DELPHES
fast simulation

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JHEP 02 (2014) 057

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Detector simulation

- Full simulation (GEANT):
  - **simulates** particle-matter interactions in very fine-grained steps → 10-100 s /ev
- Experiment Fast simulation (ATLAS, CMS ...):
  - **simplifies** by simulating most interactions, but in a point-like way (i.e. once per detector layer or block)
  - mixes G4, parametric, libraries → 1 s /ev
- Parametric simulation:

Delphes, PGS**:**

  - **parameterize** detector response, reconstruct complex objects → 10 ms /ev

Overview

- The Delphes Project
- The Particle Flow Emulation
- PU Implementation
- Other new features
- Conclusion

The Delphes Project

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...)

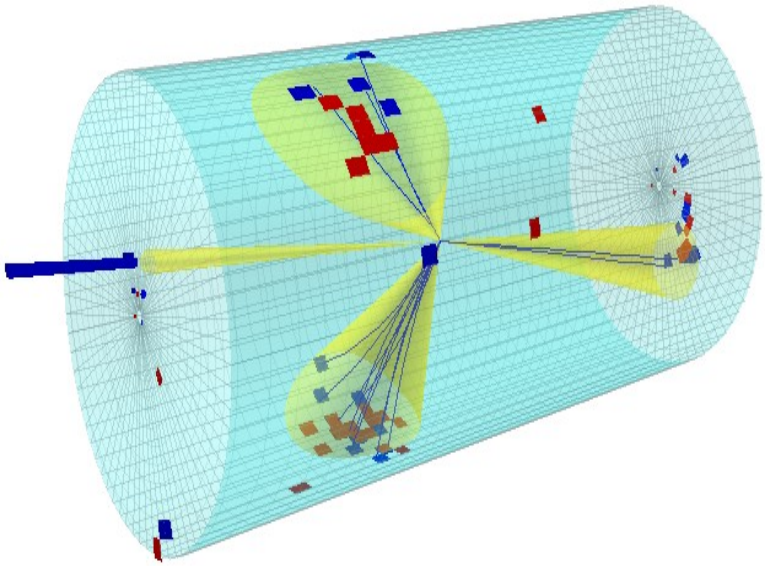
- Website and manual: https://cp3.irmp.ucl.ac.be/projects/delphes

- Paper: JHEP 02 (2014) 057

The Delphes project: Delphes in a nutshell

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

- **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

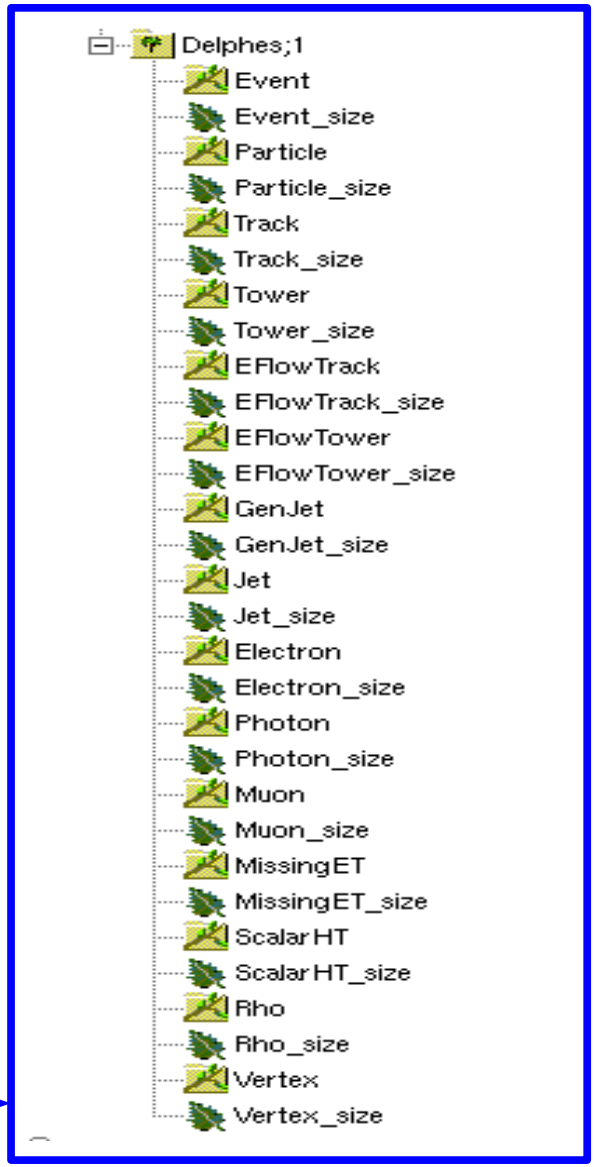
- **modular** C++ code

- 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

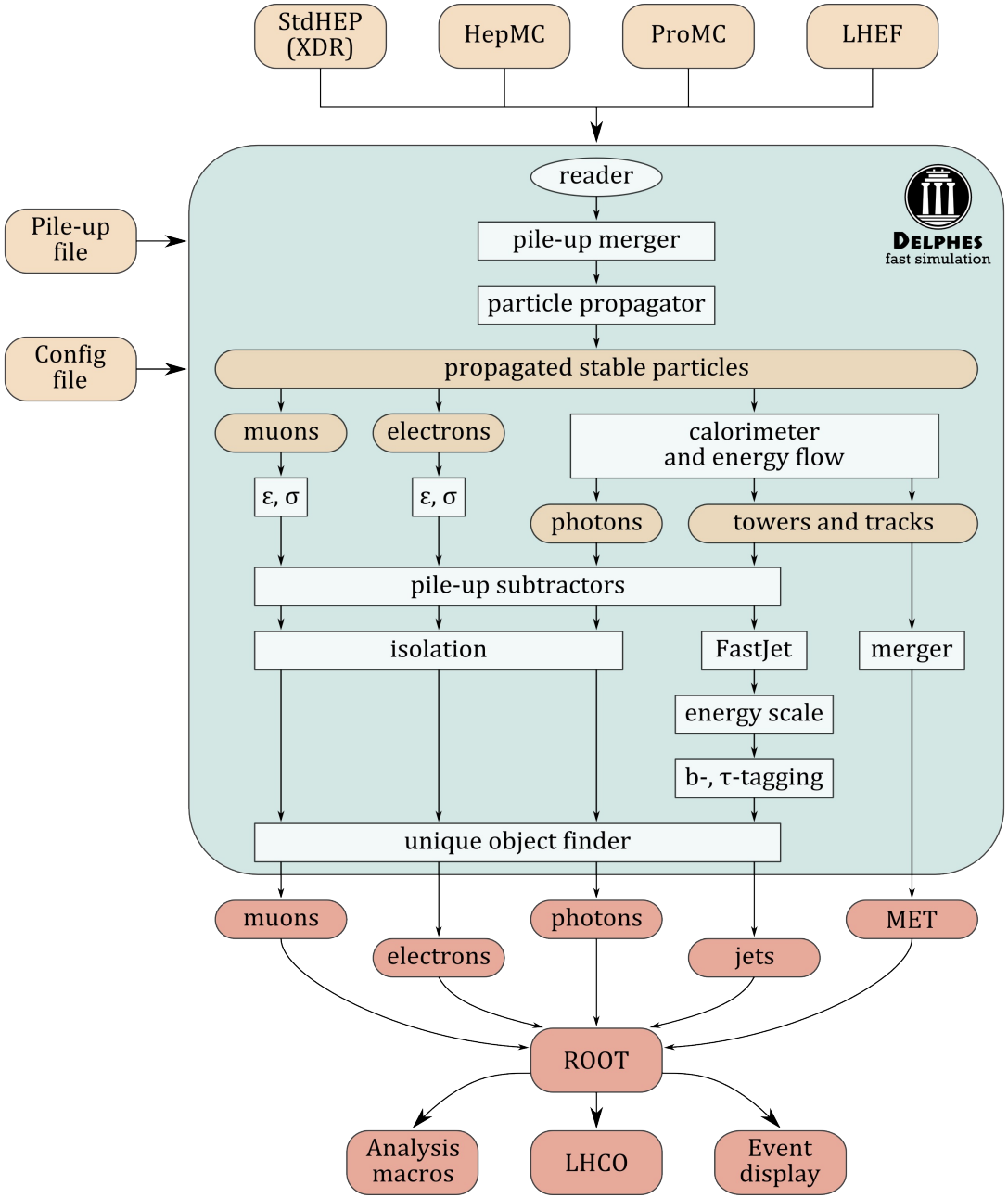
- Configuration file
  - Define geometry
  - Resolution/reconstruction/selection criteria
  - Output object collections

- Output
  - ROOT trees



default **CMS** and **ATLAS** configurations are included in any Delphes release

The Delphes project: A modular structure



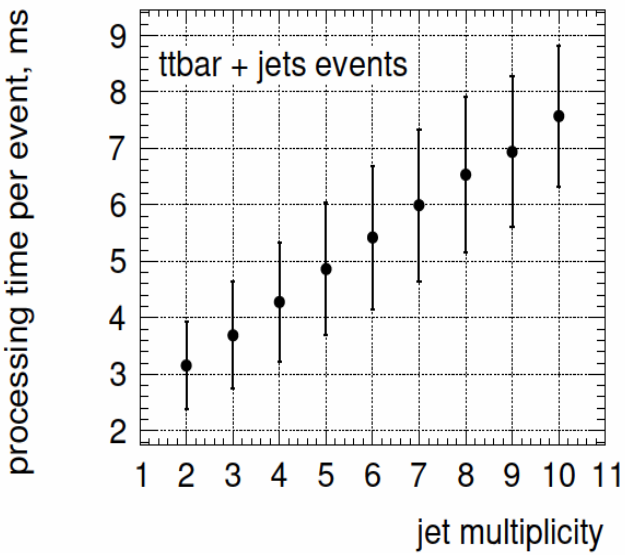
- Every Object in Delphes is a **Candidate**.
- All **modules** consume and produce **Arrays** of **Candidates**.
- Any module can **access** Arrays produced by other modules using **ImportArray** method: *ImportArray("ModuleName/arrayName")*
- The Delphes team provides a set of modules.
- A user can create **new modules** and define its **own sequence**.

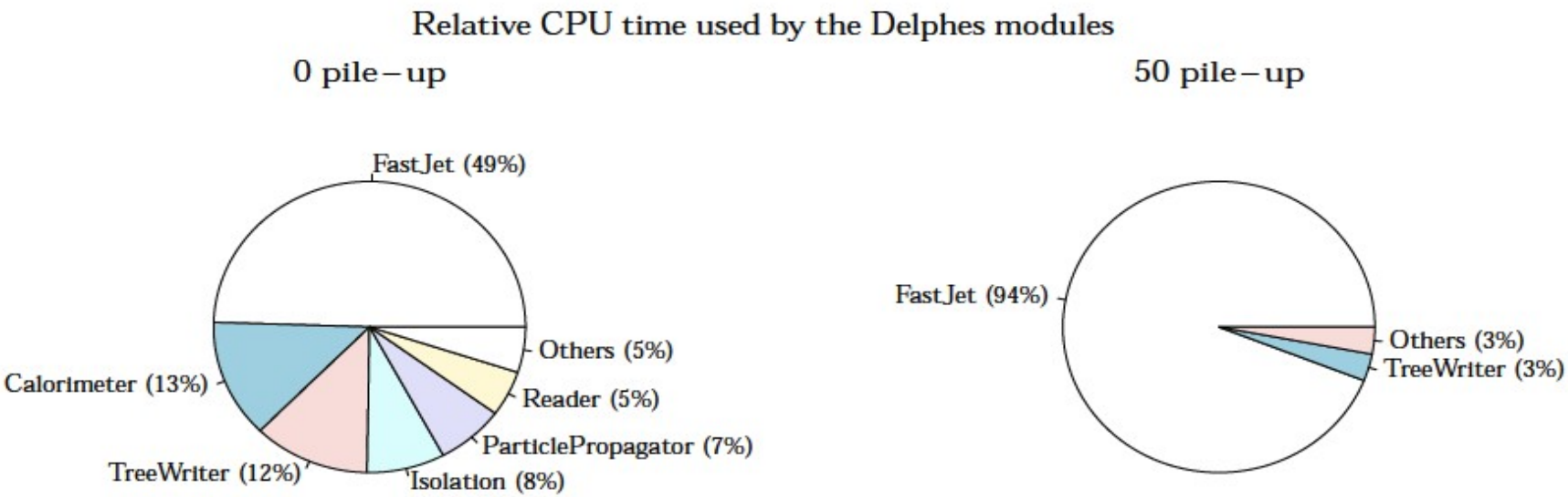
The Delphes Project: CPU time

Delphes reconstruction:

1ms (0 PU) – 1s (150 PU)

Mainly spent in the FastJet algorithm:





Particle Flow

Particle-Flow Emulation

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

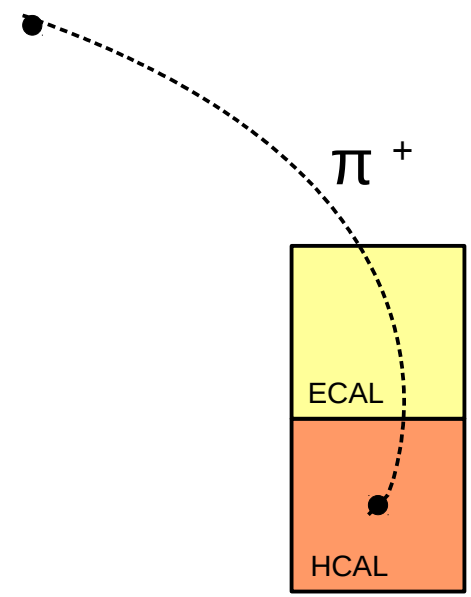
- In practice, in DELPHES use **tracking and calo** info to reconstruct high reso. input objects for later use (jets, E_T^{miss}, H_T)

  → assume **σ(trk) < σ(calo)**

Example 1: A pion of 10 GeV

→ $E^{HCAL}(\pi^+) = 15$ GeV

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



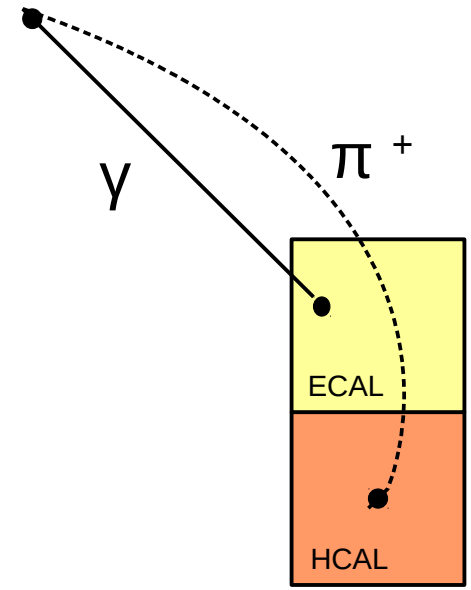
Particle-Flow algorithm creates:

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

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

Particle-Flow Emulation

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



→ $E^{ECAL}(\gamma) = 18$ GeV

→ $E^{HCAL}(\pi^+) = 15$ GeV

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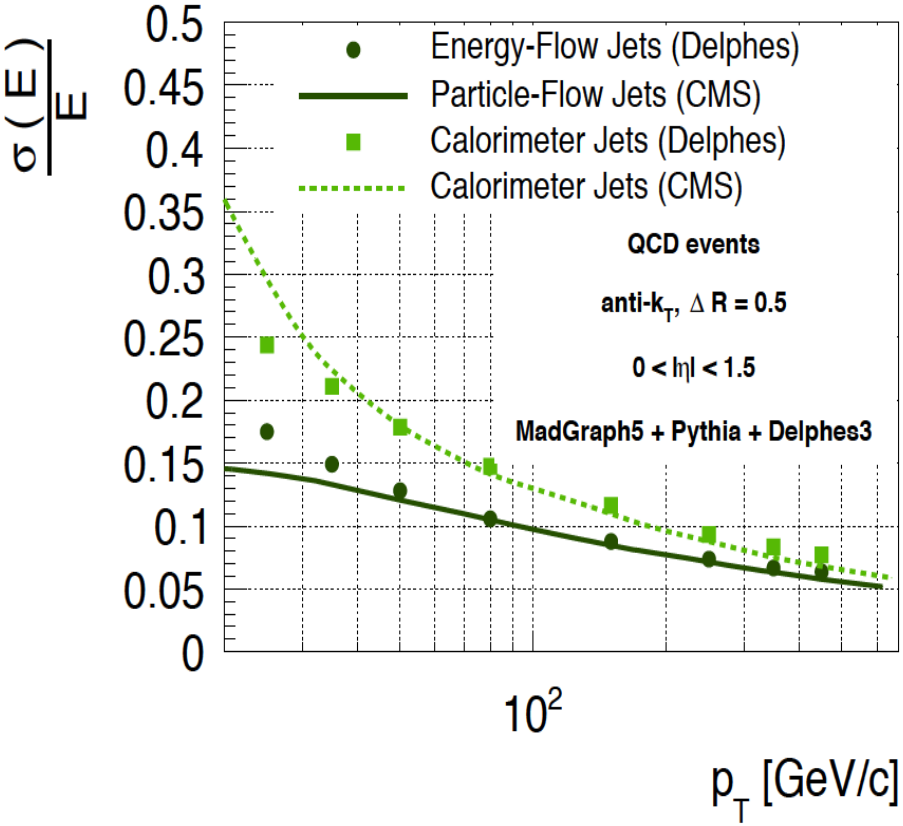
Particle-Flow algorithm creates:

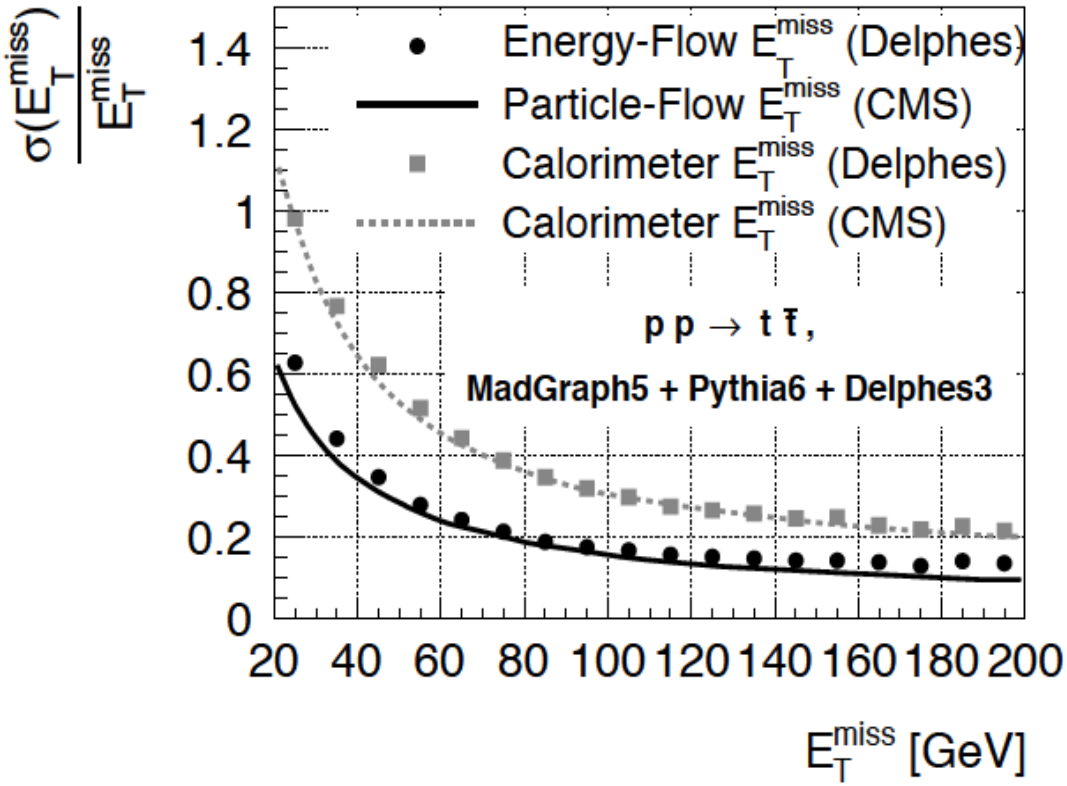
→ PF-track, with energy $E^{PF\text{-}trk} = 11$ GeV

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

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

Particle Flow: Validation





→ **good agreement**

Particle Flow: Physics example

- Reproduce part of **top mass measurement** in semi-leptonic decay (arXiv:1209:2319)

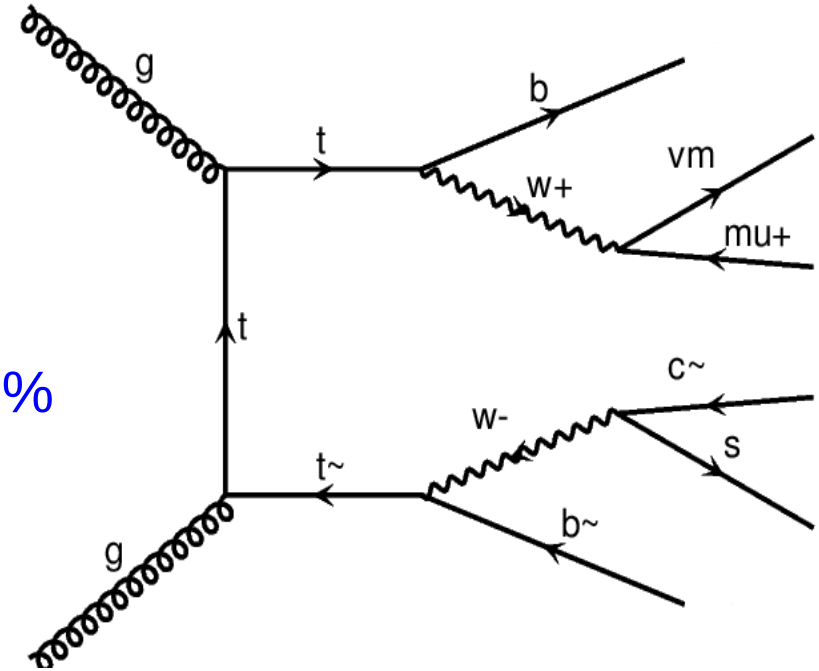
- **Signal** produced with MG5+Pythia+Delphes3

- Selection criteria:

  → = 1 lepton p_T > 30 GeV, |η| < 2.1
  → ≥ 4 jets p_T > 30 GeV, |η| < 2.4
  → ≥ 2 b-tagged jets, ≥ 2 light jets

- eff(Delphes) = 2.8% vs. eff(CMS) = 2.3%

→ **good agreement**

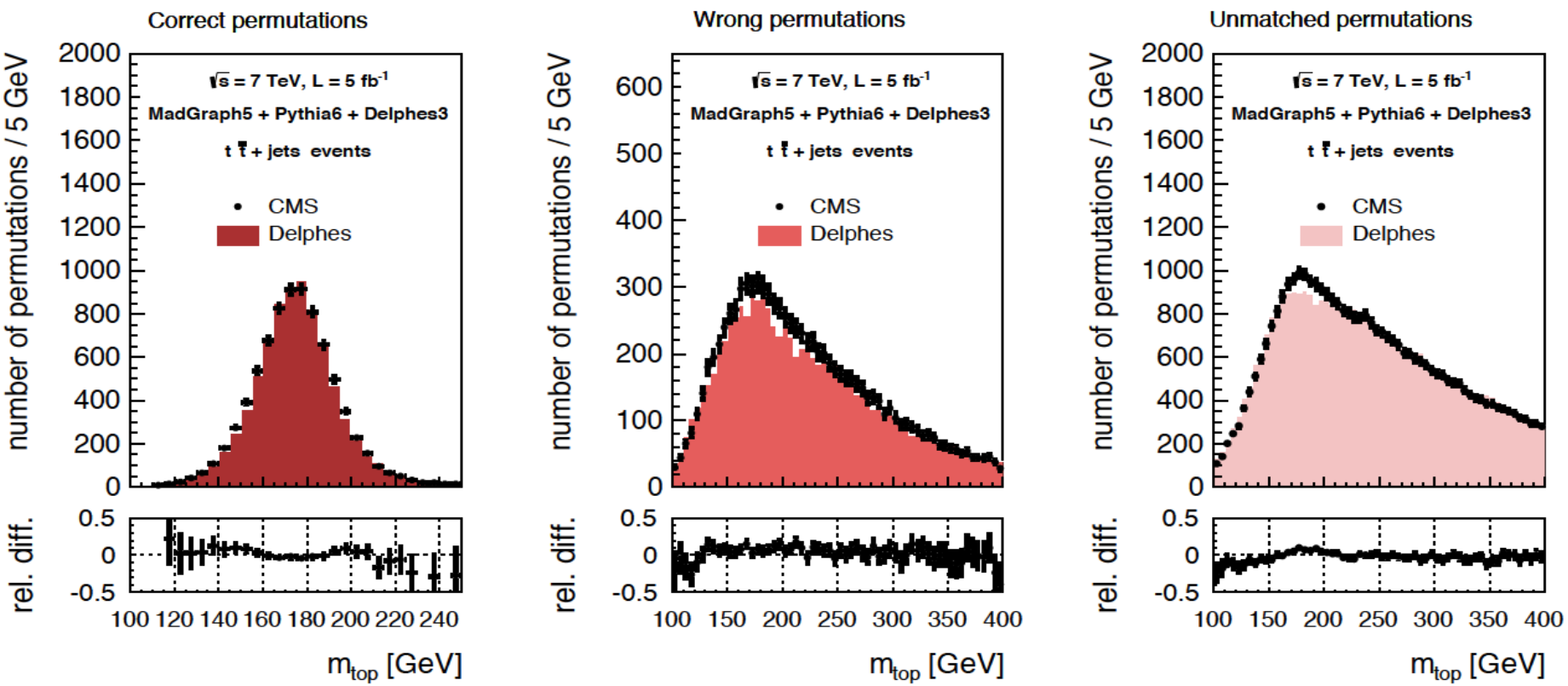


Particle Flow: Physics example

Look at **hardest** 2 b-tagged and 2 light jets (à la CMS):

- correct : 4 jets are good, associate right b with lights
- wrong : 4 jets are good, associate wrong b with lights
- unmatched : at least one of the jets doesn't match

	CMS	DELPHES
correct	15.5 %	15.8 %
wrong	17.4 %	16.5 %
unmatched	67.1 %	67.7 %



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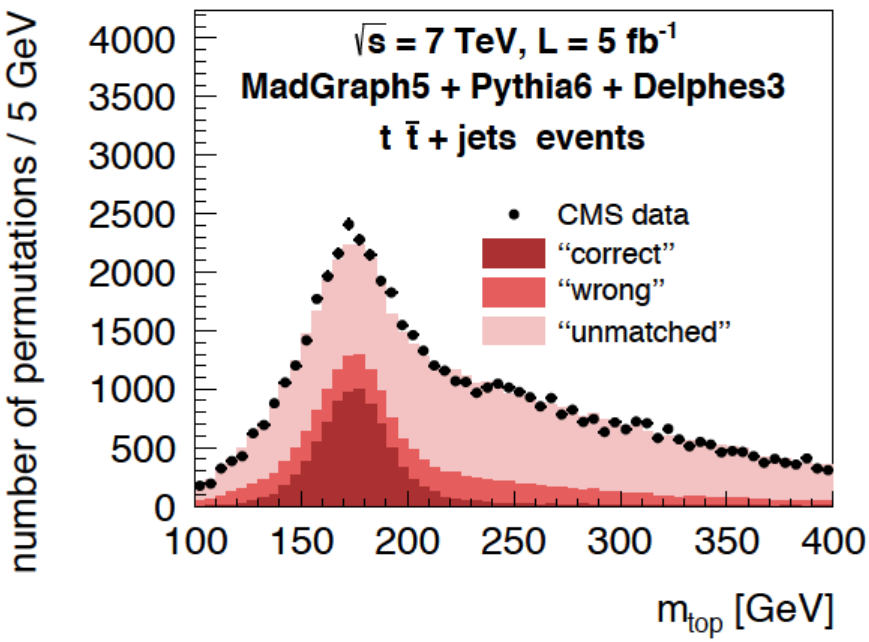
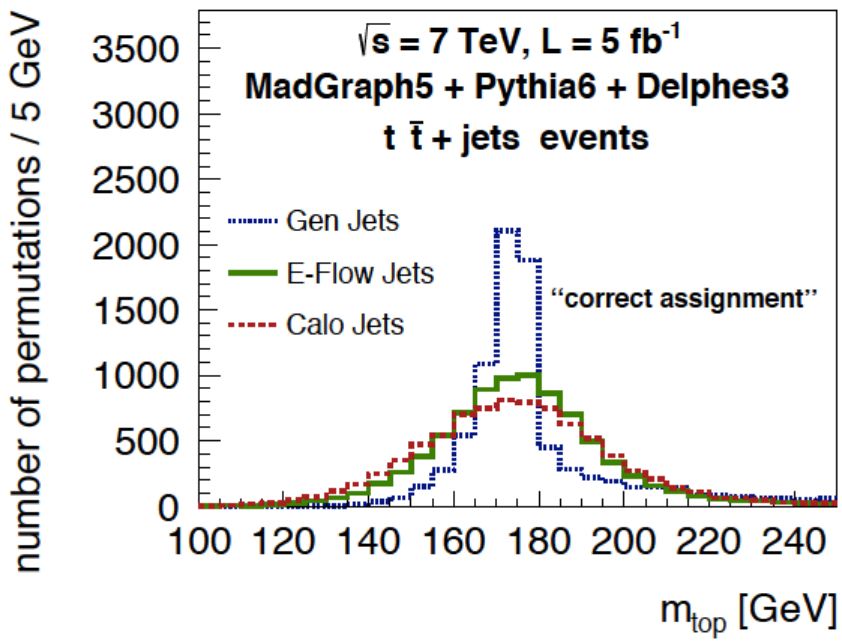
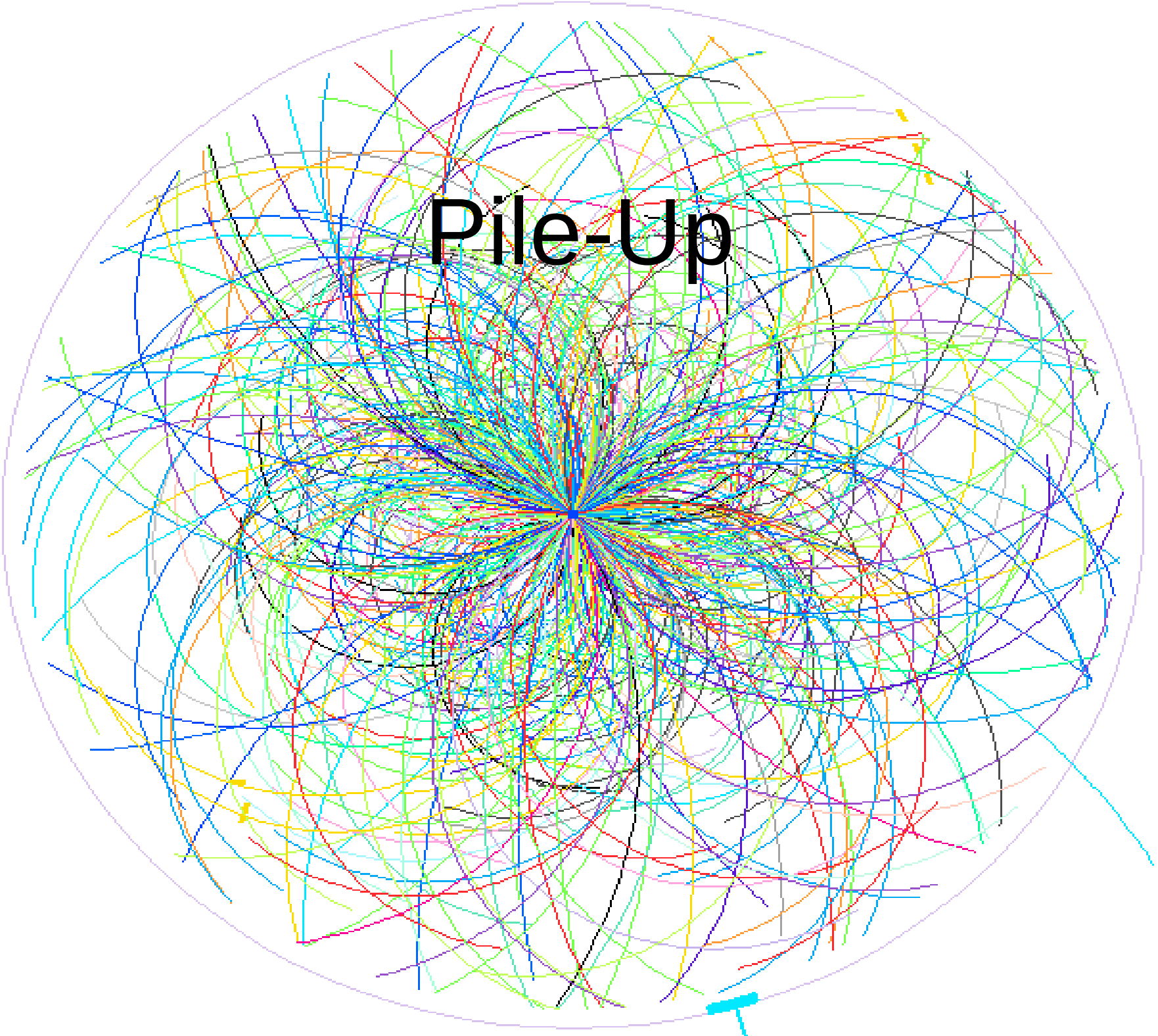




Pile-Up



Pile-up motivations

- **Pile-up** becomes an issue at **high luminosity** LHC
  - reduced **efficiency**
  - worsened **resolution** (jets, E_T^{miss})
  - degraded **isolation**
  - **fake** tracks, jets

- **Efficiencies** and **resolutions** can be **tuned by hand** to mimic pile-up
- Fake objects (jets) need to be simulated. Also, we want to have some predictive power:

  → We therefore introduced: tunable **simulation** of pile-up

  pile-up **substraction** procedure.

Pile-up: implementation

- **Pile-up** is implemented in Delphes **since version 3.0.4**
  - **mixes** N minimum bias events with hard event sample
  - spreads **poisson(N)** events along z-axis with configurable spread
  - rotate event by random angle φ wrt z-axis

- **Charged** Pile-up subtraction (most effective if used with PF algo)

  - if **z < |Zres|** keep all **charged and neutrals** (→ ch. particles too close to hard scattering to be rejected)

  - if **z > |Zres|** keep only **neutrals** (perfect charged subtraction)

  - allows user to tune amount of charged particle subtraction by **adjusting Z spread/resolution**

- **Residual** pile-up subtraction is needed for jets and isolation.
  - Use the FastJet Area approach (Cacciari, Salam, Soyez)
    - compute ρ = event pile-up density
    - jet correction : $pT \rightarrow pT - \rho A$ (JetPileUpSubtractor)
    - isolation : $\sum pT \rightarrow \sum pT - \rho\pi R^2$ (Isolation module itself)
  - Subtraction can be |η| dependent

Pile-Up : Event Display

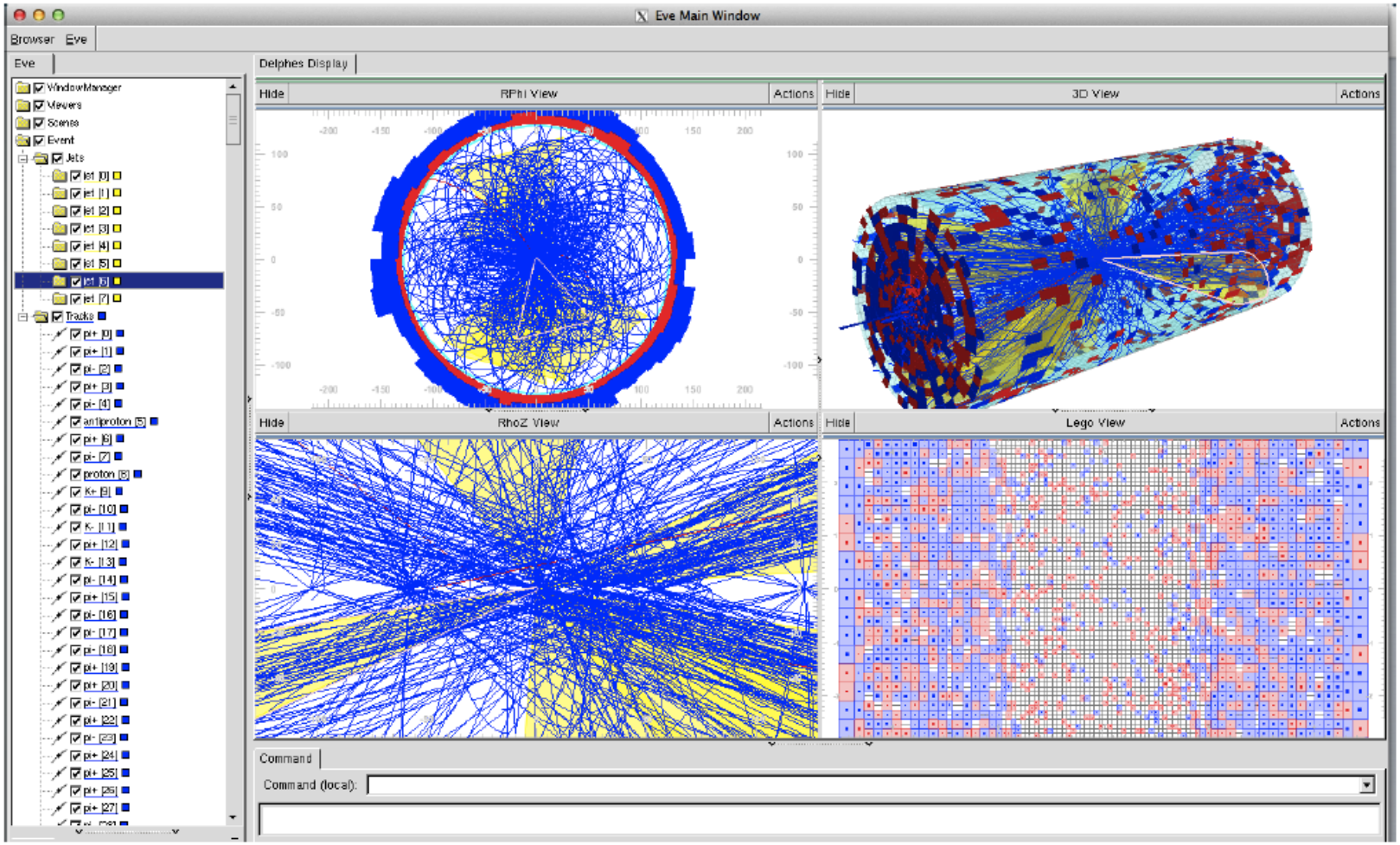
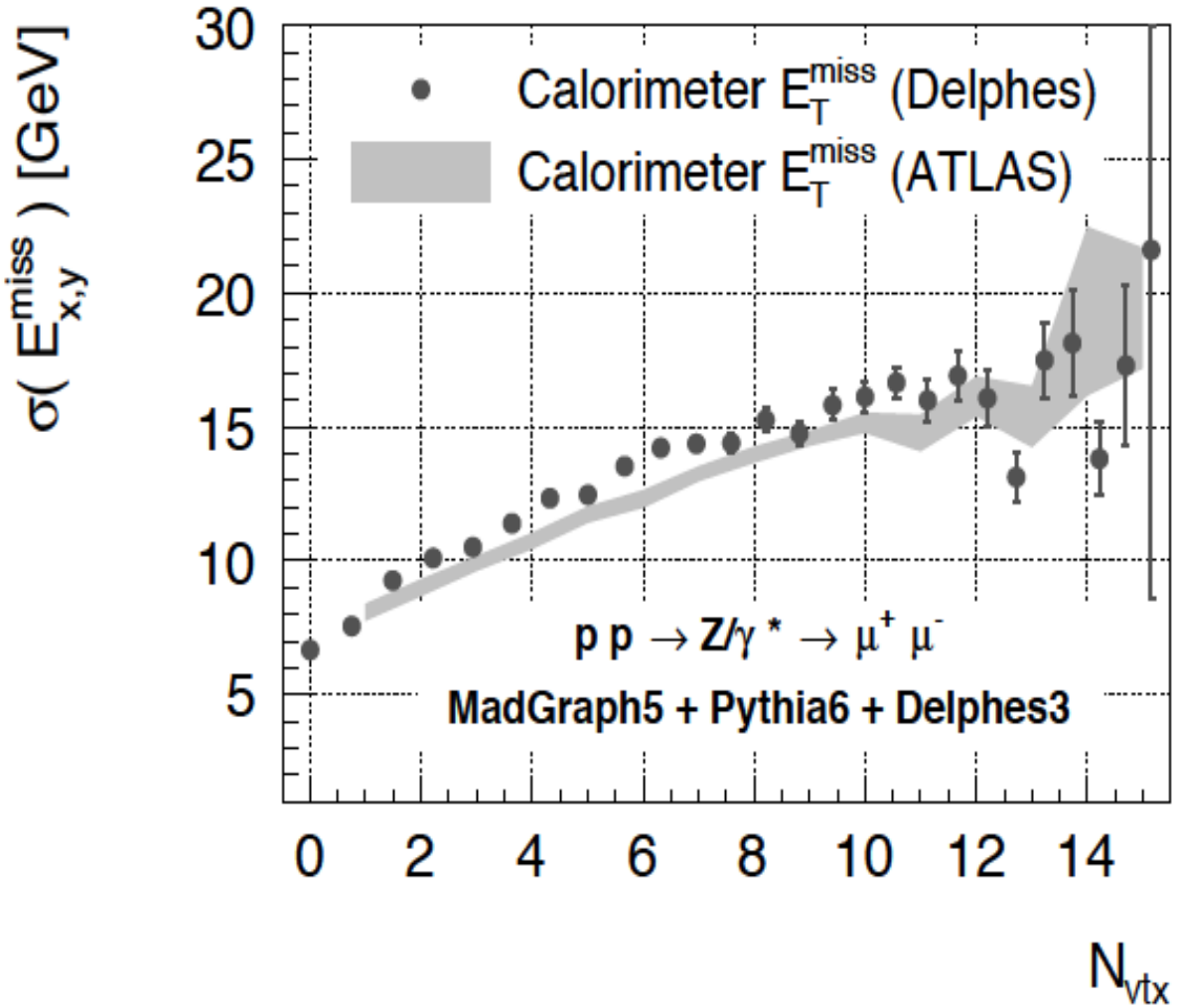


Figure 3. QCD event with 50 pile-up interactions shown with the DELPHES event display based on the ROOTEVE libraries [12]. Transverse view (top left), longitudinal view (bottom left), 3D view (top right), (η,ϕ) view (bottom right).

Pile-Up: Validation



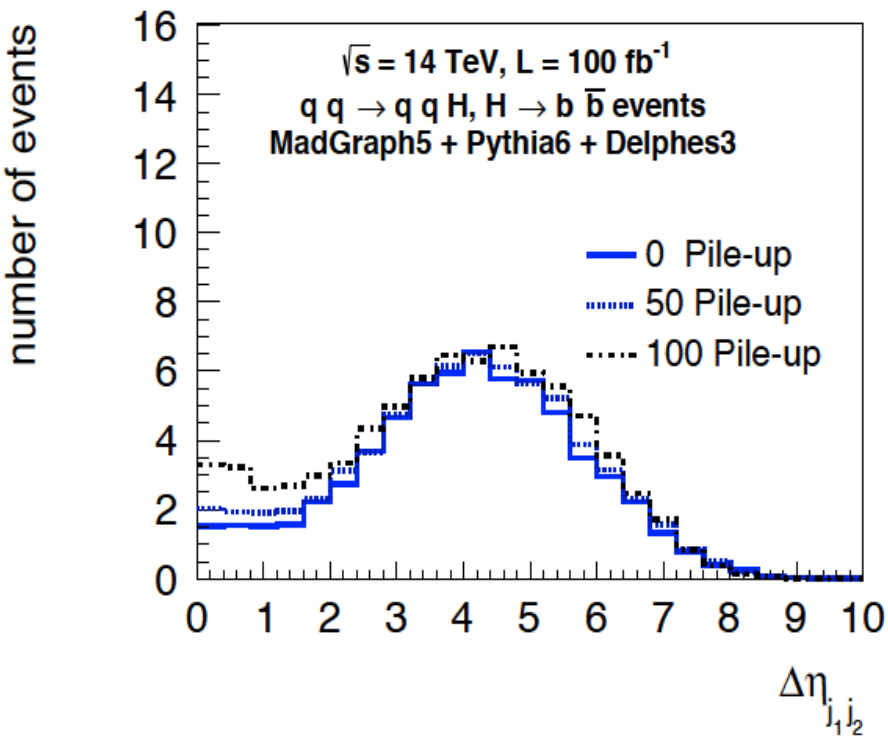
→ **good agreement**

Pile-Up: Physics example

- H → bb in **VBF channel** expected to be highly affected by pile-up
- Irreducible background **bb+jets**
- Select >4 jets with pT > 80, 60, 40, 40 (at least 2 b-tagged, at least 2 light)

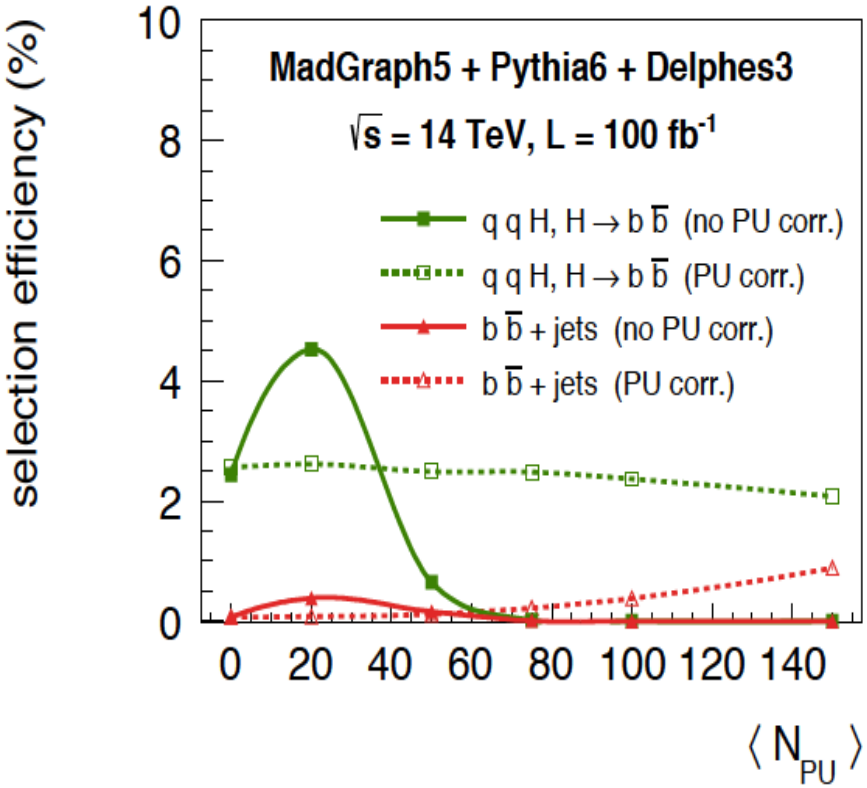
Emergence of pile-up jets in the central region:

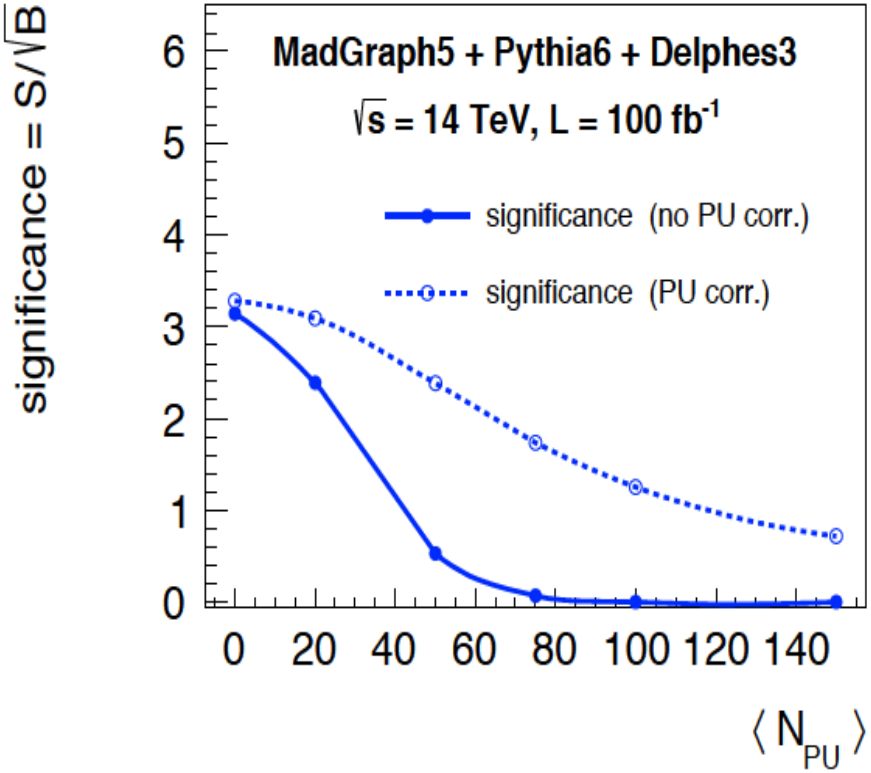
→ **depletion of rapidity gap**



Pile-Up : Physics example

- Require **large rapidity gap** between light jets, **no hadronic activity** in between
- 100 < m(bb) < 200 GeV



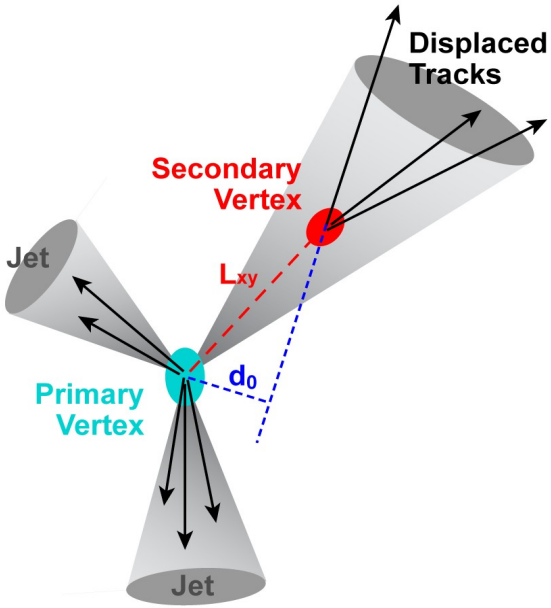


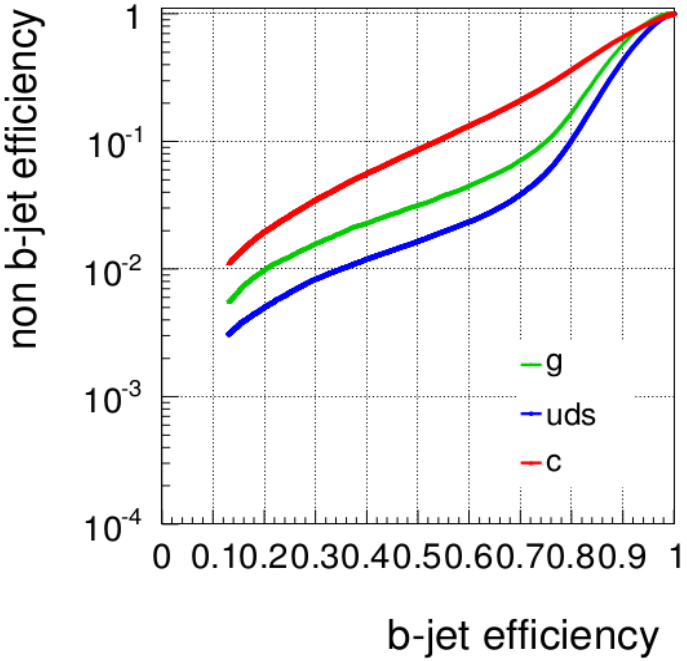
Other new features

Track Counting B-tagging

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

Track Counting :
- Smearing the impact parameter (d_0) of each track inside a jet.
- Application of the **Track Counting** algorithm.
- Provide comparable performances to CMS results
- **Predictive**

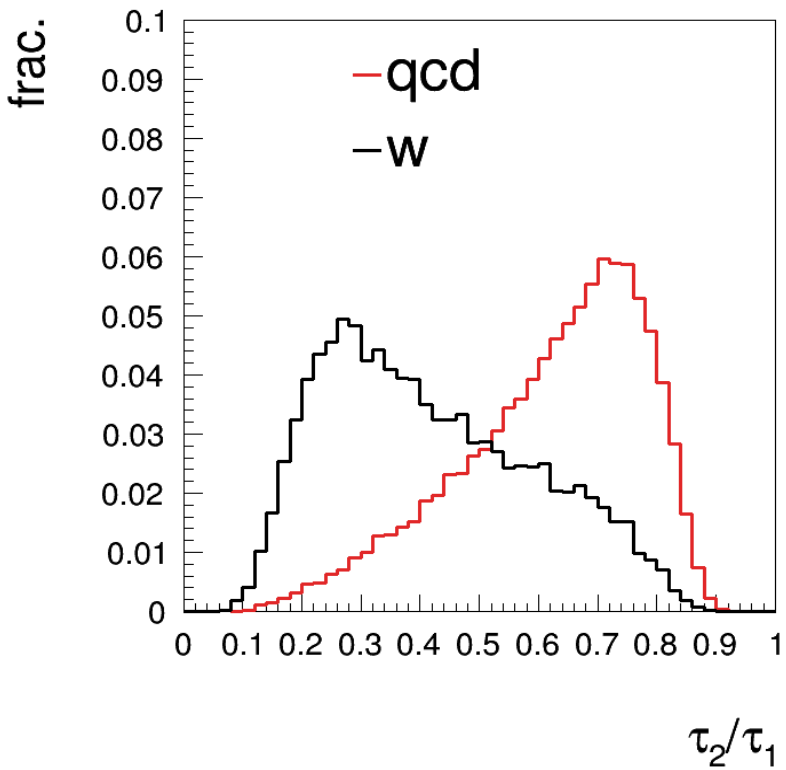




Jet Sub-structure (N-subjettiness)

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)

Used in the context of hyperboosted jets

- Impact of calorimeter cell size [M. Selvaggi*]

* https://indico.cern.ch/event/302395/session/20/contribution/43/material/slides/0.pdf

Conclusions

- **Delphes** is an advanced parametric simulation program

  - Allow a ~10.000 time gain in CPU time.
  - Widely tested by the community.

- **Delphes 3** has been out for one year now, with **major improvements**:

  - Modularity.
  - Pile-Up, Particle Flow, Predictive B-tagging, jet sub-structure.
  - Development ongoing (new communities of users, new features, etc..)

- Able to mimic CMS and ATLAS **performances** and reproduce analysis.

  - FCC, LHCb and Alice simulation under preparation.

- Only software in the market able to tackle the 200 PU scenario for future LHC runs.

  - Used for next run of the LHC and future accelerator proposals

- Test it, and give us feedback and **contribute**!

People

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

the community ...

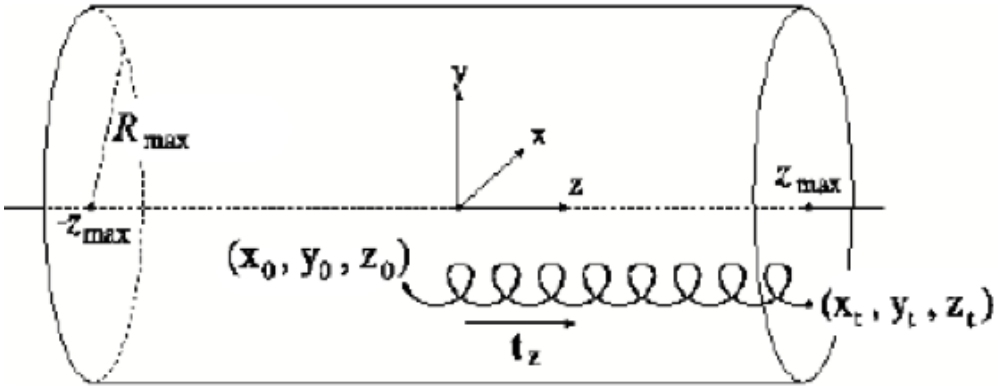
Back-up

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: 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)**

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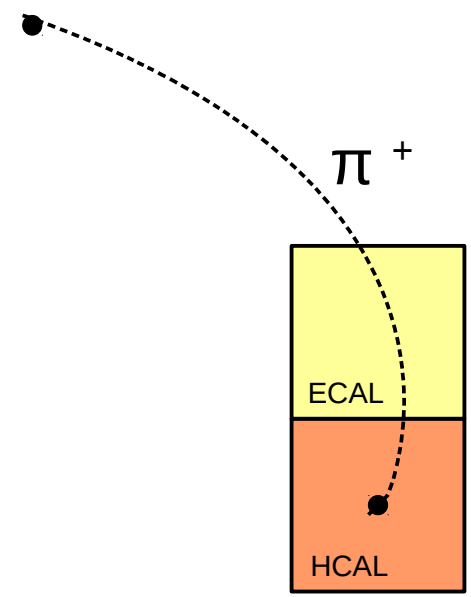

Particle-Flow algorithm creates:

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

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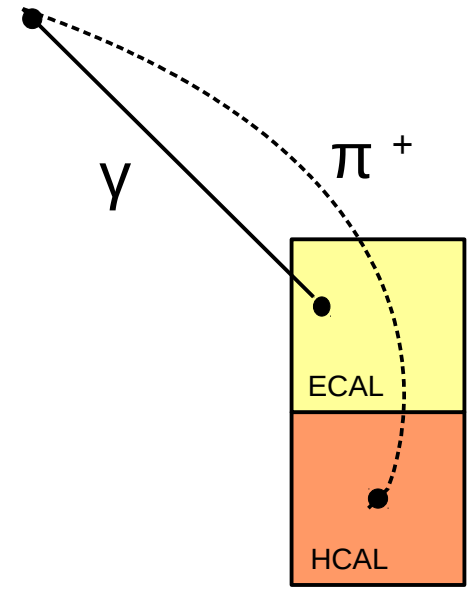
The modules: Particle-Flow Emulation

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



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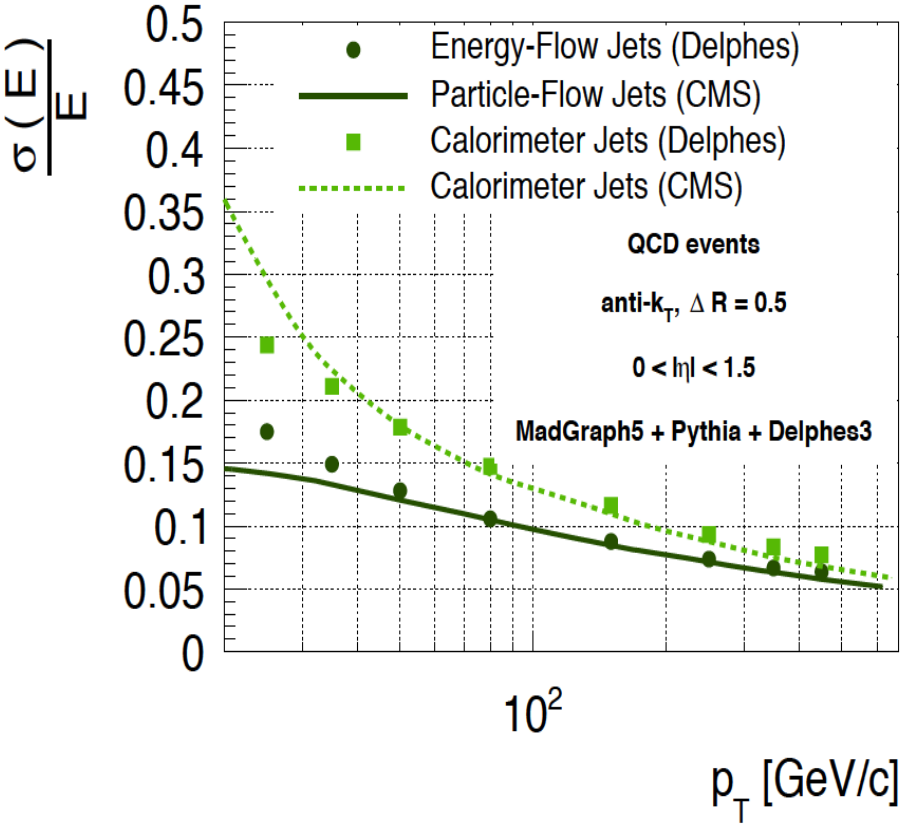
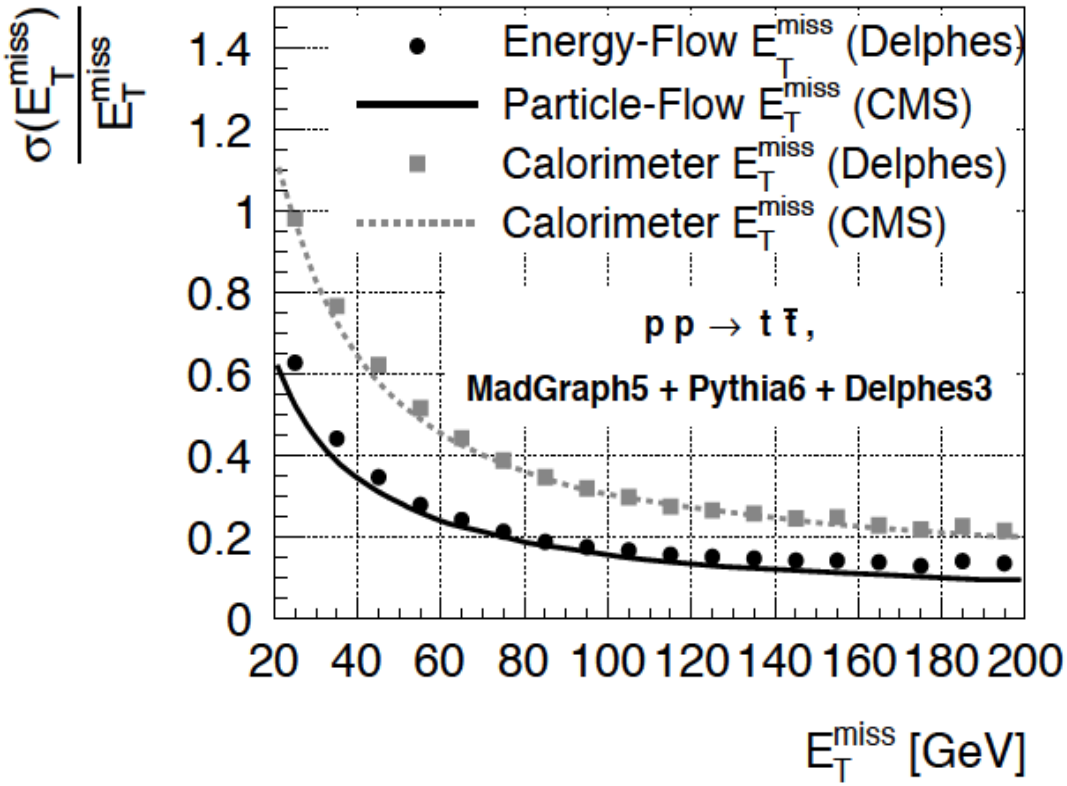
→ PF-tower, with energy $E^{PF\text{-}tower} = 4 + 18$ GeV

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: Validation of the PF emulation





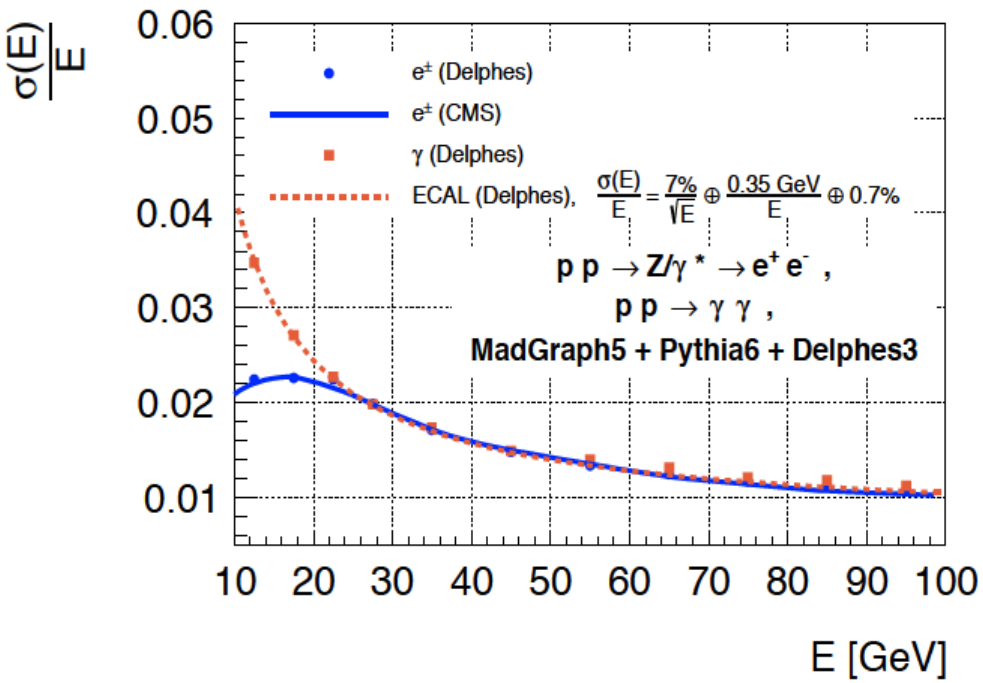
→ **good agreement**

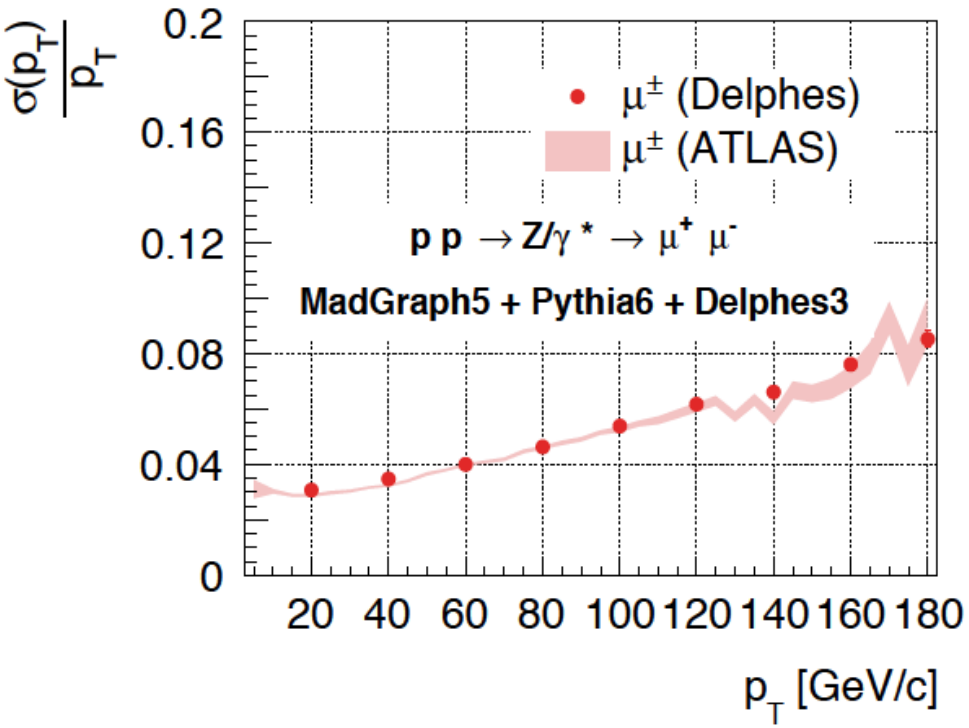
The modules: Jets / E_T^{miss} / H_T

- 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: Validation for leptons and photons





→ **excellent agreement (by construction)**

The modules: b-jets (tau-jets)

Parametric **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)}
}
```

Not Predictive