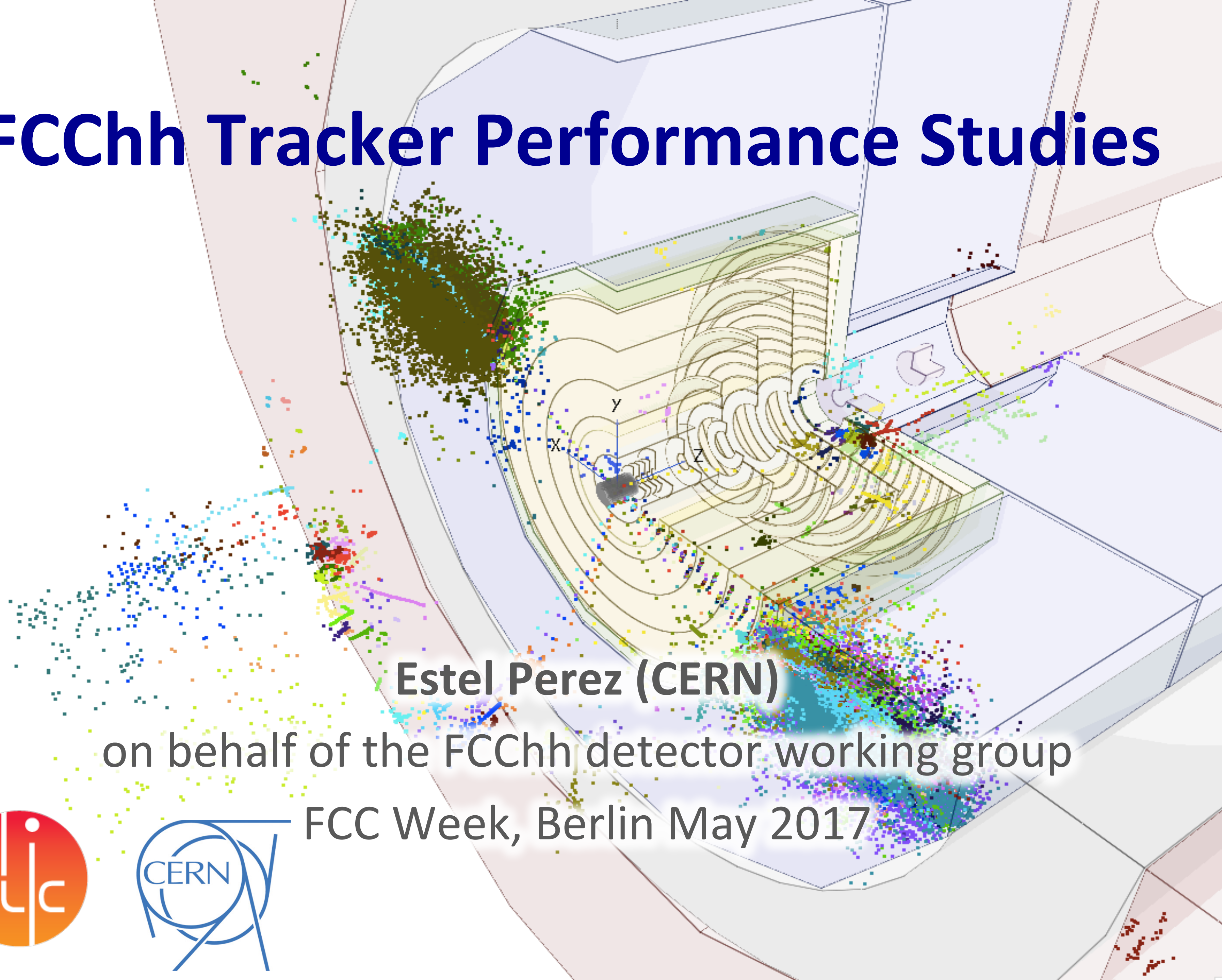
FCChh Tracker Performance Studies



Estel Perez (CERN)

on behalf of the FCChh detector working group

FCC Week, Berlin May 2017

Introduction and Outline

- Goal: show **performance studies** leading to changes in the **FCChh tracker detector** design*

1. Tools and validation
2. **Pattern recognition** studies
   - dependence on detector layout, material and granularity
3. Reconstruction of **boosted objects**
   - dependence on granularity
4. **Flavor tagging** performance
   - dependence on granularity, material, jet energy

*see Zbynek Drasal's talk

Tools

- Different software tools were required for the various performance studies:

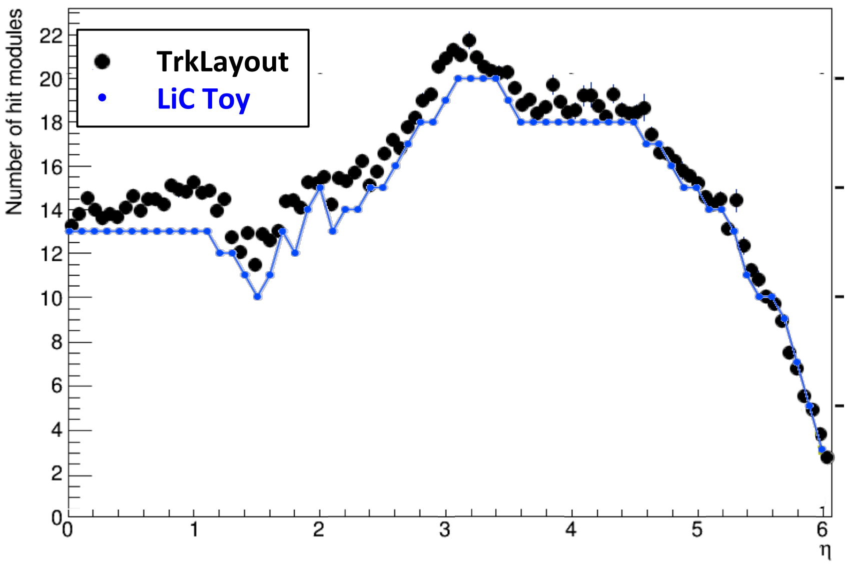
Software previously used by	**tkLayout*** (CMS)	**LicToy** (ILC, CLIC)	**CLIC SW** (CLIC)	**SiD SW** (SiD, CLIC)
Simulation	Fast analytic method to compute covariance matrix	Fast full track reconstruction, outside-in	Full pattern recognition	Full full reconstruction chain
used for studying	**pattern recognition**	**pattern recognition**	**boosted objects**	**flavor tagging**
geometry	v3.00	v3.00	v3.01	v3.02

- Validated the different tools against each other

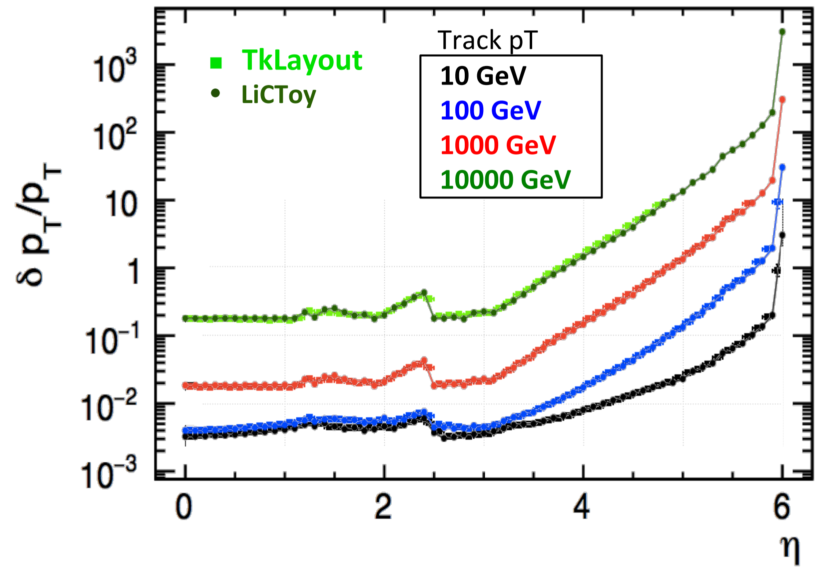
*see Valentin Volkl's talk

Validation of tkLayout against LiCToy

Number of modules with at least one hit



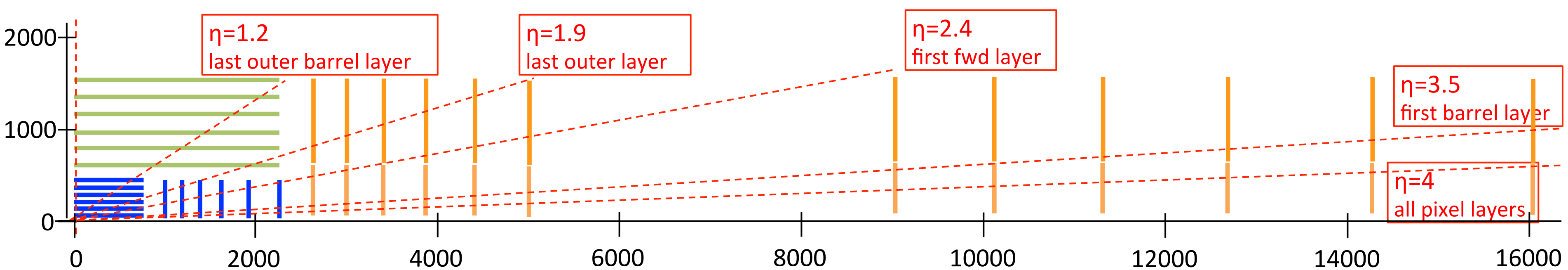
pT resolution



Small differences due to tkLayout allowing several hits per layer

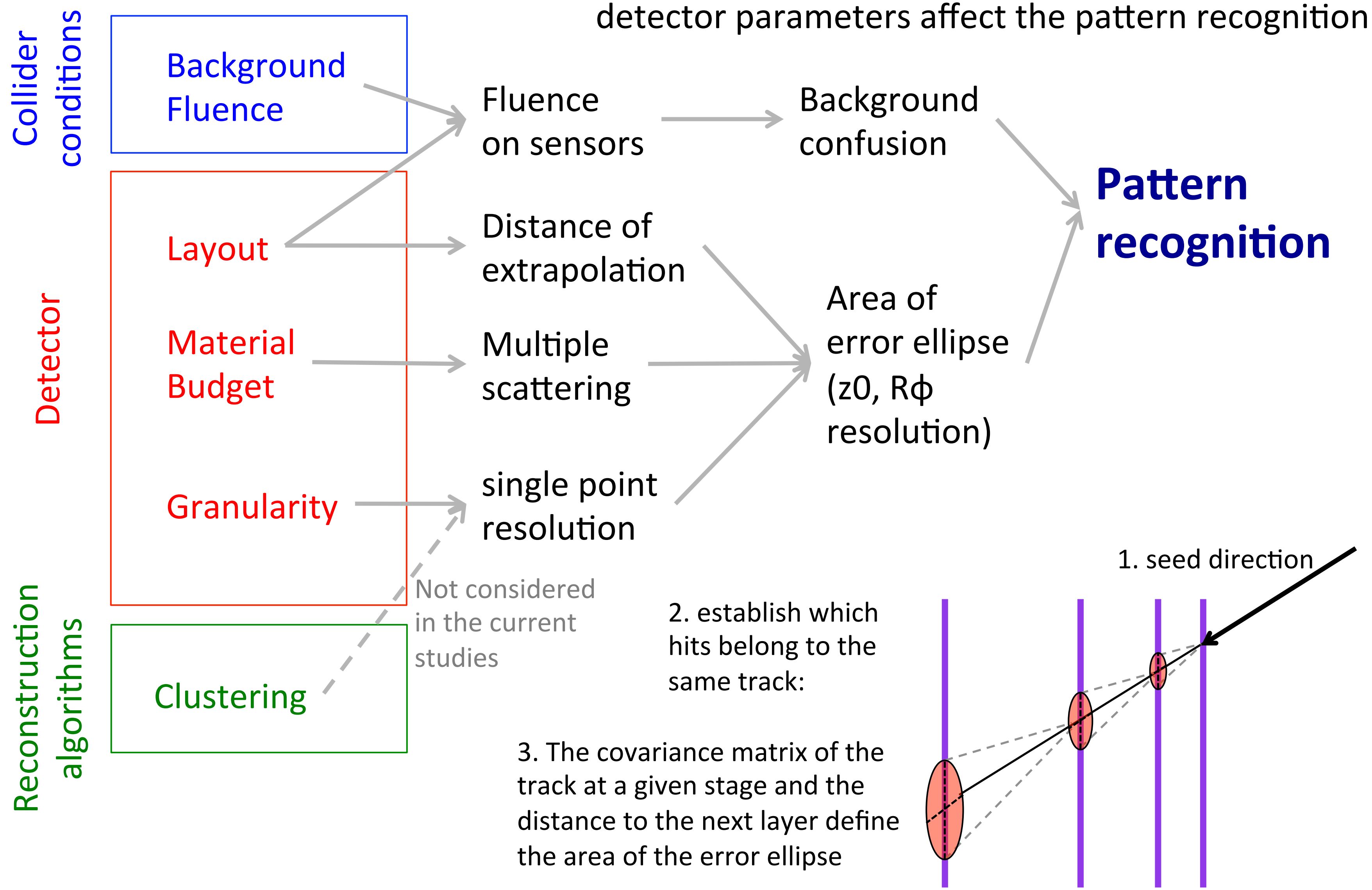
Very good agreement in the pT resolution at all pTs

Nhits and Resolution reflects the layout structure, the **two tools give consistent results**

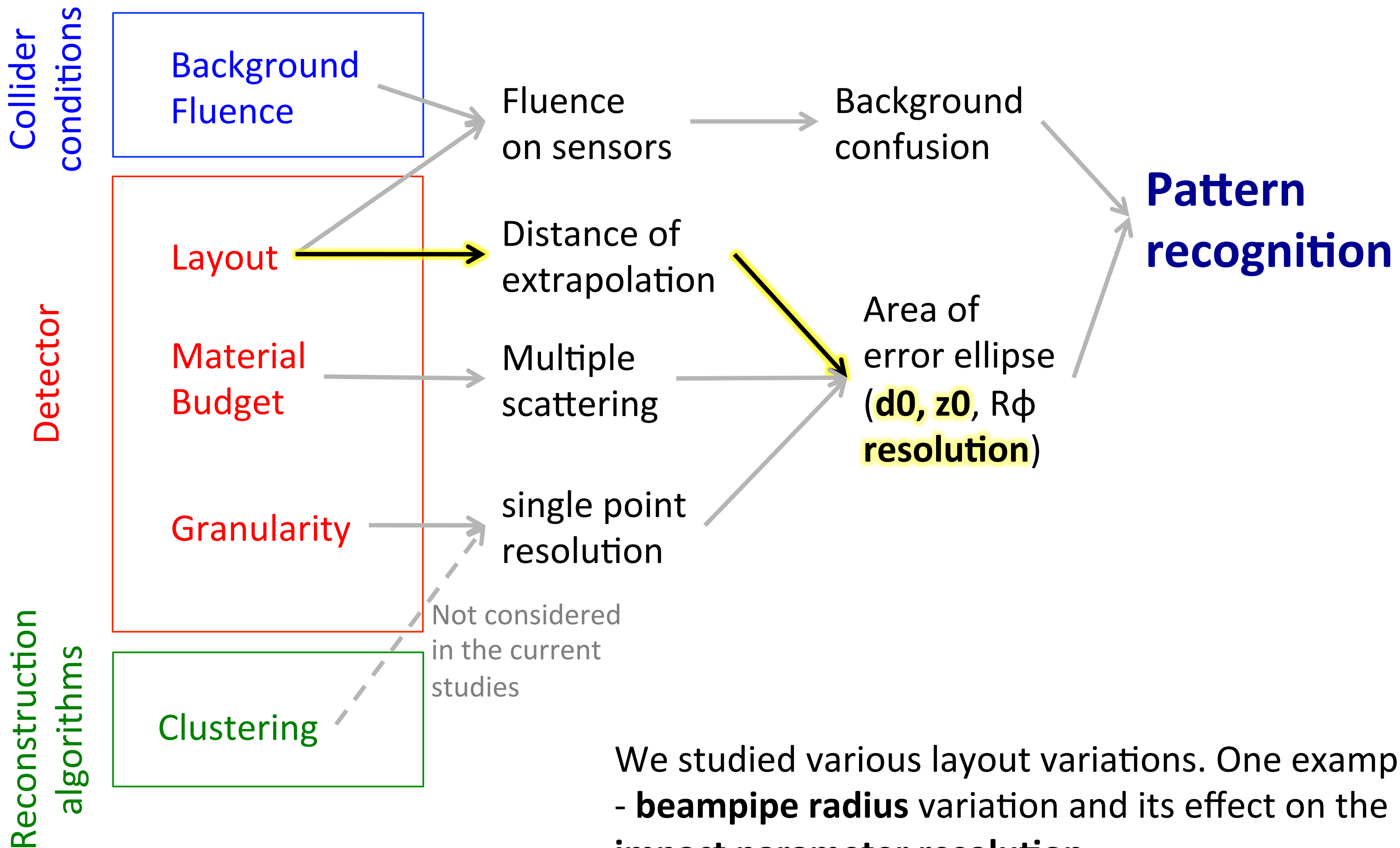


Pattern recognition studies

Technique to study in fast simulation how the detector parameters affect the pattern recognition:

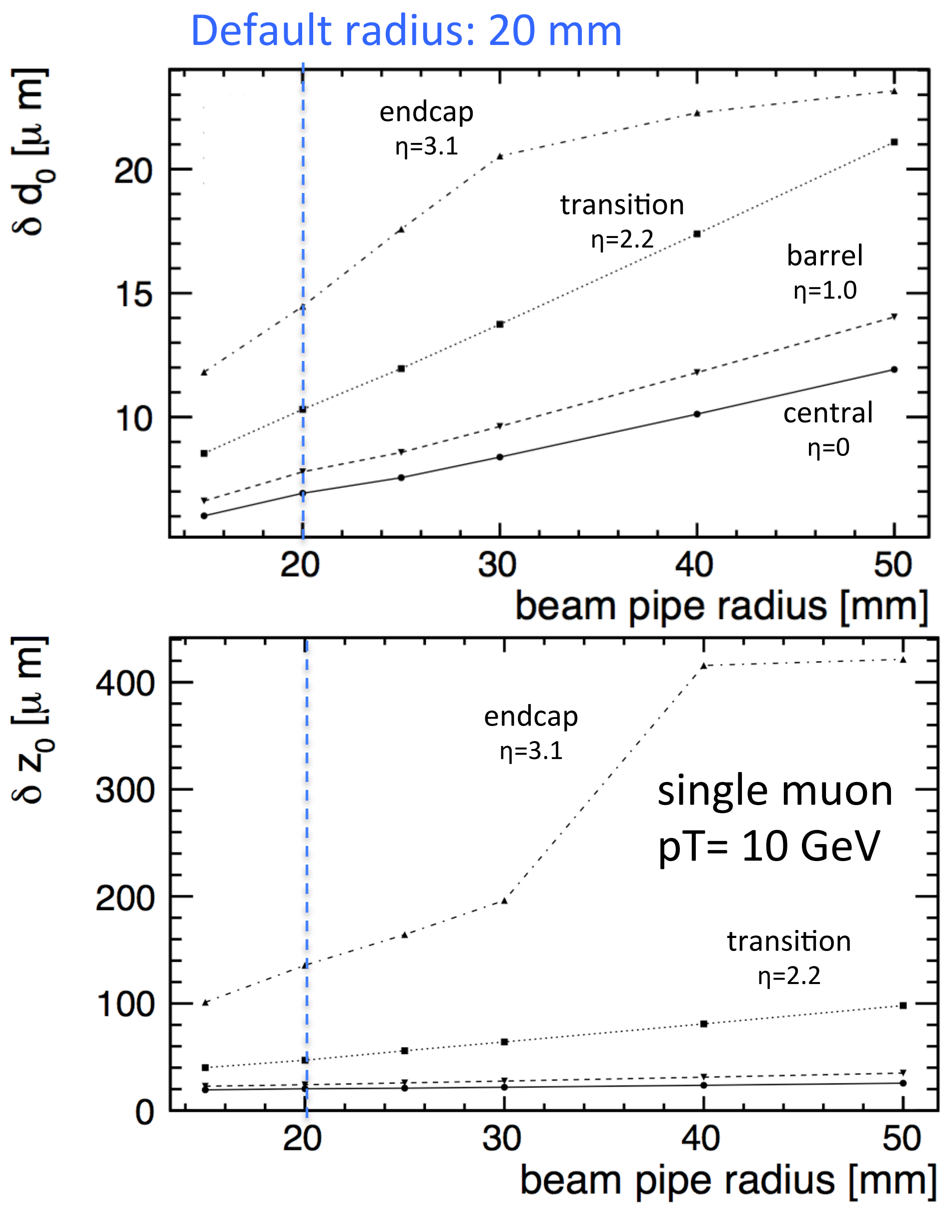


Pattern recognition studies



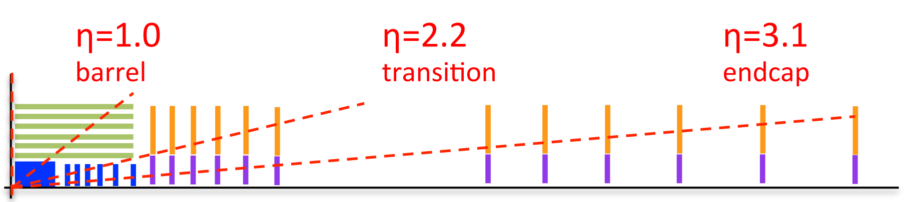
We studied various layout variations. One example:
- **beampipe radius** variation and its effect on the **impact parameter resolution**

Dependence of the impact parameter resolution on the beampipe radius

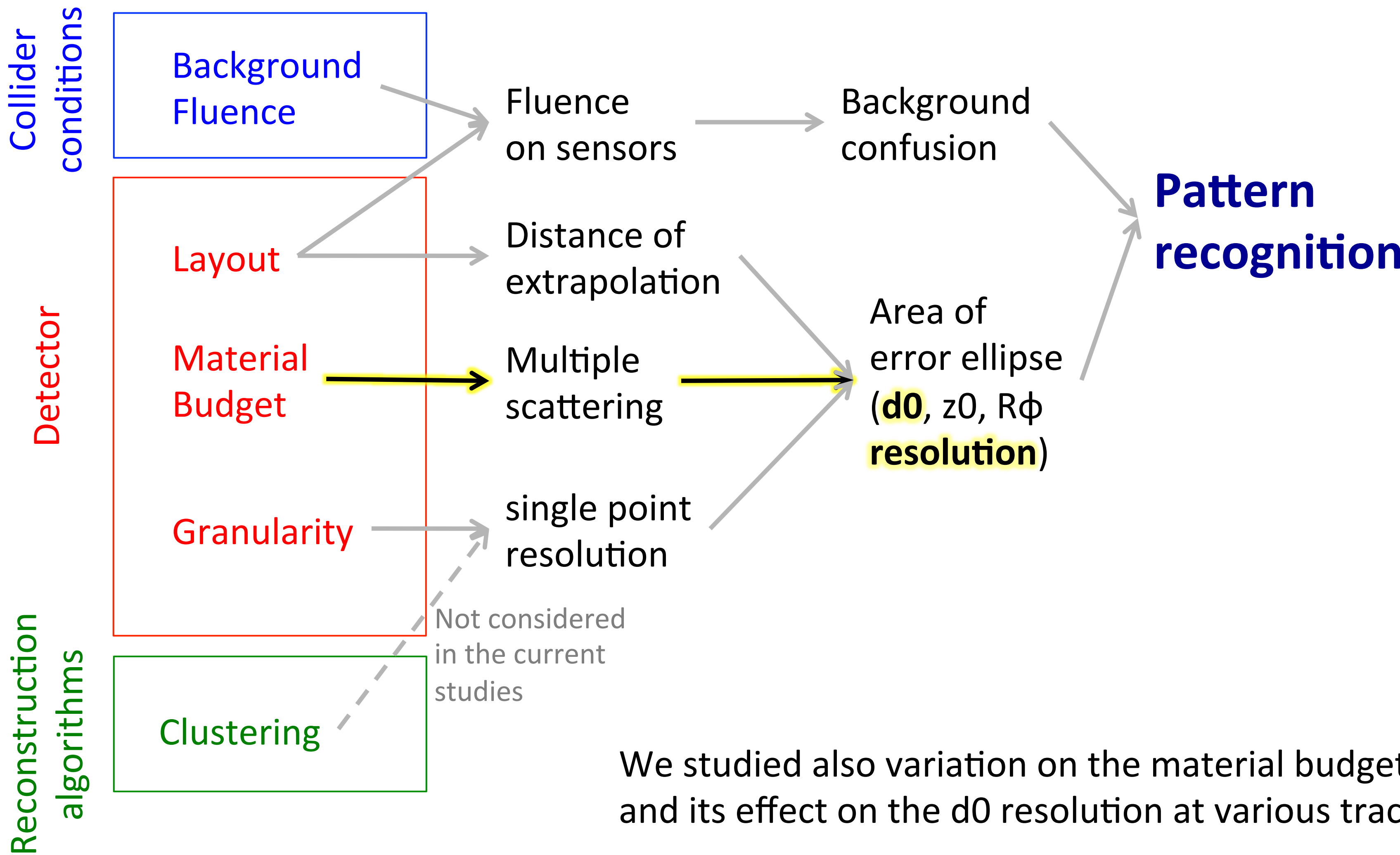


By increasing the beampipe radius, the very forward particles will cross the beampipe more perpendicularly and will be less affected by multiple scattering.

Moving out the innermost barrel layer by **1 cm** would **degrade** the impact parameter resolution by **45%** for very forward tracks of pT=10 GeV. → keep radius as small as possible



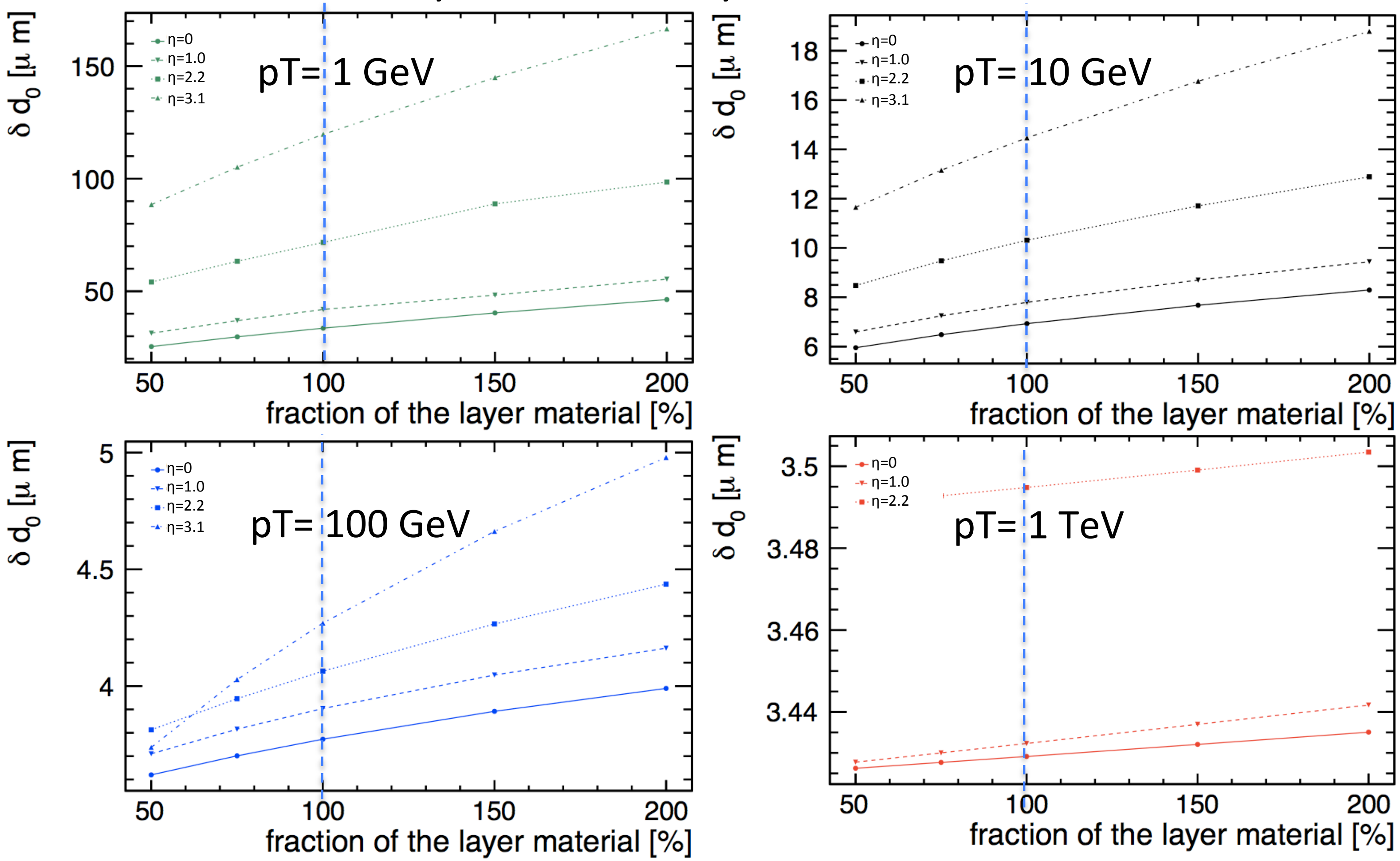
Pattern recognition studies



We studied also variation on the material budget and its effect on the d0 resolution at various track pT

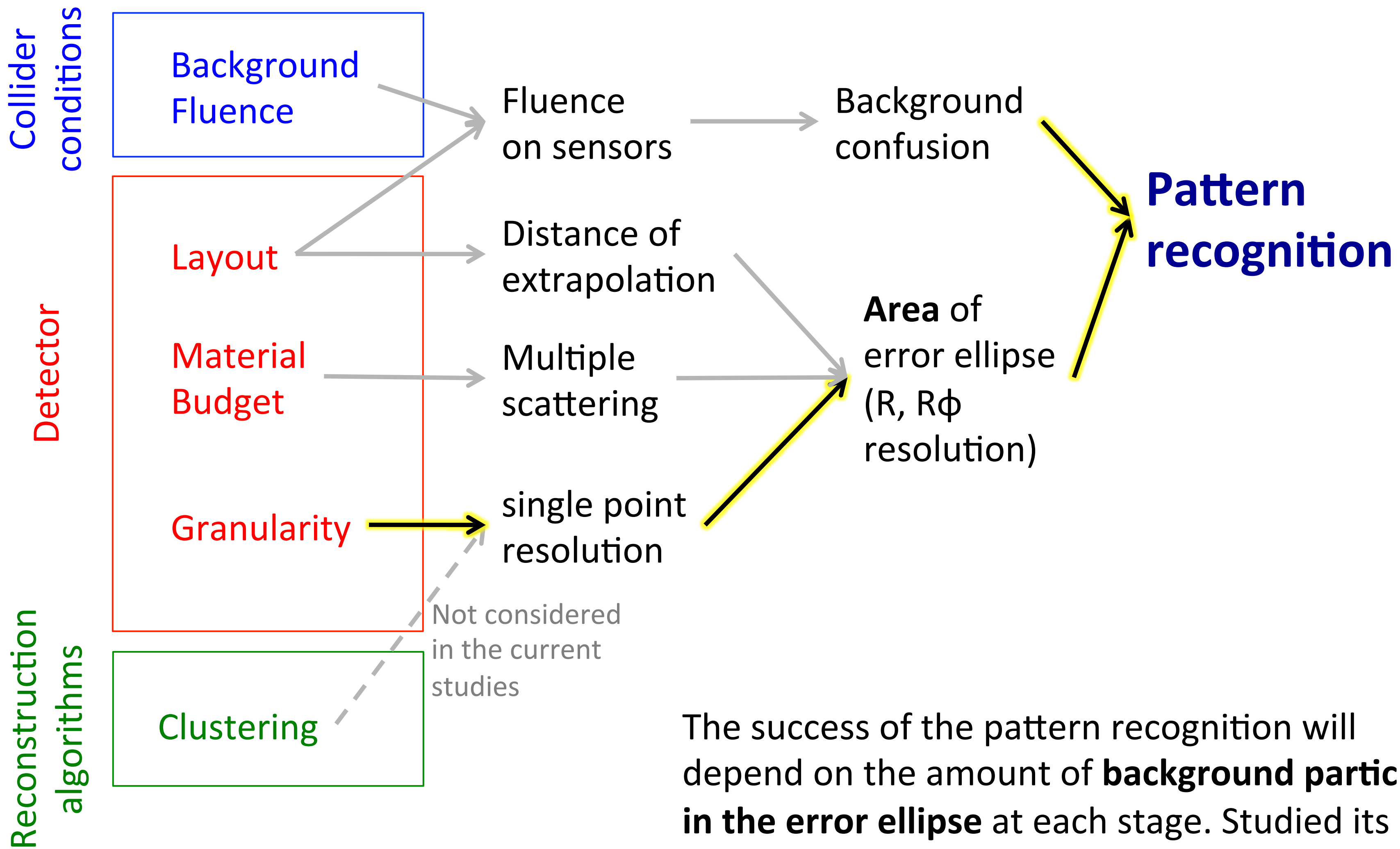
Dependence of the d0 resolution on the layers material budget

Reduce/increase all layers material by: 50%, 75%, . . , 150%, 200%



Reducing the material budget by 50% would improve the d0 resolution by 20% (25%) for a forward track of η=3.1 and pT=10GeV (1GeV)

Pattern recognition studies



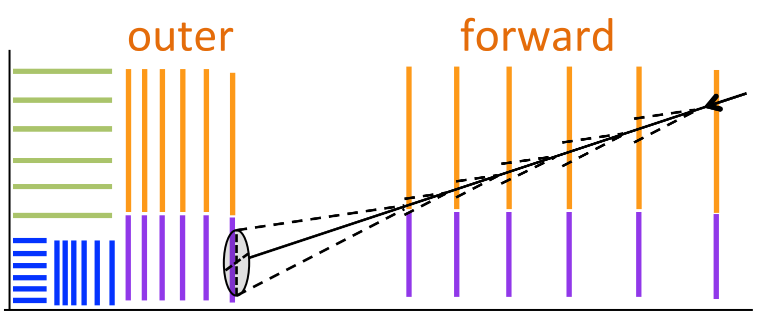
The success of the pattern recognition will depend on the amount of **background particles in the error ellipse** at each stage. Studied its dependence on the sensors granularity.

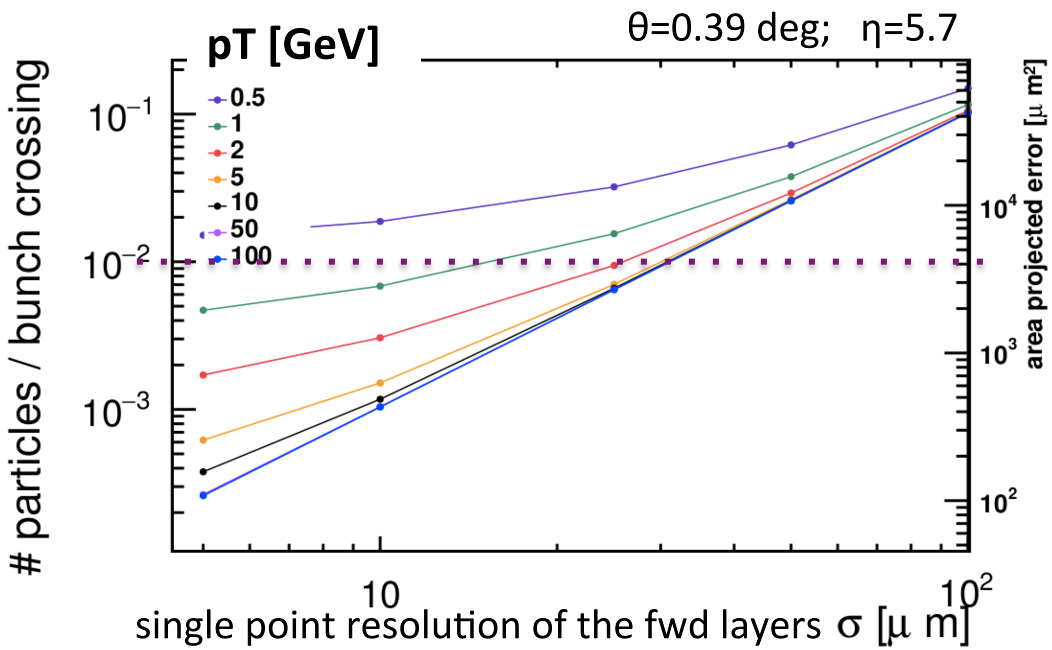
Background in the error ellipse vs granularity

 # bkg particles in error ellipse = Ellipse Area * Pile up * Fluence

Ellipse Area = ¼ $\pi \sigma_{R\phi} \sigma_z \tan\theta$
Assume # Pile up interactions per bunch crossing **=1100**
Granularity: Assume squared pixels and single point resolution = pitch/√12

Most critical stage**: extrapolation to the outer tracker**. Outside-in: depends on the **granularity of the forward disks**



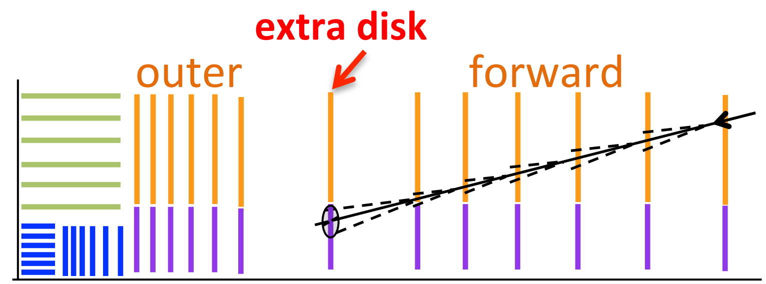


In order to have less than **0.01 background particles** per bunch crossing in the error ellipse area, **would need σ=10x10μm** single point resolution in the forward disks.
Not possible to do **pattern recognition** for tracks **below pT=1 GeV** with this layout

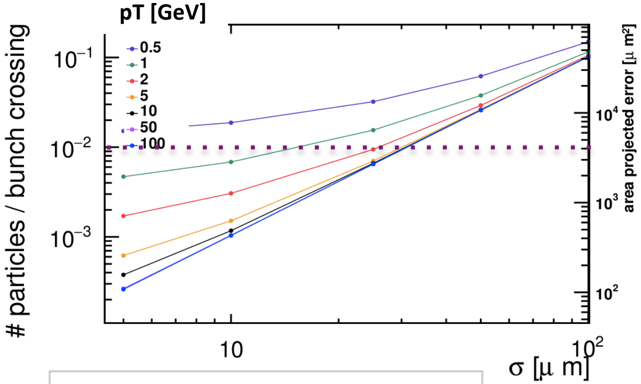
at η=5.7, pT=1 GeV → p=150 GeV

Background in the error ellipse vs layout

One can reduce the error ellipse area by adding an **intermediate disk** and thus reducing the extrapolation distance

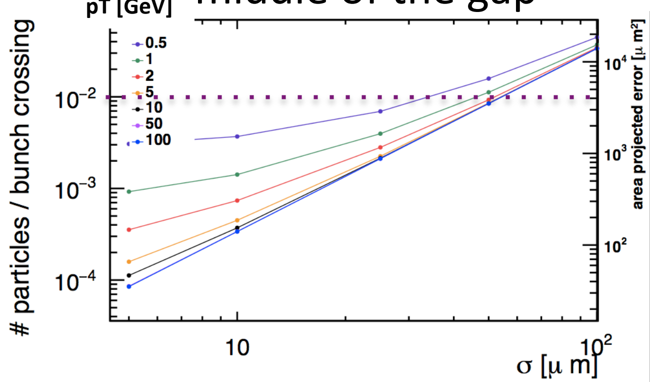


Reference



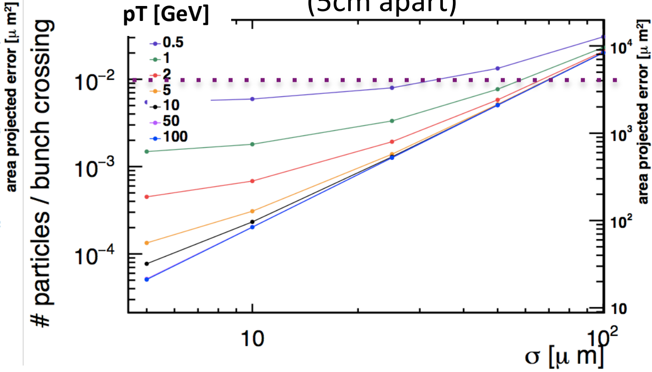
η=5.7 track
Line at # particles in the error ellipse area per BC = **0.01**
Assume #PU/BC = 1100

extra disk in the middle of the gap



→ **factor of 5 less ellipse area**

pair of extra disks in the middle of the gap
(5cm apart)



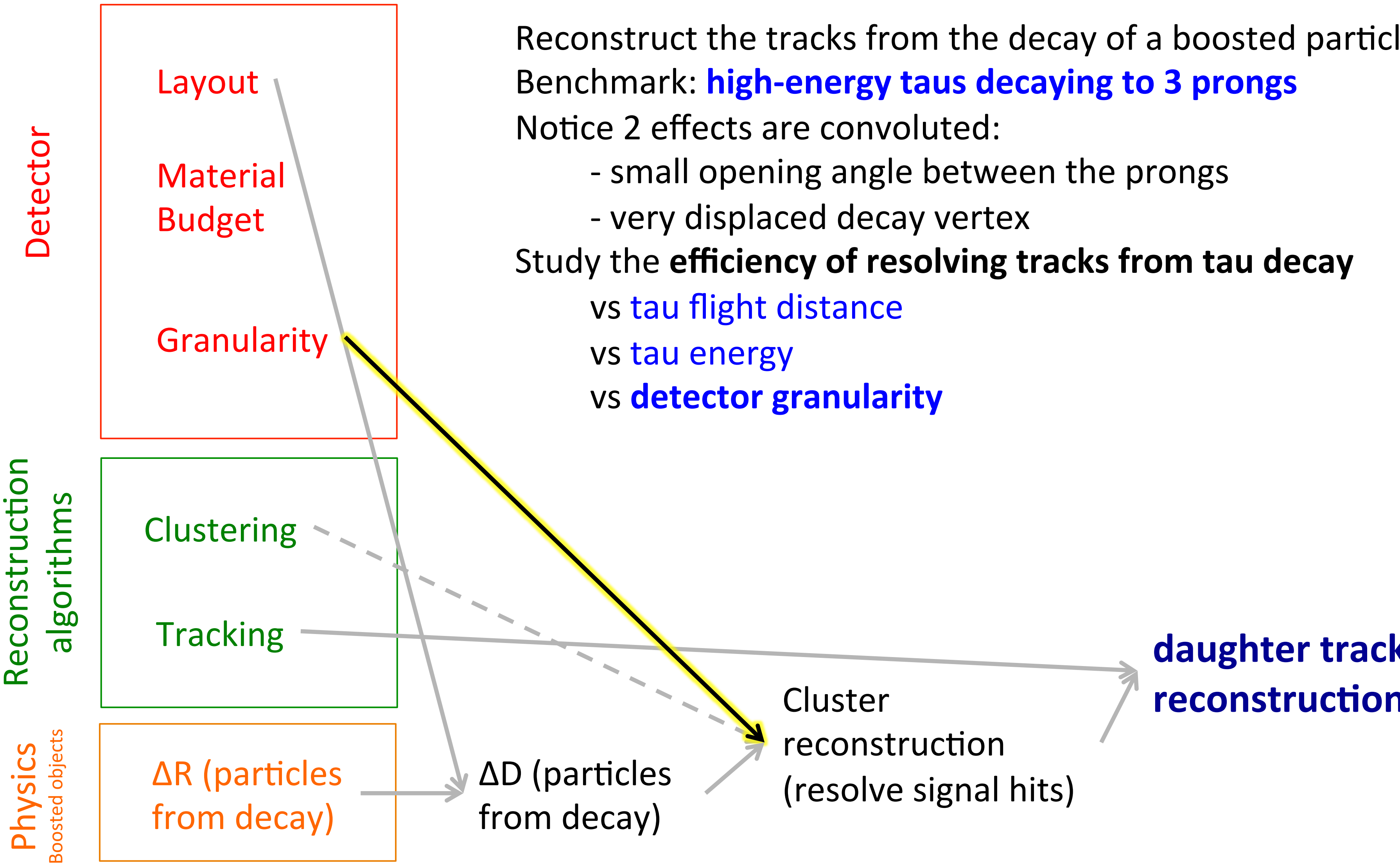
→ extra material is counter-productive for low pT tracks

By adding one **intermediate disk**, we can use **σ=25x25 μm single point resolution for the forward disks** and reconstruct tracks down to **pT=0.5 GeV**.

Boosted particle decay

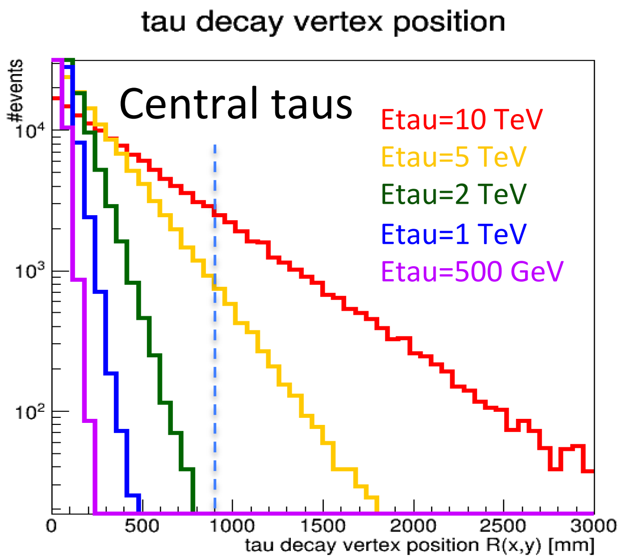
Reconstruct the tracks from the decay of a boosted particle
Benchmark: **high-energy taus decaying to 3 prongs**
Notice 2 effects are convoluted:
- small opening angle between the prongs
- very displaced decay vertex

Study the **efficiency of resolving tracks from tau decay**
- vs tau flight distance
- vs tau energy
- vs **detector granularity**



Efficiency definition

- Tracks from taus decaying too far into the detector will be impossible to reconstruct: **assume we need to resolve the hits in at least 4 layers**



«**Acceptance**»:

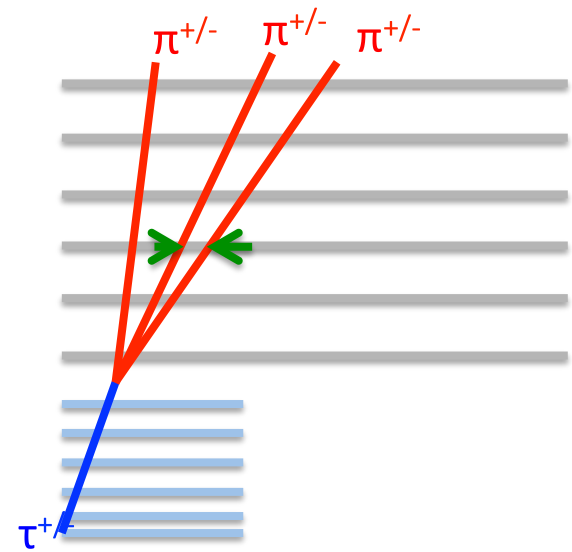
Fraction of **central** taus decaying before the **4th-to-last barrel layer**

Etau=10 TeV : 0.86

Etau=5 TeV : 0.98

Etau=2 TeV : 0.9999

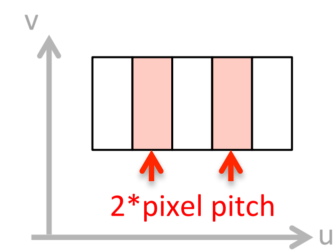
Etau=1 TeV : 1



Assume: single-hit clusters

Resolved hits = distance between two particles > 2*pixel pitch

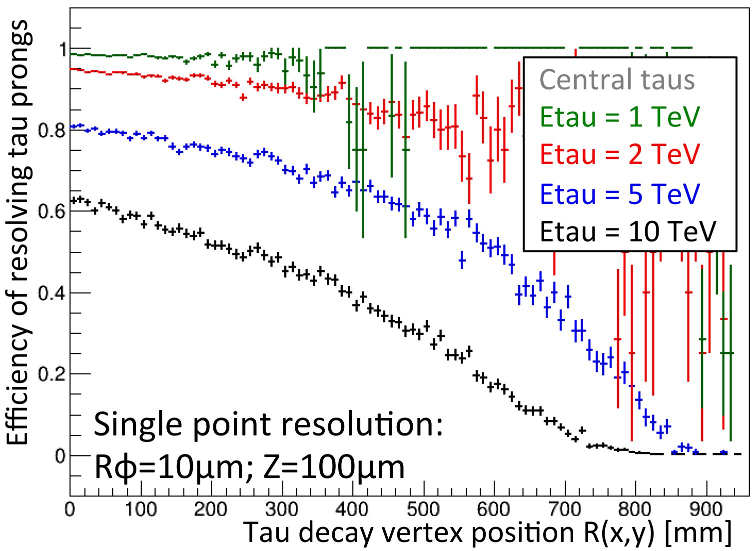
(In either the Rϕ(u) or Z(v) direction)



Efficiency = # resolved hit pairs / closest pair of pion hits in the 4th-to-last layer

Efficiency vs single point resolution

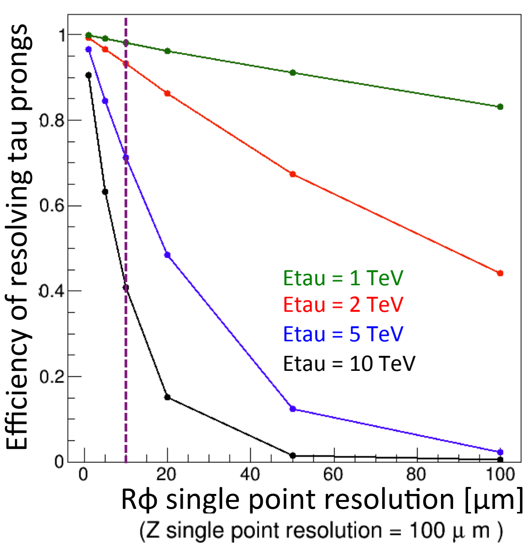
Efficiency vs decay vertex position

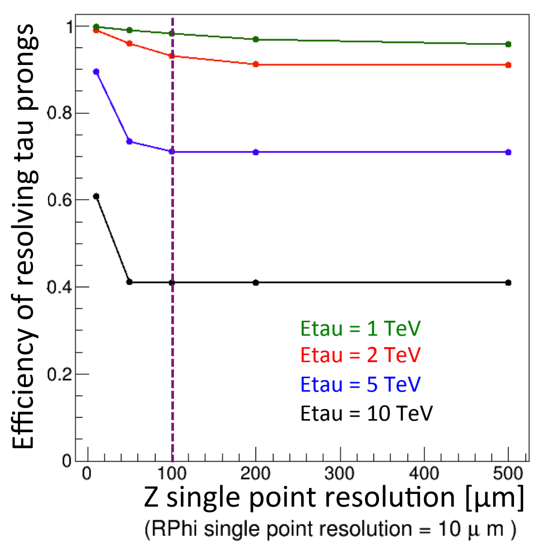


Efficiency vs tau **decay vertex position**:

- 10 TeV “prompt” taus (decaying inside the beampipe) have ~**60% efficiency** only due to the small **opening angle** between their decay products
  - Could be improved by using higher detector **granularity**
- Efficiency drops in R due to tau displaced decay

No significant inefficiency for taus of E < 1 TeV





Efficiency vs **single point resolution:**

- Strong dependence on single point resolution, specially for high energy taus
- In the current design, efficiency driven by Rϕ. Not much gain by improving Z resolution unless comparable to Rϕ.

Efficiency vs single point resolution

- Benchmark: **B-hadrons**
- Acceptance: Fraction of **central** B hadrons decaying before the **4th-to-last barrel layer**

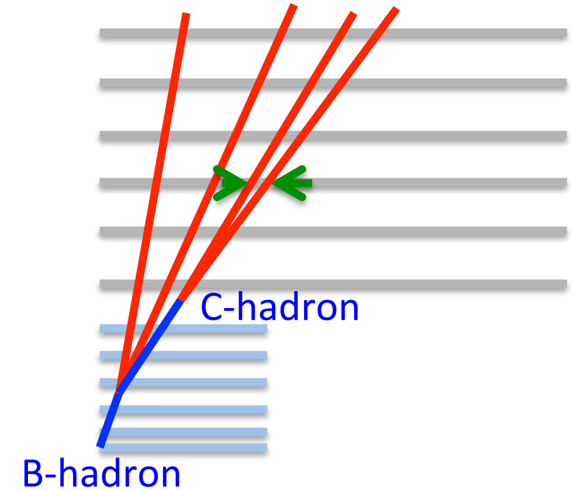
«**Acceptance**»:

$E_{b\text{-quark}}$=10 TeV : 0.88

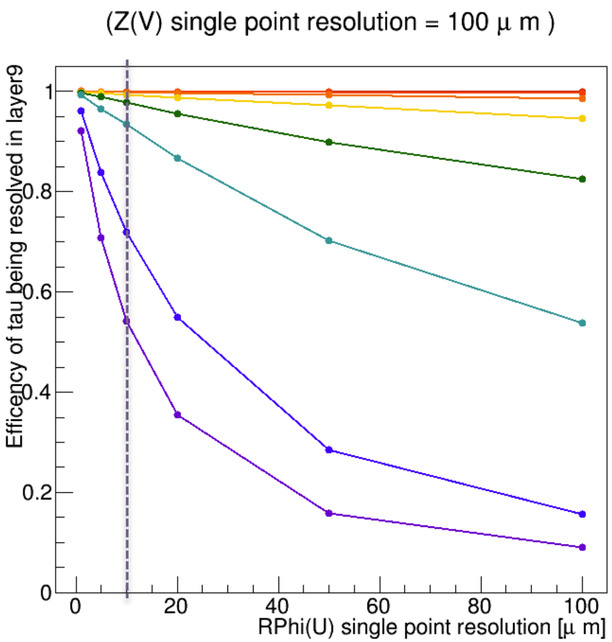
$E_{b\text{-quark}}$=5 TeV : 0.97

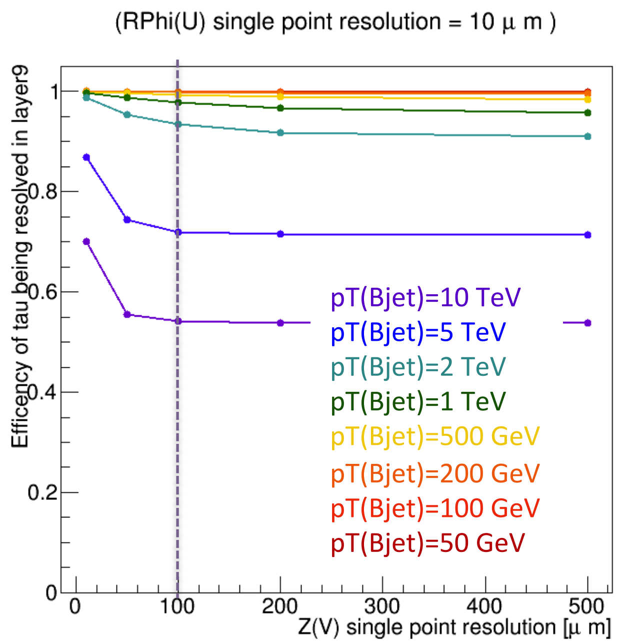
$E_{b\text{-quark}}$=2 TeV : 0.999

$E_{b\text{-quark}}$=1 TeV : 1



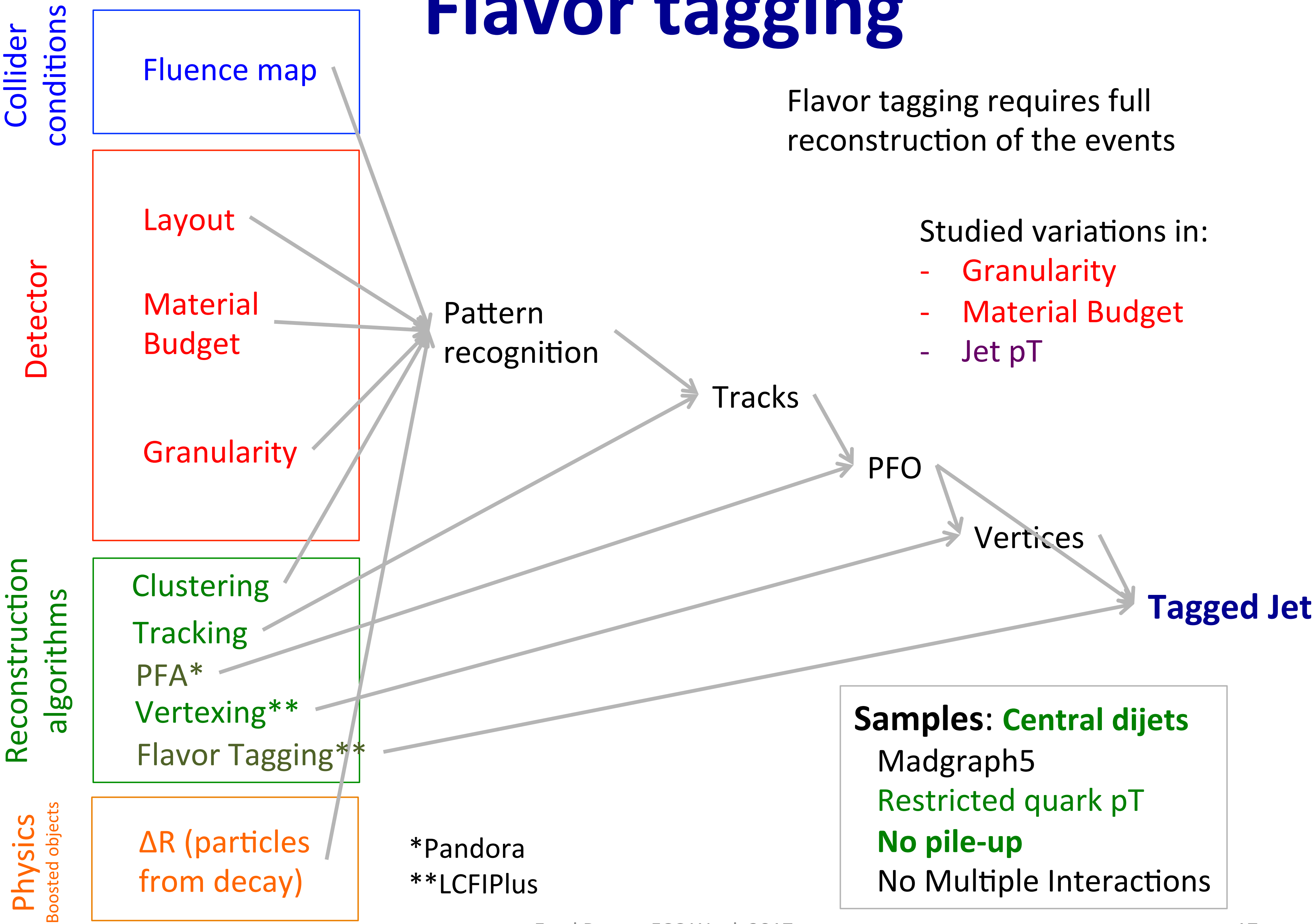
Vertical line shows the default 10x100 [μm] single point resolution





Improving the single point resolution in Rϕ by a factor of 2 would improve the **efficiency from 55%→70% for 10 TeV b-jets**

Flavor tagging



Flavor tagging requires full reconstruction of the events

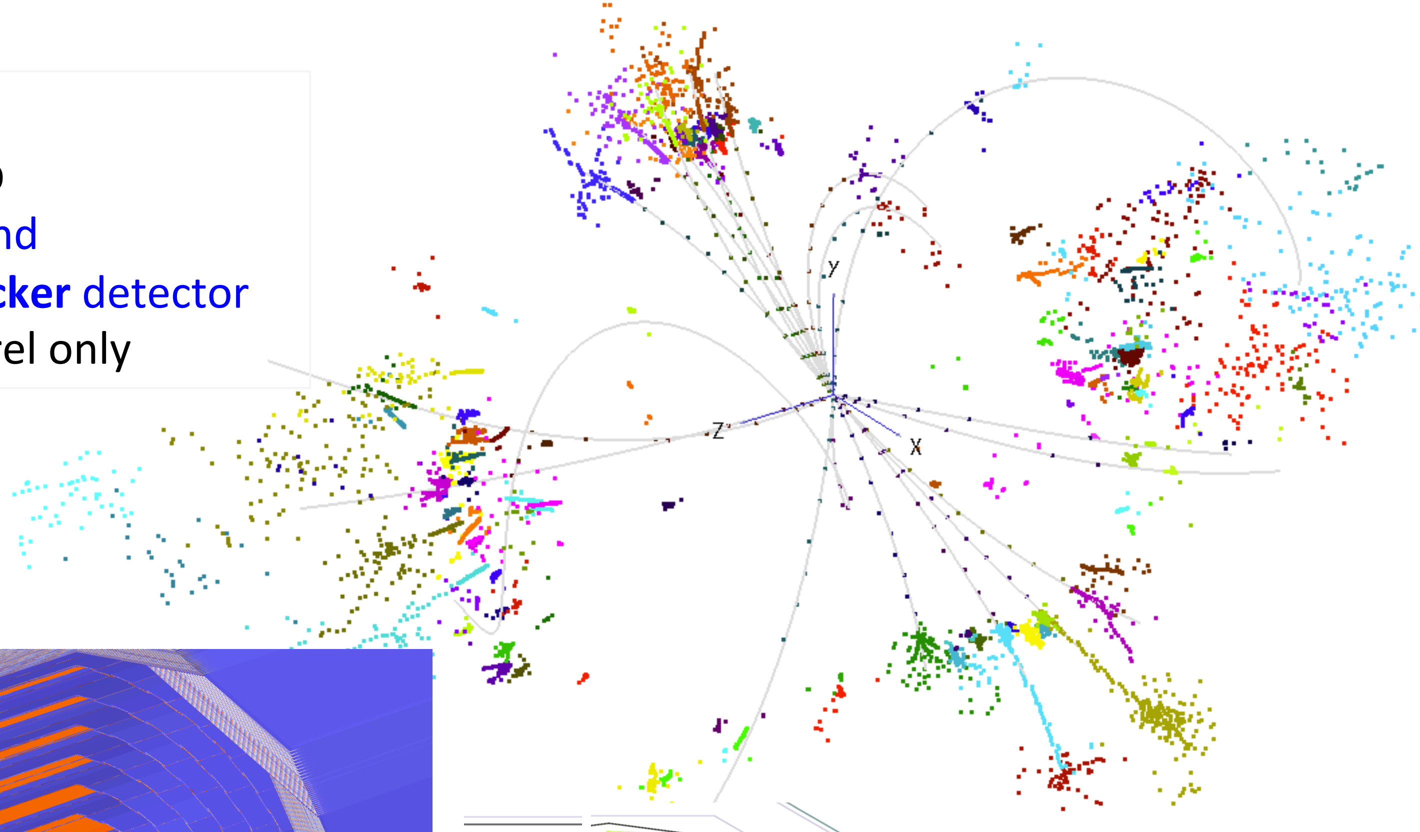
Studied variations in:
- Granularity
- Material Budget
- Jet pT

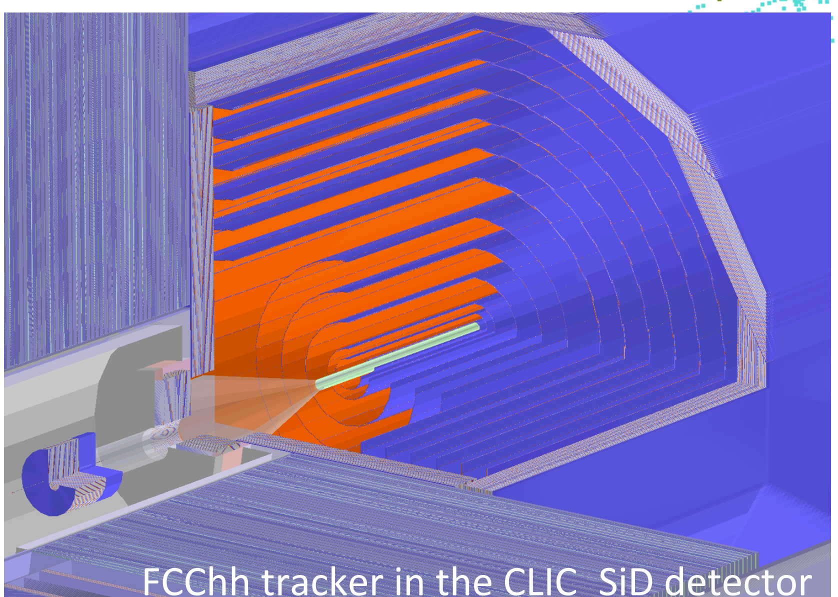
Samples: **Central dijets**
Madgraph5
Restricted quark pT
No pile-up
No Multiple Interactions

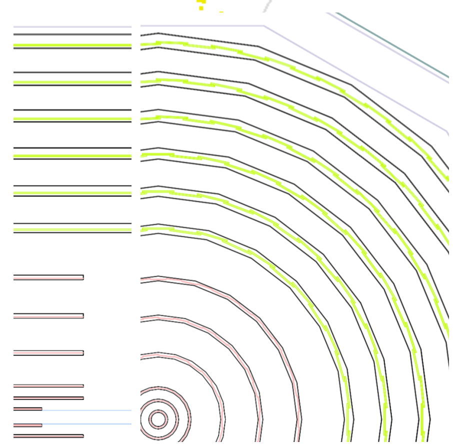
*Pandora
**LCFIPlus

Detector model

Detector Model:
based on CLIC_SiD
with **FCC vertex** and
squeezed FCC tracker detector
Implemented barrel only



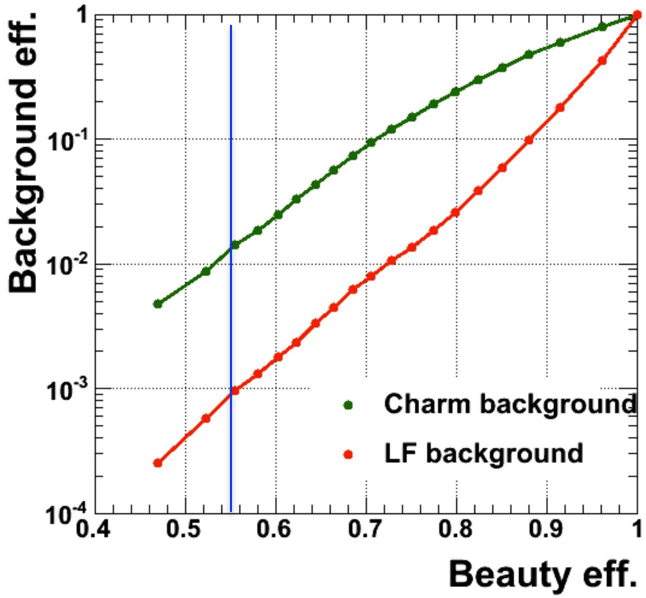




dijet (bb)
pT(b)=50GeV

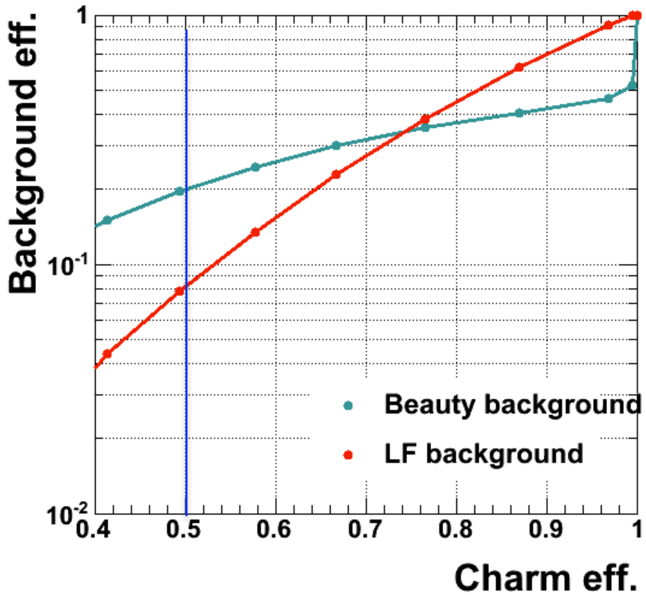
using geometry version with 3 close-by vertex layers

FCC Flavor tagging performance



central dijets , **pT(quark)=50GeV**

For 55% B-tagging efficiency, the background efficiency is about 1% for C-jets and 0.1% for light flavor jets



For 50% C-tagging efficiency, the background efficiency is of the order of 10%.

Reasonable performance compared to that achieved in CLIC and LHC *

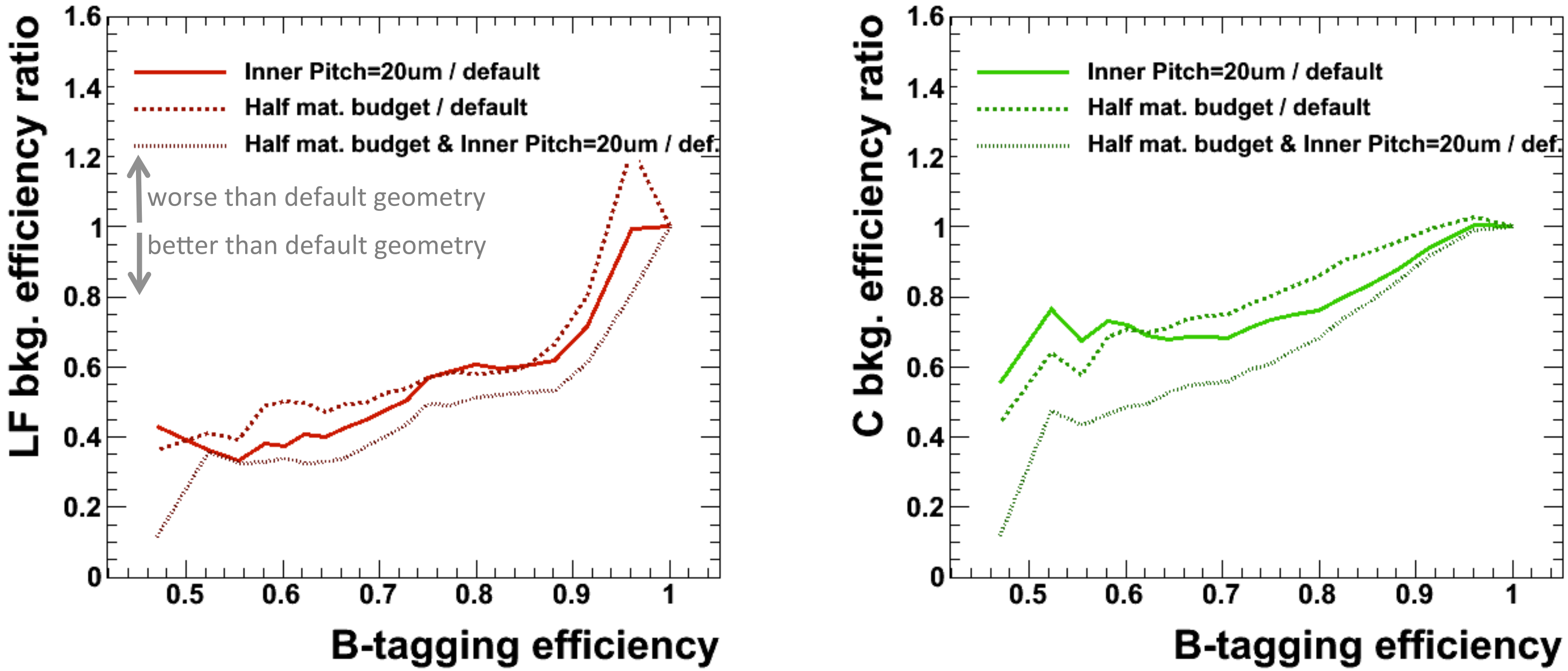
(* = see backup)

Flavor tagging – variations

Variations:

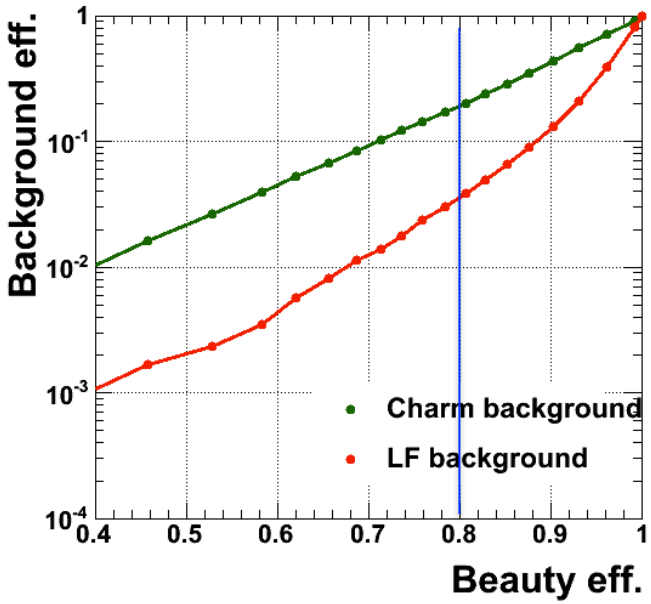
- Granularity: Use **20x20µm pitch** (instead of 25x50µm pitch) in the **3 innermost layers**
- Material Budget: using **half of the material budget** in all layers
- Granularity and Material Budget combined

performance for central dijets of pT(quark)=50GeV



Both variations give a 30-60% improvement in the background rejection.
Combining both, gives only a moderate improvement on top of that.

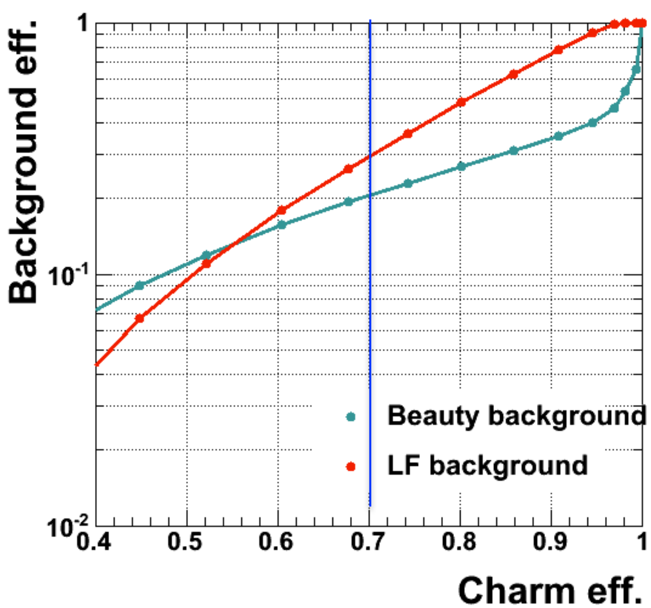
FCC Flavor tagging performance



central dijets , **pT(quark)=500 GeV**

Somewhat worse B-tagging performance for higher pT jets

For **40%** B-tagging efficiency, the background efficiency is about 1% for C-jets and 0.1% for light flavor jets



C-tagging performance similar to 50 GeV jets

Plan to study performance at even higher pTs

Conclusions & Outlook

- Performance evaluation and optimisation **tools** (using fast and full simulation) are in place and **validated**
- **Studies serve as an input for the vertex and tracker optimization**
  - Need interconnecting disks between outer endcap and forward tracker, to facilitate pattern recognition
  - Boosted particle decay reconstruction strongly depends on the sensor granularity, need high granularity also in the outer layers.
  - Achieved reasonable flavor tagging performance for jets up to pT=500 GeV, showing significant dependence on granularity and material budget

Next steps:

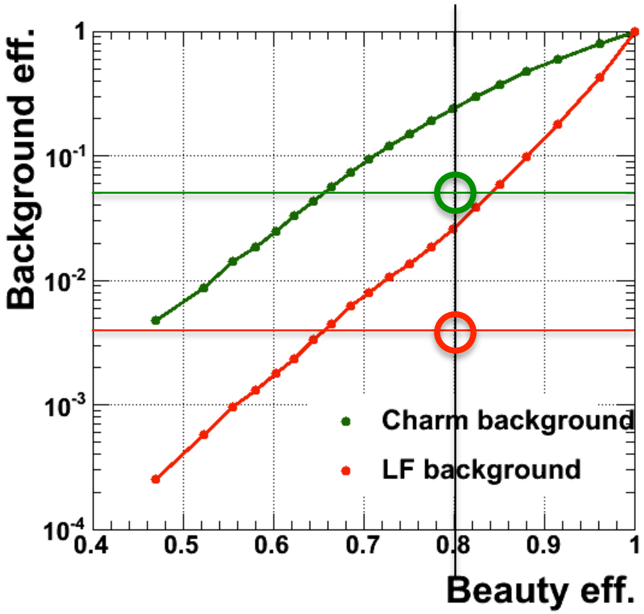
- Perform further flavor tagging studies at **higher jet pT**, including evaluation of the performance for a **detector layout** with more barrel layers closer to the interaction point.

BACKUP

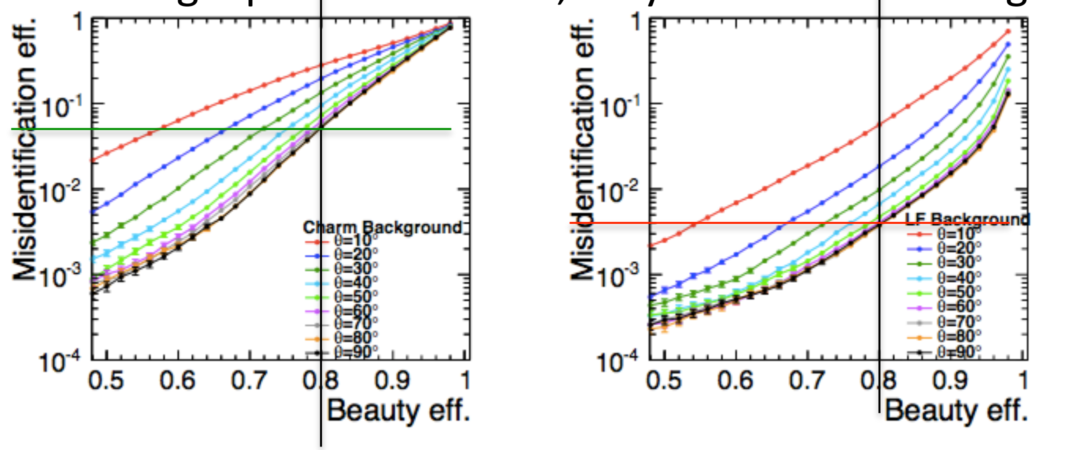
Flavor Tagging

central dijets ,
pT(quark)=50GeV

50GeV – Comparison with CLIC

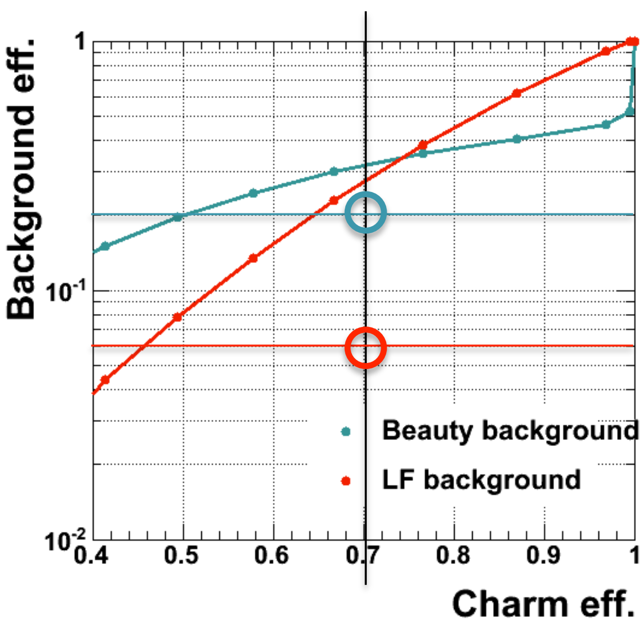


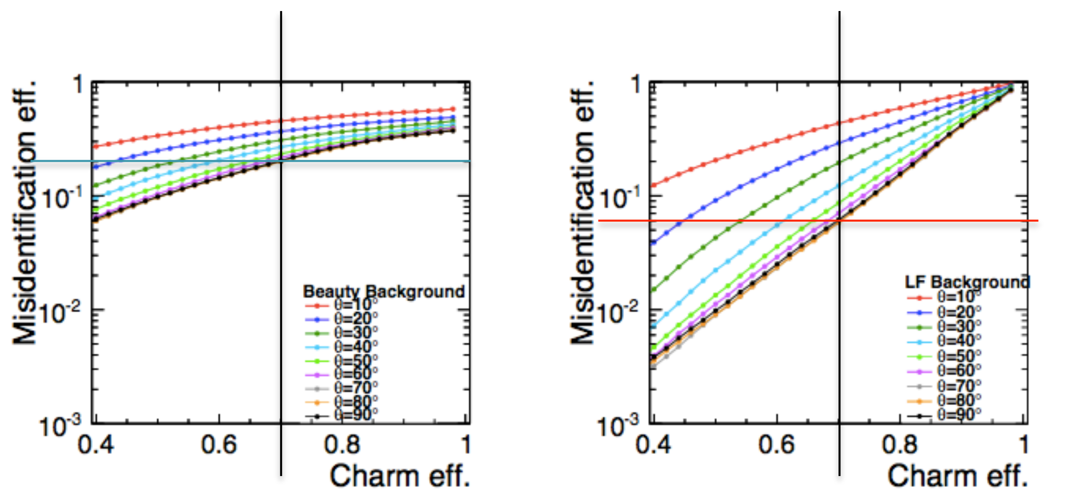
ee->jj , No ISR, narrower pT spectrum, x50 more stats
better single point resolution, very low material budget



(a) (b)

Figure 53: b-tag efficiency for jets in dijet events at $\sqrt{s}$ =91 GeV with different polar angles using the *double_spirals* geometry.



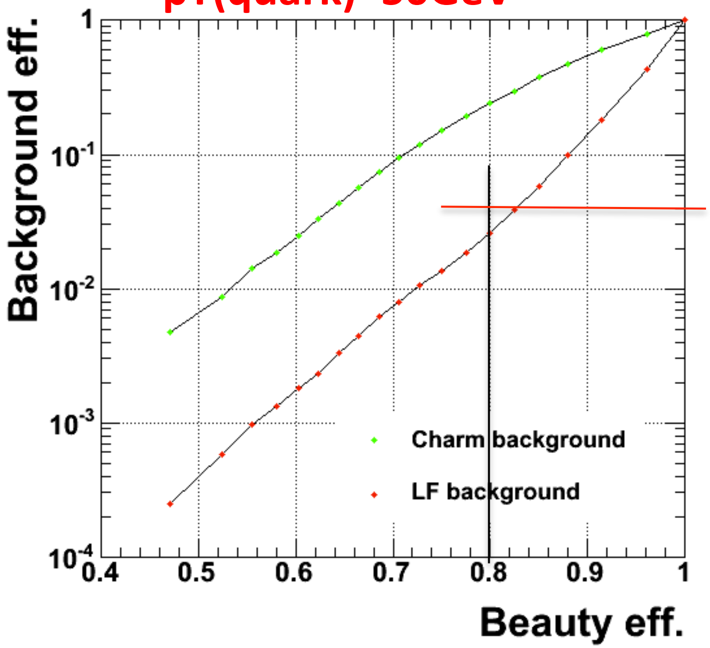


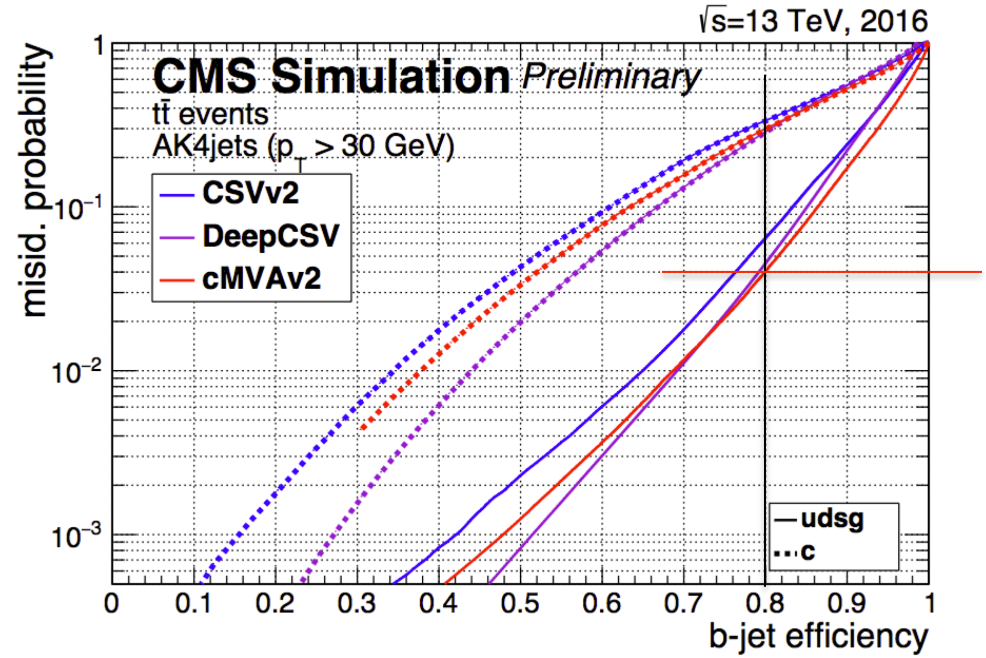
(a) (b)

https://cds.cern.ch/record/1606436?ln=en

Comparison to CMS run 2

central dijets ,
pT(quark)=50GeV





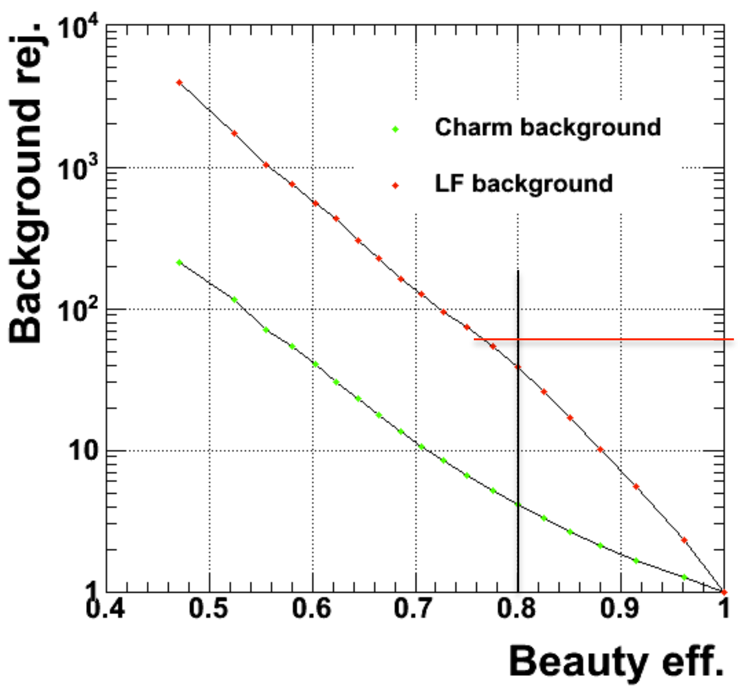
https://twiki.cern.ch/twiki/bin/view/CMSPublic/BTV13TeVDPDeepCSV

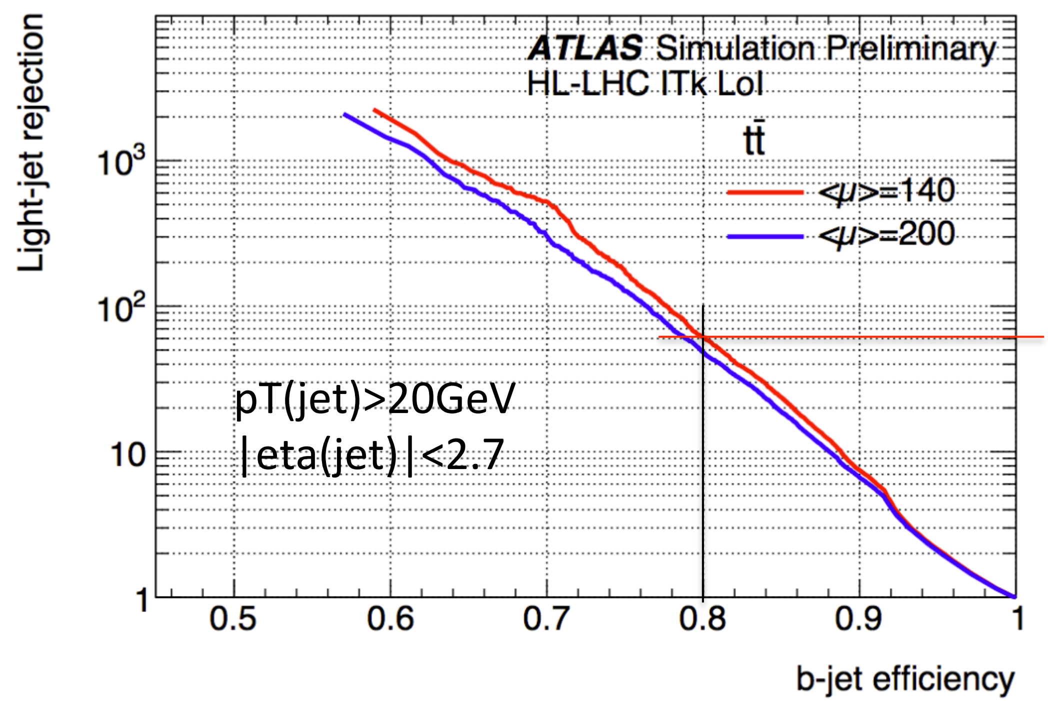
Similar performance as CMS run 2.
FCC factor of ~1.5 better at LF-rejection(FCC result does not include pile-up)

Comparison to HL-LHC

central dijets ,

pT(quark)=50GeV



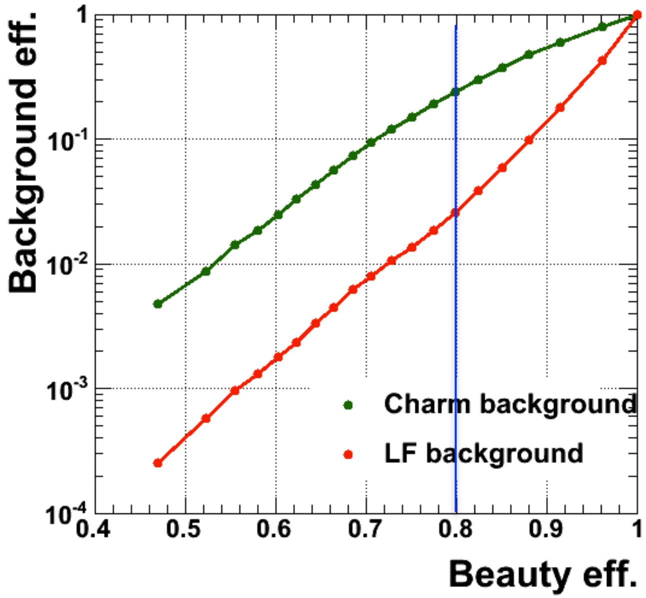


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2016-026/

Similar performance as ATLAS HL-LHC

FCC factor of 1.5 worse at LF-rejection (for HL-LHC pile up of mu=140)

FCC Flavor tagging performance

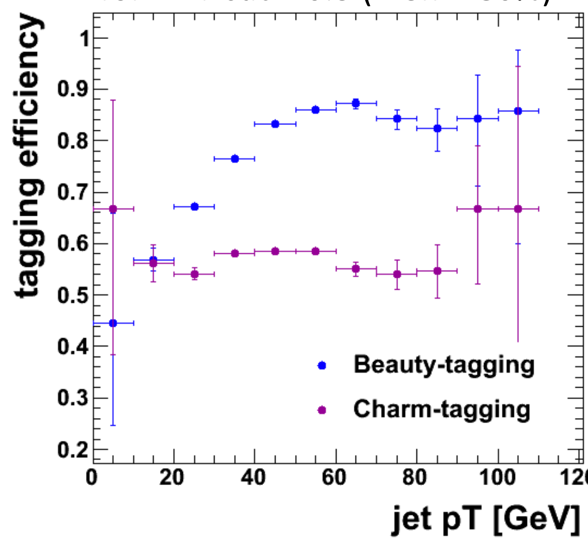


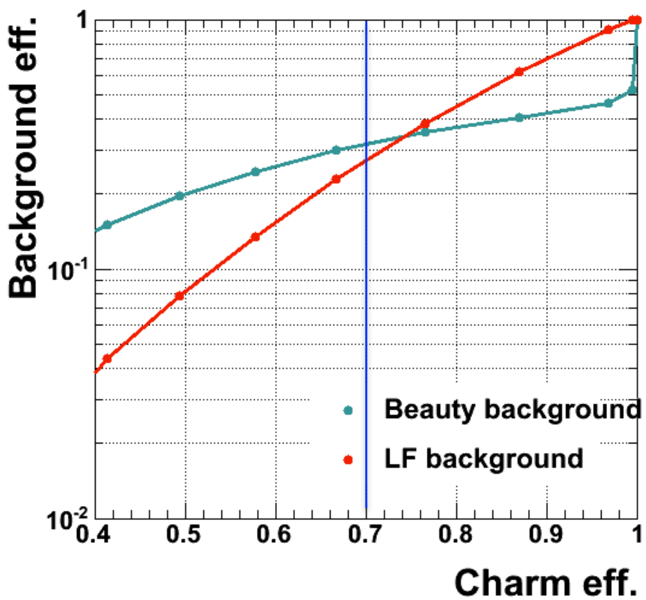
central dijets , pT(quark)=50GeV

FCC B-tagging

B eff. = 80%	FCC
LF bkg eff.	2.6 x 10^-2
C bkg eff.	2.4 x 10^-1

for BDT cut = 0.3 (B eff = 80%)



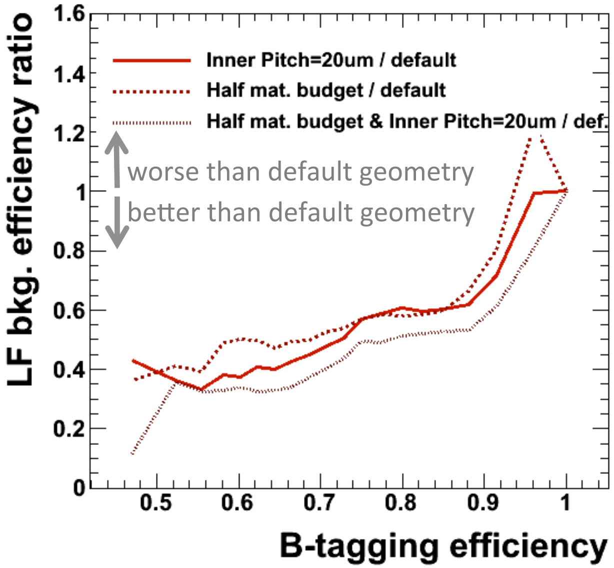


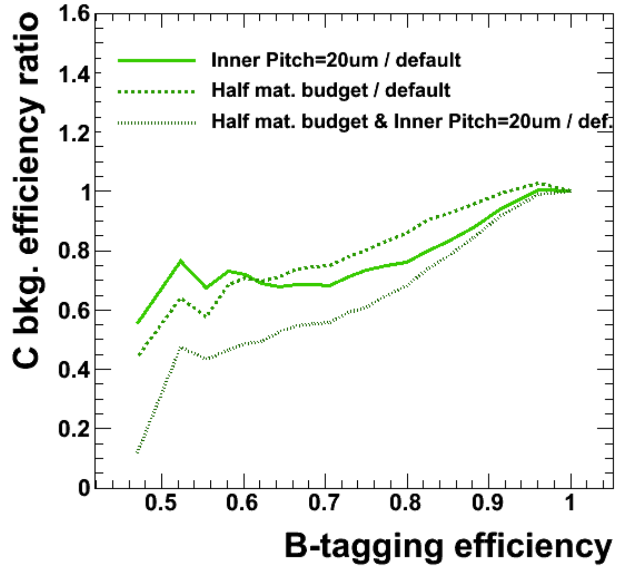
FCC C-tagging

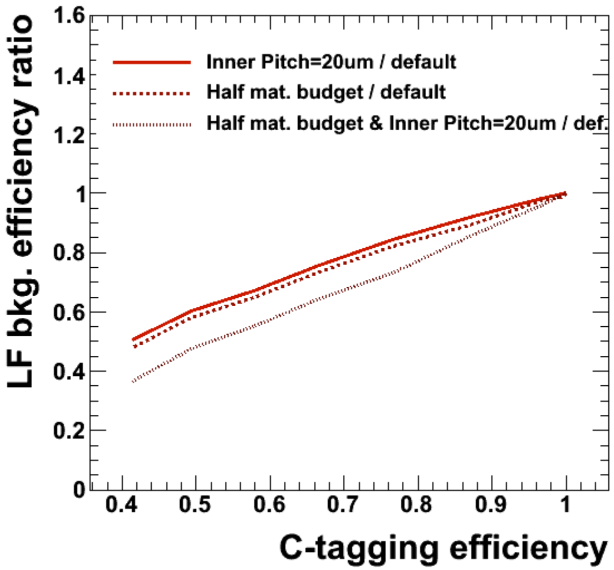
C eff. = 70%	FCC
B bkg eff.	3.2x 10^-1
LF bkg eff.	2.8 x 10^-1

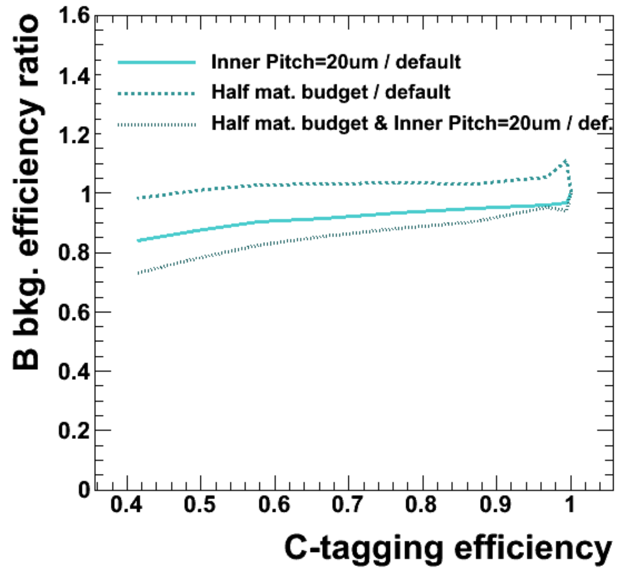
Reasonable performance
Tagging efficiency relatively **flat in jet pT above 40 GeV**

Flavor tagging – variations









Variations

- Granularity
- Material Budget
- Granularity+Mat.Budget

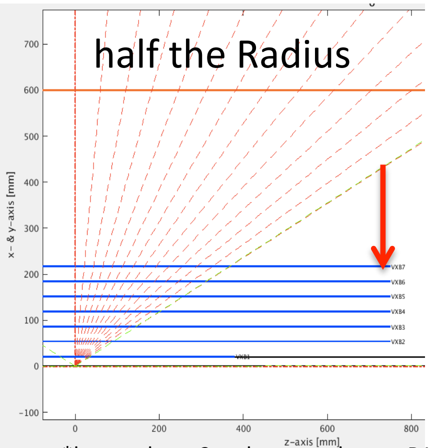
Using **20x20µm pitch** (instead of 25x50µm pitch) in the **3 innermost layers,** or using **half of the material budget** in all layers*, improves the light flavor rejection by 60-40%.

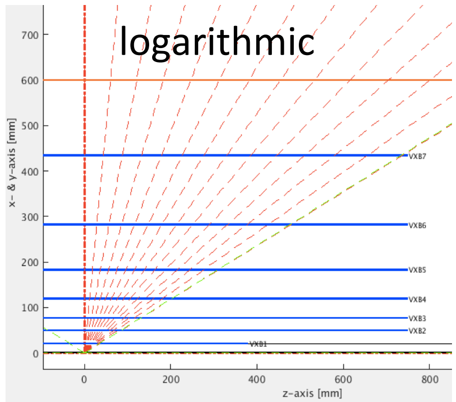
The two modifications combined do not add up in terms of improvement in LF rejection, but they do for C background rejection

performance for central dijets of pT(quark)=50GeV

Fast Simulation
Pattern recognition studies

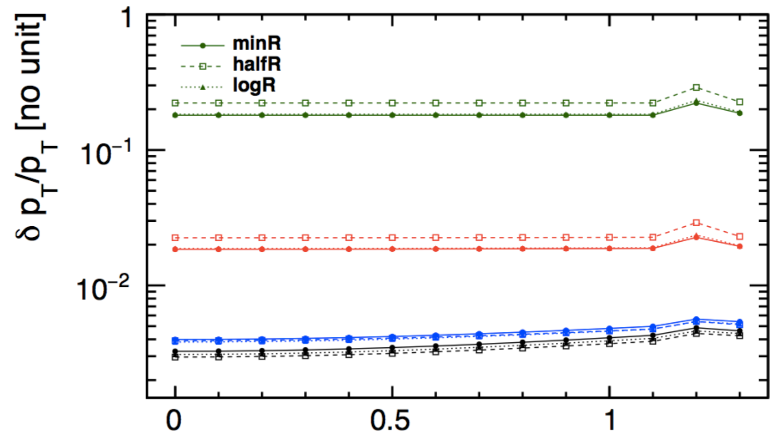
Variation (II) vertex layers radius



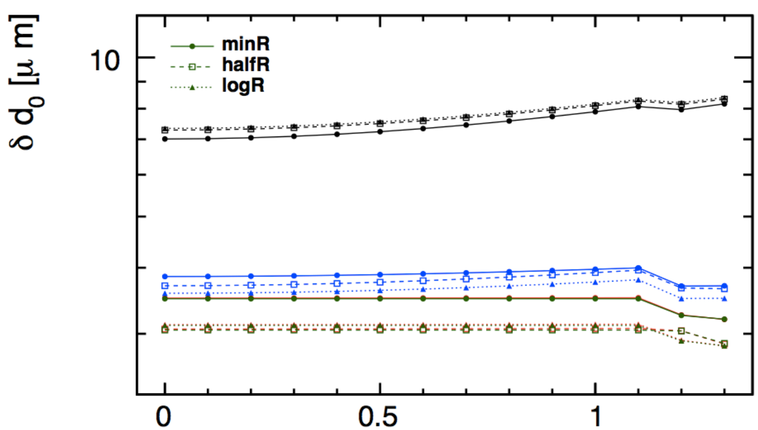


*kept at least 3cm between layers: R1=21mm R2=50mm in all cases

Small differences in the resolution (single particle). Will become relevant when we take into account occupancy



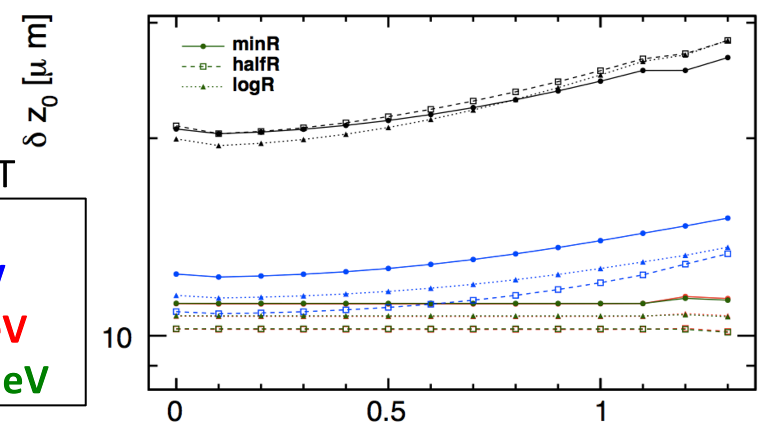
Equidistant option is the best in terms of pT resolution at high pT



half R and log. R options perform similarly in d0 resolution

Track pT

10 GeV
100 GeV
1000 GeV
10000 GeV

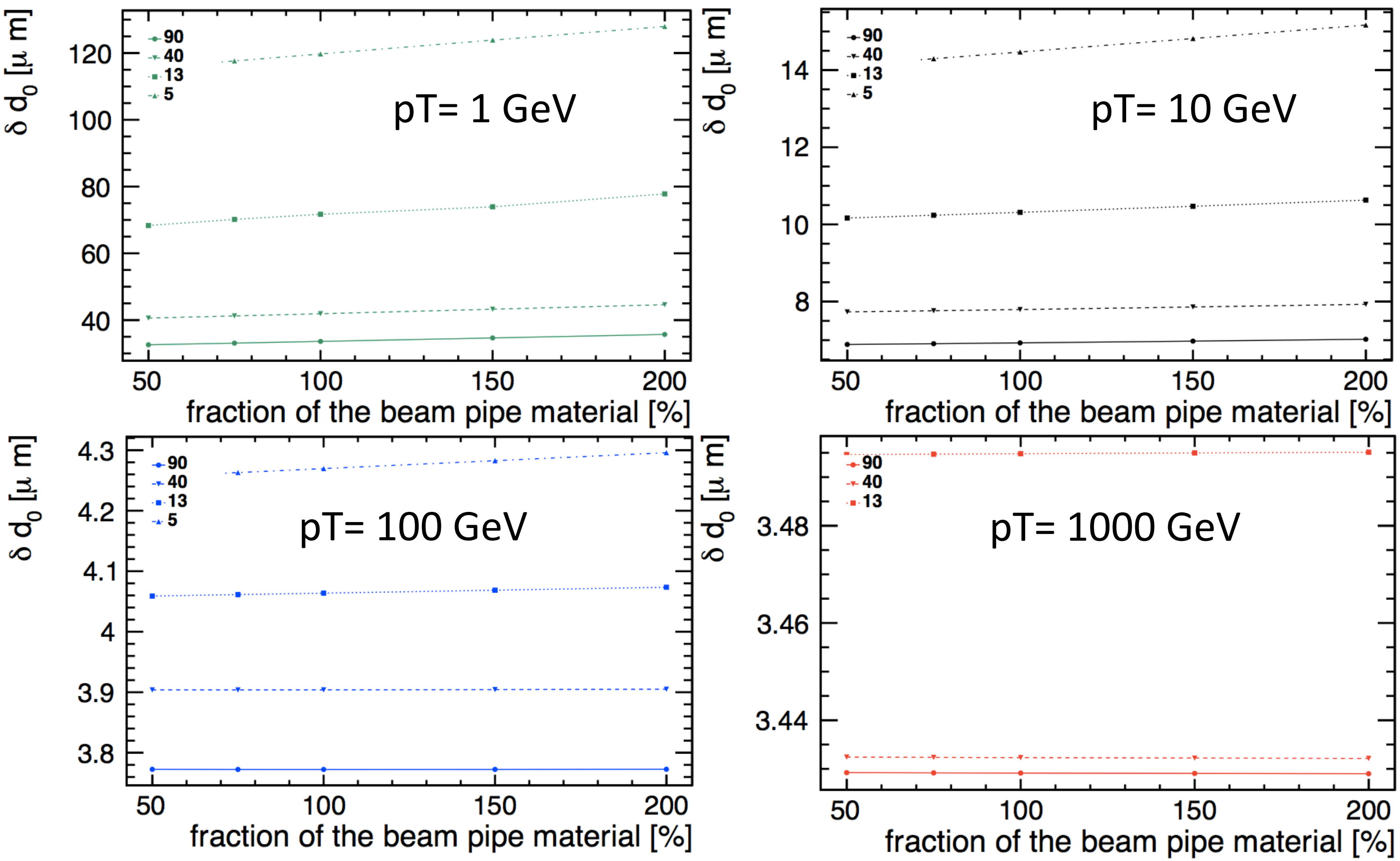


half R is the best at z0 resolution for high pT tracks

d0 resolution dependence on the beampipe material

Baseline: beampipe X/X_0=0.00286.

Reduce/increase the beampipe material by: 50%, 75%, . . , 150%, 200%

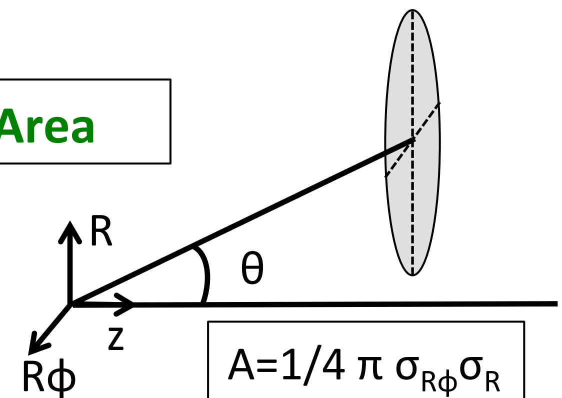


significant dependence for low pT forward tracks

of background particles in the error ellipse ?

1. Area of the error ellipse projected at the last endcap disk:
   $$\mathbf{EllipseArea} = \tfrac{1}{4}\,\pi\,\sigma_{R\phi}\,\sigma_z\,\tan\theta$$
2. Multiply by fluence at the last endcap disk

 # bkg particles in error ellipse = Fluence * Pile up * EllipseArea

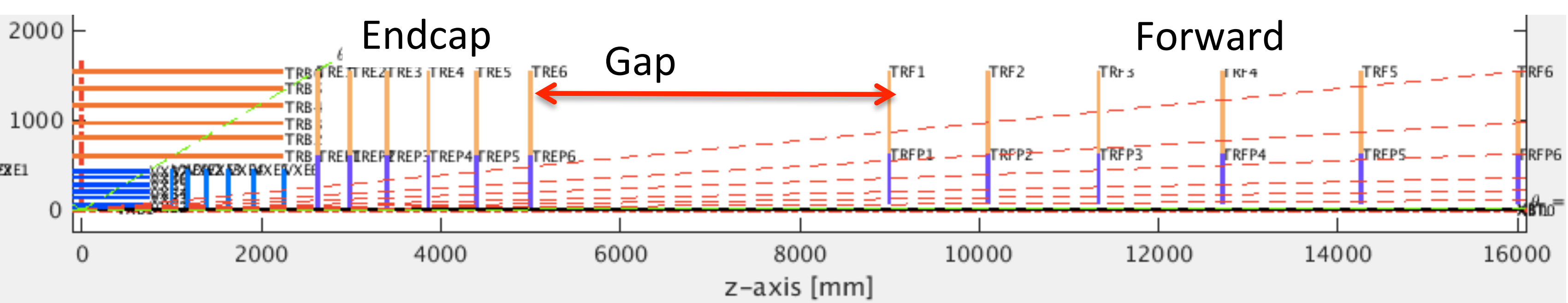


$A = 1/4\,\pi\,\sigma_{R\phi}\sigma_R$

$\sigma_R = \sigma_z \tan\theta$

Study, for **forward tracks**: (going through all fwd layers)

- **Area as a function of the single-point resolution** of the forward layers
- **Area as a function of the gap distance** (endcap – forward)



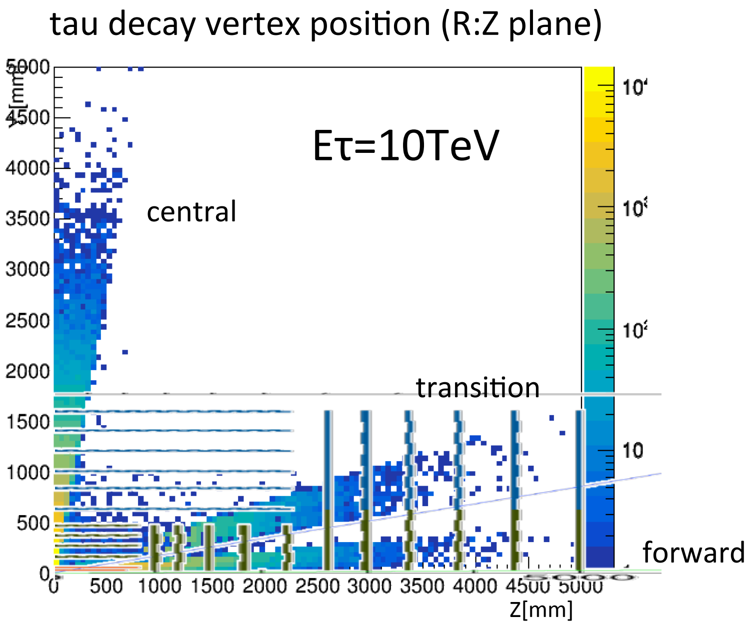
θ=5.49 deg; η=3

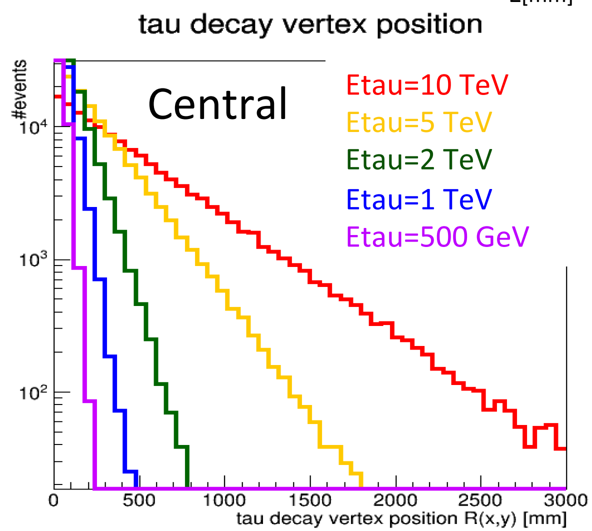
θ=0.39 deg; η=5.7

Note: In this study the upper and lower part of the disks have the same material budget and resolution

Boosted object studies

Tau samples used





Z'-> tau tau events (no ISR, taus back-to-back) with at least one 3-prong tau

Fraction of central **taus decaying inside the beampipe** (within **R(x,y)<20mm**)

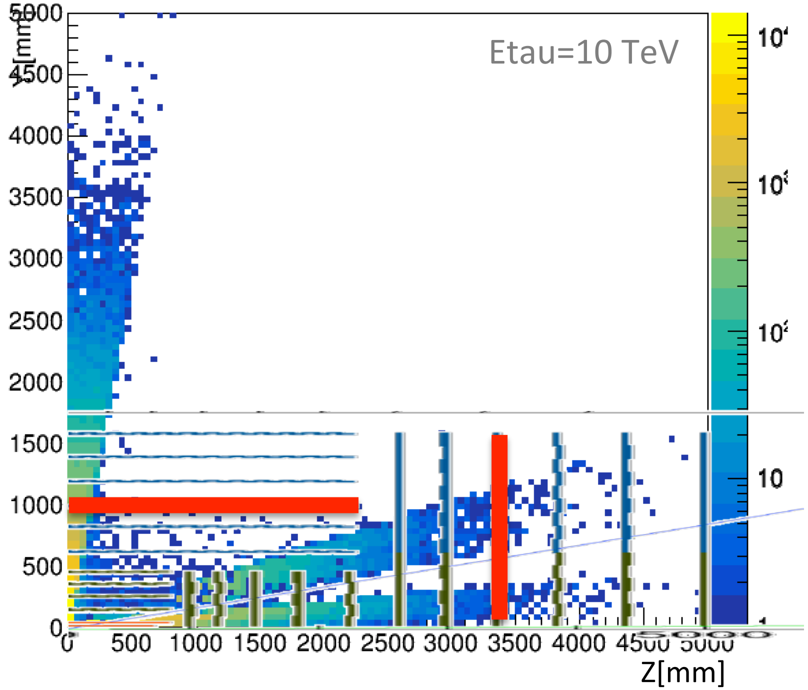
Etau=10 TeV :	0.045
Etau=5 TeV :	0.088
Etau=2 TeV :	0.201
Etau=1 TeV :	0.357
Etau=0.5 TeV :	0.586
Etau=0.2 TeV :	0.888
Etau=0.1 TeV :	0.987

While **99% of central 100 GeV taus** decay within the beampipe, only **4% of 10TeV** central taus do.

Efficiency definition (I)

- Resolve all prongs → reconstruct all tracks → have enough hits per track
- Assume: we need at least 3+1(backup) non-shared hits per track
- Assume: outside-in tracking
- → the hits from different prongs must be resolved in the 4th-to-last layer of the tracker

tau decay vertex position



«Acceptance»:
Fraction of **central** taus decaying before the **4th-to-last barrel layer**
Etau=10 TeV : 0.857
Etau=5 TeV : 0.978
Etau=2 TeV : 0.9999
Etau=1 TeV : 1

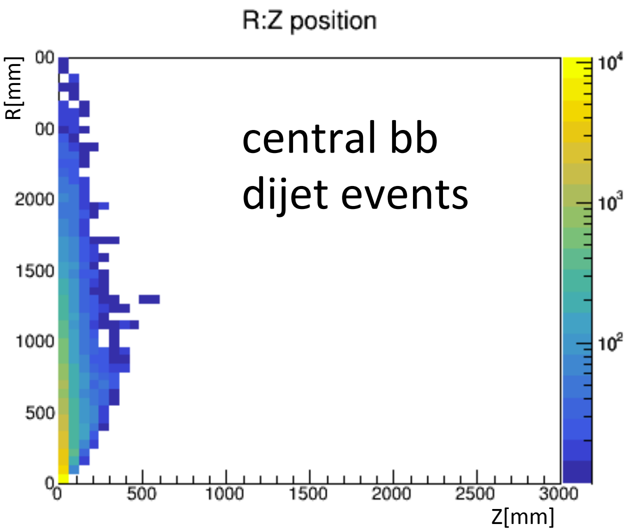
Fraction of **forward** taus decaying before the **4th-to-last barrel layer**
Etau=10 TeV : 0.9992

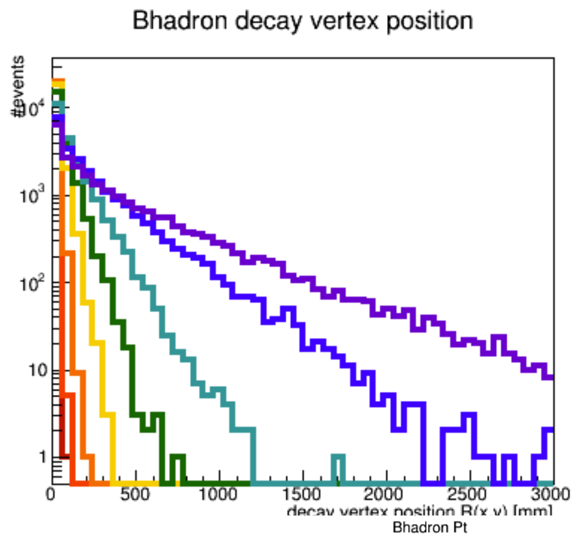
This problem is less important in the endcaps since we have a larger lever arm

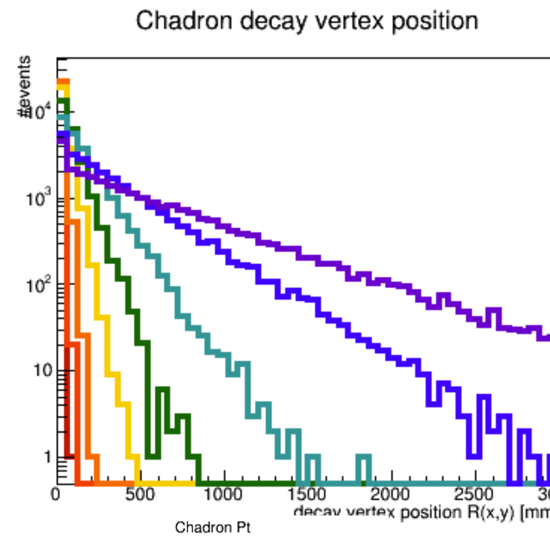
B-jets

- Similarly, study the long-lived hadrons in a B-jet
- Select B-hadrons as well as their C-hadron daughters
- For different b-jet energies, use bb dijet events in the barrel

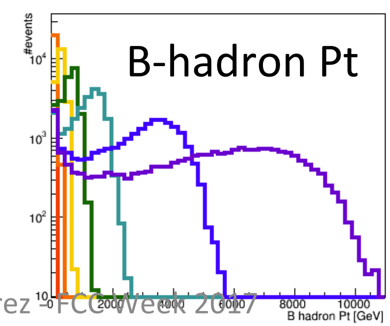
pT(Bjet)=10 TeV
pT(Bjet)=5 TeV
pT(Bjet)=2 TeV
pT(Bjet)=1 TeV
pT(Bjet)=500 GeV
pT(Bjet)=200 GeV
pT(Bjet)=100 GeV
pT(Bjet)=50 GeV

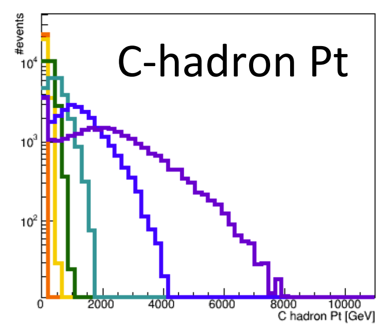




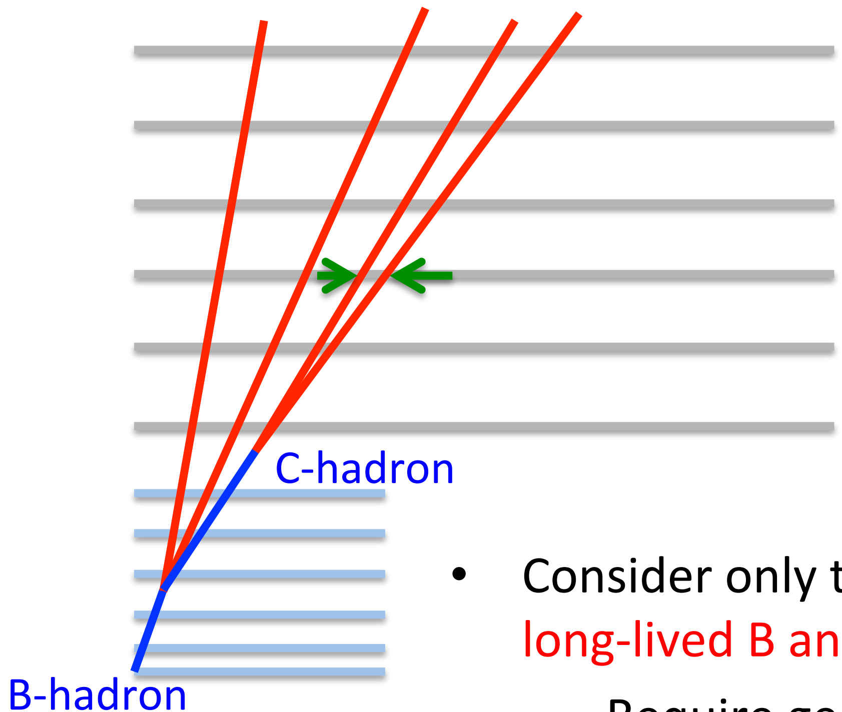


Flight distance distribution deviates from straight line because hadrons are not mono-energetic





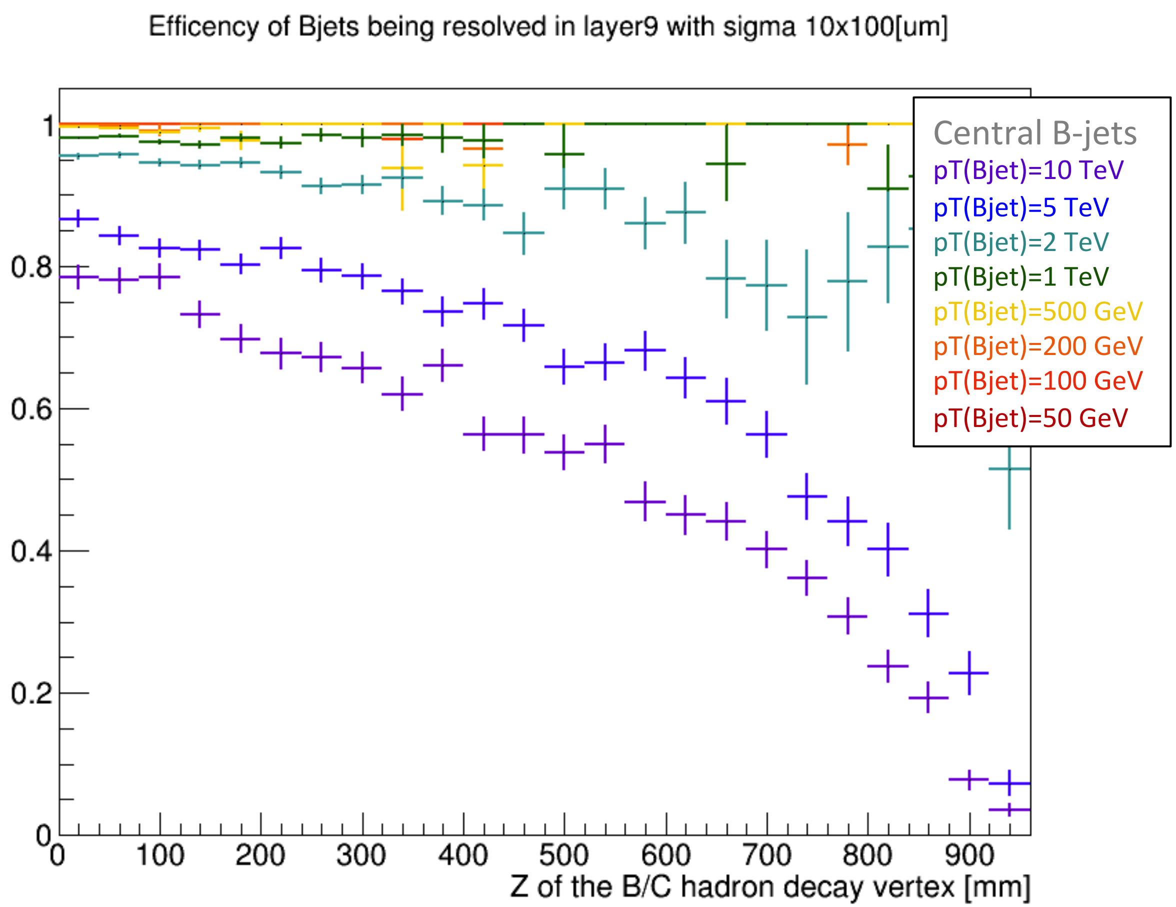
Efficiency definition (II)



- Consider only the hits produced by the daughters of the long-lived B and C-hadrons
  - Require generator status==1
- Assume: we need to separate the closest pair of daughters
- → Consider the closest pair of hits in the 4th-to-last layer

Efficiency vs decay vertex position

For various B-jet energies



- For 10 TeV B-jets, with B or C-hadrons decaying before the beampipe: ~**80% efficiency** only due to the small opening angle between decay products
- No significant inneficiency for B-jets of Pt < 1 TeV

B jets acceptance

- B hadrons

pT(b-quark) [GeV]	Fraction of B-hadrons decaying before R=20mm	Fraction of B-hadrons decaying before R=925mm (4^{th}-to-last layer)
50	0.996848	
100	0.959081	
200	0.829957	
500	0.583421	
1000	0.398114	1
2000	0.275022	0.999217
5000	0.192235	0.965865
10000	0.161509	0.875244

B jets acceptance

- C hadrons

pT(b-quark) [GeV]	Fraction of C-hadrons decaying before R=20mm	Fraction of C-hadrons decaying before R=925mm (4^{th}-to-last layer)
50	0.991606	
100	0.92315	
200	0.719064	
500	0.407441	
1000	0.233609	1
2000	0.147122	0.997447
5000	0.113189	0.934408
10000	0.102258	0.793054

Flavor tagging using full simulation

Software chain: Summary

- **Generation**: MG5 central dijets, restricted quark pT.
- **Hadronization**: Pythia6. No Pile-up. Multiple interactions: off, ISR/FSR: on.
- **Detector Model**: CLIC_SiD with FCC vertex and squeezed FCC tracker (Option3_v02). Barrel only. Tracker outer layer R reduced from 1541mm (FCC) to 1206mm (CLIC)
- **Simulation**: FCC material budget (services included in the module)
- **Digitization**: FCC pixel sizes. Smear simulated hit position by a Gaussian of $\sigma=\text{pitch}/\sqrt{12}$.
- **Tracking**: Nhits>=6, chi2<10, d0<10 [mm] (under study)
- **Particle flow**: Pandora
- **Vertexing**: LCFIPlus. Use only PFOs in 2 kT jets R=0.5.
- **Flavour Tagging**: LCFIPlus. (BDT using same variables as CLIC)

Event Generation

- Event generation in MadGraph5:
  - pp->bb / cc / ll (udsg) at √s=100TeV
  - **restricted quark pT**: Ex: **47.5 < pT(b) < 52.5 GeV**
  - **Central** eta: **|η(b)|<0.05**
  - DR(bb)>0.4
- Samples:
  - Quark pT in GeV: **50, 100, 200, 500, 1000, 2000, 5000, 10000**
  - 20k events per sample
  - 1M events for 50 & 500 GeV samples

- Hadronization in Pythia6:
  - No Pile up
  - **Multiple Interaction: OFF**
  - FSR: ON
  - ISR: ON

Tracking

- Tracking parameters used

MinPT=	0.2 GeV
MinHits=	**6**
MaxD0=	**10.0 mm**
MaxZ0=	10.0 mm
MaxChisq=	10.0

- Tracking strategies trained with **displaced** single muon tracks (to account for missing inner hits)

Under review & optimization

Preliminary track resolution comparison

*Full Sim
E=100GeV prompt muon
|η|<0.175 (θ=80-100 degrees)

**Fast Sim
pT=100GeV prompt muon
0.001<|η|<1.5

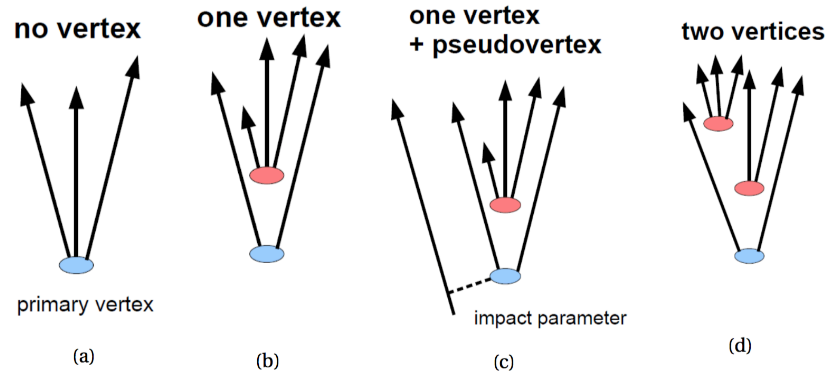
resolution	Full Sim*	Fast Sim**
δpT/pT	0.75%	0.48 %
δd0[μm]	6.1	5.02
δz0[μm]	13.1	10.59

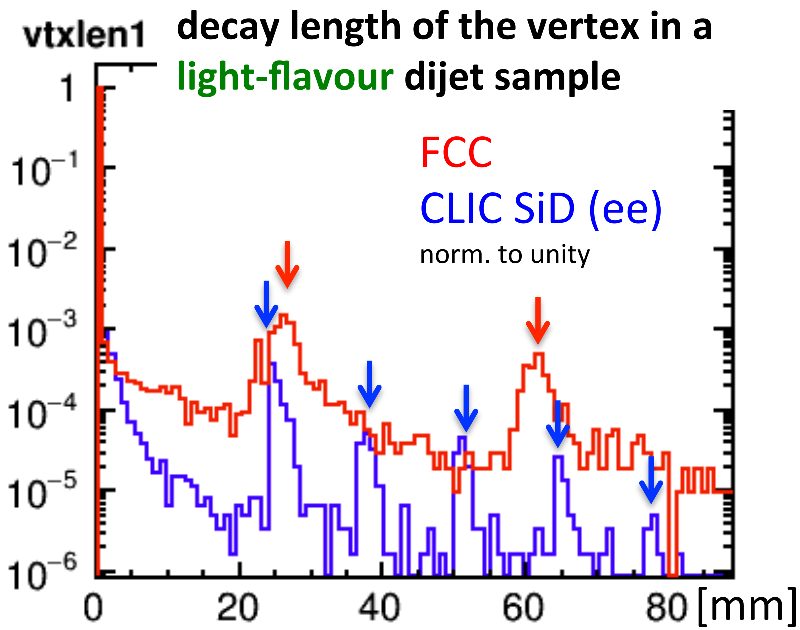
(remember: we have **squeezed the tracker**, and fast sim averages over a larger eta range)

good enough approximation for our purposes

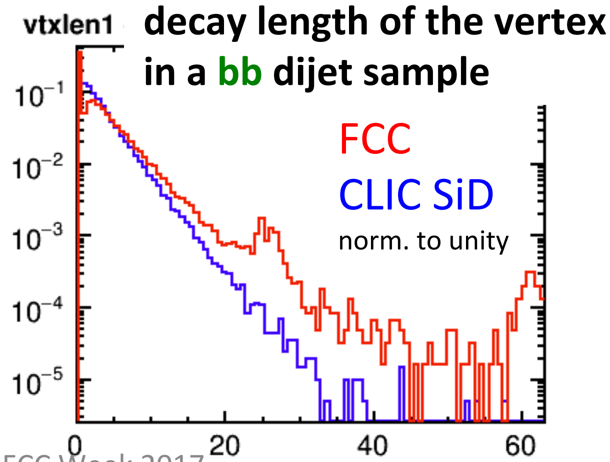
Flavor Tagging

- Jets are classified in 4 categories according to the number of secondary vertices
- BDTs are trained using variables related to: [ref]
  - track d0/z0/momentum
  - vertex mass/momentum/angle/decay length





In the light flavor sample, vertices due mainly to **interaction with the material**



small differences due to **energy spectrum**