Advanced Particle Flow with Timing Information?

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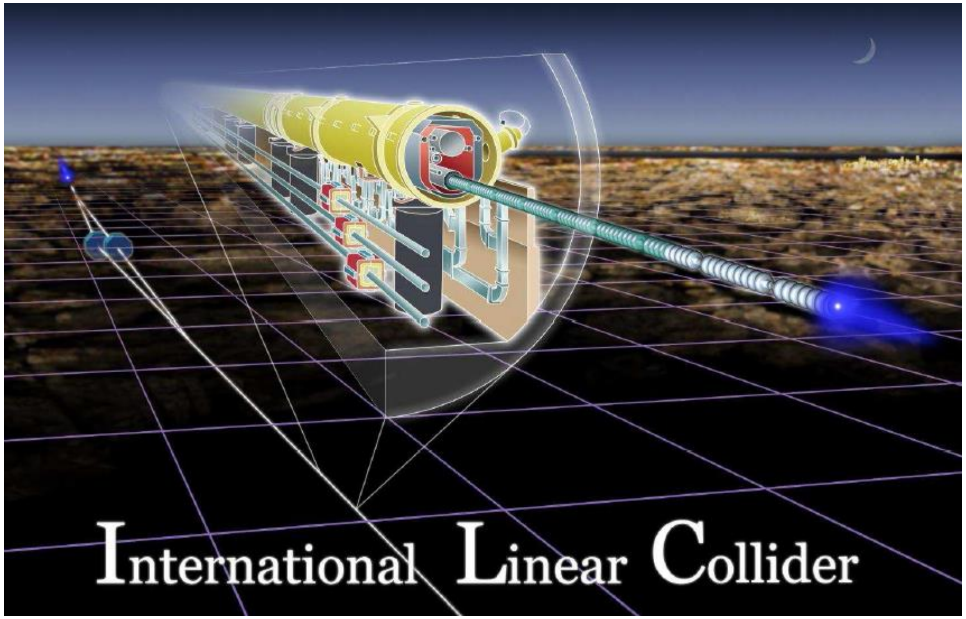
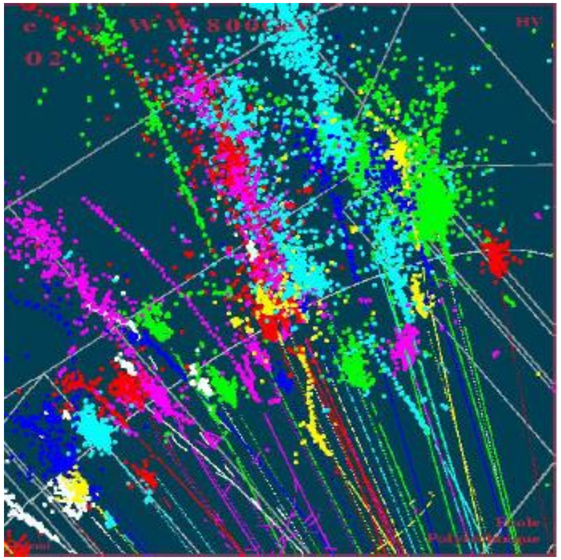
Sept. 17th 2016

Talk title slide from Pico-second Timing Workshop, Chicago 2006 …

Fast Timing for ILC detectors ?





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((OPAL) / DØ / ILC)

(After working for 3×10^{20} ps on ILC issues, a clean start signal would be great !)

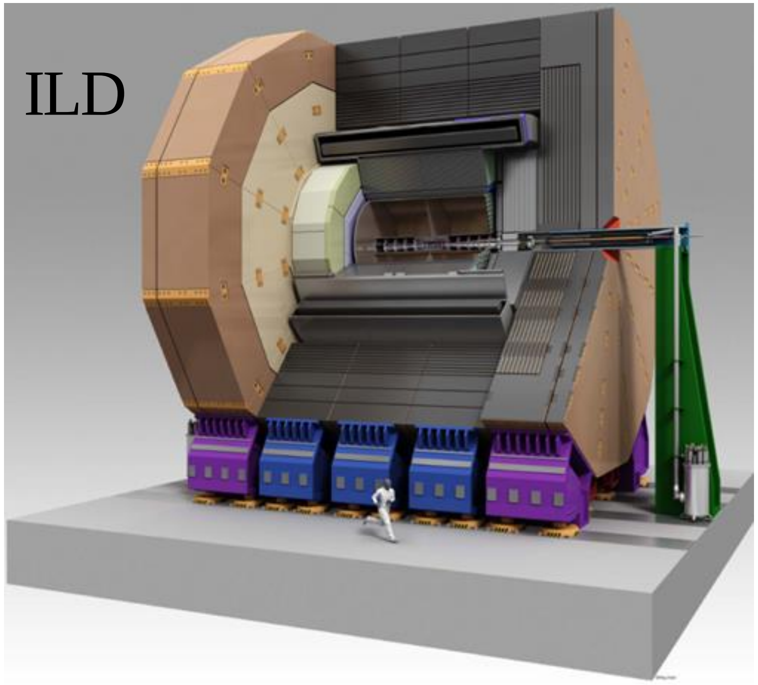
Conclusions Revisited

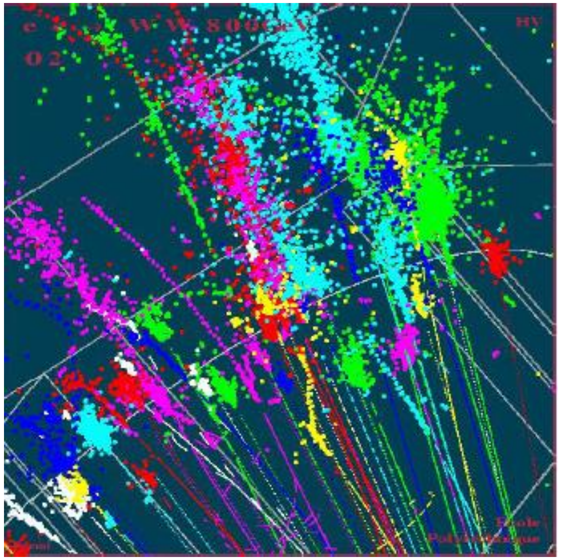
- Old Conclusion: ILC detectors should take advantage of some of the possibilities for implementing fast timing at the sub-100 ps level in a strong B-field, IF they can be implemented in ways which clearly enhance the overall performance of a general-purpose detector.
- At the time - not at all obvious that precision timing per se would be much use for particle-flow. Some strategically placed timing layers for TOF can be helpful – but in no way a game-changer for the overall particle-flow performance.
- Now with calorimetry timing per cell becoming feasible in a high granularity calorimeter in an integrated way – timing can and I think will be very important for particle-flow performance.
  - To date. Very little dedicated work on timing though.

Today’s Talk

- Ideally stimulate discussion on how to scale up fast timing developments to full scale collider implementations. Hopefully thinking in that direction can be stimulated.
- In practice, given my expertise, the talk focusses on particle flow that relates closely to overall detector design for ILC - with a view to where timing may play a role.
    - This is a direction which is being pushed also by the adoption of ILC-like calorimetry for CMS HGC and the need there for pile-up mitigation
- What I would like is input on what are sensible and implementable target resolutions – so that studies that show off the potential capabilities for a future detector can be done.
    - In contrast to HL-LHC, there is still time for development.

Advanced Particle Flow with Timing Information?





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Univ. of Kansas
Sept 17th, 2016

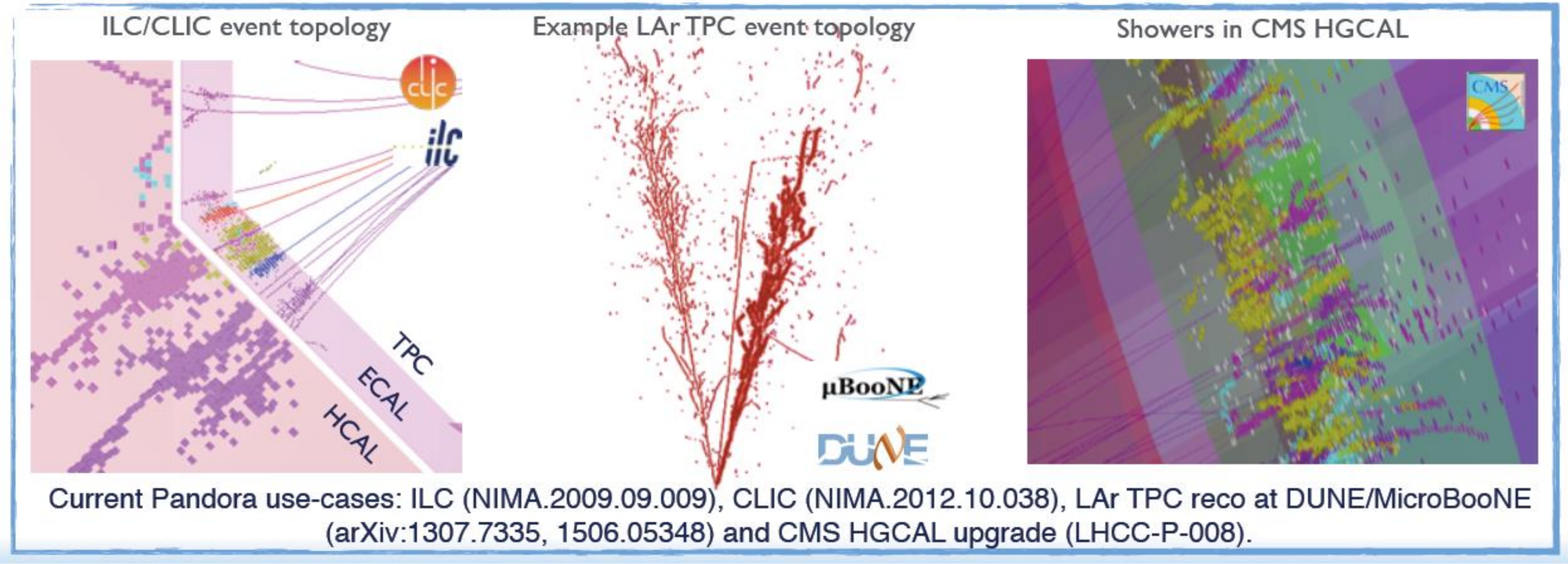
(After working for some part of 6×10^{20} ps on ILC issues, a clean start signal would be great !)

Motivation

- A primary detector performance driver for new collider experiments, especially e^+e^-, like ILC, is the mass resolution for particles decaying hadronically.
  - Particles we know: W, Z, H, t.
  - Γ values of 2.0 GeV, 2.5 GeV, 4 MeV, 1.4 GeV.
  - Γ/M values of 2.5%, 2.8%, 32 ppm, 0.8%.
  - W/Z separation => $\sigma_E/E \approx 3\%$.
- Advanced Particle Flow. Vision = Reconstruct event as fully as possible. Like a bubble chamber – but better.
  - Use all possible information including priors to reconstruct event particle by particle.
  - Measure mass and its uncertainty event-by-event.
  - Detector performance = raw resolution $\oplus$ algorithms.
  - Does precision timing have a role ?

Particle Flow

- Now widely used in design of future detectors.



Current Pandora use-cases: ILC (NIMA.2009.09.009), CLIC (NIMA.2012.10.038), LAr TPC reco at DUNE/MicroBooNE (arXiv:1307.7335, 1506.05348) and CMS HGCAL upgrade (LHCC-P-008).

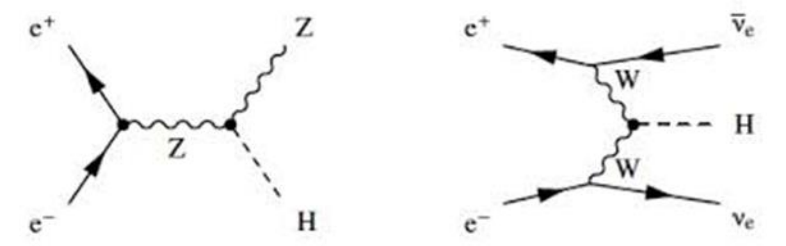
- Lots of work already on the algorithm side for various detector/experiments.

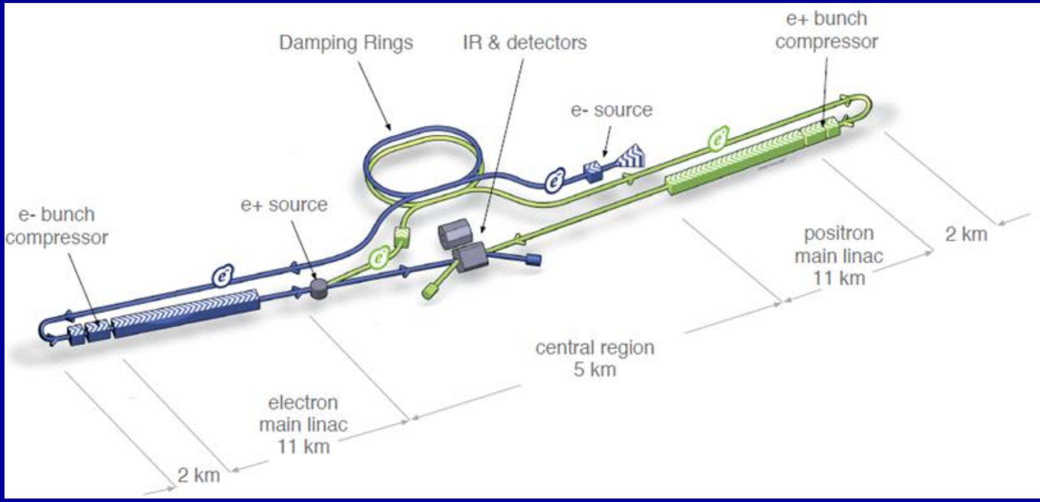
Advanced Particle Flow

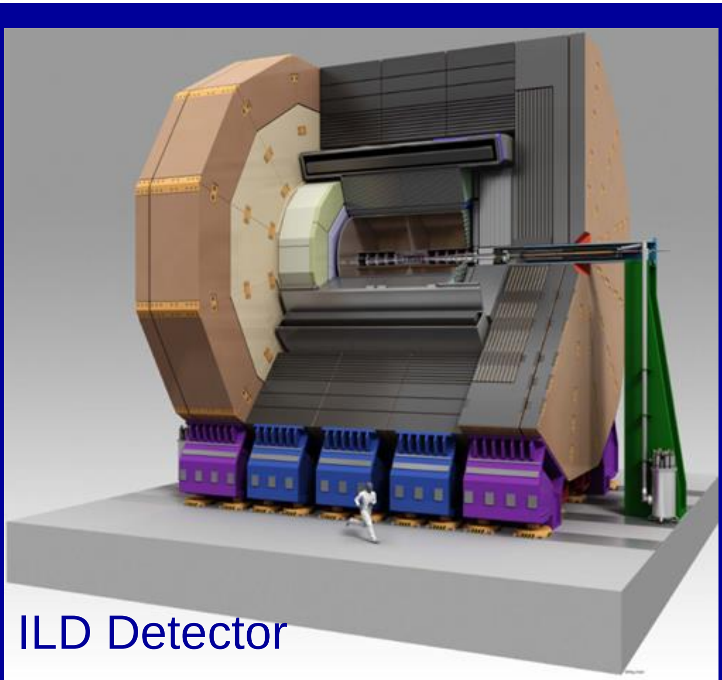
- Improve jet energy resolution beyond apparent “perfect particle-flow” intrinsic resolution limitation.
- Understand and estimate errors jet by jet
- Use physics constraints like
  - Mass constraints – example $\pi^0 \to \gamma\gamma$ (*)
  - Vertex constraints
  - Charge conservation
  - Baryon-number conservation
  - Particle ID. Charged particle ID, but also neutral hadron ID.
    - Use dE/dx, timing, shower shapes, range etc.
  - Throwing the PDG at the jet

International Linear Collider (ILC)

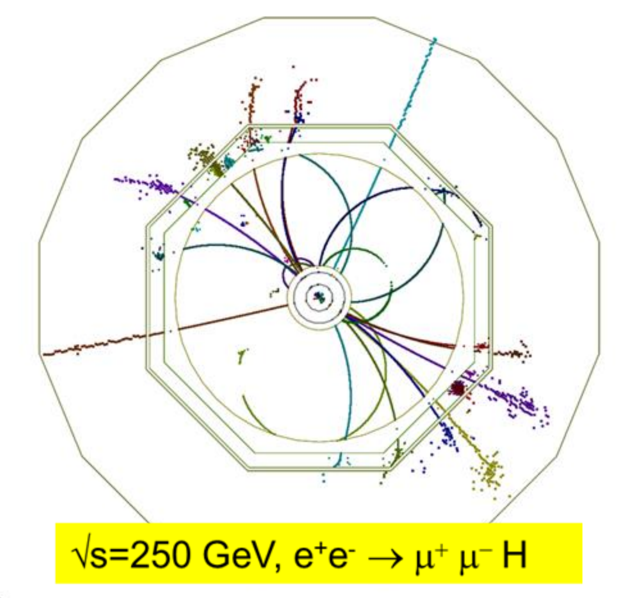
$\sqrt{s}=200$ – 1000 GeV. Start at $\sqrt{s}=500$ GeV






ILD Detector

Proposed e^+e^- collider facility to precisely measure Higgs particles and top.
At KU working on physics issues and overall detector concept. Japan considers hosting.


$\sqrt{s}=250$ GeV, $e^+e^- \rightarrow \mu^+ \mu^- H$

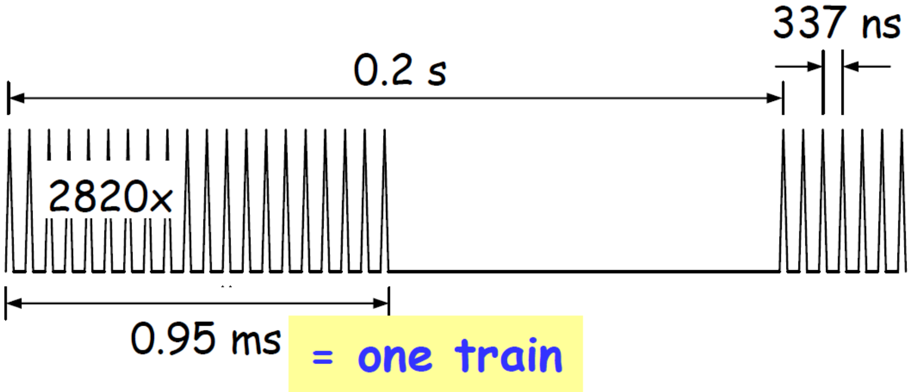
ILC Detector Overview

- Rather clean environment.
  - No L1 trigger needed. Minimal multiple interactions.
- Emphasis on measuring complete events (tracks, photons, neutral hadrons, missing E_T)
  - the focus is on easily integrable and robust detector technologies which will just work, with high precision, reliability, redundancy and robustness.
  - High granularity, hermeticity, low-mass tracking.
- Particle-flow paradigm for reconstructing hadronic jets promises circa 3% energy resolution per jet. Detector designs with the ECAL and HCAL inside coil.
  - Constrains opportunities for additional PID like devices, but also offers opportunities.
  - Bubble-chamber like reconstruction of complete events.
  - eg. temporal calorimetry ??

Basic ILC Parameters

Designed for $\sqrt{s}$=200 – 1000 GeV. Start at $\sqrt{s}$=500 GeV.

- Bunch structure:
- $(\Delta t)_{BX} \approx 337$ ns.
- 2820 bunches per bunch-train. 5 bunch-trains/s.
- $\sigma_x = 474$nm, $\sigma_y = 6$nm
- $\sigma_z = 300\mu$m

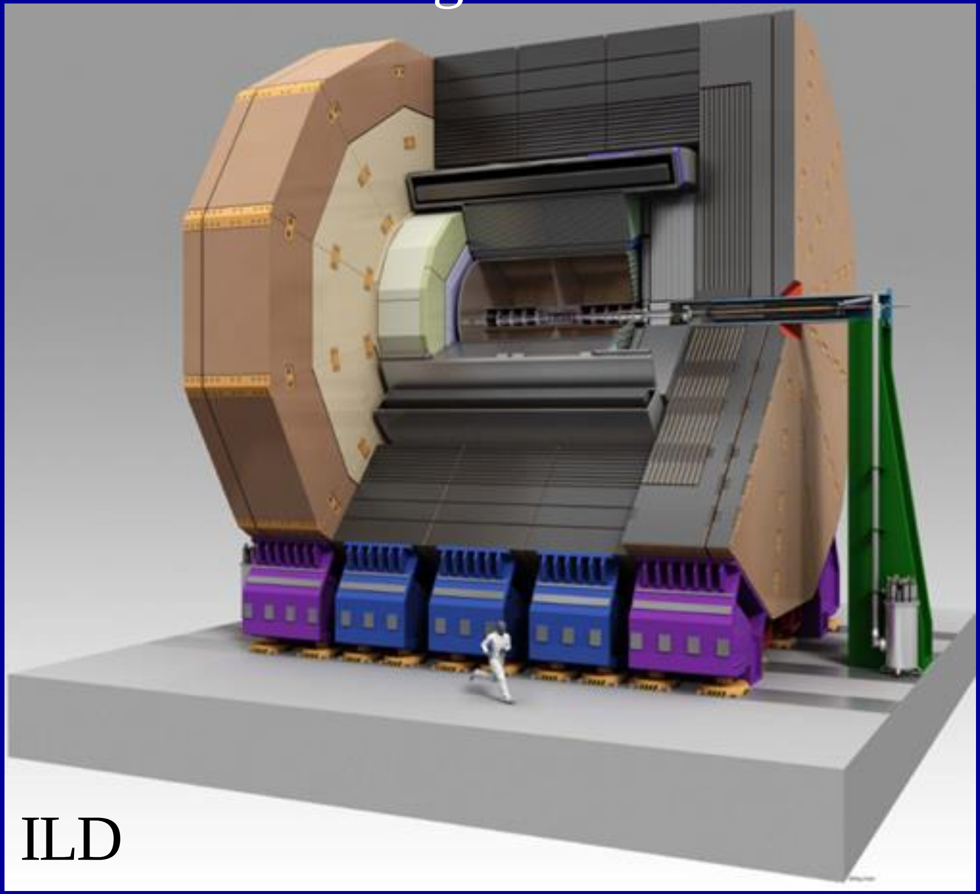


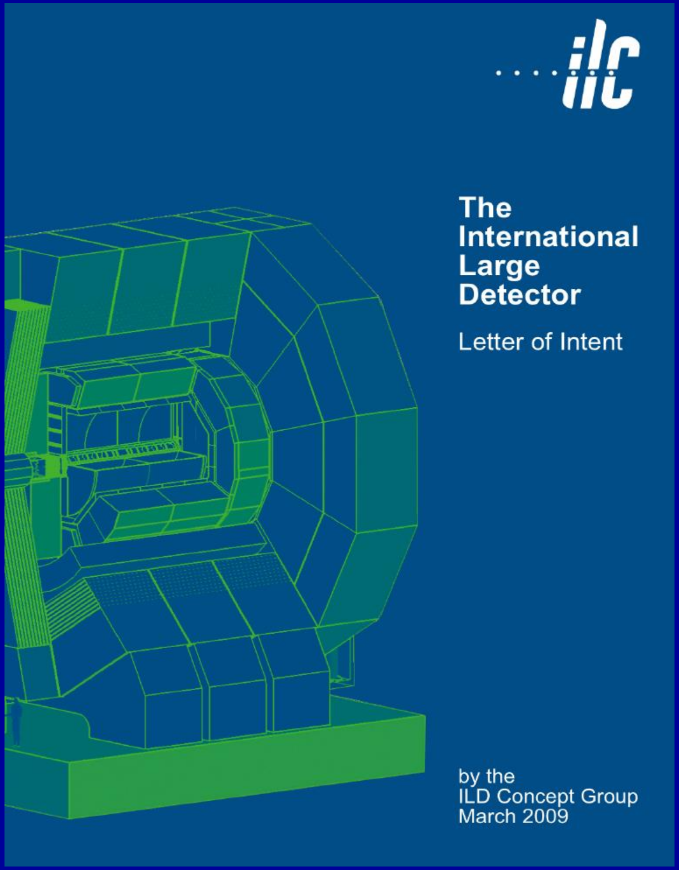
- Only around 0.5% duty factor needed.
- Can reduce average power consumption.
- Pile-up not a primary concern

Note CLIC
$(\Delta t)_{BX}$=0.5ns

What is ILD ?

International Large Detector





The International Large Detector

Letter of Intent

by the
ILD Concept Group
March 2009

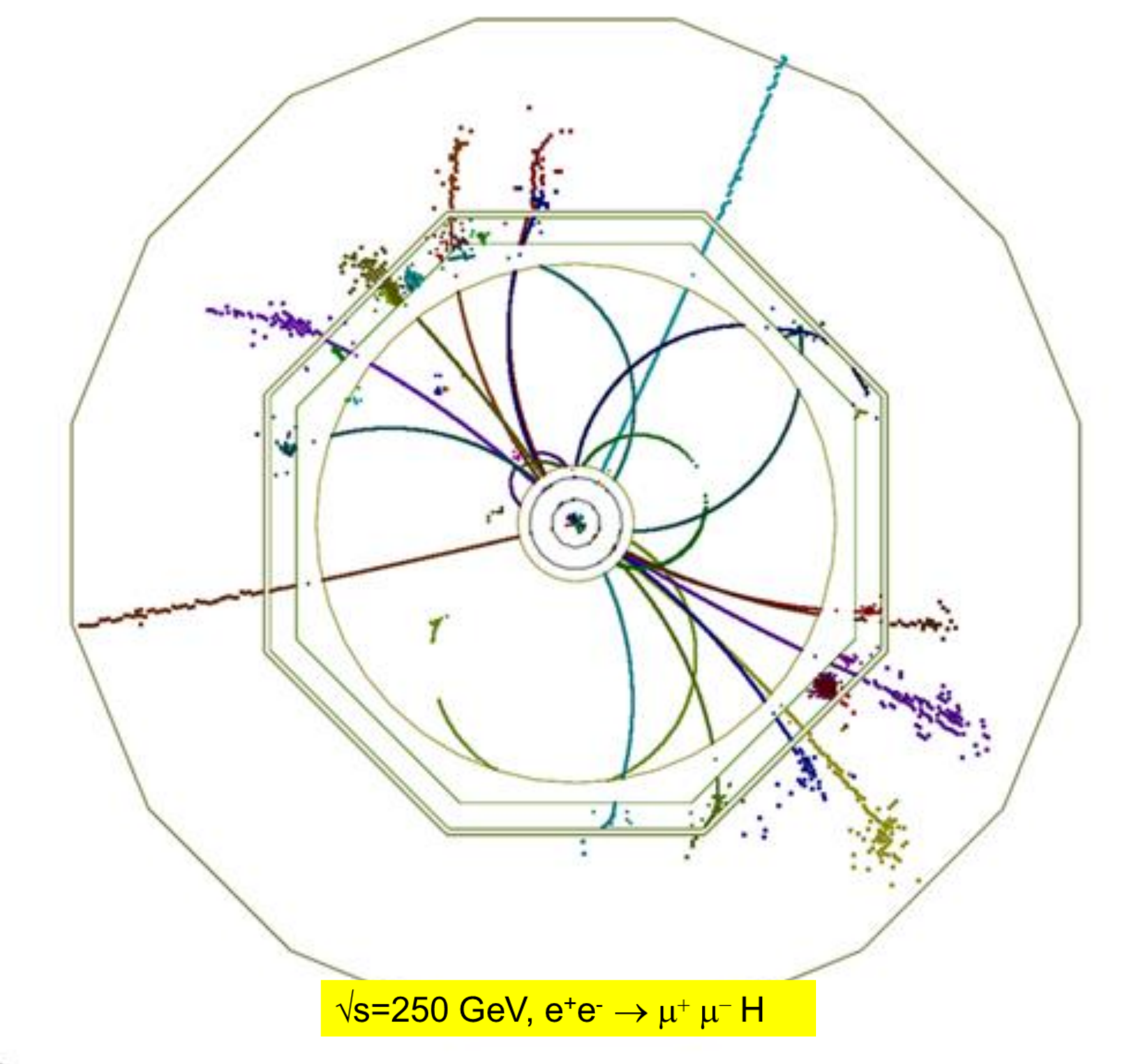
A modern detector designed for ILC. Similar size to CMS.
ILC: higher energy (x 5), higher luminosity (x 1000), much better detector.

Detector Design Philosophy

Designed based on the **particle-flow** approach to complete reconstruction of the event.

Major emphasis on granularity so that individual particles are separated and unambiguously reconstructed.

Requires hardware and software in the design process.

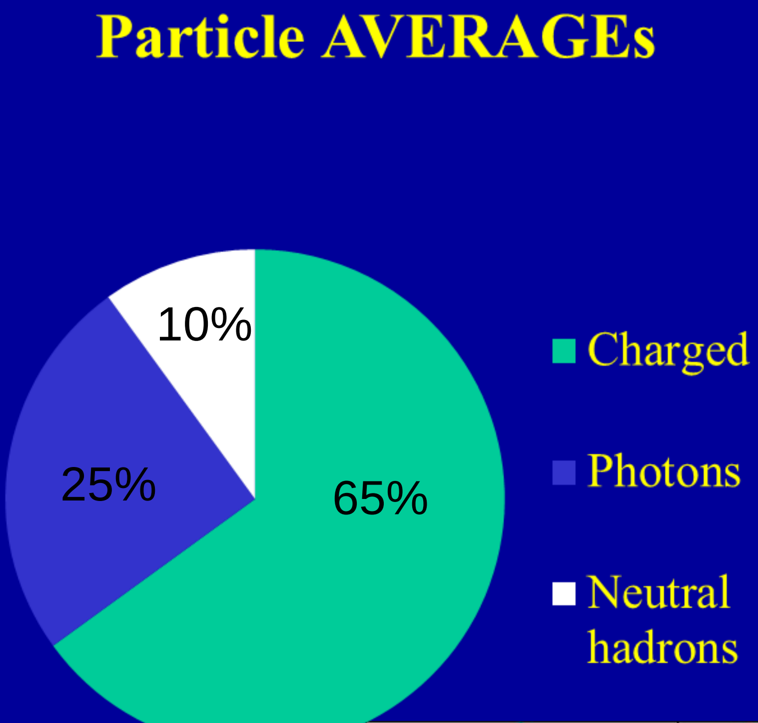


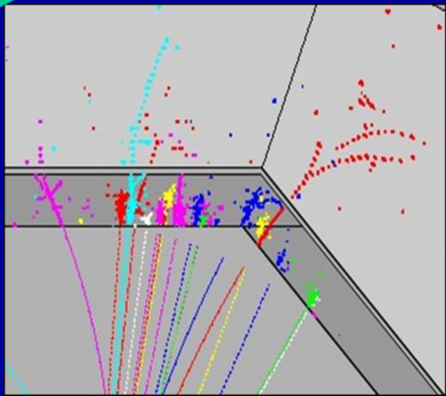
$\sqrt{s}$=250 GeV, $e^+e^- \rightarrow \mu^+ \mu^- H$

Particle-Flow in a Nut-Shell

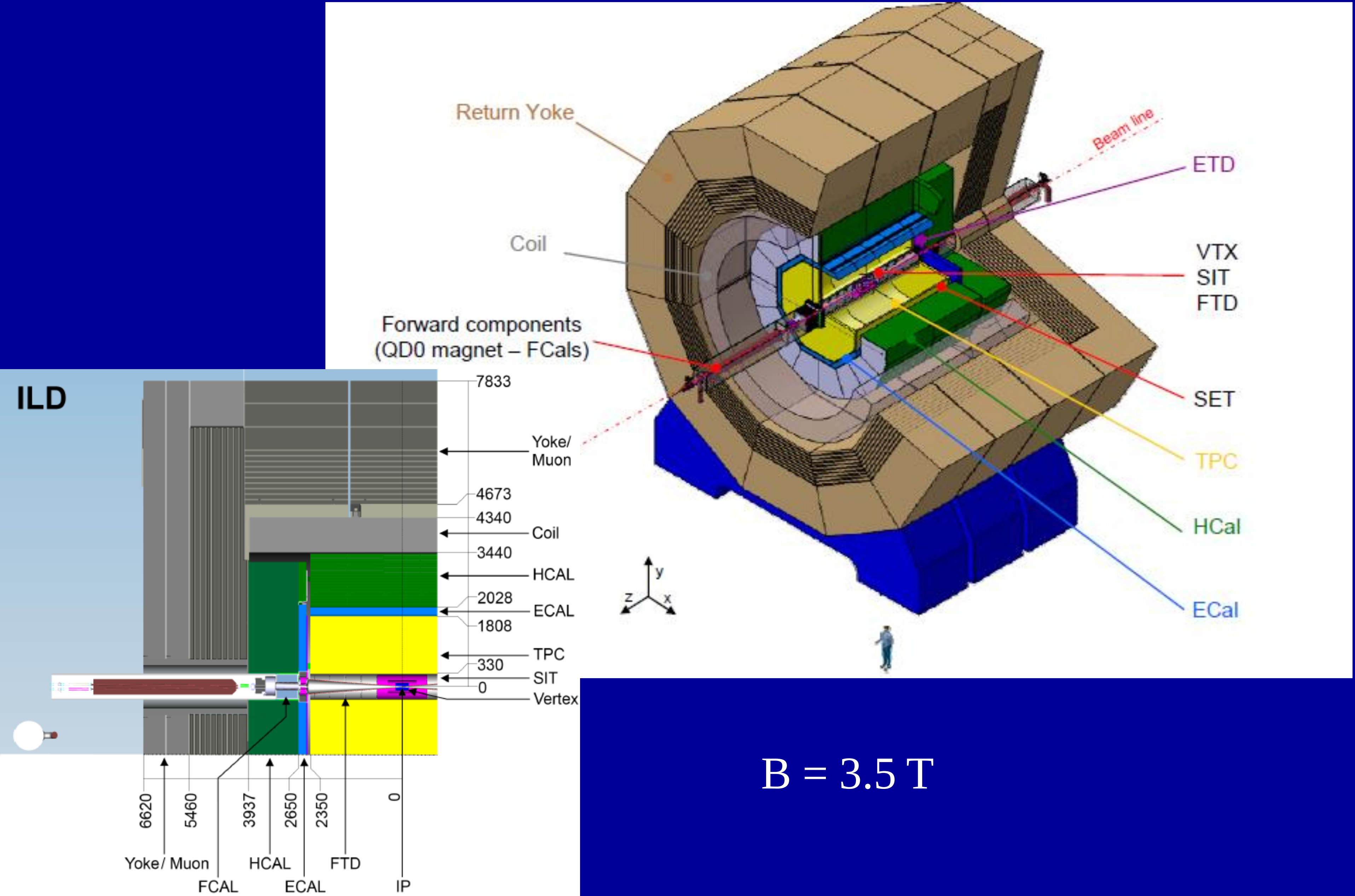
E(jet) = E(charged) + E(photons) + E(neutral hadrons)

- Outsource **65%** of the event-energy measurement responsibility from the calorimeter to the tracker
    - Emphasize particle separability (large R) and tracking
    - Leading to better jet energy precision
- Reduce importance of hadronic leakage
    - Now only 10% instead of 75% of the average jet energy is susceptible
    - Detector designs suited to wide energy range
- Maximize event information
    - Aim for full reconstruction of each particle including V^0s, kinks, π^0 etc.
    - Understand energy response and resolution event-by-event.


Particle AVERAGEs

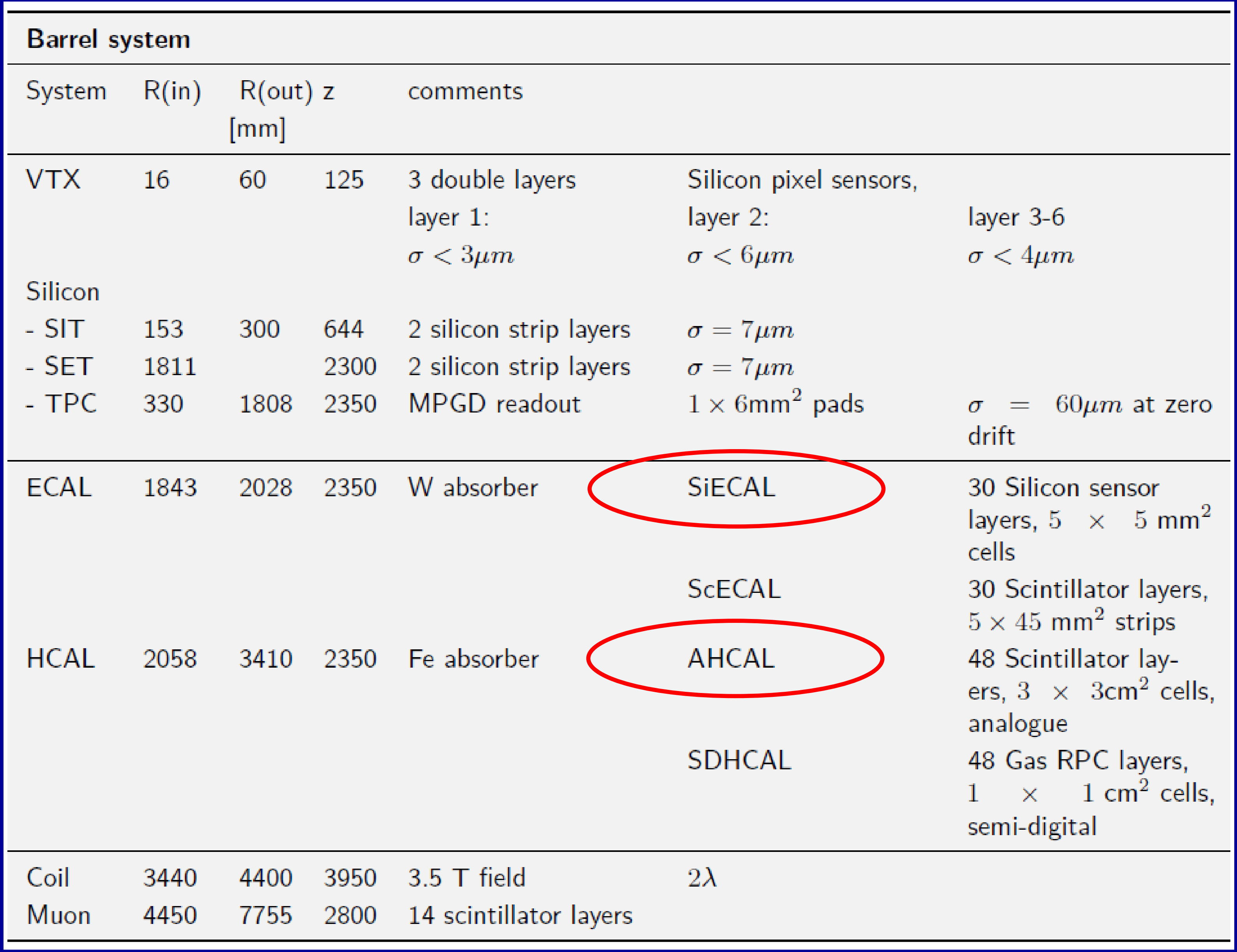


ILD Detector Sub-systems



B = 3.5 T

Barrel Detector Parameters

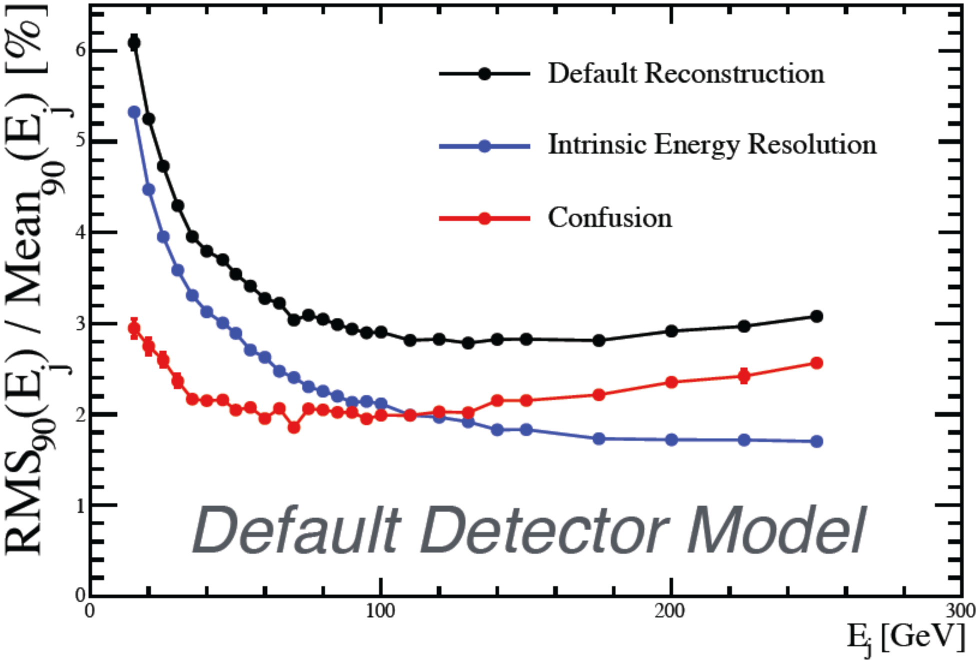


Barrel system

System	R(in)	R(out) [mm]	z	comments		
VTX	16	60	125	3 double layers	Silicon pixel sensors,	
				layer 1:	layer 2:	layer 3-6
				$\sigma < 3\mu m$	$\sigma < 6\mu m$	$\sigma < 4\mu m$
Silicon						
- SIT	153	300	644	2 silicon strip layers	$\sigma = 7\mu m$	
- SET	1811		2300	2 silicon strip layers	$\sigma = 7\mu m$	
- TPC	330	1808	2350	MPGD readout	$1 \times 6\text{mm}^2$ pads	$\sigma = 60\mu m$ at zero drift
ECAL	1843	2028	2350	W absorber	SiECAL	30 Silicon sensor layers, 5×5 mm^2 cells
					ScECAL	30 Scintillator layers, 5×45 mm^2 strips
HCAL	2058	3410	2350	Fe absorber	AHCAL	48 Scintillator layers, $3 \times 3\text{cm}^2$ cells, analogue
					SDHCAL	48 Gas RPC layers, 1×1 cm^2 cells, semi-digital
Coil	3440	4400	3950	3.5 T field	2λ	
Muon	4450	7755	2800	14 scintillator layers		

ILD Particle Flow Performance

Status with current algorithm (v01-17-07, PandoraPFA v02-00-00 and ILD_o1_v5 model). (Marshall, Green)

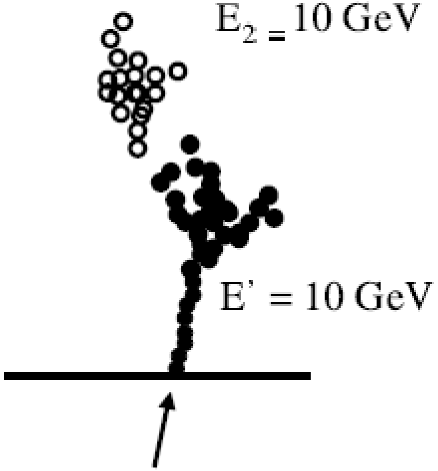


Confusion = Energy deposits mis-assigned (double-counted or wrongly ignored).

Timing and Particle-Flow

- There are two main areas.
- 1. Particle time-of-flight for mass assignment
  - Charged particles
  - Neutral particles (neutral hadrons)
- 2. Using timing at the cell and cluster level for confusion reduction.

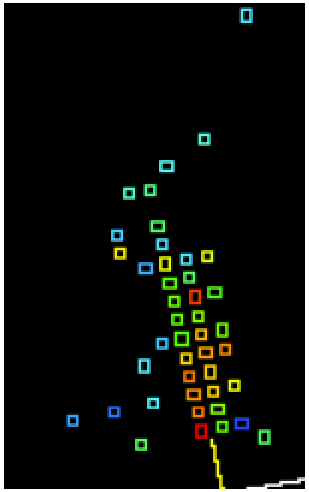
Energy Confusion in Particle Flow



- Charged Hadron – Neutral Hadron confusion
  - Fake neutral hadrons from charged hadron shower fragments
  - Neutral hadrons lost in nearby charged hadron showers
- Photon – Charged Hadron confusion
  - Photons lost in nearby charged hadron showers
- Photon – Neutral Hadron confusion
  - Minor issue for energy. Importance depends on e/h ratio.

Timing potentially can be very helpful

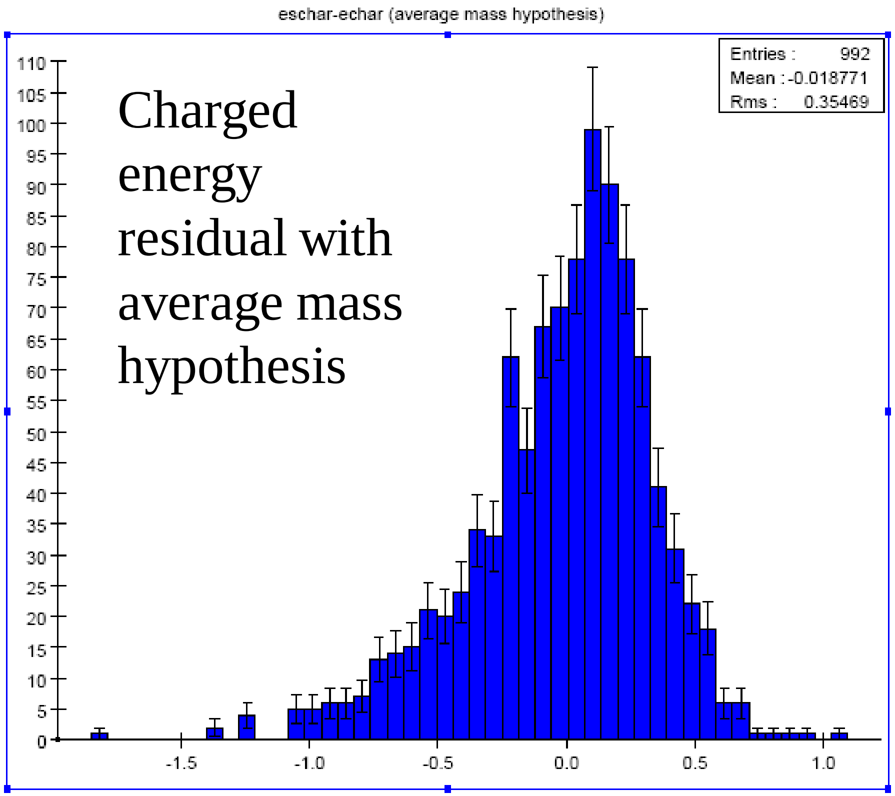
Temporal Calorimetry



2 GeV γ (4mm x 4mm pixels)

- Time assignments to cells, to clusters, to particles.
- Cluster time resolution depends on individual cell time resolution, f (E_{dep}), and number, N, of cells, validity of time propagation model and intra-shower time dispersion.
  - Note. Some of the shower particles go backwards ...

Is TOF and/or PID important for particle flow?



Charged energy residual with average mass hypothesis

Contribution of charged-track mass ignorance to overall event energy at Z^0.

σ = 0.35 GeV equivalent to 3.7%/√E (NOT COMPELLING FOR TOF!, especially given other tools like dE/dx)

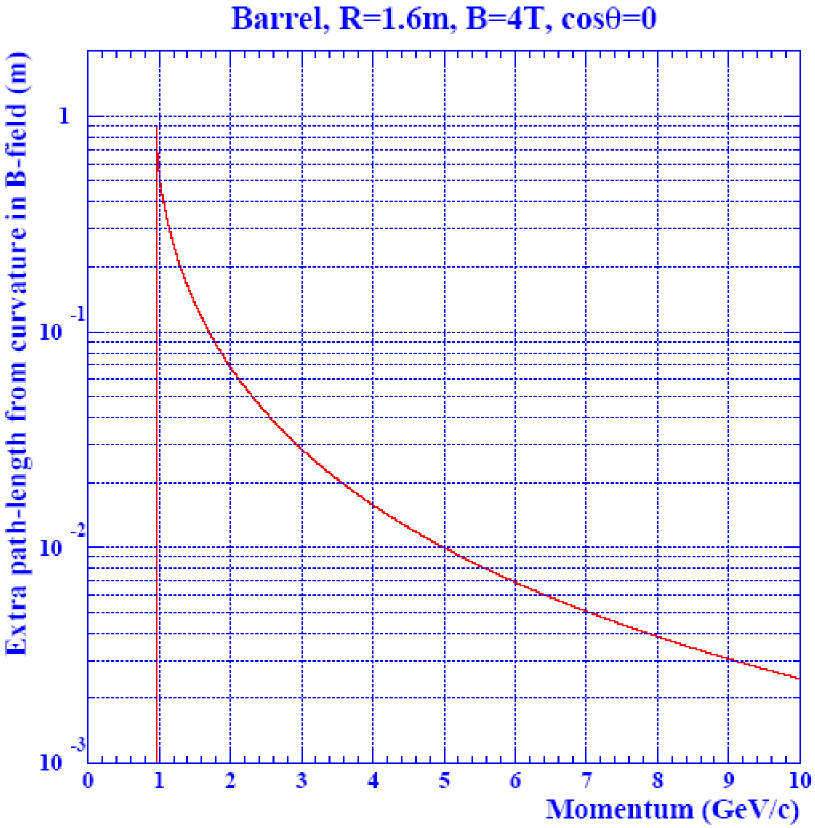
TOF has potential for resolving some confusion in the calorimetry.

Positive time ID of photons.

Use time differences caused by bending in field to distinguish clusters originating from charged / neutral clusters ? Useful for eg K^-/ K^0_L discrimination ?

Particle-by-particle jet reconstruction systematics will demand good control of π/K/p particle fractions. Most particles in energetic jets are still soft ..

Additional path-length for charged particles



3.3 ns (for β=1)

330 ps

33 ps

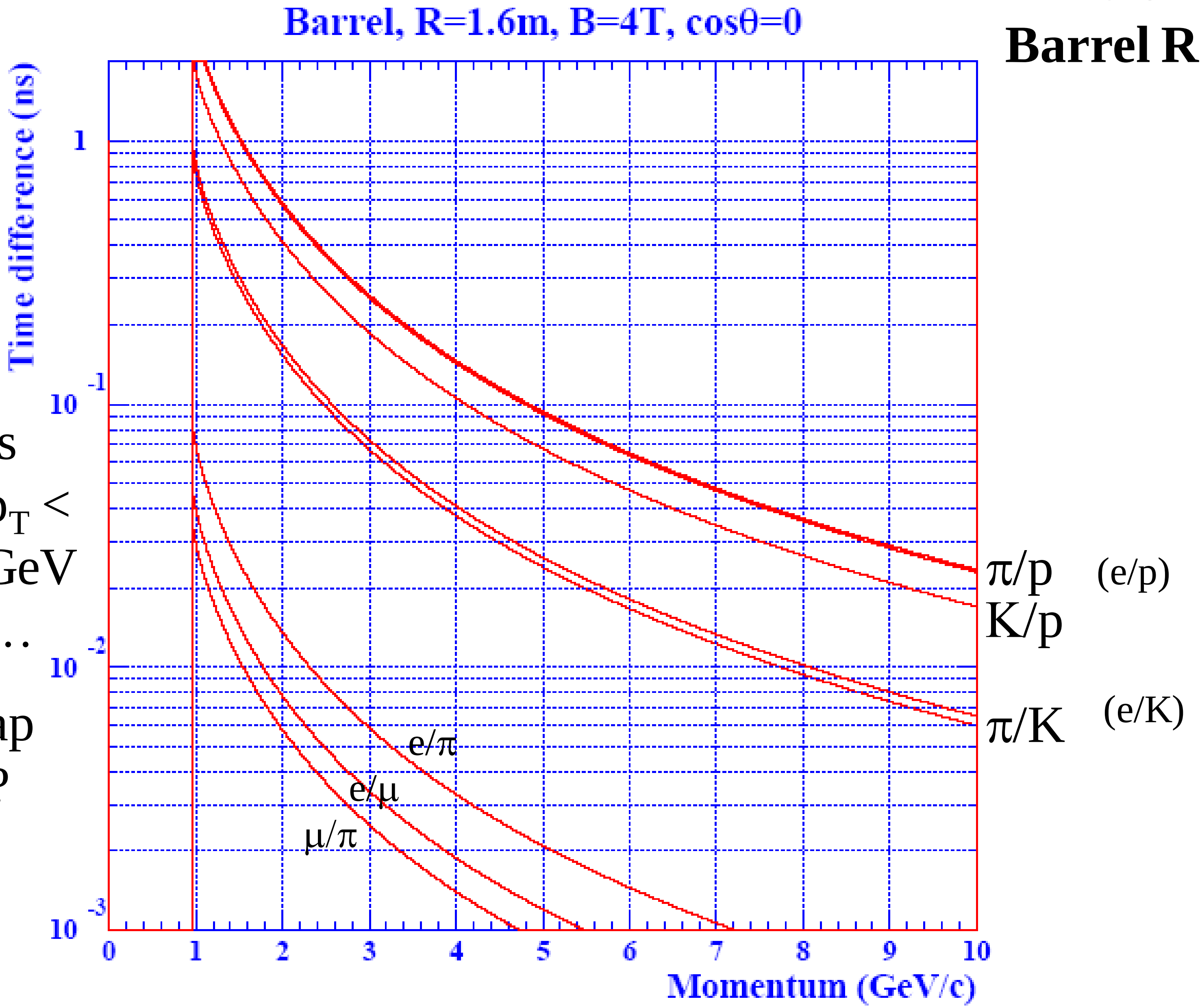
3.3 ps

(High B-fields have some advantages for timing enthusiasts)

Time-of-Flight in Barrel Region

Tracks with $p_T <$ 0.96 GeV loop …

Endcap TOF ?

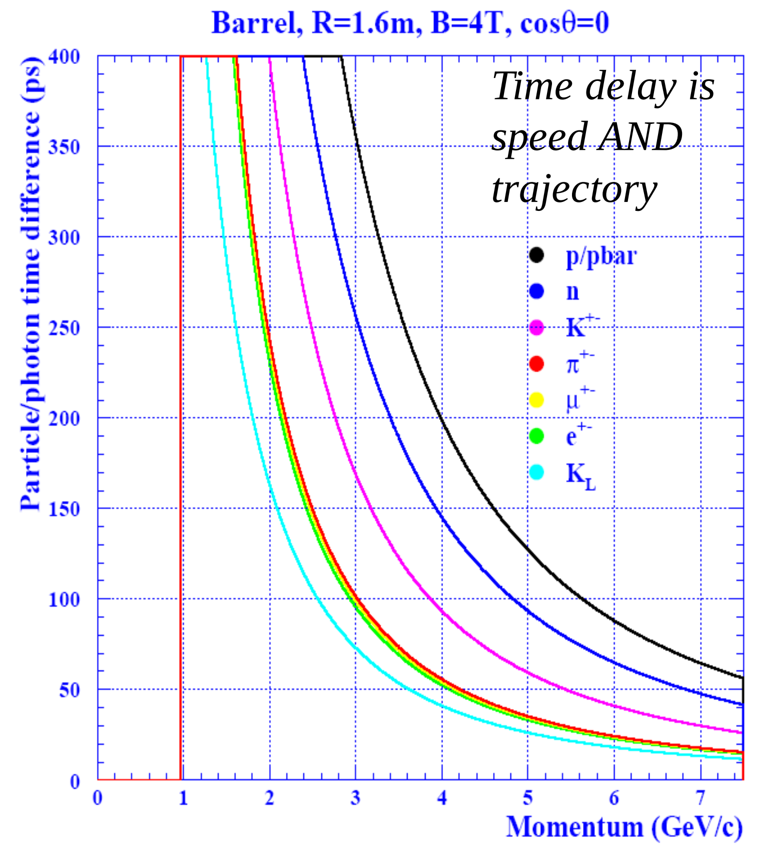


Low momentum μ/π is an interesting new capability which psec-TOF could address !

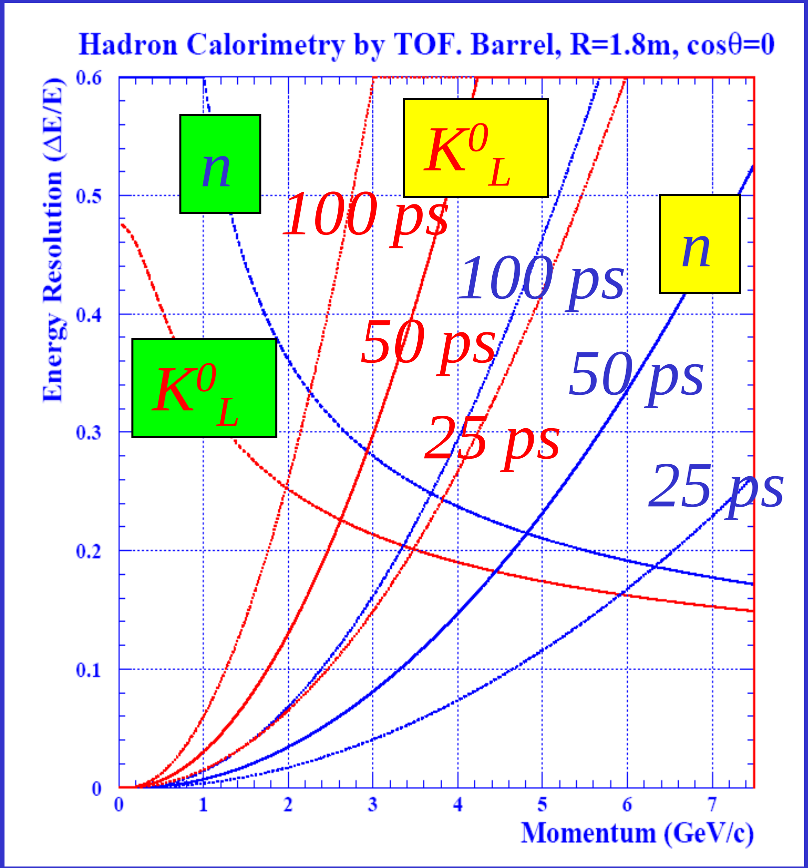
Fast Timing / Temporal Calorimetry

Idea: time resolution at below the 100 ps level is easily achievable with dedicated detectors. Can it be applied in a useful way in an ILC detector ?

Can TOF help measure neutral hadrons at low p ?



Time delay is speed AND trajectory



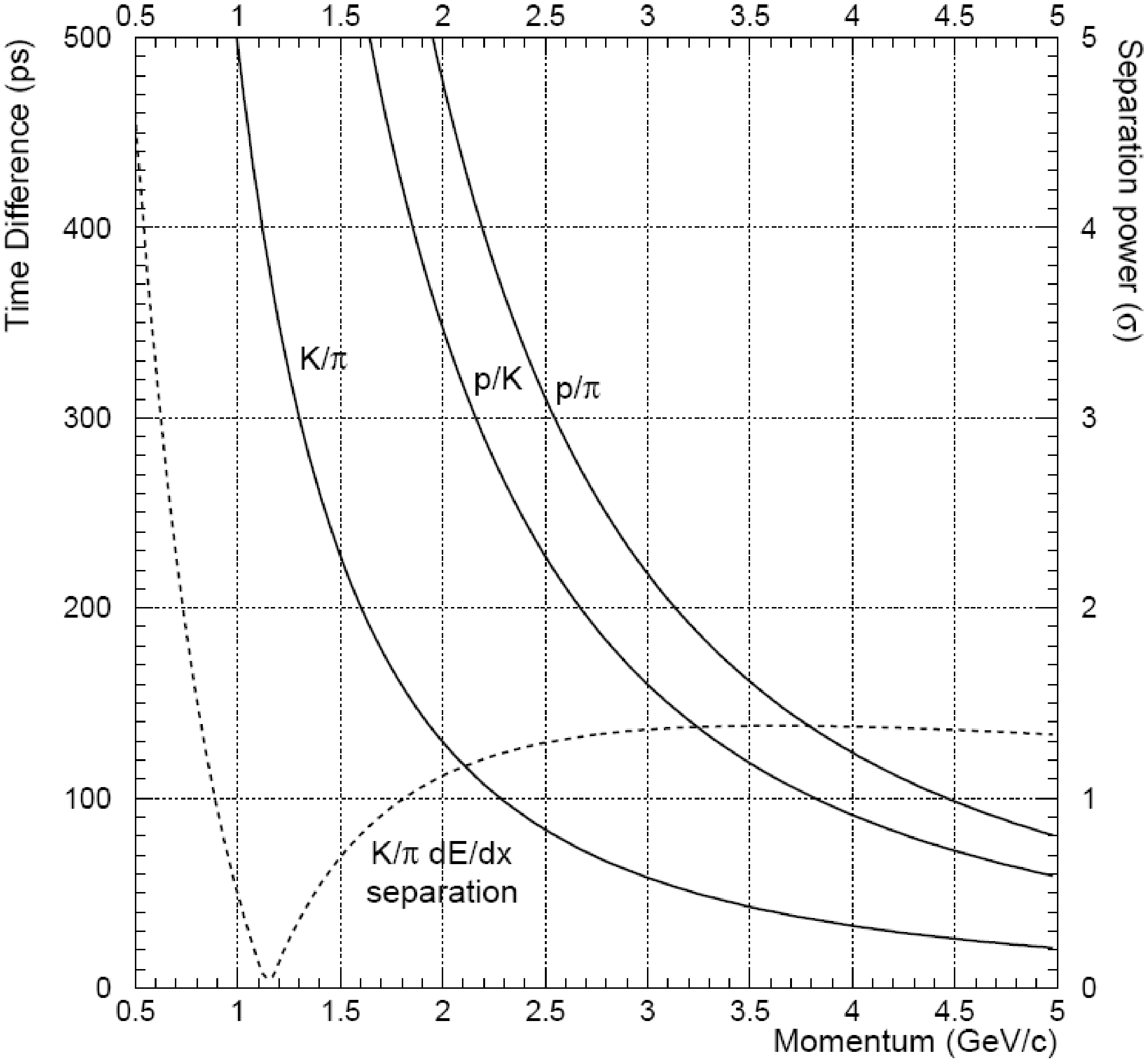
Can help resolving γ/π. (PID by TOF possible – in addition to dE/dx in a TPC-based detector). Resolve confusion.

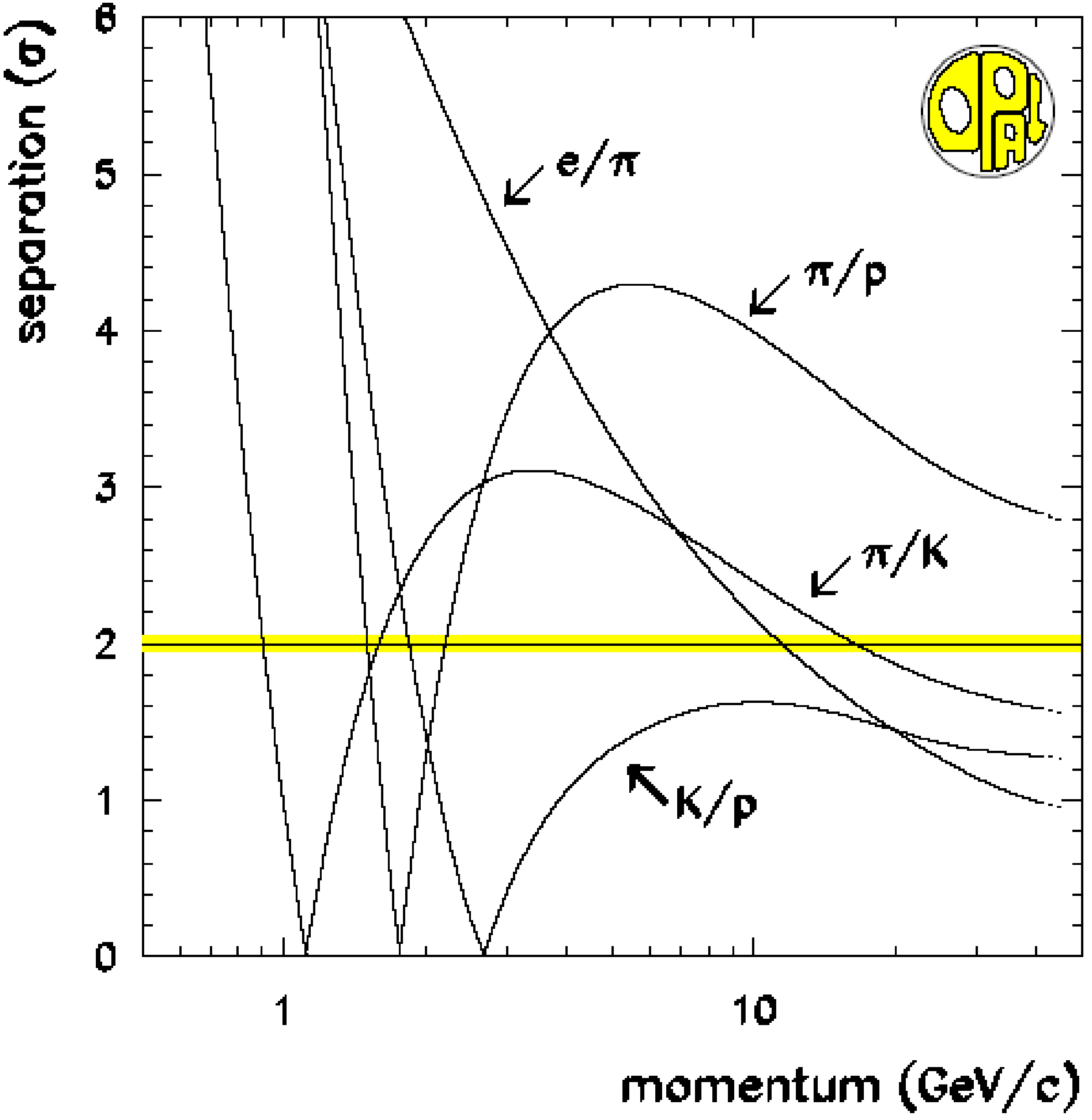
HCAL (LDC DOD) *TOF*

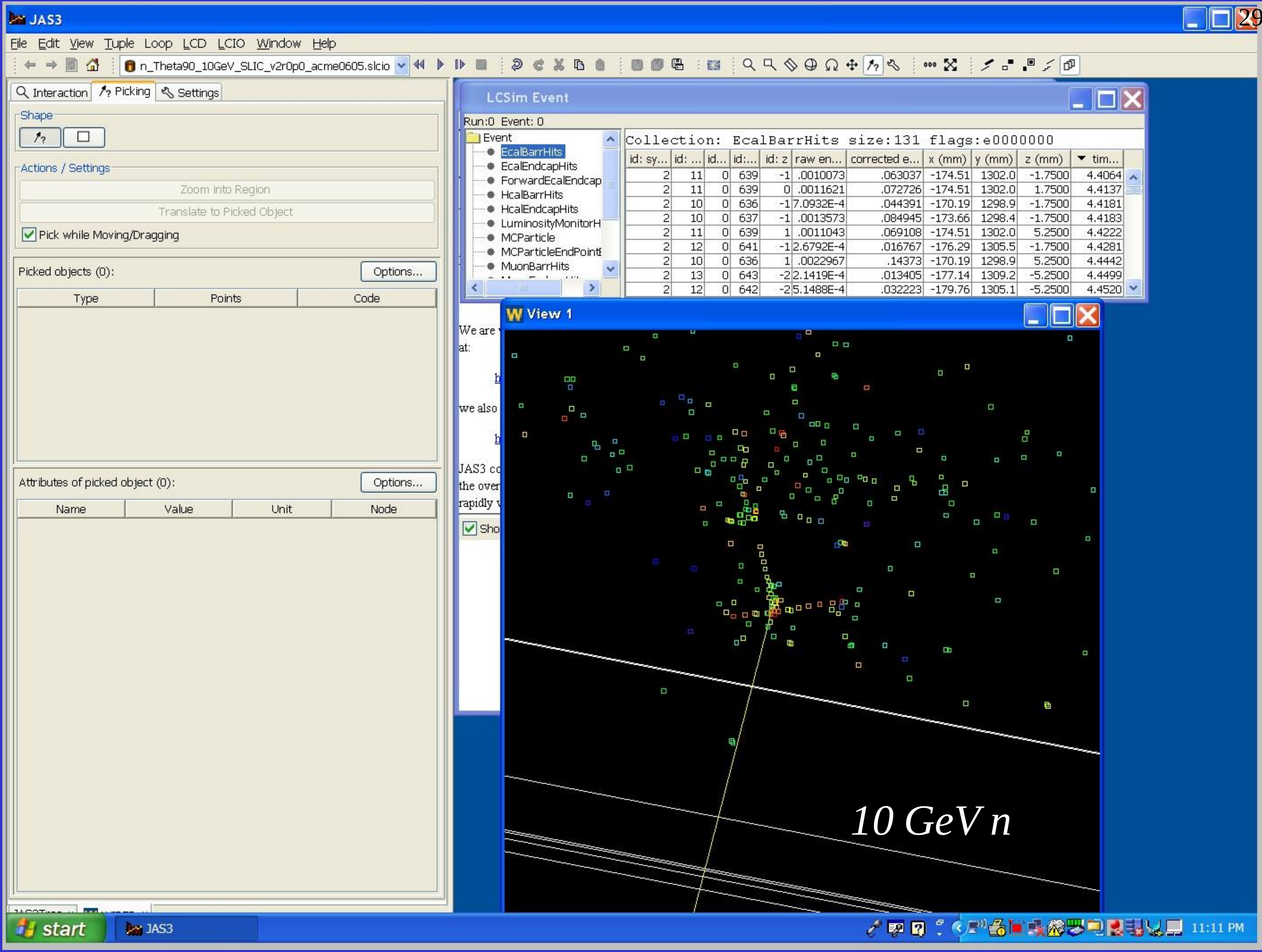
Outlook

- ILC detectors envisage high granularity ECAL (5mm x 5mm x 30) and HCAL (30mm x 30mm x 48).
  - Timing for each cell is on our radar.
  - Demonstrating that calorimeter timing is necessary remains to be done
  - I am optimistic that timing will be very beneficial
    - Good input on reasonable assumptions very welcome.
    - Great to see the CMS test beam results.
- Certainly scope for ILC detectors to adopt non-invasive precision timing layers for charged particle TOF. Especially now that 35 ps with Si is feasible.
  - VTX, SIT, SET
- Defensible integrated timing concepts + target resolutions welcome

Backup Slides


Time Difference (ps)
Separation power (σ)
Momentum (GeV/c)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
100
200
300
400
500
0
1
2
3
4
5
K/π
p/K
p/π
K/π dE/dx separation


separation (σ)
0
1
2
3
4
5
6
1
10
momentum (GeV/c)
e/π
π/p
π/K
K/p



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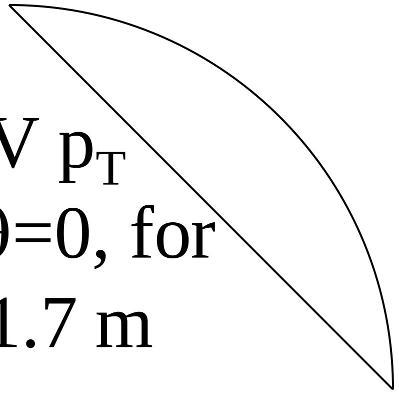
2	11	0	639	0	.0011621	.072726	-174.51	1302.0	1.7500	4.4137
2	10	0	636	-1	7.0932E-4	.044391	-170.19	1298.9	-1.7500	4.4181
2	10	0	637	-1	.0013573	.084945	-173.66	1298.4	-1.7500	4.4183
2	11	0	639	1	.0011043	.069108	-174.51	1302.0	5.2500	4.4222
2	12	0	641	-1	2.6792E-4	.016767	-176.29	1305.5	-1.7500	4.4281
2	10	0	636	1	.0022967	.14373	-170.19	1298.9	5.2500	4.4442
2	13	0	643	-2	2.1419E-4	.013405	-177.14	1309.2	-5.2500	4.4499
2	12	0	642	-2	5.1488E-4	.032223	-179.76	1305.1	-5.2500	4.4520

10 GeV n

Temporal calorimetry for particle flow ?

Really OLD SLIDE

Idea: Use time difference between $\beta=1$ straight line (photon) and $\beta<1$ curved track (charged pi, K, p)



- ΔT for 1.5 GeV p_T tracks at $\cos\theta=0$, for B=4.0 T, R=1.7 m
  - pi : 0.59 ns
  - K : 0.89 ns
  - p : 1.68 ns

ΔT for 3.0 GeV p_T tracks at $\cos\theta=0$, for B=4.0 T, R=1.7 m
  - pi : 0.12 ns
  - K : 0.19 ns
  - p : 0.39 ns

Loopers have pT = 1.02 GeV here.

(OLD) Conclusion: of order 100 ps resolution needed for time differences of the primary particle to be useful => looks impractical

Related Meetings

- ILC
- ILD
- CALICE
- Energy and Time Measurement with High Granularity Silicon Devices, DESY June 2016.