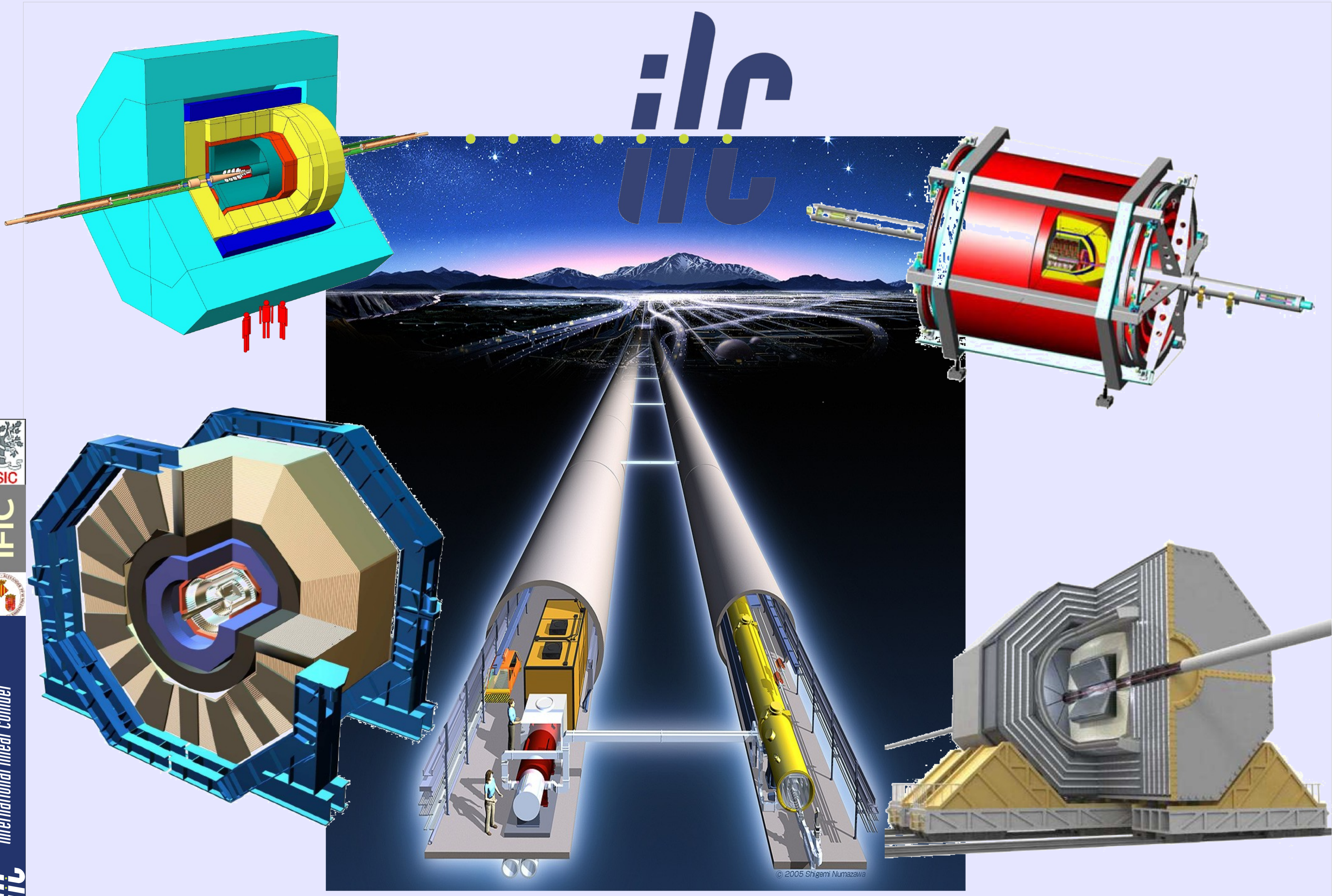
Tracking and alignment at the ILC



Tracking and alignment at the ILC

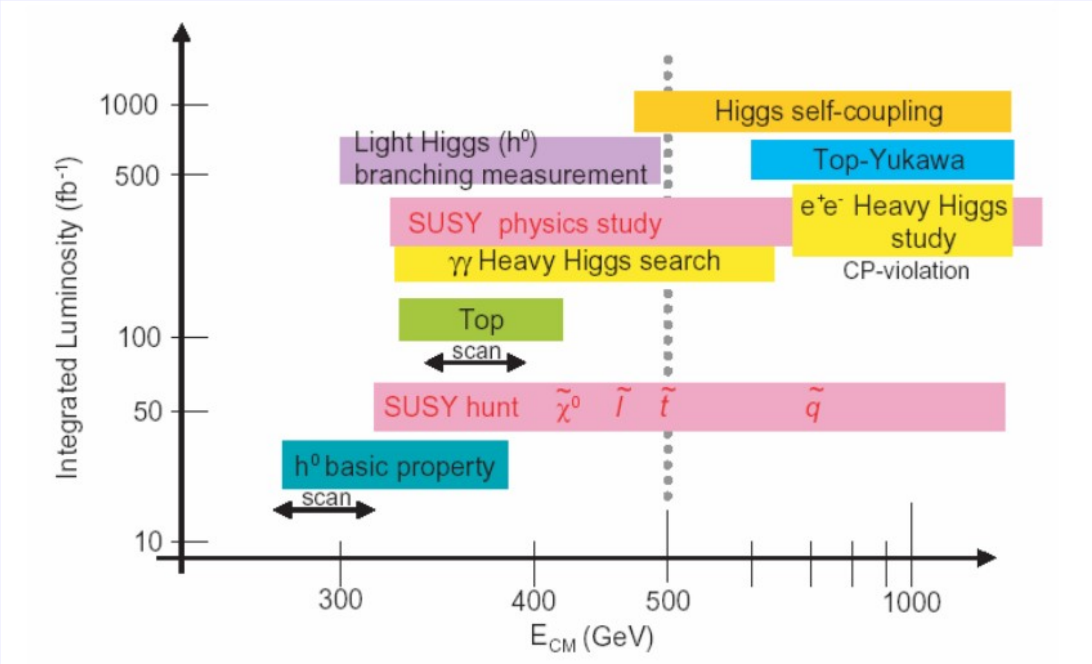
Marcel Vos, IFIC, U. Valencia/CSIC

- ✓ Some goals
- ✓ Some philosophy / detector concepts
- ✓ Important requirements
- ✓ The “benign” environment
- ✓ The technology – ILC detector R & D

The Goals

Much has been said about the complementarity of LHC and ILC hysics interplay of the LHC and the ILC.

- LHC/LC Study Group (G. Weiglein et al.).Phys.Rept.426:47-358,2006
- the Linear collider physics resource book for Snowmass 2001 hep-ex/0106055 (part 1), hep-ex/0106056 (part 2), hep-ex/0106057 (part 3), and hep-ex/0106058 (part 4)
- the GLC report:



Graphical overview of the accessible physics programme as a function of √s, from GLC report

Complete discussion beyond the scope of this talk: pick a few items that have a large impact on detector design

The goal : precision EW physics

Precision EW or signal of strong EWSB?

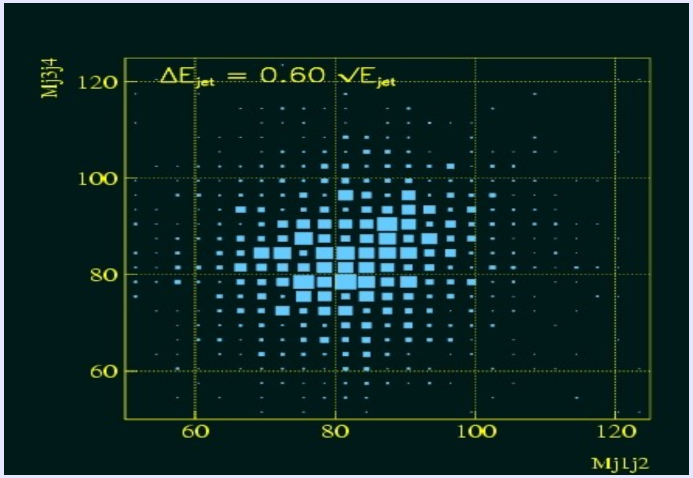
Unconstrained kinematics needs **high resolution** cal to discriminate WWνν, WZeν, and ZZνν events.

$$e^+e^- \longrightarrow WW\nu\bar{\nu} \;,\; e^+e^- \longrightarrow ZZ\nu\bar{\nu}$$

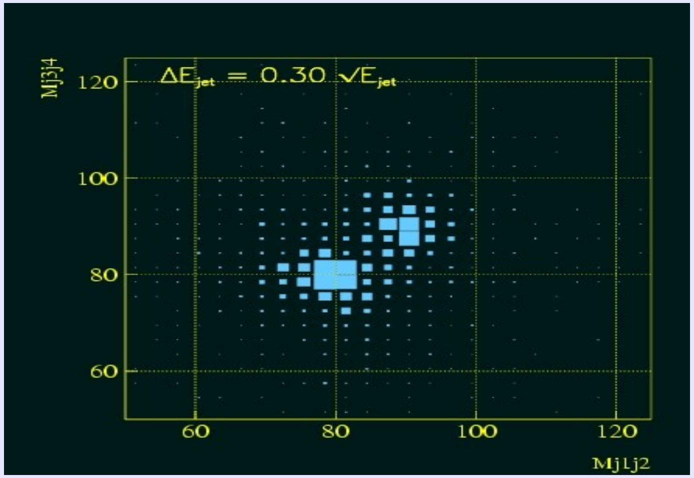
Measure Higgs Self Coupling λ_{hh}

Tiny (0.2 fb @ 500 GeV) signal on large multi-jet backgrounds is only visible with **high resolution**

$60\%\sqrt{E}$



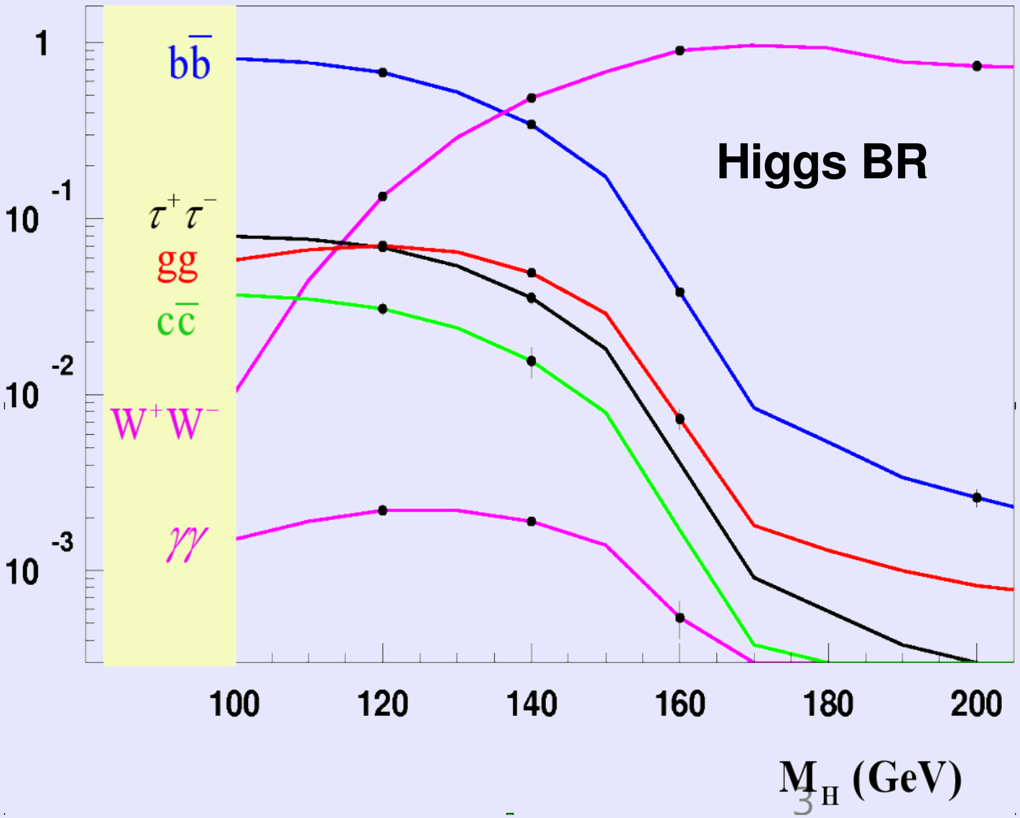
$30\%\sqrt{E}$

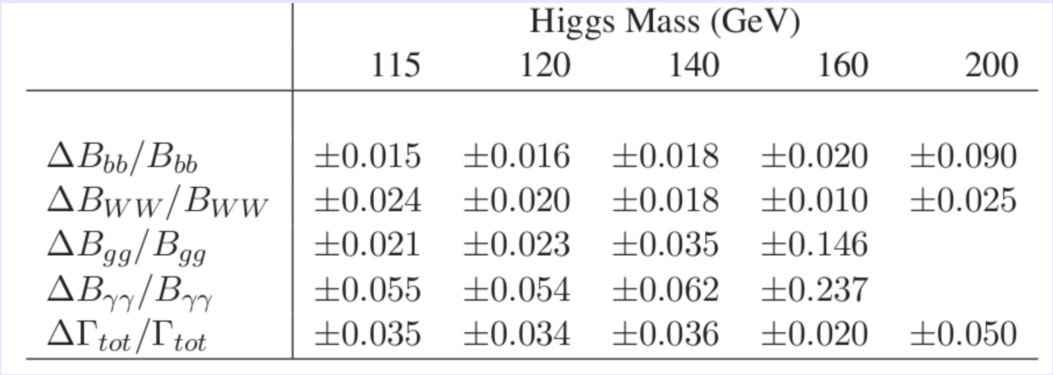


The goal: study Higgs properties

- ✔ **Study Higgs couplings.**

  Measurement of higgs branching fractions requires excellent flavour tagging (in particular b/c separation)



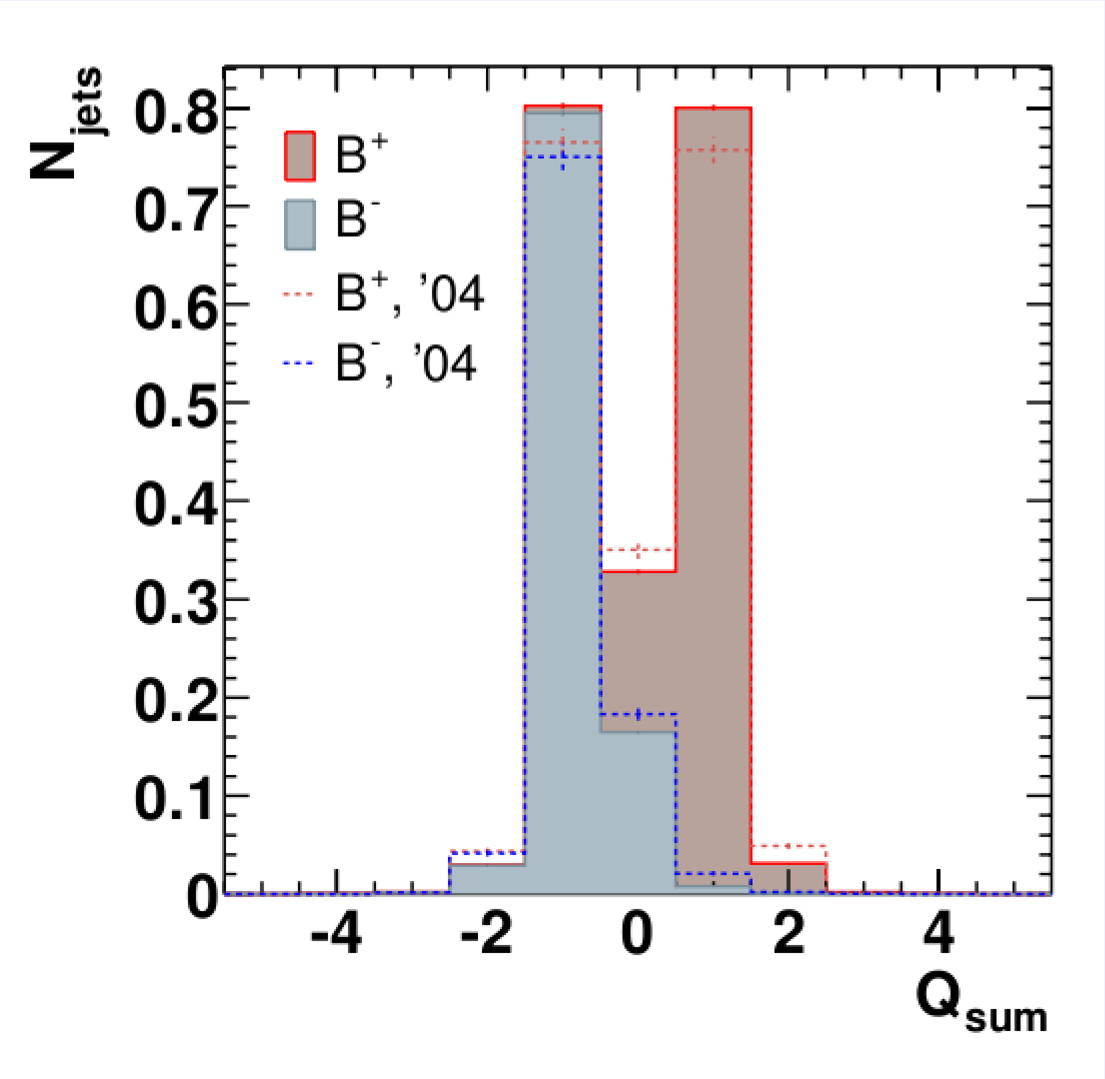


	Higgs Mass (GeV)				
	115	120	140	160	200
$\Delta B_{bb}/B_{bb}$	±0.015	±0.016	±0.018	±0.020	±0.090
$\Delta B_{WW}/B_{WW}$	±0.024	±0.020	±0.018	±0.010	±0.025
$\Delta B_{gg}/B_{gg}$	±0.021	±0.023	±0.035	±0.146	
$\Delta B_{\gamma\gamma}/B_{\gamma\gamma}$	±0.055	±0.054	±0.062	±0.237	
$\Delta\Gamma_{tot}/\Gamma_{tot}$	±0.035	±0.034	±0.036	±0.020	±0.050

Estimated precision for Higgs BR combining results from a 350 GeV and a 1 TeV linear collider, T. Barklow, Les Houches 2003, hep-ph/0406152

The goal: precision measurements

- **Vertex charge** (challenging since it demands correct track association even for very low momentum)
    - Top polarization,
    - W helicity,
    - qqbar asymmetries



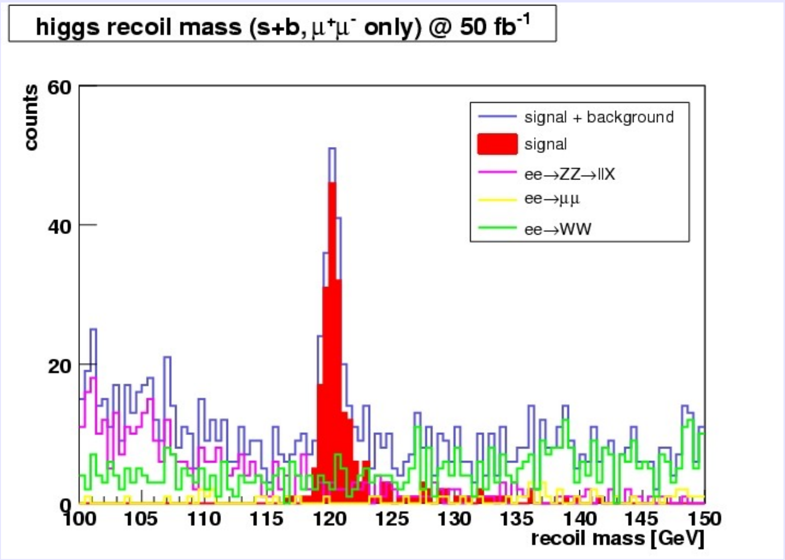
Vertex charge measurement

S. Hillert for the LCFI collaboration,
2005 International Linear Collider
Workshop - Stanford, U.S.A.

The goal : Higgs mass measurement

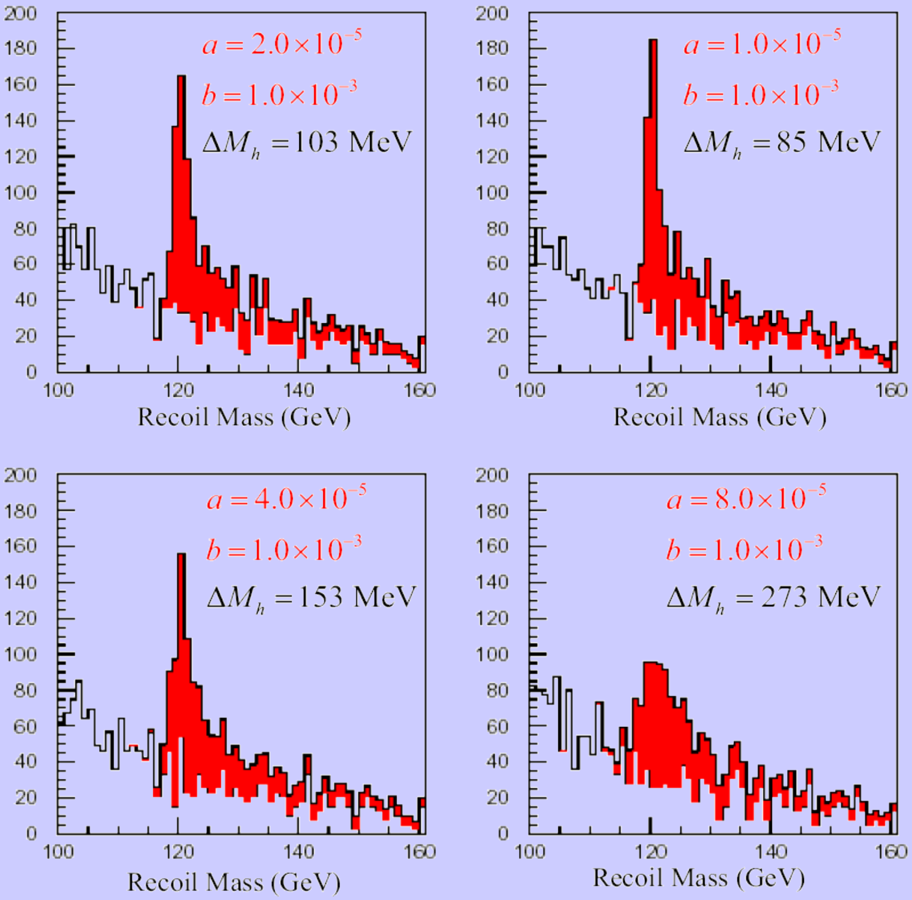
- ✔ Recoil mass analysis in ZH systems allows to determine the Higgs mass precisely, even for invisible Higgs decay.
- ✔ Beam spread has small influence: mass resolution dominated by tracker performance down to

  $\Delta p/p^2 \sim 1 \times 10^{-5}$ (Yang and Riles)
- ✔ Expected precision (Tesla): 40 MeV to 70 MeV for m_H between 120 GeV and 180 GeV.



Golden channel e+e- → HZ → μμX

Model independent measurement of Higgs mass



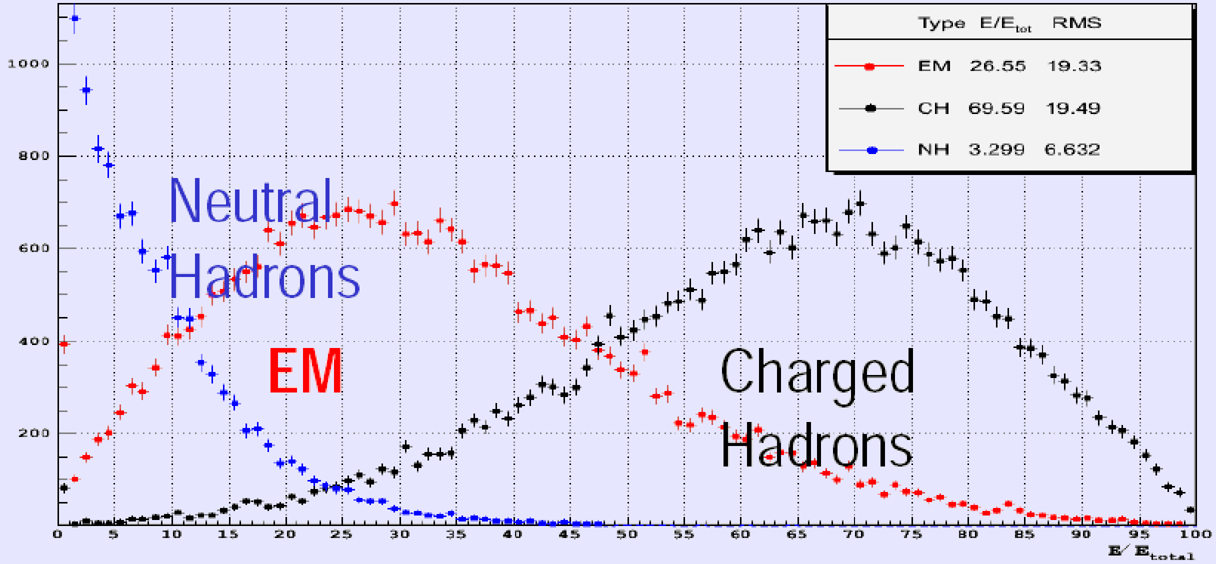
Full simulation study, M. Ohlerich, A. Raspereza, W. Lohmann, ACFA linear collider workshop, Beijing 2007

The philosophy: reconstruction

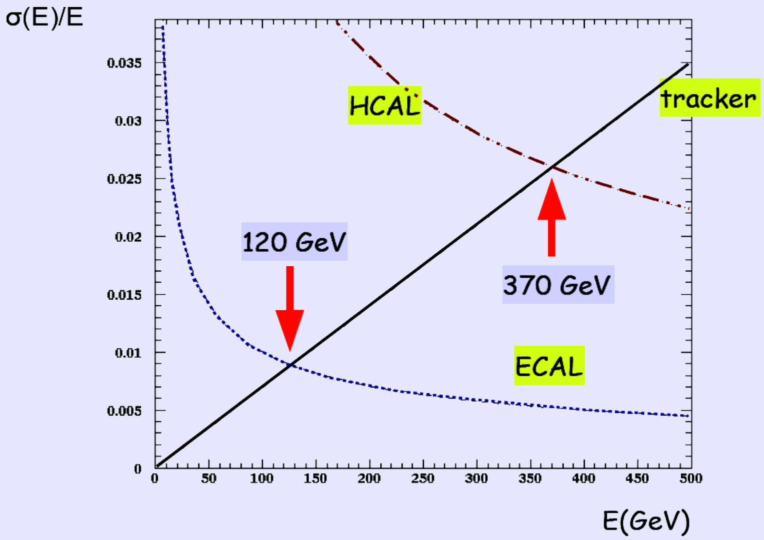
ILC precision is limited by the detector rather than by the environment

- ✓ Hadronic final states (jets):
  - ➔ precise jet energy measurement is crucial
  - ➔ flavour tagging, jet charge
- ✓ Leptons up to √s / 2
  - ➔ P_T resolution requirement driving tracker design

The philosophy: particle Flow

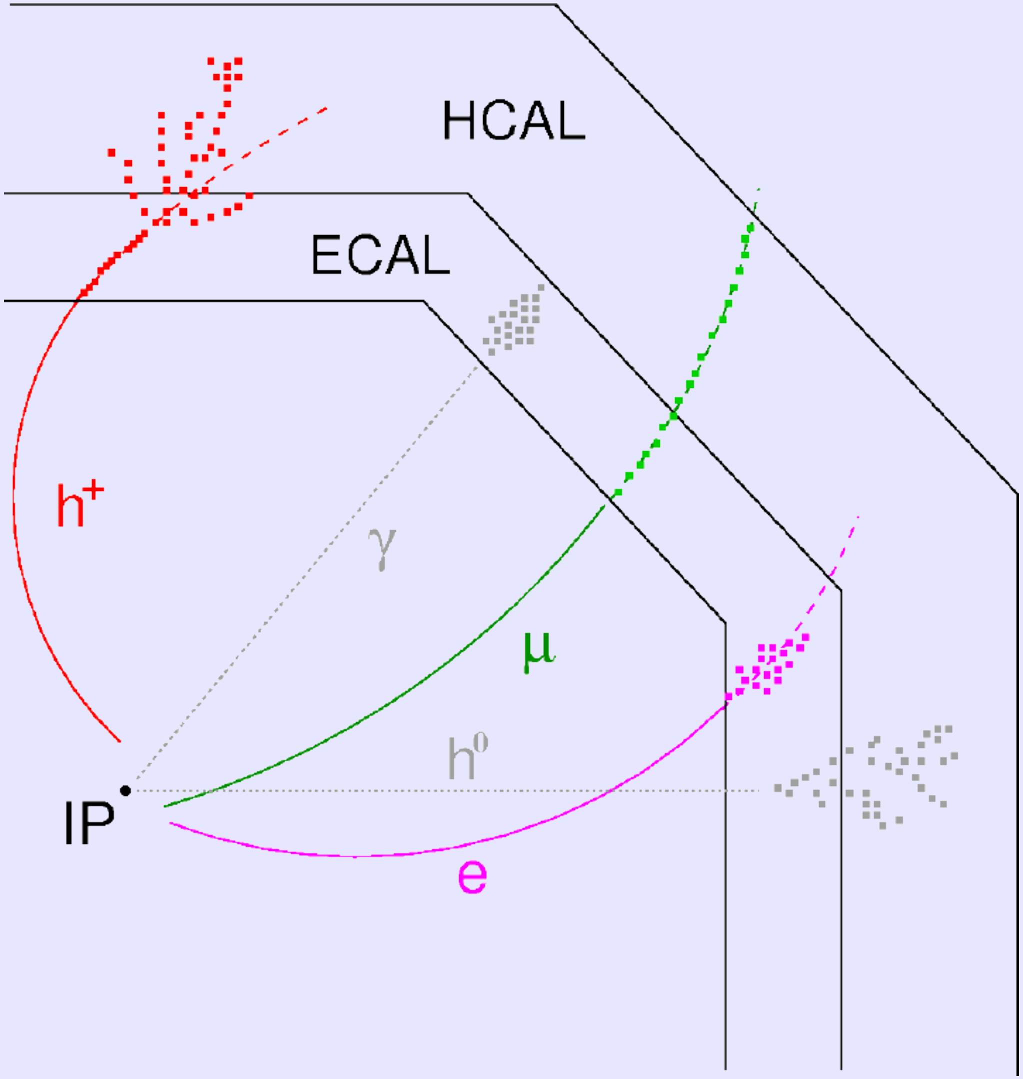


- In the LC the visible jet energy is ~64% due to charged particles
- For the ILC energies the tracker is more precise than the calorimeters: combine p (tracker) and E (calorimeter) measurements
- Novel high-granularity calorimeters are very fit to this concept
- Particle flow emphasizes the role of the tracker in jet physics



Particle Flow: How does it work ?

- ✔ Track reconstruction
- ✔ Extrapolate tracks to calorimeters
- ✔ Assign MIP stubs to tracks
- ✔ Clustering in calorimeters
- ✔ Particle ID for charged particles



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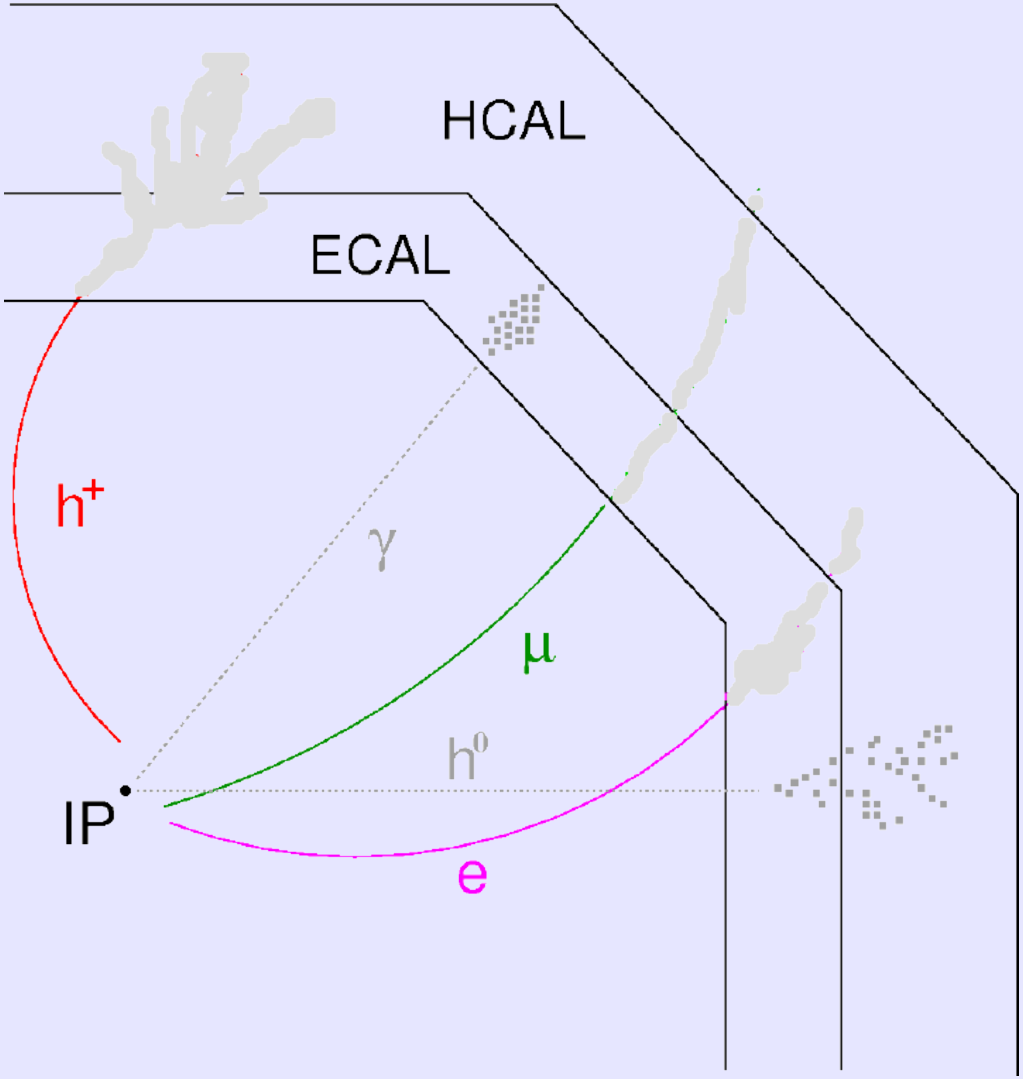
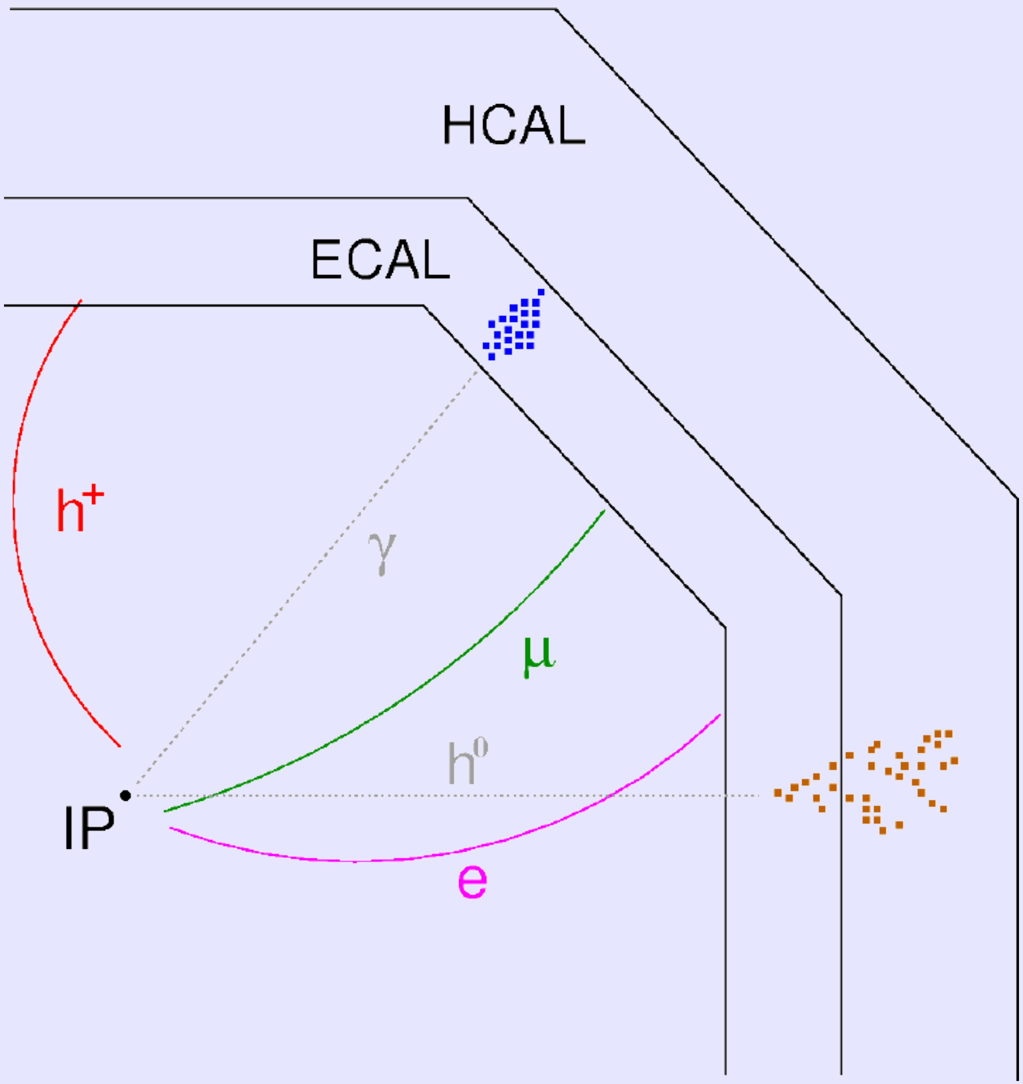
- ✔ Remove charged particle hits in calorimeter



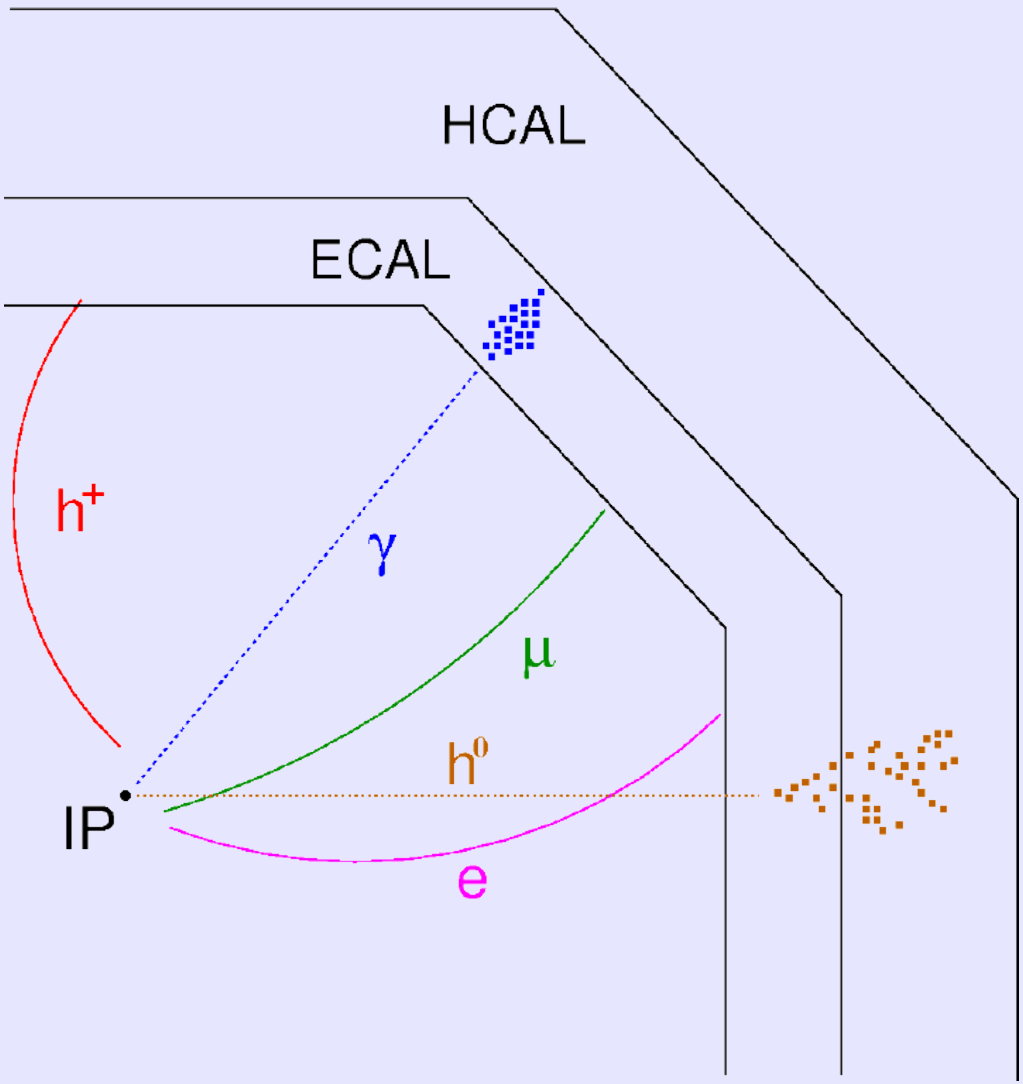
Particle Flow: How does it work ?

- ✔ Track reconstruction
- ✔ Extrapolate tracks to calorimeters
- ✔ Assign MIP stubs to tracks
- ✔ Clustering in calorimeters
- ✔ Particle ID for charged particles
- ✔ Remove charged particle hits in calorimeter
- ✔ Clustering of neutral hits



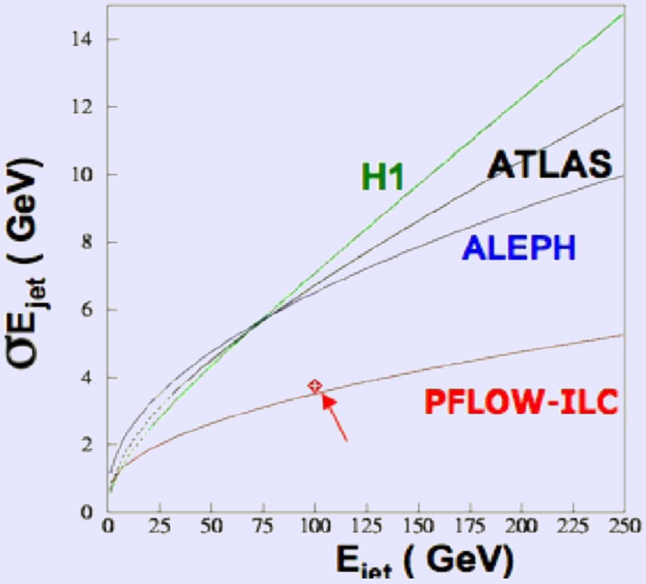
Particle Flow: How does it work ?

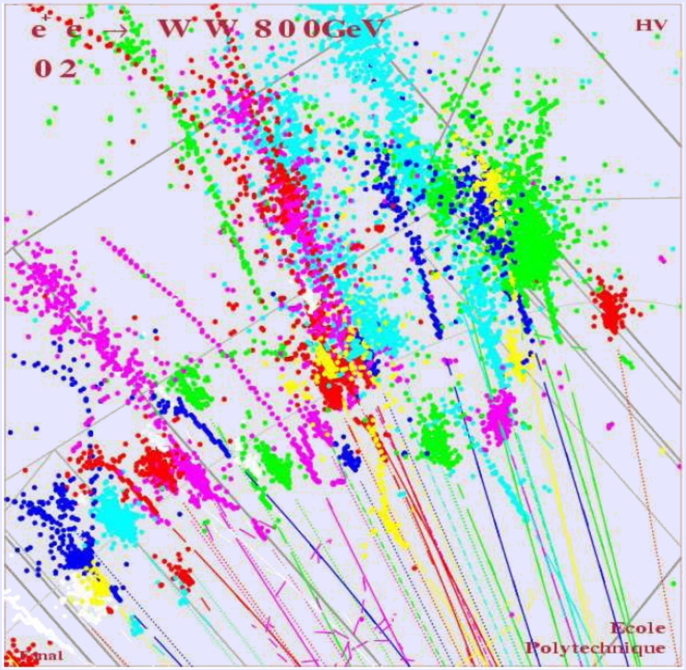
- ✓ Track reconstruction
- ✓ Extrapolate tracks to calorimeters
- ✓ Assign MIP stubs to tracks
- ✓ Clustering in calorimeters
- ✓ Particle ID for charged particles
- ✓ Remove charged particle hits in calorimeter
- ✓ Clustering of neutral hits
- ✓ Particle ID for neutrals



Particle flow

- ✔ Particle flow concept studies show that the required performance can be achieved at low energy (E < 150 GeV)
- ✔ The ILC detectors are designed having in mind the PFA which in a large extent defines the detectors
- ✔ Main problem: confusion
  - ➔ At high energies jets are very narrow
    - ➘ Difficult to associate hits to tracks
    - ➘ Yet more difficult to separate charged and neutral particles.
  - ➔ Need high granularity and sophisticated software to separate showers
- ✔ The key issue is particle separation rather than intrinsic energy resolution.

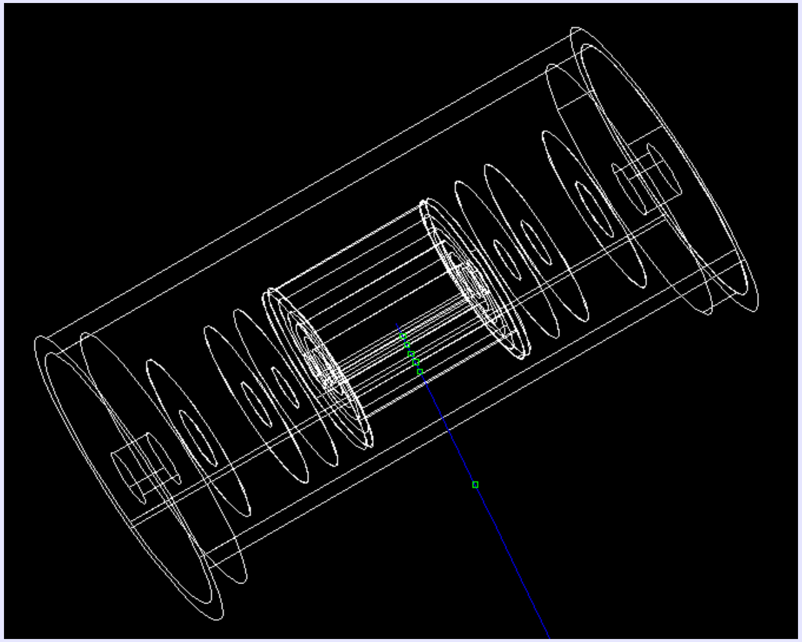




The philosophy: vertexing

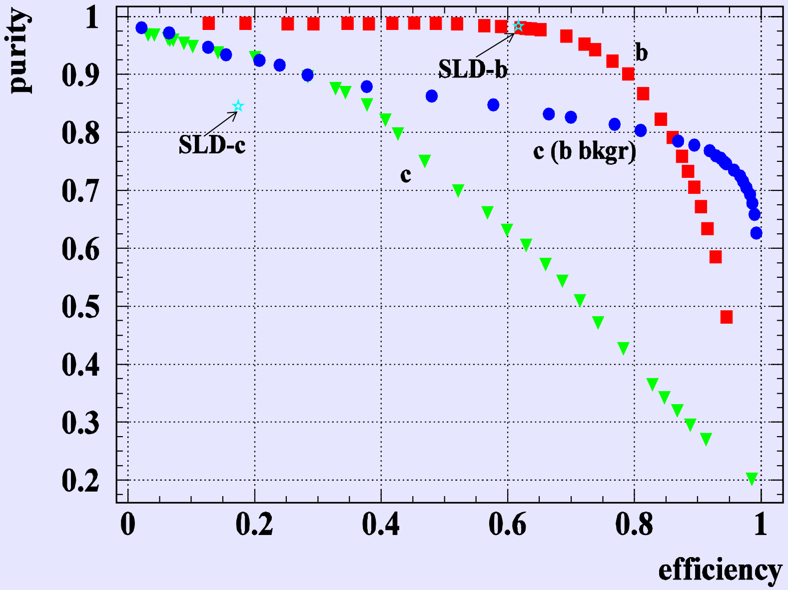
To Achieve ($5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)$)

- get real close: 12 – 20 mm inner radius!
- Excellent spacepoint precision ($< 5\ \mu m$)
- Transparency (~0.1% X_0 per layer)
- Occupancy innermost layers -> integration over <150 bunch crossings (45 µsec)

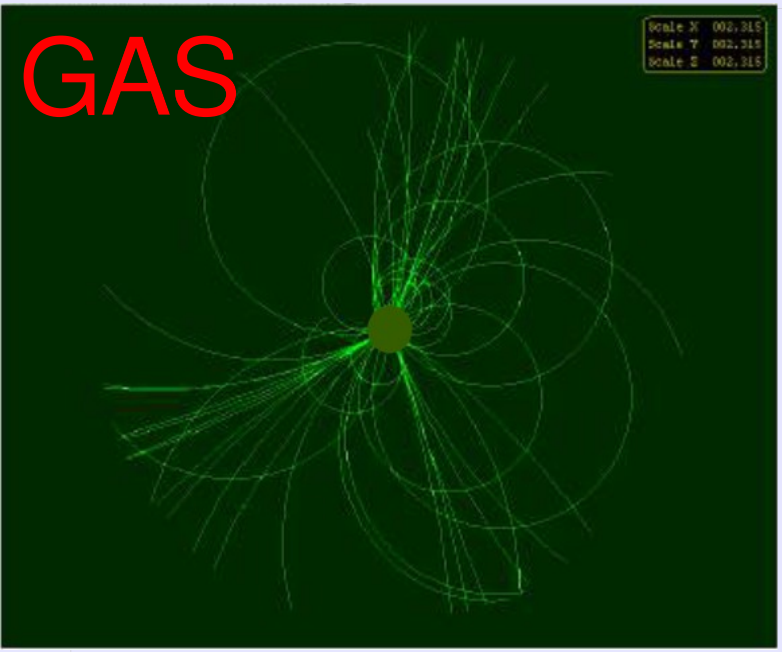


To determine Jet charge

- fully efficient and pure reconstruction down to 100 MeV -> excellent pattern recognition (5-6 high-granularity layers)



Central tracking: two philosophies



TESLA/LDC/GLD gaseous/solid tracker

TPC design/specifications

length: 5.46 m, diameter: 3.4 m, 3-4 T field

single point resolution: ~100 μm

200 space points per track

$\Delta p/p^2 = 1.5 \times 10^{-4}$ GeV^{-1} (TPC stand-alone)

dE/dx accuracy: 5 %

several % X_0 in field cage, 30-50 % X_0 in end-plate

SiD: all silicon solution

similar dimesions and magnetic field 5 T

6+5 high precision measurements per track

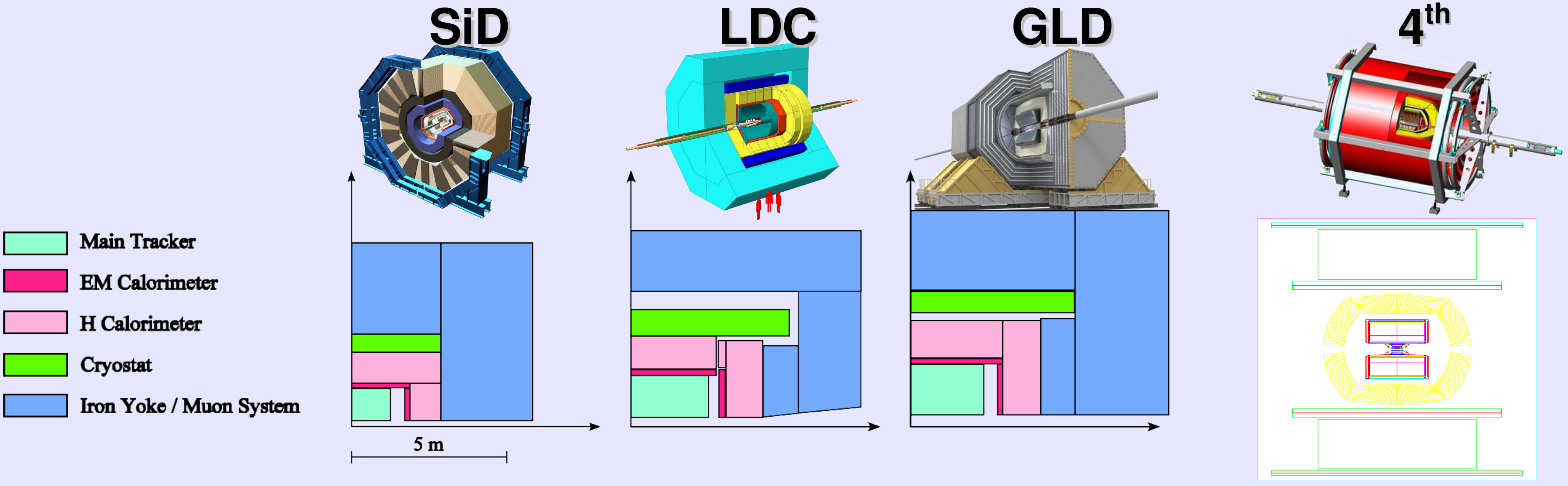
single point resolution: 10 μm

$\Delta p/p^2 = 1 \times 10^{-5}$ GeV^{-1} (including VTX)

Detector concepts

- There are 4 concepts
  - The different concepts differ mainly in size and aspect ratio
  - The main parameter is the inner radius of the ECAL

Same vertex detector



SiD

Small: $\mathbf{B}R_{in}^2$

Tracking: Silicon

Si-W ECAL

High field (5T)

LDC

Large: $\mathbf{B}R_{in}$

Tracking: TPC+Si

Si-W ECAL

4T field

GLD

Huge: $\mathbf{B}R_{in}$

Tracking:TPC+Si

W-scint. ECAL

3T field

4th

Tracking:TPC+Si

Dual readout ECAL

4T field

Driven by PFA

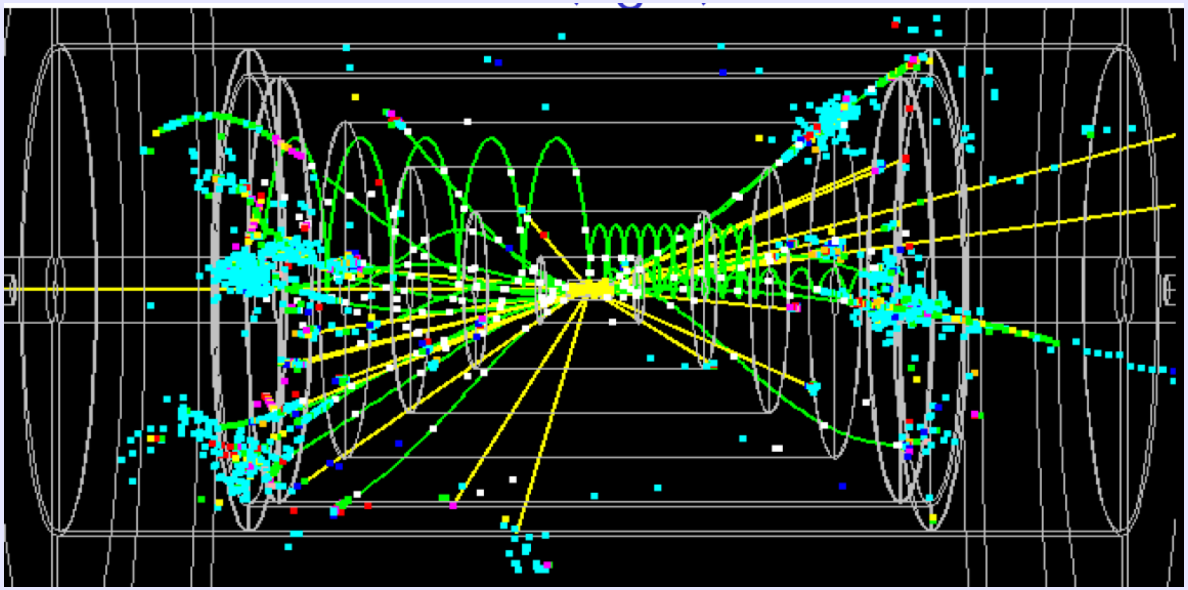
Iron return yoke

no PFA

Iron-free dual solenoid

Forward Tracking

- ✔ Forward region has a very important role in the ILC
  - ➔ Because of increased importance of t-channels and
  - ➔ Event topology (many jets almost isotroically distributed)
- ✔ PFA algorithms need good tracking to |cosθ|~0.98
- ✔ Should be thin enough not to
  - ➔ degrade forward calorimetry nor
  - ➔ spoil electron ID
- ✔ Robust to track loopers
- ✔ Differential luminosity requires extreme angular precision: $\Delta\theta/\theta \sim 10^{-5}$
- ✔ Never been done (right) !!!

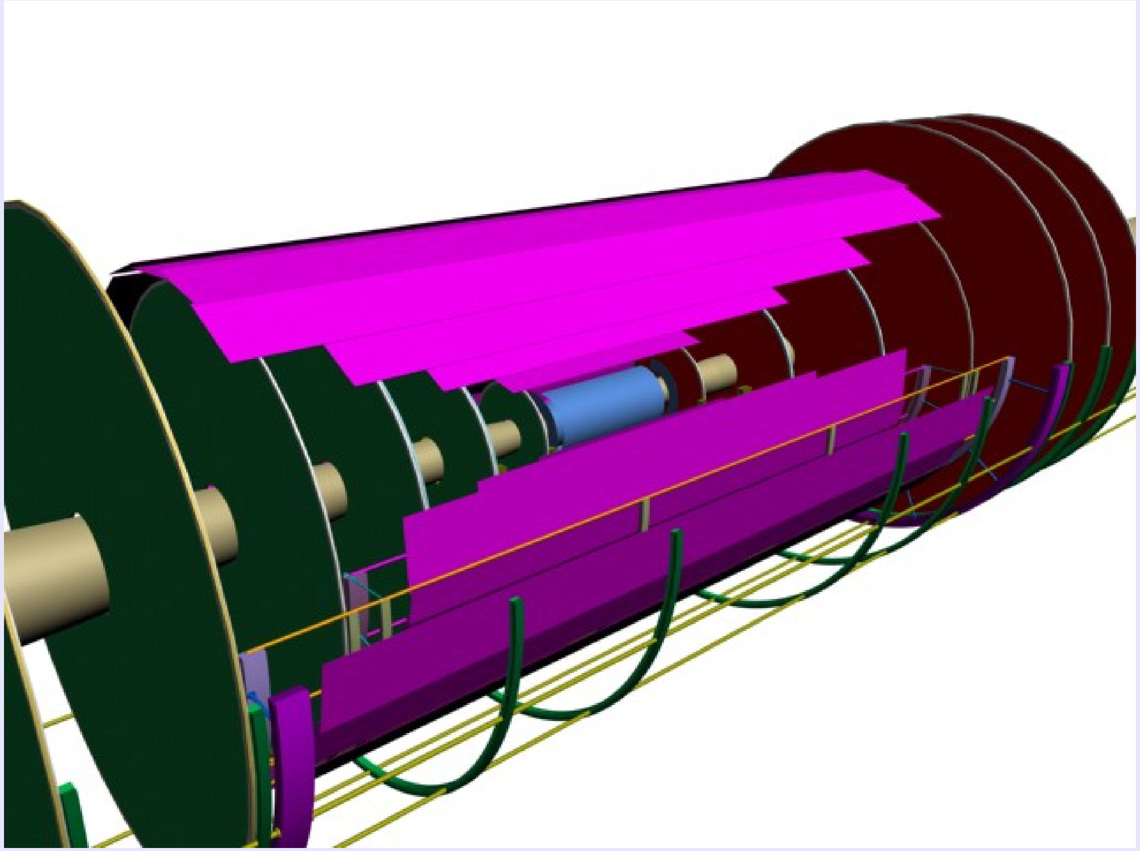


Forward tracking: the philosophy

In all concepts: silicon detector disks covering angles from 6 – 20 degrees.

Technologies: pixel/strip

Total area (FTD in LDC) < 3 m^2



Forward tracking: material budget

CMS KF fit on toy geometry for a 20 degrees track in LDC (4 Tesla)

- 3 VXD barrel layers

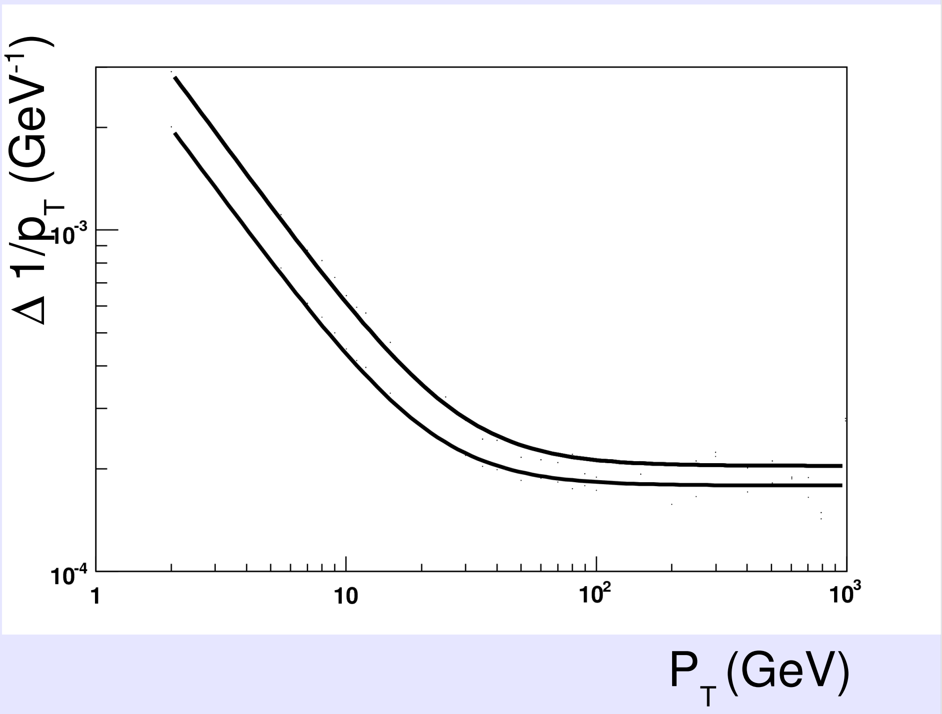
  ΔR = 1.1 cm, 1.2 ‰ X_0, σ ($R\phi$, z) = 2 μm

- 3 pixel disk

  Δz = 12 cm, 1.2‰ /1.2 % X_0, σ ($R\phi$, R) = 5, 50 μm

- 4 strip disks

  Δz = 25 cm, 8 ‰ X_0, σ ($R\phi$, R) = 10, 1000 μm



CMS KF track fit for θ = 20°

$\sigma(p_T)/p_T^2$ = $1.8 \times 10^{-4} \oplus 4.0 \times 10^{-3}/p_T$ *for 0.12 % X_0 FTD1-3*

= $2.0 \times 10^{-4} \oplus 5.8 \times 10^{-3}/p_T$ *for 1.2 % X_0 FTD1-3*

LiCToy

$\sigma(p_T)/p_T^2$ = $1.8 \times 10^{-4} \oplus 4.3 \times 10^{-3}/p_T$ *for 0.12 % X_0 FTD1-3*

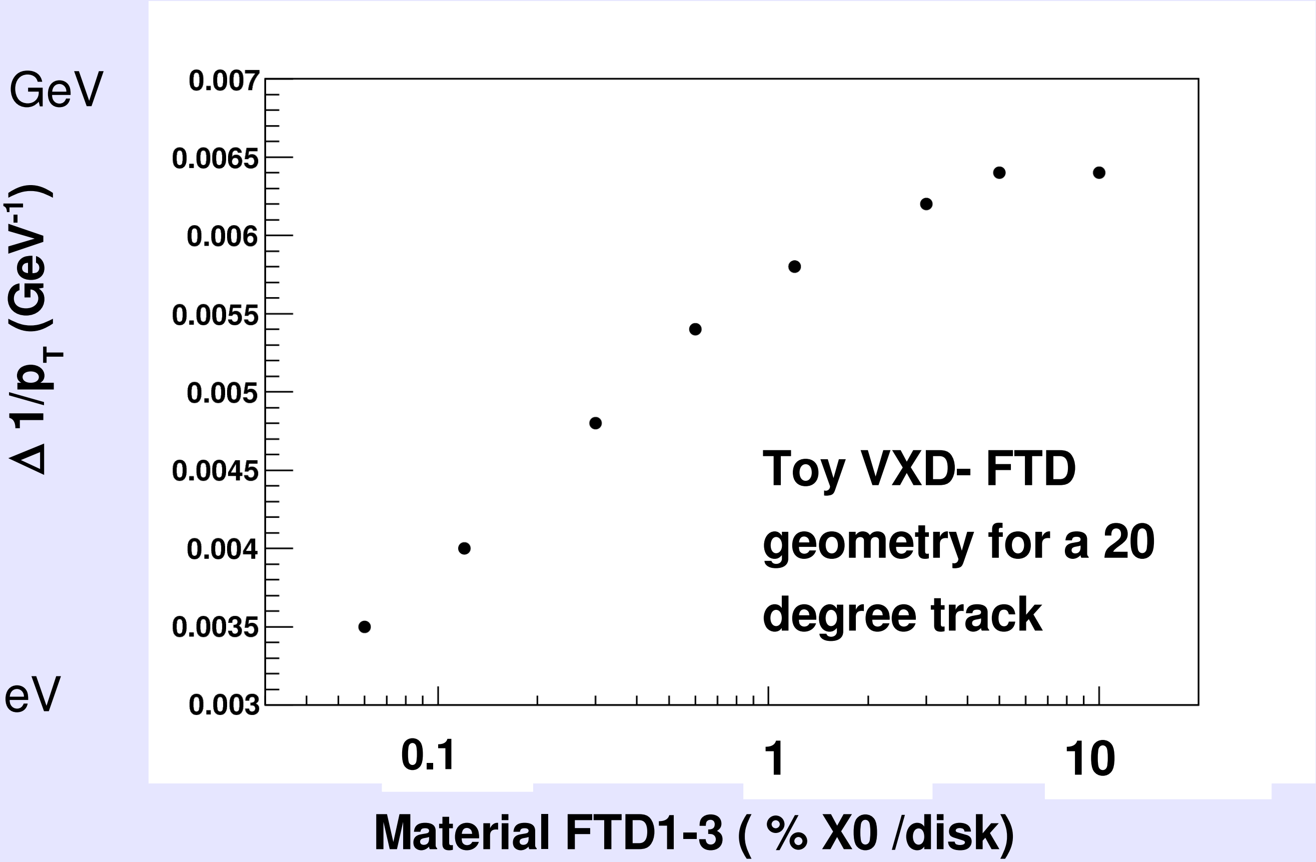
= $1.9 \times 10^{-4} \oplus 6.2 \times 10^{-3}/p_T$ *for 1.2 % X_0 FTD1-3*

Forward tracking: material budget

Impact of the material in the first three FTD disks on the tracking performance of low momentum tracks: vary material per layer from rather optimistic (factor two better than VXD layers) to disastrous (10% X_0).

$7x\ 10^{-3}\ GeV^{-1}$ @ 1 GeV

$3x\ 10^{-3}\ GeV^{-1}$ @ 1 GeV



The tracking and vertexing requirements in a nutshell

Momentum resolution spec. beyond current state-of-the-art

Goal: **$\Delta(1/p) \sim 2\text{-}5\times10^{-5}$ (GeV^{-1})**

An order of magnitude better than previously achieved

Vertexing performance:

Goal: **$\Delta(d_0) \sim 5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)$**

Not achieved recently (SLD came close)

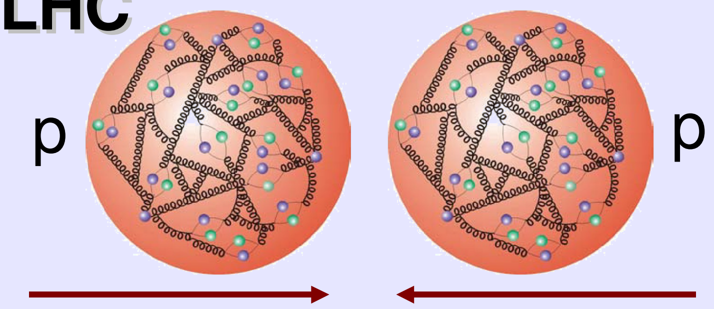
Hermetic coverage: **Full solid angle** for tracks in a **broad momentum range** (from the beam energy to very low momenta required by FPA, flavour tagging and missing energy measurements).

Fully efficient/pure: excellent **pattern recognition** for all tracks

Non-disruptive: only a very ***transparent*** *detector* allows to preserve lepton ID and calorimeter performance, and to achieve the required momentum resolution.

Environment

LHC



Protons collide at **E_{cm}~14 TeV**

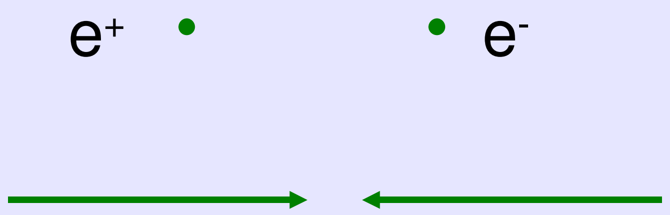
Undefined initial state of proton constituents

Huge QCD backgrounds

Low S/B ratios

10^9 events/s. Trigger sees 1 every 10^7

ILC



$e^+ e^-$ colliding at **E_{cm}~ 0.5-1 TeV**

Clean environment

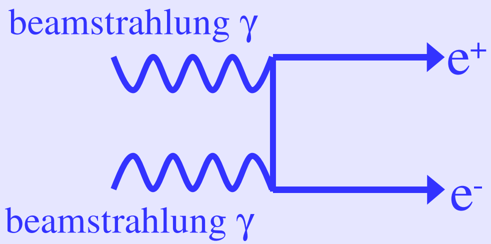
Well defined initial state, beam polarization,...

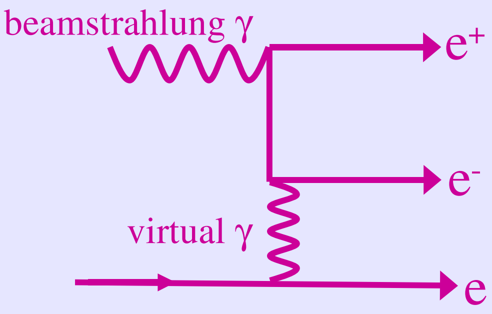
Triggerless operation

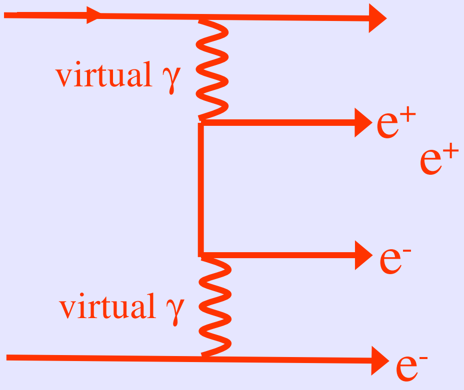
	LHC	ILC
Event rates inclusive	1 GHz (min. bias)	1 kHz (γγ→hadrons)
Bunch crossings	25 ns (40 Mhz) DC	300 ns (15kHz) 0.5% duty factor
Triggering Level 1 & 2 Level 3	40 MHz → 1 kHz ~100 Hz (software)	No hardware trigger ~ 100Hz (software)

Background: incoherent e+ e- pairs

3processes : Breit-Wheeler Bethe-Heitler Landau-Lifshitz

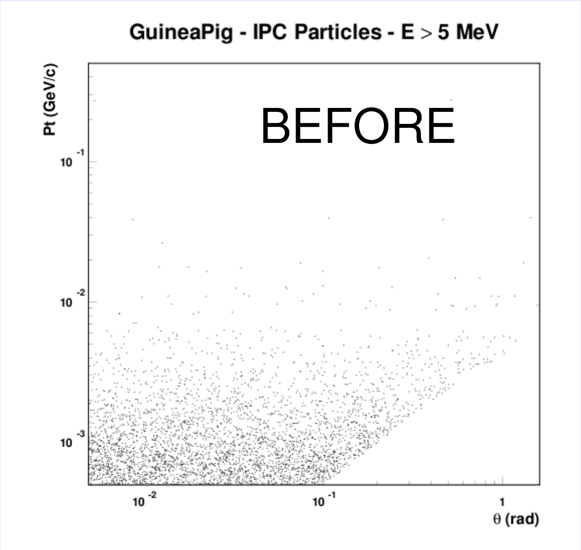


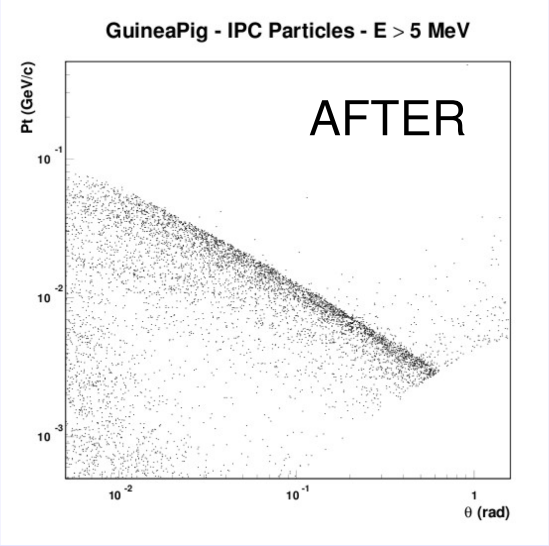




Breit-Wheeler (real-real) calculated explicitly by Guinea-Pig/CAIN

Bethe-Heitler (real-virtual), Landau-Lifshitz (virtual-virtual) use Equivalent Photon Approximation (treat virtual photons as real below virtuality cut-off)





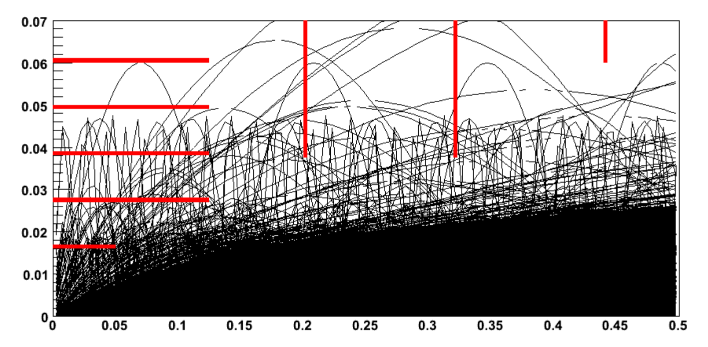
Pairs are deflected by electro-magnetic field of opposite beam. Same-charge particles are focused.

C. Rimbault, P. Bambade, K. Moenig, D. Schulte, Study of incoherent pair generation in Guinea-Pig, EUROTeV report 2005-015-1

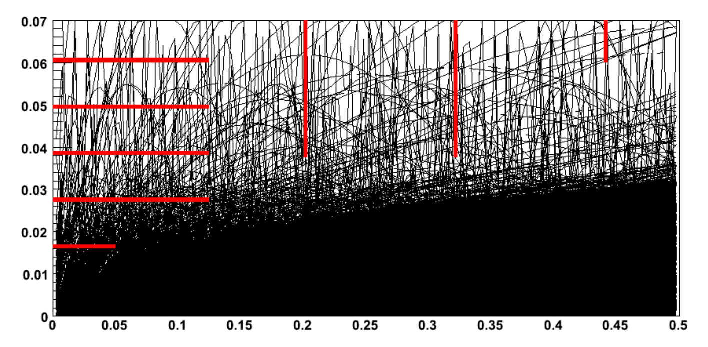
Machine background

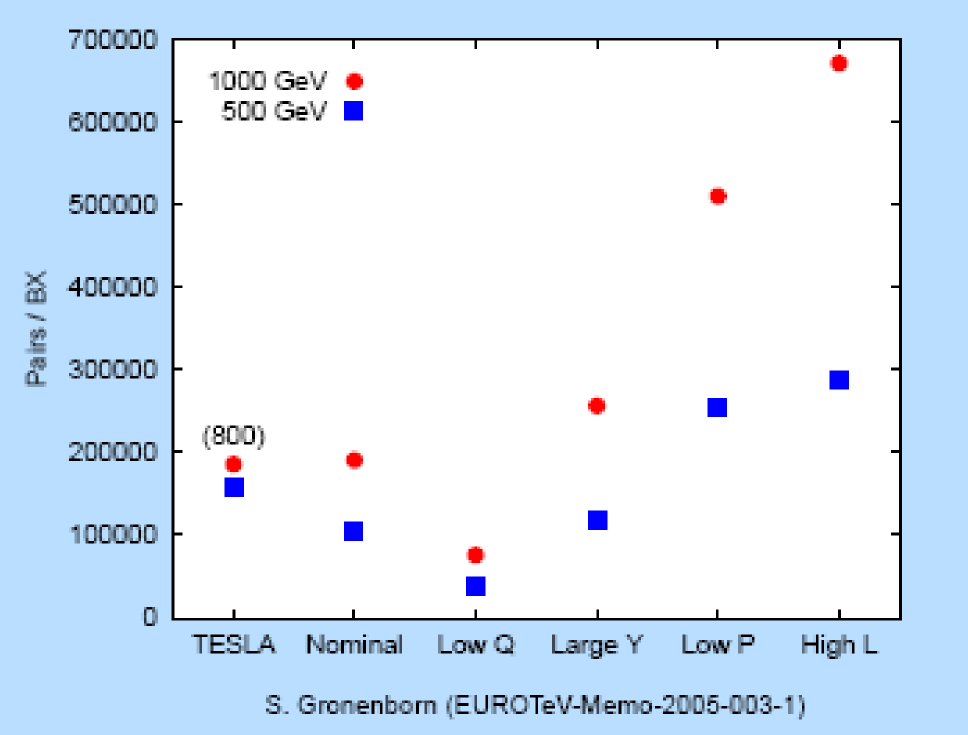
Fast (simple helix) simulation of pair background as it comes out of Guinea Pig (thanks to Cecile Rimbaud) for two parameter sets of the final focus

NOMINAL



LOW-P





S. Gronenborn (EUROTeV-Memo-2005-003-1)

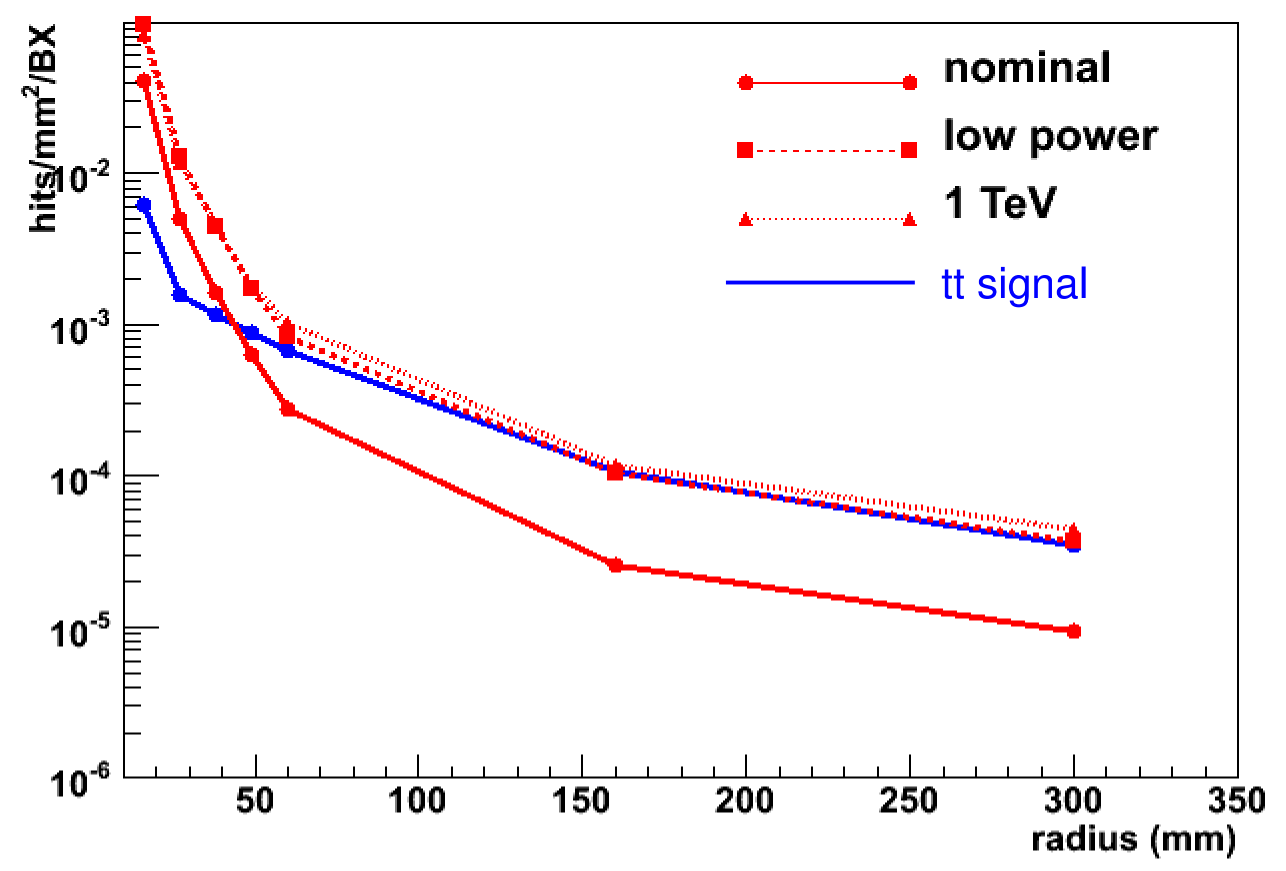
Pair background (# pairs/BX) for a range of machine parameters

Machine background: central tracker

Dense signal topology (tt events)

Pair production background due to beamstrahlung,

(GUINEAPIG and Mokka simulation by A. Vogel)



NOTE: low power option has double BX spacing

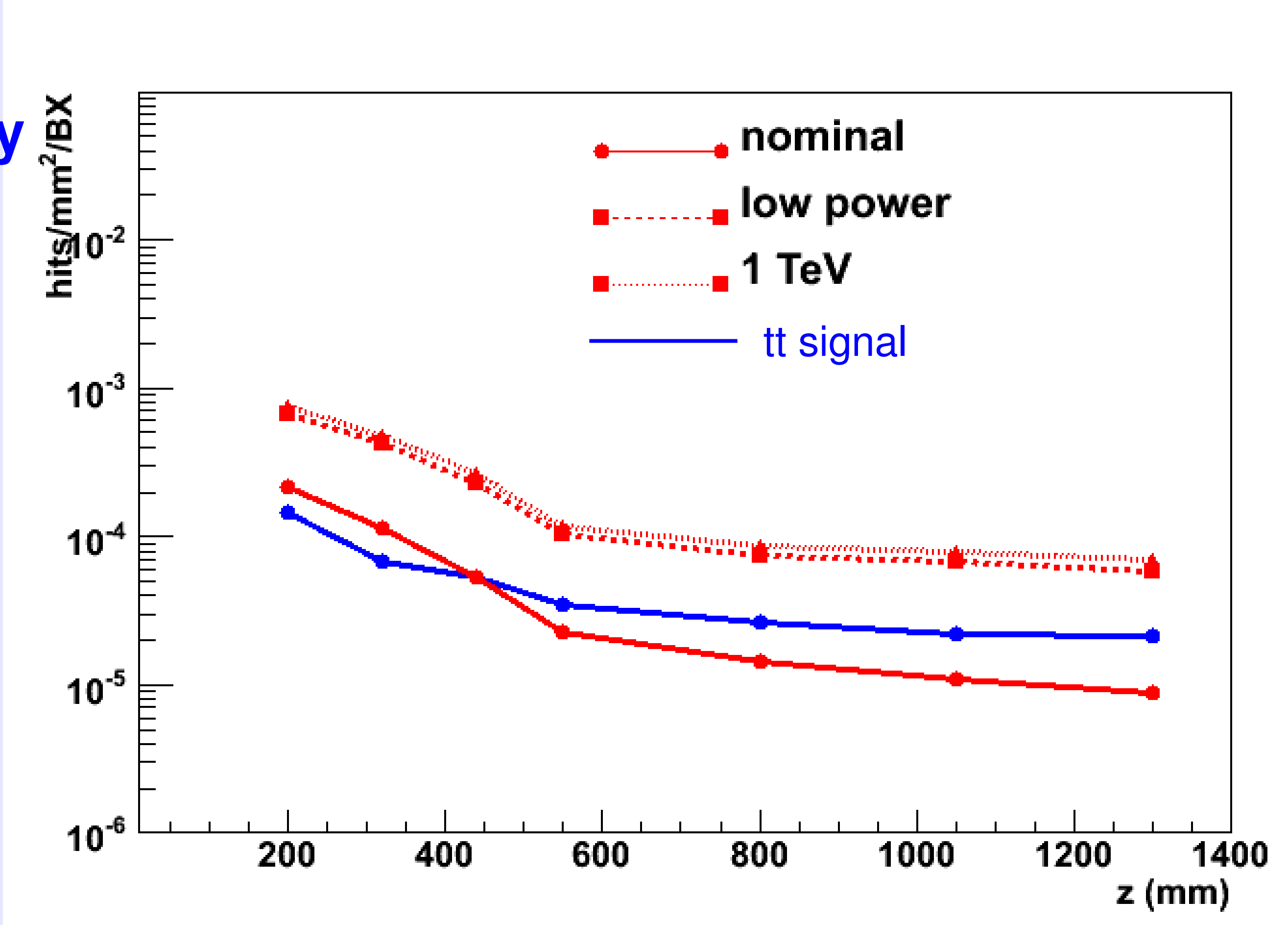
SIT hit density due to pair bkg an order of magnitude below that of outermost VXD layer (but cell size is of the order of 50 µm x 10 cm, 3 orders of magnitude larger)

Machine background: forward tracker

Dense signal topology (tt events)

Pair production background due to beamstrahlung,

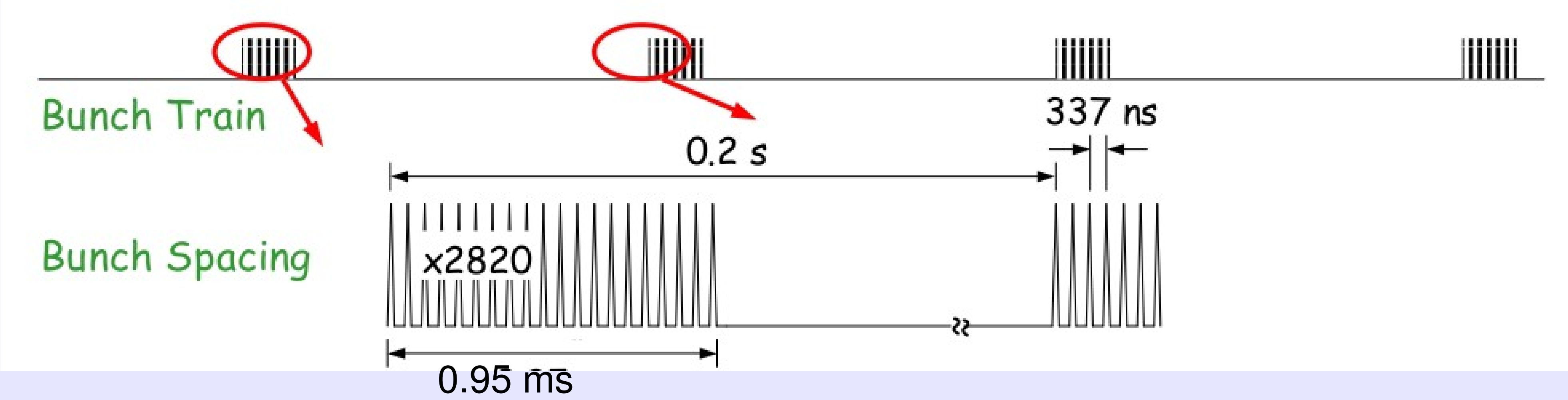
(GUINEAPIG and Mokka simulation by A. Vogel)



NOTE: low power option has double BX spacing

Inner rings of first 3 FTD disks suffer large hit density from pair bkg.

Occupancy (bunch structure)



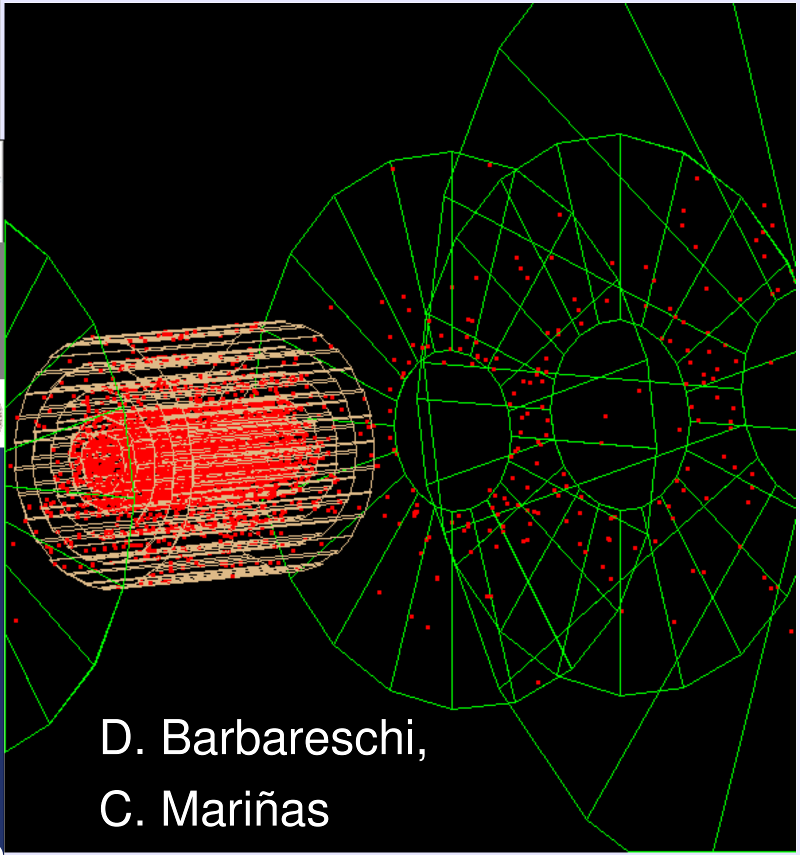
Long (2 ms) empty period between bunch trains

2820 bunches in a 0.95 ms train (337 ns spacing)

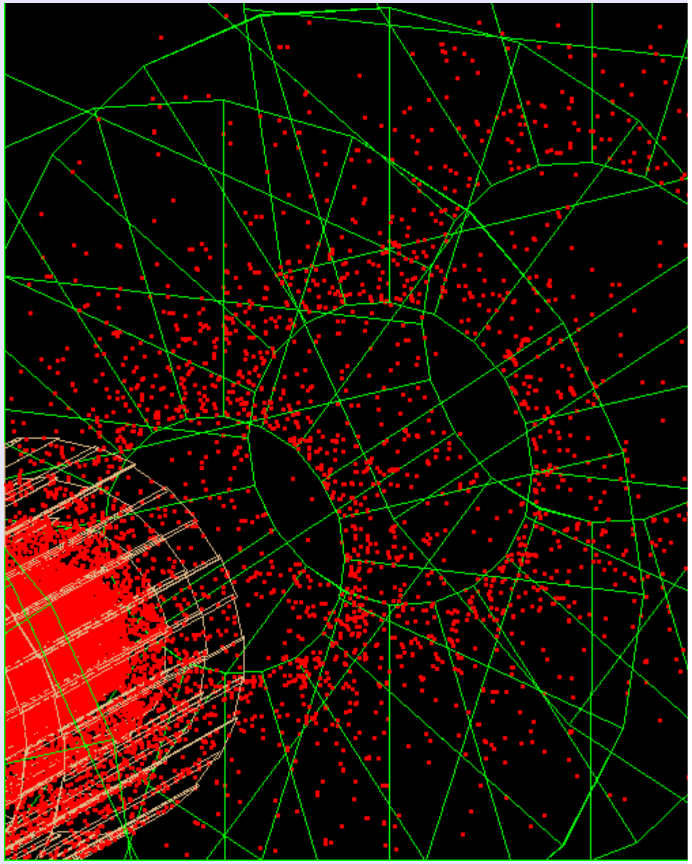
Background

Hit densities due to background: an impression

14 BX

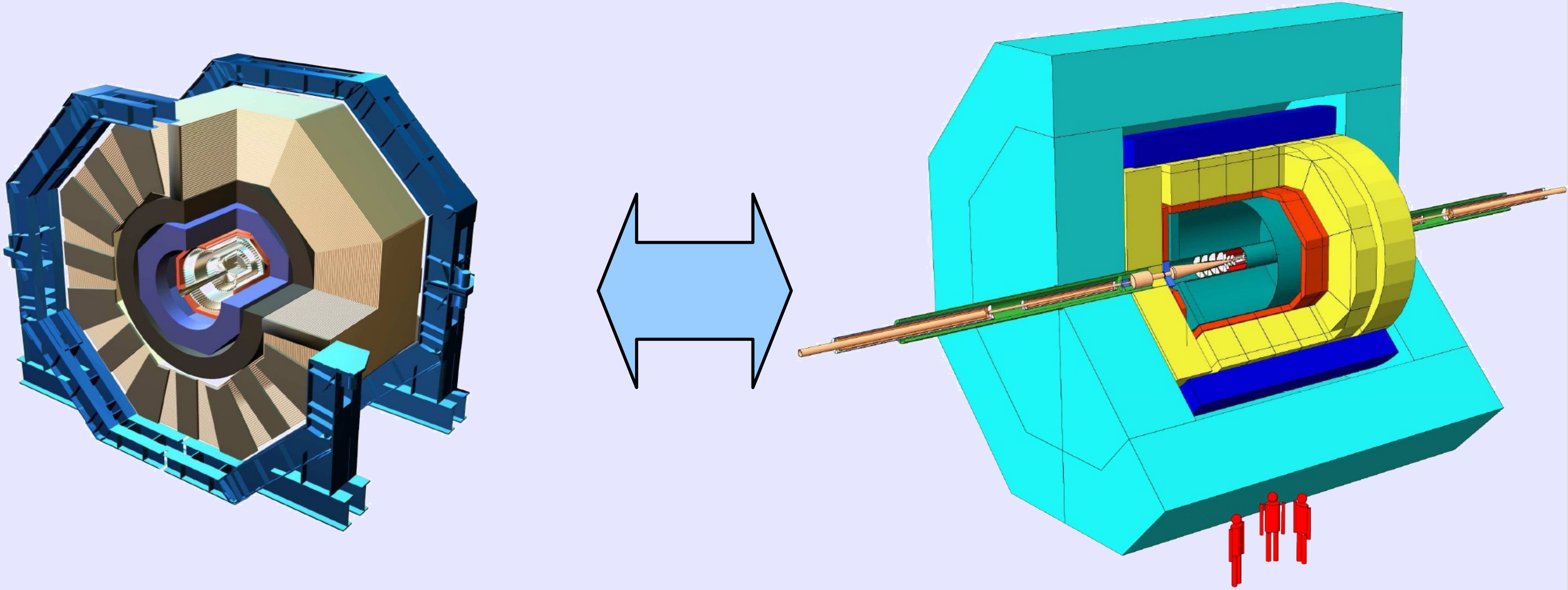


D. Barbareschi,
C. Mariñas



140 BX

Push-Pull



The push-pull scenario saves cost (of a second interaction point, with all its expensive optics)

Every X fb^{-1} (order of several months) swap experiment: move experiment A out of the interaction point, move in experiment B

(Switch-over time 4-5 days.

detector brought to its “old” position within O(mm))

Pulsed power

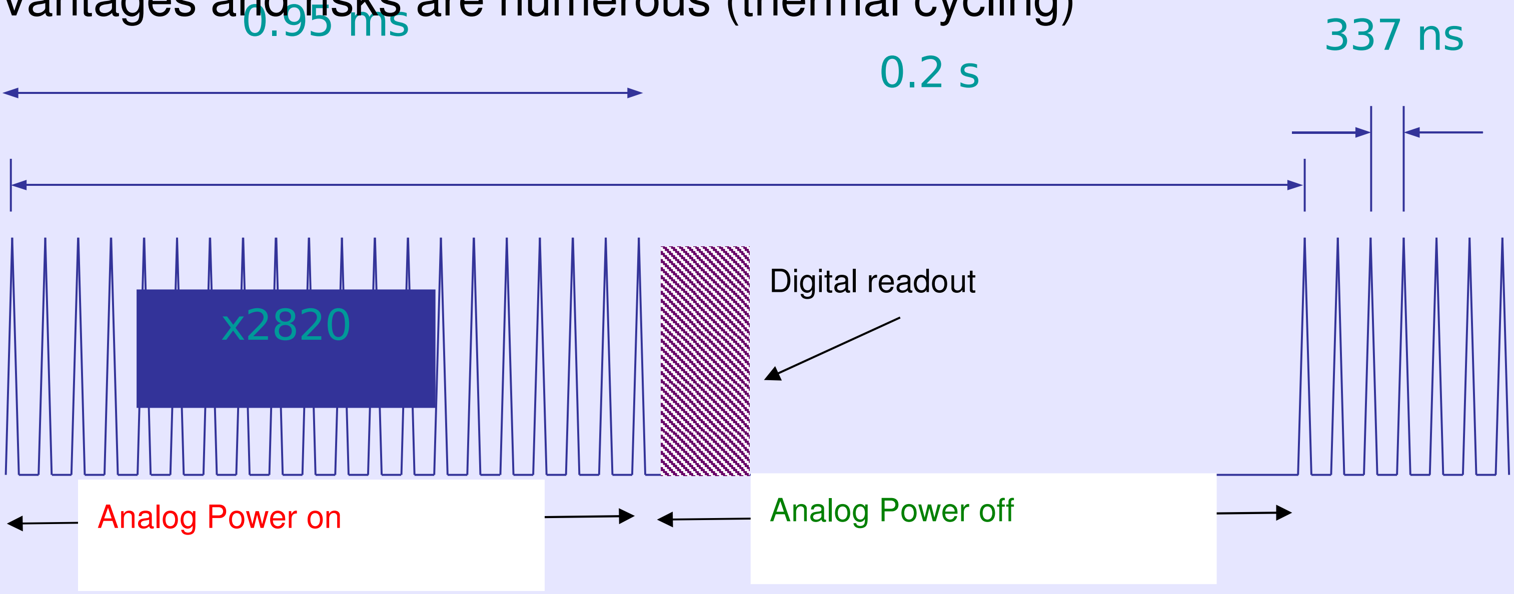
Pulsed power???

In first approximation, it consists of switching off the detector in the long inter-bunch period.

Gains a duty factor of maximally 200 in power consumption (which makes all the difference between being condemned to use liquid cooling and the possibility to rely on gas flow)

Several Front End prototype already incorporate this possibility

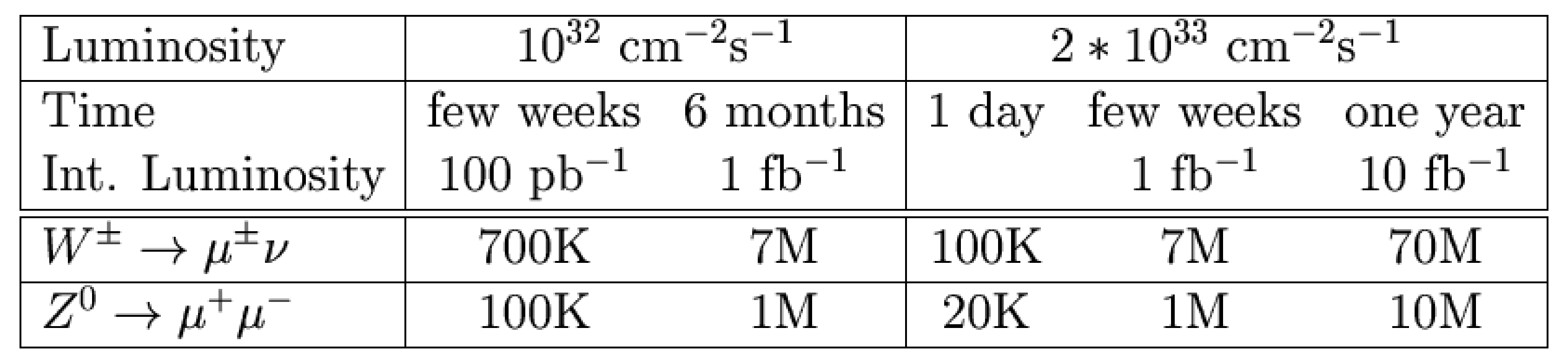
Disadvantages and risks are numerous (thermal cycling)



Calibration samples

- Center-of-mass energy variable from 200-500 GeV
- Running at the Z foreseen for calibration (but not too often, large energy change takes “a few weeks”)
- integrate 500 fb^{-1} at $\sqrt{s}$ = 500 GeV in 4 years
- $\sigma(e^+e^- \rightarrow \mu^+ \mu^-)_{pT(\mu) > 10\ GeV/c} \sim$ 440 fb

- Compare rates at the LHC $\sigma(pp \rightarrow \mu^+ \mu^-)_{pT(\mu) > 10\ GeV/c} \sim$ 1000 pb



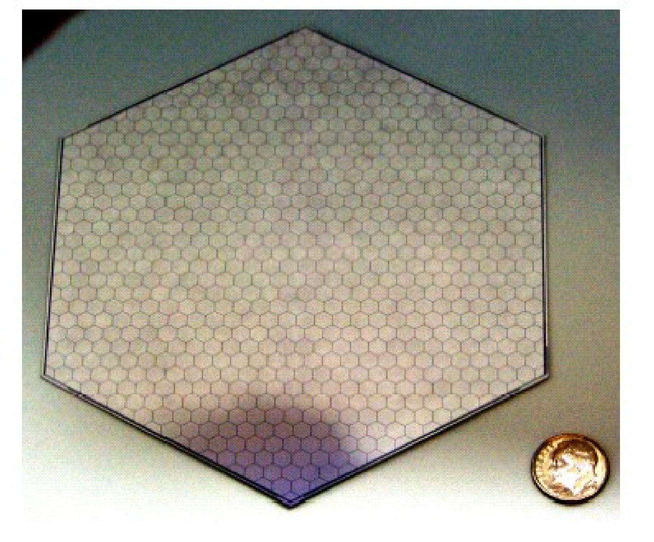
Luminosity	$10^{32}\ cm^{-2}s^{-1}$		$2 * 10^{33}\ cm^{-2}s^{-1}$		
Time	few weeks	6 months	1 day	few weeks	one year
Int. Luminosity	100 pb^{-1}	1 fb^{-1}		1 fb^{-1}	10 fb^{-1}
$W^\pm \rightarrow \mu^\pm \nu$	700K	7M	100K	7M	70M
$Z^0 \rightarrow \mu^+ \mu^-$	100K	1M	20K	1M	10M

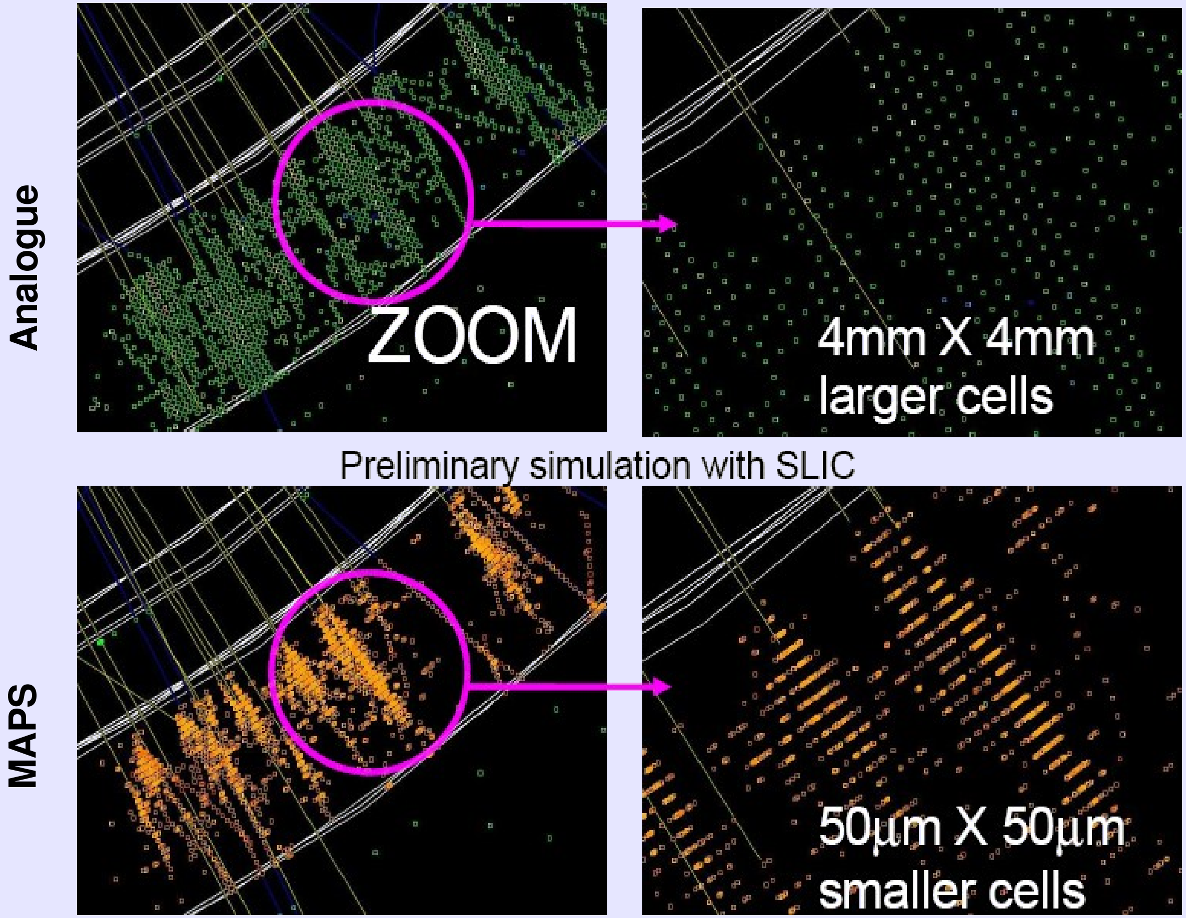
Tracker/vertex environmental constraints

- **Inner vertex detector layers moderately radiation hard**
  - » **<1 Mrad**
- **Occupancy inner vertex detector layers requires:**
  - ✓ very small pixels and/or fast read-out
  - » **400 μm^2 ⊗ 45 μs, alternative: 25 μm^2 ⊗ 2 ms**
- **Radiation hardness/occupancy requirement less stringent by a factor 10 for forward tracking**
- **Time-stamping**
  - » **single BX identification for all tracks**
- **Bunch structure allows for pulsed powering**

EM calorimeters

- ✔ Si/W calorimeter is one of the options considered for the EM calorimeters in the central detector
  - ➔ Baseline proposes silicon pads to reconstruct the showers



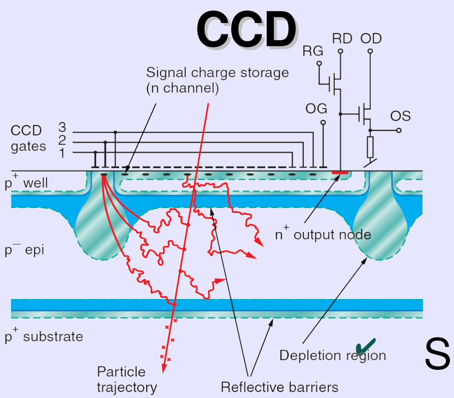


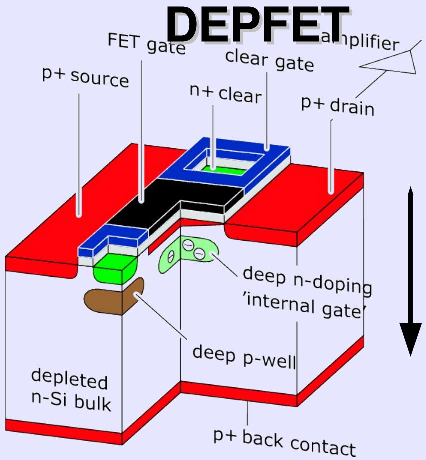
Preliminary simulation with SLIC

Recently “*binary*” MAPS have been proposed

In the forward region, diamond is considered to cope with radiation

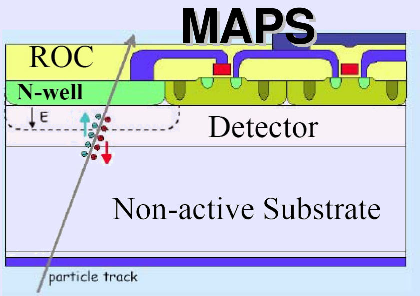
R&D for vertex detectors


CCD

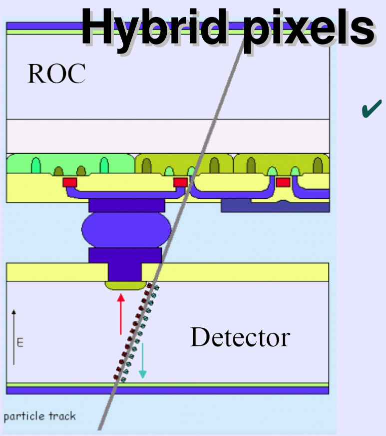

DEPFET

Charge collection from full sensor thickness

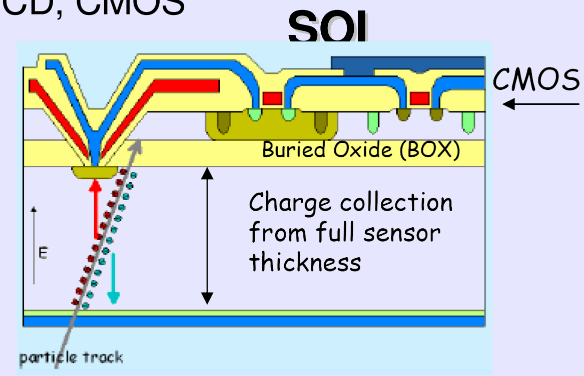
- ✔ Silicon pixel detectors is the way
  - ➔ Fast and light
  - ➔ With ~10^9 channels, consume, on average, less than a light bulb (~10W)
  - ➔ The classic hybrid pixels probably discarded because of material bugdet
    - ➘ Look for monolithic detectors with some kind of charge storage to be readout at end of train
- ✔ We can distinguish
  - ➔ Depleted: DEPFET, SOI
  - ➔ Undepleted: CCD, CMOS


MAPS

MAPS Principle


Hybrid pixels

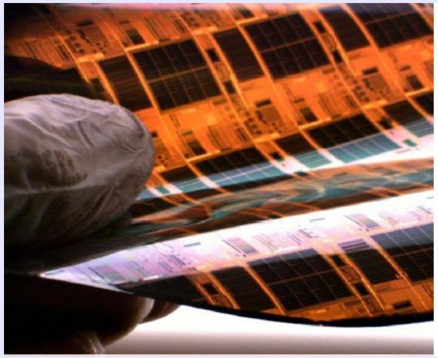
Probably too thick
to be used at the ILC

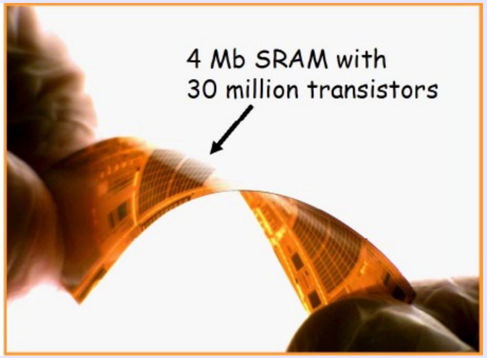

SOI

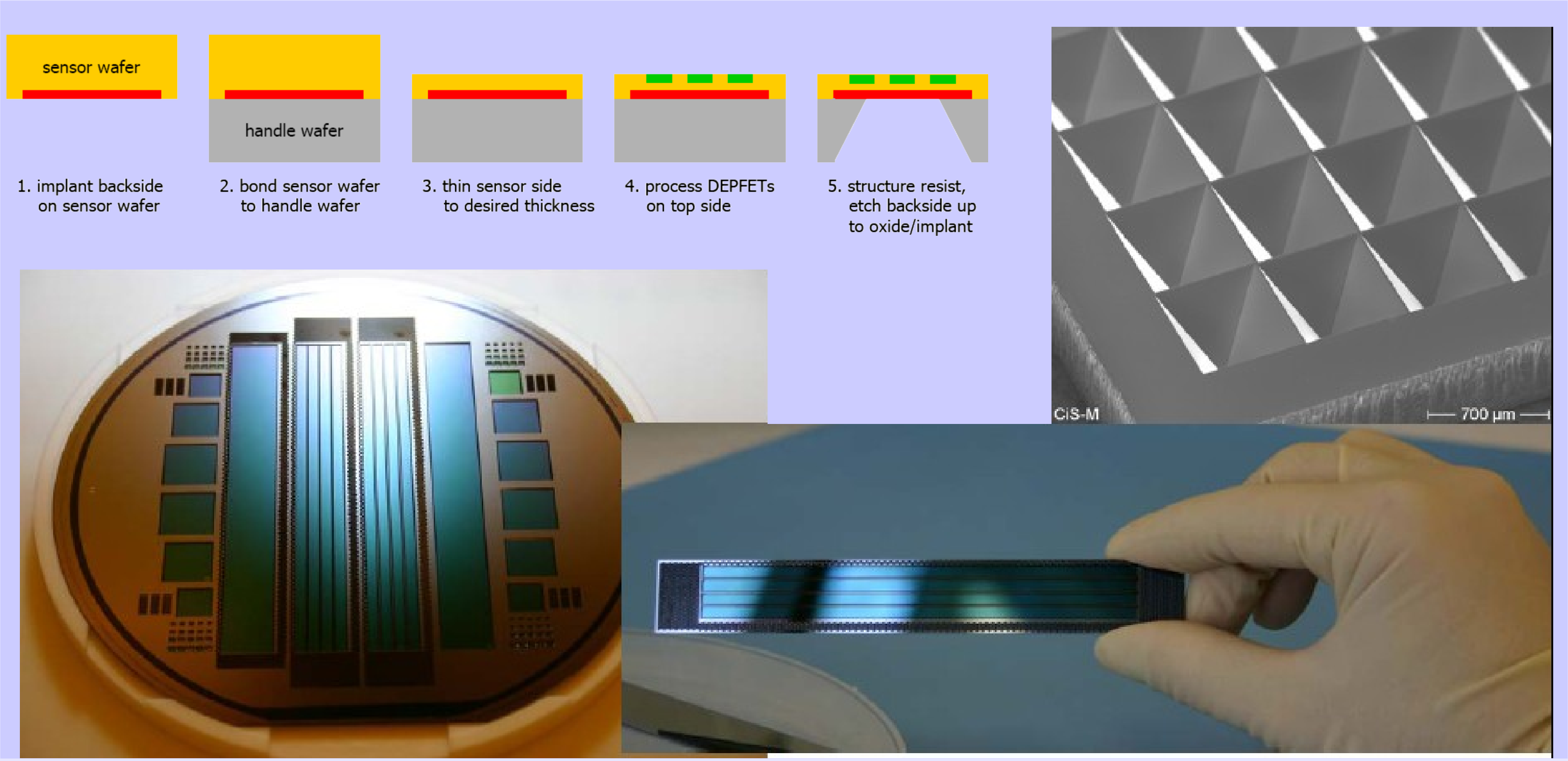
Charge collection from full sensor thickness

Vertex detectors (thinning)

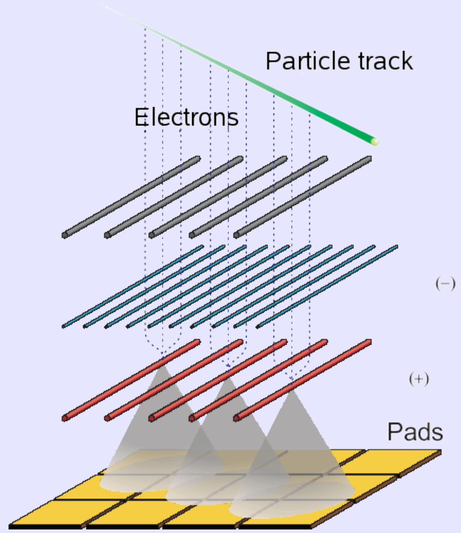
- ✔ **Thinning**: max rad. length is 0.1% X_0/layer
  - ➔ 100 µm of Si is 0.1% X_0,
    - ➘ sensors should therefore be **50 µm thick**
- ✔ DEPFET coll. has developed an interesting thinning technology (see S. Rummel's talk in this conference)



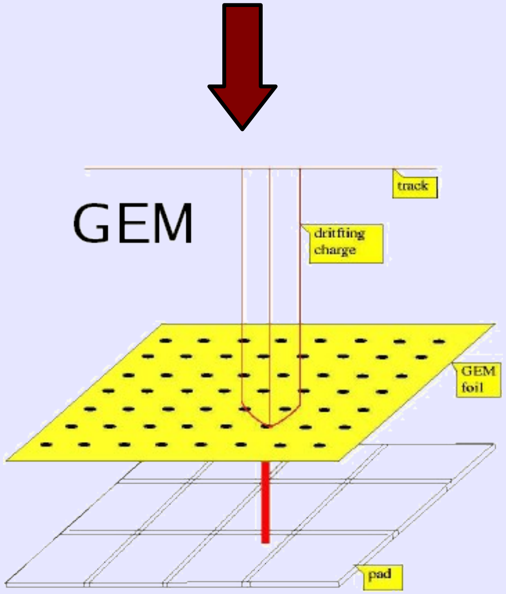




R&D for gaseous tracking (TPC)



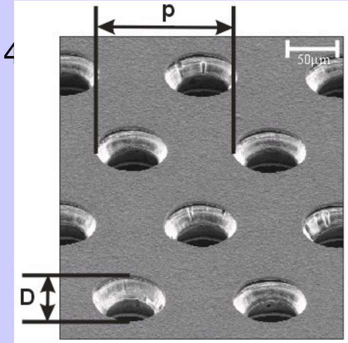
- ✔ Unprecedented requirements for a TPC, in particular on spatial resolution.
  - ➔ Spatial resolution: Rφ: 100µm, Z≤1mm
  - ➔ 2 track separation: Rφ≤2mm, Z≤10mm
  - ➔ $\Delta p_T/p_T \sim 10^{-4}$ (TPC alone)
  - ➔ Identification: dE/dx ~ 4%
  - ➔ High background from photons and neutrons (~600 n/BX)
- ✔ "*Classic*" TPCs cannot achieve this
  - ➔ Replace conventional MWPC system by Micro Pattern Gas Detectors (MPGD)
    - ➘ Gas Electron Multiplier (GEM)
    - ➘ Micromegas



GEM

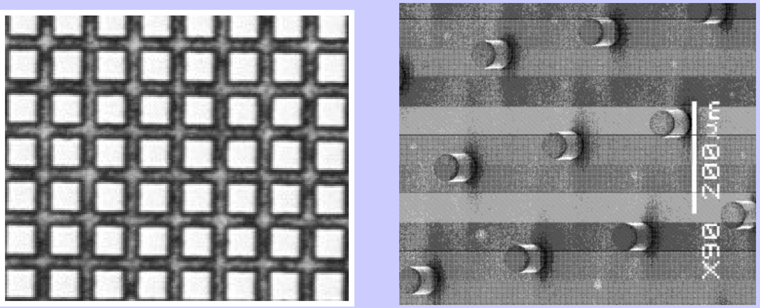
2 copper foils separated by kapton. Multiplication takes places in holes. Uses 2-3 stages

P~14

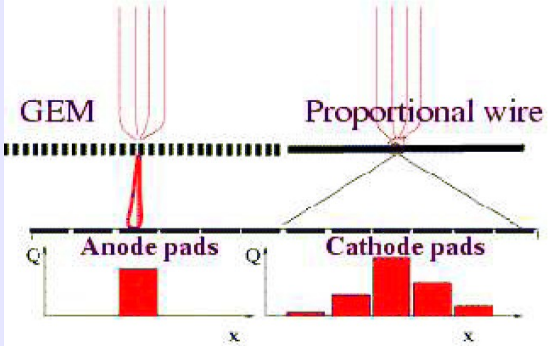


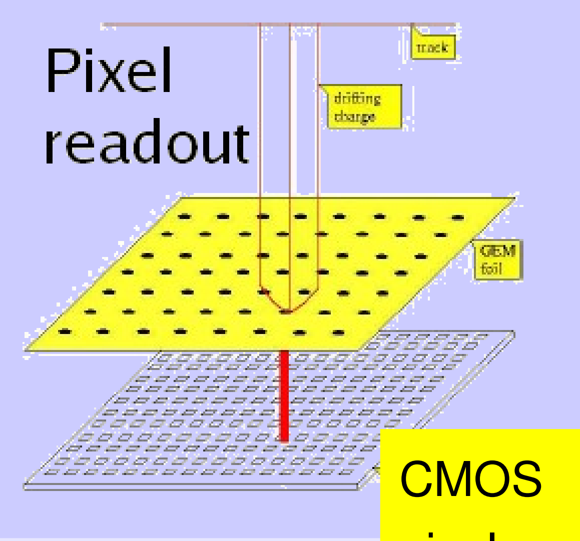
Micromegas

Micromesh sustained by 50 µm pillars. Multiplication between anode and mesh. One stage.



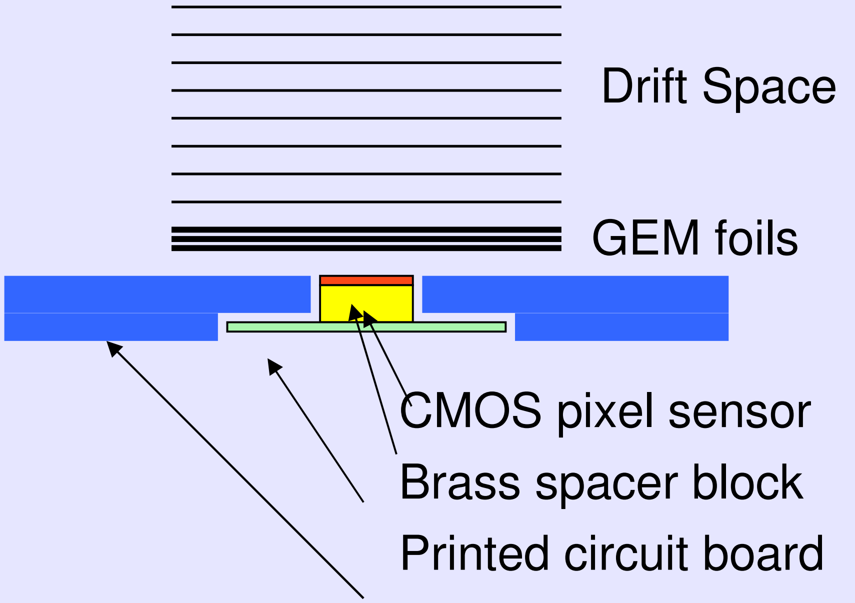
Digital TPC





CMOS pixel readout chip

- ✔ Electron signal “*too*” small to use center of gravity methods...
  - ➔ Resolution is not as good as it could be
- ✔ *Attractive* solution is to use a pixel readout chip with higher granularity instead of the conventional pads.

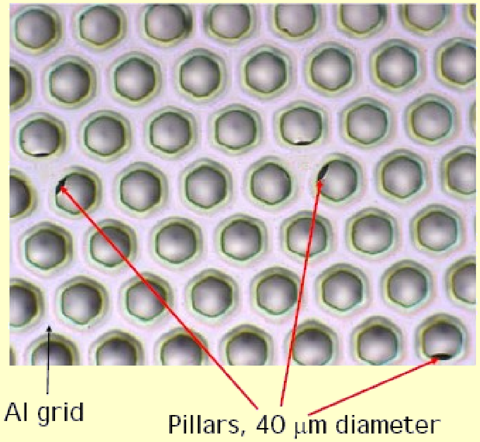


Single electron detection

Achievable spatial resolution ~50µm

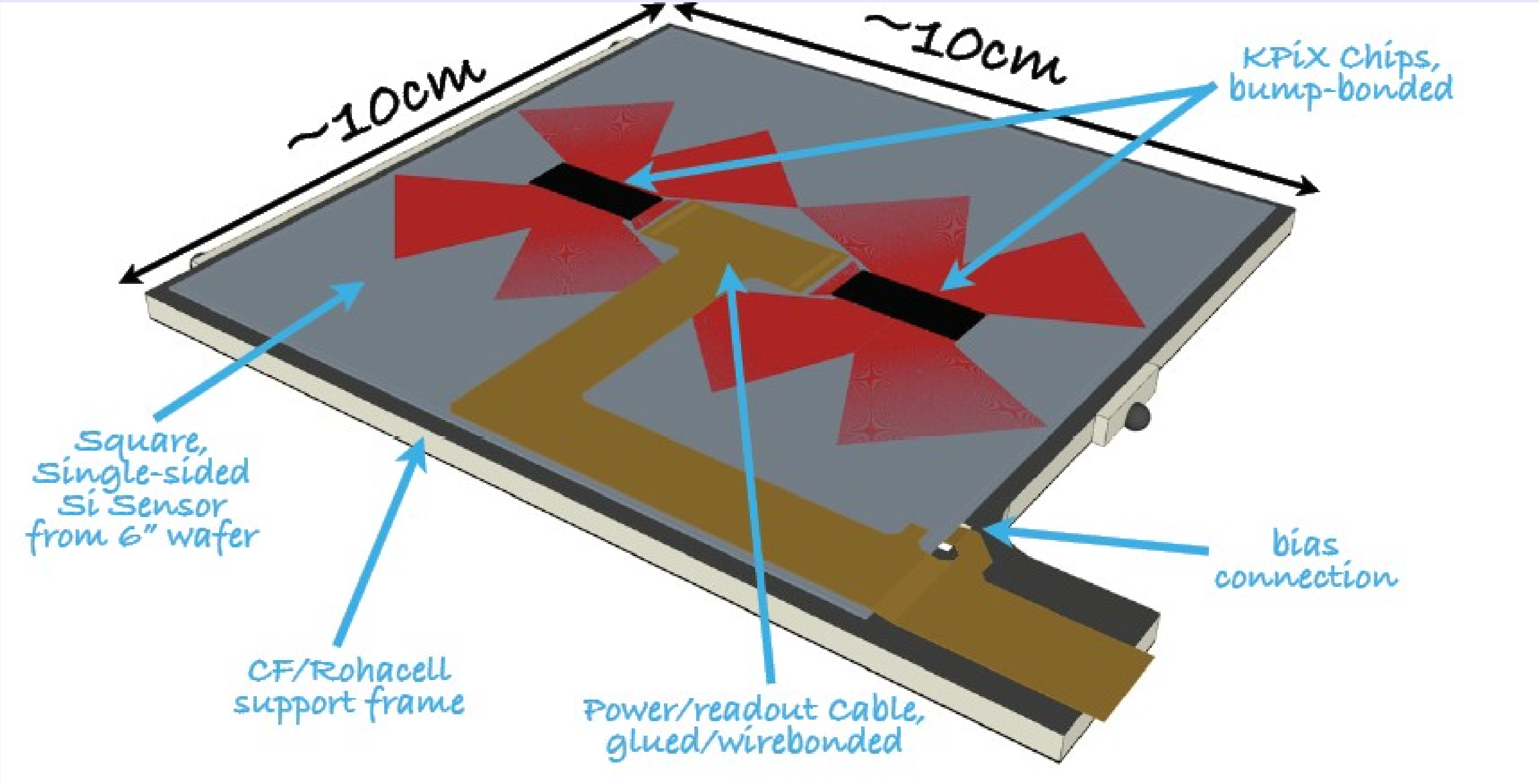
Integrate GEM/Micromega and pixel chip by wafer post-processing

InGrid process



No inefficiency

µ-strip developments: SiD module

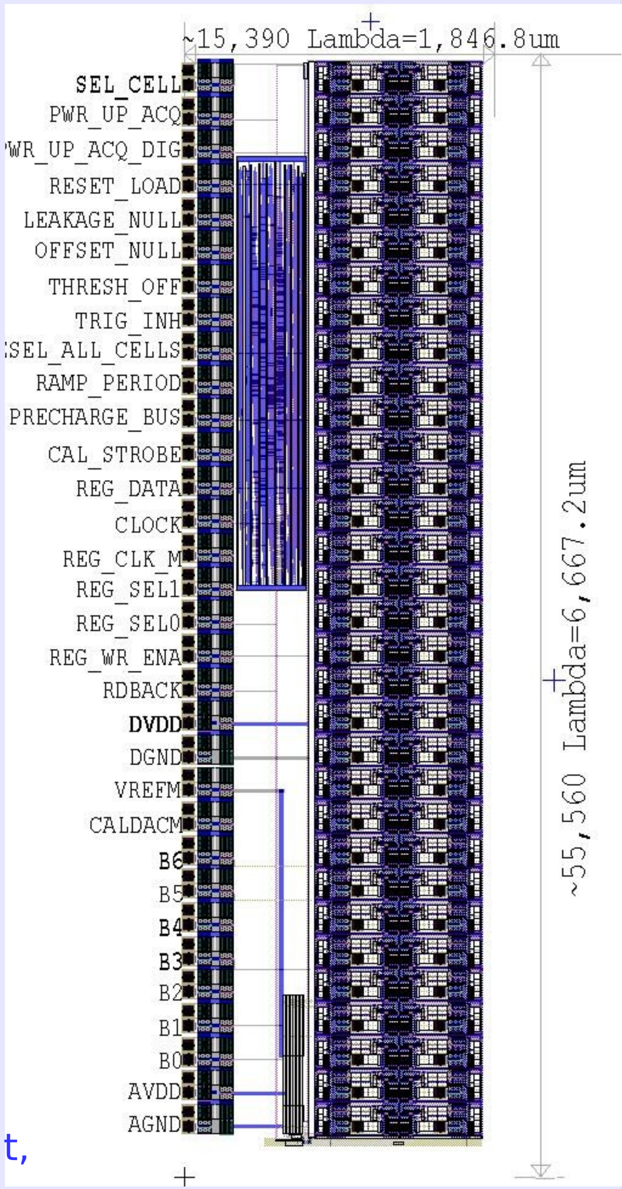


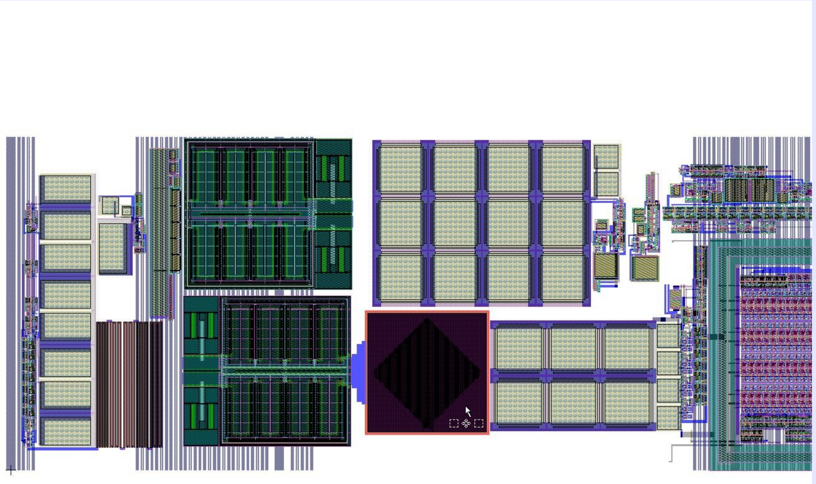
Marcel Demarteau, WWS tracking review, Beijing, 2007

Module design by Tim Nelson

μ-strip developments: SiD "kPiX" Readout Chip

- ✔ Was already under development at SLAC for SiD ECAL
- ✔ 1024 Channels
- ✔ Power-pulsed, average power ~20mW
- ✔ 4 time-stamped analog buffers for readout between trains
- ✔ Designed for bump-bonding directly to silicon - no hybrid
- ✔ Third prototype has been submitted
  - ➔ 2X32 channels

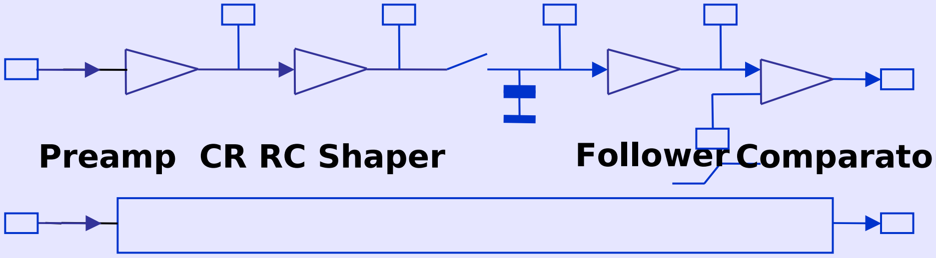




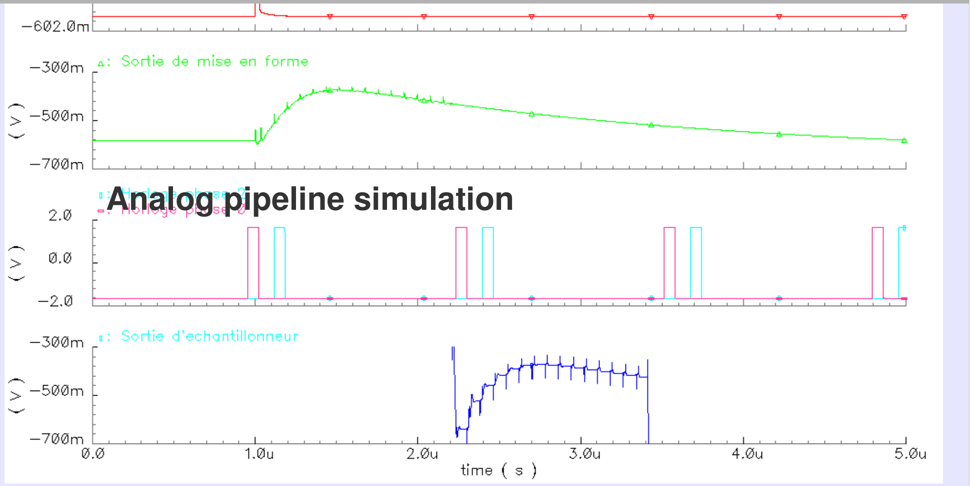
One cell. Dual range, time measuring, 13 bit, quad buffered

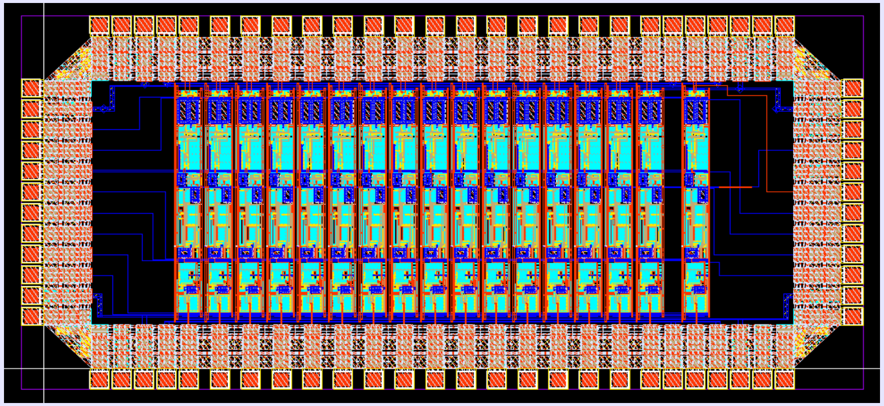
µ-strip developments: Silicon for the Linear Collider

First prototype in CMOS UMC 180nm (2005):SiTR-180 (J.F. Genat, LPHNE)

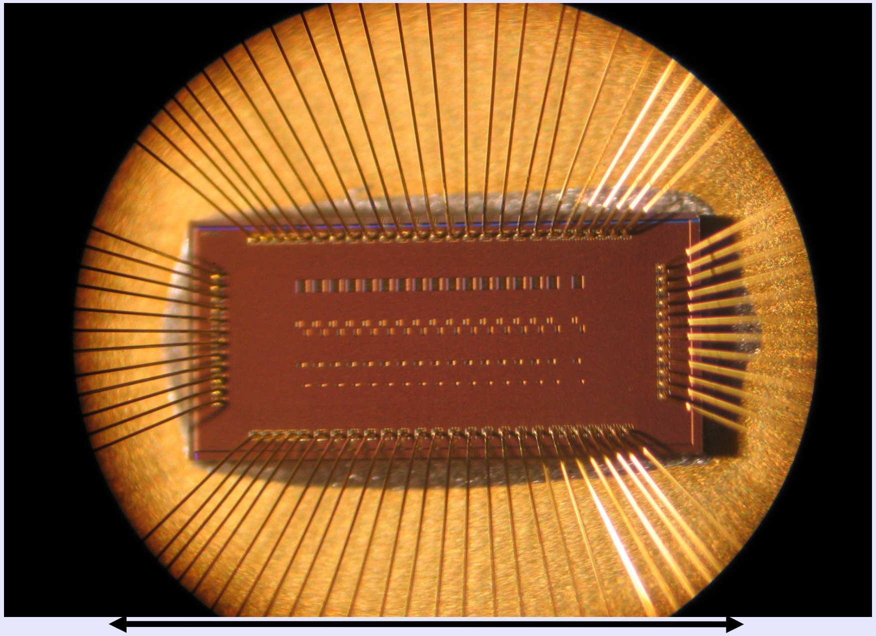

Preamp **CR RC Shaper** **Follower** **Comparator**

16 identical channels


Analog pipeline simulation



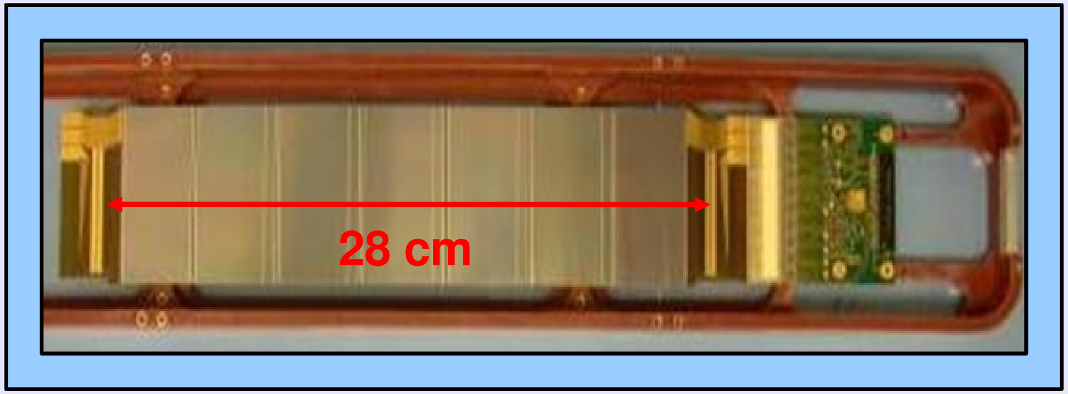
- Preamp
- Shaper
- Sample & Hold
- Comparator


3mm

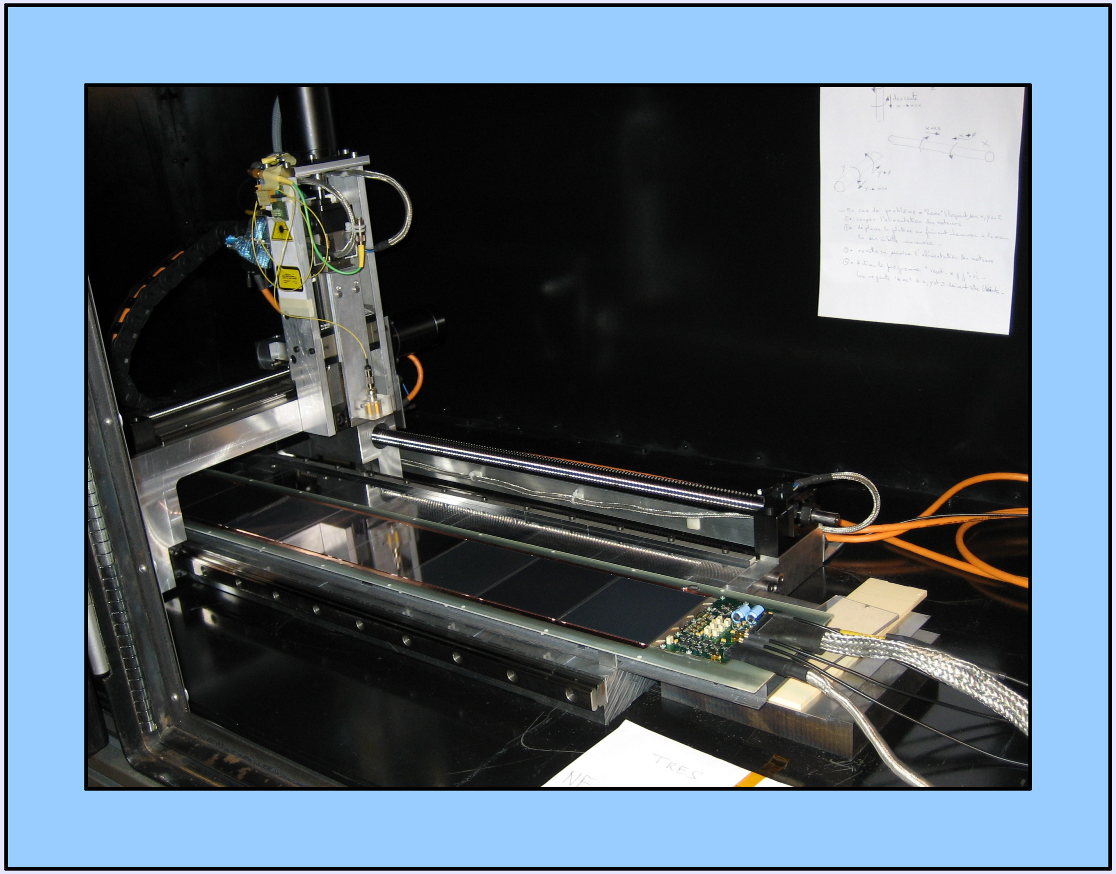
Power consumption:

575 mW Analog (measured) + 66 mW Digital (expected)

μ-strip developments: Silicon for the Linear Collider

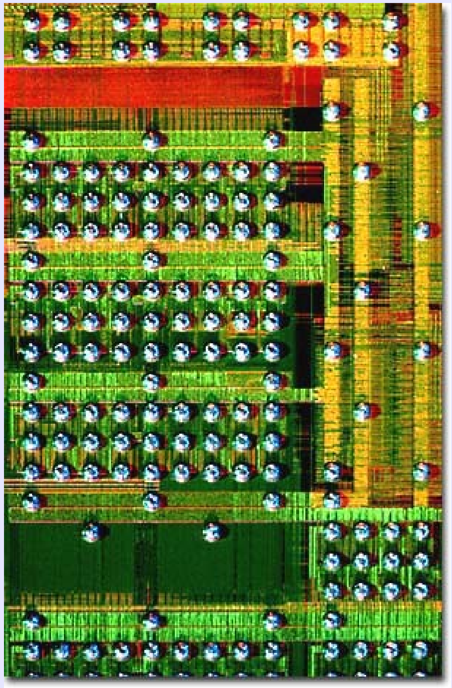


Long ladders for outermost layers to reduce number of FE channels (= power = material)



Chip connection on µ-strips

- Wire bonding
  - – Only periphery of chip available for IO connections
  - – Mechanical bonding of one pin at a time (sequential)
  - – Cooling from back of chip
  - – High inductance (~1nH)
  - – Mechanical breakage risk
- Flip-chip
  - – Whole chip area available for IO connections
  - – Automatic alignment
  - – One step process (parallel)
  - – Cooling via balls (front) and back if required
  - – Thermal matching between chip and substrate required
  - – Low inductance (~0.1nH)



Challenges to tracking/vertexing

- Precision physics programme
- Material budget: extremely thin sensors, large low-mass mechanical support
- Space point resolution (2-5 μm for vertex detector, 5-10 μm for silicon tracker elements, 100 μm in large gaseous detector)
- Air cooling (vibrations)
- Pulsed powering (vibrations, ΔT @ 5 Hz)
- Push-pull
- Alignment/calibration sample statistics

Conclusions

ILC precision physics programme relies on detector performance:

very challenging detector requirements

Detector R&D for ILC is a fast-moving field:

can technology meet the challenge?
can we keep up with technology?

And then it all comes down to calibrations:

best achievable performance of our detector ?