Detector Challenges at Linear Colliders

Fermilab Accelerator Seminar
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The Physics case on 1 page

- Assuming the LHC will discover new physics ...
- Will need a precision machine for measuring
  - The mass of the new particles, e.g. the Higgs Boson
  - Their cross-sections
  - Their branching ratios
- If the LHC doesn't find new physics
  - A Linear Collider has the precision to tell you what is wrong with the Standard Model
- The detector requirements are quite independent
  - Doesn'matter if the Higgs mass is 120 or 180 GeV ...

Example: The Higgs boson

- LEP & Tevatron
  - EW fits say that the Higgs is light $m_H < \sim 180$ GeV
  - LEP direct searches : $m_H > 114$ GeV
  - Tevatron excludes area from $m_H = 158\text{-}175$ GeV
- LHC
  - Will find the Higgs unless ..
    - there is none
    - nature is very nasty
  - But which Higgs is it ?
  - Standard Model, SUSY ....

Higgs properties

- Mass
  - fixed parameter in the SM
- Width
  - depends on the mass
  - very small for light Higgs Bosons
- Spin
  - Should be Spin 0
- Branching ratios
  - can be very different for different models

An example

m_H=120 GeV

	Standard Model	MSSM case 1	MSSM case 2
bb	68%	74%	70%
$\tau\tau$	7%	8%	7%
WW	13%	10%	12%
ZZ	2%	1%	1%
cc	3%	2%	3%
gg	7%	5%	7%

- Distinguishing between SM and MSSM becomes difficult, if the SUSY particles are very heavy

LHC potential

- From various TDR's ...
- Branching ratios can be measured with 10 % precision at best
- Measuring rare Higgs decays probably impossible
  - cc, gg, $\mu\mu$,$\gamma\gamma$
- Understanding the Higgs requires a precision e^+e^- machine
  - Clean environment
  - Superior detector

What do we need ?

Looking at the Higgs again

Channels	Requires
bb	Jets + b-tagging
$\tau\tau$	tracking, *ECAL+HCAL*, PID
WW	Jets + tracking + PID
ZZ	Jets + tracking + PID
cc	Jets + c-tagging
gg	Jets
$\gamma\gamma$	ECAL
$\mu\mu$	Tracking+PID

Higgs physics requires excellent tagging, tracking and calorimetry.
Much better than anything ever done before

LC Detector requirements

- Impact parameter resolution
- Momentum resolution

- Jet energy resolution goal

$$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}} \quad \frac{\sigma_E}{E} \approx 4\%$$

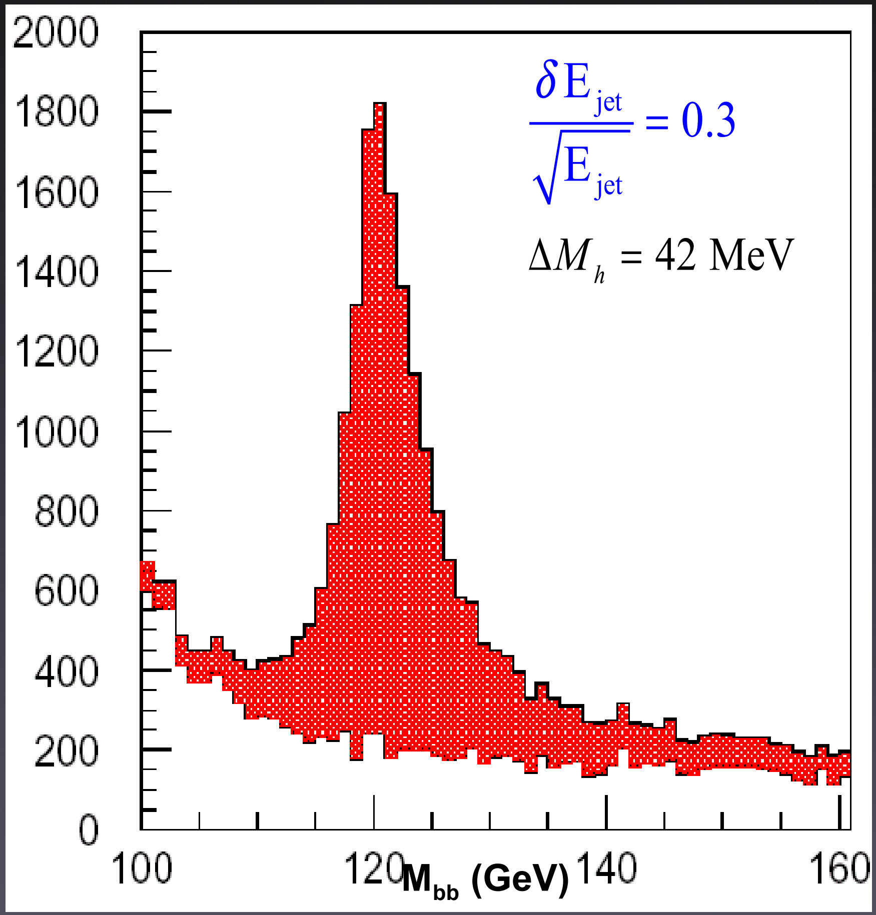
- Detector implications
  - Calorimeter granularity
  - Pixel size
  - Material budget, central
  - Material budget, forward

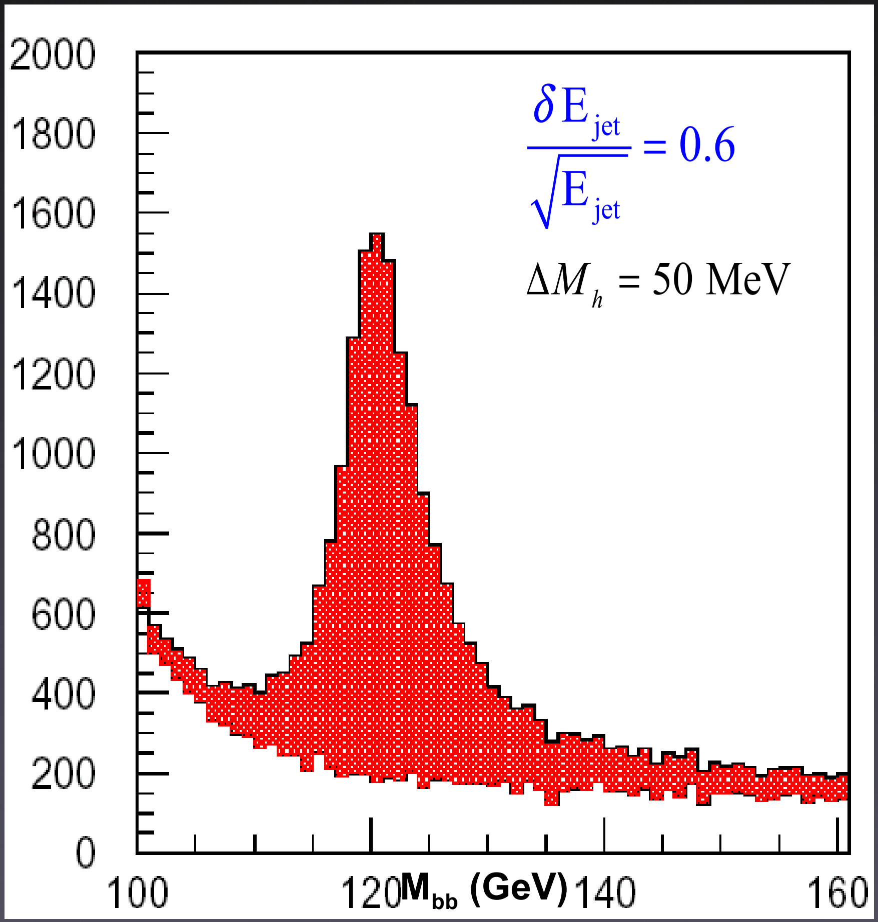
- Need factor 3 better than SLD
- Need factor 10 (3) better than LEP (CMS)
- Need factor 2 better than ZEUS

$$\frac{\sigma_E}{E} = \frac{60\%}{\sqrt{E}}$$

- Detector implications
  - Need factor ~200 better than LHC
  - Need factor ~20 smaller than LHC
  - Need factor ~10 less than LHC
  - Need factor ~ >100 less than LHC

Impact of Jet Performance



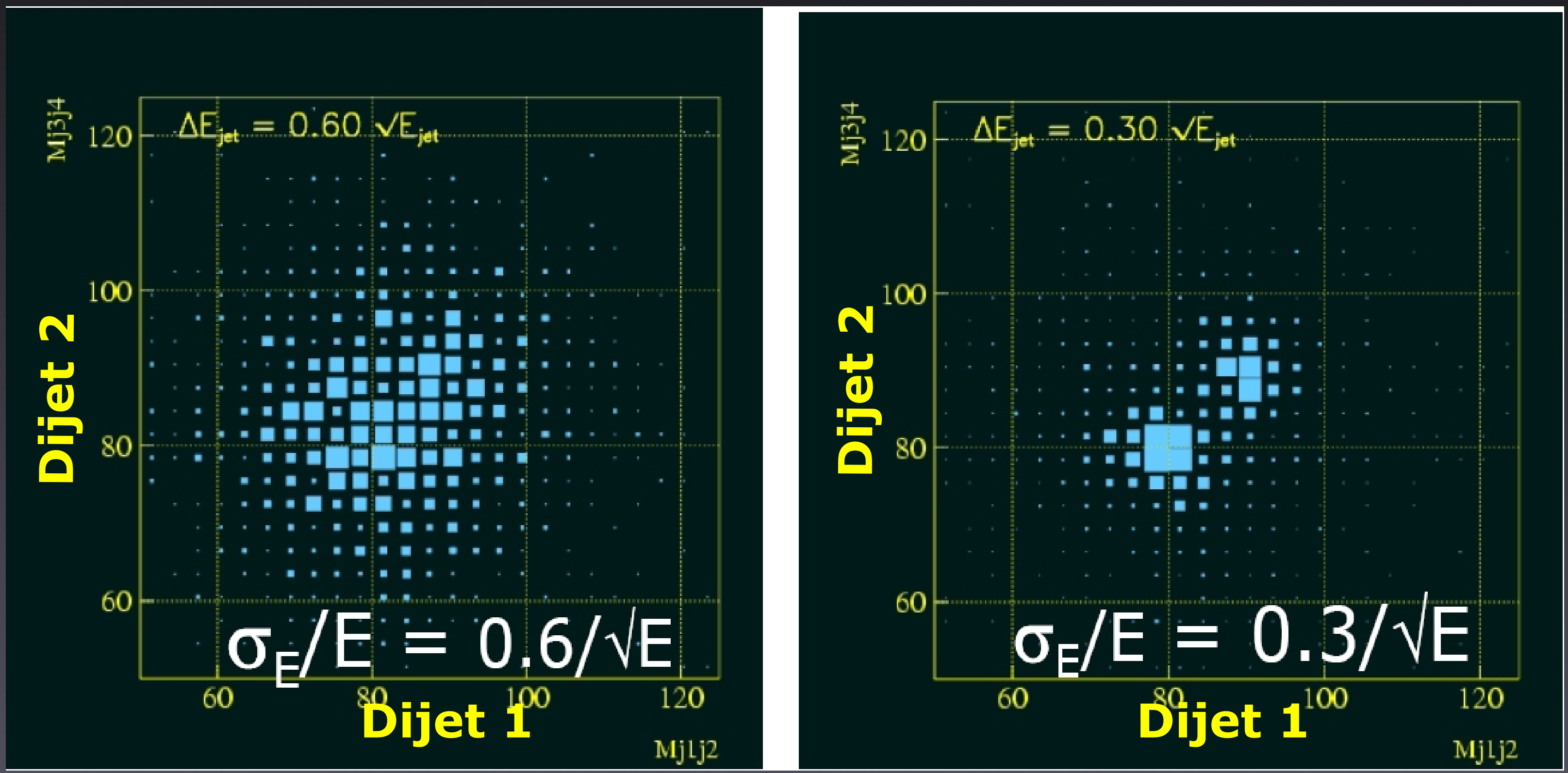


$e^+e^- \rightarrow ZH \rightarrow qqbb$ @ 350GeV, 500fb^{-1}

M_{jj} of two b-jets for different jet energy resolution.

→ **40% luminosity gain**

W/Z separation



Separation hadronic WW/ZZ pairs !

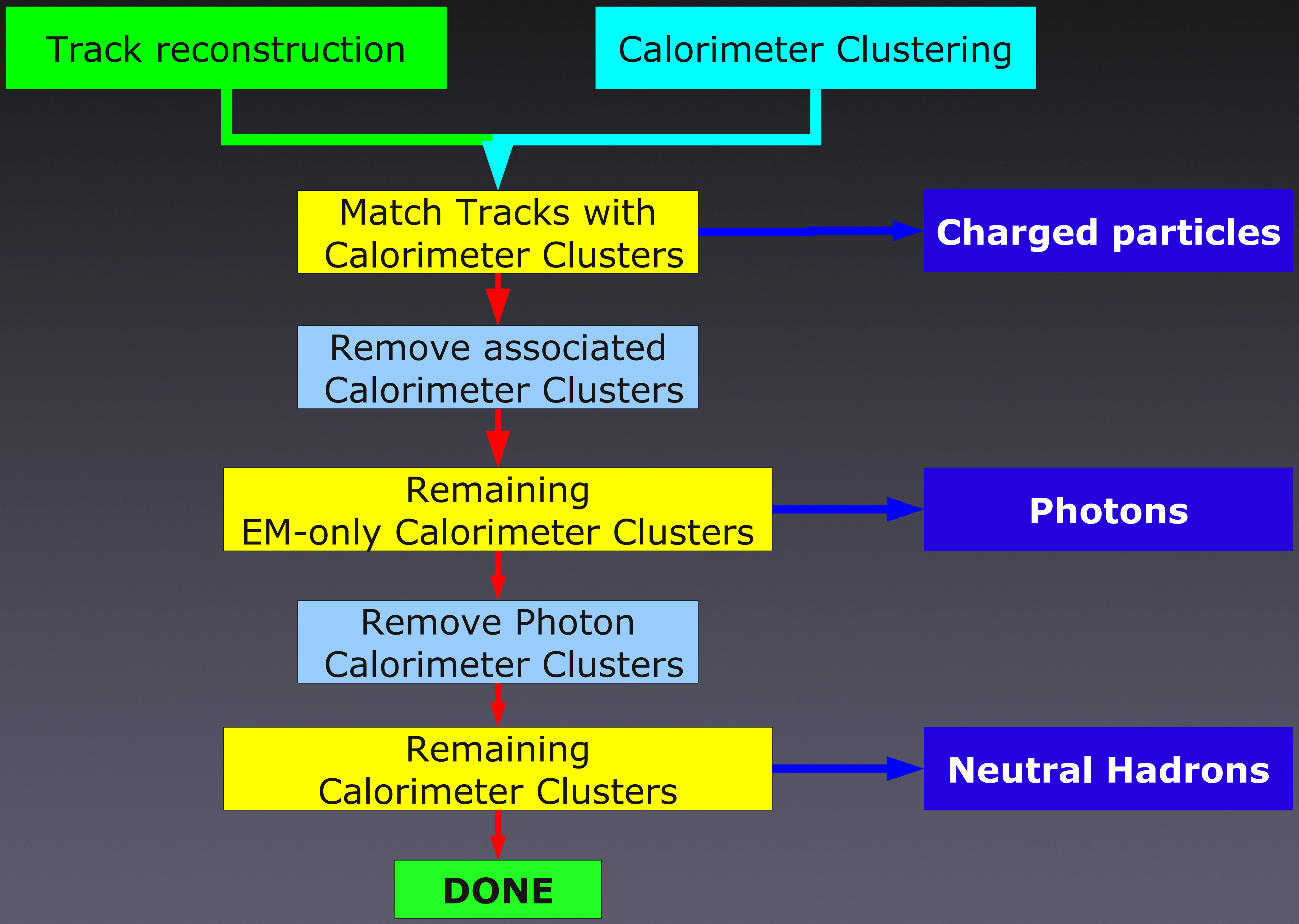
Design choices

- Excellent Vertex Detector
  - Low mass, highly granular, close to interaction region
- Tracking
  - Barrel + Forward tracking
  - Low mass + high momentum resolution
- Calorimetry
  - Exceptional Jet energy resolution
- Low Material budget
  - Powering, cooling

Calorimetry thoughts

- Classical “LHC style” calorimetry cannot delivered desired performance
  - HCAL resolution is the limiting factor
- Need for better approach: Particle Flow Algorithms (PFA)
  - Particle Flow has been done at LEP .. to some extend
  - But never been a key design goal
- In a typical ILC jet event on average
  - 60 % charged particles
  - 30 % photons
  - 10 % neutral hadrons

PFA in a nutshell



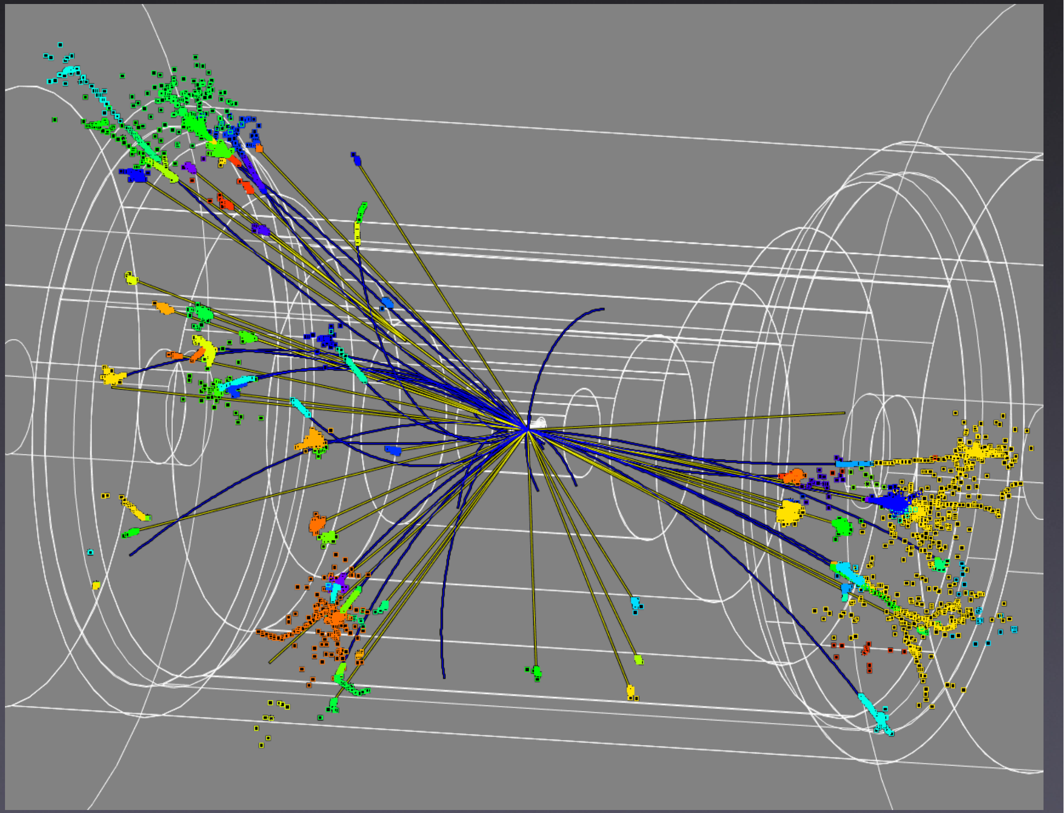
Jet Resolutions

Particle Class	SubDetector	Jet energy fraction	Particle Resolution	Jet Energy Resolution
Charged	Tracking	60%	$10^{-4}\ \sqrt{E_{charged}}$	neg.
Photons	ECAL	30%	$11\ \%\ \sqrt{E_{EM}}$	$6\ \%\ \sqrt{E_{jet}}$
Neutral Hadrons	HCAL (+ECAL)	10%	$40\ \%\ \sqrt{E_{hadronic}}$	$13\ \%\ \sqrt{E_{jet}}$

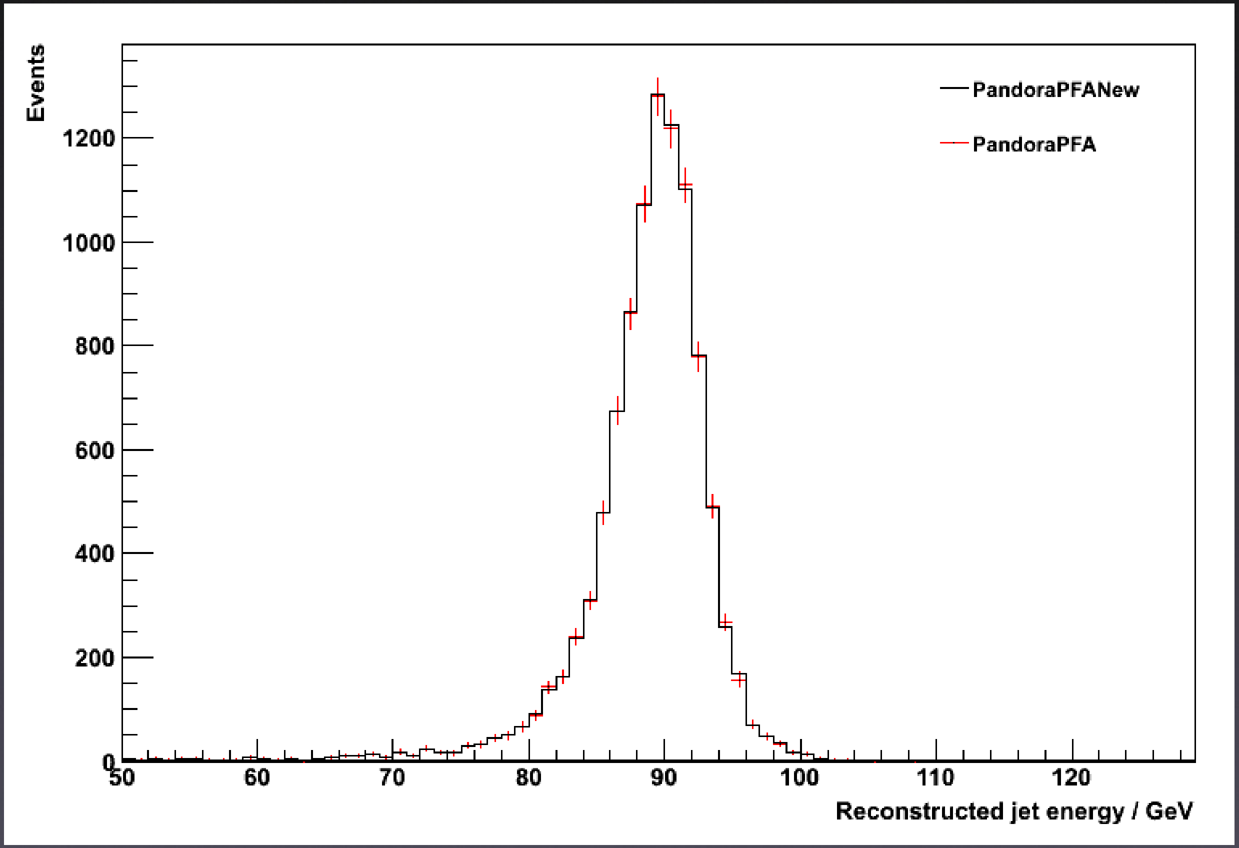
- Energy resolution about 14% (driven by HCAL)
- Confusion terms have bigger impact
  - $\sigma_{jet}^2 = \sigma_{charged}^2 + \sigma_{EM}^2 + \sigma_{hadronic}^2 + \sigma_{confusion}^2 + \sigma_{threshold}^2 + \ldots$
- Performance not limited by Calorimetry
  - Need high granularity to reduce confusion !

Sounds easy

- Associating showers to tracks
  - showers can overlap
  - track ambiguities
  - leakage
- Hadronic showers are very difficult
- PFA calorimeters
  - Shower Images
  - Huge number of channels



Current Status

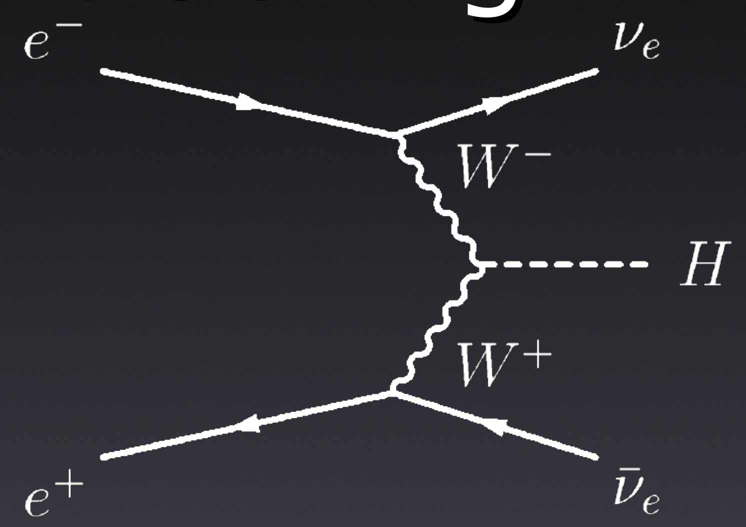


- Pandora (Cambridge) is the most successful PFA
- Fulfills LC requirements
  - $$\frac{rms_{90}(E_{Jet})}{E_{Jet}} = 3.62 \pm 0.05$$

Tracking thoughts

- Vertex detector with 5 layers
  - 20 µm pixels
- Tracking detector linking the vertex detector and the Calorimeters
  - Several approaches
- Low material budget
  - Low Power
  - Gas cooling
- Keep Occupancy low
  - Segmentation
  - Time information

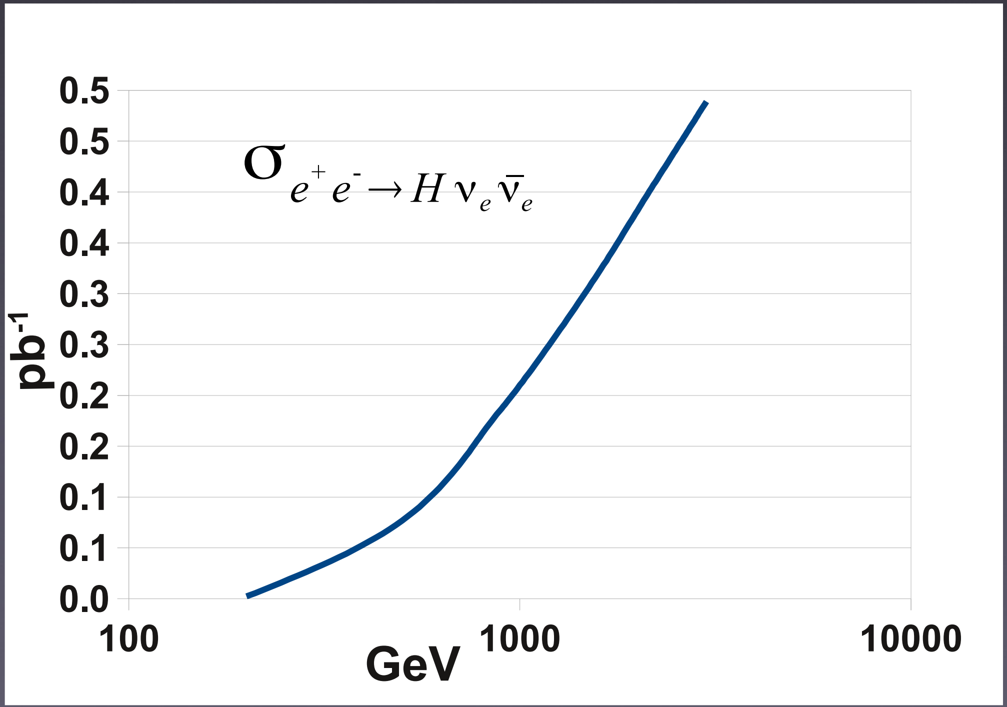
Why Forward tracking



- Let's again take the Higgs

$$e^+ e^- \to H \nu_e \bar{\nu}_e$$

- Dominant process for Higgs production at higher energies
- Tendency to be forward boosted
- Need decent tracking (and calorimetry) in the forward region



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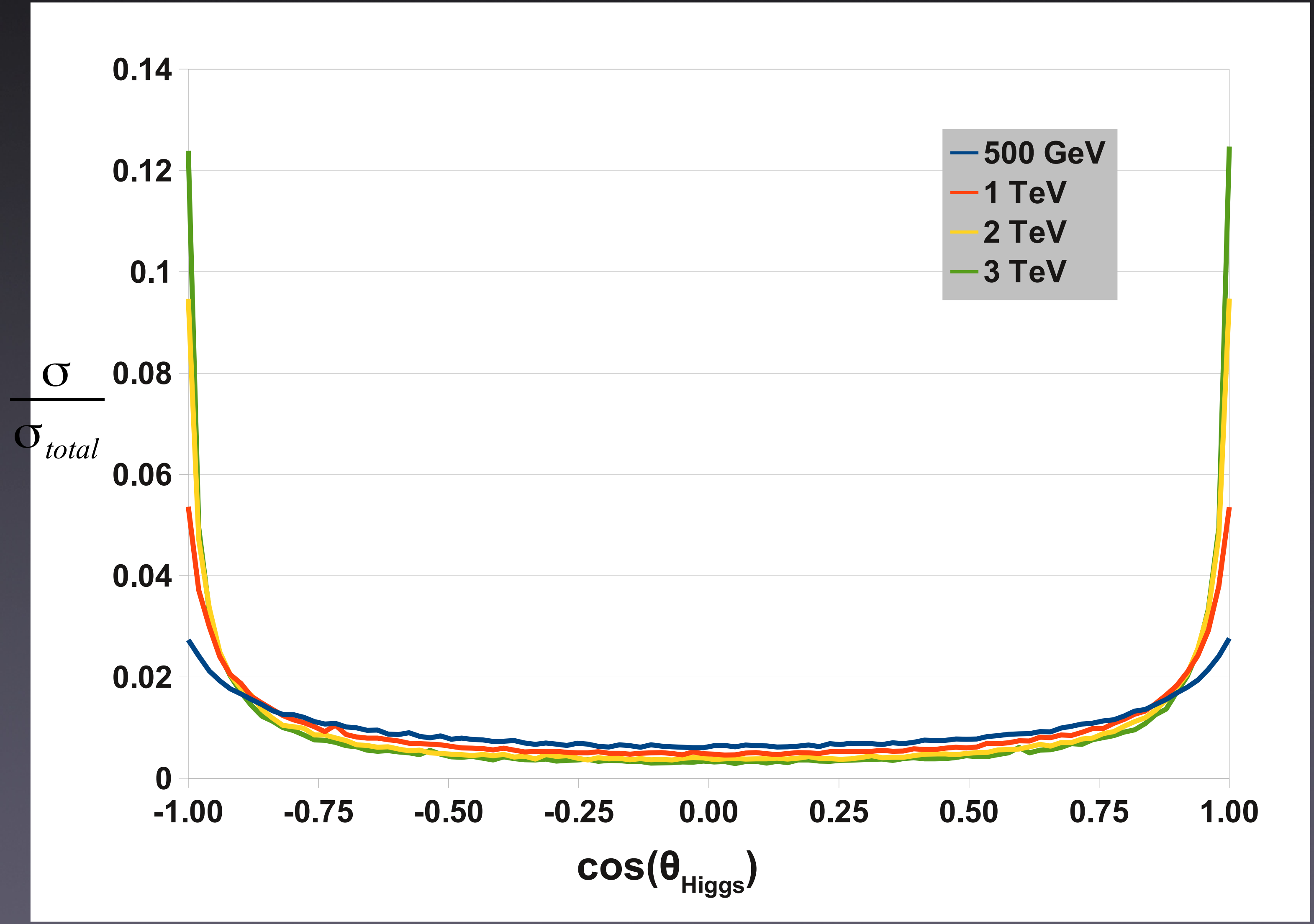
Differential Cross-section



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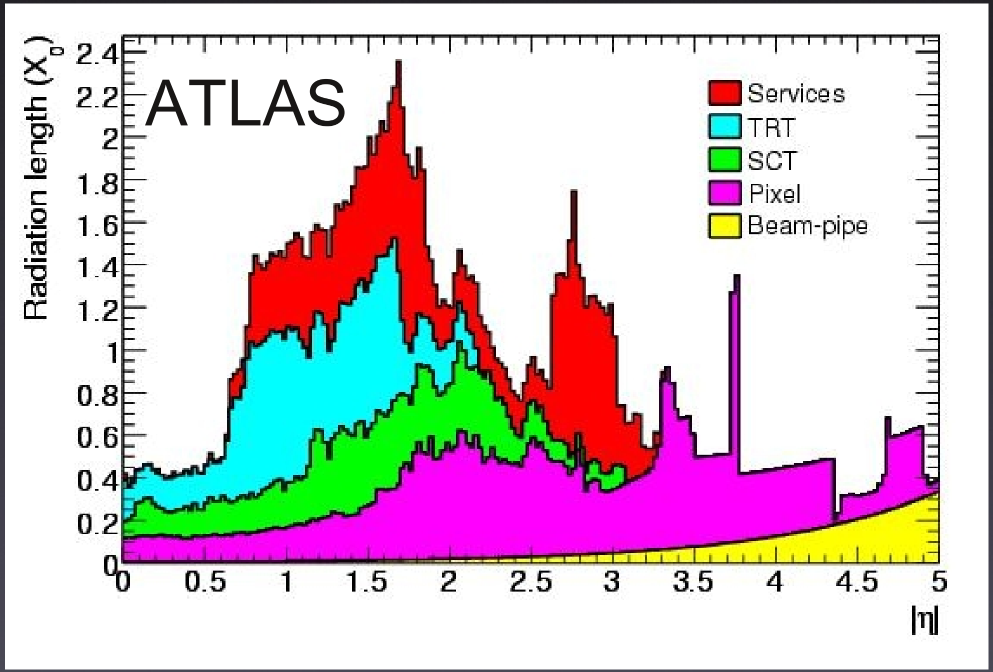
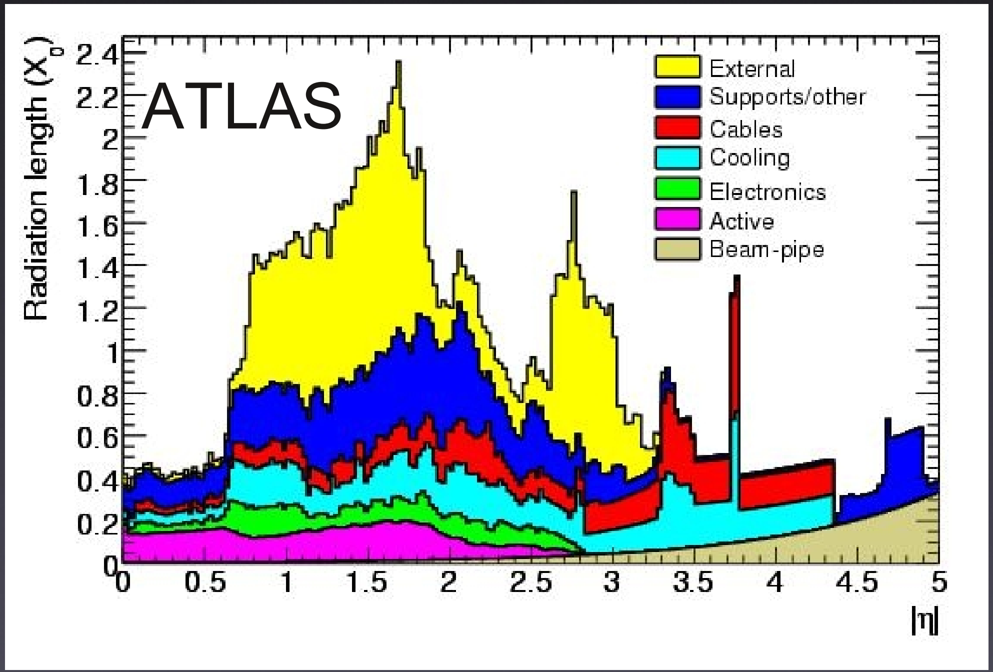
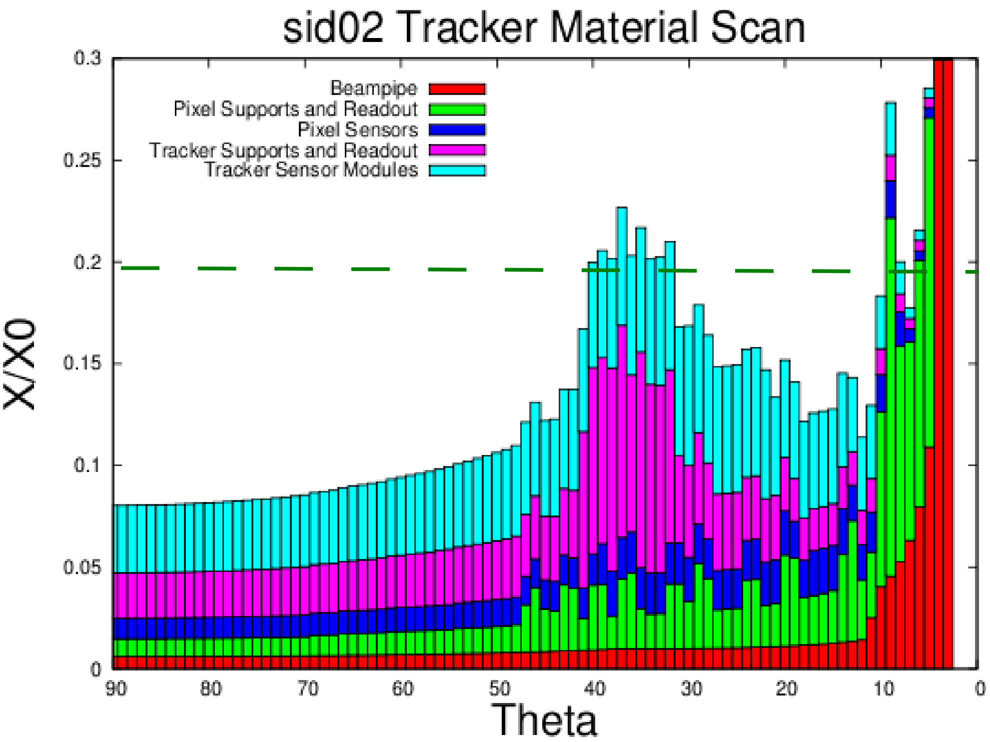
Example : Material budget

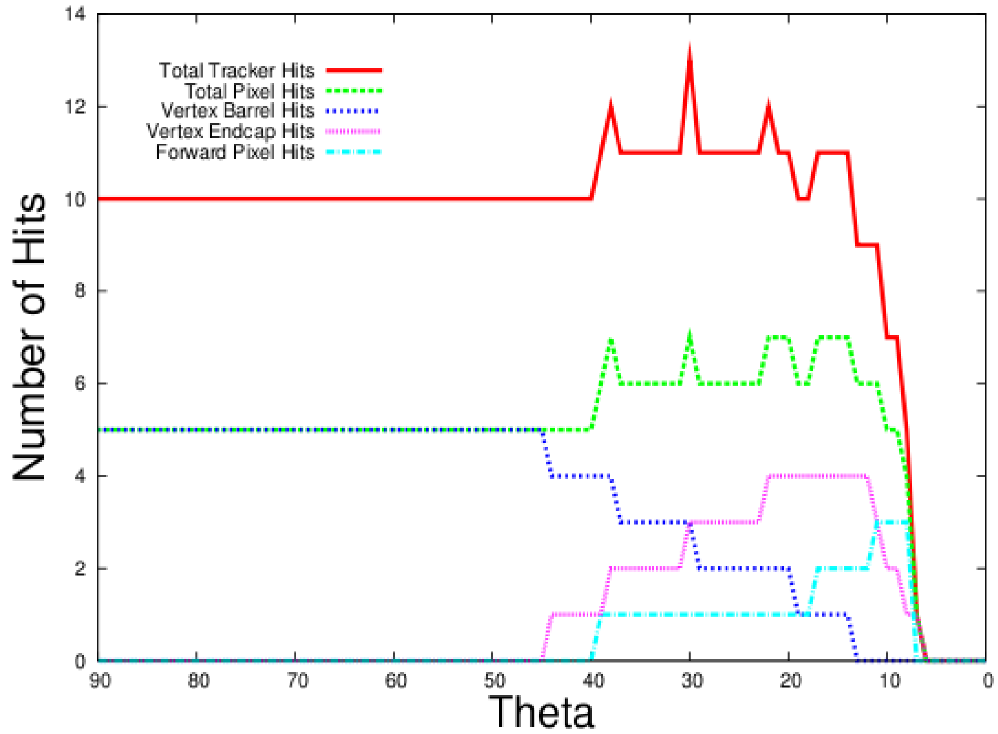




The material budget of the ATLAS tracker

Current Estimates





- This is the current estimate for a Tracking system of an ILC detector
- We're there ... in simulation

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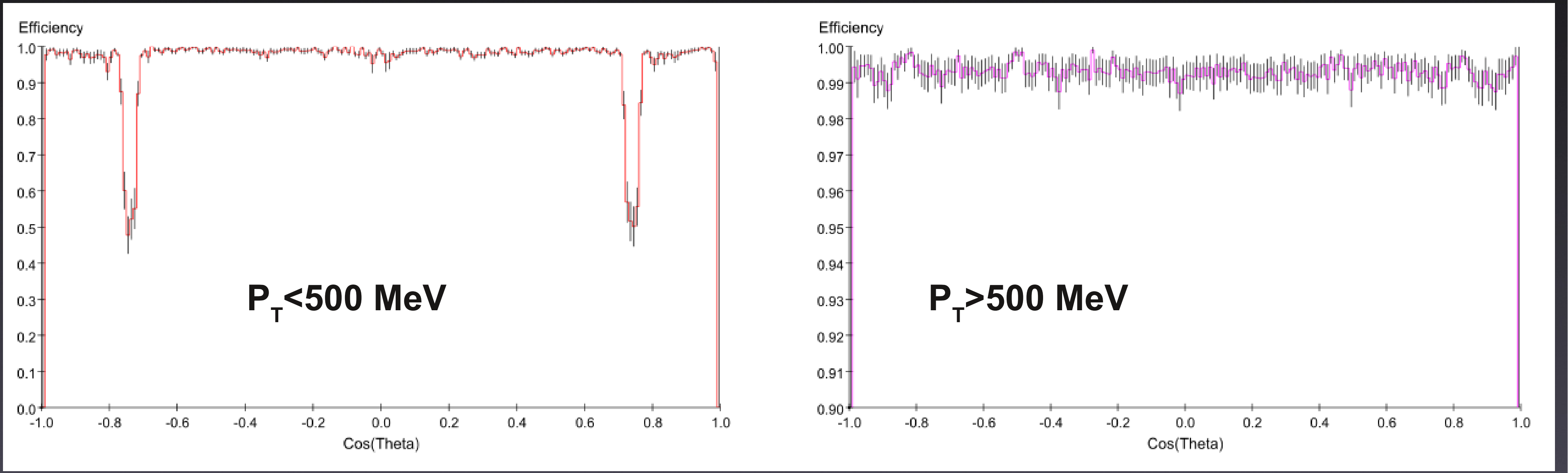
Tracking Status



- Tracking performance is already very promising
- Need to monitor performance with more realistic detector description

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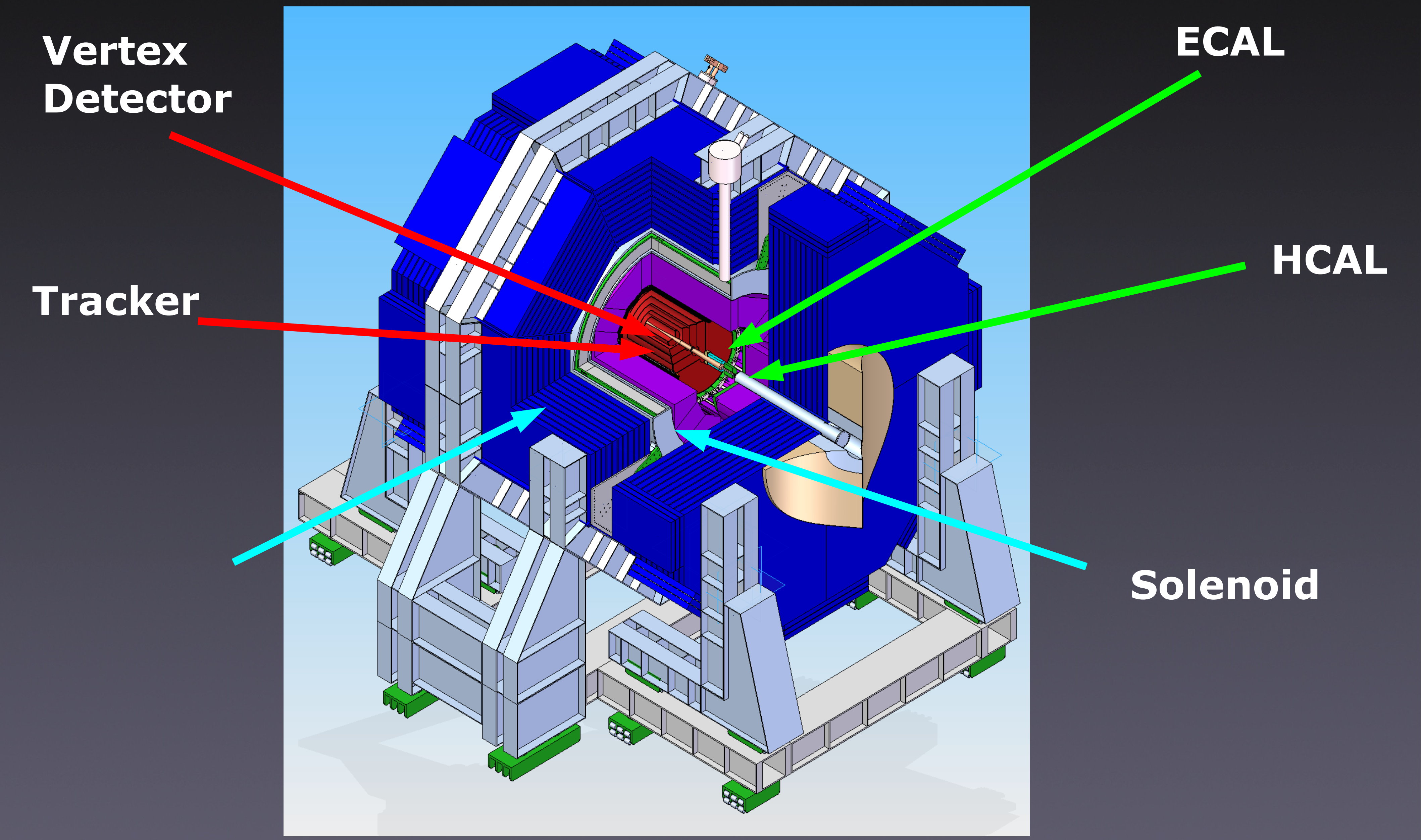
Designing a detector for PFA

- Particle Flow Algorithms (PFA) combines tracking and calorimeter information
- New design paradigm
  - *Detector is viewed as single fully integrated system, not a collection of different subdetectors*
- PFA requires tracking **and** calorimetry to be inside the coil !
  - This becomes a limiting factor
  - Compactness is very important
- Keep an eye on the material budget

SiD a PFA detector



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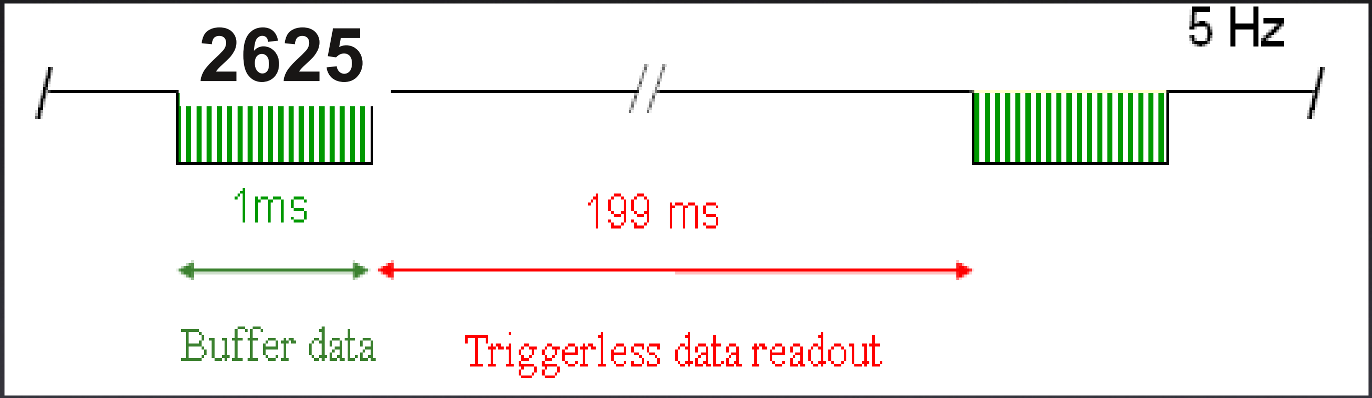
System issues

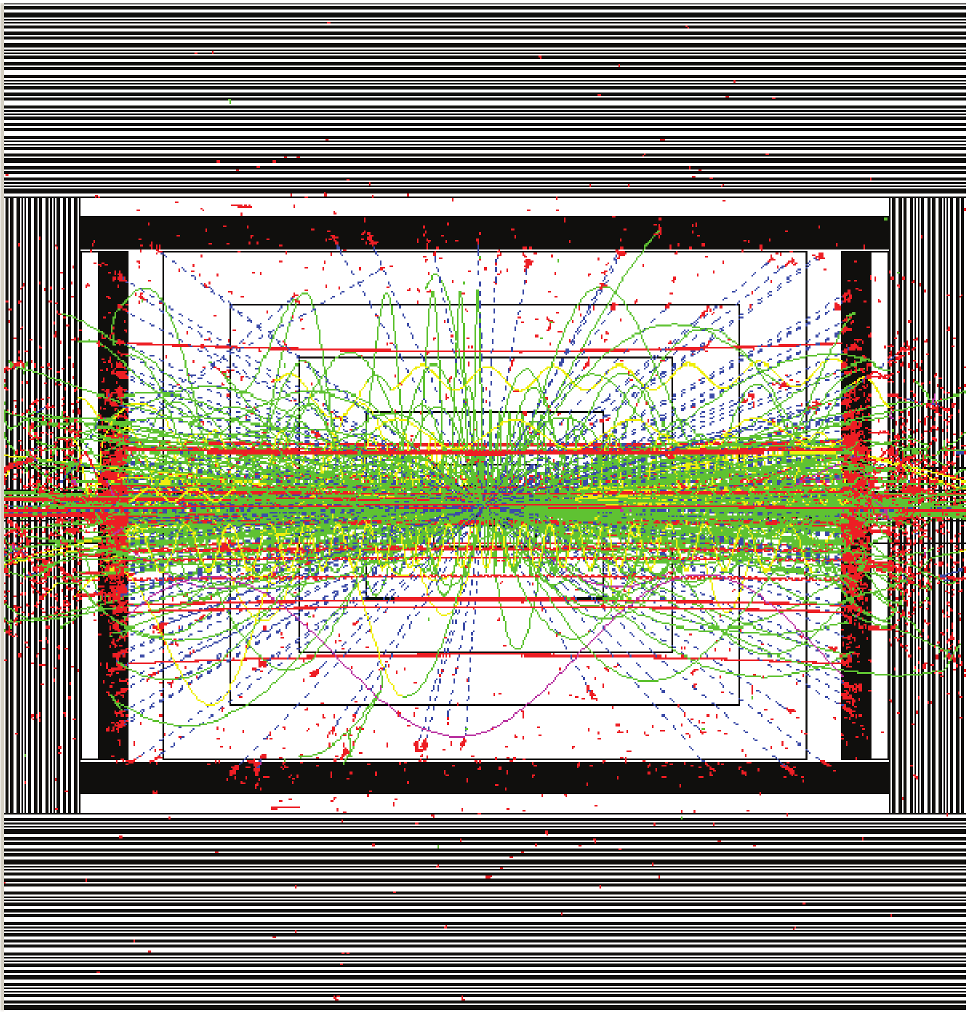
- LC detectors run without triggering
  - But Time-stamping of data is used
- Power distribution is challenging
  - DC-DC conversion or serial powering
  - Power-pulsing
- Closely related
  - Material budget
  - Cooling
- Push&Pull
- R&D on many issues has just started

ILC Timing structure

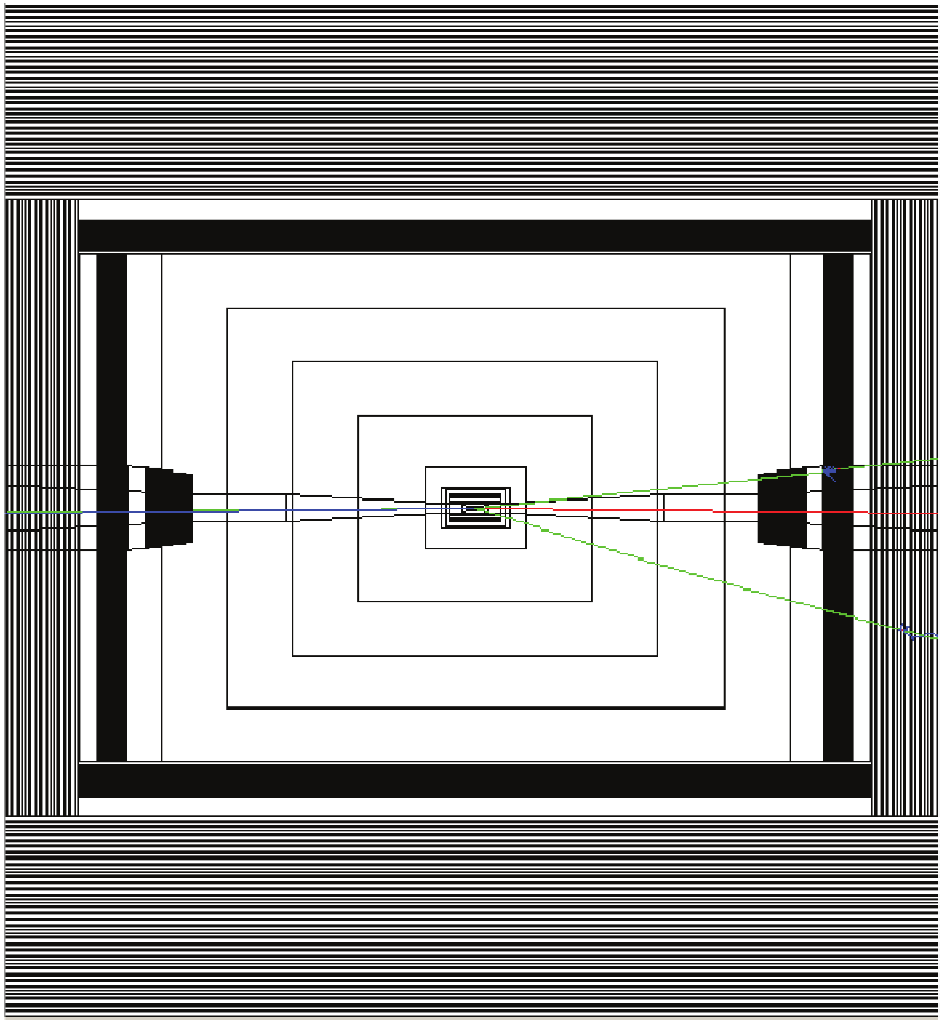


- ILC timing is very different to LHC
  - Bunch spacing of ~ 300 ns (LHC 25 ns)
  - 2625 bunches in 1ms
  - 199 ms quiet time
- No Triggers
- Occupancy dominated by beam background & noise
- Rule of thumb : ~ 1 hadronic event per bunch train

Benefits of time-stamping



150 BX integrated



Applying Time-Stamping

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CLIC Bunch structure

Train repetition rate 50 Hz

CLIC: 1 train = 312 bunches 0.5 ns apart 50 Hz

ILC: 1 train = 2680 bunches 337 ns apart 5 Hz

Consequences for a CLIC detector:

- Assess need for detection layers with dedicated time-stamping
  - Other layers may integrate over the entire bunch
- Readout electronics will be different from ILC
  - Consequences for power pulsing not clear yet

Power Pulsing

- Highly Granular detectors
  - Lots of channels
  - Lots of power-> Heat development
- But Duty-cycle does help
  - ILC case 0.5 %
  - Reduction of ~ 200 theoretically possible
- Powering off front-ends during quiet time
  - Not that trivial
  - Power pulsing in 4 or 5 T fields ...
  - My opinion , a factor 100 would be already good

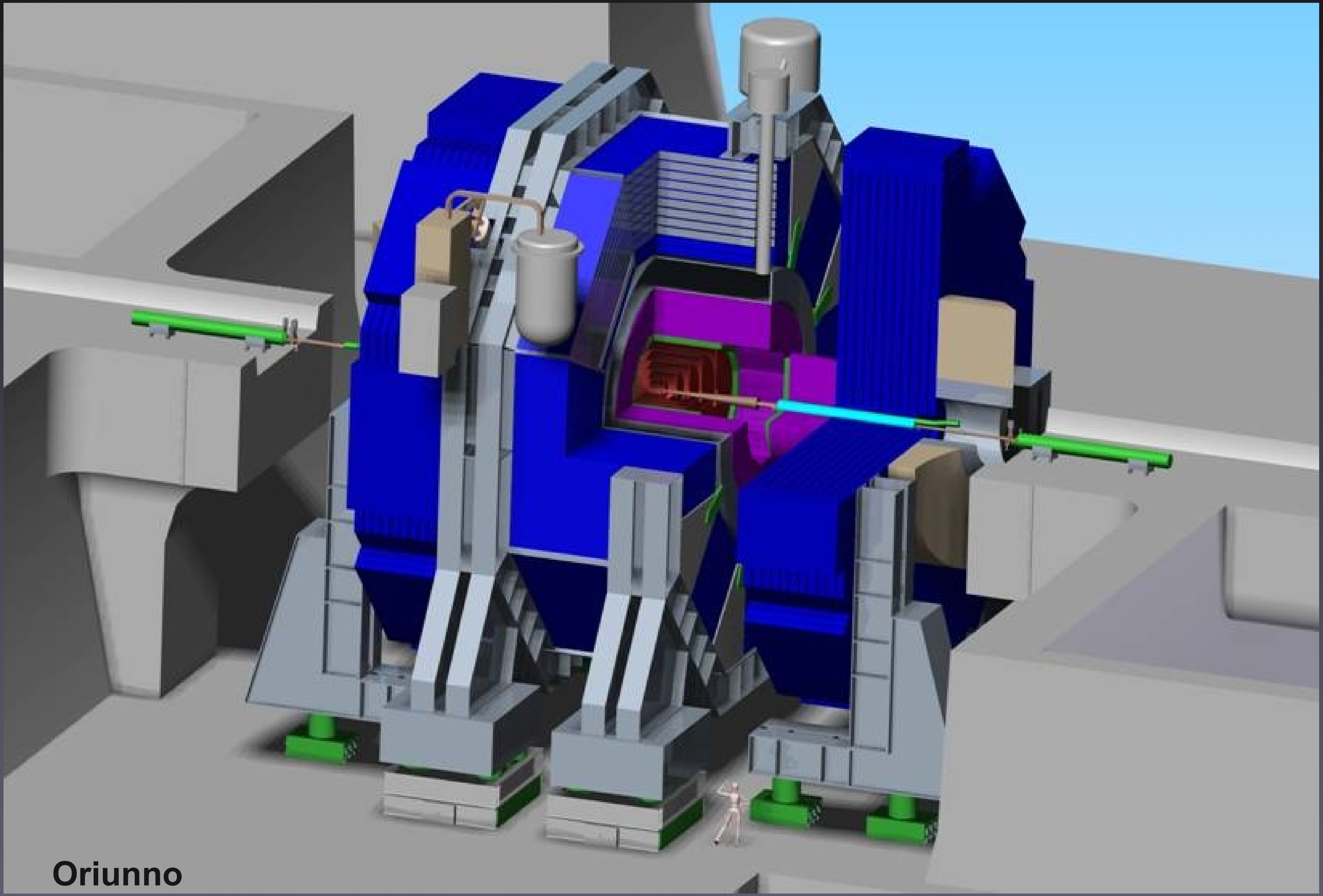
Power Delivery

- Current Experiments use point-to-point cables
  - One supply → one module
  - Low Voltage & High current → Lots of material
- Several new approaches
  - Serial Powering
  - DC-DC Conversion
- Serial Powering
  - Daisy-chaining approach (Christmas tree lights)
  - One cable for many modules
- DC-DC Conversion
  - Bring Power as HV, generate LV locally

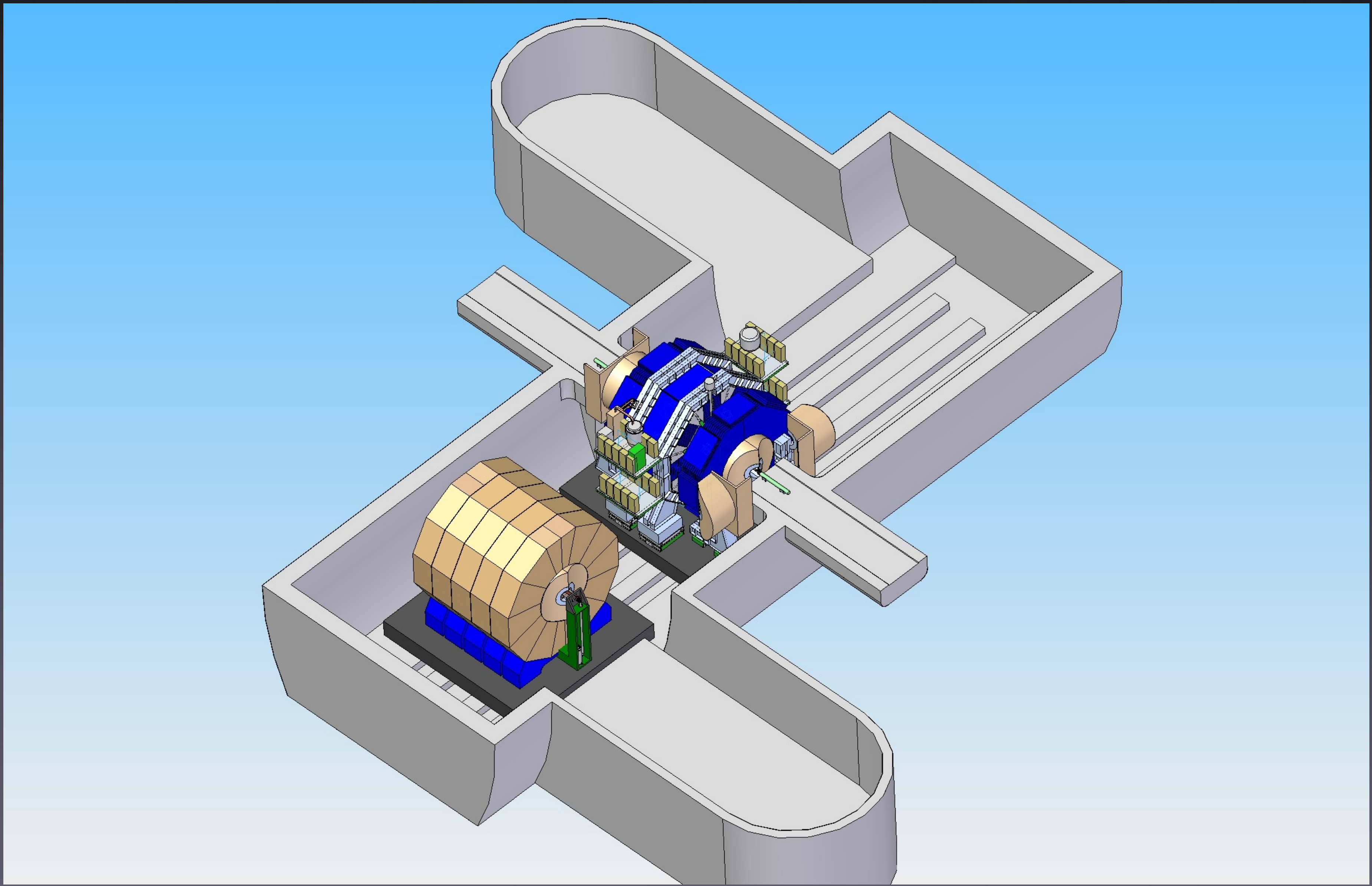
Push-Pull

- Community would like two detectors
  - Different technologies
  - Cross-check
  - Good experience in the past (CDF, D0...)
- Accelerator team prefers one interaction region
  - Main driver is cost
- Push-Pull idea
  - Detectors share one interaction region
  - Swap-over every few weeks
  - Never been done before
  - Engineering challenge (nightmare)

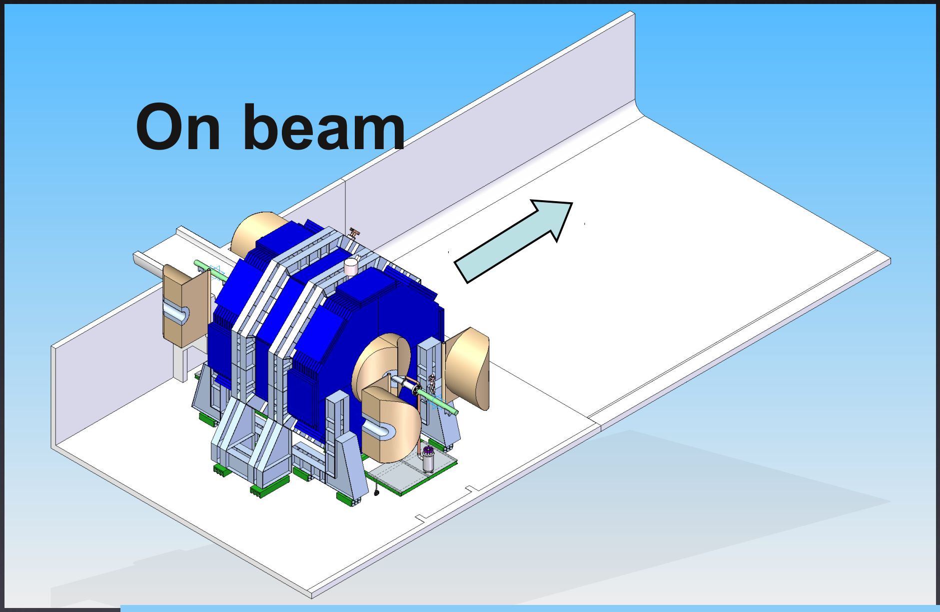
SiD in the hall

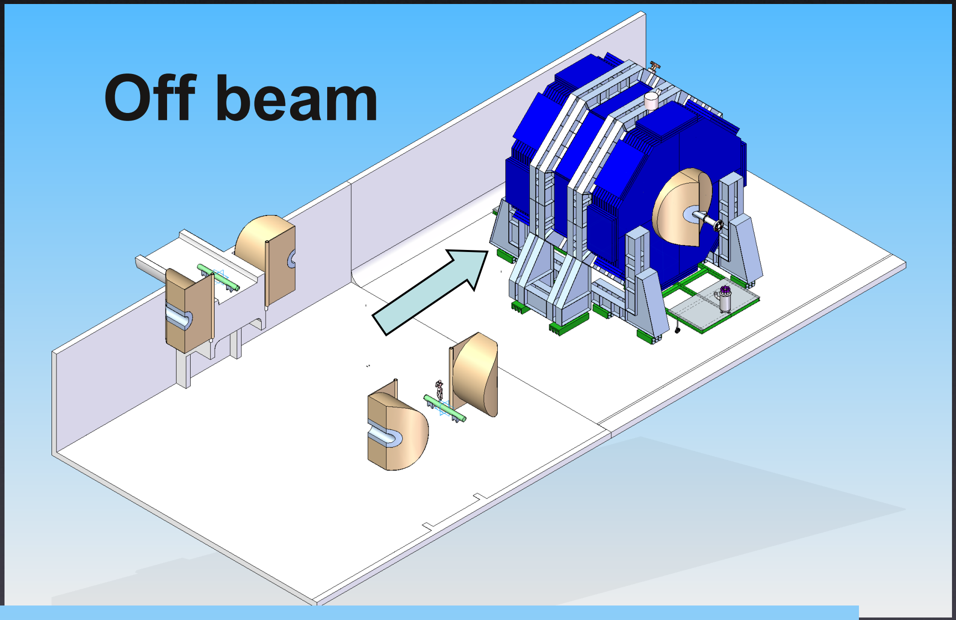


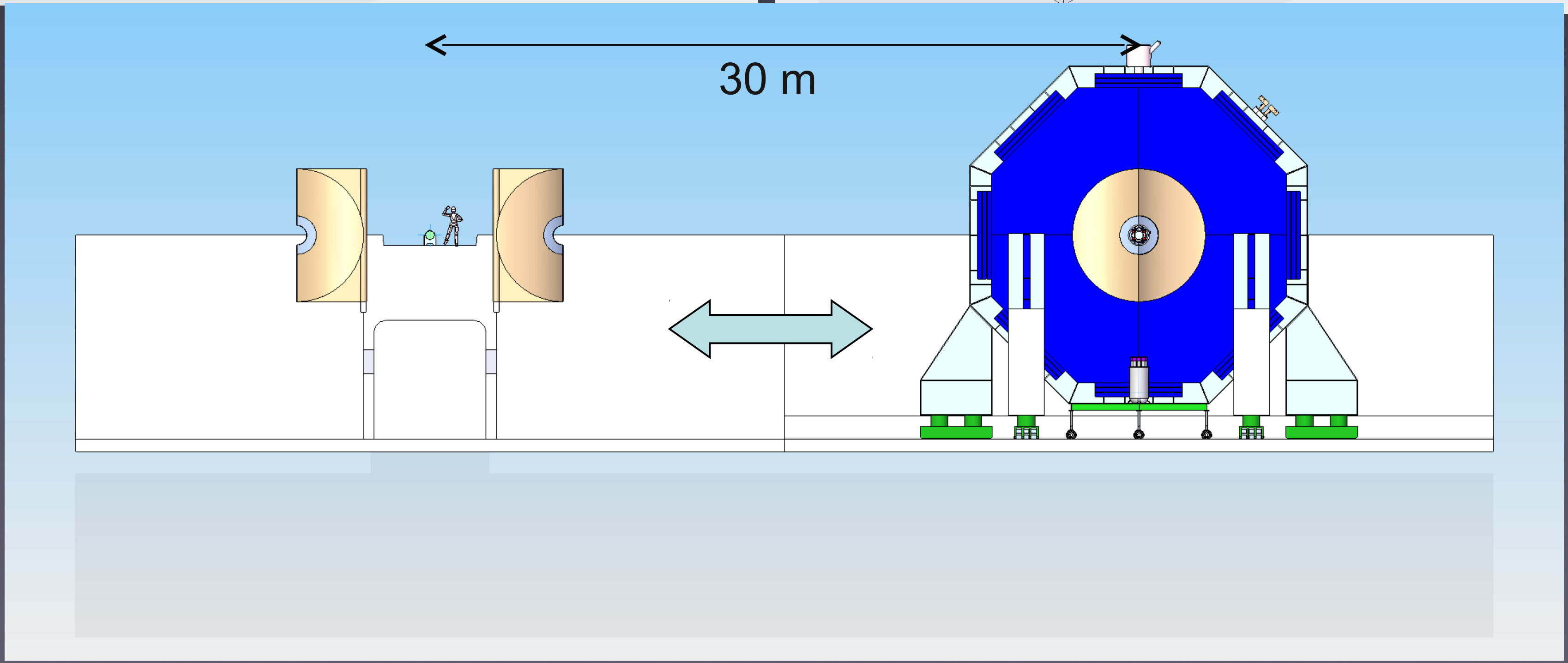
Collision hall design



Push & Pull







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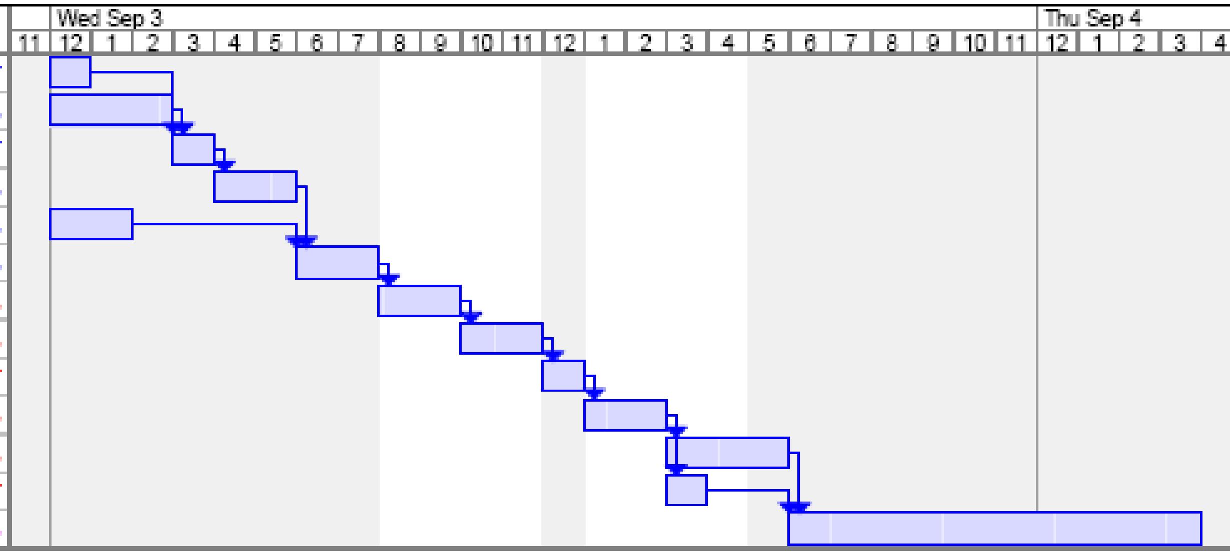
Timeline

ID	Task Name	Duration
1	Secure ILC Beams	1 hr
2	De-energize magnets	3 hrs
3	Open Beamline Shielding	1 hr
4	Disconnect Beamlines	2 hrs
5	Checkout Detetctor Transport s	2 hrs
6	Transport Detector 20 m	2 hrs
7	Transport other detector on bea	2 hrs
8	Connect beamline	2 hrs
9	Close Beamline shielding	1 hr
10	Check gross detector alignment	2 hrs
11	Energize magnets	3 hrs
12	Safety Checks before beams	1 hr
13	Begin Beam Based alignment	10 hrs



The time intervals in this estimate appear conservative.

With careful engineering and an experienced, well rehearsed crew, it seems plausible to make the push-pull cycle, not including the beam based alignment and re-tuning of the machine, in less than a day.

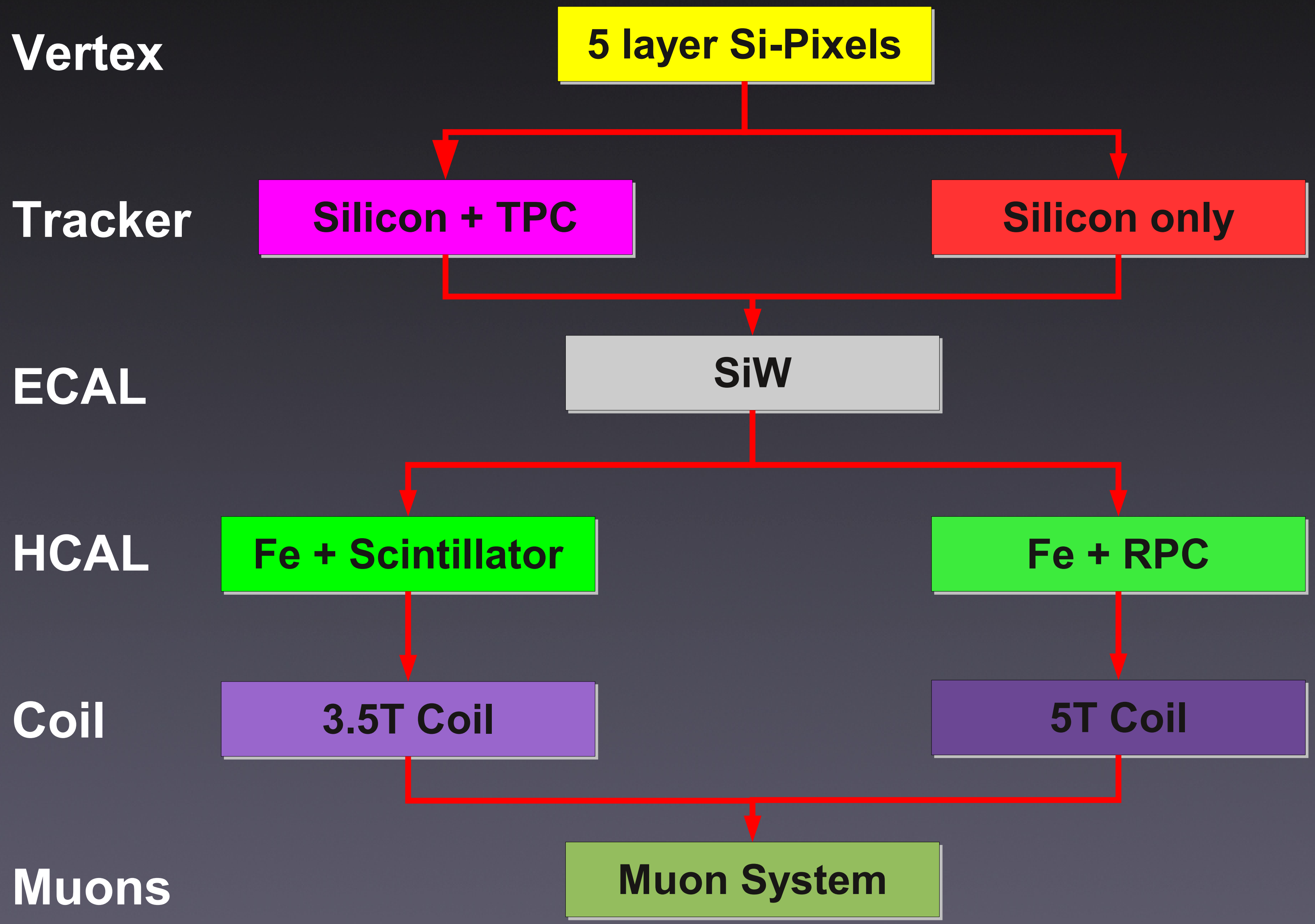
The converse is also true!

M. Breidenbach TILC2009

Current Detector Status

- 3 Detector "Letters of Intent" submitted (1/Apr/2009)
  - ILD, SiD and 4th Concept
  - ILD and SiD built on Particle Flow
  - 4th based of Dual-Readout Calorimetry
- International Detector Advisory Group (IDAG) Review
  - Validated ILD and SiD in Aug 2009
  - Go-ahead for a Detailed Baseline Design
  - Due End 2012
- SiD and ILD have two different approaches to PFA
  - SiD : Compact & High Field
  - ILD: Large & Low Field

ILD + SiD



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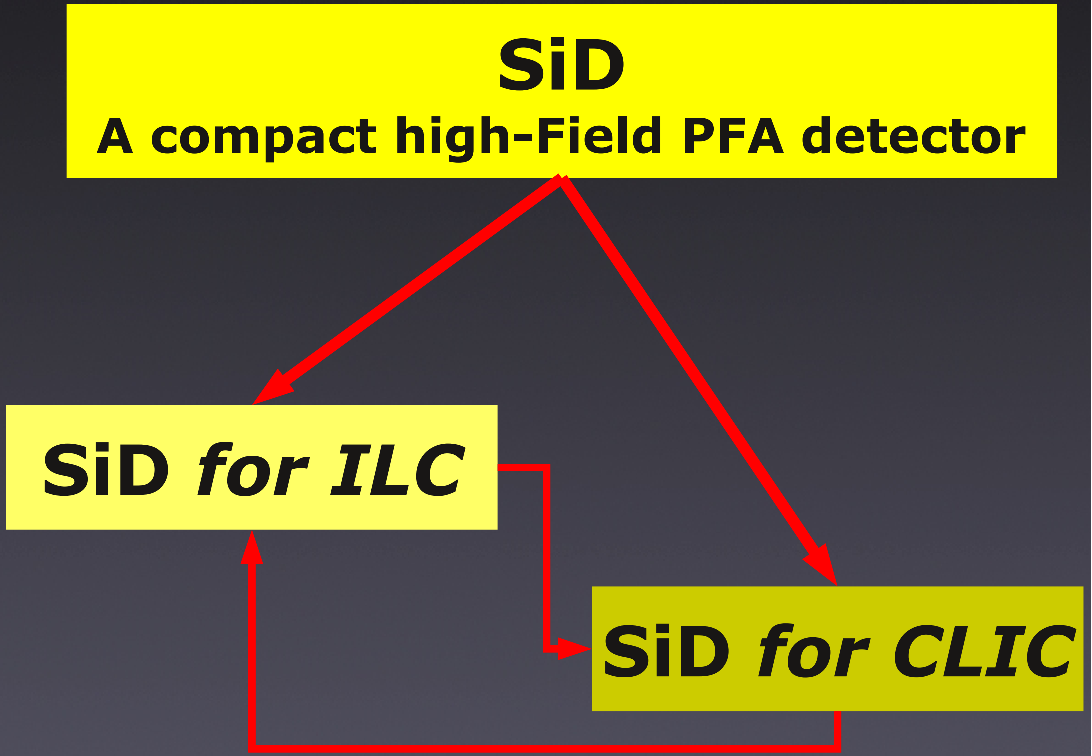
Variants for CLIC

- Both SiD and ILD have adapted versions for CLIC
- Vertex detector moves out r ~ 4 cm
  - More background
- Tungsten as HCAL absorber
  - Minimize leaking at 3 TeV
  - Has to fit inside the coil
- Electronics, timing
  - Already mentioned that



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What would we want the machine to do ?

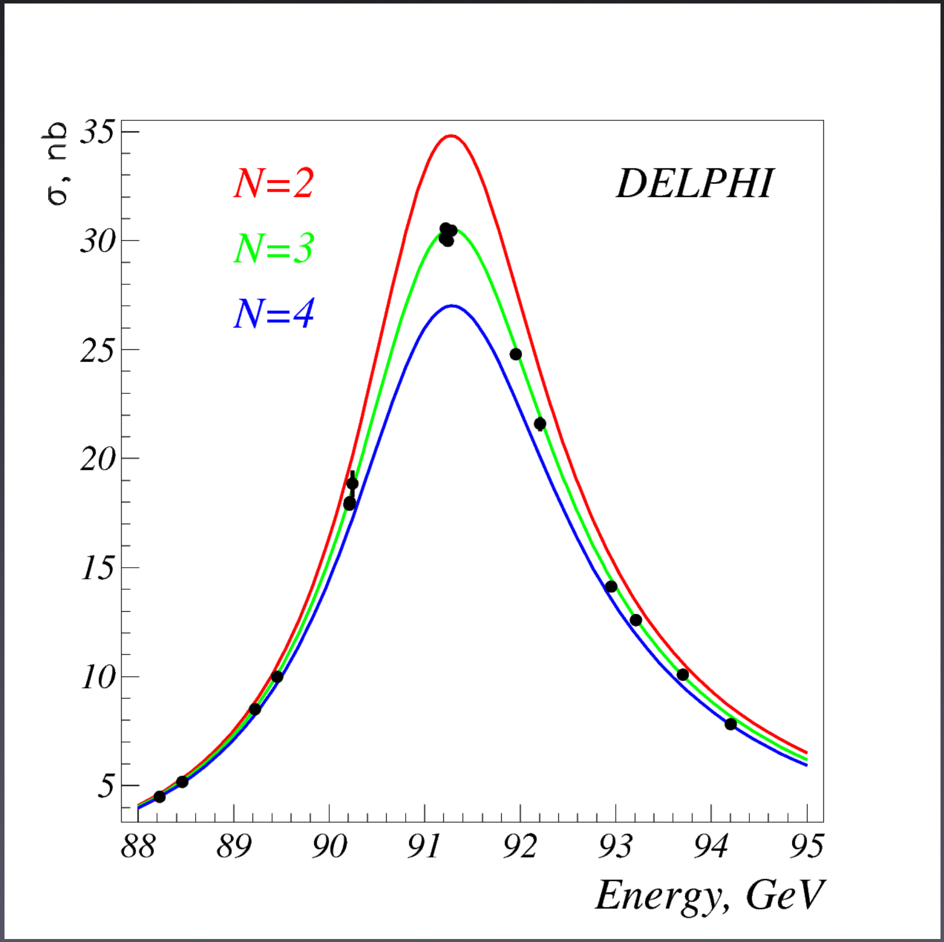
- Vary beam energy
- Threshold scans
- Small Beam spread
- Low background rates
- High luminosity at every energy
- Supportive of push-pull

Varying the beam energy

- Examples from the LEP era
  - Z
  - W^+W^-
- Linear Collider Studies
  - $t\bar{t}$
- Energy range of the machine
  - Ultimately depends on LHC results

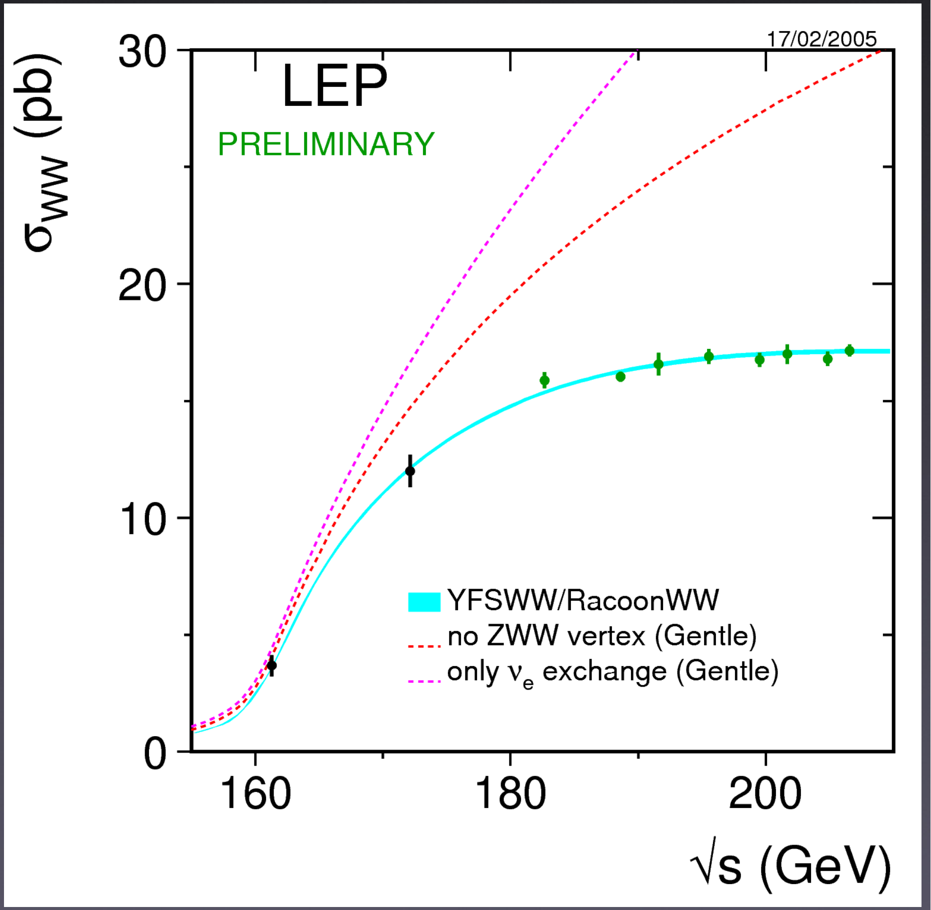
LEP -I

- Measuring the width of the Z Boson
- Determination of the number of generations in the SM
- Ability to modify beam energy was crucial to this measurement



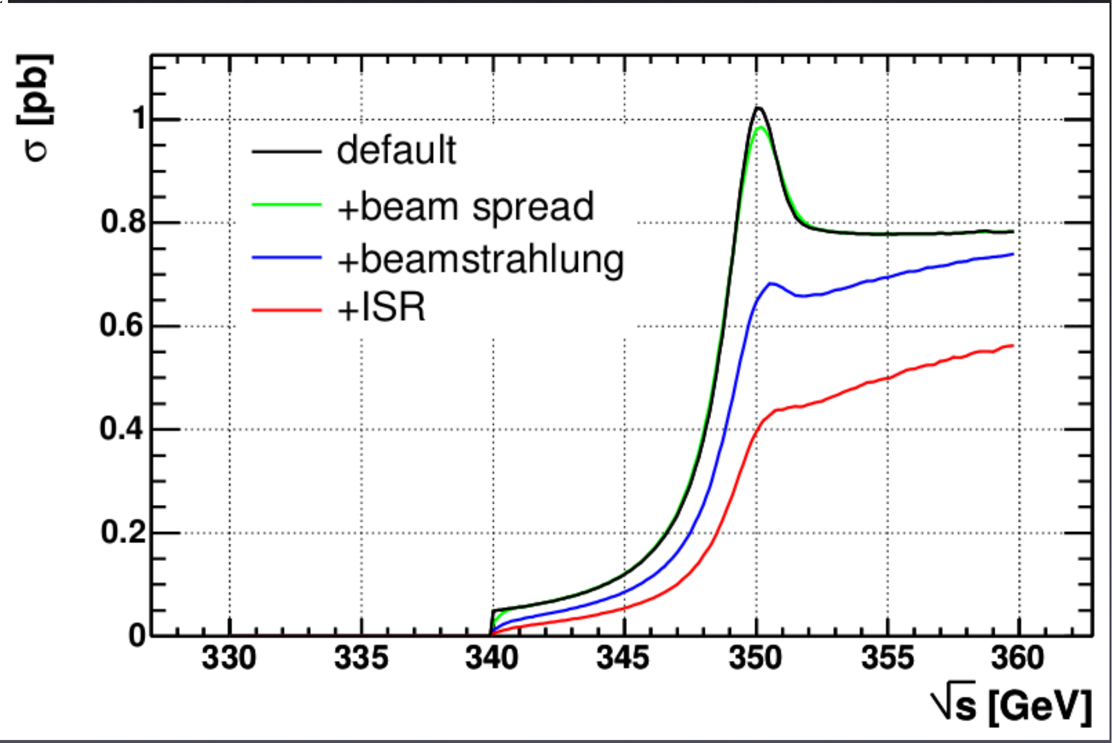
LEP-II

- LEP-II measured
  - W^+W^- cross-section
  - W mass
- Important result confirming the SM
- W Mass measurement
  - From Threshold (~ 40 pb^{-1})
  - Direct reconstruction (~ 2.5 fb^{-1})
- Result
  - M_W(direct) = 80.387 ± 0.026(stat.) ± 0.024(syst.) GeV/c^2
  - M_W(threshold) = 80.40 ± 0.20(stat.) ± 0.07(syst.) ± 0.03(LEP) GeV/c^2



Top mass measurement

- Scan around Top threshold
- Requires precise measurement of beam energy, ISR ..
- Potential accuracy on top mass
  - 100-200 MeV
- LHC (projected)
  - 1 GeV
- Tevatron (measured)
  - 1.1 GeV



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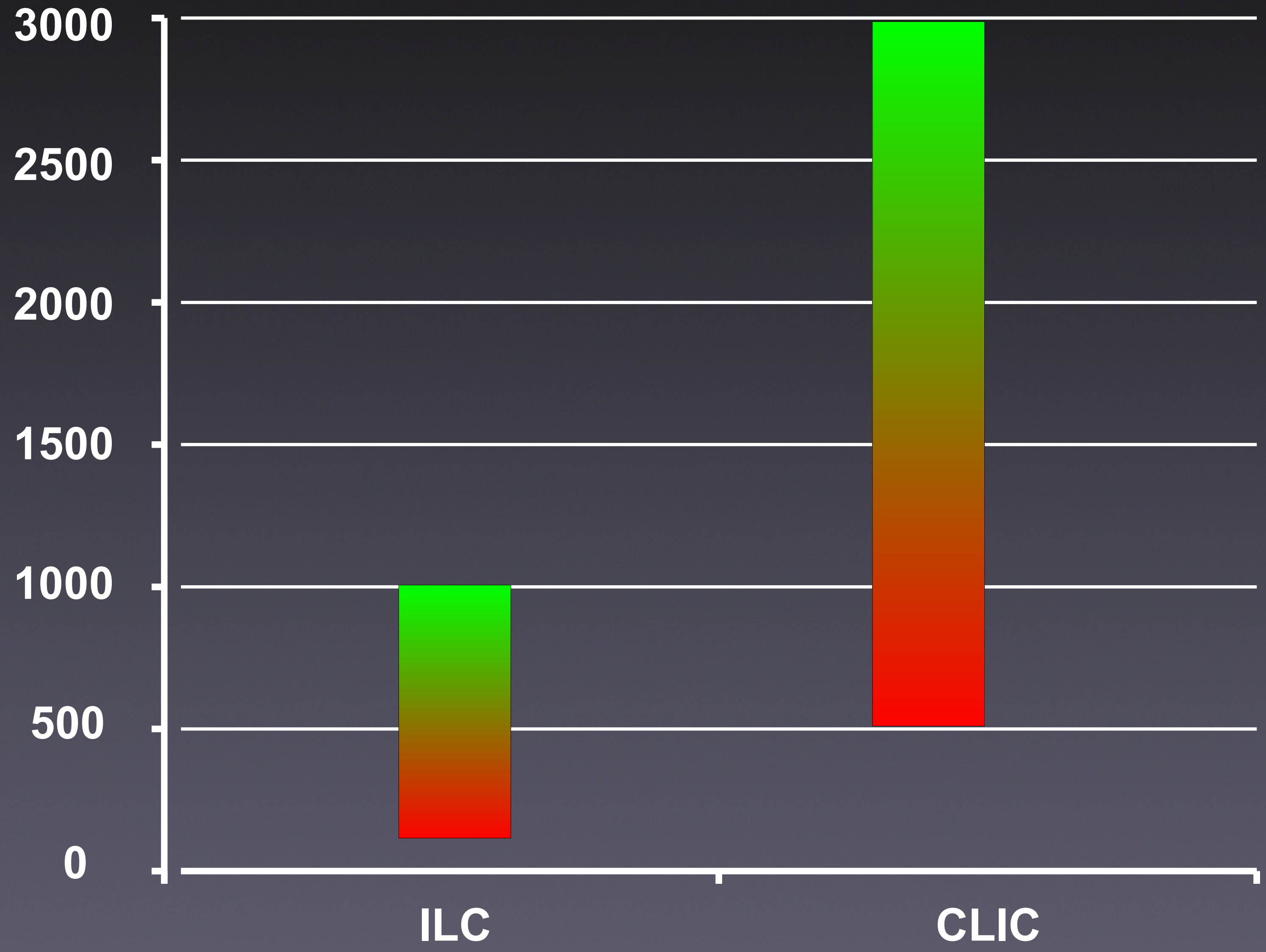
Energy of the machine



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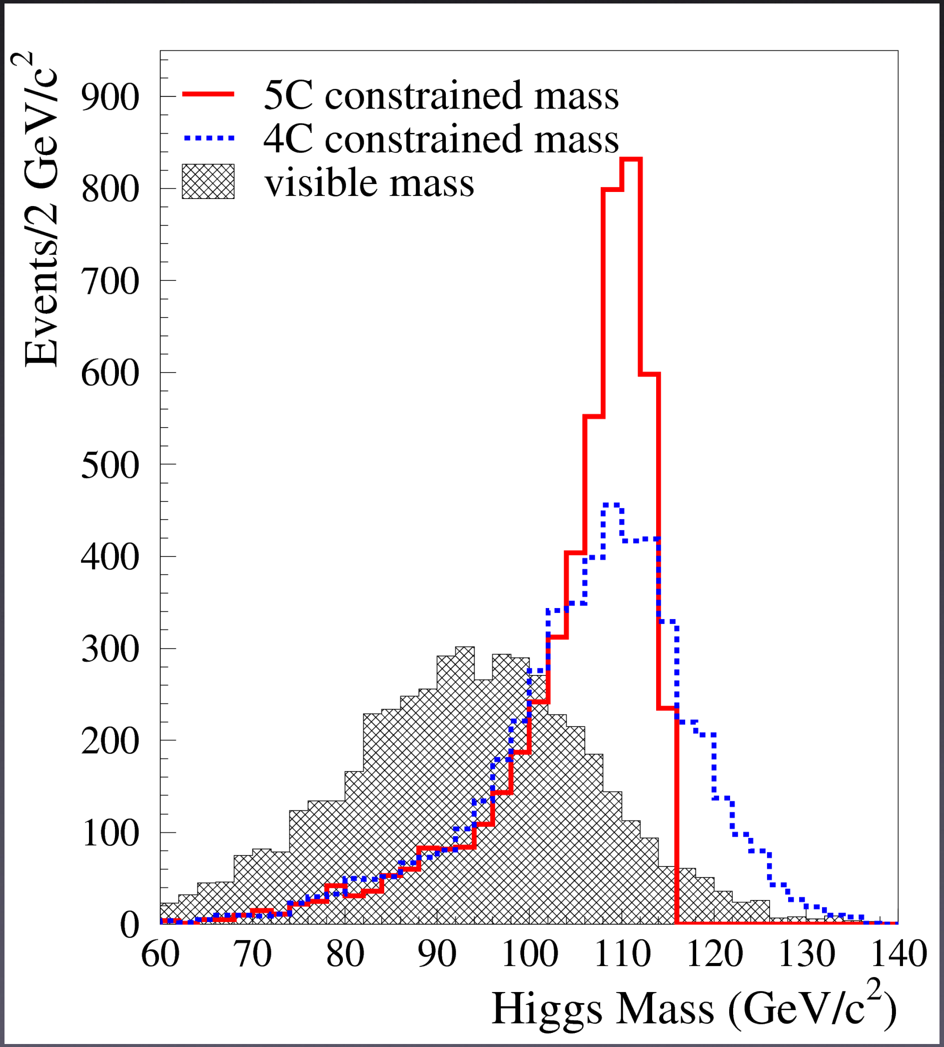
A exemplary run plan ...

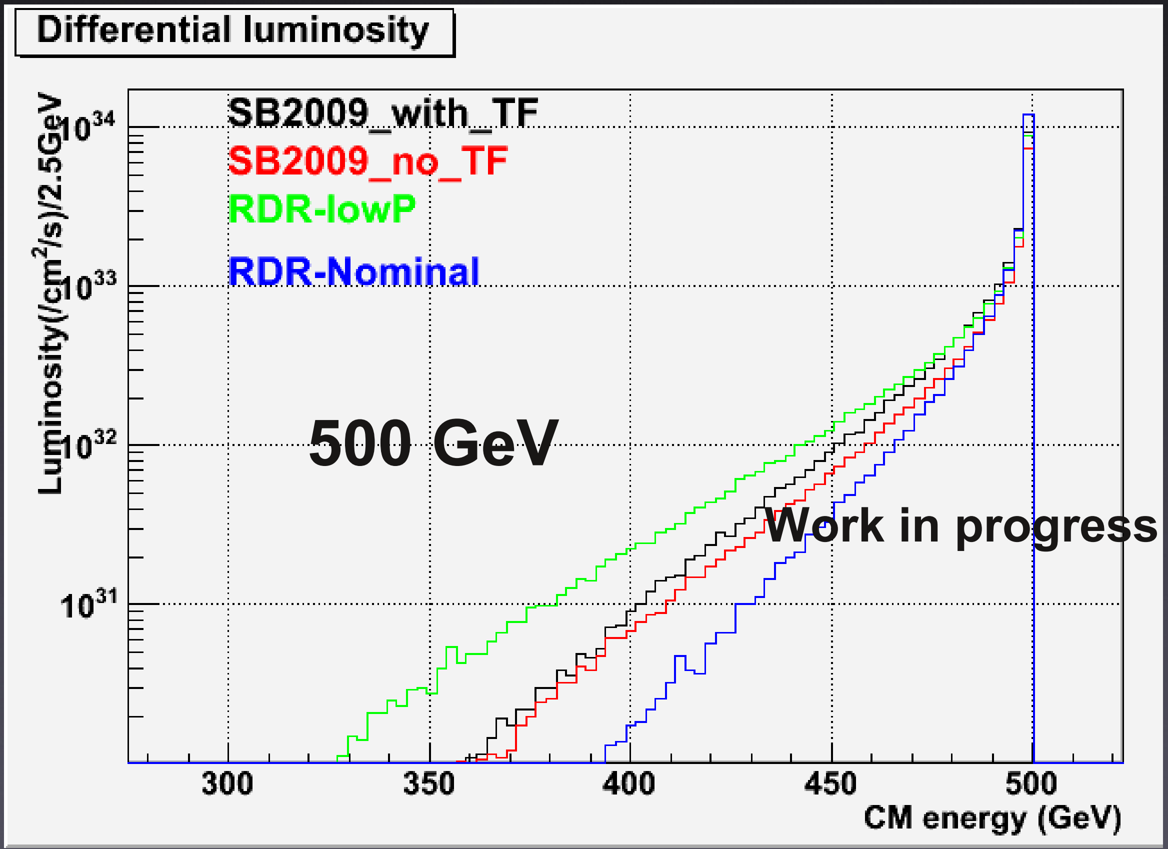
- Baseline
  - 250 GeV for light Higgs measurements
  - 350 GeV run (mainly top quark)
  - 500 GeV High energy run
  - Potential GigaZ program
- Upgrade to 1 TeV
  - 780 GeV run (A SUSY particle threshold)
  - 1 TeV High energy run
- Important to have decent luminosity at all points

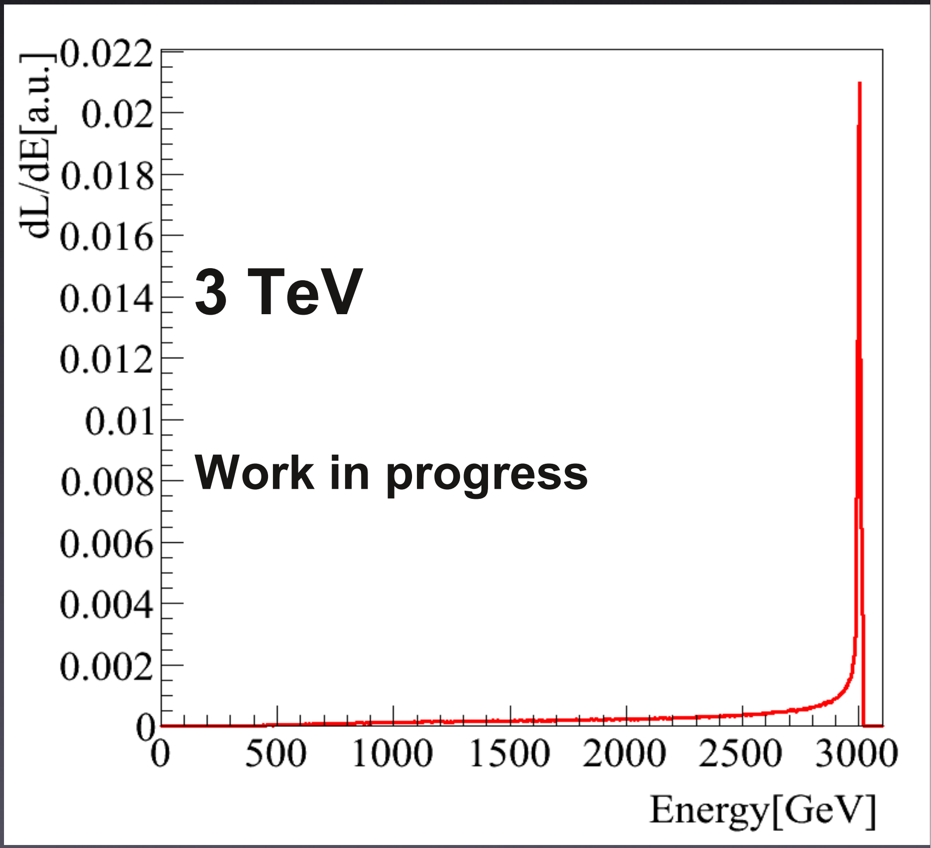
Beam energy constraints

- The Beam Constraint is a very powerful tool
- Classic 4C approach
  - Total momentum=0
  - Total energy=$\sqrt{s}$
- Additional mass constraints like Z mass help
- e.g.
  - $e^+e^- \rightarrow HZ \rightarrow ZWW^* \rightarrow qqqqqq$



ILC & CLIC example

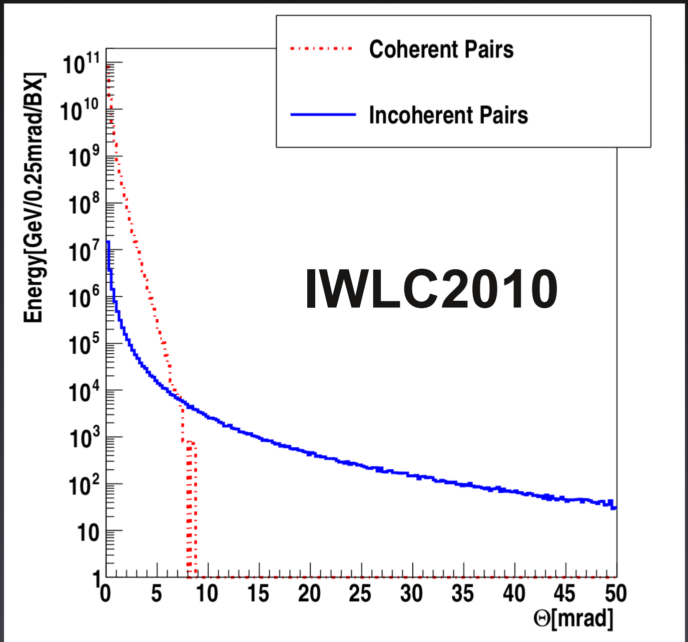


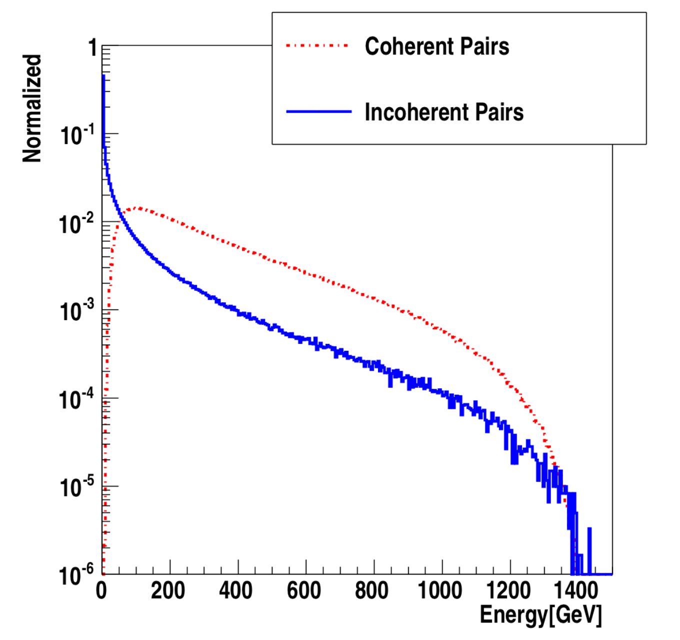


- Maximize luminosity in the peak
- Long tails need to be modeled in Simulation

Beam backgrounds : CLIC

- Incoherent e^+e^- Pairs
  - Photons interacting with other electron/photon
  - Peak at lowest Energies
  - few 10^5 particles/BX
- Coherent e^+e^- pairs
  - Direct photons conversion in strong fields
  - Cutoff at near 10 mrad
  - 10^8 particles/BX





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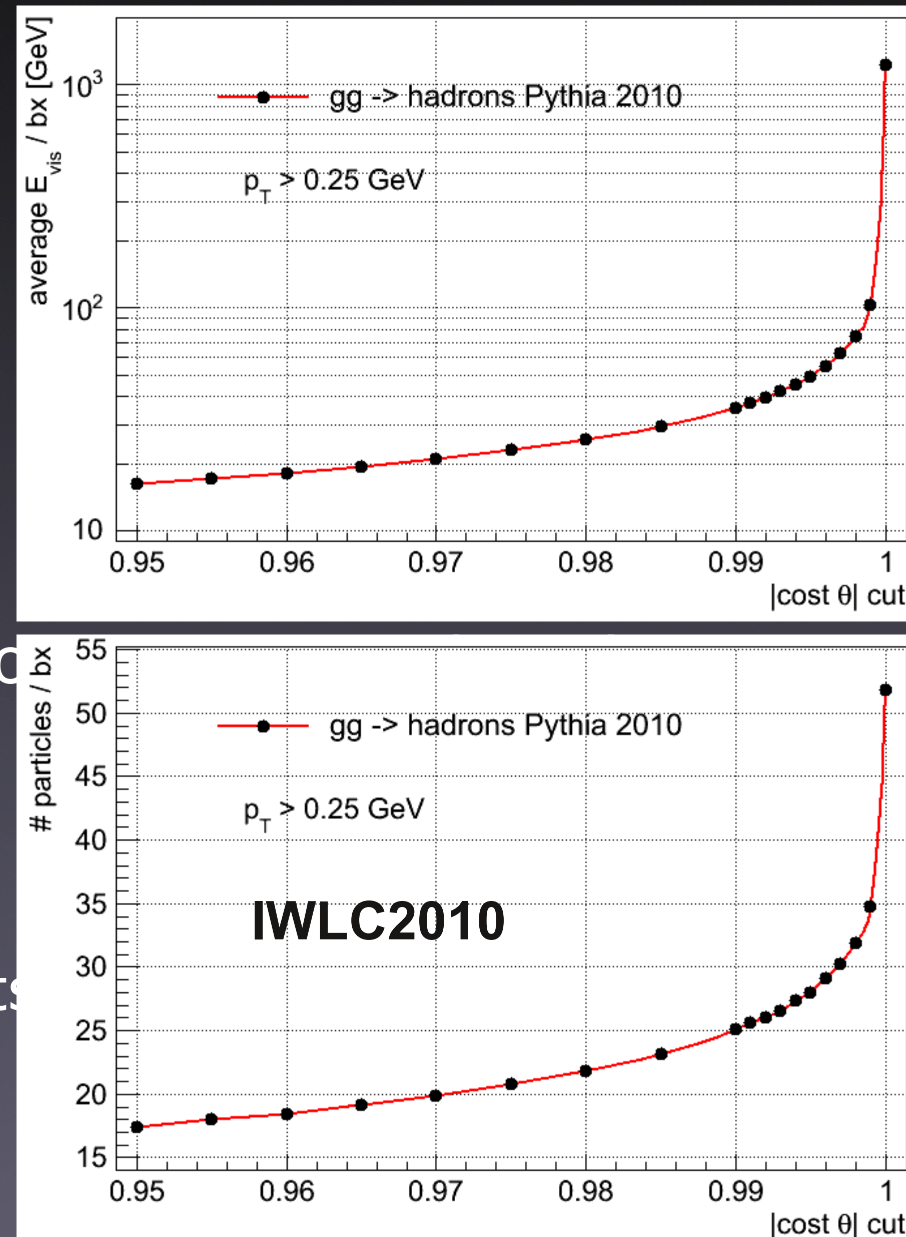
Beam background : CLIC

- $\gamma\gamma$ pairs
- 3.3 events/BX
  - 30 particles hit detector
  - Deposit ~ 50 GeV
  - Forward-peaked
- 15 TeV dumped in the detecto
- Reconstruction Challenge
  - Mini-jets
  - Overlap with physics events



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Summary

- Lots of challenges for LC detectors
  - Too many for just 45 minutes
- Lots of R&D activity to address them
  - Material for several seminars
- Impressive Progress
  - Interplay between Machine and Detectors more important than ever
- Acknowledgments
  - Thanks to M. Oriunno, J. Marshall, R. Partridge, J. Brau, M. Thomson, A. Sailer, M. Breidenbach and T. Barklow for material and discussion