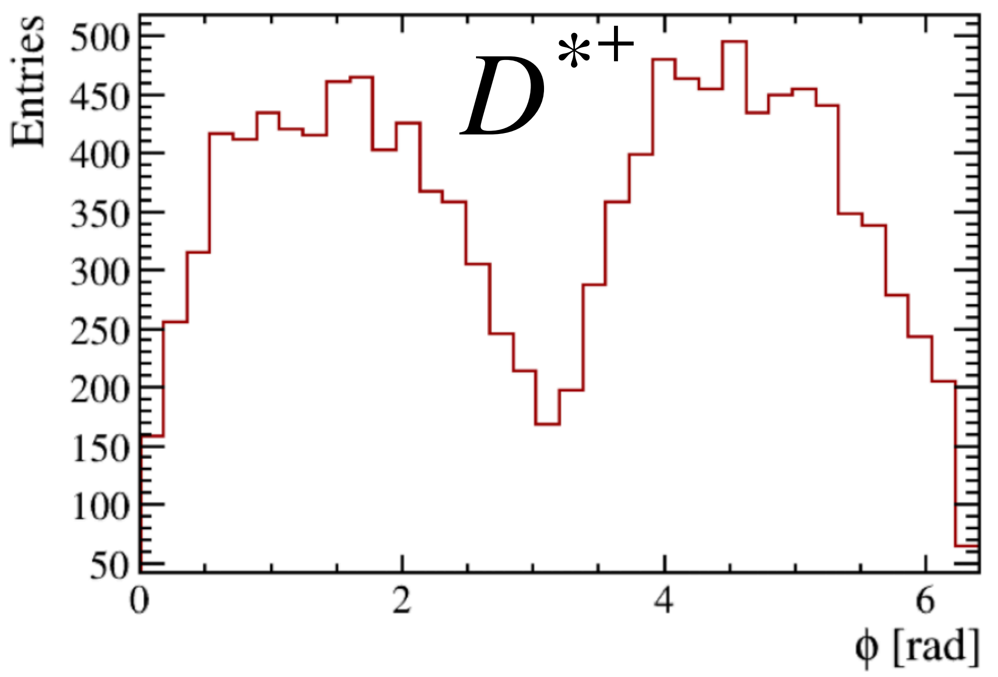
RapidSim setup

- Very limited statistics in our official simulated samples until now
  - Needed to constrain the fit models
  - Mandatory to properly study background shapes

- Alternative solution: **RapidSim** (+ EvtGen)
  - Fast simulations
  - Modified to reproduce our **Run 3** data
  - Possibility to simulate mis-ID or partially reconstructed backgrounds

RapidSim - setup

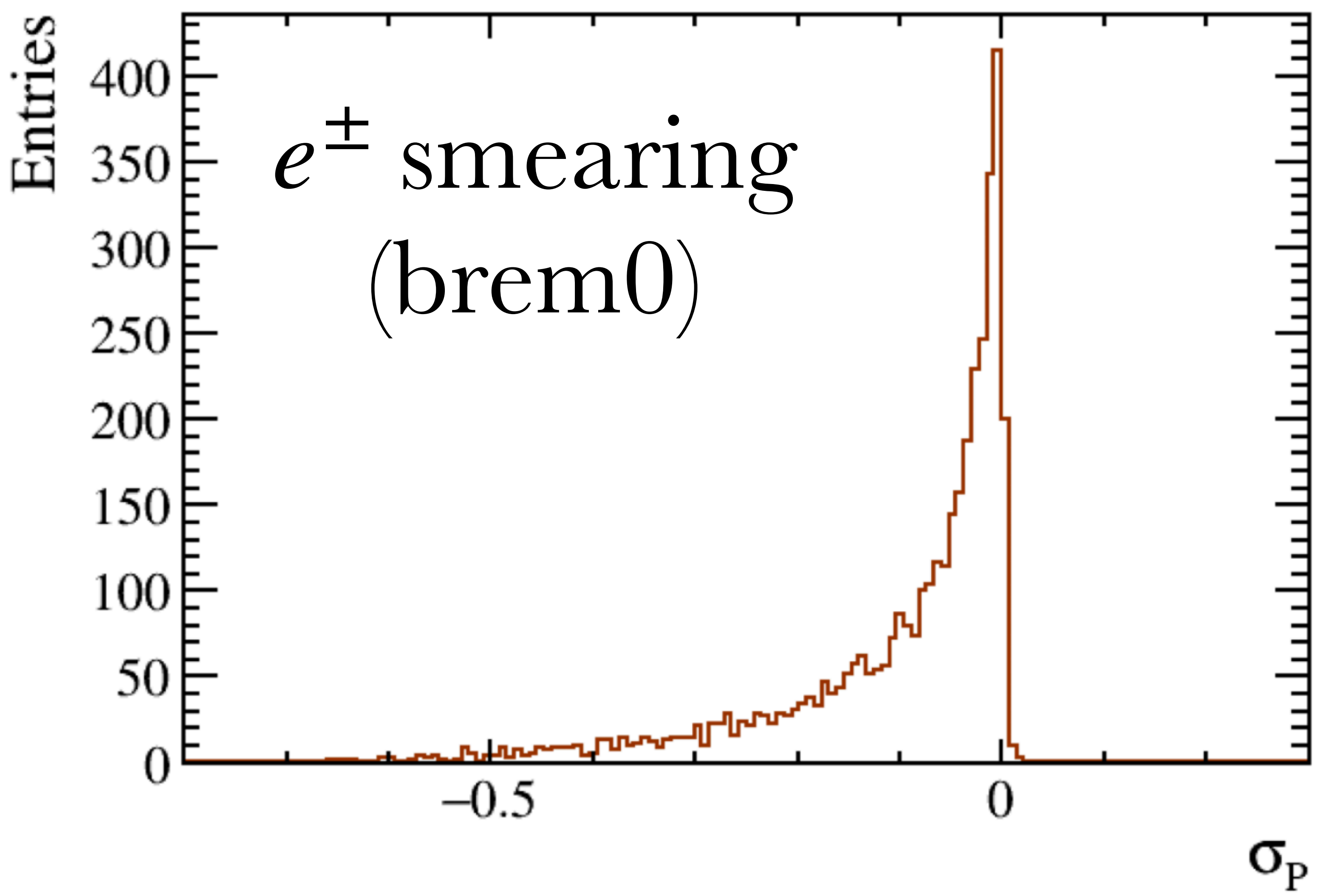


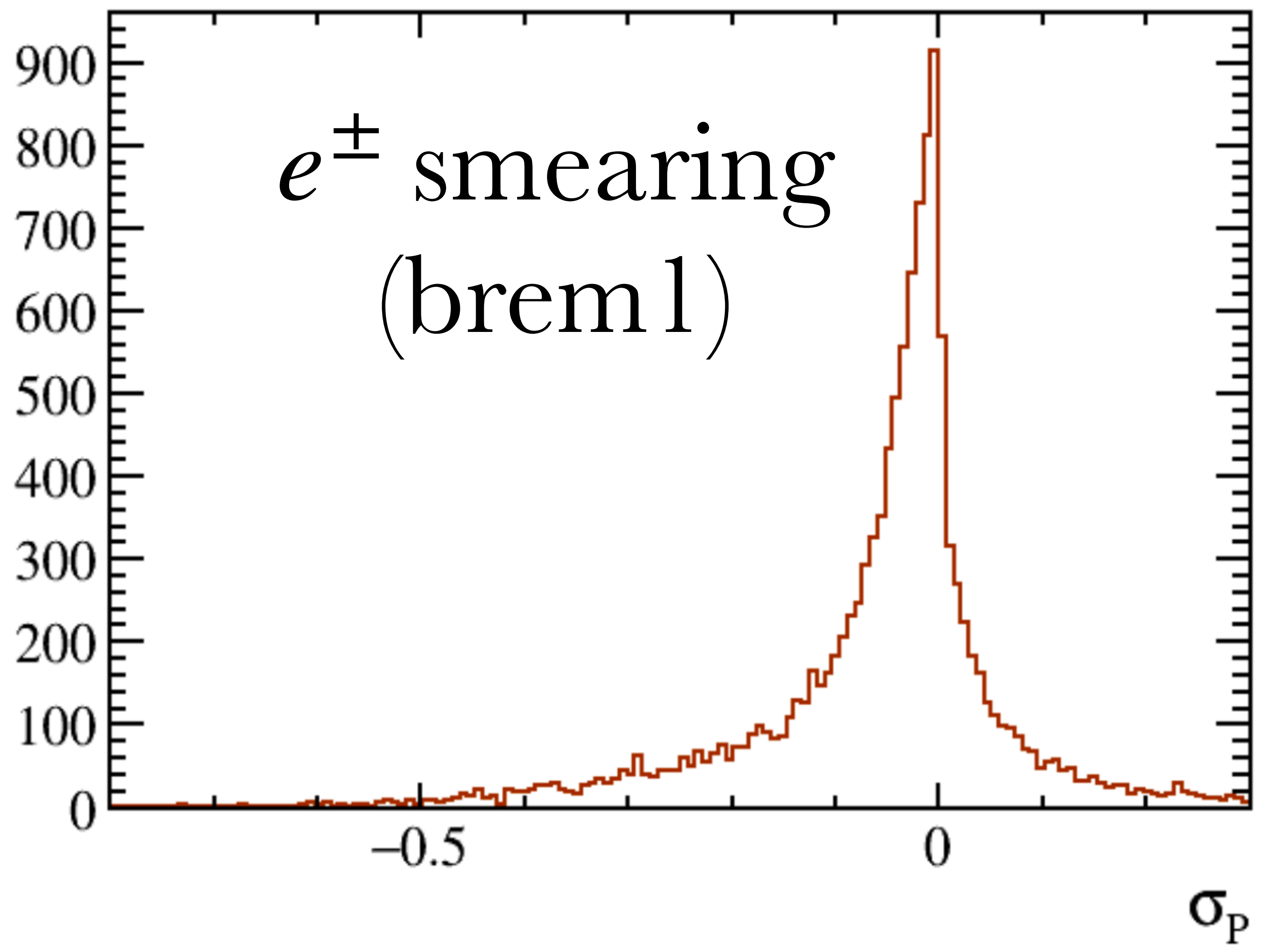


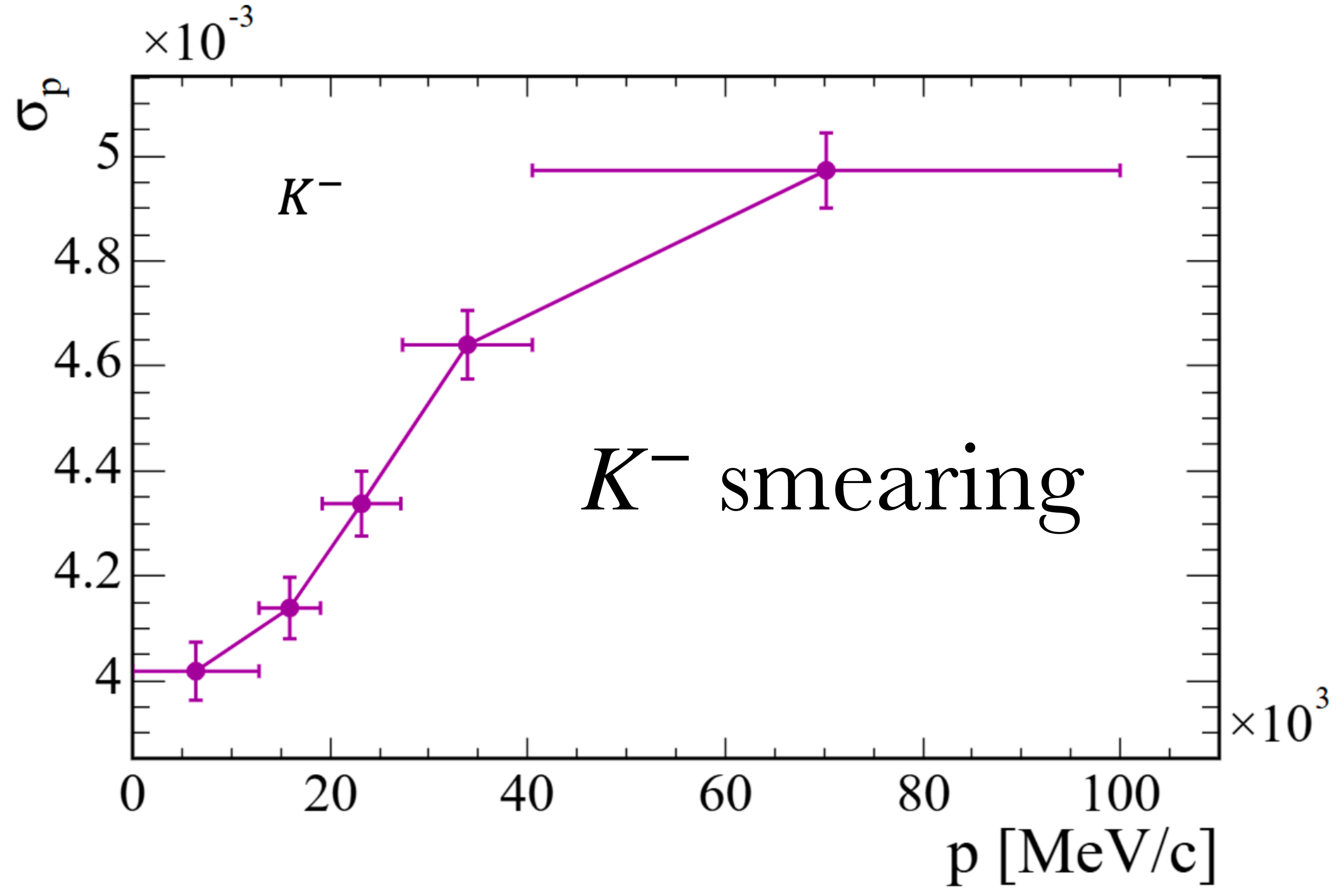
- Takes as input:
  - ✓ D^{*+} distributions (η, p_T, ϕ) to generate the events
  - ✓ Smearing distributions for the particles momenta

➡ <u>Different tuning between brem0 and brem1</u>

$$\sigma_p = \frac{p^{MC} - p^{MC}_{true}}{p^{MC}_{true}}$$







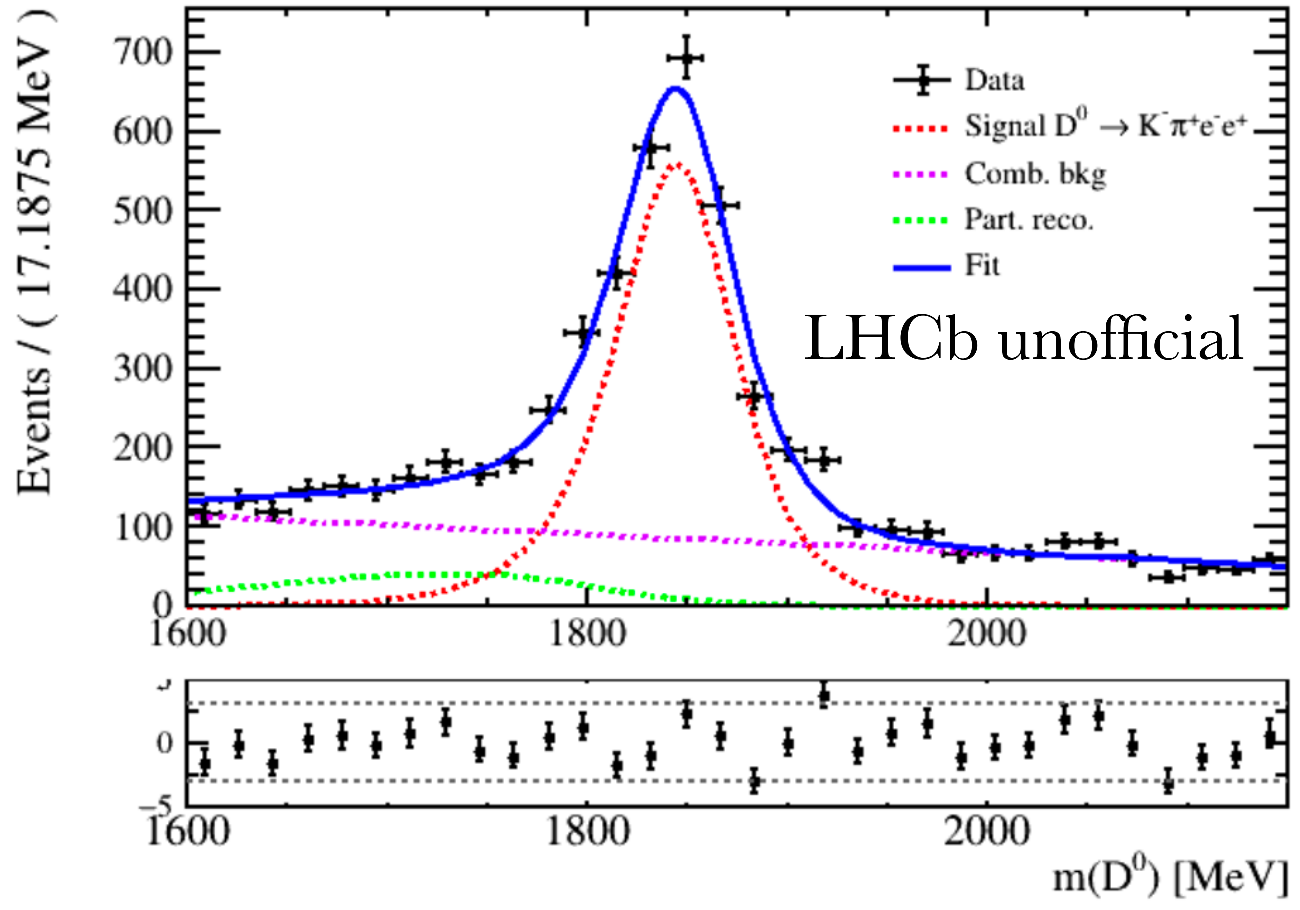
Brem1 fit

- **Signal**: Johnson PDF
  [μ and σ free to vary, tail parameters (δ, γ) fixed from MC]

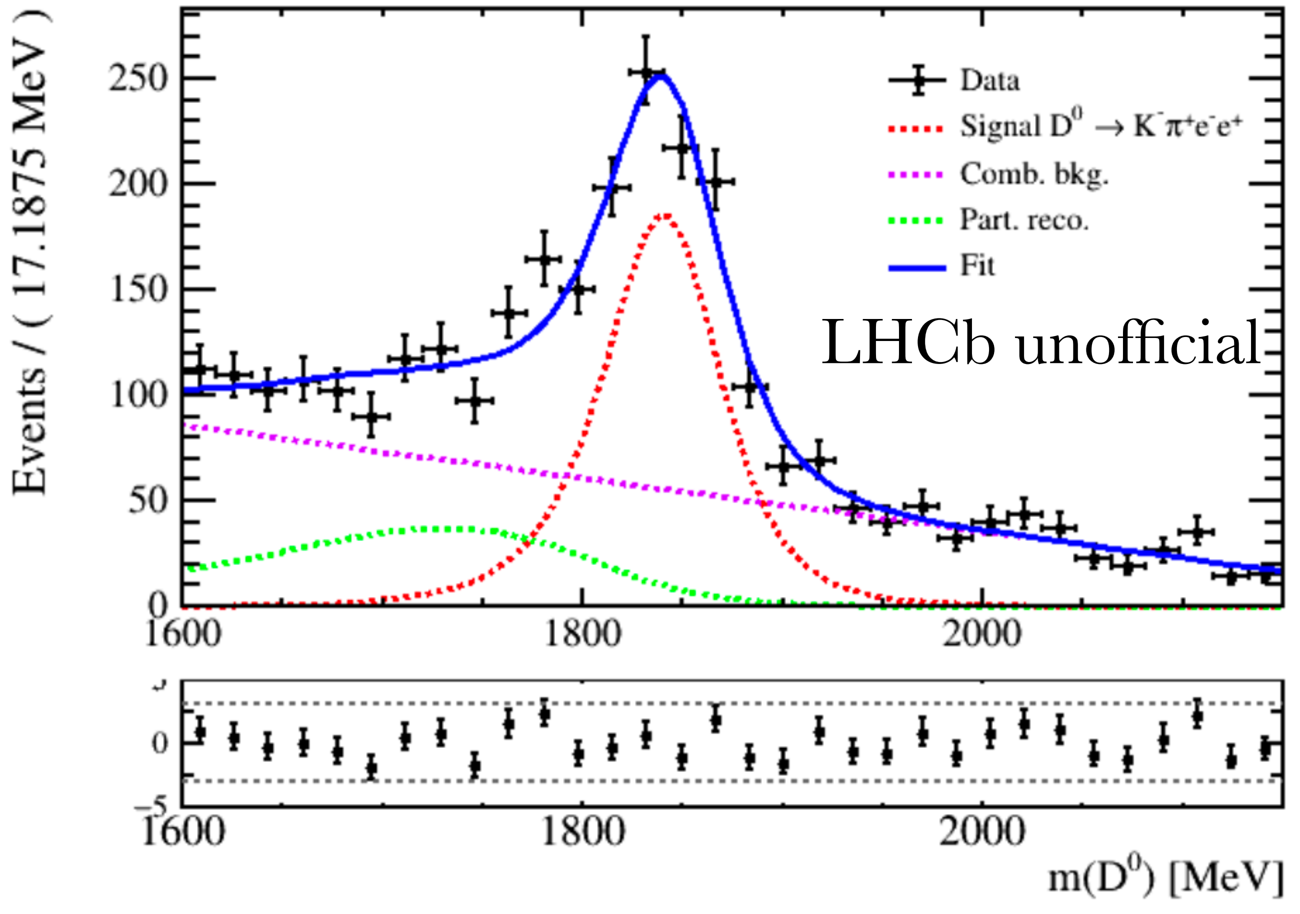
- **Partially reconstructed** bkg: Bukin PDF
  [shape fixed from $D^0 \to K^-\pi^+e^+e^-\gamma$ and $D^0 \to K^-\pi^+\pi^+e^-\bar{\nu}_e$ RapidSim studies]

- **Combinatorial** bkg: 1st order polynomial

Electrons AND TrackMVAs *Hlt1*

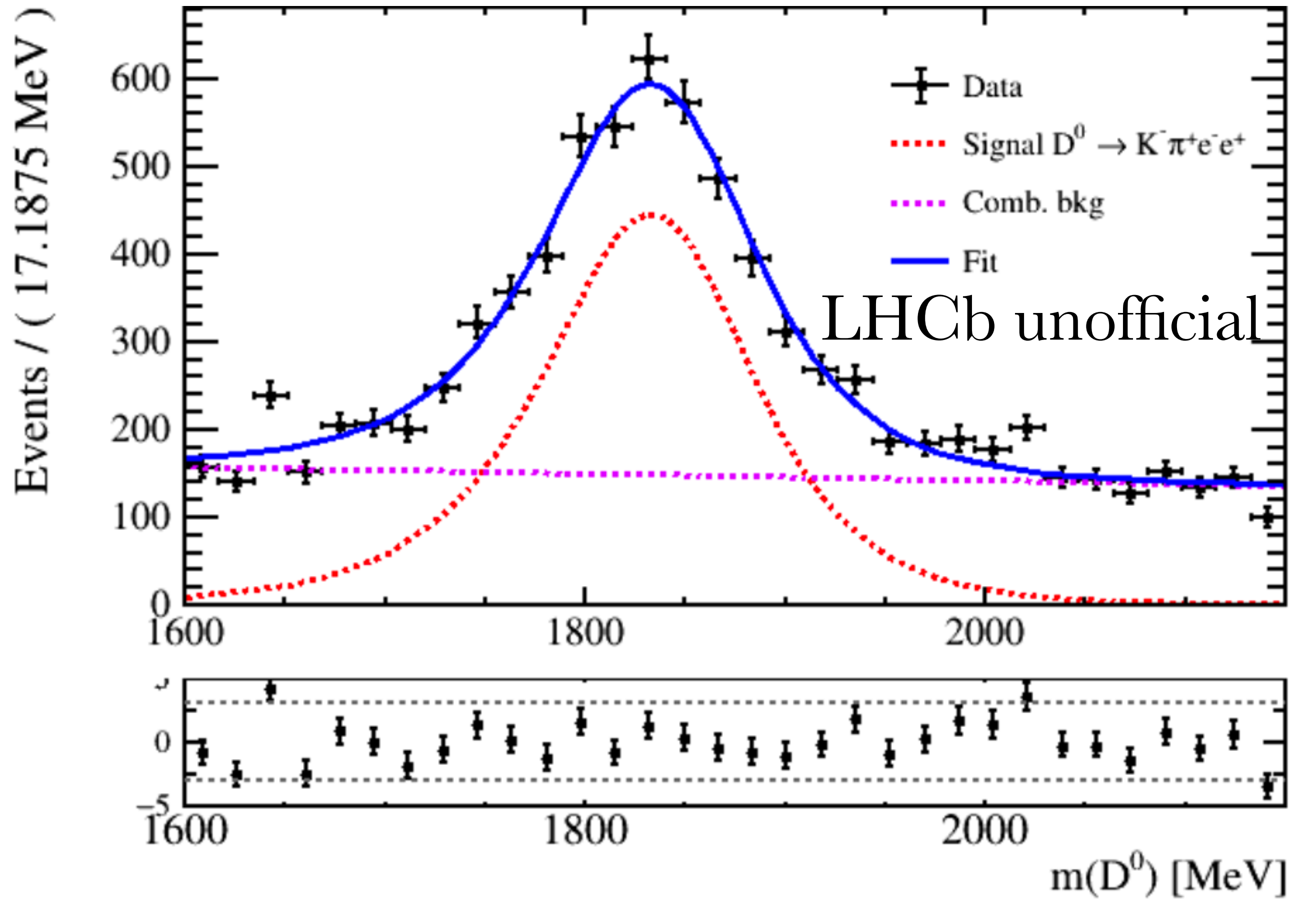


Only Electrons *Hlt1*



	AND	Only E	TrackMVAs
μ_{sig}	1848.6 ± 1.0	1844 ± 2	1840.3 ± 1.6
σ_{sig}	47.3 ± 1.7	46 ± 3	83 ± 4
γ_{sig}	0.20 [C]	0.20 [C]	0.20 [C]
δ_{sig}	1.42 [C]	1.42 [C]	1.42 [C]
μ_{bkg}	1731.5 [C]	1731.5 [C]	-
σ_{bkg}	85.7 [C]	85.7 [C]	-
$asymm_{bkg}$	-0.191 [C]	-0.191 [C]	-
$\rho_{L,bkg}$	-0.39 [C]	-0.39 [C]	-
$\rho_{R,bkg}$	-0.70 [C]	-0.70 [C]	-
c_{comb}	-0.38 ± 0.06	-0.67 ± 0.06	-0.07 ± 0.03
n_{sig}	2729 ± 79	889 ± 53	3771 ± 143
n_{comb}	2647 ± 147	1643 ± 109	4712 ± 146
$n_{part.\ reco}$	449 ± 123	404 ± 96	-

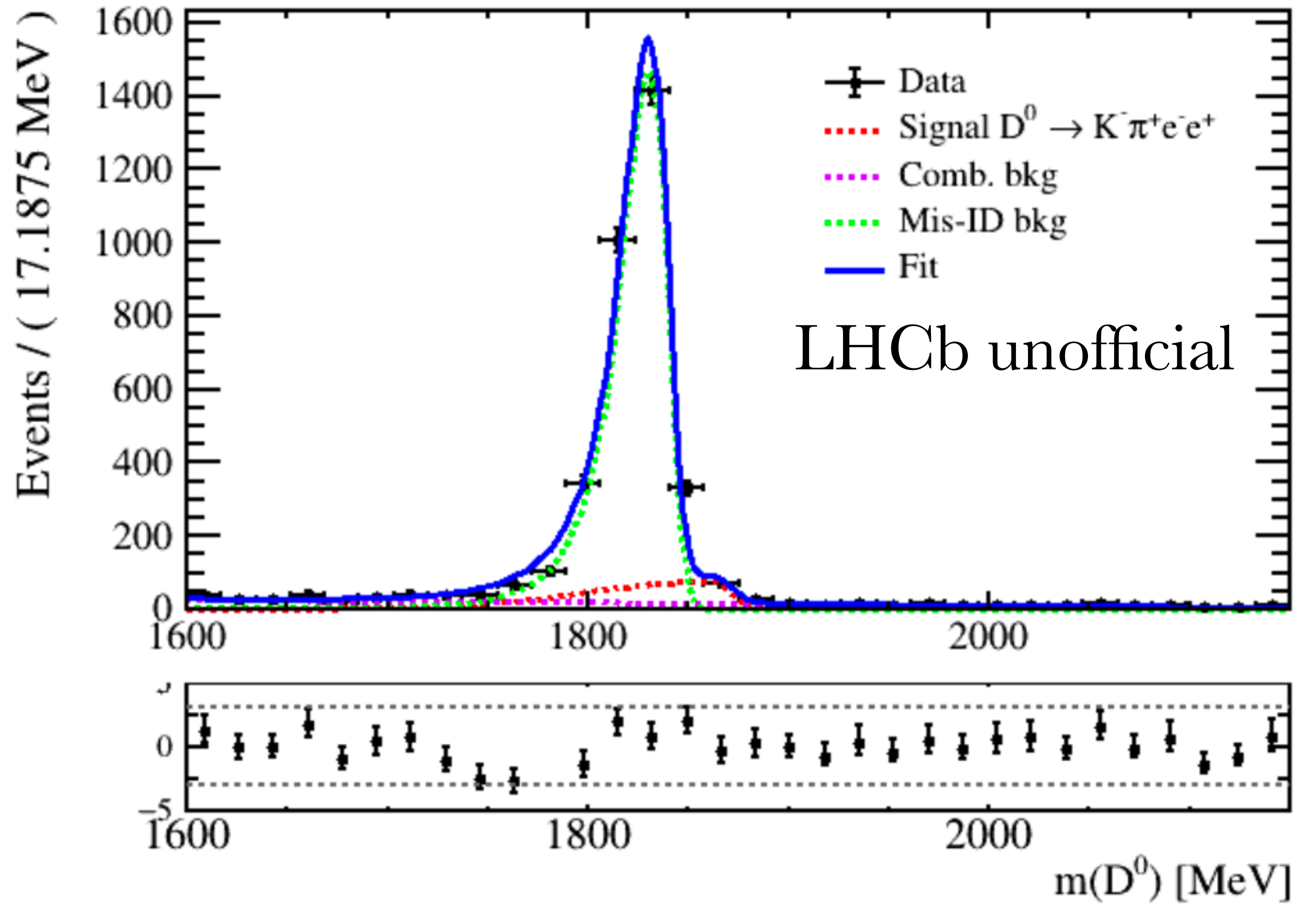
Only TrackMVAs *Hlt1*



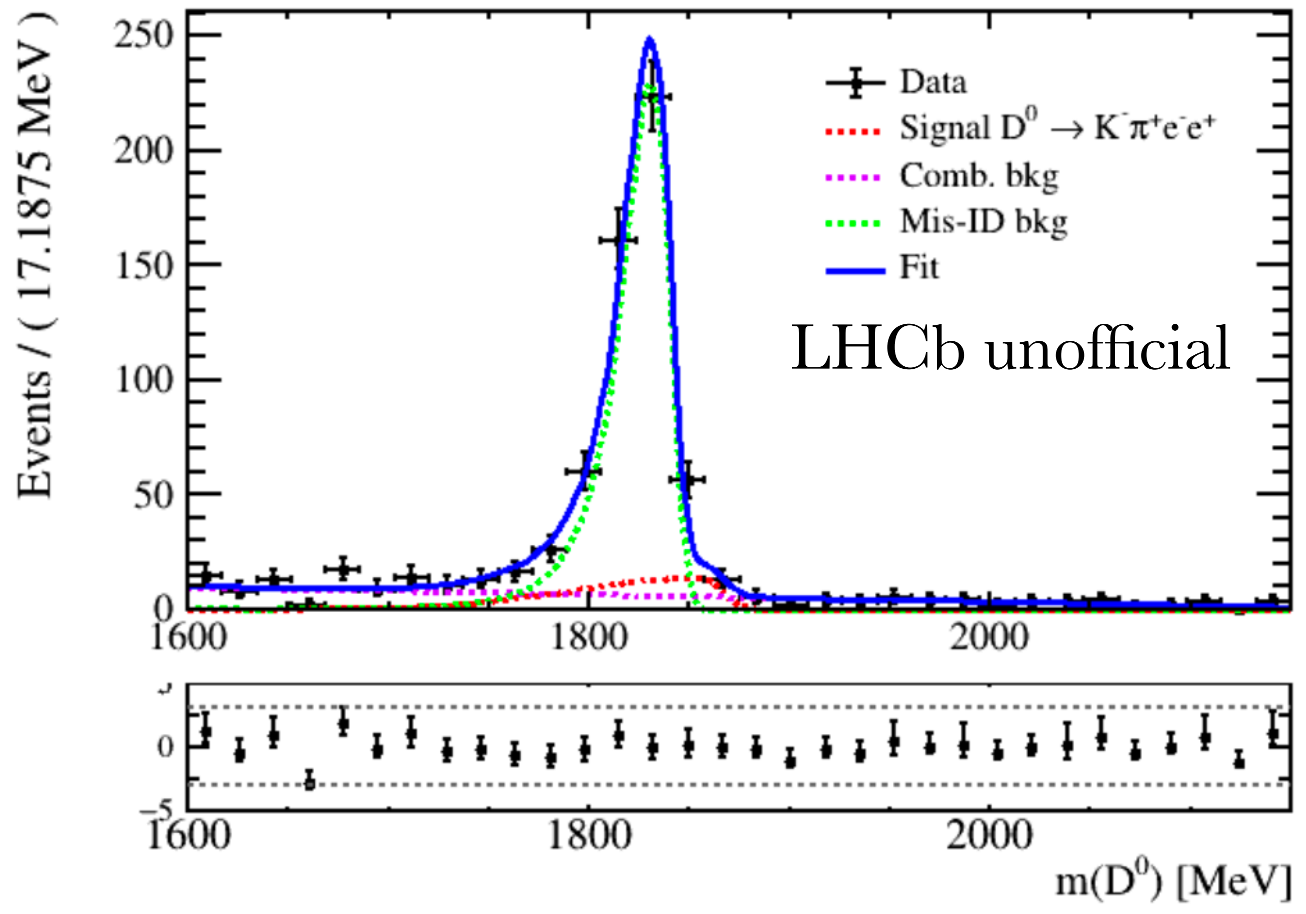
Brem0 fit

- **Signal**: double-sided Crystall-Ball PDF [shape fixed from MC]
- **Mis-ID $D^0 \to K^-\pi^+\pi^-\pi^+$**: Bukin PDF [shape fixed from RapidSim + PIDcalib]
- **Combinatorial** bkg: 1st order polynomial

Electrons AND TrackMVAs *Hlt1*

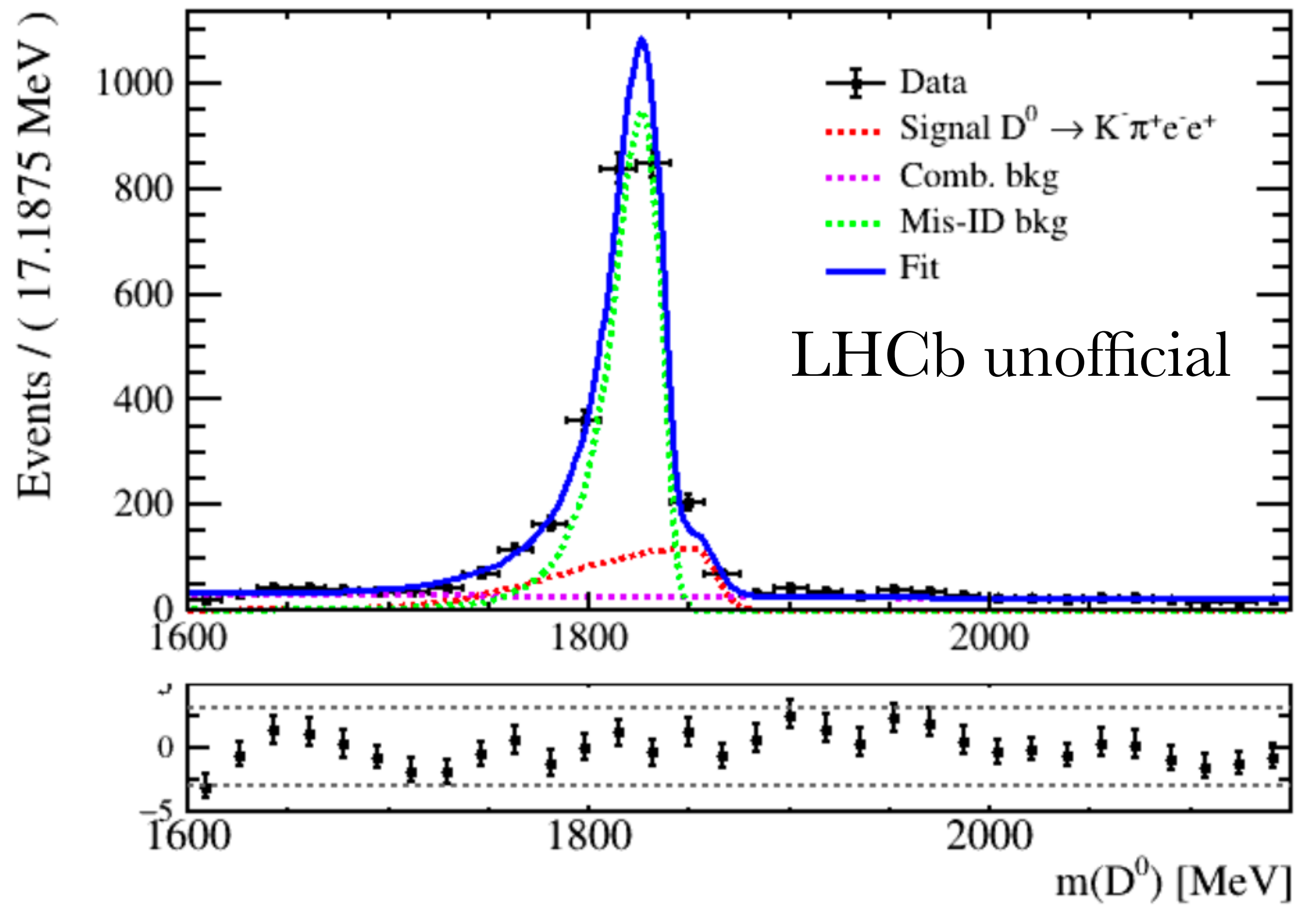


Only Electrons *Hlt1*



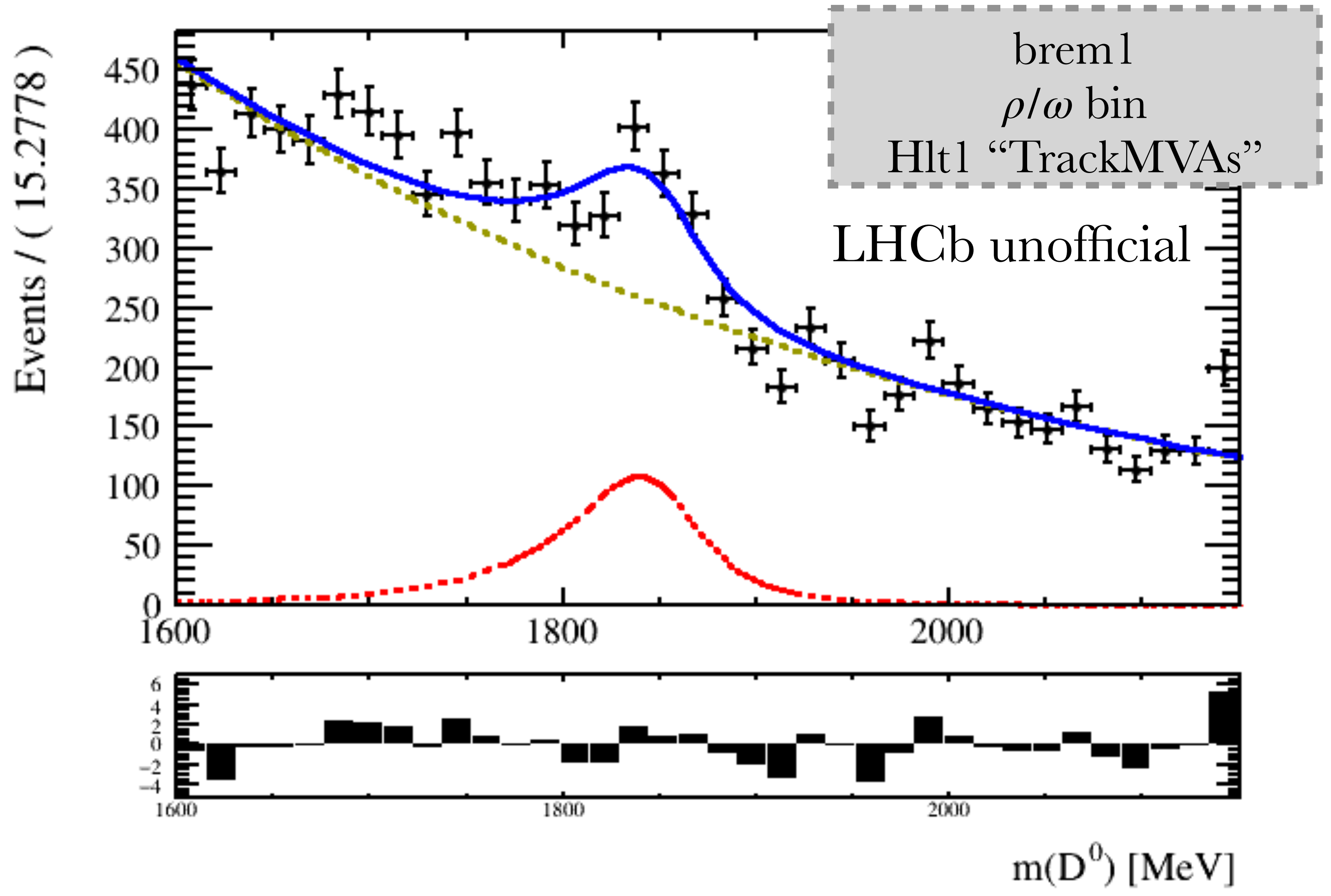
	AND	Only E	TrackMVAs
μ_{sig}	1861 ± 2	1856 ± 4	1852.6 ± 1.6
$\sigma_{L,sig}$	63.7 [C]	63.7 [C]	63.7 [C]
$\sigma_{R,sig}$	9.8 [C]	9.8 [C]	9.8 [C]
$\alpha_{L,sig}$	2.07 [C]	2.07 [C]	2.07 [C]
$n_{L,sig}$	3.0 [C]	3.0 [C]	3.0 [C]
$\alpha_{R,sig}$	4.47 [C]	4.47 [C]	4.47 [C]
$n_{R,sig}$	0.00 [C]	0.00 [C]	0.00 [C]
μ_{bkg}	1830 ± 0.3	1830 ± 0.7	1826 ± 0.4
σ_{bkg}	12.2 [C]	12.2 [C]	12.2 [C]
$asymm$	-0.21 [C]	-0.21 [C]	-0.21 [C]
$\rho_{L,bkg}$	0.06 [C]	0.06 [C]	0.06 [C]
$\rho_{R,bkg}$	-1.8 [C]	-1.8 [C]	-1.8 [C]
c_0	-0.64 ± 0.07	-0.79 ± 0.09	-0.18 ± 0.07
n_{sig}	412 ± 47	76 ± 24	642 ± 58
n_{comb}	514 ± 29	176 ± 17	825 ± 36
n_{misID}	2900 ± 66	452 ± 28	1869 ± 61

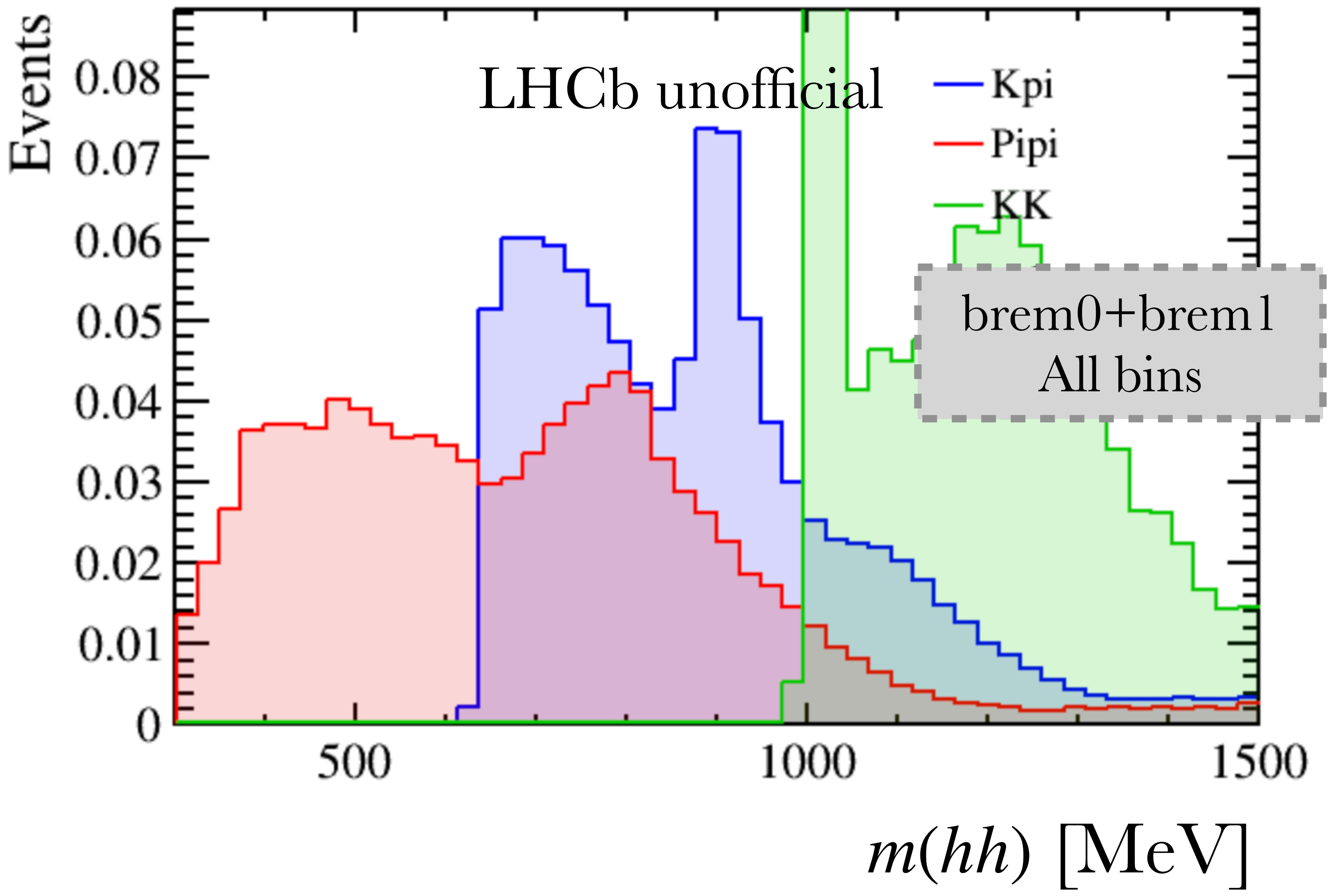
Only TrackMVAs *Hlt1*



First look at $D^0 \to \pi\pi ee$

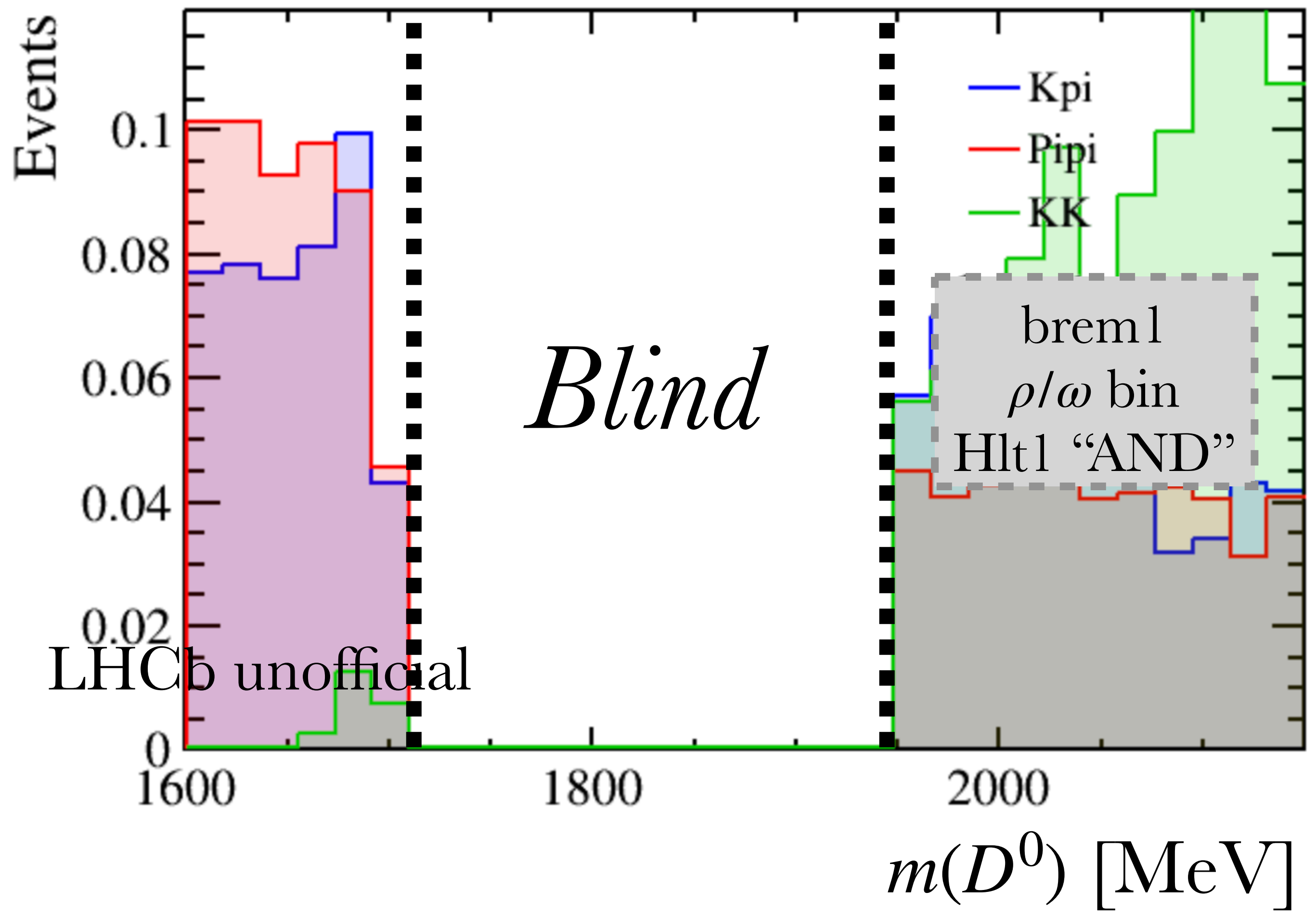
- **Loose preselection + BDT cut**
  - Difficulties in BDT optimization due to lack of proper background modeling
  - Uncertainty on signal yield ~10% (~20% in Run 2)
- **Large background on the left remaining**
- Large contributions not coming from main resonant peak in the $m(h^-h^+)$ spectrum for all the channels





Low $m(\pi\pi)$ corresponds to low $m(D^0)$ bkg

High $m(KK)$ corresponds to high $m(D^0)$ bkg



Efficiency determination

- **Acceptance** ($\sim 20\,\%$): from MC
- **Reconstruction/Tracking**: from MC
  - Correct data/MC differences with data-driven TrackCalib package
  - $\mathcal{O}(0.1\%)$ in Run 2

Tag and probe method with $J/\psi \to \mu^+\mu^-$ or $B^+ \to J/\psi(\to e^+e^-)K^+$

- **Offline selection**: from MC
- **PID**: data-driven efficiency using the PIDcalib package
- **Trigger**:
  - Data-driven efficiency maps ∀ HLT1 trigger line and ∀ final-state particle which might trigger it
  - Same for lines involving a pair of daughters (TwoTrackMVA)
  - TISTOS method

TIS = **T**rigger **I**ndependent of **S**ignal
TOS = **T**rigger **O**n **S**ignal

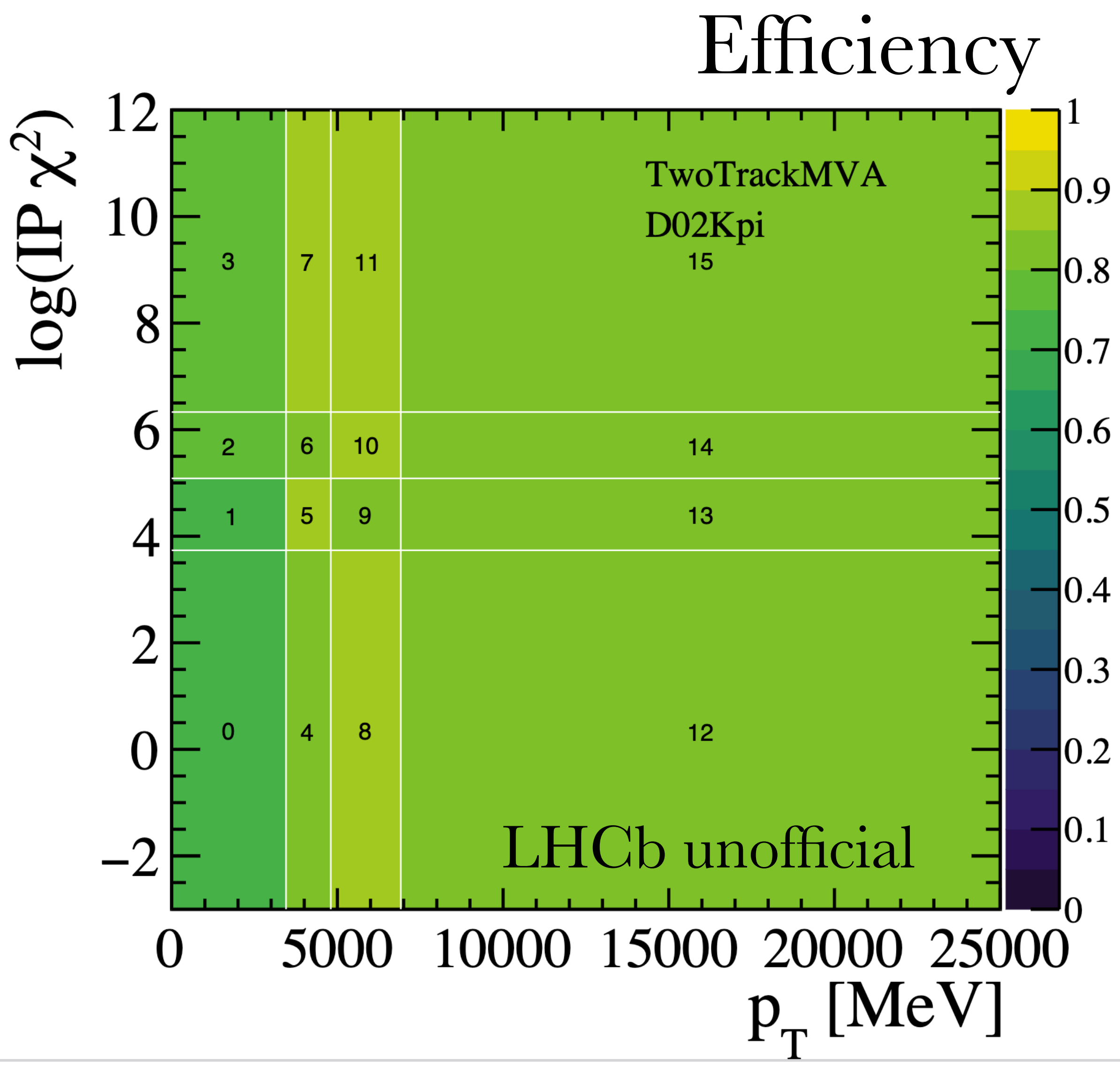
Trigger efficiency

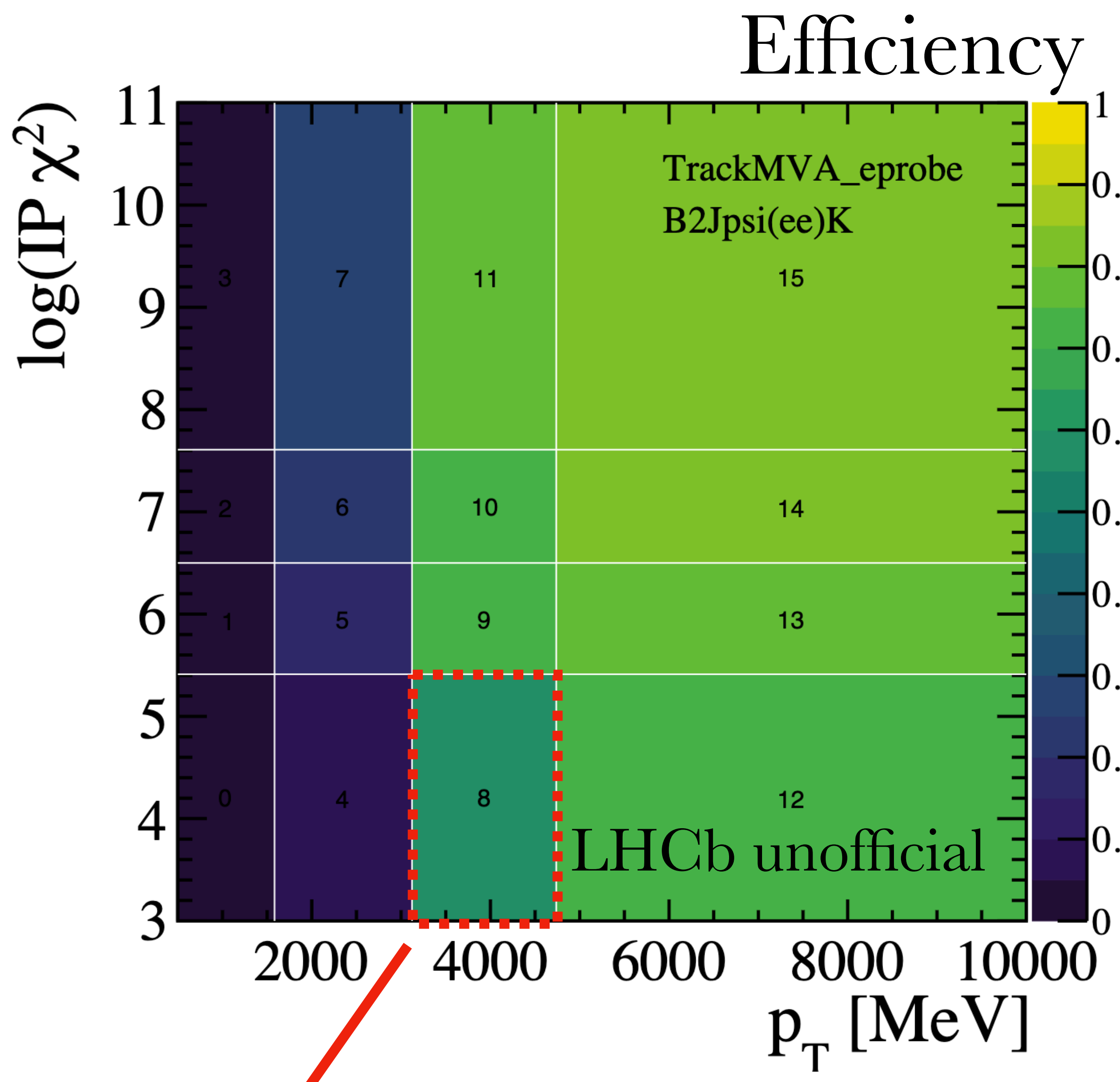
- **Data-driven** TISTOS method for data/MC differences corrections in bins of IPχ^2 and p_T:
  - Count the number of events passing a trigger line with control samples

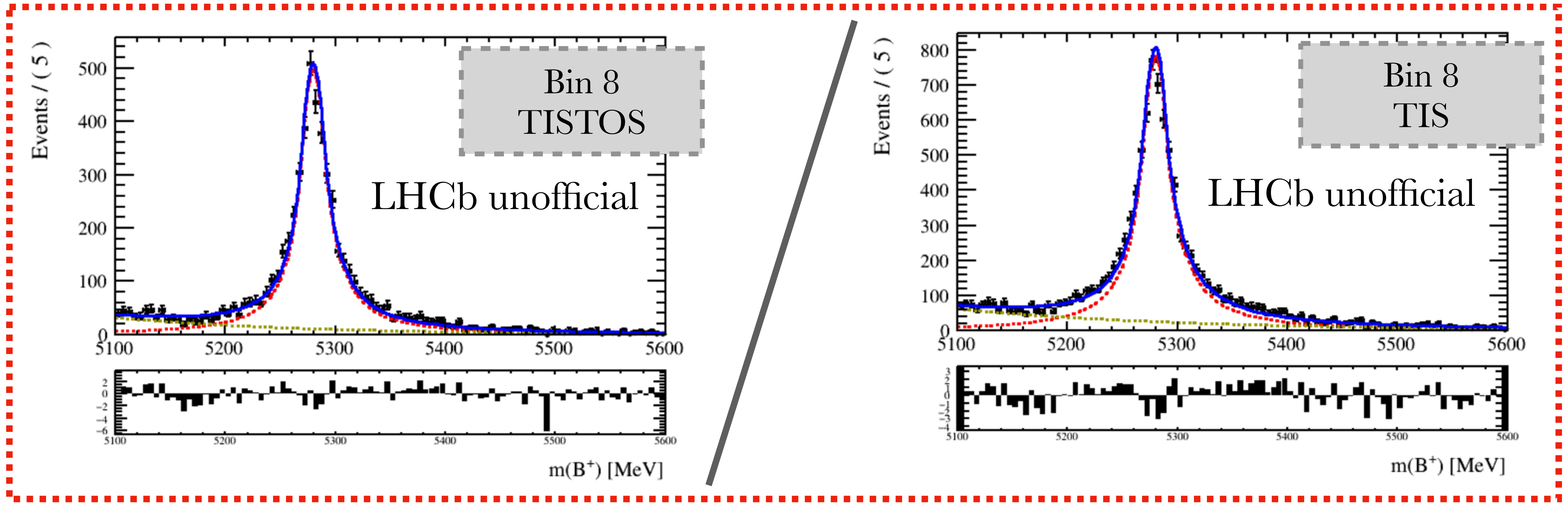
$$\varepsilon_{TOS} = \frac{N_{TISTOS}}{N_{TIS}}$$

- <u>TrackMVA lines for hadrons</u>: $B^0 \to D^{*+}(\to D^0\pi^+)\mu^-$
  - $D^0 \to K^-\pi^+$, $D^0 \to K^-K^+$, $D^0 \to \pi^-\pi^+$
  - μ TIS trigger line

- <u>For electrons:</u> $B^+ \to J/\psi(\to e^+e^-)K^+$
  - K^+ TIS trigger line
  - Requires event selection + BDT to extract yields from fits to $m(B^+)$







Outline

- Introduction and motivation (+ Run 2 results)
- First look at Run 3 data
    - RapidSim setup
    - Normalization channel
    - First look at $D^0 \to \pi\pi ee$
- **Outlook and conclusions**

Conclusions and outlook

- Run 2 analysis lead to the first observation of $D^0 \to \pi\pi ee$ in the ρ/ω and ϕ bins
- We set up **RapidSim** in order to reproduce well Run 3 samples, also considering brem categories
- First look at $D^0 \to K^-\pi^+e^-e^+$ data shows an increase in statistics per unit of luminosity
  - Comparing with Run 2, we expect ~ 3-4 times increase in signal candidates per unit of luminosity for the rare channels $D^0 \to \pi^-\pi^+e^-e^+$ and $D^0 \to K^-K^+e^-e^+$
- Very preliminary fit to $D^0 \to \pi^-\pi^+[e^-e^+]_{\rho/\omega}$ shows **high contributions from partially reconstructed or mis-ID backgrounds**
  - Studies ongoing to reach a better understanding
- Started efficiency determination exploiting data-driven methods

Thank you for your attention!

Backup

Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Strategy

- Dominated by radiative $D^0 \to h^- h^+ \gamma$ and partially reconstructed $D^0 \to h^- h^+ \pi^0 (\to e^+ e^- \gamma)$
- Not kinematically available for the muons mode

- Dominated by η, ρ, ω and ϕ resonances contributions

- Not kinematically available for the Kaons mode

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

Run 3 - Normalization channel

- First look at normalization channel **2024 data**
- Rough estimation of expected signal $D^0 \to \pi\pi ee$ and $D^0 \to KKee$ events
- Few changes compared to Run 2 analysis strategy (at the moment)

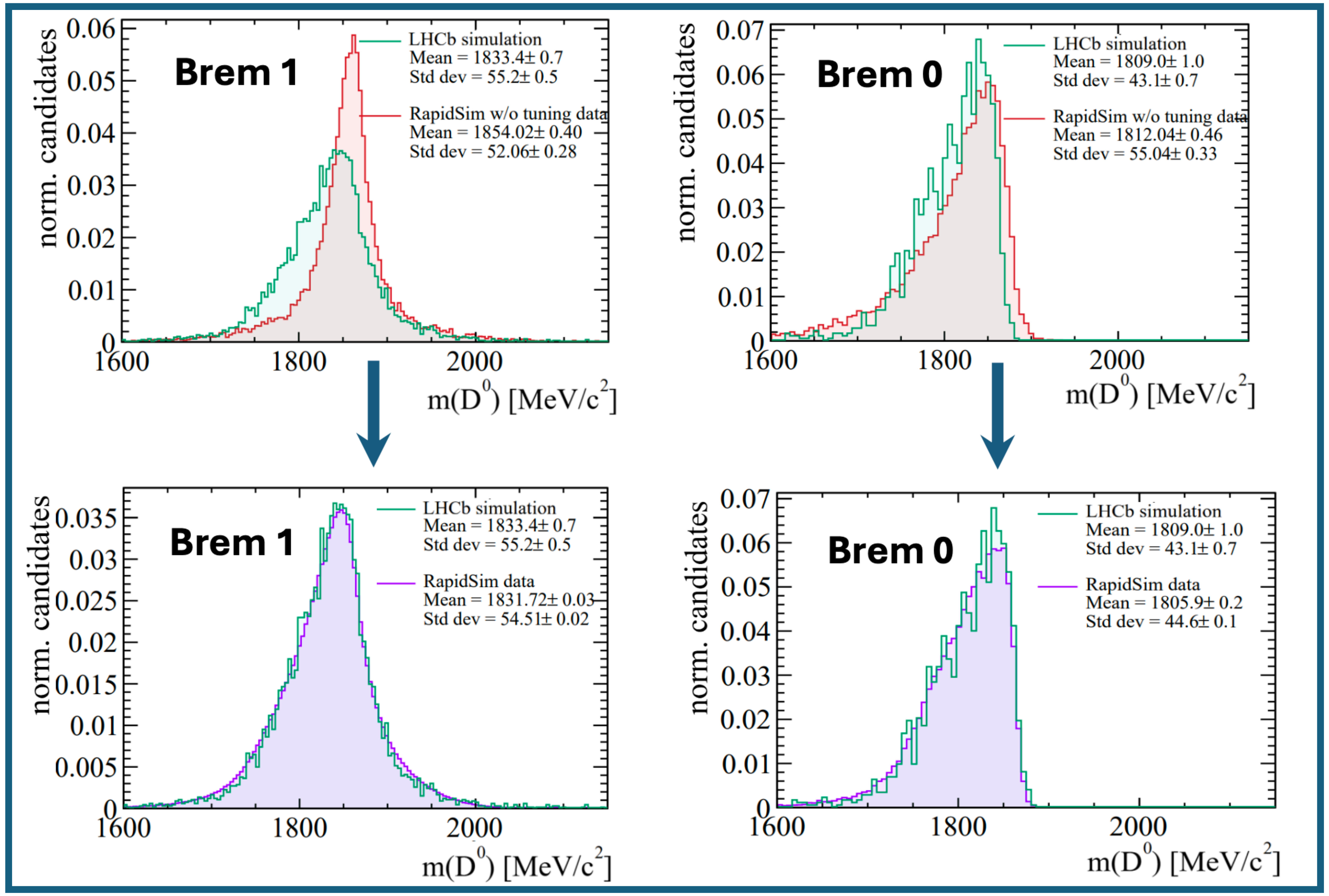
➡ Dataset split into 3 HLT1 selections —> different background levels and shapes

- (D0_Hlt1TrackMVADecision_TOS || D0_Hlt1TwoTrackMVADecision_TOS) **&&** **!**(D0_Hlt1DiElectronDisplacedDecision_TOS ||D0_Hlt1TrackElectronMVADecision_TOS) — Only TrackMVAs
- (D0_Hlt1TrackMVADecision_TOS || D0_Hlt1TwoTrackMVADecision_TOS) **&&** (D0_Hlt1DiElectronDisplacedDecision_TOS ||D0_Hlt1TrackElectronMVADecision_TOS) — TrackMVAs && Electrons
- **!**(D0_Hlt1TrackMVADecision_TOS || D0_Hlt1TwoTrackMVADecision_TOS) **&&** (D0_Hlt1DiElectronDisplacedDecision_TOS ||D0_Hlt1TrackElectronMVADecision_TOS) — Only Electrons

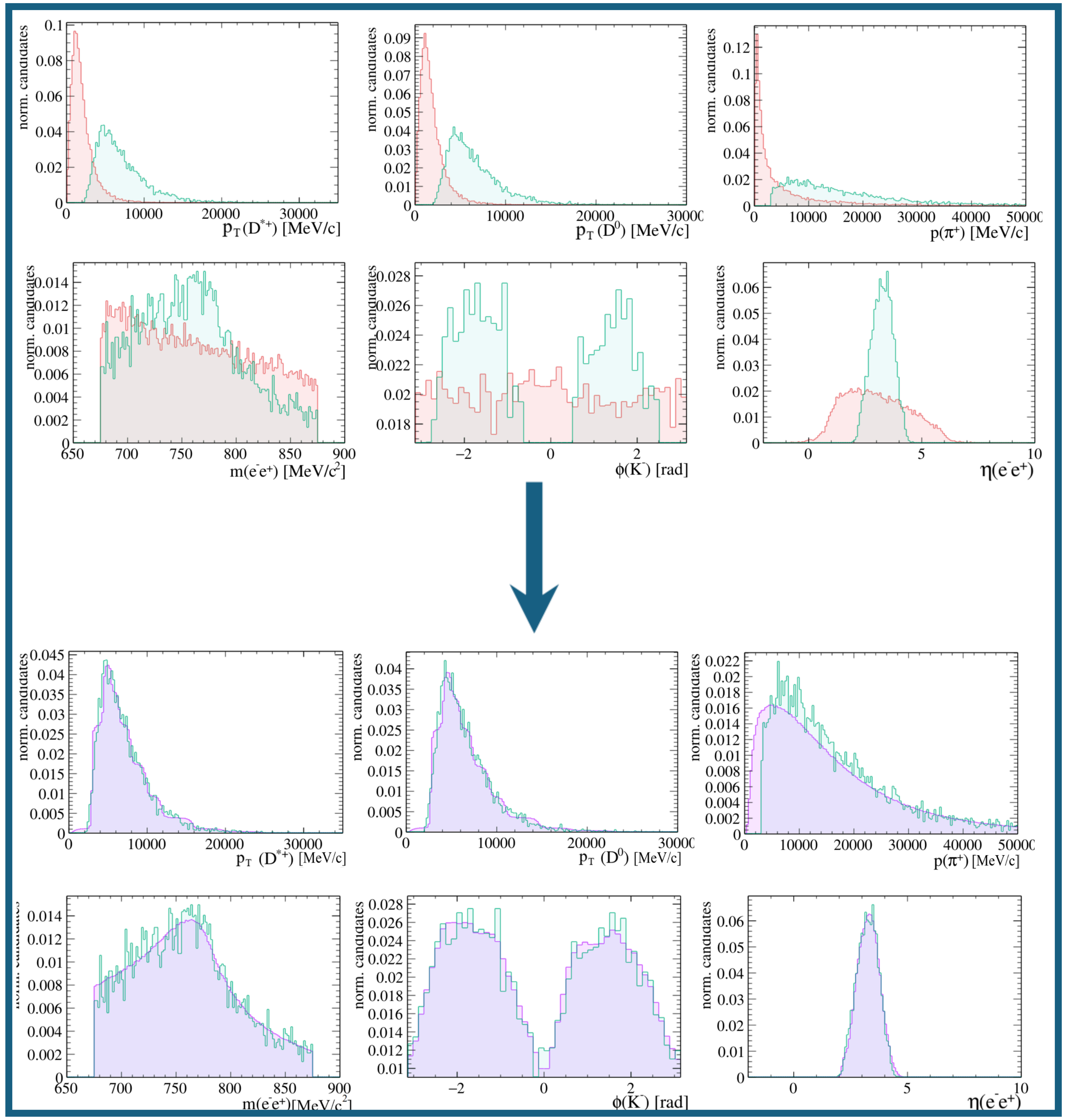
RapidSim - validation

➡ Now RapidSim reproduces well the distributions for both brem categories

$m(D^0)$

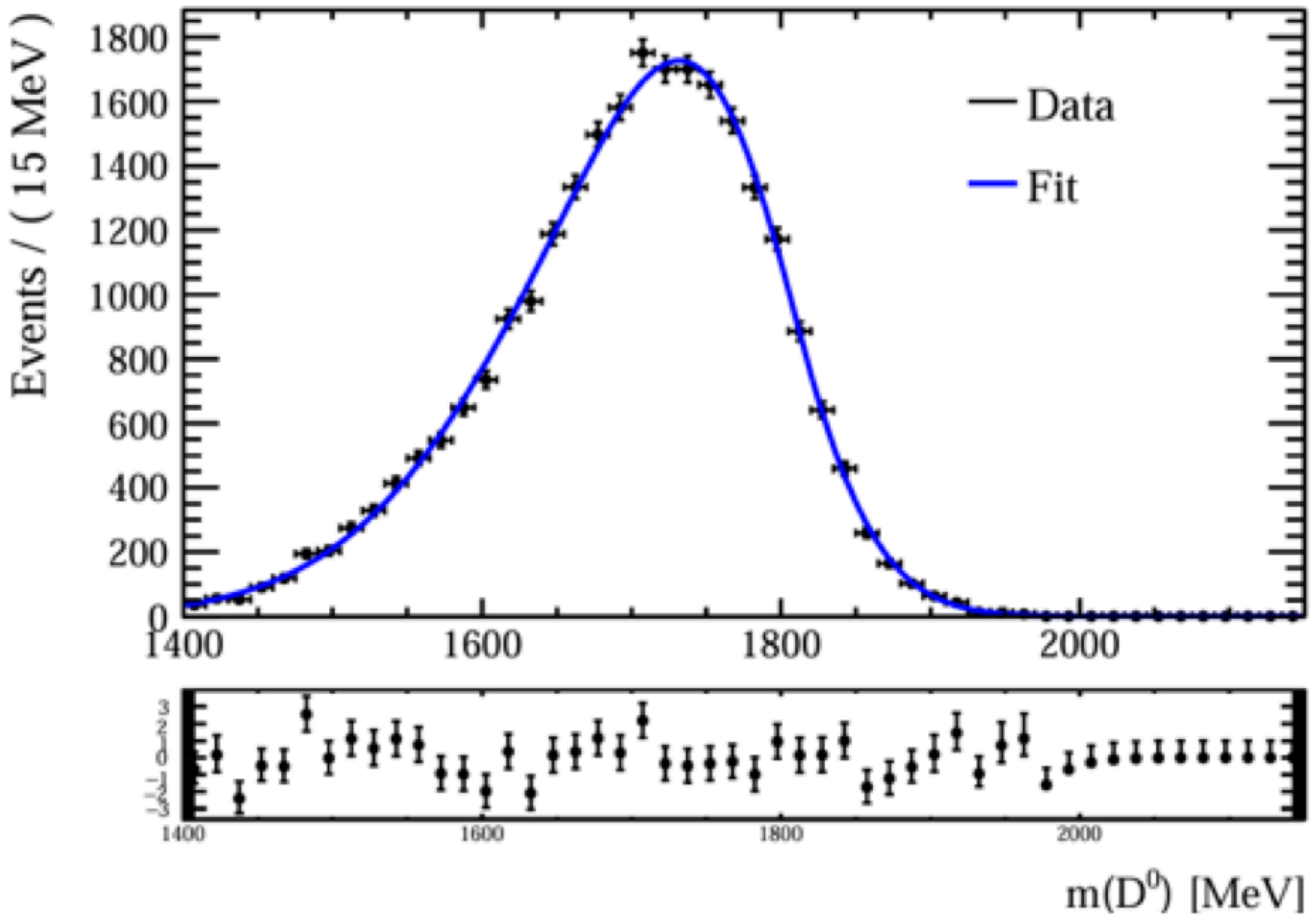


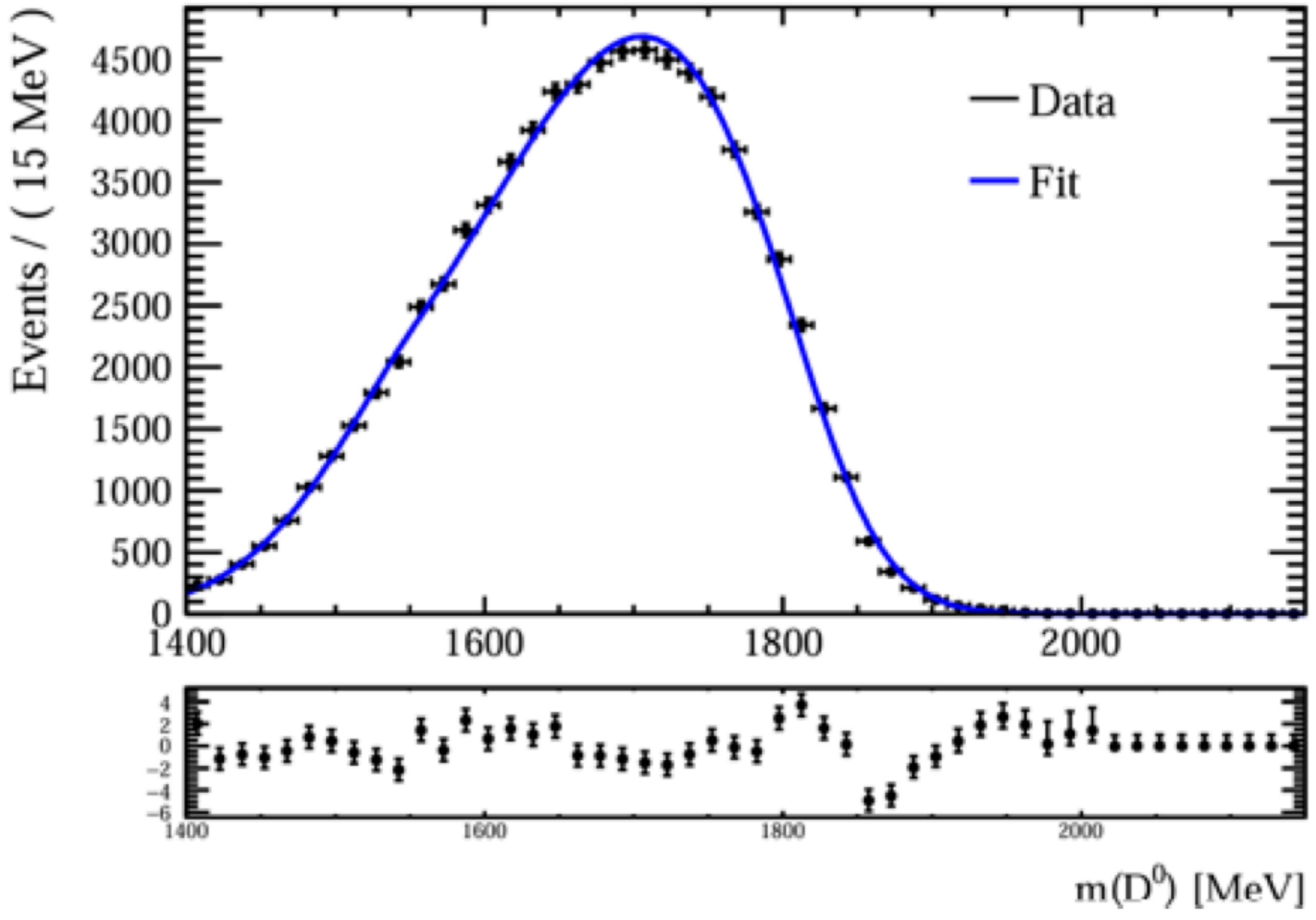
other variables



RapidSim - brem1 studies

- Two possible (similar) background modes have been studied for the brem1 category:
  - $D^0 \to K^-\pi^+e^+e^-\gamma$ (γ missed)
  - $D^0 \to K^-\pi^+\pi^+e^-\bar{\nu}_e$ (π^+ mis-ID as e^+, $\bar{\nu}_e$ missed)
- Peaking at ~ 1700 MeV, very similar shapes

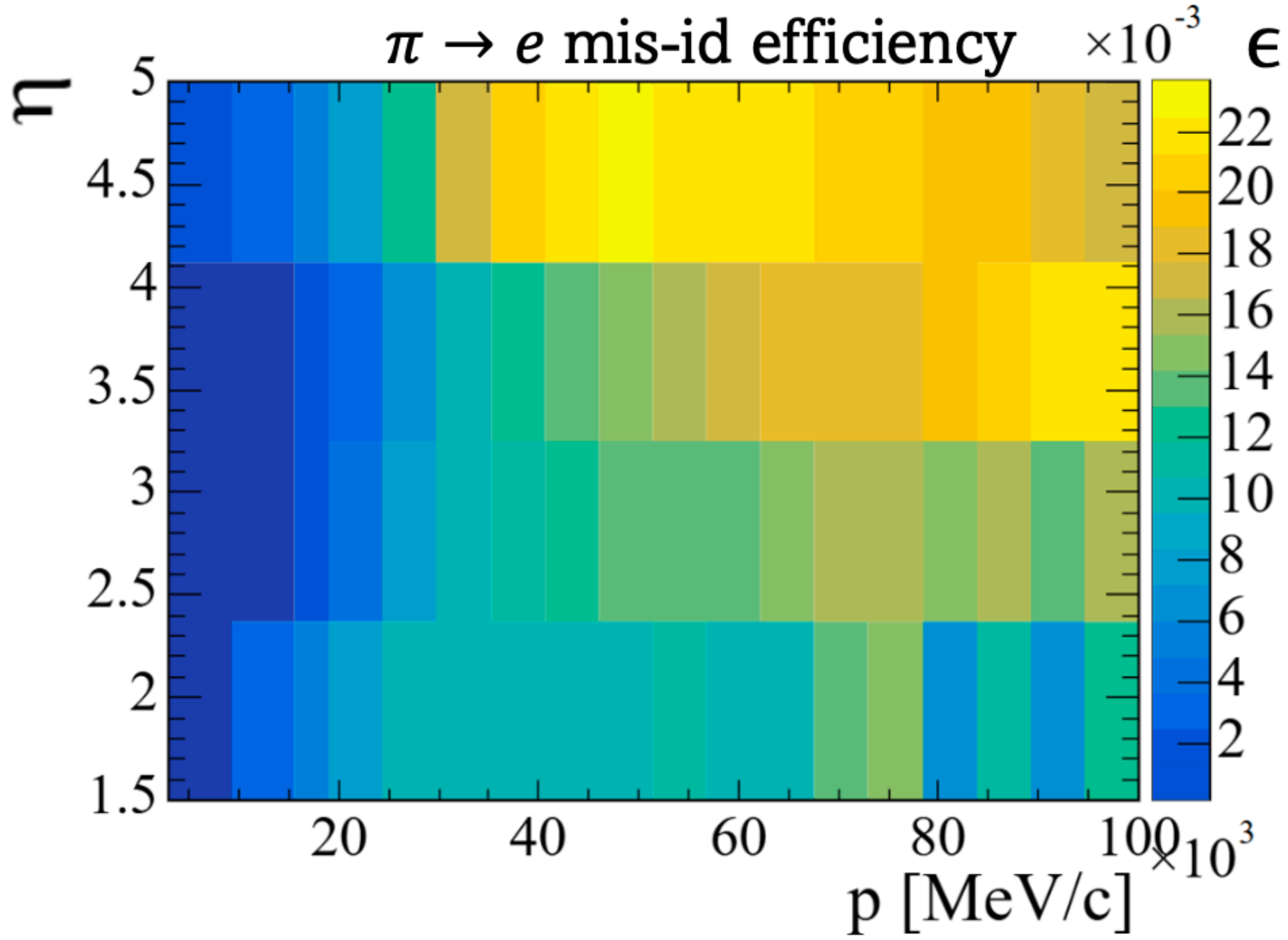


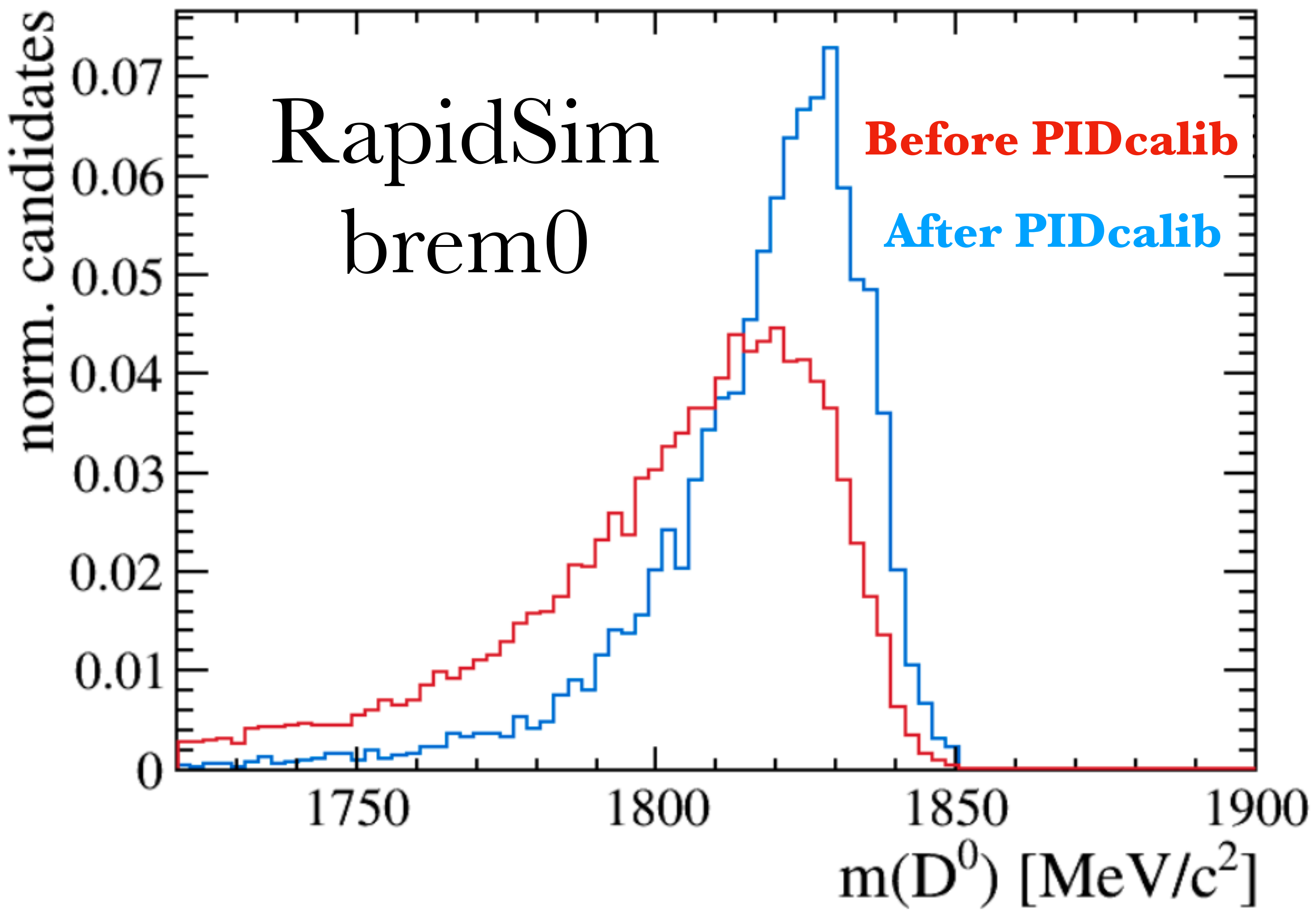


RapidSim - brem0 studies

- Main bkg in brem0 category: $D^0 \to K\pi\pi\pi$ (with $\pi^-\pi^+$ mis-ID as e^-e^+)
- Generated with RapidSim and weighted using the [PIDcalib package]
    - Efficiency maps for cuts on PID variables
    - Data-driven

[Electrons PID cuts present in the trigger]





First look at $D^0 \to \pi\pi ee$

- Tried a refined strategy:
  - 1st BDT trained on $D^0 \to K\pi ee$
    - Reduce combinatorial bkg
    - Maximize $S/\sqrt{S+B}$
  - 2nd BDT trained on $D^0 \to \pi\pi ee$ [$m(\pi\pi) < 450$ MeV]
    - Reduce partially reconstructed bkg
    - Maximize $S/\sqrt{S+B}$
  - 3rd BDT trained on $D^0 \to \pi\pi ee$
    - Reduce combinatorial bkg
    - Maximize Punzi Figure of Merit

- **Large background on the left**
  - We are trying to reduce it using variables related to the $\pi^-\pi^+$ angle and the PV pointing