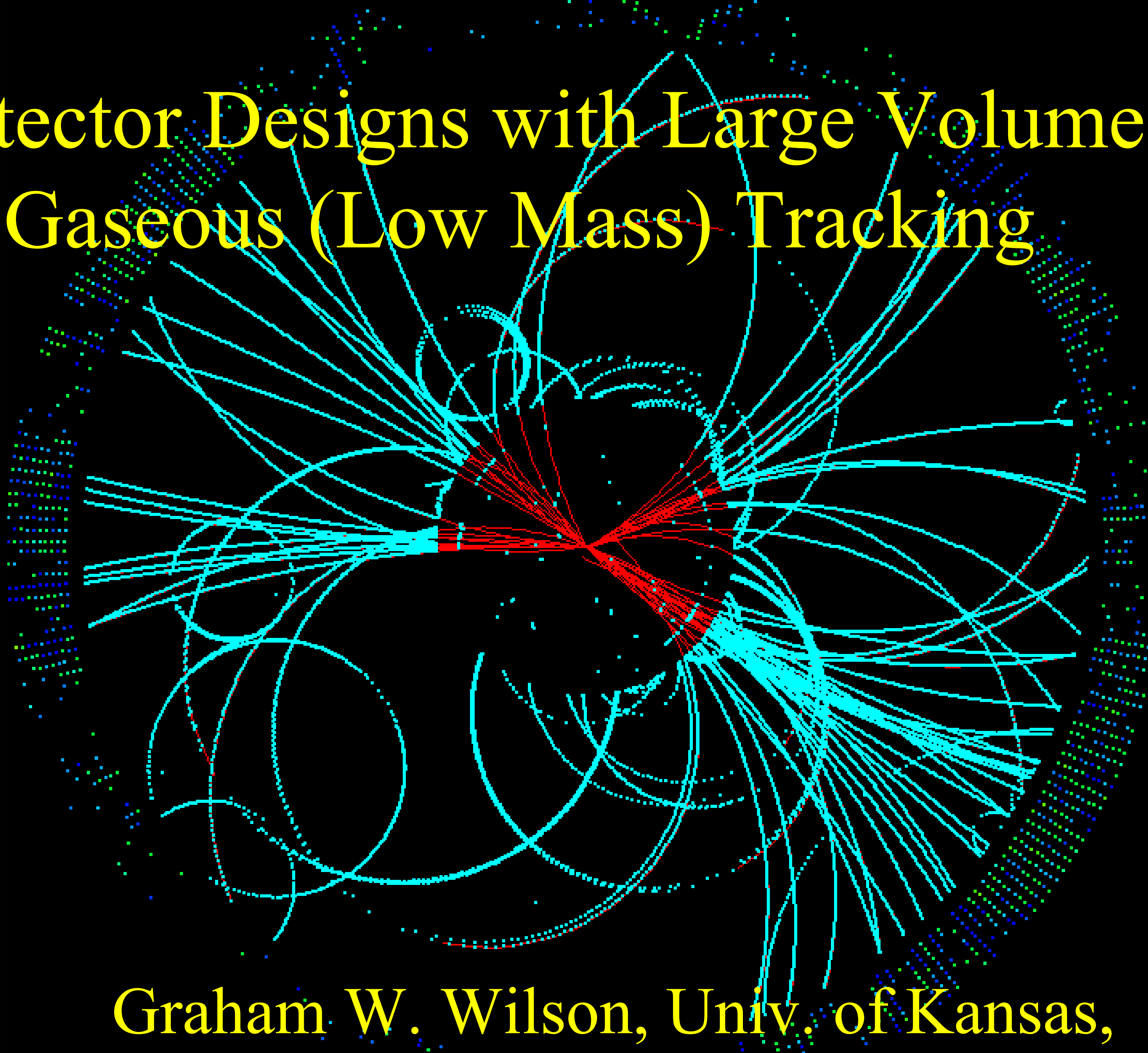
Detector Designs with Large Volume Gaseous (Low Mass) Tracking



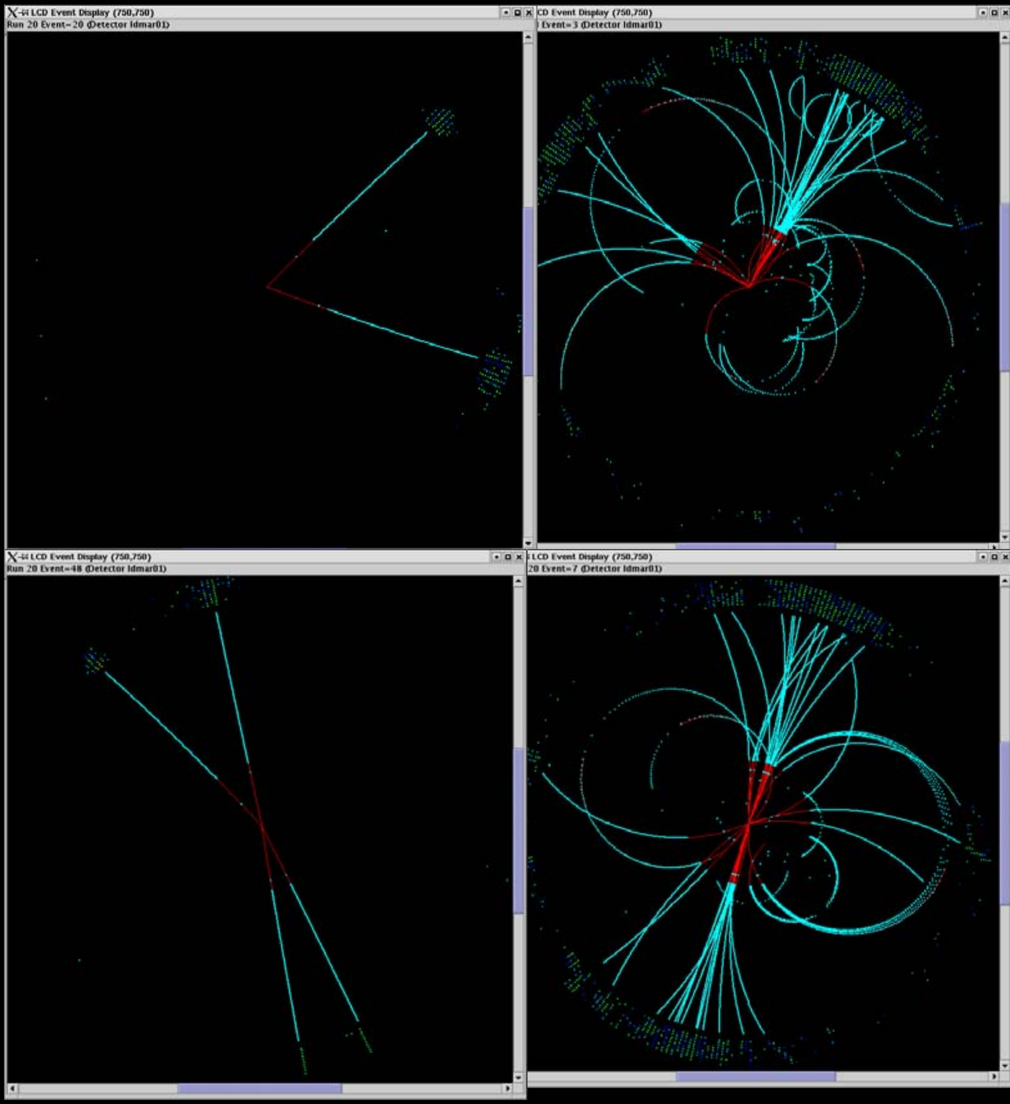
Graham W. Wilson, Univ. of Kansas,

Victoria Workshop, July 30th 2004

Plan

- Introduction
- Design overview
- Key choices
  - What E-flow performance do we want/need ?
  - Tracker
  - B-field (for vertexing)
  - Calorimetry
  - Magnet design

This talk is NOT a detailed intro to a particular detector design



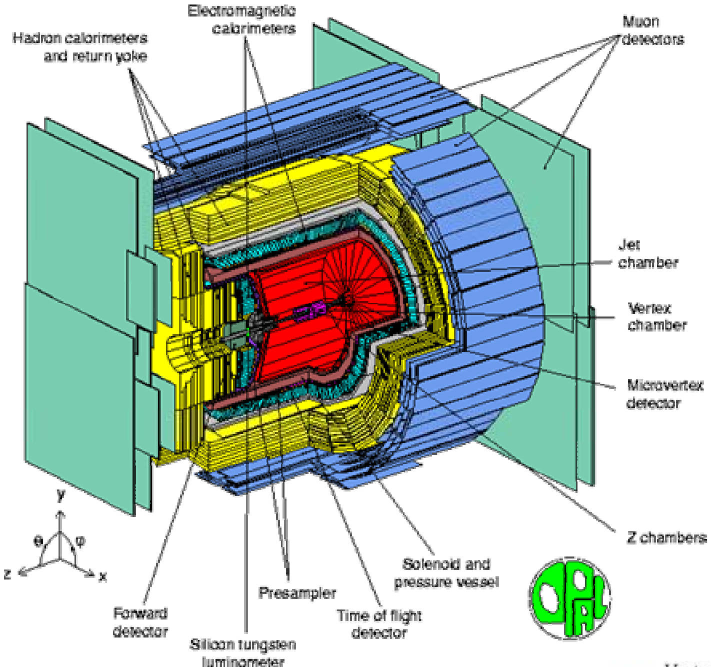
Z H events

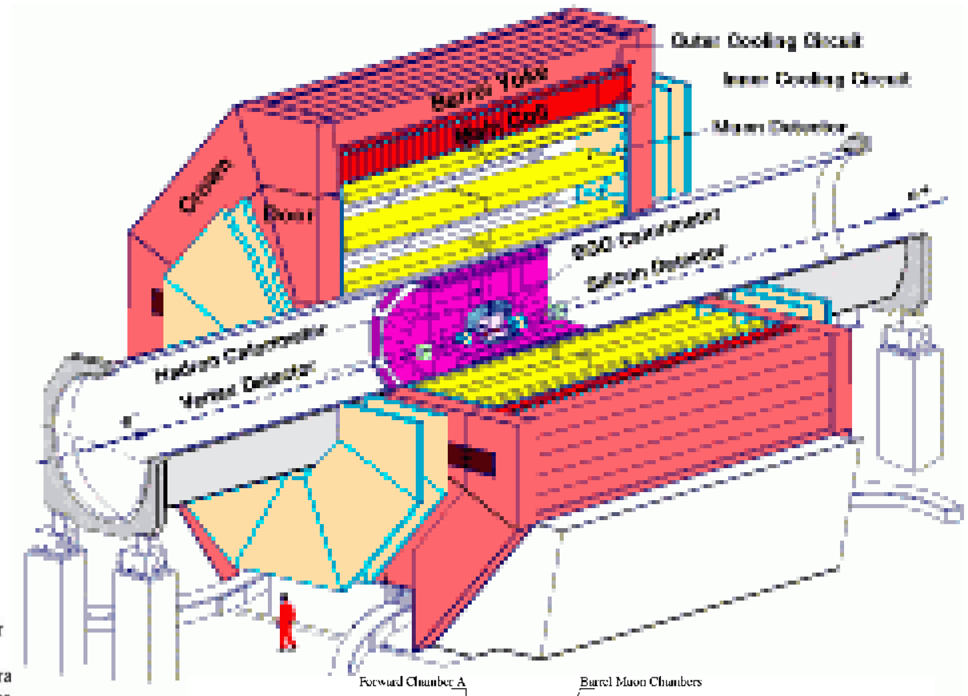
Sociology

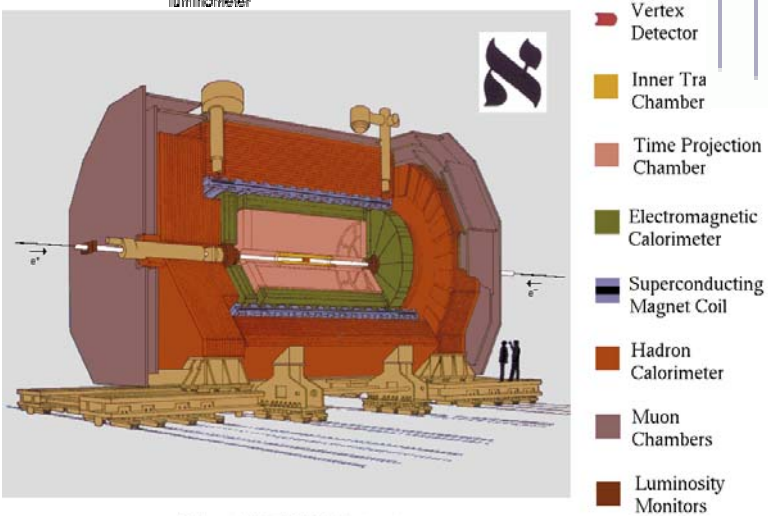
- Many of us think we know how (not) to do things from our previous experiments.
  - Can yield valuable insight. (eg. e^+e^- at $\sqrt{s}$=210 GeV, SLC)
  - Can lead to the right answer for the wrong reason (this is OK)
  - Can lead to the wrong approach because of blinkered thinking
- => Essential to bounce ideas around and not accept conventional wisdom

It is interesting to see how the PETRA detectors did or did not lead to the more successful LEP experiments !

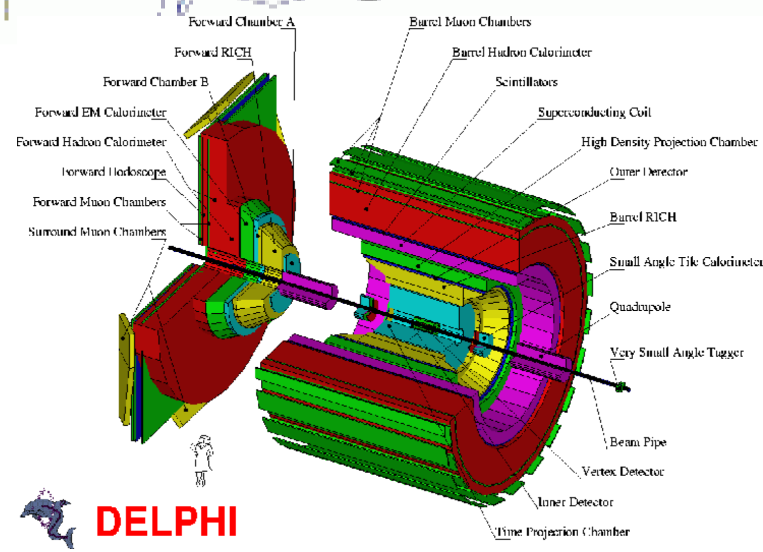
The LEP Detectors – same scale



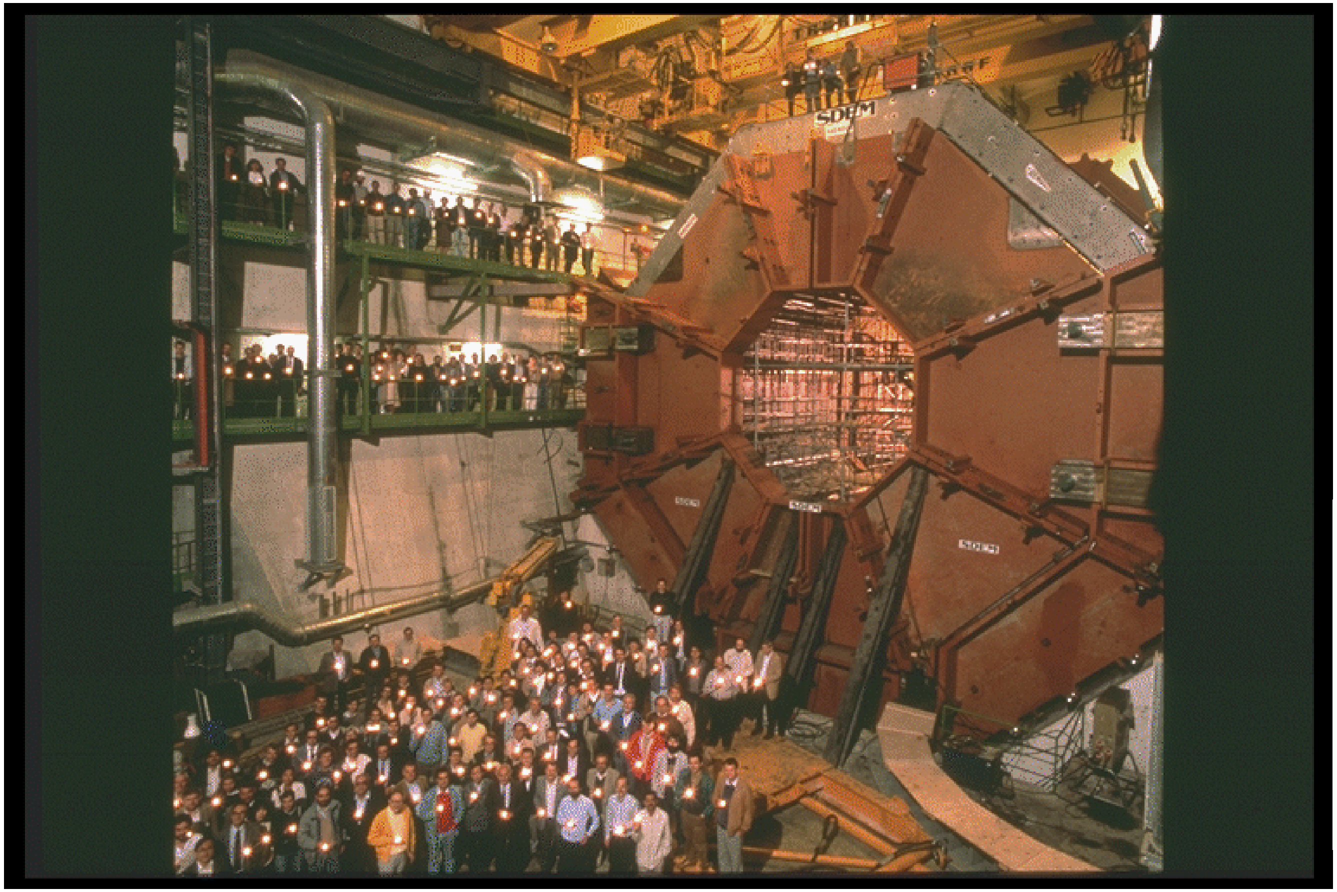


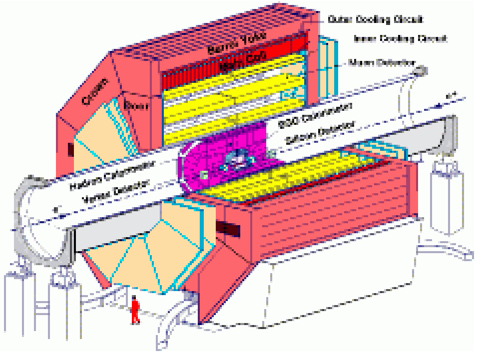


The ALEPH Detector



A really Large Detector: L3

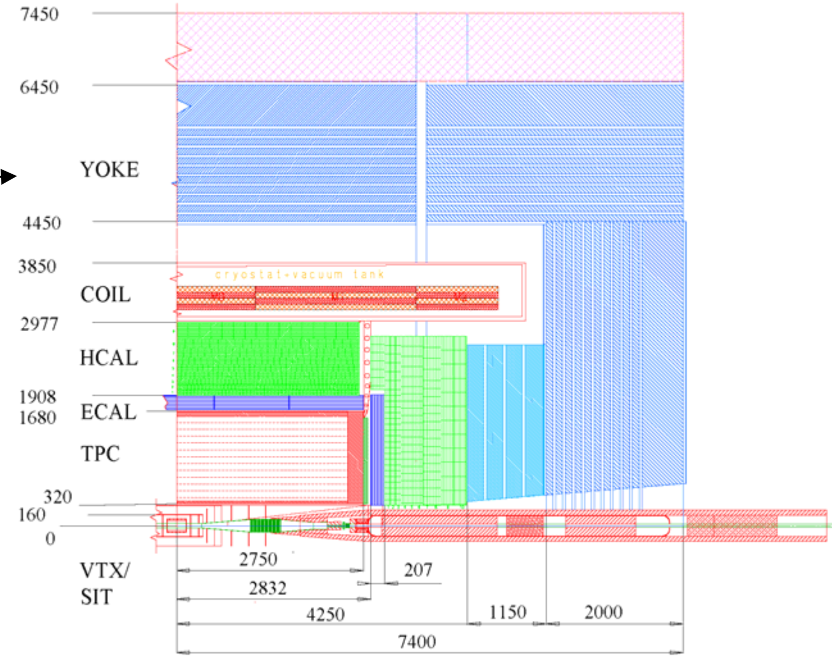




This is not the kind of large detector that is being considered !

References to previous work

- TESLA TDR
- Snowmass ResourceBook (LD)
- GLC
- TESLA CDR
- JLC



Also new initiative, discussed by S. Komamiya, similar to LDmar01, emphasizing large R calorimetry

Global effort can pool resources, take advantage of existing work, and with a cooperative spirit, advance this type of detector design towards the real world of physics opportunity

Detector design overview

- Detector design should be able to do excellent physics in a cost effective way.
  - both the physics we expect, and the new unexpected world that awaits
- Very good vertexing and momentum measurements are desirable.

$$\sigma_b = 5 \oplus 10/(p\beta\sin^{3/2}\theta)\ \mu m \qquad \sigma(1/pT) \leq 7 \times 10^{-5}\ GeV^{-1}$$

- Reasonably good electromagnetic energy measurement.

$$\sigma_E/E \approx 10\%/\sqrt{E\ (GeV)} \oplus 1\%$$

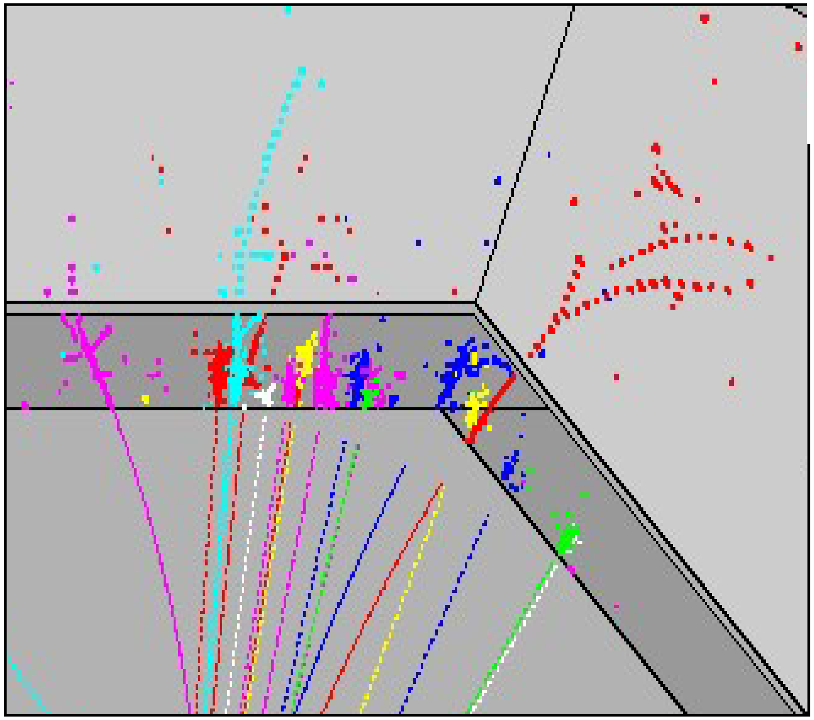
- The physics demands hermeticity and the physics reach will be significantly greater with state-of-the art energy flow
  - Close to 4π steradians.
  - Bubble chamber like track reconstruction.
  - An integrated detector design.
  - Calorimetry designed for resolving individual particles.

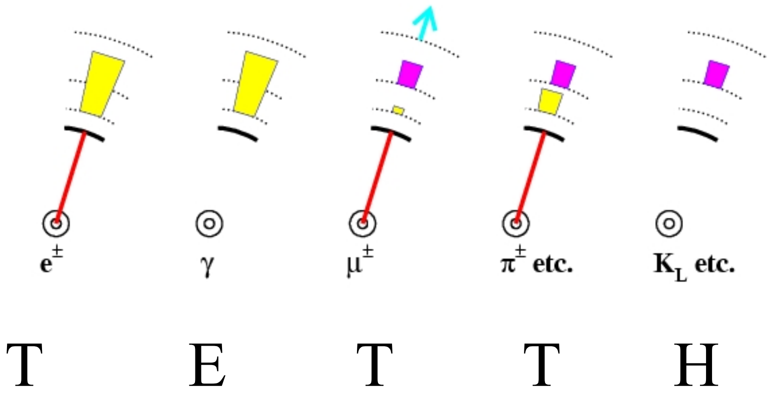
$$\sigma_{E_{jet}}/E_{jet} \approx 30\%/\sqrt{E_{jet}\ (GeV)}$$

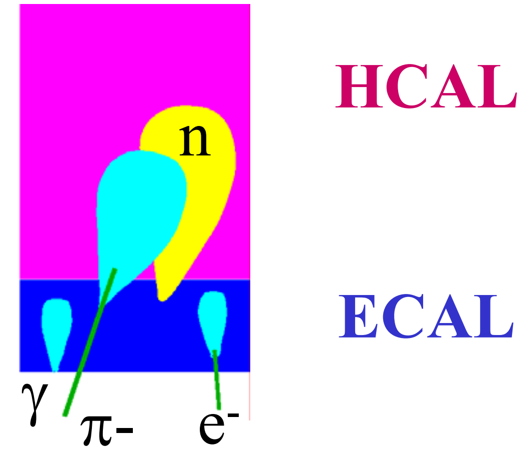
What is E-flow ?

See Henri Videau's talk at Paris LCWS for a thorough introduction

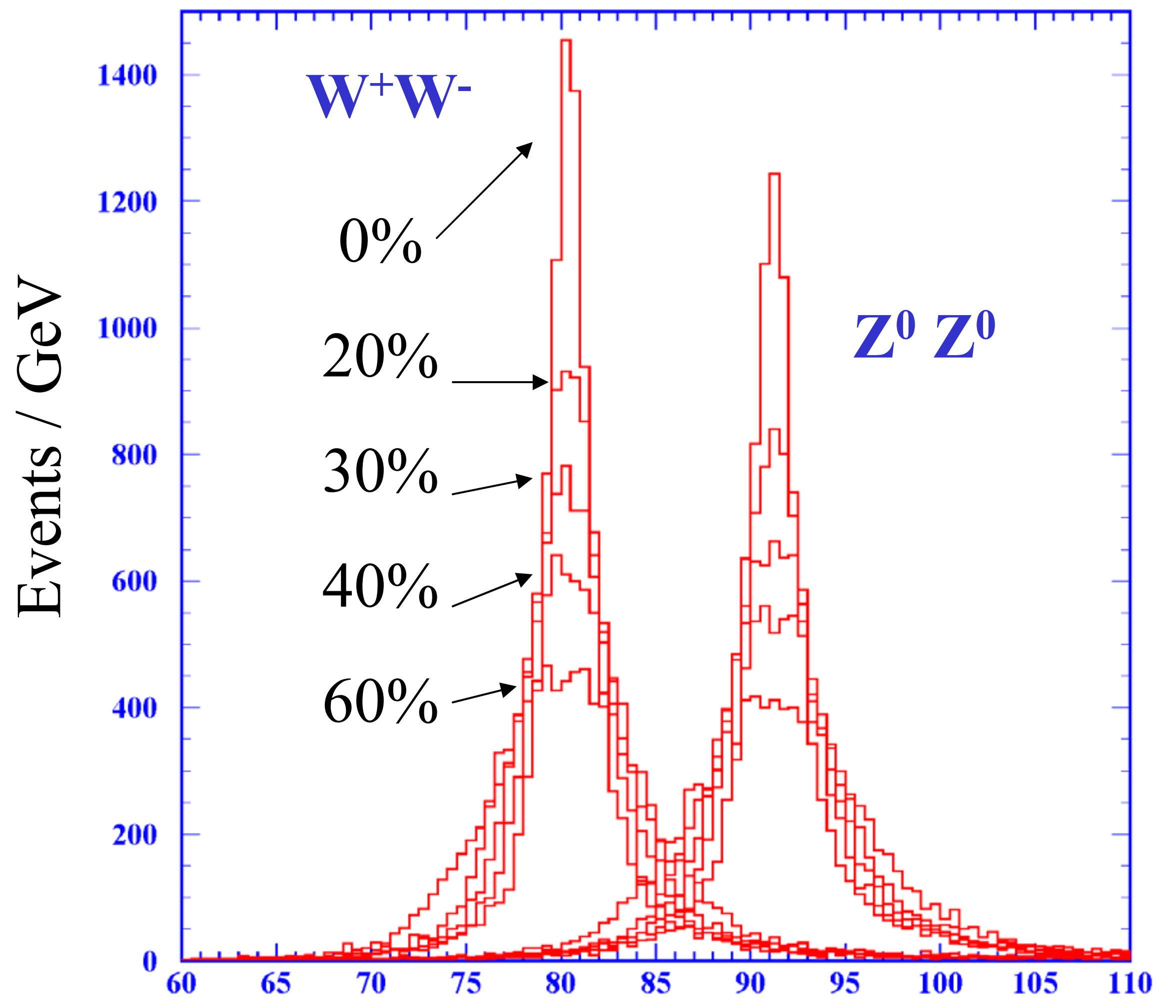
Particle-by-particle event reconstruction







Di-jet mass distribution vs E_{jet} resolution



No kinematic fits, just direct measurement

Average di-jet mass (GeV)

Comparing $e^+e^- \rightarrow WW$ and

$e^+e^- \rightarrow ZZ$ at $\sqrt{s}$=300 GeV

(hadronic decays only, assume WW:ZZ = 1:1 for illustration)

Reality = 7:1 !

$\sigma(E_{jet})$ = xx%$\sqrt{E_{jet}}$(GeV)

30%$\sqrt{E_{jet}}$ is a good target. Physics (Γ_W=2 GeV) may demand even more !

Physics benchmarks – do not oversell !

- Chosen benchmarks can become scientifically questionable.
  - Eg. We may really not care all that much about separating ννWW from ννZZ (if light Higgs found)
- If we plan to take these seriously for detector design decisions, we really should be using all of the detector's capabilities, and doing the ultimate analysis ~ **impossible !**
  - Applicable kinematic fits (see previous slide !!)
  - Non-hadronic decays of W and Z
  - b and c-tagging
  - electron vetoes
  - Including backgrounds
  - Including systematics
  - Etc, etc.
- Let's use some common sense too !

Example: TESLA TDR analysis retains large eνWZ contamination

My crystal ball predicts that at Durham :

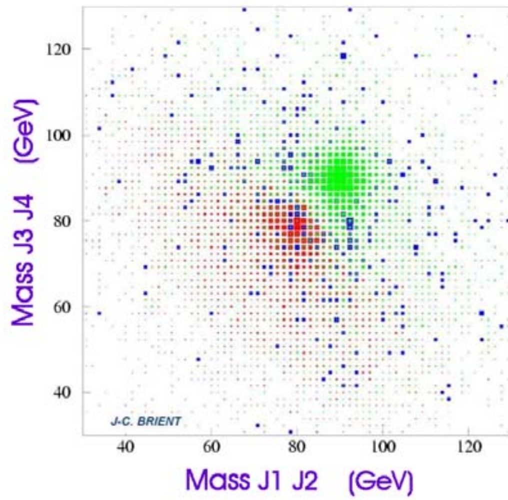
Reject if

Electron Energy >100GeV (50 at low angle)

MM^2<500 and Electron Energy >5GeV

MM^2<250 and Electron Energy >2.5GeV

Low angle coverage for electron **ESSENTIAL**



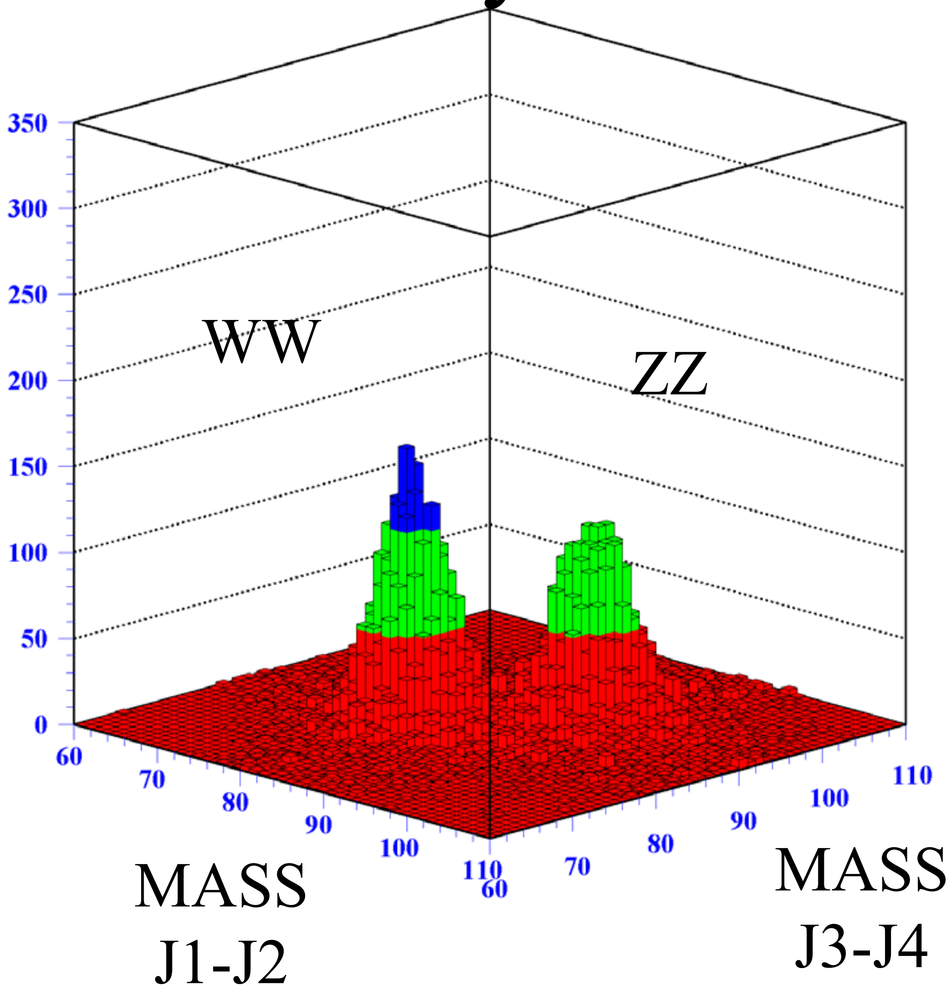
process e+ e− → $e^{\pm}\,\nu\,W^{\mp}\,Z$ (blue) almost disappear, while leaving processes (1) and (2) unchanged

What about the leptonic decays (GWW)?

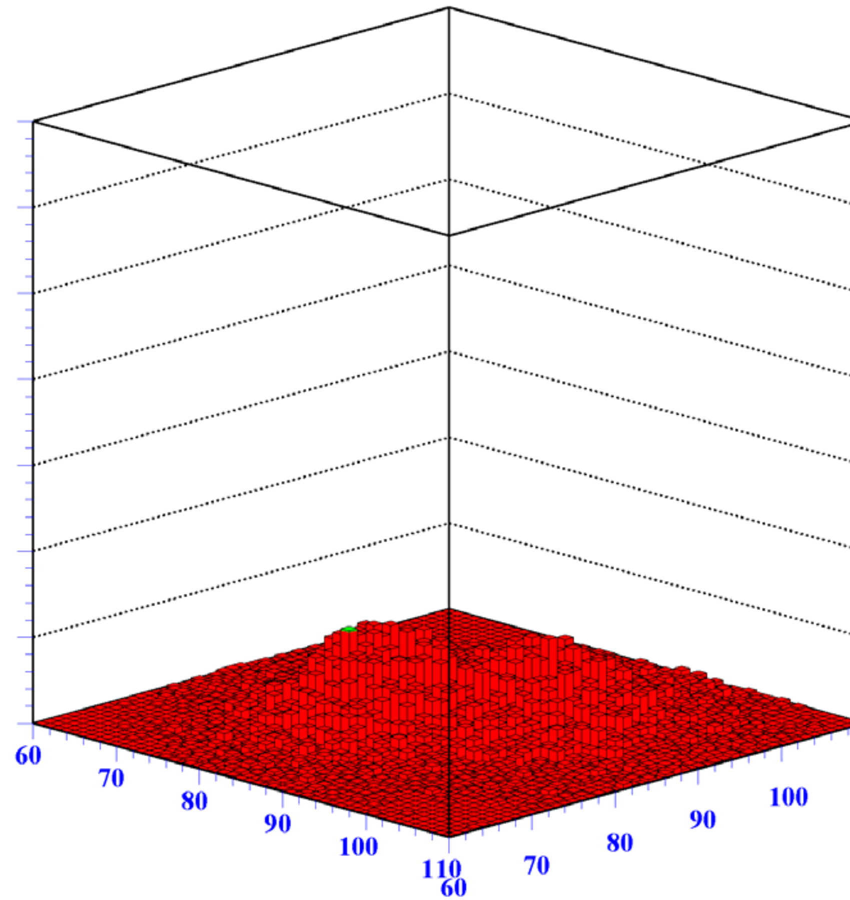
ECFA workshop Durham J.C. BRIENT 4

Jean-Claude shows it can be removed and claims the best way to do the analysis is to also use b-tagging (see extra slides)

The (in)famous plot – now as a lego plot from my $e^+e^- \rightarrow WW, ZZ$ toy study

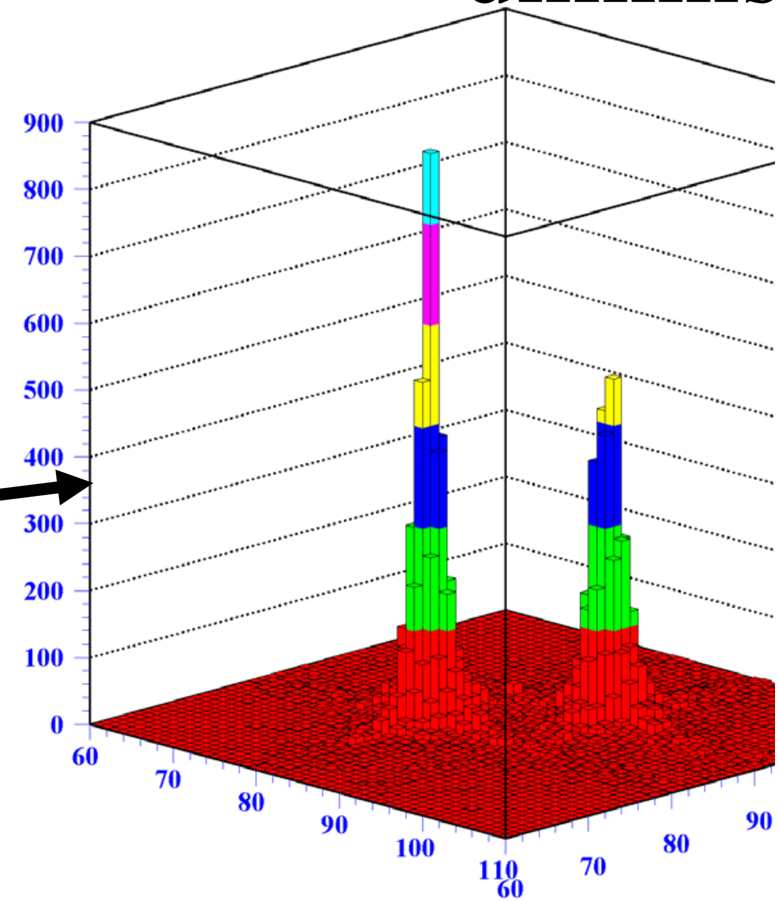


$30\%\sqrt{E_{jet}}$

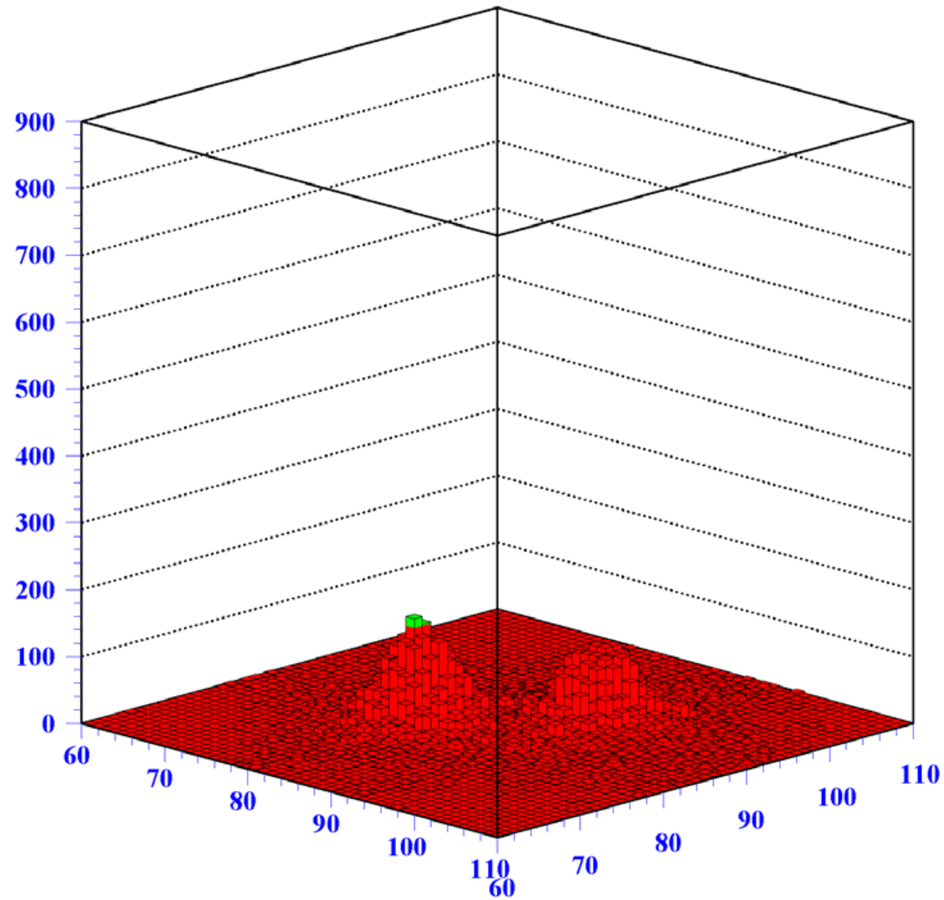


$60\%\sqrt{E_{jet}}$

But, clearly 30% is far from the point of diminishing returns !

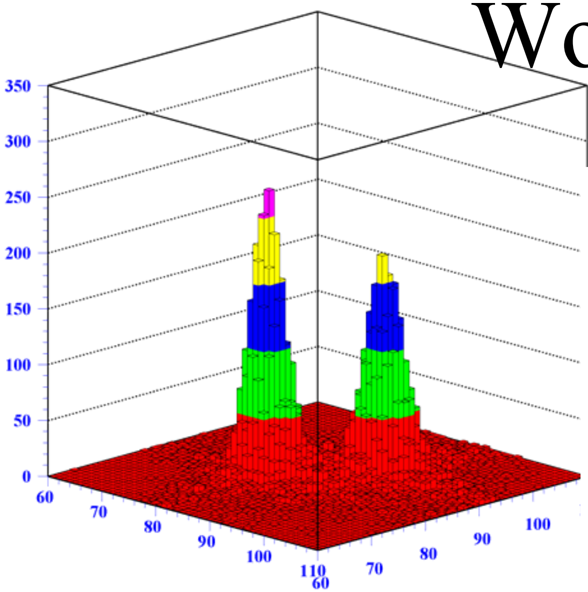


Intrinsic W, Z width only
(perfect resolution)

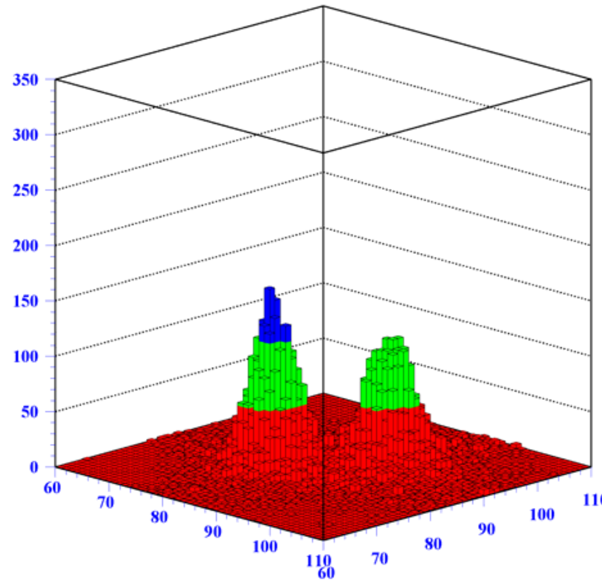


$30\%\sqrt{E_{jet}}$

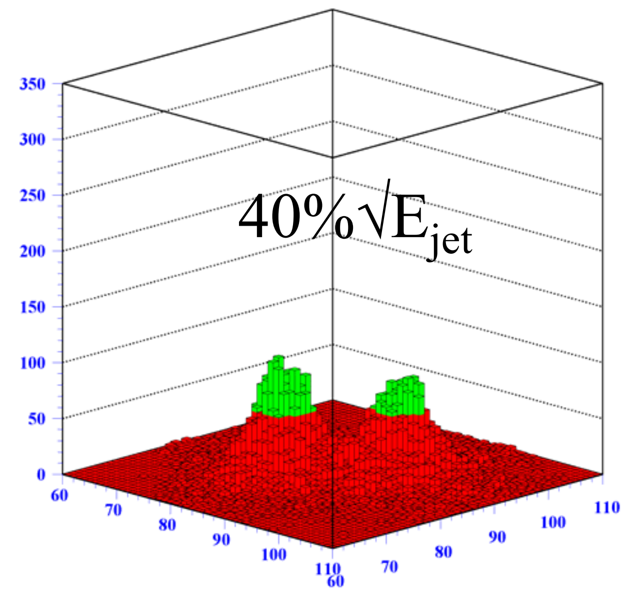
Wouldn't 20% be really something !



$20\%\sqrt{E_{jet}}$



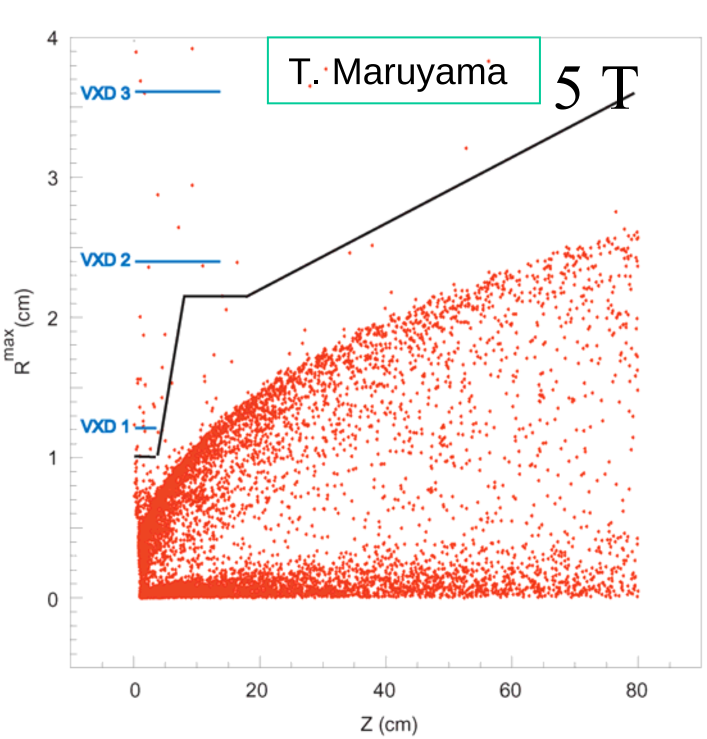
$30\%\sqrt{E_{jet}}$



$40\%\sqrt{E_{jet}}$

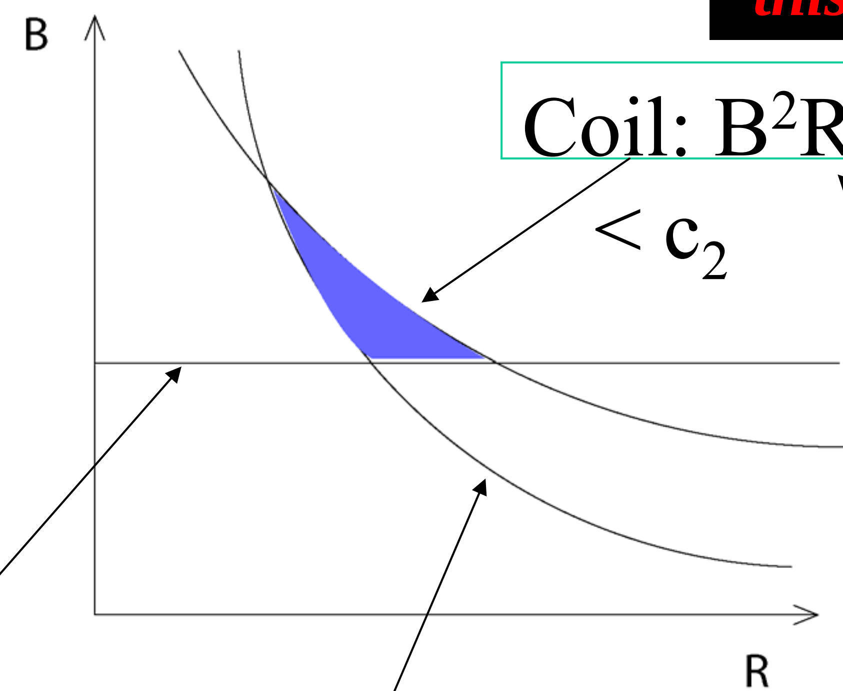
Large or small detector ?

Will return to this later



The pairs background and
the VXD inner radius
⇒ minimum B

A naïve approach



Coil: B^2R^2L

$< c_2$

(Rcoil !, GWW)

Particle flow:

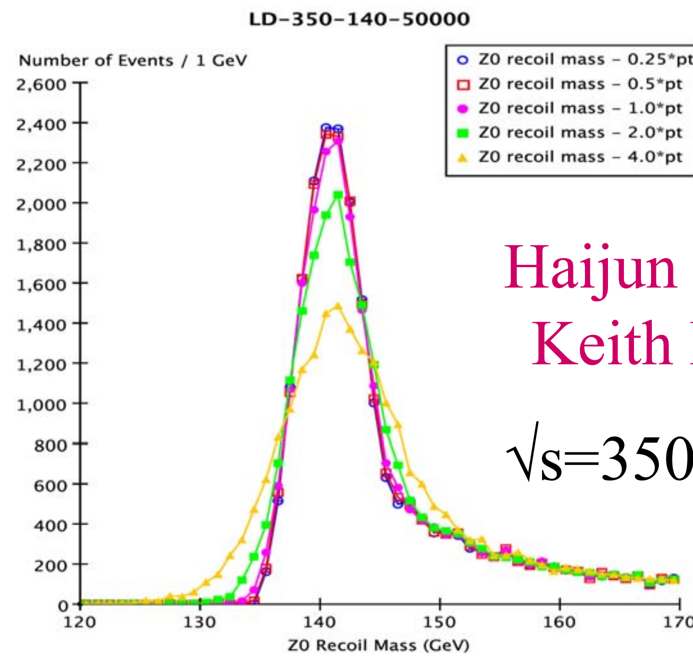
$BR^2 > c_1$ $\qquad$ R_{ECAL} !

(R. Frey, LCWS2004)

Momentum resolution constraints on tracker

- Long standing performance driver assumed to be recoil mass to dimuon in Z H.
- LDMar01 detector has $\Delta(1/p_T) = 3 \times 10^{-5}$
- Plots include beam constraint
- Definitely good enough for Warm. Should be reverified *again* if the decision is Cold (less beamstrahlung)
- LD assumes point resolution of 120 μm in TPC. R&D suggests 50-70 μm achievable.
- **TPC Tracker does not need to be "truly huge" to meet the momentum resolution specs.**

Higgs Mass Distributions



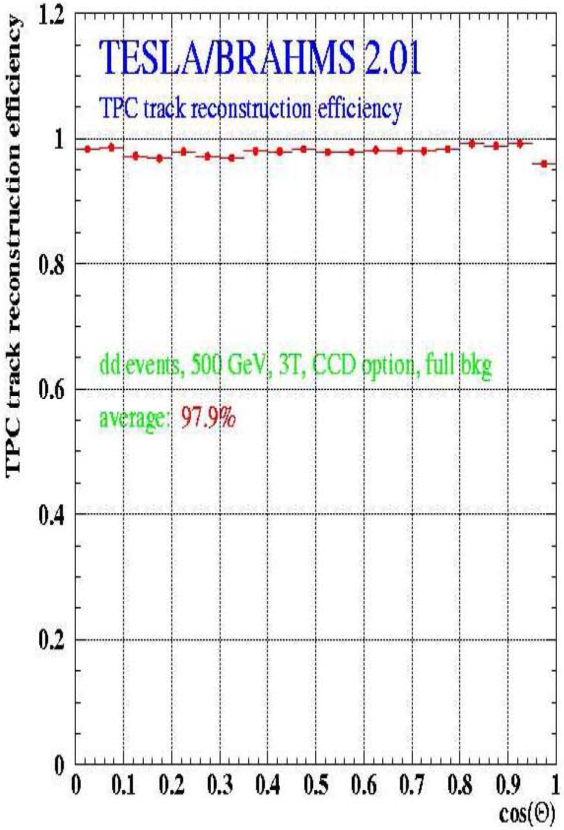
Haijun Yang, Keith Riles

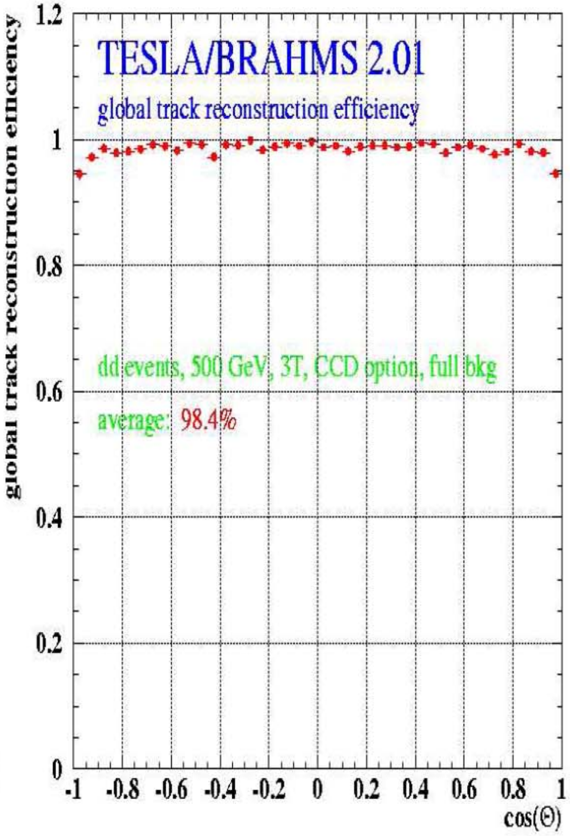
$\sqrt{s}$=350 GeV

- FAST MC: $ZH \to \mu^+\mu^- X(\gamma)$, $M_H = 140$ GeV, LDMAR01
- Higgs mass distributions. Track momentum resolutions $\Delta(\frac{1}{P_t})$ are re-scaled by factor fac(0.25, 0.5, 1.0, 2.0, 4.0).

Tracking Performance

- preliminary results for tracking performance:
  - look at dd events





Using real expt. (ALEPH+DELPHI+OPAL) reconstruction software

Fake rate:	0.4%
CCD only:	97.4% / 10%
APS only:	92.4% / 0.7%
split tracks	3%

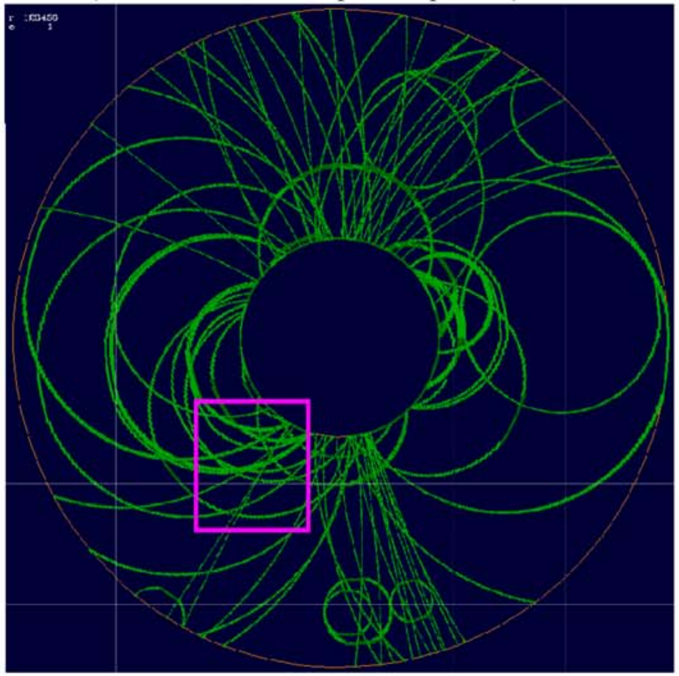
Will do even better

Simulation includes full background, including backsplashes from the outer detectors

- excellent reconstruction efficiencies even in complicated environment

Remaining track overlap when taking advantage of Z separation

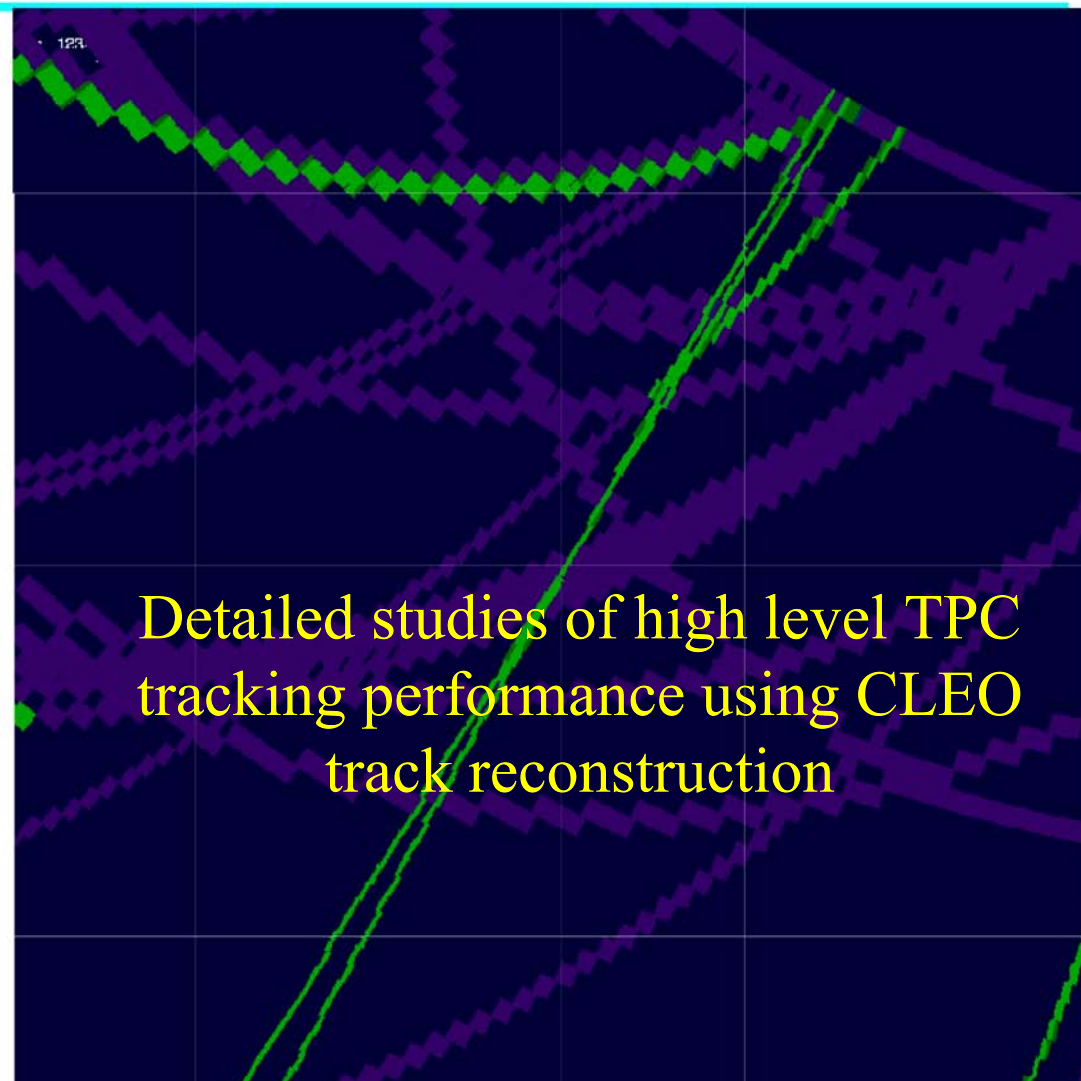
(Same event, same pad response)



The z separation is often
too small to provide track separation.

crossing tracks in r-f, and
z-separation = **1 mm** .

But, track reconstruction can be efficient for very close tracks by using information from regions where the tracks are isolated. This is an advantage of the pat. rec. used in this study.



Active cone: Z=[r * (-6 / 40)] +/- 4.7 cm

Tracker technology choice

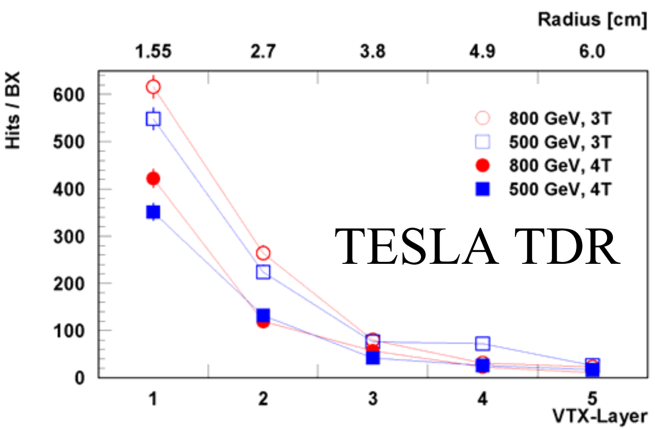
- For, $BR_{tracker}^2 > 7.5$ T m^2 , proponents are confident that a TPC can deliver the momentum performance (in combination with VTX)
  - True 3-D imaging tracker with > 10^9 volume pixels
  - Pattern recognition very robust wrt occupancy
  - Provides modest dE/dx (4-5%) for "free". Will make low p electron-ID superb. (but e-ID probably already superb)
  - Robust V^0-finding
  - Can increase safety margin re backgrounds with gas choices, R_{in} (see M. Ronan talk)
  - Long-standing strong international R&D program
- While a solid-state detector could also deliver the high-p_T momentum performance, such a device is challenged by
  - track reconstruction robustness
  - material budget
  - z-segmentation

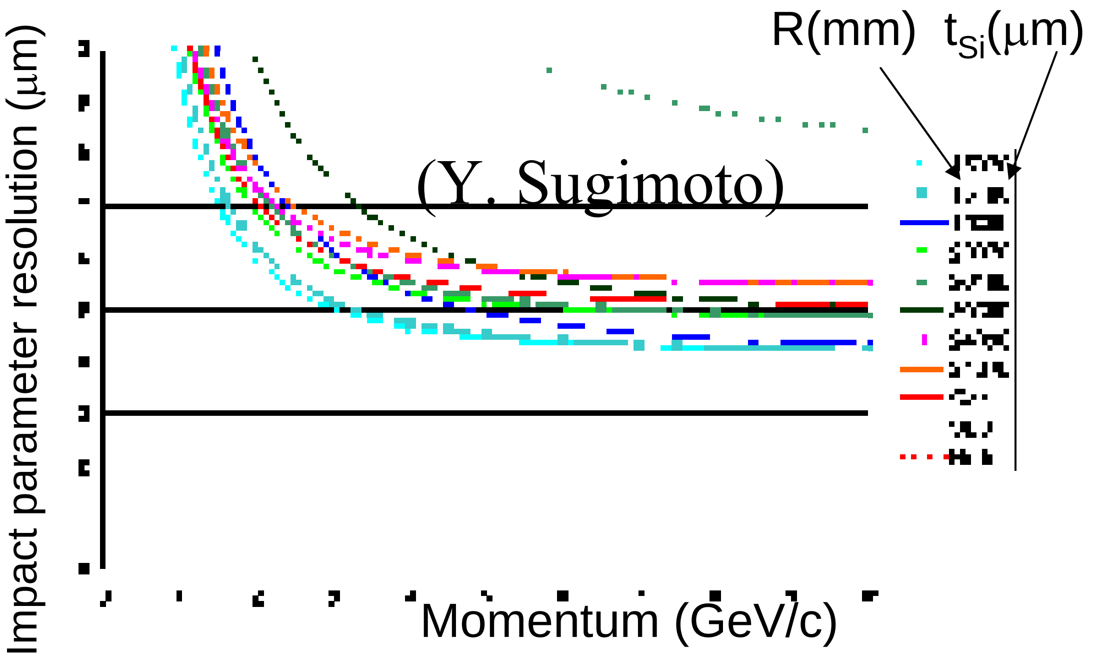
Vertexing constraints ?

need something like: $\sigma_b = 5 \oplus 10/(p\beta \sin^{3/2}\theta)$ μm

Driven by R_{out}/R_{in} (magnification factor)

Driven by R_{in}, material





May need to compromise a little if B-field is lowered, but is superb charm-tagging really so paramount ?

How to do E-flow well ?

- 1) Reconstruct charged tracks robustly, with high efficiency and reasonable p resolution.
  - Performance = f (B $R_{tracker}^2$, N_{hits}, σ_{point}, PATREC)
- 2) Measure photons in ECAL. Avoid double counting of charged tracks in ECAL. Mainly charged-hadron/photon separation.
  - Performance = f (B R_{ECAL}^2, ECAL properties, algorithms)
  - For the same R_M and X_0, the higher **B R_{ECAL}^2** wins.
  - Tungsten and a compact readout is the key to keeping R_M low
- 3) Measure neutral hadron energy in ECAL and HCAL avoiding contamination from charged particles, photons.
  - Performance = f (above factors, granularity, etc)

Intrinsic resolution / $\sigma_{\text{confusion}}$

- $\sigma^2_{\text{jet}} = \sigma^2_{\text{intrinsic}} + \sigma^2_{\text{confusion}}$
- Generic intrinsic resolution assumptions lead to jet energy resolutions ≈18%$\sqrt{E_{\text{jet}}}$ (see backup slides)
- So, if ≈ 30%$\sqrt{E_{\text{jet}}}$ is the goal, then $\sigma_{\text{confusion}}$ needs to be ≤ 24%$\sqrt{E_{\text{jet}}}$.

⇒ Detector concept should focus on resolvability of particles within jets.

⇒ Large R_{ECAL},

⇒ Large R_{HCAL}

What are the components of $\sigma_{\text{confusion}}$?

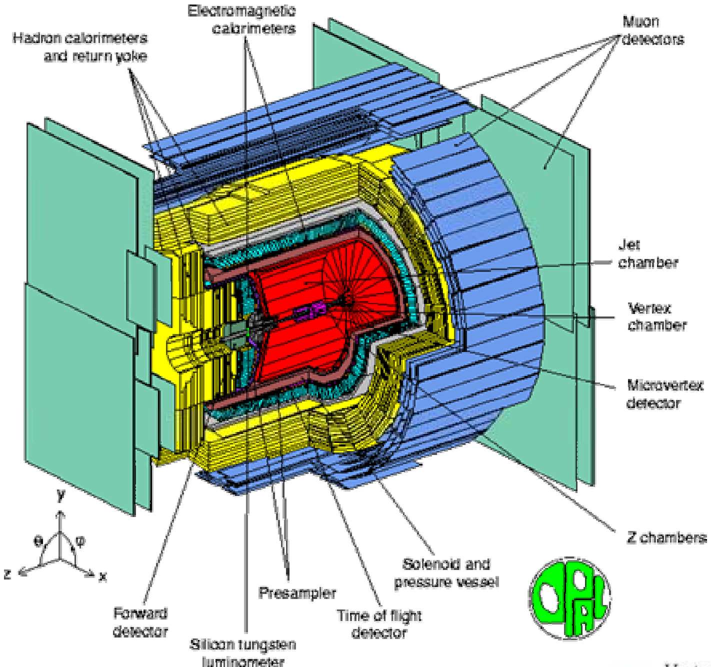
What's most important ?

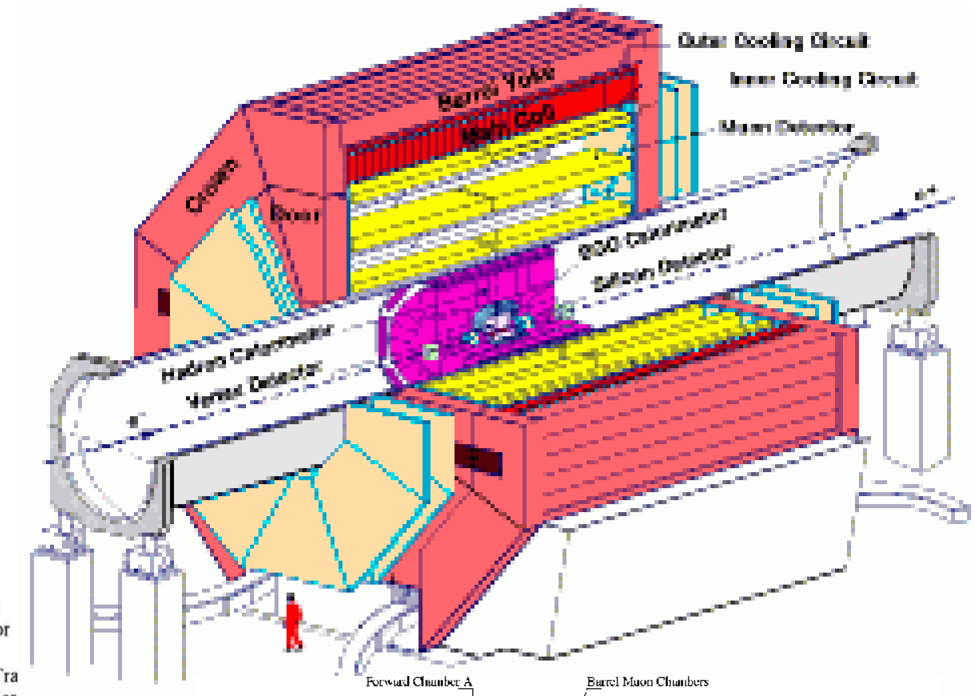
Design studies must answer this systematically. Here's my take.

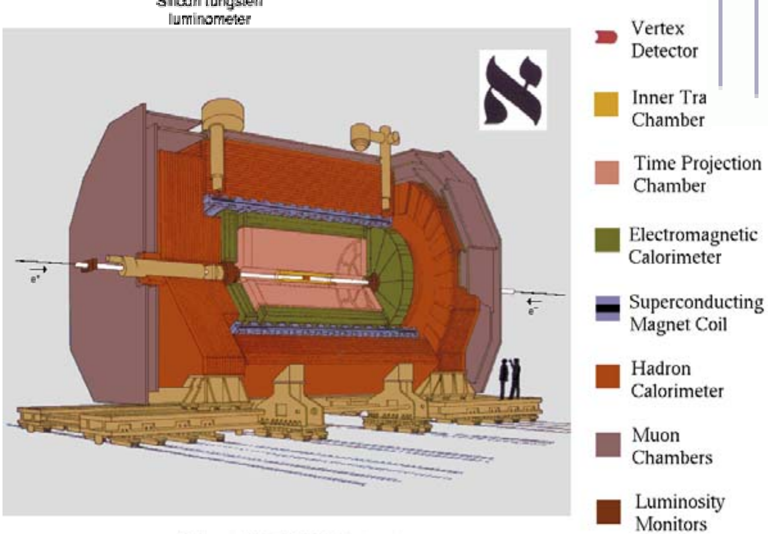
- 1) Reconstruct charged tracks robustly, with high efficiency and correct track parameters (in z too!).
  - Obviously a pre-requisite
- 2) Measure photons in ECAL. Avoid double counting of charged tracks in ECAL. Mainly charged-hadron/photon separation.
  - **Seems to be the heart of the problem**
- 3) Measure neutral hadron energy in ECAL and HCAL avoiding contamination from charged particles, photons.
  - At some level, doing 1 and 2 well, will take care of 3 ??

The calorimetry is key !

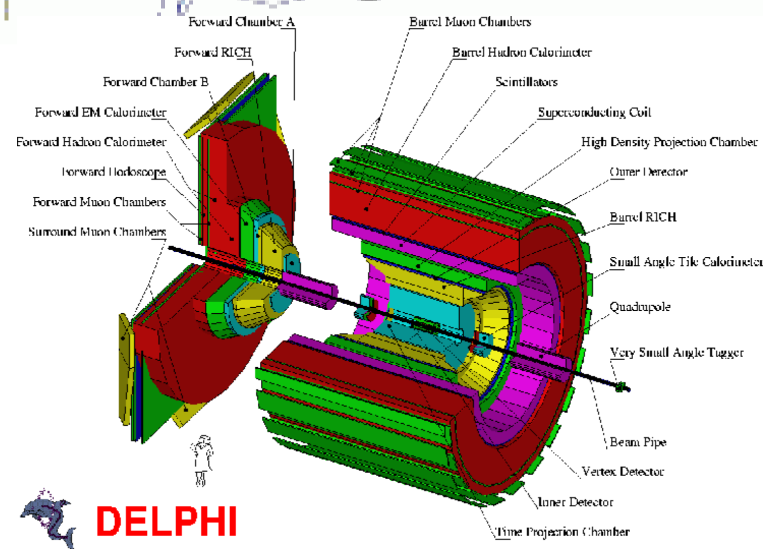
The LEP Detectors – same scale





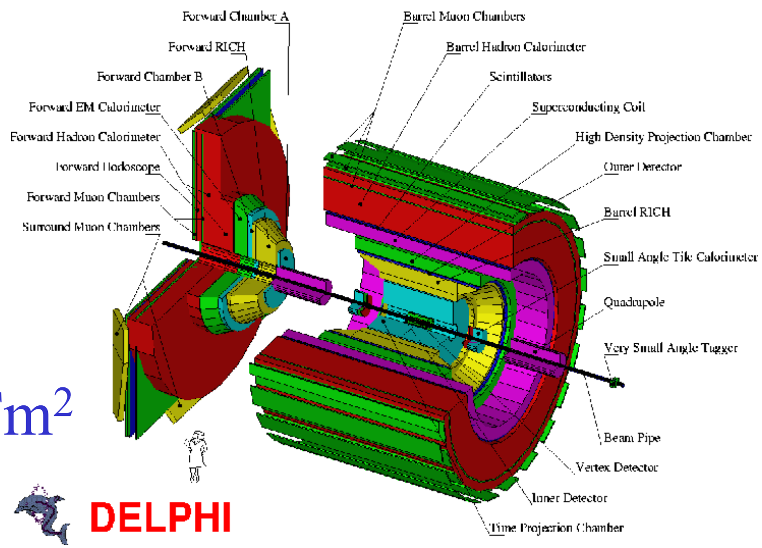


The ALEPH Detector

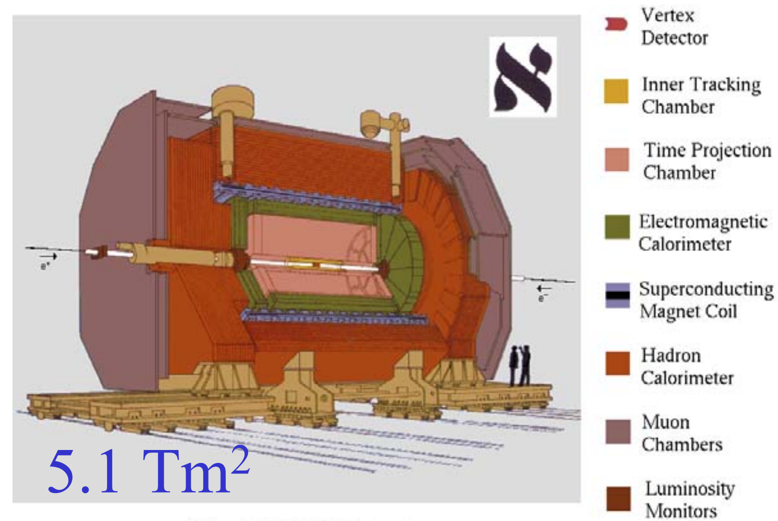


The LEP Detectors – BR_{ECAL}^2 scaling

(in visual area)

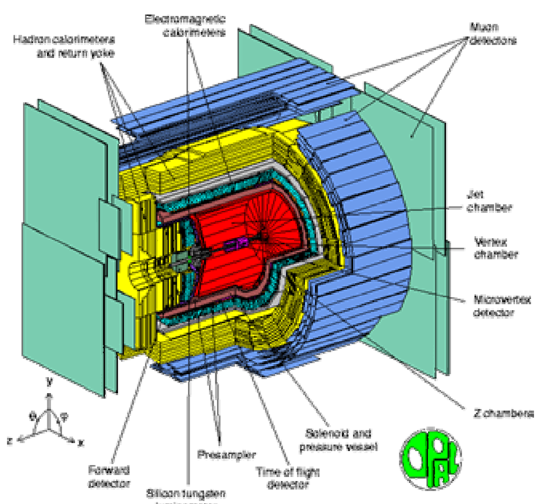


5.2 Tm^2

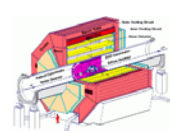


5.1 Tm^2

The ALEPH Detector



2.6 Tm^2 (B=0.435T)



L3: 0.14 Tm^2

The LC detector should be aiming for $BR_{ECAL}^2 > 10\ Tm^2$

NB. CMS has only 8 Tm^2

Starting points

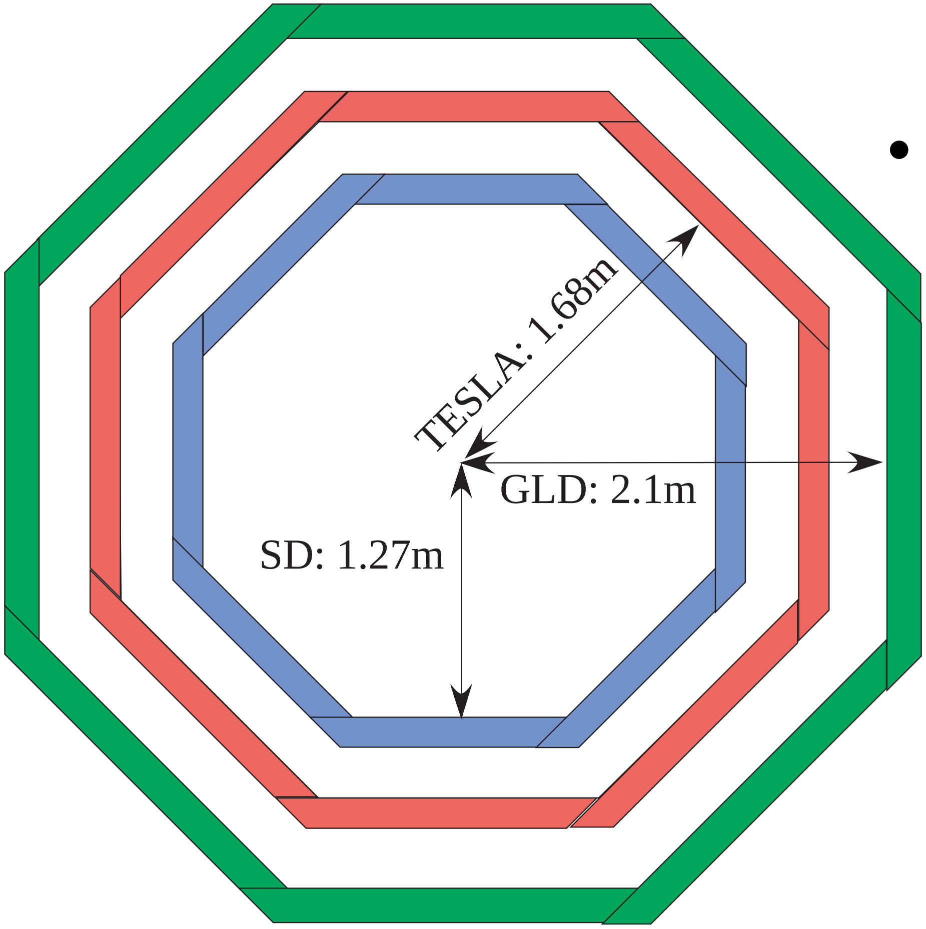
- JLC report 1992. Scale up OPAL?
- TESLA CDR circa 1996. Led by Ron Settles : scale up ALEPH. B=3T.
  - TDR. Iterated to 4T (because CMS think it's possible)
- North American "Large Detector". Build a detector with a TPC tracker (Mike Ronan).
- This talk starts from the perception/prejudice that indeed "the calorimetry is key".

Why is the calorimetry key ?

- Calorimetry technology choices dictate R_{ECAL}
- EM calorimeters will be expensive
- Costs of particular EM calorimeters with the same compactness (R_M and X_0) scale with R_{ECAL}^2
- The arguably best solution, "Si-W partout", inevitably has a high cost per unit volume. The TESLA TDR Si-W ECAL may cost as much as 250 M$ (R_{ECAL}= 1.68 m, B R_{ECAL}^2=11.3 Tm^2).
- Alternative solutions eg. W-Scintillator or Si-W-Scintillator hybrid may give competitive performance more cost effectively. (the key is the W and the compactness)

From S. Komamiya

EM Calorimeters



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

GWW : $BR_{ECAL}{}^2 = 8, 11.3, 12.0, 13.2\ Tm^2$

Some opening gambits & possible consequences

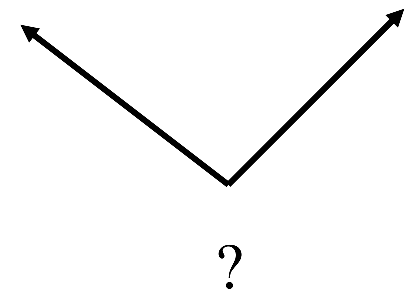
- "Physics can make do with $BR_{ECAL}{}^2 < 10\ Tm^2$, Si-W is cost effective"
- "Let's do Si-W"
- How can you build it for just xxx/2 M$?
  - Reduce R_{ECAL}
  - And/or, worsen σ_E/E (less layers)
  - Not enough Rtracker for gaseous tracker.
  - Silicon tracker
    - Add material.
    - Lose PATREC robustness
    - Lose dE/dx
  - Answer: "If proposal A gets xxx/2 M$, we really need zzz M$ to be competitive in energy flow with proposal A"

- "Physics needs $BR_{ECAL}{}^2 > 10\ Tm^2$ and Si-W is probably not the most cost effective solution"
- "can't afford nominal Si-W"
  - Develop ECAL design with lower cost per unit volume and competitive R_M, X_0
  - Increase R_{ECAL}, investigate HCAL outside coil
  - Lots of space for a gaseous tracker
- How can you build it for just xxx/2 M$?
  - Answer: "We really need yyy M$ to meet our revised upward physics specs. With xxx/2 M$, we would reduce R_{ECAL} a little and still do much better than proposal B"

Take with a grain of salt

My hermeticity pecking order

In most physics analyses with missing energy the first priority is identifying that there is genuine missing transverse momentum, how well you measure Σp_T is another issue.



- Electrons
- Photons
- Multi-particle Jet
- Isolated charged particles
- Muons
- Occupancy – eg. Background, cosmics etc ?
- Taus
- Last and by far least important: K^0_L, neutron

Cost Estimates

- Published cost estimates for TESLA, SD and LD are in TESLA TDR, Snowmass
- Given the uncertainties, extensive discussion is inappropriate.
  - Major cost for SD, LD : magnet.
  - Major cost for TESLA : Si-W ECAL.

Magnet prices are scary !

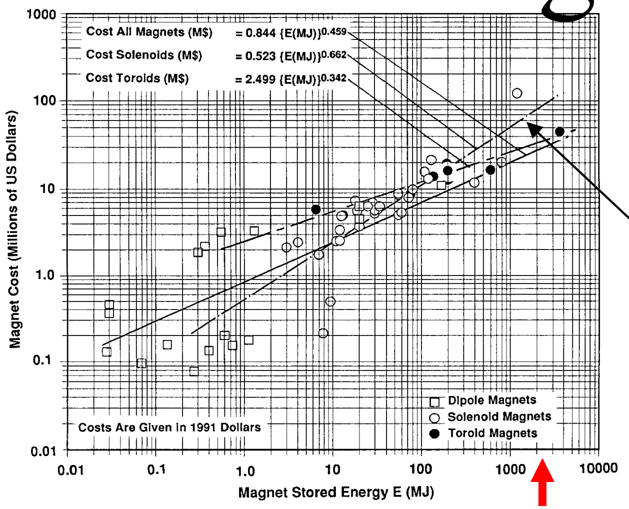


Figure 1. Superconducting Magnet Costs Versus Magnet Stored Energy.

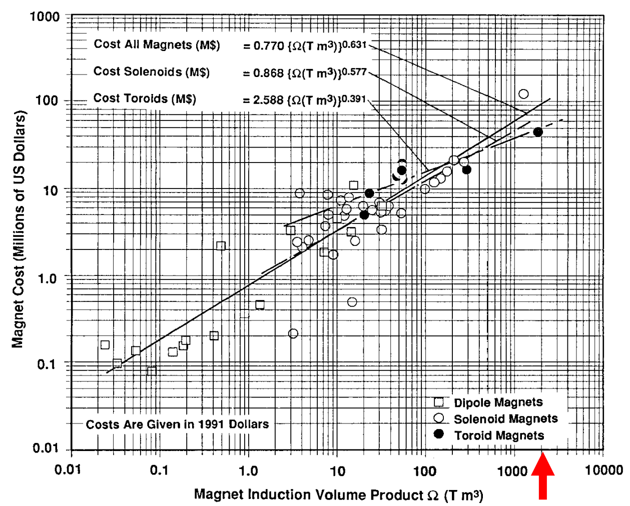


Figure 2. Superconducting Magnet Cost Versus Field-Magnetic Volume Product.

Green, Byrns, St. Lorant, 1992

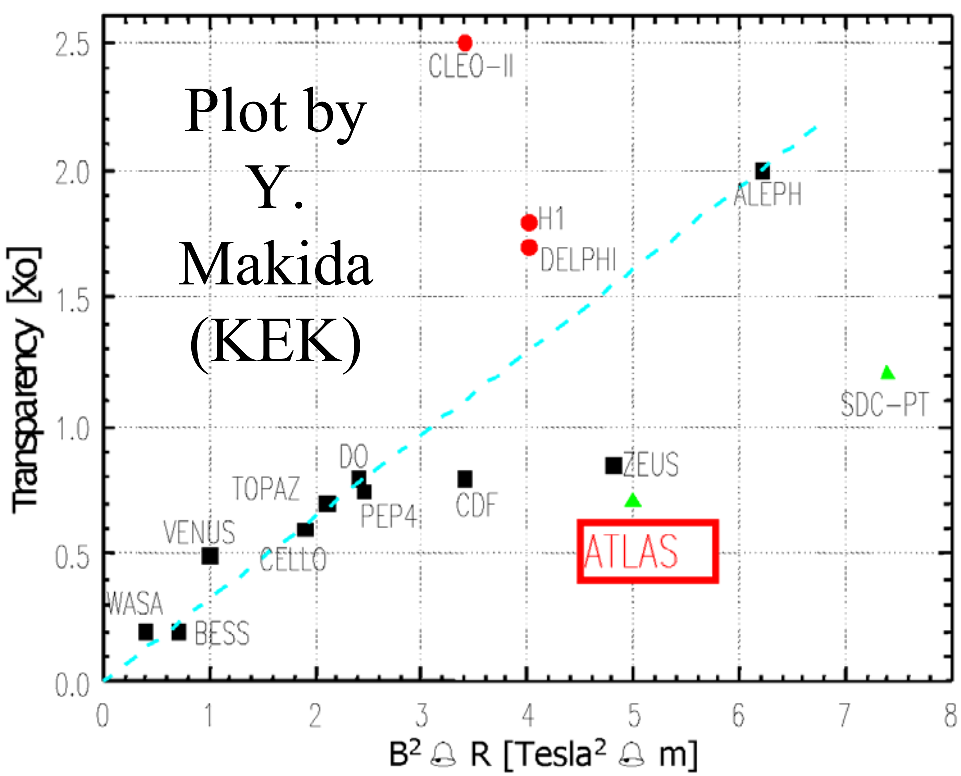
- Seems hard to envisage something much more aggressive than CMS in stored energy (**2.5 GJ**).
- PDG quotes, cost ~ $U^{0.66}$ but based on old, scarce unreferenced data (in 1991$)
- Suggests we should be careful about assuming less than linear scaling of cost vs stored energy cf CMS

R&D on magnet design ??

- The choices regarding the solenoid geometry and engineering design have a major impact on the detector design and cost.
- HCAL outside solenoid option → emphasize "transparency" in X_0, λ ($\sim B^2 R$ for X_0)
  - Could a detector internal to the cryostat be remotely feasible with a multi-conductor approach ? (liquid He ! – not liquid N_2.)
- Shouldn't there be more effort in the direction of magnet R&D ?

HCAL outside coil ?

Transparency of the ATLAS solenoid and other solenoid

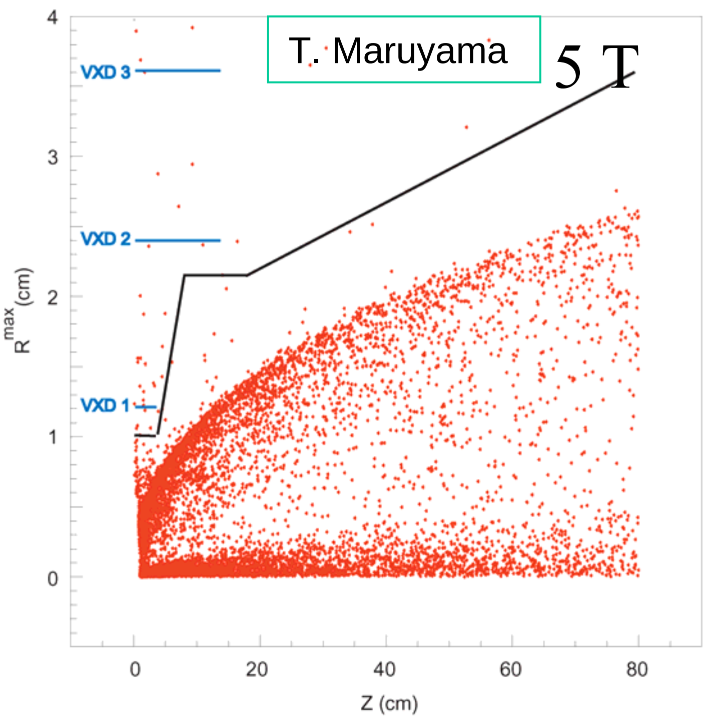


For B=3 T, R_{ECAL}=2.0 m, maybe 6 X_0 is feasible

How does E-flow performance change as HCAL is placed outside a “thin” solenoid ?

N.B. R_{HCAL} increases too !

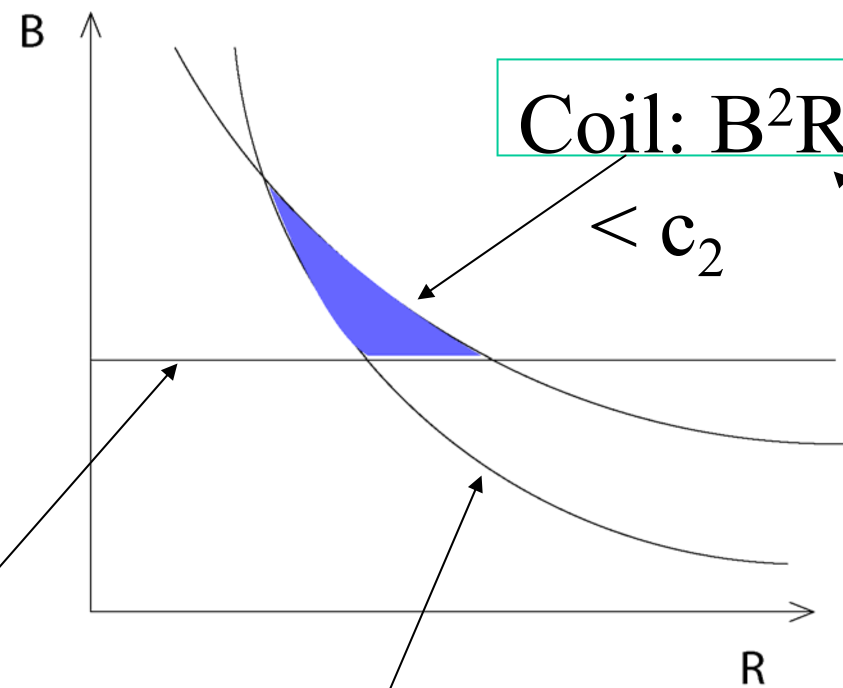
Large or small detector ?



The pairs background and the VXD inner radius

$\Rightarrow$ minimum B

A naïve approach



Coil: B^2R^2L

$< c_2$

(R_{coil} !, GWW)

Particle flow:

$BR^2 > c_1$

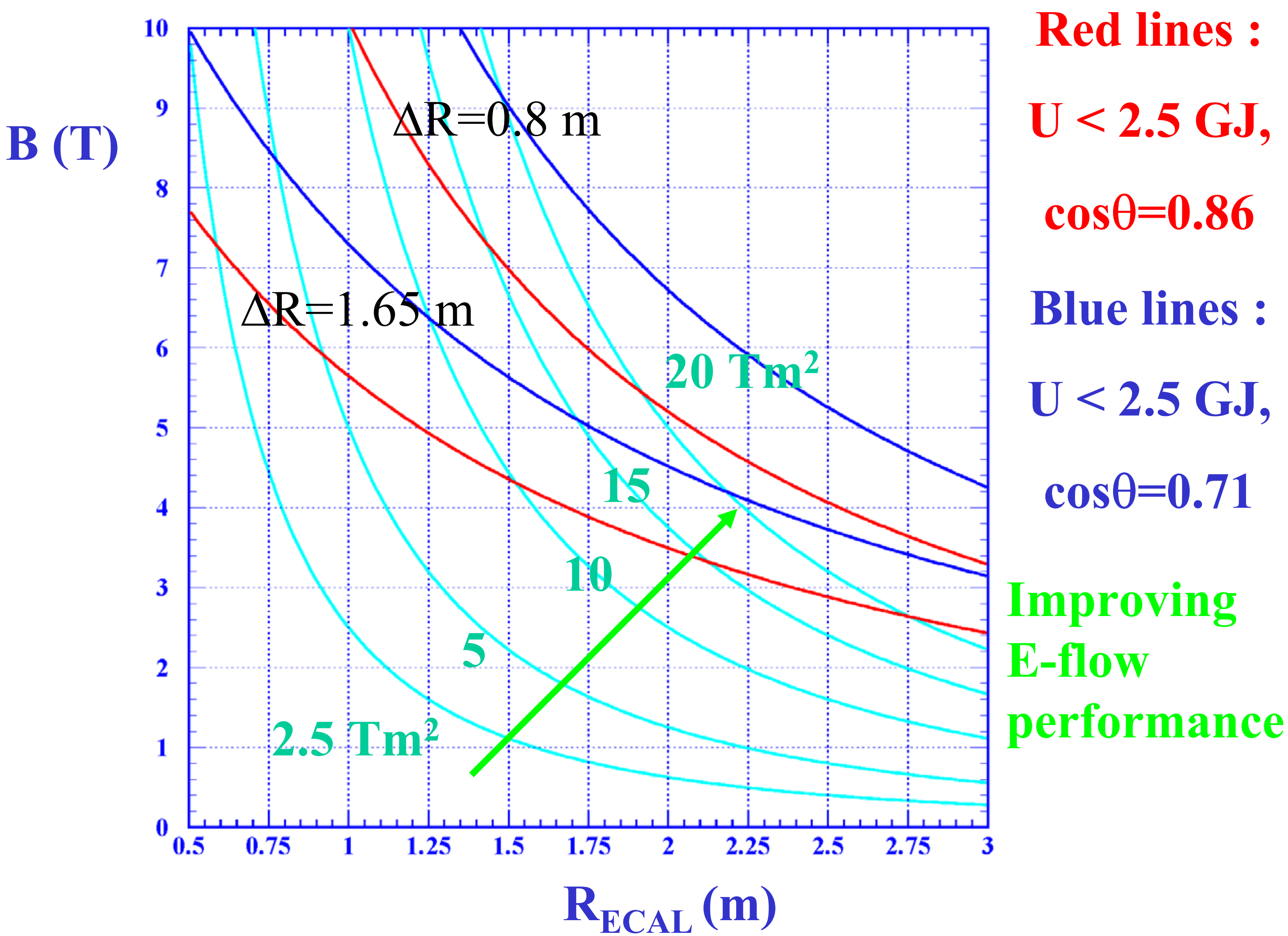
R_{ECAL} !

(R. Frey, LCWS2004)

Basic assumptions/dependencies

- Stored energy in coil: $U \approx 0.5(\pi/\mu_0)B^2R_{coil}^2L_{coil}$
- Assume 2.5 GJ (CMS) is a practical technical and fiscal upper limit.
- Energy flow performance depends on BR_{ECAL}^2 (R_{ECAL} = inner radius of ECAL)
- Detector aspect ratio. (relates R_{coil} to L_{coil}).
  - Take $\cos\theta = 0.86$ by default. Study 0.80, 0.71 too.
  - (needs to be revised, I used the ECAL aspect ratio, not the coil in slides)
- $R_{coil} = R_{ECAL} + \Delta R$, where ΔR accounts for space for calorimetry internal to the mean coil radius and coil cryostat, inner windings etc.
- Two choices.
  - i) : ΔR=1.65 m (CMS-like, substantial room for HCAL inside coil)

    ii) : ΔR=0.8 m (ALEPH-like, ECAL only inside coil).



B (T)
R_ECAL (m)
ΔR=0.8 m
ΔR=1.65 m
20 Tm²
15
10
5
2.5 Tm²
Red lines :
U < 2.5 GJ,
cosθ=0.86
Blue lines :
U < 2.5 GJ,
cosθ=0.71
Improving
E-flow
performance

Cosθ=0.86. U < 2.5 GJ, HCAL inside coil (ΔR=1.65m)

B (T)

Red line : U = 2.5 GJ

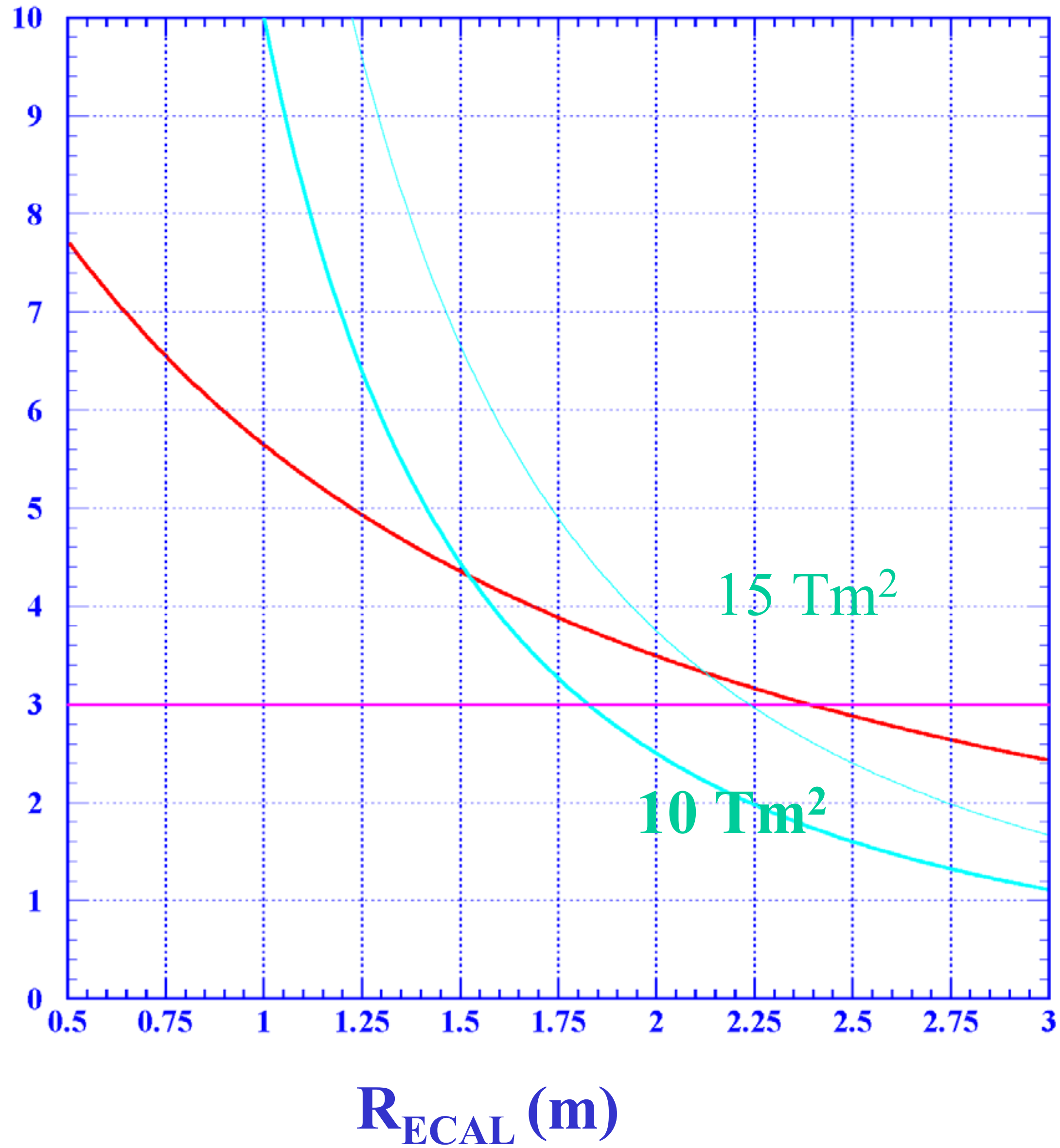
Heavy cyan line :

10 T m^2 contour.

Light cyan line :

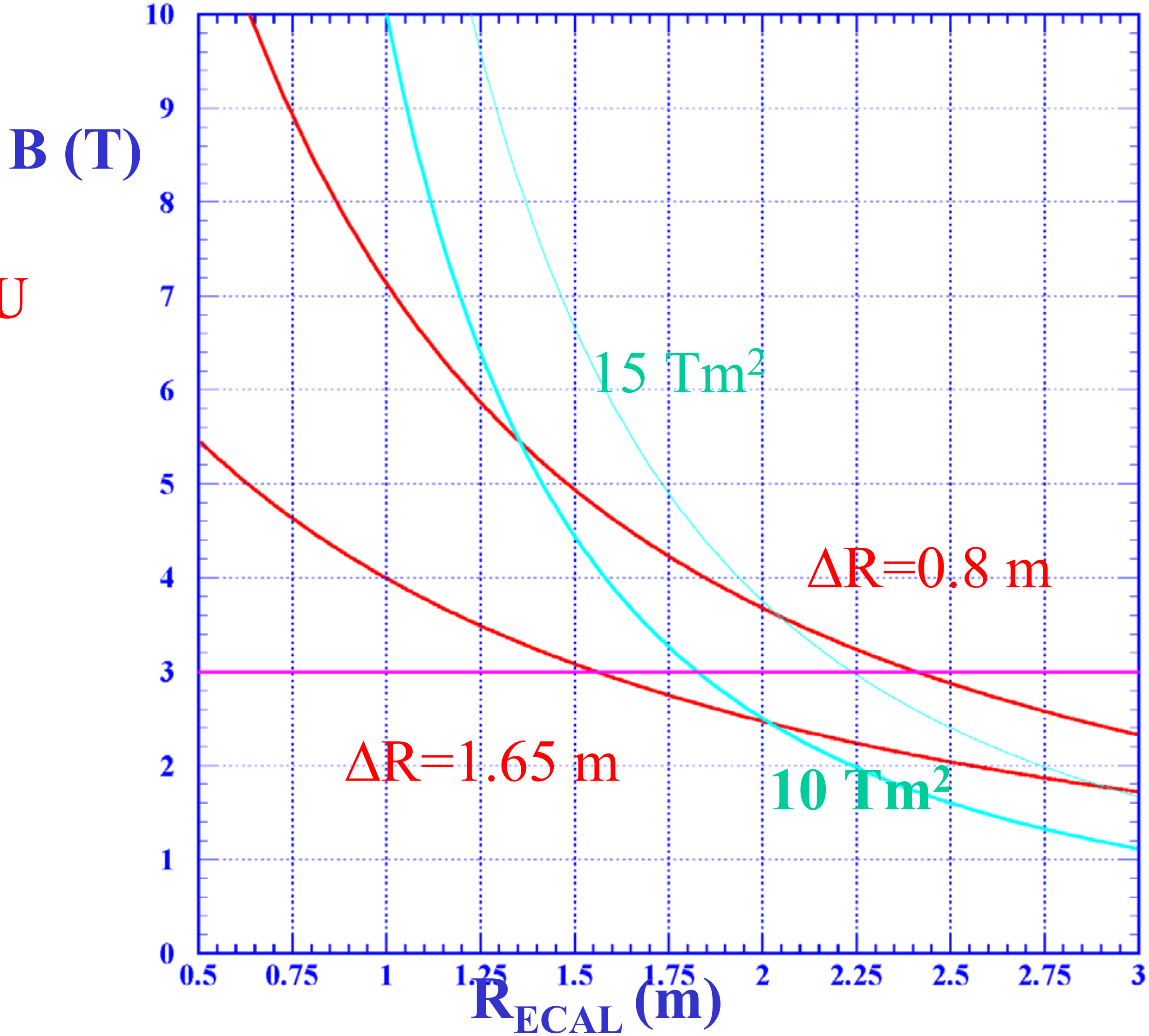
15 T m^2 contour.

Purple line: minimum B-field needed ?



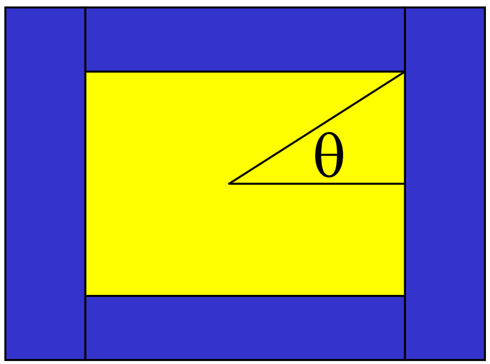
CMS magnet (2.5 GJ) is challenging !

What about U < 1.25 GJ ?



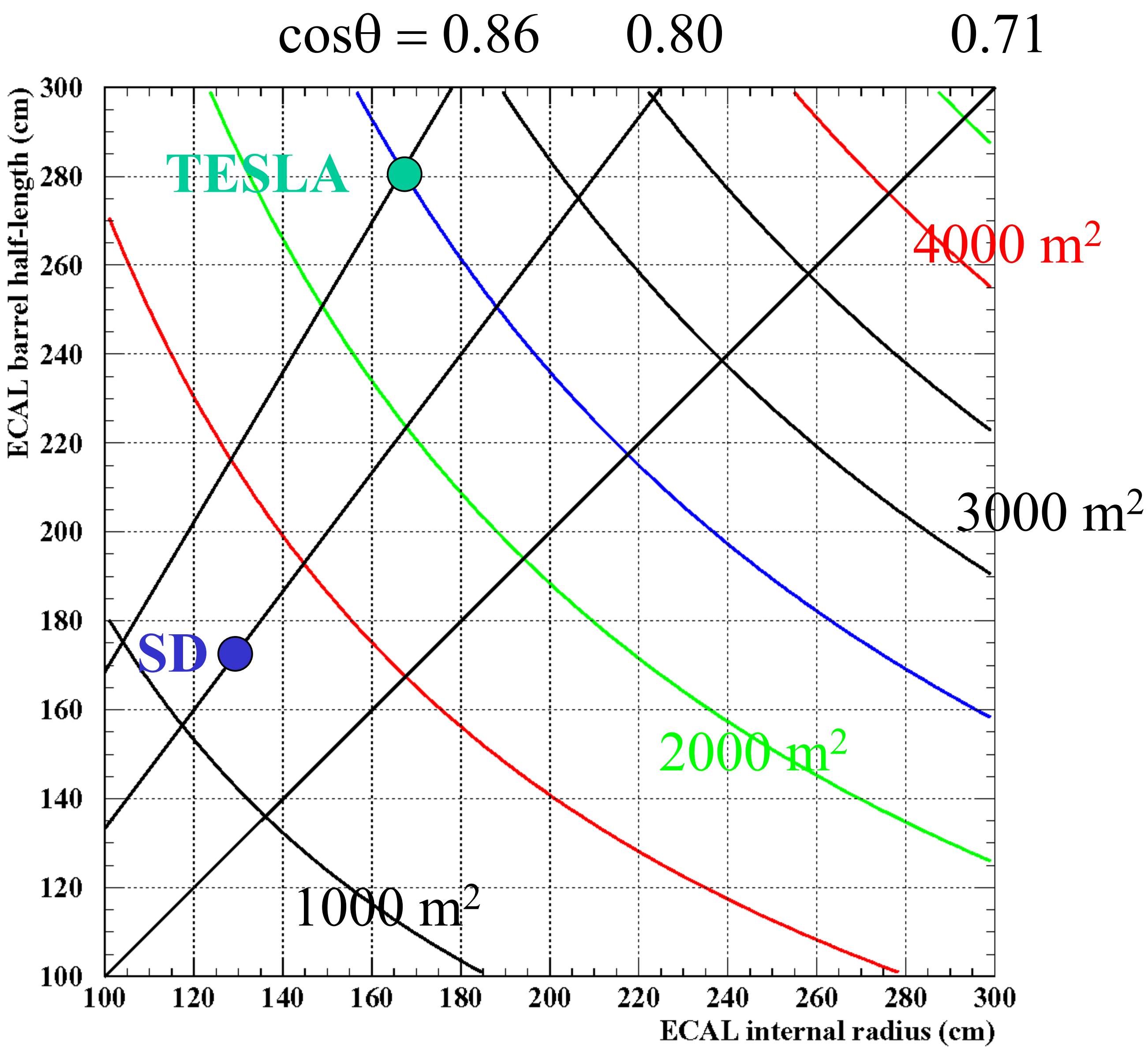
ECAL geometry

See also J-C Brient talk at LCWS04



Silicon area for 40 layers, 20 cm depth.

Barrel cylinder + 2 endcap disks



How much should we fight for superb E-flow in the endcap ?

Concluding remarks

The detector design concept with large volume gaseous tracking has broad support in each region.

- It appears to be a detector concept that is feasible.
- Needs R&D support in North America.
- TPC tracking is a natural front-runner for such a detector.
- The calorimetry solution is key to the physics and costing.

- A concerted inter-regional effort, with open participation, focussed on the main design issues, can explore the design parameters, and deliver a design concept worthy of the LC accelerator
- Scientific cross-checks DEMAND 2 viable detectors
  - SiD is a development which will foster a complementary detector design.
  - Is it viable ?
  - Urge cooperation on issues of common interest (eg. magnet, calorimetry)

Acknowledgements

T. Behnke, M. Breidenbach, J Brau, J-C Brient,
S. Komamiya, K. Riles, M. Ronan, R. Settles,
H.Yamamoto, H. Yang

mistakes are mine though !

Backup slides

Dependence of E-jet resolution on EM energy resolution (stochastic term)

11

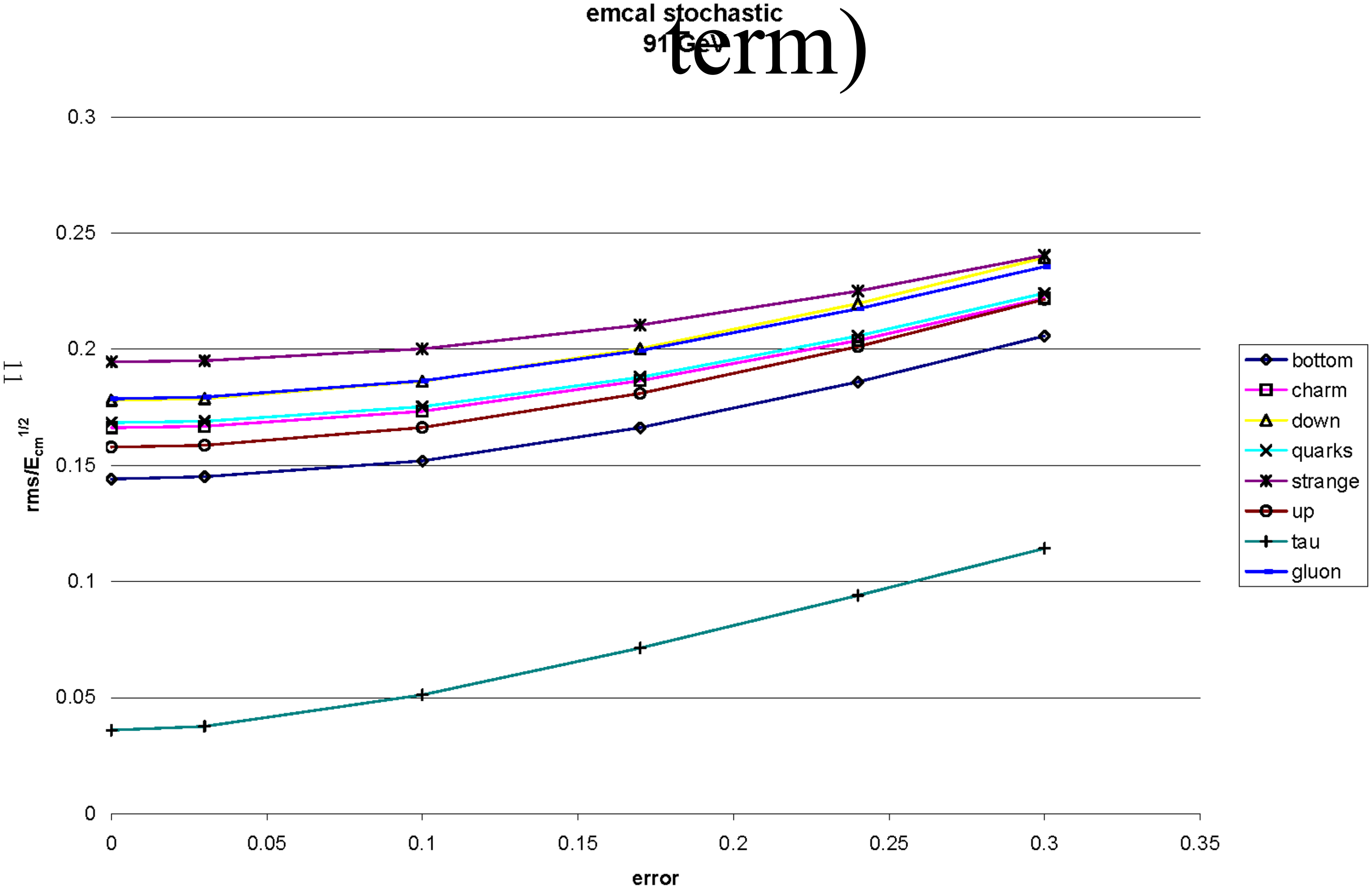
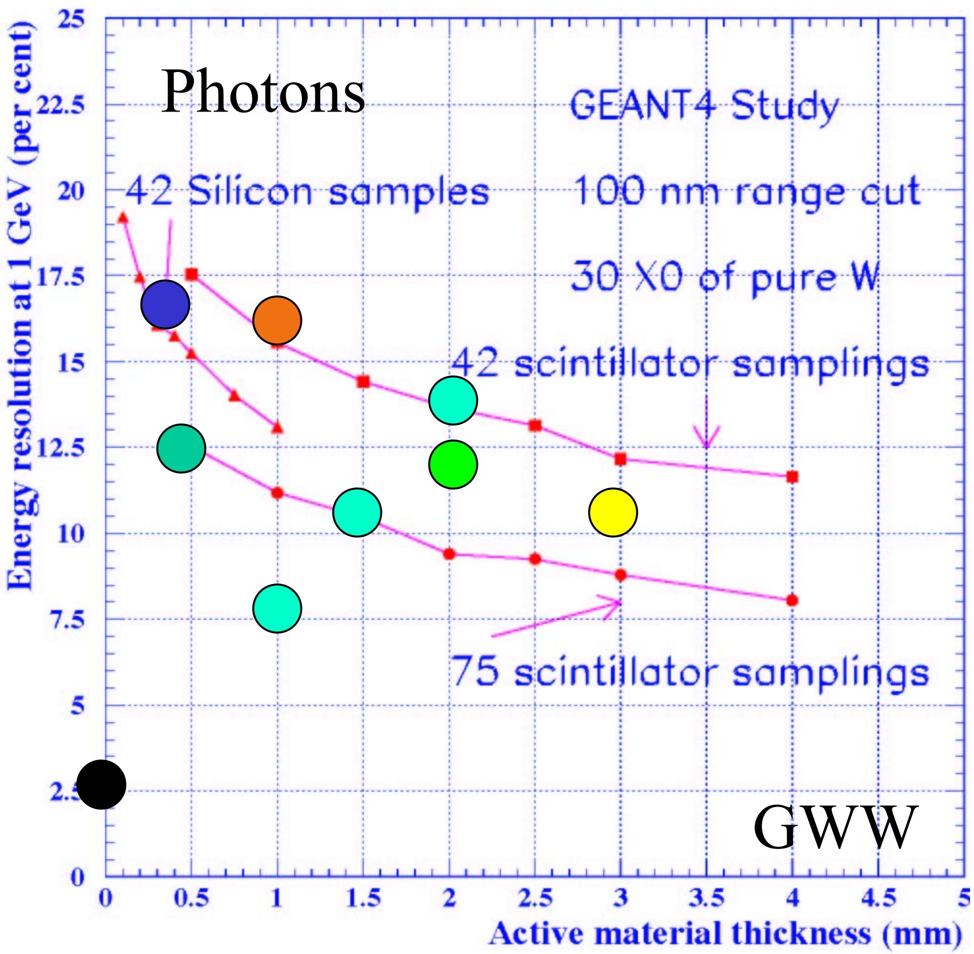


Figure 2

Energy resolution for sampling W calorimeters



Also plotted, CALICE, Asian, LCCAL, $PbWO_4$

42 layers = 2.5 mm W

56 layers = 1.75 mm W

75 layers = 1.4 mm W

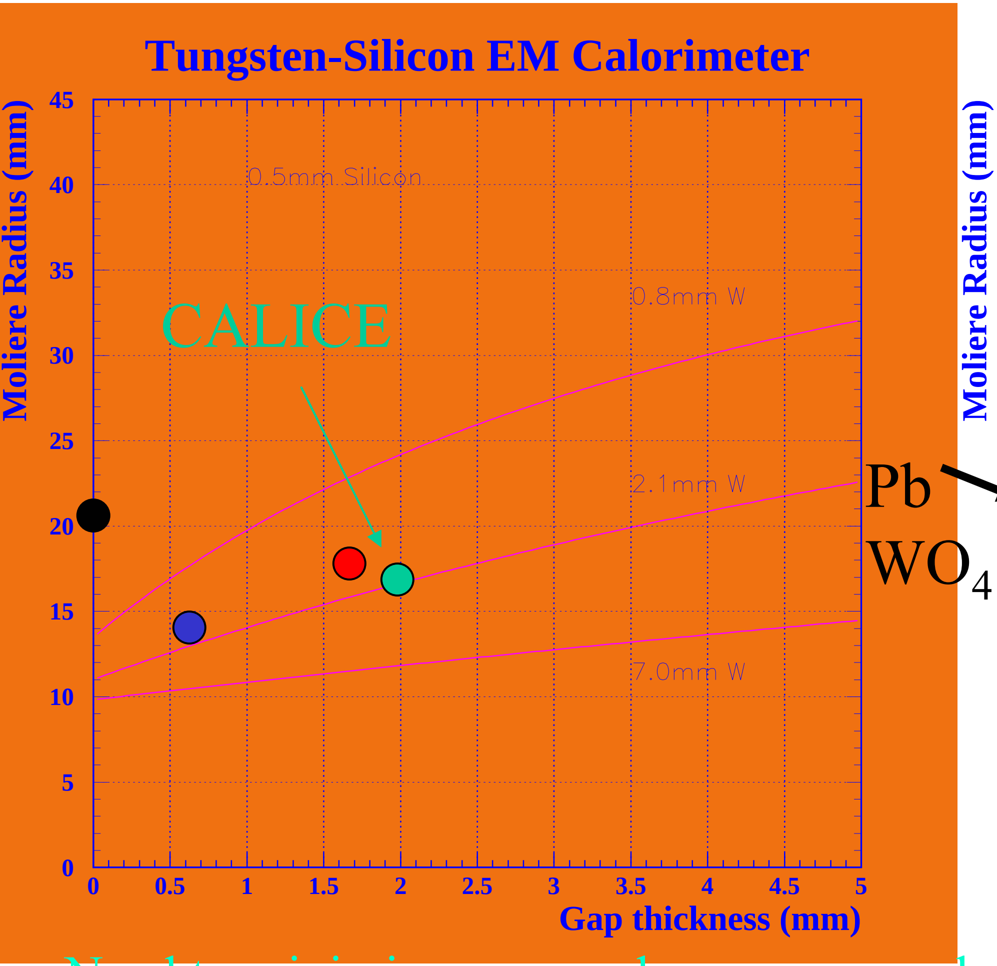
135 layers = 0.78 mm W

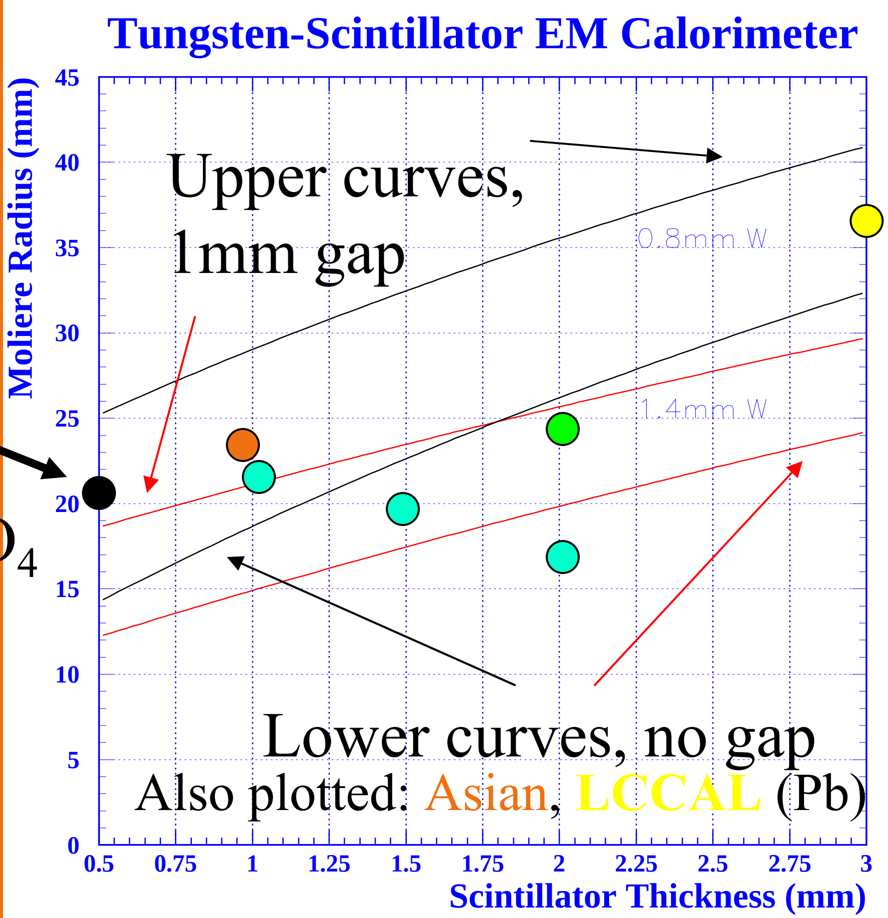
Cost issues:

W cost ≈ independent of thickness if rolled ?

Si and scintillator scale as area, and can be more expensive if thinner.

Compactness



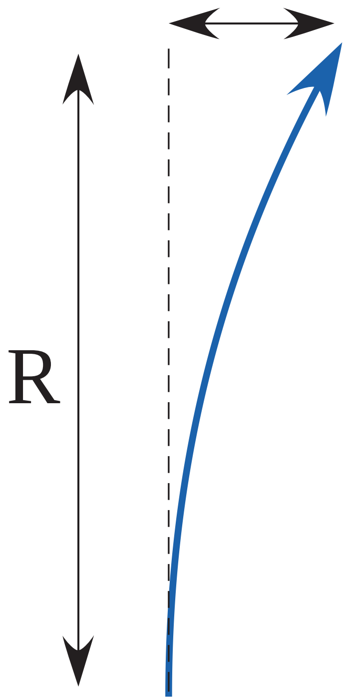


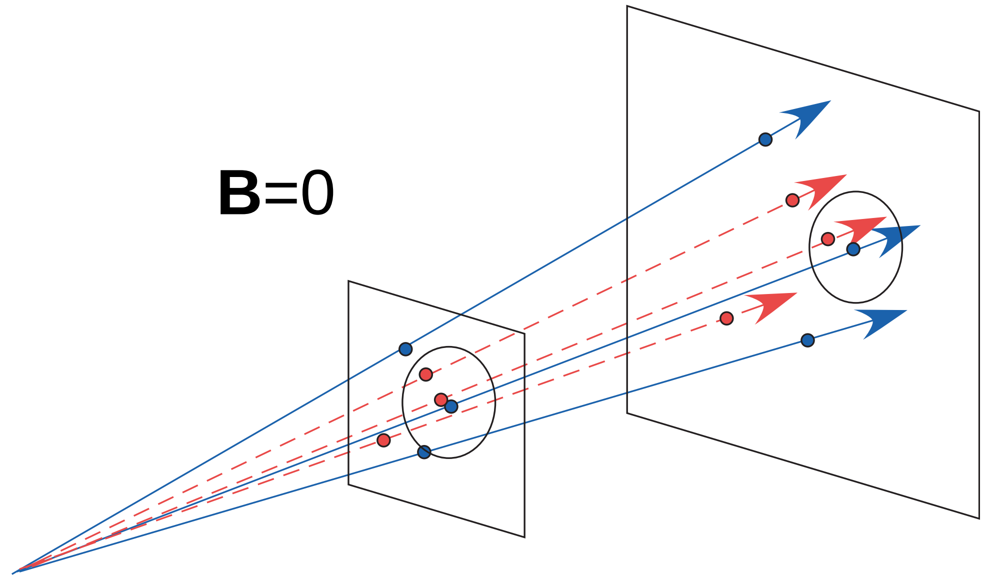
Need to minimise gaps, reduce space needed for fiber routing, by sharing fiber routing gaps among layers

Assume 25% of scintillator thickness used for readout

S. Komamiya

$$d = 0.15 B R^2 / p_t$$





S. Komamiya

- Figure of merit : Calorimeter
  - $\sigma_{jet}^2 = \sigma_{ch}^2 + \sigma_\gamma^2 + \sigma_{nh}^2 + \sigma_{confusion}^2 + \sigma_{threashold}^2$
  - Separation of charged particles and γ/nh is important (See H.Videau's talk at LCWS2004)
  - Charged particles should be spread out by B field
  - Lateral size of EM shower of γ should be as small as possible (~ $R_m^{effective}$: effective Moliere length)

    ~~Barrel: $B R_{in}^2 / R_m^{effective}$~~

    ~~Endcap: $B Z^2 / R_m^{effective}$~~

    R_{in} : Inner radius of Barrel ECAL

    Z : Z position 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 $\sim R_{in}^2$)

Merits of Huge Detector

Good Jet Energy (Particle) Flow Measurement

Good charged track separation in a jet at the inner surface of the calorimeter

large BR^2

Pattern recognition is easier

large n with thin material, small number of low momentum curling tracks

Good momentum resolution for charged particles

large $BR^2 \sqrt{n}$

S. Komamiya

Good dE/dx measurement for charged particles

large n

Smaller relative volume of the dead space

small $\Delta V/V$ for constant $\Delta V \propto n$

Two track separation, Larger efficiency for Ks and Λ (any long lived)

large BR^2 , larger R

Comparison of Detector Models

LD = Minimally modified one

		SD	**TESLA**	**LD**
Solenoid	B(T)	5	4	3
	Rin(m)	2.48	3.0	3.75
	L(m)	5.8	9.2	*8.4*
	E_{st}(GJ)	1.4	2.3	*1.2*
Tracker	R_{min} (m)	0.2	0.36	*0.40*
	R_{max}(m)	1.25	1.62	*2.05*
	σ(μm)	7	150	*150*
	N_{sample}	5	200	*220*
	$\delta pt/pt^2$	3.9e-5	1.5e-4	*1.1e-4*

S. Komamiya

S. Komamiya

Comparison of Detector Models

		SD	TESLA	LD
ECAL	R_{in}(m)	1.27	1.68	*2.1*
	p_t^{min} (GeV/c)	1.9	2.0	*1.9*
	BR_{in}^2	8.1	11.3	*13.2*
	Type	W/Si	W/Si	*W/Sci*
	R_m(mm)	18	24.4	*16.2*
	BR_{in}^2/R_m	448	462	*817*
	Z	1.72	2.83	*2.8*
	BZ^2/R_m	822	1311	*1452*
	X_0	21	24	27
Total	λ	5.5	5.2	*6.0*
	t (m)	1.18	1.3	*1.4*

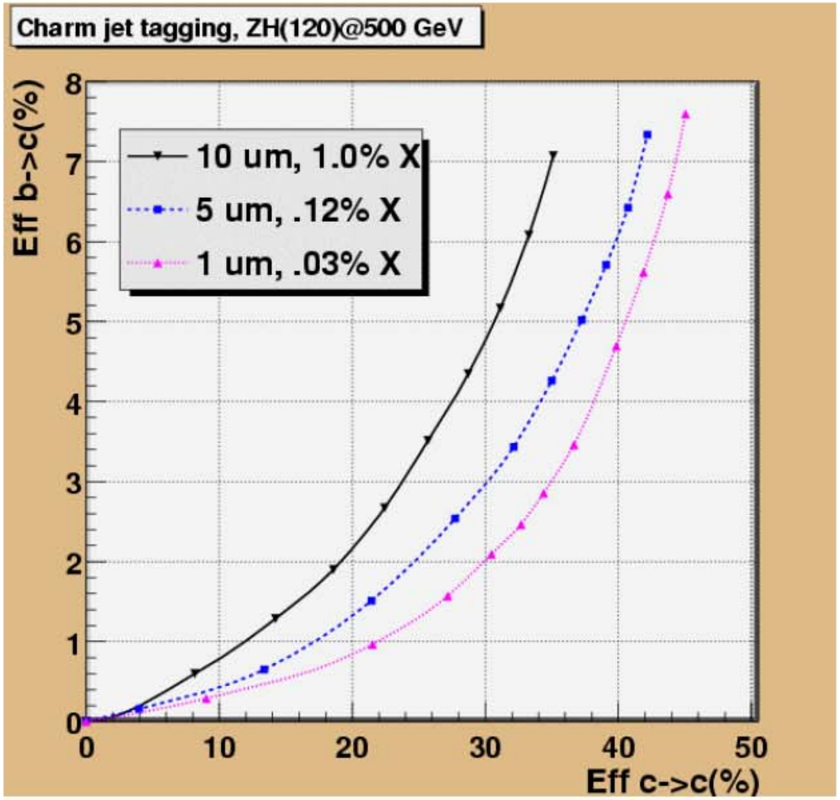
S. Komamiya

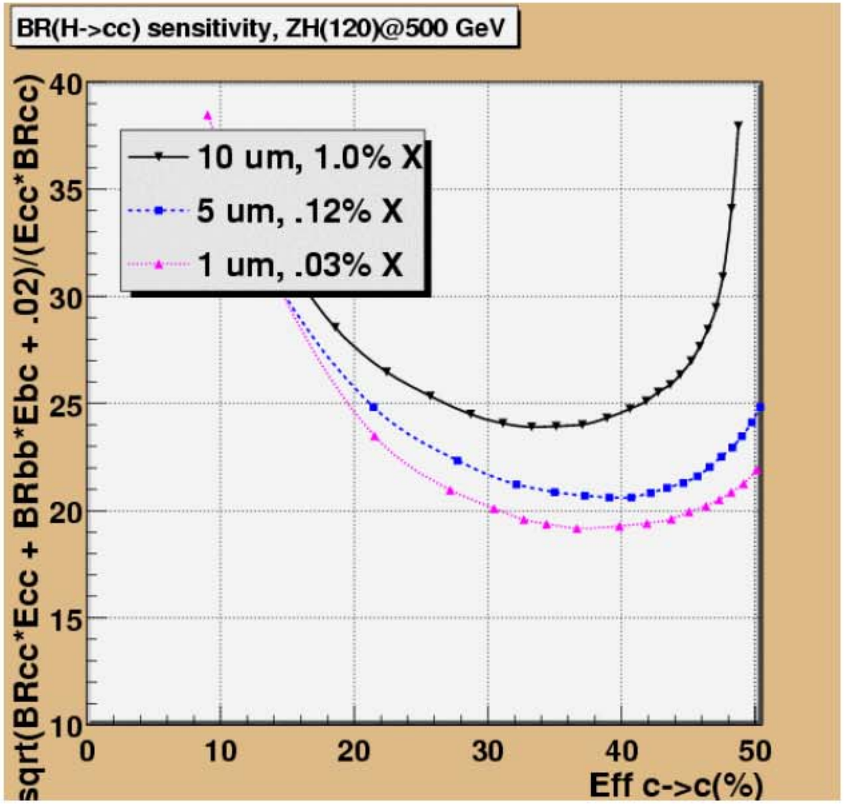
- The LC detector optimized for “Energy Flow Algorithm” is realized with a “Huge/Truly large detector”
- There are a lot of space for improvements/challenges.

  A global efforts are needed and we are looking for equal footing partners in the world.
- The smaller detectors are not always inexpensive.

The key is Calorimeter

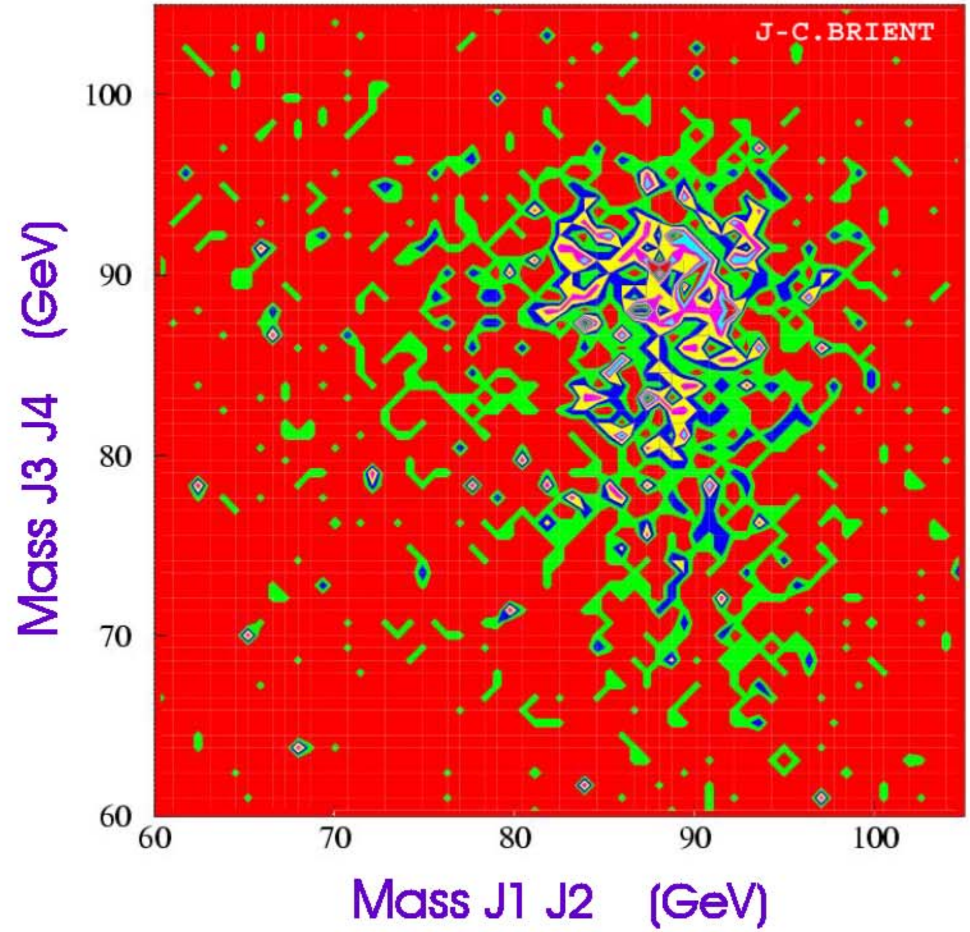
Studies of performance – A. Chou (SLAC)
(comparing extremes in resolution/material)





Select ≥ 2 b-jets

$$\frac{S(ZZ)}{B(WZ,WW)} \approx 12.2$$

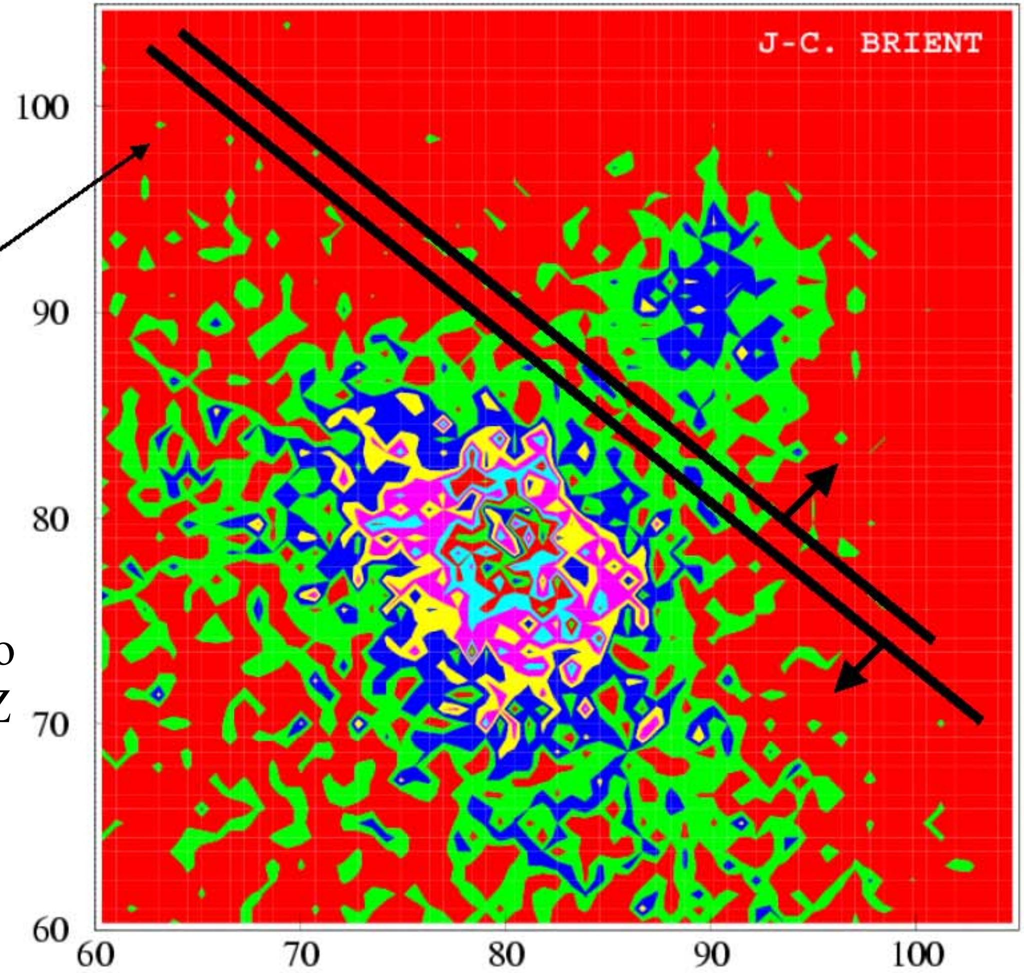


Select < 2 b-jets

Before di-jet mass cut

$$\frac{S(WW,ZZ)}{B(WZ)} \approx 100$$

GWW : Note by using b-tagging to separate, the low mass tail of the Z from semileptonic b's can be suppressed too.



After cut

WW region:

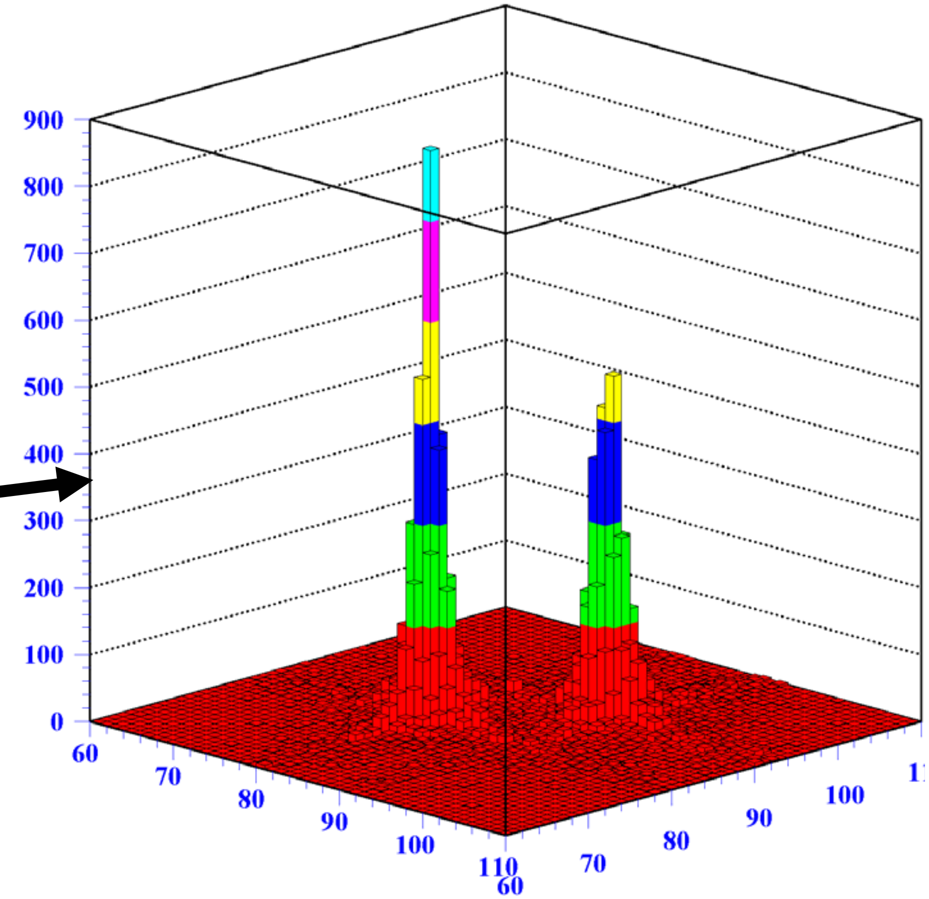
Contains 89 % of the WW and

$$\frac{S(WW)}{B(ZZ, WZ)} \approx 18.6$$

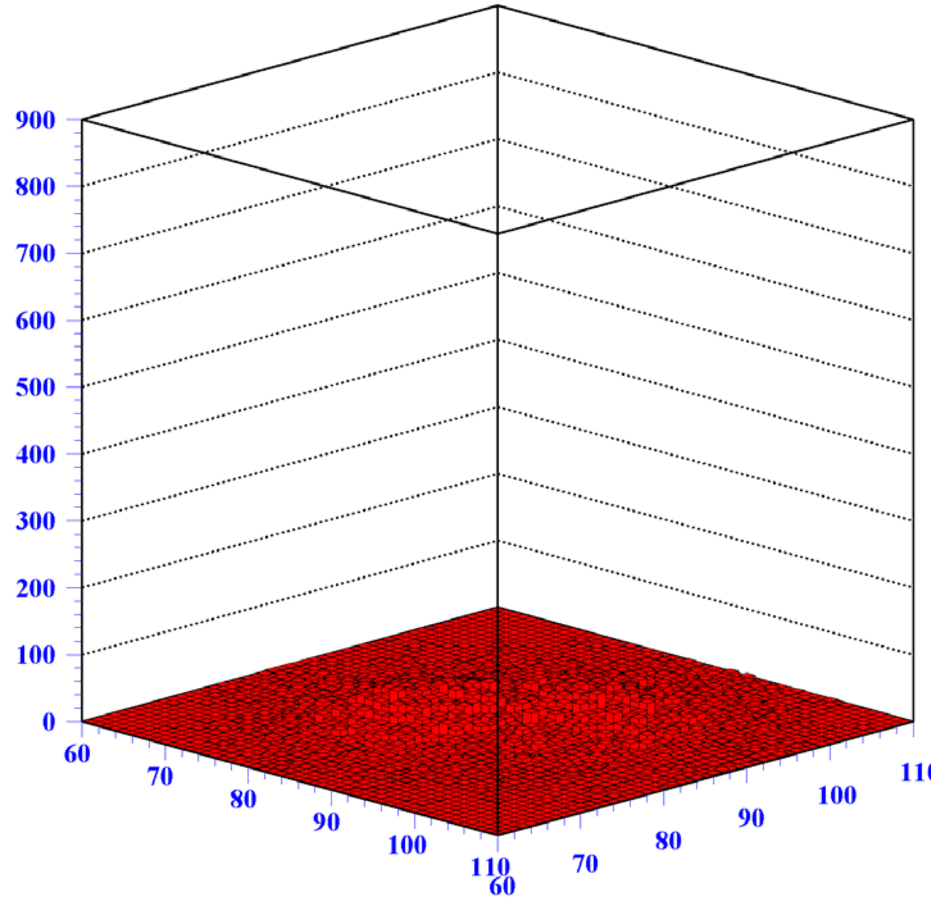
ZZ region:

Contains 71 % of the ZZ

$$\frac{S(ZZ)}{B(WW, WZ)} \approx 2.4$$



Intrinsic W, Z width only
(perfect resolution)



60%$\sqrt{E_{jet}}$

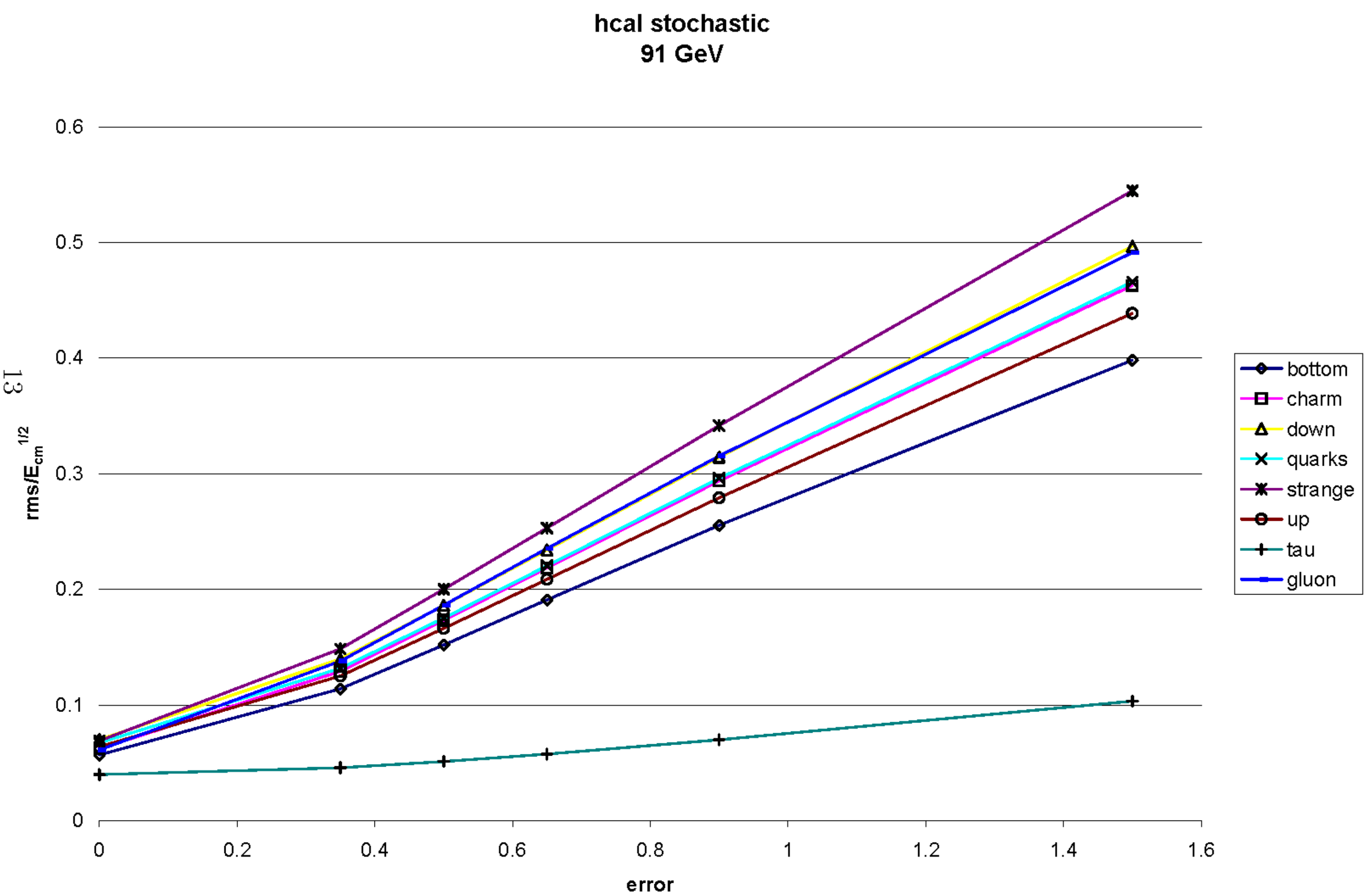
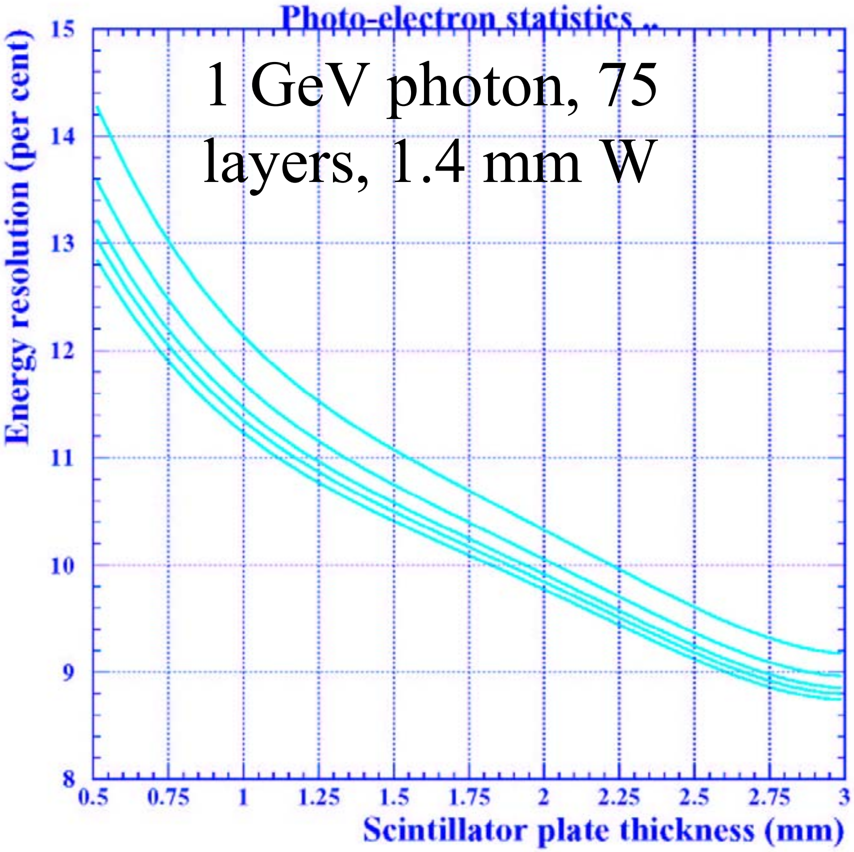

hcal stochastic
91 GeV
rms/E_cm^1/2
error
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
bottom
charm
down
quarks
strange
up
tau
gluon

Figure 4

Scint. Thickness – critical parameter for small R_M

Developments in tile-HCAL R&D, suggest light yields of 5 pe/mip/mm achievable with Silicon PMs – up to 20 pe/mip/mm with high QE devices.

Light-yield does not look to be overly critical. Can probably live with straight fibers.



Curves are for 2.5, 5,10,20,∞ pe/mip/mm