HF O^2 analysis framework

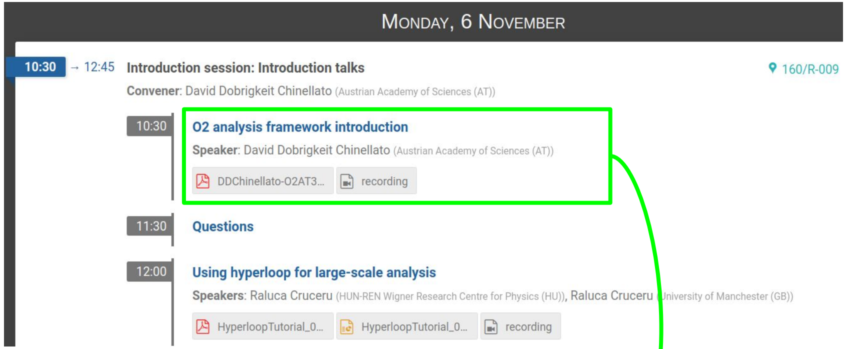
Mattia Faggin, on behalf of the HF O^2 team
University and INFN, Trieste (Italy)

O^2 analysis tutorial 3.0
Wednesday 8th November 2023

Previous tutorials

- [2021, December] HF O^2 software hackathon: https://indico.cern.ch/event/1101005/
- [2022, October] O^2 analysis tutorial: https://indico.cern.ch/event/1200252/timetable/#20221013.detailed
- [2023, April] O^2 analysis tutorial 2.0: https://indico.cern.ch/event/1267433/timetable/#20230417.detailed

- [2023, November] O^2 analysis tutorial 3.0: https://indico.cern.ch/event/1326201/timetable/



MONDAY, 6 NOVEMBER

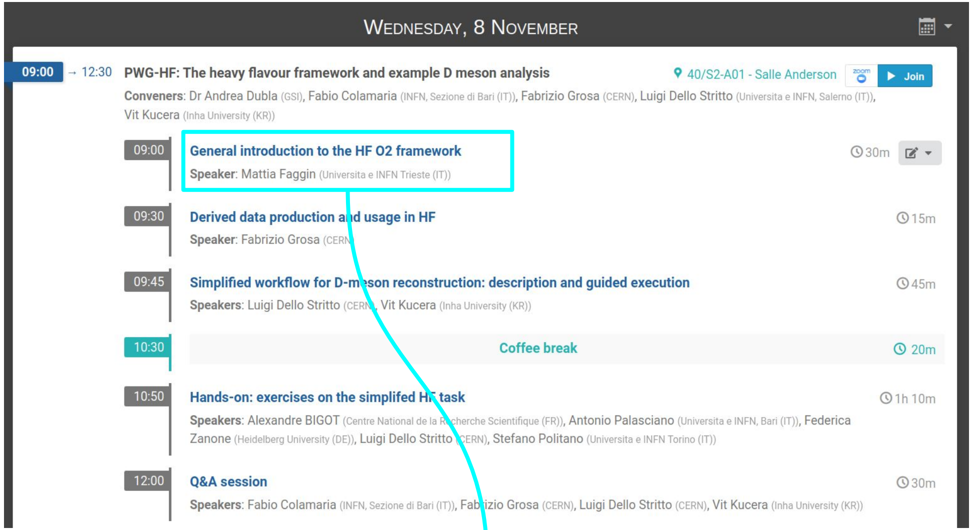
10:30 → 12:45 **Introduction session: Introduction talks** 160/R-009

Convener: David Dobrigkeit Chinellato (Austrian Academy of Sciences (AT))

10:30 **O2 analysis framework introduction**
Speaker: David Dobrigkeit Chinellato (Austrian Academy of Sciences (AT))
DDChinellato-O2AT3... | recording

11:30 **Questions**

12:00 **Using hyperloop for large-scale analysis**
Speakers: Raluca Cruceru (HUN-REN Wigner Research Centre for Physics (HU)), Raluca Cruceru (University of Manchester (GB))
HyperloopTutorial_0... | HyperloopTutorial_0... | recording



WEDNESDAY, 8 NOVEMBER

09:00 → 12:30 **PWG-HF: The heavy flavour framework and example D meson analysis** 40/S2-A01 - Salle Anderson

Conveners: Dr Andrea Dubla (GSI), Fabio Colamaria (INFN, Sezione di Bari (IT)), Fabrizio Grosa (CERN), Luigi Dello Stritto (Universita e INFN, Salerno (IT)), Vit Kucera (Inha University (KR))

09:00 **General introduction to the HF O2 framework** 30m
Speaker: Mattia Faggin (Universita e INFN Trieste (IT))

09:30 **Derived data production and usage in HF** 15m
Speaker: Fabrizio Grosa (CERN)

09:45 **Simplified workflow for D-meson reconstruction: description and guided execution** 45m
Speakers: Luigi Dello Stritto (CERN), Vit Kucera (Inha University (KR))

10:30 **Coffee break** 20m

10:50 **Hands-on: exercises on the simplifed HF task** 1h 10m
Speakers: Alexandre BIGOT (Centre National de la Recherche Scientifique (FR)), Antonio Palasciano (Universita e INFN, Bari (IT)), Federica Zanone (Heidelberg University (DE)), Luigi Dello Stritto (CERN), Stefano Politano (Universita e INFN Torino (IT))

12:00 **Q&A session** 30m
Speakers: Fabio Colamaria (INFN, Sezione di Bari (IT)), Fabrizio Grosa (CERN), Luigi Dello Stritto (CERN), Vit Kucera (Inha University (KR))

- Basics of O^2 framework

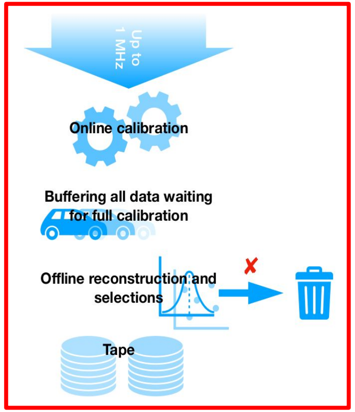
- Today: introduction to HF framework in O^{2}Physics

Upgrades and challenges in Run 3

HF goal: **precise charm- and beauty- hadron measurements down to p_T = 0**

- Large combinatorial background
- Small S/B ratio, difficult triggering

→ HF reconstruction and selection as the most challenging process in Run 3



Up to 1 MHz

Online calibration

Buffering all data waiting for full calibration

Offline reconstruction and selections

Tape

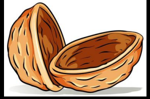
Experimental upgrades:

- new ITS → based on ALPIDE technology
  - improved low p_T tracking efficiency (> 90% for p_T > 200 MeV/c)
  - improved pointing resolution to the PV (factor 2 (4) in rφ (z))
- upgraded TPC readout and frontend electronics
  - MWPC → GEM: similar performance as in Run 2 for dE/dx and tracking, but lower ion backflow (no more gating grid)
- **continuous readout up to 1 Mhz (50 kHz) in pp (Pb-Pb) collisions**
  - 100 times more Pb–Pb data than in Run 2

Framework-design requirements:

- Minimize disk space occupied by derived analysis objects
- Maximize CPU performance, minimize running time

The O^2 framework in a nutshell



1.

Data stored in flat tables interlinked via indices
Example: collisions, tracks in AO2D

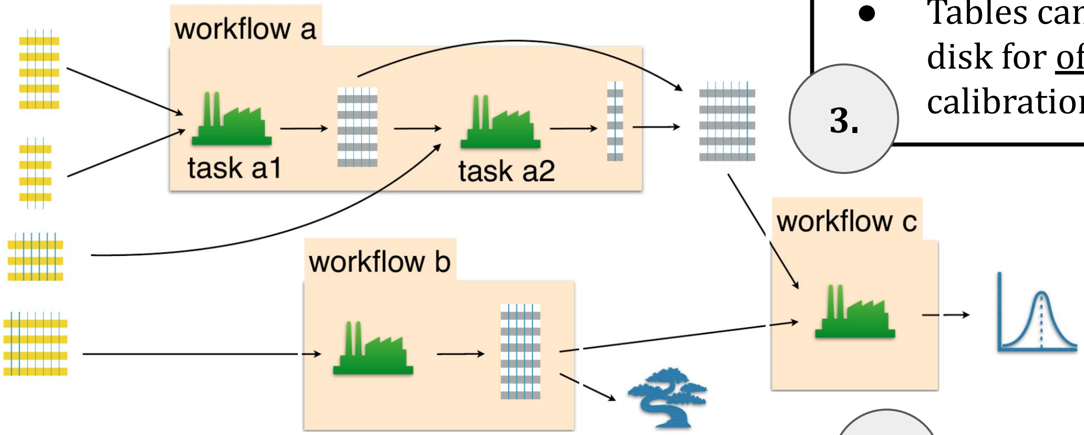
2.

- Analysis task: **struct**
- Tasks organised in **workflows**
- 1 or more tasks in a single workflow

"O2 analysis framework introduction"
6th November

3.

- Tables can be saved as **TTree** on disk for offline analysis (e.g.: QA, calibrations, ML, ...)



4.

- A task can
  - read an existing table
  - create and fill a new table → available as input for the next task
  - extend an existing table → available as input for the next task

5.

End of the chain: finale objects (TH1, TH2, THnSparse, TEfficiency, ...) stored in **AnalysisResults.root**

HF signal reconstruction - the strategy

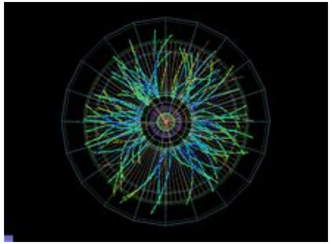
mfaggin@cern.ch

- **Step 0: Event selection**

1.

Tracks

- Quality selections
- Particle Identification (PID) with central barrel detectors (e.g. TPC, TOF)

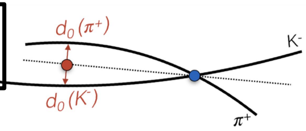


2.

Candidate reconstruction and filtering

- 2/3 track loop to reconstruct candidate from 2/3 - body decays
- Secondary vertex determination
- Filtering with “loose” selections

$D^0 \rightarrow K^- \pi^+$



Pb-Pb in Run 2

- On disk: only indices of tracks belonging to reconstructed secondary vertices
- Secondary vertex information recomputed at the analysis level

→ Same concept in the current HF framework

NEW

HF derived data
(more later)

3.

Candidate selection

- Application of analysis selections (topological variables, track PID)
- (MC) matching to generated particles

4.

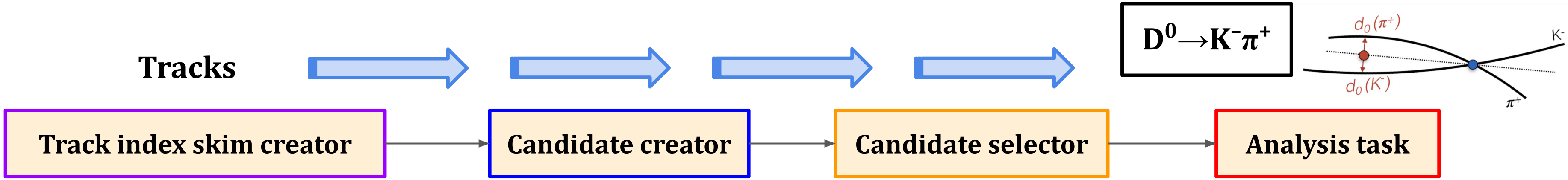
Physics analysis

- Store information into analysis objects (TH1, TH2, THnSparse, TTree, …)

Perform the analysis:

- ○ M_{inv} fits → signal
- ○ Corrections (eff × acc, f_{prompt})
- ○ Systematic uncertainties
- ○ Results

HF O^2 analysis framework



Tracks

Track index skim creator

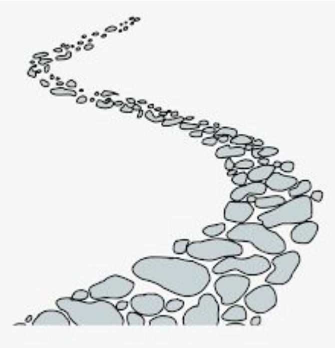
Candidate creator

Candidate selector

Analysis task

$D^0 \rightarrow K^- \pi^+$

Let’s go through all the steps…



HF O^2 analysis framework

PWGHF/TableProducer/trackIndexSkimCreator.cxx

1.

Track index skim creator

Doing a $D^0 \rightarrow K^- \pi^+$ analysis…
Here we flag the candidate Kπ pairs, with loose preselections

Input: **tracks, collisions**

Event and track selections

- p_T, η, DCA, quality

Labelling for skimming (filtering)

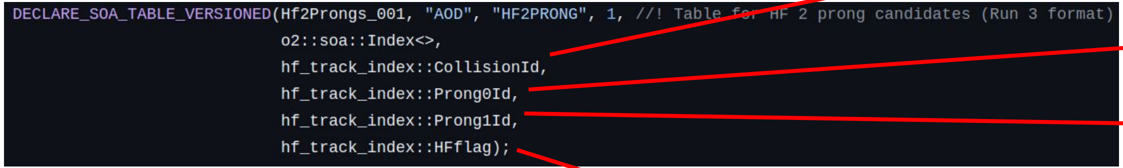
- Double/triple loop over tracks
- *Loose* candidate preselection (invariant mass, p_T, cosθ_p,…)

Output: pairs/triplets of track indices for candidates (**Hf2Prongs**)

HF derived data
(more later)

NEW

PWGHF/DataModel/CandidateReconstructionTables.h



```
DECLARE_SOA_TABLE_VERSIONED(Hf2Prongs_001, "AOD", "HF2PRONG", 1, //! Table for HF 2 prong candidates (Run 3 format)
                            o2::soa::Index<>,
                            hf_track_index::CollisionId,
                            hf_track_index::Prong0Id,
                            hf_track_index::Prong1Id,
                            hf_track_index::HFflag);
```

global index of the collision the candidate is associated to

1st track global index

2nd track global index

flag to identify the 2-prong candidate surviving the pre-selections

HF O^2 analysis framework

PWGHF/TableProducer/candidateCreator2Prong.cxx

2.

Candidate creator

Doing a $D^0 \rightarrow K^- \pi^+$ analysis...
Here we reconstruct the $D^0 \rightarrow K\pi$ candidates and their secondary vertex

Input: pairs/triplets of track indices for candidates (**Hf2Prongs**)

Candidate creation

- Secondary-vertex reconstruction and candidate building
- Full info for candidate selection and analysis

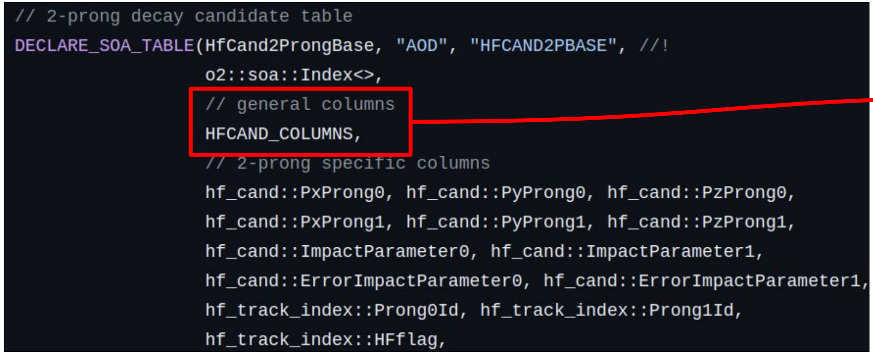
MC matching

- Rec. level (candidate)
- Gen. level (MC particle)
- MC origin tracing (non-)prompt (from c/b quark)

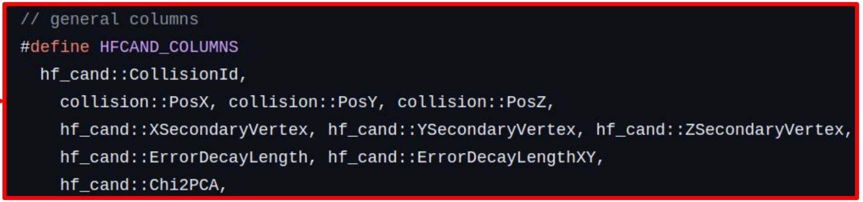
Output:

- Reconstructed HF candidates (**HfCandProng2Base**)
- MC flags

PWGHF/DataModel/CandidateReconstructionTables.h



```
// 2-prong decay candidate table
DECLARE_SOA_TABLE(HfCand2ProngBase, "AOD", "HFCAND2PBASE", //!
                  o2::soa::Index<>,
                  // general columns
                  HFCAND_COLUMNS,
                  // 2-prong specific columns
                  hf_cand::PxProng0, hf_cand::PyProng0, hf_cand::PzProng0,
                  hf_cand::PxProng1, hf_cand::PyProng1, hf_cand::PzProng1,
                  hf_cand::ImpactParameter0, hf_cand::ImpactParameter1,
                  hf_cand::ErrorImpactParameter0, hf_cand::ErrorImpactParameter1,
                  hf_track_index::Prong0Id, hf_track_index::Prong1Id,
                  hf_track_index::HFflag,
```



```
// general columns
#define HFCAND_COLUMNS
  hf_cand::CollisionId,
    collision::PosX, collision::PosY, collision::PosZ,
    hf_cand::XSecondaryVertex, hf_cand::YSecondaryVertex, hf_cand::ZSecondaryVertex,
    hf_cand::ErrorDecayLength, hf_cand::ErrorDecayLengthXY,
    hf_cand::Chi2PCA,
```

… plus many other **dynamic columns**, for which the values are derived from those shown here

HF O^2 analysis framework

NEW

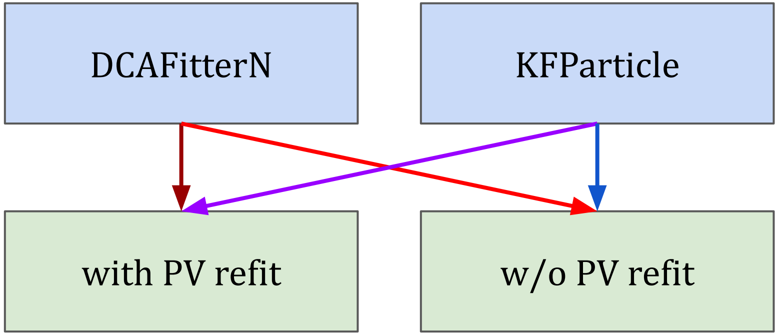
2.

Candidate creator

Doing a $D^0 \rightarrow K^-\pi^+$ analysis…
Here we reconstruct the $D^0 \rightarrow K\pi$ candidates and their secondary vertex

secondary-vertex fitting

candidate-daughter removal from PV determination



Possibility to build HF-candidate **secondary vertex** with **two** different **algorithms**: **DCAFitterN** or **KFParticle**

Beware

- **Different tables** created! Binary choice, be consistent with it during next steps (i.e. `candidate-selector,task`)
- Currently available **only** for **2-prong** candidates

`processPvRefitWithDCAFitterN`

`processNoPvRefitWithDCAFitterN` (default)

`processPvRefitWithKFParticle`

`processNoPvRefitWithKFParticle`

PWGHF/TableProducer/candidateCreator2Prong.cxx

HF O^2 analysis framework

PWGHF/TableProducer/candidateSelectorD0.cxx

3.

Candidate selector

Doing a $D^0 \rightarrow K^- \pi^+$ analysis...
*Here we **define** the selections on topological variables and PID to $D^0 \rightarrow K\pi$ candidate daughters*

Input:

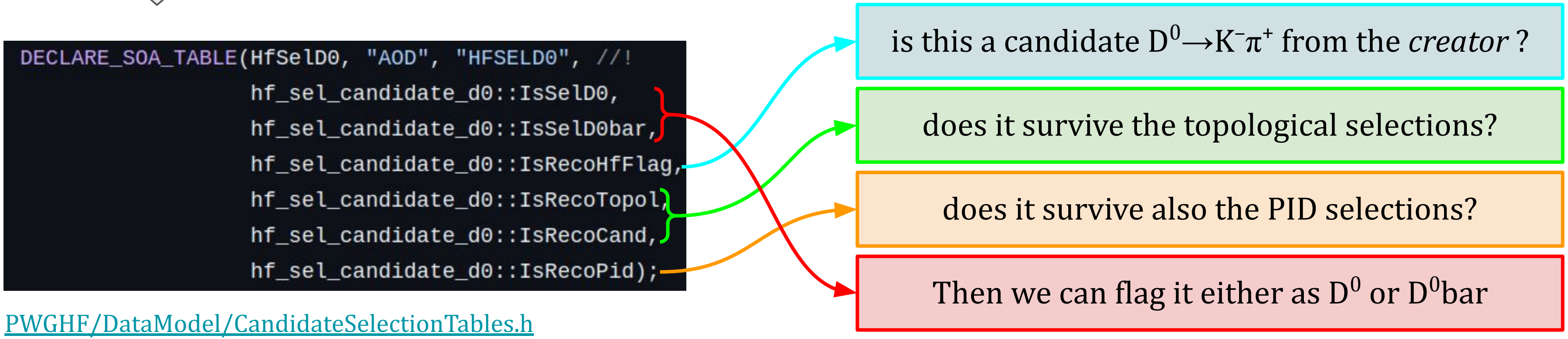
- Reconstructed HF candidates (**Hf2Prongs**)
- Track PID

Candidate selection definition

- Topological cuts
- Daughter PID cuts

Output: selection flags (**HfSelD0**)

NB: just flagging! Selections applied at the next step!



```
DECLARE_SOA_TABLE(HfSelD0, "AOD", "HFSELD0", //!
                  hf_sel_candidate_d0::IsSelD0,
                  hf_sel_candidate_d0::IsSelD0bar,
                  hf_sel_candidate_d0::IsRecoHfFlag,
                  hf_sel_candidate_d0::IsRecoTopol,
                  hf_sel_candidate_d0::IsRecoCand,
                  hf_sel_candidate_d0::IsRecoPid);
```

is this a candidate $D^0 \rightarrow K^- \pi^+$ from the *creator* ?

does it survive the topological selections?

does it survive also the PID selections?

Then we can flag it either as D^0 or D^0bar

PWGHF/DataModel/CandidateSelectionTables.h

HF O^2 analysis framework

PWGHF/D2H/Tasks/taskD0.cxx

4.

Analysis task

Doing a $D^0 \rightarrow K^- \pi^+$ analysis...
Here we apply the selections and fill the histograms with $D^0 \rightarrow K\pi$ candidate information: M_{inv}, L_{xy}, $\cos\theta_p$, …

Input:

- Selected candidates (**HfSelD0**)
- MC particles
- MC flags

Analysis task

- Histogram filling for selected candidates

Output: **histograms** (kinematic properties, signal vs. background, efficiency, …), in stored .root file

HF O^2 analysis framework

PWGHF/D2H/Tasks/taskD0.cxx

4.

Analysis task

Doing a D^0→K$^-$π$^+$ analysis...
Here we apply the selections and fill the histograms with D^0→Kπ candidate information: M_{inv}, L_{xy}, cosθ_p, ...

- Take into account only the 2-prong candidates selected as D^0(bar) in the `candidateSelectorD0`

```
using D0Candidates = soa::Join<aod::HfCand2Prong, aod::HfSelD0>;

Partition<D0Candidates> selectedD0Candidates = aod::hf_sel_candidate_d0::isSelD0 >=
selectionFlagD0 || aod::hf_sel_candidate_d0::isSelD0bar >= selectionFlagD0bar;

if (candidate.isSelD0() >= selectionFlagD0) {
    registry.fill(HIST("hMass"), massD0, ptCandidate);
    registry.fill(HIST("hMassFinerBinning"), massD0, ptCandidate);
    registry.fill(HIST("hMassVsPhi"), massD0, ptCandidate, candidate.phi());
}
```

PWGHF/D2H/Tasks/taskD0.cxx

4.

Analysis task

Doing a $D^0 \rightarrow K^-\pi^+$ analysis…
Here we apply the selections and fill the histograms with $D^0 \rightarrow K\pi$ candidate information: M_{inv}, L_{xy}, $\cos\theta_p$, …

- Take into account only the 2-prong candidates selected as D^0(bar) in the `candidateSelectorD0`
- Fill the histograms for your analysis!

NEW

Beware of the **secondary-vertex fitter** you used in the `candidate-creator`, to use the correct `process` function!

`processDataWithDCAFitterN` (default)

`processDataWithKFParticle`

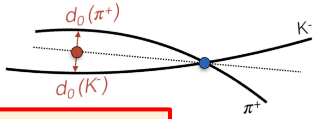
… and equivalent for MC

```
using D0Candidates = soa::Join<aod::HfCand2Prong, aod::HfSelD0>;

Partition<D0Candidates> selectedD0Candidates = aod::hf_sel_candidate_d0::isSelD0 >=
selectionFlagD0 || aod::hf_sel_candidate_d0::isSelD0bar >= selectionFlagD0bar;

if (candidate.isSelD0() >= selectionFlagD0) {
    registry.fill(HIST("hMass"), massD0, ptCandidate);
    registry.fill(HIST("hMassFinerBinning"), massD0, ptCandidate);
    registry.fill(HIST("hMassVsPhi"), massD0, ptCandidate, candidate.phi());
}
```

Recap of the D^0 reconstruction and analysis

Tracks → → → →

$D^0 \to K^-\pi^+$



Track index skim creator → **Candidate creator** → **Candidate selector** → **Analysis task**

1. ***Doing a $D^0 \to K^-\pi^+$ analysis...***
Here we flag the candidate $K\pi$ pairs, with loose preselections

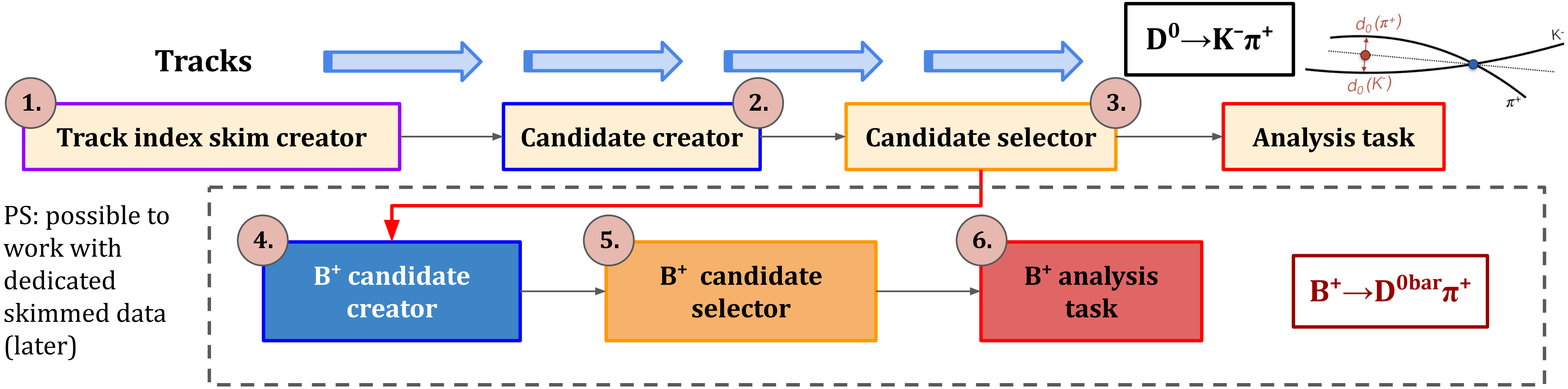
2. ***Doing a $D^0 \to K^-\pi^+$ analysis...***
Here we reconstruct the $D^0 \to K\pi$ candidates and their secondary vertex

3. ***Doing a $D^0 \to K^-\pi^+$ analysis...***
Here we define the selections on topological variables and PID to $D^0 \to K\pi$ candidate daughters

4. ***Doing a $D^0 \to K^-\pi^+$ analysis...***
Here we apply the selections and fill the histograms with $D^0 \to K\pi$ candidate information: M_{inv}, L_{xy}, $\cos\theta_p$, ...

A more complex analysis: $B^+ \to D^{0bar}\pi$

The modularity of O^2 workflows allows to build analyses of multi-stage decays on top of analyses of direct ones



Tracks

1. Track index skim creator

2. Candidate creator

3. Candidate selector

Analysis task

$D^0 \to K^- \pi^+$

PS: possible to work with dedicated skimmed data (later)

4. B^+ candidate creator

5. B^+ candidate selector

6. B^+ analysis task

$B^+ \to D^{0bar}\pi^+$

B^+ candidates built from:

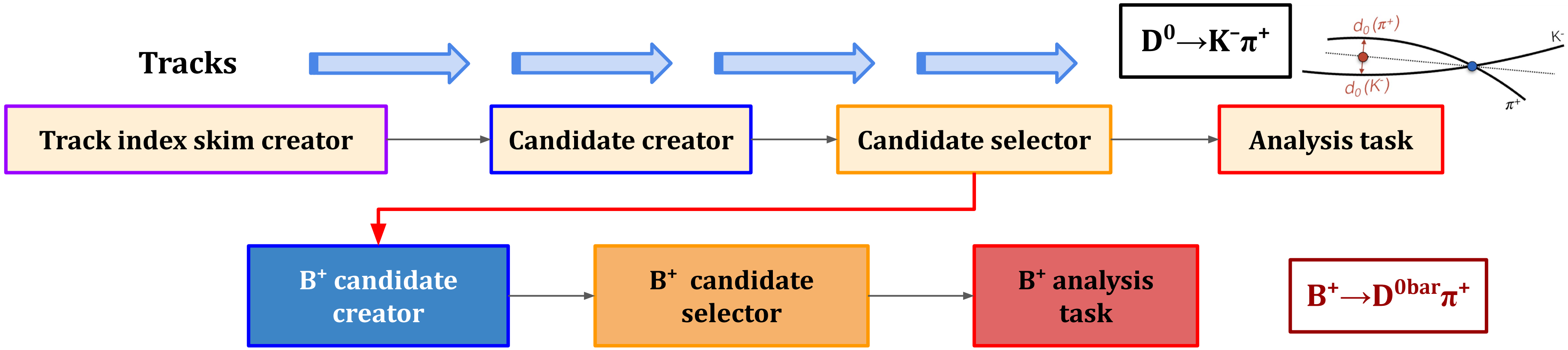
- **tracks**, from input AO2Ds
- **candidate $D^{0(bar)}$**, i.e. 2-prong candidates selected in the `candidateSelectorD0`

```
Filter filterSelectCandidates = (aod::hf_sel_candidate_d0::isSelD0 >=
selectionFlagD0 || aod::hf_sel_candidate_d0::isSelD0bar >= selectionFlagD0bar);
```

PWGHF/TableProducer/candidateCreatorBplus.cxx

More complex analyses

The modularity of O^2 workflows allows to build analyses of multi-stage decays on top of analyses of direct ones



Tracks

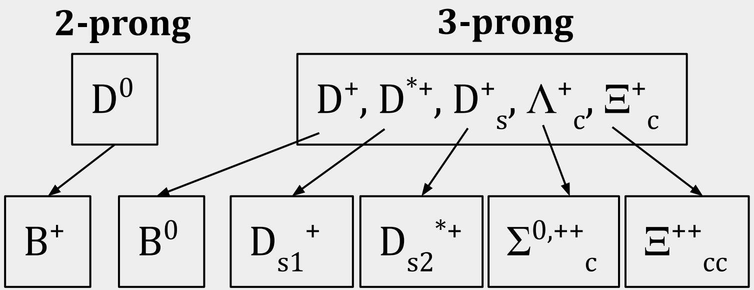
Track index skim creator → Candidate creator → Candidate selector → Analysis task

$D^0 \rightarrow K^- \pi^+$

B$^+$ candidate creator → B$^+$ candidate selector → B$^+$ analysis task

$B^+ \rightarrow D^{0bar} \pi^+$

… many more analyses are possible!



2-prong

D^0

3-prong

$D^+, D^{*+}, D^+_s, \Lambda^+_c, \Xi^+_c$

B^+ | B^0 | D_{s1}^+ | D_{s2}^{*+} | $\Sigma^{0,++}_c$ | Ξ^{++}_{cc}

$D^0 \rightarrow \pi^+ K^-$
$B^0 \rightarrow D^- \pi^+$
$B^+ \rightarrow D^{0bar} \pi^+$
$D^+ \rightarrow \pi^+ K^- \pi^+$
$D^+_s \rightarrow \pi^+ K^- K^+$

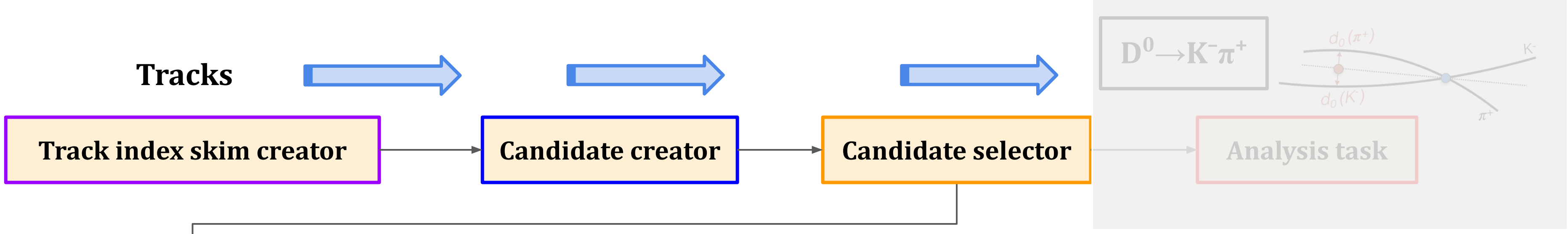
$D_{s1}^+ \rightarrow D^{*+} K^0_s$
$D_{s2}^{*+} \rightarrow D^+ K^0_s$

$\Lambda^+_c \rightarrow p K^- \pi^+, p K^0_S$
$\Sigma^{0,++}_c \rightarrow \Lambda^+_c \pi^{-,+}$

$\Xi^+_c \rightarrow p K^- \pi^+$
$\Xi^{++}_{cc} \rightarrow \Xi^+_c \pi^+$

Tree creators and Machine Learning

NEW

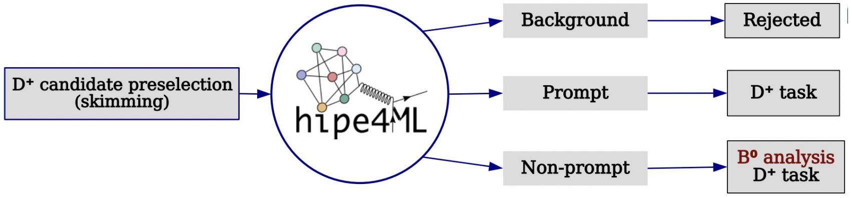


Tree creator

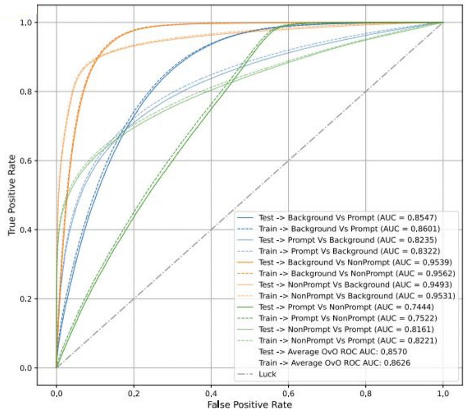
$B^0 \to D^-\pi^+$
$B^+ \to D^{0bar}\pi^+$
$B_s^0 \to D_s^-\pi^+$
$\Lambda_b^0 \to \Lambda_c^+\pi^-$,

$D^0 \to K^-\pi^+$
$D^+ \to \pi^+K^-\pi^+$
$D_s^+ \to K^-K^+\pi^+$
$\Lambda_c^+ \to p\,K^-\,\pi^+$, $p\,K^0_S$
$\Xi_c^+ \to p\,K^-\,\pi^+$
$\Xi_c^0 \to \Xi^-\,\pi^+$
$\Xi_{cc}^{++} \to \Xi_c^+\,\pi^+$

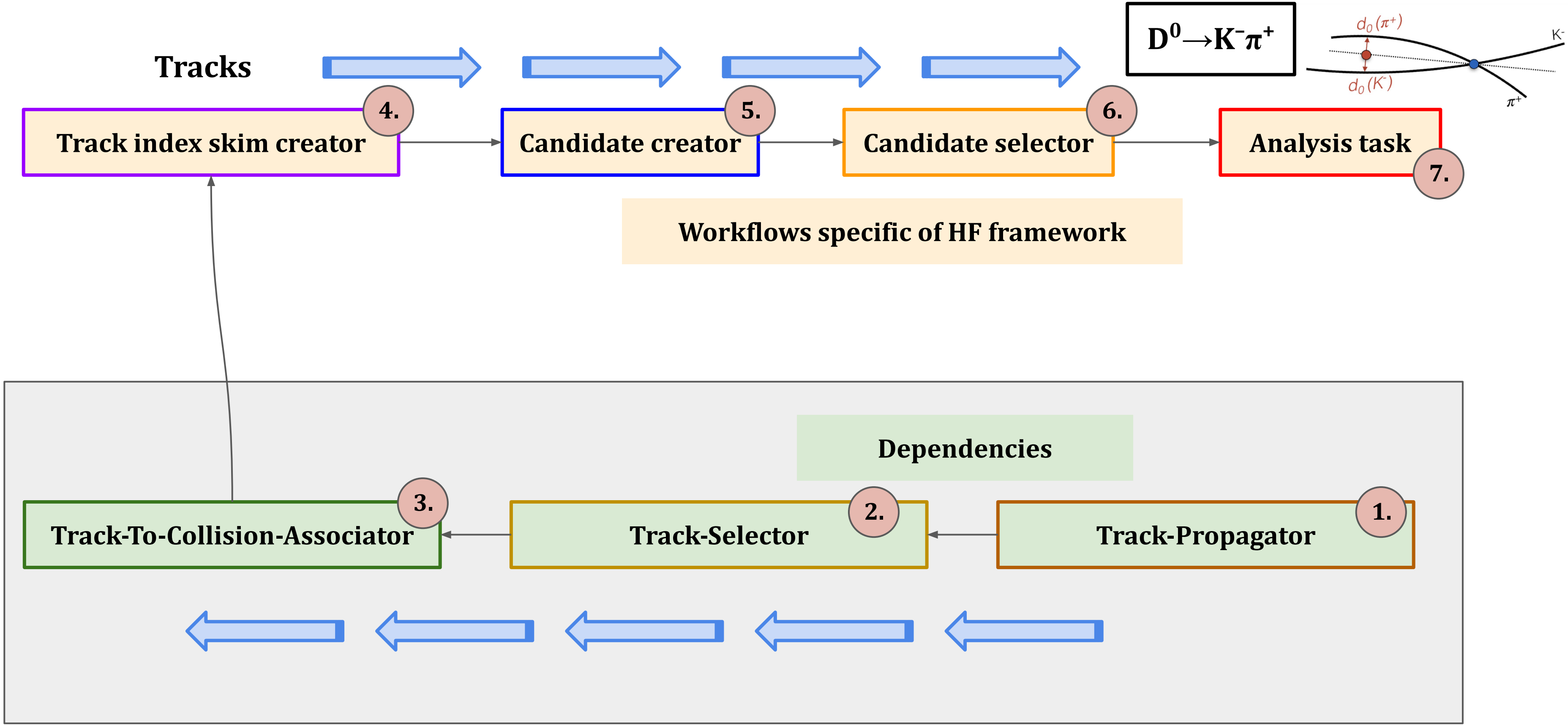
Additional material
https://indico.cern.ch/event/1328768/#1-update-on-general-hf-ml-inte
https://indico.cern.ch/event/1320178/#2-ml-response-class



- Tree creator: reduced tables on output AO2Ds.root files
- Input for Machine Learning-based analyses
  - model training doable offline (e.g. scikit-learn, hipe4ML)
  - model application doable on GRID via ONNX
    - Tools/ML/MlResponse.h
    - PWGHF/Core/HfMlResponse.h



HF O^2 analysis framework - dependencies



Tracks

4. Track index skim creator

5. Candidate creator

6. Candidate selector

7. Analysis task

Workflows specific of HF framework

Dependencies

3. Track-To-Collision-Associator

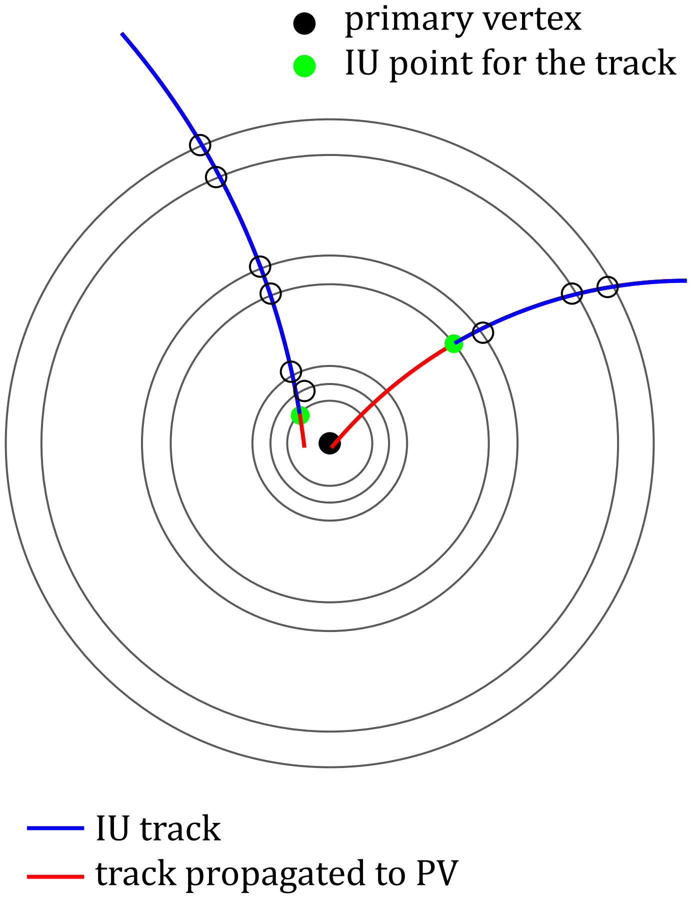
2. Track-Selector

1. Track-Propagator

$D^0 \rightarrow K^- \pi^+$

Track propagator

Common/TableProducer/trackPropagation.cxx



- In AO2Ds: **TracksIU**
    - **IU: Innermost Update** point
    - Track-parametrization at the IU written in AO2Ds → not the same radius ↔ `track.x()`
    - Table written in the AO2Ds
- In analysis: **Tracks**
    - Track-parametrization after the propagation to the distance of closest-approach (DCA) to the primary vertex
    - In the workflow: dca$_{XY}$ and dca$_{Z}$ calculated as well
    - Table **not** written in the AO2Ds, but created by the track-propagation workflow

`processStandard`

- track parameters
- dca$_{XY}$, dca$_{Z}$ values

`processCovariance`

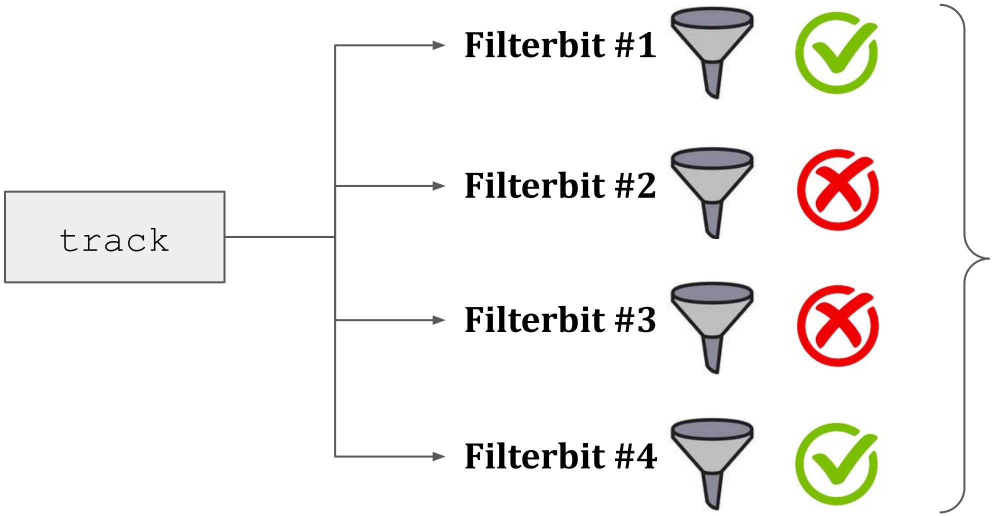
- track parameters and covariance matrix
- dca$_{XY}$, dca$_{Z}$ values and uncertainties

→ much more resources consumed!

Track selector

Common/TableProducer/trackSelection.cxx

Predefined sets of selections: Common/Core/TrackSelectionDefaults.cxx



`aod::TrackSelection`

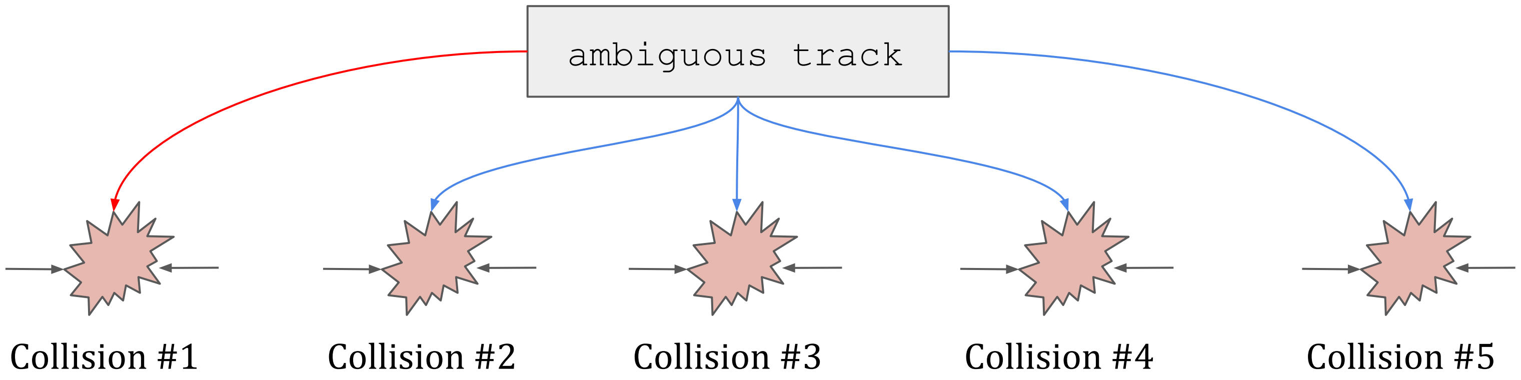
	FB #1	FB #2	FB #3	FB #4
track0	✓	✗	✗	✗
track1	✗	✓	✗	✗
track2	✓	✓	✓	✗
track3	✓	✓	✓	✓
track4	✗	✗	✓	✗

- For each (propagated!) track the following check is done: does it satisfy the selections defined in the *i*-th predefined set (filterbit)?
- Track-by-track filling of `aod::TrackSelection` table, according to the responses

- This table contains for each track the flag for each filterbit
- To have a flag for each single cut: use the `aod::TrackSelectionExtension` table (not filled by default!)

Track-to-collision associator

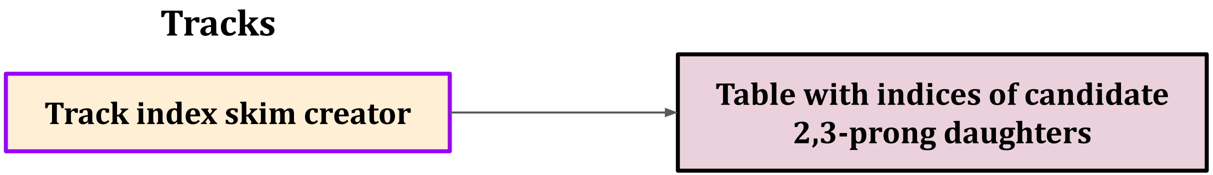
Common/TableProducer/trackToCollisionAssociator.cxx-



- Continuous readout → **ambiguous tracks**: tracks with more than 1 collision possible
- By default, in the AO2D the `track.collisionId()` is that of the first compatible collision
- `track-to-collision-associator` : duplication of the track to each collisions compatible in time
    - recovery of 2,3-prong decay topologies!
    - possible signal duplication if all the daughters are ambiguous and are duplicated in many collisions → under investigation in MC

Linked derived data

NEW

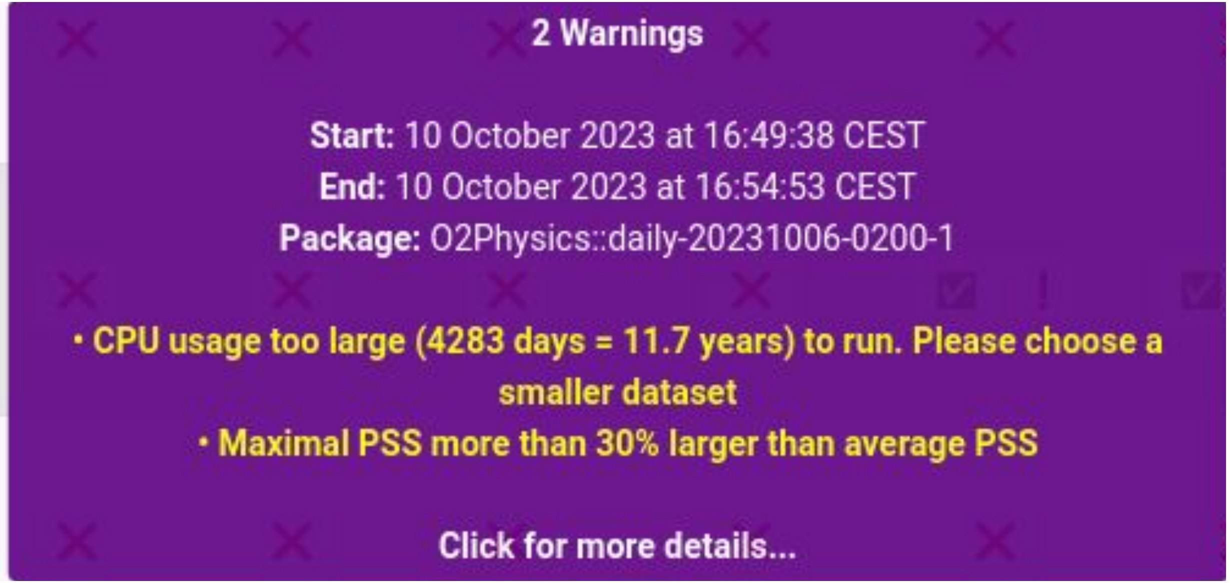


Tracks

Track index skim creator

Table with indices of candidate 2,3-prong daughters

- Large resource consumption in the combinatorics
- Not possible to run on large datasets: only `_small` ones allowed w/o PB approval



2 Warnings

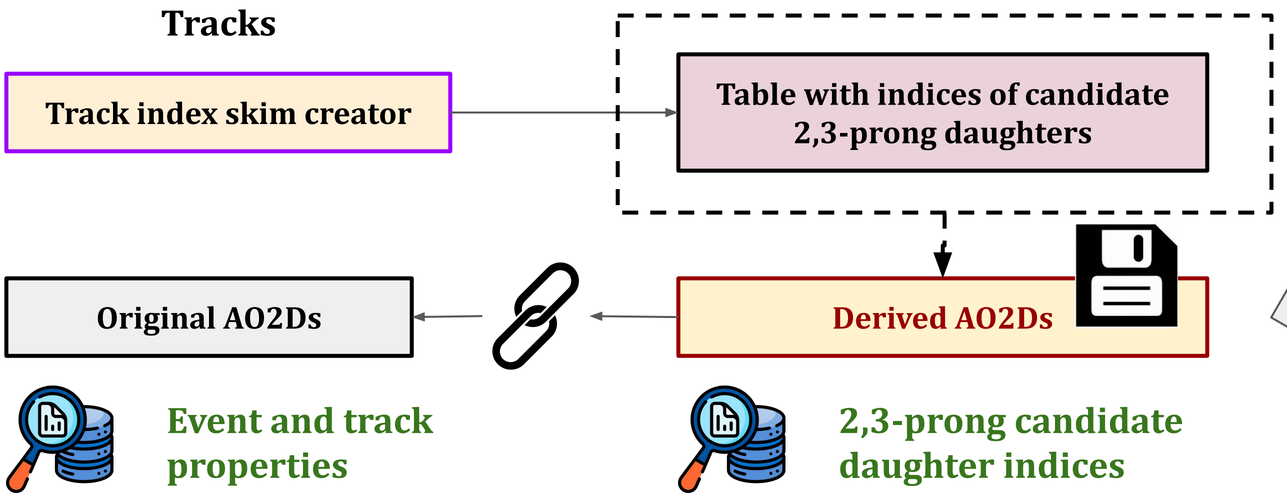
Start: 10 October 2023 at 16:49:38 CEST
End: 10 October 2023 at 16:54:53 CEST
Package: O2Physics::daily-20231006-0200-1

- CPU usage too large (4283 days = 11.7 years) to run. Please choose a smaller dataset
- Maximal PSS more than 30% larger than average PSS

Click for more details...

Linked derived data

NEW



Tracks

Track index skim creator

Table with indices of candidate 2,3-prong daughters

Original AO2Ds

Derived AO2Ds

Event and track properties

2,3-prong candidate daughter indices

- **Derived AO2Ds**: .root files saved on disk containing the **table with indices of candidate 2,3-prong daughters**
- Each analysis runs on these derived AO2Ds, w/o the need to rerun the combinatorics anymore!
- Derived AO2Ds linked to the original AO2Ds.root from the data reconstruction in Hyperloop
  → **query of original or derived AO2Ds depending on the requested info**

Execution for each big dataset once for all by PWG conveners

Start (shorter) analysis workflow from here!

- Preparation ongoing on different data and MC datasets
- **Self-contained** derived data creation possible for multi-staged analyses (e.g. B mesons) → **to be produced by the analysers**

DO NOT MISS!

09:30 Derived data production and usage in HF

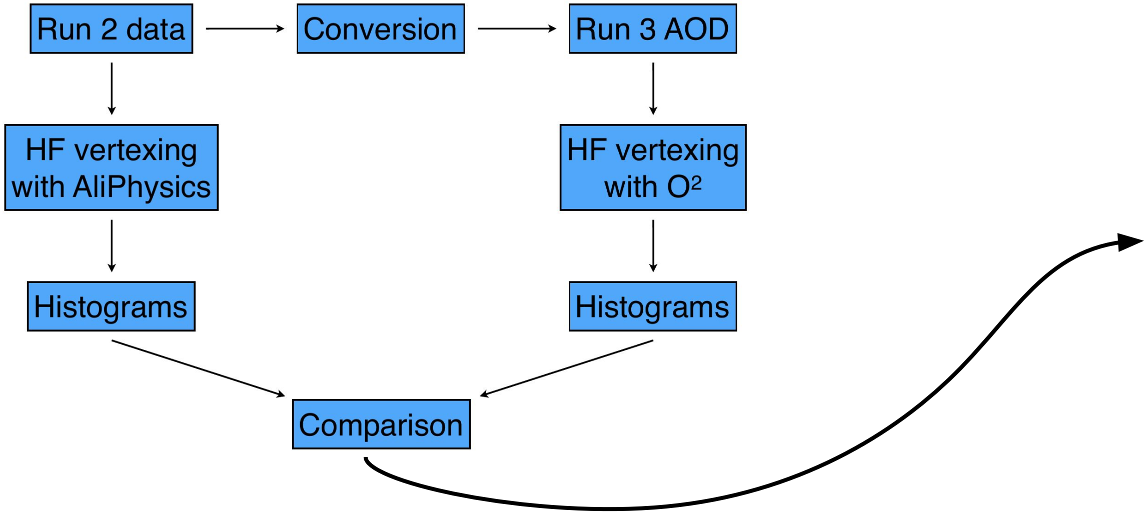
Speaker: Fabrizio Grosa (CERN) link

Validation framework

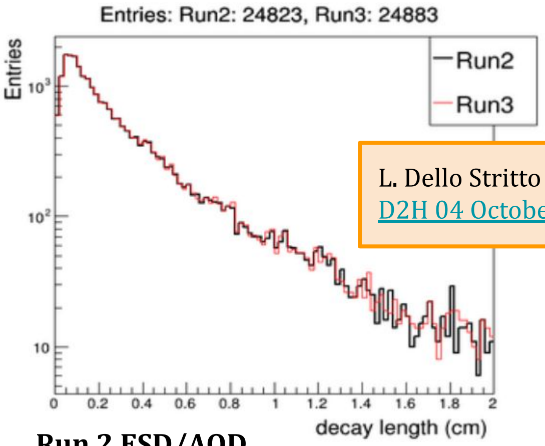
Tool for an easy execution, testing and validation of O^{2}Physics tasks
https://github.com/AliceO2Group/Run3Analysisvalidation

- ESD → AO2D conversion (or centrally Run 2 converted data)
- Execution of [Ali/O^2]Physics analysis tasks
- Job parallelisation, output merging, error checking, postprocessing
- Easy generation of the O^2 pipeline from a database of workflows and options

Detailed explanation of the framework in HF O^2 hackathon, 7-9 December 2021



Example: $\Lambda_c^+ \rightarrow pK^-\pi^+$



L. Dello Stritto
D2H 04 October 2022

Run 2 ESD/AOD
Run 2 converted into AO2D (O^2 format)

References and useful information

Mattermost: https://mattermost.web.cern.ch/alice/channels/hf-o2-analysis

Documentation:
https://aliceo2group.github.io/analysis-framework/docs/advanced-specifics/pwghf.html

O^{2}Physics code:
https://github.com/AliceO2Group/O2Physics/tree/master/PWGHF

Validation framework & postprocessing analysis tools:
https://github.com/AliceO2Group/Run3Analysisvalidation

Meetings:

- PAG/PWGHF meetings for all the technical- and analysis-related discussions
- (on demand) dedicated “technical” meetings for cross-pag issues/developments: (last: 12th September 2023)
  → Core HF development, utilities, processing, MC tools,. . .

Thanks a lot for your attention …

… and enjoy the hands-on session!

Backup