DELPHES
fast simulation

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JHEP 02 (2014) 057

Tutorial
8 May 2014

Outline of tutorial

- General Delphes introduction **(~ 20')**

  - *brief overview*
  - *new features*

    track counting b-tagging

    simple calorimeters

    N-subjettiness

- Hands-on session **(~ 1h 30')**

  - *Higgs invariant mass in bb final state (FCC-ee)*

    run Delphes, glance at output tree
    run simple macro on output
    modify configuration card (change calo granularity, resolution)
    write a Delphes module

  - *Jet substructure and pile-up (FCC-hh)*

    run a simple analysis with pile-up, see impact of pile-up on
    N-subjettiness for two jet topologies (light and top jets)

Outline of tutorial

- Open discussion **(remaining time)**

  - un-addressed topics:

    → using Delphes as an external library

    → possible improvements:

    - transverse energy sharing
    - longitudinal segmentation
    - frozen showers
    - calorimeter clustering (and implications on particle-flow)

    → suggestions from the audience?

Overview

The Delphes project: A bit of history

- Delphes project started back in 2007 at UCL as a side project to allow **quick feasibility studies**

- Since 2009, its development is **community-based**
  - **ticketing system** for improvement and bug-fixes
    → user proposed patches
  - **Quality control** and **core development** is done at the UCL

- In 2013, **DELPHES 3** was released:
  - modular software
  - new features
  - also included in MadGraph suite

- **Widely** tested and used by the community (pheno, Snowmass, CMS ECFA efforts, etc...)

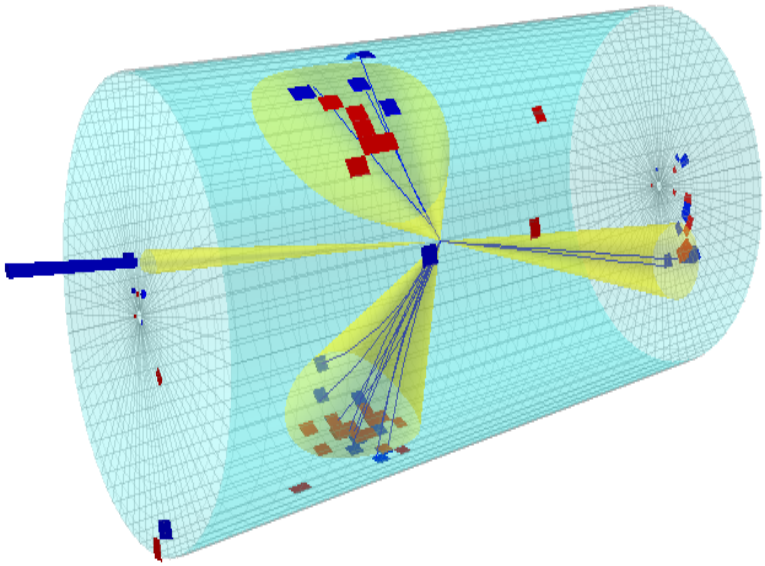
- Website and manual: https://cp3.irmp.ucl.ac.be/projects/delphes

- Paper: JHEP 02 (2014) 057

The Delphes project: Delphes in a nutshell

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

- **Includes**:
  - pile-up
  - charged particle **propagation** in magnetic field
  - electromagnetic and hadronic **calorimeters**
  - **muon** system



- **Provides**:
  - leptons (electrons and muons)
  - photons
  - jets and missing transverse energy (particle-flow)
  - taus and b's

The Delphes project: I/O and configurations

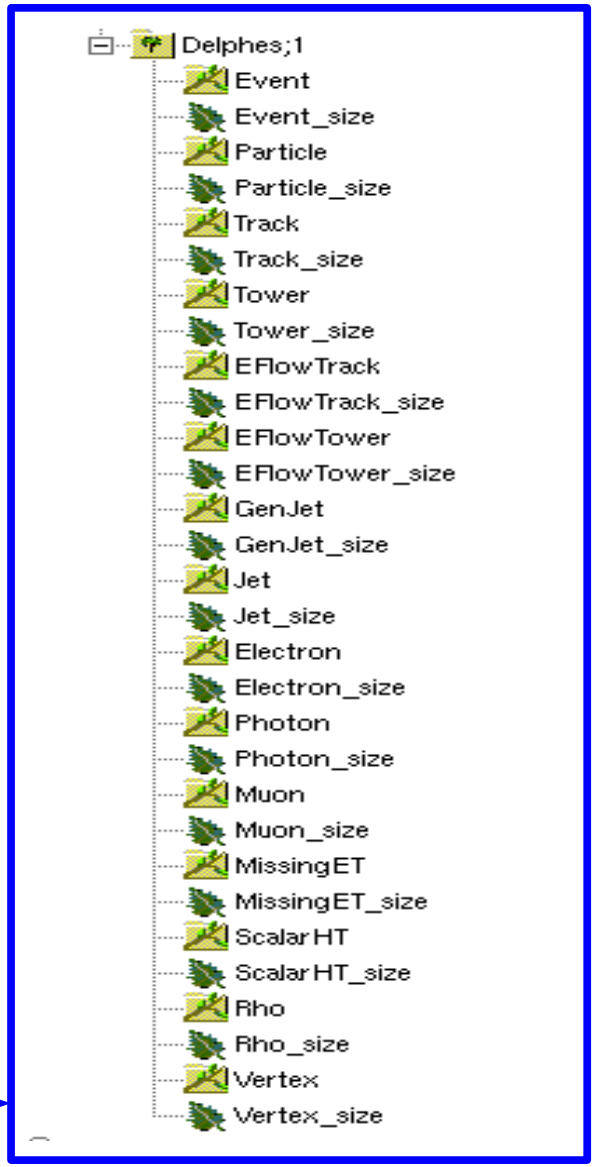
- **modular** C++ code

- Uses
  - ROOT classes [Comp. Phys. C. 180 (2009) 2499]
  - FastJet package [Eur. Phys. J. C 72 (2012) 1896]

- Input
  - Pythia/Herwig output (HepMC,STDHEP)
  - LHE (MadGraph/MadEvent)
  - ProMC

- Configuration file
  - Define geometry
  - Resolution/reconstruction/selection criteria
  - Output object collections

- Output
  - ROOT trees



New features

Track Counting B-tagging

Parametric b-tagging

Parametrized **b-tagging**:

- Check if there is a b,c-quark in the cone of size DeltaR
- Apply a **parametrized Efficiency** (PT, eta)

```
module BTagging BTagging {
  set PartonInputArray Delphes/partons
  set JetInputArray JetEnergyScale/jets

  set BitNumber 0
  set DeltaR 0.5
  set PartonPTMin 1.0
  set PartonEtaMax 2.5

  # default efficiency formula (misidentification rate)
  add EfficiencyFormula {0} {0.001}

  # efficiency formula for c-jets (misidentification rate)
  add EfficiencyFormula {4} {                                    (pt <= 15.0) * (0.000) + \
                                                  (abs(eta) <= 1.2) * (pt > 15.0) * (0.2*tanh(pt*0.03 - 0.4)) + \
                                (abs(eta) > 1.2 && abs(eta) <= 2.5) * (pt > 15.0) * (0.1*tanh(pt*0.03 - 0.4)) + \
                                (abs(eta) > 2.5)                                  * (0.000)}

  # efficiency formula for b-jets
  add EfficiencyFormula {5} {                                    (pt <= 15.0) * (0.000) + \
                                                  (abs(eta) <= 1.2) * (pt > 15.0) * (0.5*tanh(pt*0.03 - 0.4)) + \
                                (abs(eta) > 1.2 && abs(eta) <= 2.5) * (pt > 15.0) * (0.4*tanh(pt*0.03 - 0.4)) + \
                                (abs(eta) > 2.5)                                  * (0.000)}
}
```

→ perfectly reproduces existing performances

→ not predictive

Track counting b-tagging

- b-jets have charged constituents with large impact parameter
- for each track inside jet, compute $sig(IP) = \frac{IP}{\sigma(IP)}$ in 2D (simpler)
- count tracks with $sig(IP) >$ cut
- if find more than 2 (high efficiency) or 3 (high purity) such tracks $\rightarrow$ jet is b-tagged

inspired from CMS NOTE 2006 019 and BTV-11-002

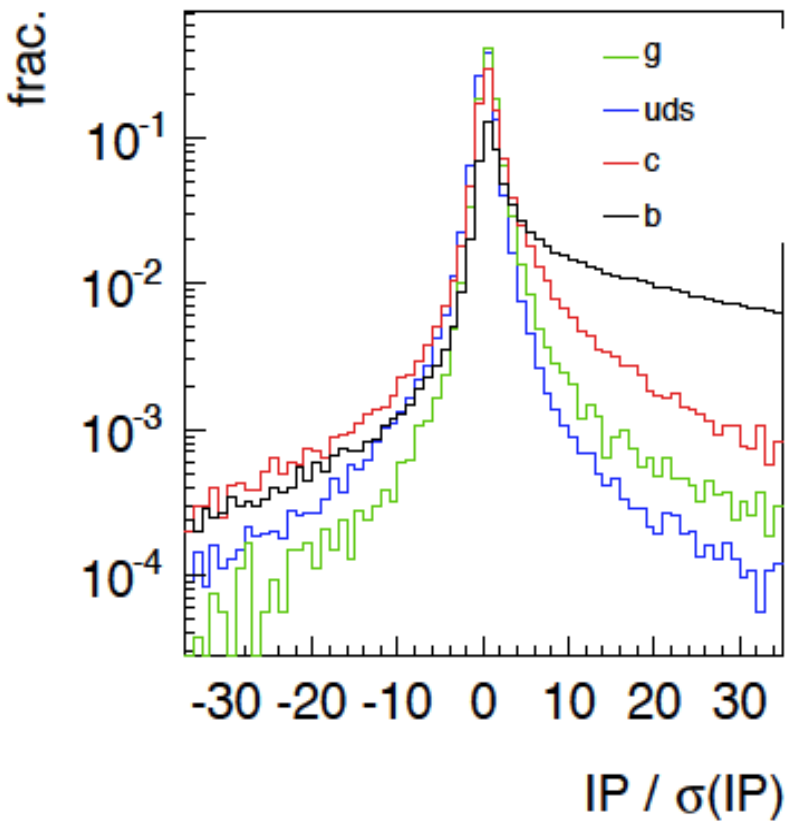
IP smearing

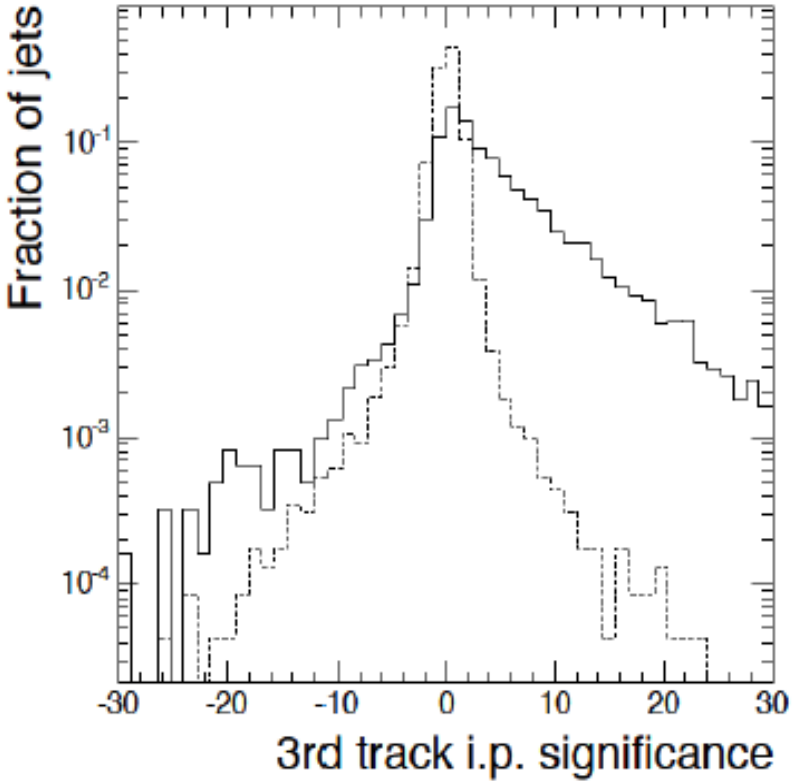
- computes coordinates of point of closest approach (X_d, Y_d) to vertex (0,0) and smears (X_d, Y_d) independently $X_d(sm) = X_d + Gaus(0, res)$ (idem for $Y_d(sm)$).
- derive IP(sm) from $(X_d(sm), Y_d(sm))$
- compute independently $\sigma(IP) = |Gaus(0, res)|$.
- save these quantities as track members.

IP btagging

- takes as input track and jet collections (alternatively could take simply jet collection using chaged jet constituents as tracks)
- parameters :
  - p_T^{min} = 1 GeV of the tracks
  - ΔR cone to associate tracks with jet (typically $\Delta R = 0.3$)
  - IP_{max} = 2 mm
  - $sig(IP)_{min}$ (algo working point)
  - N_{tracks}, defines algorithm. Minimum number of tracks that pass sig(IP) cut (= 2 for HE, = 3 for HP)
- compute sig(IP) = sign($\mathbf{p_T^{jet}} \cdot \mathbf{IP}$) IP.
- flag BTAG set to true if at least N_{tracks} with $sig(IP) > sig(IP)_{min}$ are found.

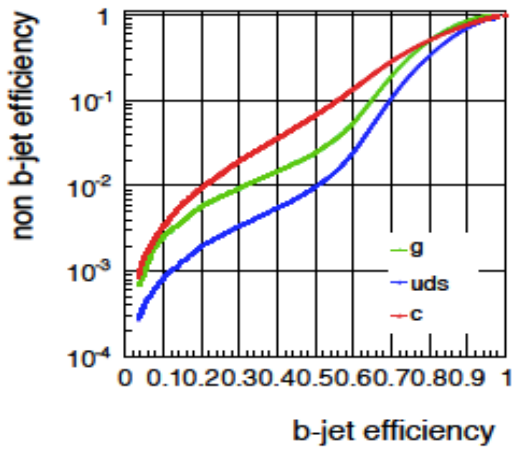
IP btagging

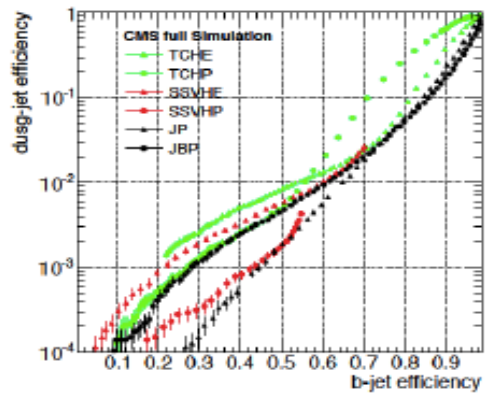

frac.
10^{-1}
10^{-2}
10^{-3}
10^{-4}
g
uds
c
b
-30 -20 -10 0 10 20 30
IP / σ(IP)

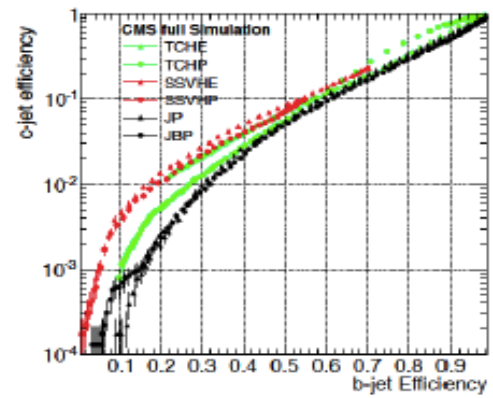

Fraction of jets
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-30 -20 -10 0 10 20 30
3rd track i.p. significance

IP btagging

Performance : High Purity







- c mistag rate agrees ok
- too pessimistic light rejection for low btagging efficiency

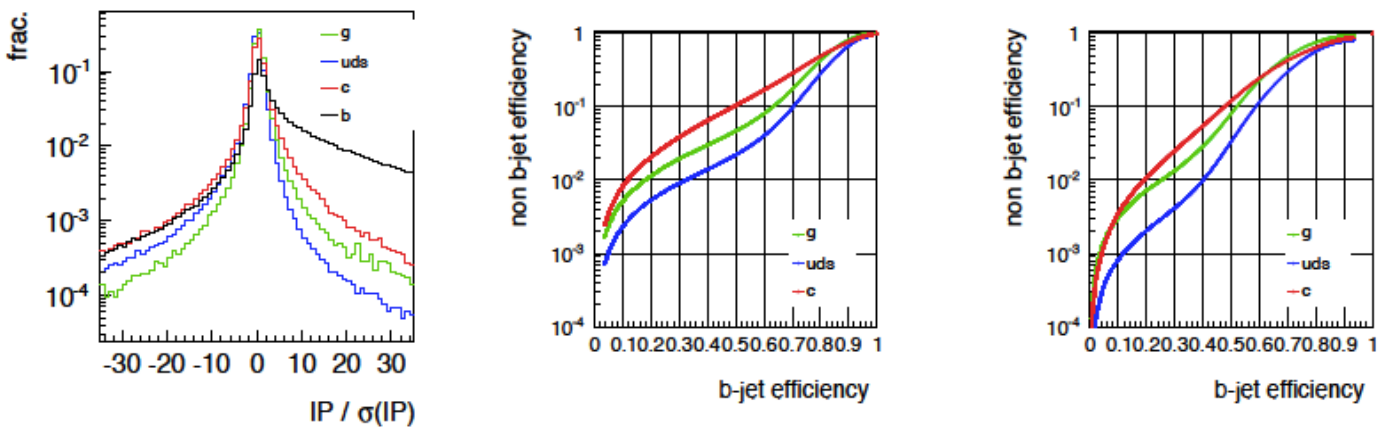
At 55% b-tagging efficiency (Medium working point) :

DELPHES : l-mis = 1.5%, c-mis = 10%
CMS : l-mis = 1.0%, c-mis = 10%

$$sig(IP)_{min} = 6.5$$

IP btagging

Performance vs impact parameter resolution (1)

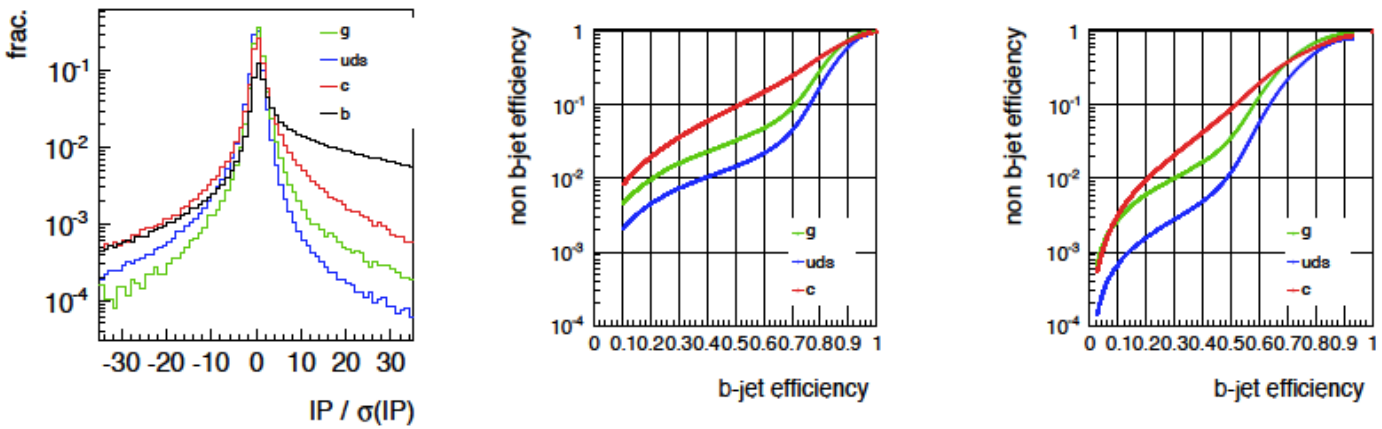


$$p_T < 5GeV \ \sigma(IP) = 20 \ \mu m$$

$$p_T > 5GeV \ \sigma(IP) = 10 \ \mu m$$

IP btagging

Performance vs impact parameter resolution (2)

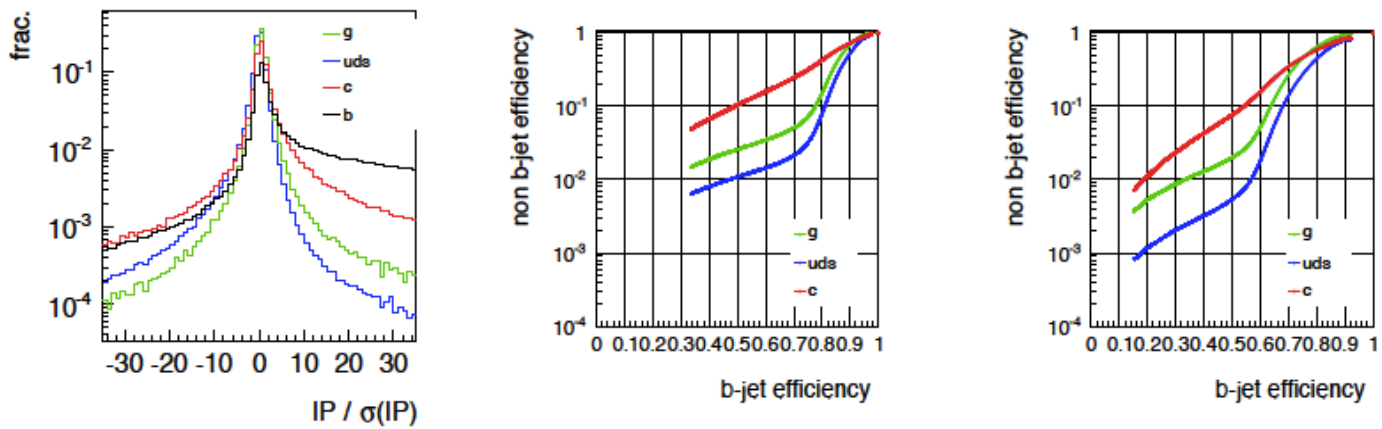


$$p_T < 5GeV \ \sigma(IP) = 10\ \mu m$$

$$p_T > 5GeV \ \sigma(IP) = 5\ \mu m$$

IP btagging

Performance vs impact parameter resolution (3)



$$p_T < 5GeV \ \sigma(IP) = 5 \ \mu m$$

$$p_T > 5GeV \ \sigma(IP) = 1 \ \mu m$$

Simple calorimeters

Calorimeters

- In **Calorimeter** module ECAL and HCAL tied together → same granularity

- New module: **SimpleCalorimeter**

  → call it once for ECAL and once for HCAL
  → can define separate:

    - granularity
    - resolution
    - fraction of energy deposit per particle

- It outputs the following objects:

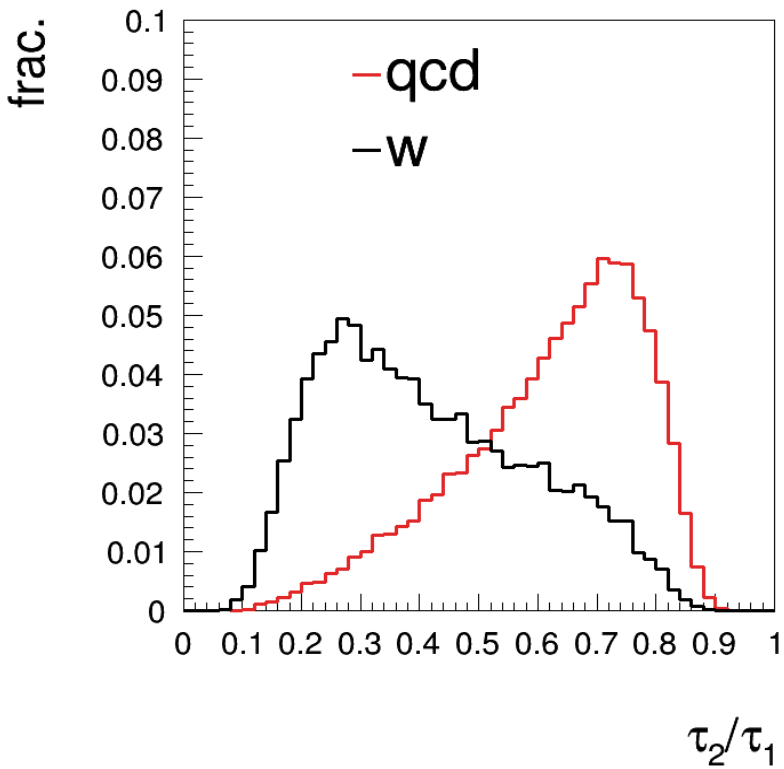
  → Towers (~ full deposit)
  → **EFlow**Towers (~ full deposit – charged deposit)

N-subjettiness

N-subjettiness and N-jettiness

JHEP 1103:015 (2011), JHEP 1202:093 (2012) and JHEP 1404:017 (2014)

- very useful for identifying **sub-structure** of highly-boosted jets.
- build ratios τ_N / τ_M to **discriminate** between **N or M-prong**



- Embedded in FastJetFinder module
- Variables τ_1, τ_2, .. , τ_5 saved as jet members (N-subjettiness)

```
##################
# N-subjettiness
##################

module FastJetFinder FastJetFinder {
#  set InputArray Calorimeter/towers
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  # algorithm: 1 CDFJetClu, 2 MidPoint, 3 SIScone, 4 kt,
  #            5 Cambridge/Aachen, 6 antikt, 7 antikt wta, 8 Njettiness

  set JetAlgorithm 7
  set ParameterR 0.5

  set ComputeNsubjettiness 1
  set Beta 1.0

  #axis mode: 1 wta, 2 wta optimized, 3 kt, 4 kt optimized
  set AxisMode 1

  set JetPTMin 1000.0
}
```

Thanks to A. Larkowski for help

People

Jerome de Favereau
Christophe Delaere
Pavel Demin
Andrea Giammanco
Vincent Lemaitre
Alexandre Mertens
Michele Selvaggi

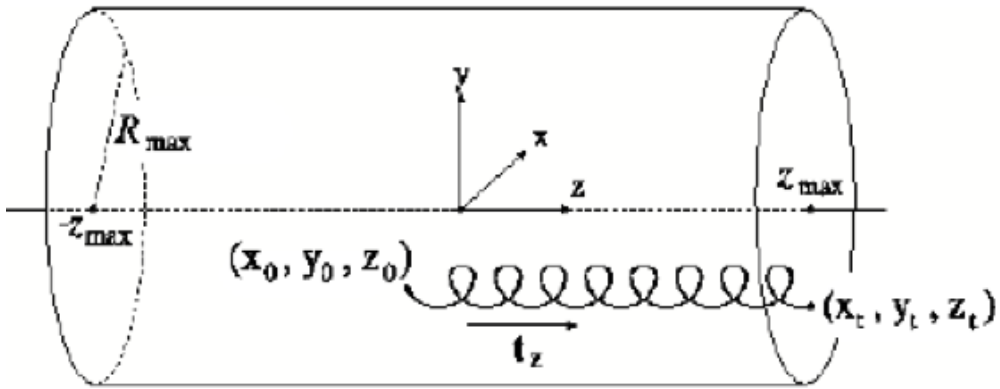
the community ...

Back-up

The modules: Particle Propagation

- **Charged** and **neutral** particles are propagated in the magnetic field until they reach the calorimeters

- Propagation parameters:
  - magnetic field **B**
  - **radius** and **half-length** (R_{max}, z_{max})



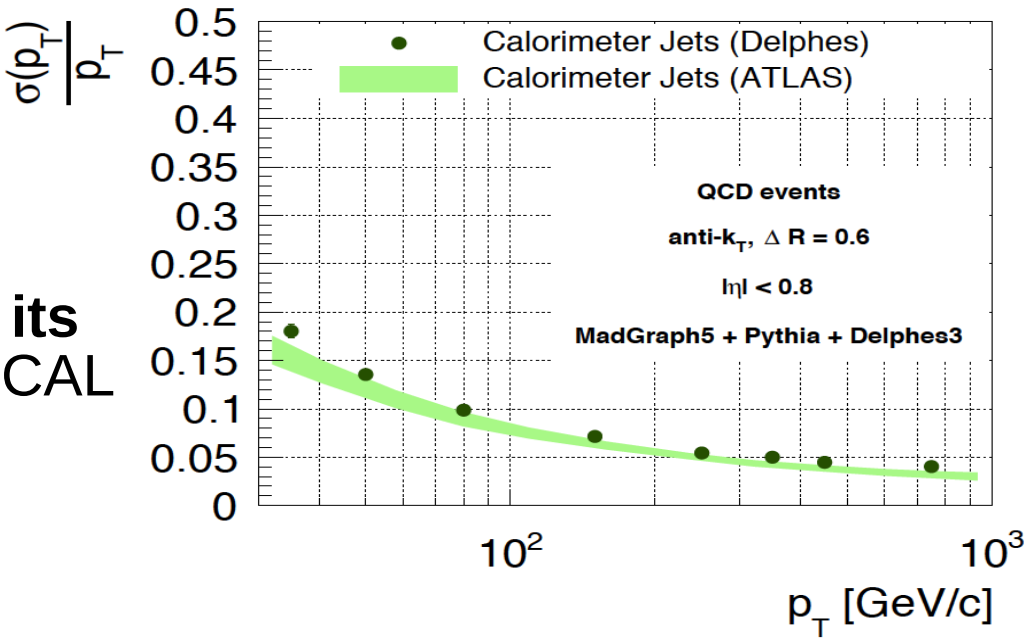
- Efficiency/resolution depends on:
  - particle ID
  - transverse momentum
  - pseudorapidity

```
# efficiency formula for muons
add EfficiencyFormula {13} {                                                    (pt <= 0.1)   * (0.000) + \
                                          (abs(eta) <= 1.5) * (pt > 0.1   && pt <= 1.0)   * (0.750) + \
                                          (abs(eta) <= 1.5) * (pt > 1.0)                  * (1.000) + \
                        (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 0.1   && pt <= 1.0)   * (0.700) + \
                        (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 1.0)                  * (0.975) + \
                        (abs(eta) > 2.5)                                                  * (0.000)}
```

No real tracking/vertexing !!
→ no fake tracks/ conversions (but can be implemented)
→ no dE/dx measurements

The modules: Calorimetry

- em/had calorimeters have same **segmentation** in eta/phi
- Each particle that reaches the calorimeters **deposits a fraction of its energy** in one ECAL cell (f_{EM}) and HCAL cell (f_{HAD}), depending on its type:



particles	f_{EM}	f_{HAD}
e γ π^0	1	0
Long-lived neutral hadrons (K^0_S, Λ^0)	0.3	0.7
ν μ	0	0
others	0	1

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

No different segmentation ECAL vs. HCAL
No Energy sharing between the neighboring cells
No longitudinal segmentation in the different calorimeters

The modules: Particle-Flow Emulation

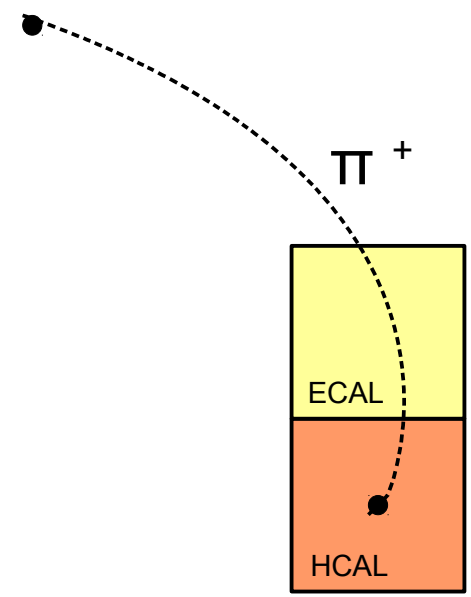
- Idea: Reproduce realistically the performances of the Particle-Flow algorithm.

- In practice, in DELPHES use **tracking and calo** info to reconstruct high reso. input objects for later use (jets, E_T^{miss}, H_T)

→ assume **σ(trk) < σ(calo)**

Example 1: A pion of 10 GeV

→ $E^{HCAL}(\pi^+) = 15$ GeV
$E^{TRK}(\pi^+) = 11$ GeV

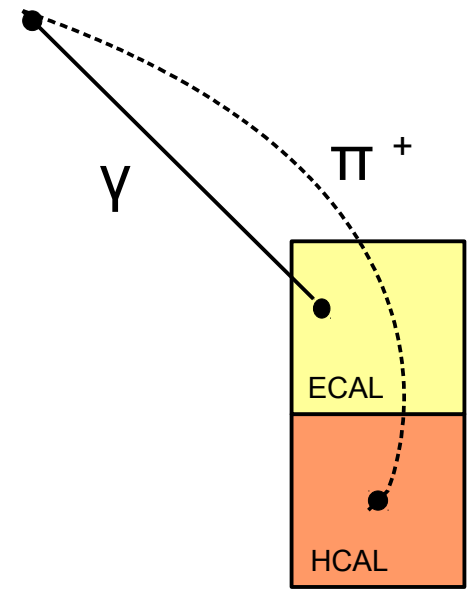


Particle-Flow algorithm creates:

→ PF-track, with energy $E^{PF\text{-}trk} = 11$ GeV
→ PF-tower, with energy $E^{PF\text{-}tower} = 4$ GeV

The modules: Particle-Flow Emulation

Example 2: A pion (10 GeV) and a photon (20 GeV)



→ $E^{ECAL}(\gamma)$ = 18 GeV
→ $E^{HCAL}(\pi^+)$ = 15 GeV
→ $E^{TRK}(\pi^+)$ = 11 GeV

Particle-Flow algorithm creates:

→ PF-track, with energy $E^{PF\text{-}trk}$ = 11 GeV
→ PF-tower, with energy $E^{PF\text{-}tower}$ = 4 + 18 GeV

Separate neutral and charged calo deposits has crucial implications for pile-up subtraction

No separation between “Photons” and “Neutral Hadrons” in the output.

The modules: Jets / E_T^{miss} / H_T

- Delphes uses **FastJet** libraries for jet clustering
- Inputs **calorimeter towers** or "**particle-flow**" objects

```
module FastJetFinder FastJetFinder {
#  set InputArray Calorimeter/towers
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  # algorithm: 1 CDFJetClu, 2 MidPoint, 3 SIScone, 4 kt, 5 Cambridge/Aachen, 6 antikt
  set JetAlgorithm 6
  set ParameterR 0.7

  set ConeRadius 0.5
  set SeedThreshold 1.0
  set ConeAreaFraction 1.0
  set AdjacencyCut 2.0
  set OverlapThreshold 0.75

  set MaxIterations 100
  set MaxPairSize 2
  set Iratch 1

  set JetPTMin 20.0
}
```

The modules: Leptons and photons reconstruction

- Muons/electrons
  - **identified** via their PDG id
  - muons do not deposit energy in calo (independent smearing parameterized in p_T and η)
  - electrons smeared according to tracker and ECAL resolution

- Isolation:

$$I(P) = \frac{\sum_{i \neq P}^{\Delta R < R,\ p_T(i) > p_T^{min}} p_T(i)}{p_T(P)}$$

If **I(P) < Imin**, the lepton is **isolated**

User can specify parameters I_{min}, ΔR, p_T^{min}

```
##################
# Photon isolation
##################

module Isolation PhotonIsolation {
  set CandidateInputArray PhotonEfficiency/photons
  set IsolationInputArray EFlowMerger/eflow

  set OutputArray photons

  set DeltaRMax 0.5
  set PTMin 0.5
  set PTRatioMax 0.1
}
```

No fakes, punch-through, brehmstrahlung, conversions

The modules: b-jets (tau-jets)

Current **b-tagging**:

- Check if there is a b,c-quark in the cone of size DeltaR
- Apply a **parametrized Efficiency** (PT, eta)

```
module BTagging BTagging {
  set PartonInputArray Delphes/partons
  set JetInputArray JetEnergyScale/jets

  set BitNumber 0
  set DeltaR 0.5
  set PartonPTMin 1.0
  set PartonEtaMax 2.5

  # default efficiency formula (misidentification rate)
  add EfficiencyFormula {0} {0.001}

  # efficiency formula for c-jets (misidentification rate)
  add EfficiencyFormula {4} {                                    (pt <= 15.0) * (0.000) + \
                                                  (abs(eta) <= 1.2) * (pt > 15.0) * (0.2*tanh(pt*0.03 - 0.4)) + \
                                 (abs(eta) > 1.2 && abs(eta) <= 2.5) * (pt > 15.0) * (0.1*tanh(pt*0.03 - 0.4)) + \
                                 (abs(eta) > 2.5)                                  * (0.000)}

  # efficiency formula for b-jets
  add EfficiencyFormula {5} {                                    (pt <= 15.0) * (0.000) + \
                                                  (abs(eta) <= 1.2) * (pt > 15.0) * (0.5*tanh(pt*0.03 - 0.4)) + \
                                 (abs(eta) > 1.2 && abs(eta) <= 2.5) * (pt > 15.0) * (0.4*tanh(pt*0.03 - 0.4)) + \
                                 (abs(eta) > 2.5)                                  * (0.000)}
}
```

No Predictive B-tagging !

IP smearing

Impact parameter smearing module

- In RECO, impact parameter IP is derived from track fitting
- $sigma(IP)$ is correlated with error on p_T, R_{curv} ... (encoded in track covariance matrix)
- Here we assume error can be simply parametrized as f(p_T,η).

Module :

- takes as input tracks
- parameters needed for computation (R_{curv}, (X_c, Y_c)) already saved as members of Candidates in the ParticlePropagator module.
- specify (absolute) impact parameter resolution f(p_T,η) in mm (here we take res = 10 μm if p_T<5 GeV and res = 5 μm if p_T>5 GeV)
- computes coordinates of point of closest approach (X_d, Y_d) to vertex (0,0) and smears (X_d, Y_d) independently $X_d(sm) = X_d + Gaus(0, res)$ (idem for $Y_d(sm)$).
- derive IP(sm) from $(X_d(sm), Y_d(sm))$
- compute independently $\sigma(IP) = |Gaus(0, res)|$.
- save these quantities as track members.

IP btagging

- takes as input track and jet collections (alternatively could take simply jet collection using chaged jet constituents as tracks)
- parameters :
  - p_T^{min} = 1 GeV of the tracks
  - ΔR cone to associate tracks with jet (typically $\Delta R = 0.3$)
  - IP_{max} = 2 mm
  - $sig(IP)_{min}$ (algo working point)
  - N_{tracks}, defines algorithm. Minimum number of tracks that pass sig(IP) cut (= 2 for HP, = 3 for HE)
- compute sig(IP) = sign($\mathbf{p_T^{jet}} \cdot \mathbf{IP}$) IP.
- flag BTAG set to true if at least N_{tracks} with $sig(IP) > sig(IP)_{min}$ are found.