DELPHES FAST SIMULATION WITH THE IDEA DETECTOR

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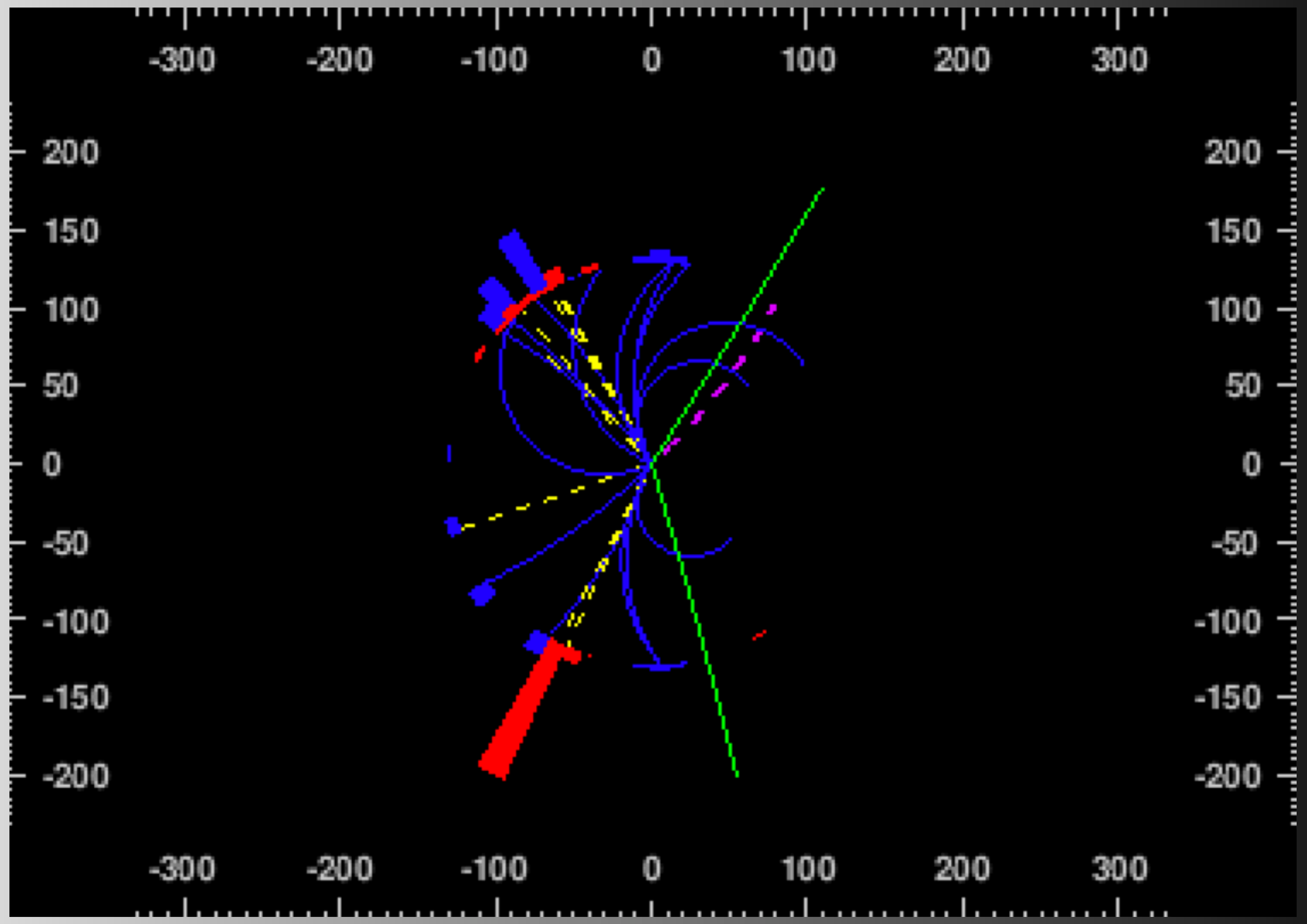
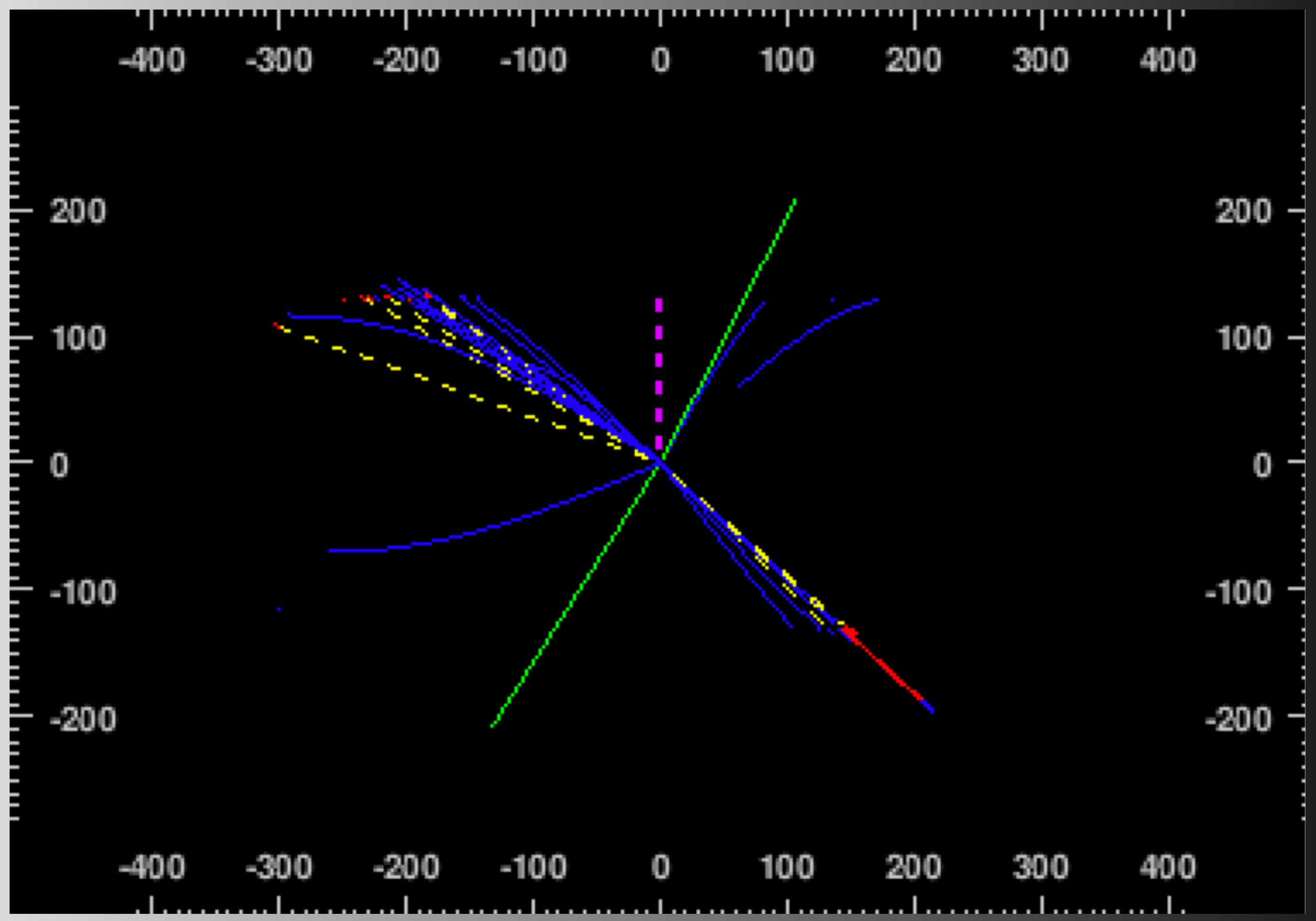
OUTLINE

- Delphes framework for IDEA fast simulation
  - Implementation of the full covariance matrix
  - Description Dual Readout calorimeter
- Benchmark physics case:
  $e^+e^- \rightarrow HZ, Z \rightarrow \mu^+\mu^-$ and $H \rightarrow X$
  - Fits and Shape-based analysis with templates
- Conclusions and outlook

$R\phi$ plane



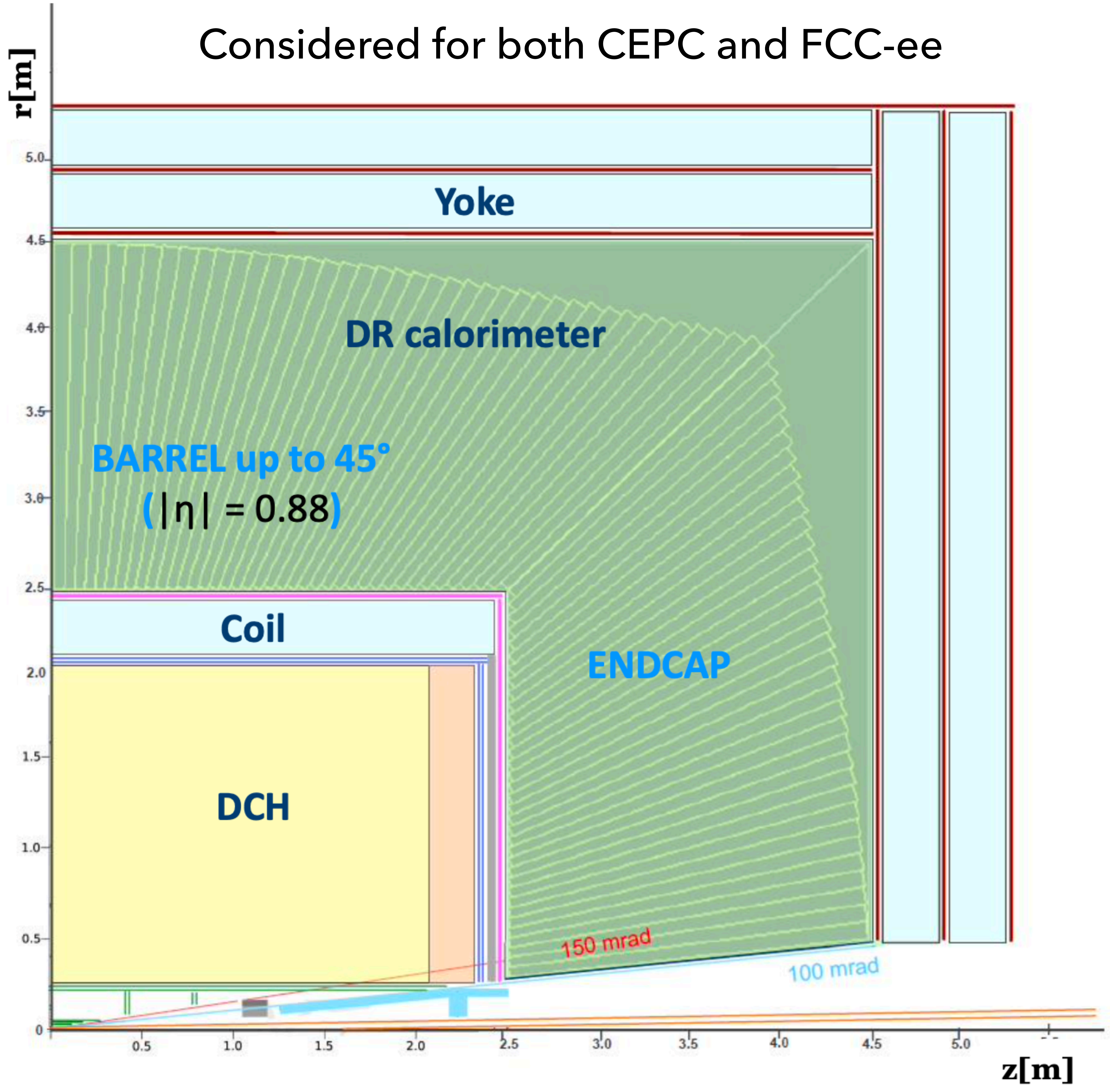
ρZ plane



In increasing distance from the IP, the IDEA detector is made of:

- a **tracker** composed of
  - Silicon pixels and silicon strips double stereo layers;
  - A light and large drift chamber (112 layers)
  - Silicon wrapper
- thin Solenoid
  - magnetic field of 2 T
  - length 5m
- a preshower ($\mu-$RWELL double layers)
- a Dual-Readout calorimeter 2 m deep/ 8λ
  Angular coverage up to 100 mrad ($\eta = 3$)
- a muon system: three $\mu-$RWELL stations (2D view)

Considered for both CEPC and FCC-ee



DELPHES FRAMEWORK

Delphes performs the fast simulation of a multipurpose detector [1].

The simulation includes:

- a track propagation system embedded in a magnetic field
- EM and HAD calorimeters
  - Special implementation of the Dual Readout calorimeter
- a muon identification system

FAST SIMULATION ABLE TO FACE LIMITED COMPUTING RESOURCES AND STILL ALLOW TO PRODUCE LARGE SAMPLES

Physics objects, necessary for data analysis, are then reconstructed from the simulated detector response

Particle energy is computed by smearing the initial particle momenta according to the detector resolution → jet, missing energy, isolated e^-, μ, τ, γ can be reconstructed

DELPHES fast simulation

Detector active volume, calorimeter segmentation and uniform magnetic field defined by the user!

[1] Delphes Fast Simulation webpage

DELPHES FRAMEWORK: IDEA DATA CARD

DELPHES fast simulation

- B field description (in the *ParticlePropagation* module)
  - Half length of the magnetic field coverage: 2.5 m
  - Radius of the magnetic field coverage 2.25 m
  - Homogeneous magnetic field: 2T

- Tracker description (*TrackingEfficiency* and *MomentumSmearing* module)

For IDEA the response of tracking detectors has been parametrised so far in the same way for electrons, muons and charged hadrons:

→ Unique efficiency formula dependent on E and η

```
module Efficiency ChargedHadronTrackingEfficiency {
    set InputArray ParticlePropagator/chargedHadrons
    set OutputArray chargedHadrons
    # We use only one efficiency, we set only 0 effincency out of eta bounds:

    set EfficiencyFormula {
        (abs(eta) > 3.0)                                        * (0.000) +
        (energy >= 0.5) * (abs(eta) <= 3.0)                     * (0.997) +
        (energy < 0.5 && energy >= 0.3) * (abs(eta) <= 3.0)     * (0.65) +
        (energy < 0.3) * (abs(eta) <= 3.0)                      * (0.06)
    }
}
```

→ p_T resolution formula: $\frac{\sigma_{p_T}}{p_T} = \sqrt{(2.093 \times 10^{-5} \cdot p_T)^2 + 0.00020242 \cdot p_T + 0.00011452}$

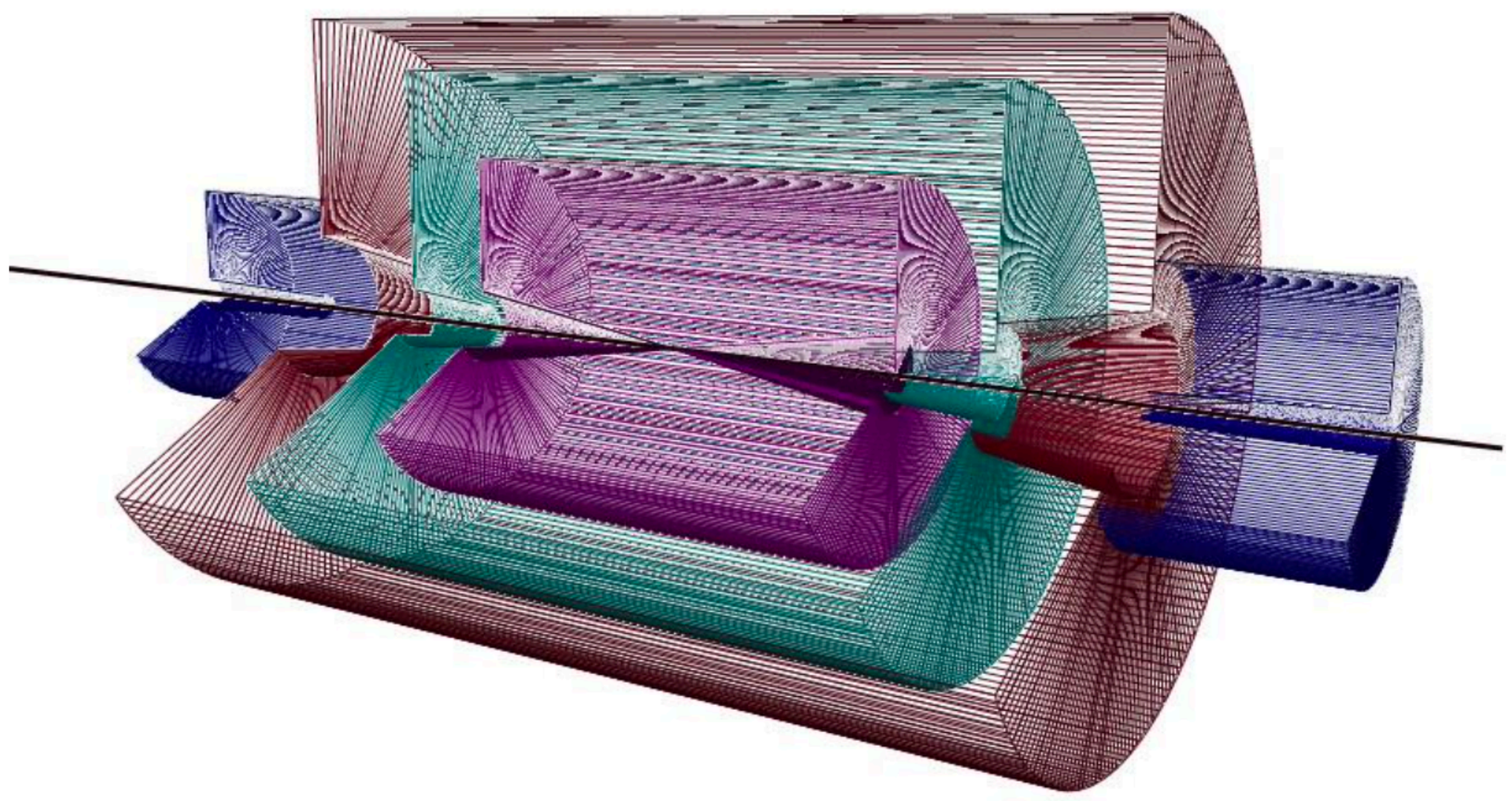
DELPHES FRAMEWORK: FULL COVARIANCE MATRIX

Implementation in Delphes of the Track Covariance module (Michele Selvaggi) based on the full covariance matrix calculation for tracks smearing as performed in the standalone fast tracking software [2].

It requires in input:

- Magnetic Field
- Detector geometry description

Schematic view of the baseline DELPHES detector

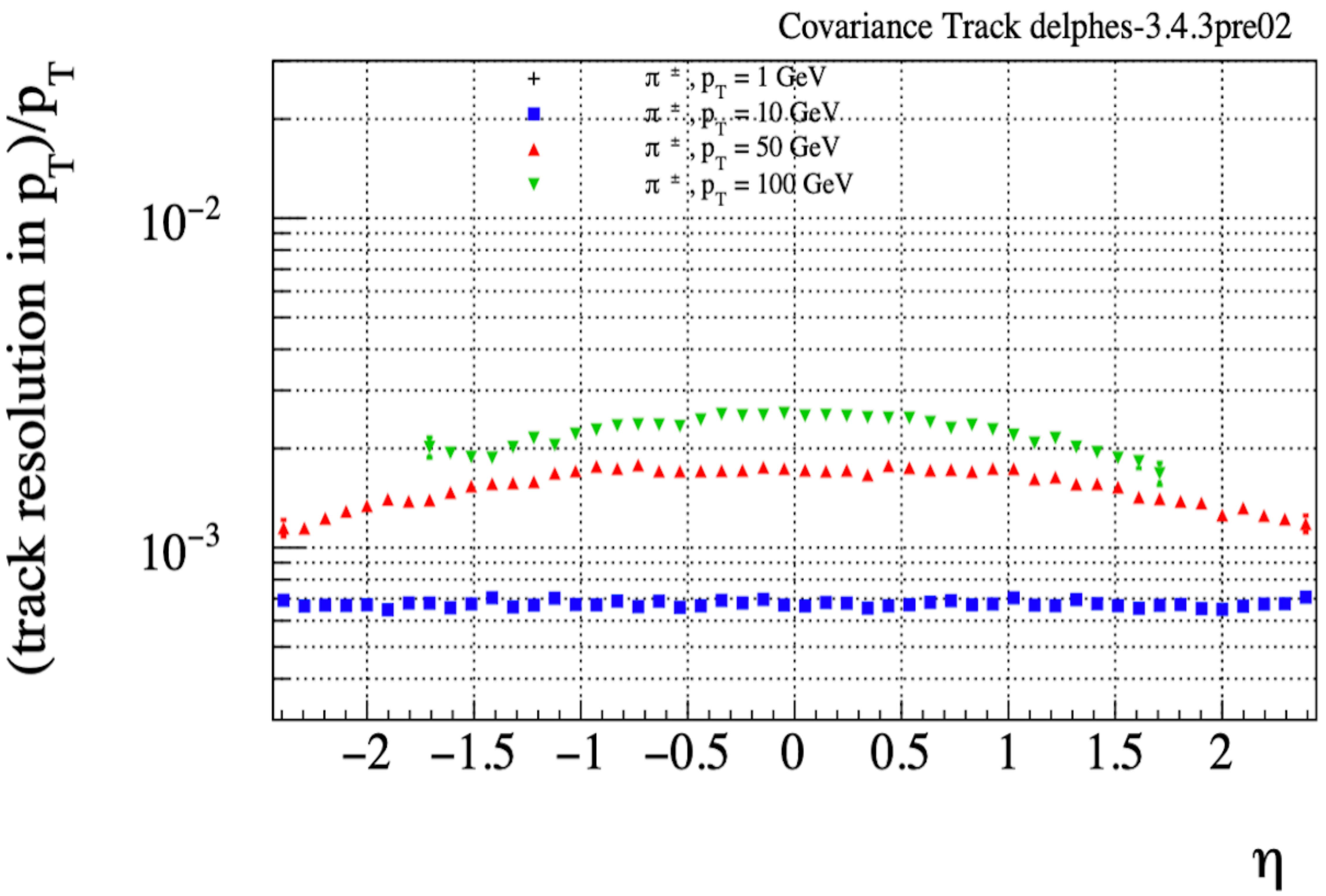



```
#########################################
# Smearing for charged tracks
#########################################

module TrackCovariance TrackSmearing {
    set InputArray TrackMergerPre/tracks
    set OutputArray tracks

    ## uses https://raw.githubusercontent.com/selvaggi/FastTrackCovariance/master/GeoIDEA_BASE.txt
    set DetectorGeometry {

      1 PIPE -100 100 0.015 0.0012 0.35276 0 0 0 0 0 0
      1 VTXLOW -0.12 0.12 0.017 0.00028 0.0937 2 0 1.5708 3e-006 3e-006 1
      1 VTXLOW -0.16 0.16 0.023 0.00028 0.0937 2 0 1.5708 3e-006 3e-006 1
      1 VTXLOW -0.16 0.16 0.031 0.00028 0.0937 2 0 1.5708 3e-006 3e-006 1
      1 VTXHIGH -1 1 0.32 0.00047 0.0937 2 0 1.5708 7e-006 7e-006 1
      1 VTXHIGH -1.05 1.05 0.34 0.00047 0.0937 2 0 1.5708 7e-006 7e-006 1
      1 DCHCANI -2.125 2.125 0.345 0.0002 0.237223 0 0 0 0 0 0
      1 DCH -2 2 0.36 0.0147748 1400 1 0.0203738 0 0.0001 0 1
      1 DCH -2 2 0.374775 0.0147748 1400 1 -0.0212097 0 0.0001 0 1
      1 DCH -2 2 0.38955 0.0147748 1400 1 0.0220456 0 0.0001 0 1
      1 DCH -2 2 0.404324 0.0147748 1400 1 -0.0228814 0 0.0001 0 1
```

[2] Franco Bedeschi talk @ CepC workshop, Oxford

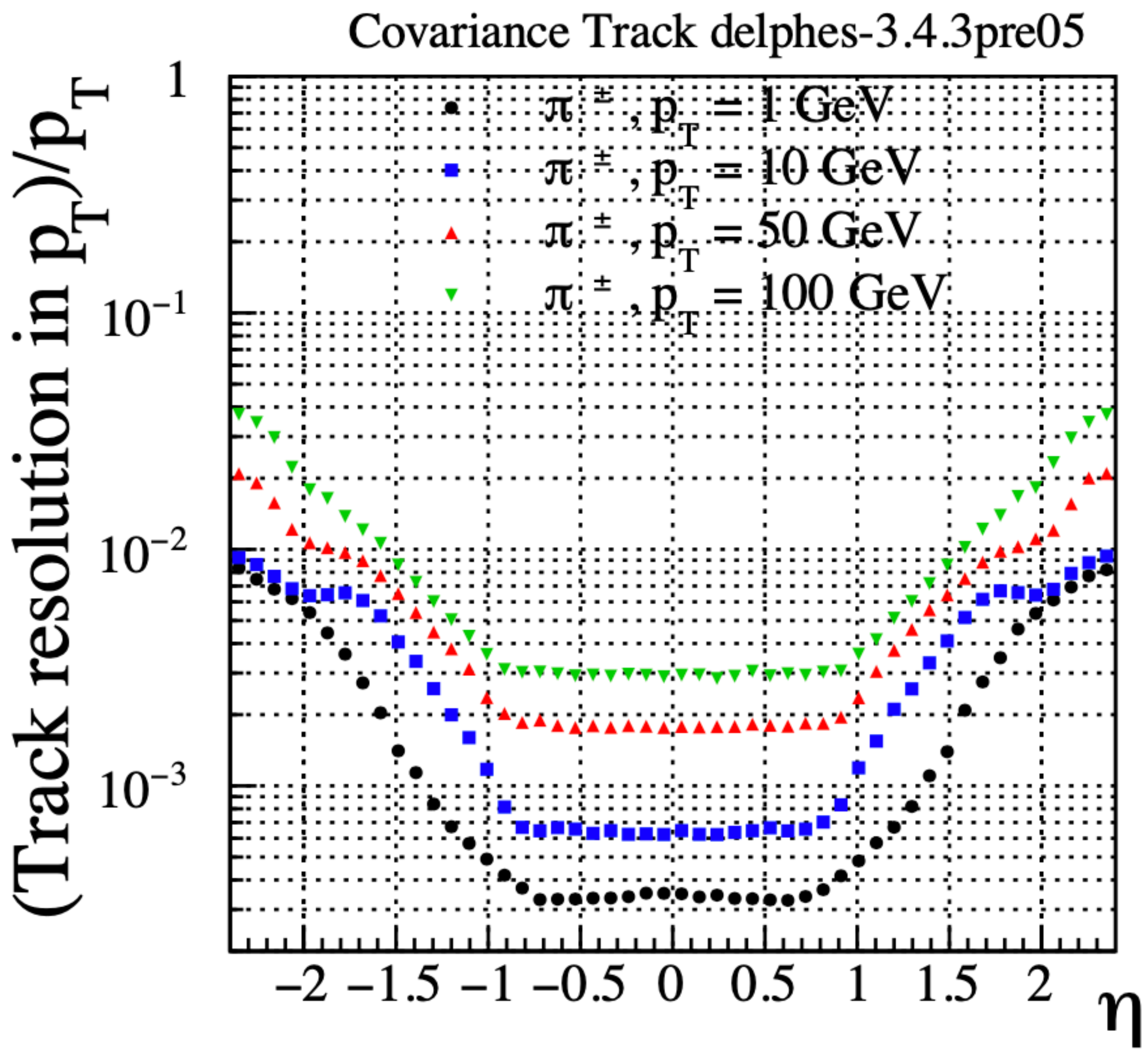
TRANSVERSE MOMENTUM RESOLUTION

DELPHES PARAMETRIC FORMULA



No discrimination in η ranges!!

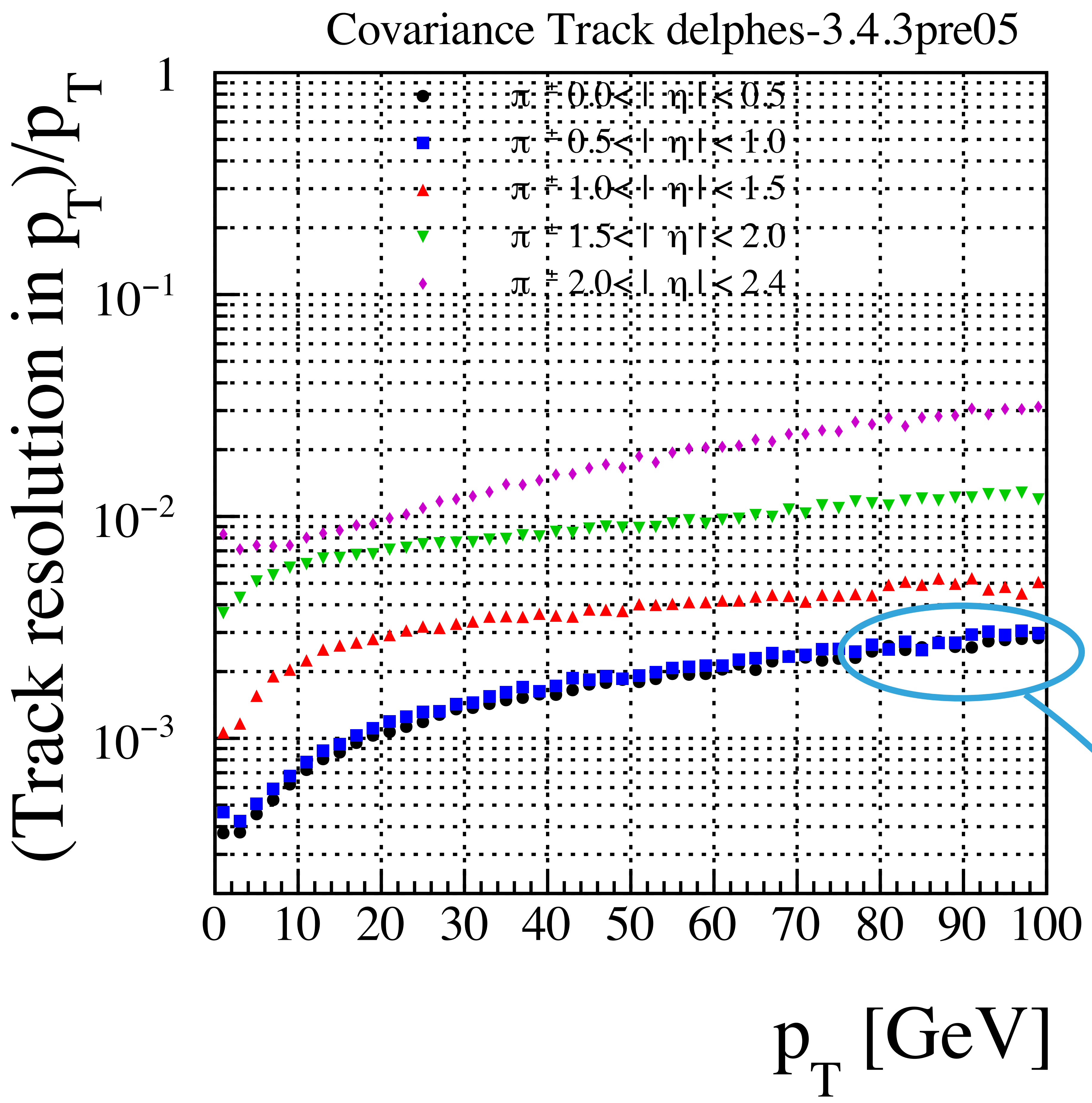
DELPHES WITH FULL COVARIANCE MATRIX



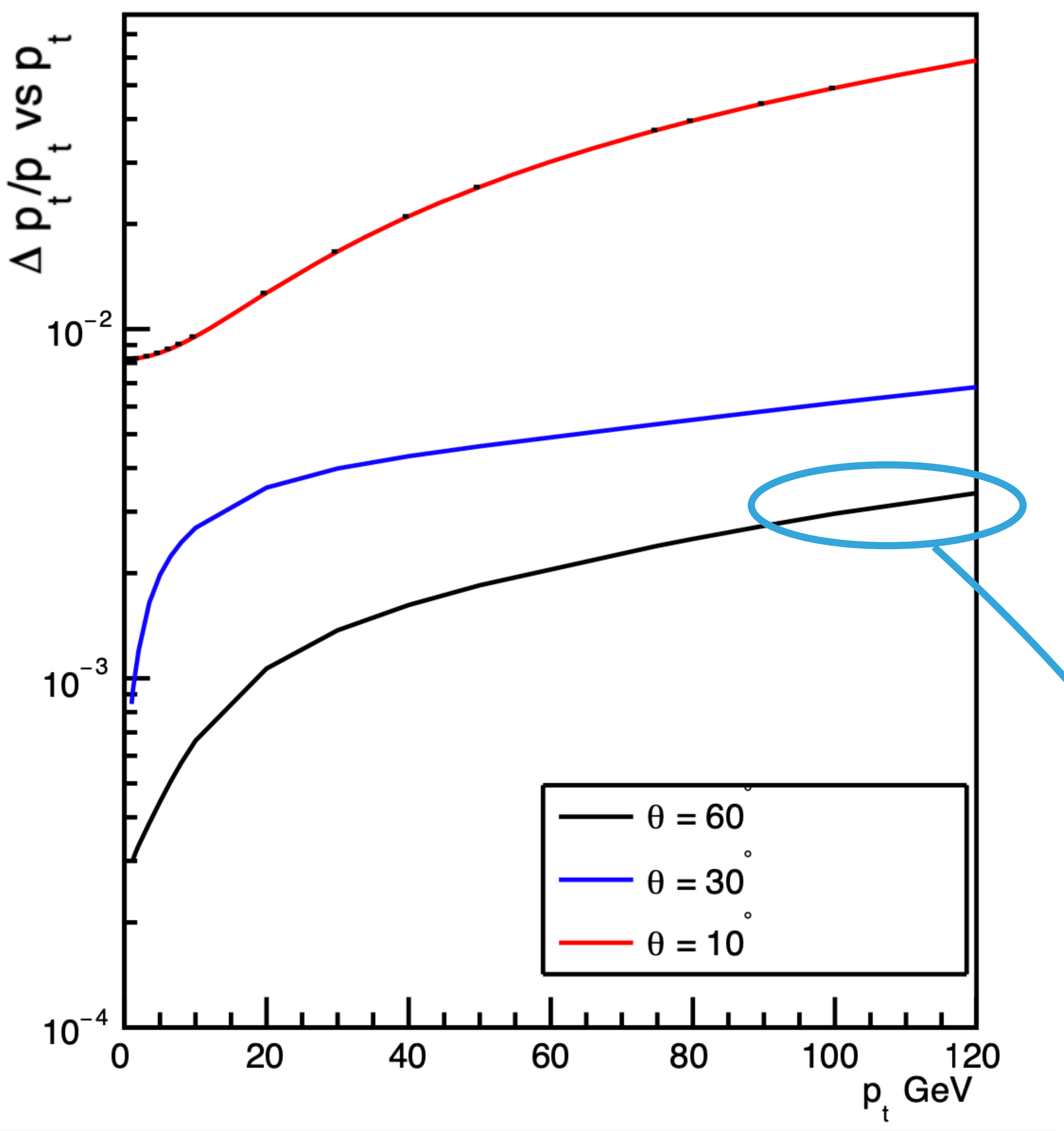
Expected variations of the resolutions in the barrel and forward region due to the different sub-detectors and layers crossed

p_T RESOLUTION VS TRANSVERSE MOMENTUM

~10º < θ < ~15º
~15º < θ < ~25º
~25º < θ < ~40º
~40º < θ < ~60º
~60º < θ < 90º

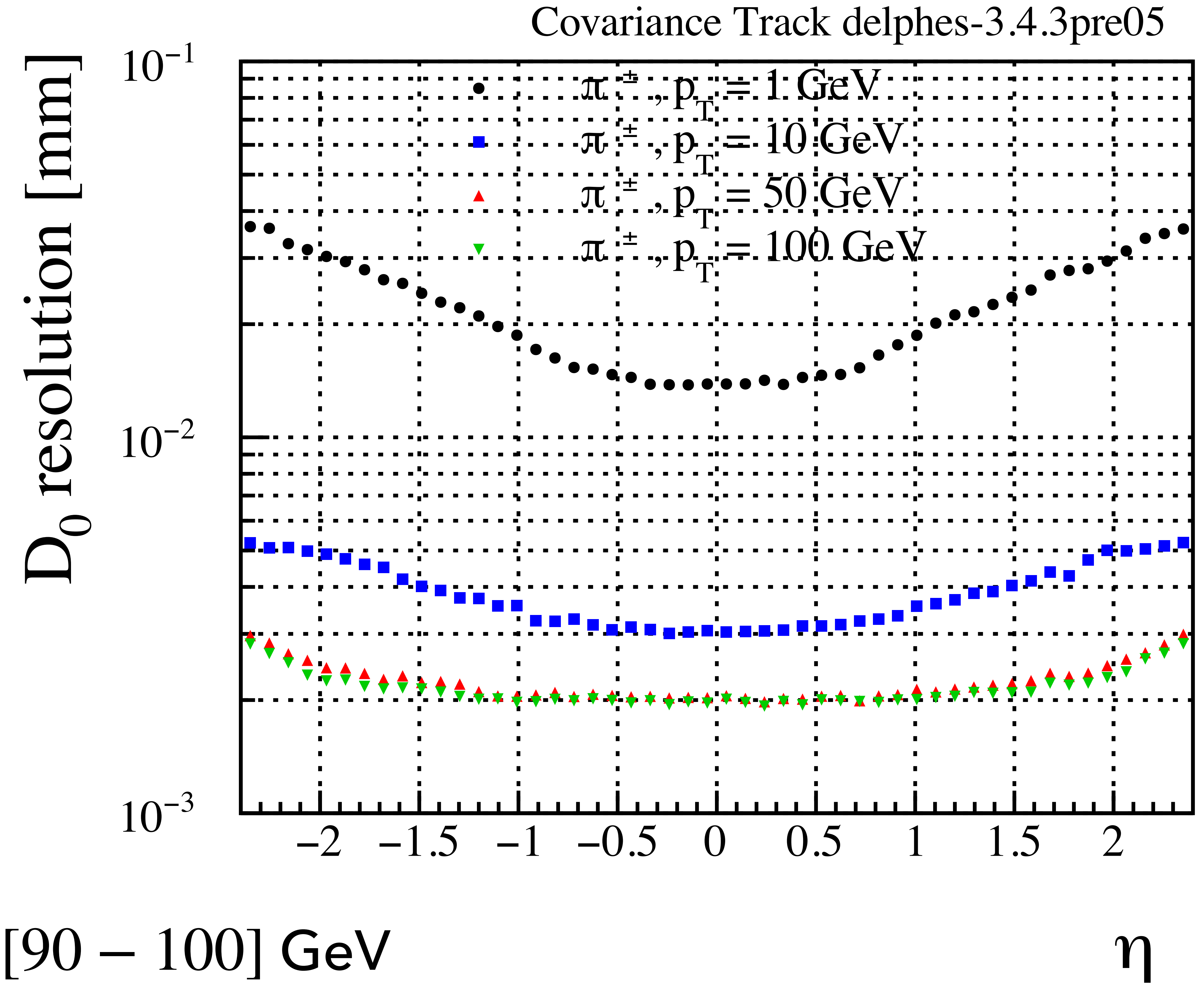


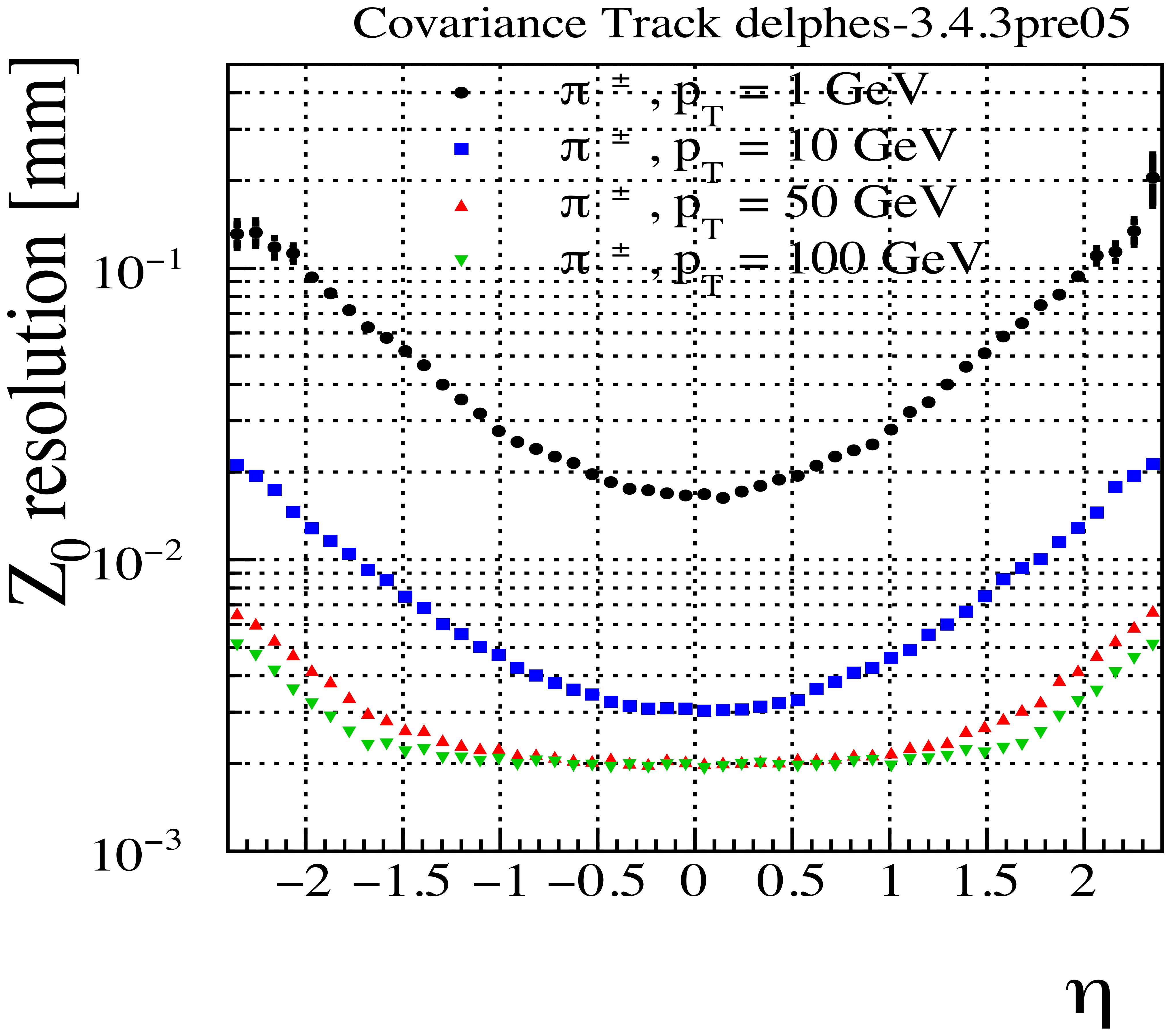
Standalone software by F. Bedeschi [2]



In the barrel @ 90-100 GeV $\frac{\sigma_{p_T}}{p_T} \approx 3 \times 10^{-3}$

d_0 AND d_z RESOLUTION VERSUS TRANSVERSE MOMENTUM





$p_T \in [90 - 100]$ GeV

$\sigma_{d_0} \approx 2\ \mu m$ in the barrel

$\sigma_{d_0} \approx 3\ \mu m$ in the endcap

$\sigma_{d_z} \approx 2\ \mu m$ in the barrel

$\sigma_{d_z} \approx 4\ \mu m$ in the endcap

DUAL READOUT CALORIMETER FAST SIMULATION

DUAL READOUT CALORIMETER FAST SIMULATION [3]

Dual-Readout (DR) calorimeter description

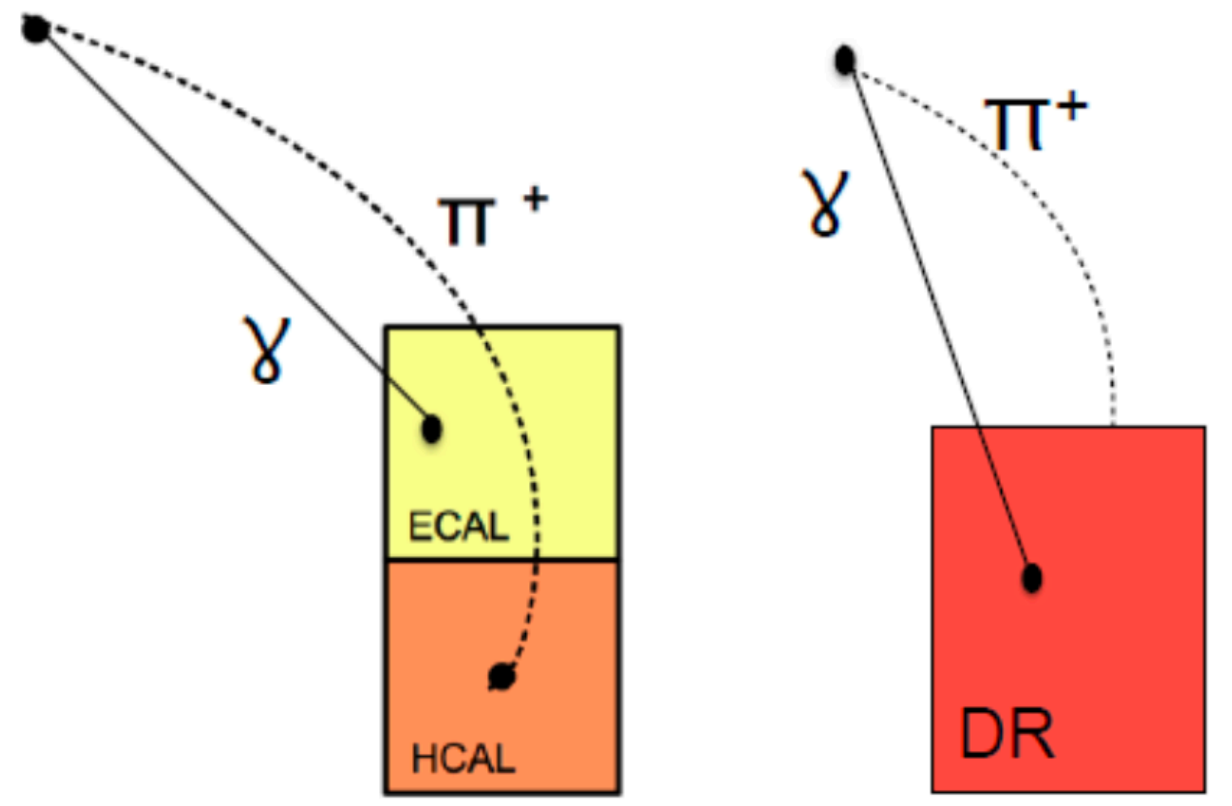
(DualReadout Calorimeter module)

Implementation of the monolithic calorimeter in a dedicated IDEA card:

- single segmentation: cell size of 6 cm x 6 cm
- different energy resolution for electromagnetic and hadronic showers

$\sim \frac{11\,\%}{\sqrt{E}}$ $\sim \frac{30\,\%}{\sqrt{E}}$

Dual-Readout Particle Flow



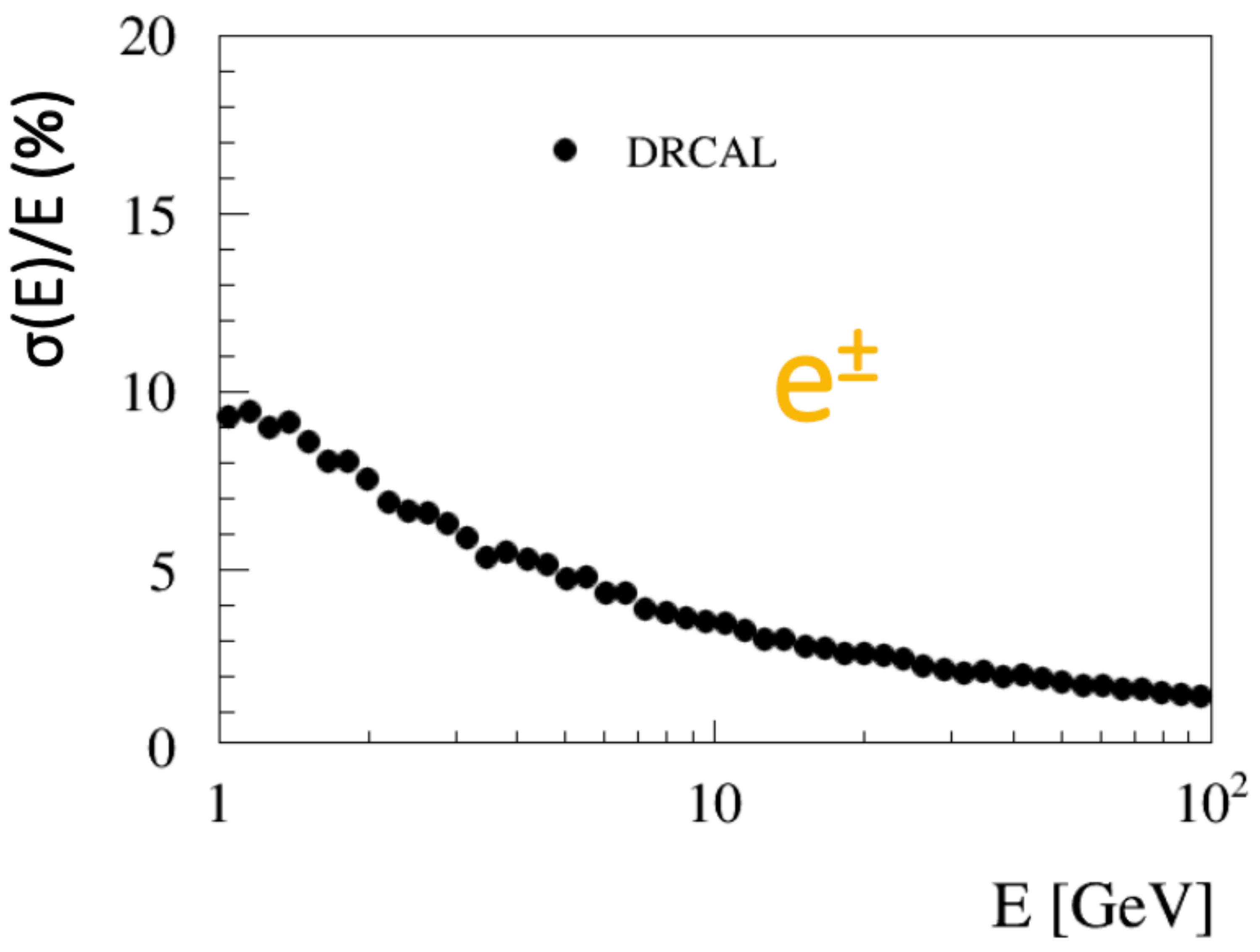
If $E_{em} > 0$ and $E_{had} = 0$ → $\sigma(EM)$ e.g. γ

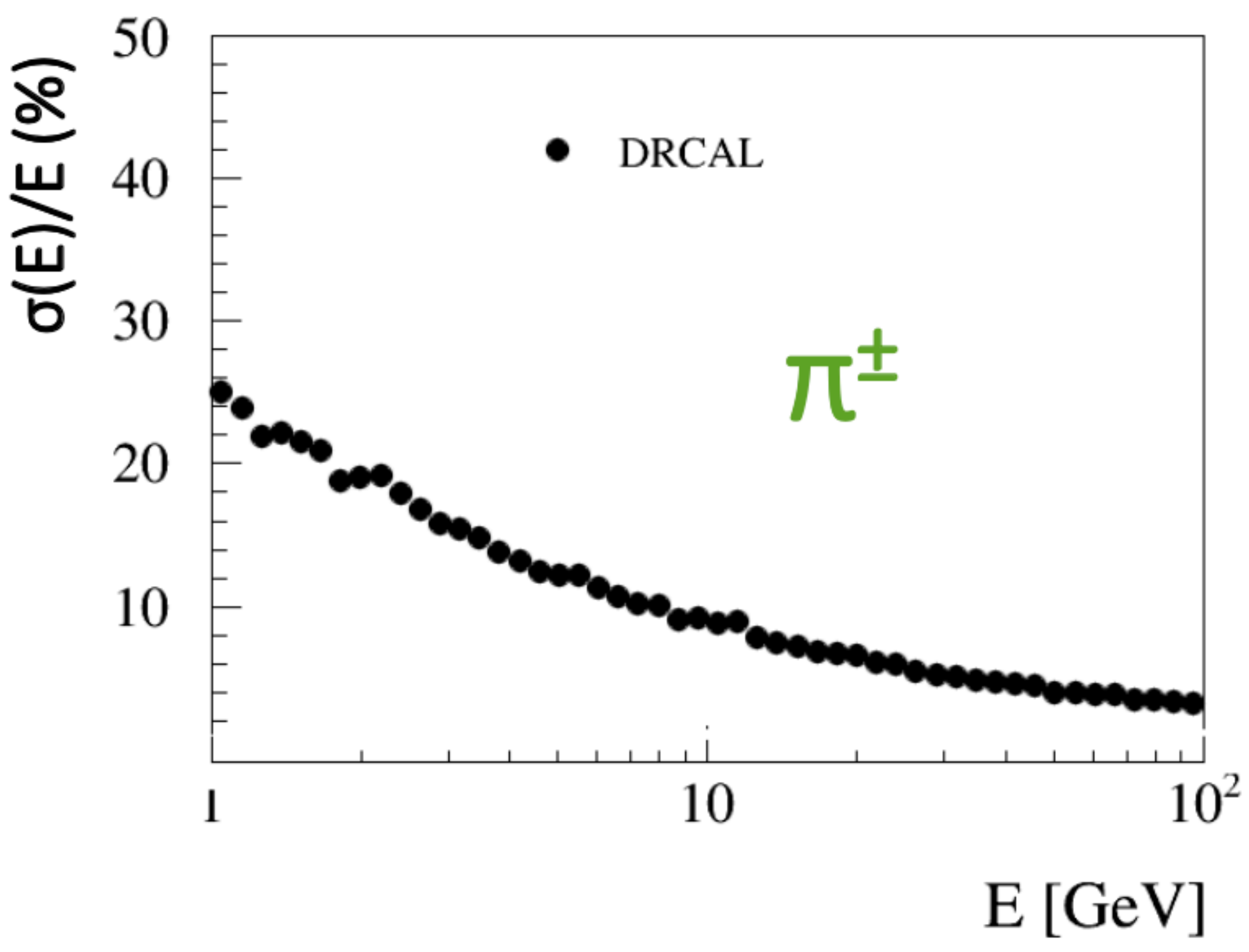
If $E_{had} > 0$ → $\sigma(HAD)$ e.g. π^+ or (γ, π^+)

DR CAL module in Delphes assumes that it is always possible disentangle if a hit in the calorimeter cell is a **charge only** or **charges + neutral** hypothesis

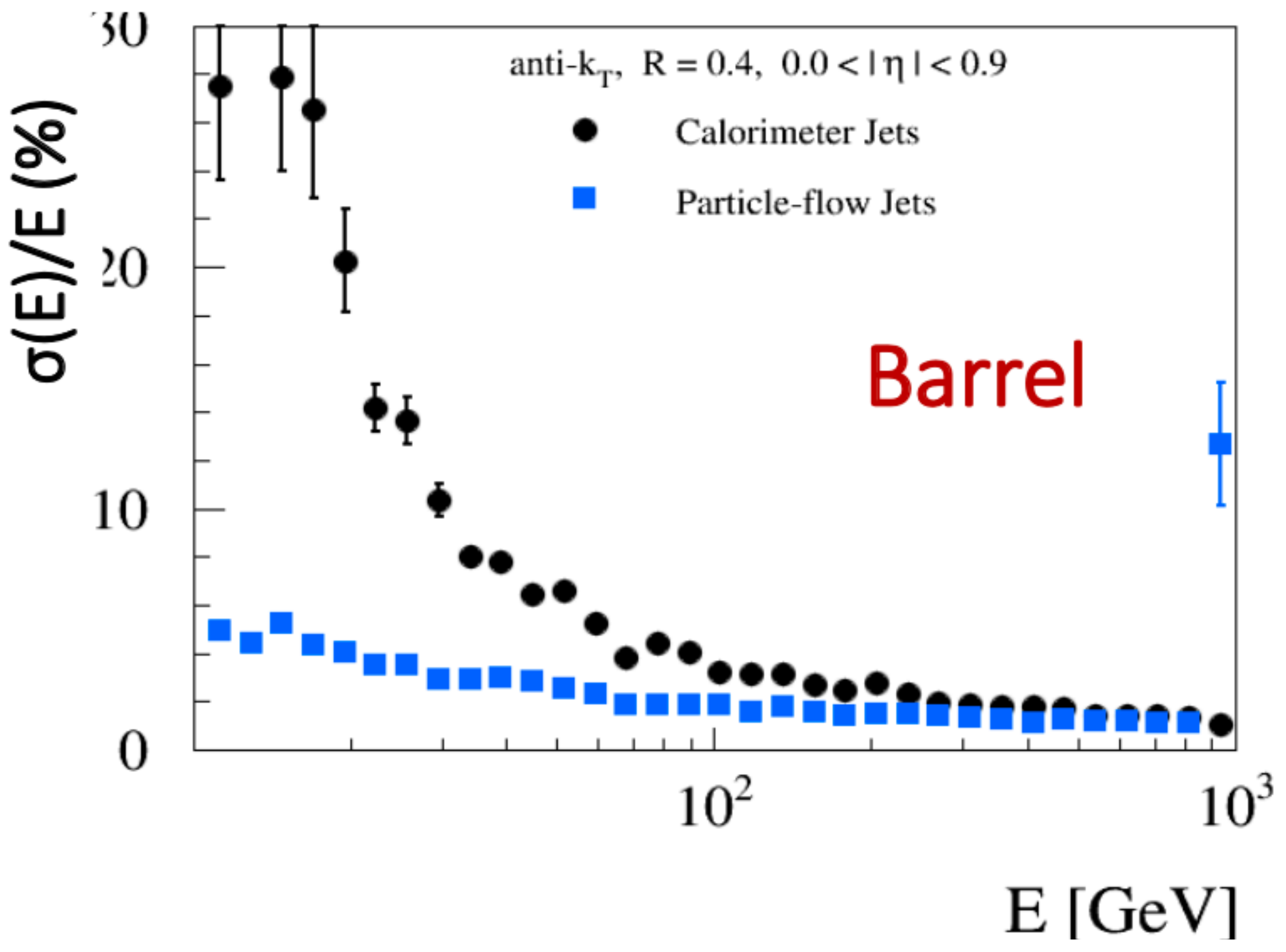
[3] E. Fontanesi 's talk @ IAS conference

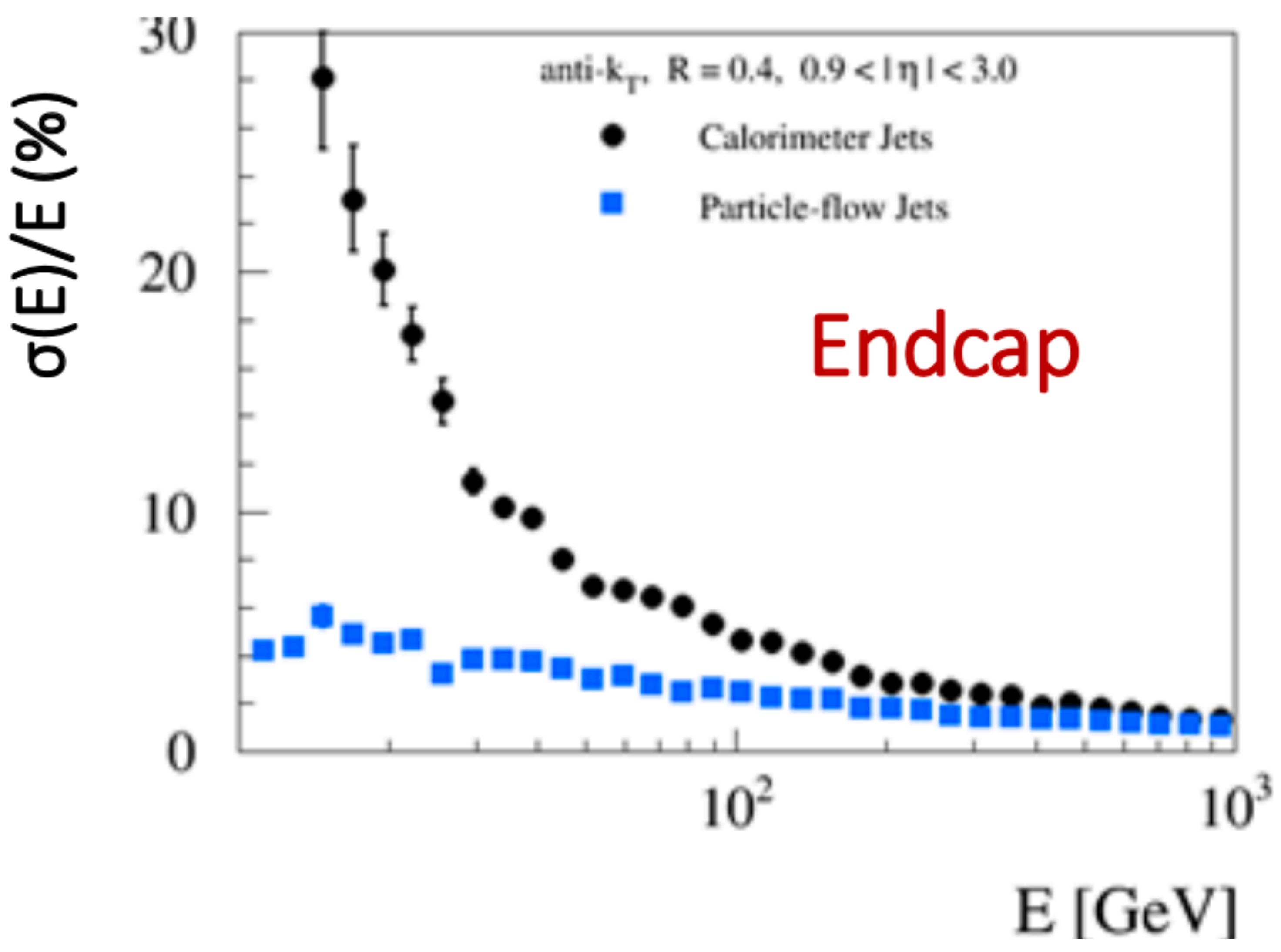
DUAL READOUT CALORIMETER FAST SIMULATION [3]





Energy resolution for reconstructed objects (both em and had particles) considering a η range with particle gun events (electrons and pions)





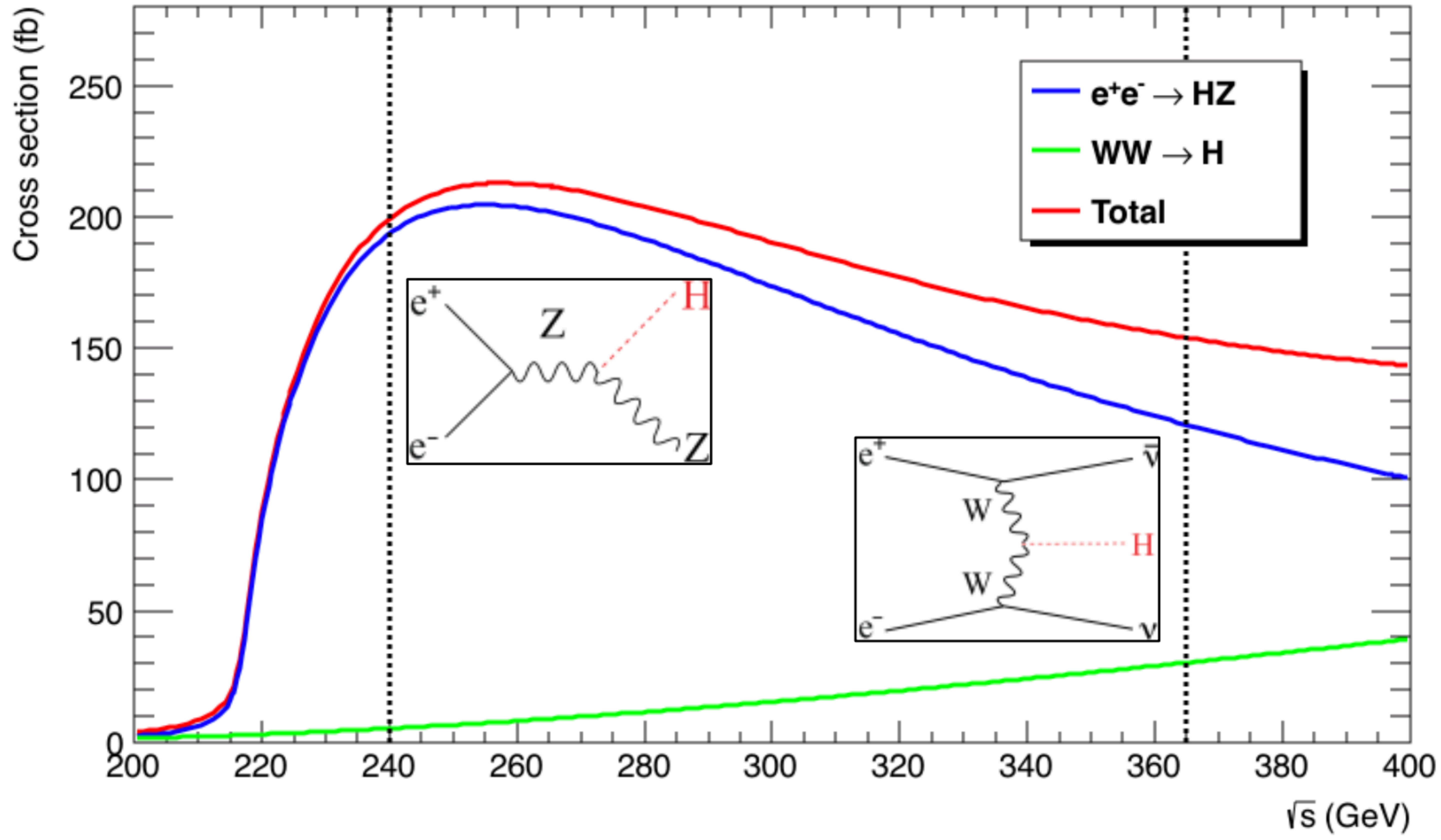
Jet Energy resolution using particle fragmentation reconstruction and calo information only

[3] E. Fontanesi 's talk @ IAS conference

BENCHMARK PHYSICS CASE: HIGGSTRAHLUNG

BENCHMARK PHYSICS CASE: HIGGSTRAHLUNG

@ 240 GeV $\sigma_{HZ} \simeq 200$ fb –> production of 10^6 Higgs



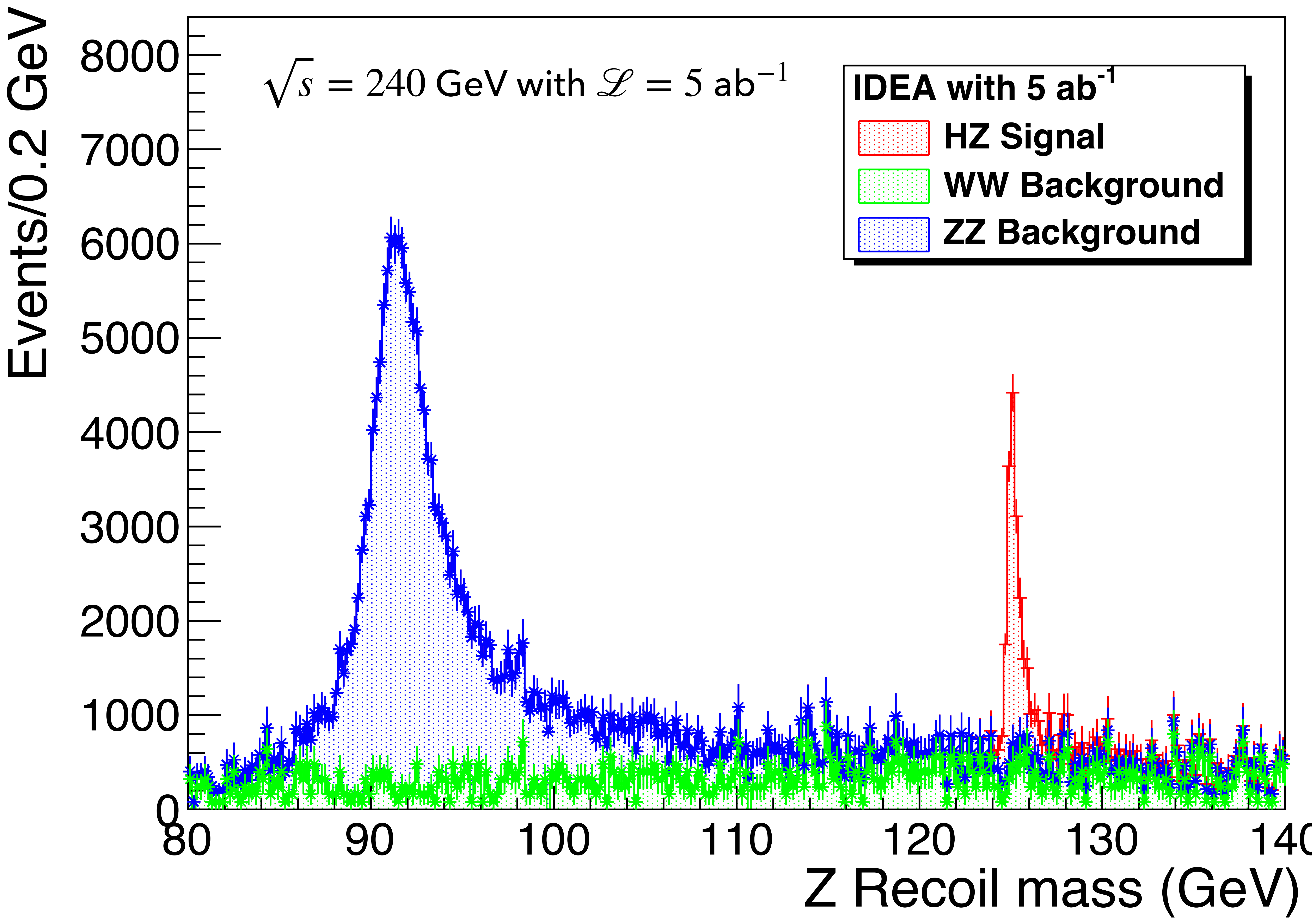
$e^+e^- \rightarrow ZH$ where
$Z \rightarrow \mu^+\mu^-$ and $H \rightarrow$ anything

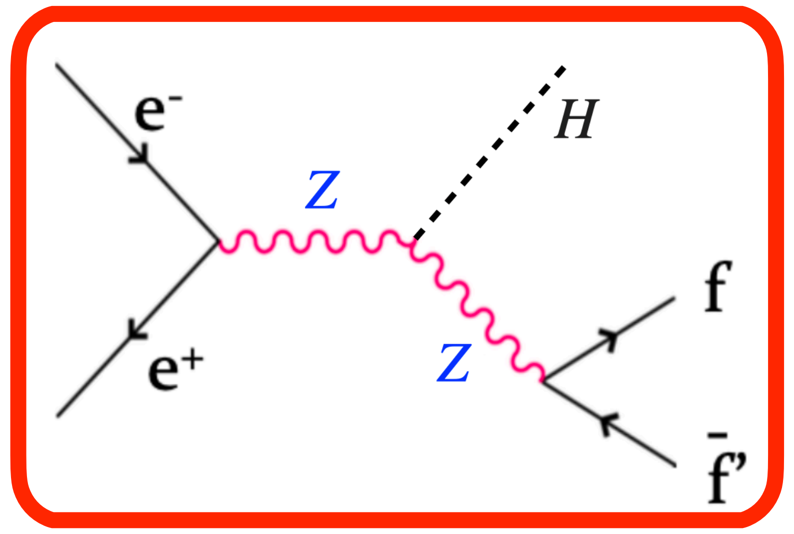
$$m^2_{\mathrm{recoil}} = s - m_z - 2\sqrt{s}(E^+_\mu + E^-_\mu)$$

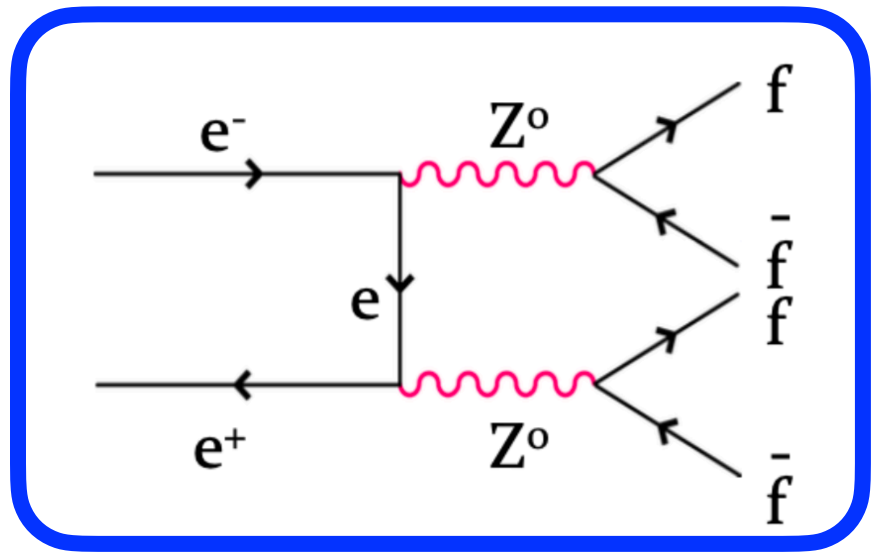
$$m_H = m_{\mathrm{recoil}}$$

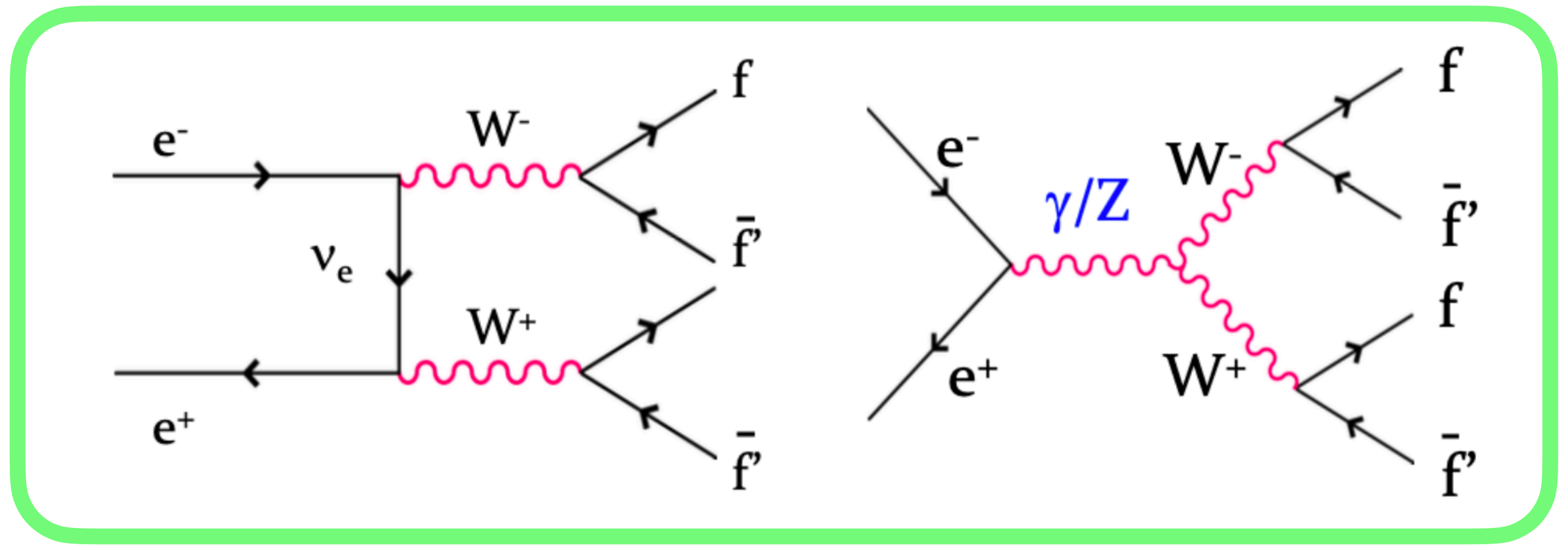
Z mass reconstruction from the lepton invariant mass provides a **model-independent determination of the Higgs couplings can be obtained at the sub-% level**.

HIGGSTRAHLUNG PROCESS: SIGNAL SELECTION









The signal selection criteria are:

- two muons of opposite charge with $p_T > 1$ GeV
- $|\eta| < 2.4$
- $m_Z \in [80,100]$ GeV

HIGGSTRAHLUNG PROCESS: FIT SETTINGS

Z and H masses fitting using functions from ROOFit:

Signal:

Crystal-Ball: RooCBShape(m, mean, sigma, a, n)

for a Crystal Ball, σ represents the Standard Deviation (RMS) of the central gaussian

Background:

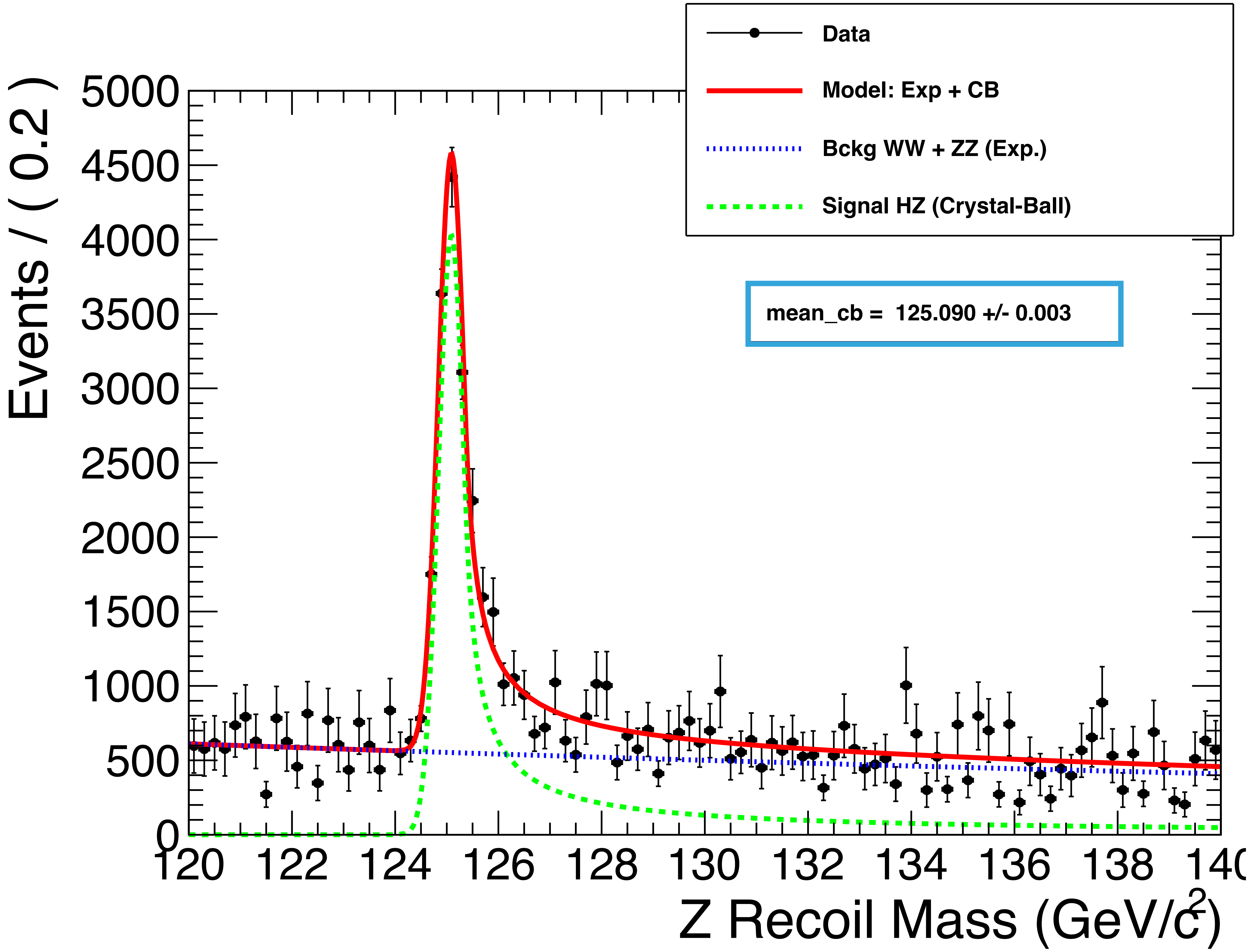
Exponential: RooExponential(m, c)

S+B = N_{sig}*Signal + N_{bkg}*Background

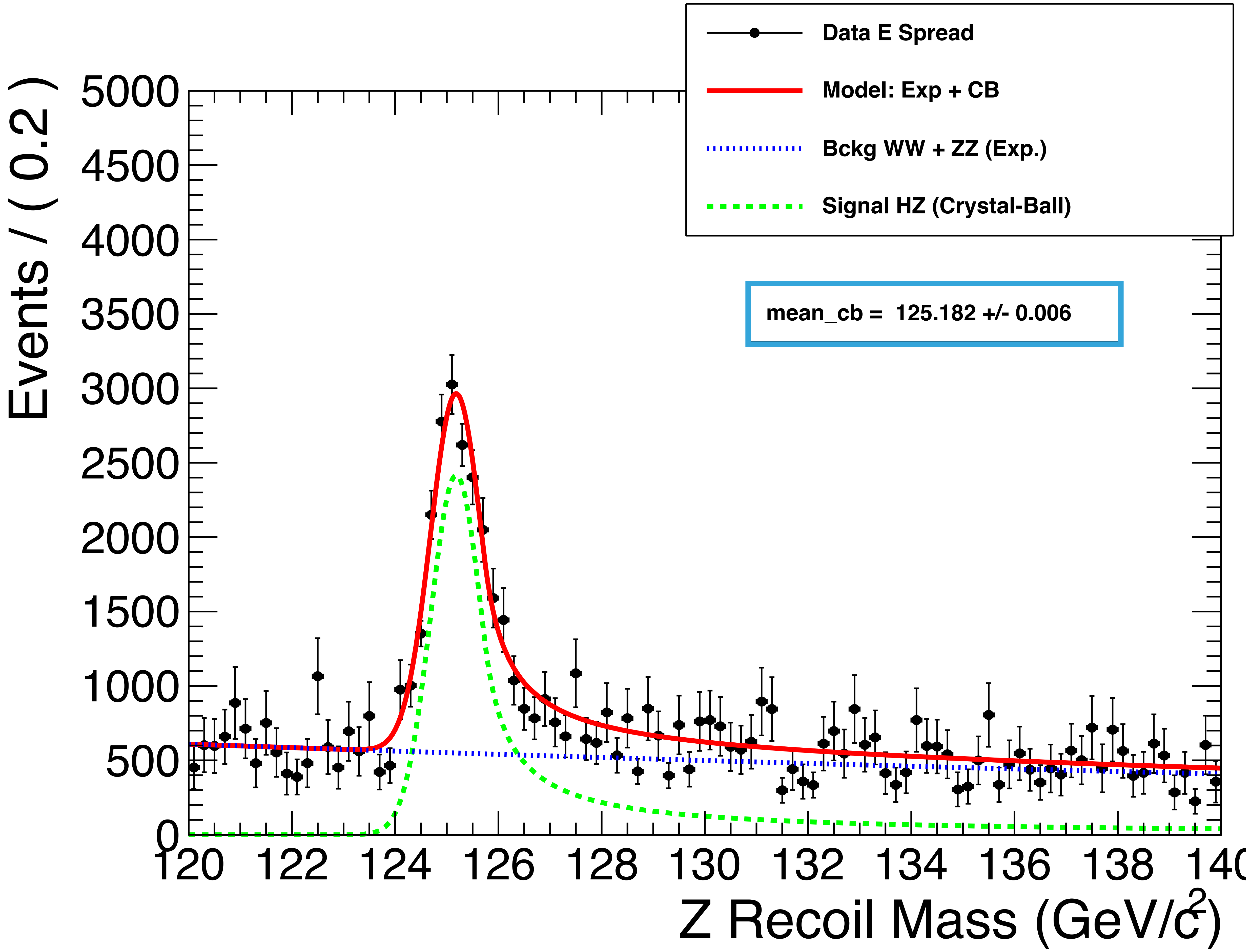
HIGGSTRAHLUNG PROCESS: HIGGS MASS FIT

Crystal-Ball (signal) + Exponential (Background)

WITHOUT BEAM ENERGY SPREAD



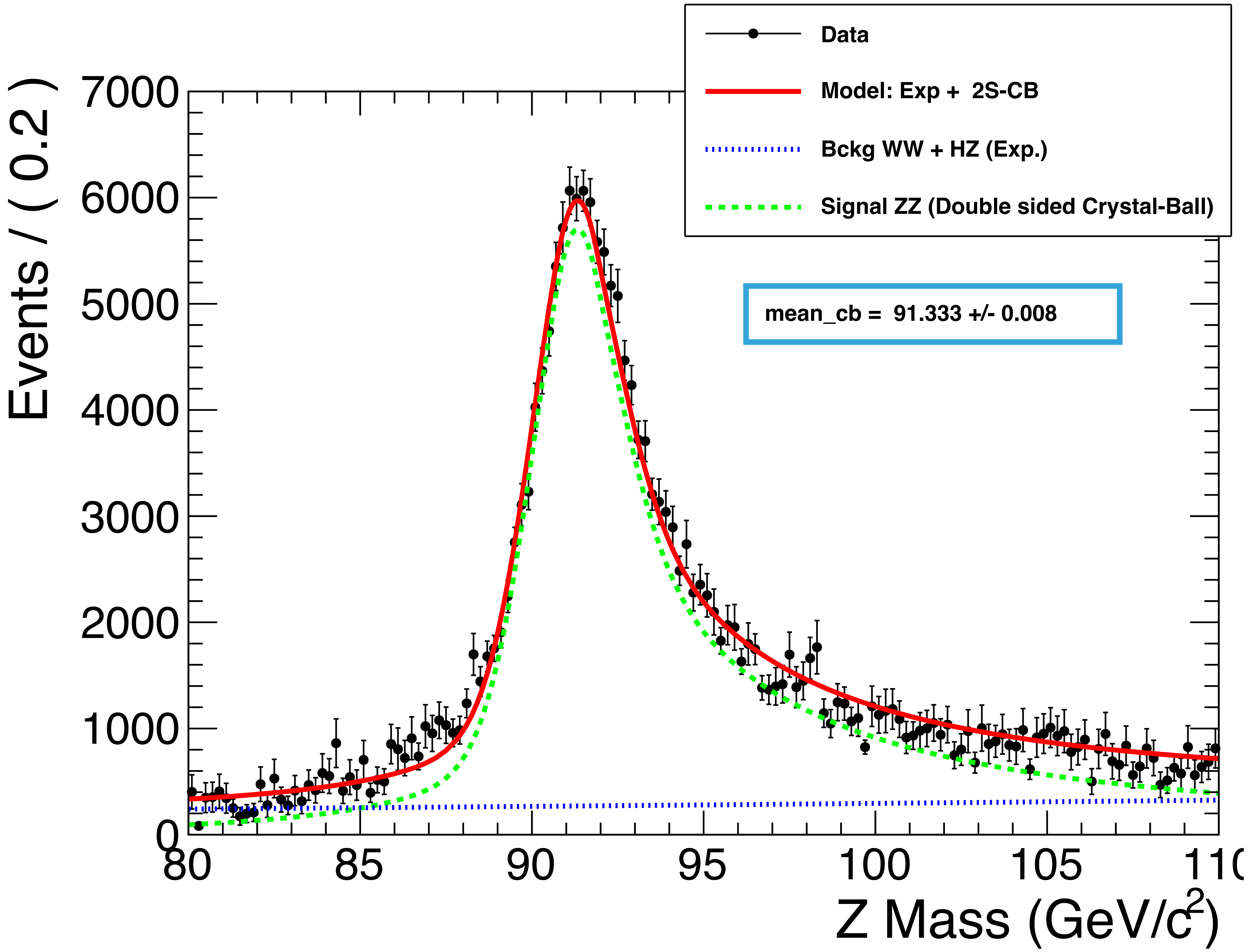
BEAM ENERGY SPREAD OF 0.192 GEV



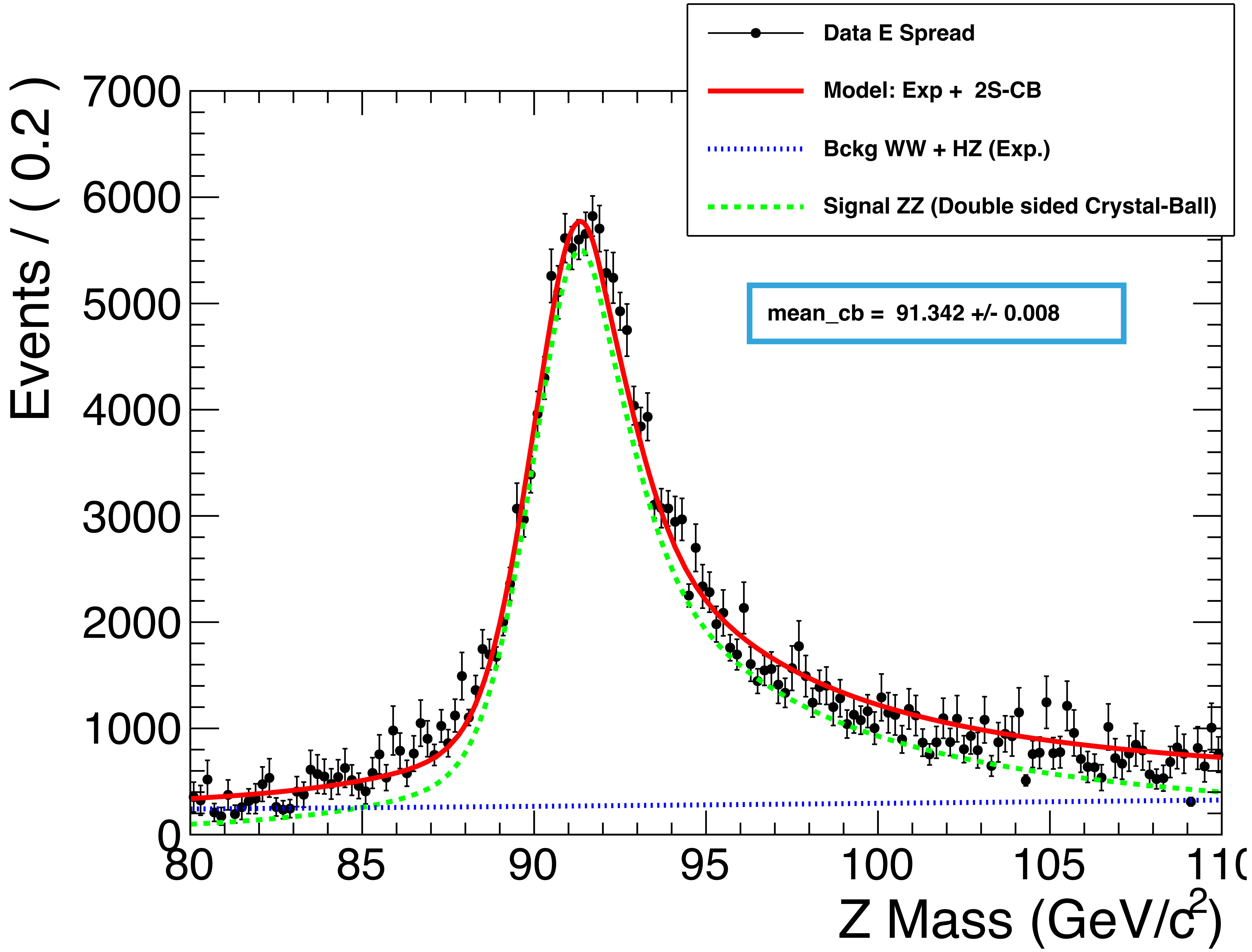
HIGGSTRAHLUNG PROCESS: Z INVARIANT MASS FIT

Double-sided Crystal-Ball (signal) + Exponential (Background)

WITHOUT BEAM ENERGY SPREAD



WITH BEAM ENERGY SPREAD OF 0.192 GEV



HIGGSTRAHLUNG PROCESS: FIT RESULTS

	M_H (GeV)	σ (GeV)
Without BES	125.09	0.003
With BES	125.182	0.006

With BES, the uncertainty of the fitted mass is increased by a factor 2

	M_Z (GeV)	σ (GeV)
Without BES	91.333	0.008
With BES	91.342	0.008

BES has negligible effect on the Z width

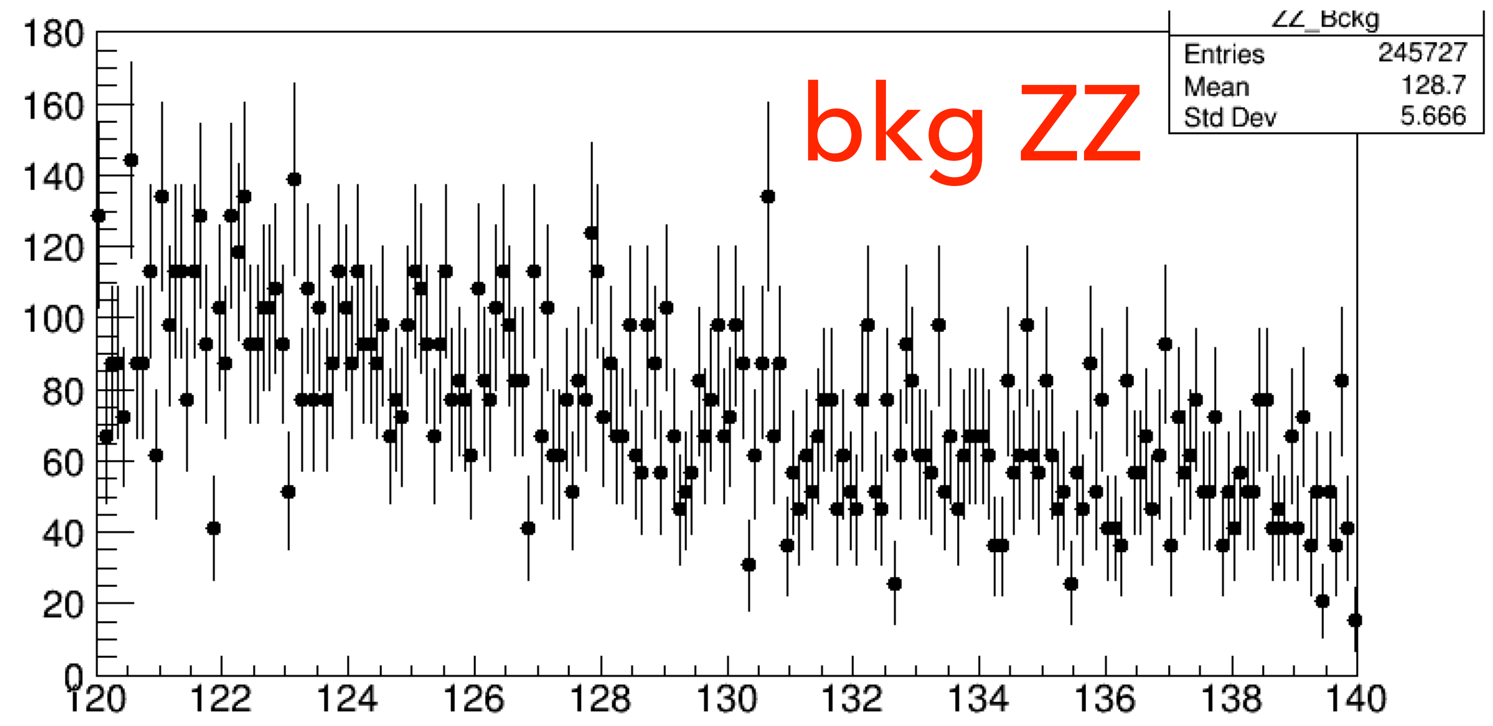
Caveat: fits not always stable

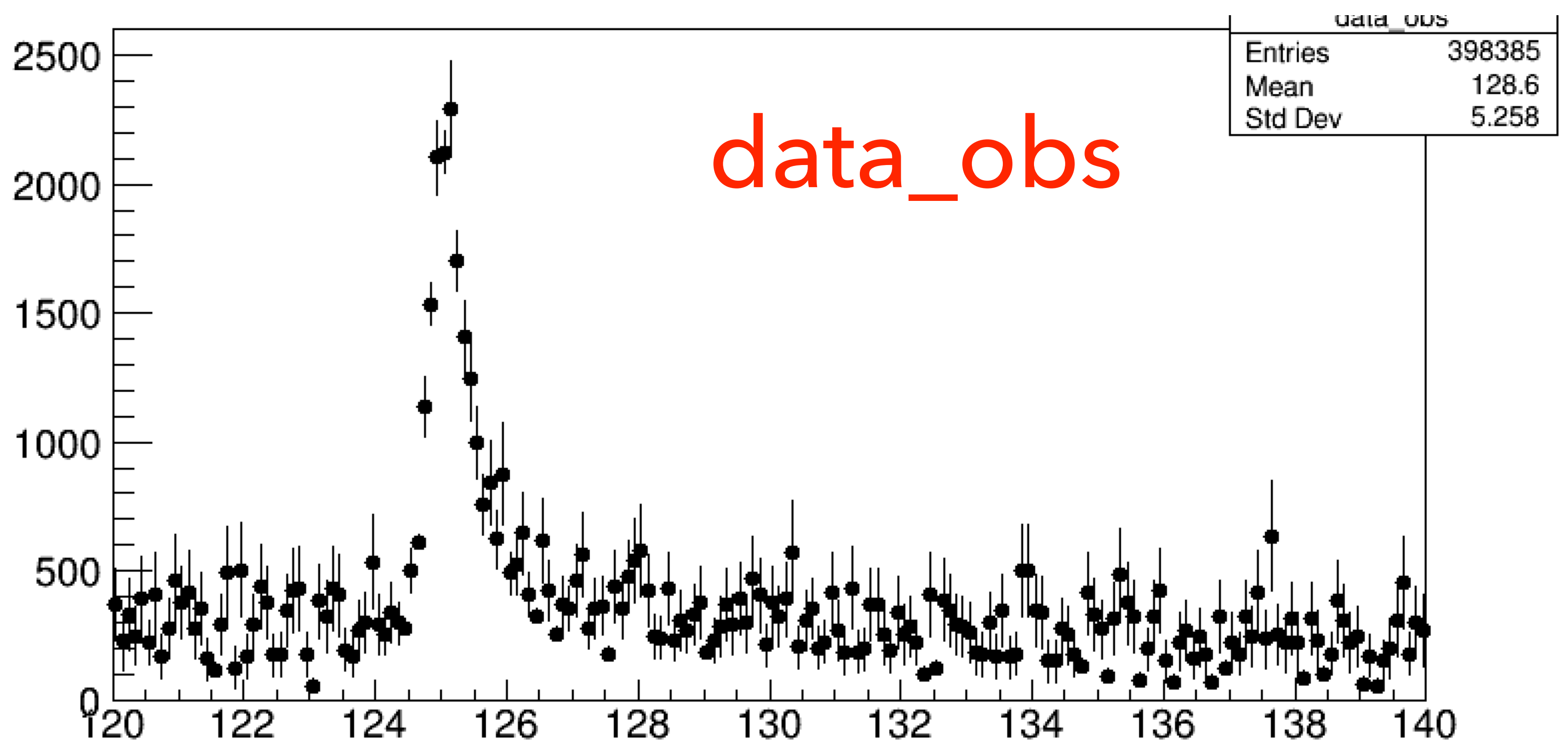
→ required fine tuning of the parameters settings

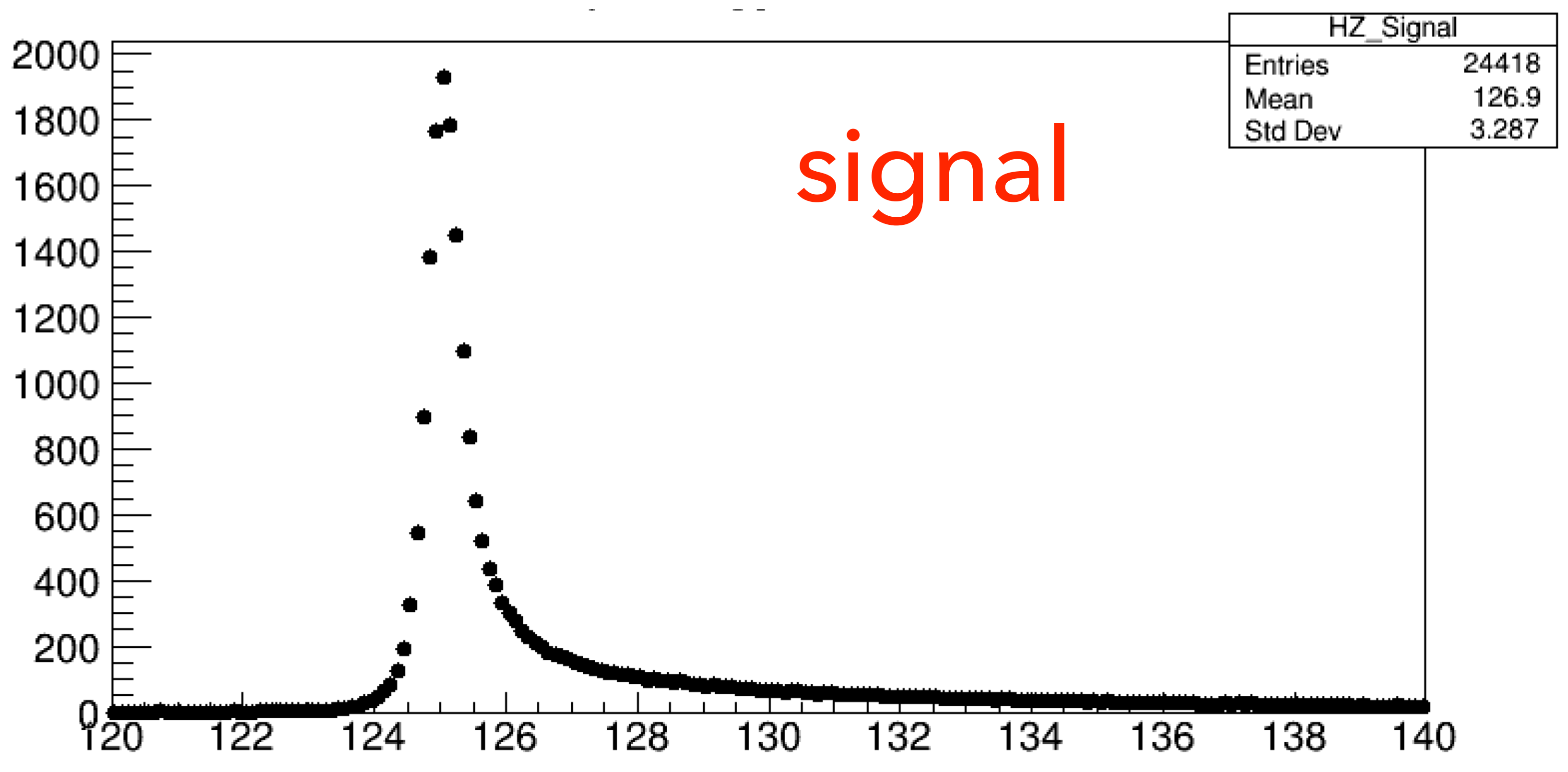
HIGGSTRAHLUNG PROCESS: SHAPE-BASED ANALYSIS WITH TEMPLATES

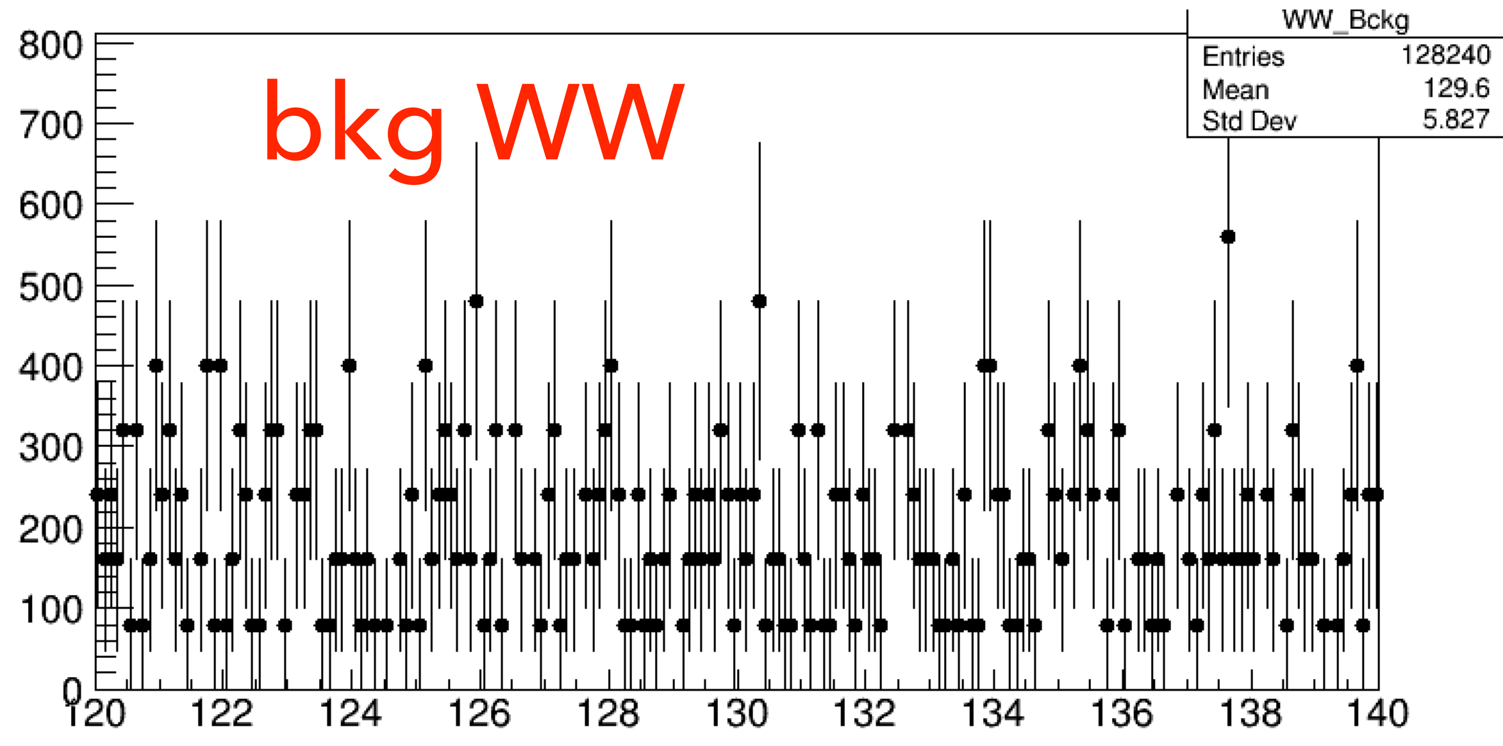
→ MOVE to a shape-based analysis with templates using *combine* software in the context of the *combine* software tool used for statistical analysis

- Instead of a one-bin counting experiment, fit a binned distribution
- Using TEMPLATES (TH1 histograms) sensitive to the presence of signal:
  - one for the data and one for each signal and background processes









HIGGSTRAHLUNG PROCESS: SHAPE-BASED ANALYSIS WITH TEMPLATES

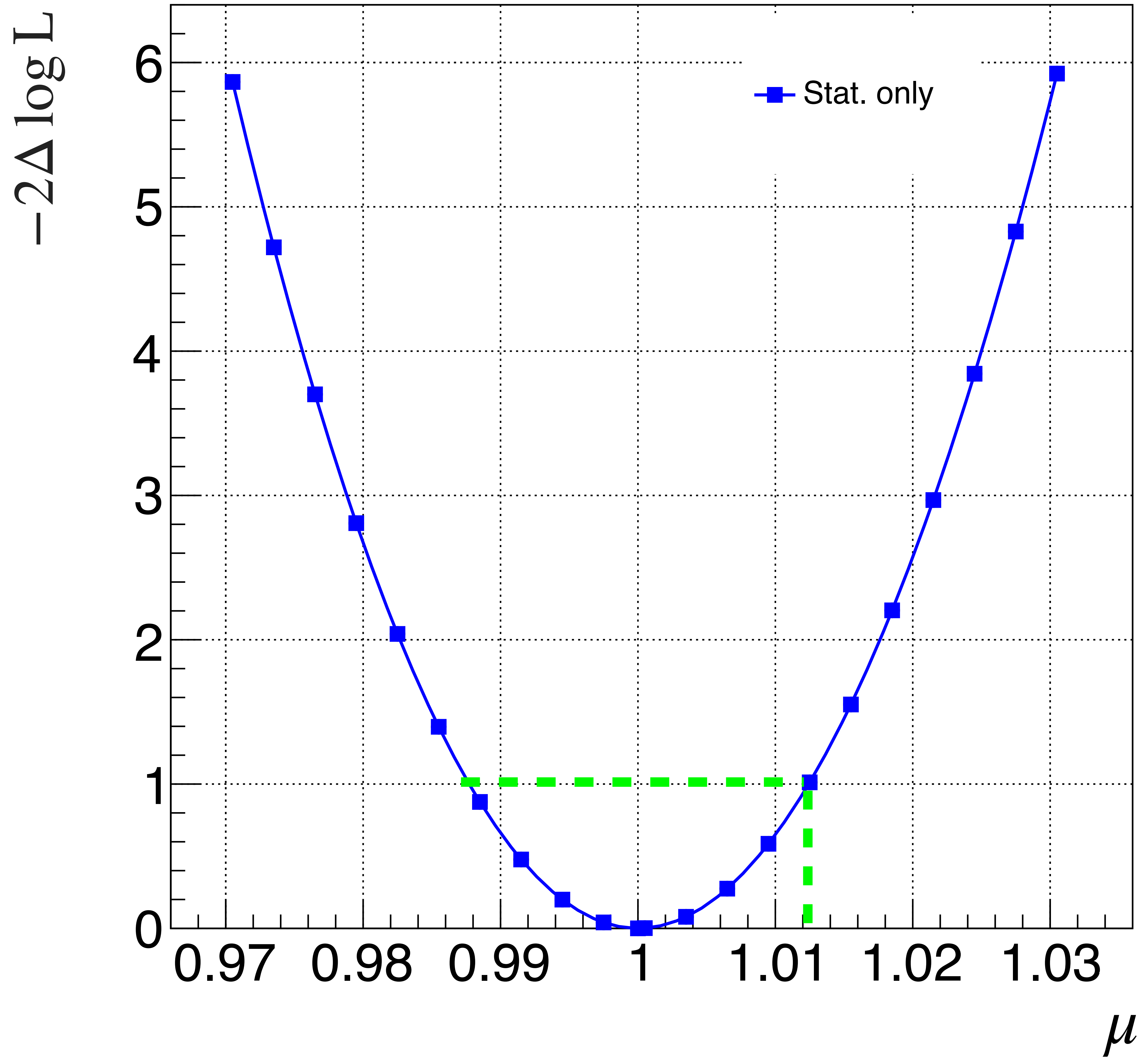
- TEMPLATES are used in the *combine* data cards using the *"shapes"*

```
imax 1  number of channels
jmax 2  number of backgrounds
kmax *  number of nuisance parameters (sources of systematical uncertainties)
-------------------------------------------------------------------------------------
# Definition of the shapes used for the fit

shapes data_obs  HZmumu AllNormHistos.root HZmumu/data_obs
shapes HZ_Signal HZmumu AllNormHistos.root HZmumu/HZ_Signal
shapes WW_Bckg   HZmumu AllNormHistos.root HZmumu/WW_Bckg
shapes ZZ_Bckg   HZmumu AllNormHistos.root HZmumu/ZZ_Bckg

-------------------------------------------------------------------------------------
bin HZmumu
observation 74042
-------------------------------------------------------------------------------------
# now we list the expected events for signal and all backgrounds in that bin
# the second 'process' line must have a positive number for backgrounds, and 0 for signal

bin             HZmumu      HZmumu      HZmumu
process         HZ_Signal   WW_Bckg     ZZ_Bckg
process         0             1          2
rate            23471        35600       14981
```

Root file containing the templates

HIGGSTRAHLUNG PROCESS: SIGNAL STRENGTH

SHAPE-BASED ANALYSIS



The signal strength is defined as

$$\mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

The signal strength is measured with a precision of 1.2 % at the 68% CL

SUMMARY

- IDEA Delphes configuration implemented with special modules for:
  - Dual-Readout Calorimeter
  - Full Covariant matrix
    - Validation of the new module within Delphes
- Study of a benchmark physics case: $e^+e^- \rightarrow HZ, Z \rightarrow \mu^+\mu^-$ and $H \rightarrow X$
  - Mass resolution studies performed using
    - RooFit (requires fine tuning of the fit parameters)
    - Started to use *Combine* Shape-based Analysis with templates

OUTLOOK

- Validation of the IDEA implementation with the full simulation
- Determination of the detector requirements
- Shape-based analysis of the $HZ \rightarrow X + \mu^{+}\mu^{-}$
  - Add the systematic uncertainties (USING TEMPLATES)
  - Obtaining the NLL curve as a function of the Higgs masses
- Make the analysis with larger statistics samples **centrally produced** https://hep-fcc.github.io/FCCeePhysicsPerformance/General/#common-event-samples

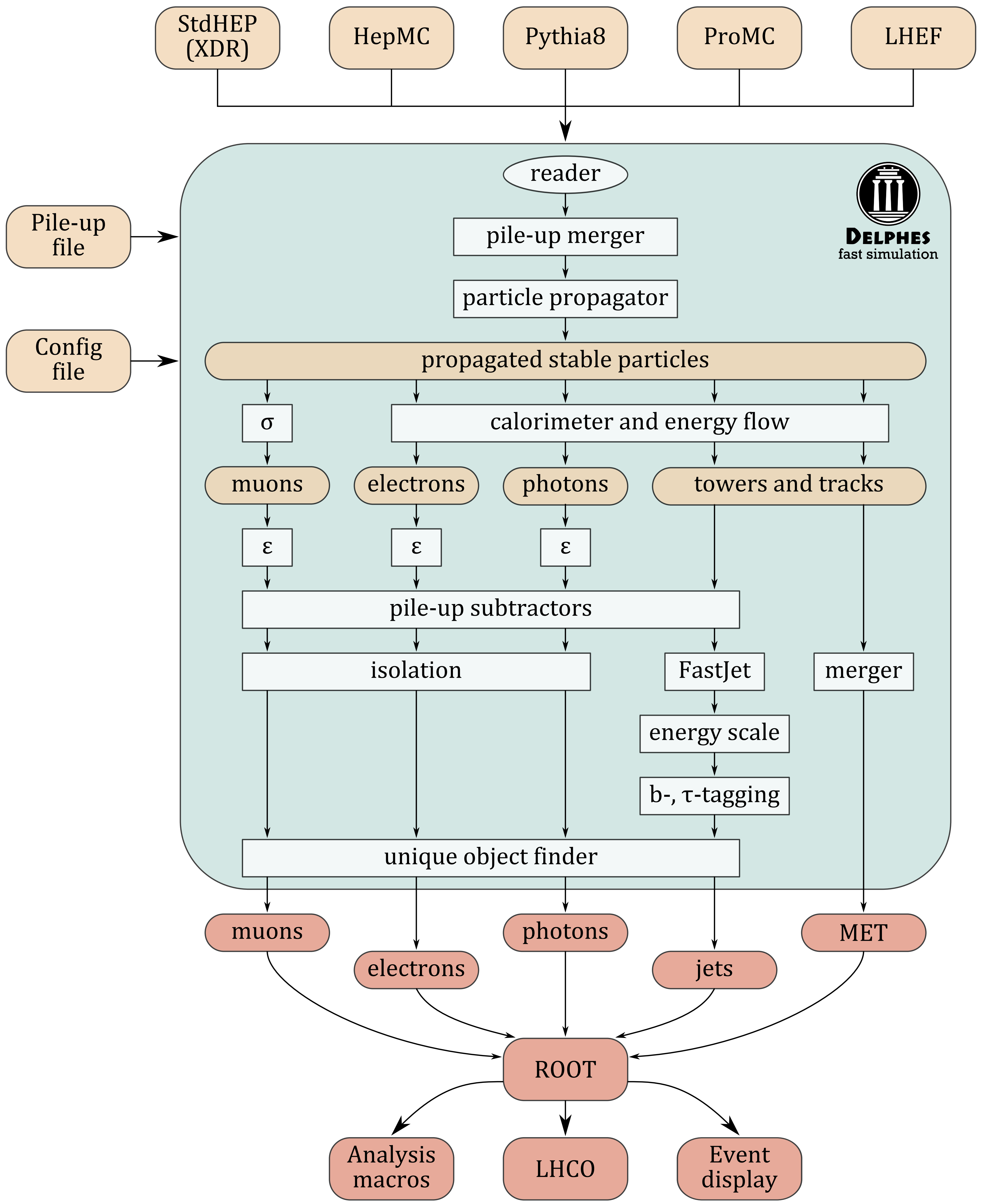
Be aware that these samples have an EDM4HEP output –> need special routines in order to read them.

It might be necessary to have a private sample production if the official production would not provide standard Delphes output.
–> make sure to use the correct validated setup of the official samples to compare results

THANK YOU

BACKUP SLIDES

DELPHES WORK FLOW CHART



Event files coming from external MC generators are processed by the reader

LLPs are propagated to the calorimeter within a uniform magnetic field parallel to the beam direction.

Particles reaching the CAL deposit their energies

The output data, as the reconstructed objects, are stored in a ROOT tree format which can be analysed

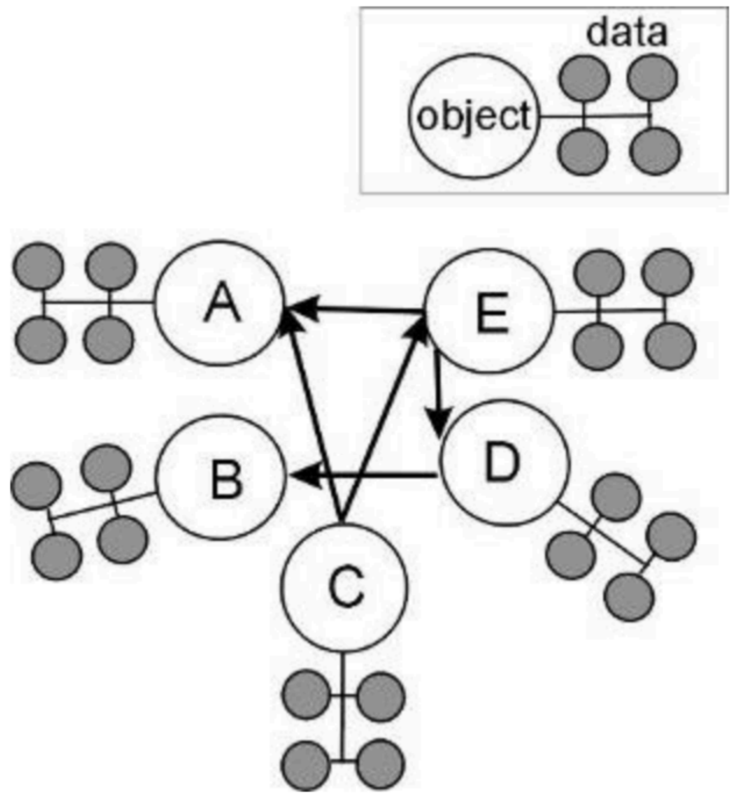
DELPHES FRAMEWORK: MODULAR STRUCTURE

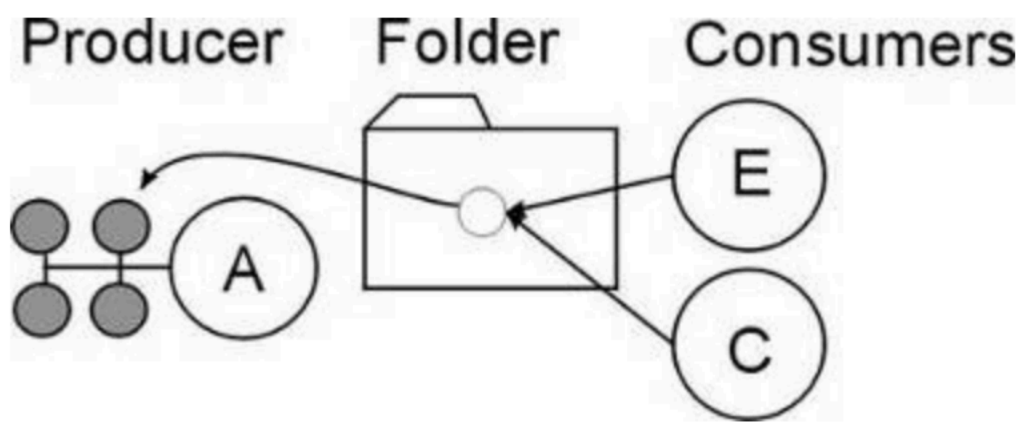
The new modular approach allows for great flexibility in the design of the simulation and reconstruction sequence.

The module system is based on the ROOT classes `TTask` and `TFolder`

Every Delphes module has a corresponding Folder that is used to store `TObjectArrays` produced by this module. Any module can access `TObjectArrays` produced by other modules using an ImportArray method.

Why use folders? Reduce class dependencies and improve modularity





It uses the maximum amount of information provided by the various sub-detectors in order to reconstruct the event.

arXiv:1307.6346v3

It produces two collections of 4-vectors

TRACKS

It contains charged particles estimated with a good resolution.

For neutral particles, the trajectory is a straight line form the production point to a calorimeter cell.
Charged particles follow an helicoidal trajectory up to the CAL.

TOWERS

It contains a combination of neutral particles, charged particles with no corresponding reconstructed tracks and additional excess deposit induced by positive smearing of the calorimeters.

They are characterised by low resolution

DELPHES FRAMEWORK: FULL COVARIANCE MATRIX

The implementation of the TrackCovariance.cc module requires in input

- Magnetic Field
- Geometry

The geometry is implemented in the Delphes data cards

Specifically

Delphes_card_IDEAtrkCov.tcl

```
#########################################
# Smearing for charged tracks
#########################################

module TrackCovariance TrackSmearing {
    set InputArray TrackMergerPre/tracks
    set OutputArray tracks

    ## uses https://raw.githubusercontent.com/selvaggi/FastTrackCovariance/master/GeoIDEA_BASE.txt
    set DetectorGeometry {

      1 PIPE -100 100 0.015 0.0012 0.35276 0 0 0 0 0 0
      1 VTXLOW -0.12 0.12 0.017 0.00028 0.0937 2 0 1.5708 3e-006 3e-006 1
      1 VTXLOW -0.16 0.16 0.023 0.00028 0.0937 2 0 1.5708 3e-006 3e-006 1
      1 VTXLOW -0.16 0.16 0.031 0.00028 0.0937 2 0 1.5708 3e-006 3e-006 1
      1 VTXHIGH -1 1 0.32 0.00047 0.0937 2 0 1.5708 7e-006 7e-006 1
      1 VTXHIGH -1.05 1.05 0.34 0.00047 0.0937 2 0 1.5708 7e-006 7e-006 1
      1 DCHCANI -2.125 2.125 0.345 0.0002 0.237223 0 0 0 0 0 0
      1 DCH -2 2 0.36 0.0147748 1400 1 0.0203738 0 0.0001 0 1
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      1 DCH -2 2 0.38955 0.0147748 1400 1 0.0220456 0 0.0001 0 1
      1 DCH -2 2 0.404324 0.0147748 1400 1 -0.0228814 0 0.0001 0 1
      1 DCH -2 2 0.419099 0.0147748 1400 1 0.0237172 0 0.0001 0 1
      1 DCH -2 2 0.433874 0.0147748 1400 1 -0.024553 0 0.0001 0 1
      1 DCH -2 2 0.448649 0.0147748 1400 1 0.0253888 0 0.0001 0 1
      1 DCH -2 2 0.463423 0.0147748 1400 1 -0.0262245 0 0.0001 0 1
      1 DCH -2 2 0.478198 0.0147748 1400 1 0.0270602 0 0.0001 0 1
      1 DCH -2 2 0.492973 0.0147748 1400 1 -0.0278958 0 0.0001 0 1
```

BACKUP – IDEA GEOMETRY DEFINITION


```
class SolGeom{
  //
  // Units are m
  //
private:
  const Int_t fNlMax = 200; // Maximum number of layers

  // B field
  Double_t fB; // B field in Tesla

  // Barrel layer properties
  Int_t fNlay;          // Total number of layers
  Int_t fBlay;          // Number of barrel layers
  Int_t fFlay;          // Number of forward/backward layers
  Int_t fNm;            // Nr. measurement layers
  Int_t *ftyLay;        // Layer type 1 = R (barrel) or 2 = z (forward/backward)
  TString *fLyLabl;     // Layer label
  // Barrel: PIPE, VTXLOW, VTXHIGH, DCHCANI, DCH, DCHCANO, BSILWRP, MAG, BPRESH
  // Fw/Bw: VTXDSK, DCHWALL, FSILWRP, FRAD, FPRESH
  Double_t *fxMin;      // Minimum dimension z for barrel  or R for forward
  Double_t *fxMax;      // Maximum dimension z for barrel  or R for forward
  Double_t *frPos;      // R/z location of layer
  Double_t *fthLay;     // Thickness (meters)
  Double_t *frlLay;     // Radiation length (meters)
  Int_t    *fnmLay;     // Number of measurements in layers (1D or 2D)
  Double_t *fstLayU;    // Stereo angle (rad) - 0(pi/2) = axial(z) layer - Upper side
  Double_t *fstLayL;    // Stereo angle (rad) - 0(pi/2) = axial(z) layer - Lower side
  Double_t *fsgLayU;    // Resolution Upper side (meters) - 0 = no measurement
  Double_t *fsgLayL;    // Resolution Lower side (meters) - 0 = no measurement
  Bool_t   *fflLay;     // measurement flag = T, scattering only = F
```

p_T RESOLUTION VS TRANSVERSE MOMENTUM

DELPHES COMPARED TO THE STANDALONE TRACKING SOFTWARE

@ 50 GeV

in the **barrel**

$$\frac{\sigma_{p_T}}{p_T} = 2 \times 10^{-3}$$ Delphes vs $$\frac{\sigma_{p_T}}{p_T} = 1.9 \times 10^{-3}$$ Standalone

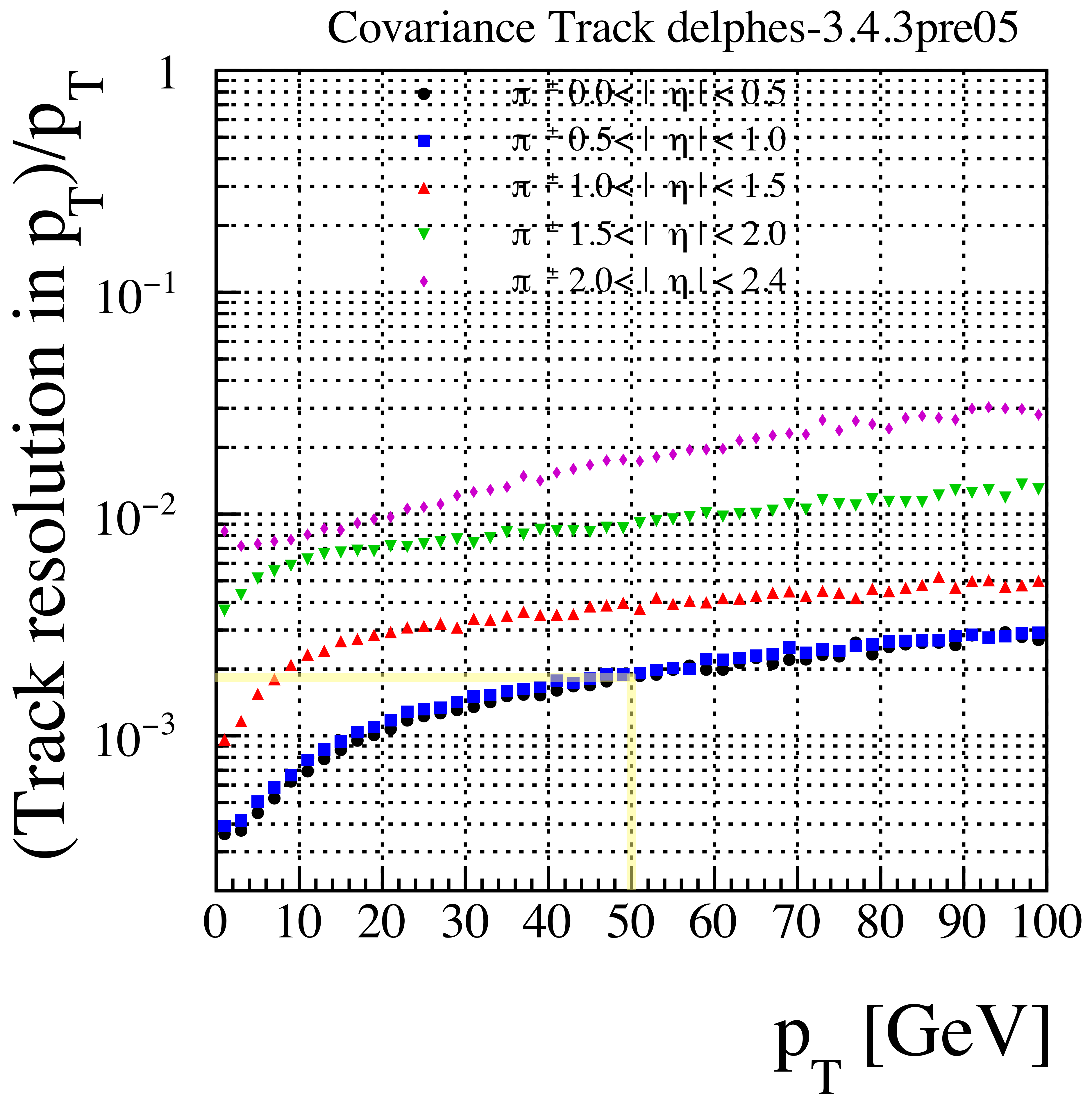
~10° < θ < ~15°

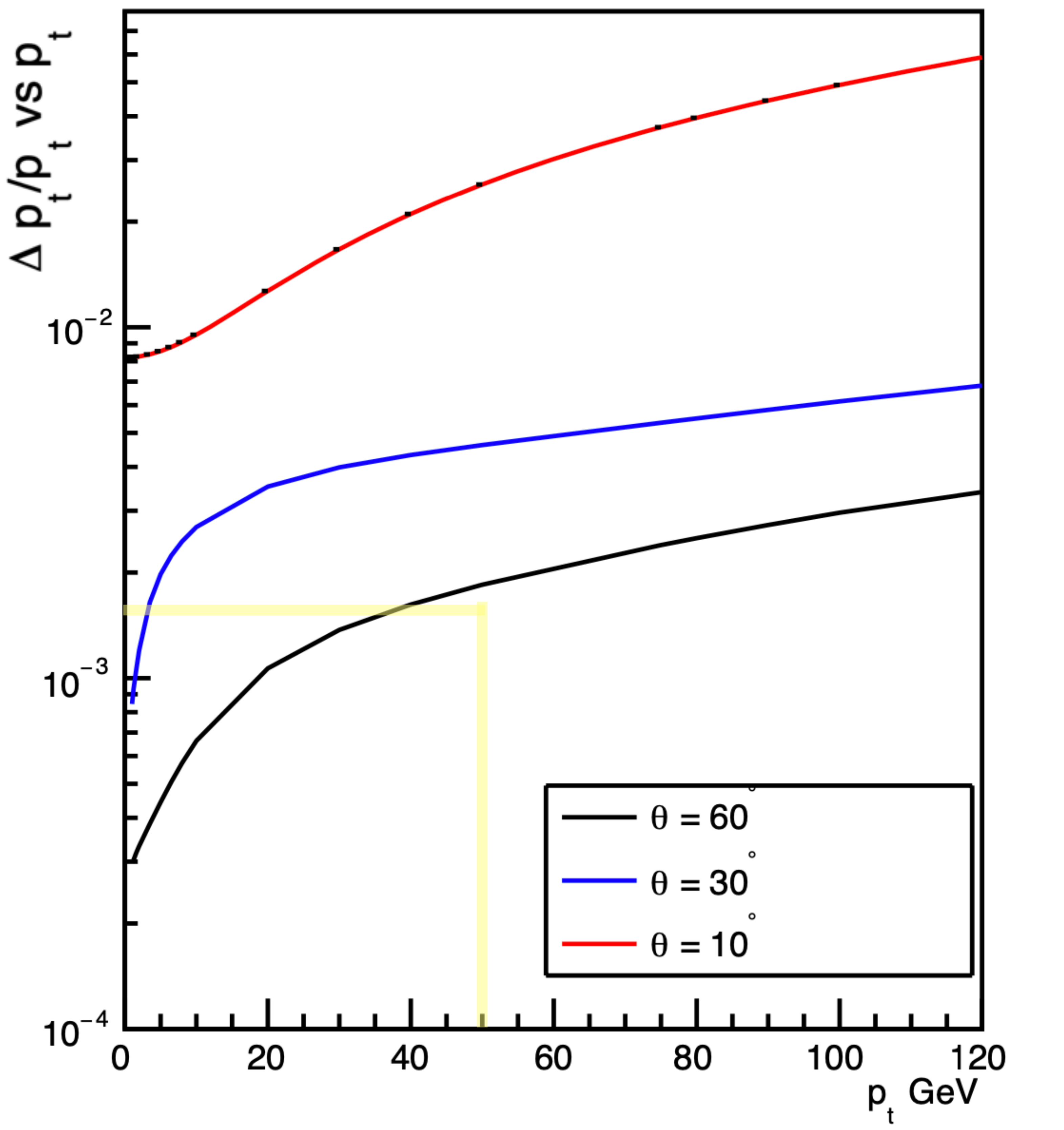
~15° < θ < ~25°

~25° < θ < ~40°

~40° < θ < ~60°

~60° < θ < 90°





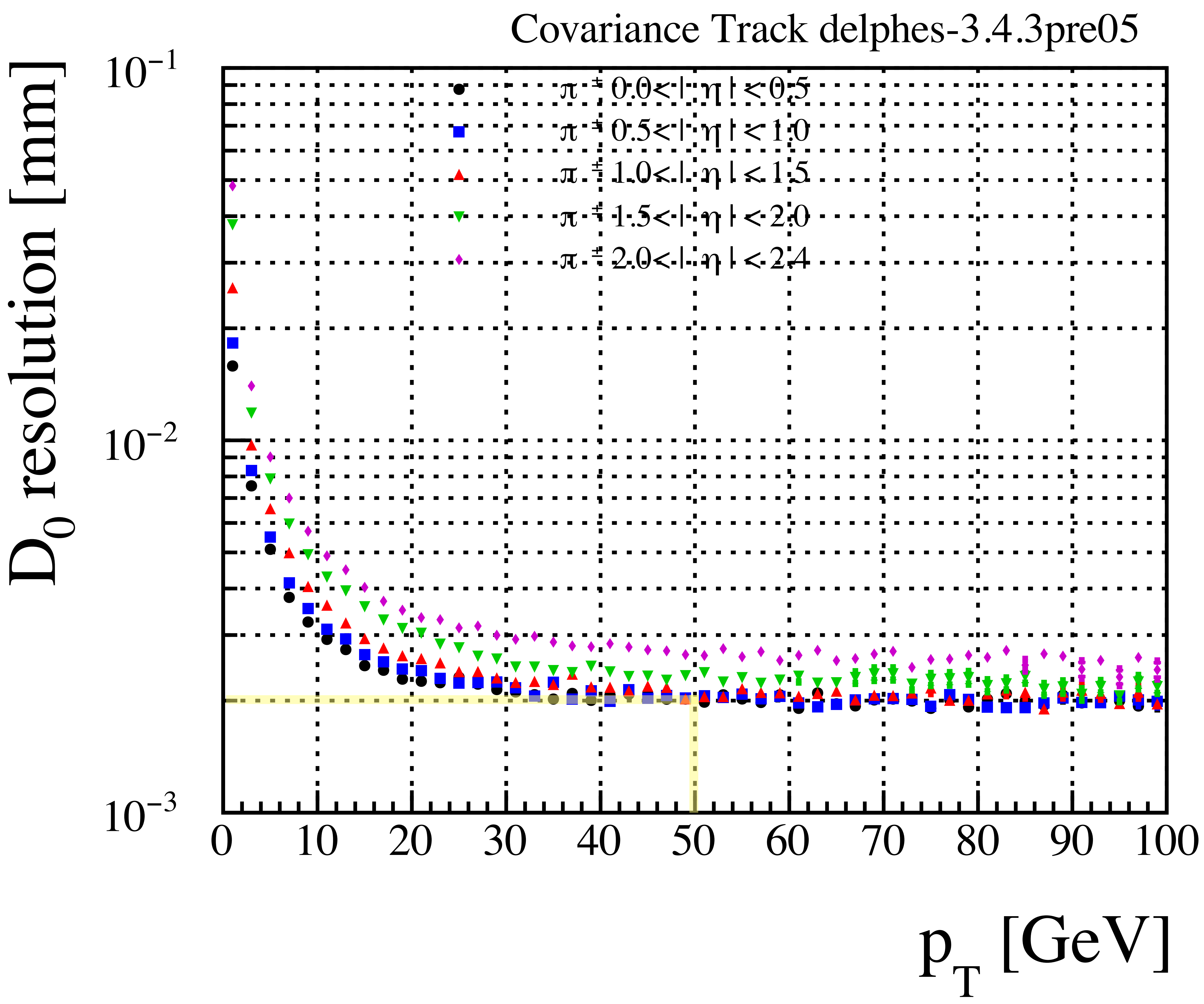
d_0 RESOLUTION VERSUS TRANSVERSE MOMENTUM

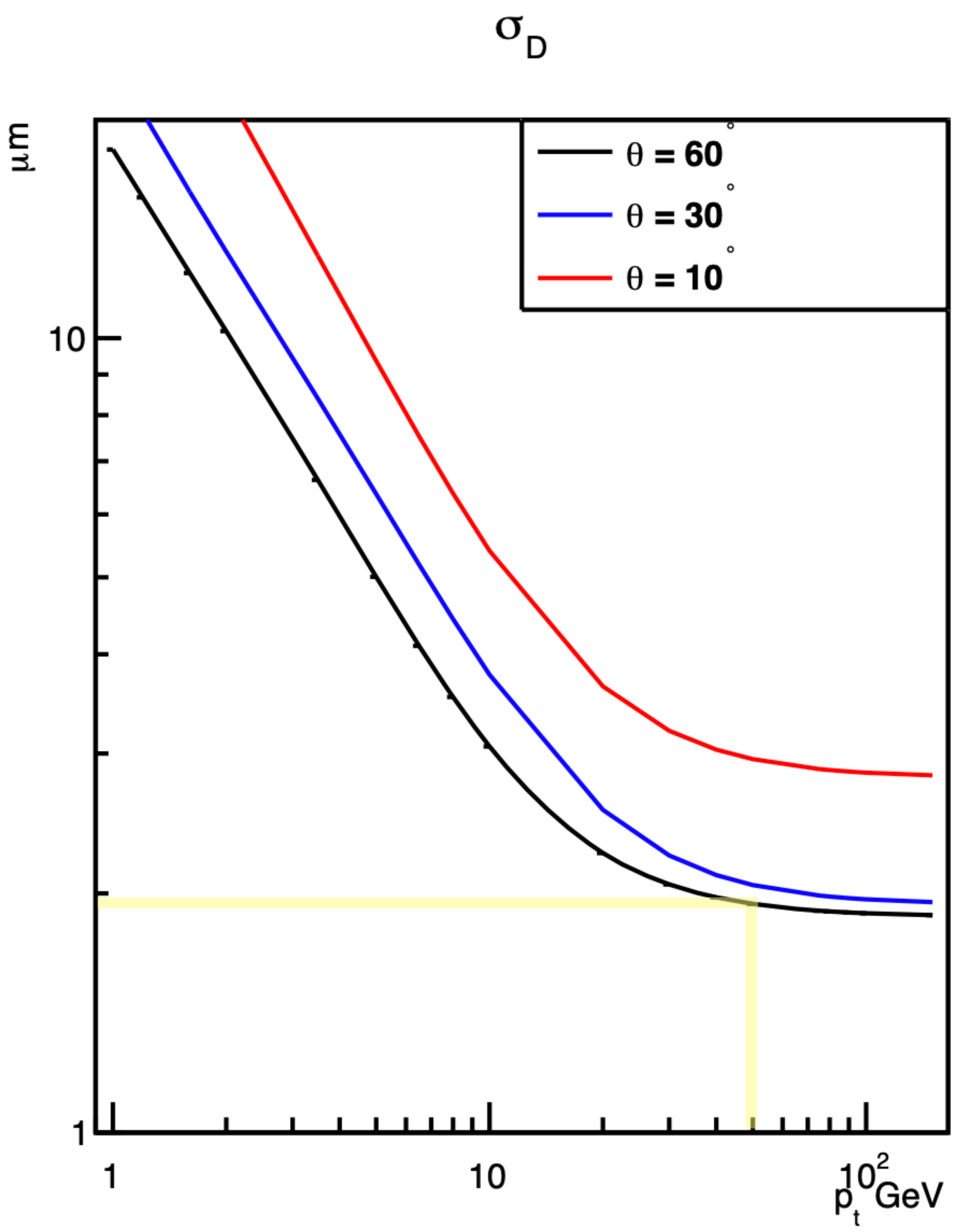
RADIAL IMPACT PARAMETER RESOLUTION

@ 50 GeV

in the **barrel**

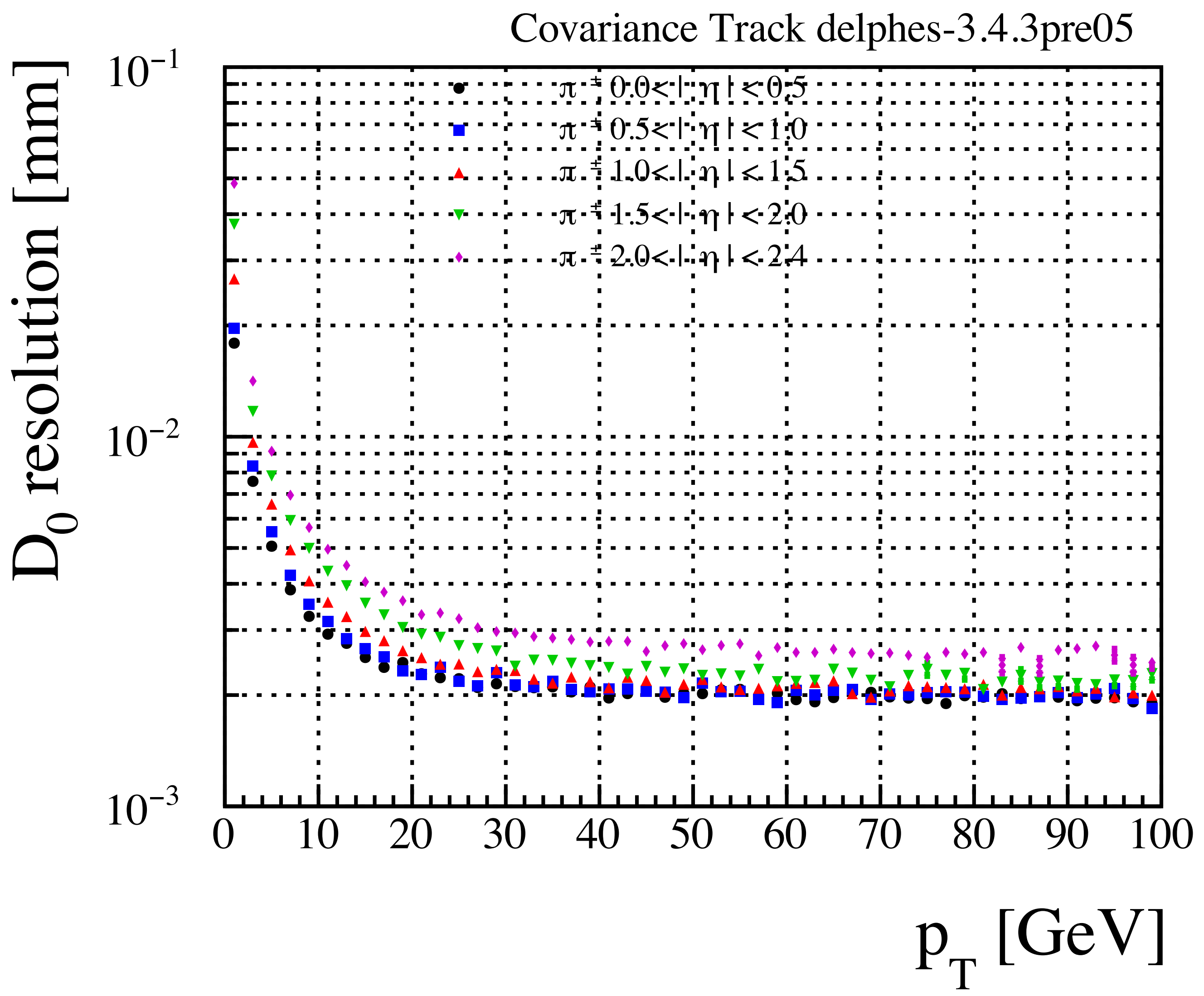
$\sigma_{d_0} = 2\ \mu$m Delphes vs $\sigma_{d_0} = 2\ \mu$m Standalone

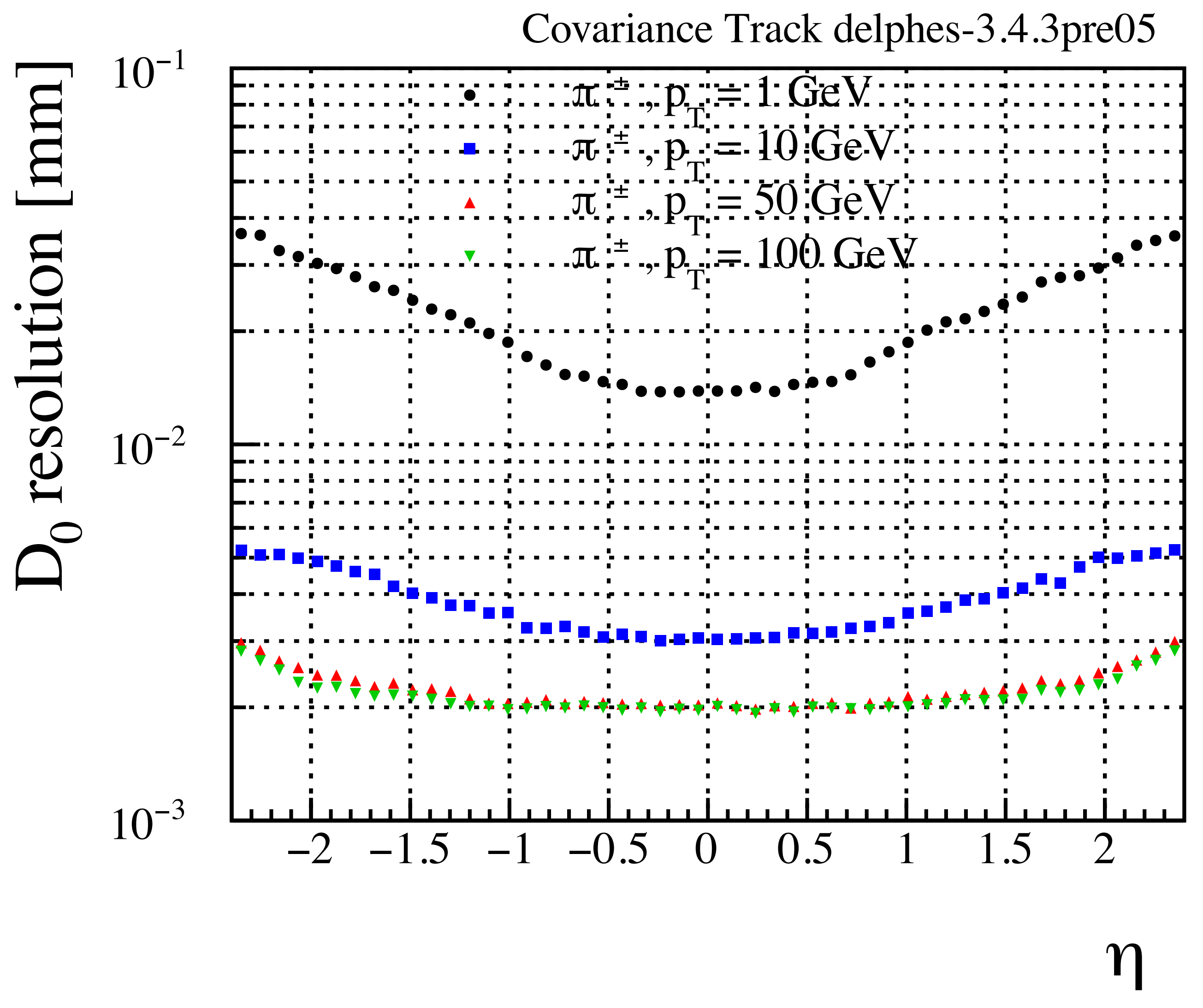




d_0 AND d_z RESOLUTION VERSUS TRANSVERSE MOMENTUM

$\sigma_{d_0} \approx 2\ \mu m$ for particles with $p_T \in [90 - 100]$ GeV



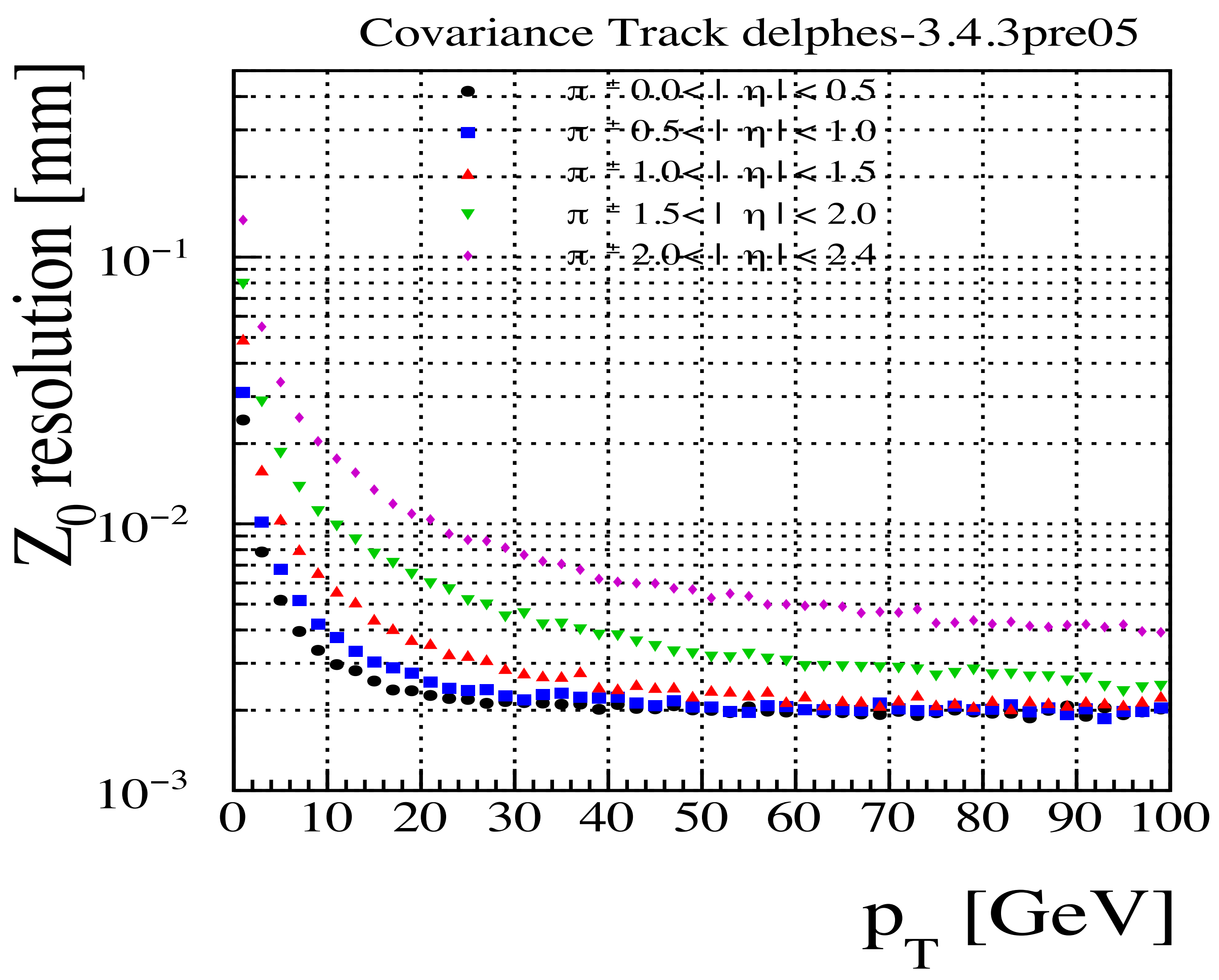


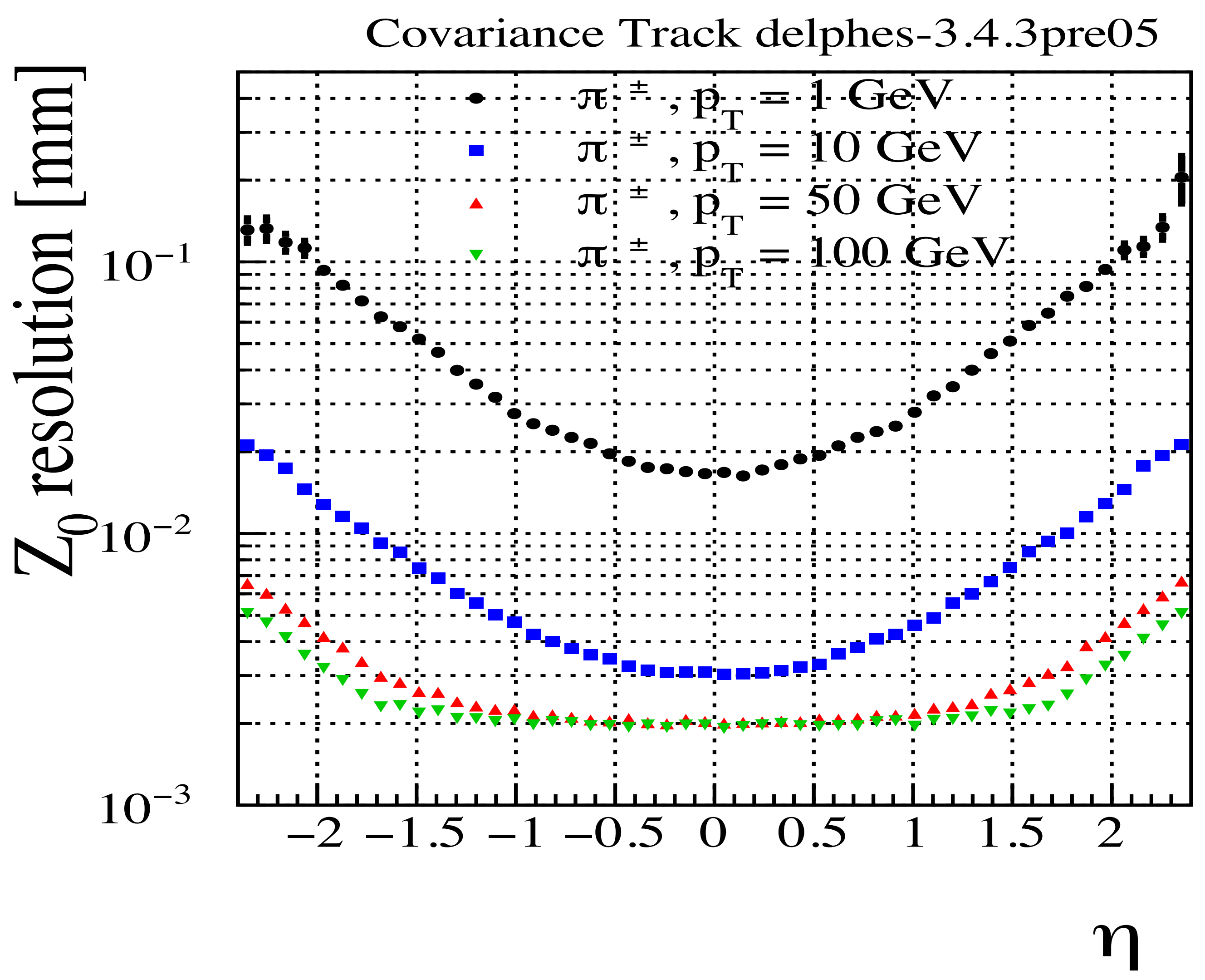
$\sigma_{d_z} \approx 2\ \mu m$ in the barrel

$\sigma_{d_z} \approx 4\ \mu m$ in the forward region

for particles with

$p_T \in [90 - 100]$ GeV





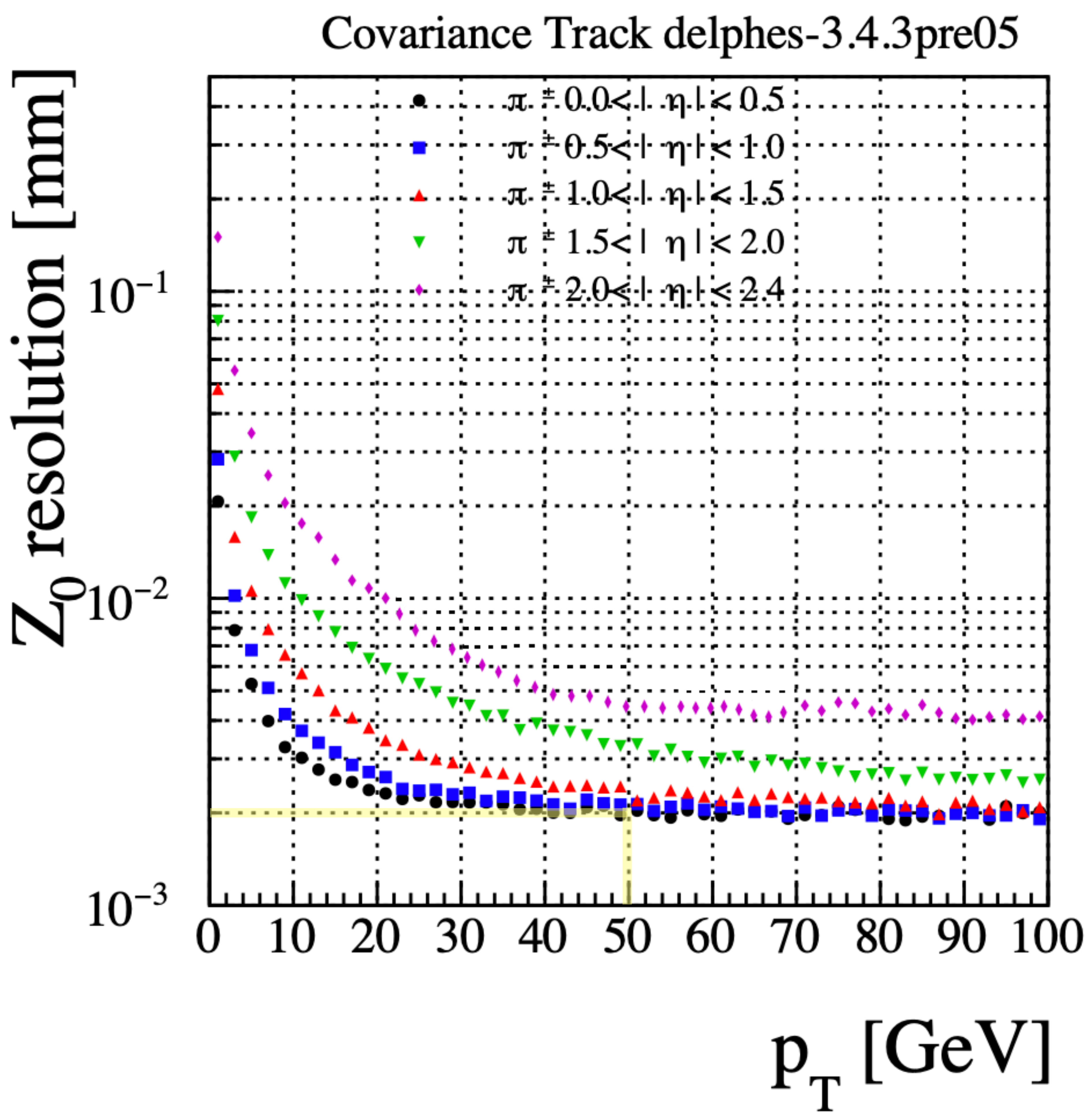
d_z RESOLUTION VERSUS TRANSVERSE MOMENTUM

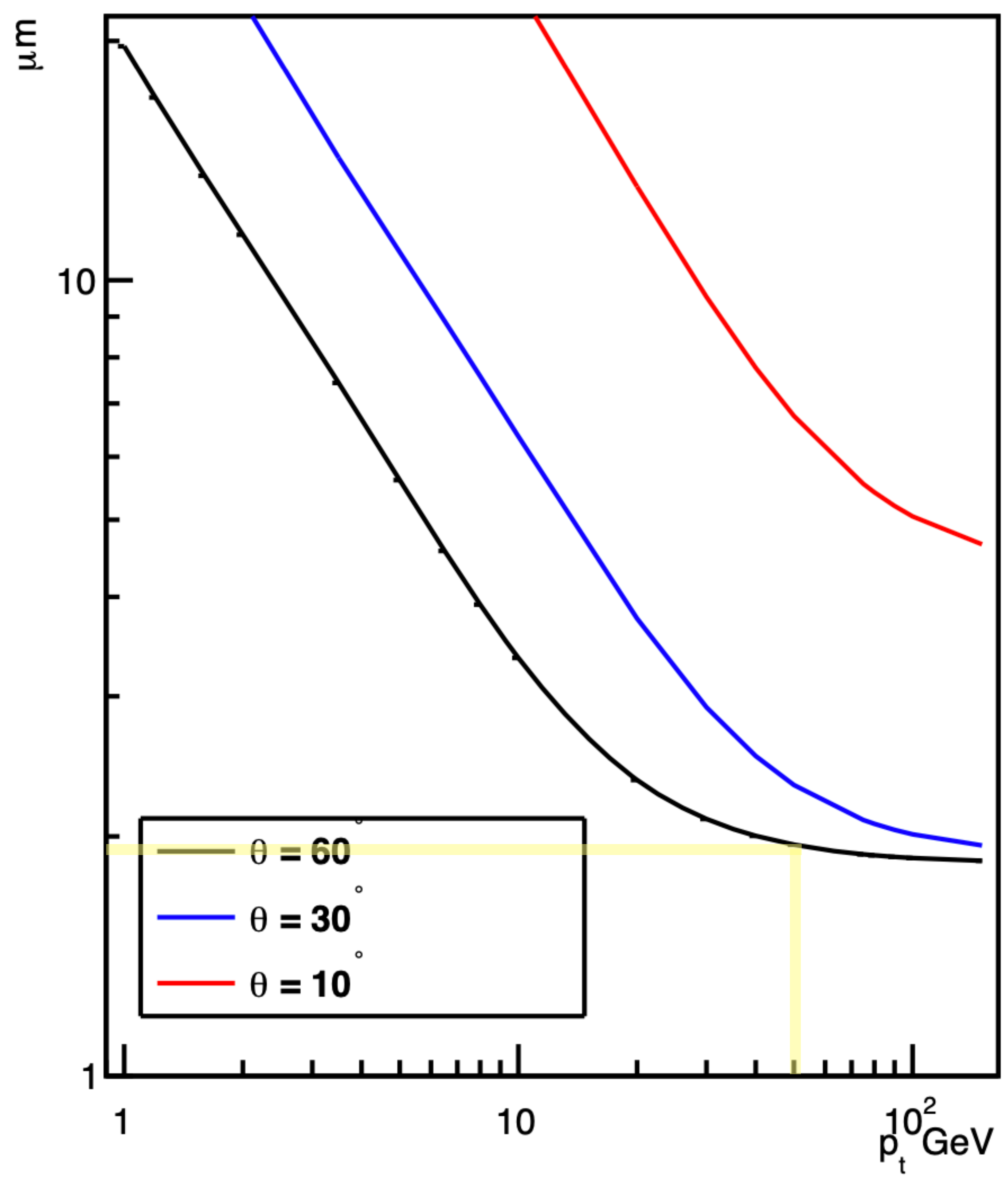
DELPHES COMPARED TO THE STANDALONE TRACKING SOFTWARE

@ 50 GeV

in the **barrel**

$\sigma_{d_0} = 2\ \mu$m Delphes vs $\sigma_{d_0} = 2\ \mu$m Standalone





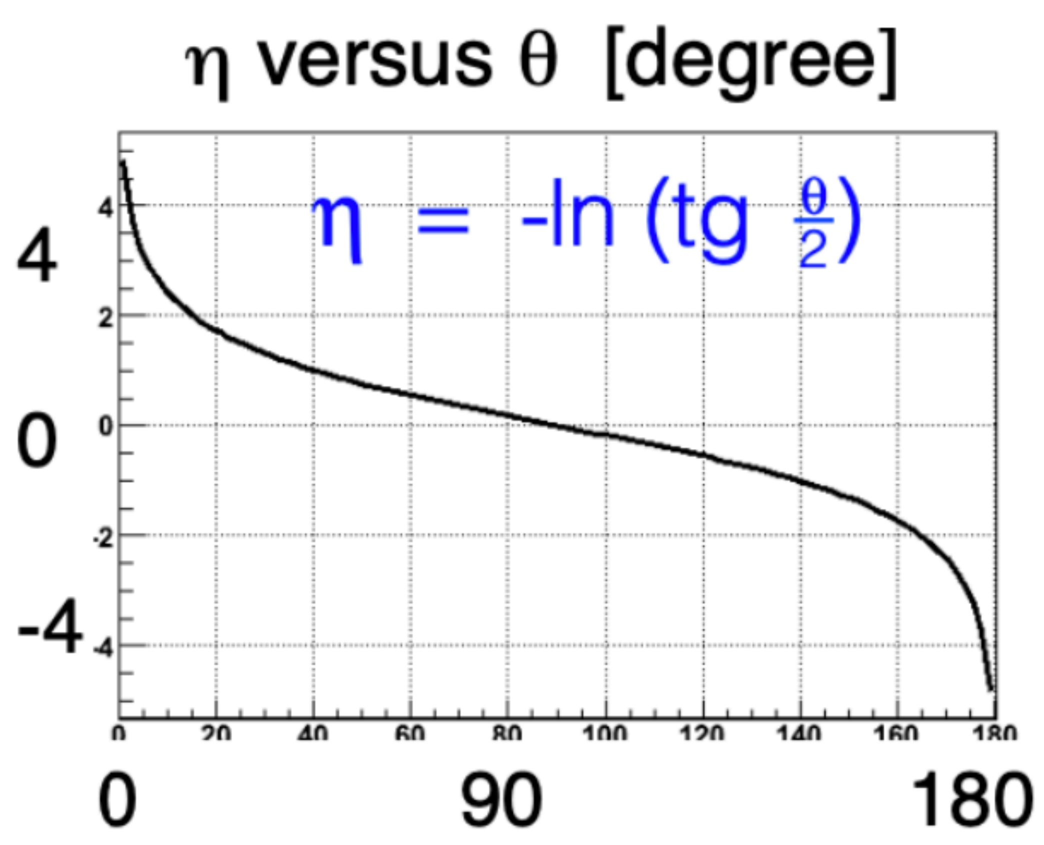
PARAMETER OF INTEREST

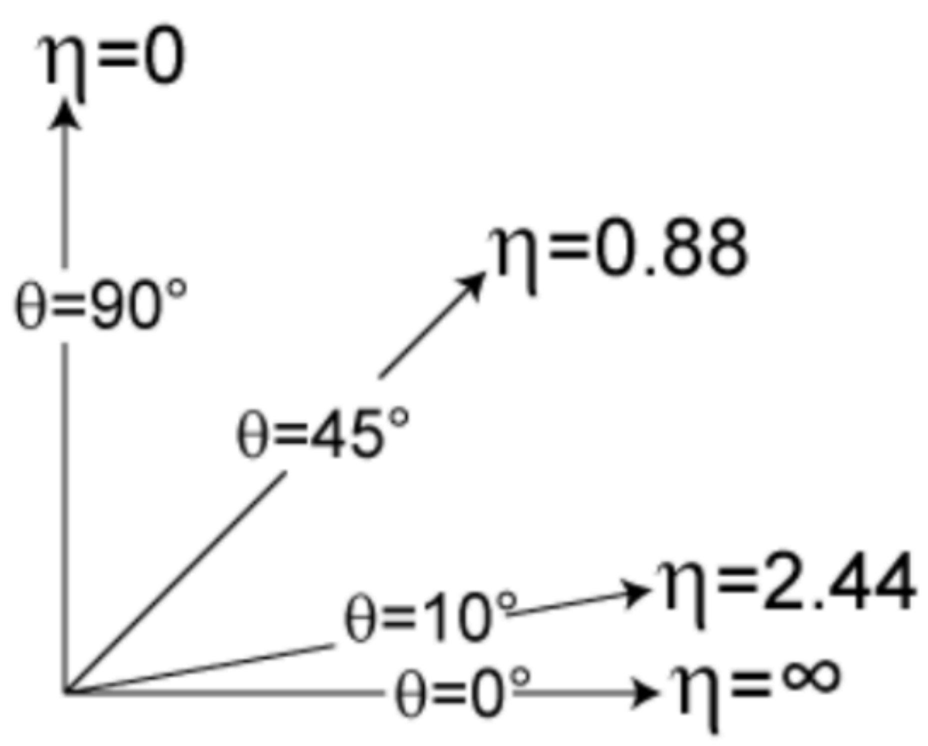
PSEUDORAPIDITY

At a circular collider the pseudorapidity η is defined as

$$\eta = \frac{1}{2} \ln \theta$$

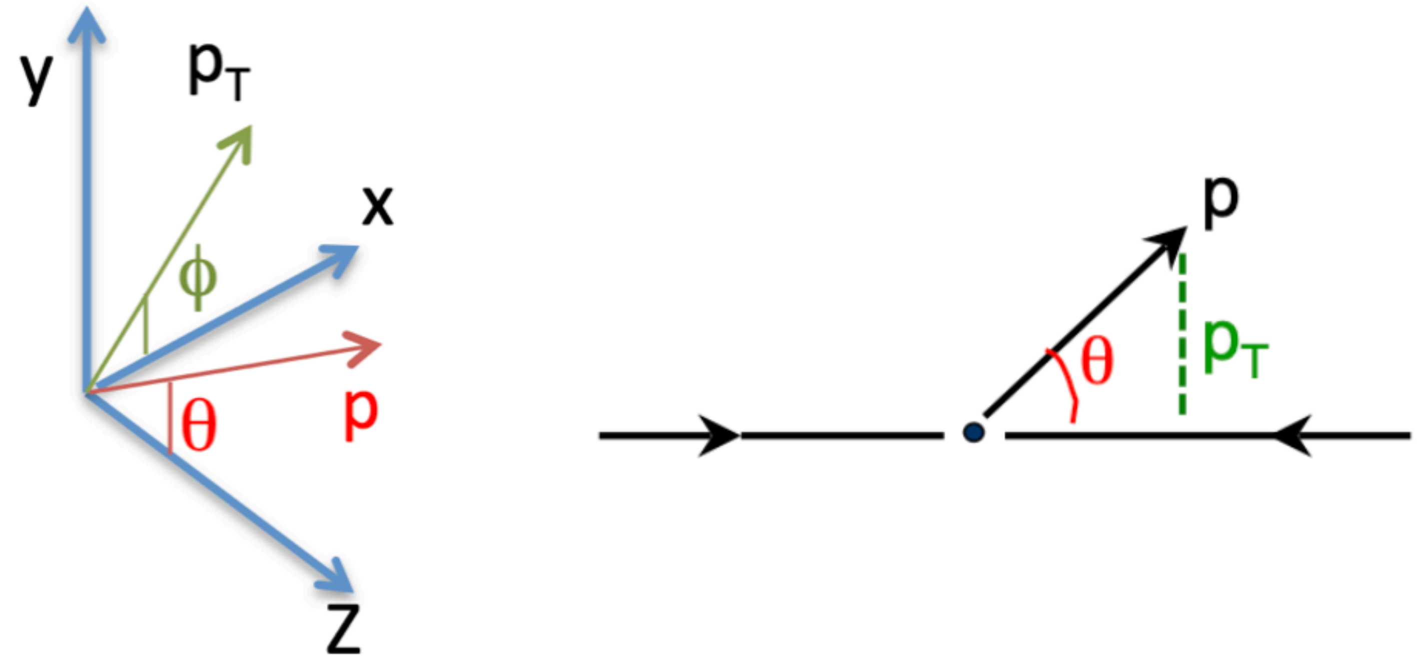
where θ is the emission angle





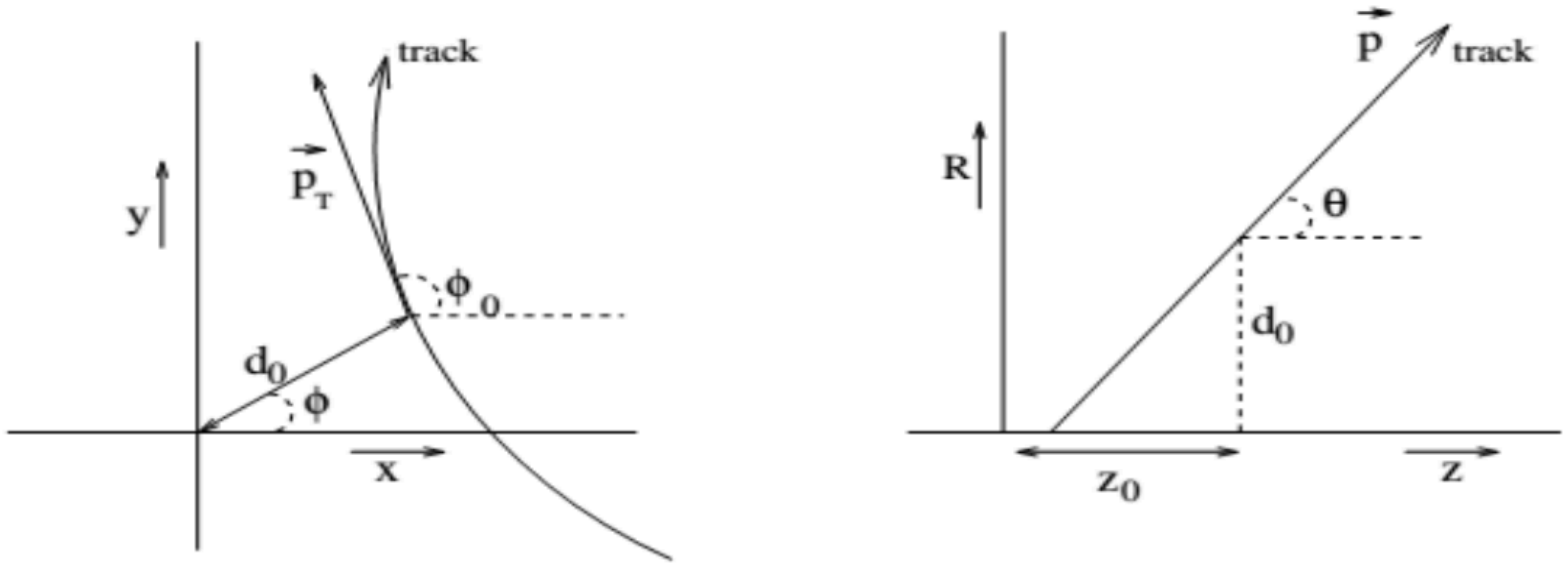
TRANSVERSE MOMENTUM

$$p_T = p \sin \theta$$



IMPACT PARAMETERS

Radial (d_0) and longitudinal (z_0)



HIGGSTRAHLUNG PROCESS: RECOIL MASS

The **total Higgs production cross section** is determined from counting $e^+e^- \rightarrow HZ$ tagged with the leptonic Z decay where $Z \rightarrow \mu^+\mu^-$, independently on the Higgs boson decay

SELECTION OF HIGGS EVENTS BY ONLY Z BOSON DECAY PRODUCTS

$$m^2_{\text{recoil}} = s - m_z - 2\sqrt{s}(E^+_\mu + E^-_\mu)$$

$$m_H = m_{\text{recoil}}$$

The error on the invariant mass will depend only on the errors of the muon track momenta and on the opening angle between the two muons.