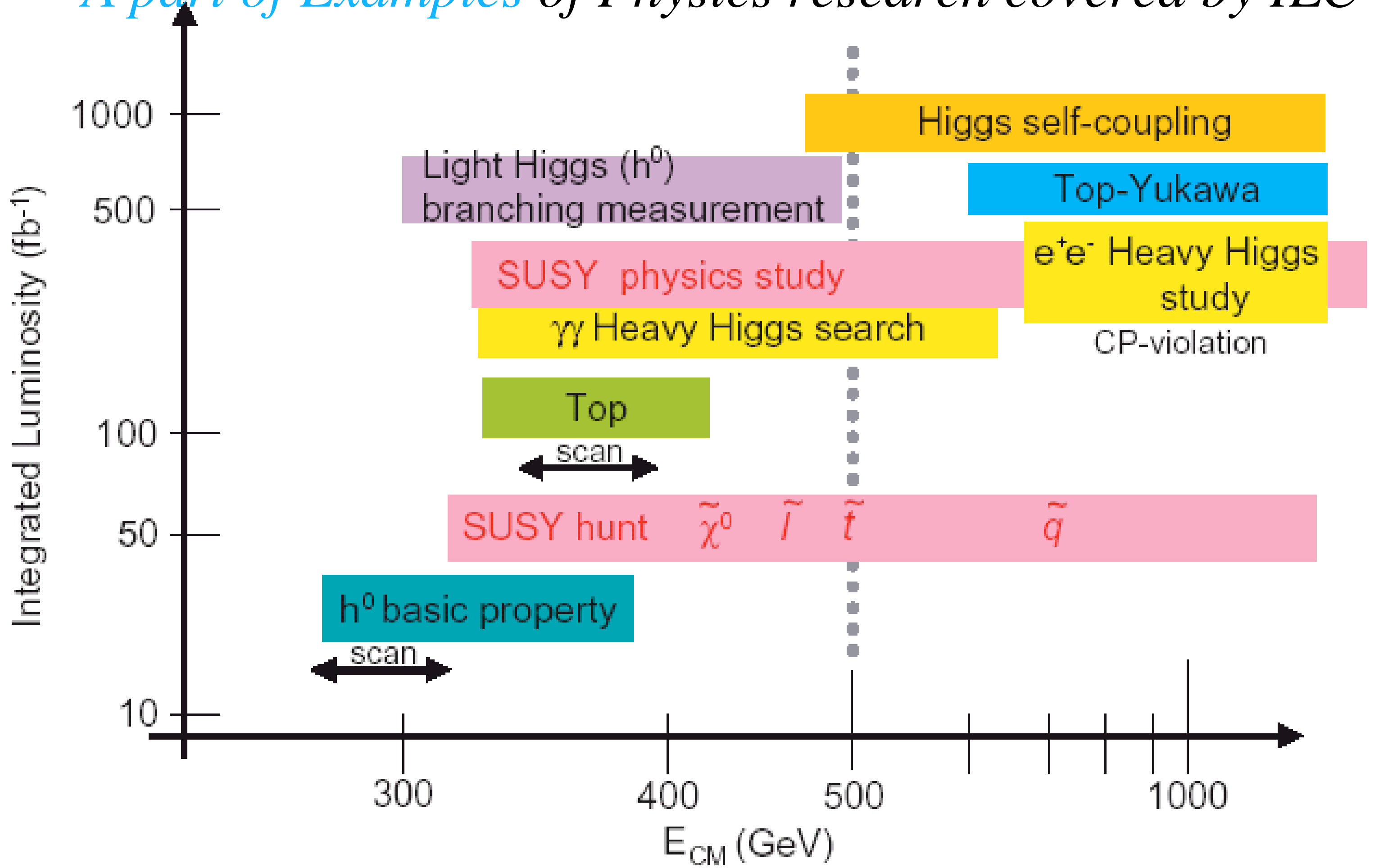
# Detector Concepts for International Linear Collider

**Higgs Physics at Future Colliders workshop**
**2004/2005**

**A.F.Żarnecki**
**17 XI 2004**

## *A part of Examples of Physics research covered by ILC*




$1^{st}$ stage: Ecm =210 -500 GeV,

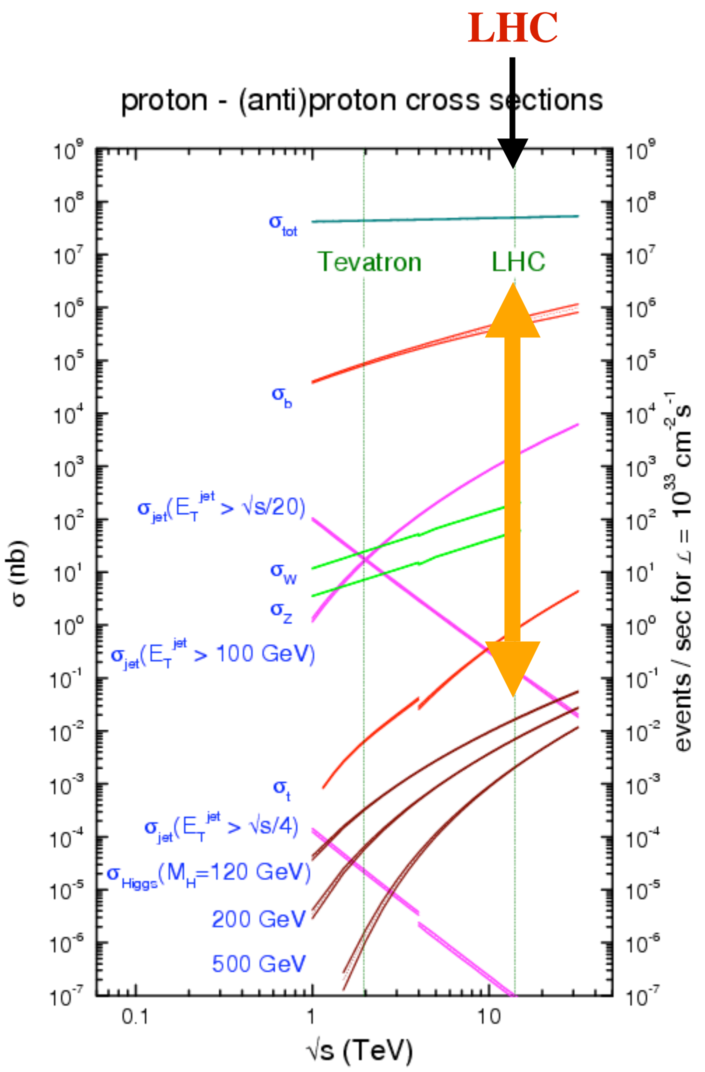
Luminosity = ~ 200 - 500 / fb / year x several years .

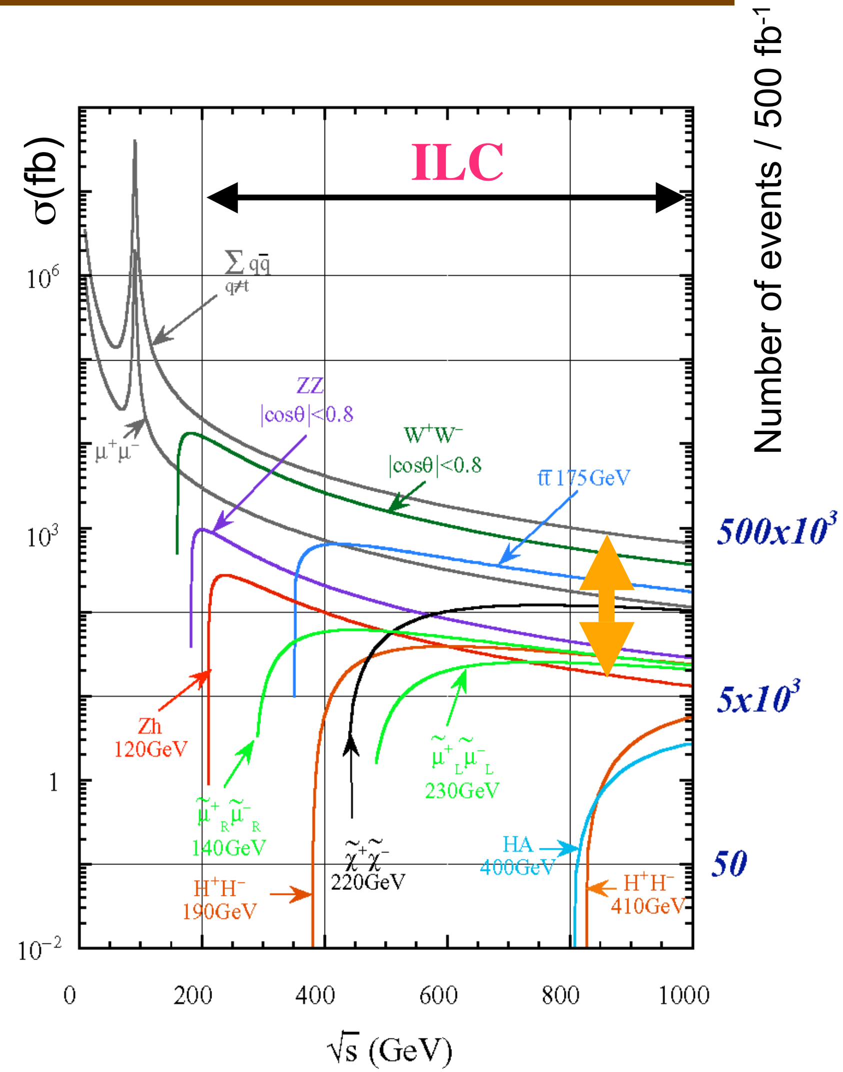
$2^{nd}$ stage: Ecm = 1 TeV

# *Goals of ILC*

1. **“Unexpected” new signals**
2. **Electroweak symmetry breaking** and mass-generation
3. Direct signals for **new physics** (SUSY, extra-dimensions, Z’…) and **determine The Physics**
4. **GUT and Planck scale** physics

# Signal and background Cross-section



# Powerful Tools at ILC

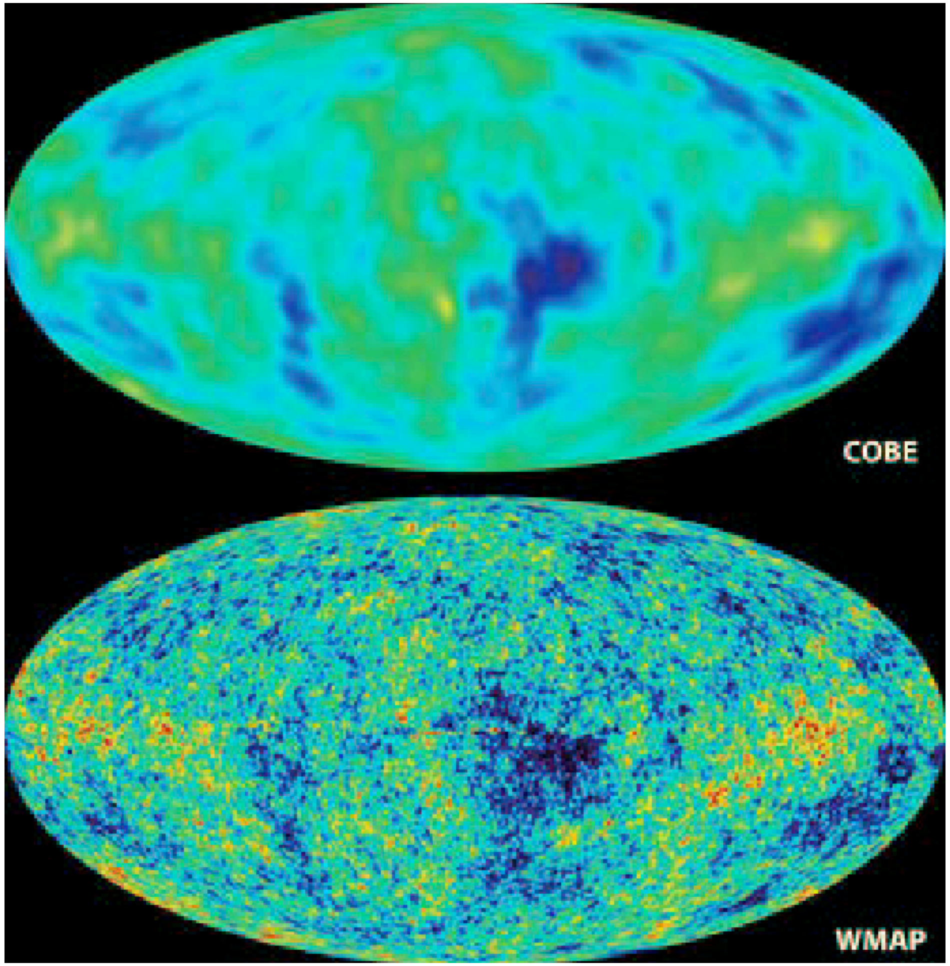
- **Electron/positron collision** (elementary process)
- **High Energy and High Luminosity**
- **Energy scan** (controllable)
- Controllable **beam polarization**
- **Very sensitive detectors** & Trigger free
- Precise **theoretical calculation** (<1%)

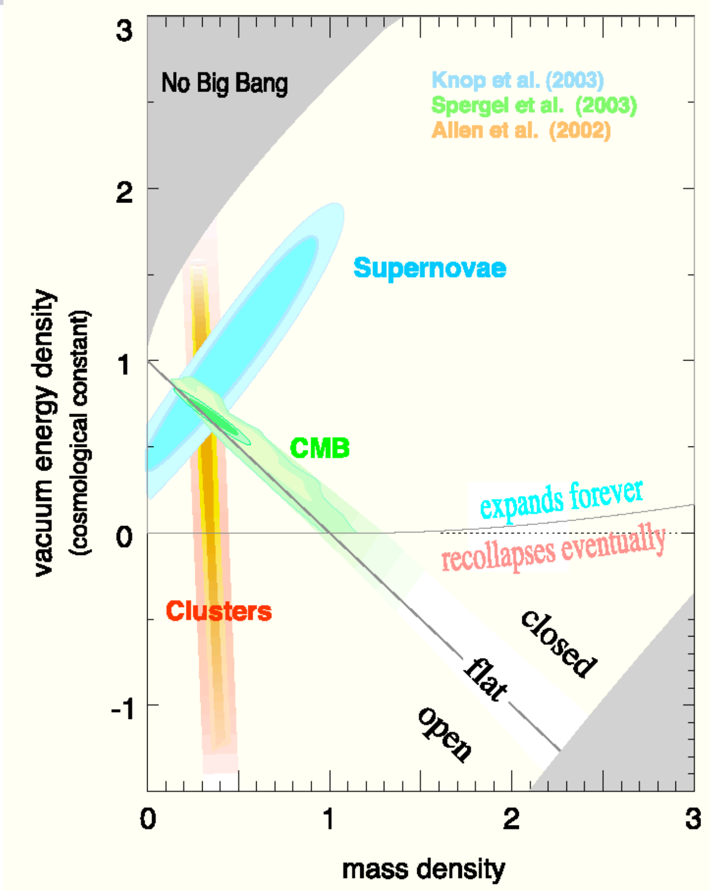
→ Precise physics information & long energy reach

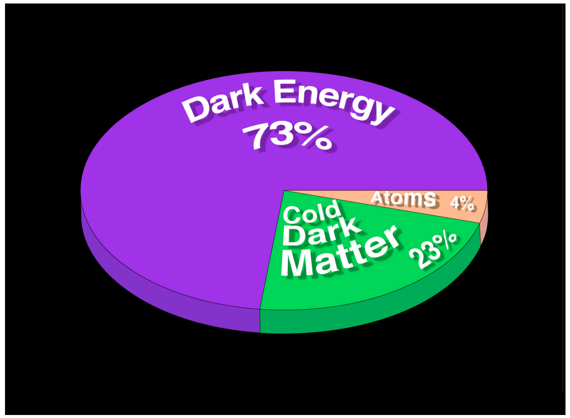
LHC gives us a **new** **global (mixed)** picture.

→ ILC gives us **new** dynamic **multi-dimensional total** views.

# Precision gives us a lot!

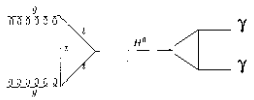


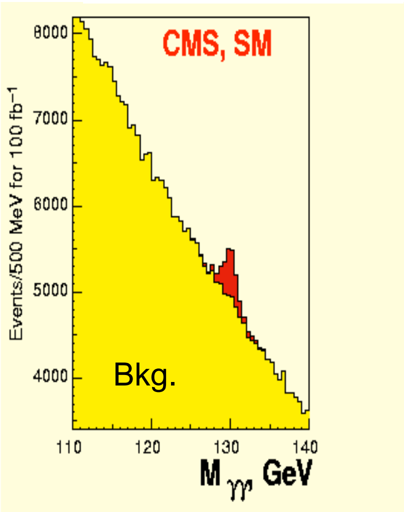



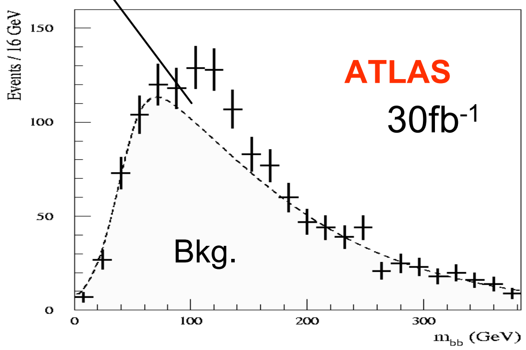
# LHC Higgs signal

$H \to \gamma\gamma$

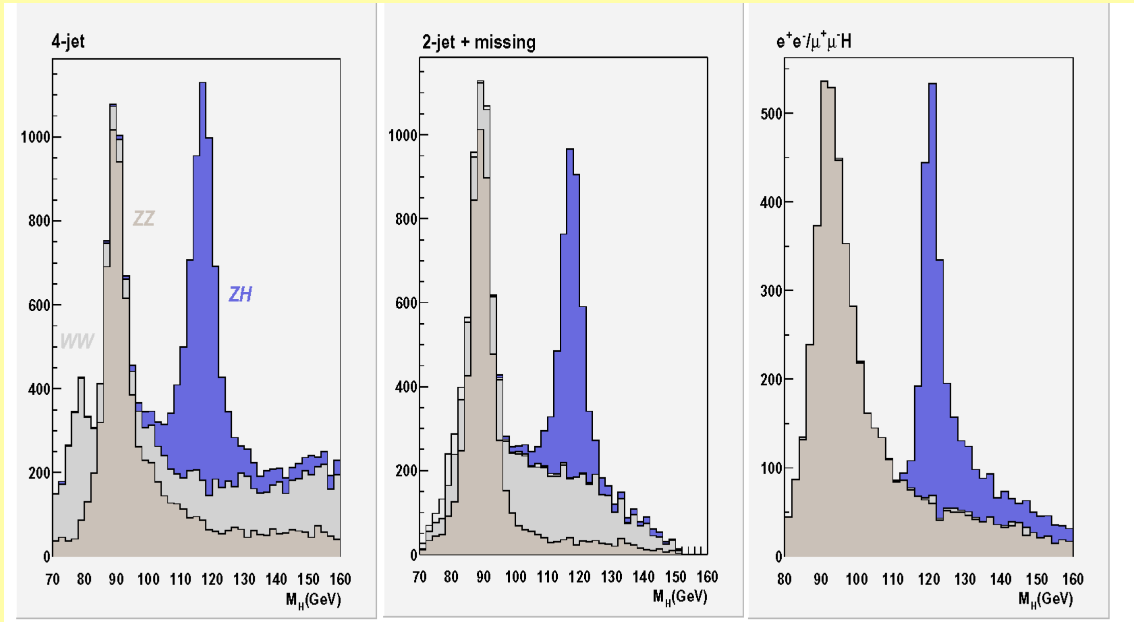


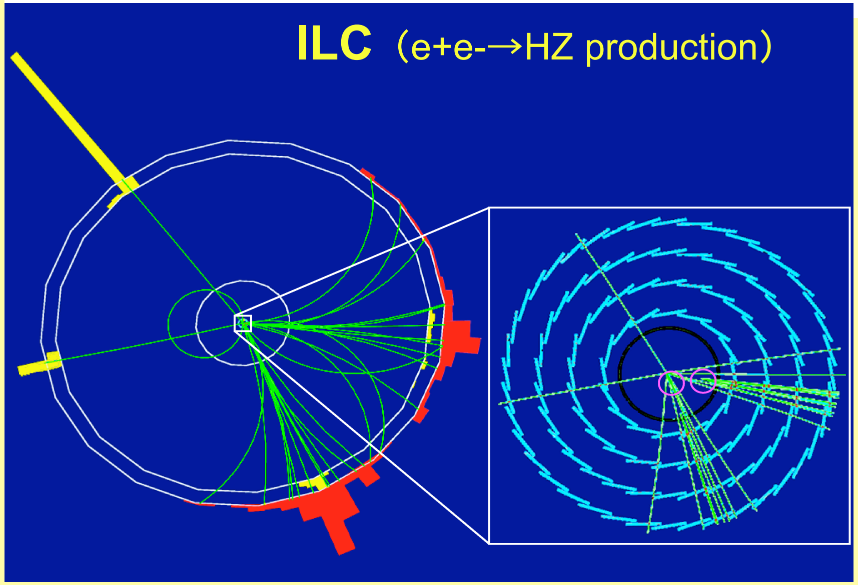



ttH→WbWbbb→$l\nu$jjbbbb




# ILC Higgs signal




Typical numbers

Tagging efficiency ~ 30-50 %

S/N > 1

Nov.9 2004

# Performance Goal of ILC Detectors

- VXT
  - Impact Parameter resolution: $< 5\mu m + 10\mu m / p(GeV) \sin^{-3/2}\theta$
- Tracker
  - Momentum resolution: $dp/p < 5 \times 10^{-5} \times p(GeV)$ (central region)
    $3 \times 10^{-4} \times p(GeV)$ for forward region
  - Angular resolution: $d\theta < 2 \times 10^{-5}$ rad (for $|\cos\theta|<0.99$)
- Jet energy resolution: $dE/E < 0.3 / \sqrt{E(GeV)}$
- Excellent Hermeticity: down to $\theta < 5$--$10$ mrad (active mask)

# Challenge

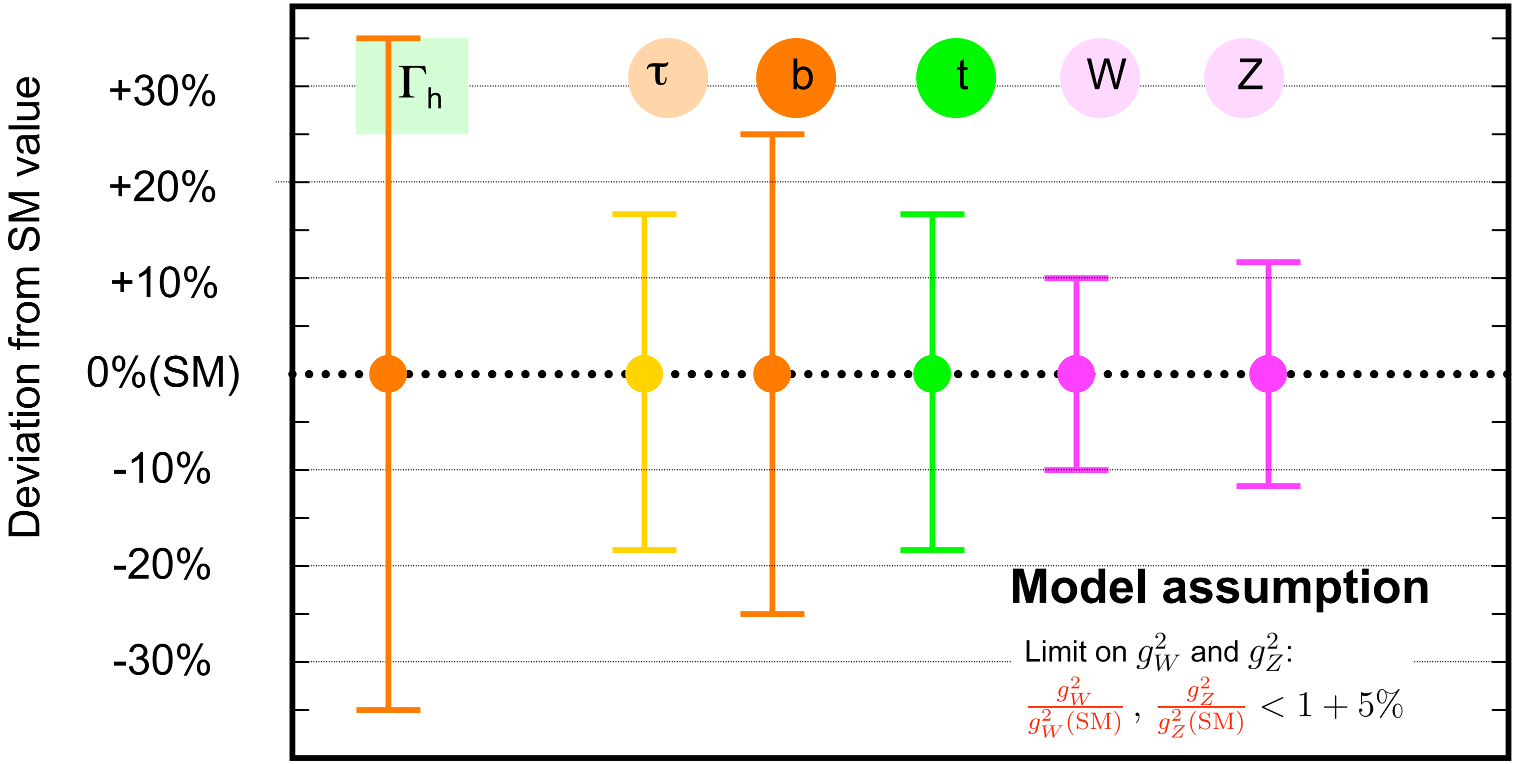
**In order to accomplish our physics goal at ILC**

With respect to detectors at LHC:

| | |
|---|---|
| ■ Inner VTX layer | 3--6 times closer to IP |
| ■ VTX pixel size | 1 / 30 |
| ■ VTX materials | 1 / 30 |
| ■ Materials in Tracker | 1 / 6 |
| ■ Track mom. resolution | 1 / 10 |
| ■ EM cal granularity | 1 / 200 !! |

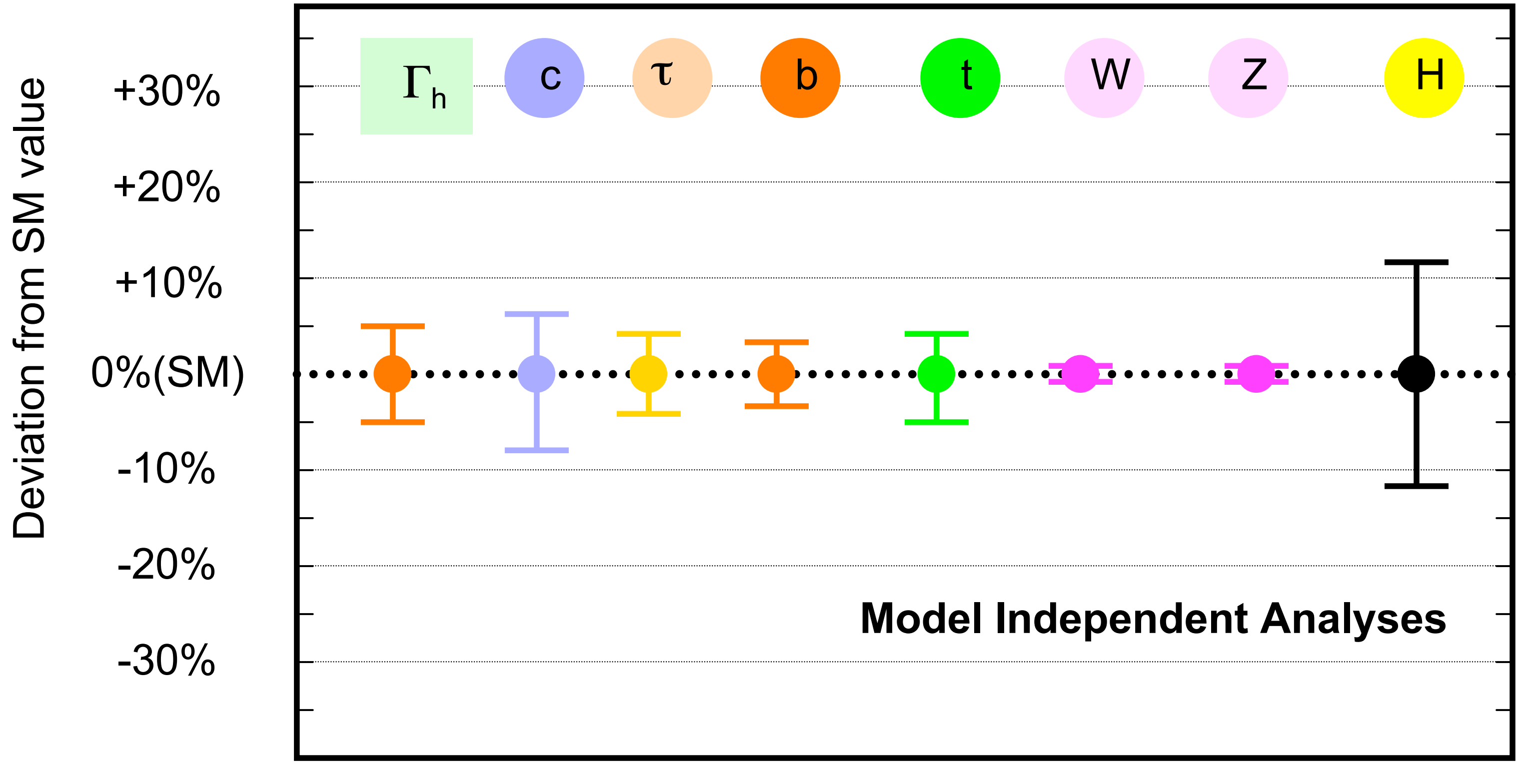
# Coupling Precision

LHC 300 $fb^{-1}$ x 2



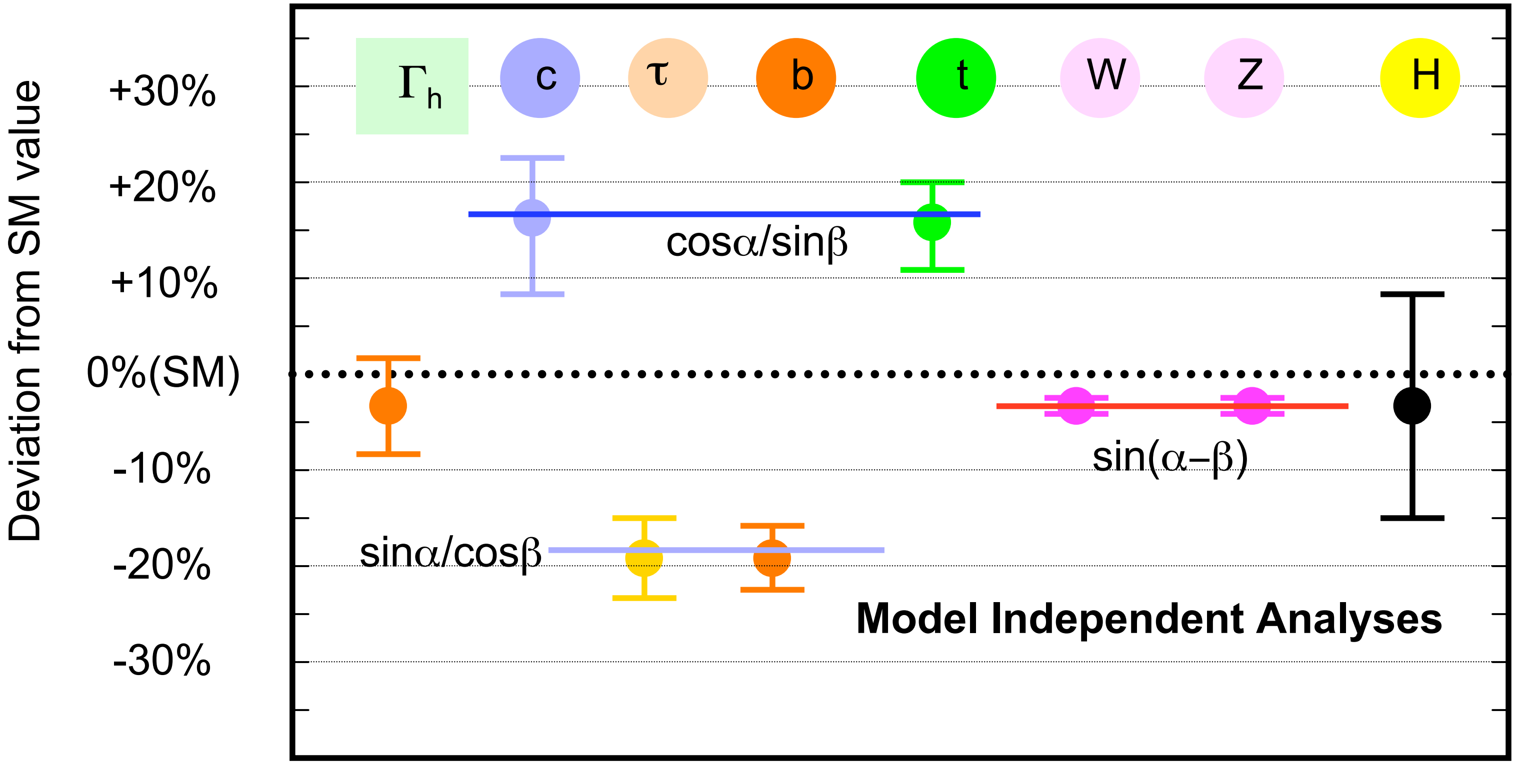
# Coupling Precision

**ILC**



# SUSY or 2HDM

**ILC**



# Collider Constraints

Linear Collider Detector R&D has had to consider two different sets of collider constraints: X-Band RF and Superconducting RF designs

With the linear collider technology selection, the detector efforts can concentrate on one set of parameters

The ILC creates requirements similar to those of the TESLA design

| | X-Band GLC/NLC | SuperRF TESLA |
|---|---|---|
| #bunch/train | 192 | 2820 |
| #train/sec | 150/120 | 5 |
| bunch spacing | 1.4 nsec | 337 nsec |
| bunches/sec | 28800/23040 | 14100 |
| length of train | 269 nsec | 950 μsec |
| train spacing | 6.6/8.3 msec | 199 msec |
| crossing angle | 7-20 mrad | 0-20 mrad |

# Detector Concept Studies

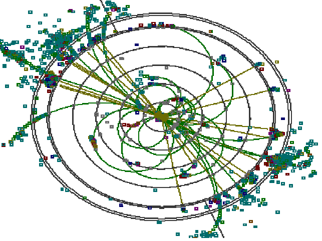
Time to re-evaluate detector concepts based on :

- up-to-date detector R&D results
- refined physics benchmarks
- some design need to be re-thought for the cold machine (longer bunch train etc.)

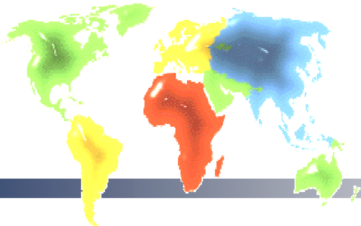
Detector concept session during this workshop

(this afternoon)

- Concept 1 : silicon-tracker-based (SiD)
- Concept 2 : 'medium' Tesla-based
- Concept 3 : 'large' GLC-based (GLD)



# LC Detector Requirements



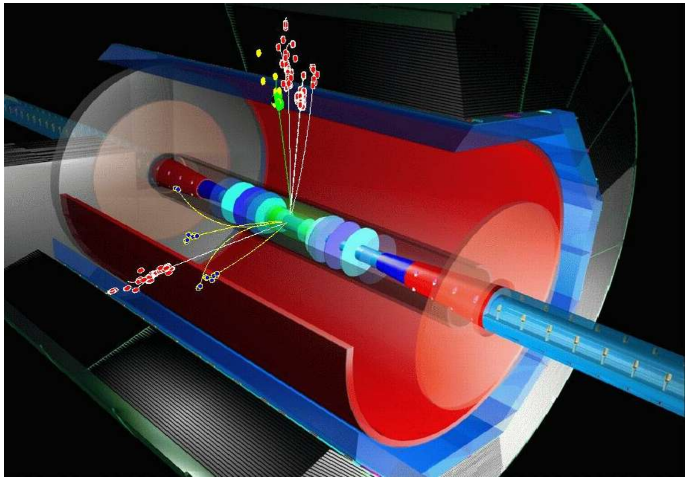
- Any design must be guided by these goals:
  - a) Two-jet mass resolution comparable to the natural widths of W and Z for an unambiguous identification of the final states.
  - b) Excellent flavor-tagging efficiency and purity (for both b- and c-quarks, and hopefully also for s-quarks).
  - c) Momentum resolution capable of reconstructing the recoil-mass to di-muons in Higgs-strahlung with resolution better than beam-energy spread.
  - d) Hermeticity (both crack-less and coverage to very forward angles) to precisely determine the missing momentum.
  - e) Timing resolution capable of separating bunch-crossings to suppress overlapping of events.

# A Medium Size Detector for the ILC

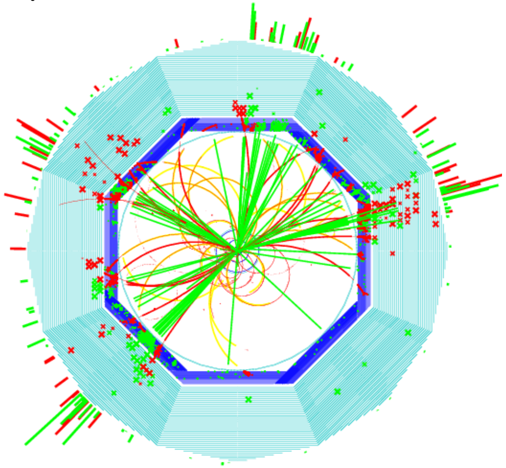
... what used to be the TESLA or LD detector concept

Ties Behnke, DESY
on behalf of the European and American large detector concept groups

A medium size detector for the linear collider:



- The concept behind the TESLA/ LD detector
  - precision tracking
  - particle flow based event reconstruction

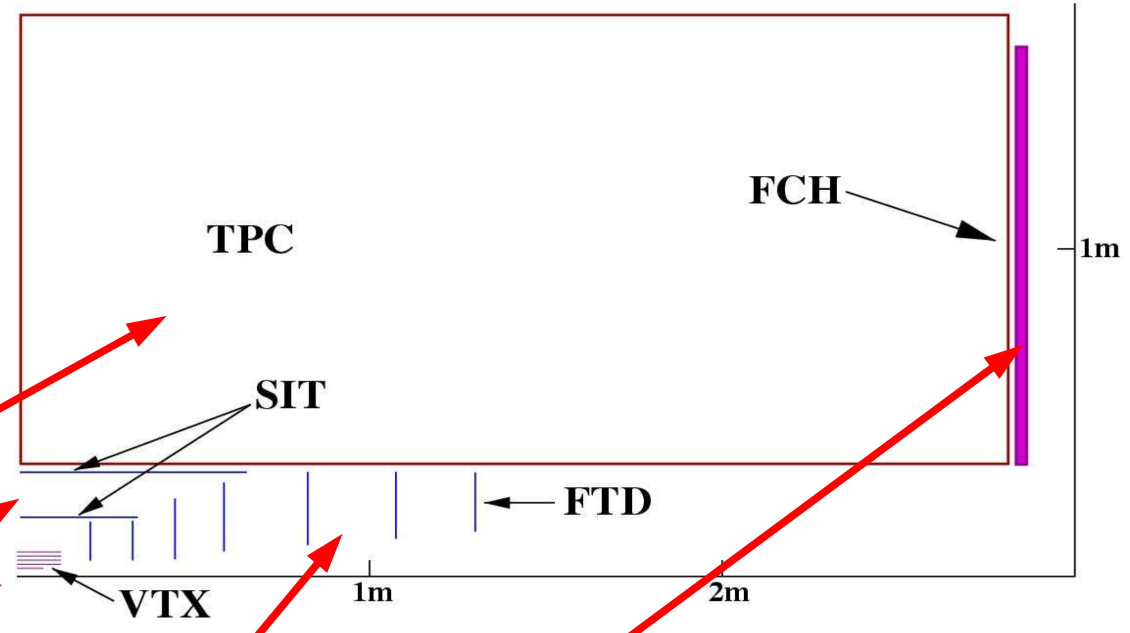


- Ways to proceed: global detector optimization

# A Precision Tracker

Ansatz
from the TESLA TDR:

(see e.g. Paolo Checcia's talk at LCWS04)




large volume gaseous tracker

medium precision SI tracker
to join the two devices

high precision VTX

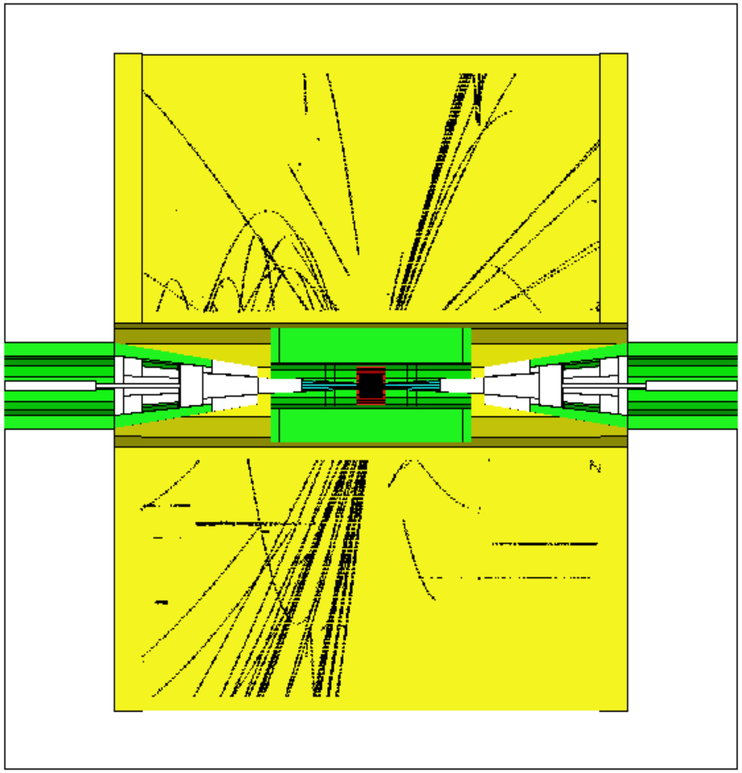
forward SI tracking for low angles

forward tracking behind TPC endplate

# Why a TPC?

advantages of a gaseous detector:

- many space points (200 for current design)
- good precision
- TPC is true 3D device: very robust against backgrounds
- long lived particles (new particles)
- Thin (little material)

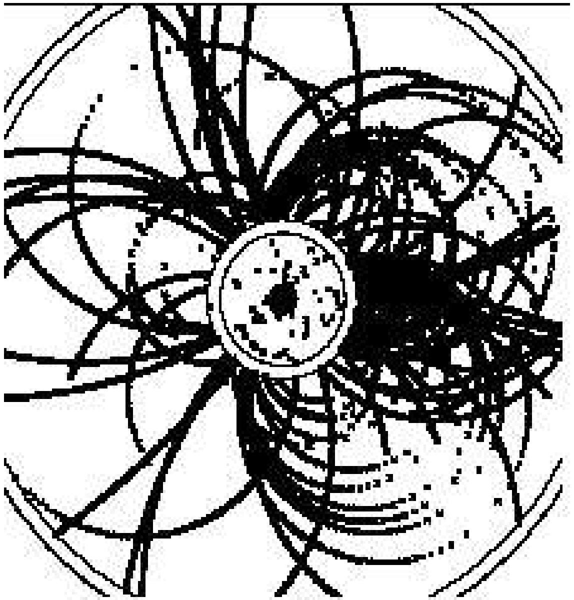


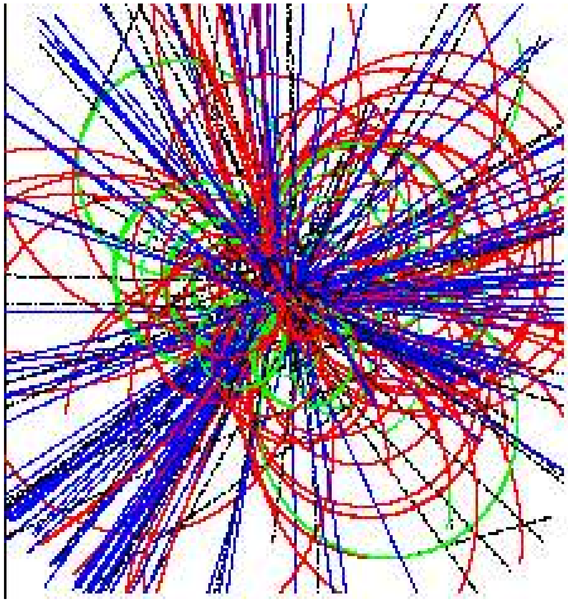
disadvantage:

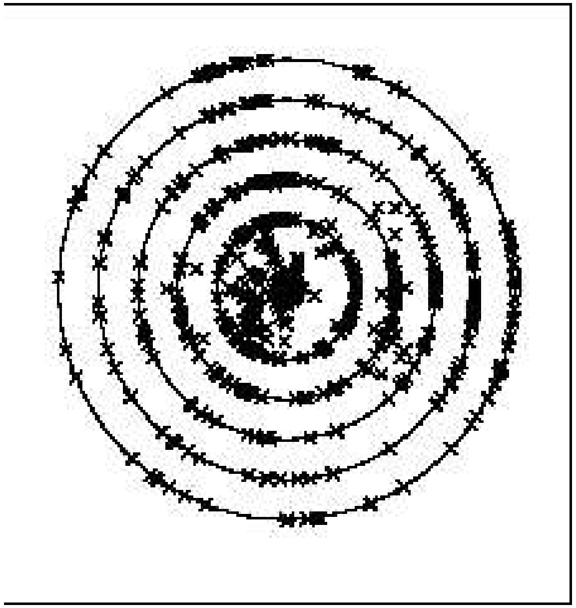
- gas amplification structures needed
- HV needed (REAL HV in case of a TPC)
- “fairly” massive endplates seem unavoidable
- readout speed is limited by gas properties

# Gaseous Tracking

$e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$







advantages of gaseous tracking:

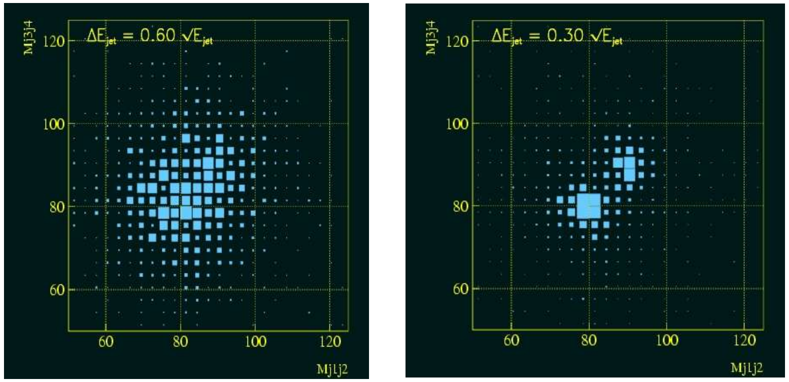
- many points
- simple pattern recognition
- redundancy

but be careful with these comparisons! Much more detailed studies are needed!

# Event Reconstruction

Jet physics: event reconstruction need excellent jet-energy (= parton energy) reconstruction

WW-ZZ separation

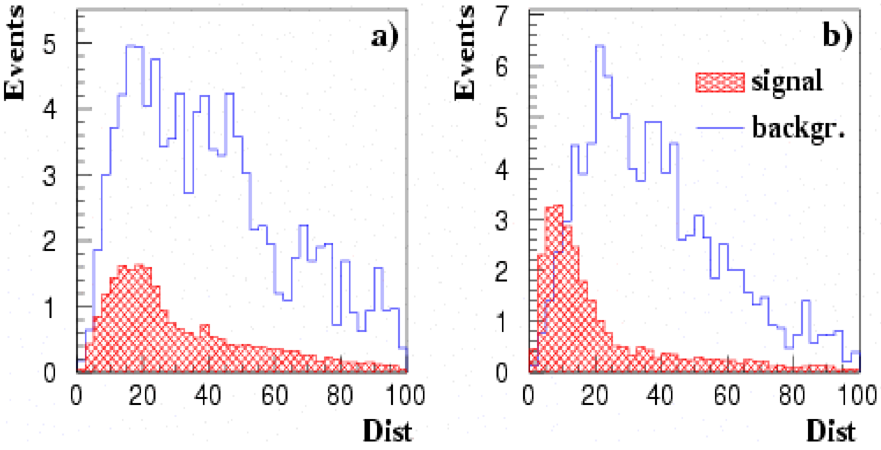



Complex hadronic final states:

- need complete topological event reconstruction
- Needed: new approach which stresses event reconstruction over individual particles:

Particle flow

Higgs self coupling reconstruction

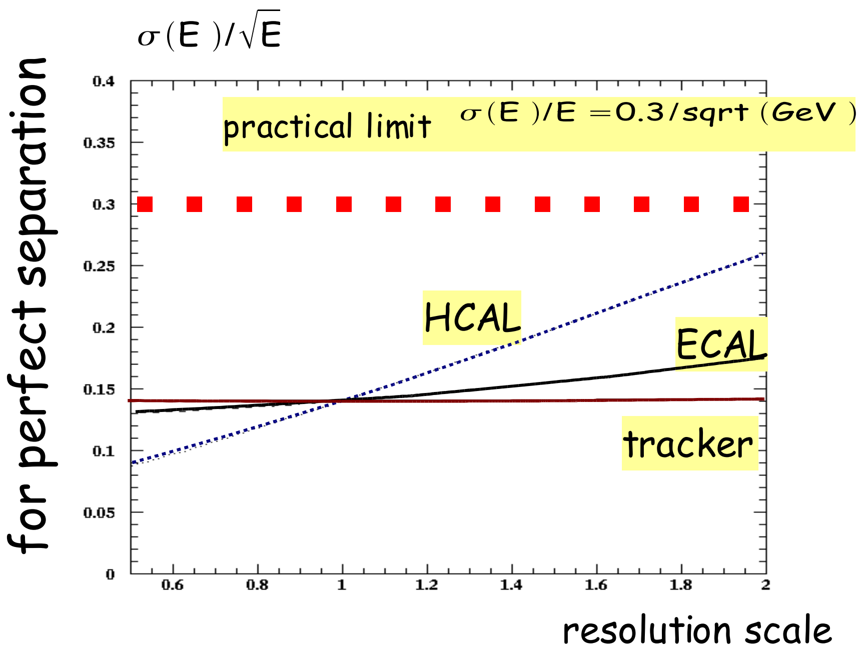



More like a revolution (though many have tried this before...)

# Particle Flow: Basics

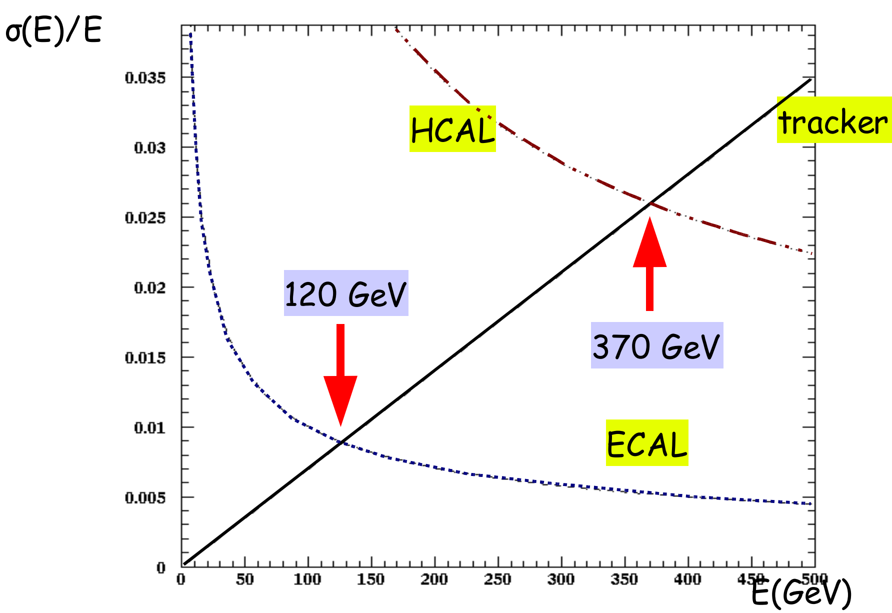
$$\sigma(Jet) = \sqrt{\sum \epsilon_T^2 E_i^4 + \sum \epsilon_{ECAL}^2 E_i + \sum \epsilon_{HCAL}^2 E_i}$$

Resolution is dominated by HCAL
and by
"confusion" resolution




Effect of changing the
resolutions by a scale factor

Resolution tracker - Calorimeter




jet energy resolution is

- nearly independent from tracker res.
- driven by HCAL res

ASSUMING:

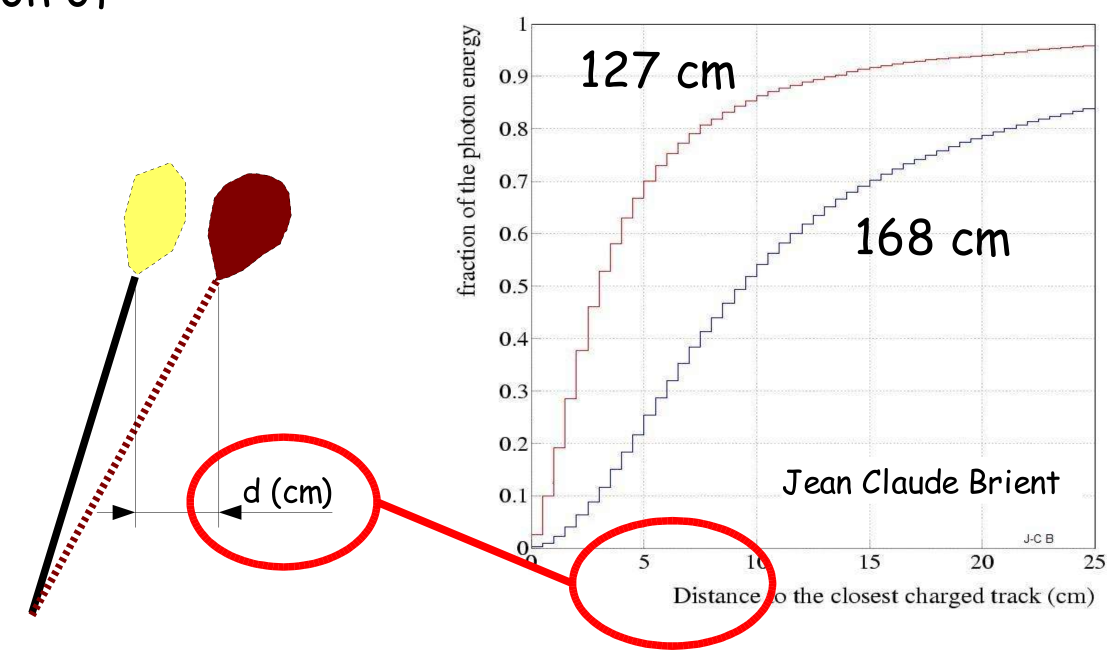
- perfect separation of particles

# Size Matters

Study confusion between charged and neutral particles as function of radius:

physics and CMS energy drive the relevant length scale

$e^+e^-$ -> ZH -> jets at $\sqrt{s}$ = 500 GeV




Energy deposited within "d" cm around a charged track

numbers:

E=20 GeV photon energy within 2.5cm of track for R=168 cm (4T, SiW)

E=65 GeV photon energy within 2.5cm of track for R=127 cm (5T, SiW)

# Particle Flow Detector

Particle Flow is influencing the detector design:

- Large inner radius of ECAL to have good separation at "moderate" fields
- Both ECAL and HCAL inside the coil
- Excellent spatial resolution of ECAL and HCAL to maximize the "shower tracking"

**ECAL**: "obvious" choice is Tungsten absorber, fine grained readout (SI seems accepted technology)
**HCAL**: less obvious, different options are under study (analogue, digital .... )

But all push the granularity ( = number of channels = cost) to new limits

Try to really optimize the size and granularity requirements to optimize the cost

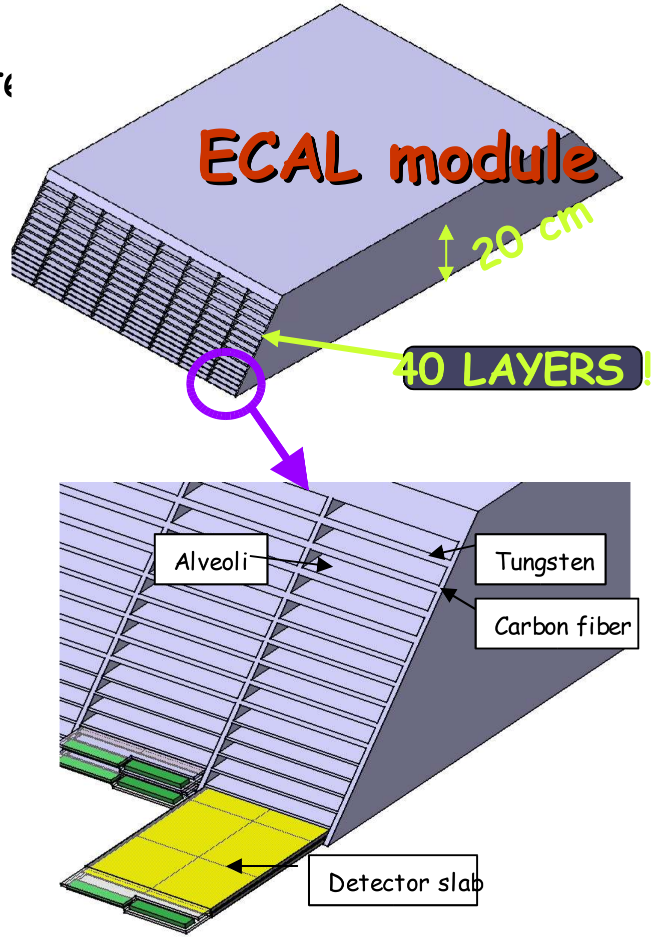
# Calorimeter Concepts

The medium detector concepts: SI-W ECAL calorimete

excellent granularity

excellent coverage

dense




followed by dense and segmented HCAL

scintillator tile

digital option

more conventional solution studied:

compensating lead-scintillator calorimeter

hybrid solutions (SI layers in conventional)

My personal opinion: we want the first, but maybe can only afford the second solution: need to wait for R&D program results!

# Status of Detector Concept

Current "invariants" of the concept:

Tracking based on TPC plus Silicon Tracker

Fine grained ECAL and HCAL to optimize particle flow

aggressive coverage to very small polar angles

The rest of the parameter space is wide open:

Need to start a real optimization

Need to fold in the results from the detector R&D which will be coming in during the next few years

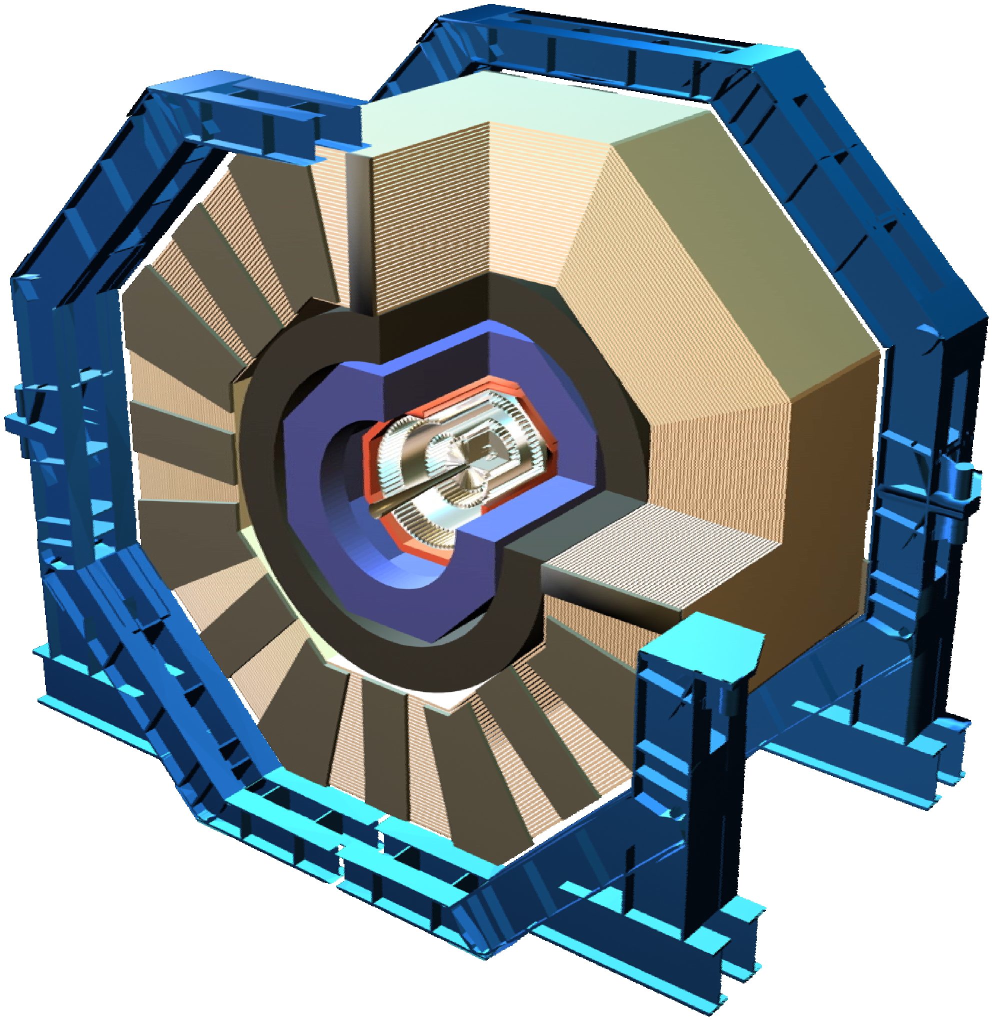
# SiD starting point (1)



Starting point: SiD concept

↓

• *Accept* notion that excellent energy flow calorimetry is required, and explore optimization of a Tungsten-Silicon EMCal and the implications for the detector architecture...



# *Calorimetry drives the Detector Design*

W's, Z's, top, H's,… are the quanta we must identify, and missing energy is the critical signature. All depend on calorimetry.

Need to measure jet four-momenta well enough to identify and discriminate W's, Z's, top, H's,…

Need ~4$\pi$ acceptance for good efficiency with multi-jet final states

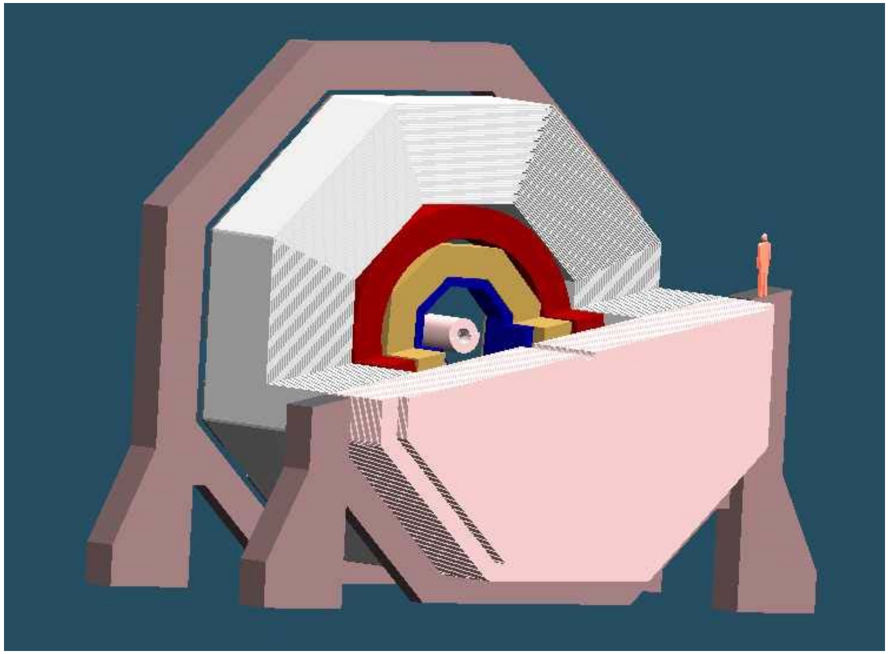
*SiD starting assumptions…*

***particle flow calorimetry will deliver the best possible performance***

***Si/W is the right technology for the ECAL***

# SiD concept sizes

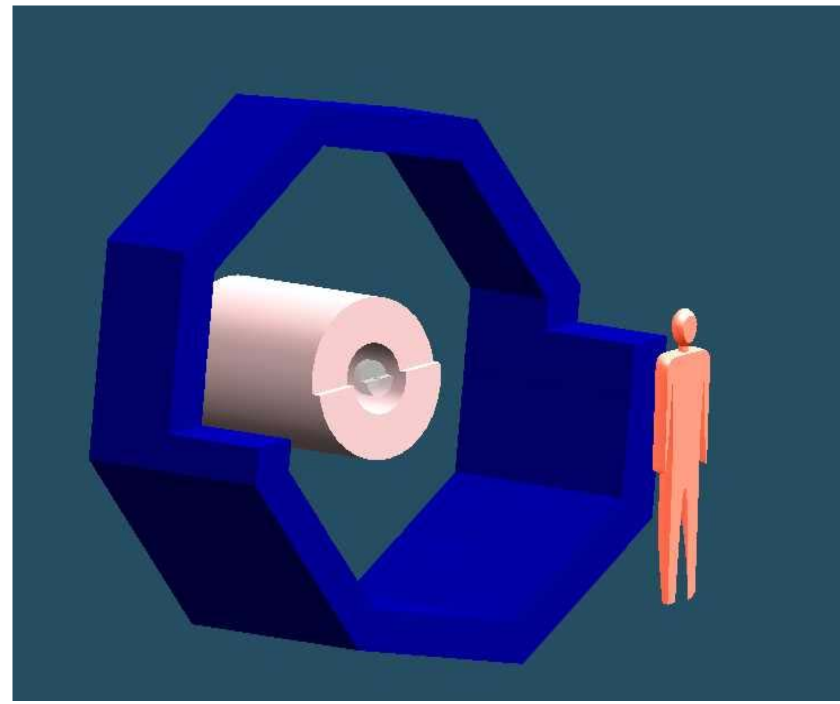
H.Weerts



Overall SiD

Size of VXD
outer cryostat
and EMCAL

(EMCAL inner radius larger than
Dzero EM cal radius)



# The SiD Rationale

***Premises:***

Excellent physics performance, constrained costs

Si/W calorimetry for excellent jet resolution

***therefore…***

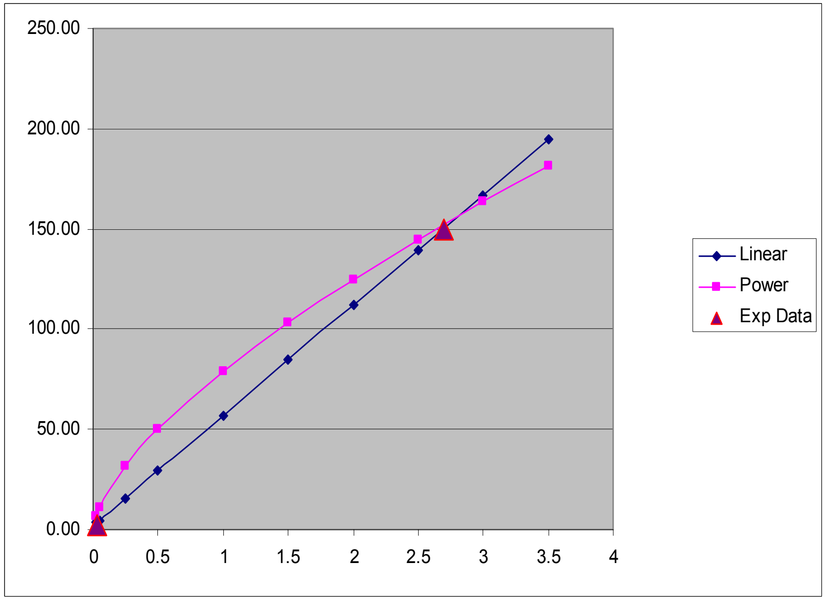
- *Limit Si/W calorimeter radius and length, to constrain cost*
- *Boost the B field to recover $BR^2$ for particle flow, improve momentum resolution for tracker, reduce backgrounds for VXD*
- *Use Si microstrips for precise tracking*

# Cost (and physics) balance R and B

High Field Solenoid and Si/W Ecal are major cost drivers.

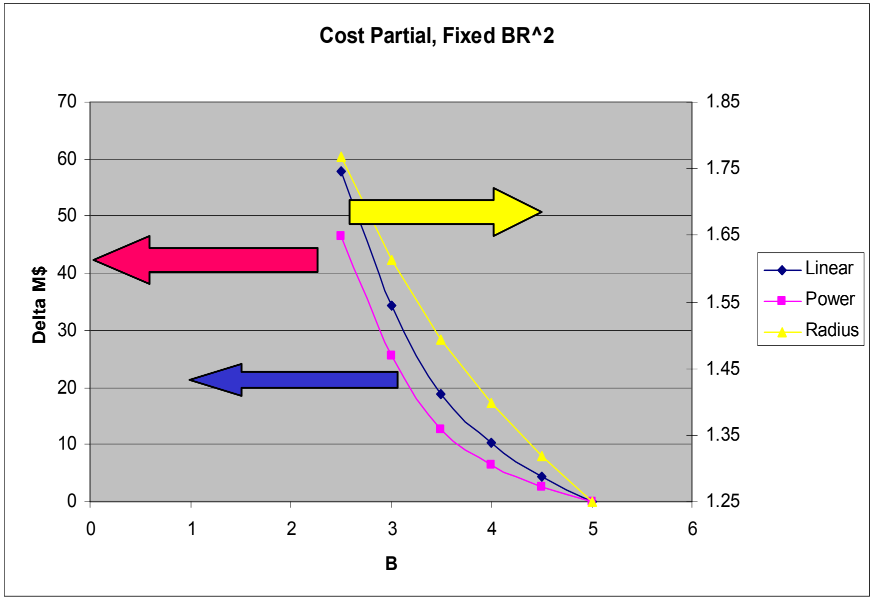
Magnet Costs ∝ Stored Energy →
(SiD ~1.1GJ → 80-100 M$)

Cost
[M$]




Stored Energy [GJ]

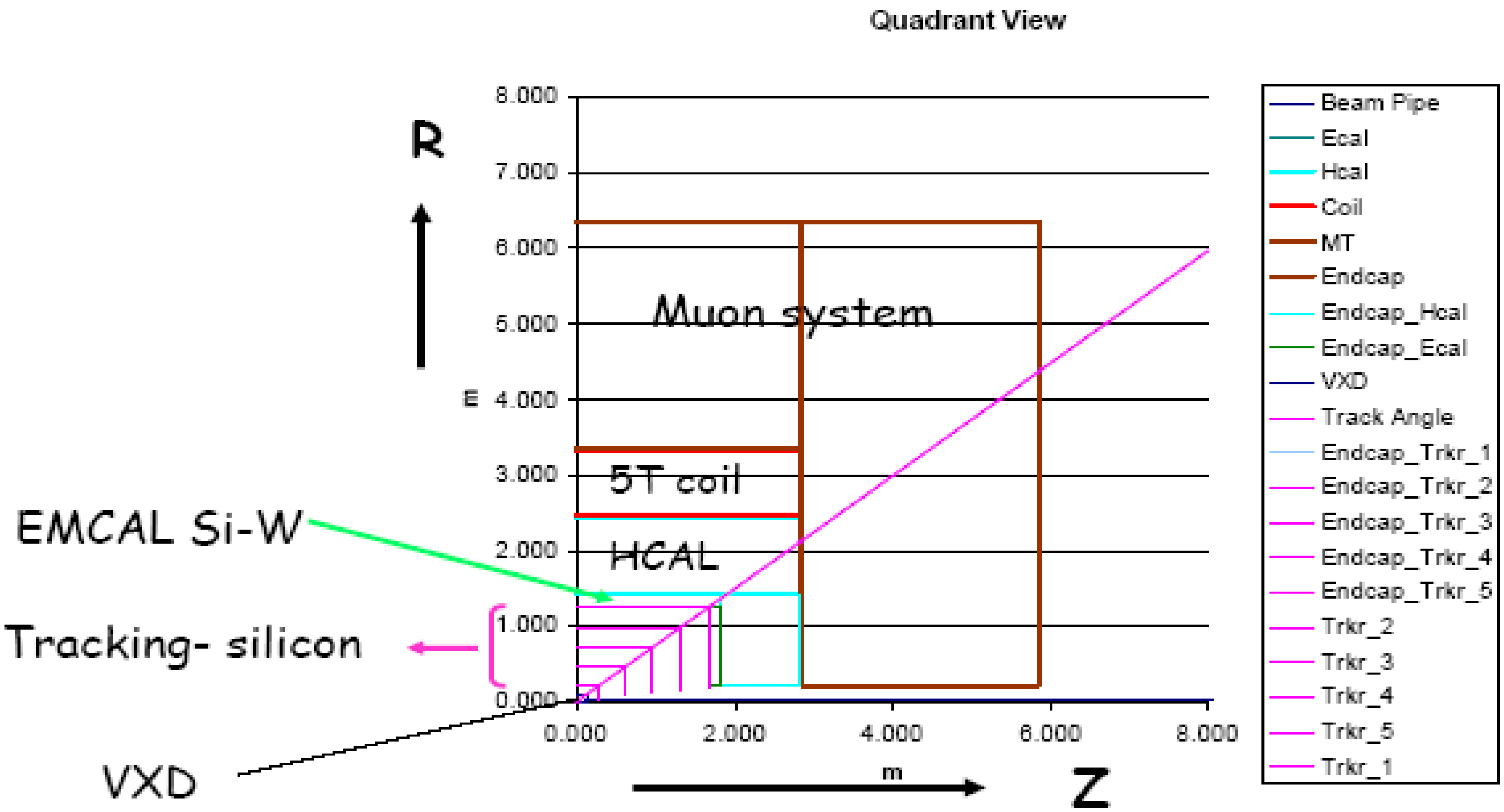
Fix $BR^2$=7.8, tradeoff B and R ↓




Delta M$ vs B, $BR^2$=7.8 [$Tm^2$]

# Result: SiD Design Starting Point

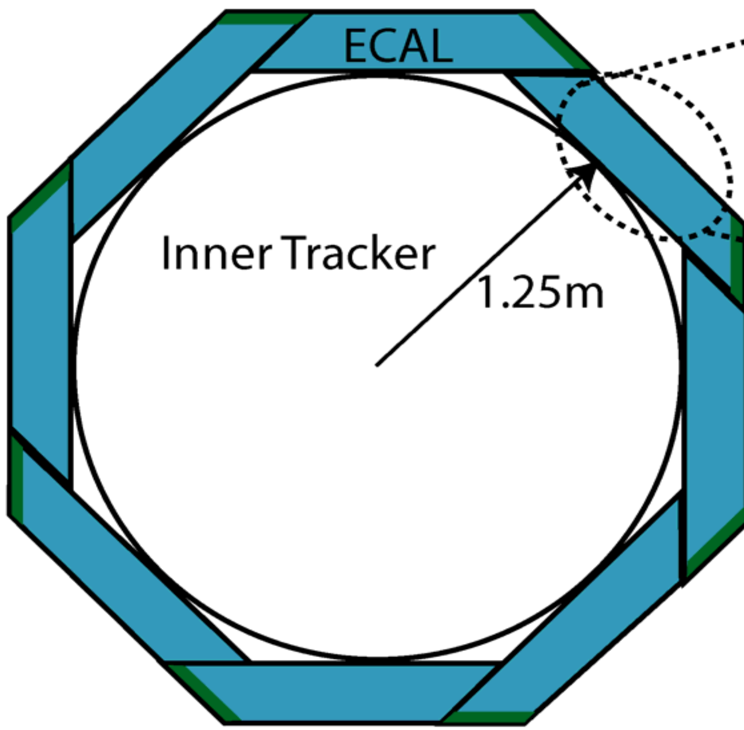
## B = 5T   $R_{ecal}$ = 1.25m   $Z_{ecal}$ = 1.74m

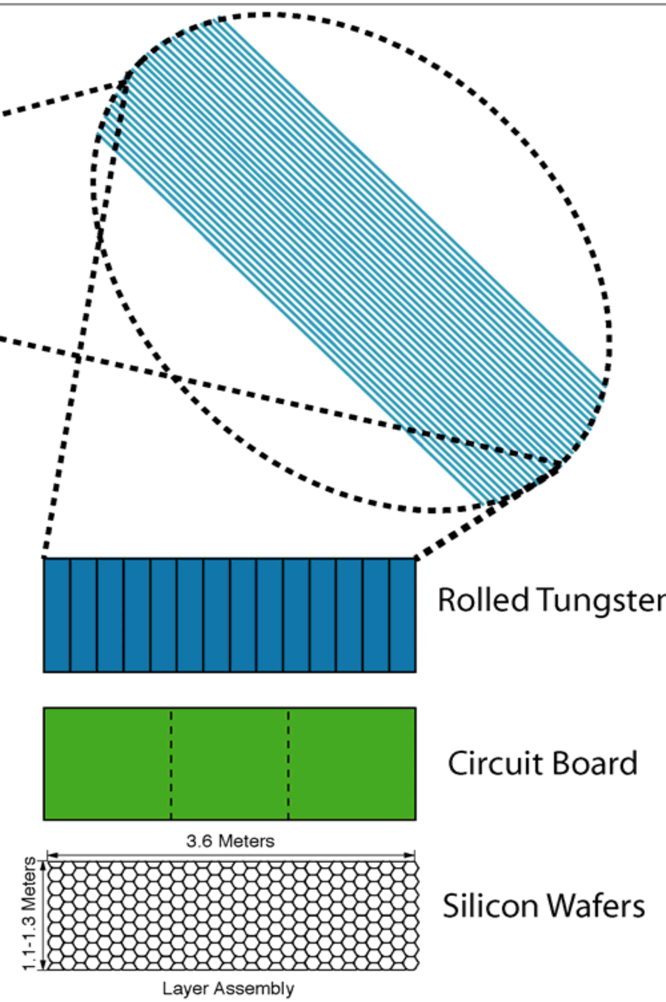



NOT A SMALL DETECTOR

# ECAL

Si-W Calorimeter Concept

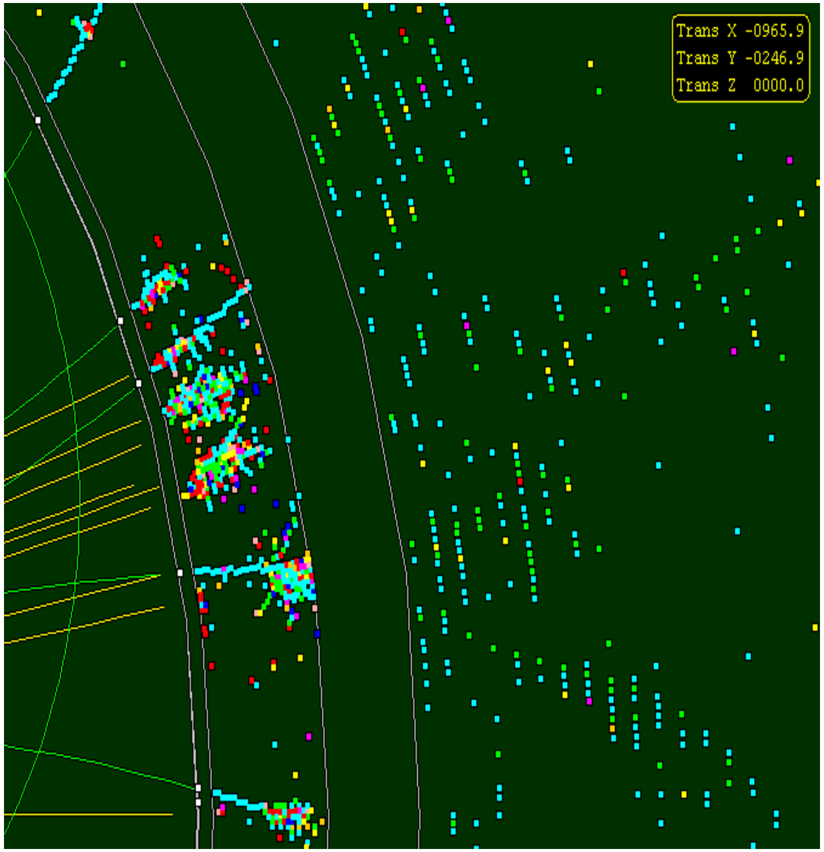



Transverse Segmentation ~5mm
30 Logitudnal Samples
Energy Resolution ~15%/$E^{1/2}$

# HCAL

- Inside the coil
- $R_{in}$= 1.42m; $R_{out}$= 2.44m
- 4λ Fe (or W, more compact)
  2cm Fe, 1cm gap
- Highly segmented
  1x1 $cm^2$ – 3x3 $cm^2$
  ~ 40 samples in depth
- Technology?
  RPC
  Scint Tile
  GEM




S. Magill (ANL)

…many critical questions for the SiD Design Study: thickness? Segmentation? Material? Technology?

Large Detector Concept

# Basic design concept

- Performance goal (common to all det. concepts)
  - Vertex Detector: $\delta(IP) \le 5 \oplus 10 / p \sin^{3/2}\theta$
  - Tracking: $\delta p_t / p_t^2 \le 5 \times 10^{-5}$
  - Jet energy res.: $\delta E / E \le 0.3 / \sqrt{E}$

    ➔ Detector optimized for Particle Flow Algorithm (PFA)
- Large/Huge detector concept
  - GLC detector as a starting point
  - Move inner surface of ECAL outwards to optimize for PFA
  - Larger tracker to improve $\delta p_t/p_t^2$
  - Re-consider the optimum sub-detector technologies based on the recent progresses

# Optimization for PFA

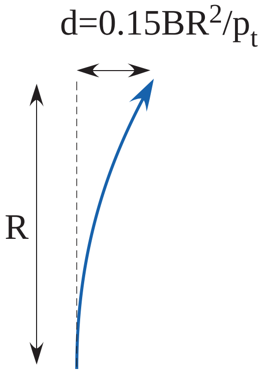
- Jet energy resolution
  - $\sigma_{jet}^2 = \sigma_{ch}^2 + \sigma_{\gamma}^2 + \sigma_{nh}^2 + \sigma_{confusion}^2 + \sigma_{threashold}^2$
  - Perfect particle separation: $\sigma_{jet} / E \sim 15\% / \sqrt{E}$
- Charged-$\gamma$/nh separation
  - Confusion of $\gamma$/nh shower with charged particles is the source of $\sigma_{confusion}$ → Separation between charged particle and $\gamma$/nh shower is important
  - Charged particles should be spread out by B field
  - Lateral size of EM shower of $\gamma$ should be as small as possible ( ~ $R_m^{effective}$: effective Moliere length)
  - Tracking capability for shower particles in HCAL is a very attractive option → Digital HCAL

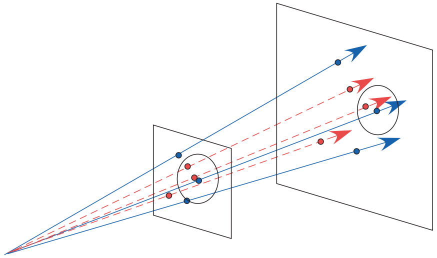
# Optimization for PFA

- Figure of merit (ECAL):
  - Barrel: $B R_{in}^2 / R_m^{effective}$
  - Endcap: $B Z^2 / R_m^{effective}$

    $R_{in}$ : Inner radius of Barrel ECAL

    Z : Z of EC ECAL front face



(Actually, it is not so simple. Even with B=0, photon energy inside a certain distance from a charged track scales as $\sim R_{in}^2$)

- Different approaches
  - $B\ R_{in}^2$ : SiD
  - $B\ R_{in}^2$ : TESLA
  - $B\ R_{in}^2$ : Large/Huge Detector

# Central Tracker

- Figure of merit:

$$\frac{\delta p_t}{p_t^{\ 2}} = \left(\frac{3.3\sigma}{BL^2}\right)\sqrt{\frac{720}{n+4}}$$

$\sigma$ : Spatial resolution

$B$ : Magnetic field

$L$ : Tracking length

$n$ : Number of samplings

*n* is proportional to *L* if sampling pitch is constant

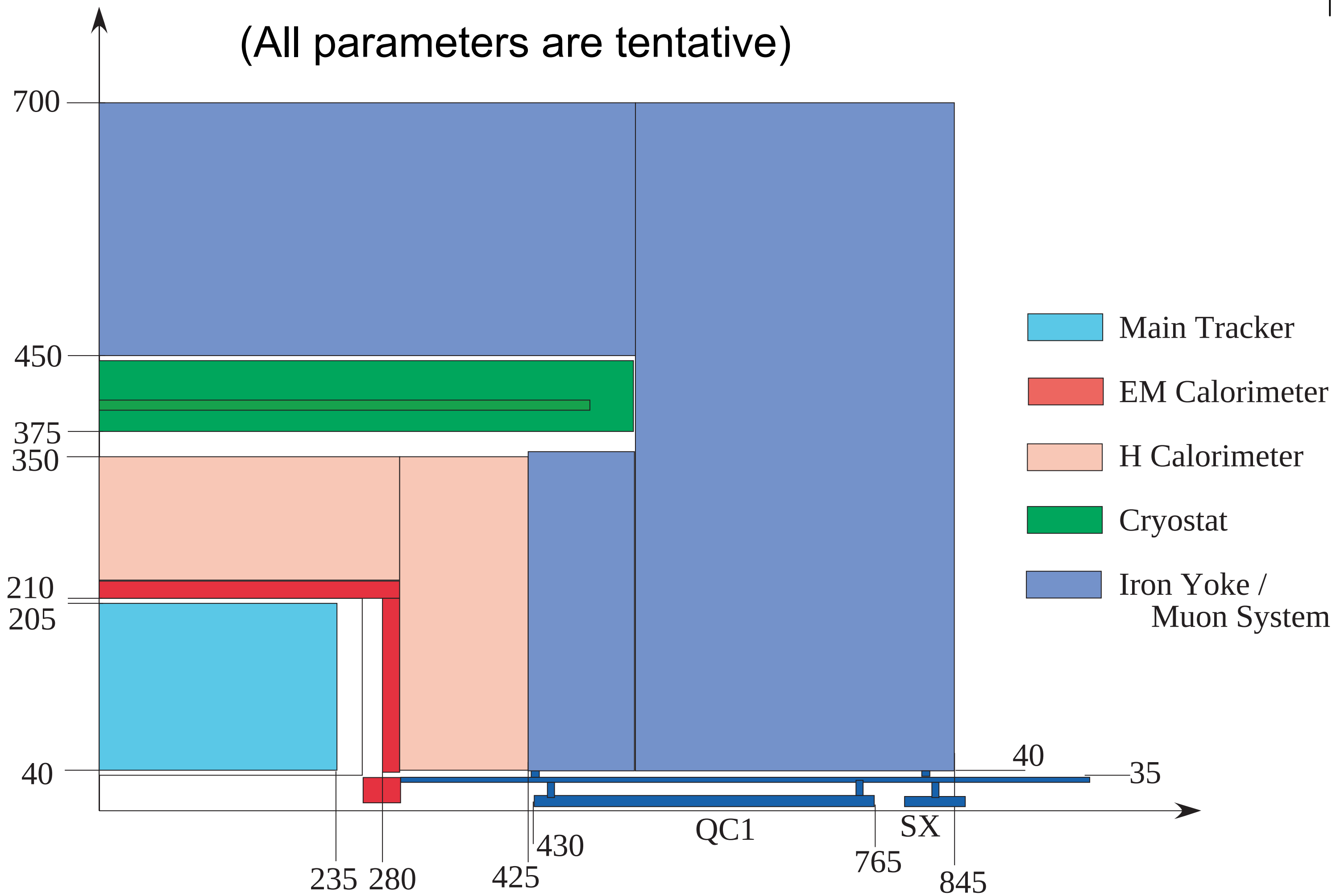
➔ $$\frac{\delta p_t}{p_t^{\ 2}} \propto \frac{1}{\underline{BL^{2.5}}}$$

# A possible modification from GLC detector model

- Larger $R_{max}$ (2.0m) of the tracker and $R_{in}$ (2.1m) of ECAL
  - TPC would be a natural solution for such a large tracker
- Keep solenoid radius same:

  ➔ Somewhat thinner CAL (but still 6$\lambda$), but does it matter?
- Use W instead of Pb for ECAL absorber
  - Effective $R_m$: 25.5mm → 16.2mm (2.5mm W / 2.0mm Gap)
  - Small segmentation by Si pad layers or scintillator-strip layers
- Put EC CAL at larger Z (2.05m→2.8m) ➔ Longer Solenoid
  - Preferable for B-field uniformity if TPC is used
- It is preferable $Z_{pole\text{-}tip} < l^*$ (4.3m?) both for neutron b.g. and QC support ($l^*$ :distance between IP and QC1)

# Global geometry



# Comparison of parameters

| | | SiD | TESLA | JLC | GLC | GLD [1] | LD |
|---|---|---|---|---|---|---|---|
| Solenoid | B(T) | 5 | 4 | 2 | 3 | 3 | 3 |
| | Rin(m) | 2.48 | 3.0 | 4.25 | 3.75 | 3.75 | 3.7 |
| | L(m) | 5.8 | 9.2 | 9.1 | 6.8 | **9.86** | 9.4 |
| | $E_{st}$(GJ) | 1.4 | 2.3 | 1.1 | | **1.8** | 1.7 |
| Main Tracker | $R_{min}$ (m) | 0.2 | 0.36 | 0.45 | 0.45 | **0.4** | 0.5 |
| | $R_{max}$(m) | 1.25 | 1.62 | 2.3 | 1.55 | **2.0** | 2.0 |
| | $BL^{2.5}$ | 5.7 | 7.1 | 9.3 | 3.8 | **9.7** | 8.3 |
| | $\sigma(\mu m)$ | 7 | 150 | 100 | 85 | **150** | 150 |
| | $N_{sample}$ | 5 | 200 | 100 | 50 | **220** | 144 |
| | $\delta pt/pt^2$ | 3.6e-5 | 1.5e-4 | 1.3e-4 | 2.9e-4 | **1.2 e-4** | 1.6e-4 |

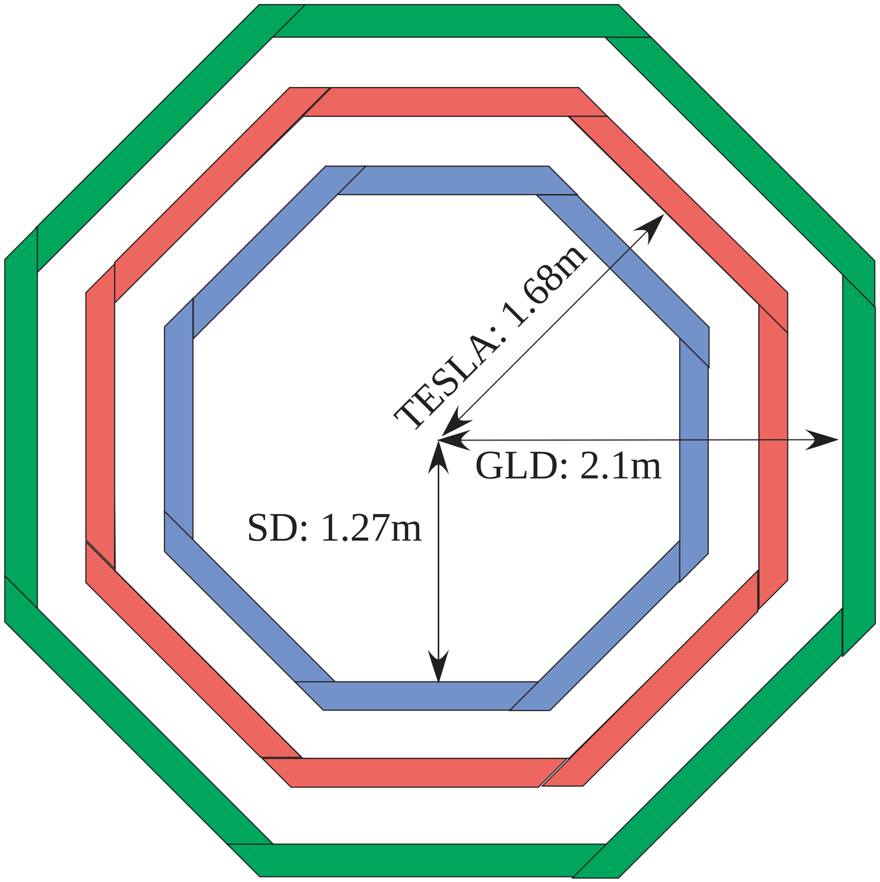
[1] GLD is a tentative name of the Large/Huge detector model.
All parameters are tentative.

# Comparison of parameters

| | | SiD | TESLA | JLC | GLC | GLD | LD |
|---|---|---|---|---|---|---|---|
| ECAL | $R_{in}$ (m) | 1.27 | 1.68 | 2.5 | 1.6 | ***2.1*** | 2.0 |
| | $BR_{in}^2$ | 8.1 | 11.3 | 12.5 | 7.7 | ***13.2*** | 12.0 |
| | Type | W/Si | W/Si | Pb/Sci | Pb/Sci | (***W/Sci***) | Pb/Sci |
| | $R_m^{eff}$ (mm) | 18 | 24.4 | 21.3 | 25.5 | ***16.2*** | 21.3 |
| | $BR_{in}^2/R_m^{eff}$ | 448 | 462 | 588 | 301 | ***817*** | 565 |
| | Z (m) | 1.72 | 2.83 | 2.9 | 2.05 | ***2.8*** | 3.0 |
| | $BZ^2/R_m^{eff}$ | 822 | 1311 | 792 | 494 | ***1452*** | 1271 |
| | $X_0$ | 21 | 24 | 29 | 27 | **27** | 29 |
| E+H CAL | $\lambda$ | 5.5 | 5.2 | 6.9 | 7.3 | ***6.0*** | 6.9 |
| | t (m) | 1.18 | 1.3 | 1.5 | 1.8 | ***1.4*** | 1.7 |

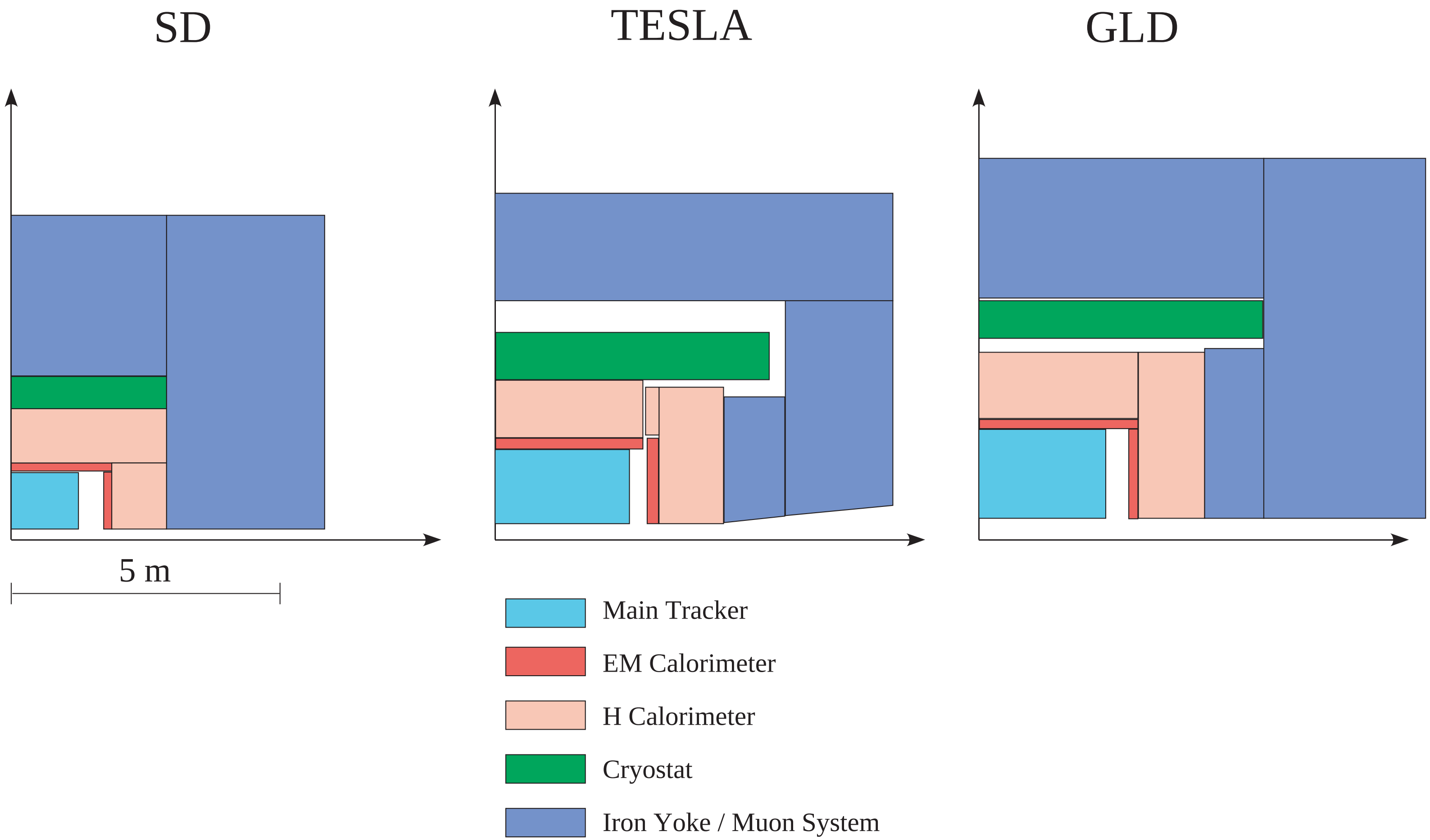
# Detector size

- EM Calorimeter

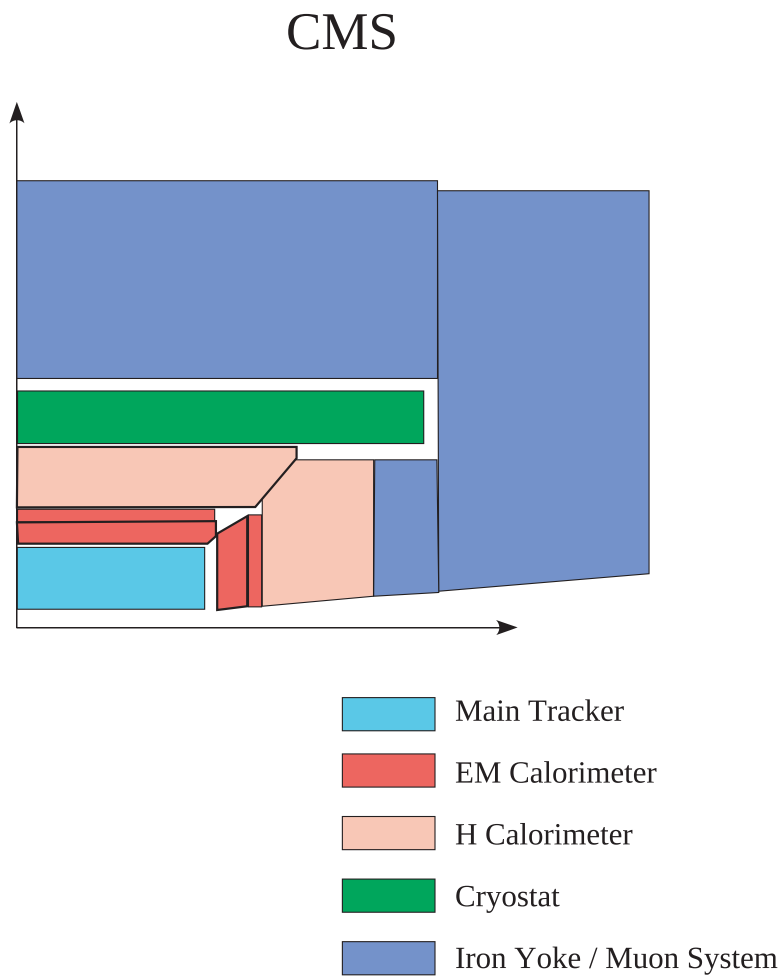


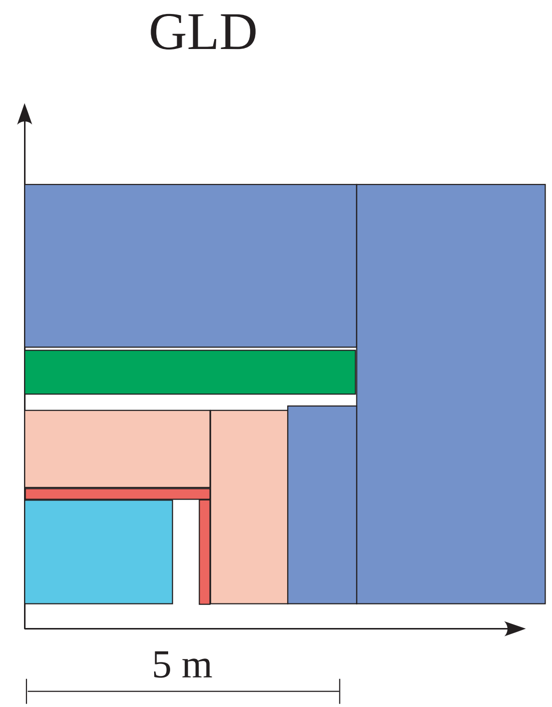

- Area of EM CAL (Barrel + Endcap)
  - SiD: ~40 $m^2$ / layer
  - TESLA: ~80 $m^2$ / layer
  - GLD: ~ 100 $m^2$ / layer
  - (JLC: ~130 $m^2$ / layer)

# Global geometry



# Global geometry



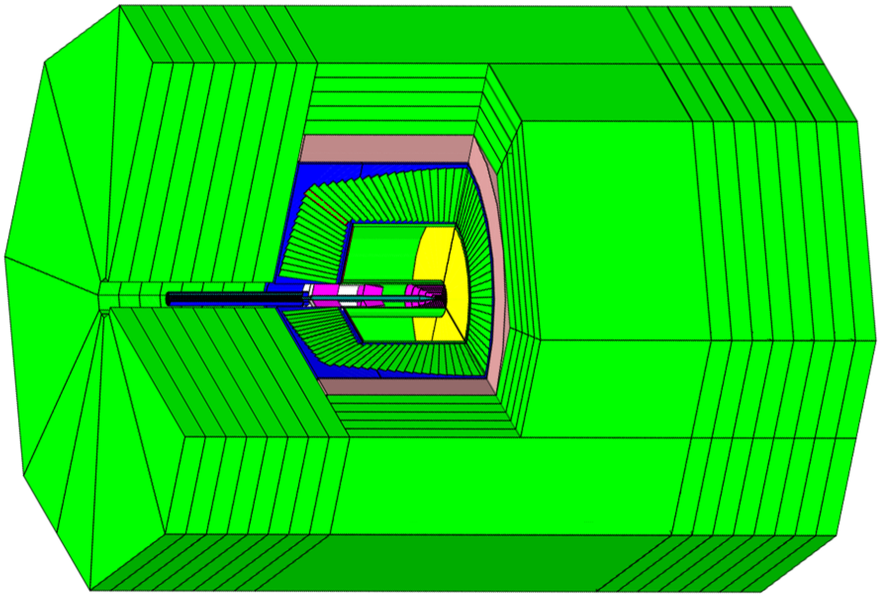

GLD is smaller than CMS
“Large” is smaller than “Compact” ☺

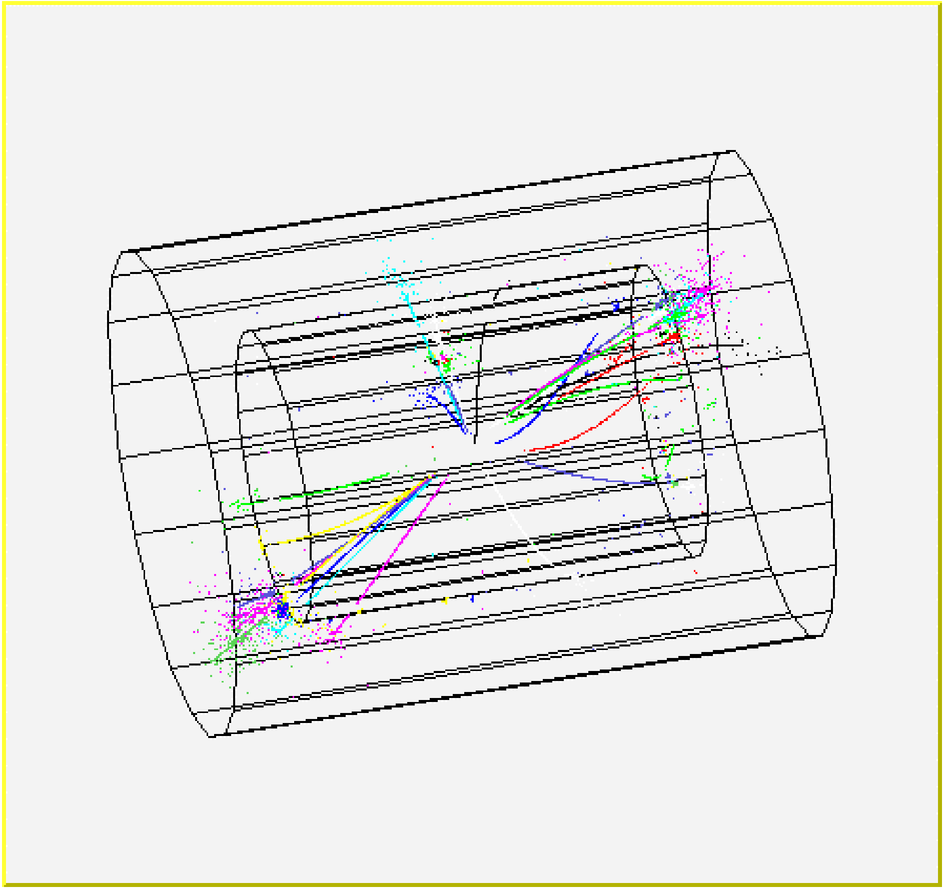
# Merits and demerits of Large/Huge detector

- Merits
  - Advantage for PFA
  - Better $p_t$ and dE/dx resolution for the main tracker
  - Higher efficiency for long lived neutral particles (Ks, $\Lambda$, and unknown new particles)
- Demerits
  - Cost ? – but it can be recovered by
    - Lower B field of 3T (Less stored energy)
    - Inexpensive option for ECAL (e.g. scintillator)
  - Vertex resolution for low momentum particles
    - Lower B requires larger $R_{min}$ of VTX because of beam background
    - $\delta(IP) \sim 5 \oplus 10/(p\beta \sin^{3/2}\theta)$ $\mu$m is still achievable using wafers of ~50$\mu$m thick

# Full Simulator

- Installation of a new geometry into a full simulator "JUPITER" is under way

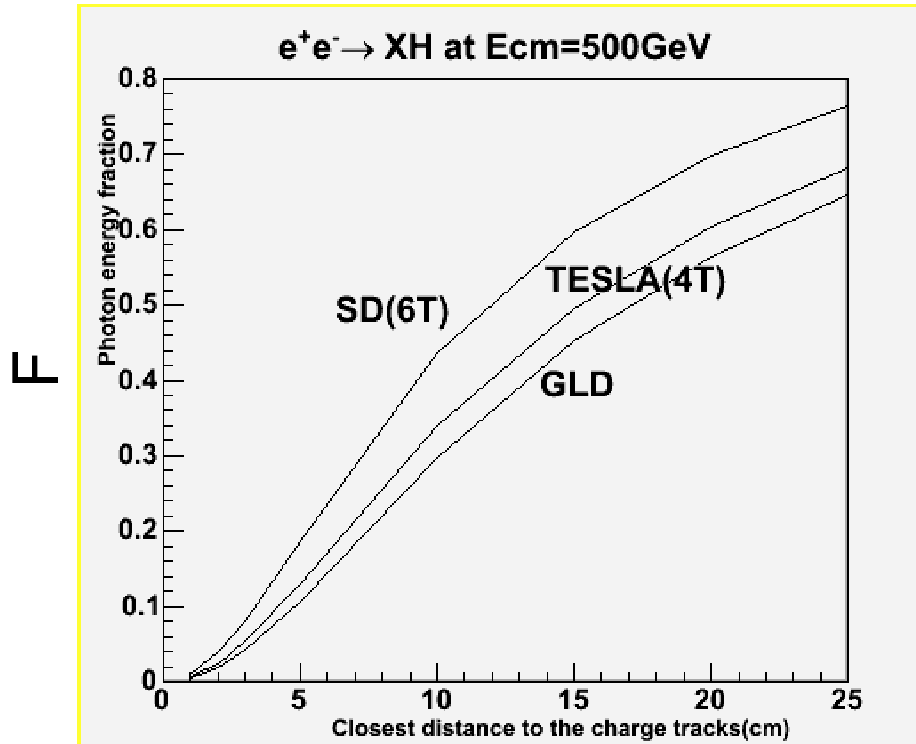




# Charged – $\gamma$ separation

- Simulation by A. Miyamoto
  - Events are generated by Pythia6.2, simulated by **Quick Simulator**
  - Particle positions at the entrance of EM-CAL
  - Advantage of Large/Huge detector is confirmed
  - Inconsistent with J.C.B's result → need more investigation

$$F \equiv \frac{\sum_{all\ \ events} E_\gamma (d < d_{cut})}{\sum_{all\ \ events} E_\gamma}$$




$d_{cut}$

# Detector R&D efforts & Design Studies

H.Weerts

| | Vxd 4-5 | SiLC | TPC | Jet | Calice EM | Calice HAD | LC cal | Cal Asia | EM OR/ SLAC | EM hybrid | muon |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SiD | X | X | | | X | X | | X | X | X | X |
| LAD | X | X | X | X | X | X | X | X | X | X | X |
| HUD | X | ? | X | X | | X | X | X | | | X |

| | Fwd trac | Fwd cal | Fwd Che | DAQ | $\gamma\gamma$ | BD IR |
|---|---|---|---|---|---|---|
| SiD | X | X | | X | | X |
| LAD | X | X | ? | X | | X |
| HUD | X | X | ? | X | | X |

Nearly all detector R&D efforts are represented in the Design Studies (DS)

Goal: At least one representative of each R&D effort in each DS

# Timeline proposed by WWS OC

| | |
|---|---|
| (2004) ITRP tech. recommendation | Set up 3 panels (costing, detector R&D, and MDI) |
| (2005) Accelerator CDR | Single preliminary-costing paper for >1 whole detector concepts |
| (2007) Accelerator TDR | WWS receives CDR from each detector concept team |
| (2008) LC site selection | Collaborations form and submit LOIs for proposal to the global lab (or GDO?) |
| Site selection + 1yr | Global lab selects experiments. |