Fast simulation of the 4th detector at CEPC with Delphes

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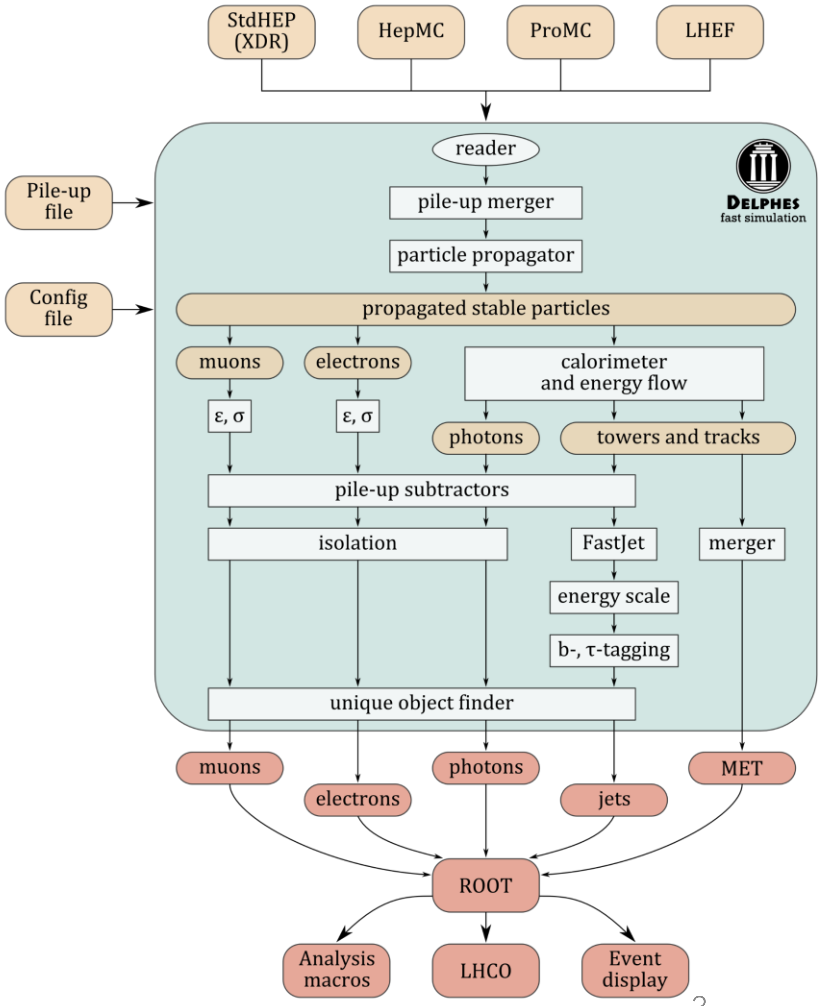
Outline

- Introduction
- Implementation and validations of the CEPC new detector with Delphes
  - Tracker
  - Particle Identification(PID)
  - Calorimeter
- Analysis examples for e^+e^-collision
- Summary

Introduction to Dephes

- Delphes is a modular framework that simulates the response of a multipurpose detector
- Simulations included:
  - Charged particle propagation in B field with full covariance
  - EM/Had showers and energy resolution
  - Ideal particle-flow
  - ……
- Physics objects provided:
  - Tracks, photons, neutral hadrons
  - Lepton/photon isolation
  - Jets, missing energy



Photon conversion and confusion among showers not included

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Simulation of the 4th detector at CEPC

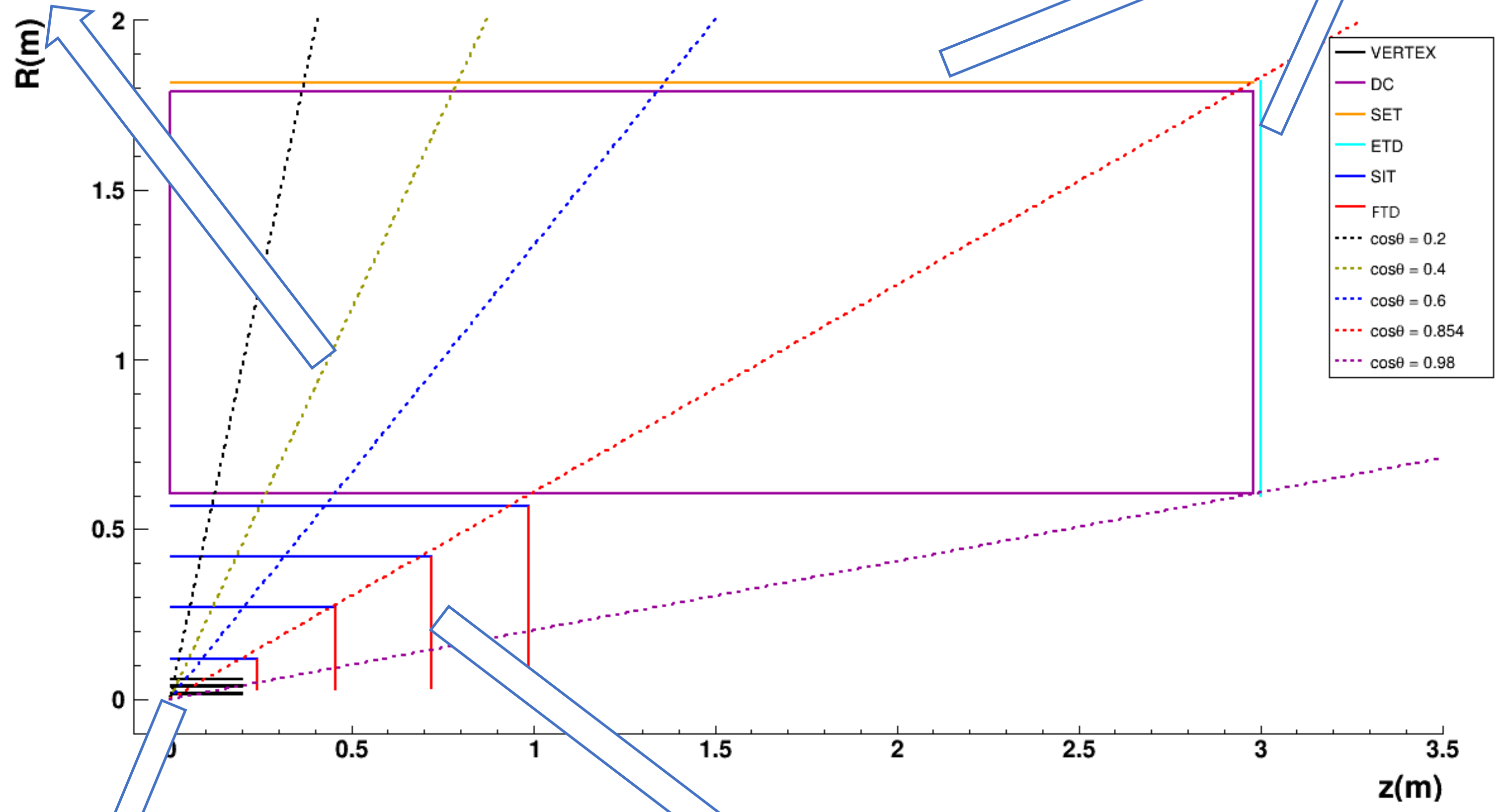
- Why simulate new CEPC detector using Delphes?
  - Fast: Delphes are two or three orders of magnitude faster than the fully GEANT based simulations
  - Good enough: detector response in Delphes is good enough for most phenomenological studies

- For physics study at the CEPC detector:
  - Implement the detector with a tcl card
  - Provide a dedicated PID module
  - Provide more flexibility between lepton/photon isolation and jet clustering
  - Provide a few analysis examples
  - ...

Tracker layout

ToF(LGAD) $(\sigma)_{tof} = 30ps$

Drift chamber (0.6-1.8m)



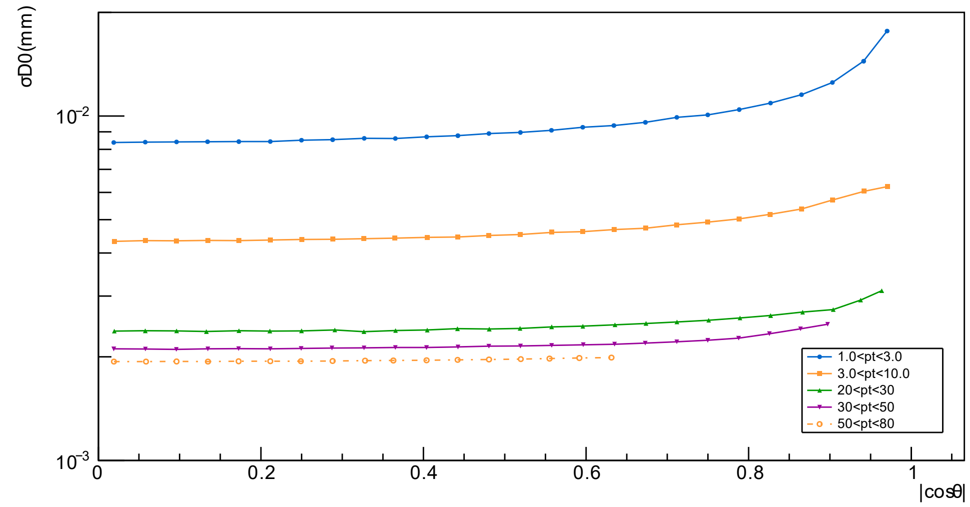
Silicon vertex

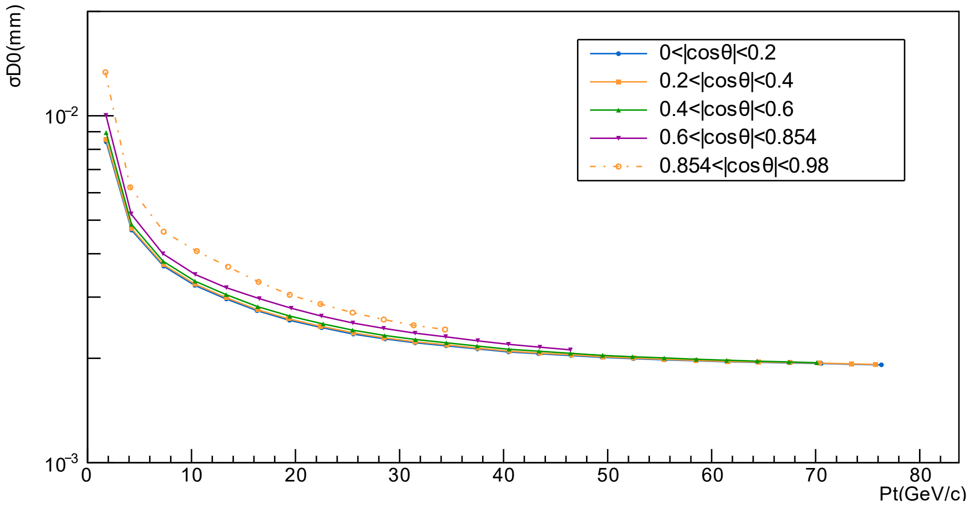
Silicon tracker

Effective coverage up to 98%

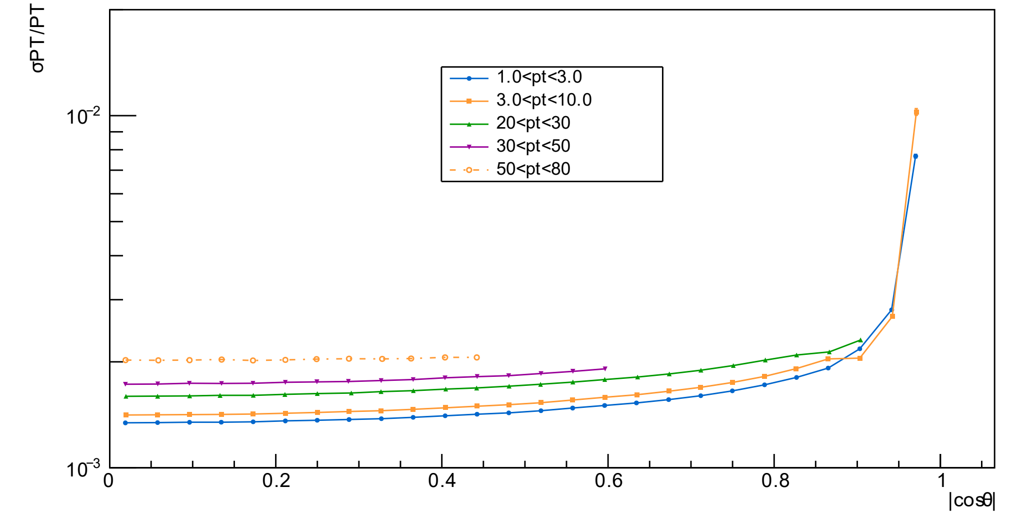
Resolution of tracker

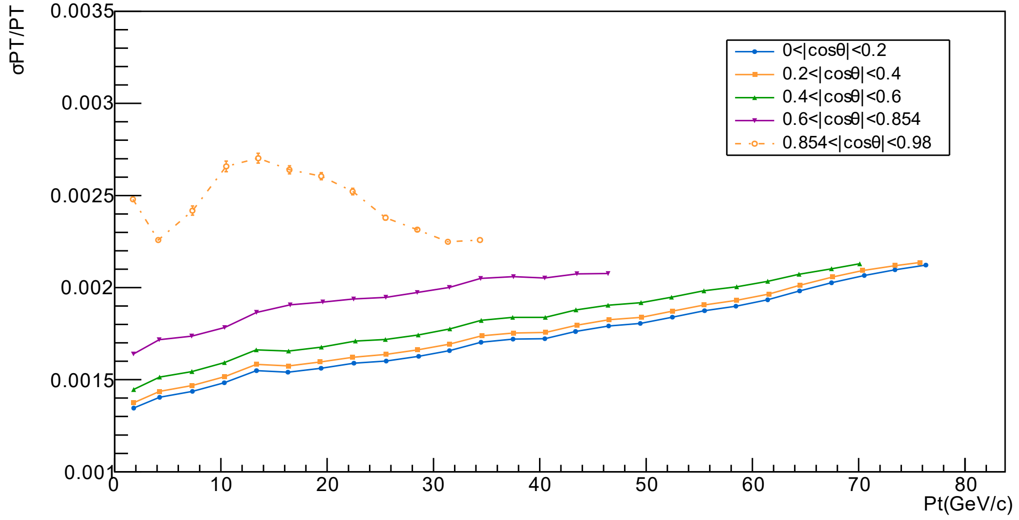
Impact parameter σ_{D0}





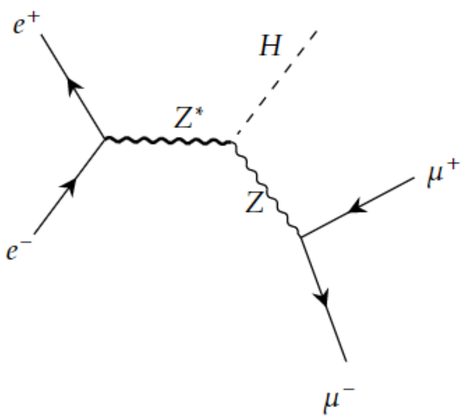
Momentum σ_{PT}/PT



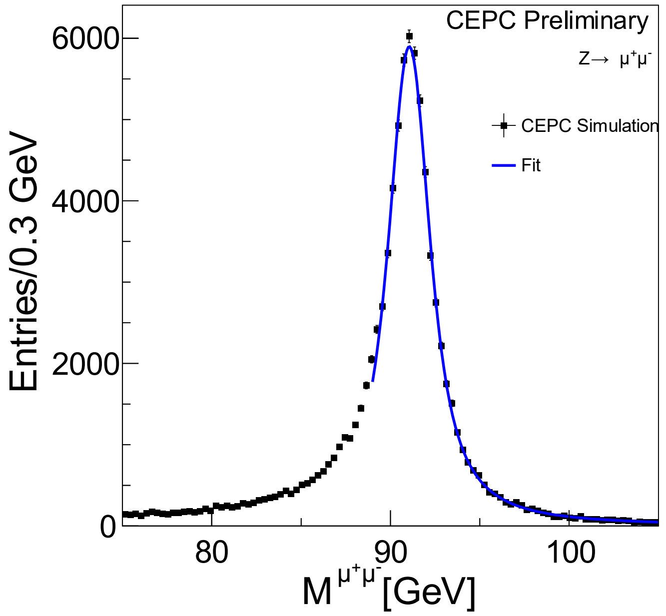


The results consistent with full simulation

Tracker performance

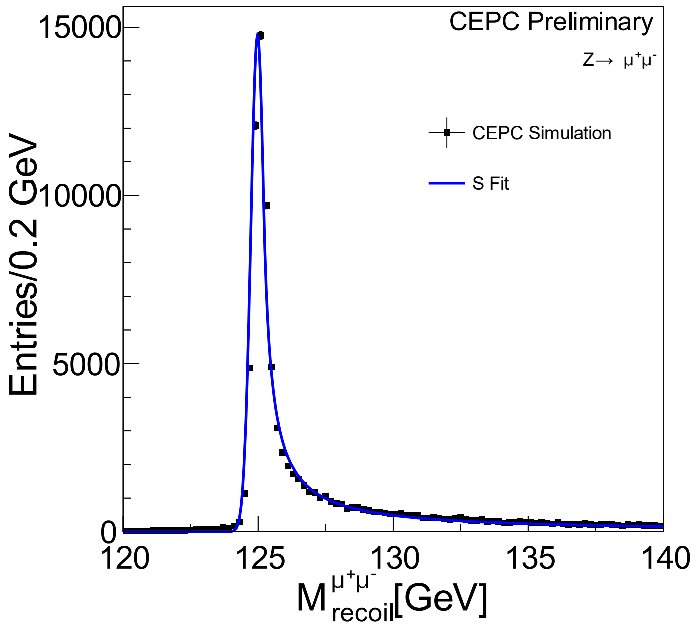
Test for  at 240GeV

Fit by a Breit Wigner function convoluted with a Gaussian function



we can choose the cut:

- a μ^+ and a μ^-
- Both momentums greater than 15 GeV
- Invariant mass consistent with 91 GeV



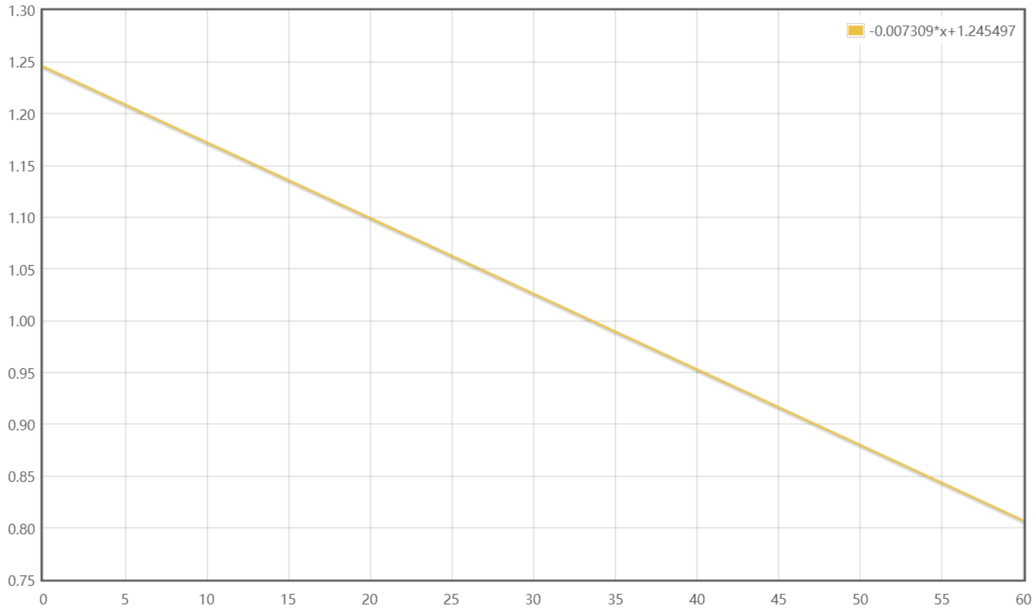
Total events =100 k， efficiency ≈94 %
Resolution of invariant mass : 0.45 GeV
Recoil mass: 125.24 GeV， resolution： 0.25 GeV
(no beam energy spread)

dN/dx

Consider effect of cluster counting efficiency as a function of dN/dx in xy plane

$$\varepsilon_{counting} = \frac{dN/dx_{meas}}{dN/dx_{real}}$$

Cluster counting efficiency curve is determined with 2% noise taken into account



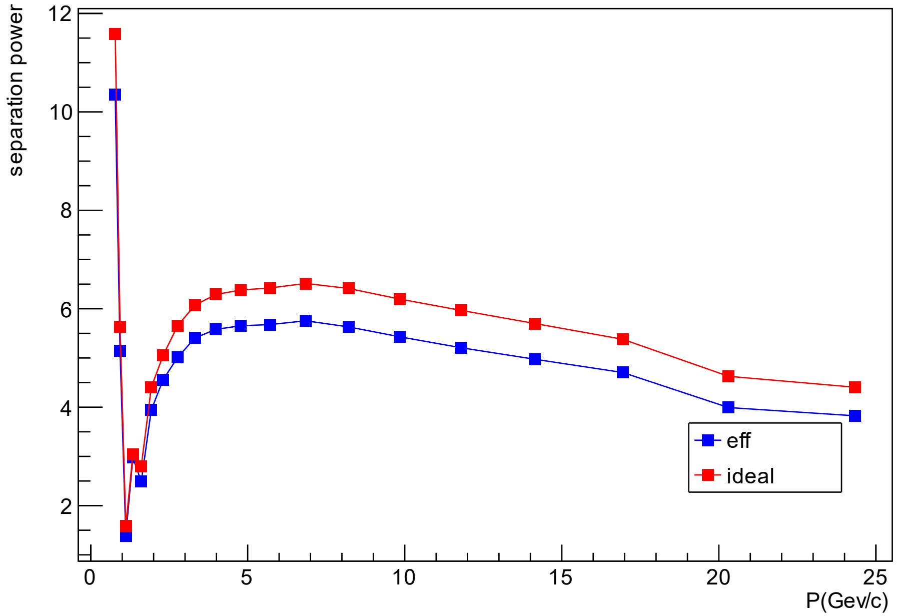
PID performance is obtained with Delphes by using above counting efficiency

Separation power

$$\frac{\left|\left(\frac{dN}{dx}\right)_{\pi} - \left(\frac{dN}{dx}\right)_{K}\right|}{(\sigma_{\pi} + \sigma_{K})/2}$$

Ideal vs considering cluster counting efficiency

k/pi separation powser $(|\cos\theta| < 0.854)$



Only considering π and K later

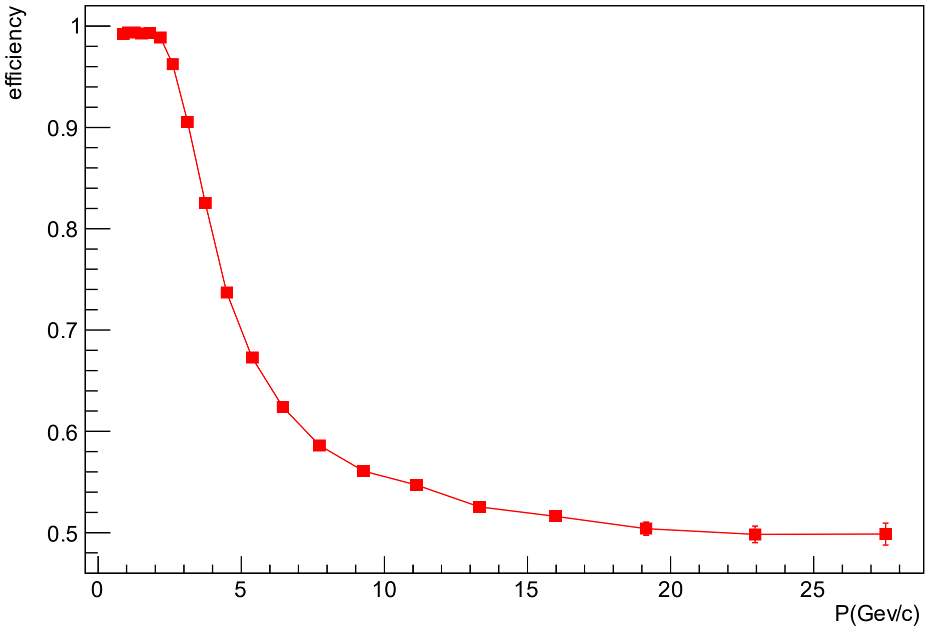
PID efficiency of kaon

$$\epsilon^K = \frac{n_{sel}^K}{n_{tot}^K}$$

- ϵ^K is Kaon PID efficiency
- n_{sel}^K is number that K is identified as K
- n_{tot}^K is number of K

ToF only

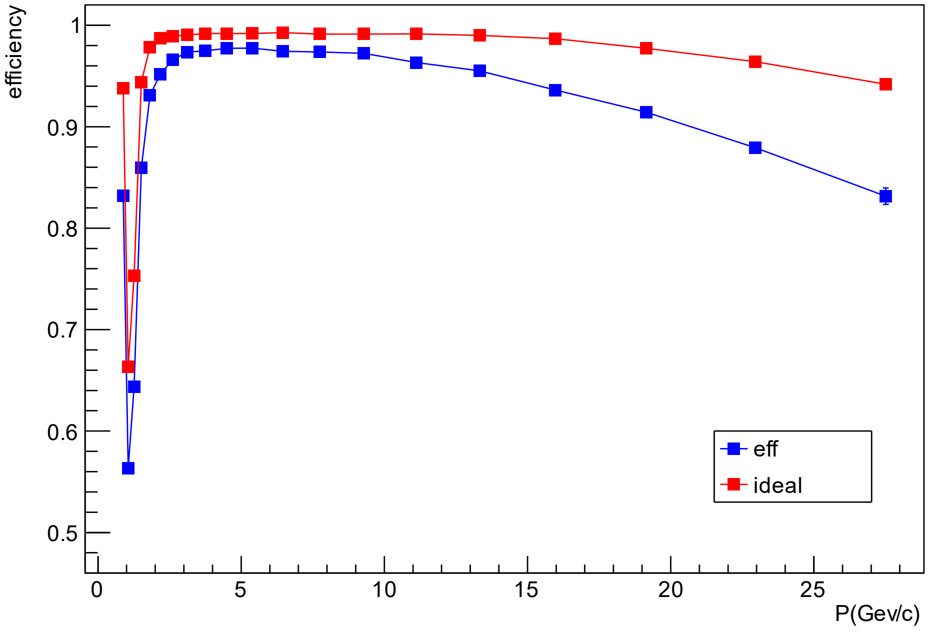
kaon PID efficiency ($|\cos\theta| < 0.854$)



dominant in the low momentum range

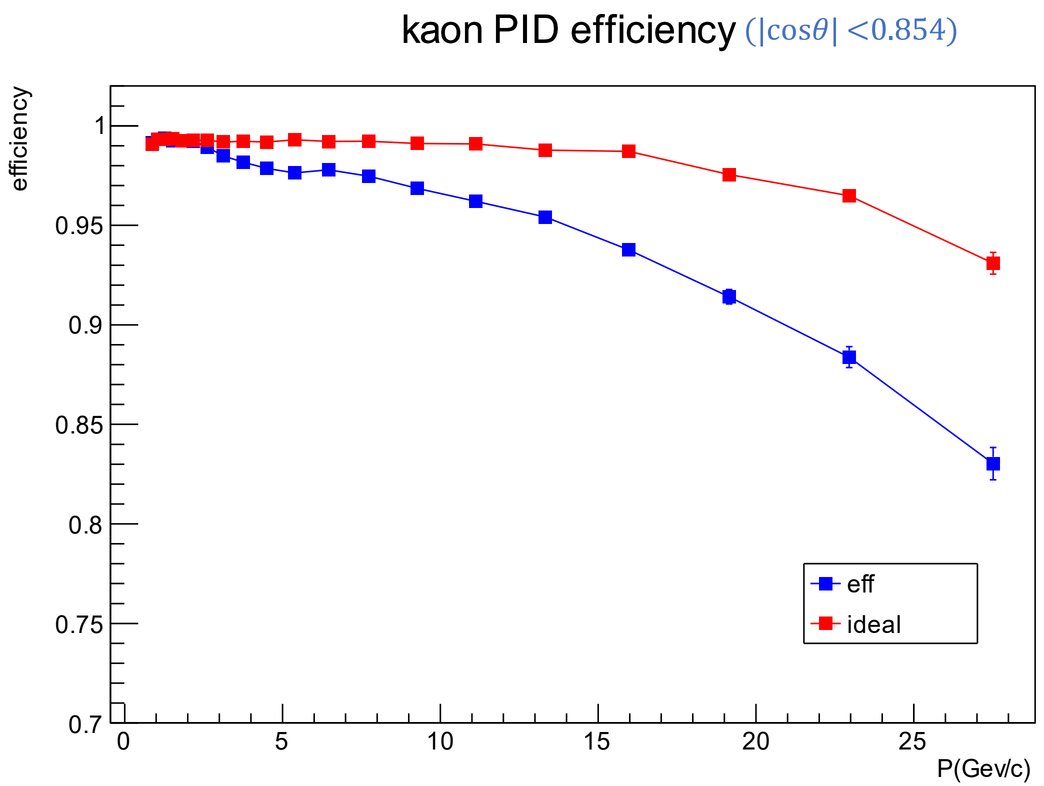
dN/dx only

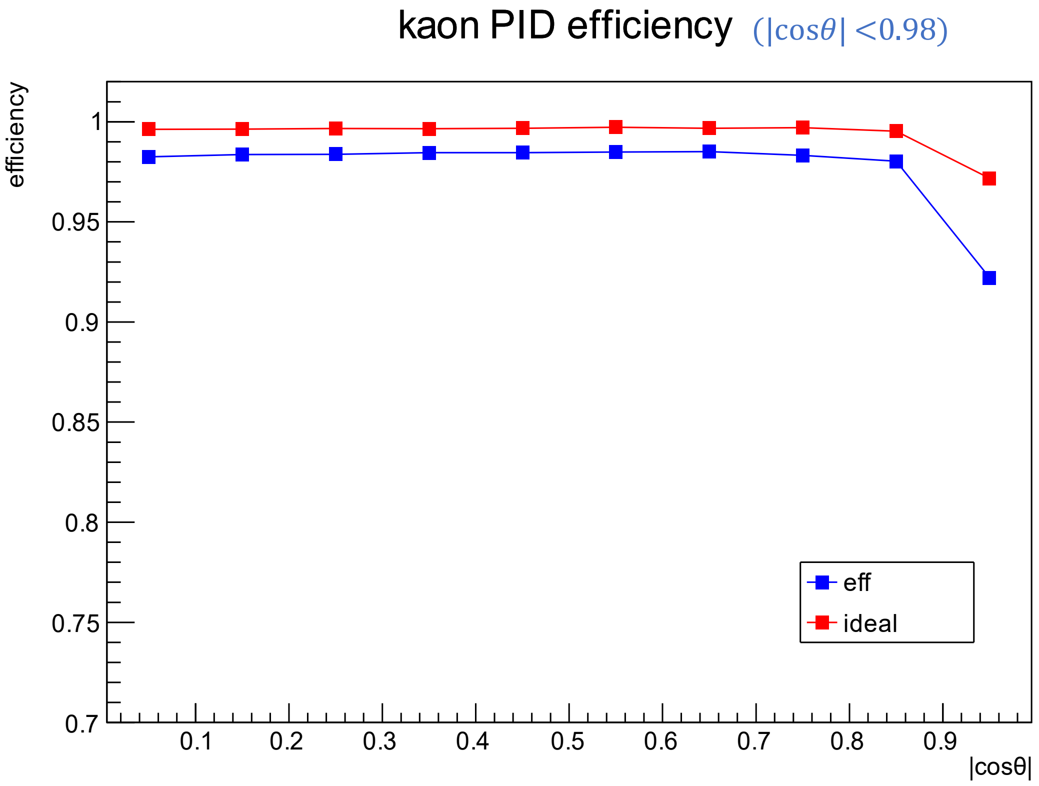
kaon PID efficiency ($|\cos\theta| < 0.854$)



dominant in the high momentum range

Combine dN/dx and ToF





Efficiency > 90% when pt less than 20 GeV

Efficiency > 96% when |cosθ| less than 0.9

Calorimeter

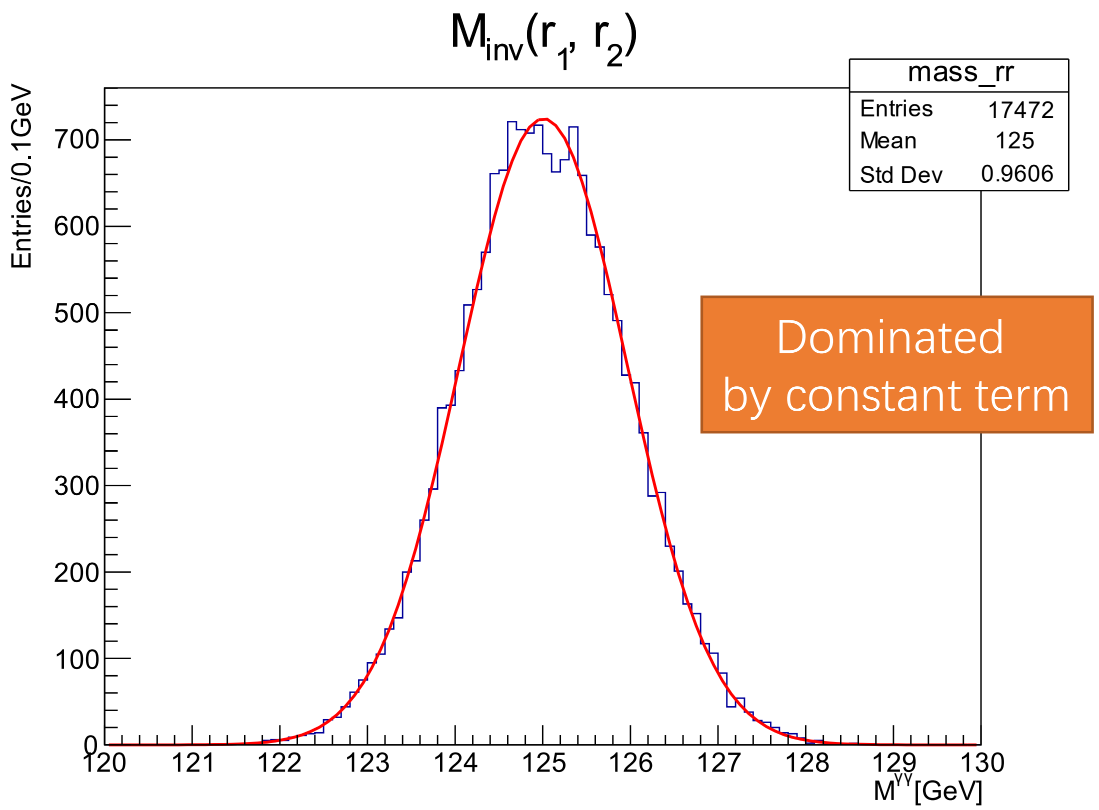
The resolution formula as a function of energy:

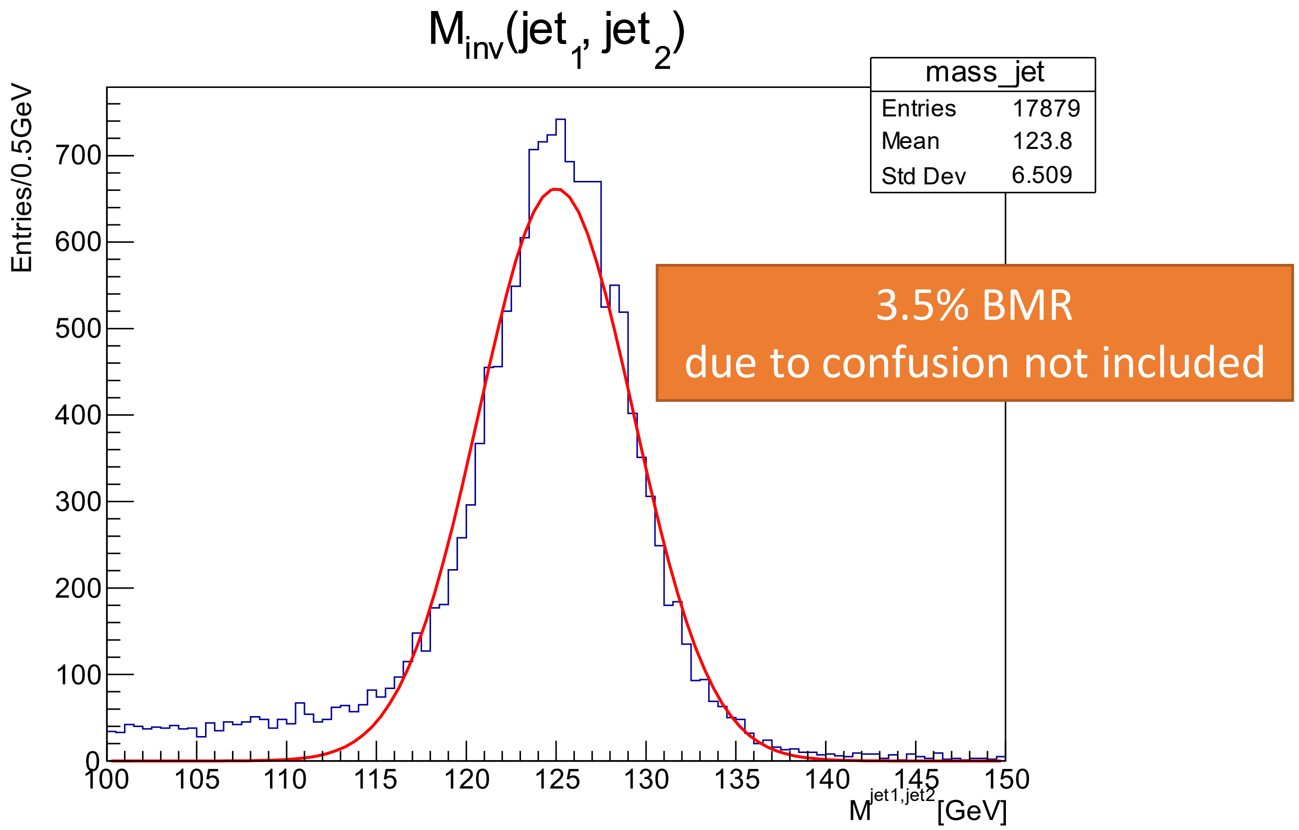
$$\frac{\sigma_E}{E} = \underbrace{\frac{a}{\sqrt{E}}}_{\text{stochastic term}} \oplus \underbrace{\frac{c}{E}}_{\text{noise term}} \oplus \underbrace{\mathrm{b}}_{\text{constant term}}$$

- For ECAL, a_E=0.03, b_E=0.01
- For HCAL, a_H=0.4,b_H=0.02
- Noise term neglected temperately

Consider H→γγ ,H→gg→2 jets, check the invariant mass spectrum

Resolutions of photon and Jet





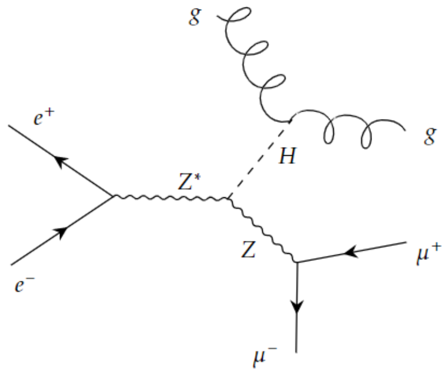
Mean = 125.01±0.01 GeV ,
Resolution = 0.96 ±0.01 GeV

Mean = 125.00±0.04 GeV ,
Resolution = 4.31 ±0.04 GeV

Exclusive analysis examples for e^+e^- collision

- Lepton/photon pair selection should go first before jet-clustering
- Lepton/photon pair selection is realized by modifying algorithms in Delphes
- Different and very important features compared with analyses at pp collision

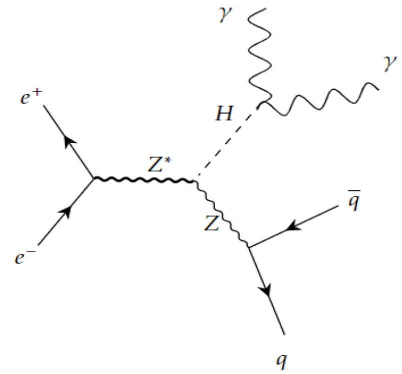
Examples:



Select muon-pair from Z:

- $\mu^+\mu^-$
- momentum greater than 15 GeV
- Invariant mass consistent with Z mass

Jet-clustering



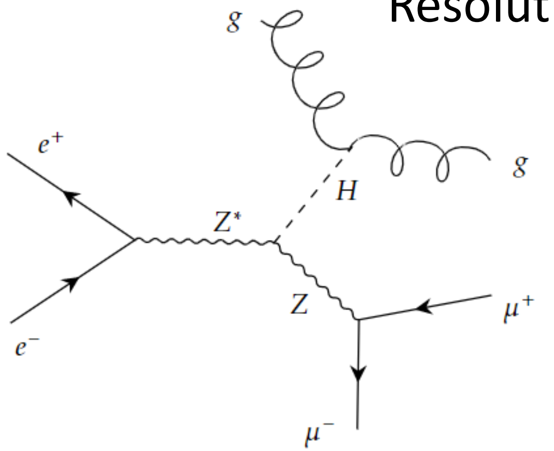
Similarly,
Select photon-pair from H:

- $\gamma\gamma$
- Energy greater than 35 GeV
- Invariant mass consistent with H mass

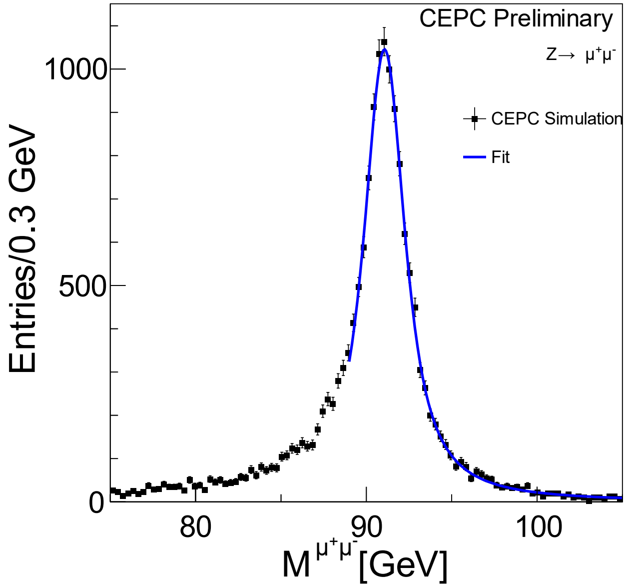
$e^+e^- \rightarrow Z(\mu^+\mu^-)H(\text{di-jets})$

```
################
# Muon filter
################

module PdgCodeFilter MuonFilter {
  set InputArray EFlowMerger/eflow
  set OutputArray1 WoMuonPair
  set OutputArray2 MuonPair
  add EnMin    {15.0}
  add MassRes {91.18}
  add NP       {2}

  add PdgCode {13}
  add PdgCode {-13}
}
###########
# Jet finder
###########

module FastJetFinder FastJetFinder {
  set InputArray MuonFilter/WoMuonPair
  set OutputArray jets
  set ExclusiveClustering true

  # algorithm: 1 CD          dPoint, 3 S
  set JetAlgorithm 10
  set ParameterR    1.5
  set ParameterP    1.0
  set JetPTMin      0.0
}
```

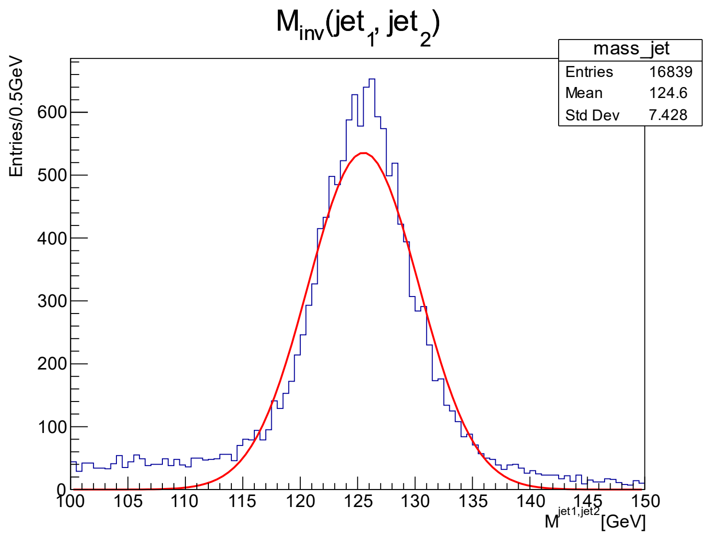
ee-kt



Resolution = 0.45 GeV



Resolution = 4.82 GeV

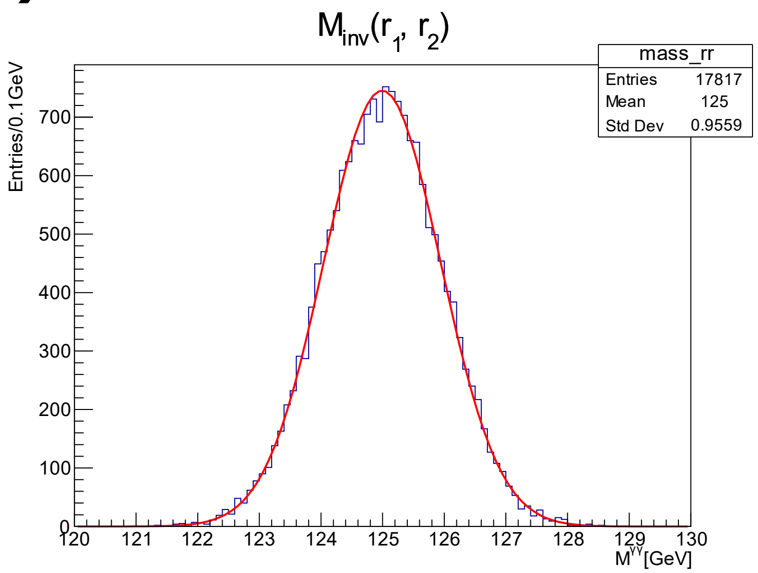


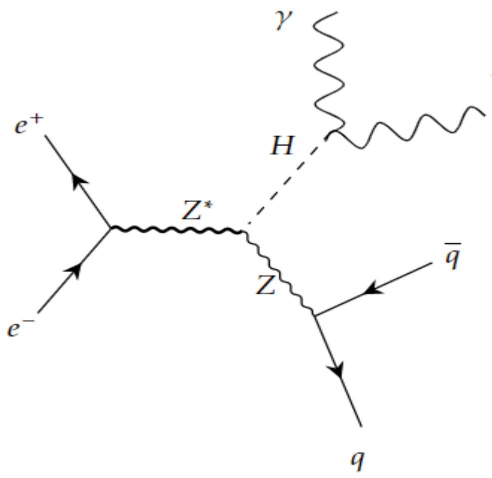
$e^+e^- \rightarrow$ Z(di-jets)H($\gamma\gamma$)

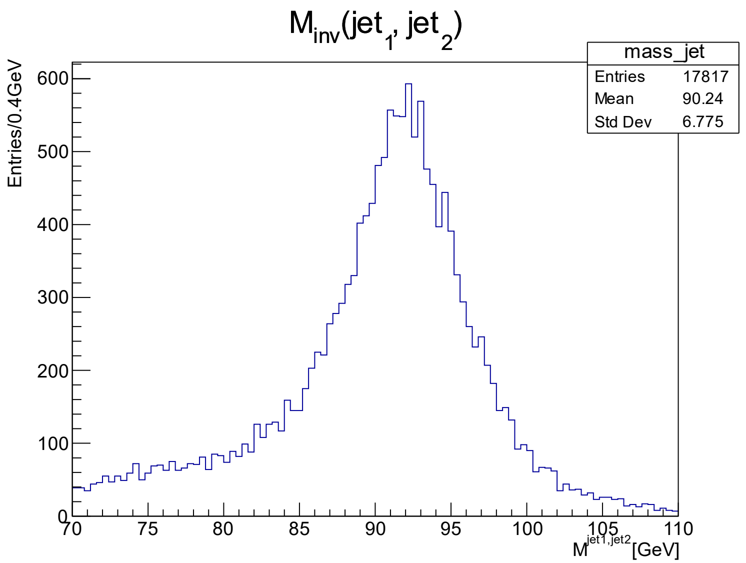
```
################
# Photon filter
################

module PdgCodeFilter PhotonFilter {
  set InputArray EFlowMerger/eflow
  set OutputArray1 WoPhotonpair
  set OutputArray2 Photonpair

  add EnMin    {35.0}
  add MassRes {125.25}
  add NP       {2}

  add PdgCode {22}
}


###########
# Jet finder
###########

module FastJetFinder FastJetFinder {
  set InputArray PhotonFilter/WoPhotonpair
  set OutputArray jets
  set ExclusiveClustering true

  # algorithm: 1 C          dPoint, 3 S
  set JetAlgorithm 10
  set ParameterR    1.5
  set ParameterP    1.0
  set JetPTMin      0.0
}
```

ee-kt

Mean = 125.00 GeV ,
Resolution = 0.95 GeV







Summary

- Simulation of CEPC the 4th detector with Delphes is ready to use
  - The detector layout is implemented and validated
  - Some necessary modifications of Delphes code were done for ee collision
  - PID : probabilities of different hypotheses of tracks provided for analyzers
  - Guarantee there is no overlap between lepton/photon isolation and jet clustering with ee-kt
  - Github repository: https://github.com/oiunun/Delphes_CEPC.git
- Still many works need to do
  - More validations
  - Angular resolutions of photons and tracks
  - Updates according to detector optimization.
  - More realistic simulation of dN/dx and cluster counting efficiency curve will be improved
  - …
- Welcome to use it and feedback!

Thanks!

Backup

Tracker layout

Detector	Layer	Radius(mm)	Halfz(m)	Material budget[x/X0]
VXD	1	16	0.2	0.0015
	2	18	0.2	0.0015
	3	38	0.2	0.0015
	4	40	0.2	0.0015
	5	58	0.2	0.0015
	6	60	0.2	0.0015
Shell	1	65	0.2	0.0015
SIT	1	120	0.241	0.0065
	2	270	0.455	0.0065
	3	420	0.721	0.0065
	4	570	0.988	0.0065
Inner wall	1	600	2.98	0.00104
DC	80	600-1800	2.98	0.002
Outer wall	1	1800	2.98	0.01346
SET	1	1815	2.98	0.0065

Tracker layout

Detector	Rin(mm)	Rout(mm)	Z(m)	Material budget[x/X0]
DSK1A	29.5	120	0.241	0.0065
DSK1B	29.5	120	-0.241	0.0065
DSK2A	30.5	270	0.455	0.0065
DSK2B	30.5	270	-0.455	0.0065
DSK3A	32.5	420	0.721	0.0065
DSK3B	32.5	420	-0.721	0.0065
DSK4A	34	570	0.988	0.0065
DSK4B	34	570	-0.988	0.0065
ETD1	600	1822	3.0	0.0065
ETD2	600	1822	-3.0	0.0065

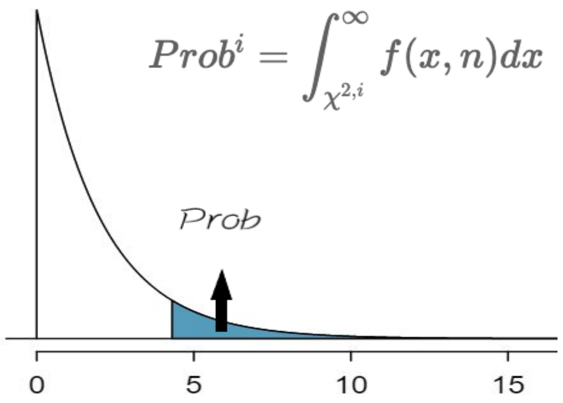
The calculation of the probability

Define chi-square:

$(\chi^i)^2 = (\chi_1^i)^2 + (\chi_2^i)$ (It follows a Chi-square distribution of 2 degrees of freedom)

$$\chi_1^i = \frac{(dN/dx)_{meas} - (dN/dx)_{exp}^i}{(\sigma)_{dN/dx}^i} \qquad \chi_2^i = \frac{(tof)_{meas} - (tof)_{exp}^i}{(\sigma)_{tof}^i}$$

- Calculate 3 chi-squares for different assumptions
- Integrate for the probabilities (integral)



- Compare the probabilities

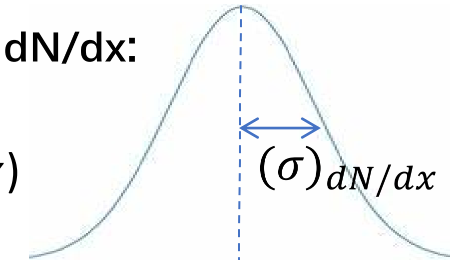
The most likely assumption is taken

The calculation of χ

- **dN/dx** $\quad \chi_1^i = \dfrac{(dN/dx)_{meas} - (dN/dx)_{exp}^i}{(\sigma)_{dN/dx}^i}$

  - ◆ dN/dx and $(\sigma)_{dN/dx}$ are functions of $\beta\gamma$
    - ◆ $dN/dx_{exp} = f(\beta\gamma) * \varepsilon_{counting}$ (f is the theoretical function that only depends on $\beta\gamma$)
    - ◆ $(\sigma)_{dN/dx} = \varepsilon_{counting} * \sqrt{f(\beta\gamma)}$
  - ◆ In the formula:
    - ◆ $(dN/dx)_{exp}$ and $(\sigma)_{dN/dx}$ are calculated with $\beta\gamma$'s for 5 particle hypotheses
    - ◆ $(dN/dx)_{meas}$ follows a Poisson distribution with mean and sigma calculated with the truth $\beta\gamma$

dN/dx:



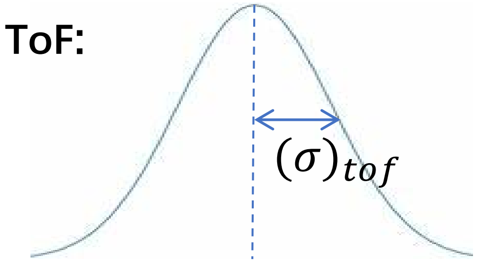
mean

mean $= (dN/dx)_{exp}$

- **ToF** $\quad \chi_2^i = \dfrac{(tof)_{meas} - (tof)_{exp}^i}{(\sigma)_{tof}^i}$

  - ◆ $(tof)_{exp} = \dfrac{L}{v} = \dfrac{L}{\beta c} \qquad \beta = \dfrac{p}{\sqrt{p^2 + (m^i)^2}}$
  - ◆ $(tof)_{meas}$: follows a Gaussian distribution with mean = $(tof)_{exp}$ and $(\sigma)_{tof}$
  - ◆ $(\sigma)_{tof} = 30ps$

ToF:



mean

mean $= (tof)_{exp}$