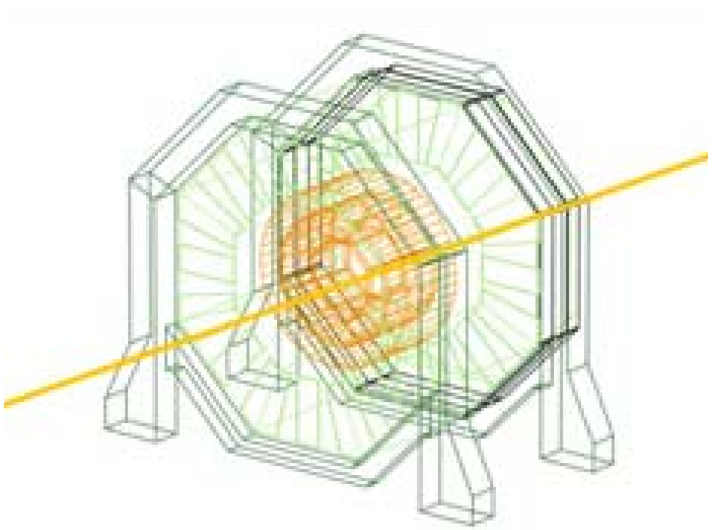
Detectors at Lepton Colliders

The Next Generation



Marcel Demarteau

Fermilab

Neutrino Factory and Muon Collider
Collaboration Meeting

Fermilab, March 17-19, 2008

Disclaimer

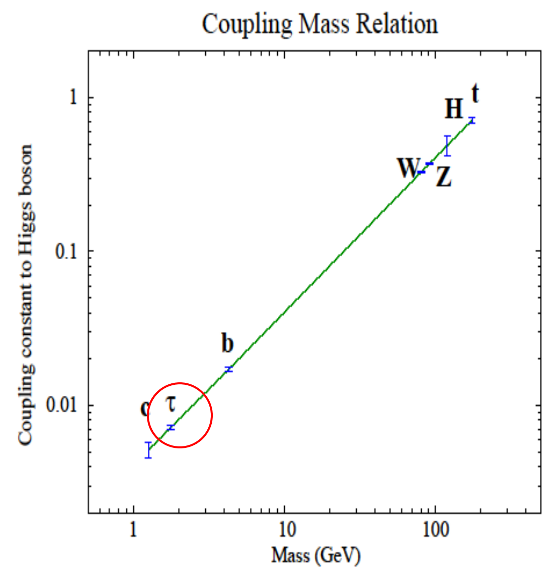
- **Please forgive my ignorance !**
- **Currently I know very little about muon colliders and am only slowly starting to learn about the detector issues**
- **A body of literature exists that I've only partially perused**

- **However, I have a strong conviction that the new detector technologies that are being studied at the lab and world-wide have a broad range of applicability and that the synergy between various projects – such as ILC / CLIC / MC / LHC Upgrades / Project X – should be vigorously pursued.**
- **Moreover, the timing for discussion about detector technologies is right**
- **Hopefully this is the start of a dialogue between the different communities to explore the synergies and perhaps develop the physics tools within a common framework**

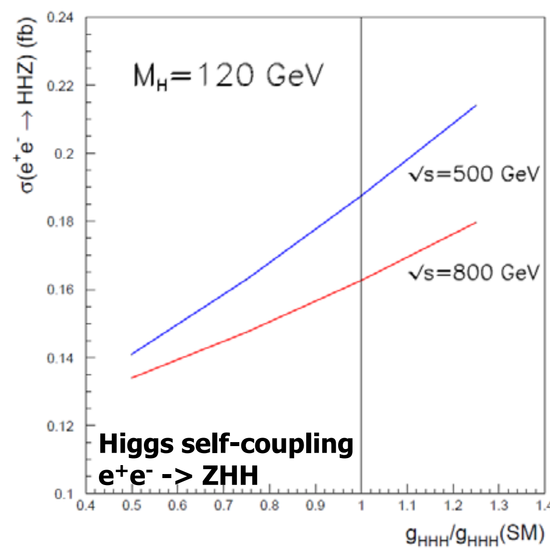
- **All comments are my personal observations; all mistakes are mine**

Detector Concept

- **Detector design is mainly driven by three criteria:**
  - **Physics goals**
    - Choice of detector technology driven by scientific "prejudice"
  - **Machine Detector Interface**
    - Beam backgrounds
    - Beam delivery system, L^*
    - Machine parameters such as bunch crossing, duty cycle, …
  - **Cost**

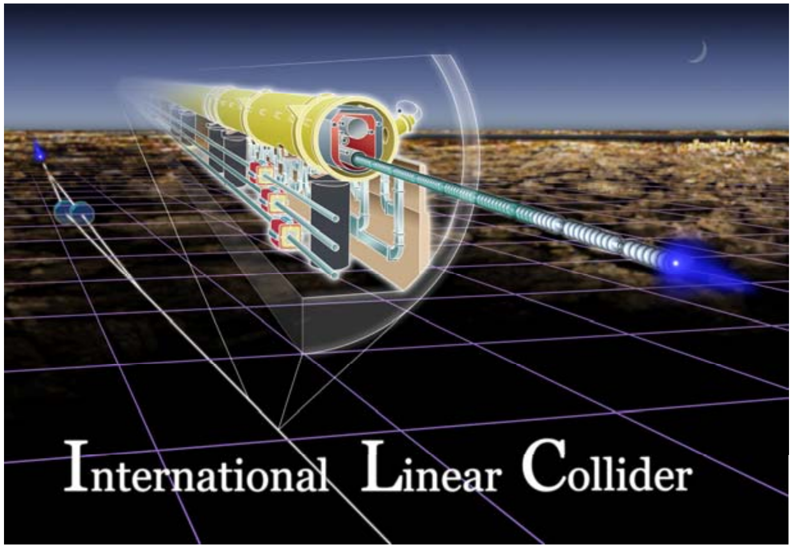


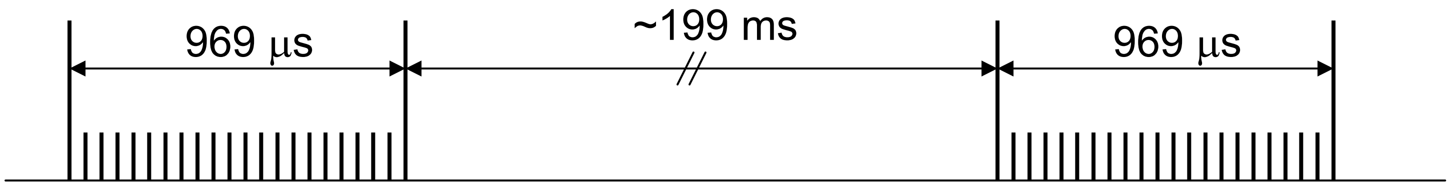
- **Each criterion is (ideally) parametrized in a physics metric**
  - **Physics**
    - e.g.: Importance of palette of physics processes to be measured
  - **Machine Detector Interface**
    - e.g.: the importance of a luminosity measurement
  - **Cost**
    - e.g.: Resolution versus integrated luminosity (running time)



An Example: the ILC

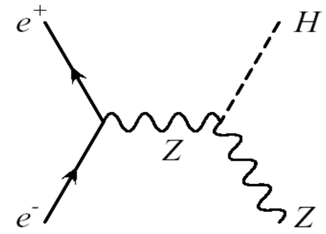
- **Baseline Machine:**
  - E_{CM} of operation 200 – 500 GeV
  - Lumi. and reliability for 500 fb^{-1} in 4 years
  - Energy scan capability between 200-500 GeV with <10% downtime
  - Beam E precision and stability below 0.1%
  - Electron polarization of > 80%
- **Upgrades:**
  - E_{CM} to 1 TeV
  - Capability of running at any E_{CM} < 1 TeV
  - $\mathcal{L}$ and reliability for 1 ab^{-1} in 3 – 4 years
- **Time structure**
  - five trains of 2625 bunches per second
  - bunch separation is 369.2 ns (LEP: 22 μs)





- **Duty cycle (1 ms of data – 199 ms idle) allows for "power pulsing"**
  - Switch power to quiescent mode during idle time
- **Single IR with 14 mrad crossing angle**
- **Beam size: σ_x = 640 nm, σ_y = 6 nm**

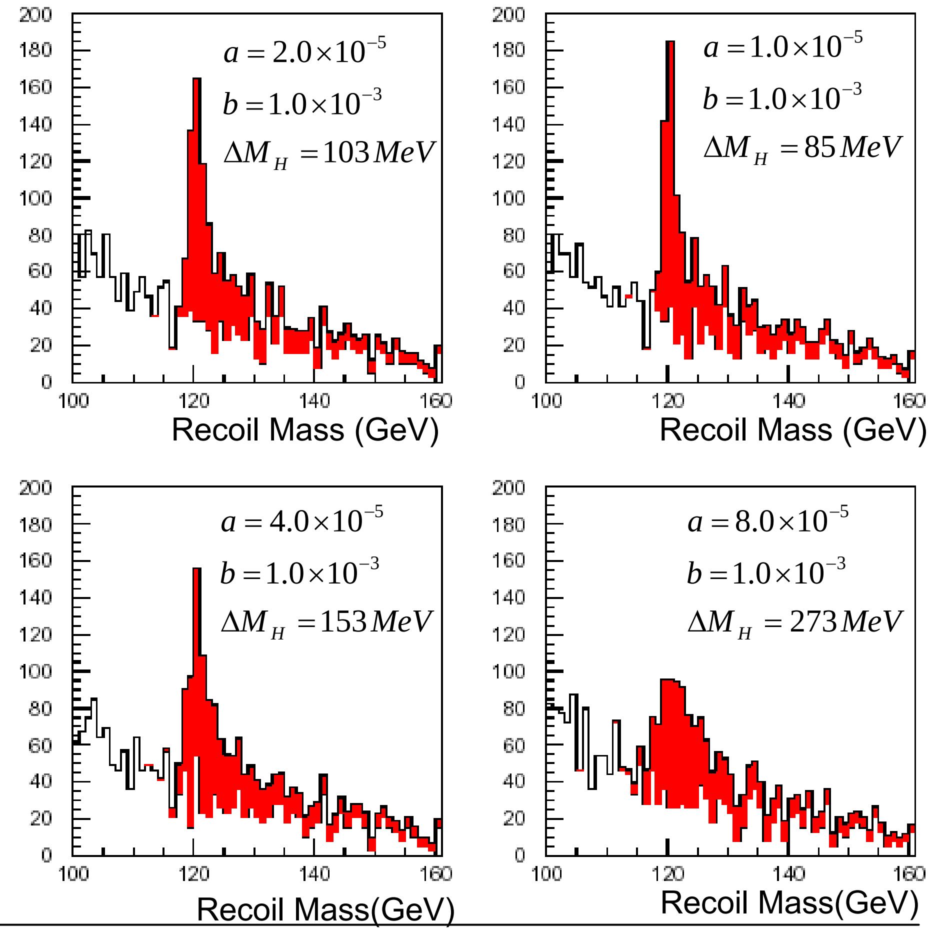
ILC: Higgs Recoil Mass



- **Benchmark measurement is the measurement of the Higgs recoil mass in the channel $e^+e^- \rightarrow ZH$**
- **Higgs recoil mass measurement improves as tracker momentum resolution improves**
  - **Study at $\sqrt{s}$ = 350 GeV and L = 500 fb^{-1}**
  - **Momentum resolution parametrized as**

$$\frac{\delta p_T}{p_T^{\ 2}} = a \oplus \frac{b}{p_T \sin \vartheta}$$

  - **Higgs recoil mass resolution improves until $\Delta p/p^2 \sim 2 \times 10^{-5}$**
  - **An eightfold improvement in resolution is worth a factor of 10 in luminosity!**

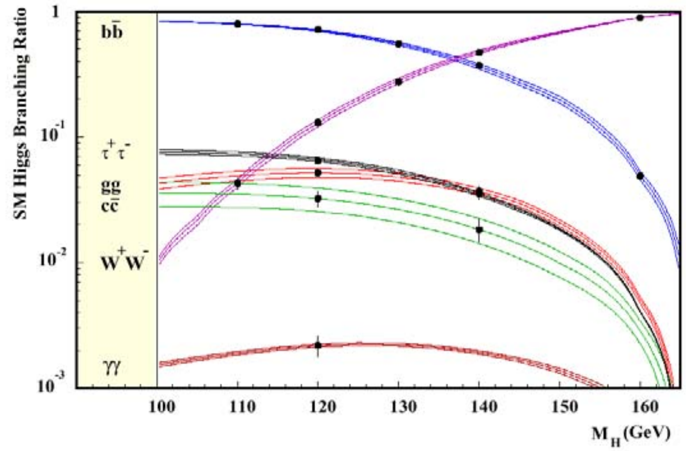


ILC: Higgs Couplings

- **Model independent measurement of absolute Higgs branching ratios: key of EW-symmetry breaking; not possible at LHC**
  - **Establish** $\Gamma(H \to f\bar{f}) \sim m_f$
  - **Needed to distinguish SM Higgs from other Higgs particles**
  - **Key process is ZH strahlung, with Z→ ℓℓ**

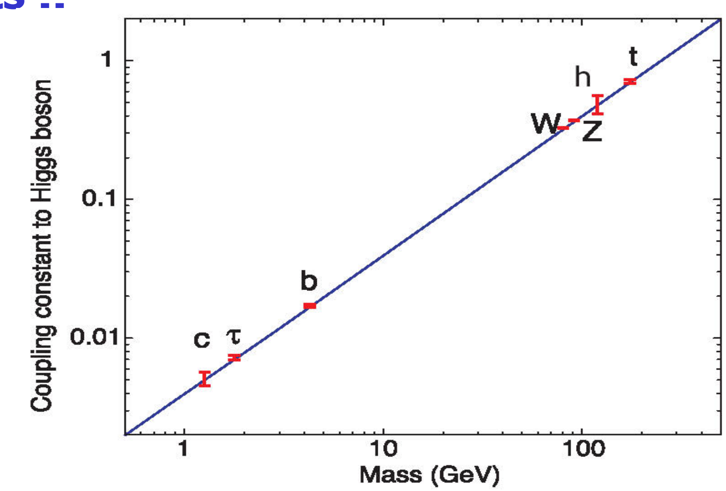
$$BR(H \to X) = \frac{\left[\sigma(HZ) \cdot BR(H \to X)\right]_{meas}}{\sigma(HZ)_{meas}}$$

  - **Completely model independent**



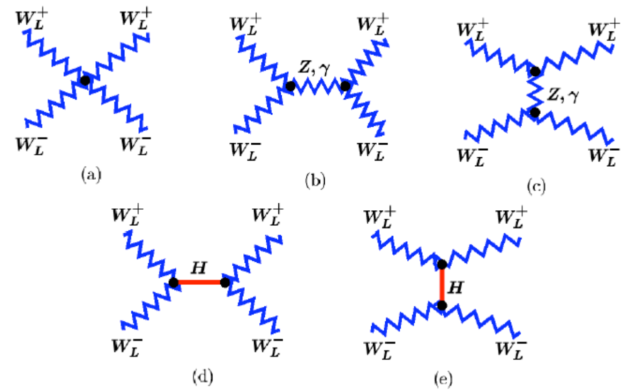
- **Requires identification of all final state objects !!**
  - **It does not suffice to only tag b-quarks !**
  - **Requires very precise impact parameter resolution**

$$\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta) \quad \mu m$$

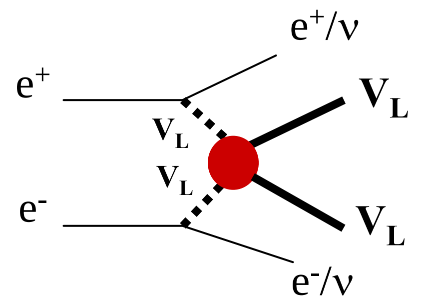


ILC: WW Scattering

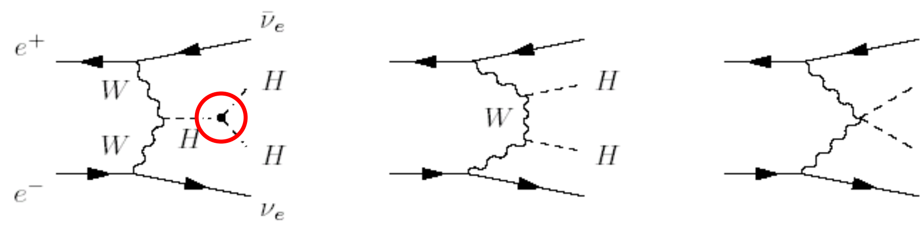
- **In the SM unitarity is conserved in the scattering of W_L through the Higgs mechanism**



- **Precise measurements of vector boson scattering can be indicative of strong EWSB**
  - **$e^+e^- \rightarrow WW\nu\nu$, $WZe\nu$ and $ZZ\nu\nu$ events**
- **Need to discriminate W- and Z-bosons, also in the hadronic decay mode**
  - **Separation of W and Z at 3σ level !**
  - **Requires jet energy resolution of ~3.8% ($\delta m/m \approx 1/\sqrt{2}\ \delta E/E$) independent of jet energy**



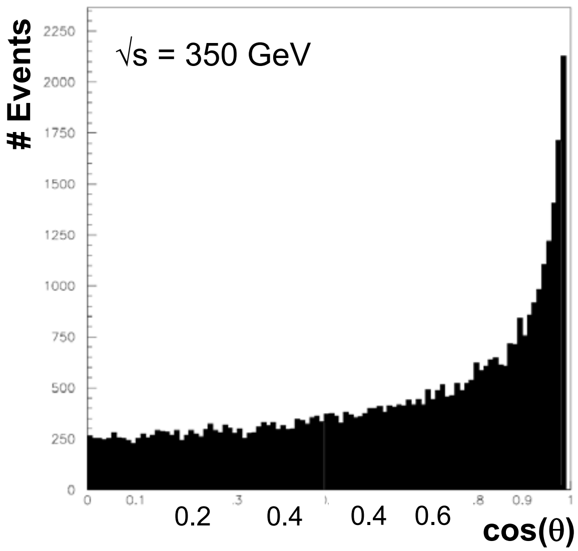
- **Note the similar signatures for the measurement of the Higgs self-coupling**

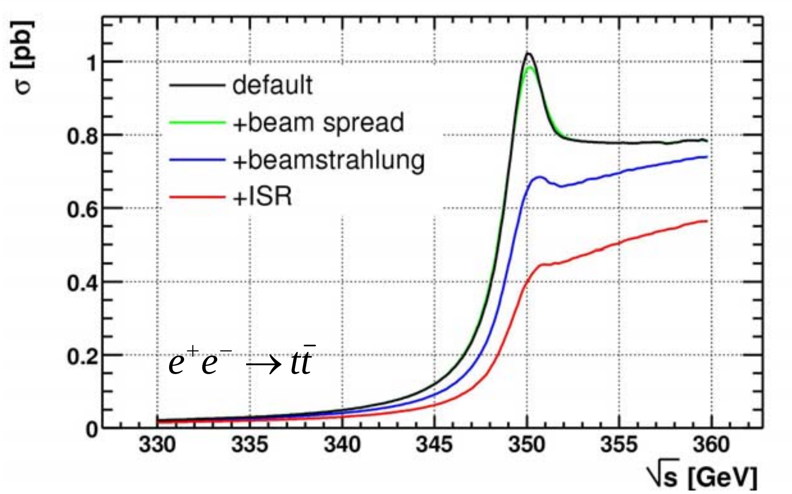


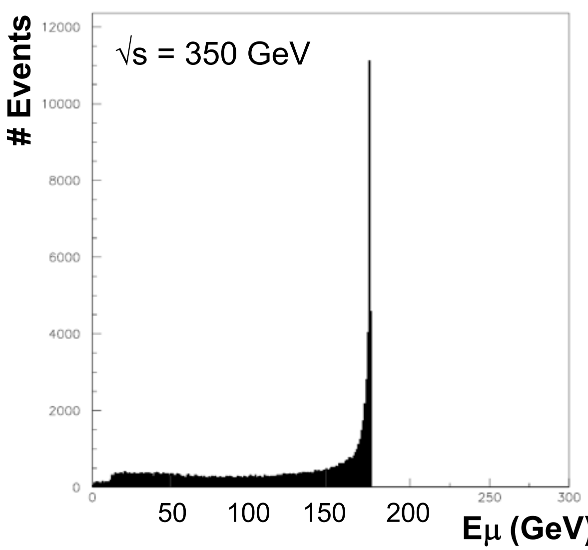
ILC: E_{CM} Determination

- **Center of mass energy requirements**
  - **Top mass: 200 ppm (Δm_t=35 Mev)**
  - **Higgs mass: 200 ppm (Δm_H=60 MeV; m_H=120 GeV)**
- **Determine E_{CM} from $e^+e^- \rightarrow \mu^+\mu^-\gamma$**
  - $e^+e^- \rightarrow \mu^+\mu^-\gamma \qquad at \sqrt{s} = 350\, GeV, \mathcal{L} = 100\, fb^{-1}$
  - **Events predominantly forward**
- **Determination of the Luminosity spectrum**
  - **top-quark pair production threshold scan**

Tim Barklow







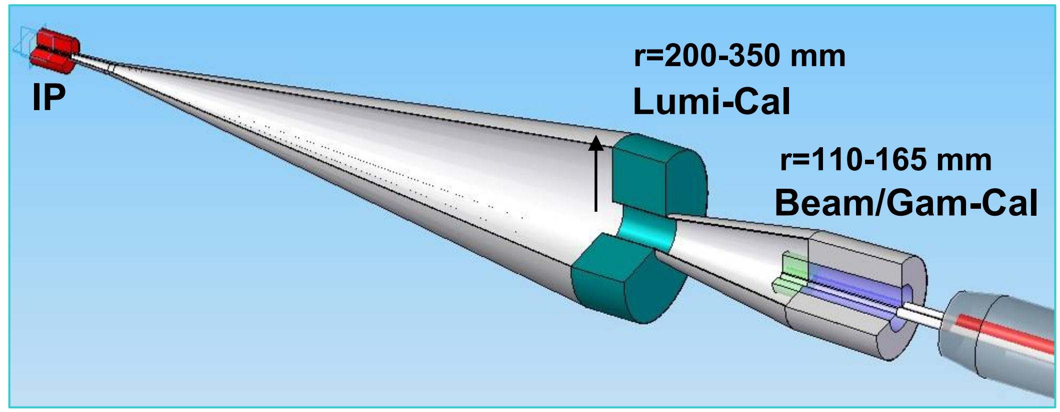
ILC: Far Forward Region

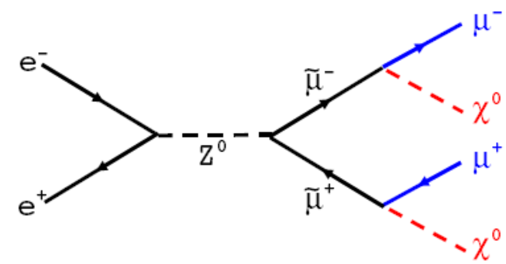
- **Far forward region has three distinct regions with different goals**

- **Lumi-Cal (40-140 mrad)**
  - **Precise measurement of the integrated luminosity ($\Delta L/L \sim 10^{-3}$) using Bhabha's**
  - **Veto for 2-γ processes**

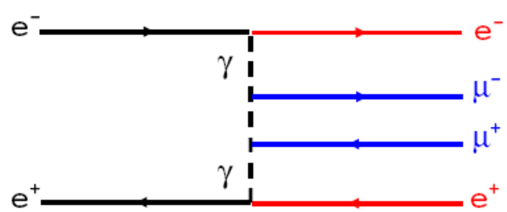
- **Beam-Cal (5-40 mrad)**
  - **Beam diagnostics using beamstrahlung pairs**
  - **Provide 2-γ process veto**

- **Gam-Cal (< 5mrad)**
  - **Beam diagnostics using beamstrahlung photons**



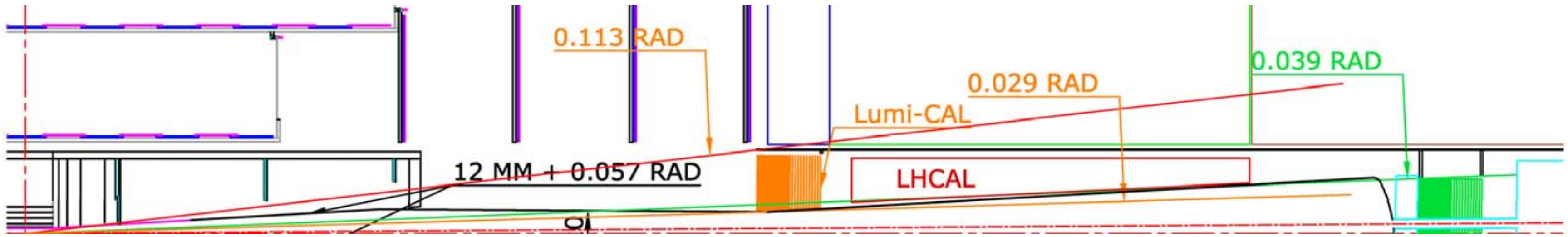


Physics signal: e.g. SUSY smuon production



Background signal: 2-photon event, may fake the above signal if the electron is not detected.

ILC: Far Forward Region



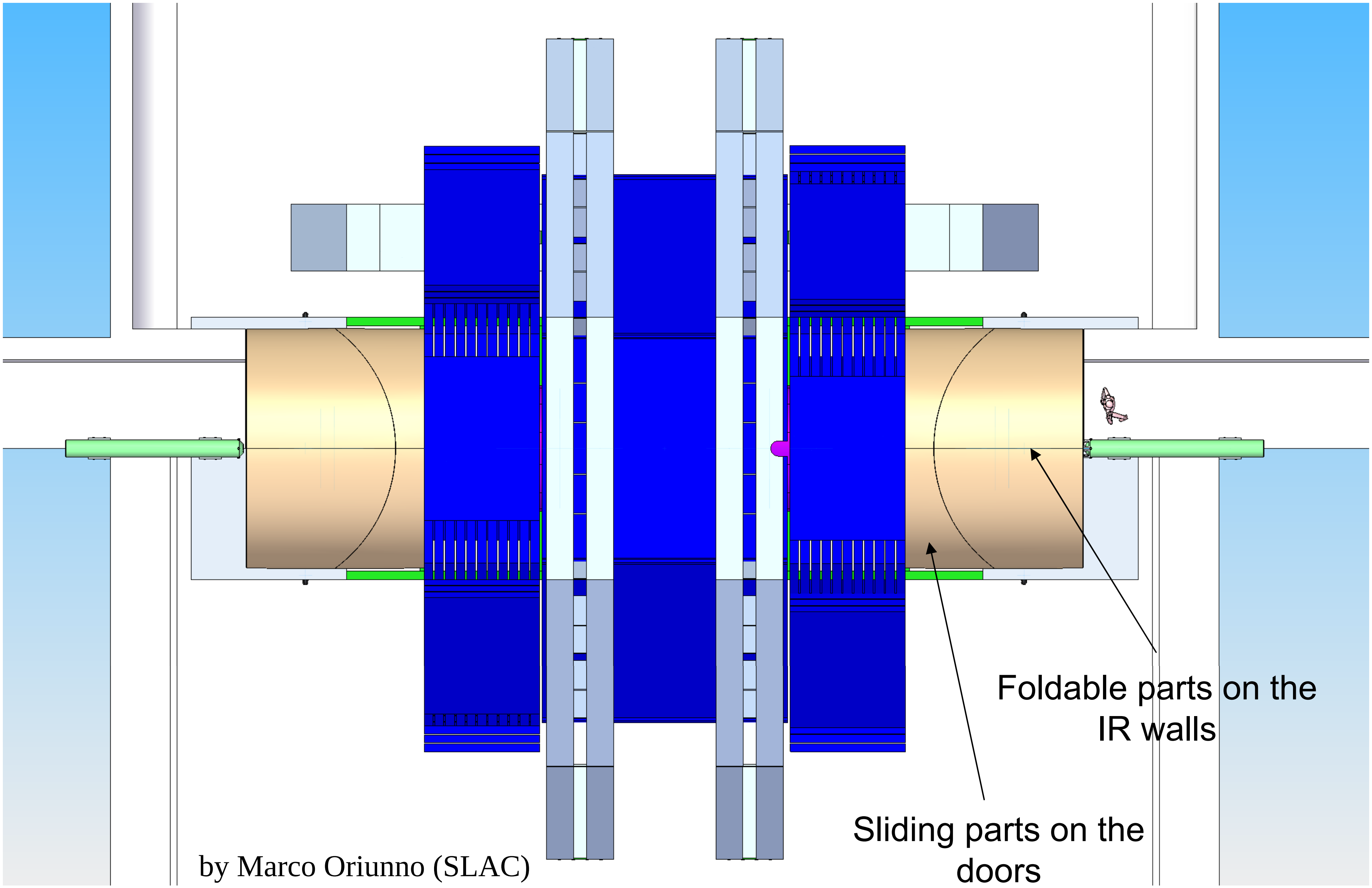
- **Low beta quadrupoles for final focus start at L = 3.5m**
- **Lumi-Cal (40-140 mrad, L = ~1.8m)**
  - **Stringent alignment requirements**

ΔL/L	$1.0\ 10^{-4}$
inner radius	4.2 μm
radial offset	640 μm
distance	300 μm

- **Beam-Cal (5-40 mrad, L = ~3.0m)**
  - **Dose ~500 MRad/annum**
  - **Energy deposit of ~200 TeV per bunch crossing**

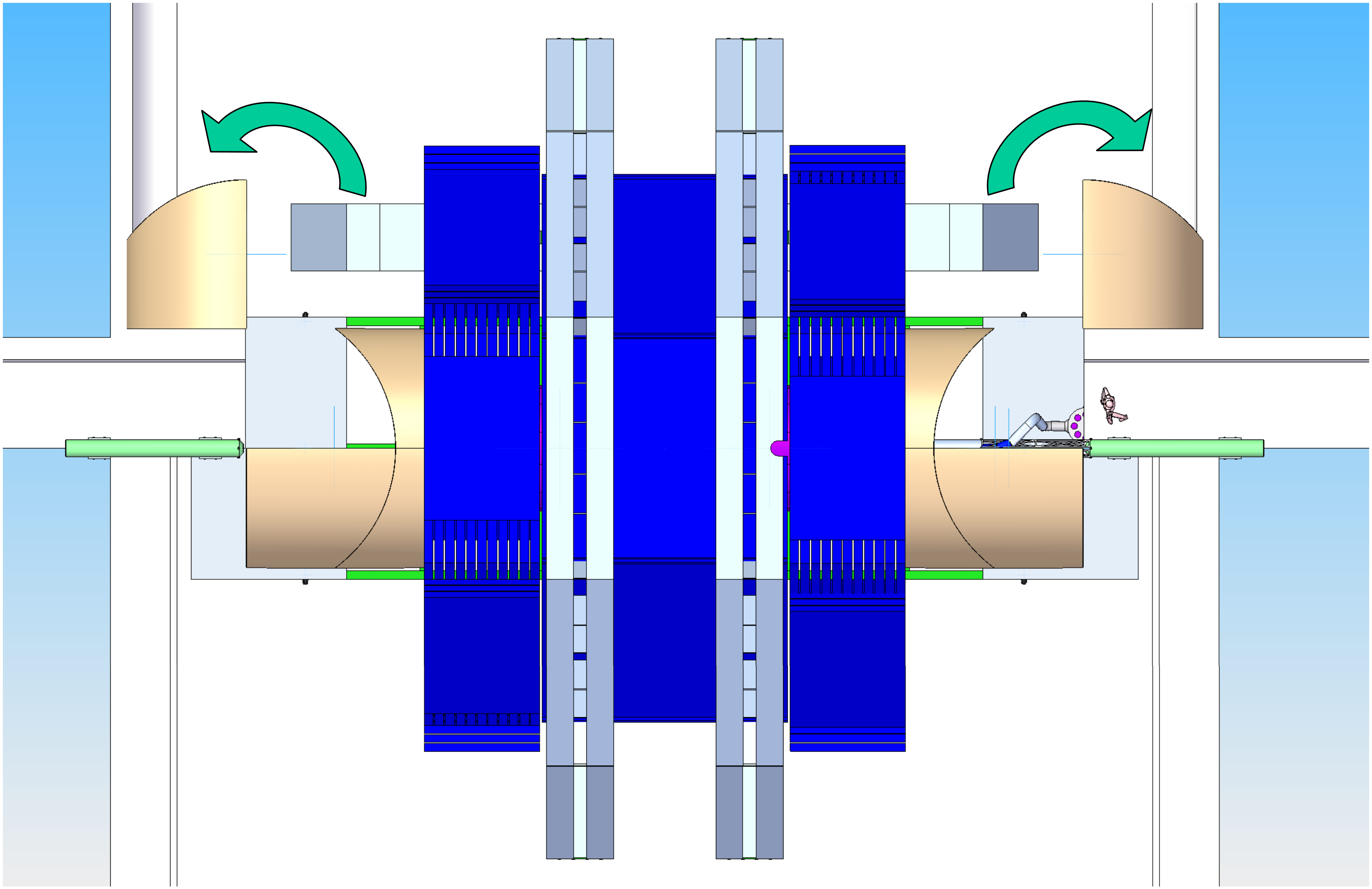
LumiCal inner edge	≈ 36mrad about outgoing
LumiCal outer edge	≈ 113mrad about 0mrad
LumiCal fiducial	≈ 46-86mrad about outgoing
BeamCal inner edge	≈ 5mrad about outgoing
BeamCal outer edge	≈ 46mrad about outgoing
GamCal outer edge	≈ 5mrad about outgoing
LumiCal	$30X_0$ Si-W
BeamCal	$30X_0$ rad-hard Si,diamond….
GamCal	rad-hard Si,diamond….

SiD Forward Shielding

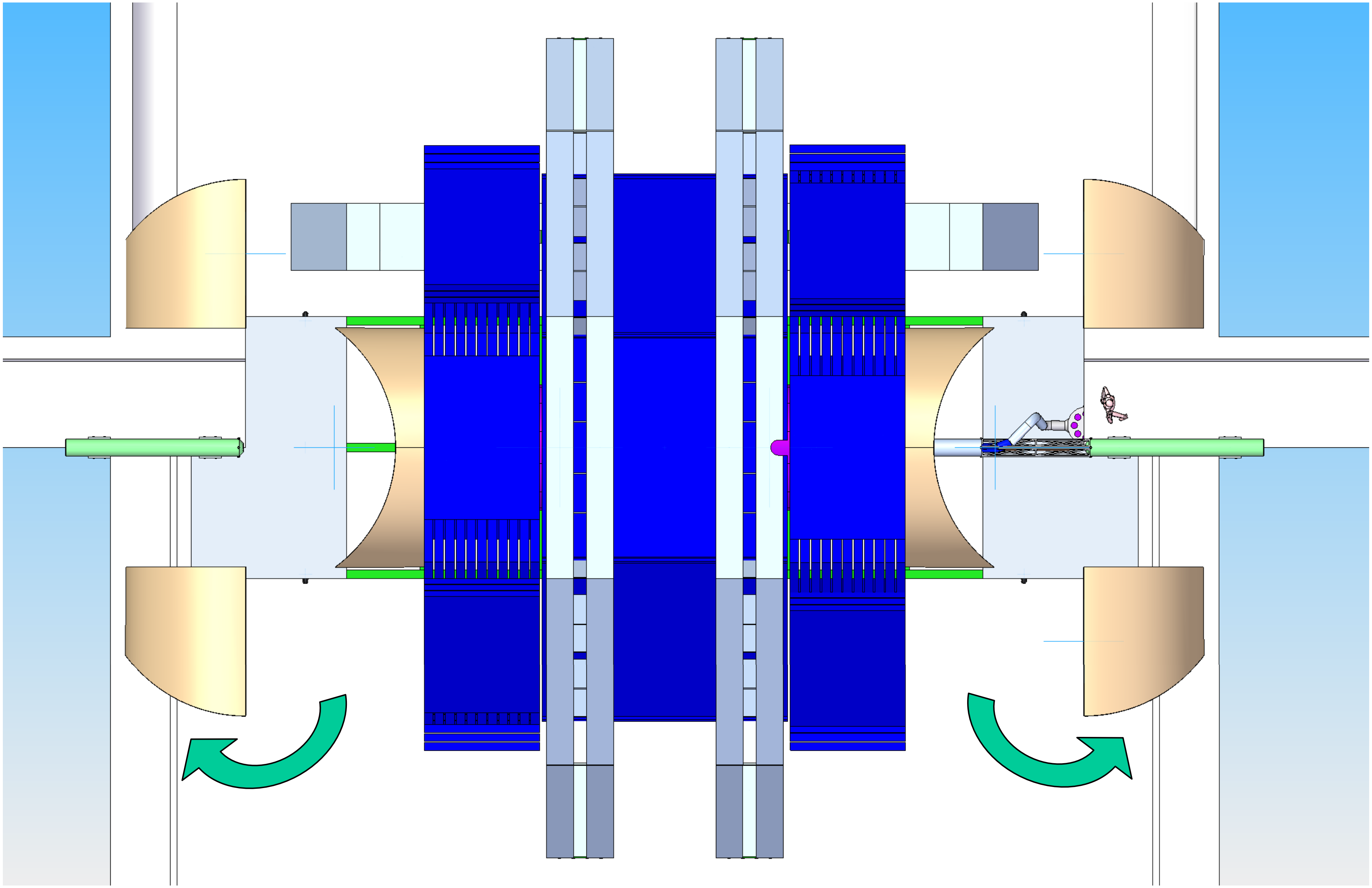


by Marco Oriunno (SLAC)

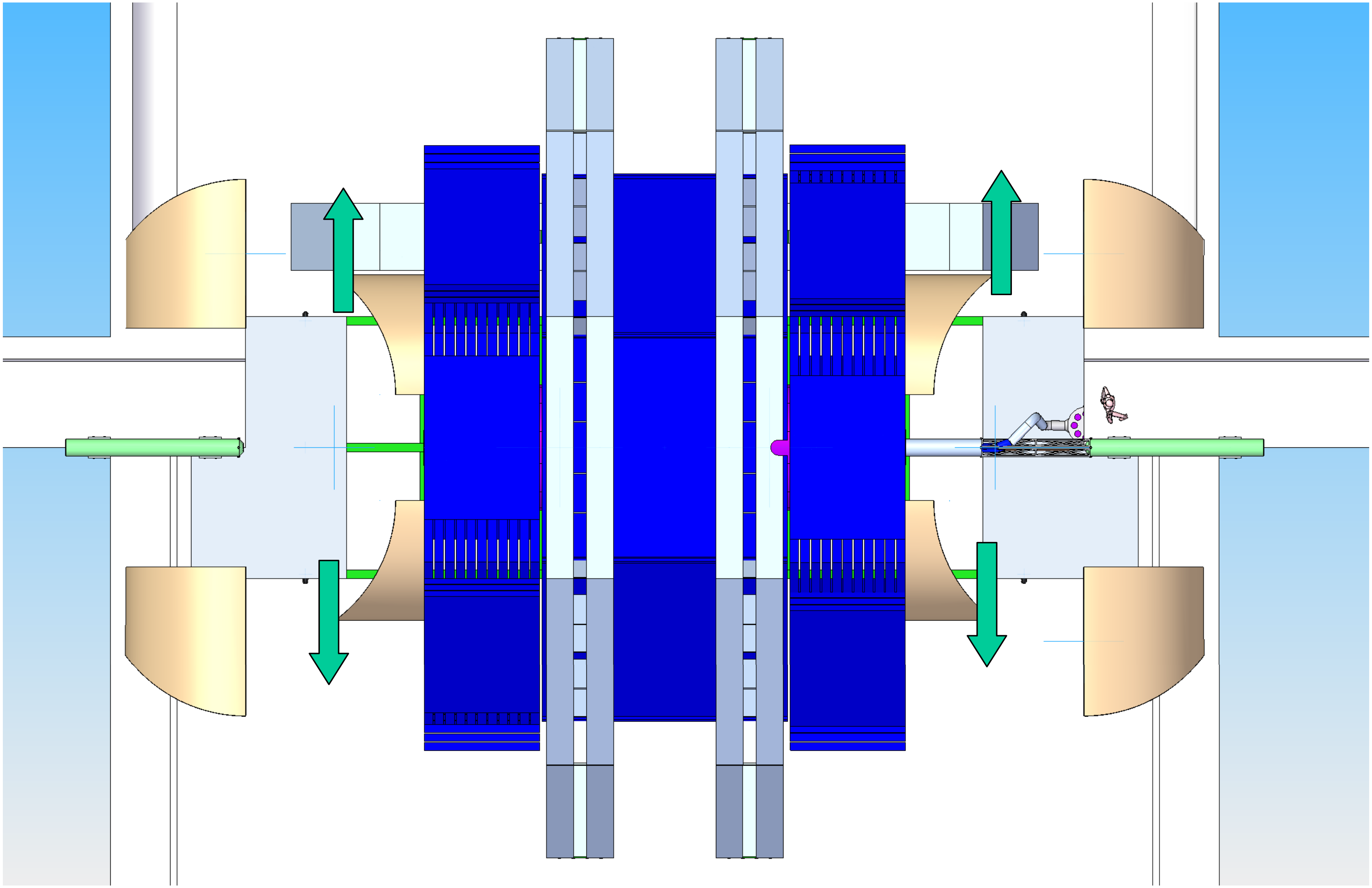
SiD Forward Shielding



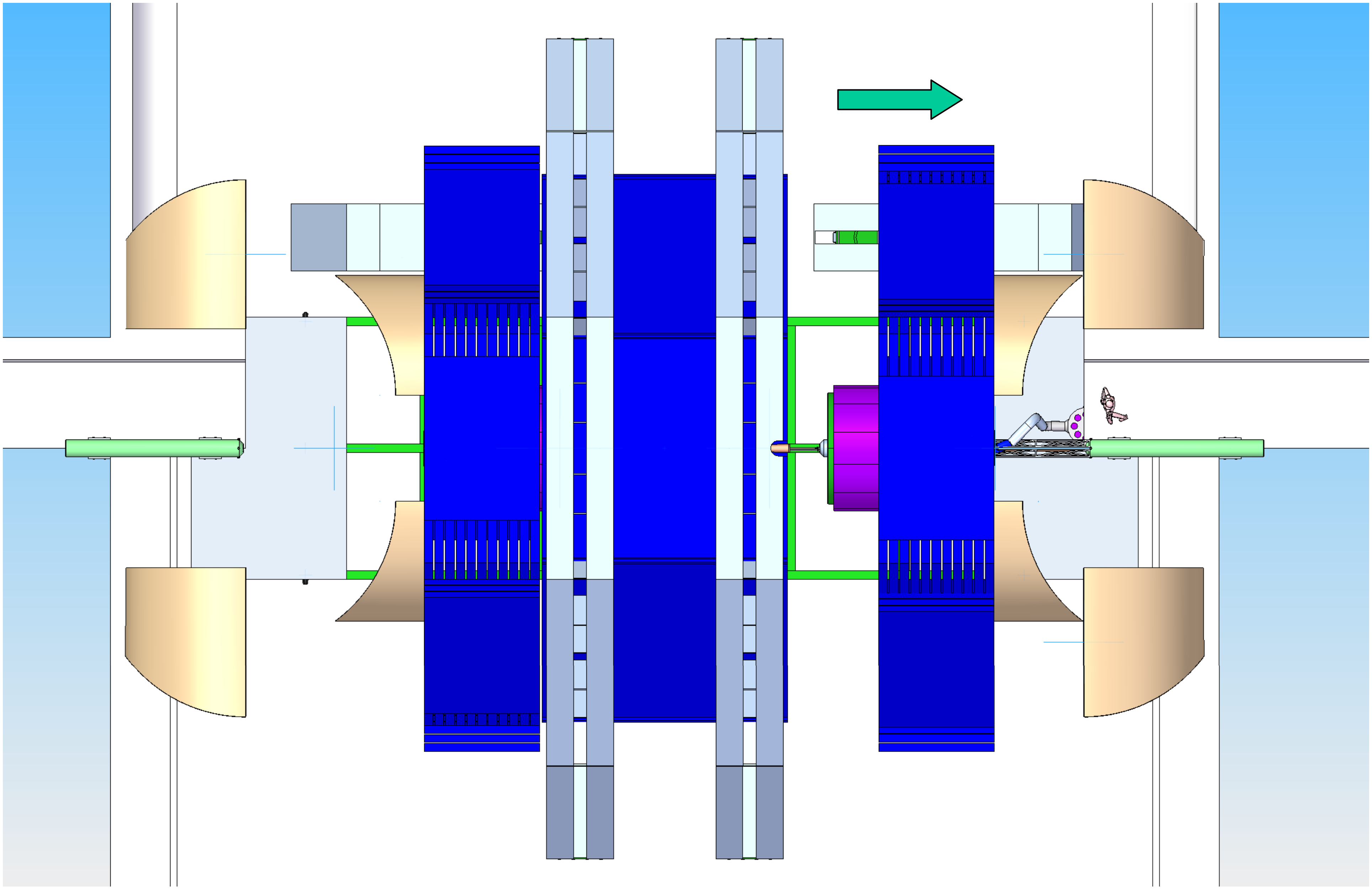
SiD Forward Shielding



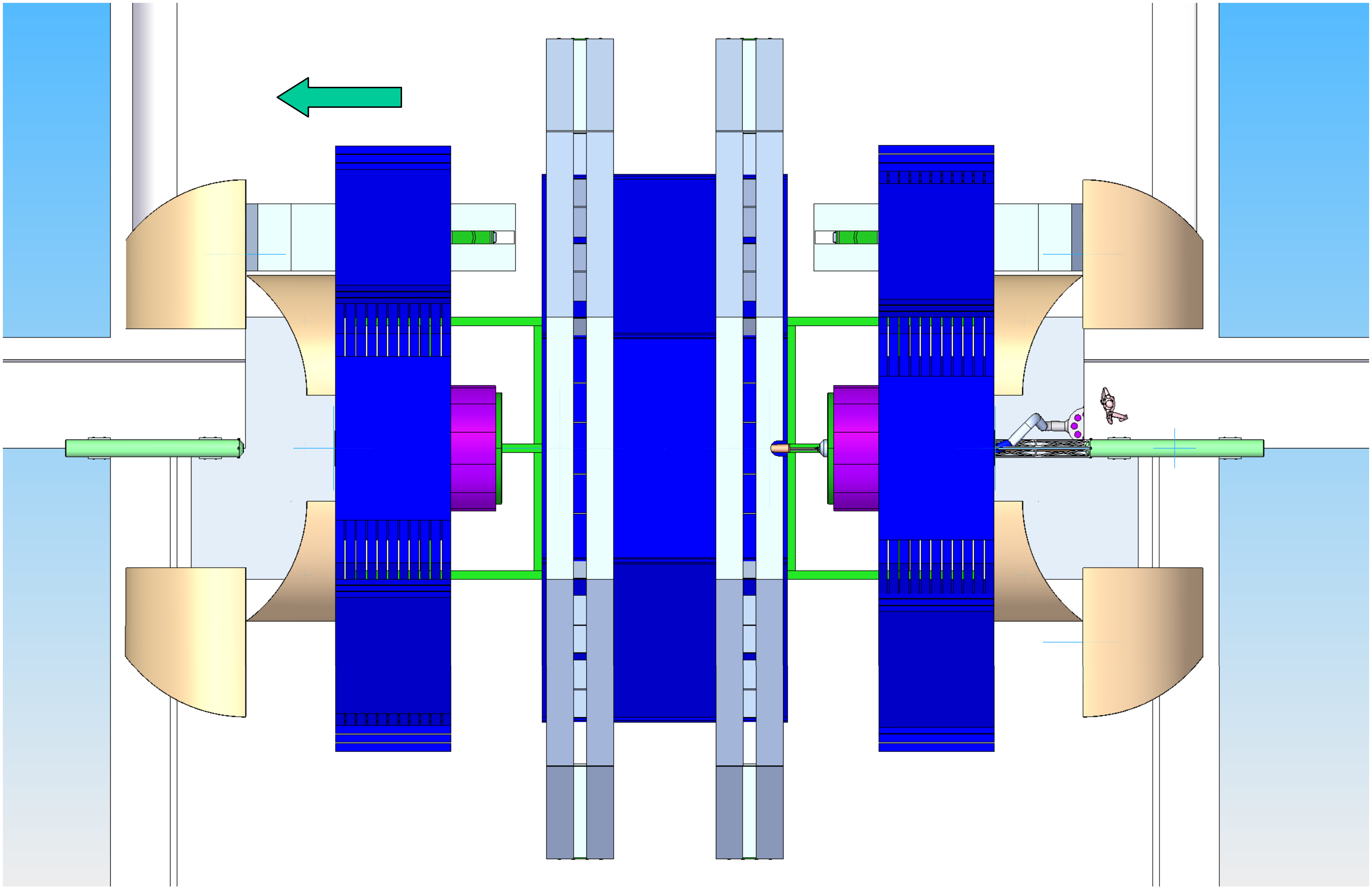
SiD Forward Shielding



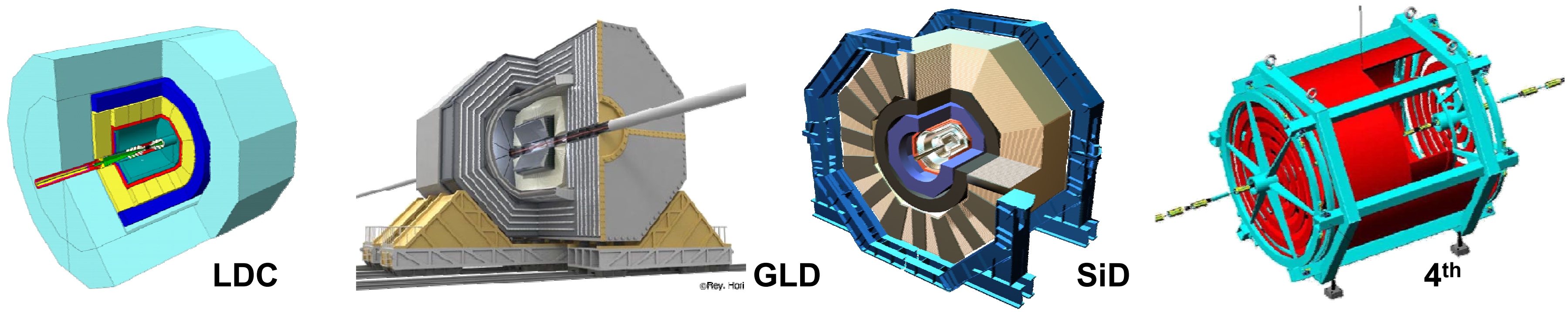
SiD Forward Shielding



SiD Forward Shielding



ILC: Detector Concepts



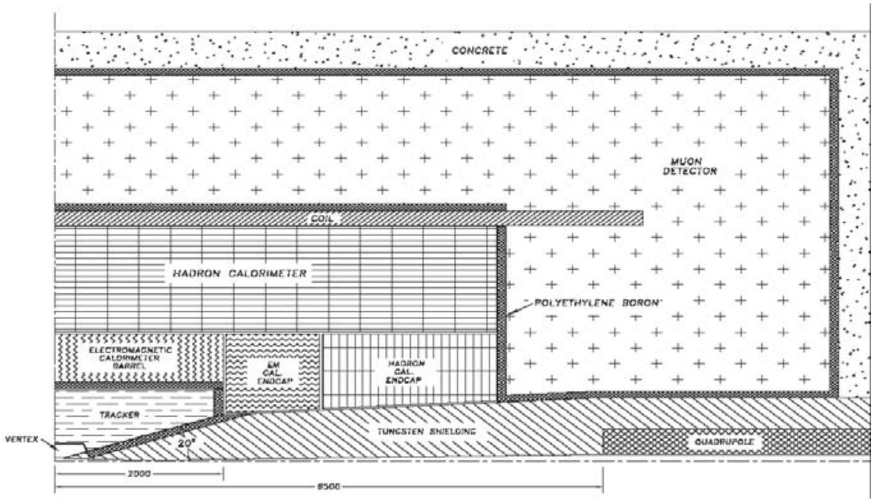
Detector	Premise	Vertex Detector	Tracking	EM calorimeter	Hadron calorimeter	Sole-noid	Muon System
LDC ILD	PFA	5-layer pixels	TPC Gaseous	Silicon-Tungsten	Analog-scintillator	4 Tesla	Instrumented flux return
GLD	PFA	6-layer fine pixel ccd	TPC Gaseous	Scintillator-Tungsten	Digital/Analog Pb-scintillator	3 Tesla	Instrumented flux return
SiD	PFA	5-layer silicon pixel	Silicon strips	Silicon-Tungsten	Digital Steel - RPC	5 Tesla	Instrumented flux return
4th	Dual Readout	5-layer silicon pixel	TPC Gaseous	2/3-readouts Crystal	2/3-readouts Tungsten-fiber	3.5 Tesla	Iron free dual solenoid

- **Many novel, unproven detector technologies employed and required to unearth the physics**

Detector Concept

- Detector concepts will naturally seek to optimize their designs using physics processes.
- The physics community would like to see demonstrated physics capabilities from mature detector designs, e.g. with a reasonable level of engineering, costing, etc.
- It is natural, then, especially with limited resources, to agree upon a common set of analyses to be used to "benchmark" the physics reach of the program and to quantitatively compare different detector concepts

  "… The evaluation of the detector performance should be based on physics benchmarks based upon an agreed upon list and some which may be chosen to emphasize the particular strengths of the proposed detector…" (from ILC 'Guideline for the definition of a Letter of Intent …", Oct. 3, '07)



ILC Benchmarks

- **ILC has proposed a set of benchmark processes to explore both the physics reach and to compare different detector technologies**

1. $e^+e^- \to Zh, \to \ell^+\ell^- X$, $l = e, \mu$; $m_h = 120$ GeV at $\sqrt{s}$=0.25 TeV
2. $e^+e^- \to Zh$, $Z \to q\bar{q}, \nu\bar{\nu}$; $h \to c\bar{c}$, $\mu^+\mu^-$; $m_h = 120$ GeV at $\sqrt{s}$=0.25 TeV
3. $e^+e^- \to \tau^+\tau^-$, at $\sqrt{s}$=0.5 TeV
4. $e^+e^- \to t\bar{t}$ at $\sqrt{s}$=0.5 TeV
5. $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- / \tilde{\chi}_2^0\tilde{\chi}_2^0 \to W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ / $ZZ\tilde{\chi}_1^0\tilde{\chi}_1^0$ at $\sqrt{s}$=0.5 TeV

N.B.: The physics observables that are to be measured have not yet been determined.

- **Stresses various critical aspects of detectors**
  - Efficiencies and resolutions for tracking and calorimetry
  - Heavy flavor tagging, secondary vertex reconstruction
  - tau reconstruction
  - multi-jet final states, dense jet environment, particle flow

Detector Evolution

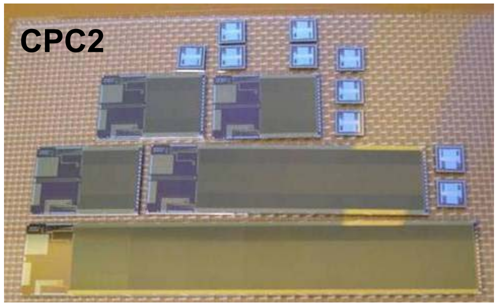
- "ILC detectors appear evolutionary, in fact they are revolutionary"
- The emphasis is on precision which is in part obtained by increasing the channel count by at least an order of magnitude for each subsystem
- Many conventional technologies are being disregarded

- What are the enabling technologies?
  - Advances in silicon technology
    - monolithic devices
    - low power, high channel asic design
  - Advances in photo-detectors

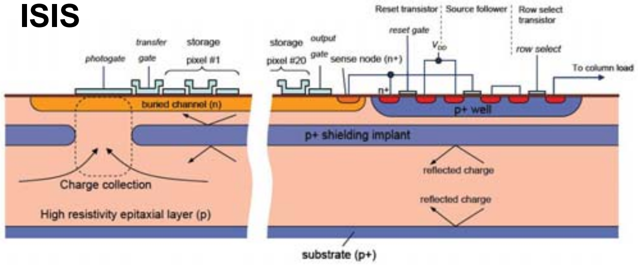
- These new technologies open up previously inaccessible venues
  - Total absorption calorimetry
  - Tera-pixel electromagnetic calorimetry
  - ...

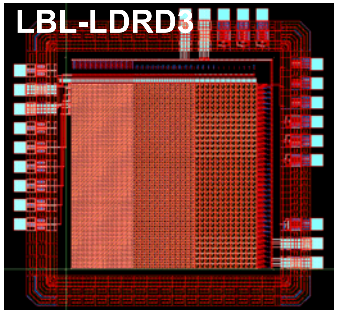
Vertex Detector Sensor Technology

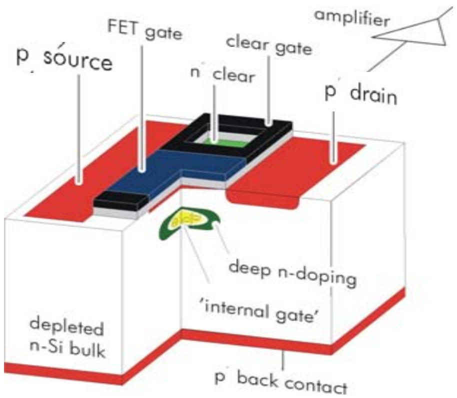
- **Many technologies being explored for vertex detectors; no "ideal" technology that performs in all categories yet.**
- **CCD's**
  - **Column Parallel (LCFI)**
  - **ISIS (LCFI)**
  - **Split Column (SLAC)**
- **CMOS Active Pixels**
  - **Mimosa series (Ires)**
  - **INFN**
  - **LDRD 1-3 (LBNL)**
  - **Chronopixel (Oregon/Yale)**
- **SOI**
  - **American Semiconductor/FNAL**
  - **OKI/KEK**
- **3D**
  - **VIP (FNAL)**
- **DEPFET (Munich)**



ISIS







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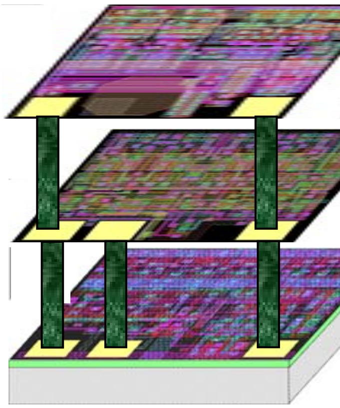
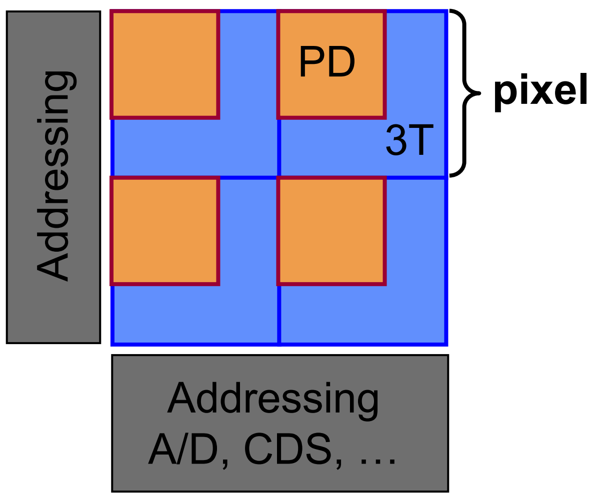


3D

Integrated Silicon Devices

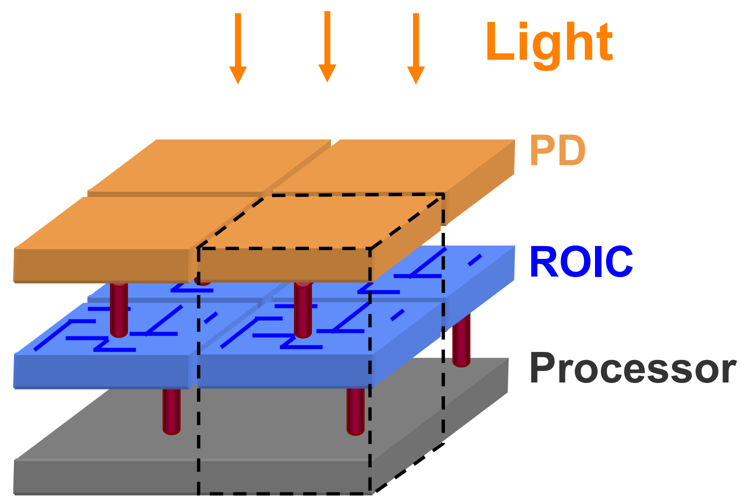
- Very promising advanced in integrated silicon devices for both Monolithic Active Pixel Sensors and 3D vertical integration

Conventional MAPS



- Pixel electronics and detectors share area
- Fill factor loss
- Co-optimized fabrication
- Control and support electronics placed outside of imaging area

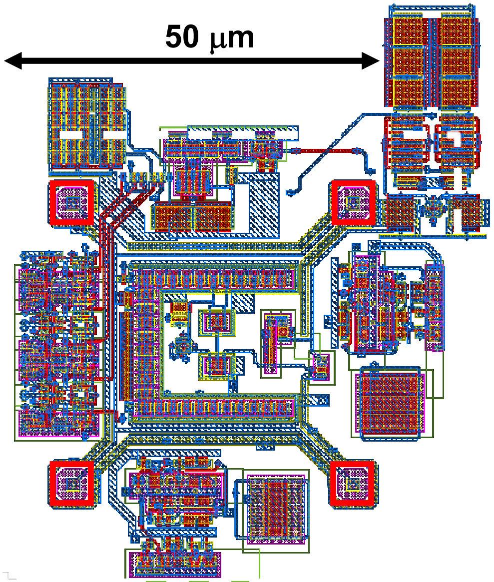
3-D Pixel

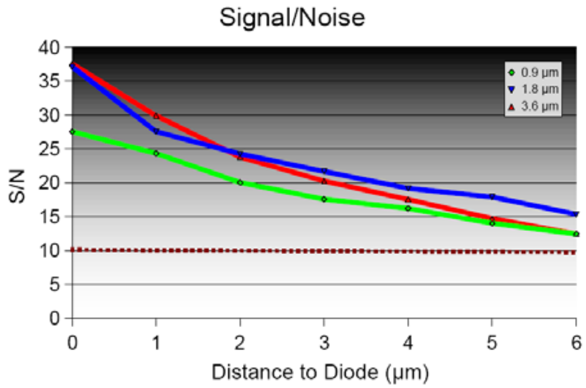


- 100% fill factor detector
- Fabrication optimized by layer function
- Local image processing
  - Power and noise management
- Scalable to large-area arrays

MAPS Based EM Calorimetry

- **EM calorimeter based on Monolithic Active Pixel Sensors**
  - **Intrinsic high granularity through wafer processing**
  - **CMOS process cheaper than high resistivity pure silicon**
- **ECAL MAPS design**
  - **Binary readout, threshold adjustment for each pixel**
  - **Pixels 50µm×50µm, 4 diodes for Charge Collection**
    - With ~100 particles/mm^2 in the shower core and 1% prob. of double hit the pixel size should be ~40×40 µm^2
  - **Time Stamping with 13 bits (8192 bunches)**
  - **Hit buffering for entire train, readout between trains**
  - **Total number of ECAL pixels around 8×10^{11}: Terapixels**

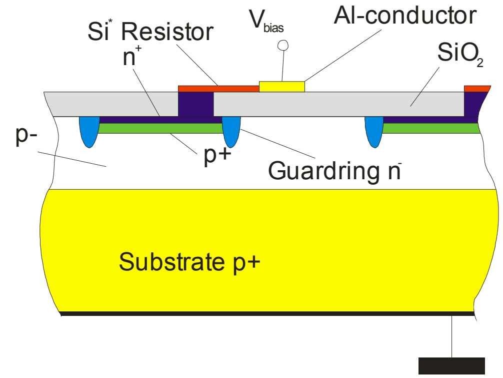


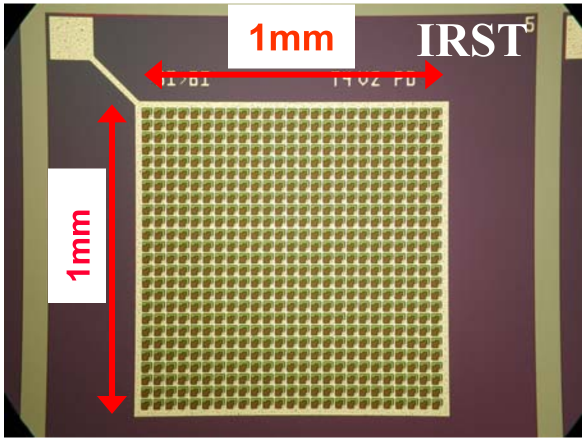


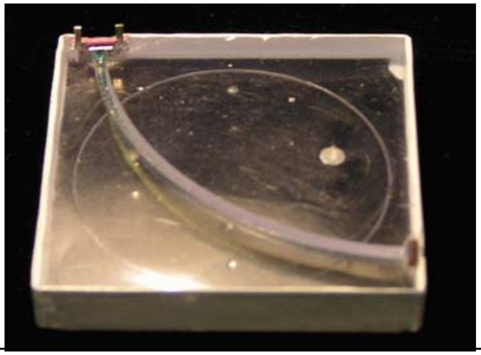
- **Device being simulated**
  - **Signal to Noise > 15 for 1.8 µm Diode Size**
  - **Critical issue for Terapixel system**

Geiger-Mode Avalanche Photo Diodes

- **Avalanche photodiode operating in Geiger mode, also called Multi-Pixel Photon Counter (MPPC) or Silicon photo-multiplier (SiPM), PPD, …**
  - **Array of pixels connected to a single output**
  - **Signal = Sum of all cells fired**
  - **If probability to hit a single cell < 1 => Signal proportional to # photons**
- **Characteristics:**
  - **Pros**
    - Very compact, High PDE (15~20% for 1600 pix)
    - Insensitive to magnetic field
    - High gain (10^5~10^6), good timing resolution
    - Operational at V_{bias}=70~80 V
  - **Cons**
    - Thermal noise rate (100kHz~300kHz @ 0.5 pe)
    - Response is non-linear due to limited number of pixels (saturation effect)
    - Sensitive to temperature change
    - Cross-talk and after-pulsing
- **Multiple applications**
  - **Analog scintillator tile hadron calorimeter**
  - **Dual readout, lead-glass – scintillator sampling calorimetry**
  - **Muon detector based on scintillator strips**

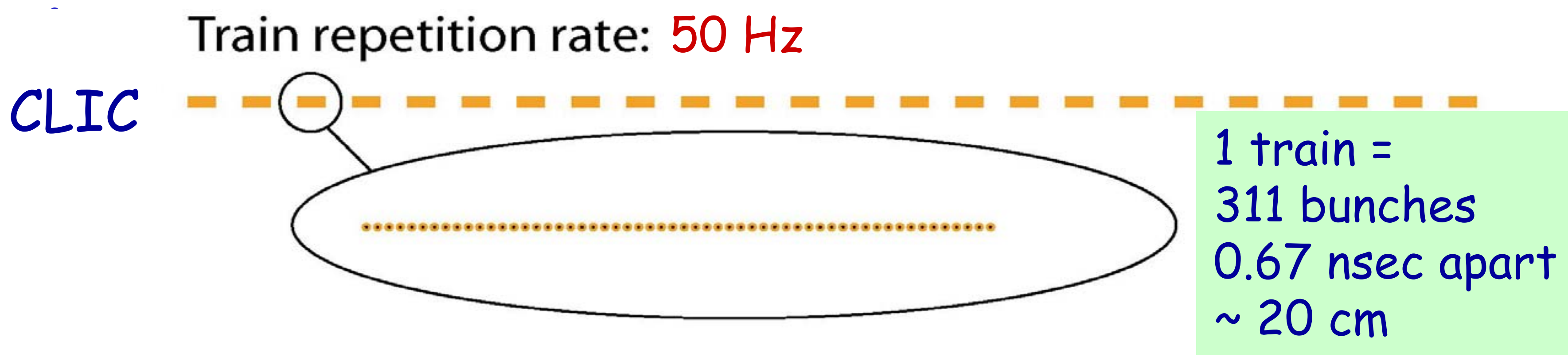






3x3x0.5 cm^3
UNIPLAST
1 mm WLS
Kuraray fiber
Y11(300)

CLIC Comparison



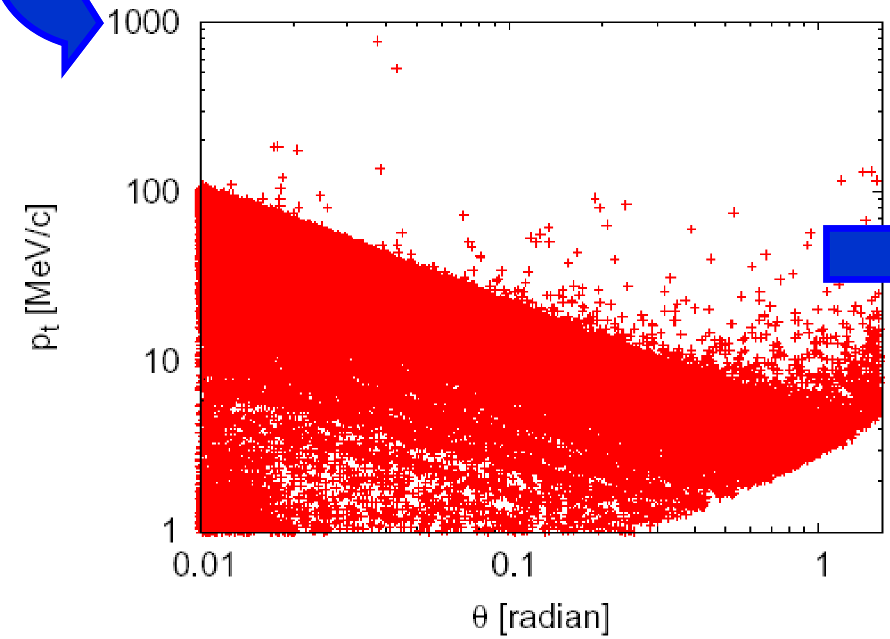
	LHC	ILC	CLIC
Energy [TeV]	14	0.5	3
BX spacing [ns]	25	369	0.67
Nb of BX/train	2808	2625	311
train time duration	70μs	1ms	201 ns
Repetition rate [Hz]	40M	5	50
Nb of BX/s	36M	13125	15500
Hit/mm^2/BX at 3cm	0.05	0.05	0.005

CLIC: e^+e^- Pair Production

- **Machine backgrounds**

Coherent pair production
- number/BX 3.8 10^8
- energy/BX 2.6 10^8 TeV

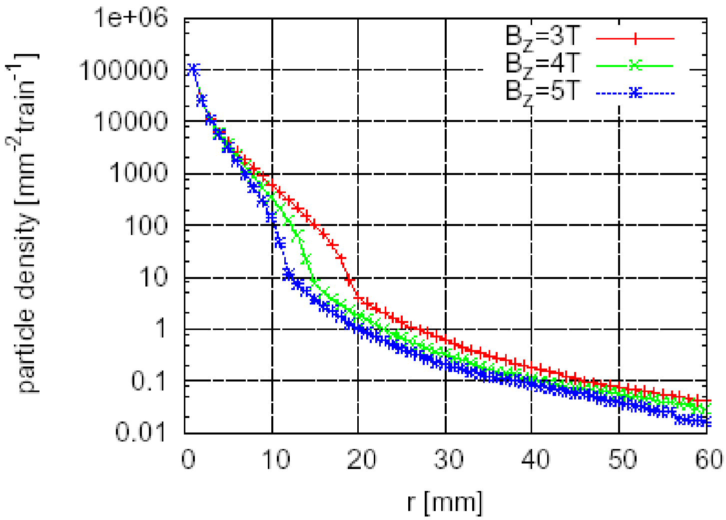
Incoherent pair production:
- number/BX 3.0 10^5
- energy/BX 2.2 10^4 TeV



Disappear in the beampipe
Can backscatter on machine elements
Need to protect detector with mask

Can be suppressed by strong magnetic field in of the detector

hits/mm²/bunch train

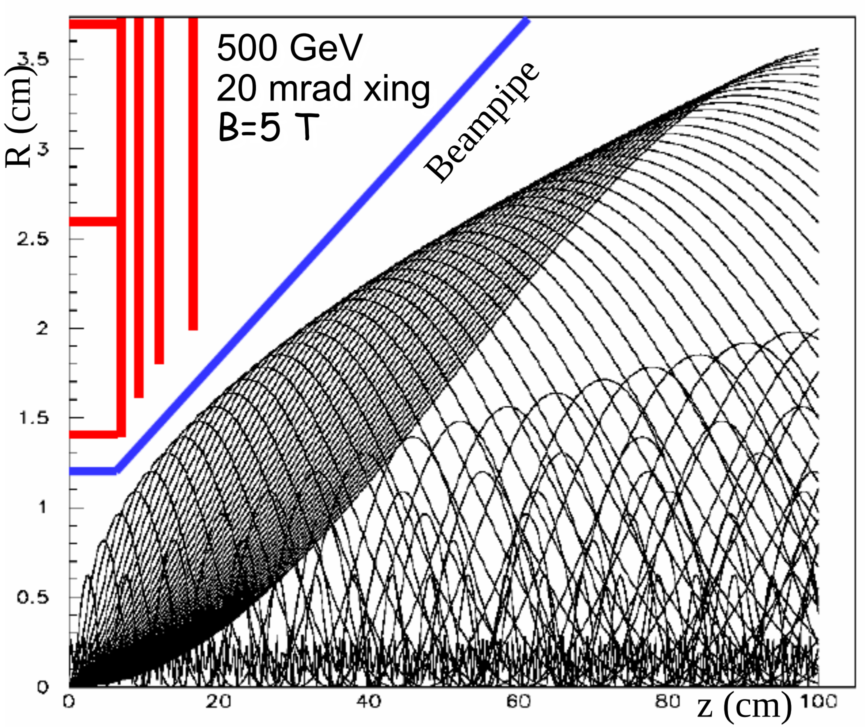


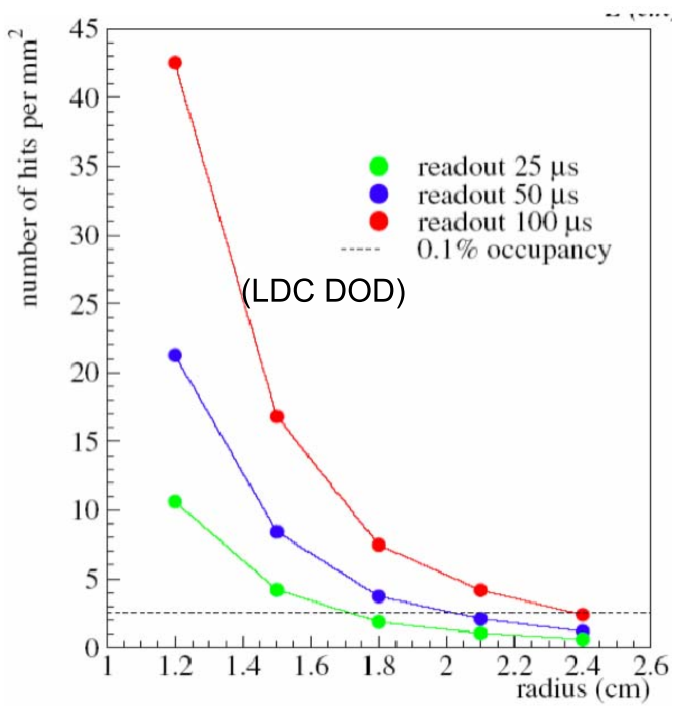
20mm and 4T $\Rightarrow$O(1) hit/mm²/bunch train

ILC: e^+e^- Pair Production

- **Estimate of beam backgrounds**

√s (GeV)	Beam	# e^+e^- per BX	Total Energy (TeV)
500	Nominal	98 K	197
1000	Nominal	174 K	1042

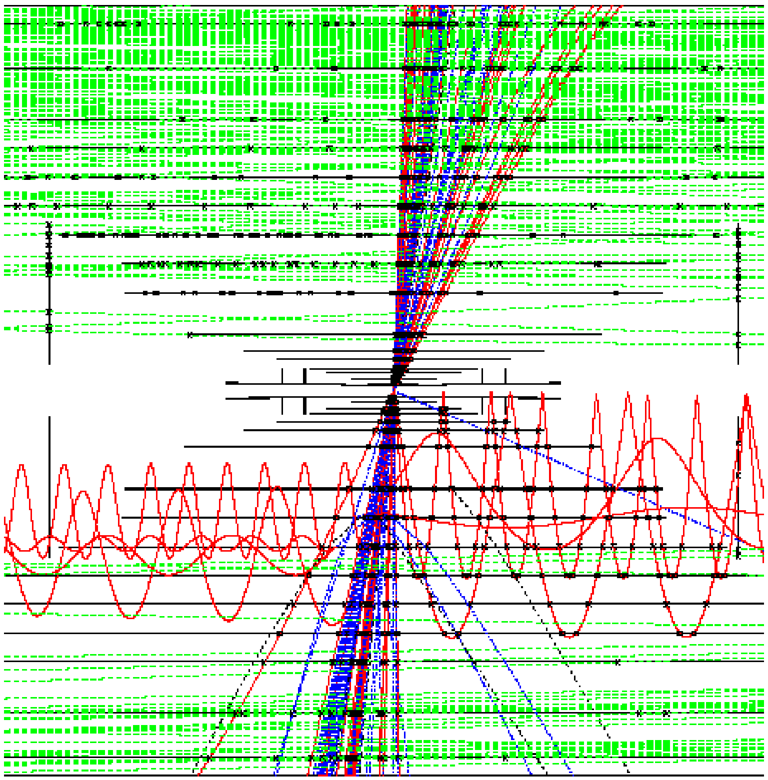




CLIC: Muon and $\gamma\gamma$ Background

- $\gamma\gamma$ **Background**
  - $\gamma\gamma \rightarrow$ **hadrons: 4 interactions/bx**
  - **Most activity at small angles**

$e^+e^- \rightarrow t\bar{t}$ AT $\sqrt{s} = 3$ TEV
$+$ MUON BACKGROUND (10 BX)



- **Muon Background**
  - **Muon pairs produced in electromagnetic interactions upstream of the IP e.g beam halo scraping on the collimators**
  - **Geant simulation, taking into account the full CLIC beam delivery system**
  - **Rate: ~ 20 muons/BX with help of tunnel fillers**

ILC: Muon and $\gamma\gamma$ Background

- **Machine related backgrounds in the SID Detector (N. Mokhov)**
  - **Simulations are done with the MARS15 code**
  - **Model describes the last ~1500 m of 20-mrad e^+ line**
- **Backgrounds in the SiD detector (2800 bunch/train, 2 10^{10} e^+/bunch) calculated for all particle species**
- **Number of particles per bunch crossing for e^+ side at the SiD detector**

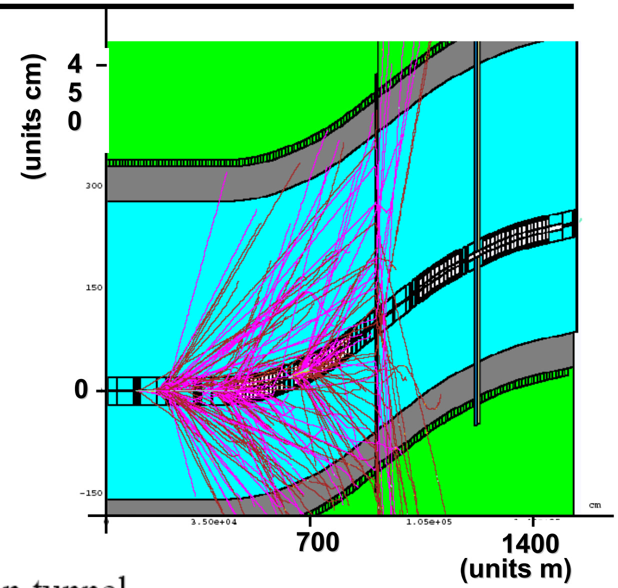


Table. 1 : Average number of particles per bunch at the SiD from positron tunnel.

	γ	$\mu^{\pm}$	e^+	e^-	neutron
With spoilers	2927	0.024	1172	$3.6 \cdot 10^{-4}$	6364
No spoilers	2942	60.4	1095	10	346

Table. 2 : Average kinetic energy (GeV) of particles at the SiD from positron tunnel.

	γ	$\mu^{\pm}$	e^+	e^-	neutron
with spoilers	$5.4 \cdot 10^{-3}$	38	251	0.13	$1.6 \cdot 10^{-3}$
no spoilers	$5.5 \cdot 10^{-3}$	28	250	0.19	$7 \cdot 10^{-4}$

Simulation Studies

- Physics is the scientific driver for the project
- The physics potential of the detectors can only be demonstrated through realistic physics simulations
- It is of critical importance to new projects, for reasons of efficiency and for building a strong user community, to have a unified, supported software framework available to carry out the simulation studies

- Fast simulations are okay for initial studies
- To explore the full physics potential and the limitations of the detectors full simulations are needed with proper treatment of all the backgrounds (beam and physics), time stamping of bunch crossings, …
- The tools that are being developed are not unique to a facility
  - For example, tools for heavy flavor tagging, pattern recognition for tracking, …

Wrong!

ILC software packages

	Description	Detector	Language	IO-Format	Region
Simdet	fast Monte Carlo	TeslaTDR	Fortran	StdHep/LCIO	EU
SGV	fast Monte Carlo	simple Geometry, flexible	Fortran	None (LCIO)	EU
Lelaps	fast Monte Carlo	SiD, flexible	C++	SIO, LCIO	US
Mokka	full simulation – Geant4	TeslaTDR, LDC, flexible	C++	ASCI, LCIO	EU
Brahms-Sim	Geant3 – full simulation	TeslaTDR	Fortran	LCIO	EU
SLIC	full simulation – Geant4	SiD, flexible	C++	LCIO	US
LCDG4	full simulation – Geant4	SiD, flexible	C++	SIO, LCIO	US
Jupiter	full simulation – Geant4	JLD (GDL)	C++	Root (LCIO)	AS
Brahms-Reco	reconstruction framework (most complete)	TeslaTDR	Fortran	LCIO	EU
Marlin	reconstruction and analysis application framework	Flexible	C++	LCIO	EU
hep.lcd	reconstruction framework	SiD (flexible)	Java	SIO	US
org.lcsim	reconstruction framework (under development)	SiD (flexible)	Java	LCIO	US
Jupiter-Satelite	reconstruction and analysis	JLD (GDL)	C++	Root	AS
LCCD	Conditions Data Toolkit	All	C++	MySQL, LCIO	EU
GEAR	Geometry description	Flexible	C++ (Java?)	XML	EU
LCIO	Persistency and datamodel	All	Java, C++, Fortran	-	AS,EU,US
JAS3/WIRED	Analysis Tool / Event Display	All	Java	xml,stdhep, heprep,LCIO,	US,EU

Some Concluding Remarks

- There is a lot of synergy between the current detector R&D and new projects that are being considered
- Detector concepts will need to demonstrate their physics capabilities from a mature detector design – with a reasonable level of engineering, costing, etc. – and exhaustive studies of physics benchmark processes
- For the Muon Collider, definition of physics benchmark processes would be a good step
- Feasibility of the machine and detector are ultimately judged by its physics capabilities which are derived from realistic simulations
- The importance of a unified software framework for the simulations cannot be overemphasized