$K^+ \rightarrow \pi^+ \mu^+ \mu^-$ at LHCb

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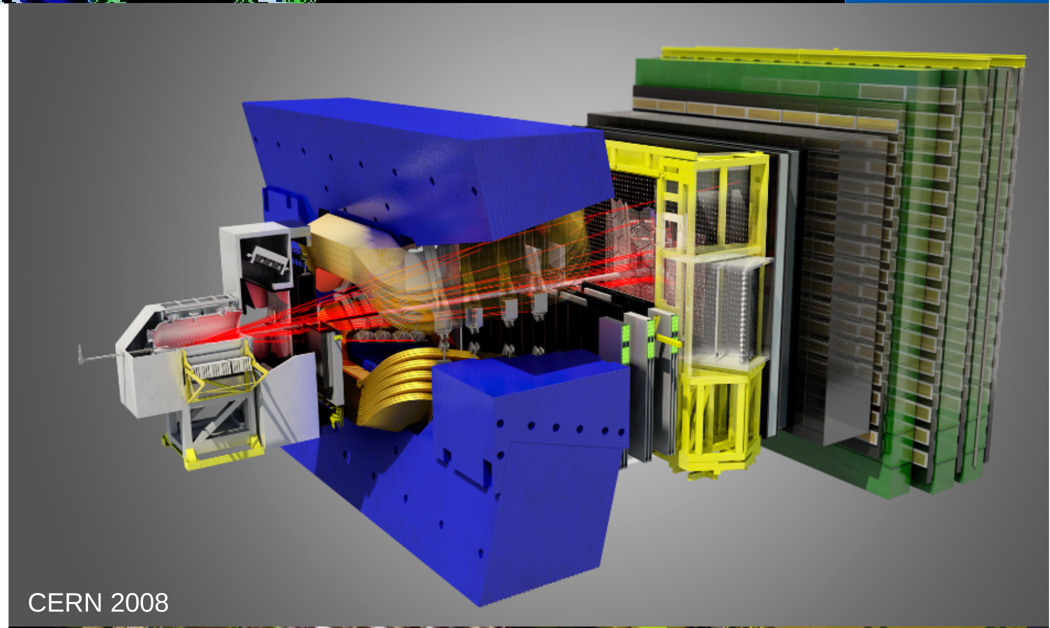
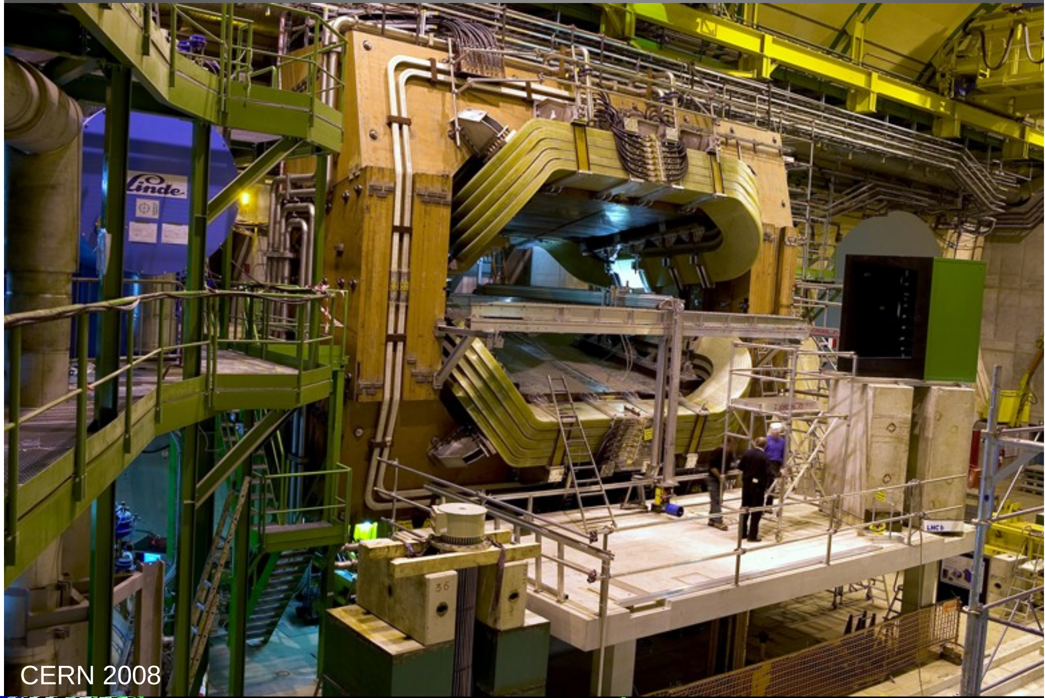
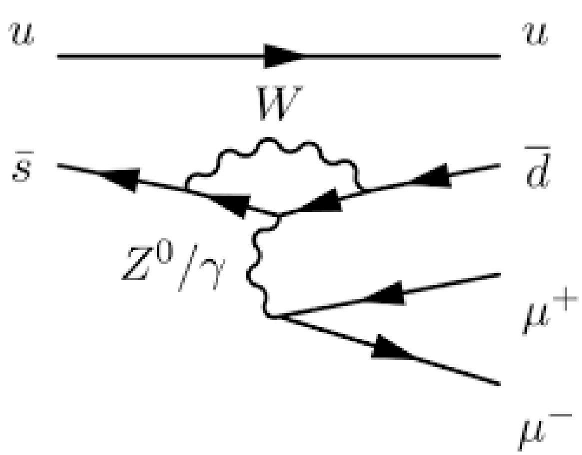
The ‘beauty’ Experiment

- Positioned at Point 8 on the LHC at CERN.
- Motivated primarily by precision measurement of **CP Violation** and **rare decays** in the b-hadron sector.
- **‘Single arm’ design** motivated by the fact b-hadrons are produced in the same direction at the LHC.
- Features an **advanced particle identification** system.
- Collisions at LHC: 7TeV for Run 1,
  13TeV for Run 2





$K^+ \rightarrow \pi^+ \mu^+ \mu^-$



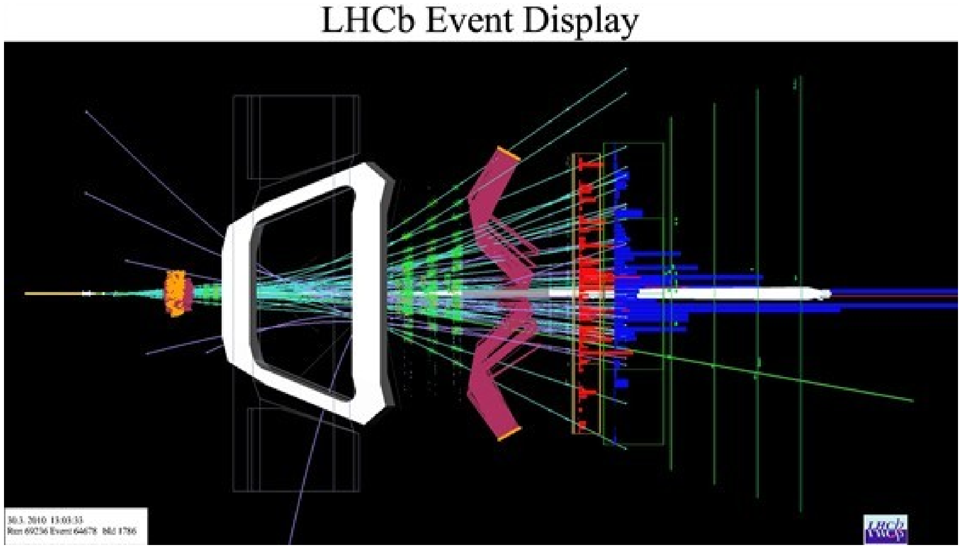
- **Heavily suppressed** decay by GIM mechanism within Standard Model constraints – loop order 'penguin' diagram.
- Branching ratio dominated by long distance contributions from γ-diagrams.
- **Sensitive to new physics** contributions within loops.
- Measurement by NA48/2 (3120 candidates):

$$BR(K^{\pm} \rightarrow \pi^{\pm} \mu^+ \mu^-) = (9.62 \pm 0.25) \times 10^{-8}$$

consistent with SM expectation.
[**Phys.Lett.B697:107-115,2011**]

Why at LHCb?

- **High production cross section** of strange hadrons at LHCb.
- **Good level of particle identification**.
- Improvements have been implemented at Run 2 for analysis into softer decays (e.g. down to a PT of 50MeV) including dedicated trigger lines.
- **Feasibility study** – improvements for future upgrades. Complementary to other strange physics searches at LHCb such as $K_s^0 \rightarrow \mu^+\mu^-$ and $\Sigma^{\pm} \rightarrow p^{\pm}\mu^+\mu^-$.



CERN 2010

Analysis Strategy

- **Obtain a measurement of single event sensitivity** for 2015-2018 data using $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ as a normalisation channel:

$$\alpha_{\pi\mu\mu} = \frac{1}{N_{\pi\pi\pi}} \frac{\epsilon_{\pi\pi\pi}}{\epsilon_{\pi\mu\mu}} BR(K^+ \rightarrow \pi^+ \pi^+ \pi^-)$$

- **Apply cuts to suppress background** and combine all efficiencies for both channels:

$$\epsilon_{tot} = \epsilon_{acc} \cdot \epsilon_{trig} \cdot \epsilon_{sel} \cdot \epsilon_{cuts}$$

extracting from Monte Carlo acceptance, trigger, selection and cut efficiency.

- **Optimise all cuts** using the measured branching ratio by NA48/2 for number of predicted signal events N_S, fit sidebands of data to get background in signal region N_B:

$$N_{\pi\mu\mu} \sim \frac{BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-)}{\alpha_{\pi\mu\mu}}$$

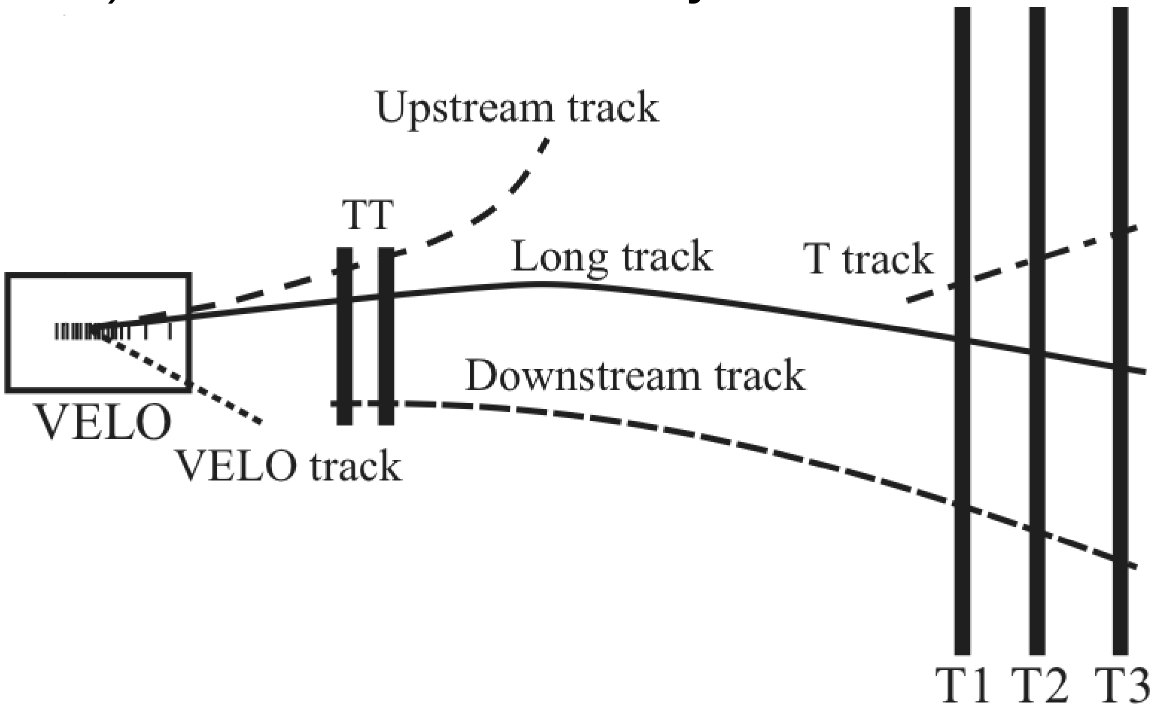
$$F.O.M. = \frac{N_S}{\sqrt{N_B}}$$

LHCb Acceptance

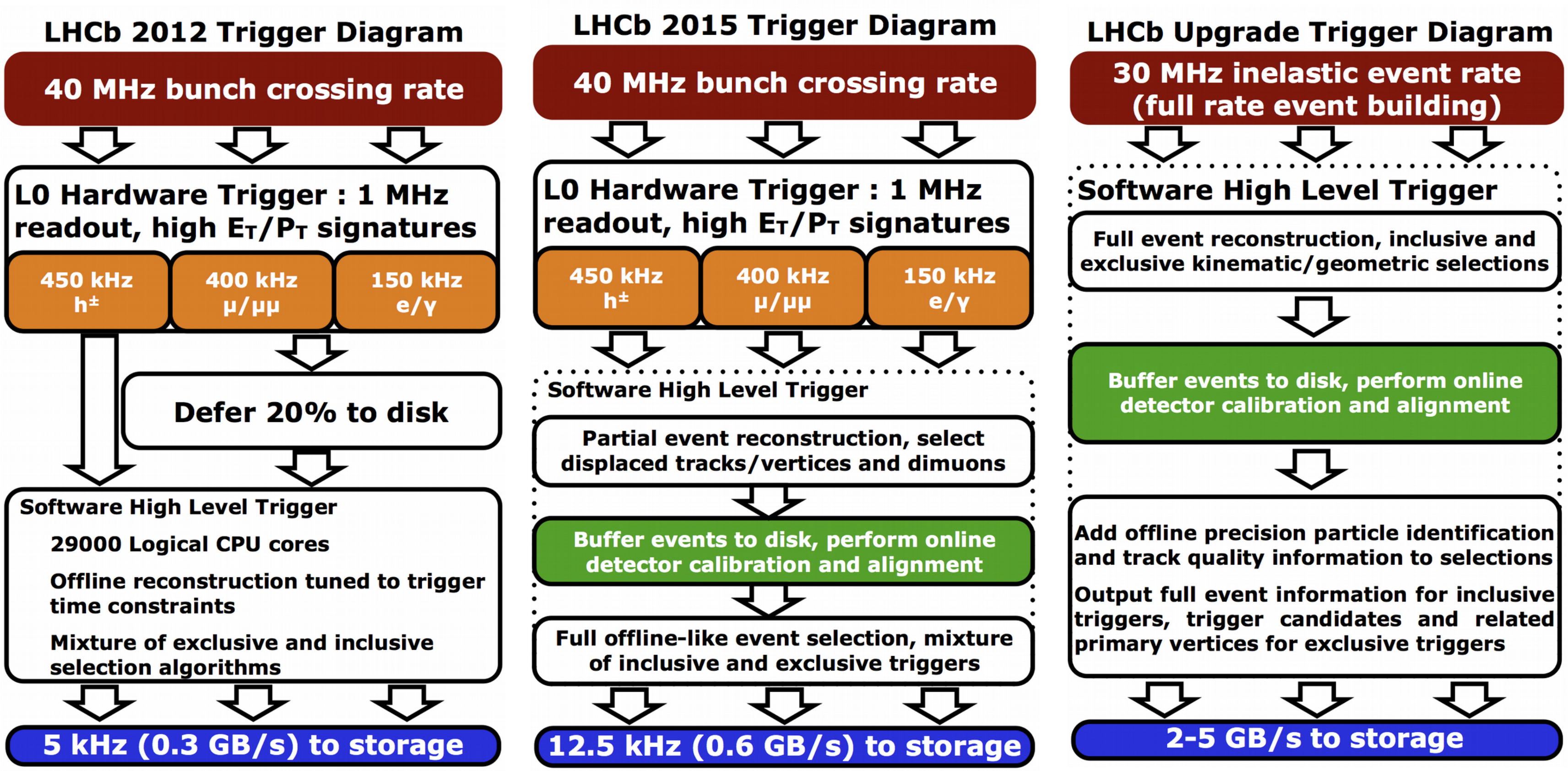
- The **long lifetime of K+** means a large proportion of decays occur **downstream** of the the Vertex Locator (VELO).

- Detector acceptance in pseudorapidity range of $2 < \eta < 5$

- At LHCb – two main types of reconstructed track:
  - **Long** (VELO + TT + T1-T3) ← **Focus of current analysis**
  - Down (TT+T1-T3)



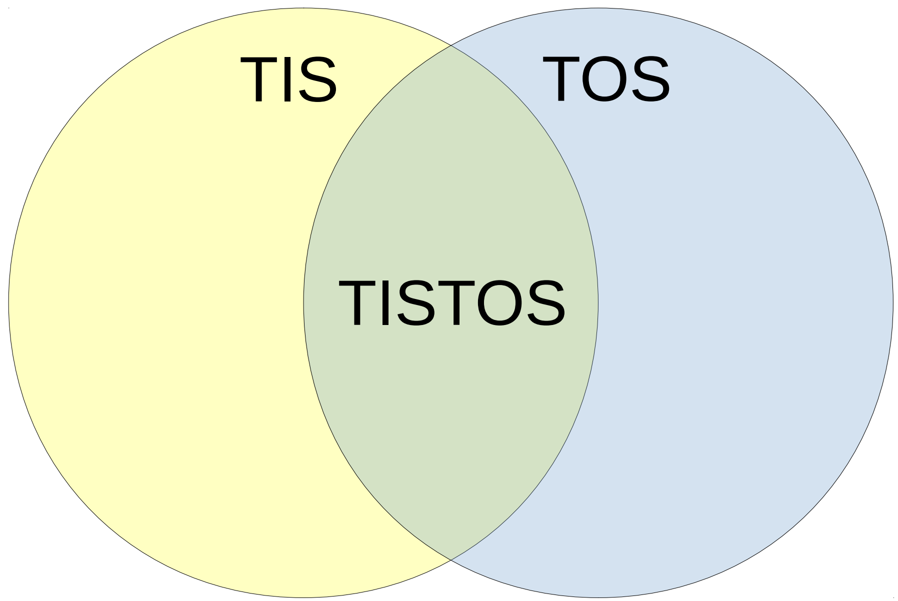
Triggering



LHCb Collaboration

Factor 100 improvement in trigger efficiency from Monte Carlo at HLT from inclusion of dedicated $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ trigger lines in Run 2.

Trigger Event Categories



TOS : Triggered On Signal – triggered by presence of signal
TIS : Triggered Independent of Signal – triggered by the rest of the event
TISTOS : TIS & TOS

TIS events form ~90% of data for rare and normalisation channels.

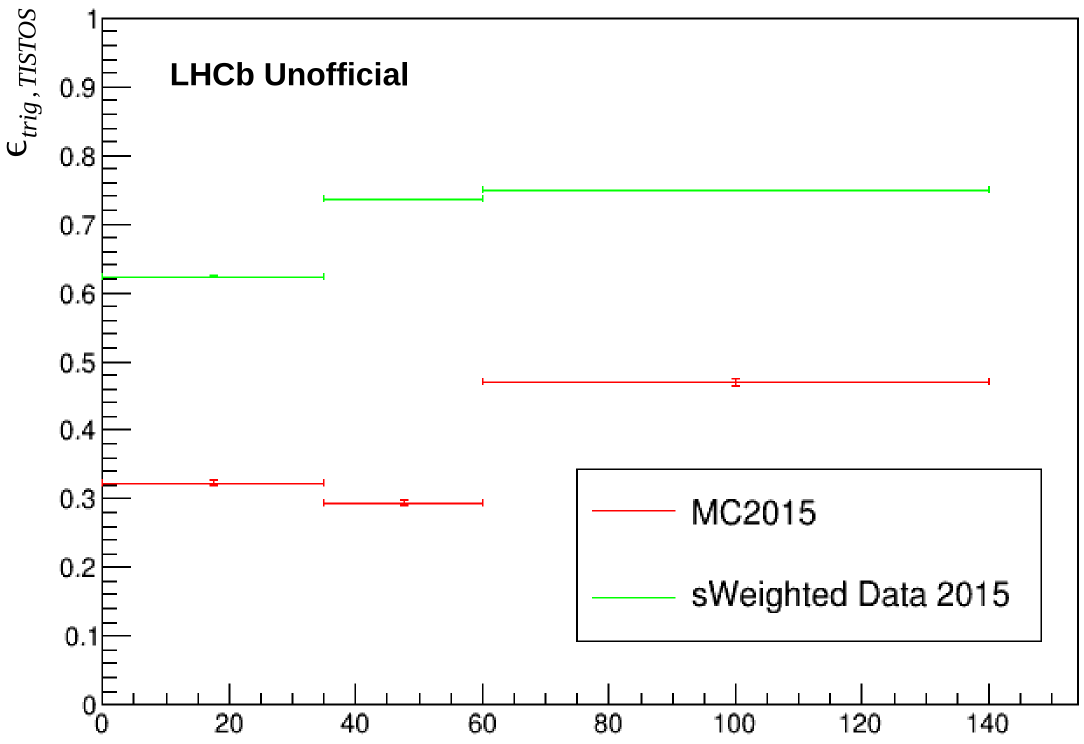
The TISTOS Method

- Cannot obtain information on discarded events in data.
- Can however **obtain trigger efficiency from the trigger categories**:

$$\epsilon_{trig,TISTOS} = \frac{N_{Sel} N_{TISTOS}}{N_{TIS} N_{TOS}}$$

- Can **reduce systematic bias by binning the phase space** and performing the calculation for each bin.
- Can compare TISTOS efficiencies in Monte Carlo (MC) and Sweighted Data for MC reweighting.
- Trigger filters out low multiplicity events – fraction of TIS events no longer sample independent – difficulty deconvolving rest of event in strange particles.

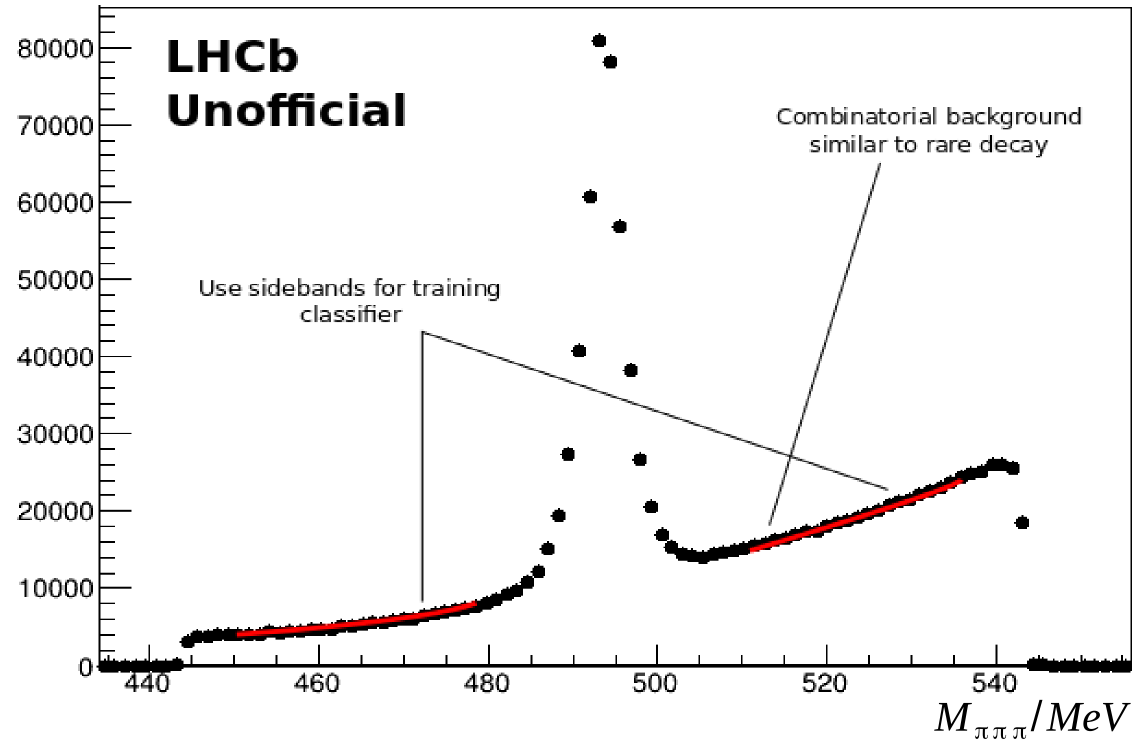
L0 Trigger: TISTOS Trigger Efficiency



$K^+ \to \pi^+\pi^+\pi^-$ as a Normalisation Channel

- If there is something we have plenty of it is $K^+ \to \pi^+\pi^+\pi^-$!
- **Proxy for studying properties** of charged kaons within detector. Also reduces systematic effects in efficiencies.
- Make assumption that TIS efficiency for both channels same (as same mother).

Invariant Mass for $K^+ \to \pi^+\pi^+\pi^-$ 2015 Data



2015 Run 2 Data after application of cut to remove clones in daughters.

Selecting Candidates

- Collected data is passed through sets of **pre-selection cuts** before being stored in bookkeeping as a data stream.

- Dedicated configuration files (for both LongLong and DownDown) apply **cuts to kinematic variables to pick out ‘soft’ kaon events**:

  - Measured K+ mass within 50MeV window around PDG mass.

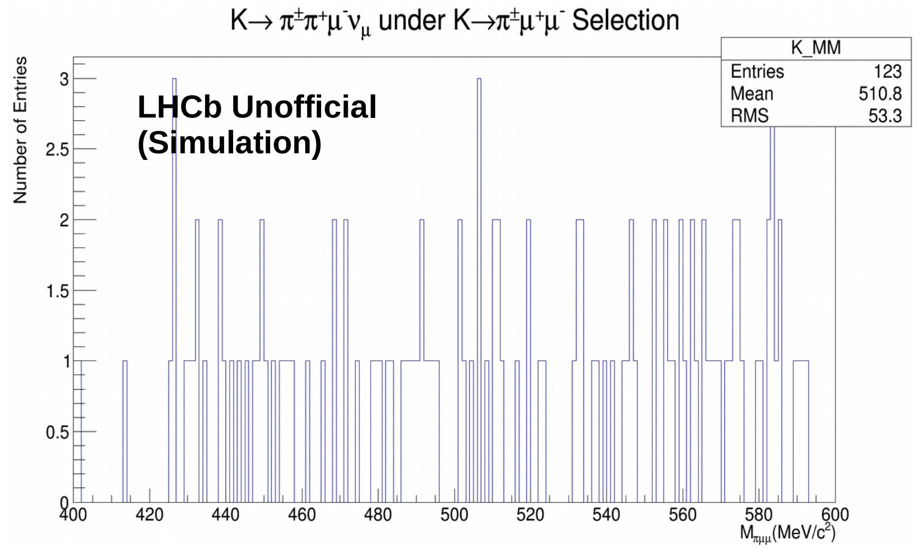
  - Transverse Momentum > 300MeV

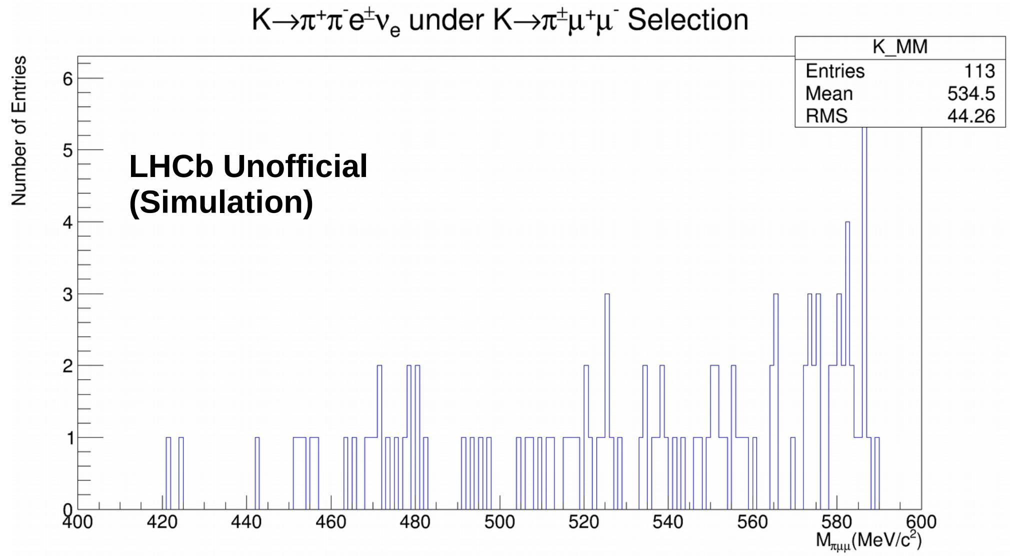
  - Further constraints on distance of closest approach and vertex fits etc.

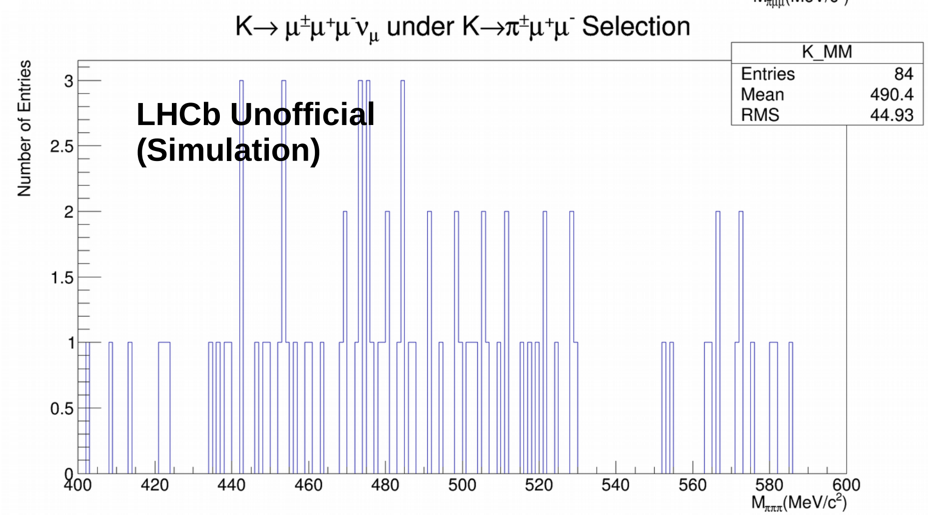
- Events then read from the output of these lines into tuples for offline analysis with constraint on decay type.

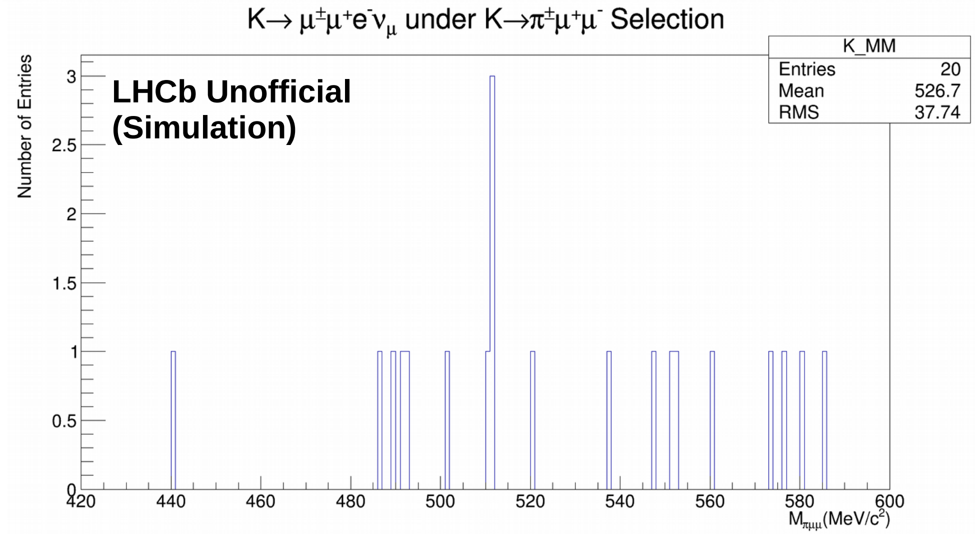
Background

Largely combinatoric



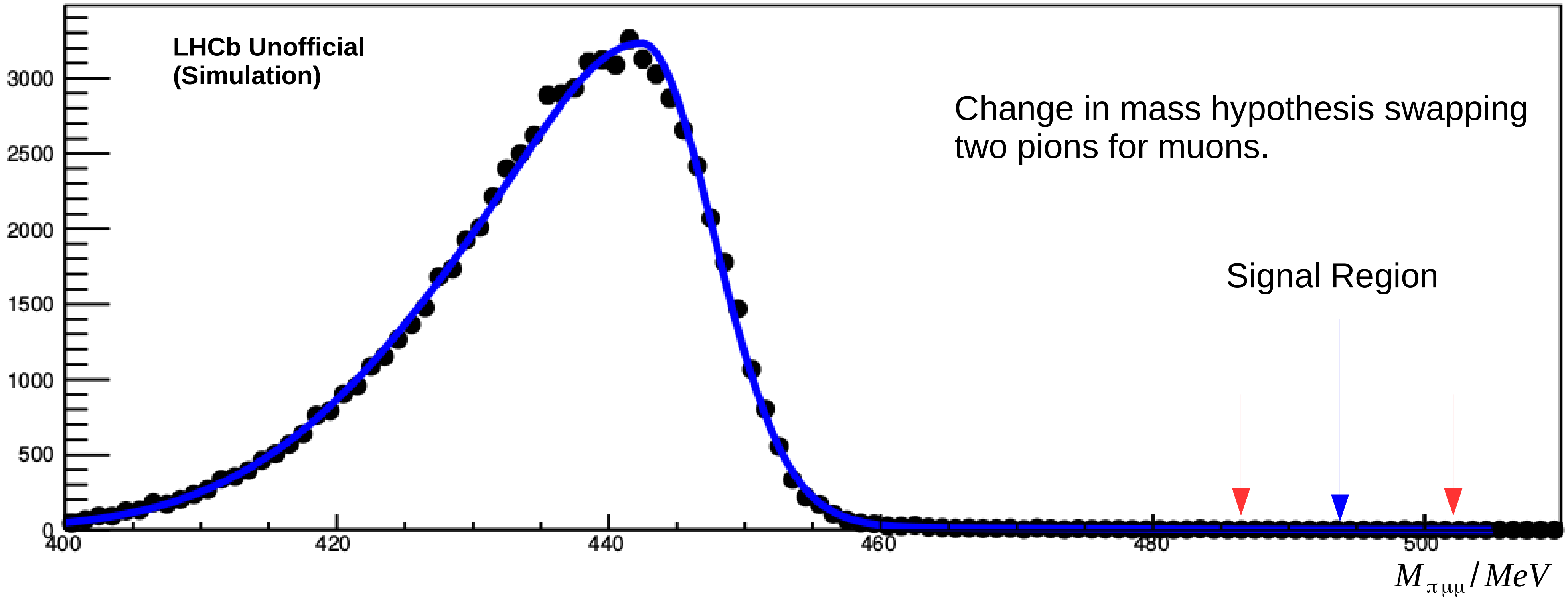






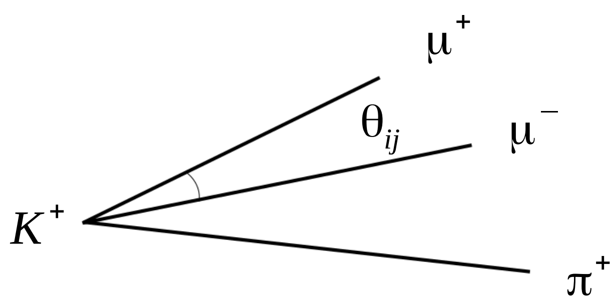
Particle Misidentification

Misidentification of π-μ Simulated with 2015 $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ Monte Carlo



Background Suppression

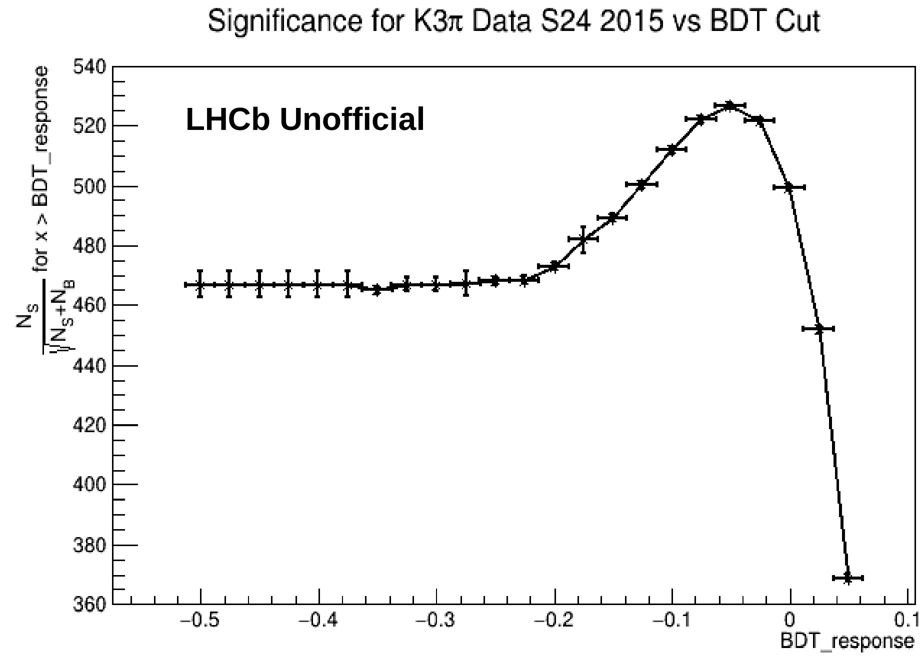
- Initially apply a loose cut on angle between daughters to **remove 'clones' from data**.
- **Use machine learning** – train classifier to distinguish between signal and background using data sidebands and Monte Carlo.
- Cuts applied to **ghost probability** and **particle identification (PID)** variables.

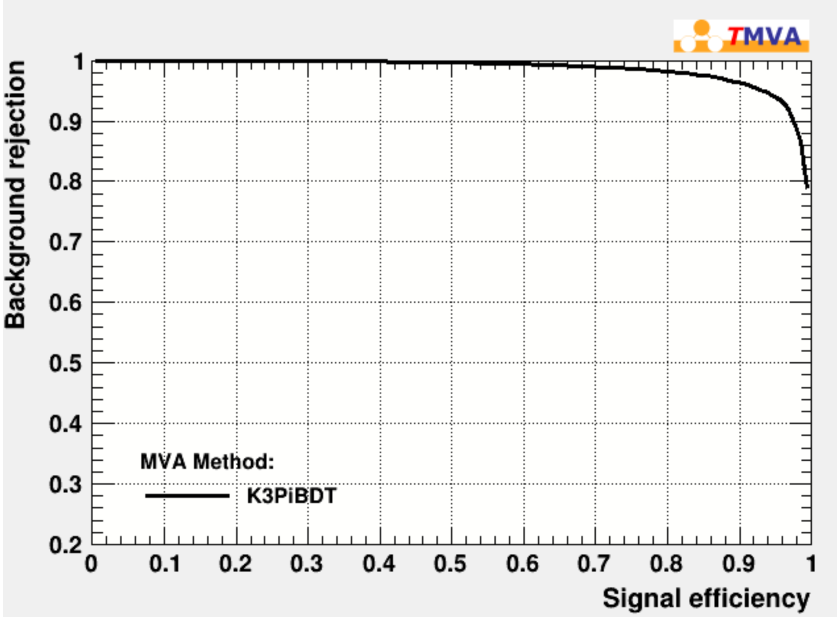


Cut on angle to remove 'clones'

Boosted Decision Tree

- **Boosted Decision Tree** (BDT) chosen as **classifier**: set of optimal cuts in all selected variables defined by computer.
- Decisions form a ‘tree’ - Depth, Number of Trees can be chosen by user.
- **Check for overtraining** – good BDT should not model statistical fluctuations.
- New ‘BDT_response’ variable created which specifies degree of cut application.
- Find optimal value using appropriate Figure of Merit – **Signal Significance**.

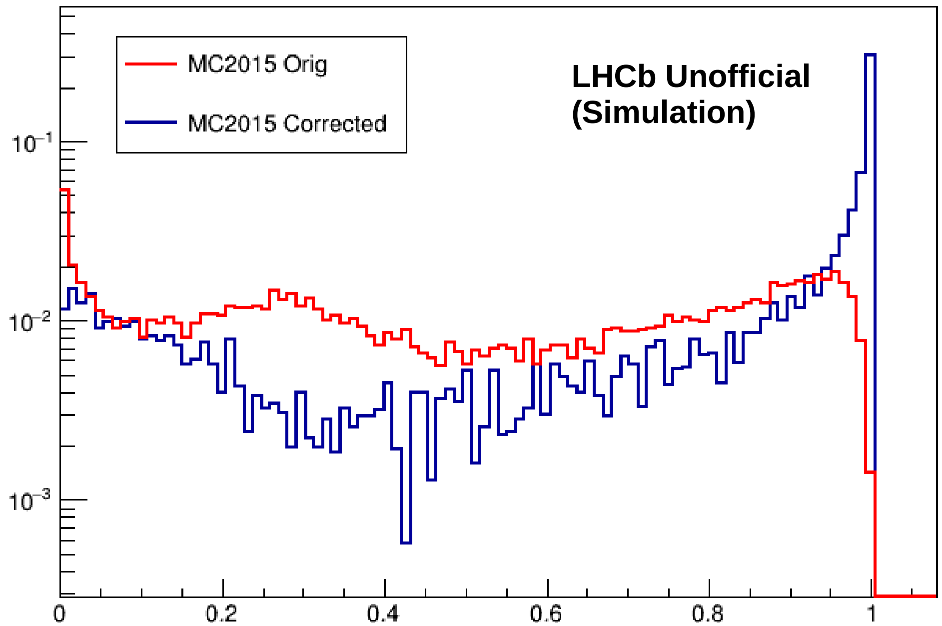




π μ μ

Particle Identification (PID)

Correction of ProbNNmu in $K \to \pi\mu\mu$ 2015 Monte Carlo



ProbNNmu for μ+

- Readout from RICH and Muon chambers combined via **neural network** to create a set of variables which can be cut on (ProbNN).
- Can cut on these variables to **suppress background** further and obtain **efficiencies using MC**.
- **PID variables not accurately modelled in MC,** have to be **corrected using PDFs** generated from data across a 4D phase space: PT, Multiplicity, η, ProbNN.

Prospects for 2015-2018 and beyond

- For Run 2 2015-2018 we expect to have **~50 events** for $K^+ \rightarrow \pi^+ \mu^+ \mu^-$:

  Single Event Sensitivity (2015) ~ 8 x 10^{-8}

- Although not competitive with NA48/2 (3120 events [**Phys.Lett.B697:107-115,2011**]) a good first ‘benchmark’ for charged kaon prospects at an LHC collider detector.
- Further improvements in **Run 3** → **Higher statistics**!
- LHCb was not designed for strange physics, factor 100 improvement just from trigger line updates in Run 2 promising start!
- Recent introduction of Turbo line method – reading events directly from online trigger as opposed to offline stripping.

Summary

- LHCb although designed primarily for *b* physics is **broadening scope into other decays within the strange sector**.

- Precision measurement incentive means **high quality particle identification system** important for π-μ distinguishment.

- Already observe a **factor 100 improvement from inclusion of dedicated trigger lines** alone.

- Although expected yield is uncompetitive the **results are promising** for the future of rare charged **kaon decay measurement at collider experiments**.

Backup

LHCb Prospects in Strange Physics

- Analysis into $K_s^0 \to \mu^+\mu^-$ at Run 1 [**arXiv:1209.4029**]

- Analysis into $\Sigma^{\pm} \to p^{\pm}\mu^+\mu^-$ at Run 1 [**LHCB-PAPER-2017-049]**

- Prospects for $K_s^0 \to \pi^0\mu^+\mu^-$ at LHCb
[**Miriam Lucio Martinez 2017 J. Phys.: Conf. Ser. 800 012033**]

- Prospects for $K_0^s \to \pi^+\pi^- e^+ e^-$ at LHCb
[**C. Marin Benito 2017 J. Phys.: Conf. Ser. 800 012031**]

Backup

Data Driven Method for Trigger Efficiencies [LHCb-PUB-2014-039]

$$\epsilon_{Trig} = \frac{N_{Trig|Sel}}{N_{Sel}} = \frac{N_{Trig|Sel}}{N_{TIS|Sel}} \times \frac{N_{TIS|Sel}}{N_{Sel}} = \frac{N_{Trig|Sel}}{N_{TIS|Sel}} \times \epsilon_{TIS}$$

$$\epsilon_{TIS|TOS} = \frac{N_{TISTOS}}{N_{TOS}}$$

If we make the assumption that the value of ϵ_{TIS} is independent of any subsample of triggered events:

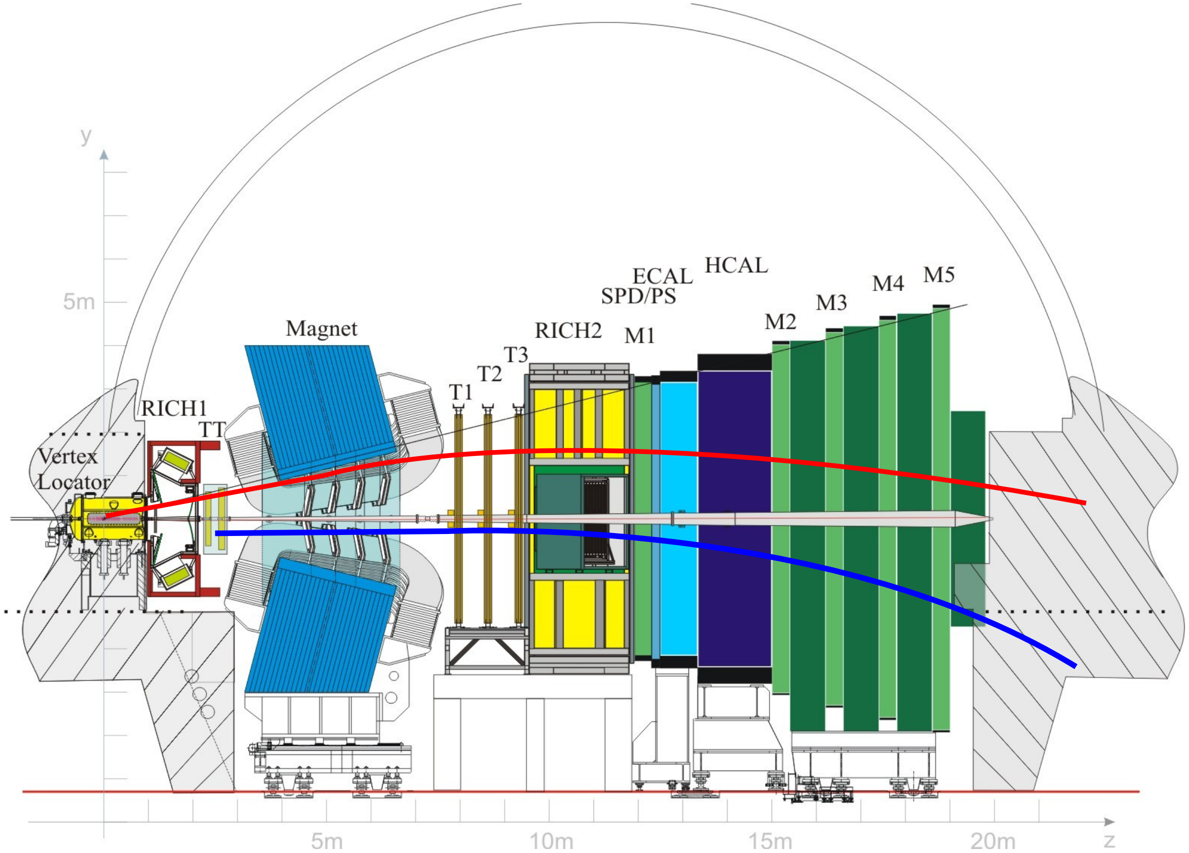
$$\epsilon_{TIS} \equiv \epsilon_{TIS|TOS}$$

We can then obtain trigger efficiency using available trigger category samples:

$$\epsilon_{Trig} = \frac{N_{Trig|Sel}}{N_{TIS|Sel}} \times \frac{N_{TISTOS}}{N_{TOS}}$$

Backup

Sweighting technique: **arXiv:physics/0402083**



Backup

3D Optimisation Independent Components: Ghost, PID& BDT