CP violation in charm decays at LHCb

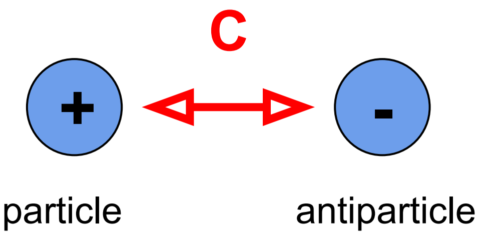
Giulia Tuci

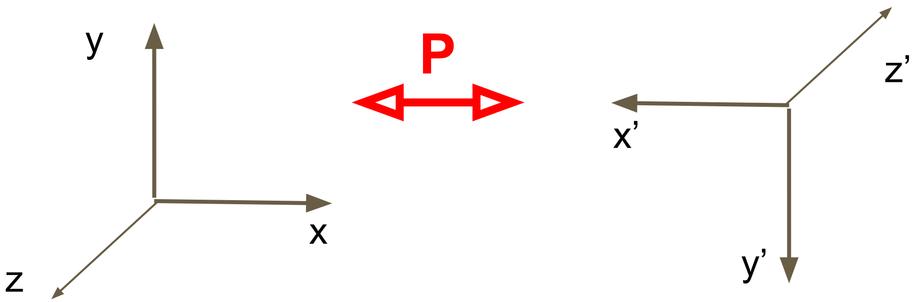
Supervisor: Prof. Giovanni Punzi

UNIVERSITÀ DI PISA

CP violation

- CP violation(CPV): non-invariance of physics law after the combined transformation of charge conjugation (C) and parity (P)





- In the Standard Model, CPV described by a complex phase **δ** in the CKM matrix (interaction between quark and $W^{\pm}$)

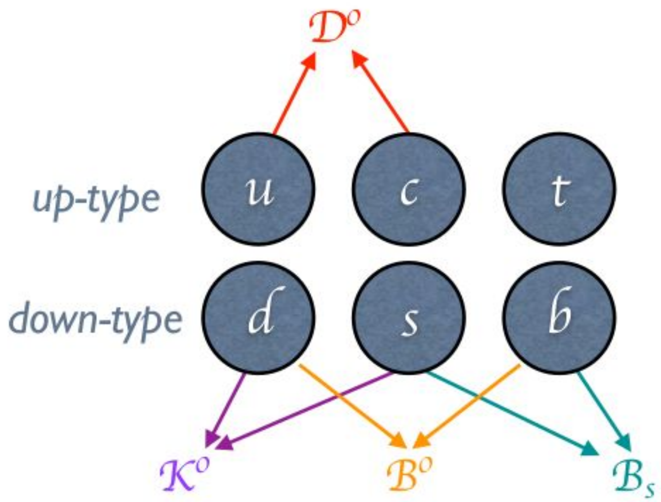
$$\mathcal{L}_{int}^{CC} = -\frac{g_2}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^{\mu} V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_{\mu}^{\dagger} + h.c.$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

3 real parameter and 1 complex phase **δ**

CPV in charm

- Charm transitions are a unique portal for obtaining a novel access to flavor dynamics
  - there might exist some New Physics coupling only to up-type quarks
  - expected CPV in charm $\lesssim 10^{-3} \rightarrow$ difficult to observe it experimentally



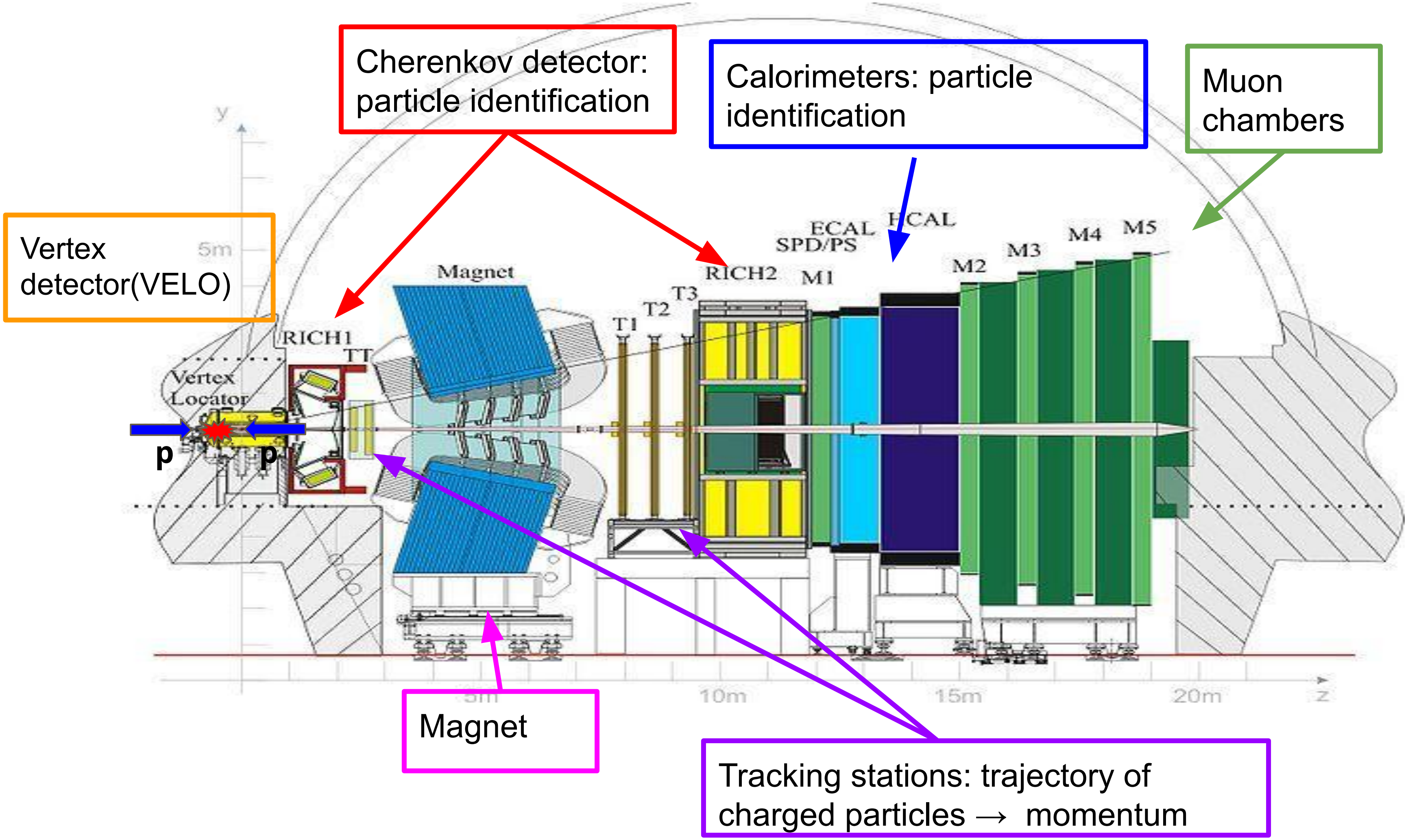
- **Finally CPV in charm has been observed!**
  - Observed by LHCb collaboration this year studying more than 60 million of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays
  - $A^{CP} = (18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})) \times 10^{-4}$ PRL 122 (2019) 211803
- Now it's time to start a systematic exploration of all the charm hadrons decay channels to do a quantitative study of CPV

Thesis goal

- **Expanding the phenomenology of charm CPV with new measurements, both from current data and near future**
- CPV in $D^0 \rightarrow K_S^0 K_S^0$ decays using 2017 and 2018 data collected by LHCb
- Development of an innovative hardware tracking device aimed at collecting even larger and better samples in the upcoming Run 3 (starting in 2021)

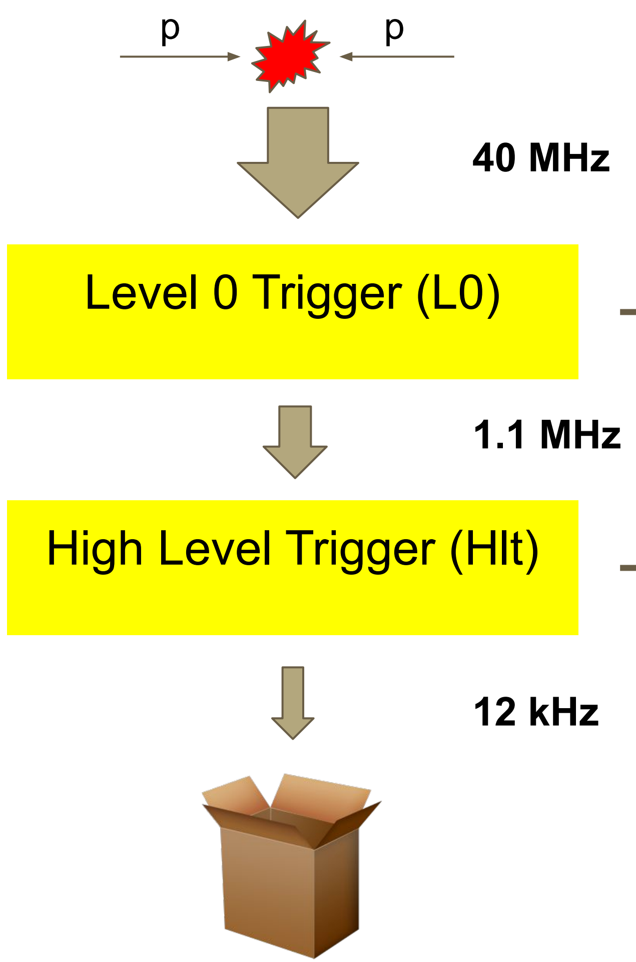
The LHCb experiment

- Single-arm forward spectrometer designed for the study of particles containing b or c quarks



The Run 2 LHCb trigger

❖ Trigger: select only interesting events to save them on disk



Hardware trigger: information from muon chambers and calorimeters

Software trigger: complete event reconstruction

- Hlt1: reconstruction of tracks in VELO
- Hlt2: reconstruction of tracks in all sub-detectors, particle identification

A^{CP} in $D^0 \rightarrow K_S^0 K_S^0$

- In $D^0 \rightarrow K_S^0 K_S^0$ decay channel amplitudes are suppressed

  → **A^{CP} could be enhanced at a level of ~1%** PRD 92 (2015) 054036

- Provides independent information on CPV: sensitive to a different mix of CP-violating amplitudes w.r.t. $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ PRD 85 (2012) 034036

B.R. $(D^0 \rightarrow K_S^0 K_S^0) = (1.8 \pm 0.4) \times 10^{-4}$

<u>Previous measurements</u>

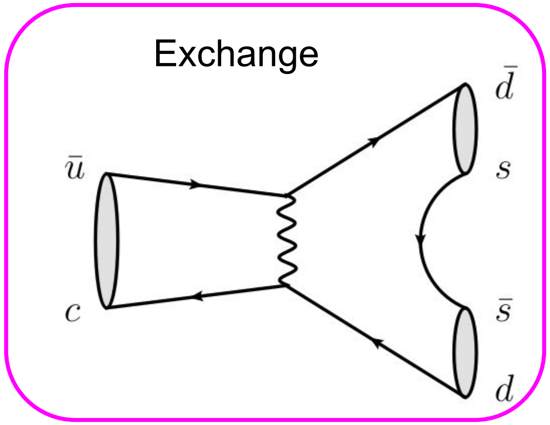
$\mathcal{A}^{CP}(K_S^0 K_S^0)(\%)$	Collaboration
-23 ± 19	CLEO
$-2.9 \pm 5.2 \pm 2.2$	LHCb Run 1
$0.02 \pm 1.53 \pm 0.17$	Belle
$4.3 \pm 3.4 \pm 1.0$	LHCb 2015+2016

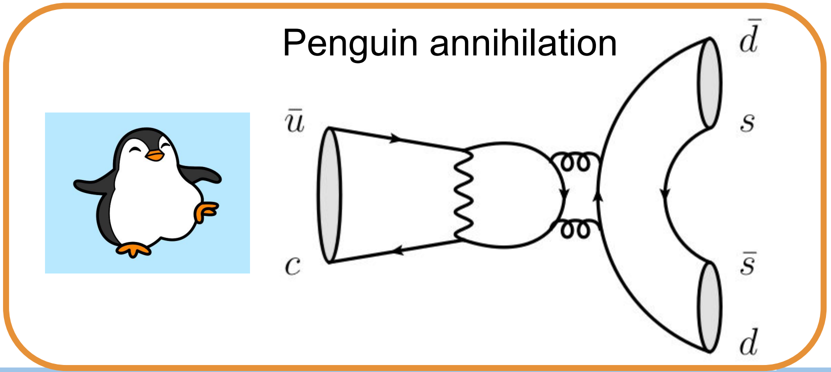
CLEO PRD 63 (2001) 071101

LHCb (Run1) JHEP 10 (2015) 055

LHCb (2015+2016) JHEP 11 (2018) 048

Belle PRL 119 (2017) 171801



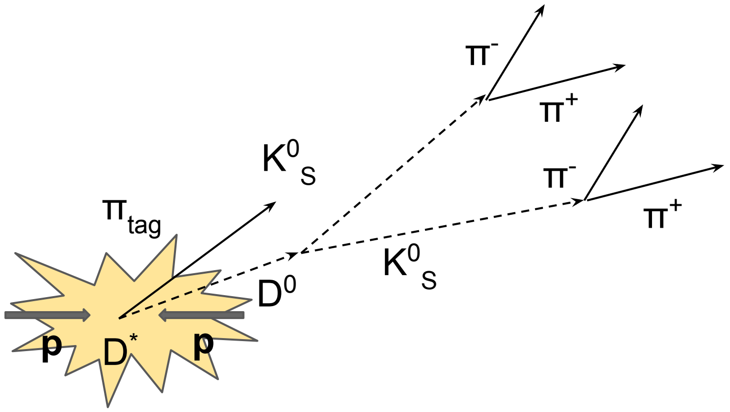


Measurement methodology

- Time-integrated measurement. Quantity that we want to measure:

$$\mathcal{A}^{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to f)}{\Gamma(D \to f) + \Gamma(\bar{D} \to f)}$$

- Quantity measured in LHCb → $\mathcal{A}^{raw} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$



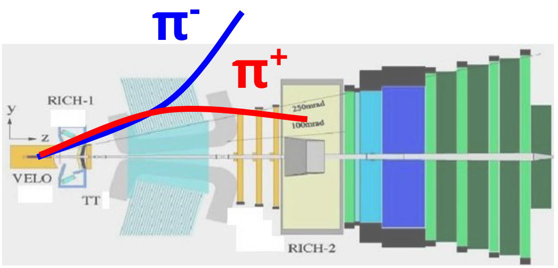
- $D^{*+} \to D^0\pi^+$ decay used to tag D^0
- K_S^0 reconstructed in the $\pi^+\pi^-$ final state

Measurement methodology (2)

Production asymmetry: initial state pp is not CP symmetric

$$\mathcal{A}^{raw} \approx \mathcal{A}^{CP} + \mathcal{A}^{prod} + \mathcal{A}^{det}$$

Asymmetric detector acceptance + material interaction different for particles/antiparticles



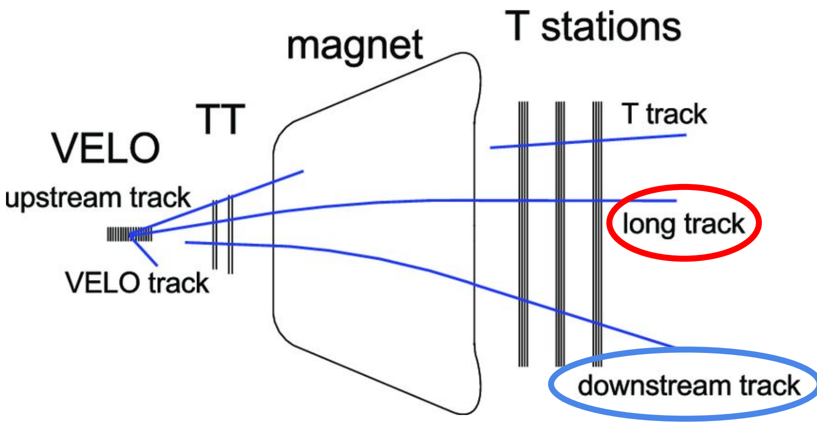
❖ To remove production and detection asymmetries $D^0 \rightarrow K^+K^-$ is used as a calibration channel ➡ $\mathbf{A^{CP}(K_S^0K_S^0) = \Delta A^{raw} + A^{CP}(K^+K^-)}$

Independently measured by LHCb on Run1 dataset with a precision of ~0.1% PLB767(2017)177

$D^0 \rightarrow K_S^0 K_S^0$ @ LHCb

- K_S^0 are difficult to select at trigger level
  - $\tau(K^0_S)$ = 0.9 x 10^{-10} s , $<\beta\gamma c\tau>$ ~ 200 cm
  - K_S^0 decays often outside vertex detector acceptance
  - No dedicated trigger in LHCb Run1
  - Great step forward made in Run2!

- Data samples collected in 2017-2018 (~3.9 fb^{-1})
  - **LL** sample: both K_S^0 reconstructed from **Long** tracks
  - **LD** sample: one K_S^0 is **Long** and the other one is **Downstream**
  - **DD** sample: both K_S^0 reconstructed from **Downstream** tracks (new: not present in 2015+2016!)

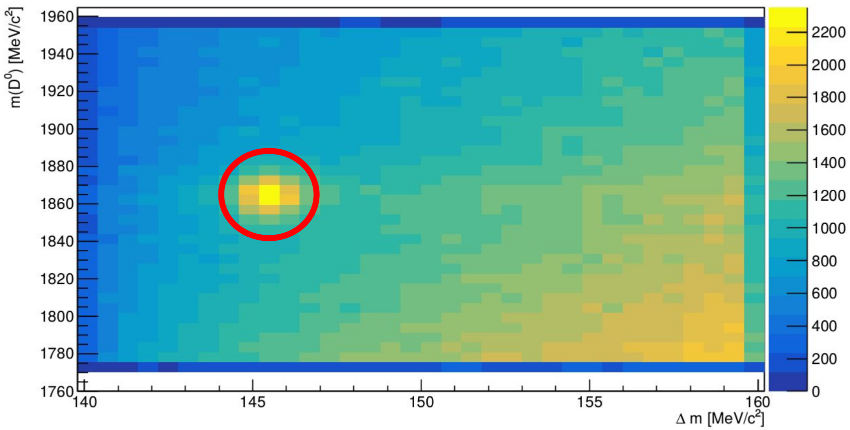


First look at the data

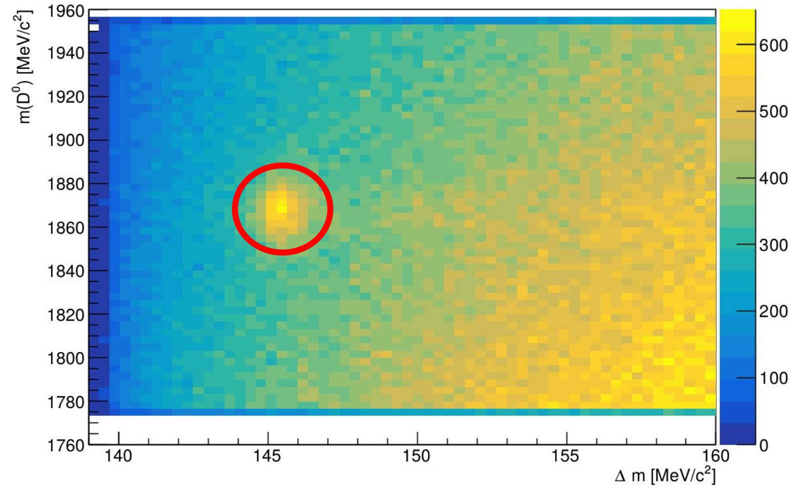
$\Delta m = m(D^{*\pm}) - m(D^0)$

= signal region

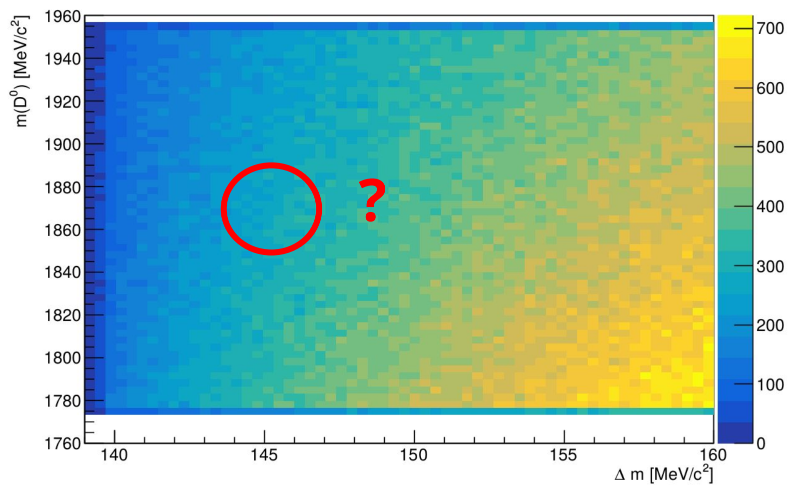
LL



LD



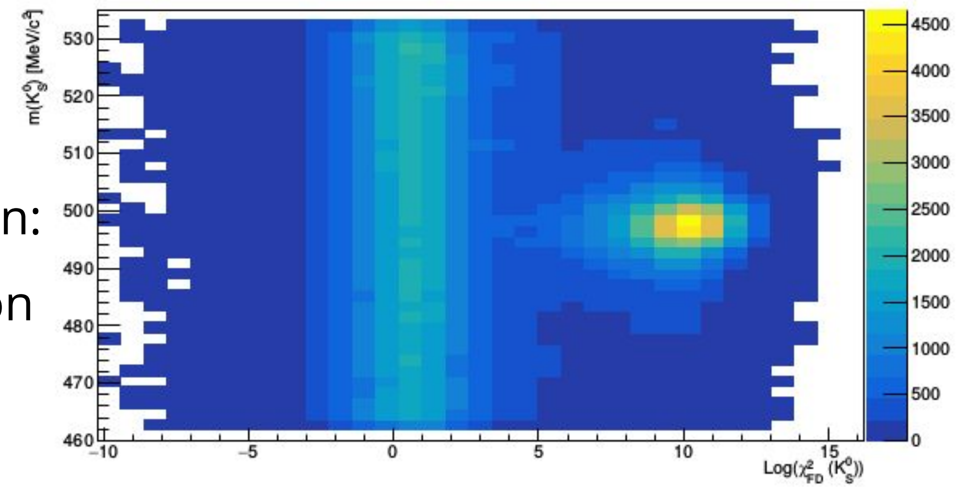
DD



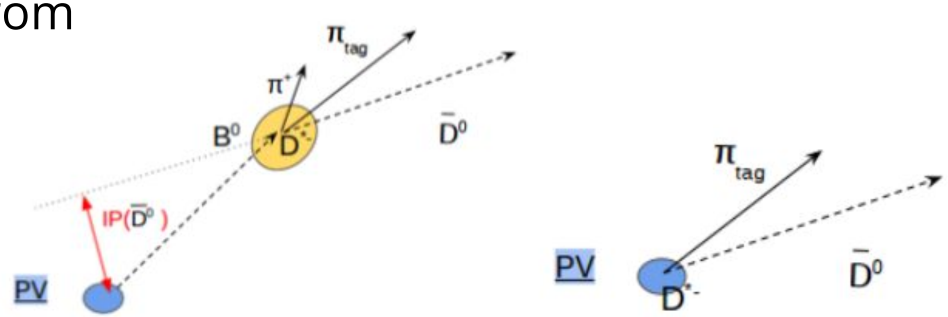
Main background sources

- To extract event
  → fit to $\Delta m = m(D^{*\pm}) - m(D^0)$

- Background peaking in Δm distribution:
  - **$D^0 \to K^0_S\pi^+\pi^-$** : reduced with cut on K^0_S flight distance



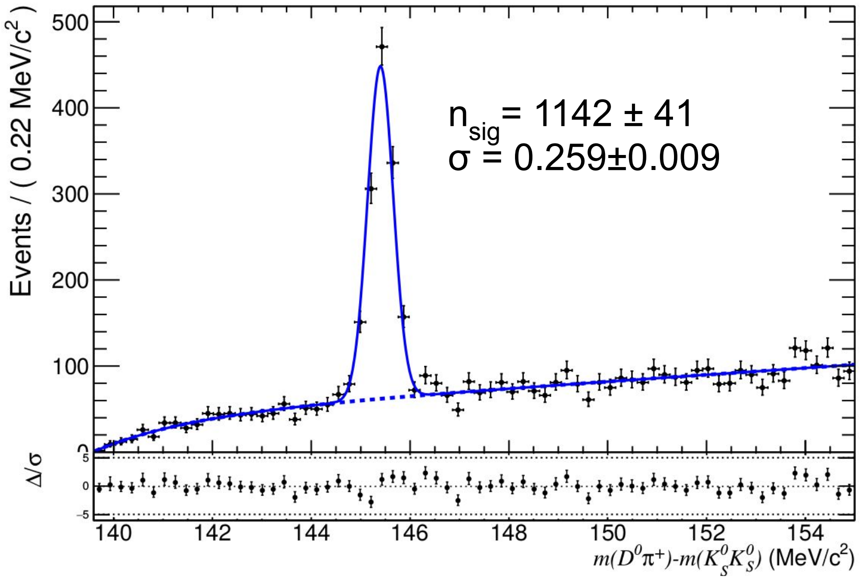
  - **Secondary decays**: D* coming from a b-hadron decay and not from primary interaction.
    Reduced with cuts on impact parameter.



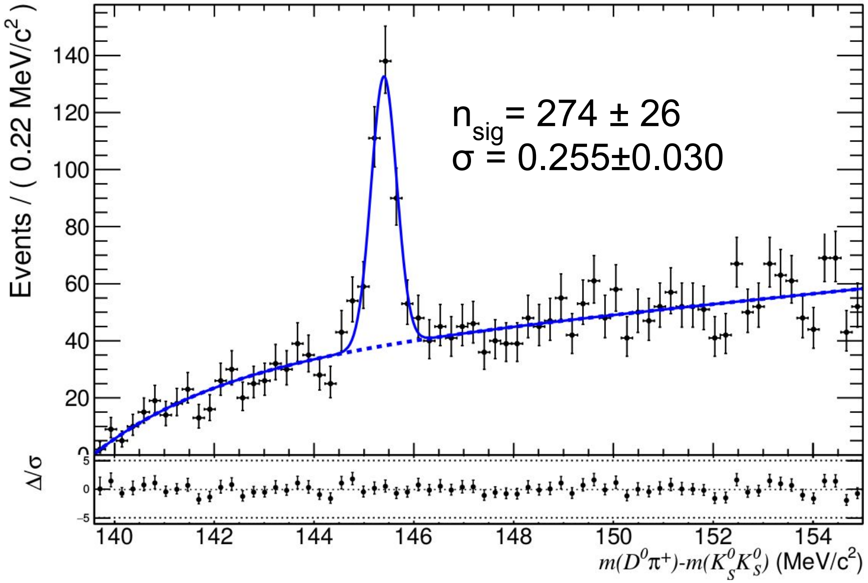
- **Combinatorial** background not peaking in Δm distribution
  - Reduced cutting on kinematic variables

Yields after selection (2017 data)

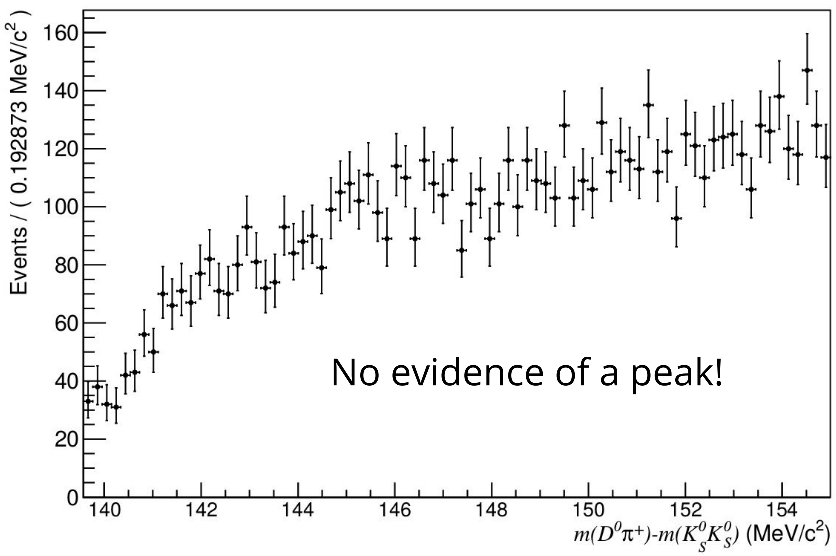
LL



LD

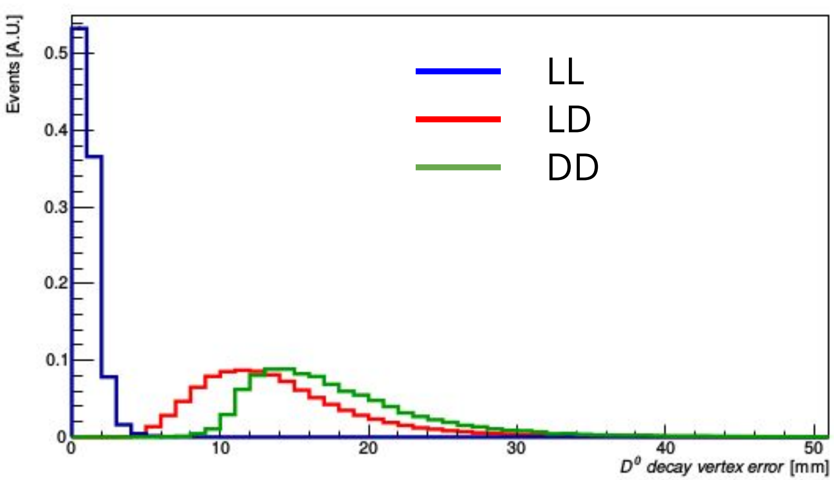


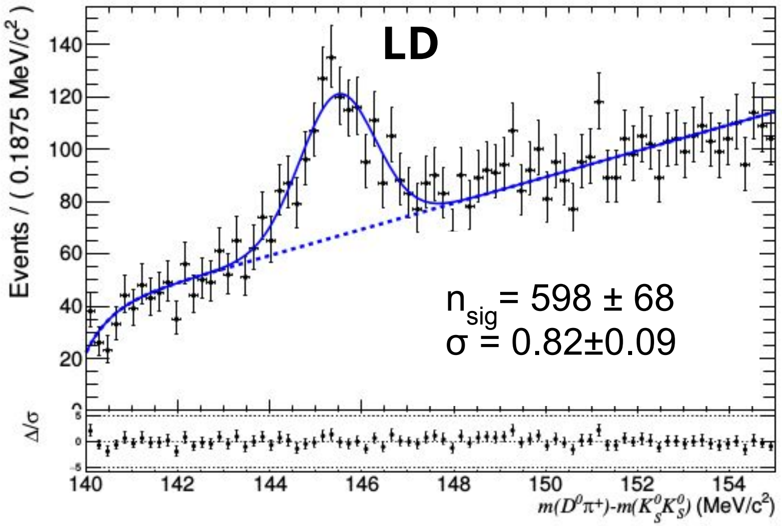
DD



A different selection approach

- Expected LD/LL ratio ~2, but observed one ~0.25 → why so small?
- $<\beta\gamma c\tau>$ of a b-hadron decaying into a D* and contaminating this sample is ~10 mm
  - Almost impossible to distinguish between primary and secondary decays in LD and DD sample
  - Cuts applied to remove secondary decays are likely to reduce also signal
- Idea: remove those cuts in the sample
  - Seems promising → possibility to double the signal in the sample, but need to take into account the possible bias introduced to the measured A^{CP} by secondary decays





Prospects with current data

- In 2017-2018: doubled 2015+2016 integrated luminosity
- Some improvements have been applied to the trigger
  - Now sensitive also to events where both K_S^0 are downstream!
- Investigating the possibility to re-optimise the selection w.r.t the presented analysis to gain more statistics
- **The final sensitivity from LHCb Run 2 is expected to be in the 1.6%–1.8% range**
- Interesting and feasible measurement that I plan to bring to publication as an outcome for my thesis, but it is not likely to show an effect yet
  - Very important to start focusing on Run 3 already and try to maximize the amount of charm that will be collected !

The Run 3 of LHCb

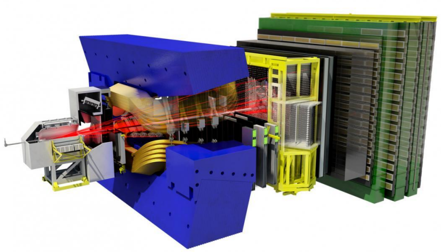
- New data will arrive in 2021 with an almost completely new detector and trigger system
  - ➢ Instantaneous luminosity will increase by a factor of 5 (2 x 10^{33} $cm^{-2}s^{-1}$)
  - ➢ Software reconstruction of tracks in real time at LHC crossing frequency (30 MHz on average)

- Because of the limited time-budget available, it is possible that some mitigation strategies need to be adopted
  - ➢ they will have a negative impact on the amount of charm samples collected and thus on the program of CPV measurements in the next run

Reconstruction of track candidates using FPGA

- Most of the computing time is being employed in highly repetitive and parallelizable track-reconstruction tasks
  - ➢ Idea: offload parts of these reconstruction to an FPGA-based system, operating in a pipeline before the events are loaded in the CPU farm

Data coming from detector



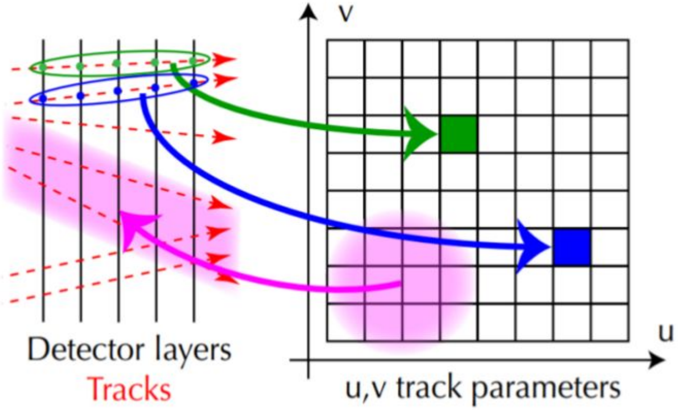
Track-reconstruction on FPGAs

Track candidates + list of hits

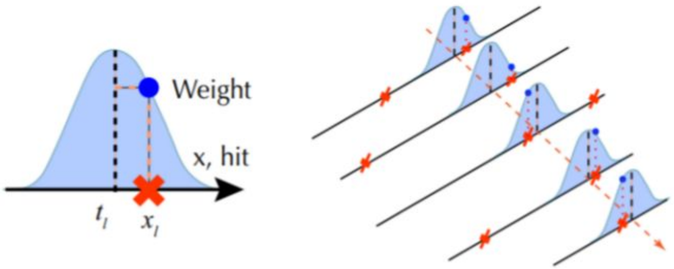
Remaining HLT1 sequence on CPUs (e.g. fitting,selections)

- Reconstruction of the VELO is the first step in the HLT1 sequence and it burns ~50% of the available CPU-time budget
  - ➢ I have been responsible for developing a standalone software emulator and using it to configure, optimize and evaluate the physics performance of the pattern recognition algorithm to be implemented in FPGA

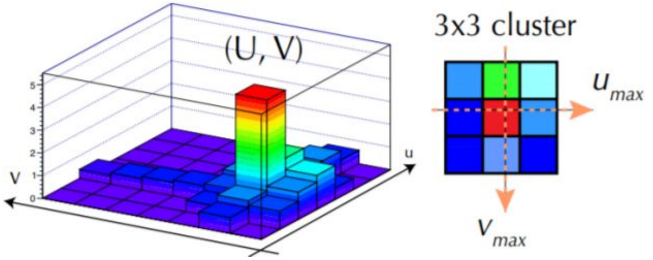
The "artificial retina" algorithm



Parameter space divided into cells.
Each cells correspond to a pattern.
Receptors: interception of pattern tracks with detector layers.



Distance hit- receptor is calculated.
A weight is assigned to each distance and for each cell all the weights are summed (excitation level)

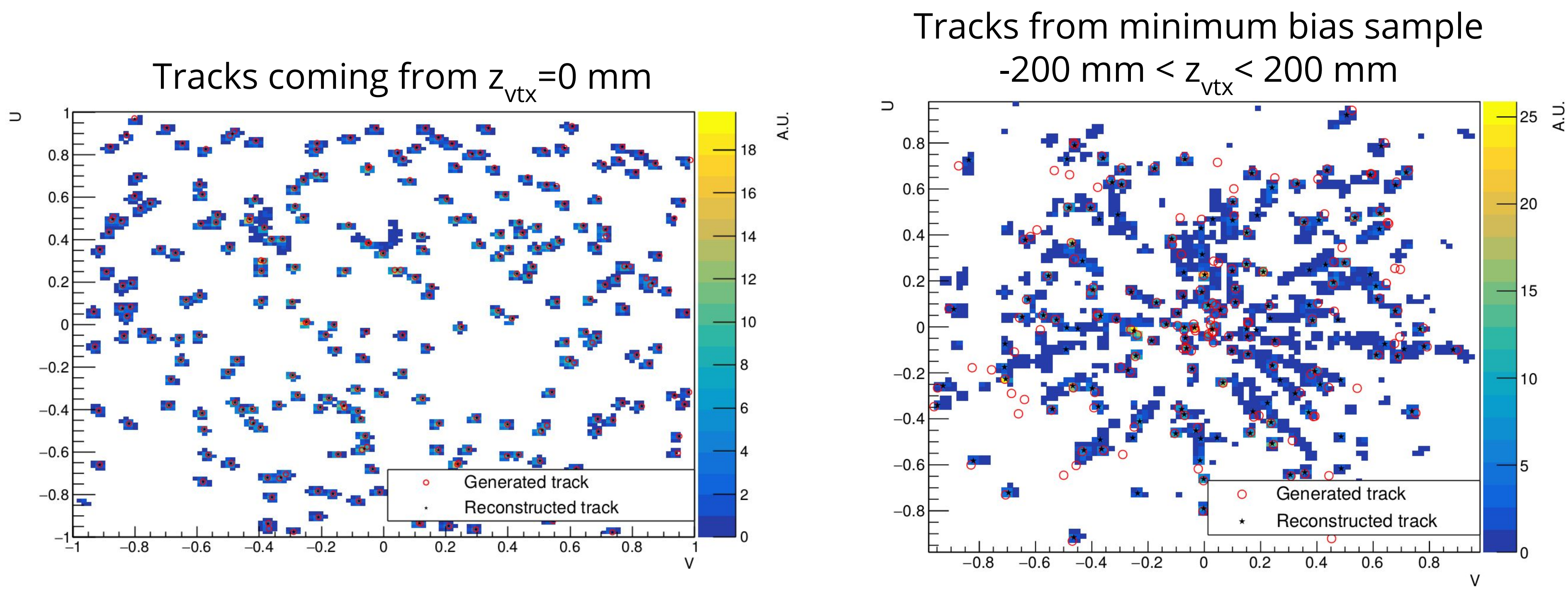


Search of local maxima over a threshold → reconstructed tracks

Everything is executed in parallel!

Distribution of excitation levels

- u,v are the x,y interception with a fixed layer

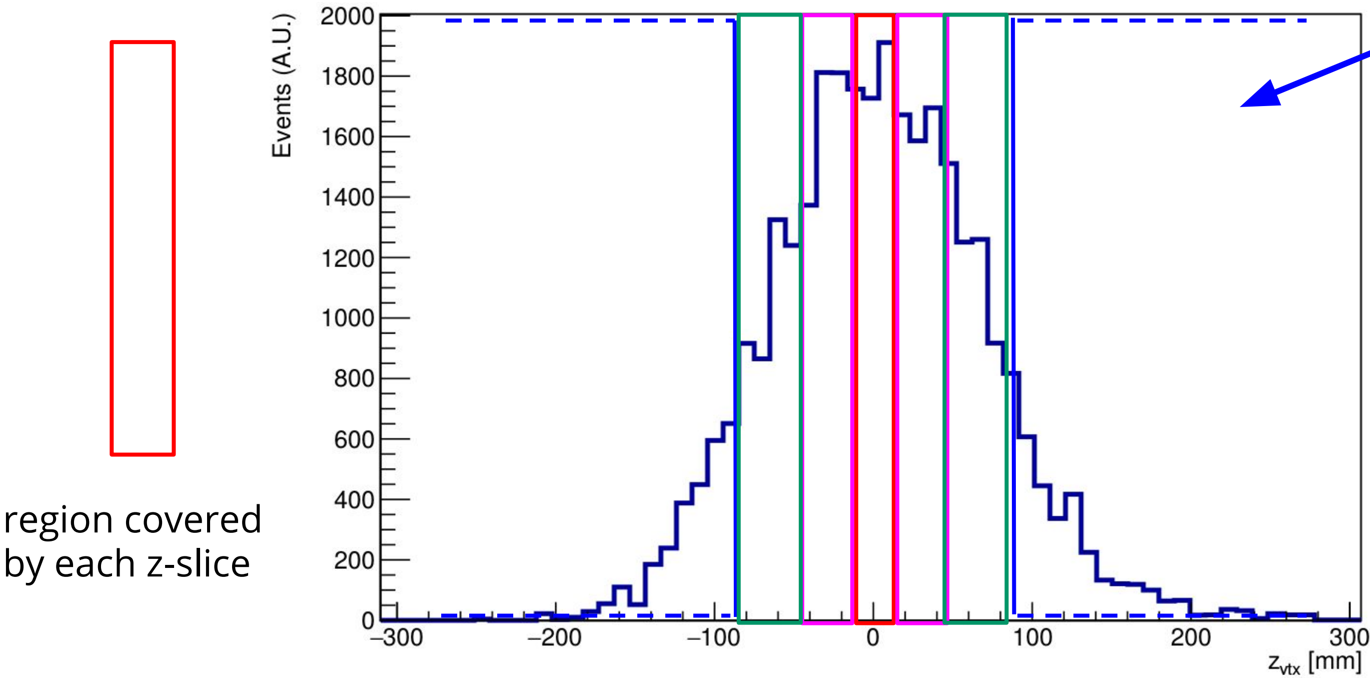


- Spread of z causes deformation of clusters → efficiency loss
- For this reason we use multiple retinas, segmenting along z
- Defined a fiducial region in which we expect the best performance
    - $2<\eta<5$, -15 cm < z_{vtx} < +15 cm

Currently used configuration

- 7 z-slices centered in: 12 cm, -7 cm , -3 cm, 0 cm, 3 cm, 7 cm, 12 cm

Distribution for generated reconstructible tracks from 1000 minimum bias events (1% of entries in overflow)



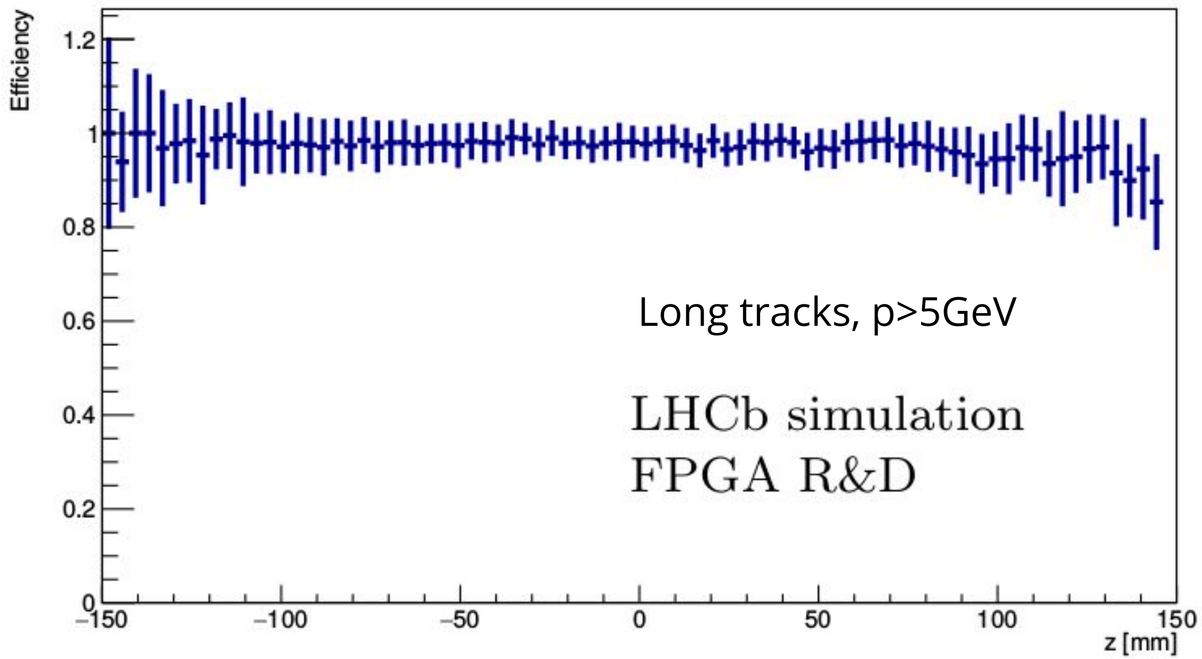
Performance obtained

- Performance obtained on 1000 $B_s \to \Phi\Phi$ simulated events (Run 3 luminosity)

Track type		CPU pat-reco (%)	FPGA pat-reco (%) all z	FPGA pat-reco (%) fiducial region	FPGA – CPU (%) all z	FPGA – CPU (%) fiducial region
Long with cut on p	ε	99.64 ± 0.03	95.25 ± 0.10	99.84 ± 0.02	-4.39 ± 0.10	$+0.20 \pm 0.03$
Long from b with cut on p	ε	99.34 ± 0.13	92.33 ± 0.44	99.66 ± 0.10	-7.01 ± 0.46	$+0.32 \pm 0.17$
Long from c with cut on p	ε	99.74 ± 0.25	93.84 ± 0.71	99.74 ± 0.16	-5.90 ± 0.75	$+0.00 \pm 0.30$

- **In the fiducial z region,** CPU and FPGA pat-reco **efficiencies are almost indistinguishable**
- However, integrating over all z, we are missing between 4% and 7% of tracks.
- → algorithm works very well, but with our 7 slices we are missing some acceptance, and we should redo the exercise with more/wider slices (and reoptimize cell size)

Performance obtained (2)



Summary

- CPV in $D^0 \rightarrow K_S^0 K_S^0$ decays using 2017 and 2018 data collected by LHCb
  - Preliminary selection applied to estimate yields in the sample
  - Alternative selection approach to maximize the number of signal events currently under study
  - Written all the code and routines necessary to extract the asymmetry
  - To do: finalize selection and evaluate systematics

Summary

- Development of an innovative hardware tracking device aimed at collecting even larger and better samples in the upcoming Run 3
  - Implemented a standalone software emulator and used it to configure, optimize and evaluate the physics performance of the pattern recognition algorithm to be implemented on FPGA
  - To do: fine-tune algorithm configuration to maximize performance

Backup slides

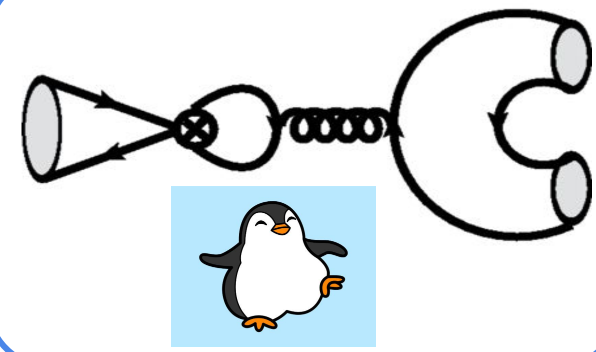
A^{CP} in $D^0 \rightarrow K_S^0 K_S^0$

$$\mathcal{A}^{\rm dir} = Im\frac{\lambda_b}{(\lambda_s - \lambda_d)} Im\frac{A_b}{A_{sd}}$$

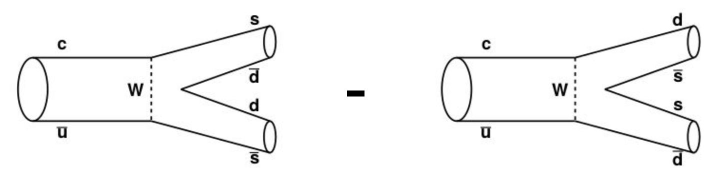
$$\lambda_q \equiv V_{cq}^* V_{uq}$$

$Im\frac{\lambda_b}{(\lambda_s - \lambda_d)}$: ~6 x 10^{-4}

A_b ← inputs to

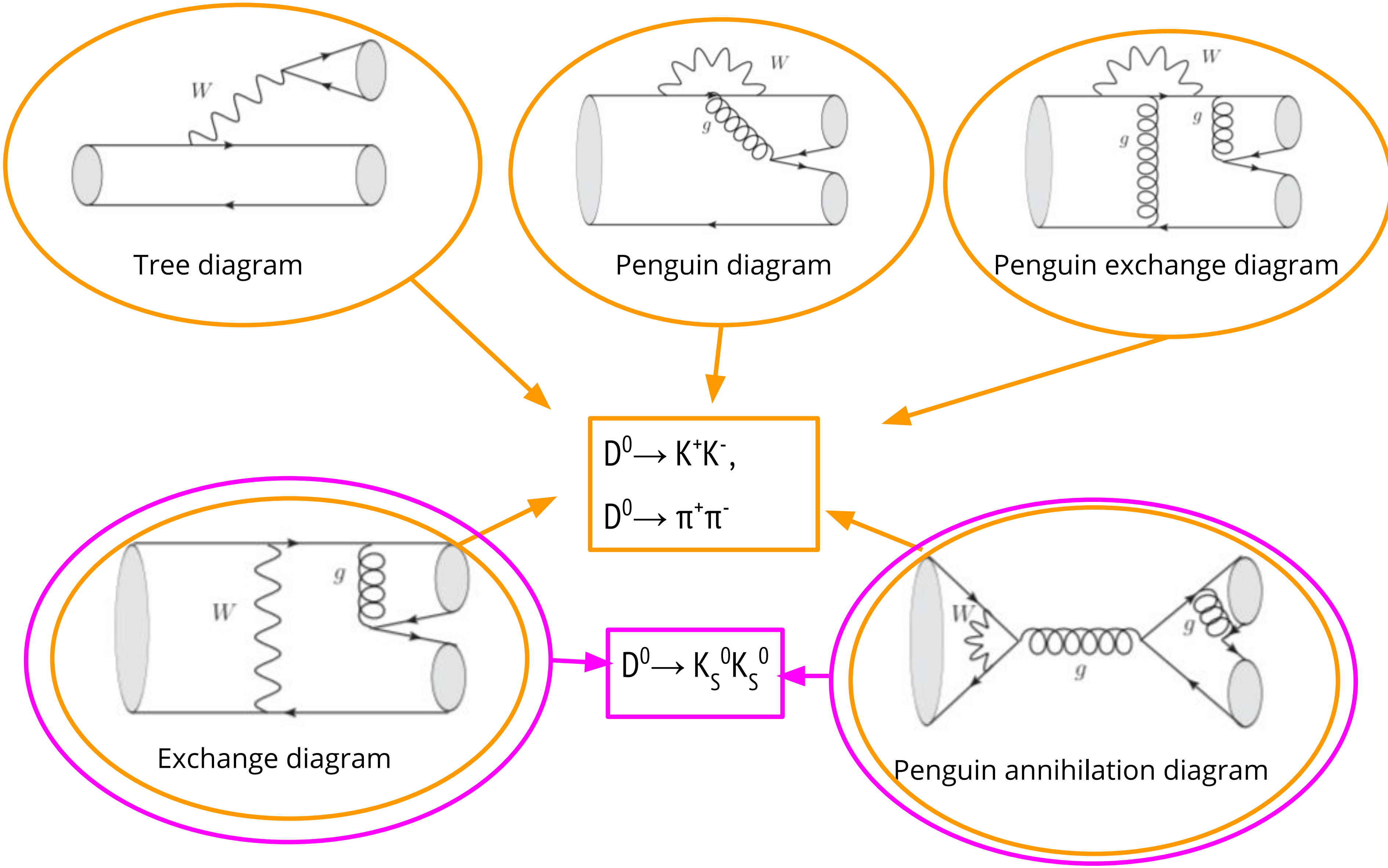


A_{sd} ← inputs to



- A_{sd}=0 in the SU(3) flavour symmetry
- A_b small ma ≠0 in the SU(3) flavour symmetry
- <u>**CPV could be as large as 1%**</u>

$D^0 \to K_S^0 K_S^0$ vs $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$



Fit function

Signal described with a Gaussian distribution

$$f(x) \propto \frac{1}{\sqrt{2\pi\sigma^2}} \exp[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2]$$

Background described with an empirical threshold function

$$B(x) \propto \{1 - \exp[-c(x - m_\pi)]\} + b(x - m_\pi)$$