Search for $D^0 \to h^+h^-e^+e^-$ rare charm decays and HLT1 tracking for the LHCb's Run3 trigger

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About myself

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Bachelor:

- JLab CLAS12 RICH detector

Master:

- LHCb tracking Upgrade2
- Test of Lepton Flavour Universality with B_s decays

UNIVERSITÉ PARIS SUD

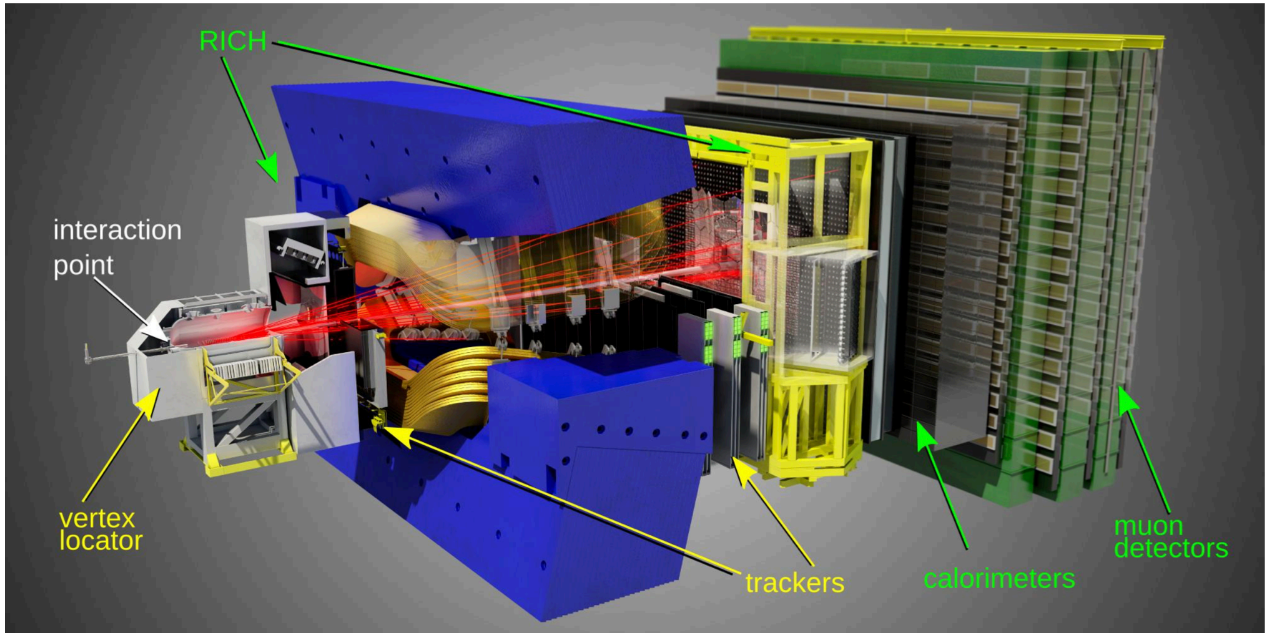
université PARIS-SACLAY

PhD thesis:

Search for $D^0 \rightarrow h^+h^-e^+e^-$ rare charm decays and long track reconstruction for the LHCb trigger

Charm at LHCb

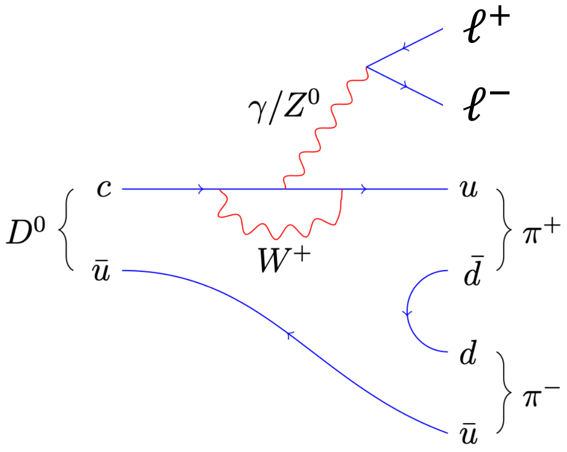
- Charm decays: a unique up-type probe for new flavour physics effects, complimentary to the K and B sectors
- Unique studies for lepton flavor and CP violation
- Large cross-section at LHCb: $\sigma(c\bar{c}, \sqrt{s} = 13\ TeV) = (2940\ \pm 240)\ \mu b$ [J. High Energ. Phys. 2016, 159]
  $\rightarrow$ 20 times larger than the $b\bar{b}$ production
- The LHCb detector:
  - Excellent particle identifcation
  - Momentum and vertex resolution
  - Fast, efficient and flexible trigger system

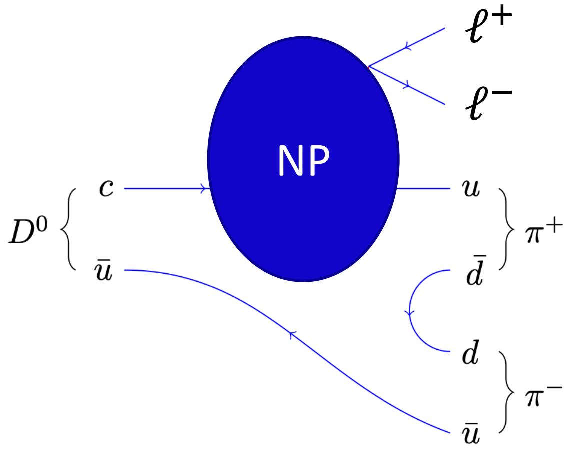


Why study Rare Charm decays?

- 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:

$$R^{D}_{P_1P_2} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D\to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D\to P_1P_2e^+e^-)}$$

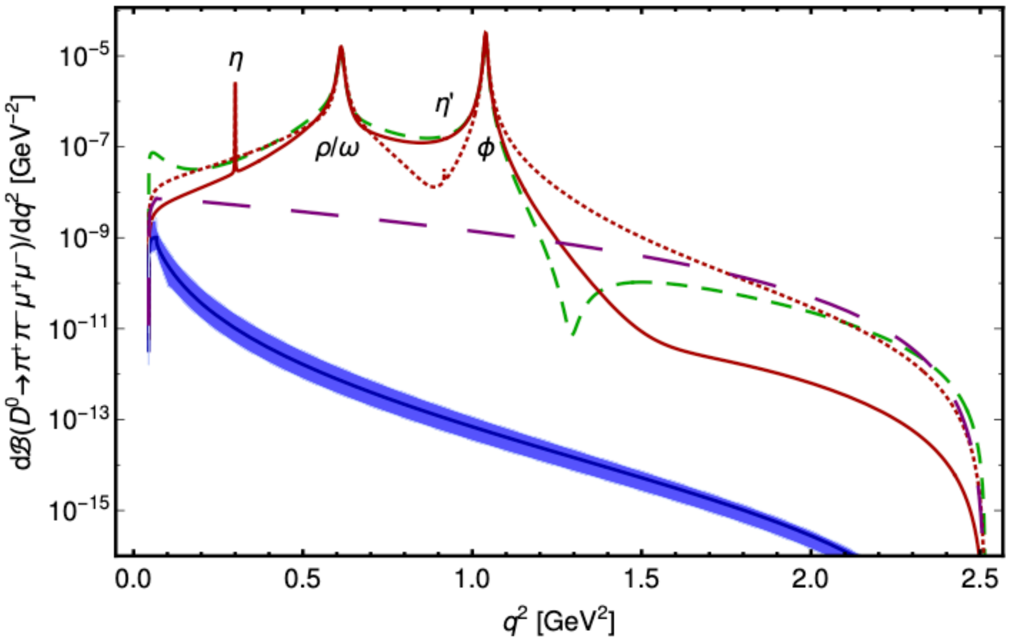




Challenges

- 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)]



$\mathbf{D^0 \to \pi^+\pi^-\mu^+\mu^-}$

non-resonant component

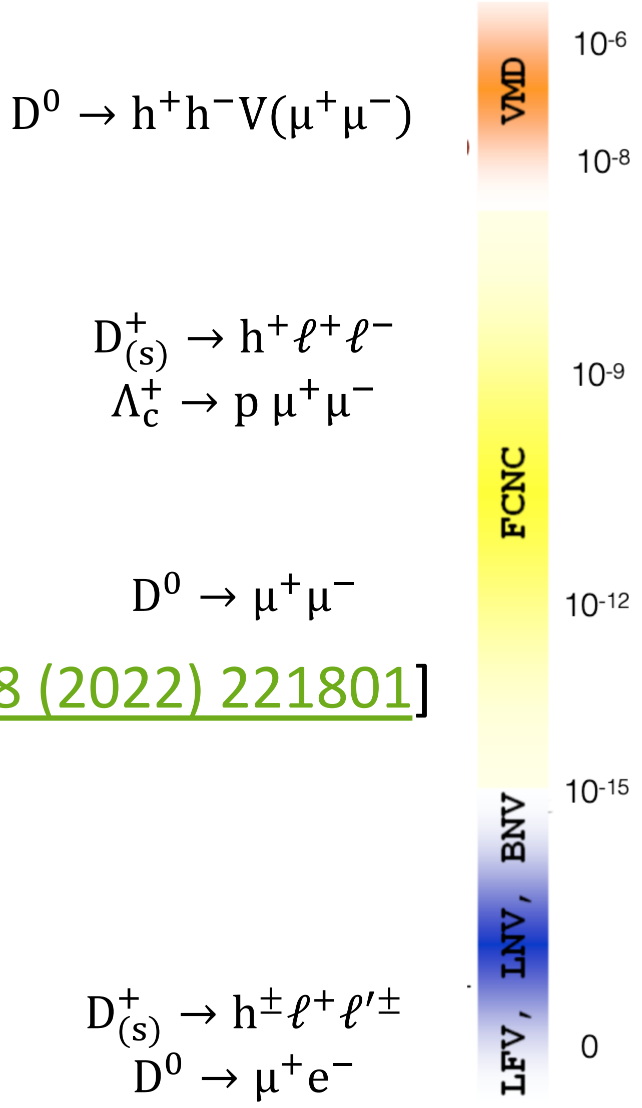
resonant component

LD different model

BSM model (dashed)

Rare Charm decays at LHCb

- Branching fractions:
  - Search for $D^0 \to \mu^+\mu^-$ [arXiv:2212.11203]
  - 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 $\mathbf{D^0 \to h^+h^-e^+e^-}$ 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)

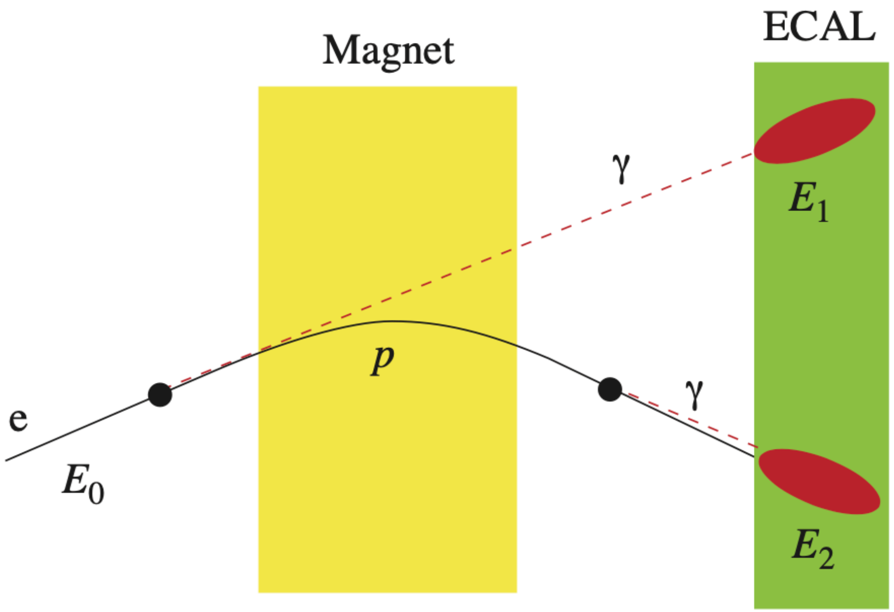
Comparing to measured muon modes BFs

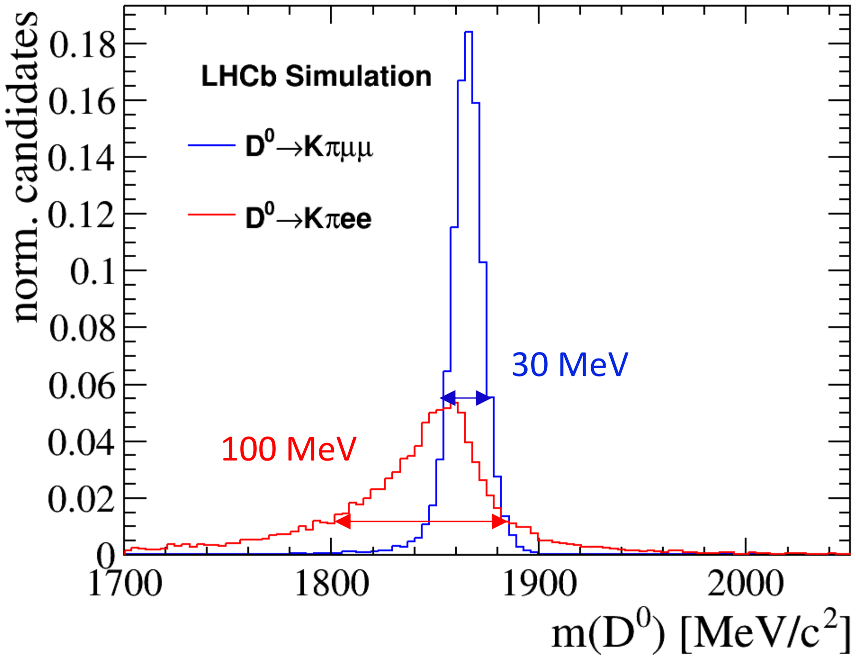
Channel	Branching fraction
$D^0 \to K^-\pi^+\mu^+\mu^-$	$(4.2 \pm 0.4) \times 10^{-6}$ in dimuon range 675-875 MeV/c^2 [3]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$(9.6 \pm 1.2) \times 10^{-7}$ [4]
$D^0 \to K^+K^-\mu^+\mu^-$	$(1.54 \pm 0.32) \times 10^{-7}$ [4]

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

Challenges with electrons

- Bremsstrahlung effects: interactions of the electrons with the detector material
- Degraded mass resolution of decays involving electrons
- Brem recovery procedure with 50% efficiency on photons emitted before the magnet
- Hardware trigger limit, tighter energy/momentum cuts on selection





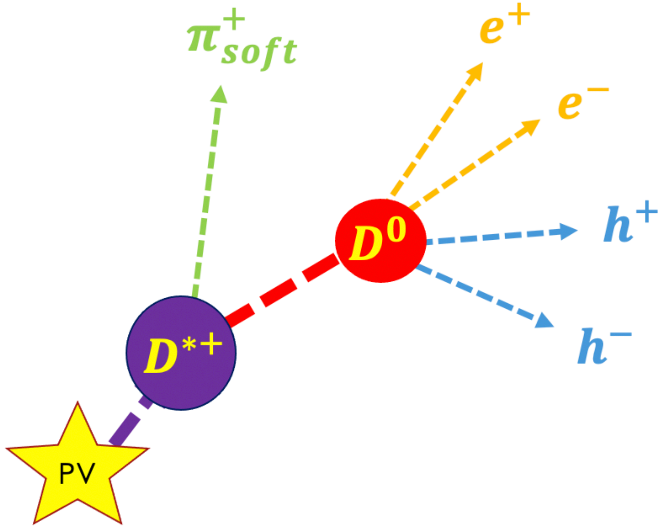
Analysis strategy

- 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

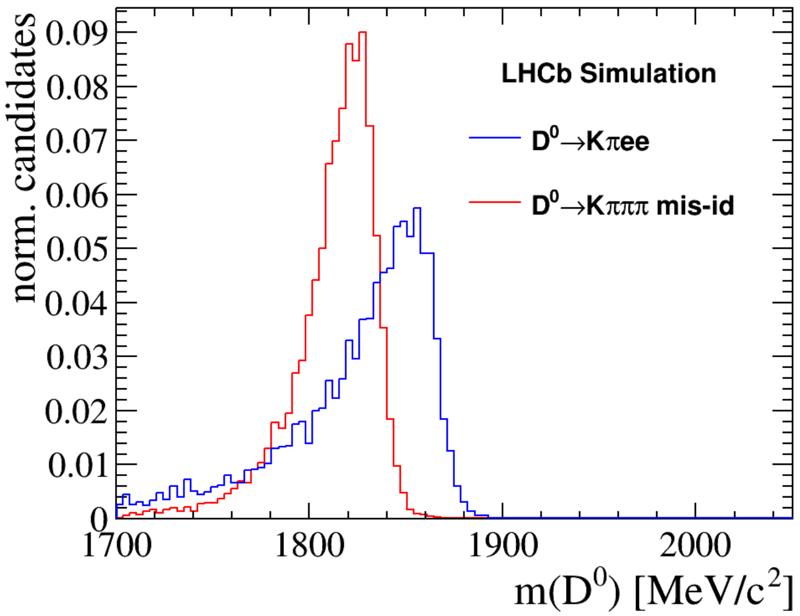
- Data sample: Run2 (2015 to 2018)
- Selecting $\boldsymbol{D^*}$-tagged decays: $\boldsymbol{D^{*+}} \to D^0(\to h^+ h^- e^+ e^-)\pi^+_{soft}$
- Blind analysis: data removed in the signal D^0 mass range [1700-1900] MeV/$\boldsymbol{c^2}$
- Samples split into decays with and without brem photons attached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



bin	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
$D^0 \to \pi^+\pi^-e^+e^-$	[✓]	✓	✓	✓	✓	✓
$D^0 \to K^+K^-e^+e^-$	[✓]	✓	✓	✓		

Background studies

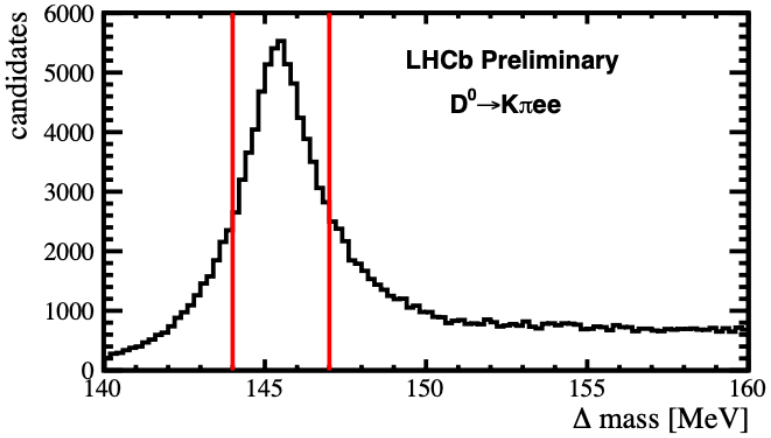
- There are two main backgrounds:
  - Combinatorial background, reduced with a multivariate analysis
  - Mis-identified backgrounds, reduced using particle identification (PID) variables:
    - Probability of mis-id two π as two e is on the order of 10^{-4}

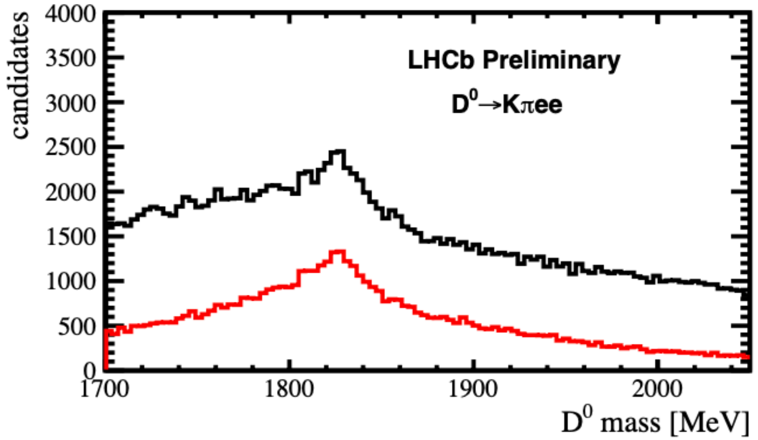


Signal and mis-id bkg	BF
$D^0 \to K^-\pi^+e^+e^-$	4×10^{-6}
$D^0 \to \pi^+\pi^-e^+e^-$	$\sim 10^{-6}$
$D^0 \to K^+K^-e^+e^-$	$\sim 10^{-7}$
$D^0 \to K^-\pi^+\pi^+\pi^-$	8×10^{-2}
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	8×10^{-3}
$D^0 \to K^+K^-\pi^+\pi^-$	2×10^{-3}

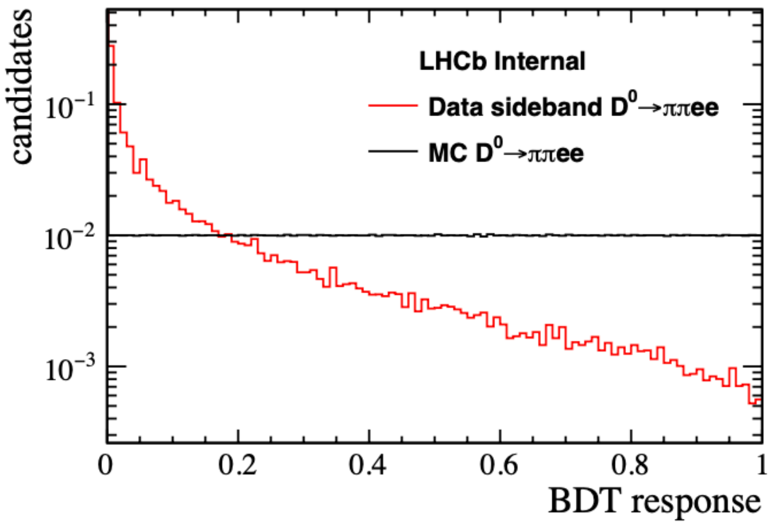
Combinatorial background

- Preselection cut on $\Delta m = \mathrm{m}(D^{*+} - D^0)$
- 3σ cut around Δm peak removes 80% of combinatorial background





- BDT trained separately for signal channels :
  - Signal proxy: MC signal samples
  - Background proxy: data samples in higher m(D) region (>1900 MeV/c^2)
  - Using topological and kinematical variables



Selection optimization

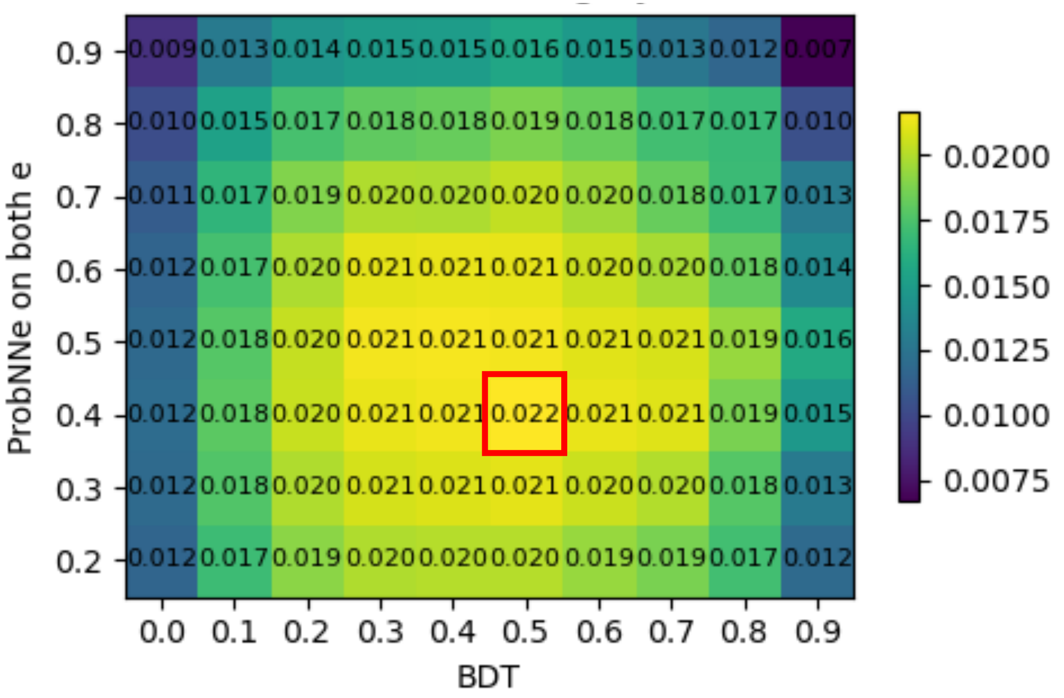
- The PID and BDT selection can be optimized maximizing the Punzi figure of merit:

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

[eConf C030908 (2003), MODT002]

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

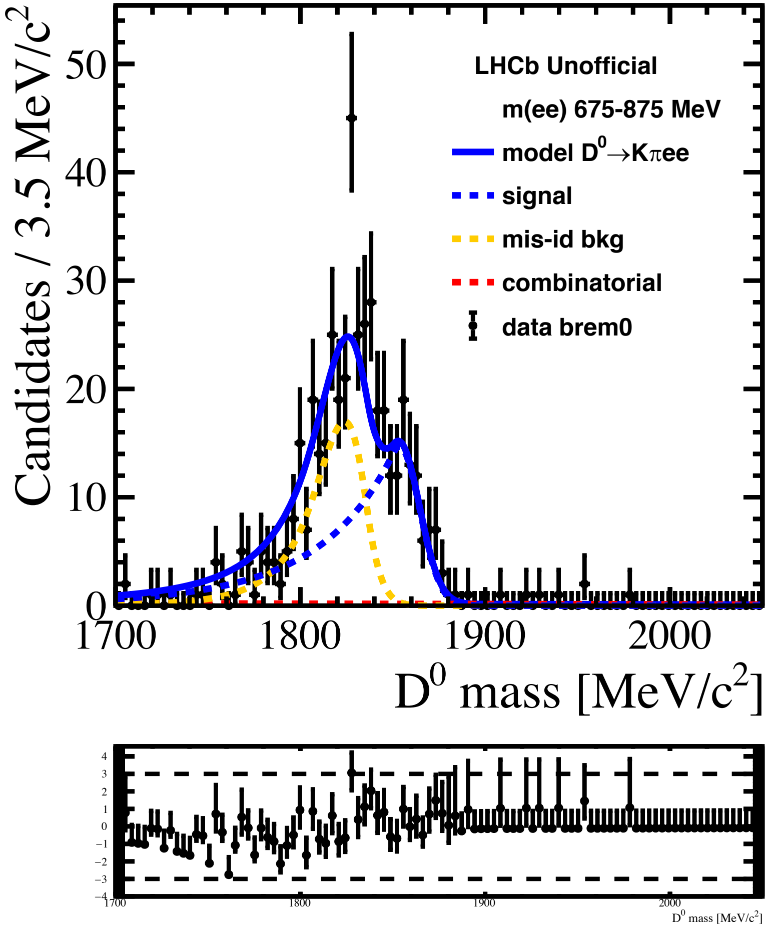
- Background yield composed of:
  - Combinatorial: extrapolated from the D^0 *high-mass* region
  - Mis-id: estimated from normalization channel

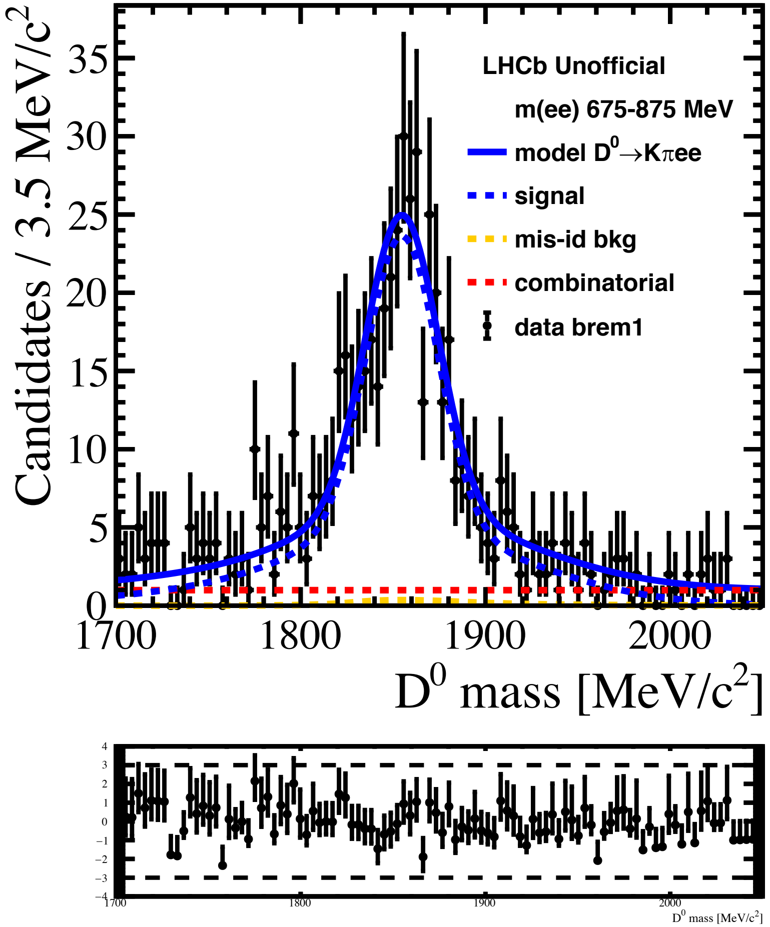


BDT vs PID FoM optimization

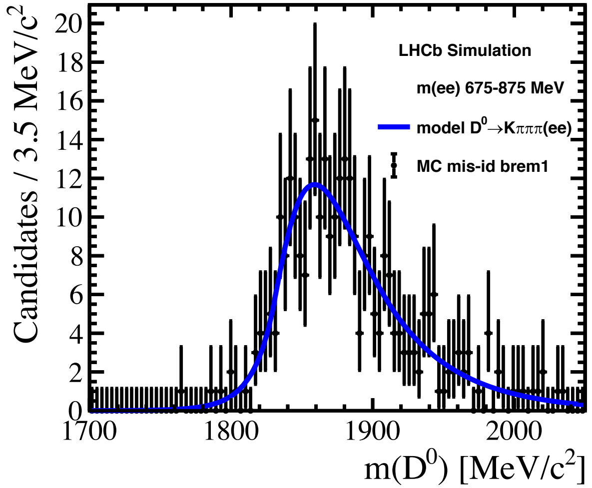
Fit on the normalization decay

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



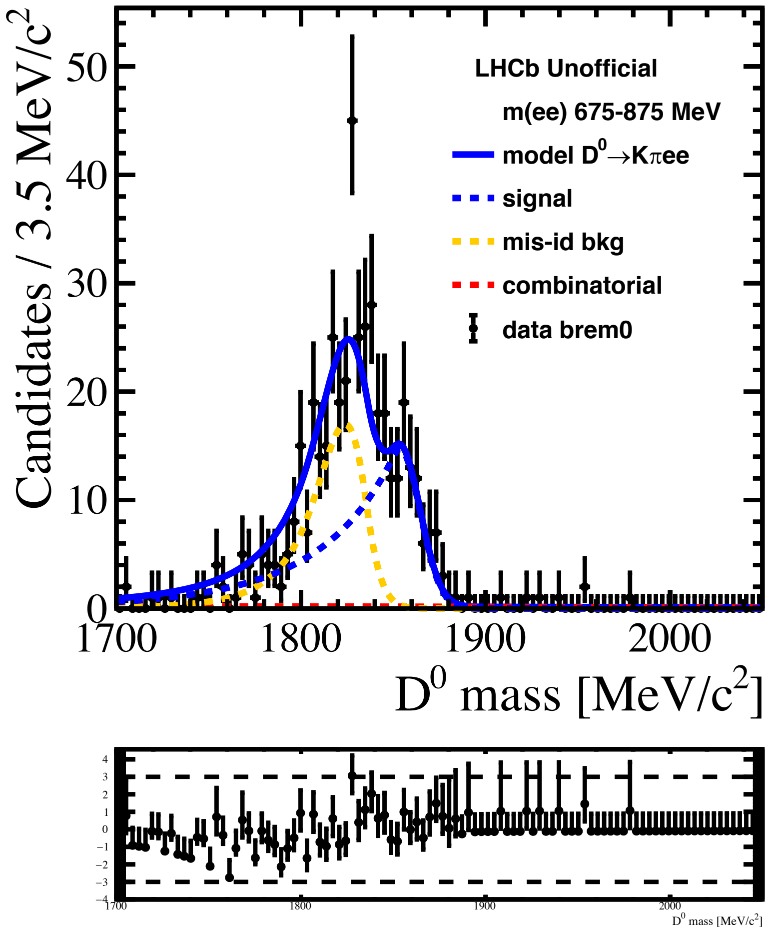


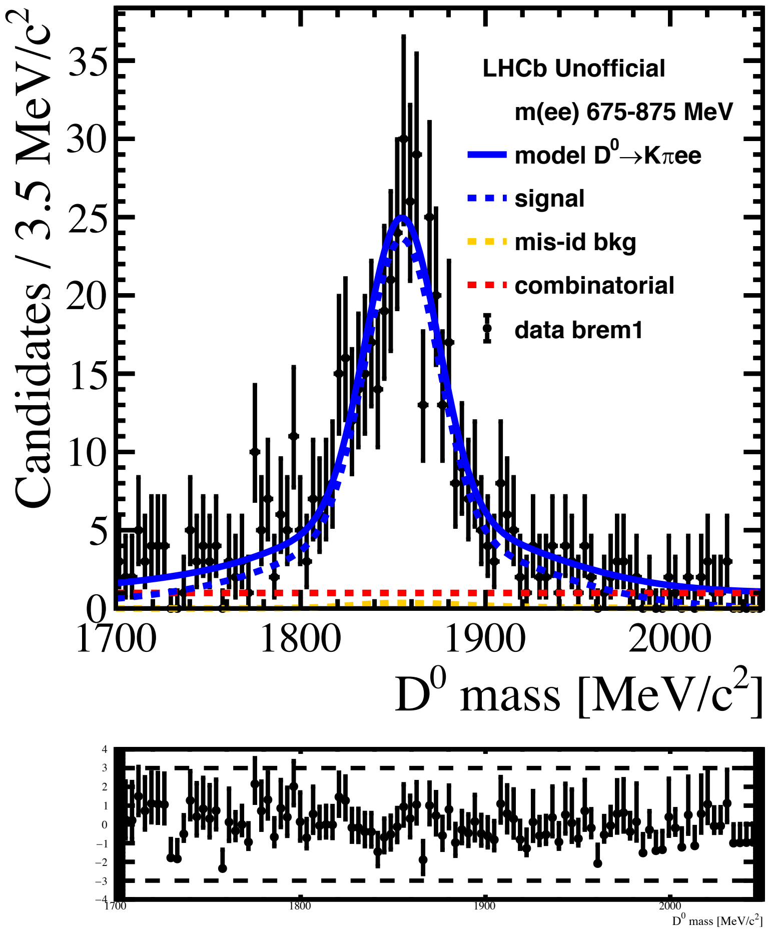
- The fit model:
  - **Signal** model from MC
  - **Mis-id** model from MC $D^0 \to K^-\pi^+\pi^+\pi^-$
  - **Combinatorial** from Data dM sideband
- Mis-id brem1 peaking under signal



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

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: TrackCalib tool for hadrons and electrons
  - PID: PIDGen tool resampling PID based on calibration samples
  - Trigger: TISTOS method for L0 and HLT1
  - m(ee) resolution: from data in different brem categories
  - Resonant model: estimated from $D^0 \to h^+h^-\mu^+\mu^-$ data analysis

Systematics

- List of systematics:
  - Normalization channel BF → 13.7 %
  - Normalization yields
  - Fit model:
    - Signal PDF
    - Mis-id model and brem0-brem1 fraction
    - Combinatorial shape
  - Efficiency ratio:
    - Tracking, PID and trigger
    - M(ee) resolution
    - Signal resonances MC model
    - Kinematics reweighting

+ Systematic relative uncertainty

→ < 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:

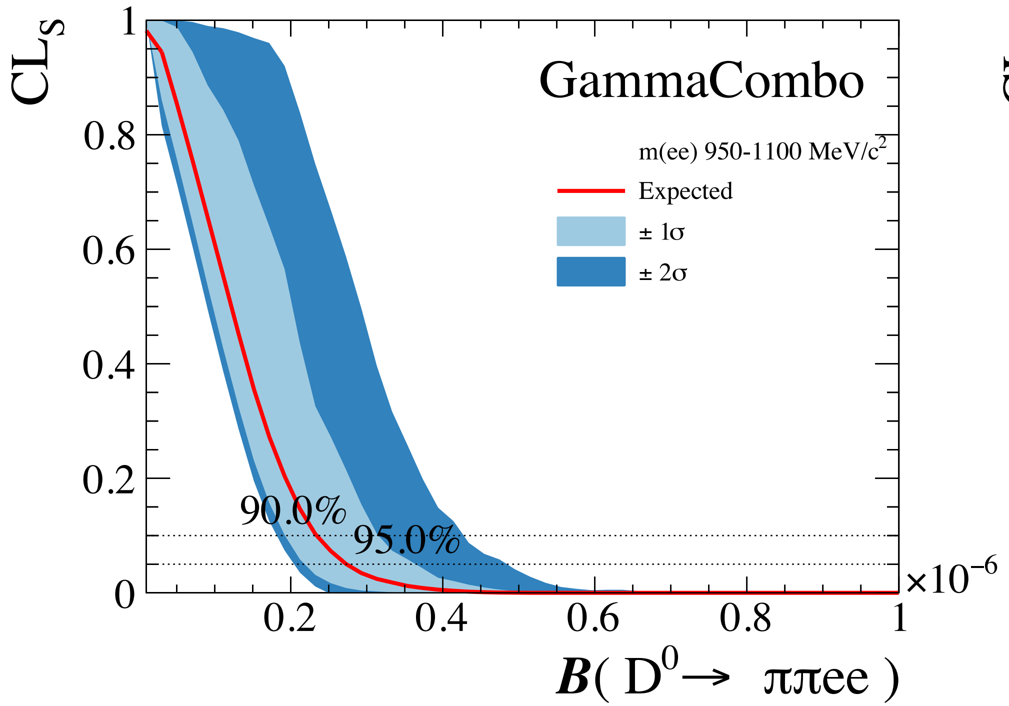
$$N_{sig,brem0} = N_{norm,brem0} \cdot \frac{\epsilon_{sig,brem0}}{\epsilon_{norm,brem0}} \cdot \frac{BF_{sig}}{BF_{norm}}$$

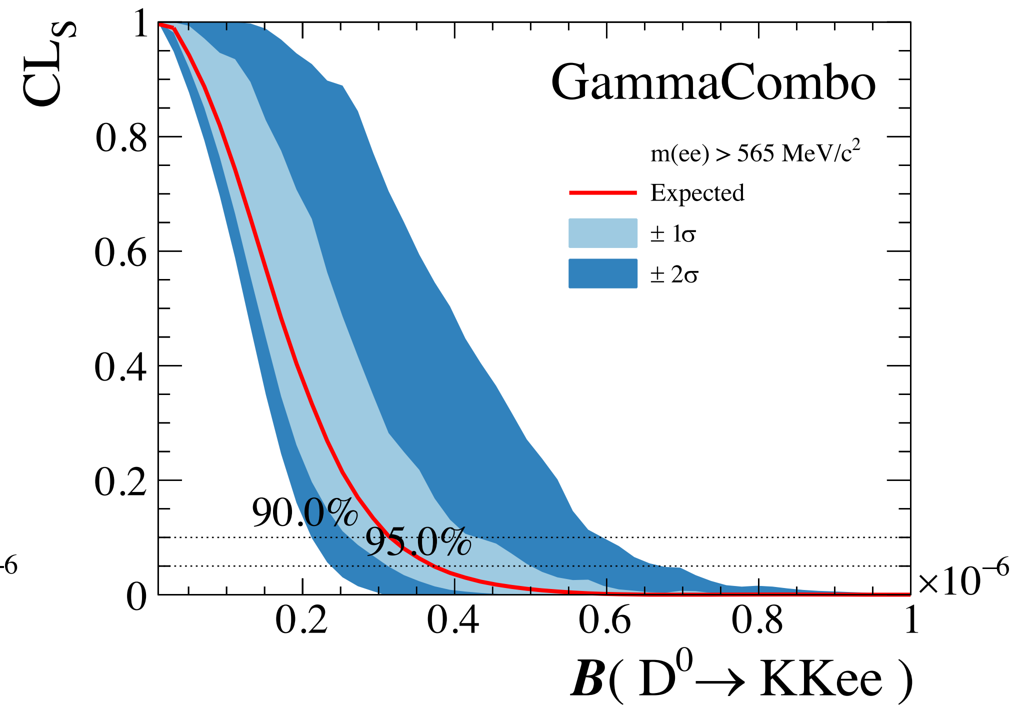
$$N_{sig,brem1} = N_{norm,brem1} \cdot \frac{\epsilon_{sig,brem1}}{\epsilon_{norm,brem1}} \cdot \frac{BF_{sig}}{BF_{norm}}$$

- 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}





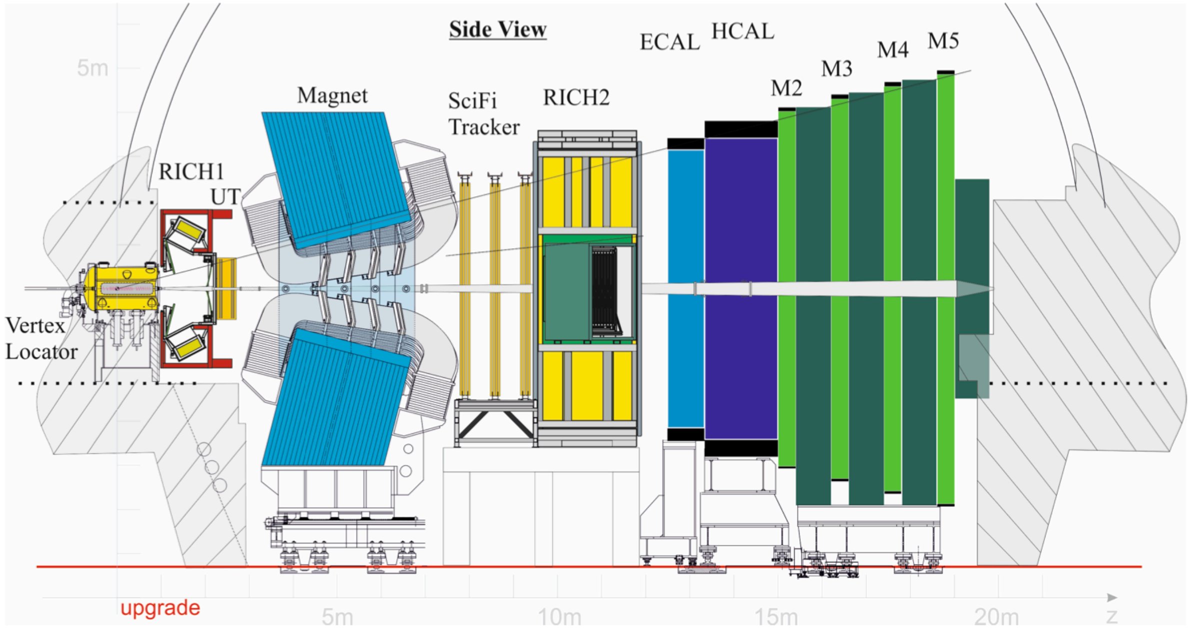
$D^0 \to h^+h^-e^+e^-$ and … beyond

- First LHCb study on the $D^0 \to h^+h^-e^+e^-$ decays: sensitivity: ~ 10^{-7}
- Expecting to observe $D^0 \to \pi^+\pi^-e^+e^-$ and observe/set limit for $D^0 \to K^+K^-e^+e^-$
- Started internal LHCb WG review

For the future:

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

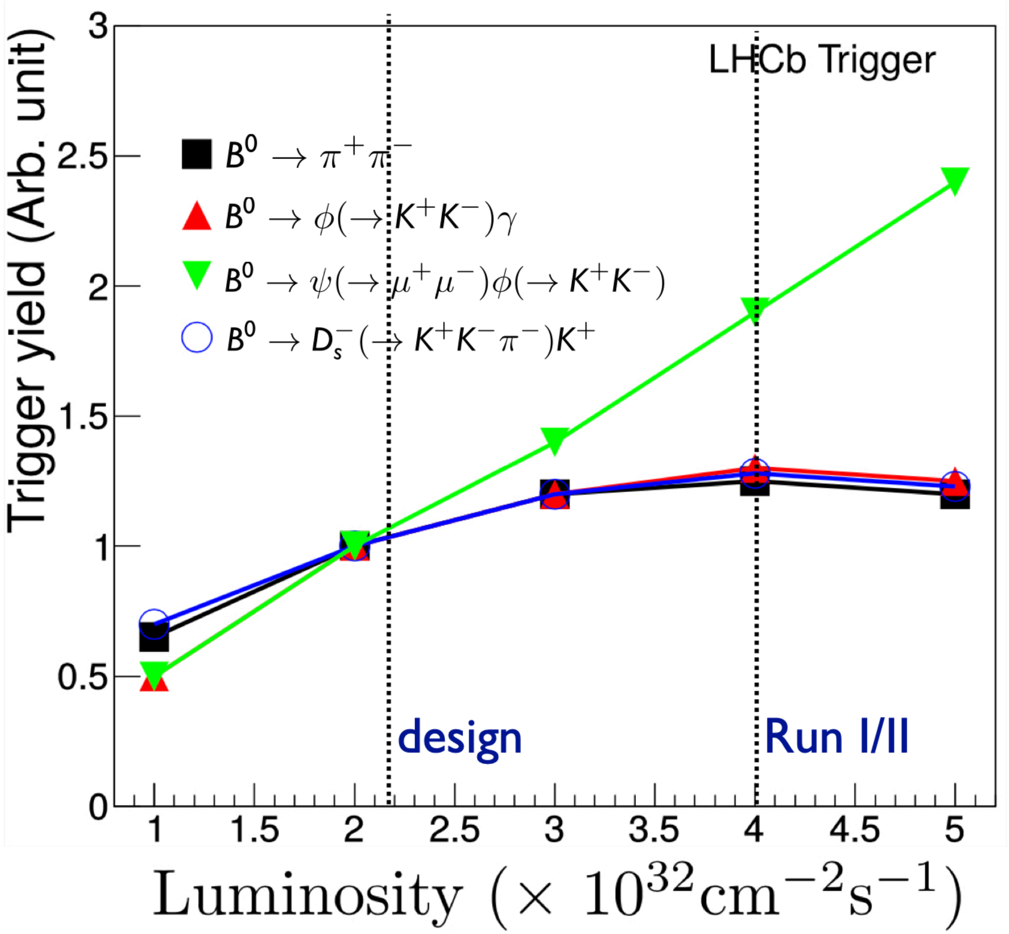
- Upgraded detector:
  - Luminosity increased by a factor 5:
  - $\mathcal{L} = 2 \cdot 10^{33}\, cm^{-2}s^{-1}$
  - Run3 and Run4: 30 fb^{-1} of data
  - Replacement of subdetectors and readout system



LHCb-TDR-12

Full software trigger

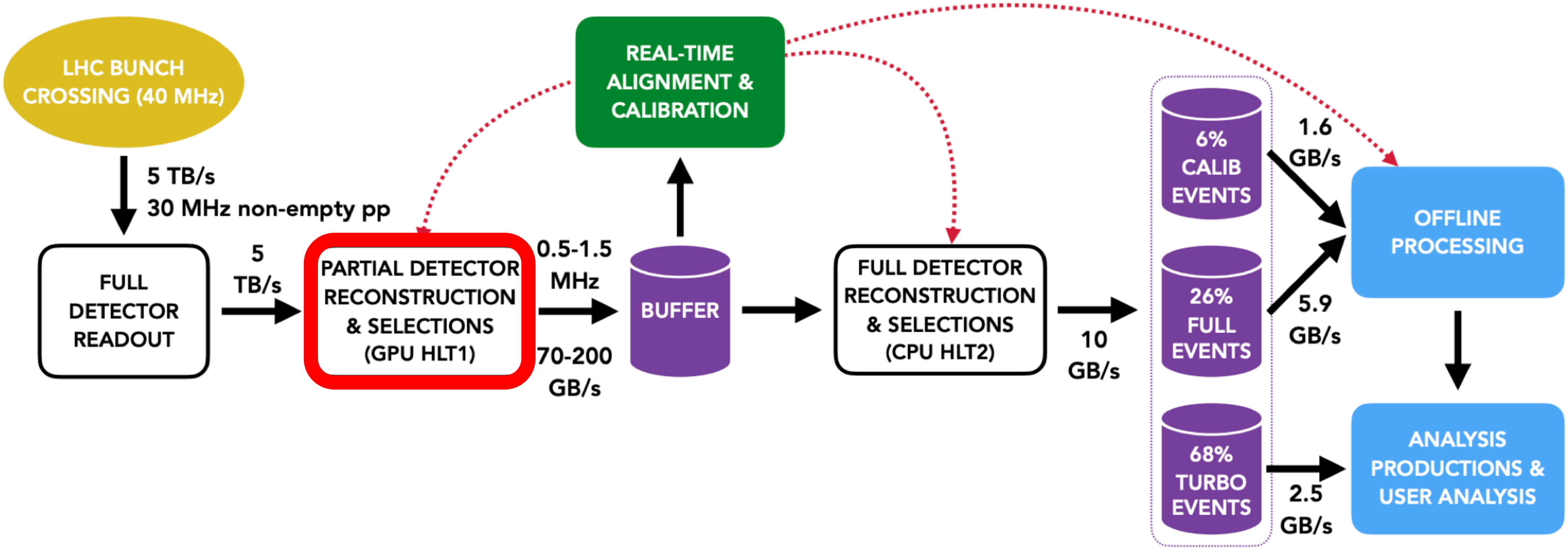
- Saturation of many hadronic channels already at Run2 luminosity
- Removing hardware trigger
- Full reconstruction of events at LHC rate of 30 MHz by a software-based trigger
- Increase of hadronic channels' triggering efficiency by a factor 2 to 4 wrt Run2
- Expected similar increase for electron modes



J. Phys.: Conf. Ser. **878** 012012

LHCb data flow

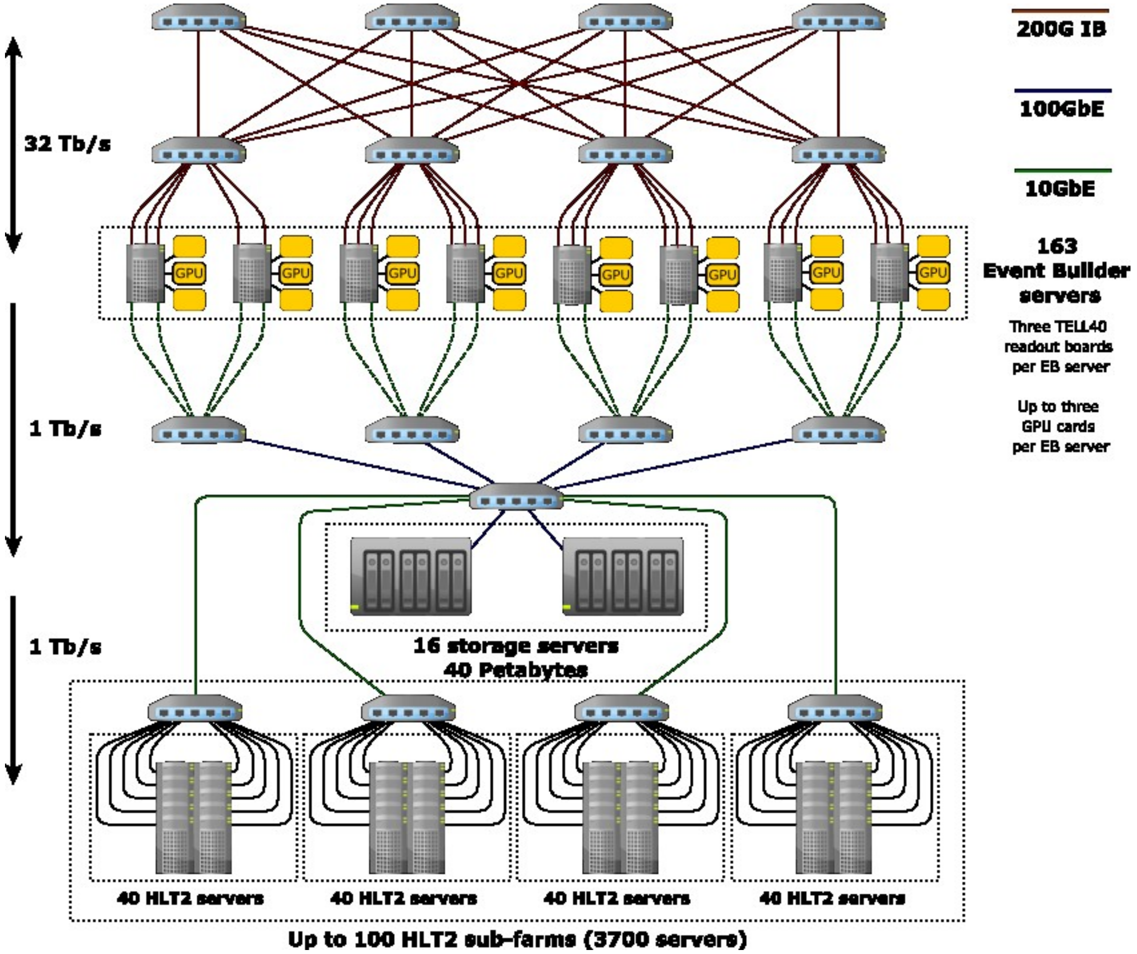
- HLT1 software reconstruction fully on Graphics Processing Units (GPUs) at non-empty pp collisions of 30 MHz rate



LHCB-FIGURE-2020-016

Why using GPUs?

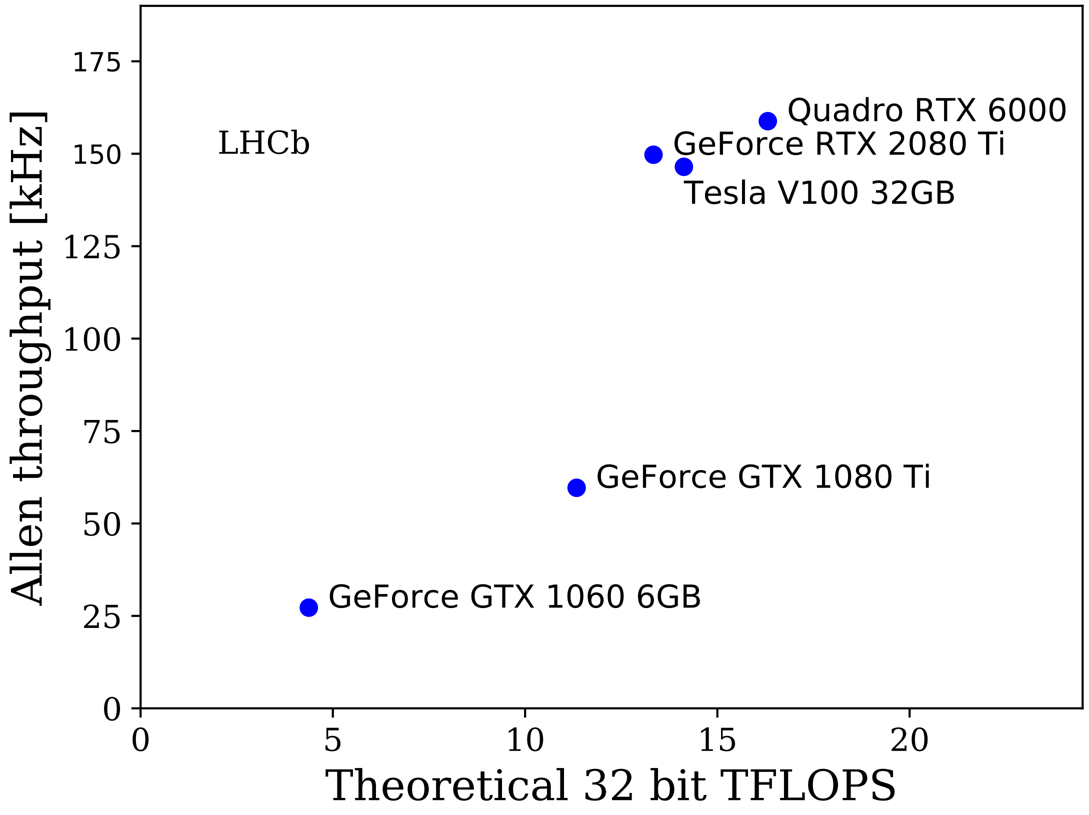
- Raw detectors info sent to a custom data processing centre
- FPGA cards receive data at average 32 Tb/s
- Event Builder (EB) CPU servers produce events packets
- EB servers contain slots to be used for up to 3 GPUs (zero overhead costs)
- Most of the HLT1 tasks naturally lend themselves to a very high degree of parallelism



[Comput.Softw.Big Sci. 6 (2022) 1, 1]

Why using GPUs?

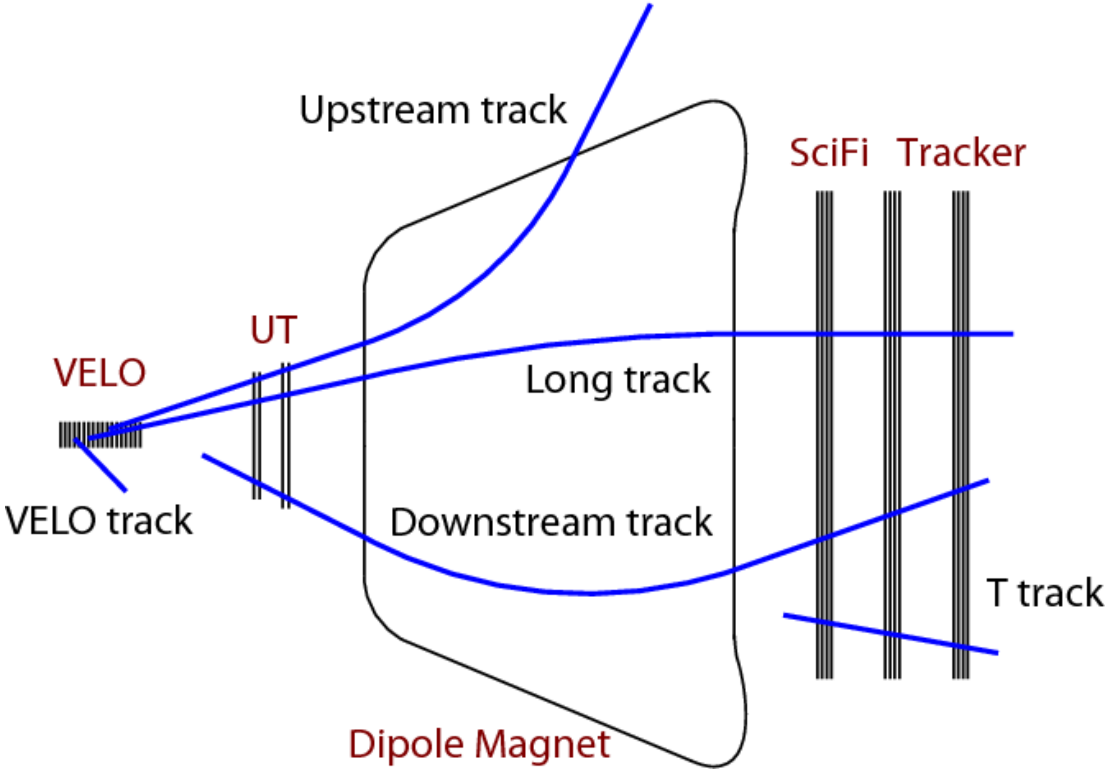
- Allen project
- Promising for the future:
  - Throughput scales linearly as a function of the theoretical peak 32-bit FLOPS performance
  - Higher luminosity can be handled by improved GPU technology (no saturation expected)



LHCB-FIGURE-2020-014

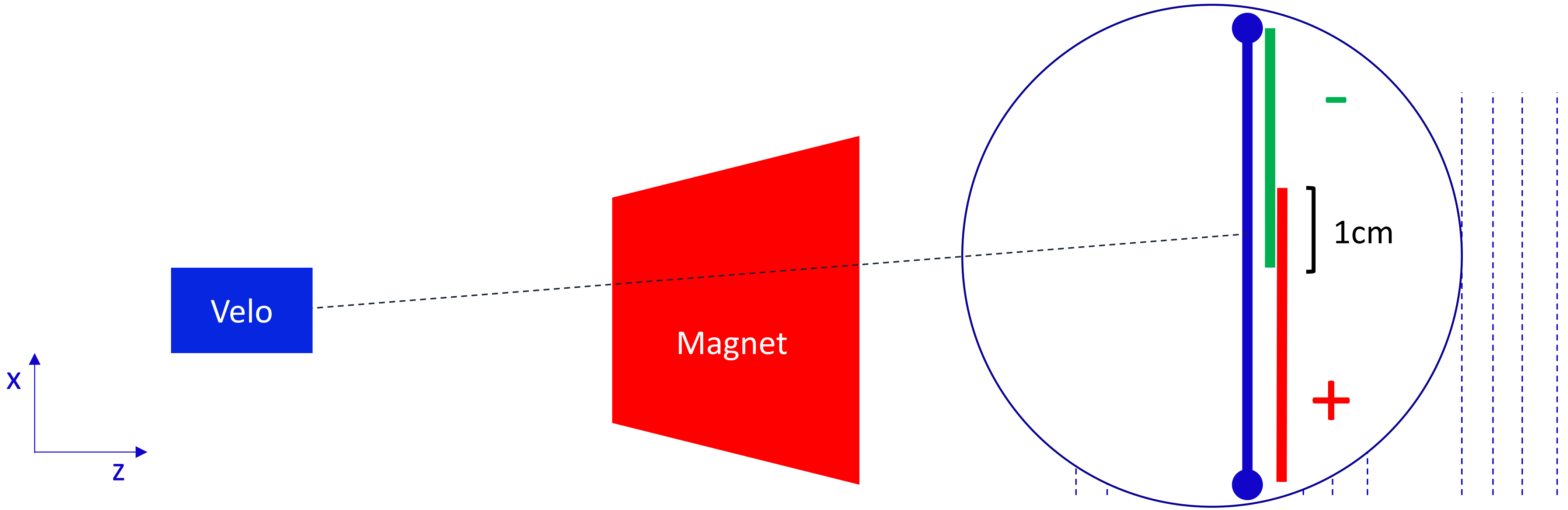
HLT1 heavily based on tracking

- HLT1 performs full upfront charged particle reconstruction
- For LHCb’s physics purposes, different types of tracks must be reconstructed
- Most of the trigger selections rely on long tracks looking high momentum and displaced signatures



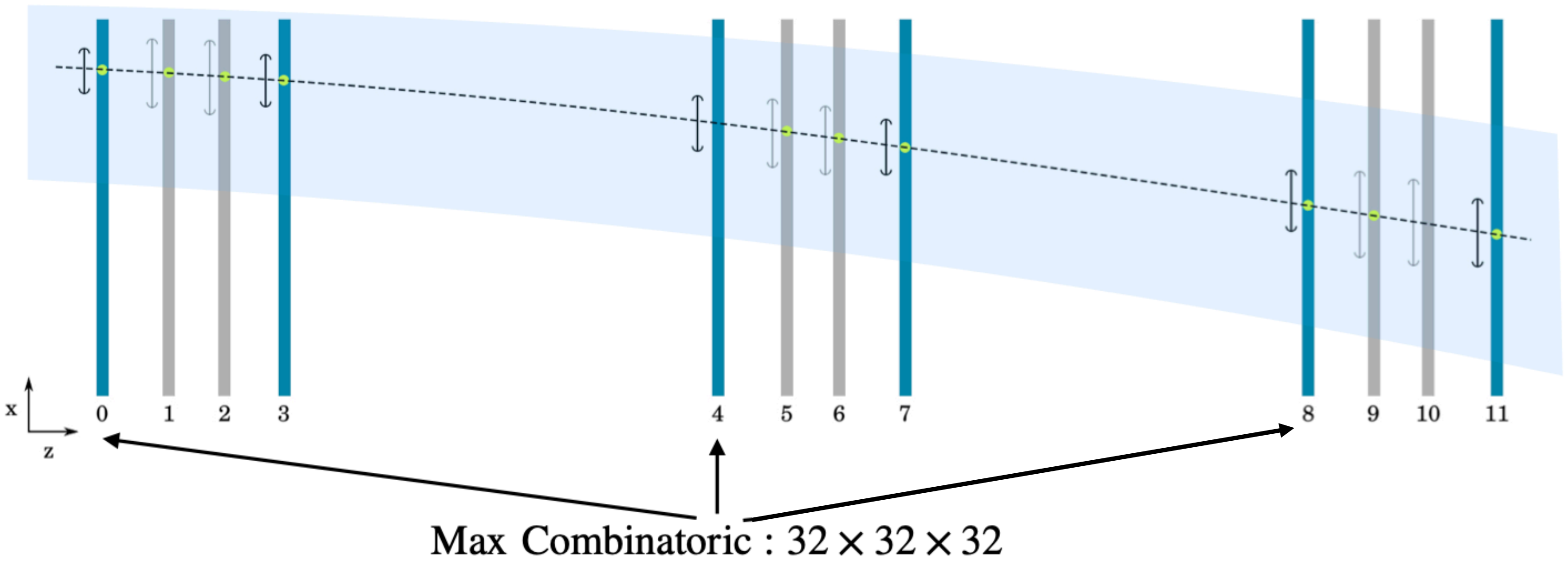
Forward tracking with no UT

- Reconstructing tracks without info from UT
- No momentum and particle charge information
- Double sided search window strategy for high momentum tracks (p > 5 GeV and pT > 1 GeV)



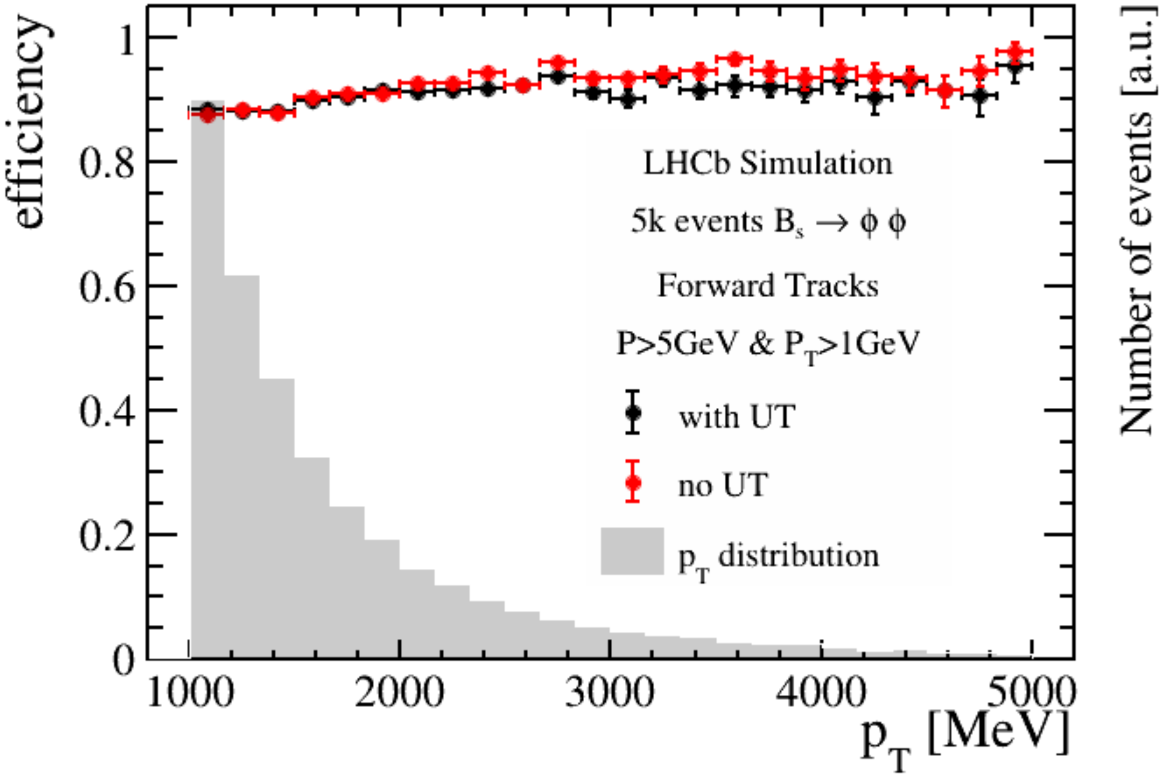
The HLT1 forward tracking algorithm

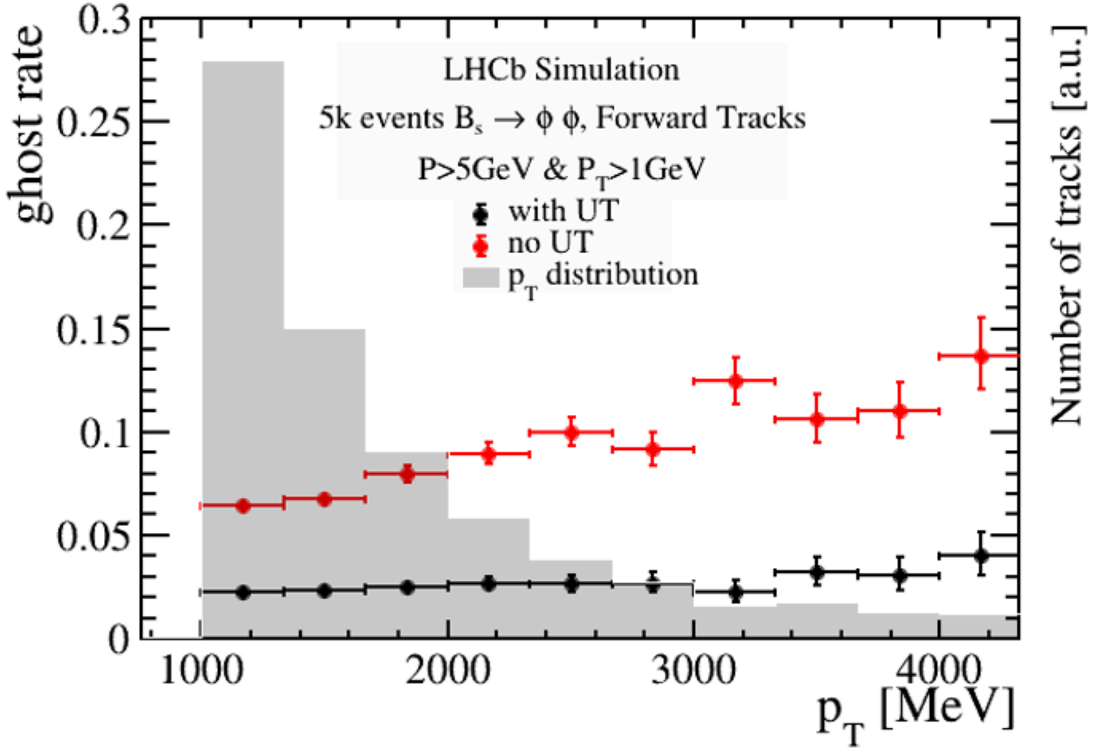
1. Opening search windows in all SciFi layers
2. Build triplets from first (or last) x layers in each T station (64 hits per layer)
3. Try to add to each triplet the other 3 x hits and 6 uv hits
4. Build χ^2 quality factor for each candidate (min 9 hits required)



Forward tracking no UT performance

- Obtaining same physics efficiency as reconstruction with UT for high momentum tracks (with an increase in ghost rate)
- Keeping the throughput comparable

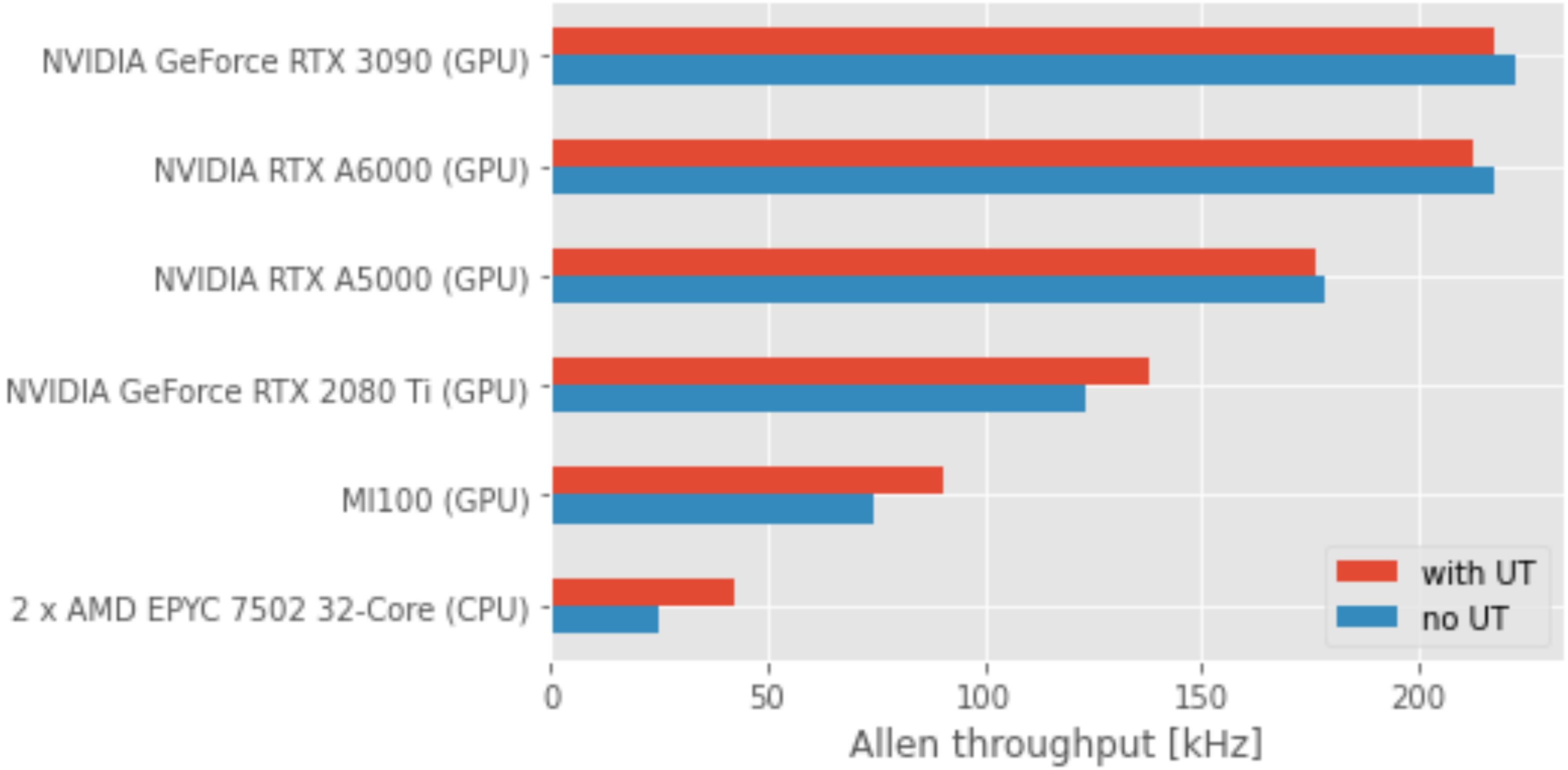




LHCb-FIGURE-2022-007

Throughput

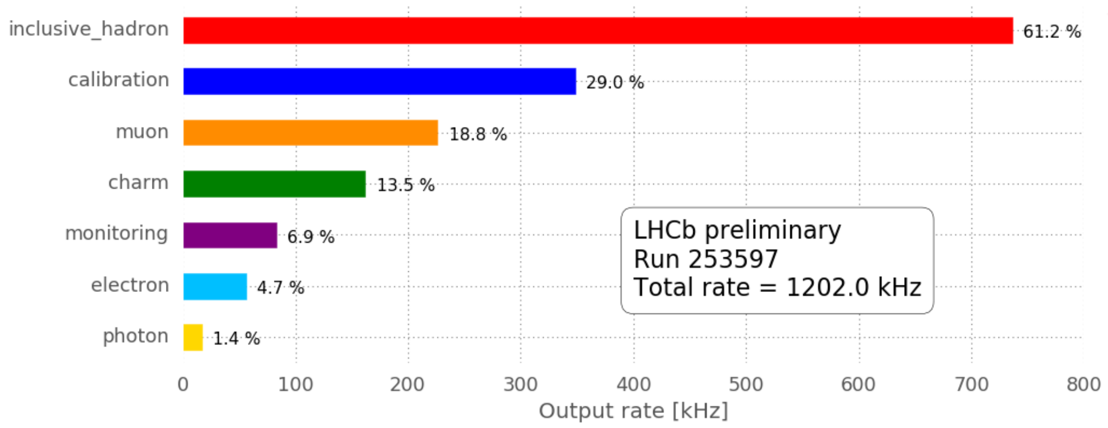
- HLT1 throughput measurement on different GPU cards
- RTX A5000 as default
- Full input rate can be processed with ~150-200 GPUs out of 500 available slots:
  - Very promising for the future!

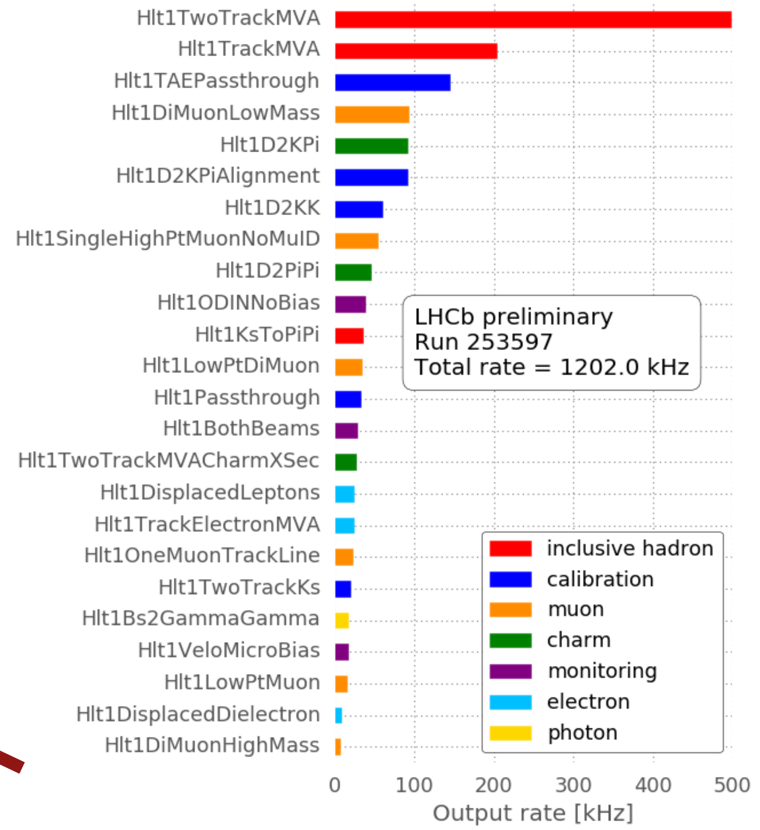


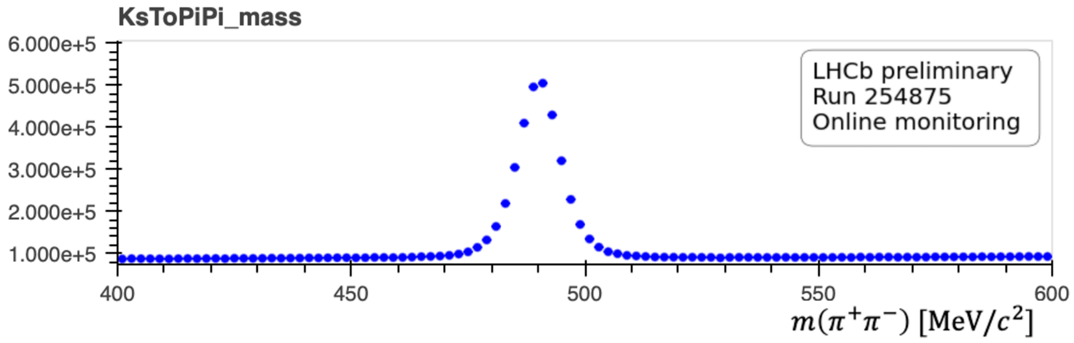
LHCb-FIGURE-2022-007

2022 data taking

- HLT1 selections with 2022 data
- One of the first Run3 mass peaks in the monitoring of HLT1







First 2022 mass peak!

Conclusions

- Rare Charm decays: first LHCb study on the $D^0 \to h^+h^-e^+e^-$ decays
  - Analysis sensitivity: ~ 10^{-7}
  - Expecting to observe $D^0 \to \pi^+\pi^-e^+e^-$ and observe/set limit for $D^0 \to K^+K^-e^+e^-$
  - Future: LFU tests with muons, CP and angular asymmetries, …
  - Upgrade needed, main limitation hardware trigger
- Fully software trigger in Run3:
  - HLT1 reconstruction at 30 MHz
  - Demanding task handled by GPUs
  - New tracking algorithm for long tracks with no UT information
  - Used for real data taking in 2022

Backup

Preselection

particle	Variable	$D^0 \to h^+h^-e^+e^-$
K, π	TRACKGhostProb	< 0.3
π_s	TRACKGhostProb	< 0.3
e	TRACKGhostProb	< 0.3
π	ProbNNpi	> 0.7
K	ProbNNK	> 0.7
D^0	IPχ^2	< 9
D^{*+}	CONE PT Asymmetry	> -0.4
D^{*+}	DTF χ^2	> 0
D^{*+}	DTF Δm	$> 144\,\mathrm{MeV}/c^2$
		$< 147\,\mathrm{MeV}/c^2$

Table 7: Preselection requirements.

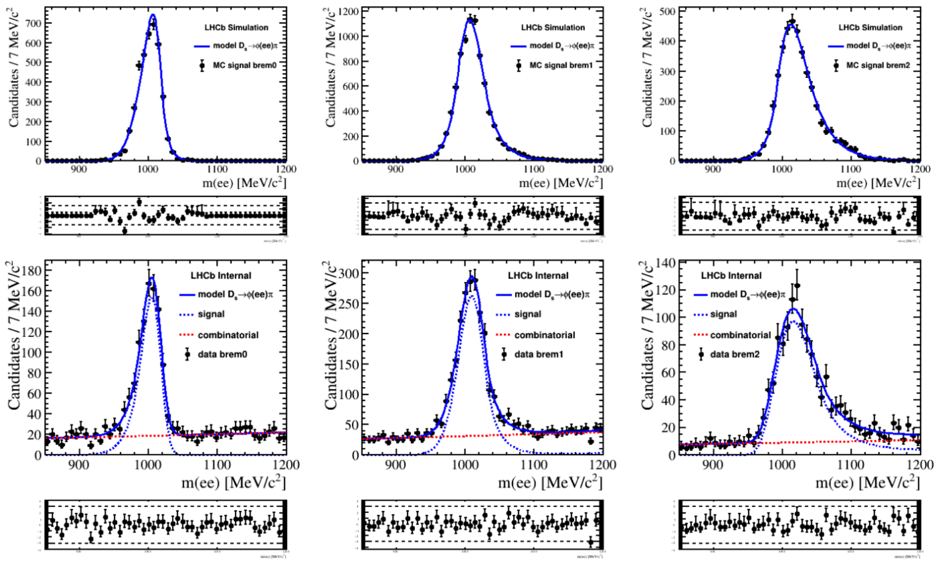
m(ee) resolution correction

- Standard procedure in the rare B decays analysis, fitting data and MC $J/\psi \to ee$ resonance from $B \to J/\psi K$ decays in different brem categories:

$$m_{smeared} = m_{true} + s_\sigma \cdot (m_{reco} - m_{true}) + (\mu_{data}^{fit} - \mu_{MC}^{fit}) + (1 - s_\sigma) \cdot (\mu_{MC}^{fit} - m(J/\psi)_{PDG})$$

With $s_\sigma = \sigma_{MC}/\sigma_{data}$ and $\mu_{MC-data}^{fit}$ respectively the mean from fit on MC and data

- The method on B decays is validated on charm decays using $D_s \to \varphi\pi$ and fitting the $\varphi \to ee$ resonance in MC and data



Resonance correction