# HBEPR*
# What is the right number of detectors?


Bill Murray
STFC-RAL / University of Warwick
bill.murray@cern.ch

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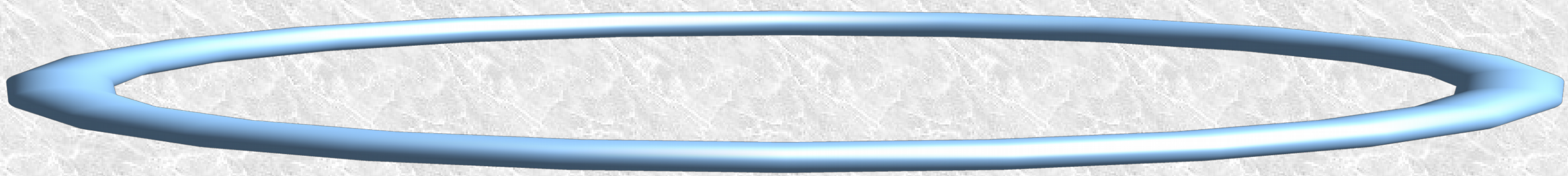
- Prejudice & scaling laws
- Hoping to spark discussion

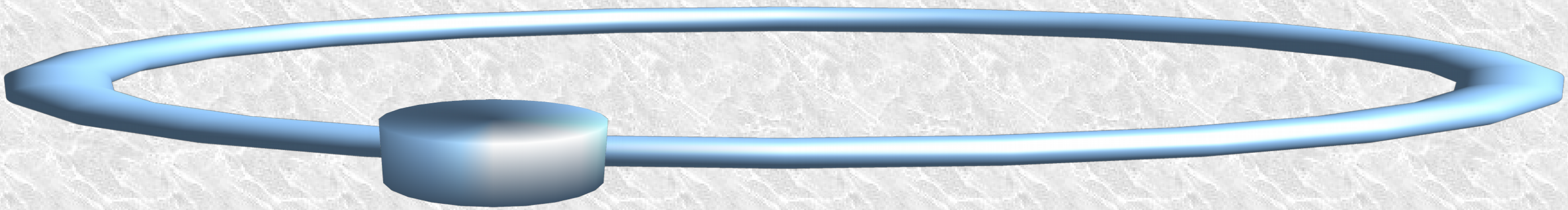
* Huge Big electron-poistron ring

# What do you do if you own this?



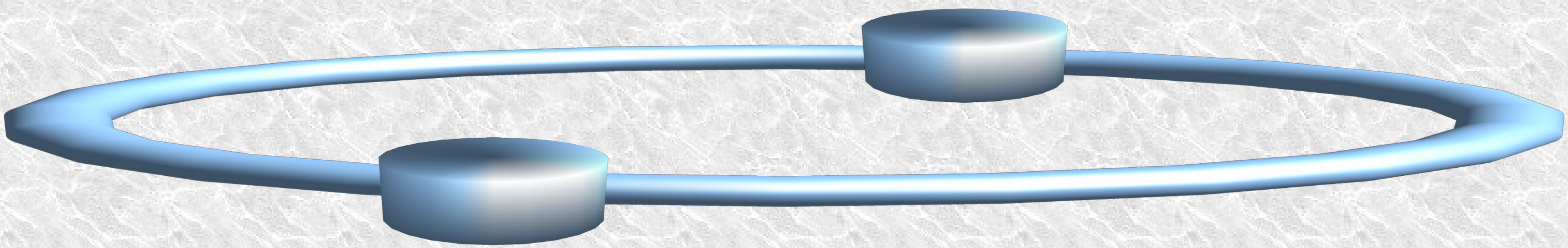
# What do you do if you own this?

- Add a detector?



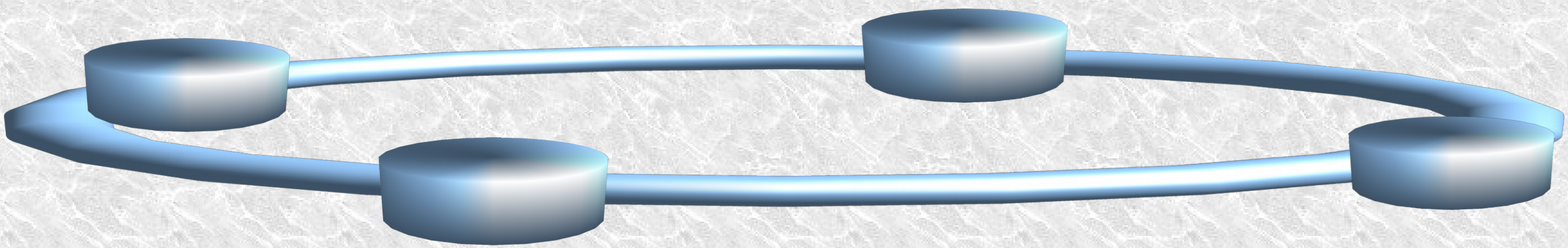
# What do you do if you own this?

- Add two detectors?



# What do you do if you own this?

- Add four detectors?



# Scaling of luminosity with $n_{Det}$

- TLEP estimate $L \approx (4/N_{IP})^{0.4}$. This comes from assumption you are beam-beam limited
- i.e. 1.74, 1.32, 1.12, 1 for 1, 2, 3 and 4 detectors
- For a total lumi 1.74, 2.66, 3.36 and 4.

- Jianming:
  - “All the physics can be summarized by this table”
  - (referring to the rates of ZH and ννH production)

# Accelerators gone by

| | |
|---|---|
| Petra | Jade, Tasso, Pluto & Mark J |
| PeP | 5 large detectors |
| Tristran | Topaz, Venus & AMY |
| LEP | ALEPH, DELPHI, L3, OPAL |
| Tevatron | CDF & D0 |
| PeP-II | Babar |
| KEK-B | Belle |

- By historical standards, 2 detectors on an 50km+ ring would seem minimalistic
- But detectors grow in ambition and cost

# So why would you not have lots?

- Cost
  - I think this is the normal reason people shy away.
  - It is what I want to understand
- Complication
  - Yes, there is complication.
  - But we have already been told to leave long straight sections for the future proton machine

# Example detector?

- ILC detectors have been optimised for e+e- physics for decades
- They must be great
- Lets take them as a baseline

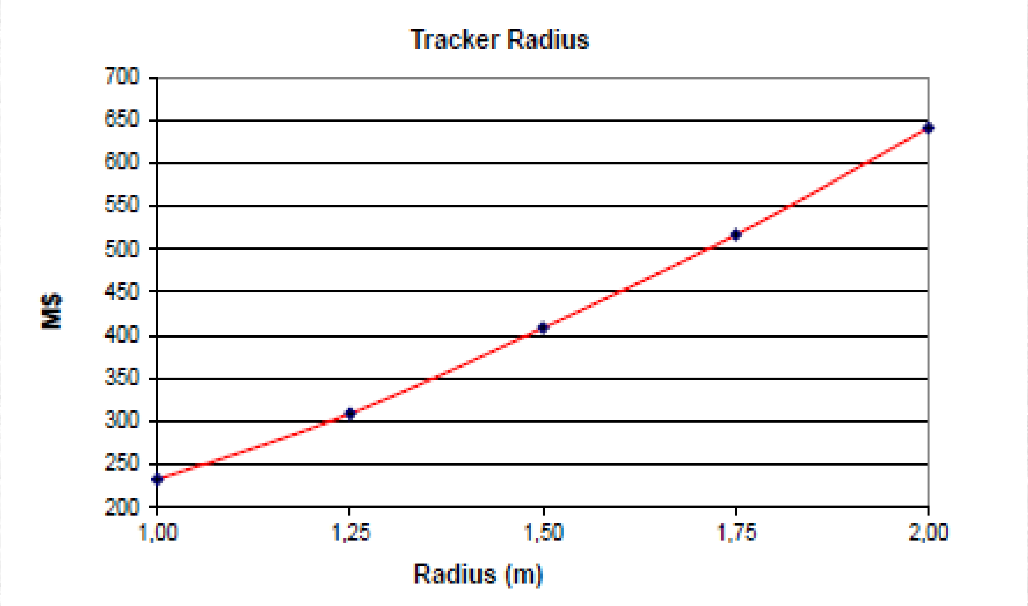
# Cost of SiD

(From SiD DBD)

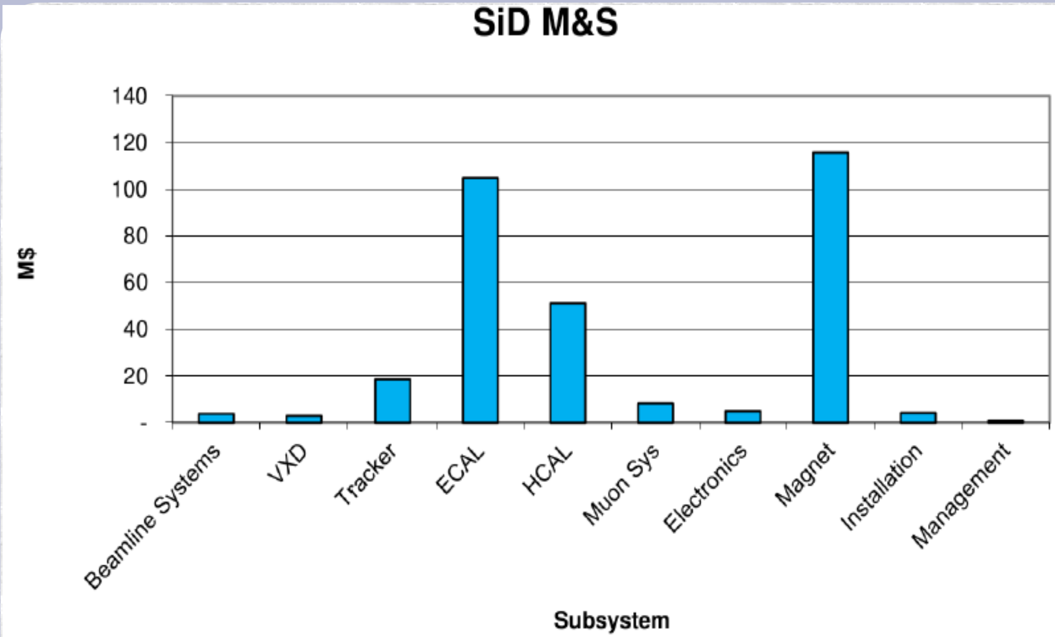
| | agreed unit cost (US-\$) | agreed error margin (US-\$) |
|---|---|---|
| Tungsten for HCAL | 105/kg | 45/kg |
| Tungsten for ECAL | 180/kg | 75/ kg |
| Steel for Yoke | 1000/t | 300/t |
| Stainless Steel for HCAL | 4500/t | 1000/t |
| Silicon Detector | $6 / cm^2$ | $2 / cm^2$ |

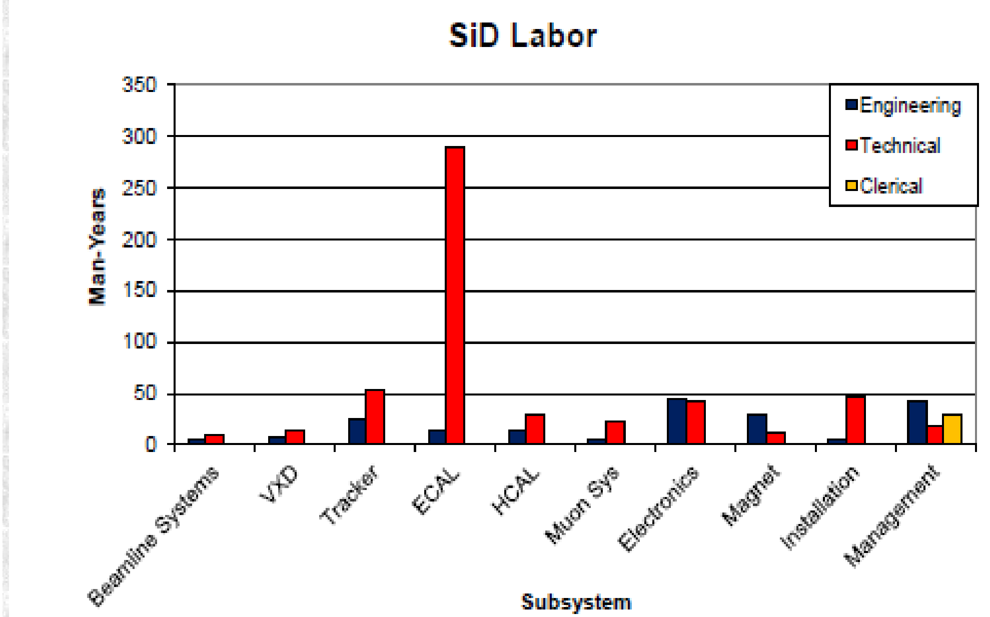
- M&S 315 M$
- Contingency 127 M$
- Labor 748 M$
- My total: 1190M$

- My guess is people have number like this in their heads



# SiD cost breadown




- Tungsten+Si ECAL, 20+10 layers
- 5 T solenoid
  - Inner radius 259cm
  - 50% of radius tracker, 50% ECAL+HCAL
- Could we get away with less?

# CEPC detector

- First try is a modified SiD
- HCAL still inside coil
- ECAL resolution still poor
- Coil reduced to 3.5T
  - Radius 3m, length 8m
  - TPC goes to 1.8m
- Great jet resolution!

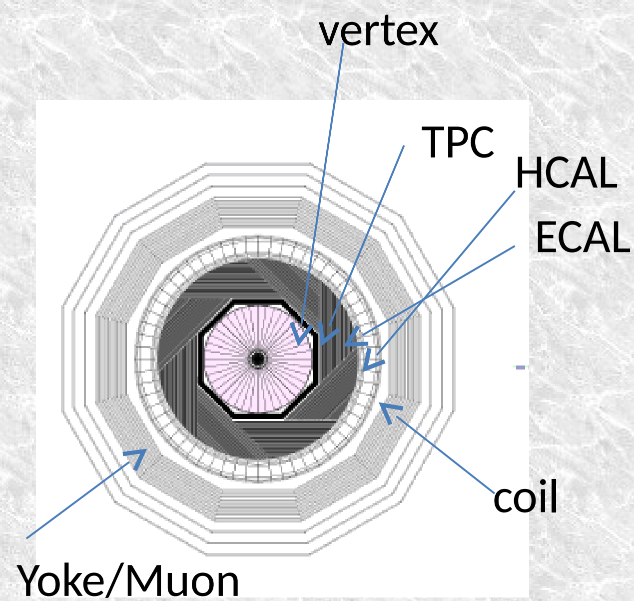



**Table 2.** Key characteristic/performance of a conceptual CEPC detector.

| | |
|---|---|
| Geometry acceptance | TPC (97%), FTD (99.5%) |
| Tracking efficiency | $\sim$ 100% within geometry acceptance |
| Tracking performance | $\Delta(1/p_T) \sim 2 \times 10^{-5}$ (1/GeV) |
| ECAL intrinsic energy resolution | $16\%/\sqrt{E} \oplus 1\%$ (GeV) |
| HCAL intrinsic energy resolution | $60\%/\sqrt{E} \oplus 1\%$ (GeV) |
| Jet energy resolution | 3-4% |
| Impact parameter resolution | 5 $\mu$m |

# How to save money?

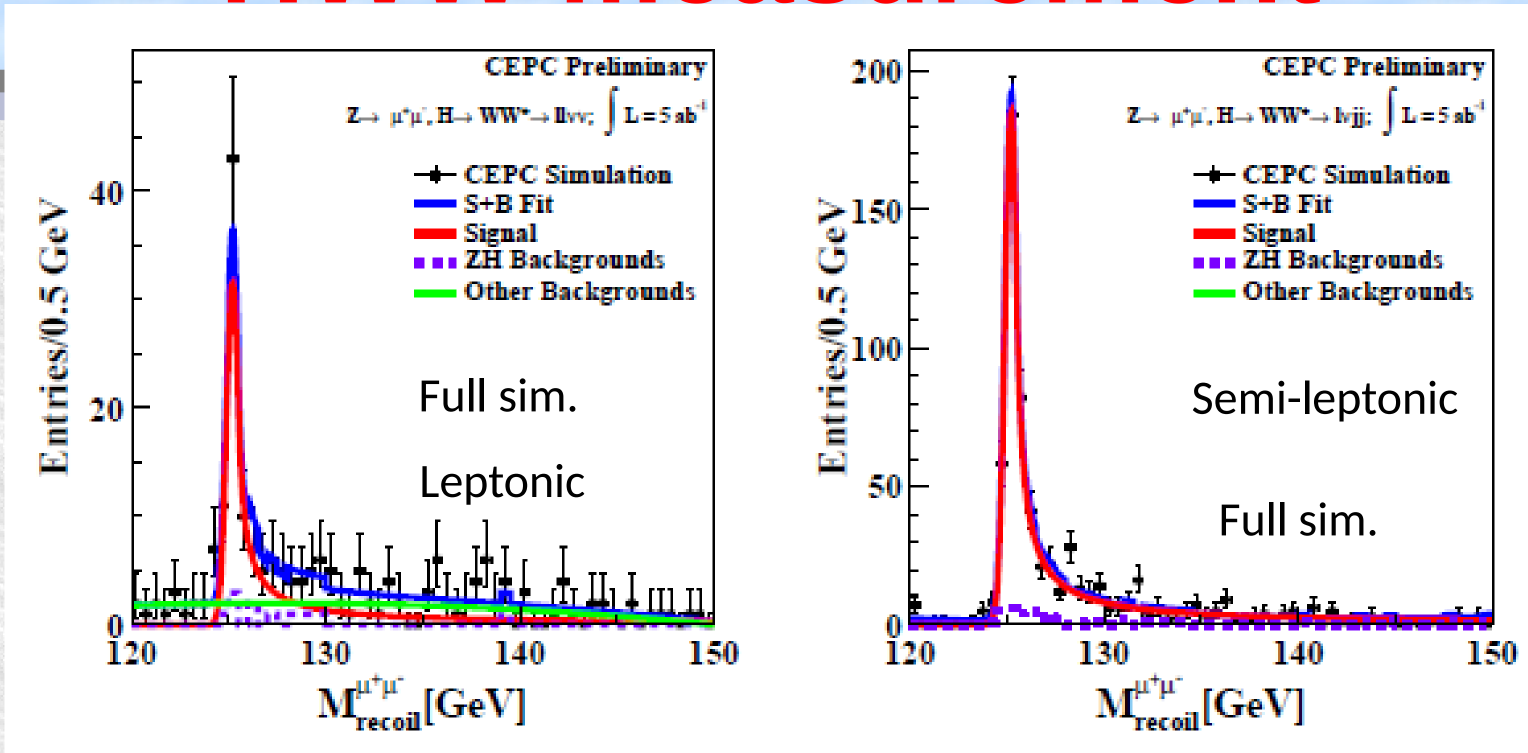
- The magnet coil was O(10%) of SiD in one item
  - What do we need?
- The finely segmented ECAL (& HCAL) are 40%
  - Is this an appropriate solution?

# A strawman scenario

- 100km circular $e^+e^-$ collider
  - As used in Ludo's slides
- Maximum energy 400 GeV
  - Lower than such a machine claims
  - Perhaps realizable in 80km tunnel

- Z peak, 91 GeV, luminosity: 2 $10^{36}cm^{-2}s^{-1}$
- WW peak, 160 GeV luminosity: 1.2 $10^{35}cm^{-2}s^{-1}$
- ZH peak, 240 GeV, luminosity: 6 $10^{34}cm^{-2}s^{-1}$
- tt peak, 350 GeV, luminosity: 1.7 $10^{36}cm^{-2}s^{-1}$
  - This will turn out not to be a detector cost driver

# HWW measurement

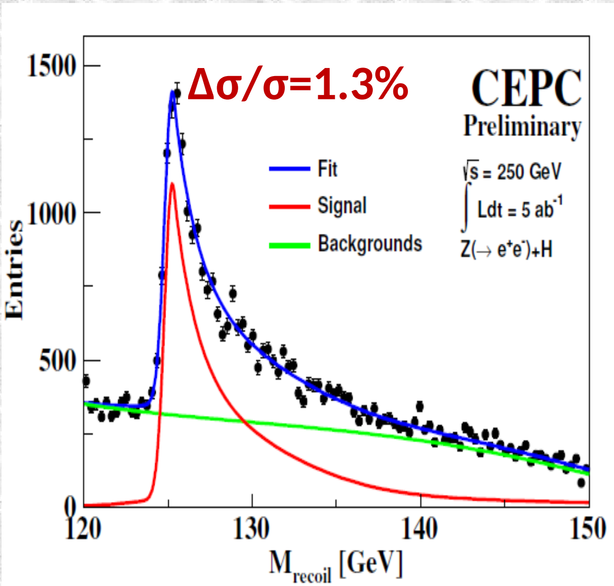



| Channel | Precision | Comment |
|---|---|---|
| $Z\to\mu\mu, H\to WW^*\to\ell\nu qq, \ell\ell\nu\nu$ | 4.9% | CEPC Full Simulation |
| $Z\to ee, H\to WW^*\to\ell\nu qq,\ \ell\ell\nu\nu$ | 7.0% | Estimated |
| $Z\to\nu\nu, H\to WW^*\to qqqq$ | 2.3% | Extrapolated from ILC result |
| $Z\to qq, H\to WW^*\to\ell\nu qq$ | 2.2% | Extrapolated from ILC result |
| Combined | 1.5% | |

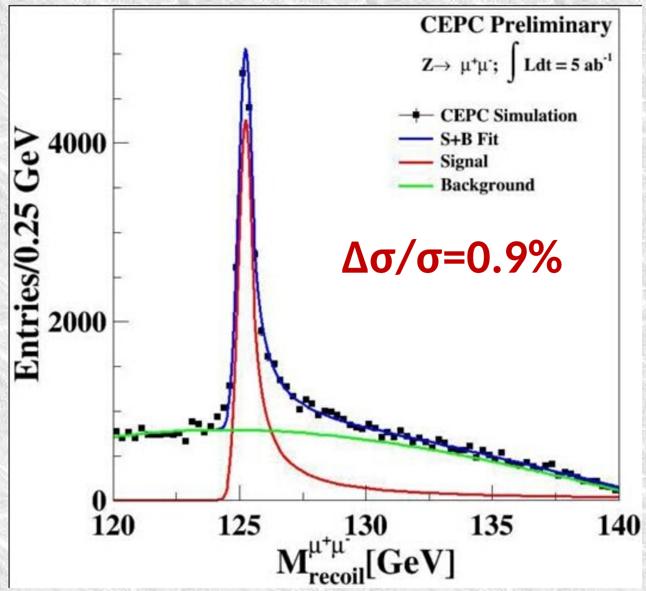
- Necessary for width measurement
  - Semileptonic modes so far.
  - *Maybe* the semi-hadronic modes need the resolution?

# Recoil mass

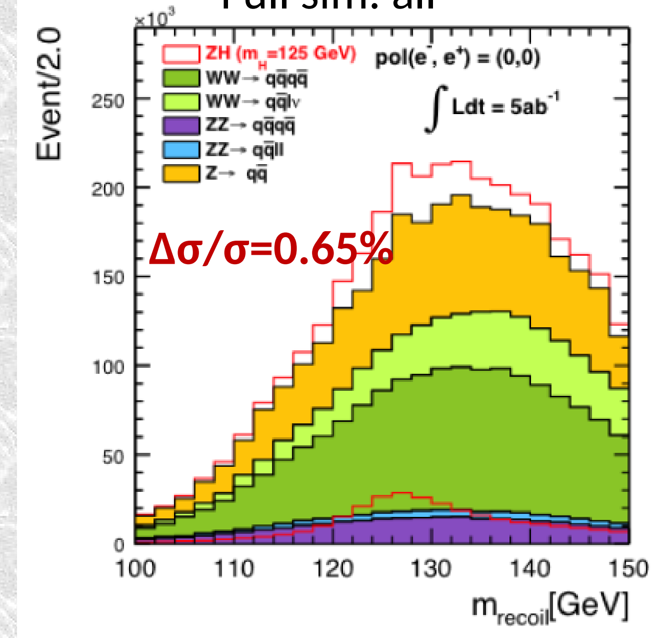
Full sim. signal




Full sim. signal




Full sim. all

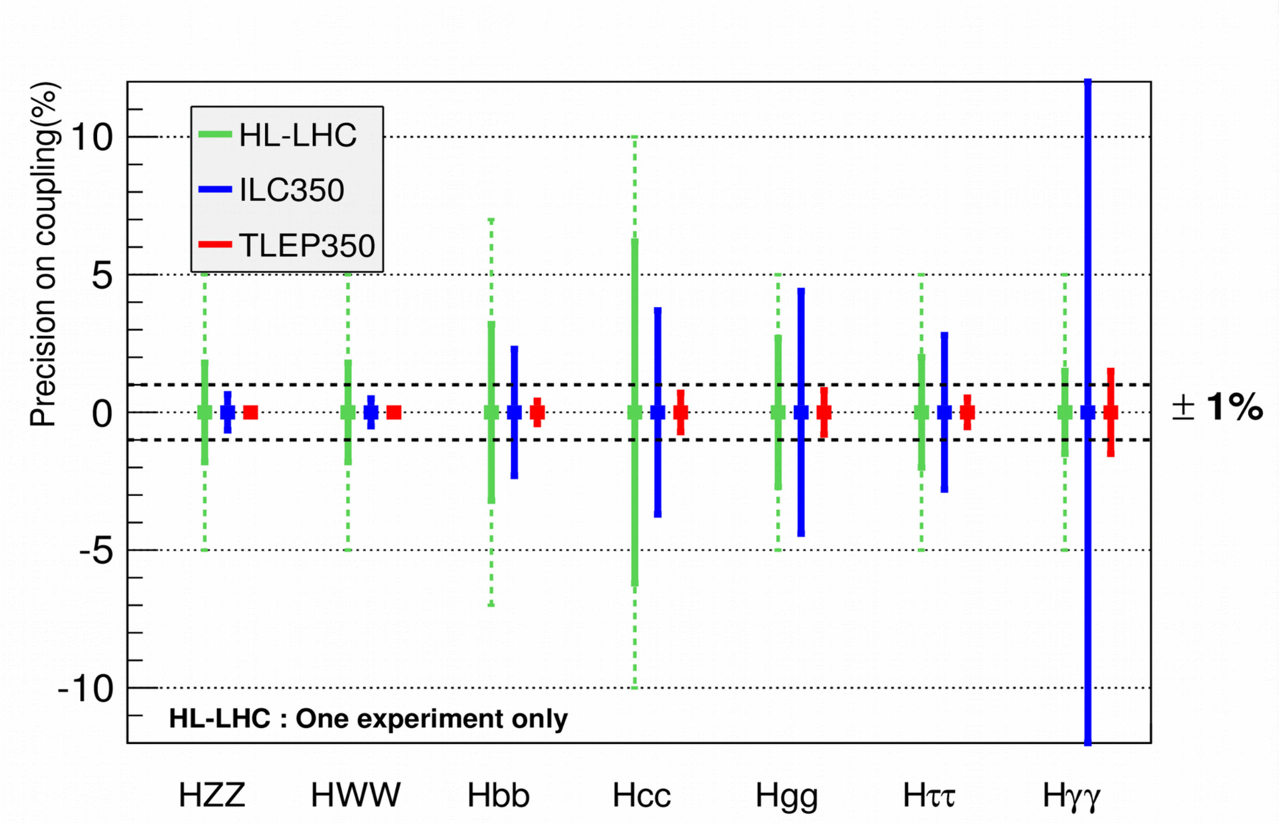



- Combined precision is Δσ/σ~0.5%
  - Hadronic channels weight best
  - FWHM~35GeV
- Electrons 40% worse than muons despite 3x worse resolution
  - Protected by low background

# Invisible Width

- Can we see the Higgs invisible decay?
- Yes!
  - Do the recoil mass measurement
  - Veto on other objects in the detector
- There will be background from e.g. $ZZ \rightarrow ll\nu\nu$
  - So mass resolution useful

# TLEP H measurements




- TLEP improves all coupling (except Hγγ)
- Couplings not dependent on hadronic resolution
  - e.g. ZH→ZZZ uses a four lepton final state
- Do need excellent glue/charm/b tagging

# Higgs Mass measurement

- The 5.5MeV error from the CEPC measurement is dominated by the muon measurement
- The electron measurement scarcely contributes
- This is because the missing mass measurement has a good knowledge of $E_{beam}$ and then the Higgs peak is given by the missing mass
  - The width is given by the e/μ momentum error
- If we degrade the $BL^2$ we will lose in $m_H$
- That would be a shame....but $m_H$ is already better known than needed ~ 300 MeV

- So here is a physics loss from tracking precision, but a small one

# Key Physics

- Z pole
  - Z mass
  - FB asymmetries, cross-section etc.
  - Rare decays, e.g. Z→e-mu
- WW threshold
  - WW mass
- HZ peak
  - H Br's: gluons, charm
  - Invisible higgs Br
- tt threshold
  - Top mass
  - Check for light neutralinos etc.

# Can we save money on coil?

# What Solenoid do we need?

- What it the outermost component inside it?
  - Gem: the muon system
  - L3: The muon system
  - OPAL: the tracker
  - ALEPH: the ECAL
  - ATLAS: the tracker
  - CMS: the ECAL
- The desire for a large radius goes with the urge for perfect calorimetry
  - Placing the calorimeter inside the solenoid means that a thick material layer in front is avoided.
  - Note that the CMS HCAL position allows a second muons measurement in the return yoke

# LEP performances

| | ALEPH | DELPHI | L3 | OPAL |
|---|---|---|---|---|
| Magnetic field | 1.5T | 1.2T | 0.5T | 0.435T |
| Magnet radius | 2.5m | 2.6m | 5.75m | 1.9m |
| qq efficiency | 99.1% | 94.8% | 99.3% | 99.5% |
| qq background | 0.7% | 0.5% | 0.3% | 0.3% |
| ee efficiency | 97.4% | 97.0% | 98.0% | 99.0% |
| ee background | 1.0% | 1.1% | 1.1% | 0.3% |
| μμ efficiency | 98.2% | 95.0% | 92.8% | 97.9% |
| μμ background | 0.2% | 1.2% | 1.5% | 1.0% |
| ττ efficiency | 92.1% | 72.0% | 70.9% | 86.2% |
| ττ background | 1.7% | 3.1% | 2.3% | 2.7% |
| $\sigma_{mZ}$, MeV | 3.1 | 2.8 | 3.0 | 3.0 |
| $\sigma^0_{had}$ [nb] | 0.057 | 0.069 | 0.054 | 0.055 |
| $A_{FB}^{0,e}$ | 0.0034 | 0.0049 | 0.0058 | 0.0045 |
| $A_{FB}^{0,\mu}$ | 0.0024 | 0.0025 | 0.0033 | 0.0023 |
| $A_{FB}^{0,\tau}$ | 0.0028 | 0.0037 | 0.0047 | 0.0030 |

# Scaling laws for solenoids

- Green and Lorant:
  - Estimating the cost of Large Superconducting thin Solenoid magnets - 1993
  - $C(M\$)=0.4\ (BV)^{0.635}$
- Compare with CMS solenoid:
  - $B=4T,\ V=340m^3$
  - C=55M$
  - Green and Lorant estimate 39M$ 10 years earlier looks good
- Or ALEPH coil:
  - $B=1.5T,\ V=154m^3$
  - C=14M$
  - G & L gives 12.7M$ - not bad...

- Cost $\int B\,dL$ is a function of BV, but tracking performance is $BL^2$
  - Unfortunately, in practice $V \sim L^3$

# Tracking requirements

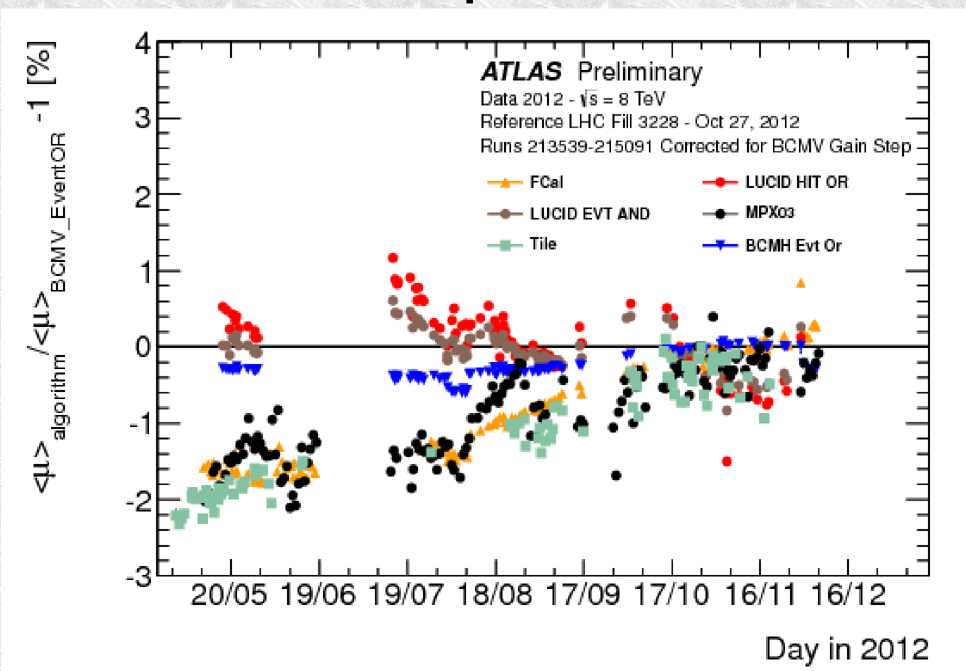
- We wish to measure a sagita, the deflection of the track from straight
- We know this: $\sigma\frac{(p_T)}{p_T}=\sqrt{3/2}\sigma_x\frac{8p_T}{0.3BL^2}$
  - The product $B.L^2$ should be maximised
- But the magnet cost is BV, $BL^3$.
- So there is a  push to large B small size solenoids
  - Hence CMS is the Compact Muon Solenoid.
- But Green has another scaling law: $t=B^2R/2\mu_0\sigma$
  - t is the coil thickness
  - Where σ is the stress in the windings and $\mu_0$ the permeability of air.
- So if the calorimetry is outside the coil there is a price for increasing field.

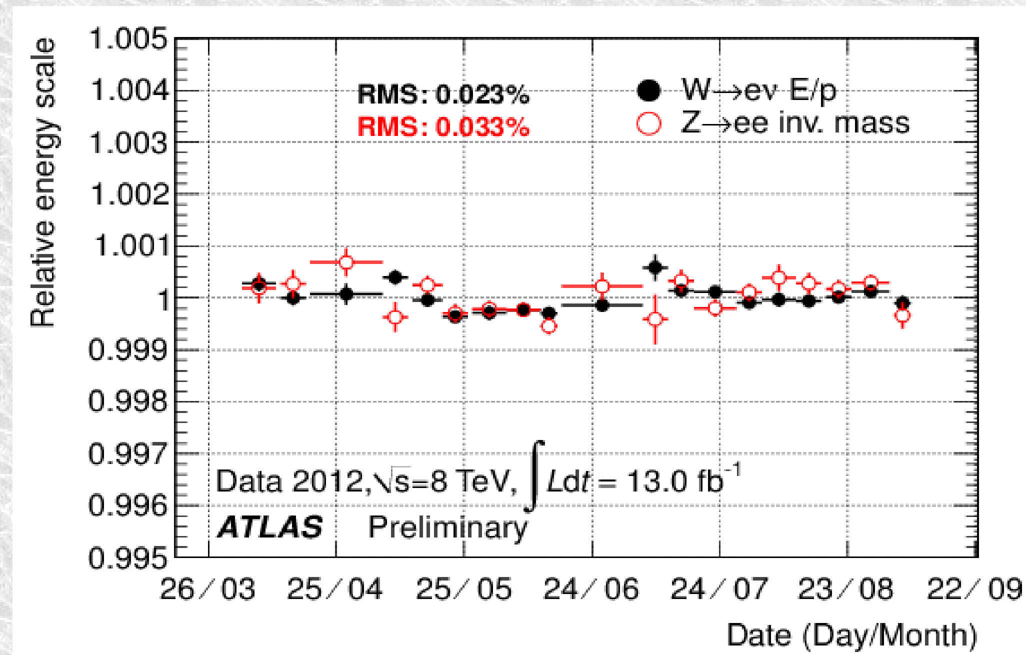
# Hadronic W from Z separation

- Sorting out W from Z hadronically is a frequently-stated goal of the calorimeter
  - Irrelevant for Z physics & WW threshold scan
  - What about HZ and tt scan?
- HZ
  - Some $10^6$ HZ expected
  - Hadronic decay modes important
  - But...W/Z separation hadronically is not key to any measurement I see.
    - Kinematic fits help resolution a lot
    - Imposing $E_{beam}$ and maybe $m_H$, $m_Z$
    - That is a lot of constraints.
- tt
  - Signature is distinct – bb plus 4 jets or lepton(s)
  - I don't see the need to reconstruct it well for m(top)

# Stability

- If we are going to measure $10^{12}$ Z we need is stability.
- Drifts of 0.1 per mille will need careful watching




- Here we see ATLAS luminosity monitors drifting 2% in 2012
- While the energy in the LAr rock solid

# Radiation: minimum

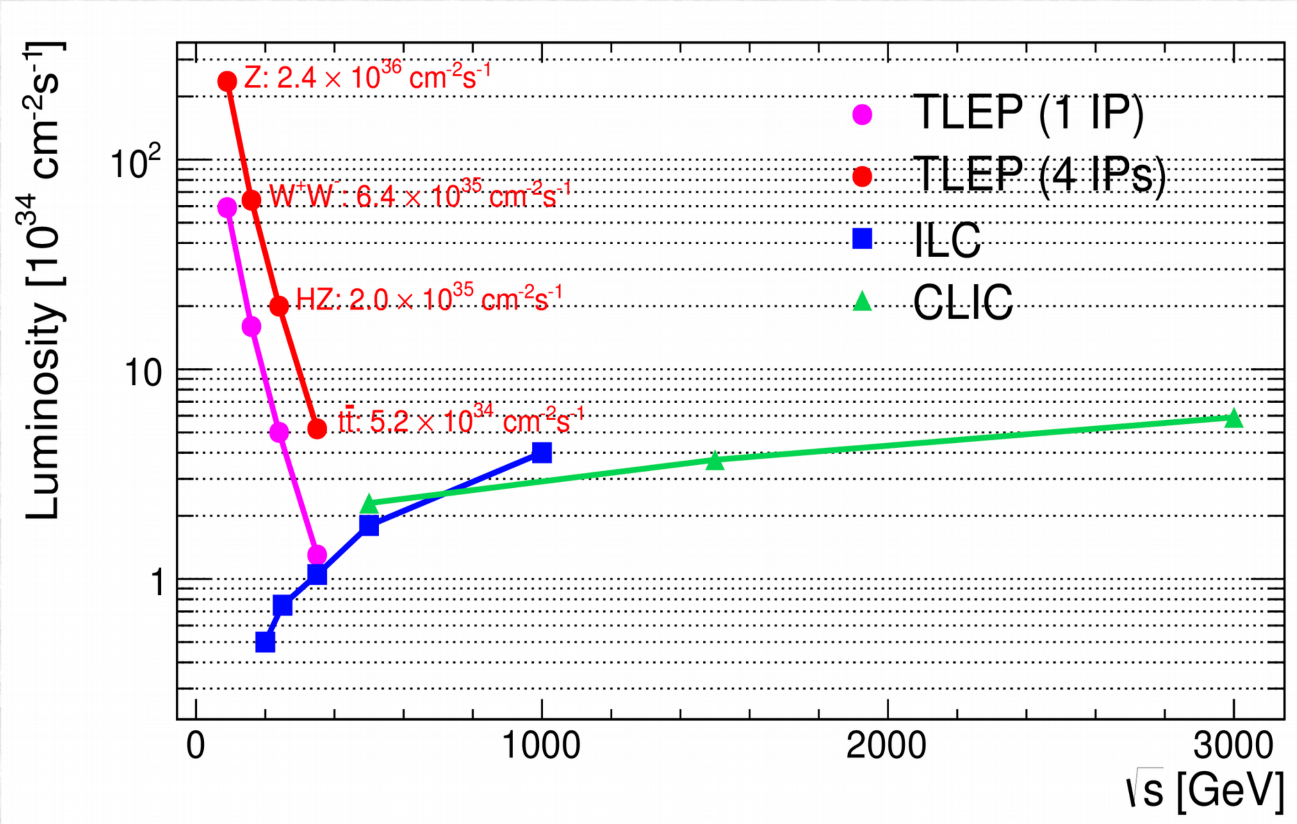
- Assume we have $10^{12}$ $Z^0$.
- Each giving some 20 charged particles,
- Impact on a sphere 16mm radius with a short beamspot
  - Area of $4\pi/3r^2 = 11cm^2$
- Some 24 charged particles per (hadronic) Z
  - Two photon rate high, multiplicity lower. Factor ~2 difference?
- 2-4 $10^{12}$ ionising particles per $cm^2$.
  - LHC detectors already designed for $10^{15}/cm^2$
  - Physics rate is not a problem
- Need to worry about machine backgrounds of course!

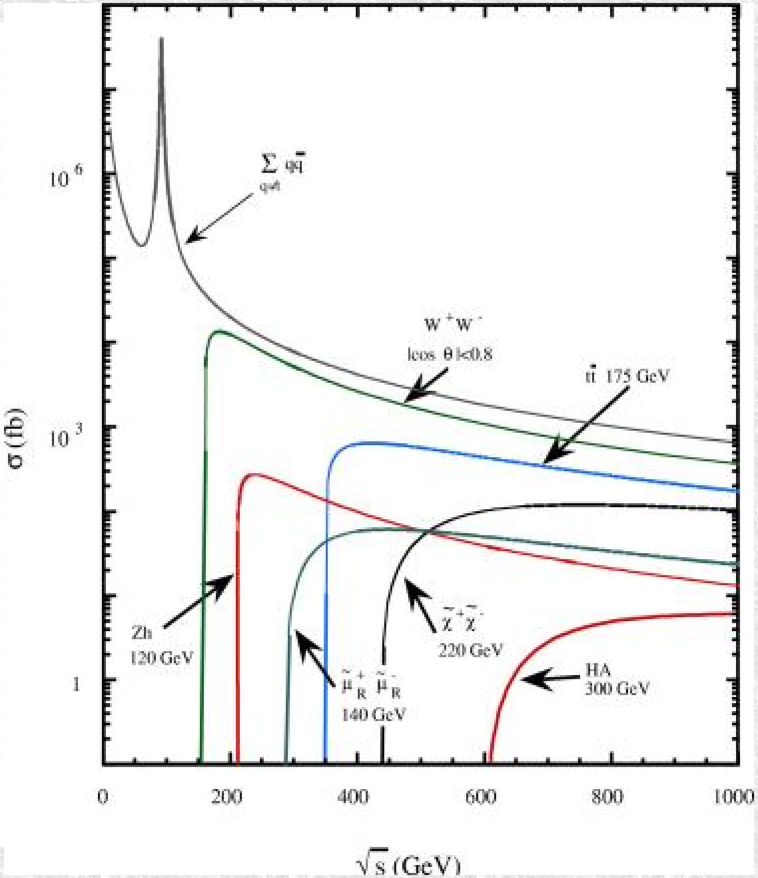
# Proposal

- Push all the calorimetry outside the coil
  - Drops radius by 40%, volume by factor 5
    - Coil 1/5 previous price
    - But still gives all the tracking you wanted
- Abandon the finely-segmented ECAL
  - Go for robust, reliable solution
  - LAr has a lot to recommend it
    - But a crystal (or lead glass) calorimeter could be good too.
  - You can reduce this cost hugely.
- Spend your money on an excellent vertex detector
  - Plus some high resolution tracking  at mid and high radius.
- But an excellent Lumi monitor
  - You can use the Tunsten+silicon there if you have enthusiasts

# The luminosity: radiation impact

- The cross-section is maximum at Z peak, so is the luminosity



# Conclusion/Prejudice

- Multiple detectors keeps physicists happy
- It need not be expensive.
- Make sure you get the detector you need, not the one someone wants to sell you.
- I may be barking up the wrong tree
  - But its a very expensive one.
  - We should do proper simulation of cheaper detectors.