# Delphes Simulation for HL/HE-LHC

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# Detector Simulation

- Full simulation (GEANT):
  - **simulates** all **particle-detector interaction** (e.m/hadron showers, nuclear interaction, brem, conversions)

$10^2$-$10^3$ s/ev

- Experiment Fast Simulation (ATLAS, CMS ..)
  - **simplify** geometry, smear at the level of detector hits, frozen showers

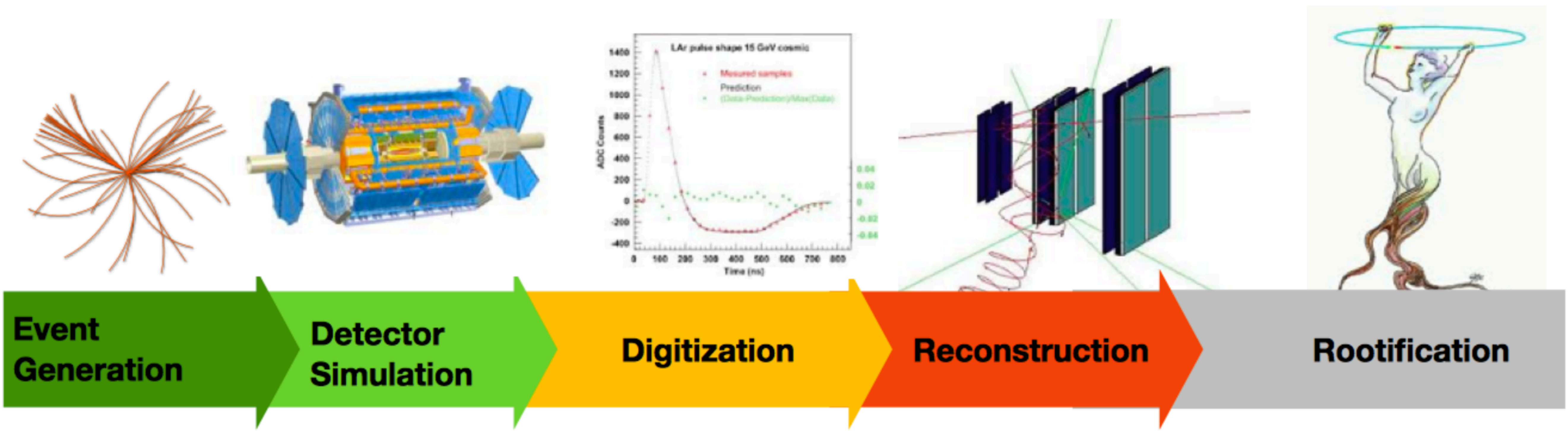
10-$10^2$ s/ev

- Parametric simulation (**Delphes**, PGS):
  - **parameterise detector response** at the particle level(efficiency, resolution on tracks, calorimeter objects)
  - reconstruct **complex objects** and observables(use particle-flow, jets, missing ET, pile-up ..)

$10^{-2}$ - $10^{-1}$ s/ev

- Ultra Fast (ATOM, TurboSim):
  - from parton to detector object (smearing/lookup tables)

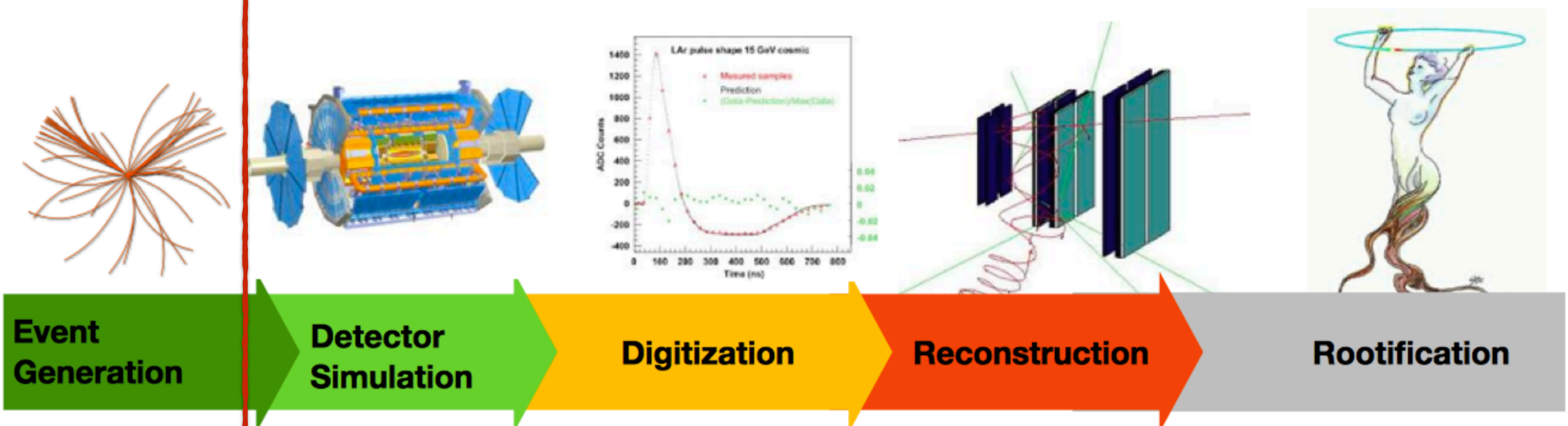
# MonteCarlo EvGen






courtesy of Andreas Salzburger

# MonteCarlo EvGen




Delphes FastSim

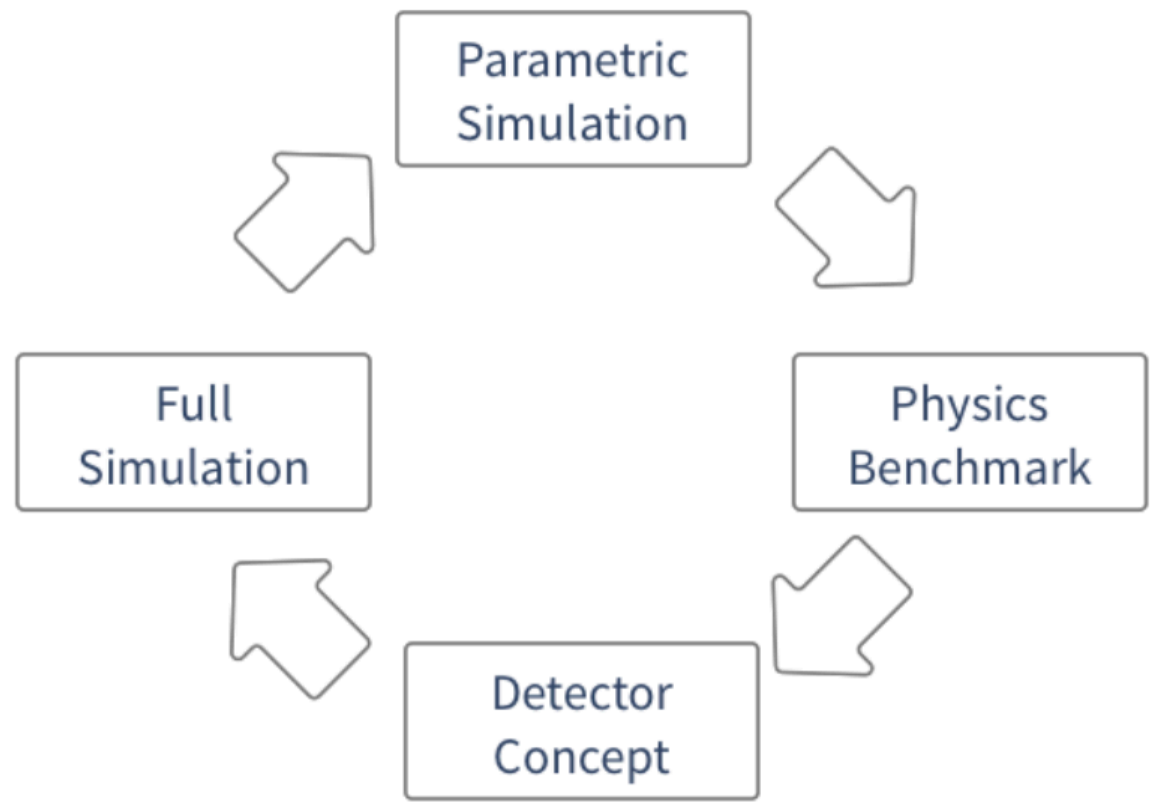


courtesy of Andreas Salzburger

# Introductory remarks

Why fast parametric detector simulation?

- Easily scan detector parameters
- Reverse engineer detector that maximises performance
- Preliminary sensitivity studies for key physics benchmarks




→ paradigm adopted in the context of FCC-hh
→ can be used in the context of HE-LHC

# What is Delphes ?

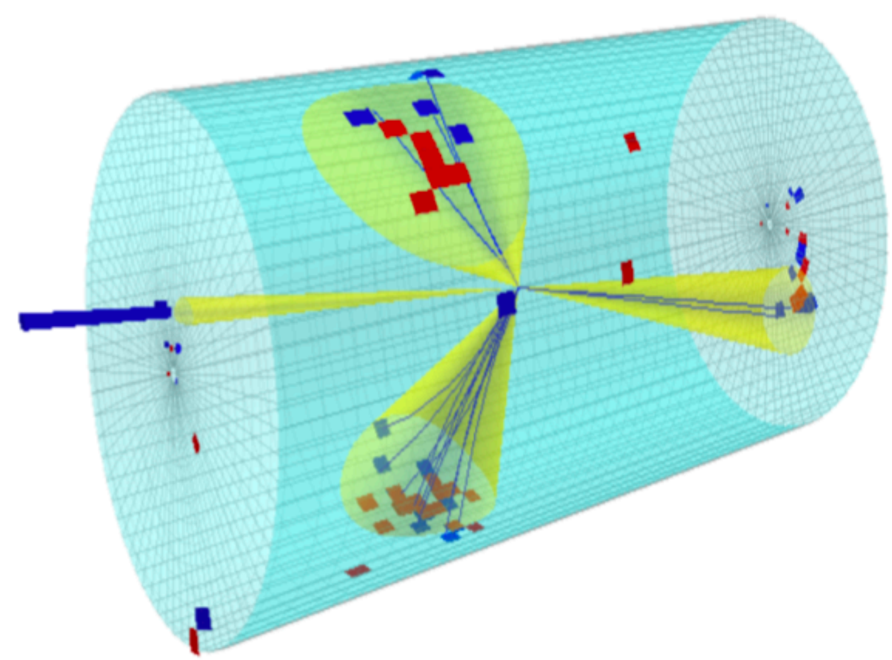
- Delphes started in 2007 as a project for Fast Detector Simulation
- Delphes 3, released in 2013 is community based:
  - on gitHub, ticket system
  - several user proposed patches
  - docker, singularity image in hepsim
- Reference FastSim tool for pheno community, SnowMass, ECFA, FCC, CMS
- Dependencies:
  - gcc, tcl, ROOT
  - is shipped with FastJet

github: github.com/delphes
website: cp3.irmp.ucl.ac.be/projects/delphes

# Delphes in a nutshell

- **Delphes** is modular framework that simulates the response of a **multipurpose detector** in a parameterised fashion

- Includes:
  - pile-up
  - charged particle propagation in B field
  - EM/Had calorimeters
  - particle-flow



- Provides:
  - leptons, photons, neutral hadrons
  - jets, missing energy
  - heavy flavour tagging

    - designed to deal with hadronic environment
    - well-suited also for e+e- studies
    - detector cards for: CMS (current/PhaseII) - ATLAS - LHCb - FCC-hh - ILD - CEPC

# Run Delphes

- Install ROOT from root.cern.ch

- Clone Delphes from github.com/delphes

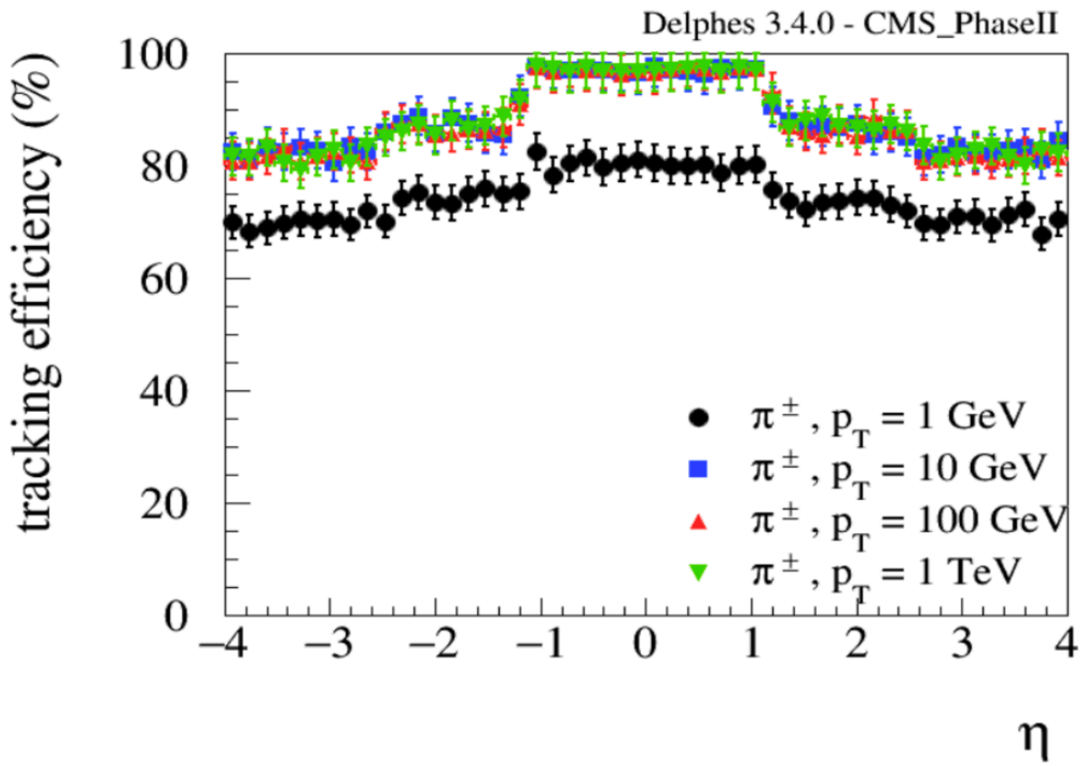
- Run Delphes:

```
>    ./configure
>    make
>    ./DelphesHepMC [detector_card] [output] [input(s)]
```

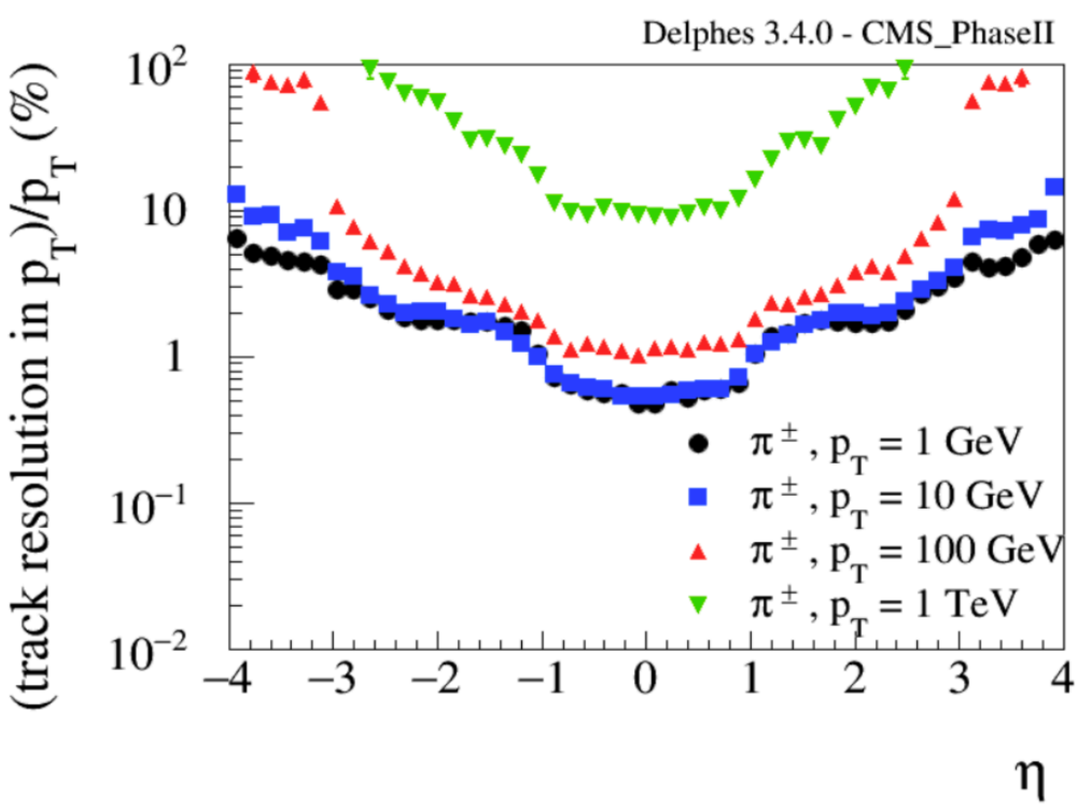
- Input formats: STDHEP, HepMC, ProMC, Pythia8

- Output: ROOT Tree

# Tracking parameterisation




```
####################################
# Charged hadron tracking efficiency
####################################

module Efficiency ChargedHadronTrackingEfficiency {
  ## particles after propagation
  set InputArray  ParticlePropagator/chargedHadrons
  set OutputArray chargedHadrons
  # tracking efficiency formula for charged hadrons
  set EfficiencyFormula {
      (pt <= 0.2) * (0.00) + \
          (abs(eta) <= 1.2) * (pt > 0.2 && pt <= 1.0) * (pt * 0.96) + \
          (abs(eta) <= 1.2) * (pt > 1.0) * (0.97) + \
          (abs(eta) > 1.2 && abs(eta) <= 2.5) * (pt > 0.2 && pt <= 1.0) * (pt*0.85) + \
          (abs(eta) > 1.2 && abs(eta) <= 2.5) * (pt > 1.0) * (0.87) + \
          (abs(eta) > 2.5 && abs(eta) <= 4.0) * (pt > 0.2 && pt <= 1.0) * (pt*0.8) + \
          (abs(eta) > 2.5 && abs(eta) <= 4.0) * (pt > 1.0) * (0.82) + \
          (abs(eta) > 4.0) * (0.00)
  }
}
```




```
set ResolutionFormula {    (abs(eta) >= 0.0000 && abs(eta) < 0.2000) * (pt >= 0.0000 && pt < 1.0000) * (0.00457888) + \
    (abs(eta) >= 0.0000 && abs(eta) < 0.2000) * (pt >= 1.0000 && pt < 10.0000) * (0.004579 + (pt-1.000000)* 0.000045) + \
    (abs(eta) >= 0.0000 && abs(eta) < 0.2000) * (pt >= 10.0000 && pt < 100.0000) * (0.004983 + (pt-10.000000)* 0.000047) + \
    (abs(eta) >= 0.0000 && abs(eta) < 0.2000) * (pt >= 100.0000) * (0.009244*pt/100.000000) + \
    (abs(eta) >= 0.2000 && abs(eta) < 0.4000) * (pt >= 0.0000 && pt < 1.0000) * (0.00505011) + \
    (abs(eta) >= 0.2000 && abs(eta) < 0.4000) * (pt >= 1.0000 && pt < 10.0000) * (0.005050 + (pt-1.000000)* 0.000033) + \
    (abs(eta) >= 0.2000 && abs(eta) < 0.4000) * (pt >= 10.0000 && pt < 100.0000) * (0.005343 + (pt-10.000000)* 0.000043) + \
    (abs(eta) >= 0.2000 && abs(eta) < 0.4000) * (pt >= 100.0000) * (0.009172*pt/100.000000) + \
    (abs(eta) >= 0.4000 && abs(eta) < 0.6000) * (pt >= 0.0000 && pt < 1.0000) * (0.00510573) + \
    (abs(eta) >= 0.4000 && abs(eta) < 0.6000) * (pt >= 1.0000 && pt < 10.0000) * (0.005106 + (pt-1.000000)* 0.000023) + \
    (abs(eta) >= 0.4000 && abs(eta) < 0.6000) * (pt >= 10.0000 && pt < 100.0000) * (0.005317 + (pt-10.000000)* 0.000042) + \
    (abs(eta) >= 0.4000 && abs(eta) < 0.6000) * (pt >= 100.0000) * (0.009077*pt/100.000000) + \
    (abs(eta) >= 0.6000 && abs(eta) < 0.8000) * (pt >= 0.0000 && pt < 1.0000) * (0.00578020) + \
    (abs(eta) >= 0.6000 && abs(eta) < 0.8000) * (pt >= 1.0000 && pt < 10.0000) * (0.005780 + (pt-1.000000)* -0.000000) + \
    (abs(eta) >= 0.6000 && abs(eta) < 0.8000) * (pt >= 10.0000 && pt < 100.0000) * (0.005779 + (pt-10.000000)* 0.000038) + \
    (abs(eta) >= 0.6000 && abs(eta) < 0.8000) * (pt >= 100.0000) * (0.009177*pt/100.000000) + \
    (abs(eta) >= 0.8000 && abs(eta) < 1.0000) * (pt >= 0.0000 && pt < 1.0000) * (0.00728723) + \
    (abs(eta) >= 0.8000 && abs(eta) < 1.0000) * (pt >= 1.0000 && pt < 10.0000) * (0.007287 + (pt-1.000000)* -0.000031) + \
    (abs(eta) >= 0.8000 && abs(eta) < 1.0000) * (pt >= 10.0000 && pt < 100.0000) * (0.007011 + (pt-10.000000)* 0.000038) + \
    (abs(eta) >= 0.8000 && abs(eta) < 1.0000) * (pt >= 100.0000) * (0.010429*pt/100.000000) + \
    (abs(eta) >= 1.0000 && abs(eta) < 1.2000) * (pt >= 0.0000 && pt < 1.0000) * (0.01045117) + \
    (abs(eta) >= 1.0000 && abs(eta) < 1.2000) * (pt >= 1.0000 && pt < 10.0000) * (0.010451 + (pt-1.000000)* -0.000051) + \
    (abs(eta) >= 1.0000 && abs(eta) < 1.2000) * (pt >= 10.0000 && pt < 100.0000) * (0.009989 + (pt-10.000000)* 0.000043) + \
```

# Identification/ Fakes

- (Mis-)Identification maps can be defined both:
  - at the particle level (IdentificationMap)
  - at the jet level (JetFakeParticle)

```
# --- pions ---

add EfficiencyFormula {211} {211} {      (eta <= 2.0)                                * (0.00) +
                                         (eta > 2.0  && eta <= 5.0) *      (pt < 0.8) * (0.00) +
                                         (eta > 2.0  && eta <= 5.0) *      (pt >= 0.8)* (0.95) +
                                         (eta > 5.0)                                 * (0.00)}

add EfficiencyFormula {211} {-13} {      (eta <= 2.0)                                * (0.00) +
                                         (eta > 2.0  && eta <= 5.0) *      (pt < 0.8) * (0.00) +
                                         (eta > 2.0  && eta <= 5.0) *      (pt >= 0.8)* (0. 05 +
                                         (eta > 5.0)                                 * (0.00)}
```

id

fake

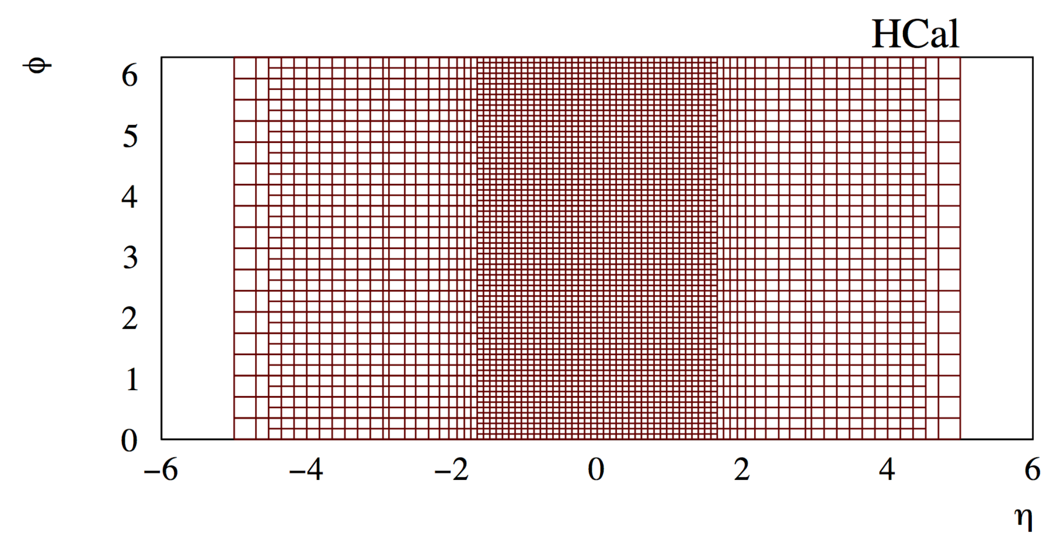
# Calorimetry

- ECAL/HCAL **segmentation** specified in (η,ϕ) coordinates
- Particles that reach calorimeters **deposits fixed fraction of energy** in $f_{EM}$ ($f_{HAD}$) in ECAL(HCAL)

| particles | $f_{EM}$ | $f_{HAD}$ |
|---|---|---|
| e γ $\pi^0$ | 1 | 0 |
| Long-lived neutral hadrons ($K^0_S$ , $\Lambda^0$) | 0.3 | 0.7 |
| ν μ | 0 | 0 |
| others | 0 | 1 |

- Particle **energy** and **position** is **smeared** according to the calorimeter it reaches

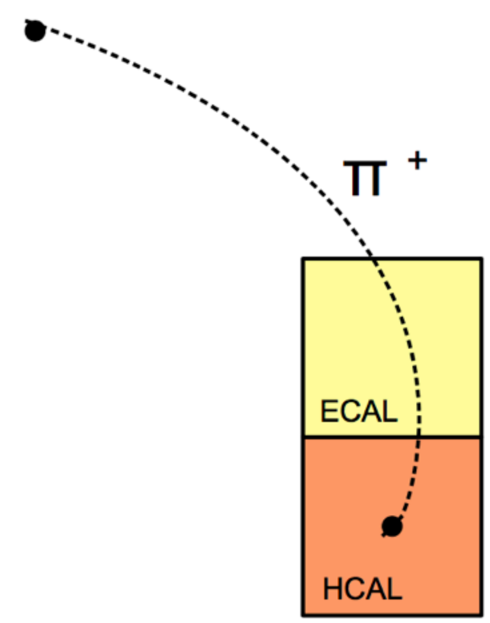
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S(\eta)}{\sqrt{E}}\right)^2 + \left(\frac{N(\eta)}{E}\right)^2 + C(\eta)^2$$



# Particle-Flow

- Given **charged track** hitting **calorimeter cell**:
  - is deposit more compatible with **charged only** or **charged + neutral** hypothesis?
  - how to **assign momenta** to resulting components?

- We have two measurements ($E_{trk}$, $\sigma_{trk}$) and ($E_{calo}$, $\sigma_{calo}$)
- Define $E_{Neutral} = E_{calo} - E_{trk}$



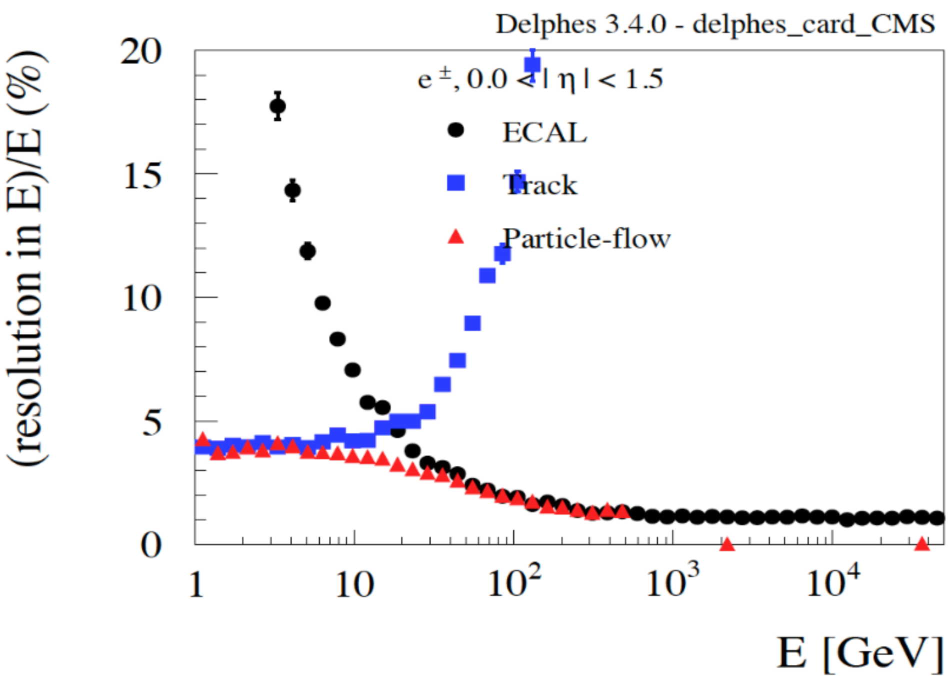

<u>Algorithm:</u>

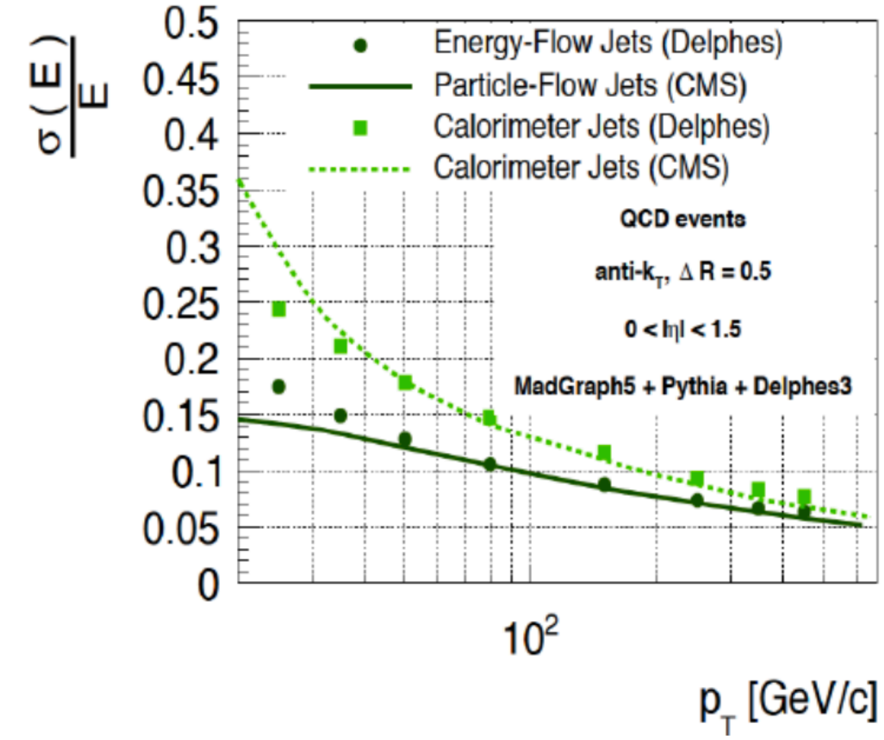
- If $E_{neutral}/\sqrt{(\sigma_{calo}^2 + \sigma_{trk}^2)} > S$:
  → create PF-neutral particle + PF-track

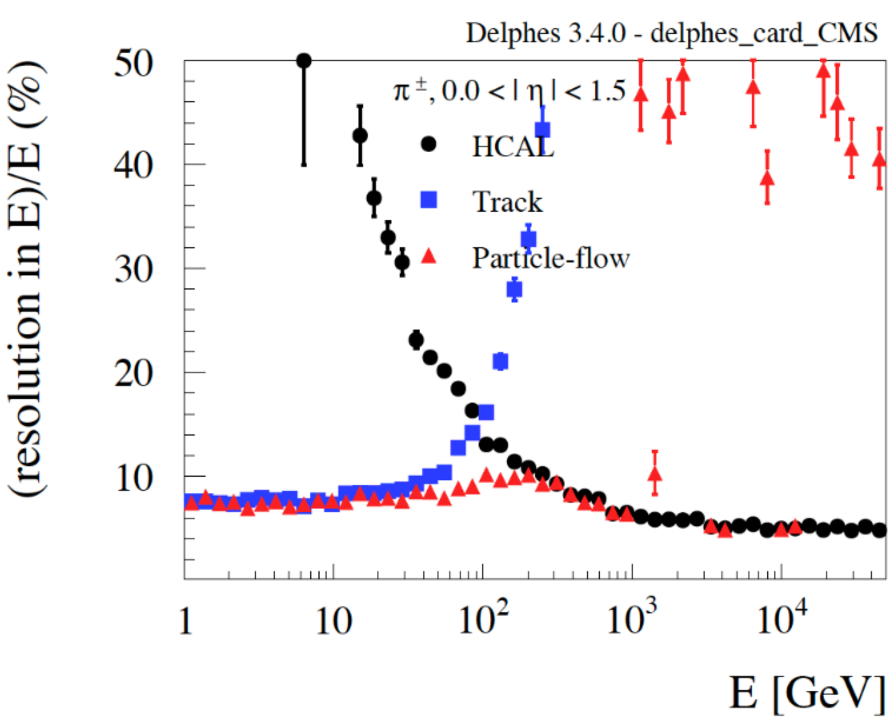
- Else:
  create PF-track and **rescale momentum** by combined calo+trk estimate

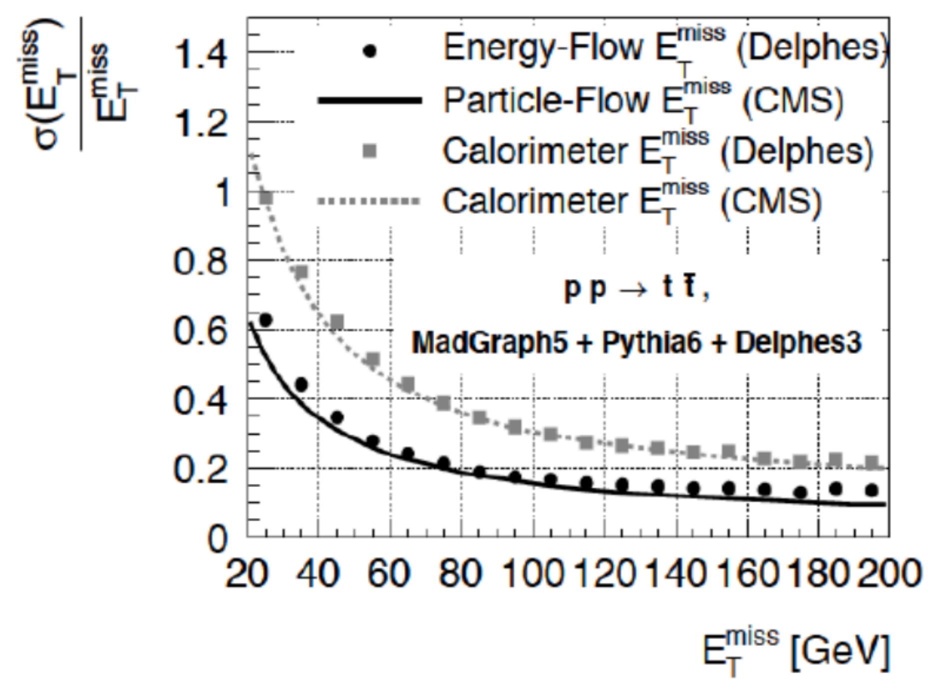
  - EM (had) deposit 100% in ECAL (HCAL)
  - No propagation in calorimeters
  - No clustering (topological) clustering, exploiting pre-defined grid

# Particle-Flow



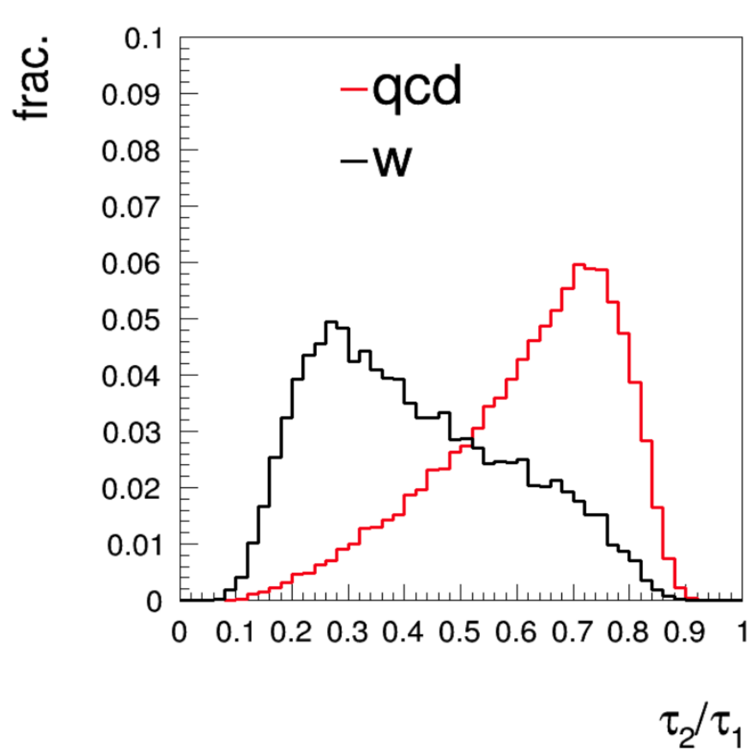



# Jets and Substructure

- FastJet performs **jet clustering** via the FastJetFinder module
- Most used Jet substructure algorithms are included (N-subjettiness, SoftDrop, Trimming, Pruning …)
- Delphes can also be used as a library for producing detector 4-vector objects: tracks, calo-towers or particle-flow candidates (see info here)

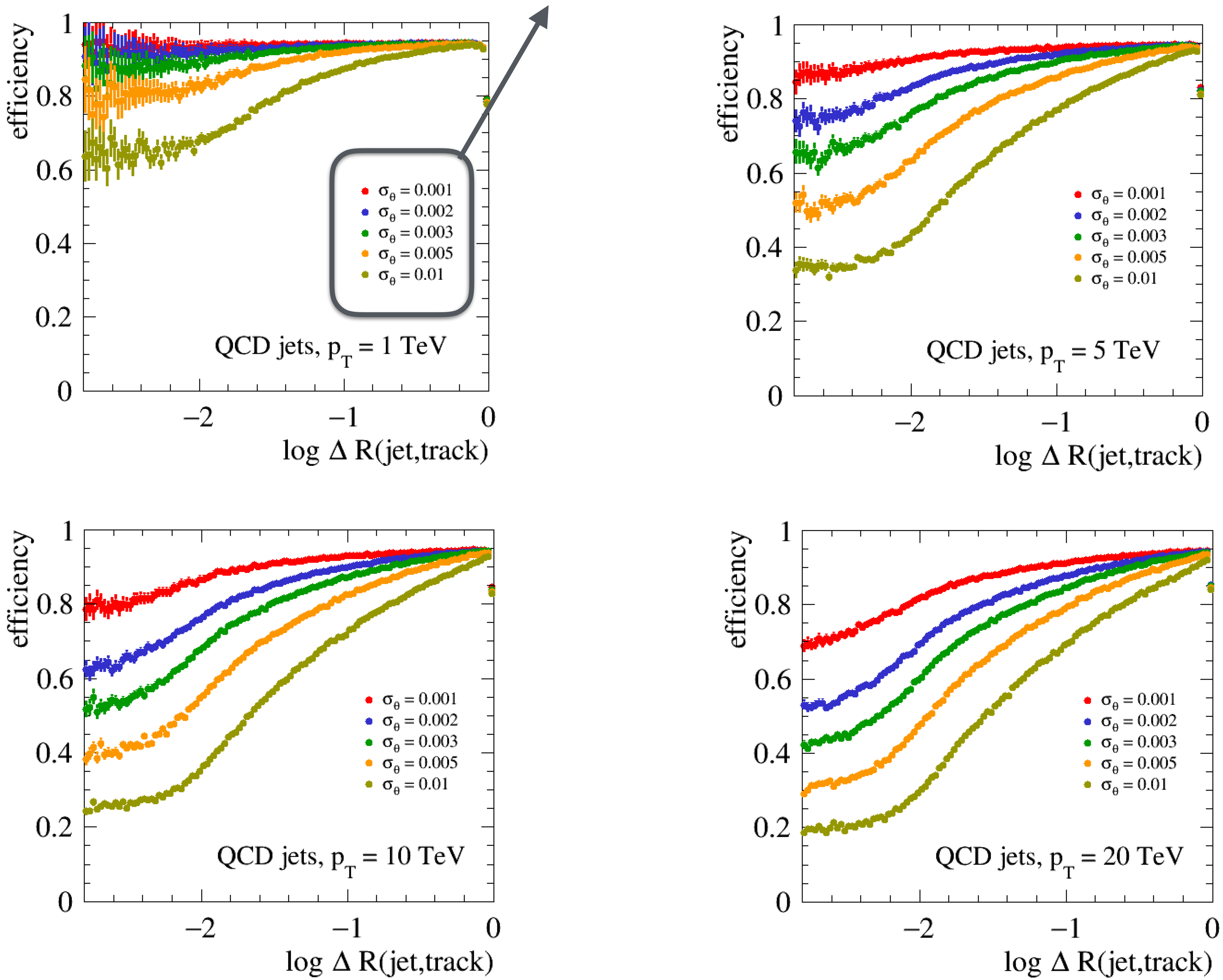
```
############
# Jet finder
############

module FastJetFinder FatJetFinder {
#  set InputArray TowerMerger/towers
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  set JetAlgorithm 5
  set ParameterR 0.8

  set ComputeNsubjettiness 1
  set Beta 1.0
  set AxisMode 4

  set ComputeTrimming 1
  set RTrim 0.2
  set PtFracTrim 0.05

  set ComputePruning 1
  set ZcutPrun 0.1
  set RcutPrun 0.5
  set RPrun 0.8

  set ComputeSoftDrop 1
  set BetaSoftDrop 0.0
  set SymmetryCutSoftDrop 0.1
  set R0SoftDrop 0.8

  set JetPTMin 200.0
}
```



# Tracking in Dense environment (NEW!)

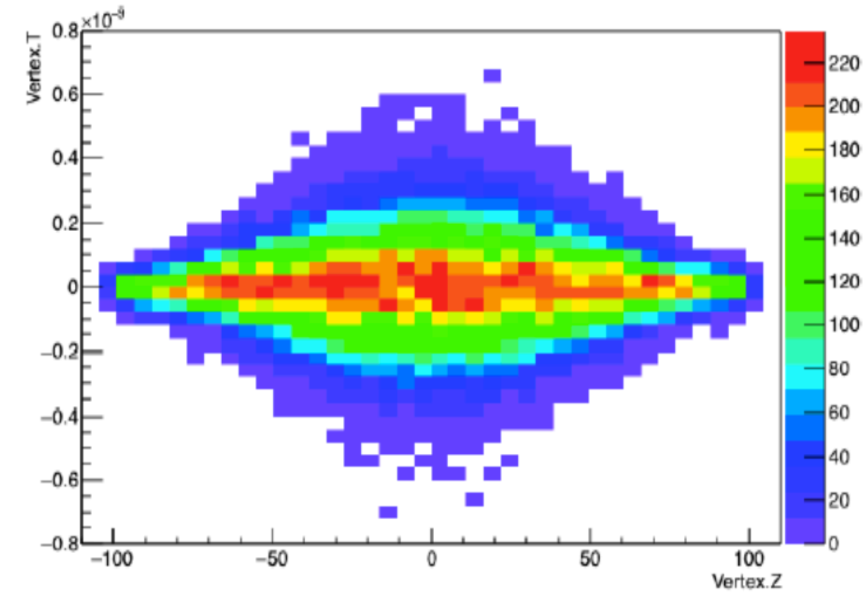
DELPHES fast simulation

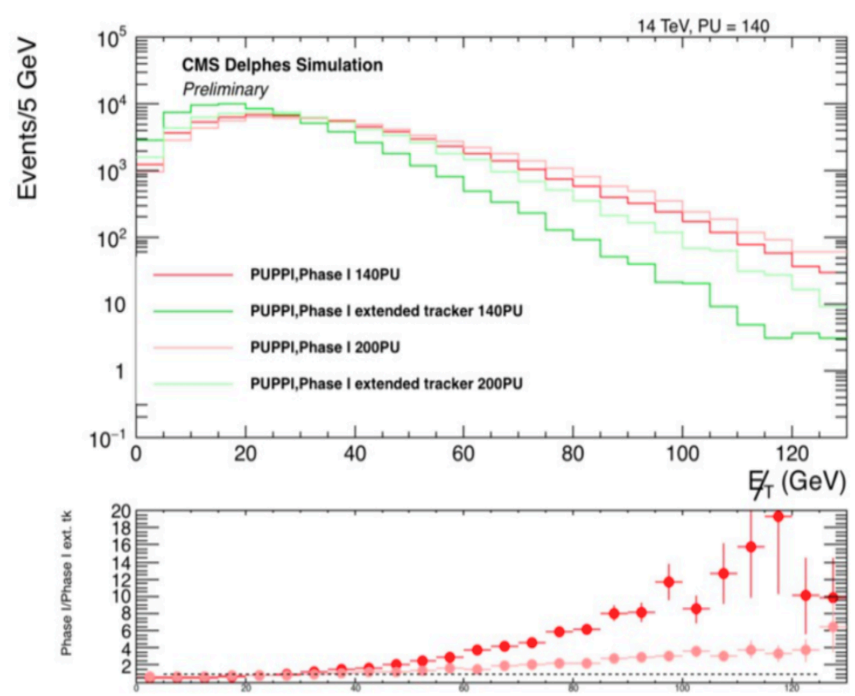
## Instrinsic tracking angular resolution



# Pile-up Simulation and Subtraction

- Pile-up can be mixed with hard event, with f(z,t) profile
- Charged Hadron Subtraction performed according to smearing longitudinal impact parameter
- Neutral Subtraction performed either with GridMedianEstimator, SoftKiller (FastJet) or PUPPI



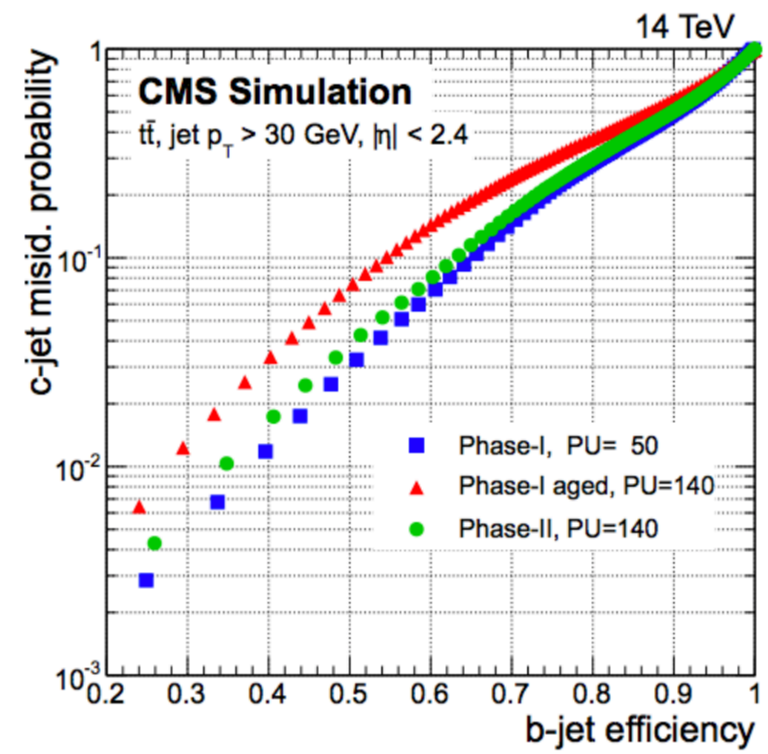



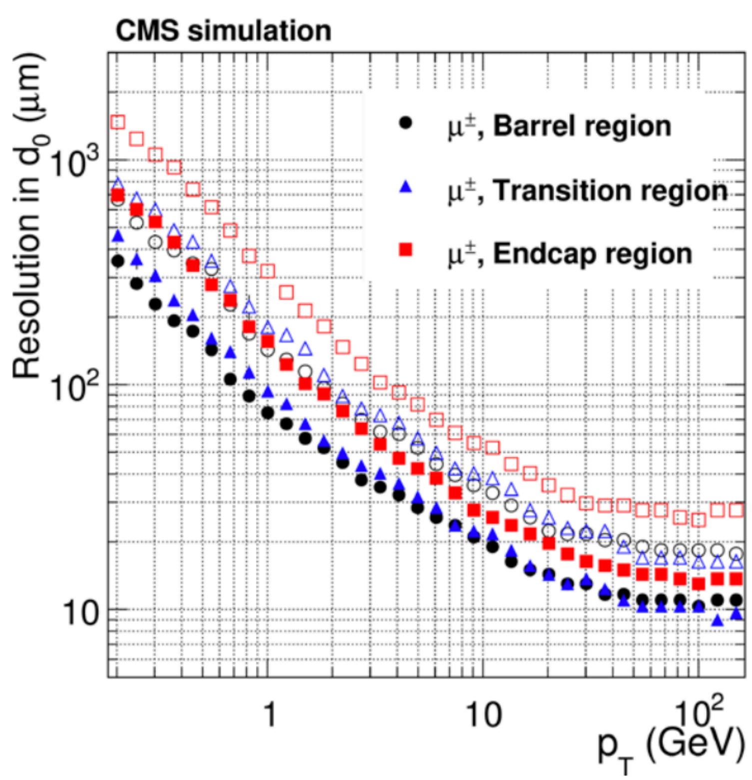
# Heavy flavour Flavor Tagging

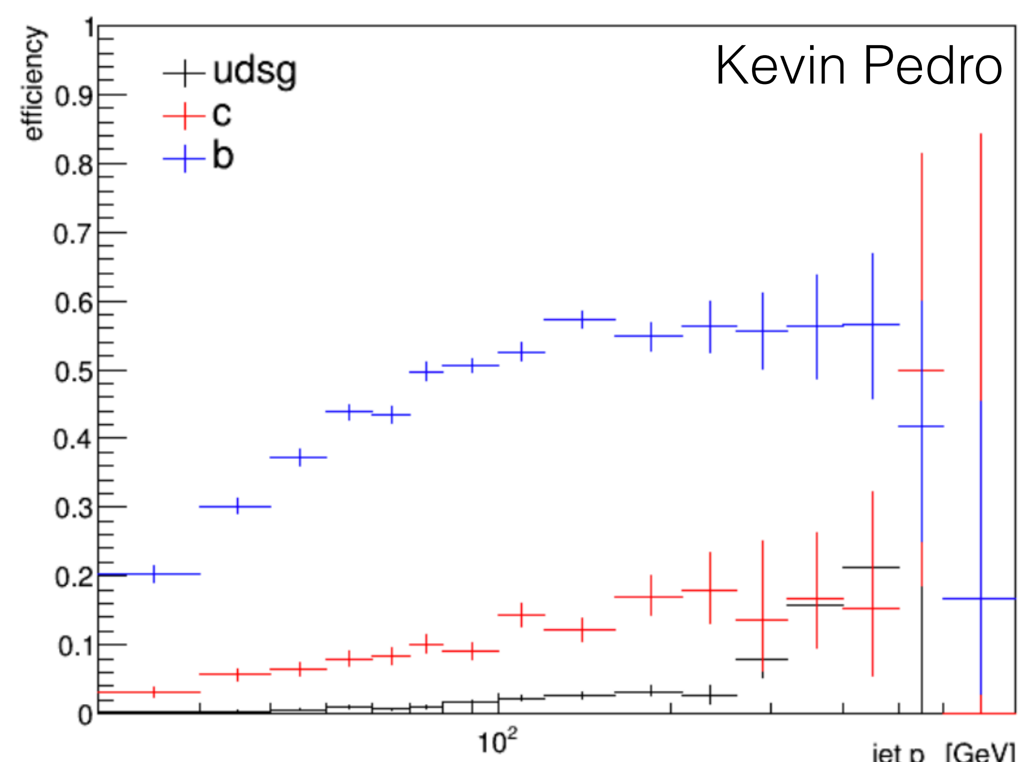
DELPHES
fast simulation

- **Parametric** efficiencies and mis-identification rates (both for b and $\tau$ tagging)

- **Track Counting B-Tagging:**
  - parameterise **longitudinal** and **transverse impact parameter resolution**
  - count number of tracks with significant displacement



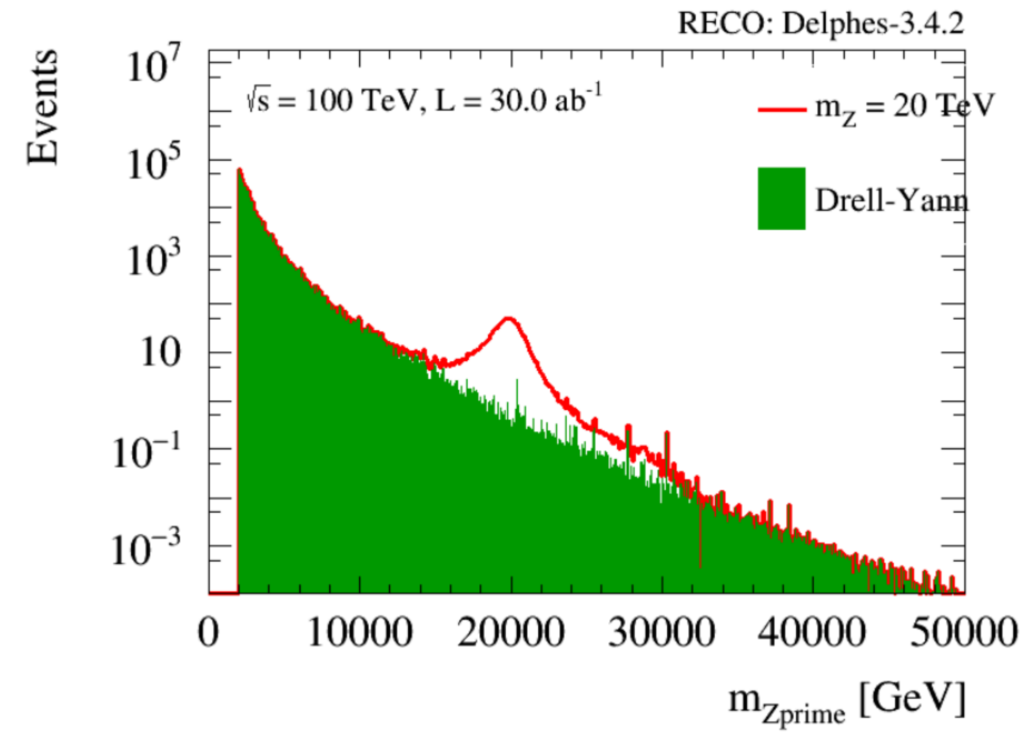



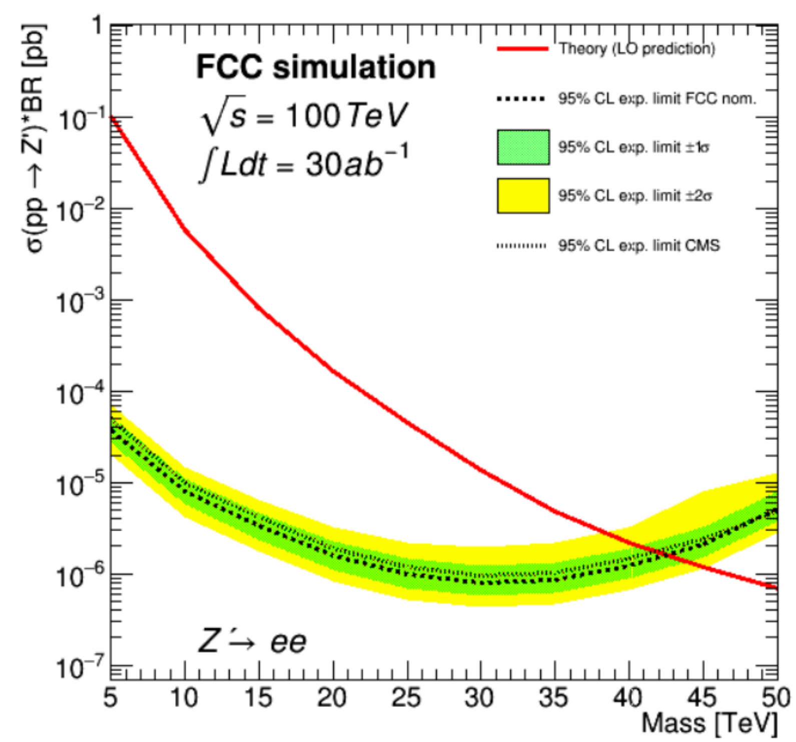



# FCC-hh MonteCarlo/Analysis FW

- GridPack Producer(1) (adapted from CMS)
  - makes MG5_aMC@NLO GridPacks (i.e standalone script that produces LHE files )
- LHE Producer
  - produces LHE files on LSF/condor queues
- FCCSW
  - Runs Pythia8 parton shower+hadronization and Delphes with FCC detector
- Analysis
  - python framework produces flat ROOT tree
- FlatTreeAnalyzer
  - python framework for optimising analysis cut flows and producing plots
- Limit Setting
  - ATLAS inspired tool, sets limits, significance

More info in Clement Helsens presentation



# Conclusion

- Delphes provides a **simple, highly modular framework** for performing fast detector simulation

- **Integrated** in MG5 suite and in the FCCSW framework

- Includes:

  - efficiency/ identification/ fake-rate maps
  - Tracking/Calorimeter **smearing** and Particle-Flow
  - Jet clustering (with FastJet) and jet substructure
  - **pile-up** simulation and modern PU subtraction techniques

- Can be used and configured for:
  - quick **phenomenological** studies
  - as an **alternative for full-sim** if accurately tuned

# Backup

# FCC-hh detector requirements

Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$ calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

- **Tracking** target : achieve **σ / p = 10-20% @10 TeV**
- **Muons** target: **σ / p = 5% @10 TeV**
- Keep calorimeter **constant term** as small as possible.
- Long-lived particles live **longer**:

ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
5 TeV **tau lepton** travels **10 cm** before decaying

→ re-think reconstruction, include **dE/dx ?**

Require **high granularity** (both in tracker and calos):

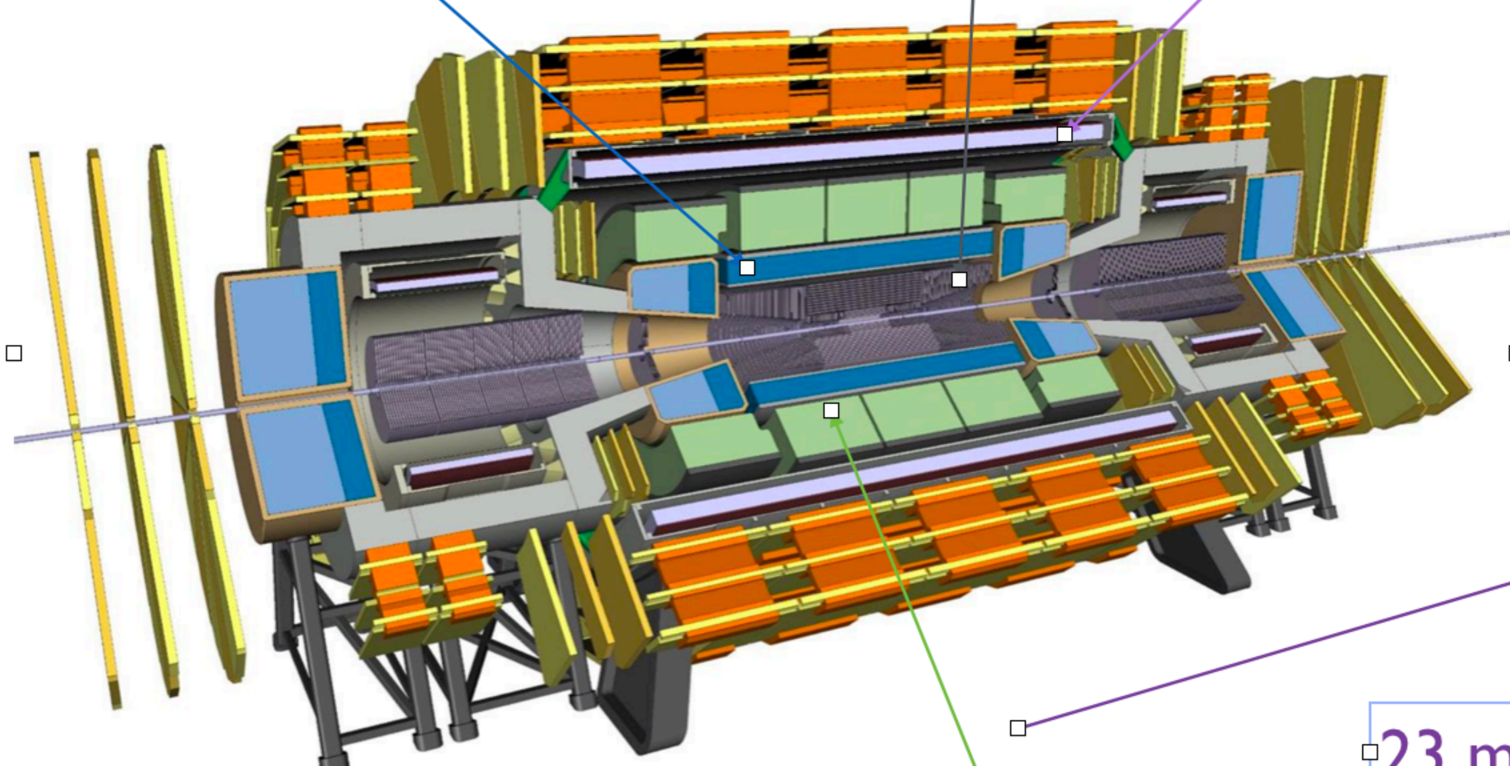
ex: W(**$p_T$ = 10 TeV**) will have **decay products** separated by **ΔR = 0.01**

# FCC-hh detector

Tracker: $\sigma_{pt}/pt$ ~ 20% at 10 TeV (1.5m radius)

Central Magnet: 4T, 5m radius

Barrel ECAL: $\sigma_E/E$ ~10%/$\sqrt{E} \oplus$ 0.7 %



9 m

23 m

Fwd detectors: to $\eta$~6

Barrel HCAL: $\sigma_E/E$~50%/$\sqrt{E} \oplus$ 3 %