



Searching for rare charm decays, performing alignment studies and improving the analysis ecosystem in HEP

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The University of Manchester



Chris Burr

LHCb UK 2020, 6th January 2020

- Thank you!
- Defended my thesis in July 2019 containing:
 - Alignment of telescope like detectors
 - Searching for $D_{(s)}^+ \rightarrow h^\pm l^+ l'^\mp$
 - Tools for analysis

DOCTORAL THESIS

Searching for rare charm decays,
performing alignment studies and
improving the analysis ecosystem in HEP

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*A thesis submitted to the University of Manchester
for the degree of Doctor of Philosophy in the*

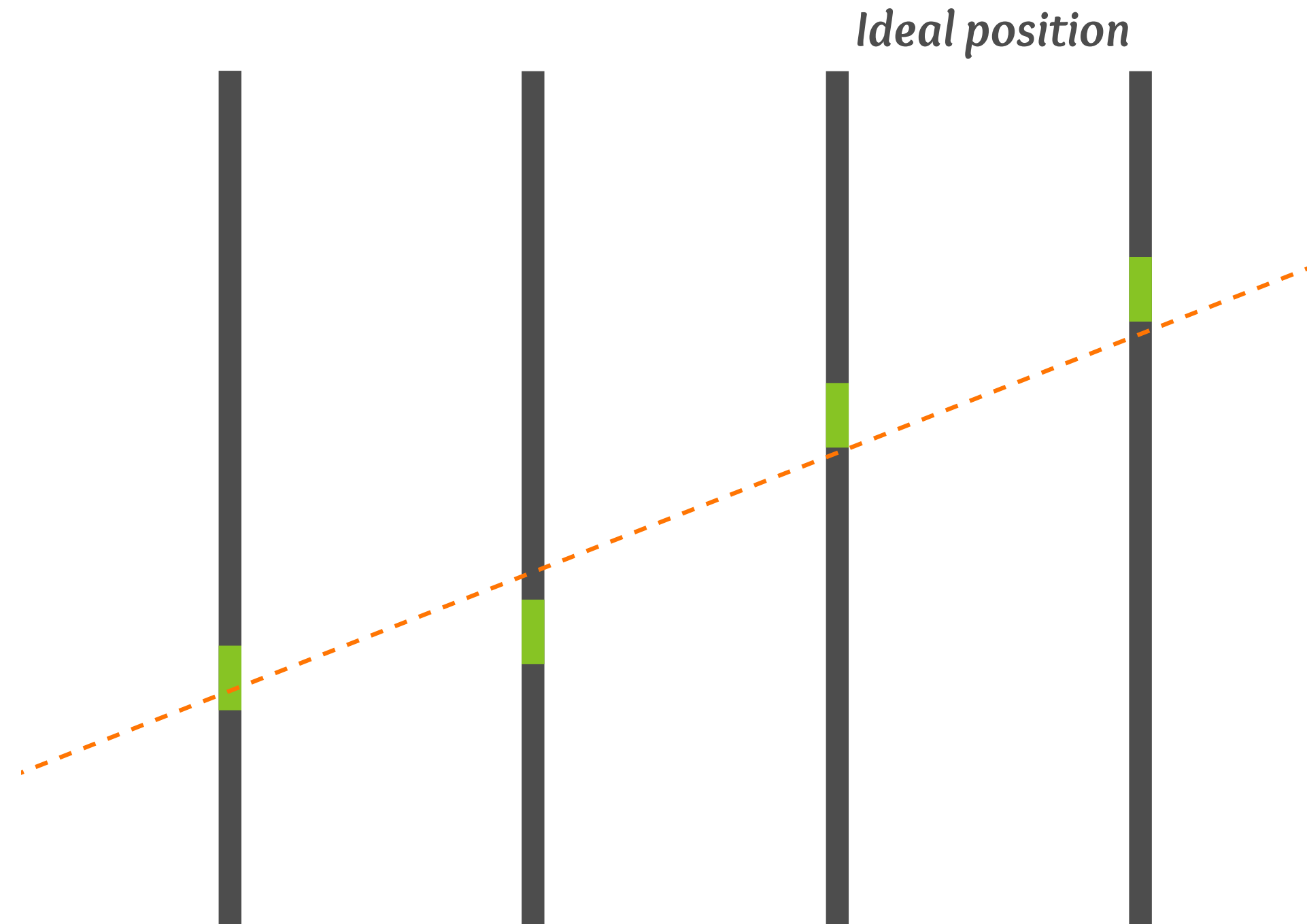
School of Physics and Astronomy
Faculty of Science and Engineering

2019

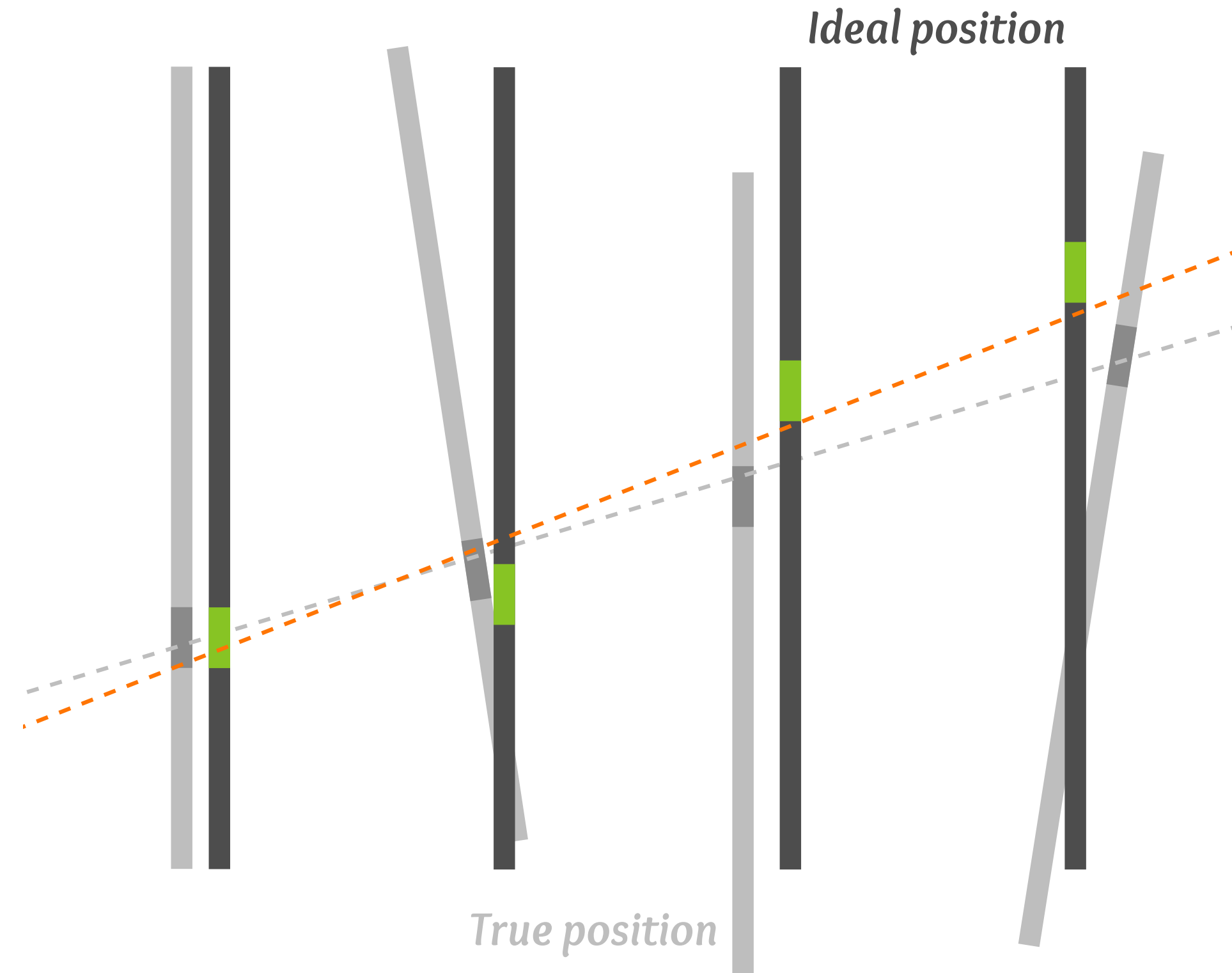


A modern building with a curved glass facade and a decorative metal structure on top, situated at a street intersection. The building features a prominent curved section with a glass facade, topped with a series of vertical, curved metal elements. The rest of the building is a multi-story structure with a light-colored, textured facade. The building is located at a street intersection with traffic lights and a road sign. The sky is blue with some clouds.

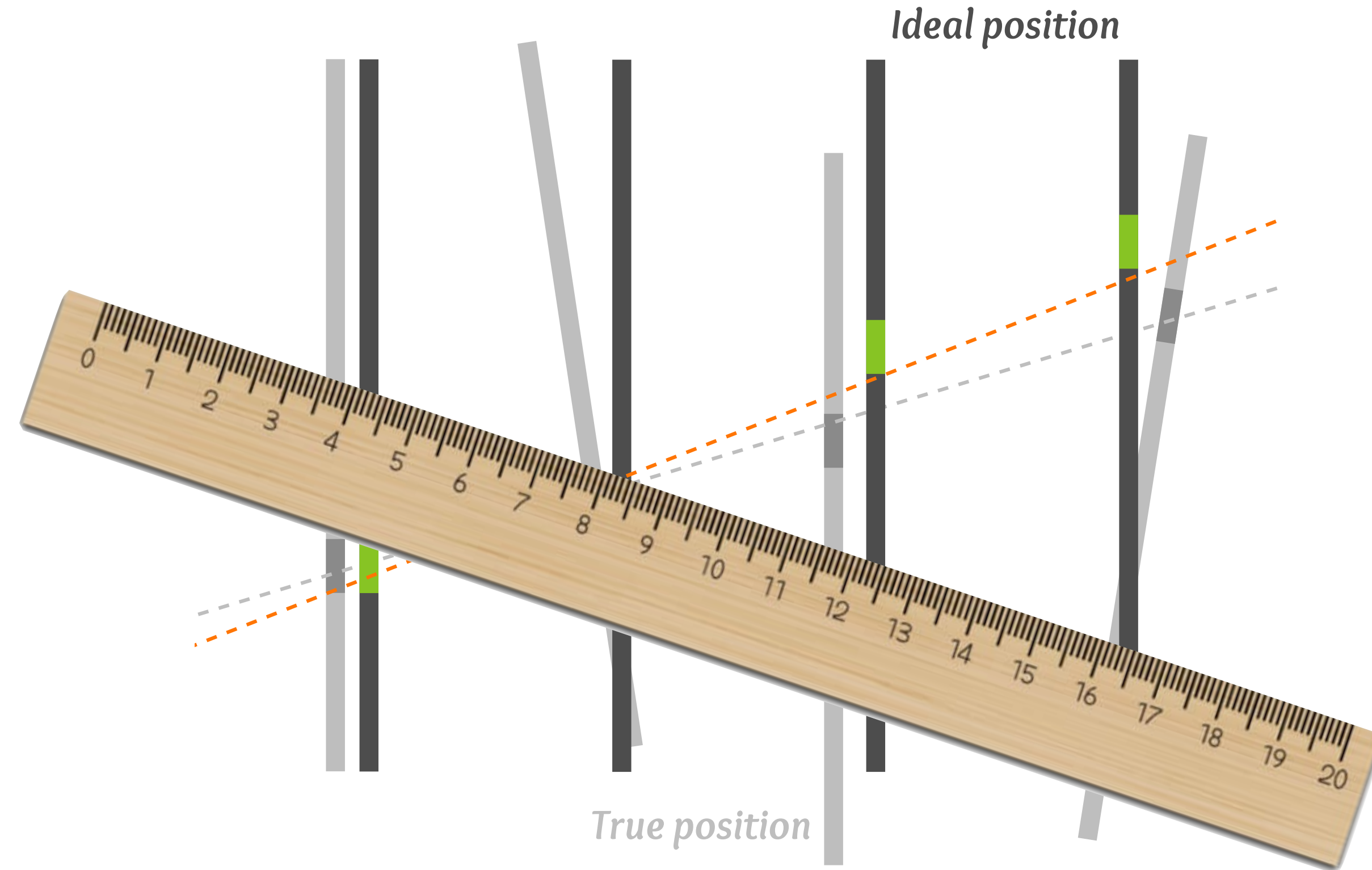
Track based detector alignment



- **Problem:** It's impossible to build a perfectly positioned detector
 - Reduces the performance of the detector
 - Can introduce biases in measurements

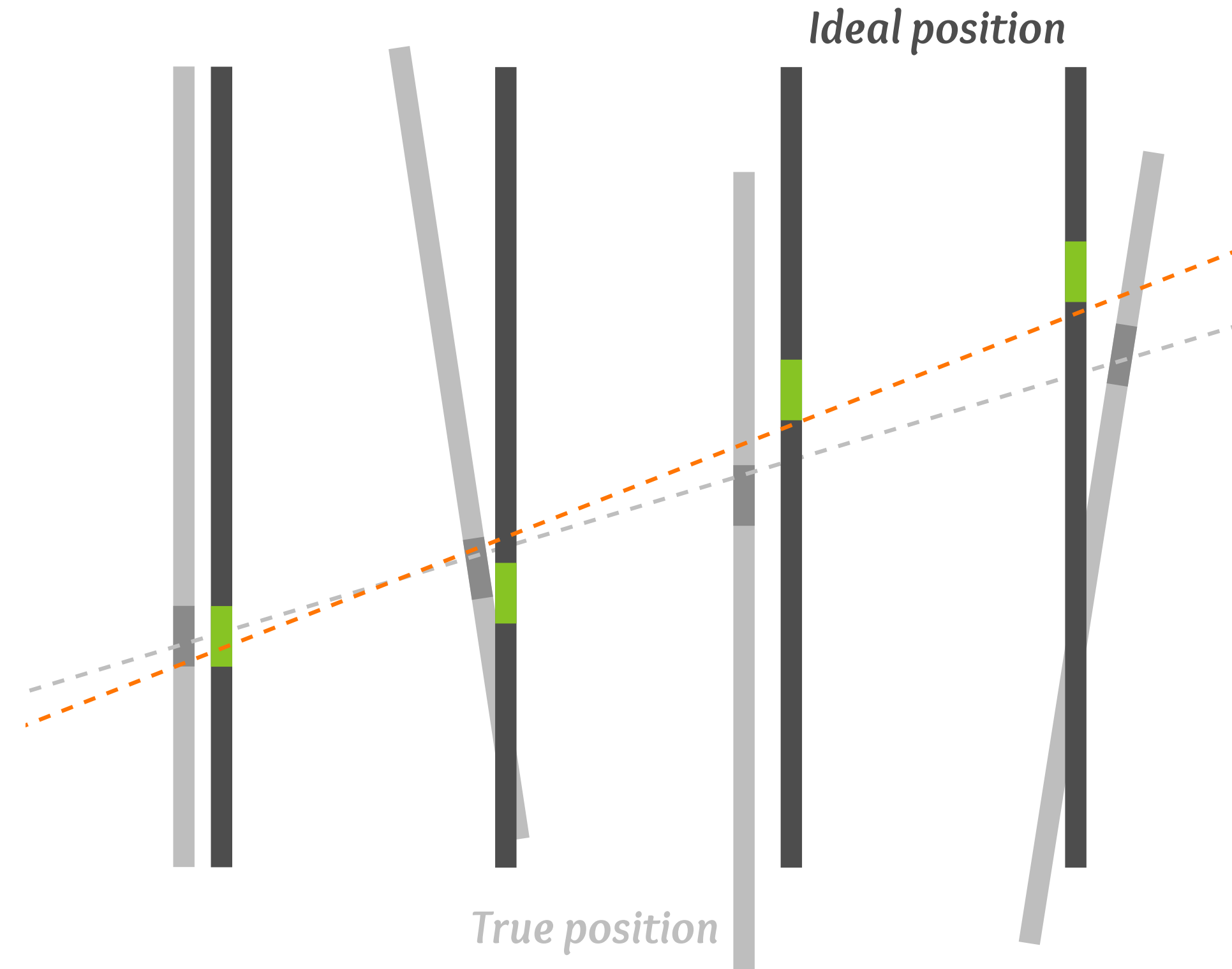


- **Problem:** It's impossible to build a perfectly positioned detector
 - Reduces the performance of the detector
 - Can introduce biases in measurements



- **Solution?** Measure the true position of each detector element?
 - Helpful but it's effectively impossible to make precise enough measurements
 - Some detectors move, e.g. VELO closing, tracking stations are moved by magnet polarity flips

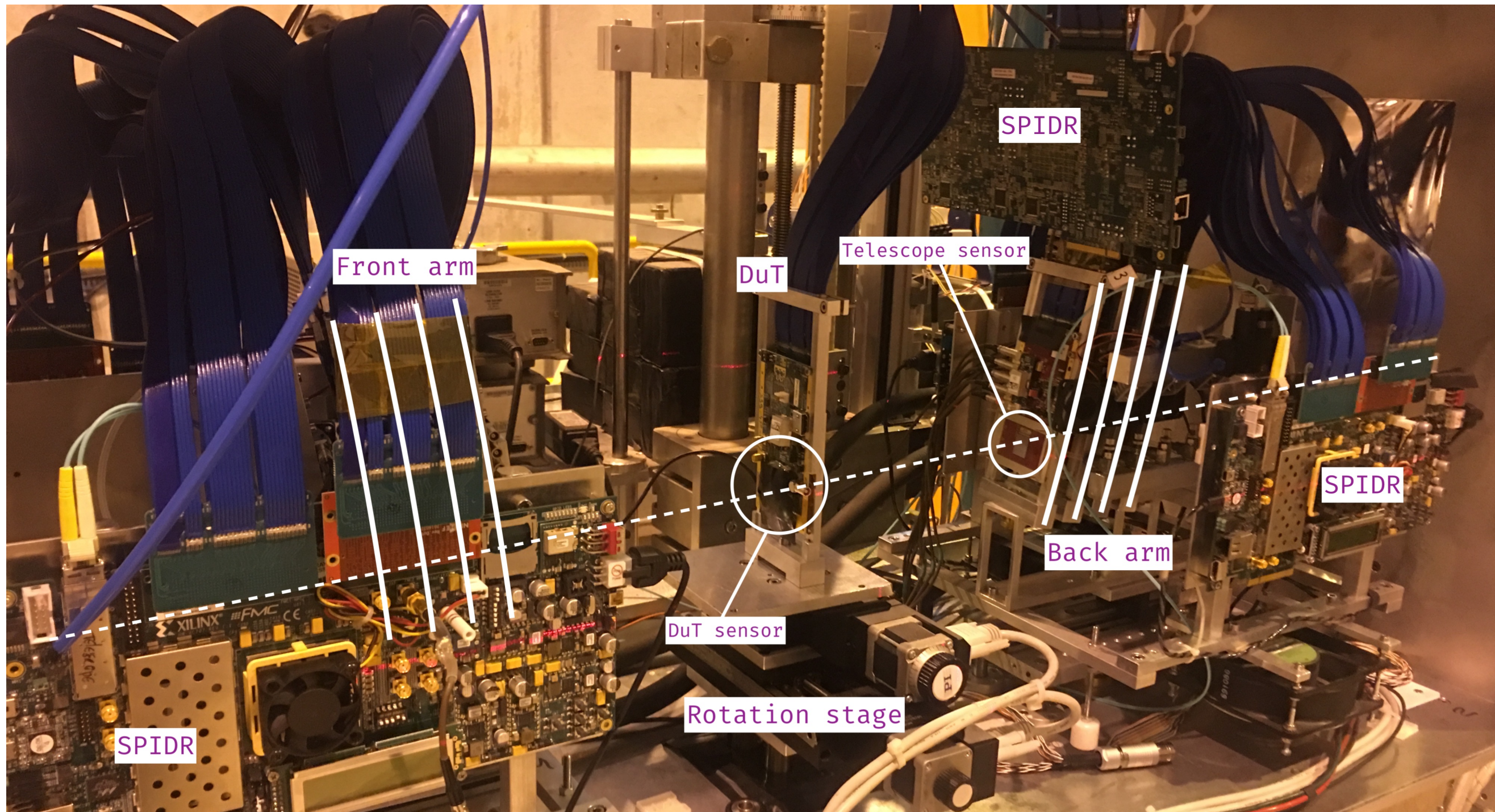
**No wooden rulers were irradiated in the construction of this presentation*



► **Solution:** Track based alignment techniques

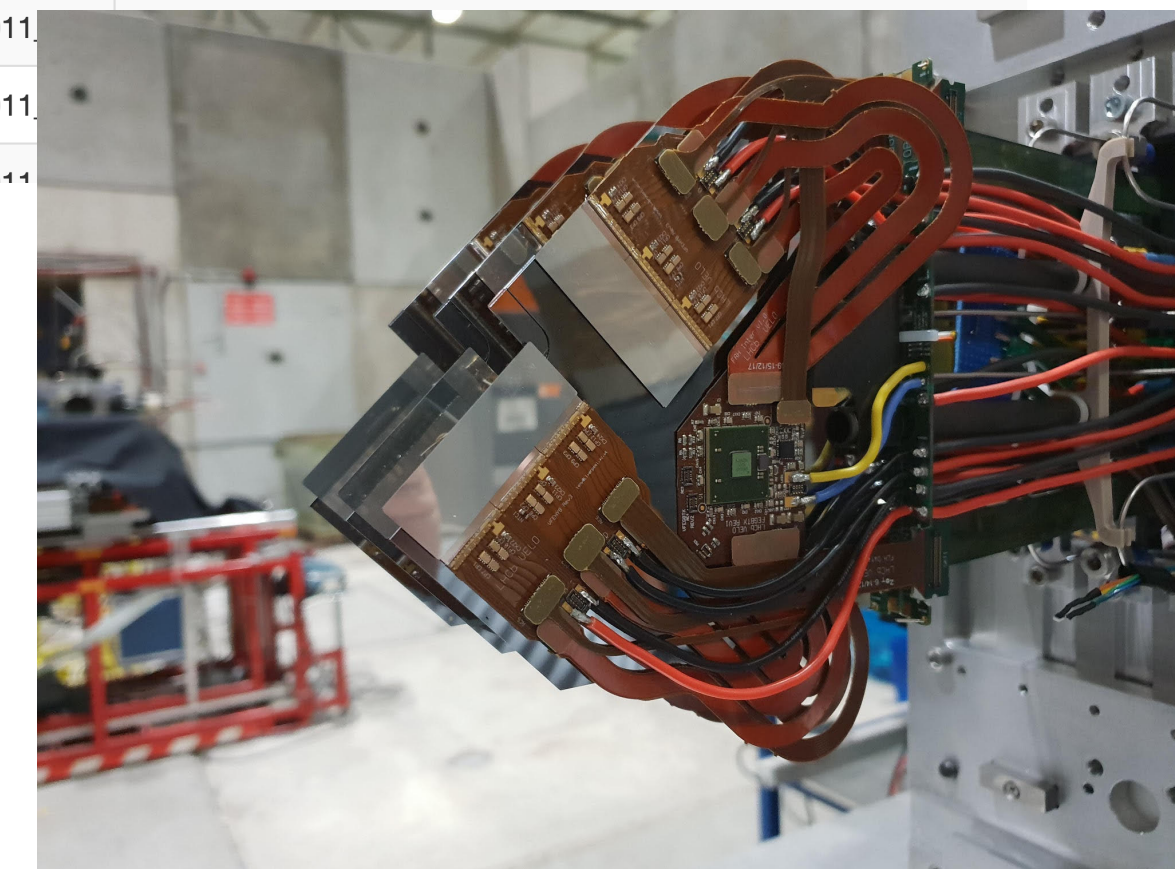
- The **grey** track has a smaller χ^2 than the **orange** track
- Move the detector elements until the χ^2 of many tracks is at a minimum

Testbeam alignment



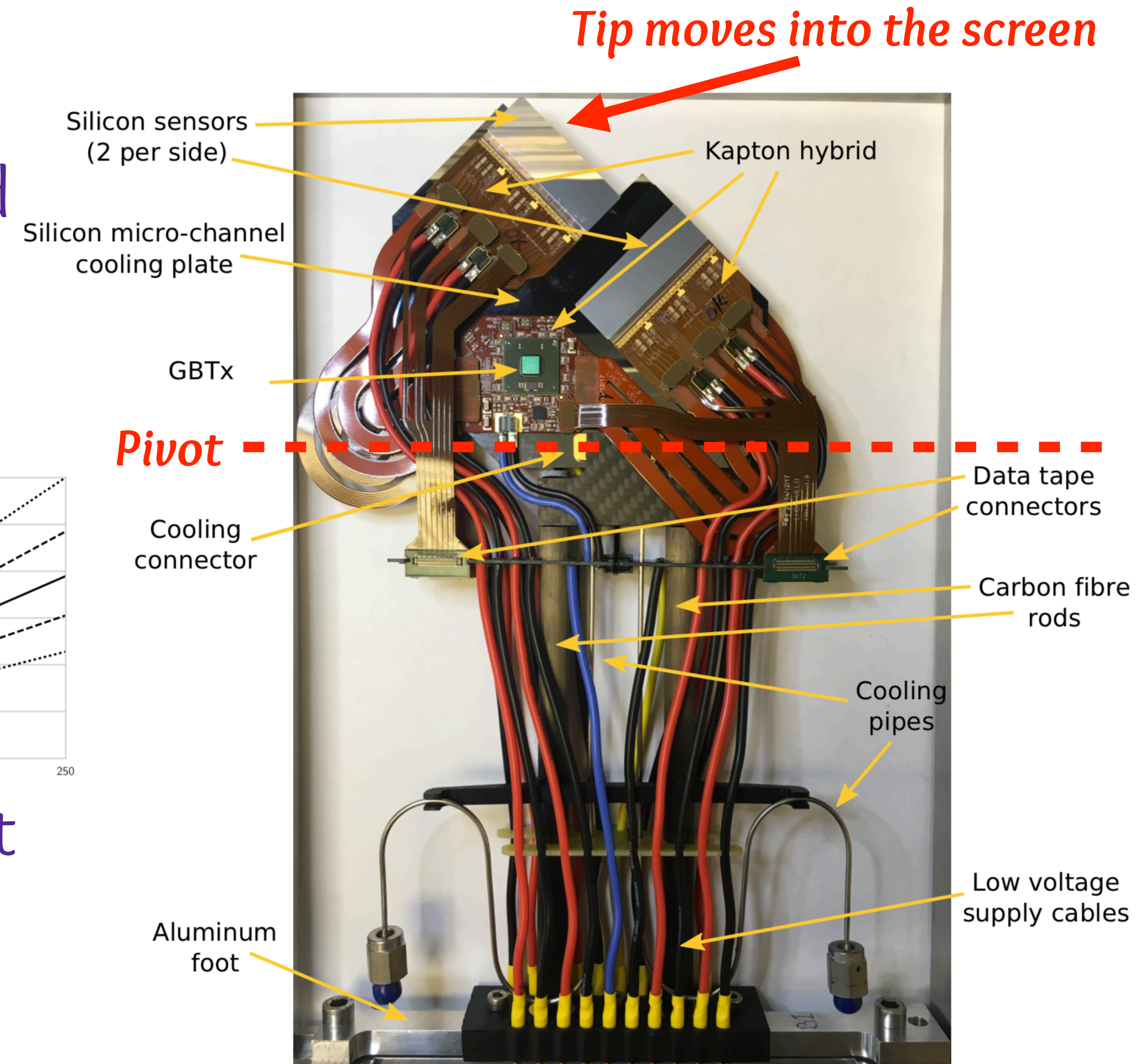
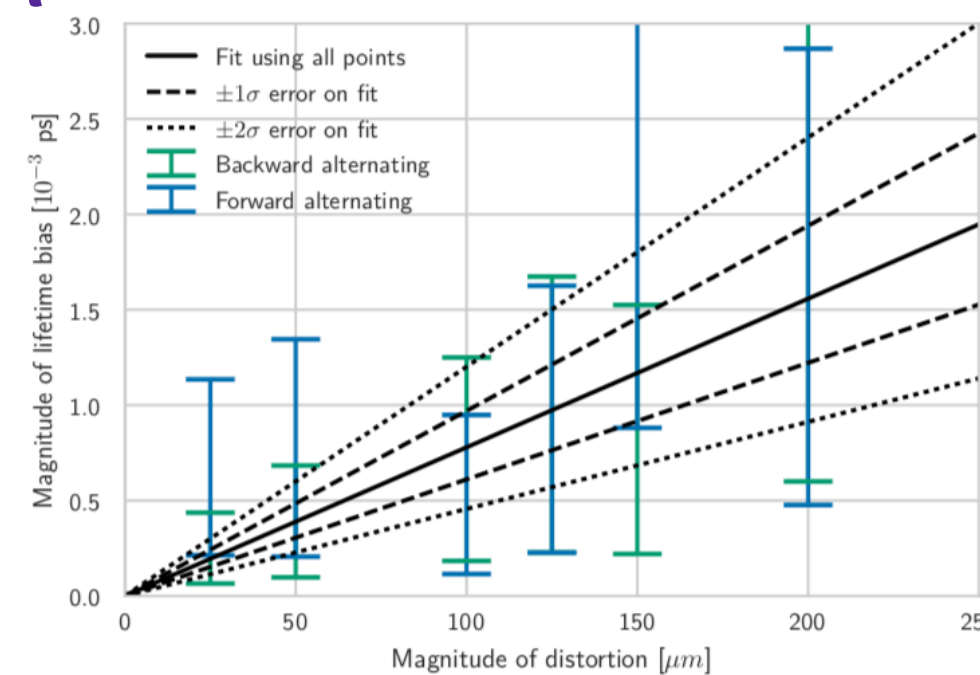
Timepix3 alignment status June2017

Status		a..z		Run	DuT	Comment
Local	EOS	Z	Shift			
OKDUT	OKDUT			22024	W0011_F04,W0011_I04,W0011_J04	x=67mm, y=26mm, bias 150V, angle -2 degrees mean cluster size =
OKDUT	OKDUT			22025	W0011_F04,W0011_I04,W0011_J04	x=67mm, y=26mm, bias 150V, angle -3 degrees mean cluster size =
GOOD	GOOD			22026	W0011_F04,W0011_I04,W0011_J04	x=67mm, y=26mm, bias 150V, angle -5 degrees mean cluster size =
ALIGNFAIL	BADDUT			22027	W0011_F04,W0011_I04,W0011_J04	x=46mm, y=26mm, bias 150V, angle 0 (-2.2)
GOOD	GOOD			22028	W0011_F04,W0011_I04,W0011_J04	x=85mm, y=26mm, bias 150V, angle 0 (-2.2)
GOOD	GOOD			22029	W0011_F04,W0011_I04,W0011_J04	x=89mm, y=26mm, bias 150V, angle 0 (-2.2)
GOOD	GOOD			22030	W0011_F04,W0011_I04,W0011_J04	x=92mm, y=30mm, bias 150V, angle 0 (-2.2)
GOOD	GOOD			22031	W0011_F04,W0011_I04,W0011_J04	x=93mm, y=22mm, bias 150V, angle 0 (-2.2) <- Good Long run. (10
GOOD	GOOD			22032	W0011_F04,W0011_I04,W0011_J04	x=93mm, y=22mm, bias 150V, angle 0 (-2.2)
GOOD	GOOD			22033	W0011_F04,W0011_I04,W0011_J04	x=93mm, y=22mm, bias 150V, angle 0 (-2.2)
GOOD	GOOD			22034	W0011_F04,W0011_I04,W0011_J04	x=93mm, y=22mm, bias 150V, angle 0 (-2.2) - We collected ~400Mb
GOOD	GOOD			22035	W0011_F04,W0011_I04,W0011_J04	x=93mm, y=22mm, bias 200V, angle 0 (-2.2)
GOOD	GOOD			22036	W0011_F04,W0011_I04,W0011_J04	
GOOD	GOOD			22037	W0011_F04,W0011_I04,W0011_J04	
GOOD	GOOD			22038	W0011_F04,W0011_I04,W0011_J04	



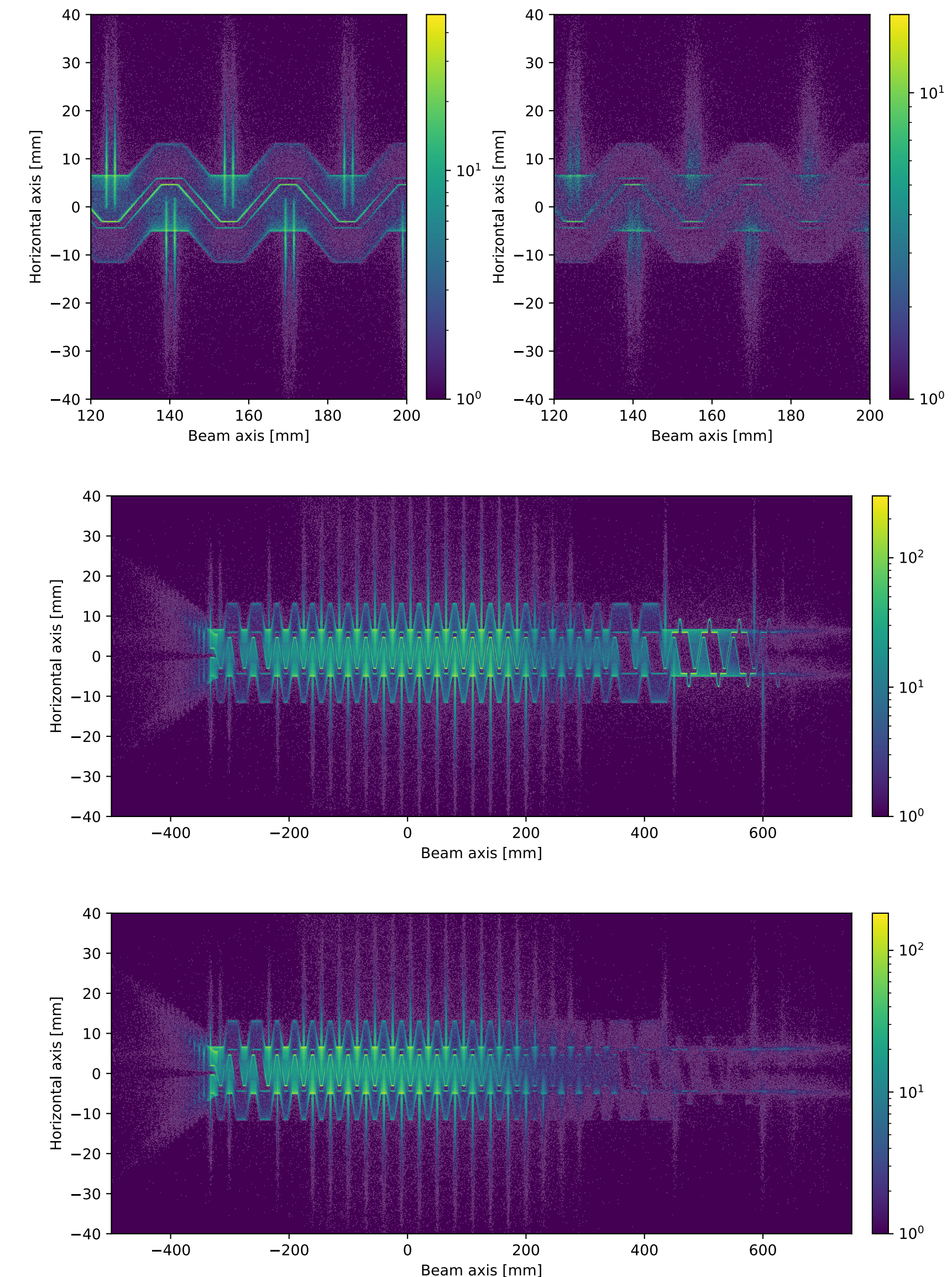
- Timepix3 telescope is mostly used for testing new LHCb detectors
- Made up of 8 planes in groups of 4
 - Test devices are placed in the middle (best resolution), in front or behind
- Many hundreds of runs have to be aligned despite detector elements moving often

- Initial studies showed the module rotated when cooled to -30°C
- Investigated the physics impact
 - Impact parameter resolution
 - Primary vertex resolution
 - Momentum resolution
 - Track quality and efficiency
- Performed a toy D^0 lifetime measurement
 - Estimated scale of potential systematic uncertainties
 - Used as input for module design



Alignment using vertices from material interactions

- **Idea: Self image the VELO for alignment**
 - Use vertices from inelastic material interactions
 - CERN summer student project supervisor
- **Initial results are promising**
 - Resolution of the image gets worse with misalignment
 - Reconstruction efficiency also drops
 - Larger samples required to make conclusive results





The search for $D_{(s)}^+ \rightarrow h^\pm l^+ l'^\mp$

- Search for 25 decays of the form $D_{(s)}^+ \rightarrow h^\pm l^+ l'^\mp$
 - h is a charged kaon or pion
 - l is an electron or muon
 - Includes LFV and LNV decays

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

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

$$D^+ \rightarrow \pi^+ \mu^+ e^-$$

$$D^+ \rightarrow \pi^- \mu^+ e^+$$

$$D^+ \rightarrow \pi^+ e^+ \mu^-$$

$$D^+ \rightarrow \pi^+ e^+ e^-$$

$$D^+ \rightarrow \pi^- e^+ e^+$$

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

$$D^+ \rightarrow K^+ \mu^+ e^-$$

$$D^+ \rightarrow K^+ e^+ \mu^-$$

$$D^+ \rightarrow K^+ e^+ e^-$$

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

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

$$D_s^+ \rightarrow \pi^+ \mu^+ e^-$$

$$D_s^+ \rightarrow \pi^- \mu^+ e^+$$

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$$D_s^+ \rightarrow \pi^+ e^+ e^-$$

$$D_s^+ \rightarrow \pi^- e^+ e^+$$

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

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

$$D_s^+ \rightarrow K^+ \mu^+ e^-$$

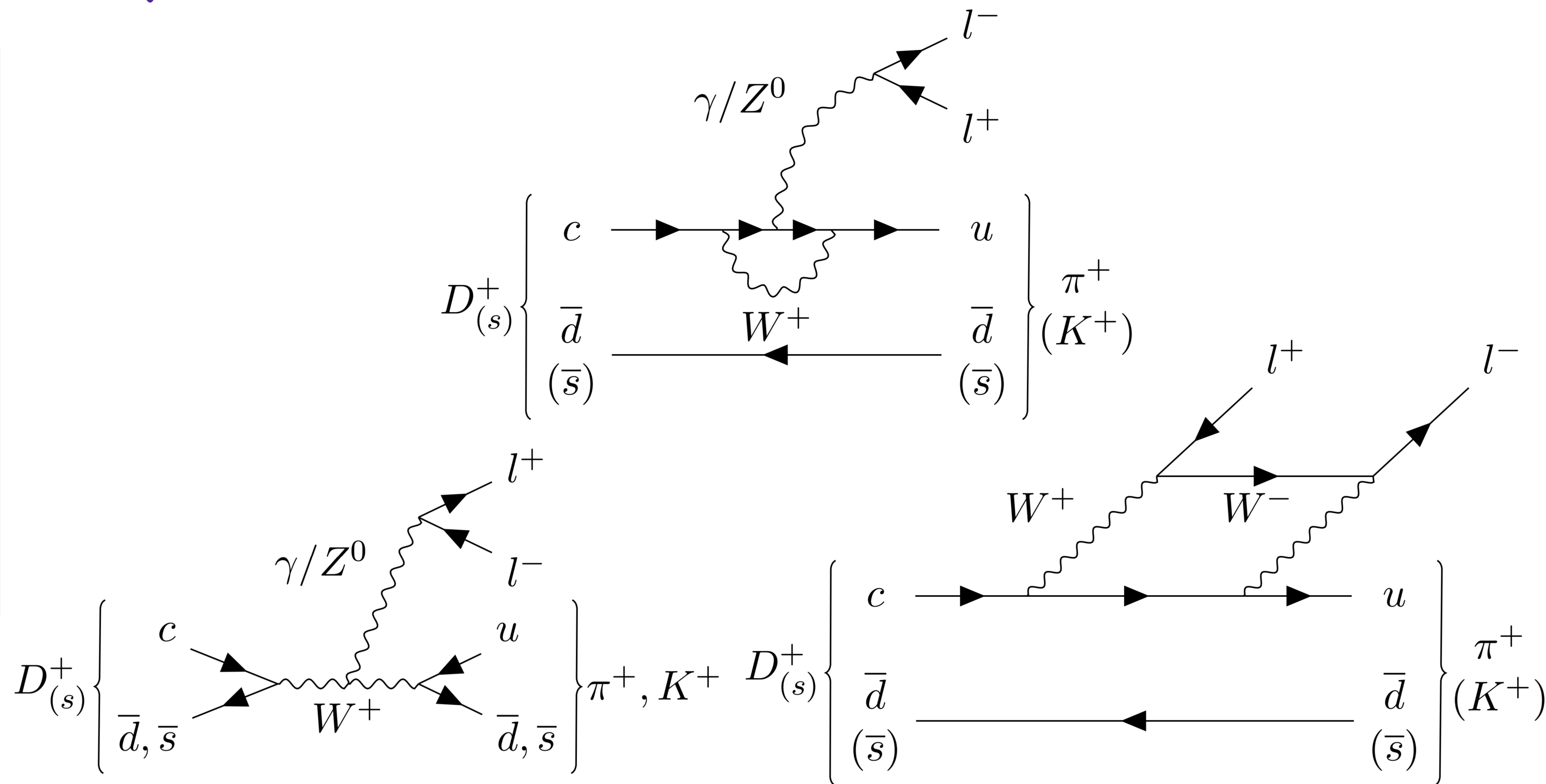
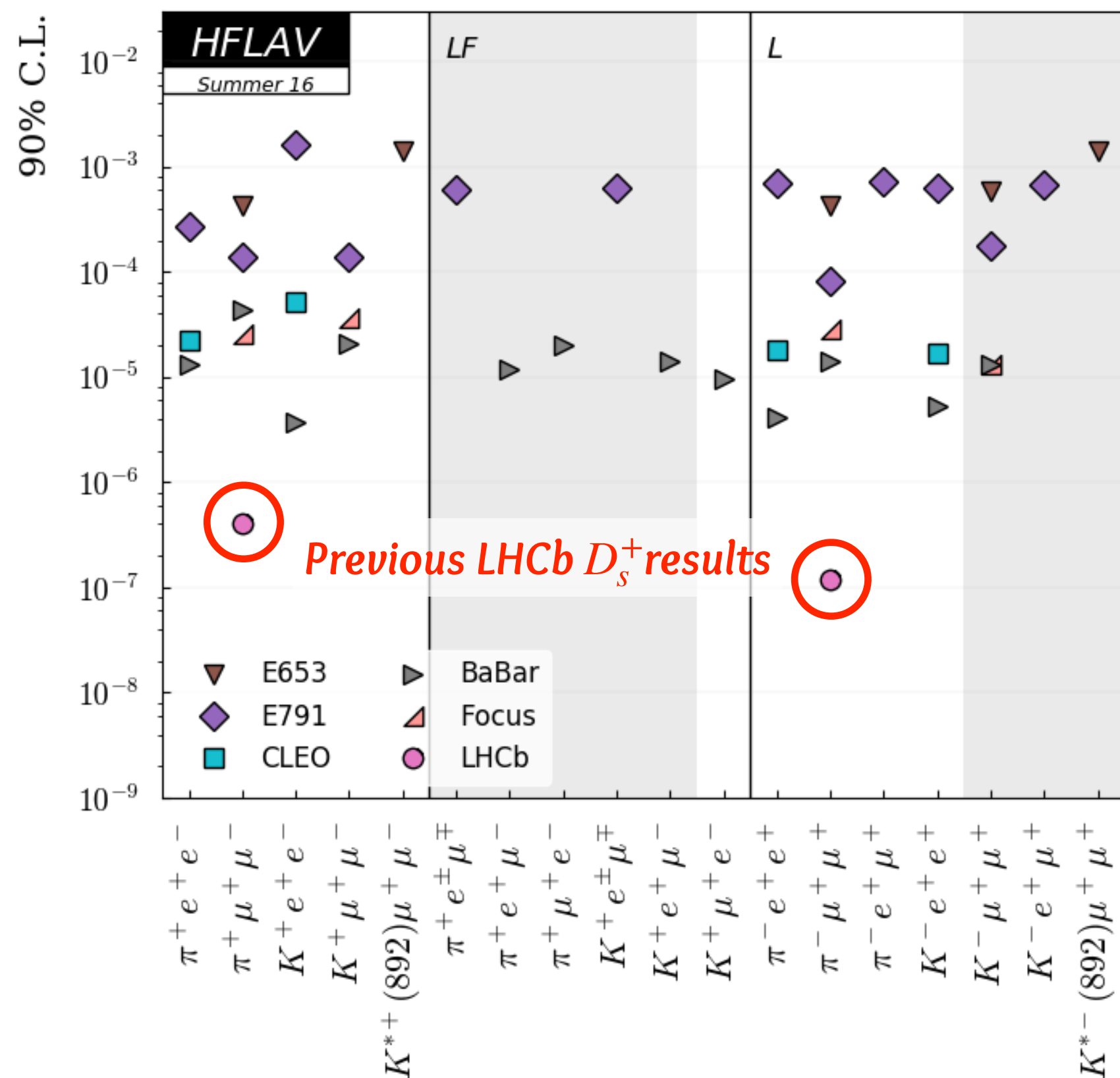
$$D_s^+ \rightarrow K^- \mu^+ e^+$$

$$D_s^+ \rightarrow K^+ e^+ \mu^-$$

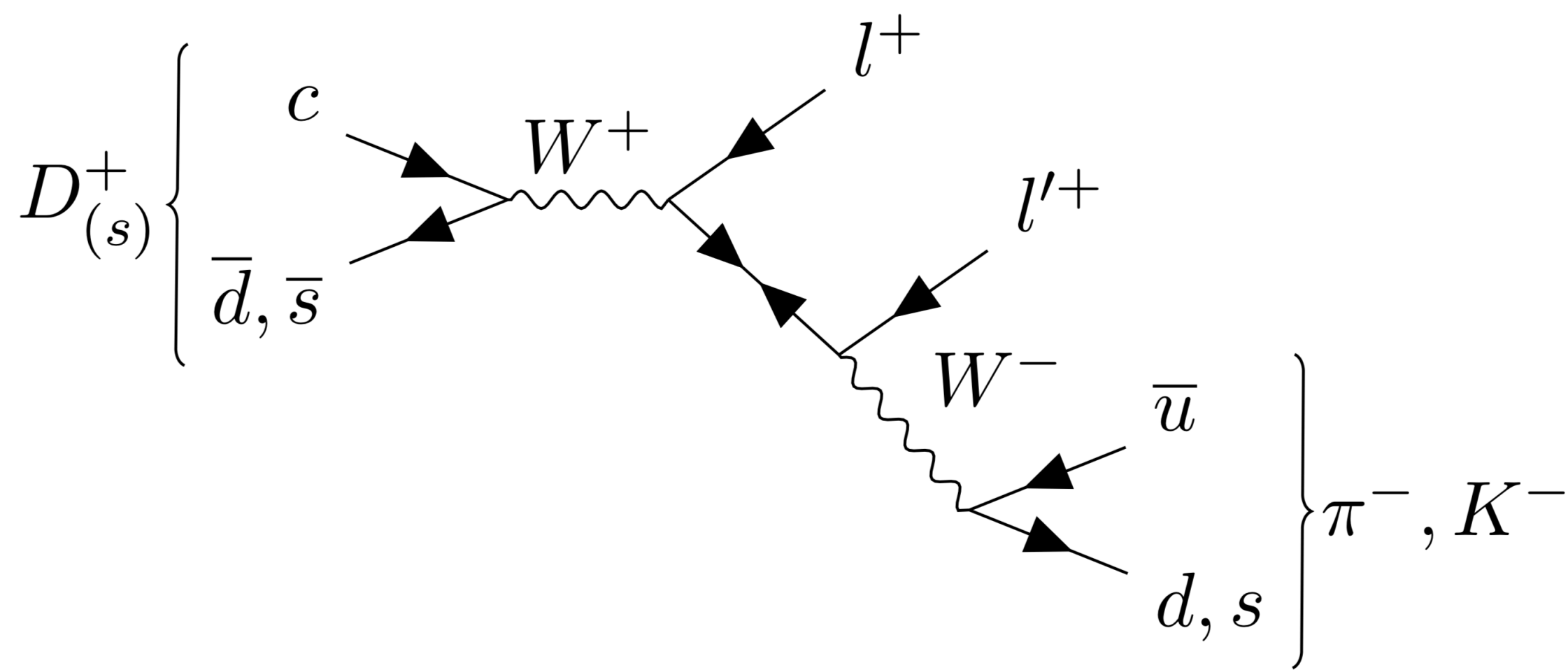
$$D_s^+ \rightarrow K^+ e^+ e^-$$

$$D_s^+ \rightarrow K^- e^+ e^+$$

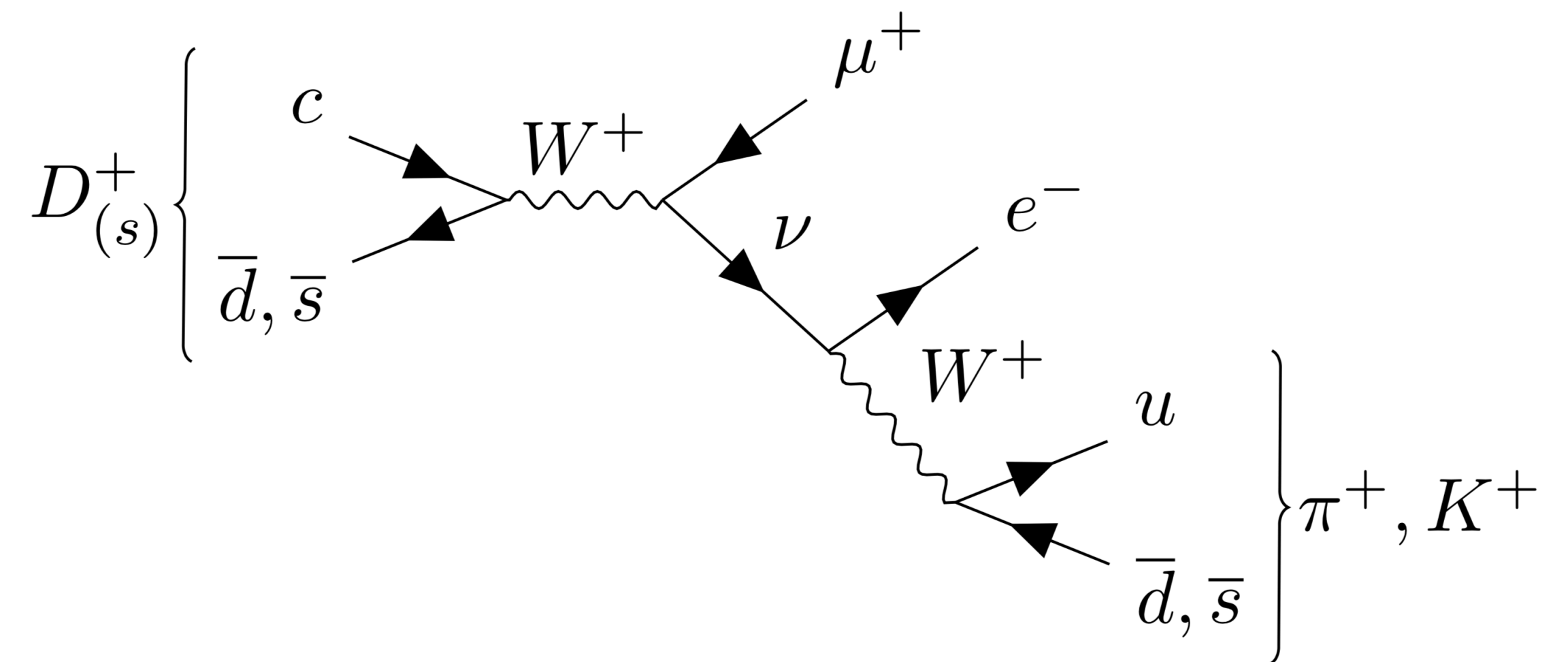
- LHCb has the world's best limit for 4 channels using 1 fb^{-1} of 7 TeV data
- Standard model allowed decays involve FCNC or Weak Annihilation



- Potential for enhancements from BSM physics (leptoquarks, MSSM, ...)
- Helps constrain Wilson coefficients
- Complimentary to other measurements



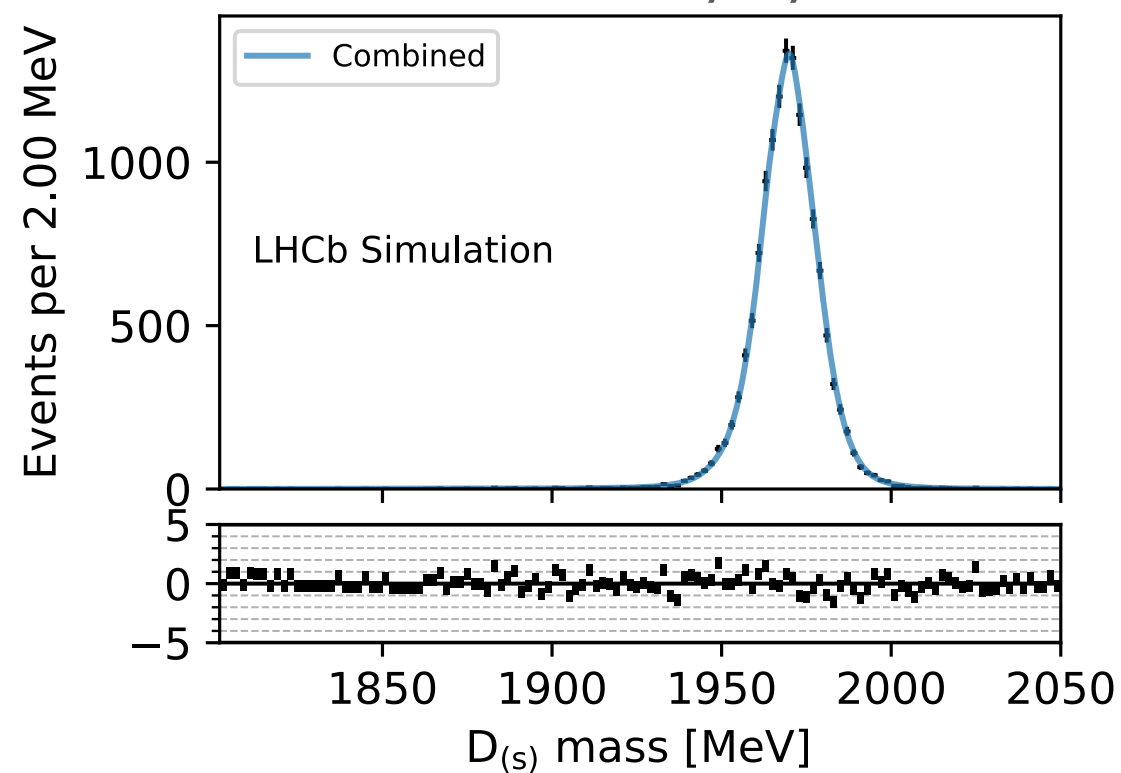
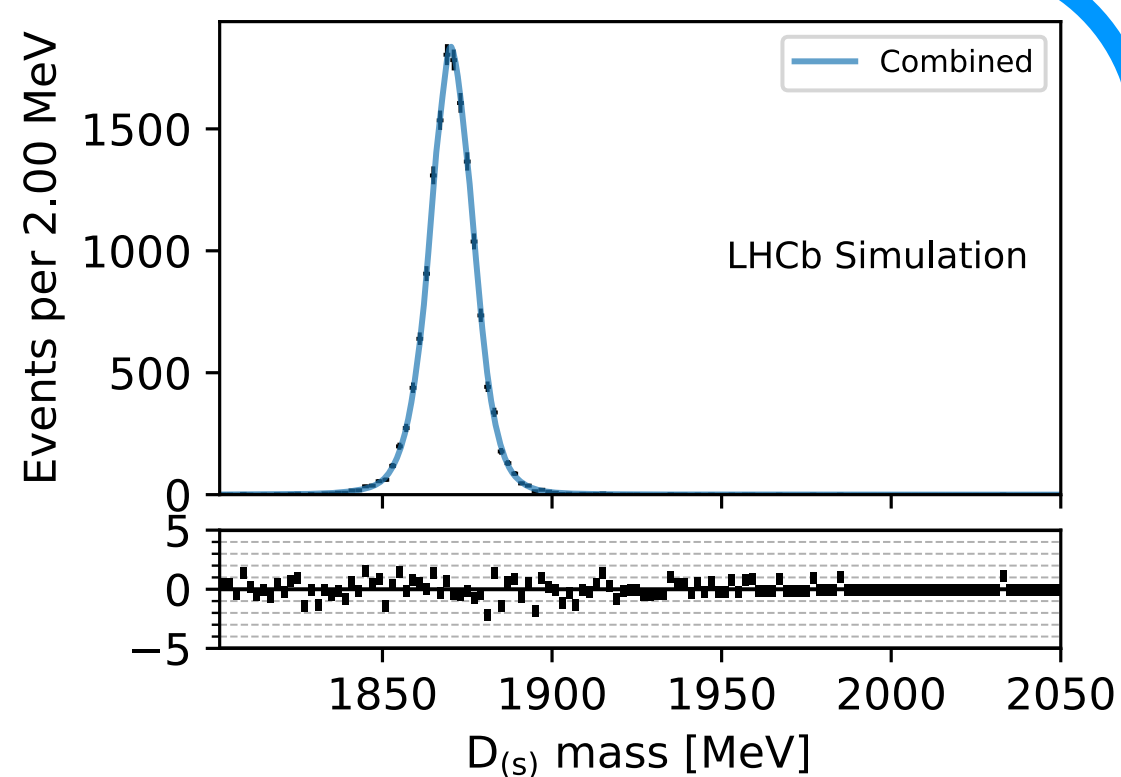
Mediated by a Majorana neutrino



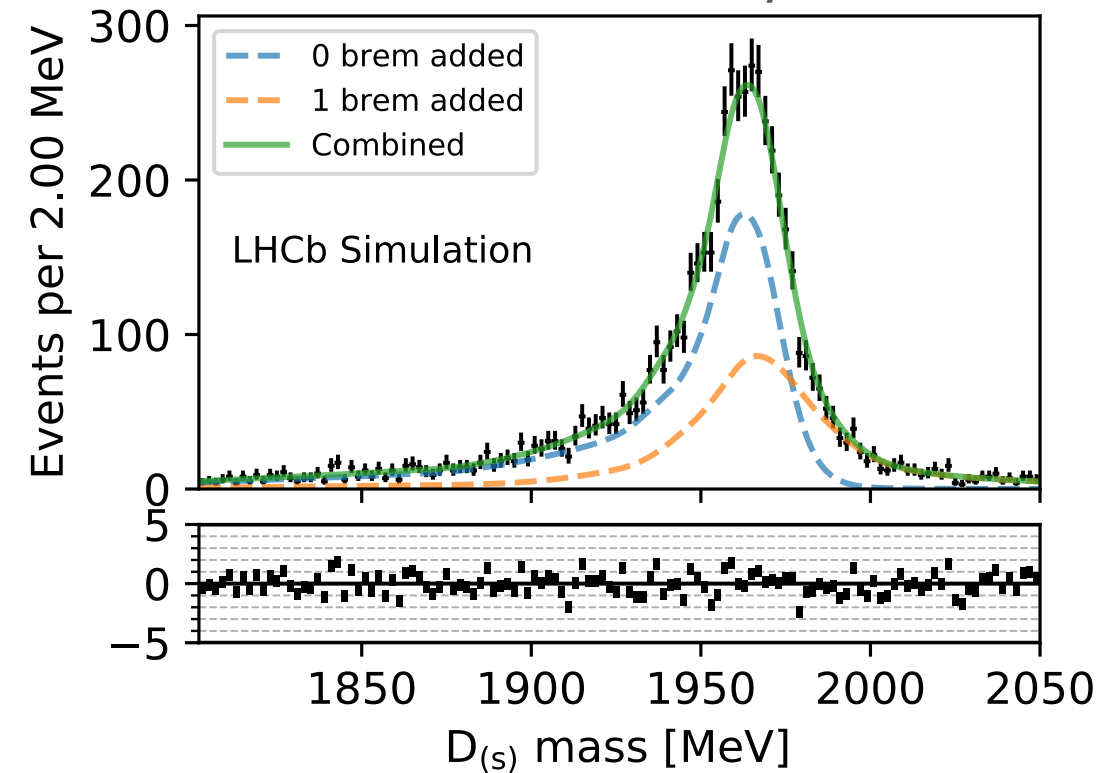
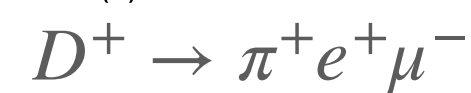
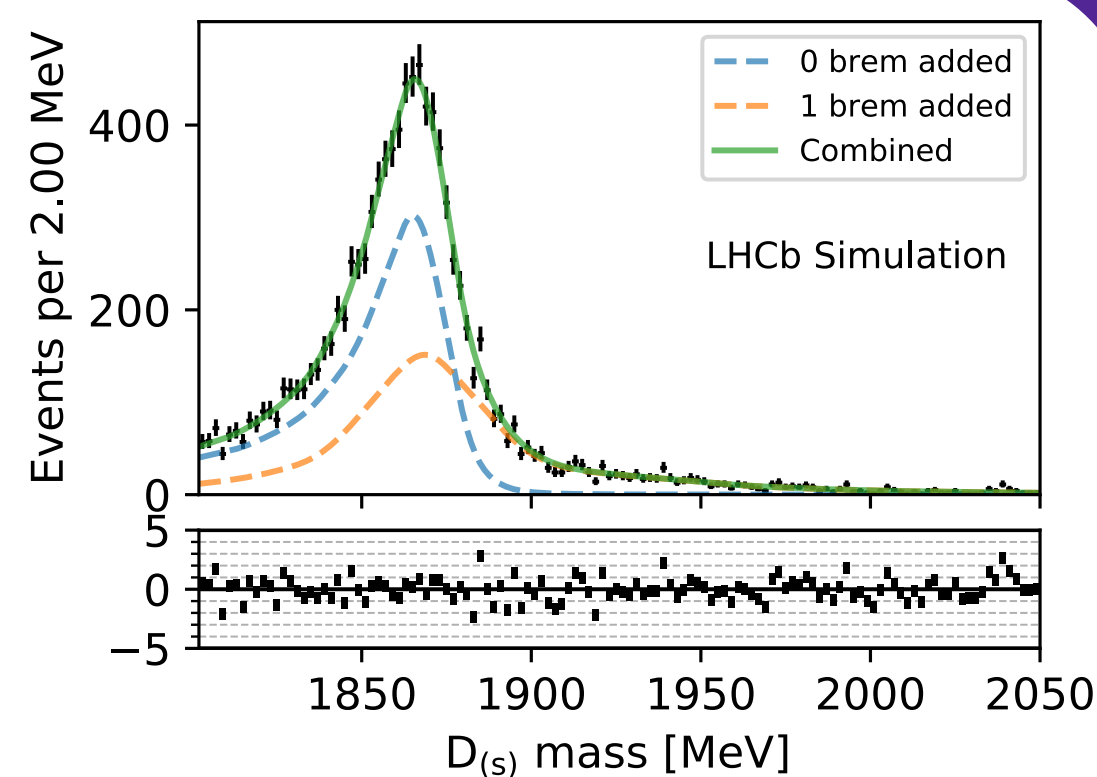
Mediated by a oscillating standard model neutrino

- Group decays into those with common features
 - Signal shape depends on the number of electrons involved
 - Use templates from full simulation depending on number of bremsstrahlung photons involved

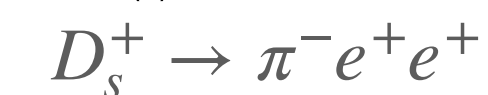
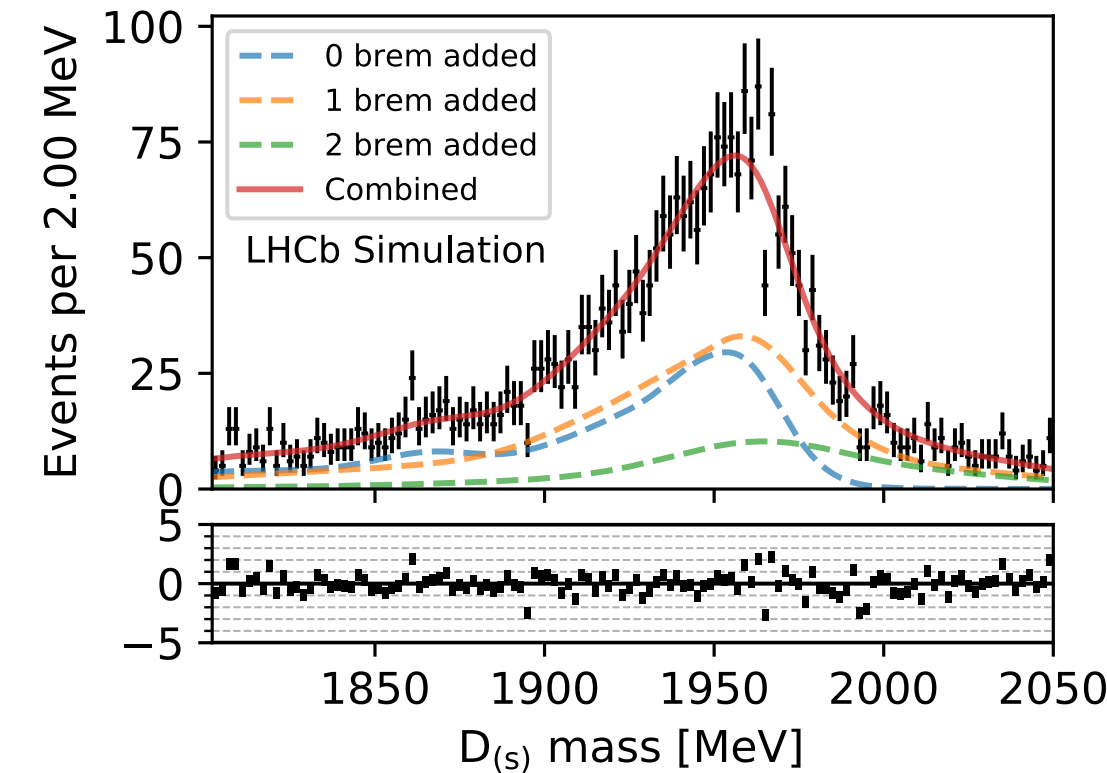
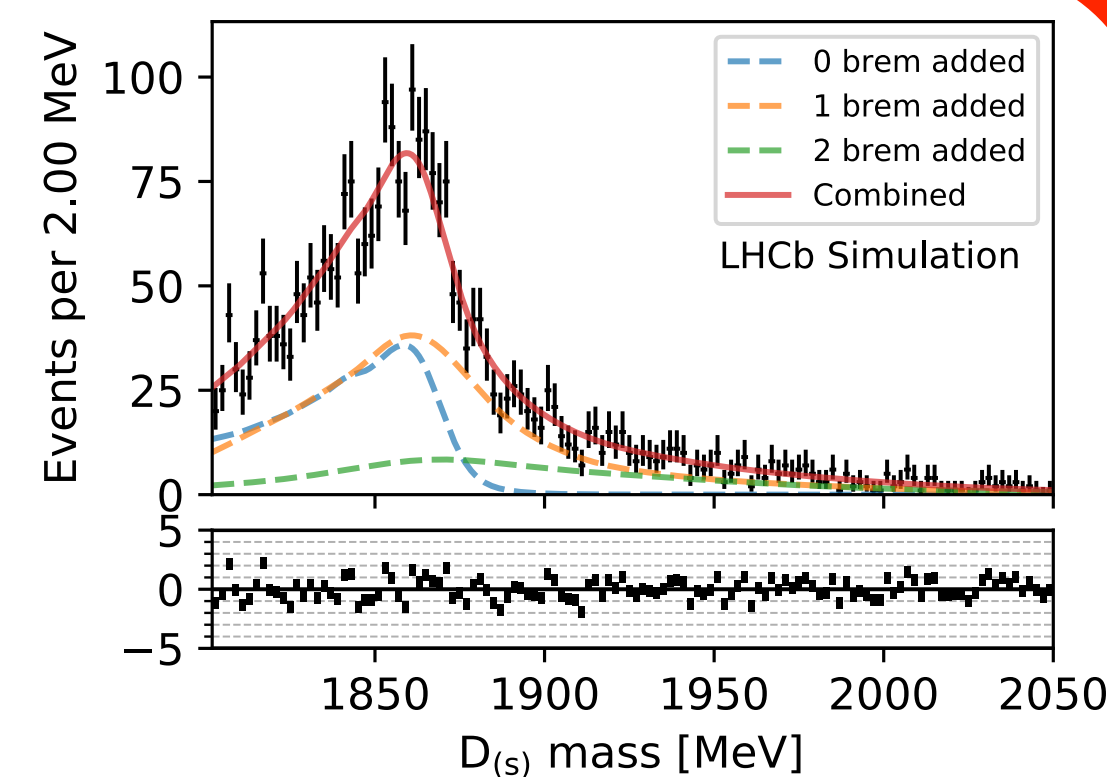
No electrons



One electron

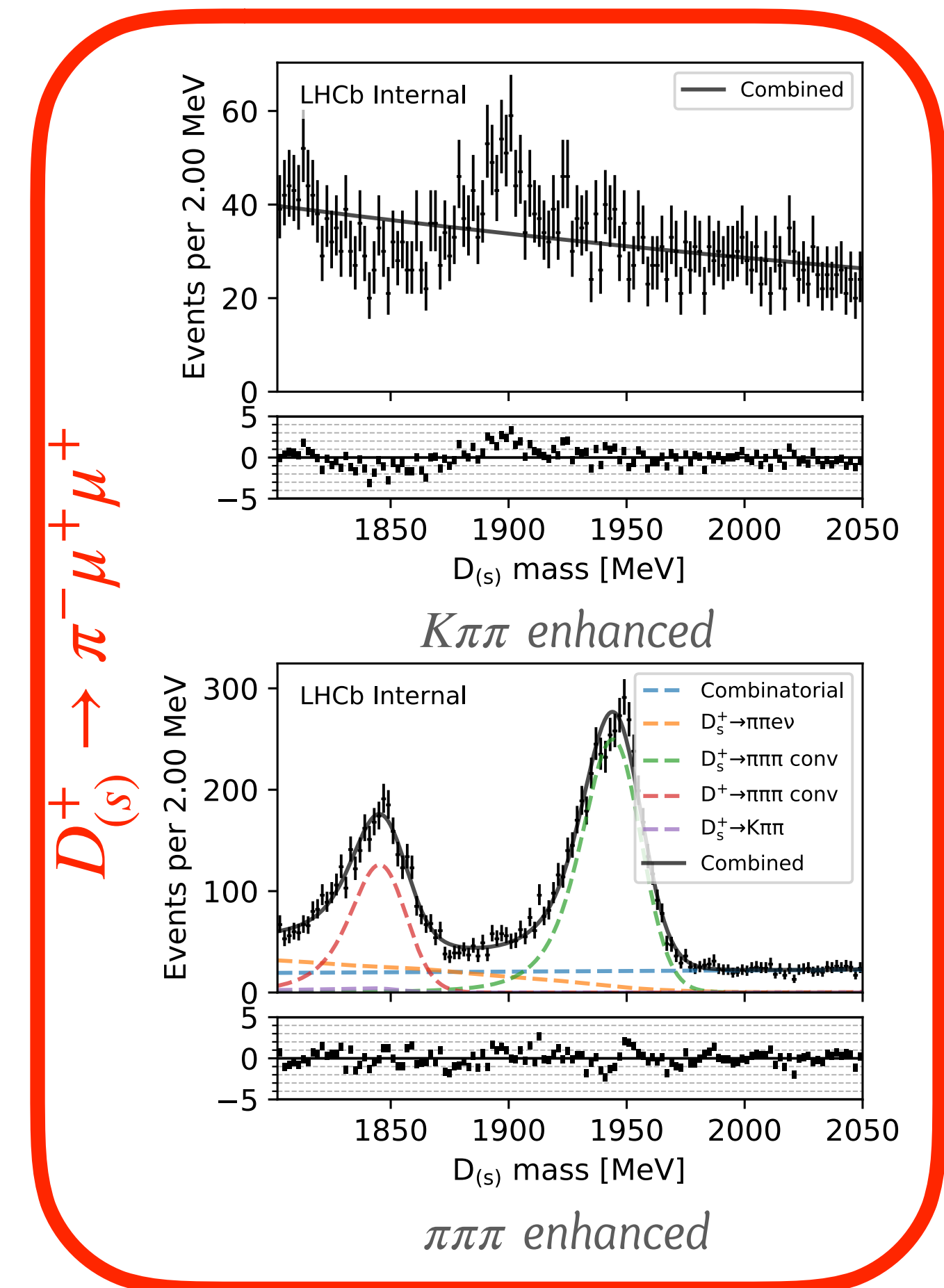
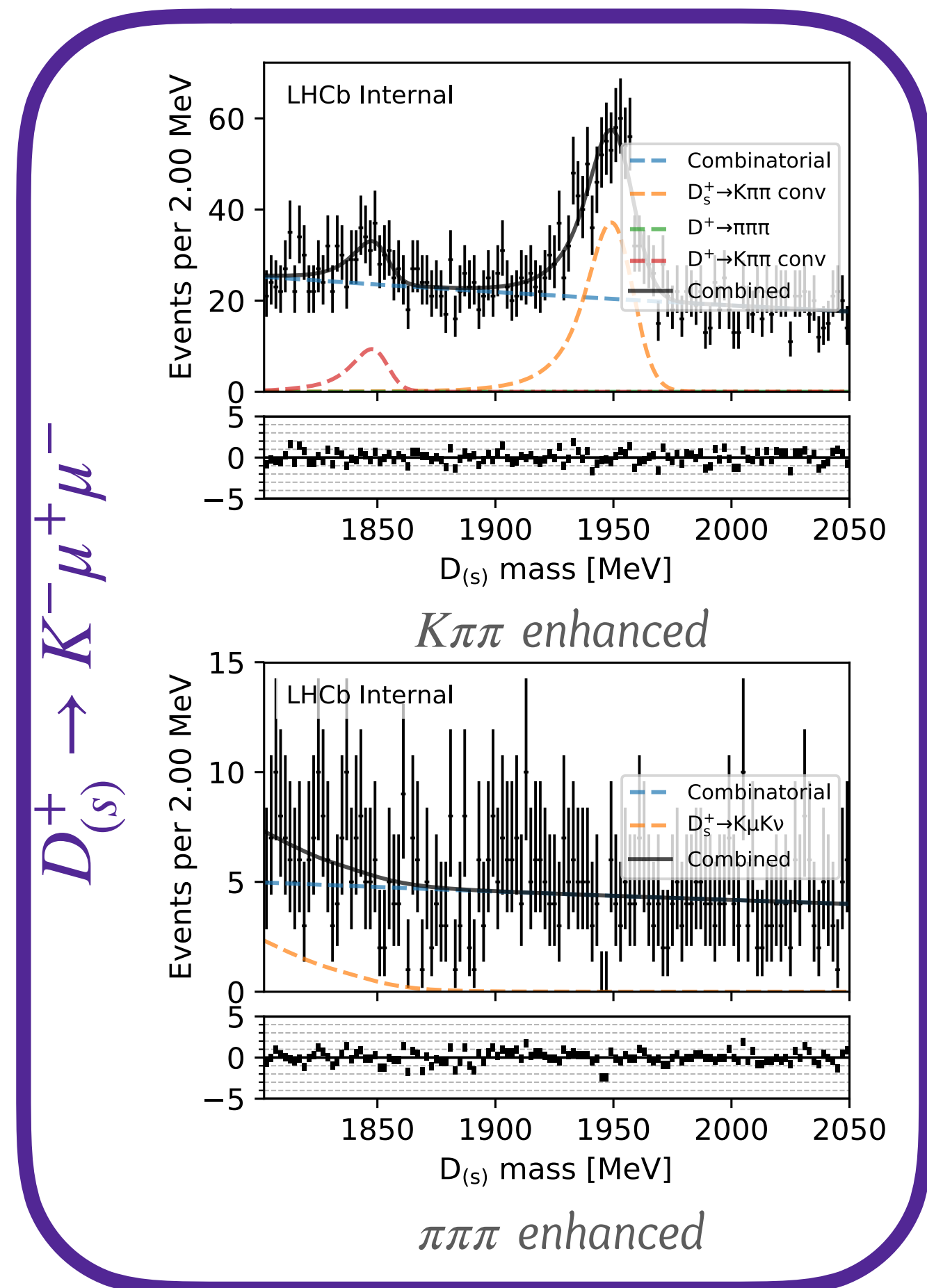
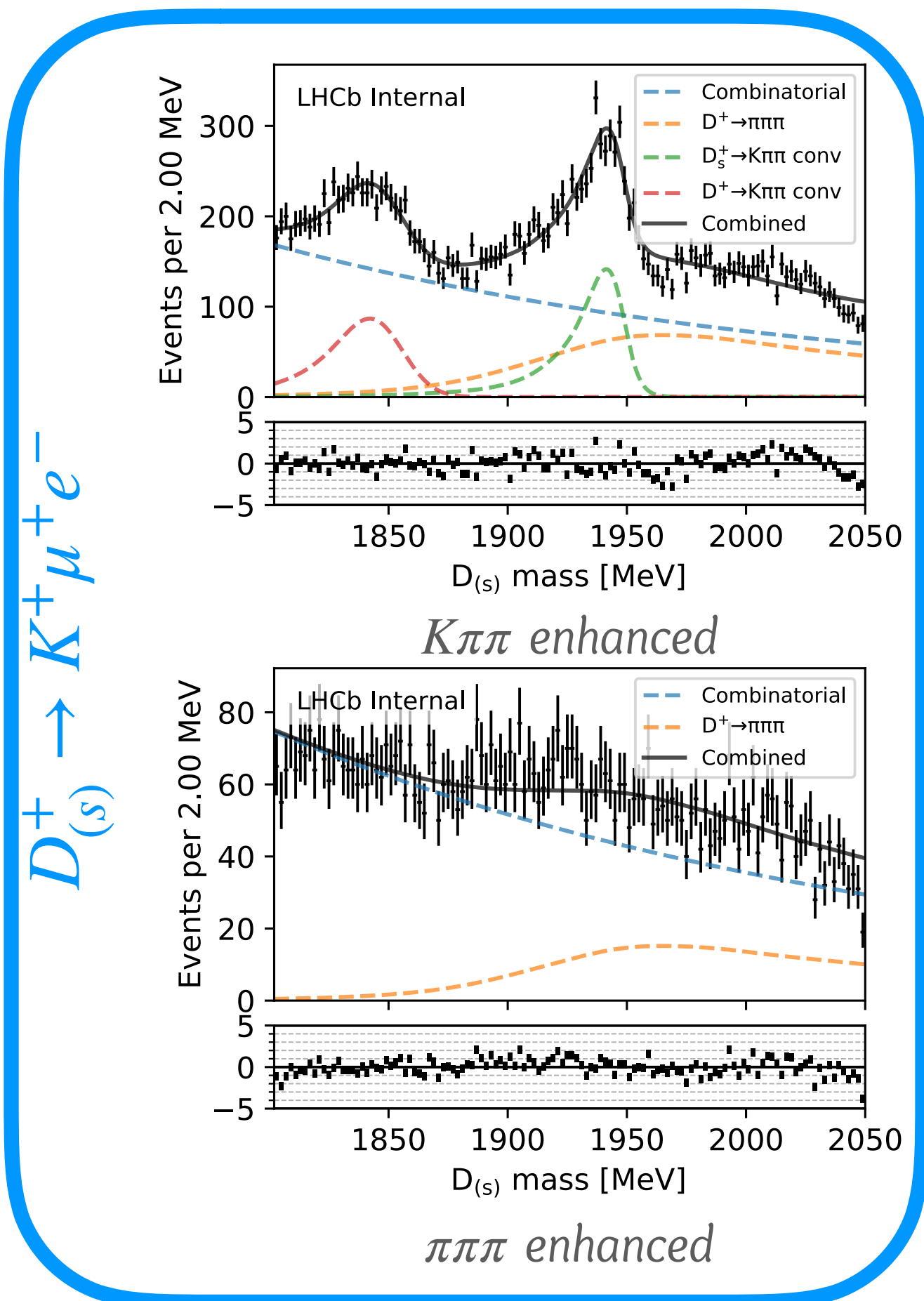


Two electrons



- Group decays into those with common features
- Background contributions depend on hadron species and charge
- 4 categories: $\pi^+l^+l'^-$, $\pi^-l^+l'^+$, $K^+l^+l'^-$ and $K^-l^+l'^+$

Blind background enhanced samples
Fit shapes based on KDEs from RapidSim



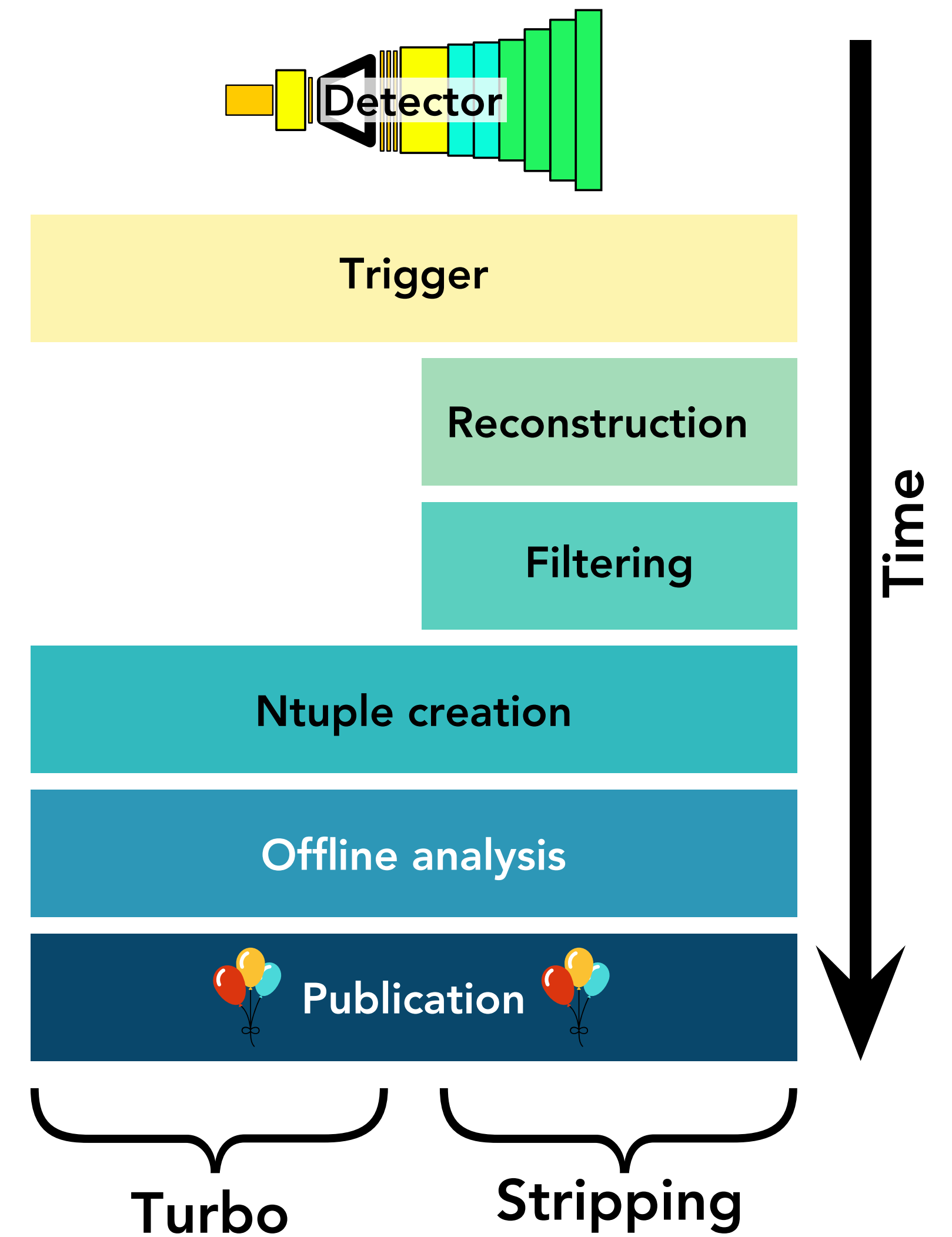


COMING SOON

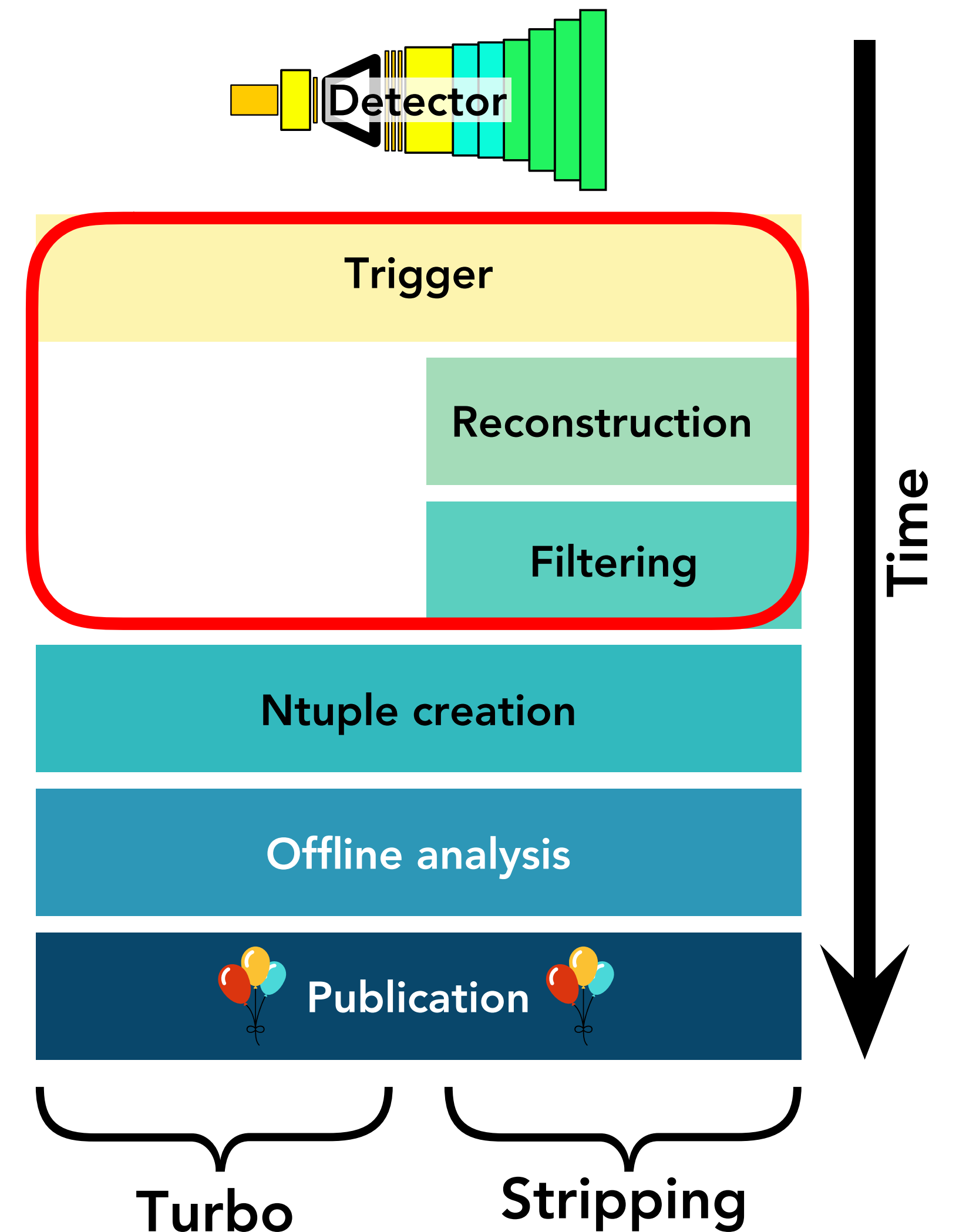


Analysis Preservation

How to preserve an analysis?

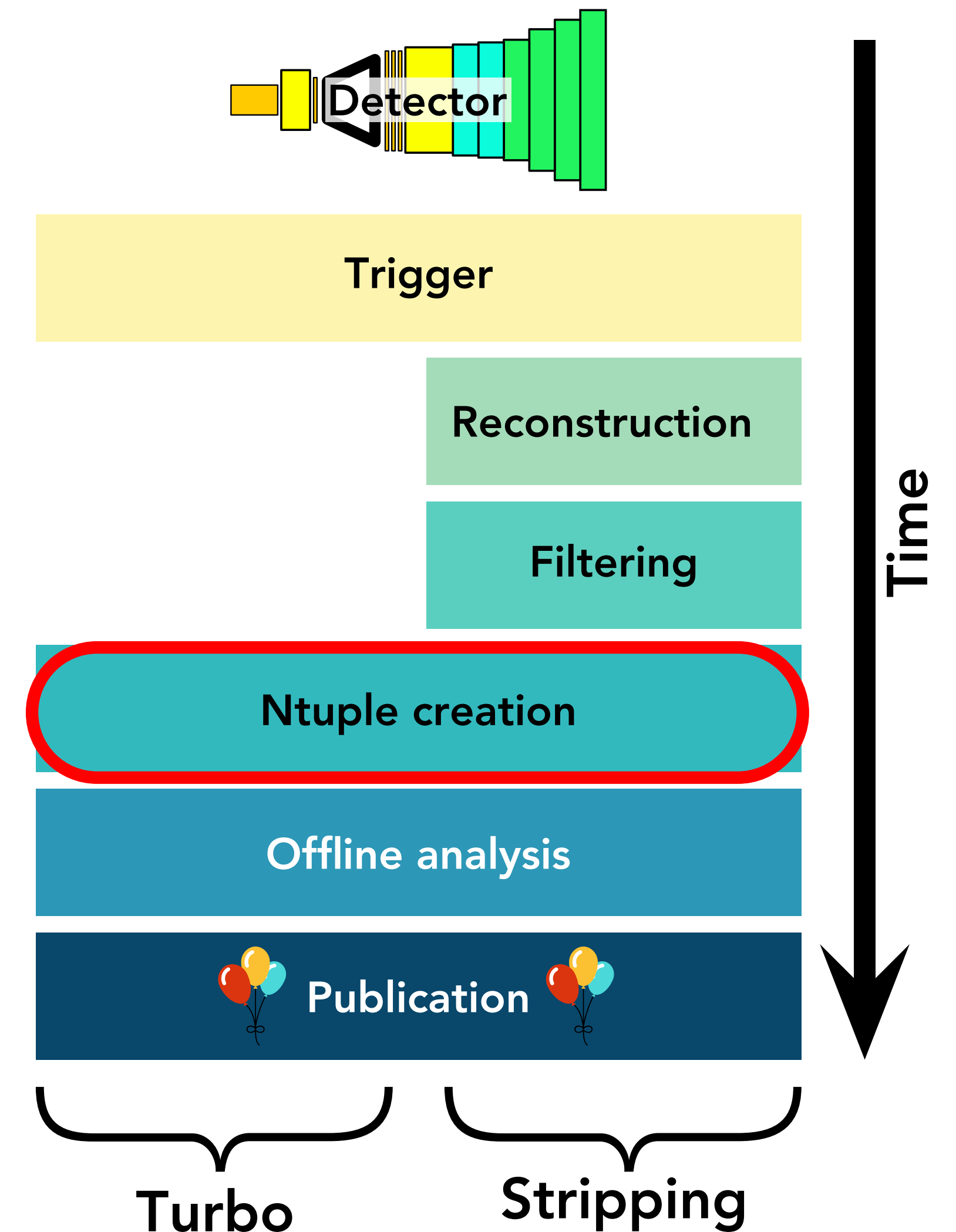


- **Centralised processing**
(Trigger, Reconstruction, Stripping, MC generation)
- **Relatively easy to preserve**
 - Small number of unique steps
 - Small number of people involved
 - Preserved in the LHCbDIRAC Bookkeeping
- **Already done**
- **Used regularly to recreate lost files**



How to preserve an analysis?

- Ntuple production*
- Typically done with user jobs
 - Does not scale well
 - Lots of time spent debugging
 - Makes it easy to submit thousands of buggy jobs
 - Requires “everyone” to know details and current status of the grid
 - Jobs are not preserved and reproducible
- DIRAC transformation system does effectively the same thing



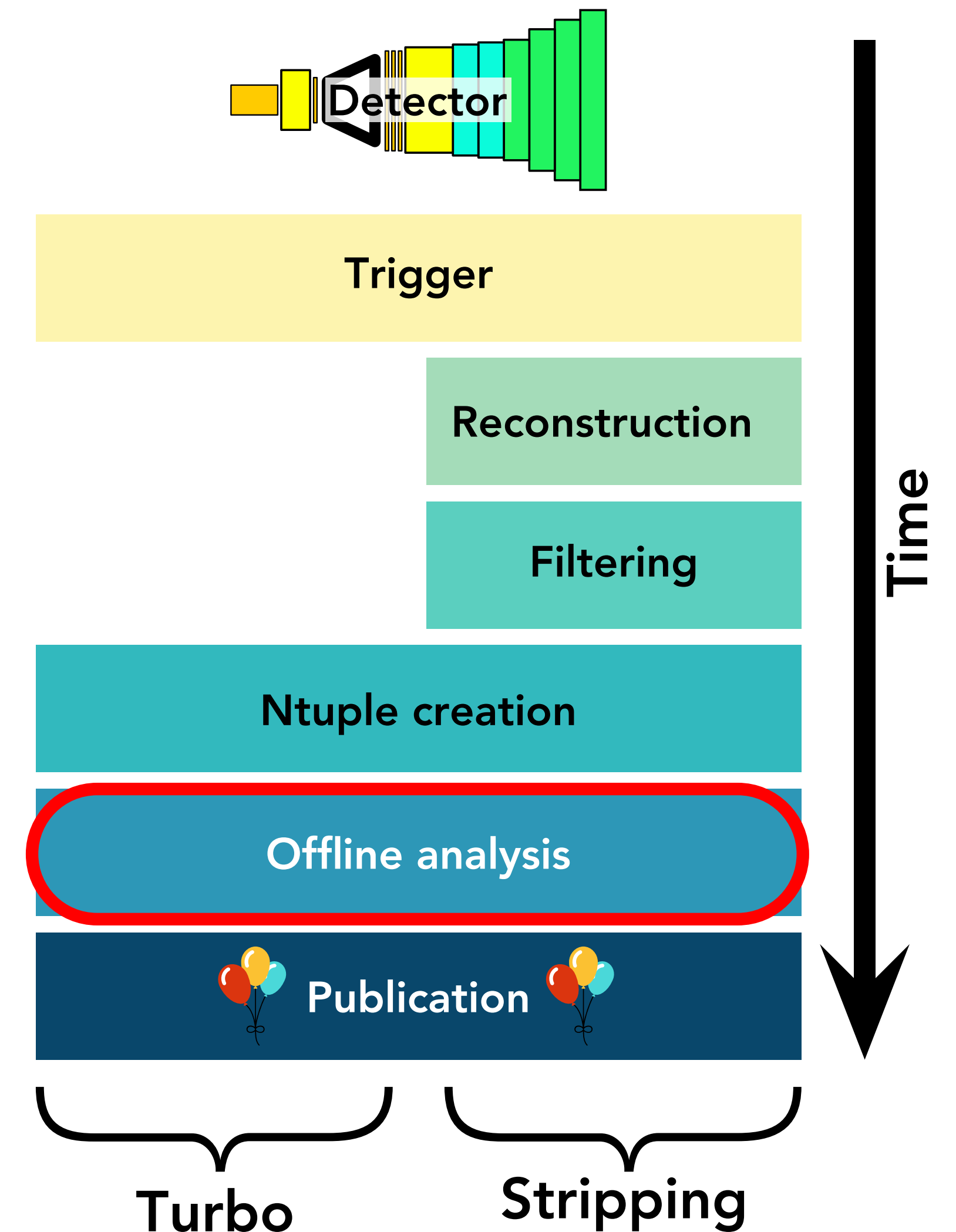
* Ntuple production also refers to other formats such as HDF5, heavily skimmed MDSTs, etc...

- A way of using the production system instead of submitting user jobs
- Worked on automating the testing and submission of productions
 - <https://gitlab.cern.ch/lhcb-datapkg/WG/CharmWGProd>
 - Over 1,000 productions have now been submitted with this
- Automatically preserved in the same way as centralised productions
 - Also requires less work from analysts

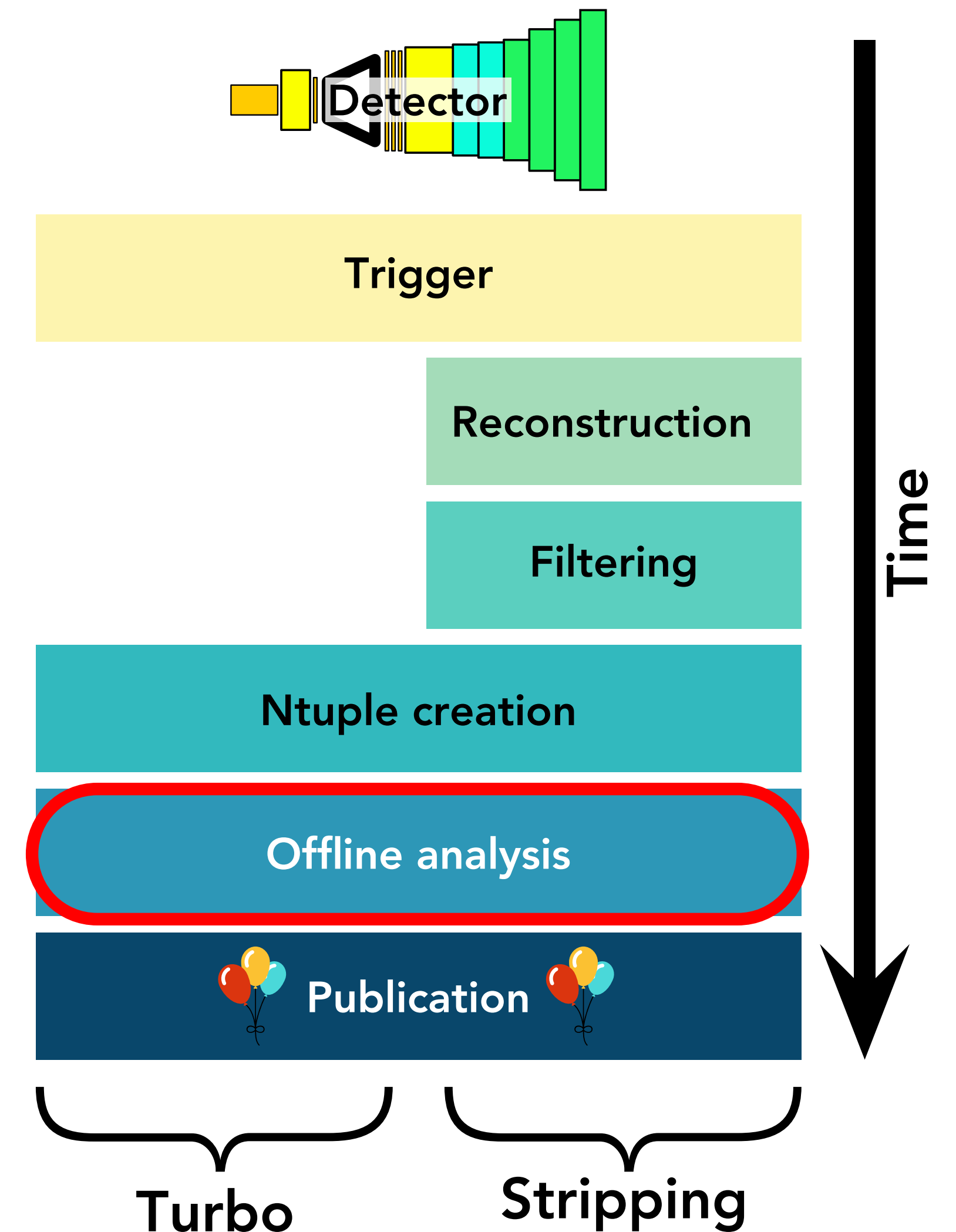
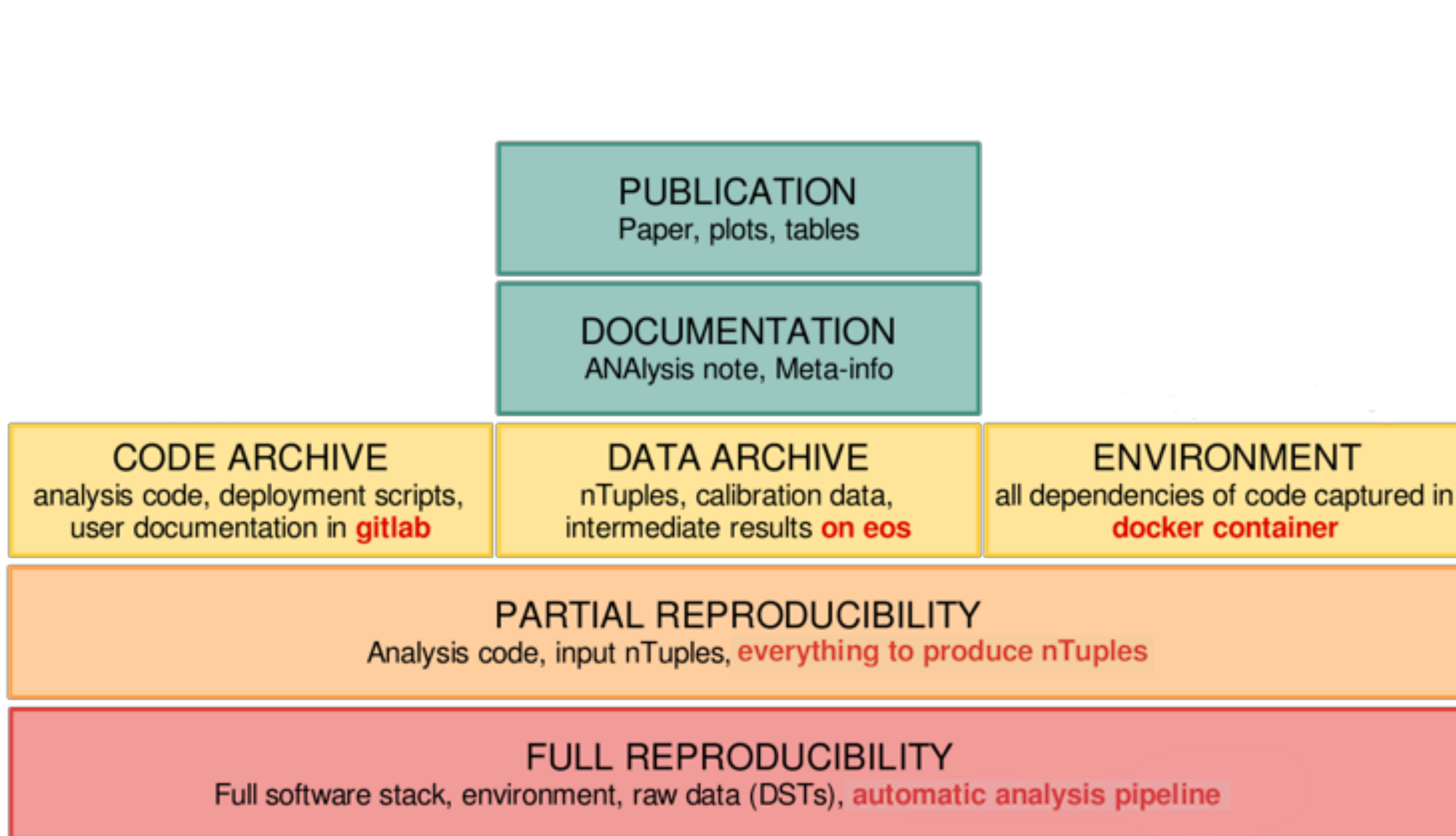
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552	Done	No	mfontana	D02mumu-2016_MagDown	52438	Done	85537	85538	Archived	Archived				20	100.00%	/eos/lhcb/grid/prod/lhcb/LHCb/Collision16/CHARM_DATA_D02MUMU_2016_MD.ROOT/00085538/*/*_root	
553	Done	No	mfontana	D02mumu-2015_MagUp	52437	Done	85539	85540	Archived	Archived				8	100.00%	/eos/lhcb/grid/prod/lhcb/LHCb/Collision15/CHARM_DATA_D02MUMU_2015_MU.ROOT/00085540/*/*_root	
554	Done	No	mfontana	D02mumu-2015_MagDown	52436	Done	85541	85542	Archived	Archived				8	100.00%	/eos/lhcb/grid/prod/lhcb/LHCb/Collision15/CHARM_DATA_D02MUMU_2015_MD.ROOT/00085542/*/*_root	
555	Done	No	dbrundu	RareCharm-HHMumu_2018_MagUp	52159	Done	84894	84895	Archived	Archived				83	100.00%	/eos/lhcb/grid/prod/lhcb/LHCb/Collision18/RARECHARM_4BODIES.ROOT/00084895/*/*_root	
556	Done	No	dbrundu	RareCharm-HHMumu_2018_MagDown	52158	Done	84896	84897	Archived	Archived				86	100.00%	/eos/lhcb/grid/prod/lhcb/LHCb/Collision18/RARECHARM_4BODIES.ROOT/00084897/*/*_root	

How to preserve an analysis?

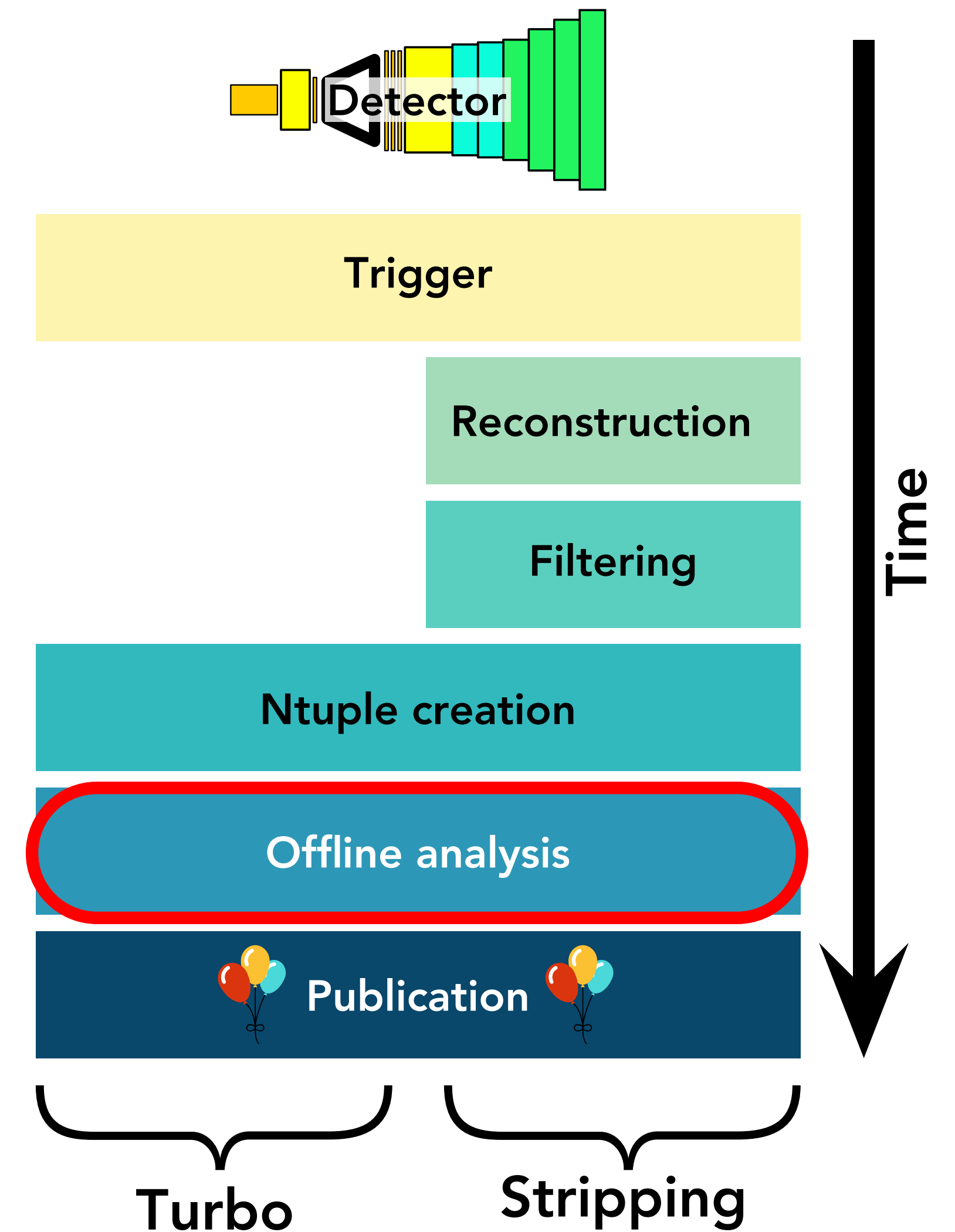
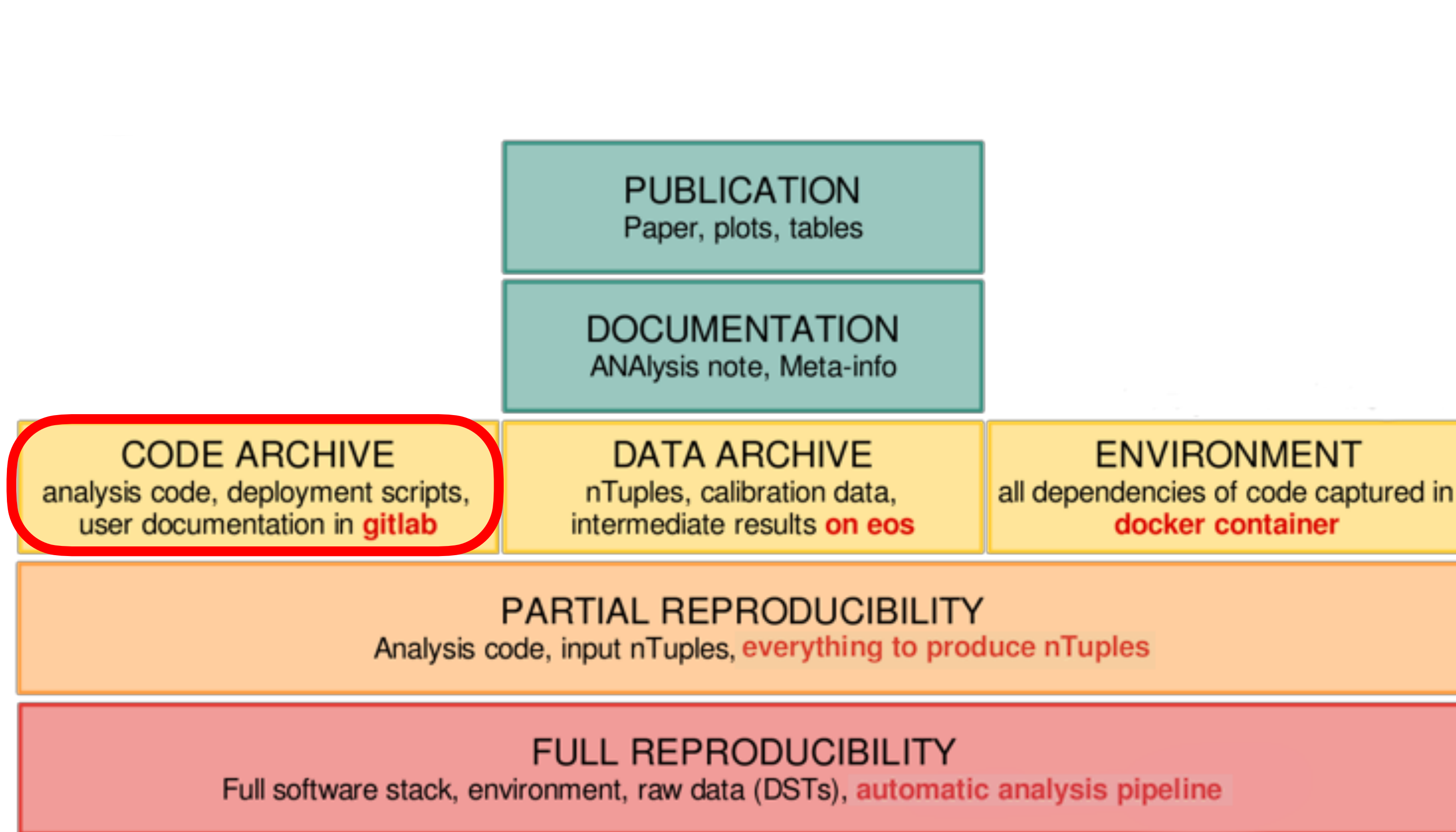
- Offline analysis
- Trickier to preserve
 - Not one way to do things (and there shouldn't be!)
 - Extremely varied in scale



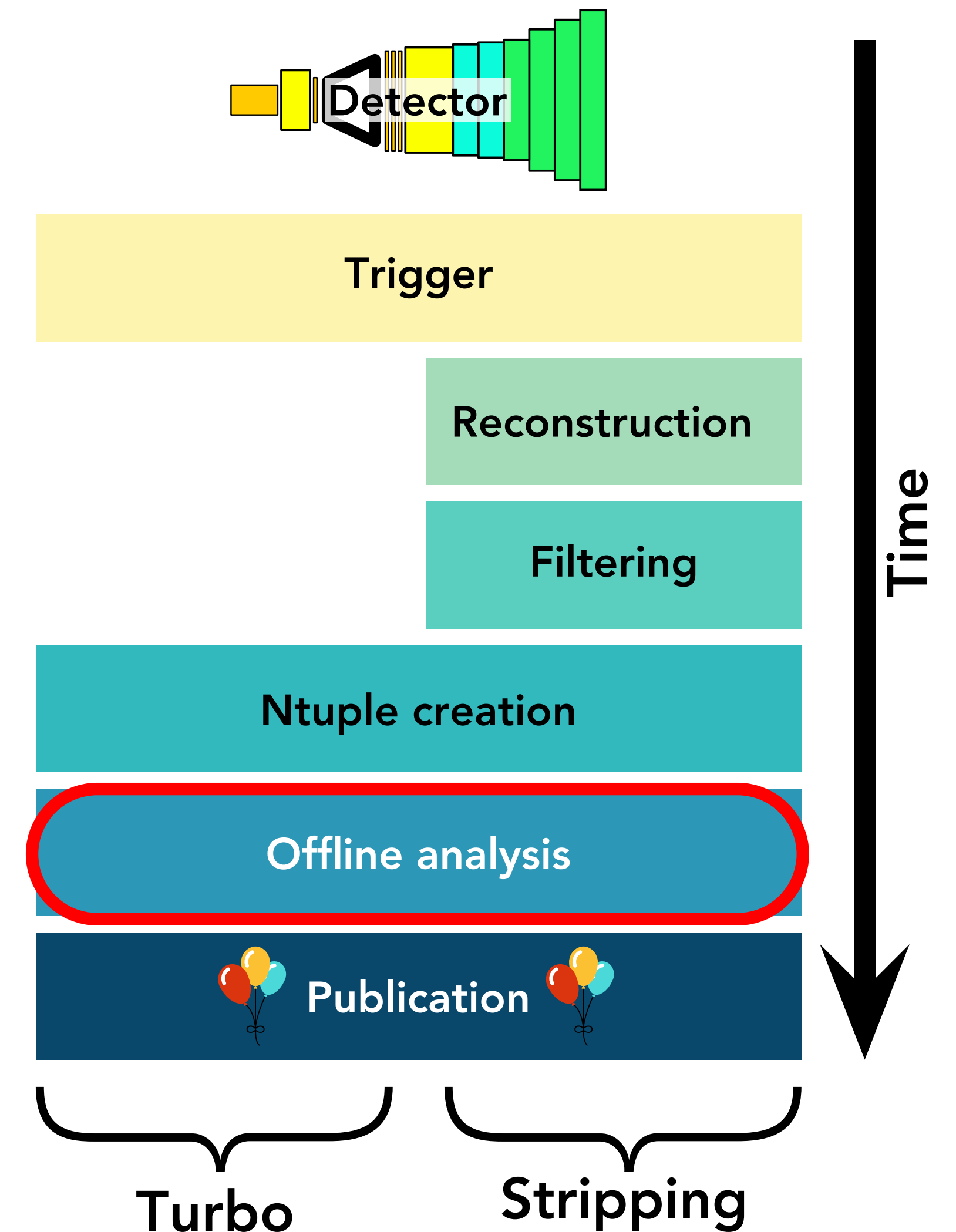
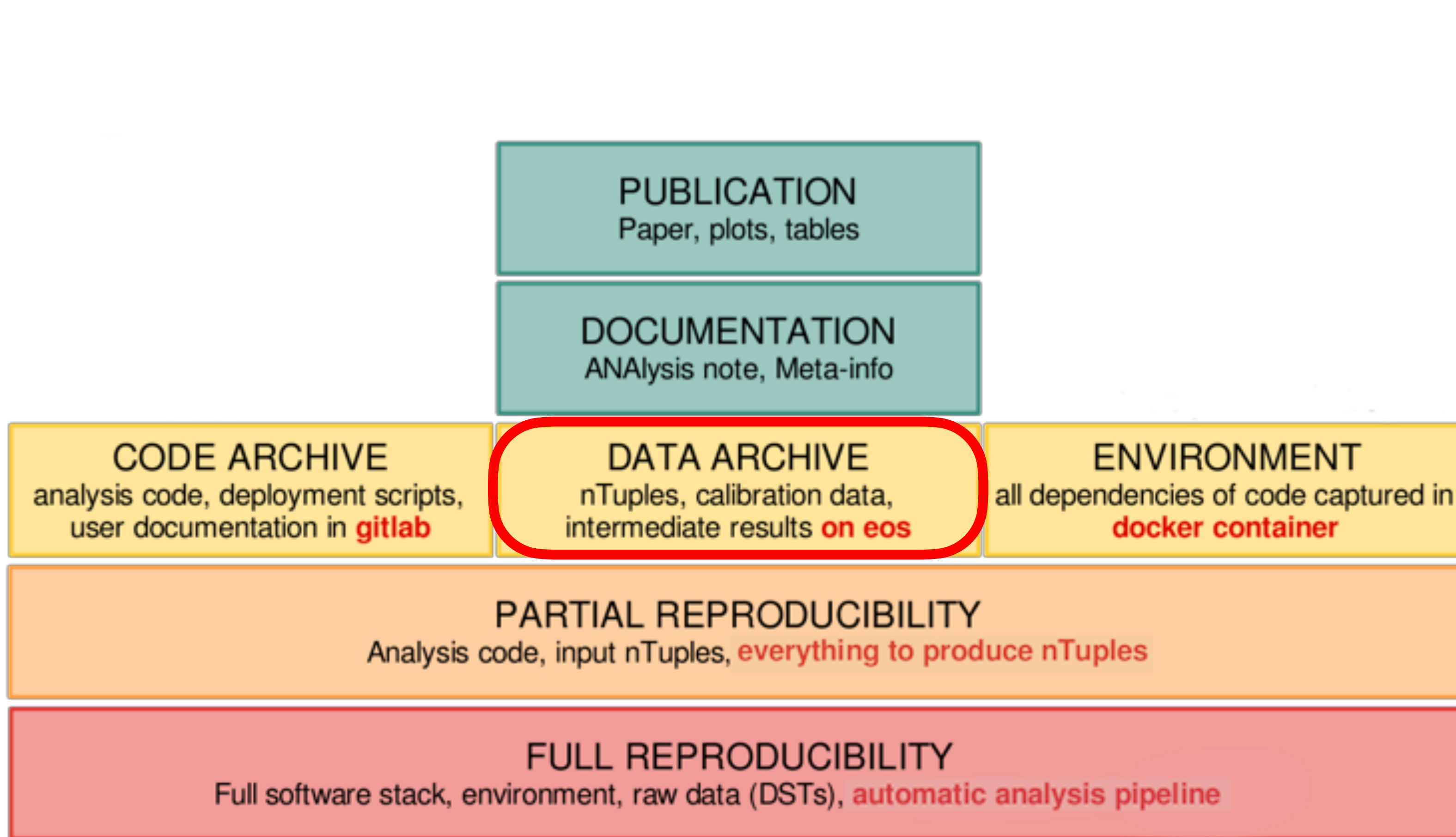
How to preserve an analysis?



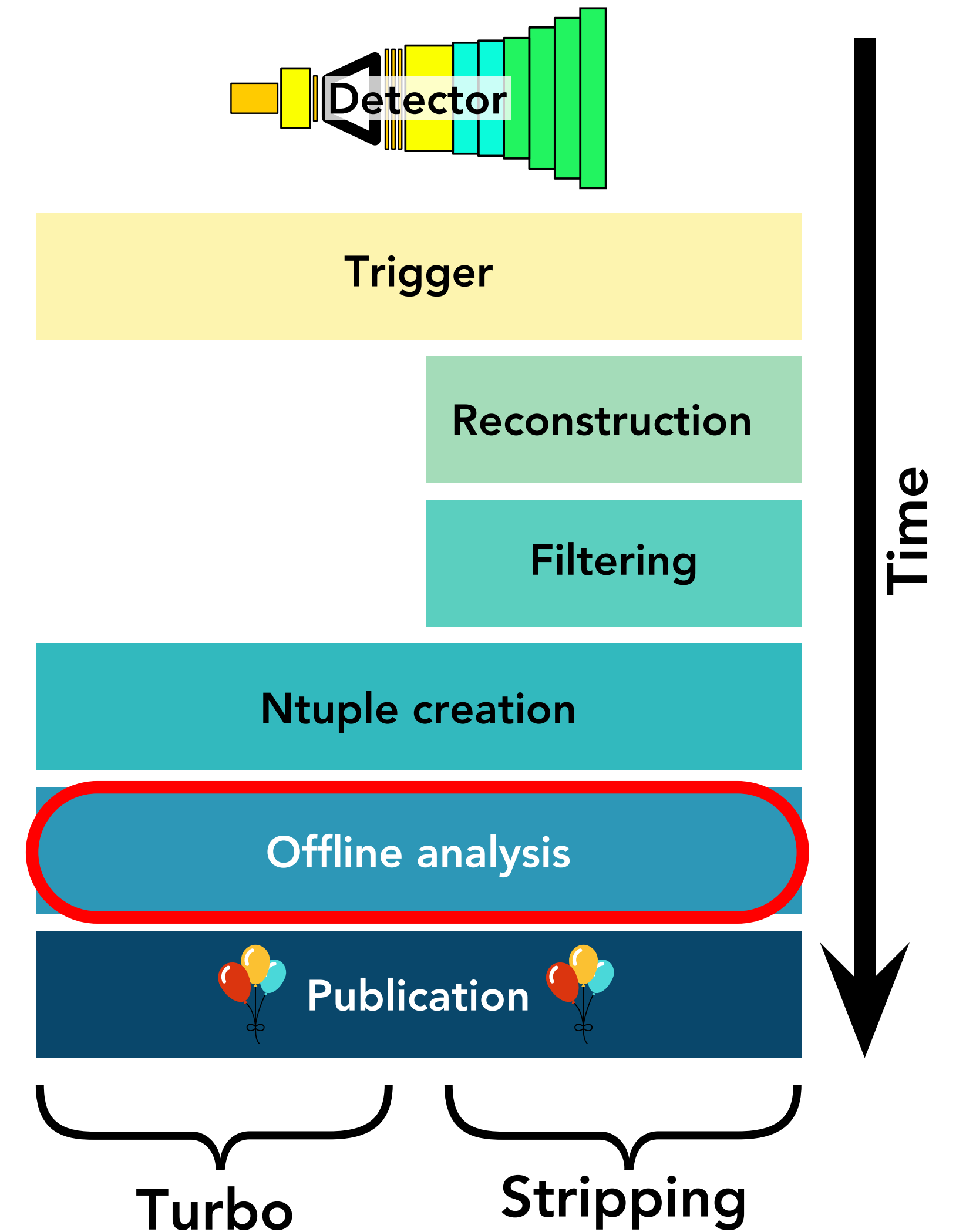
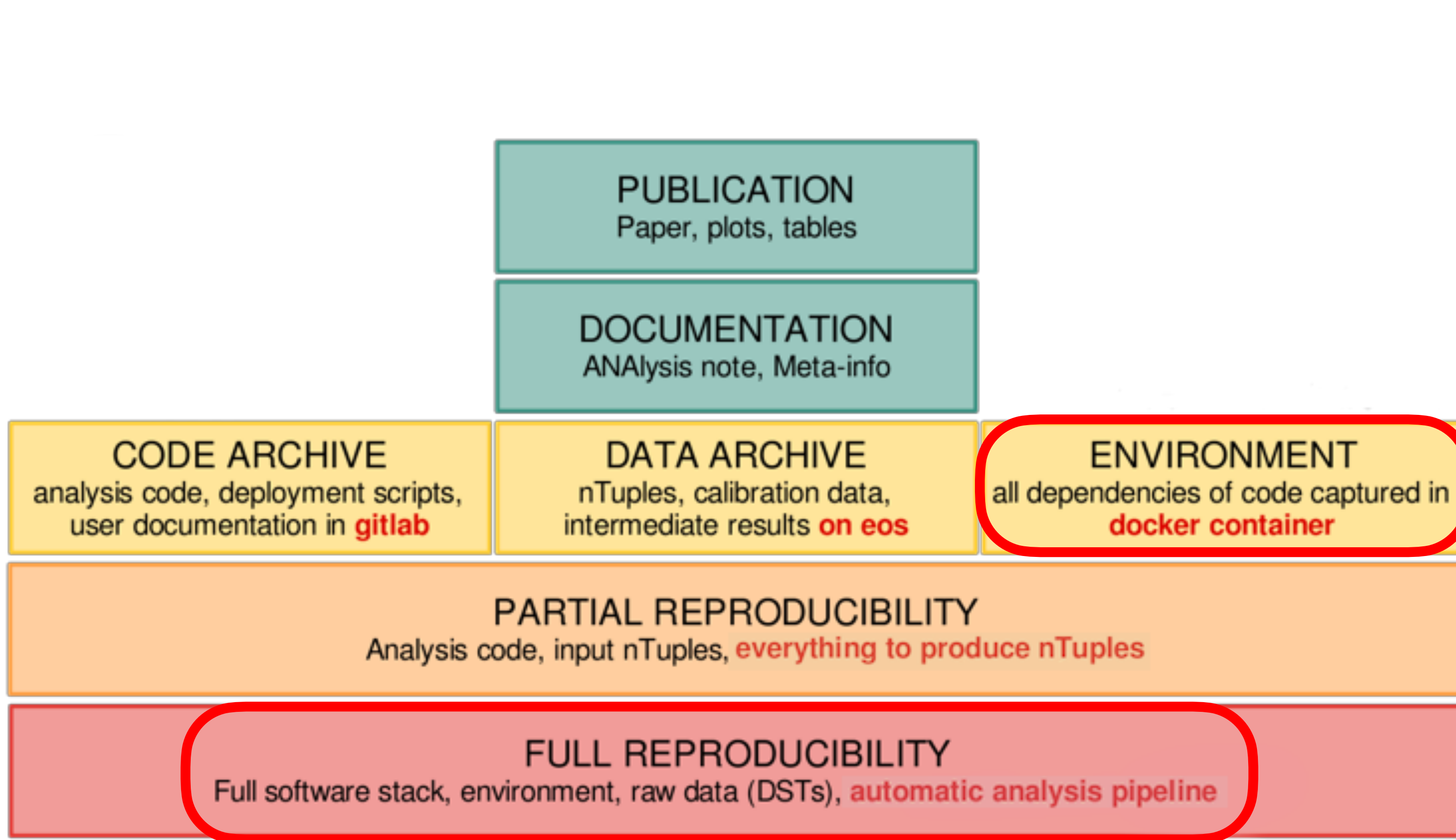
How to preserve an analysis?



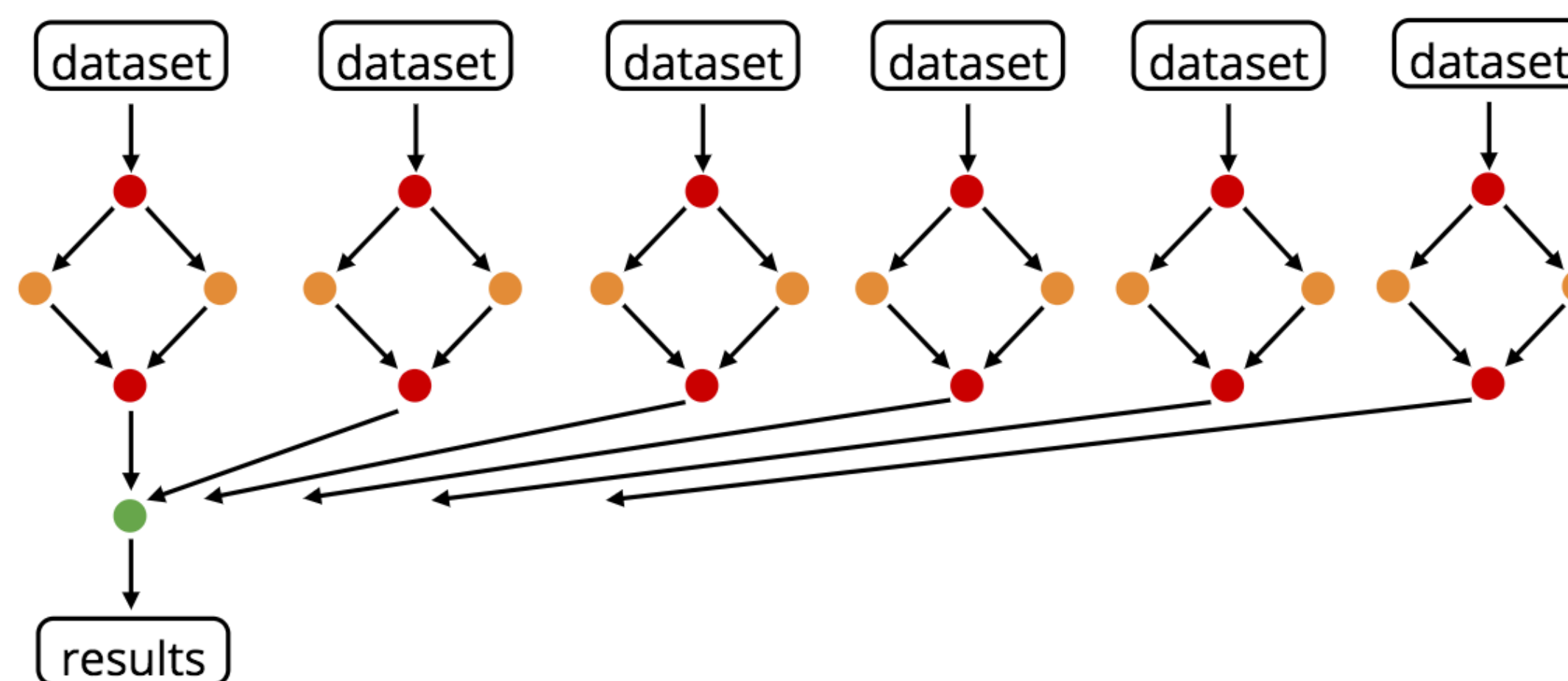
How to preserve an analysis?



How to preserve an analysis?



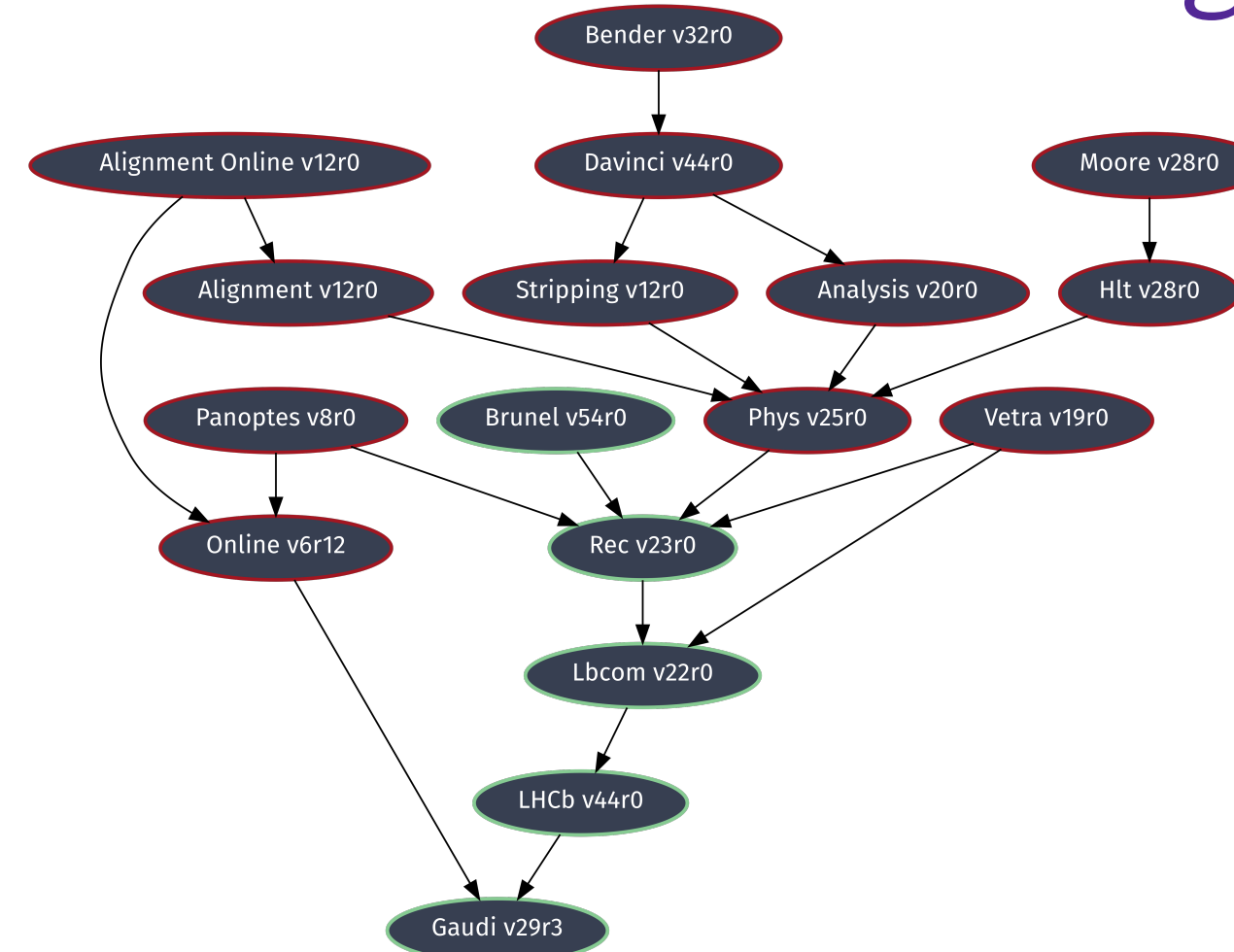
- Analysis work naturally lends itself towards using pipelines
 - Like how make is used to make a pipeline for compiling code
- Can be as simple as a bash script
- My personal favourite is snakemake but FAST carpenter also looks interesting



Johannes Köster - Snakemake Tutorial 2017

<https://indico.cern.ch/event/866964/>

- Investigated using Nix in LHCb and built the LHCb stack up to Brunel
- Developed (and now maintain) the ROOT package in conda-forge
 - Downloaded over 75,000 times in 2019
- Also maintain ~65 other packages
 - XRootD, GEANT4, grid middleware, various scikit-hep packages
- Also a member of the “staged recipes” team in conda-forge



```
1 { stdenv, fetchurl, boost, cmake, python, ninja, root, gaudi
2 , clhep, xercesc, cppunit, libxml2, openssl, relax, gsl, eigen, aida, graphviz
3 , qt5, mysql57, sqlite, hepmpc, cool, coral, libgit2, pkgconfig, vdt, cpp-gsl
4 , oracle-instant-client, xrootd
5 # Data packages
6 , det-sqlddb, fieldmap, gen-decfiles, paramfiles, prconfig, raweventformat
7 , tck-hittck, tck-10tck };
8
9 stdenv.mkDerivation rec {
10   name = "LHCb-${version}";
11   version = "v44r0";
12
13   src = fetchurl {
14     url = "https://gitlab.cern.ch/lhcb/LHCb/repository/${version}/archive.tar.gz";
15     sha256 = "0h5wph3p3ha7h34byyamdl1dv27hs5xpjbf363y8r43dsk4pa";
16   };
17
18   buildInputs = [
19     cmake ninja boost gaudi clhep xercesc cppunit libxml2 openssl relax eigen
20     gsl aida graphviz qt5.qtbase mysql57 sqlite hepmpc cool coral libgit2
21     pkgconfig vdt cpp-gsl oracle-instant-client xrootd root
22     (python.withPackages (ps: with ps; [ xenv pyqt5 lxml ]))
23     det-sqlddb fieldmap gen-decfiles paramfiles prconfig
24     raweventformat tck-hittck tck-10tck
25   ];
26
27   propagatedBuildInputs = [ python ];
28
29   cmakeFlags = [
30     "-GNinja"
31     "-DMYSQL_INCLUDE_DIR=${mysql57}/include/"
32     "-DGRAPHVIZ_INCLUDE_DIR=${graphviz}/include/"
33     "-DCOOL_PYTHON_PATH=${cool}/python"
34     "-DCORAL_PYTHON_PATH=${coral}/python"
35   ];
36
37   checkPhase = ''
38     ninja test
39   '';
40   doCheck = true;
41
42   postInstall = ''
43     for fn in $out/lib/lib*.so; do \
44       ${gaudi}/bin/listcomponents.exe $fn >> "${fn%.so}.components"
45     done
46   '';
47
48   enableParallelBuilding = true;
49
50   meta = {
51     homepage = http://lhcbdoc.web.cern.ch/lhcbdoc/lhcb/;
52     description = "General purpose classes used throughout the LHCb software.";
53     platforms = stdenv.lib.platforms.unix;
54   };
55 }
```

EPJ Web of Conferences 214, 05005 (2019)

<https://www.youtube.com/watch?v=Ee8k97Rx3DA>

LHCb-TALK-2019-395

1a) Download Linux and Windows Subsystem for Linux*

```
wget -nv http://repo.continuum.io/miniconda/Miniconda3-latest-Linux-x86_64.sh -O miniconda.sh
```

1b) Download macOS

```
wget -nv http://repo.continuum.io/miniconda/Miniconda3-latest-MacOSX-x86_64.sh -O miniconda.sh
```

2) Install conda

```
bash miniconda.sh -b -p $HOME/miniconda  
source $HOME/miniconda/etc/profile.d/conda.sh # Can be safely added to your bashrc  
conda config --add channels conda-forge
```

3) Create an environment and activate it

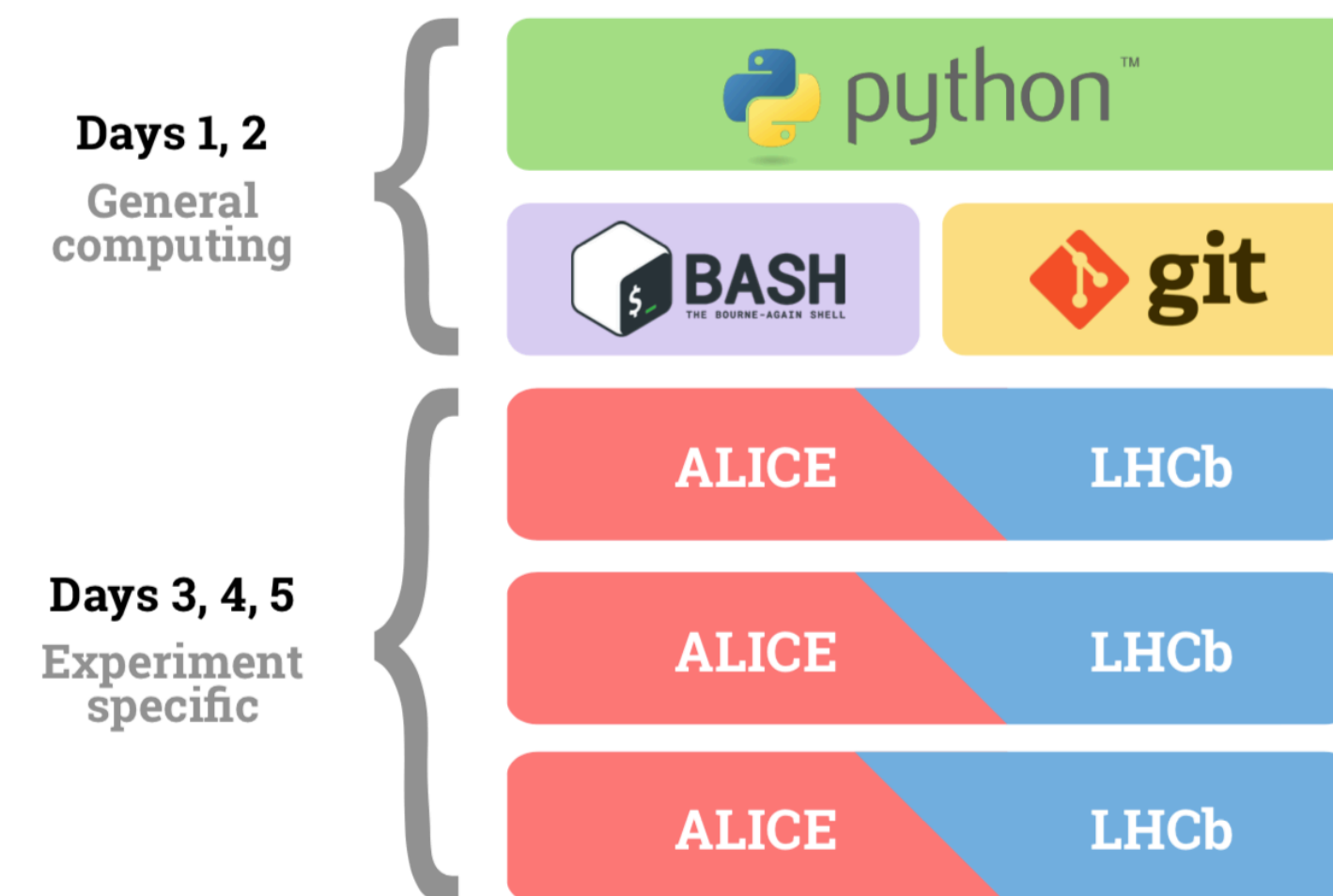
```
conda create --name my-environment python=3.7 ipython root jupyterlab  
conda activate my-environment
```

*WSL only as ROOT doesn't support native 64-bit Windows



The Starterkit

- Software training for new PhD students
- Mostly ran by PhD students and early post docs
- I co-organised the 2017 Starterkit and 2018 Impactkit
- Helped get ALICE and SHiP involved



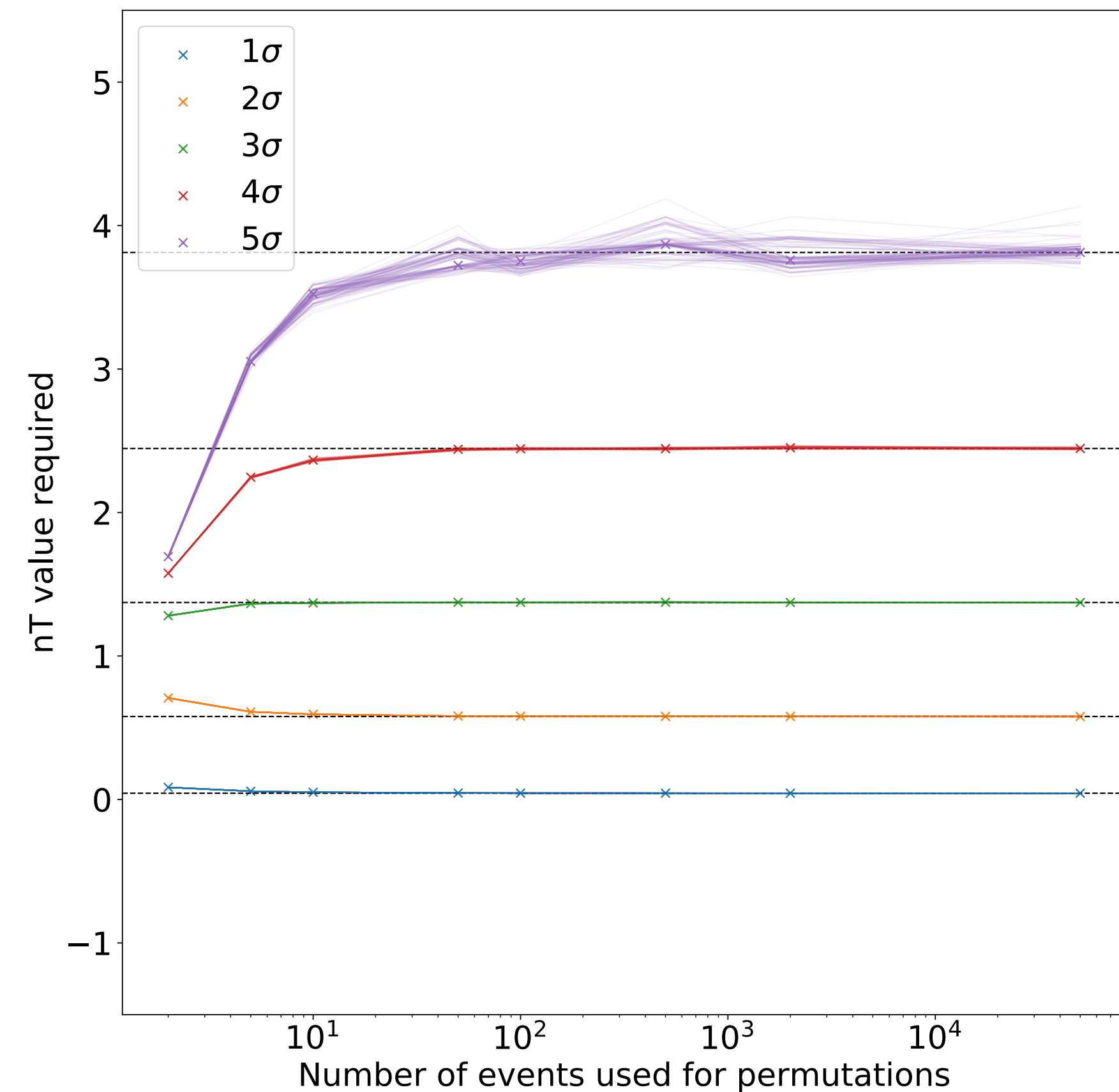
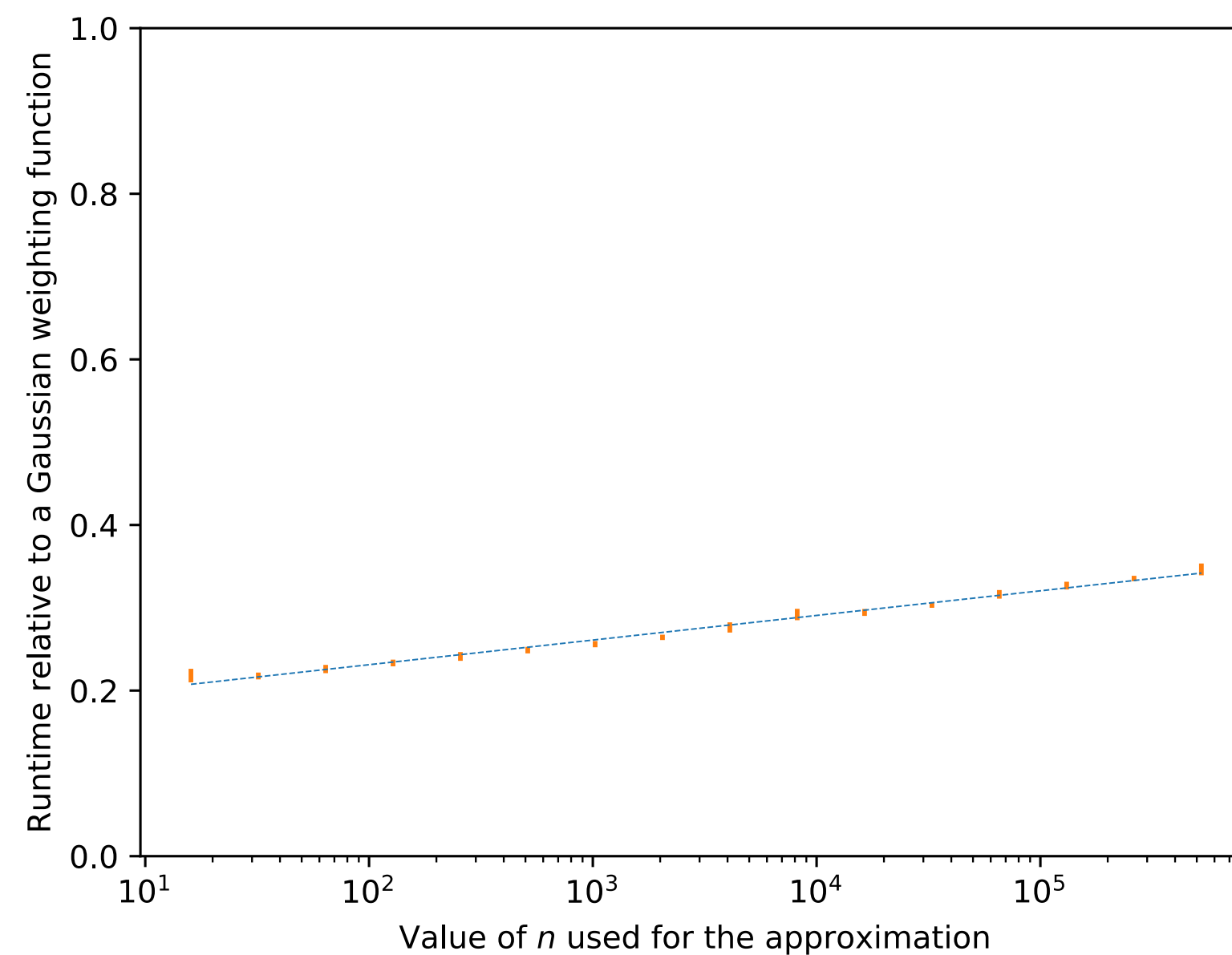
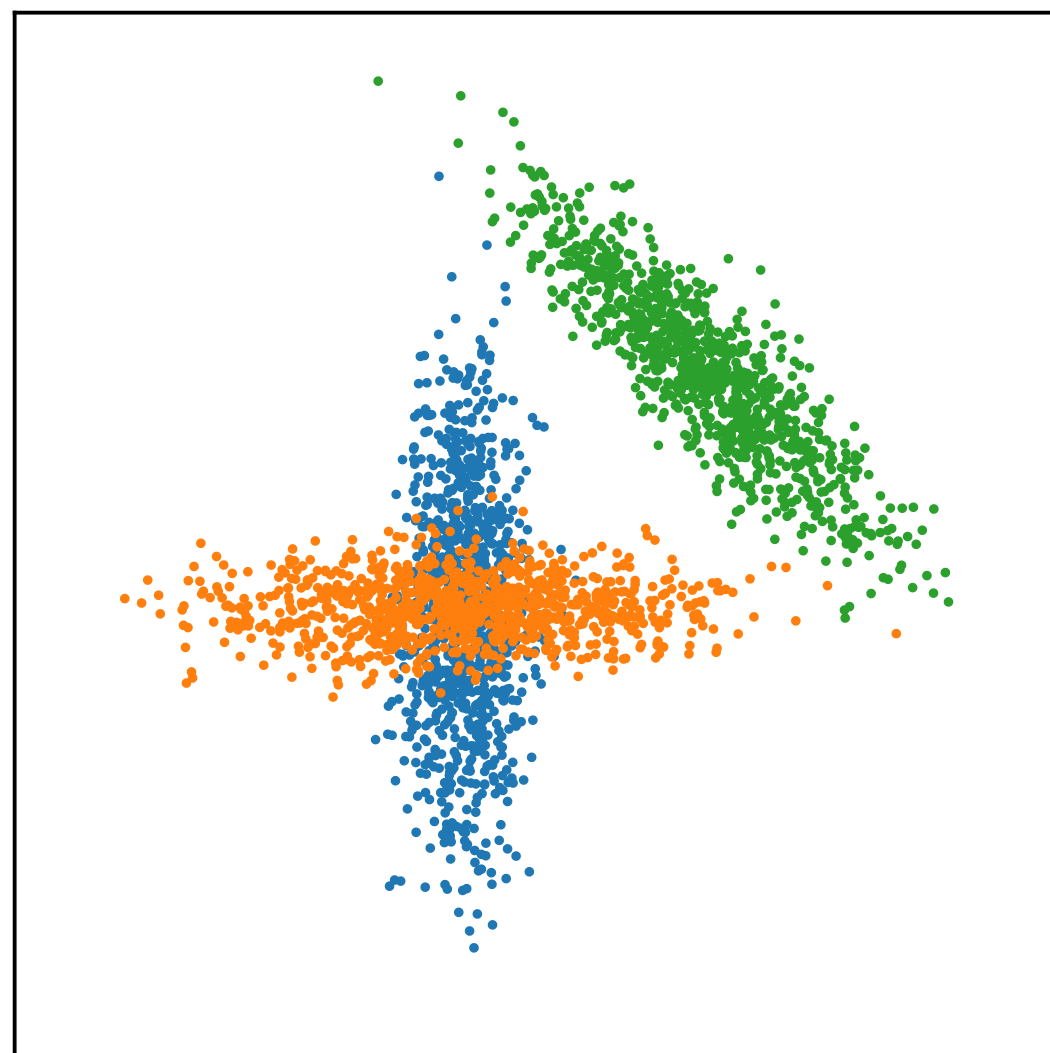


The Energy Test

- Statistical test that can be used to improve CP violation searches

$$T = \frac{1}{n(n-1)} \sum_{i>j}^n \psi_{ij} + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i>j}^{\bar{n}} \psi_{ij} - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi_{ij}$$

- Computing significance of differences is $\mathcal{O}(mn^2)$
- Helped show it can be simplified to $\mathcal{O}(n)$





What's Next?

- Thank you for the LHCb-UK PhD prize
- Thank you for inviting me here and listening
- Thank you to everyone who has helped me over the years
- Thank you for making LHCb a wonderful collaboration to be a part of!





Questions?