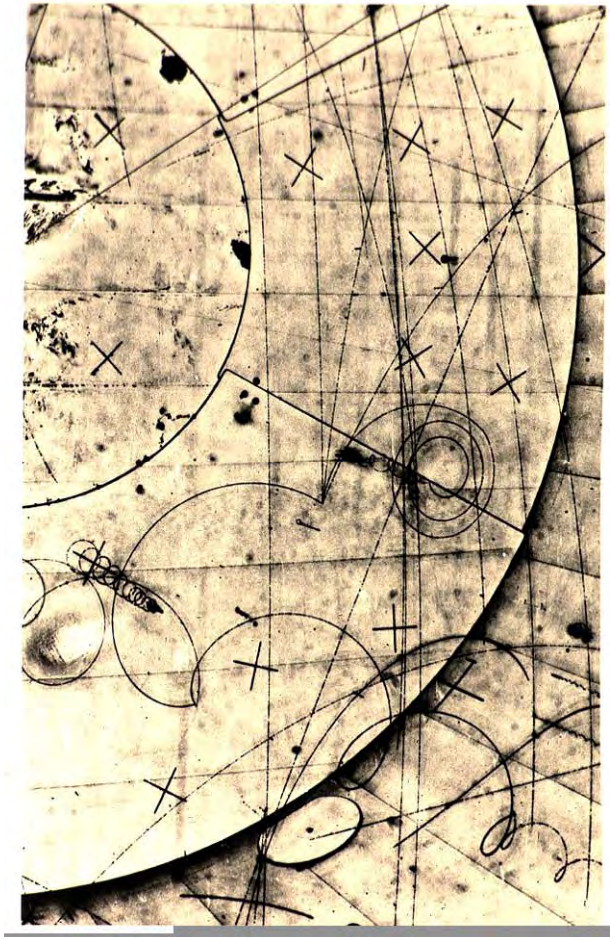
Metody eksperymentalne w fizyce wysokich energii

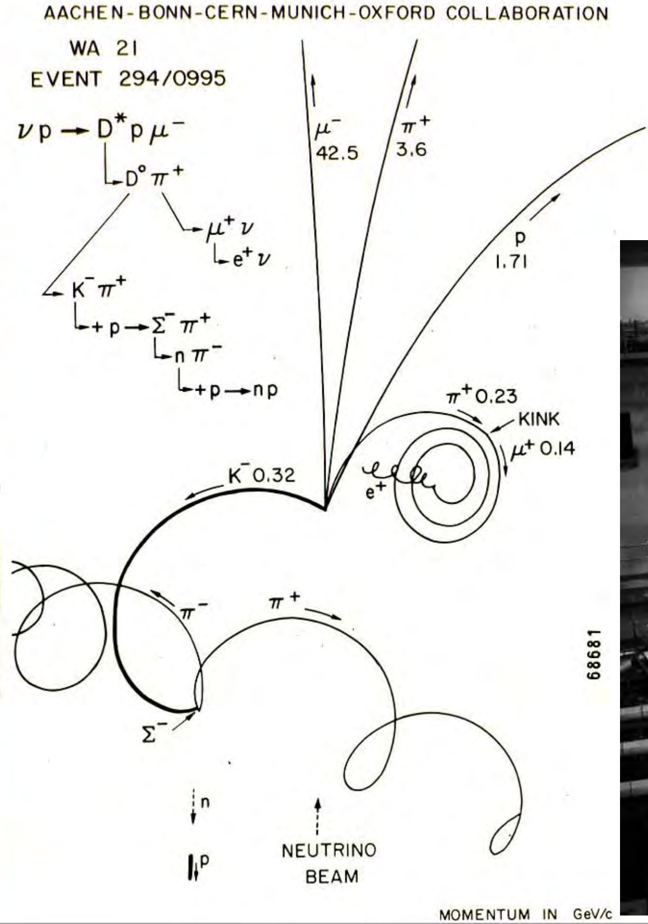
prof. dr hab. A.F.Żarnecki
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład IX

- Eksperymenty akceleratorowe

Ideałem jest pełna rekonstrukcja przypadku





BEBC, equipped with the largest superconducting magnet in service at the time.

D* (excited D-meson, carrying the "charm" quantum number): production and decay during a wide band exposure in experiment WA21, in the BEBC liquid hydrogen bubble chamber.

O. Ullaland/2006

Pojedyncze detektory pozwalają bardzo precyzyjnie zmierzyć:

- pozycję cząstki (detektory krzemowe, detektory śladowe)

- tor cząstki (detektory śladowe)
  => w polu magnetycznym: pęd cząstki

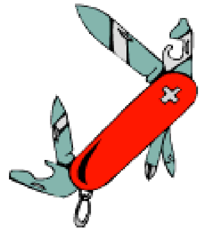
- prędkość cząstki (TOF, detektory Czerenkowa)

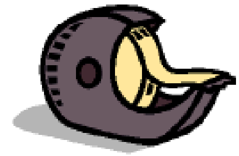
- energię cząstki (kalorymetry)

- typ cząstki (TRD, na podstawie oddziaływania w materii)

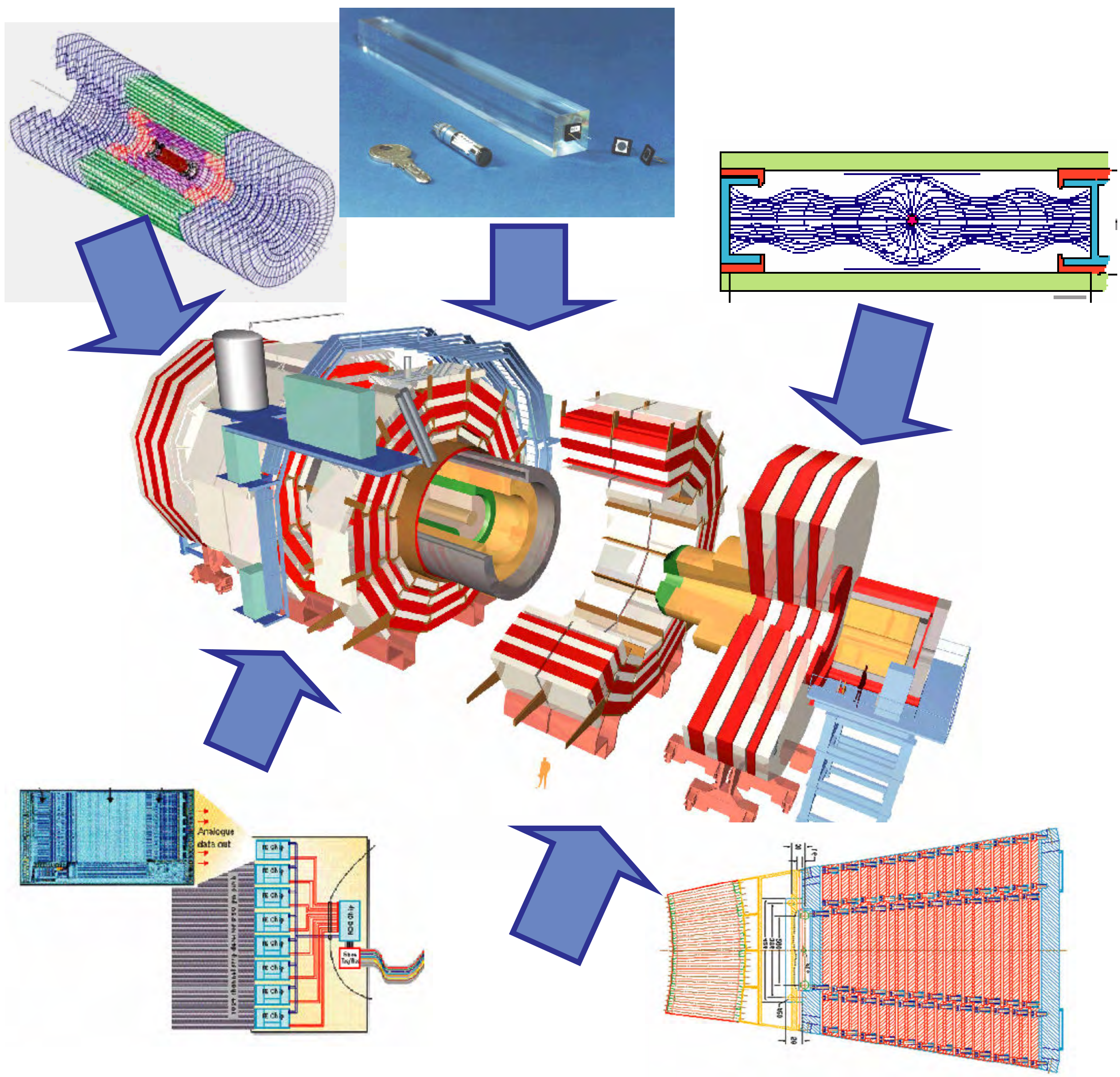
Na tej podstawie jesteśmy często w stanie zidentyfikować cząstkę
ale naogół tylko w ograniczonym zakresie kinematycznym

Let's find some tools …





and put everything together !



How do you design a detector?

Robert Roser (FNAL), Hadron Collider Summer School 2006

It starts with the Physics

- What is the physics measurement that is driving the experiment?
- What are the final states – how will you measure them? Examples include
  - Pizero ID (separation of two photons?)
  - J/Psi – good tracking
  - Light quarks – good calorimeter
  - b and c quarks (tagging)
- What level of precision are you after?
  - Precision has a cost; dollars, complexity, and readout speed

It continues with the Physics

- Can you trigger on the physics process of interest?
  - Separate the unique signature of the physics of interest from the literally billions of collisions that go on each day
- What is the rate?
  - Drives both the trigger and data acquisition system
  - Do you need to worry about "dead-time"?
  - How will you calibrate your detector?
  - How will you measure the various detector efficiencies

Global Detector Systems

Overall Design Depends on:

–Number of particles

–Event topology

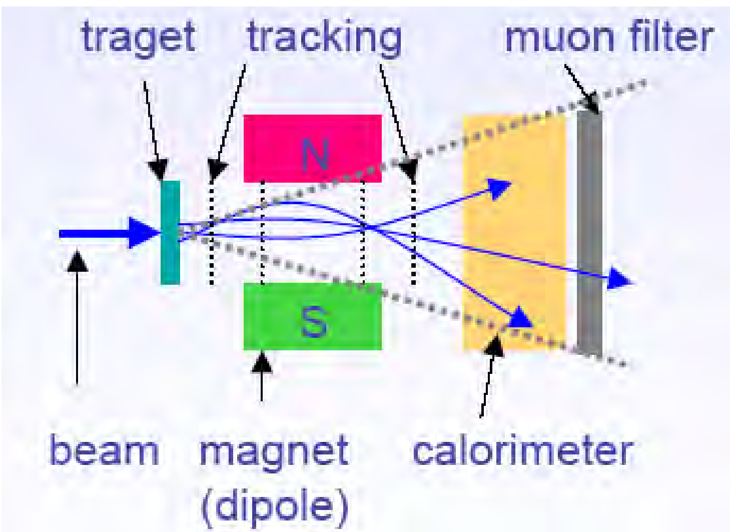
–Momentum/energy

–Particle identity

No single detector does it all…

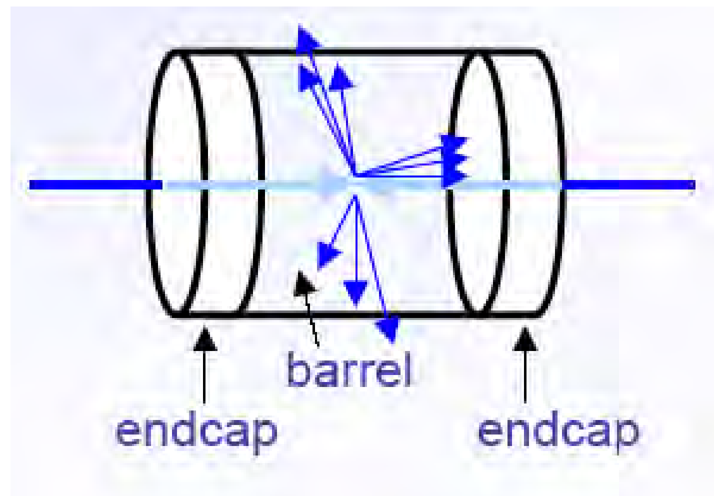
→ Create detector systems

Fixed Target Geometry



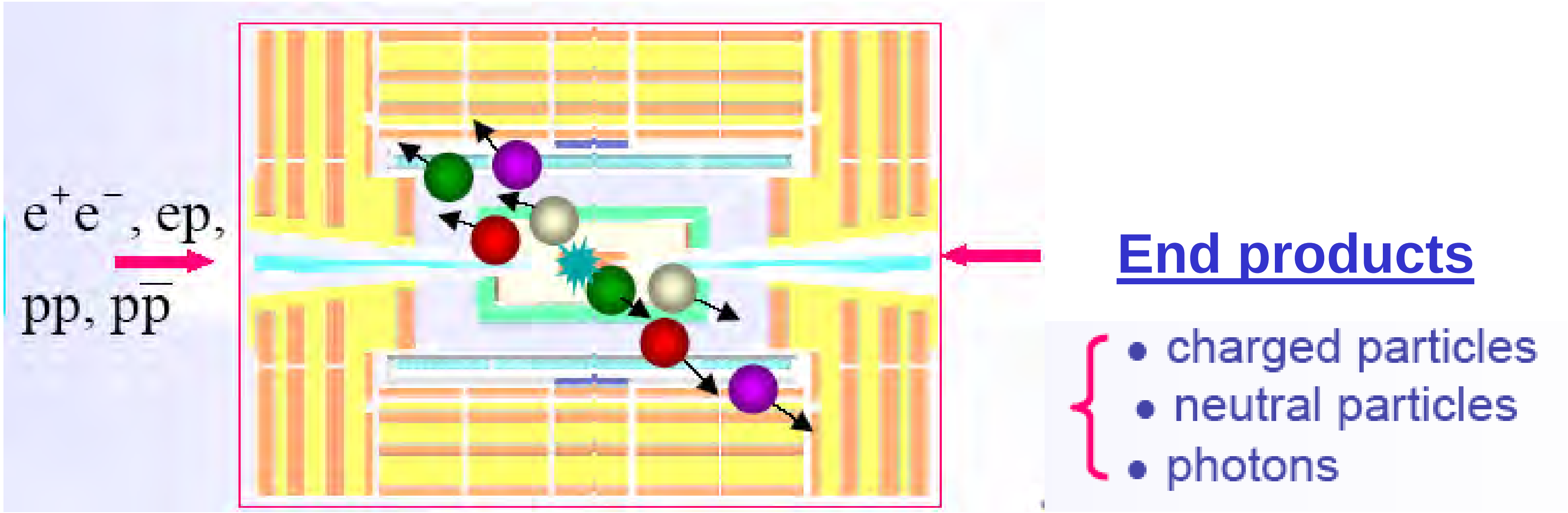
- Limited solid angle ($d\Omega$) coverage (forward)
- Easy access (cables, maintenance)

Collider Geometry



- "full" solid angle $d\Omega$ coverage
- Very restricted access

Ideal Detectors



An "ideal" particle detector would provide...

- Coverage of full solid angle, no cracks, fine segmentation
- Measurement of momentum and energy
- Detection, tracking, and identification of all particles (mass, charge)
- Fast response: no dead time

However, practical limitations: Technology, Space, Budget, and engineering prevent perfection...

We can’t build a perfect detector

- A perfect detector has no “holes”
  - Reality is that in order to read the detector, we need to get the signals out. This is done with cables. Cable paths force us to have “seams” in the detector where we don’t know what is happening
- A perfect detector is identical in every direction with respect to the collision point
  - We need to support these detectors which means that the material is not isotropic.
- A perfect detector is 100% efficient

Detector Design Constraints

- What is the current technology and where do we expect technology to be when the experiment is ready to take data
  - Most experiments these days take a long time. The time between “the expression of interest” to “ready for collisions” is measured in years
  - All of the technology required for the experiment to work does not have to be “ready” (commercial) at the proposal stage
  - Typically time for R&D
  - Moore’s law for computing is often relied upon

Detector Design Constraints

- Total construction cost
  - How much $$$ do you have to work with
  - How many physicists are available to participate in construction (how big is your collaboration?)
  - When do you want to be ready for collisions?
  - How "hard" will you be pushing current technology –
    - how much financial and schedule contingency is required? (more below)
  - An honest assessment of how well the collaborations skills and interests align to the work that lies ahead
- Amount of time it takes to read the detector out after a collision – or reversed, how quickly do you need to read out the detector
  - Sets the drift time tracking chambers,
  - Integration time in calorimeters
  - Digitization time
  - Logging Time

Detector Design Constraints

– Size of the collision hall and specific characteristics of the building
  - Floor space
  - Weight?
  - How far underground?
  - Crane coverage?
  - Accessability of detector components
  - Gasses, cryogens, flammability, explodability, and ODH issues
  - Available AC power
  - Cooling

RISK!

- Is the level tolerable
  - Can't push the envelope of technology for every detector
    - Will guarantee a blown schedule and cost over runs
    - Need to use new technologies judiciously
    - New Technology should not be used as a "carrot" to draw in collaborators that might otherwise pass.

The Bottom Line!

- There is no single “correct” answer to the above constraints
  - Every experiment finds its own “way”
- Detector designers perform a difficult and almost impossible optimization task

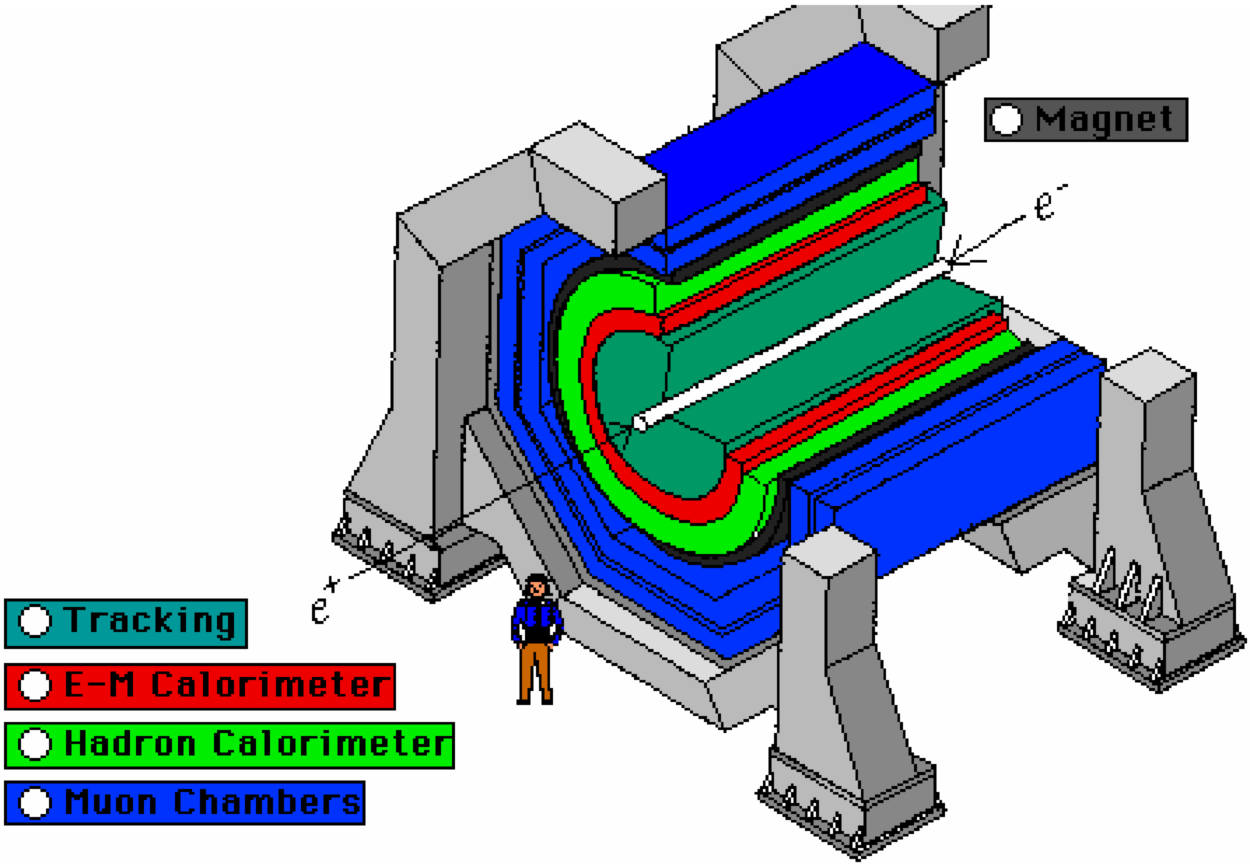
Detectors are an amazing blend of science, engineering, management and human sociology

Individual Detector Types

Modern detectors consist of many different pieces of equipment to measure different aspects of an event.

Measuring a particle's properties:

1. Position
2. Momentum
3. Energy
4. Charge
5. Type

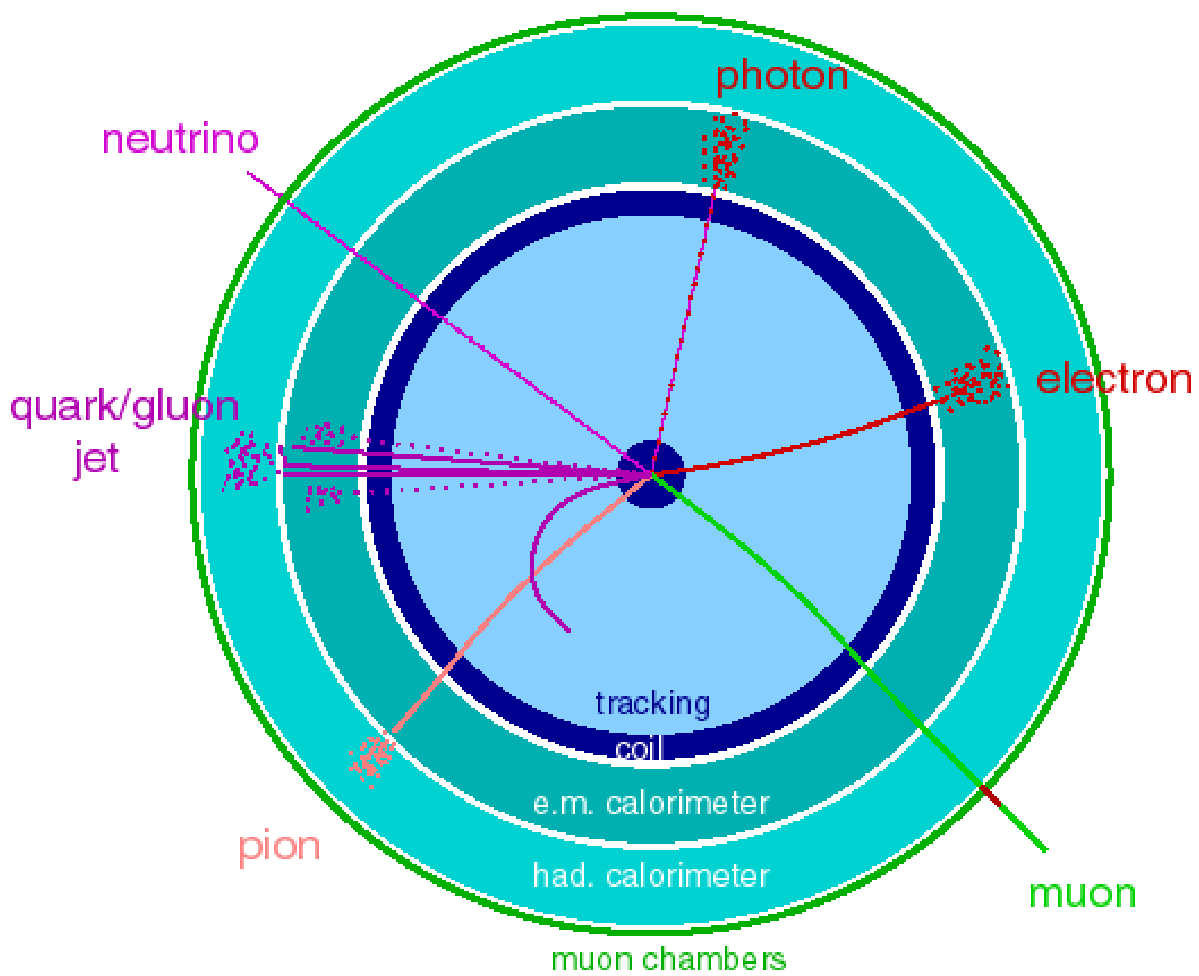


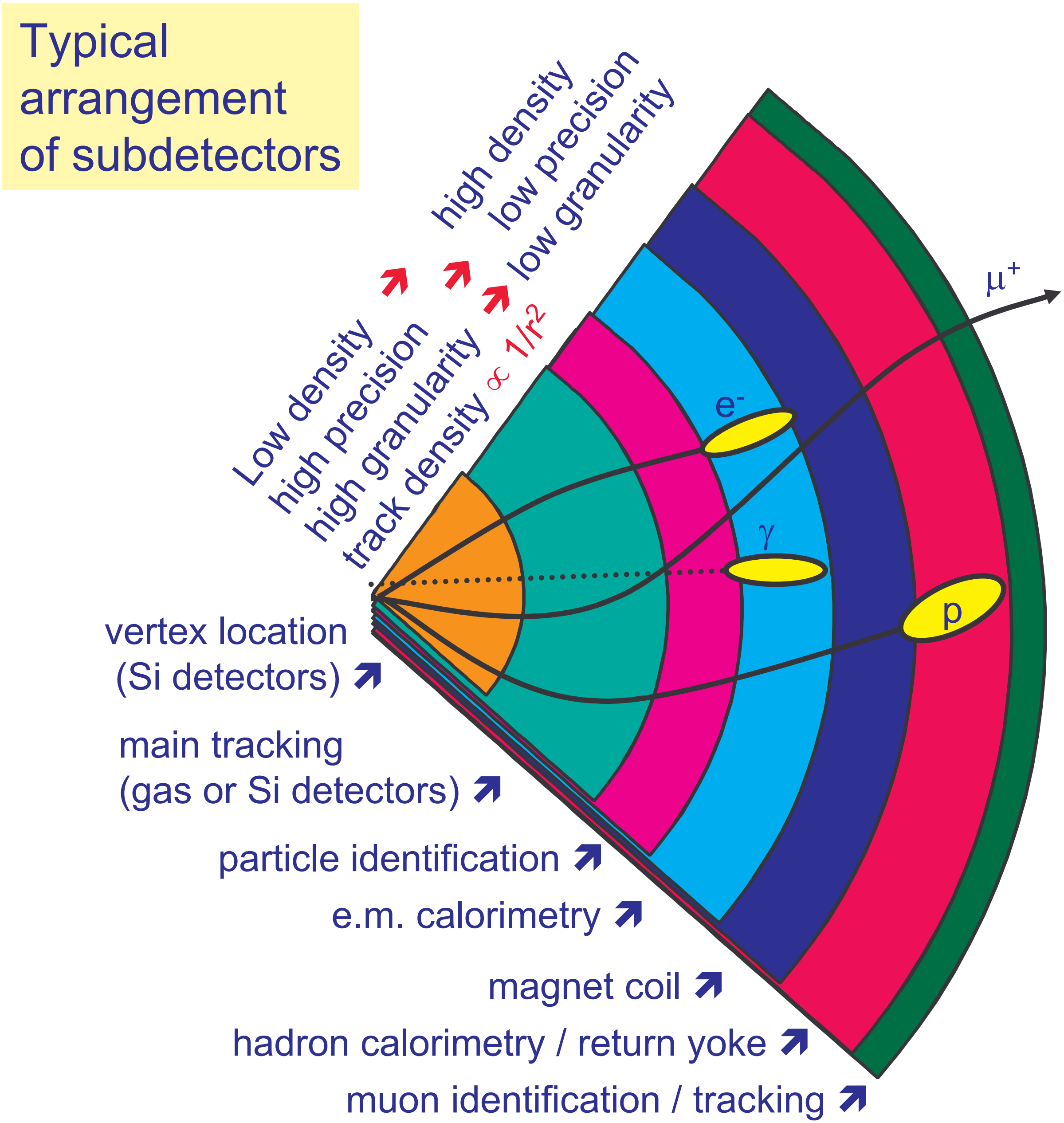
Modern Collider Detectors

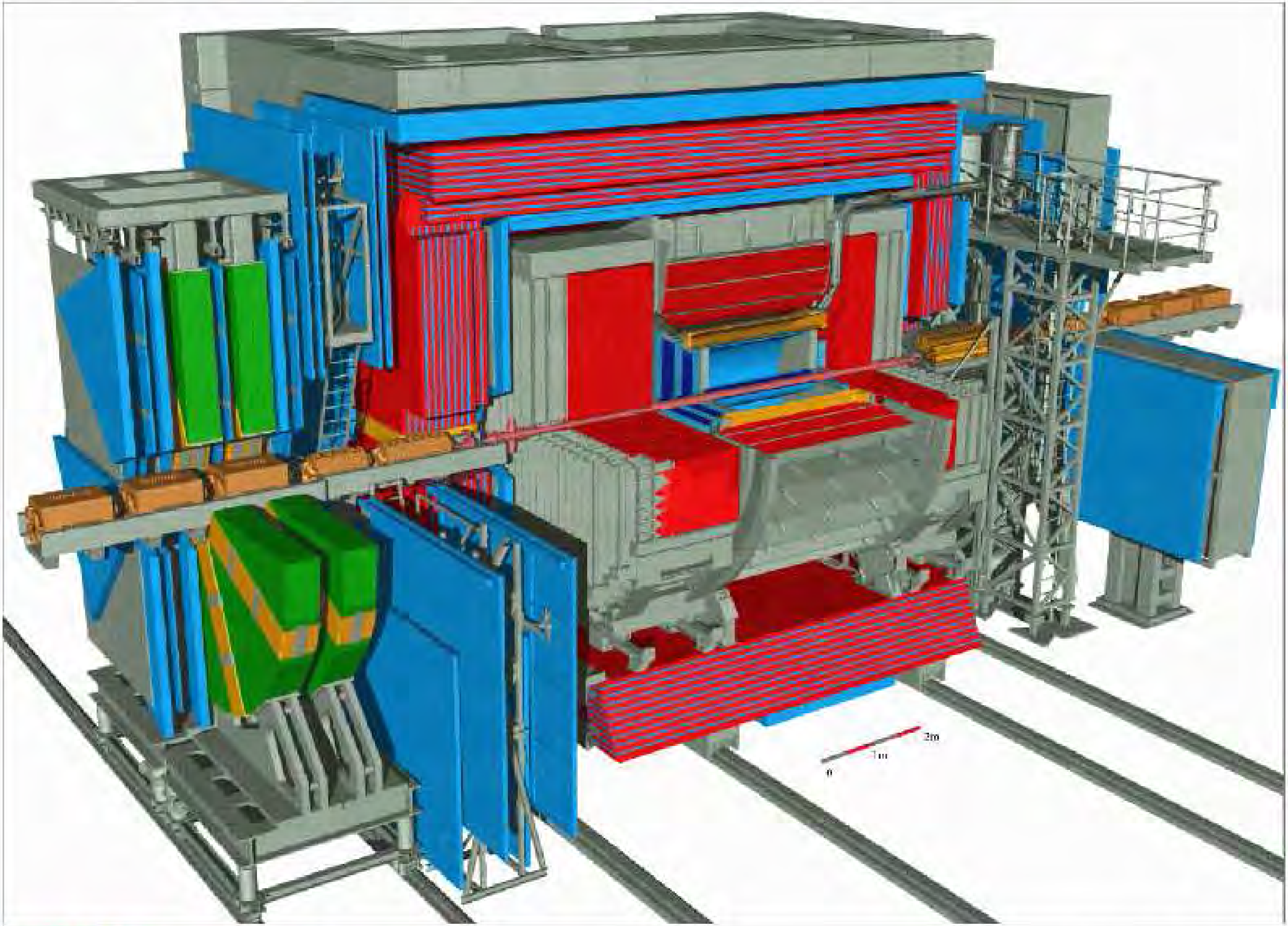
- **the basic idea is to measure charged particles, photons, jets, missing energy accurately**

- **want as little material in the middle to avoid multiple scattering**

- **cylinder wins out over sphere for obvious reasons!**



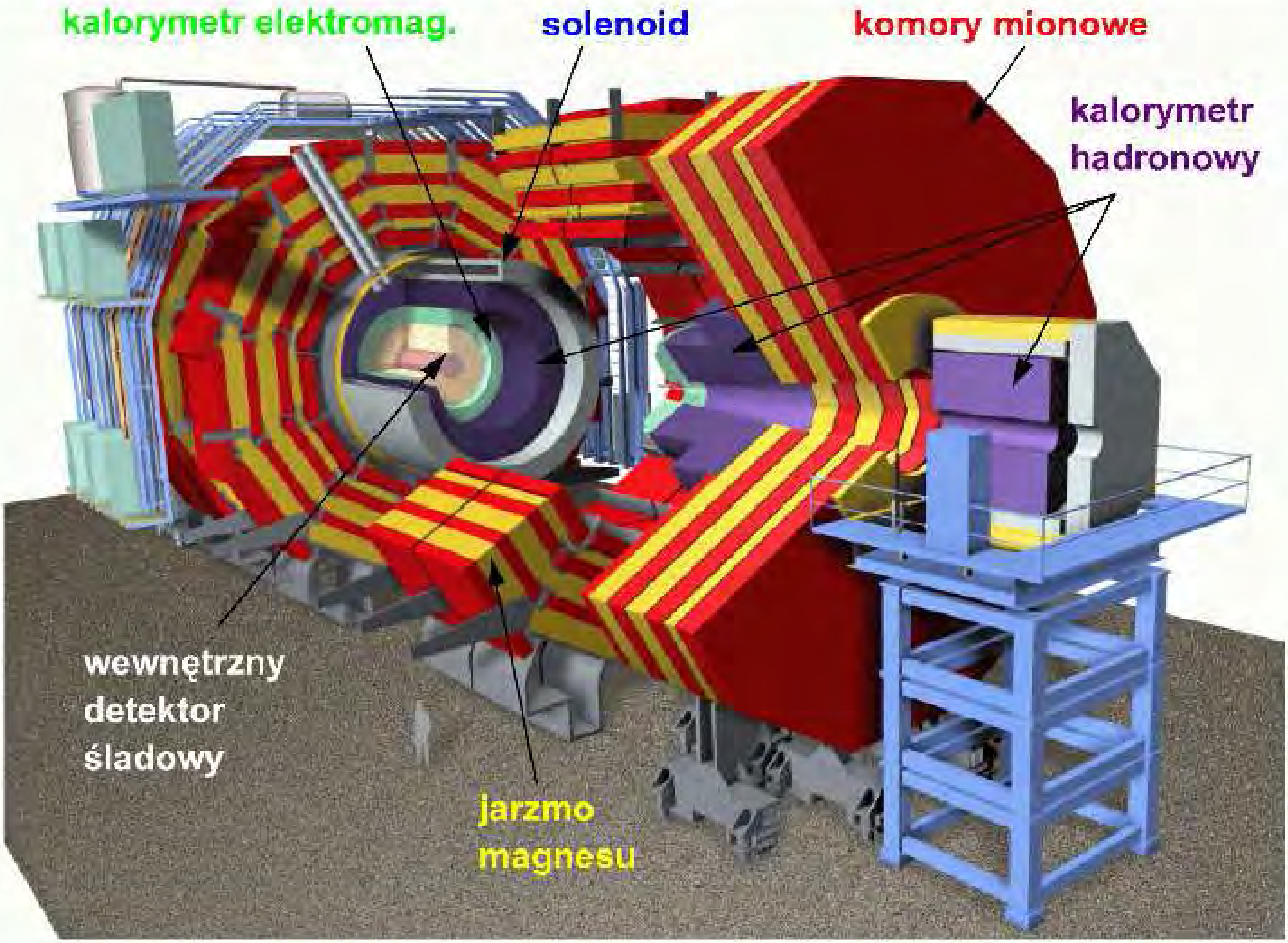

Typical arrangement of subdetectors
Low density
high precision
high granularity
track density ∝ 1/r²
high density
low precision
low granularity
μ⁺
e⁻
γ
p
vertex location (Si detectors)
main tracking (gas or Si detectors)
particle identification
e.m. calorimetry
magnet coil
hadron calorimetry / return yoke
muon identification / tracking



ZEUS (HERA)

Software :SDRC-IDEAS level VIi
Performed by : Carsten Hartmann
Status : October 1993

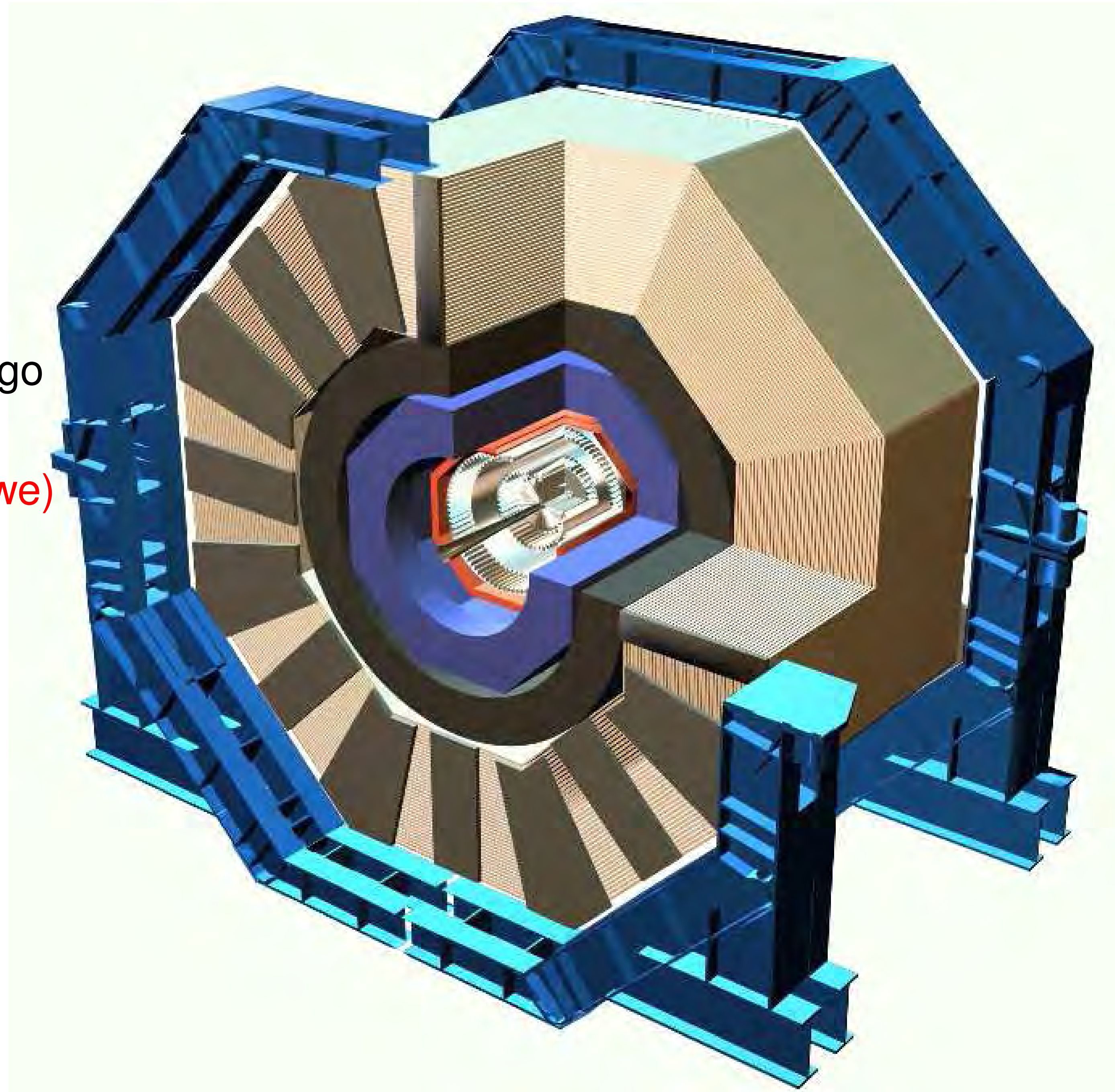
Compact Muon Solenoid

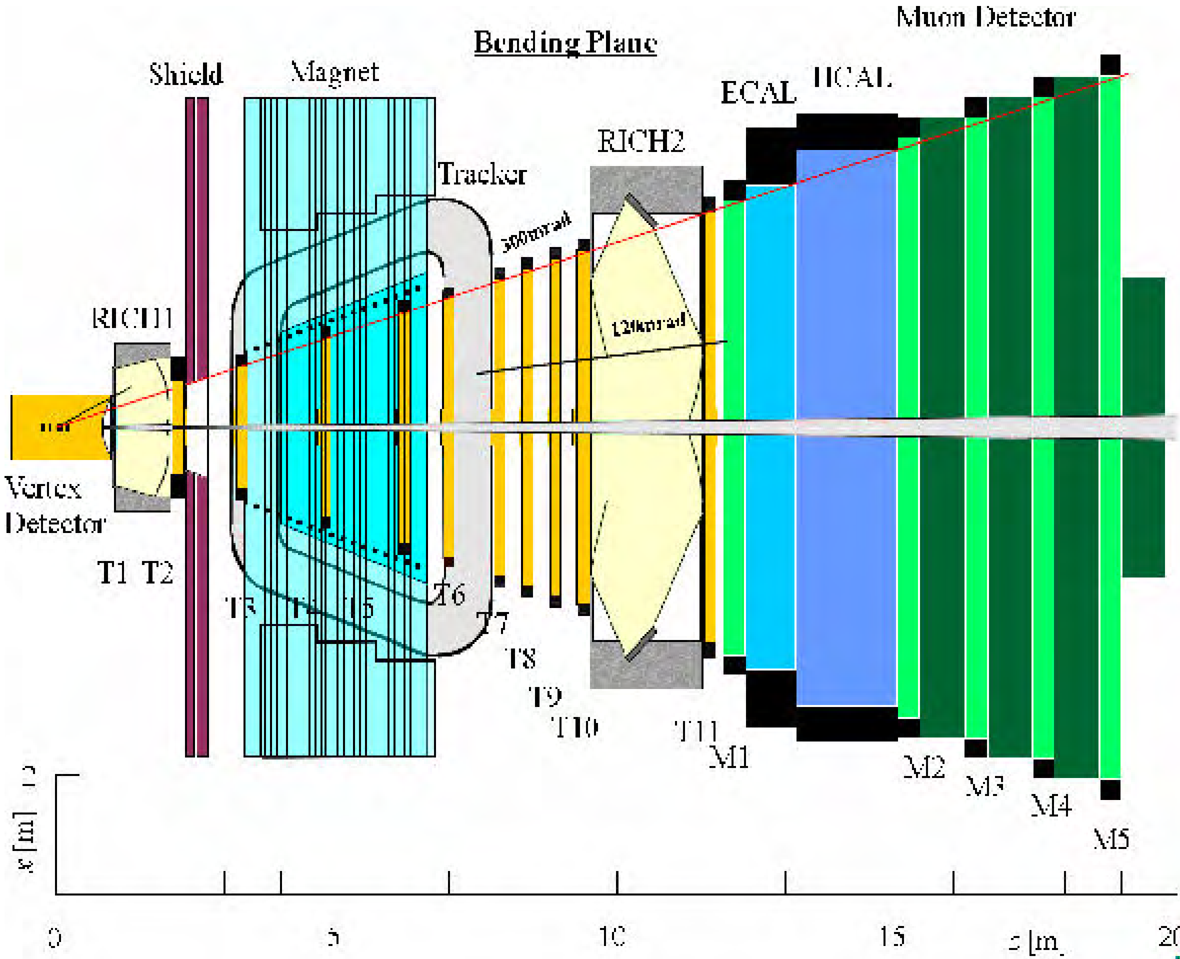


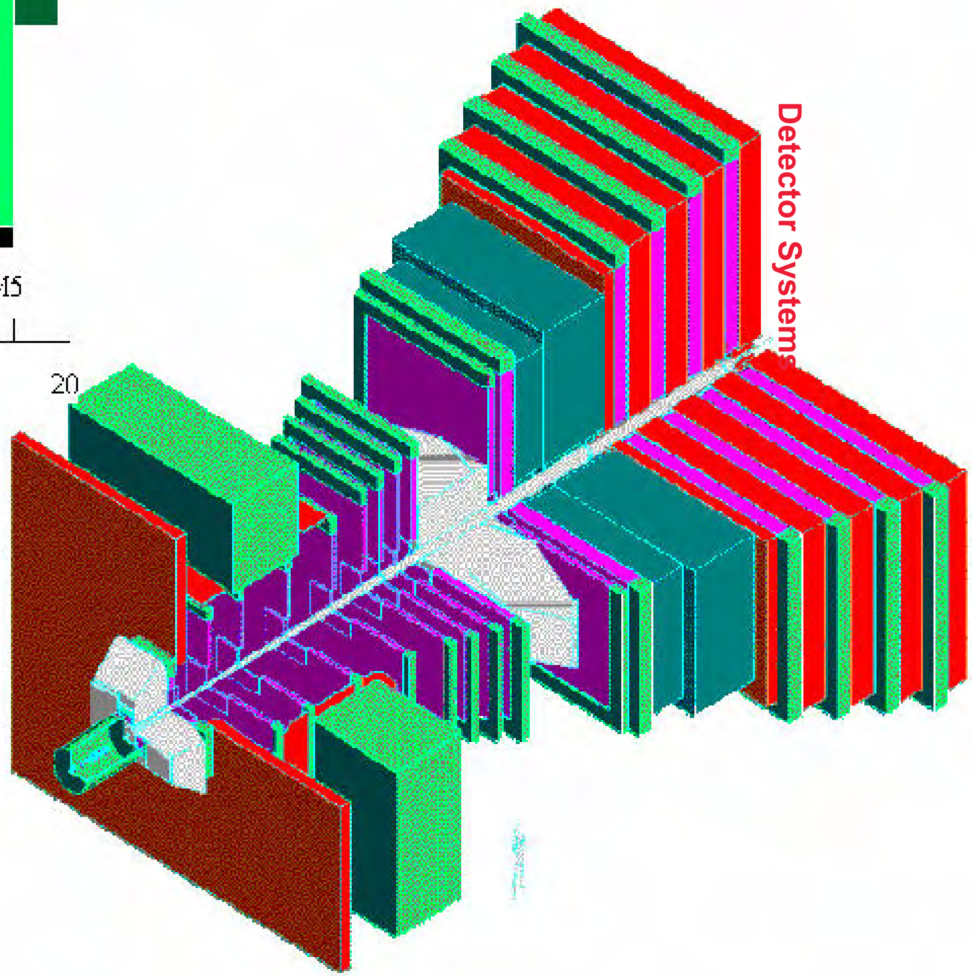
SiD

Projekt detektora dla eksperymentu przy ILC

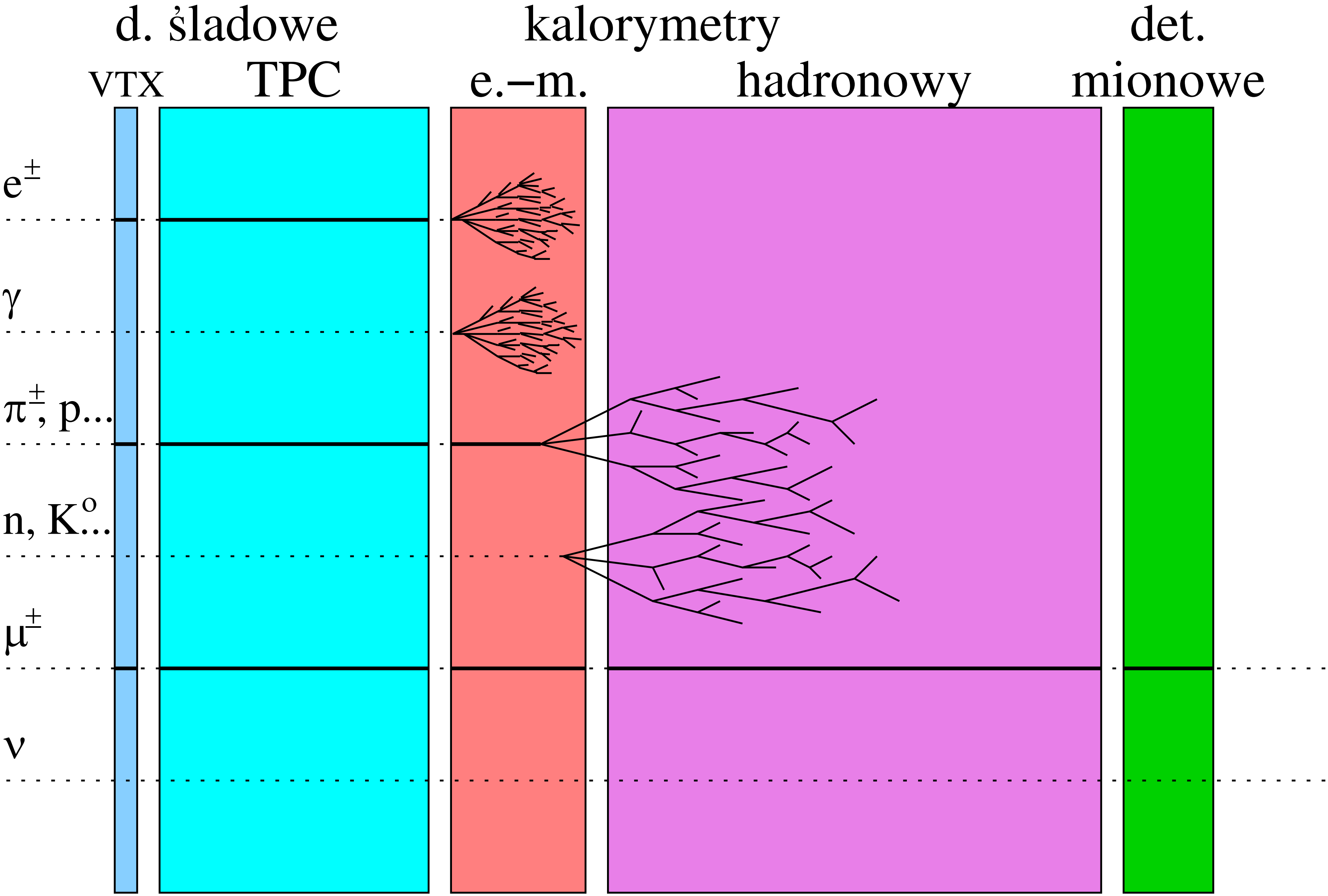
Koncepcja detektora opartego w całości o detektory półprzewodnikowe (krzemowe)





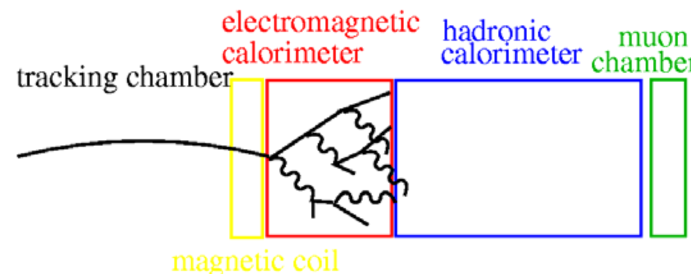


Detector Characteristics
Length: 20 m
Width: 12 m
Height: 12 m
Weight: 2'000 tons

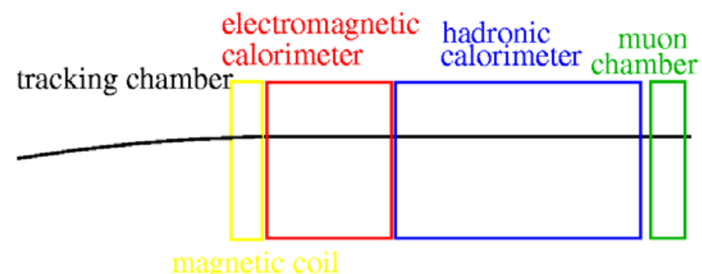

d. śladowe
kalorymetry
det.
VTX
TPC
e.–m.
hadronowy
mionowe
$e^{\pm}$
γ
$\pi^{\pm}$, p...
n, K^{o}...
$\mu^{\pm}$
ν

Lepton Identification

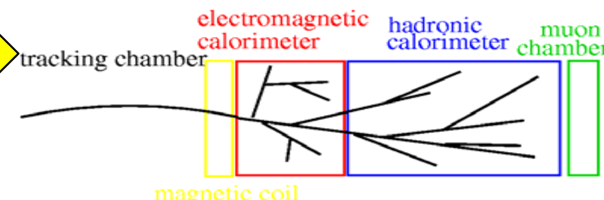
- **Electrons:**
  - compact electromagnetic cluster in calorimeter
  - Matched to track



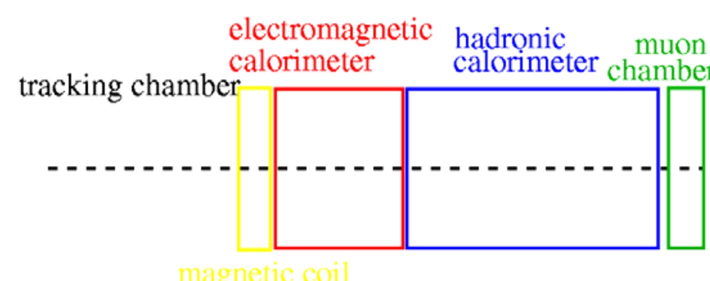
- **Muons:**
  - Track in the muon chambers
  - Matched to track



- **Taus:**
  - Narrow jet
  - Matched to one or three tracks



- **Neutrinos:**
  - Imbalance in transverse momentum
  - Inferred from total transverse energy measured in detector



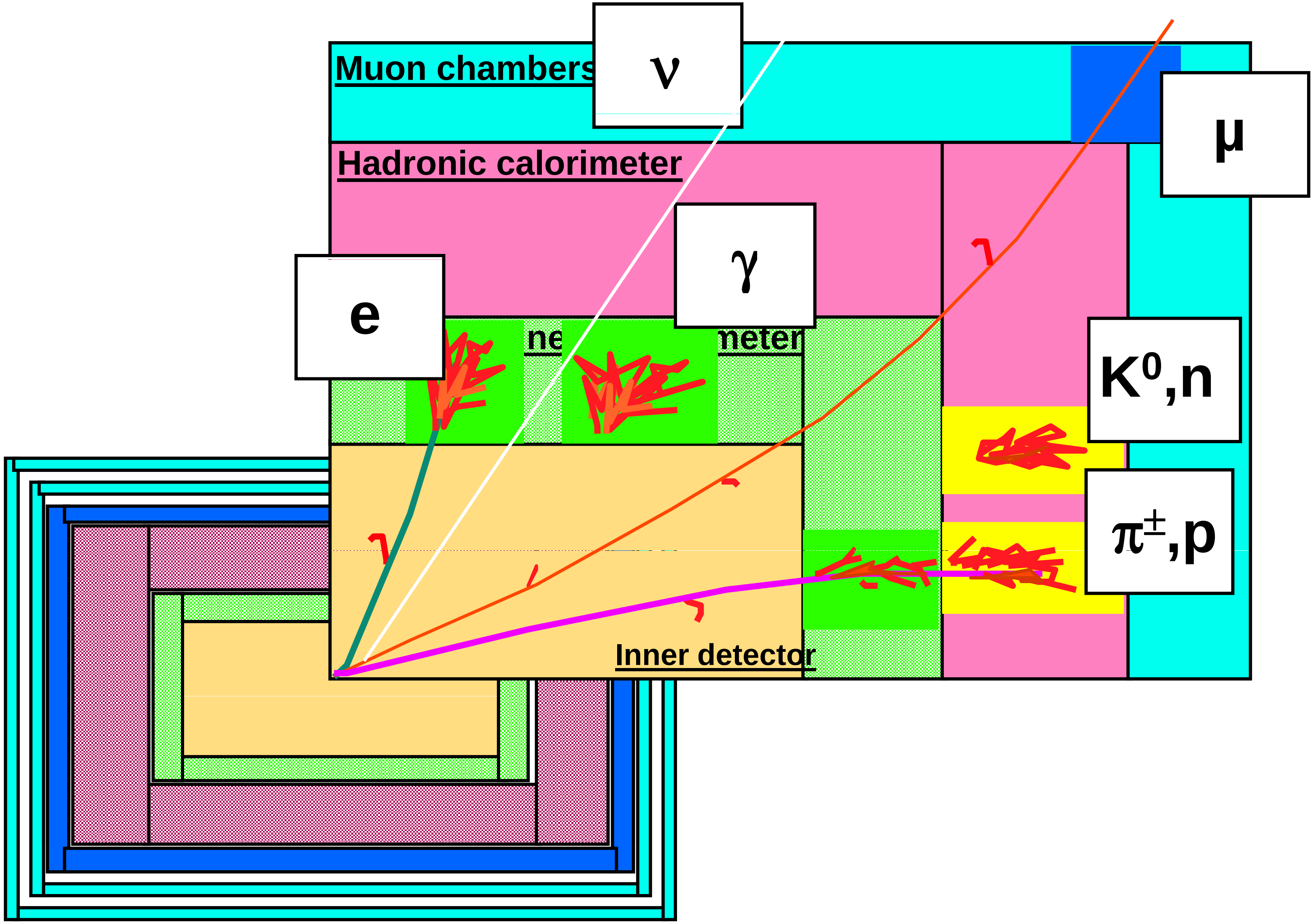
Particle Identification Methods

Constituent	Si Vertex	Track	PID	Ecal	Hcal	Muon
electron	primary	🗐	🗐	🗐	—	—
Photon γ	primary	—	—	🗐	—	—
u, d, gluon	primary	🗐	—	🗐	🗐	—
Neutrino ν	—	—	—	—	—	—
s	primary	🗐	🗐	🗐	🗐	—
c, b, τ	secondary	🗐	🗐	🗐	🗐	—
μ	primary	🗐	—	MIP	MIP	🗐

PID = Particle ID
(TOF, Č, dE/dx)

MIP = Minimum
Ionizing Particle

Higgs at the LHC: the challenge



Generic features required of ATLAS and CMS

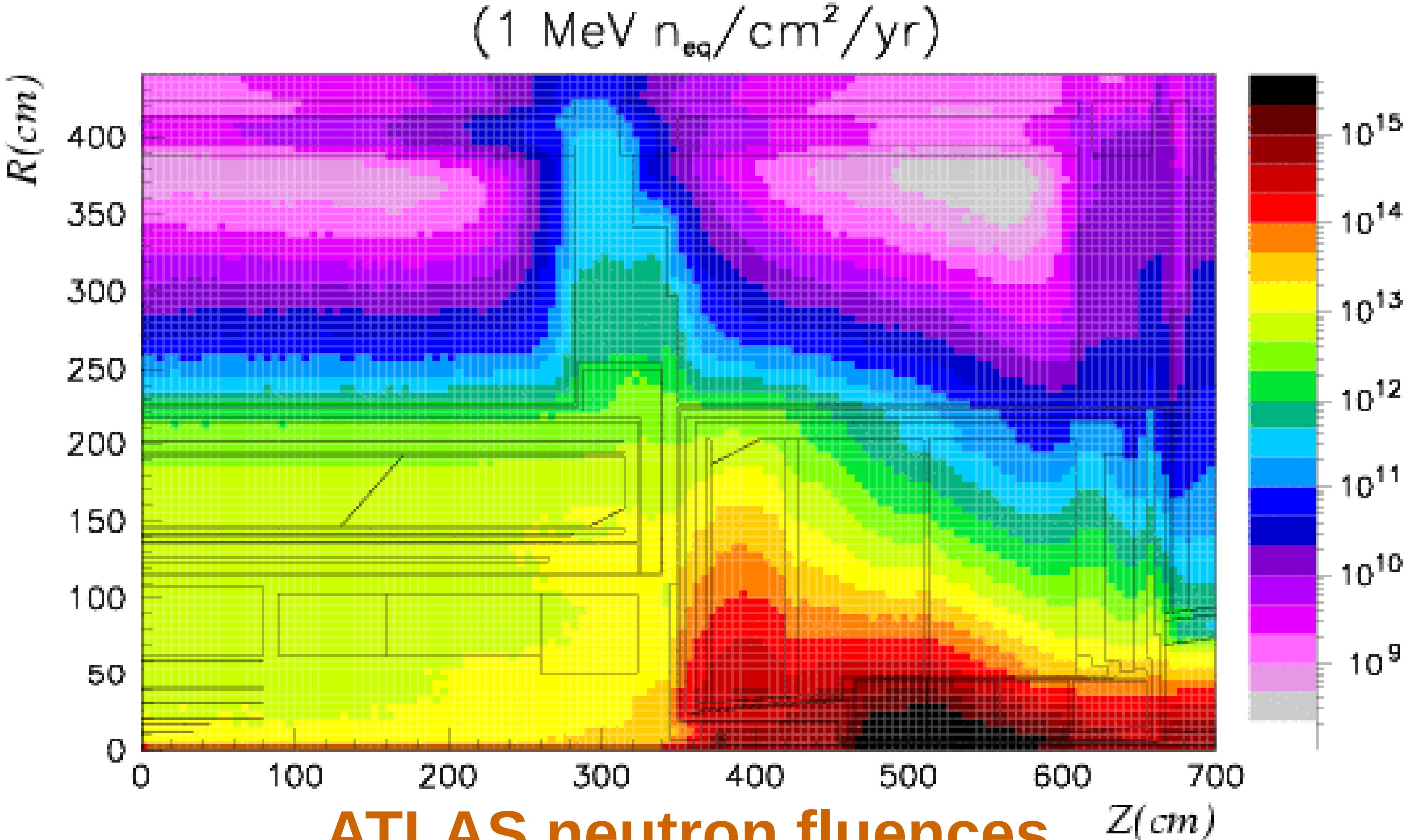
- <u>Detectors must survive for 10 years or so of operation</u>
  - Radiation damage to materials and electronics components
  - Problem pervades whole experimental area (neutrons): NEW!

- <u>Detectors must provide precise timing and be as fast as feasible</u>
  - 25 ns is the time interval to consider: NEW!

- <u>Detectors must have excellent spatial granularity</u>
  - Need to minimise pile-up effects: NEW!

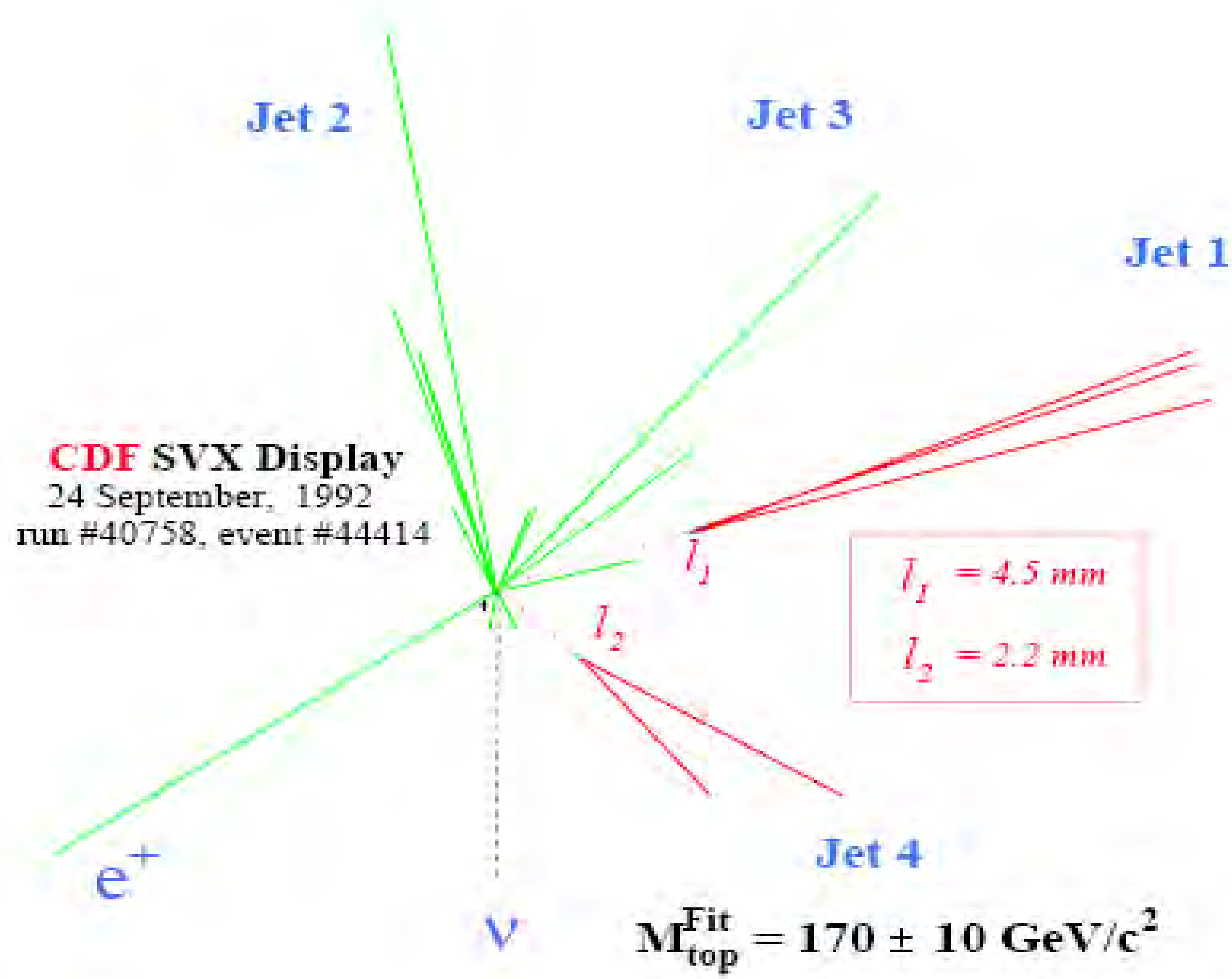
- <u>Detectors must identify extremely rare events, mostly in real time</u>
  - Lepton identification above huge QCD backgrounds (e.g. /jet ratio at the LHC is ~ 10^{-5}, i.e. ~ 100 worse than at Tevatron)
  - Signal X-sections as low as 10^{-14} of total X-section: NEW!

Physics at the LHC: the environment



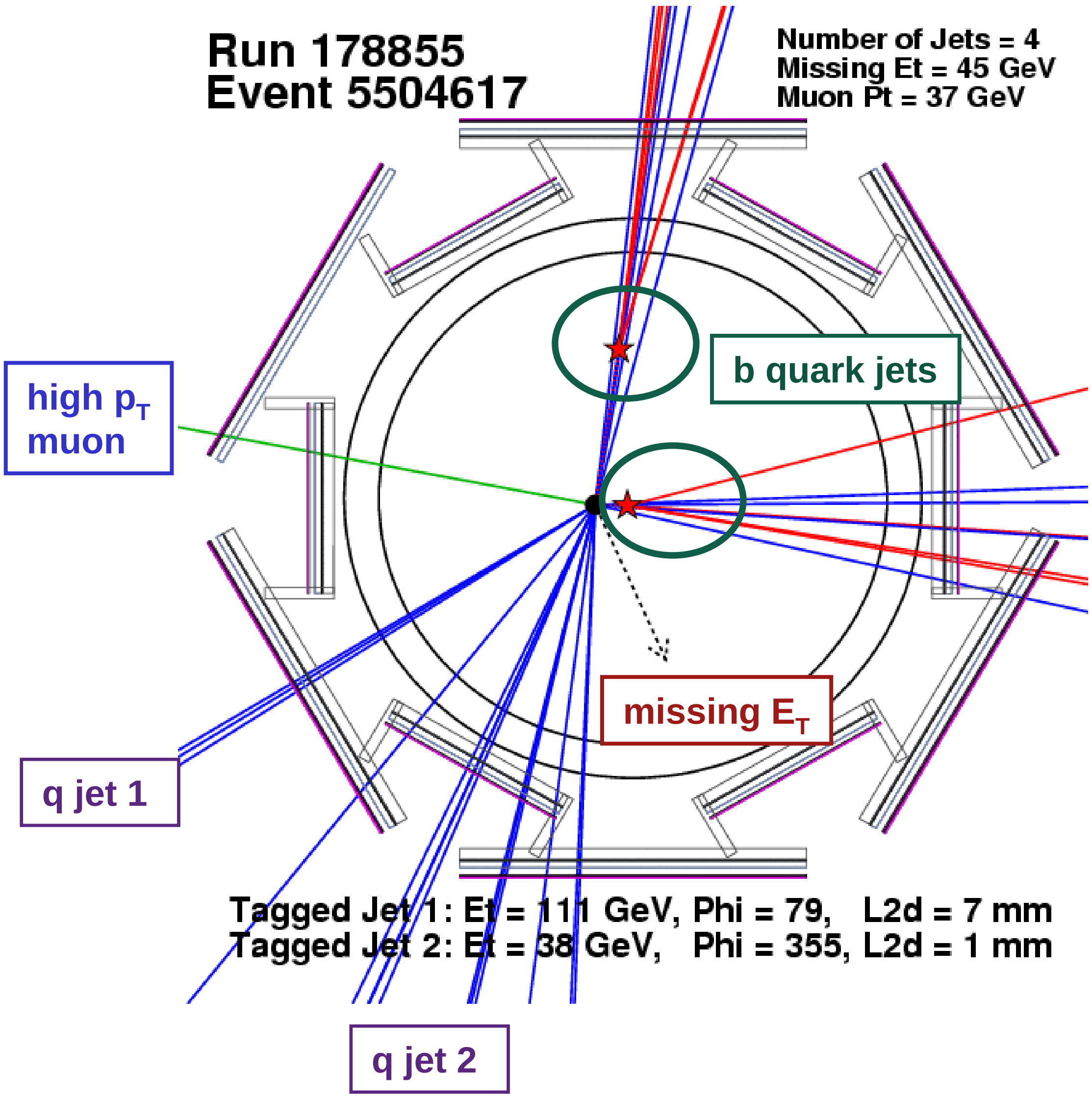
ATLAS neutron fluences

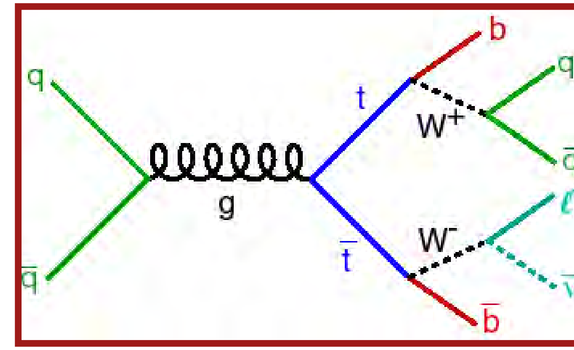
CDF's 1st Top Event… (run 1)

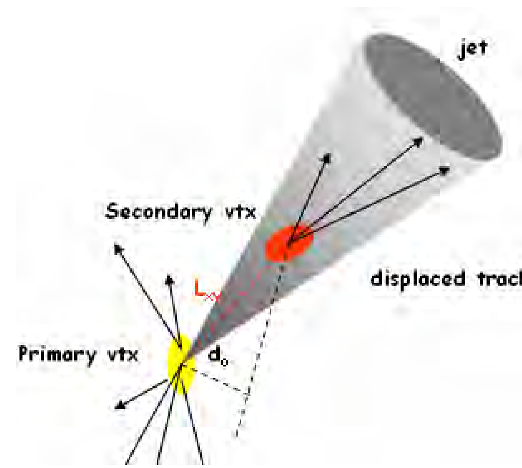


How to get best possible vertex resolution?

CDF Top Pair Event







b-quark lifetime:

$c\tau \sim 450\mu m$

→ b quarks travel ~3 mm before decay

Vertex Resolution

$x1, x2 =$ measurement planes

$y1\ , y2 =$ measured points, with errors δy

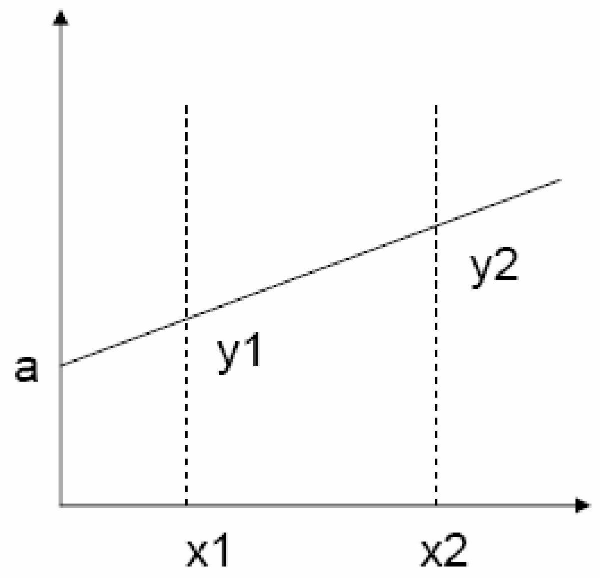
$y = a + bx$

$$b = \text{slope} = \frac{y1 - y2}{x1 - x2} = \frac{y1 - y2}{\Delta x}$$

$$a = \text{intercept} = \frac{1}{2}(y1 + y2) - \frac{1}{2}(y1 - y2)\left(\frac{x1 + x2}{\Delta x}\right) = \bar{y} - b\bar{x}$$

$$(\delta b)^2 = \left(\frac{\partial b}{\partial y1}\right)^2 (\delta y)^2 + \left(\frac{\partial b}{\partial y2}\right)^2 (\delta y)^2 \Rightarrow \delta b = \frac{\sqrt{2}\delta y}{\Delta x}$$

$$\delta a = \frac{\delta y}{2}\sqrt{1 + \frac{8\bar{x}}{\Delta x}}$$

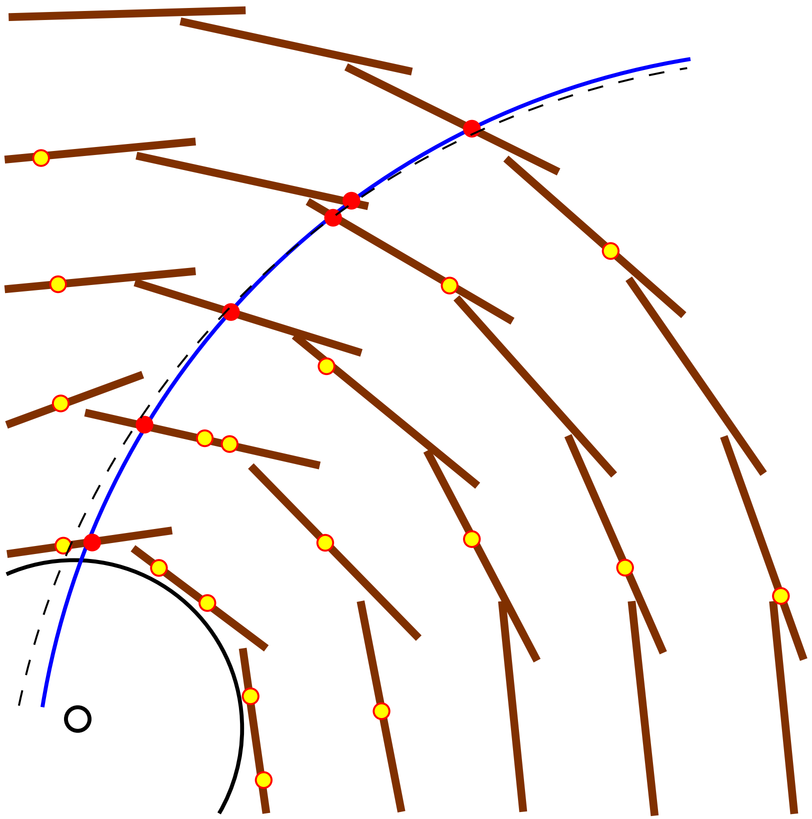


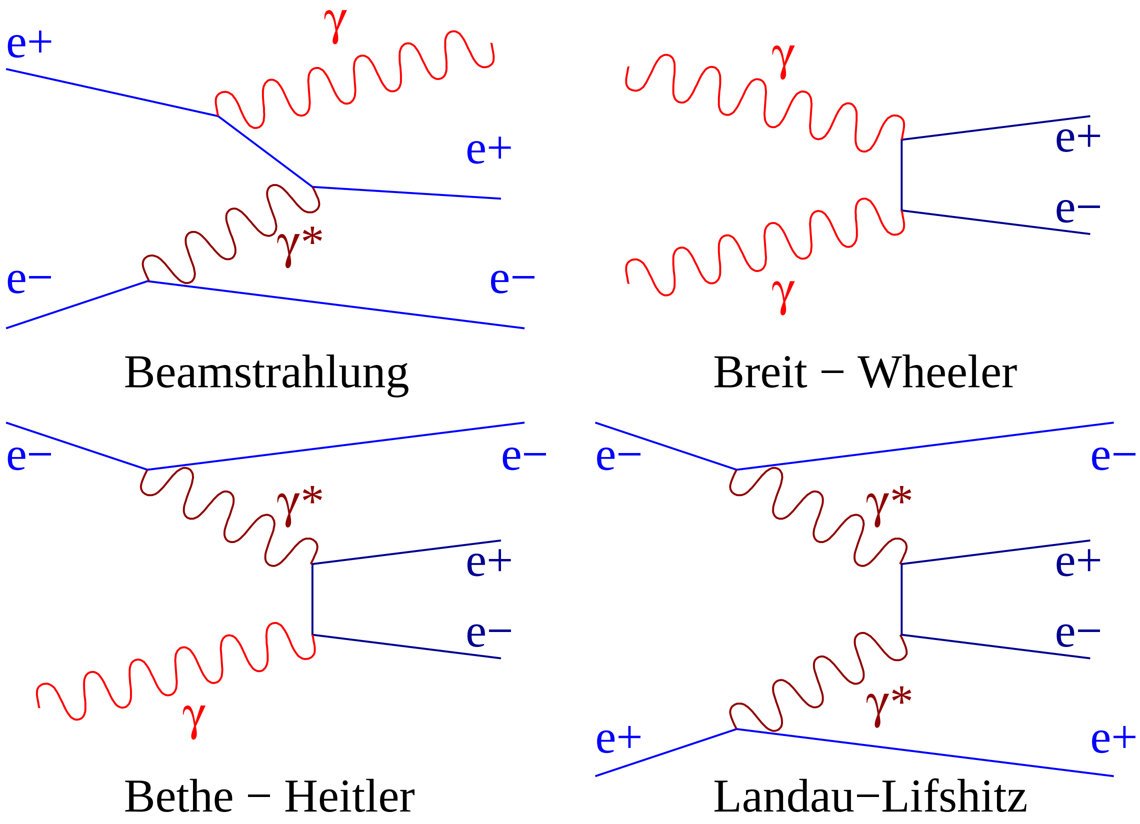
for good resolution on angles (ϕ and θ) and intercepts (d, z_0)

- Precision track point measurements
- Maximize separation between planes for good resolution on intercepts
- Minimize extrapolation - first point close to interaction

Co jeszcze wpływa na precyzję pomiaru?

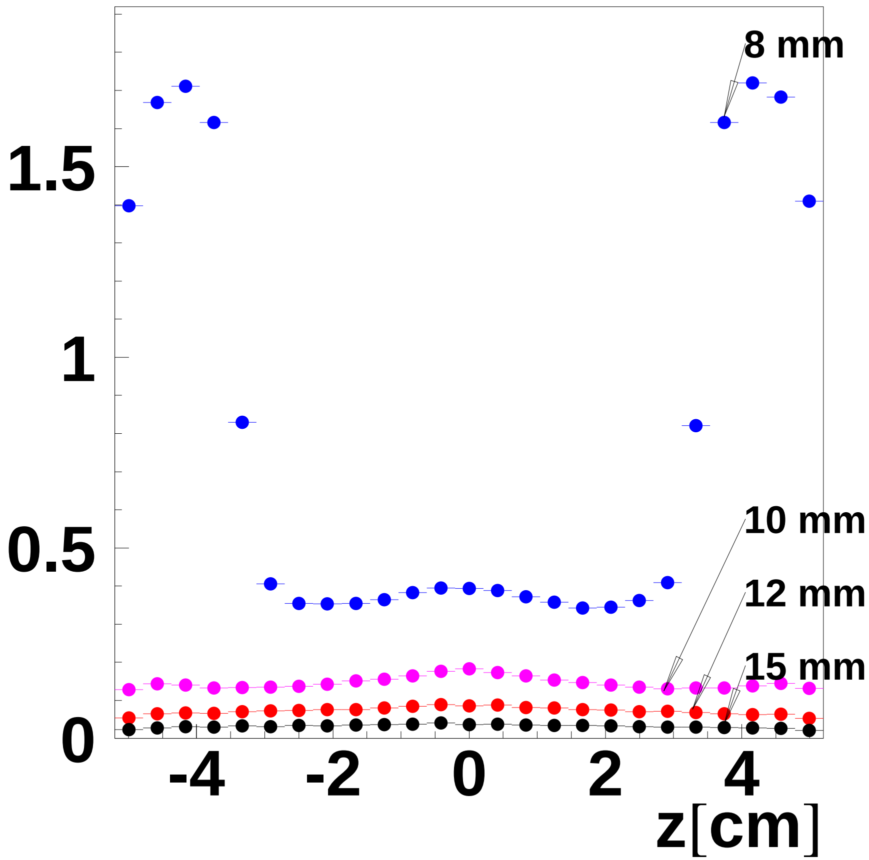
W oddziaływaniu pomiędzy wiązkami powstają pary e^+e^- o małych pędach poprzecznych, z których część zostawia ślady (ang. "hit") w detektorze wierzchołka utrudniając rekonstrukcję innych torów. W pięciowarstwowym detektorze oczekuje się około 60 000 dodatkowych "hitów".

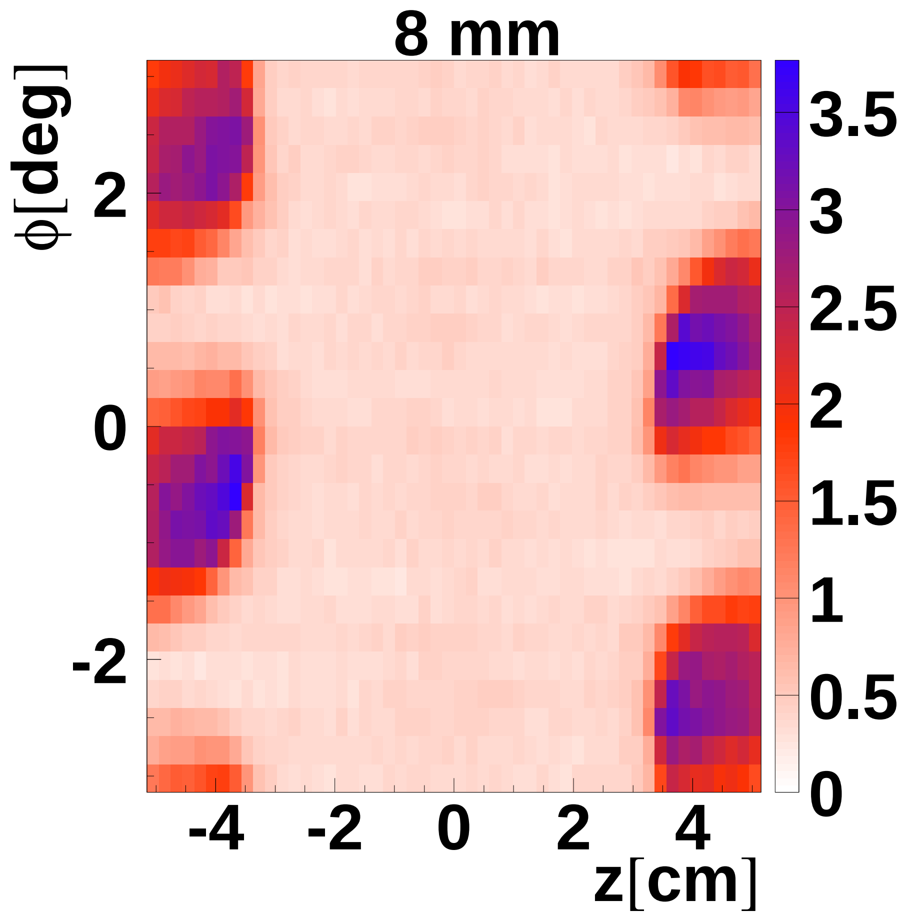




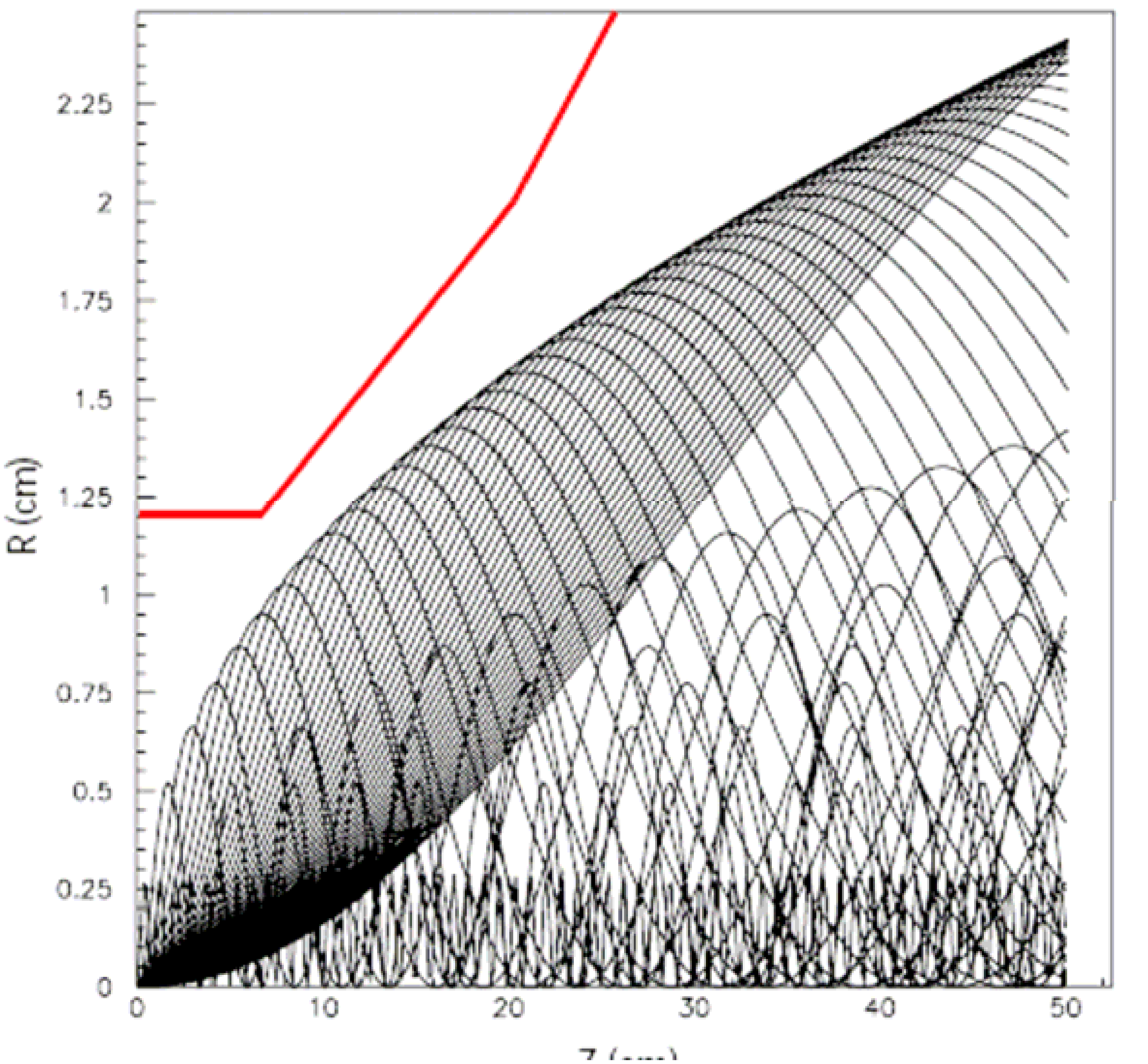
Gęstość śladów w pierwszej warstwie [1/mm^2/BX]

Pary e^+e^- symulowane za pomocą Guinea Pig. Gęstości liczone dla różnych wartości promienia pierwszej warstwy.





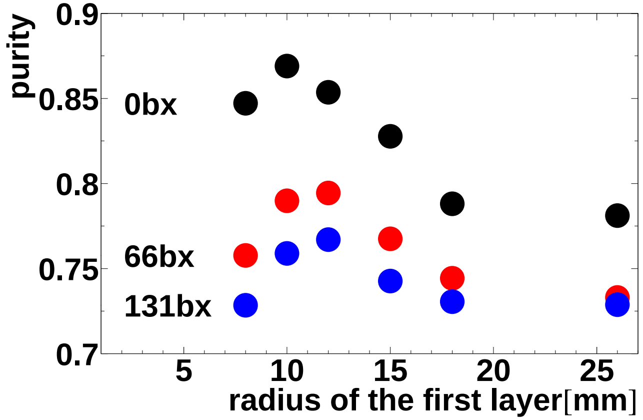
Background level at ILC depends strongly on B

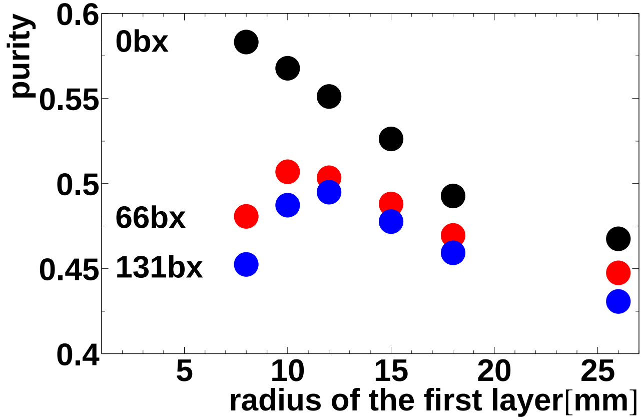


Jet flavour tagging performance

b selection | **c selection**

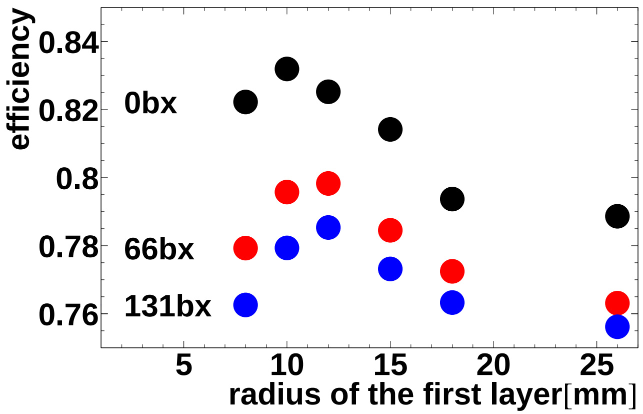
Efficiency 0.8

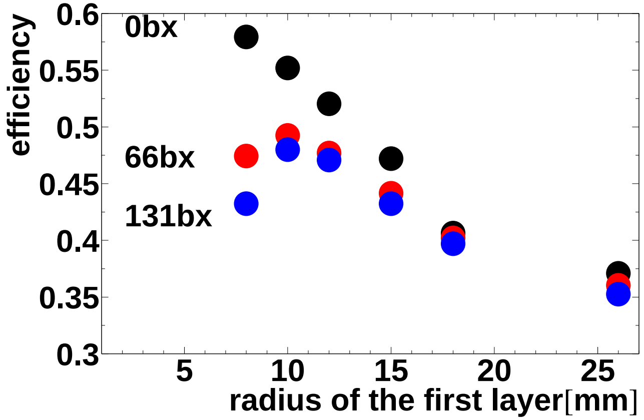




Efficiency 0.6

Purity 0.8



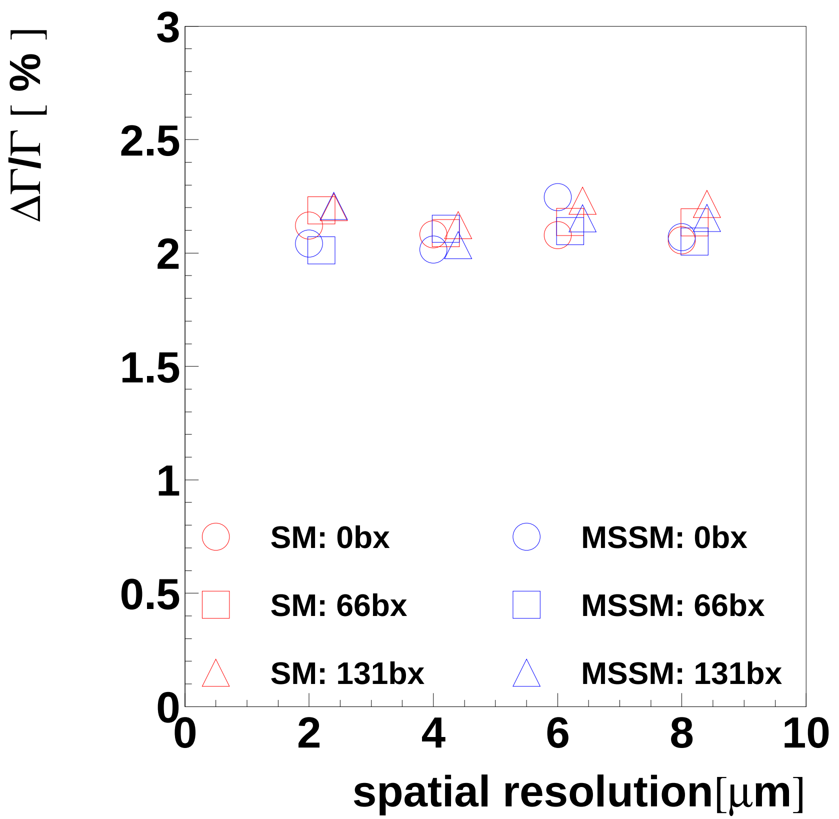


Purity 0.6

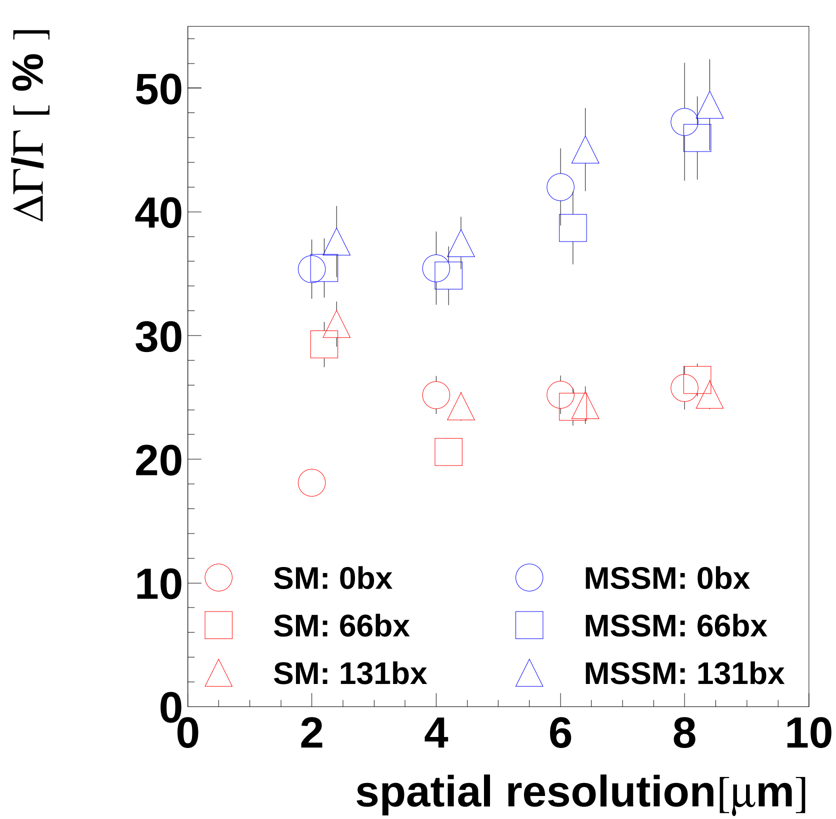
Spatial resolution 4 μm, layer thickness 0.1% X_0. R$_1 = 26$ mm - only 4 layers.

Measurement of the Higgs Boson Branching Ratios

$H \to b\bar{b}$

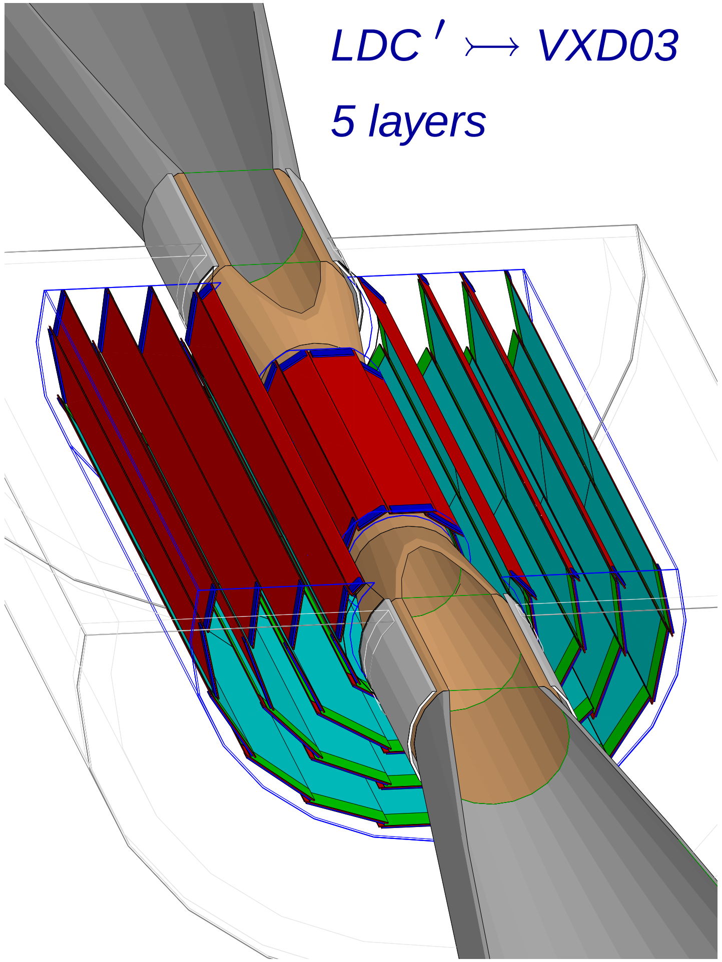


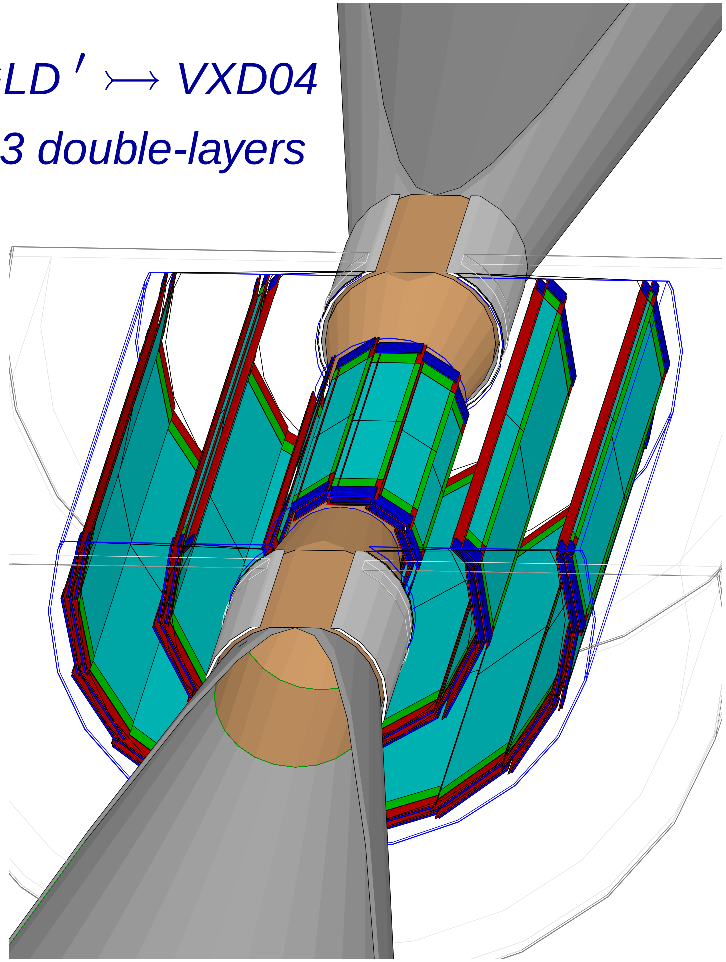
$H \to c\bar{c}$



Layer thickness 0.1% X_0, radius of the first layer 15 mm.

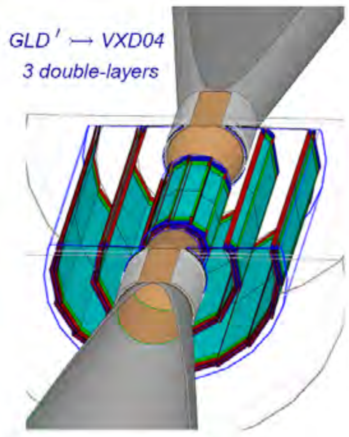
- Maintain 2 alternative long-barrel approaches :

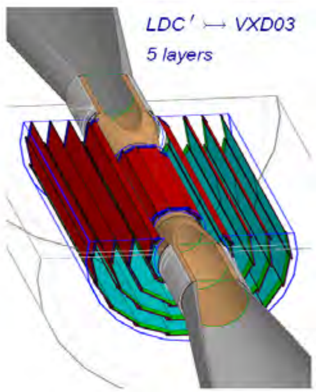


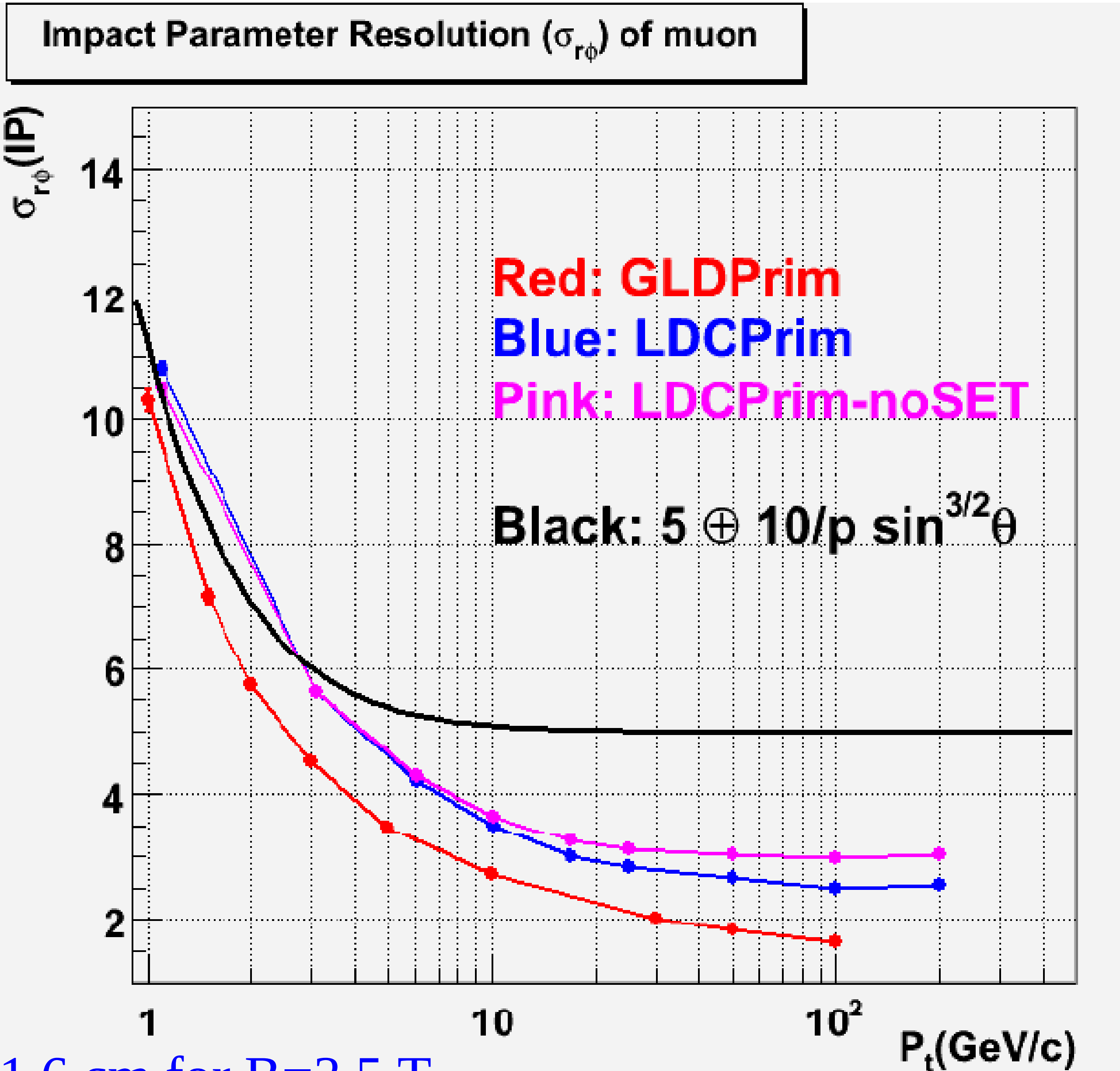


- Two read-out modes considered :
  - **continuous** *read-out*
  - *read-out* **delayed** *after bunch-train ⟼ 3 double layers expected to help*
    ⇛ mini-vectors

Vertex Detector



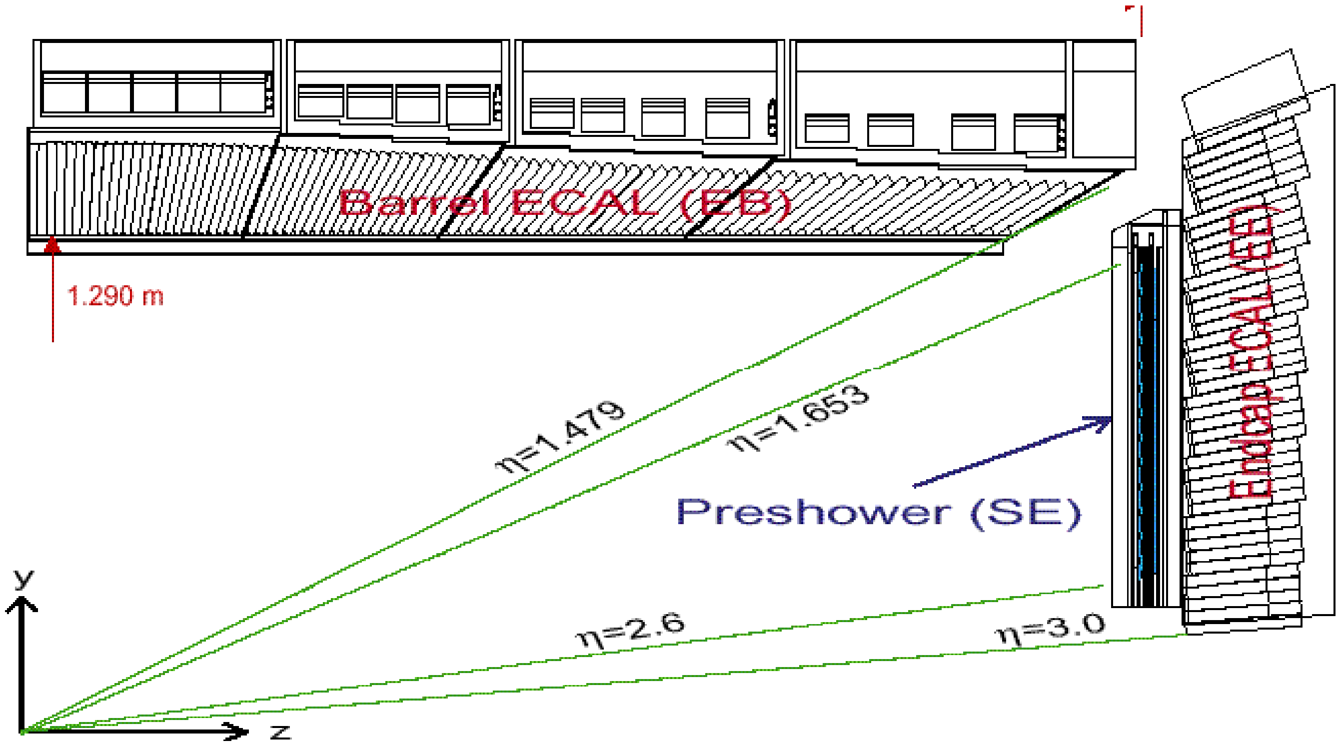




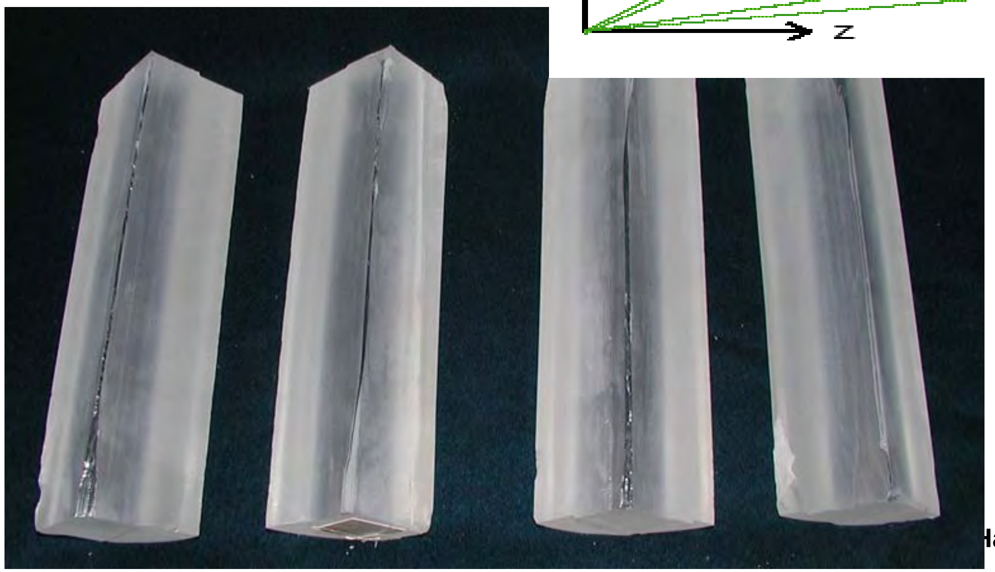
Inner layer at r=1.6 cm for B=3.5 T

Electrons and photons in ATLAS/CMS

CMS $PbWO_4$ crystal calorimeter

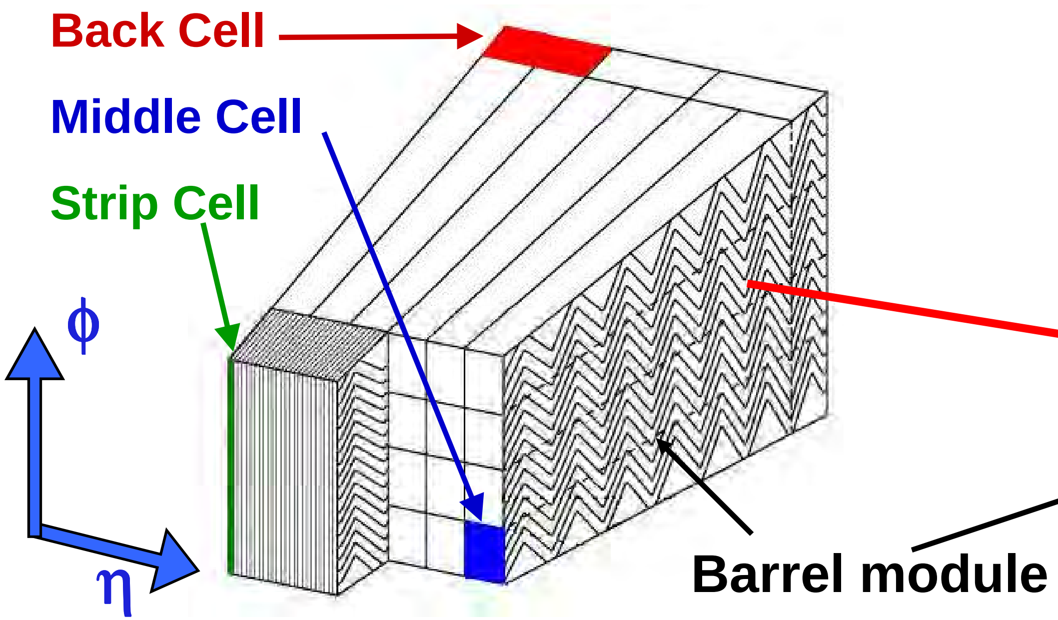


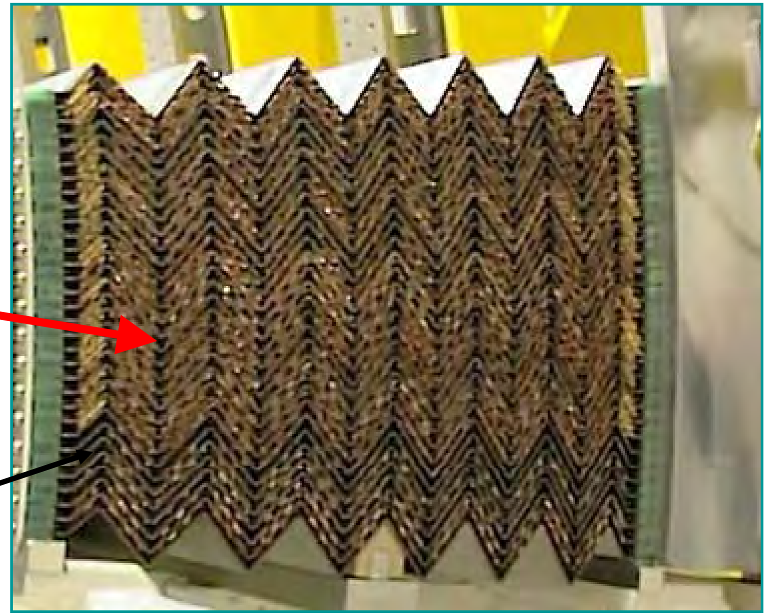
- Barrel: 62k crystals 2.2 x 2.2 x23 cm
- End-caps: 15k crystals 3 x 3 x 22 cm



Electrons and photons in ATLAS/CMS

ATLAS LAr EM Calorimeter description





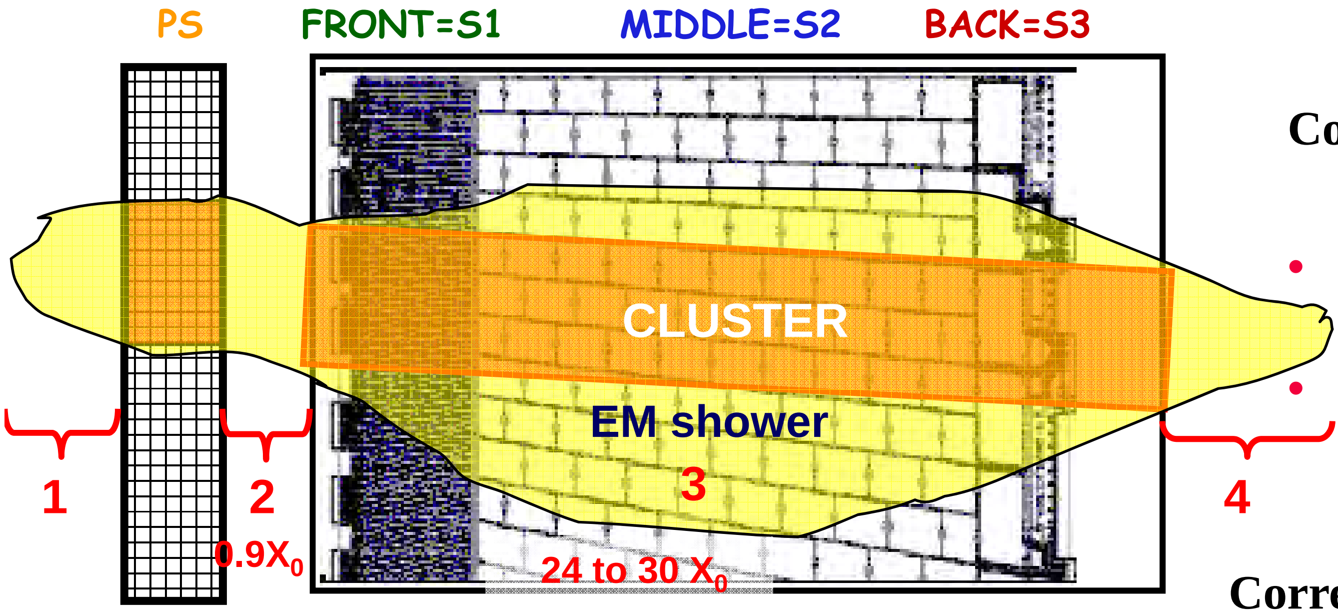
EM Calo (Presampler + 3 layers):

- **Presampler** 0.025x0.1 (ηxϕ)
  ⇒ *Energy lost in upstream material*
- **Strips** 0.003x0.1 (ηxϕ)
  ⇒ *optimal separation of showers in non-bending plane, pointing*
- **Middle** 0.025x0.025 (ηxϕ)
  ⇒ *Cluster seeds*
- **Back** 0.05x0.025 (ηxϕ)
  ⇒ *Longitudinal leakage*

•LAr-Pb sampling calorimeter (barrel)
•Accordion shaped electrodes
•Fine longitudinal and transverse segmentation
•EM showers (for $e^{\pm}$ and photons) are reconstructed using calorimeter cell-clustering

Electrons and photons in ATLAS/CMS

ATLAS EM Calorimeter energy reconstruction



Corrections due to cluster position:

- **Δη (S-shape modulation) ±0.005**
- **Δϕ (offset in accordion) ±0.001**

Corrections for energy losses:

1. **Before PS**
2. **Between PS & Calo**
3. **Outside cluster: depends on clustering method**
4. **After calorimeter: ~ Energy in BACK**

2-7% overall energy correction

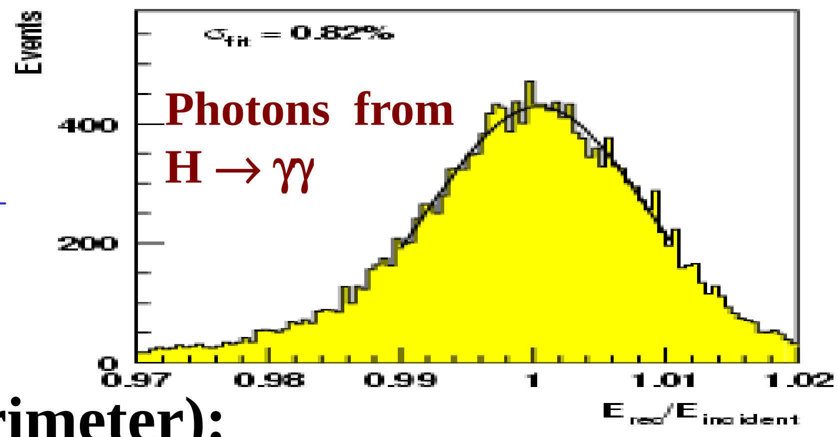
>7% at low energy, high η

Two main clusterization methods:

- **Fixed size sliding window:**
  - •3×3, 3×7… cells, 2nd sampling η×ϕ;
  - •Some energy left out, especially for small sizes.
- **Topological clusters:**
  - •Variable size cluster, minimize noise impact;
  - •Additional splitting algorithm is also provided.

SM $H \to \gamma\gamma$

CMS, full simulation high L



Energy resolution

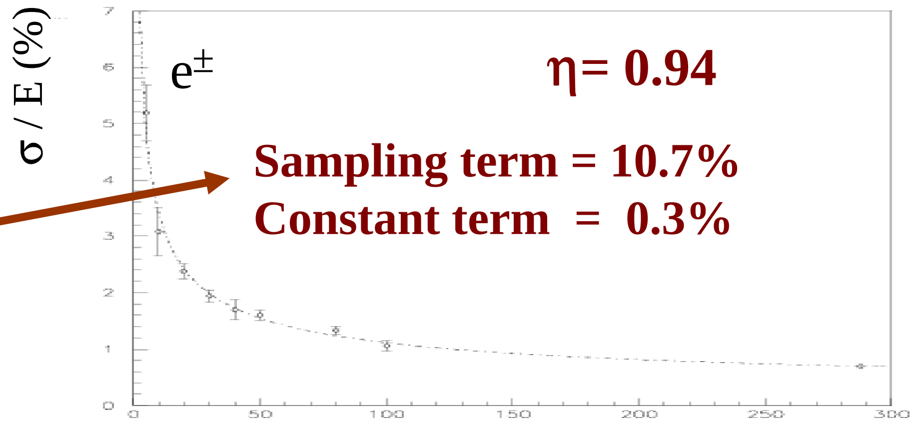
CMS EM calorimeter
(crystals):

$$\frac{\sigma(E)}{E} \approx \frac{3\text{-}5\%}{\sqrt{E}}$$

ATLAS EM calorimeter
(liquid-argon/lead sampling calorimeter):

$$\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}}$$

Module zero test beam data



Mass resolution
(m_H=100 GeV, low L):
ATLAS : 1.1 GeV
CMS : 0.6 GeV

$$\frac{S}{\sqrt{B}} \sim \frac{1}{\sqrt{\sigma_m}}$$

SM H→ γγ

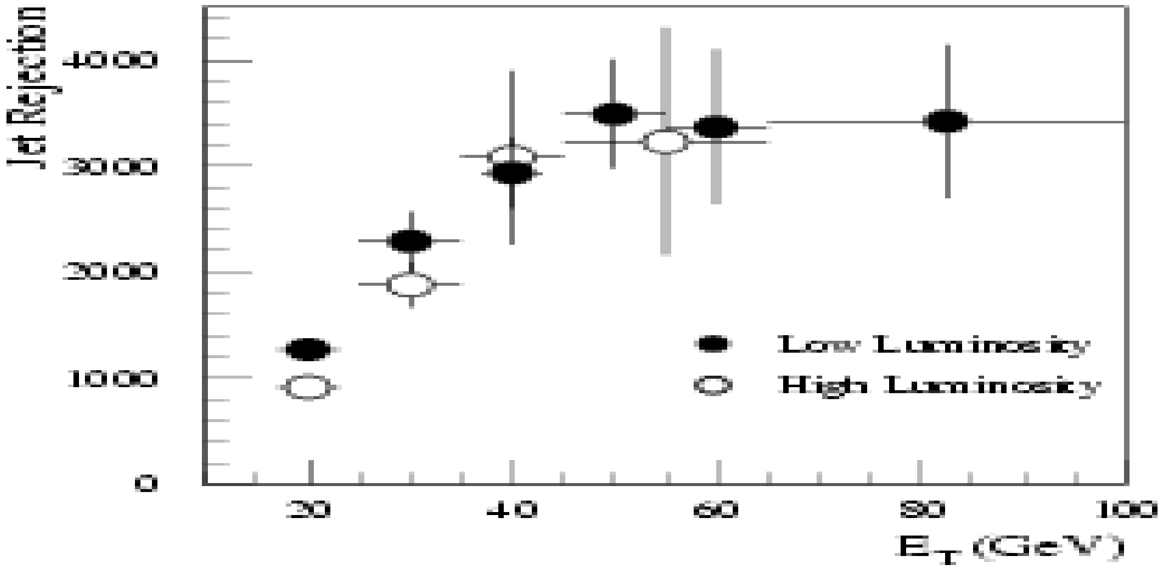
Backgrounds

1) Irreducible background from qq → γγ and gg → γγ (box)

2) Reducible background from π^0,η (→ γγ) in jet fragmentation:
   - final states with many photons → look for single photons
   - non-isolated photons inside jets → look for isolated photons
   - Very difficult problem: at $p_T \approx$ 50 GeV, jet-jet / γγ ≈ 10^7
     → need to reject each jet by a factor 10,000 to bring the reducible background well below the irreducible one
   - However, at $p_T \approx$ 50 GeV, π^0/jet ≈ 10^{-3}
     → separate isolated photons from π^0 decays at 50 GeV
     → photons from π^0 decays will be distant by ≈ 1 cm
     → need granular position detector after ~ 4-5 X_0 in

SM H$\rightarrow \gamma\gamma$

Rejection of QCD jet background



ATLAS EM calo : full simulation

$\varepsilon_\gamma = 80\%$

Most rejection from longitudinal calo segmentation and 4 mm η-strips in first compartment (γ / π^0 separation)

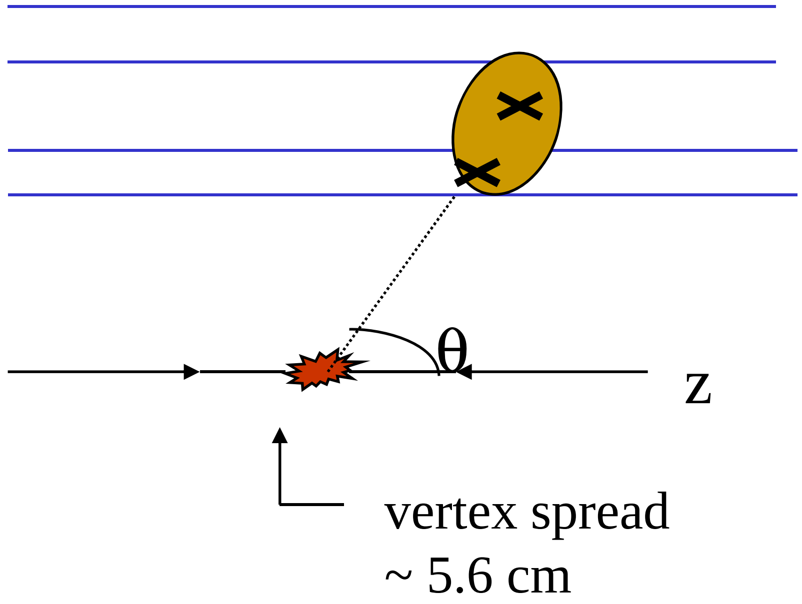
SM H→ γγ

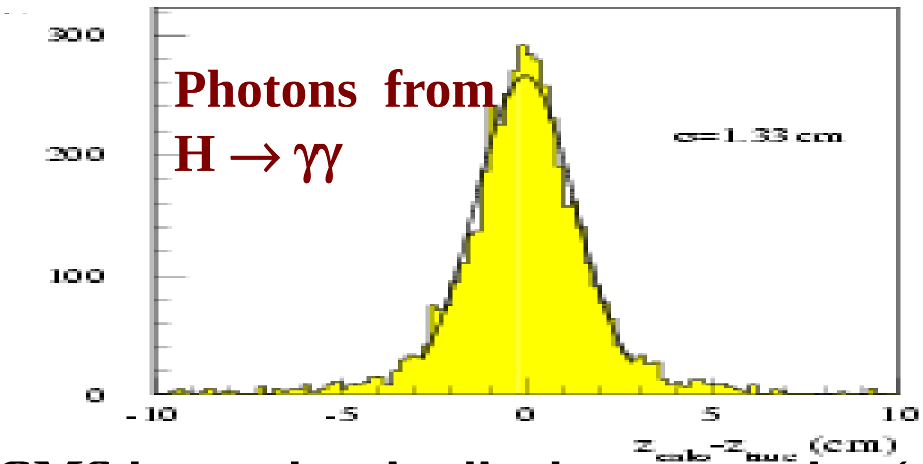
<u>Angular resolution and acceptance</u>

- ATLAS calorimeter has longitudinal segmentation

→ **can measure γ direction**

ATLAS, full simulation
Vertex resolution using EM
calo longitudinal segmentation





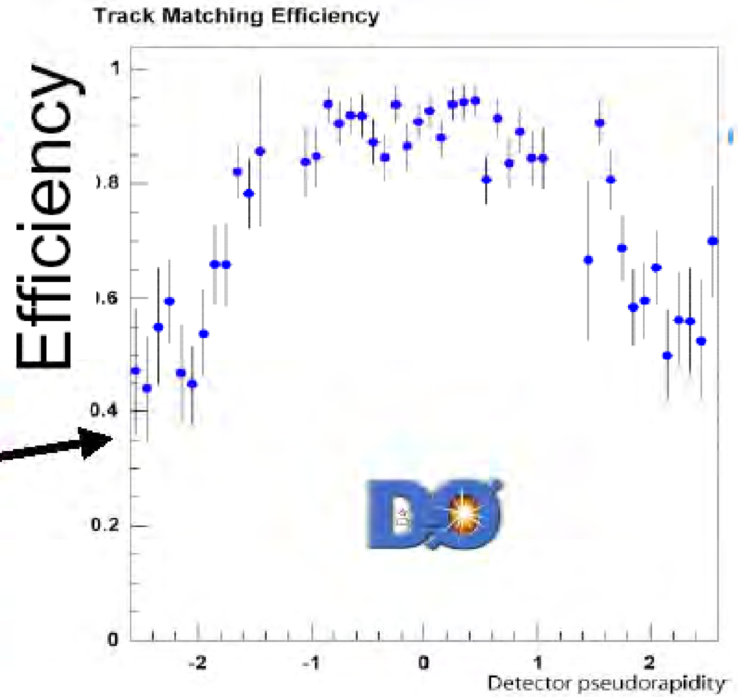
$$\sigma(\theta) \approx \frac{50 \text{ mrad}}{\sqrt{E}}$$

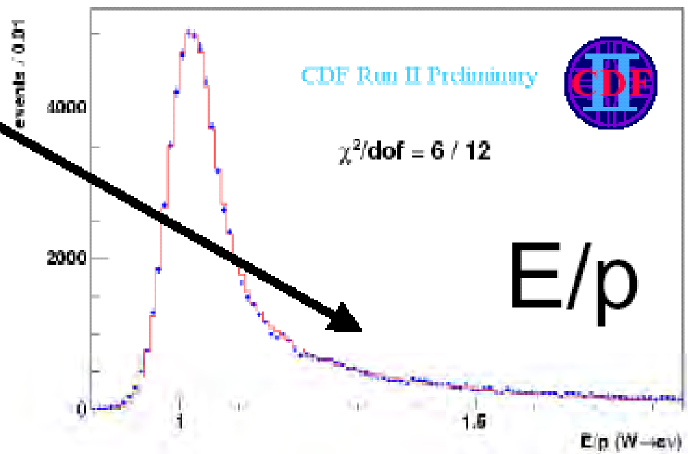
CMS has no longitudinal segmentation (and no preshower in barrel)
→ vertex measured using secondary tracks from underlying event
→ often pick up the wrong vertex
→ smaller acceptance in the Higgs mass window

Can lessons be learned from Tevatron?

ID: Tracking

- Tracking important part of electron/photon ID
- Requiring or vetoing a high p_T track reduces background by x10
- Tracking more difficult in forward regions
- Very sensitive to the amount of material
  - → Radiation reduces track p_T
  - → Converted photons are lost
  - → Uncertainty in acceptance dominated early W/Z cross section mesurements
    - ➢ 5.5% X_0 uncertainty in material gave a 4.7% uncertainty in the acceptance for $Z \rightarrow ee$

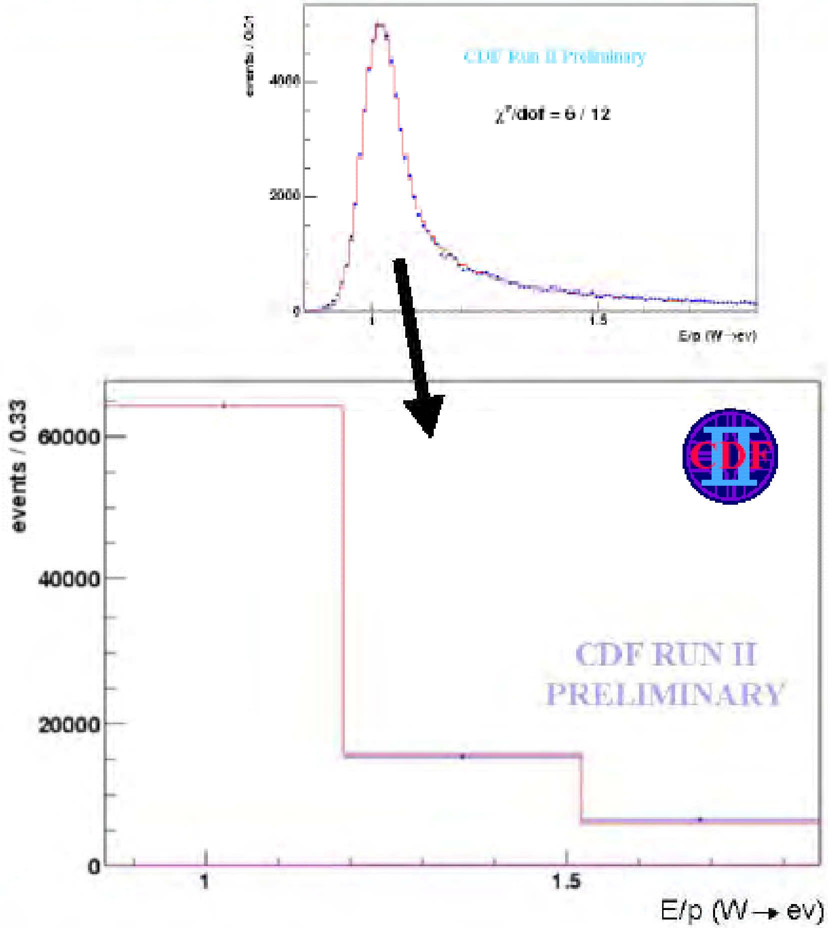




Can lessons be learned from Tevatron?

Material from E/P

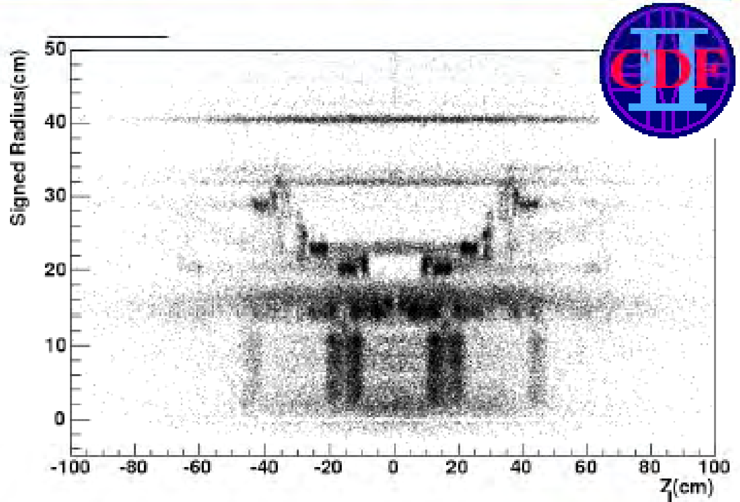
- Use radiative tail of E/P to measure material
- Gives average material
- Can be combined with energy-loss measurements of muons (J/ψ) to give roughly type of material
  - → CDF discovered it was missing Copper cables this way

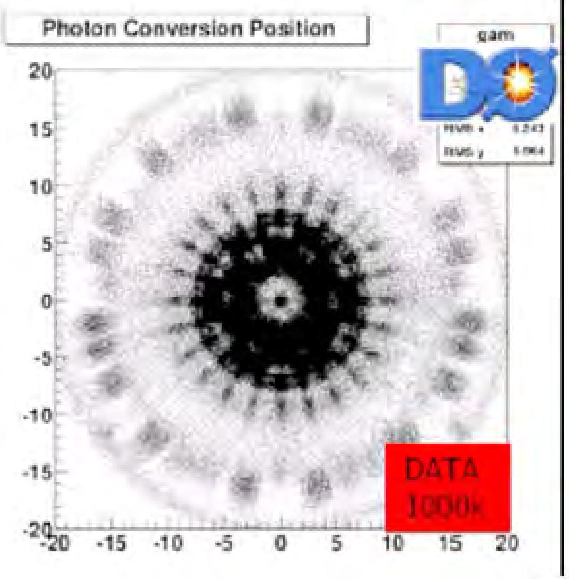


Can lessons be learned from Tevatron?

Material: X-raying the detector

- Conversions can indicate location of material in detector
  - ➔ Normalized to inner cylinder of tracking chamber
  - ➔ Overall normalization difficult
    - ➢ Acceptance and efficiency depend on r
- Useful to find missing (or misplaced!) pieces





Electrons and photons in ATLAS/CMS

ATLAS and CMS will know the amount of material
in their Inner Detector sub-systems very well
(15 years of simulation work and preparation).
But there is a lot more material than in Tevatron/LEP detectors
(0.4 to 1.5 X_0 compared to 0.1-0.2 X_0)!!

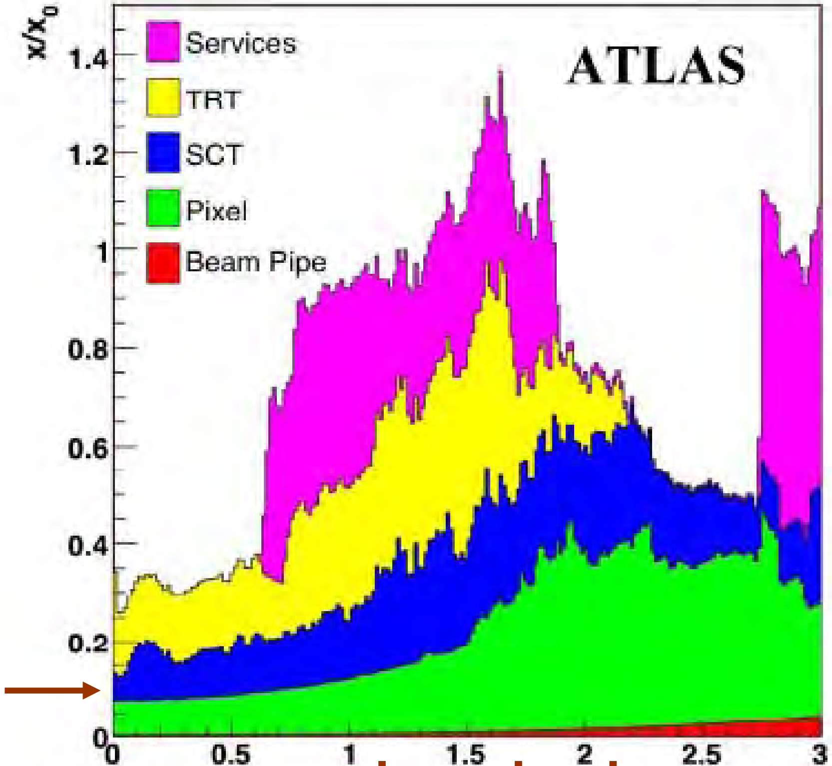
Example: weight of an ATLAS pixel stave (2005)

	Simulation (2003)	Measurement
13 Modules	25.48 g	25.74 g
TMT+omega+Tube (no liquid)	32.35 g	37.95 g +glue
Cooling liquid	~ 4.2 g	10.9 g (estimate)
Pigtails+connectors+ cables	6.39 g	7.8+13.2=21.0 g

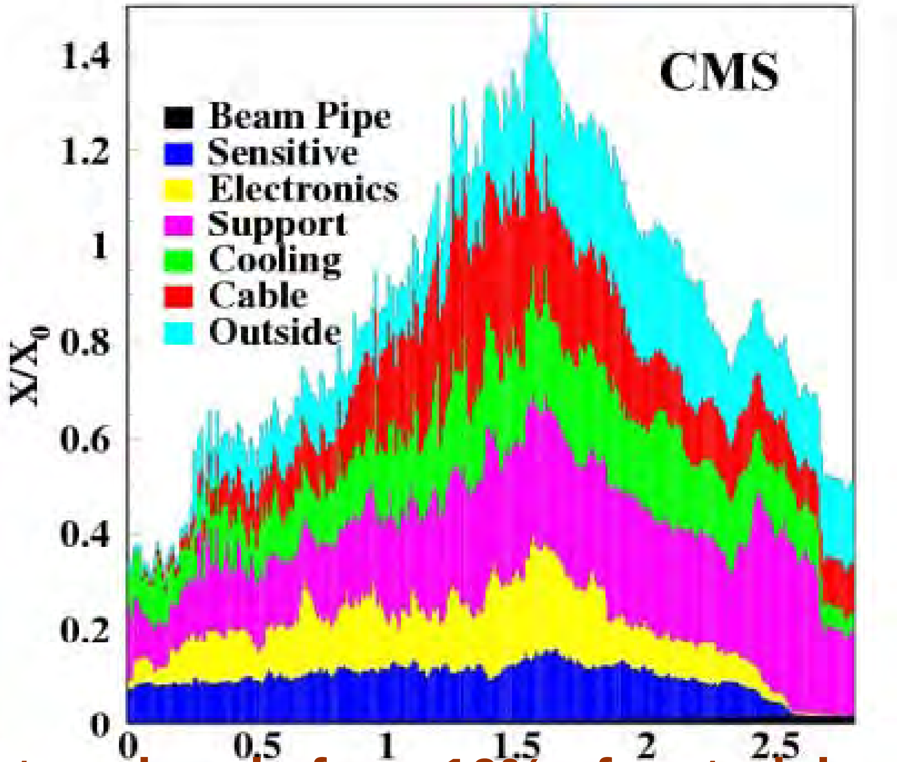
ATLAS/CMS: from design to reality

Amount of material in ATLAS and CMS inner tracker

Weight: 4.5 tons



Weight: 3.7 tons

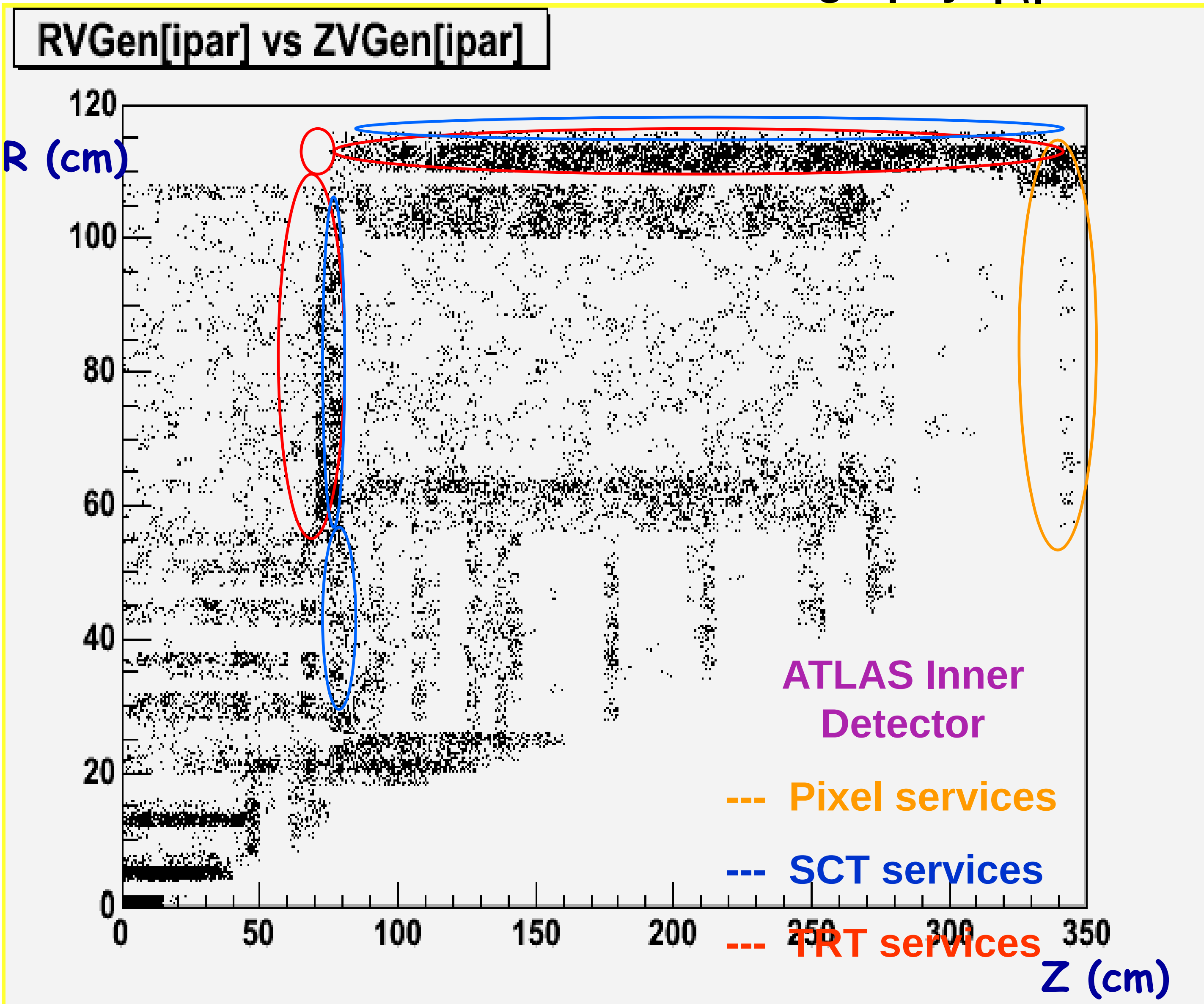


LEP detectors

- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

Electrons and photons in ATLAS/CMS

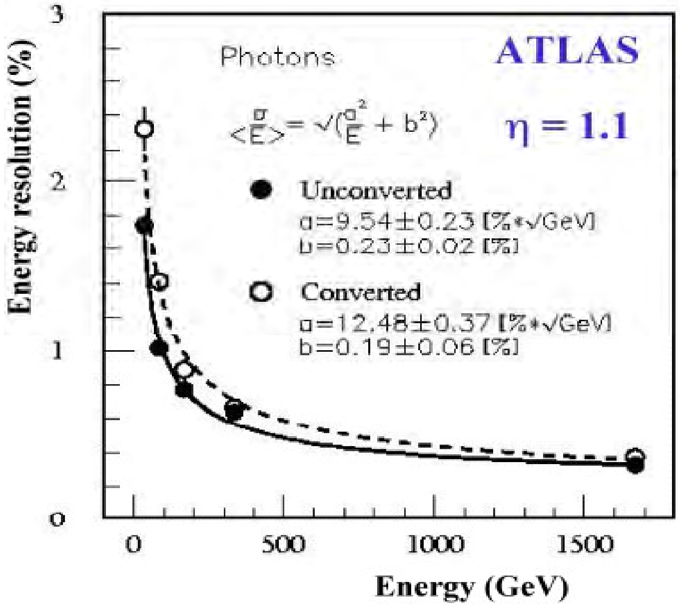
Radiography |η| < 2.5 ATLAS tracker

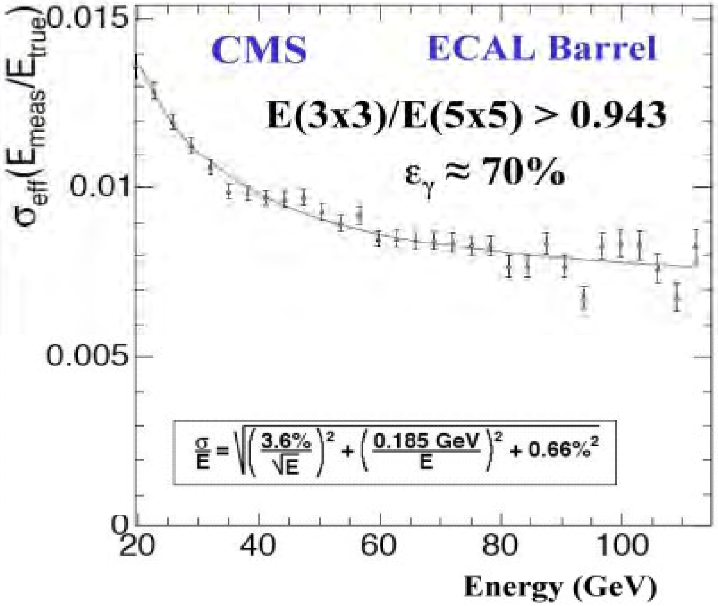


ATLAS/CMS: from design to reality

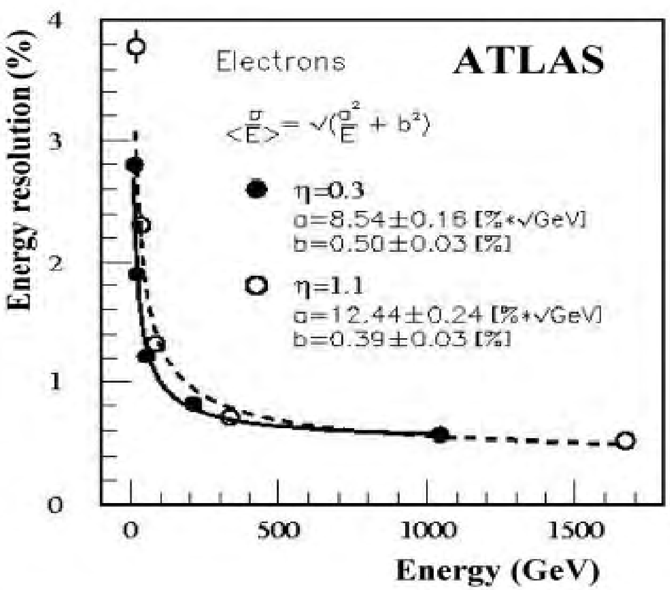
Actual performance expected in real detector quite different!!

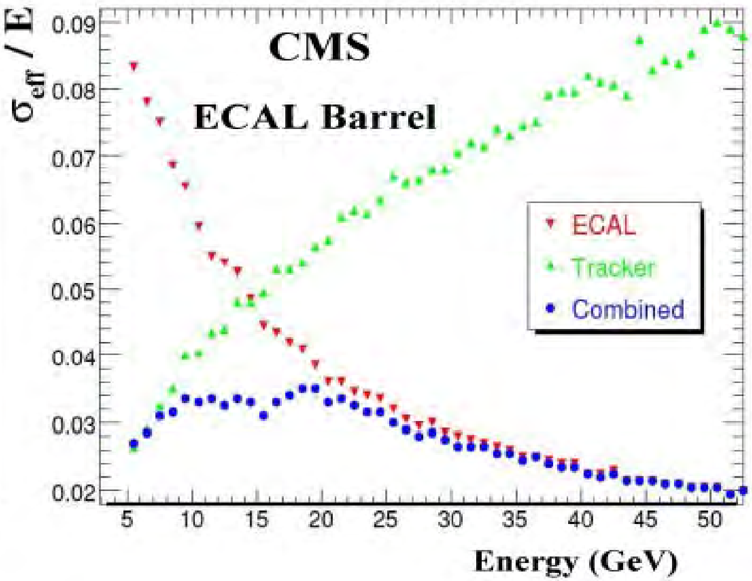
Photons at 100 GeV ATLAS: 1-1.5% energy resol. (all γ) CMS: 0.8% energy resol. (ε_γ ~ 70%)



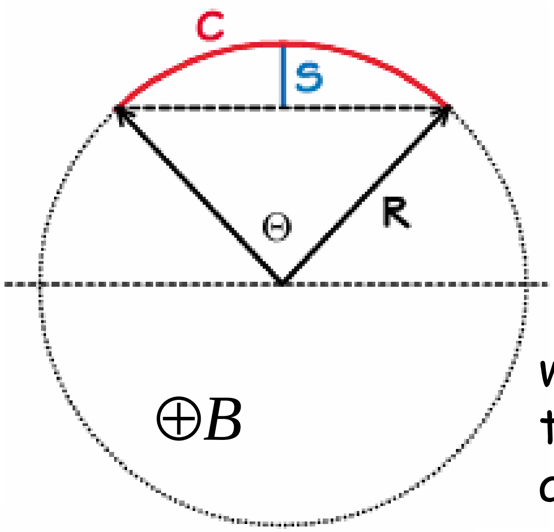


Electrons at 50 GeV ATLAS: 1.3-2.3% energy resol. (use EM calo only) CMS: ~ 2.0% energy resol. (combine EM calo and tracker)





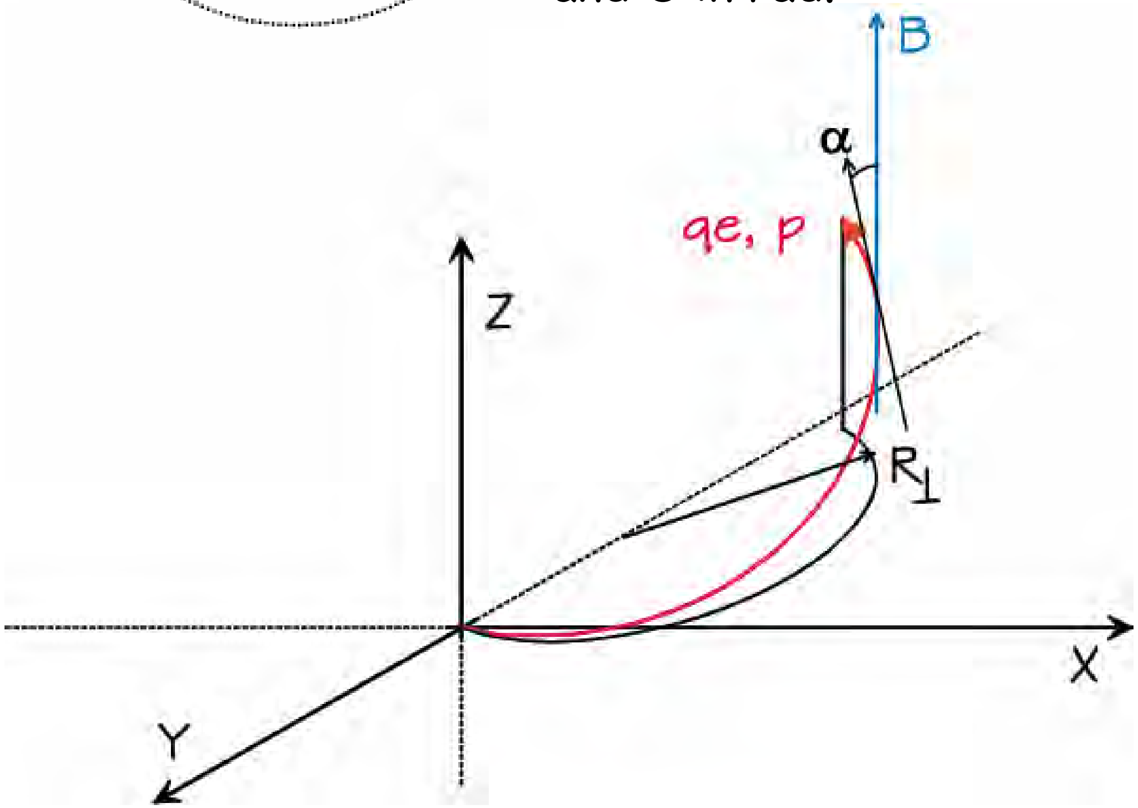
Momentum measurement.



For a uniform magnetic field along the particle trajectory

$$p \cong 0.3q \frac{\int B_\perp dl}{\Theta} \cong 0.3qB\left(\frac{C^2 \sin\alpha}{8S} + \frac{S \sin\alpha}{2}\right)$$

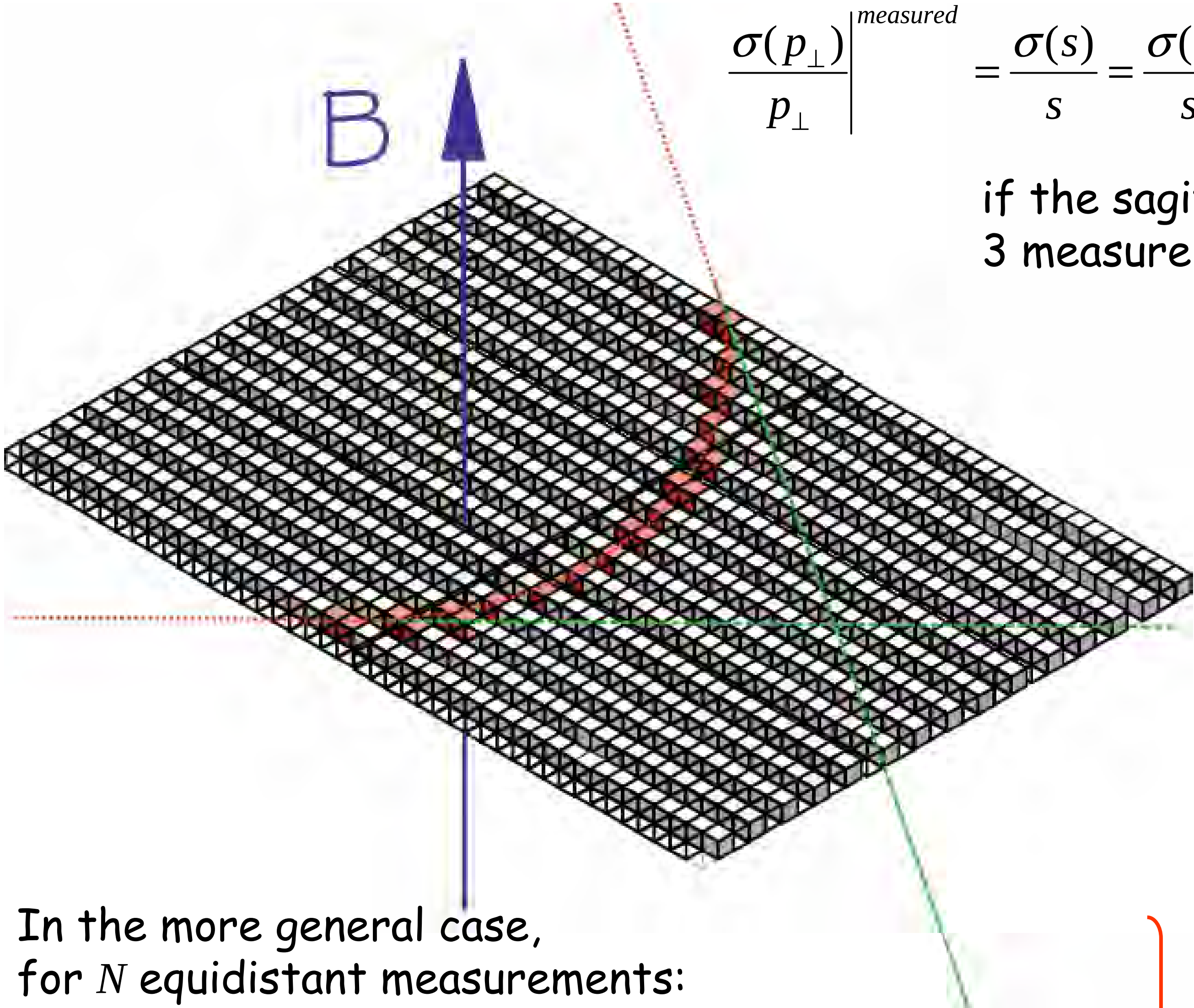
where α is the angle between the trajectory and B. B in tesla, p in GeV/c, q in electron charge, C, S and R in m and α and Θ in rad.



We can clearly also measure the charge, q, of the particle.

O. Ullaland/2006

Error in momentum measurement



$$\left.\frac{\sigma(p_\perp)}{p_\perp}\right|^{measured} = \frac{\sigma(s)}{s} = \frac{\sigma(x)}{s}\sqrt{\frac{3}{2}} = \frac{1}{0.3}\frac{\sigma(x)\cdot p_\perp}{BL^2}\sqrt{\frac{387}{2}}$$

if the sagitta, s, is determined by 3 measurements with error $\sigma(x)$

In the more general case, for N equidistant measurements:

$$\left.\frac{\sigma(p_\perp)}{p_\perp}\right|_{measured} = \frac{1}{0.3}\frac{\sigma(x)\cdot p_\perp}{BL^2}\sqrt{\frac{720}{N+4}}$$

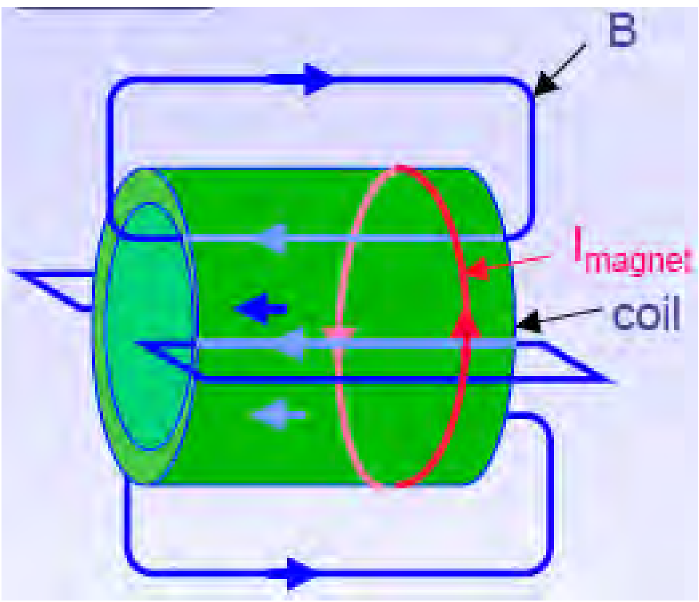
for $N \geq \sim 10$

In short → $\frac{\sigma(p_\perp)}{p_\perp^2} = const.$

Magnets for 4π Detectors

Solenoid

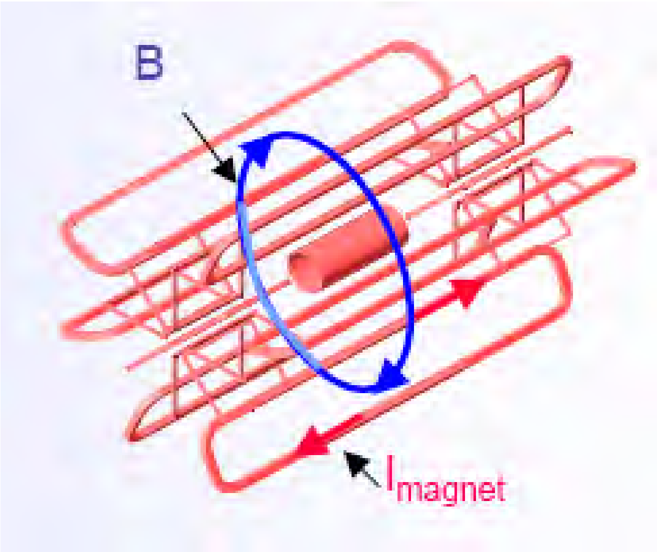
+ Large homogeneous field inside
- Weak opposite field in return yoke
- Size limited by cost
- Relatively large material budget



Examples:
•Delphi: SC, 1.2 T, 5.2 m, L 7.4 m
•CDF: SC, 1.4T, 2 m, L 6m
•CMS: SC, 4 T, 5.9 m, L 12.5 m

Toroid

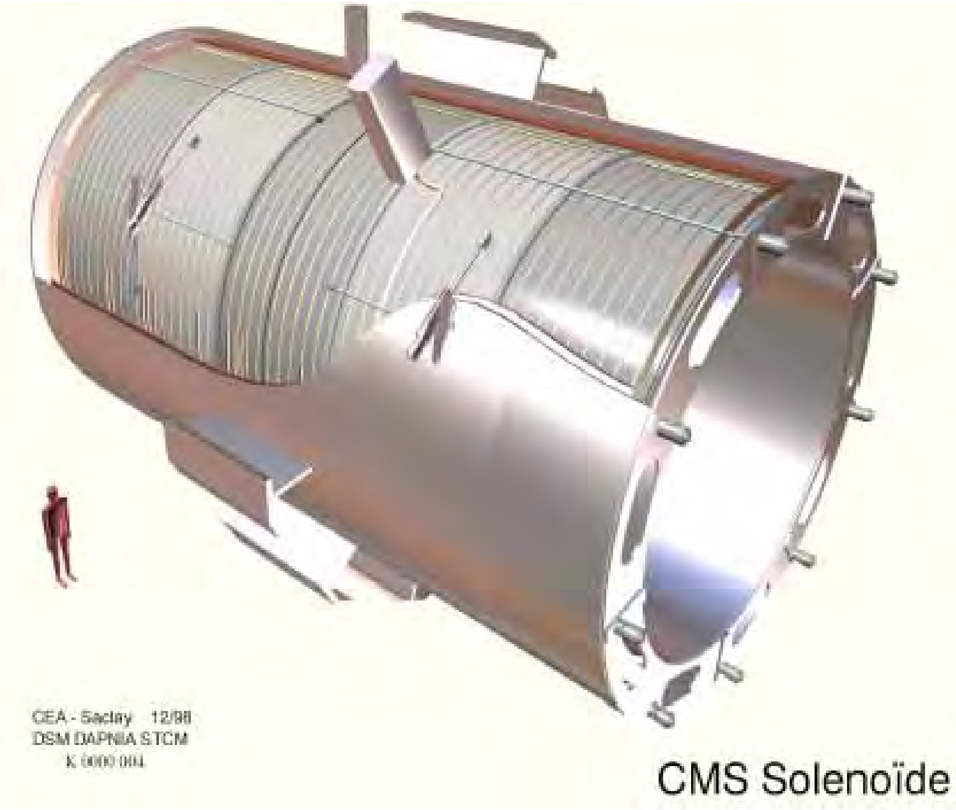
+ Field always perpendicular to p
+ Rel. large fields over large volume
+ Rel. low material budget
- Non-uniform field
- Complex structural design



Example:
•ATLAS: Barrel air toroid, SC, ~1 T, 9.4 m, L 24.3 m

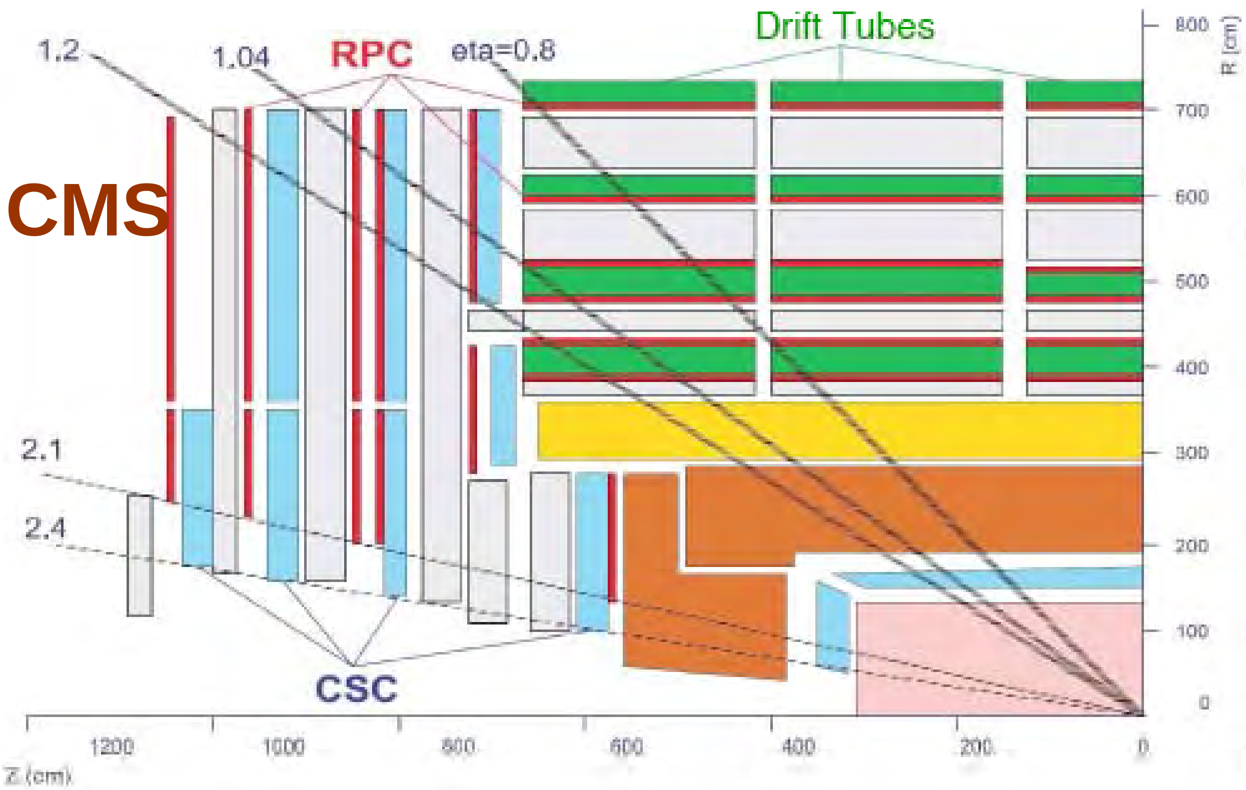
Charge and Momentum

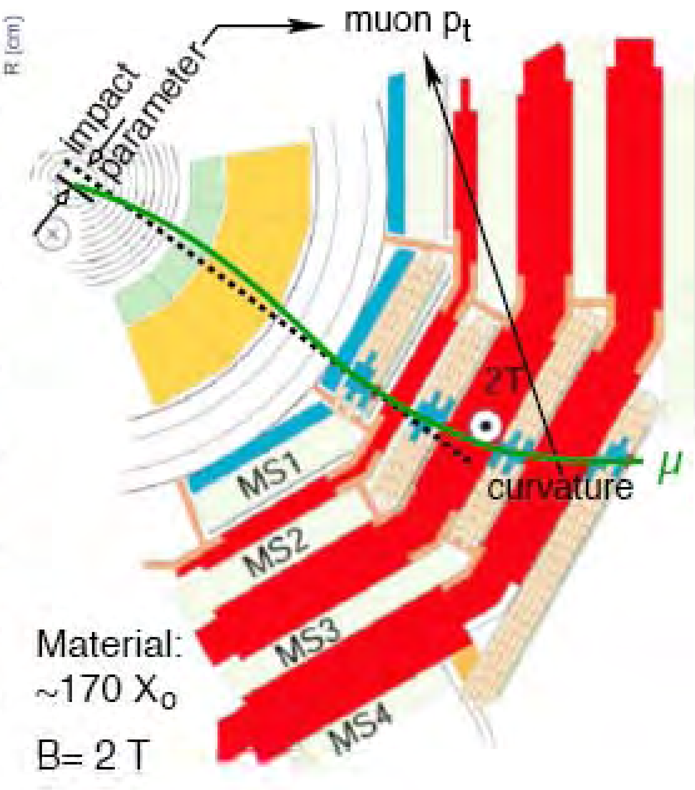
Two ATLAS toroid coils



Superconducting CMS Solenoid Design

ATLAS/CMS: muon measurements

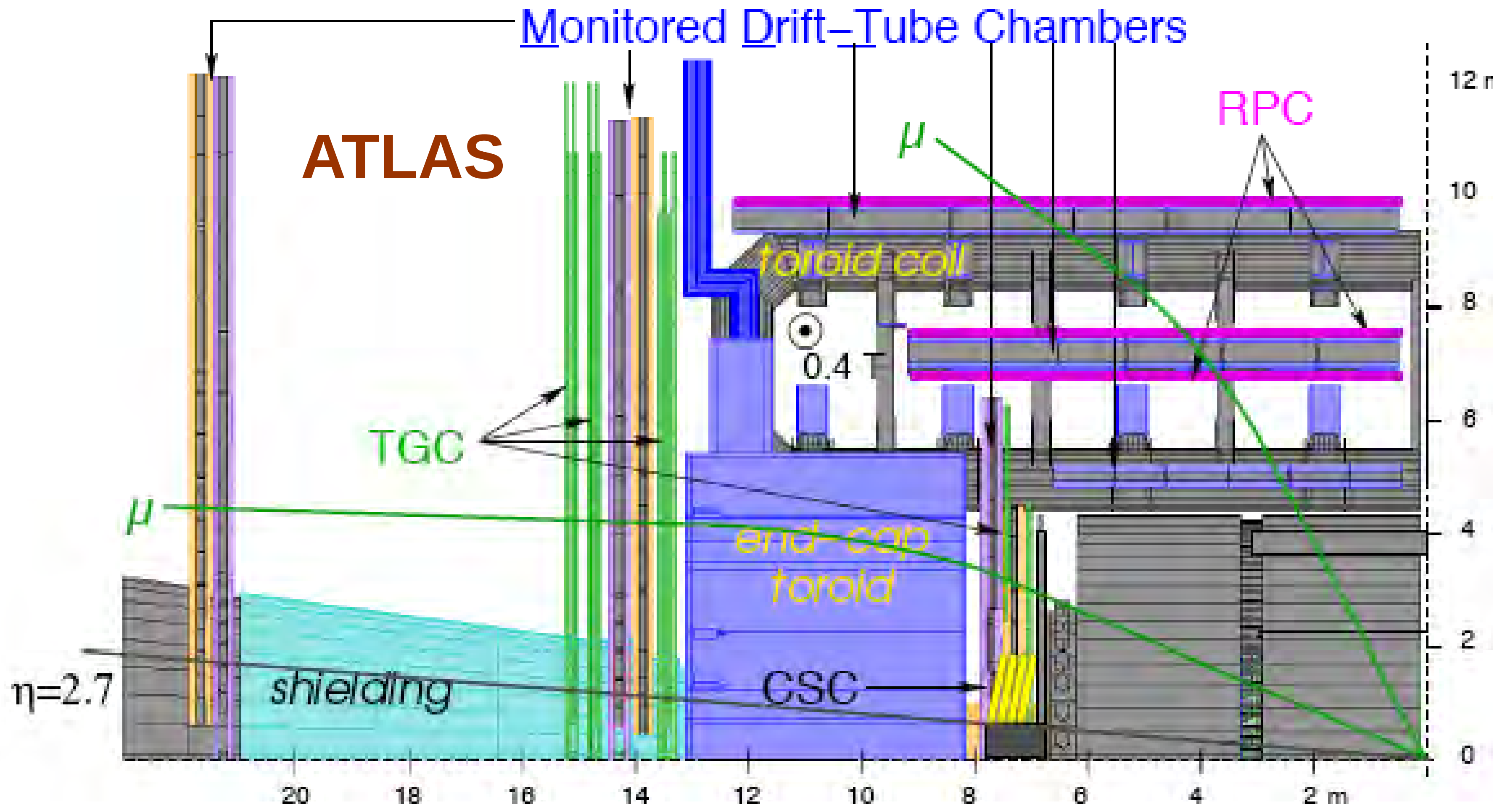




CMS muon spectrometer

- **Superior combined momentum resolution in central region**
- **Limited stand-alone resolution and trigger (at very high luminosities) due to multiple scattering in iron**
- **Degraded overall resolution in the forward regions ($|\eta| > 2.0$) where solenoid bending power becomes insufficient**

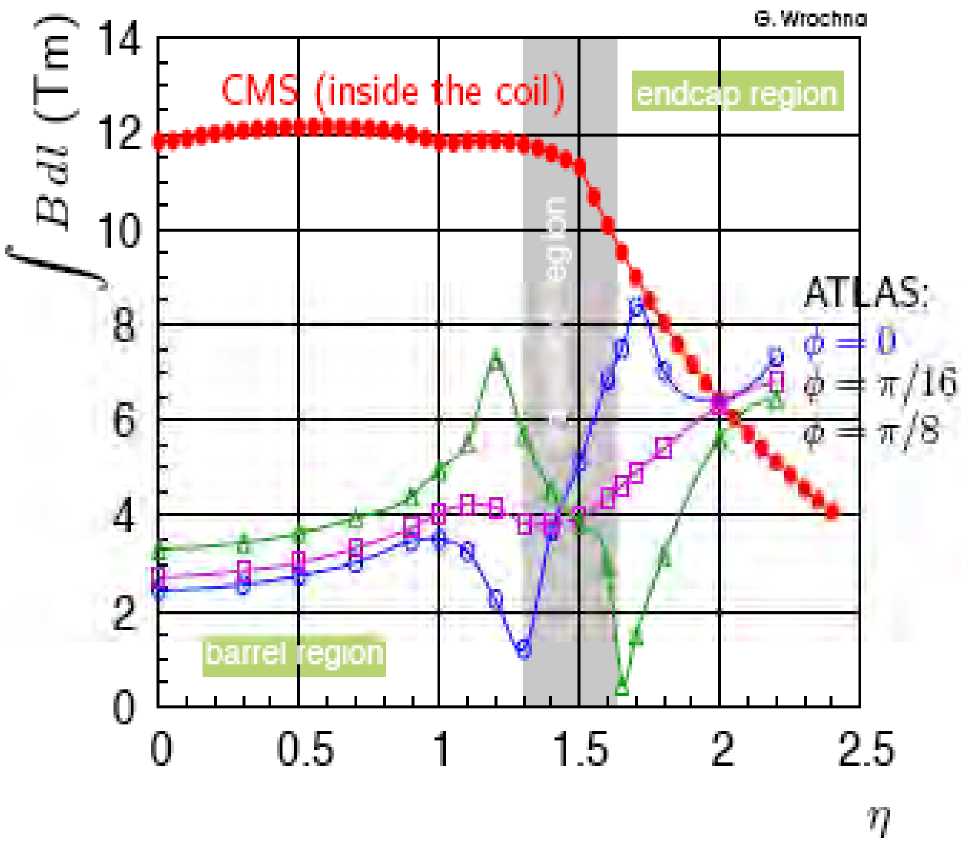
ATLAS/CMS: muon measurements



ATLAS muon spectrometer

- **Excellent stand-alone capabilities and coverage in open geometry**
- **Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential η x φ coverage (|η| < 2.7)**

ATLAS/CMS: muon measurements



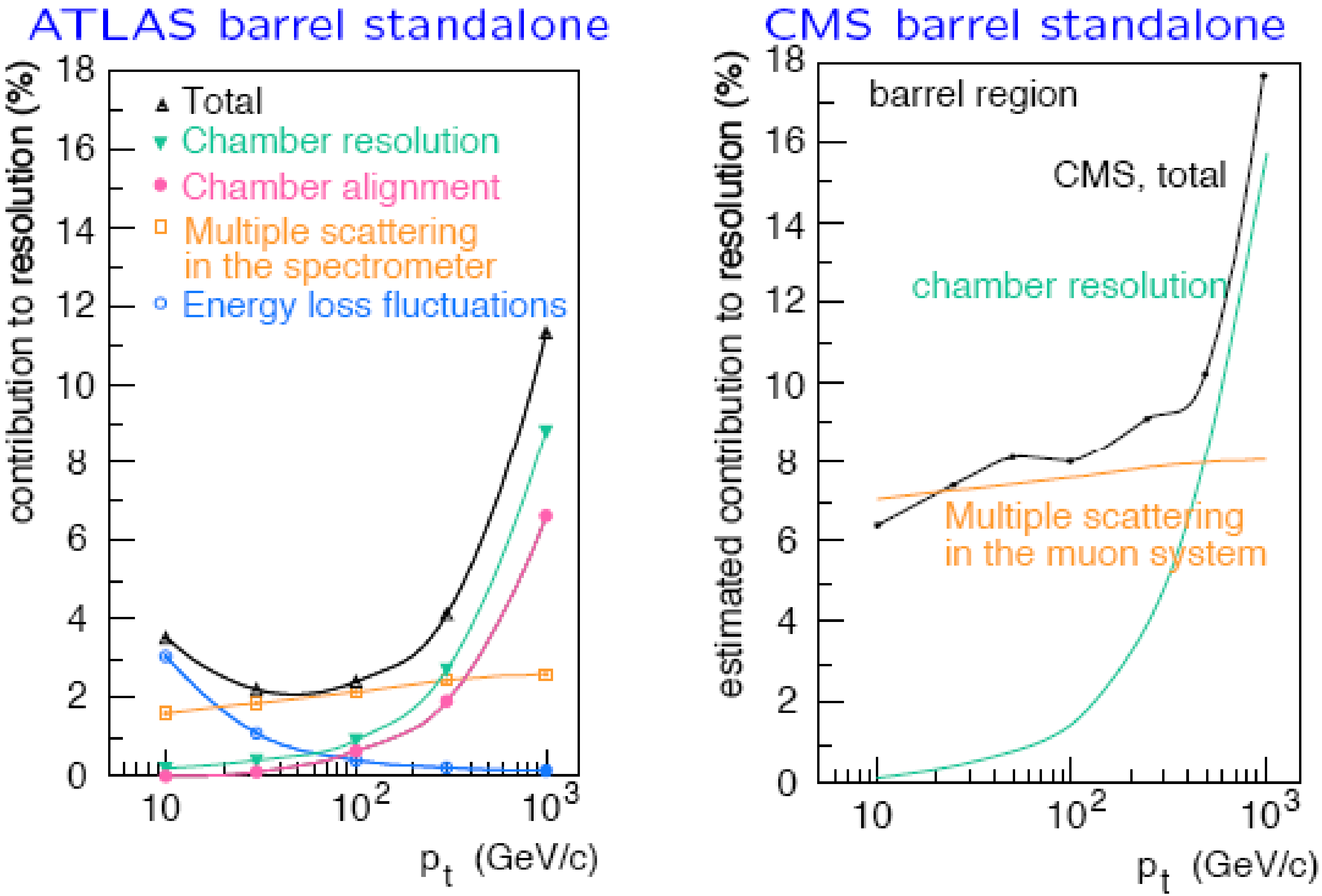
Barrel: $\approx 5\times$ higher bending power in CMS, **but** $\approx 14\times$ larger multiple scattering.

$\rightarrow$ $\approx 3\times$ worse p_t resolution in CMS.

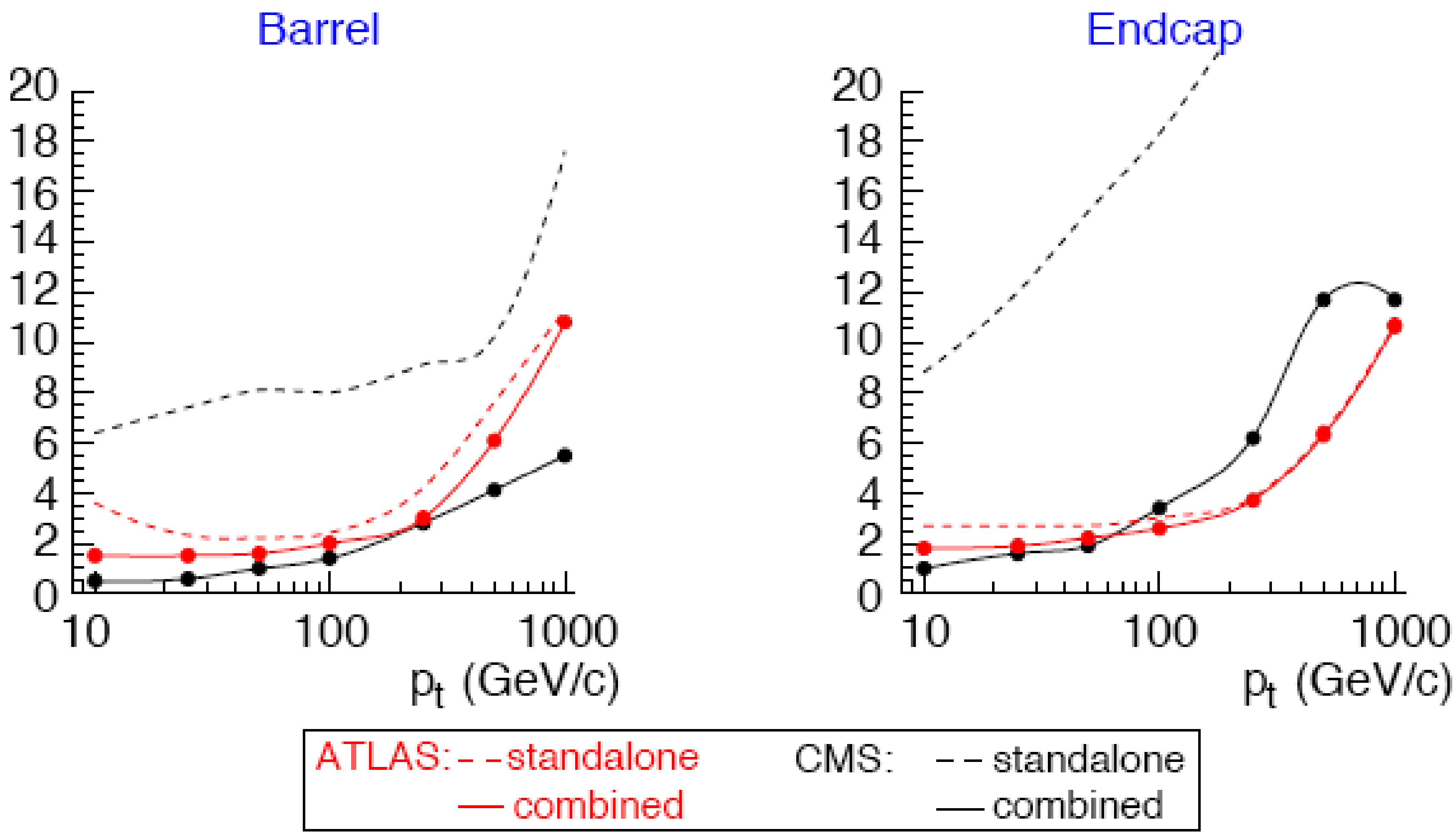
Endcap: similar bending powers, $\approx 10\times$ large multiple scattering.

$\rightarrow$ $\approx 5\times$ worse p_t resolution in CMS.

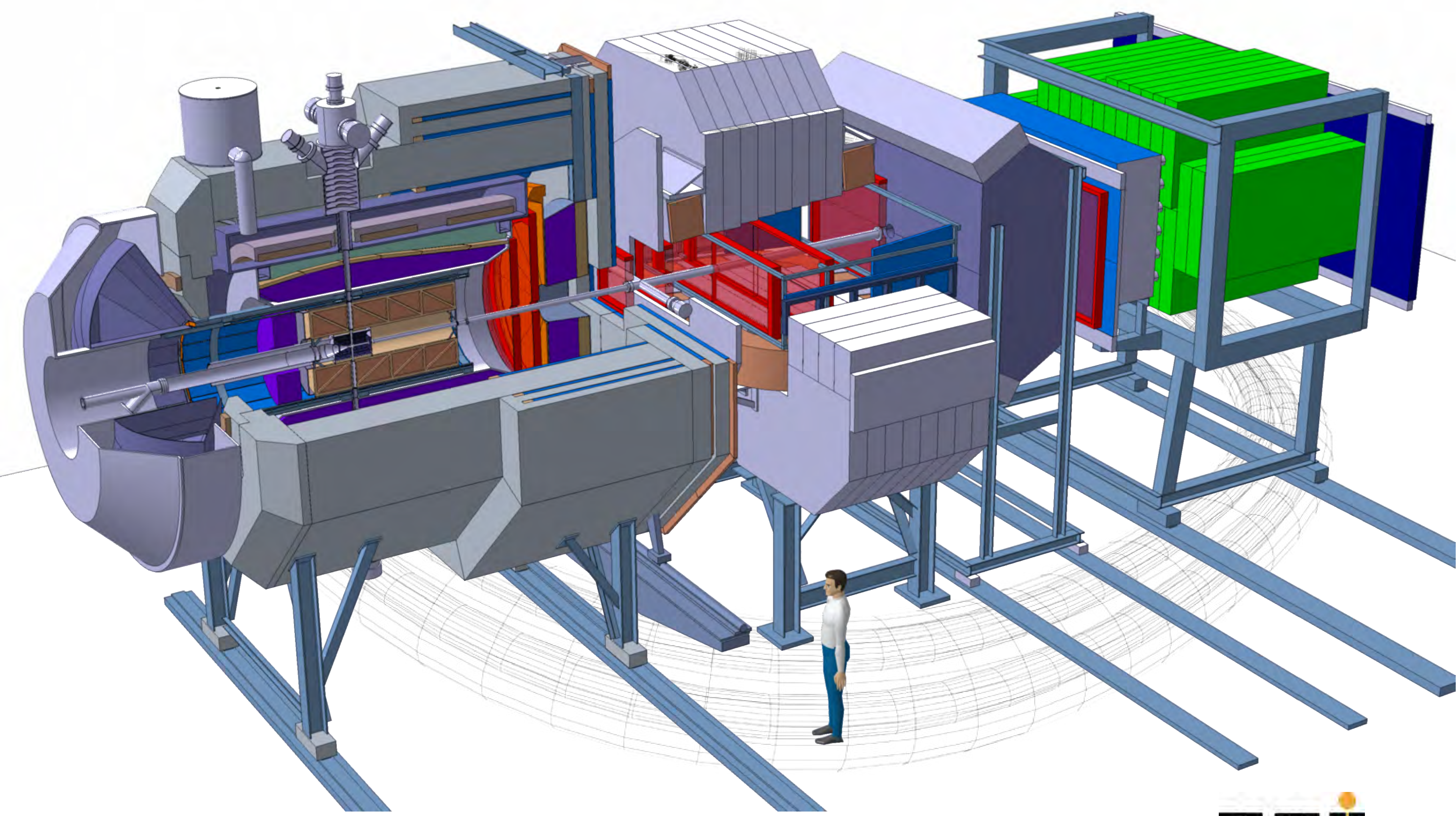
ATLAS/CMS: muon measurements



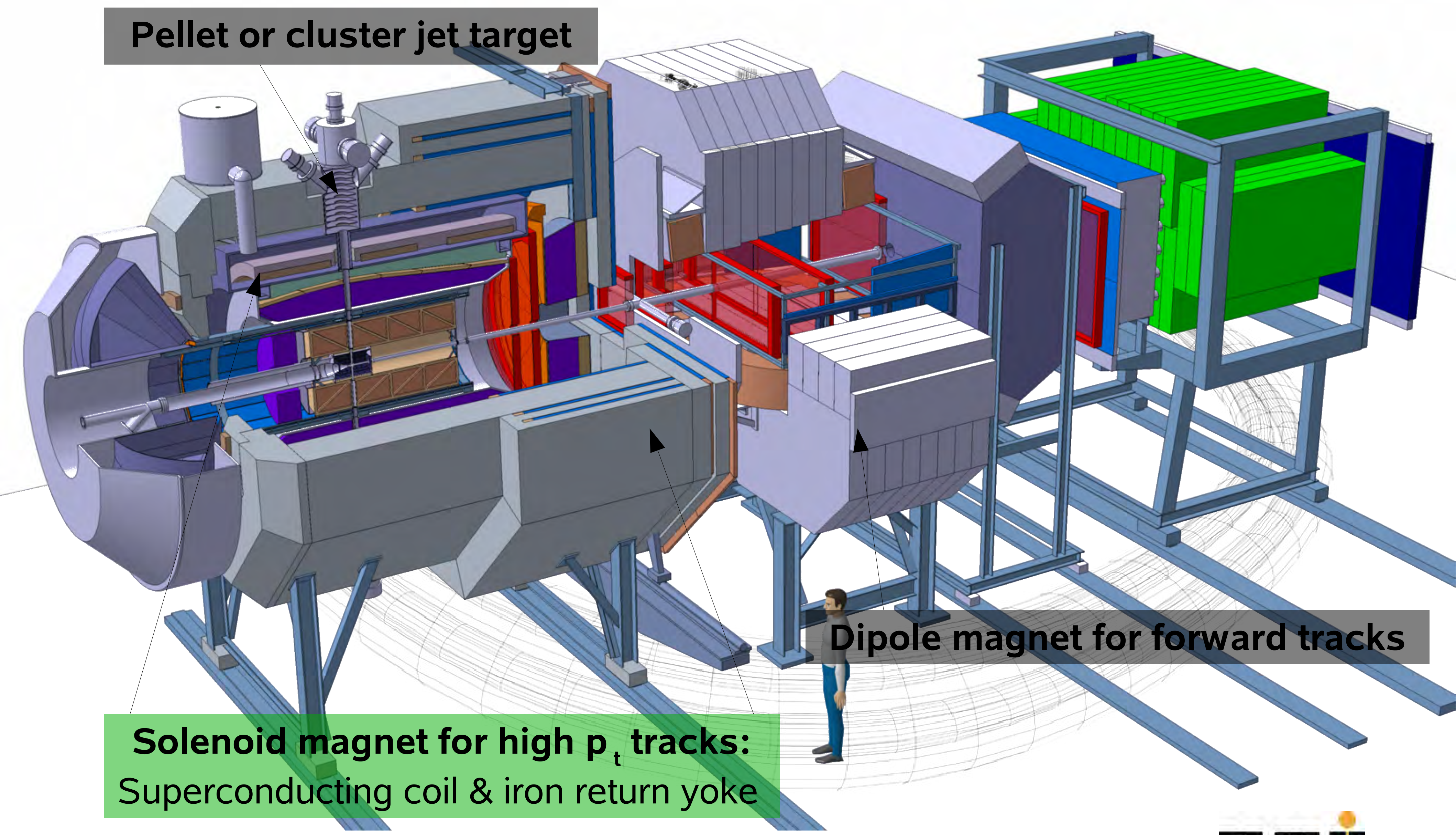
ATLAS/CMS: muon measurements



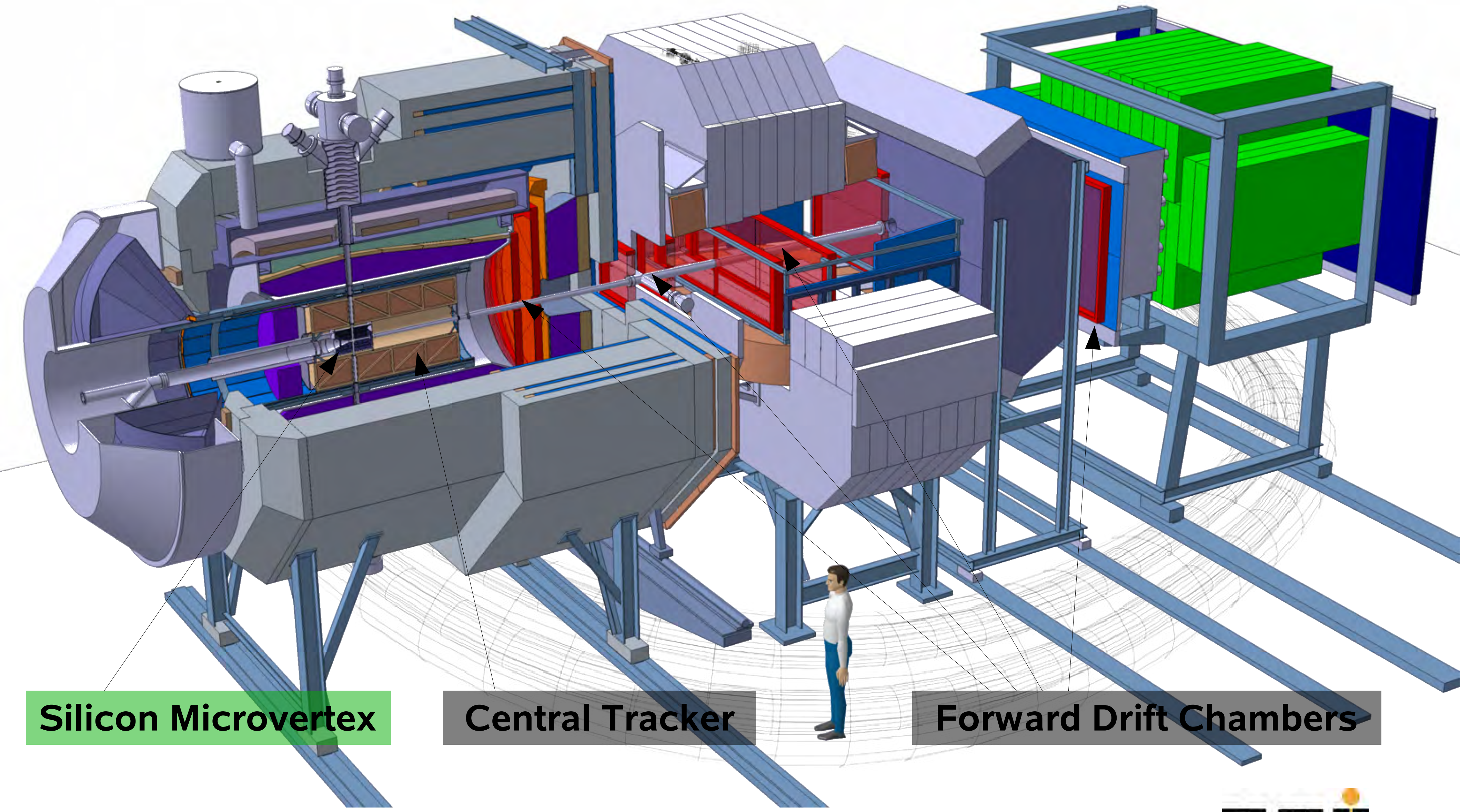
PANDA Spectrometer



PANDA Spectrometer



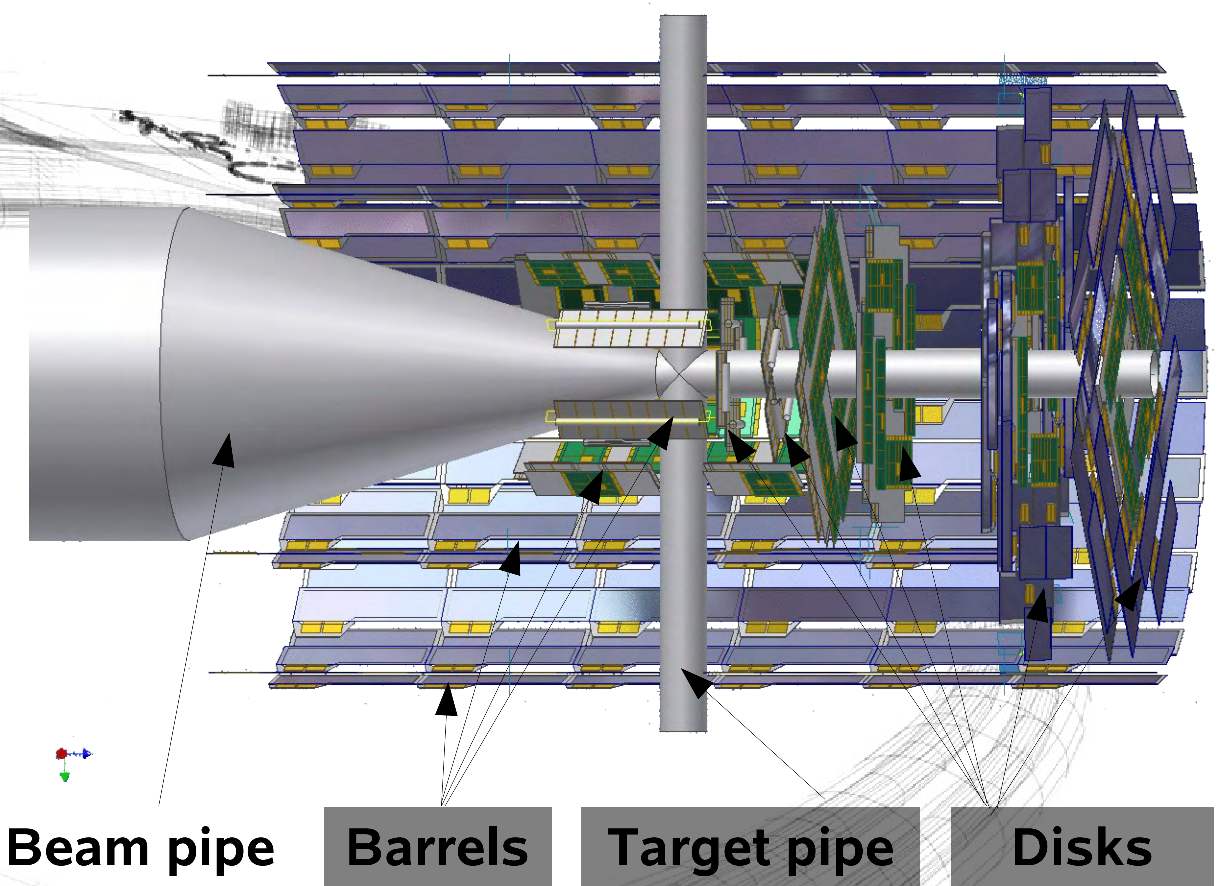
PANDA Spectrometer



Silicon Micro Vertex Detector

Layout of MVD

- General structure:
  - 4 Barrels & 6 disks
  - Inner layers pixels
  - Outer layers strips
    (forward mixed)
- Pixel part:
  - Hybrid pixels 100 x100 μm^2
  - 140 modules
  - 13 M channels
  - 0.15 m^2
- Strip part:
  - Double sided silicon
  - 400 modules
  - 70k channels
  - 0.5 m^2



Central Tracker - TPC Option

General layout: GEM-TPC

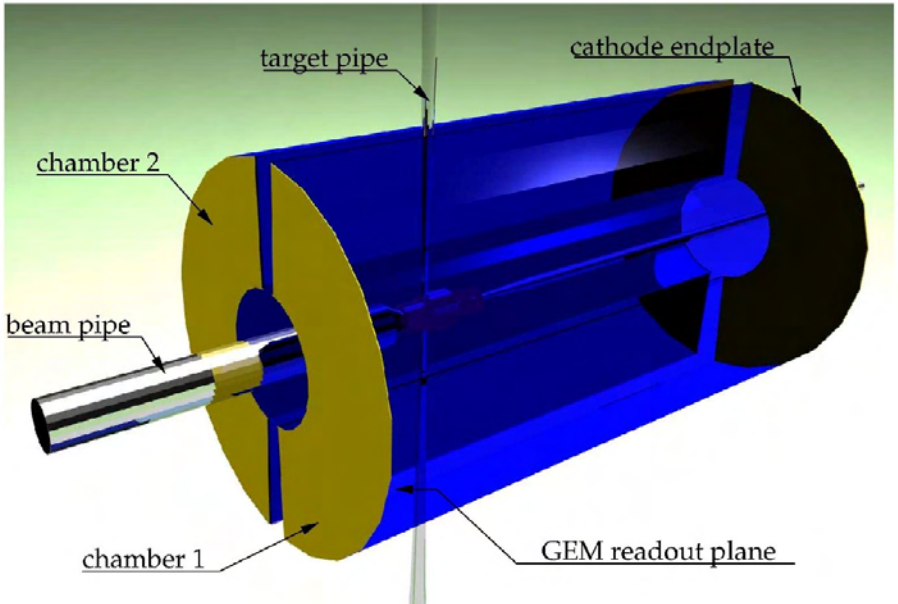
- 2 half cylinders
- Drift field *E* || *B*
- Gas: Ne/CO_2 $(+CH_4/CF_4)$
- Multi-GEM stack for amplification and ion backflow suppression
- 100 k pads of 2 x 2 mm^2
- 50-70 μs drift, 500 events overlap

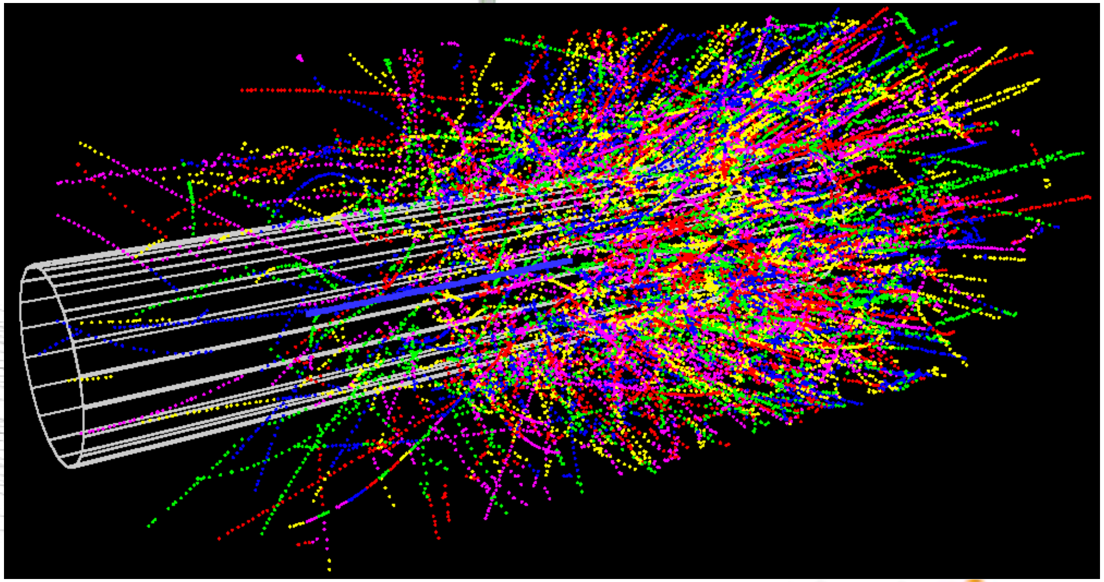
Simulations:

- $\delta p/p \sim 1\%$
- d*E*/dx resolution ~ 6%

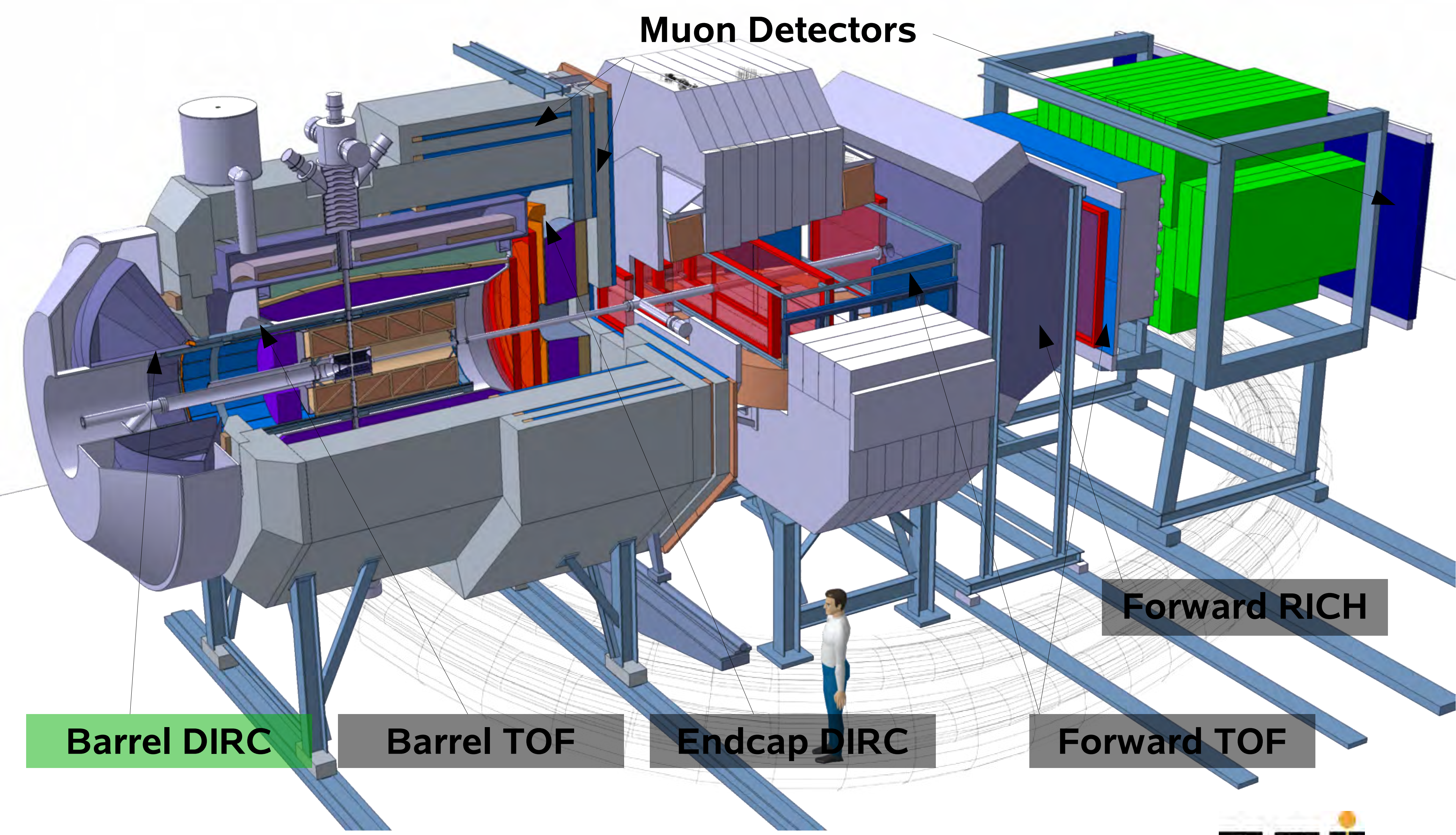
Challenges:

- space charge build-up
- continuous sampling





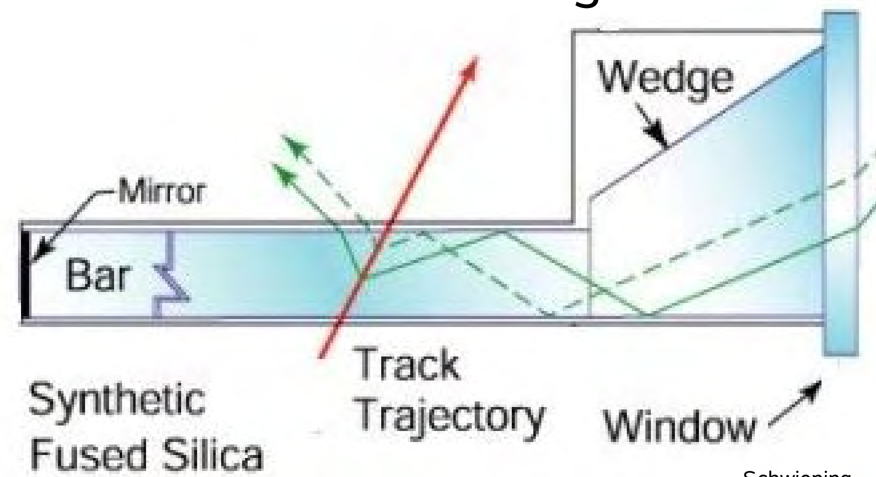
PANDA Spectrometer

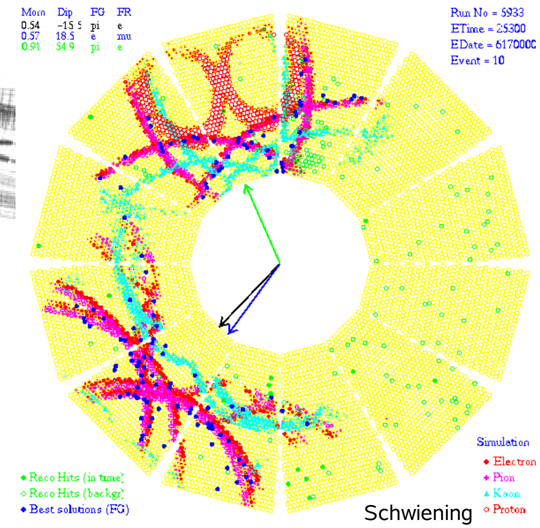


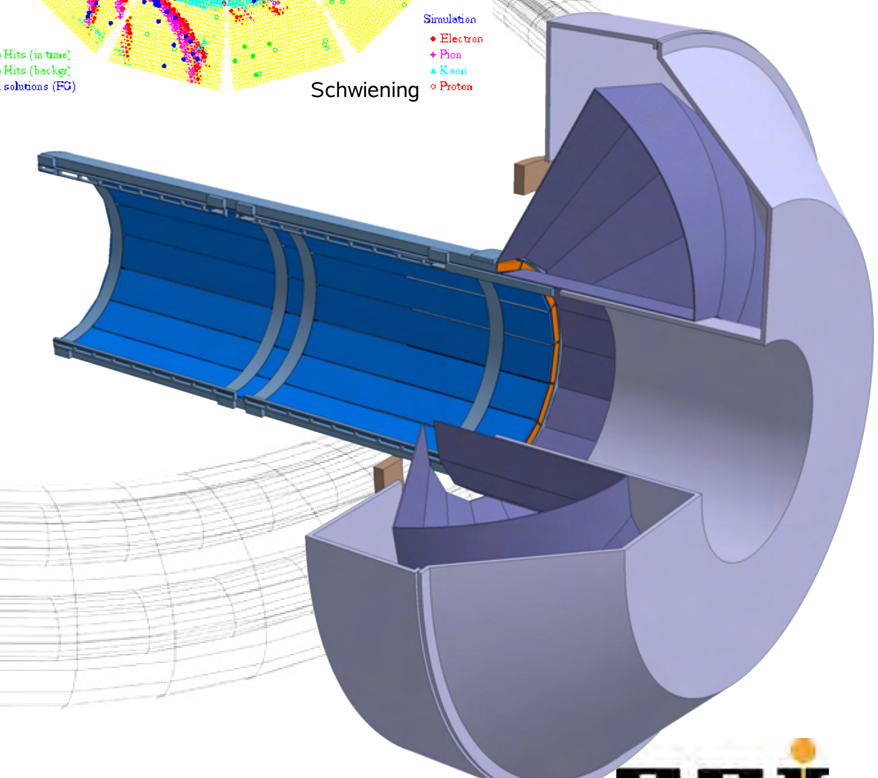
DIRC Concept

Detection of Internally Reflected Cherenkov light

- Different Cherenkov angles give different reflection angles





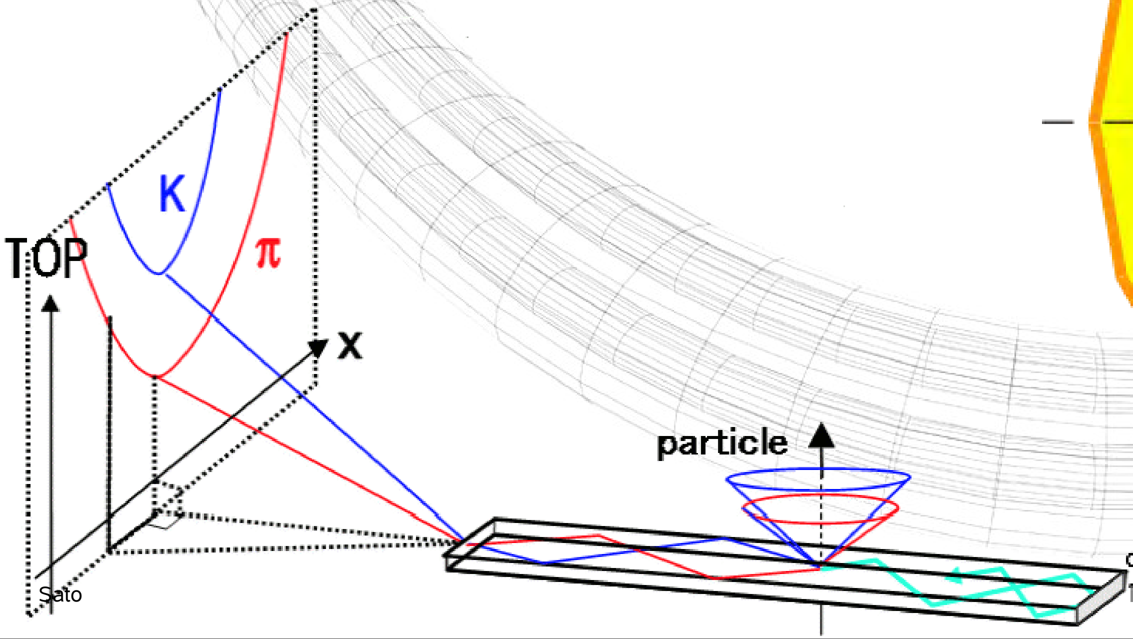


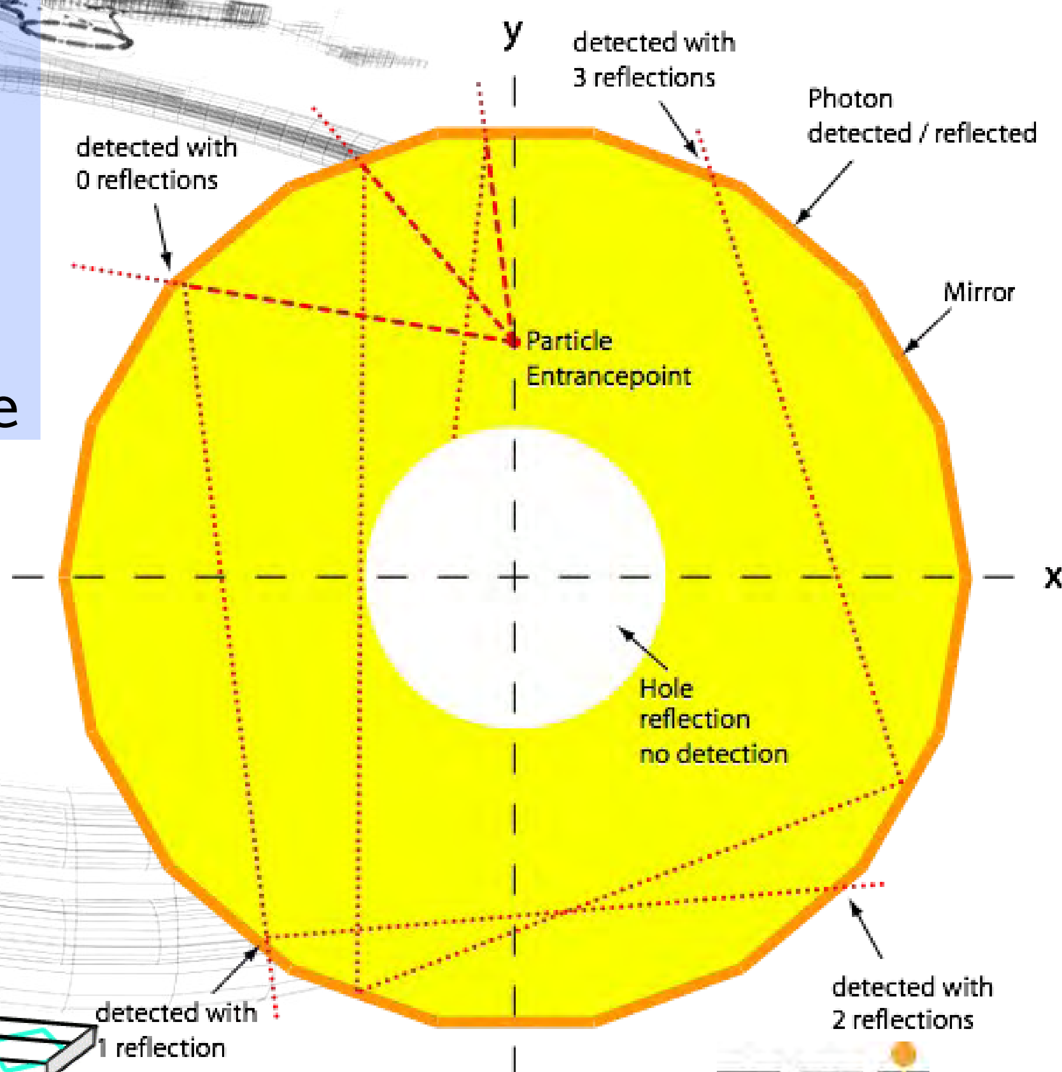
PANDA DIRC similar to BaBar

- 96 Fused silica bars, 2.6m length
- Water tank & 7000 PMTs
- *Alternative readout:* (x,y,t), mirrors

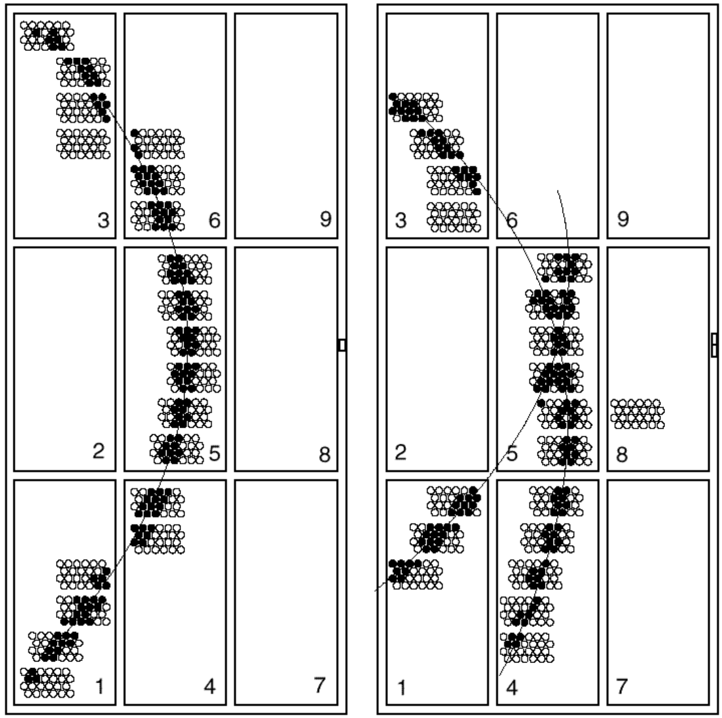
Setup of Endcap Cherenkov

- DIRC principle
- Disc shaped fused silica radiator
  2.1 m diameter
- Measure coordinate and time
- Dispersion correction through dichroic filters or second coordinate



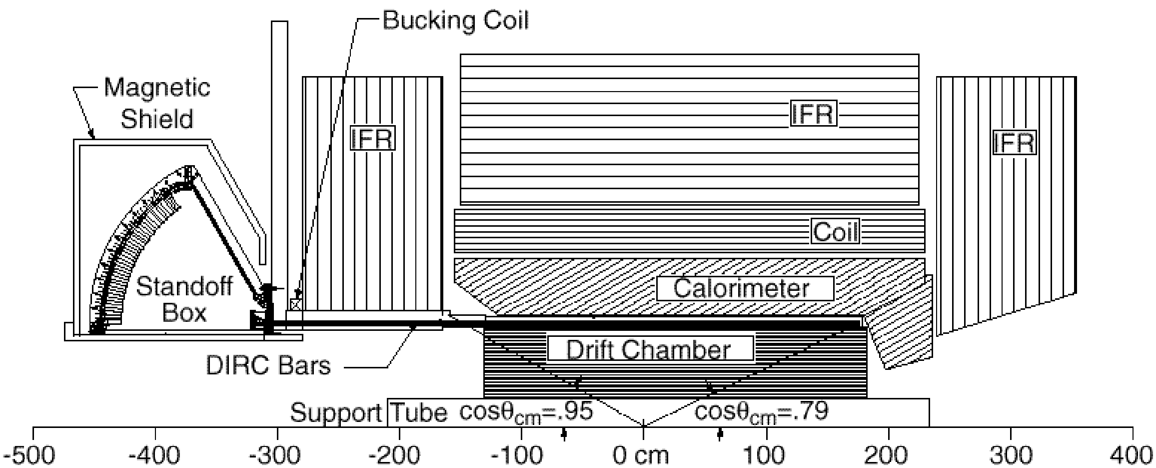


Prototype in test beam

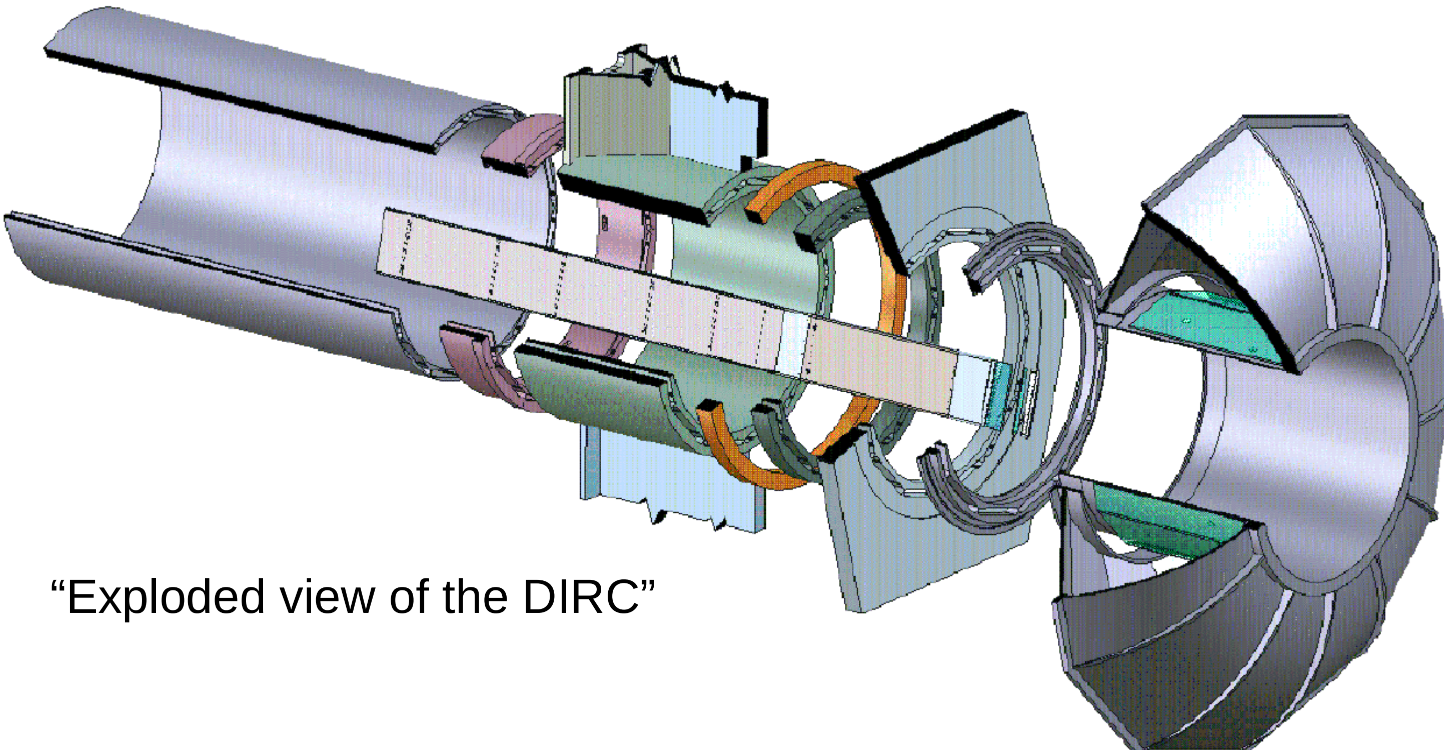


σ_C = 10.0 mrad
(single photon)

The DIRC in the BaBar experiment at SLAC.



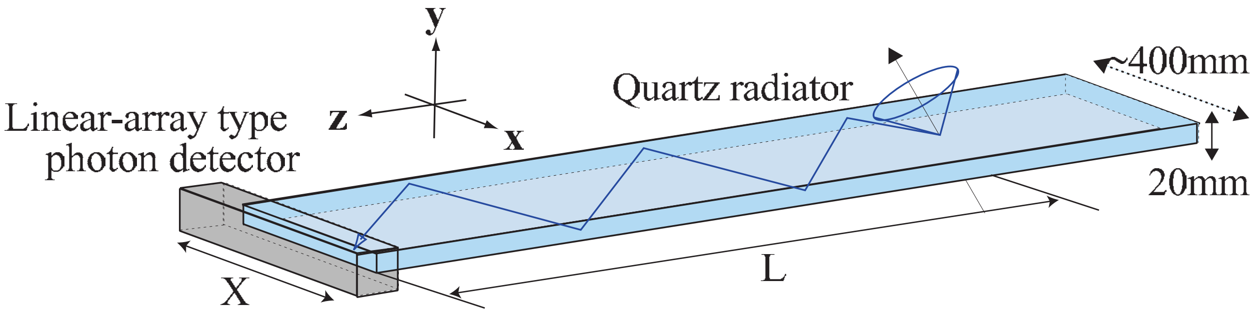
Big advantage: Minimum amount of material in front of ECAL.



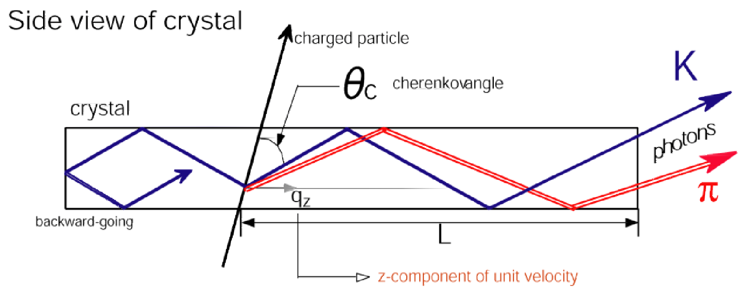
“Exploded view of the DIRC”

TOP counter

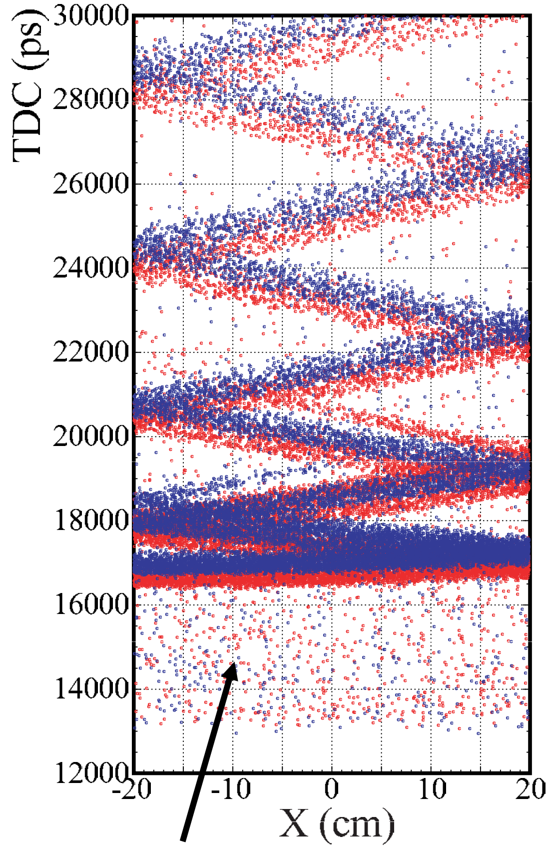
- Cherenkov ring imaging using timing information



$$cos\theta_c = \frac{1}{n(\lambda)\beta}$$



Simulation
2GeV/c, θ=90 deg.

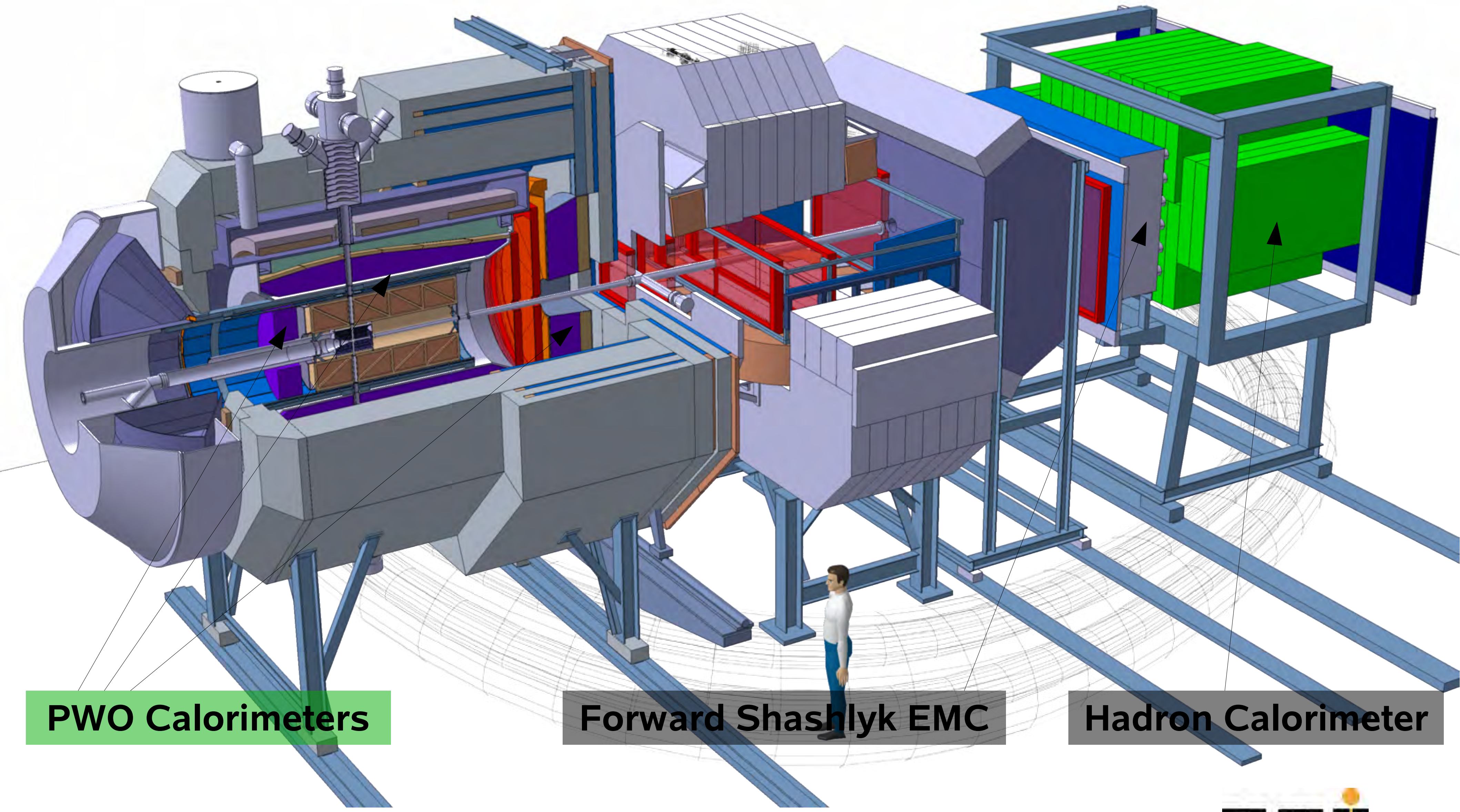


δ-ray,
had. int.

Difference of path length
→ Difference of time of propagation (TOP)

150~200ps from TOP + TOF from IP
with precise time resolution (σ~40ps) for each photon

PANDA Spectrometer



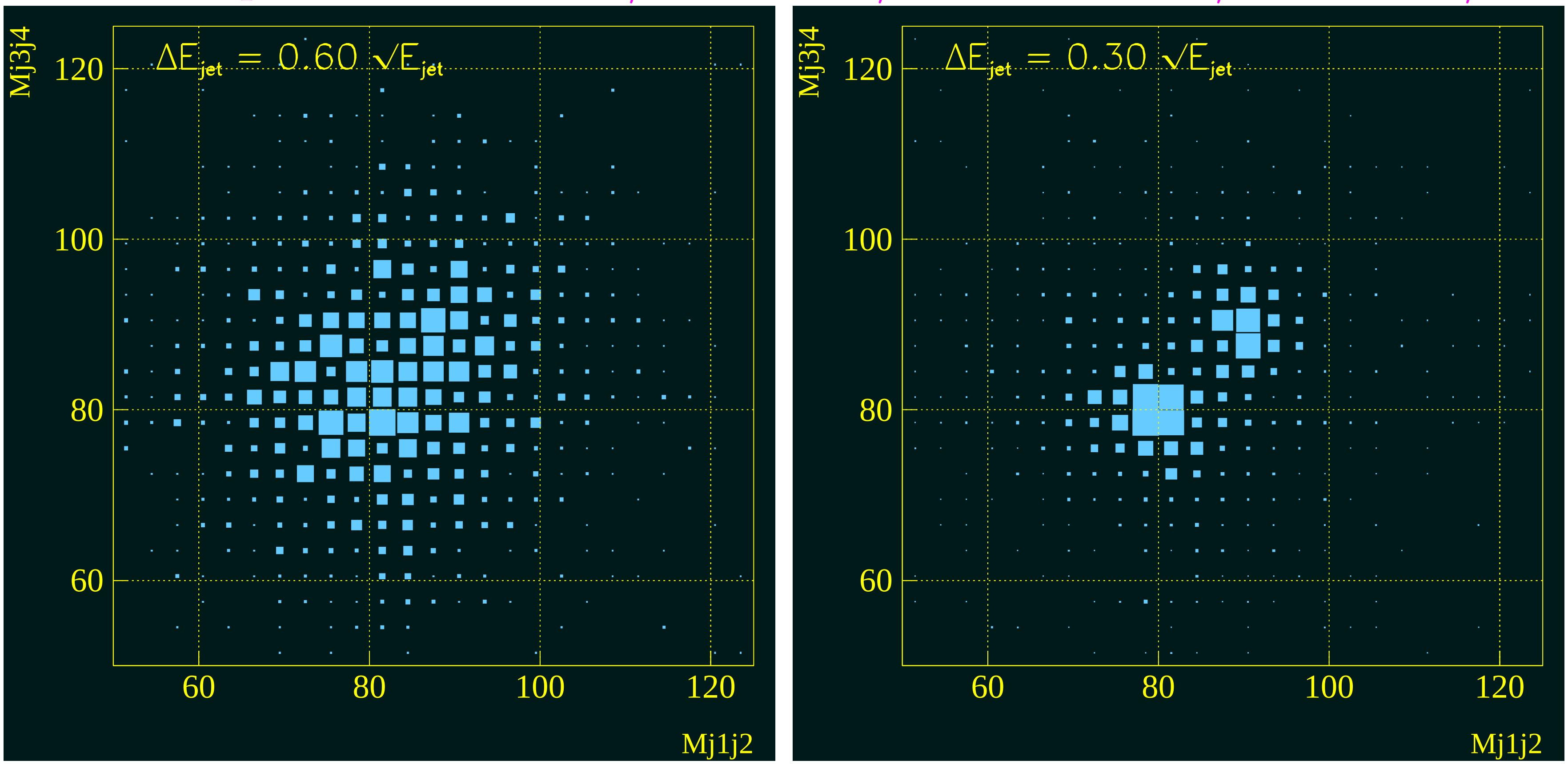
ILC Detector Requirements

- Two-jet mass resolution comparable to the natural widths of W and Z for an unambiguous identification of the final states.
- Excellent flavor-tagging efficiency and purity (for both b- and c-quarks, and hopefully also for s-quarks).
- Momentum resolution capable of reconstructing the recoil-mass to di-muons in Higgs-strahlung with resolution better than beam-energy spread.
- Hermeticity (both crack-less and coverage to very forward angles) to precisely determine the missing momentum.
- Timing resolution capable of separating bunch-crossings to suppress overlapping of events .

Energy flow in jets

- Some processes where WW and ZZ need to be separated without beam constraints (e.g. $e^+e^- \to \nu\nu WW$, $\nu\nu ZZ$)
- This requires a resolution of about $\Delta E/E = 30\%/\sqrt{E}$

WW-ZZ separation for $\Delta E/E = 60\%/\sqrt{E}$ and $\Delta E/E = 30\%/\sqrt{E}$



Jet Reconstruction @ ILC

- Q. How to achieve the best attainable jet energy resolution?

- A. Since the momentum resolution for the charged particle measured by trackers is much better than the energy resolution of calorimeters, the best energy resolution is obtained by reconstructing momenta of individual particles avoiding double counting among Trackers and Calorimeters.
    - Charged particles (~60%) measured by Tracker.
    - Photons (~30%) by electromagnetic CAL (ECAL).
    - Neutral hadrons (~10%) by ECAL + hadron CAL (HCAL).

$$E_{TOT} = p_e + p_\mu + p_{charged\ hadron} + E_\gamma + E_{neutral\ hadron}$$

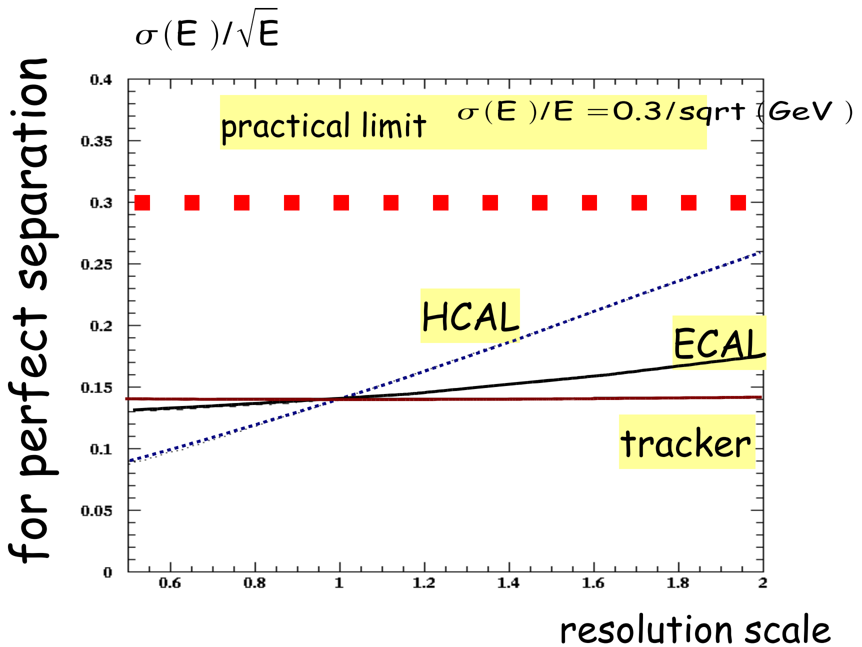
[tracks only] [calorimeter only]

Particle Flow Algorithm (PFA)

Particle Flow: Basics

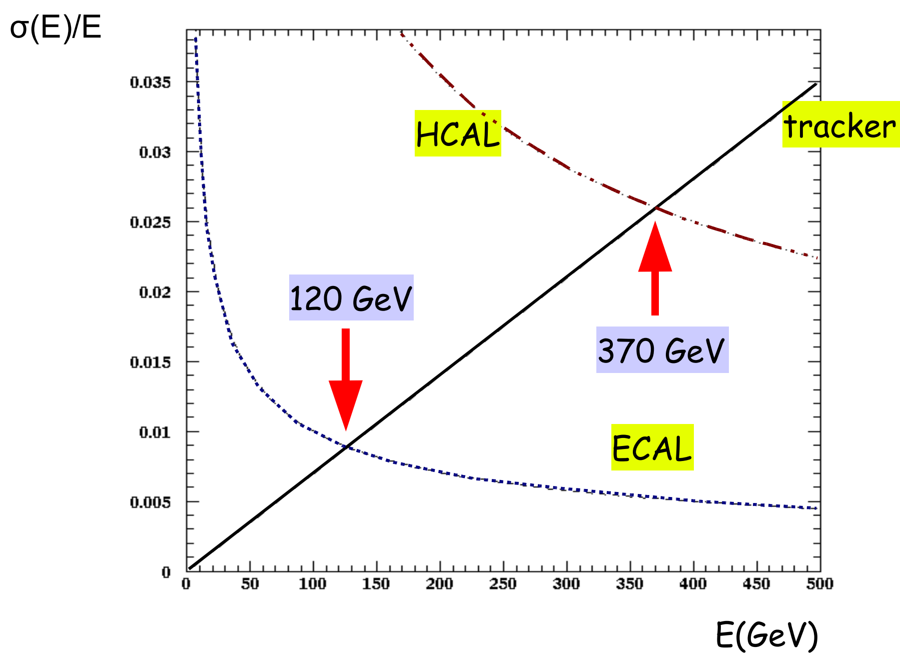
$$\sigma(Jet) = \sqrt{\sum \epsilon_T^2 E_i^4 + \sum \epsilon_{ECAL}^2 E_i + \sum \epsilon_{HCAL}^2 E_i}$$

Resolution is dominated by HCAL
and by
"confusion" term



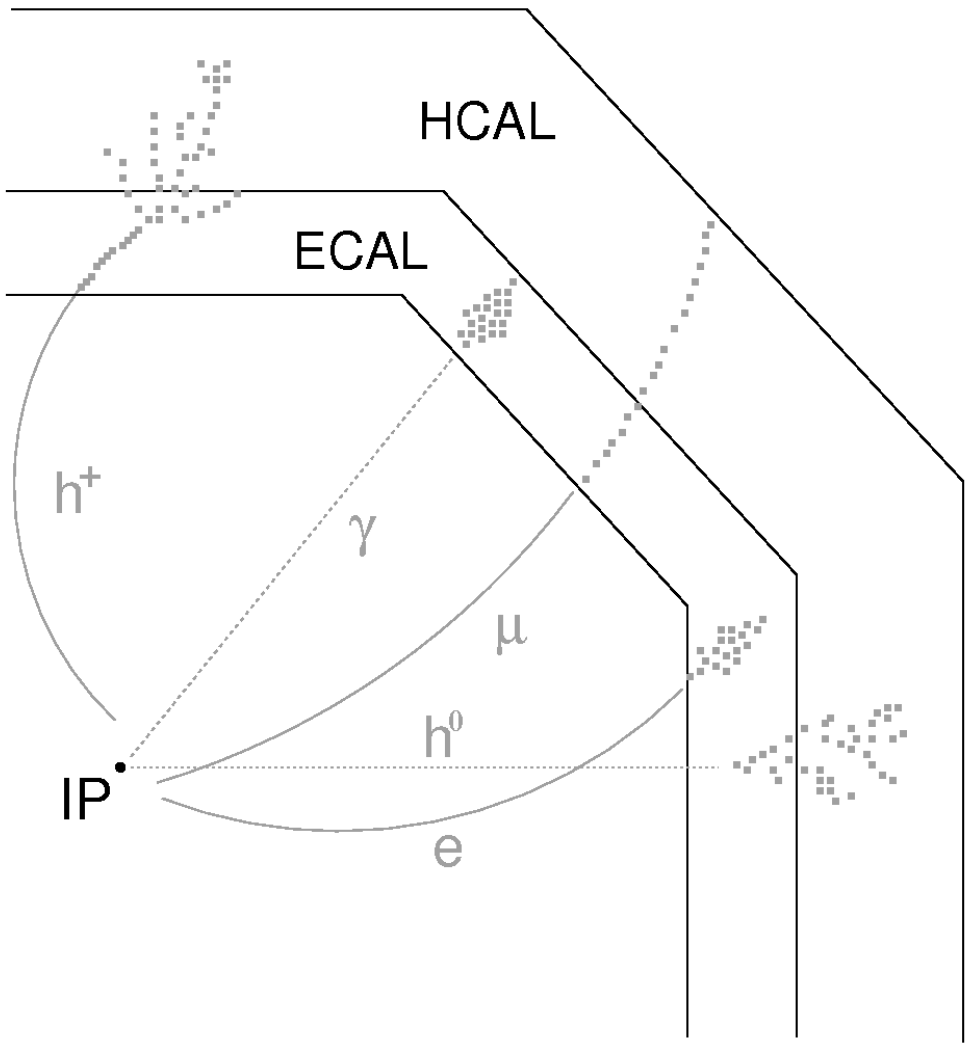
Effect of changing the resolutions by a scale factor

Resolution tracker - Calorimeter



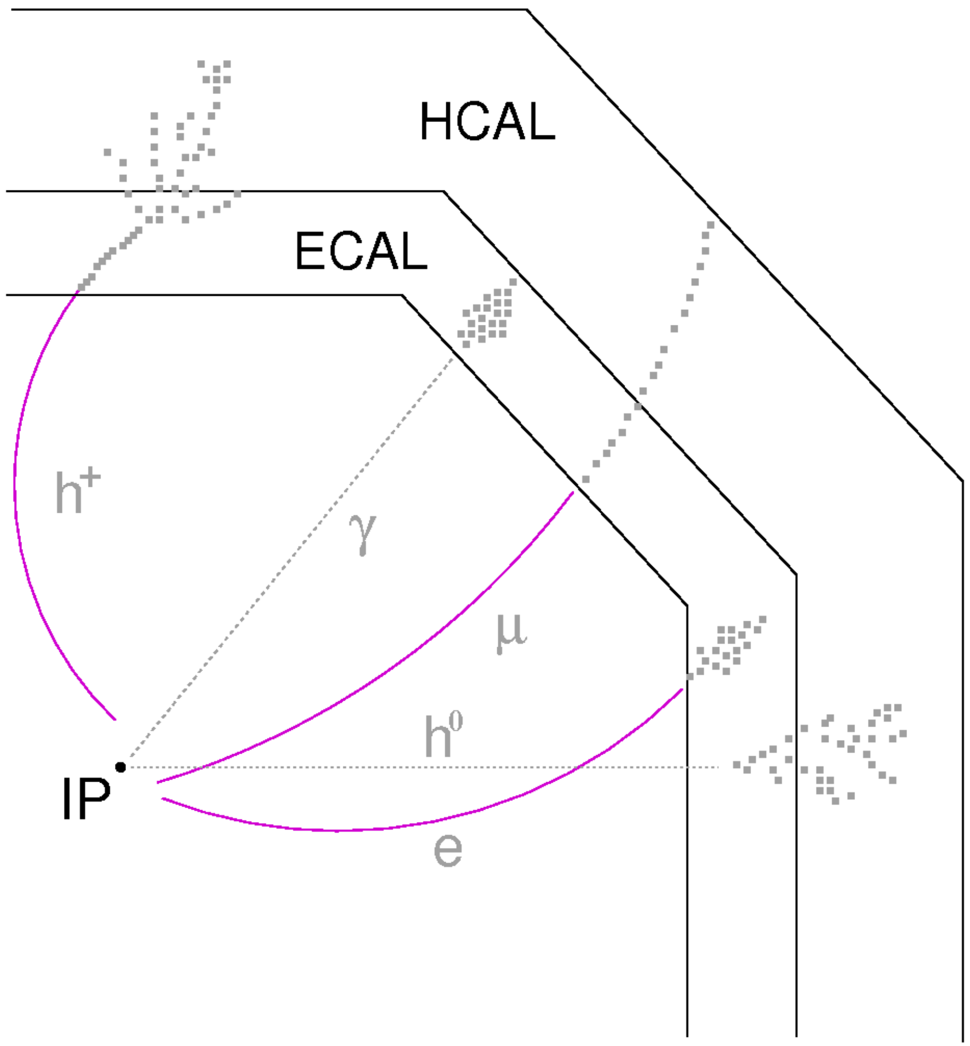
design detector to
- minimize confusion term
- minimize the role of the HCAL
- for the rest: build the best HCAL possible

Track-Based Particle Flow Concept



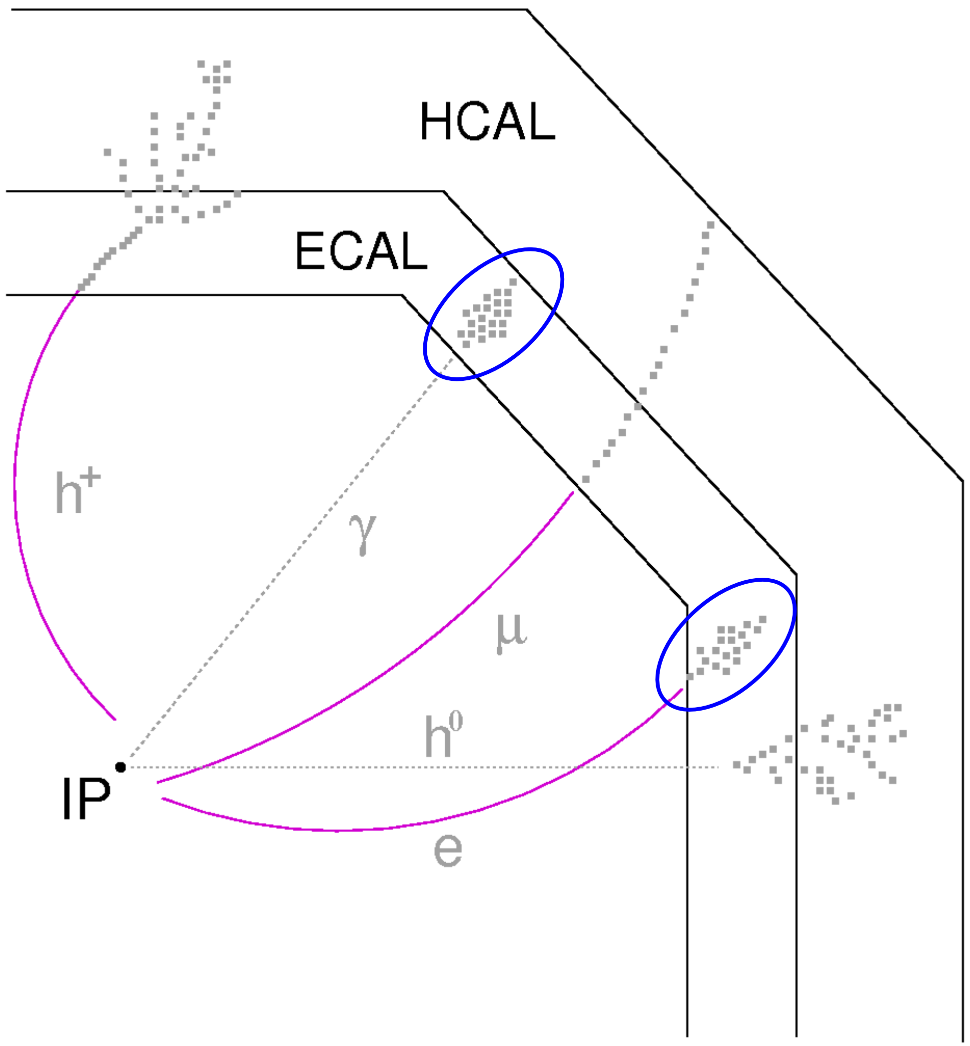
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)



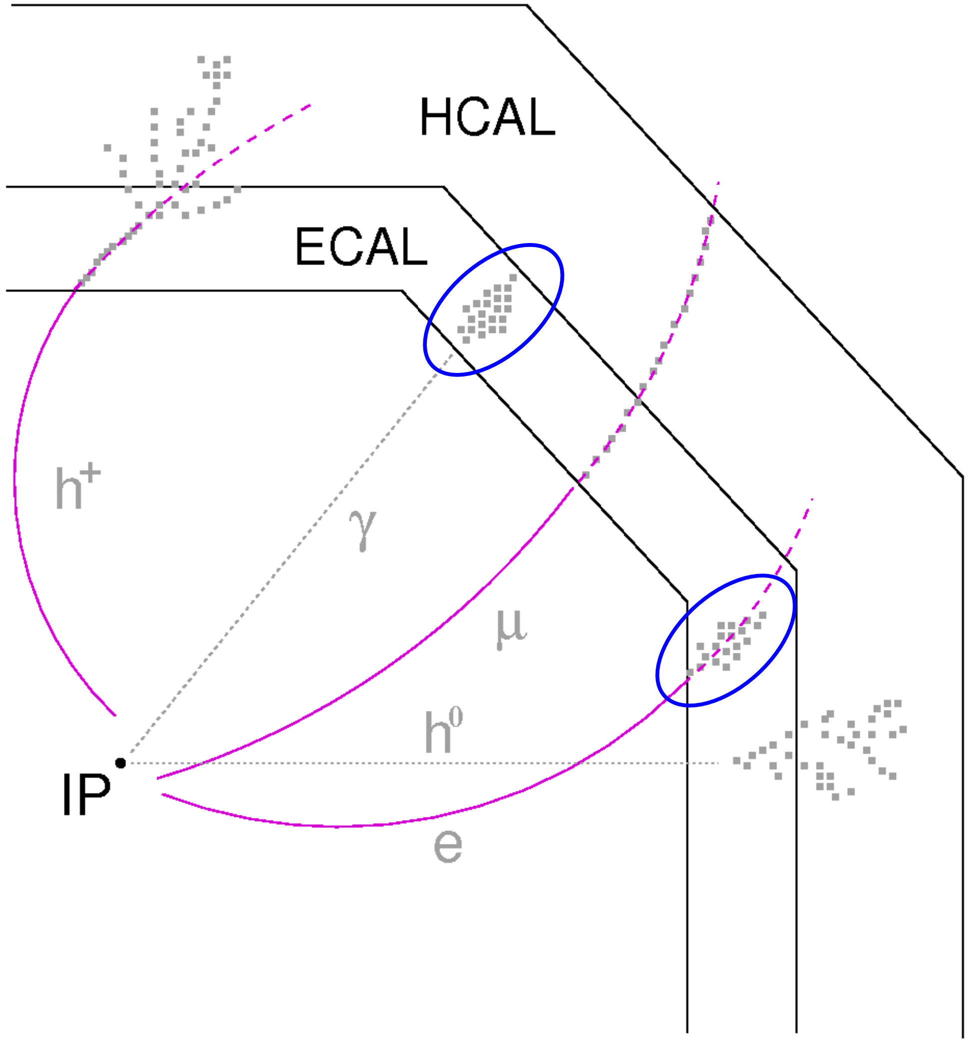
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates



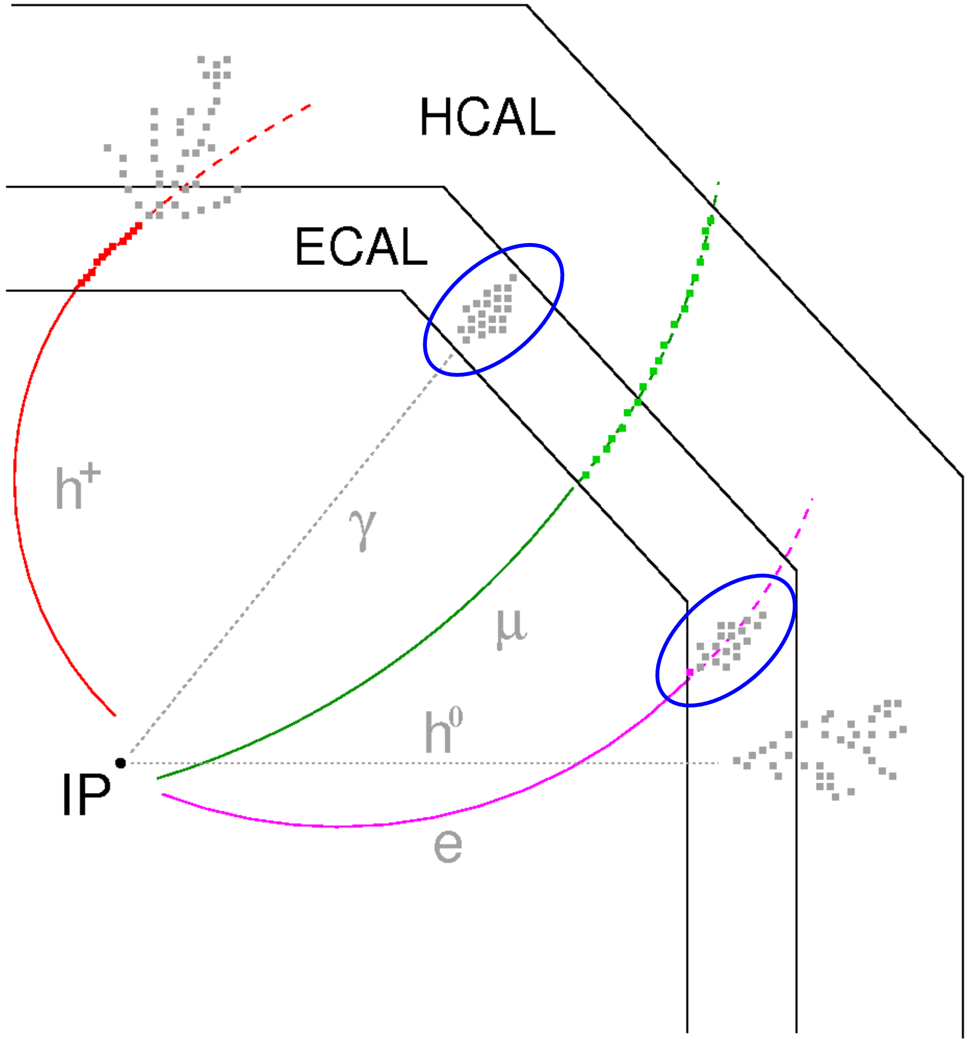
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed



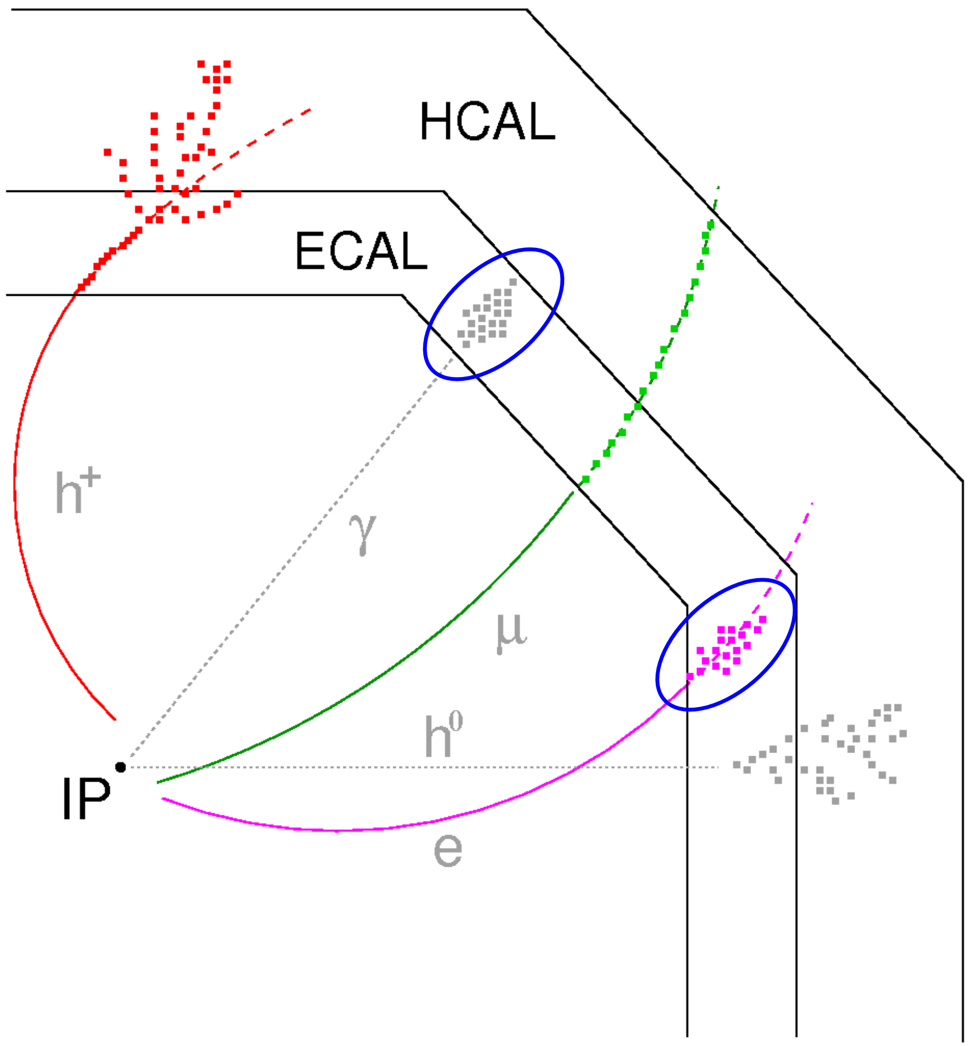
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons



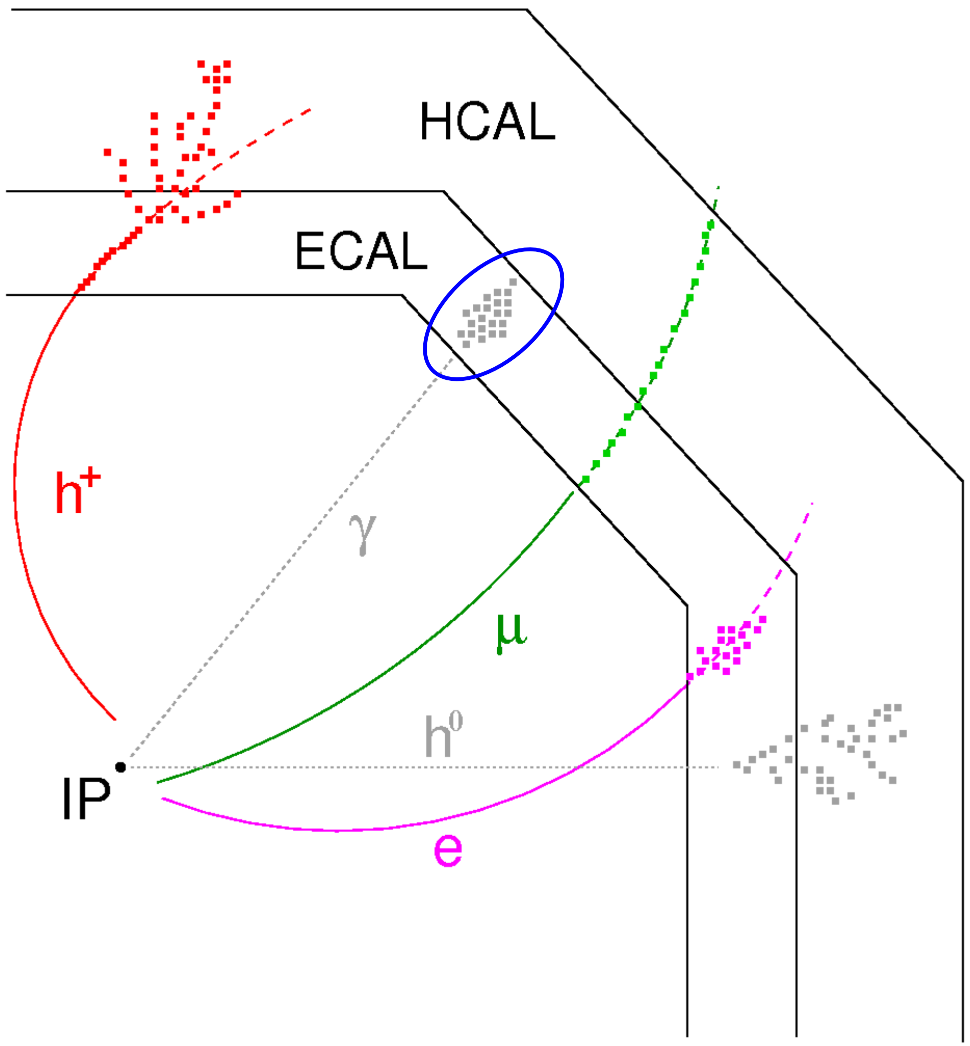
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms



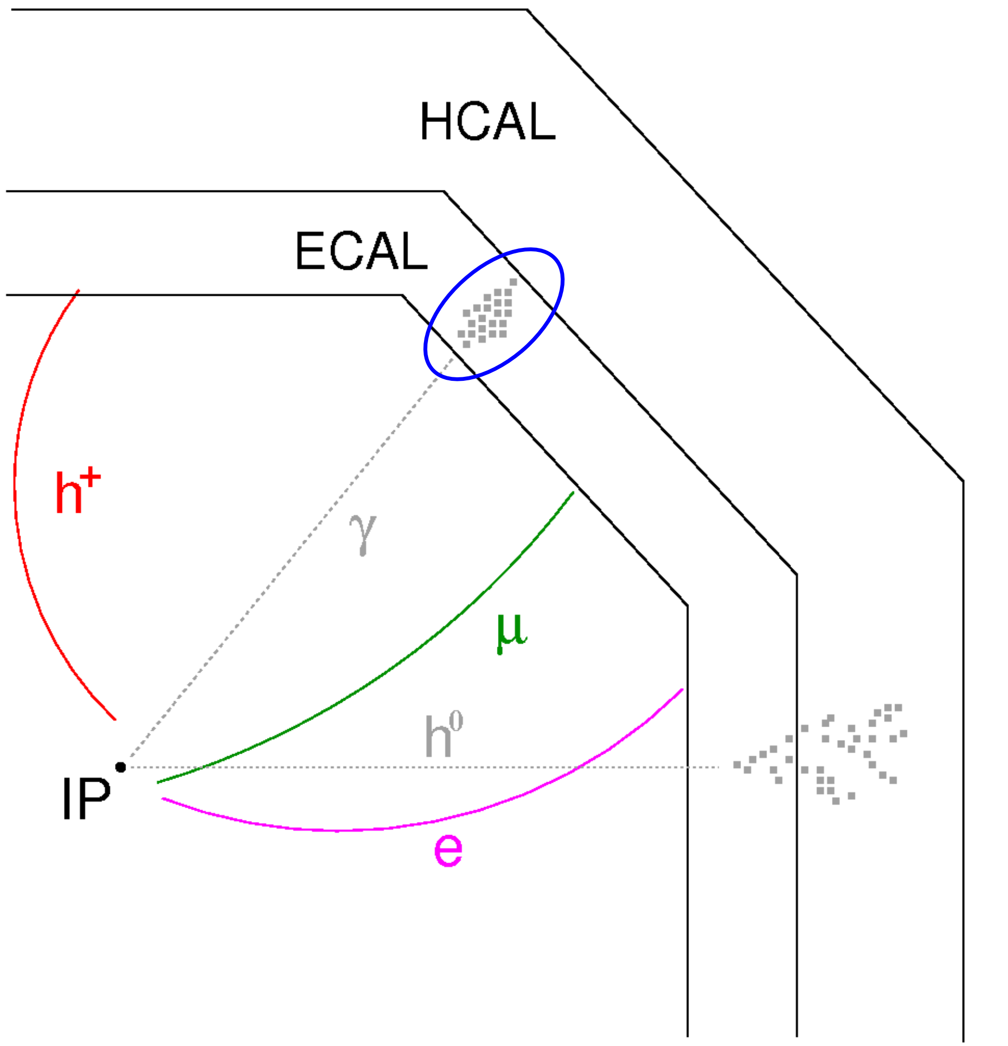
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$



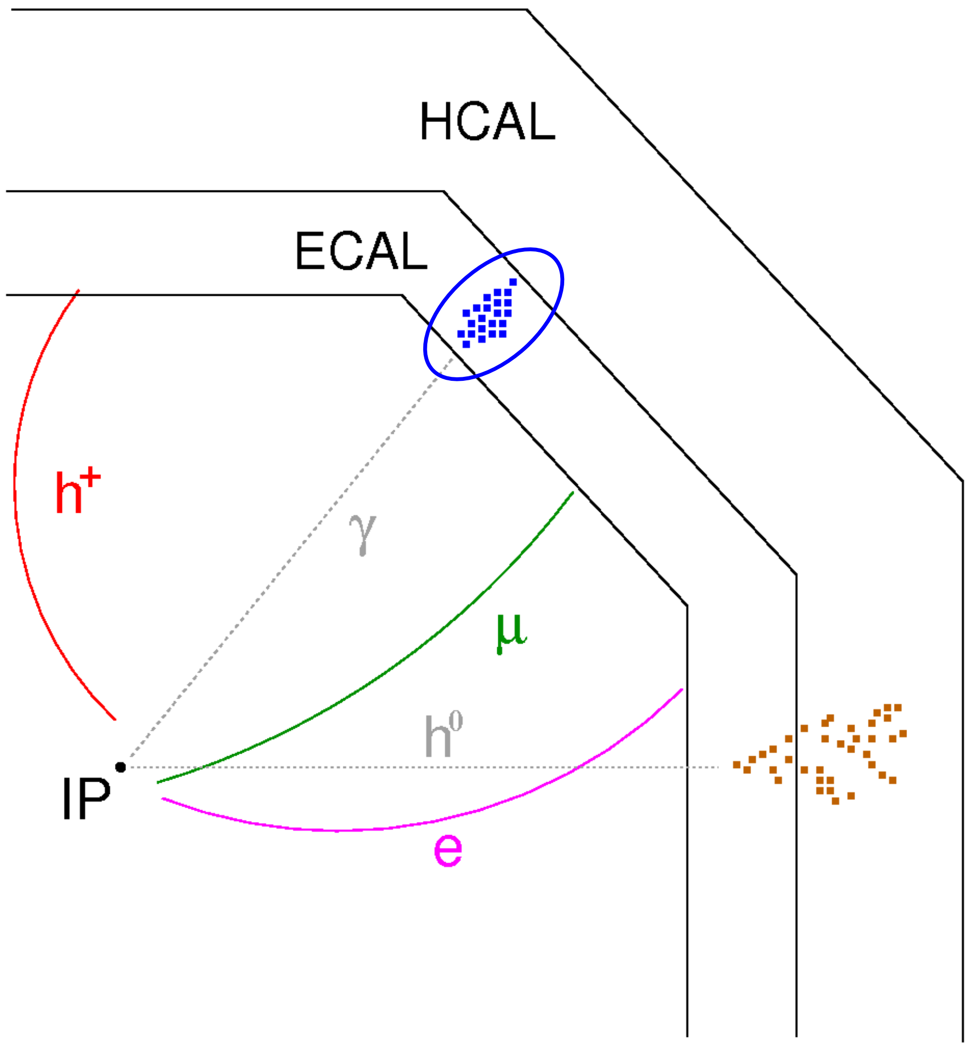
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
    - different models, with and w/o energy loss, multiple scattering, ...
    - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
    - variable, depending on track and photon candidates
    - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$
7. remove 'charged' Calorimeter hits



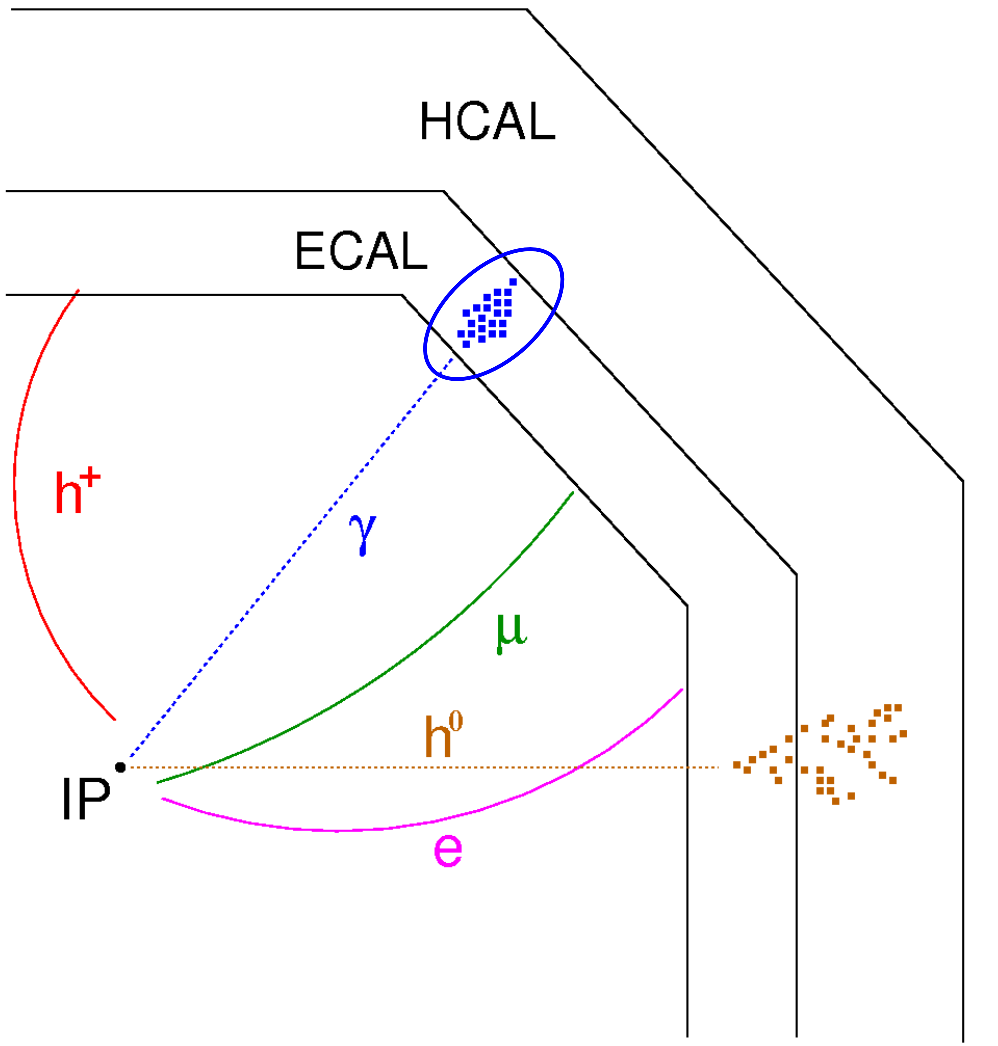
Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$
7. remove 'charged' Calorimeter hits
8. clustering on 'neutral' hits



Track-Based Particle Flow Concept

1. tracking (Silicon and TPC)
2. find photon candidates
3. extrapolate tracks into Calorimeter
   - different models, with and w/o energy loss, multiple scattering, ...
   - dedicated Geometry description needed
4. assign MIP stub to track, find muons
5. clustering (ECAL and HCAL)
   - variable, depending on track and photon candidates
   - different algorithms
6. particle ID for $e^{+/-}$, $h^{+/-}$
7. remove 'charged' Calorimeter hits
8. clustering on 'neutral' hits
9. particle ID for photons and h^0



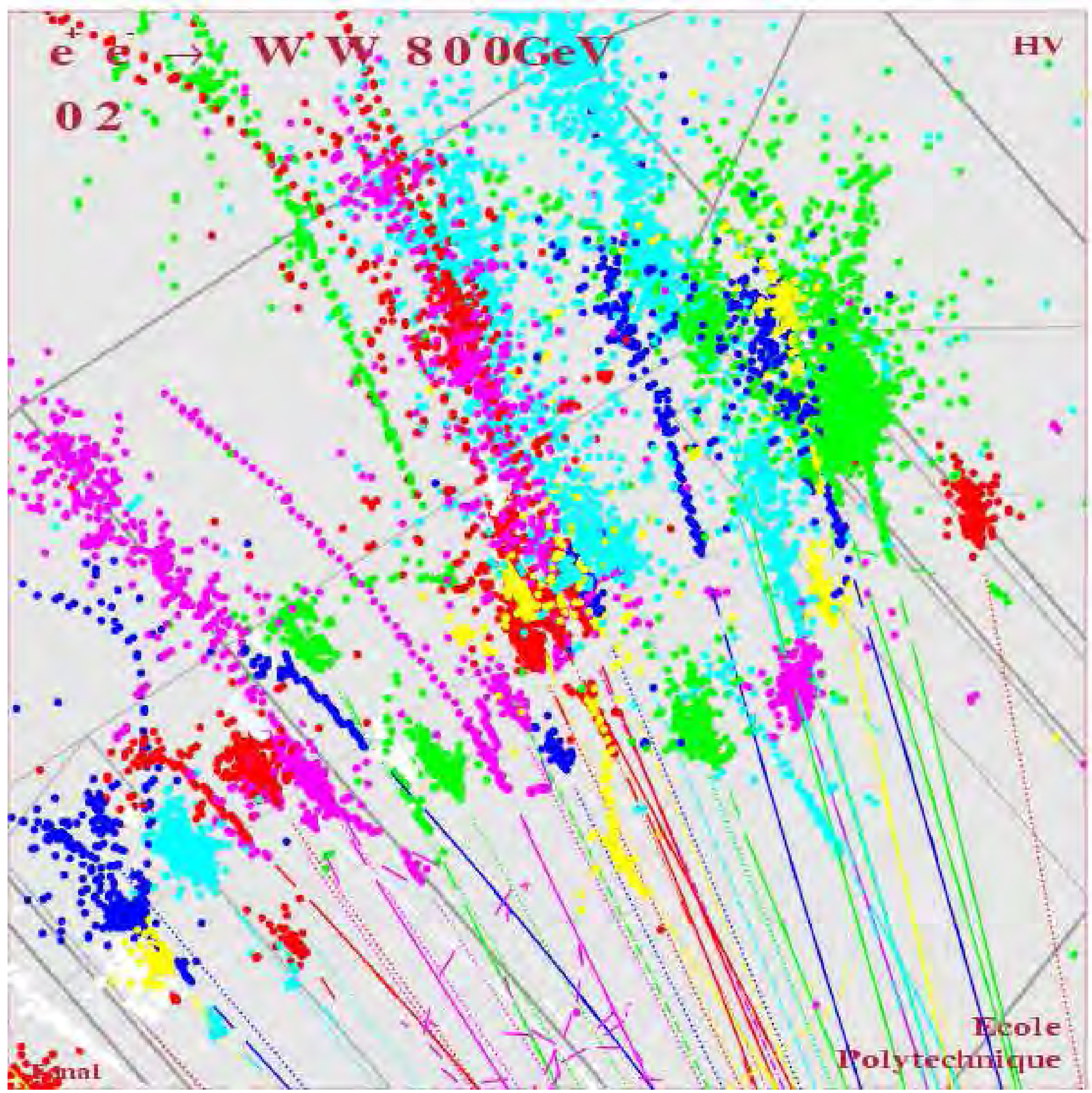
Main problem: Confusion

- At high energy jets are very narrow

➠ Tracks are very close at the calorimeter

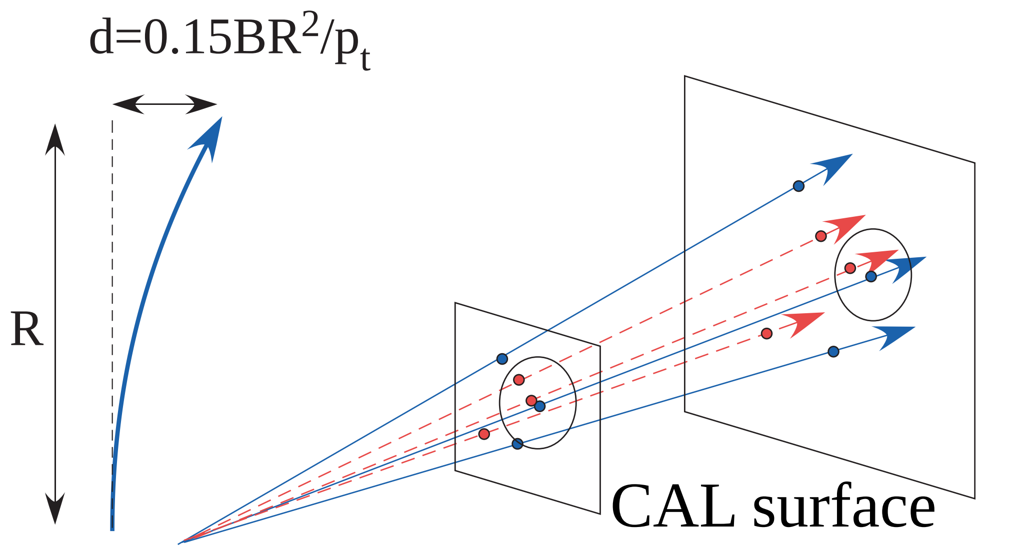
- Need very fine granularity of calorimeter and sophisticated software to separate showers

- Energy resolution still dominated by confusion term



Particle Flow Algorithm

- In order to get good energy resolution by PFA, separation of particles is important. → Reduce the density of charged and neutral particles at calorimeter surface.



Often quoted "Figure of Merit"

$$\frac{BR^2}{\sqrt{\sigma^2 + R_M{}^2}}$$

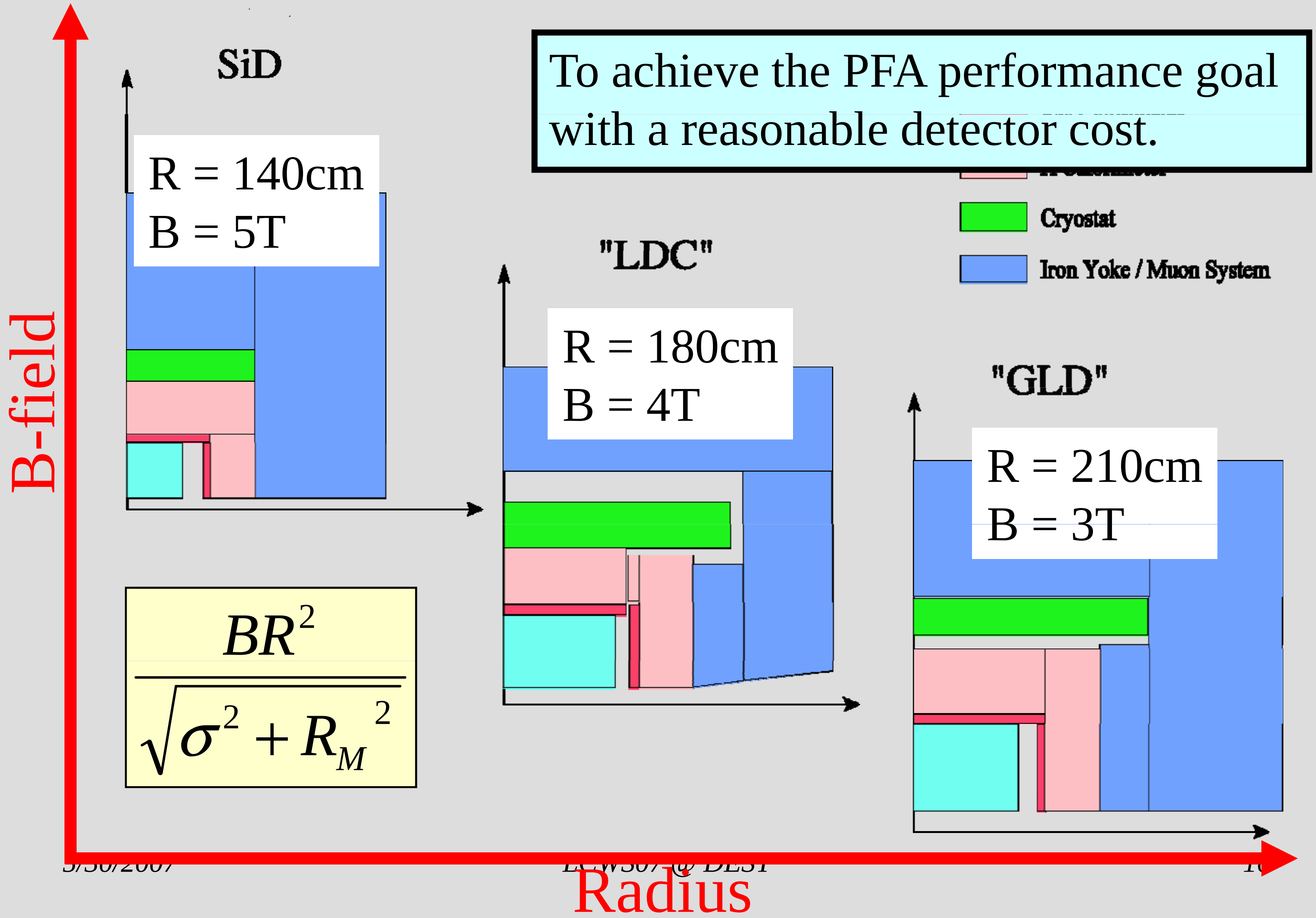
B : Magnetic field
R : CAL inner radius
σ: CAL granularity
R_M : Effective Moliere length

- For transverse separation of particles at the ECAL surface, stronger B-field and/or large ECAL radius are preferable.

* Fine segmentation of CAL is also important for pattern recognition.

Radius vs. B-field

To achieve the PFA performance goal with a reasonable detector cost.



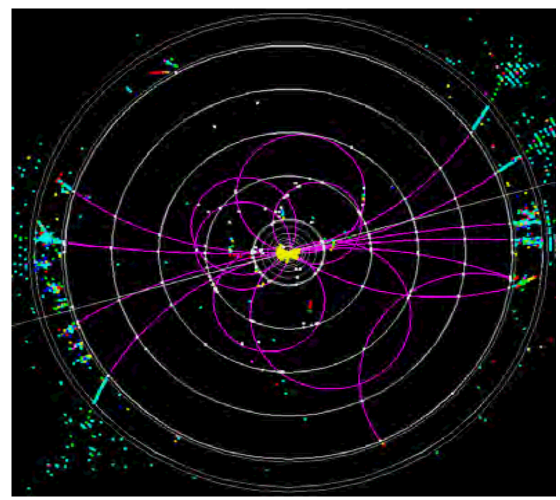
$$\frac{BR^2}{\sqrt{\sigma^2 + R_M^{\ 2}}}$$

SiD (the Silicon Detector)

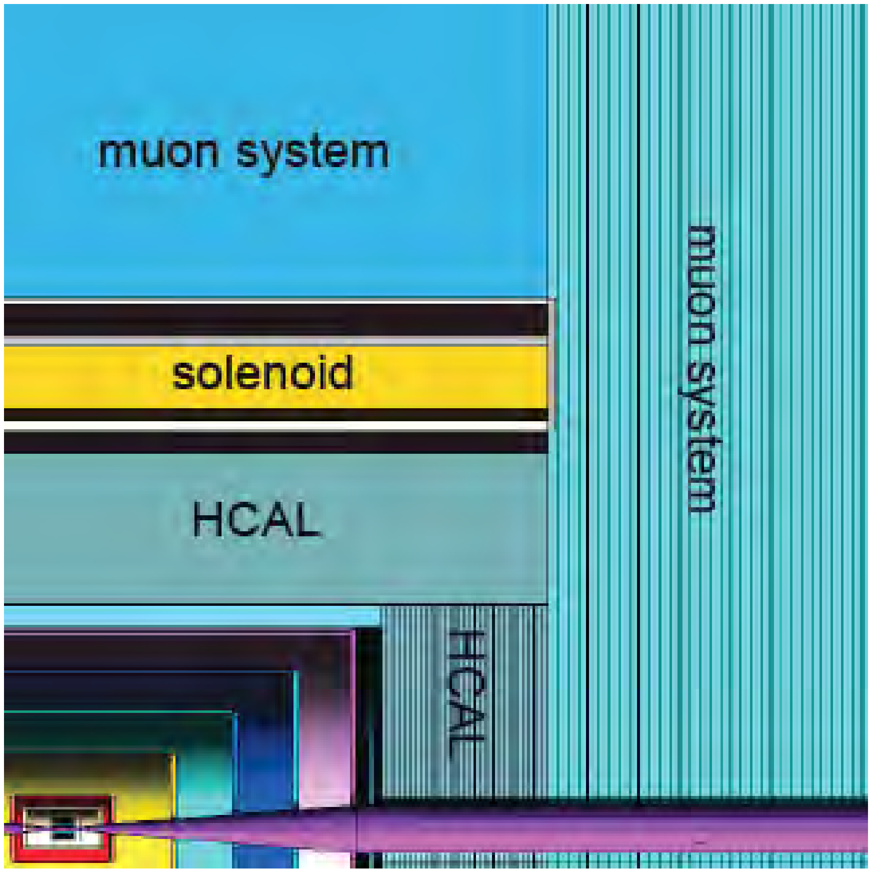
CALORIMETRY IS THE STARTING POINT IN THE SiD DESIGN

assumptions

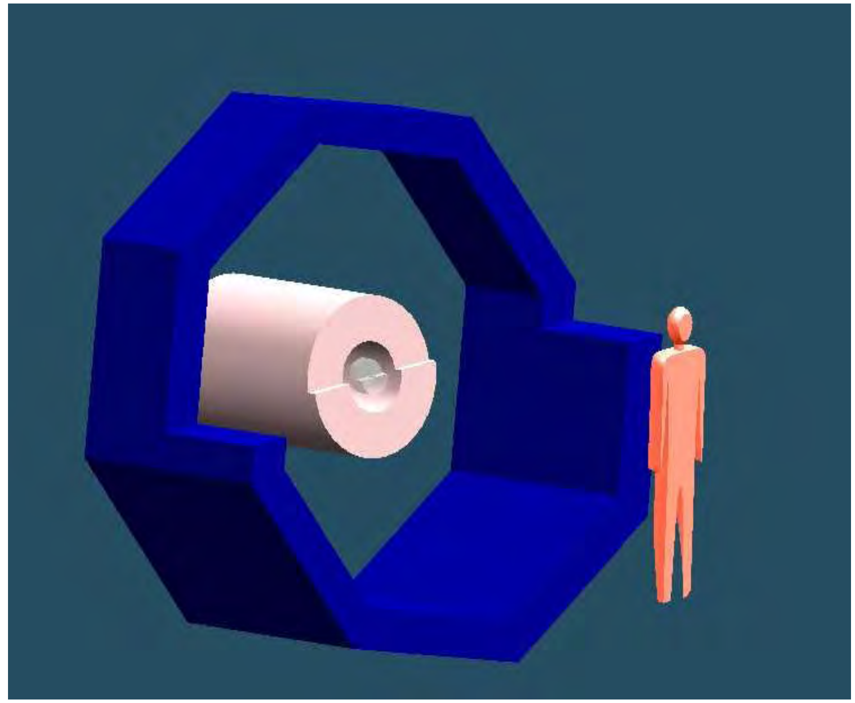
- Particle Flow Calorimetry will result in the best possible performance
- Silicon/tungsten is the best approach for the EM calorimeter
- Silicon tracking delivers excellent resolution in smaller volume
- Large B field desirable to contain electron-positron pairs in beamline
- Cost is constrained



SiD Configuration



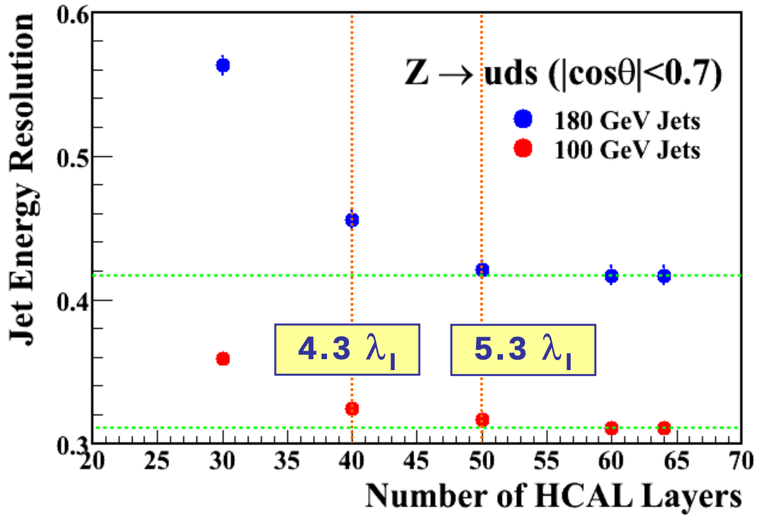
5 Tesla

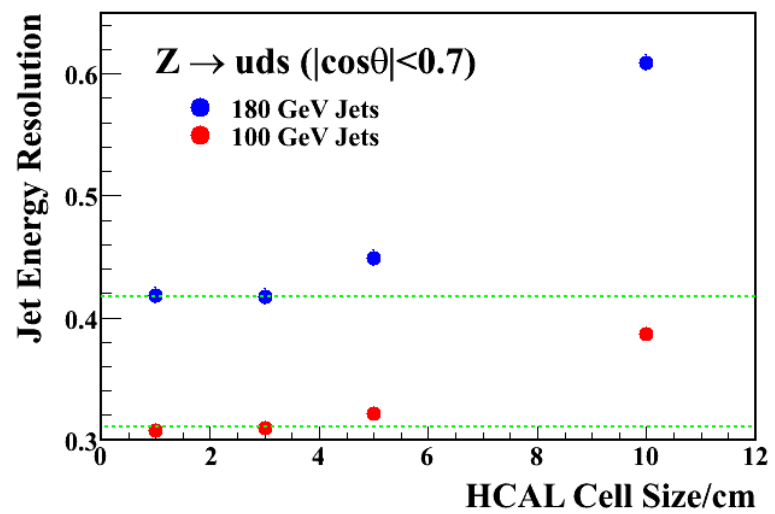


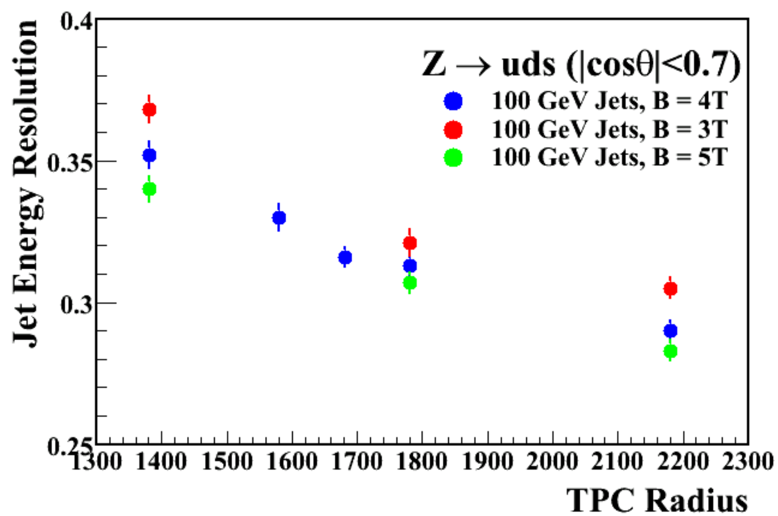
Scale of EMCal
& Vertex Detector

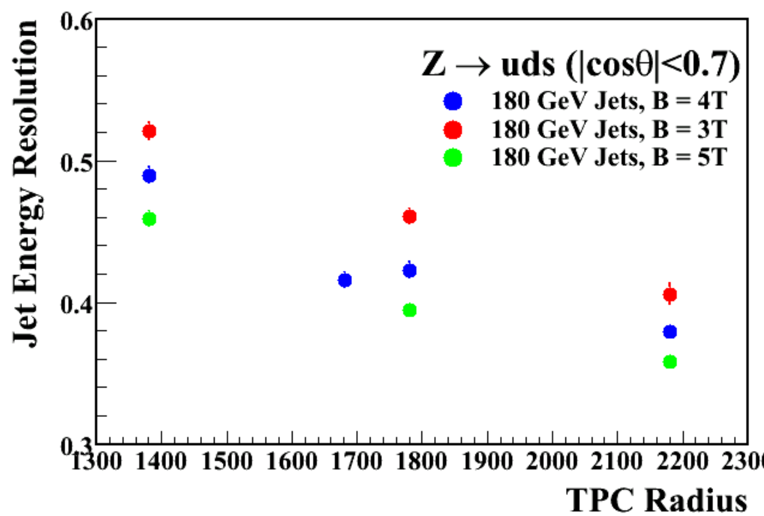
❻ Detector Optimisation Studies

★ Lots of progress… …no time





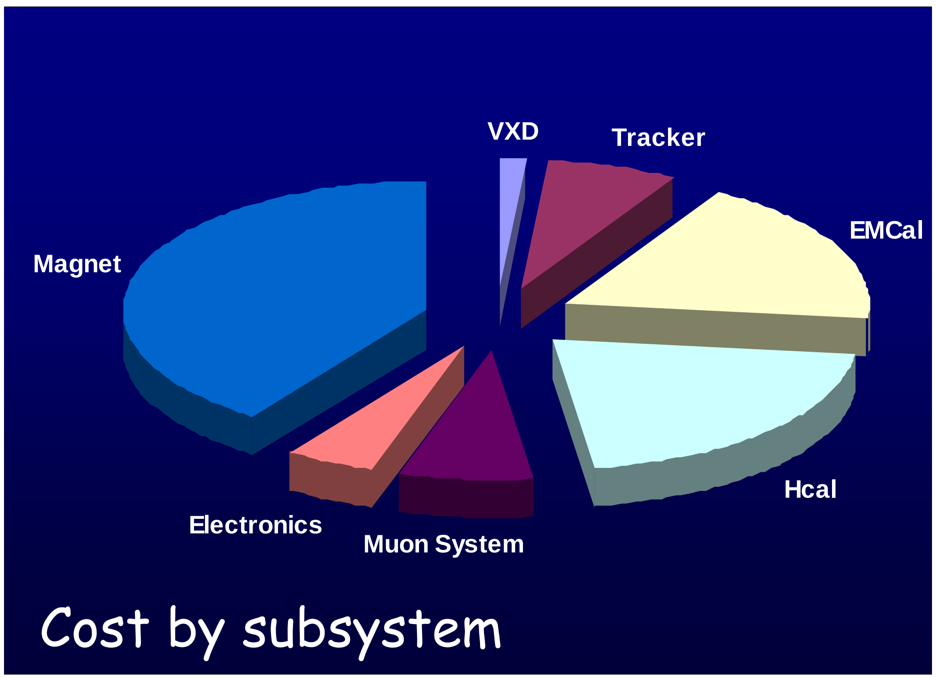


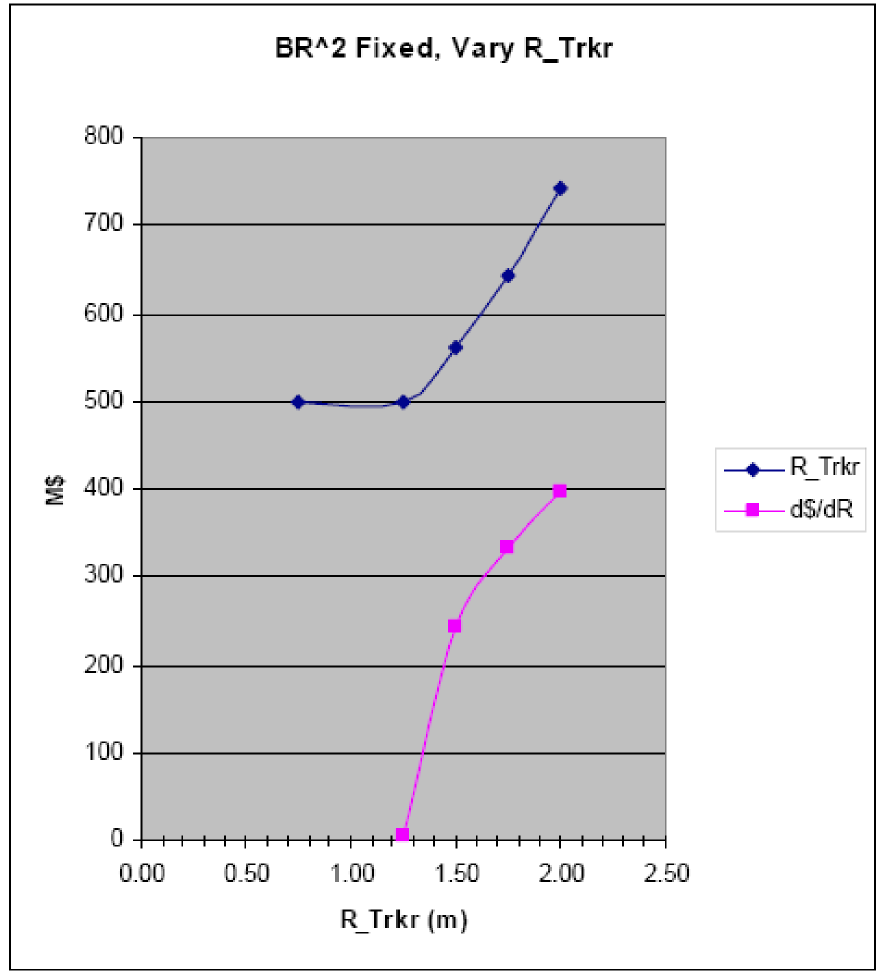


Cost

Parametric Cost Model

Cost = f (B-field, R_{TRK}, ….)

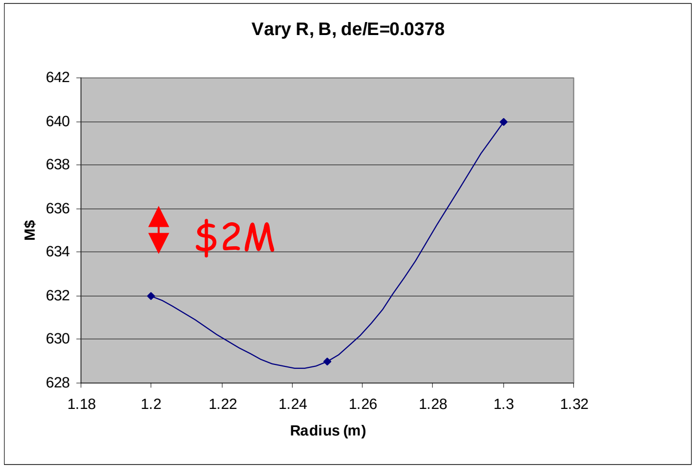


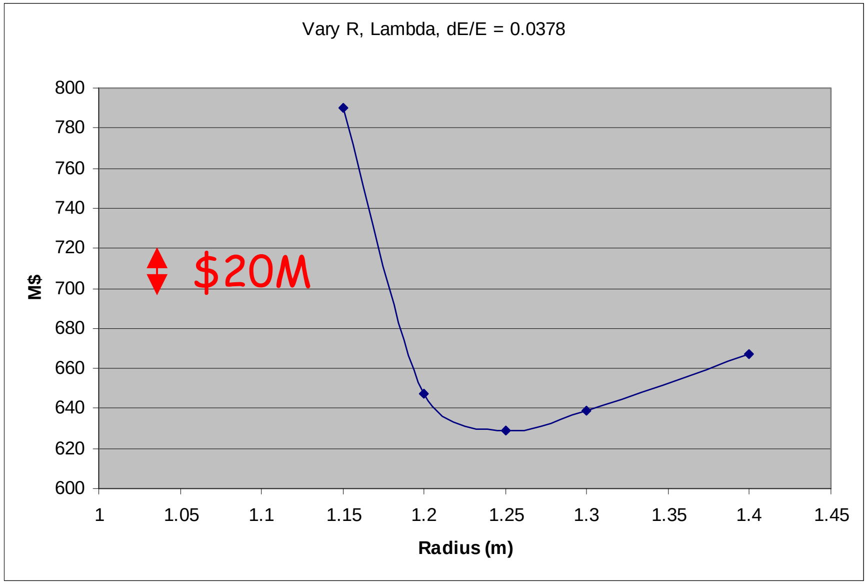


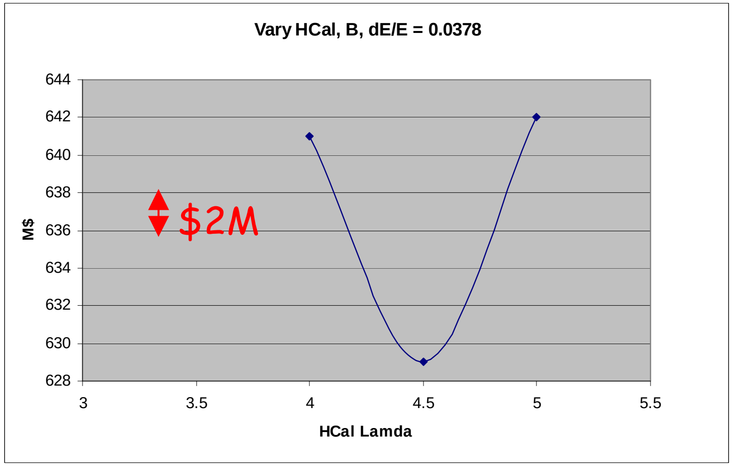
Cost vs. tracker radius

SiD "Baseline"

- Rtrkr = 1.25 m
- B = 5 T
- HCalλ = 4.5
- ΔE/E(180 Gev) = 0.0378

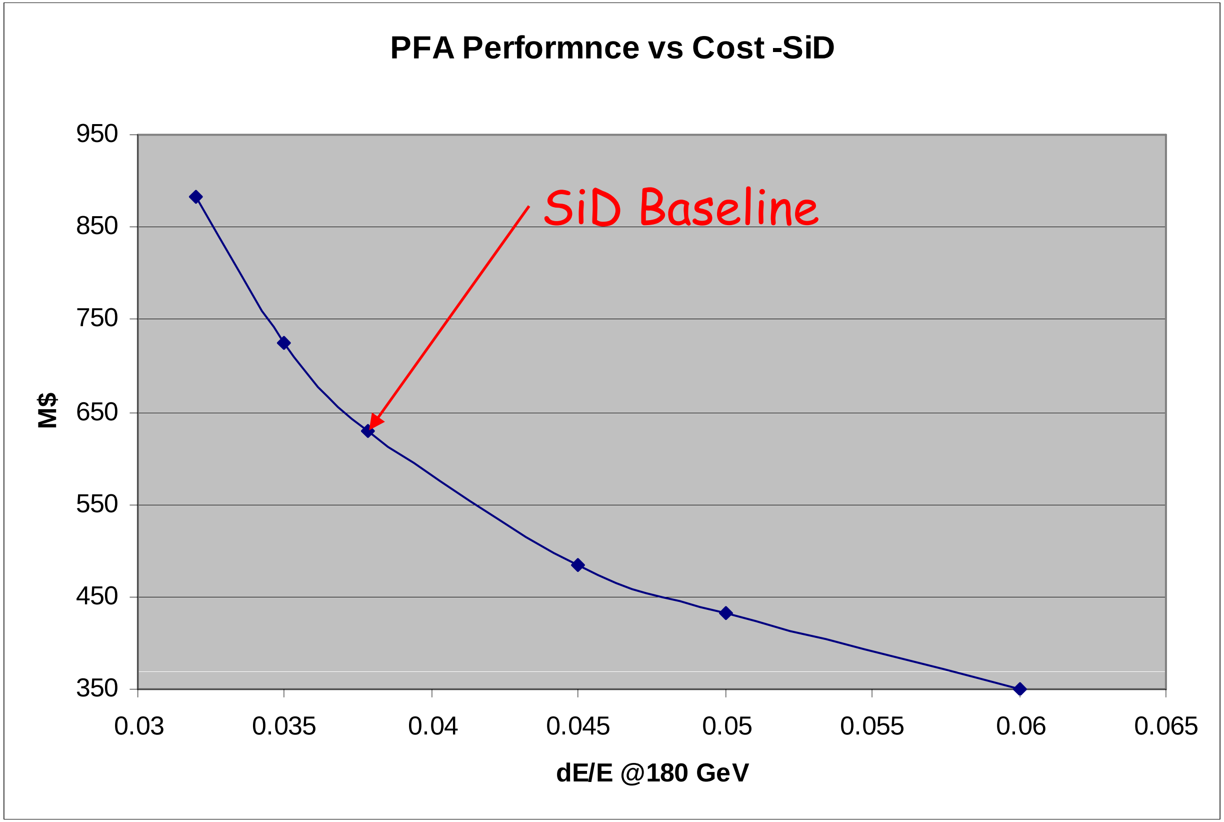






SiD "Baseline" is optimal for this value of ΔE/E(180 Gev) (Pandora parameterization, Checked with Pandora version of SiD, SiD PFA)

A sequence of "Optimized SiD's"



Selected Physics Process Errors vs Cost