



# Overview of the CLIC detector including reconstruction/performance

Emilia Leogrande (CERN), on behalf of the CLICdp Collaboration



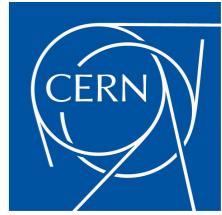
# Content of the talk



- Overview of the CLICdet
  - Optimization of the vertex detector
  - Optimization of the tracker
  - Optimization of the calorimeters F. Simon's talk
- Software tools for simulation/reconstruction
- Detector performances for lower level physics observables
- Impact/mitigation of 3 TeV beam-induced backgrounds
- Conclusions and future improvements



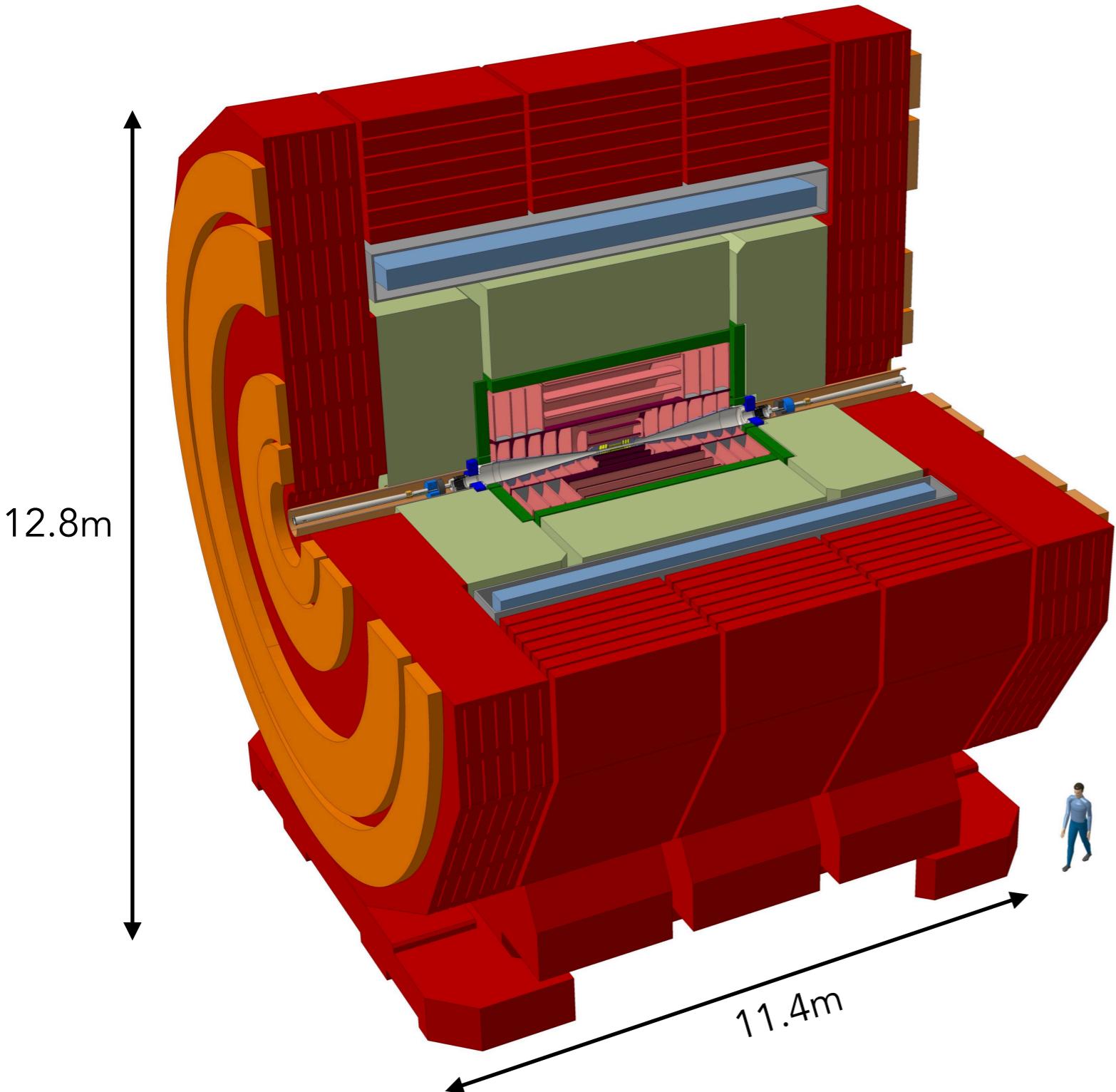
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# The CLICdet

optimized for the 3 TeV



- Tracking system
  - Vertex
  - Tracker

- Calorimeters
  - ECal
  - HCal

- Superconducting solenoid 4T

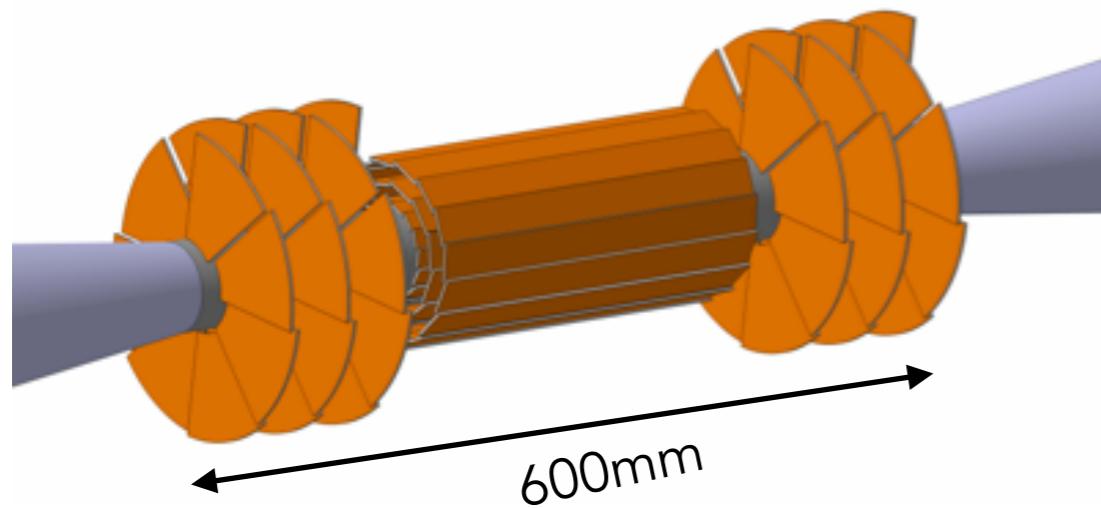
- Forward calorimeters

- Return yoke + muon ID system

- End coils

# Vertex detector

- beam pipe radius = 29mm => inner barrel radius = 31mm



## Dimensions

- Total sensitive area = 0.84 m<sup>2</sup>
- 25x25  $\mu\text{m}^2$  pixel size
- 50  $\mu\text{m}$  sensor thickness

## Layout

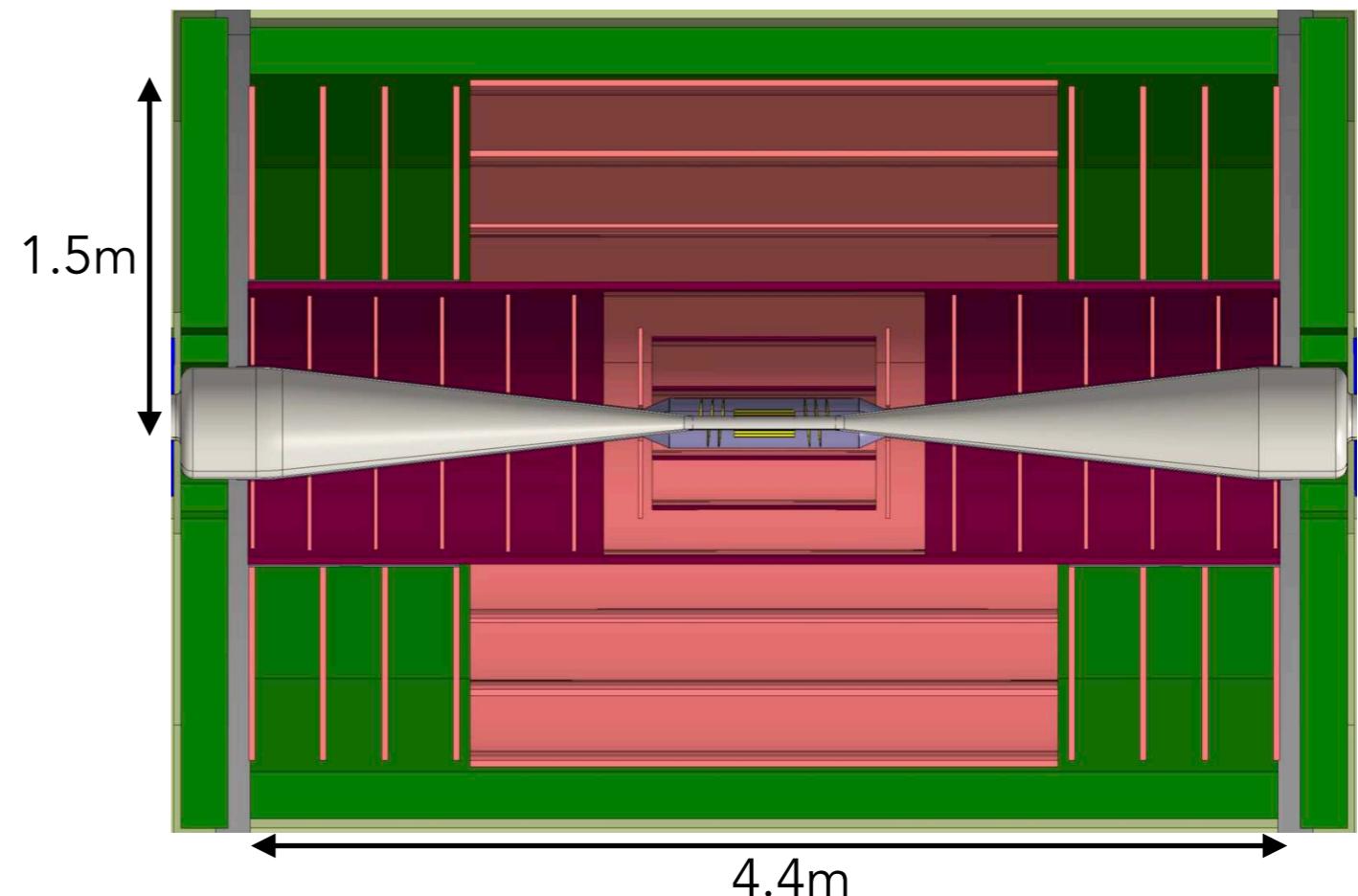
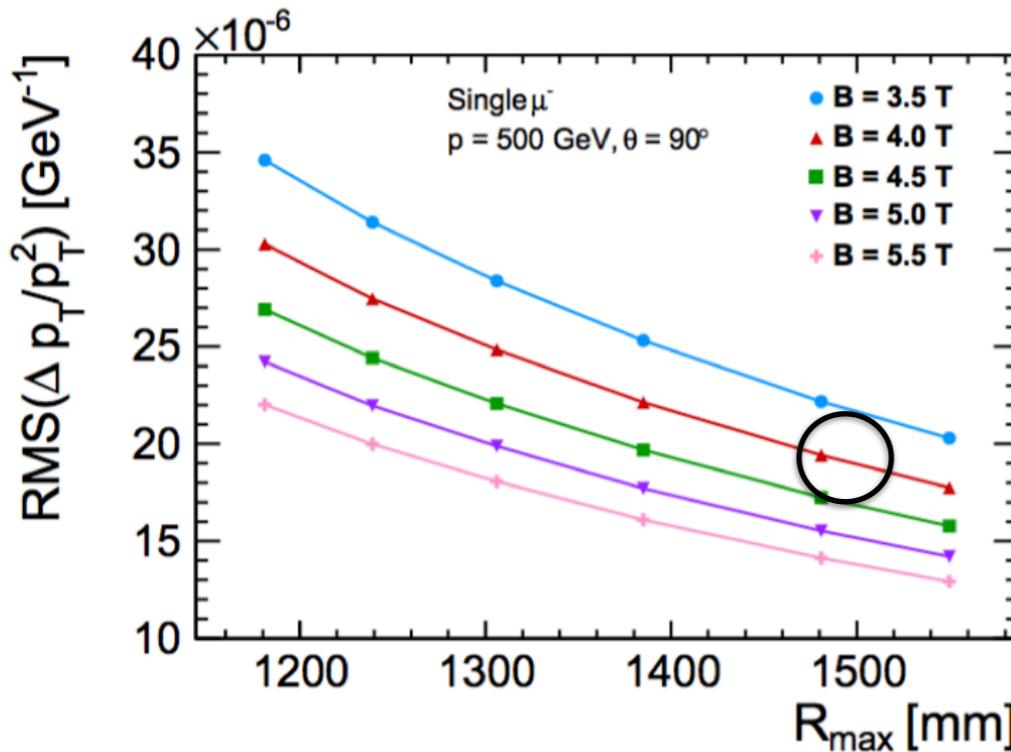
- 3 **double** layers in the barrel
  - minimize support material
- 3 **double layer spiral** forward disks
  - cooling via air-flow

## Resolutions in the simulation

- spatial resolution = 3  $\mu\text{m}$ 
  - cell size + charge interpolation
- timing resolution  $\sim 5$  ns

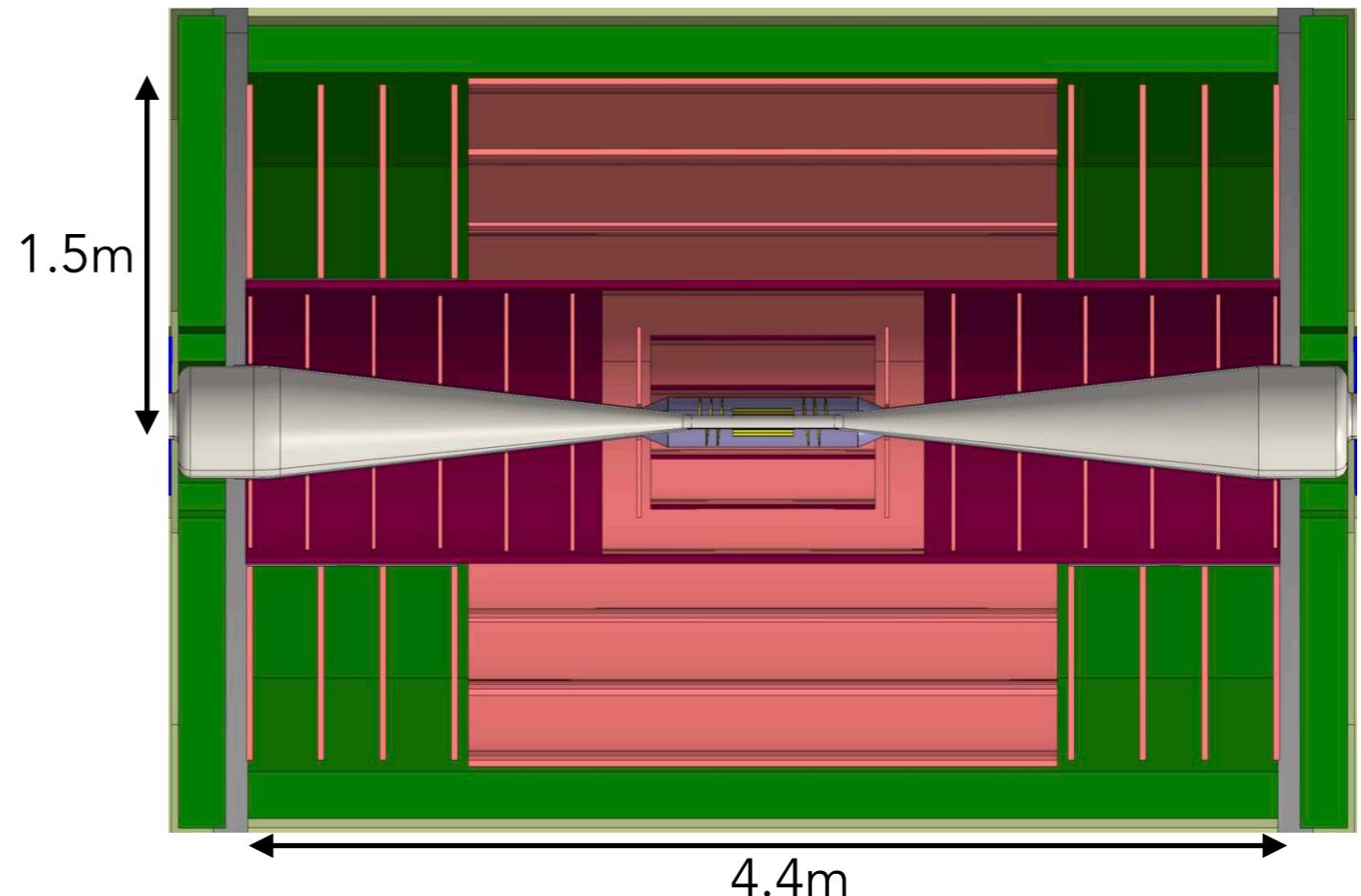
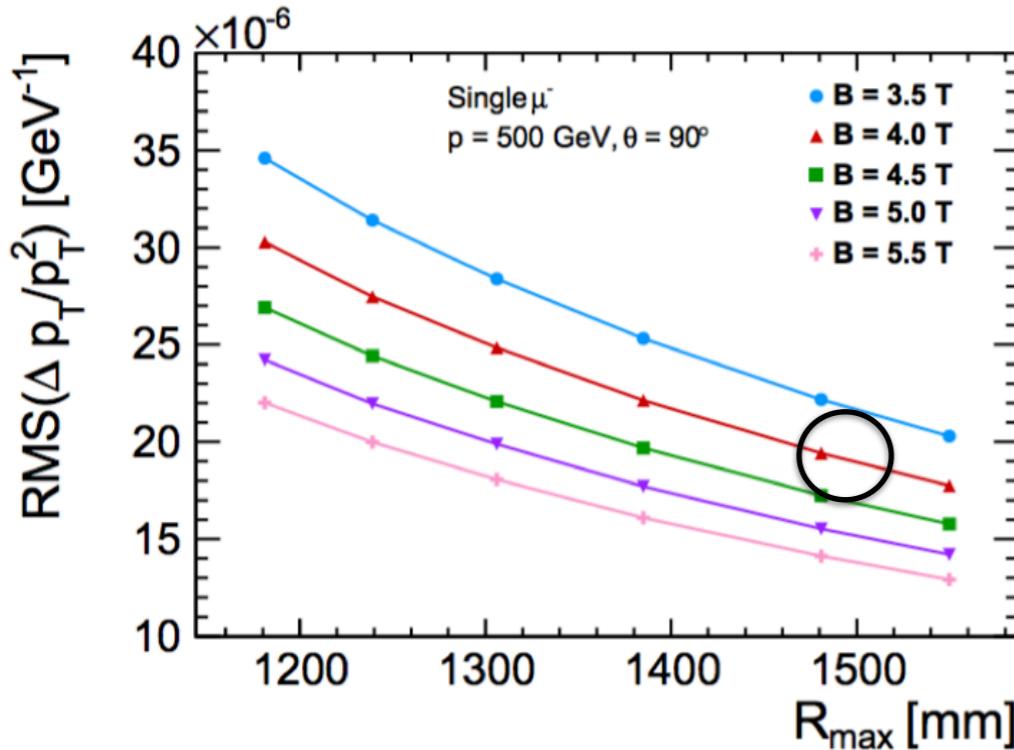
# Tracker detector (I)

- $p_T$ -resolution goal  $2 \times 10^{-5} \text{ GeV}^{-1}$
- Trade-off between achievable coil radius and B field => outer tracker radius = 1.5 m



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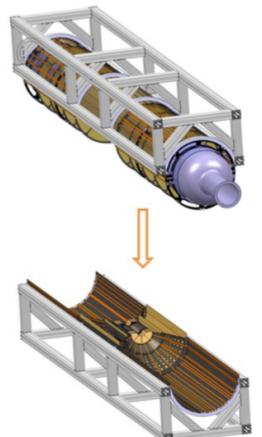
- $p_T$ -resolution goal  $2 \times 10^{-5} \text{ GeV}^{-1}$
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## Layout

- inner tracker
  - 3 barrel layers + 7 forward disks per side
- outer tracker
  - 3 barrel layers + 4 forward disks per side

- carbon fibre support tube
  - mechanical integration, stability



# Tracker detector (II)

## Dimensions

- Total sensitive area =  $137\text{m}^2$
- cells sizes:

subdetector	layout sizes*
Inner Tracker Disk 1	$25 \times 25 \mu\text{m}^2$
Inner Tracker Disks 2–7	$50 \mu\text{m} \times 1 \text{ mm}$
Outer Tracker Disks	$50 \mu\text{m} \times 10 \text{ mm}$
Inner Tracker Barrel 1–2	$50 \mu\text{m} \times 1 \text{ mm}$
Inner Tracker Barrel 3	$50 \mu\text{m} \times 5 \text{ mm}$
Outer Tracker Barrel 1–3	$50 \mu\text{m} \times 10 \text{ mm}$

\* disks:  $R\Phi \times R$  barrel:  $R\Phi \times z$

- $200 \mu\text{m}$  sensor thickness

More details in D. Dannheim's talk

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driven by **occupancy** studies <https://cds.cern.ch/record/2261066>

- 3% readout occupancy goal over the full bunch train

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More details in D. Dannheim's talk

<https://cds.cern.ch/record/2062208>

motivated by track reconstruction needs

- avoid confusion in pattern recognition

driven by occupancy studies <https://cds.cern.ch/record/2261066>

- 3% readout occupancy goal over the full bunch train

# Tracker detector (III)

## Resolutions in the simulation

subdetector	layout sizes	resolution ( $\sigma$ ) [ $\mu\text{m}$ ]	• spatial resolutions: from cell size + charge sharing
Inner Tracker Disk 1	$25 \times 25 \mu\text{m}^2$	$5 \times 5$	
Inner Tracker Disks 2–7	$50 \mu\text{m} \times 1 \text{ mm}$	$7 \times 90$	
Outer Tracker Disks	$50 \mu\text{m} \times 10 \text{ mm}$	$7 \times 90$	
Inner Tracker Barrel 1–2	$50 \mu\text{m} \times 1 \text{ mm}$	$7 \times 90$	
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• timing resolution $\sim 5\text{ns}$			

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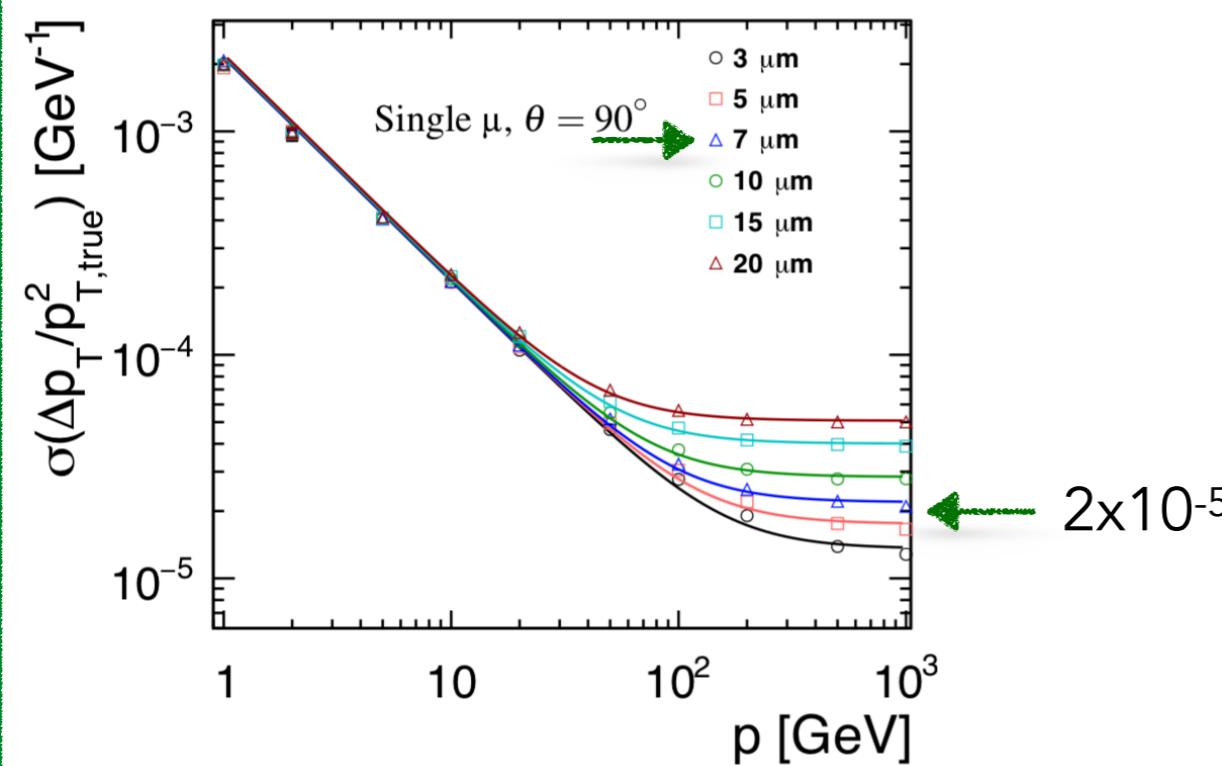
- spatial resolutions:

from cell size +  
charge sharing

resolution ( $\sigma$ ) [ $\mu\text{m}$ ]

5×5  
7×90  
7×90  
7×90  
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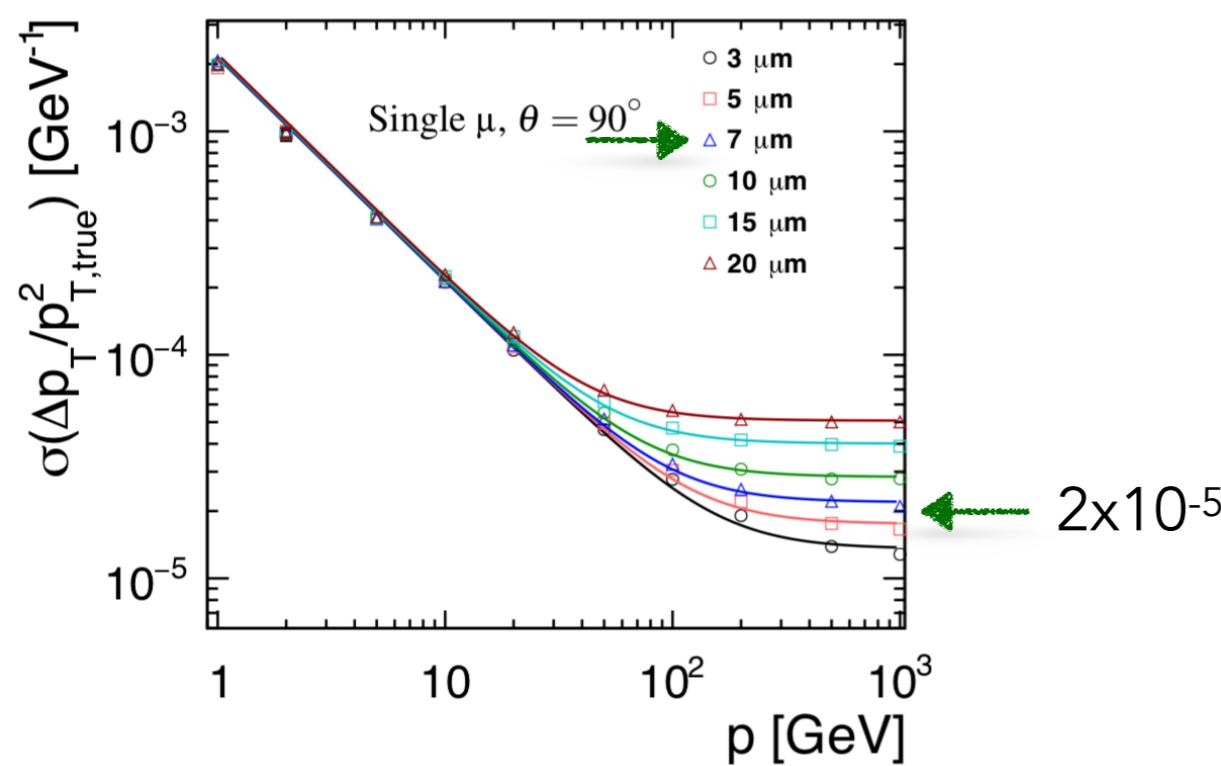
resolution ( $\sigma$ ) [ $\mu\text{m}$ ]

from cell size +  
charge sharing

$5 \times 5$

$7 \times 90$   
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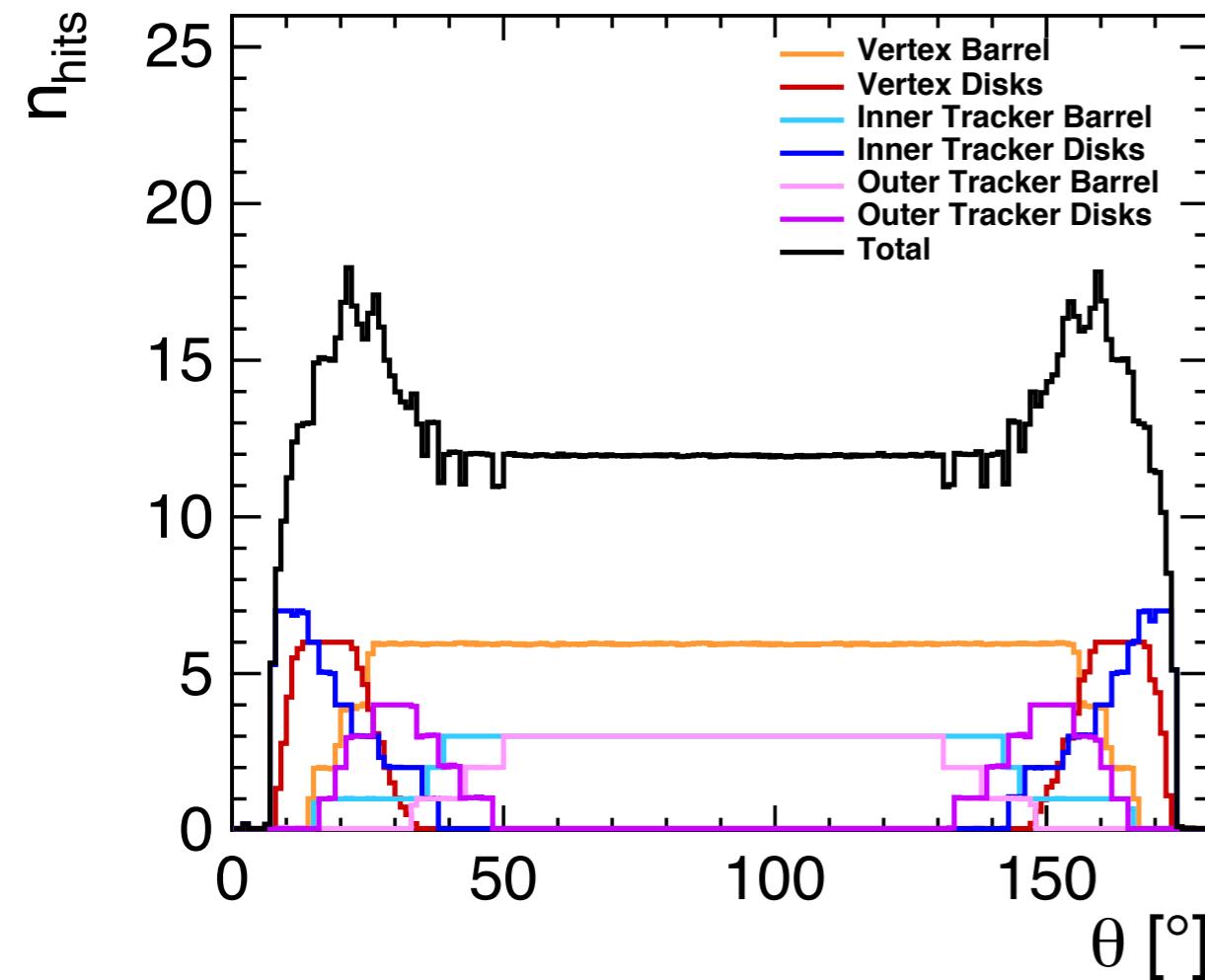
- timing resolution  $\sim 5\text{ns}$



- proven to be sufficiently small for desired  $z_0$  resolution
- not proven to be necessary => optimization foreseen (reduce readout channels)



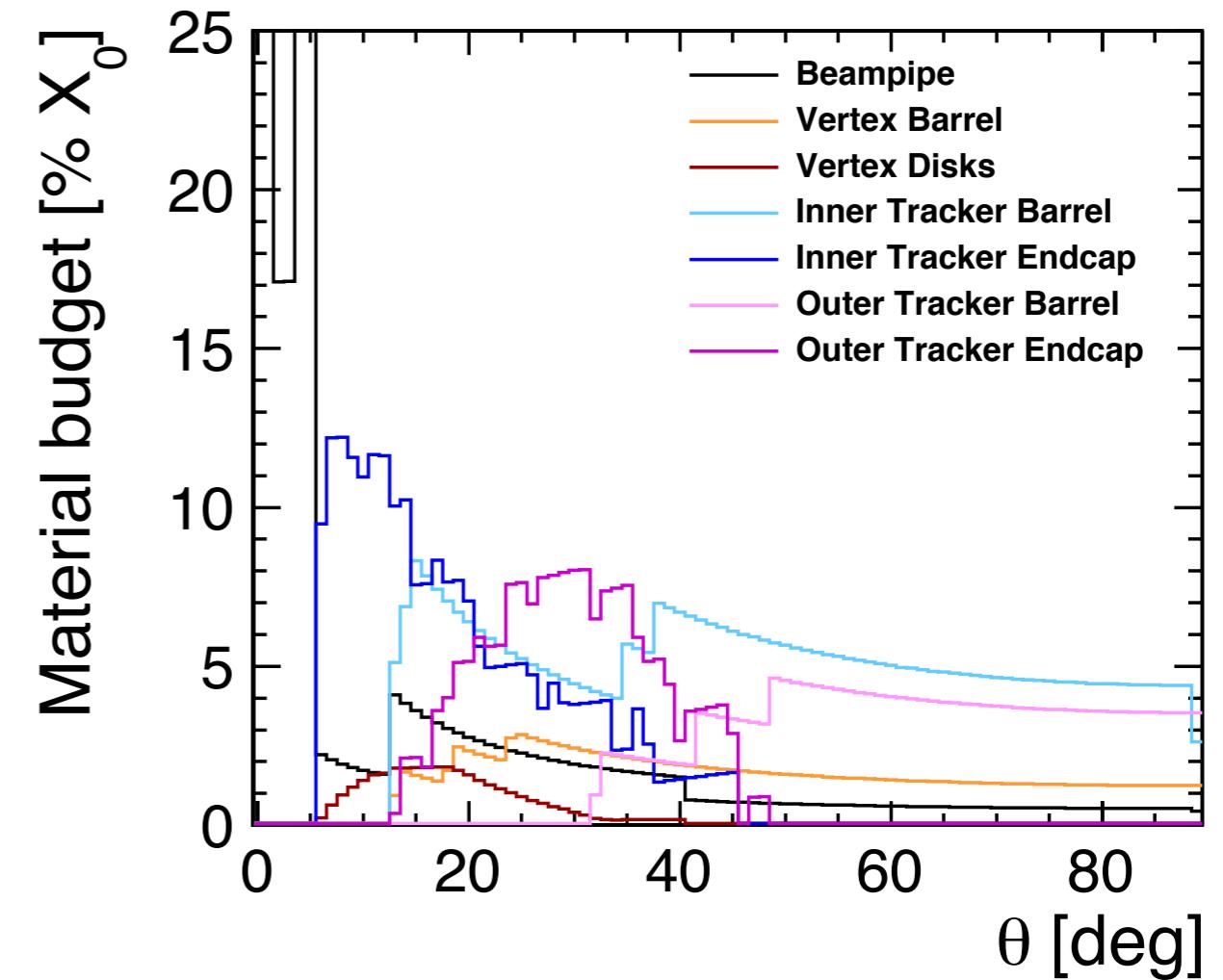
# Tracking system (vertex + tracker) coverage and material budget



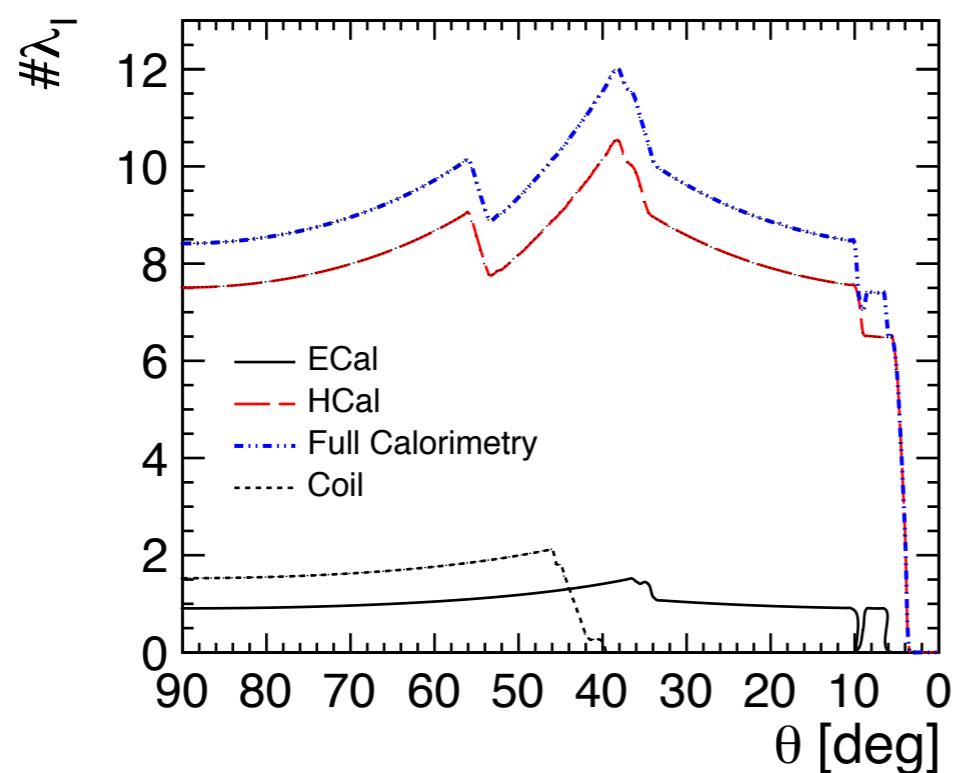
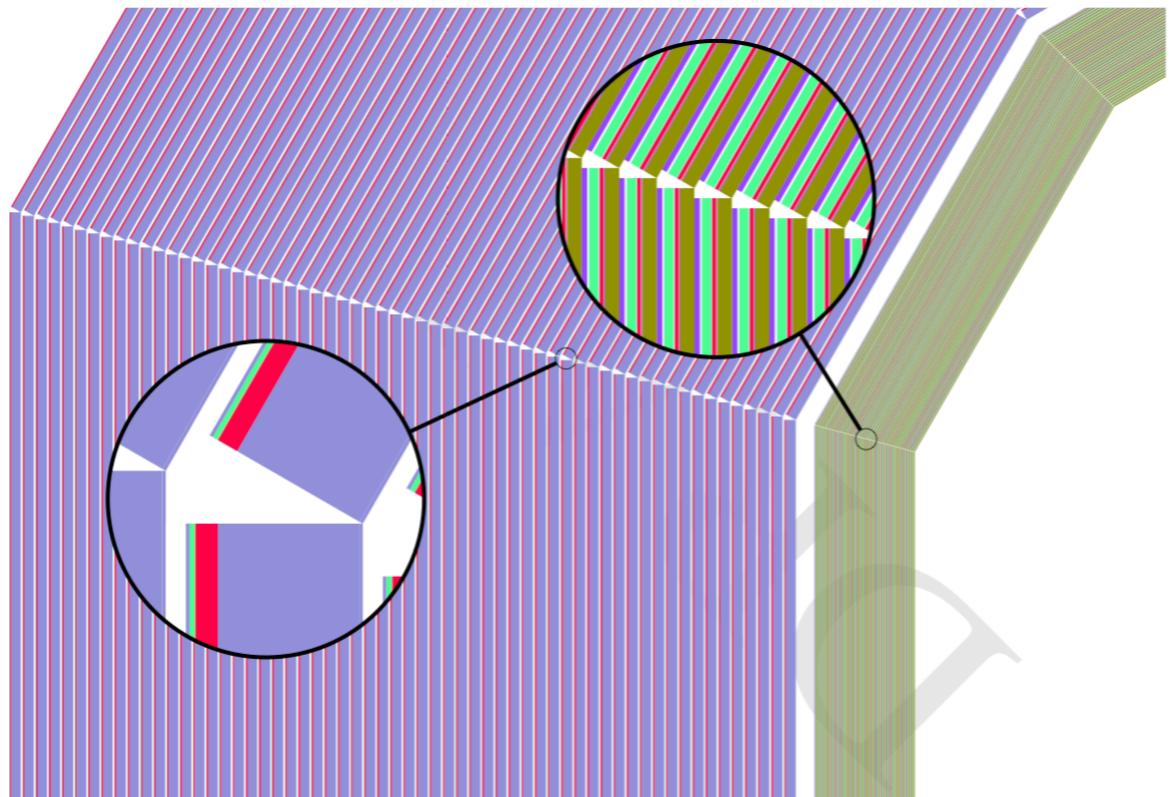
Tracking system optimized to have full coverage for tracking reconstruction

## Material budget

- vertex =  $0.2\%X_0$  per single layer
- tracker =  $1\%X_0$  per layer
- main support tube + cables =  $2.5\%X_0$



# ECal and HCal



## ECal

- Si-W sampling calorimeter
- cell size  $5 \times 5 \text{ mm}^2$
- 40 layers (1.9 mm thick W plates)
- $22X_0, 1\lambda_l$

## HCal

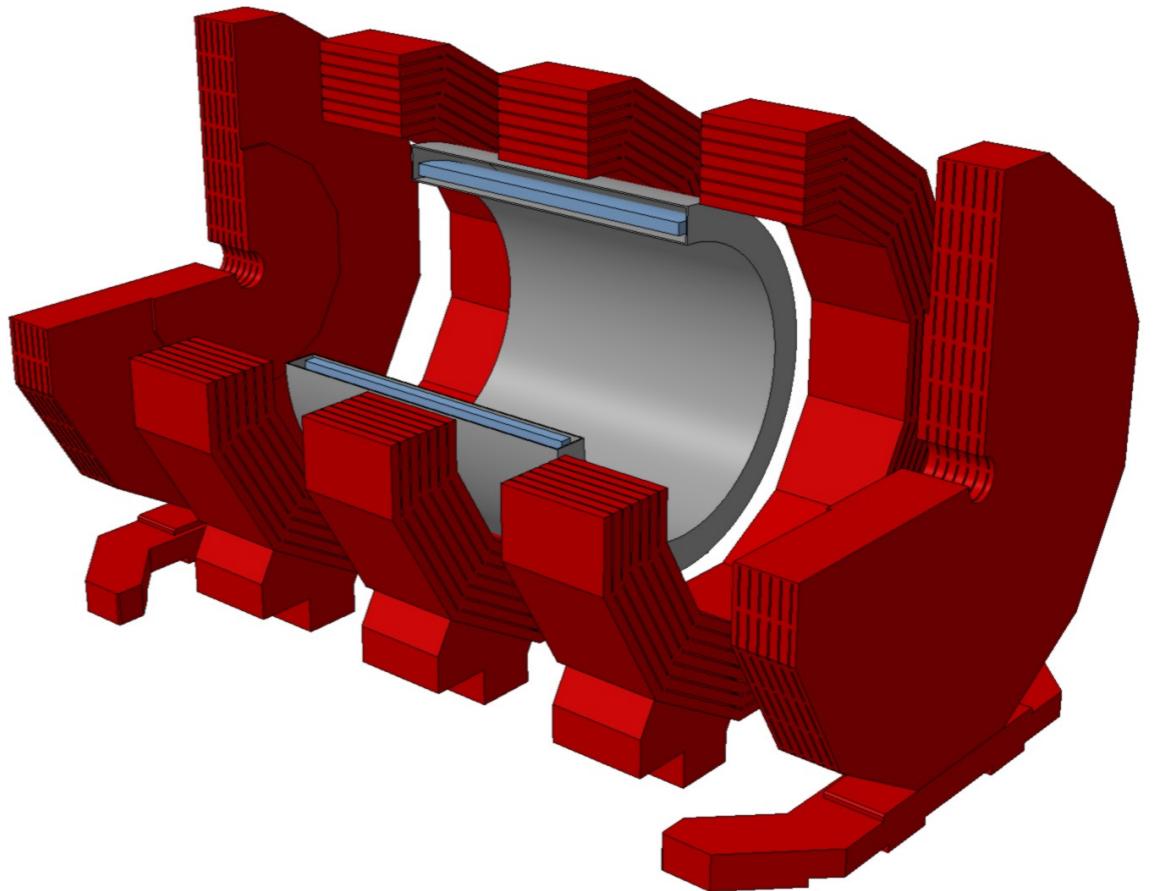
- Scintillator-steel sampling calorimeter
- SiPMs read-out
- cell size  $30 \times 30 \text{ mm}^2$
- 60 layers (20 mm thick steel plates)
- $7.5\lambda_l$

More details in F. Simon's talk

# Magnet and muon ID system

## The magnet system in the simulation

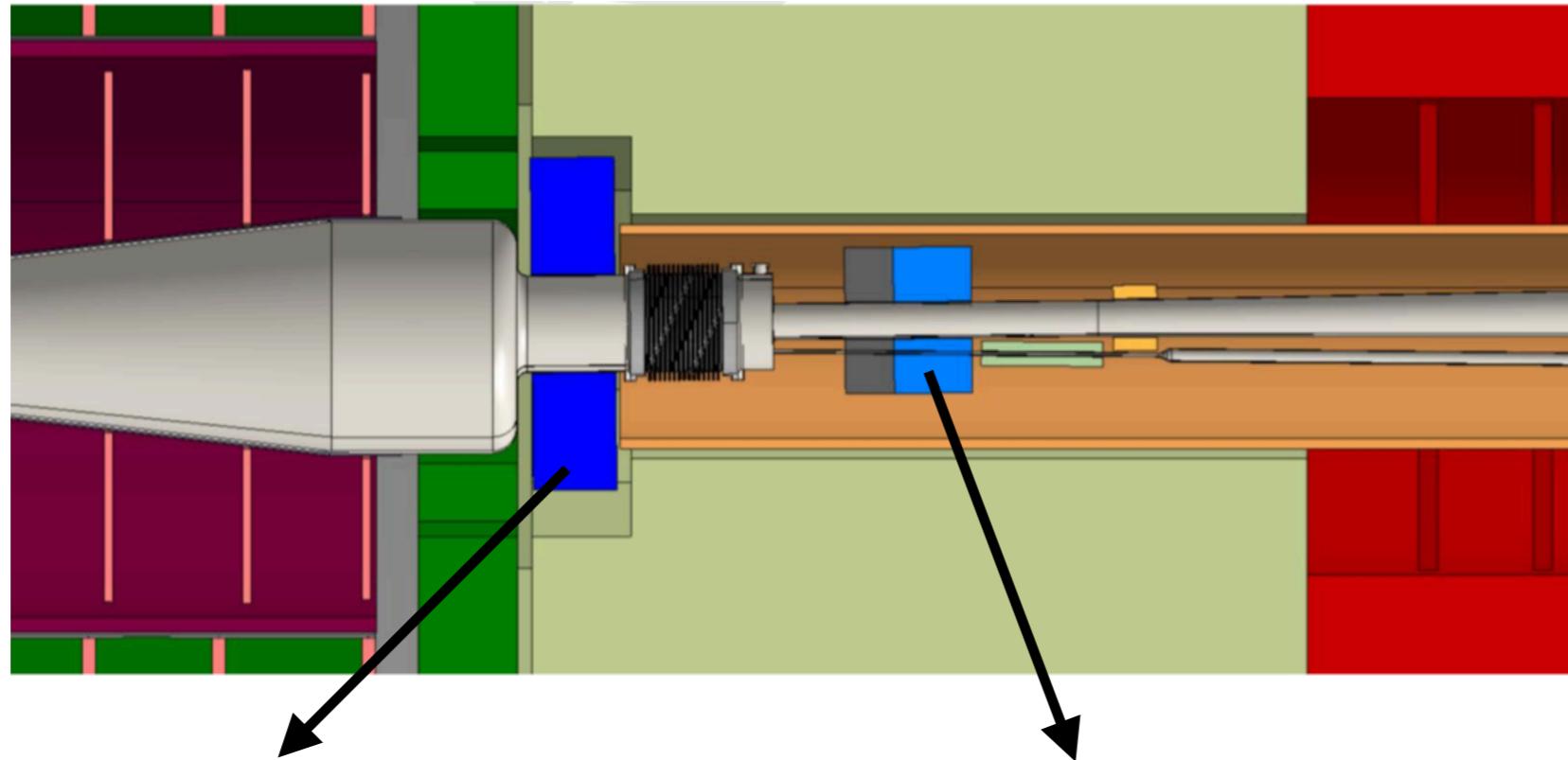
- superconducting coil
  - 4T homogeneous field
- return yoke
  - barrel: 1.5T field
  - endcap: no field



## The muon system in the simulation

- RPC chambers imbedded in the steel yoke
  - 6 layers in the barrel, 6 layers in each endcap
  - possible 7th barrel layer close to the coil, as tailcatcher for hadron showers
  - cell size  $30 \times 30 \text{ mm}^2$

# Forward calorimeters



## LumiCal

- Si-W calorimeter
- 40 layers (3.5 mm thick W plates)
- transverse segmentation
  - 64 radial
  - 48 azimuthal
- $\theta$  coverage: (39-134) mrad

## BeamCal

- GaAs-W calorimeter
- 40 layers (3.5 mm thick W plates)
- cell size  $8 \times 8 \text{ mm}^2$
- $\theta$  coverage: (10-46) mrad
- 100 mm thick graphite layer on the side facing the IP



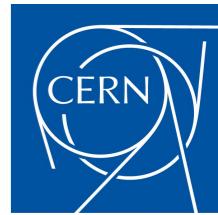
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# Event simulation and hit digitization



- Linear Collider community software: [iLCSoft](#)

- simulation framework: [DDSim](#) (based on [DD4hep](#))

- Event (physics and background) simulation
  - Geant4 particle list
  - unified geometry for simulation & reconstruction
  - homogeneous magnetic field

## Simulation

- reconstruction framework: [Marlin](#)

- Simulated background events overlaid to physics
  - timing cuts to reduce the integration window based on detector timing resolutions

## Background overlay

- Pixels/strips approximated with Gaussian smearing
  - $\sigma$  equal to the single point resolution

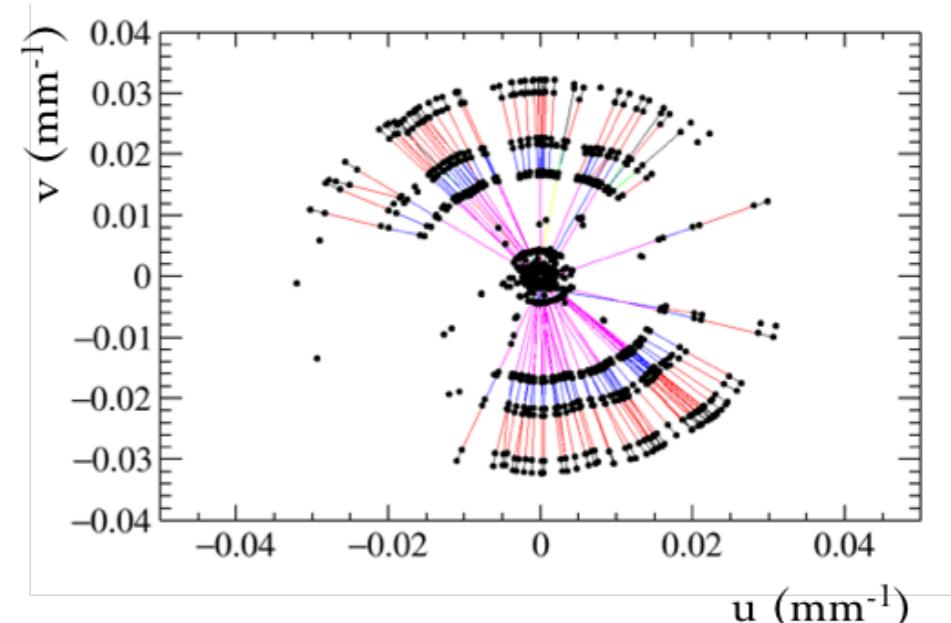
## Digitization

# Conformal tracking

## Pattern recognition in conformal space

- cellular automaton for straight line search
- prompt tracks
  - minimum number of hits for track reconstruction = 4
  - from vertex to tracker hits
- displaced tracks
  - minimum number of hits for track reconstruction = 5
  - from tracker to vertex hits

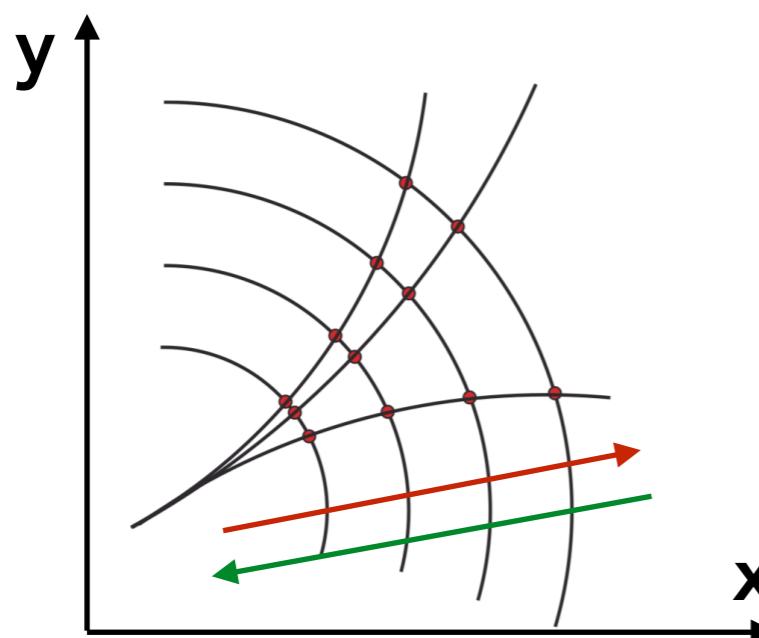
$$\begin{cases} u = x/(x^2 + y^2) \\ v = y/(x^2 + y^2) \end{cases}$$



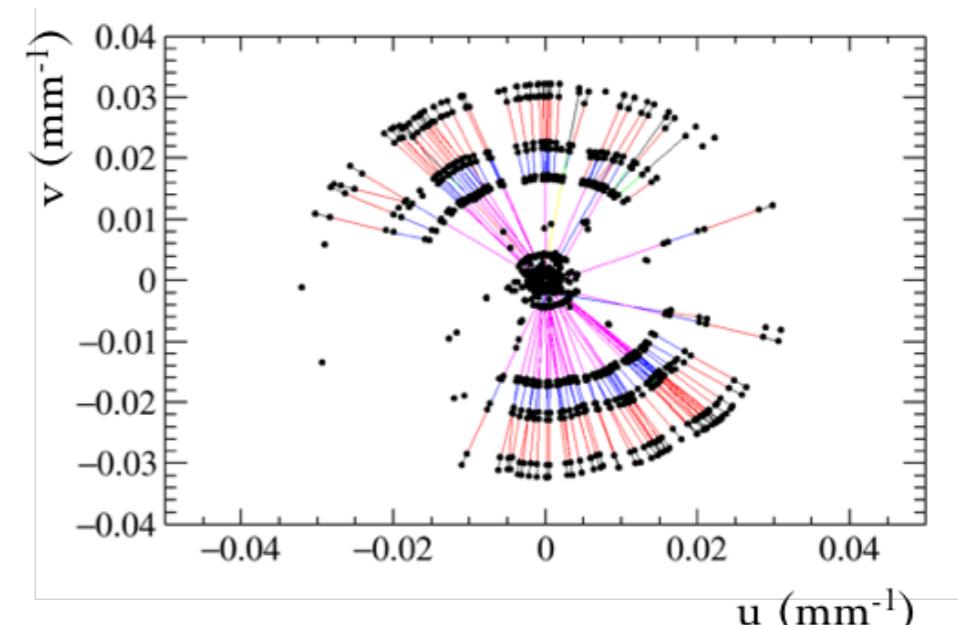
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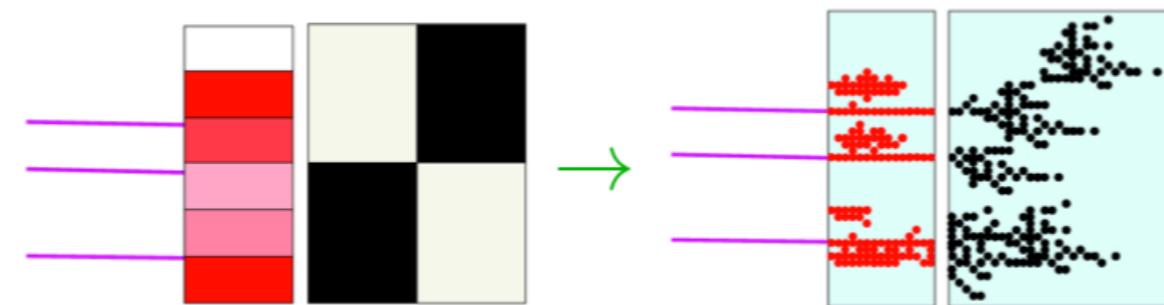


## Track fit

- helix prefit with 3 hits
- iterative Kalman filter
- **fit forward** and **smooth backward**

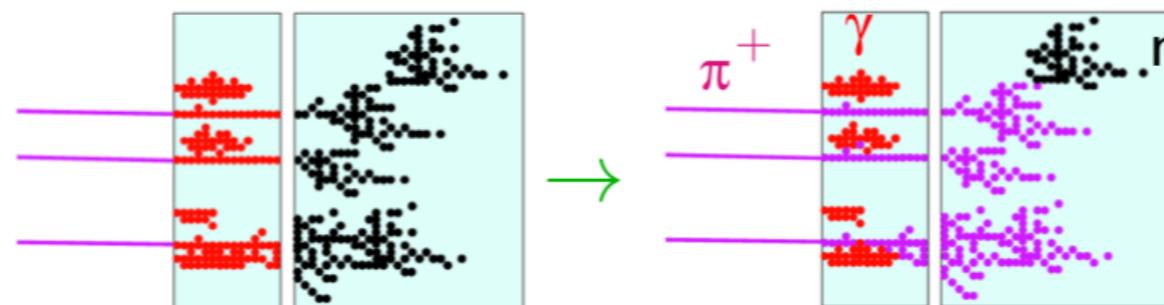
# Pandora Particle Flow Algorithm

- Pandora PFA = hardware + software
  - high-granular calorimeters to define energy deposit from different particles



$$E_{\text{jet}} = E_{\text{ECal}} + E_{\text{HCal}}$$

- knowing the jet composition, profit from the detectors with best resolution
  - 60% charged particles → tracker
  - 30% photons → ECal
  - 10% neutral hadrons → HCal

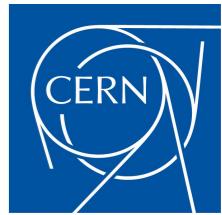


$$E_{\text{jet}} = E_{\text{track}} + E_{\gamma} + E_n$$

- PFOs = Particle Flow Objects (objects reconstructed with Pandora PFA)



# Reconstruction in forward calorimeters



Clustering algorithm is used for reconstruction in forward calorimeters

- nearest neighbour search with pads with significant remaining energy after subtraction of background
  - subtraction of expected background energy from total energy in each pad
  - pad selection based on standard deviation of background energy deposited
  - selected pads with same  $r$  and  $\Phi$  are used to create towers in  $z$
  - towers energy and position are estimated
    - energy = sum energy of all pads
    - position = energy-weighted position of pads



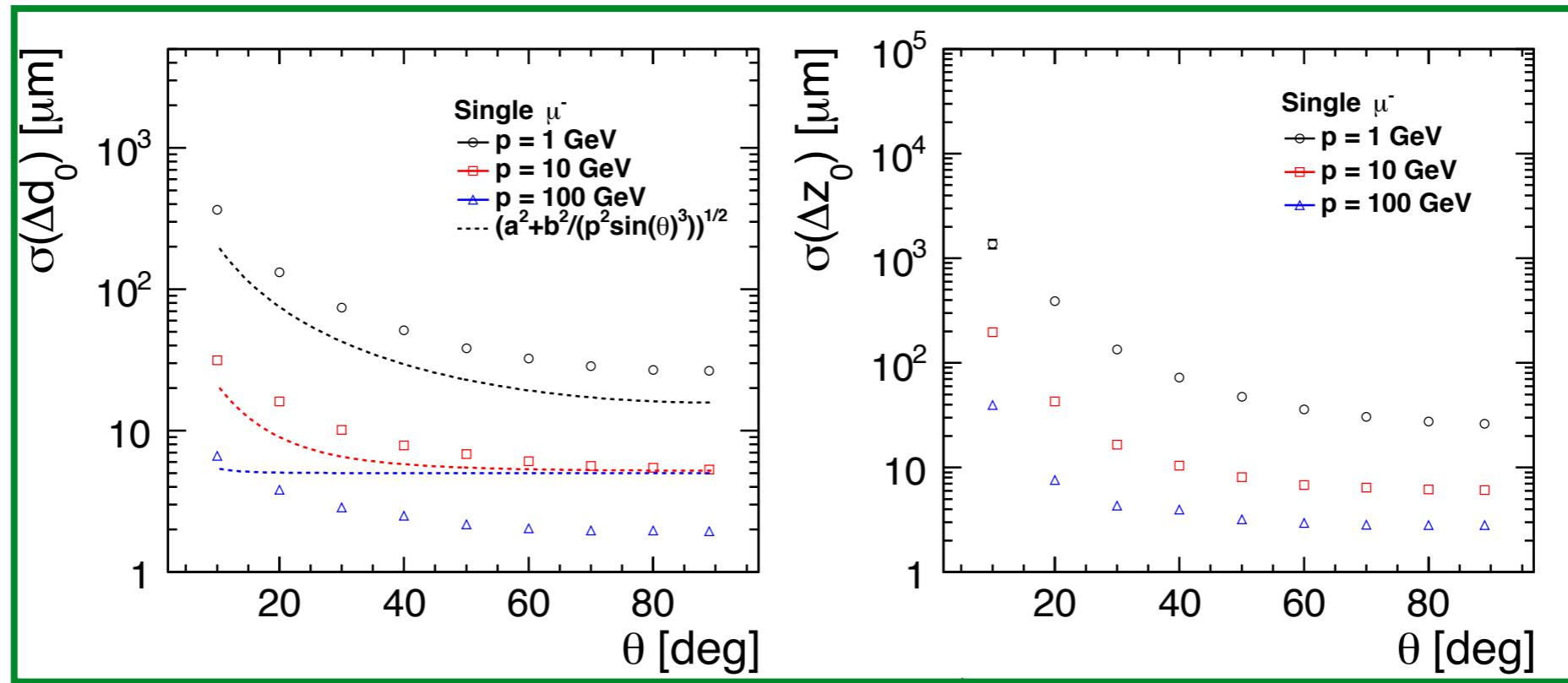
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# Tracking resolutions

## single muons

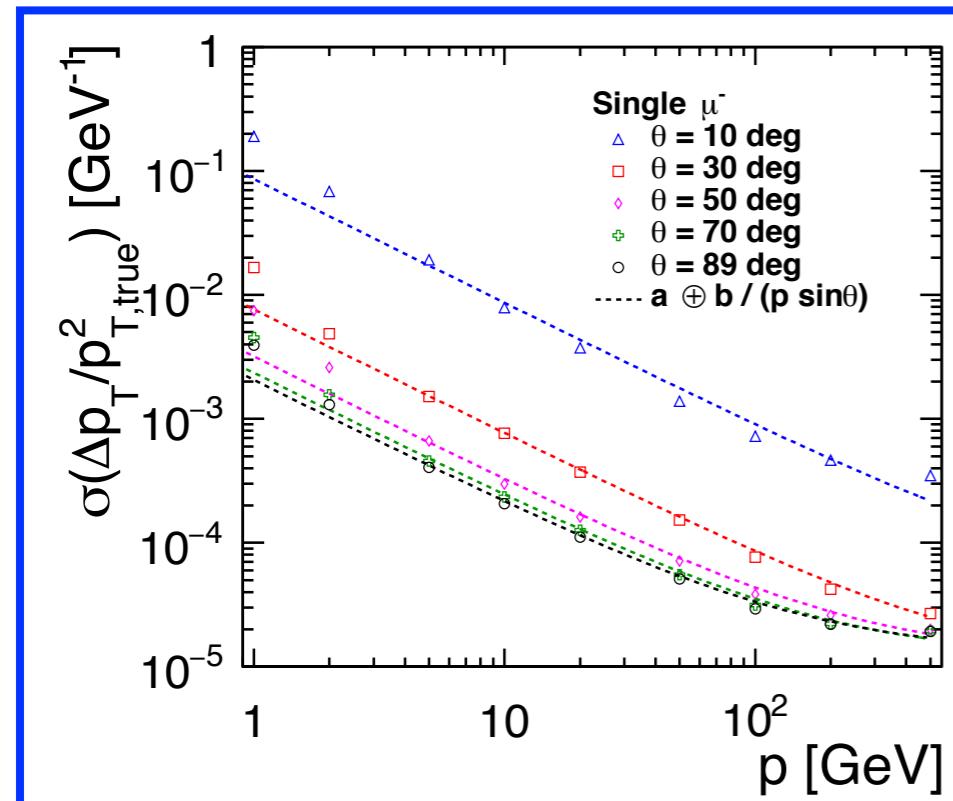
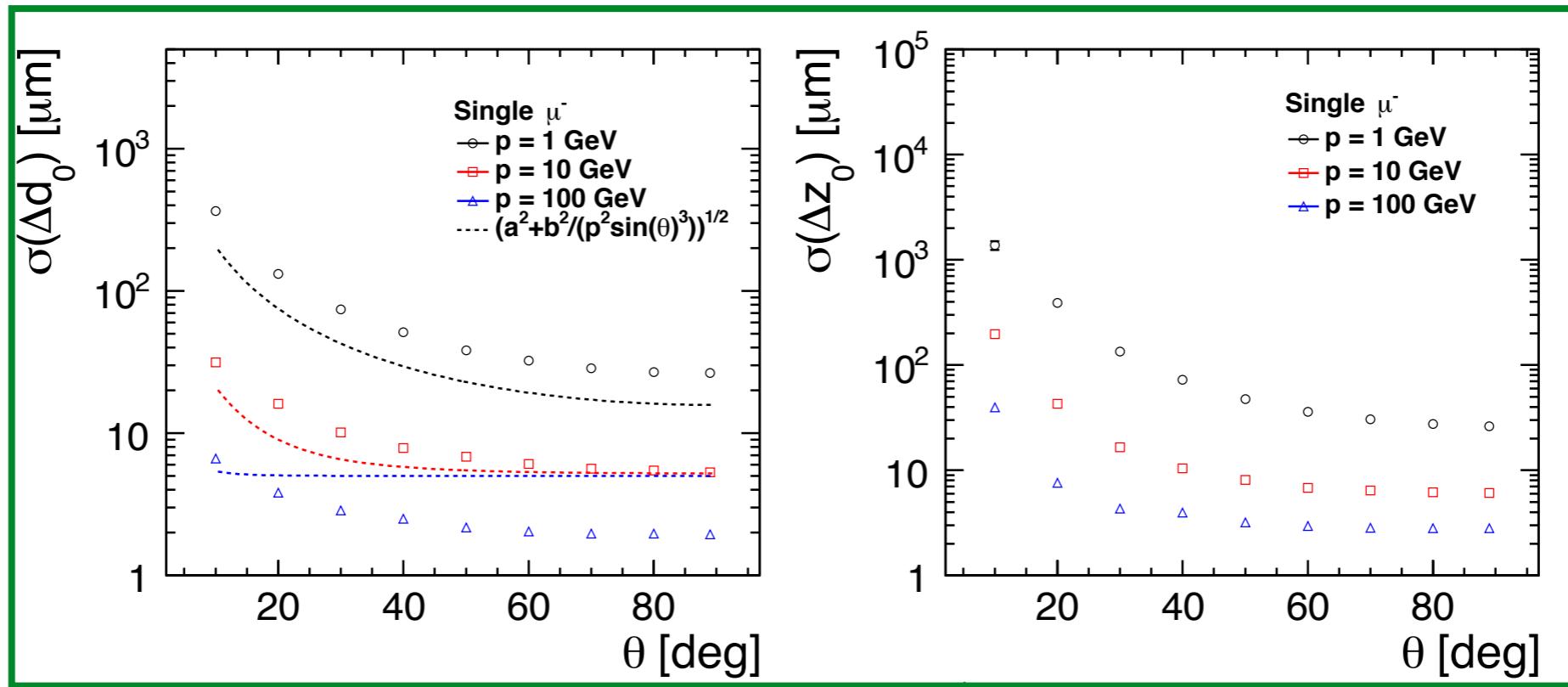


Achieved desired impact parameter resolutions:

- $d_0$  for high-energy muons well below the high-momentum limit of  $5 \mu\text{m}$
- $z_0$  for high-energy muons smaller than longitudinal bunch length ( $44 \mu\text{m}$  at  $3 \text{ TeV}$ )

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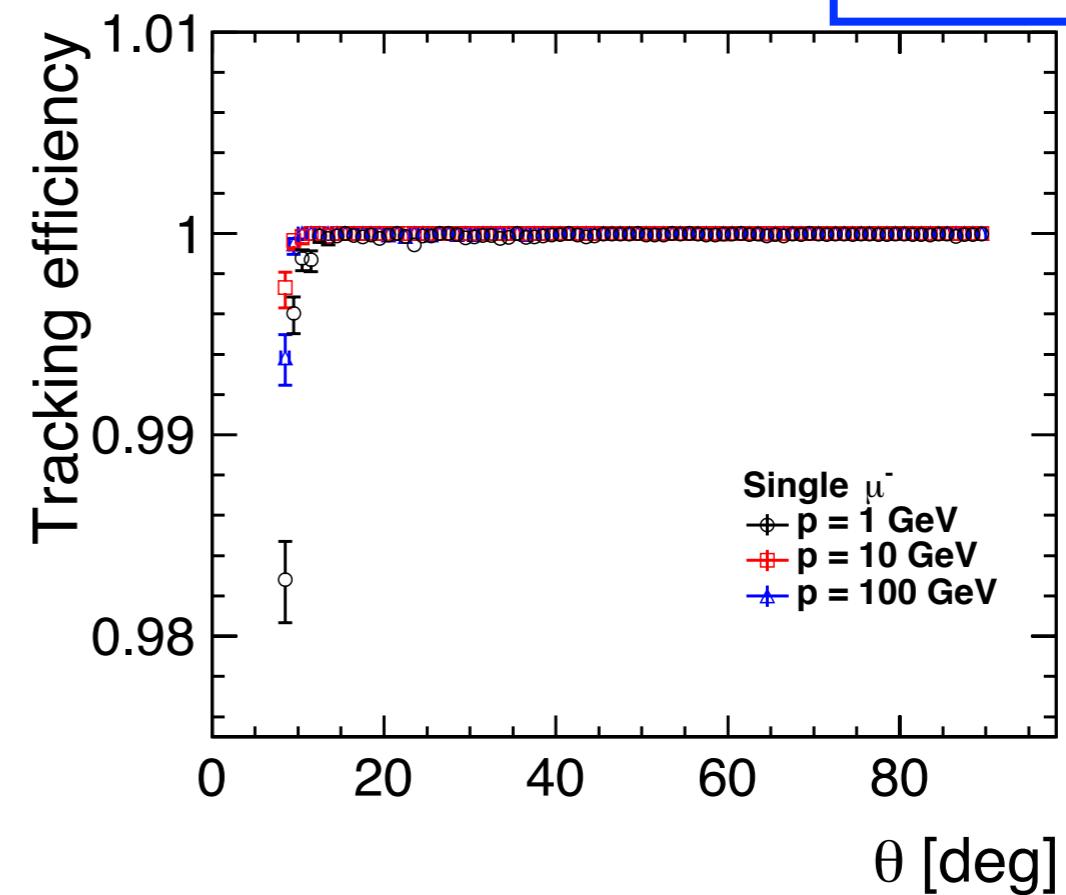
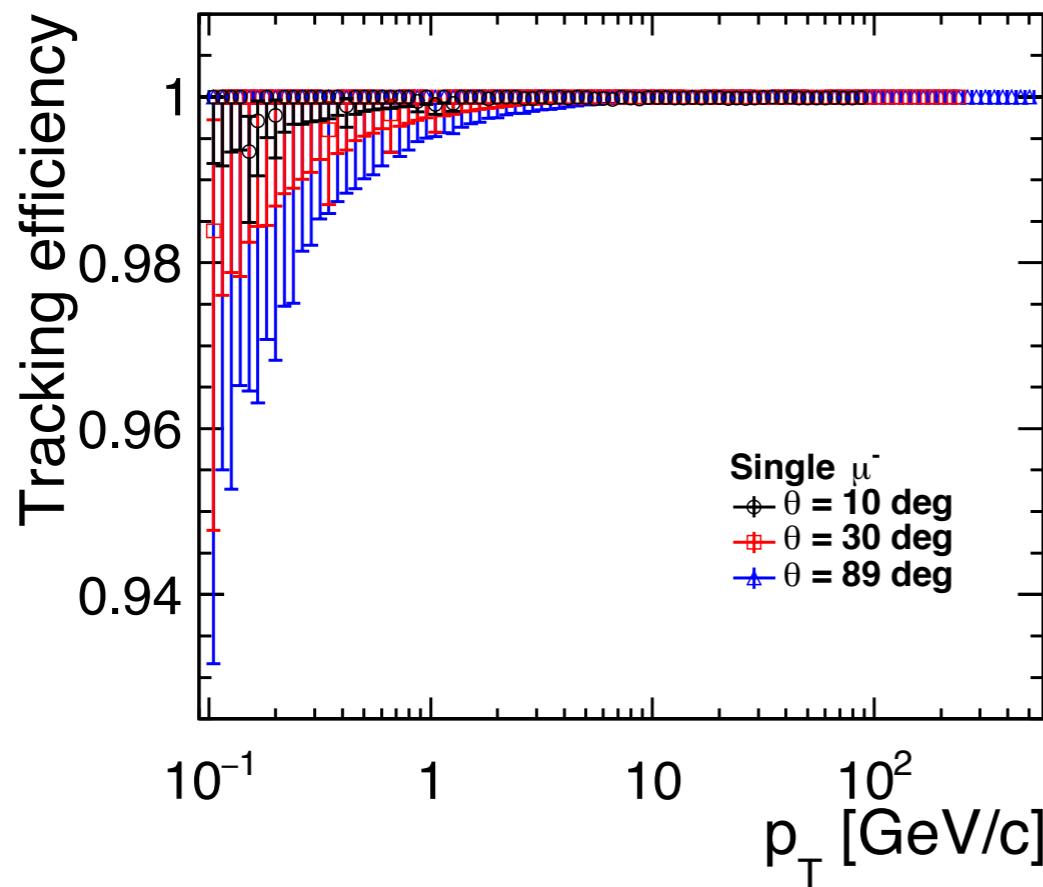
Achieved transverse momentum resolution goal of  $2 \times 10^{-5} \text{ GeV}^{-1}$  for high-energy muons in the barrel

# Tracking efficiency (I)

single muons

Efficiency = fraction of reconstructed particles out of the reconstructable

- stable
- $p_T > 0.1 \text{ GeV}/c$
- $|l \cos \theta| < 0.99$
- $\# \text{unique hits} \geq 4$

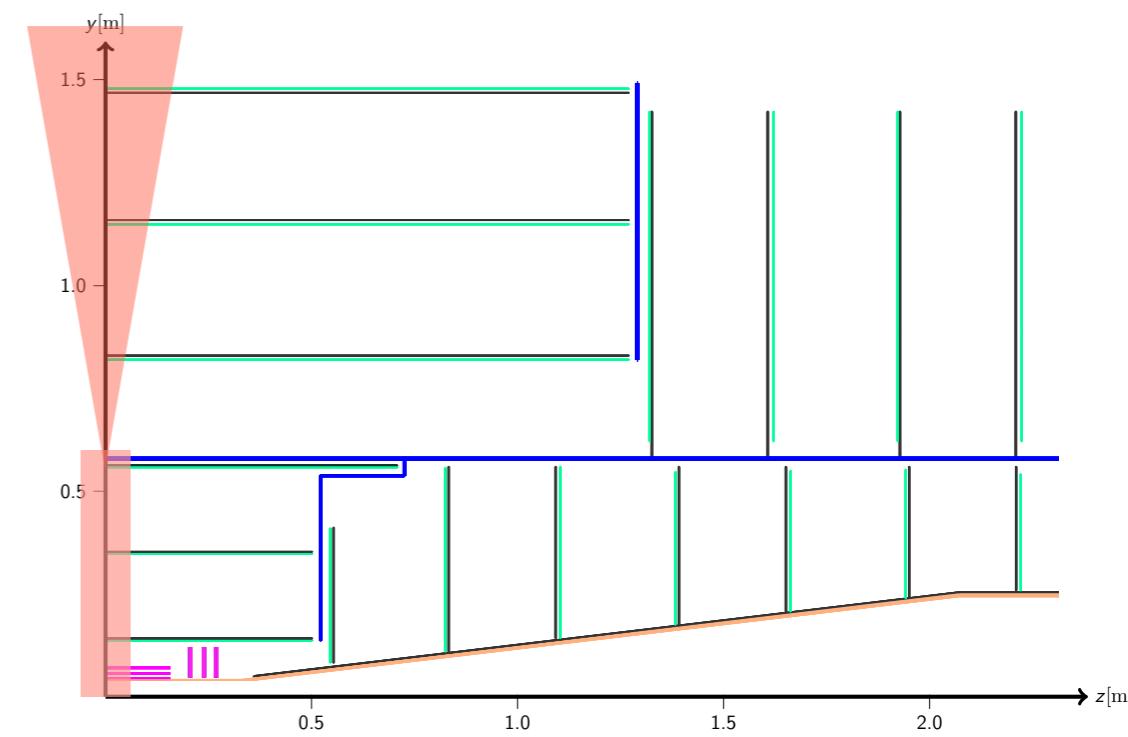
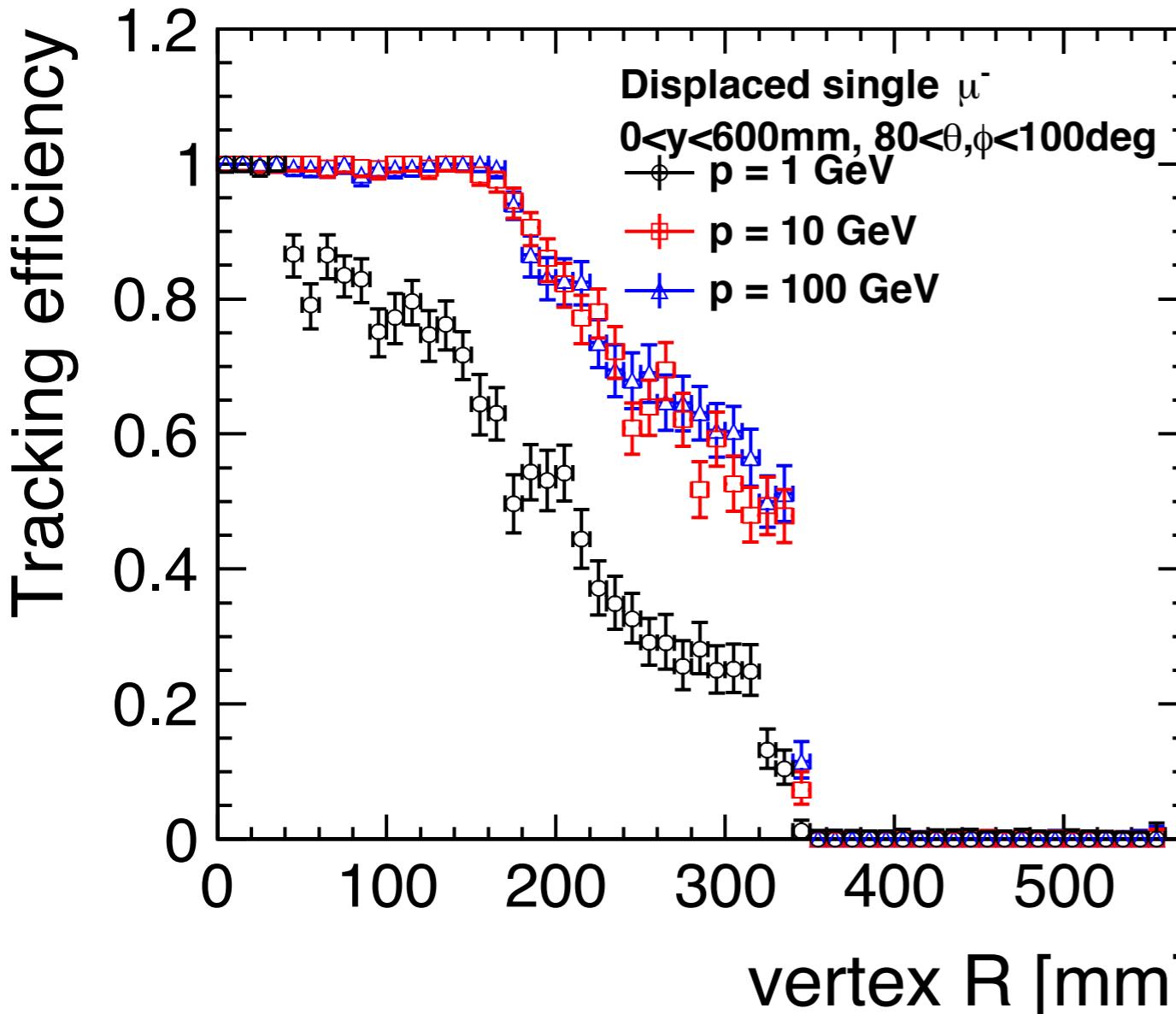


100% tracking efficiency for single muons at any energy above 10 degrees

# Tracking efficiency (II)

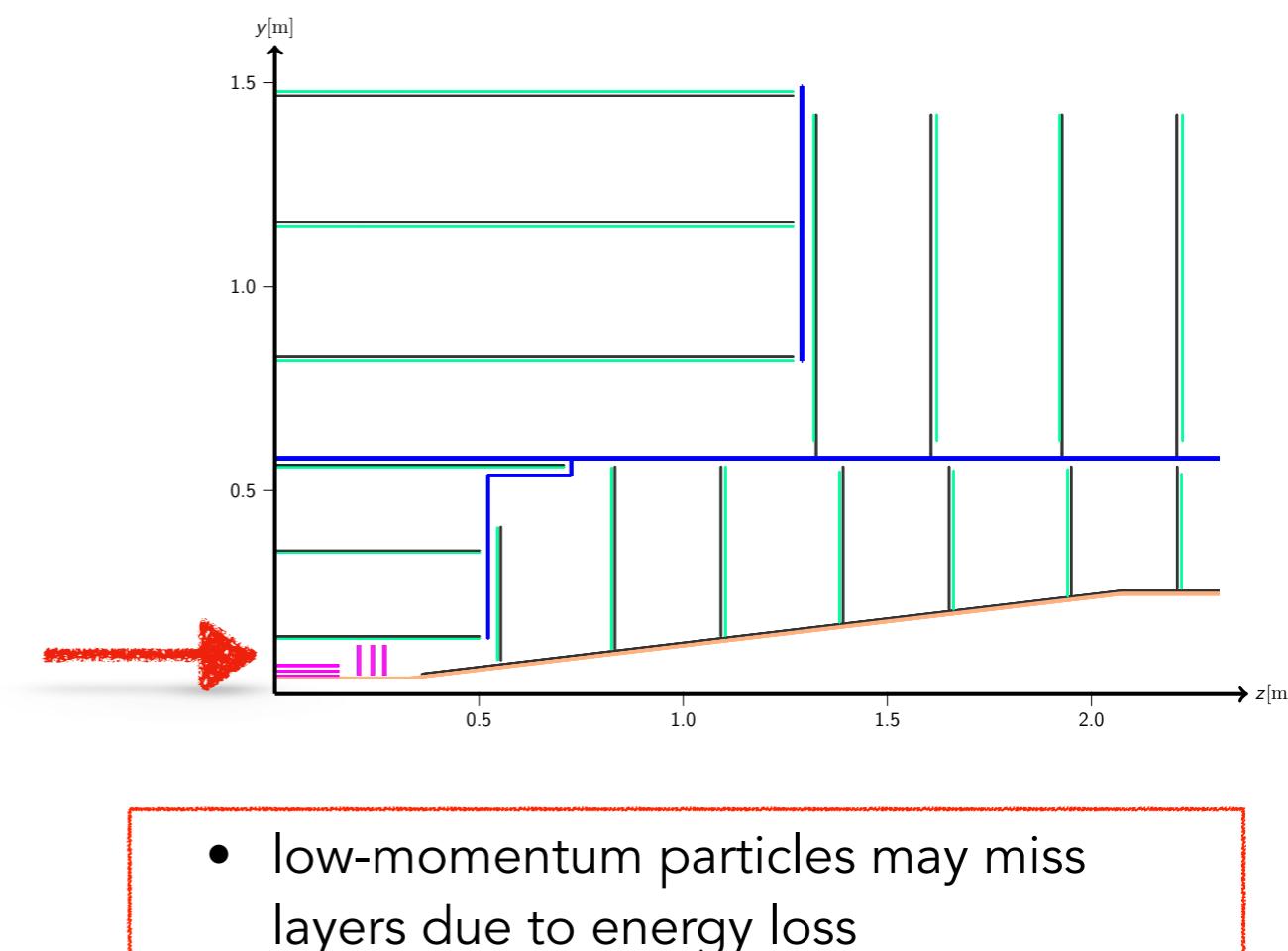
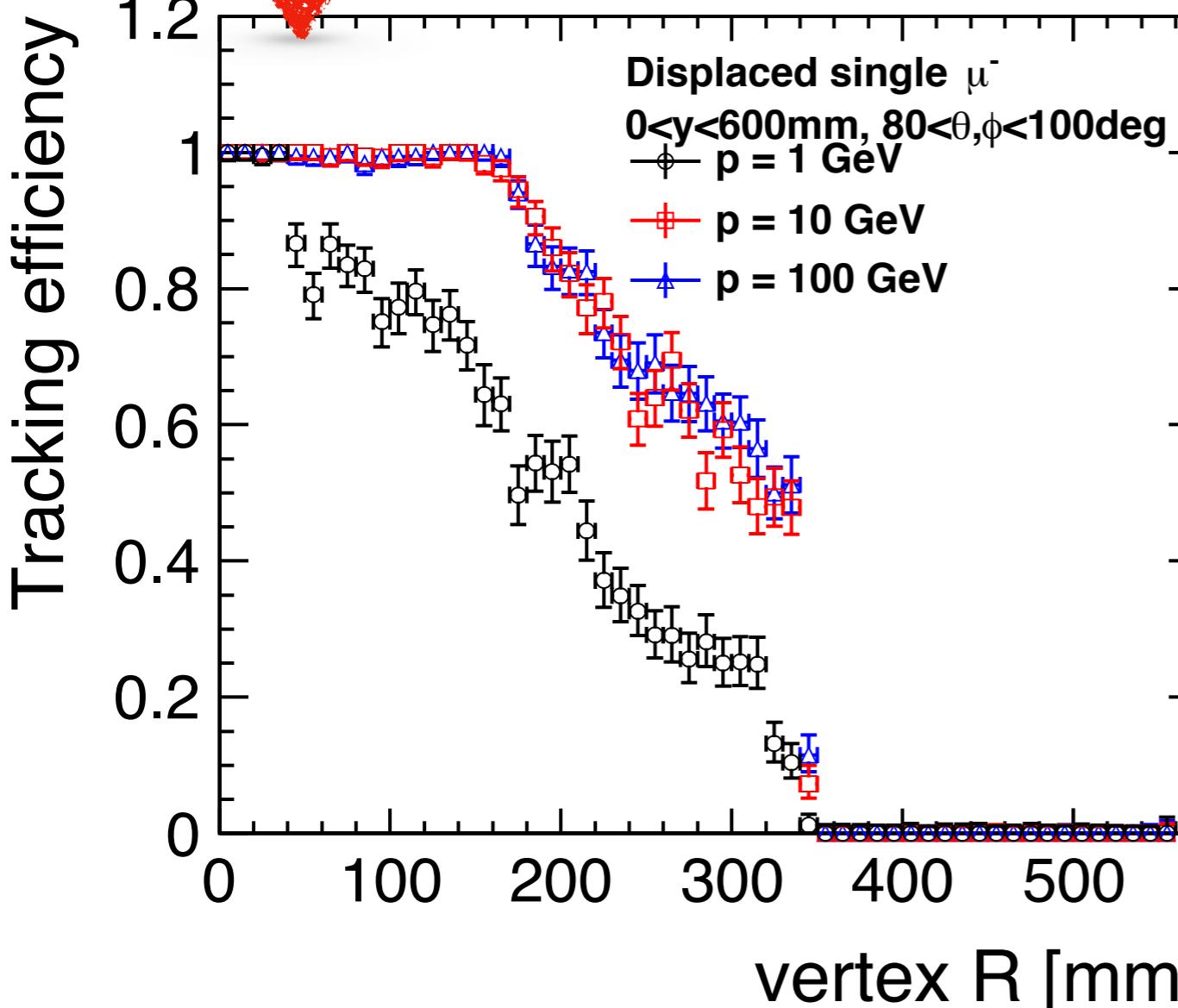
single displaced muons

minimum number of hits for reconstructing displaced tracks = 5



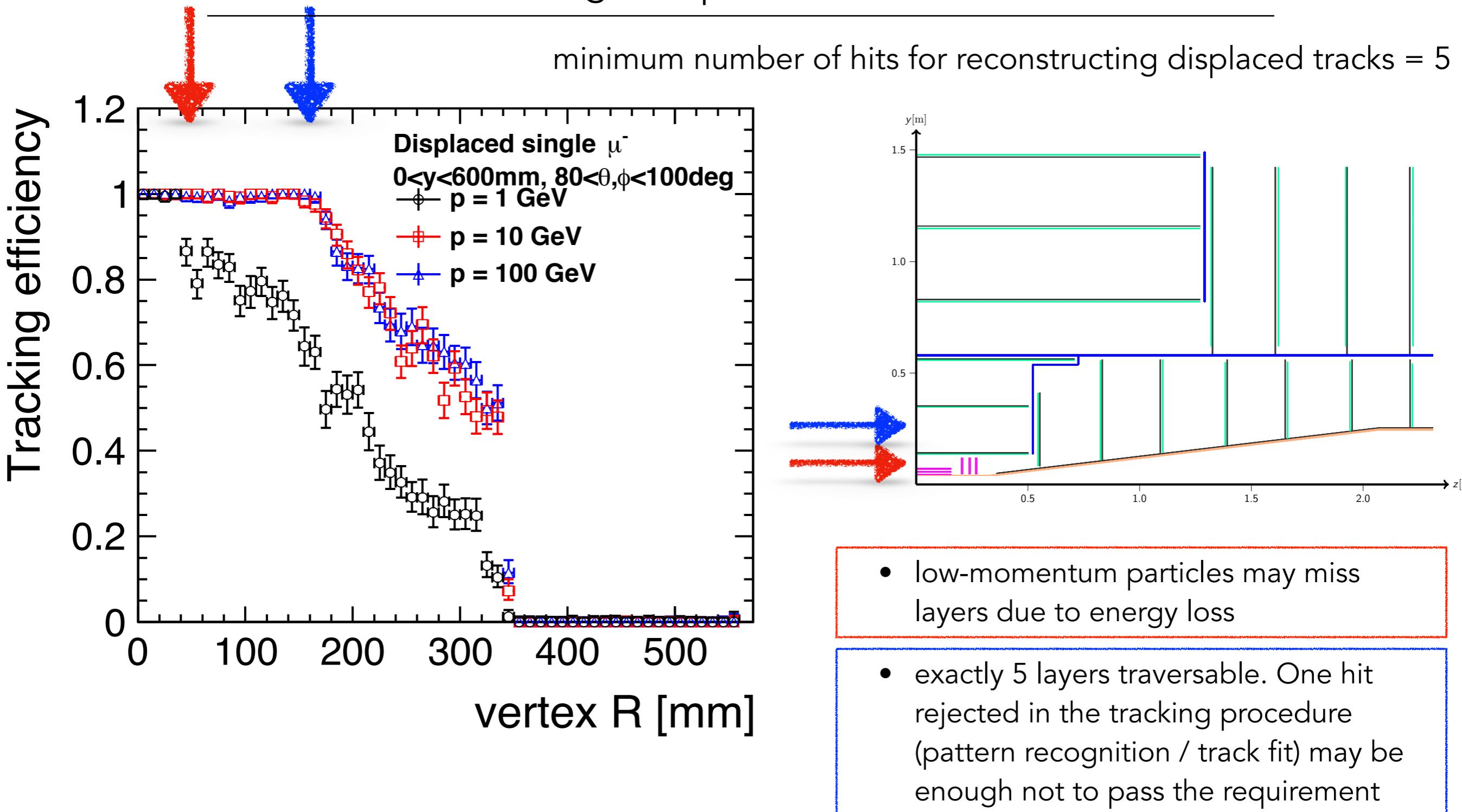
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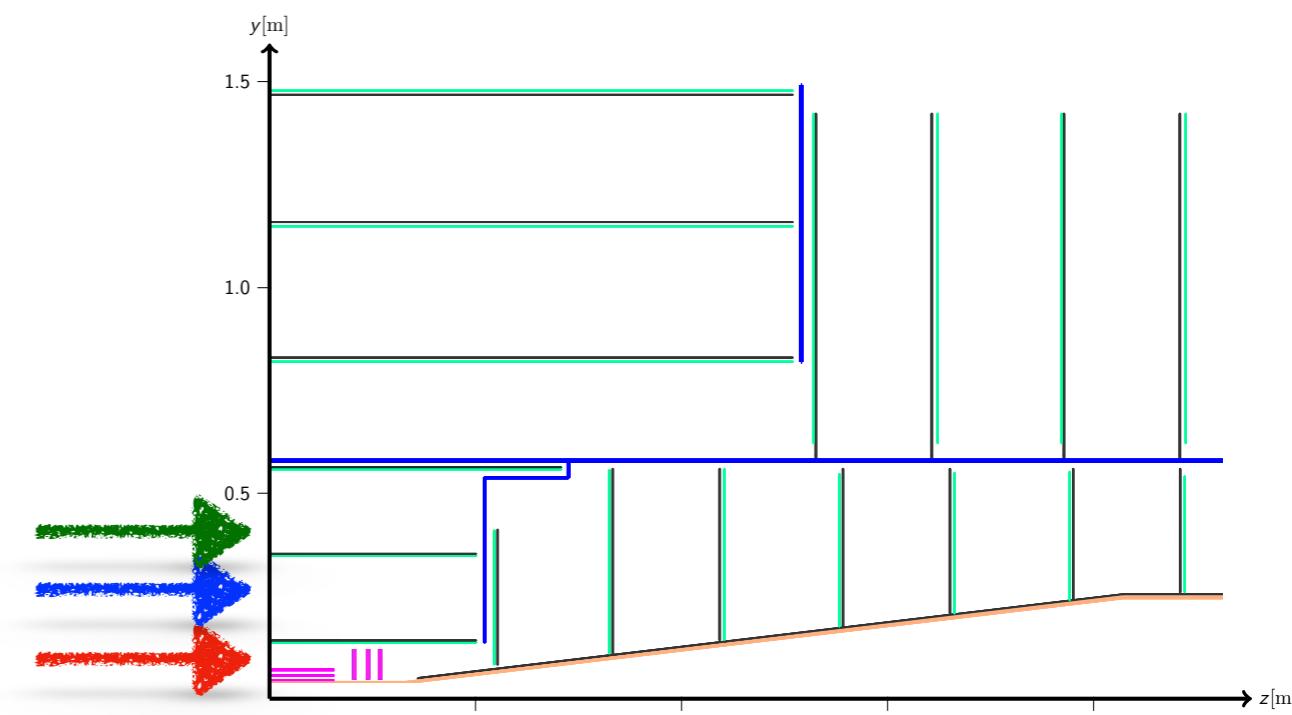
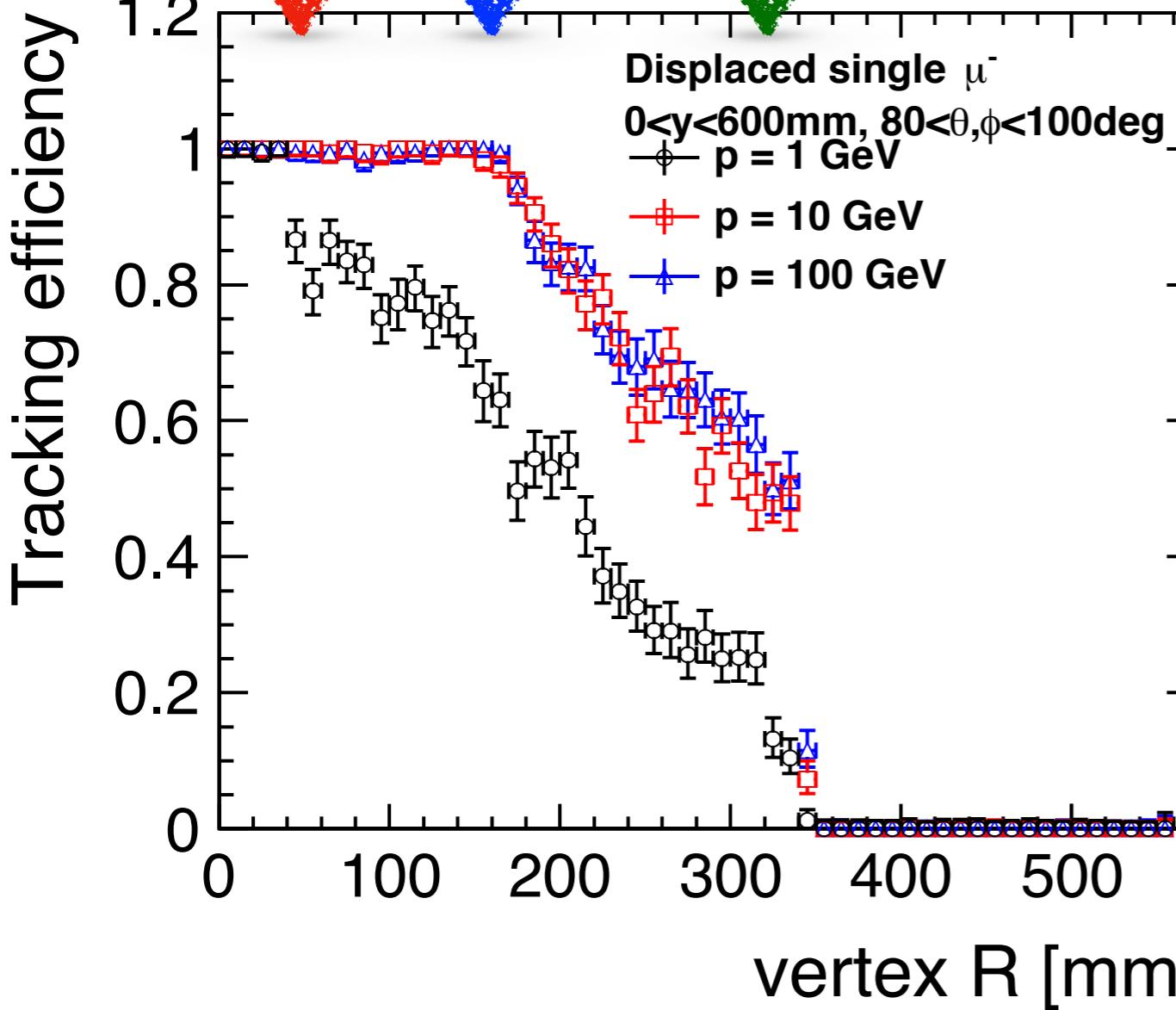
# Tracking efficiency (II)

## single displaced muons



# Tracking efficiency (II)

single displaced muons



- low-momentum particles may miss layers due to energy loss
- exactly 5 layers traversable. One hit rejected in the tracking procedure (pattern recognition / track fit) may be enough not to pass the requirement
- less than 5 traversable layers

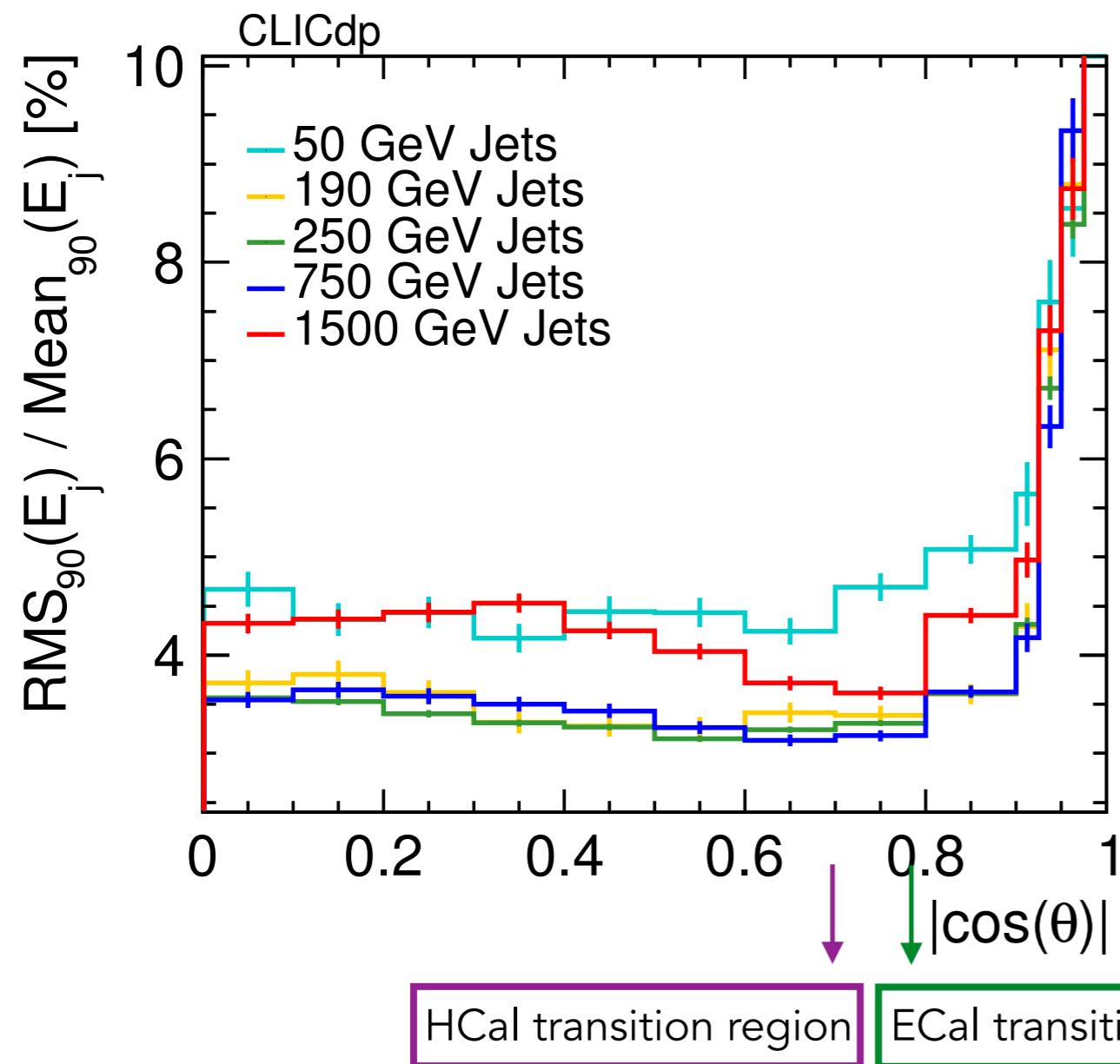
# Jet energy resolution

Z boson-like events decaying in light quark dijets

Jet energy resolution:

$$\frac{\text{RMS}_{90}(E_j)}{\text{mean}_{90}(E_j)} = \frac{\text{RMS}_{90}(E_{jj})}{\text{mean}_{90}(E_{jj})} \sqrt{2}$$

$E_{jj}$  = sum of energies of all reconstructed objects



Achieved jet energy resolution of 3.5-4.5% in the barrel, with the exception of

- low-energy: calorimeter resolution
- high-energy: too collimated jets

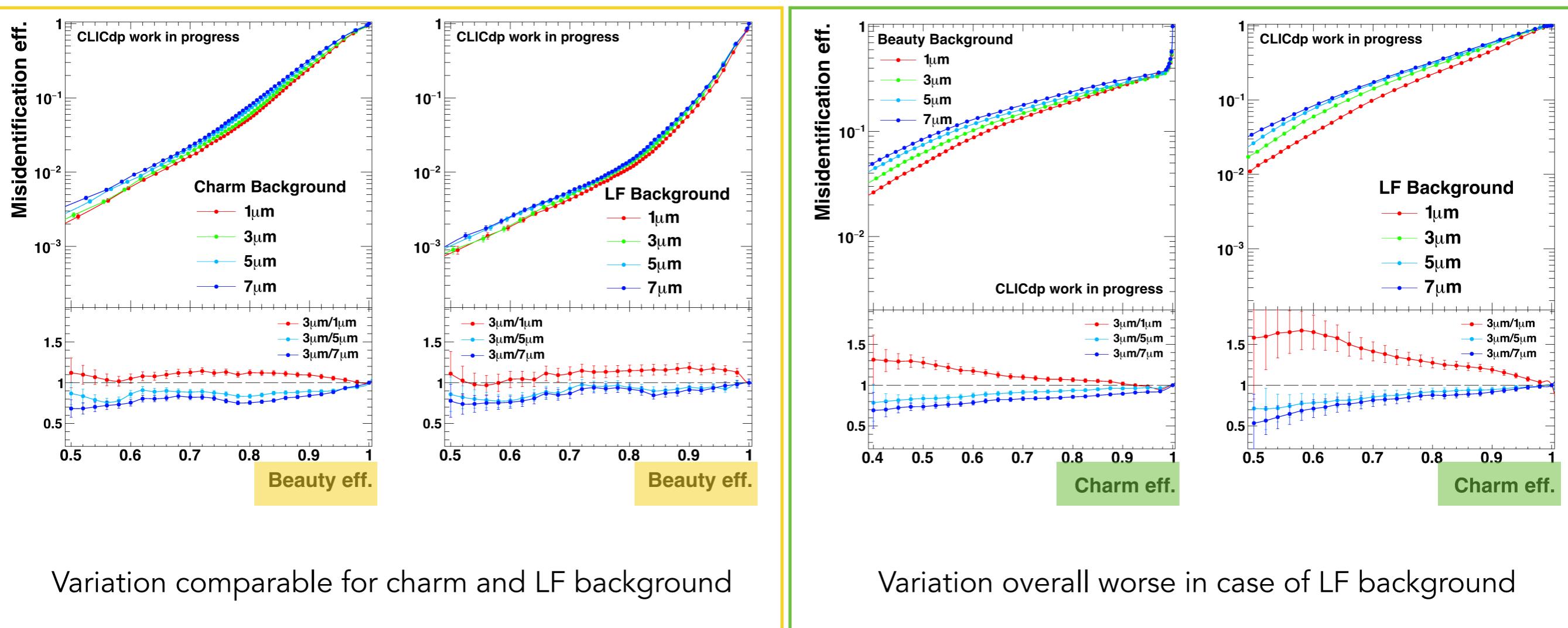
Jet-energy resolution in the very forward region suffer from difficulties in track reconstruction, resulting in bad cluster matching or in failing the tracks to pass Pandora requirement



# Flavour tagging

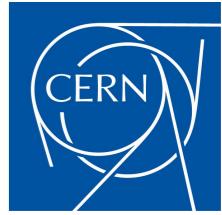
dijet events at 500 GeV center-of-mass energy

Flavour tagging variation with spatial resolution in the vertex detector (3  $\mu\text{m}$  standard configuration)





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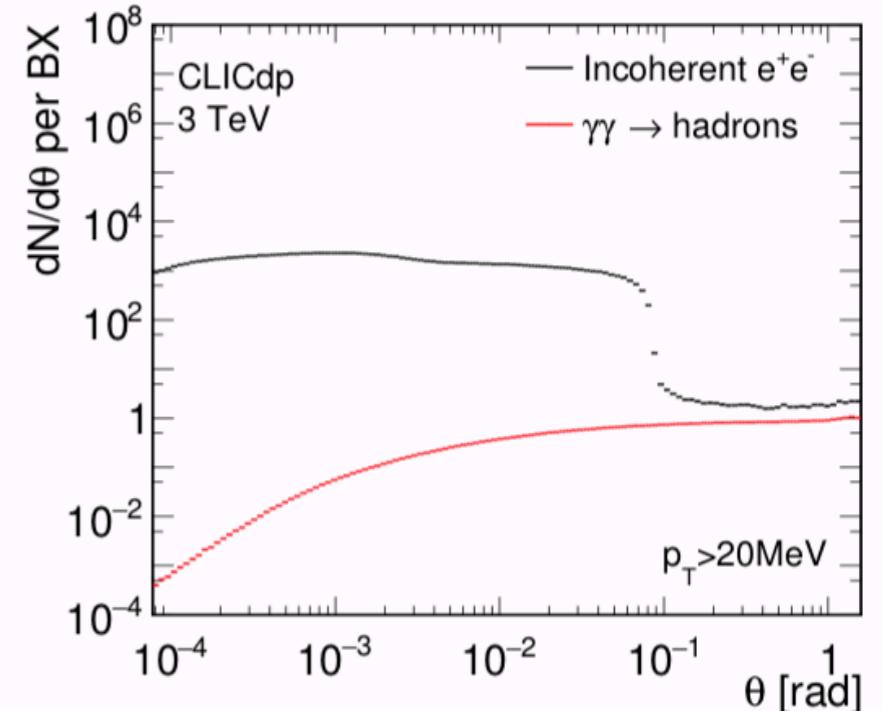
# Beam-induced backgrounds

The effect of 3 TeV (worst case scenario) background is presented  
(380 GeV background discussed in the note)

More details in A. Sailer's talk

In this talk

- effect of  $\gamma\gamma \rightarrow \text{hadrons}$  to:
  - tracking performances
  - single particle ID efficiency
  - missing momentum distribution
    - different preselections on particle flow objects
  - beauty and charm misidentification efficiency
- effect of incoherent  $e^+e^-$  pairs to:
  - LumiCal and BeamCal efficiency



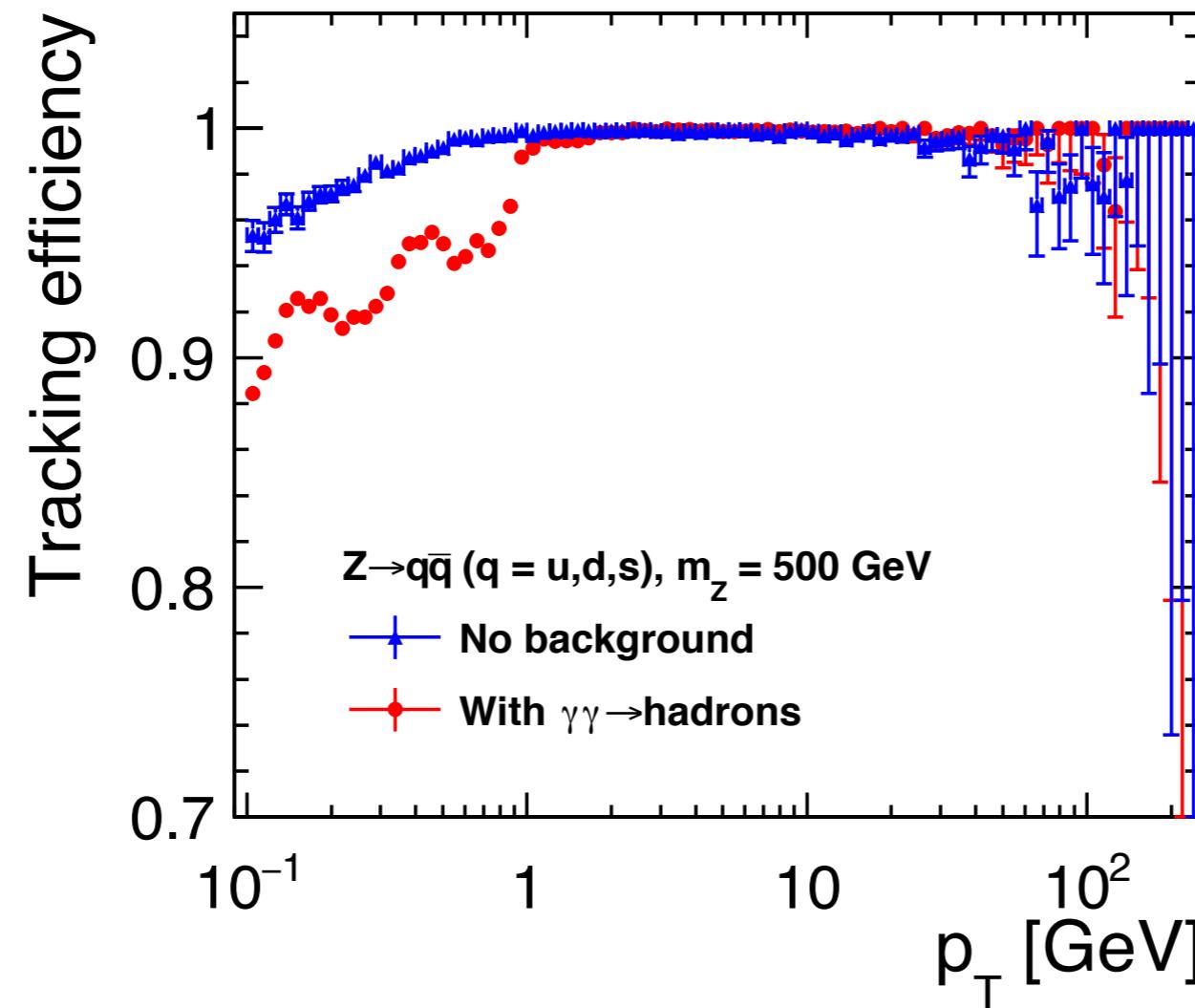
# Tracking efficiency

Z boson-like events at 500 GeV decaying in light quark dijets  
with 30BX of  $\gamma\gamma \rightarrow$ hadrons at 3 TeV

Efficiency = fraction of **pure** reconstructed particles out of the **reconstructable**

whose majority of hits ( $\geq 75\%$ ) belong to the same particle

- stable
- $p_T > 0.1 \text{ GeV}/c$
- $|l \cos \theta| < 0.99$
- #unique hits  $\geq 4$



Reached 100% efficiency for  $p_T > 1 \text{ GeV}/c$ . Background mostly affects low- $p_T$  region.

# Tracking efficiency and fake rate

ttbar events at 3 TeV center-of-mass energy

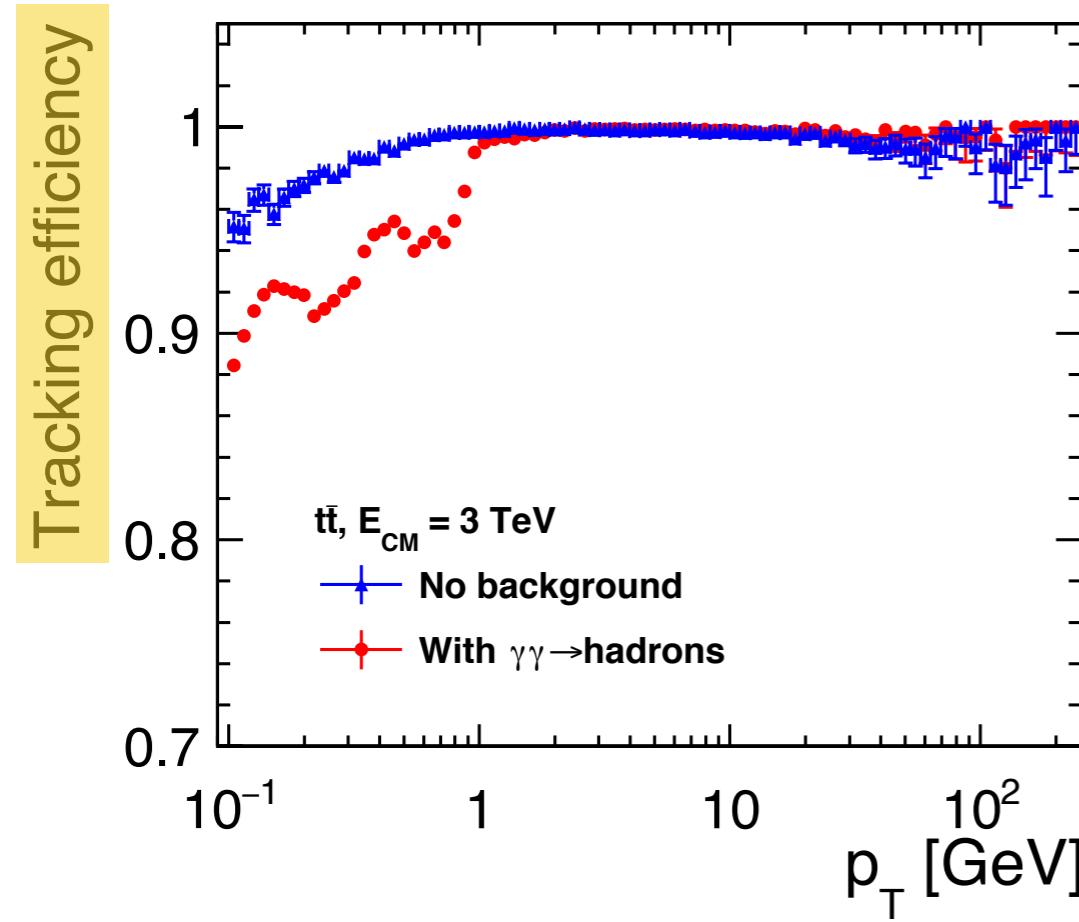
with 30BX of  $\gamma\gamma \rightarrow$ hadrons at 3 TeV

**Efficiency** = fraction of **pure** reconstructed particles out of the **reconstructable**

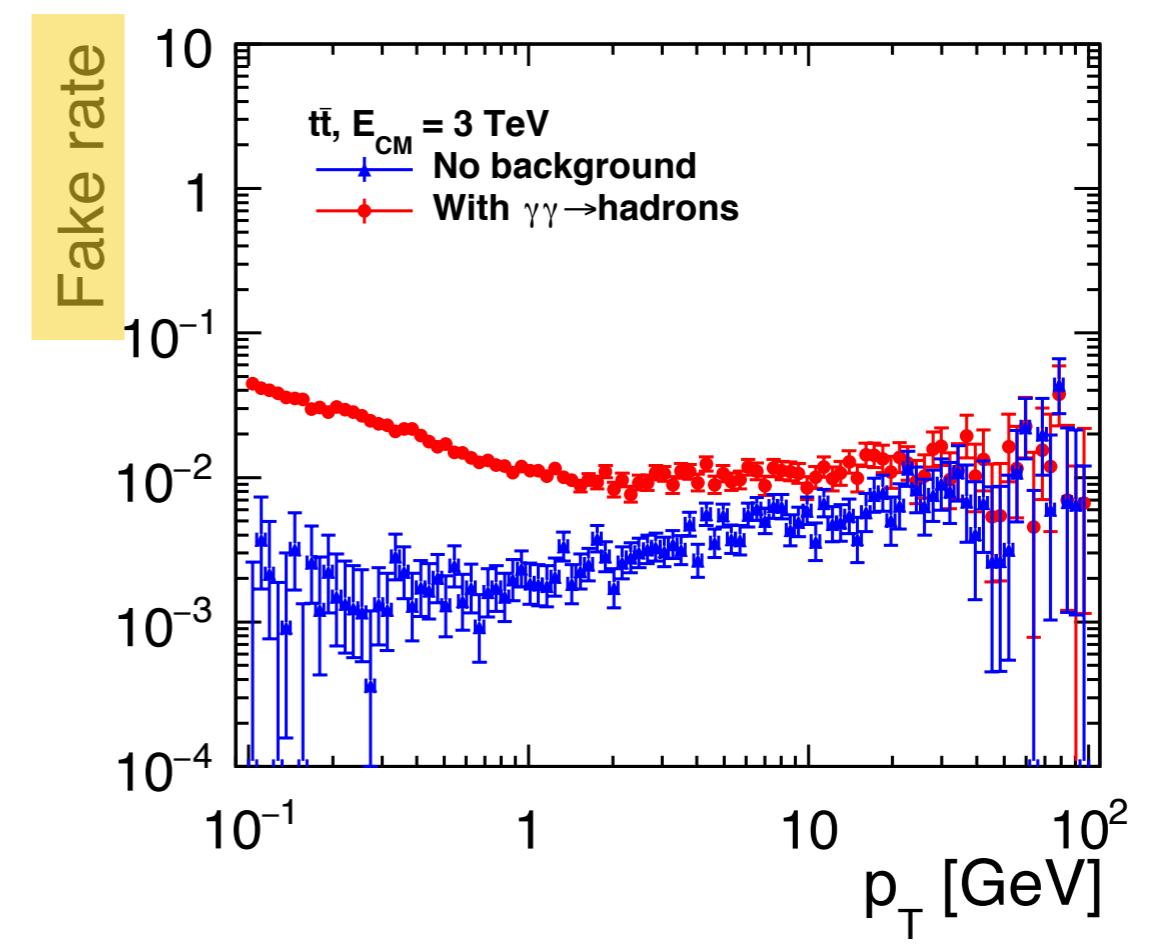
**Fake rate** = fraction of **impure** reconstructed particles out of the reconstructed



less than 75% of its hits belong to the same particle



Efficiency comparable with previous slide => performance independent on physics process and center-of-mass energy



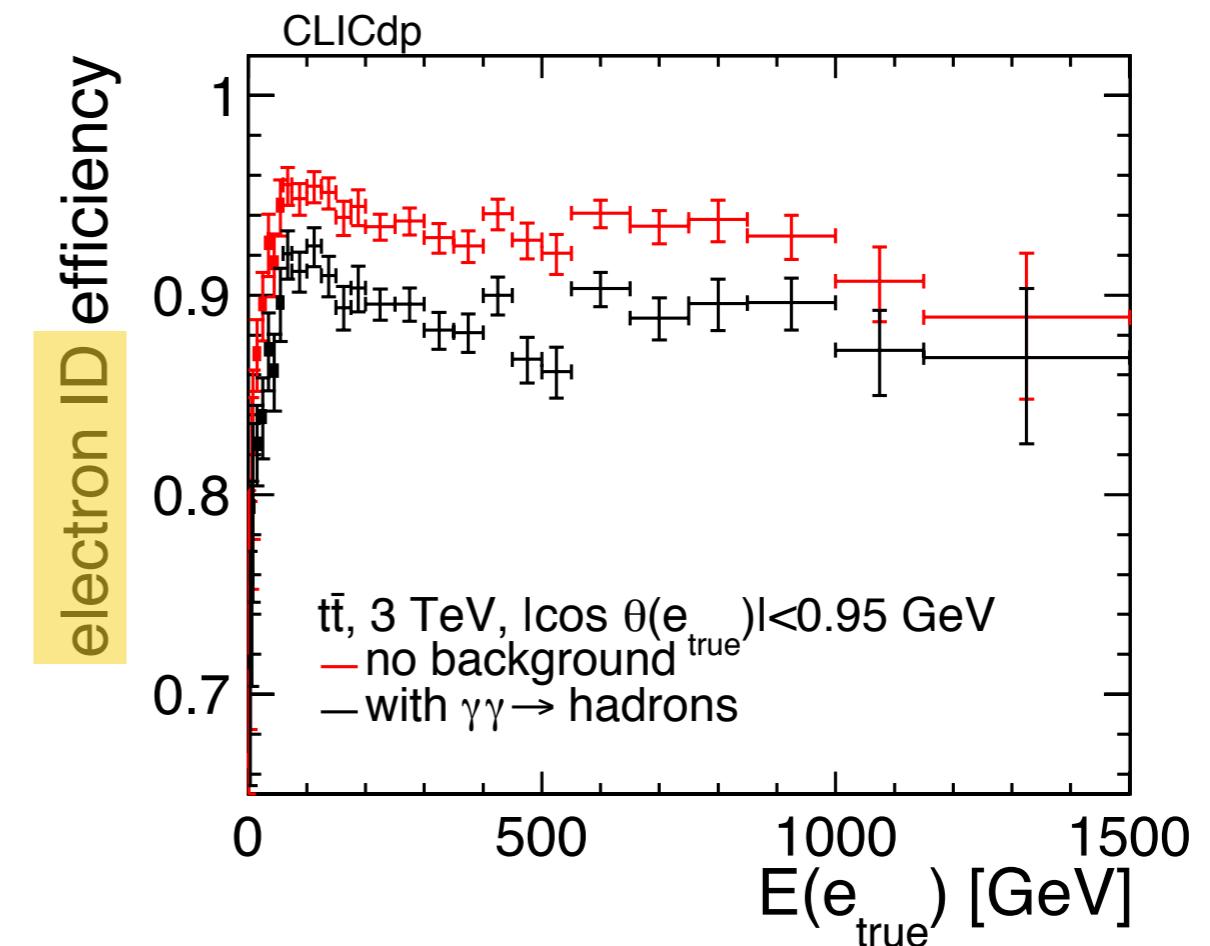
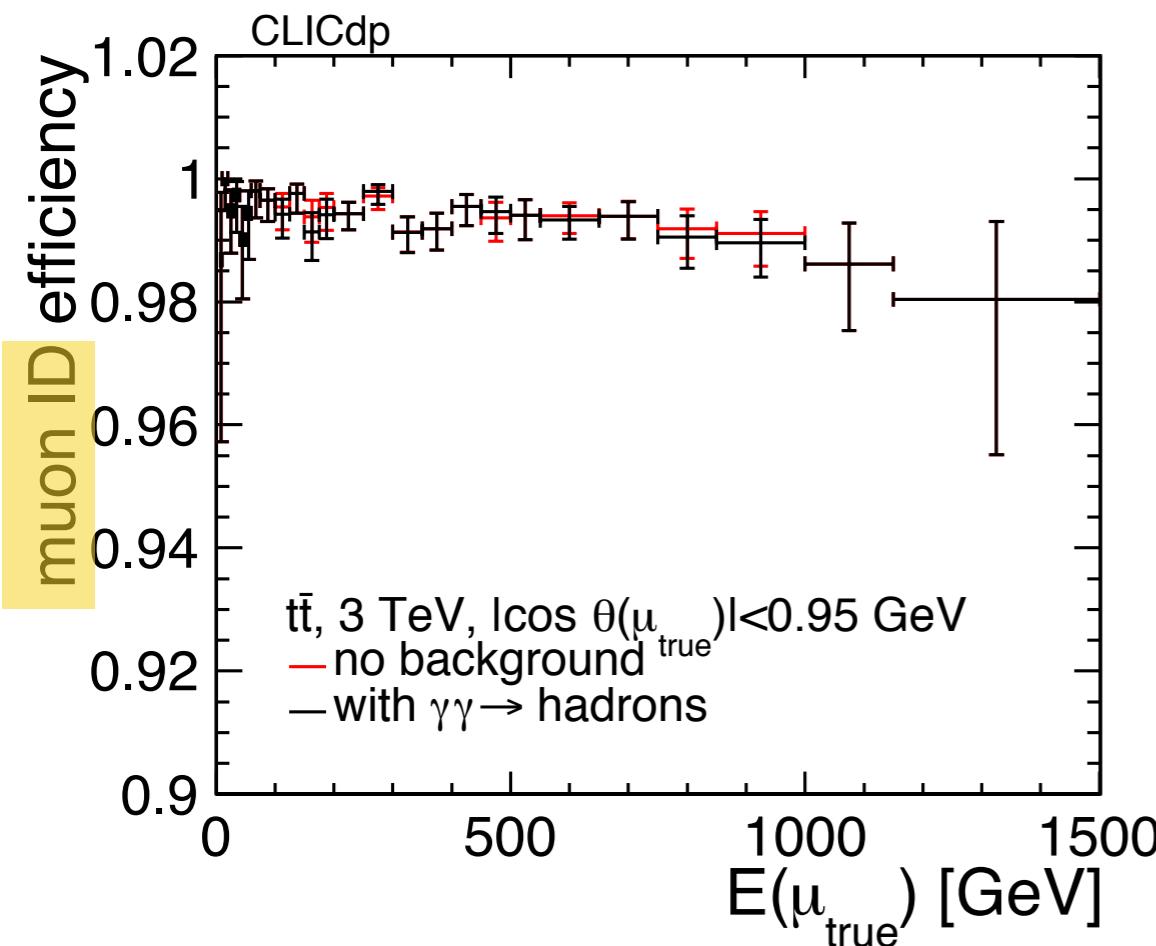
Fake rate dominates at low  $p_T$  when background is overlaid

# Single particle ID efficiency

ttbar events at 3 TeV center-of-mass energy

with 30BX of  $\gamma\gamma \rightarrow$  hadrons at 3 TeV

- Direct leptons from W decays
- Reconstructed leptons required to match “true” leptons within an angle of 1 degree



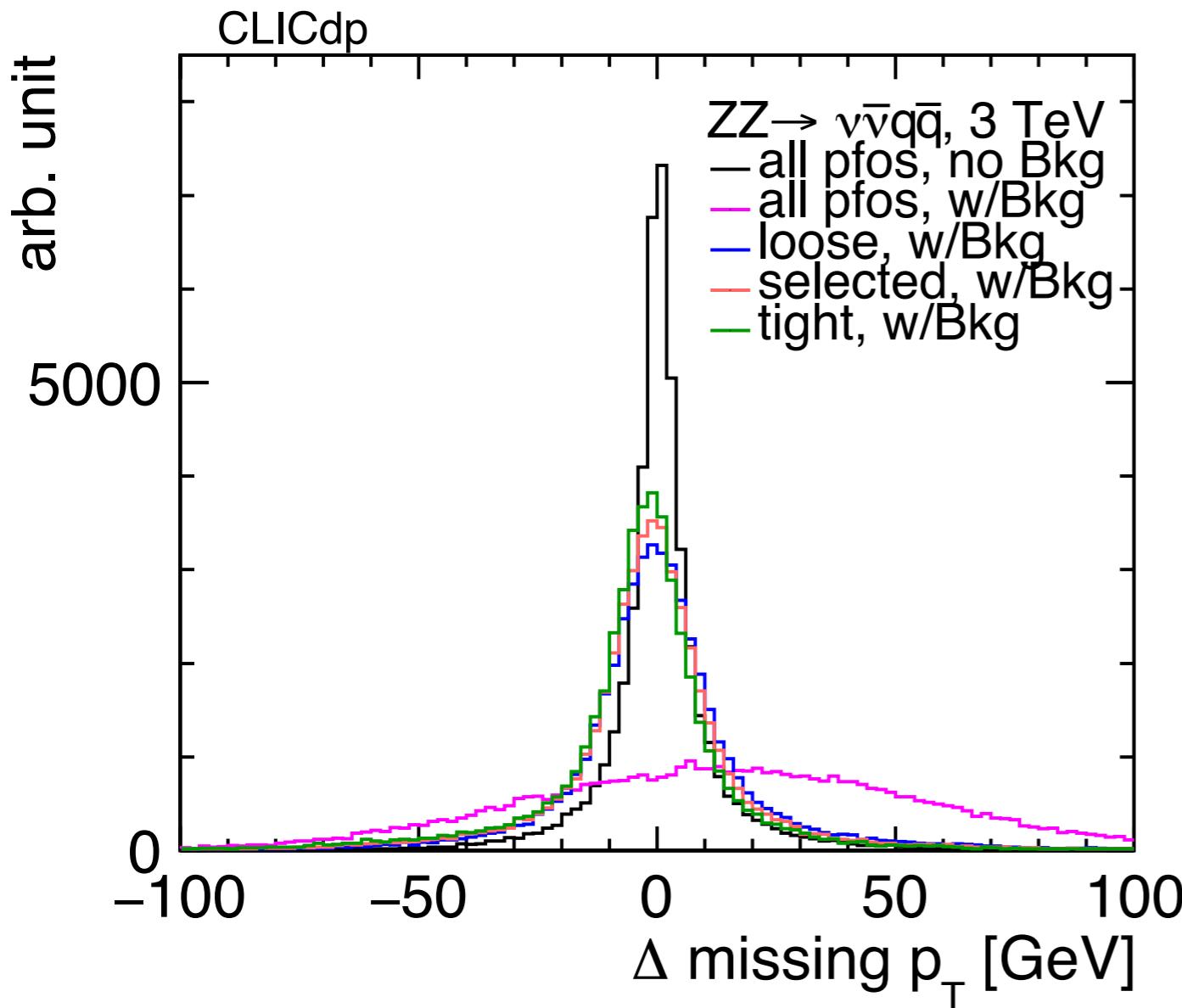
Muons identified with more than 98% efficiency  
Impact of background negligible

Electrons identified with in 90-95% of cases above 20 GeV  
Background causes efficiency loss by 5%

# Missing transverse momentum

double Z boson-like events at 3 TeV decaying in light quark dijets and neutrinos  
with 30BX of  $\gamma\gamma \rightarrow$ hadrons at 3 TeV

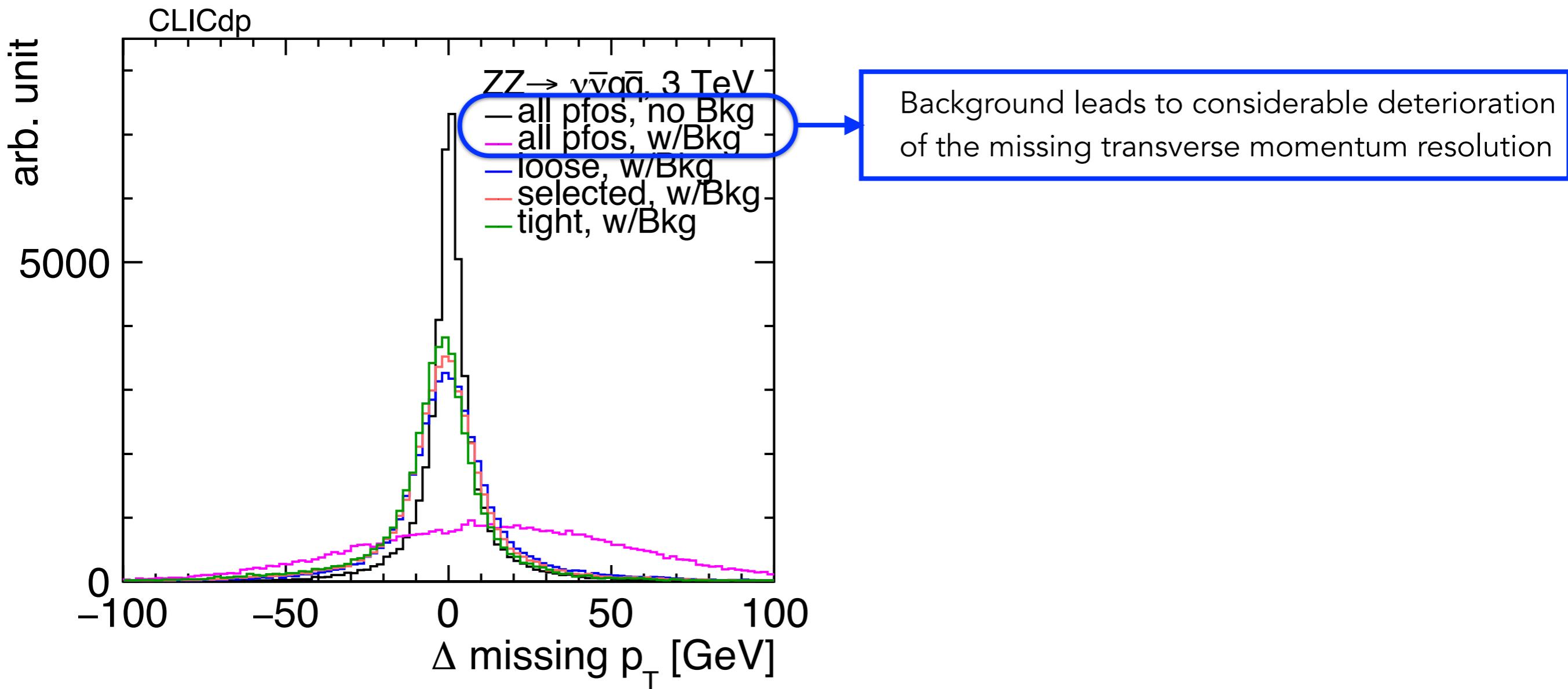
Difference between true and reconstructed missing transverse momentum



# Missing transverse momentum

double Z boson-like events at 3 TeV decaying in light quark dijets and neutrinos  
with 30BX of  $\gamma\gamma \rightarrow$ hadrons at 3 TeV

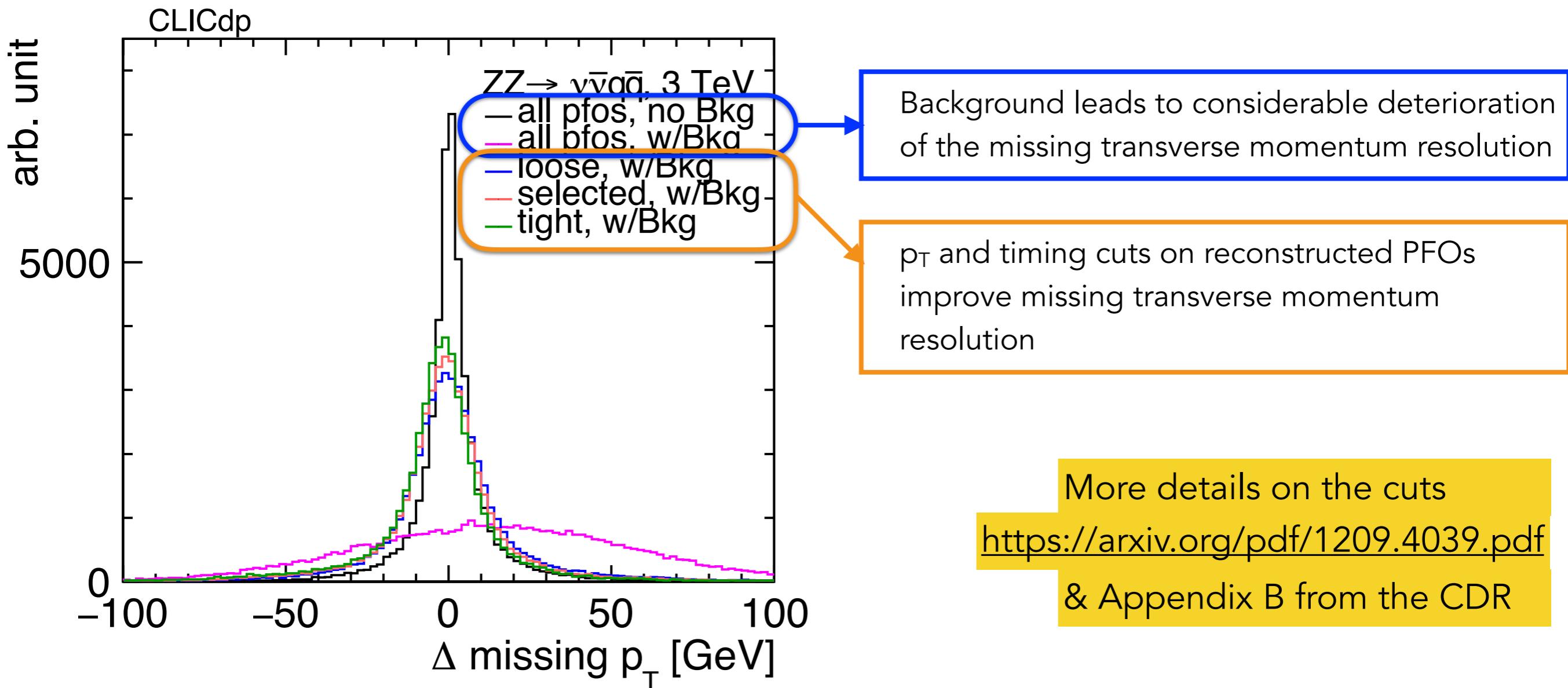
Difference between true and reconstructed missing transverse momentum



# Missing transverse momentum

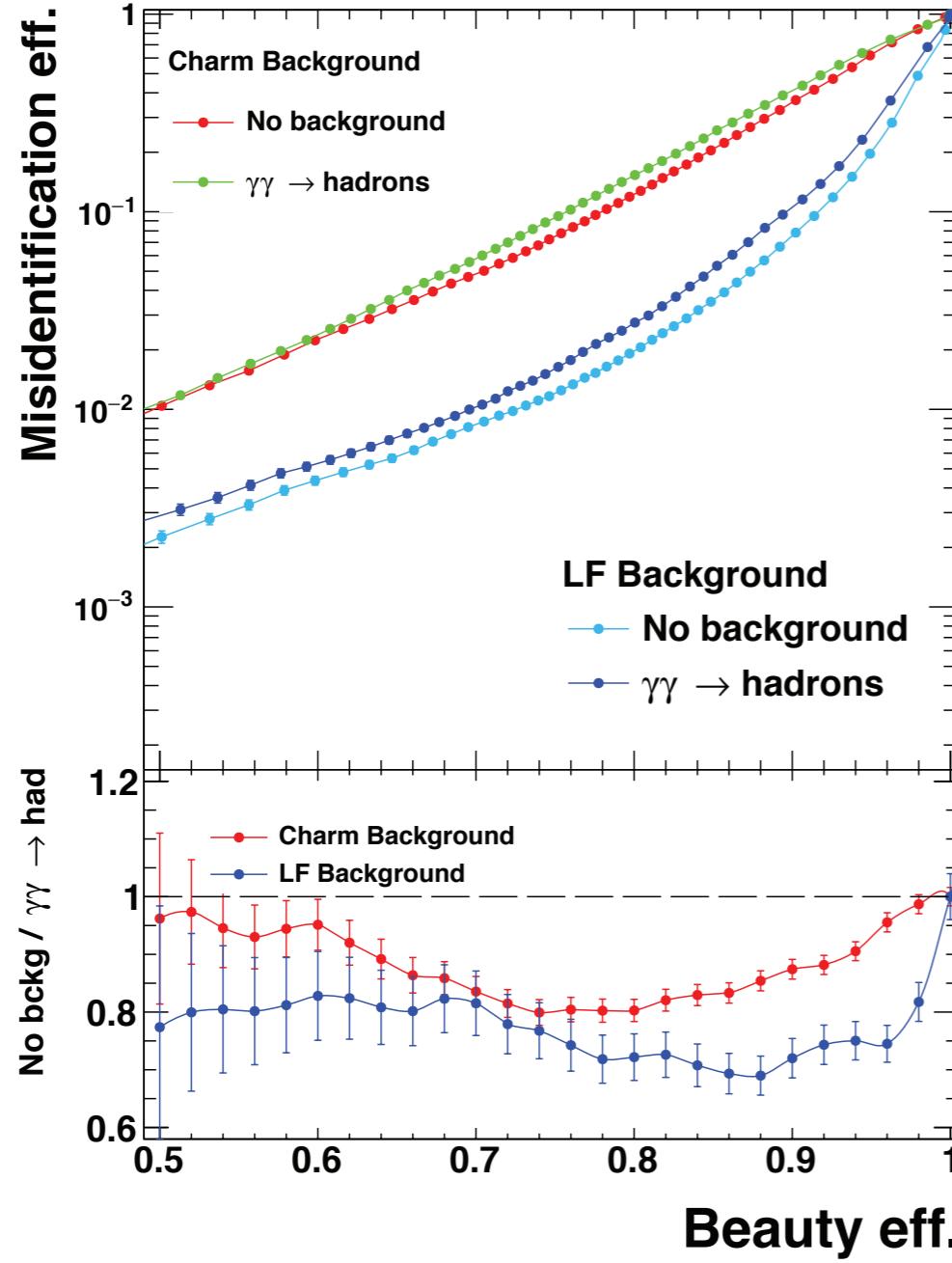
double Z boson-like events at 3 TeV decaying in light quark dijets and neutrinos with 30BX of  $\gamma\gamma \rightarrow$  hadrons at 3 TeV

Difference between true and reconstructed missing transverse momentum

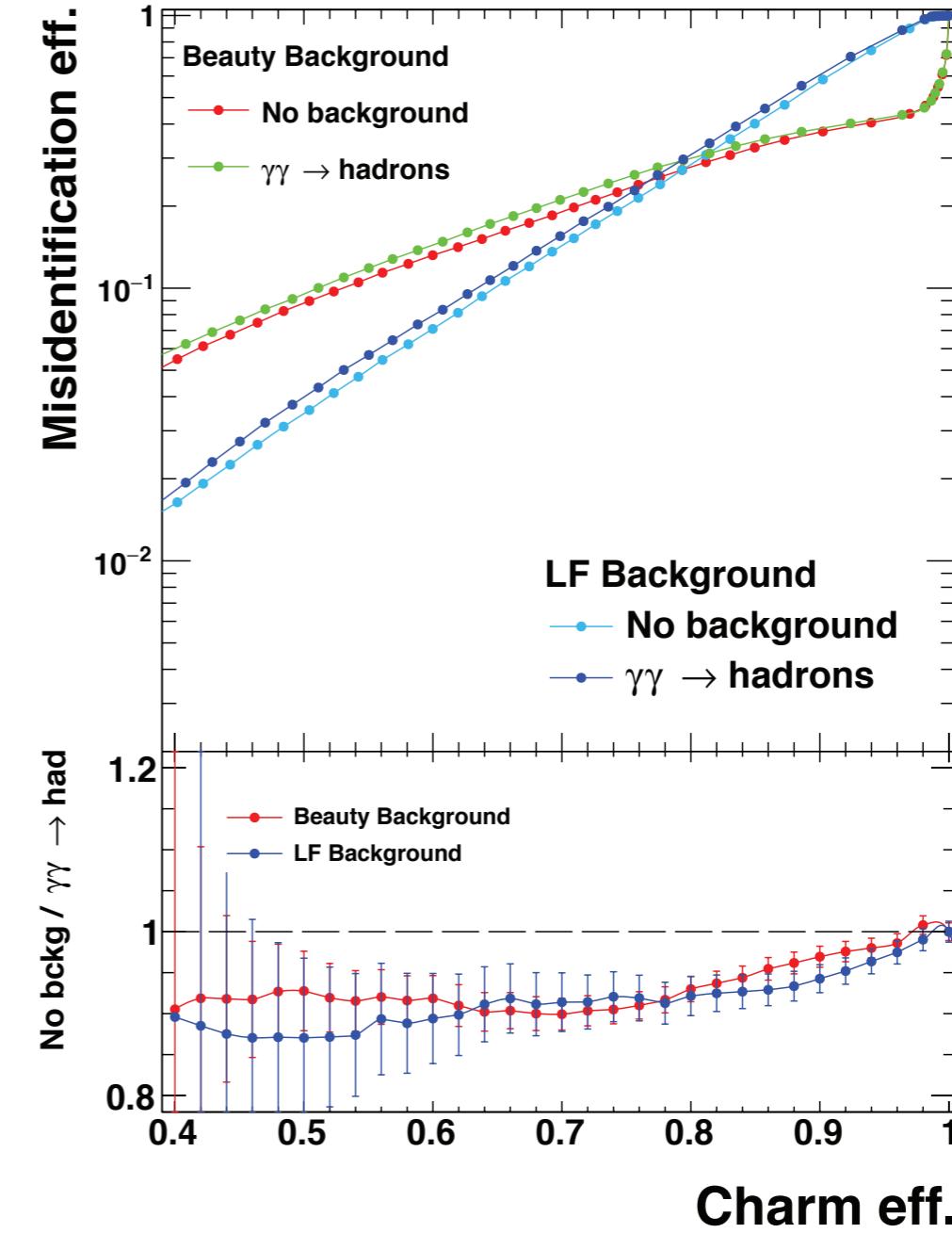


# Flavour tagging

dijet events at 500 GeV center-of-mass energy  
with 30BX of  $\gamma\gamma \rightarrow$ hadrons at 3 TeV



Worsened by 20-30% due to background



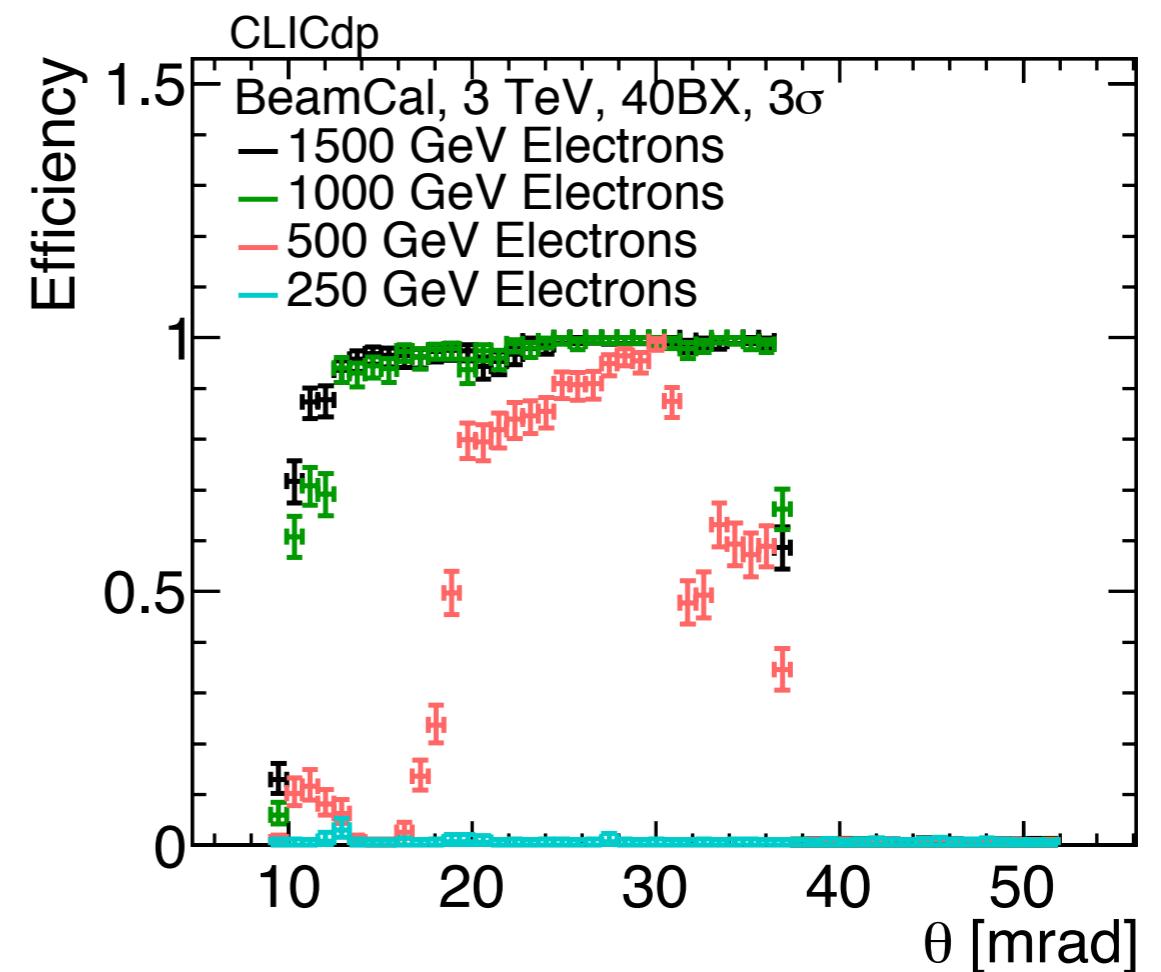
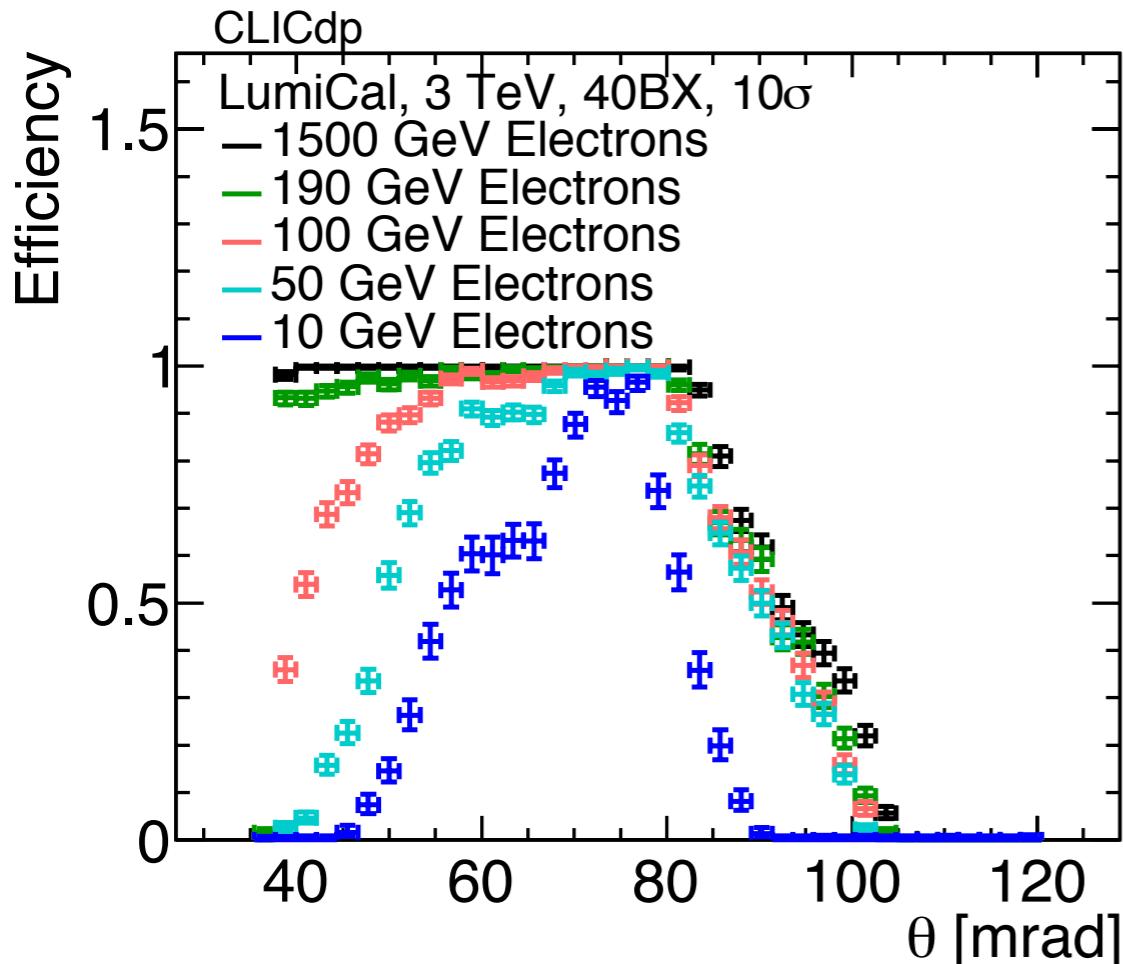
Worsened by up to 15% due to background

# LumiCal and BeamCal efficiency

mono-energetic single electrons

with 40BX of incoherent pairs at 3 TeV

Angular and energy matching between "true" electron and reconstructed cluster required



The lower the electron energy, the higher the impact of background in both LumiCal and BeamCal

This efficiency plays a fundamental role in background rejection for many physics analyses



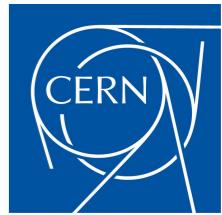
# Content of the talk



- Overview of the CLICdet
  - Optimization of the vertex detector
  - Optimization of the tracker
- Software tools for simulation/reconstruction
- Detector performances for lower level physics observables
- Impact/mitigation of 3 TeV beam-induced backgrounds
- Conclusions and future improvements



# Conclusions and future improvements



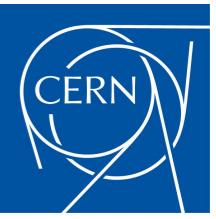
- A high-performing detector has been designed and optimized for CLIC
- A software suite for full simulation and reconstruction is tested and used
- The detector and the reconstruction algorithms show very good performances, matching the requirements from physics goals
- Hardware and software techniques are employed with excellent results to mitigate the effect of 3 TeV background on detector and physics performances
- Further optimizations, foreseen in the reconstruction algorithms, are expected to improve even more the current performances



# References

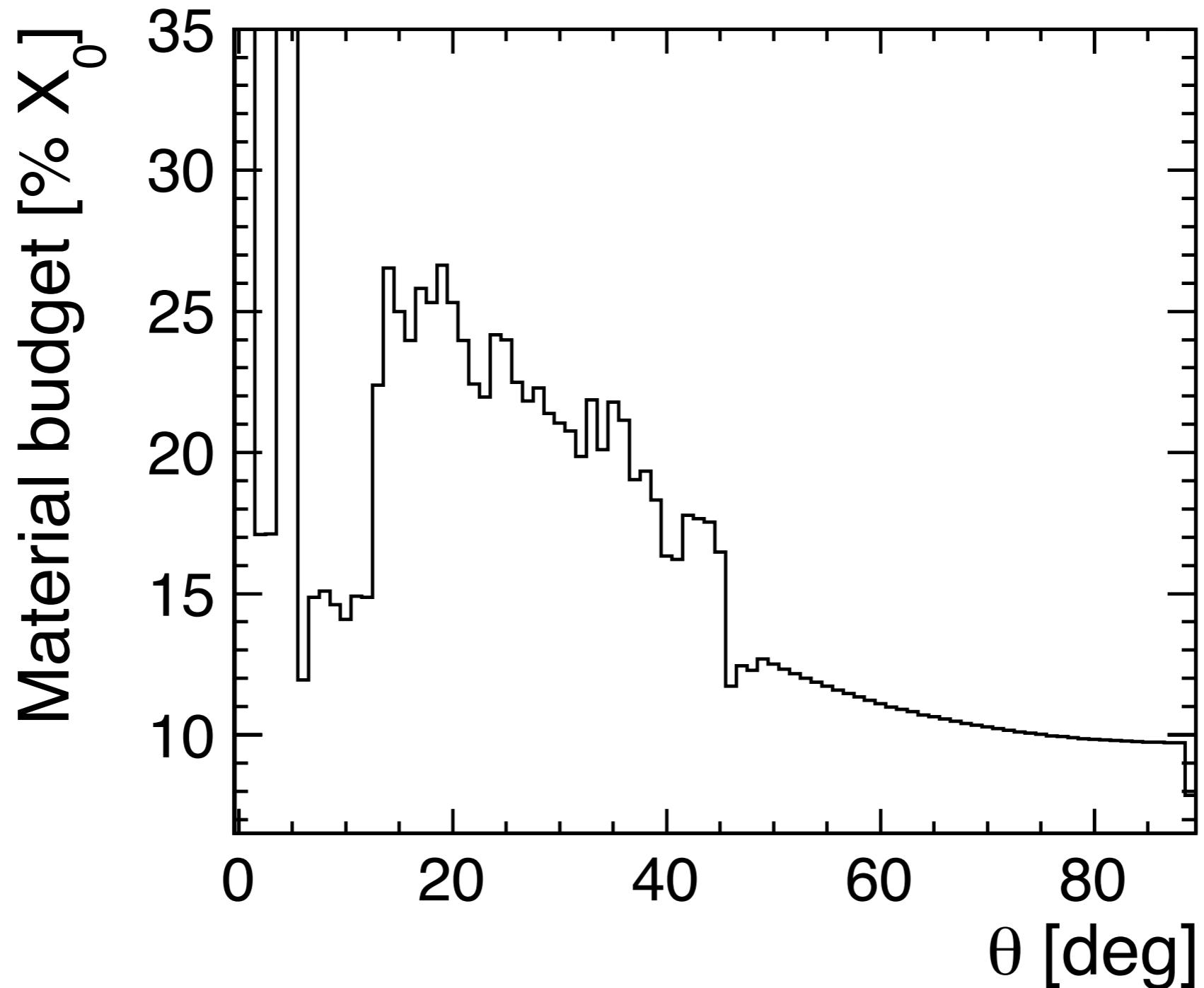


- » Physics and Detectors at CLIC: CLIC Conceptual Design Report  
<https://arxiv.org/abs/1202.5940>
- » CLICdet: the post-CDR CLIC detector model  
<https://cds.cern.ch/record/2234145>
- » Requirements for the CLIC tracker readout  
<https://cds.cern.ch/record/2261066>
- » Optimization studies for the CLIC vertex-detector geometry  
<https://cds.cern.ch/record/1742993>
- » A detector for CLIC: main parameters and performance  
[https://gitlab.cern.ch/CLICdp/Publications/DraftDocuments/Note\\_DetectorPerformance/-/jobs/1235599/artifacts/file/DetectorPerformance.pdf](https://gitlab.cern.ch/CLICdp/Publications/DraftDocuments/Note_DetectorPerformance/-/jobs/1235599/artifacts/file/DetectorPerformance.pdf)

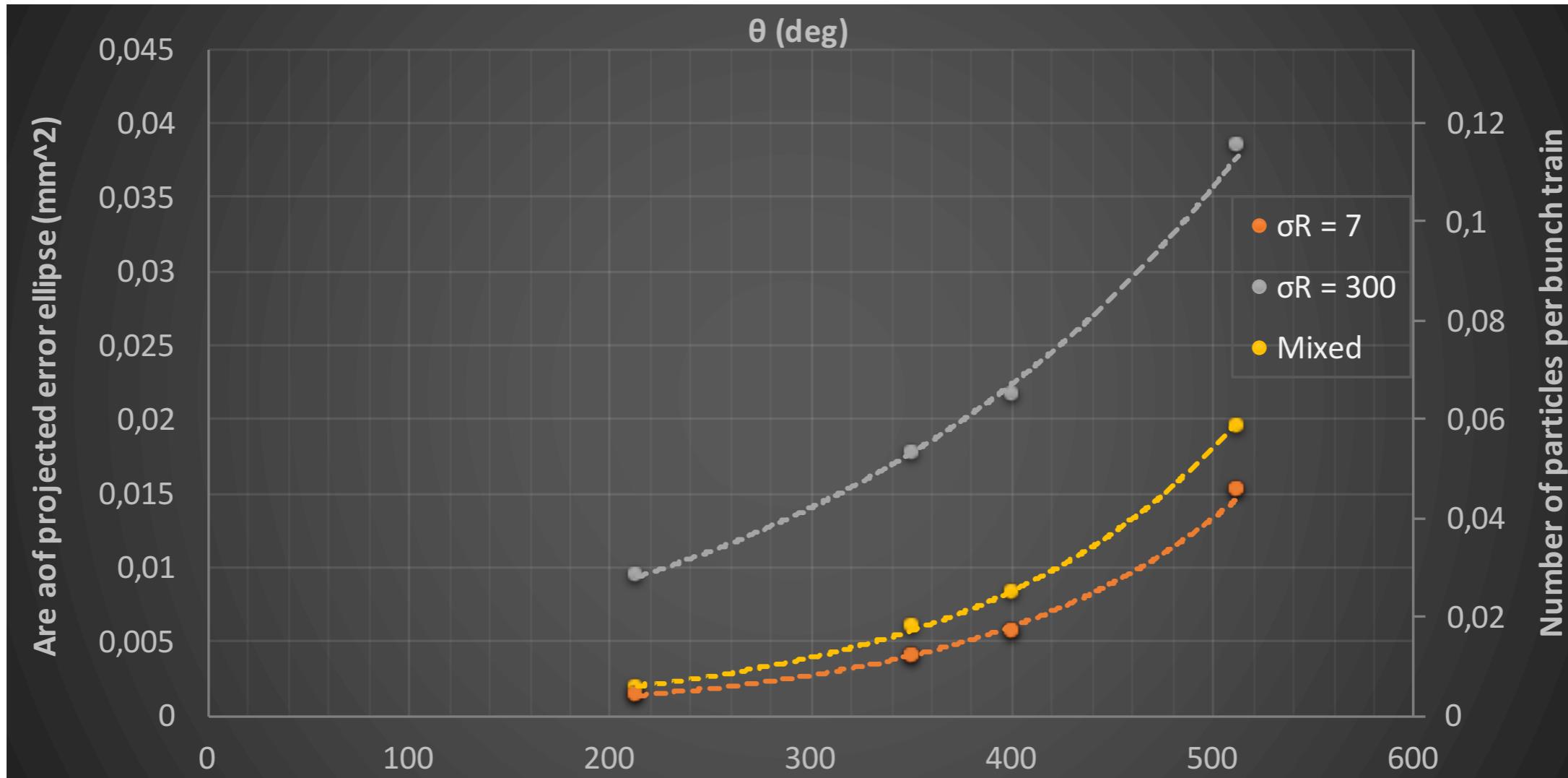


# Extras

## Tracker - total material budget

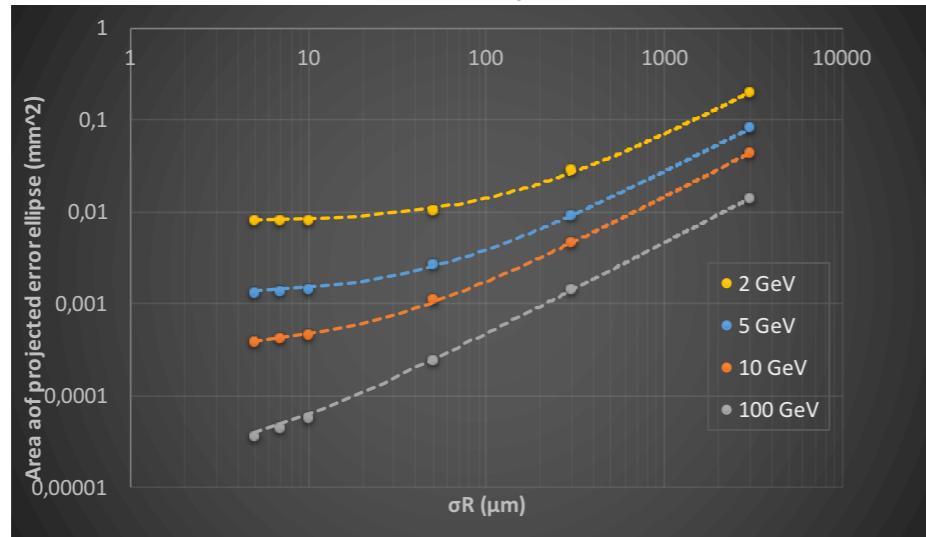


# Tracker - pixelated first inner disk

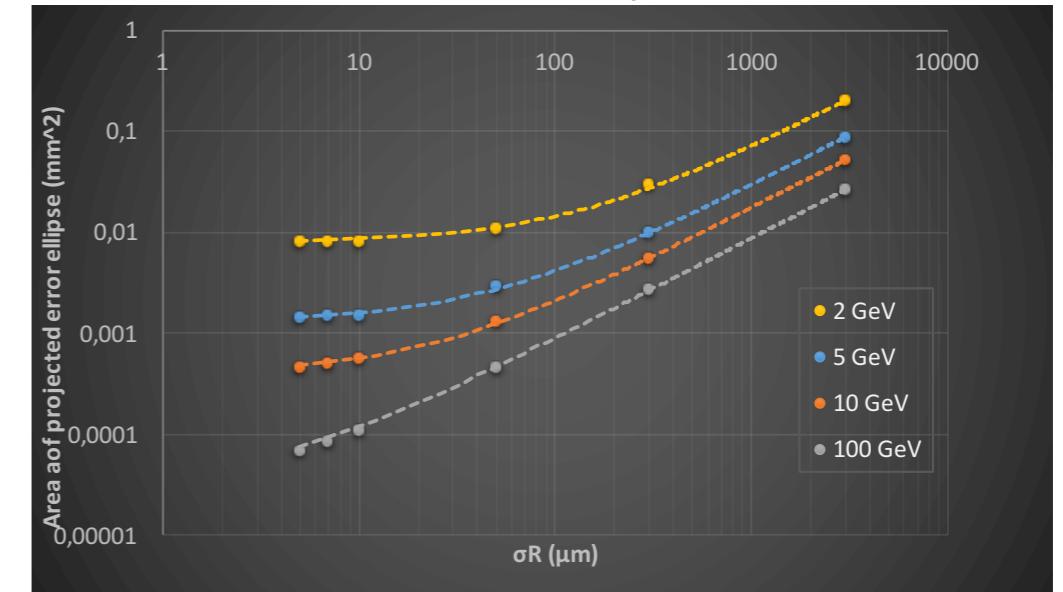


# Tracker - pixelated first inner disk

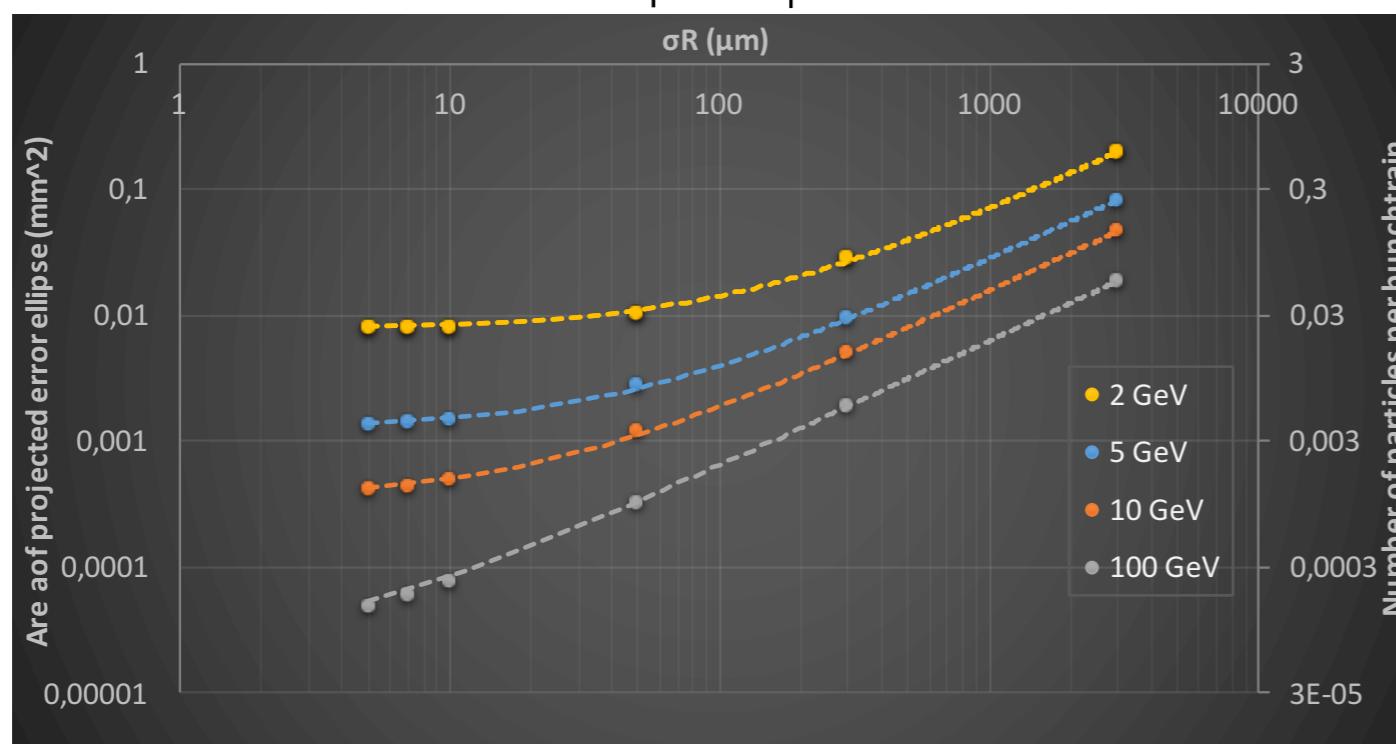
$\sigma R\phi = 5 \mu\text{m}$



$\sigma R\phi = 10 \mu\text{m}$

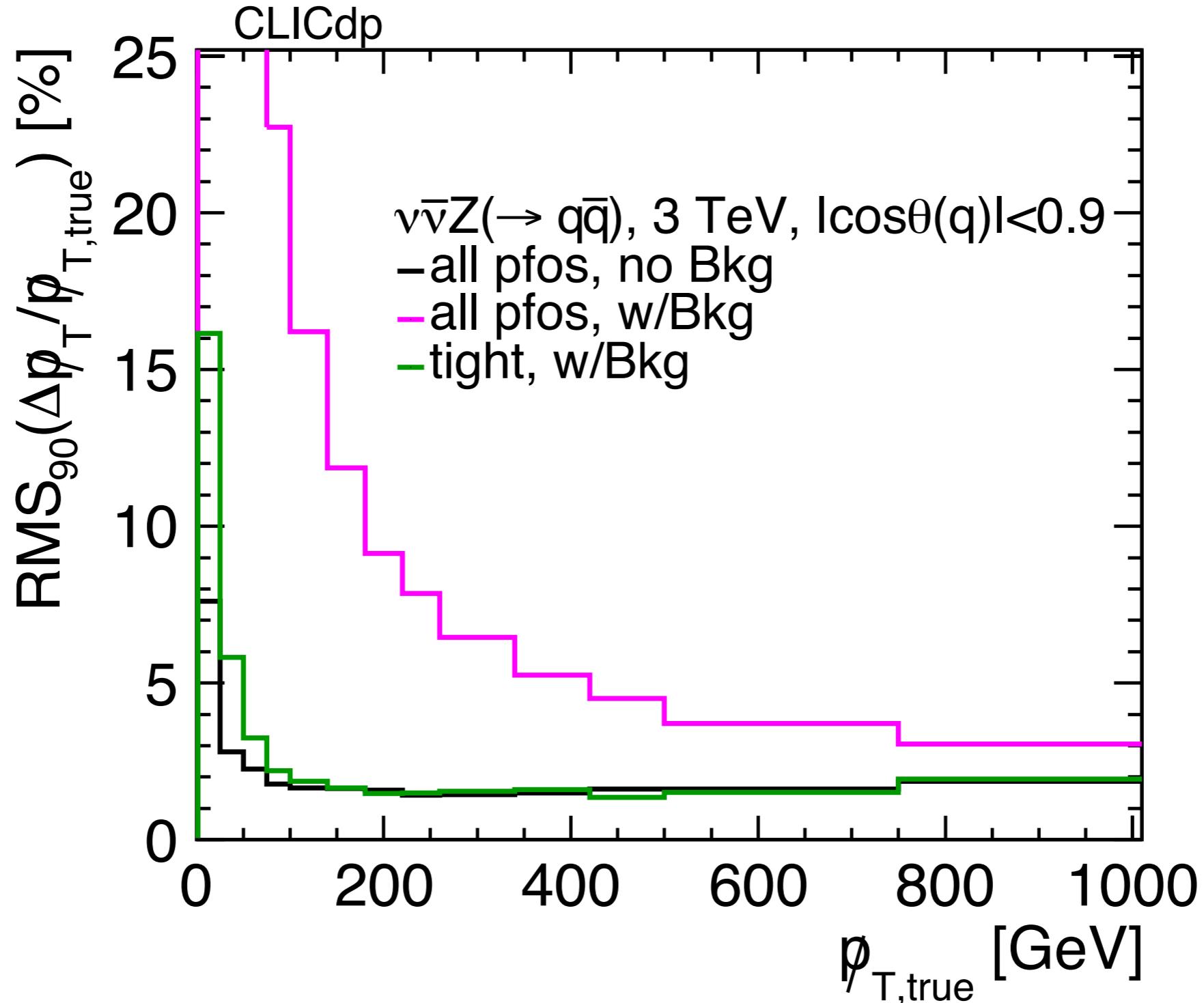


$\sigma R\phi = 7 \mu\text{m}$



Forward disk 1 added to geometry  
at 213 mm from vertex

Small dependence on  $R\phi$  resolution

Missing  $p_T$  resolution



# $\Phi$ resolution

