Global concepts for an FCC-ee detector: IDEA and CLD

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Workshop FCC-France
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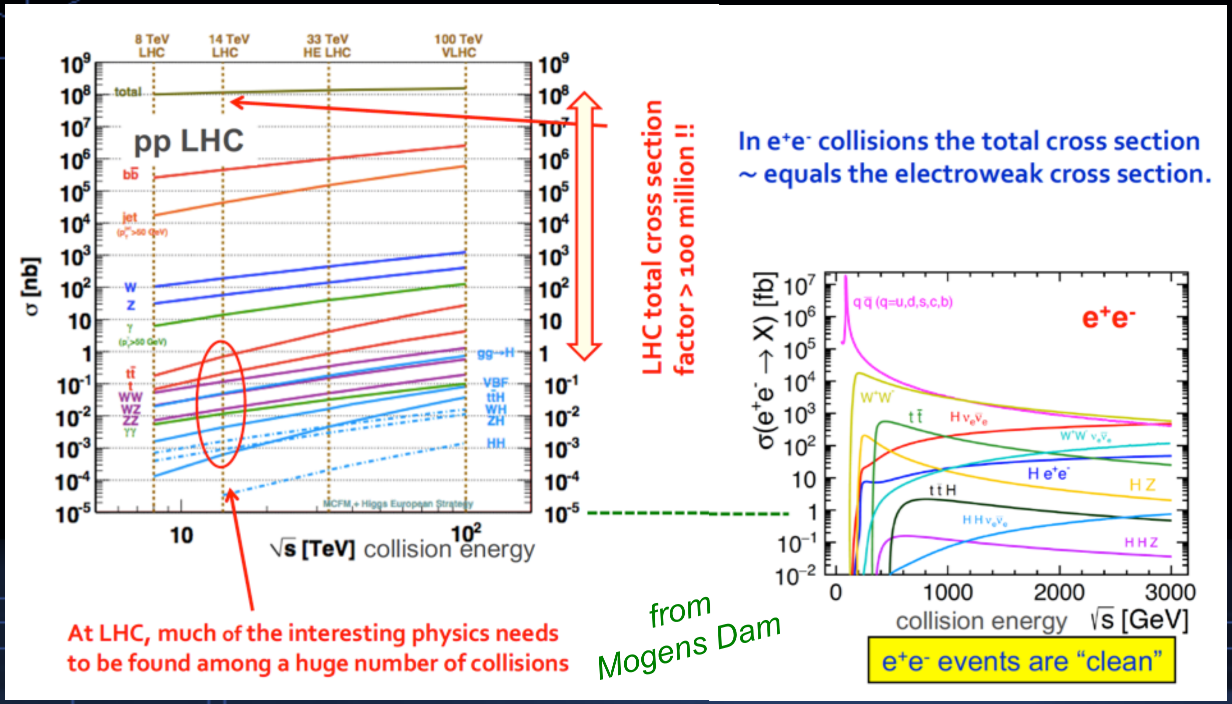
advantages of e^+e^-



LHC total cross section factor > 100 million !!

In e^+e^- collisions the total cross section ~ equals the electroweak cross section.

At LHC, much of the interesting physics needs to be found among a huge number of collisions

from Mogens Dam

e^+e^- events are “clean”

partial vs total cross section

clean experimental environment

no pile-up,
no underlying events

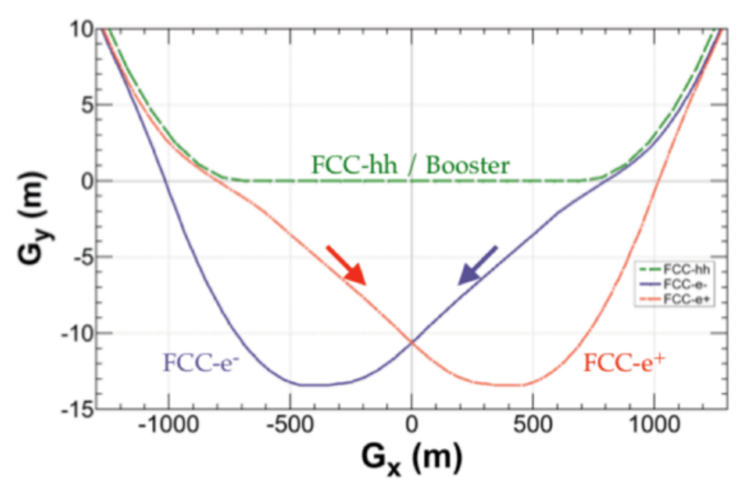
kinematical constraints (initial E, **p**)

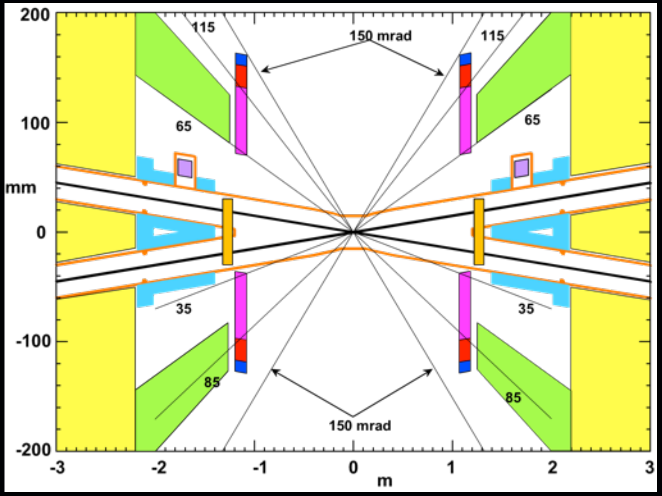
low radiation levels

challenges

- **Extremely high luminosities**:
  large statistics (high statistical precision) – control of systematics (@10^{-5} level)
- **Physics event rates up to 100 kHz** (at Z pole)
  strong requirements on sub-detectors DAQ systems
- **Bunch spacing down to 20 ns** (at Z pole)
  "continuous" beams (no power pulsing),
- **Large beam crossing angle** – very complex MDI
- **Large beam crossing angle** – emittance blow-up with detector solenoid field (< 2T)

MDI





🟧 HOM absorbers

🟦 shielding

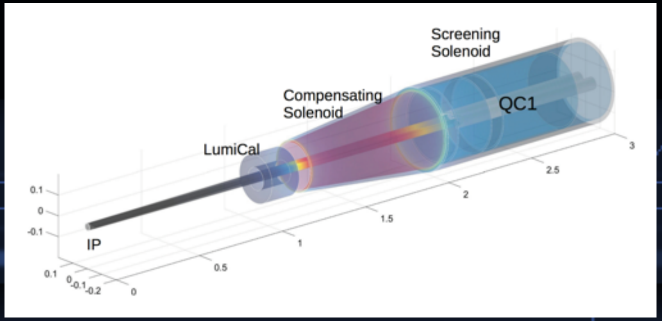
🟩 compensating solenoid

🟪 luminometer

🟨 QC1

- beam crossing angle = 30 mrad
- small bend before IP to limit synchrotron radiation in detector
- larger bend after IP

(all bends in the horizontal plane)



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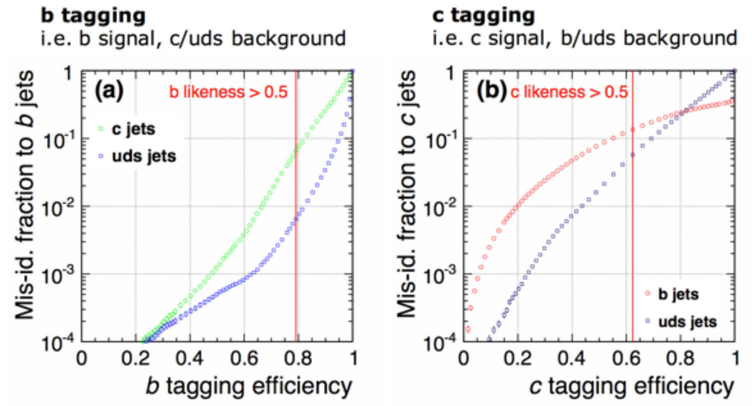
  "continuous" beams (no power pulsing),
- **Large beam crossing angle** – very complex MDI
- **Large beam crossing angle** – emittance blow-up with detector solenoid field (< 2T)
- **More physics challenges at Z pole**:
  - luminosity measurement at 10^{-5} – luminometer acceptance ≈1-2 µm
  - detector acceptance definition at $<10^{-5}$ – detector hermeticity (no cracks!)
  - stability of momentum measurement – stability of magnetic field wrt Ecm (10^{-6})
  - b/c/g jets separation – flavor and τ physics – vertex detector precision
  - particle identification (preserving hermeticity) – flavor physics (and rare processes)

Detector requirements: impact parameter resolution

from ILC studies



Tanabe at IAS-HEP 2017

$$\sigma_{d_0} = a \oplus \frac{b}{p\,\sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\mathrm{m}; \quad b \simeq 15\,\mu\mathrm{m\,GeV}$$

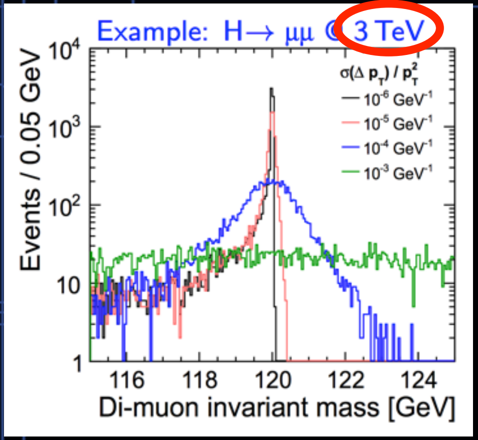
very challenging!

Accelerator	**a** (μm)	**b** $(\mu m \cdot GeV/c)$
LEP	*25*	*70*
SLC	*8*	*33*
LHC	*12*	*70*
RHIC-II	*13*	*19*
ILD	< 5	< 10

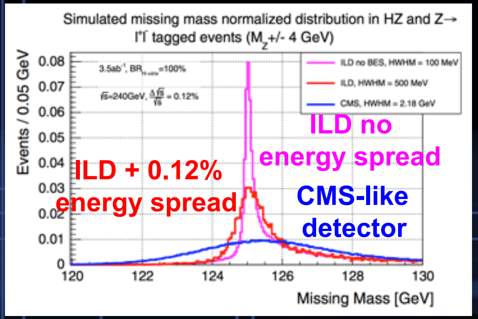
- a single point accuracy of 3 μm;
- a vertex detector geometry providing a first measured point of tracks at ~15 mm from the IP.
- a material budget between the IP and the first measured point restricted to a few per mill of radiation length.

Detector requirements: momentum resolution

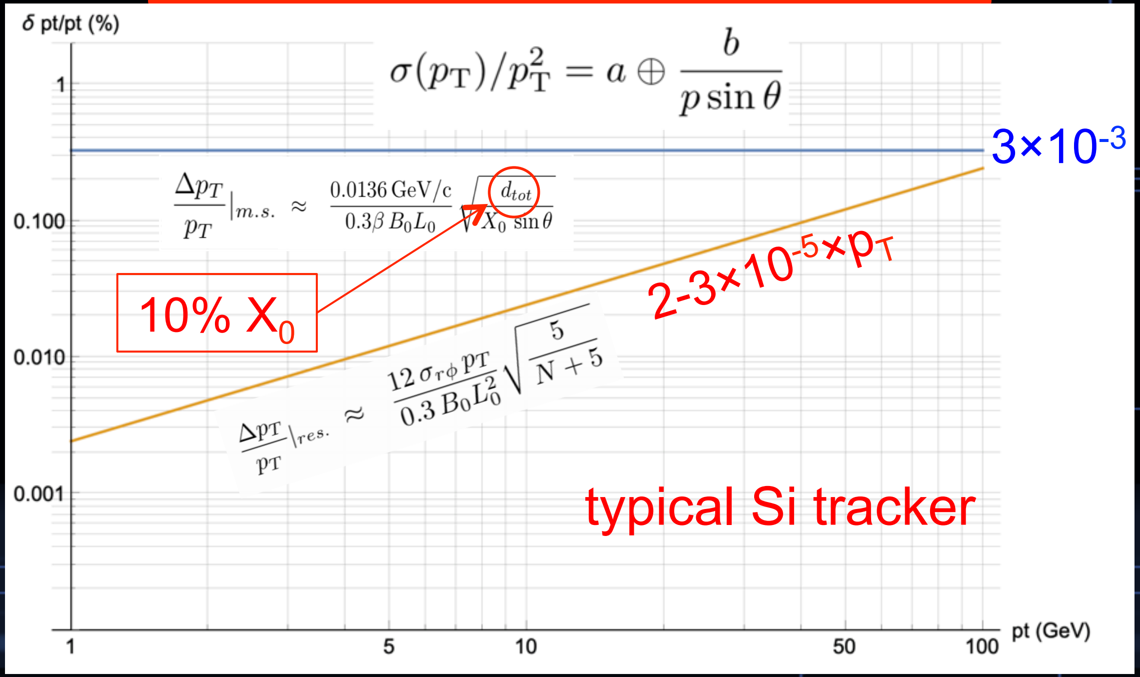
$$\sigma_{p_T} / p_T^2 \approx 2\times10^{-5}\, GeV^{-1}$$



Sicking at TIPP2017



Cerri et al, Eur. Phys. J. C (2017) 77:116



Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

Detector requirements: energy resolution

Energy coverage < 200 GeV (22 X_0, 7λ)

Jet energy δE/E ≤ 30%/√E [GeV]

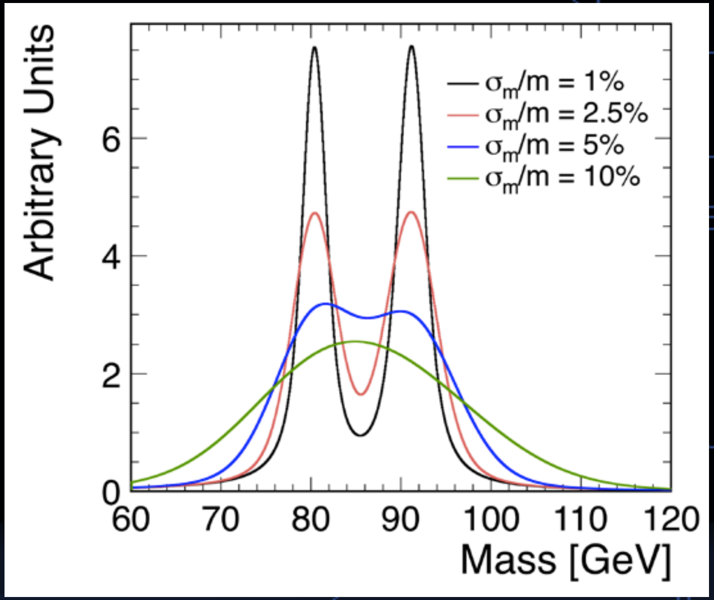
e/γ energy δE/E ≤ 15%/√E [GeV]
(down to 300 MeV)

Particle identification Excellent e/γ ID

Time stability and **acceptance knowledge**
(Normalization to 10^{-5} level)

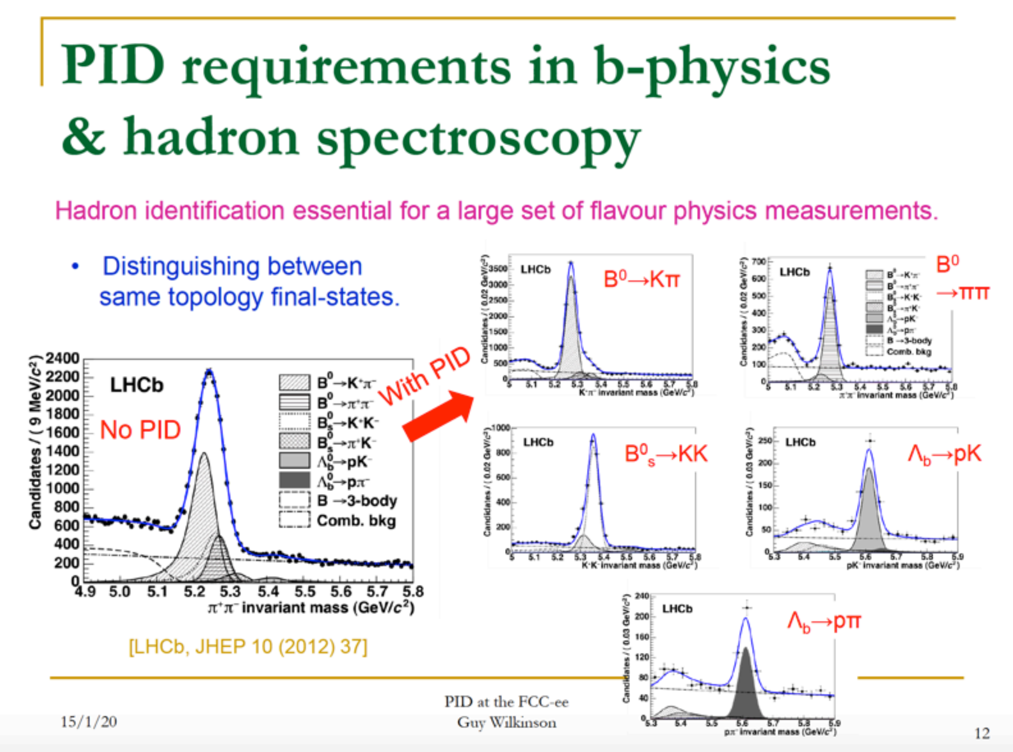
π^0 identification for τ physics

W/Z/H separation



σ (E)/E ~3−5% for E≥50GeV

Detector requirements: particle identification



PID requirements in b-physics & hadron spectroscopy

Hadron identification essential for a large set of flavour physics measurements.

- Distinguishing between same topology final-states.

[LHCb, JHEP 10 (2012) 37]

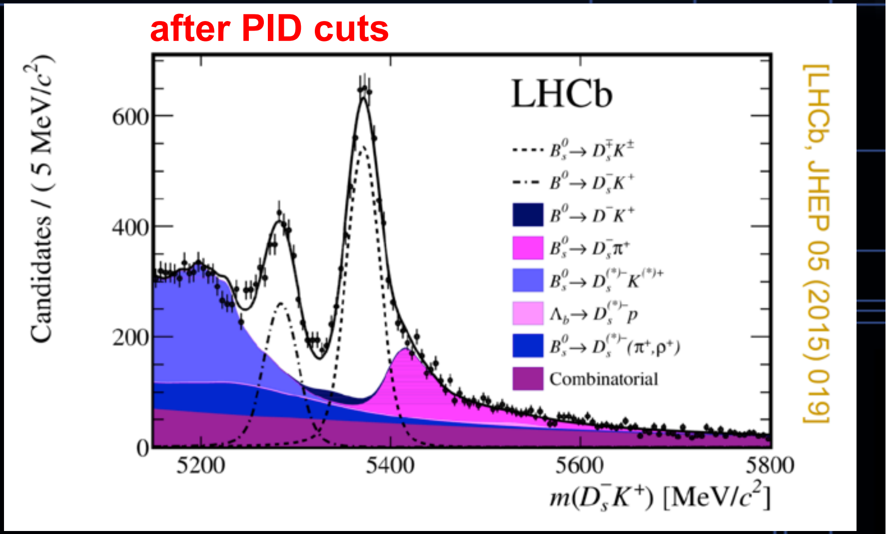
15/1/20

PID at the FCC-ee
Guy Wilkinson

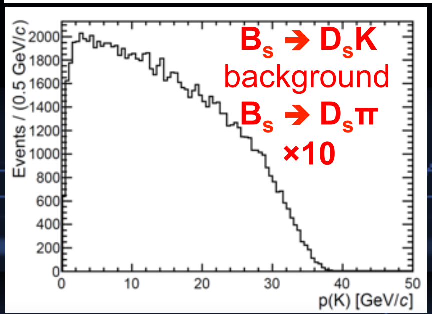
12

from: Wilkinson at 3rd FCC Physics and Experiments Wkshp

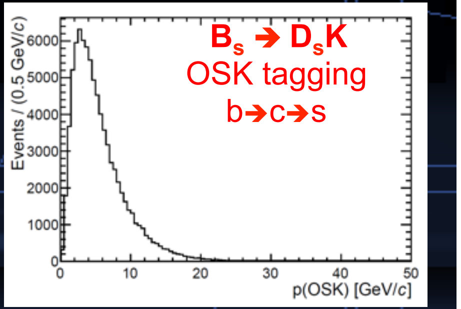
after PID cuts



[LHCb, JHEP 05 (2015) 019]



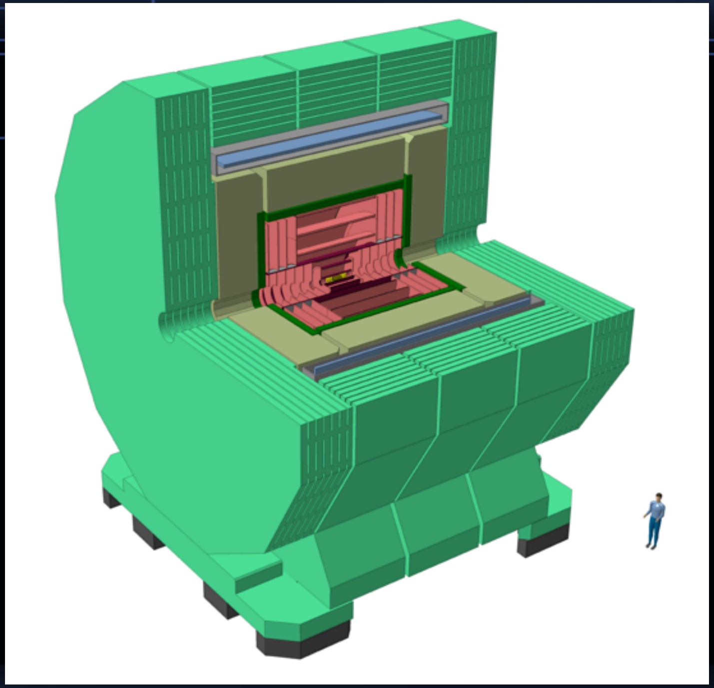
$B_s \to D_s K$
background
$B_s \to D_s \pi$
×10

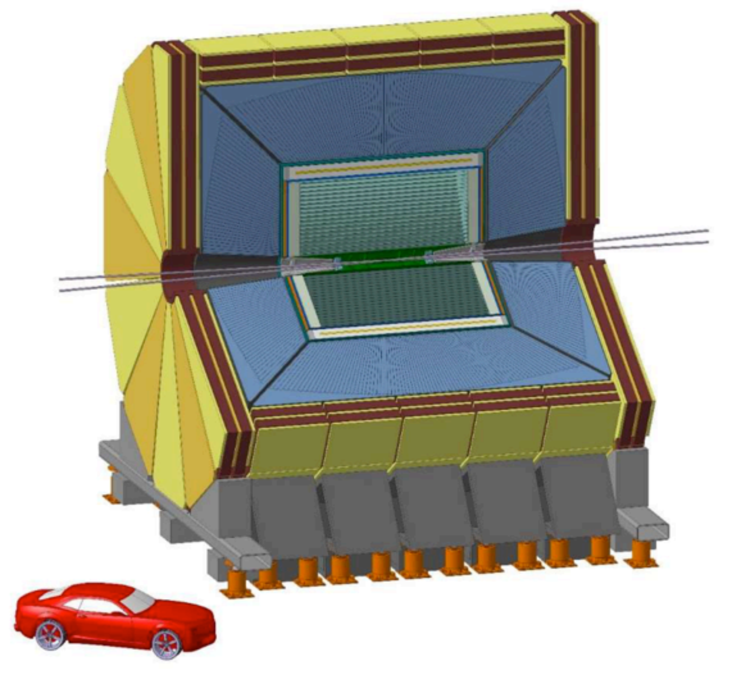


$B_s \to D_s K$
OSK tagging
b→c→s

CLD

IDEA





Adaptation from CLIC detector

Full silicon tracker

High granularity PFA calorimeter

Solenoid outside calorimeter

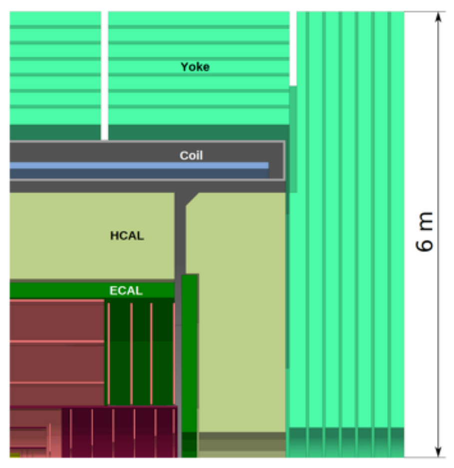
New, innovative (cheaper?) detector

Ultra-light drift chamber

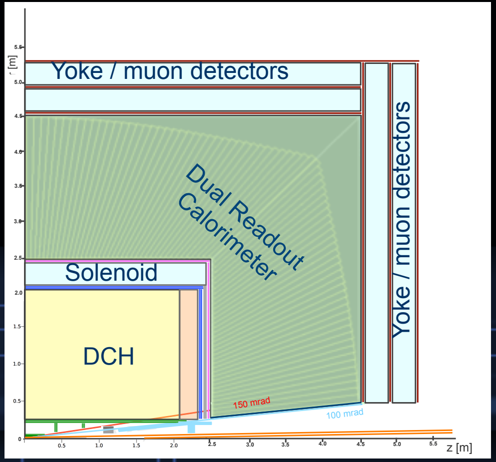
Dual Readout calorimeter

Solenoid inside calorimeter

CLD

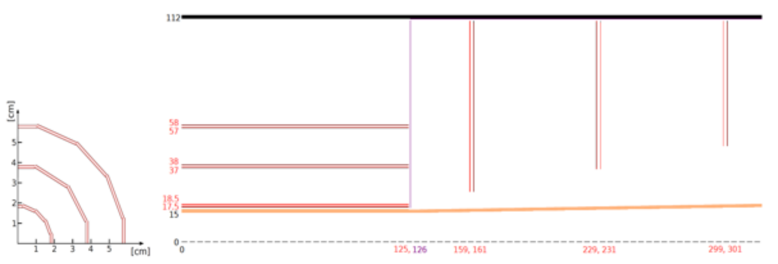


IDEA



	vertex detector	**tracker**	**calorimeter**	**magnet and muon detector**
CLD	3 double layers + 3 double disks 25μm×25μm pixel 50μm sensor 0.6-0.7% X_0 per double layer	pixel and μ-strips 7μm×90μm (5μm×5μm 1^{st} layer) point resolution 3 layers + 7 disks inner tracker 3 layers + 4 disks outer tracker 1-1.5% X_0 per layer	ECAL 20cm 5m×5m Si-W 1.9mm W 40 layers 22X_0, 1λ HCAL 117cm 30mm×30mm Sci-steel 19mm steel 44 layers 5.5λ	90 mm Al coil 2T field 1.5m steel yoke 6 layers RPC 30mm×30mm granularity
IDEA	3 double layers 20μm×20μm double μ-strips 50μm×1mm 4 forward disks 50μm×50μm 0.6-1% X_0 per double layer	112 layers 1.4 cm square cells 100μm×750μm point resolution Si wrapper 50μm×1mm 1.5% X_0 radially 5% X_0 forward	fully projective towers $\Delta\vartheta = 1.125°$ $\Delta\phi = 10.0°$ 2880 in barrel 2×1260 end-cap 2m Cu 8.2λ	30cm total envelope 2T field cold mass + cryostat 0.28 + 0.46 X_0 0.6m steel yoke 3 layers μ-RWELL 1.5mm×500mm granularity

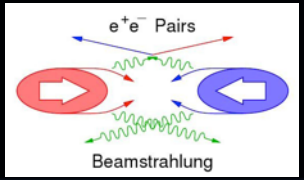
CLD Vertex detector IDEA



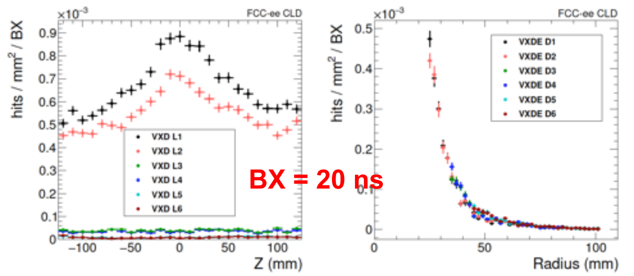
0.5 m^2
≈ 10^9 ch.

- Silicon pixels (25 x 25 μm^2), 3 μm single point resolution
- 3 double layers in barred R = 17, 27, 57 mm
- 3 double layers in end-cap disks Z = 160, 230, 300 mm
- Material budget: 0.6%/0.7% X0 per double layer in barrel/e-c

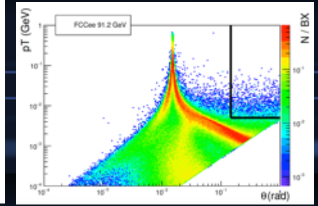
Full MC simulation

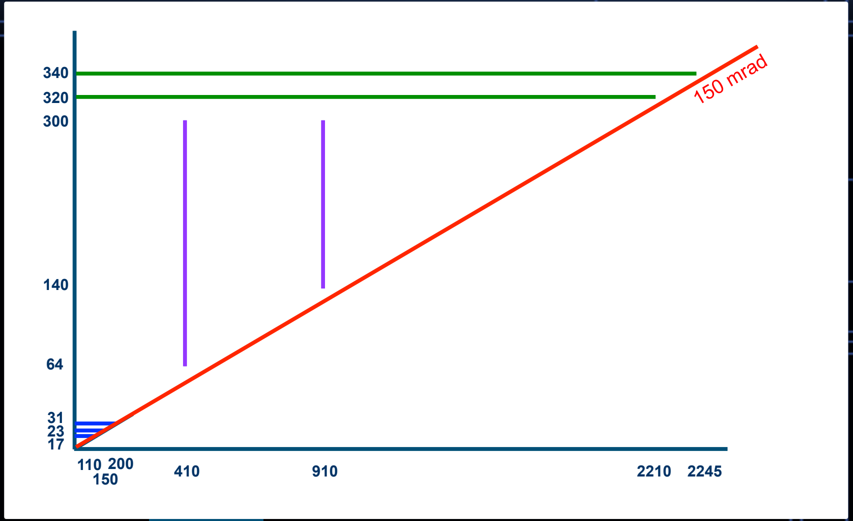


Occupancy at Z pole < 1-2×10-3 hits/pixel



BX = 20 ns





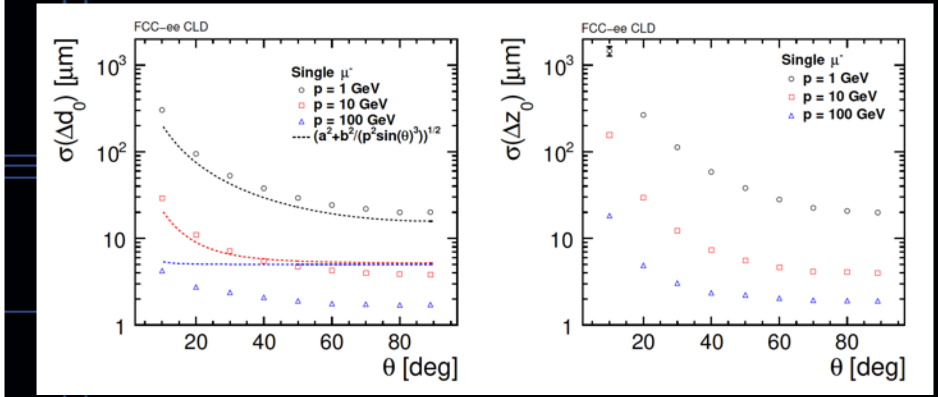
Inspired by ALICE ITS based on MAPS technology

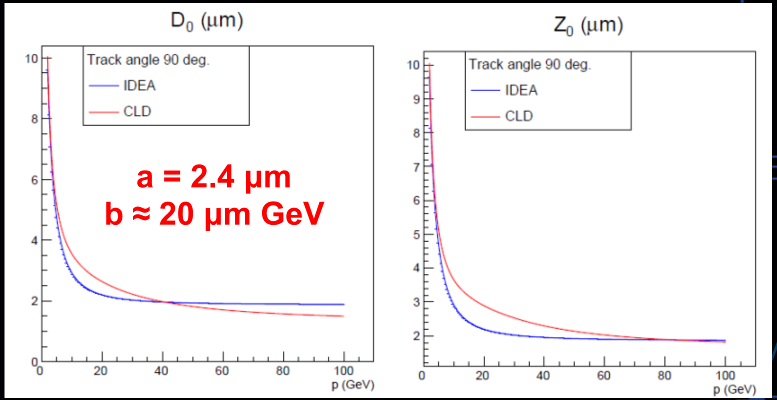
- inner layers 20×20 μm^2 pixel 0.3% X_0 per layer
  expected point resolution 3μm
- outer layers 0.05×1 mm^2 strips 1% X_0 per layer
- disks 50×50 μm^2 pixel 0.3% X_0 per layer

to be optimized ...

2 m^2, ≈ 1.2×10^9 ch. (+ 20 m^2, ≈ 0.4×10^9 ch.)

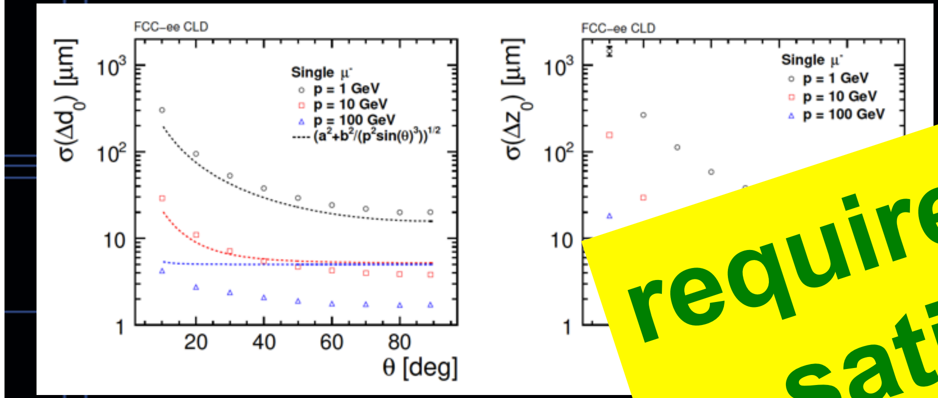
CLD Vertex detector IDEA

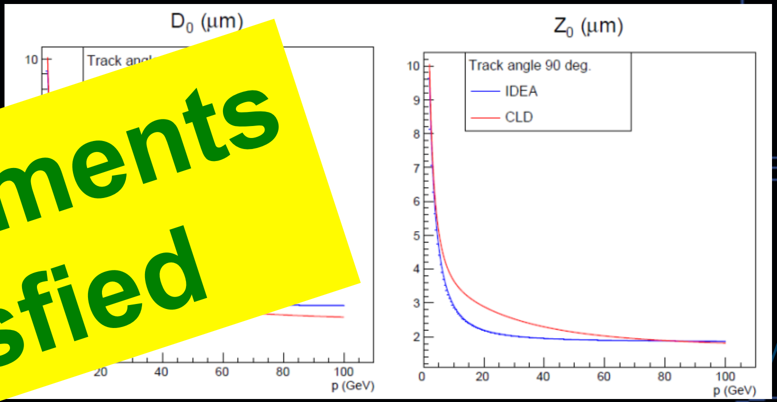




a = 2.4 μm
b ≈ 20 μm GeV

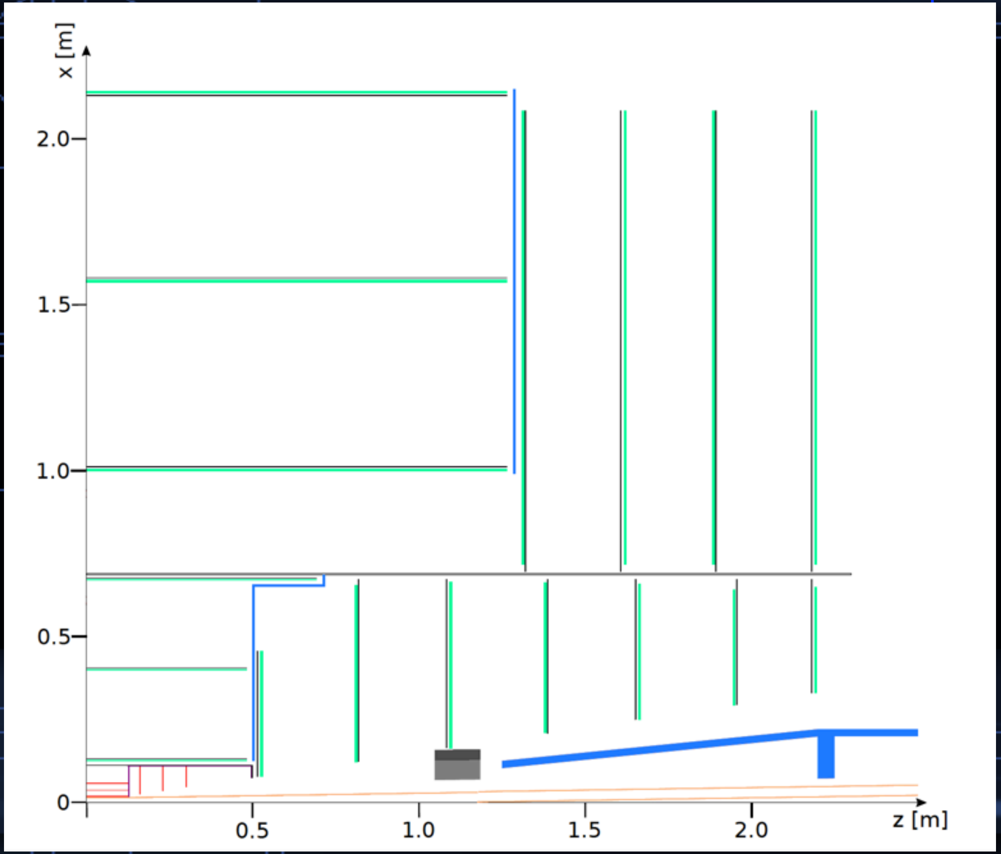
CLD Vertex detector IDEA





requirements satisfied

CLD Tracker

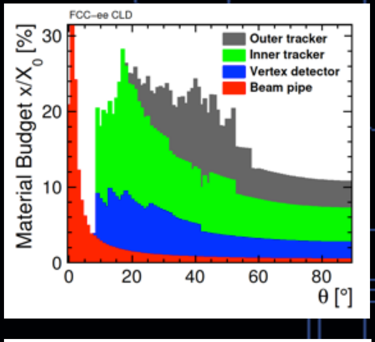


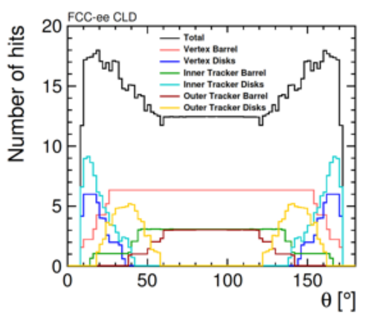
200 m^2
3×10^9 ch.

- **Inner Tracker**:
  3 barrel layers
  0.05×1 mm^2
  + 7 disks
  25×25 μm^2, 0.05×1 mm^2
- **Outer Tracker**:
  3 barrel layers + 4 disks
  0.05×10 mm^2

- Single point resolution:
  1st IT disks: 5×5 μm^2
  rest: 7×90 μm^2

- Material budget:
  1.1 - 1.6% X_0 per layer
  + C-fiber + support tube + …

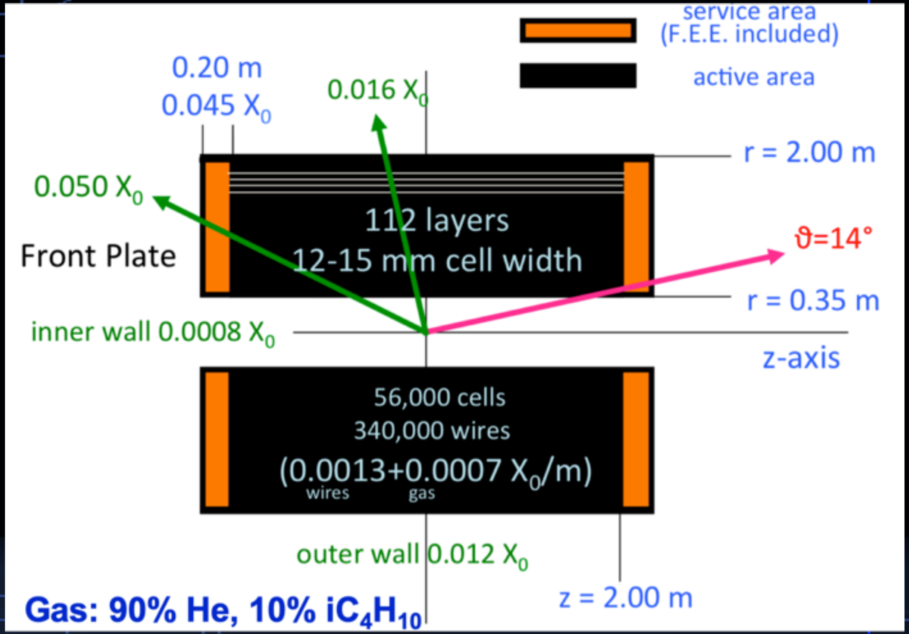




from 12 to 18 space points per track, angle dependent

IDEA Tracker

Drift Chamber with cluster timing/counting

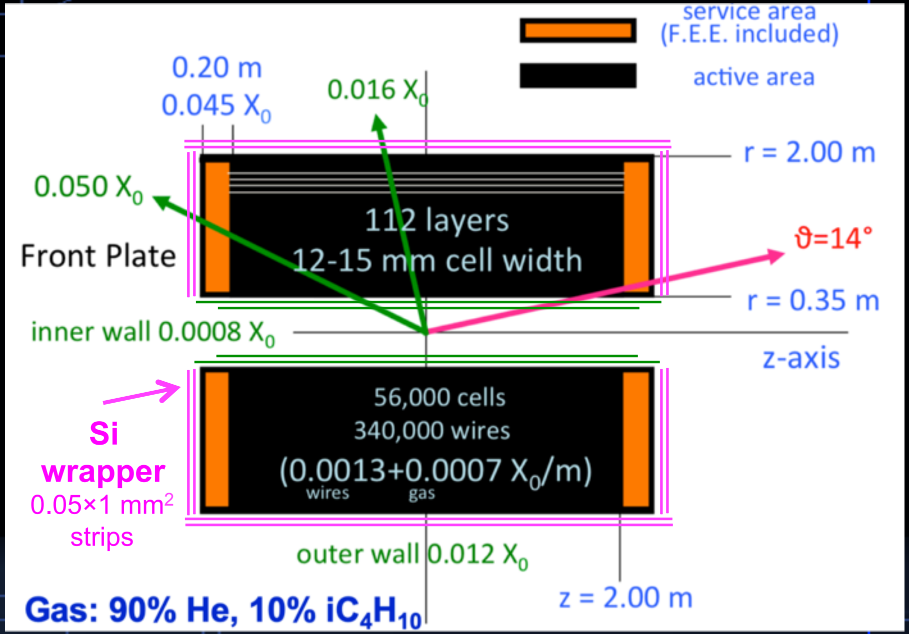


Gas: 90% He, 10% iC_4H_{10}

IDEA Tracker

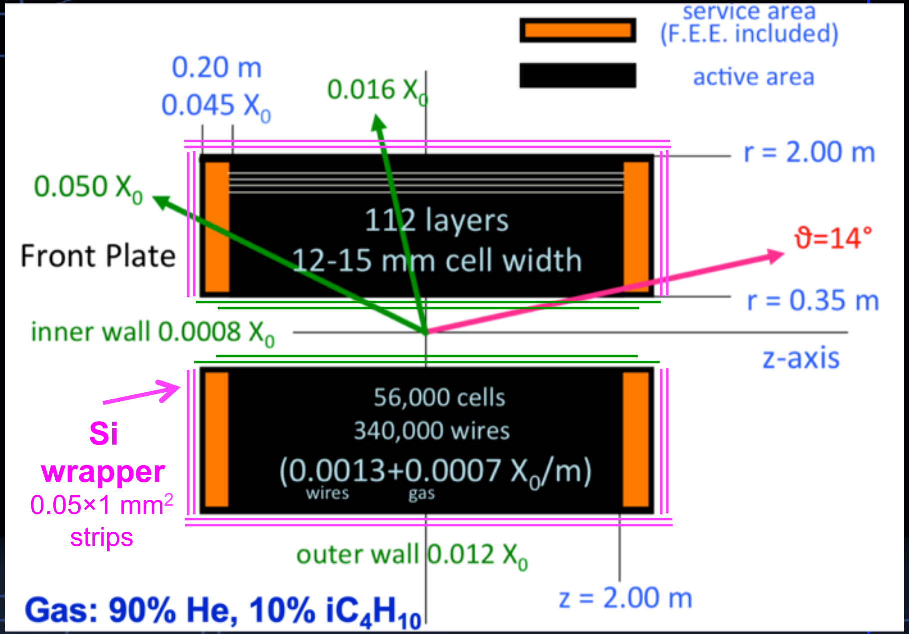
Drift Chamber with cluster timing/counting

+ Silicon wrapper



IDEA Tracker

Drift Chamber with cluster timing/counting + Silicon wrapper



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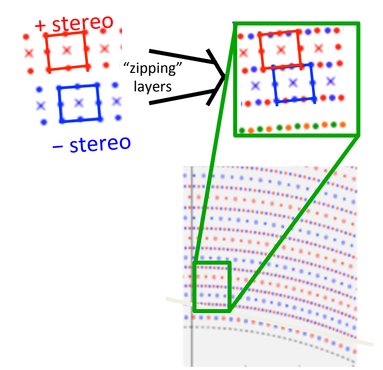
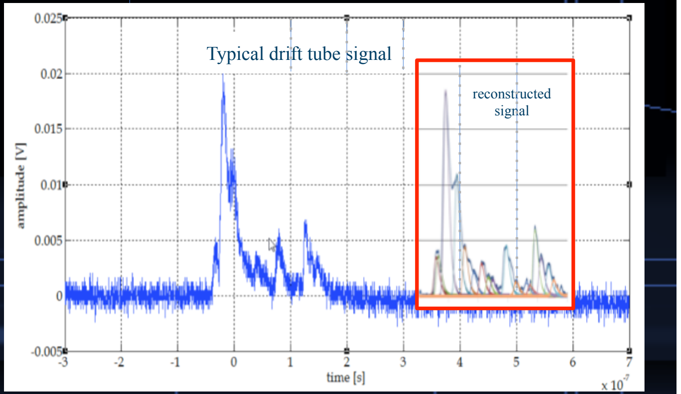


Drift chamber
≈50 m^3
112000 ch.

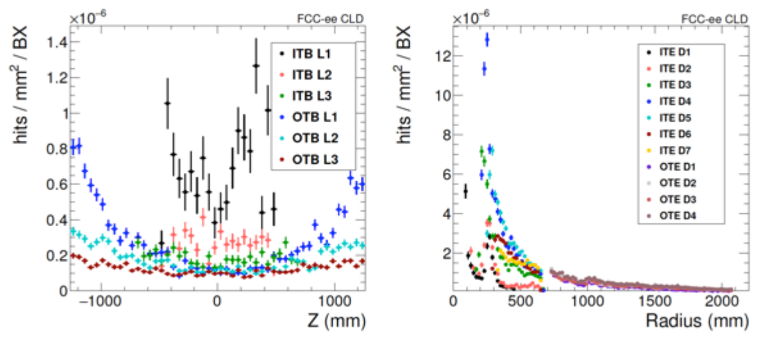
S wrapper
175 m^2
3.5×10^8 ch.

Cluster timing/counting

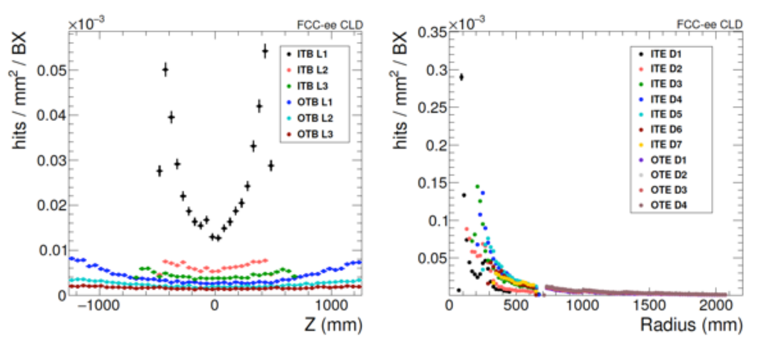


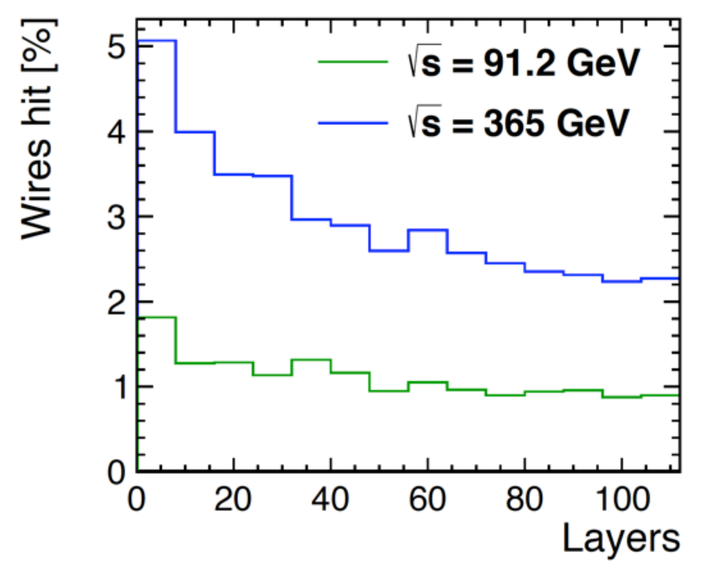
CLD Tracker Occupancy IDEA

IPC background at Z pole: **< 1% occupancy**



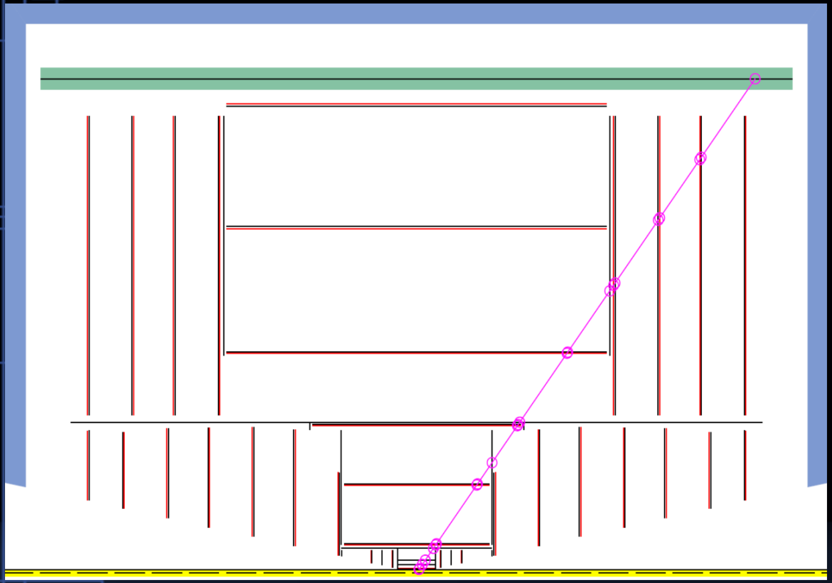
IPC background at ttbar: **< 0.2% occupancy**
similar contribution from synchrotron radiation

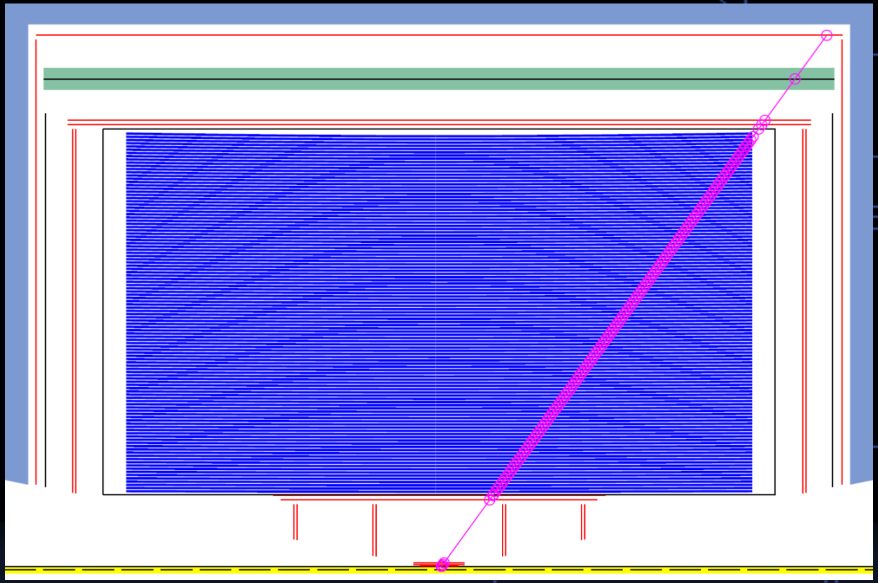




Background	Average occupancy $\sqrt{s}$ = 91.2 GeV	Average occupancy $\sqrt{s}$ = 365 GeV
e^+e^- pair background	1.1%	2.9%
$\gamma\gamma \to$ hadrons	0.001%	0.035%
Synchrotron radiation	negligible	0.2%

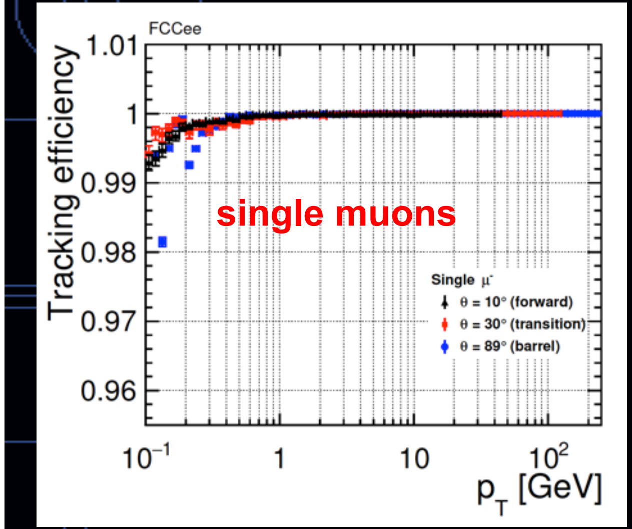
CLD Tracking IDEA



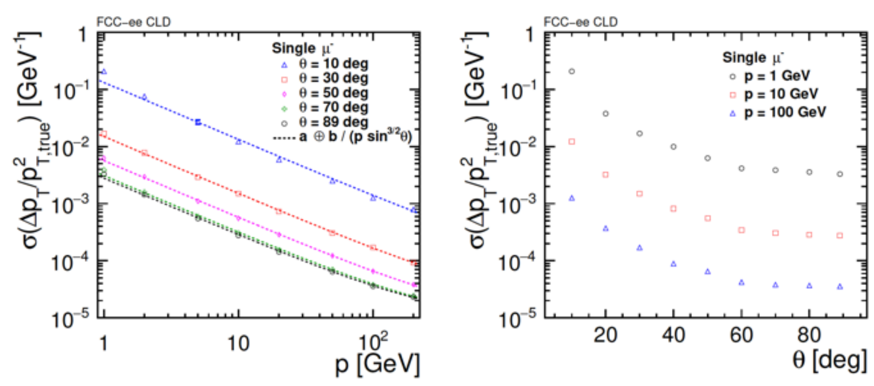


CLD Tracker Resolution

efficiency

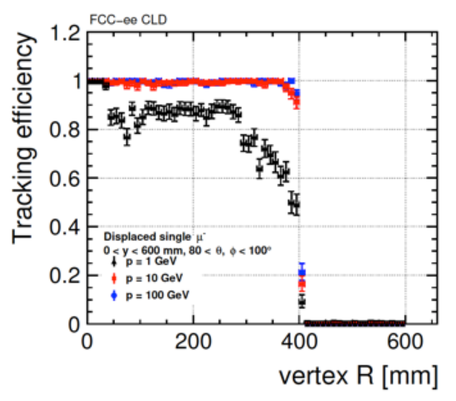


resolutions (full simulation)

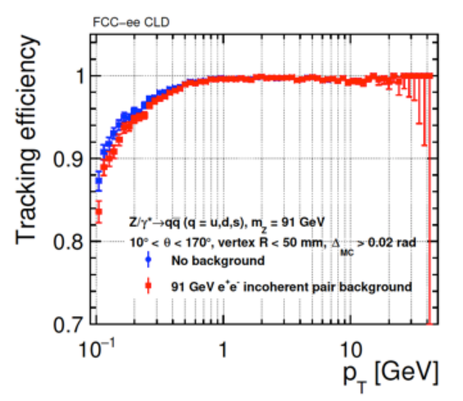


$$\sigma(\Delta p_{\mathrm{T}}/p_{\mathrm{T}}^2) = a \oplus \frac{b}{p\sin^{3/2}\theta}$$

θ	a	b
10°	$7.4\cdot10^{-5}$	0.010
30°	$1.8\cdot10^{-5}$	0.005
50°	$9.2\cdot10^{-6}$	0.004
70°	$8.3\cdot10^{-6}$	0.003
89°	$8.6\cdot10^{-6}$	0.003

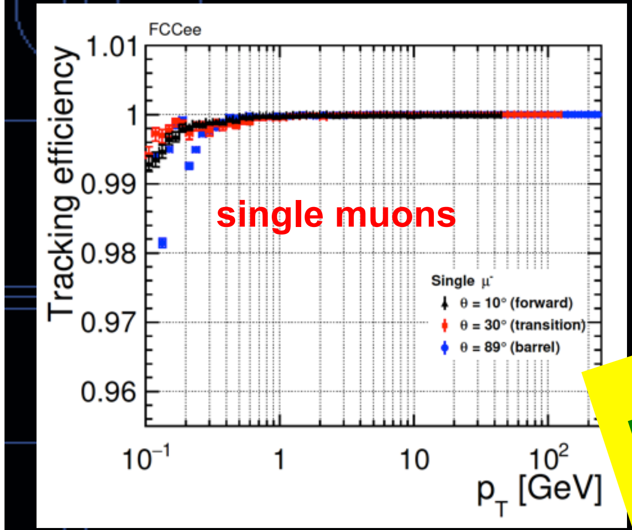


efficiency for muons at displaced vertices



CLD Tracker Resolution

efficiency



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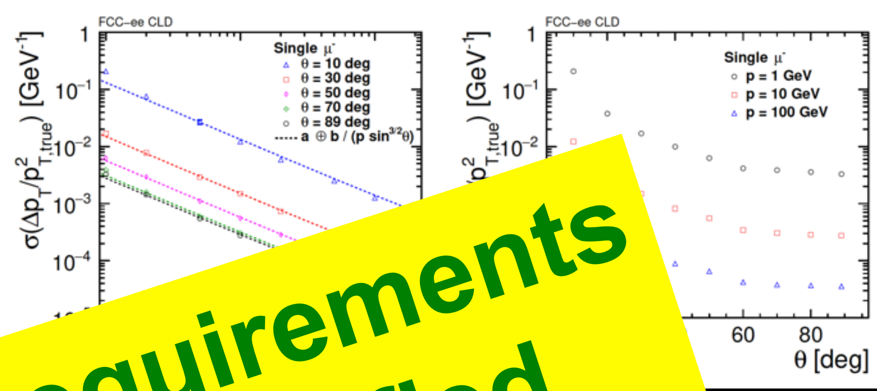

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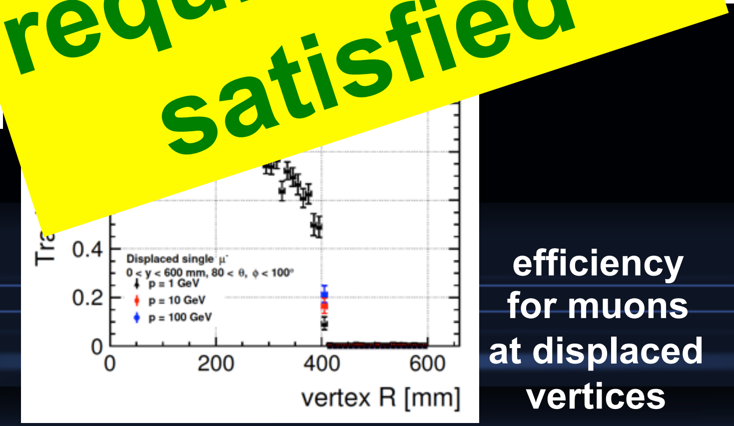
requirements satisfied



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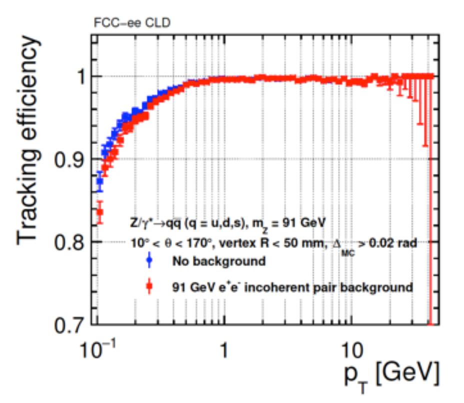
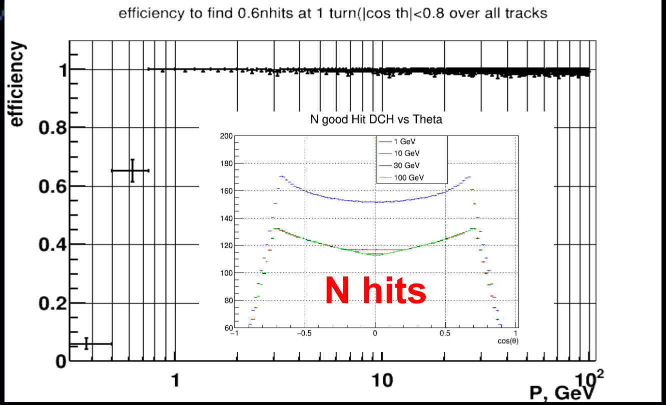
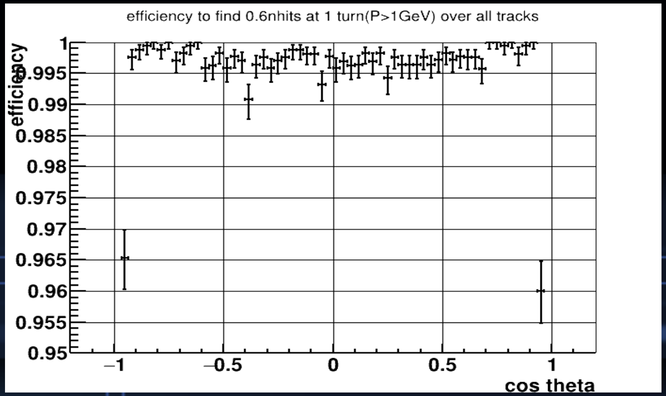
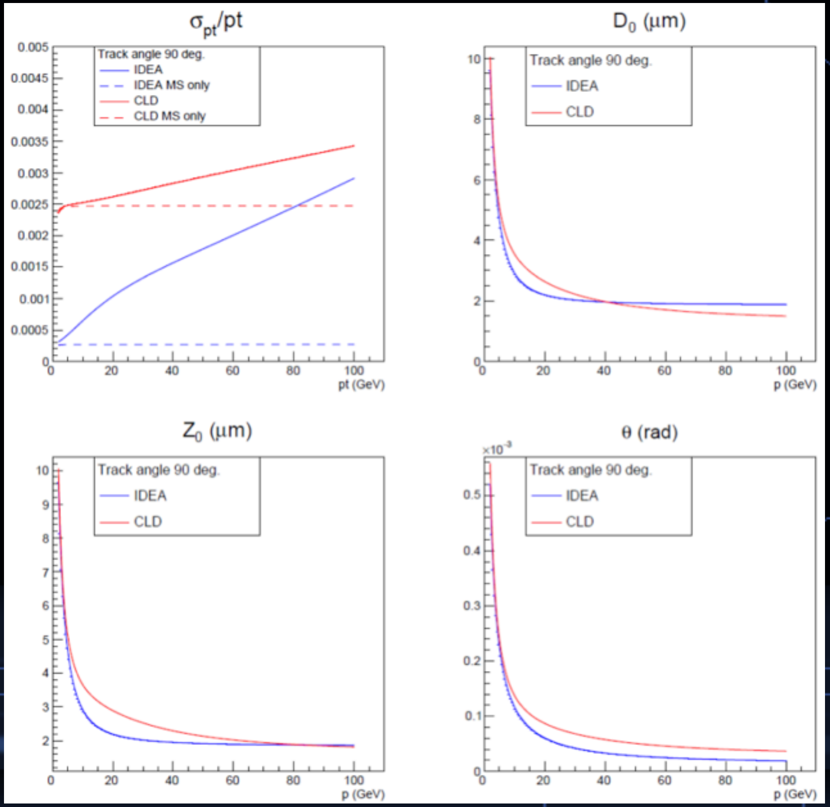


IDEA Tracker Resolution

efficiency

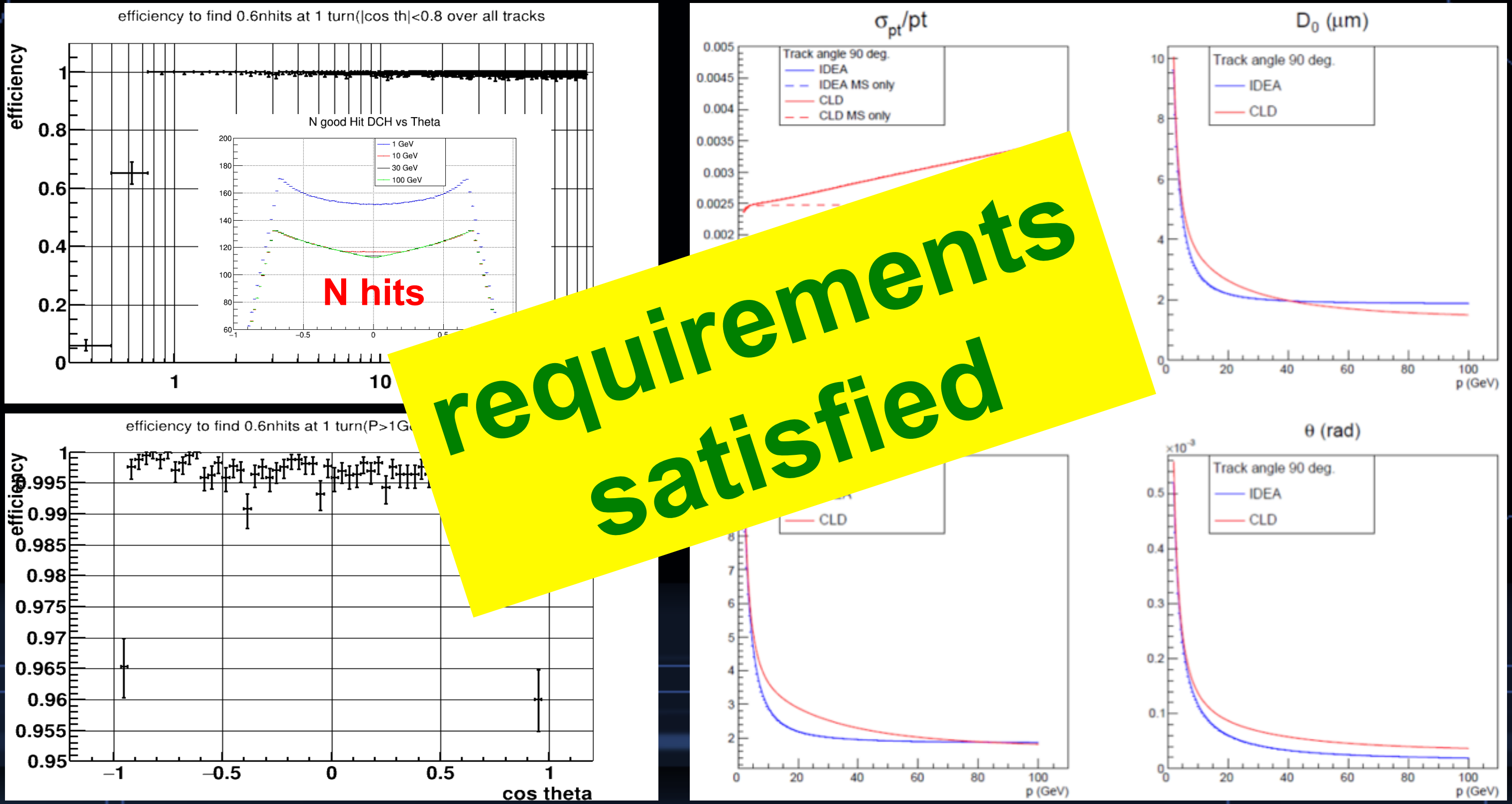






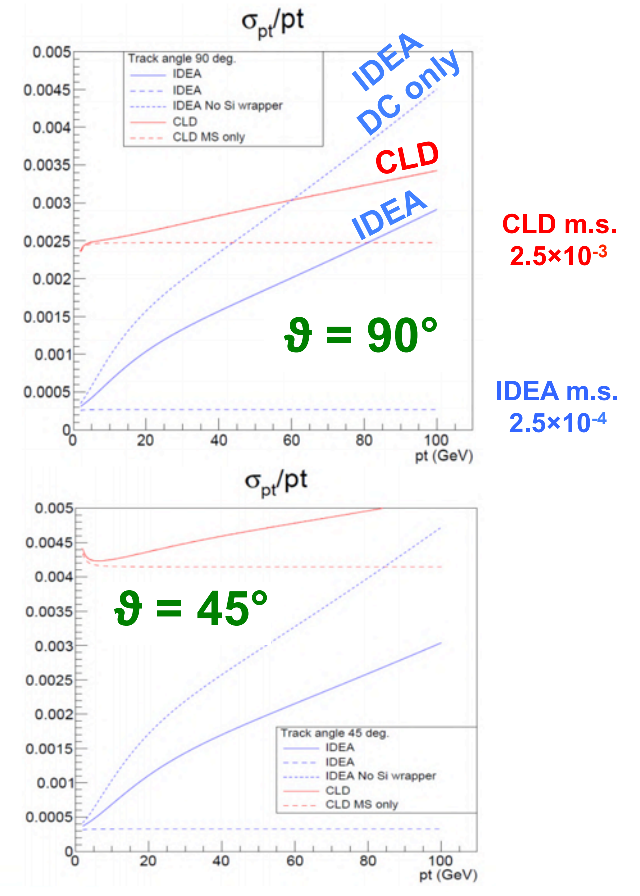
IDEA Tracker Resolution

efficiency



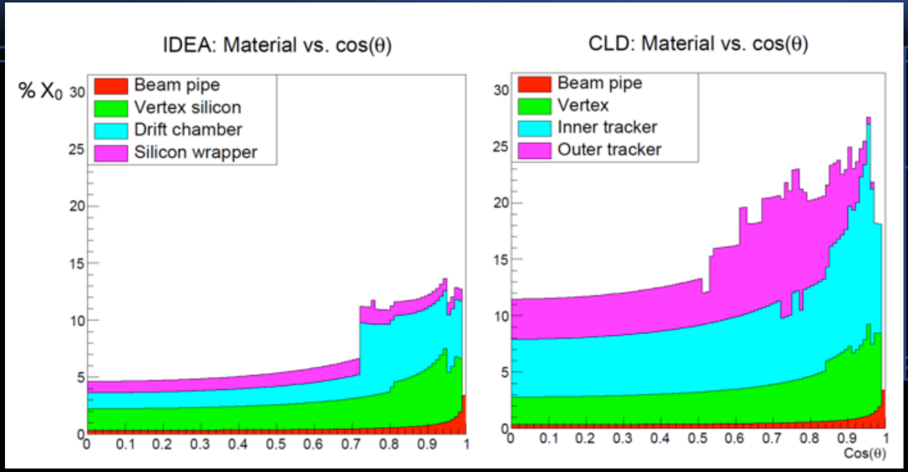
requirements satisfied

Momentum resolution

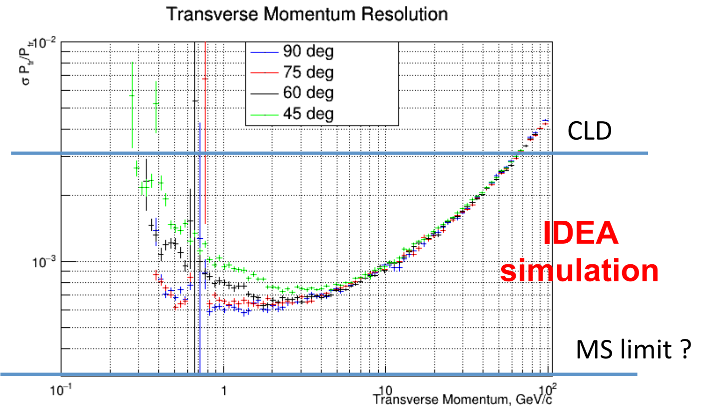


CLD m.s. 2.5×10^{-3}

IDEA m.s. 2.5×10^{-4}



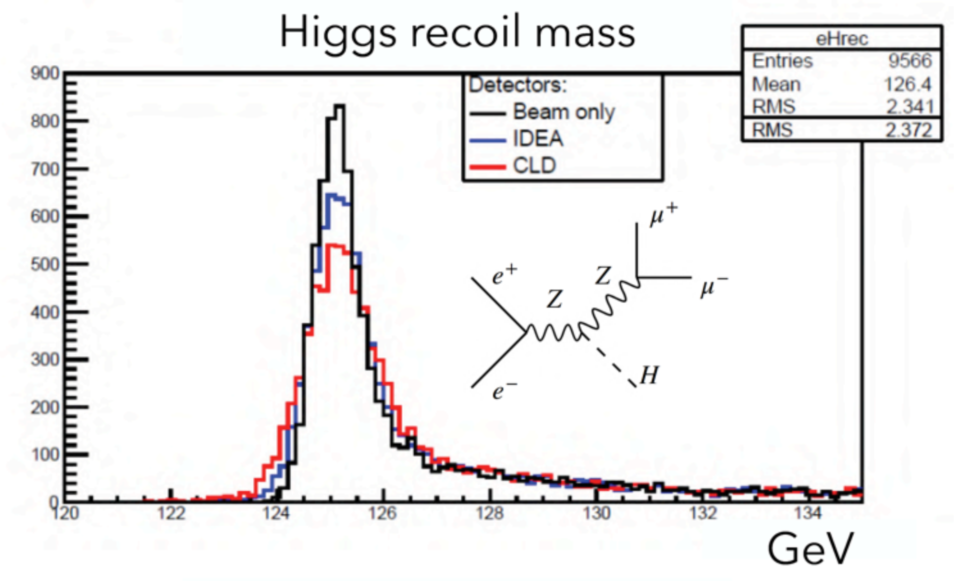
p [GeV]

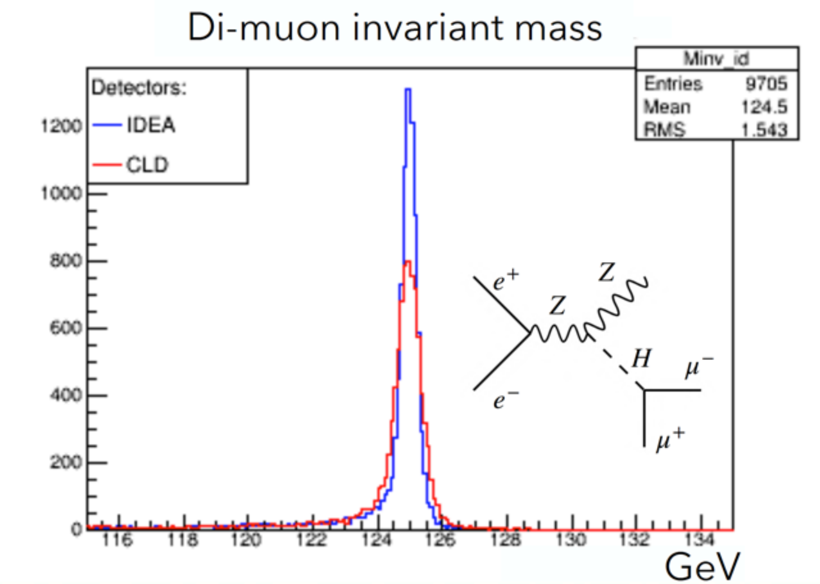


IDEA simulation

from Riegler at 11th FCC-ee Wrkshp

Momentum resolution

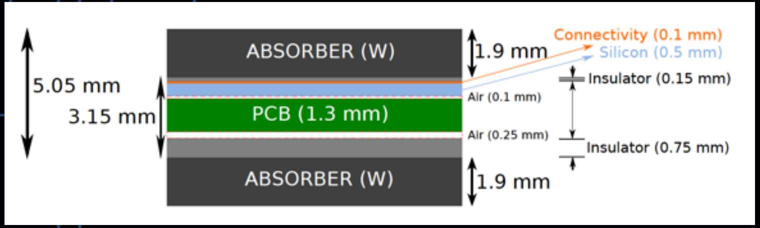




CLD Calorimeter

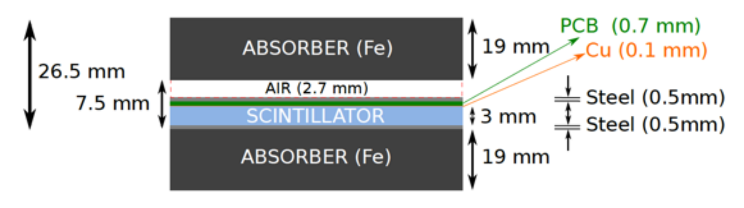
High granularity for **PFA**

ECAL

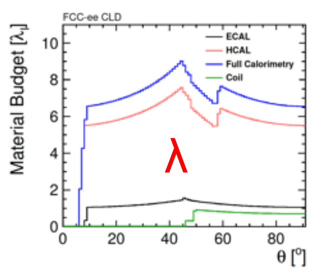


4000 m²
5×5 mm²
1.6×10^8 ch.
40 layers
22-23 X_0
200 cm deep
4.4 m long
2.5 m radius

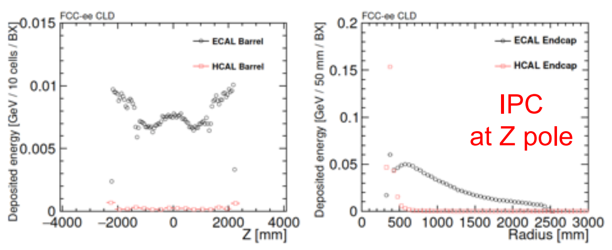
HCAL



8400 m²
30×30 mm²
9.2×10^6 ch.
44 layers
5.5 (+1) λ
1.2 m deep
4.4 m long
2.5 m radius

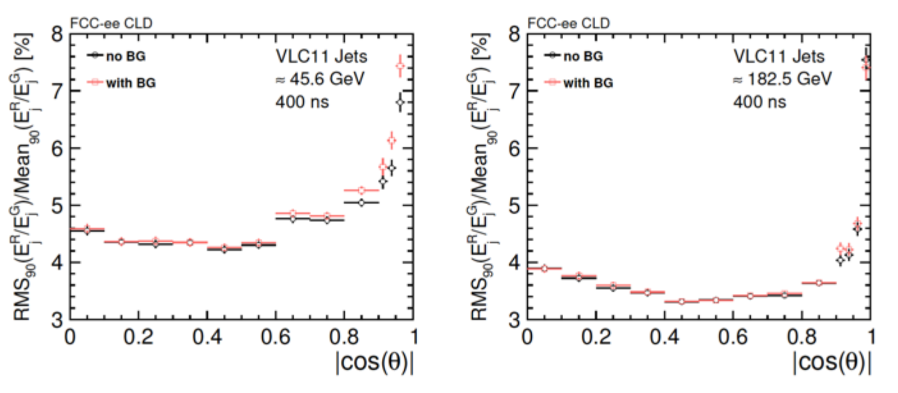


λ

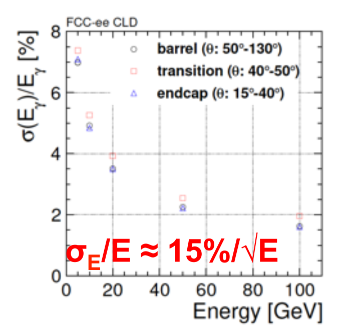


IPC
at Z pole

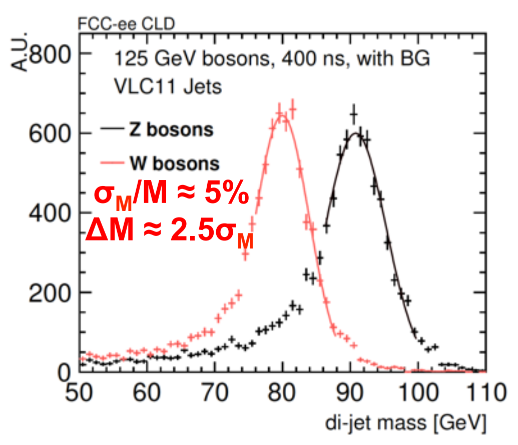
$q\bar{q}$ jet energy resolution



photons



$\sigma_E/E \approx 15\%/\sqrt{E}$

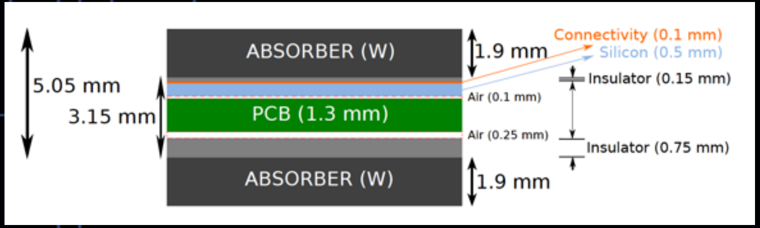


$\sigma_M/M \approx 5\%$
$\Delta M \approx 2.5\sigma_M$

CLD Calorimeter

High granularity for **PFA**

ECAL



4000 m²
5×5 mm²
1.6×10^8 ch.
40 layers
22-23 X_0
200 cm deep
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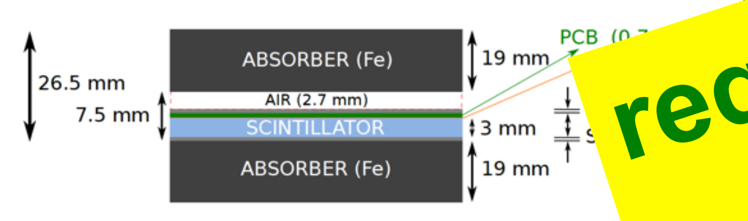
HCAL

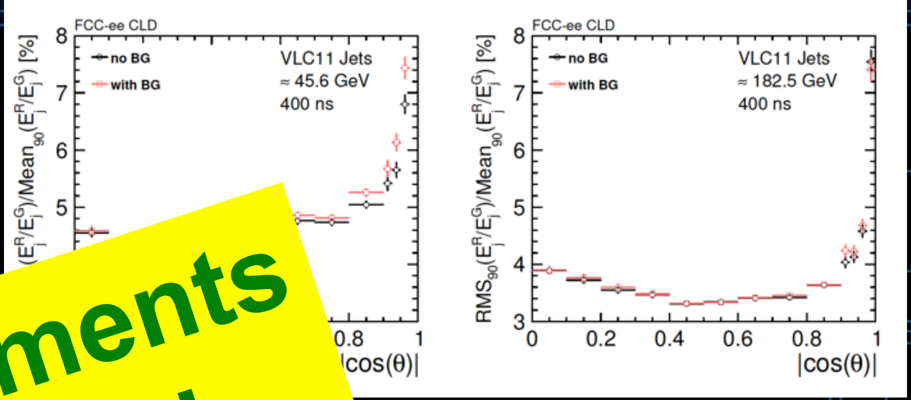


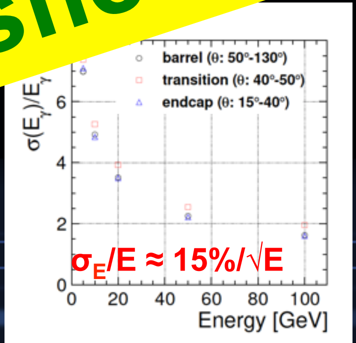
8400

adius

requirements satisfied

$q\bar{q}$ jet energy resolution





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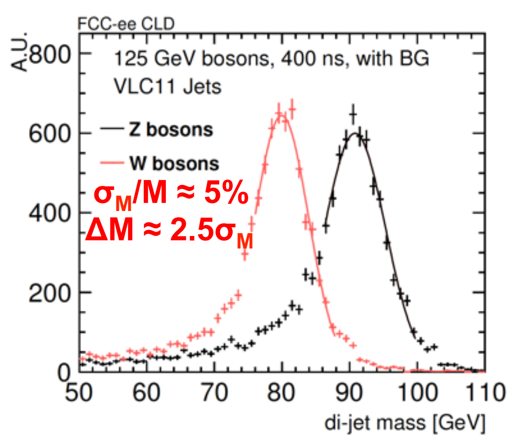
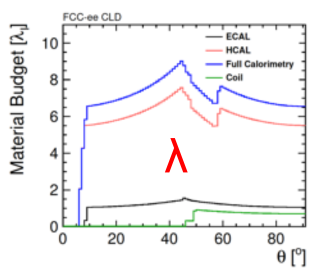
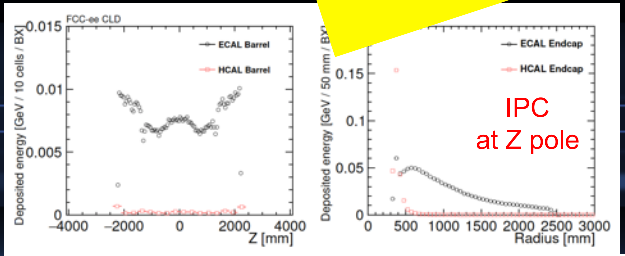


$\sigma_M/M \approx 5\%$
$\Delta M \approx 2.5\sigma_M$

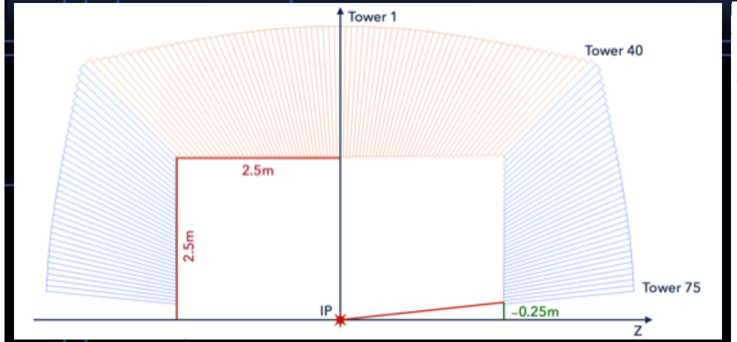


λ

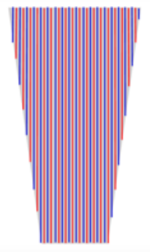


IPC
at Z pole

IDEA Calorimeter

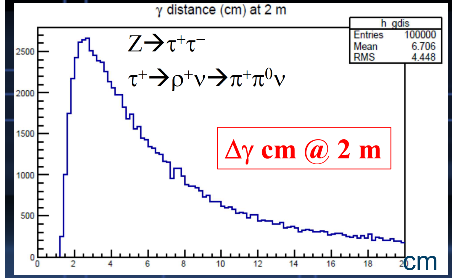


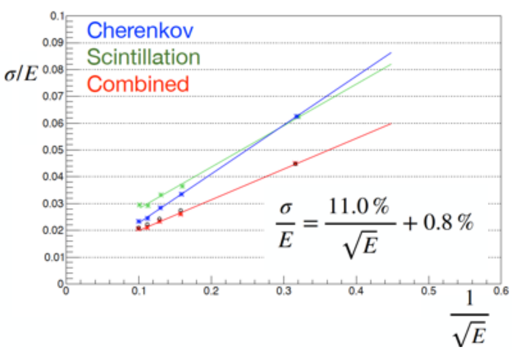
5400 towers
$\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
2 m Cu based towers: ~ 8.2 λ
both C/S fibers: 1 mm diameter
0.5 mm absorber in between
Total number of fibers: ~131 M

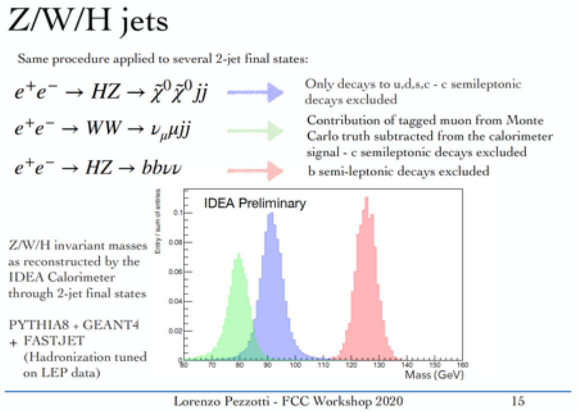


constant sampling fraction

< 1×1 cm²adequate granularity







Z/W/H jets

Same procedure applied to several 2-jet final states:

$e^+e^- \to HZ \to \tilde{\chi}^0\tilde{\chi}^0 jj$ → Only decays to u,d,s,c - c semileptonic decays excluded

$e^+e^- \to WW \to \nu_\mu \mu jj$ → Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal - c semileptonic decays excluded

$e^+e^- \to HZ \to bb\nu\nu$ → b semi-leptonic decays excluded

Z/W/H invariant masses as reconstructed by the IDEA Calorimeter through 2-jet final states

PYTHIA8 + GEANT4
+ FASTJET
(Hadronization tuned on LEP data)

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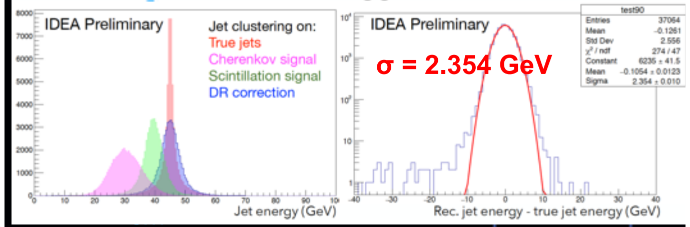
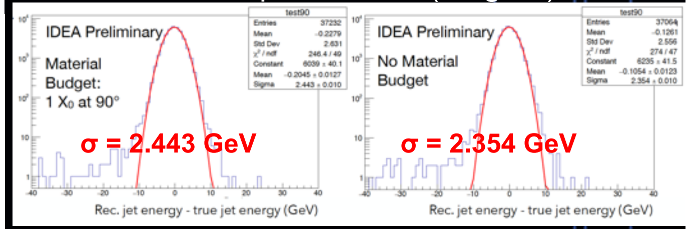
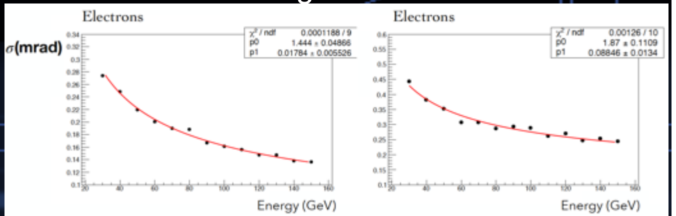
$$e^+e^- \to Z \to jj \ @90\ GeV$$



effect of pre-shower (magnet)

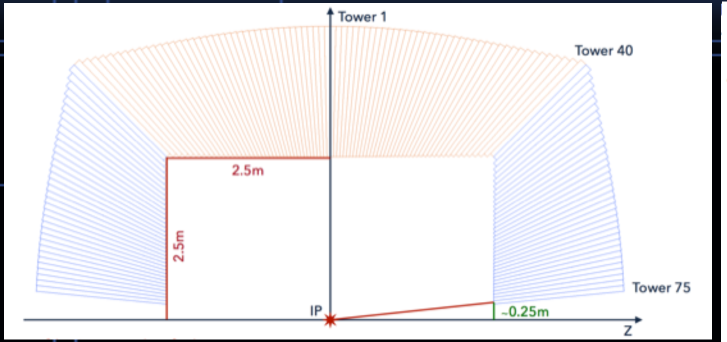


electron angular resolutions



$$\sigma_\theta = \frac{1.4}{\sqrt{E}} + 0.018 \qquad \sigma_\phi = \frac{1.8}{\sqrt{E}} + 0.088$$

IDEA Calorimeter



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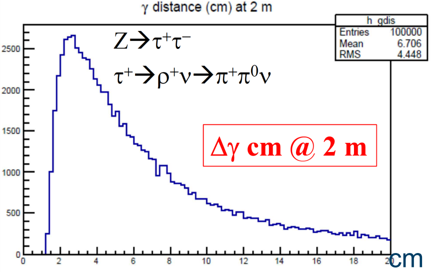
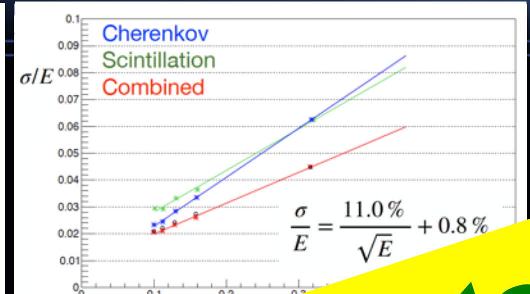
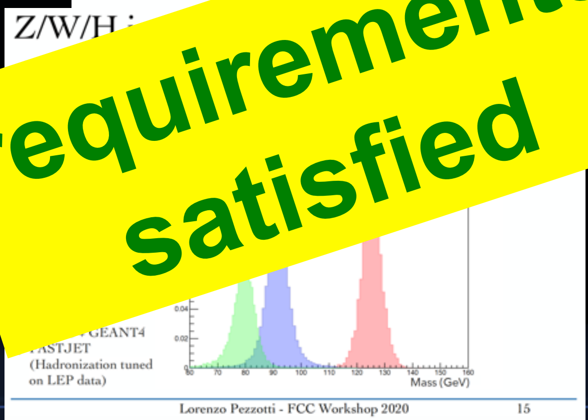


constant
sampling fractio



$$\frac{\sigma}{E} = \frac{11.0\,\%}{\sqrt{E}} + 0.8\,\%$$

requirements satisfied



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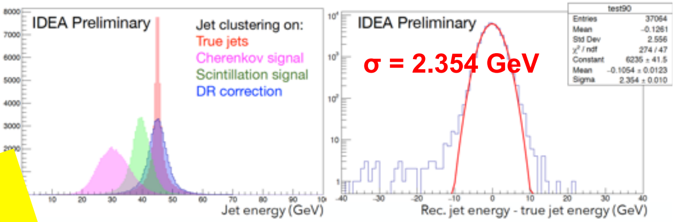
$$e^+e^- \rightarrow Z \rightarrow jj \;@90\;GeV$$



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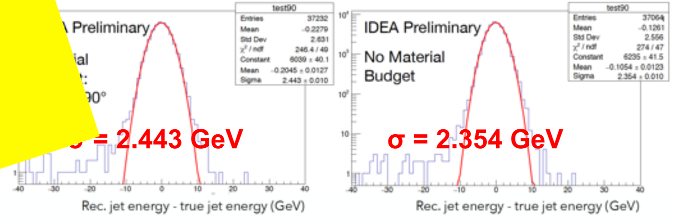
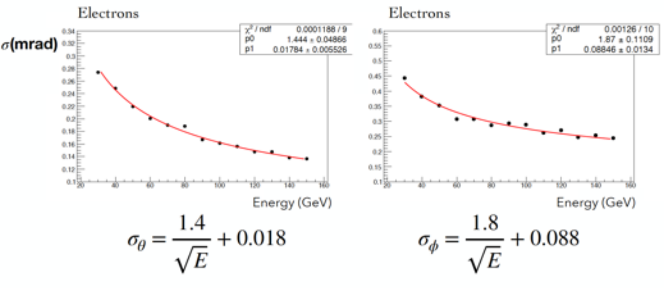


electron angular resolutions



$$\sigma_\theta = \frac{1.4}{\sqrt{E}} + 0.018 \qquad \sigma_\phi = \frac{1.8}{\sqrt{E}} + 0.088$$

Particle Identification

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

from *Walenta parameterization (1980)*

versus

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2}$$

from *Poisson distribution*

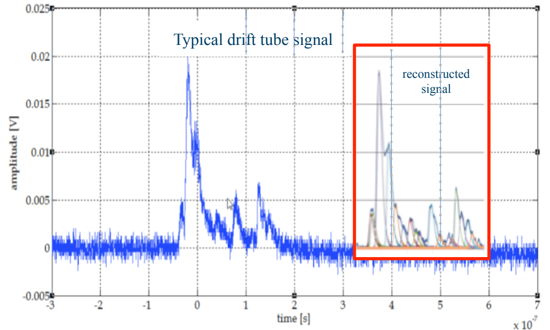
dE/dx

truncated mean cut (70-80%) reduces the amount of collected information

***n* = 112** and a **2m track** at **1 atm** give

σ ≈ 4.3%

Increasing ***P*** to 2 atm improves resolution by 20% (σ ≈3.4%) but at a **considerable**

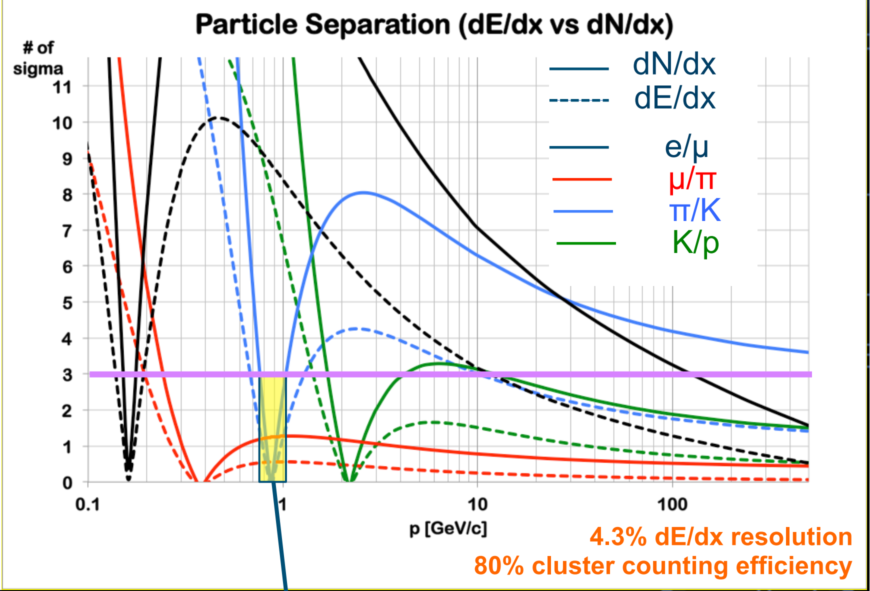


dN$_{cl}$/dx

***δ$_{cl}$* = 12.5/cm** for He/iC$_4$H$_{10}$=90/10 and a **2m track** give

σ ≈ 2.0%

A small increment of iC$_4$H$_{10}$ from 10% to 20% (δ_{cl} = 20/cm) improves resolution by 20% (σ ≈1.6%) at only a **reasonable** cost of multiple scattering contribution to momentum and angular resolutions.



4.3% dE/dx resolution
80% cluster counting efficiency

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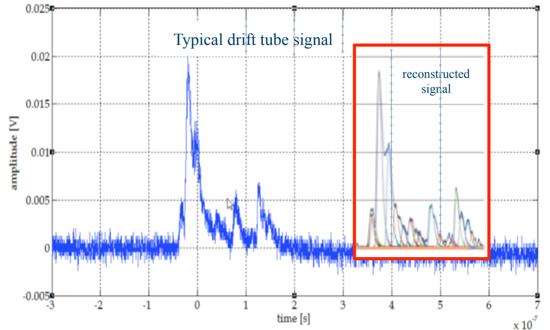

dN_{cl}/dx

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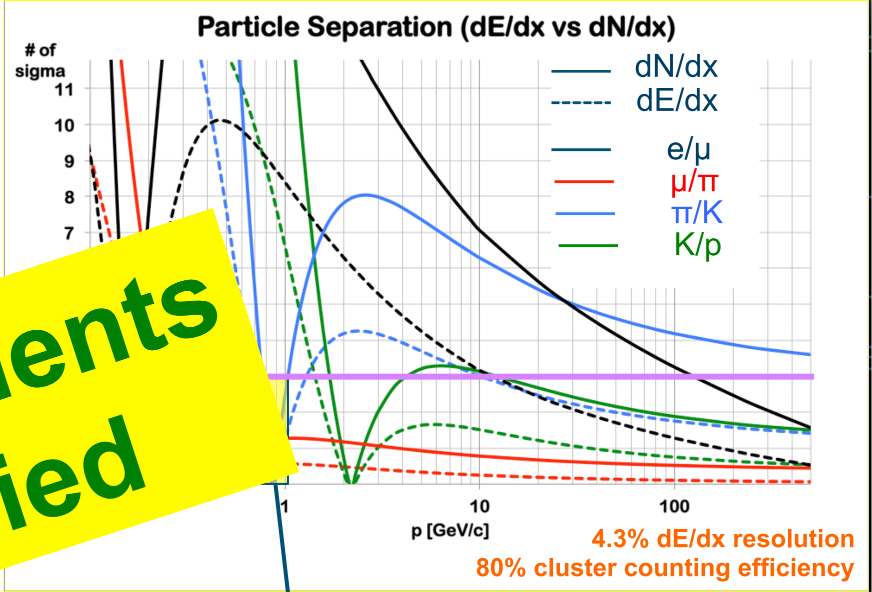
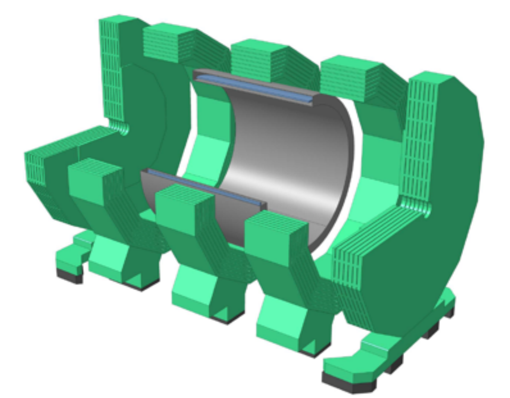
σ ≈ 2.0%

requirements satisfied

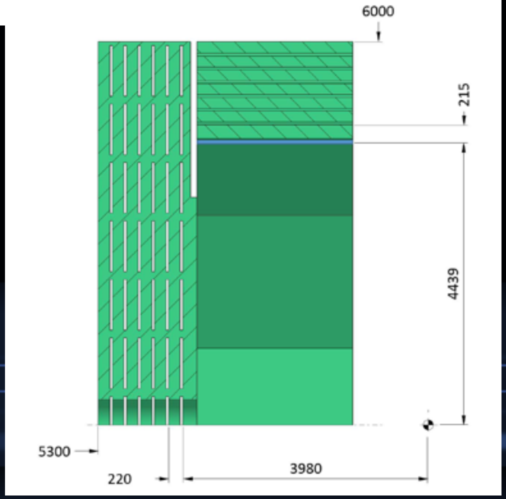


4.3% dE/dx resolution
80% cluster counting efficiency

CLD Magnet and muons IDEA



return yoke
1.5 m steel



muon detector
6 (+1) layers
30×30 mm^2 RPC
(crossed sci. bars
as option)
in 40 mm gap

self-supporting single layer coil
inside DR calorimeter
0.75% X_0
30 cm thick

return yoke
1.0 m steel

16,000 m^2
1.5×500 mm^2
2×10^6 ch.

µRwell