Detector R&D and Capabilities for Snowmass 2013

Marcel Demarteau

on behalf of
Instrumentation Frontier Conveners
(Ron Lipton, Howard Nicholson, MD)

CPAD chairs
(Ian Shipsey, MD)

Snowmass Preparatory Workshop on Frontier Capabilities
University of Chicago, Feb. 25 – 26, 2013

Outline

- Organization of Instrumentation
- Areas for capability needs
- European Model

The DPF Instrumentation Task Force

From Universities

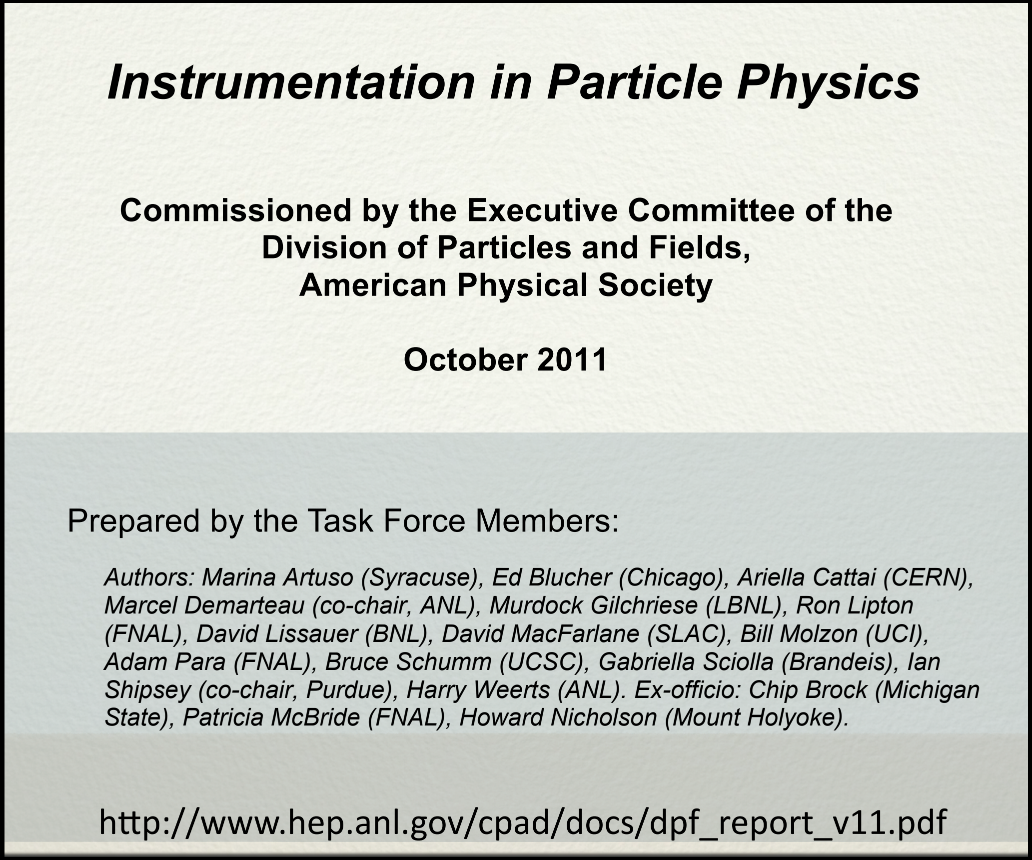
- Marina Artuso, Syracuse
- Ed Blucher, Chicago
- Bill Molzen, Irvine
- Gabriella Sciolla, Brandeis
- Ian Shipsey*, Purdue
- Andy White, UT Arlington

From laboratories

- Marcel Demarteau*, Argonne
- David Lissauer, Brookhaven
- David MacFarlane, SLAC
- Greg Bock, Fermilab
- Gil Gilchriese, LBNL
- Harry Weerts, Argonne

Ex-officio

- Chip Brock, DPF MSU
- Patty McBride, DPF Fermilab
- Howard Nicholson, DOE Emeritus



Instrumentation in Particle Physics

Commissioned by the Executive Committee of the
Division of Particles and Fields,
American Physical Society

October 2011

Prepared by the Task Force Members:

Authors: Marina Artuso (Syracuse), Ed Blucher (Chicago), Ariella Cattai (CERN), Marcel Demarteau (co-chair, ANL), Murdock Gilchriese (LBNL), Ron Lipton (FNAL), David Lissauer (BNL), David MacFarlane (SLAC), Bill Molzon (UCI), Adam Para (FNAL), Bruce Schumm (UCSC), Gabriella Sciolla (Brandeis), Ian Shipsey (co-chair, Purdue), Harry Weerts (ANL). Ex-officio: Chip Brock (Michigan State), Patricia McBride (FNAL), Howard Nicholson (Mount Holyoke).

http://www.hep.anl.gov/cpad/docs/dpf_report_v11.pdf

Taskforce created Spring 2011

Report submitted October 2011

- Key recommendation formation of a panel on instrumentation

- CPAD: to promote, coordinate and assist in the research and development of instrumentation for High Energy Physics nationally, and to develop a detector R&D program to support the mission of High Energy Physics for the next decades.

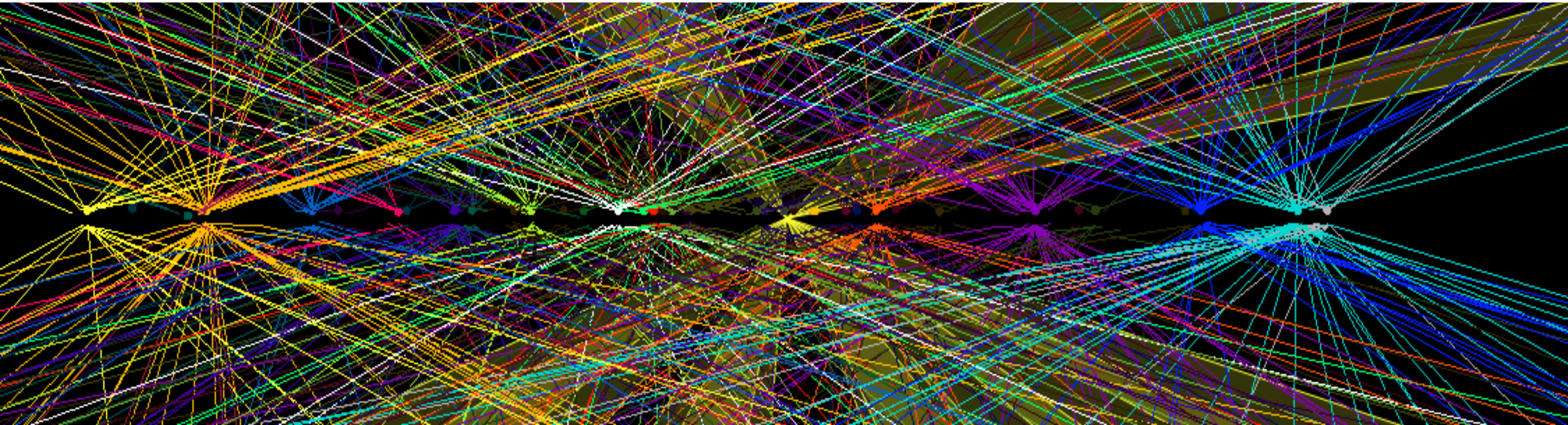
- CPAD Membership
- From Universities
  - Jim Alexander (Cornell)
  - Marina Artuso (Syracuse)
  - Ed Blucher (Chicago)
  - Ulrich Heintz (Brown)
  - Howard Nicholson (Mt. Holyoke)
  - Abe Seiden (UCSC)
  - Ian Shipsey* (Purdue)
- From Laboratories
  - Marcel Demarteau* (Argonne)
  - David Lissauer (Brookhaven)
  - David MacFarlane (SLAC)
  - Ron Lipton (Fermilab)
  - Gil Gilchriese (LBNL)
  - Bob Wagner (Argonne)
- International
  - Ariella Cattai (CERN)
  - Junji Haba (KEK)

CPAD appointed spring 2012

http://www.hep.anl.gov/cpad/

(*) = co-chair

ENERGY FRONTIER



Energy Frontier Facilities

Machine	Under study	$\sqrt{s}$ in TeV	Luminosity for 5 years in ab^{-1}	Peak luminosity $\times 10^{34}$ cm^{-2} s^{-1}
pp	HL-LHC HE-LHC VHE-LHC	13 33 100	3 (10 years) 0.3 0.3	5 (leveled)
e^+e^- Linear	ILC CLIC	0.25-1 1-3	0.5-1 2	2 2.4
e^+e^- Circular	LEP3 (in LHC tunnel) TLEP (80 km tunnel => VHE-LHC)	Up to 0.24 Up to 0.35	2	1 0.7-50
$\mu^+\mu^-$	LEMC HEMC	0.125 3-6	2	1 2-4
$\gamma\gamma$	CLICHE PLC SAPPHIRE	0.125-0.30	1	0.36
ep	LHeC	1.4	0.01-0.1	

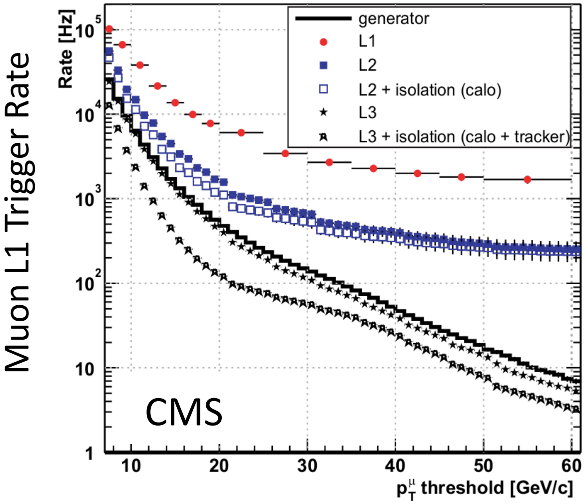
Performance Goals of the HL/HE-LHC

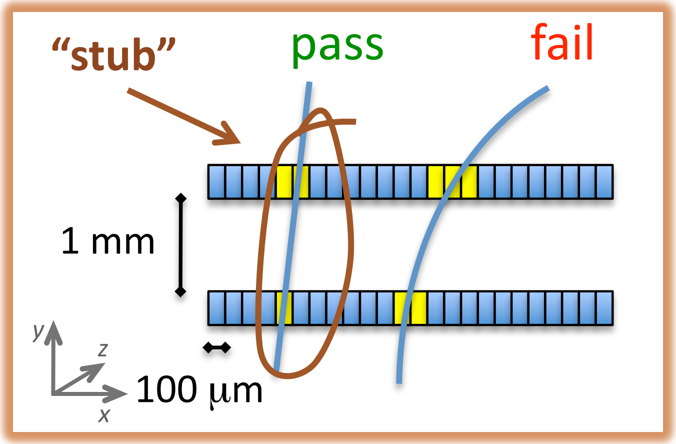
- Good muon ID, momentum resolution, dimuon mass resolution (1% at 100 GeV)
- Good charged-particle momentum resolution and reconstruction efficiency
- Efficient triggering and offline tagging of **t**aus and b-jets, requiring pixel detectors close to the interaction region
- Good electron and photon identification, energy resolution, diphoton and dielectron mass resolution (1% at 100 GeV)
- Good missing-transverse-energy and dijet-mass resolution, requiring large hermetic geometric coverage and segmentation.

Detector component	Required resolution	η coverage Measurement	η coverage Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	± 3.2 $3.1 < \lvert\eta\rvert < 4.9$	± 3.2 $3.1 < \lvert\eta\rvert < 4.9$
μ spectrometer	$\sigma_{p_T}/p_T = 10\%$ @ p_T=1 TeV	± 2.7	± 2.4

HL-LHC Challenges

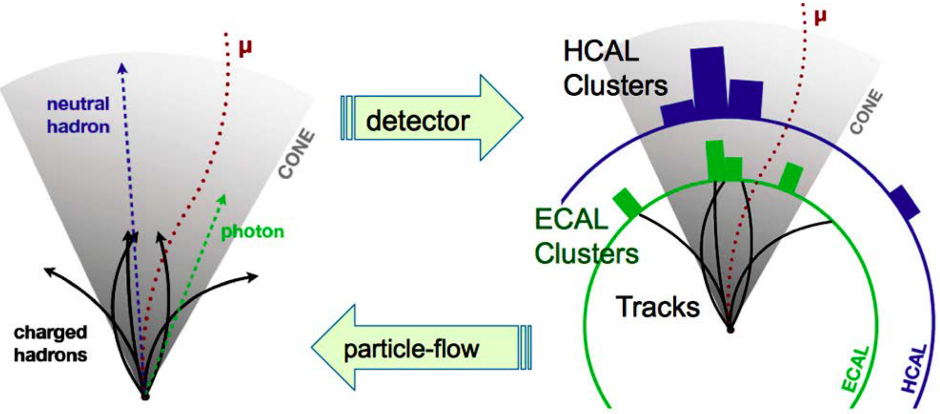
- HL-LHC: pile-up O(140) @ 5x10^{34} cm^{-2} s^{-1} leveled with 25 ns bunch crossing
- Trigger challenge





Mitigation through new trigger primitives

- Analysis challenge
  - maintain high and stable efficiency for e, mu, tau, jets, met, b-jets …
  - Mitigation through timing, vertexing, particle flow, ...



Implications for Capabilities

- Challenged for LHC detector development should be well addressed by current test beam facilities (CERN, Fermilab, SLAC) and irradiation facilities (see Erik's talk).
- There are two important observations:

1) **The demand for test beams will be very high and a key issue will be the *availability* of the test beam**

The duty cycle of Mtest is modest. Can it be improved?

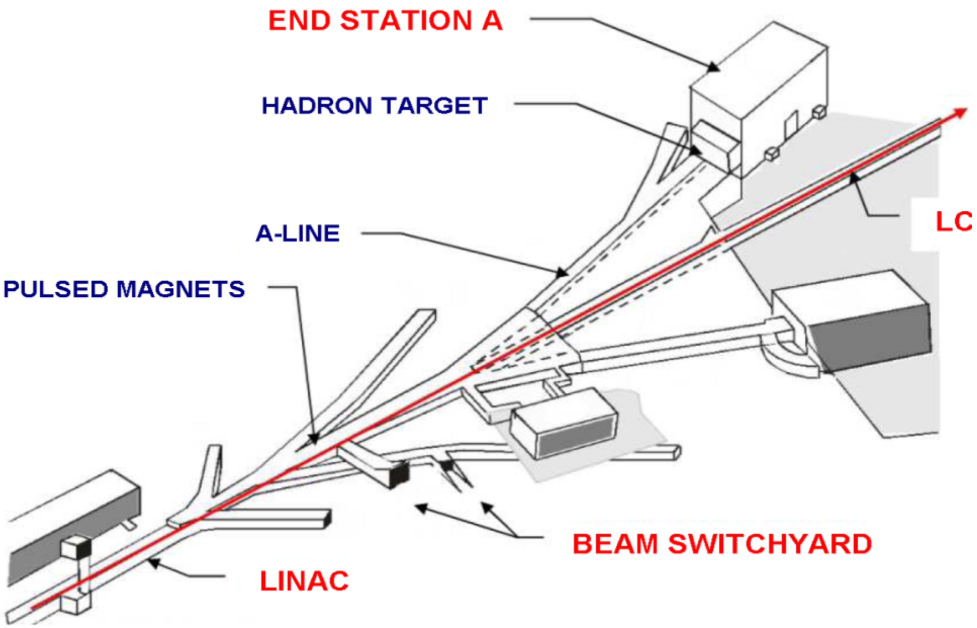
The duty cycle of the SLAC test beam is very modest, but fixed.

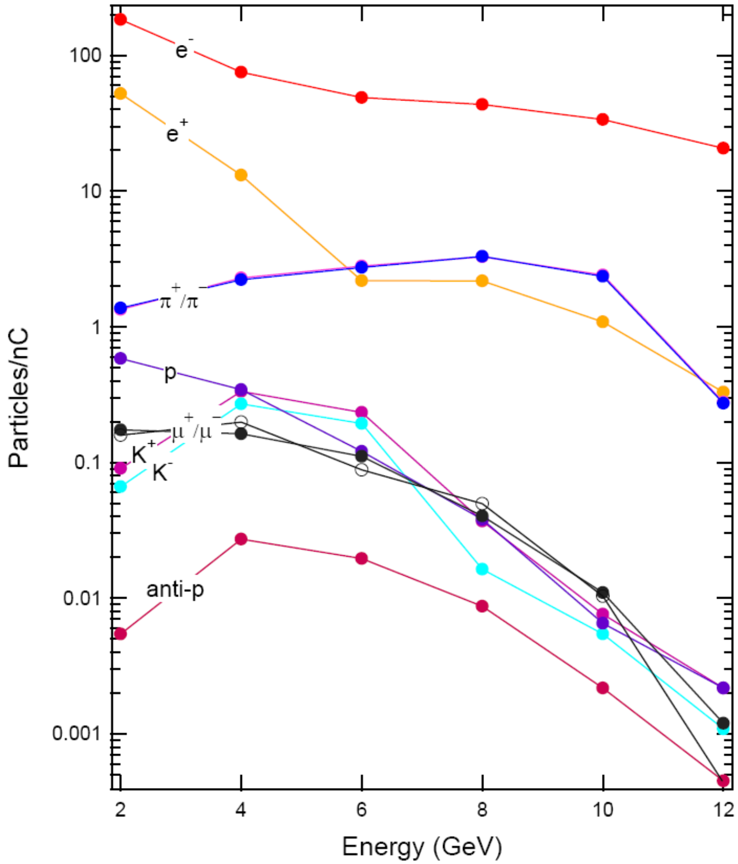
Can the number of beamlines be increased ? Can the future demand be quantified ?

2) **The demand for extremely well understood, reproducible test beams will increase given the demands on precision and data volume**

A further investment in beam line instrumentation and test beam support could be very valuable to the community

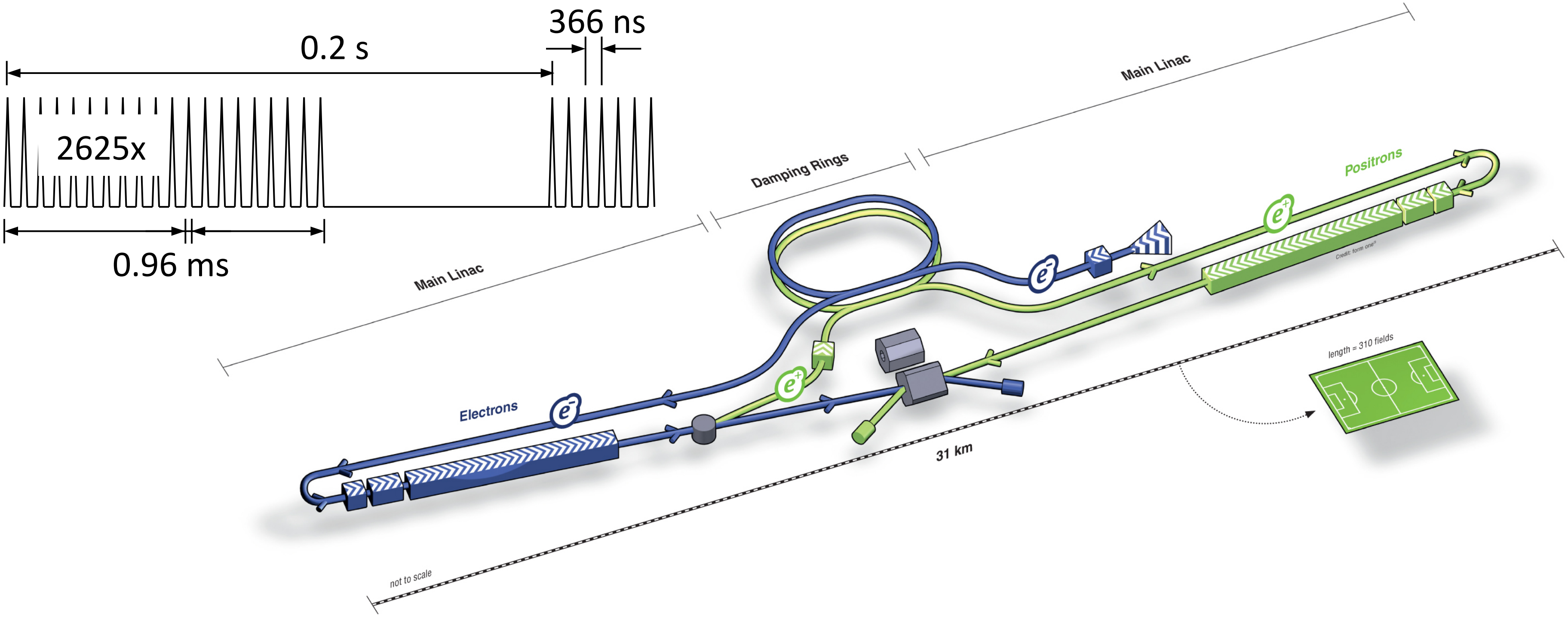
SLAC End Station A Test Beam





- Uses LCLS beam parasitically
- Kick 13.6 GeV LCLS beam to ESA at 5 Hz, 2 x 10^9 e$^-$/ pulse primary beam
- Clean secondary electrons/positrons, p < 13.6 GeV, 0.1/pulse to 2 x 10^9 e$^-$/pulse
- Secondary hadrons ~1 π / pulse < 12 GeV/c

ILC

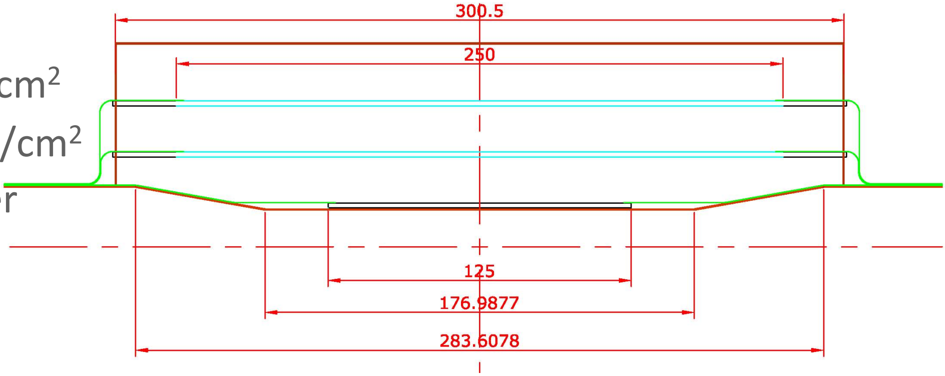


- Beam structure of the ILC allows for power-pulsing, and the detector design requires it: 200ms duty cycle (5Hz) with 1ms beam

- The capability to mimic the ILC time structure in a test beam would add allow to address some crucial ILC detector issues in a realistic experimental setting

Power Delivery

- Sample ILC vertex detector
  - Inner layers: 2.2 W per sensor; 0.92 W/cm^2
  - Outer layers: 0.6 W per sensor; 0.136 W/cm^2
  - Need a factor of >80 to stay within power budget: power-pulsing



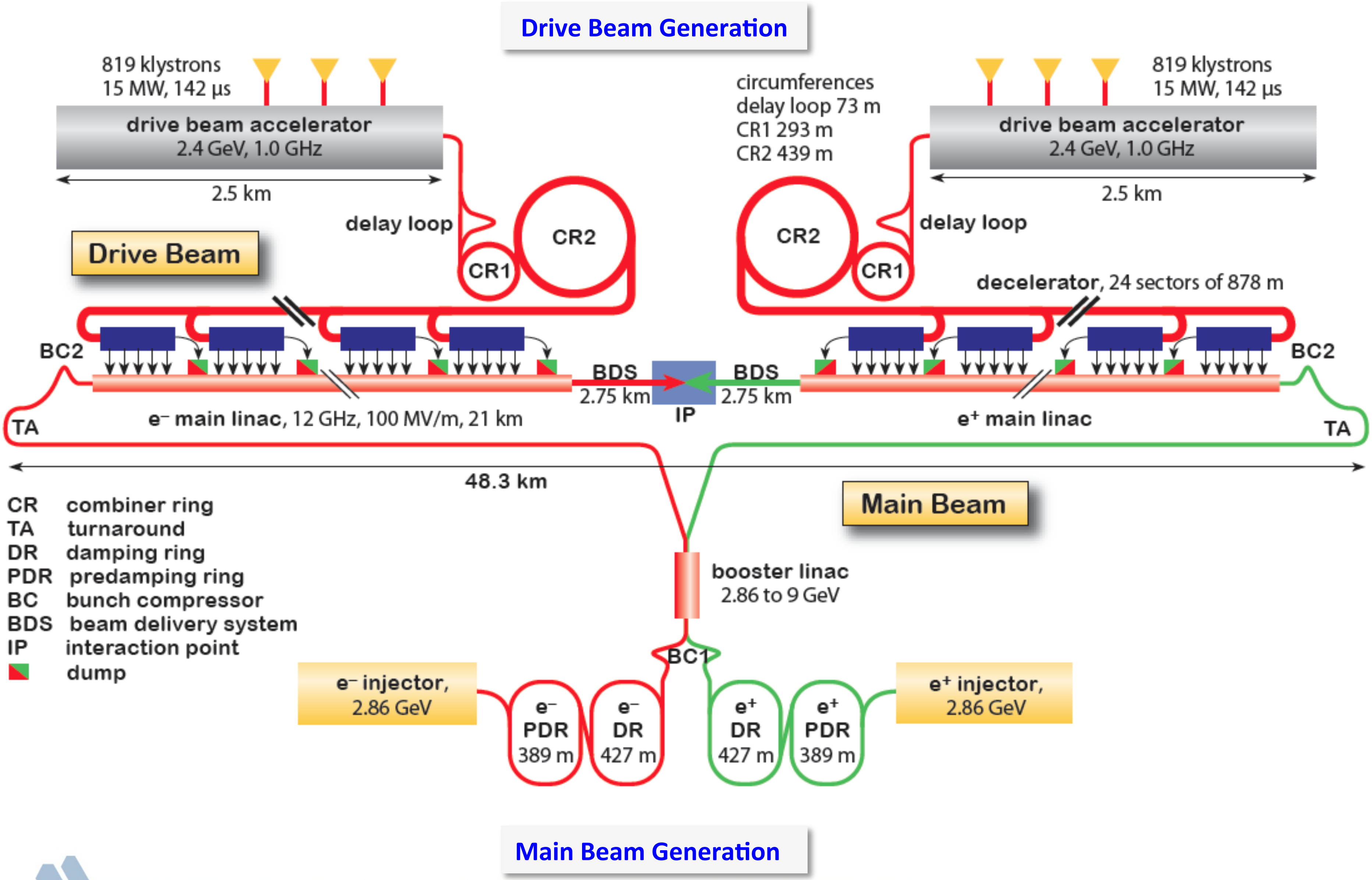
Units = cm

Pulsed power factor 80 V_sensor 1.8

Layer	Number of locations	Active Width	Active Length	P/A W/cm^2	P_layer Average W	P_layer Peak W	I_layer Average A	I_layer Peak A	I_sensor Average A	I_sensor Peak A
1a	12	1.11	12.49	0.013	2.16	172.8	1.20	96.0	0.10	8.00
1b	12	1.11	12.49	0.013	2.16	172.8	1.20	96.0	0.10	8.00
2a	12	2.20	24.99	0.0022	1.45	116.3	0.81	64.6	0.07	5.38
2b	12	2.20	24.99	0.0022	1.45	116.3	0.81	64.6	0.07	5.38
3a	18	2.20	24.99	0.0022	2.18	174.5	1.21	96.9	0.07	5.38
3b	18	2.20	24.99	0.0022	2.18	174.5	1.21	96.9	0.07	5.38
Totals	84				11.59	927.1	6.44	515.1		

- Large currents in magnetic field
- How important is beam test compared to lab test?

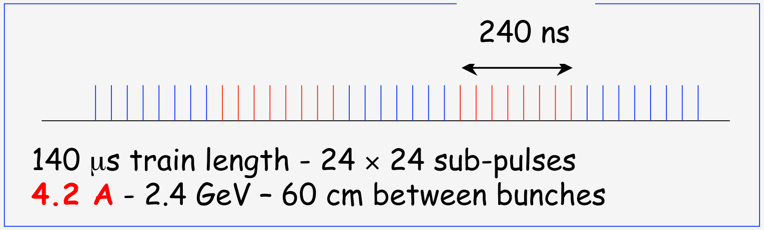
CLIC



CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
◪	dump

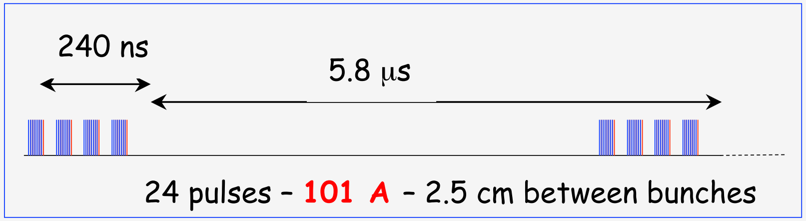
CLIC

Drive beam time structure - initial

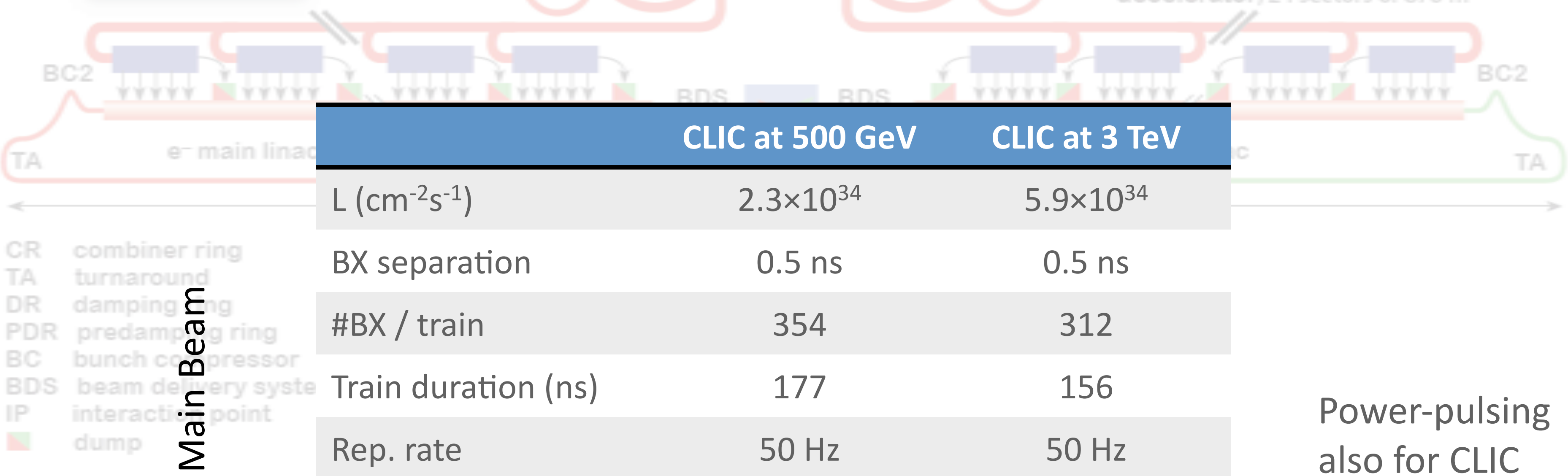


140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



24 pulses – 101 A – 2.5 cm between bunches



Main Beam

	CLIC at 500 GeV	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	2.3×10^{34}	5.9×10^{34}
BX separation	0.5 ns	0.5 ns
#BX / train	354	312
Train duration (ns)	177	156
Rep. rate	50 Hz	50 Hz
σ_x / σ_y (nm)	≈ 200 / 2.3	≈ 45 / 1
σ_z (μm)	72	44

Power-pulsing also for CLIC crucial

CLIC

t_0 physics event (offline)

- Triggerless readout of full train anticipated
- Reconstruction window from 10 - 100ns
- Powerpulsing at 50 Hz

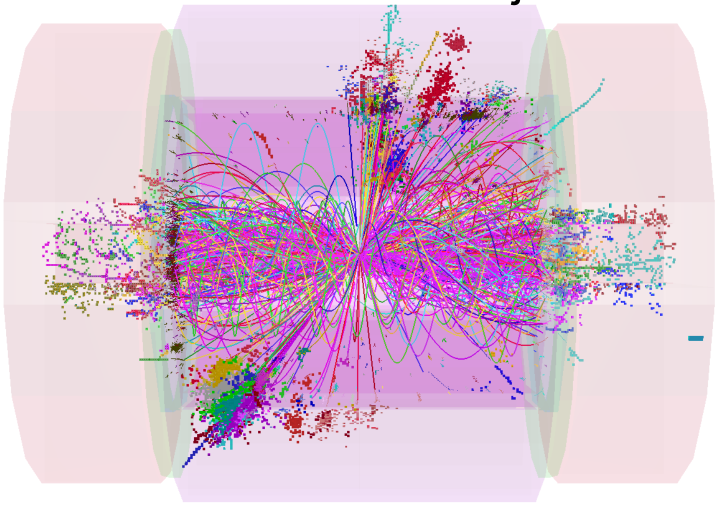
Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
HCAL Endcap	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$
TPC (CLIC_ILD)	Entire train	n/a

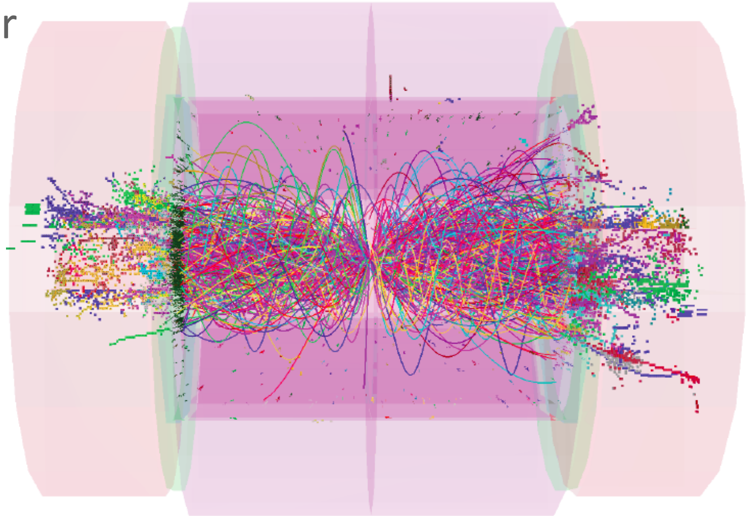
- Example: hadron calorimetry at CLIC and a Muon Collider
- Hadron showers take time to develop – nuclear processes take more than the ns time scale one would like
- How is resolution affected by integration time for various schemes?
  - Dual readout
  - PFA
- How is resolution affected by choice of absorber and sensor material and pixelation

CLIC

- Full event reconstruction + PFA analysis with background overlaid
  - => physics objects with precise p_T and cluster time information
  - Time corrected for shower development and TOF
- Apply cluster-based timing cuts
  - Cuts depend on particle-type, p_T and detector region
  - Allows to protect high-p_T physics object
- Use well-adapted jet clustering algorithms
  - Making use of LHC experience (FastJet)

$e^+e^- \to H^+H^- \to 8$ jets



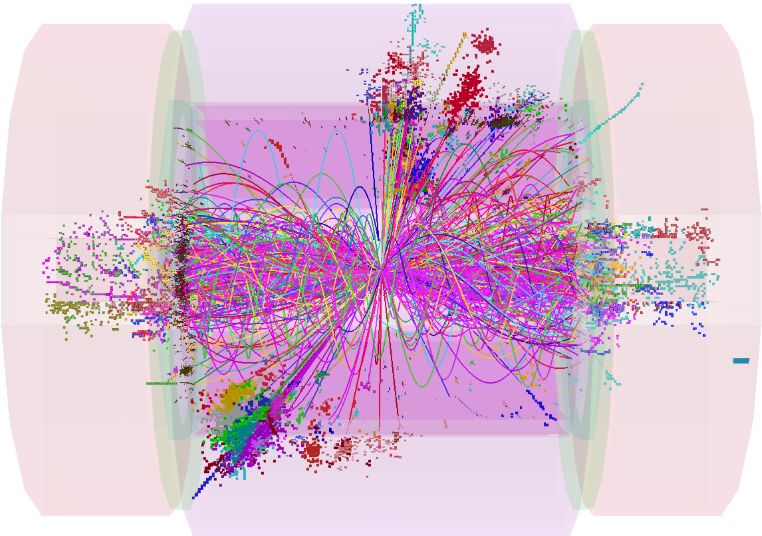


20 BXs = 10 ns of $\gamma\gamma \to$ hadrons

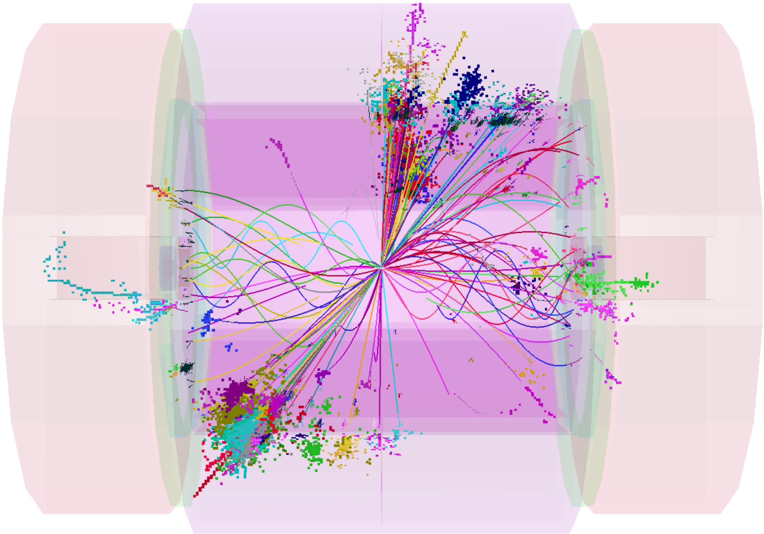
CLIC

t_0 physics event (offline)

- Triggerless readout of full train anticipated; Reconstruction windows from 10 - 100ns; Powerpulsing at 50 Hz



1.2 TeV background in reconstruction time window



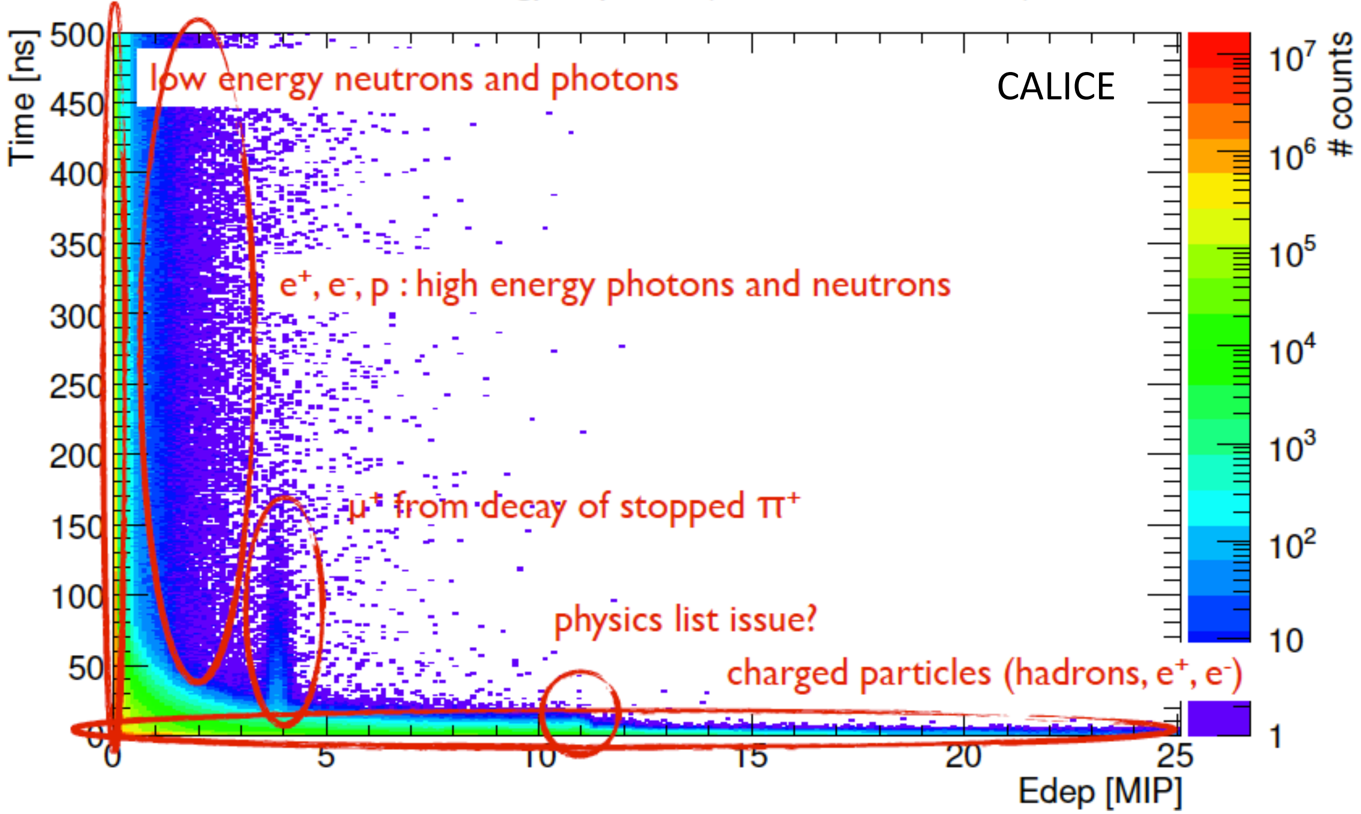
100 GeV background after tight p_T and timing cuts

$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8 \text{ jets}$$

Particle Flow Challenge

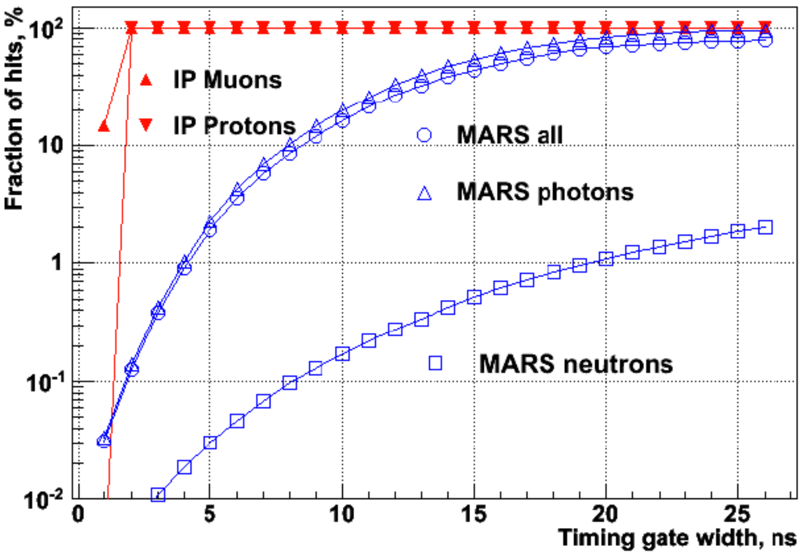
- Timing is a key control of the backgrounds
- Tension between signal formation and calorimeter integration and background control

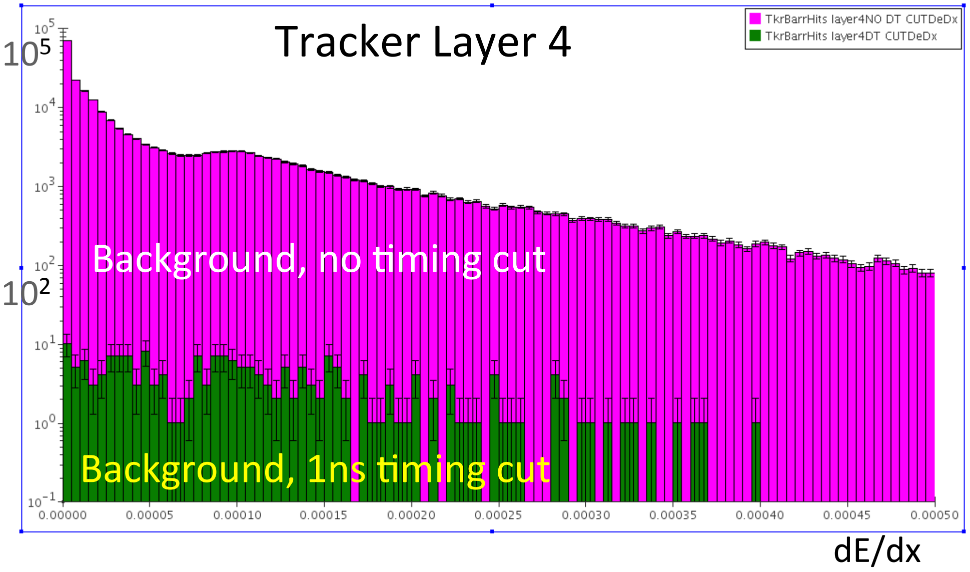
- Geant4 simulation of a 30 layer Scintillator-W calorimeter (QGSP_BERT)
  - Time distribution of energy deposits (no detector effects!)



Muon Collider Background Challenge

- Muon decays from the beams are the dominant background at a muon collider
  - For a 62.5 GeV muon beam of 2×10^{12}, 5×10^{6} decays/m per bunch crossing
  - For a 0.75 TeV muon beam of 2×10^{12}, 4.28×10^{5} decays/m per bunch crossing; 0.5 kW/m.



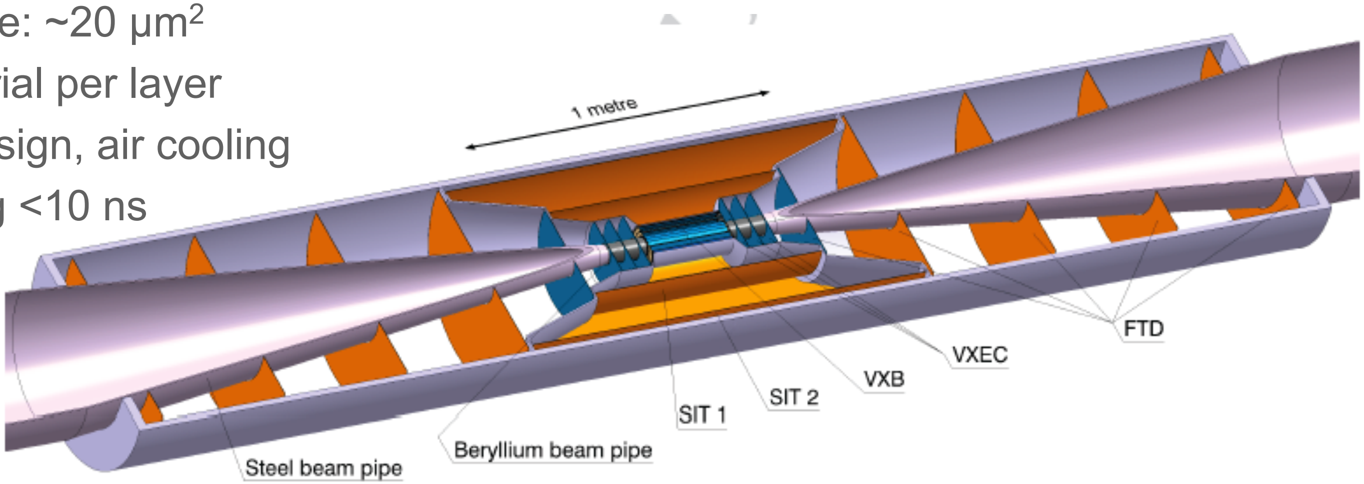


- Timing is the most important handle to reduce the background at a Muon Collider
  - Reduces backgrounds by 3 orders of magnitude
  - dE/dx also is also needed for S/N and time walk corrections
- Also critical for ILC/CLIC

Vertex Detector Challenge at CLIC

- Very large pixel detectors, power pulsed
  - Radiation level $<10^{11}$ n_{eq} cm^{-2} yr^{-1}
  - Small pixel size: ~20 µm^2
  - 0.1% X_0 material per layer
  - Low-power design, air cooling
  - Time stamping <10 ns

CLIC vertex detector

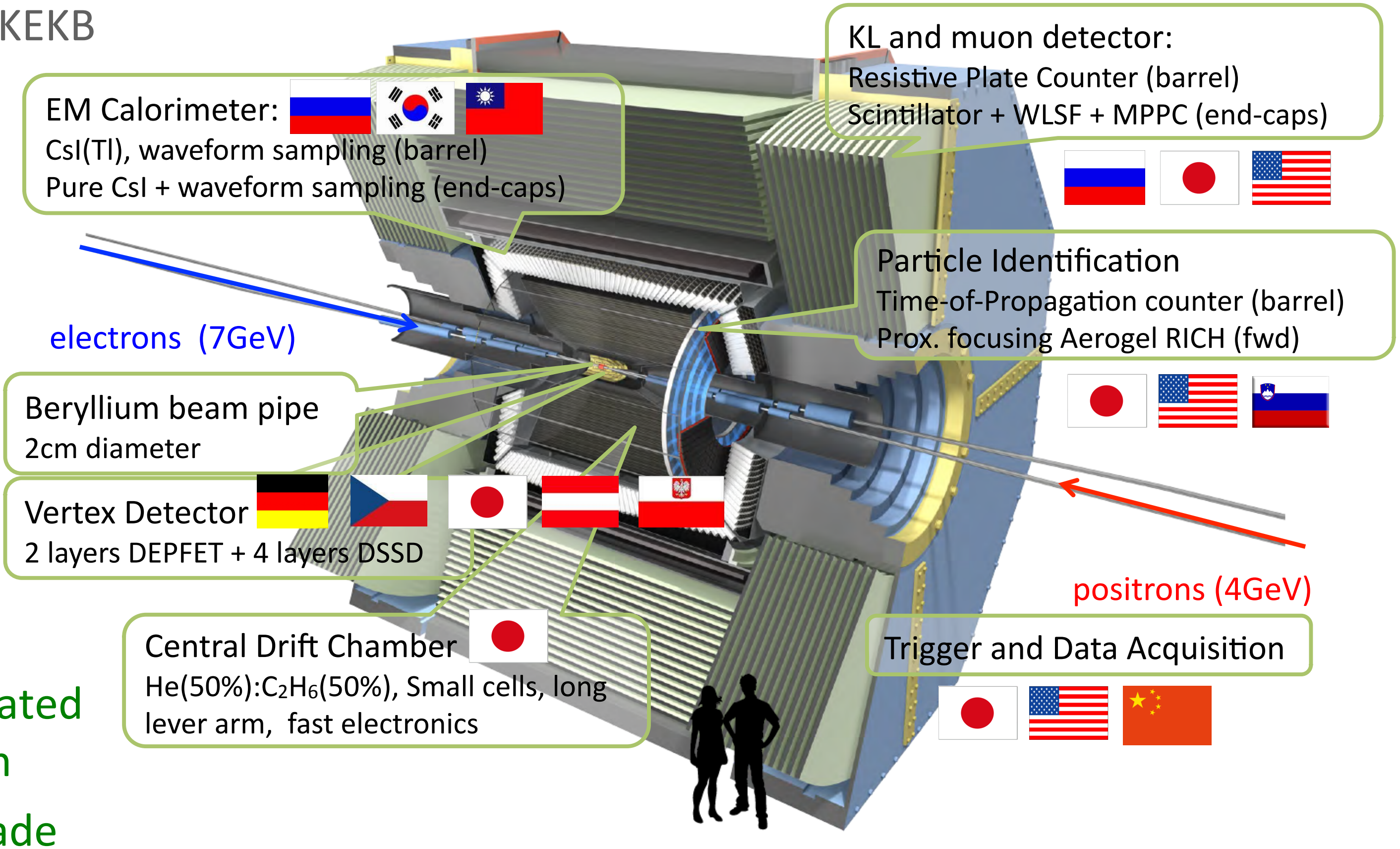


	CLIC_ILD	CLIC_SiD	CMS
Material X/X0 (90º)	~0.9% (3x2 layer)	~1.1% (5 layer)	~10% (3 layer)
Pixel size	20 x 20 µm^2	20 x 20 µm^2	100 x 150 µm^2
# pixels	2.04 G	2.76 G	66 M
Time resolution	~10 ns	~10 ns	<~25 ns
Avg. power/pixel	<~0.2 µW	<~0.2 µW	28 µW

INTENSITY FRONTIER

B-Factories

- Belle II at SuperKEKB



KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electrons (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4GeV)

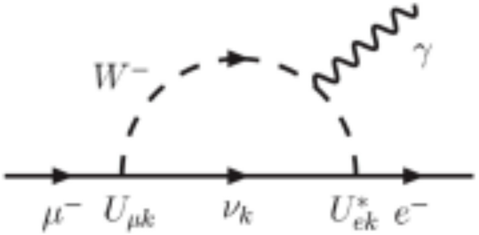
Central Drift Chamber
$He(50\%):C_2H_6(50\%)$, Small cells, long lever arm, fast electronics

Trigger and Data Acquisition

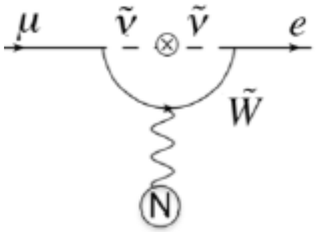
- Very well motivated physics program
- BELLE II.V Upgrade
  - Endcap crystal calorimeter
  - Replacement of Belle II pixels with radiation hard pixel detector
  - Cluster counting (dN/dx) in drift chamber for PID
  - Trigger/DAQ/electronics

Charged Lepton Flavor Violation

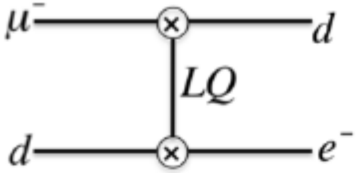
- MEG and Mu2e experiments aimed at CLFV



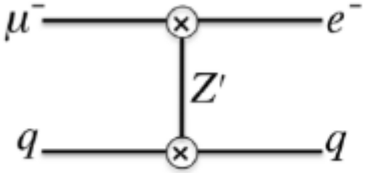
Br(μ-> eγ) < 10^{-54}



SUSY

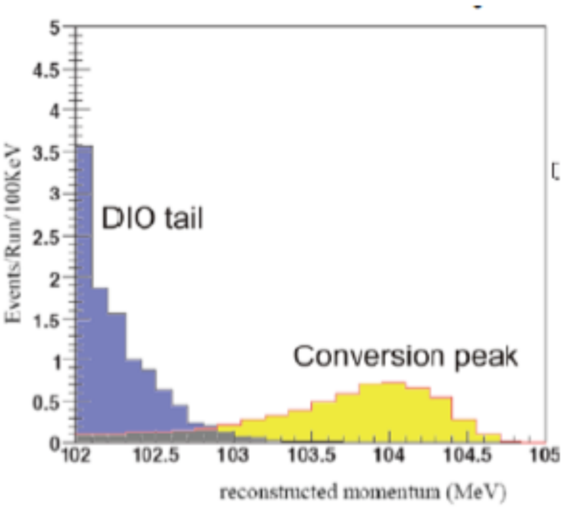


Leptoquarks



FCNC with Z'

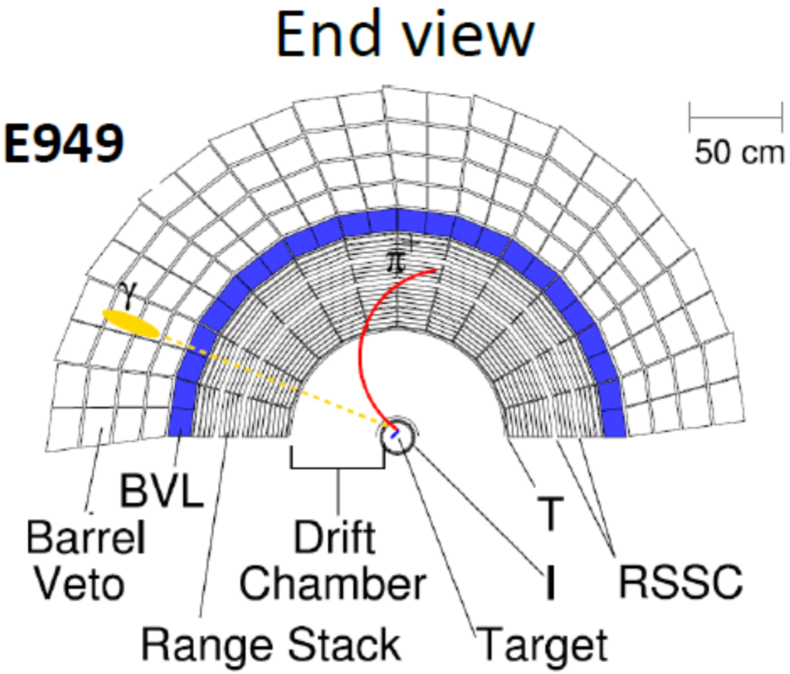
- Limiting factors for the Mu2e conversion experiment are:
  - Precision tracking with very low (<0.1% X_0) mass to reject decays in orbit from conversions:
    $\delta p/p$ of 0.1% on 100 MeV electrons.
  - Intensity: high rates imply need for low latency and resistance to radiation damage
  - Proposed Straw tracker:
    21600 straws, 12.5 μm wall straws in vacuum
    100 kHz per straw

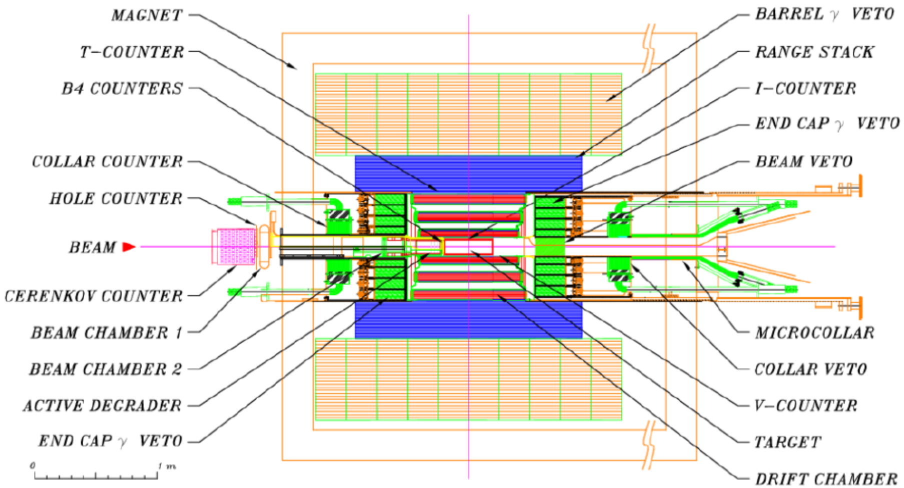


B. Svobodo

Rare K-Decays

- ORKA experiment uses stopped Kaon beam
- Resolve K^0 -> π^0 $\nu\nu$ from background

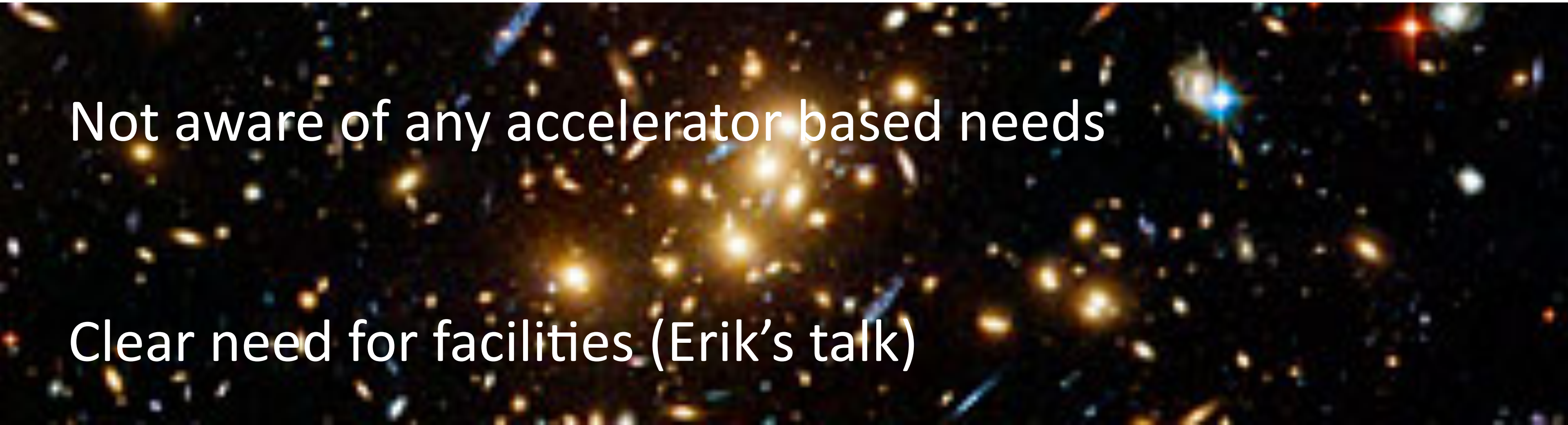




- Very low-mass tracking needed
  - 0.2% X_0 in tracking volume
  - $\sigma(p)/p < 1\%$ at 150-250 MeV
  - B = 1.3 Tesla
  - 150 kHz rate per wire for drift chamber configuration

- Need for well-understood, high rate, background free low momentum particle beams

COSMIC FRONTIER



Not aware of any accelerator based needs

Clear need for facilities (Erik's talk)

Observations

- There is a very strong demand for beam tests, especially for the LHC experiments and for ILC/CLIC
  - Particle compositions of the beam
  - Momentum range of the beam
  - Flux of the beam
  - Particle time spacing
  - Repetition rate: Optimized duty cycle for beam tests to allow for rapid collection of data is desirable

- The issue of beam time structure that mimics actual running conditions deserves further investigation

- Improvements to overall infrastructure to enable larger scale, realistic beam tests very beneficial
  - Would a formulation of a test beam infrastructure program along the lines of the EUDET program be a worthwhile exercise?

Conclusion

- We are in the process of understanding the anticipated needs of various frontier physics goals to determine the details and their criticality

- Some requests could be quite difficult to accomplish, such as dedicated time structures with external beam clock trigger signals

- Jaehoon Yu, Erik Ramberg and Carsten Hast are writing a whitepaper that will compile existing test beam, irradiation and low-background facilities inside and outside of the country and will outline the future needs

- Your input is appreciated

European Framework Program: EUDET

- EUDET was a Detector R&D program to develop research infrastructure for detector R&D in Europe for the International Linear Collider.
- Supported by the European Union in the 6th Framework Program
- Funding: €21.5M, of which €7M from EU
- Participation: 31 partner institutes from 12 countries
- Funding period: 2006-20010
- Very successful in building infrastructure for detector development

Activities
Management of Infrastructure Initiative
Detector R&D Network
Access to DESY Test Beam Facility
Access to R&D Infrastructure
Test Beam Infrastructure
Infrastructure for Tracking Detectors
Infrastructure for Calorimeters

- The EUDET project was officially closed on 31st December 2010 followed by AIDA

European Framework Program: AIDA

- Advanced Infrastructures for Detectors at Accelerators (AIDA)
- Supported by the European Union in the 7th Framework Program
- Targets infrastructures required for detector development for future particle physics experiments: SLHC, Linear Colliders, neutrino facilities, B-factories in line with European strategy
- Project coordination: CERN
- Funding: €26M, of which €8M from EU
- Participation: 80 partner institutes from 23 countries
- Funding period: 2011-2014

- Broad base of infrastructures covered:
  - Test beams, irradiation facilities, common software tools, common microelectronics tools and engineering coordination offices.
  - AIDA will work closely with industry to develop new technology to lead to new applications for society.

AIDA

Advanced European Infrastructures for Detectors at Accelerators

AIDA Structure

- Work Package structure for AIDA

WP1: Project management and communication
Scientific coordinator Laurent Serin, LAL-CNRS, Deputies : T. Benhe (DESY) & P. Soler (STFC)
Svet Stavrev, CERN administrative coordinator

Networking

WP2: Common software tools (Frank Gaede, DESY, Pere Mato, CERN)

WP3: Microelectronics and interconnection technology (Hans-Gunter Moser, MPG, Valerio Re, UNIBG)

WP4: Relation with industry (Jean-Marie Le Goff, CERN)

Transnational access

WP5: Transnational access DESY (Ingrid Gregor, DESY)

WP6: Transnational access CERN (Horst Breuker, CERN)

WP7: Transnational access European irradiation facilities (Marko Mikuz, JSI)

Joint research

WP8: Improvement and equipment of irradiation and test beamlines (Michael Moll, CERN)

WP9: Advanced infrastructure for detector R&D (Marcel Vos, IFIC Valencia, Vincent Boudry, LLR-CNRS)

AIDA

Advanced European Infrastructures
for Detectors at Accelerators

Muon Collider

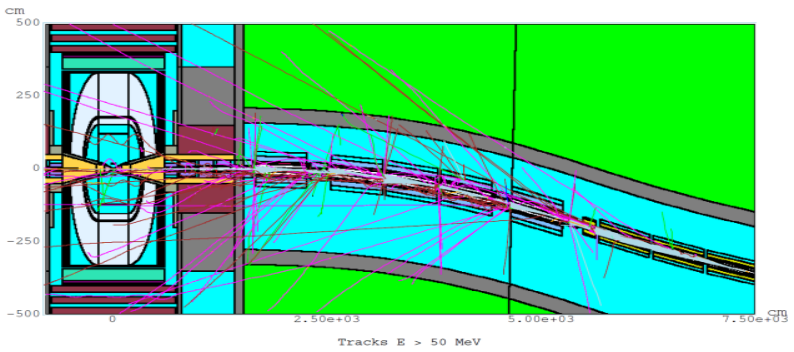
	Physics	Background
#cluster	1166	4x10^9
#tracks found	89	2110

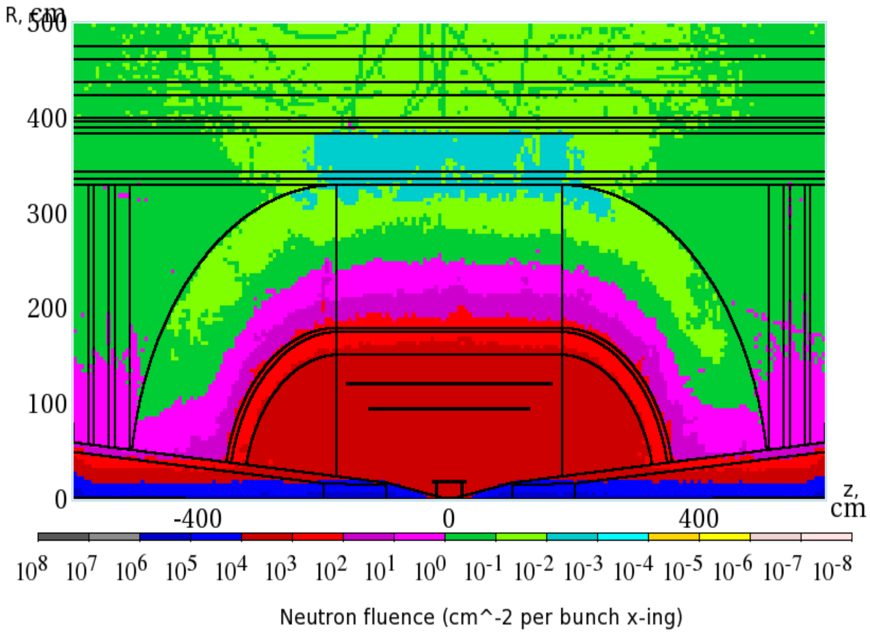
Physics tracks w/ >1 fake cluster: <5%

	γ	n	e
#particles	1.7 10^8	0.4 10^8	1.0 10^6
Fraction w/hits	2.8%	4.2%	43%
#particles w/hits	5.0 10^6	1.7 10^6	0.4 10^6

No timing cut

Timing cut crucial to reduce backgrounds





Neutron fluence:

~10% LHC at 1st lyr silicon